Tevatron Results on the Search for a High Mass Higgs Boson

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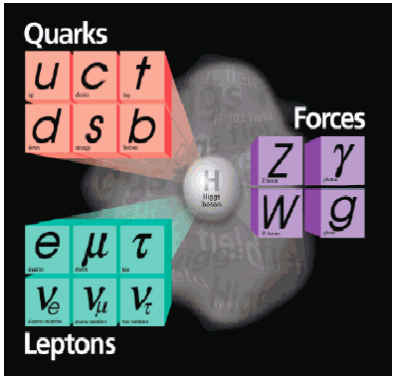
The Higgs boson in a nutshell

Fundamental interest :

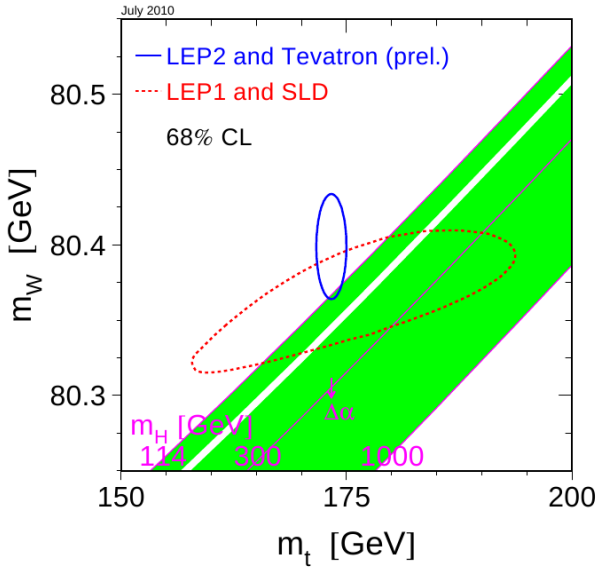
The Higgs boson is the relic particle of the Electroweak symmetry breaking :

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{em}$$

(Lagrangien symmetry) (Vacuum symmetry)



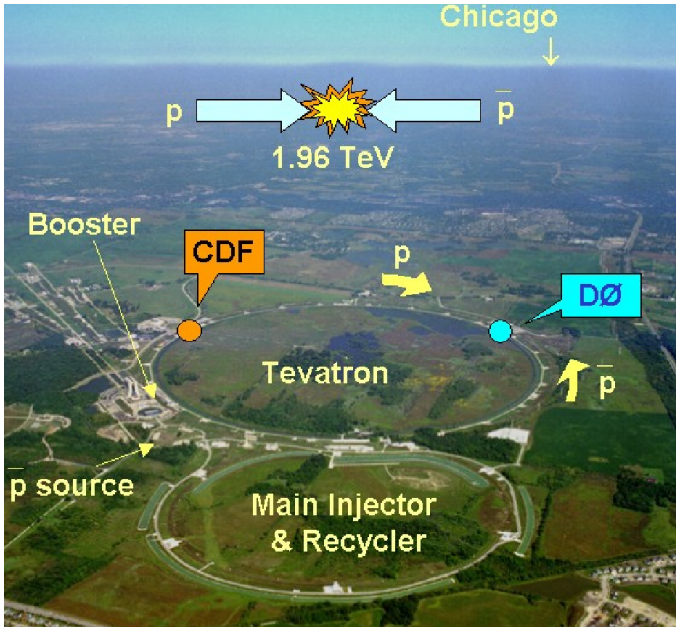
What do we know about the Higgs boson ?

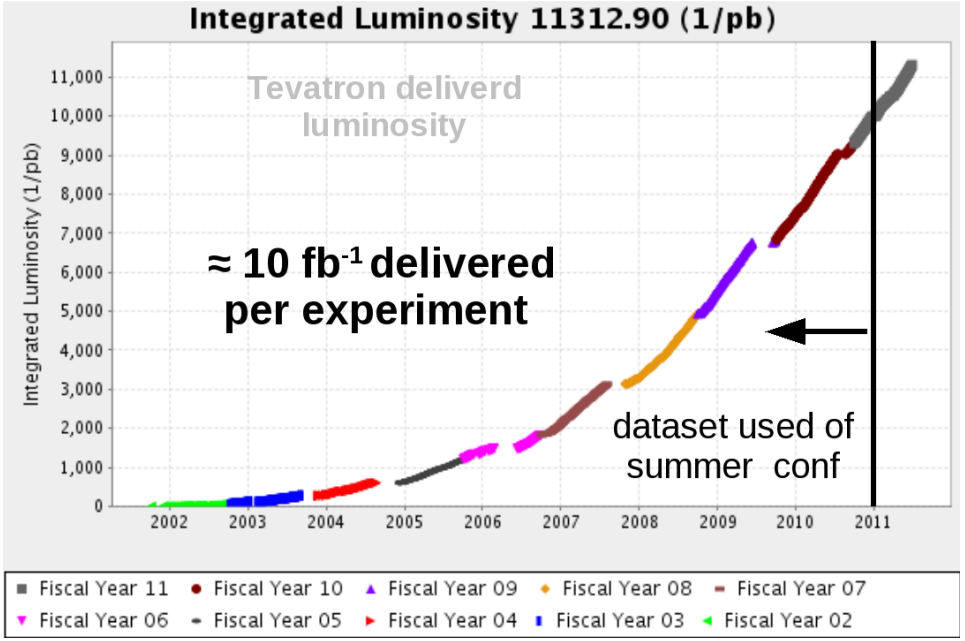


If the Higgs boson exists, a light mass is favoured from EW precision measurements

It can be produced at a sufficient rate at the Tevatron !

The Tevatron collider





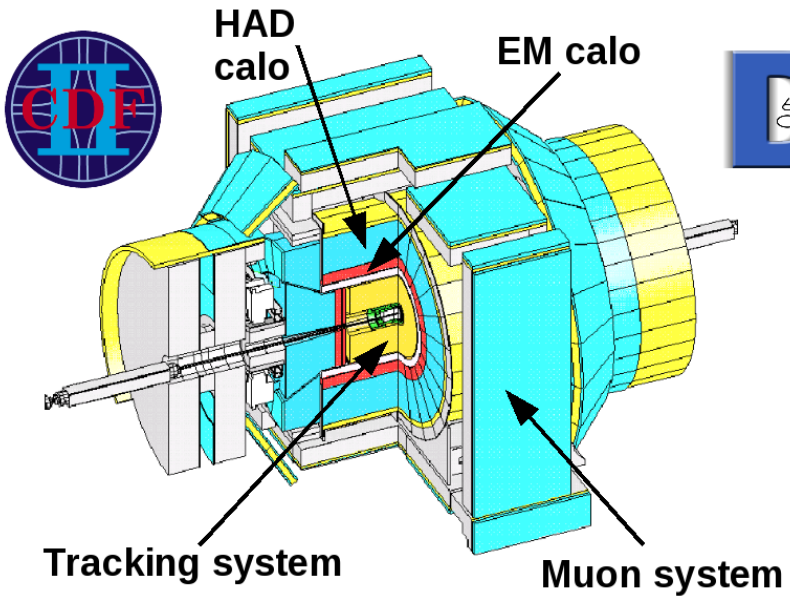
Fermilab collider :

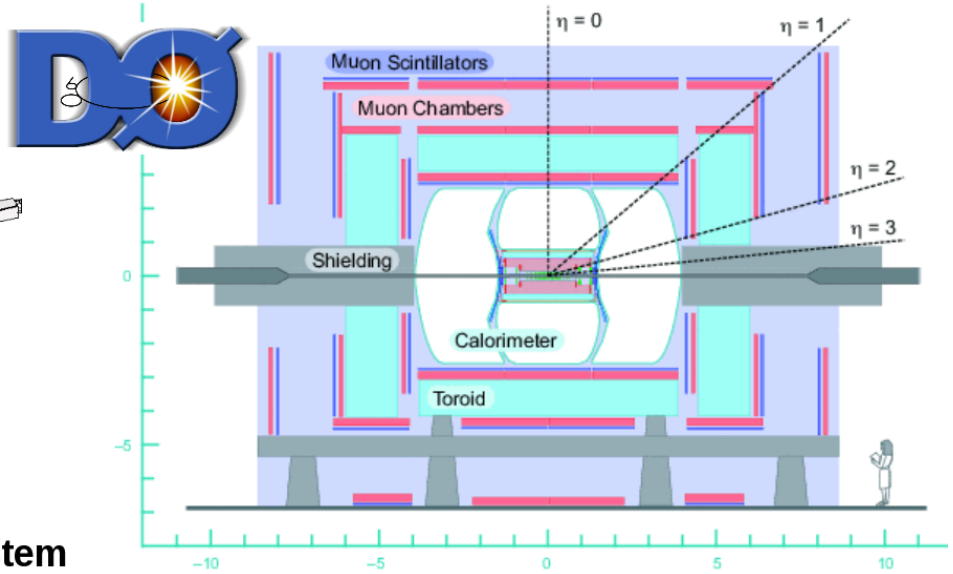
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- $\mathcal{L}_{\max} \sim 400\ \mu b^{-1}\ s^{-1}$

Two interaction points with detectors
CDF & DØ

The CDF and DØ experiments

Multi purposes detectors with large angular coverage





- Tracker $|\eta| < 2 - 2.5$
- Calorimeter $|\eta| < 3.6$
- Muon chambers $|\eta| < 1.5$

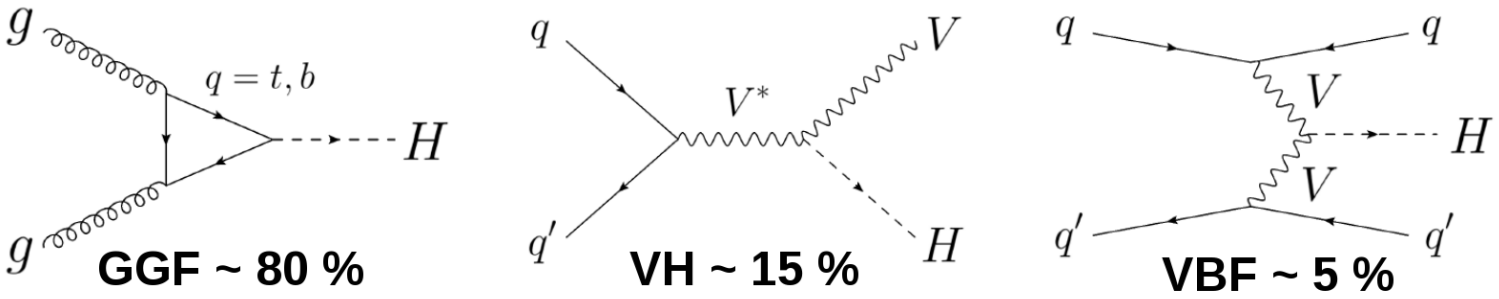
- Tracker $|\eta| < 1.7 - 3$
- Calorimeter $|\eta| < 4$
- Muon chambers $|\eta| < 2$

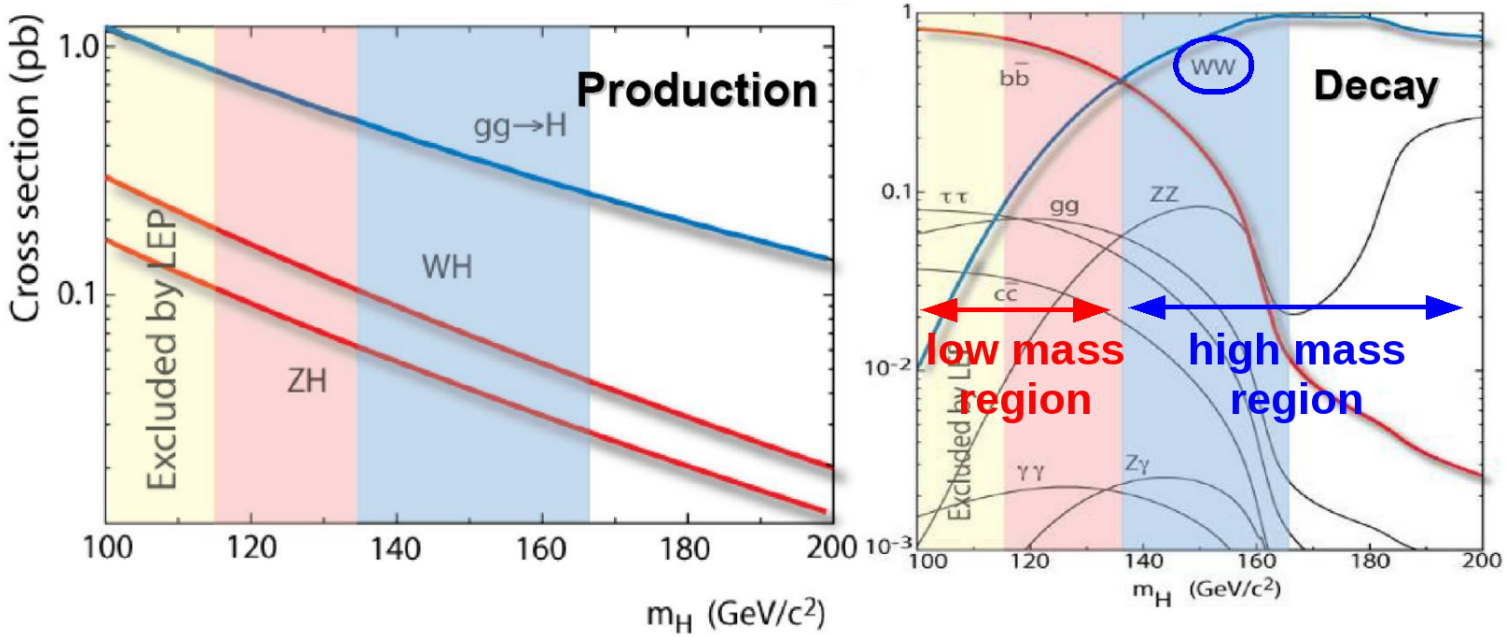
Overview

1. **Introduction**
   - Phenomenology at the Tevatron and strategy overview
   - Background for the WW final state
   - State of the art in Winter 2011 & news
2. **Description of the search in each final state**
   - Dileptons events
   - Single leptonic events
   - Events with τ lepton
   - Same sign leptons and trileptons events
3. **Upper limit on Higgs boson production at Tevatron**
   - In the Standard Model
   - In a fourth fermion generation model

Higgs boson production at Tevatron

$\sigma_{p\bar{p}\to H} \approx 0.2 - 1.3$ pb

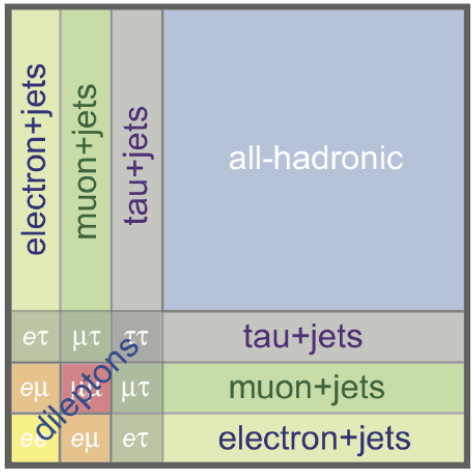




For $m_H \gtrsim 135$ GeV : final state determined by WW decays

Hadrons collisions : need of leptonic and/or MET signature

W Branching Fractions



Relevant final states to exploit $gg \to H$:

- dilepton $(e, \mu) + (e, \mu)$, $\mathcal{BR} \sim 6\%$
  lowest bkg : most sensitive final state
- single lepton $(e, \mu) + qq'$, $\mathcal{BR} \sim 30\%$
  more signal ($\times 5$) but larger bkg
- with τ lepton $(e, \mu) + \tau_{\text{had}}$, $\mathcal{BR} \sim 4\%$
  larger bkg (τ_{had}), additional sensitivity

$\sim 1\%$

S/B

$\sim 0.1\%$

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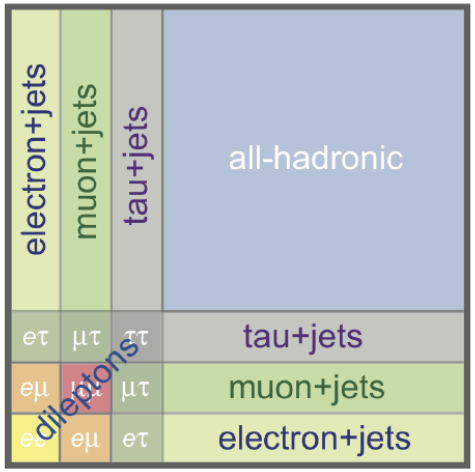

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Exploiting the associated production :

- $WH \to WWW \Rightarrow$ same sign leptons
- $ZH \to ZWW \Rightarrow$ trileptons

small $\sigma \times \mathcal{BR}$ but very low SM bkg

Hadrons collisions : need of leptonic and/or MET signature

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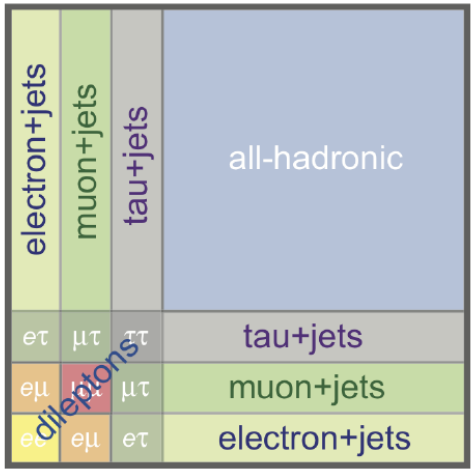

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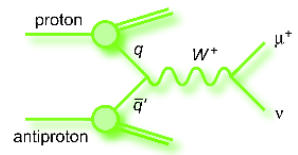
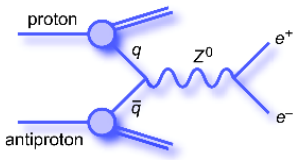
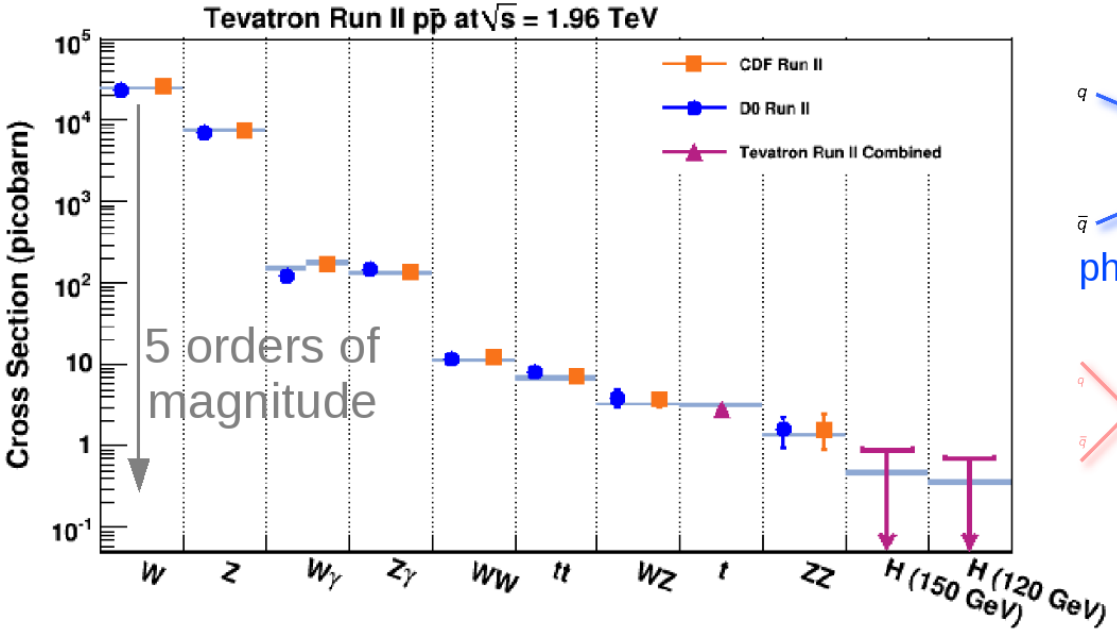
Strategy

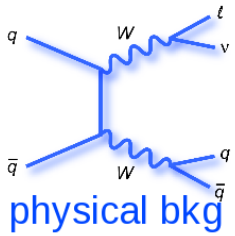
- Low S/B ratio at final selection : cut based analysis not sufficient,
- Improve sensitivity by exploiting signal/bkg event differences (kinematic, topology, ...) in MVA,
- Divide the search in many sub-channels.

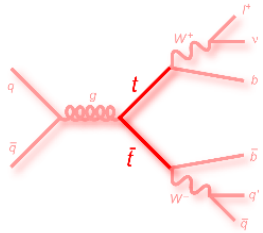
Background for the WW final state











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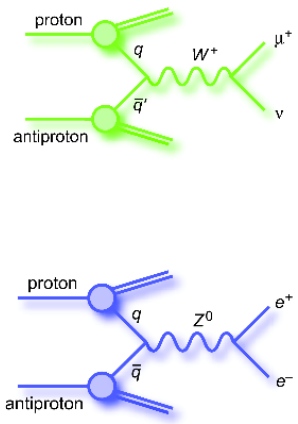
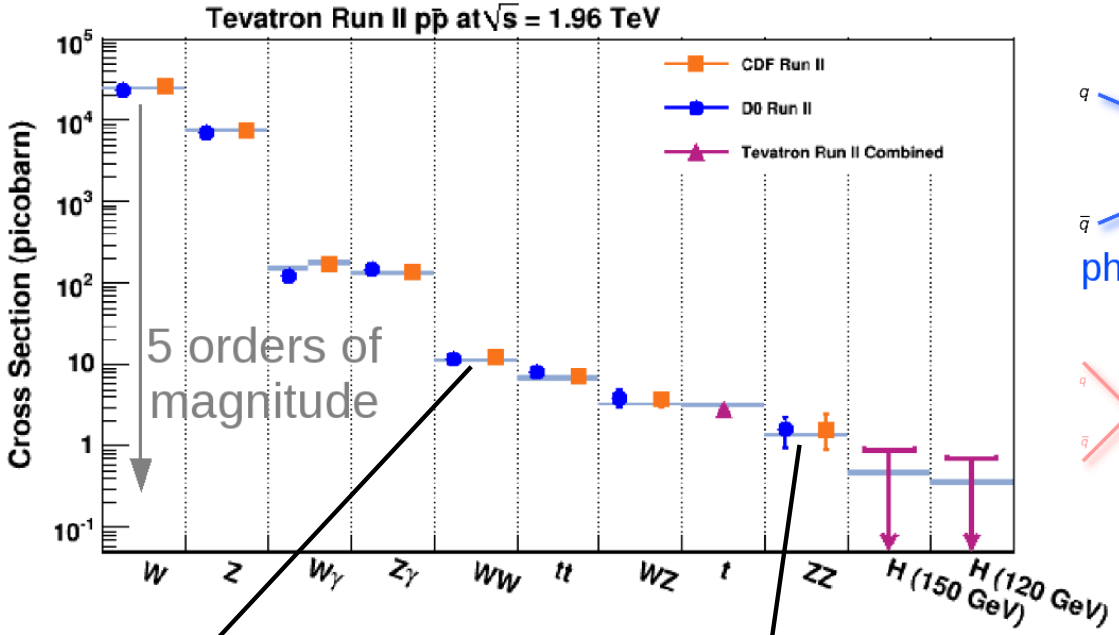
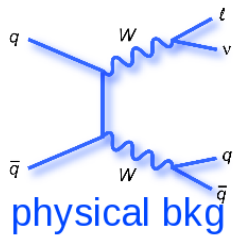
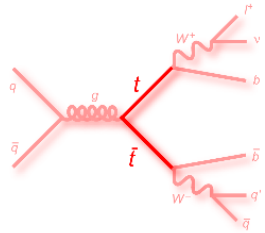
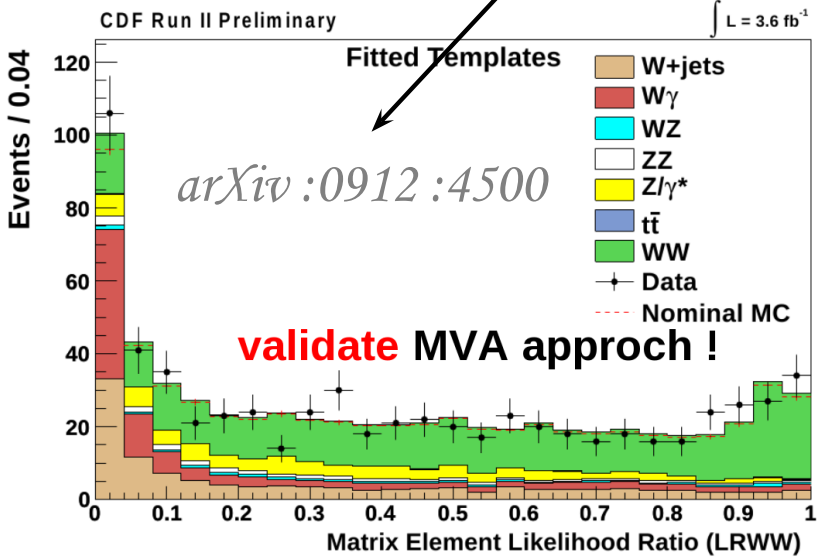
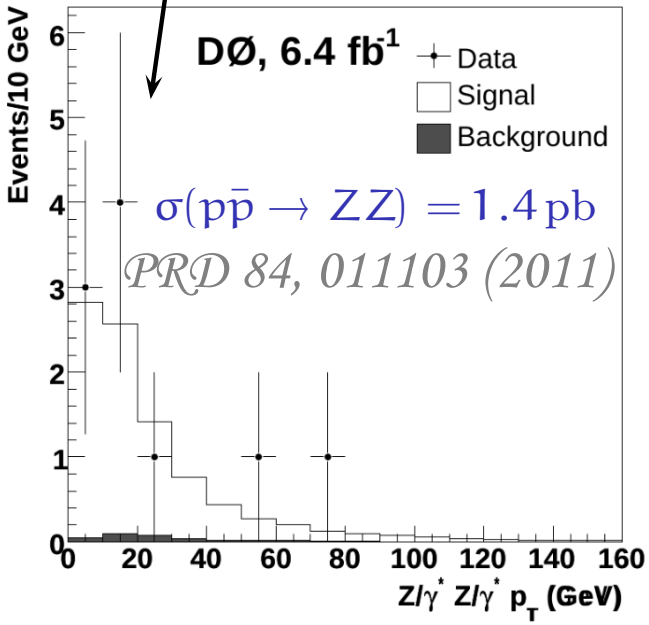


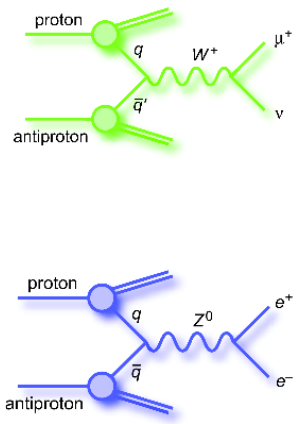


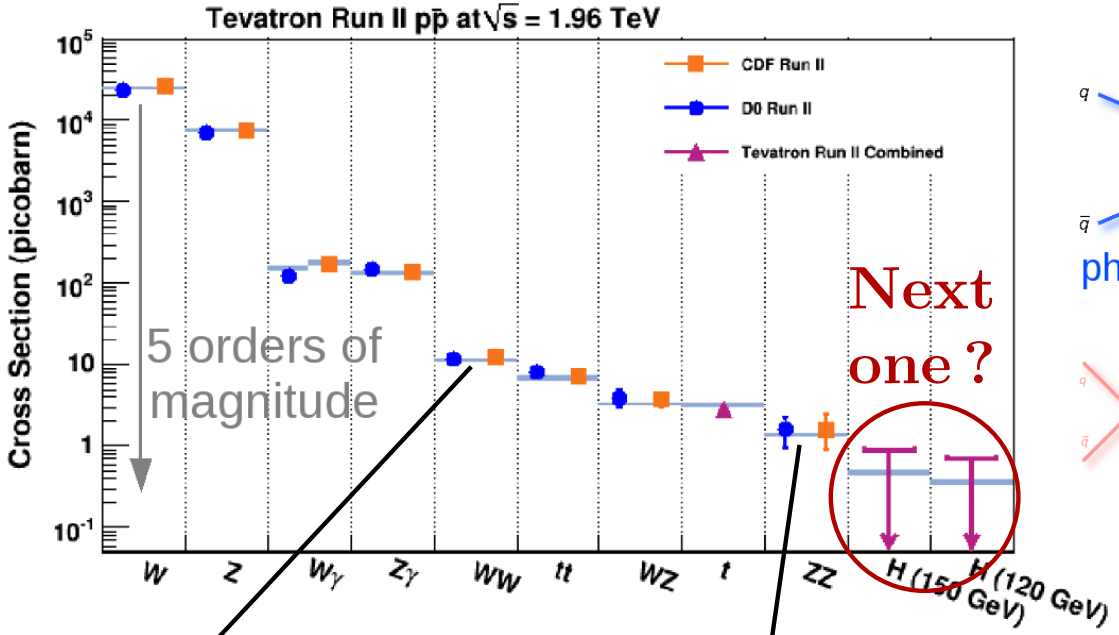


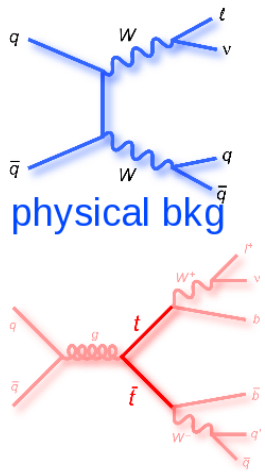


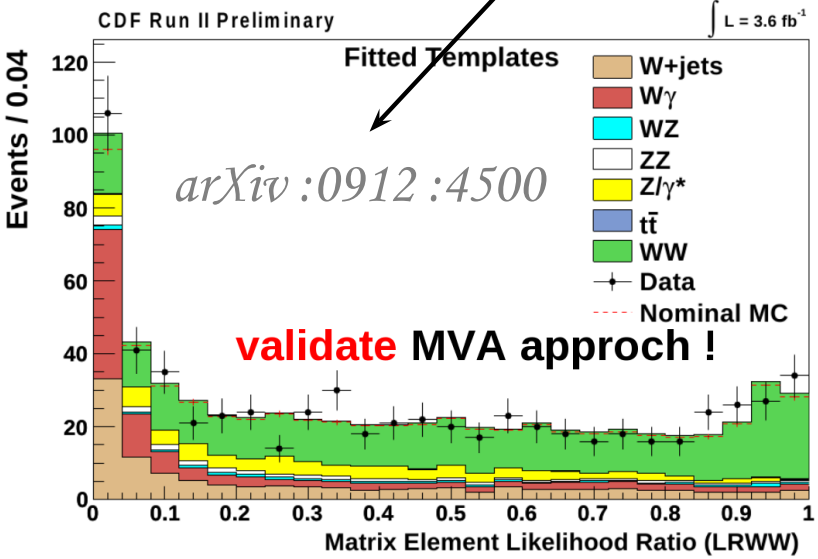


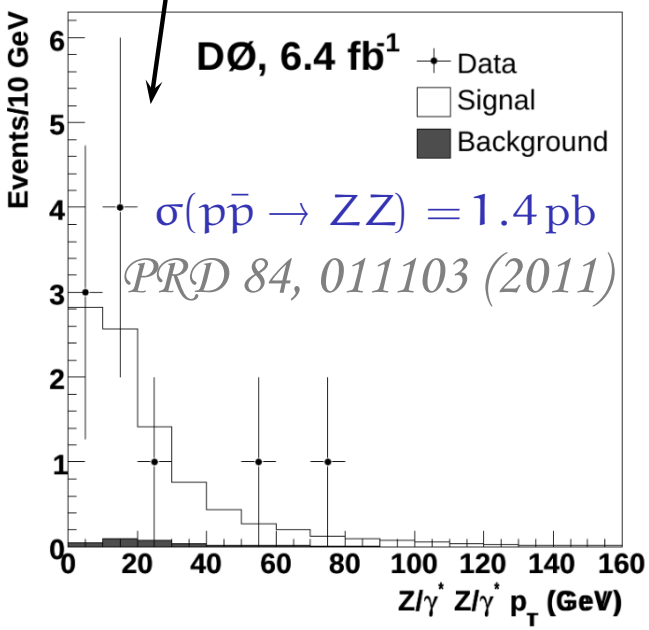



proton
antiproton
proton
antiproton

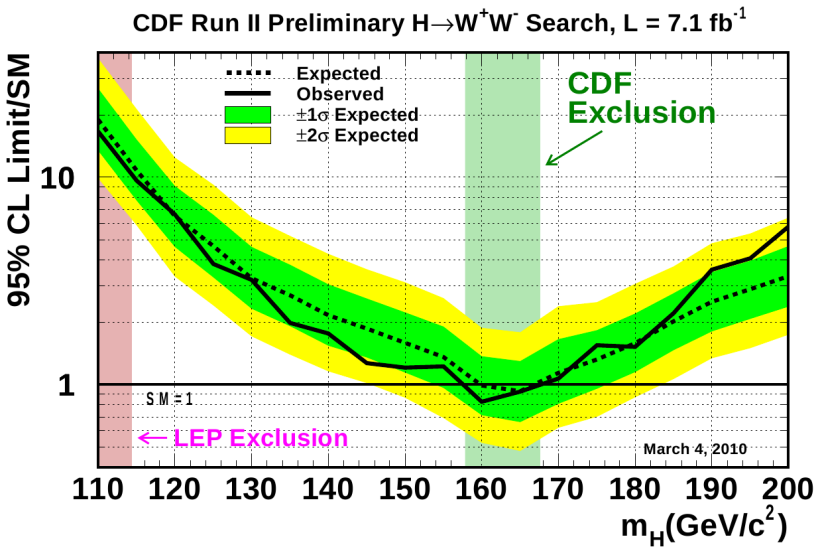

Tevatron Run II pp̄ at √s = 1.96 TeV
Cross Section (picobarn)
CDF Run II
D0 Run II
Tevatron Run II Combined
5 orders of magnitude
Next one ?
W
Z
Wγ
Zγ
WW
tt
WZ
t
ZZ
H (150 GeV)
H (120 GeV)


physical bkg

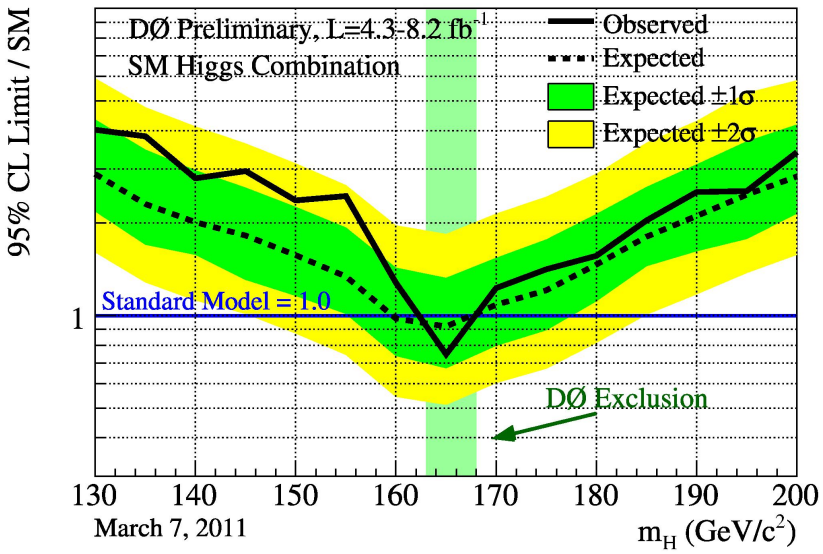

CDF Run II Preliminary
∫ L = 3.6 fb⁻¹
Fitted Templates
W+jets
Wγ
WZ
ZZ
Z/γ*
tt̄
WW
Data
Nominal MC
Events / 0.04
arXiv :0912 :4500
validate MVA approch !
Matrix Element Likelihood Ratio (LRWW)


DØ, 6.4 fb⁻¹
Data
Signal
Background
Events/10 GeV
σ(pp̄ → ZZ) = 1.4 pb
PRD 84, 011103 (2011)
Z/γ* Z/γ* p_T (GeV)

State of the art in Winter 2011



CDF : single experiment exclusion
($158 < m_H < 168$ GeV at 95% C.L.)
$(\Delta m)^{excl} \sim 10$ GeV



DØ : single experiment exclusion
($163 < m_H < 168$ GeV at 95% C.L.)
$(\Delta m)^{excl} \sim 5$ GeV

Can we extend this excluded mass window ?

Main updates :

- **CDF** : 7.1 $fb^{-1} \rightarrow$ 8.2 fb^{-1}, acceptance gain (lepton ID & triggers), add $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ channel,
- **DØ** : same data sample but selection optimizations
- **Both** : updated theoretical predictions of $\sigma_{p\bar{p}\rightarrow H} \times \mathcal{BR}$

Channels	CDF	DØ
dileptonic final state ($H \rightarrow WW \rightarrow \ell\nu\ell\nu$)		
$\ell = e, \mu + 0, 1, \geq 2$ jets	8.2 fb^{-1}	8.1 fb^{-1}
$\ell = e, \mu + 0, 1, \geq 2$ jets, low $M_{\ell\ell}$	8.2 fb^{-1}	-
single leptonic final state ($H \rightarrow WW \rightarrow \ell\nu q q'$)		
$\ell = e, \mu + 2$ jets	-	5.4 fb^{-1}
τ lepton final state ($H \rightarrow WW \rightarrow \ell\nu\tau\nu$)		
$\ell = e, \mu + \tau_{had}$	8.2 fb^{-1}	7.3 fb^{-1} (μ only)
$\ell = e, \mu + \tau_{had} + \geq 2$ jets	-	4.3 fb^{-1}
Associated production ($VH \rightarrow VWW$)		
Same Sign dilepton	8.2 fb^{-1}	5.3 fb^{-1}
Trilepton	8.2 fb^{-1}	-
$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$		
$\ell = e, \mu$	8.2 fb^{-1}	-

Overview

$H \rightarrow WW \rightarrow \ell\nu\ell\nu \ (\ell = e, \mu)$

Event topology :

- 2 opposite sign isolated leptons of high p_T (reduce Wjets and MJ bkg)
- Missing transverse energy due to neutrinos (reduce Z/γ^*+jets bkg).

$H \to WW \to \ell\nu\ell\nu$ $(\ell = e, \mu)$

Event topology :

- 2 opposite sign isolated leptons of high p_T (reduce Wjets and MJ bkg)
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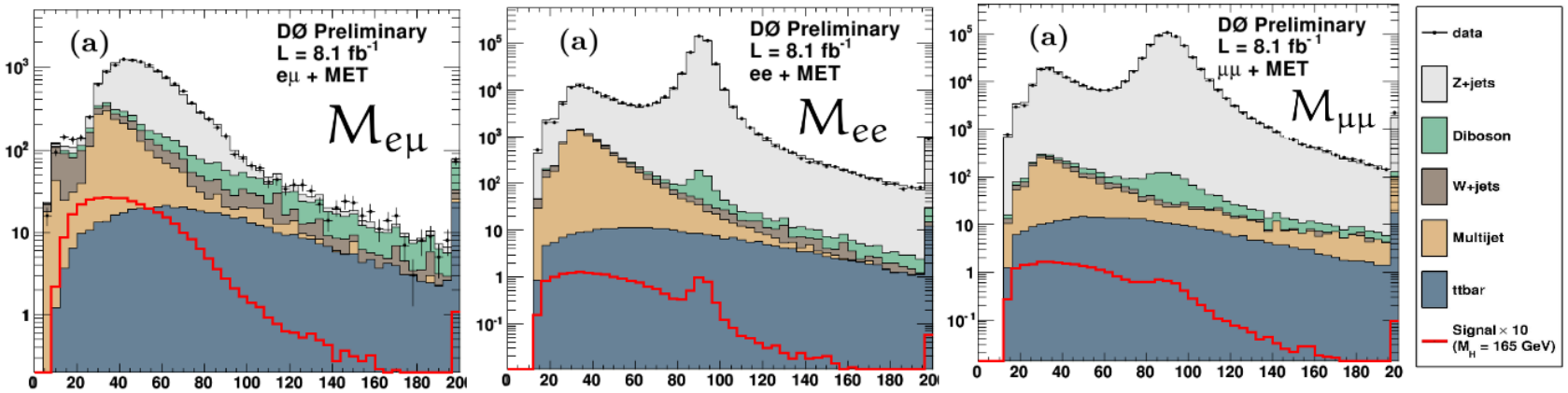
First sample splitting :

- DØ : lepton flavour, $ee, e\mu, \mu\mu$
- CDF : lepton flavour and quality criteria

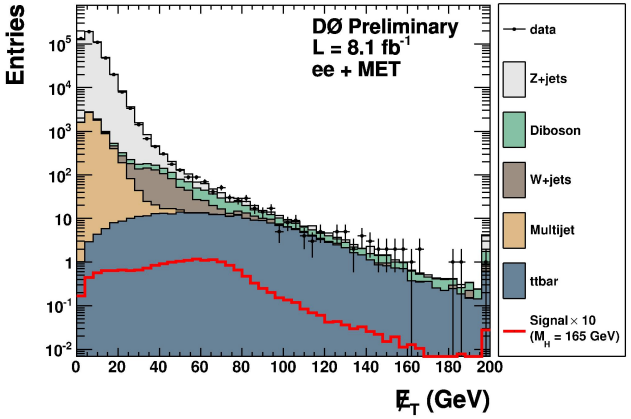
$\Longrightarrow$ samples of low and high S/B due to different efficiencies and resolutions



$H \to WW \to \ell\nu\ell\nu$ ($\ell = e, \mu$)

Final selections : remove the Z/γ^*+jets bkg

- CDF : select events with large missing transverse energy
- DØ : BDT to reject DY events based on several MET related variables



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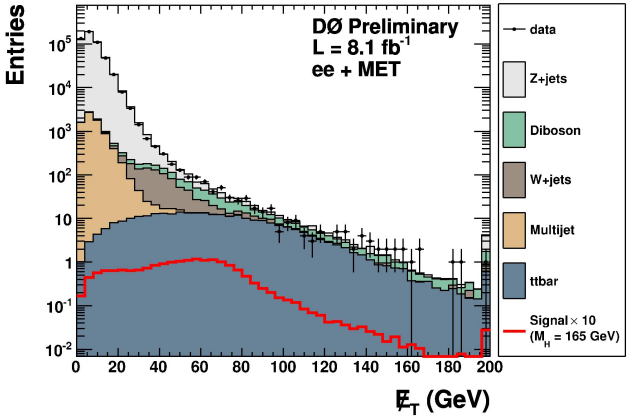
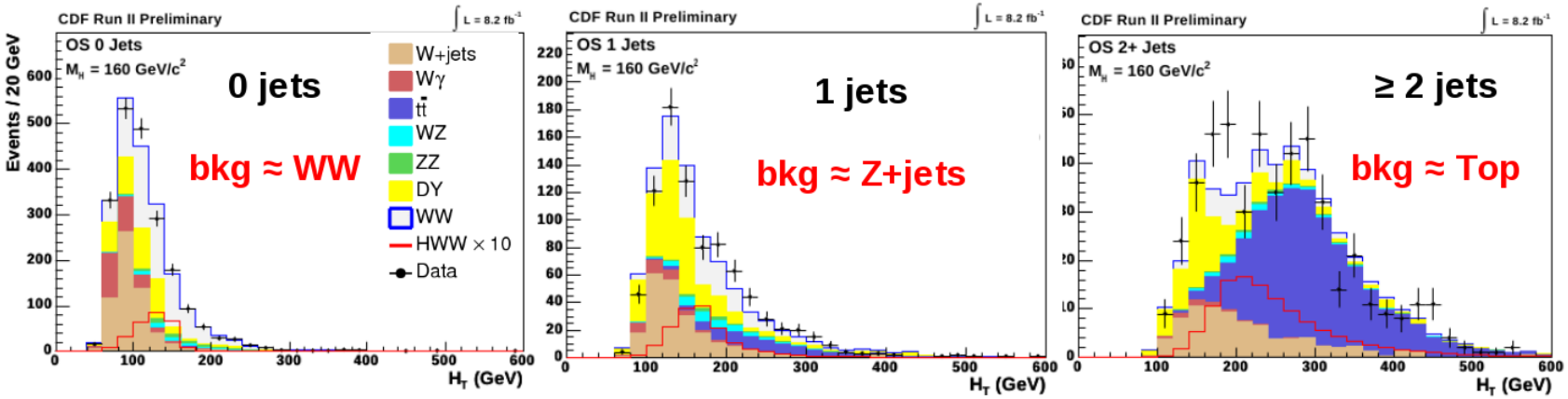
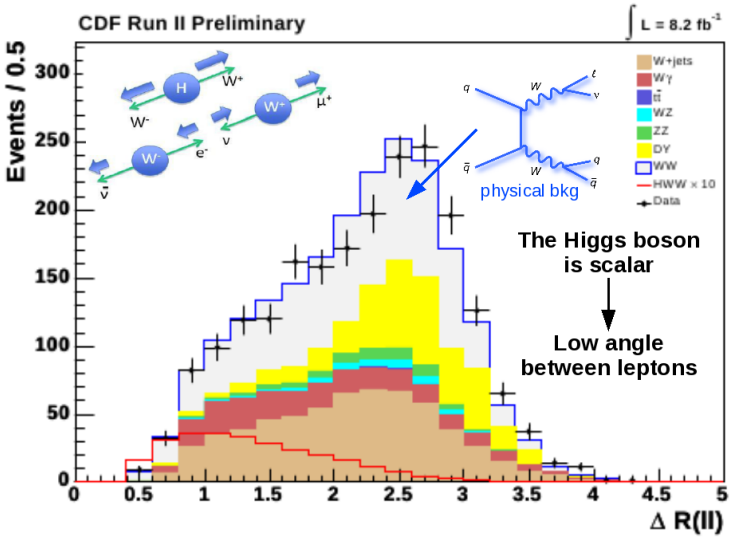


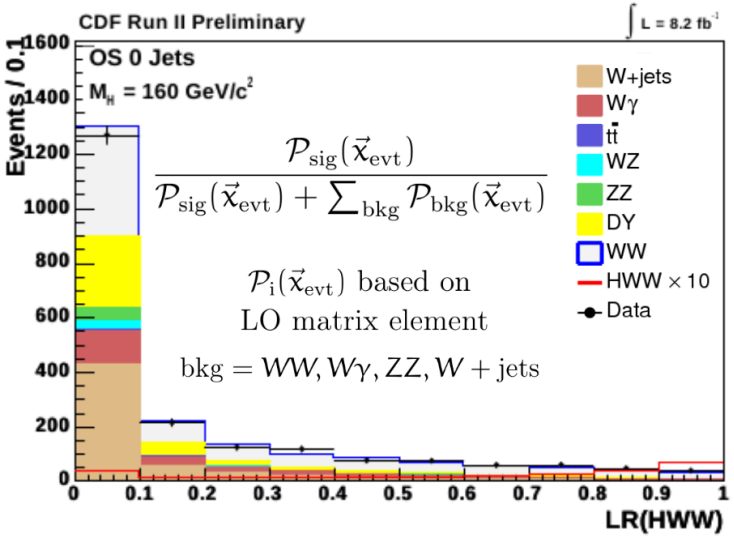
Second sample splitting : based on jet multiplicity
$\Longrightarrow$ optimisation of sig/bkg differences for specific bkg composition



S/B ~ 1.3 % S/B ~ 1.8 % S/B ~ 2.5 %

Sophisticated signal extraction : against instrumental and physical bkg





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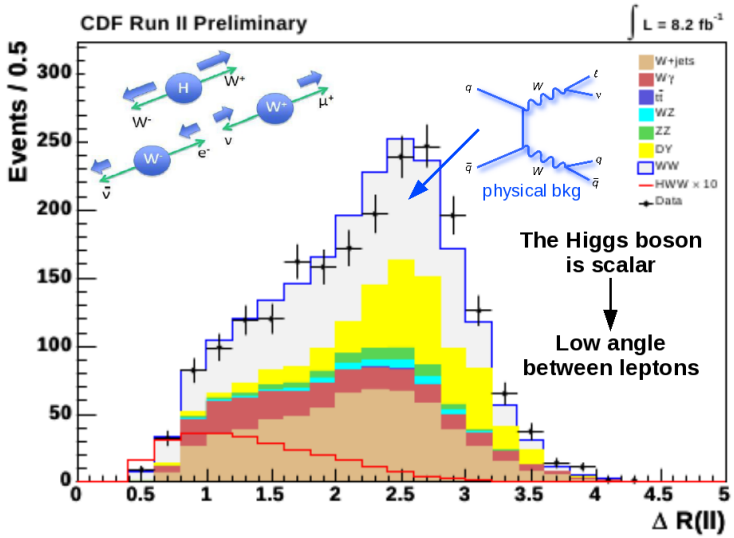
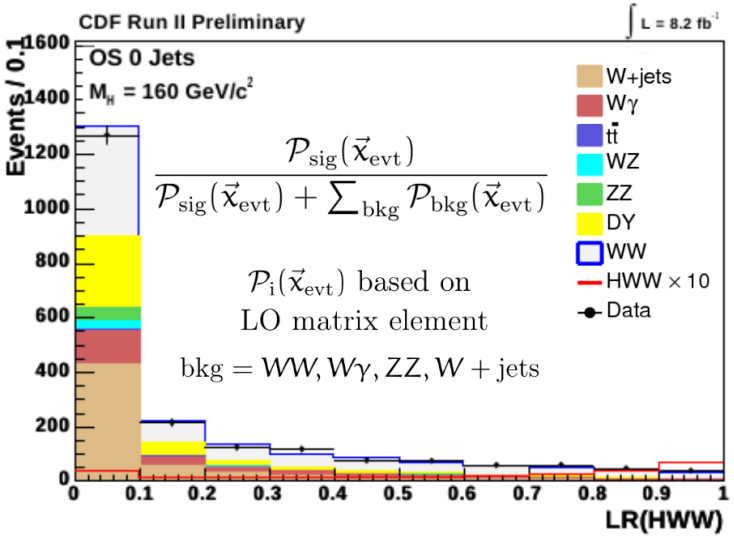
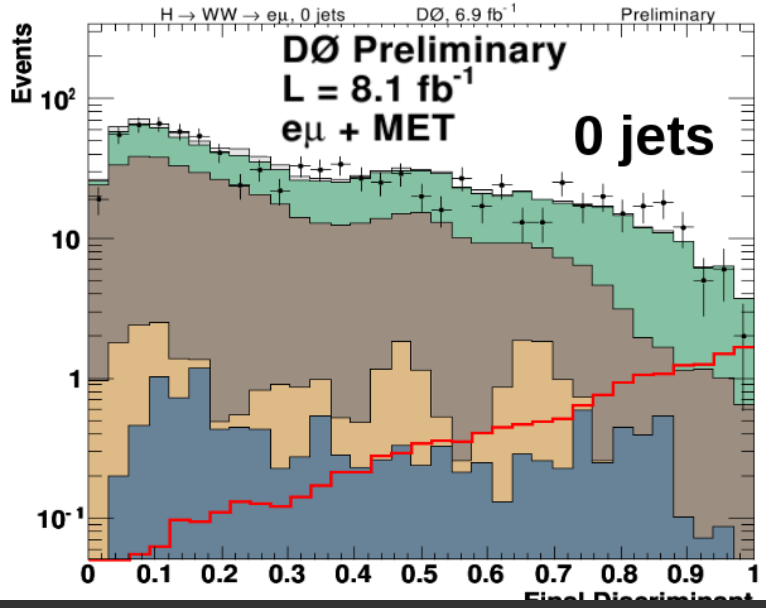
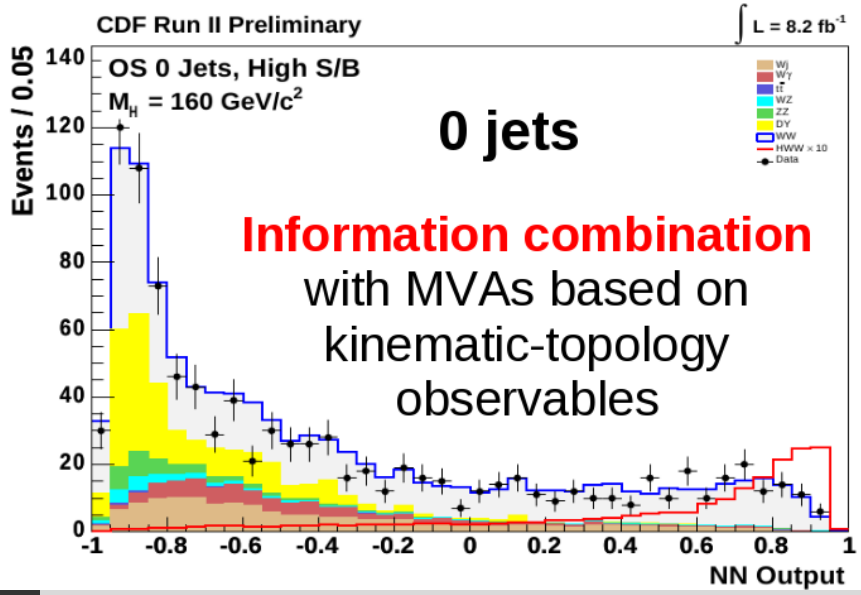




Final discriminant : used to derive upper limit on $(\sigma \times \mathcal{BR})_H$





Overview

$H \to WW \to \ell\nu qq'$ ($\ell = e, \mu$)

Phys. Rev. Lett. 106, 171802 (2011)

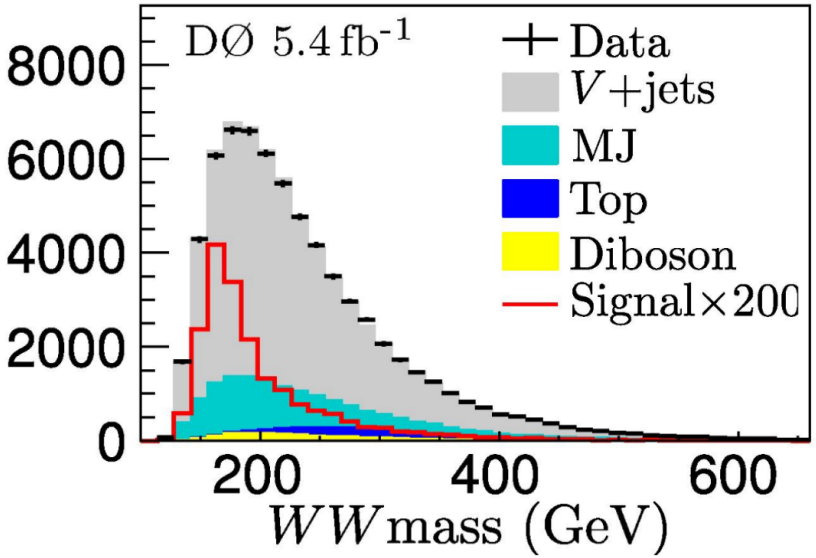
Selections

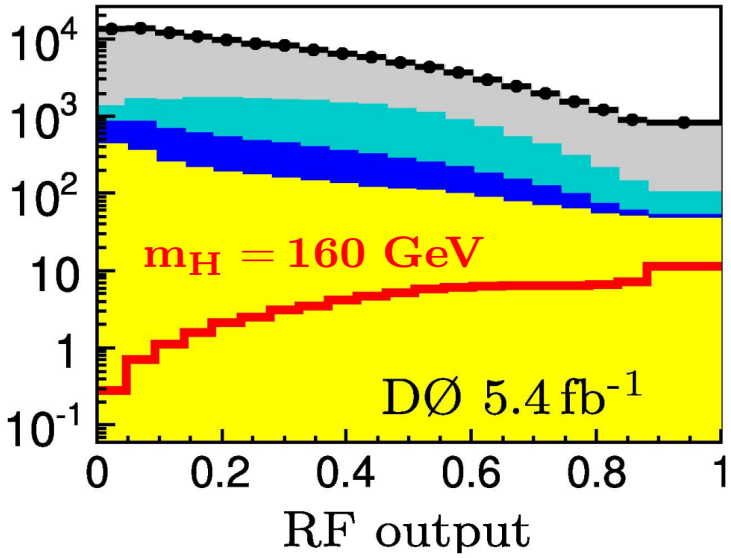
- one isolated high p_T lepton
- at least 2 jets and missing transverse energy due to neutrino

$\Longrightarrow$ main bkg W+jets ($\sigma_{W+\text{jets}} \sim 10^5\, \sigma_H$)

Kinematic

- full reconstruction of $\vec{p}_\nu$ thanks to $(p_\nu + p_\ell)^2 = m_W^2$
- from full W's reco : possible extraction of $m_H = \sqrt{(p_{W_1} + p_{W_2})^2}$





Overview

$H \to WW \to \ell\nu\,\tau\nu \;\; (\ell = e, \mu)$

Reconstruction of hadronic τ lepton

- challenging at hadrons collider : large contamination from jets
- sophistocated algo based on calorimeter and tracking signatures

$H \to WW \to \ell\nu\tau\nu$ $(\ell = e, \mu)$

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Strategy to complete the Higgs boson search

- **CDF** : exploit $\ell + \tau$ inclusively, mainly sensitive to $H \to WW \to \ell\nu\tau\nu$
- **DØ** : exclusive analysis according to the number of reconstructed jets
  - $\ell + \tau + 0, 1$ jet ($\ell = \mu$ only) mainly sensitive to $H \to WW \to \ell\nu\tau\nu$
  - $\tau_\ell + \tau + \geq 2$ jets allows to benefit from

$H \to WW \to \ell\nu\tau\nu$ $(\ell = e, \mu)$

Reconstruction of hadronic τ lepton

- challenging at hadrons collider : large contamination from jets
- sophistocated algo based on calorimeter and tracking signatures

Strategy to complete the Higgs boson search

- **CDF** : exploit $\ell + \tau$ inclusively, mainly sensitive to $H \to WW \to \ell\nu\tau\nu$
- **DØ** : exclusive analysis according to the number of reconstructed jets
  - $\ell + \tau + 0, 1$ jet ($\ell = \mu$ only) mainly sensitive to $H \to WW \to \ell\nu\tau\nu$
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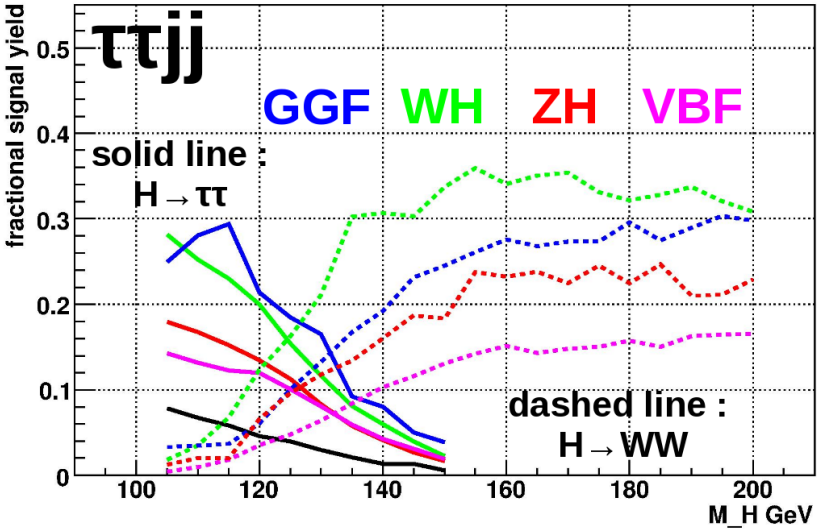
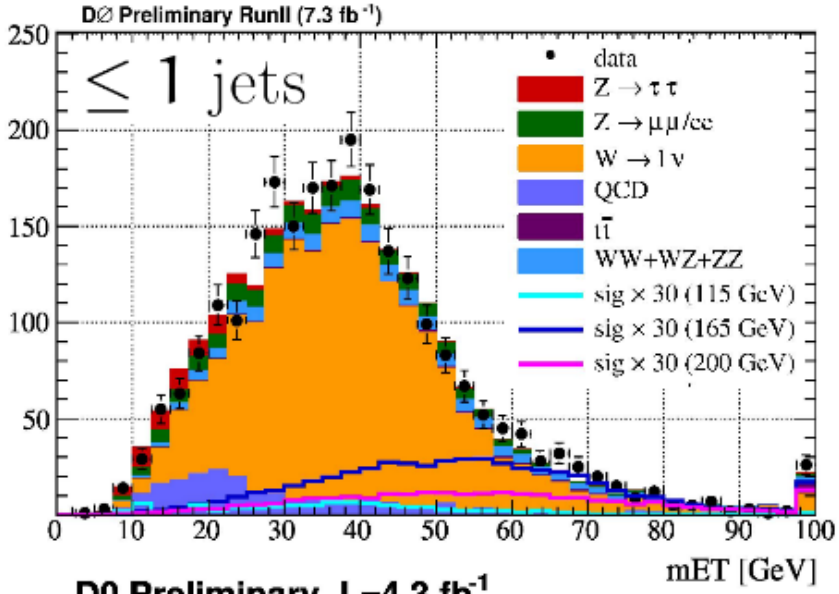
$\Rightarrow$ $H \to \tau\tau$ decay at low mass

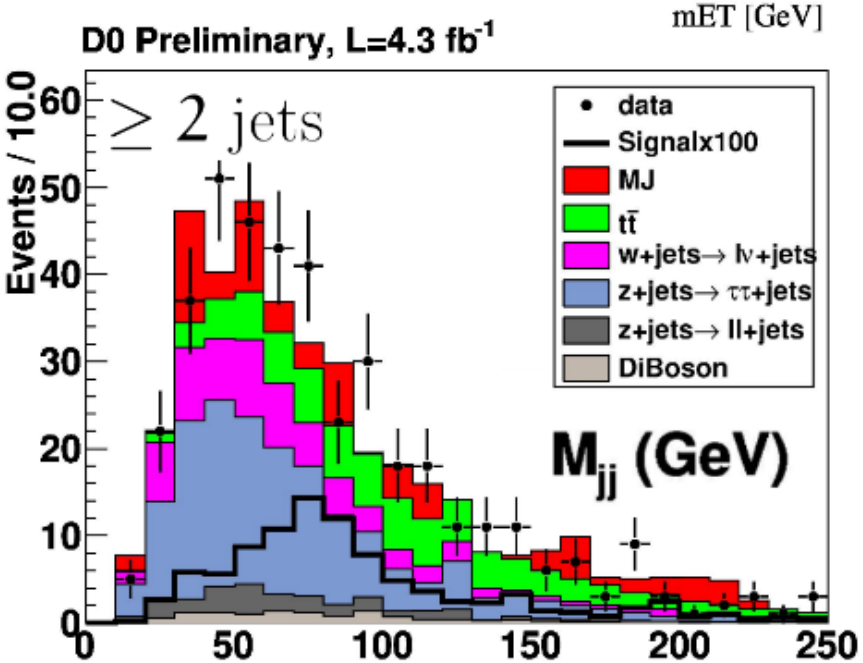
$\Rightarrow$ several production modes

providing a flat sensitivty over the whole range of mass

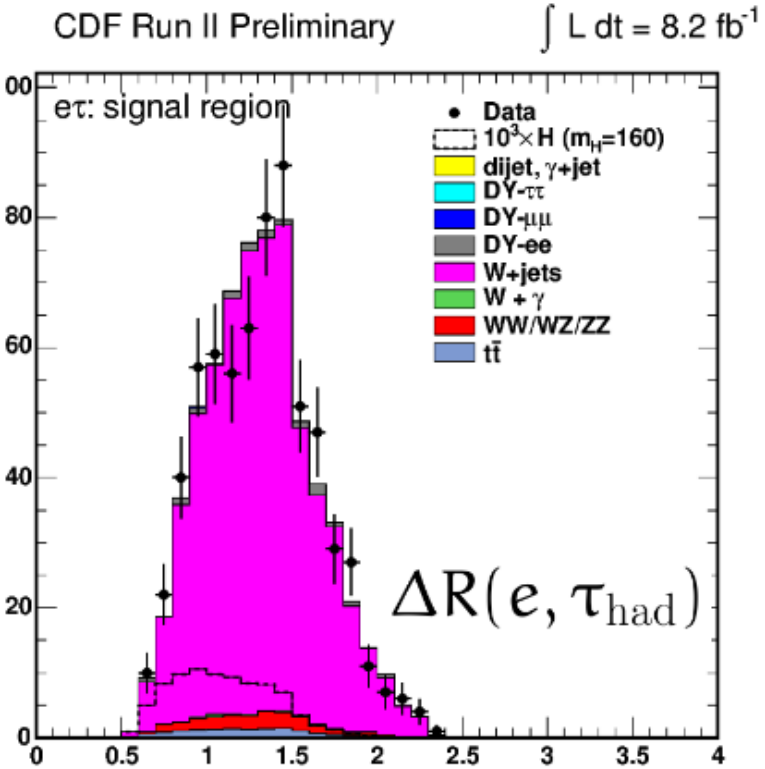


$\mu + \tau_{had}$





$e + \tau_{had}$



Overview

$VH \rightarrow VWW \rightarrow \ell^{\pm}\ell^{\pm}(\ell^{\mp})$ $(V = W, Z)$

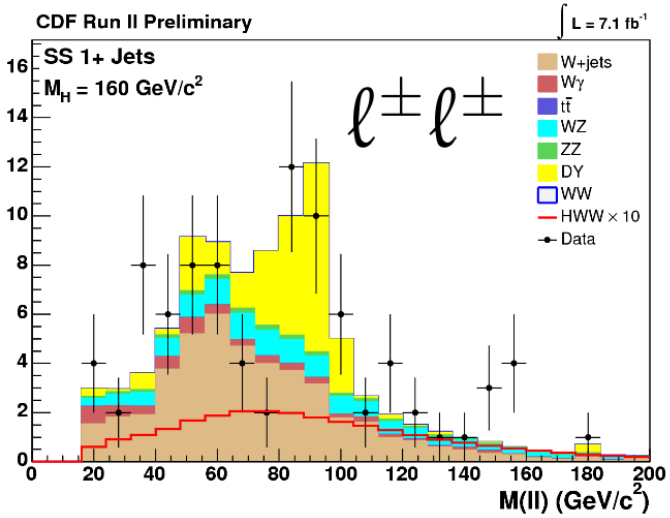
Exploit Higgs boson production in association with a vector bosons

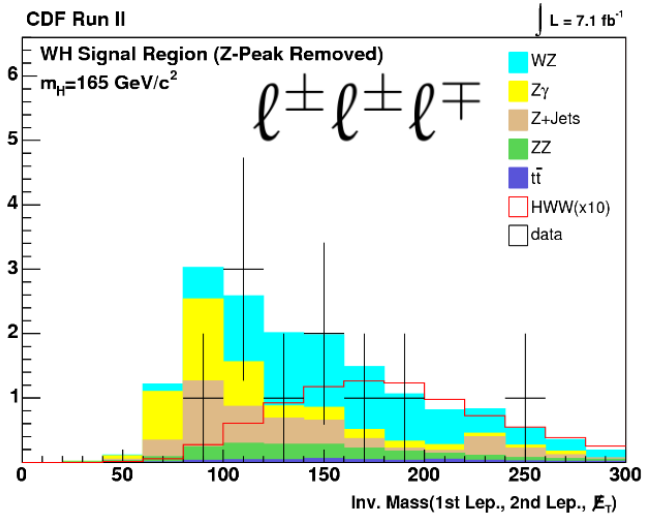
Event selection

- two same sign leptons (+ one opposit sign lepton) and missing E_T
- define a Z region with $M(\ell^{\pm}\ell^{\mp})$ between same flavor leptons

Backgrounds

- SM bkg highly supressed : dominated by WZ and ZZ production
- important instrumental bkg (charge mismeasurement)



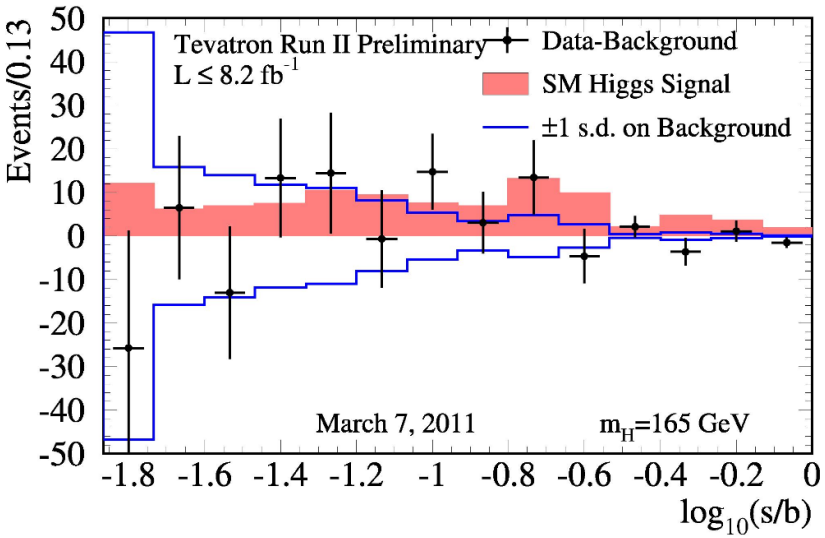


Overview

Combination and uncertainties

Channels combination

For each region of s/b, cumulate the number of events from bkg, sig and data over all the channels.



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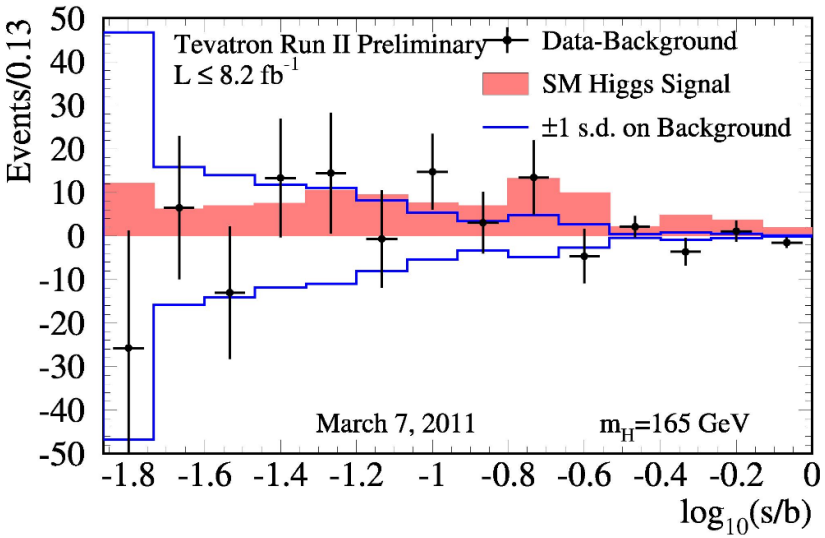

Overview of uncertainties

Exp. uncert.

- integrated luminosity 6%
- trigger efficiencies $\leq 5\%$
- ID/reco eff for leptons ($\leq 5\%$) and jets ($\leq 25\%$)

Theo. uncert. on $\sigma^{NNLO+NNLL}_{gg\to H}$

- Perturbative calculation : μ_F/μ_R variations $7-33\%$ (n_{jets}-dep.)
  JHEP 0908, 099 (2009)
  Phys. Rev. D 81, 74023 (2010)
- PDFs : follow PDF4LHC recommendations $8-30\%$ (n_{jets}-dep.)

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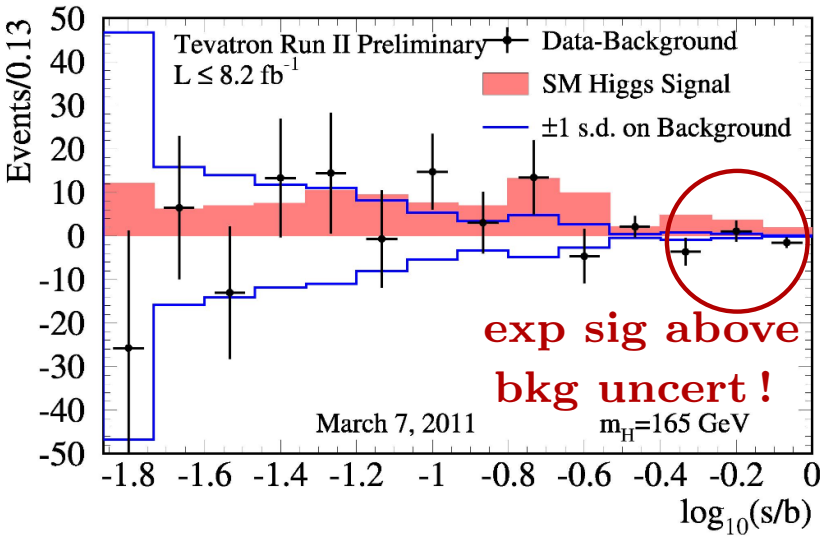

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Upper limit for the SM Higgs boson

- No excess are observed in data
- find $\sigma_{p\bar{p}\to H}/\sigma^{SM}_{p\bar{p}\to H}$ which is excluded at 95% C.L. (the probability that such an excess is due to a bkg fluctuation is 5%)

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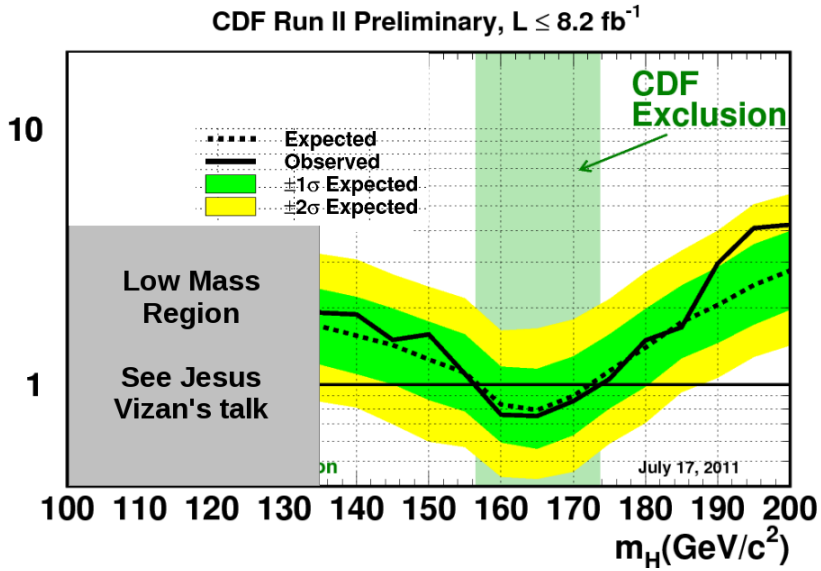
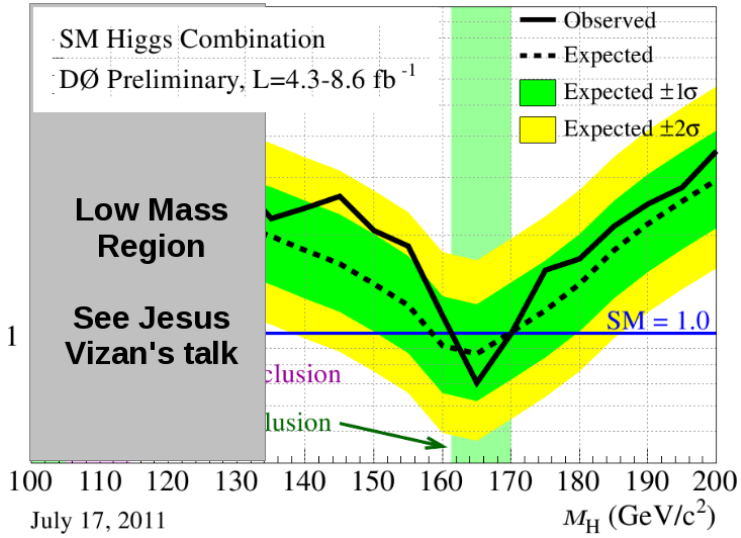


CDF : exp. exclusion
$156 < m_H < 174$ GeV
$(\Delta m)^{excl} \sim 20$ GeV

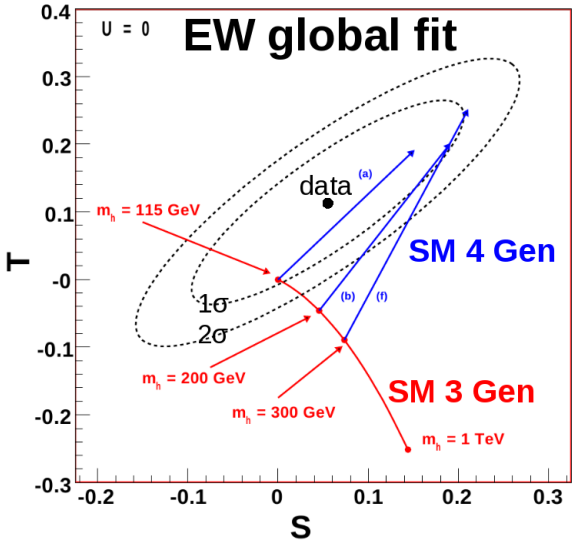


DØ : exp. exclusion
$159 < m_H < 170$ GeV
$(\Delta m)^{excl} \sim 10$ GeV

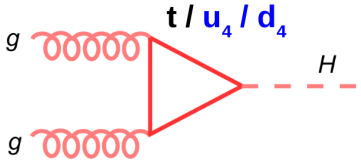
Compared to Winter 2011, the sensitivity increases faster than luminosity !

Overview

relax tension for $m_H \gtrsim 200$!



Experimentally accessible



$$\mathcal{M}_{4G^{th}}(gg \to H) \overset{m_{q_4} \gg m_H}{\approx} 3\,\mathcal{M}_{SM}(gg \to H)$$

$$\boxed{\begin{aligned}&\sigma_{4G^{th}}(gg \to H)\\ &\quad \approx 9\sigma_{SM}(gg \to H)\end{aligned}}$$

$\Longrightarrow$ neglect other prod. modes

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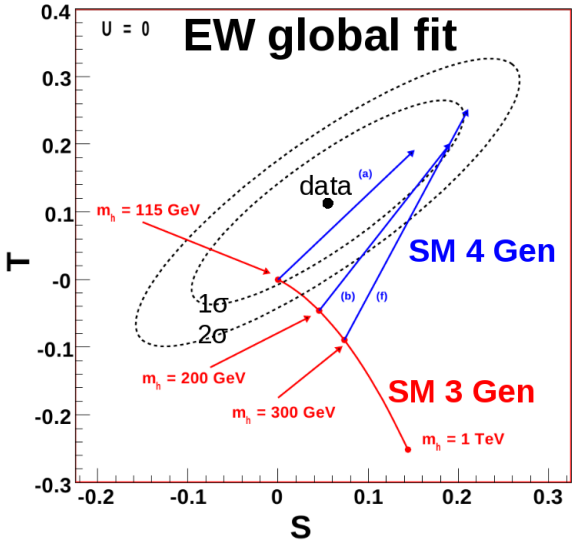

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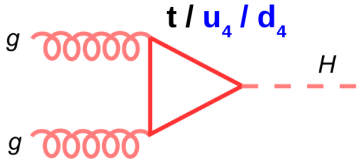

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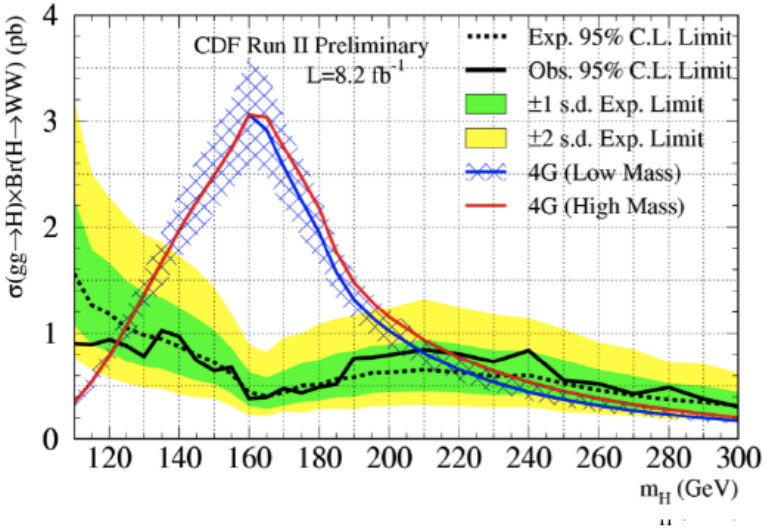
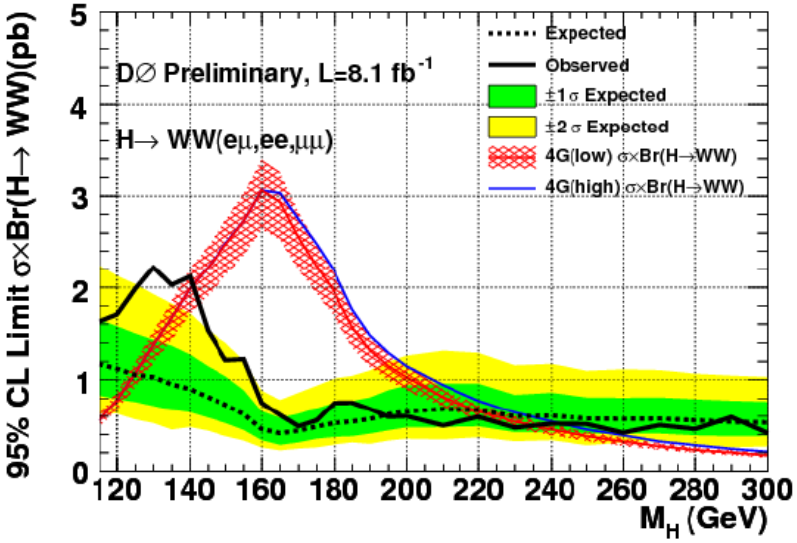




Conclusions

Status for summer 2011

- a complex and sophisticated high mass Higgs boson search :
  - exploiting all differences between signal and backgrounds
  - optimized for many sub-channels
- reach an exlusion of an appreciable mass window per experiment
- sensitivity is increasing faster than luminosity
- able to probe fourth generation models in a significant way

Future of Higgs boson search at Tevatron

- more data can be analyzed ($8.X \rightarrow 11$ fb^{-1}),
- improvement of objects ID and systematic reduction,
- optimization of WW final state for the low mass region ~ 130 GeV,
- additional channels such as $H \rightarrow ZZ$ (DØ) or $\ell\nu qq'$ (CDF)

BACKUP SLIDES

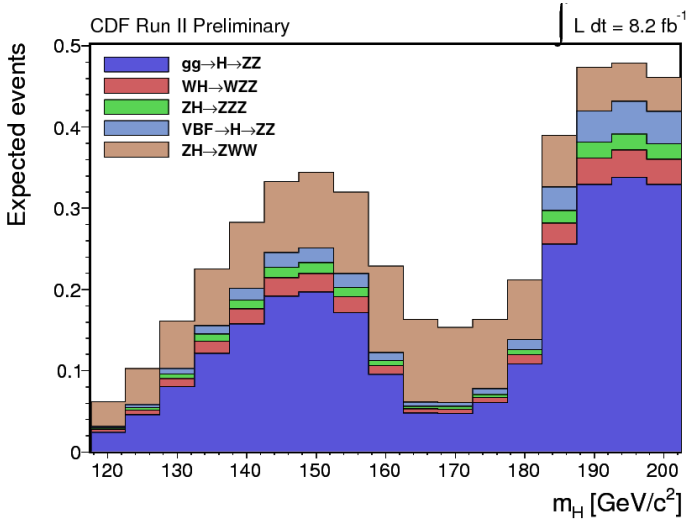
$H \to ZZ \to \ell\ell\ell\ell$

Events selection :

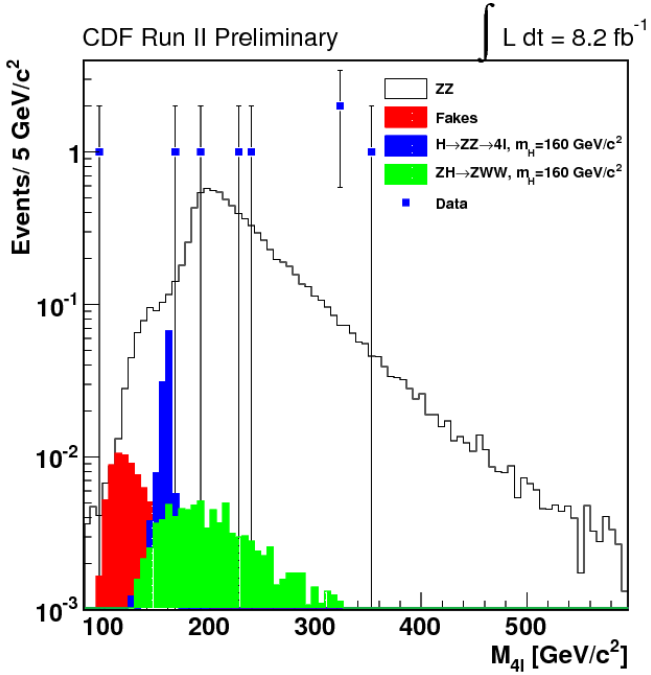
- 4 isolated leptons of high p_T
- the condition $50 < M_{4\ell} < 600$ is requiered.

Backgrounds

- very clean signature !
- SM bkg : ZZ production

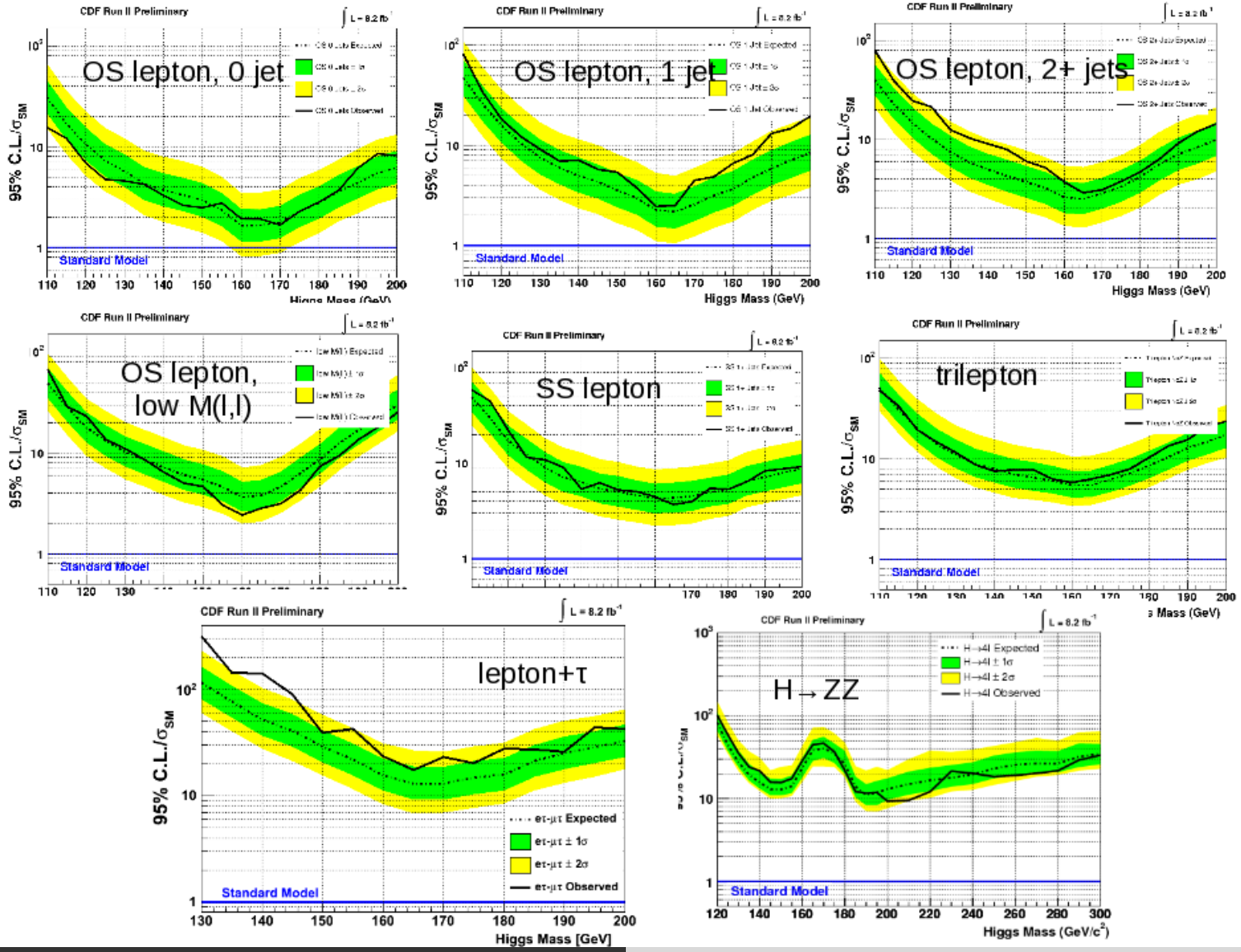


benefit from $gg \to H \to ZZ$ and $ZH \to ZWW$

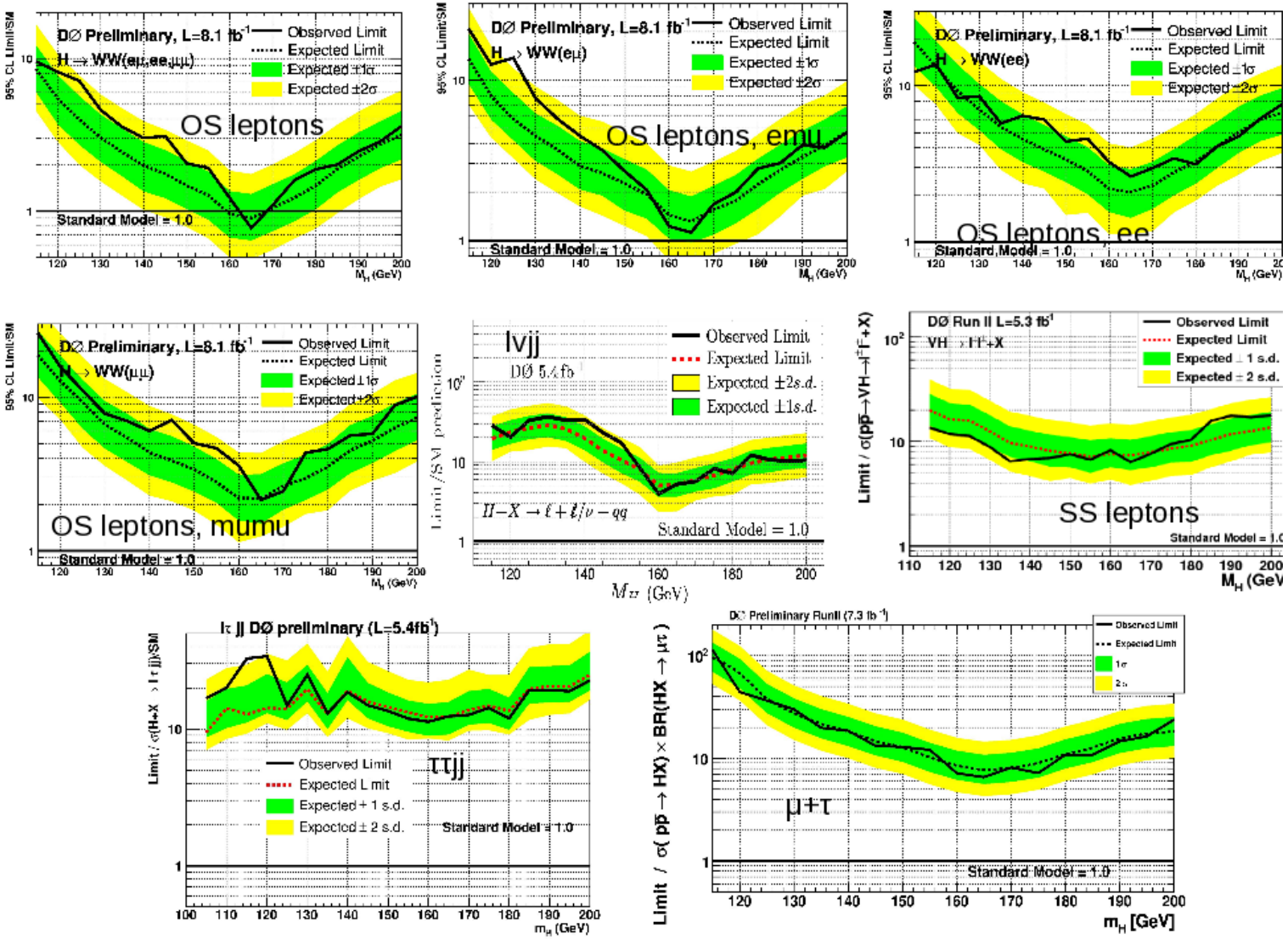


used to derive uper limit on $(\sigma \times \mathcal{BR})_H$

Limit for each CDF channel



Limit for each DØ channel



Discussion on the Tevatron Higgs exclusion I

Scale Variations (μ_R & μ_F)

- Is our treatment of assessing cross section uncertainties due to scale variations reasonable?
- We obtain our gluon fusion production cross sections from:

  D. de Florian, M. Grazzini, Phys. Lett. **B674**, 291-294 (2009). [arXiv:0901.2427 [hep-ph]].

  C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].
- We use a scale variation of a factor of 2 from the central value ($\mu=m_H/2$) to estimate the magnitude of potential contributions from higher-order processes
- The authors confirmed that higher order corrections to these cross sections are small and that the standard $\kappa=2$ scale variations are perfectly reasonable for assigning uncertainties
- Another recent, independent publication argues for even smaller scale uncertainties than those being currently assigned in our searches:

  V. Ahrens, T. Becher, M. Neubert *et al.*, Eur. Phys. J. **C62**, 333-353 (2009). [arXiv:0809.4283 [hep-ph]];

  V. Ahrens, T. Becher, M. Neubert *et al.*, [arXiv:1008.3162 [hep-ph]].

Discussion on the Tevatron Higgs exclusion II

Additional Theoretical Uncertainties

- Should there be an additional theoretical uncertainty assigned to our gluon fusion cross sections coming from the effective field theory (EFT) approach used to integrate electroweak contributions from heavy and light loop particles?
- Such an uncertainty is already included:

  C. Anastasiou, R. Boughezal, F. Petriello, JHEP **0904**, 003 (2009). [arXiv:0811.3458 [hep-ph]].

- Uncertainties on the gluon fusion cross section used in Tevatron Higgs searches incorporate a ~2% level component to account for this effect
- The same authors find that when they entirely remove corrections from light quark diagrams (clearly too conservative), the total cross section changes by less than 4%
- **Our current treatment of EFT effects is on solid ground**

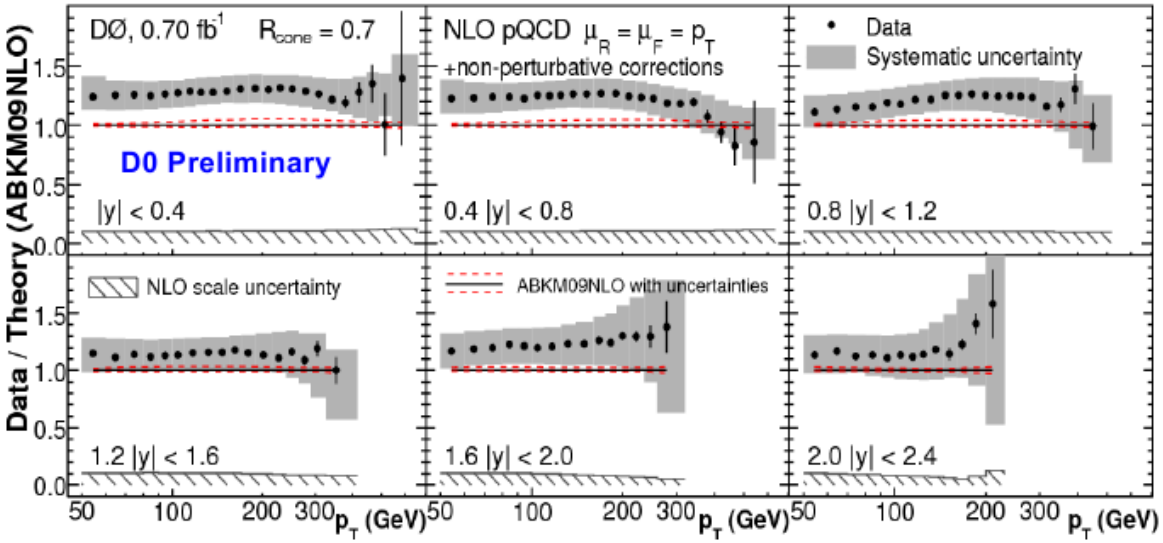
Discussion on the Tevatron Higgs exclusion III

PDF Uncertainties

- Should our PDF uncertainties account for observed differences in cross sections obtained using our default MSTW model and ABKM/HERAPDF models?
- See Juan Rojo's talk on "Recent Developments and Open Problems in Parton Distributions" in the Tuesday afternoon session
- ABKM09 & HERAPDFs do not include Tevatron data, which provide the best constraints on the relevant high-x gluon distributions at Tevatron energies
- A comparison of high E_T Tevatron data with ABKM09 & HERAPDF shows large disagreement:

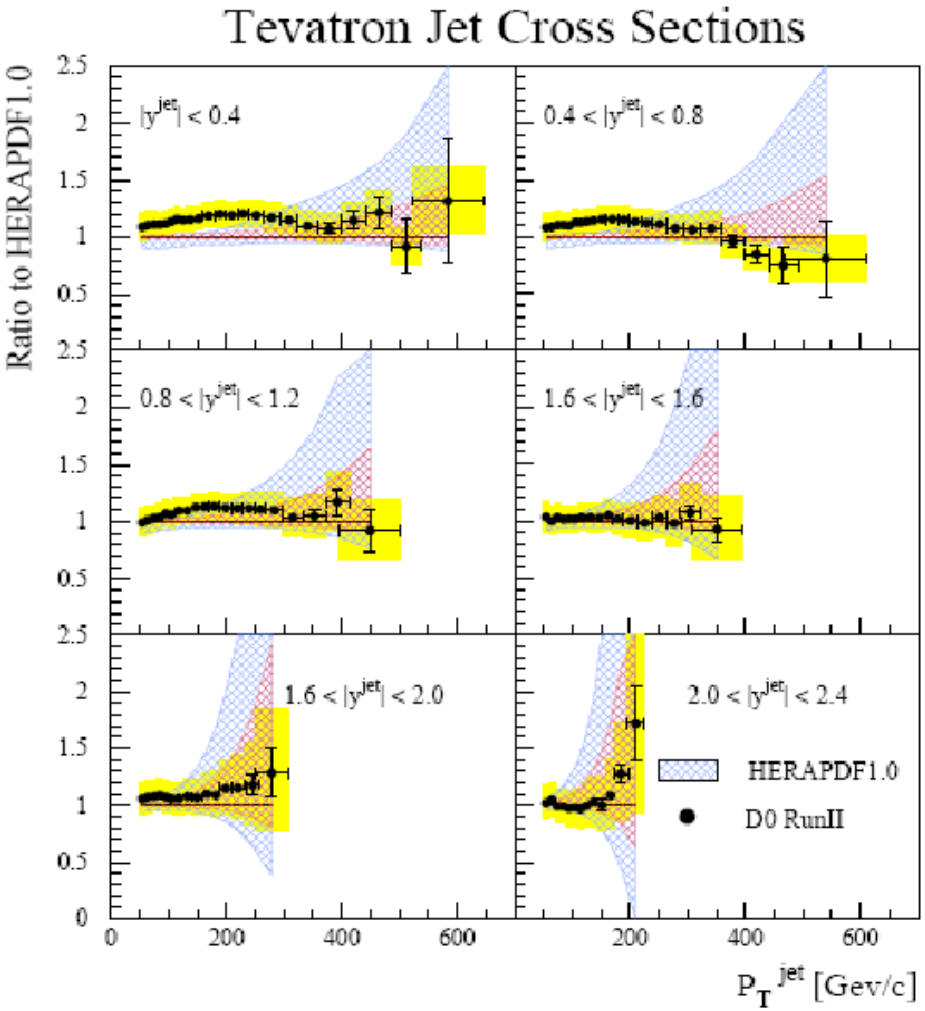
ABKM09 at the Tevatron:
Ratio of D0 High-ET jet cross-section to ABKM09 prediction (Data vs central PDF value)

(→ Uncertainty on ABKM Prediction)



Discussion on the Tevatron Higgs exclusion IV

PDF Sets



HERAPDF1.0 at the Tevatron:
Ratio of D0 High-ET jet cross section to HERAPDF1.0 prediction (Data vs central PDF value)

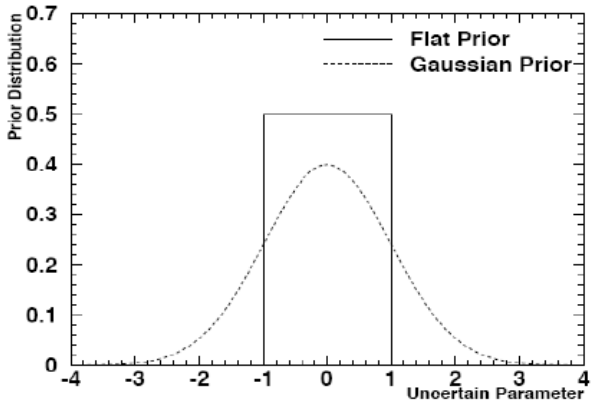
→ Total PDF uncertainty
→ Experimental PDF uncertainty
→ Systematic experimental error

- Our choice is also consistent with recommendations by the PDF4LHC working group, which is charged to provide guidance to experiments with respect to the use of PDF sets: http://www.hep.ucl.ac.uk/pdf4lhc/
- **Our PDF uncertainties are appropriate**

Discussion on the Tevatron Higgs exclusion V

Treatment of Theoretical Uncertainties

- Most theoretical uncertainties are rather loosely stated. They are interpreted in terms of a maximum range of variations (*flat prior*)
- We treat theoretical uncertainties as gaussian (*gaussian prior*)
- Are we underestimating our uncertainties?
- We use the maximum bound as 1σ. This means we allow even larger variations than the given bounds. (See figure)
- We also tested the flat prior approach and found no significant change in our limits
- **We are not underestimating our uncertainties**



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Discussion on the Tevatron Higgs exclusion VI

Emulation of Tevatron Limit Calculation

- Care needs to be taken when trying to emulate Tevatron limits
- Correlations between different input channels need to be properly taken into account:
  - Our limit calculation uses these correlations to constrain the backgrounds
  - Our backgrounds are better constrained by the data, as compared to the theory. This can be viewed as a measurement of the true rate and the a posteriori uncertainty is an experimental determination of the true error.
- An estimation of the sensitivity increase due to MVA is not straightforward:
  - Our pre-selection cuts are kept as loose as possible to maximize signal acceptance and cannot be interpreted as an optimized cut-based analysis
  - MVAs are used to separate signal from background
  - To estimate MVA sensitivity gains: compare fully optimized cut-based results with MVA results
  - MVAs typically improve limits by ~30% over optimized cut-based
- Impact of theoretical uncertainties:
  - Theoretical uncertainties are statistically accounted for together with other systematics
  - Increasing theoretical cross section uncertainties is not equivalent to decreasing the central prediction

slides of Marc Buehler for the On behalf of the Tevatron New Phenomena and Higgs Working Group – La Thuile 2011