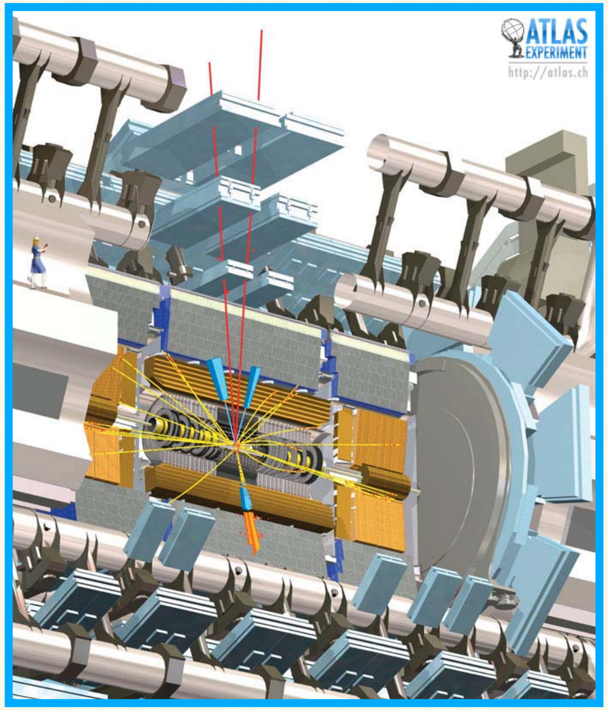
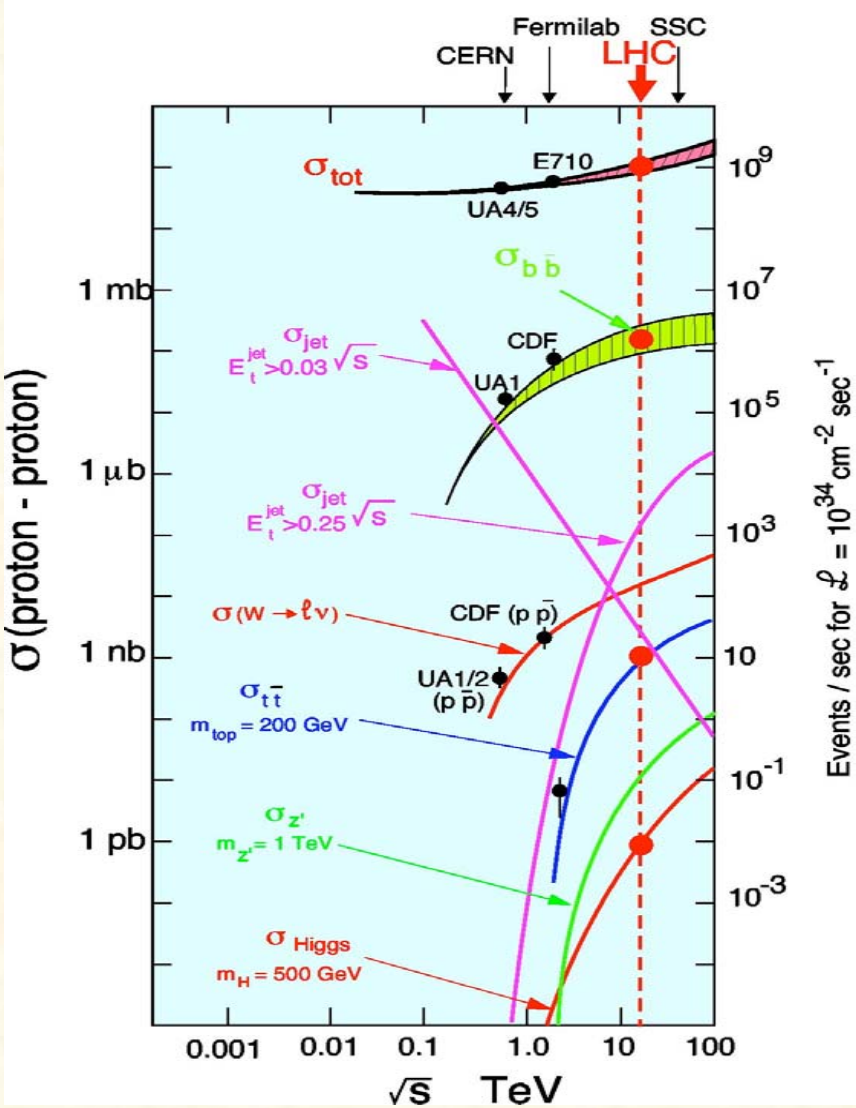
Higgs boson searches at hadron colliders

Part 2



- SM Higgs search at the Tevatron
    - Low and high mass channels
    - Statistical combination
    - Prospects for the next years
- Test of Monte Carlo generators

Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

- Inelastic proton-proton reactions: 10^9 / s

- bb pairs $5 \; 10^6$ / s
- tt pairs 8 / s

- W → e ν 150 / s
- Z → e e 15 / s

- **Higgs (150 GeV) 0.2 / s**
- **Gluino, Squarks (1 TeV) 0.03 / s**

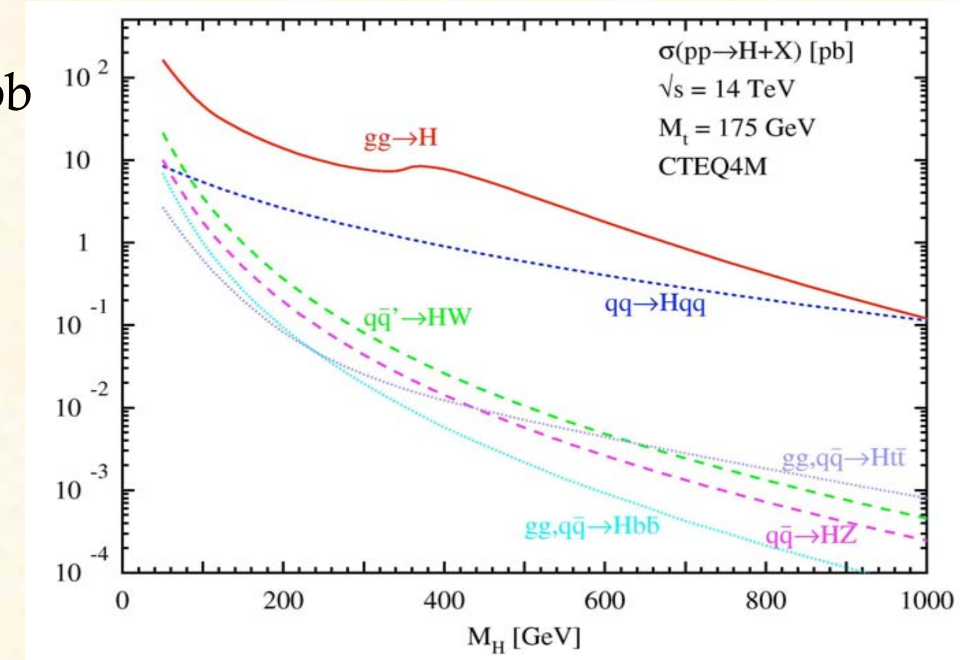
Large production rates, however, overwhelmed by large backgrounds from:

- jet production via QCD processes
- tt production (for lepton final states)
- W/Z + jet production (lepton final states)

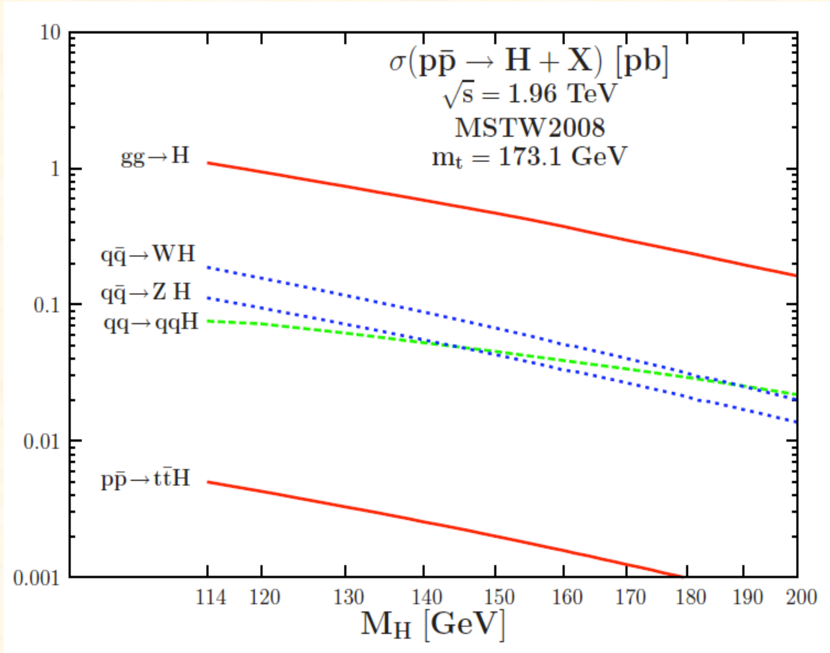
Higgs Boson Production cross sections

LHC M. Spira et al.

pb



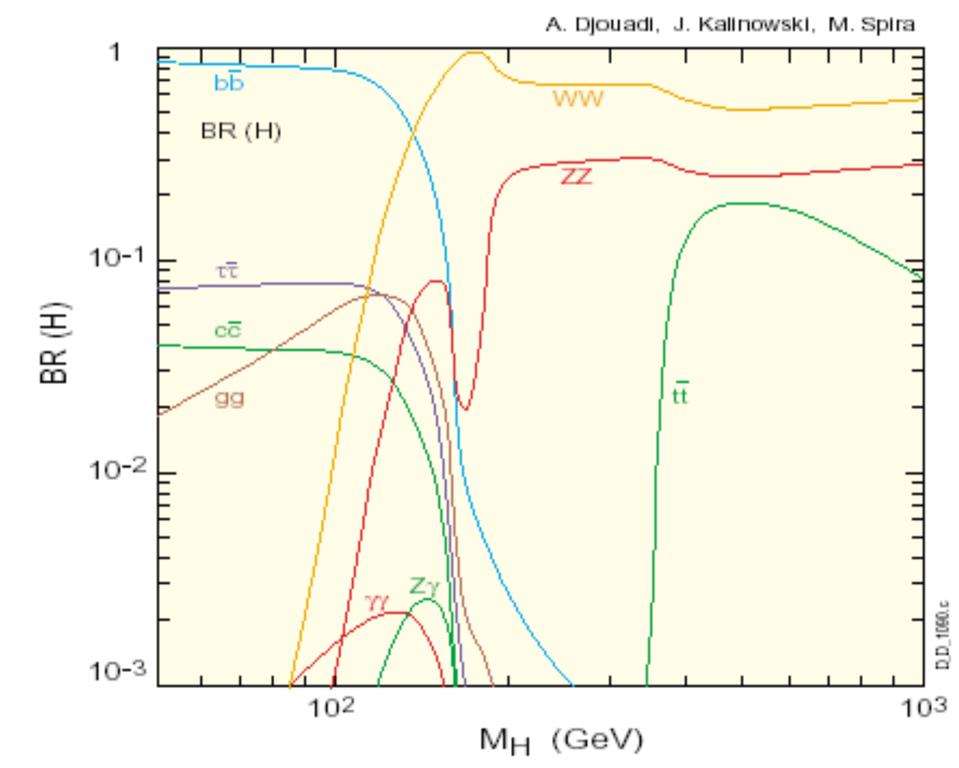
Tevatron



qq → W/Z + H cross sections ~10 x larger at the LHC

gg → H ~70-80 x larger at the LHC

Useful Higgs Boson Decays at Hadron Colliders



at high mass:
Lepton final states
(via H → WW , ZZ)

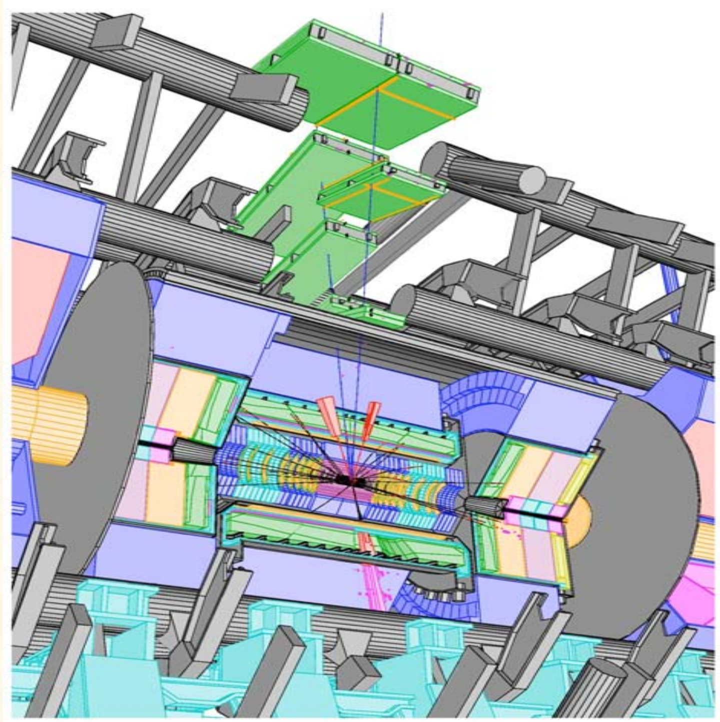
at low mass:
Lepton and Photon final states
(via H → WW*, ZZ*)

Tau final states

The dominant **bb decay mode** is only useable in the associated production mode (ttH, W/Z H)

(due to the huge QCD jet background, leptons from W/Z or tt decays)

Detector requirements for Higgs physics



- Good measurement of leptons and photons with large transverse momentum P_T

- Good measurement of missing transverse energy (E_T^{miss})

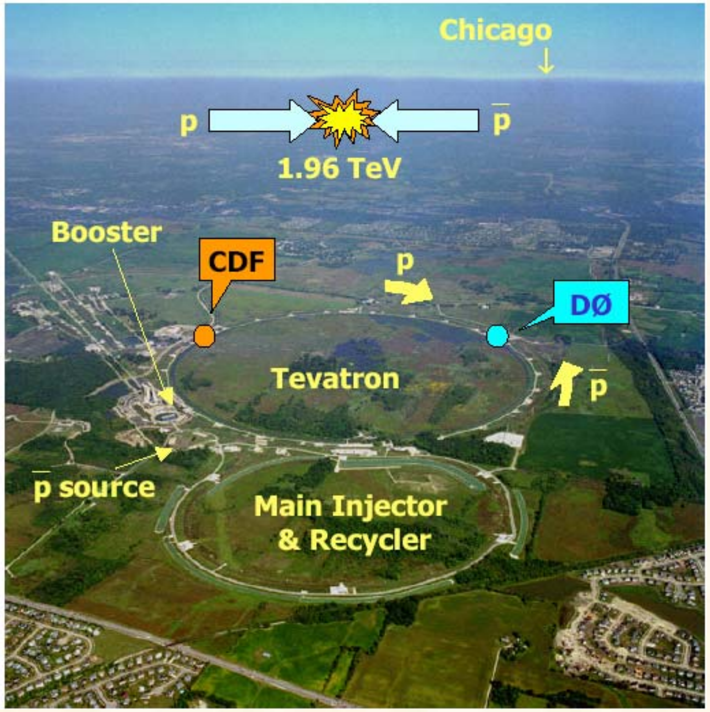
  and

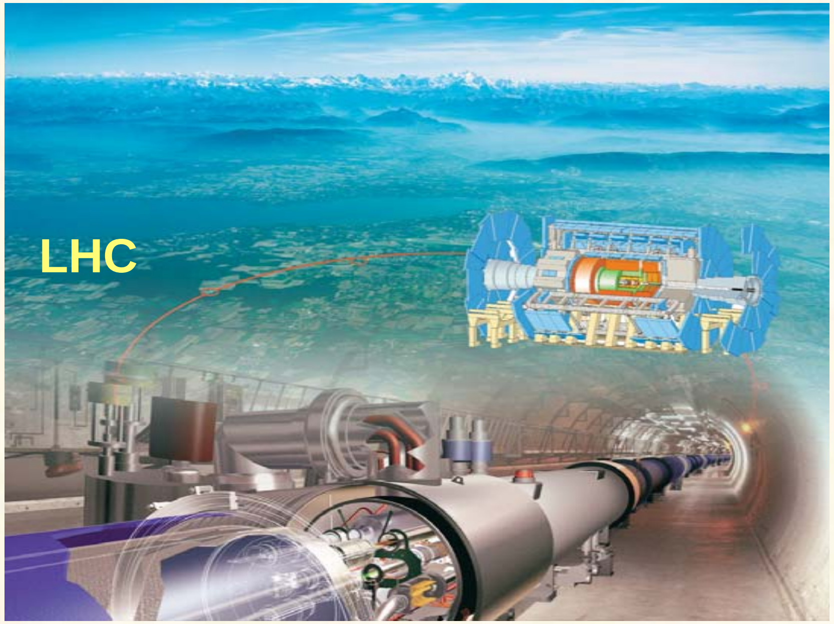
  energy measurements in the forward regions
  $\Rightarrow$ calorimeter coverage down to $\eta \sim 5$

- Jet tagging in the forward regions (Vector boson fusion process)

- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

The accelerators





The Tevatron Collider at Fermilab

- **Proton antiproton collider**

  - 6.5 km circumference

  - Beam energy 0.98 TeV, **$\sqrt{s}$ = 1.96 TeV**

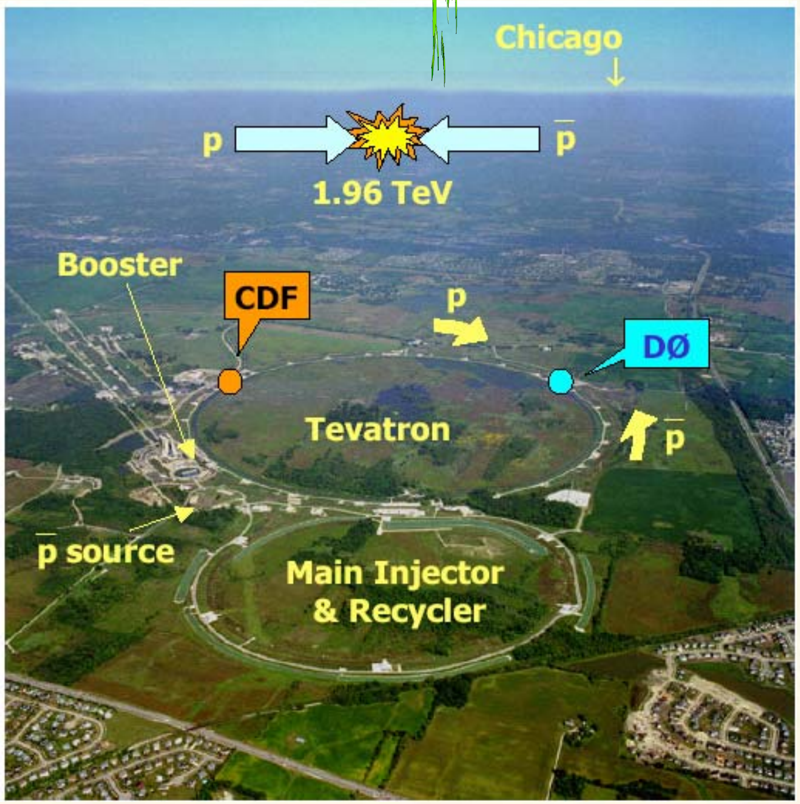
  - 36 bunches, 396 ns separation
  (time between crossings)

- **2 Experiments: CDF and DØ**

- **Main challenges:**

  - Antiproton production and storage

  → luminosity, stability of operation

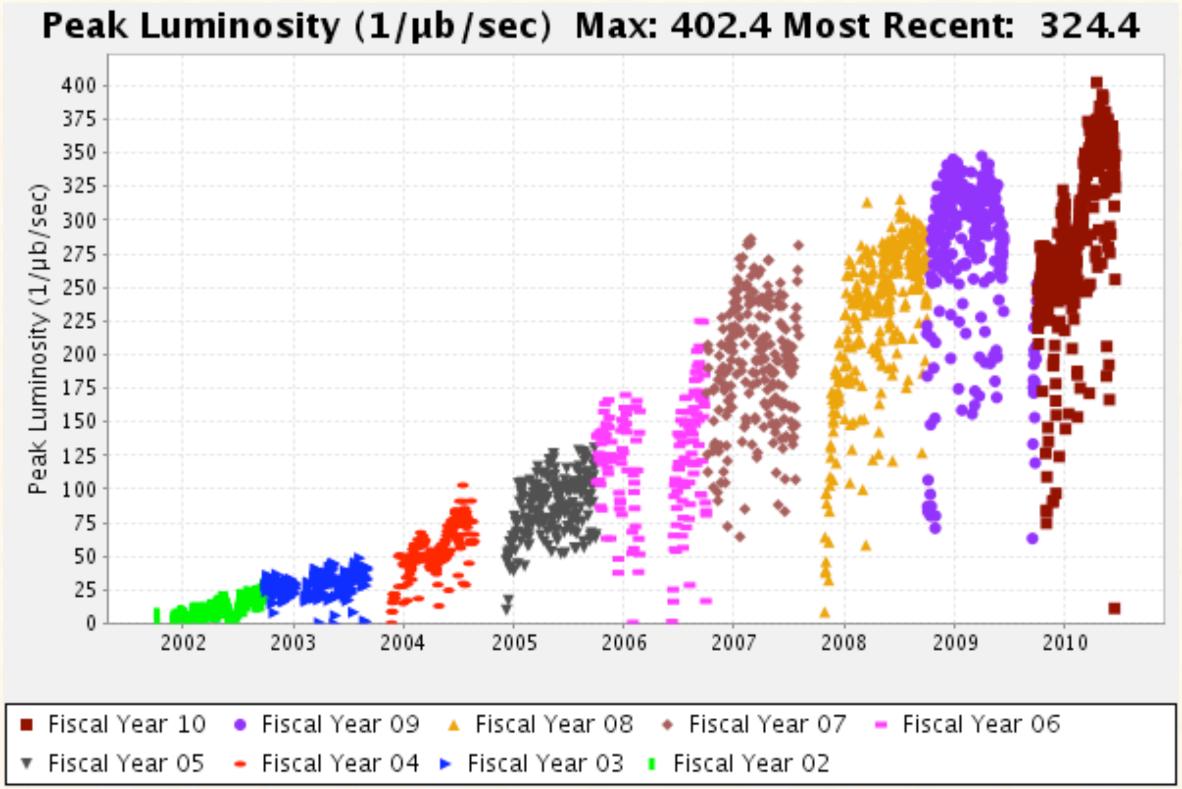


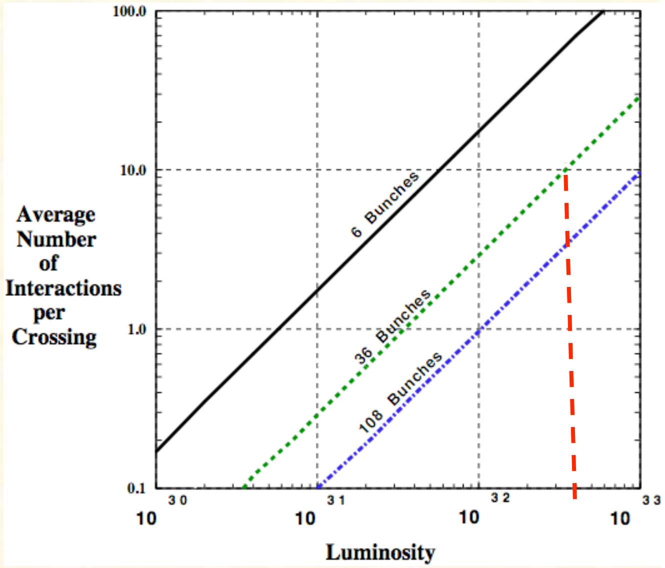
Collider is running in so called Run II (since 2001)
[Run I from 1990 – 1996, int. luminosity: 0.125 fb^{-1}, Top quark discovery]

- **March 2001 – Feb 2006: Run II a, $\int L\,dt$ = 1.2 fb^{-1}**
- **July 2006 - 2010 (11 / 12)?: Run II b, $\int L\,dt$ = 10 -12 fb^{-1}**

Tevatron performance

Peak luminosities of the machine as a function of time

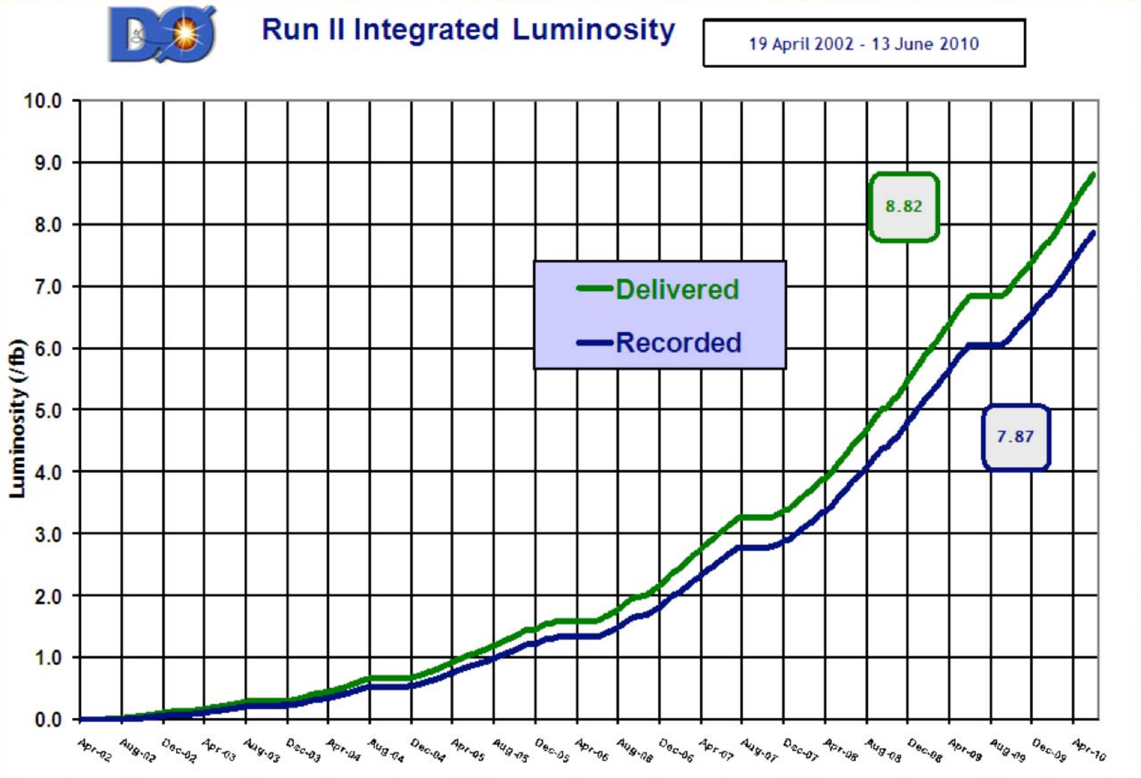




- Peak luminosity of $4.02 \cdot 10^{32}$ cm^{-2} s^{-1}
- Corresponds to ~10 interactions per bunch crossing
  (superposition of minimum bias events on hard collision)

The integrated Tevatron luminosity (until June 2010)

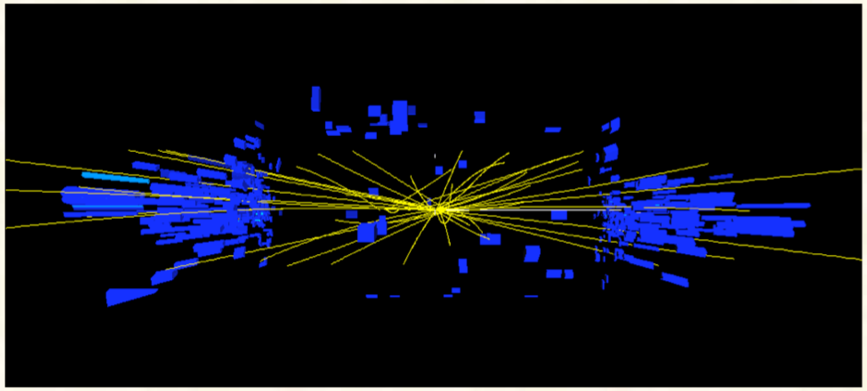
- After a slow start-up (2001 – 2003), the Tevatron accelerator has reached an excellent performance
- Today, Tevatron delivers a data set equal to Run I (~100 pb^{-1}) every 2 weeks
- Integrated luminosity delivered to the experiments so far ~ 8.8 fb^{-1}
- Anticipate an int. luminosity of ~10 fb^{-1} until end of 2010, with a potential increase to 12 - 13 fb^{-1}, if Tevatron will run until end of 2011

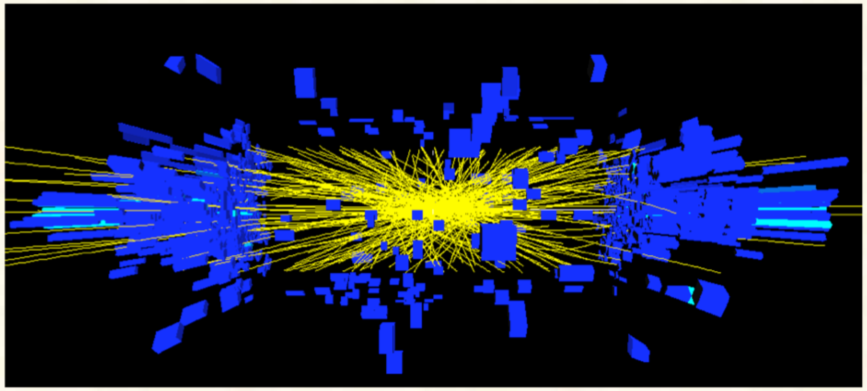


Data corresponding to an int. luminosity of up to 5.4 fb^{-1} analyzed…

Challenges with high luminosity

Min. bias pileup at the Tevatron, at $0.6 \cdot 10^{32}$ cm^2s^{-1} ... and at $2.4 \cdot 10^{32}$ cm^2s^{-1}

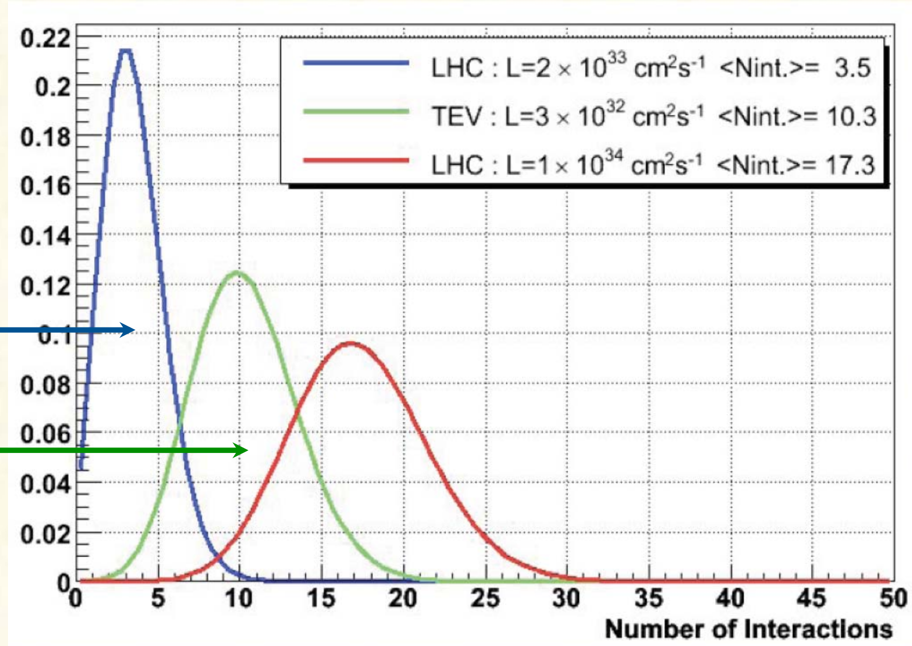




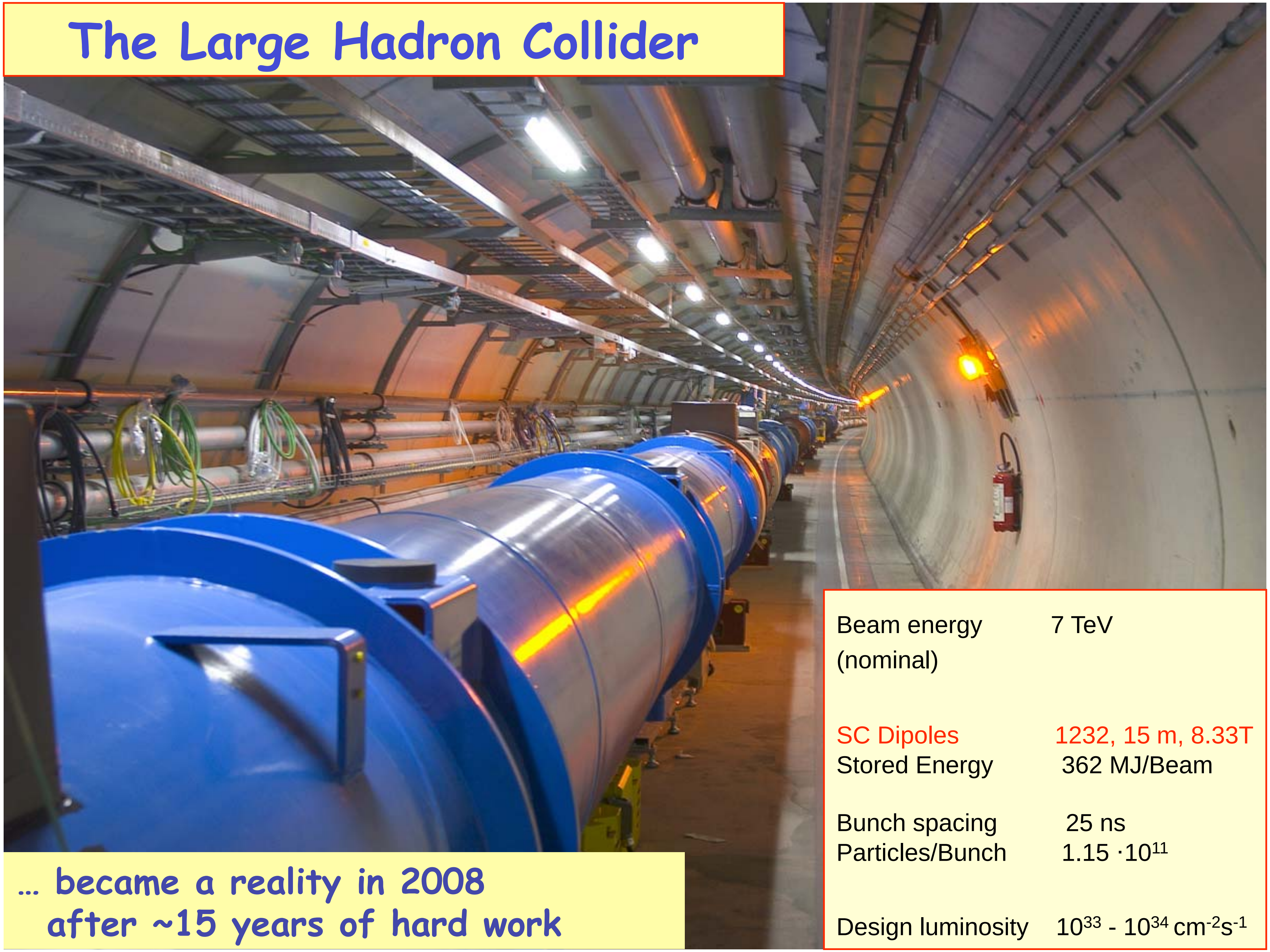
Average number of interactions:

LHC: initial “low” luminosity run
(L=2 $\cdot 10^{33}$ cm^2s^{-1}): <N>=3.5

TeV: (L=3 $\cdot 10^{32}$ cm^2s^{-1}): <N>=10



The Large Hadron Collider



Beam energy (nominal)	7 TeV
SC Dipoles	1232, 15 m, 8.33T
Stored Energy	362 MJ/Beam
Bunch spacing	25 ns
Particles/Bunch	$1.15 \cdot 10^{11}$
Design luminosity	10^{33} - 10^{34} $cm^{-2}s^{-1}$

… became a reality in 2008 after ~15 years of hard work

Comparison of the LHC and Tevatron machine parameters

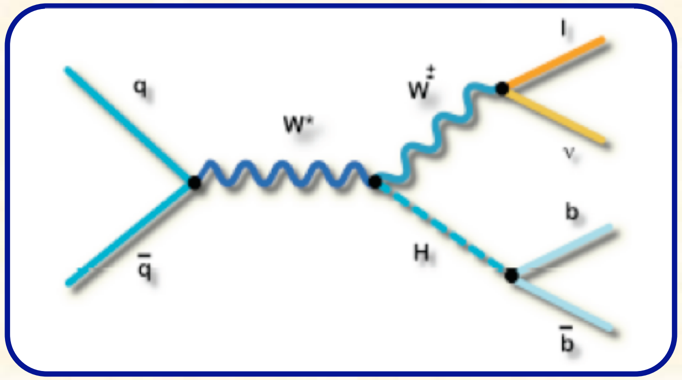
	LHC (design)	Tevatron (achieved)
Centre-of-mass energy	14 TeV	1.96 TeV
Number of bunches	2808	36
Bunch spacing	25 ns	396 ns
Energy stored in beam	360 MJ	1 MJ
Peak Luminosity	10^{33}-10^{34} $cm^{-2}s^{-1}$	4 x 10^{32} $cm^{-2}s^{-1}$
Integrated Luminosity / year	10-100 fb^{-1}	~ 2 fb^{-1}

- 7 times more energy (after initial 3.5 TeV phase)
- Factor 3-30 times more luminosity
- Physics cross sections factor 10-100 larger

The Search for

The Higgs boson at the Tevatron

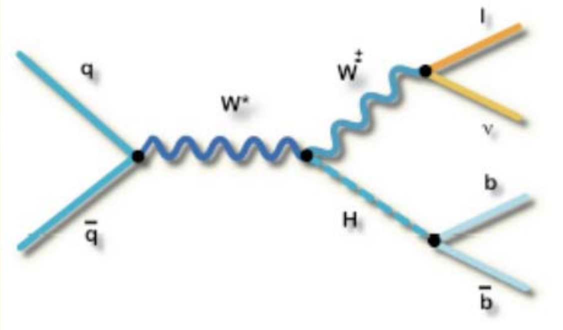
Searches for a low mass Higgs boson at the Tevatron



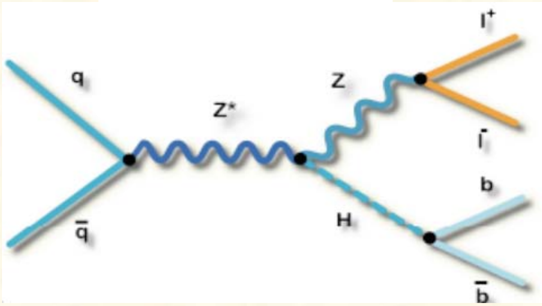
$m_H < 135$ GeV:

Associated production WH and ZH with H→bb decay

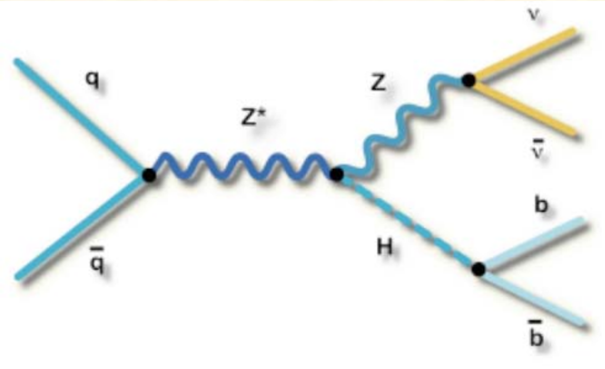
Main low mass search channels



ℓ + E_T^{miss} + bb: $WH \rightarrow \ell\nu bb$
Largest *VH* production cross section, however, severe backgrounds

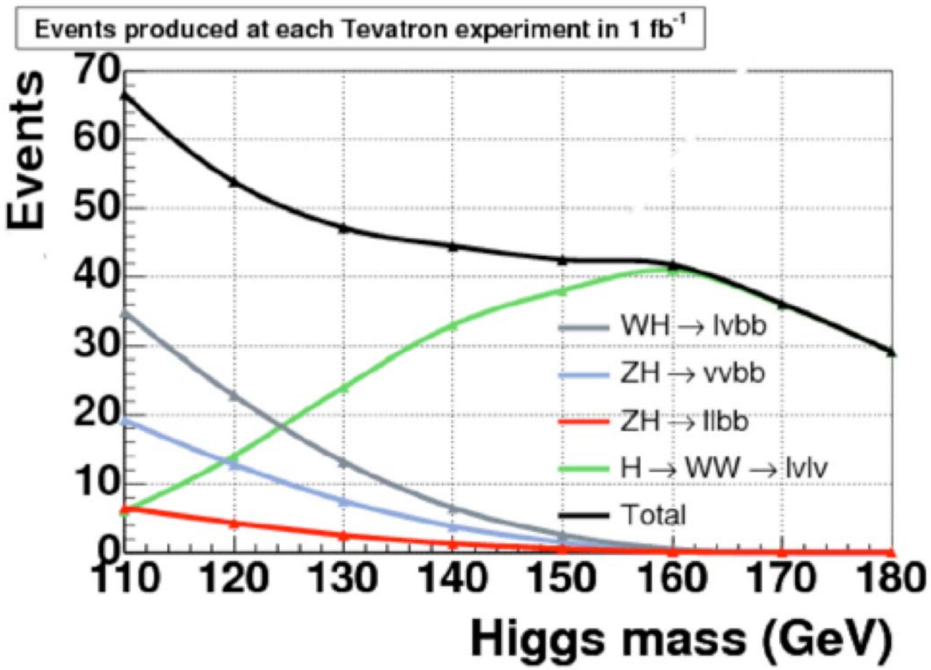


$\ell\ell$+bb: $ZH \rightarrow \ell\ell bb$
Less background than WH
Smallest Higgs signal



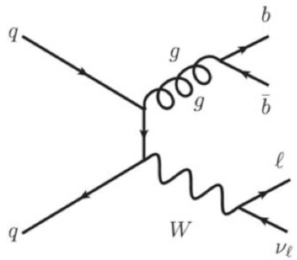
E_T^{miss} + bb: $ZH \rightarrow \nu\nu bb$
3x more signal than $ZH \rightarrow \ell\ell\, bb$
(+$WH \rightarrow \ell\nu\, bb$ when lepton non-identified)
Large backgrounds which are difficult to handle

Number of produced events (incl. decays) per 1 fb^{-1}



WH (H→bb)   Signal, m_H = 115 GeV:
σ×BR = 14 fb   (per lepton)

Large backgrounds: W+jet production



W+bb: σ×BR = 4×10^4 fb
W+cc: σ×BR = 1×10^5 fb
W+qq: σ×BR = 2×10^6 fb

Additional backgrounds:

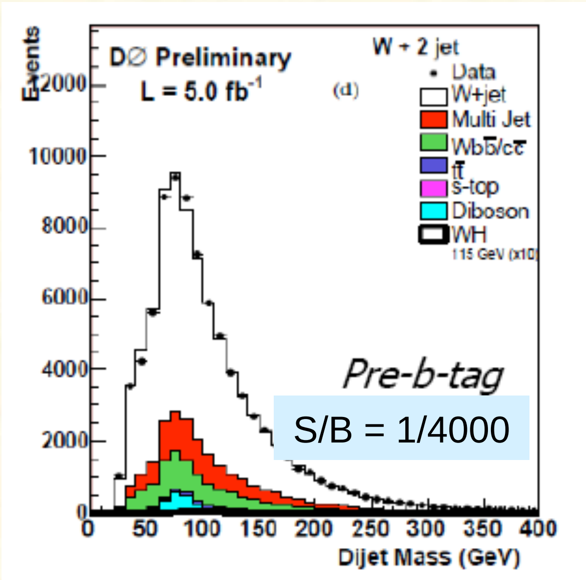
WW:	σ×BR = 13 pb
tt:	σ×BR = 7 pb
single top:	σ×BR = 3 pb

+ multijet QCD background

General Search Strategy

Example: WH → ℓν bb

(i) Select events consistent with Z/W + 2 jets
(large W+jet and Z+jet backgrounds)

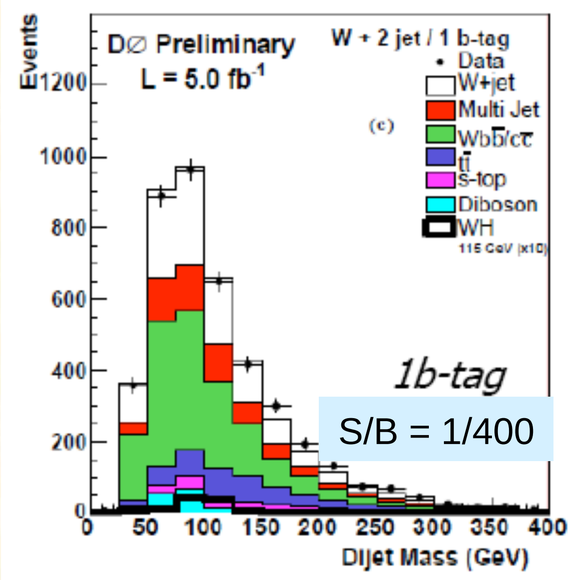


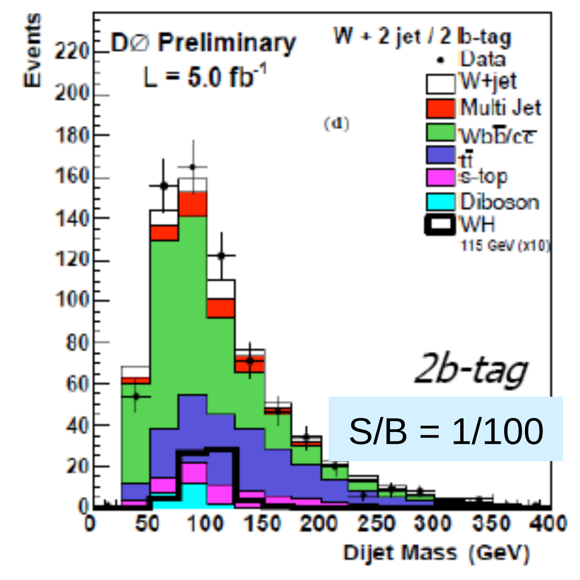
(ii) Apply b-tagging
(most discriminating variable: dijet inv. mass)

even after b-tagging S:B ratio remains small,
→ needs advanced (multivariate) analysis tools

(iii) Optimize separation power by multivariate discrimination (neutral networks, matrix elements, ….)

Major input variables:
- dijet mass
- P_T of the dijet system
- P_T of W/Z
- Sphericity
- ΔR_{jj}, $\Delta\phi_{jj}$, $\Delta\eta_{jj}$





b tagging

- Several methods have been established at the Tevatron during the past years:

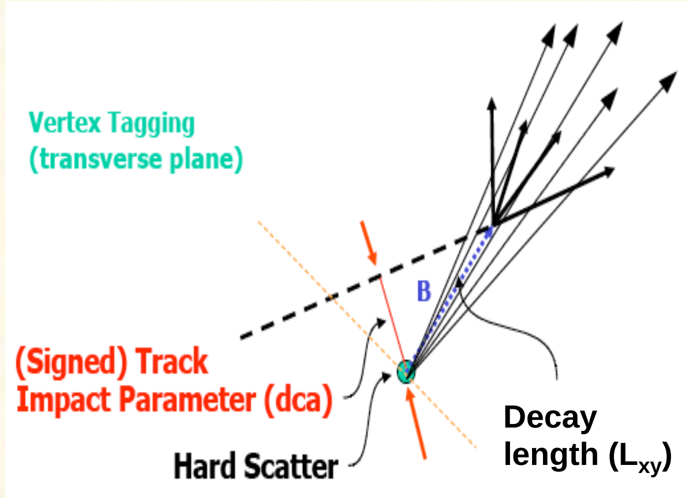
  - lifetime tags, signed impact parameters
  - reconstructed secondary vertices

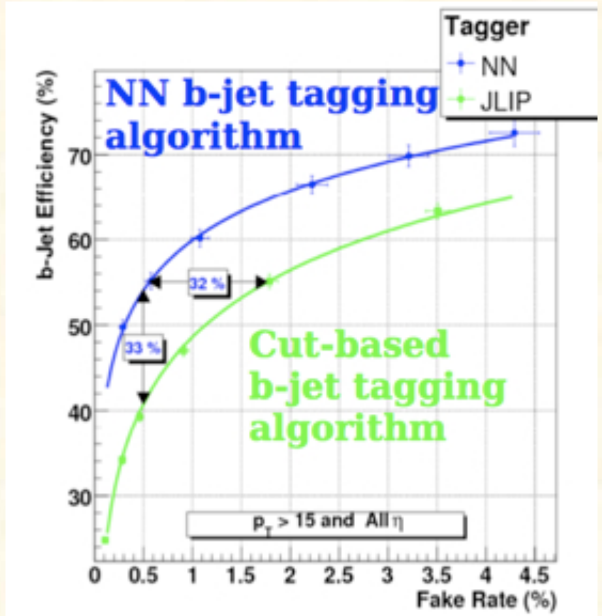
- Most powerful methods combine information using neural networks

- Typical performance figures:

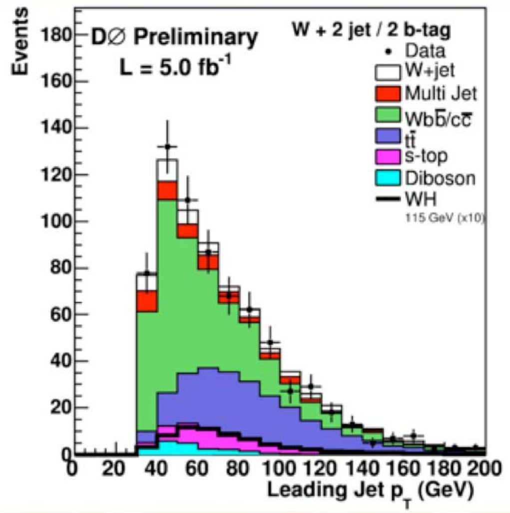
  D0: Neural net (Impact parameter, sec. vertex)
  “Tight”: 70% b-tag efficiency, 3.5% mistag
  “Loose”: 50% b-tag efficiency, 0.3% mistag

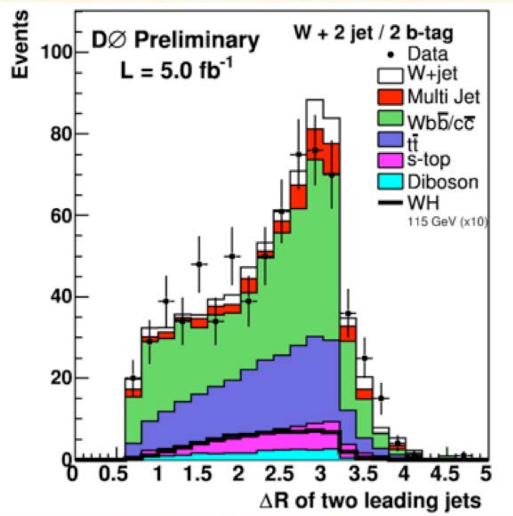
  Similar results for CDF

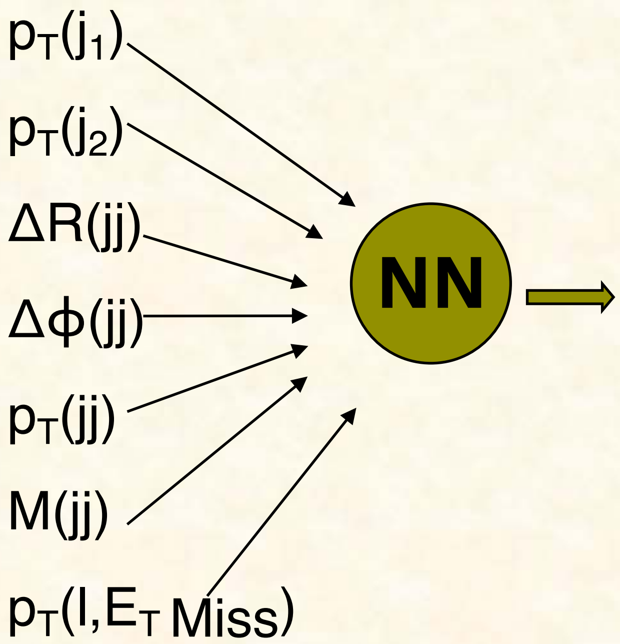


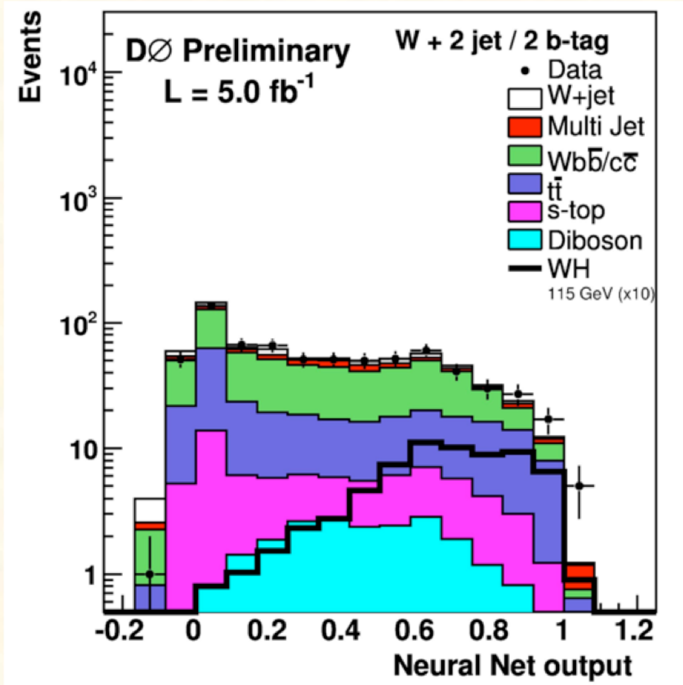


DØ: WH→lν bb (l=e,μ) neural net



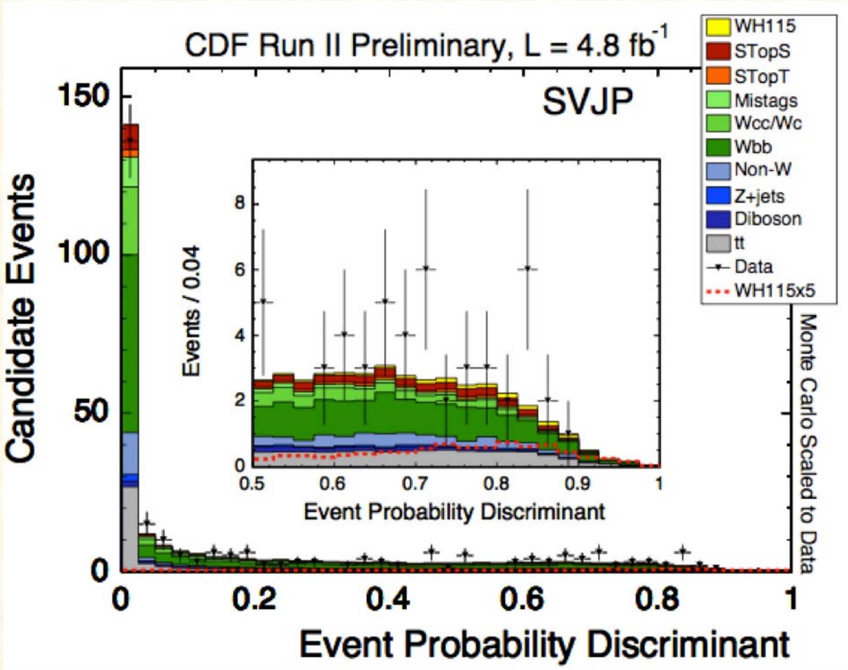






CDF discriminant output:

Example: WH → $\ell\nu$ bb

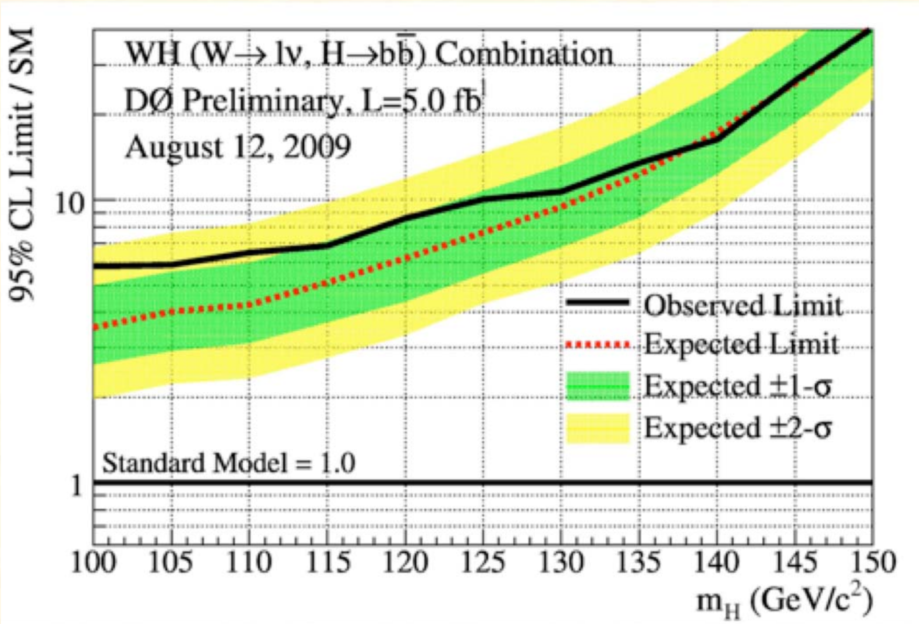


(iv) Split data into several sub-samples with different final state topologies
- maximize sensitivity due to S:B variations
- different background composition in the different classes
  (e.g. 1 b-tag, 2 b-tags)

(v) Final step: Statistical combination of all sub-samples in each experiment and of both experiments

Sensitivity in the low mass region

- Limits for individual channels a factor of 5-10 away from SM cross section at m_H = 115 GeV
- → The combination of all contributing channels is crucial

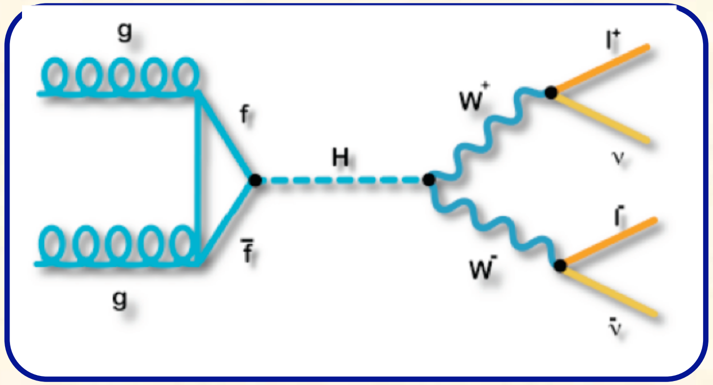


Excluded cross section:
(95% C.L., m_H = 115 GeV)

D0: $\sigma_{95} = 6.9 \cdot \sigma_{SM}$
CDF: $\sigma_{95} = 4.3 \cdot \sigma_{SM}$

- Main systematic uncertainties for low mass channels:
  - Signal (total 15%): cross section, b-tagging, ID efficiencies
  - Background (total 25-30%): normalization of W/Z+jets heavy flavour samples, modelling of the multijet and W/Z+jet backgrounds, b-tagging

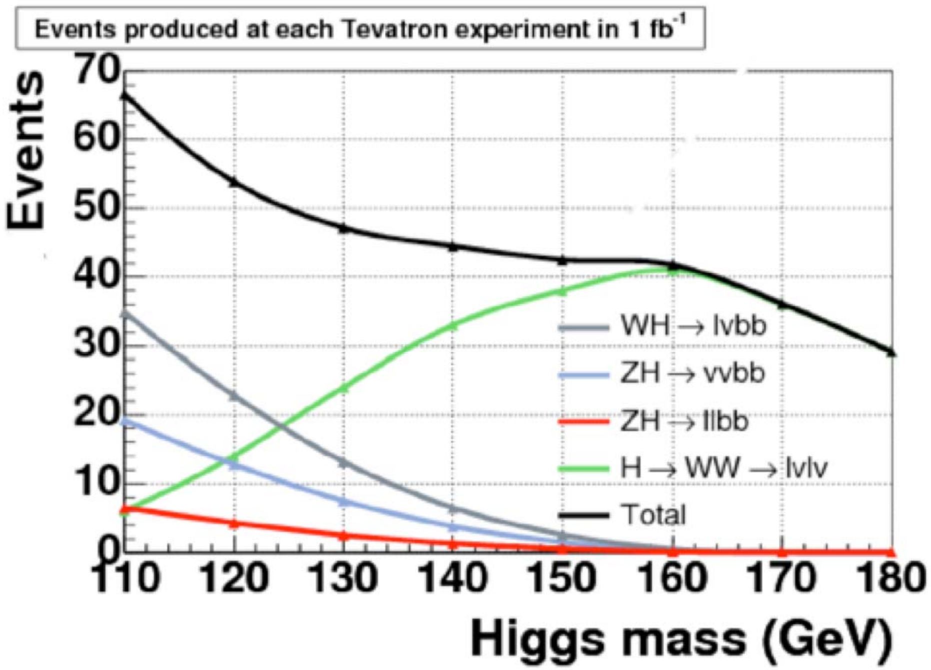
Searches for a high mass Higgs boson at the Tevatron



m_H > 135 GeV:

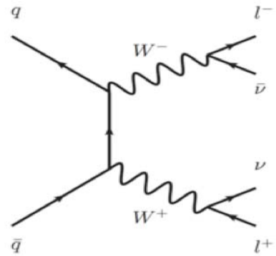
$gg \to H \to WW \to \ell\nu\ \ell\nu$

Number of produced events (incl. decays) per 1 fb^{-1}



<u>gg → H →WW→llνν)   Signal, m_H = 160 GeV:</u>
σ×BR = 40 fb
Associated WH and qqH production increase signal by ~30%

Significant di-boson backgrounds:

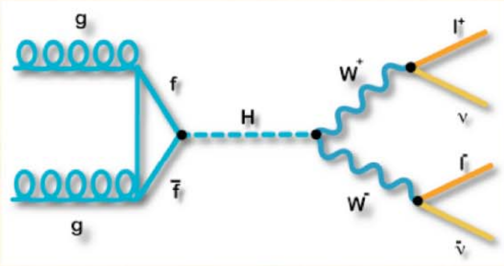


<u>Di-Boson</u>
WW: σ×BR = 13 pb
WZ: σ×BR = 4.0 pb
ZZ: σ×BR = 1.5 pb

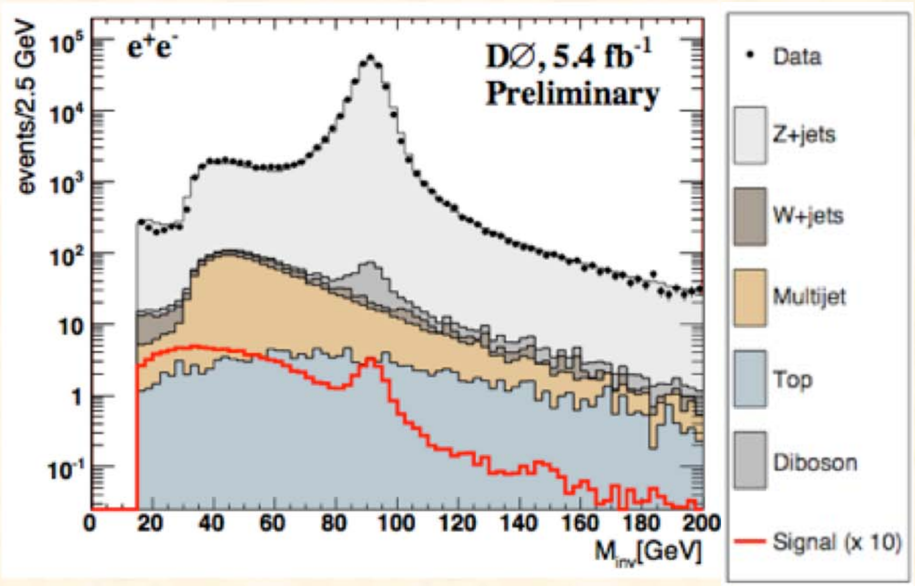
<u>Additional backgrounds:</u>
tt: σ×BR = 7 pb
single top: σ×BR = 3 pb

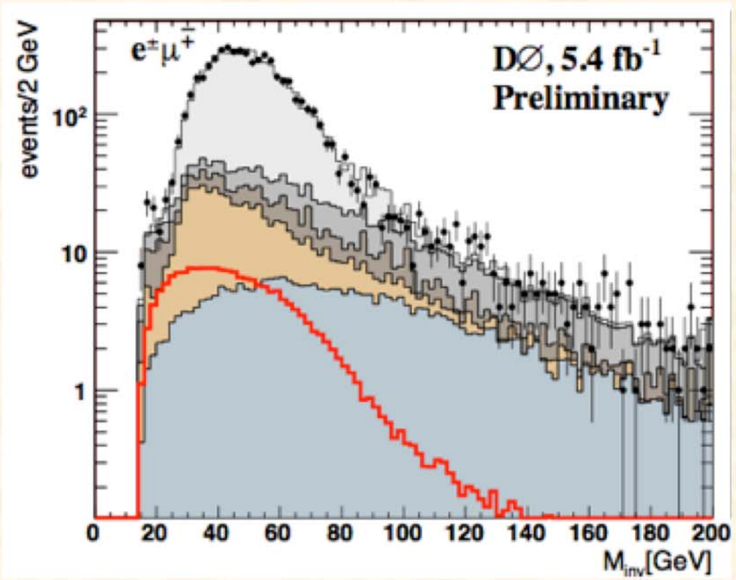
+ multijet QCD background

$H \to \ell^+\ell^- \nu\nu$



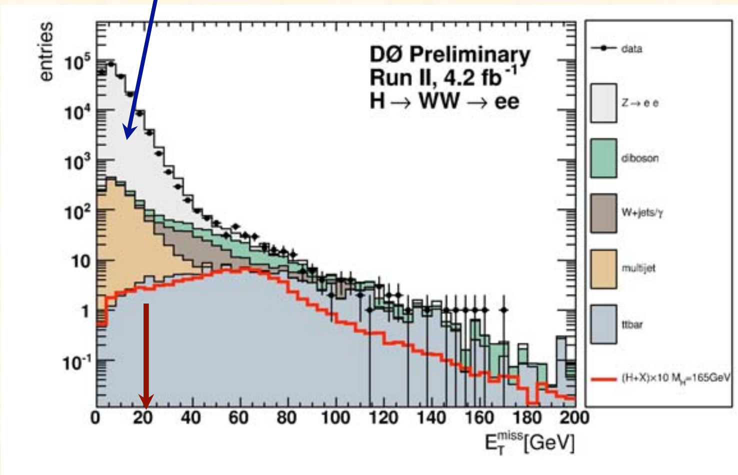
- Dominant decay for m_H >135 GeV: $H \to W^*W$
- Leptons in final state
  → exploitation of gg→H is possible
- Signal contribution also from $W/Z+H$ *and* qqH production
  → Consider all sources of opposite sign di-lepton + E_T^{miss}
  Split analysis in ee, $\mu\mu$, and eμ final states
- Backgrounds: Drell-Yan, dibosons, tt, W+jet, multijet production

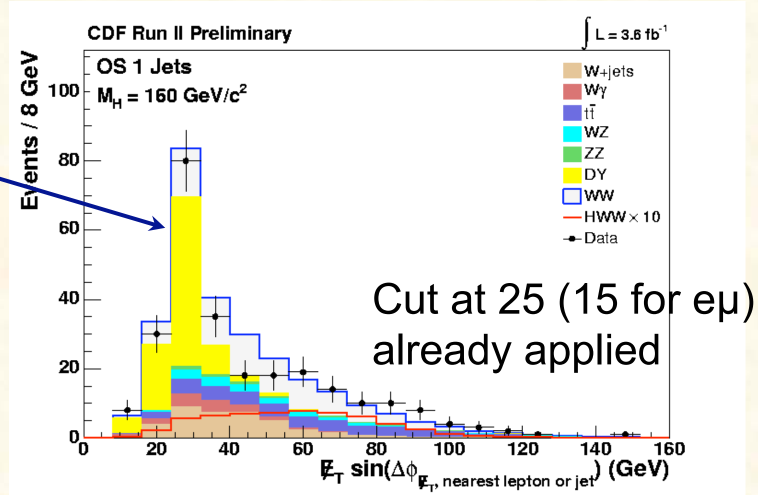




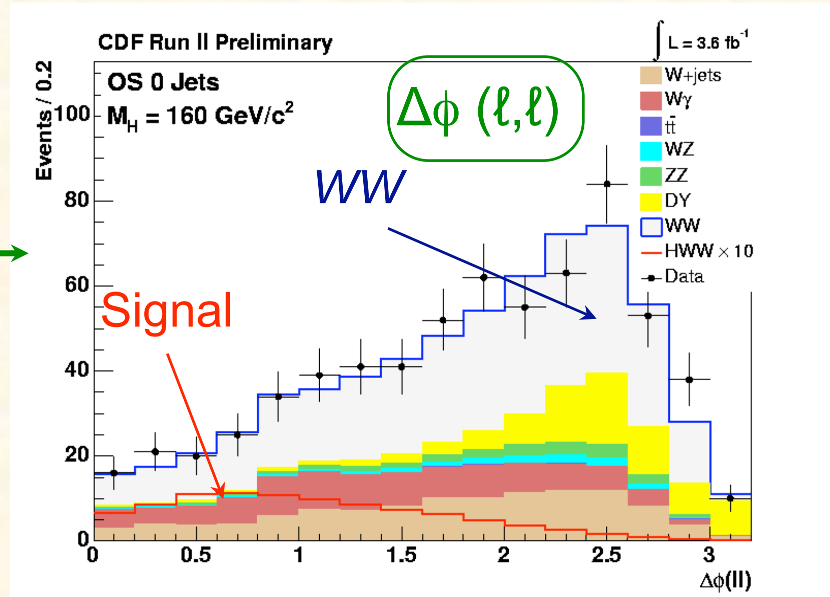
$H \rightarrow \ell^+\ell^- \nu\nu$

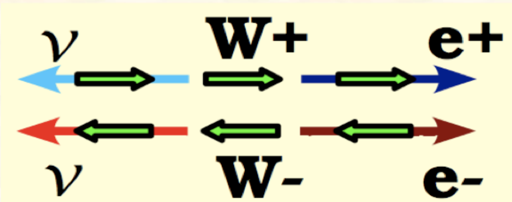
Dominant Drell-Yan background can be reduced with cuts on E_T^{miss} and its isolation (distance to nearest object)





Spin correlation gives main discrimination against irreducible background from non-resonant *WW* production

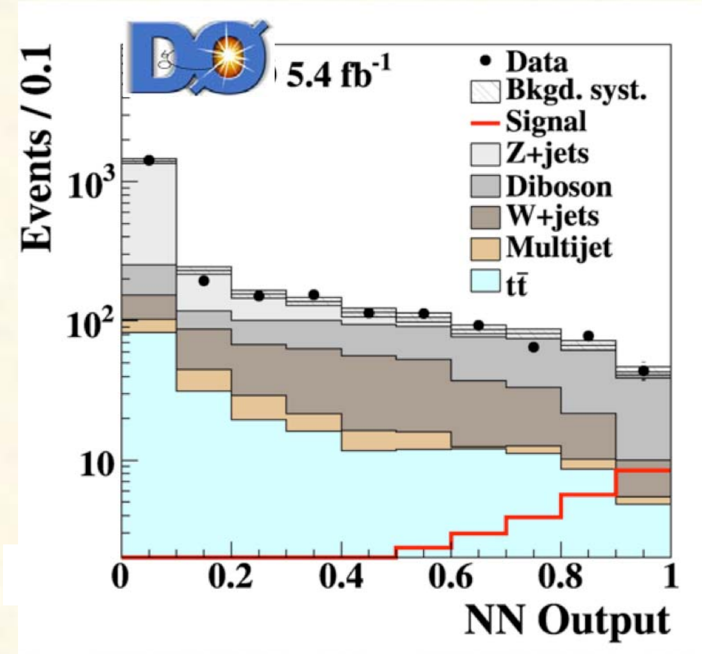


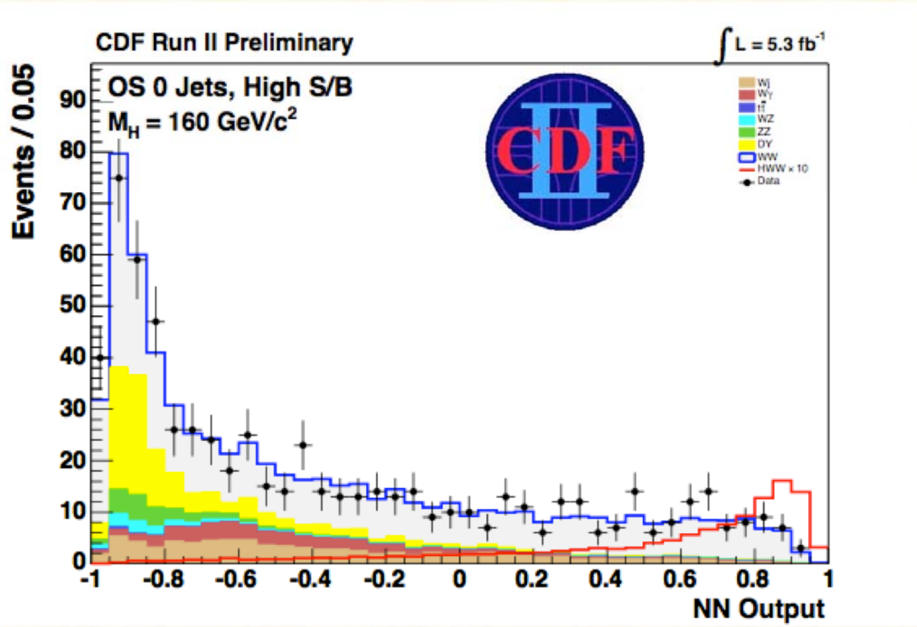


$H \rightarrow \ell^+\ell^- \nu\nu$

To increase sensitivity:

DØ: Split the samples according to lepton flavour and combines the result



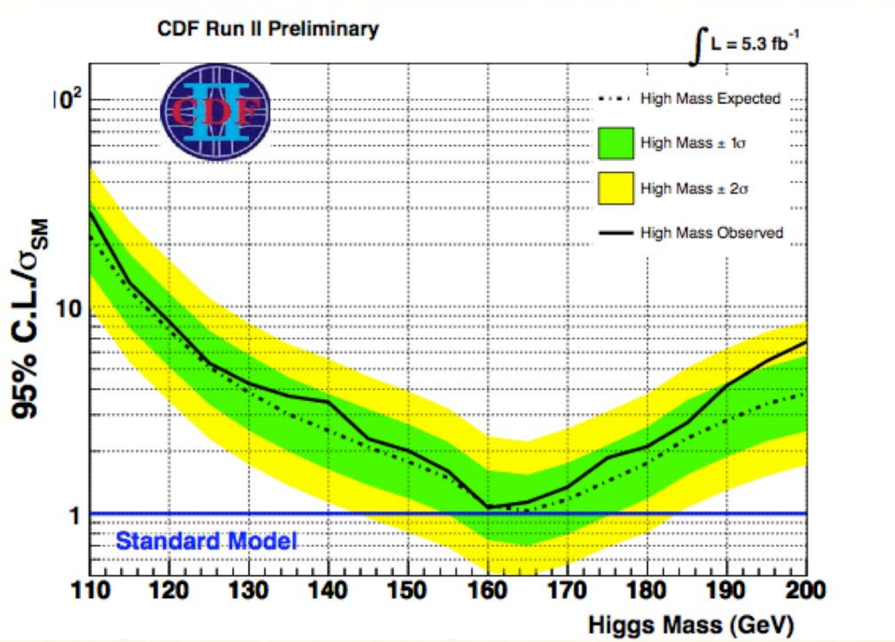


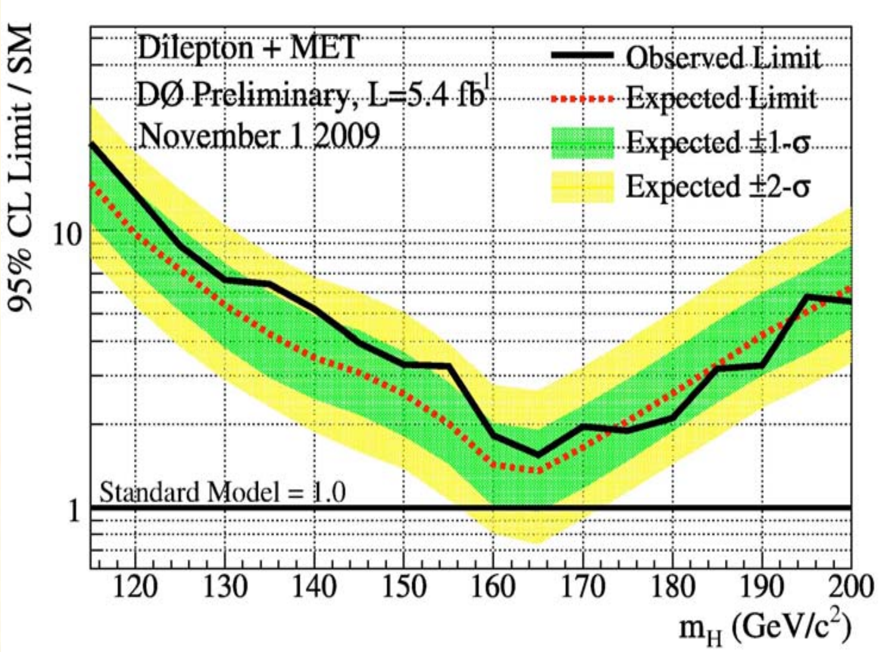
CDF: Split samples into jet multiplicity and lepton ID criteria: different signal and background composition

Veto events with tight b-tagged jet

$H \rightarrow \ell^+\ell^- \nu\nu$

Excluded cross section per experiment:

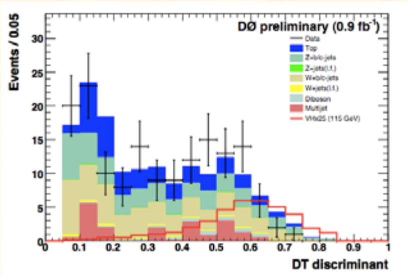


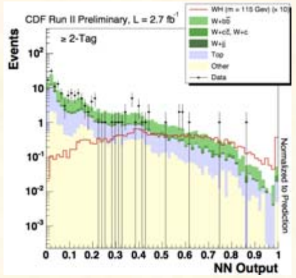


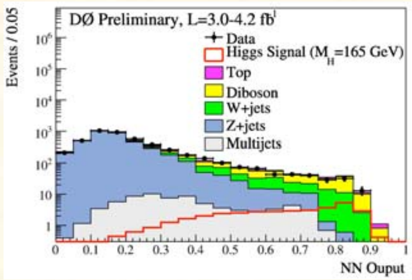
Expected limits: CDF: $\sigma_{95} = 1.03 \cdot \sigma_{SM}$ D0: $\sigma_{95} = 1.36 \cdot \sigma_{SM}$
Observed limits: CDF: $\sigma_{95} = 1.13 \cdot \sigma_{SM}$ D0: $\sigma_{95} = 1.55 \cdot \sigma_{SM}$

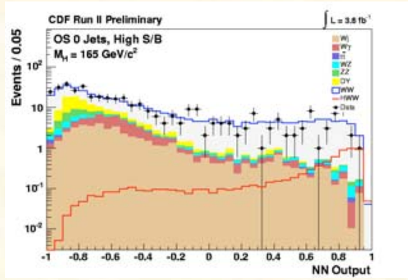
Combination → limit setting

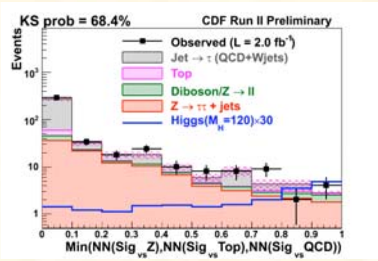
Combination of all channels and of the two experiments:
(note that exclusion is not possible in a single channel / experiment)

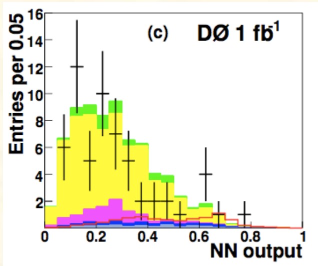


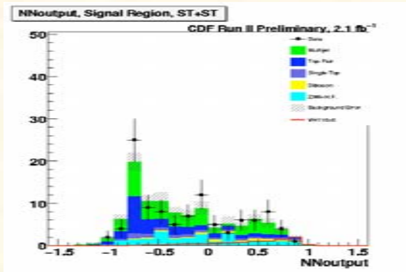












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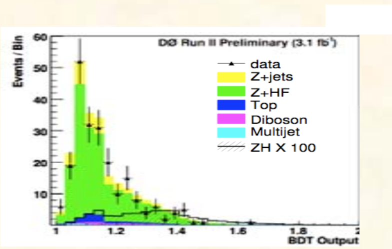
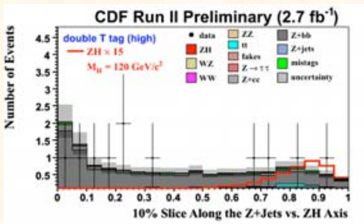
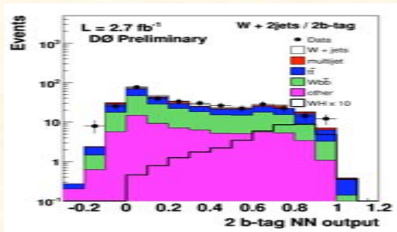
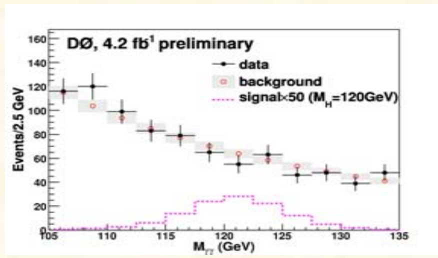








List of final states considered

- 90 mutually exclusive final states
- New analyses have been added during 2009
- Acceptance improvements, e.g. loose lepton ID or high p_T tracks

TABLE II: Luminosity, explored mass range and references for the different processes and final state ($\ell = e, \mu$) for analyses

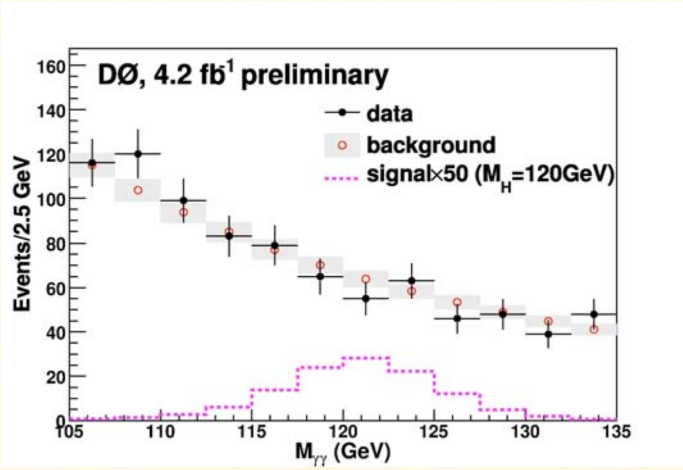
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2-jet channels 3×(TDT,LDT,ST,LDTX)	4.3	100-150	[4]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT,ST)	4.3	100-150	[5]
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	3.6	105-150	[6]
$ZH \to \ell^+\ell^- b\bar{b}$ (low,high s/b)×(TDT,LDT,ST)	4.1	100-150	[7]
$H \to W^+W^-$ (low,high s/b)×(0,1 jets)+(2+ jets)+Low-$m_{\ell\ell}$	4.8	110-200	[8]
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	4.8	110-200	[8]
$H + X \to \tau^+\tau^- + 2$ jets	2.0	110-150	[9]
$WH + ZH \to jjb\bar{b}$	2.0	100-150	[10]

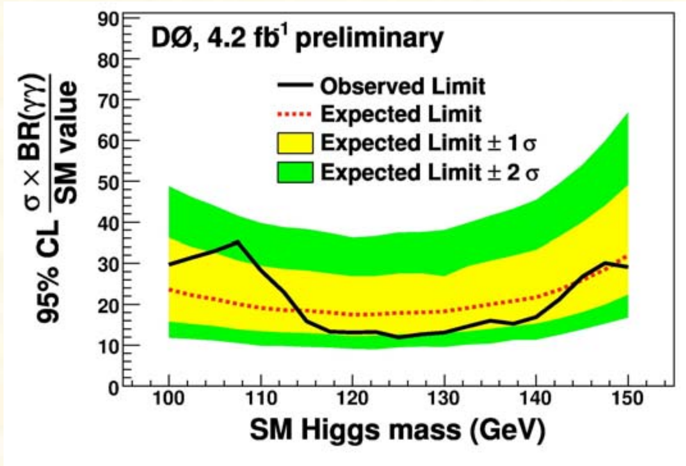
TABLE III: Luminosity, explored mass range and references for the different processes and final state ($\ell = e, \mu$) for analyses

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2×(ST,DT)	5.0	100-150	[11]
$VH \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$	4.9	105-145	[12, 13]
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)	5.2	100-150	[14]
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(ST,DT)	4.2	100-150	[15]
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	3.6	120-200	[16, 17]
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	5.4	115-200	[18]
$H \to \gamma\gamma$	4.2	100-150	[19]
$t\bar{t}H \to t\bar{t}b\bar{b}$ 2×(ST,DT,TT)	2.1	105-155	[20]

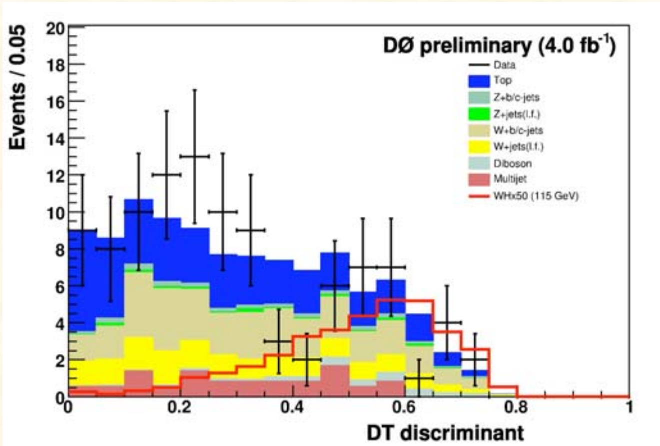
“Tevatron exotic” channels

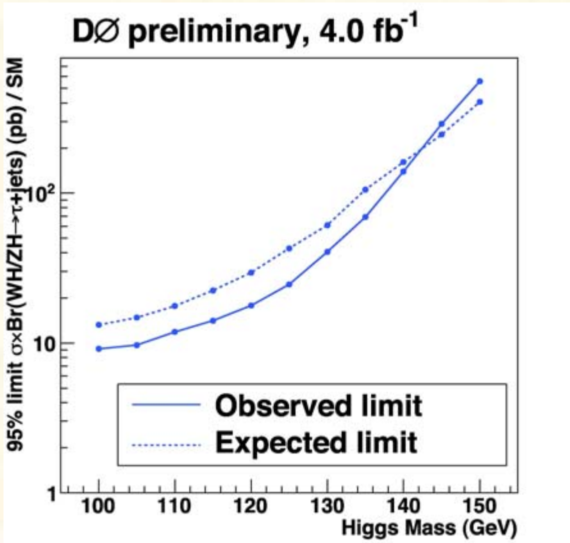
$H \rightarrow \gamma\gamma$





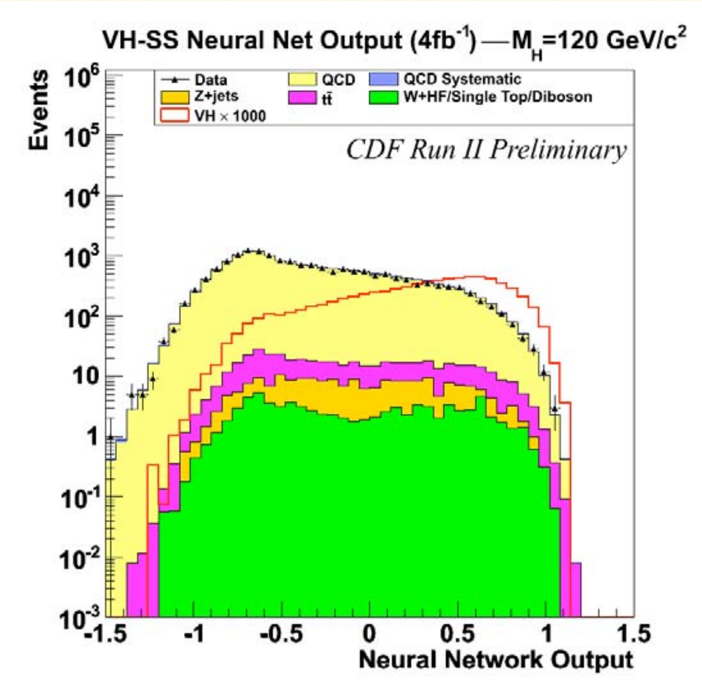
$WH \rightarrow \tau\nu\ bb$

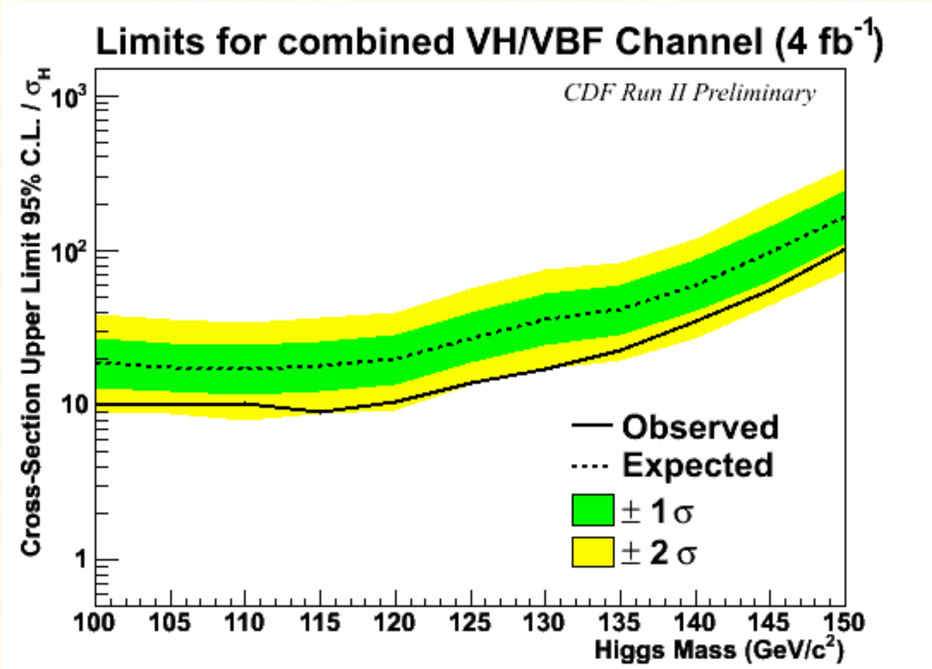




“Tevatron exotic” channels

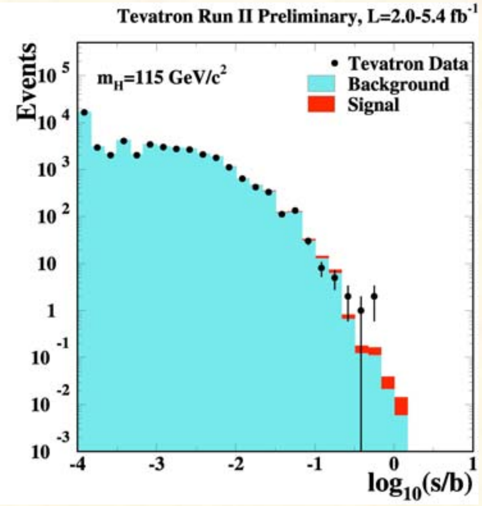
W/Z H → qq bb

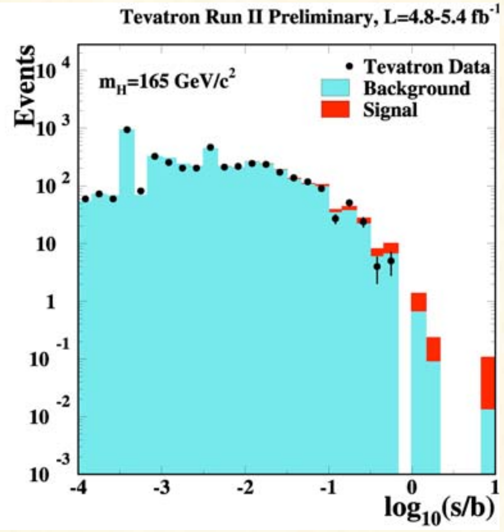


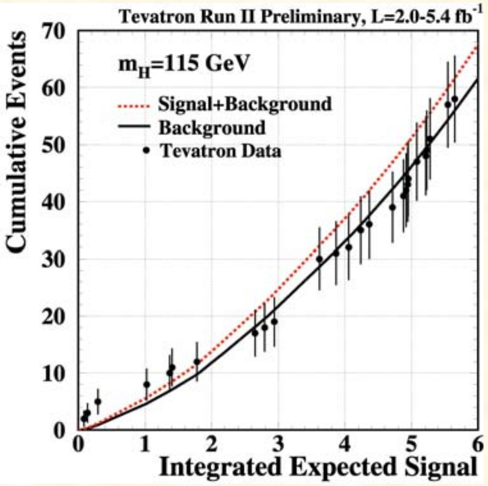


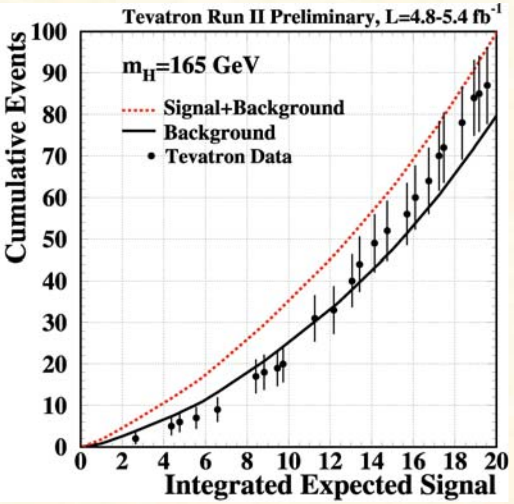
List of channels that enter the combination (cont.)

- Channels difficult to add (for comparison of data vs. expectations)
  → use bins in S/B





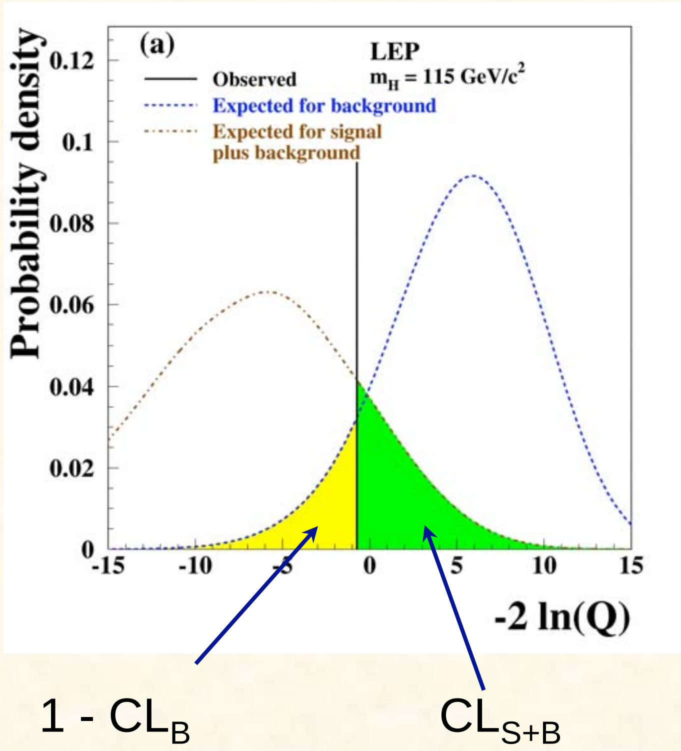




Hypothesis testing

The observed data are subjected to a likelihood ratio test of two hypothetical scenarios: Background scenario (no Higgs signal assumed)
Signal + Background scenario (Higgs signal with assumed mass added)

Compute likelihood for B and (S+B) hypothesis

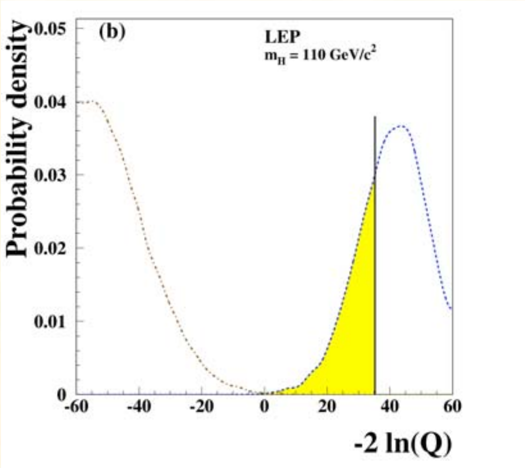


Likelihood ratio Q : = L_{S+B} / L_B

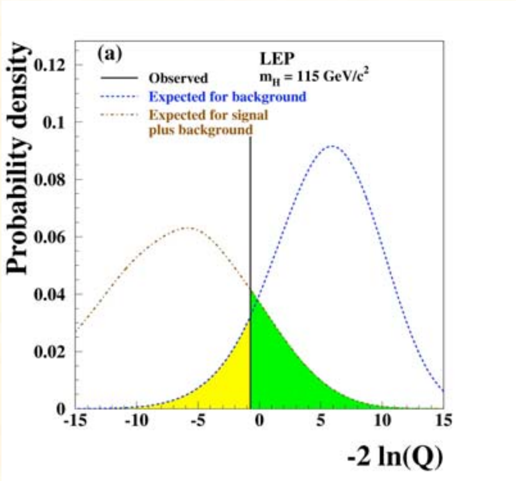
Test statistics: LLR : = - 2 ln Q
(log-likelihood ratio (LLR))

Distribution (pdf) of -2 ln Q can be calculated in MC experiments for (S+B) and B-hypothesis

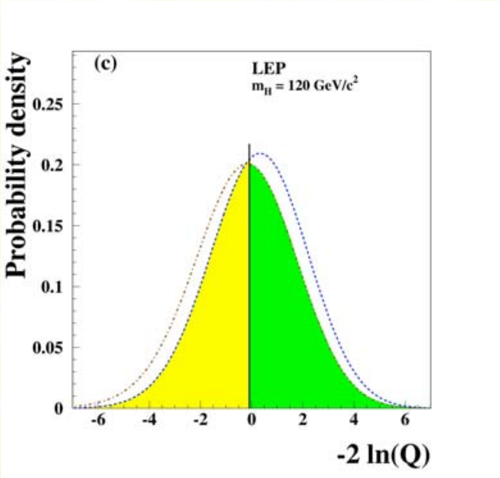
Example from LEP: Likelihood ratio distributions for different assumed Higgs boson mass values



m_H = 110 GeV/c^2



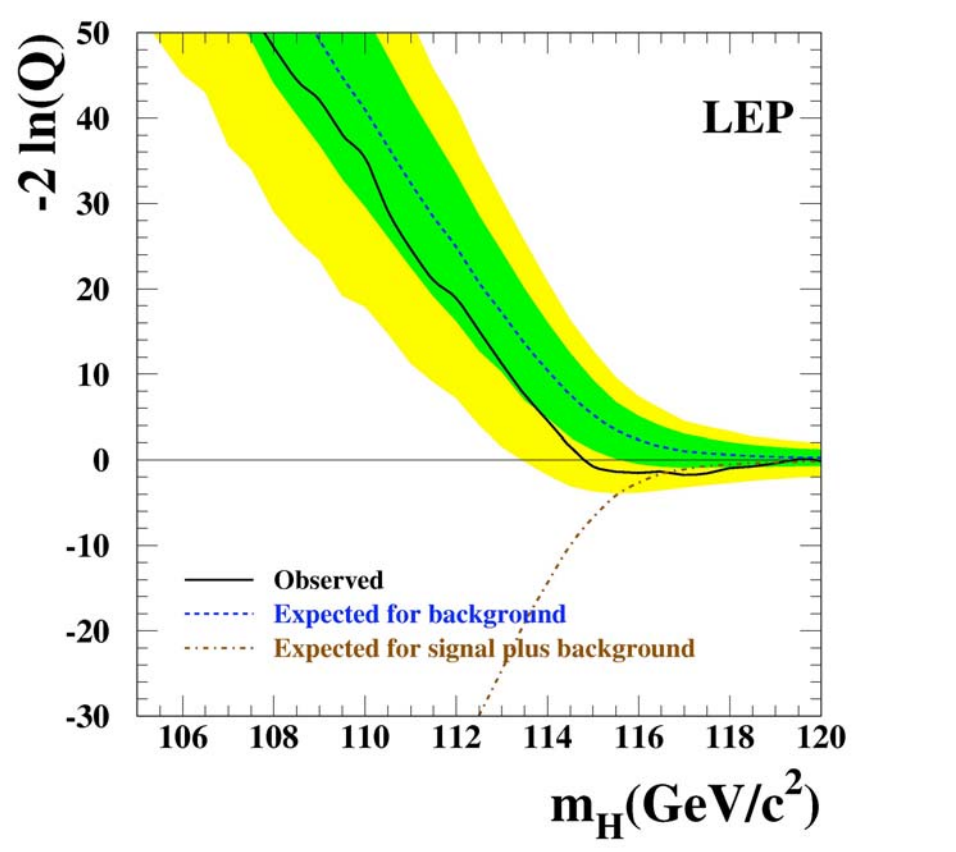
m_H = 115 GeV/c^2



m_H = 120 GeV/c^2

Difference between the median values between the S+B and B hypothesis is a measure of the sensitivity

LEP: Observed and expected behavior of -2 ln Q

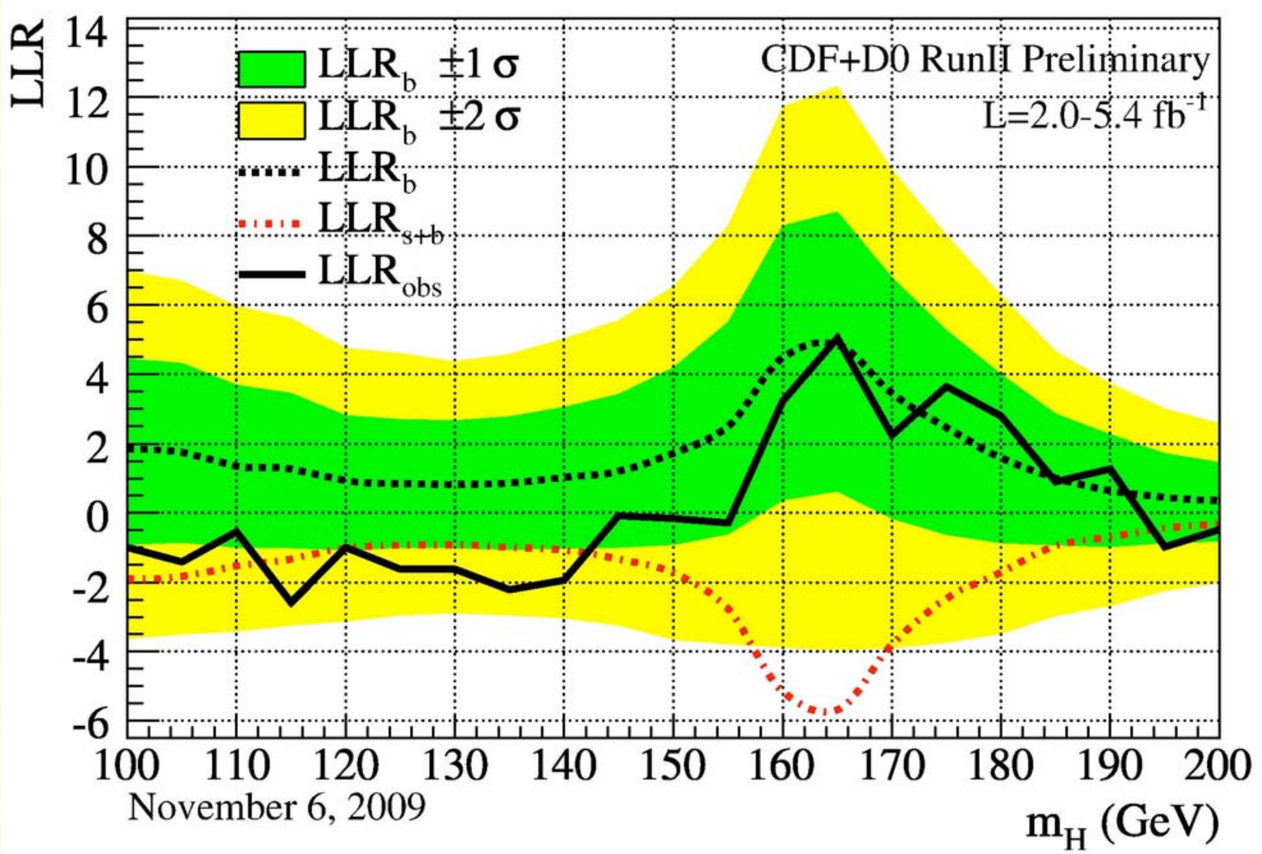


Broad minimum around 115 GeV/c^2

Neg. value of -2 ln Q in data indicates that the (S+B) hypothesis is more favored than the B-hypothesis,

however, at low significance

Tevatron 2010: Distribution of the LLR



- Sensitivity is largest around 165 GeV
- Observed LLR is consistent with background hypothesis, although at low mass, S+B is slightly favoured

Systematic uncertainties

Analyses are affected by significant systematic uncertainties;

Example: The two most significant DØ analyses:

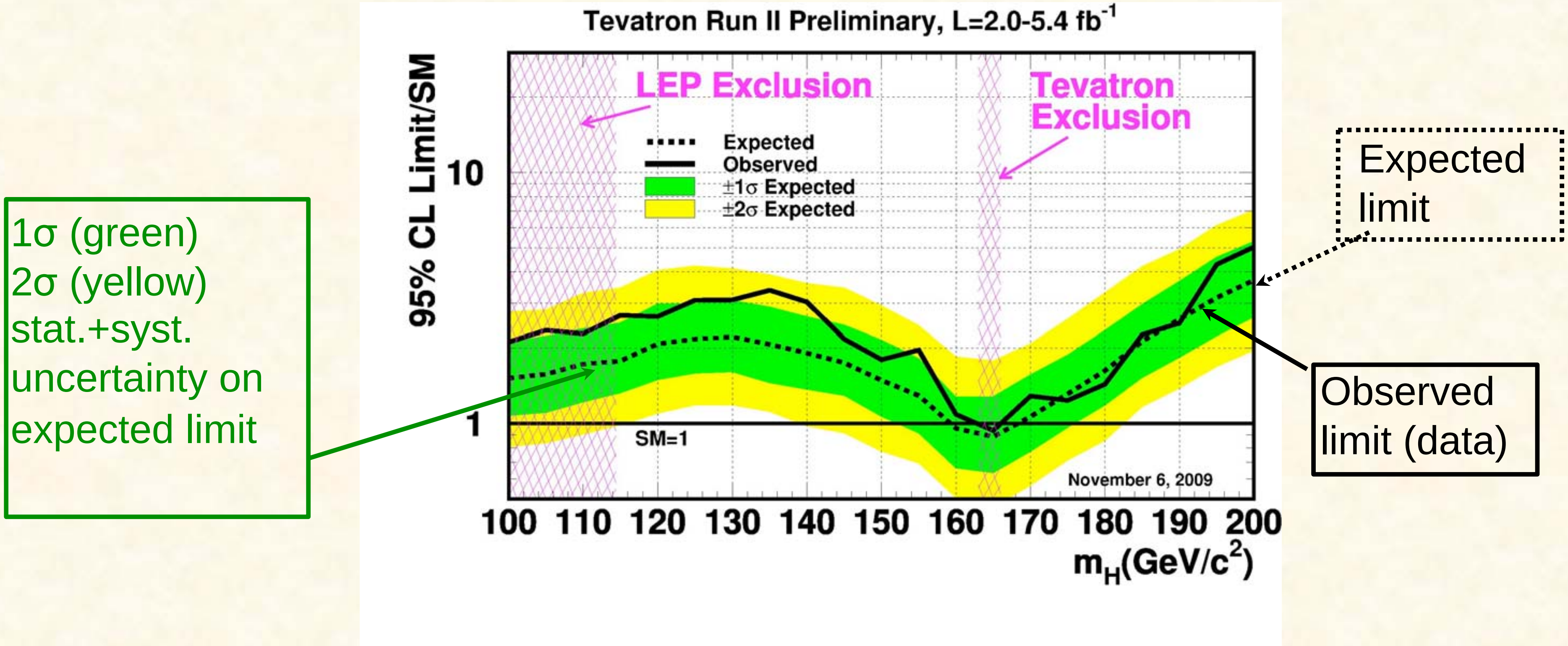
Source	$WH \to e\nu b\bar{b}$
Luminosity	6.1
Normalization	-
Jet Energy Scale	3.0
Jet ID	5.0
Jet Triggers	-
Electron ID/Trigger	4.0
Muon ID/Trigger	-
b-Jet Tagging	3-9
Background σ	7-20
Multijet	14
Shape-Dependent Bkgd Modeling	2-10

Source	$H \to W^+W^-$
Luminosity	6.1
Jet Energy Scale	3.0
Jet ID	1-2
Tau Energy Scale/ID	-
Electron ID/Trigger	3-10
Muon ID/Trigger	7.7-10
b-Jet Tagging	-
Background σ	7-10
Signal σ	11
Multijet	2-20
Shape-Dependent Bkgd Modeling	5-20

- Systematic uncertainties for background rates are generally several times larger than the signal expectation itself
- To minimize the degrading effect of systematic uncertainties on the search sensitivity, the individual background contributions are fitted to the data observation by maximizing a likelihood function

  Nuisance parameters allow for variations within errors
- Each systematic uncertainty (incl. uncertainty on signal cross section) is folded into the signal and background expectation via Gaussian distributions (correlations preserved)

Combined Tevatron limits



Tevatron experiments set a 95% CL exclusion of a SM Higgs boson in the mass region 162−166 GeV (first direct exclusion since LEP)

At m_H = 115 GeV Expected limit: 1.8 x σ_{SM}

Observed limit: 2.7 x σ_{SM}

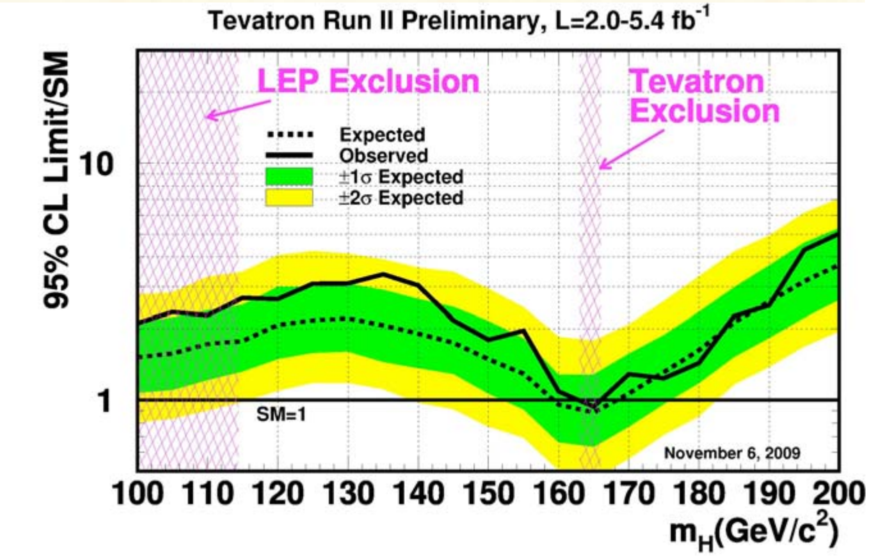
Comments on this combination

• Use best knowledge on signal cross sections
  NNLO + NNLL calculations for the gluon fusion
  NLO cross sections for VBF + W/ZH associated production

• Background cross sections normalized using either experimental data or NLO calculations (e.g. MCFM for W+heavy flavour processes)
  Finally constrained via nuisance parameters in a likelihood fit

• Assessment of systematic uncertainties is difficult !

  In particular treatment of signal cross section uncertainties might be considered to be optimistic



Conclusions on the Tevatron Higgs search

- The Tevatron experiments have reached sensitivity (expected limit) for the SM Higgs boson in the mass range around 160 GeV

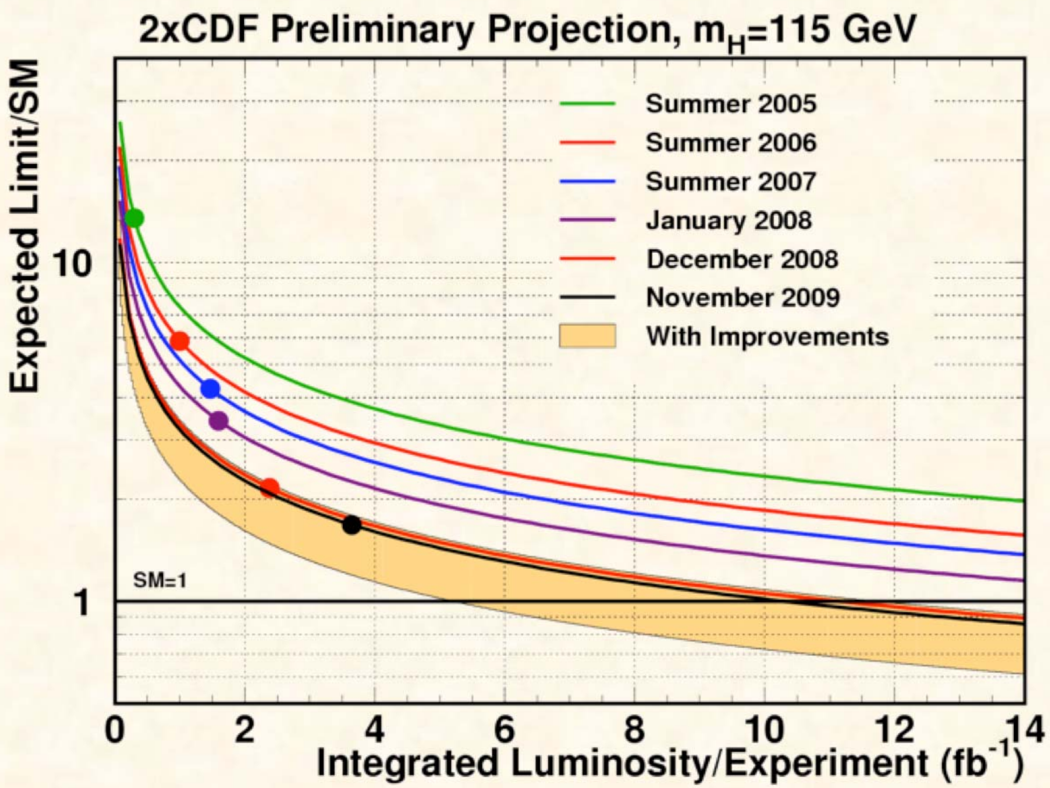
- With increased luminosity the sensitivity in this region is expected to reach the 3σ level
  → Either a large mass region can be excluded with 95% C.L. or first evidence (3σ) for a SM Higgs boson can be found;

  However: not a single "evidence channel" available
  needs the combination of many channels and of the two experiments

- The Higgs search in the mass range below ~130 GeV is difficult (also at the LHC);

  Search for the bb final state at the Tevatron will provide important complementary information to the LHC Higgs search in the $H \rightarrow \gamma\gamma$ and $qqH \rightarrow qq\,\tau\tau$ channels

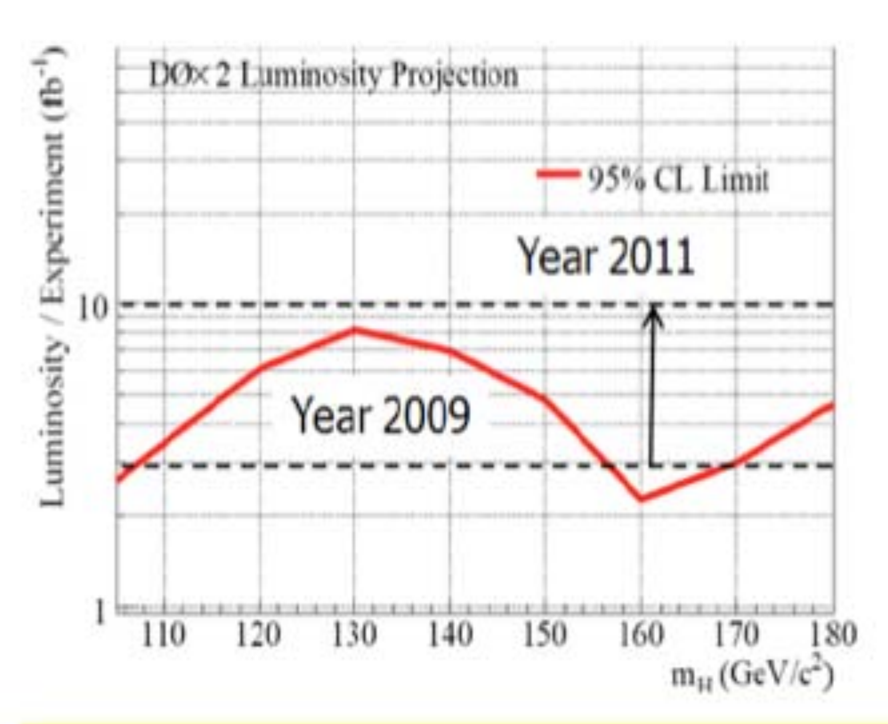
Expected Tevatron sensitivity



- For 10 fb^{-1}, expect 95% C.L. exclusion for a Higgs boson mass of 115 GeV
- Can be reached faster, if analysis improvements can be achieved

Expected Tevatron sensitivity (cont.)

Possible improvements: - improved m_{bb} mass resolution
- improved b-tagging, c-tagging, lepton ID, ...



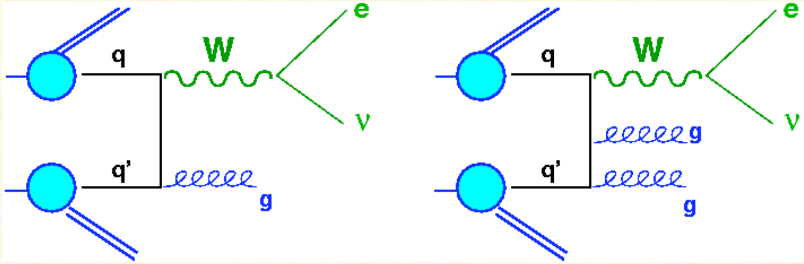
G. Bernardi, Lepton-Photon Hamburg, 2009

- With improvements, 95% C.L. exclusion might be reached over mass range up to ~200 GeV

What can be learned on Test of Monte Carlo Models ?

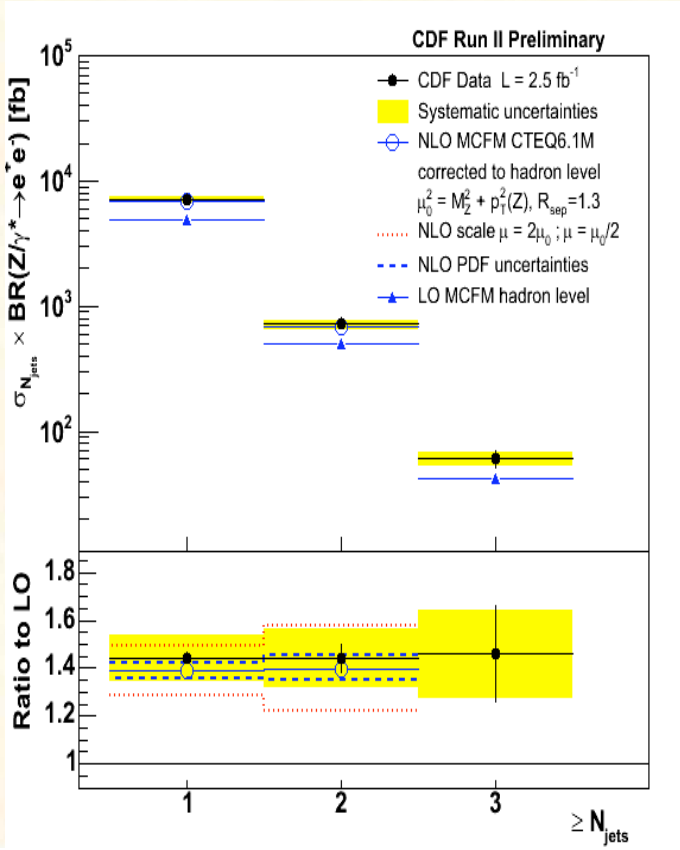
- W/Z production as an example -

QCD Test in W/Z + jet production

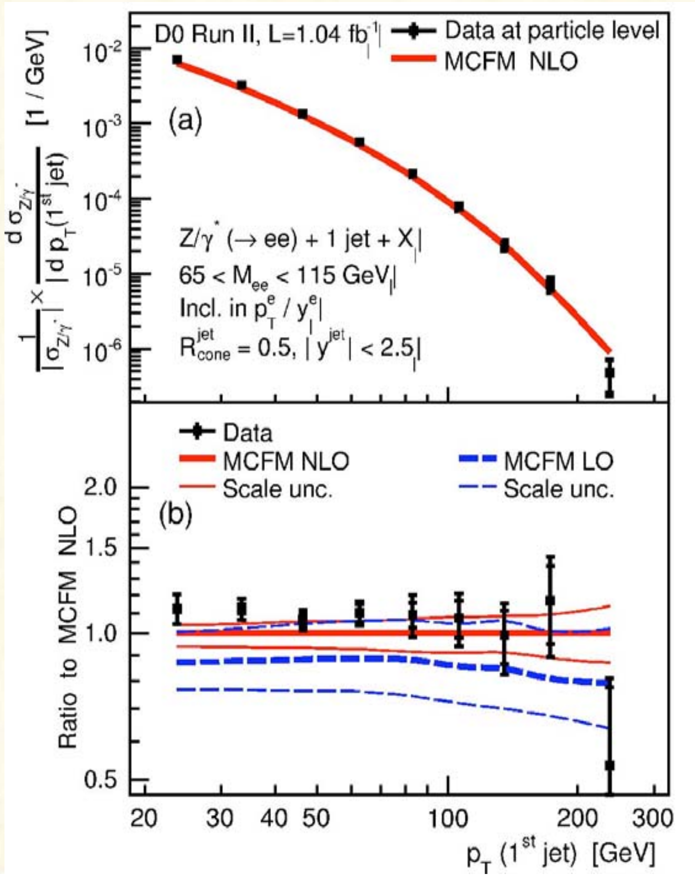


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors; NLO central value ~10% low

Jet multiplicities in Z+jet production

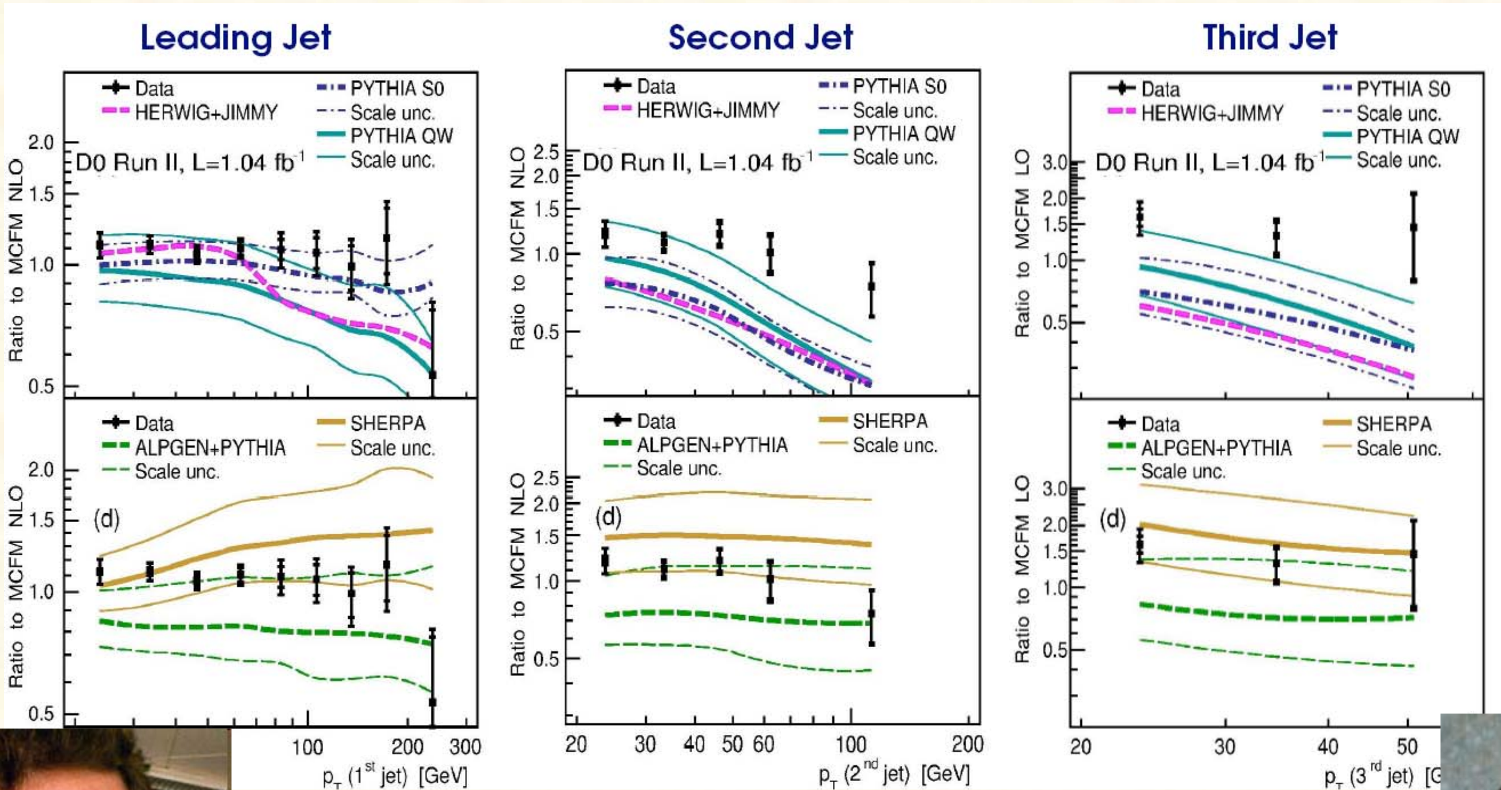


p_T spectrum of leading jet



comparison to different Monte Carlo predictions

- Comparison of p_T spectra of leading, second and third jet in Z+jet events to
  - PYTHIA and HERWIG (parton shower based Monte Carlos)
  - ALPGEN and SHERPA (explicit matrix elements (tree level) matched to parton showers)



….they might have to try harder