MANCHESTER 1824

The University of Manchester

Higgs - SM/MSSM

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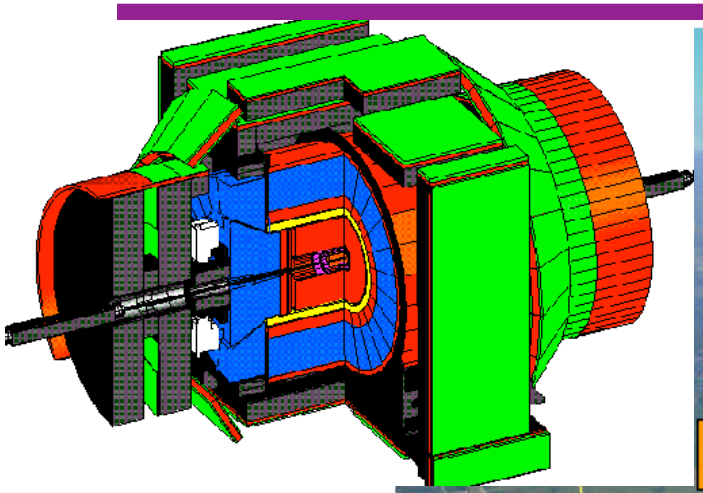
Outline

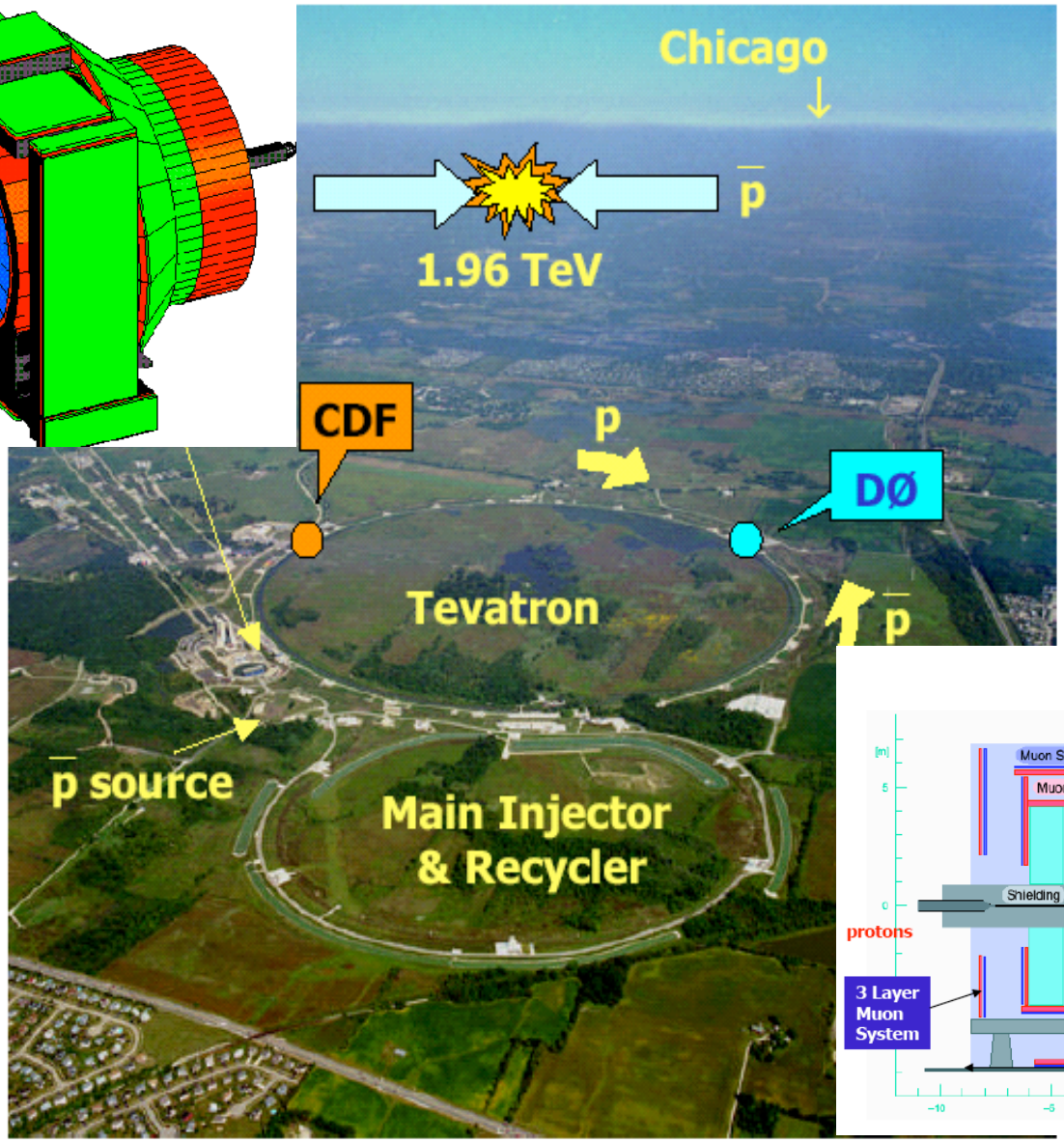
SM Higgs Boson
- Low mass Higgs (associated production)
- High mass Higgs ($H \rightarrow WW$)
- Combination

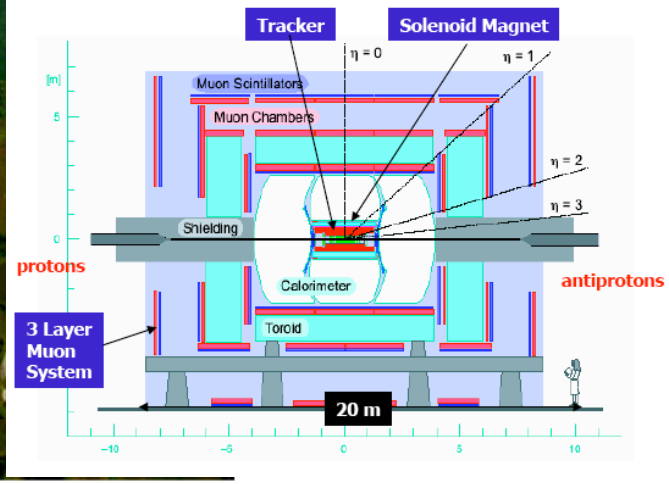
MSSM Higgs Bosons (φ=h,H,A)
- $\varphi \rightarrow \tau\tau$ (inclusive)
- $b\varphi \rightarrow bbb$ and $b\varphi \rightarrow b\tau\tau$ (exclusive)
- charged Higgs

Beyond the MSSM:
- doubly-charged Higgs
- fermiophobic Higgs

Tevatron Experiments

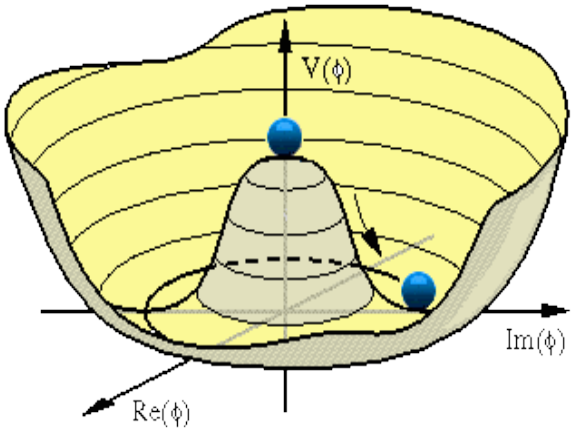






Higgs in a Nutshell

In the Standard Model, the Higgs field is a complex scalar field, $V(\phi)$:

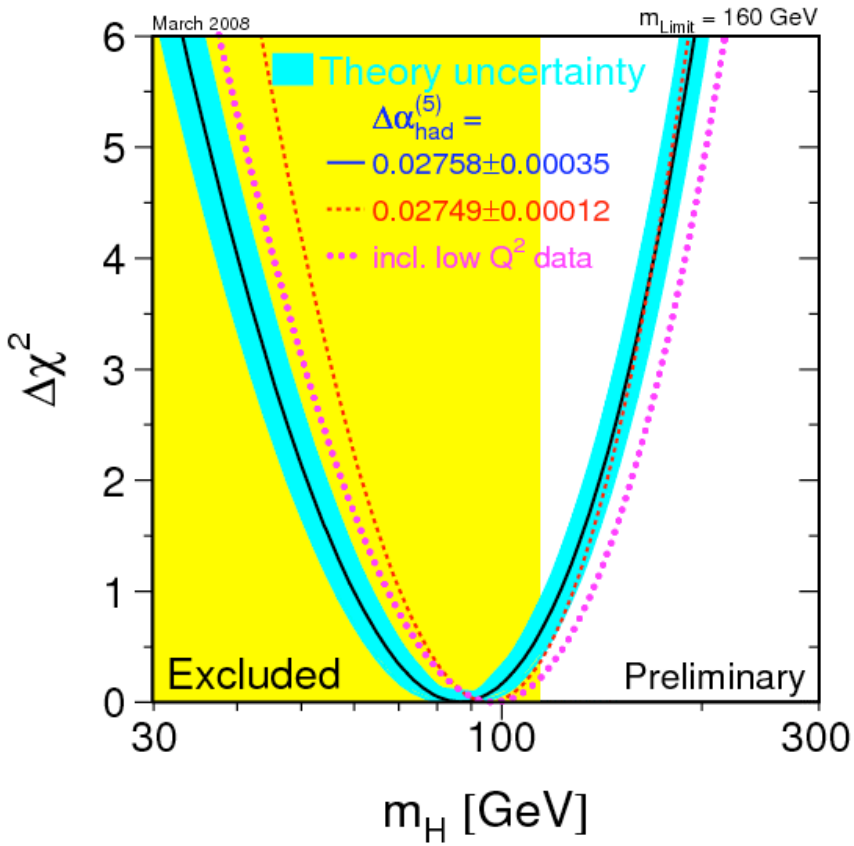


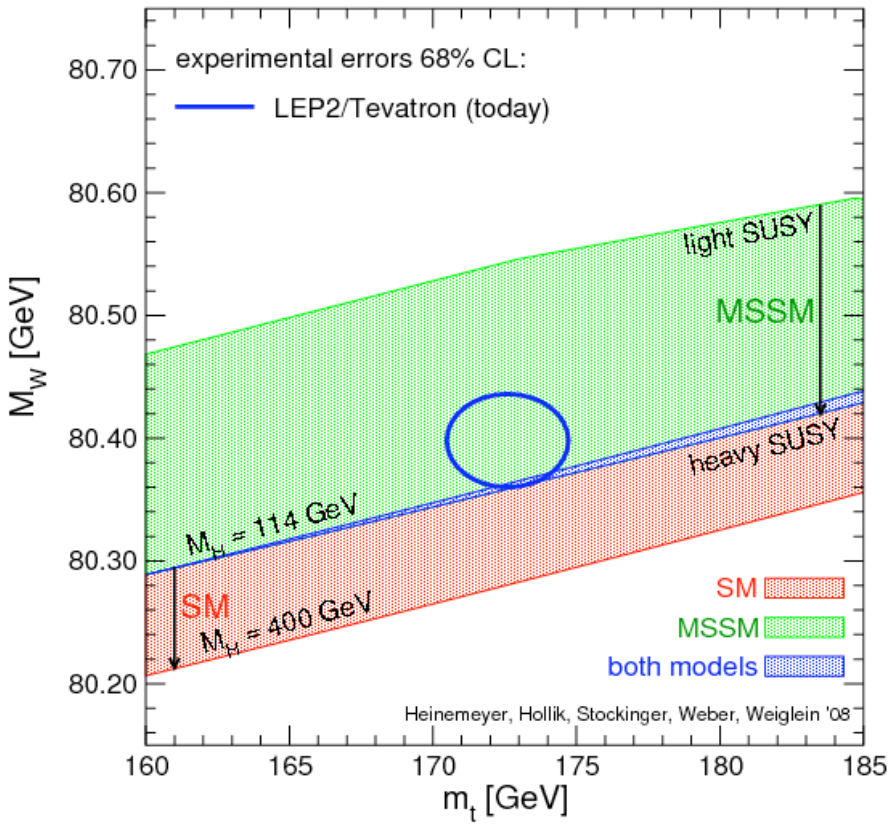
Through electroweak symmetry breaking, the gauge bosons (W, Z) acquire mass.

A single Higgs boson with spin 0 appears.
The only free parameter is its mass.

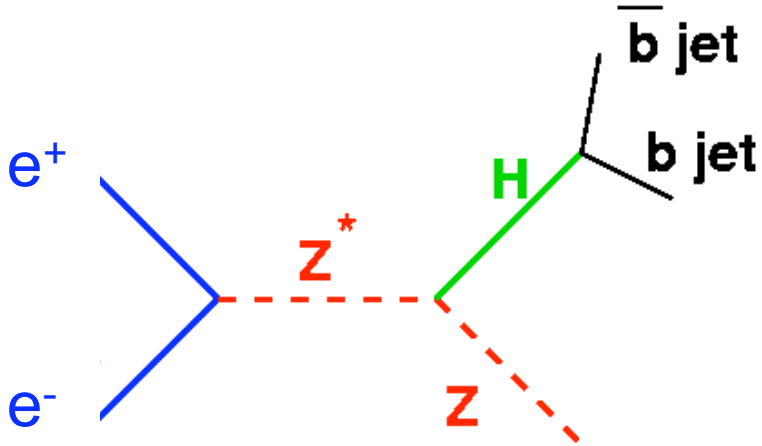
A light Higgs might be around the corner (if the SM is correct)

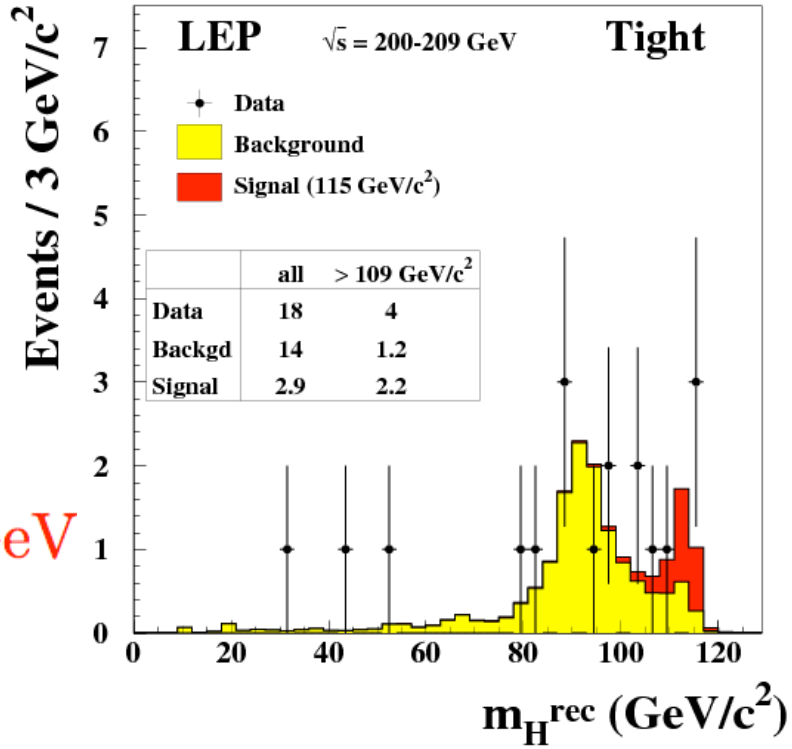
$$m_H = 87 \pm {}^{36}_{27}\ \text{GeV}$$



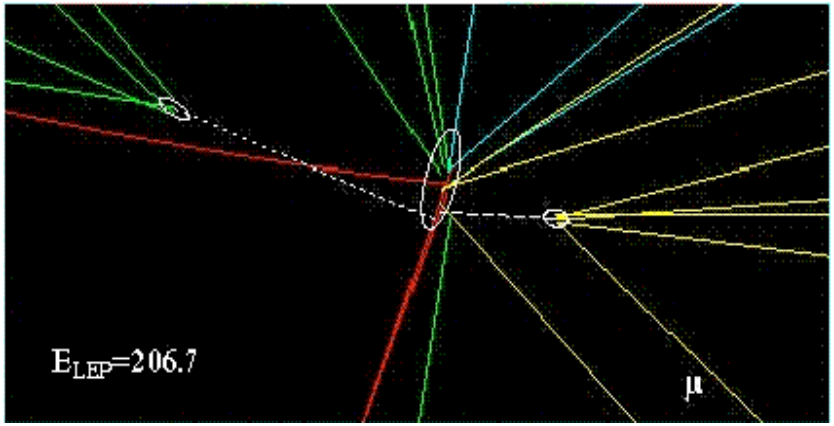


LEP's Legacy



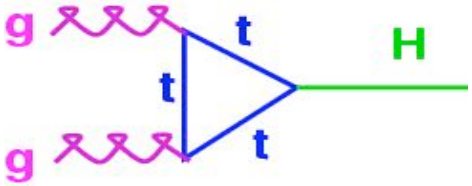


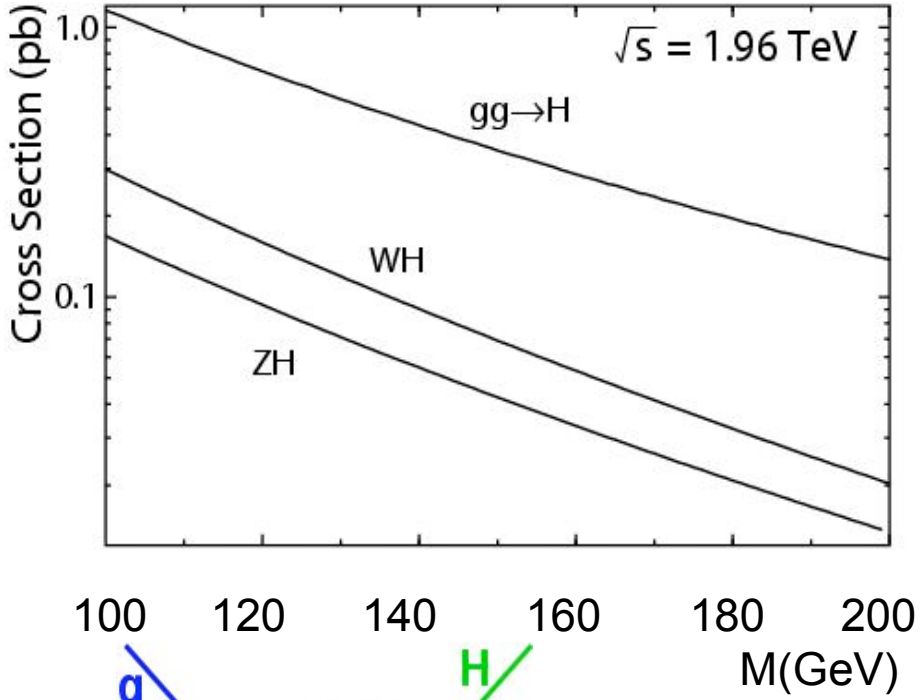
$$\sqrt{s} - m_Z = 206.6 - 91.2 = 115.4 \text{ GeV}$$

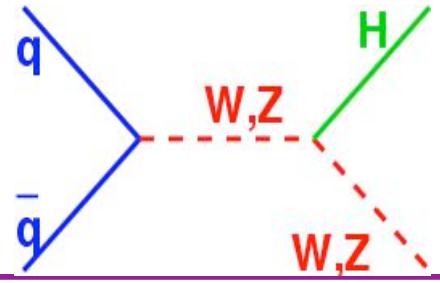


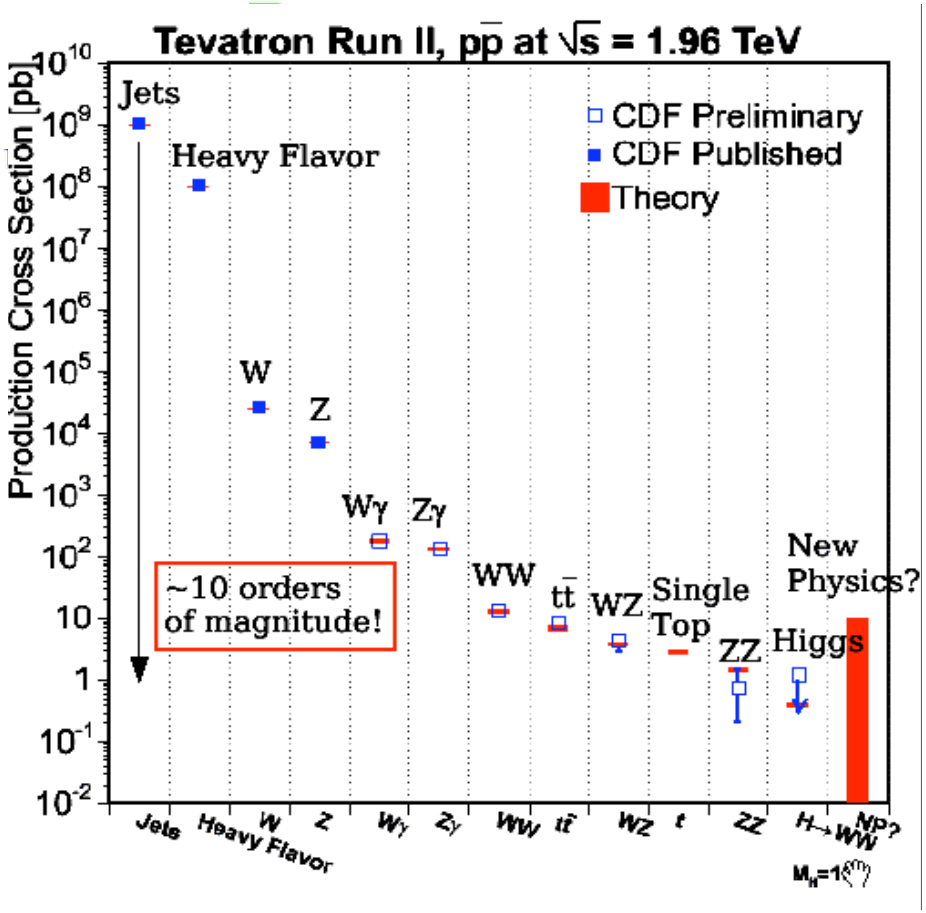
Search for the Standard Model Higgs boson at LEP
Phys. Lett. B565 (2003) 61.

Production at the Tevatron..



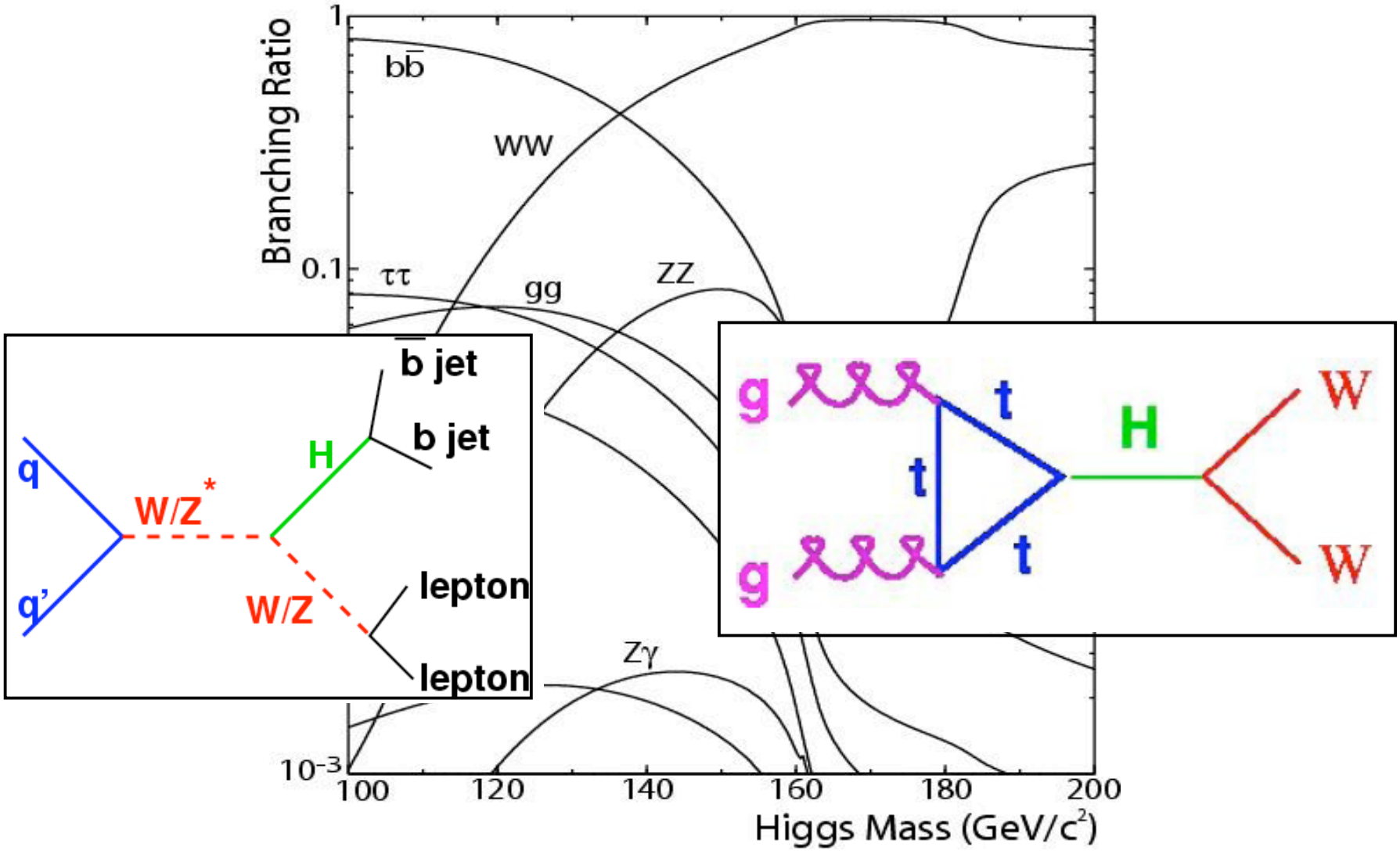






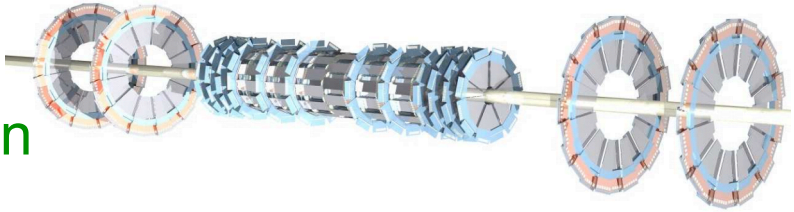
one in ~$10^{10\text{-}12}$ events will be a Higgs boson

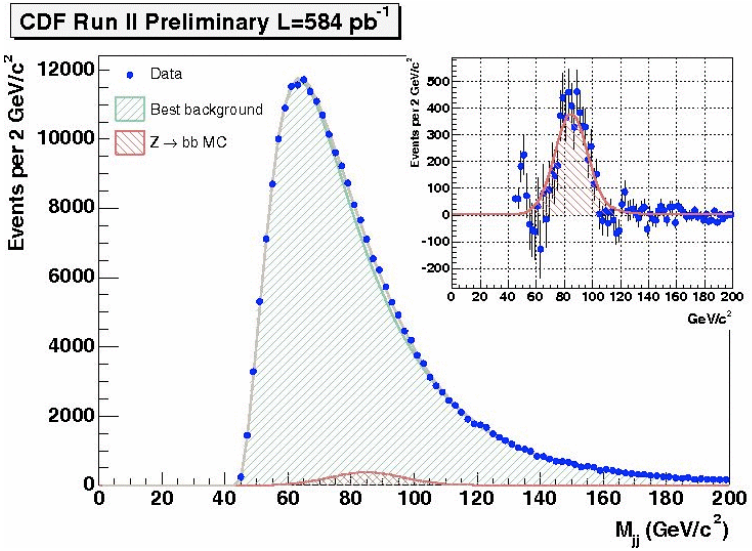
Search Strategy at the Tevatron

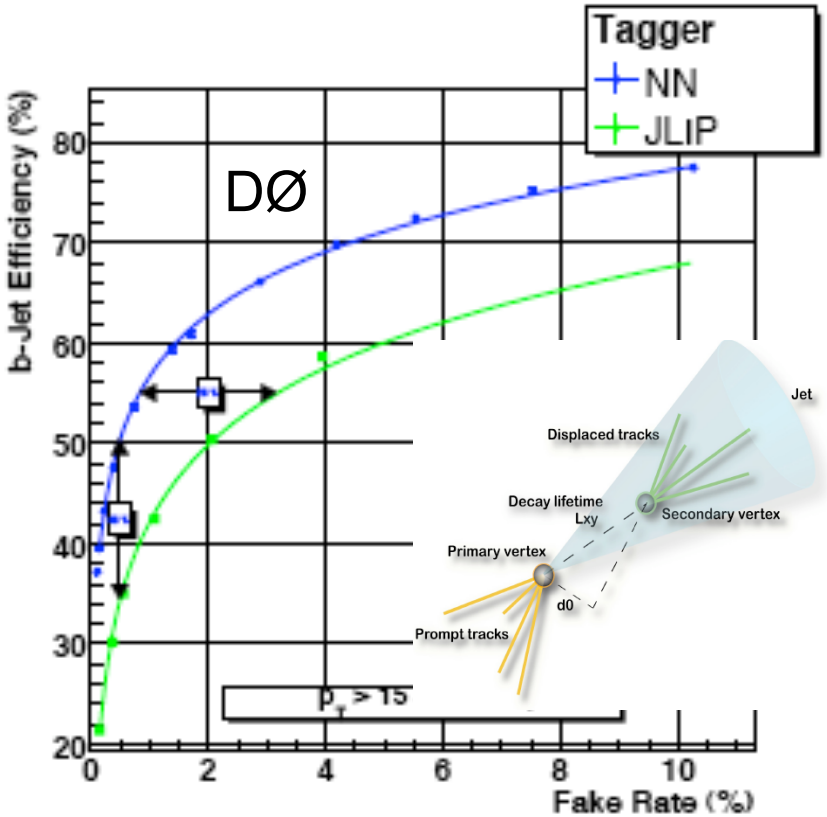


Tools

- for all masses:
  lepton identification
- at low masses:
  Neural Net b tagging
  di-jet mass resolution
  and jet energy scale







di-jet mass distribution for b tagged jets

Background

- Electroweak background: W(+jets), Z(+jets), WW, WZ, ZZ,
  also tt and single top

  kinematic distributions using Monte Carlos, e.g.:
  PYTHIA (LO + parton shower)
  ALPGEN (LO+MLM parton shower/matrix element matching)

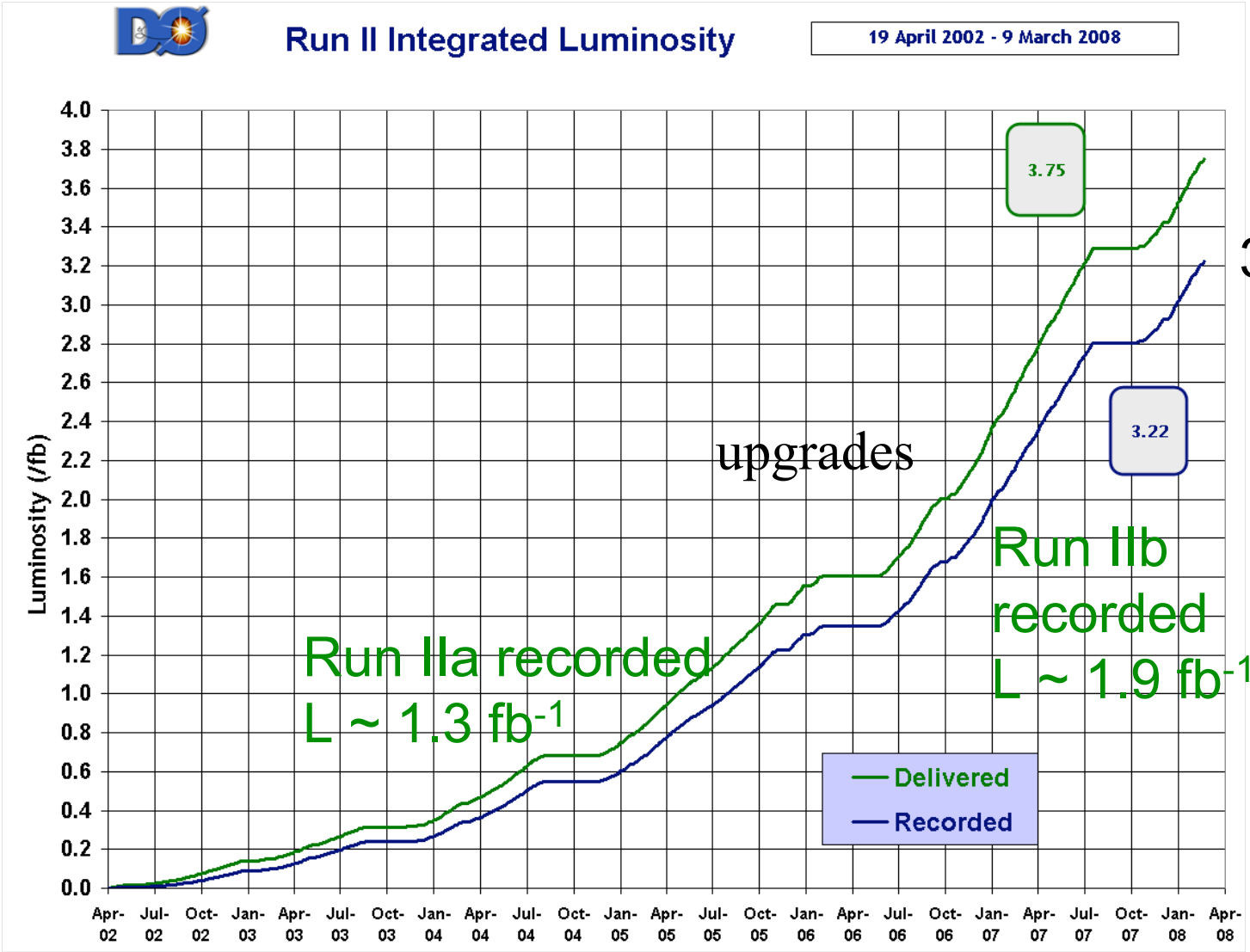
  normalised using (N)NLO cross-sections and k factors
  verified by data

Jet production (QCD) and instrumental background

  data using control samples

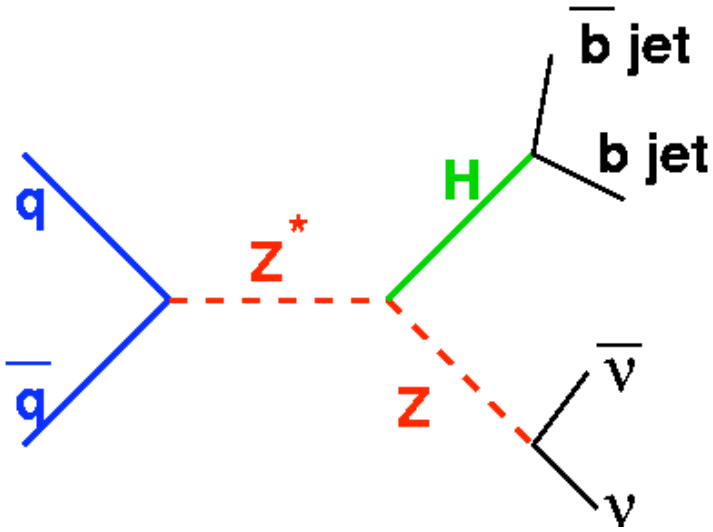
Typical signal/background ratio of 1/100 in final distributions:
requires advanced analysis techniques (e.g. NN, Limit Setting..)

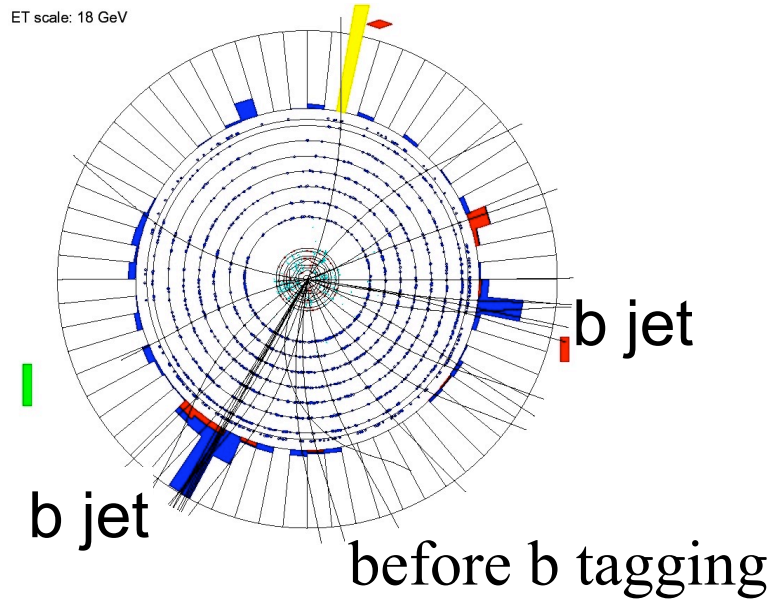
Data set



3.2 fb^{-1}

ZH →ννbb

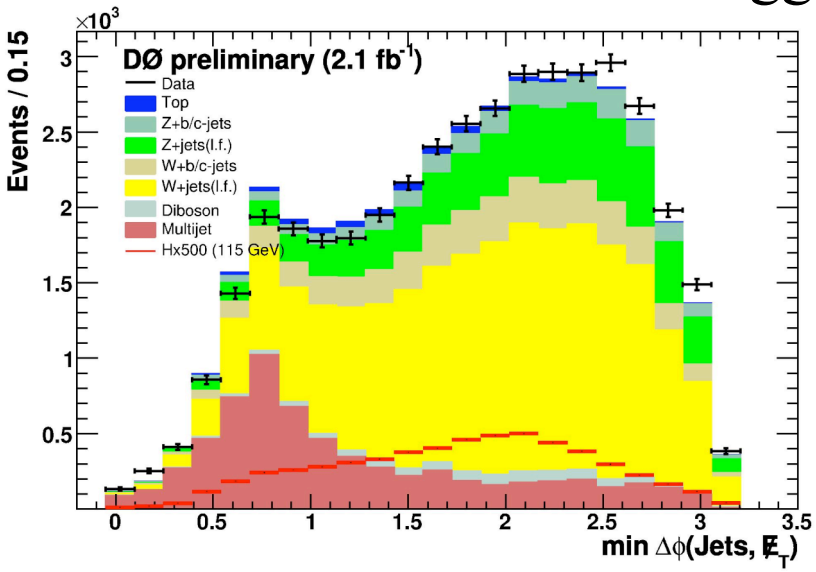




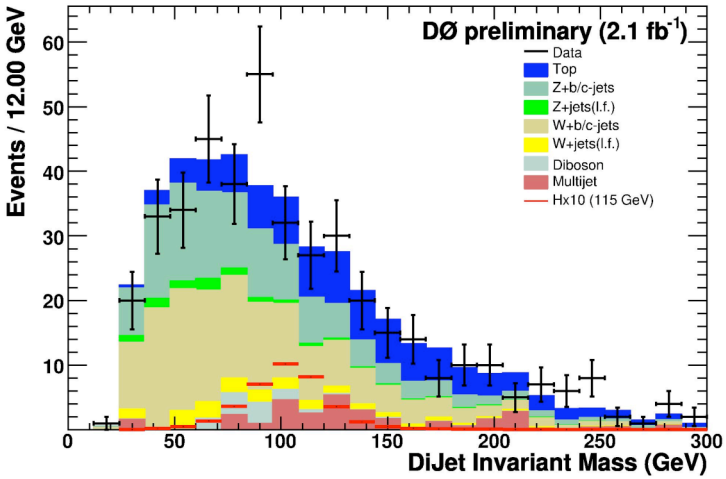
Typical selection:

two acoplanar jets

$\not{E}_T > 50$ GeV



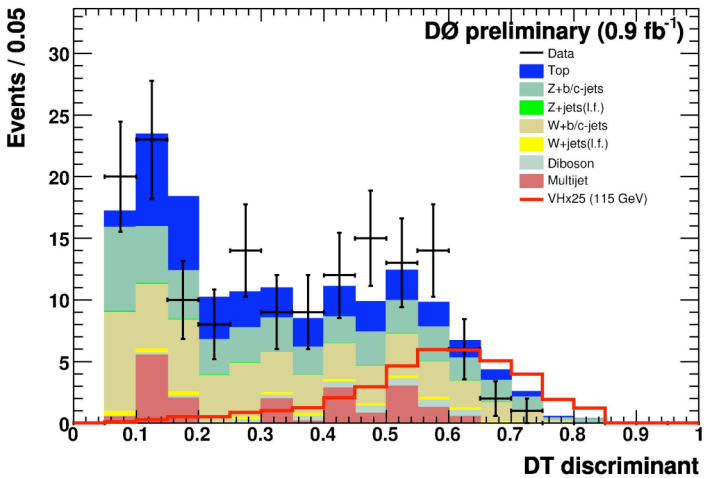
ZH →ννbb



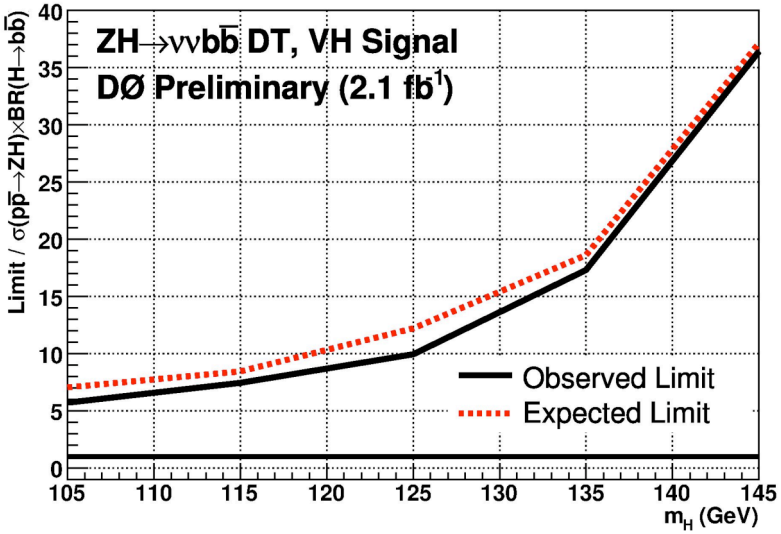
Two asymmetric b tags (one loose, one tight)

Backgrounds :

- W+heavy flavour jets
- Z +heavy flavour jets
- top pairs

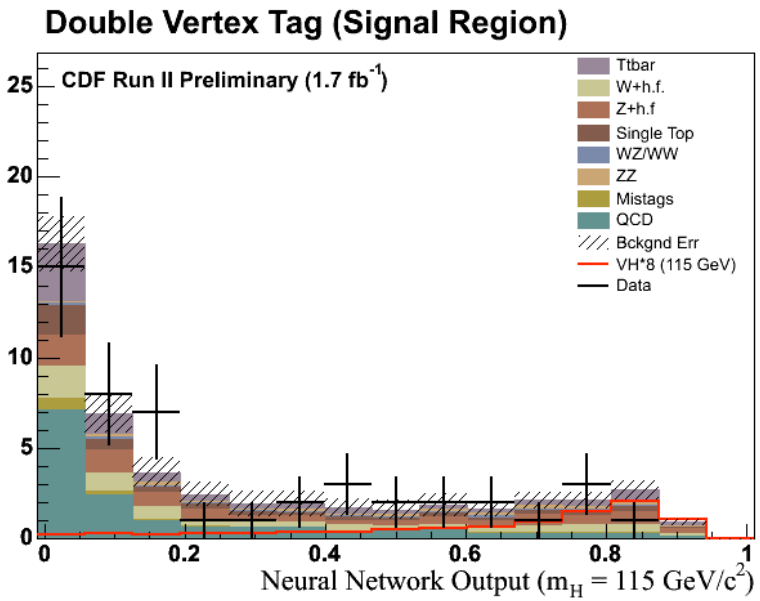


Decision Tree Output

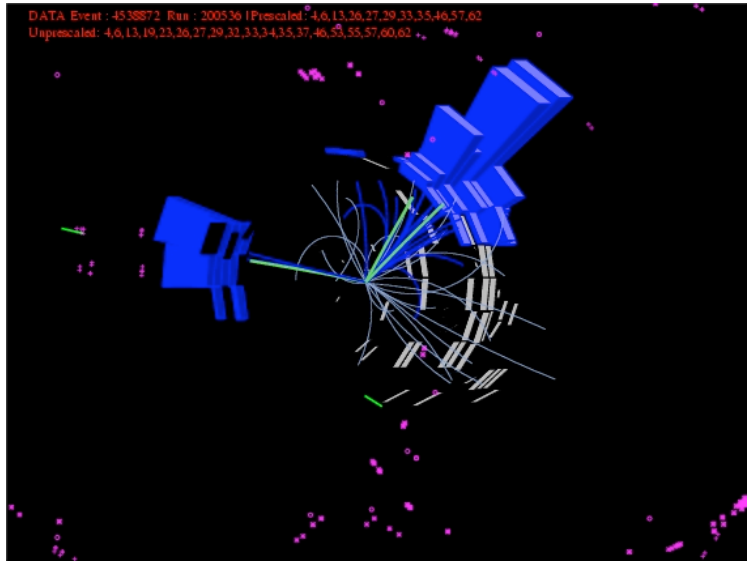


ZH →ννbb

Neural Networks



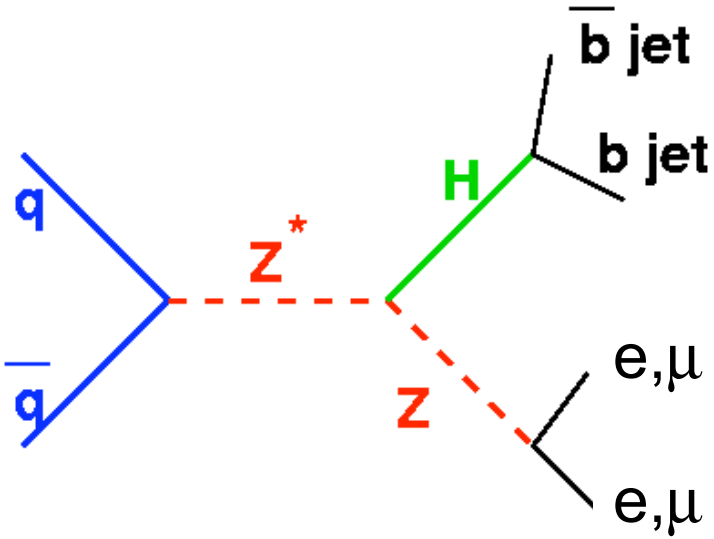
most signal-like CDF event

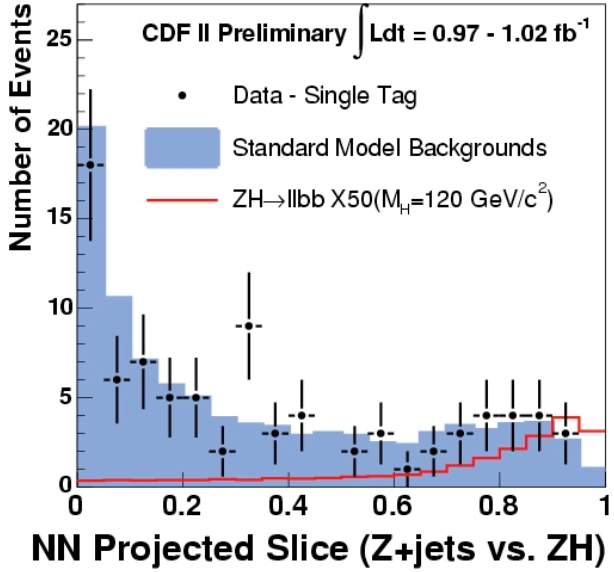


m_H=115 GeV	CDF exp,obs	DØ exp,obs
σ_{95}/SM =	8.3,8.0	8.4,7.5

These searches include WH signal where charged lepton is lost.

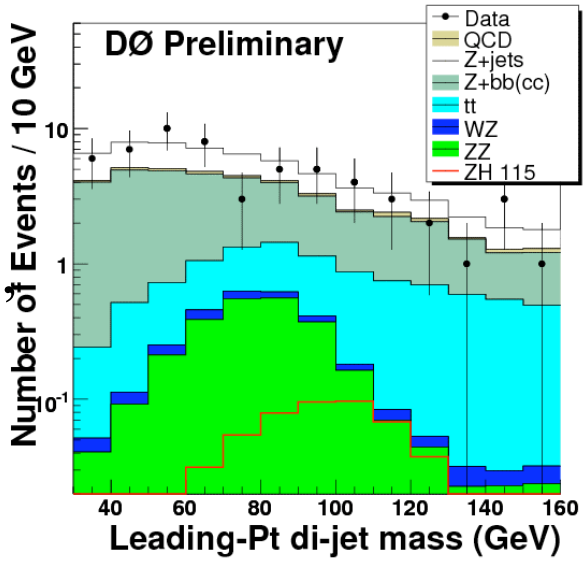
ZH →llbb





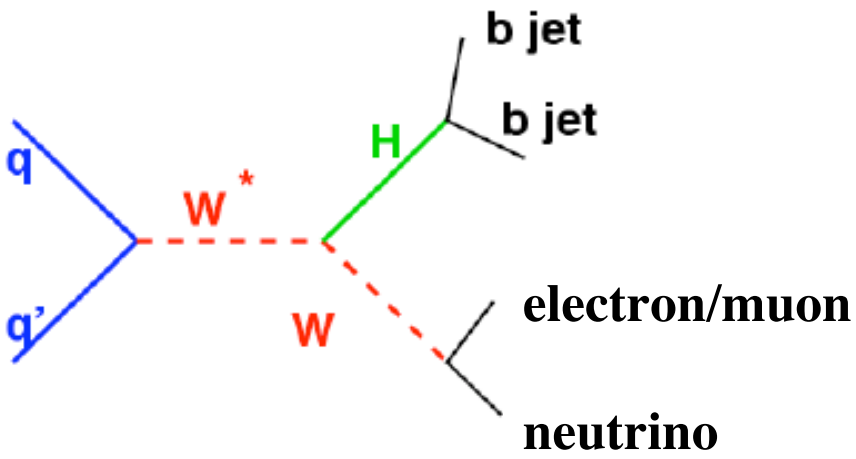
$$L = 1\ \mathrm{fb}^{-1}$$

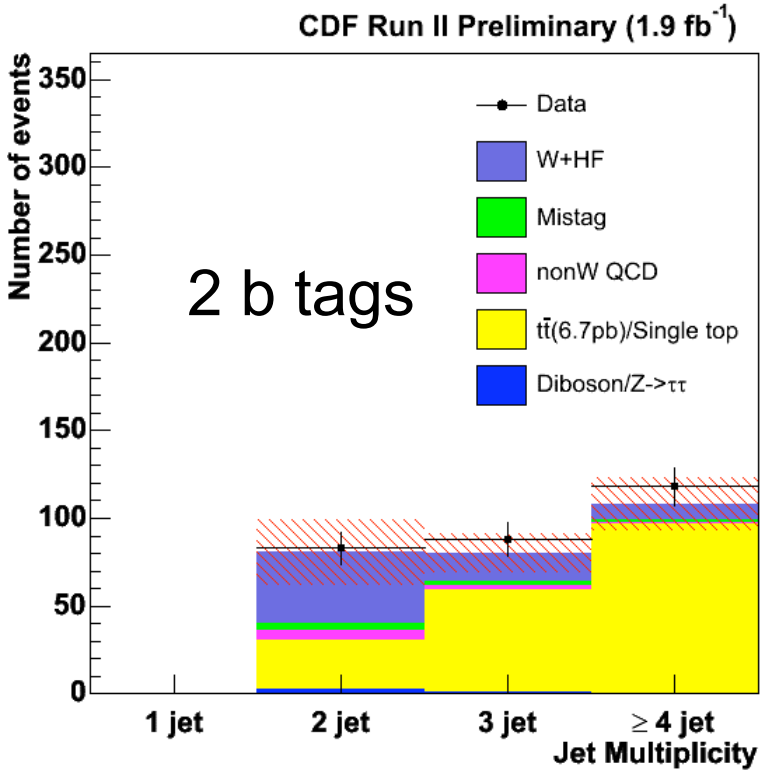
1 'tight'
or
2 'loose'
b-tags



m_H=115 GeV	CDF exp,obs	DØ exp,obs
σ_{95}/SM =	16,16	20.4,17.8

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



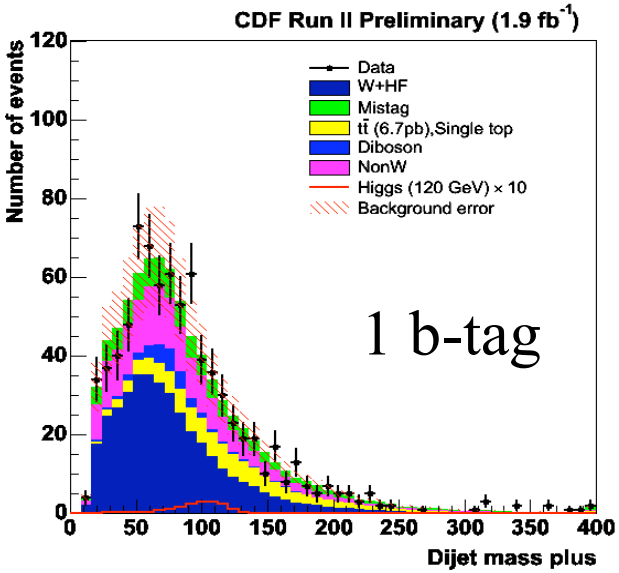


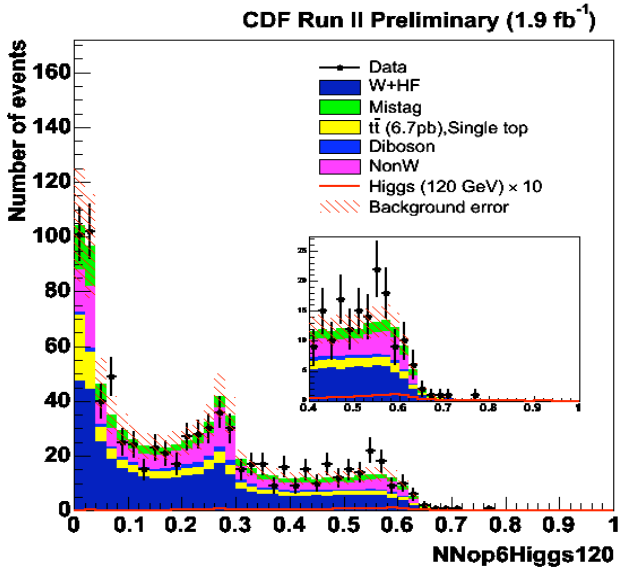
Basic selection

- one or two tagged b-jets
- electron or muon with $p_T > 20$ GeV
- $E_T^{miss} > 20$ GeV

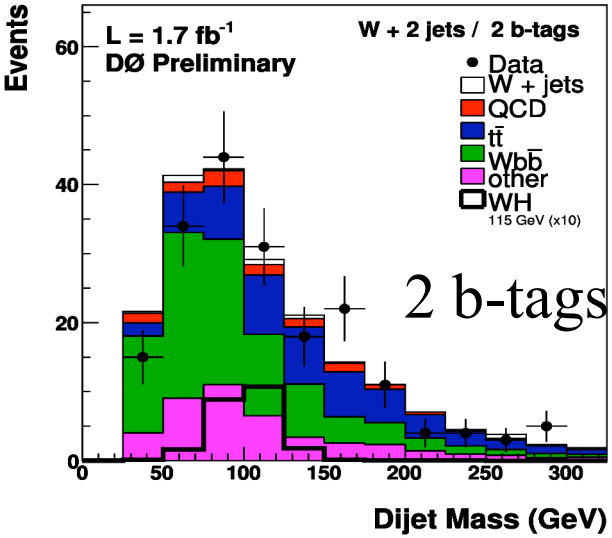
Top pairs: yesterday's signal is today's background..!

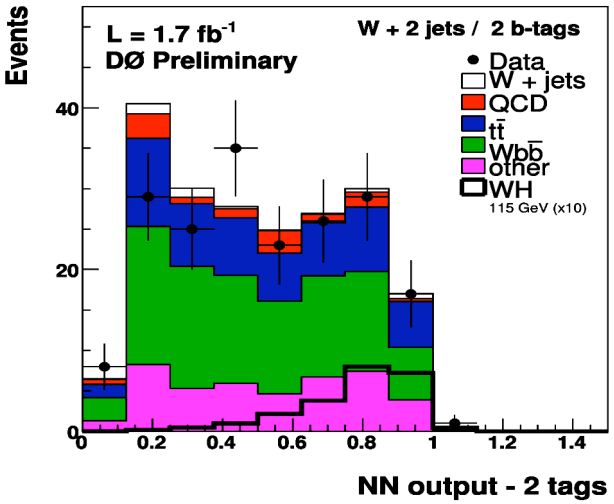
$WH \rightarrow \ell\nu b\bar{b}$



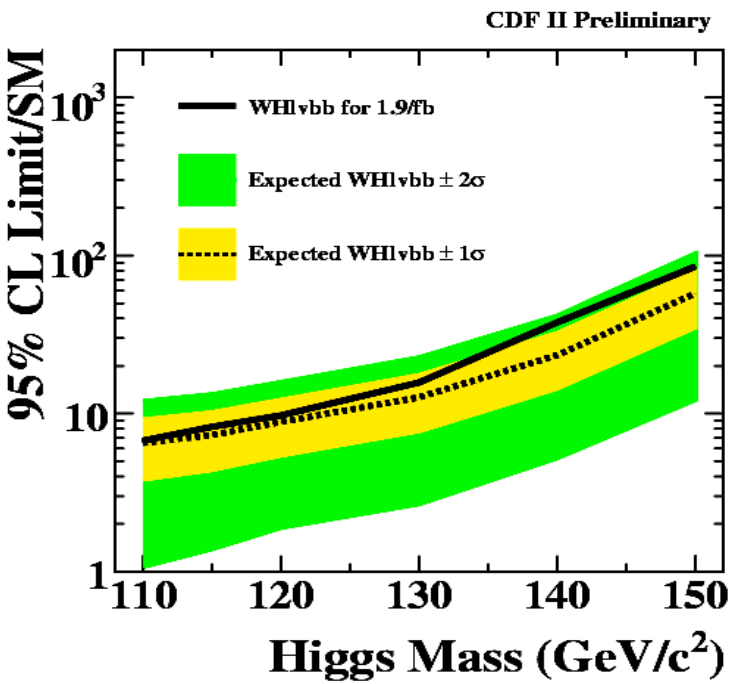


Neural Nets trained on event kinematics





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

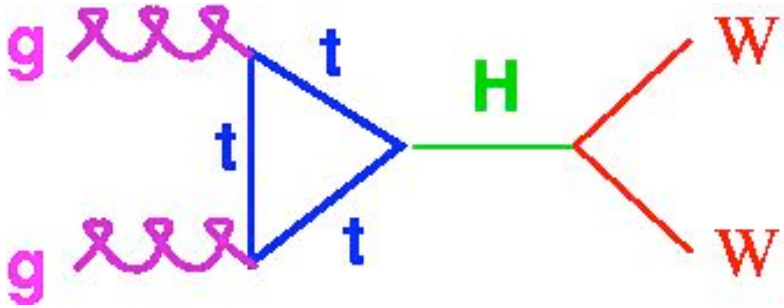


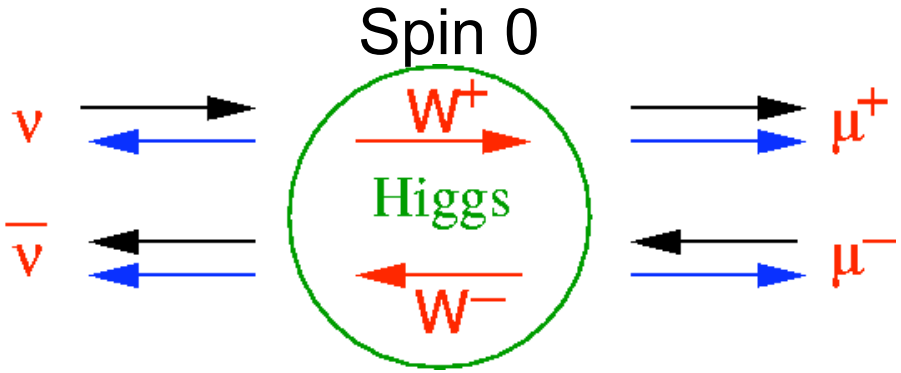
Exclusive samples exploiting different s/b:

- different b tagging algorithms (CDF)
- single / double b-tags
- lepton identification

m_H=115 GeV	CDF exp,obs	DØ exp,obs
σ_{95}/SM =	7.3,8.2	9.0,11.1

$H \to WW \to l\nu l\nu$





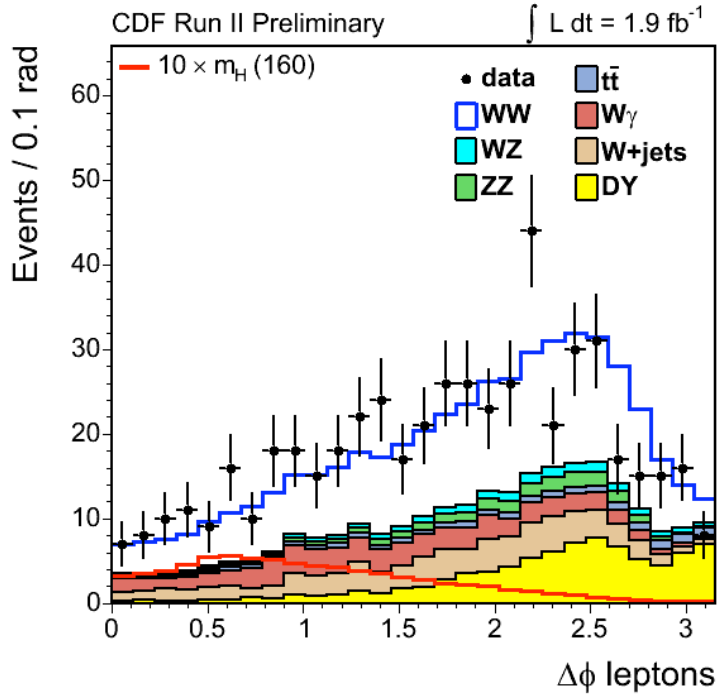
Higgs: small $\Delta\varphi_{ll}$
WW: large $\Delta\varphi_{ll}$

Typical selection:
two isolated leptons

$$p_T^{\ell} > 10 \text{ GeV}$$

$$\not{E}_T > 20 \text{ GeV}$$

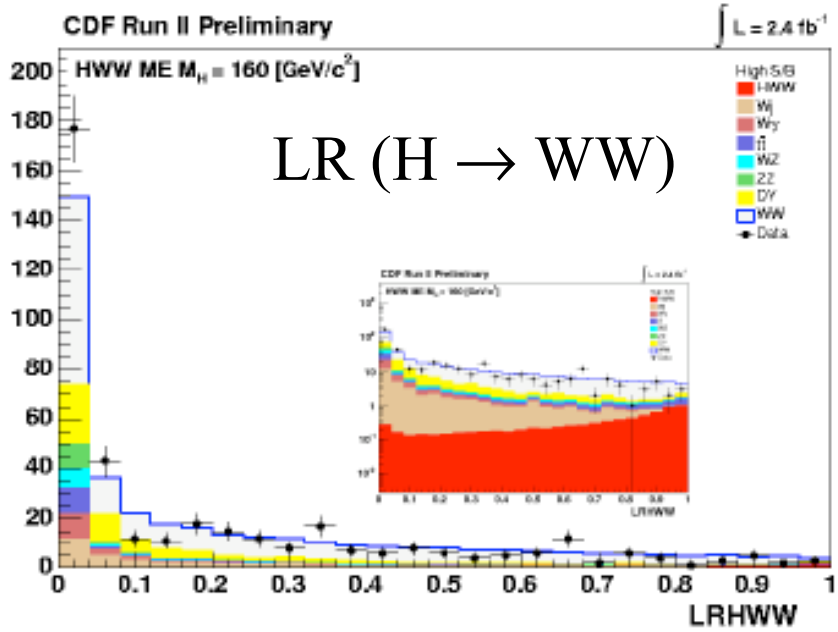
$$\Delta\phi_{\ell\ell} < 2.5$$

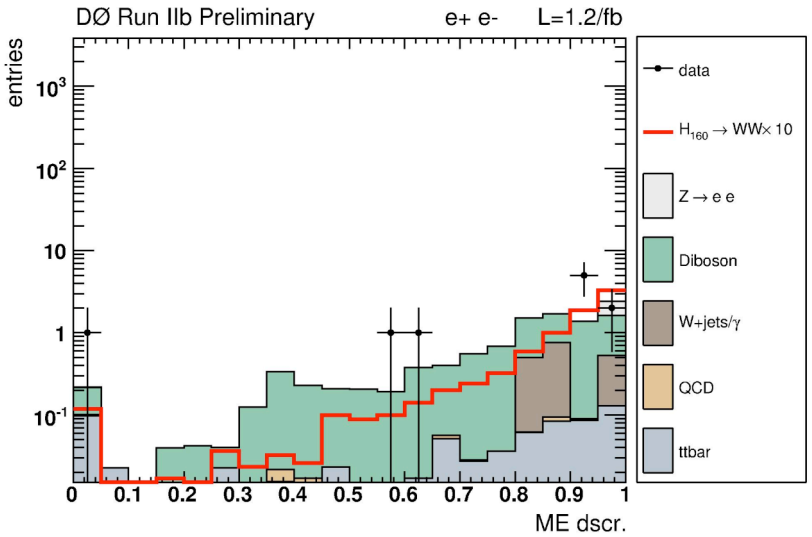


Matrix Elements

$$P_m(\vec{x}_{obs}) = \frac{1}{\langle \sigma_m \rangle} \int d^n \sigma_m^{theory}(y) \epsilon(y) G(\vec{x}_{obs}, y)$$

P_m : Event-by-event probability for process n
y : true lepton kinematics, incl. neutrinos
$\vec{x}_{obs}$: observed kinematics
ϵ : lepton efficiencies
G : detector resolution function



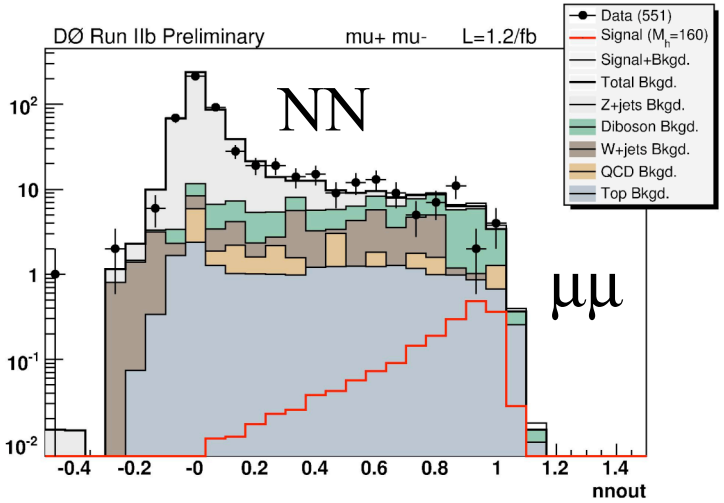


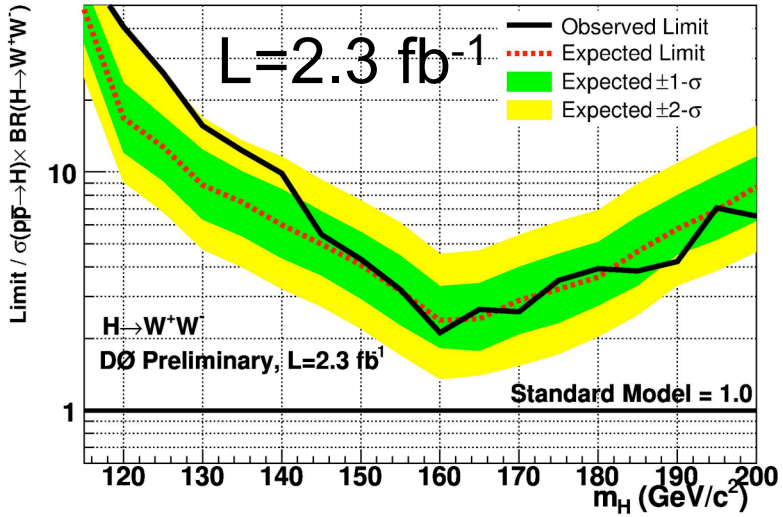
$$LR(m_H) = \frac{P_{Higgs}(m_H)}{P_{Higgs}(m_H) + \sum_{bg=WW,WZ,tt,..} f_{bg} P_{bg}}$$

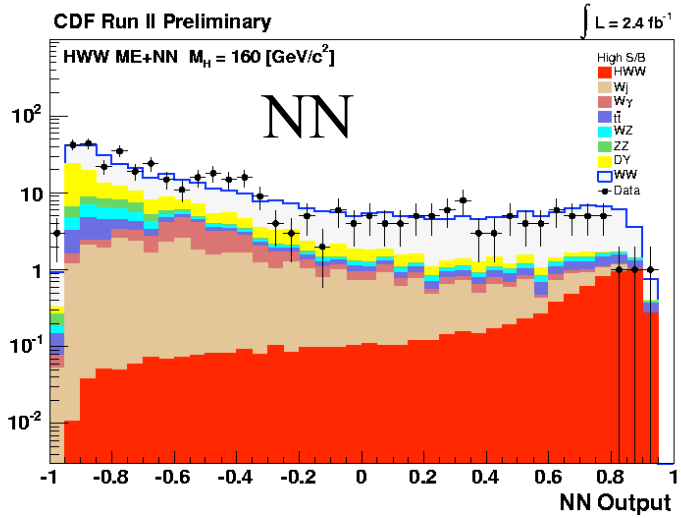
Matrix Element Technique (→top)

most sensitive at high masses

$H \rightarrow WW \rightarrow l\nu l\nu$



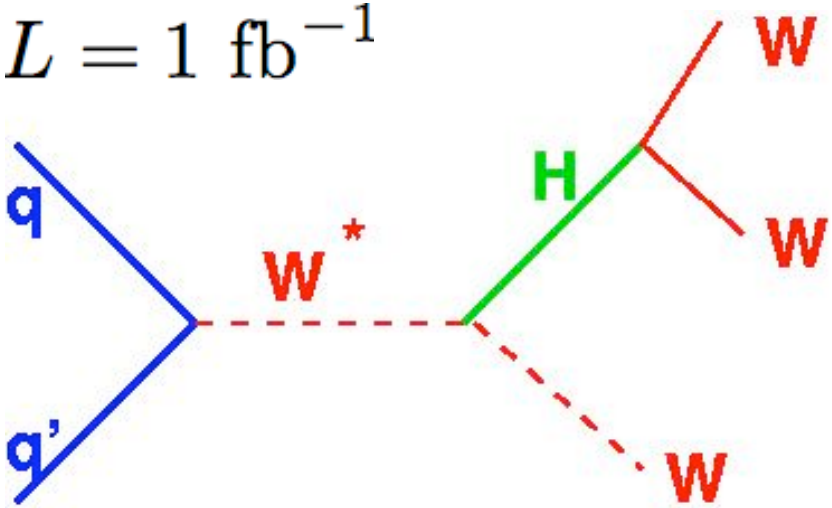




m_H=160 GeV	CDF exp,obs	DØ exp,obs
σ_{95}/SM =	2.5,1.6	2.4,2.1

$HW \rightarrow WWW \rightarrow l\nu l\nu + X$

$L = 1\ \mathrm{fb}^{-1}$



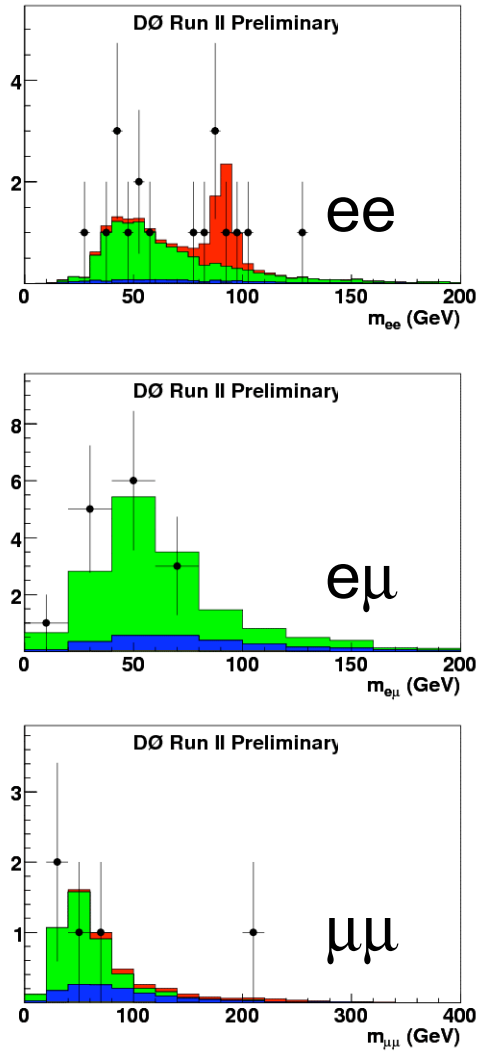
→ X (h,l)

→ e or μ

same charge

→ e or μ

di-lepton mass



Selection:
- two isolated leptons (electrons,muons)
- both leptons have p_T > 15 GeV
- kinematic likelihood selection

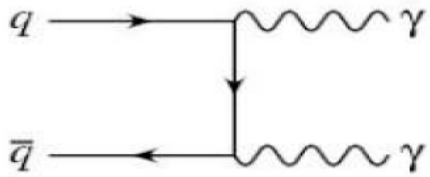
Charge mis-identification ('flips') from data:
- muons: solenoid vs toroid
- electrons: solenoid vs $\Delta\varphi$(track,calorimeter)

relatively low background,
important at intermediate masses, σ_{95}/SM(exp) ~ 20

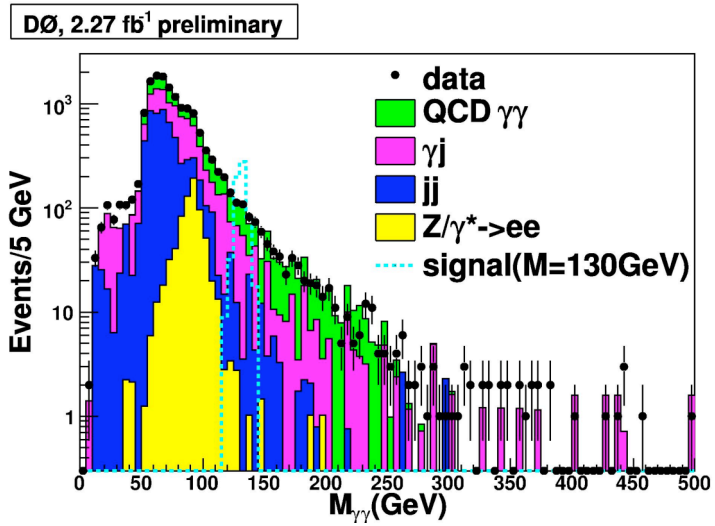
$gg \rightarrow H \rightarrow \gamma\gamma$

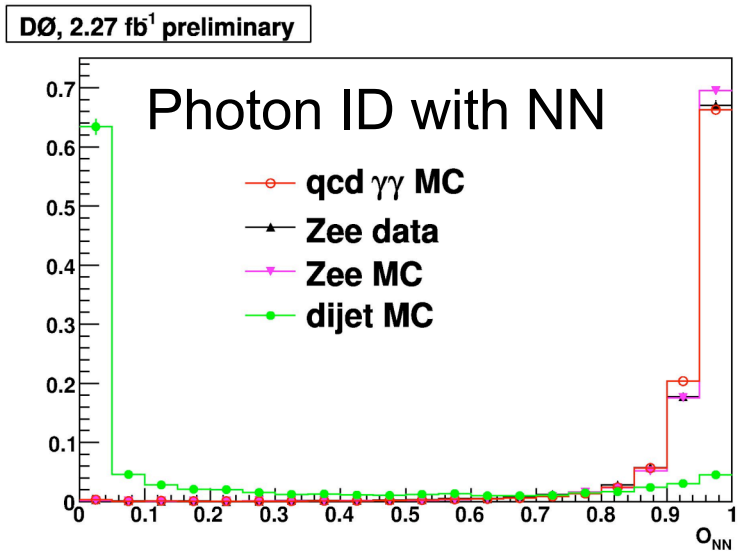
small BR ~ 0.002, but clear signature not only at the LHC !

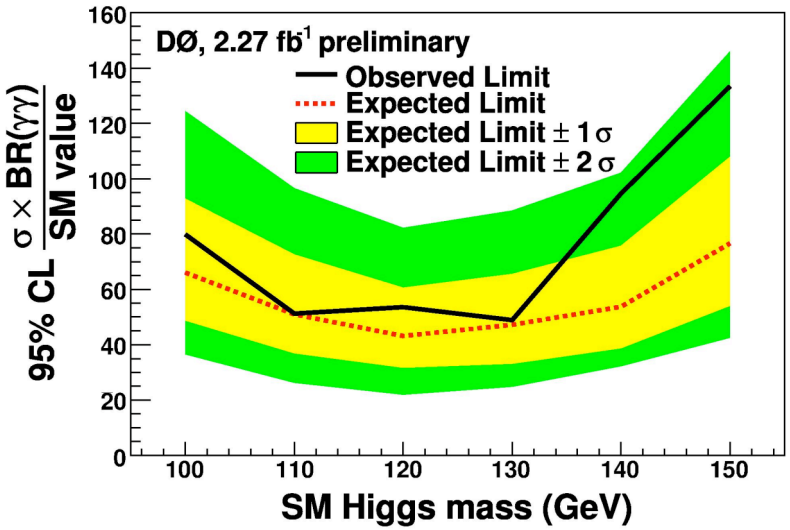
simulation + NLO cross section:



from data: - photon + jet (π^0)
- jet (π^0) + jet (π^0)

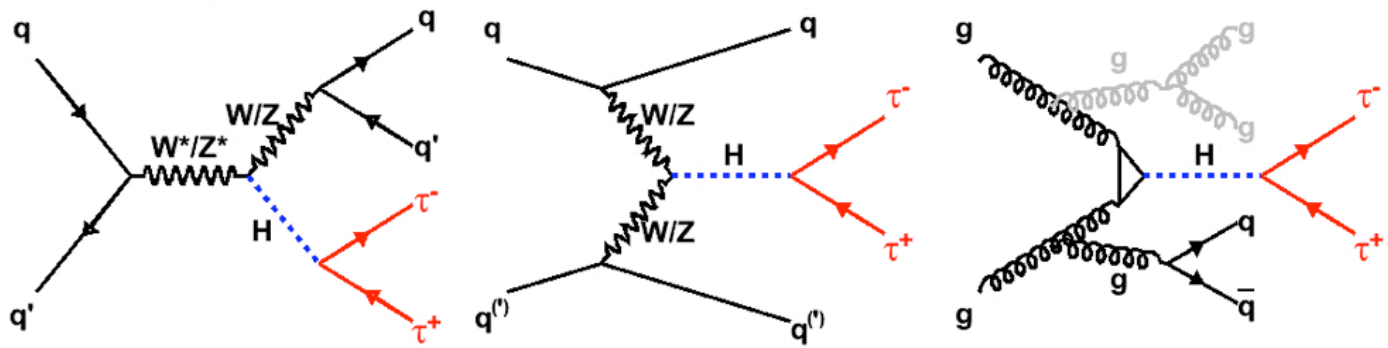






ττ+jj

N_{exp} 0.35 0.13 0.28

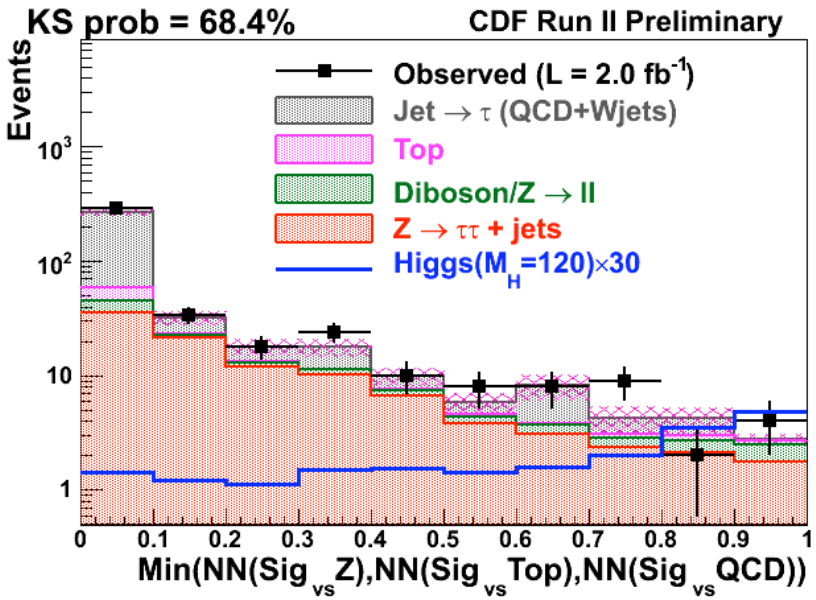


Basic selection:

$\tau \rightarrow e/\mu$ plus $\tau \rightarrow$hadronic

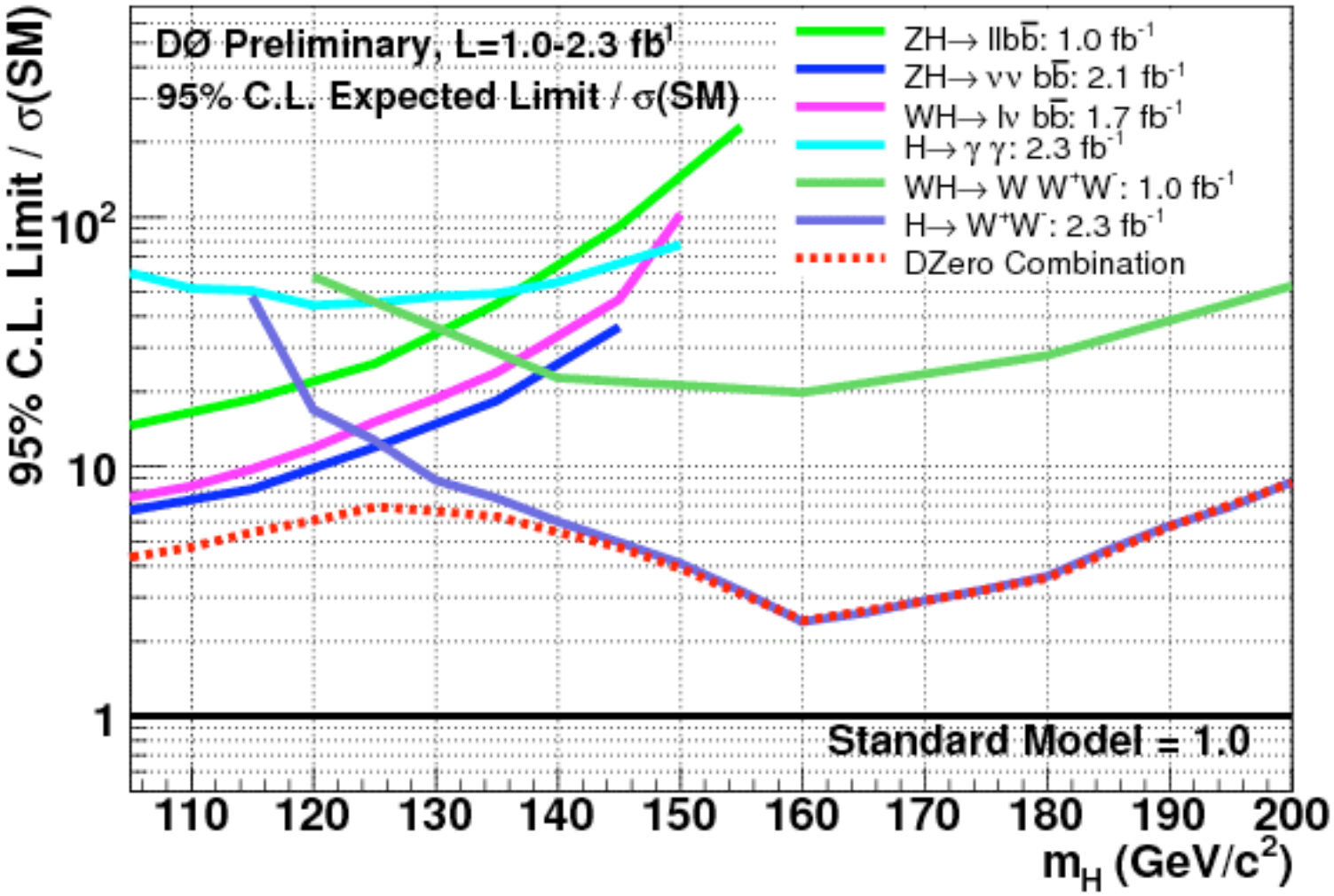
two jets with $E_T > 15$ GeV

Set of Neural Networks

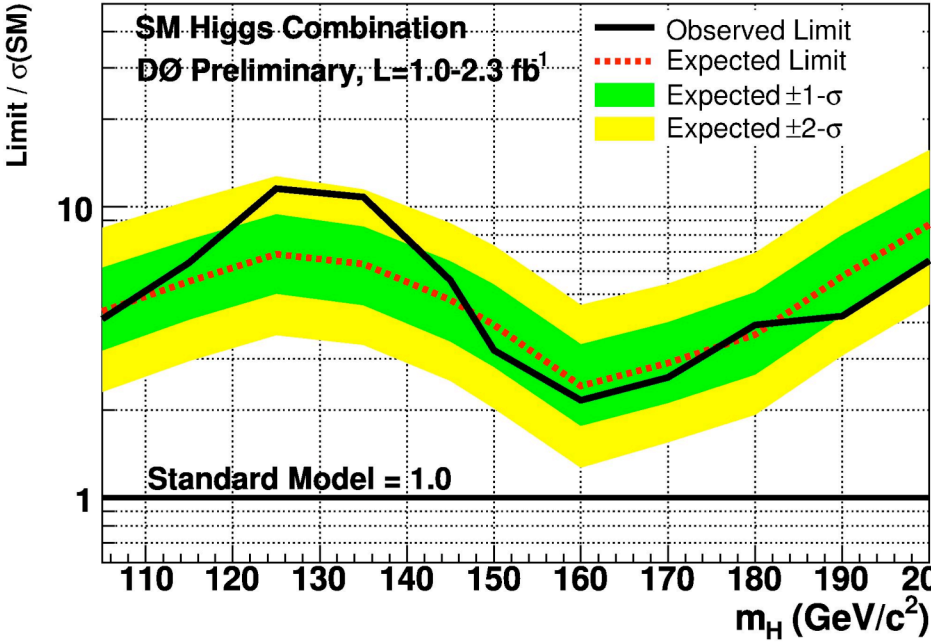


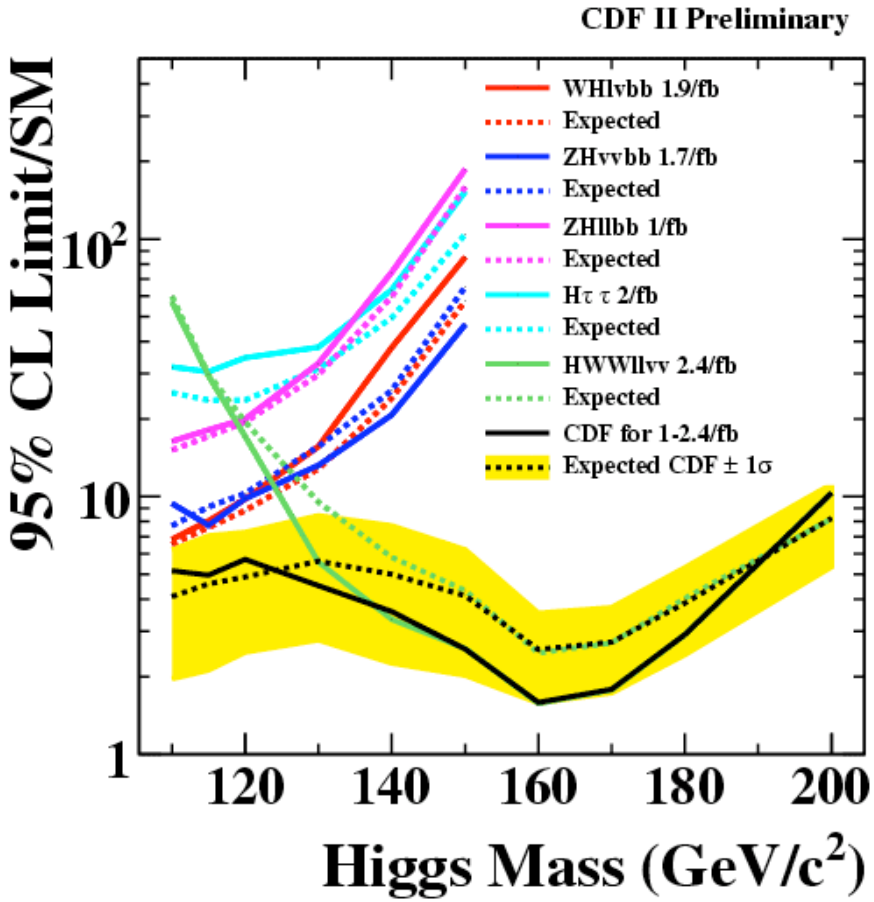
M=115 GeV: σ_{95}/SM = 24.8(exp),30.8(obs)

Expected sensitivities (DØ only)

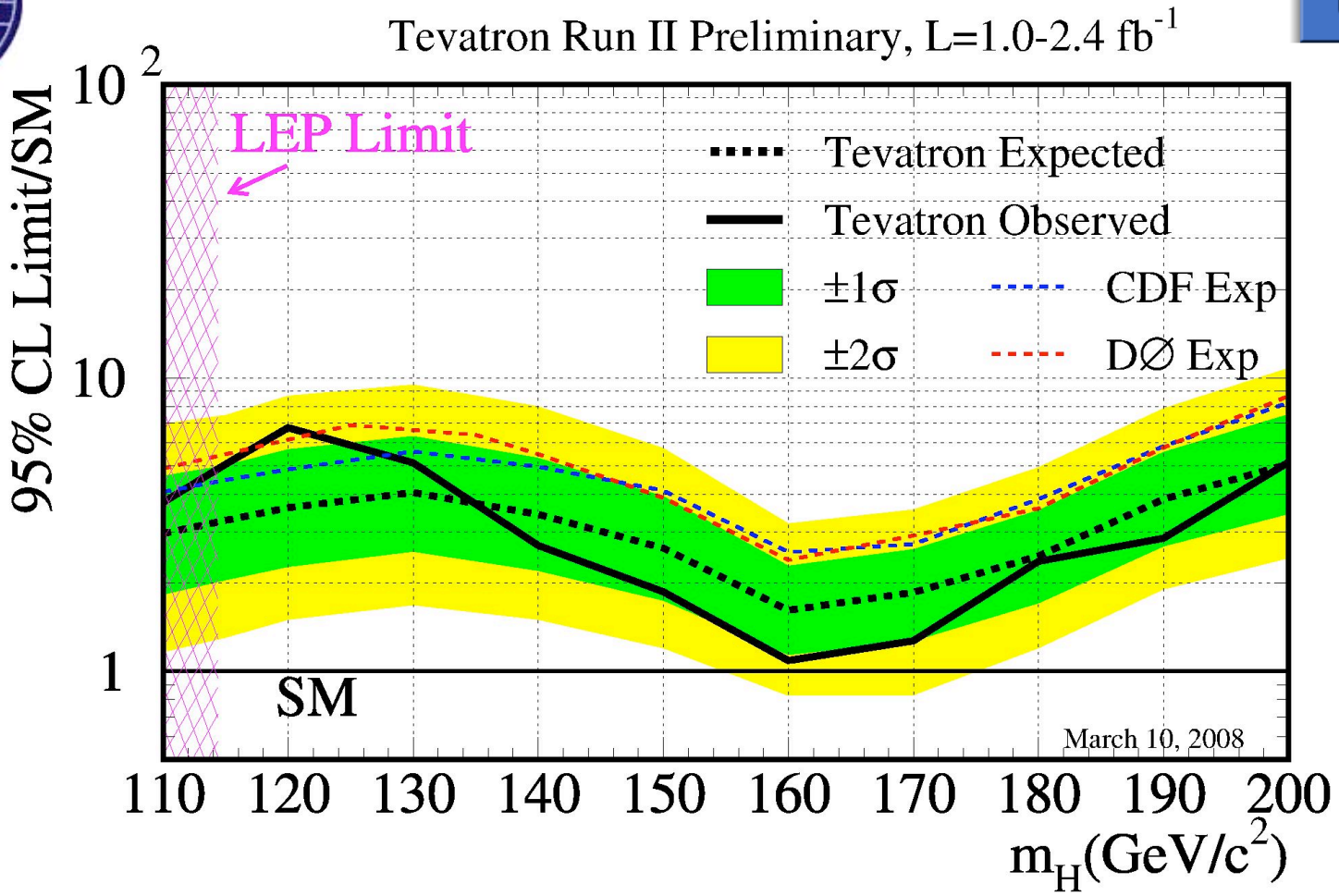


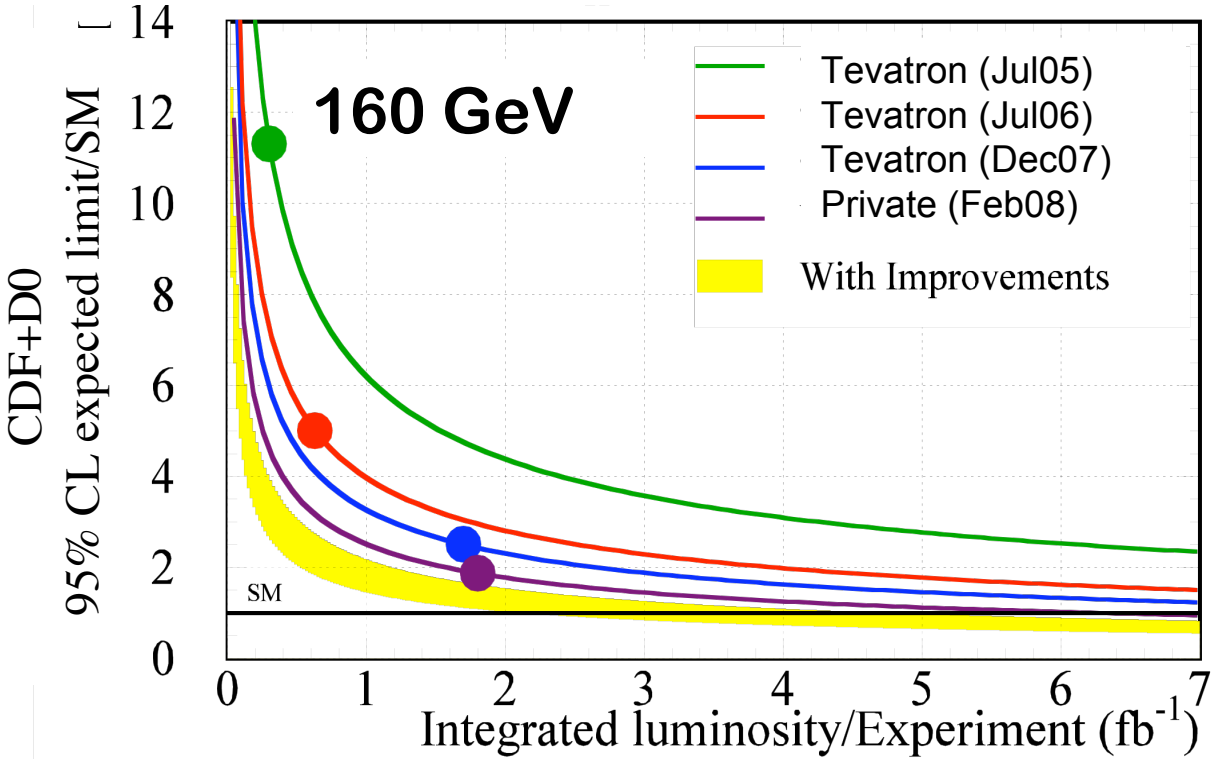
DØ and CDF combinations



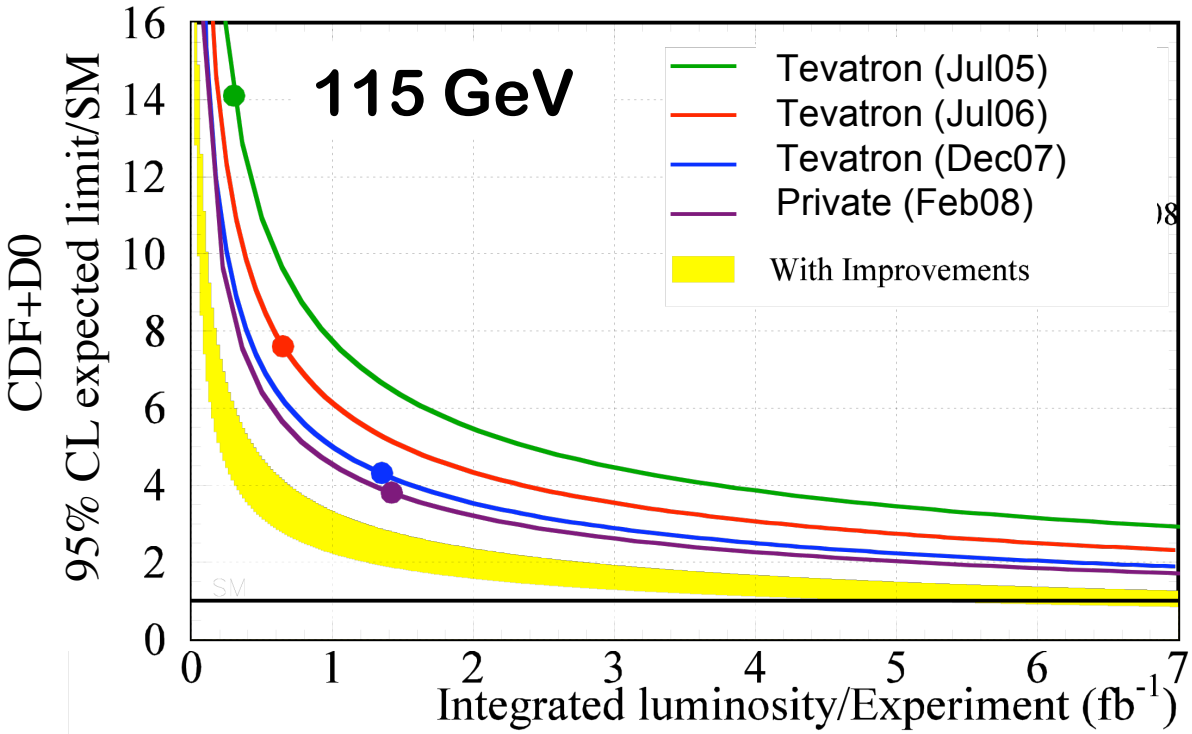


Tevatron Combination

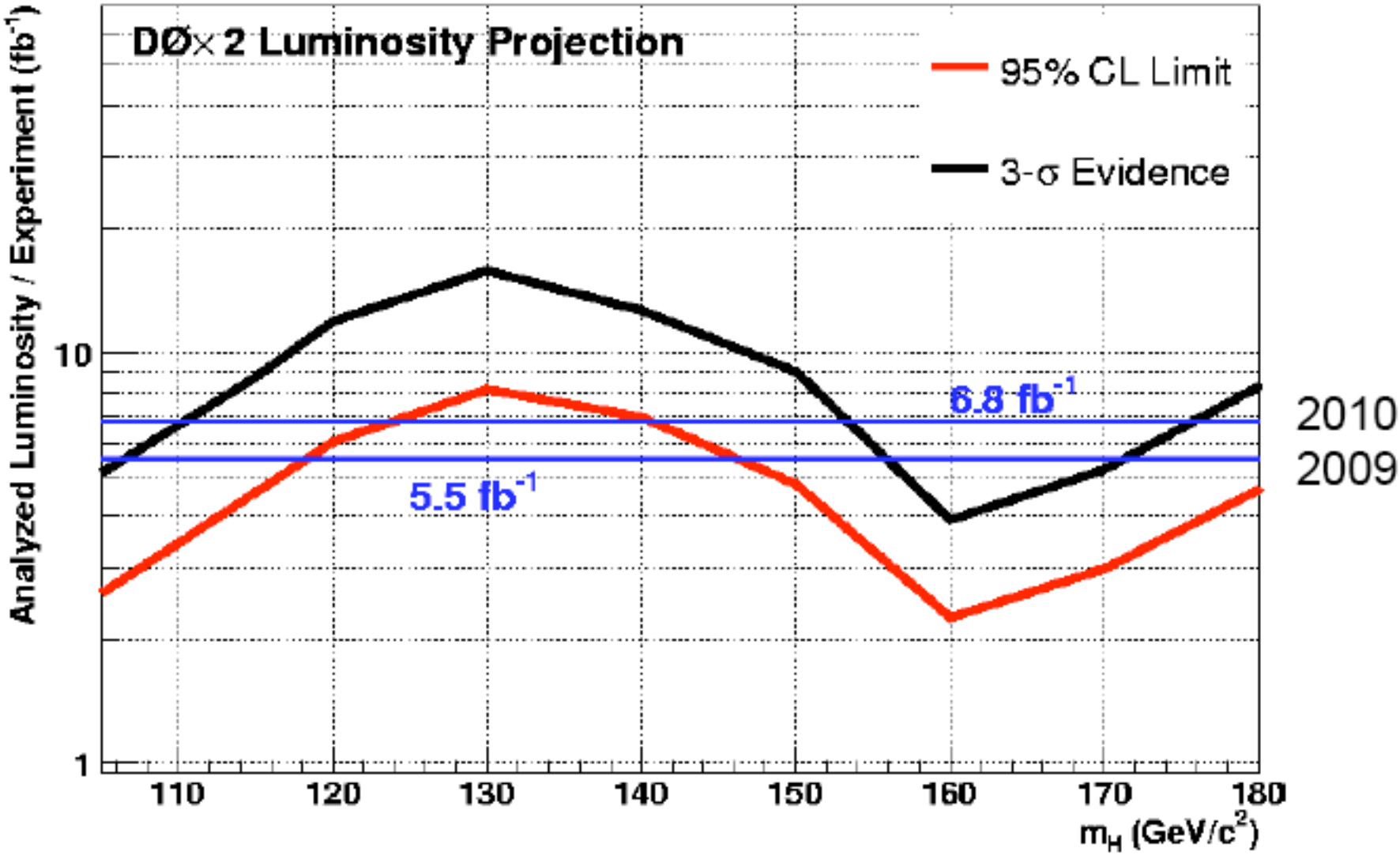




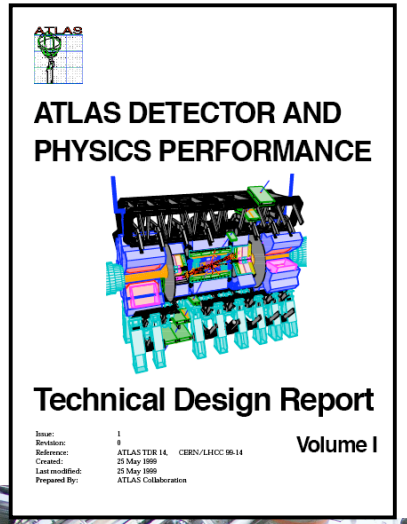
Better than √ L !

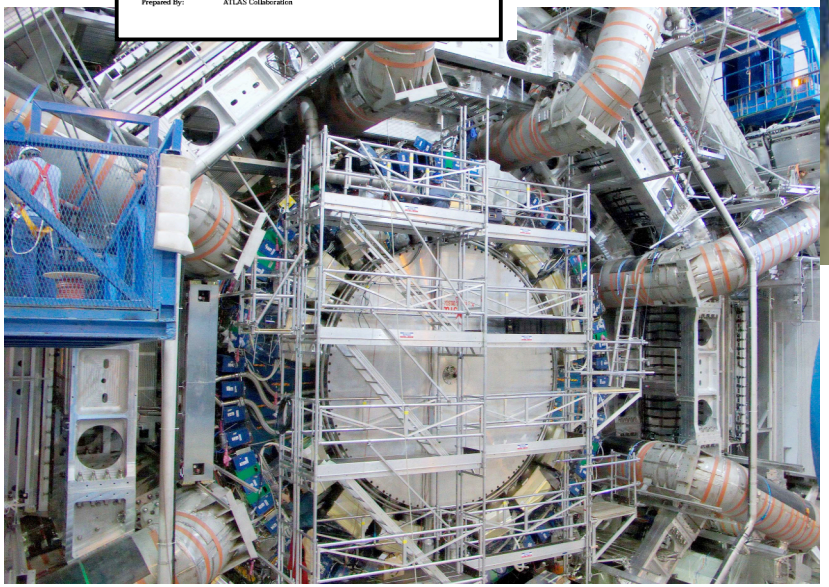

115 GeV
Tevatron (Jul05)
Tevatron (Jul06)
Tevatron (Dec07)
Private (Feb08)
With Improvements
CDF+D0
95% CL expected limit/SM
Integrated luminosity/Experiment (fb^{-1})
SM
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6
7

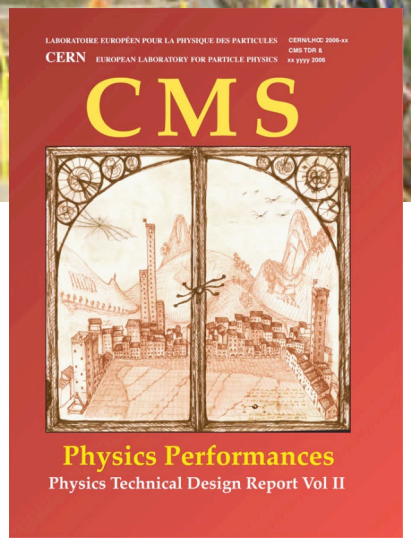
Projection


DØ× 2 Luminosity Projection
95% CL Limit
3-σ Evidence
6.8 fb-1
5.5 fb-1
2010
2009
Analyzed Luminosity / Experiment (fb-1)
10
1
110
120
130
140
150
160
170
180
mH (GeV/c2)

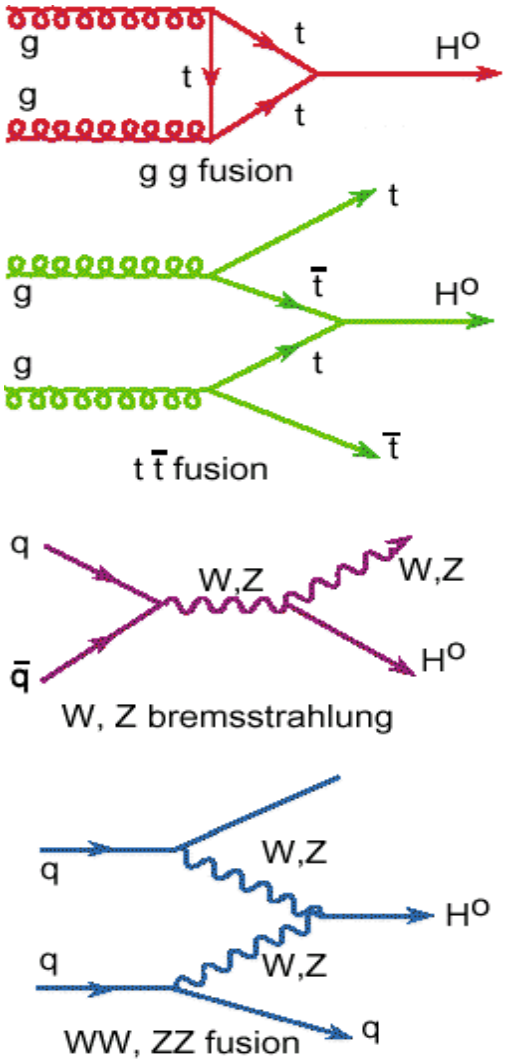
and finally: from Chicago to Geneva

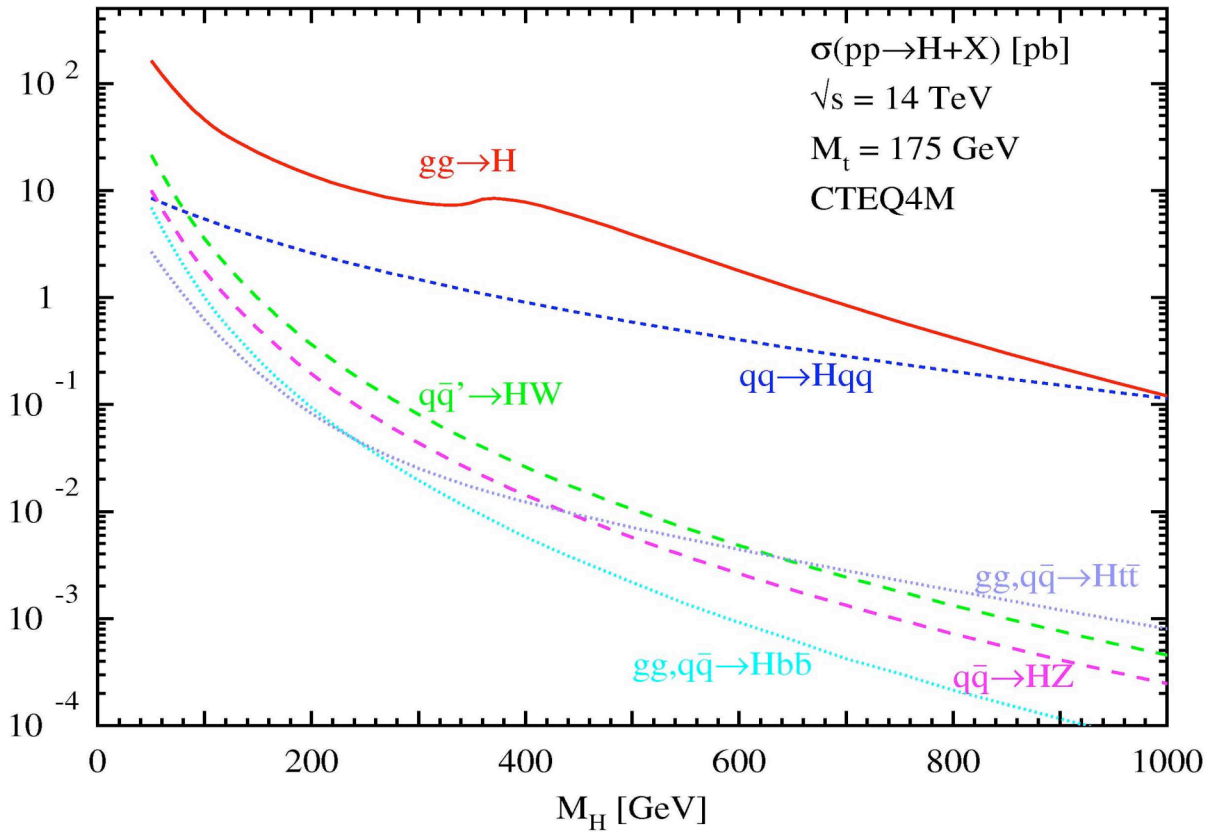






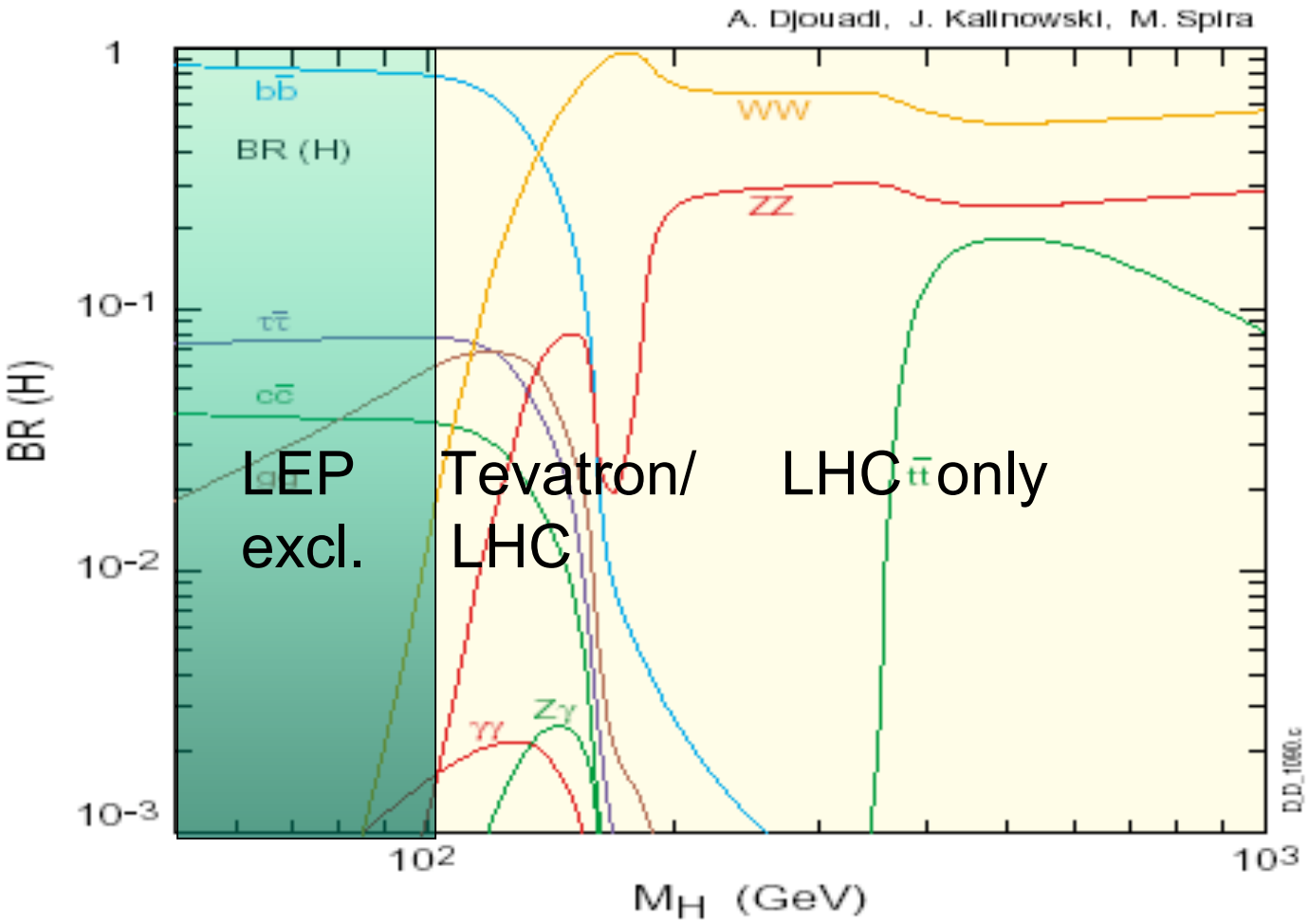
Production at the LHC





Two orders of magnitude larger than at the Tevatron

..and decay

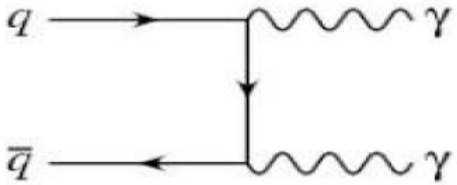

A. Djouadi, J. Kalinowski, M. Spira
BR (H)
1
10-1
10-2
10-3
bb̄
WW
ZZ
ττ̄
cc̄
gg
γγ
Zγ
tt̄
LEP excl.
Tevatron/ LHC
LHC only
10²
10³
M_H (GeV)

$H \to \gamma\gamma$

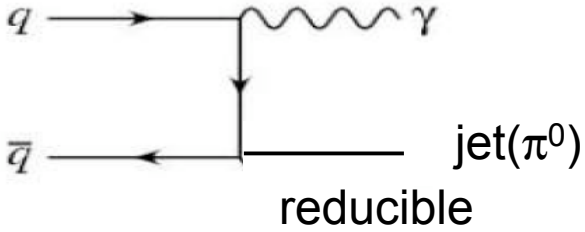
small BR ~ 0.002, but clear signature

main background:

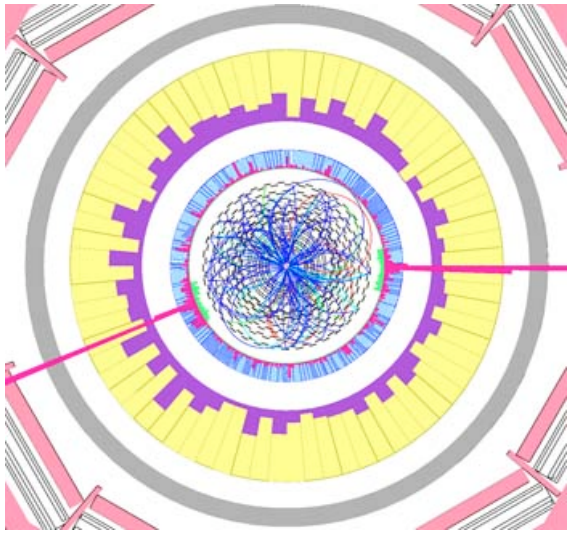
$\sigma_{H\to\gamma\gamma}/\sigma_{pp\to\gamma\gamma} \simeq 10^{-3}$

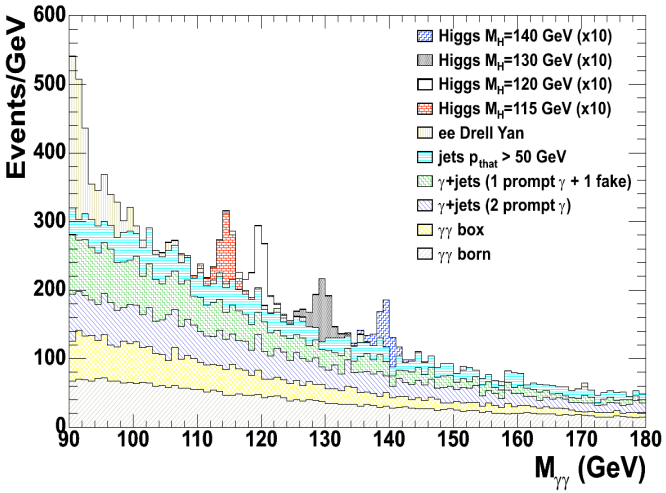


$\sigma_{H\to\gamma\gamma}/\sigma_{pp\to\gamma+jet} \simeq 10^{-6}$

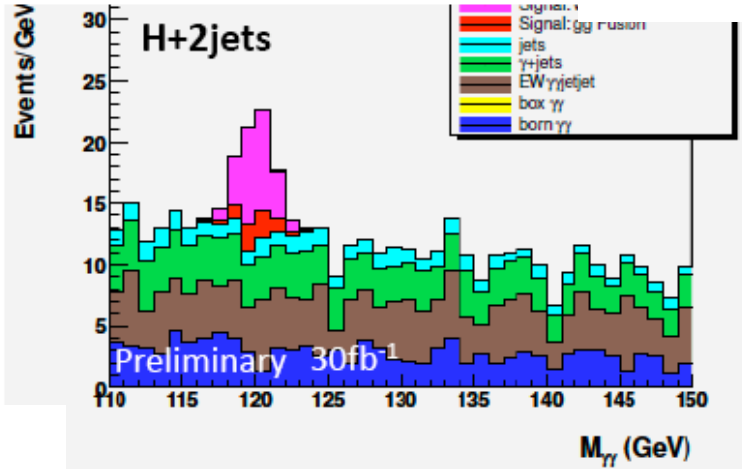


reducible

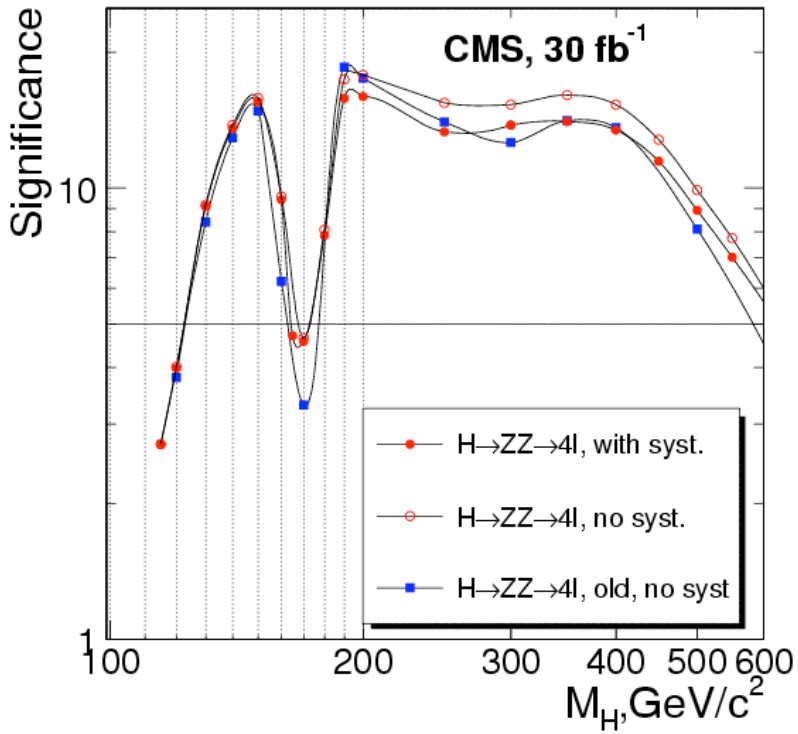




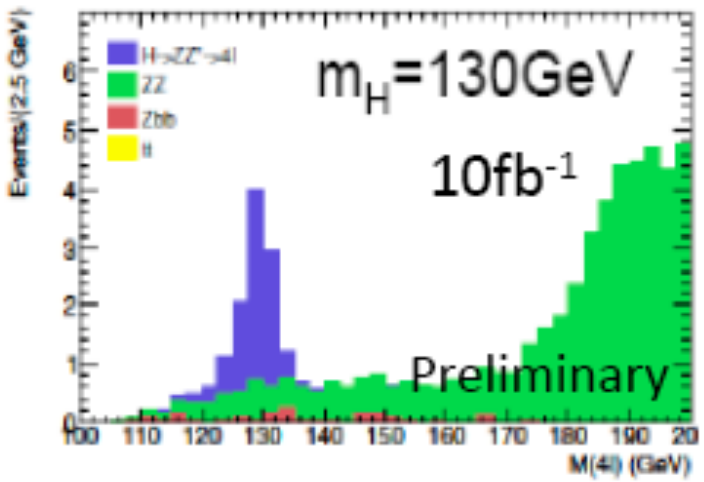
CMS, 1 fb^{-1}, signal x10

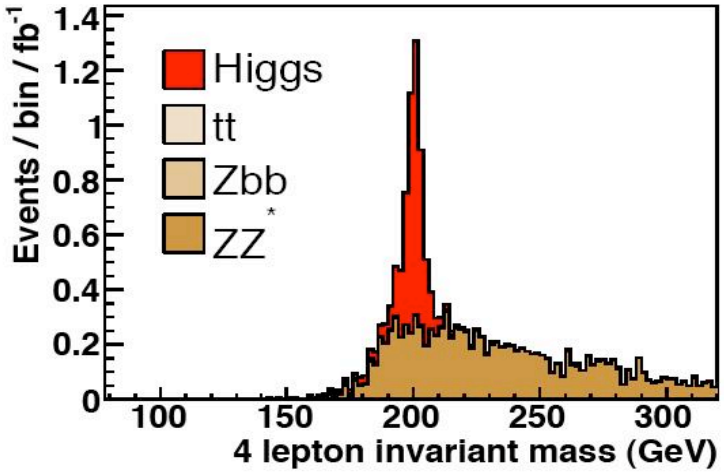


H → ZZ → 4 leptons



'golden channel'

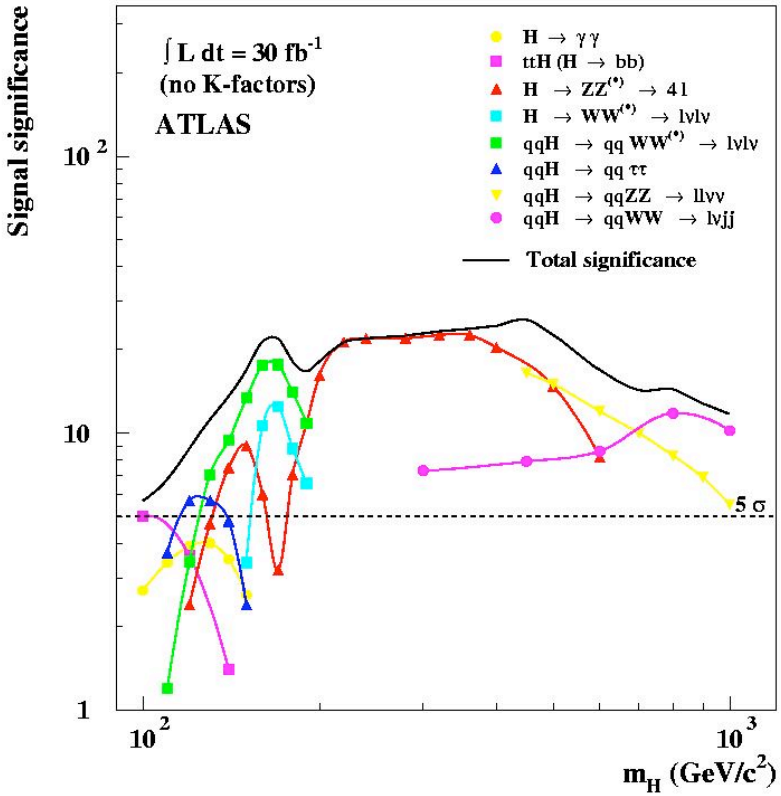




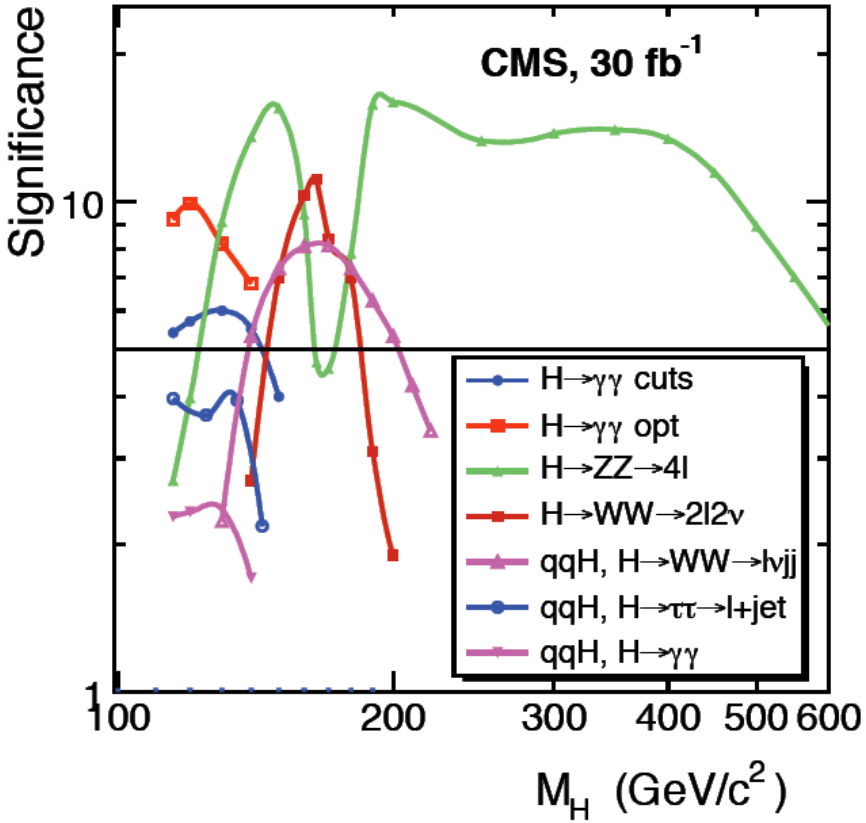
also H → WW

LHC Discovery Potential

2003, no k factors

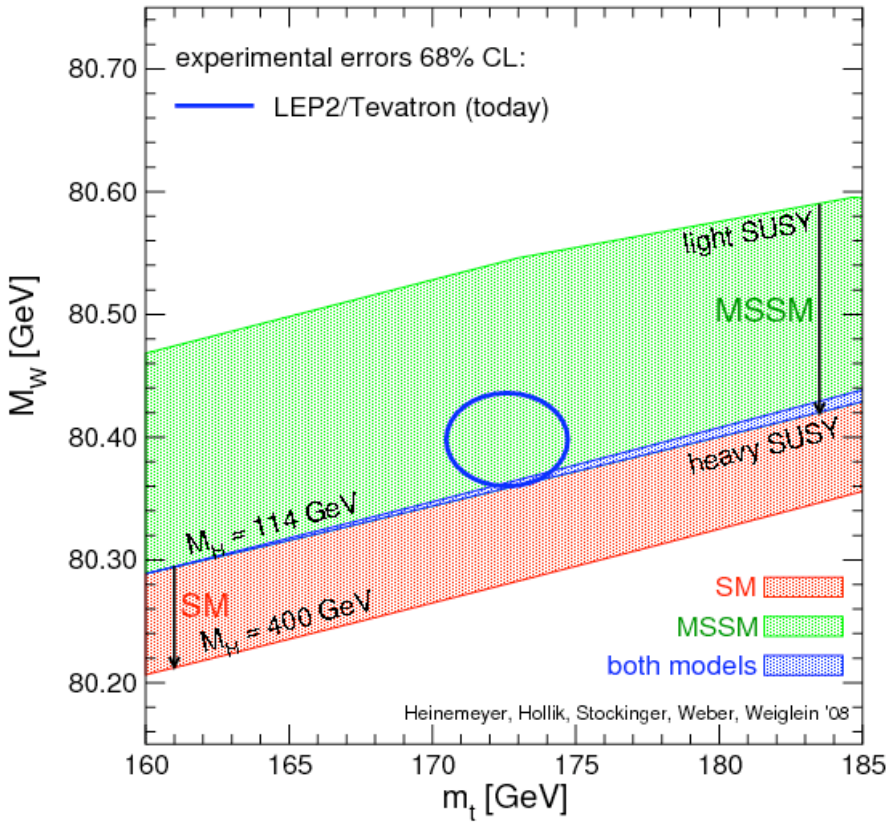


2006, k factors



updates in progress

..MSSM ?


experimental errors 68% CL:
LEP2/Tevatron (today)
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08
M_W [GeV]
m_t [GeV]
80.70
80.60
80.50
80.40
80.30
80.20
160
165
170
175
180
185

MSSM Higgs

Two Higgs doublets lead to five physical Higgs boson:

h,H: CP-even, neutral
A: CP-odd, neutral
$H^{\pm}$: charged

In lowest order MSSM Higgs sector can be specified by two parameter, M_A and tan β, all other Higgs masses can be calculated from MSSM parameters.

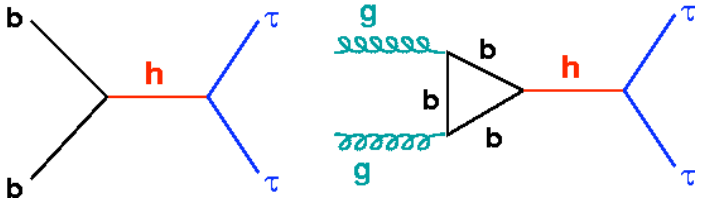
- m_h should be less than 135 GeV
- at large tan β, couplings to down type fermions (b, τ) enhanced

tan β = ratio of Higgs doublet vev's

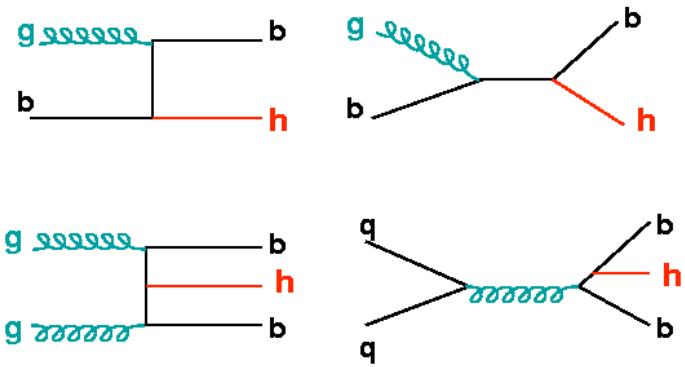
MSSM Higgs

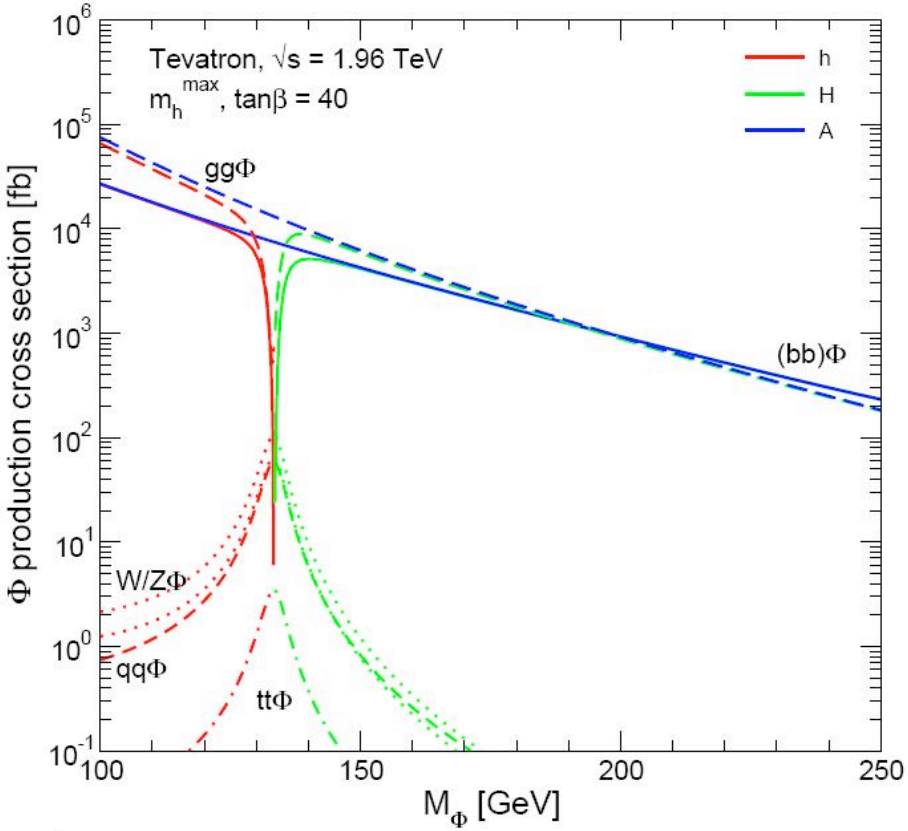
$BR(H \to \tau\tau) \approx 10\%$, $BR(H \to bb) \approx 90\%$

inclusive searches:



exclusive searches (with b):

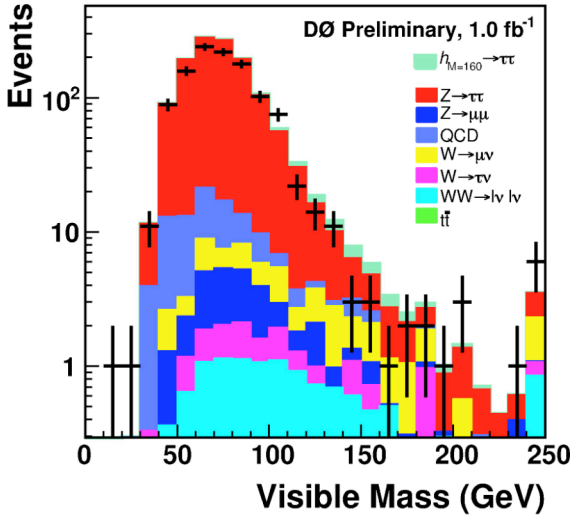


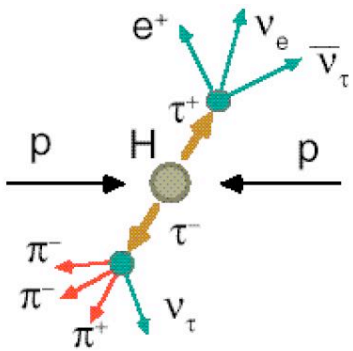


$$\sigma_\phi \approx 2\sigma_A$$

Inclusive h,H,A → ττ

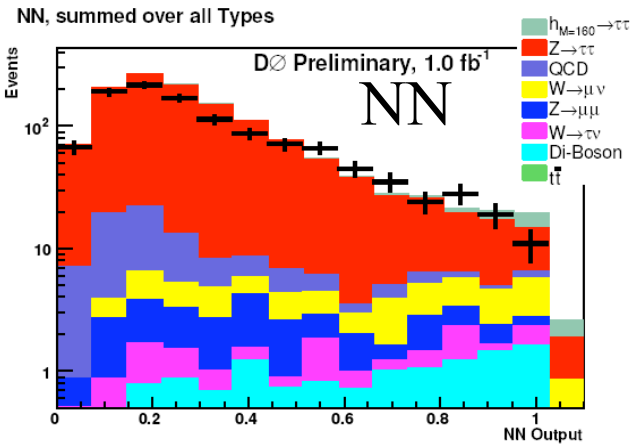
$\tau_\mu \tau_h$ channel



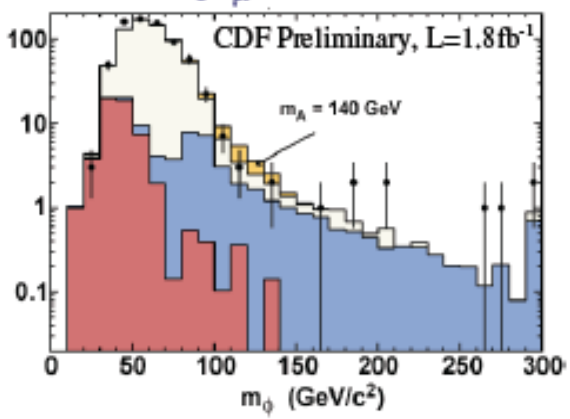


large background from $Z \to \tau\tau$

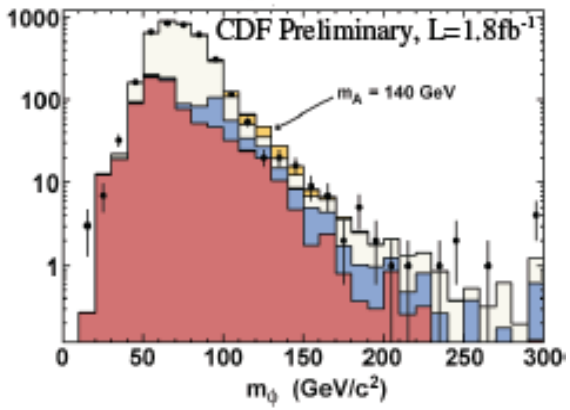
$$M_{vis} = \sqrt{(P_{\tau 1} + P_{\tau 2} + \not{P}_T)^2}$$



$\tau_e \tau_\mu$ channel



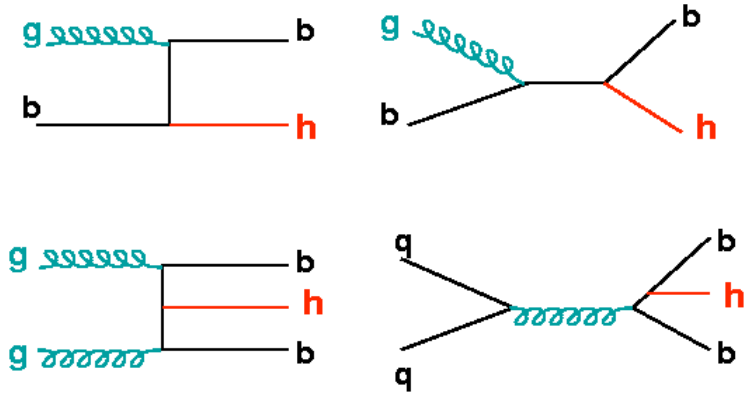
$\tau_e \tau_h + \tau_\mu \tau_h$ channels

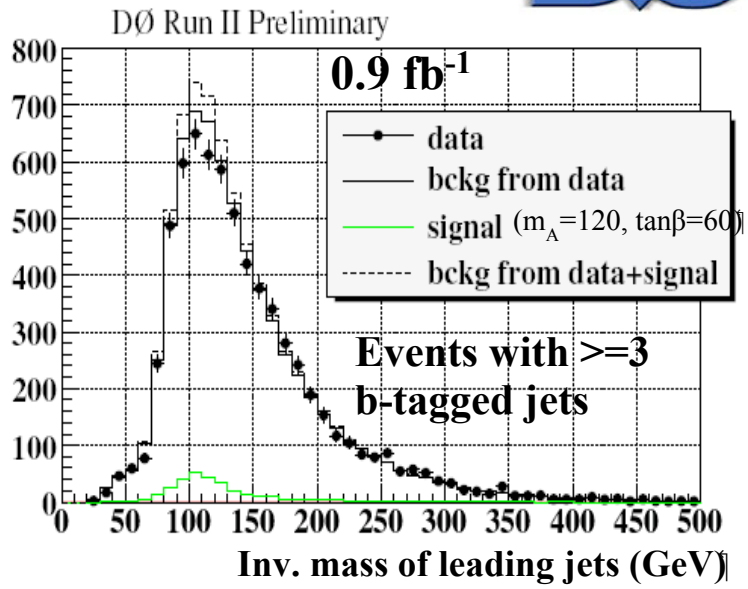


b(h/H,A) to bbb

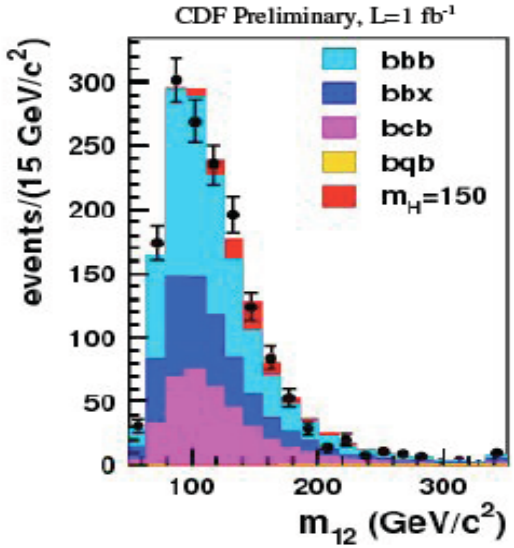
(h/H,A) → bb swamped by QCD background

– look for associated b production





Require at least 3 b-tagged jets and search for peak in di-jet mass spectrum



Background shape based on the double b-tagged data sample, corrected for kinematic bias from the 3rd b-tag.

Limits are interpreted in m_A - tan β plane

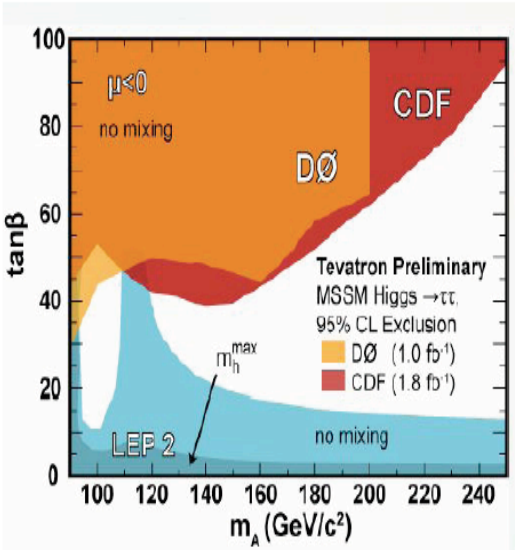
Benchmark scenarios:

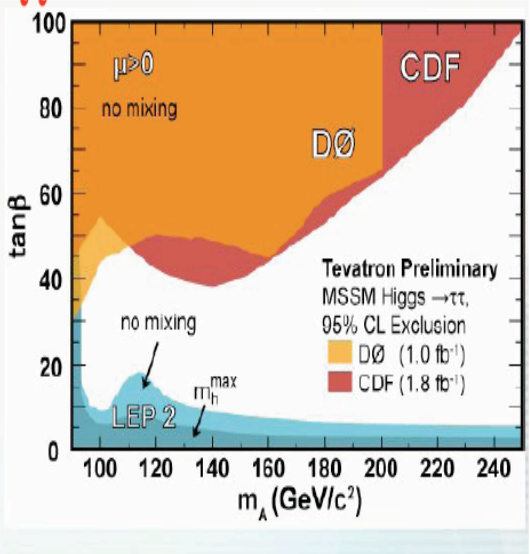
- m_h^{max}: maximum mass of lightest CP-even state h

- no-mixing: stop mixing parameter $X_t = 0$

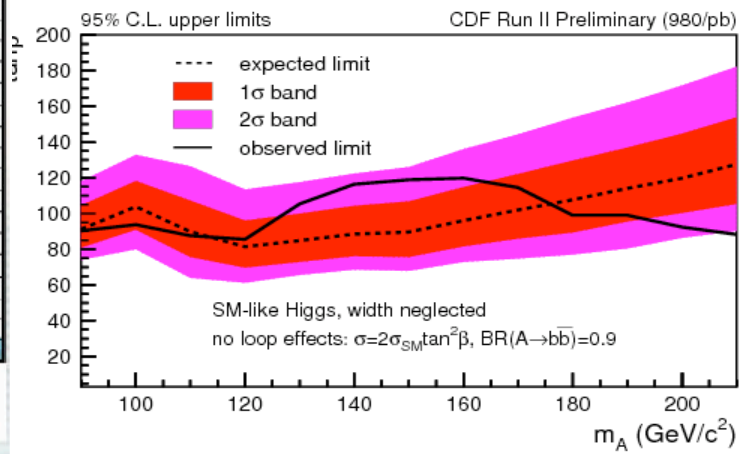
- $\mu < 0$ and $\mu > 0$: 'Higgs mass parameter' describes Higgs mixing, $\mu > 0$ favoured by $(g-2)_\mu$

H -> ττ



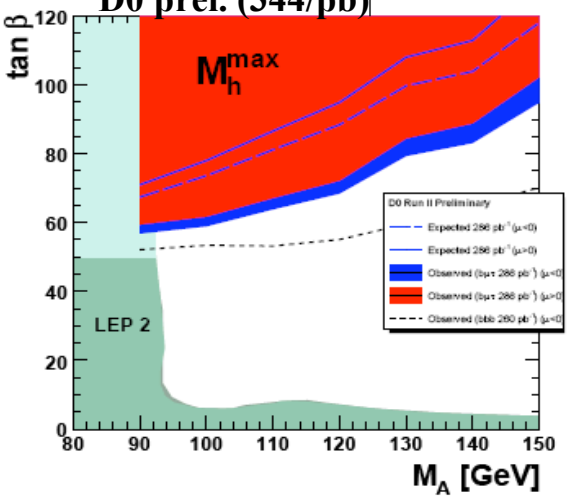


bH→bbb

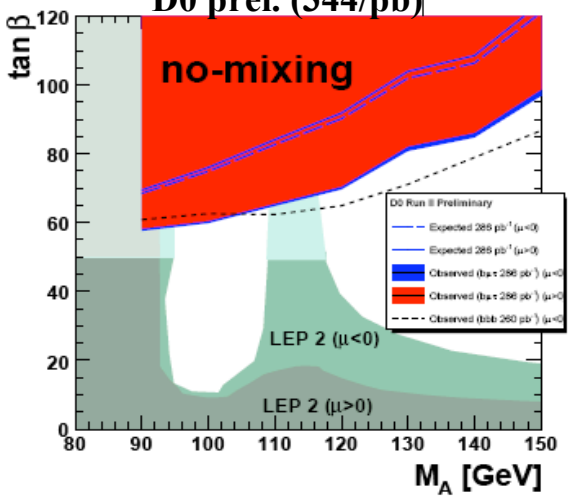


bH→bττ

D0 prel. (344/pb)

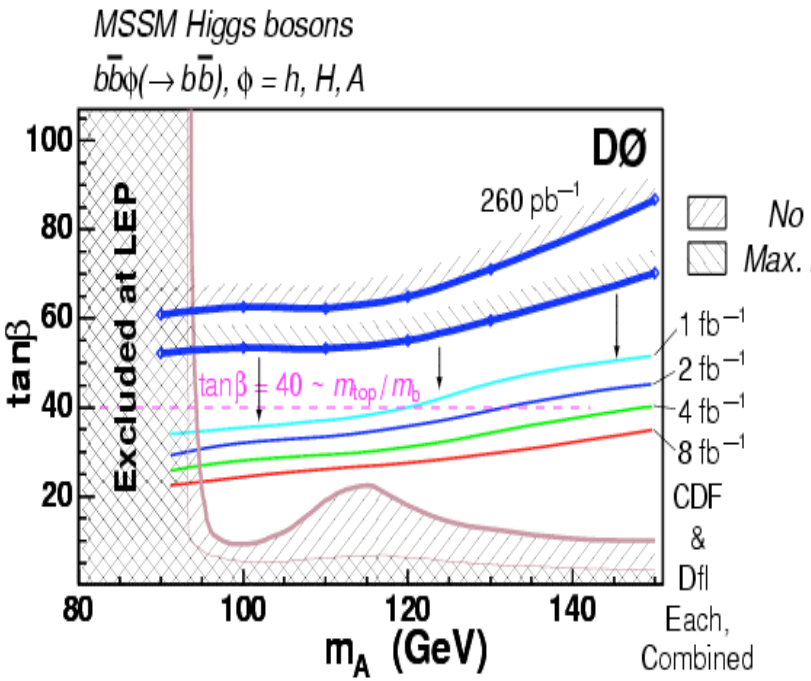


D0 prel. (344/pb)

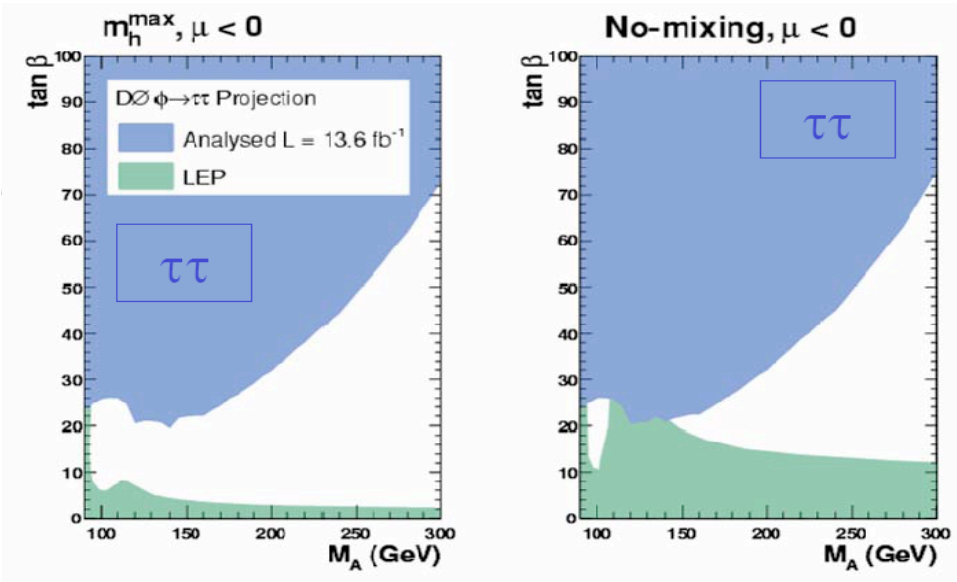


Combination urgently needed

Projections

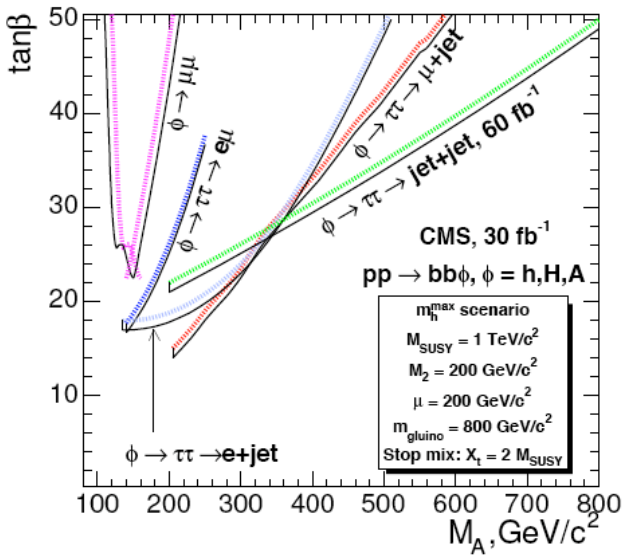


Projection for 2010 running



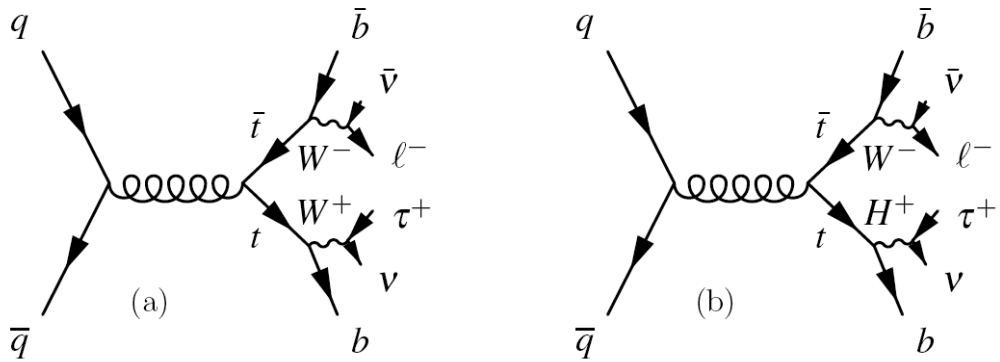
Tevatron has potential to exclude down to $\tan\beta \approx 20$ for low m_A

CMS

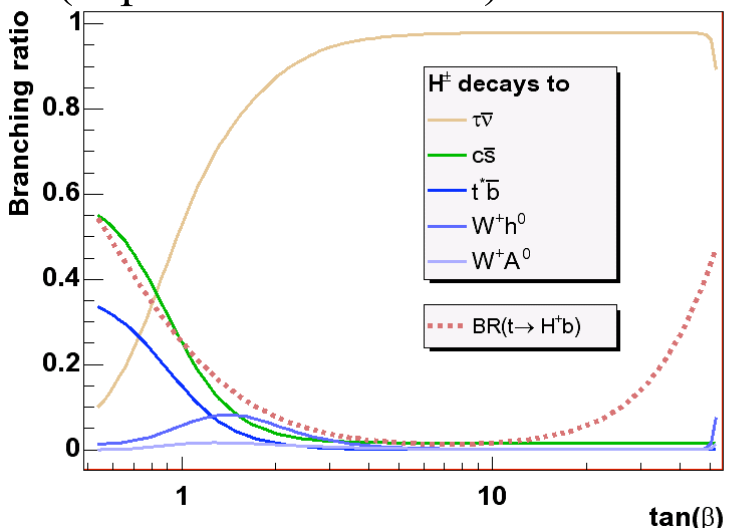


Charged Higgs

Charged Higgs interpreted in 2HDM

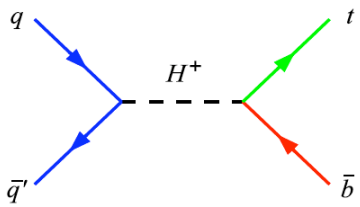


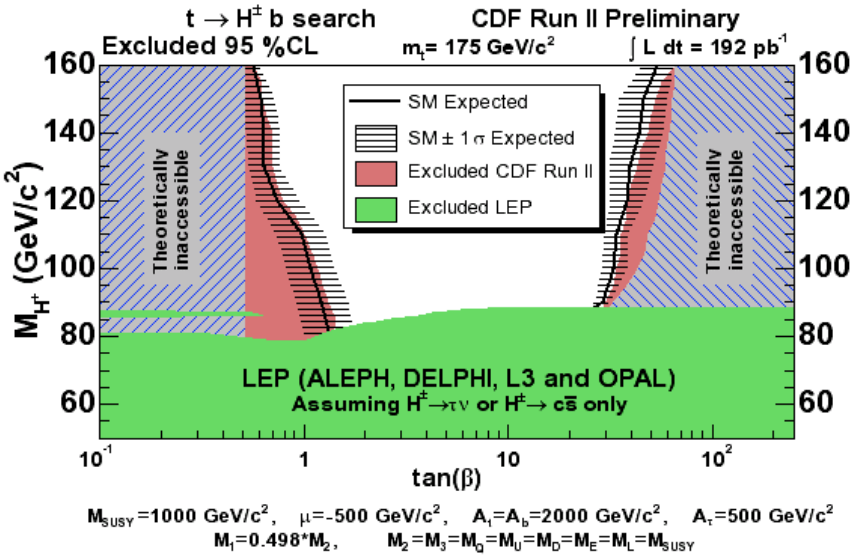
(depends on scenario) M_{H^+}=120 GeV



Tevatron limits from

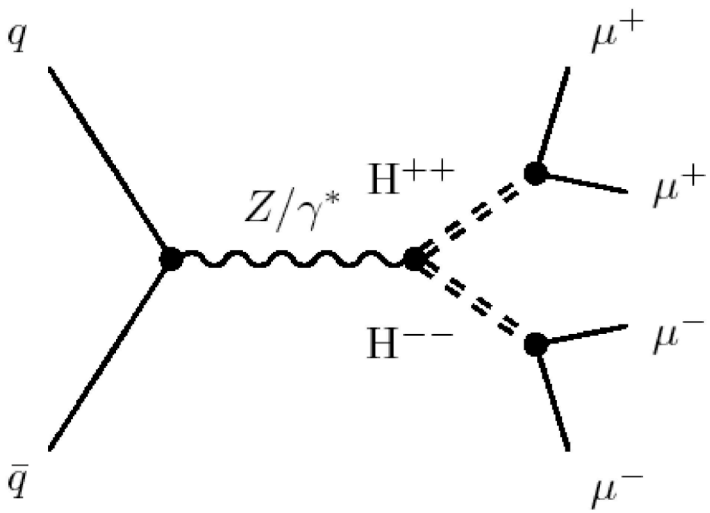
- top pair cross sections
- top pairs with tau final states
- direct searches



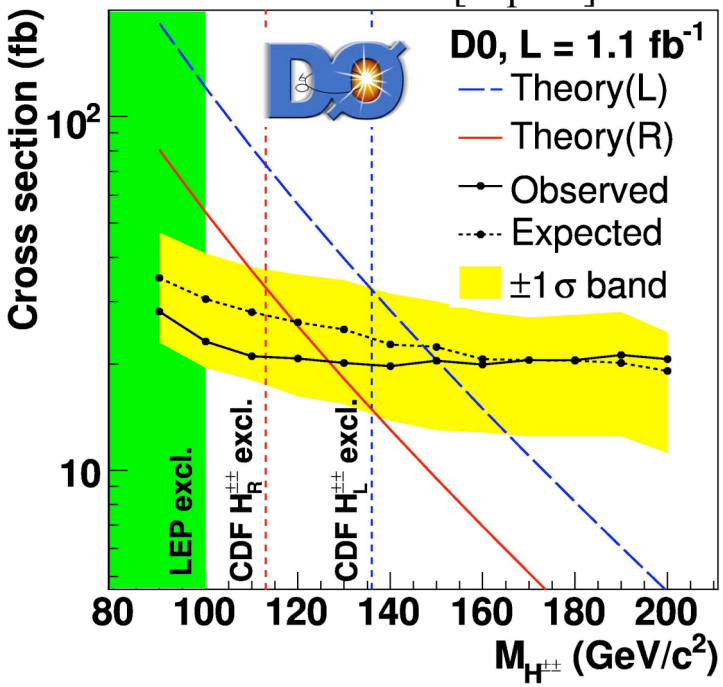


Limit from B decays (W± ↔ H±)

Beyond the MSSM: Doubly charged Higgs



arXiv:/0803.1534 [hep-ex]



H_R > 127 GeV
H_L > 150 GeV

-LR symmetric models
-Higgs triplet models

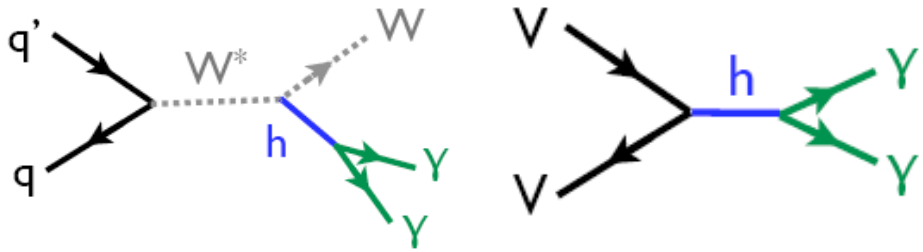
Lepton flavour violating decay into any lepton flavor

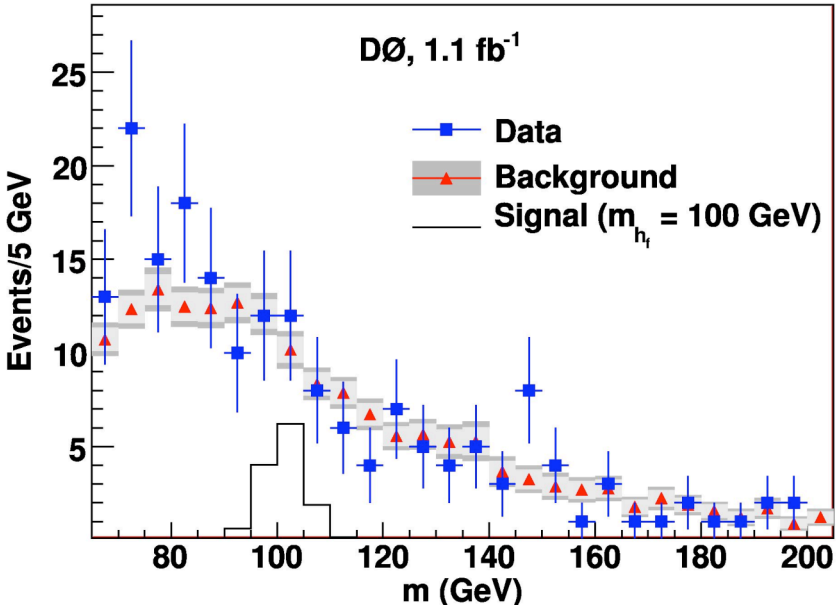
Striking signature:
same charge di-leptons

CDF also searched for e/tau final states

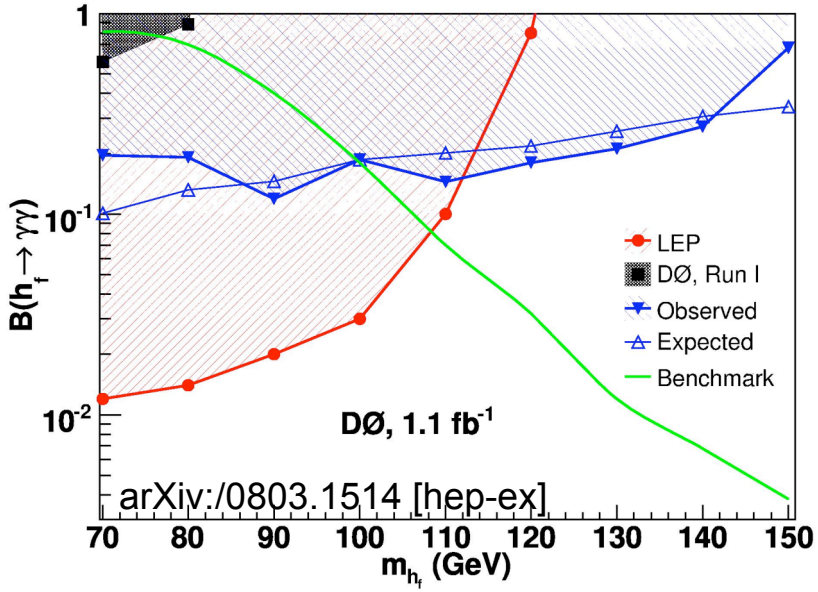
Beyond the MSSM: Fermiophobic Higgs

- 2HDM type I
- only one doublet couples to fermions





$$q_T^{\gamma\gamma} > 35 \text{ GeV}$$



Benchmark model:

- SM Higgs coupling to W,Z
- no coupling to fermions

$$m(h_f) > 100.0 \text{ GeV (D0)}$$

$$m(h_f) > 109.7 \text{ GeV (LEP)}$$

Summary

Tevatron experiments are searching for SM Higgs in the mass range 100-200 GeV.
Preliminary results for 1-2.4 fb^{-1} data set.
Final data set expected to be 6-7 fb^{-1} per experiment.

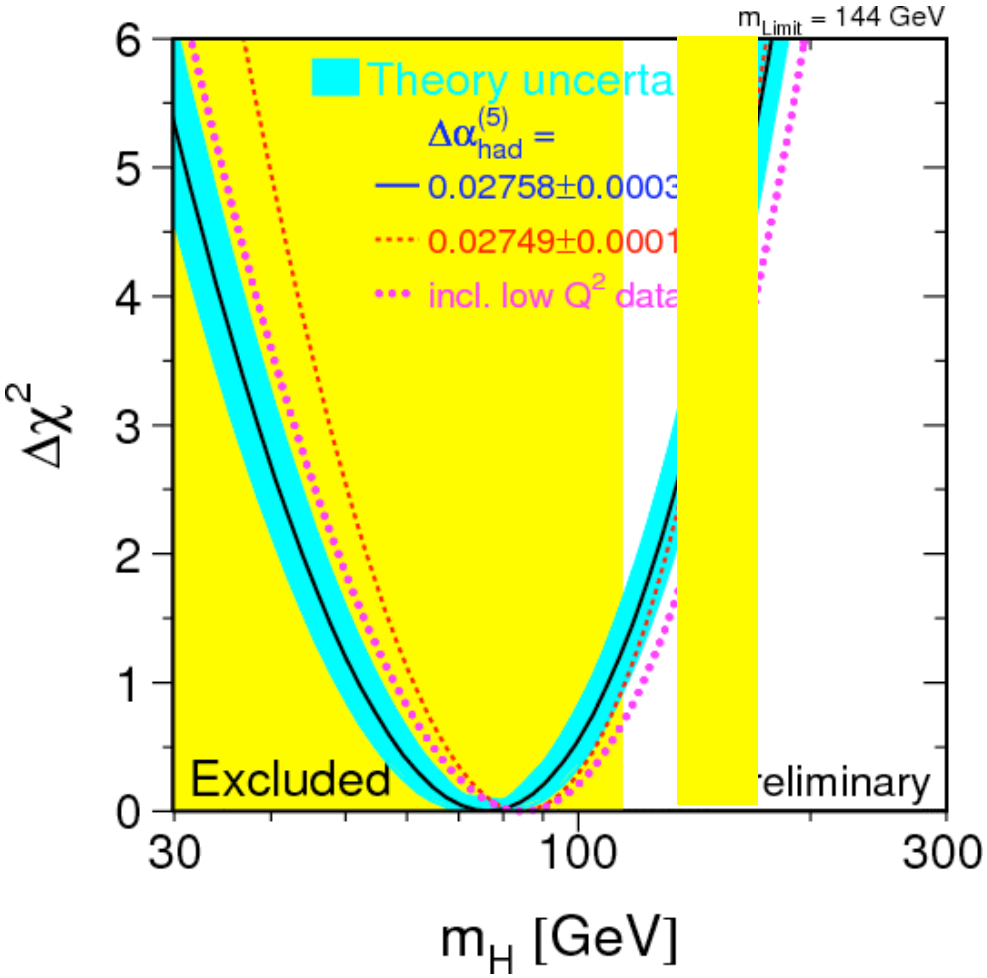
In most channels, limits improve than $\sqrt{L}$ due to improved calibrations and analysis techniques.

LHC will take over from Tevatron and cover complete SM mass range.

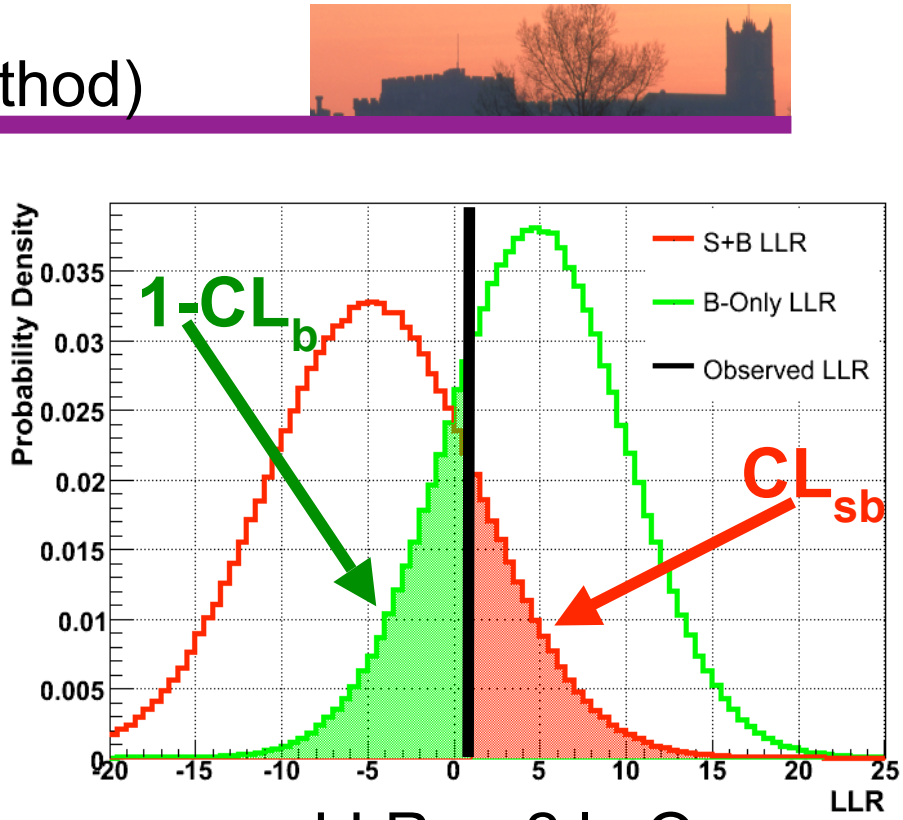
Tevatron are also searching for MSSM Higgs in a large part of the (m_A-tan β) plane.

Outlook

ICHEP08 ?



Limit Setting (CLs method)



Background only (b) and signal plus background (s+b) hypotheses are compared to data using Poisson likelihoods.

Probability density function is obtained through Gaussian smearing.

LLR = -2 ln Q

Systematic uncertainties are included in the likelihood ('profile likelihood')

$$Q(m_H) = \frac{L_{s+b}}{L_b}$$

Background is constrained by maximising profile likelihood ('sideband fitting').

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

CDF uses a Bayesian method, results agree within 10%