# Physics Program
## of the experiments at
## Large Hadron Collider

## Lecture 10

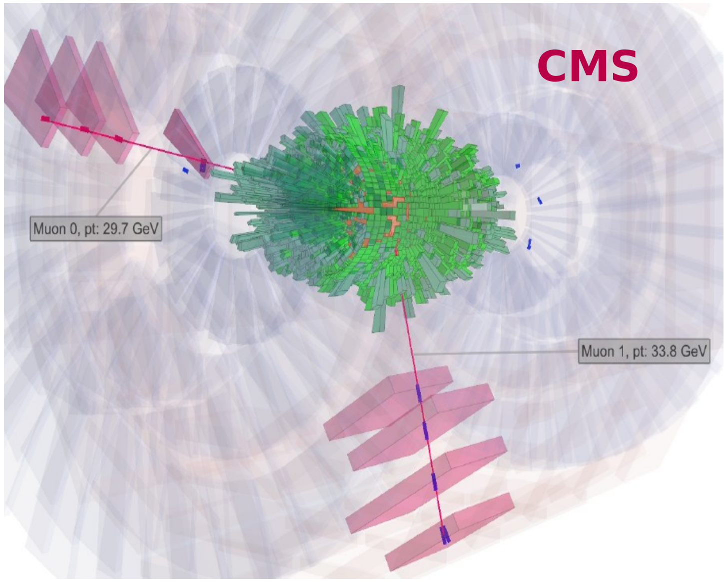
- **Higgs boson**
  - **Standard Model sector**
    - **LEP, Tevatron, LHC**

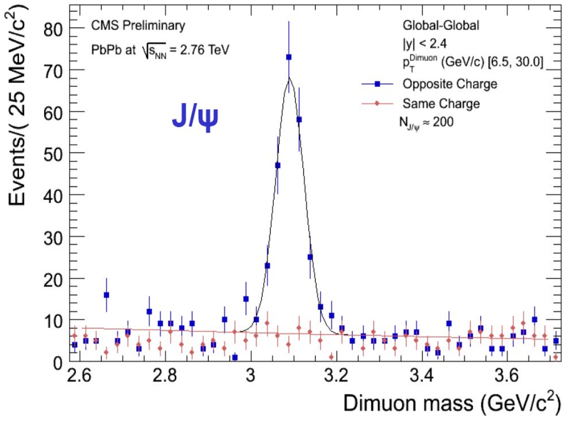
***parts based on slides from K. Jakobs, CERN, Academic Training, 2010**

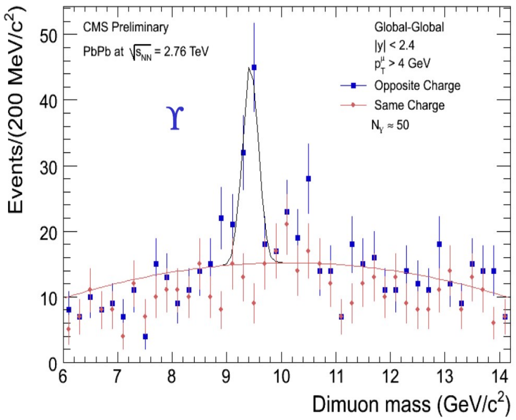
# ***Latest news!!!***

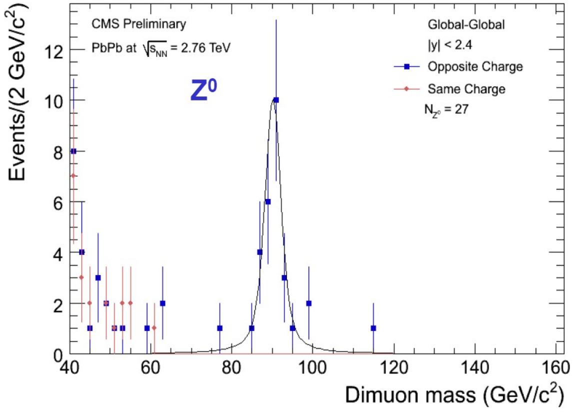
- We stopped taking data for the year 2010
- Heavy ion run recorded about 10μb$^{-1}$
- End of the year Jamboree at CERN

  on 17-th December

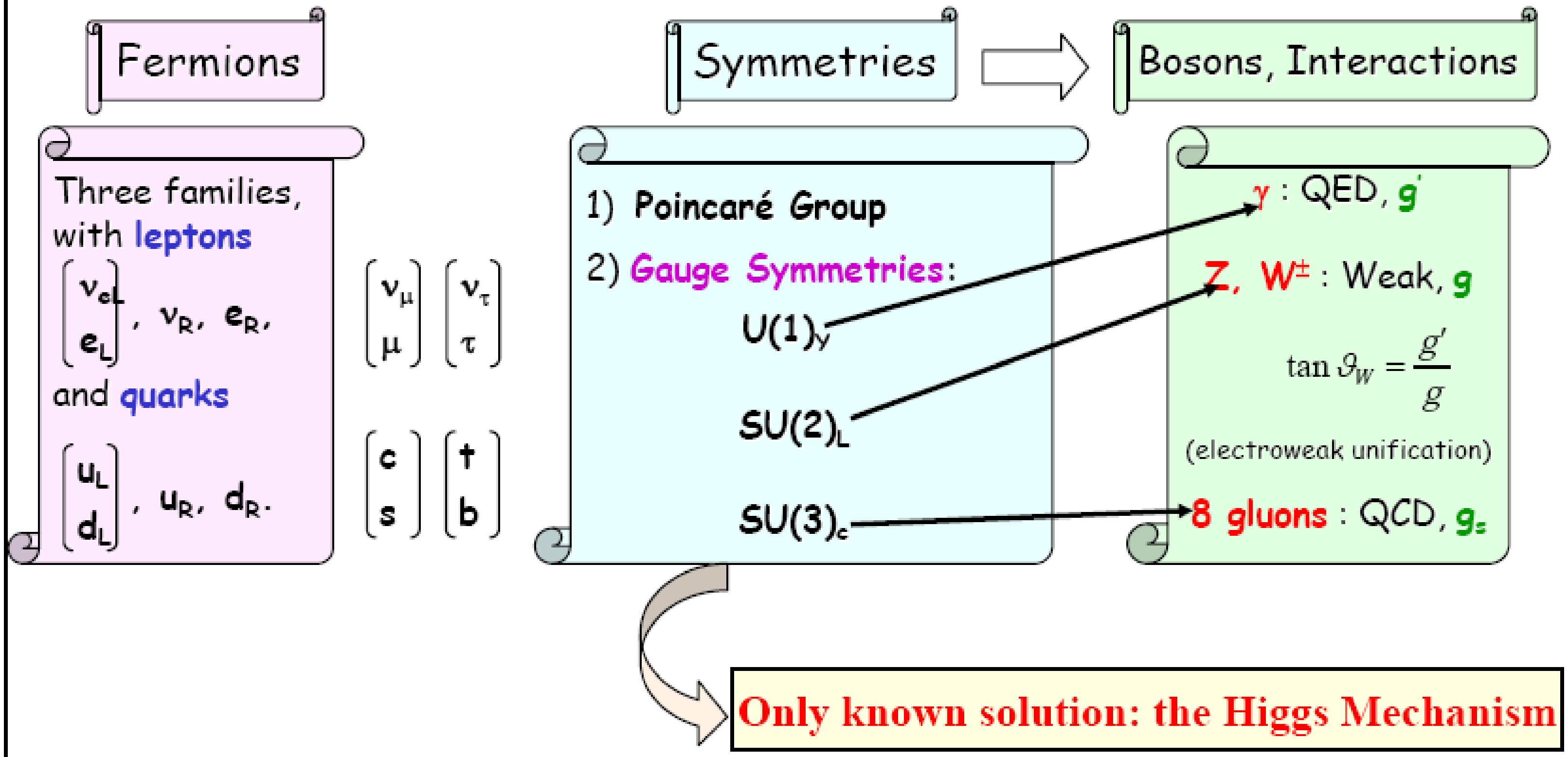








# Building blocks of the Standard Model



Fermions

Three families, with **leptons**

$\begin{pmatrix}\nu_{eL}\\ e_L\end{pmatrix}$, $\nu_R$, $e_R$, $\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}$ $\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$

and **quarks**

$\begin{pmatrix}u_L\\ d_L\end{pmatrix}$, $u_R$, $d_R$. $\begin{pmatrix}c\\ s\end{pmatrix}$ $\begin{pmatrix}t\\ b\end{pmatrix}$

Symmetries

1) **Poincaré Group**

2) **Gauge Symmetries**:

$U(1)_Y$

$SU(2)_L$

$SU(3)_c$

Bosons, Interactions

$\gamma$ : QED, $g'$

Z, $W^\pm$ : Weak, $g$

$$\tan \vartheta_W = \frac{g'}{g}$$

(electroweak unification)

**8 gluons** : QCD, $g_s$

**Only known solution: the Higgs Mechanism**

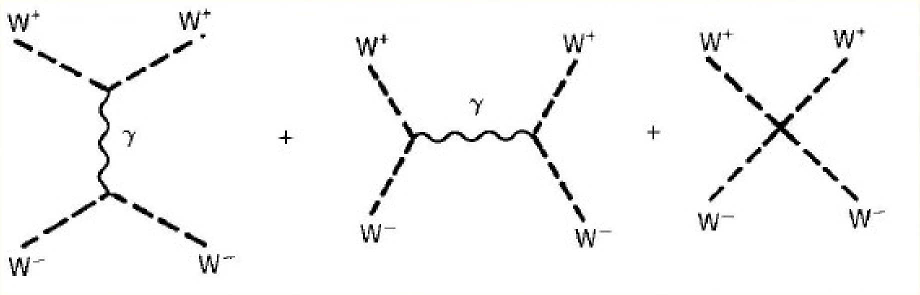
# Problem at this stage

- **Masses of the vector bosons W and Z:**

Experimental results: $M_W = 80.399 \pm 0.023$ GeV / $c^2$
$M_Z = 91.1875 \pm 0.0021$ GeV / $c^2$

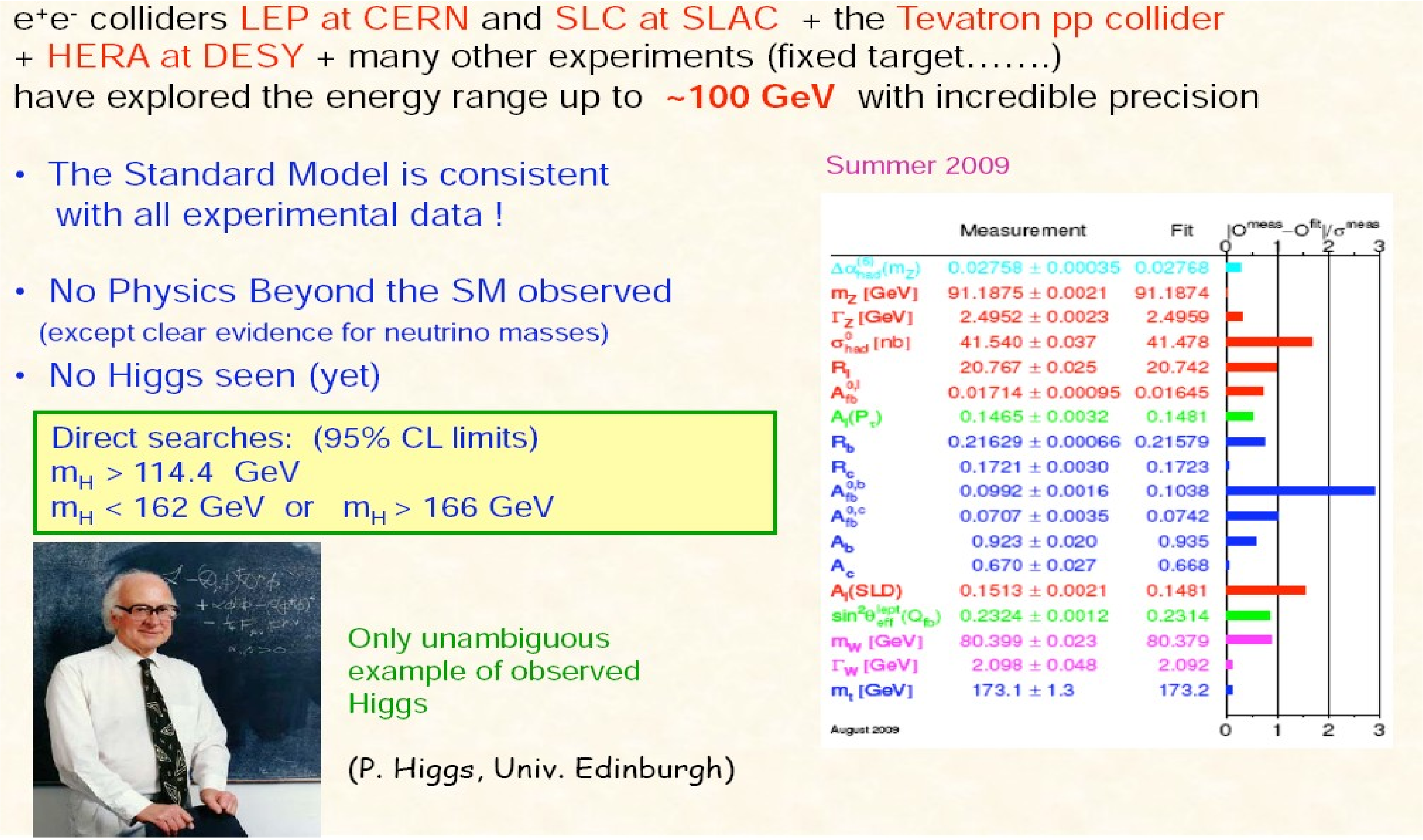
A local gauge invariant theory requires massless gauge fields

- **Divergences in the theory (scattering of W bosons)**



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$

# Present status



$e^+e^-$ colliders LEP at CERN and SLC at SLAC + the Tevatron pp collider + HERA at DESY + many other experiments (fixed target.......) have explored the energy range up to ~100 GeV with incredible precision

- The Standard Model is consistent with all experimental data !
- No Physics Beyond the SM observed

  (except clear evidence for neutrino masses)
- No Higgs seen (yet)

Direct searches: (95% CL limits)
$m_H > 114.4$ GeV
$m_H < 162$ GeV or $m_H > 166$ GeV

Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)

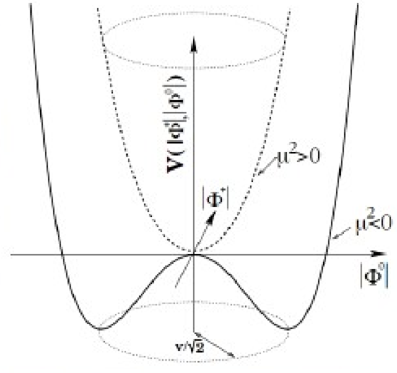
Summer 2009

|  | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^0$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01645 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1481 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1481 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.399 ± 0.023 | 80.379 |
| $\Gamma_W$ [GeV] | 2.098 ± 0.048 | 2.092 |
| $m_t$ [GeV] | 173.1 ± 1.3 | 173.2 |

# The Higgs mechanism

- Scalar fields are introduced $\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$

  Potential : $V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$



- Lagrangian for the scalar fields:
  g, g' = SU(2), U(1) gauge couplings

$$L_2 = \left| \left( i\partial_\mu - g\mathbf{T}\cdot\mathbf{W}_\mu - g'\frac{Y}{2}B_\mu \right)\phi \right|^2 - V(\phi)$$

- For $\mu^2 < 0$, $\lambda > 0$,
  minimum of potential:

$$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \qquad v^2 = -\mu^2/\lambda$$

- Perturbation theory around ground state:

$$\phi_0(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix} \Rightarrow$$

# Particle content and masses

- Mass terms for the W± bosons: $\boxed{M_{W^\pm} = \frac{1}{2} v g}$

- Remaining terms off-diagonal in $W_\mu^3$ and $B_\mu$:

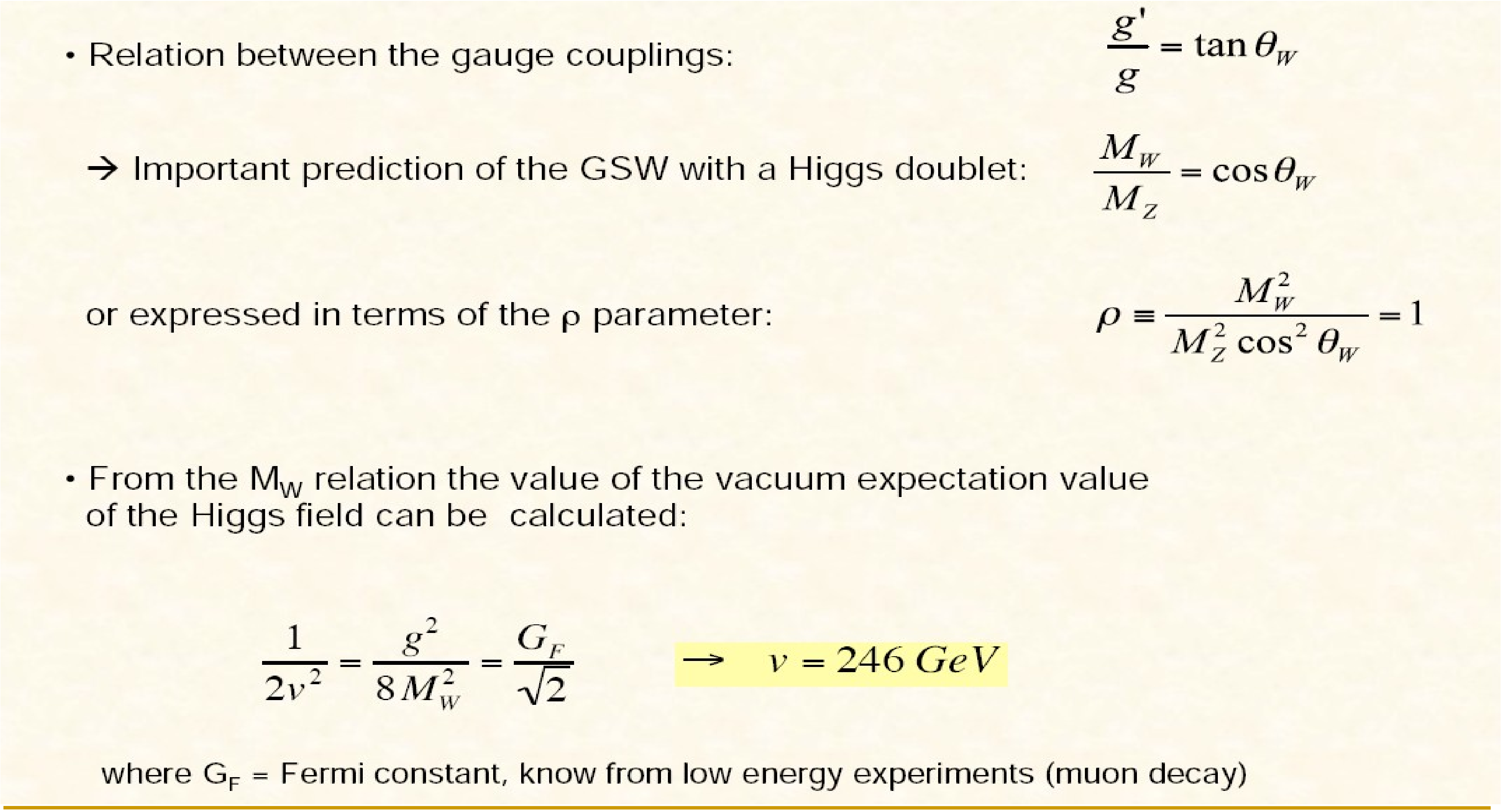
$$\frac{1}{8} v^2 (W_\mu^3, B_\mu) \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} = \frac{1}{8} v^2 \left[ g W_\mu^3 - g' B_\mu \right]^2$$

$$+ 0 \left[ g' W_\mu^3 + g B_\mu \right]^2$$

- Massless photon: $A_\mu = \dfrac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}}$ *with* $\boxed{M_A = 0}$

- Massive neutral vector boson: $Z_\mu = \dfrac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}}$ *with* $\boxed{M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}}$

# Important relations in the Glashow-Salam-Weinberg model



- Relation between the gauge couplings: $\frac{g'}{g} = \tan\theta_W$

→ Important prediction of the GSW with a Higgs doublet: $\frac{M_W}{M_Z} = \cos\theta_W$

or expressed in terms of the ρ parameter: $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$

- From the $M_W$ relation the value of the vacuum expectation value of the Higgs field can be calculated:

$$\frac{1}{2v^2} = \frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \qquad \rightarrow \quad v = 246\ GeV$$

where $G_F$ = Fermi constant, know from low energy experiments (muon decay)

# Masses of the fermions

- The same Higgs doublet which generates W± and Z masses is sufficient to give masses to the fermions (leptons and quarks):

  e.g. for electrons: use an arbitrary coupling $G_e$

$$L_3 = -G_e \left[ (\bar{\nu}_e, \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R + \bar{e}_R (\phi^-, \bar{\phi}^0) \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right]$$

- Spontaneous symmetry breaking:

$$\phi = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

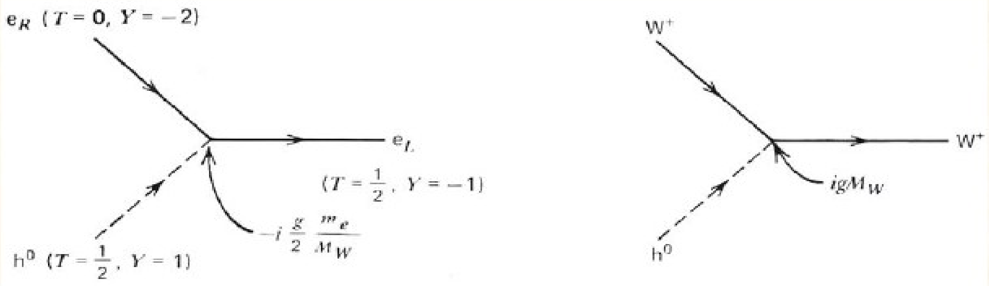
$$L_3 = -\frac{G_e v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) h$$

mass term

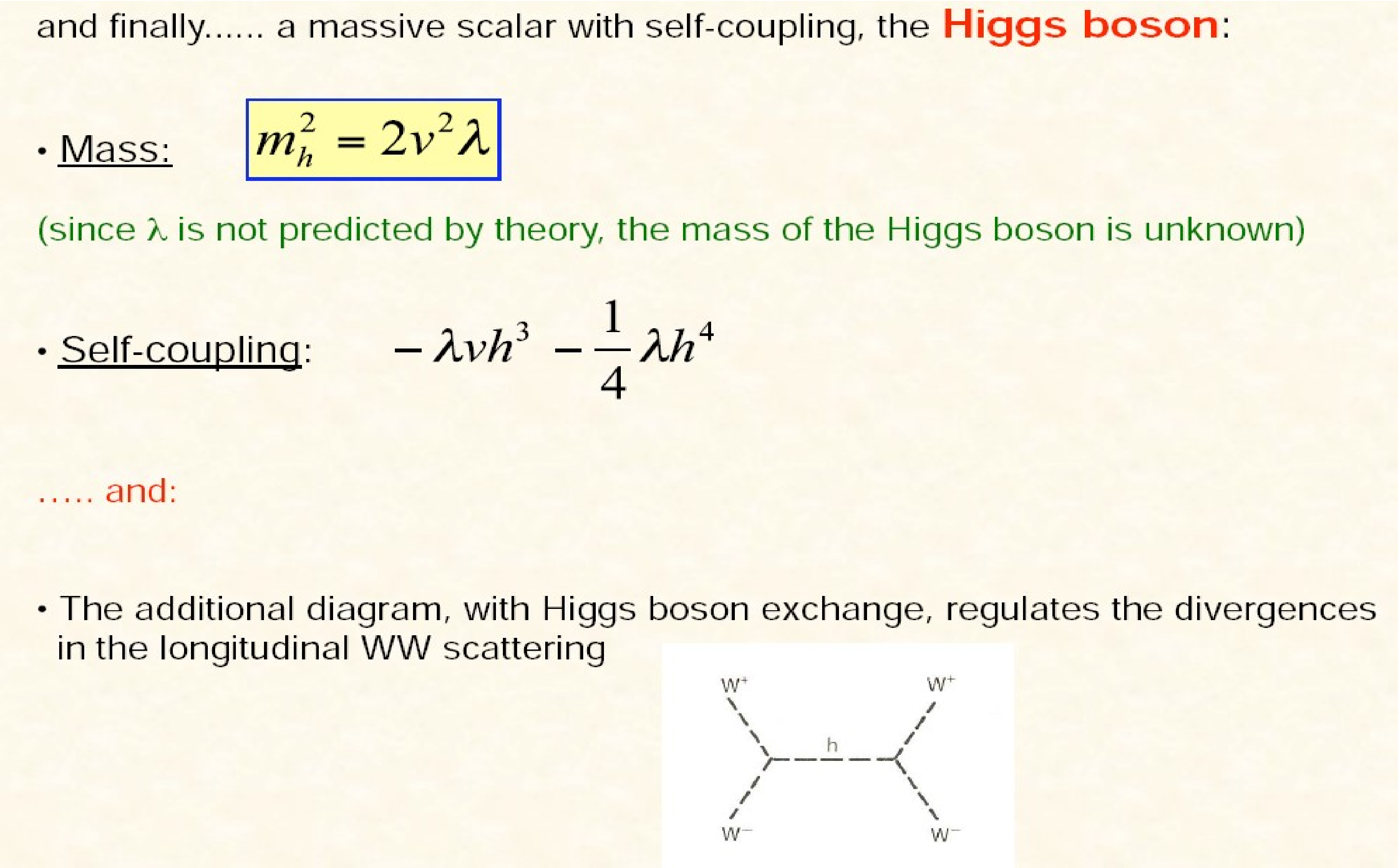
interaction term with the Higgs field

- Important relation: coupling of the Higgs boson to fermions is proportional to their mass

$$\boxed{G_f = \frac{\sqrt{2}\, m_f}{v}}$$



# The Higgs sector



and finally...... a massive scalar with self-coupling, the **Higgs boson**:

- Mass: $\boxed{m_h^2 = 2v^2\lambda}$

(since λ is not predicted by theory, the mass of the Higgs boson is unknown)

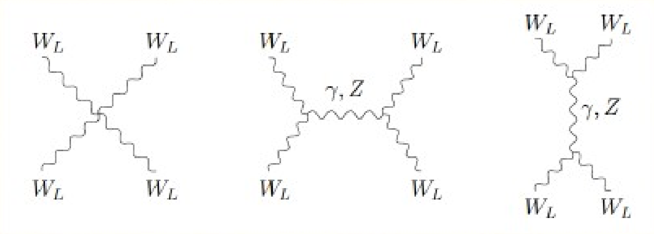
- Self-coupling: $-\lambda v h^3 - \frac{1}{4}\lambda h^4$

….. and:

- The additional diagram, with Higgs boson exchange, regulates the divergences in the longitudinal WW scattering

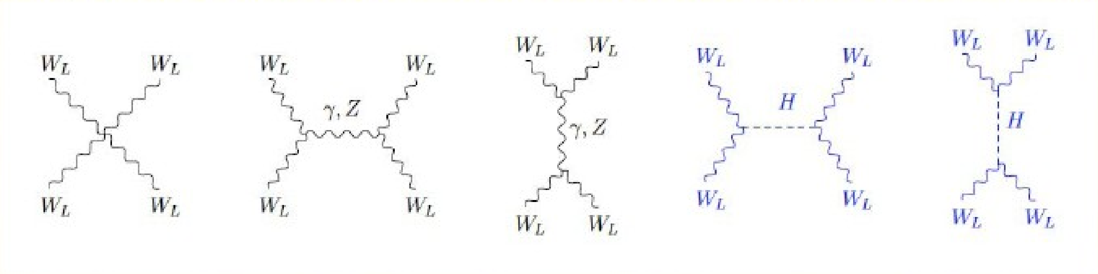
# Higgs boson as UV regulator

Scattering of longitudinally polarized W bosons



$$-iM(W^+W^- \to W^+W^-) \sim \frac{s}{m_W^2} \quad \text{for} \quad s \to \infty$$

Higgs boson guarantees unitarity (if its mass is < ~1 TeV)



$$-iM(W^+W^- \to W^+W^-) \sim m_H^2 \quad \text{for} \quad s \to \infty$$

# Theory constrain on the Higgs boson mass

- Unitarity limit:

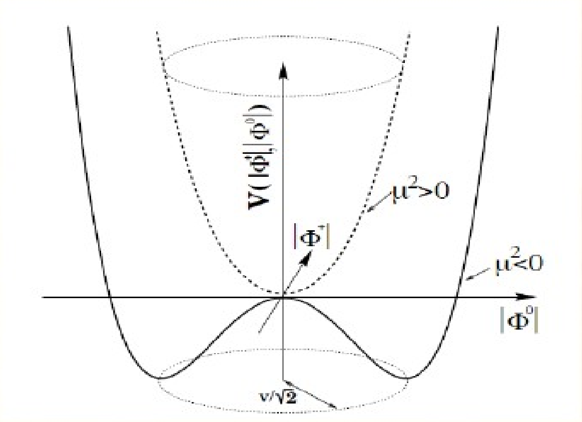
  If Higgs boson too heavy, the regulation of the WW cross section is less effective and unitarity is violated again

  → $m_H <$ ~1 TeV (as just discussed)

- Stricter limits from the energy dependence of the Higgs boson self coupling $\lambda$

  - Stability of the vacuum
  - Diverging coupling $\lambda(Q^2)$

  → next slides

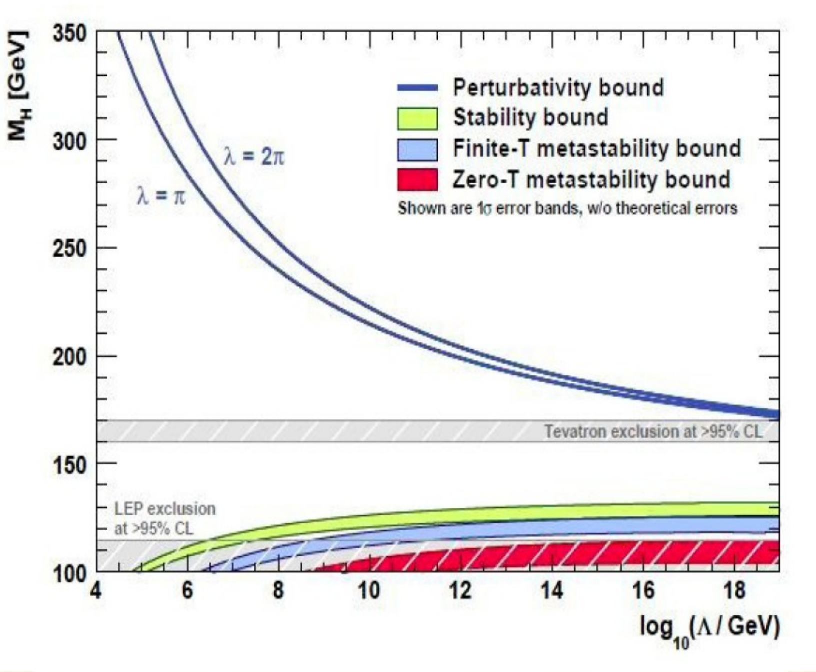


# Higgs mass constraints

Stronger bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda\,(Q^2)$

(if the Standard Model is assumed to be valid up to some scale $\Lambda$)

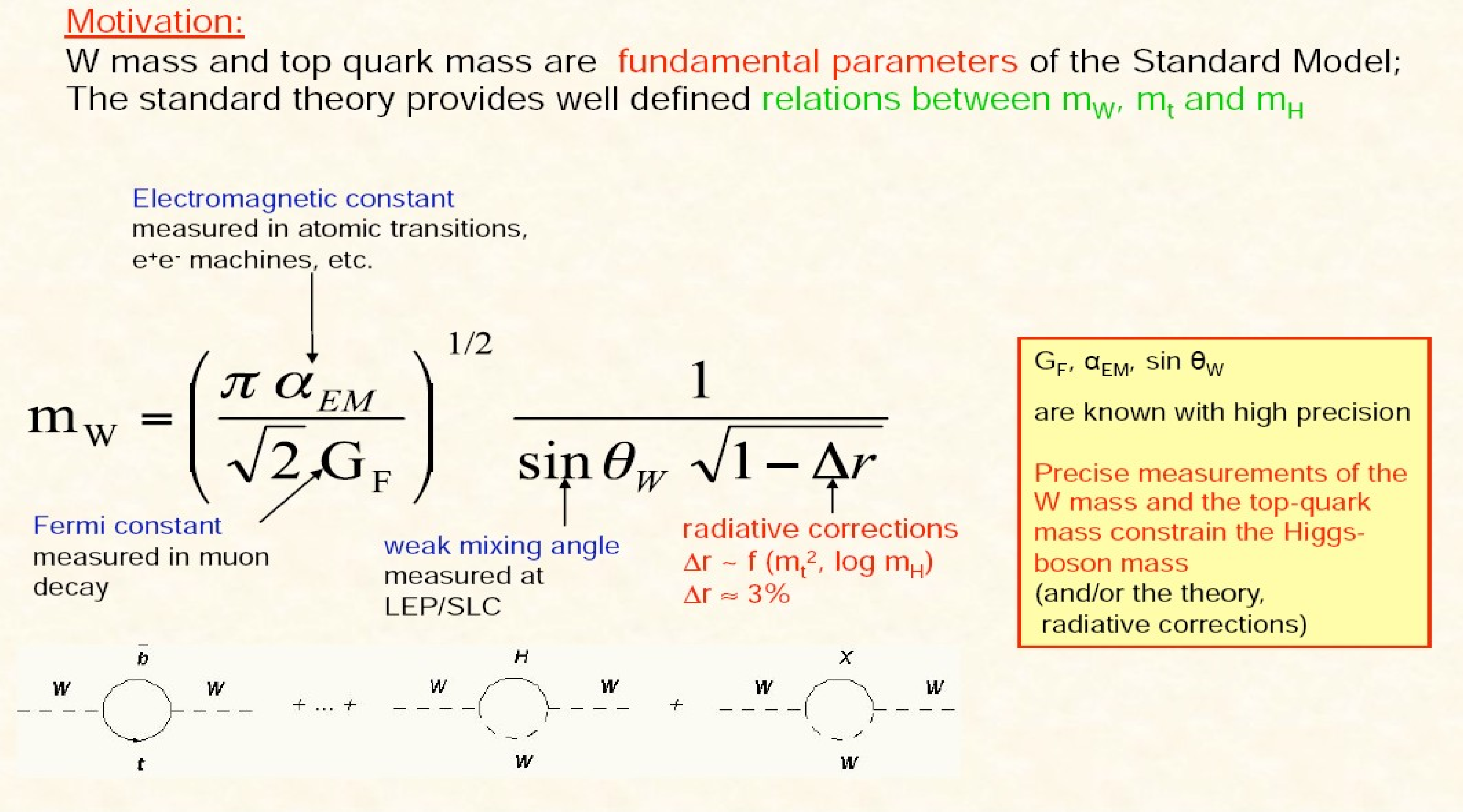
$$\lambda(Q^2) = \lambda_0 \left\{ 1 + \frac{3\lambda_0}{2\pi^2} \log\,(2\frac{Q^2}{v^2}) + \ldots - \frac{3g_t^4}{32\pi^2} \log\,(2\frac{Q^2}{v^2}) + \ldots \right\} \qquad \text{where} \quad \lambda_0 = \frac{m_h^2}{v^2}$$



| | |
|---|---|
| Upper bound: | diverging coupling (Landau Pole) |
| Lower bound: | stability of the vacuum (negative contribution from top quark dominates) |

Mass bounds depend on scale $\Lambda$ up to which the Standard Model should be valid

# Indirect limits from electroweak precision data



Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between $m_W$, $m_t$ and $m_H$

Electromagnetic constant
measured in atomic transitions,
$e^+e^-$ machines, etc.

$$m_W = \left(\frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F}\right)^{1/2}\frac{1}{\sin\theta_W\,\sqrt{1-\Delta r}}$$

Fermi constant
measured in muon
decay

weak mixing angle
measured at
LEP/SLC

radiative corrections
$\Delta r \sim f(m_t^2, \log m_H)$
$\Delta r \approx 3\%$

$G_F$, $\alpha_{EM}$, $\sin\theta_W$

are known with high precision

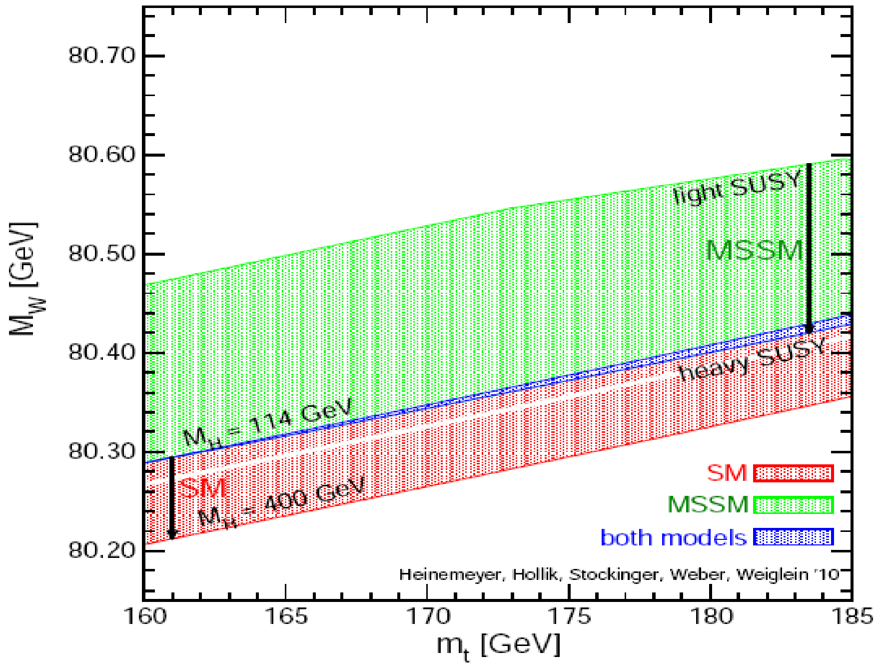
Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory,
radiative corrections)

# Relation between $m_W$, $m_t$ and $m_H$

- Prediction for $m_W$ in the MSSM and the SM as a function of the $m_t$.

Example: Prediction for $M_W$ in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A. Weber, G. Weiglein '07]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{SM}$

# The W and top mass measurement

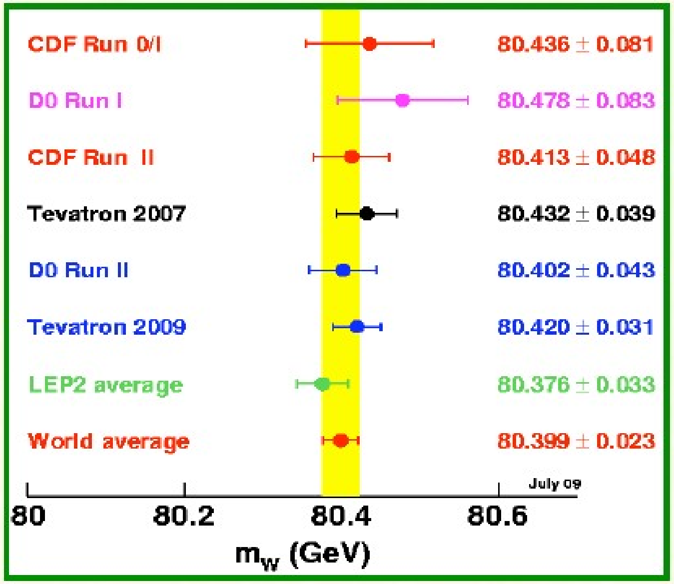
$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

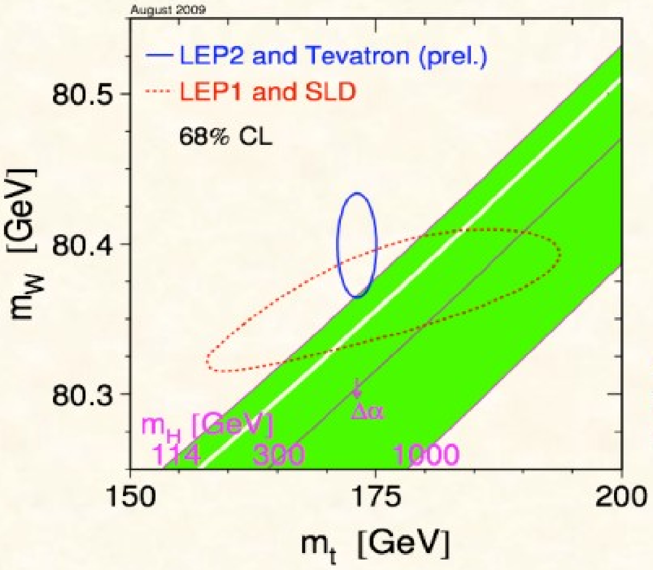
$3 \cdot 10^{-4}$

$m_W$ (from LEP2 + Tevatron) = 80.399 ± 0.023 GeV

$m_{top}$ (from Tevatron) = 173.1 ± 1.3 GeV

0.8%



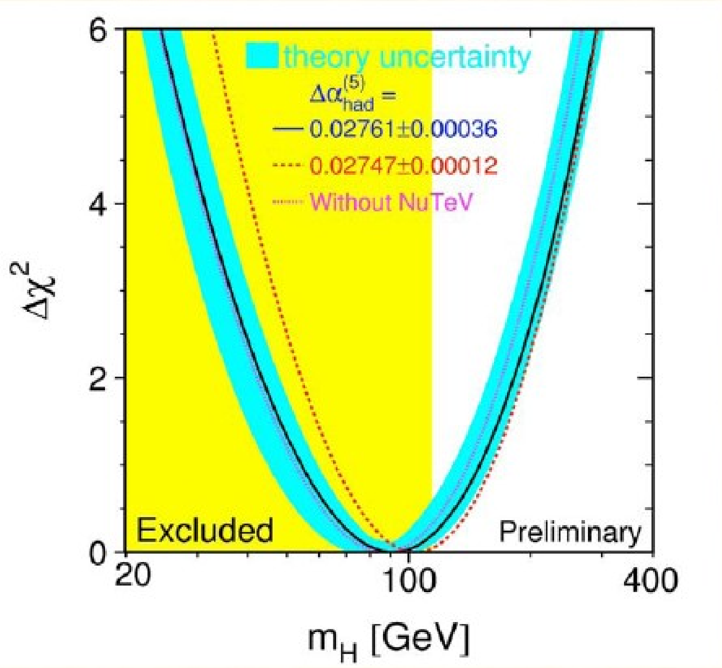


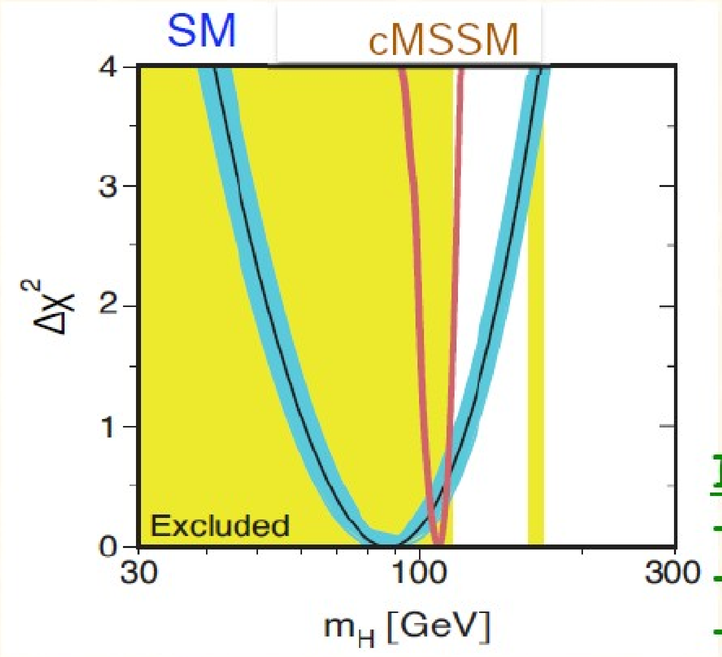
A light Higgs boson is favoured by present measurements

Ultimate test of the Standard Model: comparison between the direct Higgs boson mass and predictions from radiative corrections….

Fit in the constrained MSSM

O. Buchmüller et al. (2010)





Includes:
- WMAP
- $b \to s\gamma$
- $a_\mu$

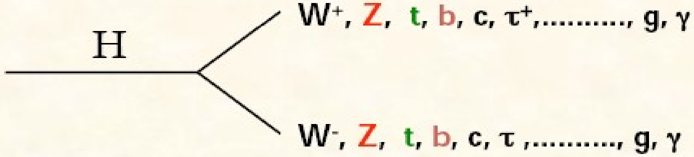
Results of the precision el.weak measurements: (LEWWG-2009):

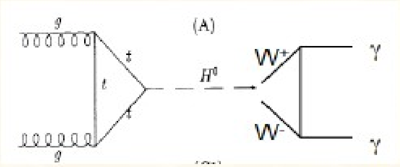
$$m_H = 87^{+35}_{-26}\ GeV$$

$$m_H = 108^{+6}_{-6}\ GeV$$

# Higgs boson decays

The decay properties of the Higgs boson are fixed, if the **mass** is known:





$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2) M_H$$

$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2)\beta_V$$

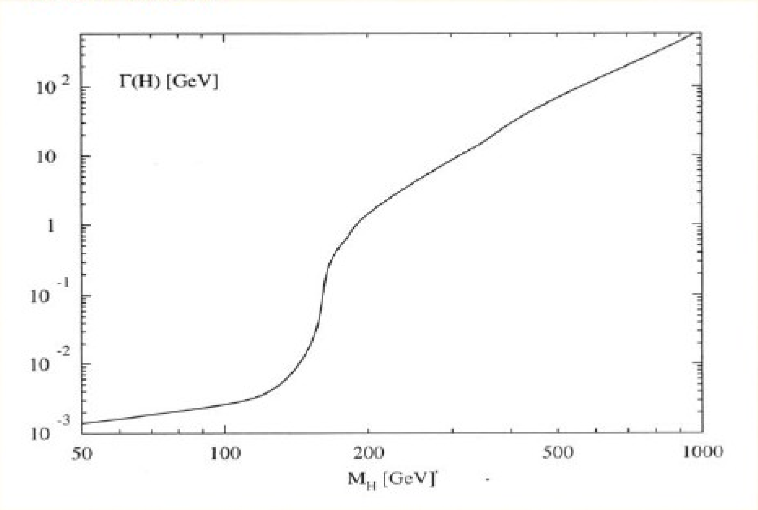
$$\text{where:} \quad \delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_V^2, \quad \beta = \text{velocity}$$

(+ W-loop contributions)

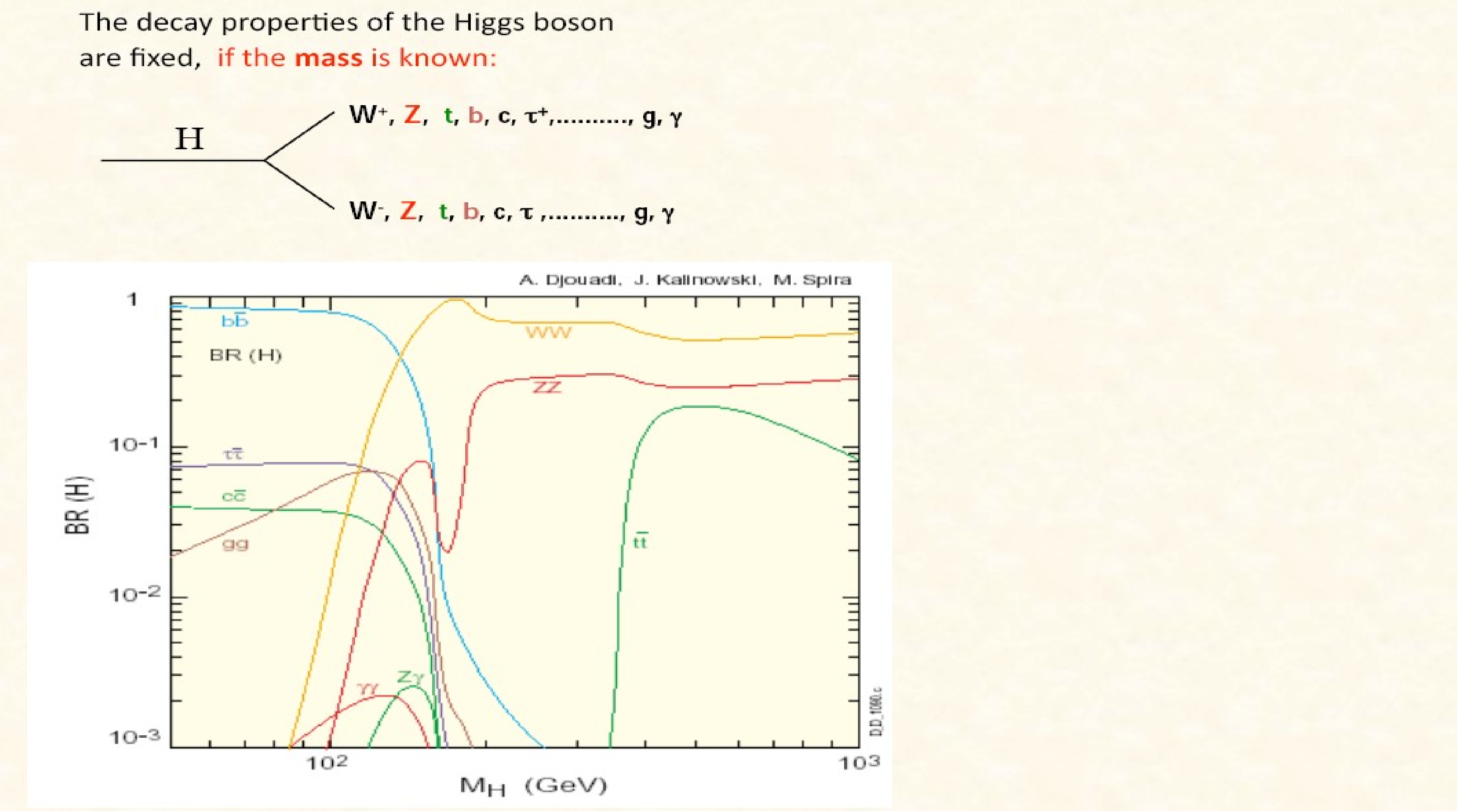
$$\Gamma(\mathrm{H} \to \mathrm{gg}) = \frac{G_F \alpha_a^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_a}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha_a^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Total width

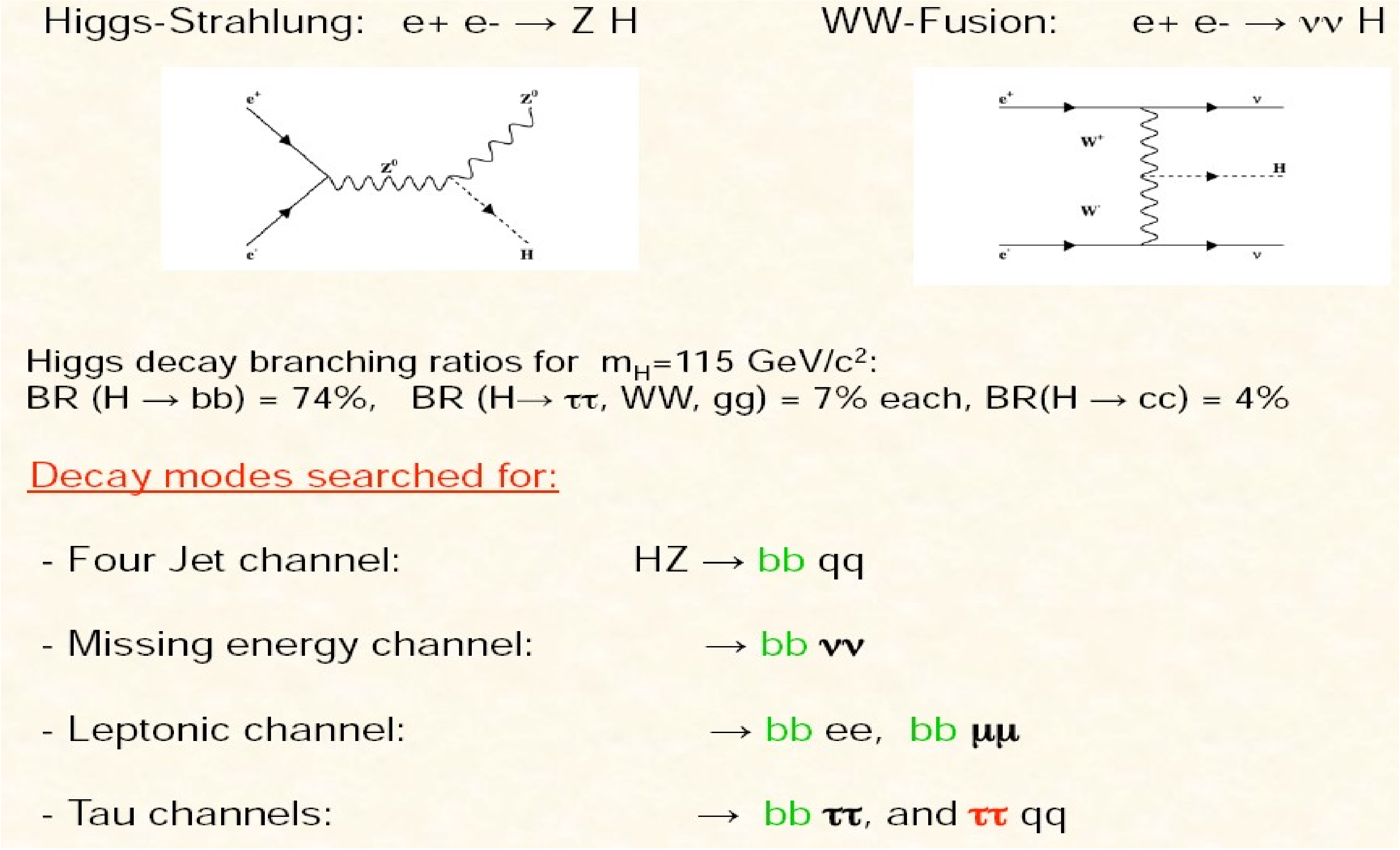


# Higgs boson decays



The decay properties of the Higgs boson are fixed, if the **mass** is known:

# Higgs boson searches at LEP



Higgs-Strahlung: e+ e- → Z H

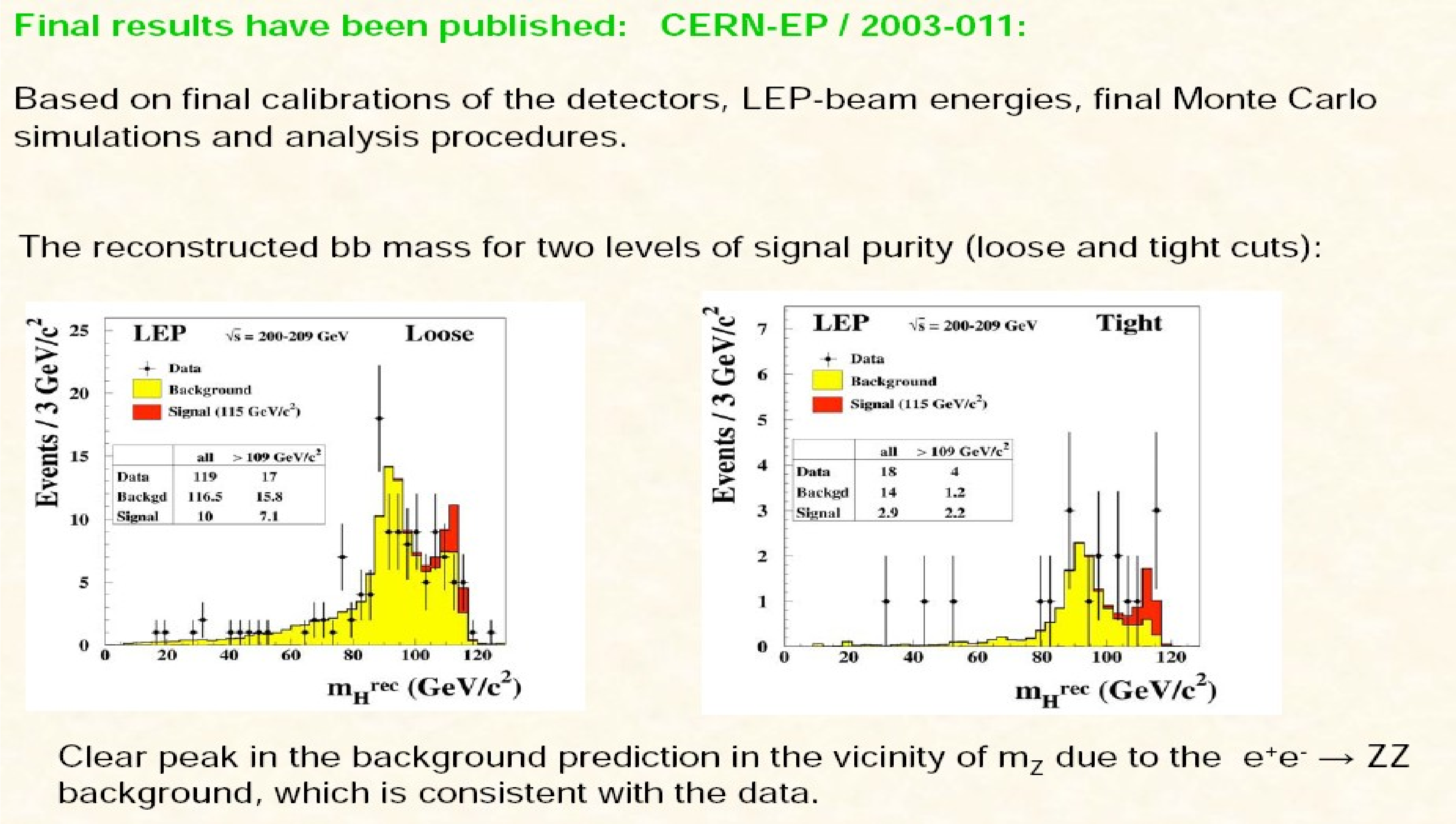
WW-Fusion: e+ e- → νν H

Higgs decay branching ratios for $m_H$=115 GeV/$c^2$:
BR (H → bb) = 74%, BR (H→ ττ, WW, gg) = 7% each, BR(H → cc) = 4%

Decay modes searched for:

- Four Jet channel: HZ → bb qq
- Missing energy channel: → bb **νν**
- Leptonic channel: → bb ee, bb **μμ**
- Tau channels: → bb **ττ**, and **ττ** qq

# Results of the final LEP analysis



**Final results have been published: CERN-EP / 2003-011:**

Based on final calibrations of the detectors, LEP-beam energies, final Monte Carlo simulations and analysis procedures.

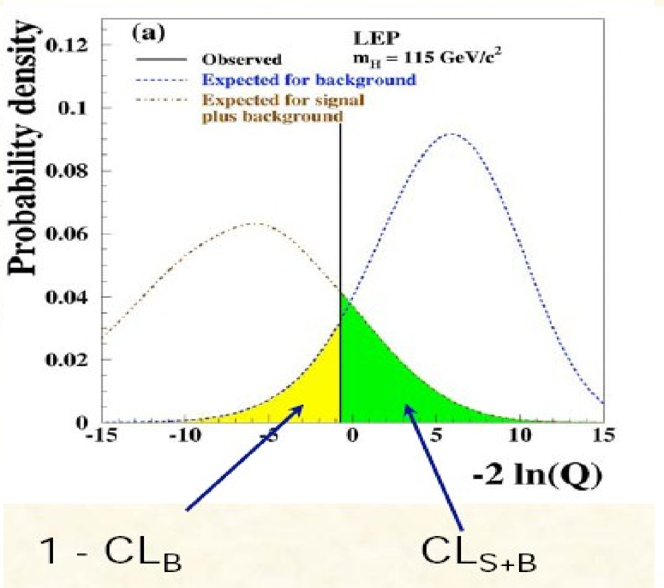
The reconstructed bb mass for two levels of signal purity (loose and tight cuts):

| | all | > 109 GeV/c² |
|---|---|---|
| Data | 119 | 17 |
| Backgd | 116.5 | 15.8 |
| Signal | 10 | 7.1 |

| | all | > 109 GeV/c² |
|---|---|---|
| Data | 18 | 4 |
| Backgd | 14 | 1.2 |
| Signal | 2.9 | 2.2 |

Clear peak in the background prediction in the vicinity of $m_Z$ due to the $e^+e^- \to ZZ$ background, which is consistent with the data.

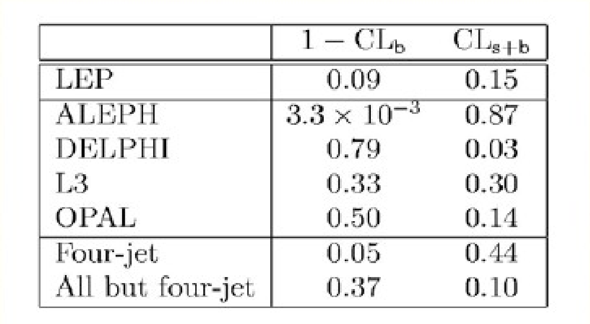
# Final combined LEP results



$1 - CL_B$

$CL_{S+B}$

Likelihood ratio $Q := L_{S+B} / L_B$
Test statistics: $-2 \ln Q$



|  | $1 - CL_b$ | $CL_{s+b}$ |
|---|---|---|
| LEP | 0.09 | 0.15 |
| ALEPH | $3.3 \times 10^{-3}$ | 0.87 |
| DELPHI | 0.79 | 0.03 |
| L3 | 0.33 | 0.30 |
| OPAL | 0.50 | 0.14 |
| Four-jet | 0.05 | 0.44 |
| All but four-jet | 0.37 | 0.10 |

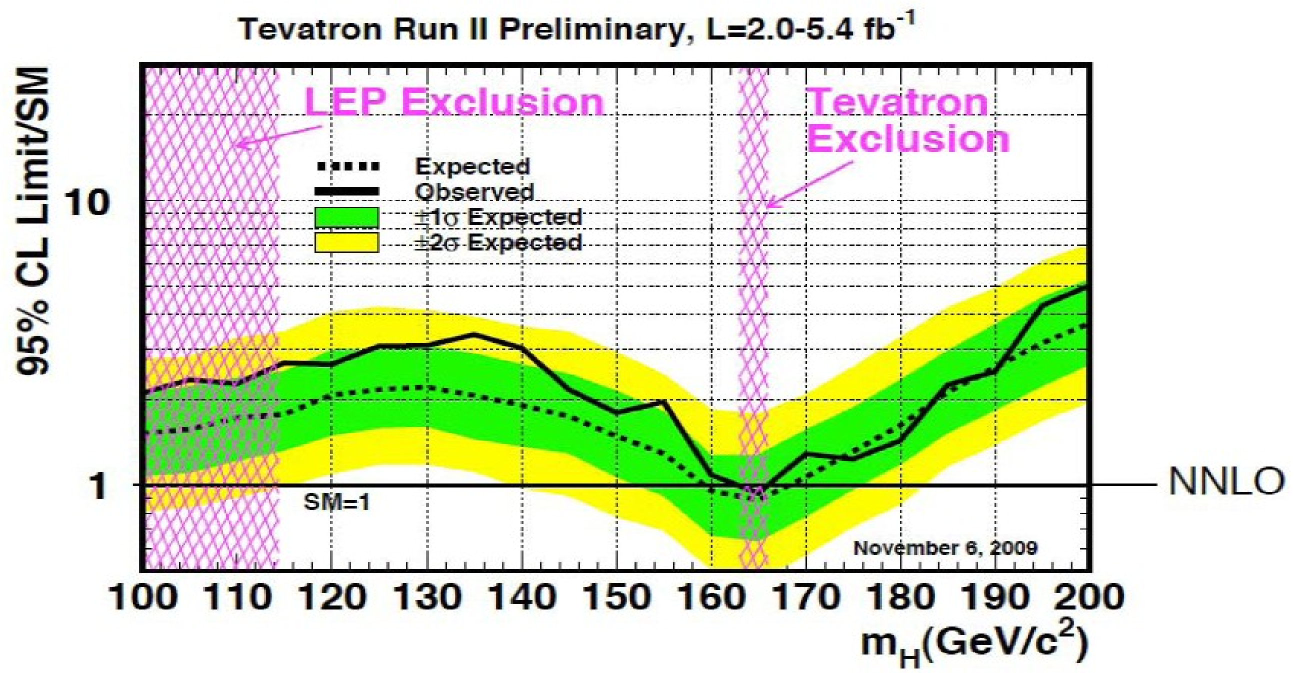
$1 - CL_B = 0.09$ ↔

**Signal significance = 1.7 σ**

**$M_H > 114.4$ GeV/$c^2$ (95% CL)**

expected mass limit: 115.3 GeV/$c^2$
(sensitivity)

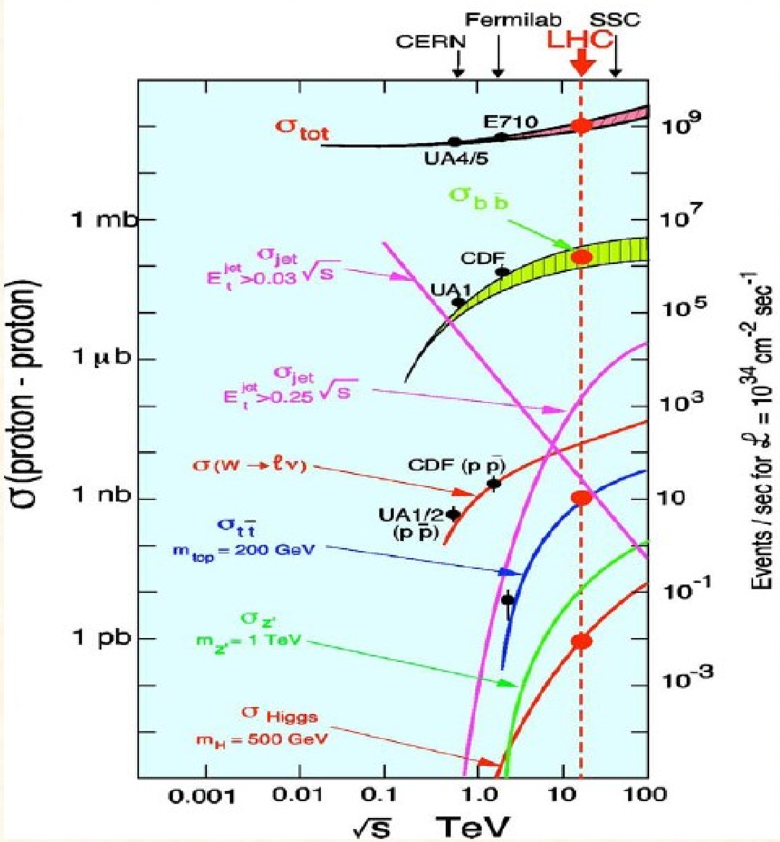
# Direct limit searches at the Tevatron



Exclude mass region between 162 and 166 GeV (95% C.L.)

(First exclusion since LEP,

# Cross-section and production rates



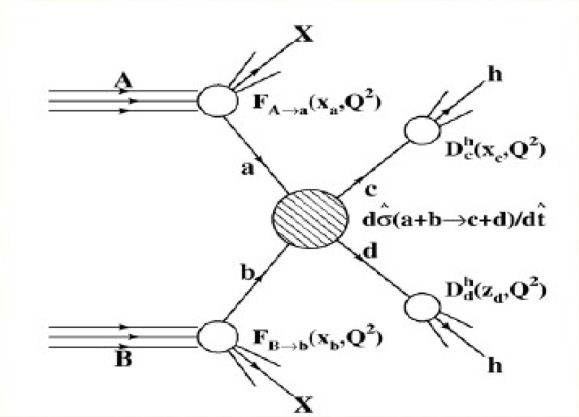
Rates for L = $10^{34}$ cm$^{-2}$ s$^{-1}$: (LHC)

| | |
|---|---|
| • 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:

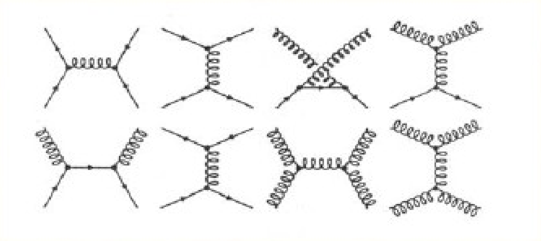
- jet production via QCD processes
- tt production (for lepton final states)
- W/Z + jet production (lepton final states)

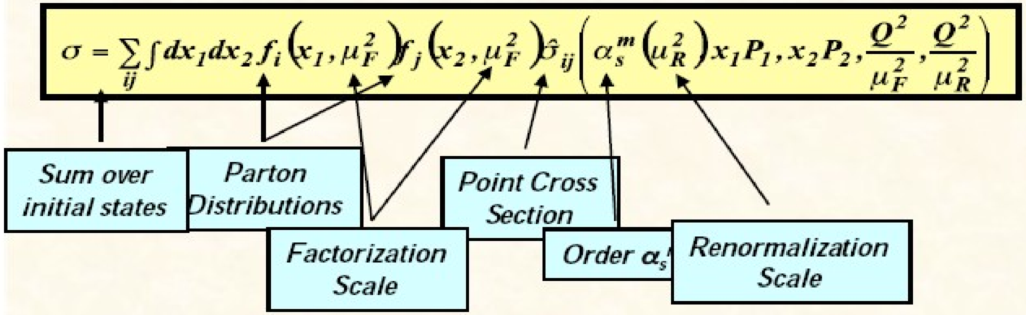
# Phenomenology of pp collision



Dominant hard scattering cross section:

„QCD Jet Production"
quark/gluon scattering





$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i\left(x_1,\mu_F^2\right) f_j\left(x_2,\mu_F^2\right) \hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right) x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

*Sum over initial states*

*Parton Distributions*

*Factorization Scale*

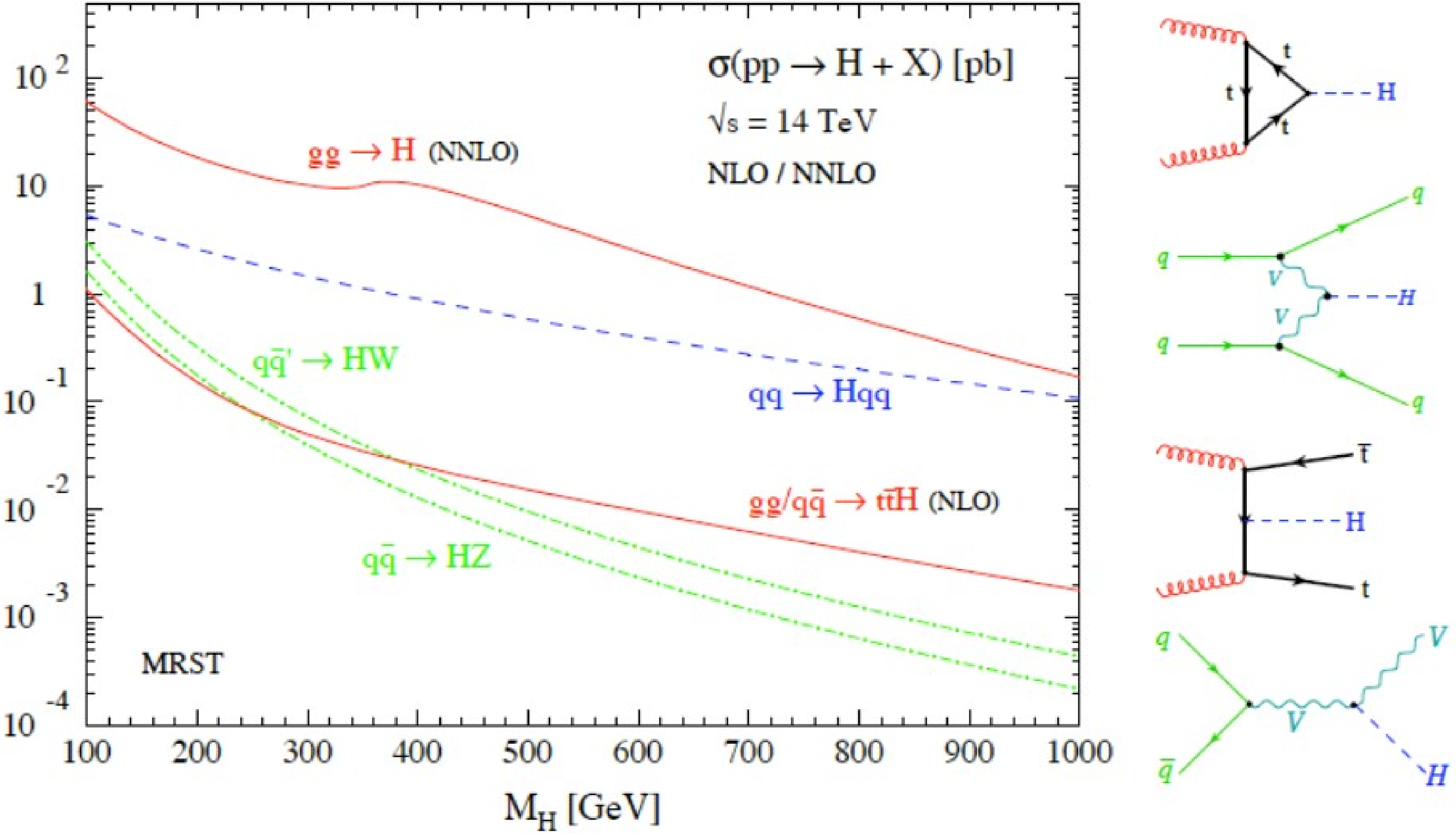
*Point Cross Section*

*Order $\alpha_s$*

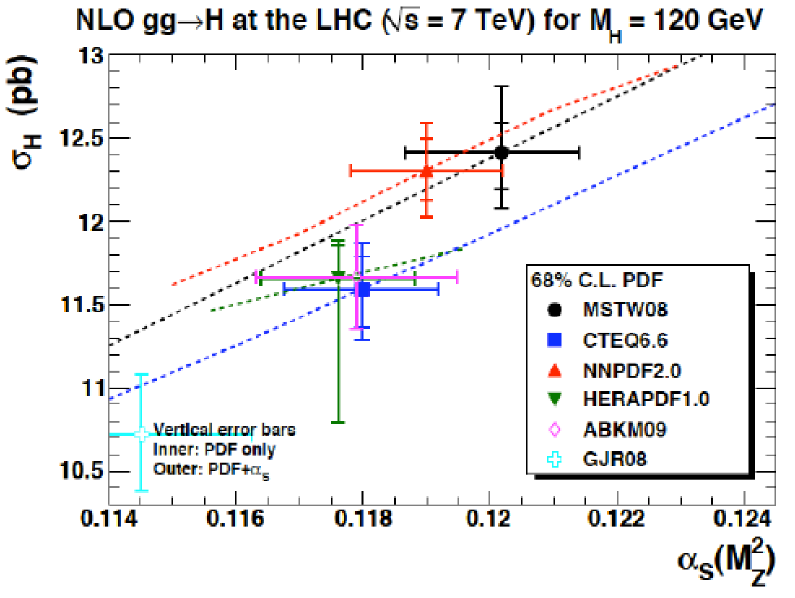
*Renormalization Scale*

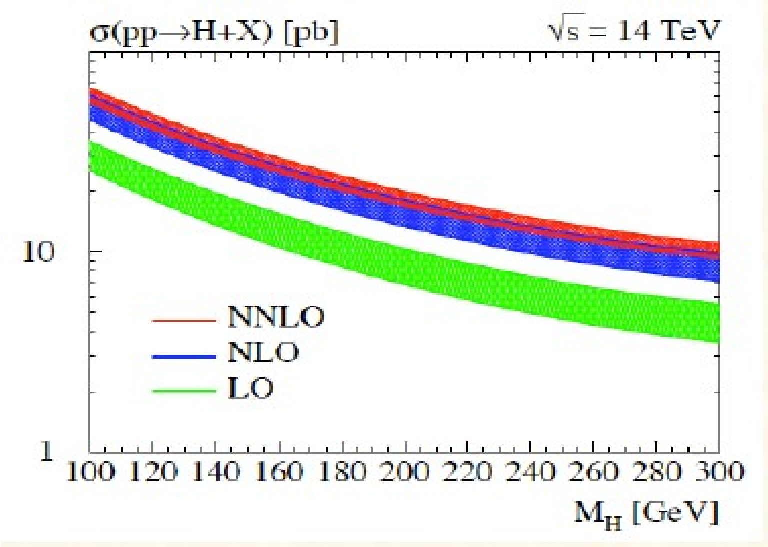
Detection of Higgs boson decays into qq (bb) final states (without associated signatures) is hopeless !!

# Production cross-section



# Higgs cross-section for various PDF parametrisations

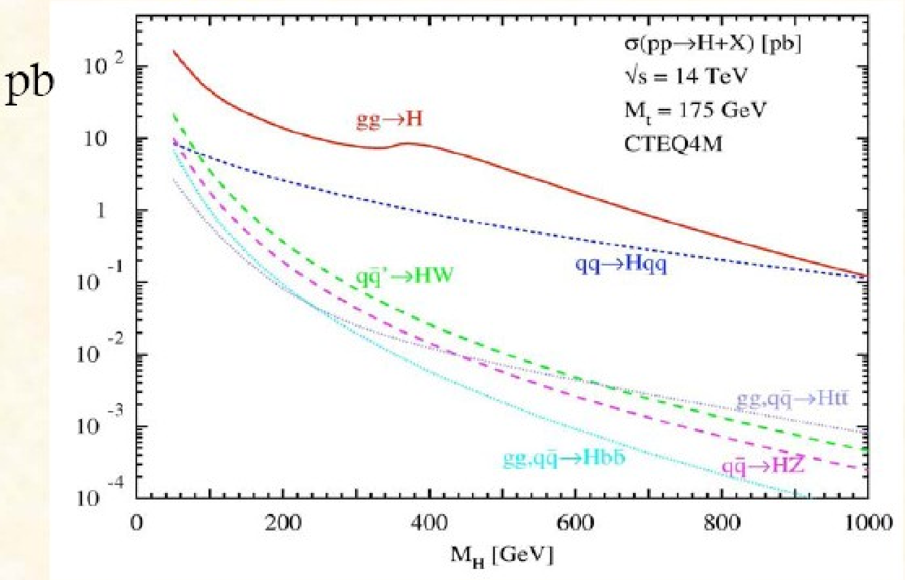




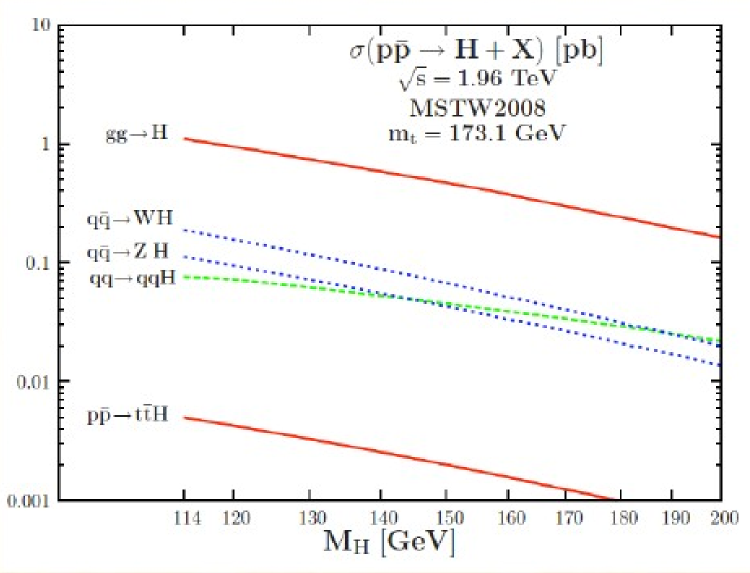
- Significant effect resulting from struture functions parametrisations and from $\alpha_s$
- Uncertainties from renormalisation and factorisation scale.

# Production cross-section at the Tevatron and LHC

LHC M. Spira et al.

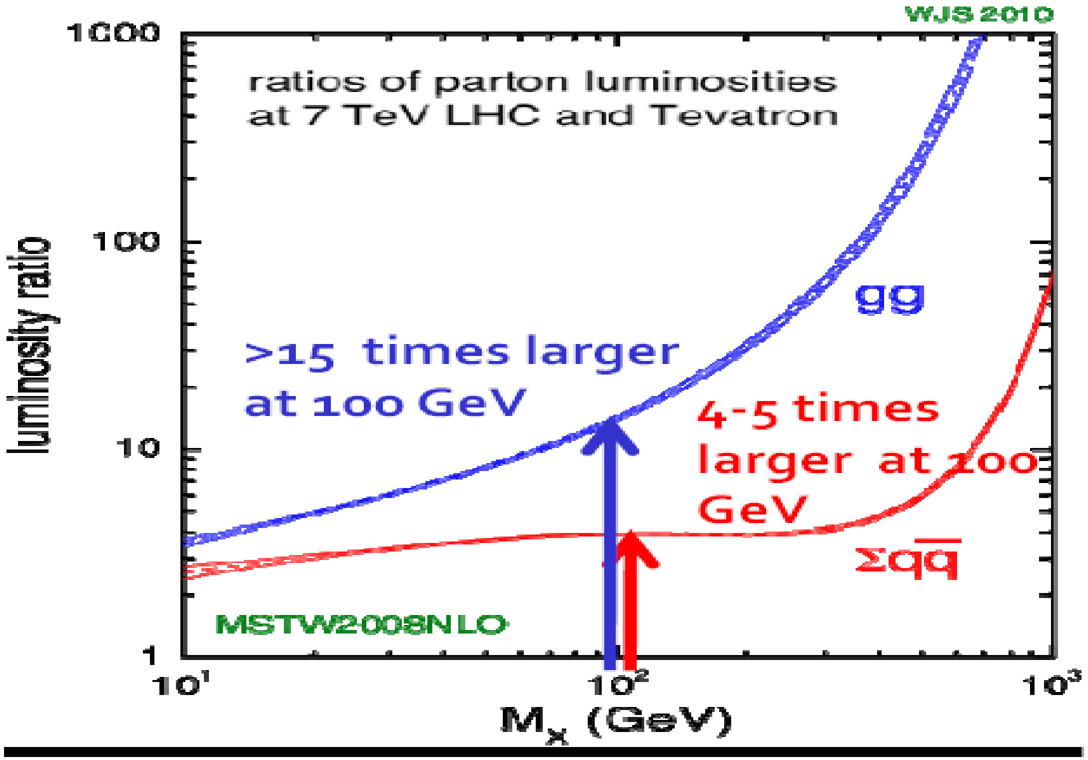


Tevatron

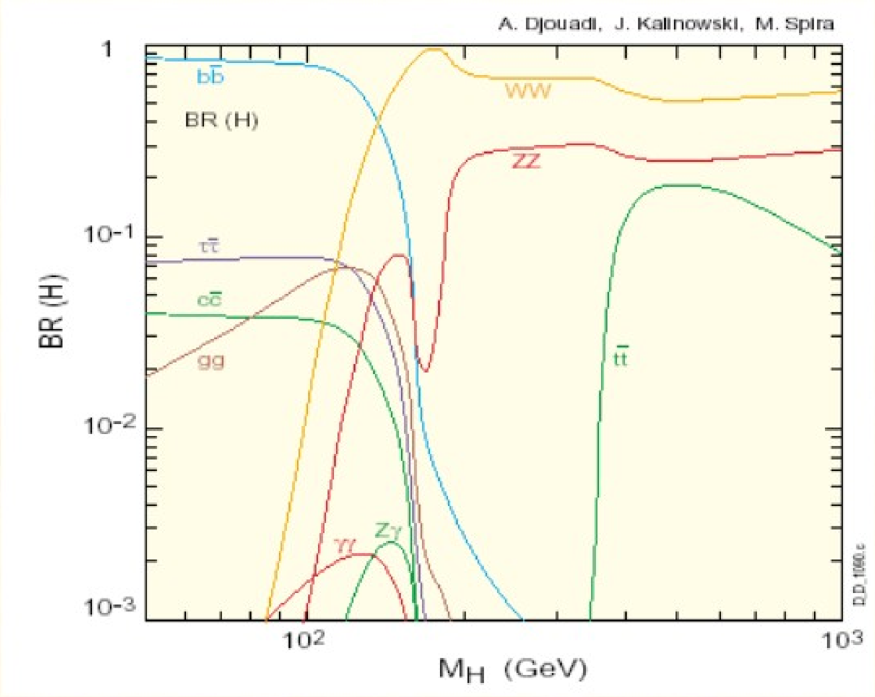


qq → W/Z + H cross sections ~10 x larger at the LHC
gg → H ~70-80 x larger at the LHC

# Production cross-section at the Tevatron and LHC



# Higgs boson decays



**at high mass:**

**Lepton** final states
(via H → WW , ZZ)

**at low mass:**

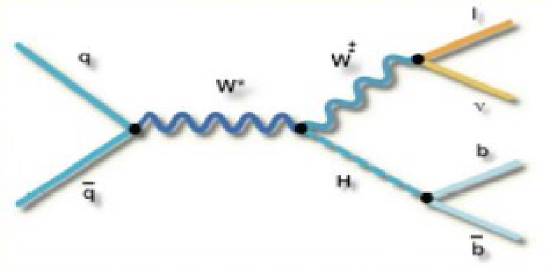
**Lepton and Photon** final states
(via H → WW*, ZZ*)

**Tau** final states

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

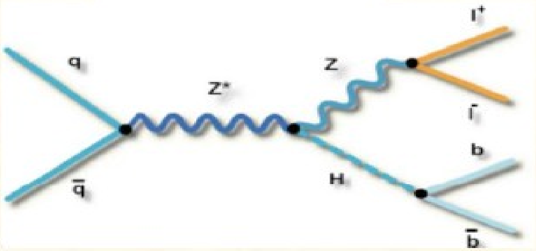
(due to the huge QCD jet background, leptons from W/Z or tt decays)

# Main channels for low mass search (Tevatron)



$\ell$ + $E_T^{miss}$ + bb: $WH \rightarrow \ell\nu bb$

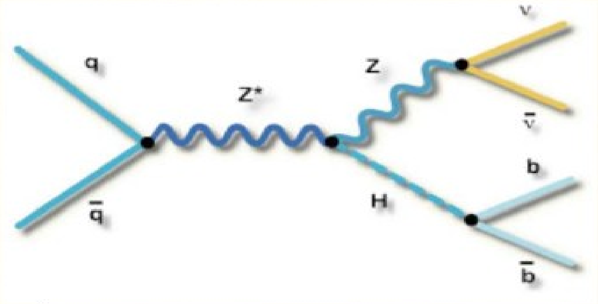
Largest *VH* production cross section, however, severe backgrounds



$\ell\ell$+bb: $ZH \rightarrow \ell\ell bb$

Less background than WH

Smallest Higgs signal



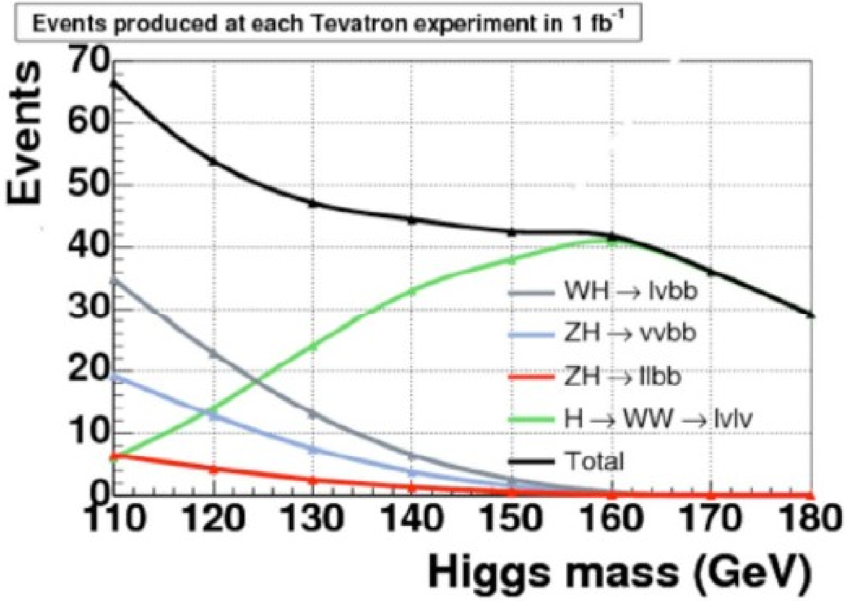
$E_T^{miss}$ + bb: $ZH \rightarrow \nu\nu bb$

3x more signal than $ZH \rightarrow \ell\ell\ bb$

(+$WH \rightarrow \ell\nu\ bb$ when lepton non-identified)

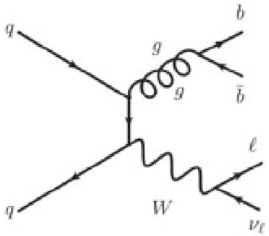
Large backgrounds which are difficult to handle

# Number of events produced including decays for 1fb$^{-1}$



WH (H→bb)   Signal, $m_H$ = 115 GeV:
$\sigma \times BR$ = 14 fb   (per lepton)

Large backgrounds:   W+jet production



W+bb: $\sigma \times BR = 4 \times 10^4$ fb
W+cc: $\sigma \times BR = 1 \times 10^5$ fb
W+qq: $\sigma \times BR = 2 \times 10^6$ fb

Additional backgrounds:

| | |
|---|---|
| WW: | $\sigma \times BR$ = 13 pb |
| tt: | $\sigma \times BR$ = 7 pb |
| single top: | $\sigma \times BR$ = 3 pb |

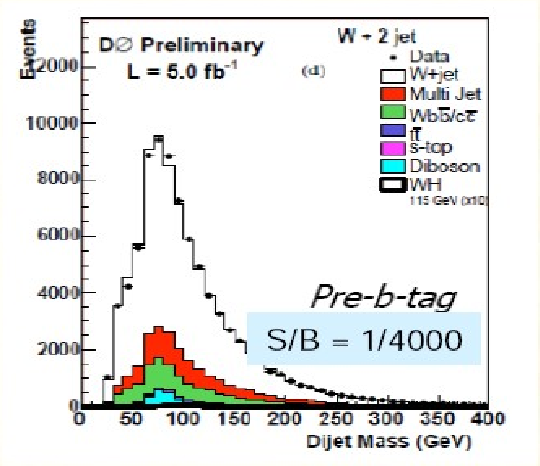
+ multijet QCD background

# General search strategy

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

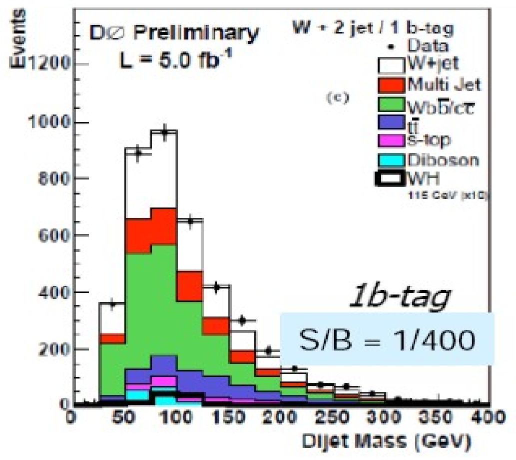
(ii) Apply b-tagging
(most discriminating variable: dijet inv. mass)

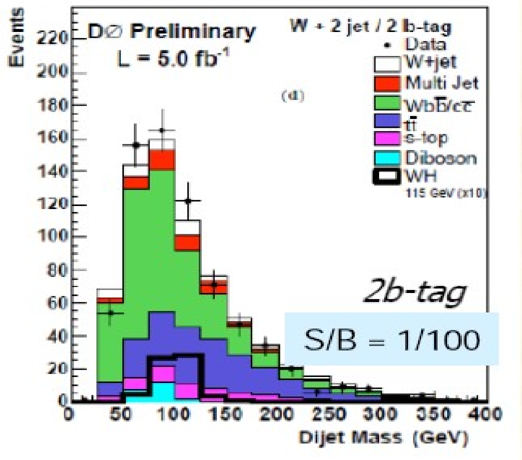
even after b-tagging S:B ratio remains small,
→ needs advanced (multivariate) analysis tools



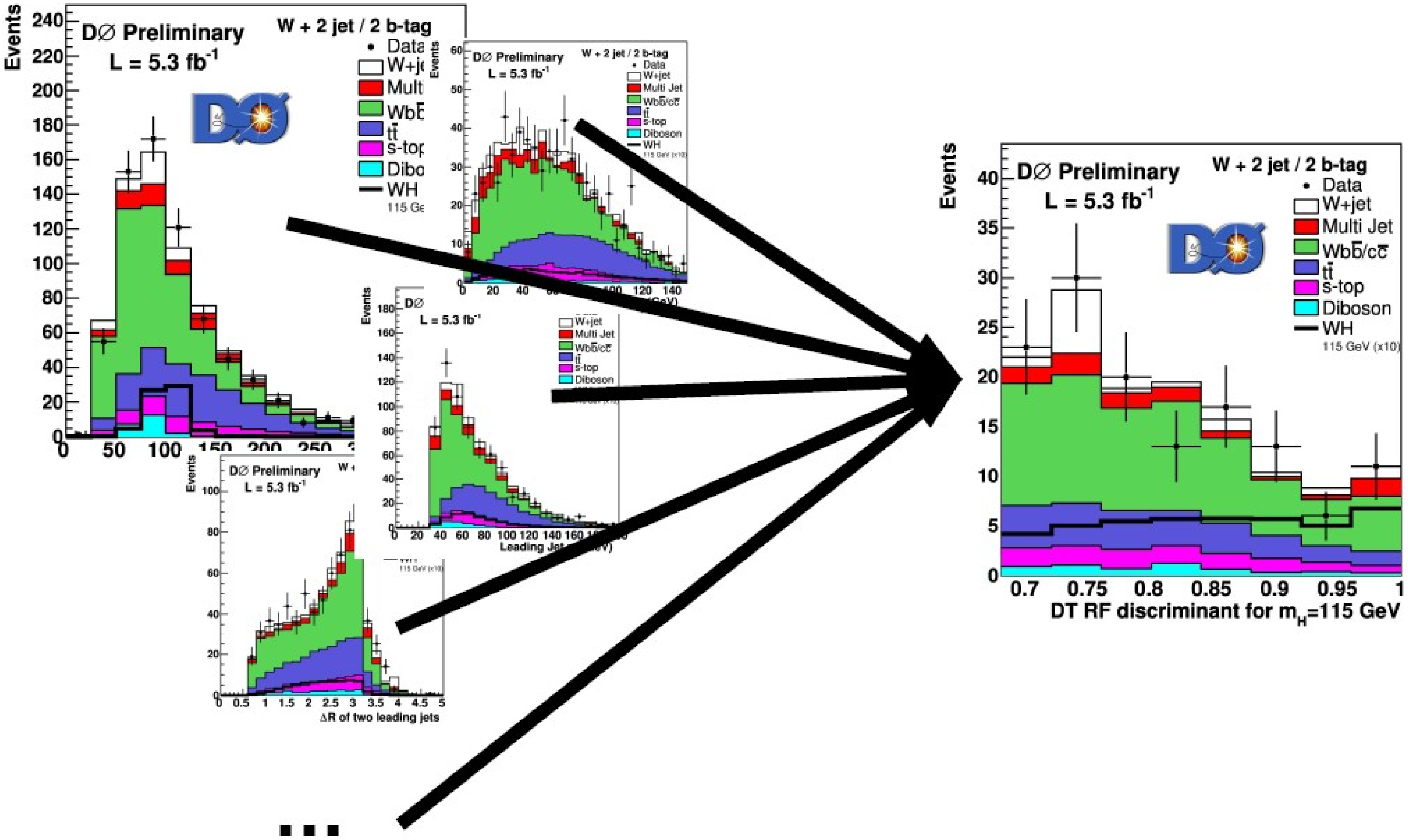
(iii) Optimize separation power
by multivariate discrimination
(neutral networks,
matrix elements, ....)

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



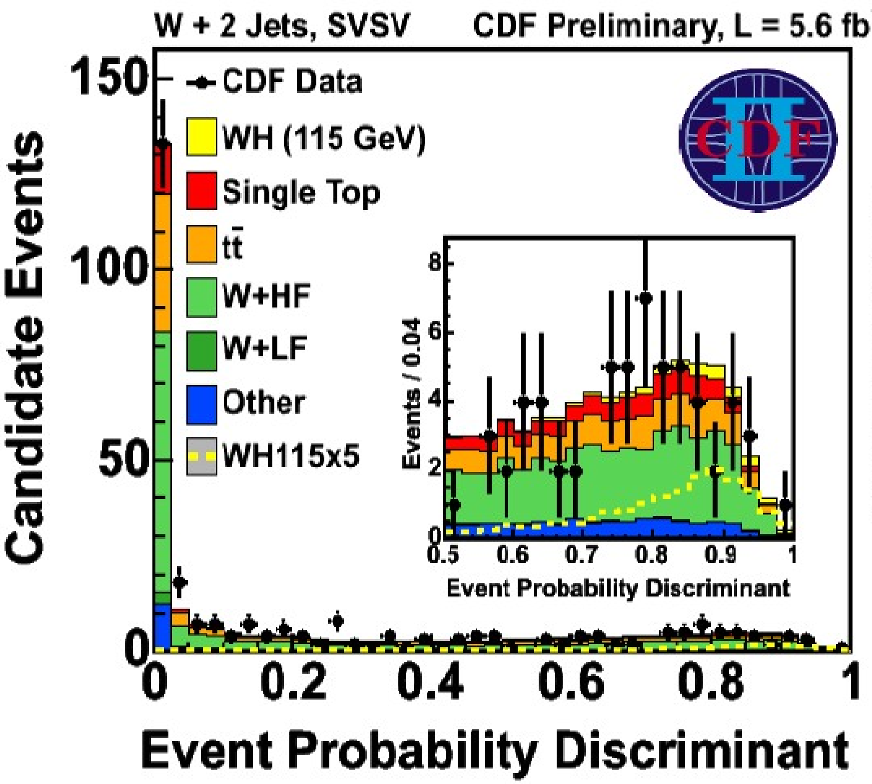


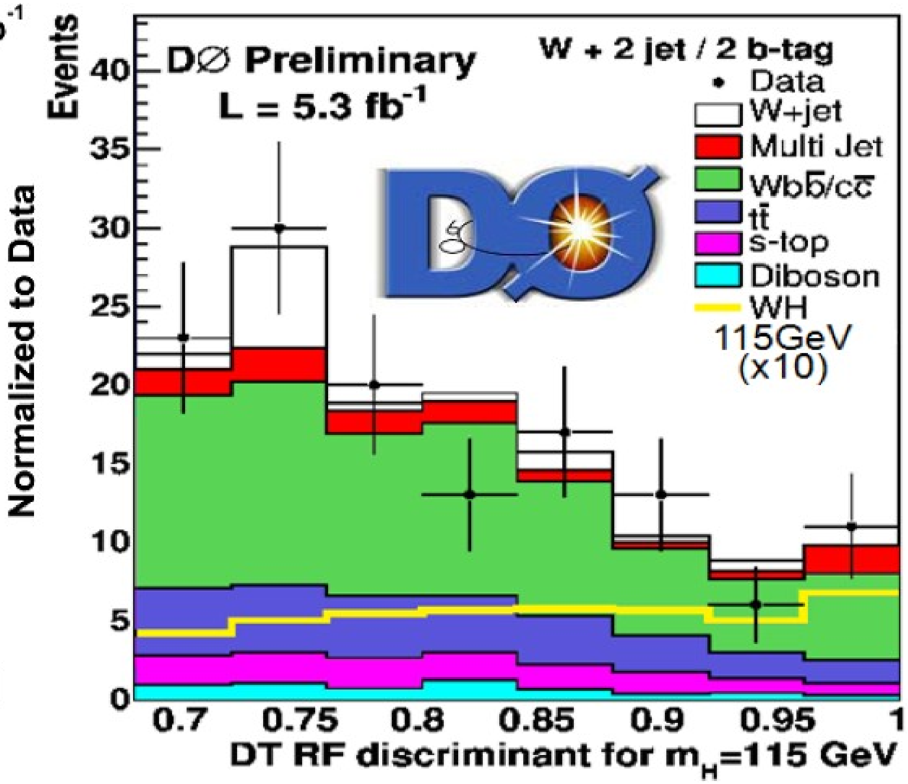
# Multivariate method



# WH, H→lνbb

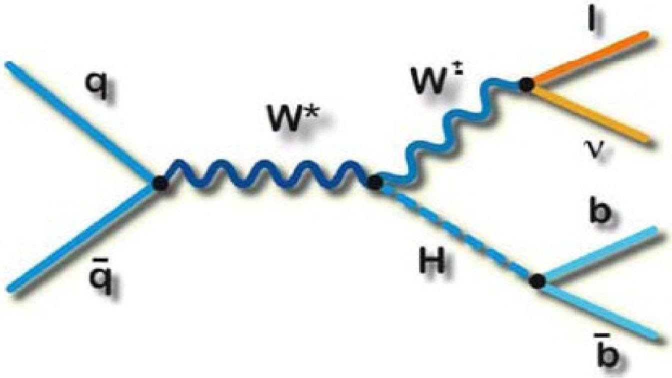
| 95% CL Limit for $m_H$=115 GeV/$c^2$ | Observed (Expected) [x $\sigma_{SM}$] | Comments |
|---|---|---|
| CDF Matrix Element 5.6 $fb^{-1}$ | 3.6 (3.5) | 2 and 3-jets |
| CDF Neural Network 5.7 $fb^{-1}$ | 4.5 (3.5) | 2-jets |
| DØ Random Forest 5.3 $fb^{-1}$ | 4.1 (4.8) | 2 and 3-jets |

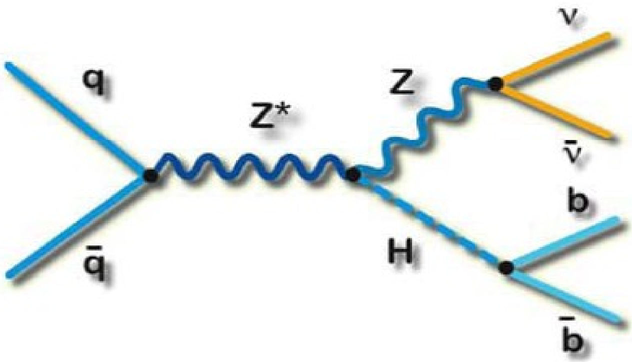




# V H, MET bb

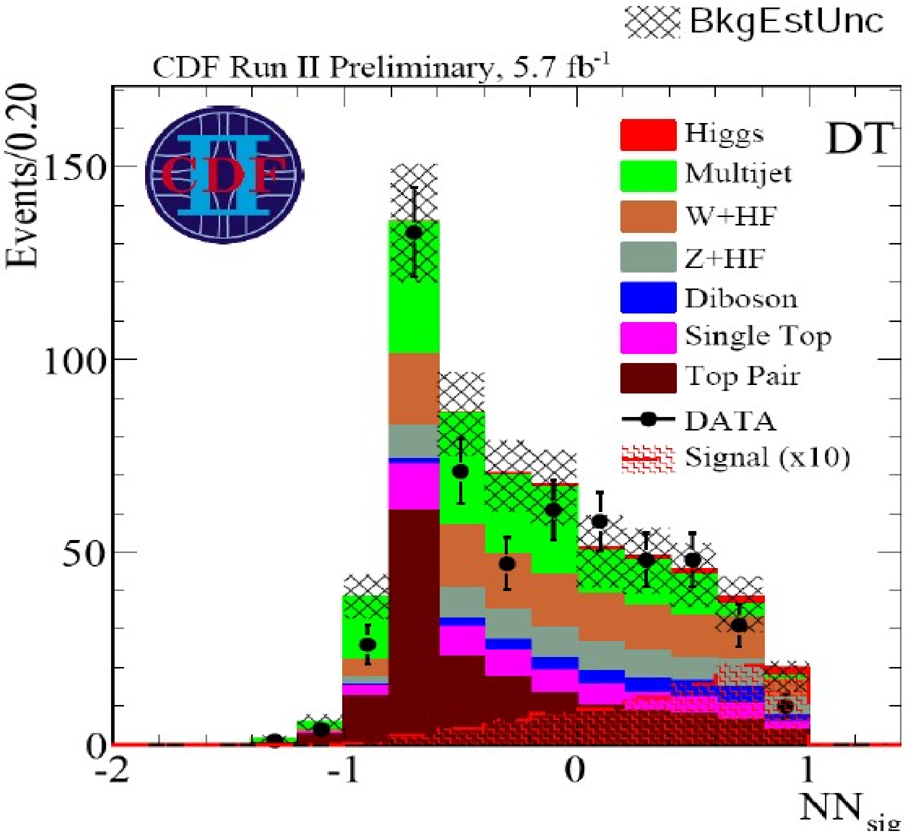
- Large signal statistics, but has large background from multi-jet processes
- Has signal contributions from:
  - ZH→vvbb, WH→(l)vbb (l not identified)
- <u>Event Selection</u>
  - large missing transverse energy (>40GeV DØ, >50GeV CDF)
  - 2 or 3 jets (>20GeV DØ, >35,25,15GeV CDF), ≥ one with b-jet ID
  - Exclude identified leptons, avoid overlap with other VH searches
- <u>Main Backgrounds</u>
  - QCD multijet (MET from Instrumental effects)
  - W/Z+jets, top, diboson (Real MET)

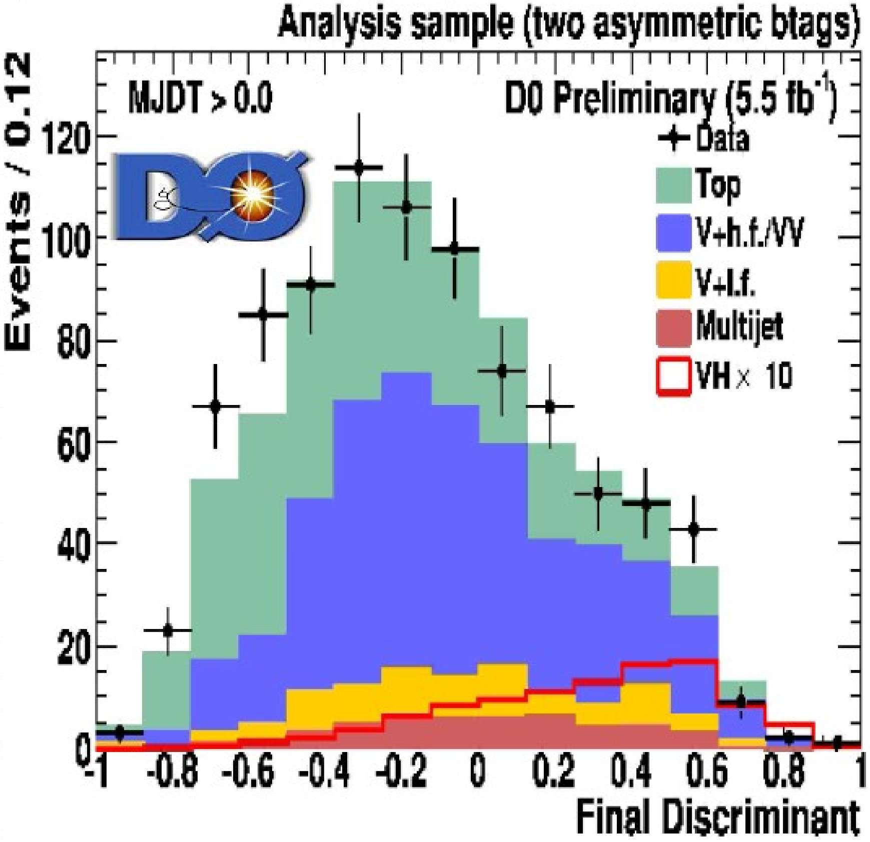




# VH, MET bb

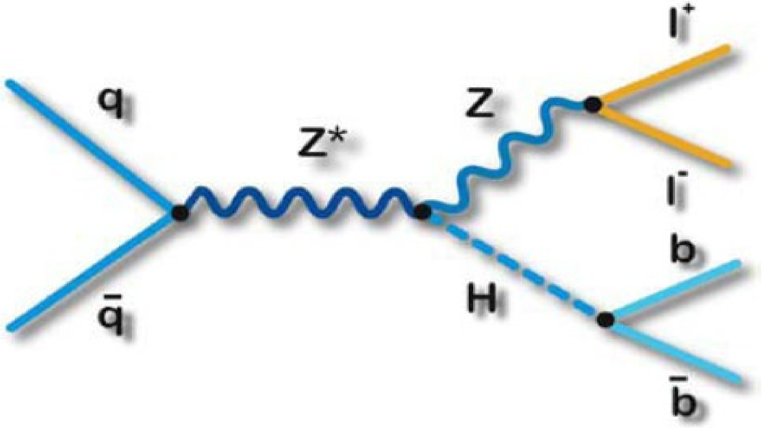
| 95% CL Limit for $m_H$=115 GeV/$c^2$ | Observed (Expected) [x $\sigma_{SM}$] |
|---|---|
| CDF Neural Network 5.7 $fb^{-1}$ | 2.3 (4.0) |
| DØ Decision Tree 5.5 $fb^{-1}$ | 3.4 (4.2) |





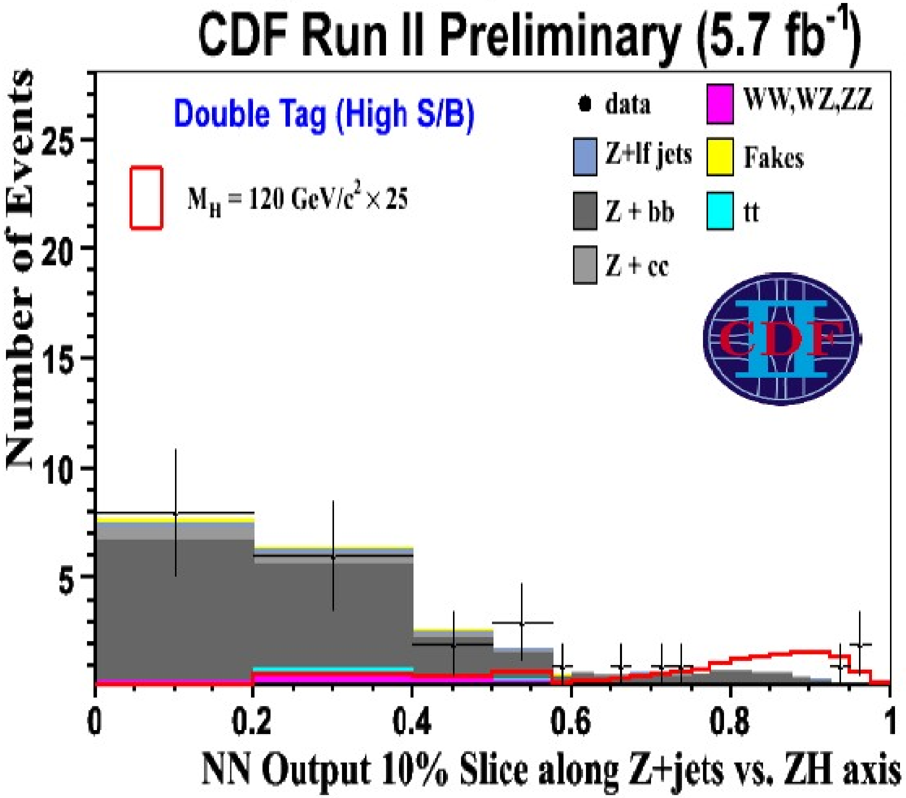
# ZH →llbb

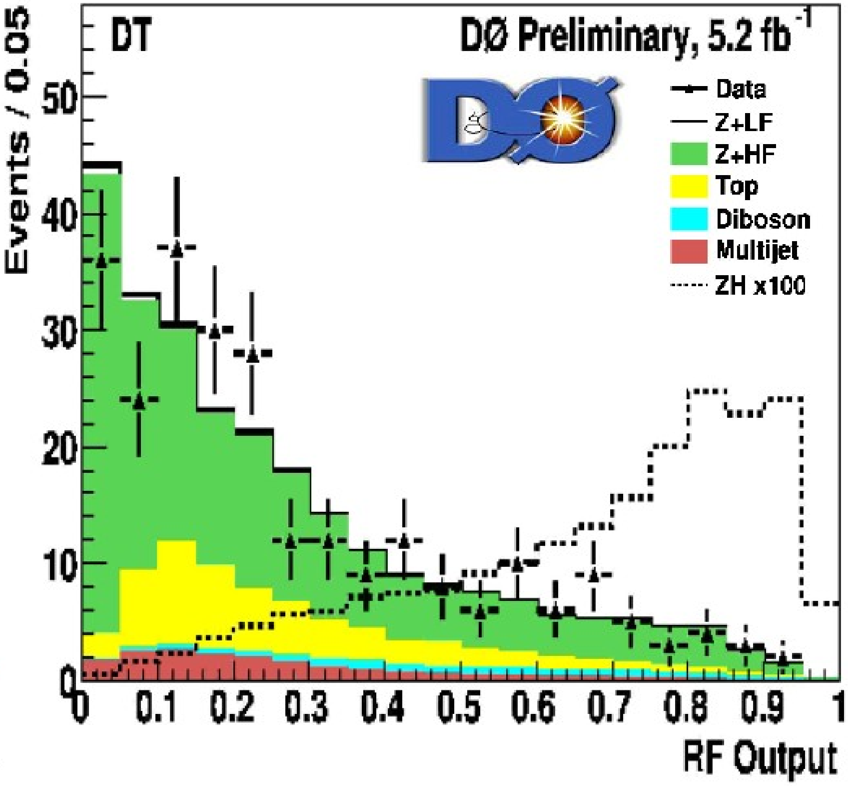
- Low signal statistics, but cleanest channel
  - Fully reconstructible final state, Z resonance
- <u>Event Selection</u>
  - Select Z candidate decaying into ee or μμ
  - 2 or 3 jets (>20,15GeV DØ, >25,15GeV CDF), >=1 with b-jet ID
- <u>Main Backgrounds</u>
  - Z+jets
  - Diboson, ttbar
- Reconstruction of Z resonance controls background rates, allowing for looser lepton selection requirements



# ZH →llbb

| 95% CL Limit for $m_H$=115 GeV/c² | Observed (Expected) [x $\sigma_{SM}$] |
|---|---|
| CDF Neural Network 5.7 fb$^{-1}$ | 6.0 (5.5) |
| DØ Random Forest 5.2 fb$^{-1}$ | 8.0 (5.7) |

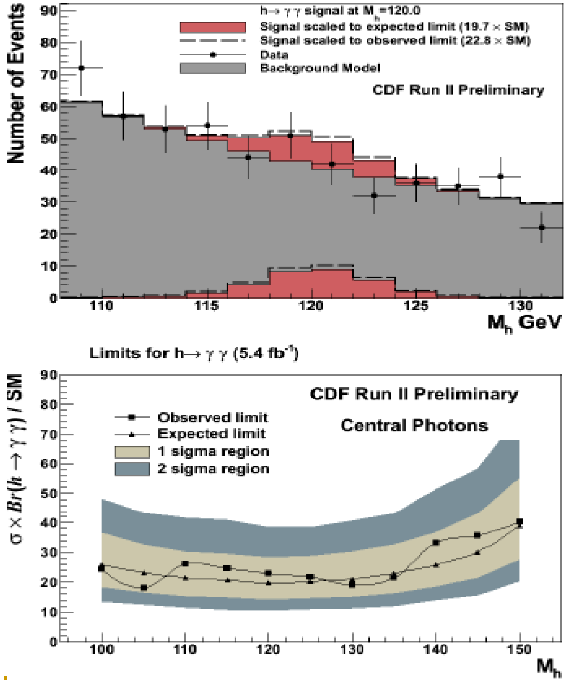




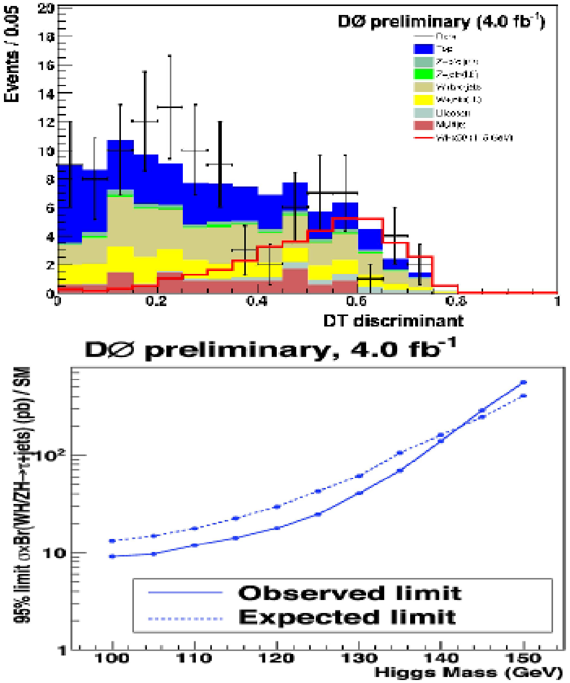
# Other low mass channels

| 95% CL limit for $m_H$=115 GeV/$c^2$ | Limit [x $\sigma_{SM}$] |
|---|---|
| CDF H→γγ Observed (Expected) | 24 (20) |
| DØ H→γγ Observed (Expected) | 16 (19) |
| DØ WH→τνbb Observed (Expected) | 14 (22) |
| CDF VH→qqbb Observed (Expected) | 9 (19) |

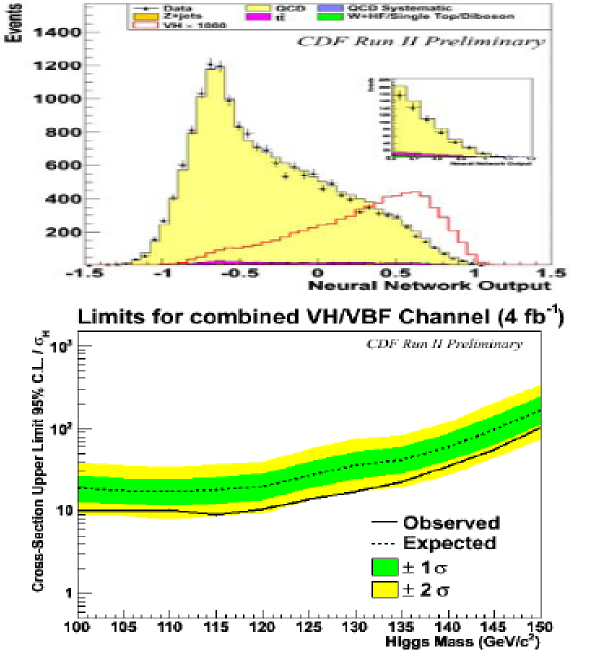
H→γγ



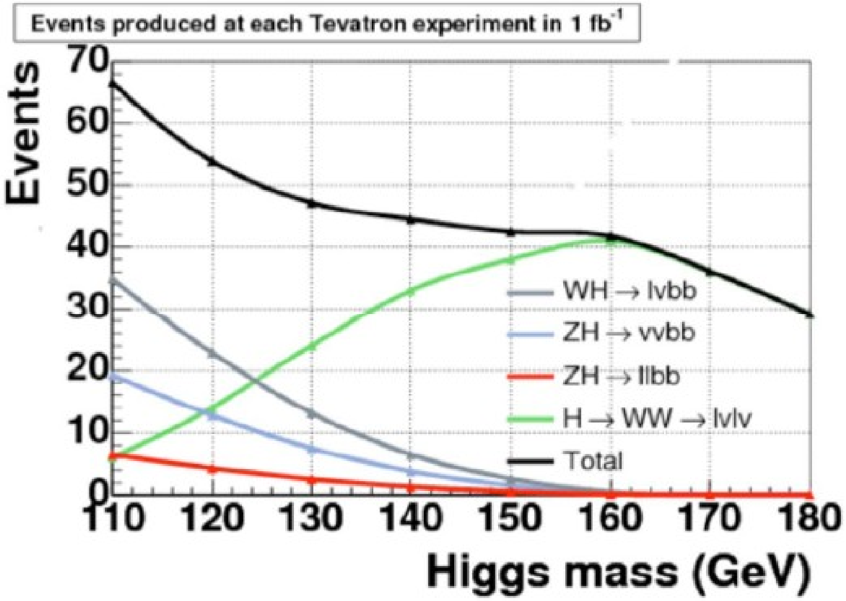
WH→τνbb



VH→qqbb

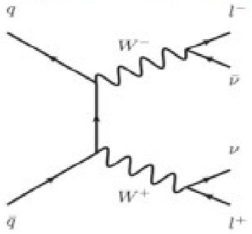


# Number of events produced including decays for 1fb$^{-1}$



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

Significant di-boson backgrounds:



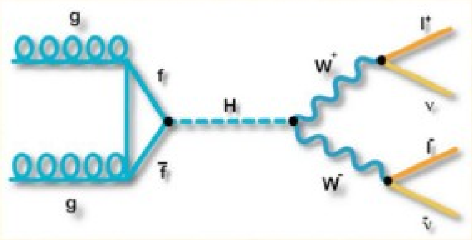
Di-Boson
WW: σ×BR = 13 pb
WZ:  σ×BR = 4.0 pb
ZZ:  σ×BR = 1.5 pb

Additional backgrounds:

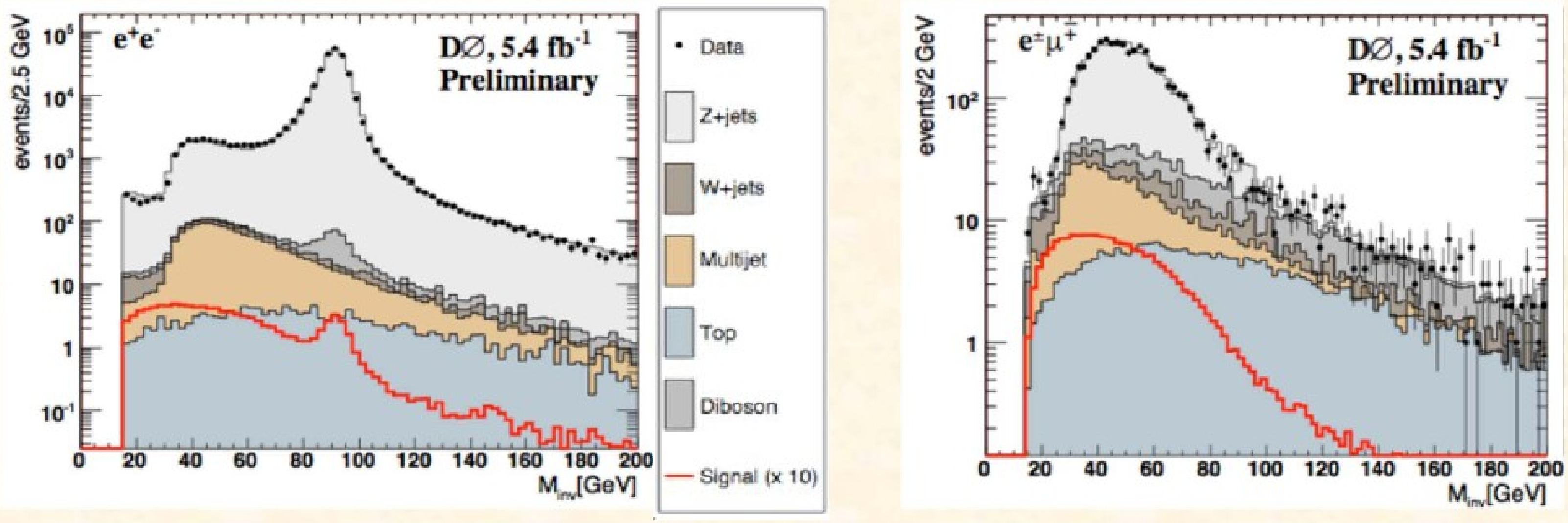
| | |
|---|---|
| tt: | σ×BR = 7 pb |
| single top: | σ×BR = 3 pb |

+ multijet QCD background

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

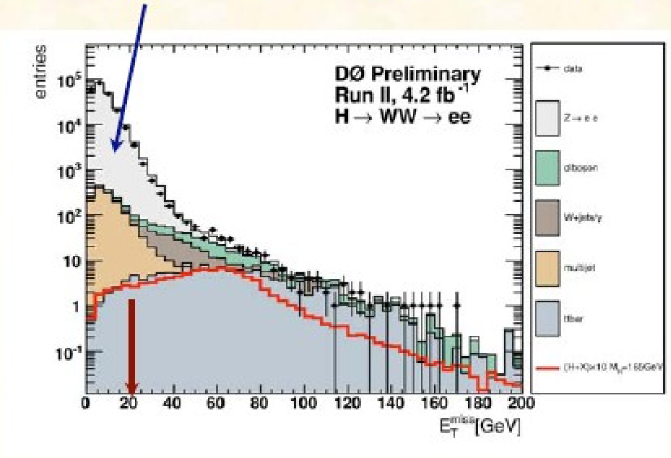


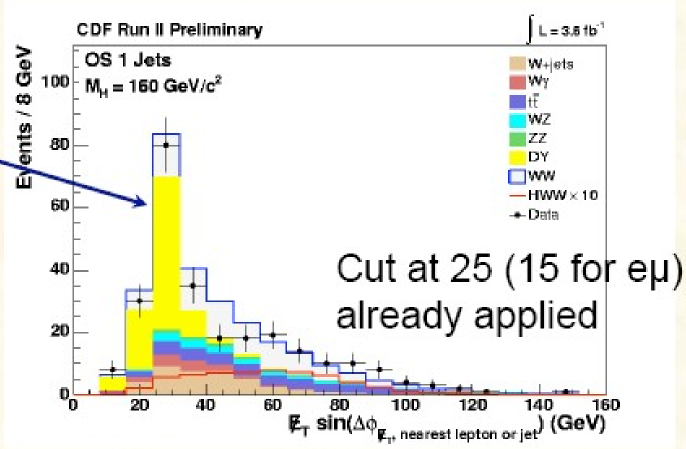
- Dominant decay for $m_H$ >135 GeV: $H \rightarrow W^*W$
- Leptons in final state
  → exploitation of gg→H is possible
- Signal contribution also from $W/Z+H$ *and* $qqH$ production
  → Consider all sources of opposite sign di-lepton + $E_T^{miss}$
  Split analysis in ee, μμ, and eμ final states
- Backgrounds: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



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

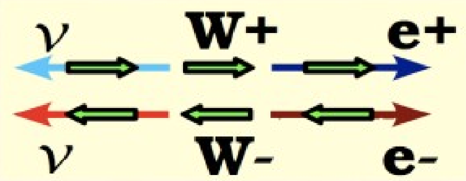
Dominant Drell-Yan background can be reduced with cuts on $E_T^{miss}$ and its isolation (distance to nearest object)

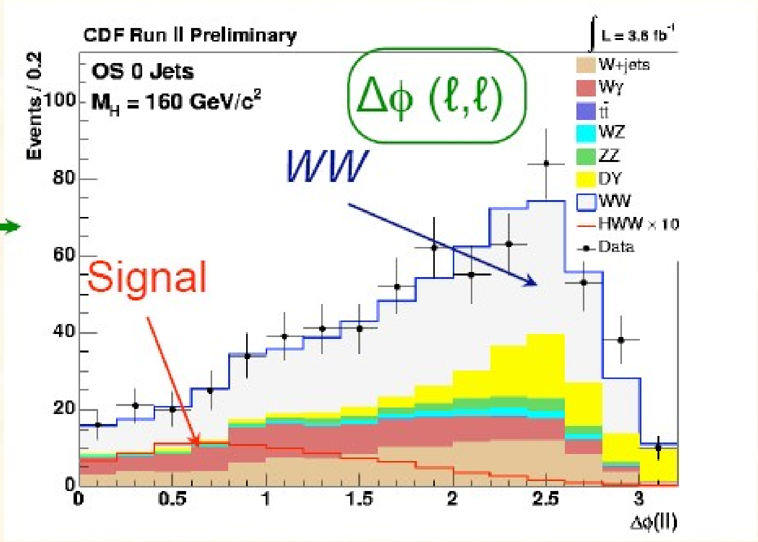




Cut at 25 (15 for eμ) already applied

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





$\Delta\phi\ (\ell,\ell)$

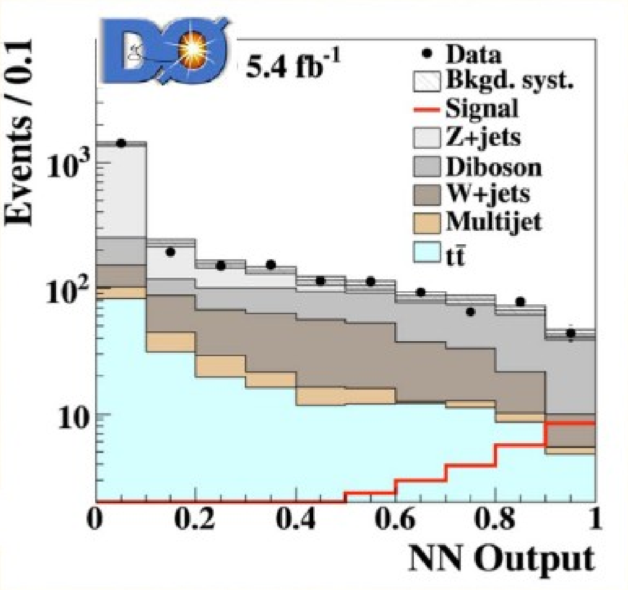
*WW*

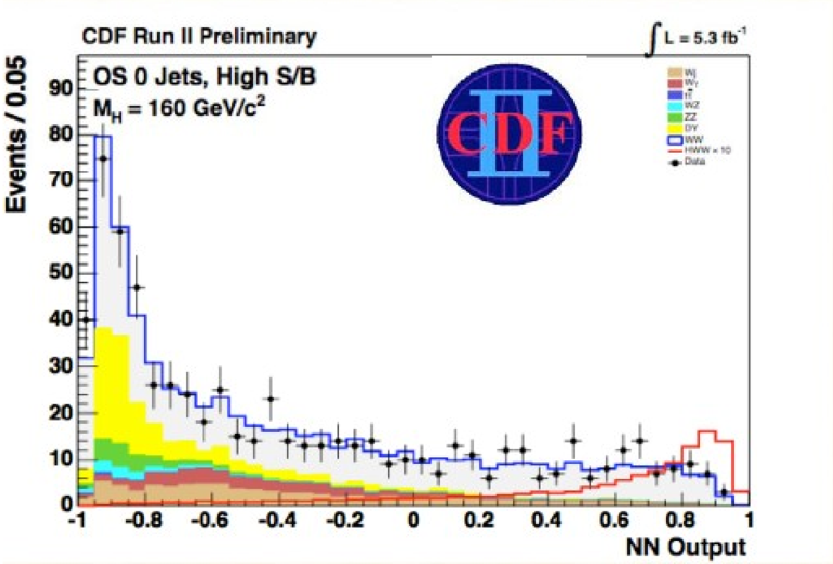
Signal

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

To increase sensitivity:

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



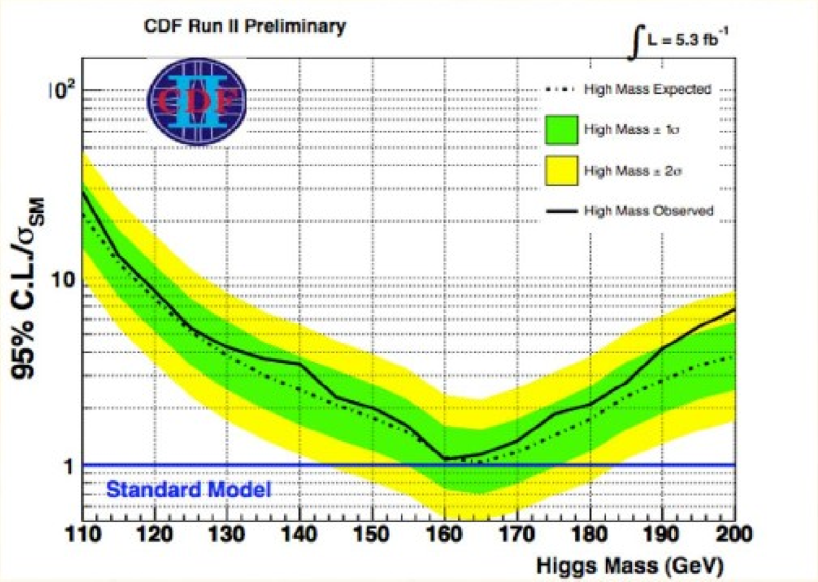


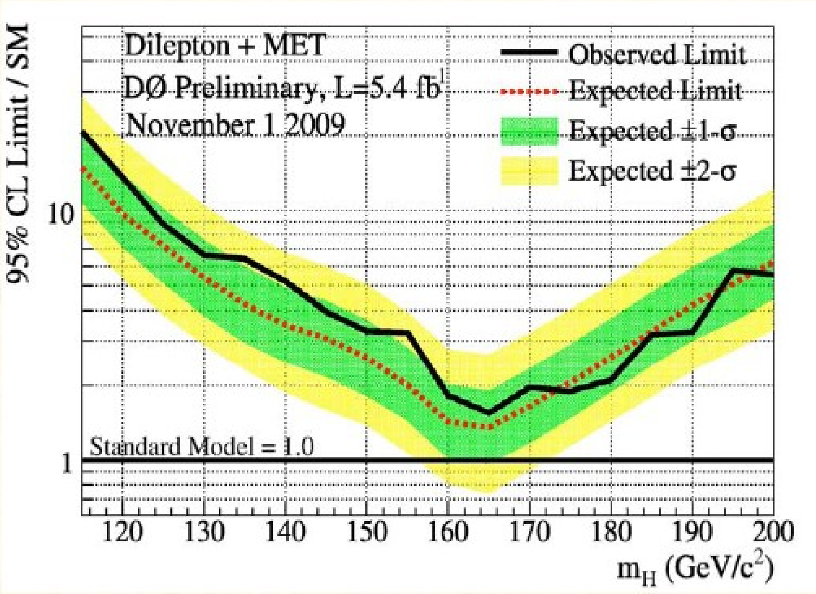
CDF: Split samples into jet multiplicity and lepton ID criteria: different signal and background composition

Veto events with tight b-tagged jet

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

Excluded cross section per experiment:

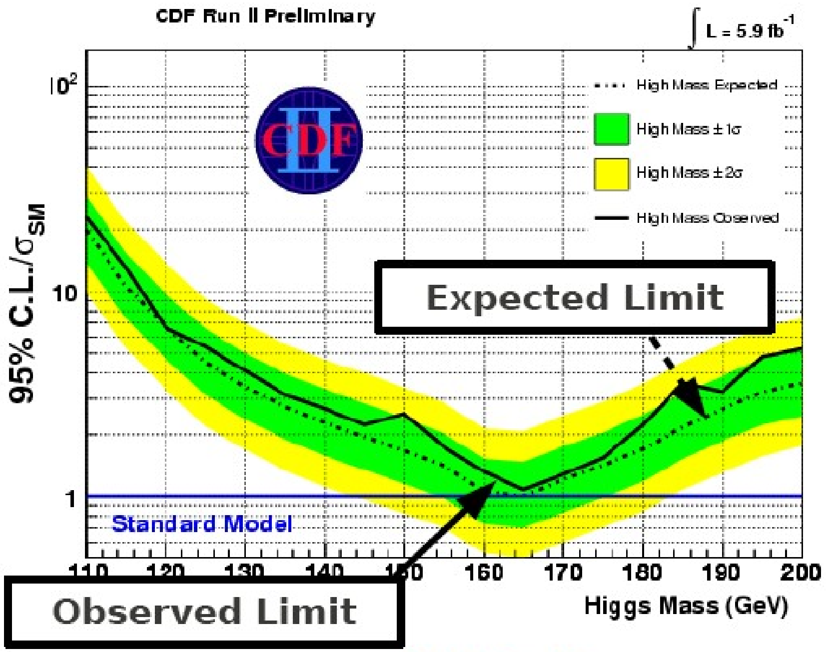




Expected limits: CDF: $\sigma_{95} = 1.03 \cdot \sigma_{SM}$ D0: $\sigma_{95} = 1.36 \cdot \sigma_{SM}$

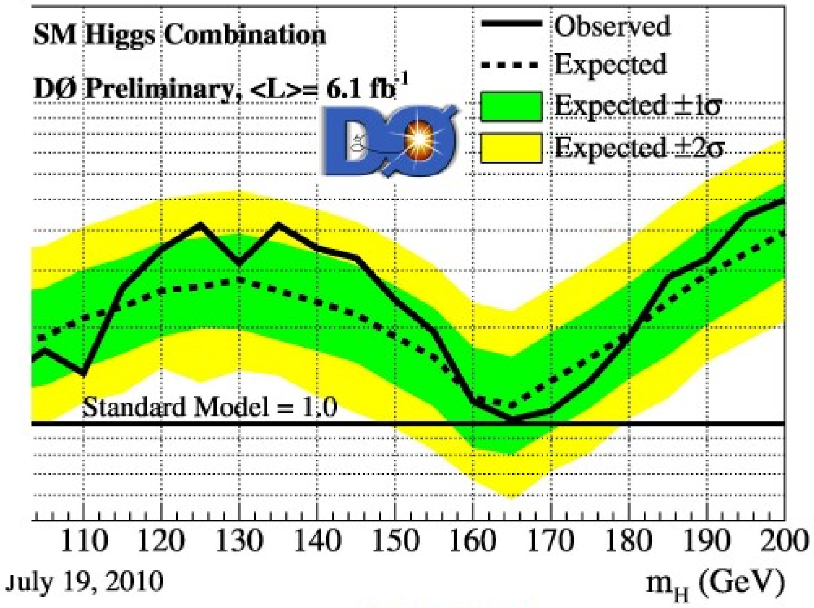
Observed limits: CDF: $\sigma_{95} = 1.13 \cdot \sigma_{SM}$ D0: $\sigma_{95} = 1.55 \cdot \sigma_{SM}$

# Individual combinations



Expected Limit

Observed Limit



$m_H$=165 GeV:

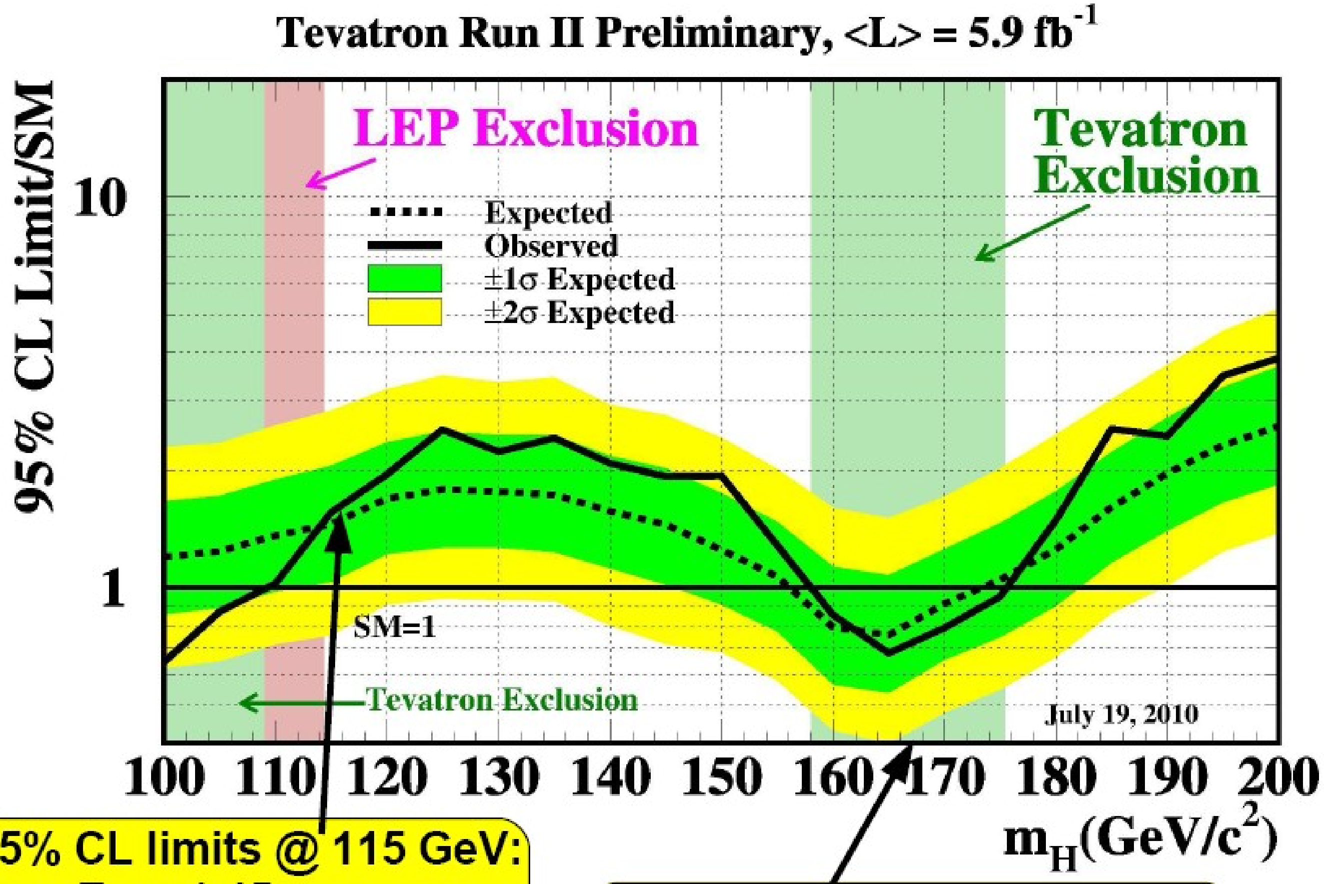
CDF exp. 1.0 obs. 1.1 x SM

$m_H$=165 GeV:

DØ exp. 1.1 obs. 1.0 x SM

SM sensitivity per experiment

# Standard Model results



95% CL limits @ 115 GeV:
Exp: 1.45 × $\sigma_{SM}$
Obs: 1.56 × $\sigma_{SM}$

Exclusion Region:
Exp: 156 GeV < $M_H$ < 173 GeV
Obs: 158 GeV < $M_H$ < 175 GeV

# Higgs mass constraints

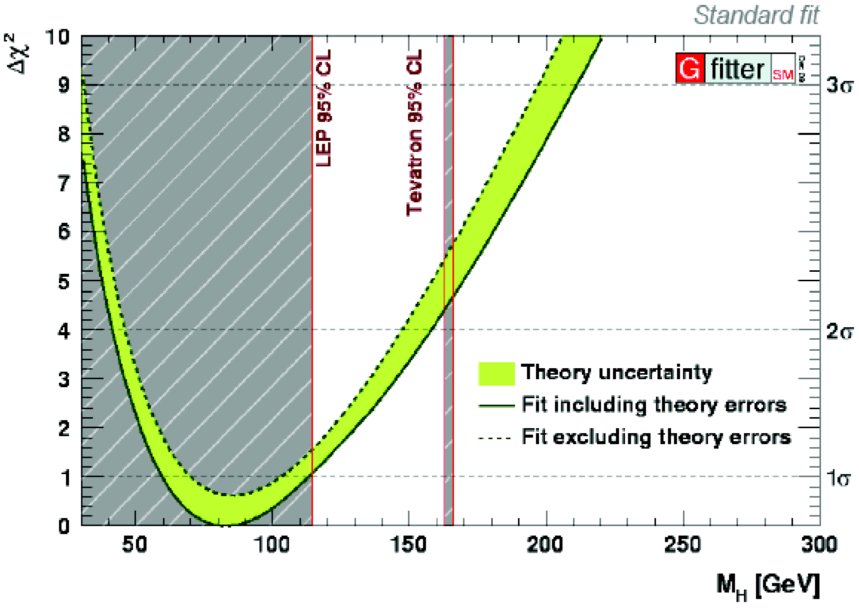
### $M_H$ from *Standard fit*:

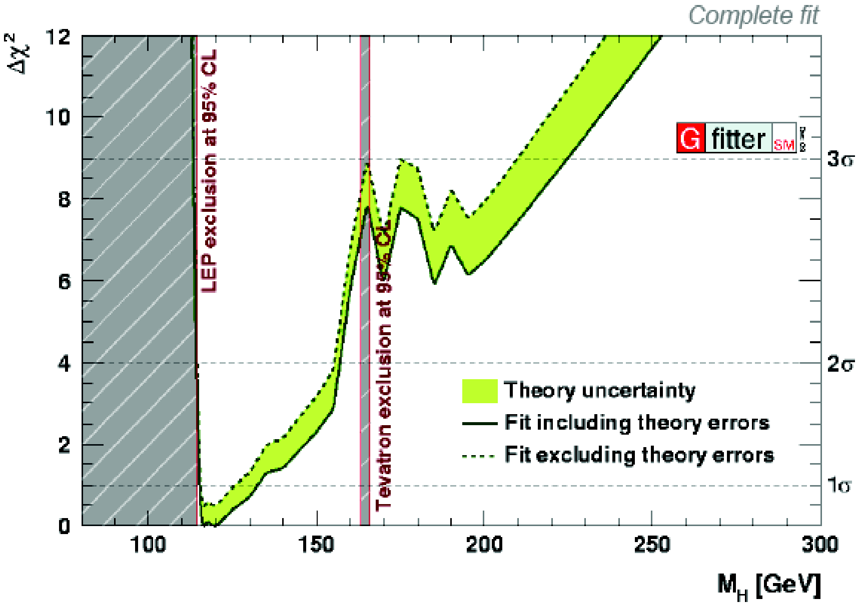
- Central value ±1σ: $M_H = 83^{+30}_{-23}$ GeV
- 2σ interval: [42, 158] GeV

Green band due to *R*fit treatment of theory errors, fixed errors lead to larger $\chi^2_{min}$

### $M_H$ from *Complete fit*:

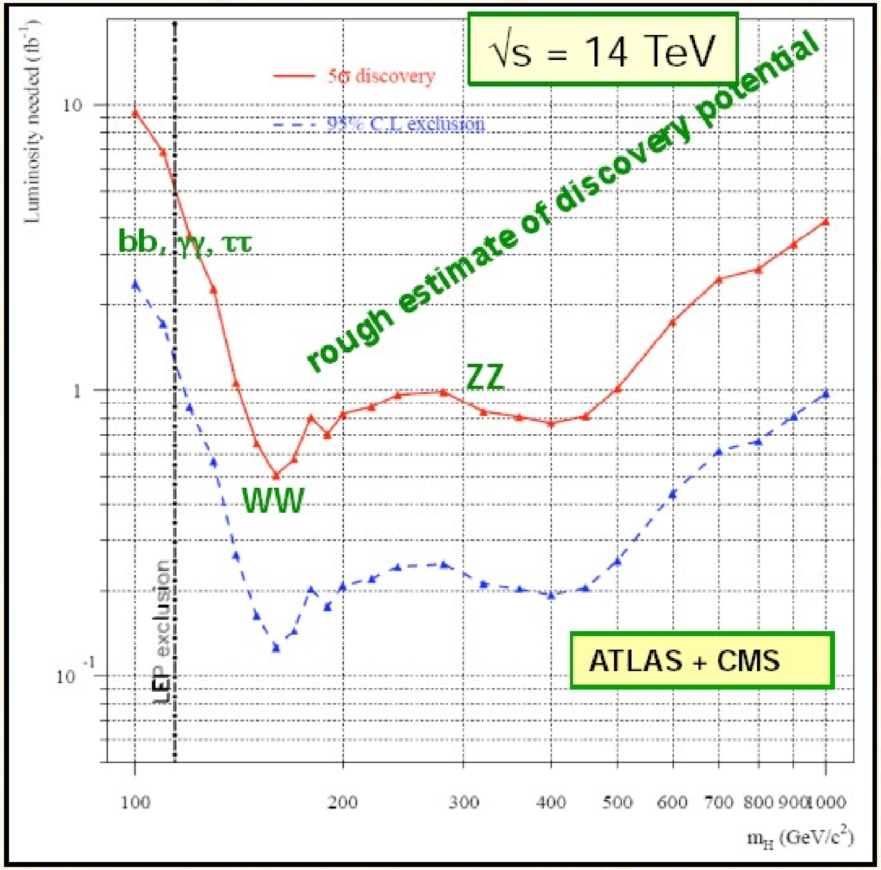
- Central value ±1σ: $M_H = 119^{+13}_{-4.0}$ GeV
- 2σ interval: [114, 157] GeV





# …. also the prospects for the discovery of the Higgs particle are good

## - Luminosity required for a 5σ discovery or for a 95% CL limit –
## (< 2006 estimates)



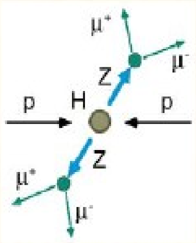
J.J. Blaising, A. De Roeck, J. Ellis, F. Gianotti, P. Janot, G. Rolandi and D. Schlatter,
**Eur. Strategy workshop (2006)**

~ < 1 fb$^{-1}$ needed to set a 95% CL limit in most of the mass range
(low mass ~ 115 GeV/c$^2$ more difficult)

comments:
- these curves are optimistic on the ttH, H→ bb performance
- systematic uncertainties assumed to be luminosity dependent (no simple scaling, σ ~ √L, possible)

# $H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

Signal: $\sigma$ BR = 5.7 fb ($m_H$ = 100 GeV)



$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

$M(\ell\ell) \sim M_Z$
$M(\ell'\ell') \sim < M_Z$

Background: Top production

$tt \rightarrow Wb\,Wb \rightarrow \ell\nu\ c\ell\nu\ \ell\nu\ c\ell\nu$

$\sigma$ BR ≈ 1300 fb

Associated production Z bb

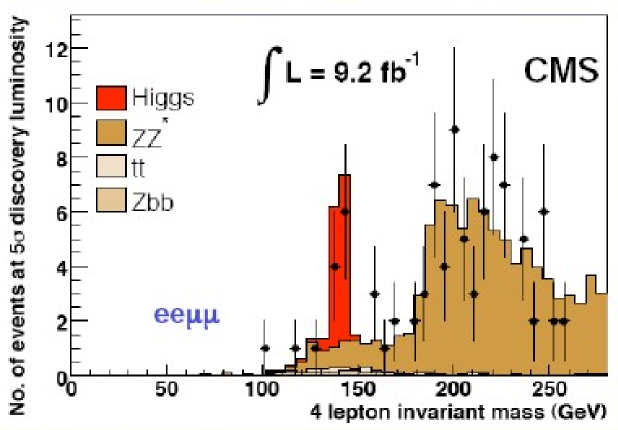
$Z\,bb \rightarrow \ell\ell\ c\ell\nu\ c\ell\nu$

Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum

# $H \rightarrow ZZ^* \rightarrow \ell\ell\ \ell\ell$

$\sqrt{s}$ = 14 TeV

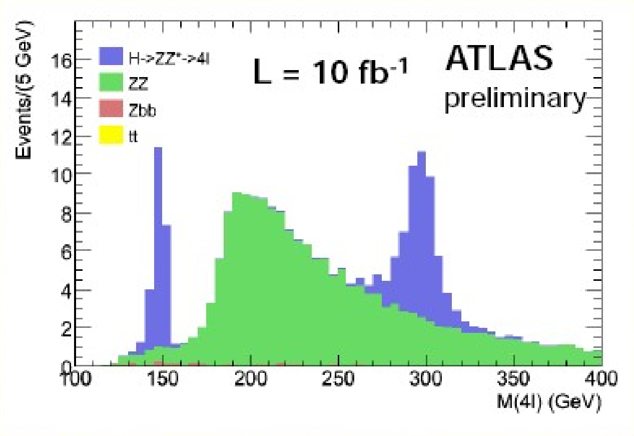


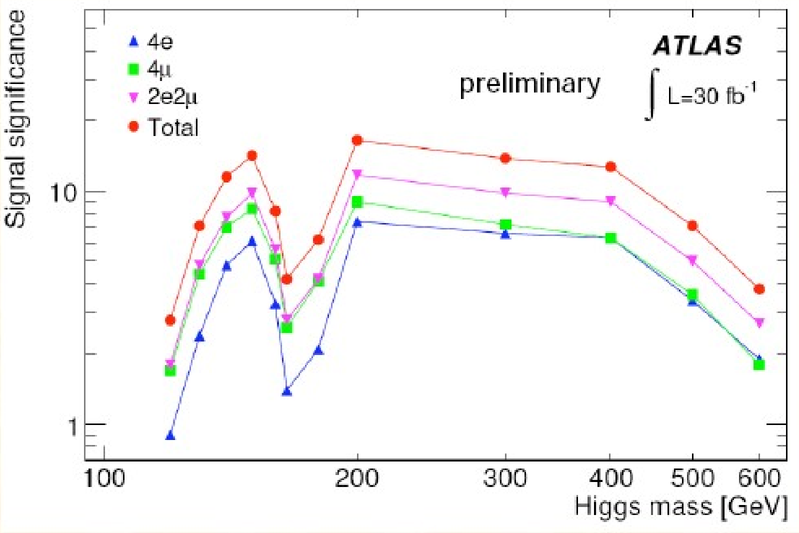
Main backgrounds: ZZ (irreducible),
tt, Zbb (reducible)

Updated ATLAS and CMS studies:

- ZZ background: NLO K factor used
- background from side bands

(gg->ZZ is added as 20% of the LO qq->ZZ)

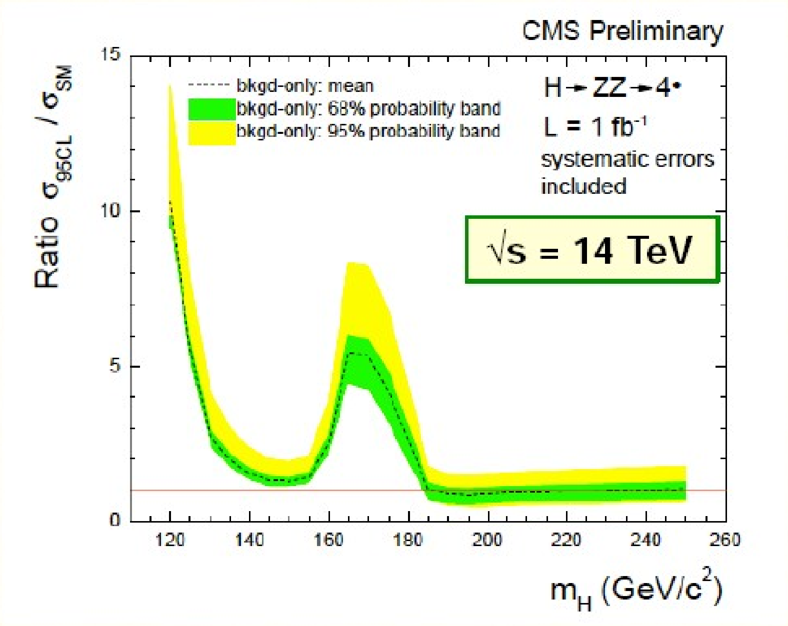


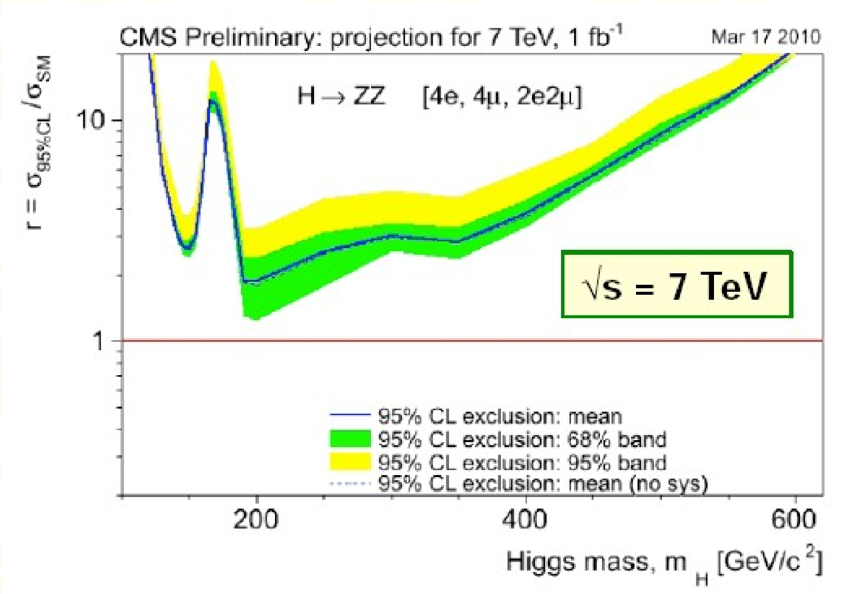


# $H \rightarrow ZZ^* \rightarrow \ell\ell\ \ell\ell$

What can be done with 1 $\mathrm{fb}^{-1}$?

95% C.L. excluded cross sections normalized to Standard Model cross section

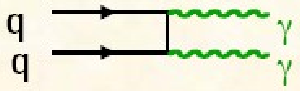




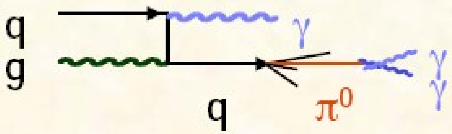
# $H \rightarrow \gamma\gamma$

Main backgrounds:

$\gamma\gamma$ irreducible background



$\gamma$-jet and jet-jet (reducible)



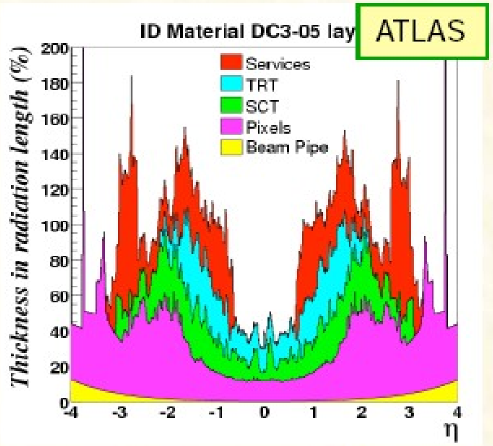
$\sigma_{\gamma j+jj} \sim 10^6 \, \sigma_{\gamma\gamma}$ with large uncertainties

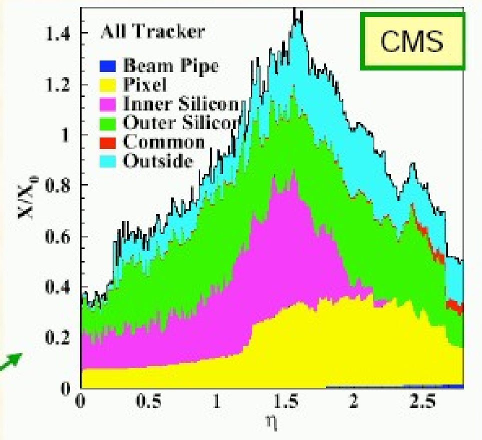
→ need $R_j > 10^3$ for $\varepsilon_\gamma \approx 80\%$ to get

$\sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma}$

- Main exp. tools for background suppression:
  - photon identification
  - $\gamma$ / jet separation (calorimeter + tracker)

  - note: also converted photons need to be reconstructed (large material in LHC silicon trackers)

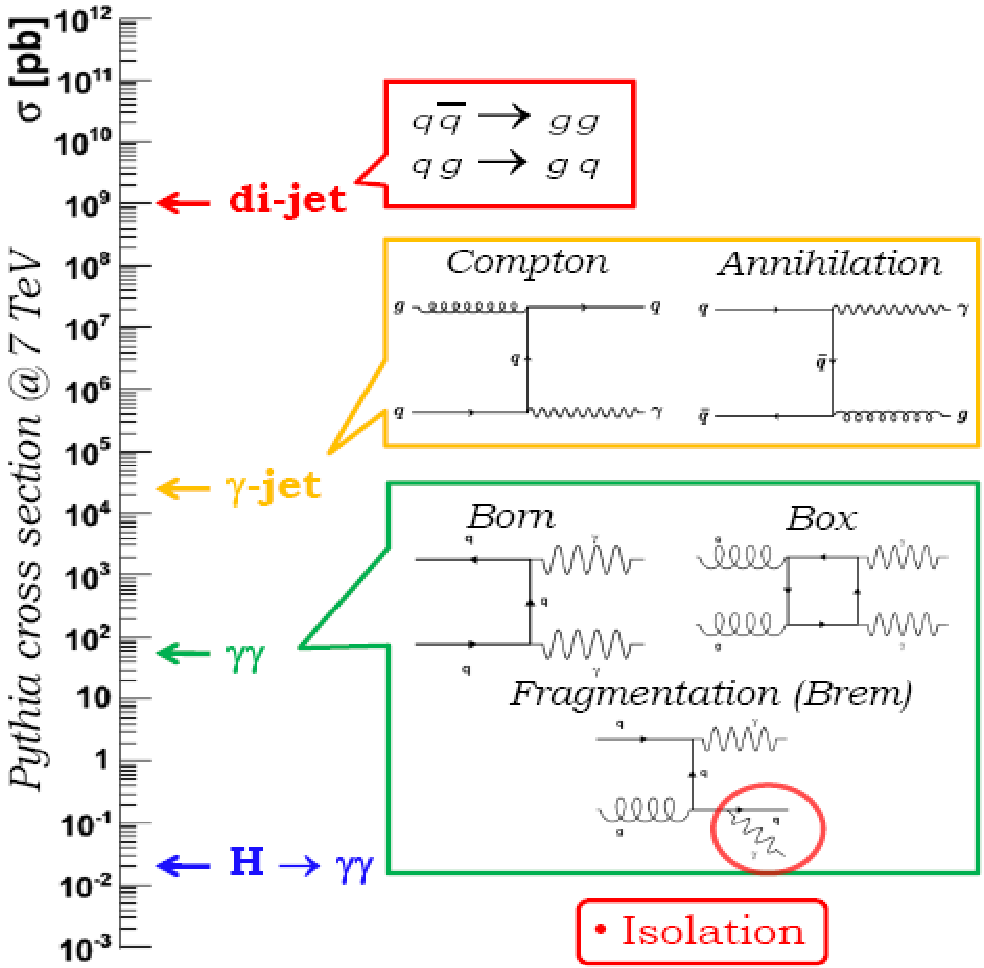




CMS: fraction of converted $\gamma$s

| | |
|---|---|
| Barrel region: | 42.0 % |
| Endcap region: | 59.5 % |

# Photon production



In today's data

- **Among reconstructed photons :**
  → Jets with high-pT $\pi^0$ misidentified as photons
  → Prompt photons
  (from ME and fragmentation)

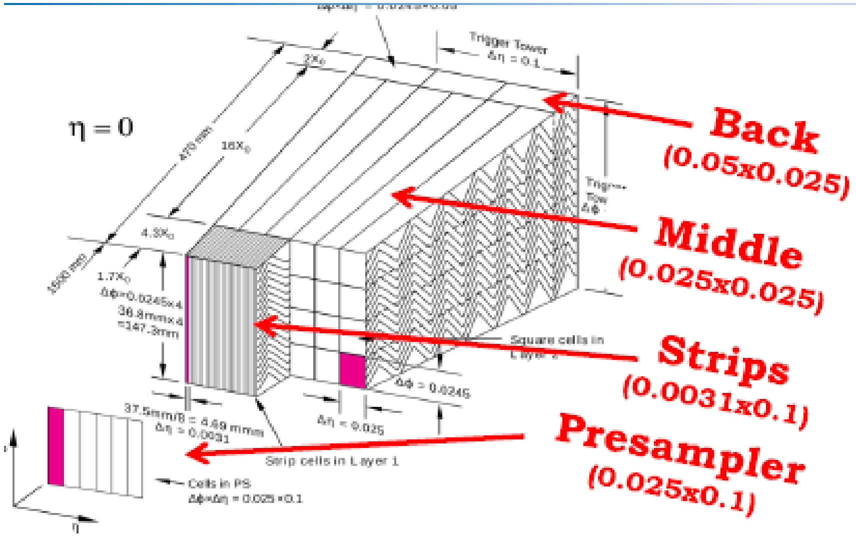
- $\gamma/\pi^0$ separation

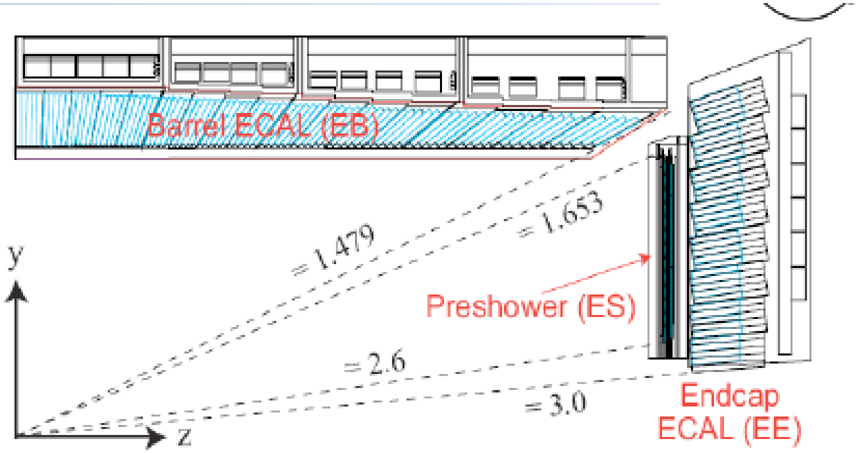
- Energy + angular resolution
- Conversion recovery

- Isolation

- **Prompt photon measurements :**
  → Background to H → γγ, …
  → Perturbative QCD tests

# Calorimetry





- Pb + LAr sampling calorimeter
- 3 radial layers + pre-shower
- Design energy resolution :

$$\frac{\Delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{300\,\mathrm{MeV}}{\mathrm{E}} \oplus 0.7\%$$

- Outside solenoid coil

- $\mathrm{PbWO_4}$ scintillating crystals
- Preshower in front of EE
- Design energy resolution :

$$\frac{\Delta E}{E} = \frac{2.9\%}{\sqrt{E}} \oplus \frac{125\,\mathrm{MeV}}{\mathrm{E}} \oplus 0.3\%$$

- Inside solenoid coil

# What can be achieved with $1\mathrm{fb}^{-1}$

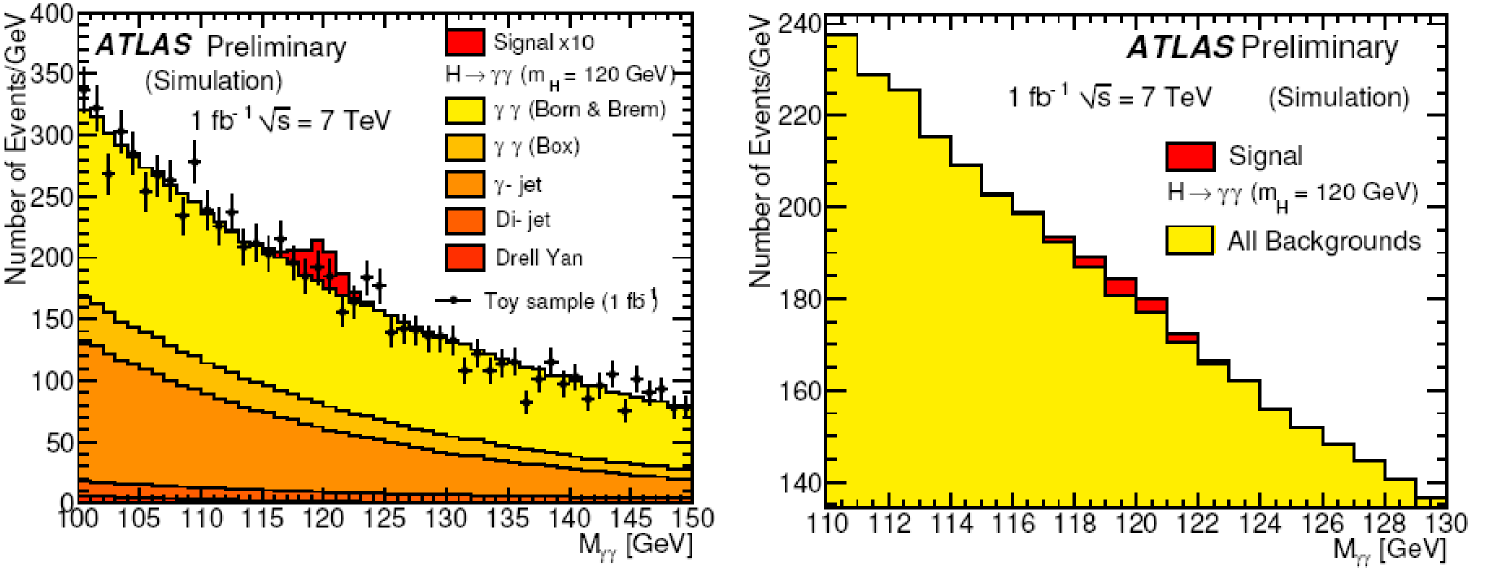
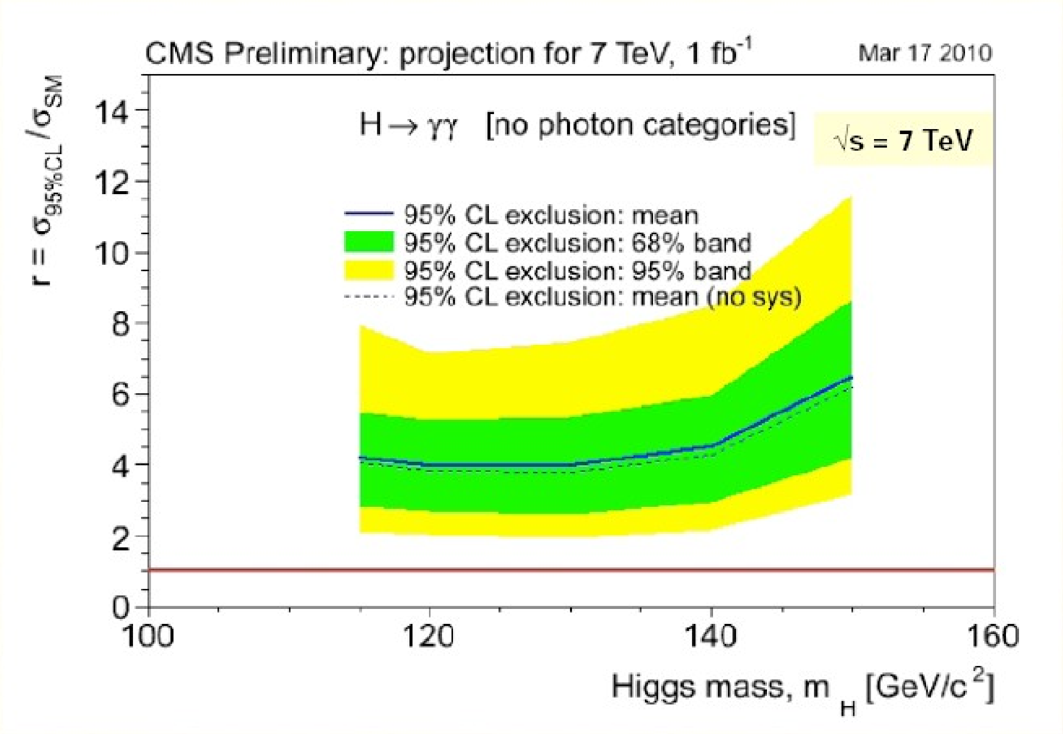


Figure 13: Expected di-photon invariant mass distribution at $\sqrt{s} = 7$ TeV for an integrated luminosity of 1 $\mathrm{fb}^{-1}$. The left-hand plot has the signal contribution enhanced by a factor 10.

# $H \rightarrow \gamma\gamma$

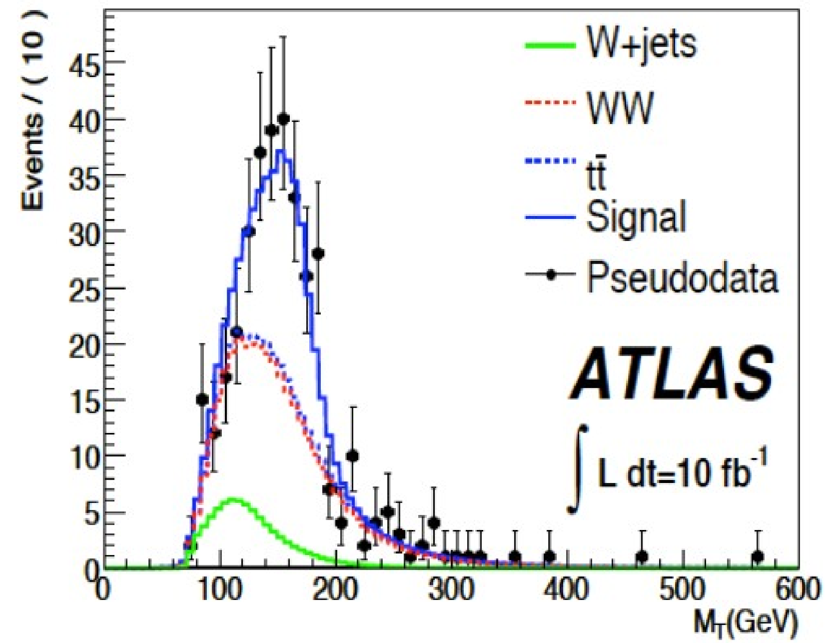
What can be done with 1 $fb^{-1}$ at $\sqrt{s}$ = 7 TeV ?

95% C.L. excluded cross sections normalized to the Standard Model cross section



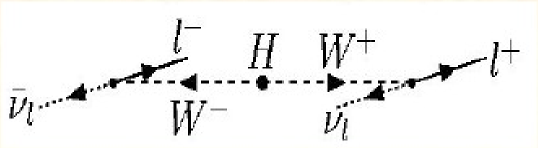
# $H \rightarrow WW \rightarrow \ell\nu\, \ell\nu$

- Large $H \rightarrow WW$ BR for $m_H \sim 160$ GeV/$c^2$
- Neutrinos → no mass peak,
  → use transverse mass
- Large backgrounds: WW, Wt, tt



- Two main discriminants:

  (i) Lepton angular correlation



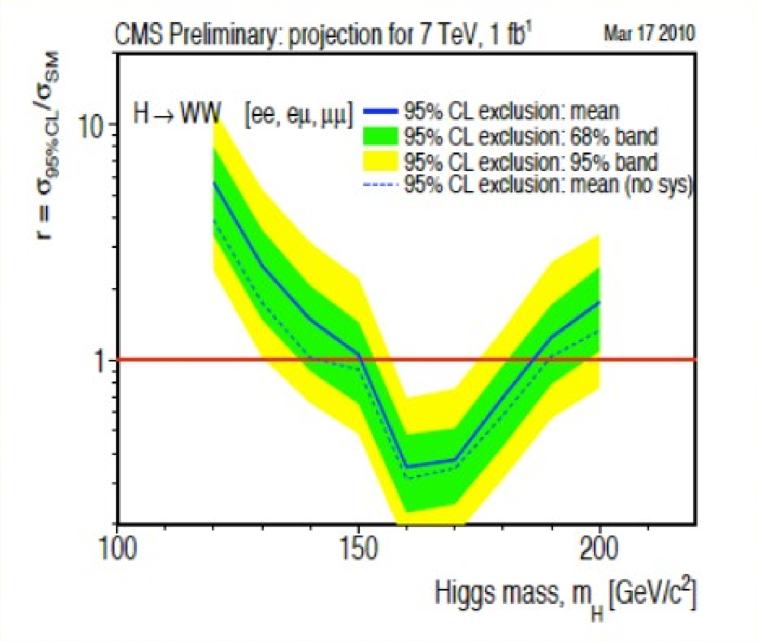
  (ii) Jet veto: no jet activity in central detector region

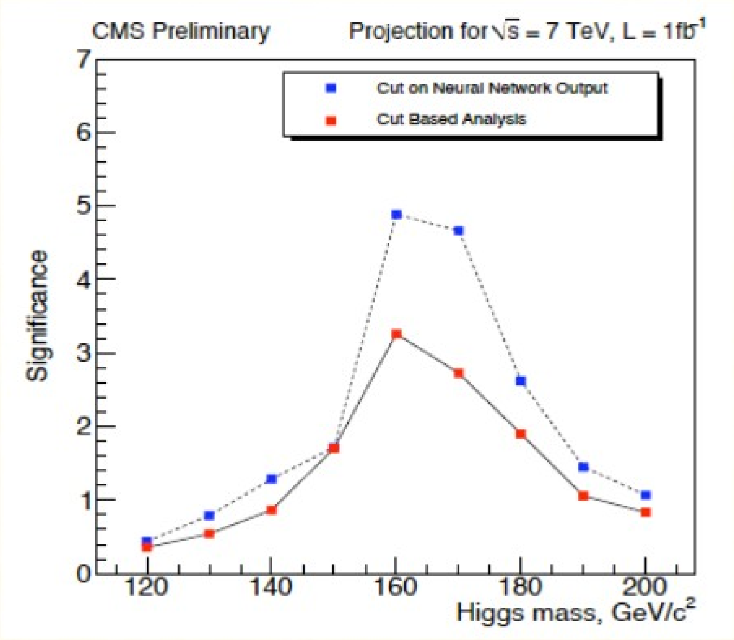
Difficulties:

(i) need precise knowledge of the backgrounds
Strategy: use control region(s) in data, extrapolation in signal region

(ii) jet veto efficiencies need to be understood for signal and background events

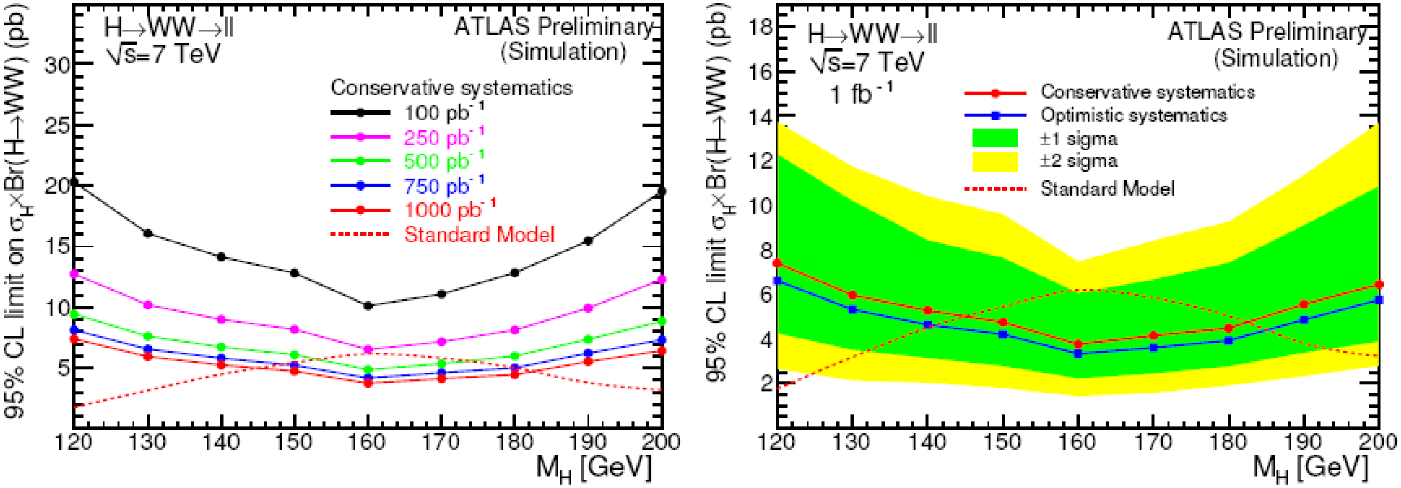
# Discovery reach in $H \to WW \to \ell\nu\,\ell\nu$ at $\sqrt{s} = 7$ TeV





- Looks promising, provided backgrounds (systematic uncertainties) can be controlled
- Exclusion reach is comparable to Tevatron reach (nominal performance) (note that a single experiment is quoted above)

# Discovery reach in the H →WW→ lνlν

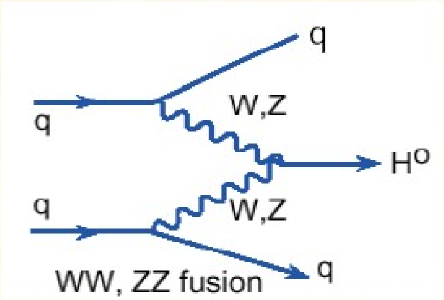


- Exclude in the range 140-185 GeV at 95%CL for the optimistic systematics.

# Vector Boson Fusion  qq H

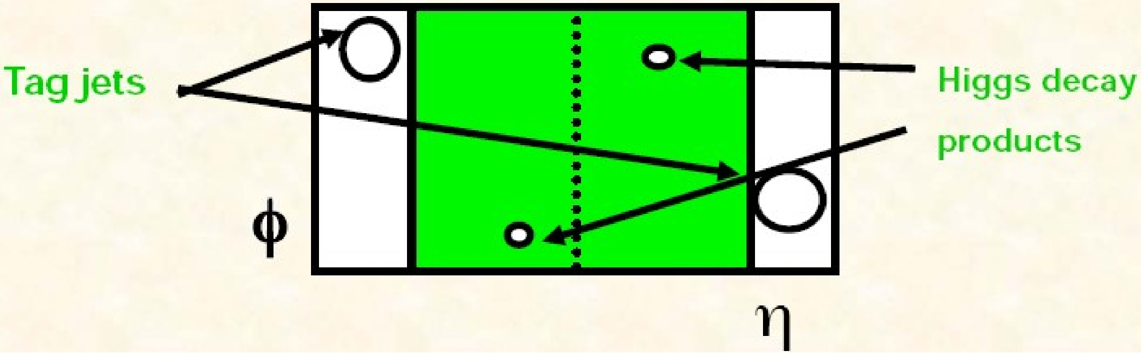
**Motivation:** Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)
Earlier studies: R.Kleiss W.J.Stirling, Phys. Lett. 200 (1988) 193;
Dokshitzer, Khoze, Troyan, Sov.J. Nucl. Phys. 46 (1987) 712;
Dokshitzer, Khoze, Sjöstrand, Phys.Lett., B274 (1992) 116.



Distinctive Signature of:

- two high $p_T$ forward jets (tag jets)
- little jet activity in the central region
  (no colour flow)
  ⇒ central jet Veto

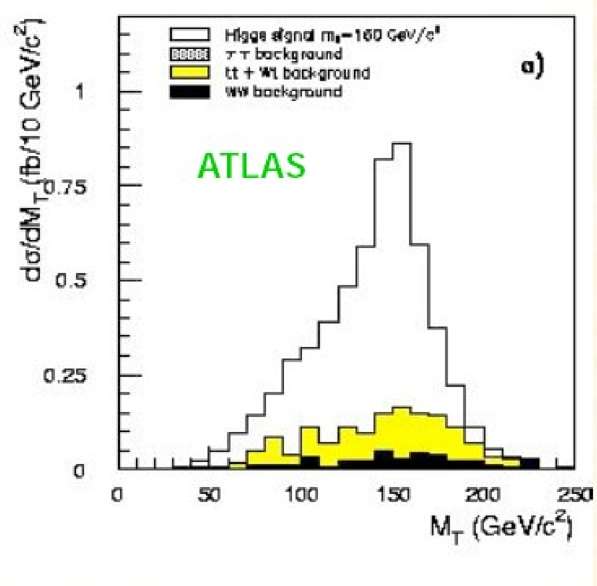


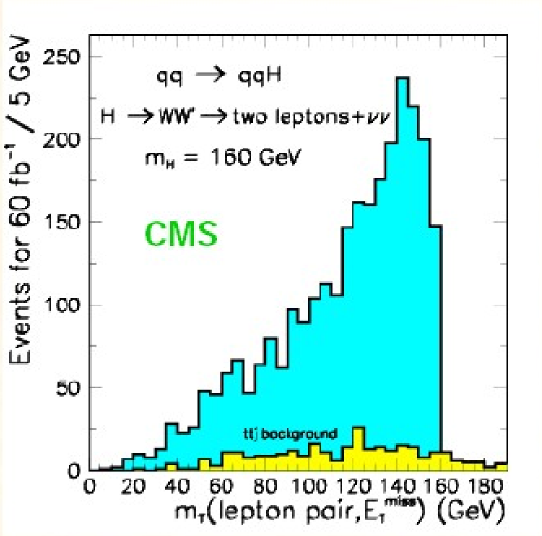
$$qq\,H \rightarrow qq\ W\,W^{*}$$
$$\rightarrow qq\ \ell\nu\ \ell\nu$$

Selection criteria:

- Lepton $P_T$ cuts and
- Tag jet requirements ($\Delta\eta$, $P_T$, large mass)
- Jet veto (important)
- Lepton angular and mass cuts

$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,miss})^2}$$





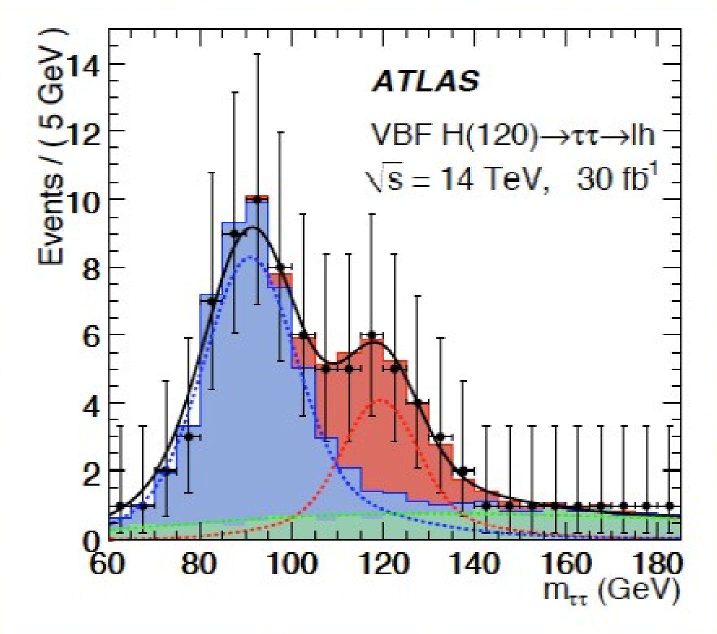
Transverse mass distributions: clear excess of events above the background from tt-production

## $H \rightarrow \tau\tau$ decay modes visible for a SM Higgs boson in vector boson fusion

$qq\,H \rightarrow qq\,\tau\,\tau$

$\rightarrow qq\ \ell\nu\nu\ \ \ell\nu\nu$

$\rightarrow qq\ \ell\nu\nu\ \ h\nu$



Experimental challenge:

- Identification of hadronic taus
- Good $E_T^{miss}$ resolution

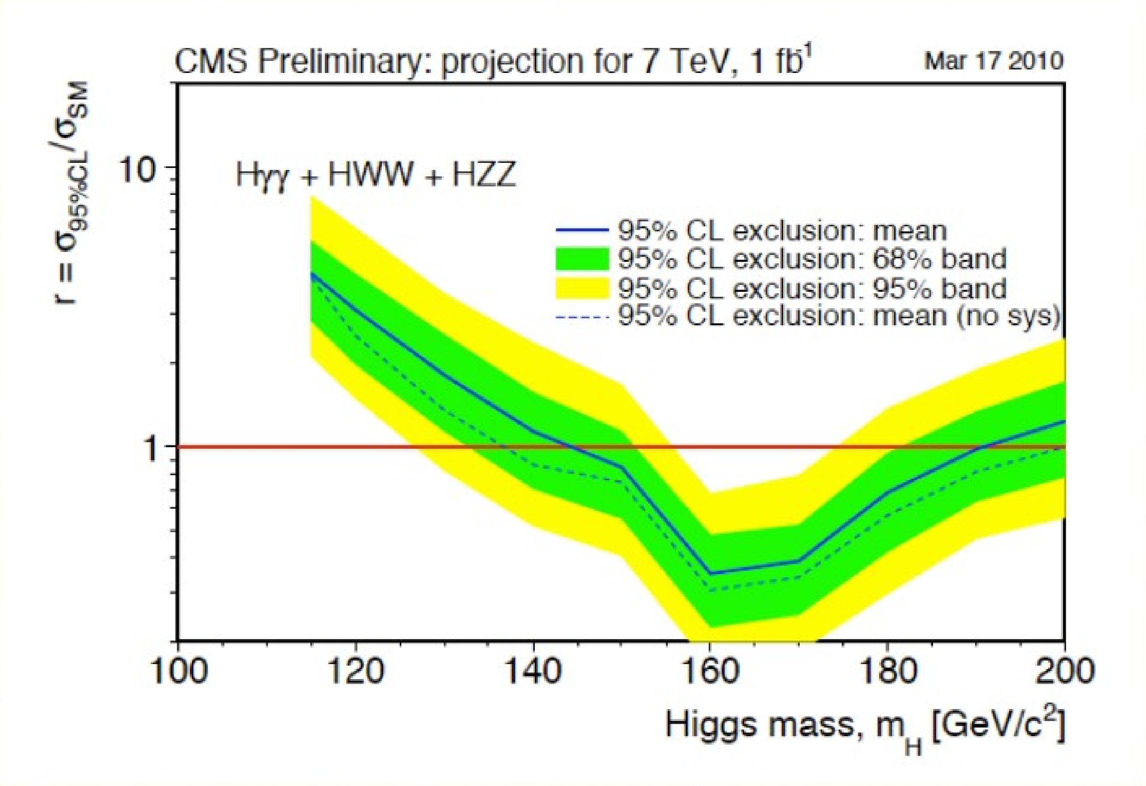
  ($\tau\tau$ mass reconstruction in collinear approximation, i.e. assume that the neutrinos go in the direction of the visible decay products, good approximation for highly boosted taus)

  → Higgs mass can be reconstructed
- Dominant background: $Z \rightarrow \tau\tau$

  the shape of this background must be controlled in the high mass region

  → use data ($Z \rightarrow \mu\mu$) to constrain it

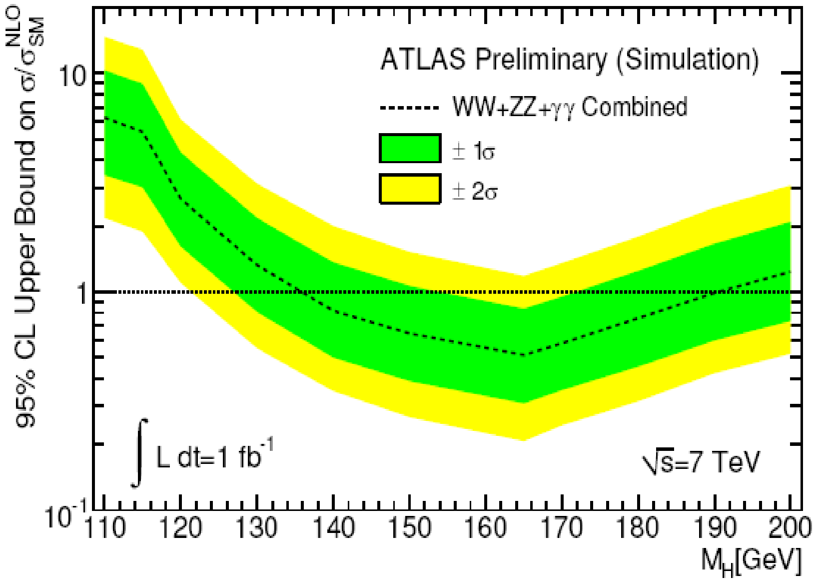
# What can be achieved with 1 $fb^{-1}$ at $\sqrt{s}$ = 7 TeV ?

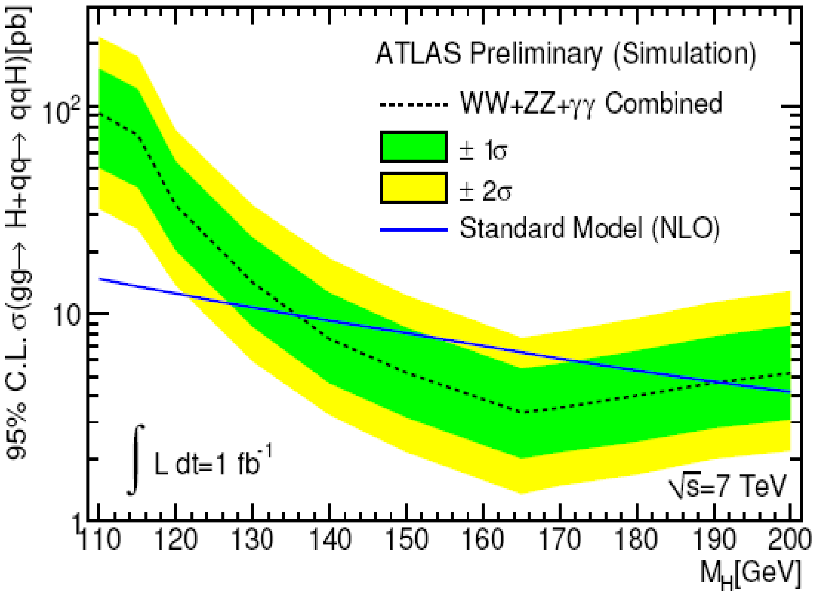


- Combination of the WW, γγ and ZZ decay channels (CMS study, preliminary, numbers from 14 TeV scaled down)

- Mass range in the region between 145 and 190 GeV can be excluded within one experiment

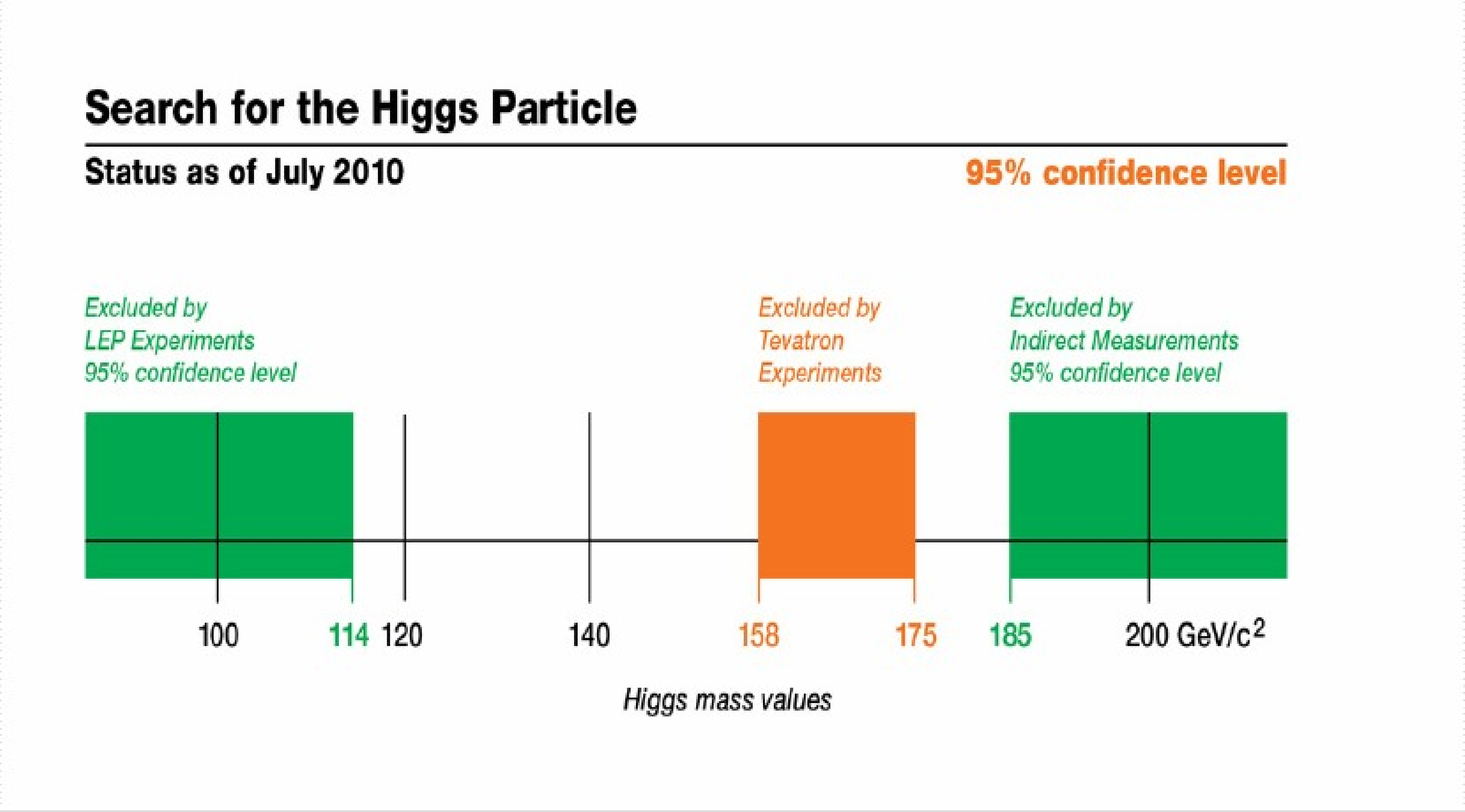
# What can be achieved with 1 fb$^{-1}$





- Higgs mass between 135 – 188 GeV can be excluded at 95% CL.

# Allowed parameter space shrinking



Search for the Higgs Particle

Status as of July 2010

# Next topics

- 15.12 – Higgs
  - Properties: masses, couplings
  - MSSM
  - Other scenarios
- 5.01 - SUSY
- 12.01 - SUSY
- 19.01 - Wrapping up on data 2010:
  - SM physics: selected public results
  - Searches: new exclusion limits

# 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)

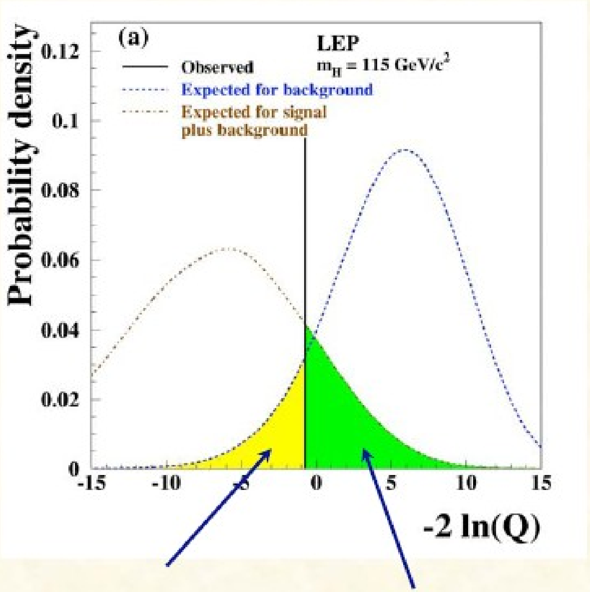
Compute likelihood for B and (S+B) hypothesis

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

**Test statistics: $LLR := -2 \ln Q$**

(log-likelihood ratio (LLR))

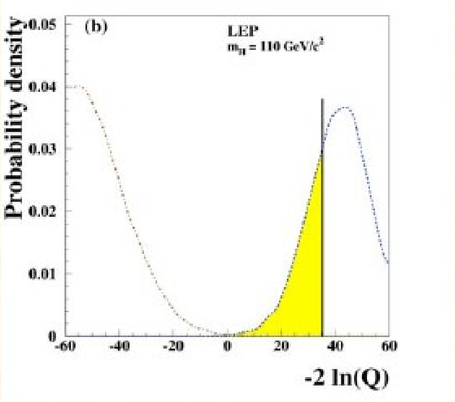
Distribution (pdf) of -2 ln Q can be calculated in MC experiments for (S+B) and B-hypothesis



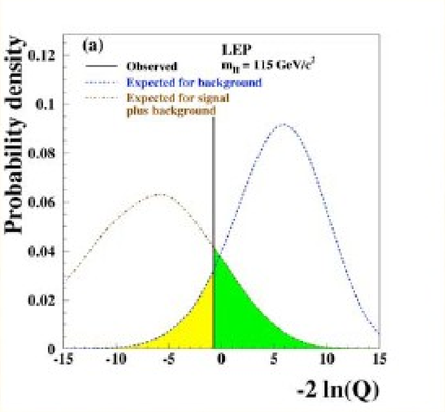
$1 - CL_B$

$CL_{S+B}$

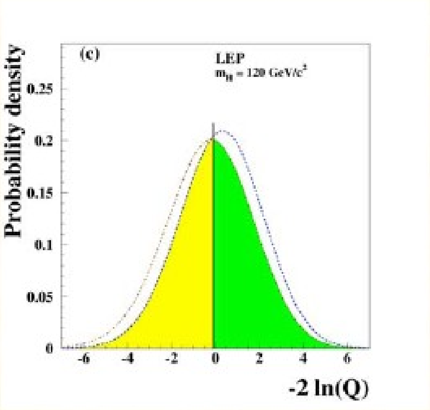
## Example from LEP: Likelihood ratio distributions for different assumed Higgs boson mass values



$m_H$ = 110 GeV/$c^2$



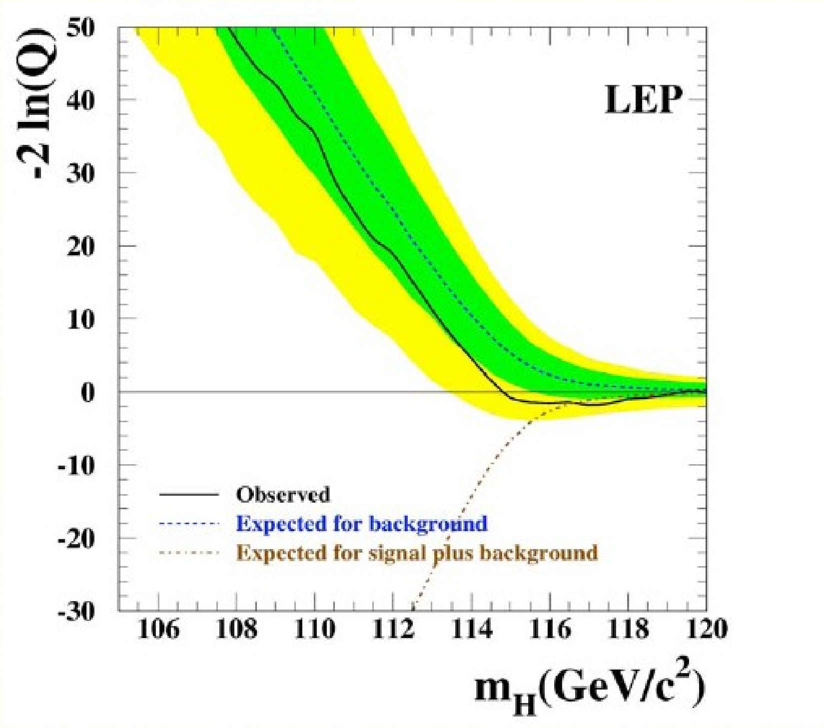
$m_H$ = 115 GeV/$c^2$



$m_H$ = 120 GeV/$c^2$

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

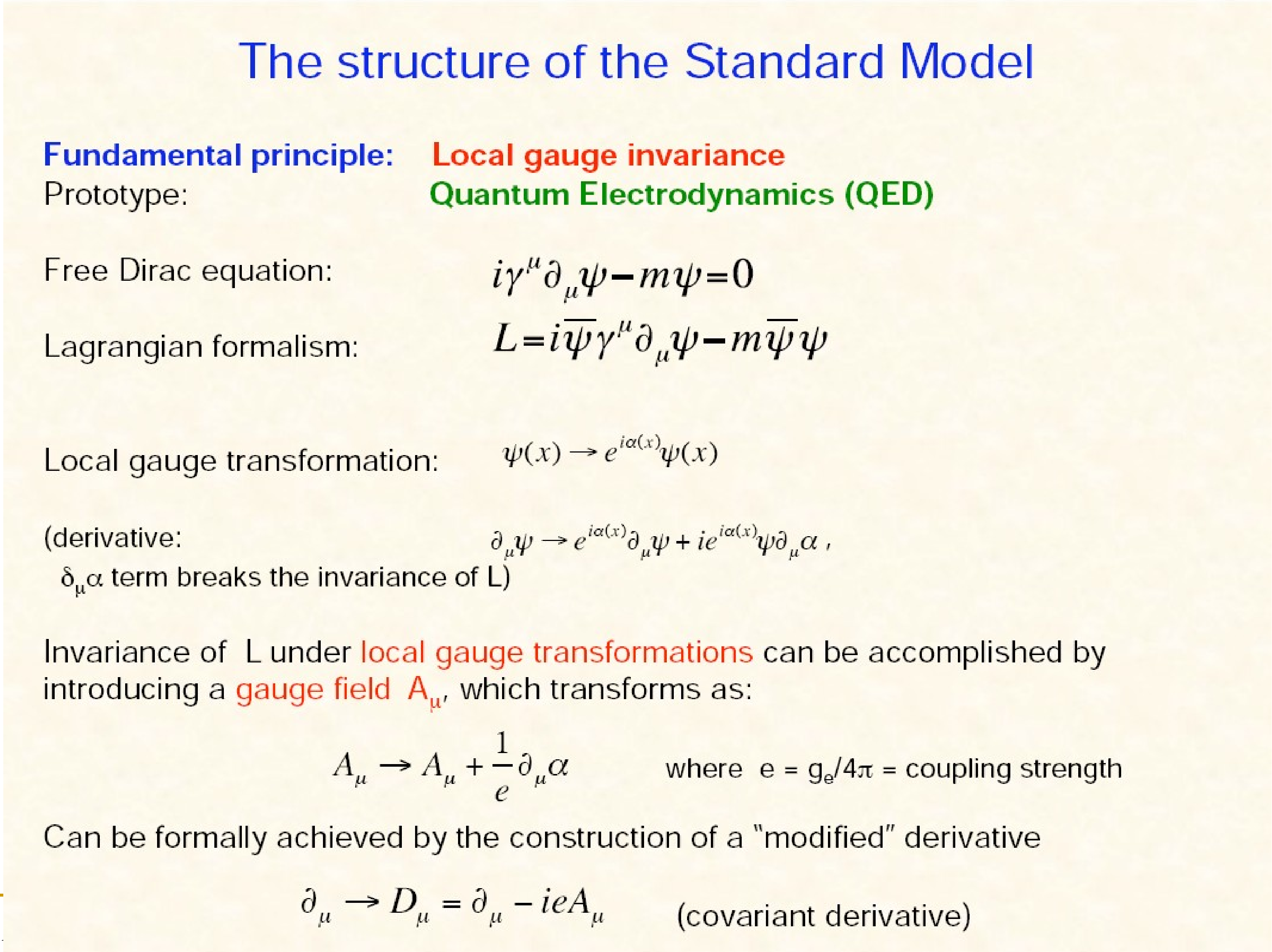
# LEP: Observed and expected behavior of -2 ln Q



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



# The structure of the Standard Model

**Fundamental principle:** **Local gauge invariance**
Prototype: **Quantum Electrodynamics (QED)**

Free Dirac equation: $i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0$

Lagrangian formalism: $L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi$

Local gauge transformation: $\psi(x) \rightarrow e^{i\alpha(x)}\psi(x)$

(derivative: $\partial_{\mu}\psi \rightarrow e^{i\alpha(x)}\partial_{\mu}\psi + ie^{i\alpha(x)}\psi\partial_{\mu}\alpha$ ,
$\delta_{\mu}\alpha$ term breaks the invariance of L)

Invariance of L under local gauge transformations can be accomplished by introducing a gauge field $A_{\mu}$, which transforms as:

$$A_{\mu} \rightarrow A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha$$

where $e = g_e/4\pi$ = coupling strength

Can be formally achieved by the construction of a "modified" derivative

$$\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} - ieA_{\mu}$$

(covariant derivative)

→ Lagrangian of QED:

$$L = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi + \underbrace{e\overline{\psi}\gamma^{\mu}A_{\mu}\psi}_{\text{interaction term}} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where $F_{\mu\nu}$ is the usual field strength tensor: $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

Note:

(i) Imposing local gauge invariance leads to the interacting field theory of QED

(ii) A mass term ( $\frac{1}{2}m^{2}A_{\mu}A^{\mu}$ ) for the gauge field $A_{\mu}$ would violate gauge invariance

# Similar for the Standard Model interactions:

## Quantum Chromodynamics (QCD):

$$D_\mu = \partial_\mu + igT_a G^a_\mu$$

$$G^a_\mu \to G^a_\mu - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G^c_\mu$$

SU(3) transformations, 8 gauge fields,
8 massless gluons, Gluon self-coupling

- $T_a$ (a = 1,…,8) generators of the SU(3) group (independent traceless 3x3 matrices)
- $G_\mu$ gluon fields
- g = coupling constant

**Electroweak Interaction** (Glashow, Salam, Weinberg):
$SU(2)_L \times U(1)_Y$ transformations,
4 gauge fields, ($W_\mu^1$, $W_\mu^2$, $W_\mu^3$, $B_\mu$)

**Physical states:**

$$W^\pm_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \mp iW^2_\mu\right)$$

$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W^3_\mu$$

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W^3_\mu$$