

The search for the (SM) Higgs Boson

- theoretical basics
- Higgs production and decay
- Higgs search in e^+e^- annihilation
 - direct search
 - indirect mass limits from electroweak radiation corrections
- Higgs searches in hadron collisions
 - Tevatron
 - LHC (-> next lecture)

The Standard Model Higgs Boson: theoretical basics and expectations

- gauge field theory with **gauge symmetry** in weak isospin/hyper charge [SU(2) x U(1)] to describe electromagnetic and weak interactions of quarks and leptons: includes **massless** gauge bosons (γ, Z^0, W^+, W^-) and fermions
- any attempt to include mass terms breaks gauge symmetry and destroys renormalizability of the theories
- Englert, Brout and Higgs (1964): **spontaneous symmetry breaking** (generates mass, keeps renormalizability):

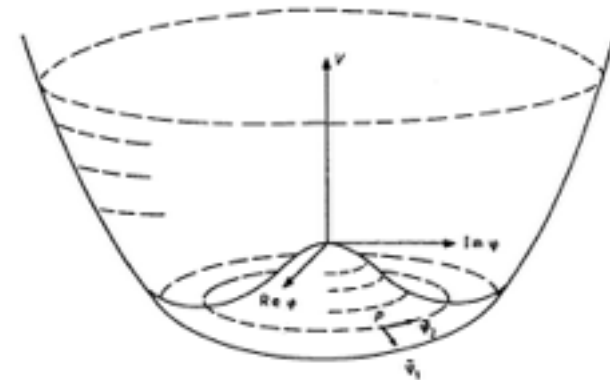
- introduction of complex SU(2) doublets of scalar fields with a potential

$$\text{of } V(\phi) = \lambda (\phi^\dagger \phi)^2 - \mu^2 \phi^\dagger \phi ; \quad \text{with } \lambda, \mu^2 > 0 ; \quad \phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

- V does not have minimum at $\phi = 0$, but at

$$|\phi| = \sqrt{\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$$

- 3 of the 4 real degrees of freedom are used to generate the longitudinal spin d.o.f. of Z^0 and W^\pm ;
- 4. d.o.f. \rightarrow physical Higgs particle!



theoretical basis and expectations

- inserting ϕ in Lagrange function results in 3 massive vector fields, 1 massless vector-field, plus one massive scalar field with

$$M_W = \frac{1}{2} g v \quad \Rightarrow \quad v = 246 \text{ GeV}$$

$$M_Z = M_W / \cos \theta_w \quad (g = e / \sin \theta_w)$$

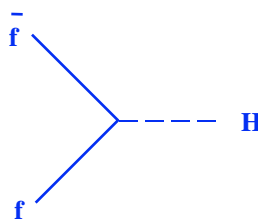
$$M_\gamma = 0$$

$$M_H = 2\mu^2 = 2\lambda v^2$$

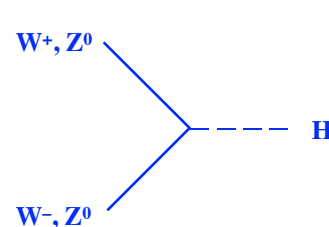
- introduction of Yukawa-couplings g_f between ϕ and the fermion fields: generates fermion masses

$$m_f = g_f v / \sqrt{2}$$

- fundamental fermion-Higgs couplings:



$$g_{f\bar{f}H} = \frac{e m_f}{2M_W \sin \theta_w}$$



$$g_{WWH} = \frac{e M_W}{\sin \theta_w}$$

$$g_{ZZH} = \frac{e M_Z}{\sin \theta_w \cos \theta_w}$$

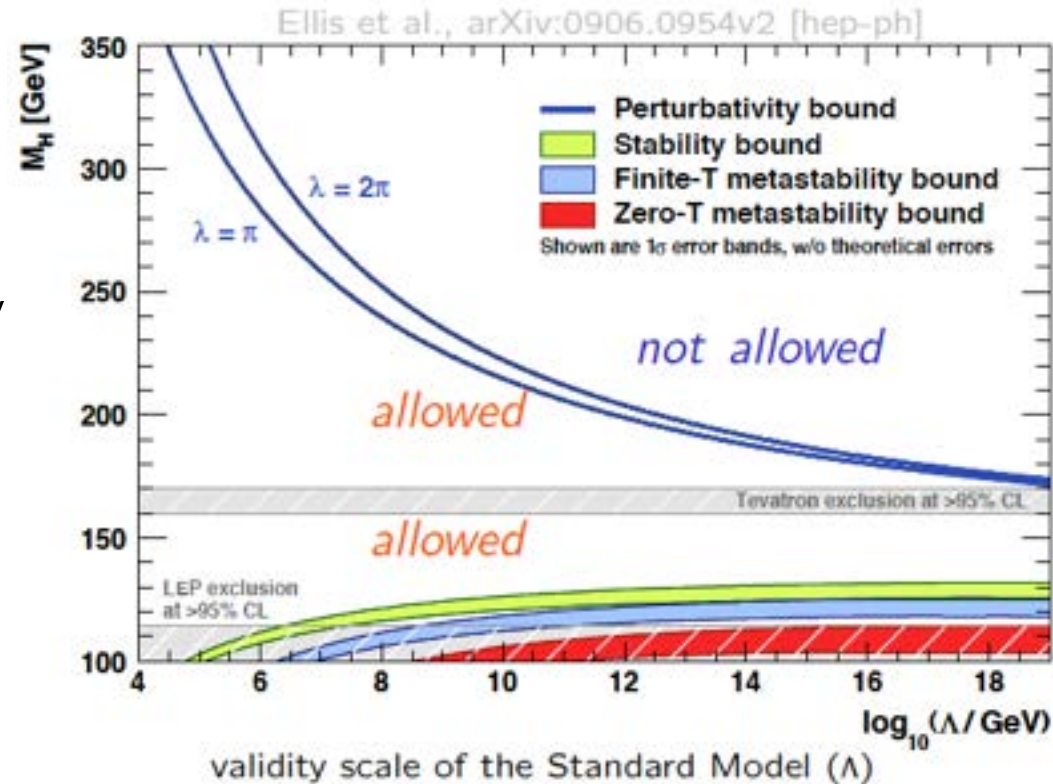
theoretical basis and expectations

theoretical bounds for M_H from self-consistency arguments of the Standard-Model:

- upper bounds: perturbativity
- lower bounds: vacuum stability

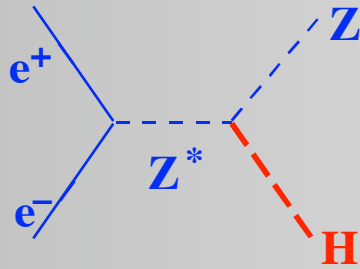
n.b.: if SM is valid only up to $\Lambda = O(1 \text{ TeV})$,
then $M_H = 50 \dots 1000 \text{ GeV}$

n.b.: if SM is valid up to $\Lambda = O(M_{\text{Planck}})$
then $M_H \sim 125 \dots 180 \text{ GeV}$

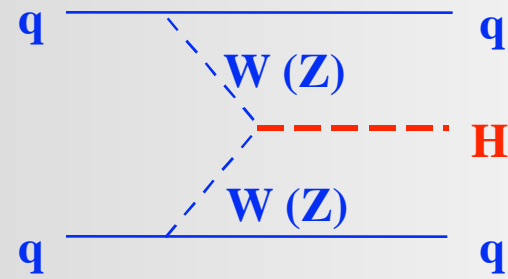


Λ : energy scale up to which SM is valid

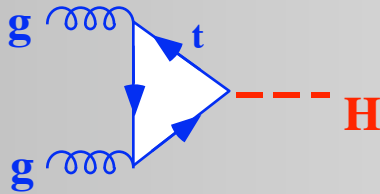
Higgs: production and decays



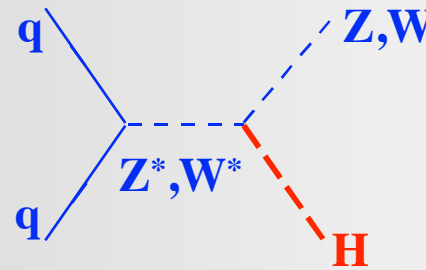
Higgs-radiation



W- (Z-) fusion



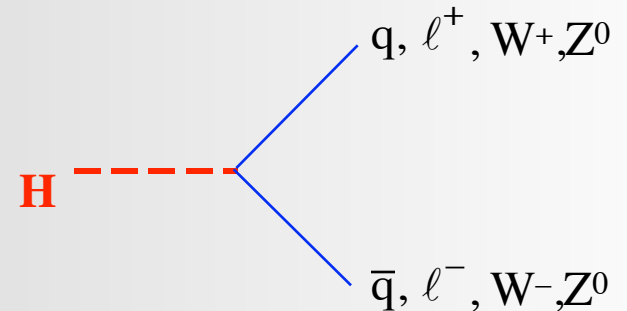
Gluon - Fusion



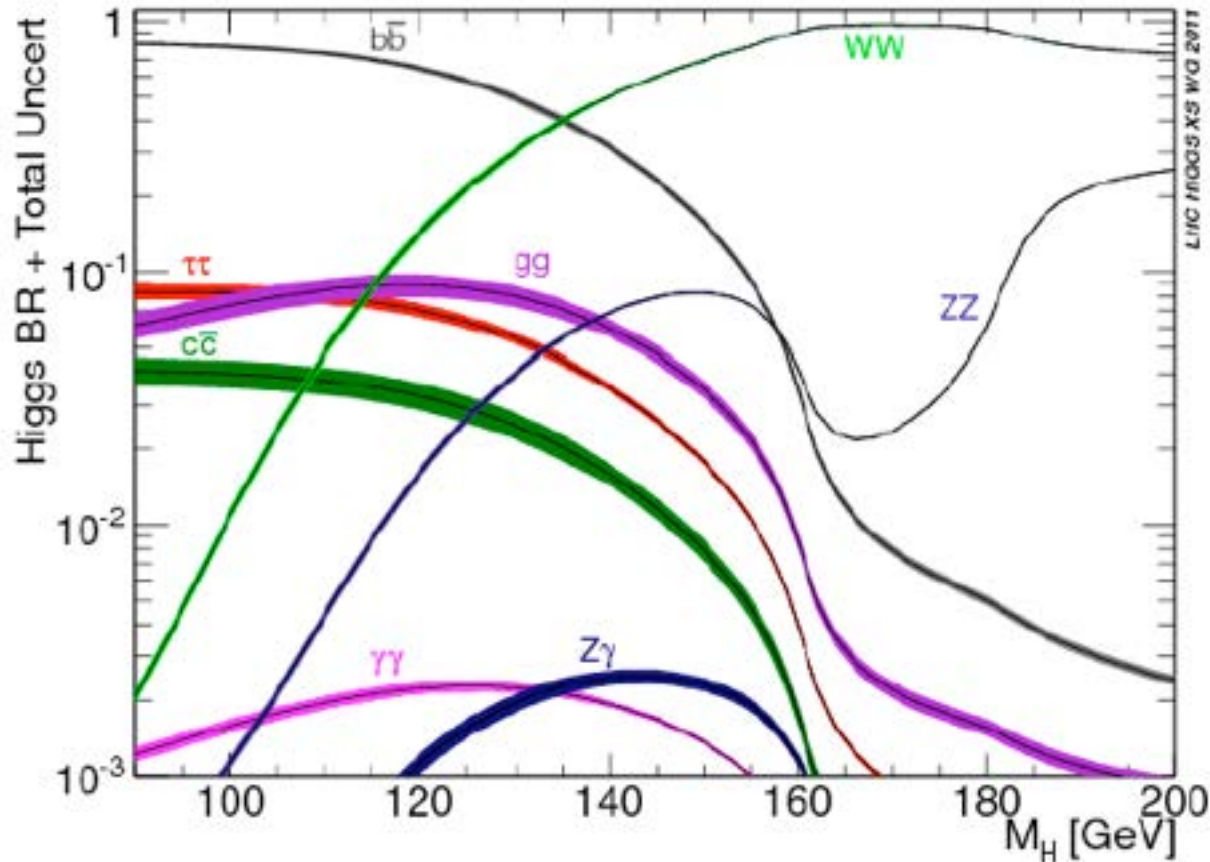
Higgs-radiation (‘‘associate production’’)

Higgs-decay:

predominantly into heaviest,
kinematically accessible pair of
leptons or bosons



Higgs: decays



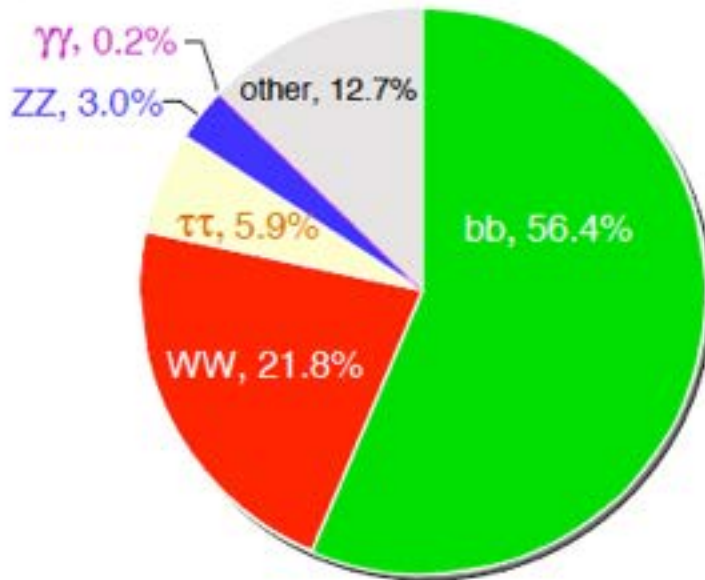
$$\text{Br}(H \rightarrow \gamma\gamma) \sim 10^{-3}$$

$M_H < \sim 135$ GeV: dominanter Zerfallskanal $H \rightarrow b b$

$M_H > \sim 135$ GeV: dominanter Zerfallskanal $H \rightarrow W^+W^-$

Higgs: decays

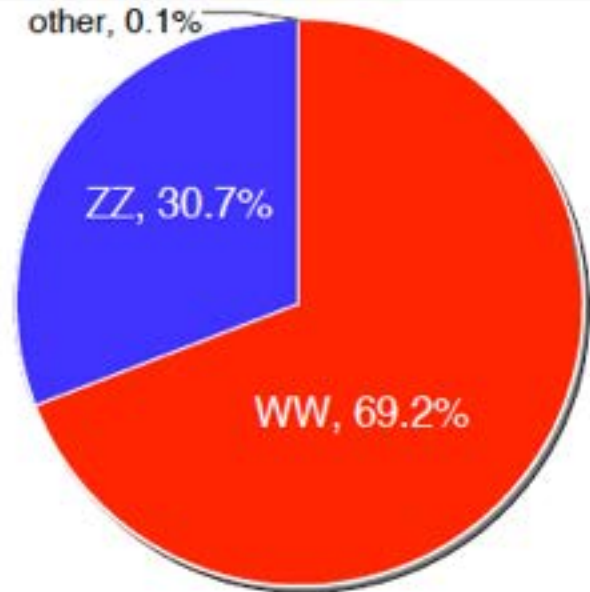
Low mass region, e.g. $m_H = 125$ GeV:



Ordered by the sensitivity to the signal:

- $H \rightarrow ZZ \rightarrow (l^+l^-)(l^+l^-)$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow WW \rightarrow (l^+\nu)(l^-\nu)$
- $H \rightarrow \tau^+\tau^-$ (large background)
- $H \rightarrow b\bar{b}$ (large background)

High mass region, e.g. $m_H = 300$ GeV:

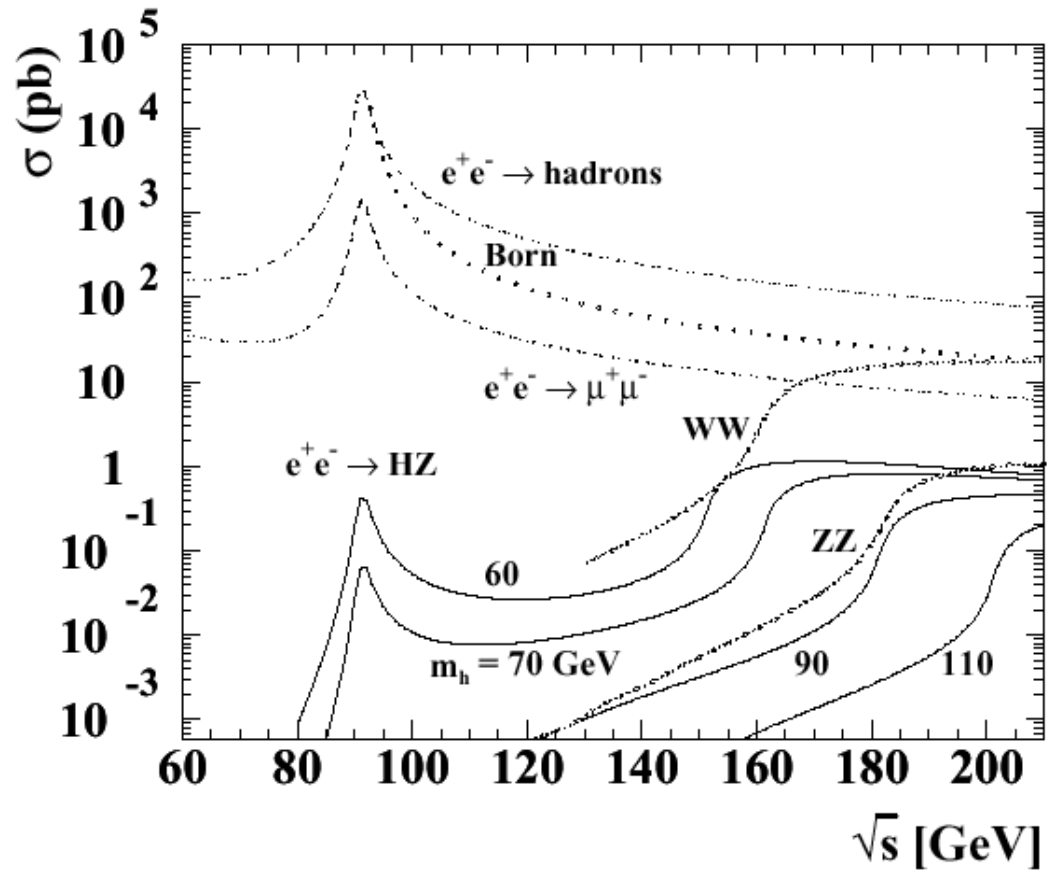


Ordered by the sensitivity to the signal:

- $H \rightarrow ZZ \rightarrow (l^+l^-)(l^+l^-)$
- $H \rightarrow ZZ \rightarrow (l^+l^-)(\nu\nu)$
- $H \rightarrow ZZ \rightarrow (l^+l^-)(q\bar{q})$
- $H \rightarrow WW \rightarrow (l^+\nu)(l^-\nu)$
- $H \rightarrow WW \rightarrow (l^+\nu)(qq)$

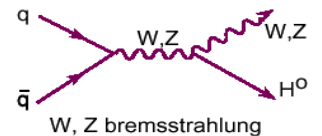
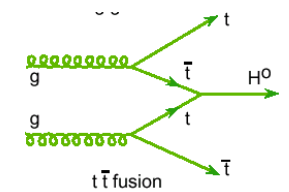
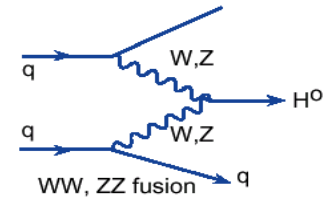
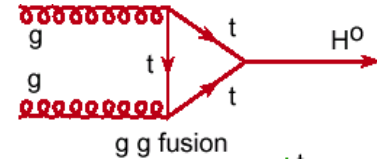
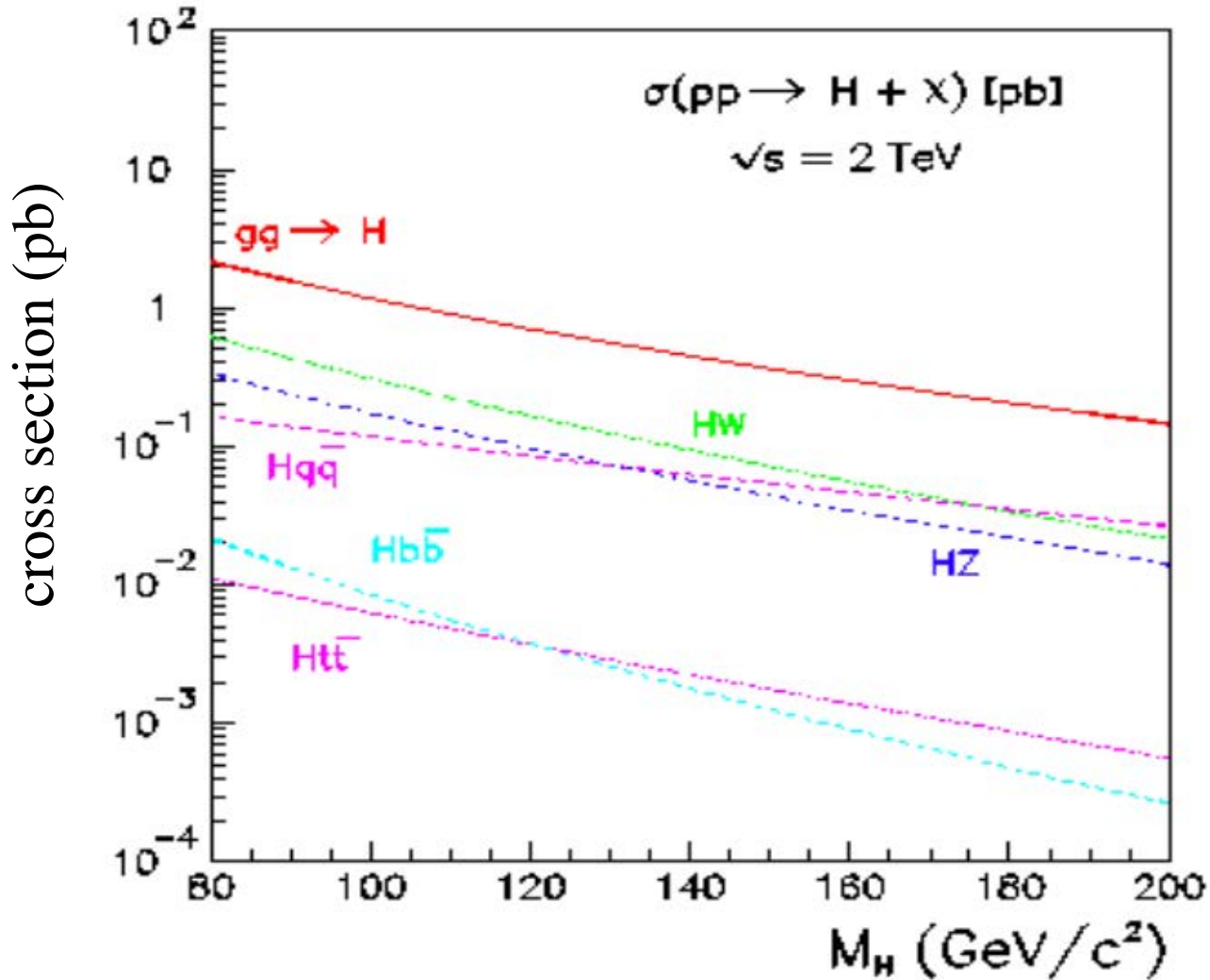
Higgs: production

e^+e^- annihilation



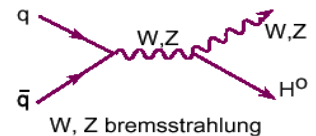
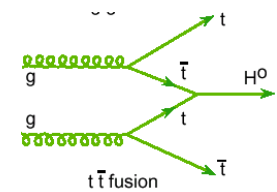
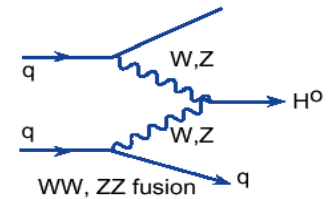
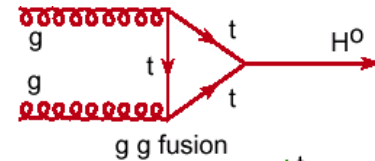
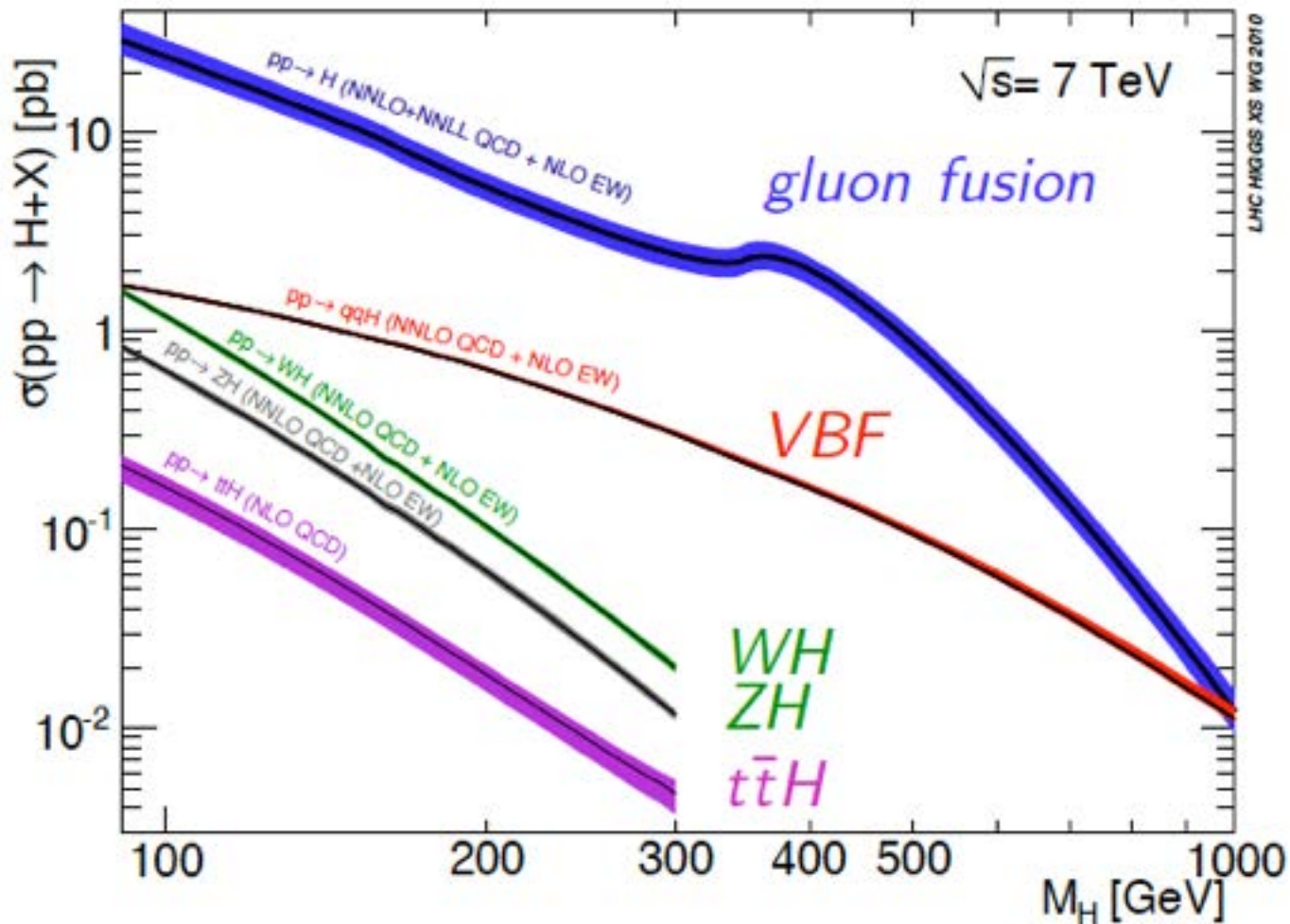
Higgs: production

Standard Model Higgs Boson @ Tevatron



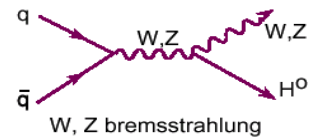
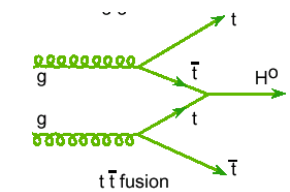
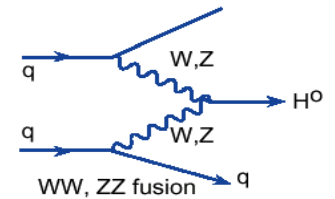
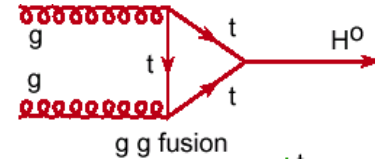
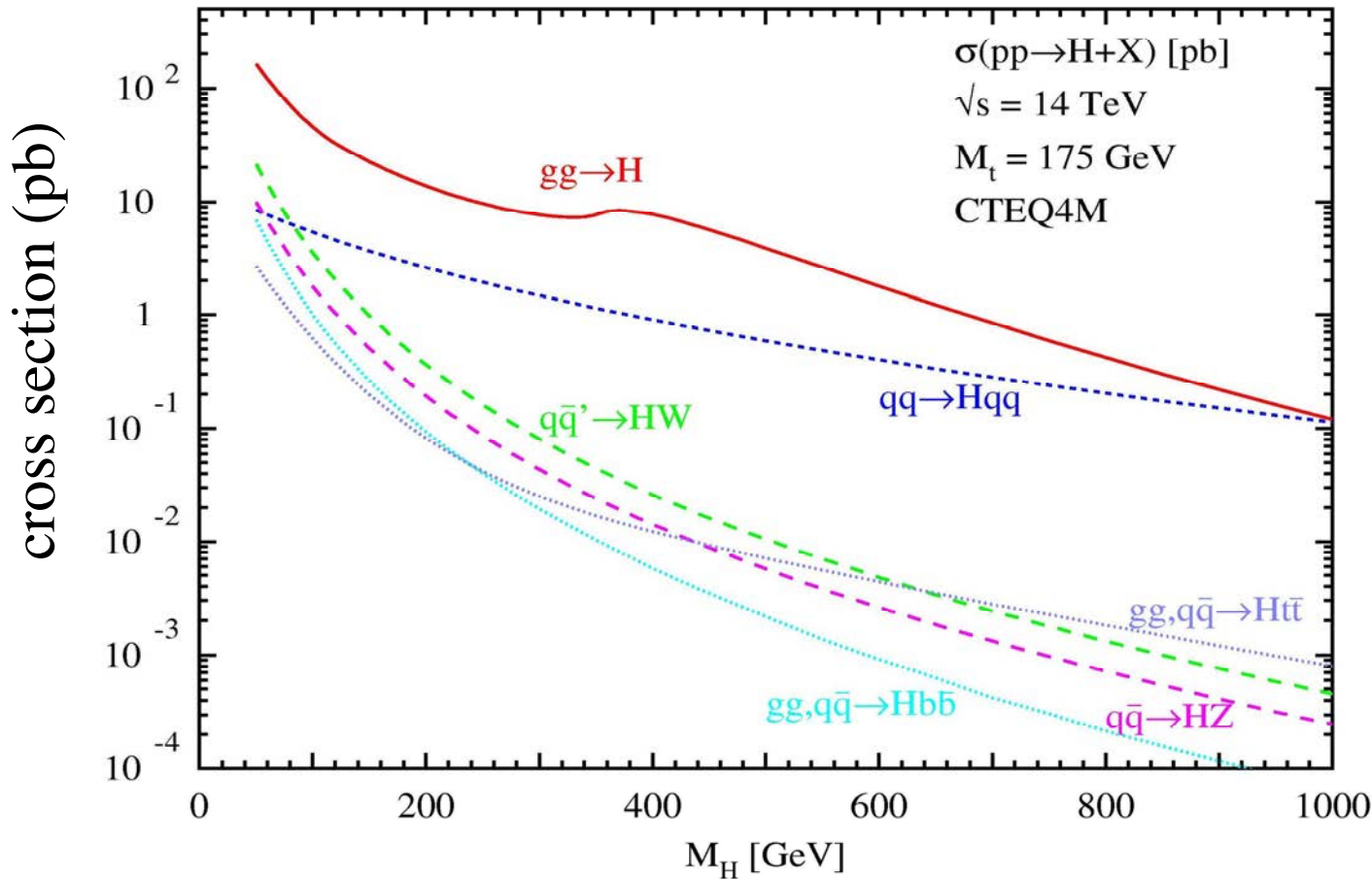
Higgs: production

Standard Model Higgs Boson @ LHC (7 TeV)

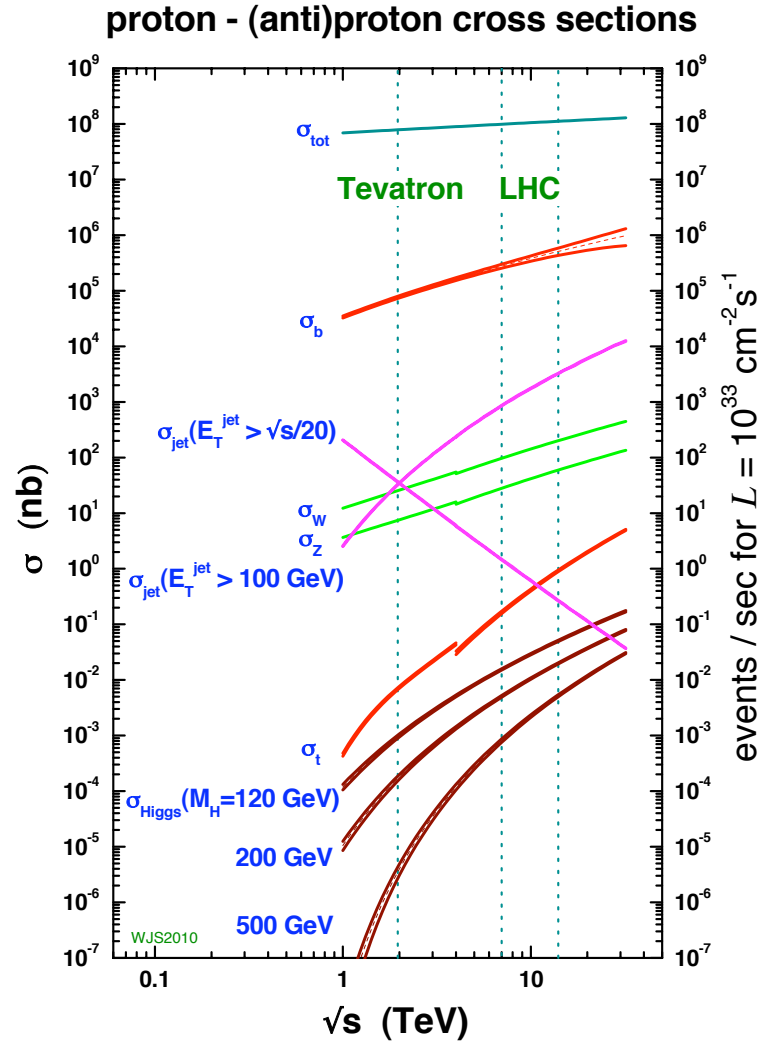


Higgs: production

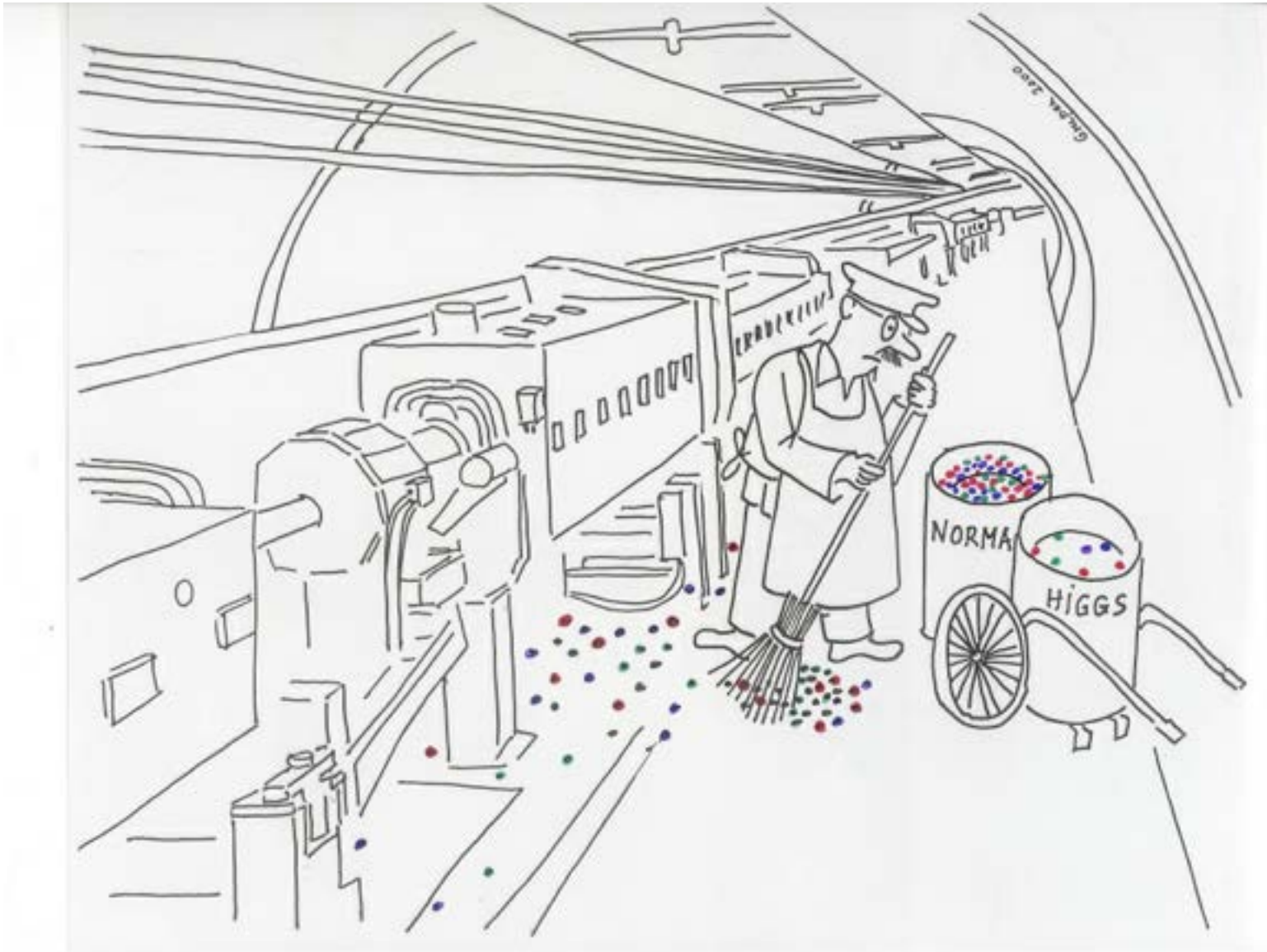
Standard Model Higgs Boson @ LHC (14 TeV)



Higgs production cross-sections

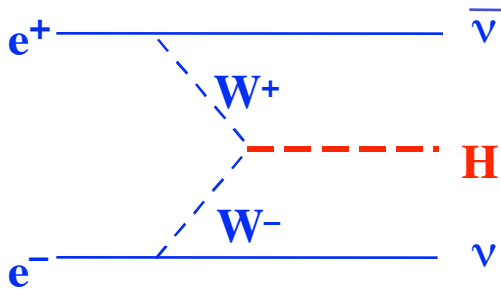
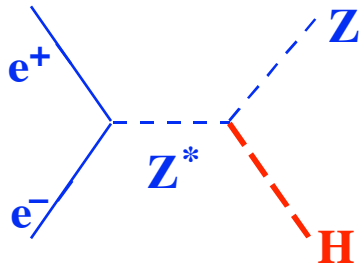


Higgs search

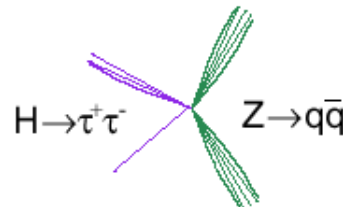
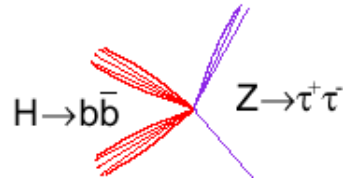
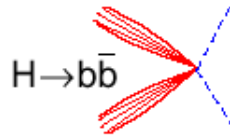
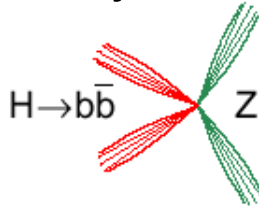


Higgs-search in e^+e^- annihilation: direct

production:



decay channel ($e^+e^- \rightarrow HZ$):



background:

$WW \rightarrow qq\bar{q}\bar{q}, ZZ \rightarrow bb\bar{q}\bar{q}$
QCD 4jets

$WW \rightarrow qq\bar{l}\nu, ZZ \rightarrow bb\nu\nu$

$WW \rightarrow qq\tau\nu, ZZ \rightarrow qq\tau\tau$
QCD (low-mult. jets)

$ZZ \rightarrow bbll$

4-Jet-Kanal

51%

Neutrino-Kanal

15%

Tau-Kanal

2.4%

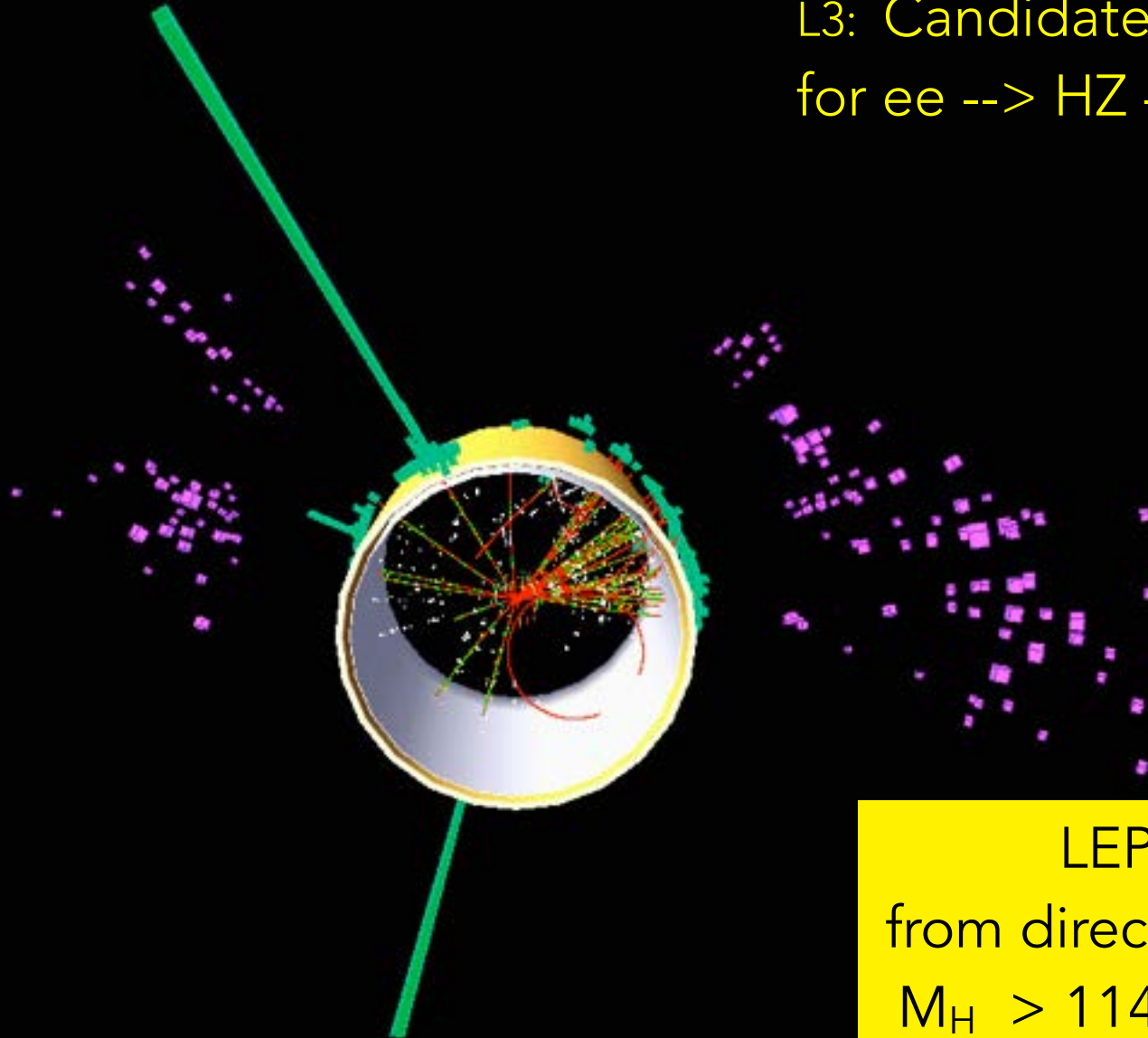
Lepton-Kanal

4.9%

search includes $\sim 80\%$ of all final states with $\sim 40 - 50\%$ selection efficiency

Higgs-search in e^+e^- annihilation: direct

L3: Candidate event
for $ee \rightarrow HZ \rightarrow eeqq$

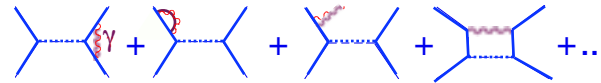


LEP:
from direct search
 $M_H > 114.1 \text{ GeV}$

Higgs-search in e^+e^- annihilation: indirect

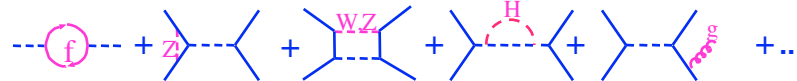
radiation corrections in SM:

photonic corrections:



corrections $\sim 100\%$, selection dependent;
factorisable: $(1 + \delta_{\text{rad}})$

non-photonic corrections:



corrections $\sim 10\%$, selection independent;
can be absorbed into running coupling constants:

- $\sin^2\theta_{\text{eff}}(s)$
- $\alpha(s) = \frac{\alpha}{1 - \Delta\alpha}$; $\Delta\alpha = +0.064$ bei $\sqrt{s} = M_Z$
- $N_{\text{cf}} \left(1 + \frac{\alpha_s}{\pi} + 1.4 \left(\frac{\alpha_s}{\pi} \right)^2 + \dots \right)$ (für Quarks)
- $\frac{M_W^2}{M_Z^2} = \rho \cdot \cos^2 \theta_w$ mit $\rho = \frac{1}{1 - \Delta\rho}$; $\Delta\rho = 0.0026 \frac{M_t^2}{M_Z^2} - 0.0015 \ln \left(\frac{M_H}{M_w} \right)$

Higgs-search in e^+e^- annihilation: indirect

insertion of running couplings into "Born"-approximation :

partial decay widths of Z: $\Gamma_f = \frac{G_f M_Z^3}{6\pi\sqrt{2}} [g_{a,f}^2 + g_{v,f}^2]$ (and thus, also the

cross sections) become dependent on:

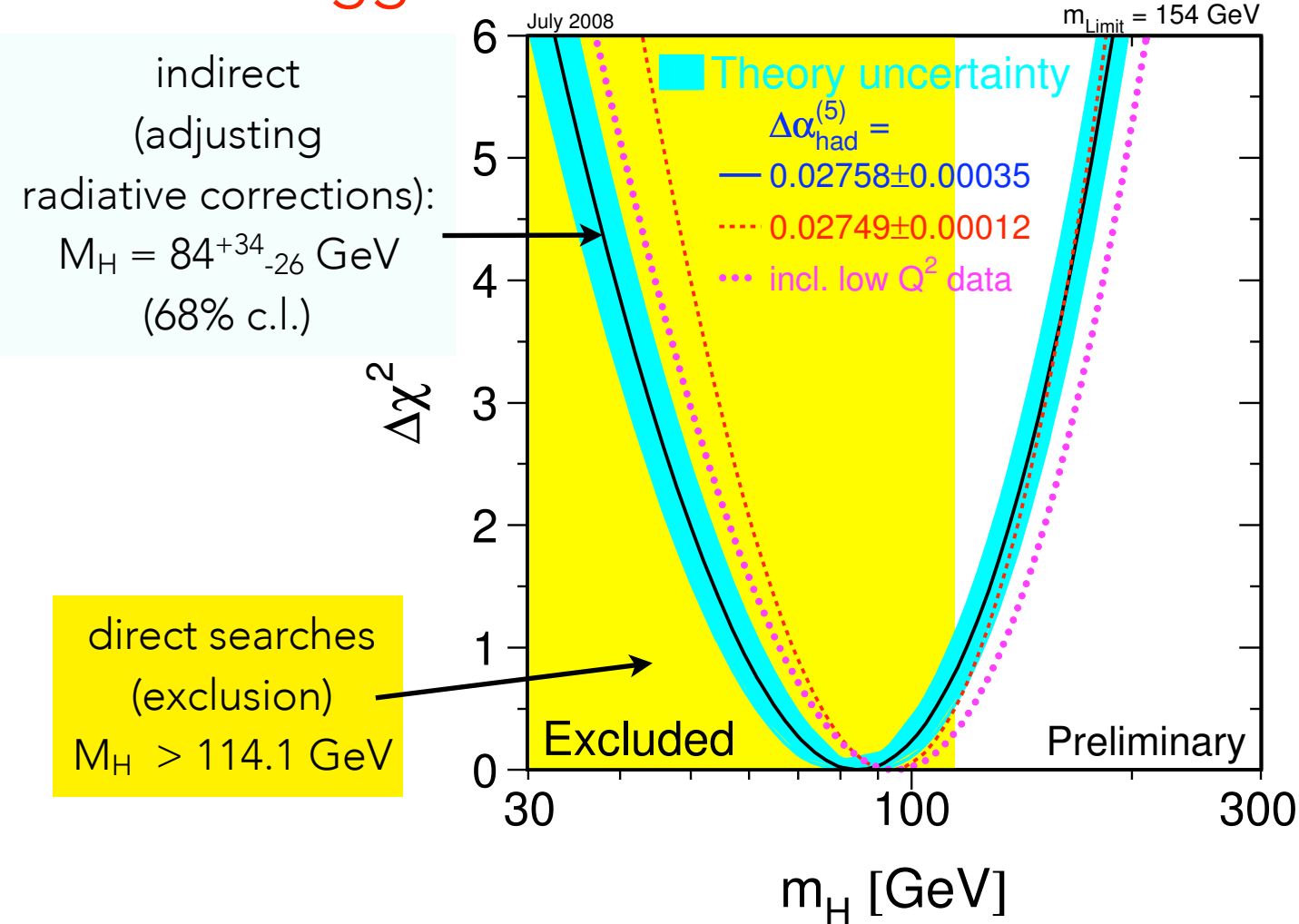
- M_t
- M_H
- α_s

==> indirect determination (fit) of M_t , M_H , und α_s from combination of all available electro-weak observables (differential cross sections, partial decay widths, forward-backward asymmetries, τ -polarisation, ...)

$$g_{a,f} = I_{3,f} \quad (3. \text{Komponente schw. Isospin; } = \pm 1/2)$$

$$g_{v,f} = I_{3,f} - 2Q\sin^2\theta_w$$

Higgs-search in e^+e^- annihilation: indirect

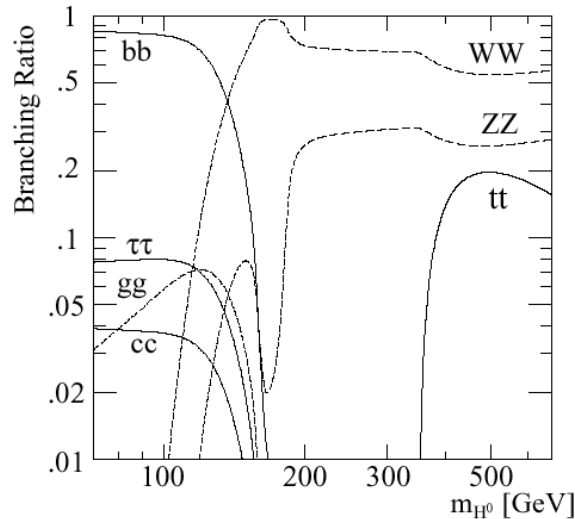


$114.1 \text{ GeV} < M_H < 154 \text{ GeV}$ (1-sided 95% c.l.)

$M_H < 185 \text{ GeV}$ (incl. 114 GeV lower limit)

n.b.: at the end of LEP (2000), indication for few events with $M_H \sim 115$ GeV (~ 2.3 std. dev.)

Higgs-Search at Hadron colliders: Tevatron



$M_H < \sim 135$ GeV: dominant decay $H \rightarrow b \bar{b}$ ($\sim 90\%$)
 $H \rightarrow \tau^+ \tau^-$ ($\sim 8\%$)

$M_H > \sim 135$ GeV: dominant decay $H \rightarrow W^+ W^-$

hadron collider: $\bar{b} b$ background from QCD processes dominates; irreducible;

$\Rightarrow g g \rightarrow H \rightarrow b \bar{b}$ cannot be used

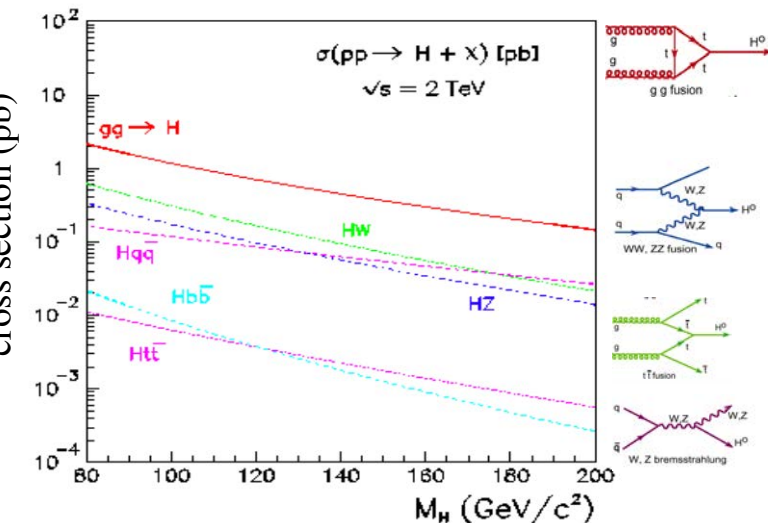
therefore:

focus on associate production

(ZH, WH) and analyse

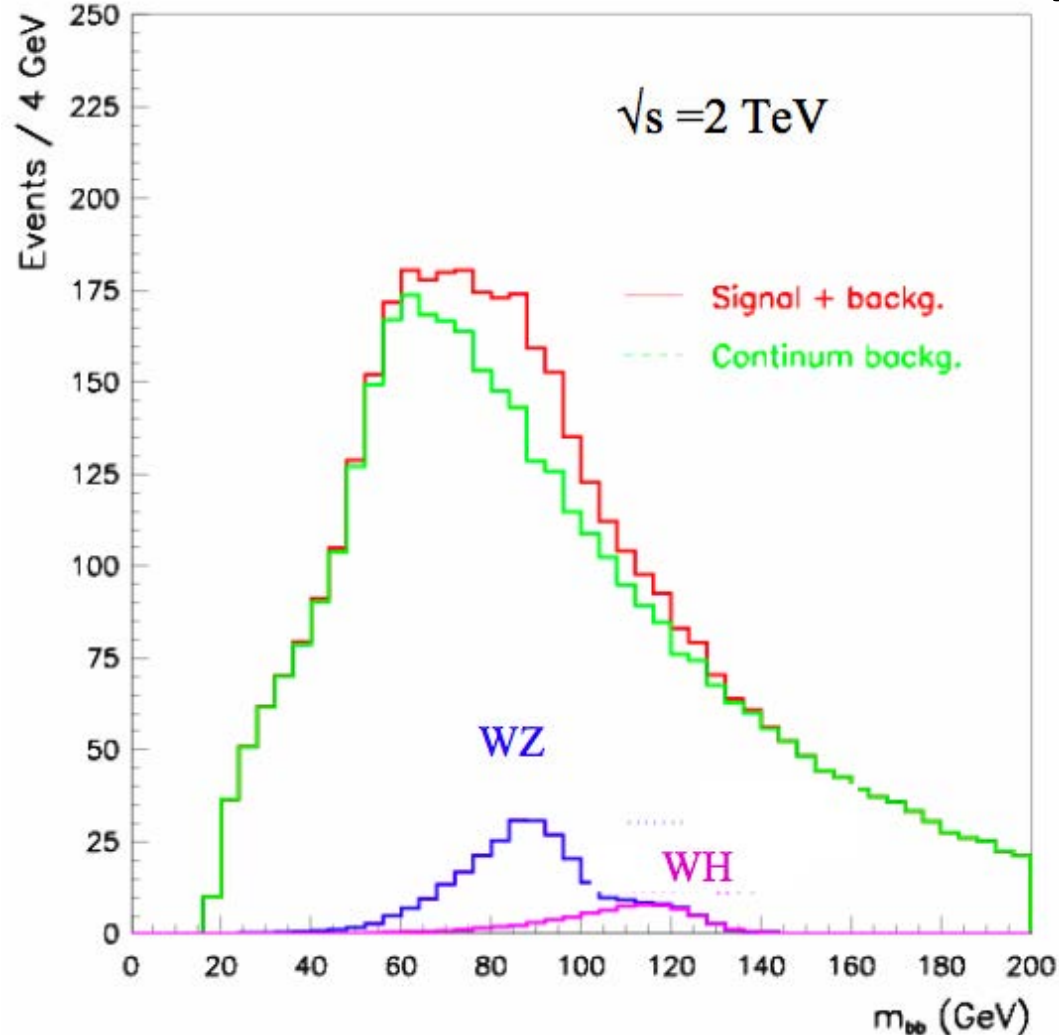
e.g. $Z \rightarrow l^+ l^-$; $H \rightarrow b \bar{b}$

$\tau\tau$ decay suitable for all production channels



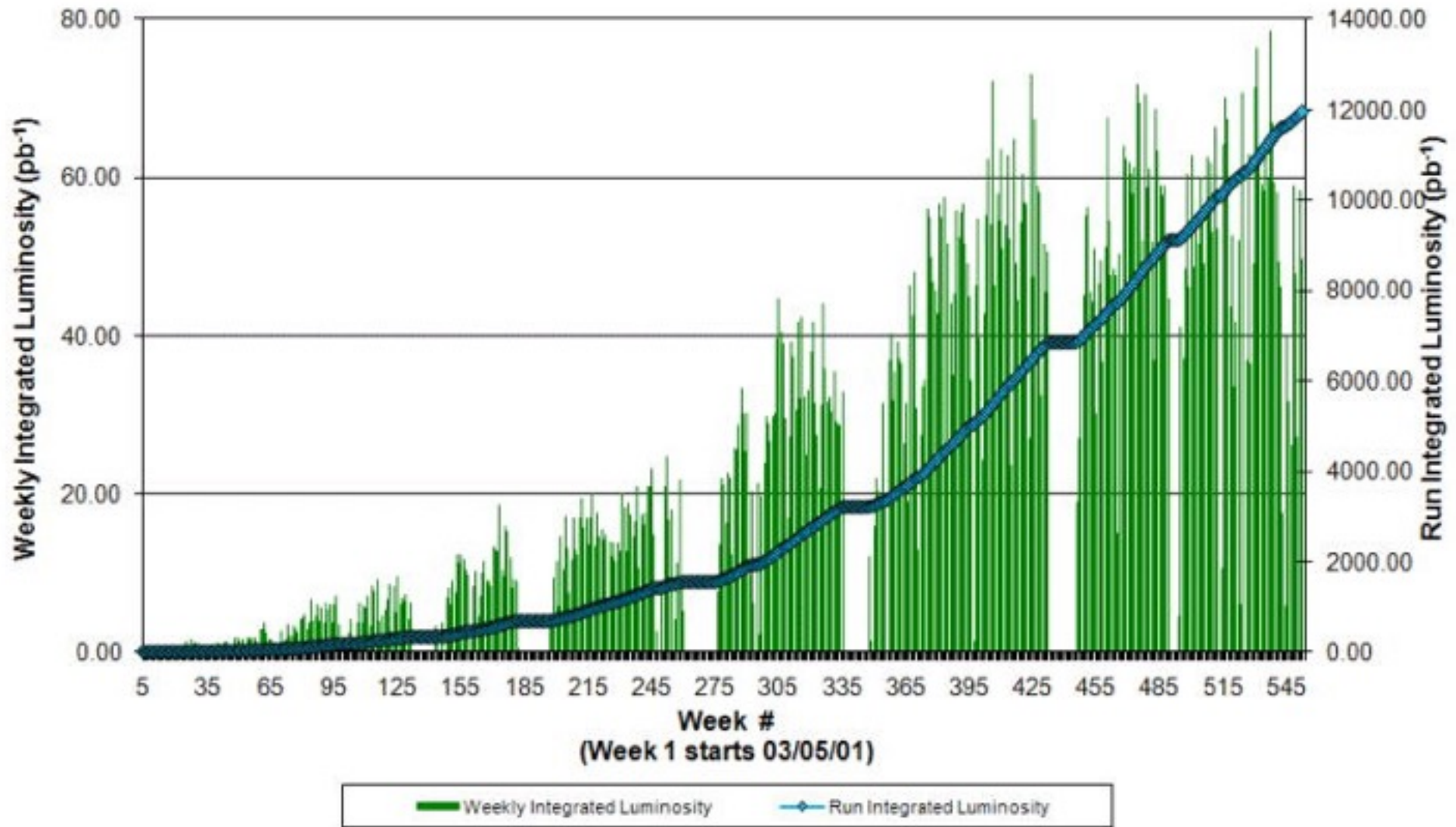
Higgs-Search at Hadron colliders: Tevatron

example: $M_H = 120 \text{ GeV}$ and 30 fb^{-1} (model study!)



very difficult measurement; background must be known extremely well!

Collider Run II Integrated Luminosity (delivered)



Tevatron was shut down on Sept. 29, 2011, after 26 years of colliding p and \bar{p}

definition of: significance of signal

● definition of significance

○ N_S : number of signal events

○ N_B : number of background events

→ $\sqrt{N_B}$ = uncertainty on number of background events

$$S = \frac{N_S}{\sqrt{N_B}}$$

● discovery: $S > 5$

→ probability to observe background fluctuation:

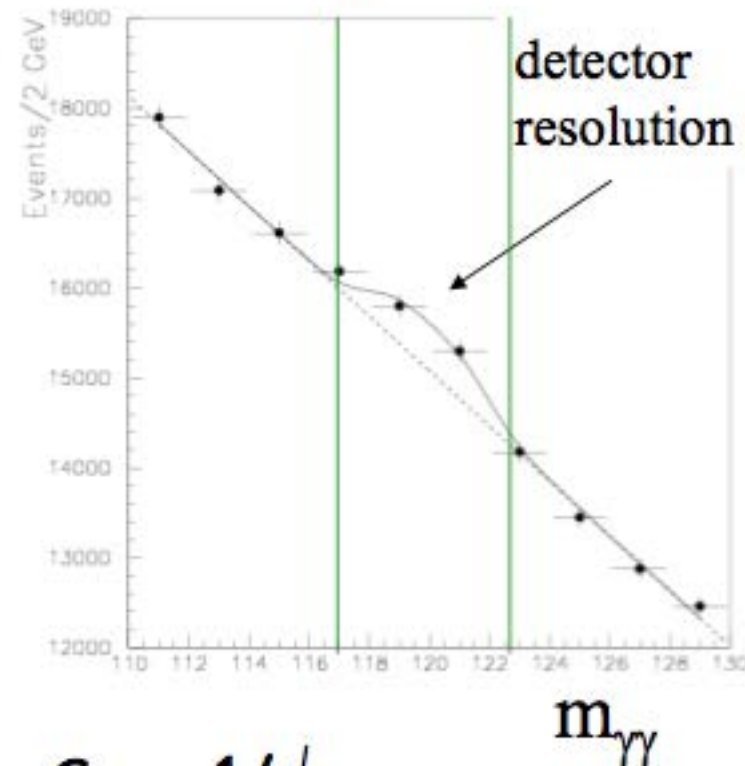
$$\approx 10^{-7}$$

● aim for high significance

→ minimize mass resolution σ_M :

→ maximize luminosity L :

→ same dependence of efficiency

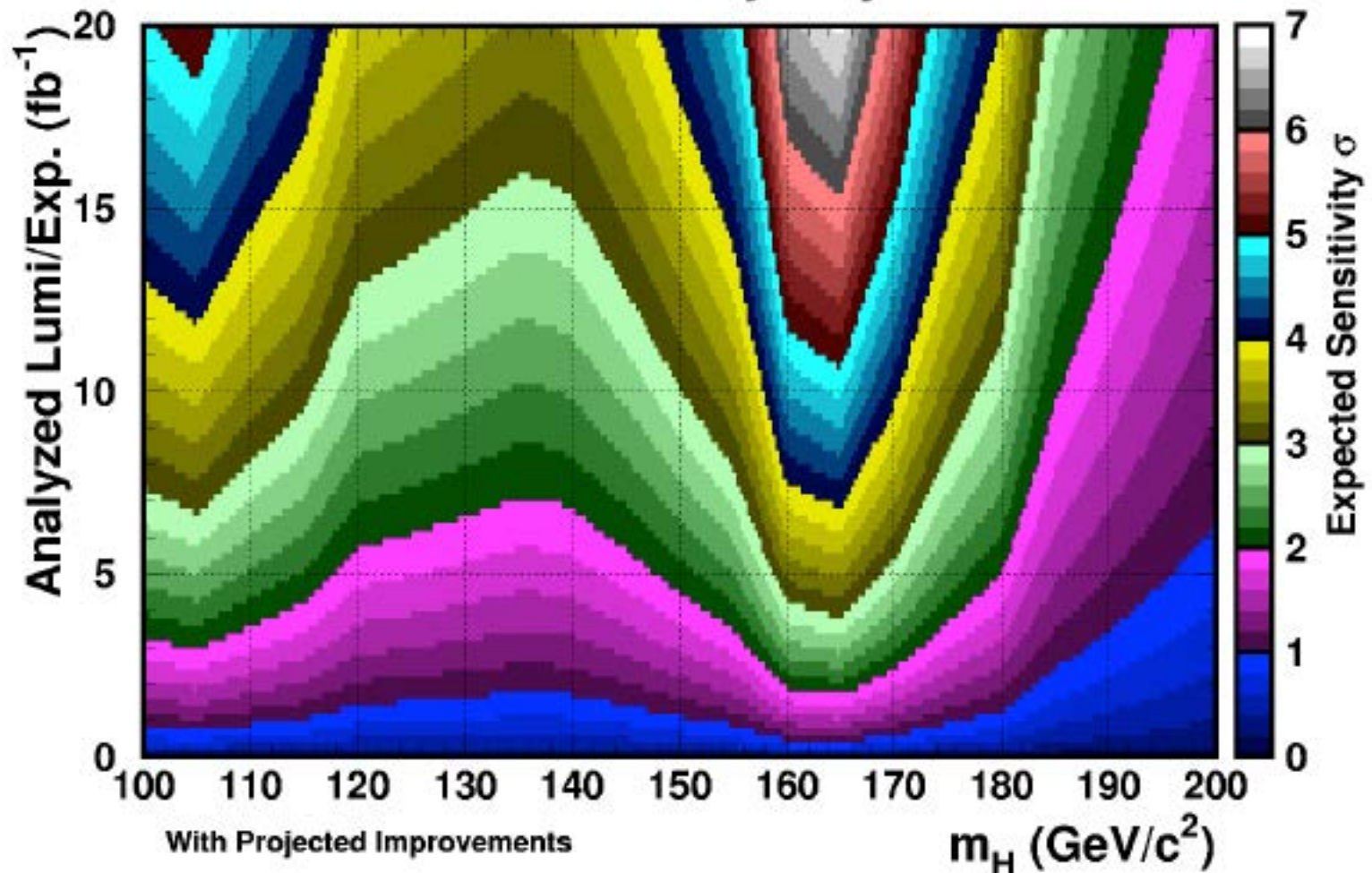


$$S \sim 1/\sqrt{\sigma_M}$$

$$S \sim \sqrt{L}$$

Expected Tevatron sensitivity

2xCDF Preliminary Projection

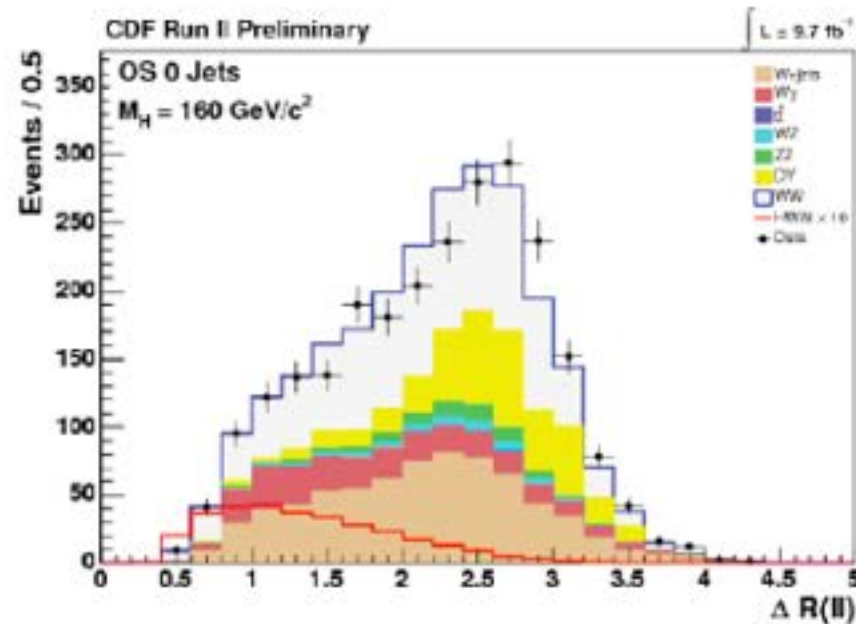
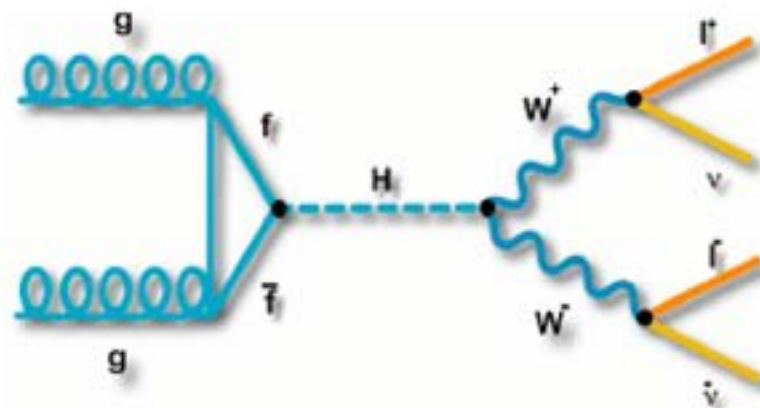


Tevatron at end-of-run (Sept. 2011): $< 12 \text{ fb}^{-1}$ / experiment

→ exclusion (3σ) expected: 100 - 117 und 150 - 179 GeV ;
5 σ discovery possible to be reached at 160 - 167 GeV .

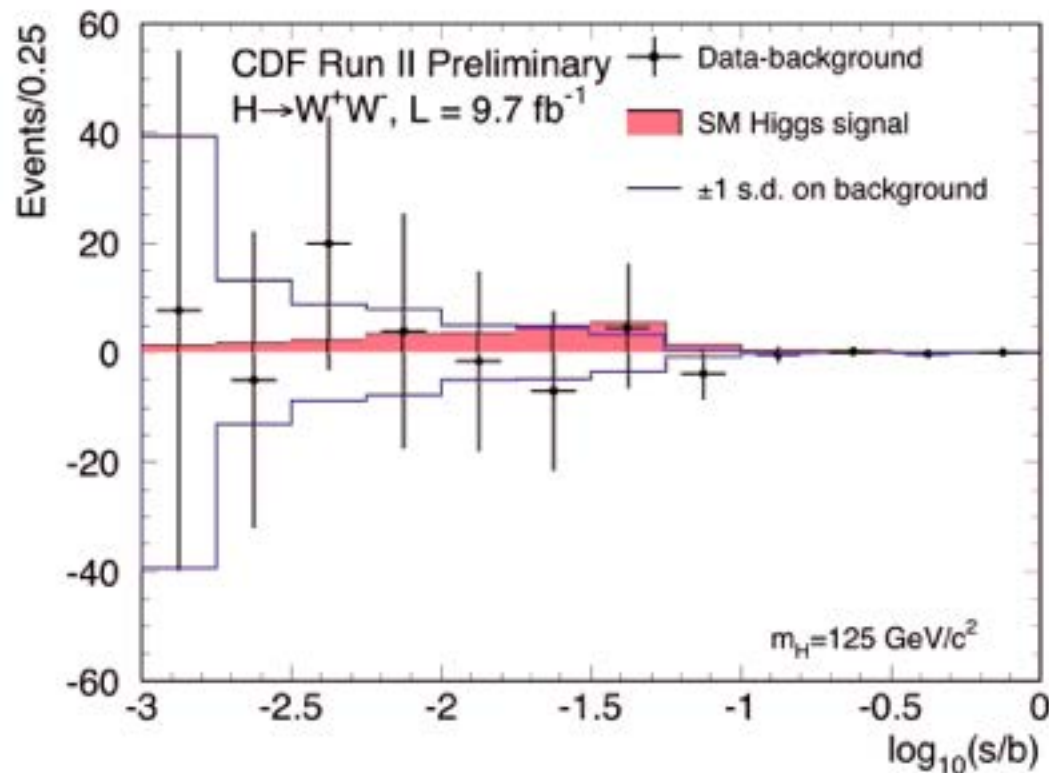
$H \rightarrow WW \rightarrow l\nu l\nu$

- Basic event selection is two reconstructed leptons and missing E_T
- Presence of two neutrinos in final state prevents complete Higgs mass reconstruction
- Separate potential signal from large backgrounds using kinematic event information



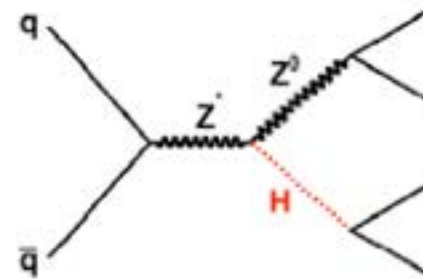
$H \rightarrow WW \rightarrow l\nu l\nu$

- Results from thirteen independent search samples are combined to obtain the best possible sensitivity
- No significant, observed excesses in data above predicted SM background contributions

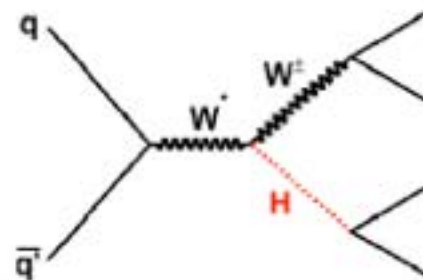


H → bb

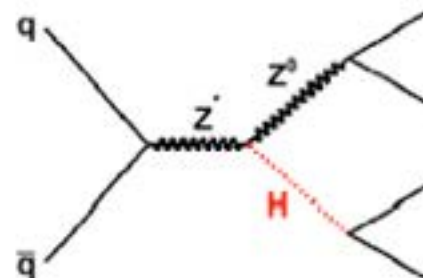
- Tevatron searches in this decay mode are still the world's most sensitive
- Basic event selection is 0, 1, or 2 leptons and/or missing E_T plus two high E_T jets
- Challenge is separating the small number of potential signal events from the much larger SM background contributions



$ZH \rightarrow \nu\bar{\nu}bb$

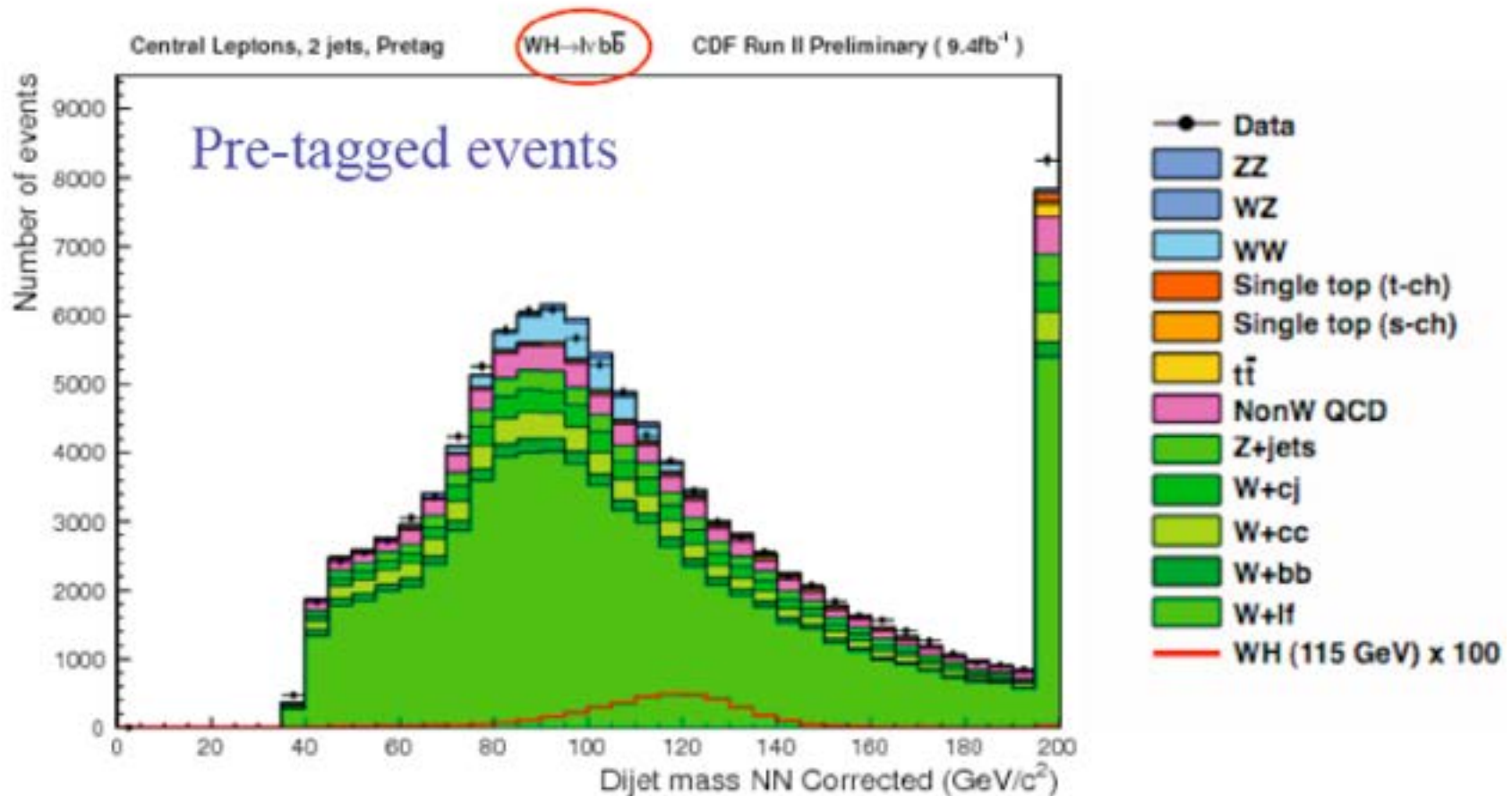


$WH \rightarrow l\bar{l}bb$



$ZH \rightarrow l\bar{l}bb$

H → bb



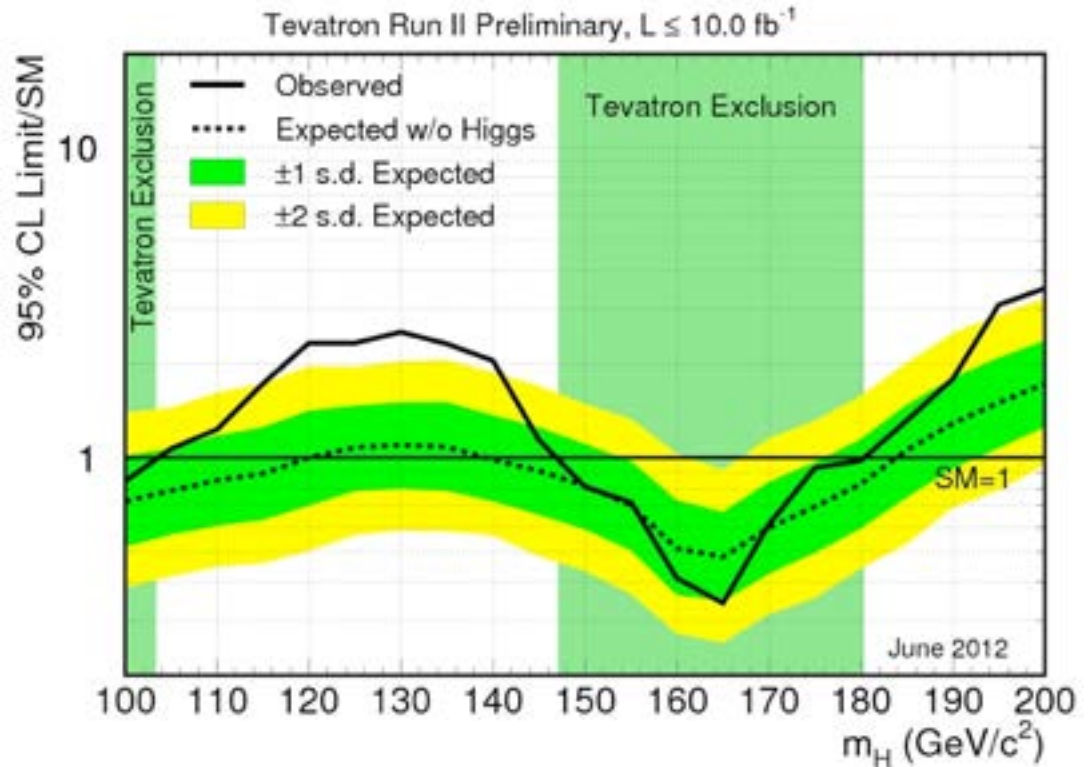
Focus on Increasing lepton reconstruction and selection efficiencies

Improving the efficiency for tagging bottom quark jets

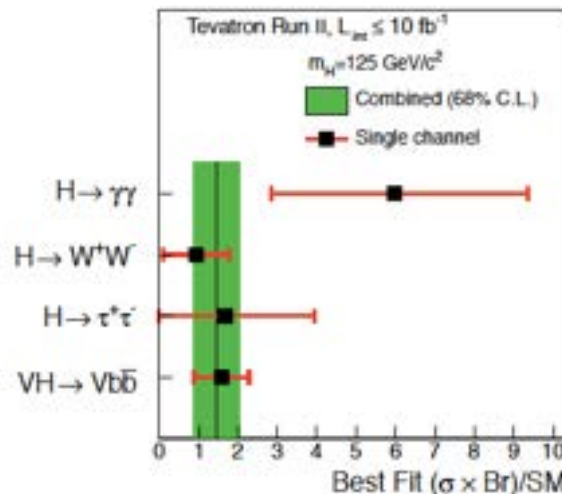
Optimizing dijet mass resolution

CDF/D0 combined conclusion (July 2012):

- SM Higgs exclusion in the range 147-180 (and 100-103) GeV @95% CL
- Expected exclusion range 139-184 GeV
- 2.5σ excess in region 115-135 GeV (3.0σ at $M_H=125$ GeV)



observed
signal strength:



Summary SM Higgs-search w/o LHC data (2012):

Precision measurements of electroweak observables, accounting for radiative corrections ($\propto \log m_H^2$):

$$m_H = 94_{-24}^{+20} \text{ GeV (68\% C.L.) and}$$

$$m_H < 171 \text{ GeV (95\% C.L.)}$$

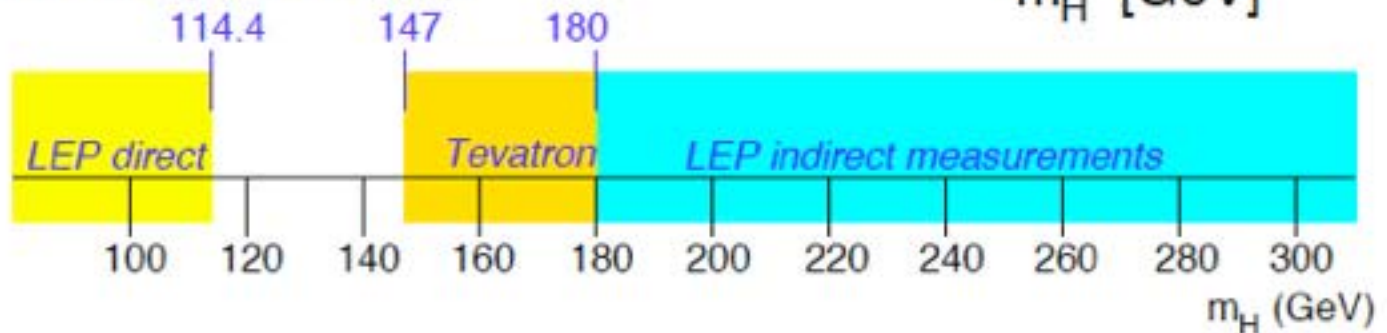
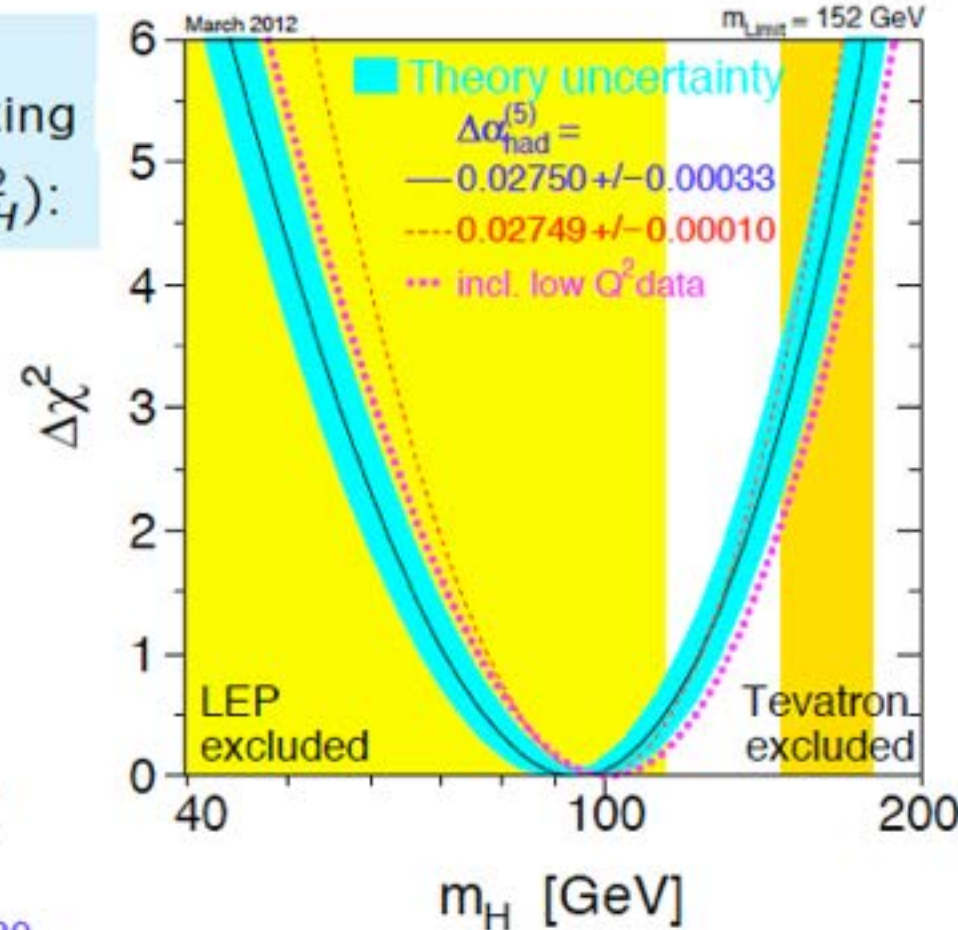
Direct searches at LEP:

$$m_H > 114.4 \text{ GeV at (95\% C.L.)}$$

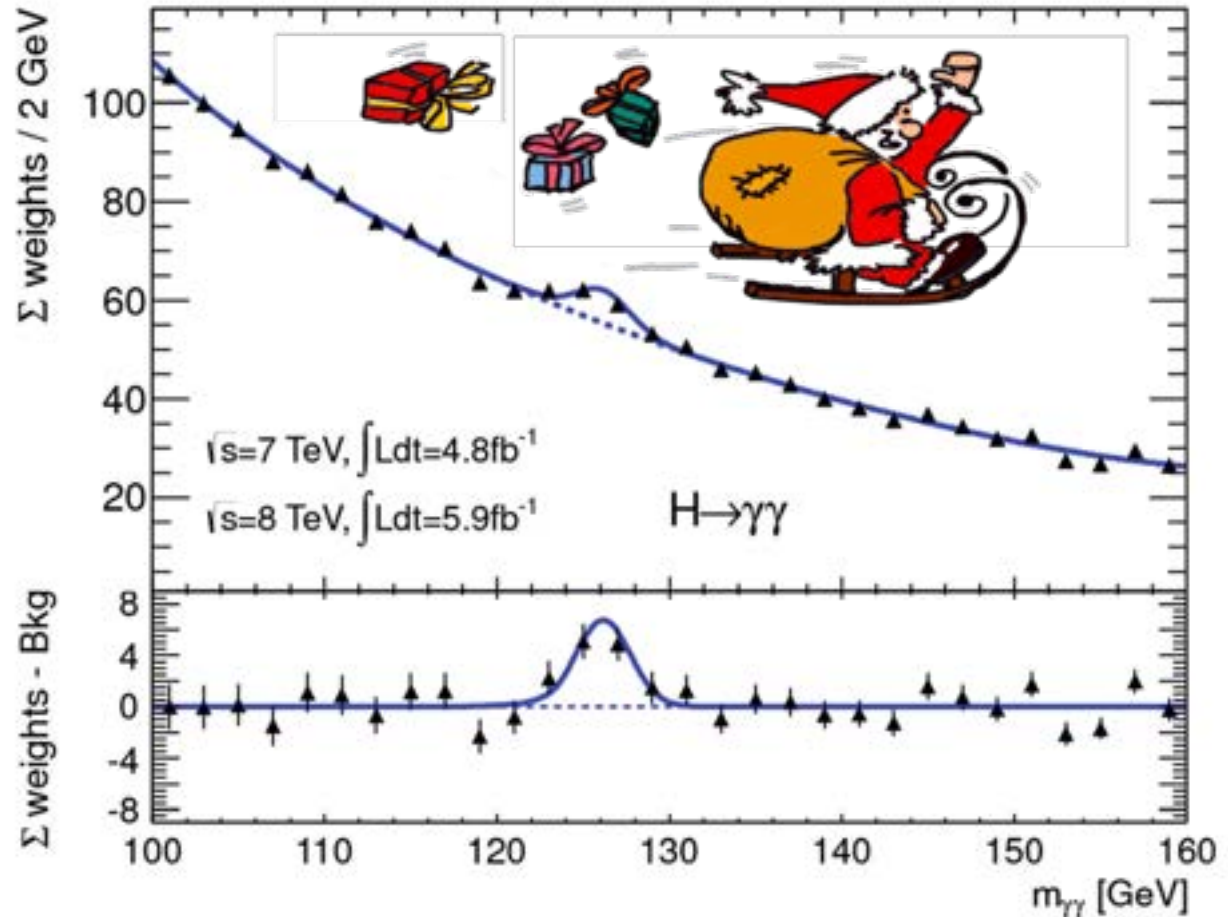
Direct searches at Tevatron:

$$m_H < 147 \text{ GeV at (95\% C.L.) and}$$

$$m_H > 180 \text{ GeV at (95\% C.L.)}$$



Higgs-search and discovery at LHC (preview):



(see next lecture; 14.12.2015)

Literatur:

- **Higgs Particle: The Origin of Mass.** [Yasuhiro Okada](#) ([KEK, Tsukuba](#) & [Tsukuba, Graduate U. Adv. Studies](#)) . KEK-TH-1171, Aug 2007. 13pp. e-Print: **arXiv:0708.2016** [hep-ph]
- **Higgs Boson Properties in the Standard Model and its Supersymmetric Extensions.** [John R. Ellis](#) ([CERN](#)) , [Giovanni Ridolfi](#) ([INFN, Genoa](#) & [Genoa U.](#)) , [Fabio Zwirner](#) ([Padua U.](#) & [INFN, Padua](#)) . CERN-PH-TH-2007-012, Feb 2007. Published in **Comptes Rendus Physique 8:999-1012,2007**. e-Print: **hep-ph/0702114**
- **The Tevatron Higgs exclusion limits and theoretical uncertainties: a critical appraisal.** [J. Baglio](#), [A. Djouadi](#), [S. Ferrag](#), [R.M. Godbole](#), . CERN-PH-TH-2010-315, LPT-ORSAY-10-107, Jan 2011. 4pp. [Temporary entry](#) e-Print: **arXiv:1101.1832** [hep-ph]
- Updated Combination of CDF and D0 Searches for Standard Model Higgs Boson Production with up to 10.0 fb⁻¹ of Data, <http://arxiv.org/abs/1207.0449>.