Lecture 9:

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 renormalizabilty of the theories

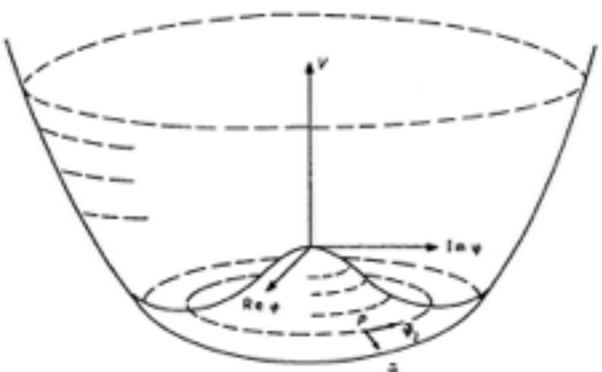
- Englert, Brout and Higgs (1964): spontaneous symmetry breaking (generates mass, keeps renormalizabilty):

- introduction of complex SU(2) doublets of scalar fields with a potential of $V(\varphi) = \lambda\,(\phi^+\phi)^2 - \mu^2\,\phi^+\phi$; with $\lambda, \mu^2 > 0$;

$$\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

- 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. –> 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

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

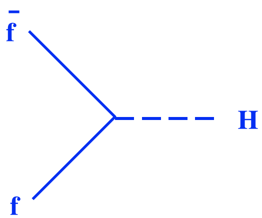
$$M_Z = M_W / \cos\theta_w \qquad (g = e/\sin\theta_w)$$

$$M_\gamma = 0$$

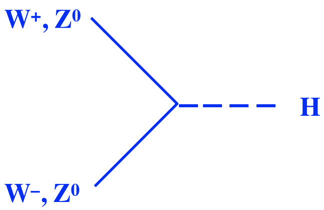
$$M_H = 2\mu^2 = 2\lambda v^2$$

- 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:



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



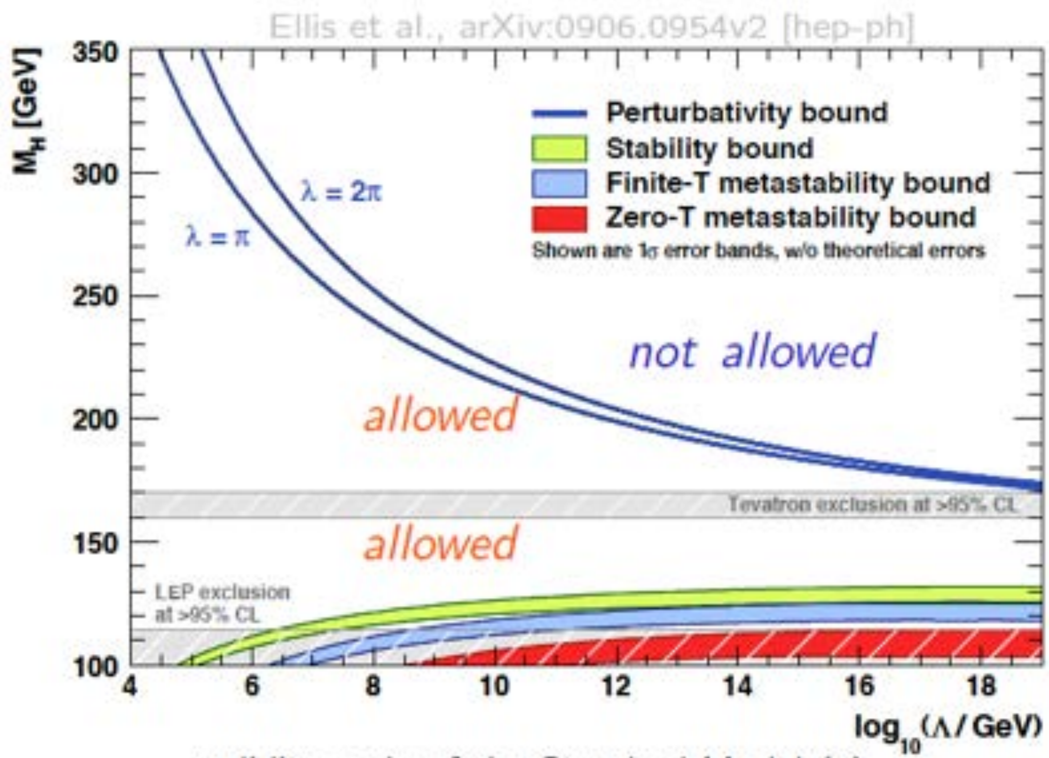
$$g_{WWH} = \frac{e\, M_w}{\sin\theta_w}$$

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

theoretical basis and expectations

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

- upper bounds: perturbativity
- lower bounds: vacuum stability



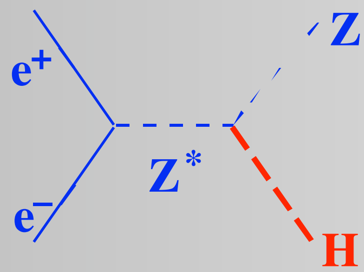
validity scale of the Standard Model (Λ)

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

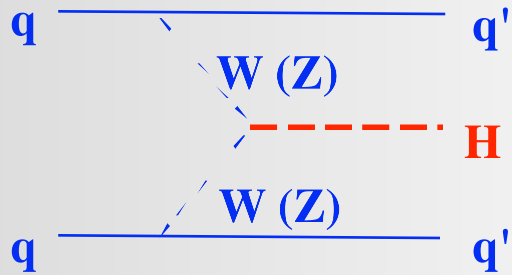
n.b.: if SM is valid up to $\Lambda = O(M_{Planck})$
then $M_H \sim 125 \ldots 180$ GeV

Λ: energy scale up to which SM is valid

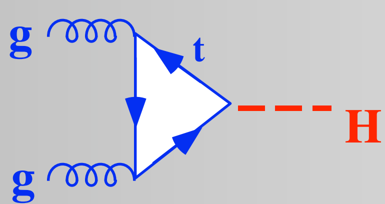
Higgs: production and decays



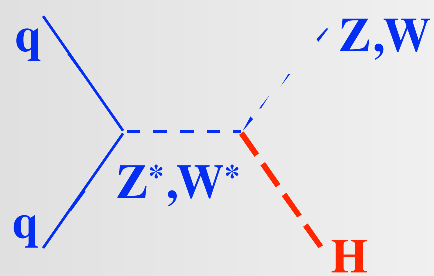
Higgs-radiation



W- (Z-) fusion



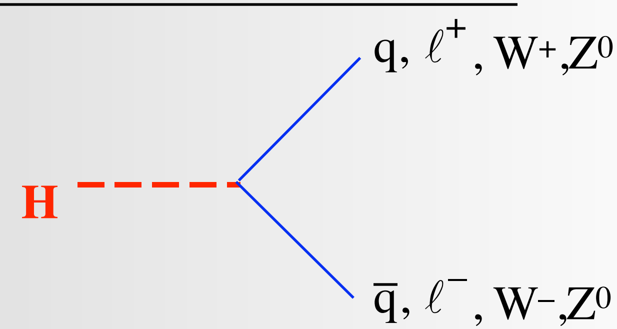
Gluon - Fusion



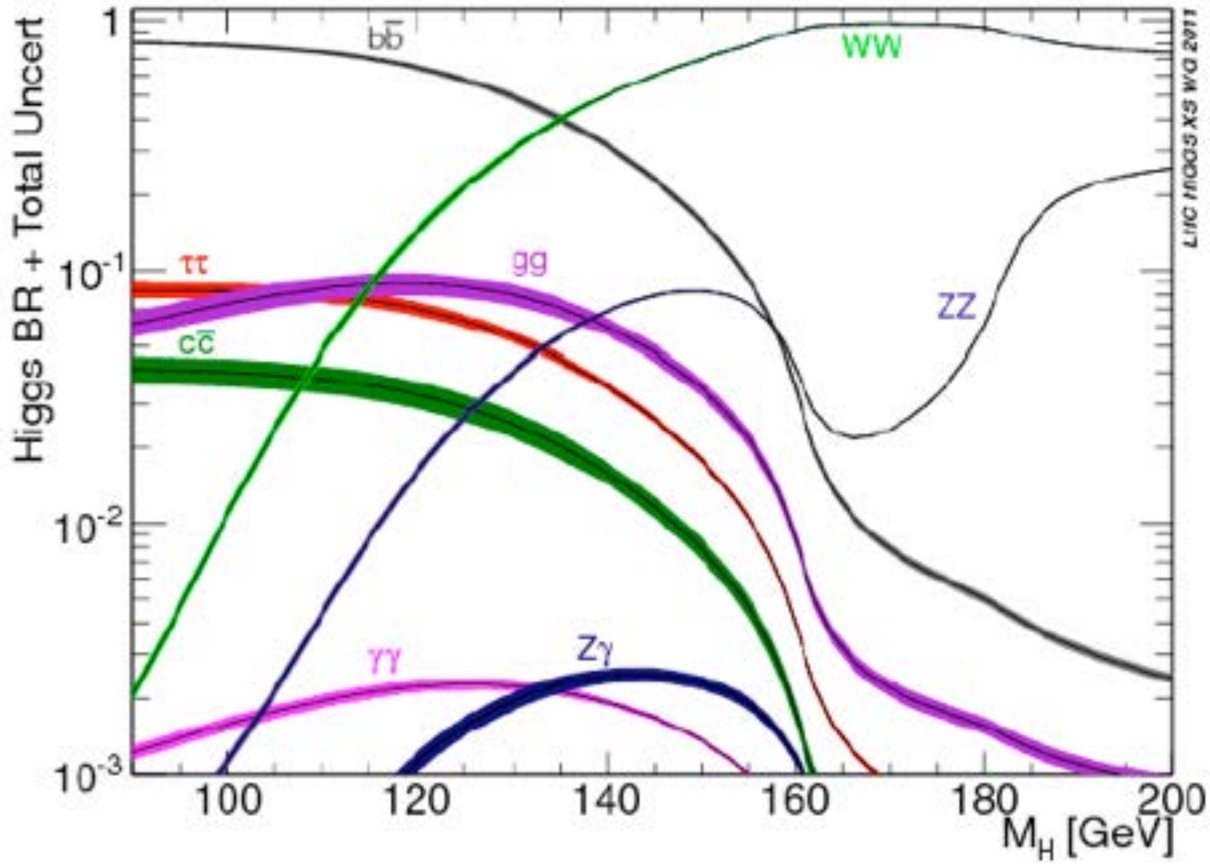
Higgs-radiation („associate production“)

Higgs-decay:

predominantly into heaviest, kinematically accessible pair of leptons or bosons



Higgs: decays



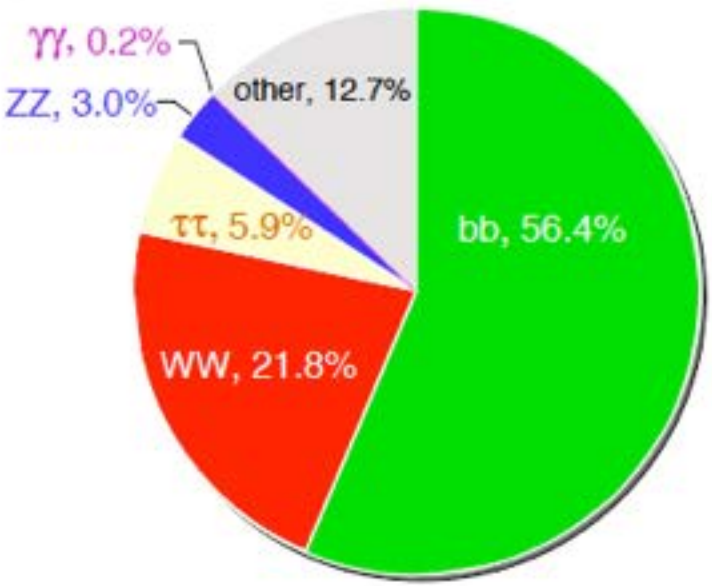
$Br(H \rightarrow \gamma\gamma) \sim 10^{-3}$

M_H < ~135 GeV: dominanter Zerfallskanal H –> b b

M_H > ~135 GeV: dominanter Zerfallskanal H –> W^+W^-

Higgs: decays

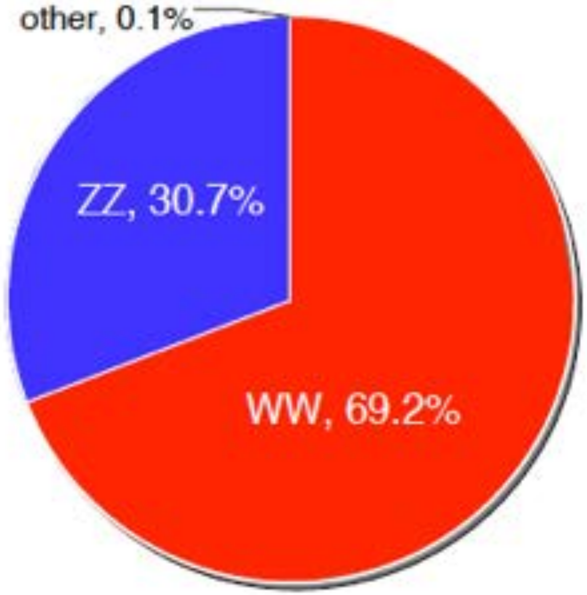
Low mass region, e.g. $m_H = 125$ GeV:



Ordered by the sensitivity to the signal:

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

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

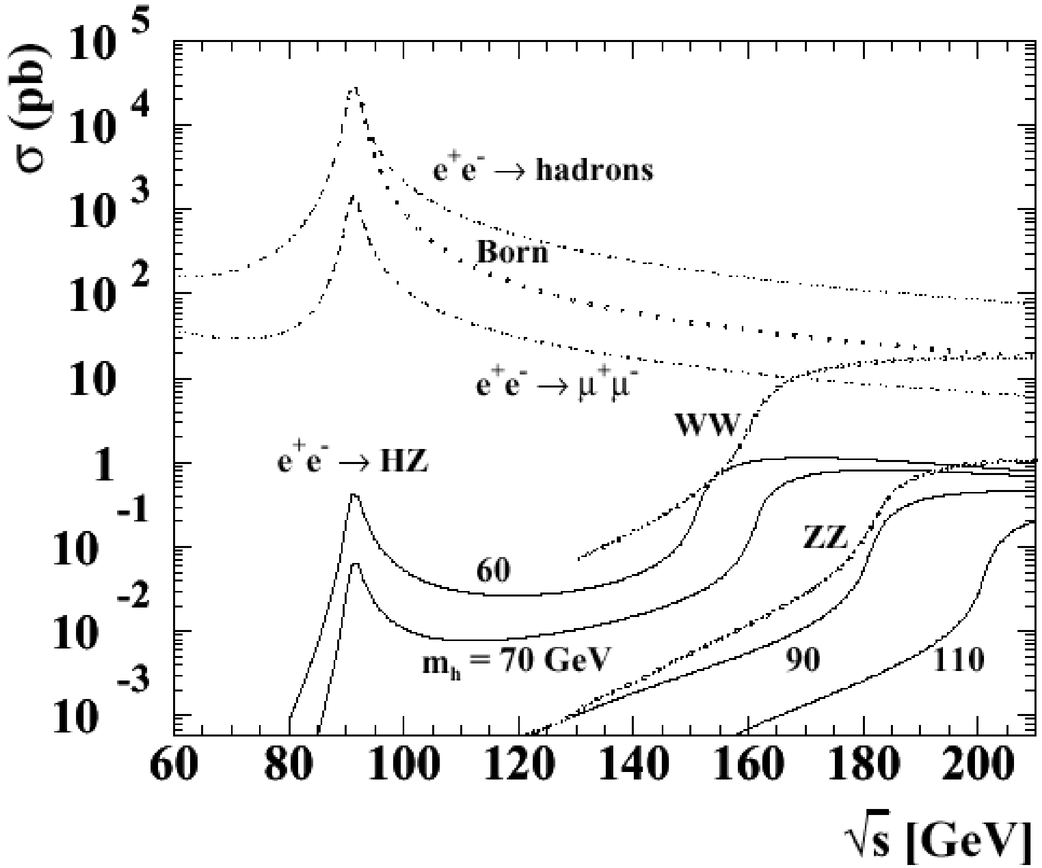


Ordered by the sensitivity to the signal:

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

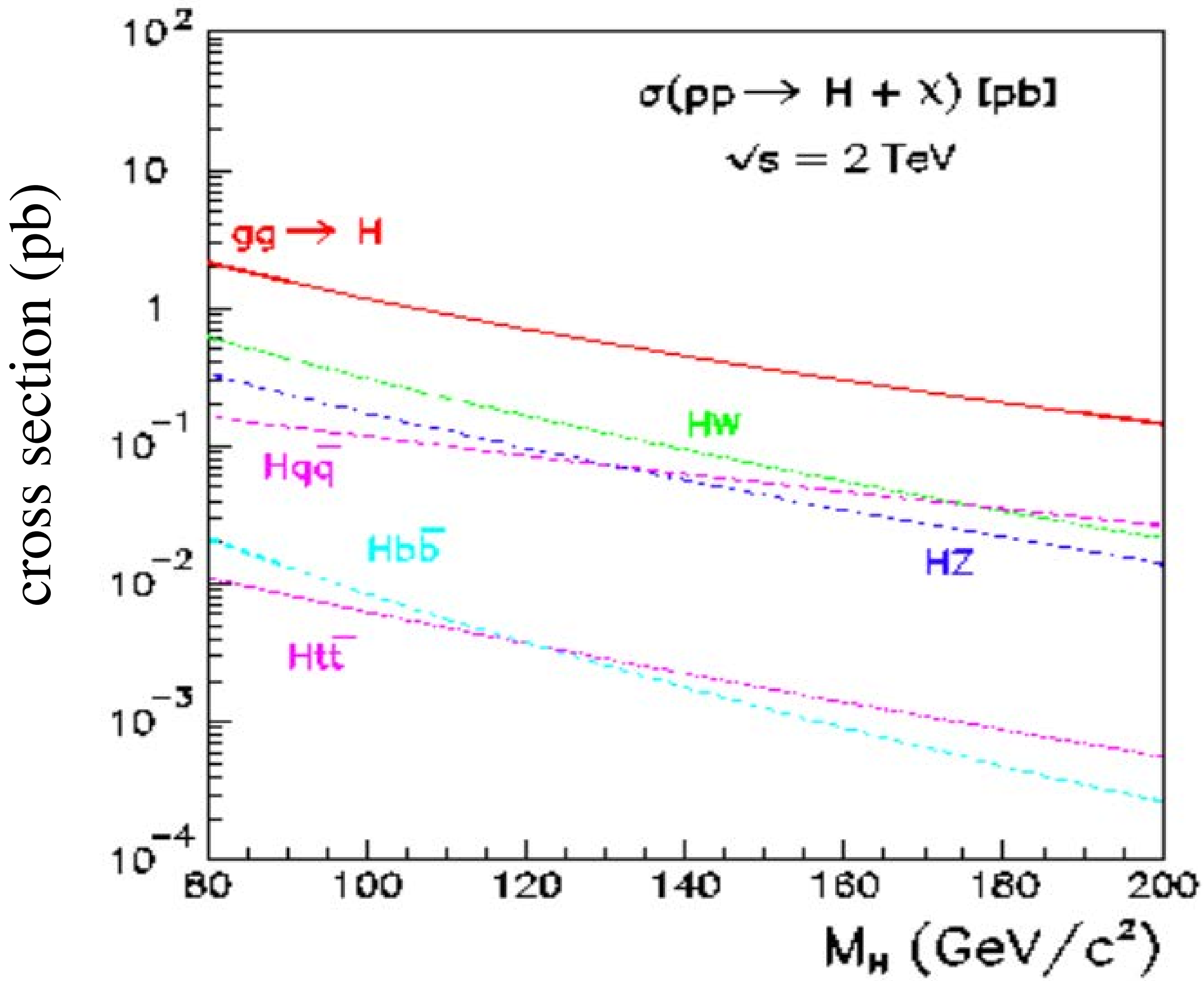
Higgs: production

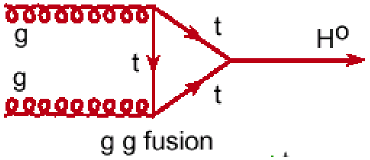
e⁺e⁻ annihilation

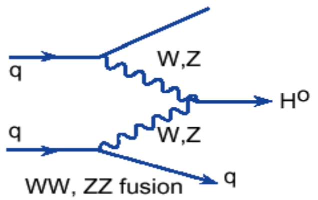


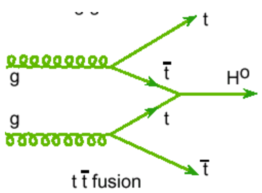
Higgs: production

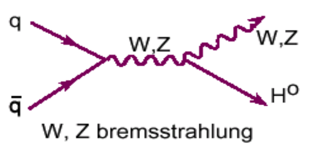
Standard Model Higgs Boson @ Tevatron





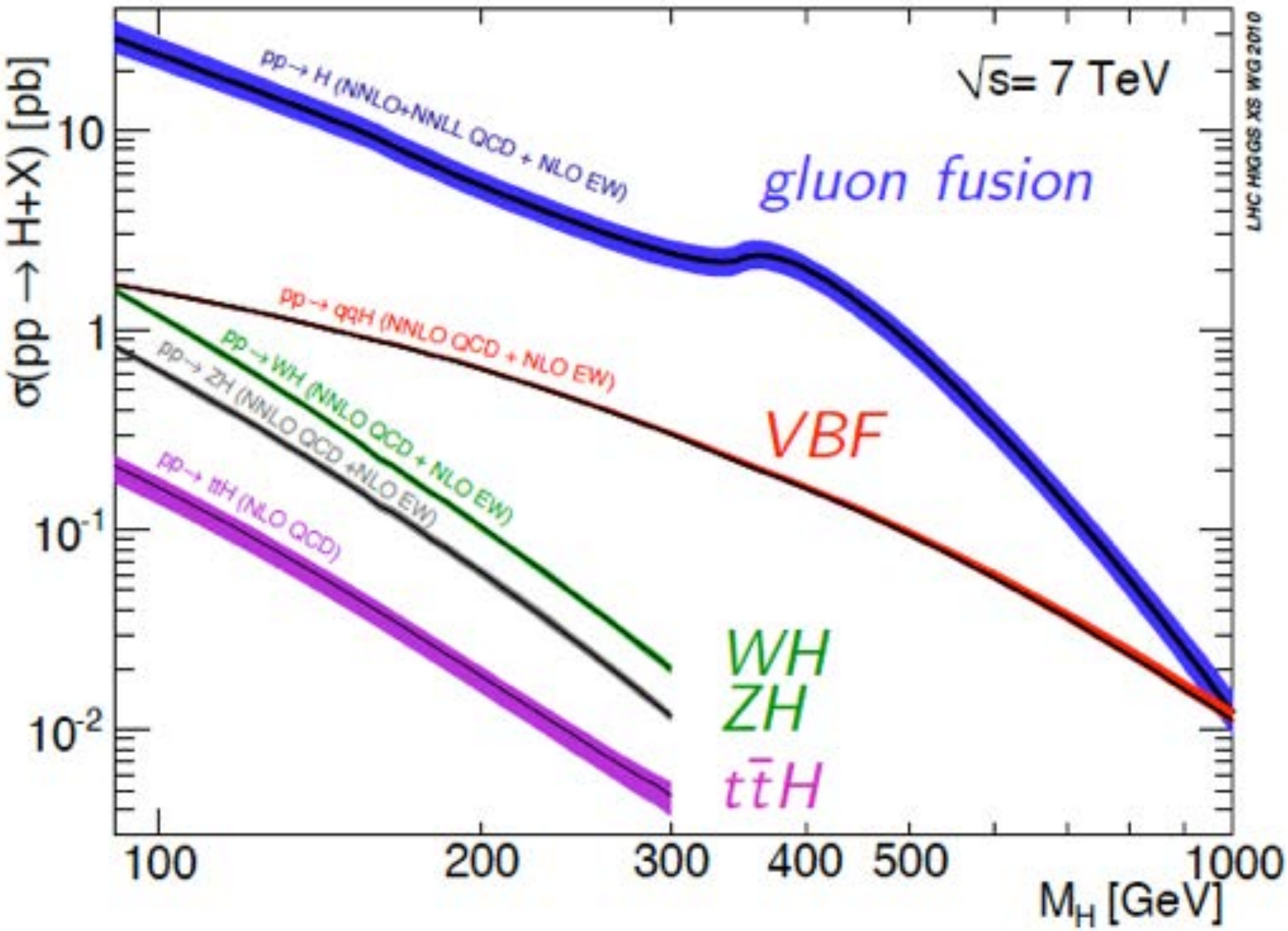


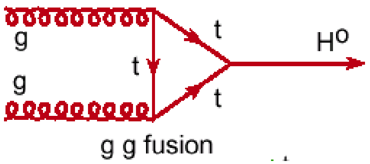


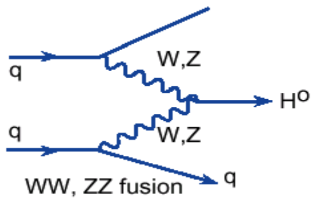


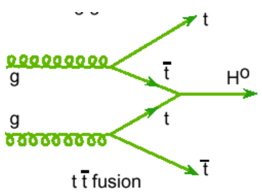
Higgs: production

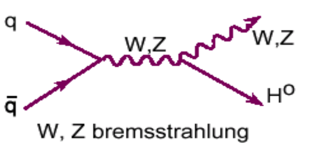
Standard Model Higgs Boson @ LHC (7 TeV)





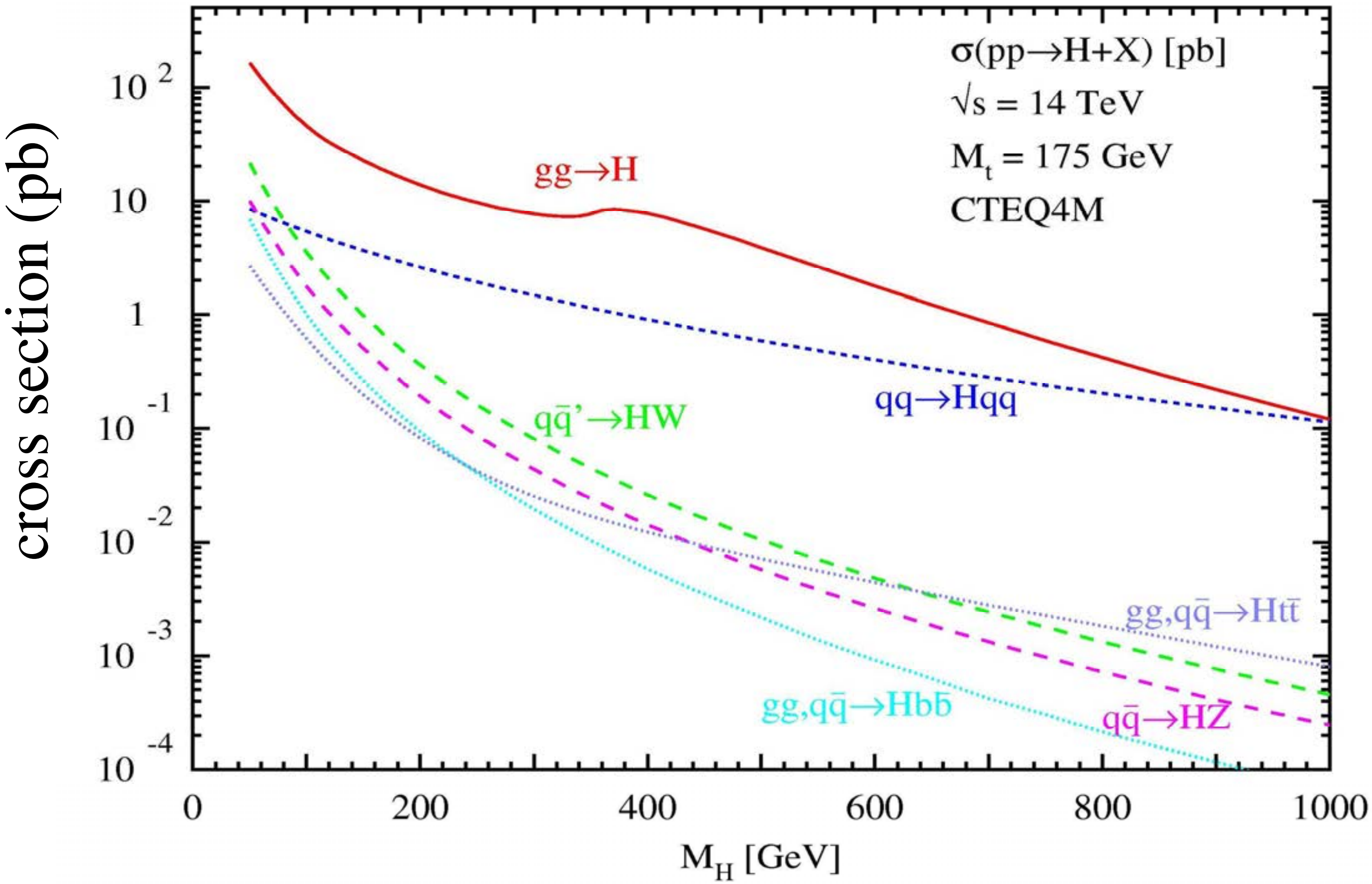


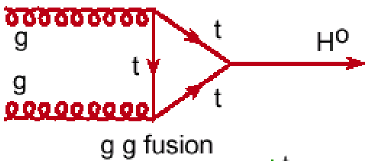


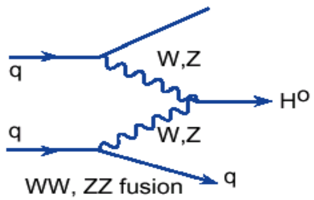


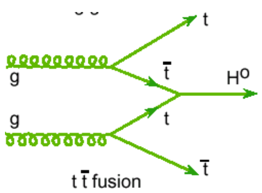
Higgs: production

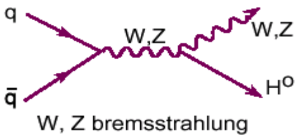
Standard Model Higgs Boson @ LHC (14 TeV)



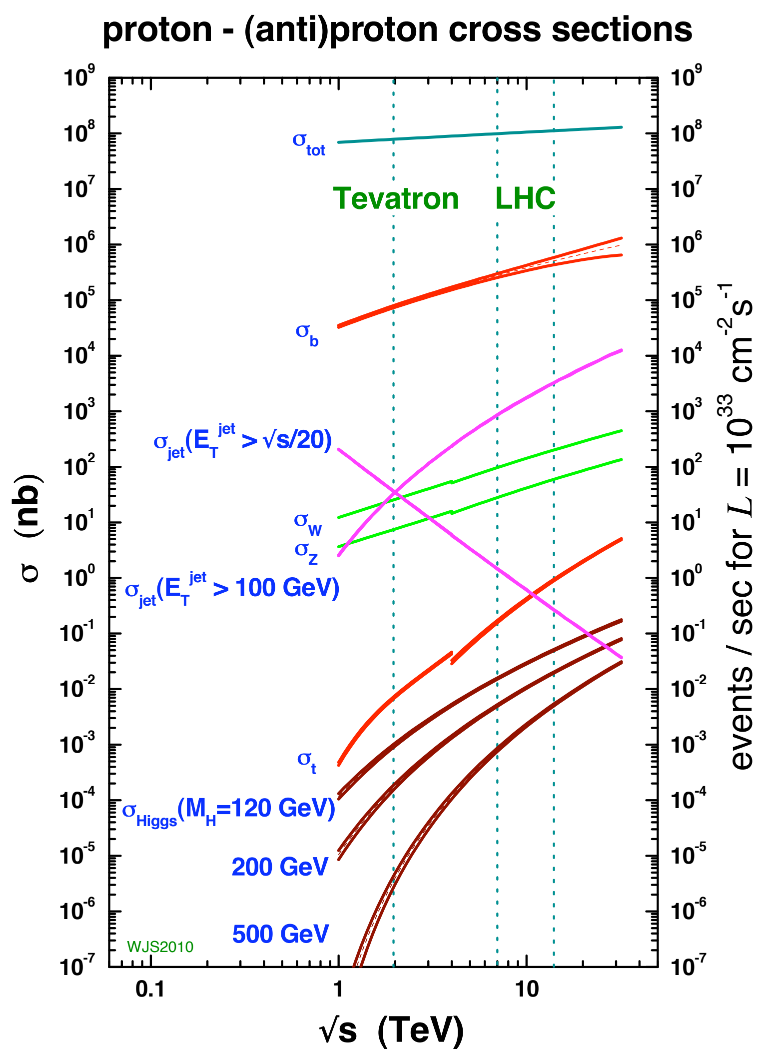




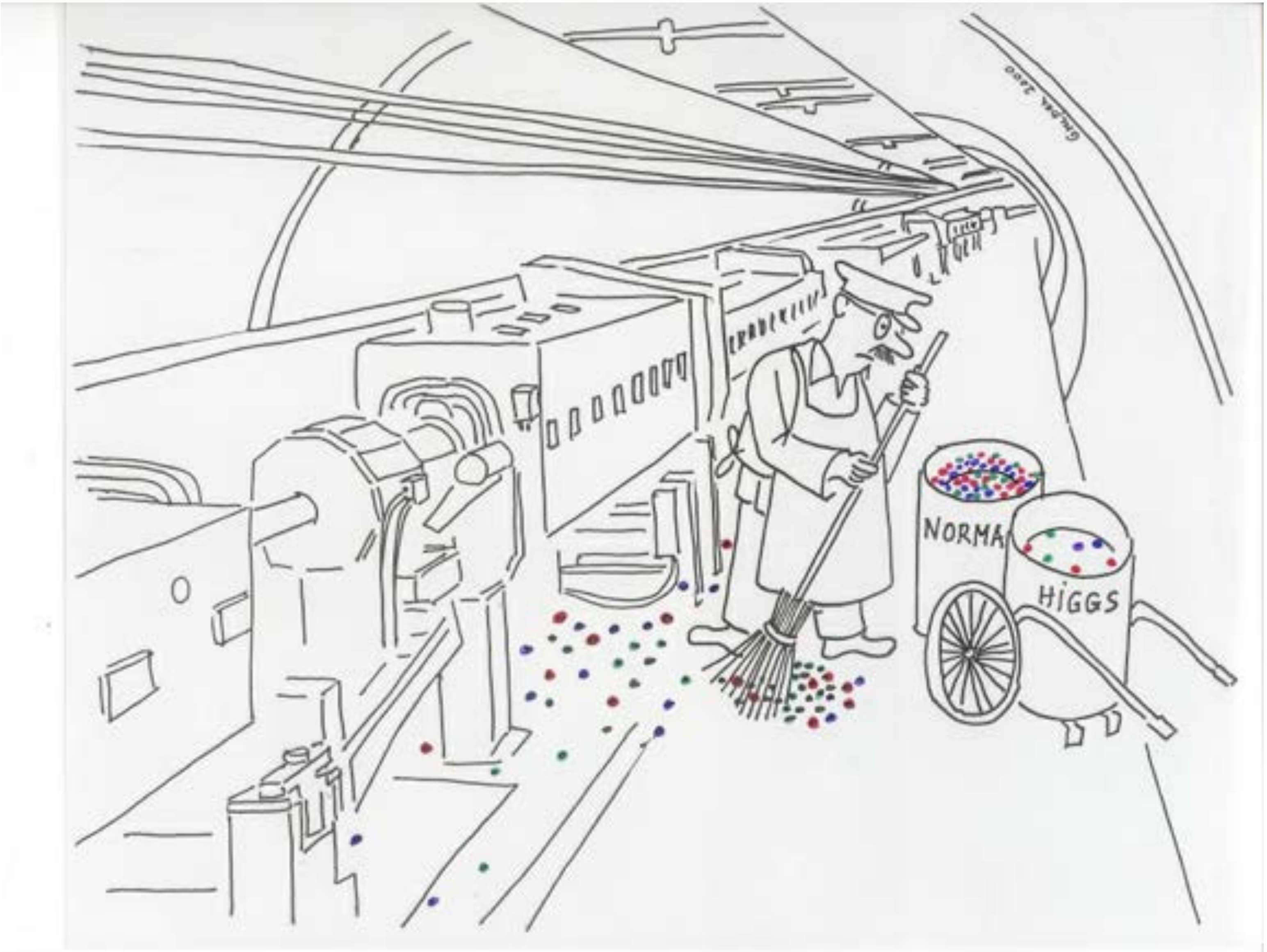




Higgs production cross-sections

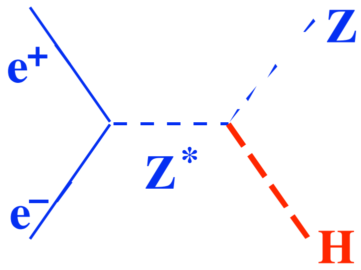


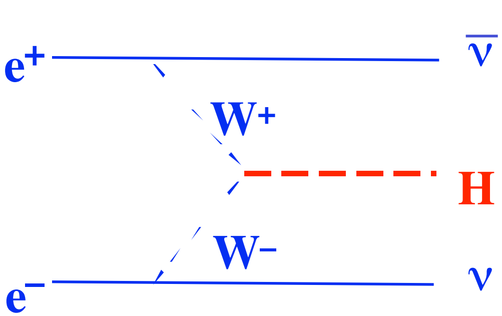
Higgs search



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

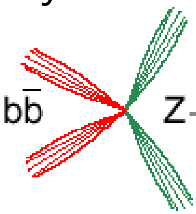
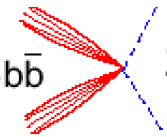
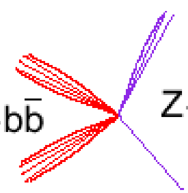
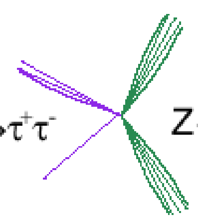
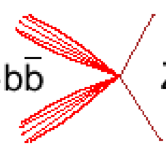
production:





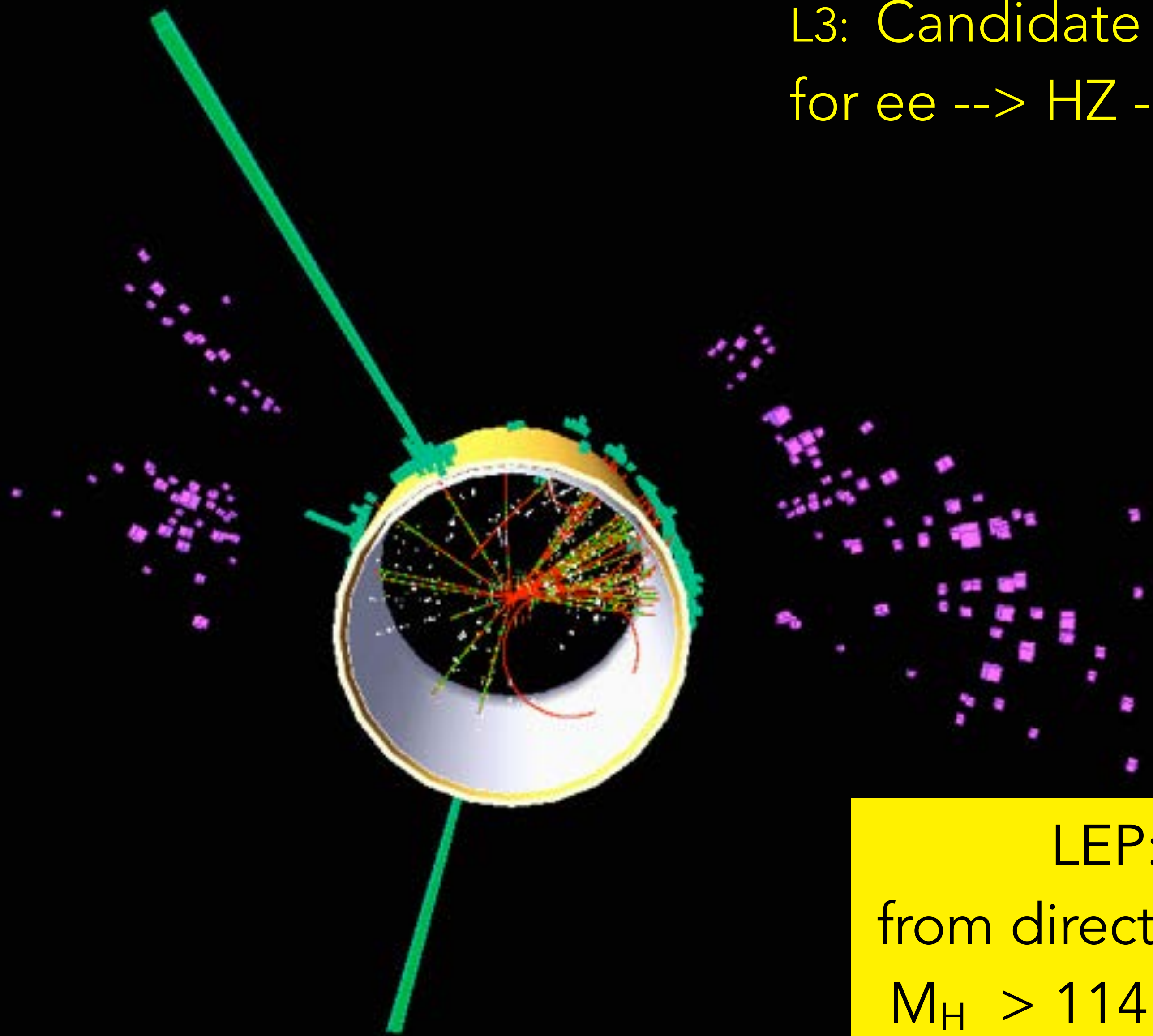
decay channel (e+e– –> HZ):

background:

decay		channel	fraction	background
$H \to b\bar{b}$, $Z \to q\bar{q}$		**4-Jet-Kanal**	51%	$WW \to qqqq, ZZ \to bbqq$ QCD 4jets
$H \to b\bar{b}$, $Z \to \nu\bar{\nu}$		**Neutrino-Kanal**	15%	$WW \to qql\nu, ZZ \to bb\nu\nu$
$H \to b\bar{b}$, $Z \to \tau^+\tau^-$		**Tau-Kanal**	2.4%	$WW \to qq\tau\nu, ZZ \to qq\tau\tau$ QCD (low-mult. jets)
$H \to \tau^+\tau^-$, $Z \to q\bar{q}$			5.1%	
$H \to b\bar{b}$, $Z \to e^+e^-$, $\mu^+\mu^-$		**Lepton-Kanal**	4.9%	$ZZ \to bbll$

search includes ~ 80% of all final states with ~ 40 - 50% selection efficiency

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



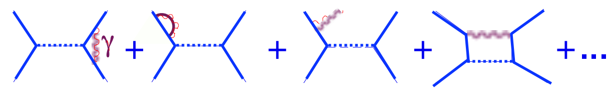
L3: Candidate event for ee --> HZ --> eeqq

LEP:
from direct search
M_H > 114.1 GeV

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

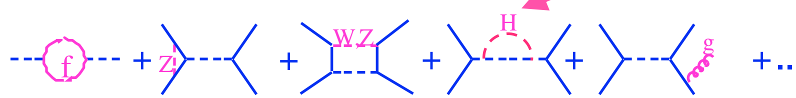
radiation corrections in SM:

photonic corrections:



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

non-photonic corrections:



corrections ~ 10%, selection independent;
can be absorbed into running coupling constants:

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

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

insertion of running couplings into "Born"-approximation :

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

cross sections) become dependent on:

- M_t
- M_H
- α_s

==> indirect determination (fit) of M_t , M_H , und $\boldsymbol{\alpha}_s$ from combination of all available electro-weak observables
(differential cross sections, partial decay widths, forward-backward asymmetries, τ-polarisation, …)

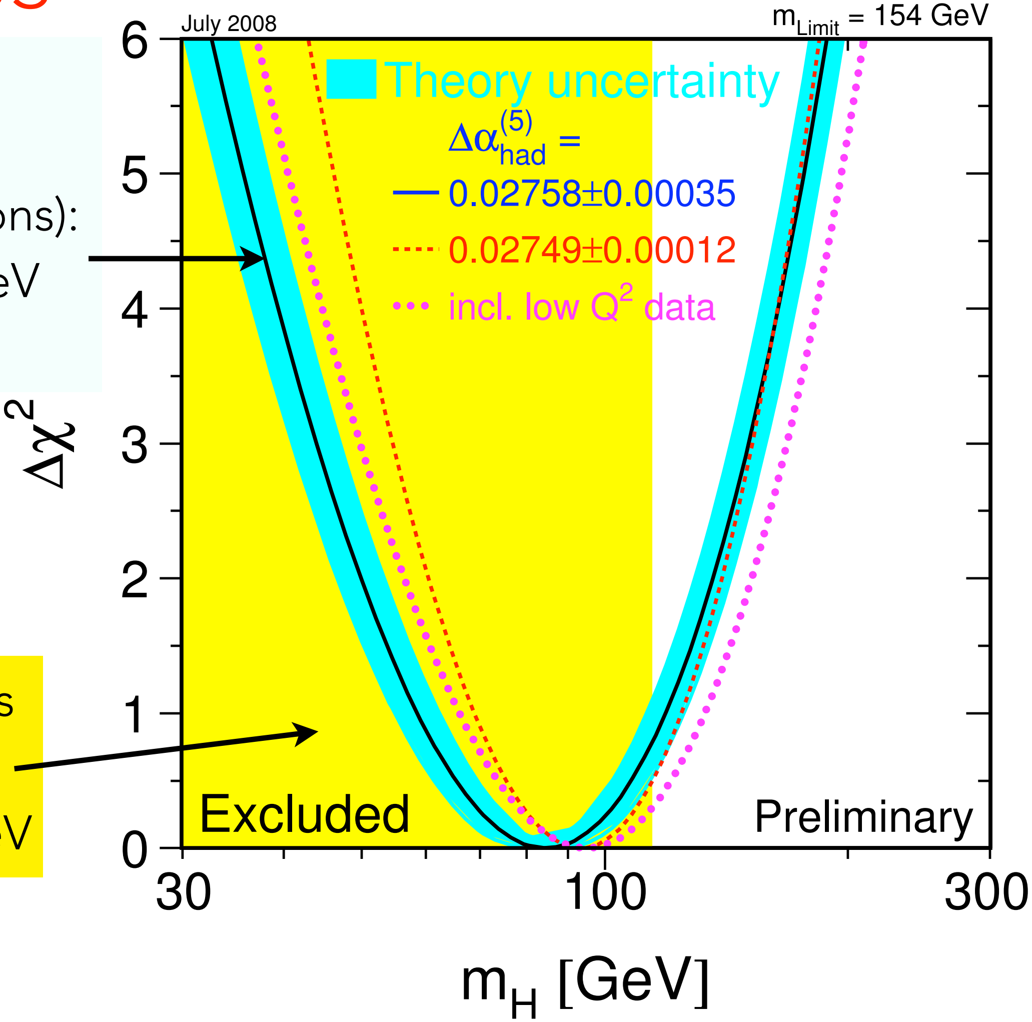
$g_{a,f} = I_{3,f}$ (3. Komponente schw. Isospin; $= \pm 1/2$)

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

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

indirect (adjusting radiative corrections): $M_H = 84^{+34}_{-26}$ GeV (68% c.l.)

direct searches (exclusion) $M_H > 114.1$ GeV

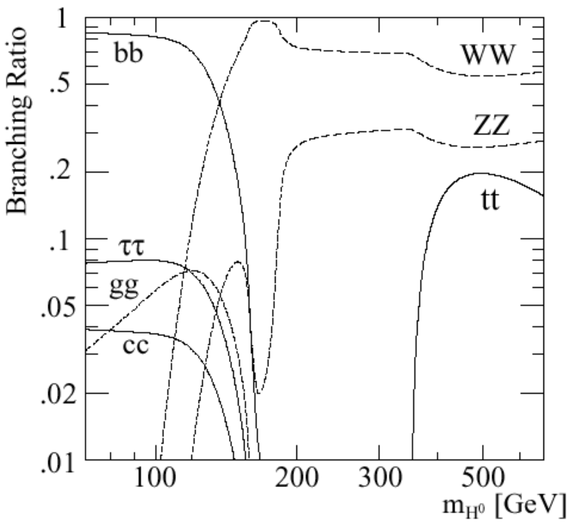


114.1 GeV < M_H < 154 GeV (1-sided 95% c.l.)

M_H < 185 GeV (incl. 114 GeV lower limit)

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

Higgs-Search at Hadron colliders: Tevatron



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

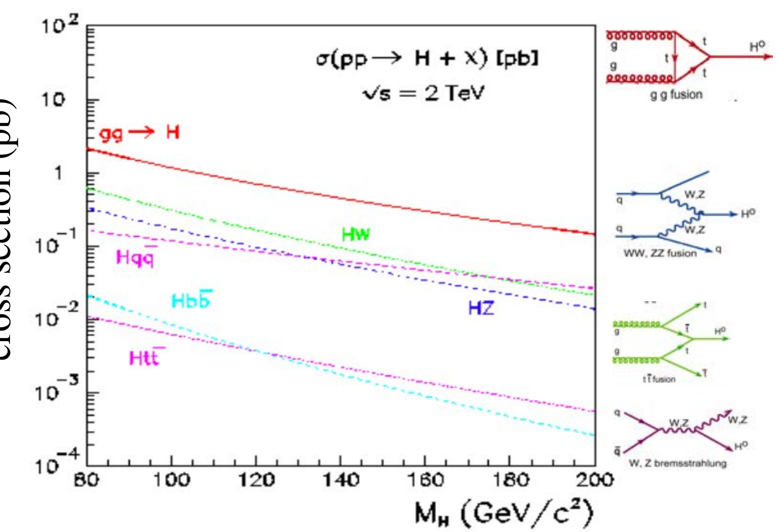
M_H > ~135 GeV: dominant decay H –> W^+W^-

Hadroncollider: $\bar{b}$ b background from QCD processes dominates; unreducible;
=> g g –> H –> b b cannot be used

therefore:

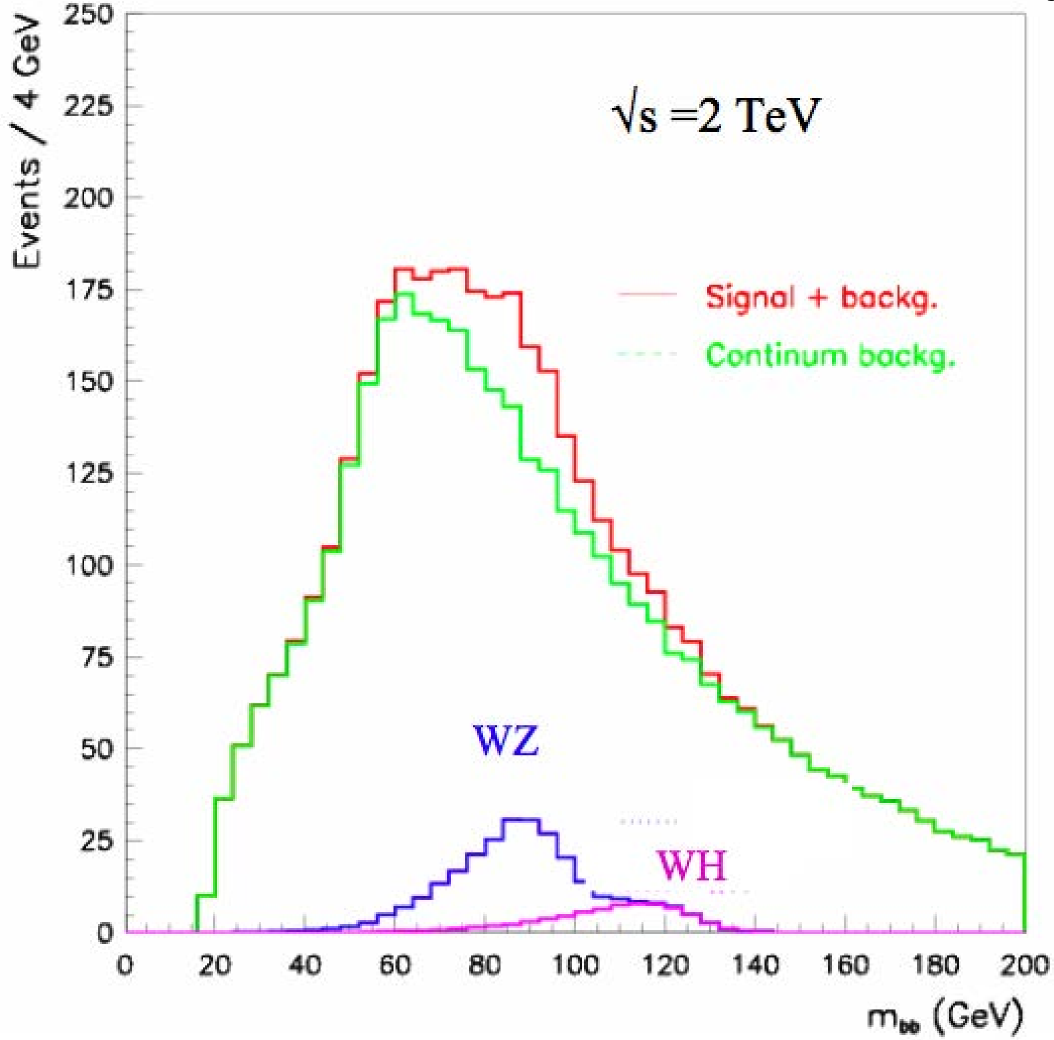
focus on associate production (ZH, WH) and analyse
e.g. Z –> l^+l^- ; H –> bb

ττ decay suitable for all production channels

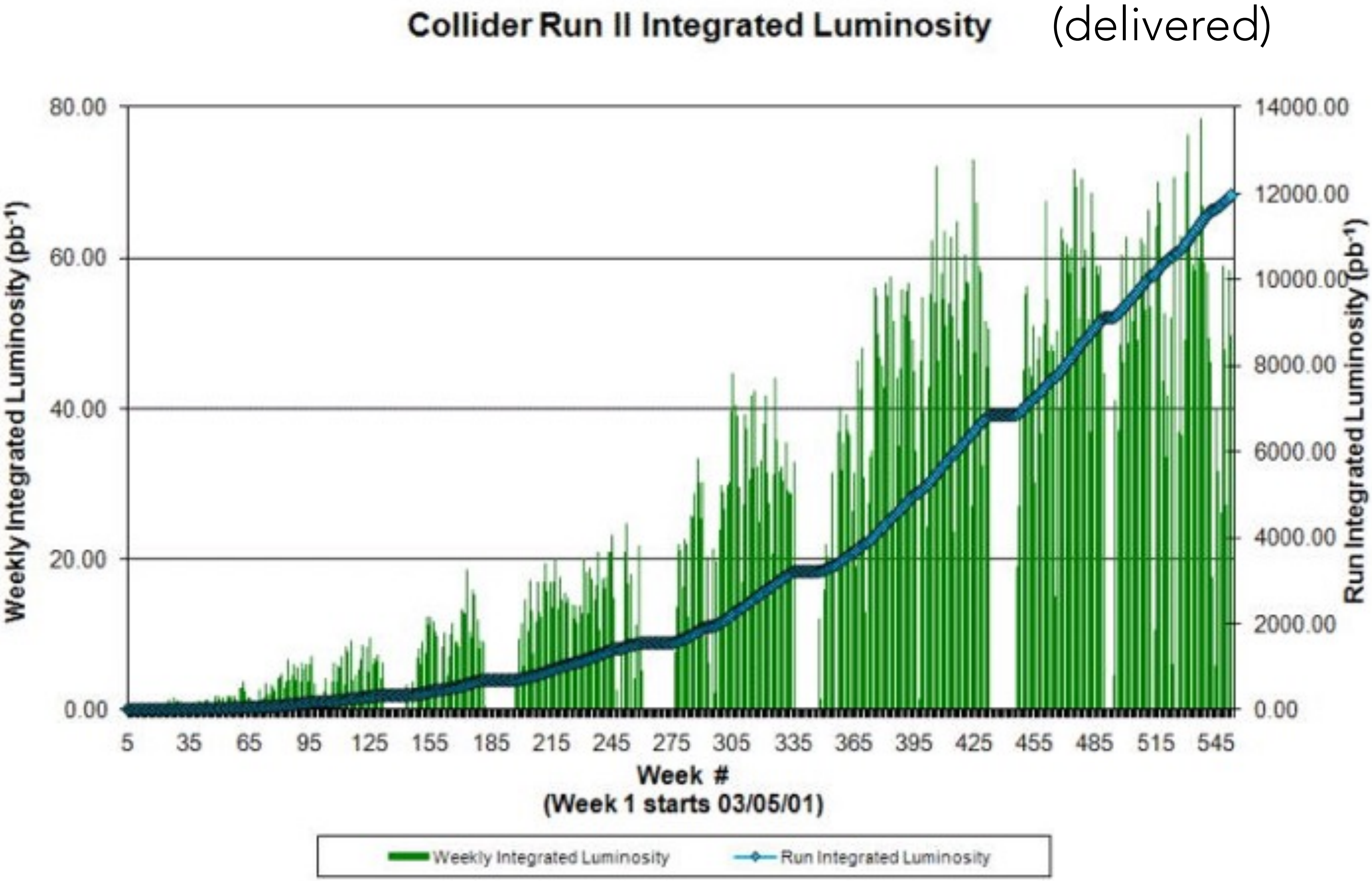


Higgs-Search at Hadron colliders: Tevatron

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



very difficult measurement; background must be known extremely well!



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

definition of: significance of signal

- **definition of significance**

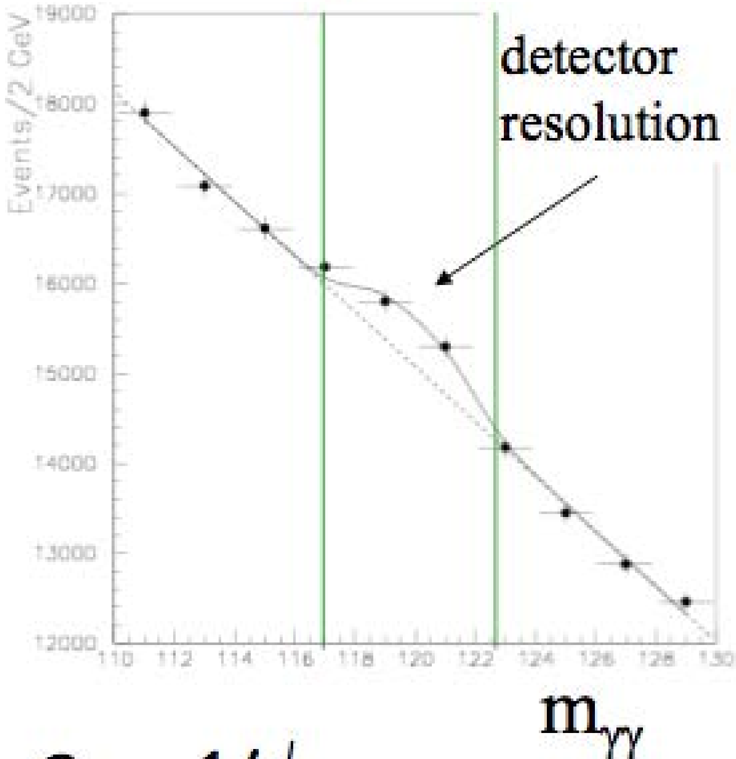
$$S = \frac{N_S}{\sqrt{N_B}}$$

  - N_S: number of signal events
  - N_B: number of background events

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

- **discovery: S > 5**

→ probability to observe background fluctuation: $\approx 10^{-7}$



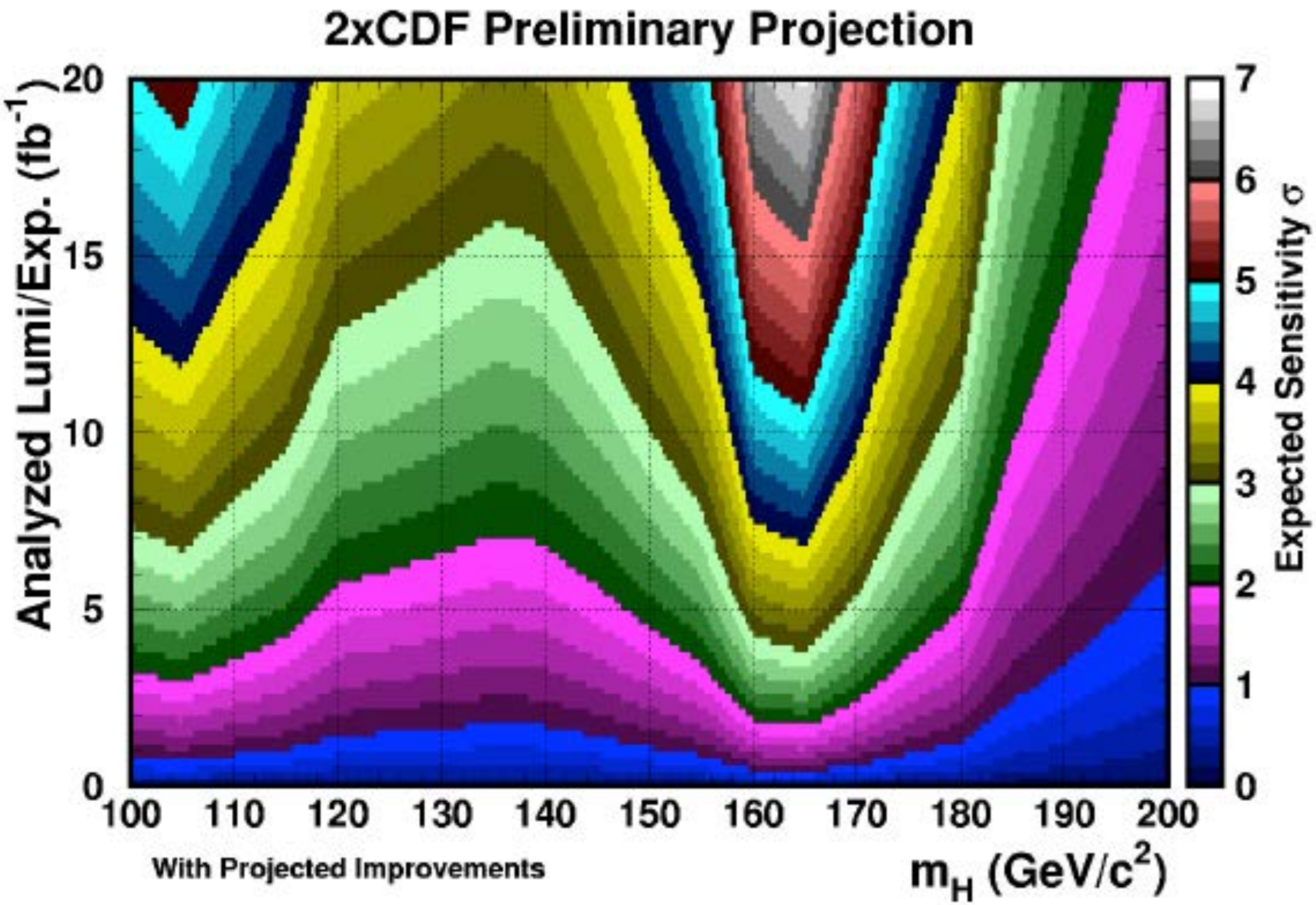
- **aim for high significance**

→ minimize mass resolution σ_M: $S \sim 1/\sqrt{\sigma_M}$

→ maximize luminosity L: $S \sim \sqrt{L}$

→ same dependence of efficiency

Expected Tevatron sensititvity

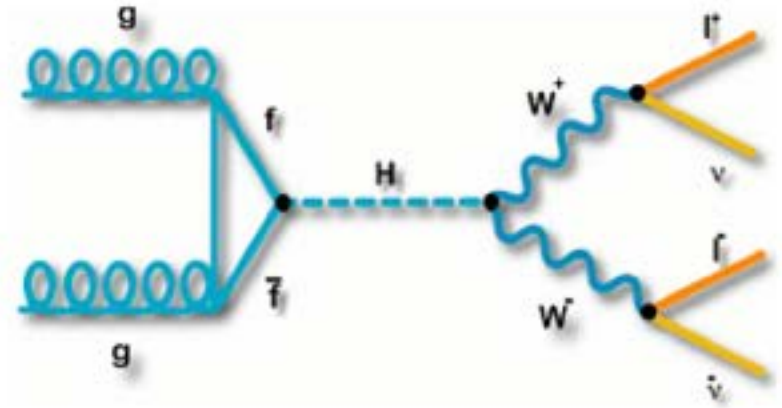


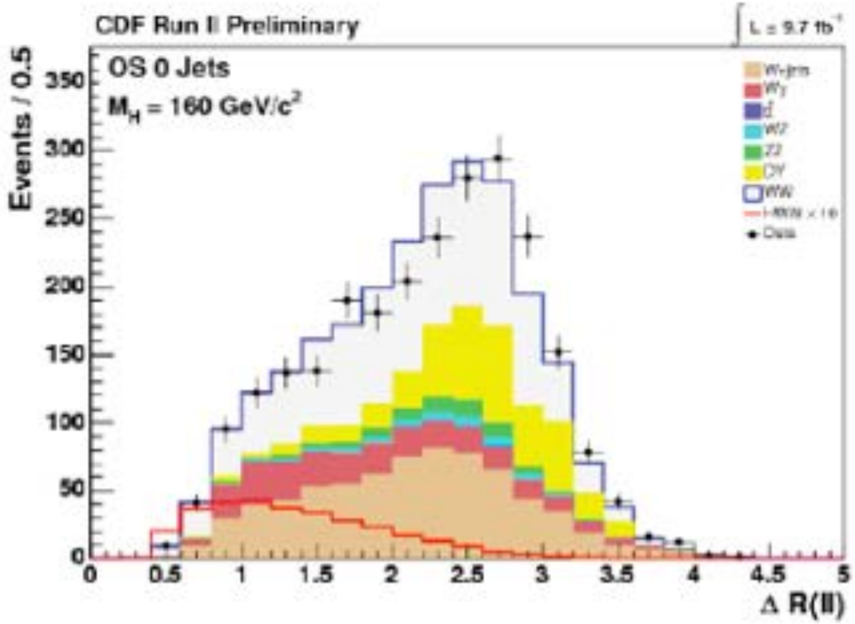
Tevatron at end-of-run (Sept. 2011): < 12 fb^{-1} / experiment

–> exclusion (3 σ) expected: 100 - 117 und 150 - 179 GeV;
5 σ discovery not reached anywhere.

H→WW→lνlν

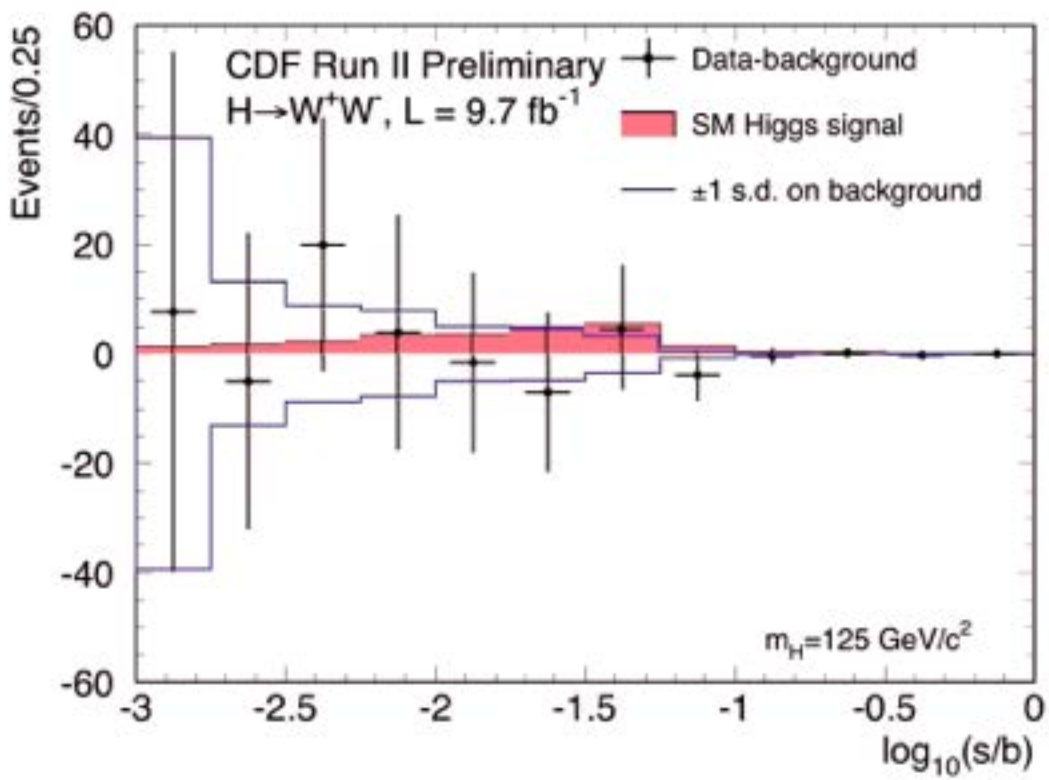
- Basic event selection is two reconstructed leptons and missing E_T
- Presence of two neutrinos in final state prevents complete Higgs mass reconstruction
- Separate potential signal from large backgrounds using kinematic event information





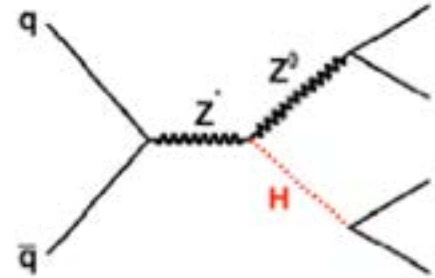
$H \rightarrow WW \rightarrow l\nu l\nu$

- 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

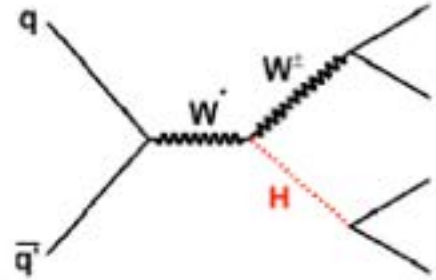


$H \rightarrow bb$

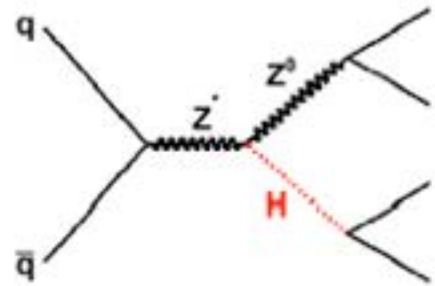
- Tevatron searches in this decay mode are still the world's most sensitive
- Basic event selection is 0, 1, or 2 leptons and/or missing E_T plus two high E_T jets
- Challenge is separating the small number of potential signal events from the much larger SM background contributions



$ZH \rightarrow \nu\nu bb$

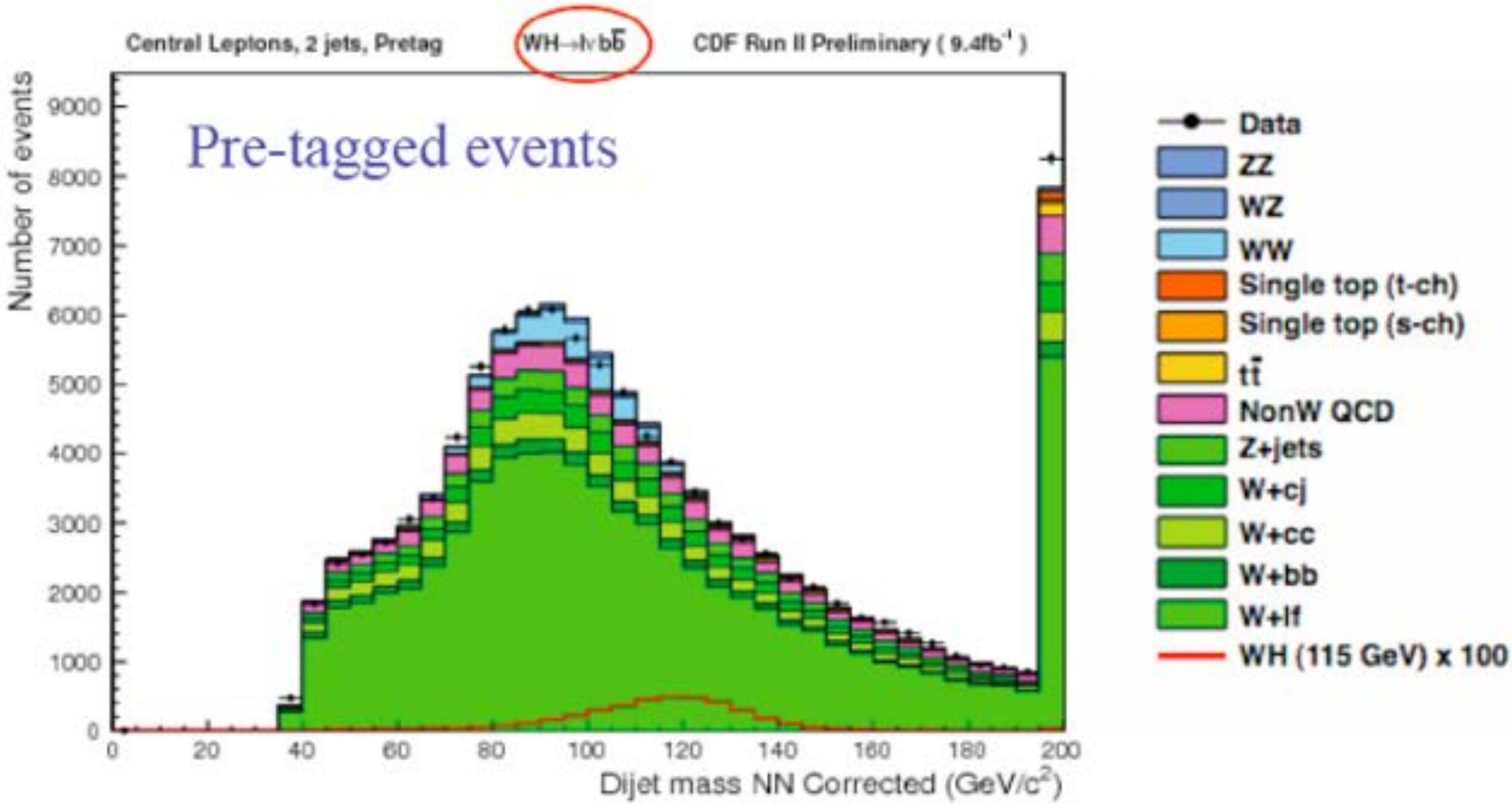


$WH \rightarrow l\nu bb$



$ZH \rightarrow llbb$

H→bb



Focus on

Increasing lepton reconstruction and selection efficiencies

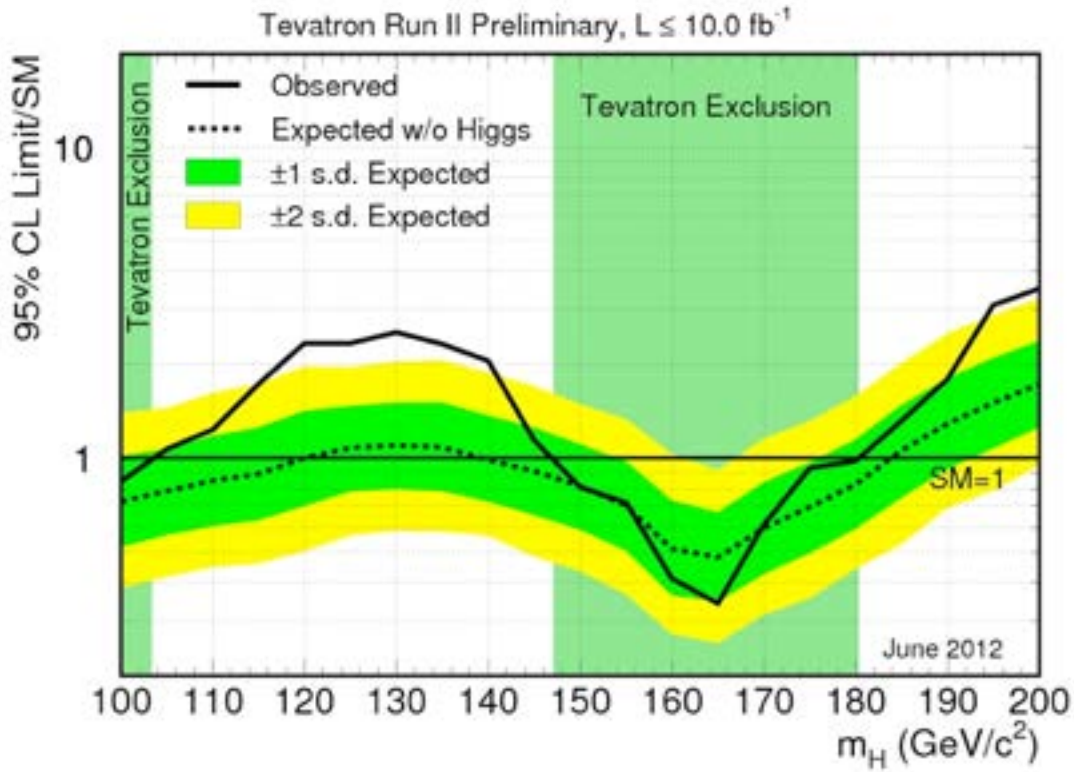
Improving the efficiency for tagging bottom quark jets

Optimizing dijet mass resolution

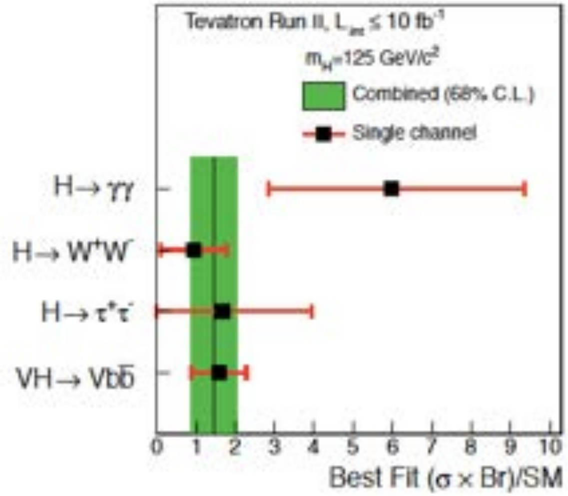
CDF/D0 combined conclusion (July 2012):

- SM Higgs exclusion in the range 147-180 (and 100-103) GeV @95% CL
- Expected exclusion range 139-184 GeV

- 2.5 σ excess in region 115-135 GeV (3.0 σ 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 ($\propto \log m_H^2$):

$m_H = 94^{+29}_{-24}$ GeV (68% C.L.) and

$m_H < 171$ GeV (95% C.L.)

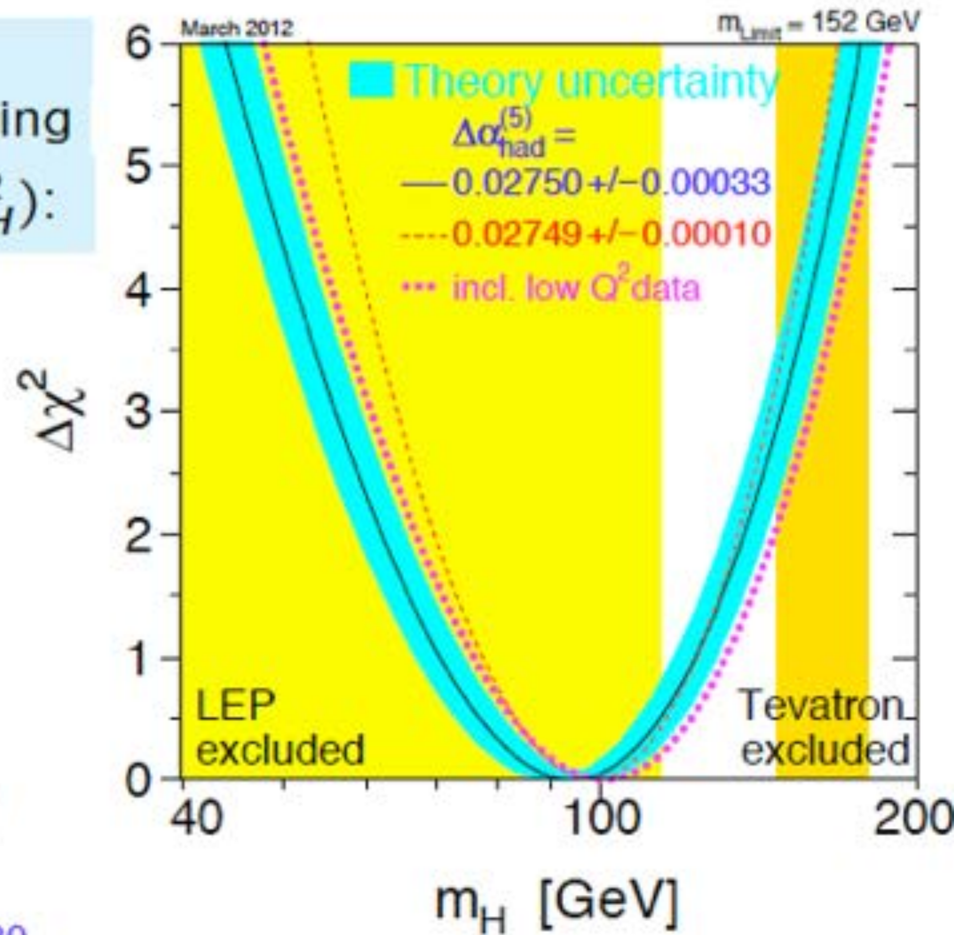
Direct searches at LEP:

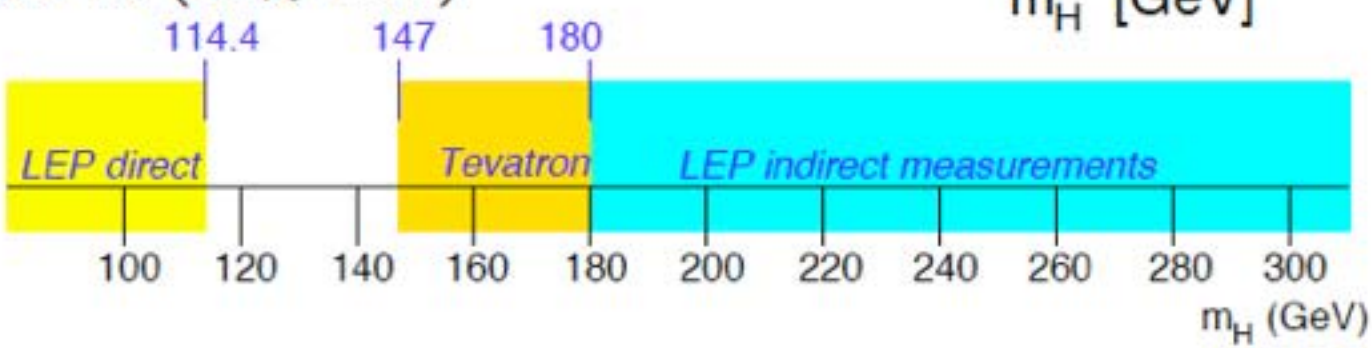
$m_H > 114.4$ GeV at (95% C.L.)

Direct searches at Tevatron:

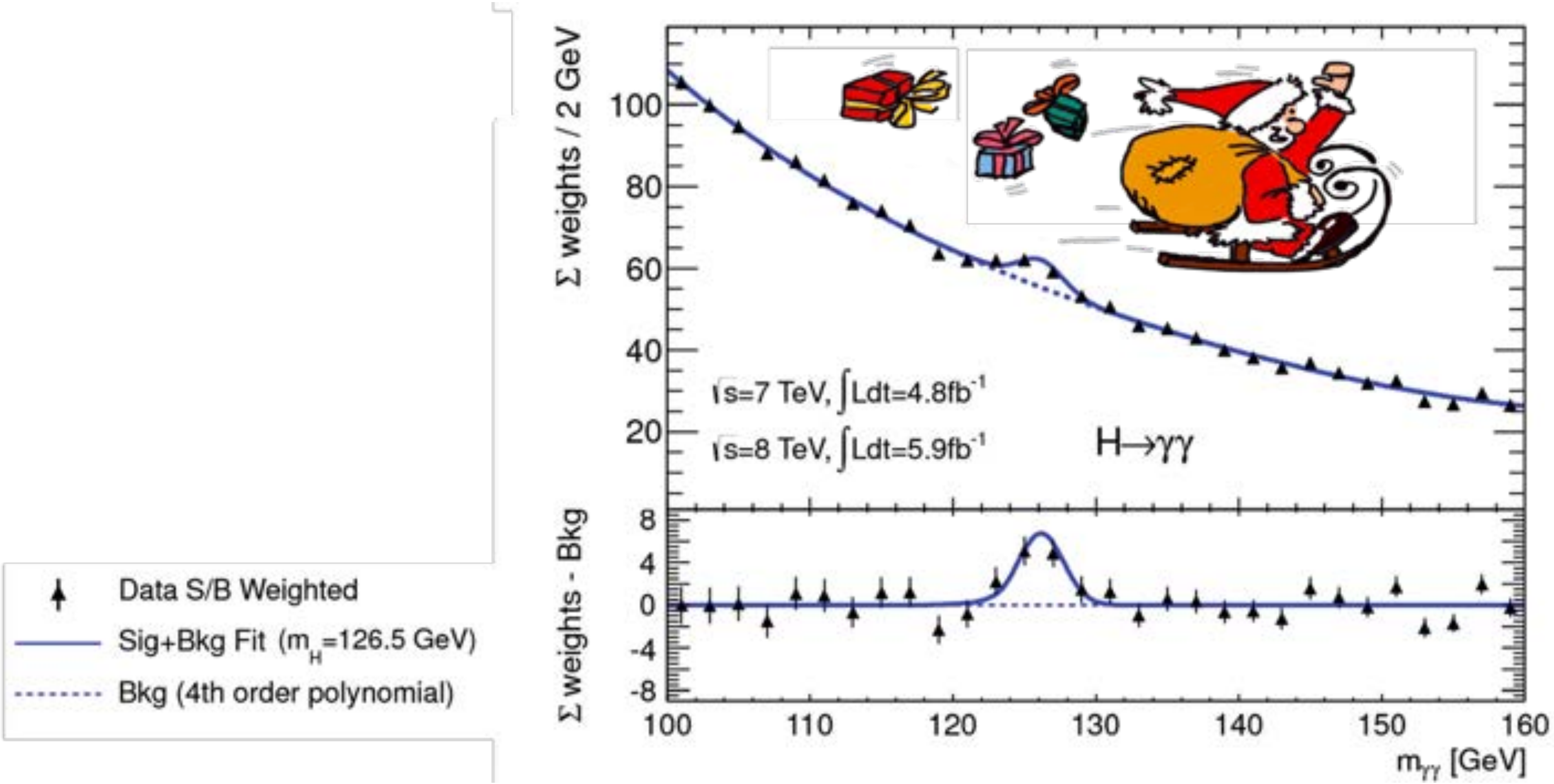
$m_H < 147$ GeV at (95% C.L.) and

$m_H > 180$ GeV at (95% C.L.)





Higgs-search and discovery at LHC (preview):



(see next lecture; 8.12.2014)

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- 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.