Higgs
the missing link of the
Standard Model

Vittorio Del Duca
INFN LNF Frascati

Physics for large and small scale   Nhatrang 5 January 2007

the Standard Model of Particle Physics

$$
\begin{aligned}
\mathcal{L}_{SM} = \quad & -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} D \psi && \text{gauge sector} \\
& + \psi_i \lambda_{ij} \psi_j H + h.c. && \text{flavour sector} \\
& + |D_\mu H|^2 - V(H) && \text{EWSB sector} \\
& + N_i M_{ij} N_j && \text{(Majorana) } \nu\text{-mass sector}
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flavour sector

EWSB sector

(Majorana) ν-mass sector

☛ are there elementary scalars in the SM ? Higgs boson ???

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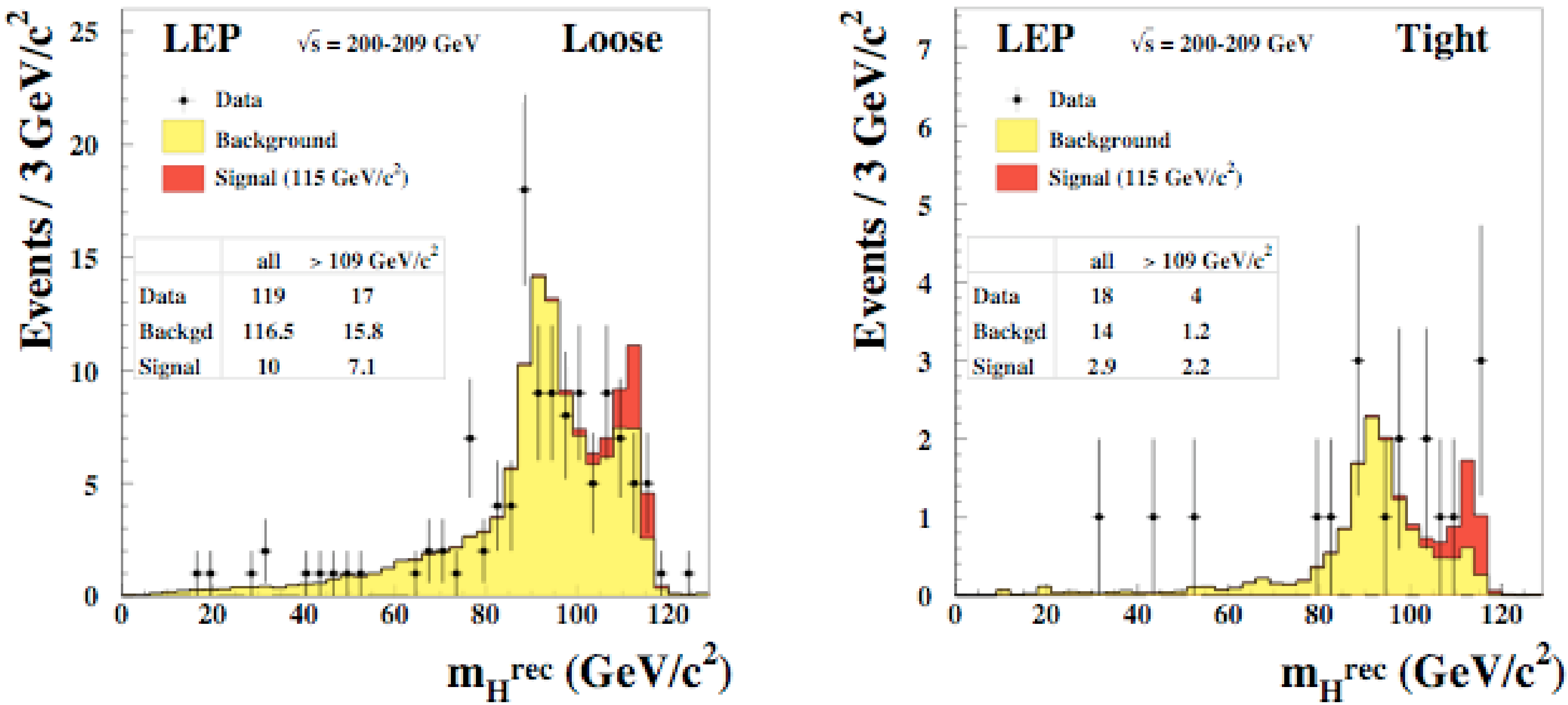
foremost task of the LHC is to find the Higgs boson

Search for the Standard Model Higgs Boson at LEP

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP Working Group for Higgs Boson Searches[1]



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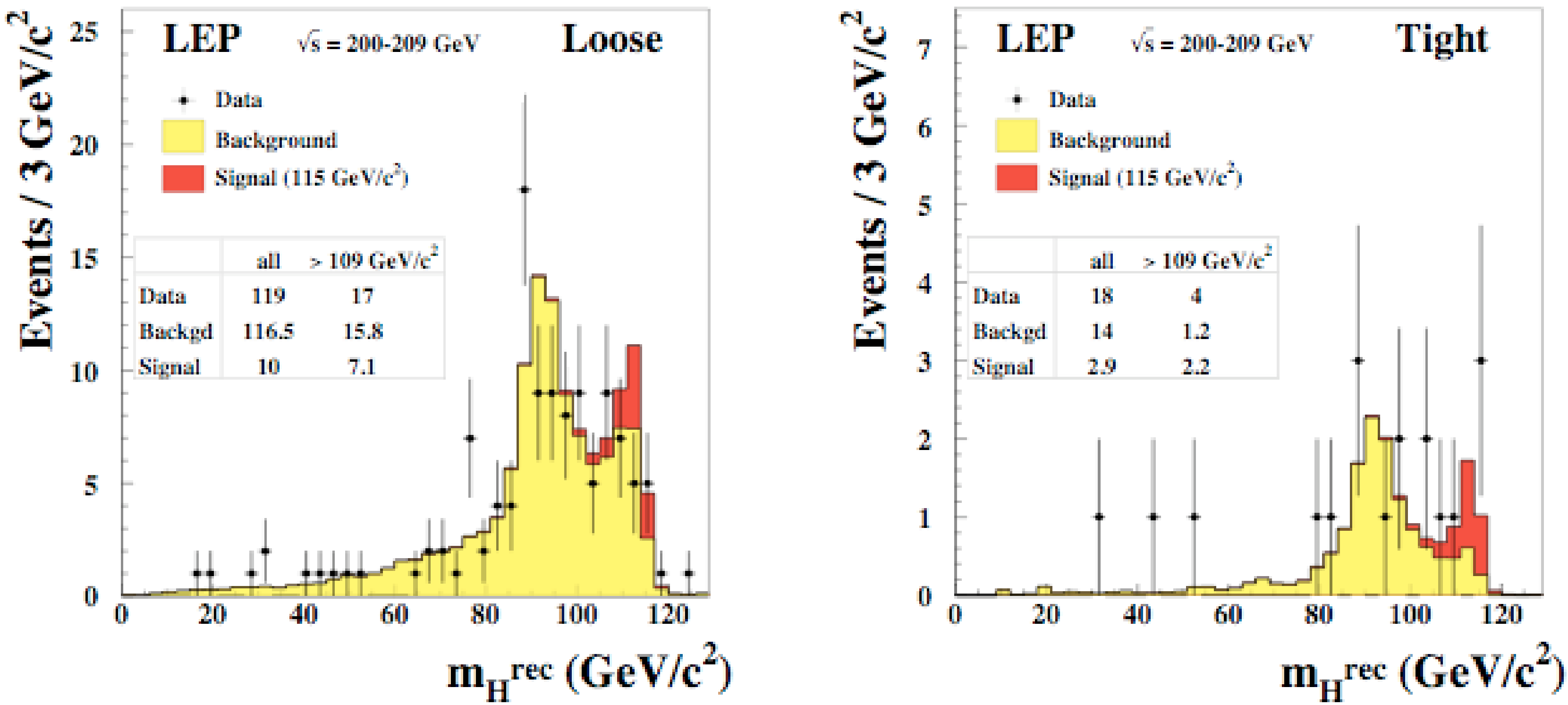

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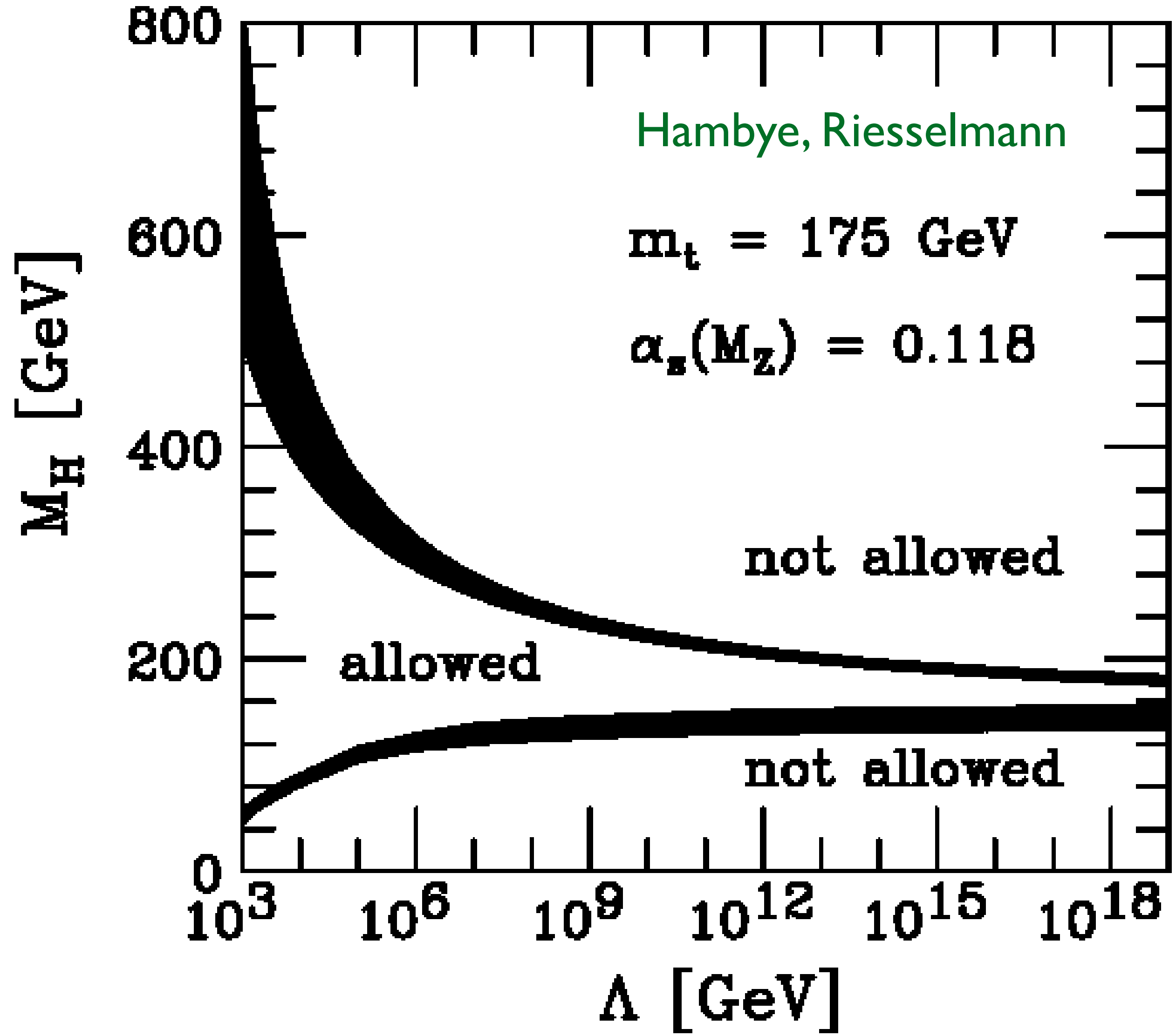
Lower bound: m_H = 114.4 GeV at 95% *CL*

Theoretical bounds on the SM Higgs mass

Λ : scale of new physics beyond the SM

Lower bound:
vacuum (meta)stability
Upper bound:
No Landau pole up to Λ



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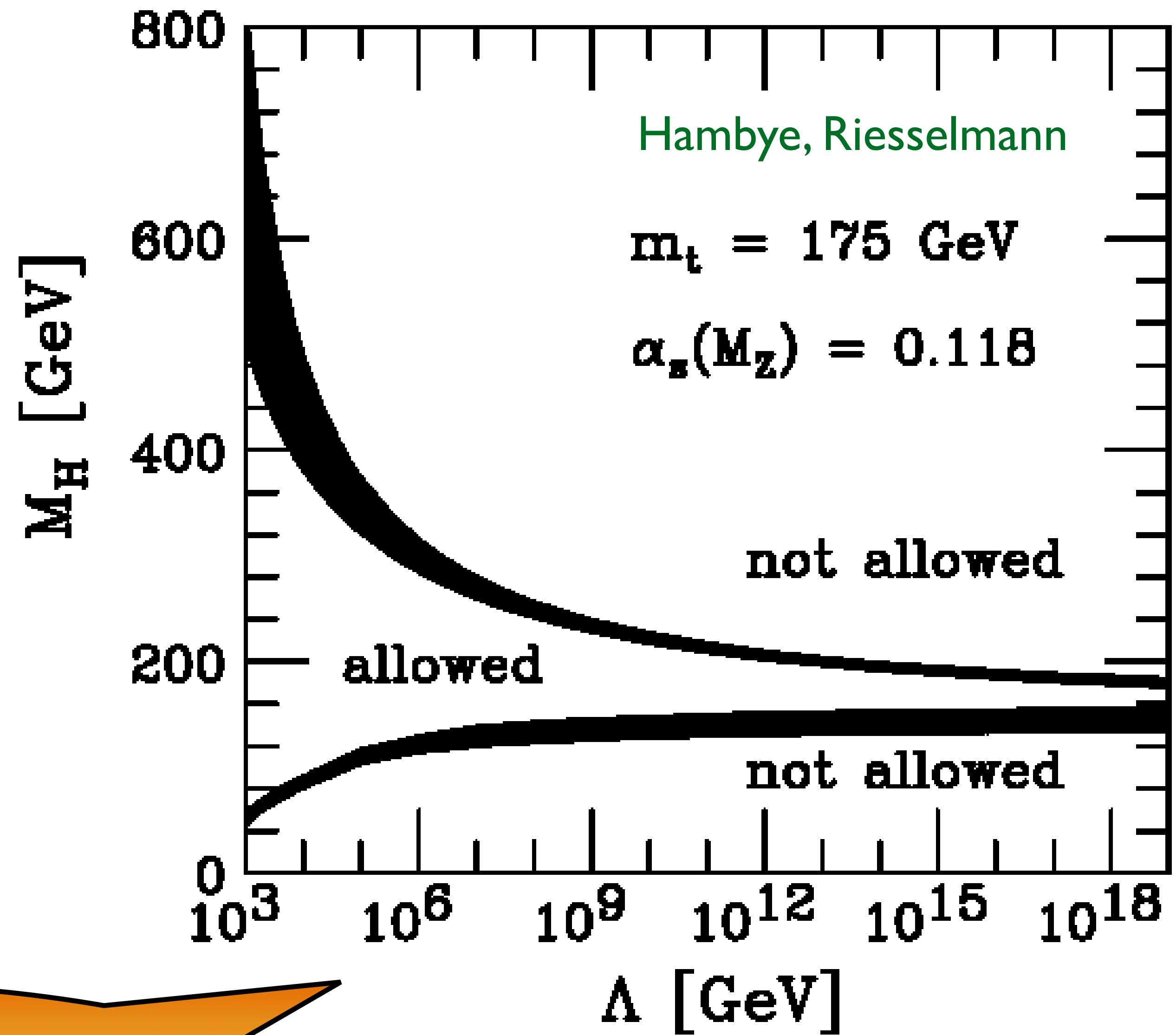

were the SM valid up to M_{Pl}, then M_H would be limited to a small range

Higgs potential (lower bound on m_H)

classic $V[\phi] = -\mu^2\phi^2 + \lambda\,\phi^4$ $\mu^2 > 0, \quad \lambda > 0$

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renormalization group improved PT

quantum corr. $\quad \lambda\phi^4 \to \lambda\phi^4\left(1 + \gamma\ln\dfrac{\phi^2}{\Lambda^2} + \dots\right) \xrightarrow{\text{RG}} \lambda(\Lambda)\,\phi'^4(\Lambda)$

$$\phi' = \left(\exp\int dt\gamma(t)\right)\phi \qquad t = \frac{\ln(\Lambda)}{\mathrm{v}}$$

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Running coupling

$$\frac{d\lambda(t)}{dt} = \beta_\lambda(t) \propto \left(\lambda^2 + 3\lambda\,h_t^2 - 9h_t^4 + \ldots\right)$$

h_t top Yukawa coupling

initial conditions (at Λ = v) $\lambda_0 = \frac{m_H^2}{4\mathrm{v}^2} \quad h_{0t} = \frac{m_t}{v}$

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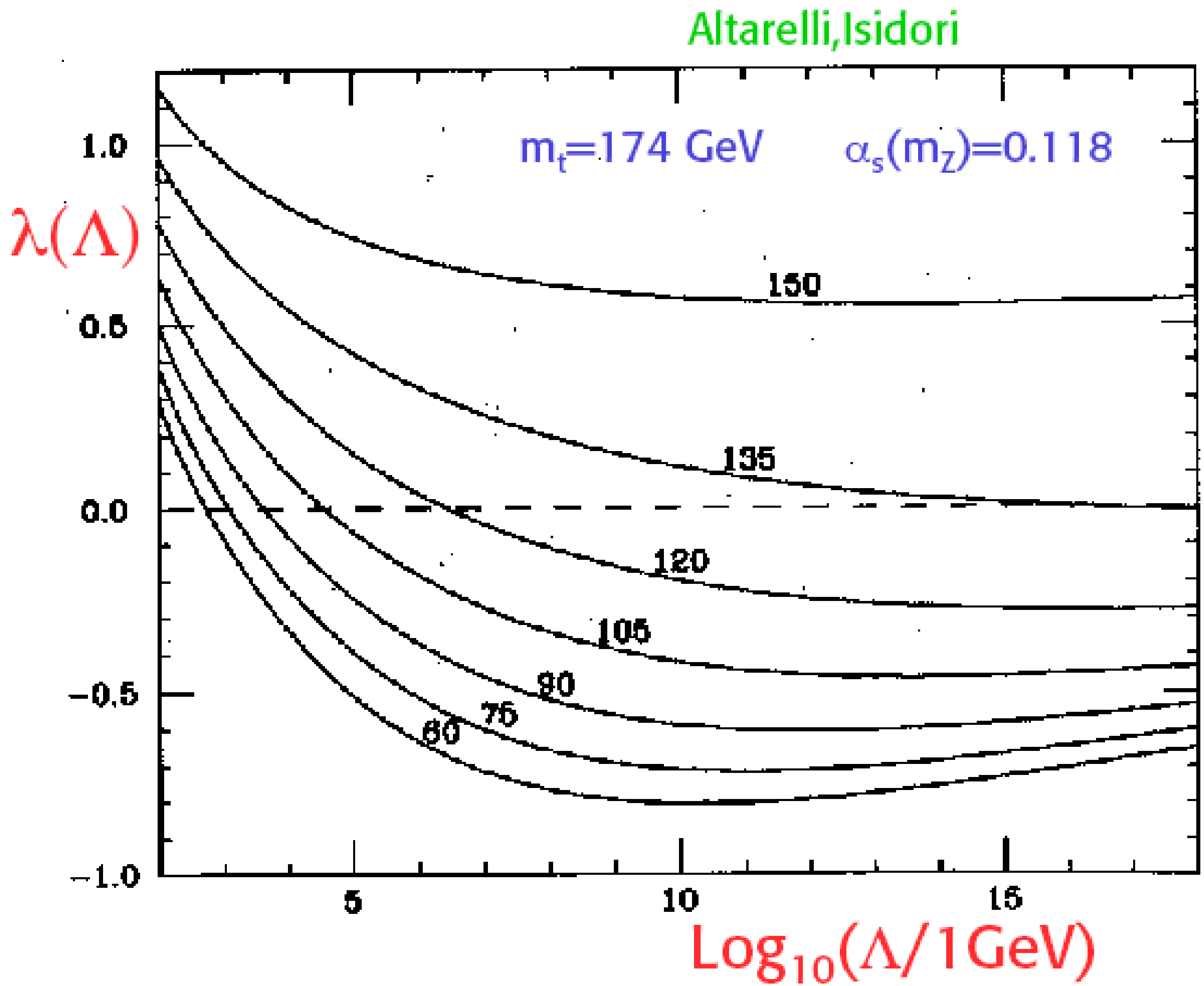
if m_H is too small, h_t dominates → $\lambda(t)$ decreases

For the vacuum to be stable, $\lambda(t)$ must be > 0 below Λ → lower bound on m_H

$$m_H > 129.5 + 2.1\,(m_t - 171.4) - 4.5\frac{\alpha_s(m_Z) - 0.118}{0.006}$$

$m_H \geq 130$ GeV at $\Lambda = M_{GUT}$

Higgs potential



Upper bound on m_H

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const = *b*

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Landau pole (signals PT breakdown)

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Landau pole (signals PT breakdown)

The upper bound on m_H is obtained
by requiring that no Landau pole occurs below Λ

$m_H \leq$ 180 GeV if $\Lambda \sim M_{GUT}$

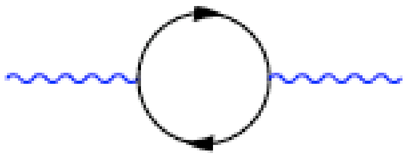
600 ÷ 800 GeV if $\Lambda \sim O(\mathrm{TeV})$

Hierarchy problem in the SM

Symmetry principles protect against power-like divergences

Hierarchy problem in the SM

Symmetry principles protect against power-like divergences



photon self-energy $\delta m_\gamma^2 \propto \cancel{\Lambda^2} + m_\gamma^2 \ln \Lambda$

gauge symmetry protects against quadratic divergence

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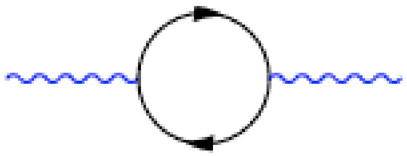

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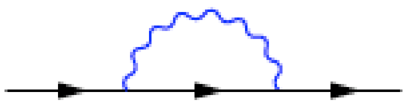

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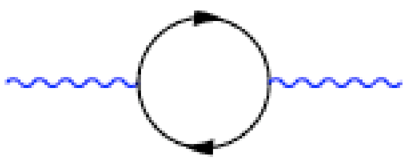

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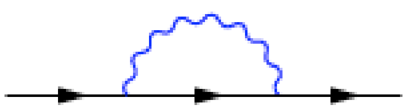

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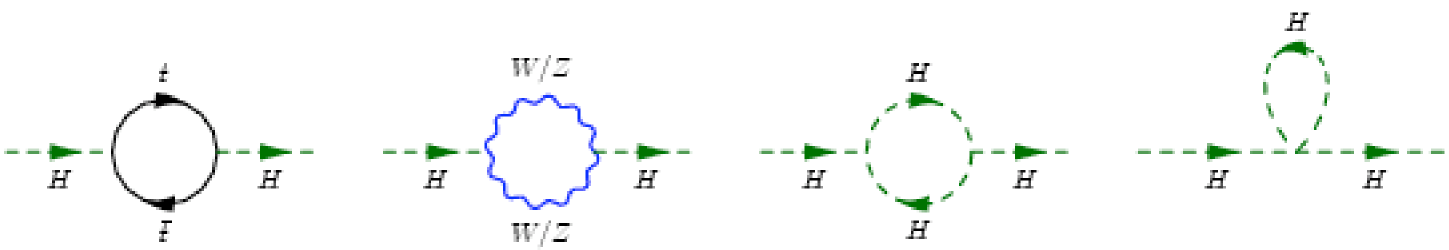

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$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2$$

no symmetry protects against quadratic divergences

Fine tuning and unnaturalness

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A *natural* solution to hierarchy: supersymmetry

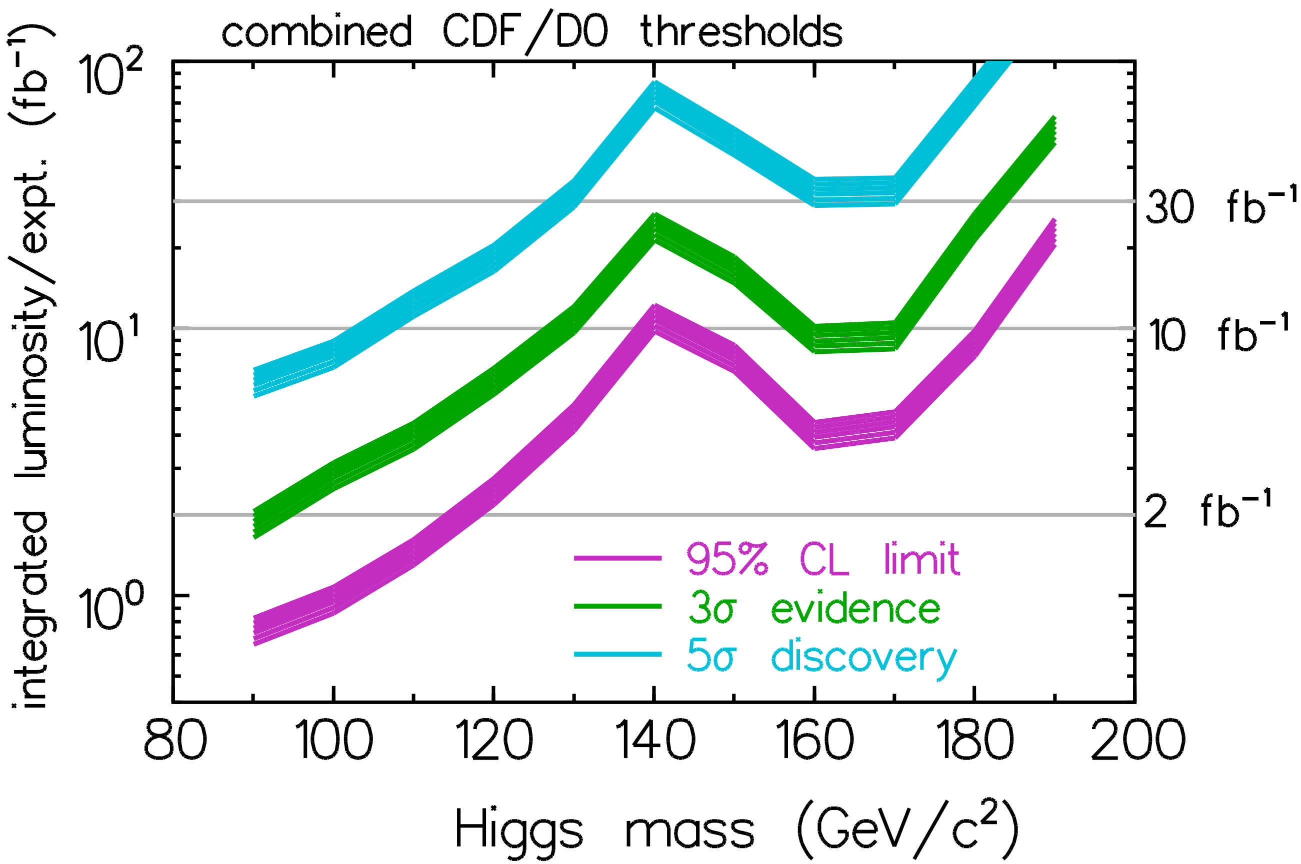
postulate a new symmetry principle, which yields new particles that cancel the quadratic divergences of the Higgs self-energy, such that

$$\delta m_H^2 \sim \mathcal{O}(m_H^2) \ln \Lambda$$

Higgs search - Tevatron reach

Tevatron has collected so far about 2 fb^{-1}

Although it cannot collect enough integrated luminosity to claim discovery above the LEP exclusion limit (114.4 GeV), it could collect enough to hint at some evidence for a signal



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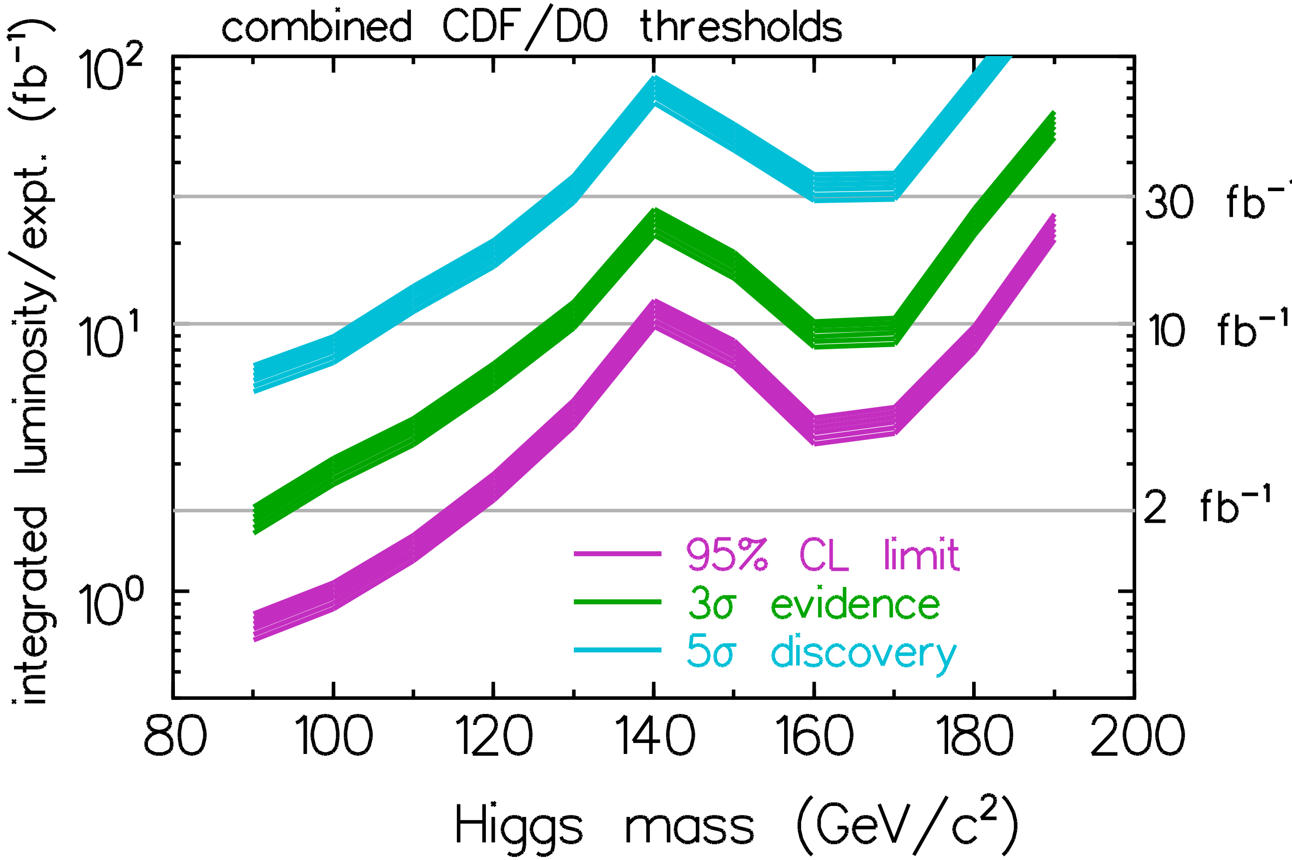
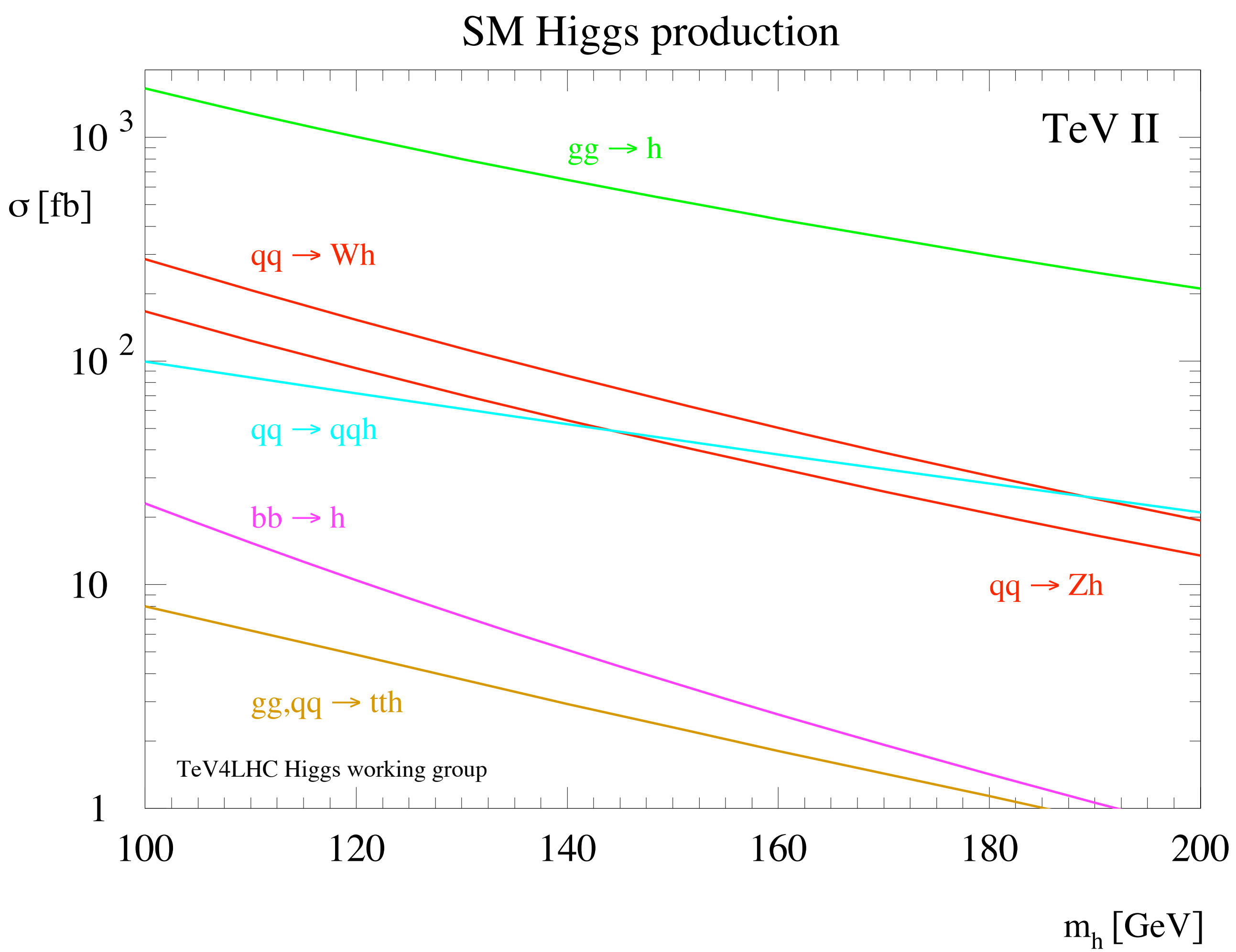


Sensitivity in the mass region above LEP limit (114 GeV) starts at ~2 fb^{-1}

With 8 fb^{-1}: exclusion 115-135 GeV & 145-180 GeV,

5 - 3 sigma discovery/evidence @ 115 – 130 GeV

Higgs production at Tevatron Run-II



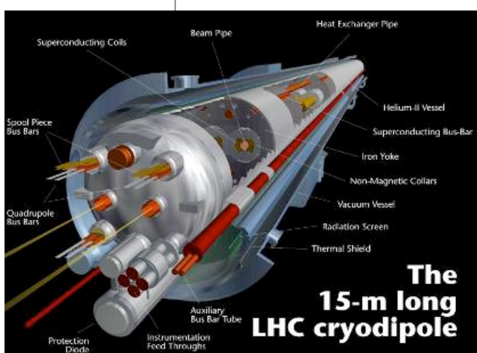
- in the intermediate Higgs mass range $M_H \sim 100 - 200\ \mathrm{GeV}$
  - gluon fusion cross section is ~ 0.2 – 2 pb
  - *WH, ZH* yield cross sections of ~ 10 – 300 fb
  - WBF cross section is ~ 20 - 100 fb

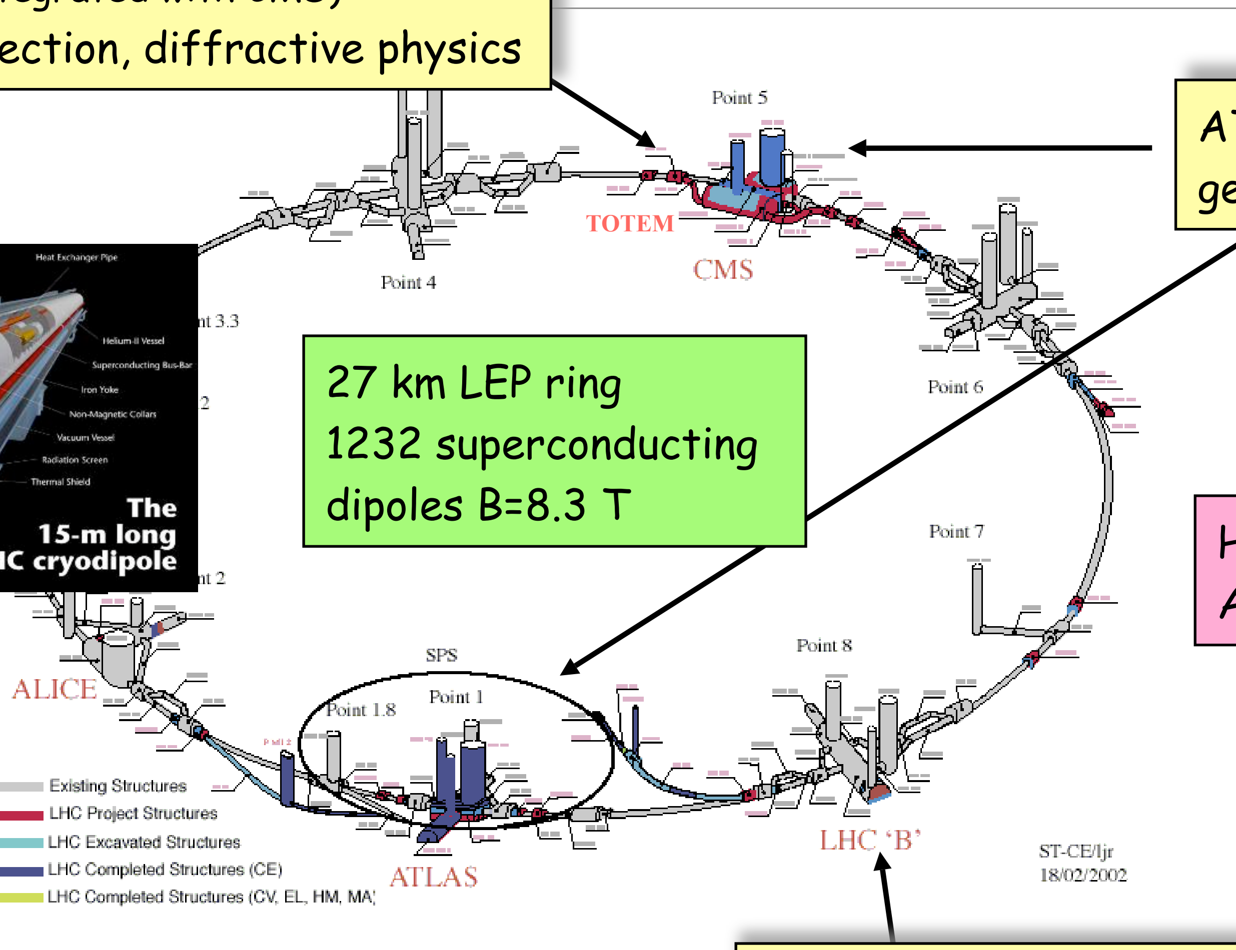
LHC

- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2009)
  $L_{initial} \leq$ few x $10^{33}\ cm^{-2}\ s^{-1}$ (until 2009)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
general purpose





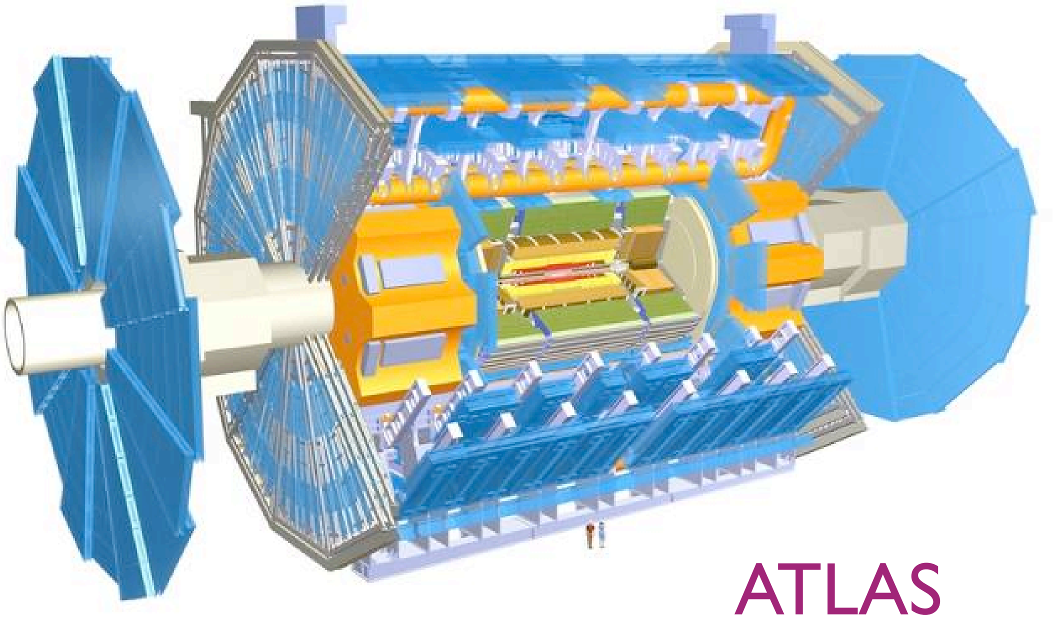
27 km LEP ring
1232 superconducting
dipoles B=8.3 T

Here:
ATLAS and CMS

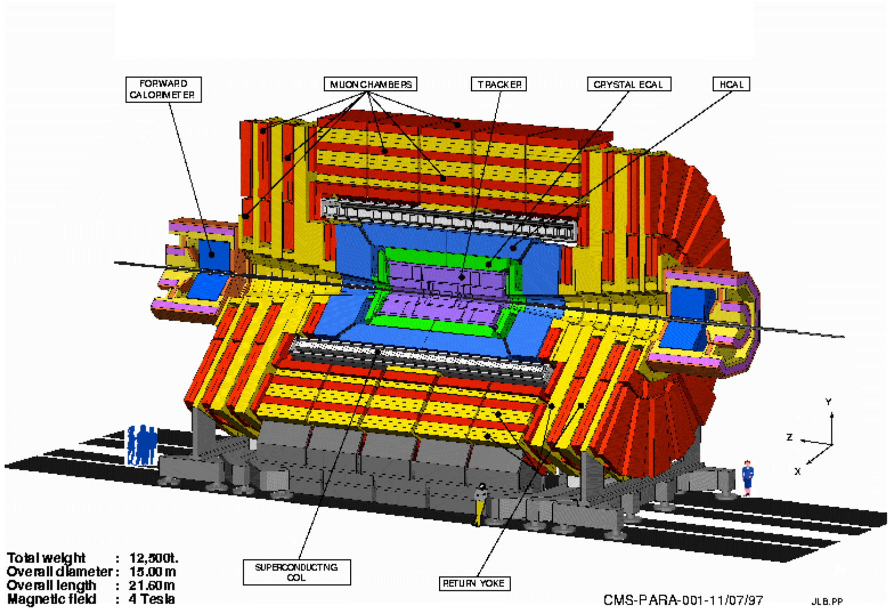
ALICE :
ion-ion,
p-ion

LHCb :
pp, B-physics, CP-violation

ATLAS & CMS



ATLAS

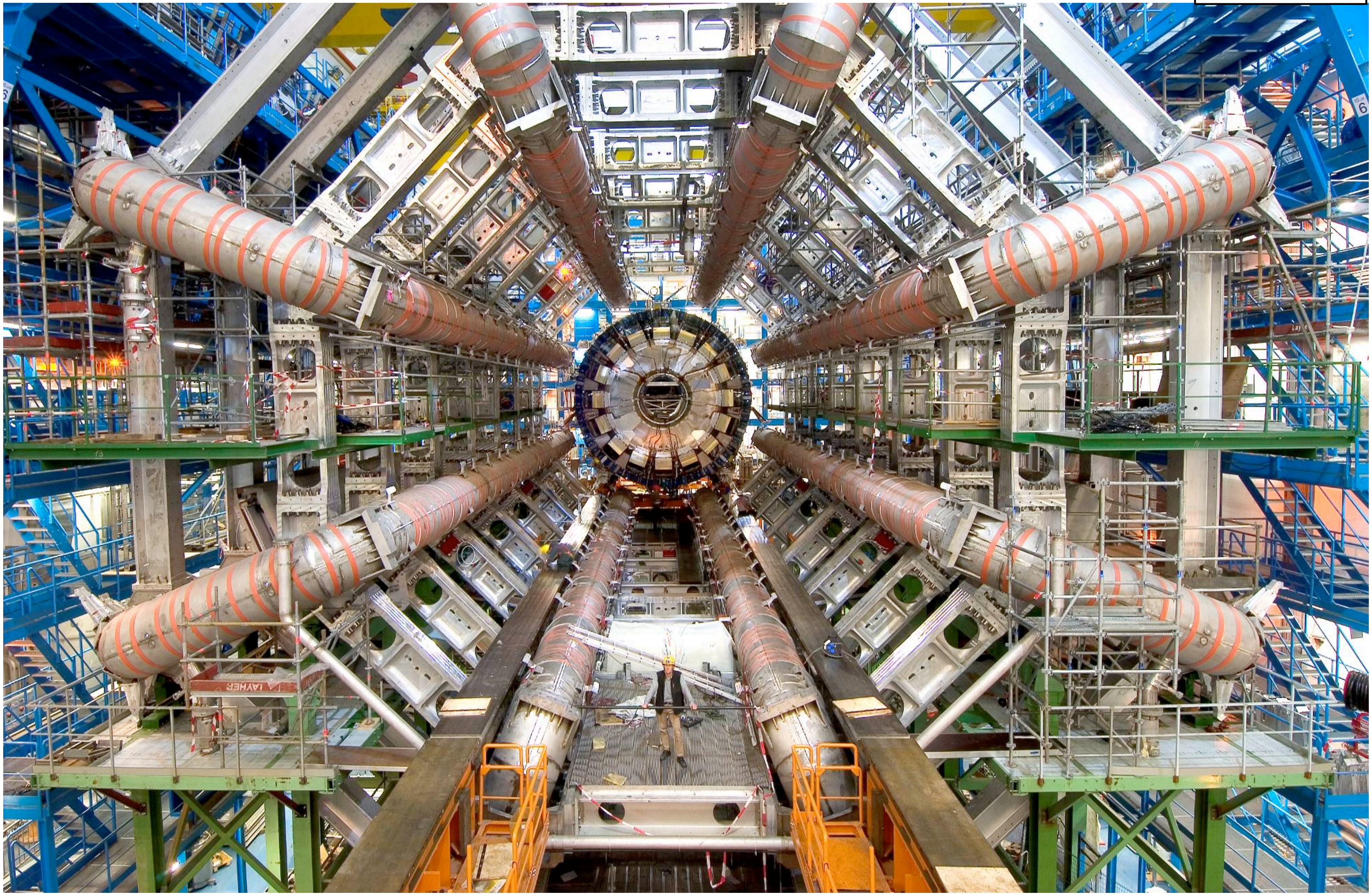


CMS

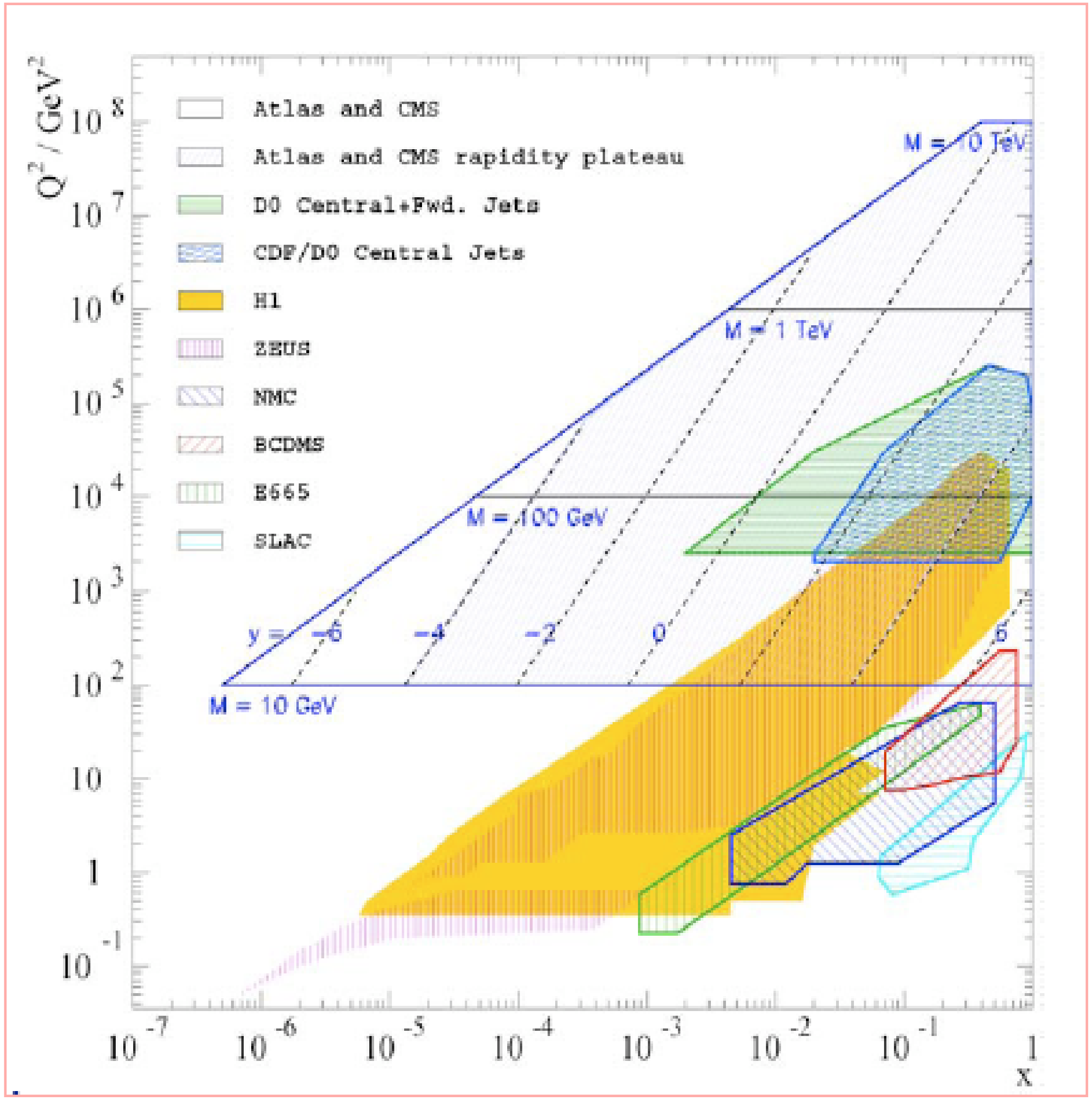
	ATLAS	CMS
Overall weight (tons)	*7000*	*12500*
Diameter	*22 m*	*15 m*
Length	*46 m*	*22 m*
Solenoid field	*2 T*	*4 T*

ATLAS

Oct. 2006



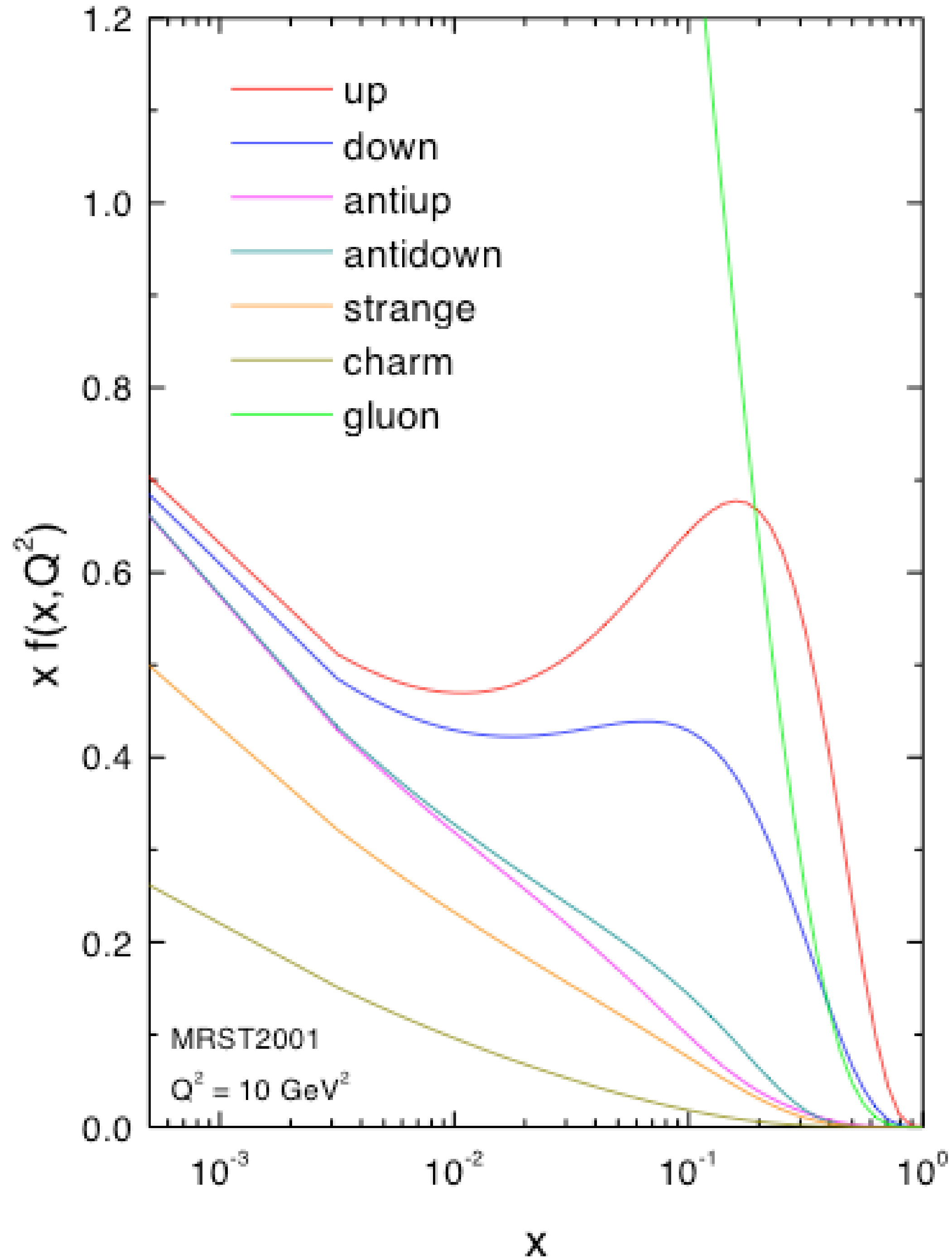
LHC kinematic reach

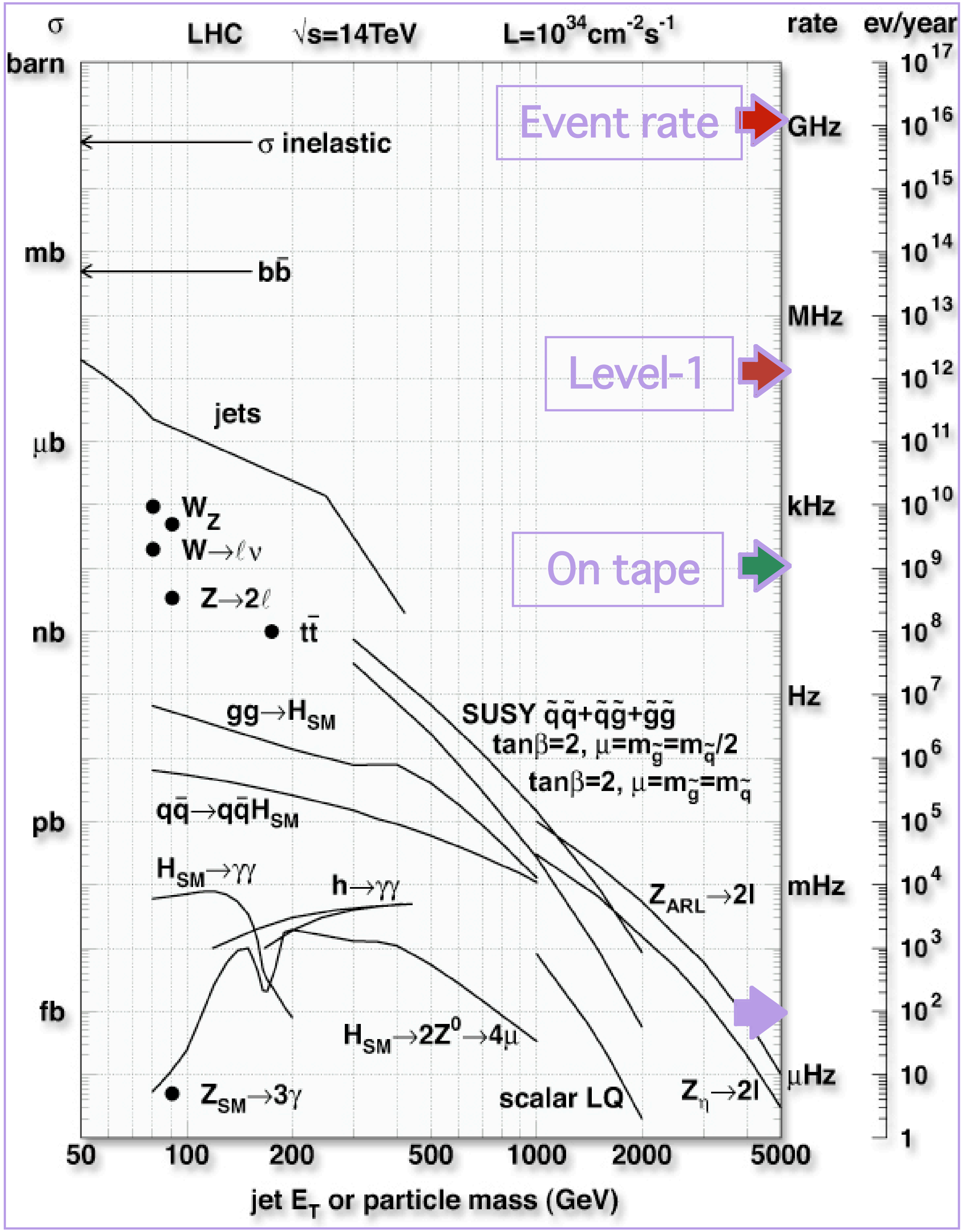


LHC opens up a new kinematic range

Feynman x's for the production of a particle of mass M $$x_{1,2} = \frac{M}{14\,\mathrm{TeV}}\, e^{\pm y}$$

MRST 2001 PDF's





LHC is a QCD machine

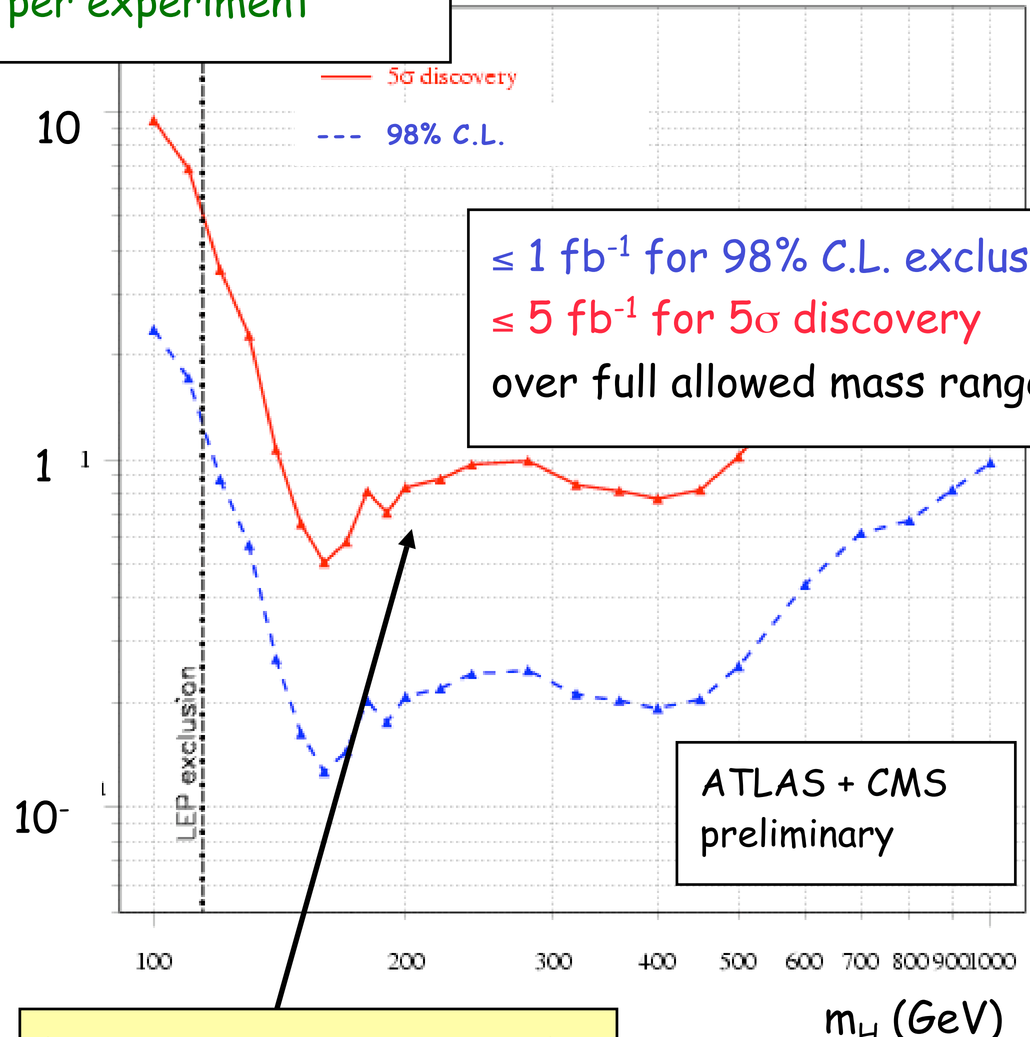
SM processes are background to New Physics signals

1 fb^{-1} (per exp)	Events on tape
$W \to \mu\nu$	7×10^6
$Z \to \mu\mu$	1.1×10^6
$t\bar{t} \to WbWb \to \mu\nu + X$	8×10^4
QCD jets p_T>150	~ 10^6
Minimum bias	~ 10^6

What about the SM Higgs boson ?

F. GIANOTTI. ICHEP 06

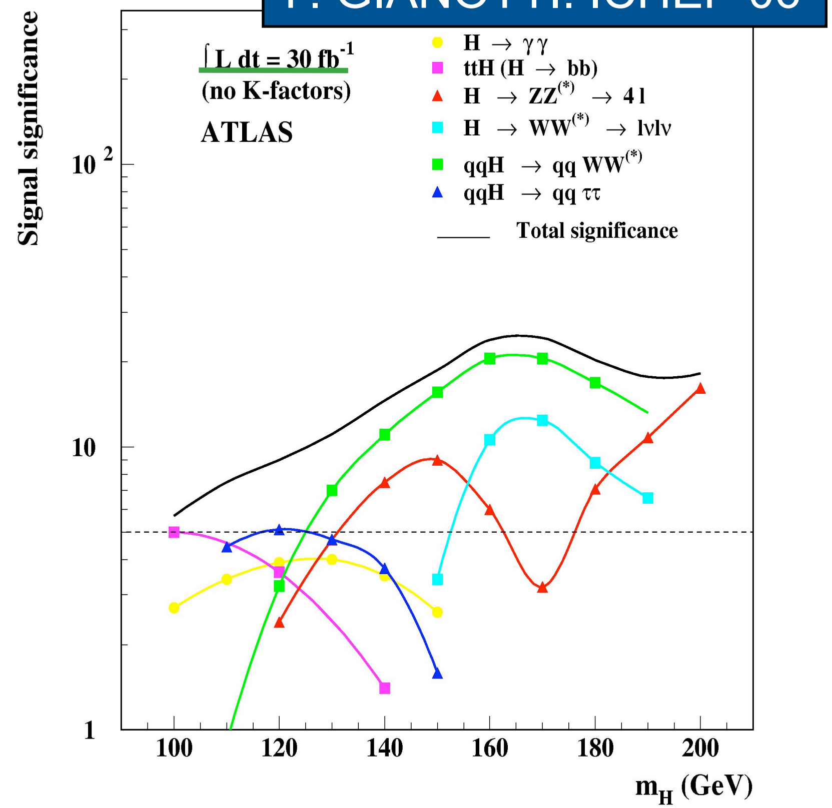
Needed ∫Ldt (fb^{-1}) per experiment



≤ 1 fb^{-1} for 98% C.L. exclusion

≤ 5 fb^{-1} for 5σ discovery

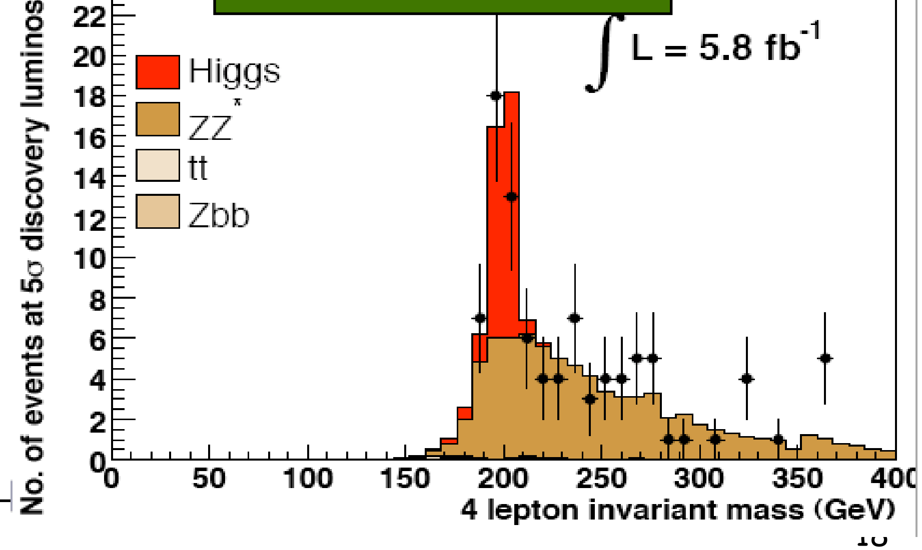
over full allowed mass range



here discovery easier with gold-plated $H \to ZZ \to 4l$

→ by end 2008 ?

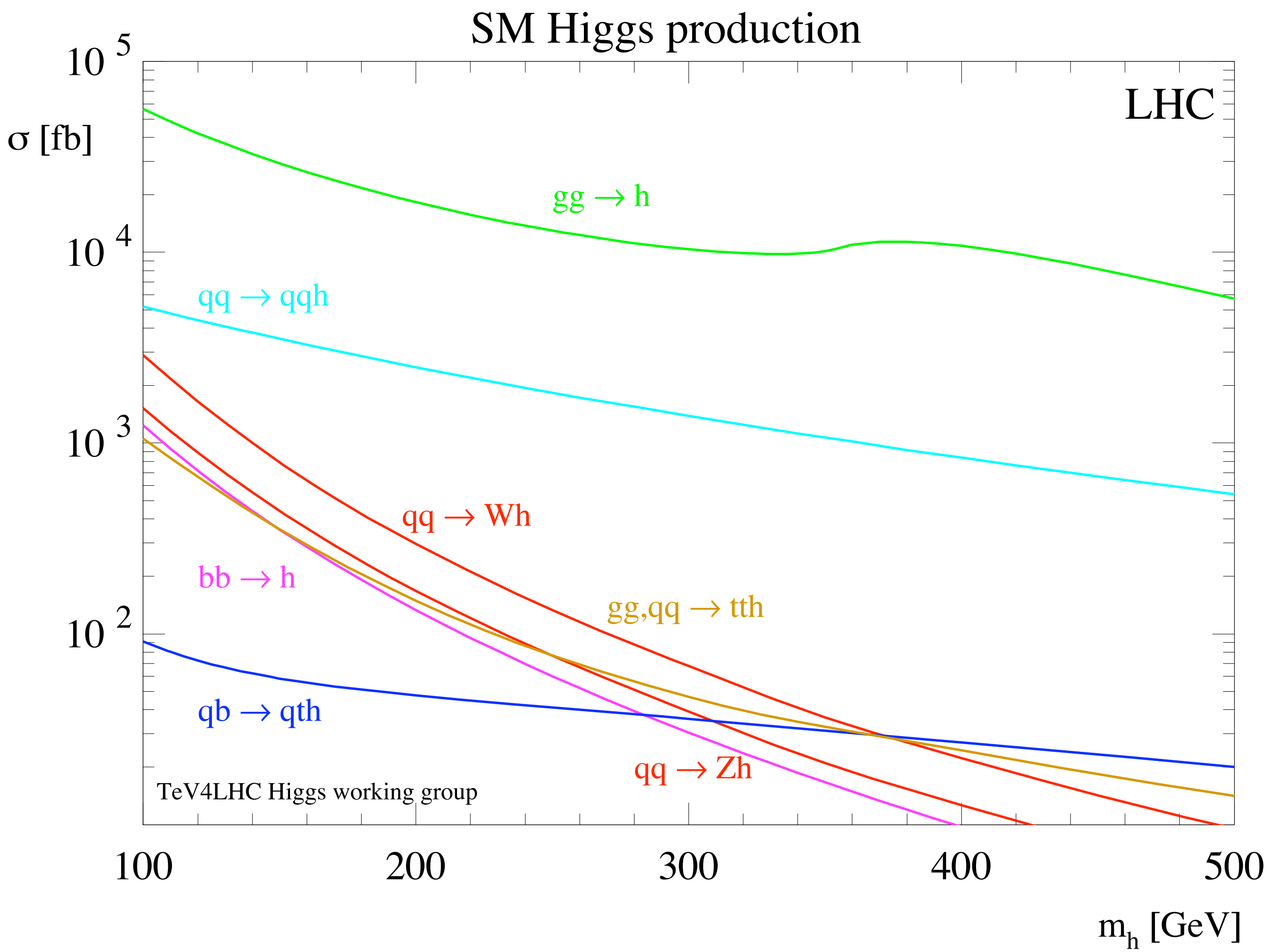
CMS, $H \to ee\mu\mu$



$H \to 4l$: narrow mass peak, small background

$H \to WW \to l\nu l\nu$ (dominant at the Tevatron): counting channel (no mass peak)

Higgs Production at LHC

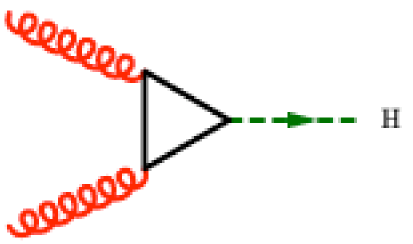


- in the intermediate Higgs mass range $M_H \sim 100 - 200$ GeV
  - gluon fusion cross section is $\sim 20 - 60$ pb
  - WBF cross section is $\sim 3 - 5$ pb
  - $WH, ZH, t\bar{t}H$ yield cross sections of $\sim 0.2 - 3$ pb

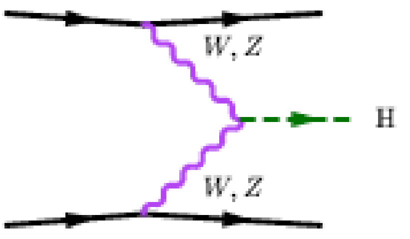
Higgs Production Modes at LHC

In proton collisions at 14 TeV, and for $M_H > 100$ GeV the Higgs is produced mostly via

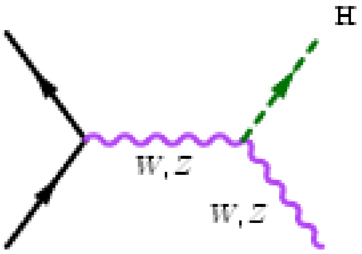
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



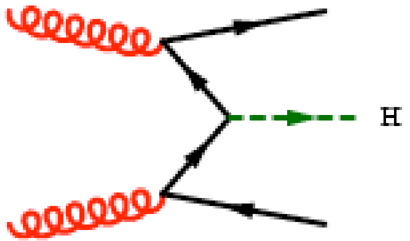
- weak-boson fusion (WBF) $qq \to qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the WWH coupling



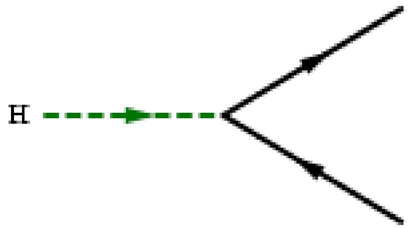
- Higgs-strahlung $q\bar{q} \to W(Z)H$
  - third largest rate
  - same coupling as in WBF



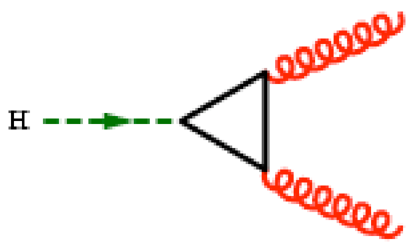
- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher x range
  - proportional to the heavy-quark Yukawa coupling y_Q



Higgs Decay Modes at LHC

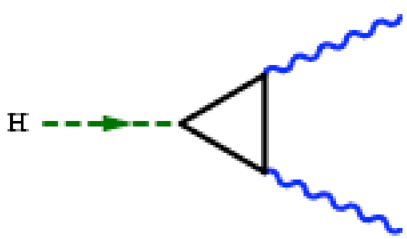


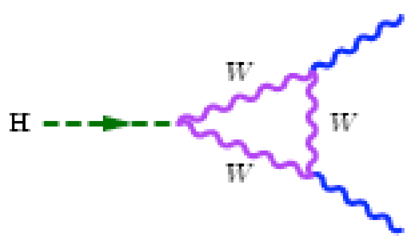
proportional to the Yukawa coupling squared,
and thus to m_f^2



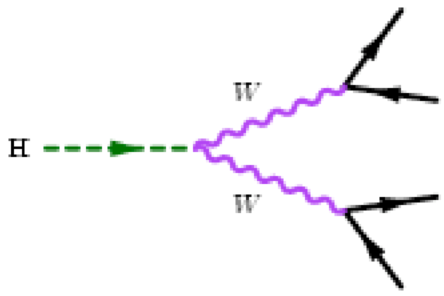
proportional to m_f^4/m_H^4

but dominated by top quark Yukawa coupling





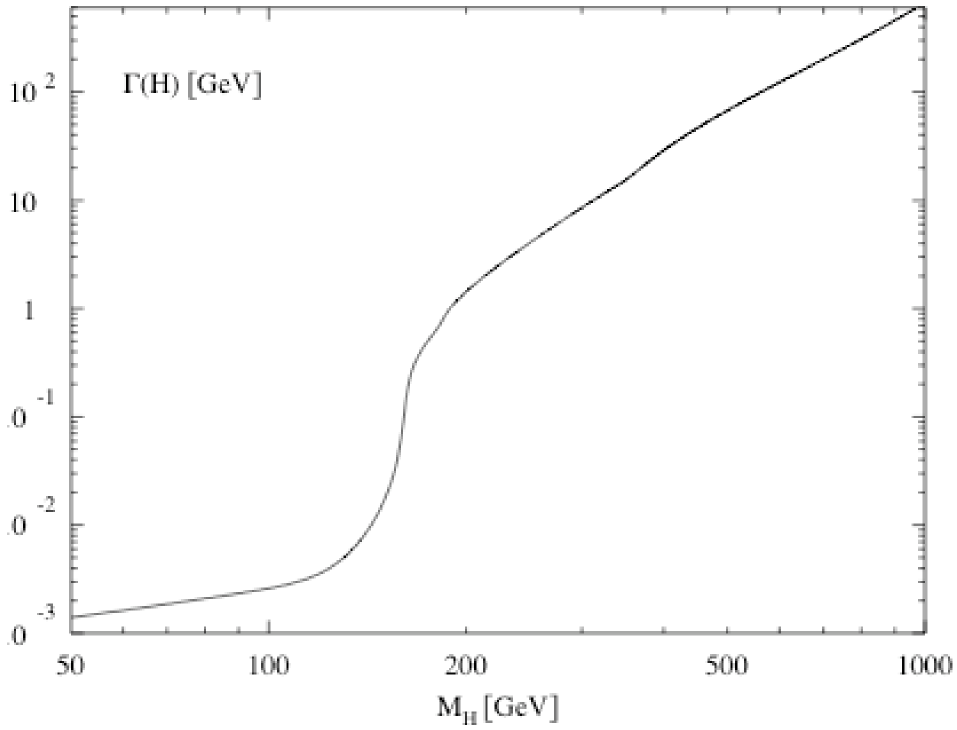
dominated by EW coupling



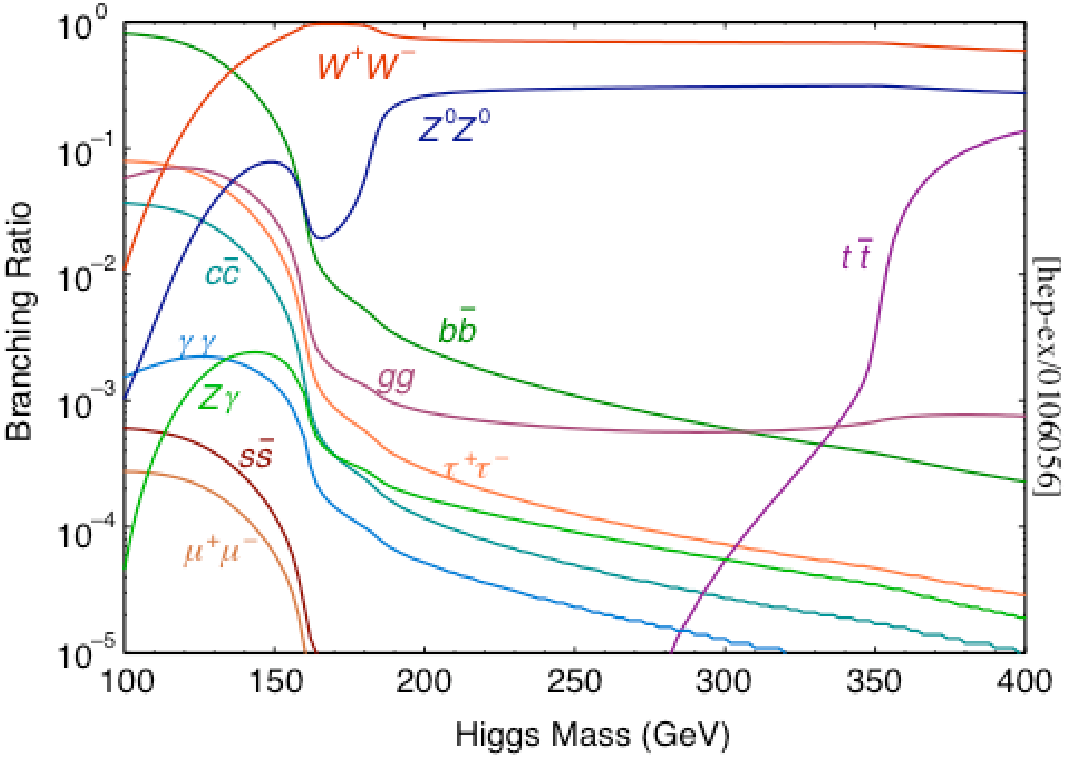
proportional to α_W

Decay width into W^*W^* plays a significant role

HIGGS DECAY AT LHC

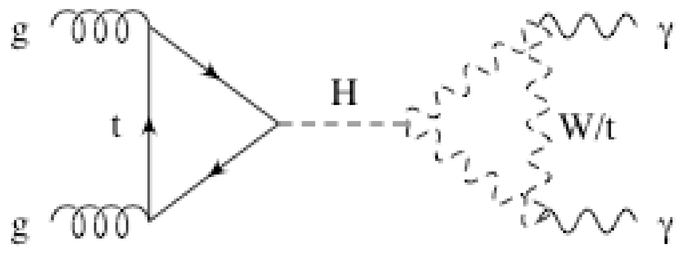


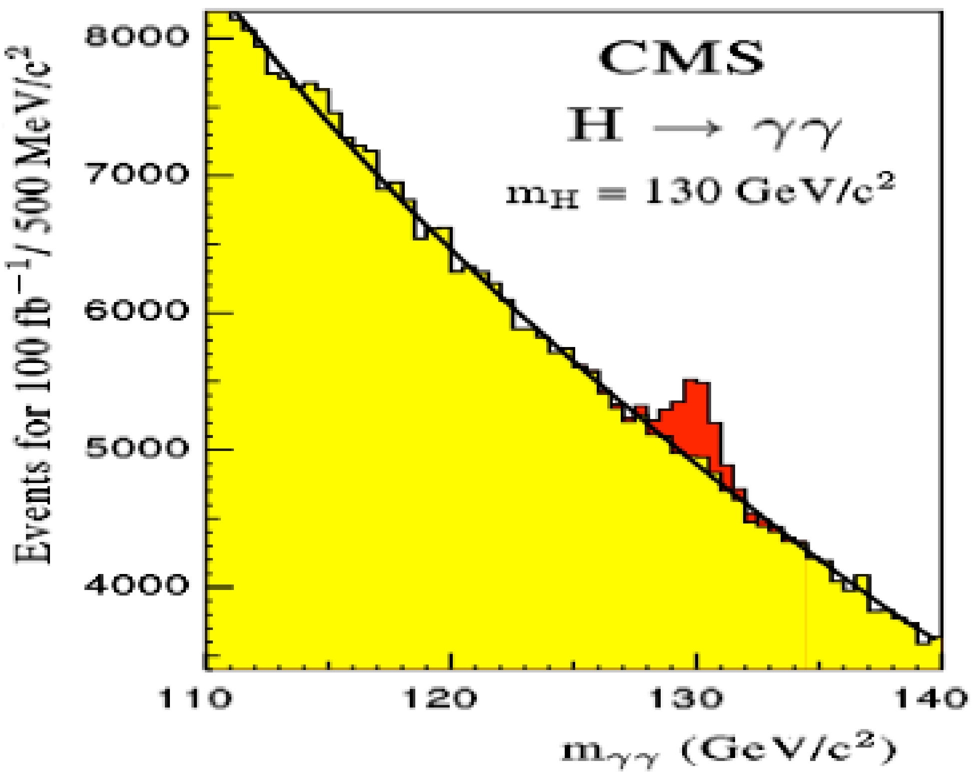
total width



branching fractions

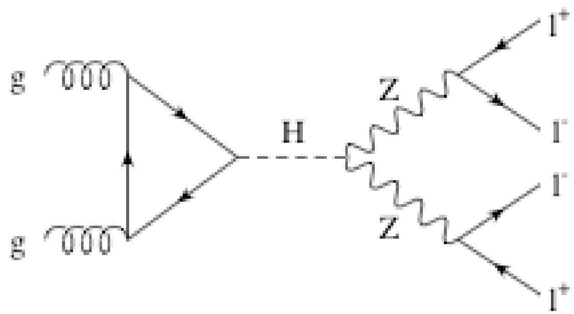
Inclusive searches: $H \to \gamma\gamma$

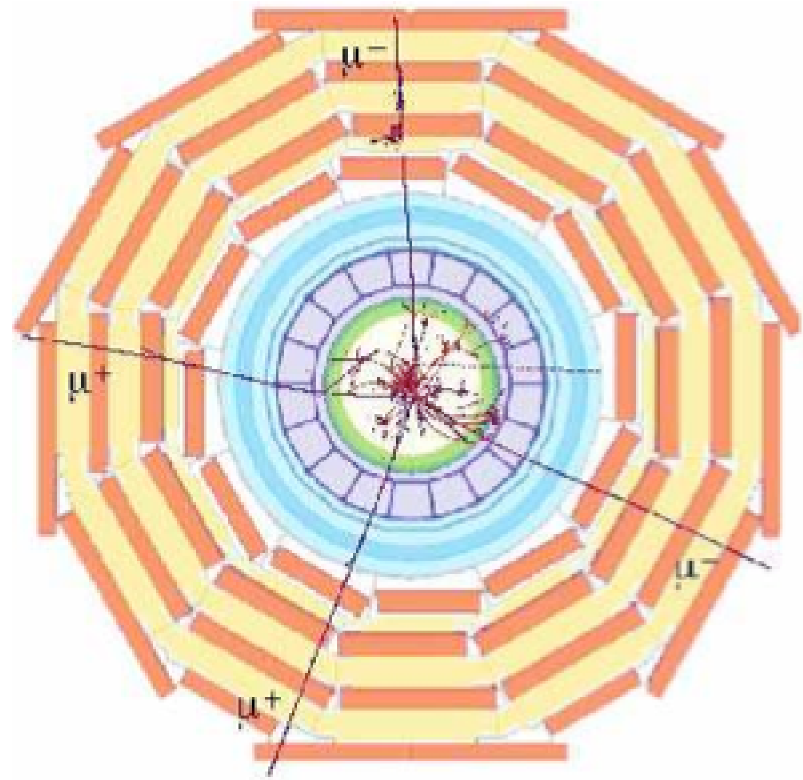




- Small BR: $\approx 10^{-3}$
- Large backgrounds from $pp \to \gamma\gamma$
- CMS and ATLAS have very good photon-energy resolution: $\mathcal{O}(1\%)$
- Search for a narrow $\gamma\gamma$ invariant mass peak, with $m_H < 150$ GeV
- Background is smooth: extrapolate it into the signal region from the sidebands

INCLUSIVE SEARCHES: $H \to ZZ \to l^+l^-l^+l^-$

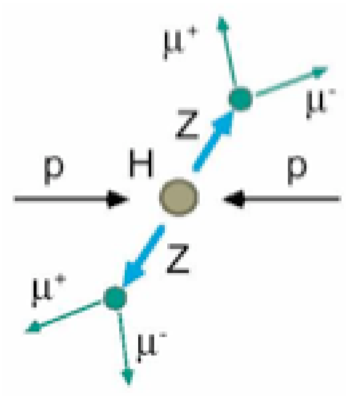


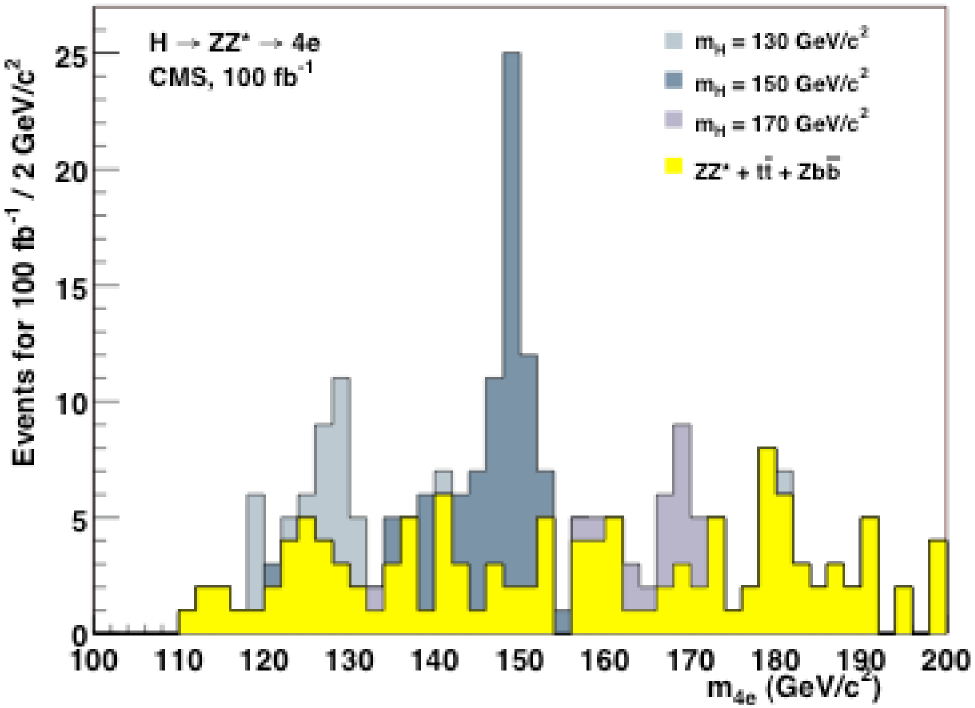


- Gold-plated mode: cleanest mode for $2m_Z < m_H < 600\ \mathrm{GeV}$
- Smooth, irreducible background from $pp \to ZZ$
- Small BR: $\mathrm{BR}(H \to ZZ)$ is a few $\%$ at threshold

INCLUSIVE SEARCHES: $H \to ZZ \to l^+l^-l^+l^-$

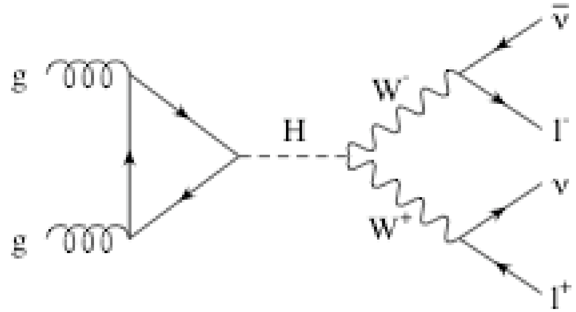
- Fully reconstructed invariant mass of the leptons





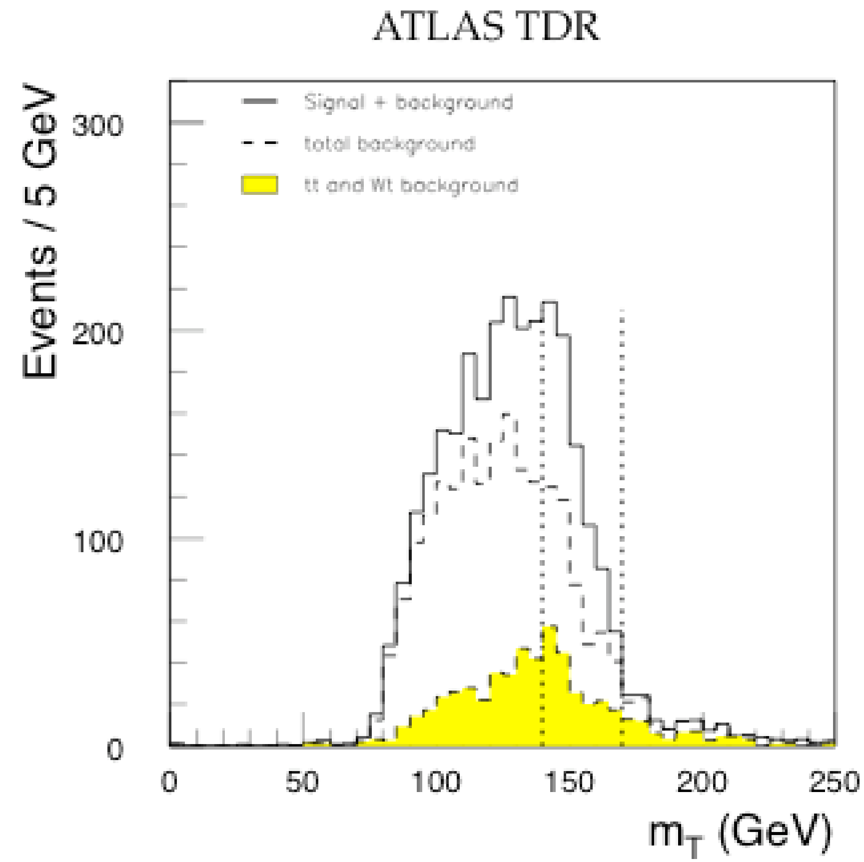
- Silver-plated mode $H \to ZZ \to l^+l^-\nu\bar{\nu}$ useful for $m_H \approx 0.8 - 1\ \mathrm{TeV}$

INCLUSIVE SEARCHES: $H \to WW \to l^+\nu l^-\bar{\nu}$



- Exploit l^+l^- angular correlations

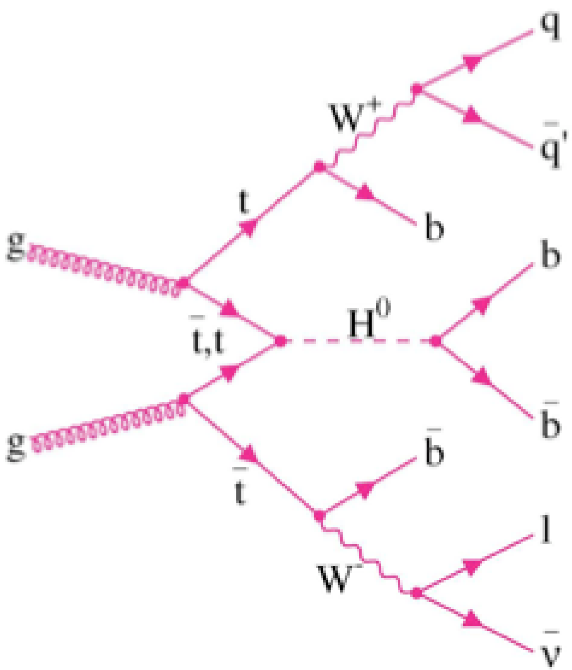
- Signal and background have similar shapes: must know background normalisation well

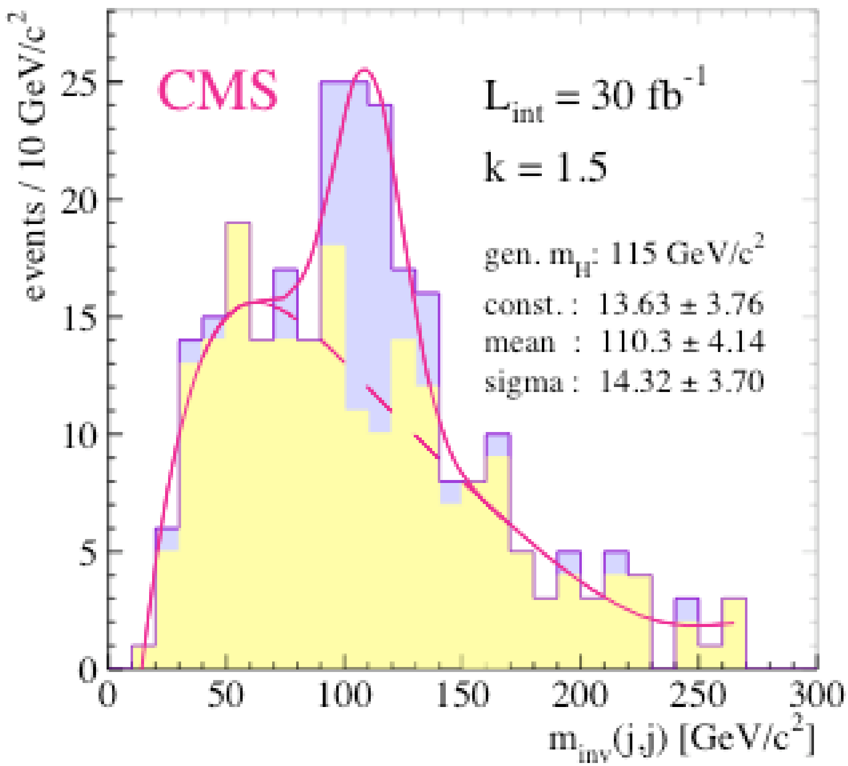


$m_H = 170$ GeV

integrated luminosity: $20\ \text{fb}^{-1}$

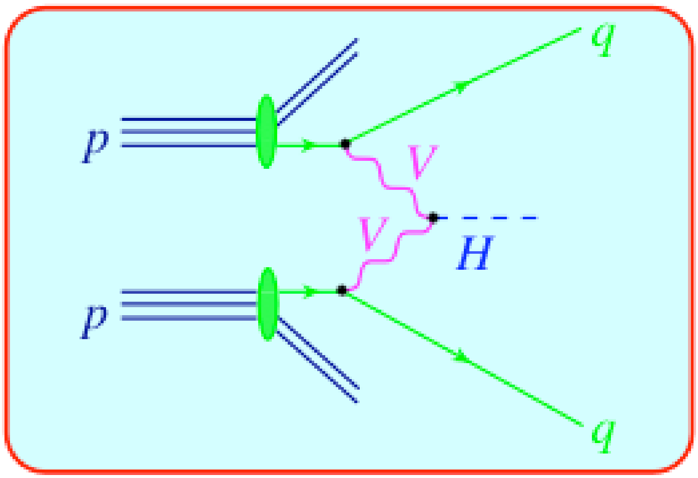
ASSOCIATED PRODUCTION: $Ht\bar{t} \longrightarrow t\bar{t}b\bar{b}$

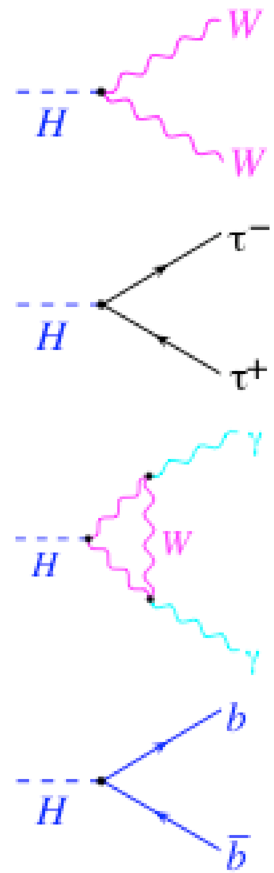




- Search channel for $m_H = 120 - 130$ GeV
- Measure $h_t^2 \, \mathrm{BR}(H \to b\bar{b})$ with $h_t = Ht\bar{t}$ Yukawa coupling
- must know background normalisation well

WEAK BOSON FUSION: $qq \longrightarrow qqH$





$m_H > 120$ GeV

$m_H < 140$ GeV

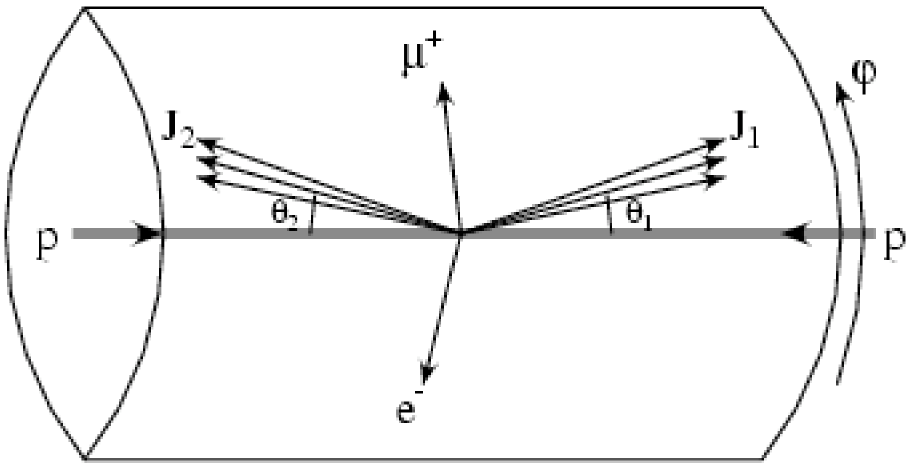
$m_H < 150$ GeV

$m_H < 140$ GeV

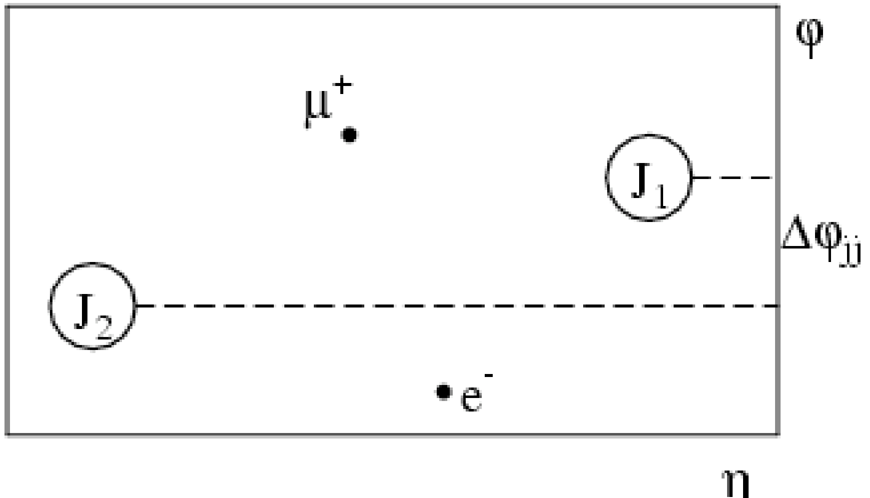
- WBF can be measured with good statistical accuracy:
  $\sigma \times \mathrm{BR} \approx \mathcal{O}(10\%)$

Weak Boson Fusion

A WBF event



Lego plot

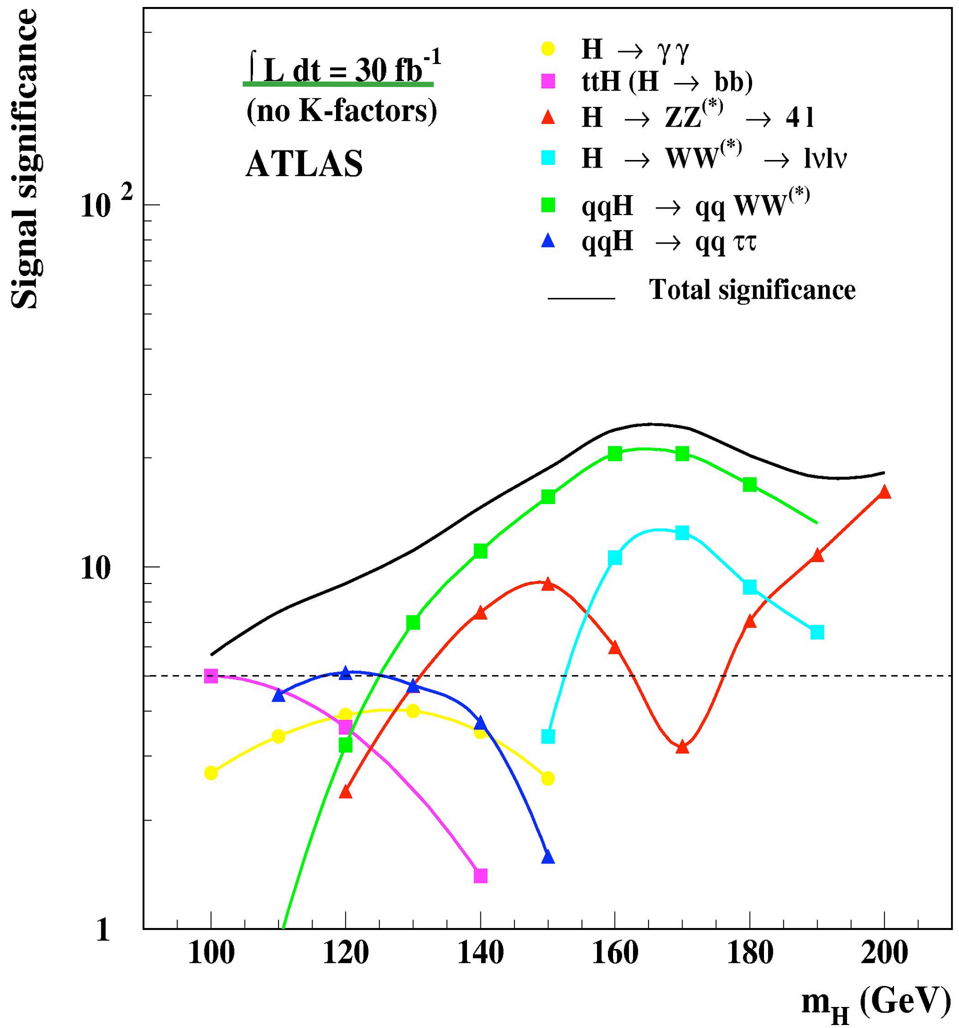


$$\eta = \frac{1}{2} \ln \frac{1+\cos\theta}{1-\cos\theta}$$

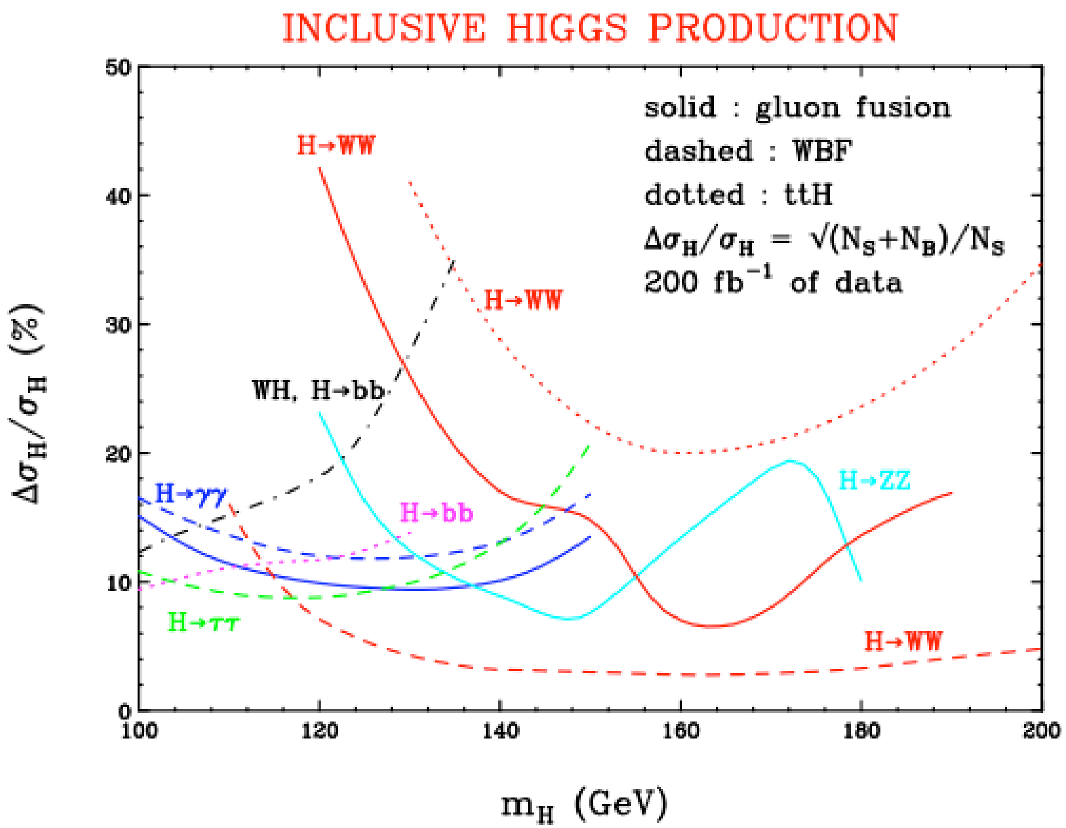
- WBF features
  - energetic jets in the forward and backward directions
  - Higgs decay products between the tagging jets
  - sparse gluon radiation in the central-rapidity region, due to colourless W/Z exchange
  - NLO corrections increase the WBF production rate by about $10\,\%$, and thus are small and under control

Campbell, Ellis; Figy, Oleari, Zeppenfeld 2003

SIGNAL SIGNIFICANCE AND (STAT + SYST) ERROR



Statistical significance: $\frac{N_S}{\sqrt{N_S + N_B}}$



hep-ph/0203187

QCD/p.d.f. uncertainties:

$\mathcal{O}(5\%)$ for WBF

$\mathcal{O}(20\%)$ for gluon fusion

luminosity uncertainties: $\mathcal{O}(5\%)$

Higgs Couplings and Quantum Numbers

The properties of the Higgs-like resonance are its

- couplings: gauge, Yukawa, self-couplings
- quantum numbers: charge, colour, spin, CP

Duehrssen et al.'s analysis hep-ph/0406323

- use narrow-width approx for Γ (fine for $m_H < 200$ GeV)
- production rate with *H* decaying to final state *xx* is

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \frac{\Gamma_p \Gamma_x}{\Gamma}$$

branching ratio for the decay is $\mathrm{BR}(H \to xx) = \dfrac{\Gamma_x}{\Gamma}$

observed rate determines $\dfrac{\Gamma_p \Gamma_x}{\Gamma}$

WBF and gluon-fusion rates yield measurements of combinations of partial widths

$\frac{\Gamma_W \Gamma_\gamma}{\Gamma}$ from $qq \to qqH,\ H \to \gamma\gamma$

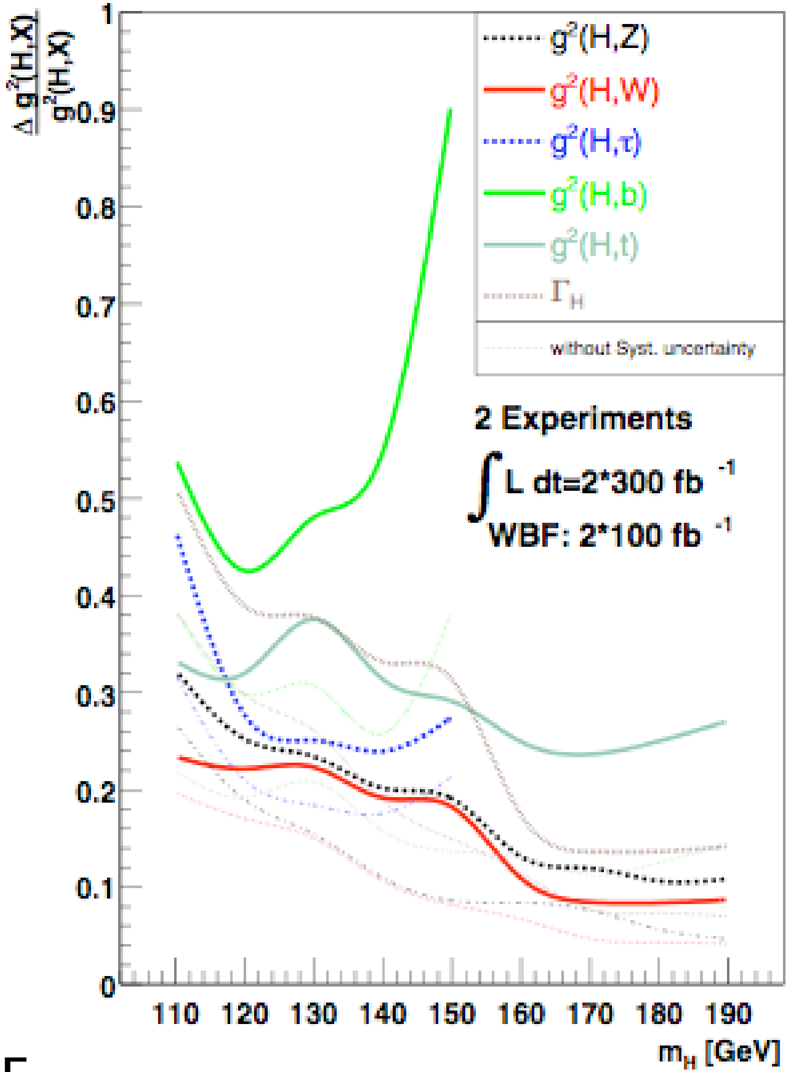
$\frac{\Gamma_W \Gamma_\tau}{\Gamma}$ from $qq \to qqH,\ H \to \tau\tau$

$\frac{\Gamma_W^2}{\Gamma}$ from $qq \to qqH,\ H \to WW^*$

$\frac{\Gamma_g \Gamma_\gamma}{\Gamma}$ from $gg \to H \to \gamma\gamma$

$\frac{\Gamma_g \Gamma_Z}{\Gamma}$ from $gg \to H \to ZZ^*$

$\frac{\Gamma_g \Gamma_W}{\Gamma}$ from $gg \to H \to WW^*$



Note that Γ can be estimated:

direct observation of *H* yields lower bound on Γ

assume $\Gamma_V \leq \Gamma_V^{SM}$ $\quad V = W, Z$

(true in any model with arbitrary # of Higgs doublets ⇒ true in MSSM)

combine $\Gamma_V \leq \Gamma_V^{SM}$ with measure of Γ_V^2/Γ from $H \to VV$

obtain upper bound on Γ

CONCLUSIONS

- The Higgs is the missing link of the Standard Model
- If a Standard Model Higgs is there, LHC will see it with 5 fb^{-1}
- LHC will begin operations in about a year
- It is going to be the most complex scientific undertaking ever