SM Higgs boson Searches

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1. Higgs past searches at LEP

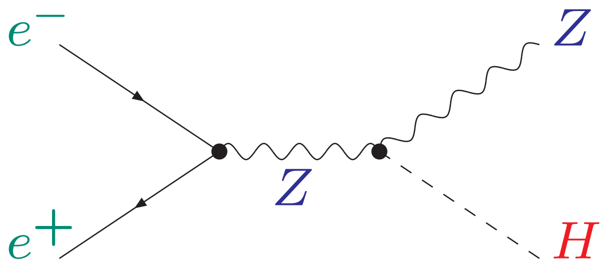
2. Higgs past searches at Tevatron

3. Higgs past, present and future searches at LHC

4. Higgs future searches at ILC

Higgs search at LEP: e^+e^- collisions at CERN

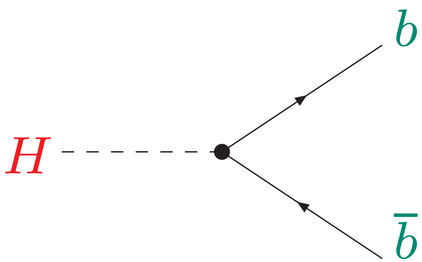
Dominant SM production process: $e^+e^- \to ZH$



$$\sigma(e^+e^- \to ZH) = \frac{G_\mu^2 M_Z^4}{96\,\pi\, s}\left[v_e^2 + a_e^2\right]\beta\,\frac{\beta^2 + 12 M_Z^2/s}{(1 - M_Z^2/s)^2}$$

with $\beta^2 = (1 - (M_H + M_Z)^2/s)\,(1 - (M_H - M_Z)^2/s)$

Dominant decay process: $H \to b\bar{b}$



LEP searches include: 1) 4-jets $(H \to b\bar{b})$ $(Z \to q\bar{q})$, 2) jets + missing E $(H \to b\bar{b})$ $(Z \to \nu\bar{\nu})$ 3) leptonic $(H \to b\bar{b})$ $(Z \to l^+l^-)$ $(l = e, \mu)$ 4) tauonic $(H \to b\bar{b})$ $(Z \to \tau^+\tau^-)$ and $(H \to \tau^+\tau^-)(Z \to q\bar{q})$

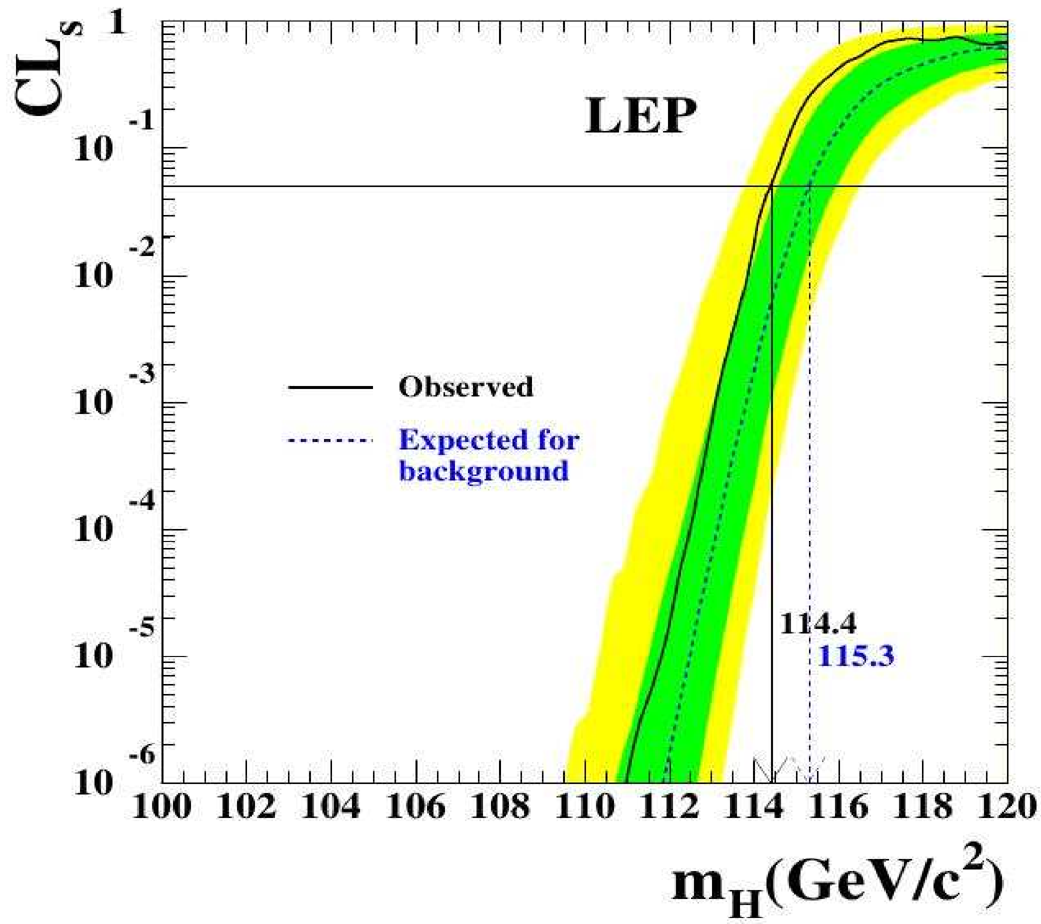
Search for the Standard Model Higgs at LEP: [*LEP Higgs WG '03*]

e^+e^- collisions at CERN
$\sqrt{s} = 189 - 209$ GeV
ALEPH,DELPHI,L3,OPAL
Final data collected (2461 pb^{-1})
$\Rightarrow$ Exclusion limit at the 95% CL:

$$M_H > 114.4 \text{ GeV}$$

expected: 115.3 GeV

$$\text{CL}_s = \text{CL}_{s+b}/\text{CL}_b$$



The confidence CL_{s+b} quantifies the compatibility of the signal (Higgs of mass m_H) plus background hypothesis with the observed events.

The intersection of the horizontal line $\text{CL}_s = 0.05$ with the "observed" curve gives the 95% CL bound.

Yelow band= 68% (1σ), Green band = 95% (2σ) around median expected background.

Similar conclusions with other statistical methods: [*LEP Higgs WG '03*]

Exclusion limit at the 95% C.L.:

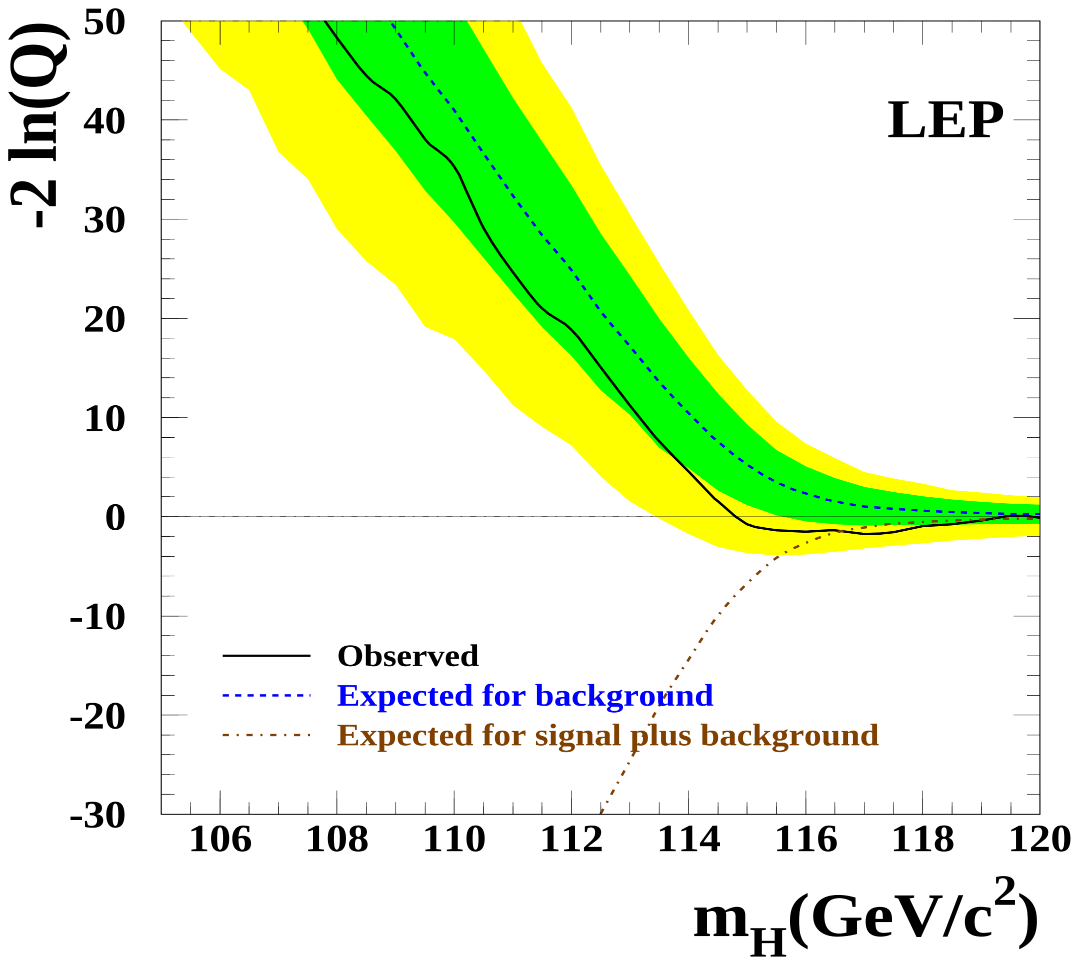
$$M_H > 114.4 \text{ GeV}$$

Test statistic: $-2\ln(Q)$

It measures if the observed data fits better signal+background than just background, and the more negative, the 'better'

$$Q(m_H) = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b}$$

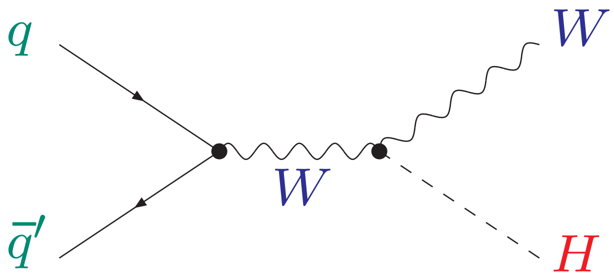
Ratio of the likelihood function for the signal (Higgs of mass m_H) plus background hypothesis to the likelihood function for the background hypothesis.

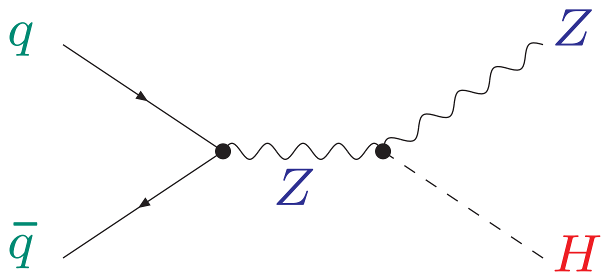


Higgs search at the Tevatron

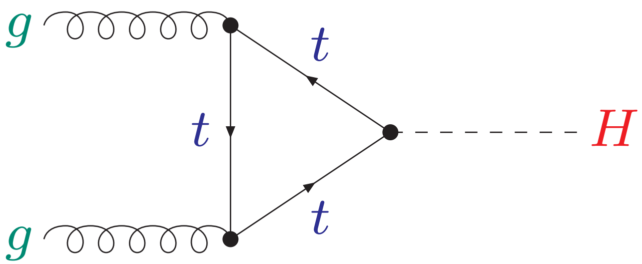
Tevatron: $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV:

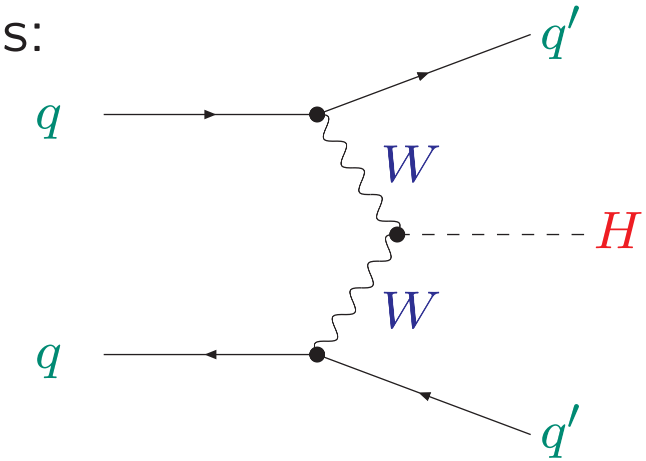
Production processes (similar to LEP):



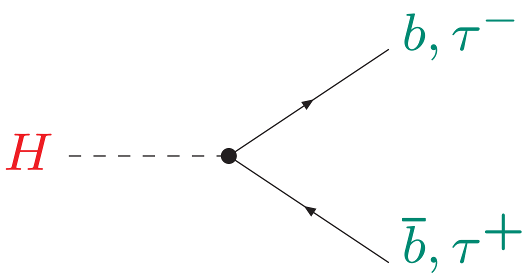


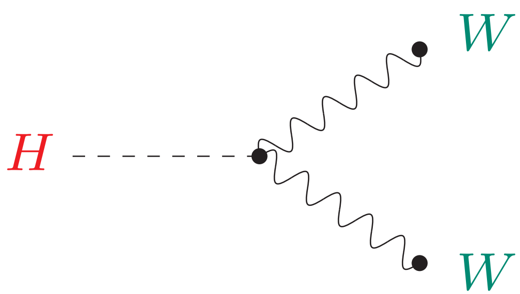
Other important production channels:





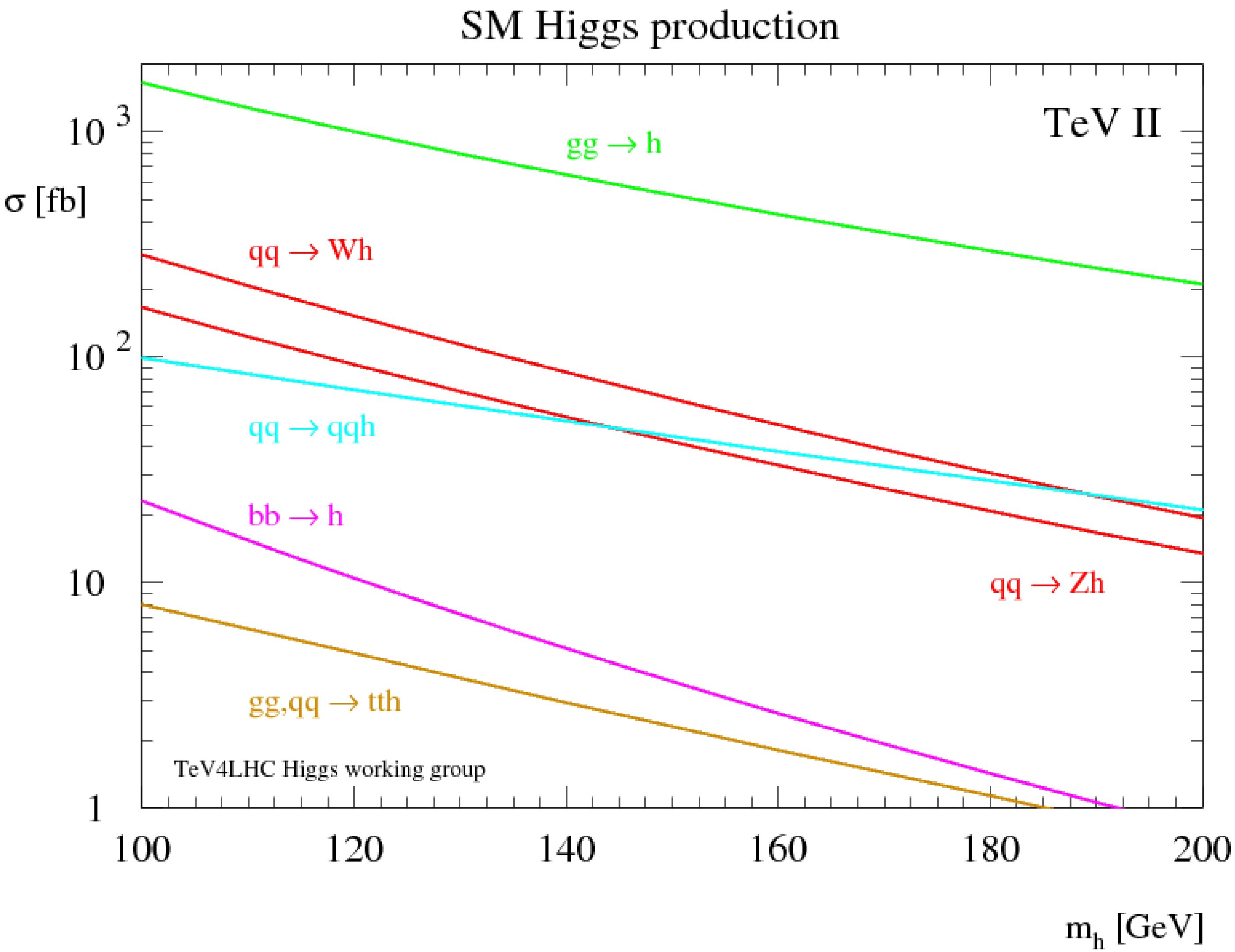
Dominant decays:



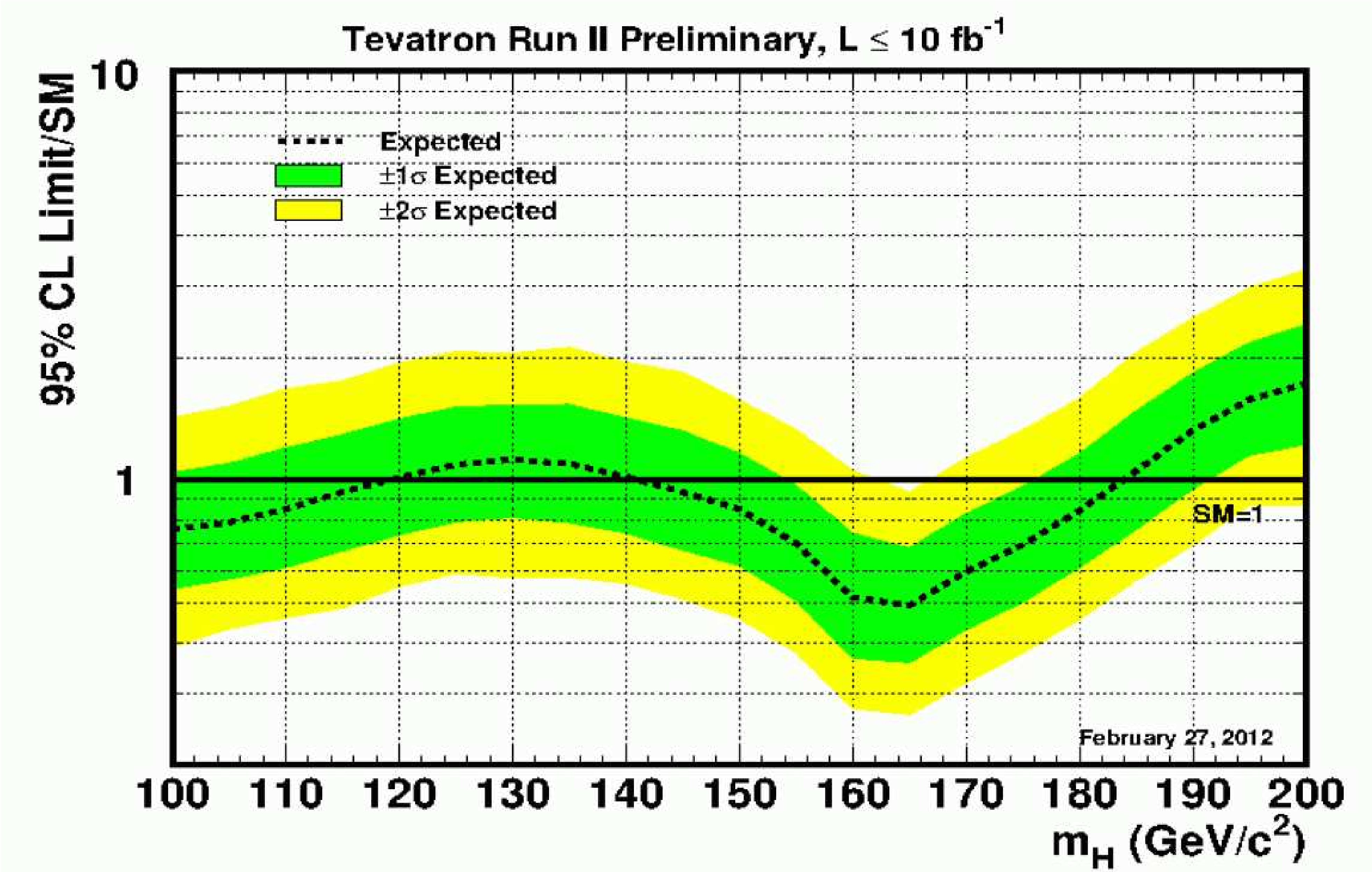


Overview of SM production cross sections:

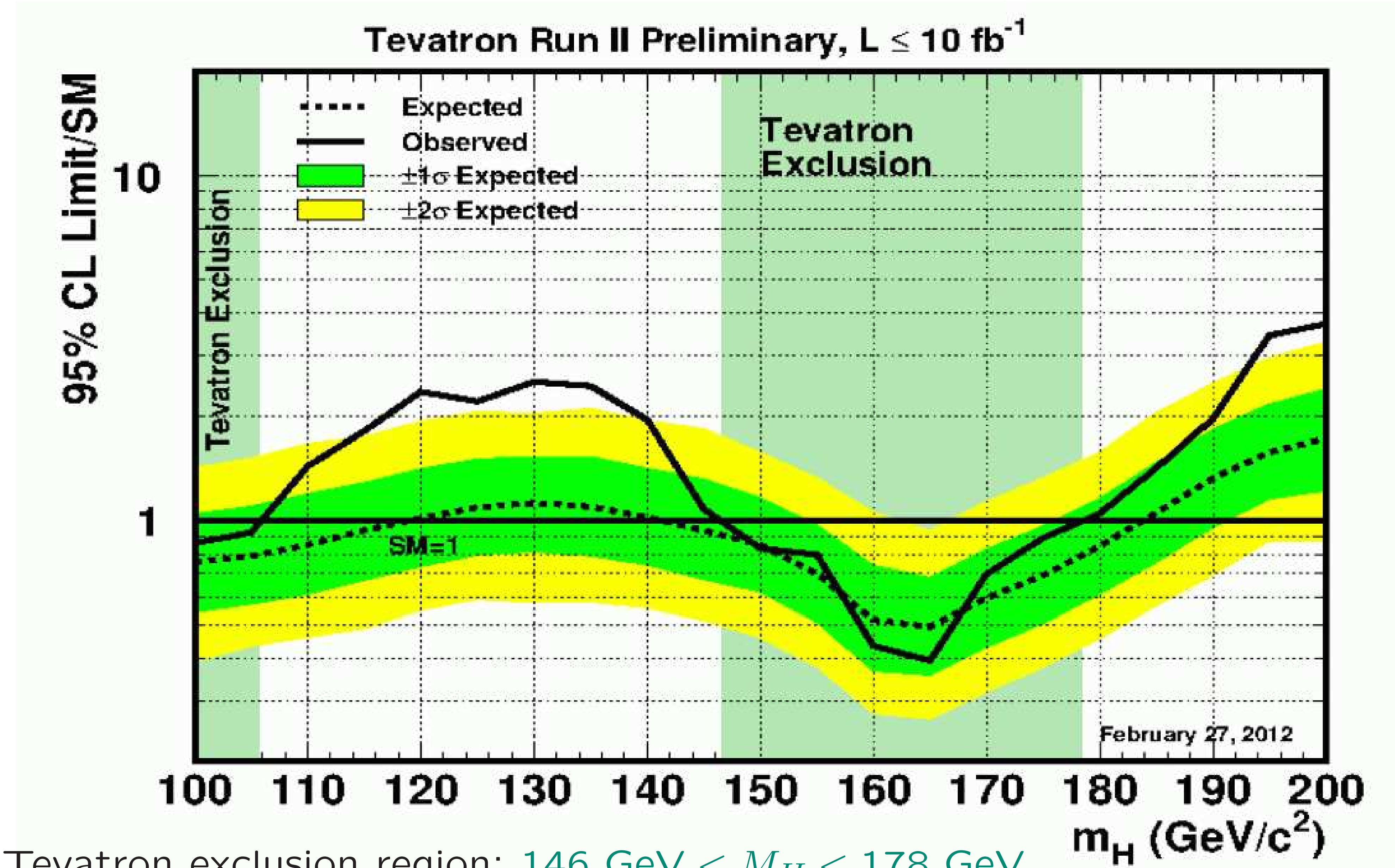
[*F. Maltoni et al. '05*]



Final result of SM Higgs searches at the Tevatron: Expected

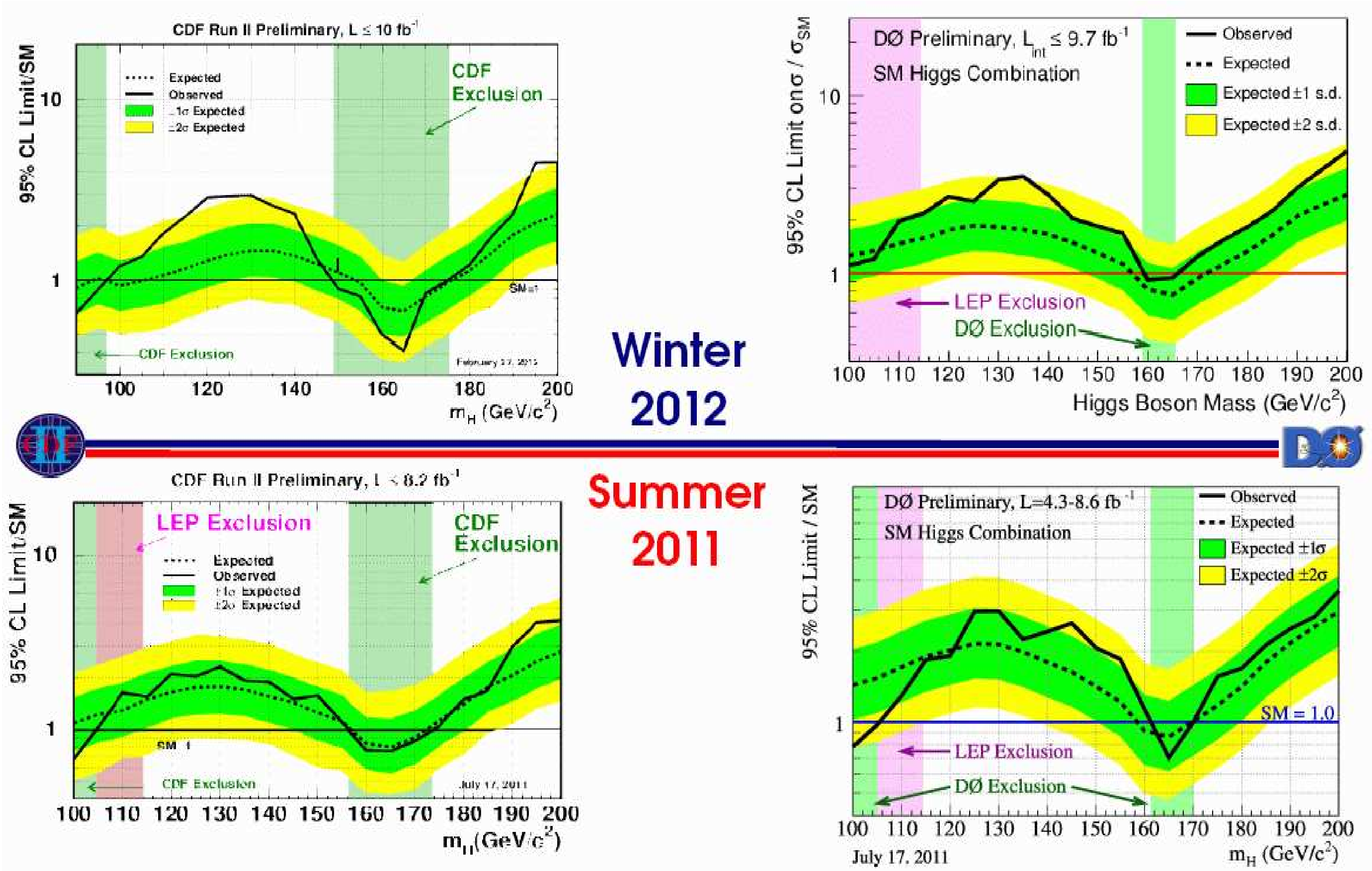


Final result of SM Higgs searches at the Tevatron: Observed



Tevatron exclusion region: 146 GeV $< M_H <$ 178 GeV

Interesting evolution in time of Tevatron plots:

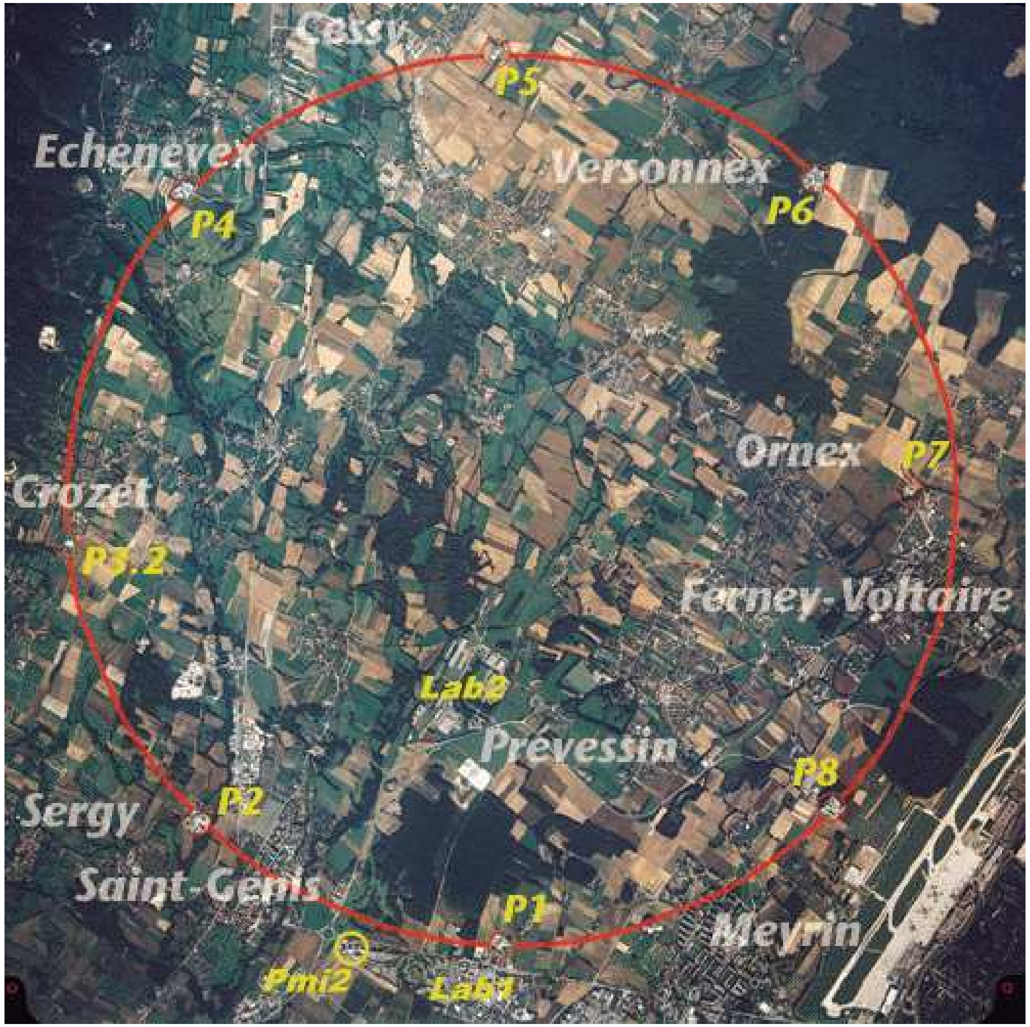


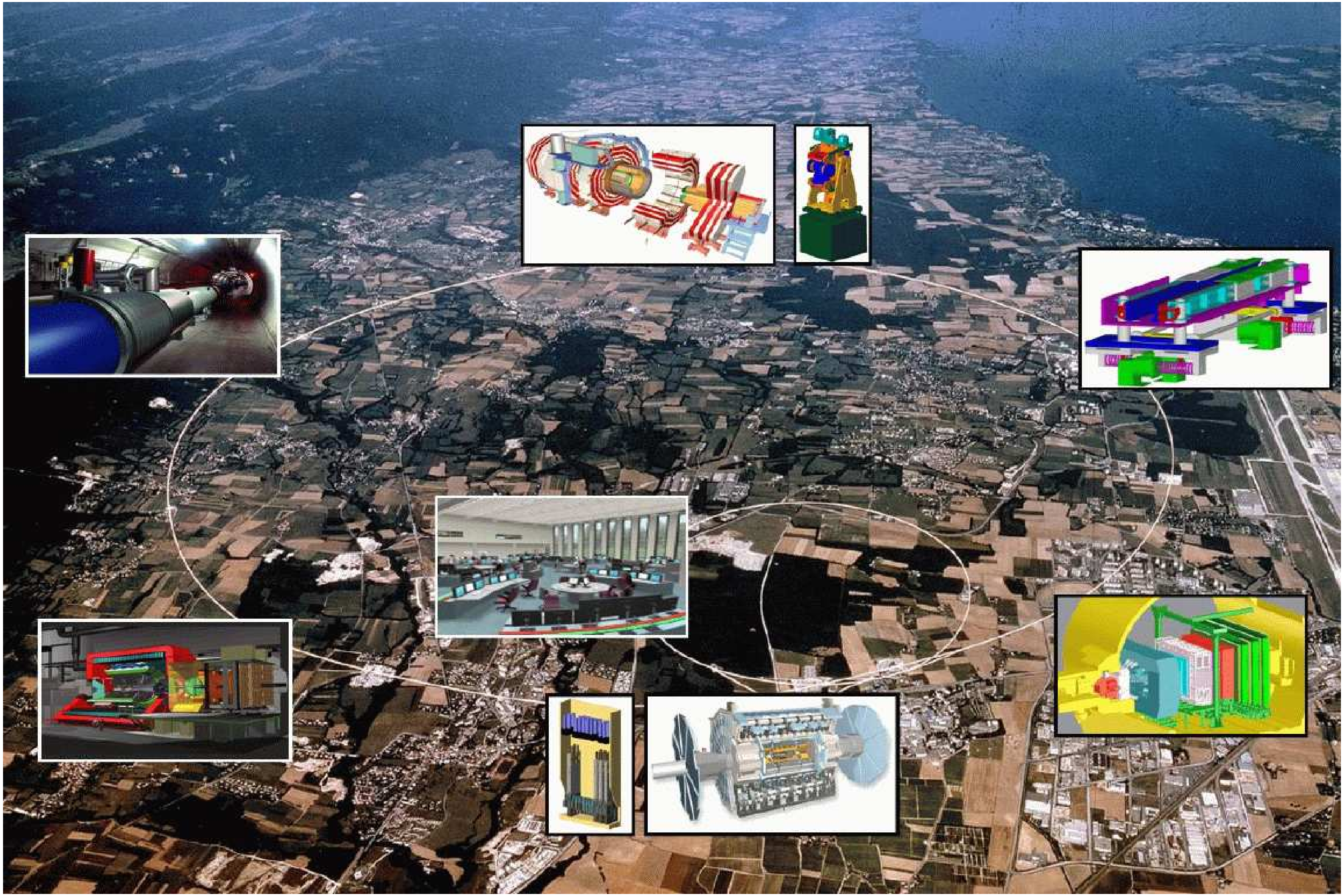
1. The Large Hadron Collider, LHC

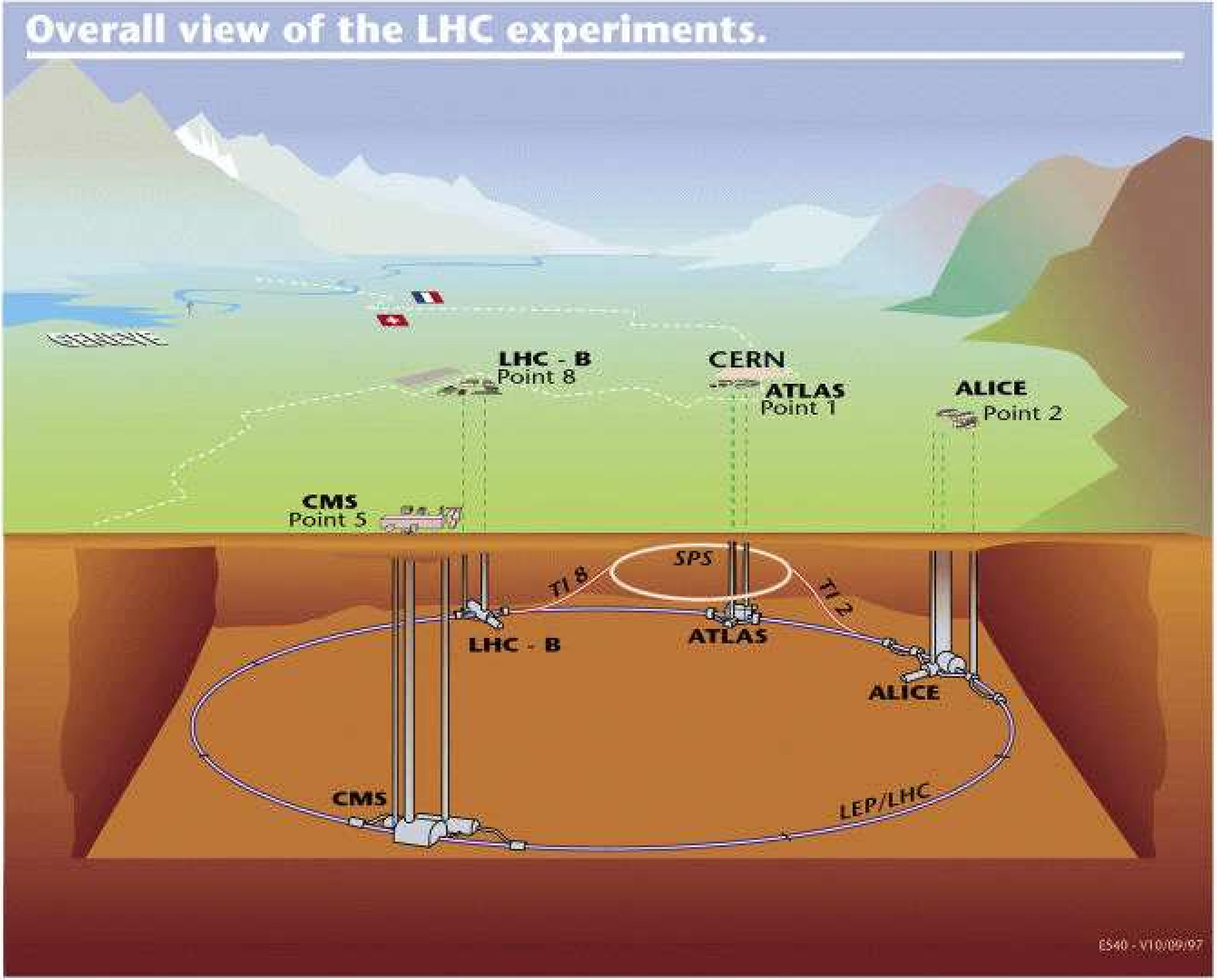
LHC:

$p\,p$ collisions at $\sqrt{s} = 14$ TeV

- 27 km circumference
- two general purpose detectors: ATLAS and CMS
- one B physics detector: LHCb
- one heavy ion detector: Alice






Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

The (un)official (optimistic?) LHC time line:

03/2010: first collisions at record breaking energy

2010: $\lesssim 0.05\,\text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV)

2011: $\lesssim 5\,\text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV) $\Rightarrow$ first physics results!

2012: $\lesssim 10\,\text{fb}^{-1}$ (at $\sqrt{s} = 8$ TeV) $\Rightarrow$ more physics results!!

2013: shutdown, further splice checks, repairs, . . .

2014 – 2016: $10\,\text{fb}^{-1}$ per year $\Rightarrow$ physics results with "low" luminosity

2017: shutdown, preparation for "high luminosity"

2018 – 2020: $100\,\text{fb}^{-1}$ per year $\Rightarrow$ physics results with "high" luminosity

2021: upgrade to sLHC with $\sqrt{s} = 14$ TeV?

2022 + X (X > 0): sLHC?

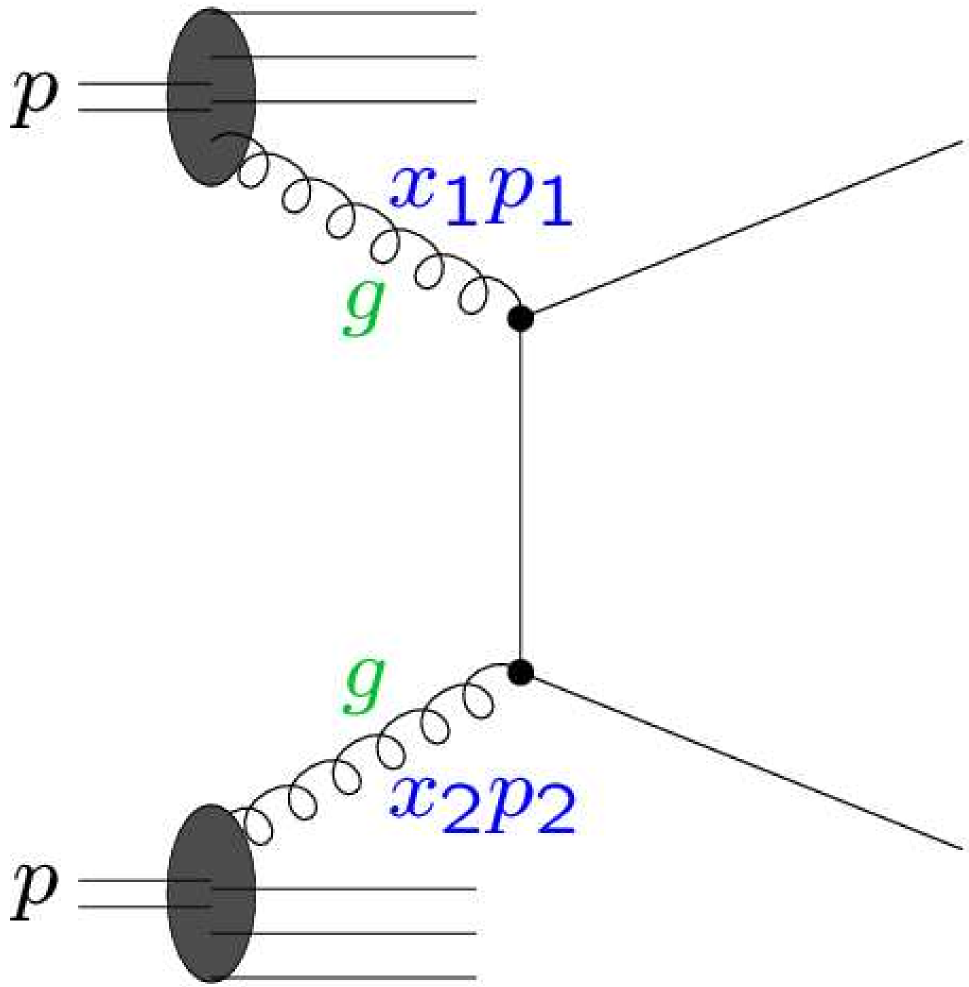
After the recent discovery of 4th July 2012, there have been changes:
Three more months of running at $8\,TeV$ before the shutdown...
Maybe more changes if more discoveries........(?)

Physics at the LHC: basics

$p\,p$ scattering at $\sqrt{s} = 14$ TeV

Scattering process of proton constituents (q, $\bar{q}$, g) with energy up to several TeV, strongly interacting

$\Rightarrow$ huge QCD backgrounds, low signal–to–background ratios



interaction rate of 10^9 events$/s$

$\Rightarrow$ can trigger on only 1 event in 10^7

How to calculate cross sections at the LHC?

First step:

Calculate cross section for incoming partons and outgoing X:

$$\hat{\sigma}(ij \to X),\ i,j = q,\bar{q},g$$

Perturbative calculation is possible:

– α_s is sufficiently small at LHC energies

– α is sufficiently small anyway

Still to be done:

1. connect incoming quarks and gluons with the (incoming) colliding protons

2. connect the outgoing particles with the observed (outgoing) jets

Making the connections:

1. To connect protons with quarks an gluons we need to know the probability that a quark or gluon is carrying a certain fraction x of the proton momentum,
   provided by parton distribution functions (PDFs):

   $$f_i(x, \mu_f)$$

   μ_f: factorization scale

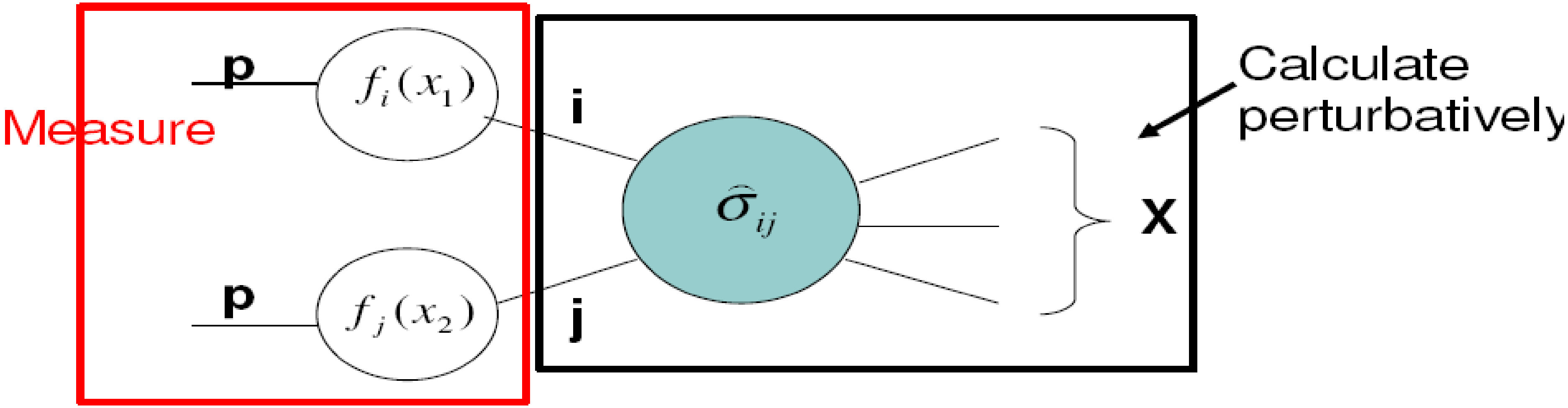
2. at lowest order: each outgoing quark or gluon is identified with a hadronic jet – provided they are well separated in
   pseudo-rapidity – azimuth space:

   $$\Delta R := \left(\Delta\eta^2 + \Delta\Phi^2\right)^{-1/2} > R_{\text{min}}$$

   Φ: angle in plane perpendicular to beam axis
   η : pseudo rapidity: $\eta = -\log(\tan\theta/2)$

The Master formula for all LHC cross section calculations:

$$\sigma(pp \to X) = \sum_{ij} \int dx_1 dx_2\, f_i(x_1, \mu_f)\, f_j(x_2, \mu_f)\, \hat{\sigma}(ij \to X)$$



$x_{1,2}$: momentum fraction carried by the incoming quarks, gluons
$\hat{\sigma}$: partonic cross section, calculated perturbatively

Parton Density Functions (PDFs):

- PDFs cannot be calculated perturbatively
  $\Rightarrow$ they have to be measured experimentally (at a certain scale)

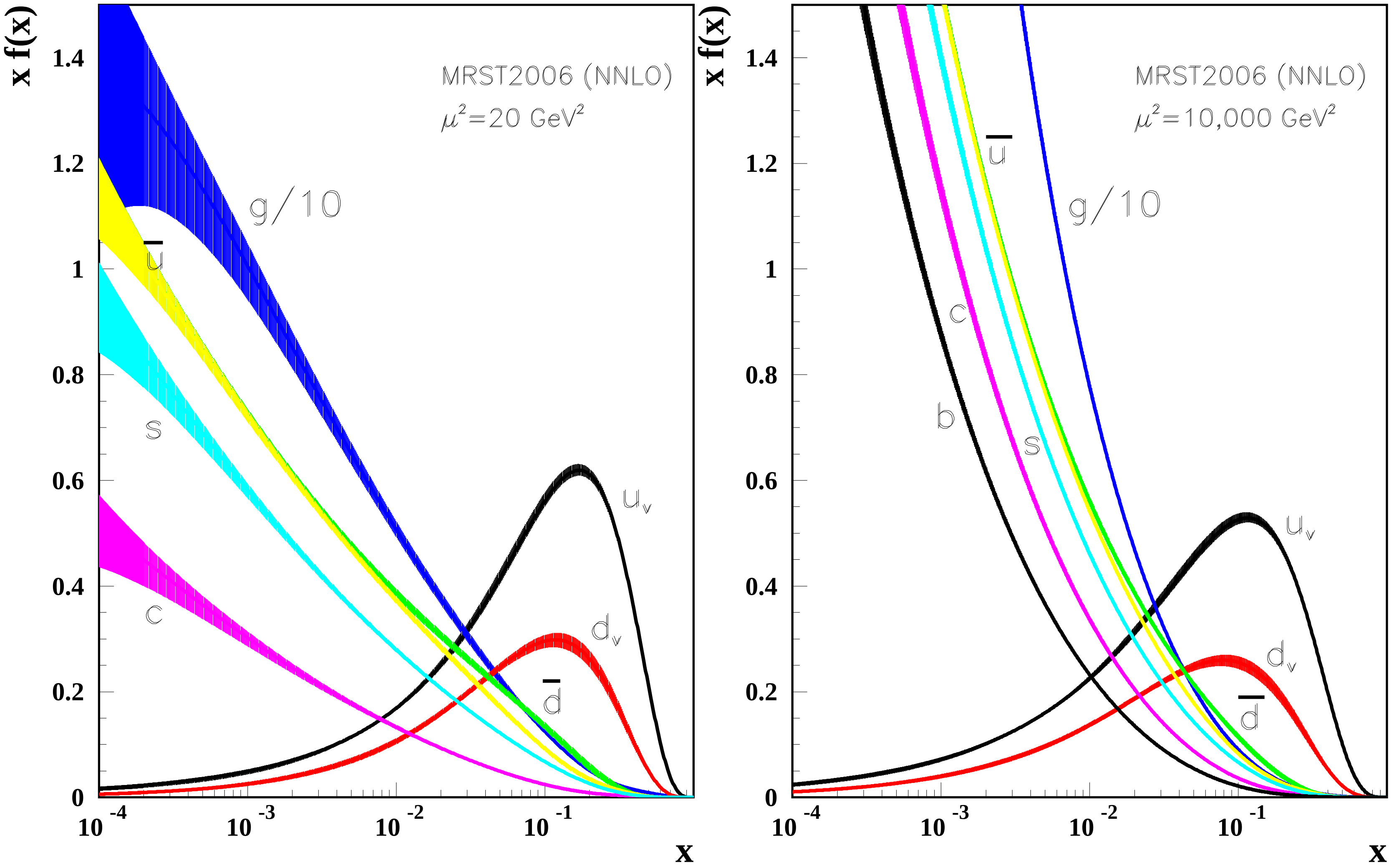
- QCD predicts the evolution of the PDFs via the
  Altarelli-Parisi equations,
  i.e. once we know the PDFs for a certain scale, QCD predicts them for all other scales

- PDFs are universal, e.g. PDFs determined at HERA can directly be used for LHC calculations

- PDFs are different for valence and sea quarks

- PDFs come in the form of Fortran codes, mainly by two groups:
  MRST and CTEQ collaborations

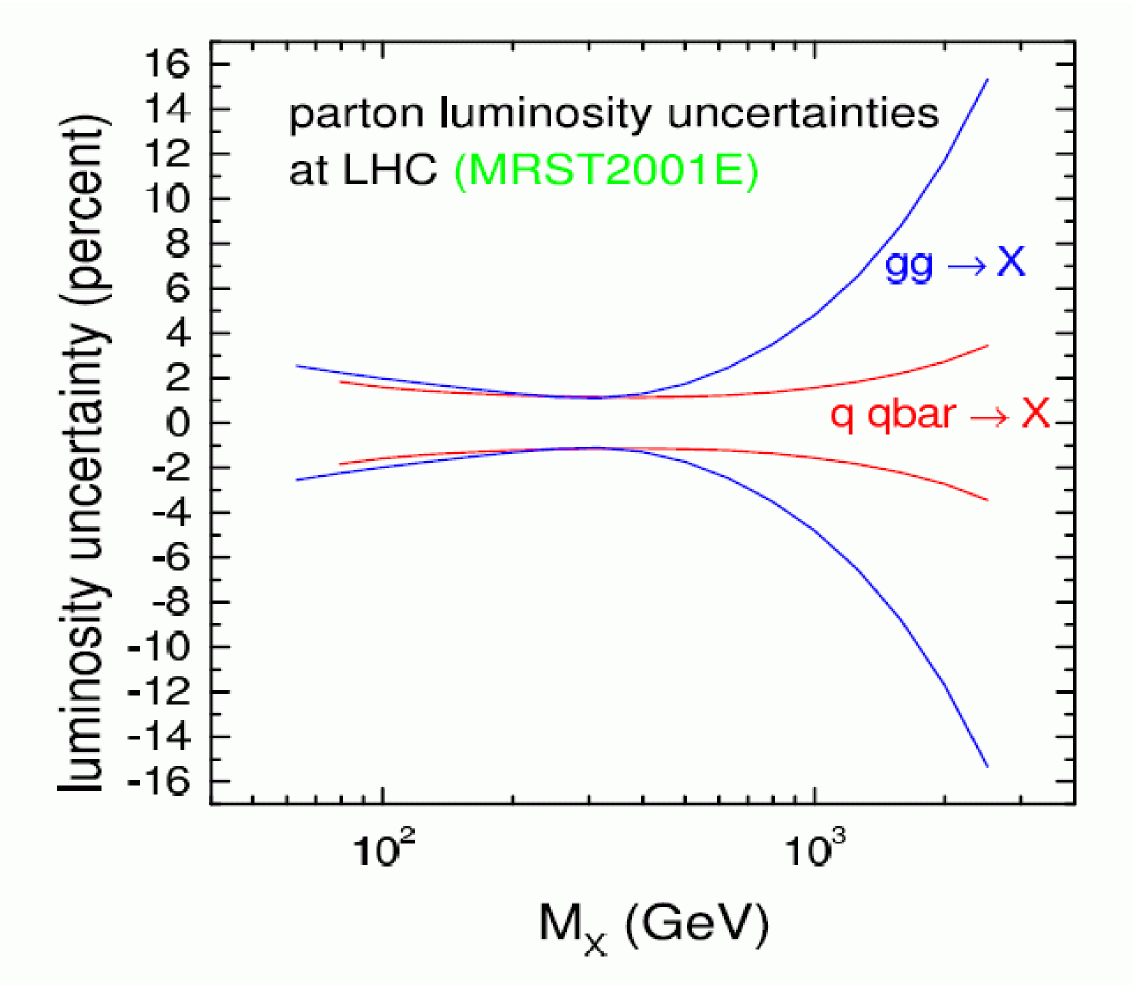
Example for PDFs of the proton:



$\Rightarrow$ The LHC is (mainly) a gluon gluon collider

Uncertainties in cross section calculations

induced by uncertainties in PDFs:



Final state X
with mass M_X:

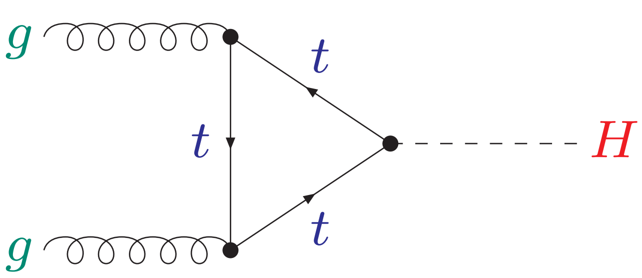
PDF induced uncertainties
mostly below 5%

[MRST, CTEQ, Alekhin, . . .]

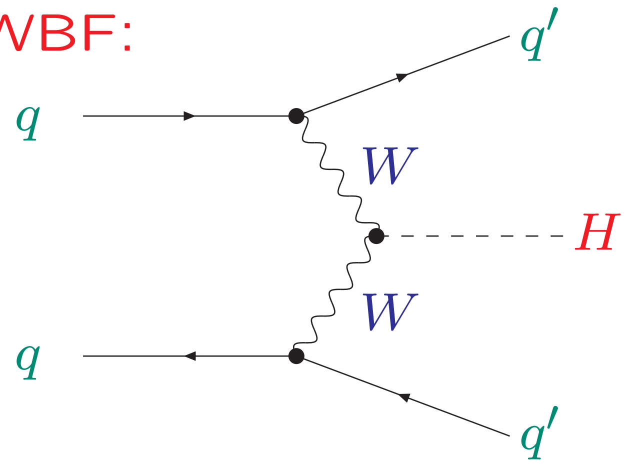
Higgs search at the LHC:

Important SM production channel at the LHC:

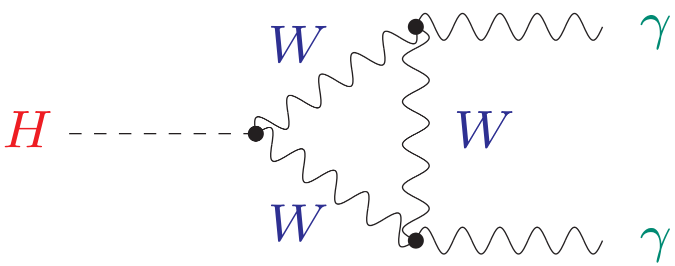
Gluon-Fusion:

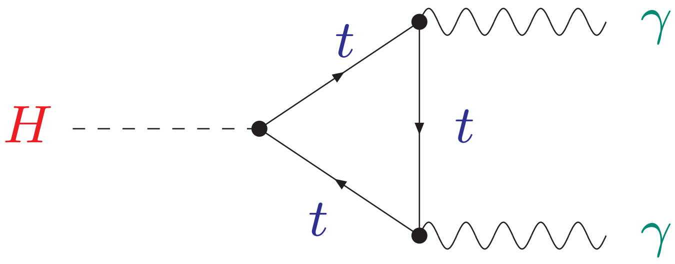


WBF:

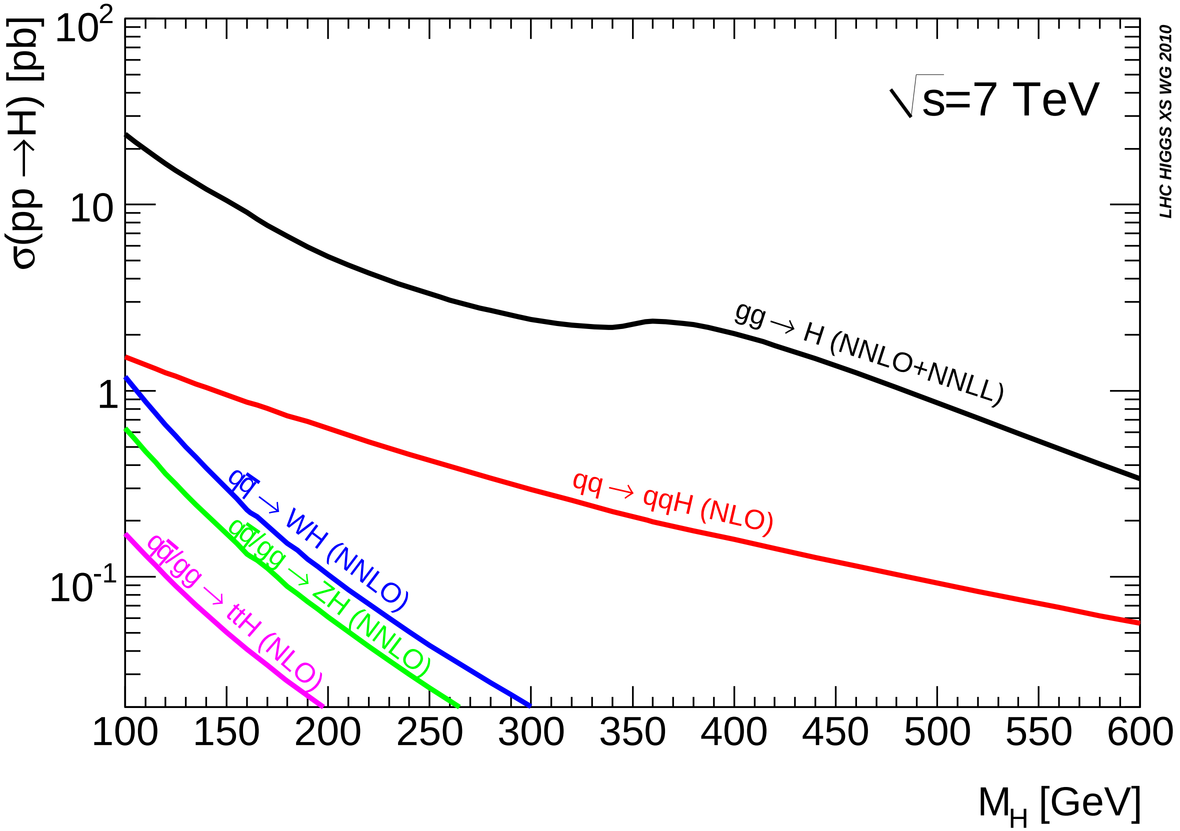


Important decay for Higgs mass measurement:





Overview of SM Higgs production at the LHC @ 7 TeV:



gluon fusion: $gg \to H$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

top quark associated production: $gg, q\bar{q} \to t\bar{t}H$

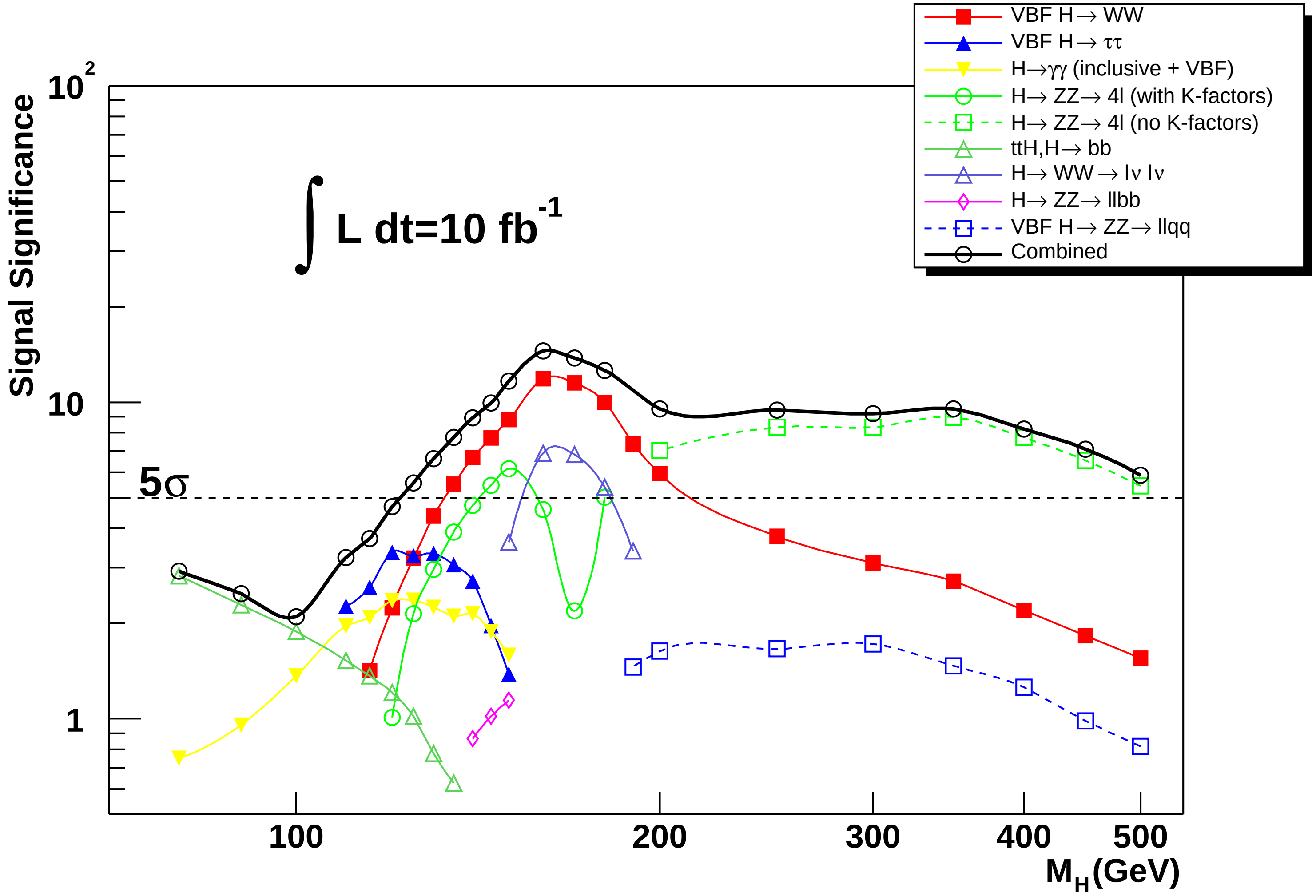
weak boson associated production: $q\bar{q}' \to WH, ZH$

SM Higgs search at the LHC: $\Rightarrow$ full parameter space accessible!?

SM Higgs search at the LHC: expectations

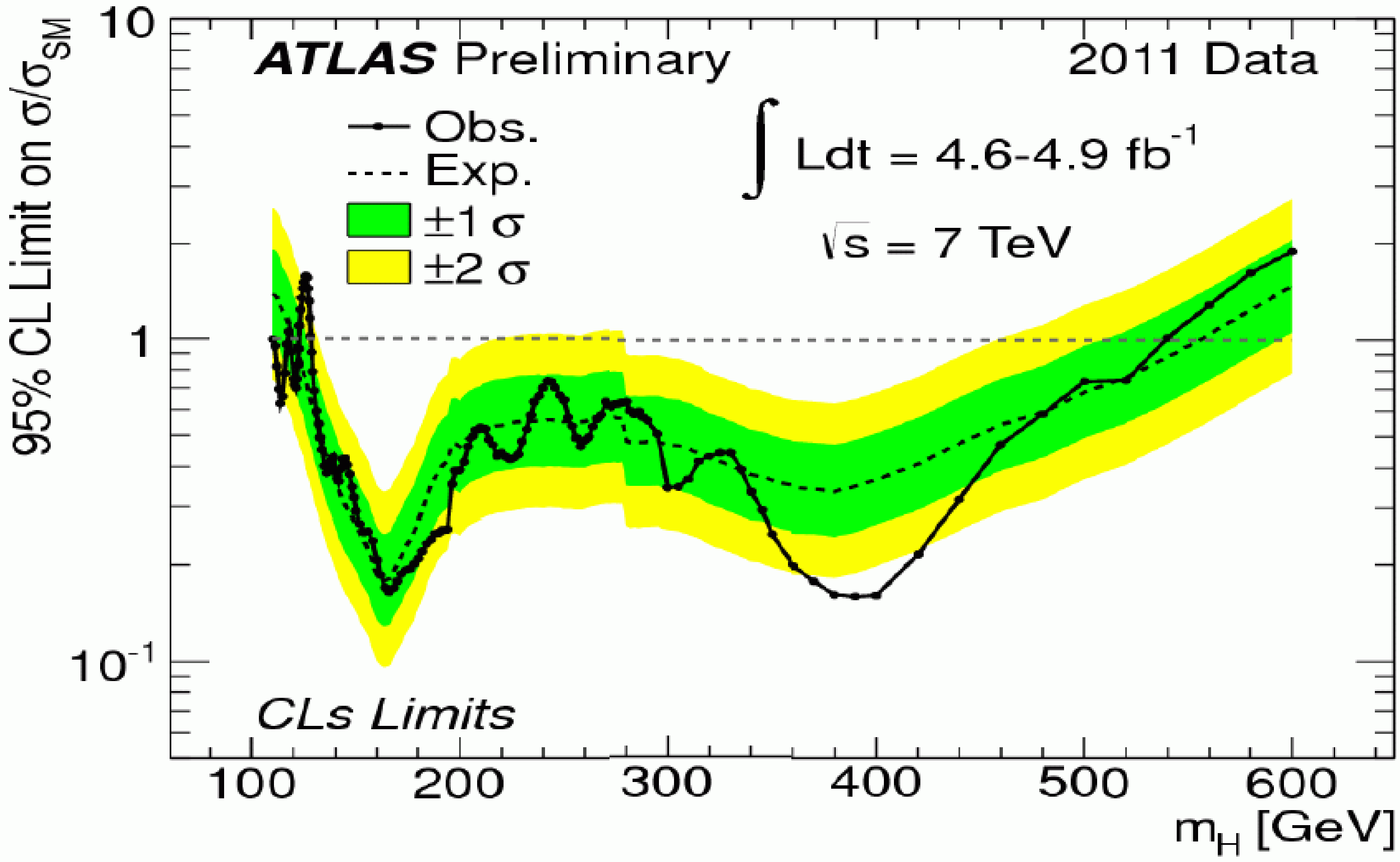
⇒ full parameter space accessible

[ATLAS '05]



LHC results on Higgs searches

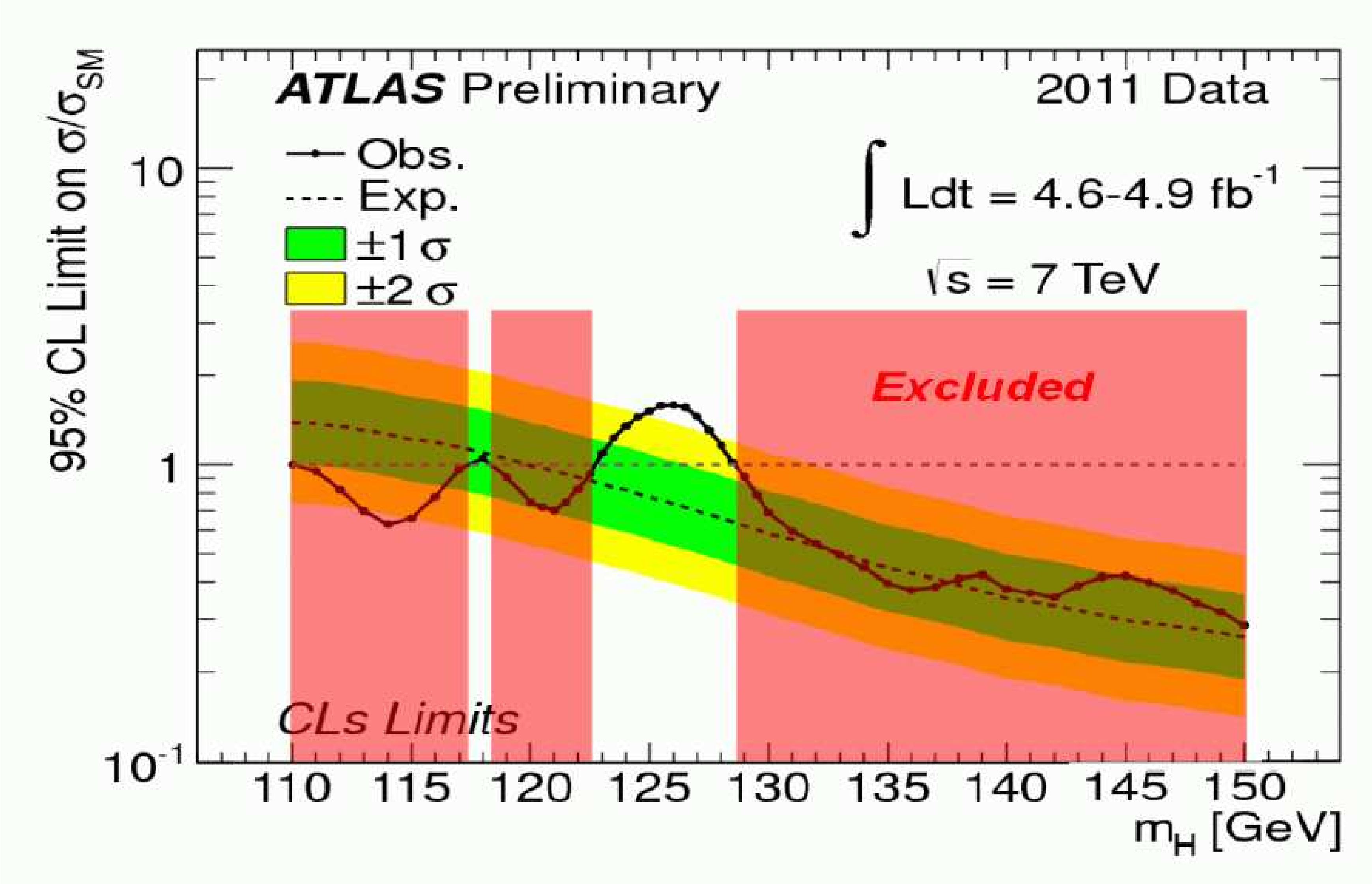
ATLAS results in search for a SM Higgs (before 4th July) [ATLAS '12]



Excluded intervals: $110 - 117.5, 118.5 - 122.5, 129 - 539$ GeV

Small excess for $M_H \simeq 126$ GeV

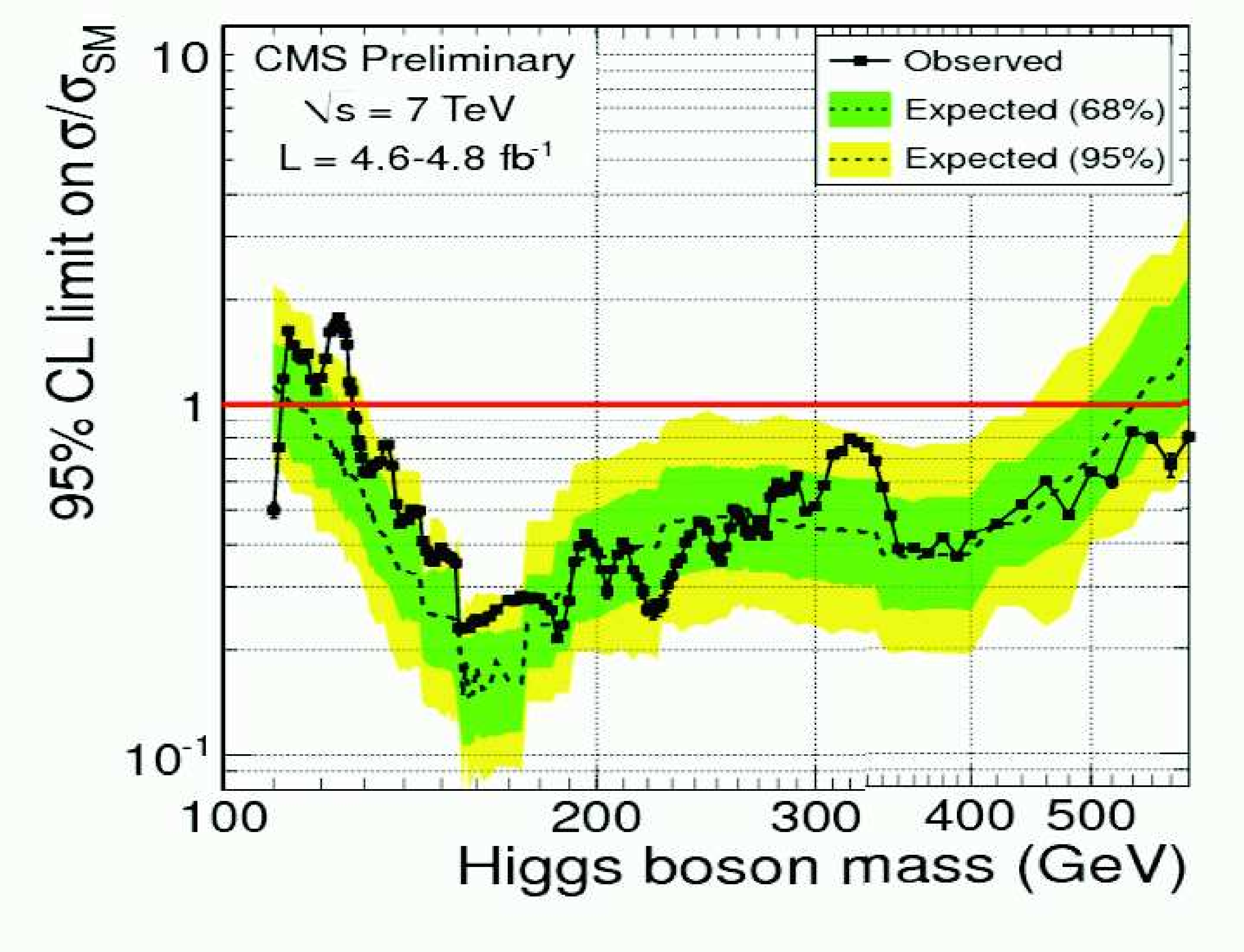
ATLAS results in search for a SM Higgs (zoom) (before 4th July) [*ATLAS '12*]



Excluded intervals: $110 - 117.5, 118.5 - 122.5, 129 - 539$ GeV

Small excess for $M_H \simeq 126$ GeV

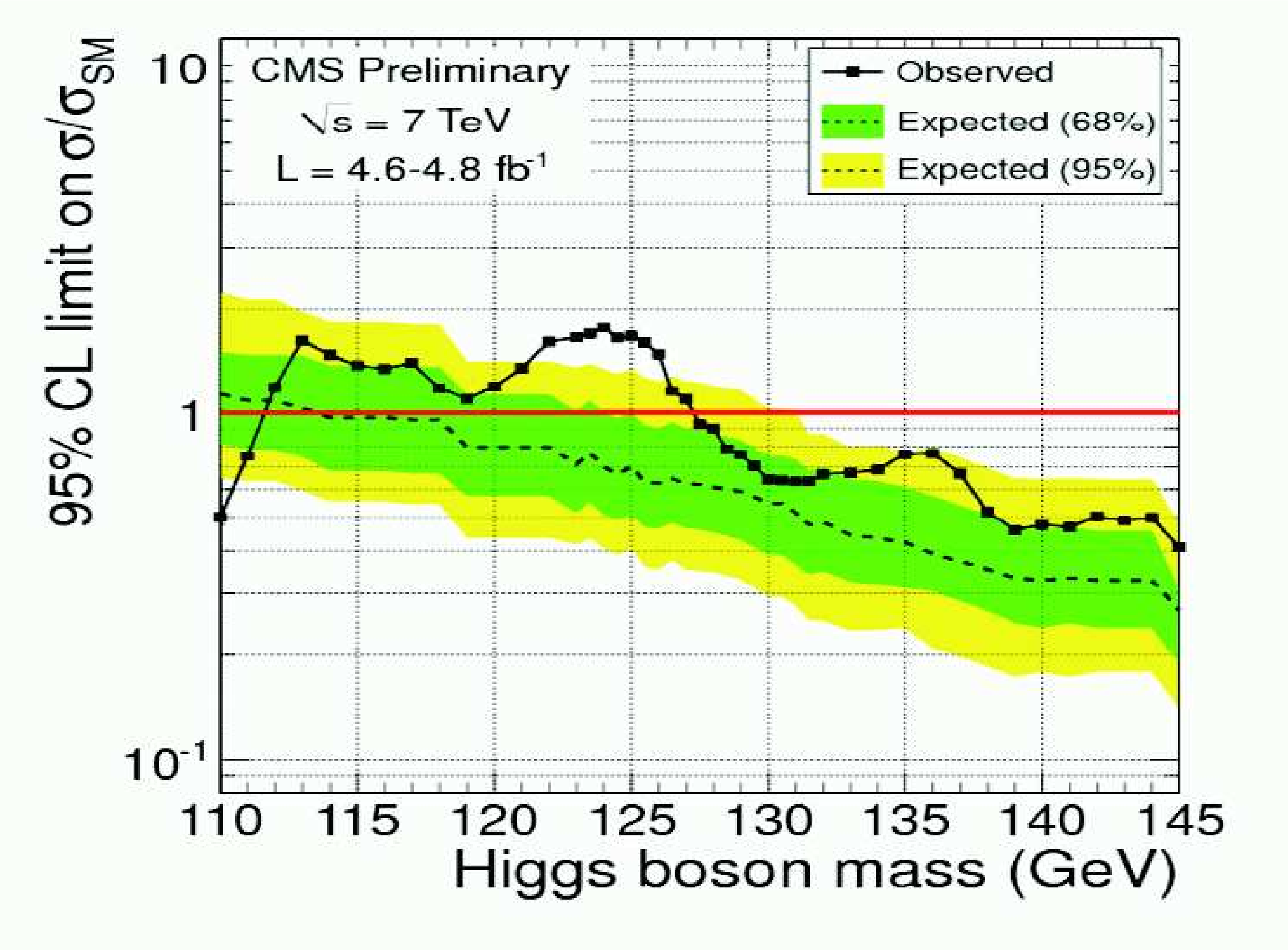
CMS results in search for a SM Higgs (before 4th July) [*CMS '12*]



Excluded interval: 127.5 – 600 GeV

Small excess for $M_H \simeq 125$ GeV

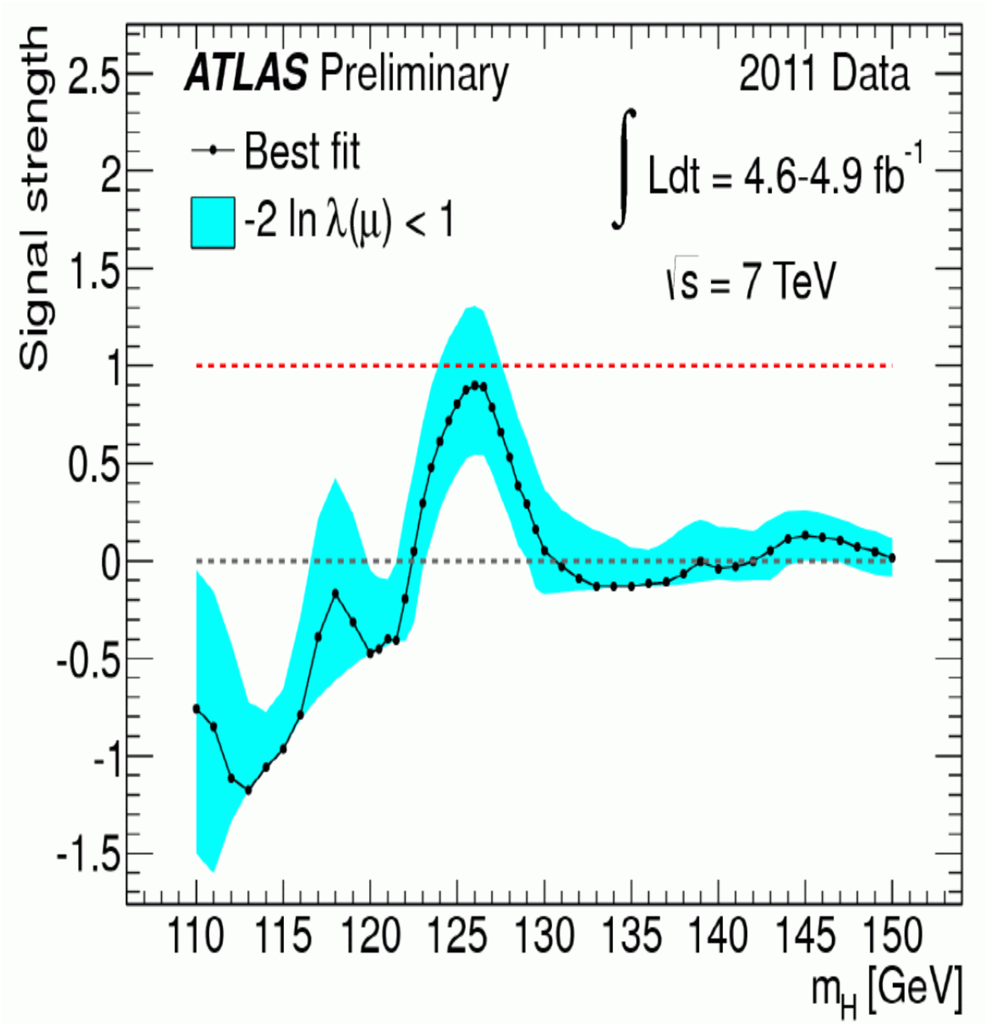
CMS results in search for a SM Higgs (zoom)(before 4th July) [*CMS '12*]

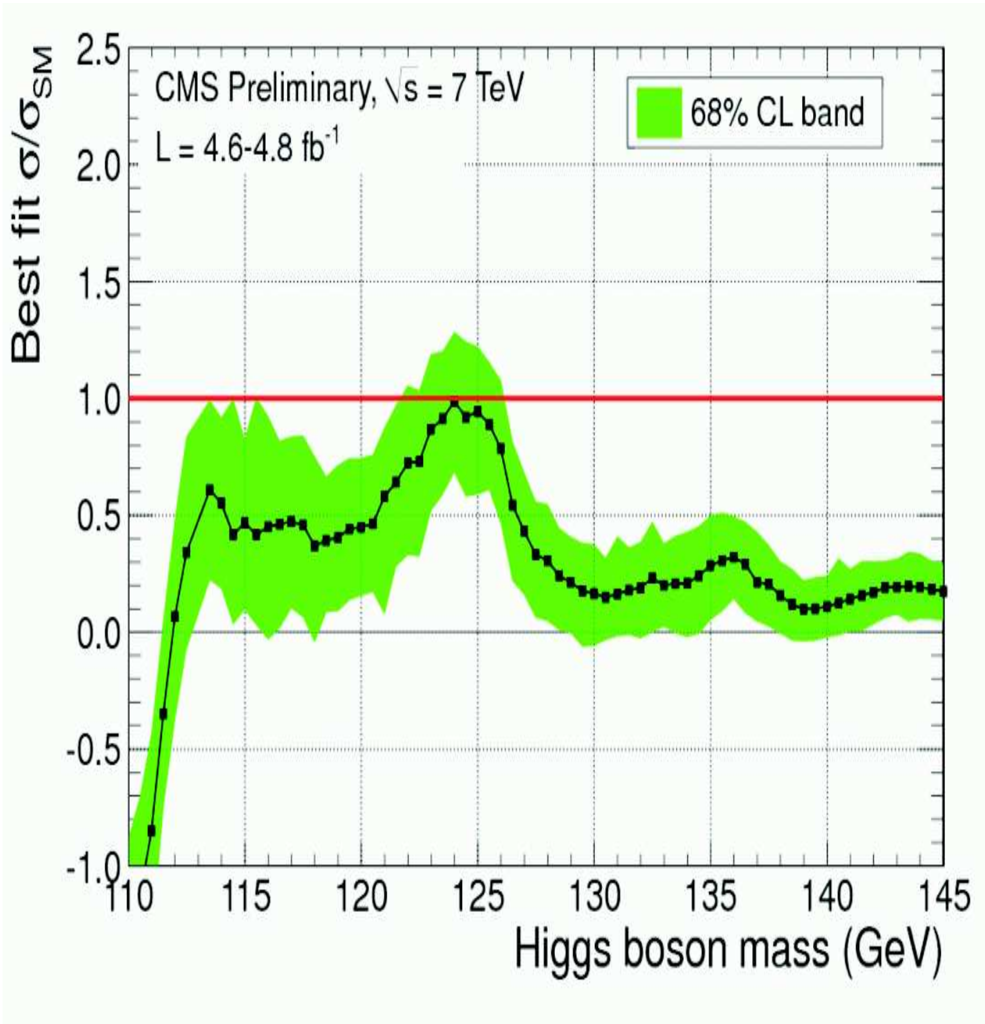


Excluded interval: 127.5 – 600 GeV

Small excess for $M_H \simeq 125$ GeV

Signal strength (before 4th July)





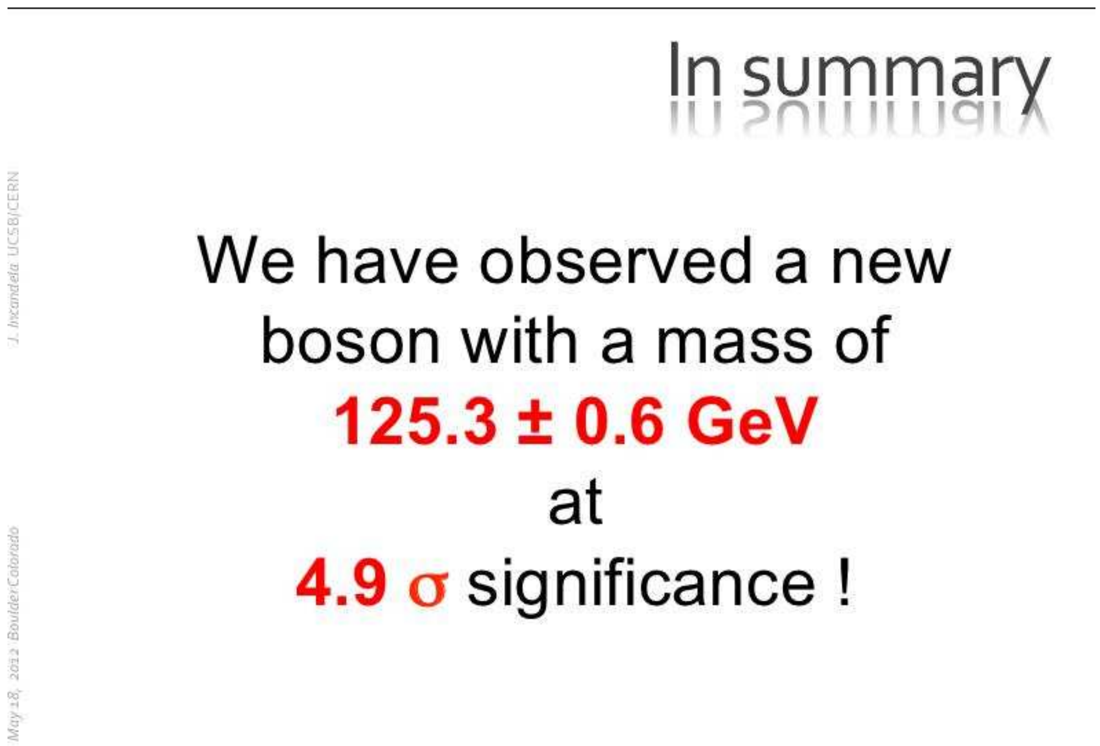
The great news of

4th July 2012......

The great news of July 2012: I

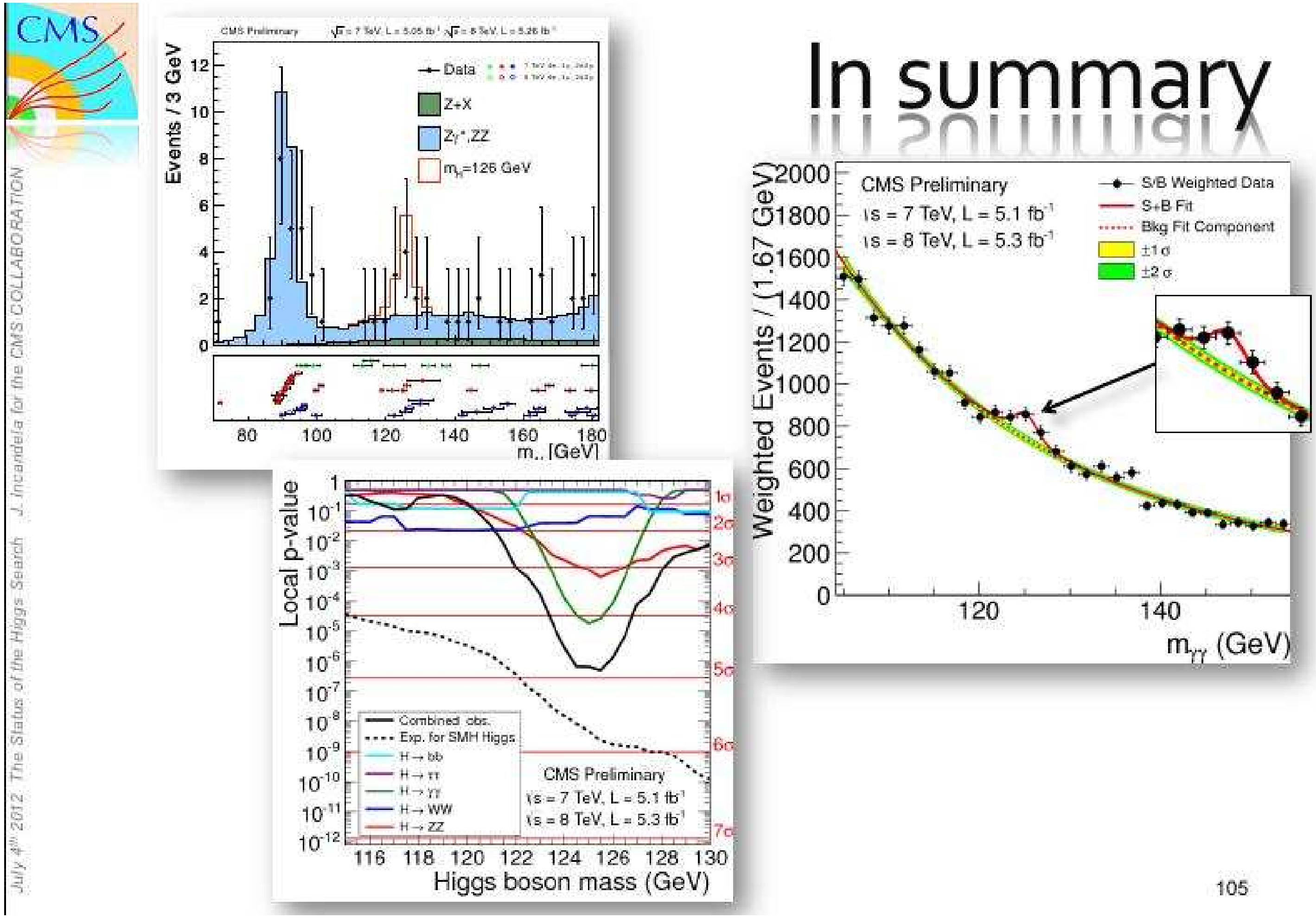
On 4th July 2012, the CMS and ATLAS collaborations have announced the observation of a new boson!!!!! .

For instance, CMS (Joe Incandela) last slide:



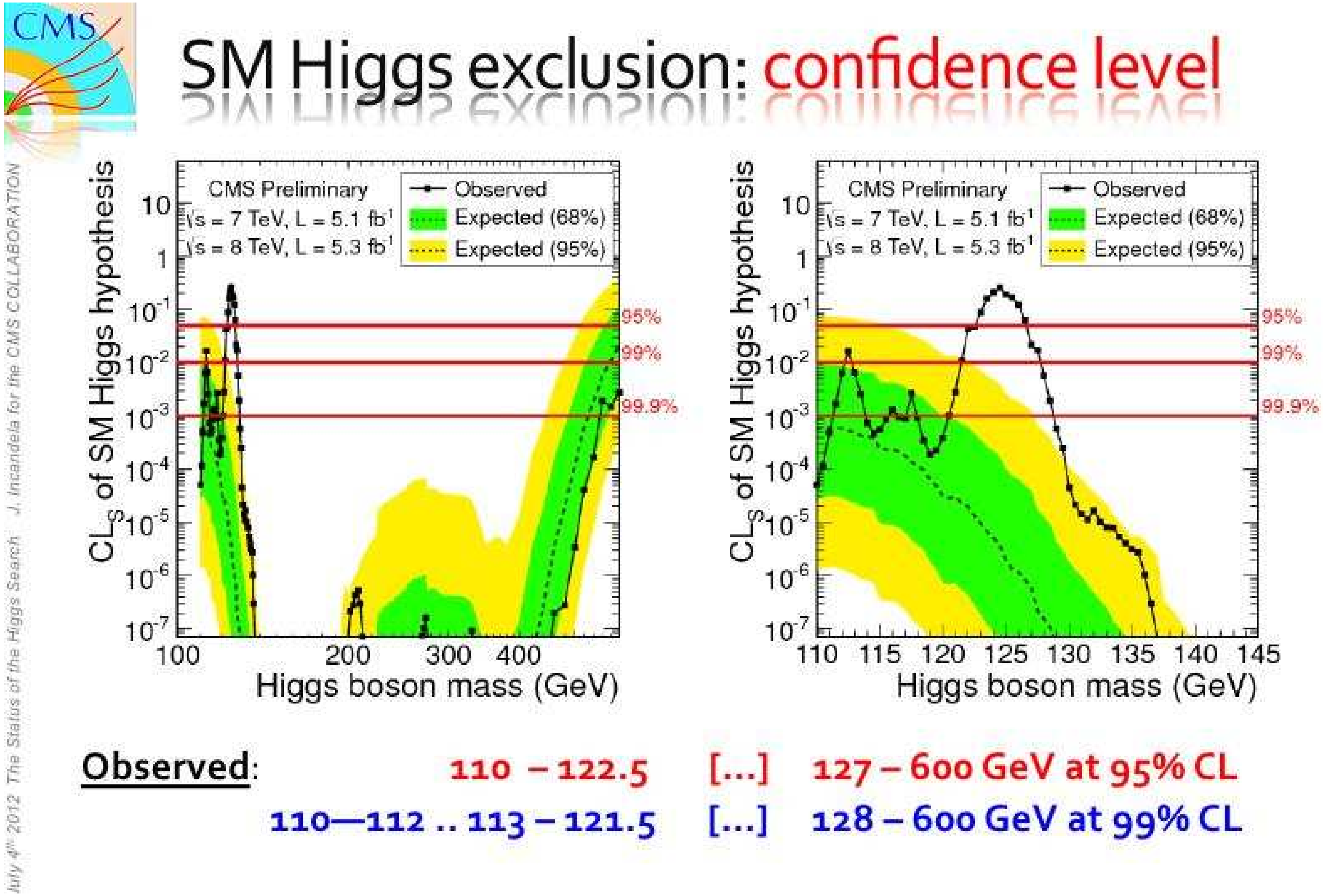
The great news of July 2012: II

Characterization of CMS excess near 125 GeV and strength of the signal in terms of p-values (probablity that background fluctuates to give an excess as large as the signal size expected for a SM Higgs).



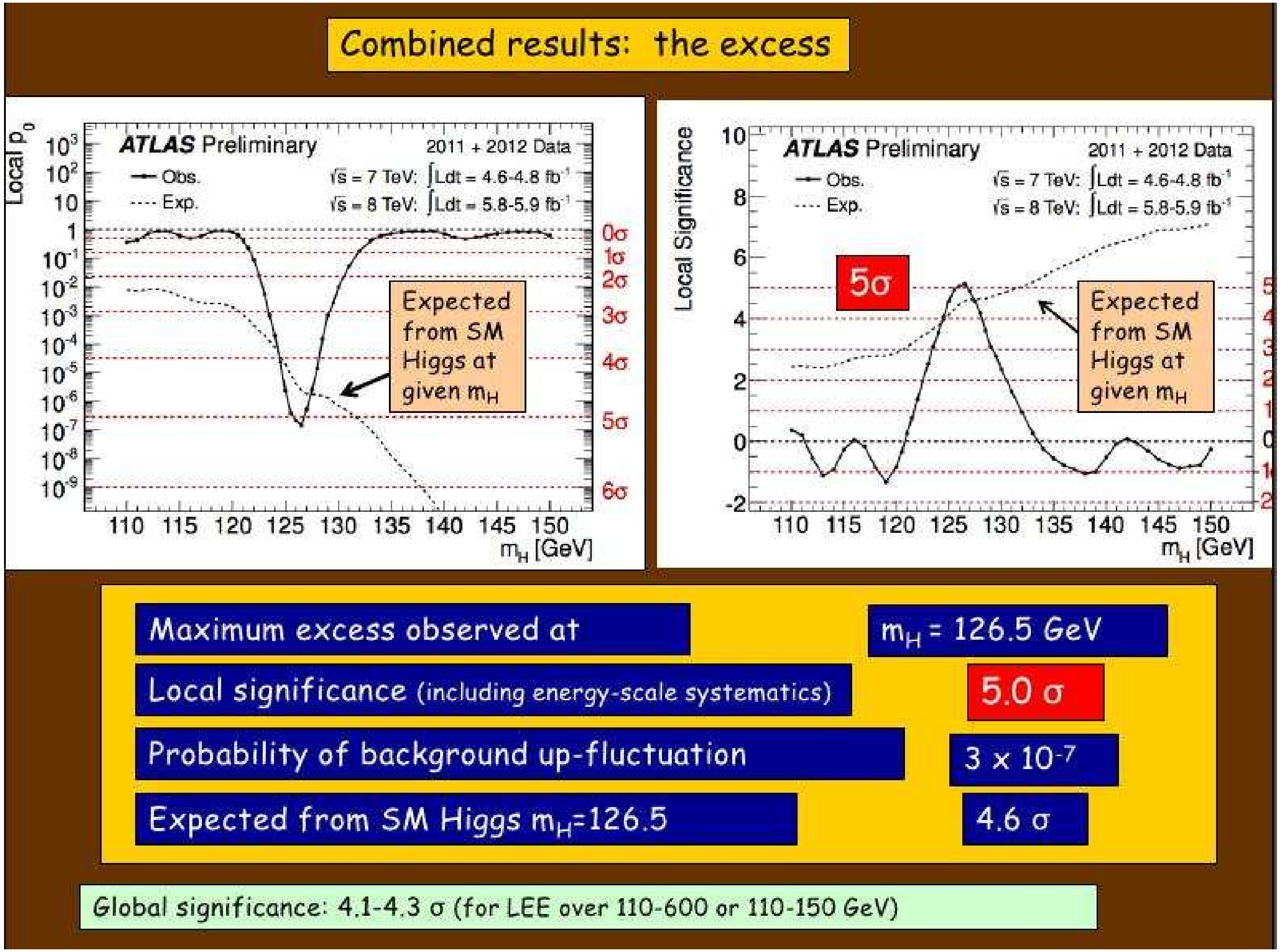
The great news of July 2012: III

New CMS Higgs boson mass exclussion limits:



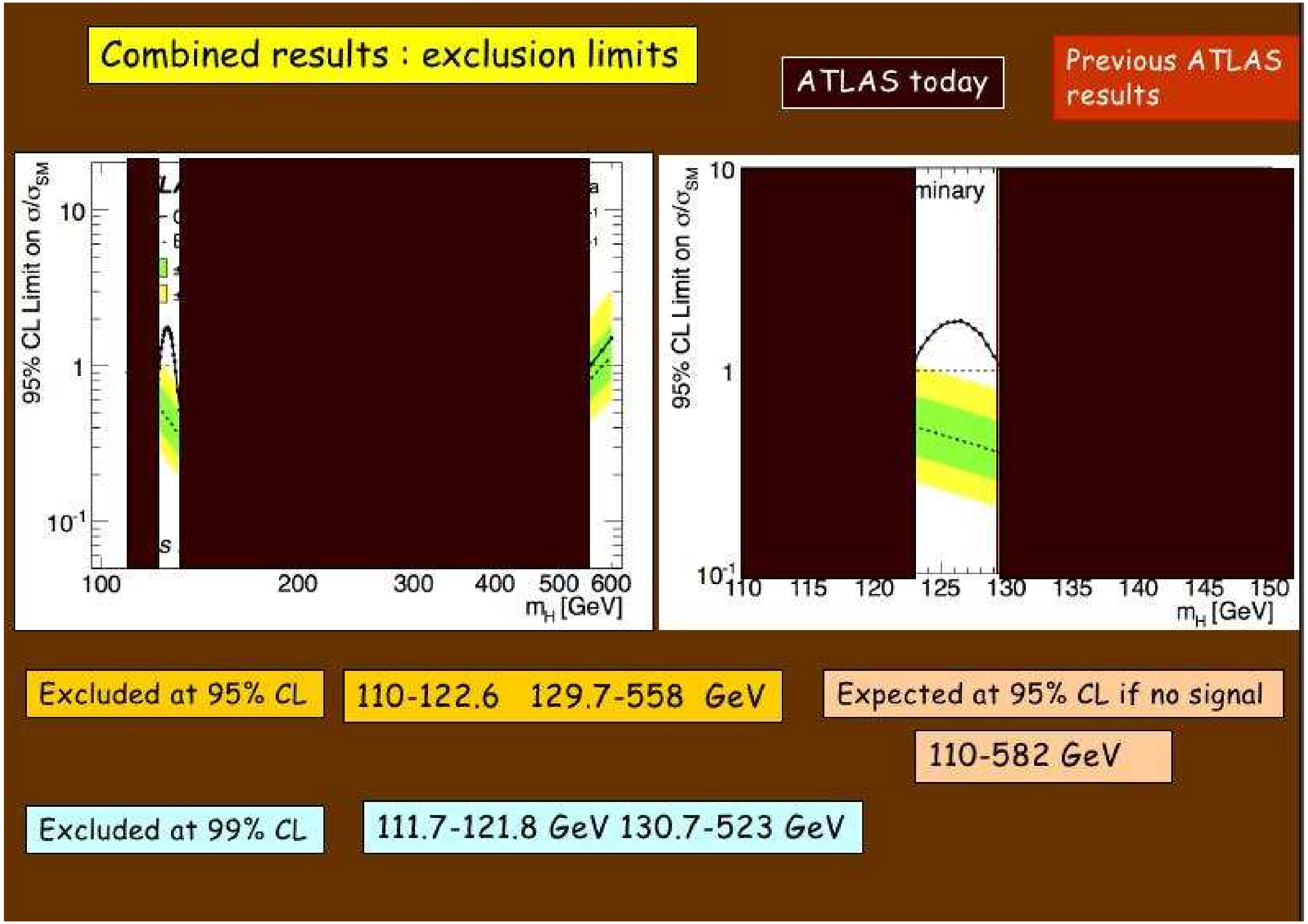
The great news of July 2012: IV

Simmilar conclusions in ATLAS (Fabiola Gianotti) presentation of 4th July.



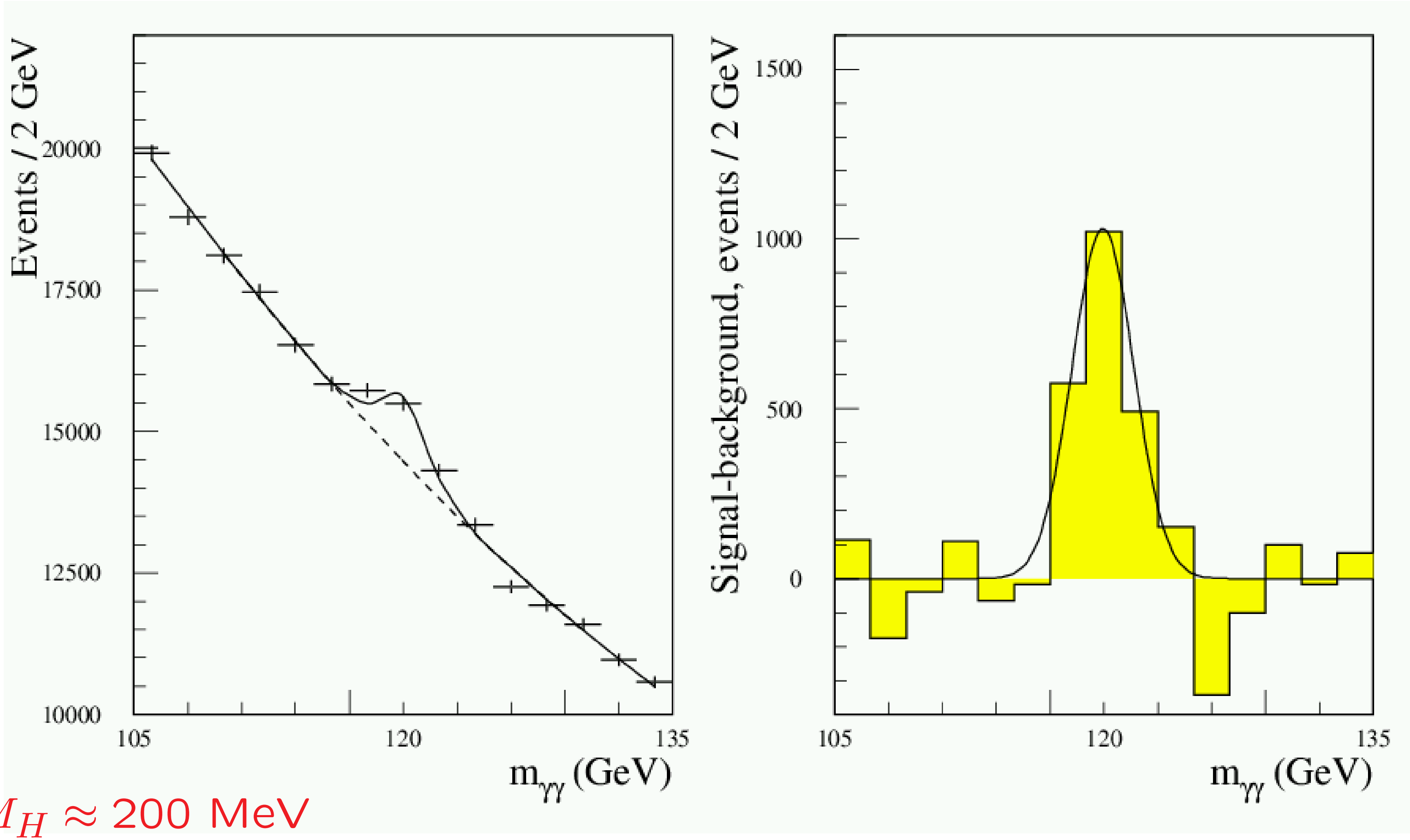
The great news of July 2012: V

New ATLAS exclussion limits:



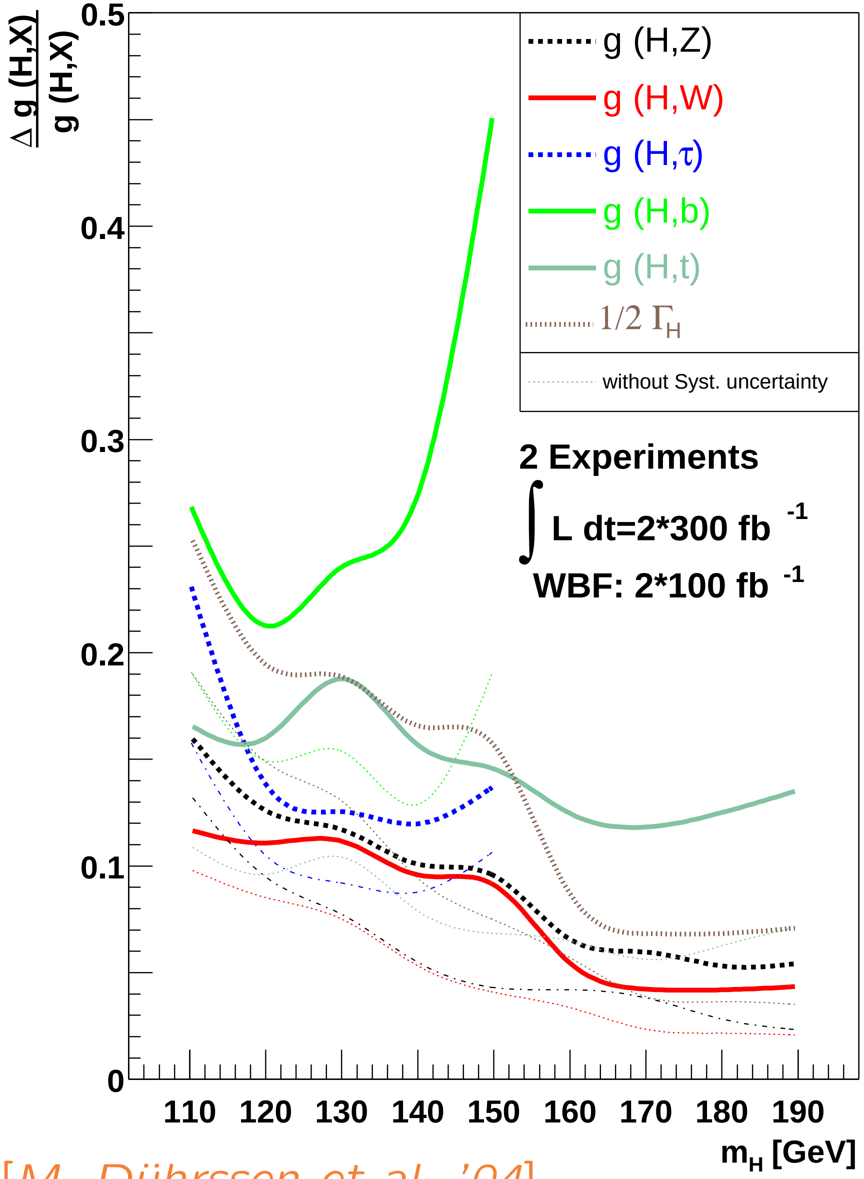
Step 2: Measurement of the mass

Best channel for mass measurement in the SM: $H \to \gamma\gamma$
[*ATLAS '99*]



$\Rightarrow \delta M_H \approx$ 200 MeV

Step 3,4: Higgs couplings at the LHC (older analysis):



[M. Dührssen et al. '04]

– mass: $\delta M_h \approx 200$ MeV

– couplings: $(2*300+2*100)\,\text{fb}^{-1}$:

typical accuracies of 20-30%
for $m_H \leq 150$ GeV

10% accuracies for HVV couplings
above WW threshold

Assumption:

– $g^2_{HVV} \leq g^2_{HVV,\text{SM}} \times 1.05$
– SM rates for the Higgs

Problems:

– old $t\bar{t}H, H \to b\bar{b}$ studies used
– valid in weakly interacting models
– rates much lower than in SM ??
– physics can/will hide in 5% margin
– self-couplings out of reach

Higgs coupling measurement at the LHC

[*LHC2FC '09*]

Assuming that $(g_{HVV})^2 \leq (g_{HVV}^{\mathsf{SM}})^2 \times 1.05$ yields for $10\,\mathrm{fb}^{-1}$ at 14 TeV:

channel / M_H [GeV]	120	130	140	150	160	170	180	190
g_{HWW}	29%	25%	20%	14%	9%	8%	8%	9%
g_{HZZ}	30%	27%	21%	16%	15%	19%	14%	11%
$g_{H\tau\tau}$	63%	39%	38%	50%				
g_{Hbb}	72%	54%	56%	73%				
g_{Htt}	87%	62%	45%	36%	31%	32%	36%	45%
Γ_H		77%	60%	42%	27%	25%	26%	29%
$\Gamma_{\mathrm{inv}}/\Gamma_H$	81%	72%	56%	39%	23%	20%	22%	24%

$\Rightarrow$ interesting, but not too convincing . . .

$\Rightarrow$ a lot of physics can hide in these uncertainties

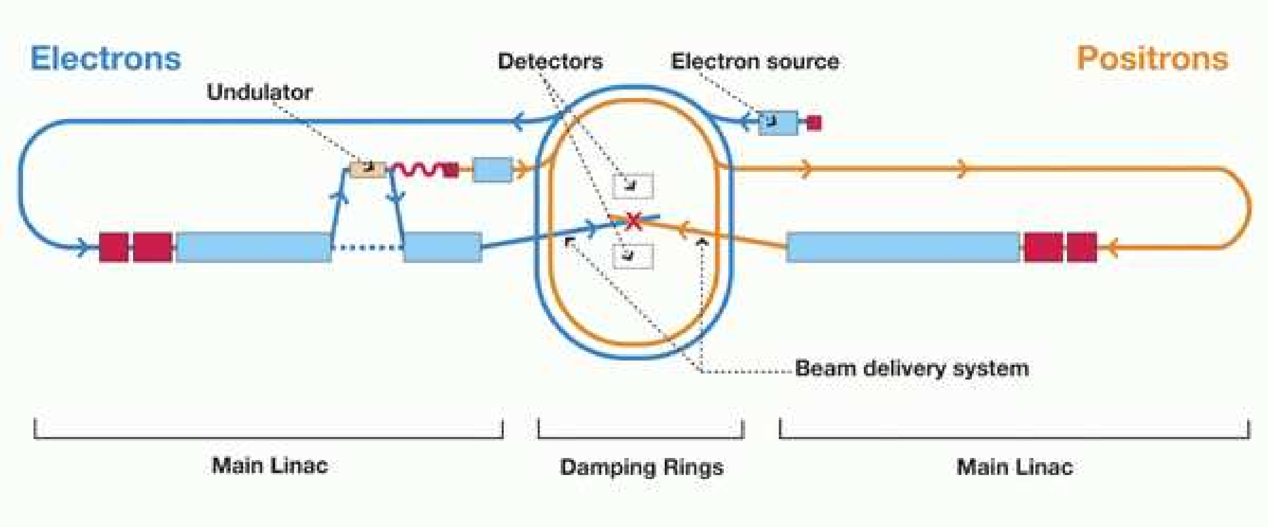
higher luminosity?

The "dirty" LHC might not be precise enough . . . what then?

Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV (ILC)

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



– two detectors in one interaction region (push-pull)

– undulator based e^+ source

– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

Other options:

- GigaZ:
  running with high luminosity at low energies (Z pole, WW threshold)

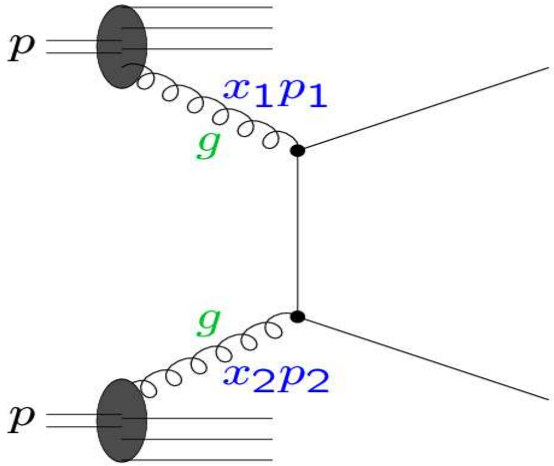
- e^-e^-:
  produce doubly charged particles in the s channel

- $e^-\gamma$:
  use one e^- beam to produce high-energy photons
  produce charged particles in the s channel

- $\gamma\gamma$:
  use both beams to produce high-energy photons
  (e.g. heavy Higgs production in the s channel)

Mini-comparison of LHC and ILC: I

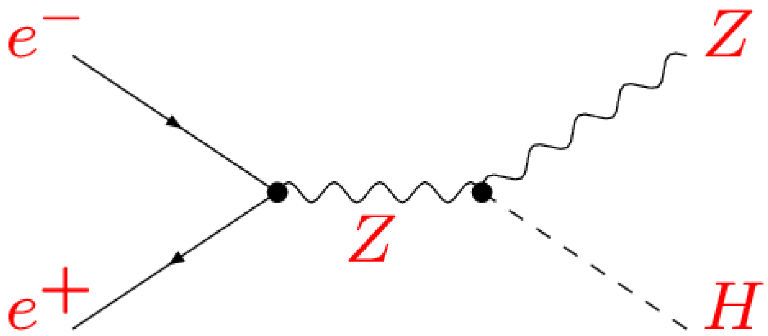
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

$\Rightarrow$ huge QCD backgrounds,
low signal–to–background ratios

ILC: e^+e^- scattering
at $\approx$0.5–1 TeV



Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, ...

$\Rightarrow$ rel. small backgrounds
high-precision physics

Mini-comparison of LHC and ILC: II

Discovering the properties of the Higgs boson

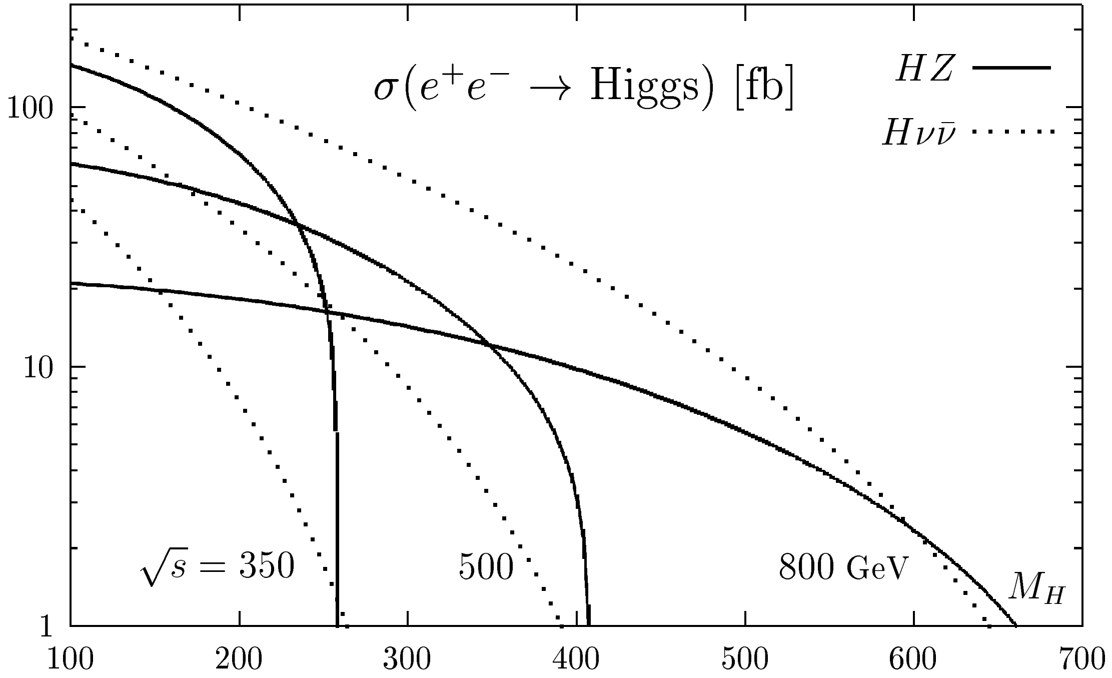
What has to be done?

1. Find the new particle	LHC	ILC
2. measure its mass ($\Rightarrow$ ok?)	LHC	ILC
3. measure coupling to gauge bosons	LHC	ILC
4. measure couplings to fermions	LHC	ILC
5. measure self-couplings		ILC
6. measure spin, . . .	LHC	ILC

We need the ILC to (re)find the Higgs
and to establish the Higgs mechanism!
The LHC can do a crucial part . . .

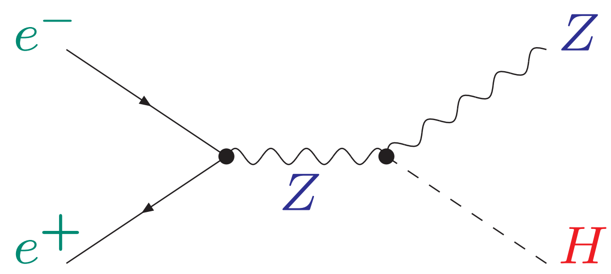
Higgs physics at the ILC

Higgs production at the ILC:



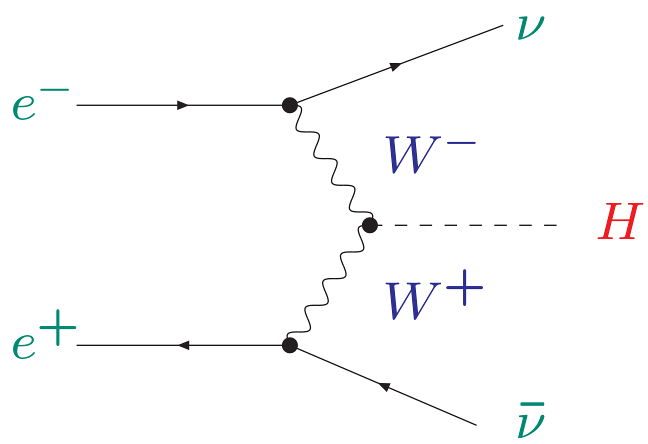
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e+e- \to \nu\bar{\nu}H$



$\Rightarrow$ Measurement of masses, couplings, ... in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \to ZH,\ Z \to e^+e^-,\ \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

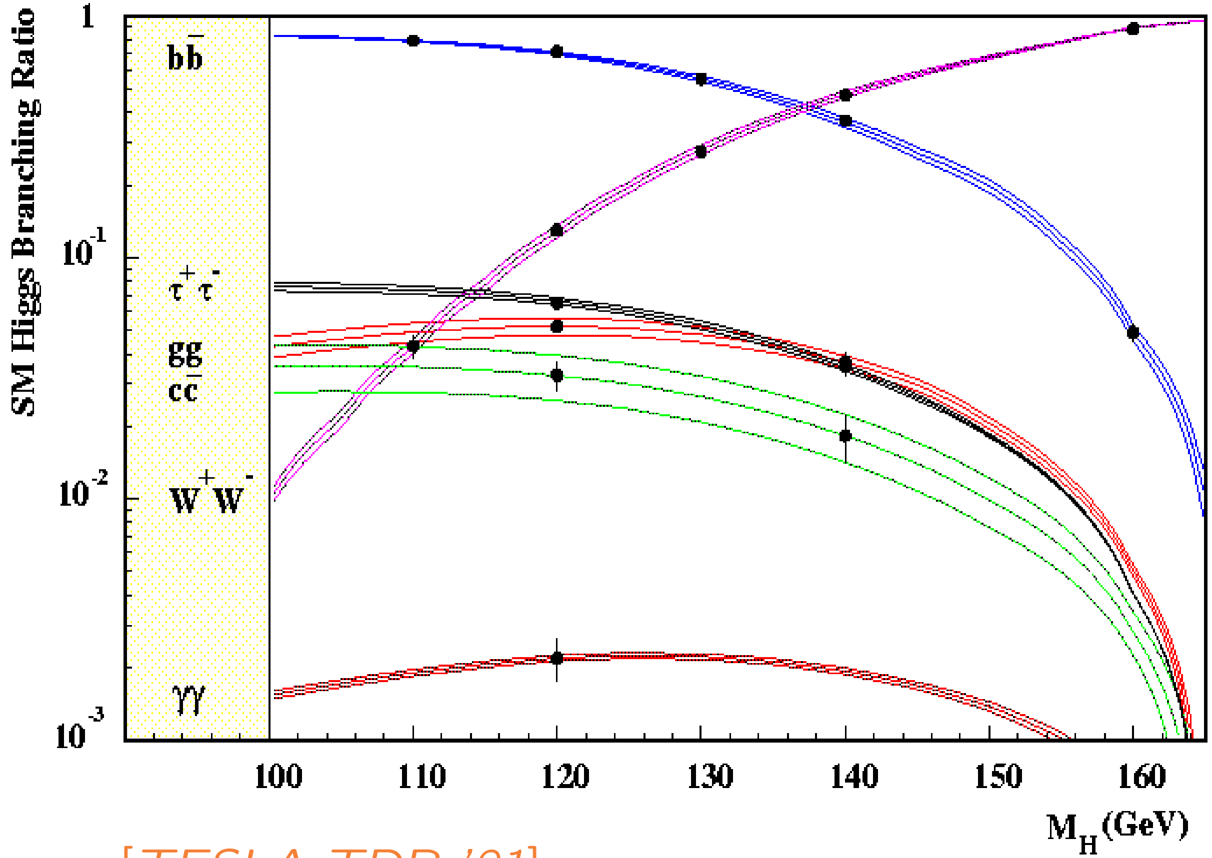
Some ILC results ($500\,\text{fb}^{-1}$@$\sqrt{s} = 350$ GeV):

$\delta M_H \approx 50$ MeV
$\delta g_{ZZH} \approx 2.5\%, \qquad \delta g_{WWH} \approx 2 - 5\%$
$\delta g_{Hb\bar{b}} \approx 1 - 2\%$ (for $M_H \lesssim 150$ GeV)

Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, . . .



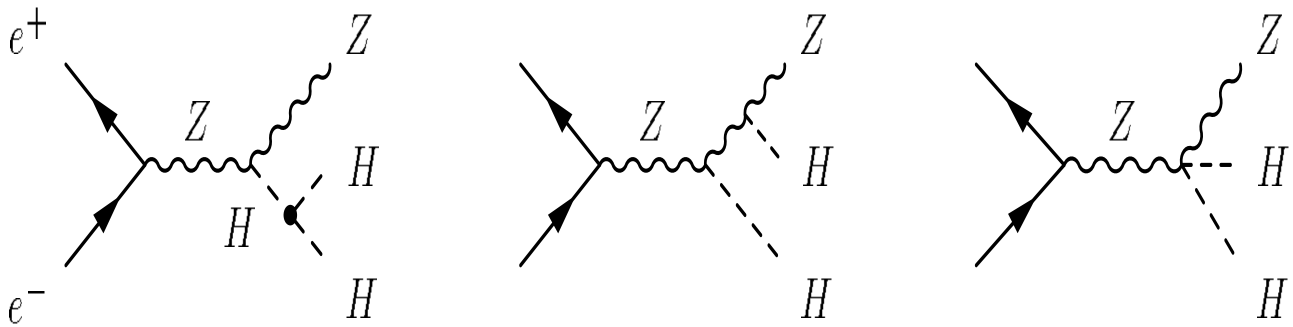
[*TESLA TDR '01*]

But do we need the ILC precision?

YES! To discriminate between the SM and extensions

Step 5: measurement of the Higgs boson self-coupling

$\Rightarrow$ only possible at the ILC

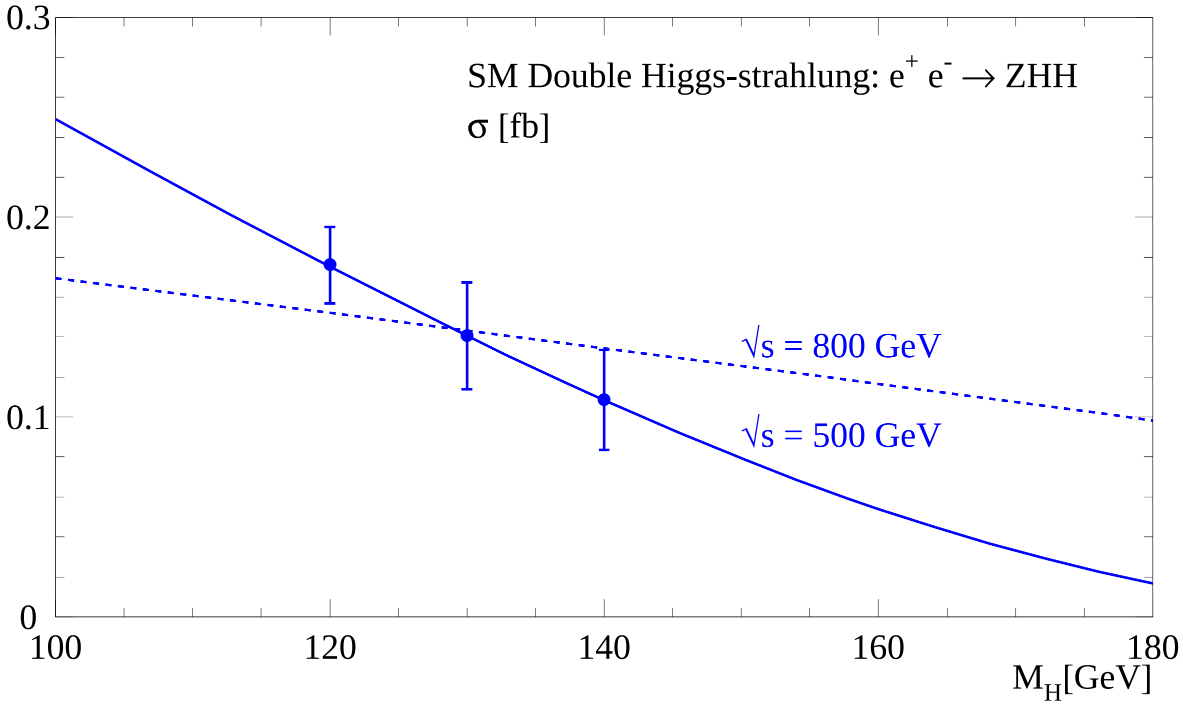


Parton-level study:

[*Djouadi, Kilian, Mühlleitner, Zerwas '99*]

$1\,\text{ab}^{-1}$ $\Rightarrow$ 20–30%

measurement of $\lambda = \lambda_{HHH}$



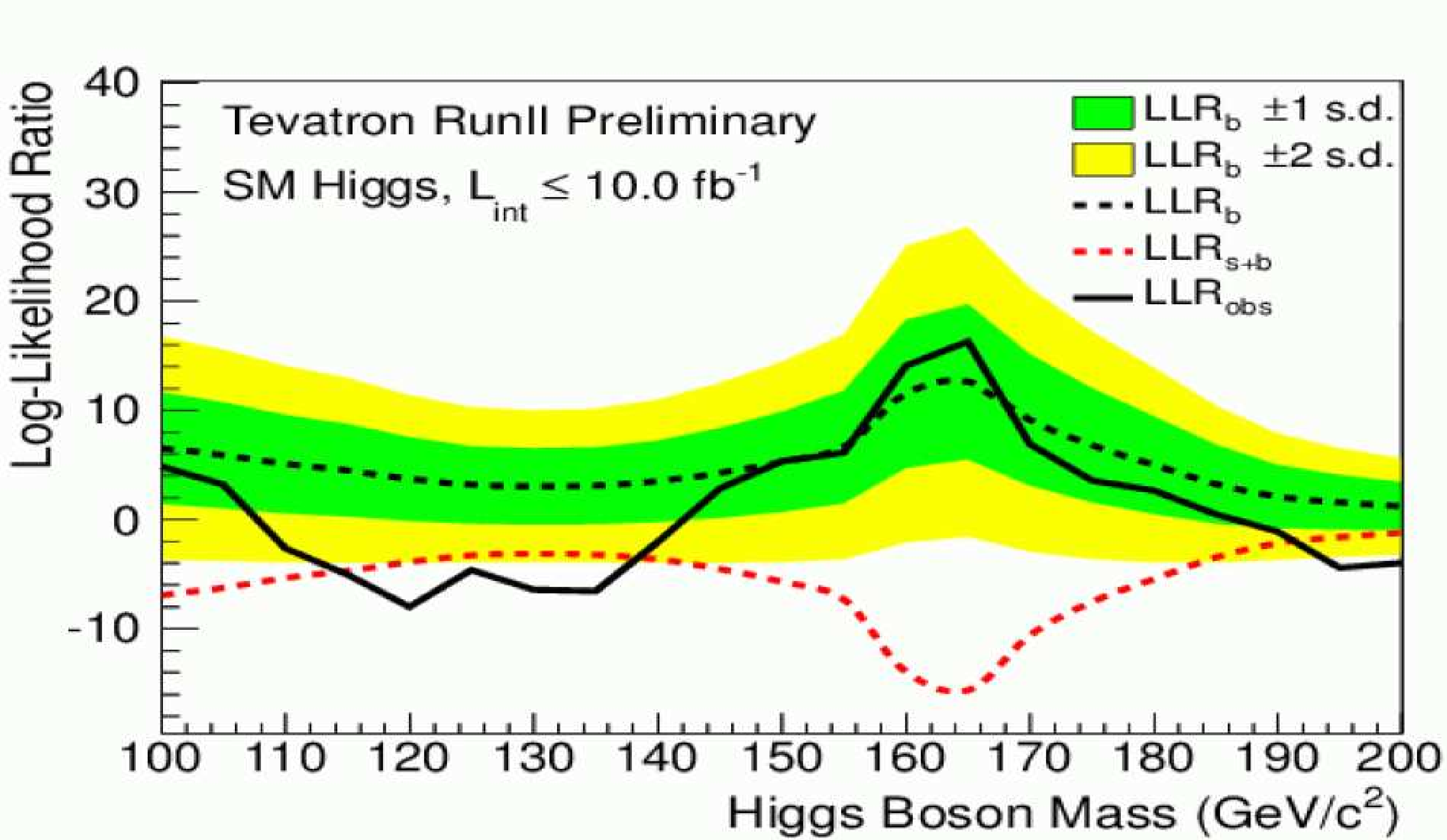
However:

$\lambda = \lambda_{HHHH}$ out of reach

for all foreseeable colliders

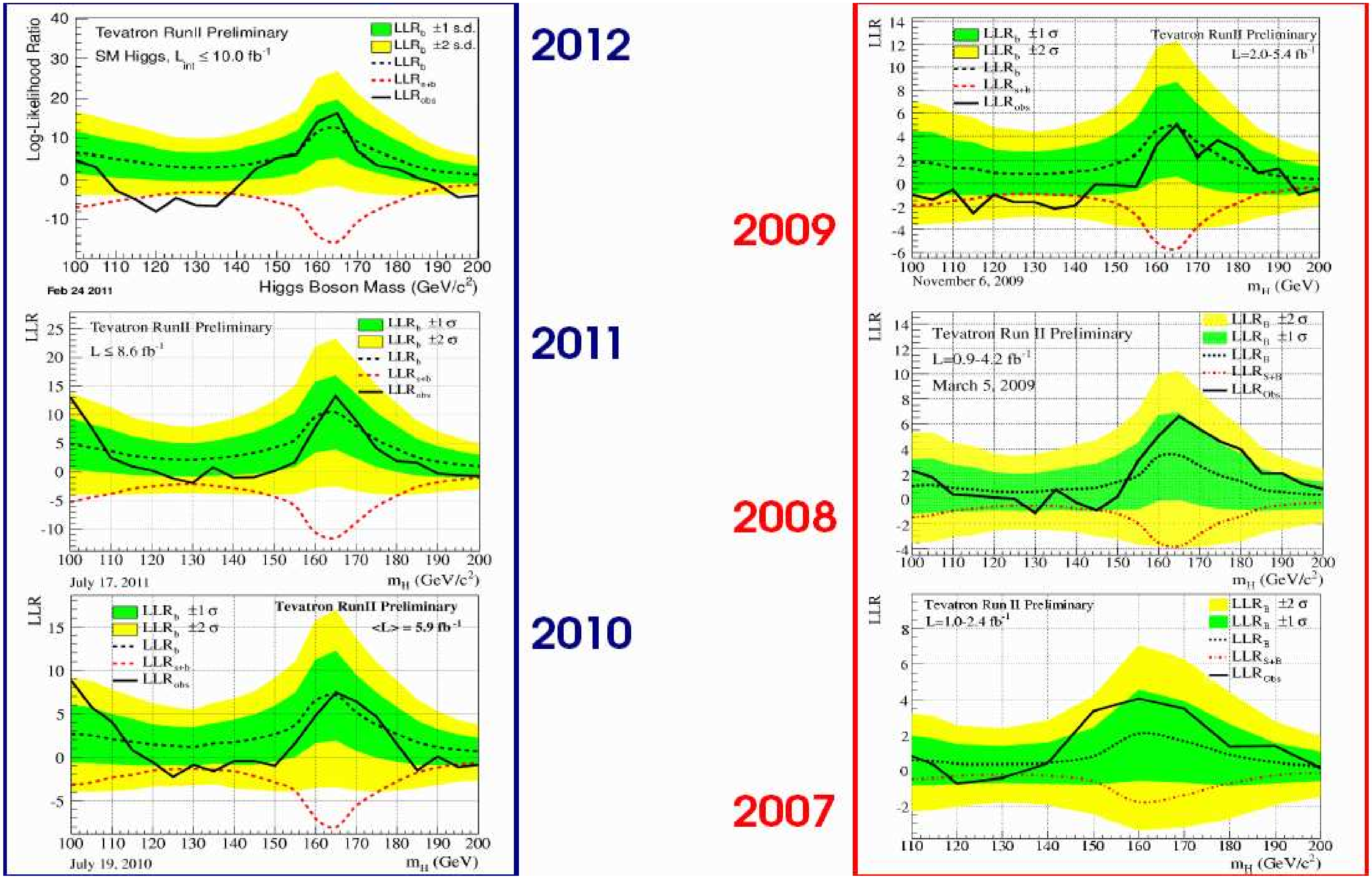
$\boxed{\text{Back-up}}$

Tevatron results in Likelihood plots:



Signal + backgr. hypothesis more compatible with observed than backgr. hypothesis

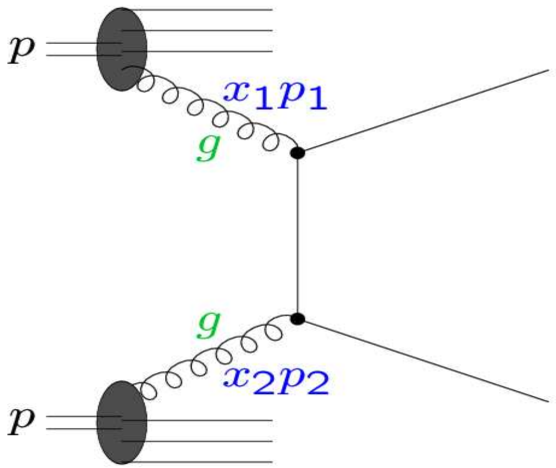
Evolution in time of Tevatron Likelihood plots



⇒ steady increase of signal (as "expected")

Mini-comparison of LHC and ILC: II

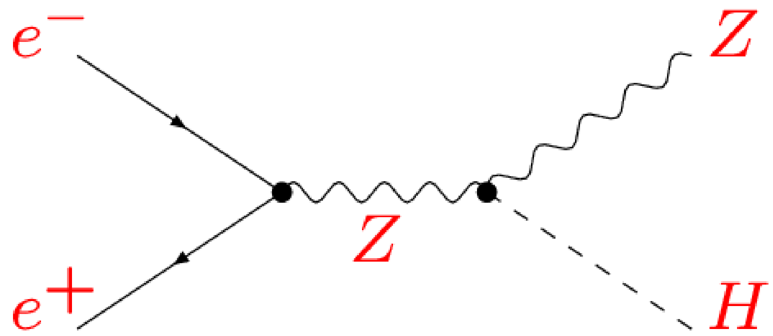
LHC: pp scattering at 14 TeV



interaction rate of 10^9 events/s

$\Rightarrow$ can trigger on only
1 event in 10^7

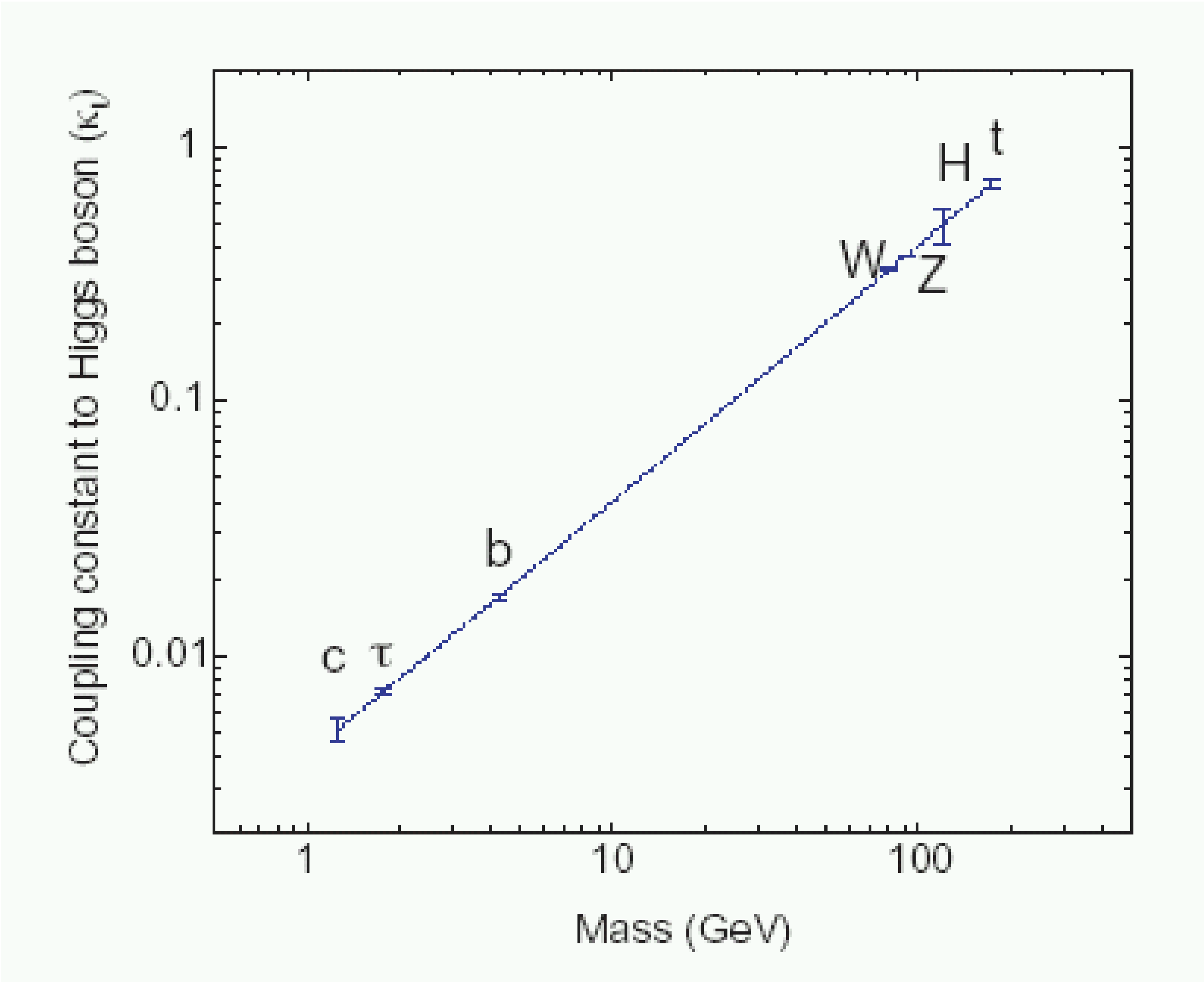
ILC: e^+e^- scattering
at ≈0.5–1 TeV



untriggered operation

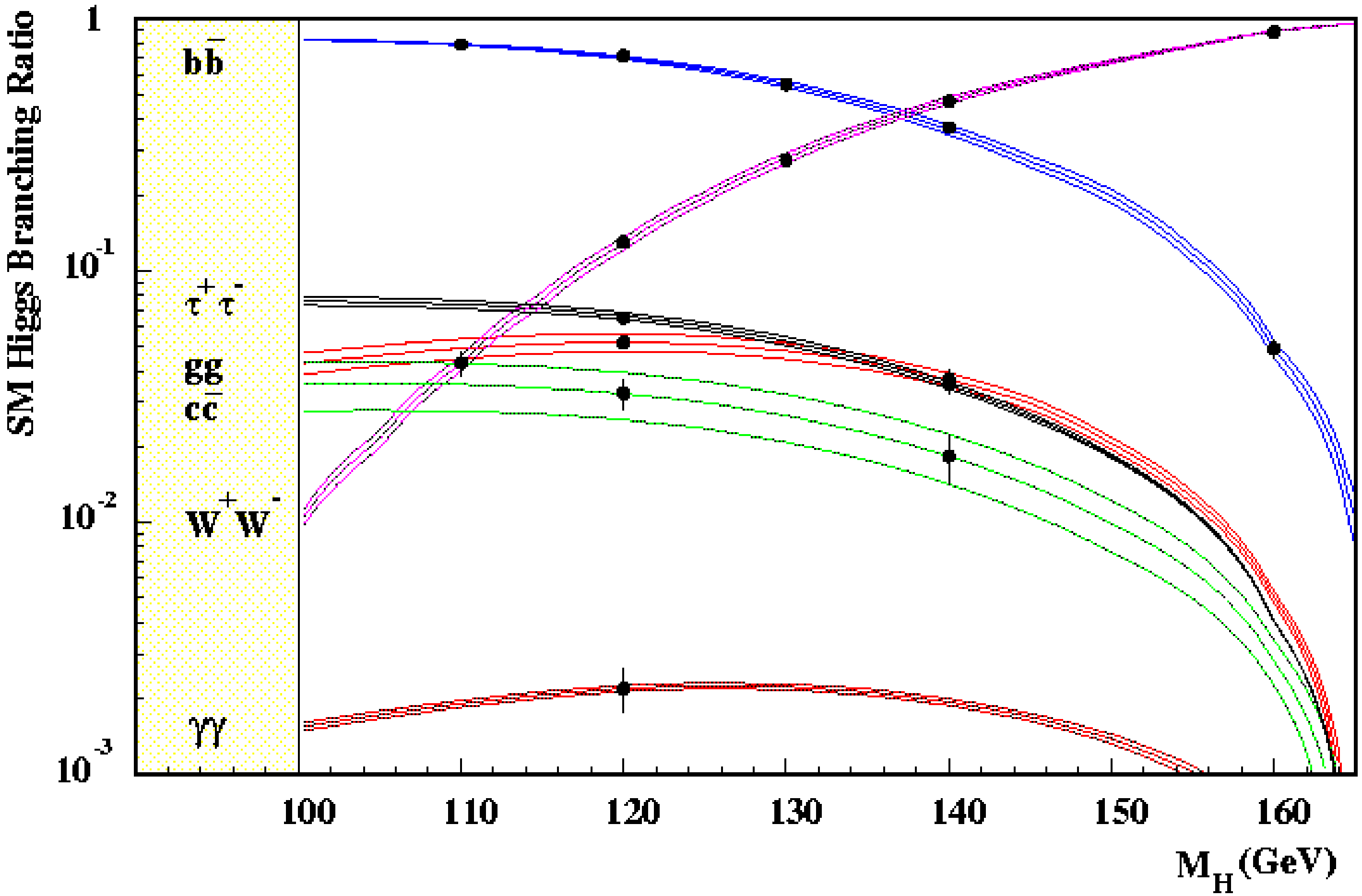
$\Rightarrow$ can find signals of unexpected new physics (direct production + large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

$\Rightarrow$ only Lepton Colliders can "verify" the Higgs mechanism



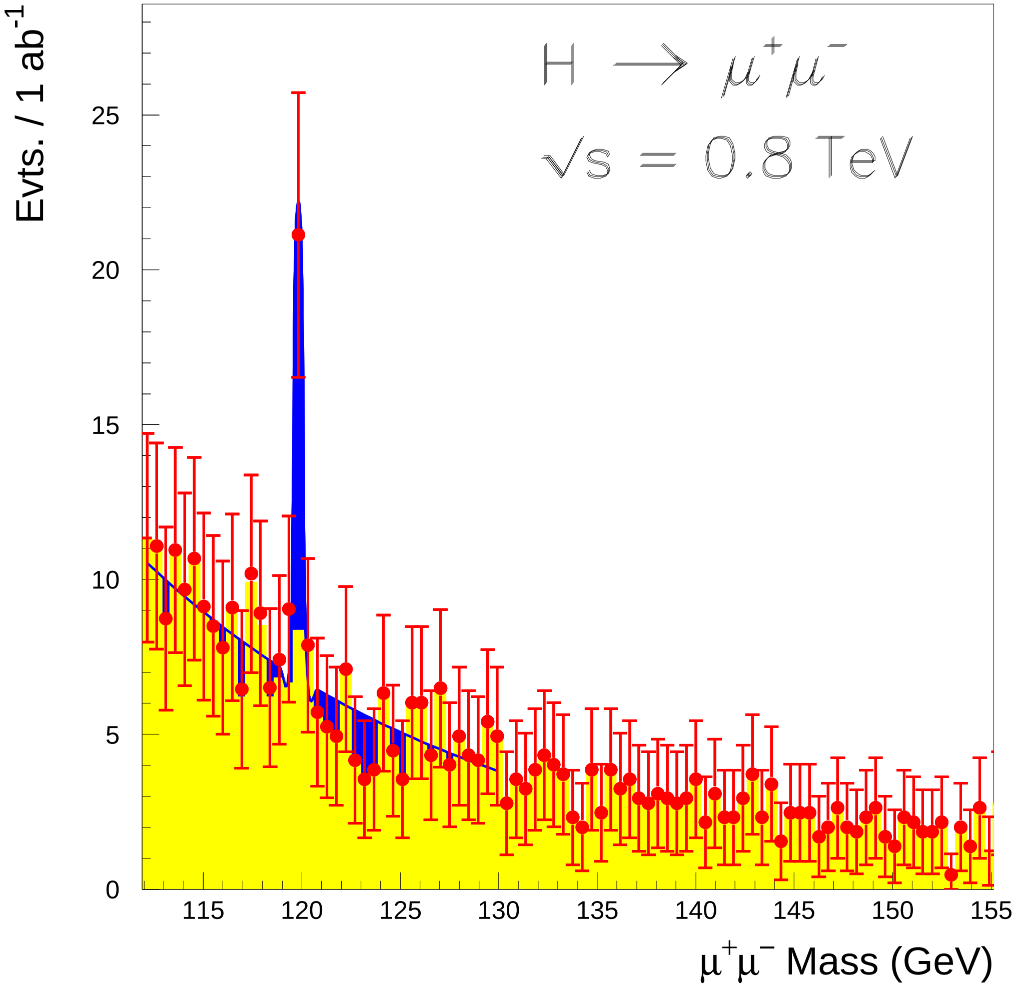
. . . including couplings to the second family!

$\Rightarrow$ coupling to the c quark:



...including couplings to the second family!

$\Rightarrow$ coupling to the muon:



$(M_H = 120$ GeV, $\sqrt{s} = 800$ GeV, $\mathcal{L}_{\rm int} = 1\,{\rm ab}^{-1})$

Step 6: measurement of the Higgs boson spin

$\Rightarrow$ easy at the ILC

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

$20\,\text{fb}^{-1}$
$\Rightarrow$ identification easy