After 25 years of LHC Higgs studies where do we stand in 2009?

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Workshop on Higgs Boson Phenomenology, 7.1.2009

- A brief history of the LHC
- Five phases of "Higgs search at the LHC":

  I Understanding the "needs": Early simulations (before 1995)

  II Establishing the ultimate and the real LHC potential (1996-2006)

  III Realism about the LHC performance (2007-2009)

  IV Searches within realistic LHC boundaries (2010-2012)

  V Discovering or excluding the Higgs:
  A "happy end" or a "nightmare"?

A brief history of the LHC (I)

Conception of the LHC:

- The apero:
  Lausanne Workshop (1984) and La Thuile Workshop (1986/87)
  "CERN's long term future"
  The LEP tunnel plus a 16 TeV pp collider with up to 100 fb^{-1}/year!
  "Almost" equivalent to the SSC 40 TeV pp project (10 fb^{-1}/year)

  Higgs search ($M_H \geq 200$ GeV), Supersymmetry etc

- The physics potential at the LHC:
  Workshops: from Aachen (1990) to Evian (1992)
  (the why and the how preparations ...)

  Higgs search becomes the "reason" to construct the LHC
  (possibility to discover the Higgs from 100 GeV-1000 GeV)

- 1992-1996: Out of the ashes of the SSC
  CERN becomes "pregnant" with the LHC and its experiments!

A brief history of the LHC (II)

Original LHC birth/childhood planning:

- CMS Letter of Intent (1 October 1992)
  "The LHC has been designed to collide protons at a centre-of-mass energy of $\sqrt{s} = 15.4$ *TeV every 15 nsec at a luminosity of* $1.7 \times 10^{34} cm^{-2} s^{-1}$
  .. It is expected that over the first one or two years of running the maximum luminosity will progressively increase from 10^{32} *to* $10^{34} cm^{-2} s^{-1}$*."*

- LHC Conceptual Design Report (CERN/AC/95-05) and E. Keil DPF-DPB Workshop Snowmass 1996
  "$\sqrt{s} = 14$ *TeV, collisions every 25 nsec and* $L = 10^{34} cm^{-2} s^{-1}$
  .. Injection tests foreseen October 2003, commissioning second half 2005"

- Revised schedule: L. Evans, EPJ C 34 s11-15 (2004).
  Ring will be closed by end 2006 with first beam injected in spring 2007 and first physics run in second half of 2007.
  Important milestone in April 2006 when a beam will be injected at Point 8 and transported around the first octant to Point 7.

- Particle collider is on schedule... just, Nature 449, 761 (17.10.2007)
  CERN's new machine still aiming for 2008 debut.
  "The next three months are going to be pretty critical" says Evans. *"If something unforeseen comes up between now and then, it will slip. There's no doubt."*

A brief history of the LHC (III)

Announcing the birth date (a few times)

- R. Bailey (25.1.2007): LHC startup plans for 2007 and 2008:
  - November 2007: Full machine checkout followed by beam commissioning run with 450 GeV protons for the last weeks of 2007
  - April 2008: Machine hand over for beam operations
  - followed by (July(?) to December): Three phase machine operations with 14 TeV pp collisions:
    assuming 40 efficient physics days the luminosity might add up to 1 fb^{-1} at the end of 2008!
  - But, a detailed planning for 2008 will only be possible after the "450 GeV run"!

- Revised LHC schedule (October 2007): a "three months delay"
  First beams in July 2008 with perhaps 0.05-0.1 fb^{-1} at 14 TeV and at the end of 2008!

A brief history of the LHC (IV)

- January 2008: "Aymar declares important dates for 2008"
  (1) Open day April and (2) LHC inauguration party 21.10.08

- Some time later: Robert Aymar (CERN Bulletin) 31.3.08:
  10 TeV instead of 14 TeV physics!
  "During the commissioning of Sector 4-5 earlier this year, three dipoles quenched below 9.5kA, despite having previously been tested to the nominal LHC operating current of 12kA. It seems that some re-training of some of the magnets will be necessary, which will take a few more weeks. After agreement with all the experiments and having informed the Council at the March session, it was decided to push for collisions at an energy of 10 TeV this year, as quickly as possible, with full commissioning to 14 TeV to follow over the winter shutdown."

- 10.9.2008: World media document the "glorious" LHC birth

- **19.9.08: "The incident": "Restart some time in summer 2009!**
  MayoClinic.com: *"A premature birth gives a baby less time to develop and mature in the womb. The result is an increased risk of various medical and developmental problems, including trouble breathing and bleeding in the brain. If you go into labor too early, your doctor may try to delay your baby's birth. Even if premature birth is inevitable, a few extra days in the womb can promote significant development. Although the rate of premature birth seems to be on the rise, there's good news. A healthy lifestyle can go a long way toward preventing preterm labor and premature birth."*

Guessing the next years for the LHC

optimistic, pessimistic, wishful thinking or realistic?

LHC Machine and ATLAS/CMS performance during 2009?

No "official" schedule so far .. thus lets hope for some useful pp collisions in 2009 at $\sqrt{s} \leq 10$ TeV with $L \leq 0.01 - 0.1$ fb^{-1}

followed by real and successful 14 TeV operation during the years 2010-2012!

L = 0.1-1.0 fb^{-1} (2010);
L = 1.0-5.0 fb^{-1} (2011);
L = 5.0-10. fb^{-1} (2012);

multiply by your guessed machine and detector "performance"!

Experience from the Tevatron Run I and II
A help for realistic guessing?

Tevatron Run I (1986-1996) and Run II (2001-2009(?))

1986/7 Engineering Run a: 0.05 pb^{-1}

1988/9 Engineering Run b: 9.2 pb^{-1}

1992-96 Run Ia + Ib: delivered 154.7 pb^{-1}, collected by CDF/D0 $\approx$ 100 pb^{-1}

2001/2 Run II(0): delivered/recorded: about 0.02 fb^{-1}

2002-5 Run IIa: delivered 1.4 fb^{-1} recorded about 1 fb^{-1}

2006/7 Run IIb: delivered about 1.4 fb^{-1}/year. CDF/D0 recorded about 70%.

2008/9 Almost 2 fb^{-1} recorded by CDF..

$\rightarrow$ startup (few years) luminosity was "always"
a factor of $\approx$ 10 below the defined goals!
$\rightarrow$ after "warm up" luminosity was "always"
a factor of $\approx$ 3 below the defined goals!

Higgs search at the LHC : Phase I

Understanding the "needs": Early simulations (before 1995) (1)

- Define a theoretical motivated LHC "purpose and goal":
  Find or exclude the Higgs (the missing link of the SM) if $M_{Higgs} \geq 100$ GeV

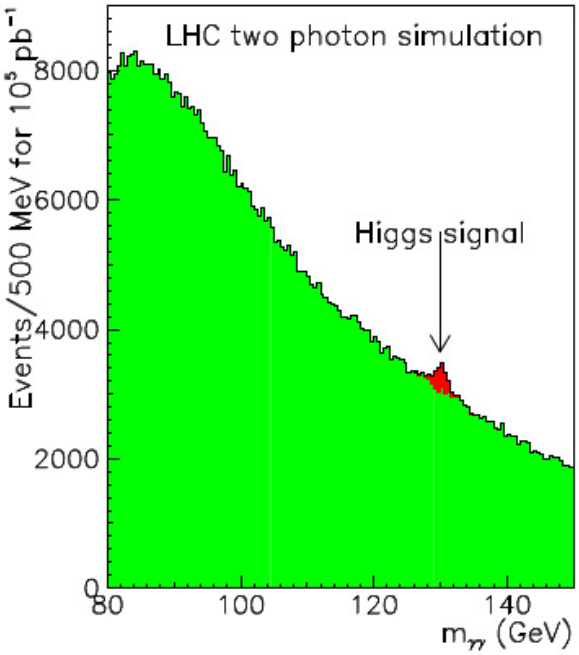
- Understand the LHC energy needs, luminosity and detector requirements.
  Simulating the Higgs search in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$
  extraordinary requirements for γ energy resolution!

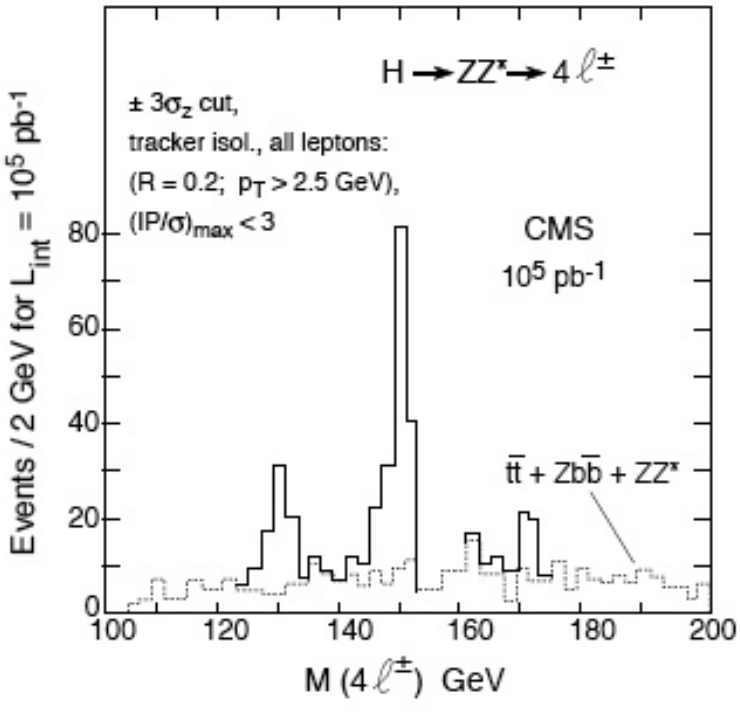
- Most important SM Higgs result(s): It can be done!
  Extras: many other discoveries/measurements can be performed at the LHC, especially if the "missing transverse" energy can be measured!
  Many other Higgs decay channels, supersymmetry (MSSM),
  additional vector bosons, Z' W' etc

For 1995 state of the art Higgs review see: Higgs Boson Discovery and Properties, Snowmass 1996 report J. Gunion et al, http://xxx.lanl.gov/abs/hep-ph/9703330

Higgs search at the LHC : Phase I

Understanding the "needs": Early simulations (before 1995) (2)

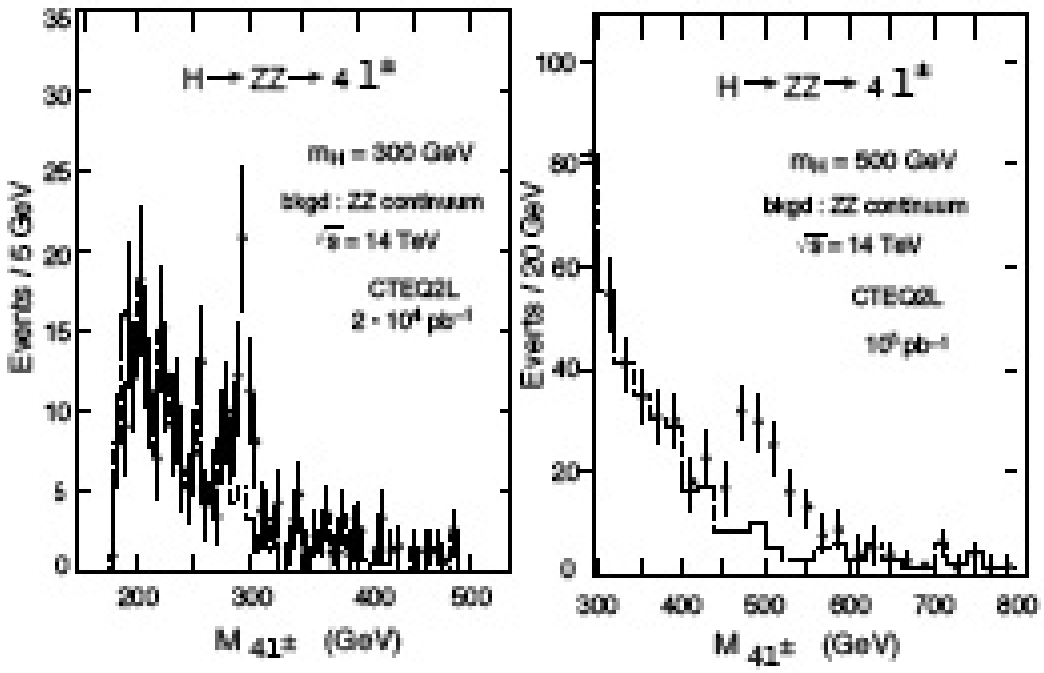




High luminosity low mass Higgs signals with 100 fb^{-1} (CMS around 1995)

Higgs search at the LHC : Phase I

Understanding the "needs": Early simulations (before 1995) (3)



$H \to ZZ \to \ell\ell\ell\ell$ M_H = 300 GeV and 500 GeV
Luminosity = 20 fb^{-1} and 100 fb^{-1}
(CMS around 1995)

Higgs search at the LHC: Phase II

The ultimate and the real potential (1996-2006)(1)

Closing the "last gap" ... M_H = 155-180 GeV

Establishing a signature with $\mathbf{H \to WW \to \ell\nu\ell\nu}$:

- oppositely charged leptons with small opening angle
  (Spin correlations and V-A interaction);
- signal events are more central
  (gluon fusion production versus $q\bar{q}$ WW continuum production);
- signal events with no or little jet activity
  (Jet veto against huge $t\bar{t}$ background);
- lepton p_t spectra close to $M_W/2$
  (low transverse momentum of W near threshhold).

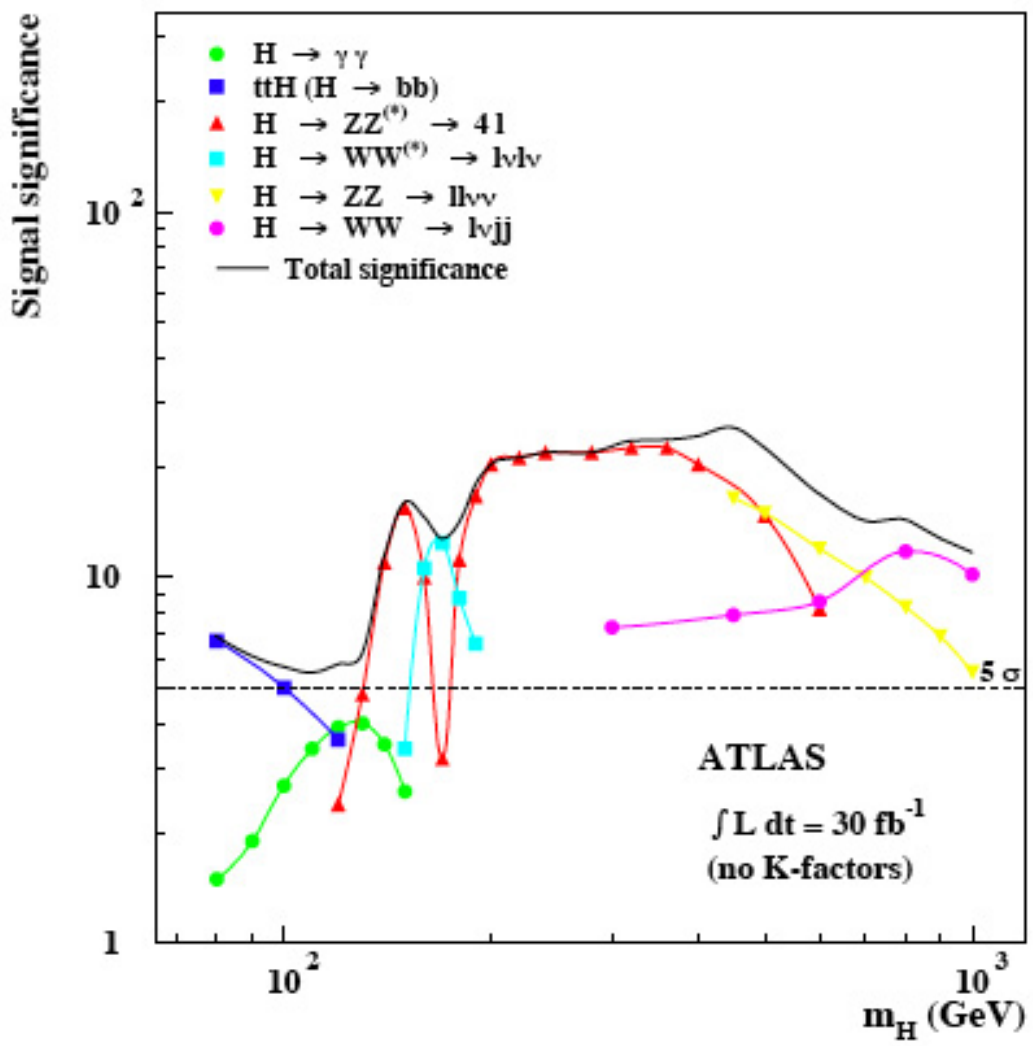
"Surprising" Result: former difficult mass region will give the first LHC Higgs results!

see M. D. and H. Dreiner, Phys. Rev. D 55, 167 - 172 (1997) and CMS note 1997/083

Higgs search at the LHC: Phase II

The ultimate and the real potential (1996-2006)(2)

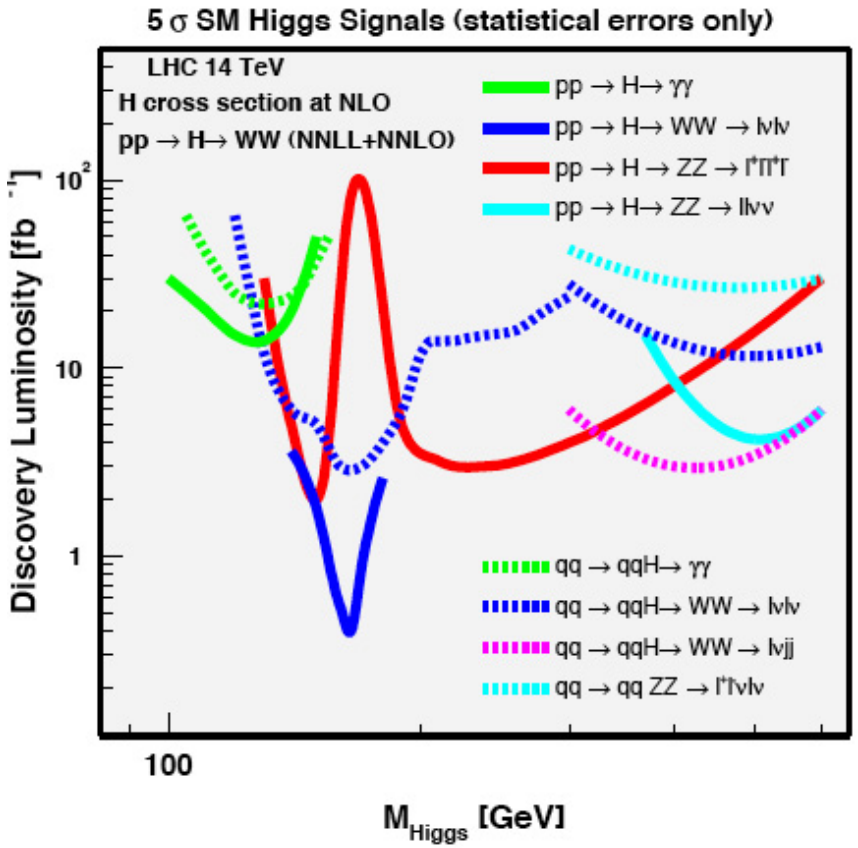
1999 The ATLAS Physics TDR: Higgs observable with many decays (largely dominated by corresponding best channel!)



Higgs search at the LHC: Phase II

The ultimate and the real potential (1996-2006)(3)

If ATLAS/CMS (and the LHC) reach design parameters:
What is the minimal discovery luminosity?



plot based on "most optimistic results from ATLAS and CMS"

Higgs search at the LHC: Phase II

The ultimate and the real potential (1996-2006)(4)

- Higgs cross section known at NNLO, often as a function of cut variables (Monte Carlos at or approaching NLO accuracies)

- Knowledge of background cross sections far less advanced!

- Higgs studies now "performed" with full (perfect!) detector simulations
  Background MC's are not perfect and often too little statistics $\rightarrow$ developing methods to "data driven" background estimates.

- Signal cross sections are "small" $\rightarrow$ statistics dominate most channels!
  For L = 30 fb^{-1}: statistical plus systematic errors at best $\pm$ 10%!
  (to get smaller errors "some advanced" studies use ultimate 2 $\times$ 300 fb^{-1})
  - 300 GeV Mass: $H \rightarrow ZZ$ (30 fb^{-1}):
    at best $\approx 100 \pm 12$(stat.) signal events
  - 165 GeV Mass: $H \rightarrow WW$ (30 fb^{-1}):
    at best $\approx 1500 \pm 50$(stat.) $\pm$ 150-200 (syst.) signal events
  - larger errors for other masses and channels!

numbers (rounded) from the CMS physics TDR 2006

Higgs search at the LHC: Phase III

Realism about the LHC performance (2007-2009)

From discovery to limits?

Higgs searches during the first real LHC year(s): with $\leq$ 1 fb^{-1} at $\leq$ 14 TeV

- If well prepared.. initial year with 1 fb^{-1} luminosity allows to "find" perhaps a 5 sigma signal with a mass from 160-170 GeV!
  Perhaps some exclusion limits ($H \rightarrow ZZ^*$) from 150-350 GeV.

- Luminosity between 0.2-0.5 fb^{-1} at 14 TeV
  perhaps some hints or limits for M_H =160-170 GeV

- with less luminosity (and less energy) nothing new about the Higgs!
  (even with perfectly prepared and working detector!)

- The good news even at 10 TeV and $\leq$ 0.05 fb^{-1}:
  Detailed understanding (experimental/theoretical) of W and Z production

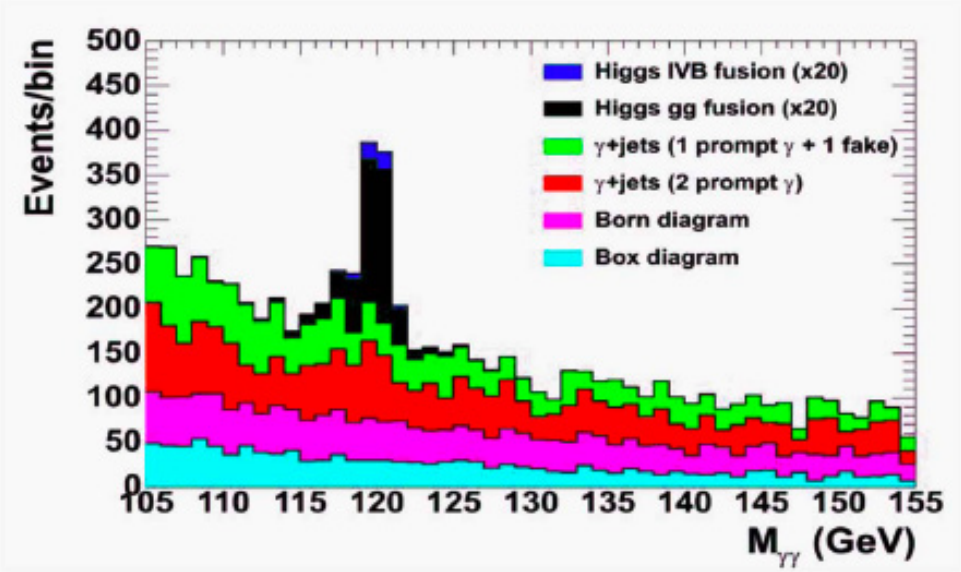
$\rightarrow$ excellent preparation for Higgs search!

Higgs search at the LHC: Phase III

Realism about the LHC performance (2007-2009)

Period of fantasies (1), depression (2) and wishful thinking(3)?

(1) Lets assume the Higgs cross section is much much larger (factor 20!!!), background probably for ≈ 1 fb^{-1}??



source: www.hep.caltech.edu

(2) no Higgs physics can be done for the next year(s) or

(3) "no matter what, discoveries just around the corner...

Consequently: "our(?) most urgent experimental problem": "Need to think now about who will give the discovery talk!"

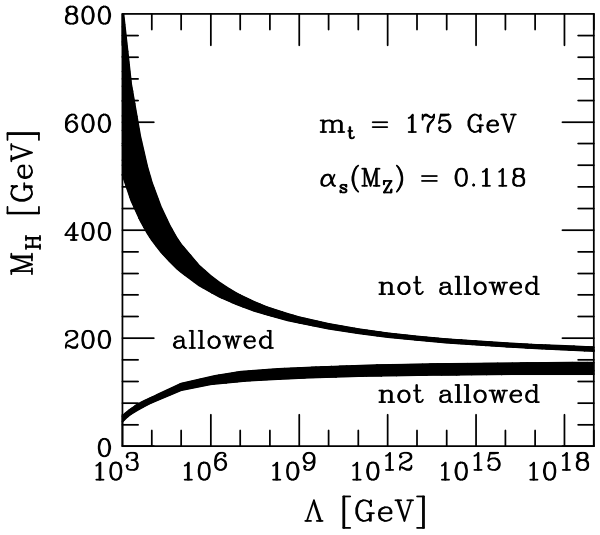
Higgs search at the LHC: Phase IV

Searches within realistic LHC boundaries (2010-2012) (1)

Where do we stand/start today?

- Direct searches from LEP II: $M_H > 114$ GeV
  indirectly ("bad fit") from electroweak parameters: $M_H < 200$ GeV
  (for more precise numbers stay tuned for the latest changes)!

- If SM and nothing else $\rightarrow M_H \approx 150 - 180$ GeV



source: T. Hambye and K. Riesselmann, PRD 55, 7255 (1997)

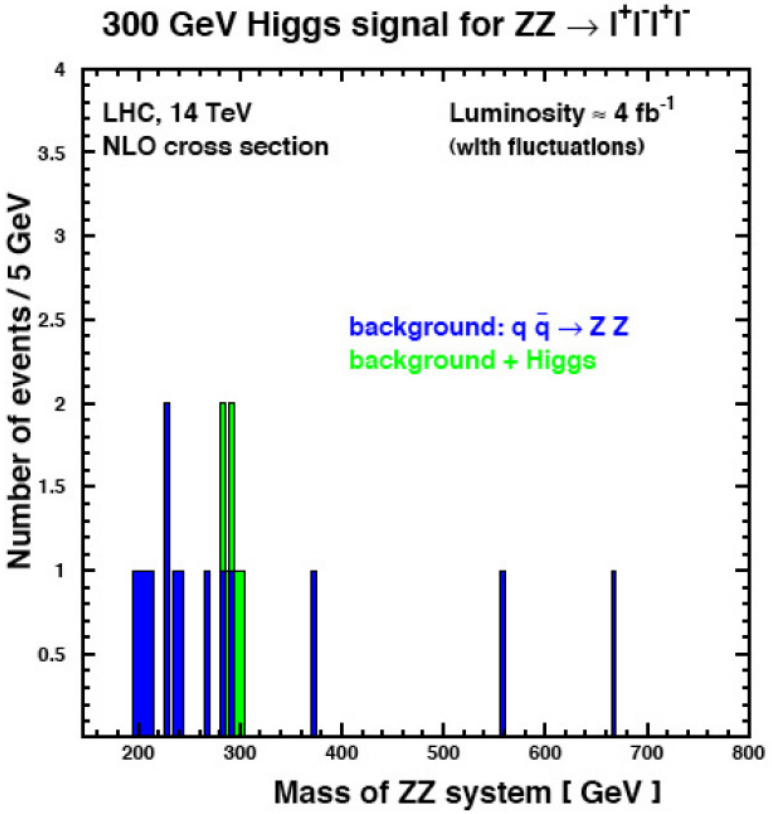
Higgs search at the LHC: Phase IV

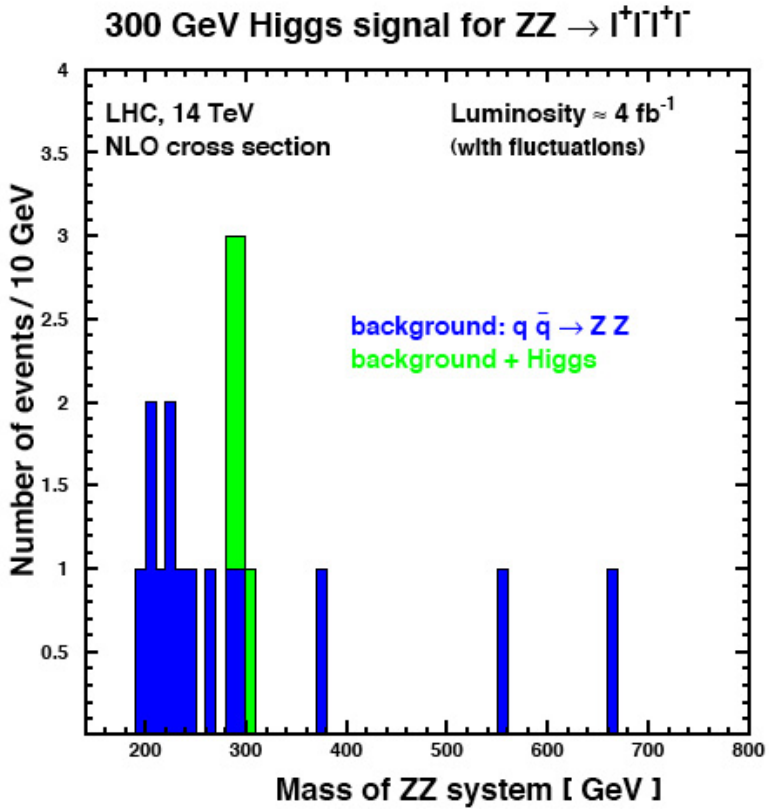
Searches within realistic LHC boundaries (2010-2012) (2)

an optimistic and not unrealistic luminosity 14 TeV scenario:

$\leq$ 1 fb^{-1} in 2010: some Higgs sensitivity near 160-170 GeV mass

with 5-10 fb^{-1} 2011-2012:
A possible 4-5 sigma signal $H \rightarrow ZZ$ 4 lepton (possible from 200-350 GeV)





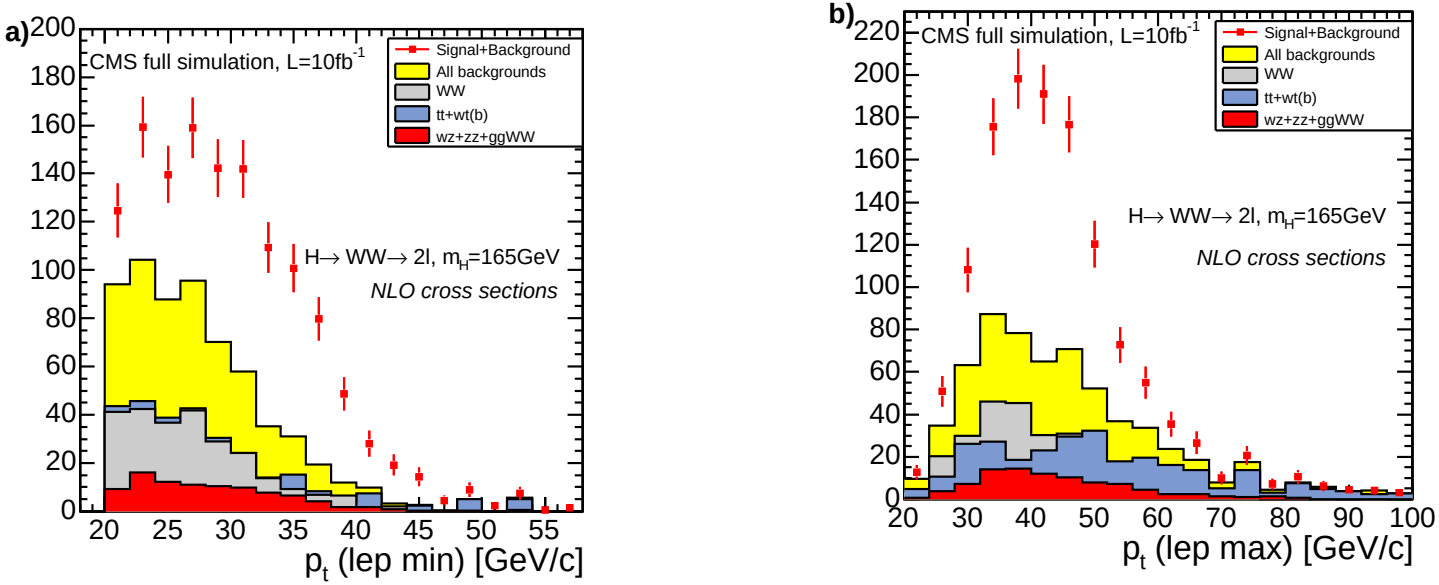
Attention: Identical events but plots with 5 GeV and 10 GeV binning!

Higgs search at the LHC: Phase V
A "happy end" or a "nightmare"? (1)

Particle Physics needs a discovery at the LHC!

Lets assume $M_H = 168$ GeV .. what would this mean?

Already with L $\approx$ 1 fb^{-1}:
It "tastes" and "smells" like a SM Higgs
with a mass near 165 GeV!



source: CMS Note 2006/047, attention plots for 10 fb^{-1}

Higgs search at the LHC: Phase V
A "happy end" or a "nightmare"? (The End!)

What would we learn from the $M_H = 168$ GeV like signal?

1. **The MSSM ($M_h \leq$140 GeV) would be excluded!**
   Other Susy Higgs bosons do not decay to WW!

2. **SM might remain a valid approximation up to very large scales ...**

A nightmare scenario for some

but a "happy end" for others!

If no $M_H \to WW \to \ell\nu\ell\nu$ signal will appear:

"Alternating" 2-3 sigma fluctuations and many Higgs limits will be reported during the years 2010-2012 ...

of course .. unexpected discoveries and events like "Black Holes", Unicorns or Yetis would change everything!

Tevatron run II performance 2001-2008