Foundations of Physics III
Quantum and Particle Physics
Lecture 15

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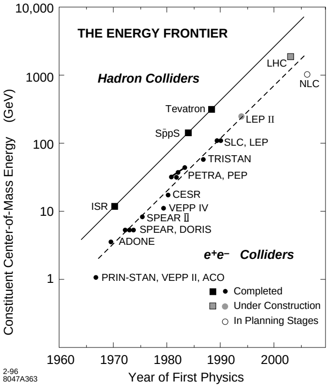
1. Physics at the LHC
2. The quest for the Higgs boson

Chasing the energy frontier

(View of the 1990's . . .)



Phenomenology at colliders

(Looking at the past up to LEP and Tevatron)

- 1950's: The particle zoo
  Discovery of hadrons, but no order criterion
- 1960's: Strong interactions before QCD
  Symmetry: Chaos to order
- 1970's: The making of the Standard Model:
  Gauge symmetries, renormalisability, asymptotic freedom
  Also: November revolution and third generation
- 1980's: Finding the gauge bosons
  Non-Abelian gauge theories are real!
- 1990's: The triumph of the Standard Model at LEP and Tevatron
  Precision tests for precision physics

LHC - The energy frontier

(Design defines difficulty)

- Design paradigm for LHC:
  1. Build a hadron collider
  2. Build it in the existing LEP tunnel
  3. Build it as competitor to the 40 TeV SSC
- Consequence:
  1. LHC is a *pp* collider
  2. LHC operates at 10-14 TeV c.m.-energy
  3. LHC is a high-luminosity collider: 100 $\mathrm{fb}^{-1}/\mathrm{y}$

Trade energy vs. lumi, thus *pp*

- Physics:
  1. Check the EWSB scenario & search for more
  2. Fight with overwhelming backgrounds, QCD always a stake-holder
  3. Consider niceties such as pile-up, underlying event etc..

Some example cross sections

(Or: Yesterdays signals = todays backgrounds)

Process	Evts/sec.
Jet, $E_\perp > 100$ GeV	10^3
Jet, $E_\perp > 1$ TeV	$1.5 \cdot 10^{-2}$
$b\bar{b}$	$5 \cdot 10^5$
$t\bar{t}$	1
$Z \to \ell\ell$	2
$W \to \ell\nu$	20
$WW \to \ell\nu\ell\nu$	$6 \cdot 10^{-3}$

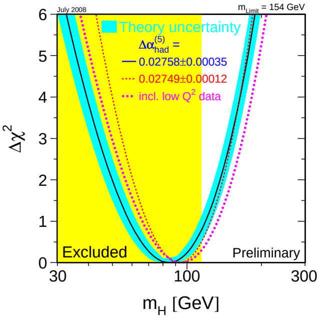
Rates at "low" luminosity, $\mathcal{L} = 10^{33}/\mathrm{cm}^2\mathrm{s} = 10^{-1}\mathrm{fb}^{-1}/\mathrm{y}$, and $s = 14$ TeV.

Physics programme: long wish-list

- There is a long list of questions to be addressed at LHC.
- Find the Higgs boson:
  - verify/falsify our ideas about electroweak symmetry breaking.
- Is there new physics beyond the Standard Model:
  - favourites: supersymmetry, extra dimensions, ...
  - many of them have hot candidates for cold dark matter!
- Constrain the standard model further:
  - Precision measurements of masses/widths
  - more on CP-violation and the mixing in the quark sector
- With heavy ions:
  - look for the quark-gluon plasma (a new state of matter)
- ... and in all this: beat backgrounds by QCD and SM!

The quest for the Higgs boson

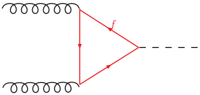
- Higgs boson not yet found, therefore $m_H \geq 114$ GeV.
- Precision data favour light m_H (see left fit)
- Higgs boson couples to heavy objects - all couplings proportional to mass.
- Problem: No heavy objects inside beams
  *p*rotons consist of light quarks (naively *uud*), and gluons.



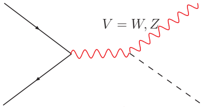
Tayloring search channels

Common feature: Higgs boson couples to heavy objects (top, W, Z)

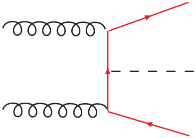
Gluon fusion:



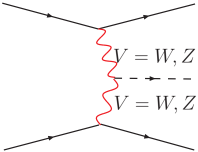
Higgs-Strahlung:



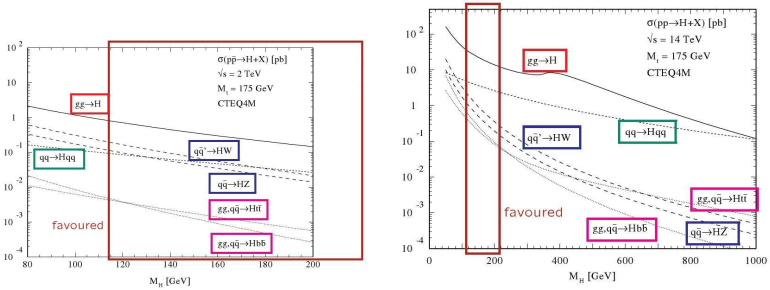
Quark-associated:



Weak boson fusion (WBF/VBF):

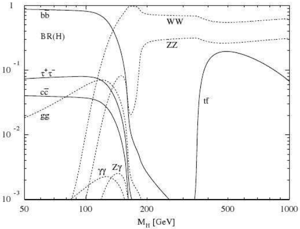


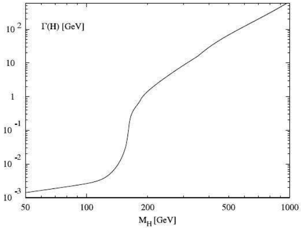
Higgs production cross sections at hadron colliders



(from M.Spira, hep-ph/9810289)

Higgs decays





(from V.Buescher & K.Jakobs, Int. J. Mod. Phys. A **20** (2005) 2523)

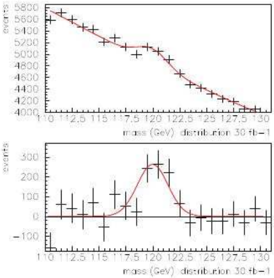
Some typical channels (mostly @ LHC)

- $gg \to H \to ZZ \to 4\mu, 2e2\mu$: "Golden plated" for $m_H > 120$ GeV.
  Key ingredients: Mass peak from excellent mass resolution (leptons).
- $gg \to H \to W^+W^- \to \ell\ell' + \not{E}_\perp$: nearly as good as ZZ
  but no mass peak. Background killed with $\angle_{\ell\ell'}$ etc..
  Very similar to current Tevatron analysis with huge stats.
- $gg \to H \to \gamma\gamma$: Good for small $m_H \lesssim 120$ GeV.
  Key ingredient: mass resolution for γ's & veto on π^0's.
- $WBF \to H \to \tau\tau$: Popular mode
  Key ingredient: QCD-backgrounds killed with rapidity gap
- $WBF \to H \to WW$: ditto.
- $WBF \to H \to b\bar{b}$: in principle ditto
  but: Hard to trigger, pure QCD-like objects (jets)
- $q\bar{q} \to VH$, $V = Z \to \ell\bar{\ell}$ or $V = W \to \ell\bar{\nu}\ell$: a renewed interest - can kill background if VH pair at high invariant masses.

Example: $gg \to H \to \gamma\gamma$

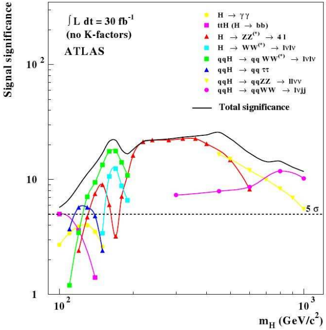
- Characteristic: Bump on a smooth background $\longrightarrow$ side-band subtraction
- Trick: Mass resolution of $\gamma\gamma$

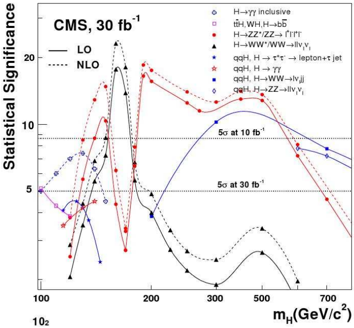
  (problems there: converted γ's, $j(\pi^0) \to \gamma$ conversions, γ direction, . . .)
- $\delta m_{\gamma\gamma} \approx 1.5$ GeV.
- $S/\sqrt{B}(30\mathrm{fb}^{-1}) \approx 6$ for $m_H \in [120, 140]$ GeV



(from ATLAS-Note Pub-2007-013)

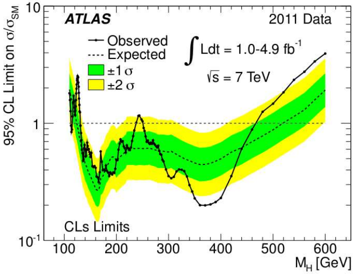
SM-Higgs boson searches at LHC: Sensitivities after 30 fb^{-1}

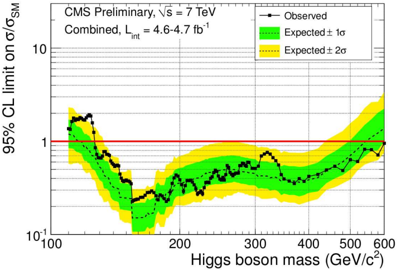




(from V.Buescher & K.Jakobs, Int. J. Mod. Phys. A **20** (2005) 2523)

State of affairs as of today





Learning outcomes

- Why the LHC was built and what is investigated there.
- Some Higgs physics:
    - Major production and decay channels
    - Strategies for finding it
    - Some idas about backgrounds

Summary of the course

You should now know/understand the following:

- Simple properties, symmetries and calculations:
  - special relativity & relativistic kinematics in two-body decays
  - addition of spins/isospins/weak isospins
  - parity and its violation as example for a discrete symmetry
  - conserved quantities/charges
- Feynman diagrams:
  - how to draw Feynman diagrams for a given model, in particular QED and the Standard Model
  - what they are (terms in pertubative expansion)
- particles & anti-particles,
  - Dirac equation & interpretation
  - hadrons (bound states): mesons and baryons, quantum numbers and quark content of the most important ones (p, n, π's, K's, Δ's)
  - the proton as a bound state (form factor, parton picture)

Summary of the course (cont'd)

You should now know/understand the following:

- the Standard Model:
  - 4 fundamental forces and which are included in the Standard Model,
  - its construction principle (global & local gauge invariance),
  - its particle content (elementary particles),
  - their properties (quantum numbers, masses) and their interactions, strong, weak and electromagnetic
  - the Feynman rules, i.e. vertices of the Standard Model.
- principles of particle detection and basic facts about the LHC:
  - building principle of a detector
  - detection through interaction with matter - specific effects
  - some basics about the search for the Higgs boson.