SM Higgs at the LHC

giuseppe bozzi

Institut für Theoretische Physik
Universität Karlsruhe

HERA and the LHC
CERN, 28.05.2008

Outline

Outline

The Higgs mechanism

- Standard Model: SU(2)×U(1) gauge theory
  $\longrightarrow$ $m_l = m_B = 0$
- "Simple-minded" insertion of mass terms in the Lagrangian
  $\longrightarrow$ both gauge invariance and renormalizability spoiled
- **SSB** leads to Goldstone bosons
  $\longrightarrow$ global symmetry: m=0
  $\longrightarrow$ local symmetry: m>0
- Local SSB (Higgs mechanism) provides masses to $W^{\pm}, Z^0$ and fermions through trilinear Yukawa couplings
- *"Remnant"*: **neutral, scalar, massive** boson **H**

Mass bounds: theoretical arguments

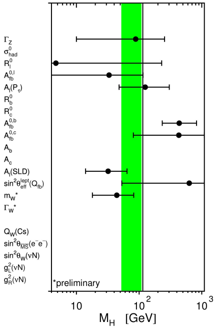
$$\text{Higgs self-coupling } 2\lambda = (M_H/v)^2$$

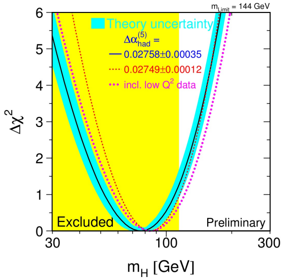
- Triviality. λ increases with energy, eventually reaching the Landau pole $\Lambda \propto \exp(v^2/M_H^2)$: the larger M_H, the closer the singularity $\rightarrow M_H \lesssim$ 200(1000) GeV for SM to be valid up to $\Lambda \sim 10^{16(3)}$ GeV
- Vacuum stability. Top quark loop corrections may cause $\lambda < 0$ and, thus, unstable EW vacuum $\rightarrow M_H \gtrsim$ 100(70) GeV to balance top loops up to $\Lambda \sim 10^{16(3)}$ GeV

$$V_L V_L \rightarrow V_L V_L$$

- Perturbative unitarity. If M_H is too large, the amplitude exceeds unitarity bound $\rightarrow M_H \lesssim$ 800 GeV

Mass bounds: experimental arguments



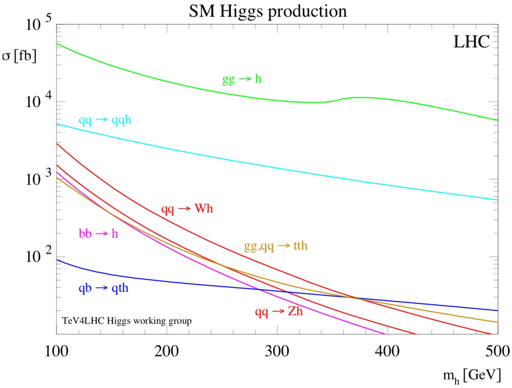


[LEPEWWG(Winter2008)]

- Direct search. "Higgs-strahlung"($e^+e^- \rightarrow HZ$) not observed at LEP $\longrightarrow M_H \geq 114.4 GeV$
- Indirect searches. Radiative corrections to EW observable vary with $M_H \longrightarrow$ global χ^2-fit allows an indirect measure:
  - $M_H = 87^{+36}_{-27}$ GeV @ 68% CL ($\Delta\chi^2 = 1$)
  - $M_H \leq 160$ GeV @ 95% CL ($\Delta\chi^2 = 2.7$)

Outline

Higgs production



[Hahn,Heinemeyer,Maltoni,Weiglein,Willenbrock(2006)]

- Gluon fusion: dominant production channel over entire mass range (large gluon luminosity)
- Vector boson fusion: very clean experimental signature
- Associated production: maybe important in the low mass region (provided a good b-tagging!)
- Higgs-strahlung: relevant at Tevatron for $M_H \leq 130$ GeV, very difficult at the LHC

The gg → H channel

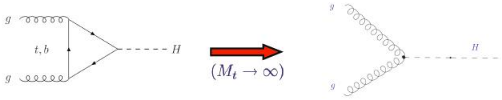
- Coupling mediated by triangular heavy quark loops
- Higgs coupling $\propto$ fermion mass $\rightarrow$ top loops dominate
- LO = $\mathcal{O}(\alpha_S^2)$ computed a long time ago...

[Georgi,Glashow,Machacek,Nanopoulos(1978)]

- NLO QCD corrections very large (K-factor $\sim$ 80-100 % !)

[Spira,Djouadi,Graudenz,Zerwas(1991,1995)]

- Higher-order calculations extremely difficult: considerable simplifications arise when $m_H \leq 2m_t$



- $\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr} G_{\mu\nu}G^{\mu\nu}$

[Ellis,Gaillard,Nanopoulos(1976)]

[Δ known to $\mathcal{O}(\alpha_S^3)$ Chetyrkin,Kniehl,Steinhauser(1997)]

- Good agreement (up to 4% for M_H < 200 GeV) with full result

State of the art: total cross section

- NNLO ($\mathcal{O}(\alpha_s^4)$): another 15-20% enhancement ($m_t \to \infty$)

  [Harlander(2000);Harlander,Kilgore(2001,2002);Catani,deFlorian,Grazzini(2001,2002);]

  [Anastasiou,Melnikov(2002);Ravindran,Smith,vanNeerven(2003)]

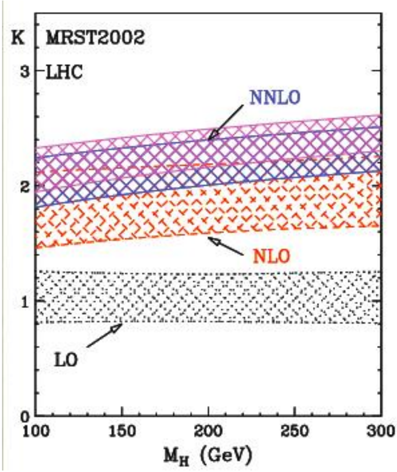
- Bulk of radiative corrections due to virtual and soft-gluon contributions $\rightarrow$ (*insensitive to top quark loop*)
- Higher-order perturbative contributions reliably estimated by resumming multiple soft-gluon emissions
- NNLL+NNLO: perturbative uncertainty reduced to $\pm 10\%$

  [Catani,deFlorian,Grazzini,Nason(2003)]

- Soft-gluon terms at NNNLO: effects consistent with NNLL+NNLO uncertainty

  [Moch,Vogt(2005);Laenen,Magnea(2006);Idilbi,Ji,Ma,Yuan(2006)]

Higgs total cross section



[Catani,deFlorian,Grazzini,Nason(2003)]

- NNLO: 10-20% increase wrt NLO
- Threshold resummation further improves stability (6% wrt NNLO)
- 10% uncertainty due to scale variation
- 2-loop EW also available: 5-8% effect below WW threshold

[Aglietti,Bonciani,Degrassi,Vicini(2004)]

State of the art: differential distributions

- Transverse-momentum distribution

[Hj:deFlorian,Grazzini,Kunszt(1999)]: NLO

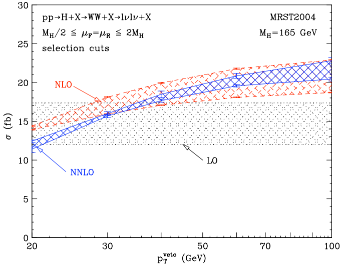
[Hj:Ravindran,Smith,vanNeerven(2002);Glosser,Schmidt(2002)]: NLO

[Hjj:Campbell,Ellis,Zanderighi(2006)]: NLO

- Fully exclusive σ with arbitrary cuts

[FEHIP: Anastasiou,Melnikov,Petriello(2004,2005)]: NNLO

- Fully exclusive parton level event generator including $H \to \gamma\gamma$, $H \to WW$, $H \to ZZ$ decays



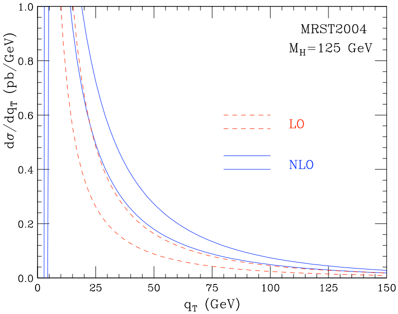
[HNNLO: Catani,Grazzini(2007)]: NNLO

The small-q_T region ($q_T \ll M_H$)

- Bulk of the events in the region $q_T \ll M_H$
- Kinematical unbalance between real and virtual contributions

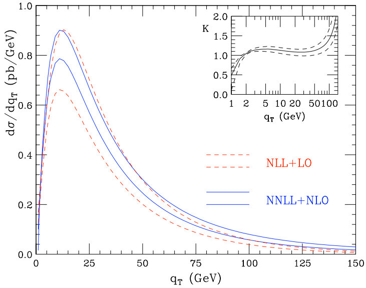
→ perturbative coefficients enhanced by $\alpha_S^n \log^m(\frac{M_H^2}{q_T^2})$

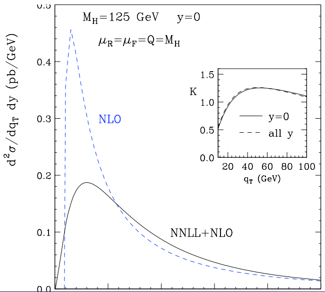
→ convergence of perturbative result completely spoiled



→ need for resummation! [Collins,Soper,Sterman(1985)]

The q_T spectrum [gb,Catani,deFlorian,Grazzini(2003,2005,2007)]





- NNLL+NLO uncertainty band overlaps with NLL+LO one
  - → very good convergence of the resummed perturbative result
- q_T-dependent K-factor

$$K(q_T) = \frac{d\sigma_{NNLL+NLO}(\mu_F, \mu_R)}{d\sigma_{NLL+LO}(\mu_F = \mu_R = M_H)}$$

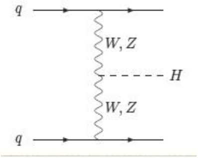
- $\sim$ 1.1-1.2 in the central region
- increase (decrease) drastically for $q_T > 50$ ($q_T < 2$)

→ no simple rescaling of NLL+LO

[HqT: http://theory.infn.it/grazzini/codes.html]

Vector boson fusion 1

- two highly energetic outgoing jets (1 TeV)
- large rapidity interval between jets
- no hadronic activity in the rapidity interval between jets



- All this is in contrast to the QCD background

$\longrightarrow$ forward-jet tagging and central-jet vetoing

- Cross-section: 20% wrt to gluon fusion, comparable when m_H ∼600 GeV

Vector boson fusion 2

- LO: Wff larger than Zff
  $\sigma(WW \to H) \sim 3\sigma(ZZ \to H)$

  [Cahn,Dawson(1984)]

- NLO QCD:
  $\sim$ 5-10% increase
  few % uncertainty
  $\longrightarrow$ very stable results!

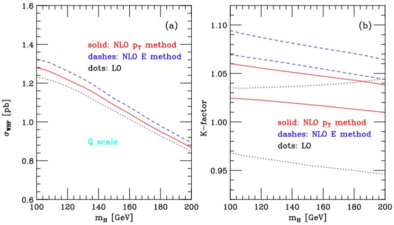
  [Han,Willenbrock(1991)]

  [Figy,Oleari,Zeppenfeld(2003)]

  [Campbell,Ellis(2003)]

- PDF dependence:
  incoming quarks in
  intermediate-x region
  $\longrightarrow$ small uncertainties

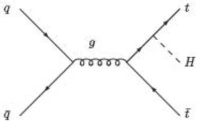
$\longrightarrow$ Very promising channel!

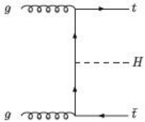


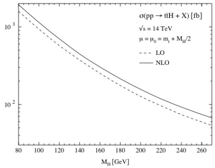
Associated production with top

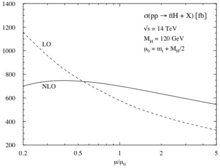
- Important in the low-mass region: allow to search for H $\rightarrow$ bb decay
- Good b-tagging and high-luminosity required
- Useful channel to measure ttH Yukawa coupling
- LO: known since long time

  [Kunszt(1984)]
- NLO QCD (massive pentagons!): $\sim$20% increase $\sim$15% scale dependence









[Beenakker,Dittmaier,Kraemer,Plumper,Spira,Zerwas(2001);Dawson,Orr,Reina,Wackeroth(2003)]

Higgs decay modes

- H $\rightarrow$ ll (mainly l=τ)

  [2-loopEW:Fleischer,Jegerlehner(1981);Kniehl(1992)]

  [2-loopQCD:Kniehl,Sirlin(1993);Djouadi,Gambino(1996)]

- H $\rightarrow$ QQ(mainly Q=t,b,c)

  [(b,c)3-loopQCD:Larin,vanRitbergen,Vermaseren(1995)]

  [(t)2-loopQCD:Harlander,Steinhauser(1997)]

- H $\rightarrow$ V(*) V(*)

  [1-loopEW:Fleischer,Jegerlehner(1981)]

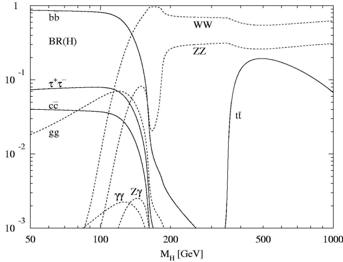
  [3-loopQCD:Kniehl,Steinhauser(1996)]

- H $\rightarrow$ gg (heavy quark loops)

  [3-loopQCD:Chetyrkin,Kniehl,Steinhauser(1996)]

- H $\rightarrow$ $\gamma\gamma$ (W and heavy quark loops)

  [3-loopQCD:Steinhauser(1996)]



- M_H < 140 GeV
  - bb $\sim$ 82% (pb vs. mb!)
  - $\tau\tau$,cc,gg $\sim$ 6% (τ>c!)
  - $\gamma\gamma \sim 10^{-3}$
- m_H > 140 GeV
  - WW $\sim$ 60-80% ($\sim M_H^3$)
  - ZZ $\sim$ 2-30% ($\sim M_H^3$)
  - tt $\sim$ 10-20% ($\sim M_H$)

Backgrounds

- $\gamma\gamma$ (measured from sidebands)
  - known at NLO with fragmentation [DIPHOX:Binoth et al(2000)]
  - gg fusion at NNNLO [Bern et al(2003)]
  - $\gamma\gamma$ + jet known at NLO [Del Duca et al(2003)]
- $WW \rightarrow l\nu l\nu$
  - known at NLO [Dixon et al(1999);Campbell,Ellis(1999)]
  - soft-gluon effects [Grazzini(2005)]
  - gg fusion at NNLO [Binoth et al(2005);Duehrssen et al(2005)]
  - spin correlations included in MC@NLO (essential for $\Delta\phi$ distribution: strong correlation between leptons [Dittmar,Dreiner(1996)])
- $ZZ \rightarrow 4l$ (measured from sidebands)
  - known at NLO [Dixon et al(2000);Campbell,Ellis(1999)]
  - gg fusion in progress [Kauer]
  - spin correlations *not* included in MC@NLO
- VV via VBF at NLO [gb,Jaeger,Oleari,Zeppenfeld(2006.2007)]

Outline

Summary

- The Higgs mechanism is > 40 years old $\rightarrow$ time to discover it!
- Enormous theoretical effort in the last years to improve predictions for both signal and background $\longrightarrow$ don't waste it!
- Still so much to do: backgrounds to NLO for a number of processes, improvement from pdfs, ...
- This knowledge will be essential to improve search strategies, exploit the various channels in the delicate low-mass region and measure the Higgs couplings
- If the Higgs boson exists, no escape route for it at the LHC!

Deductions

”Of course the LHC will find the Higgs!
We have found so many fundamental scalars in the past!”

[Edward ’Rocky’ Kolb]

$\downarrow$

”Try hard to get a permanent position before the first run...”

[gb]