# QCD and Higgs at the LHC

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#### Outline

## QCD and Higgs

The Higgs boson at the LHC



### Hadronic cross sections in perturbative QCD



#### • $h_1, h_2$ = initial state hadrons (with momenta $p_1, p_2$ )

- $f_a, f_b$  = parton distribution functions
- C = coefficient functions (partonic splitting)
- H = perturbatively computed partonic event
- *F* = final state particle(s)
- S = resummation of soft radiation from incoming partons
- Precise predictions depend on good knowledge of f,C,H and S!

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- Reliable results start at NLO

 $K = \frac{\sigma_{HO}(pp \to H + X)}{\sigma_{LO}(pp \to H + X)}$ 

- $\alpha_S$  and pdfs have to be consistently evaluated at HO and LO as well (otherwise K could be larger,since  $\alpha_S(NLO) < \alpha_S(LO)$ )
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- Then  $\mu_R, \mu_F$  are independently or collectively varied within

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- Dependence on  $\mu_R, \mu_F \rightarrow$  evaluation of theoretical uncertainty ?
  - The narrower the uncertainty band is, the smaller the HO corrections are expected to be (not always true!)
  - In principle the scale uncertainty should be reduced when going to higher orders (not always true!)
  - BUT remember that all this is unphysical and there is no rigorous way to estimate the theoretical uncertainty other than performing the higher-order calculation!

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 $\rightarrow m_l = m_B = 0$ 

- "Simple-minded" insertion of mass terms in the Lagrangian
  - ightarrow both gauge invariance and renormalizability spoiled
- SSB leads to Goldstone bosons
  - $\rightarrow$  global symmetry: m=0
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### Mass bounds: experimental arguments



• Direct search. "Higgs-strahlung" ( $e^+e^- \rightarrow HZ$ ) not observed at LEP  $\rightarrow M_H \ge 114.4 GeV$ 

• Indirect searches. Radiative corrections to EW observable vary with  $M_H \longrightarrow$  global  $\chi^2$ -fit allows an indirect measure:

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giuseppe bozzi (ITP Karlsruhe)

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- Vector boson fusion: very clean experimental signature
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- 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)]

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

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

### Higgs total cross section



- NNLO: 10-20% increase wrt NLO
- 10-15% uncertainty due to scale variation
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#### Transverse-momentum distribution

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

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

• Fully exclusive parton level event generator including  $H \rightarrow \gamma \gamma, H \rightarrow WW, H \rightarrow ZZ$  decays



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QCD and Higgs at the LHC

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QCD and Higgs at the LHC

Perugia, 02.02.2008 17 / 28

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- Bulk of the events in the region  $q_T \ll M_H$
- Kinematical unbalance between real and virtual contributions
- $\rightarrow$  perturbative coefficients enhanced by  $\alpha_S^n \log^m(\frac{m_H}{\sigma^2})$
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→ **need for resummation!** [Collins, Soper, Sterman (1985)]

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

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#### NNLL+NLO uncertainty band overlaps with NLL+LO one

- $q_T$ -dependent K-factor

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

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

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QCD and Higgs at the LHC

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- → very good convergence of the resummed perturbative result
- q<sub>T</sub>-dependent K-factor

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# QCD and Higgs at the LHC



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# CCD and Higgs at the LHC



## Associated production with top

- Important in the low-mass region: allow to search for H → bb decay
- Good b-tagging and high-luminosity required
- Useful channel to measure ttH Yukawa coupling
- LO: known since long time (Runset (1984))
- NLO QCD (massive pentagons!): ~20% increase ~15% scale dependence





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giuseppe bozzi (ITP Karlsruhe)

Perugia, 02.02.2008 22 / 28

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# Associated production with bottom

- Small σ but enhanced at large tan β MSSM
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- $H \rightarrow II$  (mainly  $I=\tau$ )
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- *M<sub>H</sub>* < 140 GeV
  - bb ∼ 82%

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- $\circ$  -m\_1 cc,  $00 \sim 6\%$  (m,cl))  $\circ$  -m\_1 ~ -10  $^{-3}$
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- \*  $m_1 cc_1 gg \sim 6\% (mcl)$ ) \*  $m_1 \sim 10^{-2}$
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○ DD ~ 82%

 $\sim m_1 c_{0.00} \sim 6\% (r-c))$  $\sim m \sim 10^{-3}$ 

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- *m<sub>H</sub>* > 140 GeV
  - WW ~ 60-80% (~ M<sup>3</sup><sub>H</sub>)
     ZZ ~ 2-30% (~ M<sup>3</sup><sub>H</sub>)
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giuseppe bozzi (ITP Karlsruhe)

QCD and Higgs at the LHC

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## Outline

# QCD and Higgs

2 The Higgs boson at the LHC



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#### The Higgs mechanism is > 40 years old → time to discover it!

- Enormous theoretical effort in the last years to improve predictions for both signal and background
- Still so much to do, i.e., backgrounds to NLO for  $t\bar{t}, VVj, Vt\bar{t}, VVb\bar{b}, t\bar{t}jj, t\bar{t}b\bar{b}, gg \rightarrow Hjj, gg \rightarrow ZZ\gamma^*...$
- This knowledge will be essential to improve search strategies, exploit the various channels in the delicate low-mass region and measure the Higgs couplings
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