Theoretical predictions for SM Higgs production

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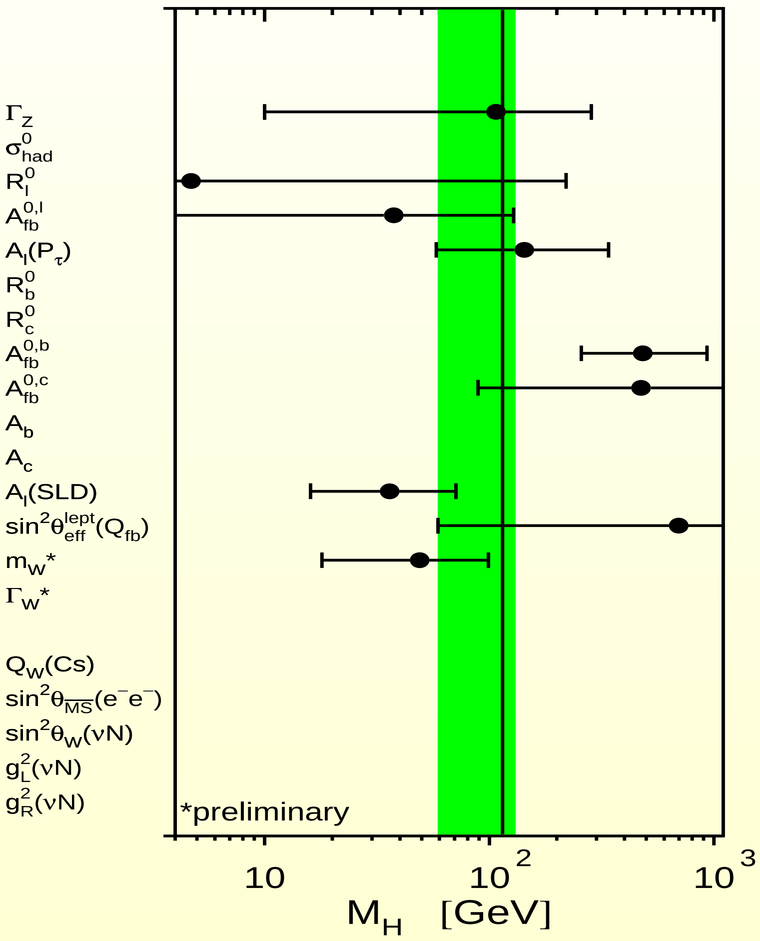
LHC Era, Paris November 2006

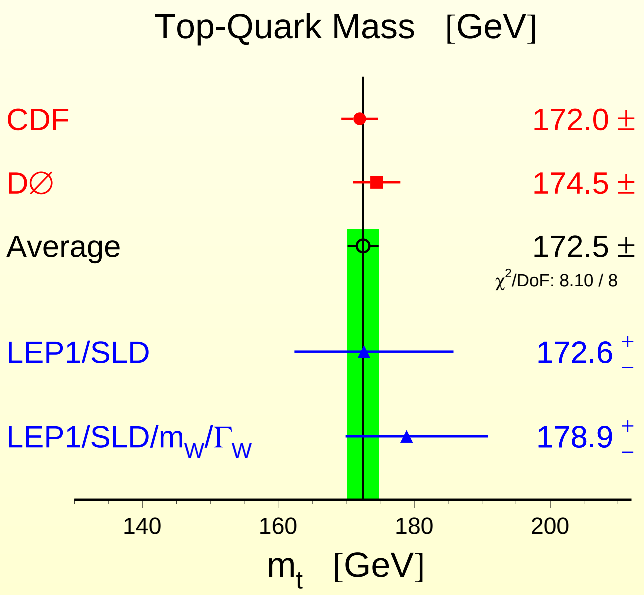
The Standard Model

- Gauge theory with matter field
  - *gauge group:* $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$
  - *Matter fields: quarks and leptons*
  - *QCD: asymptotic freedom , quark confinement, chiral symmetry breaking, instantons, etc.*
  - *Electroweak sector: only perturbation theory, well tested with quantum fluctuations*
- Mass generation with Higgs mechanism
  - *Isodoublet scalar matter field, with spontaneously broken symmetry* $O(4) \Rightarrow O(3)$
  - *The* $O(4)/O(3)$ *Goldstone bosons transmute to* $W_{\mathrm{L}}^{\pm}, Z_{\mathrm{L}}$
  - *one scalar particle Higgs boson in the spectrum*
  - *EWPD:* $114\,GeV < m_h < 290\,GeV$

EW parameters

Latest EWWWG fit to M_H and m_t





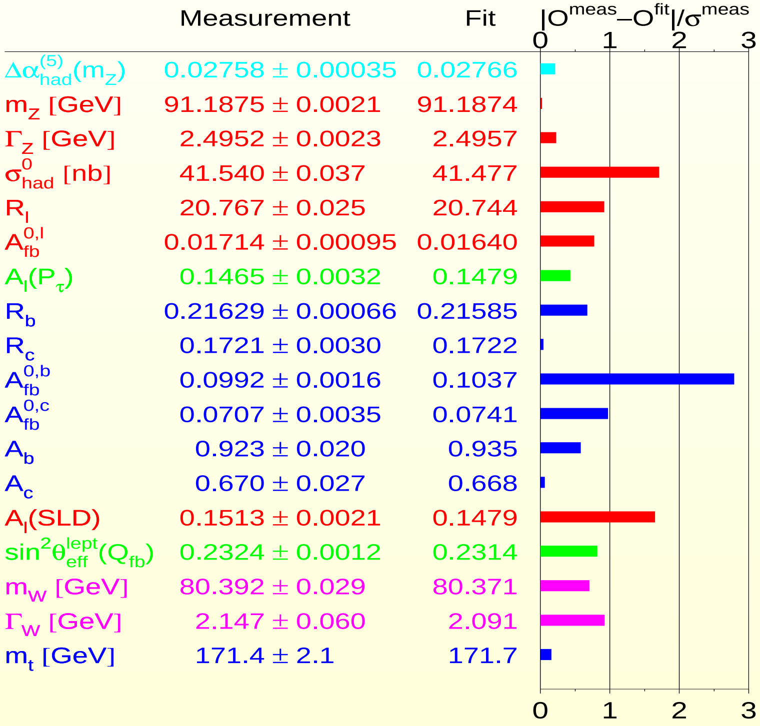
Hard to conclude on the scale of new physics. . .

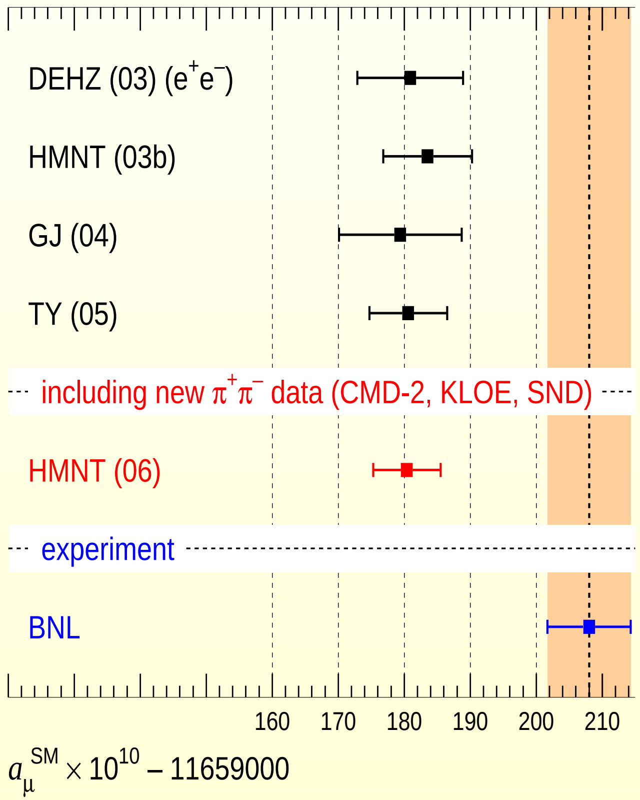
Will the SM break down at the LHC?

- Scalar matter field is problematic:
  - * unitarity, triviality and stability
  - * big (GUT,gravity) and little($\delta m_H/m_H \leq 1\,, \Delta calL = \frac{1}{\Lambda^2}O_{(6)}\,, \Lambda \approx 5-10\mathrm{GeV}$ hierarchy problem
  - * large variety of BSM models: elementary scalar:MSSM composite scalars: little higgs, higgsless models, M5DCHM,..
  - * Dark matter, baryon genesis, neutrino oscillations
  - * Tensions in the EWPD: Puzzling $\approx 3\sigma$ differences in precision measurements
- No conclusion about the scale of new physics
- We CAN NOT predict what REALLY will happen at the LHC
- We CAN predict what will happen if the SM remain valid:

The Higgs boson will be found with epxerimental bound of
114 GeV $< m_h < 290$ GeV and
theoretical upper bound of about 700 GeV

Tensions in the EWPD





Under estimated experimental error or new physics ?

LHC and its challenges

- High collision energy $14\,\mathrm{TeV}$
  high luminosity $30fb^{-1}$ per year
- Immense rates: pentabyte data base
  - Very large number of SM processes. They have to be well described to disantangle New Physics
  - Different signals require different accuracy
- Hard processes can be described in perturbation theory
  - Proton beams: wide band beams of quarks and gluons
    quark, gluon luminosities are scale dependent
  - W, Z production and Higgs production require NLO, NNLO accuracy with resummation
  - generic multi jet processes are also need in NLO accuracy
- Monte Carlo programs for data analysis
  - Partonic final states undergo hadronization
  - Non-perturbative model $+$ as much perturbative QCD as possible (MC@NLO).

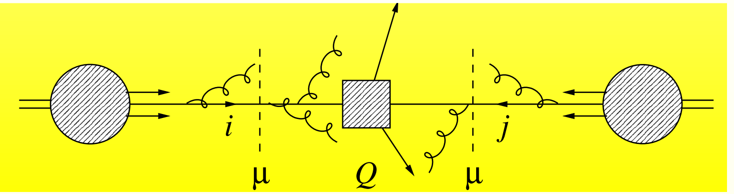
How to find the Higgs boson?

- The LHC has the energy and luminosity to find it in the whole allowed range $m_H = 114 - 700\mathrm{GeV}$.
- When can we claim a discovery ?
  - * Find an observable which is characteristic of Higgs production and caclulate its rate
  - * Suppress the usually large background
  - * Collect data, estimate efficiencies

$$\text{Significance} = \frac{\text{Signal}}{\text{Error in Background}}$$

  - * Extract the value of the mass , the width, and the couplings of the Higgs boson (precision test).
  - * Quantitative theory predictions are required both for the signal and the background!

QCD improved parton model



$$N = \mathcal{L} \times \left(\sum_{ij} \int f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}(\alpha_S, M_H, \mu^2)(i + j \Rightarrow H + X) \right) \times BR(H \Rightarrow \gamma\gamma)$$

- Absolute prediction for the number of events
- Theory errors of the predictions ought to be smaller than the statistical error. They come from
  - Production cross-sections and branching ratios
  - Strong couplings
  - Parton distribution functions
  - Luminosity (or partonic luminosities: $\mathcal{L}_{ab}(\tau) = \int f_a(x_1) f_b(x_2) \delta(x_1 x_2 - \tau)$)
- Similarly for any hard process

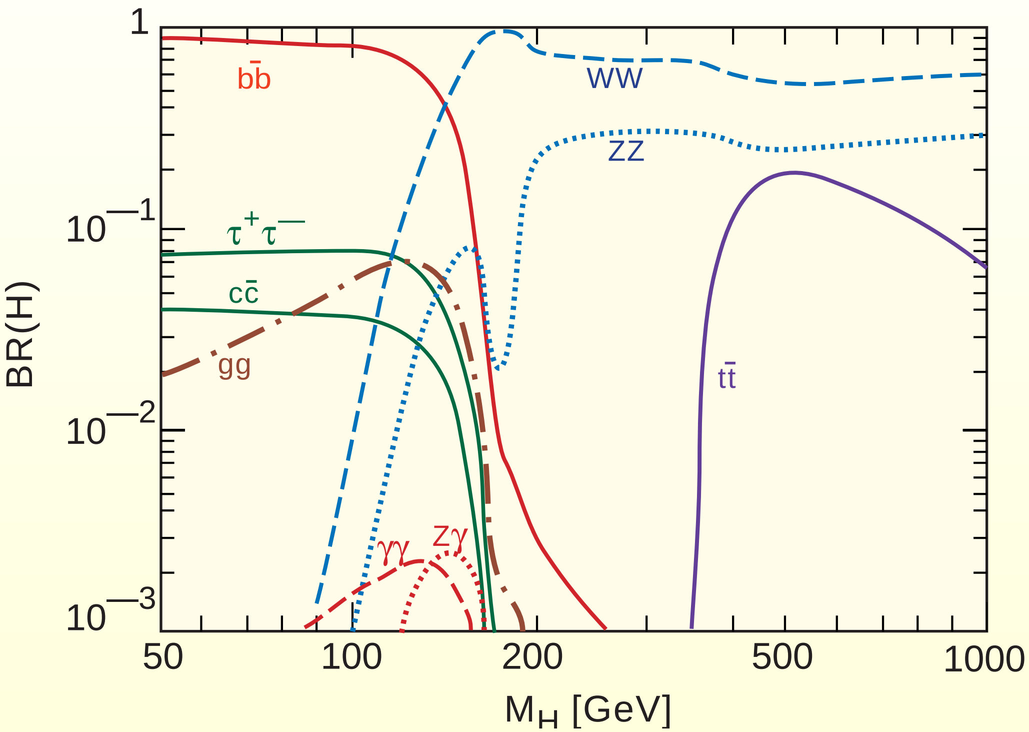
Do we need higher order corrections?

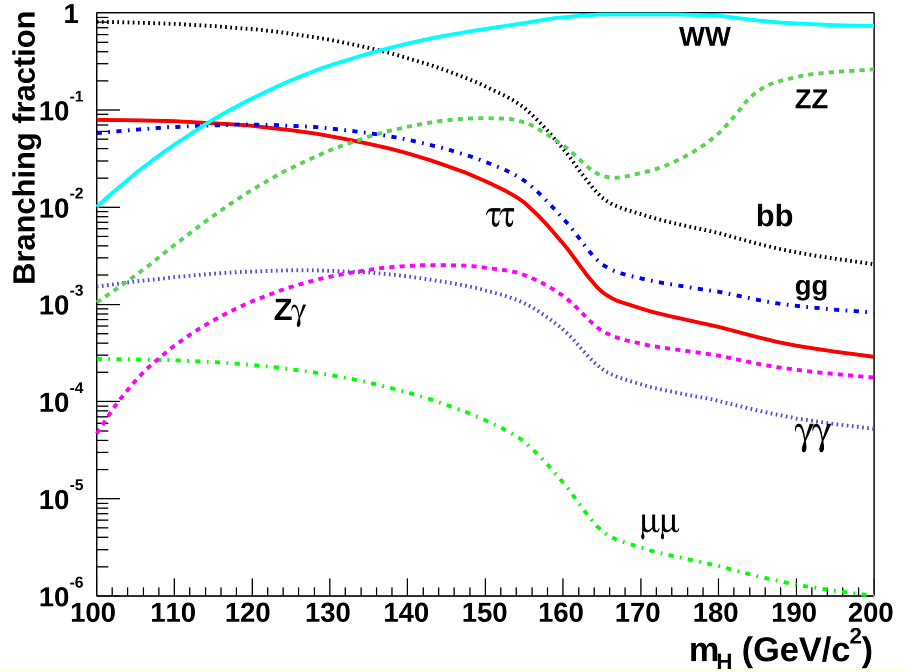
$$\sigma = \alpha_s^n \sigma_0 + \alpha_s^{n+1} \sigma_1 + \alpha_s^{n+2} \sigma_2 + \ldots$$

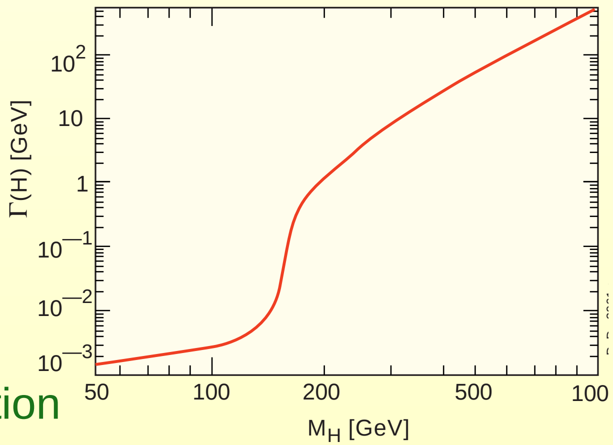
The rule of thumb is:

- Leading order (LO) is an order of magnitude estimate
- First order corrections (NLO) give a good quantitative prediction with error of $\approx 10 - 30\%$
- With NNLO corrections we achieve precision of the few percent level.

Higgs decay branching ratios

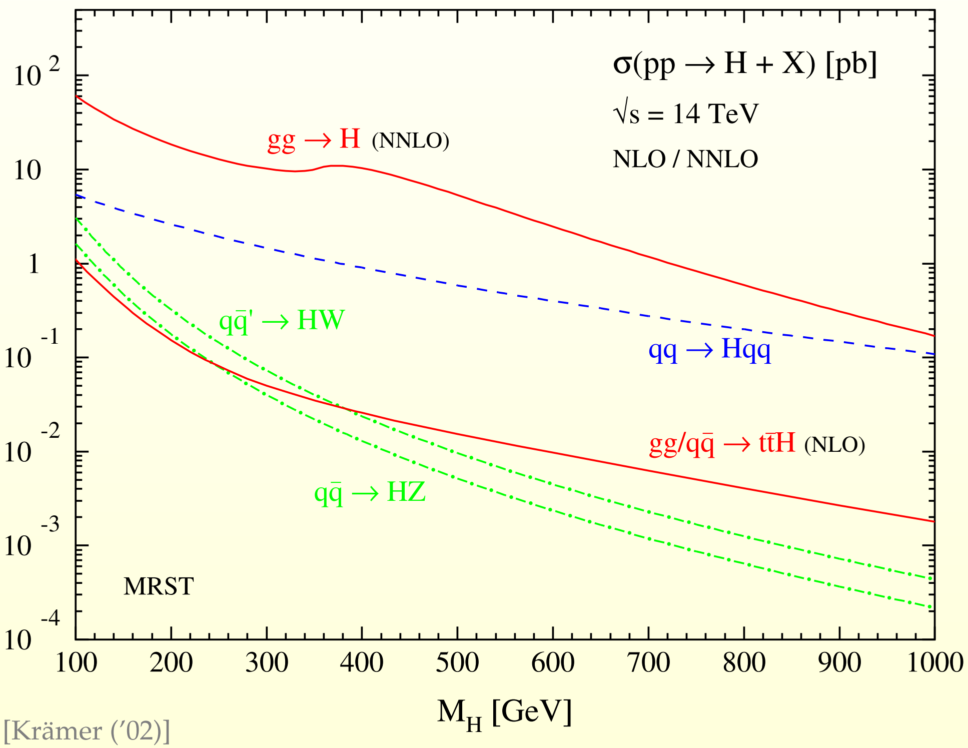




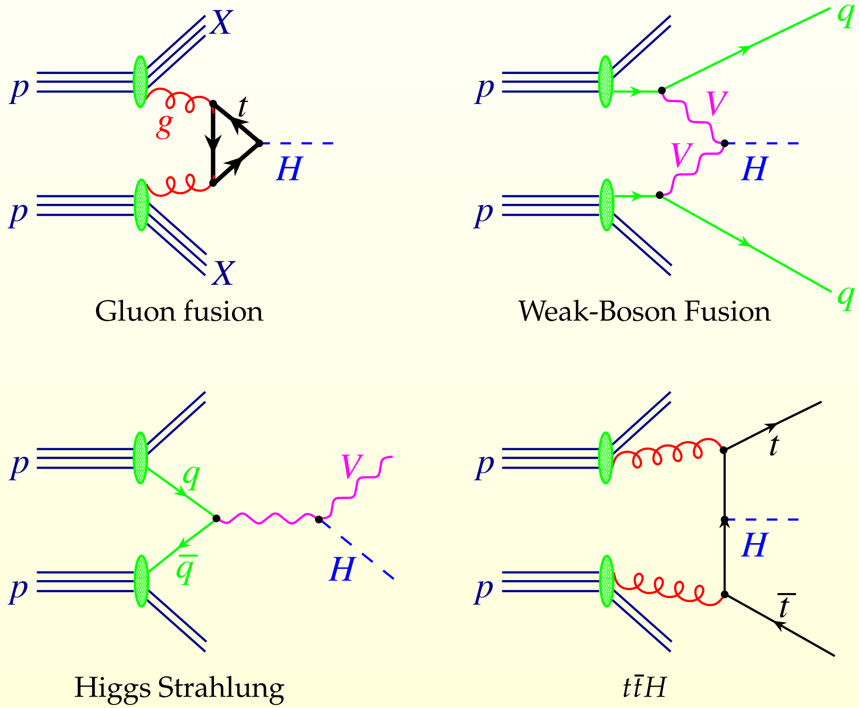


- The higgs couplings to the fermions grow with their masses . Its coupling to W_L, Z_L grows as m_H^2 (equivalence theorem).
- Narrow resonance for $m_H < 170 GeV$
- New physics can change significantly this prediction

Higgs producion mechanisms



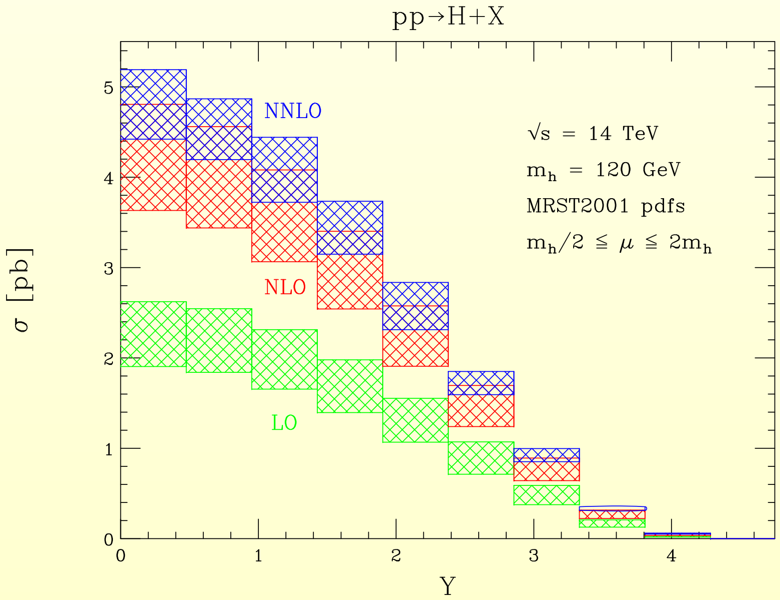
[Krämer ('02)]

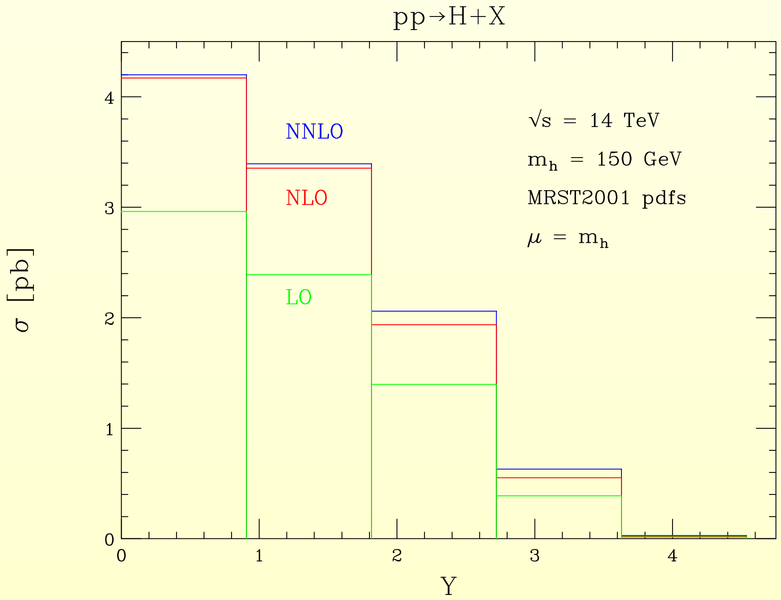


- The subdominant mechanisms are important in measuring the Higgs-couplings
- Physics signal depends on the decay modes

NLO and NNLO corrections to $gg \Rightarrow H$

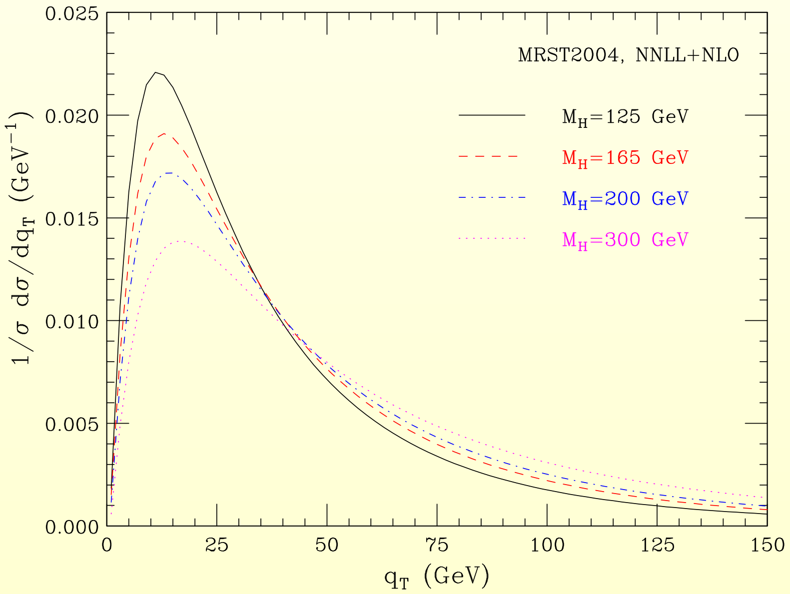
- dominant Higg production mechanism
- singularly large next-to-leading order (NLO) QCD corrections
  - $K_{NLO} \sim 1.7$ Djouadi, Graudenz, Spira, Zerwas; Dawson
  - $K_{NLO+NNLO} \sim 2$ about $\approx 20\%$ increase for LHC
    Harlander, Kilgore; Anastasiou, Melnikov , van Neerven Ravindaran, Smith
- The origin of large QCD corrections is well understood

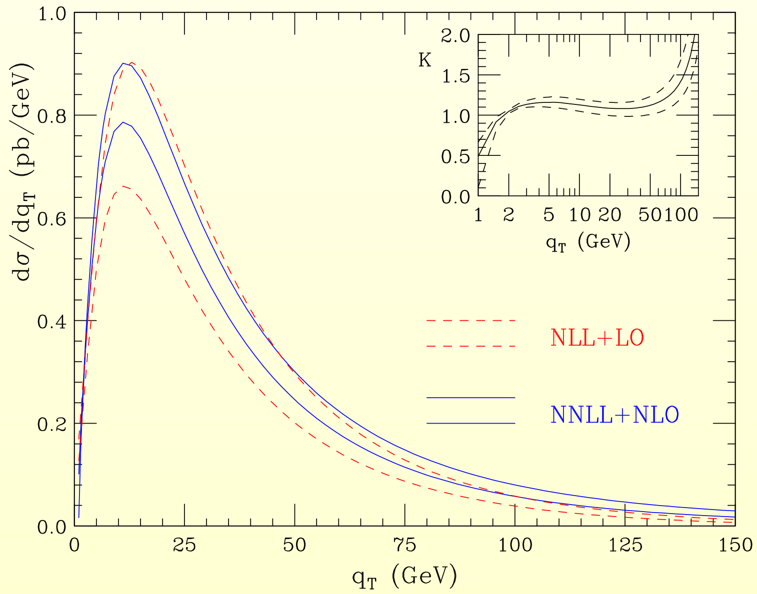




Resummations

- Bulk of the large K-factor is due to virtual and soft-gluon terms.
  - Explains the validity of the large $M_{\rm top}$ approximation
  - Allows to estimate higher order QCD contributions with all order resummation of the log enhanced terms due to multiple soft gluon emission.
- Resummation for transverse momentum distributions



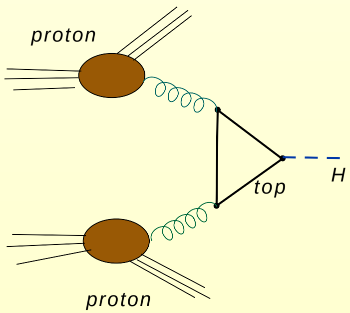


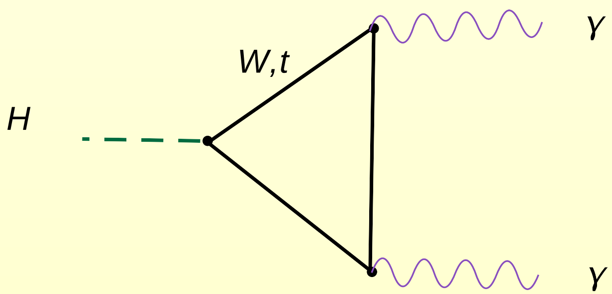
Discovery Channels

Three important discovery channels

- m_H : $114 - 140\,\mathrm{GeV}$: $\gamma\gamma\,(H \Rightarrow \gamma\gamma)$
- m_H : $140 - 175\,\mathrm{GeV}$: $2l + E^T_{\mathrm{miss}}\,(H \Rightarrow WW^{(*)})$
  also $4l(H \Rightarrow ZZ^{(*)})$
- m_H : $175 - 600\,\mathrm{GeV}$: $4l\,(H \Rightarrow ZZ^{(*)})$

Signal rate = production x-section $\times$ decay branching ratios





Signal channel: $H \Rightarrow \gamma\gamma$

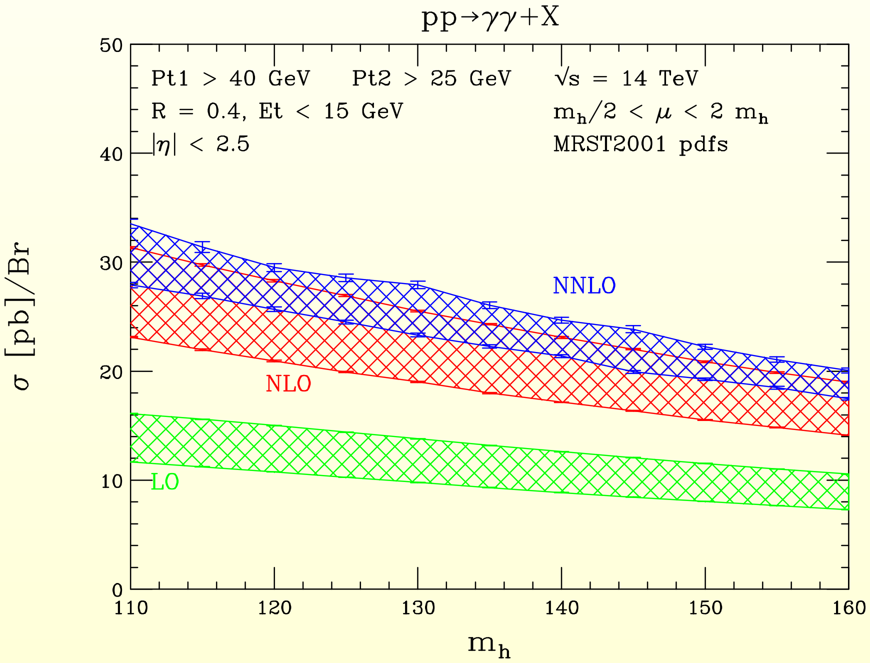
Full MC simulation

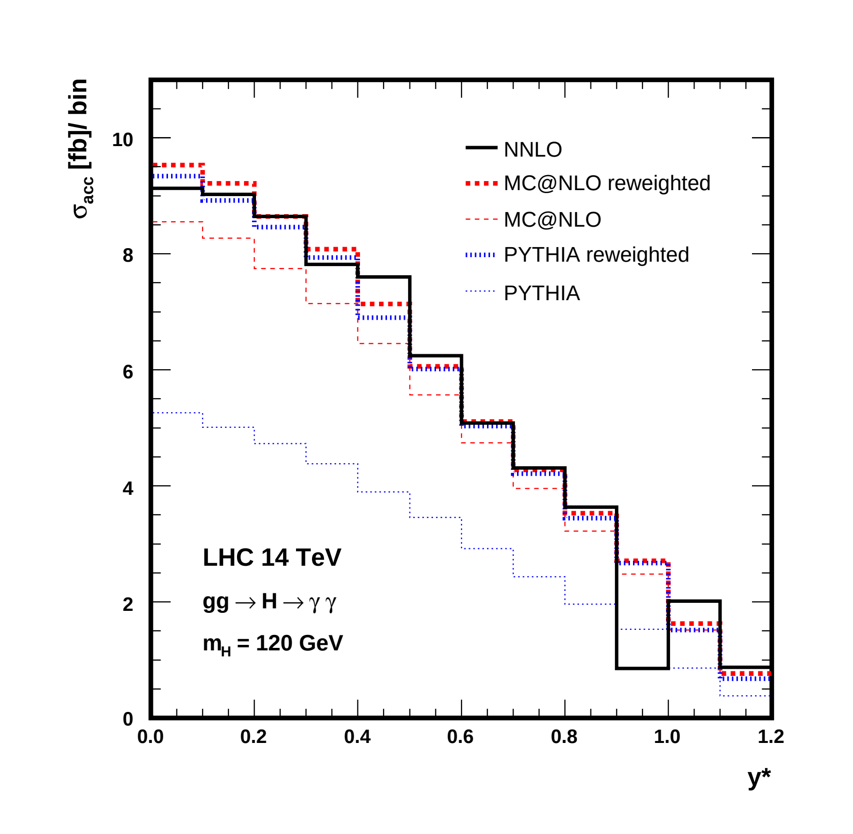
- MC@NLO Herwig for signal
- reweighting in Pythia to match NLO results both for signal and background.
- reweighting for NNLO

Background suppression:

- Reducible background : 2 jet, 1 jet $+$ direct γ production
  Irreducibel background : 2 direct γ (QCD) production
- cuts on the final photons
  - Isolation cuts: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\Phi^2} < 0.4, E_{\mathrm{T,hadr}} < 15\mathrm{GeV}$
  - Kinematical cuts: $p_{\perp}^{(1)} \geq 25\mathrm{GeV}\, p_{\perp}^{(2)} \geq 40\mathrm{GeV}\, |\eta_{1,2}| \leq 2.5$
- Fully differential calculation is needed also for the NLO and NNLO QCD corrections

Precision results for $H\gamma\gamma$ signal

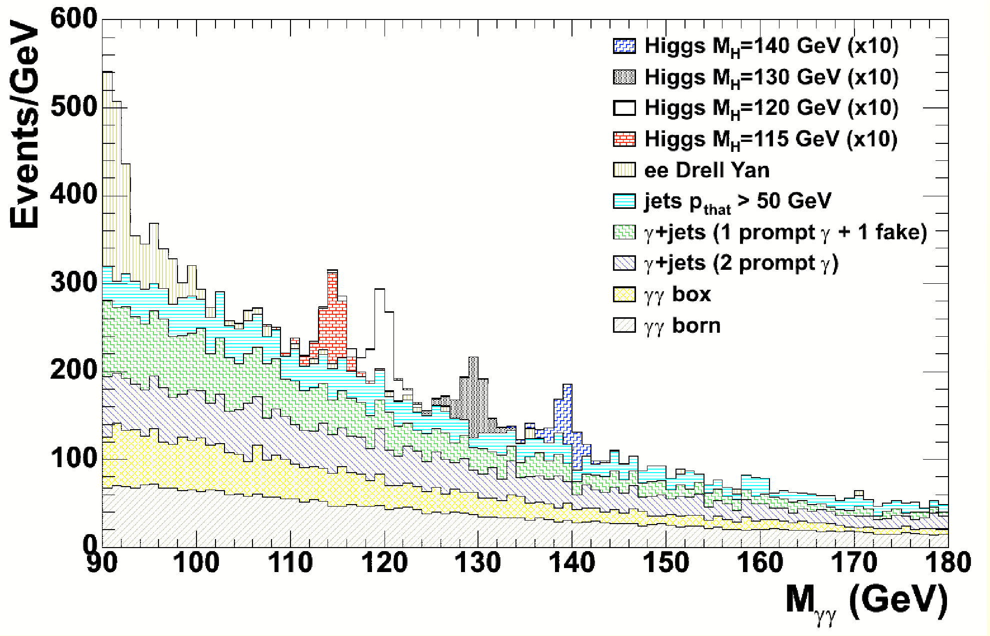


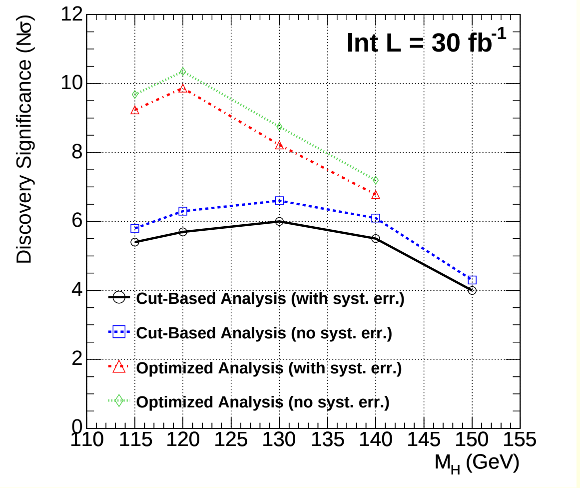


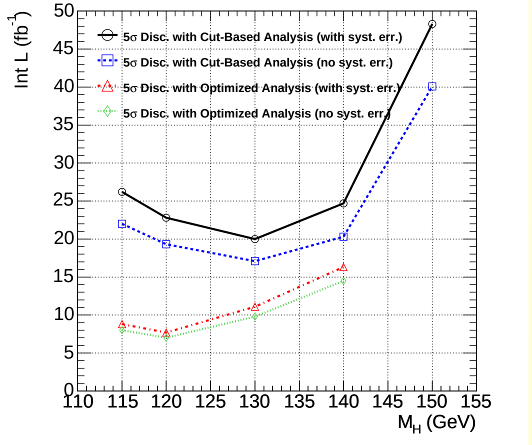
The cross-section at NNLO is two times of the LO result.

pseudo rapidity difference distributions for di-photon events

Signal channel: $H \Rightarrow \gamma\gamma$, final result

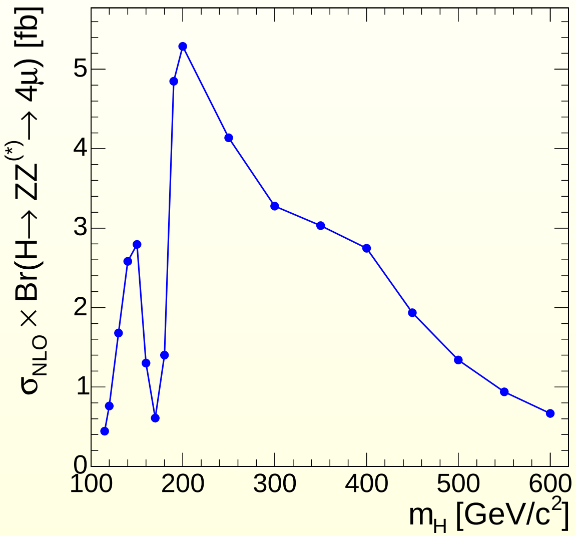


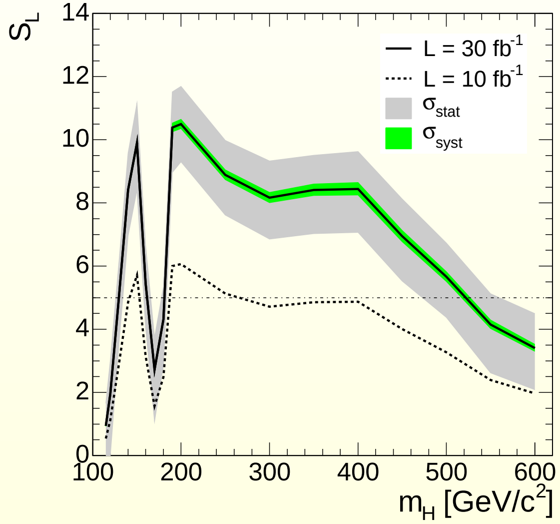


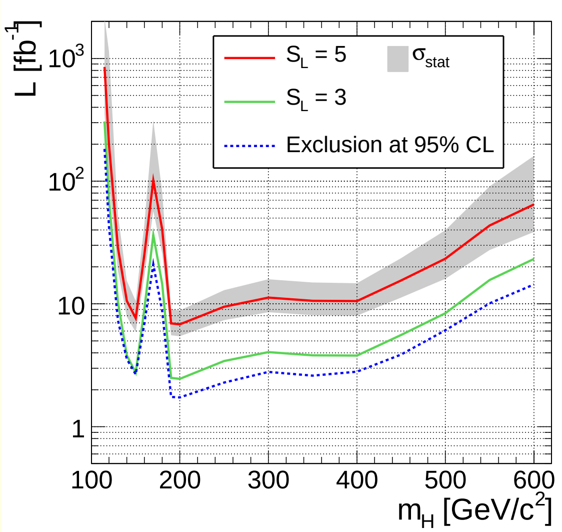


- $1\mathrm{fb}^{-1}, 10\, S + B$
- optimized(neuro network) + standard significance
- opt. + standard luminosity

Signal channel: $H \Rightarrow ZZ^{(*)} \Rightarrow 4\mu$

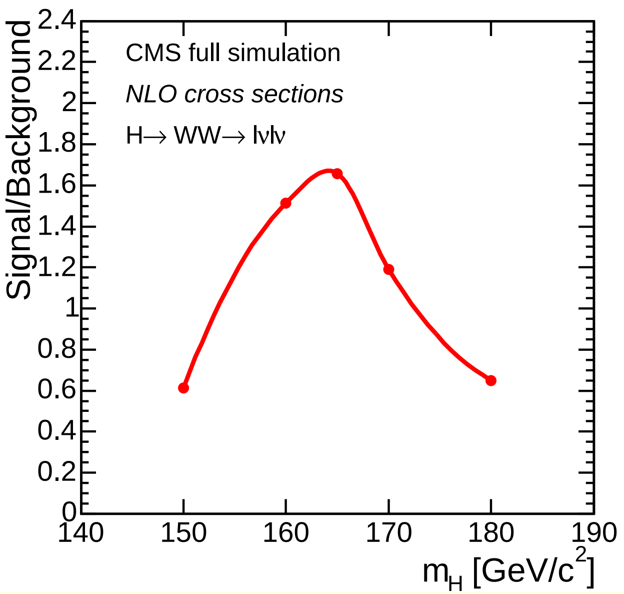


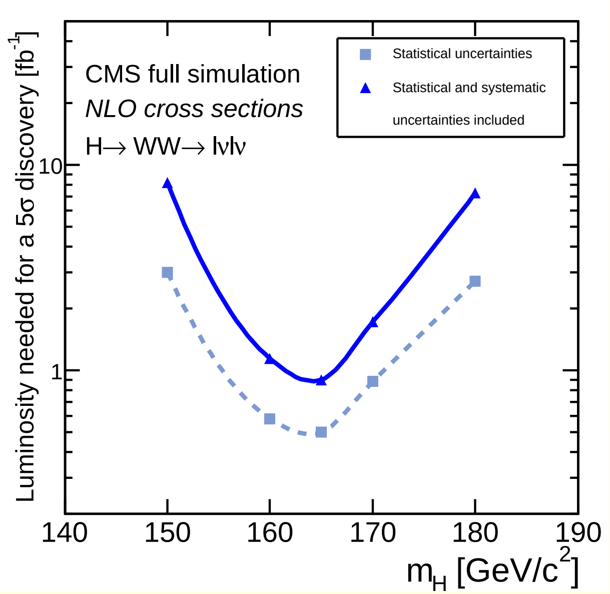




- Total NLO $\sigma \times BR$ as function of M_H
- statistical significance at luminosities 10 and 30 fb^{-1}
- integrated luminosity for discovery and exclusion
- similar (or better) for electron decay channels

Signal channel: $H \Rightarrow WW^{(*)} \Rightarrow 2l + E^{T}_{\mathrm{miss}}$





- Total NLO $\sigma \times BR$ as function of M_H
- integrated luminosity for discovery and exclusion

Signal and background at higher orders

- $q\bar{q} \Rightarrow WW$ increases by $70\ \%$ at NLO if no cuts are applied. With a jet veto, it only increases by about $20 - 30\ \%$

  Dixon, Kunszt, Signer.

- the $gg \Rightarrow WW$ process is formally NNLO; it increases the background by 30 %

  Dührssen et al, Binoth et al.

- The Higgs total cross-section increases by $\sim 100\ \%$ at NNLO

  Harlander,Kilgore; CA, Melnikov; Ravindran, Smith, van Neerven

- With a jet-veto it increases by $\sim 85\ \%$

  Catani, de Florian, Grazzini;

  Davatz, Dissertori, Dittmar, Grazzini, Pauss;

  CA, Melnikov, Petriello

Additional Signal Channels at Higher Luminosity

- Five channels with Vector Boson Fusion
  $pp \Rightarrow ppV^{(*)}V'^{(*)} \Rightarrow (2j)_{\rm tagged} + H$ with four possible decay channels of the Higgs-boson and with two possible decay channels of the WW pair
  - $H \Rightarrow \tau^+ + \tau^-$,
  - $H \Rightarrow \gamma + \gamma$,
  - $H \Rightarrow W + W^{(*)} \Rightarrow 2l + E^T_{\rm miss}$,
  - $H \Rightarrow W + W^{(*)} \Rightarrow 1l + E^T_{\rm miss} + 2j$,
  - $H \Rightarrow Z + Z^{(*)} \Rightarrow 4l$
- Four channels for associated production of the Higgs boson with $t\bar{t}$ and W or Z
  $pp \Rightarrow t + \bar{t} + H$ and $pp \Rightarrow W + H$ and $pp \Rightarrow Z + H$ and
  - $t + \bar{t} + H \Rightarrow \gamma + \gamma + t + \bar{t}$,
  - $t + \bar{t} + H \Rightarrow b + \bar{b} + t + \bar{t}$,
  - $W + H \Rightarrow 1l + E^T_{\rm miss} + \gamma\gamma$
  - $Z + H \Rightarrow 2l + \gamma\gamma$

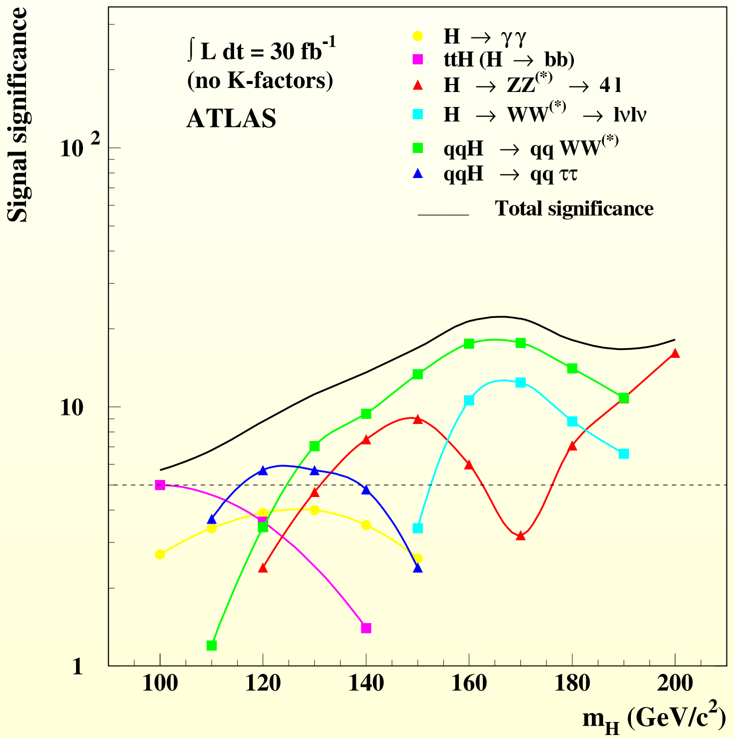
VV Scattering at high energy

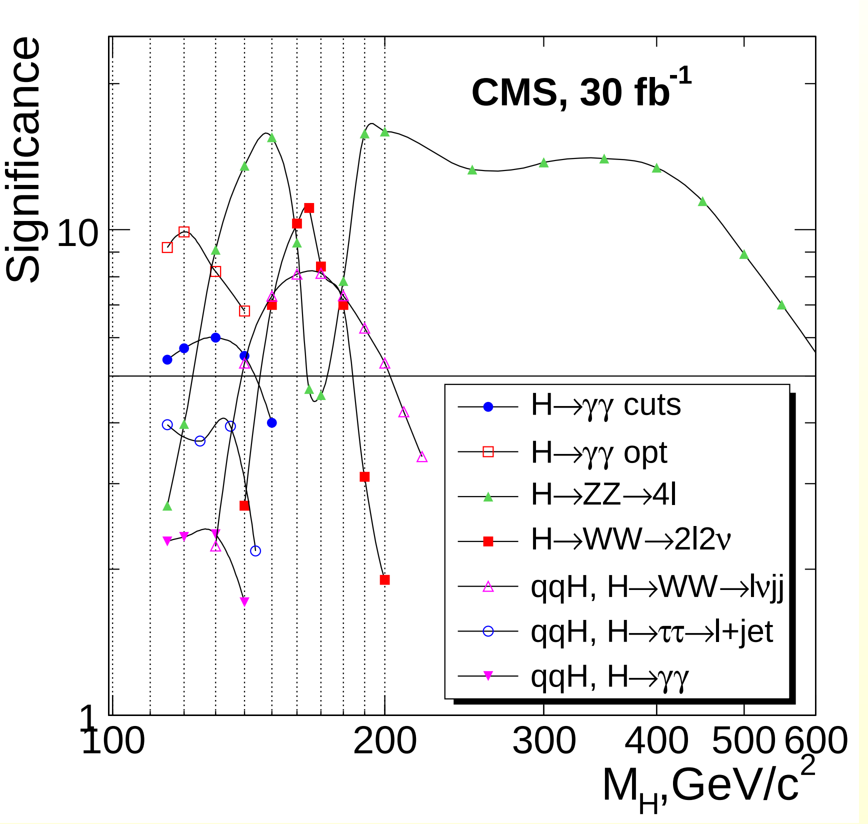
- Heavy Higgs in WW scattering ?
- VBF diagrams describe weak vector boson scattering of the effective theory obtained by removing the Higgs boson.
  The effective Lagrangian of the Goldstone bosons

$$\mathcal{L} = \frac{1}{v^2}\mathrm{Tr}(D_\mu\Sigma(D^\mu\Sigma)^\dagger)\,, \quad \Sigma(x) = \exp\left(-iw\vec{(x)}/v\right)$$

- 8fermion processes, EW, QCD Accomado, Ballestrero,Belhouari,. . . Zeppenfeld et.al.

Discovery potential according to Atlas and CMS





note

- Note difference in ranges (m_H and significance)
- Note difference concerning K-factors
- Note $ttH \Rightarrow t\bar{t}b\bar{b}$ process ??
- Missing: $qqVV' \Rightarrow (2j)_{\text{tagged}} + V + V'$ for $M_H > 220$GeV

Higgs search results as benchmark for LHC studies

- Large number of physics signals with huge background in rate and variety.
- Quantitative description is the clue to suppress the background
- Similar approaches have to be followed also to extablish new physics if its signal is weak.

Comments on LO Results

- LO is (almost) fully automatized
  MADGRAPH, ALPGEN, COMPHEP, HELAC, AMEGIC+++
- Applicable up to 9 external partilces (legs)
- Can be used in conjunction with shower Monte Carlos
- New recursion relations (twistor techniques)
- Large scale dependence and normalization dependence
- Testing the predictions of LO shower MC results.

Comments on NLO Calculations

Big progress, many new ideas.

- Traditional approaches up to five particles.
  With better computers it can be further pushed
- “Twistor techniqe” for six leg processes
- New reduction methods
- Seminumerical implementation
- Less sensitivity to factorization and renormalization scales

More and better physics if we have the NLO corrections

- It is needed for MC@NLO and resummation
- More partons for merging and radiation

What is the challenge for the future?

- Full automatization up to 6 or more particle processes? $(ggttbb, ggqqWW, \ldots)$
- NNLO jet production, top-antitop production,..
- Automatized calculation of predictions of BSM physics with NLO QCD corrections??
- Bottleneck I: calculation of the virtual corrections
- Bottleneck II: constructing fully differential parton level numerical codes for physical measurables
- Sector decomposition

Dreams and Realities

MCFM list of processes (Campbell, K.Ellis)

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}\leq 3j$	$W+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}\leq 3j$	$W+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$Z+b\bar{b}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{b}\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$	$ZZZ+\leq 3j$	$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}\leq 3j$	$\gamma\gamma+b\bar{b}\leq 3j$		single top
$\gamma+c\bar{c}\leq 3j$	$\gamma\gamma+c\bar{c}\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}\leq 3j$		
	$WZ+c\bar{c}\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

$p\bar{p}\to W^\pm/Z$	$p\bar{p}\to W^+ + W^-$
$p\bar{p}\to W^\pm + Z$	$p\bar{p}\to Z+Z$
$p\bar{p}\to W^\pm+\gamma$	$p\bar{p}\to W^\pm/Z+H$
$p\bar{p}\to W^\pm+g^\star(\to b\bar{b})$	$p\bar{p}\to Zb\bar{b}$
$p\bar{p}\to W^\pm/Z+$ 1 jet	$p\bar{p}\to W^\pm/Z+$ 2 jets
$p\bar{p}(gg)\to H$	$p\bar{p}(gg)\to H+$ 1 jet
$p\bar{p}(VV)\to H+$ 2 jets	$p\bar{p}\to t+q$
$p\bar{p}\to H+b$	$p\bar{p}\to Z+b$

Note the enormous discrepancies

Present status of NLO results

- $2 \Rightarrow 1, 2 \Rightarrow 2$ all known in SM and beyond
- $2 \Rightarrow 3$ few calculation is still missing, their calculation is in progress
- $2 \Rightarrow 4$ Only two full calculations
  - $e^+e^- \Rightarrow 4\ \mathrm{fermions}$ (EW) Denner et.al. '05
  - $e^+e^- \Rightarrow HH\nu\overline{\nu}$ (EW) GRACE '05
- No $2 \Rightarrow 5$ full calculations are available

Recent developments: Analytic results

- new recursion techniques using twistors (Witten, Cachazo, Bern, Dixon , Kosower, Britto, Feng, et.al.)
- analytical calculation 6g processes at NLO (Bern et.al.,),
- Unitarity cut method, spinorail integrals, also in d-dimensions
- multiloop simplicity for n-leg processes in $N = 4$ SYM gauge theory (Anastasiou,Bern, Dixon, Kosower,...)
- NNLO calculations for Higgs, jet and gauge boson production (Anastasiou et.al., A. Gehrmann et.al., Harlander et.al. ...)
- NNLO parton level programs for Higgs production FEHIP (Anastasiou, Melnikov, Petriello)
- NNLO parton level Monte Carlo programs for three jet production in e^+e^- annihilation: (A. Gehrmann,T. Gehrmann, Glover,Heinrich)

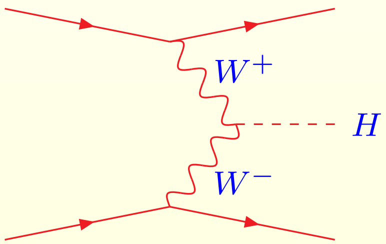
Recent developments on numerical methods

- semi-analytic (Ellis, Giele, Glover,Zanderighi).
  * Use standard packages to generate the amplitude for a give process QGRAF/MAPLE/FORM
  * Use Davidyvchev formula to reduce tensor integrals to scalar integrals
  * Use complete set of recursion to reduce all integrals to basic set
- completely numerical multi-loop calculation for multi-leg processes (Anastasiou, Daleo; Czakon) is based on the Mellin-Barnes technique

First applications

- Virtual six gluon amplitudes. Agrees with analytic results of (Berger, Bern, Dixon, Forde, Kosower).
- Higgs and dijet cross section in large p_t limit

Vector Boson Fusion

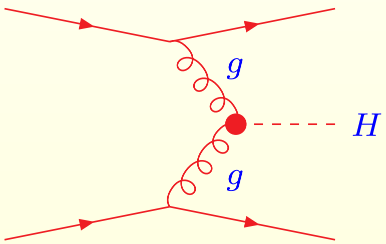


$\mathcal{O}\left(\alpha_{ew}^2\right)$

- small QCD uncertainties
- suitable for Higgs coupling measurements
- known at NLO

Figy, Oleari, Zeppenfeld, '03

Gluon Gluon Fusion



$\mathcal{O}\left(\alpha_s^4\right)$

- large QCD uncertainties
- despite kinematical cuts remains dominant background
- *NLO new!*

Calculation the NLO cross section of the processes $WW + \text{jet}, WWW, WWZ, WW + 2\text{jets}$ are in progress

Conclusions

- Weak signals of Higgs production can be fished out from the noisy data to be collected by CMS and ATLAS.
- It is a challanging experimental and phenomenological problem. It requires excellent detectors and outstanding phenomenological analysis.
- For quantitative studies NLO QCD corrections are neccessary. The dream of fully automated NLO packages up to 6 or 7 legs appears to be feasible by the time the LHC requires higher precision.
- There are impressive recent progress in both the analytic and numerical methods.
- The new methods obtained for the Higgs search have more general validity. They will be important also if new physics is found.