Higgs Production and Decay @ Colliders
a Mini-Review

Giampiero PASSARINO

Dipartimento di Fisica Teorica, Università di Torino, Italy
INFN, Sezione di Torino, Italy
HEPTOOLS Network
Higgs XS WG

ICHEP 2010 Paris

Reporting on work done within the Higgs XS Working group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics

Thanks: All Members, in particular

A. Denner, S. Dittmaier, S. Farrington, M. Felcini, M. Grazzini, F. Maltoni, C. Mariotti, F. Petriello, M. Spira, R. Tanaka

ggF: Djouadi et al, Harlander, Catani, De Florian, Grazzini, Anastasiou, Melnikov, Nason, Moch, Aglietti et al, Actis et al, Petriello, Boughezal

VBF: Spira, Zeppenfeld, Denner, Dittmaier, Mück, Bolzoni, Maltoni, Moch

ttH: Beenakker, Dawson, Bevilaqua et al, Bredenstein et al, Dittmaier, Krämer, Zerwas, Reina, Wackeroth

VH: Djouadi, Harlander, Dittmaier, Ciccolini et al, Spira, Han, Willenbrock, Krämer, Denner

Outlines

(1, 2,)

1. *From Tevatron to LHC*
2. *Higgs production and decay,*

what else, but the inevitable!

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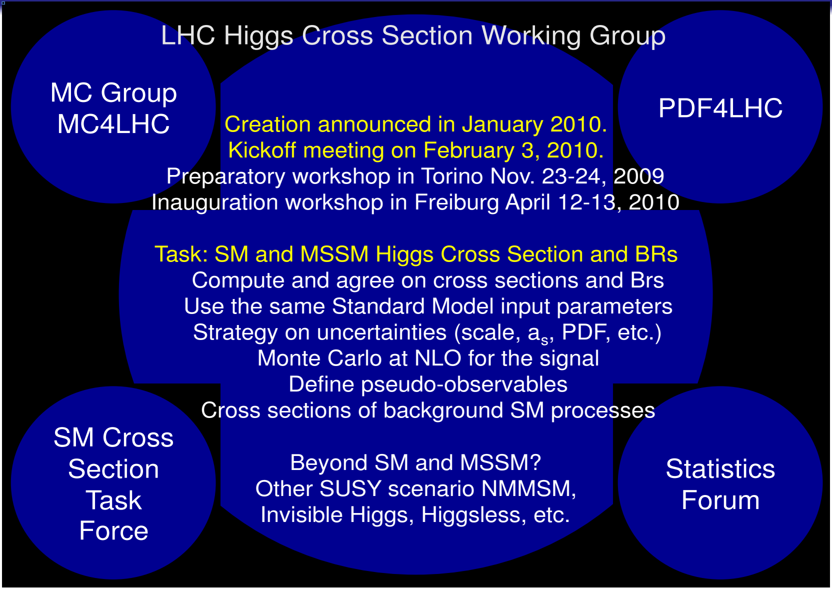

LHC Higgs Cross Section Working Group
MC Group
MC4LHC
PDF4LHC
Creation announced in January 2010.
Kickoff meeting on February 3, 2010.
Preparatory workshop in Torino Nov. 23-24, 2009
Inauguration workshop in Freiburg April 12-13, 2010
Task: SM and MSSM Higgs Cross Section and BRs
Compute and agree on cross sections and Brs
Use the same Standard Model input parameters
Strategy on uncertainties (scale, a_s, PDF, etc.)
Monte Carlo at NLO for the signal
Define pseudo-observables
Cross sections of background SM processes
Beyond SM and MSSM?
Other SUSY scenario NMMSM,
Invisible Higgs, Higgsless, etc.
SM Cross
Section
Task
Force
Statistics
Forum

R. Tanaka

ggF, VBF, WH/ZH, ttH, MSSM Higgs

Cross Section

ggF
HIGLU (NLO QCD+EW)
HPro (NLO QCD)
FEHiPro (NNLO QCD+EW)
HNNLO (NNLO QCD)
ggh@NNLO (NNLO QCD)

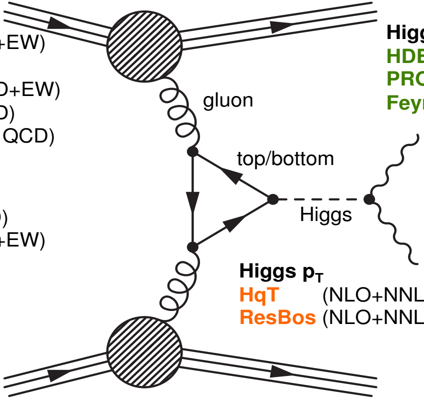
VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)

WH/ZH
V2HV (NLO)

ttH
HQQ (QCD LO)

bbH
bbH@NNLO (NNLO)

+ private codes.



Higgs Decay
HDECAY (NLO)
PROPHECY4f (NLO)
FeynHiggs, CPSuperH

← H propagator?

background?

Higgs p_T
HqT (NLO+NNLL)
ResBos (NLO+NNLL)

PDF: MSTW, CTEQ, NNPDF, etc.

LHC Status

Goal =1fb^{-1}

by the end of 2011

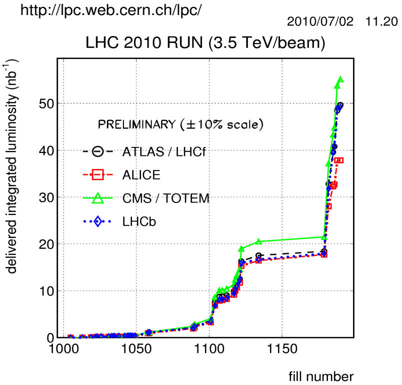
New record last week

with 7x7 bunches

Peak lumi. L~10^{30} cm^{-2} s^{-1}

2010 goal: L=10^{32} cm^{-2} s^{-1}

(800 bunches, ’ =3.5m)



>50nb^{-1} delivered LHC luminosity.

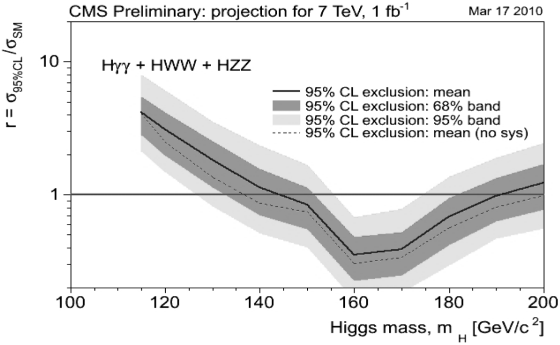
" Each ATLAS/CMS should have observed ~1 event of 120 GeV/c^2 Higgs (H"bb)

($_{SM}$(ggF+qqH+VH+ttH)=13.6 pb @ 7 TeV

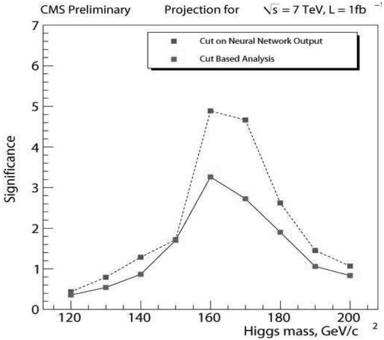
Example: SM Higgs Expectations @ 7 TeV & 1 fb^{-1}

CMS NOTE -2010/008

Expected Exclusion Limits



Expected significance of
+ : : : : O O search



Expected Higgs mass range to be excluded (1 experiment): 145

SM Higgs Search Tools

M_H [GeV]	Prod.	Decay	Back.
$114 - 150$	ggH	$H \to \gamma\gamma$	QCD
$114 - 150$	qqH	$H \to \tau\tau$	$Z, tt, W +$ jets
$140 - 200$	ggH, qqH	$H \to WW$	WW, ZZ, tt
$114 - 700$?	ggH	$H \to ZZ$	ZZ, Zbb, Ztt

Data & Theory

Example

When Theory helps

Control - Region

- some observable, **background** and **signal**;
- invert cuts: from s enhancement to b enhancement;
- use data to normalize b;
- use theory to compute change in b when inverting cuts.

Systematic Uncertainties

Theory driven

related to **s & b** TH predictions

- Total XS $\longrightarrow$ event yield normalization;
- Differential XS $\longrightarrow$ shape of discriminating quantities.

Exp driven

- $\cdots$ but they are uncorrelated to the TD ones.

To quantify TDU

- TH error range;
- base-line selection cuts

are needed

MC at NLO

Unprecedented precision

This area will become important as next step for exclusive calculations:

1. differential distribution for **Higgs signal**, for example Higgs p_T
2. comparison between **LO PS MC and NLO MC**, how to normalize to NNLO ?

SM background processes I

- Important:
  study theoretically the SM backgrounds for Higgs search, such as W/Z +jets, WW^*/ZZ^*, Wbb/Zbb, tt, $ttbb$ etc.
- Background estimation via ”data-driven methods”:
  rely on theory to relate XS in different kinematic regions
  $\Rightarrow$ reliability of result needs theoretical input
- Proposal:
  study theoretical errors of SM backgrounds to Higgs search with common ATLAS and CMS cuts.
- Related issue:
  interference between Higgs signal and backgrounds

SM background processes II

Examples:

1. $WW^{(*)} \to l\nu l\nu$: background $qq/gg \to WW$ from data ?
2. $ZZ^{(*)} \to 4\,l$: background $qq/gg \to ZZ$ from data ?
3. VBF: central jet-veto, effect of UE, QCD background

Questions:

- Shall we study theoretically these SM background processes? How accurate should they be predicted?
- Shall we study the theoretical error for background estimation via "data-driven method"?
- Shall we study $\gamma\gamma$, $WW^{(*)}$, and $ZZ^{(*)}$ with priority?
- Interferences between Higgs signal and backgrounds?

The importance of being $\mathrm{N}^n\mathrm{LO}$

Loops & Legs

Recent years have seen an impressive amount of new results at $\mathrm{N}^n\mathrm{LO}$

NLO

- is the **first order** where reliable predictions can be obtained

NNLO

- is the **first order** at which a reliable estimate of the error can be given

Usually, (fully) inclusive, but EXPs have finite acceptances!

Why? Example: ggF

Different differential calculations

σ_{acc} [fb] jet algorithm	$\mu = \frac{m_H}{2}$ SISCone	k_T	$\mu = 2\,m_H$ SISCone	k_T
LO	21.00 ± 0.02		14.53 ± 0.01	
HERWIG	11.16 ± 0.04	11.59 ± 0.04	7.60 ± 0.03	7.89 ± 0.03
NLO	22.40 ± 0.06		19.52 ± 0.05	
MC@NLO	17.42 ± 0.08	18.42 ± 0.08	13.60 ± 0.06	14.39 ± 0.06
R^{NLO}(HERWIG)	19.79 ± 0.07	20.56 ± 0.07	14.61 ± 0.05	15.17 ± 0.05
NNLO	18.18 ± 0.43	18.45 ± 0.54	18.76 ± 0.31	19.01 ± 0.27
R^{NNLO}(MC@NLO)	19.33 ± 0.09	20.43 ± 0.09	17.24 ± 0.07	18.24 ± 0.07
R^{NNLO}(HERWIG)	22.02 ± 0.08	22.88 ± 0.08	18.65 ± 0.07	19.38 ± 0.07

Table 1: Cross-sections after the *signal cuts* of Ref. [33] are applied for different calculation methods. The statistical integration errors are shown expicitly. The MC@NLO and HERWIG cross-sections are evaluated with 1,000,000 generated events. The fixed-order results were computed in Ref. [33] and require the Monte-Carlo integration of multiple sectors [17].

- Good agreement between NNLO differential codes and MC@NLO, HERWIG rescaled to correct inclusive result

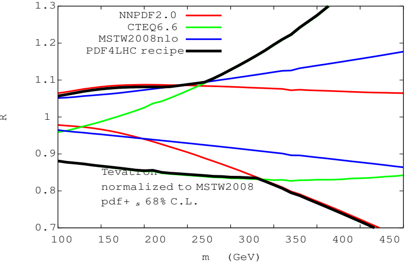
[see Petriello's tak toda

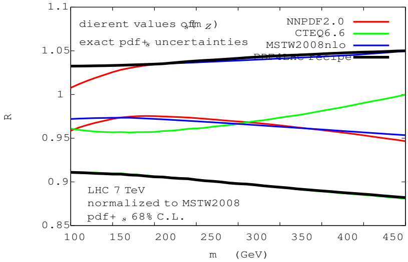
PDF4LHC Recipe

- In February, we have asked PDF4LHC working group the recommendation on PDFs and in alphas values (and their uncertainties).
- PDF4LHC group decided to study LHC benchmark processes: $W^{\pm}$, Z^0, $t\bar{t}$, $gg \to H$ $(M_H = 120, 180, 240 \text{ GeV})$
- PDF4LHC Recipe (June 2010)
  - Use global fit PDF sets: MSTW, CTEQ and NNPDF
    - HERAPDF, ABKM and (G)JR are optional but recommend to check.
  - Take midpoint for central value
  - alphas =±0.0012 for 68% C.L. and ±0.0020 for 90% C.L.
  - Envelope method for errors
  - Use NLO PDF error estimation via envelope method for NNLO

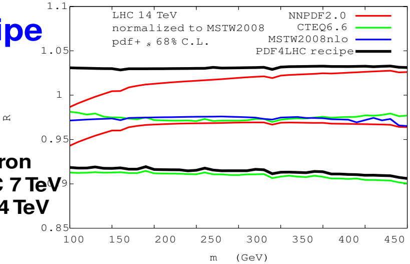
PDF4LHC http://www.hep.ucl.ac.uk/pdf4lhc/

Bands including pdf + as uncertainty (normalized to MSTW2





the envelope represents
the result of the PDF4LHC recipe



from ± 9% (MH=100) to ± 12% (MH=250) Tevatron
from ± 5.5% (MH=100) to ± 6.5% (MH=250) LHC 7 TeV
from ± 5% (MH=100) to ± 5% (MH=250) LHC 14 TeV

TH errors

- For signal XS:
  - parametric errors and their propagation
  - EW corr, renormalization scheme
  - QCD $\otimes/\oplus$ EW corr (factorized or added) ?
  - QCD scales (ren: μ_R, fact: μ_F)
    define central value and range and scan strategy
- PDF uncertainties
- Background treatment:
  LO $\times$ K factor or NLO, interference with signal, etc. ?
- Possible approximations ?

Note: TH errors are 100% correlated between the two exp.
(if using the same programs!)

The μ_R problem

QED

- Is there a μ_R in QED? **Yes**
- Is it a problem? **No**, $q^2 = 0$ is physical!

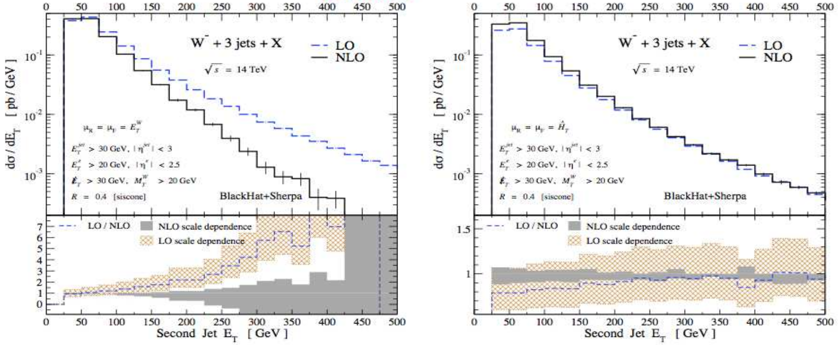
EW

- Is there a μ_R in EW? **Yes**
- Is it a problem? **No**!
- Are there large **logs**? **Yes**
- Use G_F - scheme and not $\alpha(0)$, i.e. **resum**

QCD one(multi)-scale? Once again, **resum** or, at least **minimize**!

Example

$$H_T = \sum_{\text{partons } i} E_T^i + E_T^e + E_{\text{miss } T}$$



The scale variation problem

Warning TH uncertainty ($\equiv$ stupidity) has No statistical meaning

ggF

- Fixed order $\rightsquigarrow$ scale = $M_H/2$
- Fully justified by NNL re-summation!

Multi - scale

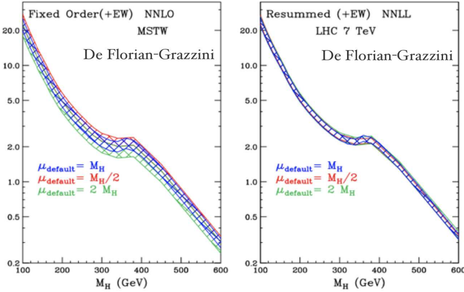
- $\mu =$ dynamical scale,
- $\mu_{\rm min} \leq \mu \leq \mu_{\rm max}$,
- are selected to (reasonably) minimize large logs

Example

$M_H/2(3) \leq \mu \leq 2(3)\, M_H$ is Not 68%(90%) C.L.

What is the 'right' scale choice?

Scale uncertainties computed with independent variations of renormalization and factorization scales around some default scale μ_D (with $0.5\,\mu_D < \mu_F, \mu_R < 2\,\mu_D$ and $0.5 < \mu_F/\mu_R < 2$).
What's the 'right' default scale μ_D?



Resummed calc. not very sensitive to default scale choice (right).

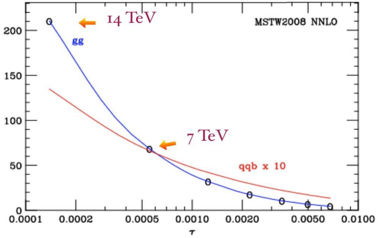
Fixed-order calc. more sensitive (left part).

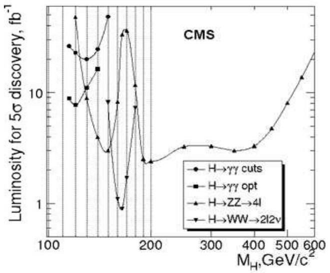
Petriello, Grazzini, Stoeckli

LHC @ 7 TeV

At 14 TeV a SM Higgs boson with $m_H \sim 160$ GeV can be discovered with about 1 fb^{-1}

From 14 to 7 TeV both signal and background cross sections decrease





But gg parton luminosity drops faster

$$\mathcal{L}_{c\bar{c}}(\tau,\mu_F^2) = \int_\tau^1 \frac{dx}{x} f_c(x,\mu_F^2) f_{\bar{c}}(\tau/x,\mu_F^2)$$

Recent NLO study shows that luminosity needed for discovery may be a factor 6-7 larger

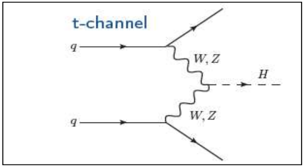
E.Berger et al. (2010)

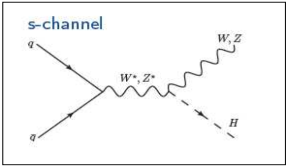
Petriello, Grazzini, Stoeckli

VBF Process

Vector boson fusion

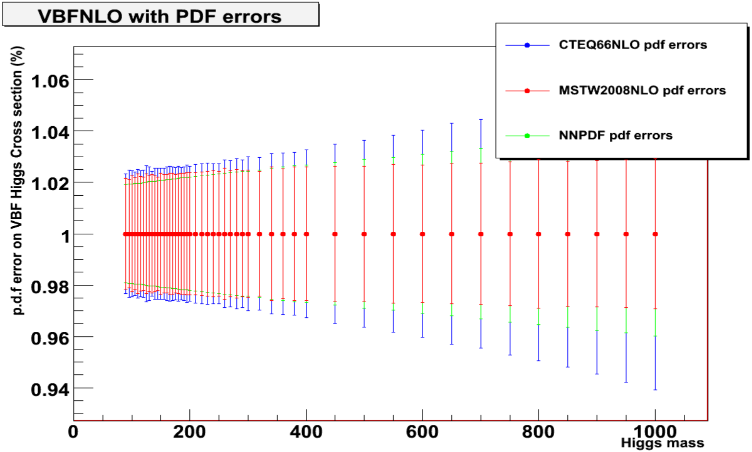
- Second to gg fusion in LHC Higgs production
- Important in low mass region
- Distinctive signature





- s-channel shares same initial and final states : interference
  - Some of the calculations include this effect
  - Typical analysis cuts minimse this contribution

p.d.f. Percentage errors



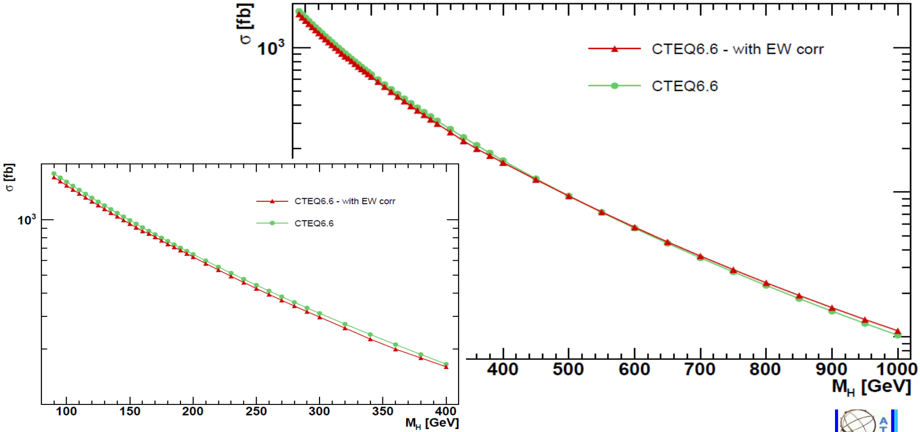
MSTW errors ~ NNPDF Errors

CTEQ errors larger

HAWK Results

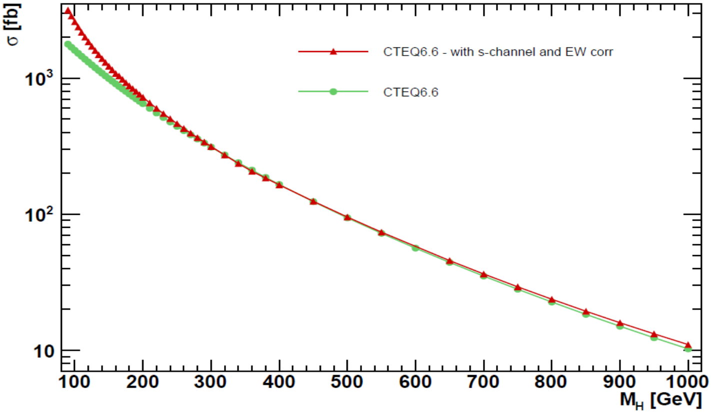
Effect of EW corrections at NLO

~5% decrease in cross section for low masses

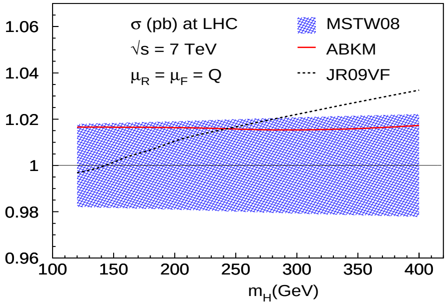


HAWK Results

Effect of EW corrections at NLO and s-channel



Cross section for VBF at LHC



Bolzoni, Maltoni, S.M., Zaro '10

- QCD corrections at second order small
- NNLO results very stable at 2% against QCD scales variation (uniformly over the full mass range)

Upshot

- apparent convergence
- scale stability
- reduction of theoretical uncertainty
- PDF + α_s uncertainty generally small (improved at NNLO) $\Delta\sigma_{NLO} \gg \Delta\sigma_{NNLO}$

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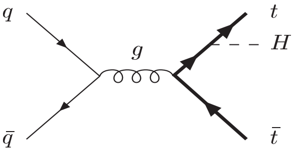
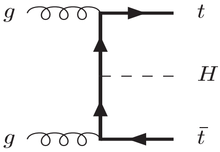
- $gg, q\bar{q} \to t\bar{t}H$ $(H \to b\bar{b}, \gamma\gamma)$ relevant for $M_H \lesssim 200$ GeV





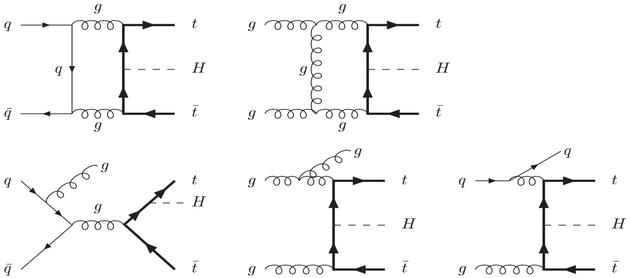
dominant

- crucial for determination of top Yukawa coupling

- backgrounds: $pp \to t\bar{t}b\bar{b}, t\bar{t}\gamma\gamma$

- LO programs: HQQ (S.)
  Madgraph/Madevent (Maltoni, Stelzer,. . .)
  MCFM (Campbell, Ellis), . . .

M. Spira



- QCD corrections $\sim 20\%$

Beenakker,...
Dawson,...

- $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ (NWA)

$\Rightarrow$ no public NLO-code so far...

Bevilacqua,...

- $pp \to t\bar{t}b\bar{b}$ (background)

Bredenstein,...
Bevilacqua,...

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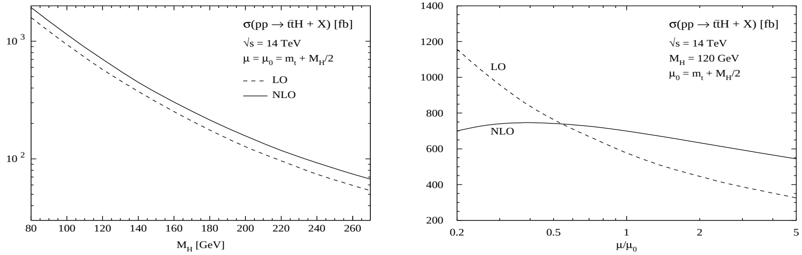
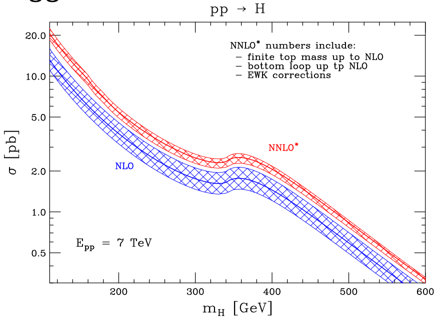
MRST2001

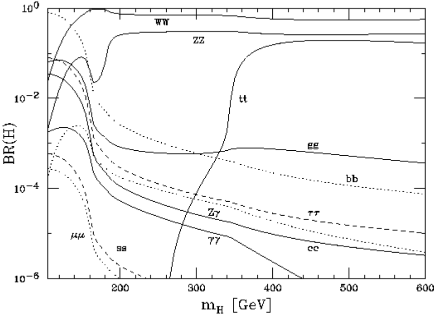


Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas
Dawson, Orr, Reina, Wackeroth

Cross-Sections & Branching Ratios

Higgs cross-sections from Fabian Stoeckli et al.





Won't discuss further, the whole workshop is about it

ggF in a nutshell

LHC @ 7 TeV, $M_H = 165\,\mathrm{GeV}$

- De Florian, Grazzini

$$\sigma = 8.45^{+0.64}_{-0.66}\,(\mathrm{scale})^{+0.33}_{-0.27}\,(\mathrm{PDF}+\alpha_s)$$

- Anastasiou et al.

$$\sigma = 8.54^{+0.64}_{-0.78}\,(\mathrm{scale})^{+0.34}_{-0.28}\,(\mathrm{PDF}+\alpha_s)$$

Perfectly consistent

Glossary for POs

Example

- **RD** = real data
- **RO** = from *real data* $\rightarrow$ distributions with cuts $\equiv$ **RO**
  - diphoton pairs $(E, p) \rightarrow M(\gamma\gamma)$;
- **PO** = transform the *universal intuition* of a *QFT-non-existing* quantity into an *archetype*, e.g. $\sigma(gg \rightarrow H), \Gamma(H \rightarrow \gamma\gamma)$,
  - $\mathrm{RO}_{\mathrm{th}}(m_H, \Gamma(H \rightarrow \gamma\gamma), \dots)$ fitted to $\mathrm{RO}_{\mathrm{exp}}$ (e.g. $\mathrm{RO} = M(\gamma\gamma)$) defines and extracts m_H etc.

LHC example of POs

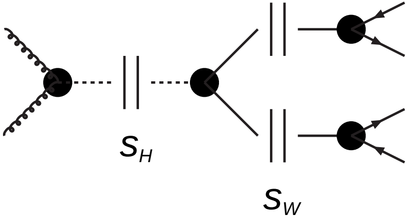


Figure: Gauge-invariant breakdown of the triply-resonant $gg \to 4\,$f signal into $gg \to H$ production, $H \to W^+W^-$ decay and subsequent $W \to \bar{f}f$ decays.

Strategy for POs

Example

$$
\begin{array}{ccc}
\mathrm{RO_{exp}} & \overrightarrow{\text{fit}} & \mathrm{RO_{th}}(\mathrm{PO}_1 \ldots \mathrm{PO}_n) \\
 & & \downarrow \\
\mathrm{PO}_1^{\mathrm{XM}} \ldots \mathrm{PO}_n^{\mathrm{XM}} & \overleftarrow{\text{comparison}} & \mathrm{PO}_1 \ldots \mathrm{PO}_n{}^{\star}
\end{array}
$$

- XM = any Model $\star$) TH consistent

Conclusions

N^{n}LO corrections are important

- QCD up to NNLO for ggF
- refinements are available: resummation, EW effects
- $\rightsquigarrow$ support that TH is well under control

Fully exclusive NLO (or higher) programs exist that allow us to compute corrections in the presence of cuts, $\rightsquigarrow$ use them!

We need a consistent PO definition of mass, width, couplings of the Higgs to publish results in such a way that theorists can later enter their general model parameters and see how well data constrain this model

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