# The LHC Higgs Cross Section Working Group:

# Results and Future Goals

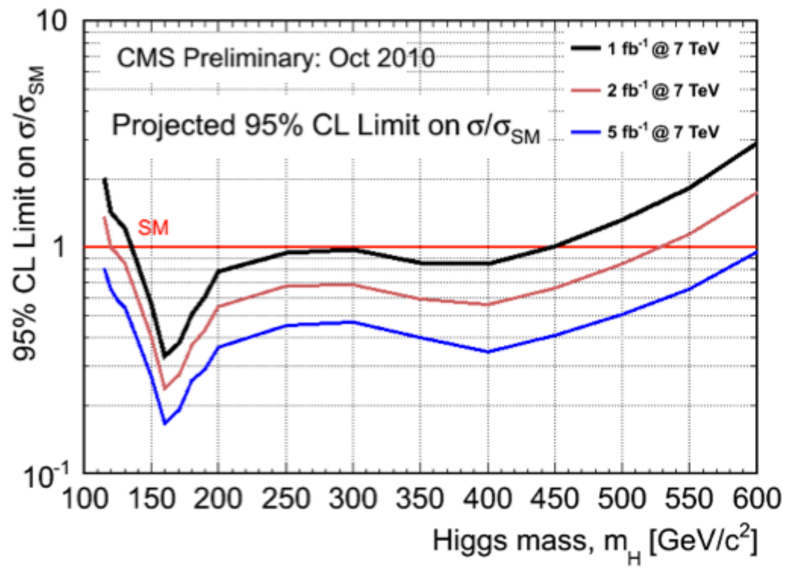
# Outline

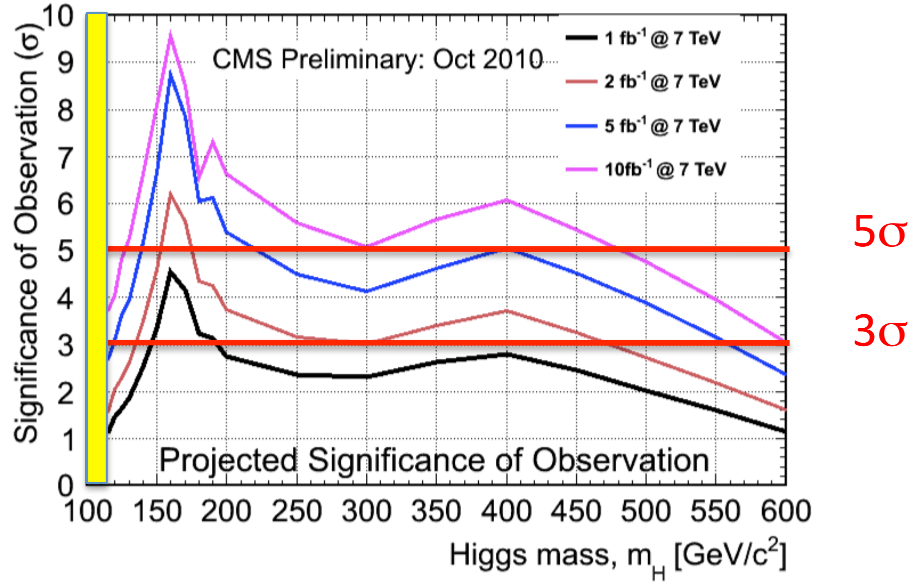
- Why precision Higgs physics now
- The status of the theoretical calculation and the results at 7 TeV: Cross Section, BR and uncertainties.
- The future work

Thanks to: S. Dittmaier, G.Passarino, R.Tanaka
+ all the contacts and members of the LHC Higgs Cross Section Working Group

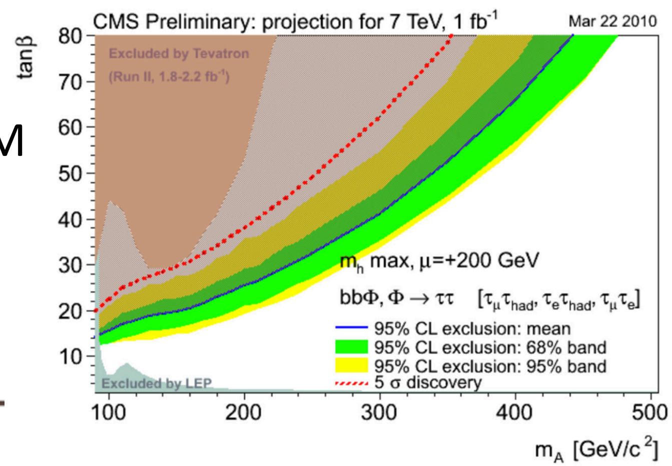
# Why ?

- By the end of the 7 TeV run, the luminosity collected will hopefully allow us to probe a wide range of Higgs-mass values



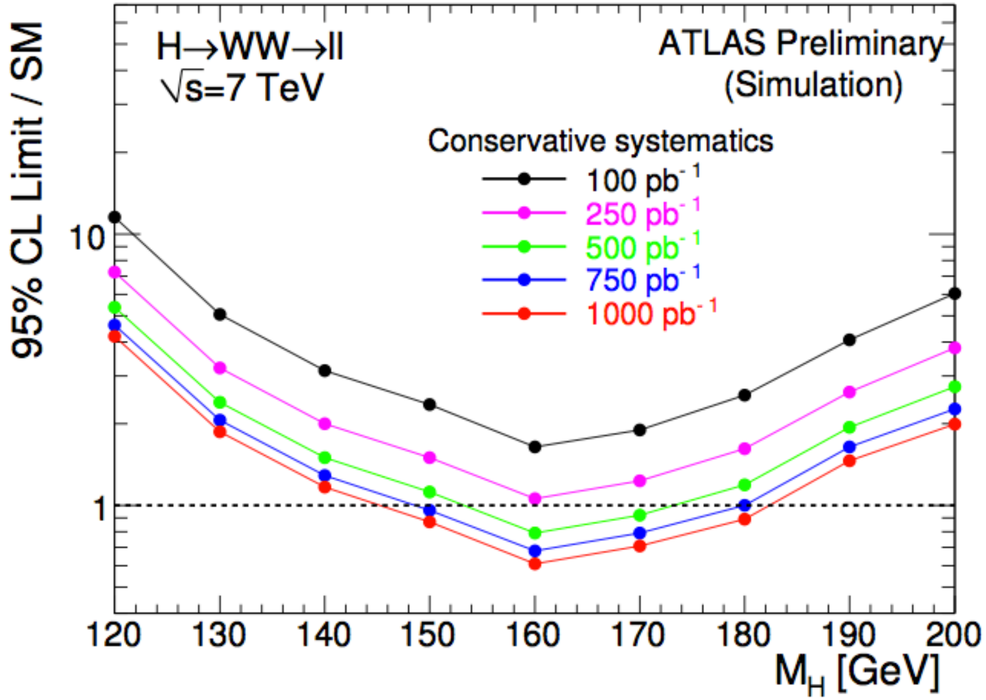




MSSM



# The first Higgs search at LHC

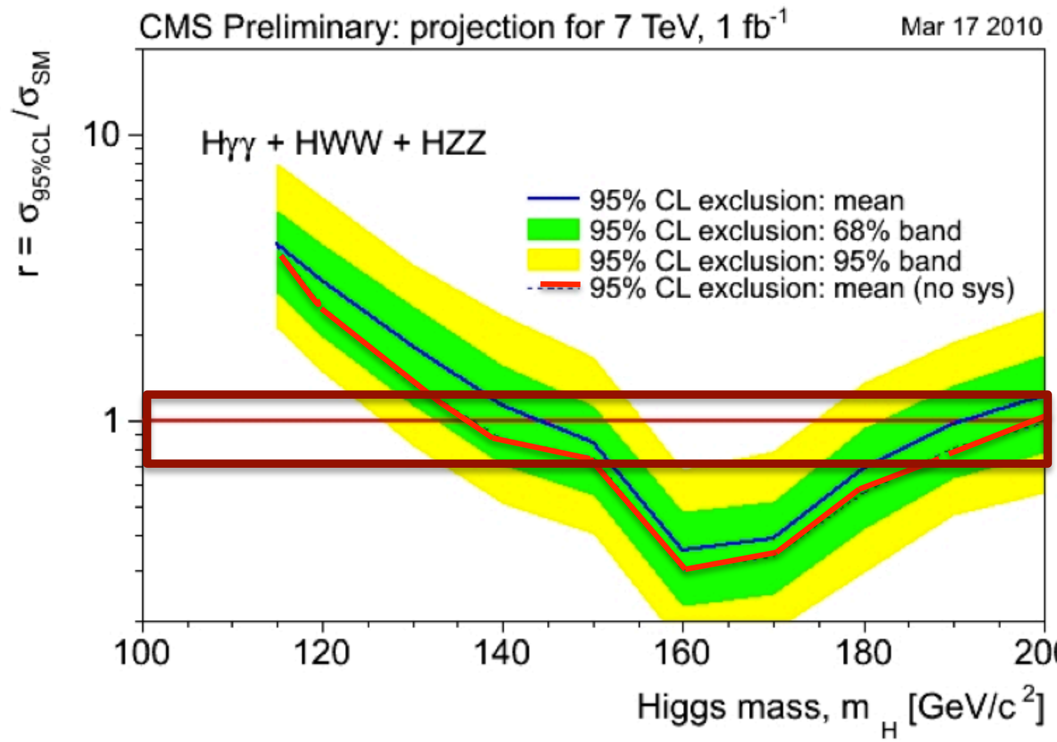
- The analyses from the experiments will first provide independent exclusions.




- To produce similar plot we will need: the experimental “curve” and the theoretical prediction, i.e. the line at “1”.

# Uncertainties

- The experimental uncertainties will determine the blue/red lines + the green/yellow band
- The theoretical uncertainties on the signal will determine where is the horizontal line. The theoretical uncertainties on the background will contribute to the red/blue line +green/yellow band



# The goal of the group

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

- Access the most advanced theory predictions for the Higgs Cross Section and Branching Ratio

- Common and correlated theoretical inputs, like cross sections, PDF, SM inputs etc. are discussed in the group.

- Experiments are/will coherently use the **COMMON INPUTS** based on the interaction with the TH community to facilitate the combination* of the individual results

*LHC Higgs Combination group. Only experimentalists

# The goal of the group (2)

- The group is formed by an equal mixture of TH and EXP (ATLAS, CMS and LHCb).
  All the members are volunteers.
  Everybody is welcome and can contribute to the process by engaging in a meaningful discussion.

- It is active since Jan 2010 and published the first results as a YR (Inclusive XS - in Dec 2010 – a snapshot of what we know right now)
  - plan to keep updating the results (if more knowhow is coming) →post them on the twiki page
  - to study differential XS (within acceptance cuts)
  - study backgrounds uncertainties in the signal region and in the "control regions"

# The Higgs Signal

- All the Higgs production cross sections have been calculated at NNLO (NLO) QCD plus resummation, with NLO EW corrections

- ALL THE **inclusive Cross Sections at 7 TeV and 14 Tev** have been computed and the uncertainty estimated

- The uncertainties have been computed in a uniform manner across the channels:
  - **PDF**: the groups followed the PDF4LHC prescription.
  - $\alpha_S$ and PDF uncertainties determined simultaneously (with correlations) for each set,

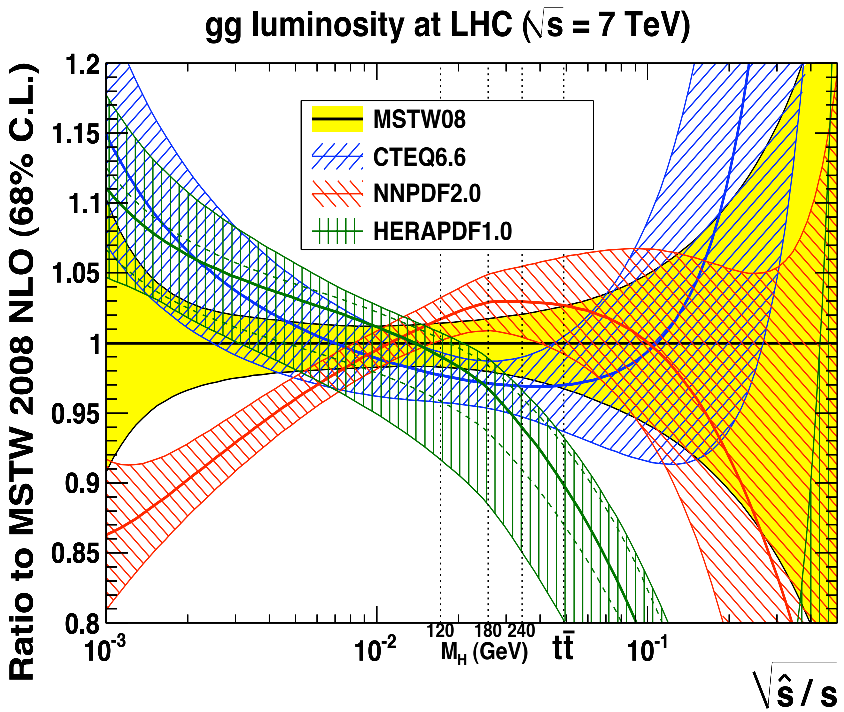
    with $\delta\alpha_S$ = **0.0012** (0.002) at 68% CL ( 90%CL) (2 x PDG 0.0007)

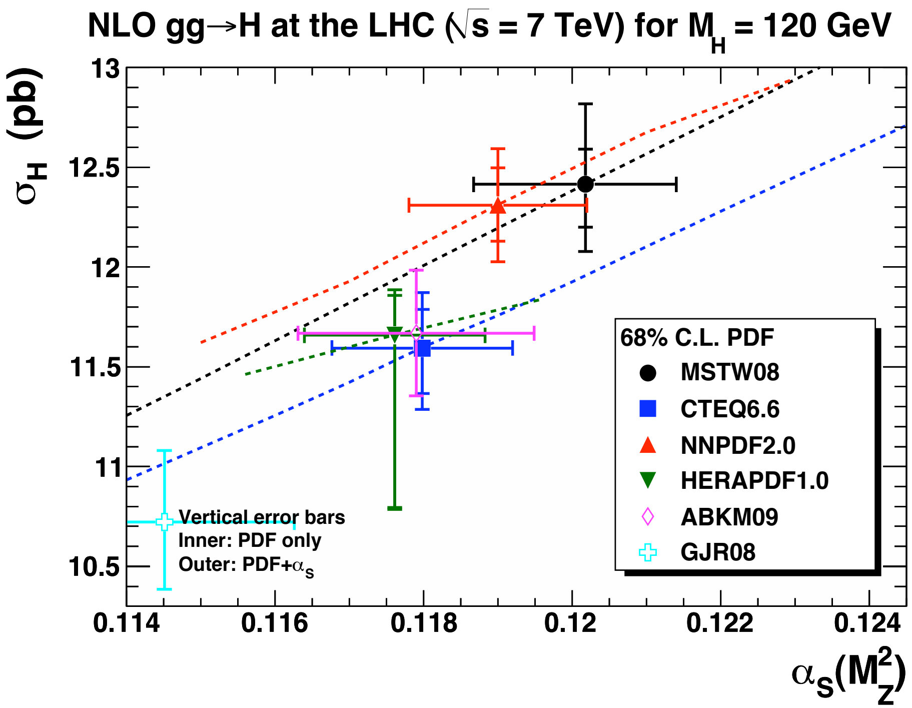
    Furthermore, each set uses different central values for $\alpha_S$ (0.118-0.119- 0.120).
  - **QCD scale**: it gives the largest of the effect. It has been varied with reasonable criteria in order to cover the "unknowns"

# PDF4LHC prescription

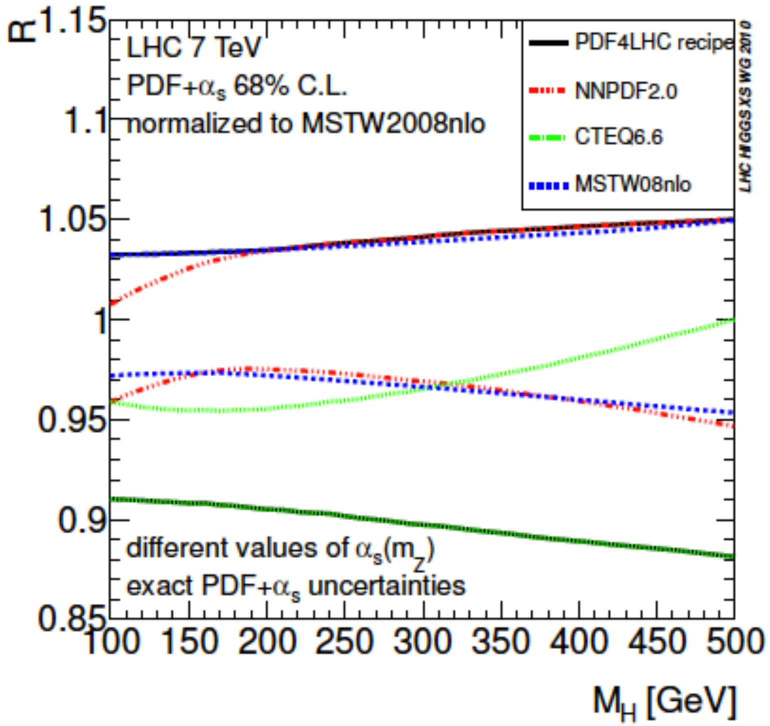
- 3 PDF are used to compute cross sections at NLO: MSTW2008, NNPDF, CTEQ. Each of them at their preferred $\alpha_S$ value.

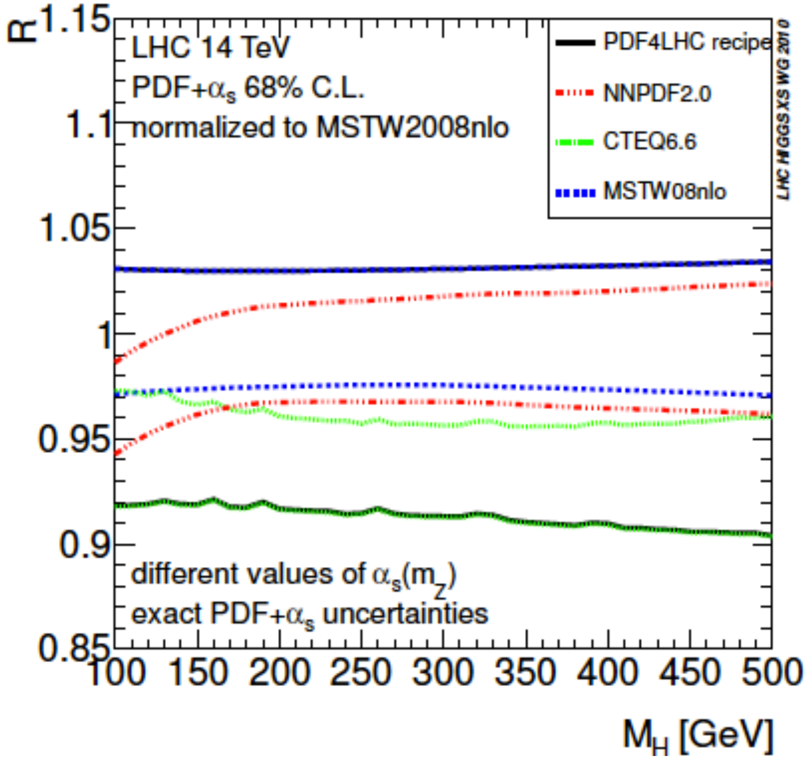
- 1 PDF is used for NNLO: MSTW2008



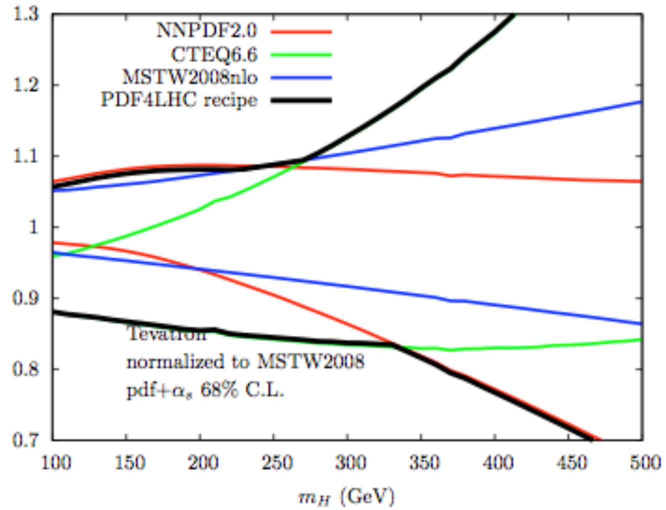
# gluon gluon luminosities




- Bands including PDF+$\alpha_S$ uncertainty (norm to MSTW2008)
- The ENVELOPE represents the results of the PDF4LHC recipe
- LHC 7 TeV:

  **5.5% (MH=100) → 6.5%(MH=250)**
- $\delta\alpha_S^{NLO}(68\%) = 0.0012$
- The uncertainty at NNLO are rescaled proportional to MSTW/PDF4LHC-NLO



# QCD scale choice

In the *full theory* there is no scale dependence.

$$s/n < \mu_{R,F} < n^* s$$

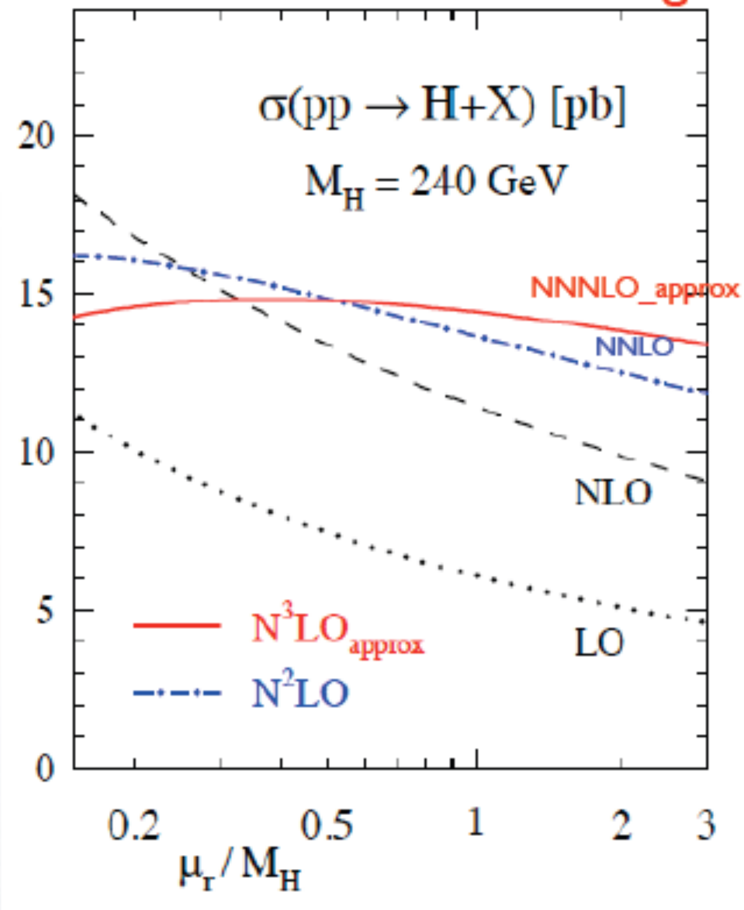
Thus: at a given order look for a plateau in the scale dependence and fix ***n*** to be such that the plateau is included.

– Allow each calculation to set the range of scale variation, but better not to allow for too small or too large variations just to enhance artificially reduce the *error*.

– Check that different calculations and different choices give consistent results.

– Drop extreme choices which are too far away from *common understanding of the problem*

Moch and Vogt




ggF: A small scale leads to a faster convergence from NLO to NNLO
- a lot is known from resummation
--small mu scales are safe!

# Theoretical Uncertainty

- All **Parametric Uncertainties** (PU), like PDF, $\alpha_S$, ... will be added in quadrature (gaussian distr.)
- **Scale Uncertainties** have flat distributions: envelope method.

**Total THU = Linear Sum of {Scale Unc. + Parametric Unc.}**

Examples:

A) ggF = Two independent calculation (dFG and ABMS)

Scale → envelope of the two Scale Unc

Average of the two PDF+$\alpha_S$ Unc (since they are ~totally correlated)

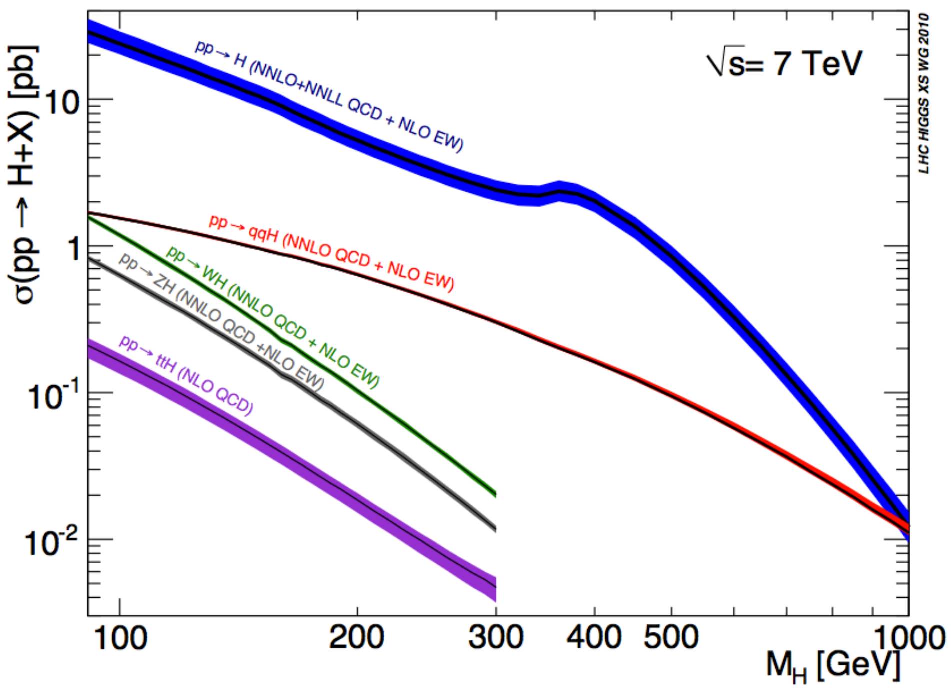
Total THU = linear sum of Scale Unc and PDF+$\alpha_S$ Unc

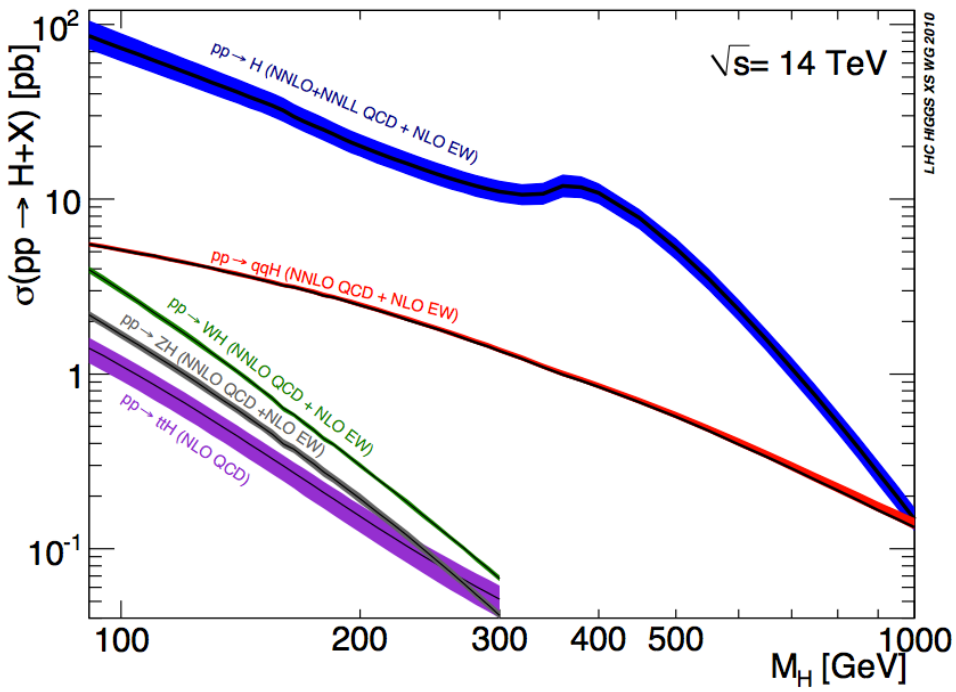
B) ggH+bbH in MSSM neutral H

Total THU = Envelope of the scale Unc + sum in quadrature of PDF+$\alpha_S$ Unc

(it has been checked that the sum in quadrature of the PDF+$\alpha_S$ Unc error is a good approx of the PDF Unc. on the sum of the XS)

# Inclusive Cross Sections



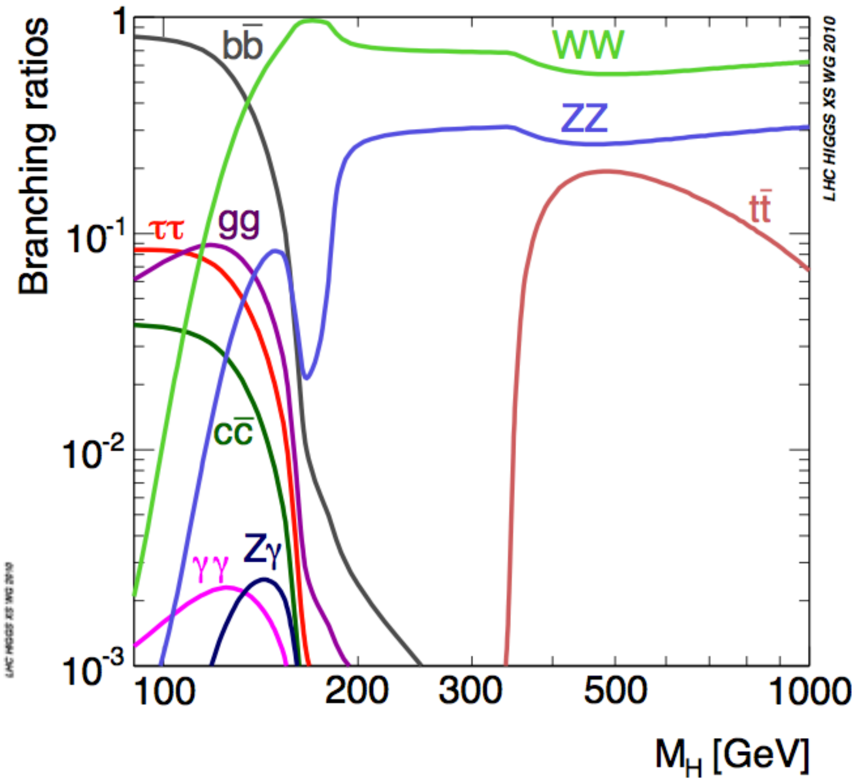

Plus tables (as a function of $m_A$ and tanβ) of Cross Sections
for Neutral and Charged H in MSSM

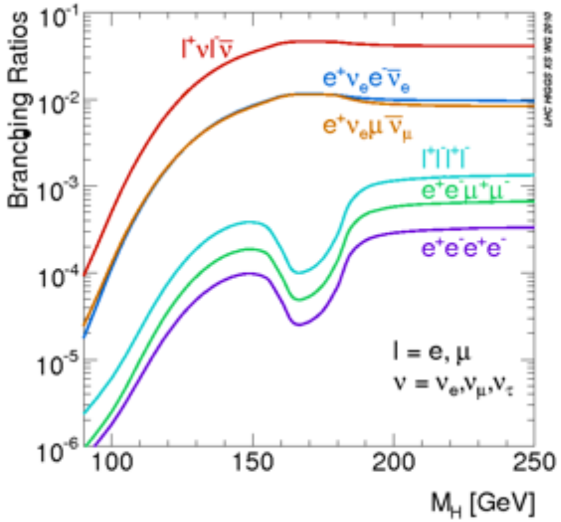
# Branching Ratios

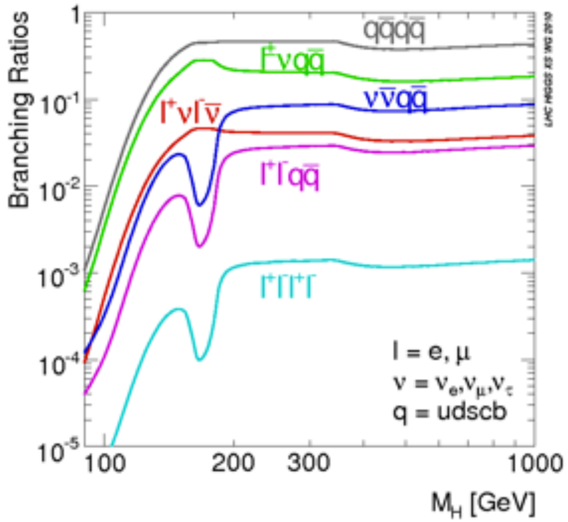
$$\Gamma_{\mathrm{H}} = \Gamma^{\mathrm{HD}} - \Gamma^{\mathrm{HD}}_{\mathrm{ZZ}} - \Gamma^{\mathrm{HD}}_{\mathrm{WW}} + \Gamma^{\mathrm{Proph.}}_{4f} + \Gamma^{\mathrm{HD}}_{\gamma\gamma}\,\delta^{\mathrm{QED}}_{\gamma f f}$$

| partial width | QCD | electroweak | total |
|---|---|---|---|
| $\mathrm{H} \to \mathrm{bb}/\mathrm{cc}$ | $\sim 0.1$–$0.2\%$ | $\sim 1$–$2\%$ for $M_{\mathrm{H}} \lesssim 135\,\mathrm{GeV}$ | $\sim 1$–$2\%$ |
| $\mathrm{H} \to \tau\tau$ | | $\sim 1$–$2\%$ for $M_{\mathrm{H}} \lesssim 135\,\mathrm{GeV}$ | $\sim 1$–$2\%$ |
| $\mathrm{H} \to \mathrm{tt}$ | $\lesssim 5\%$ [a] | $\sim 2\%$ for $M_{\mathrm{H}} < 500\,\mathrm{GeV}$ | $\sim 5\%$ |
| | | $\sim 0.1(\frac{M_{\mathrm{H}}}{1\,\mathrm{TeV}})^4$ for $M_{\mathrm{H}} > 500\,\mathrm{GeV}$ | $\sim 5$–$10\%$ |
| $\mathrm{H} \to \mathrm{gg}$ | $\sim 10\%$ [b] | $\sim 1\%$ | $\sim 10\%$ |
| $\mathrm{H} \to \gamma\gamma$ | $< 1\%$ | $< 1\%$ | $\sim 1\%$ |
| $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ}$ | | $\sim 0.5\%$ for $M_{\mathrm{H}} < 500\,\mathrm{GeV}$ | $\sim 0.5\%$ |
| $\to 4f$ | | $\sim 0.17(\frac{M_{\mathrm{H}}}{1\,\mathrm{TeV}})^4$ for $M_{\mathrm{H}} > 500\,\mathrm{GeV}$ | $\sim 0.5$–$15\%$ |

Uncertainties from missing higher order



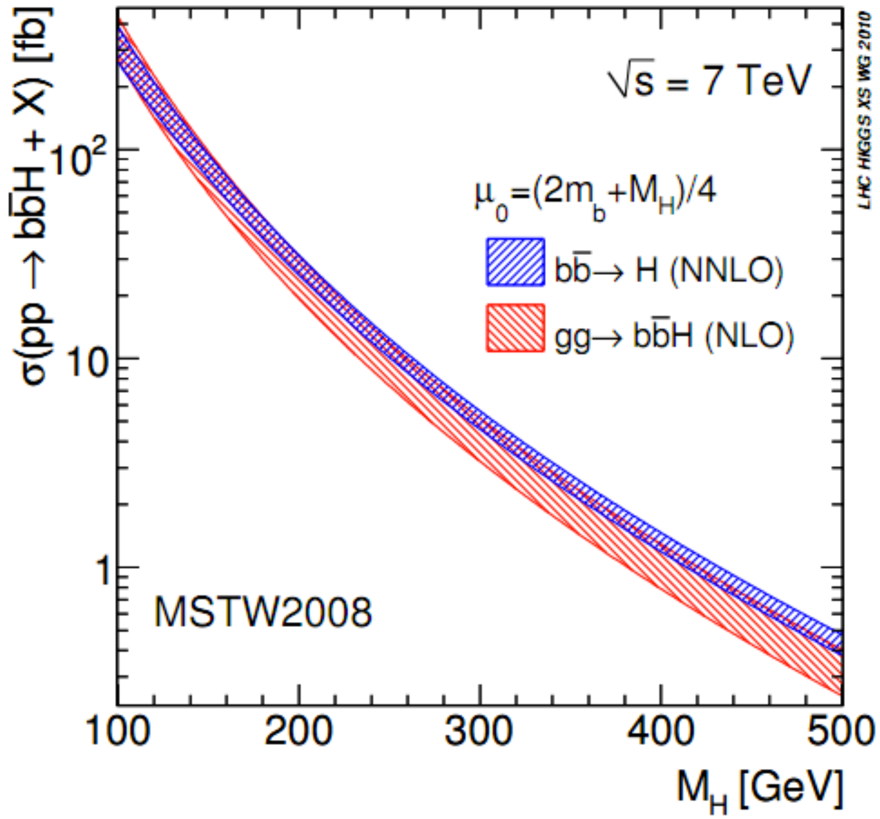




HD=HDecay

Proph = Prophecy4f

# A new recipe for MSSM h




- ATLAS and CMS presented MSSM H->ττ exclusion plot, using 4F and 5F predictions respectively.
- The theoretical community found a sound solution to combine the 2 approaches:

  The "Santander matching"

$$\sigma(b\bar{b} \to h + X) = \frac{1}{1+t}\left[\sigma^{4\mathrm{FS}} + t\,\sigma^{5\mathrm{FS}}\right]$$

$$t = \ln\frac{M_H}{m_b} - 2$$

$$\Delta\sigma = \frac{\left[(\Delta\sigma^{4\mathrm{FS}})^2 + (t\Delta\sigma^{5\mathrm{FS}})^2\right]^{1/2}}{1+t}$$

$M_H$ > 200 dominated by 5F and
$M_H$ small ~equal weight

# Theory: Next Step

- Differential distributions:
  Careful comparison between different generators
  (partially done done in Les Houches and in the group - to be expanded).
  Comparison of the NLO MC +PS distributions with the NNLO and NNLL calculations.

- Cross section with acceptance cuts: how much the K factor change?

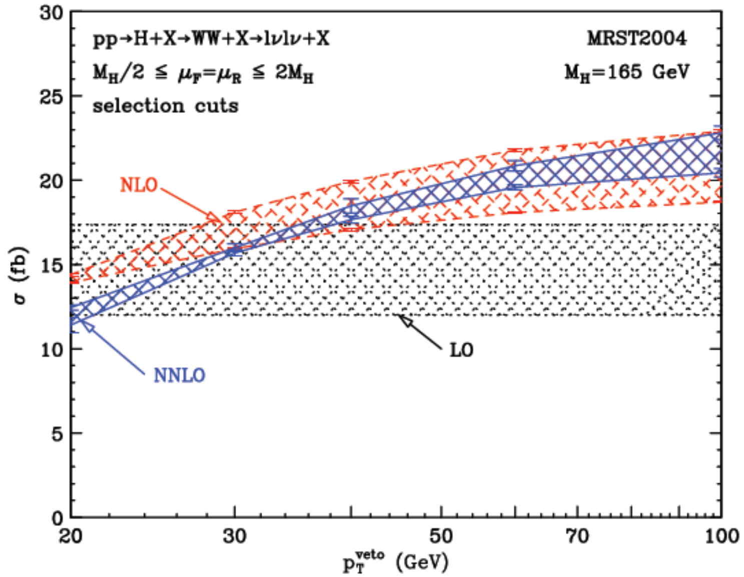
- A well define strategy for the uncertainties to
  $\sigma$ x Acceptance.

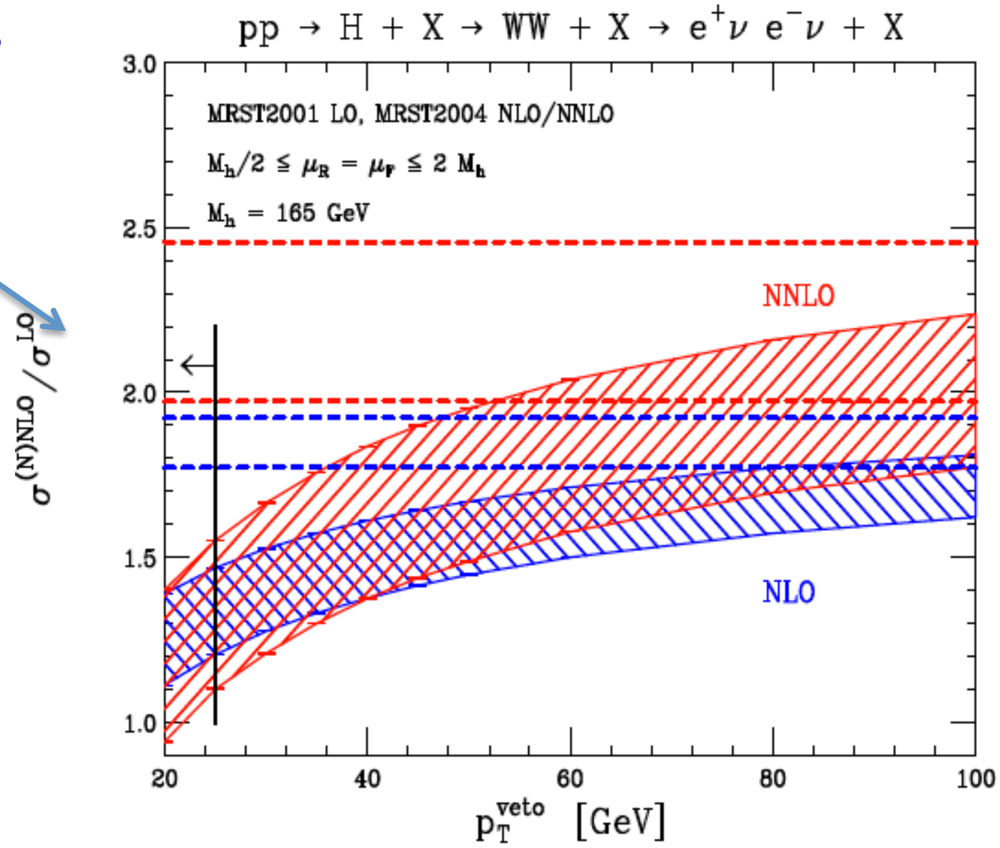
# Inclusive XS vs XS with cuts

**Impact of higher order corrections strongly reduced by selection cuts**

$$K_{(N)NLO}(\mu) = \frac{\sigma_{(N)NLO}(\mu)}{\sigma_{LO}(\mu)}$$

The NNLO band overlaps with the NLO one for $p_T^{veto} \geq 30$ GeV

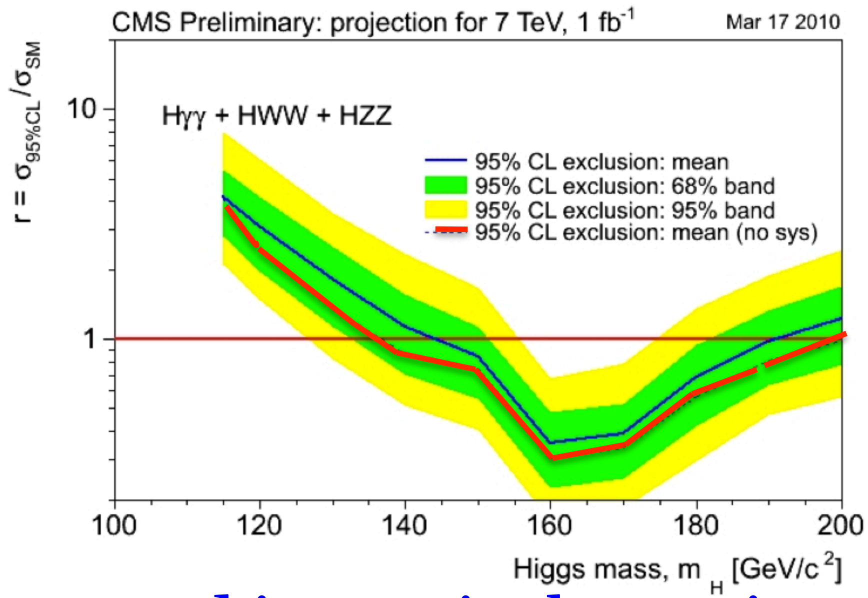



Studies done by Anastasiou et al., Grazzini

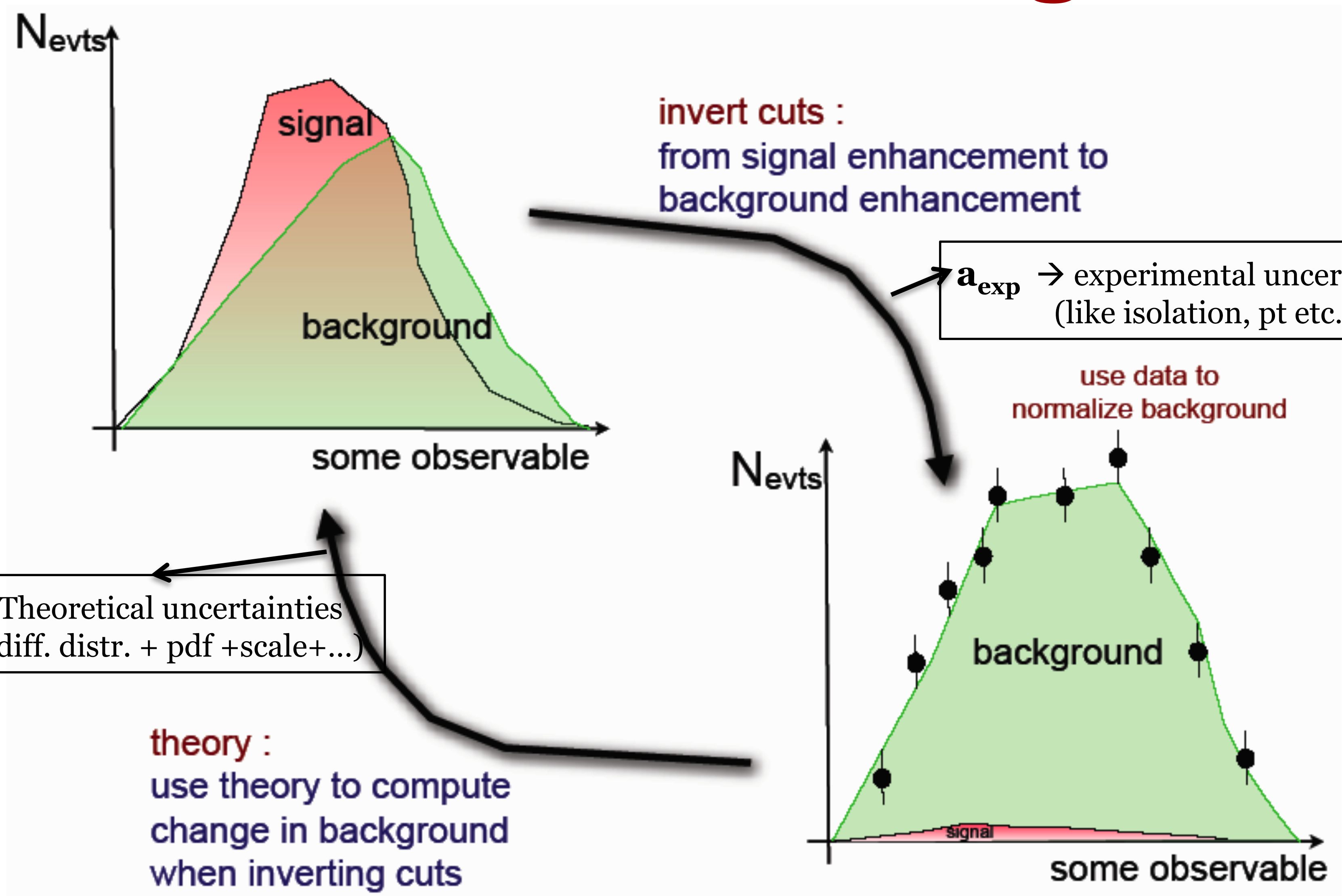
# Uncertainty on Background

- The first step is "exclusion". This mean background understanding. In case of no Higgs signal, what we observe is "background only".




- BUT background in particular region of the parameters.
- Experiments should validate the MC in these regions and in the "control regions" , where the experiments control the background with "data driven methods"

# The control of the background




**$a_{exp}$** → experimental uncertainties (like isolation, pt etc…)

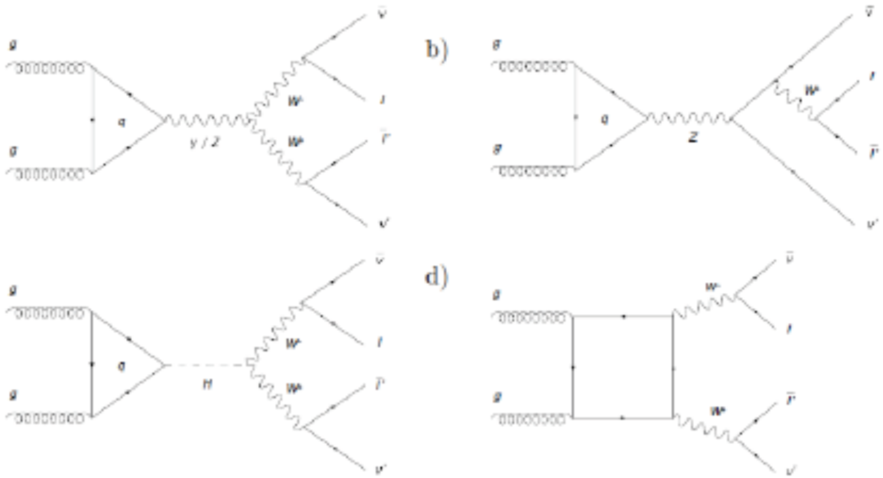
**$a_{TH}$** → Theoretical uncertainties (diff. distr. + pdf +scale+…)

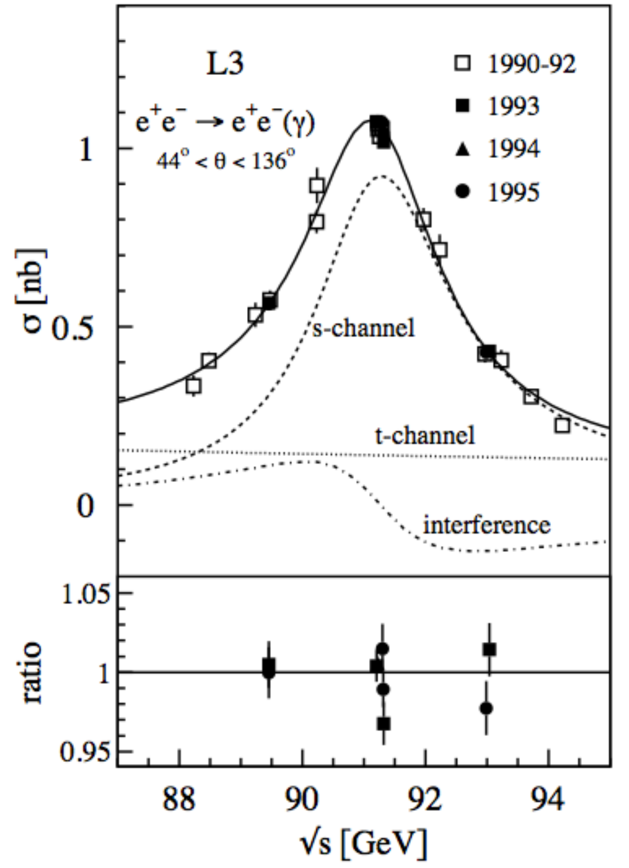
$$N^B_{(\text{signal region})} = a_{exp} * a_{TH} * N^B_{\text{control region}}$$

$a_{exp}$ - uncorr between exp
$a_{TH}$ - 100% correlated

# Pseudo Observables

- What the experiments observe in the final state is not always directly connected to the theoretical variable.
  In between there is
  - the acceptance of the detector (cuts),
  - "approximations" (like production x decay)
  - the interference of signal and background



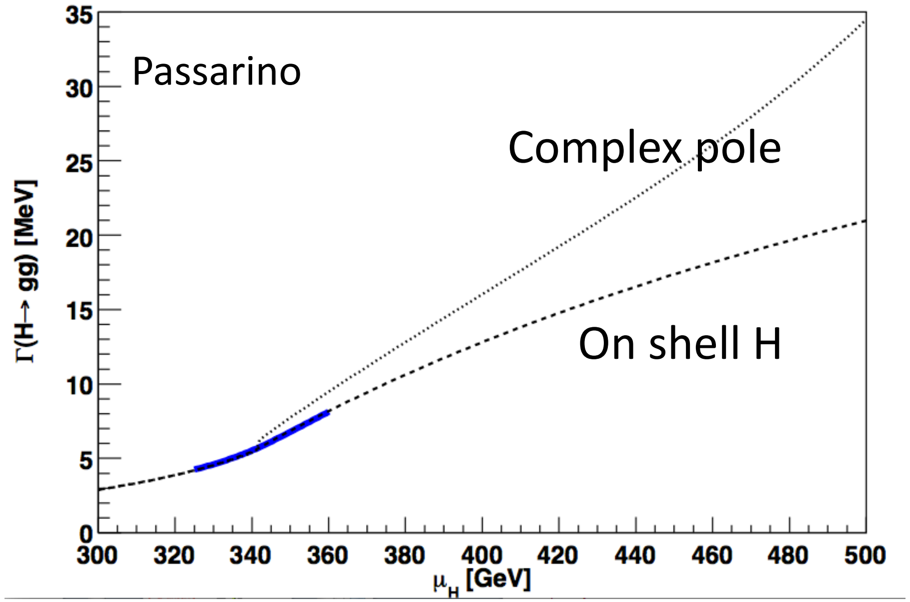

A corrected definition of the Higgs mass and width, i.e. of all the "**pseudo-observables**" is needed.

# PO: the high mass region

- At high mass ($M_H$>500 GeV) the width become large and the correct propagator should be used:

$$1/s\text{-}s_p\ ,\quad s_p=\mu^2\text{-}i\mu\Gamma$$

The mass is the real part of the complex pole of the propagator




- What is the limitation of narrow Higgs approximation (Higgs production x decay), adopting ad-hoc Breit-Wigner for high mass Higgs decay in MC? (all MC PS and NLO use this approx – good for $\Gamma$<<M)

- What is the effect of interference due to large Higgs width with the SM backgrounds ?

  (well studied in VB scattering - for example)

# Summary

- ATLAS and CMS have used the agreed Higgs XS and BR for winter conferences 2011. We have been speaking a common language since the very beginning of LHC physics era.

- Very first results of this WG →

*Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables.*

*By LHC Higgs Cross Section W.G*

*(editors: S.Dittmaier, C.Mariotti, G.Passarino. R.Tanaka)*

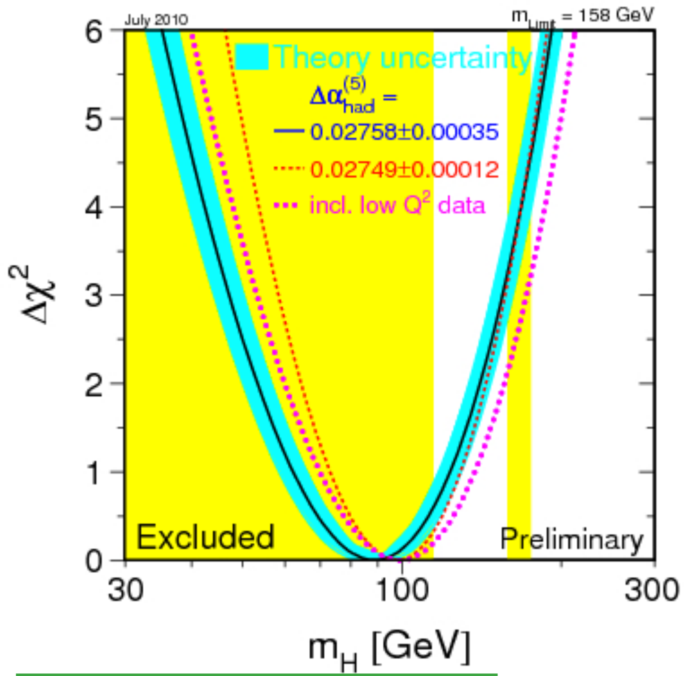
*CERN 2011-002 (arXiv: 1101.0593)*

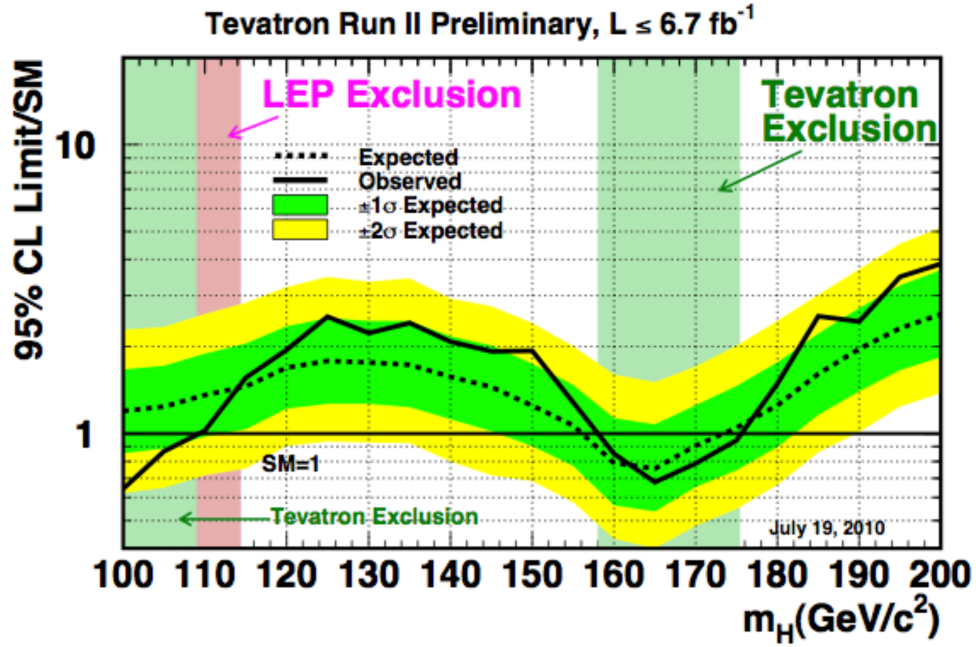
- Next steps:
  - Cross section within acceptances
  - Evaluate the impact of theory uncertainties on the estimation of the background in the “control regions” and in the signal regions
  - Pseudo-observables

**→ We want to use the BEST of our knowledge to probe EWSB**

# Backup

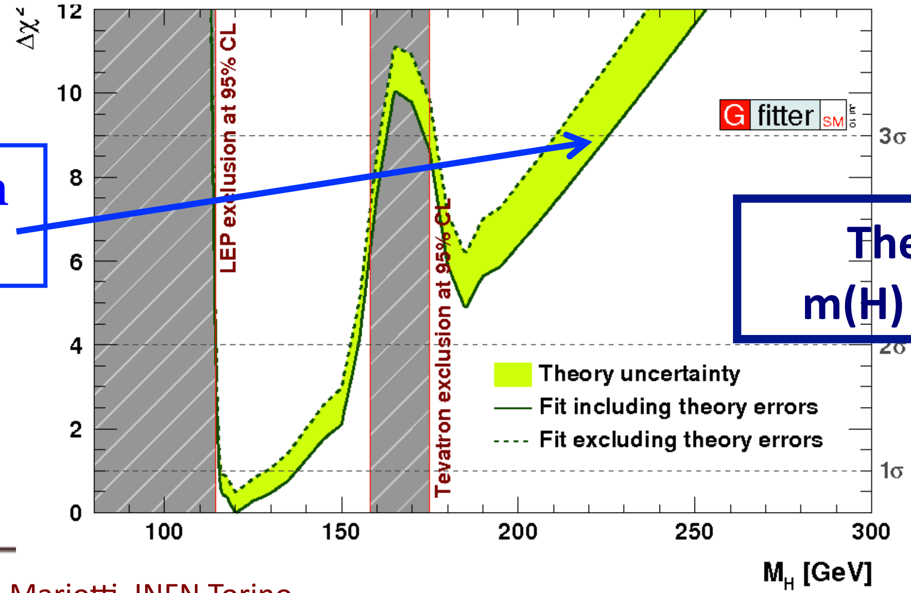
# The Higgs as of today




**EW precision measurements**
**m(H)= $87^{+35}_{-26}$ GeV/c²**

Plus Tevatron and LEP DS




**Theory**
**m(H) < TeV**

**LEP Direct Search**
**m(H) ≥ 114.4 GeV/c²**
at 95% CL

# The Higgs XS WG

Preparatory workshop in Torino Nov. 23-24, 2009

Creation announced on January 2010

Kickoff meeting on February 2010

Inauguration workshop in Freiburg April 12-13, 2010

Second workshop at CERN July 5-6,2010

Third workshop in Bari, November 4-5, 2010

Next workshop at BNL, May 4-6, 2011

**Task: SM and MSSM Higgs Cross Section and BRs**

- Use the same Standard Model input parameters
- Strategy on uncertainties (scale, $\alpha_s$, PDF, etc.)
- Monte Carlo at NLO for the signal
- Define pseudo-observables
- Cross sections of background in Higgs region

In the future: Beyond SM and MSSM, Other SUSY scenario, NMMSM, Invisible Higgs, Higgsless, etc.

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

## Overall Contacts

| ATLAS | CMS | THEORY | |
|---|---|---|---|
| Reisaburo Tanaka (LAL) | Chiara Mariotti (Torino) | Stefan Dittmaier (Freiburg) | Giampiero Passarino (Torino) |

## Subgroup Contacts and Link for Subgroup Wiki

| Group | ATLAS | CMS | LHCb | THEORY | |
|---|---|---|---|---|---|
| 1. ***ggF*** | Jianming Qian (Michigan) | Fabian Stöckli (CERN) | | Massimiliano Grazzini (Firenze) | Frank Petriello (Wisconsin) |
| 2. ***VBF*** | Daniela Rebuzzi (Pavia)<br>Sinead Farrington (Oxford) | Christoph Hackstein (Karlsruhe) | | Ansgar Denner (PSI) | Carlo Oleari (Milano-Bicocca) |
| 3. ***WH/ZH*** | Giacinto Piacquadio (CERN) | Jim Olsen (Princeton) | Clara Matteuzzi (Milano-Bicocca) | Stefan Dittmaier (Freiburg) | Robert Harlander (Wuppertal) |
| 4. ***ttH*** | Simon Dean (UCL) | Chris Neu (Virginia) | | Laura Reina (Florida) | Michael Spira (PSI) |
| 5. ***MSSM neutral*** | Markus Warsinsky (Freiburg) | Monica Vazquez Acosta (IC) | | Michael Spira (PSI) | Georg Weiglein (DESY) |
| 6. ***MSSM charged*** | Martin Flechl (Freiburg) | Sami Lehti (Helsinki) | | Michael Krämer (Aachen) | Tilman Plehn (Heidelberg) |
| 7. ***PDF*** | Joey Huston (Michigan State) | Kajari Mazumdar (TIFR) | | Stefano Forte (Milano) | Robert Thorne (UCL) |
| 8. ***Branching ratios*** | Daniela Rebuzzi (Pavia) | Ivica Puljak (Split) | | Ansgar Denner (PSI) | Sven Heinemeyer (IFCA) |
| 9. ***NLO MC*** | Jae Yu (Texas) | Marta Felcini (UCLA/IFCA) | | Fabio Maltoni (Louvain) | Paolo Nason (Milano-Bicocca) |
| 10. ***Pseudo-observables*** | Michael Dührssen (CERN) | Marta Felcini (UCLA/IFCA) | | Sven Heinemeyer (IFCA) | Giampiero Passarino (Torino) |

Everybody is welcome to join!!!
We need more people

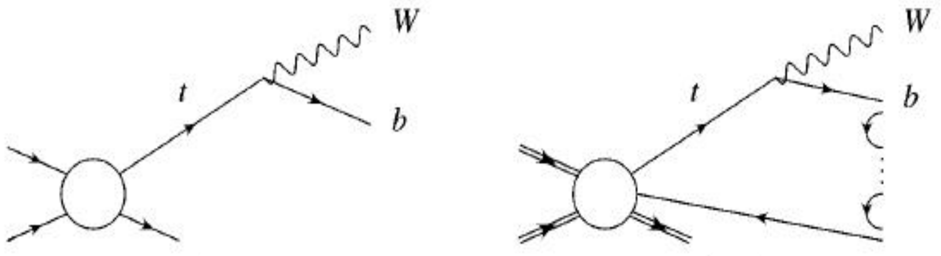
# Phase 2:

- Contact people for the final states:

| Group | ATLAS | CMS | LHCb |
|---|---|---|---|
| 1. $\gamma\gamma$ | Marumi Kado (LAL) | Susan Gascon-Shotkin (Lyon) | |
| 2. $ZZ^*$ | Stathes Paganis (Sheffield) | Nicola De Filippis (Bari) | |
| 3. $WW^*$ | Tiesheng Dai (Michigan) | Javier Cuevas (Oviedo) | |
| 4. $\tau\tau$ | Markus Schumacher (Freiburg) | Alexander Nikitenko (Imperial College) | |
| 5. $bb$ | Chris Potter (Oregon) | Jim Olsen (Princeton) | Clara Matteuzzi (Milano-Bicocca) |
| 6. $H+-$ | Martin Flechl (Freiburg) | Sami Lehti (Helsinki) | |

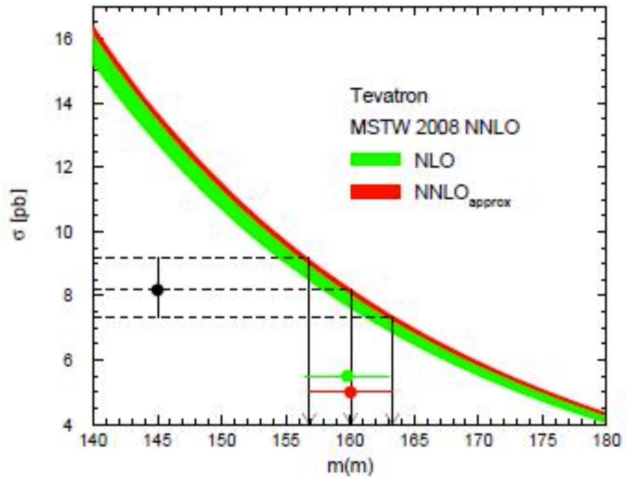
Everybody is welcome to join!!
We need more people

# Pseudo Observables




Because of NLO, the Wb invariant mass from the reconstructed final state is NOT equal to the pole mass

By measuring the "running mass" from the cross section value, the result is:
$M_{top}\ (M_{top})_{\overline{MS}}$ = 160.0 ±3.3 GeV




That translates into a pole mass of 168.2±3.6 GeV

While the measured mas is: 173.1 ± 1.3