Higgs theory

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ATLAS HSG2 meeting

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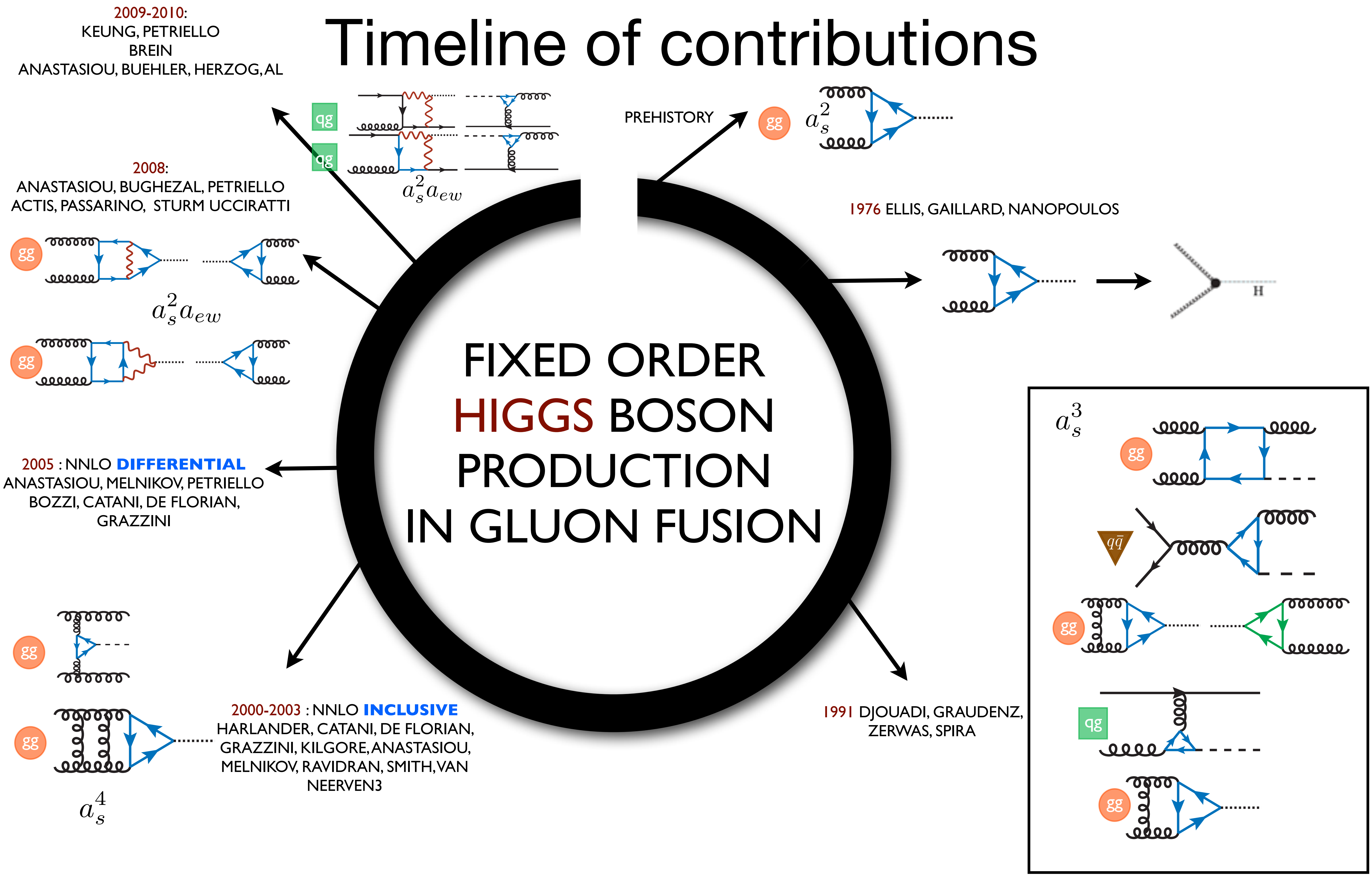
Why is Higgs production different

- In the dominant channel, gluon fusion, it starts already at second order in a_s, so it's extra sensitive to its value.
- The perturbative convergence of the cross section is slow: we found 100% corrections at NLO and 20% at NNLO.
- The Higgs boson couples practically to everything in the SM: different contributions with mixed e/w and QCD couplings, sensitive to coupling alterations in BSM scenaria, etc.
- In the dominant channel, gluon fusion, it depends on gluon pdfs from both initial state hadrons: those are the less constrained by data.
- Diverse energy scales: Higgs mass, Higgs recoil energy, twice the quark energy etc.


Timeline of contributions
FIXED ORDER HIGGS BOSON PRODUCTION IN GLUON FUSION
PREHISTORY
gg a_s^2
1976 ELLIS, GAILLARD, NANOPOULOS
H
a_s^3
gg
$q\bar{q}$
gg
qg
gg
1991 DJOUADI, GRAUDENZ, ZERWAS, SPIRA
2000-2003 : NNLO INCLUSIVE
HARLANDER, CATANI, DE FLORIAN, GRAZZINI, KILGORE, ANASTASIOU, MELNIKOV, RAVIDRAN, SMITH, VAN NEERVEN3
gg
gg
a_s^4
2005 : NNLO DIFFERENTIAL
ANASTASIOU, MELNIKOV, PETRIELLO
BOZZI, CATANI, DE FLORIAN, GRAZZINI
2008:
ANASTASIOU, BUGHEZAL, PETRIELLO
ACTIS, PASSARINO, STURM UCCIRATTI
gg
$a_s^2 a_{ew}$
gg
2009-2010:
KEUNG, PETRIELLO
BREIN
ANASTASIOU, BUEHLER, HERZOG, AL
qg
qg
$a_s^2 a_{ew}$

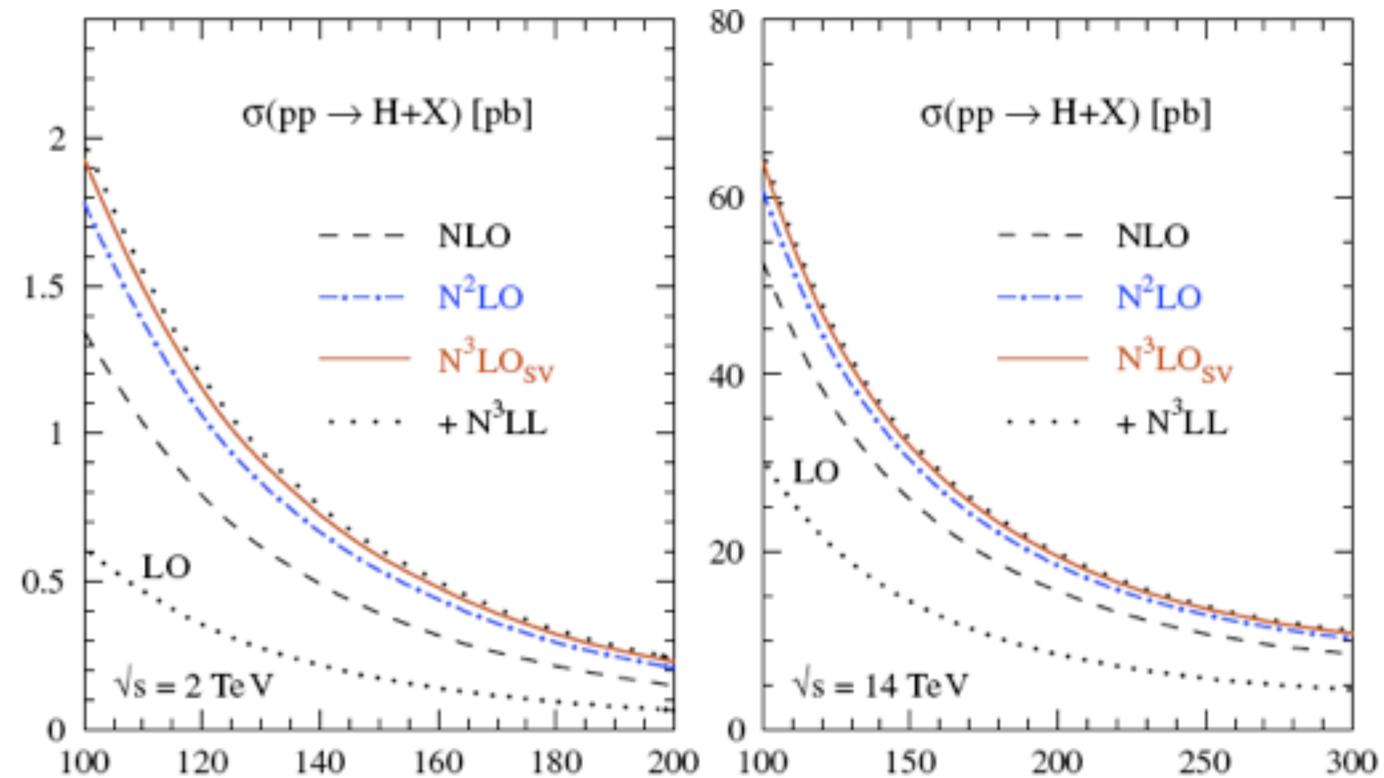
Resummation

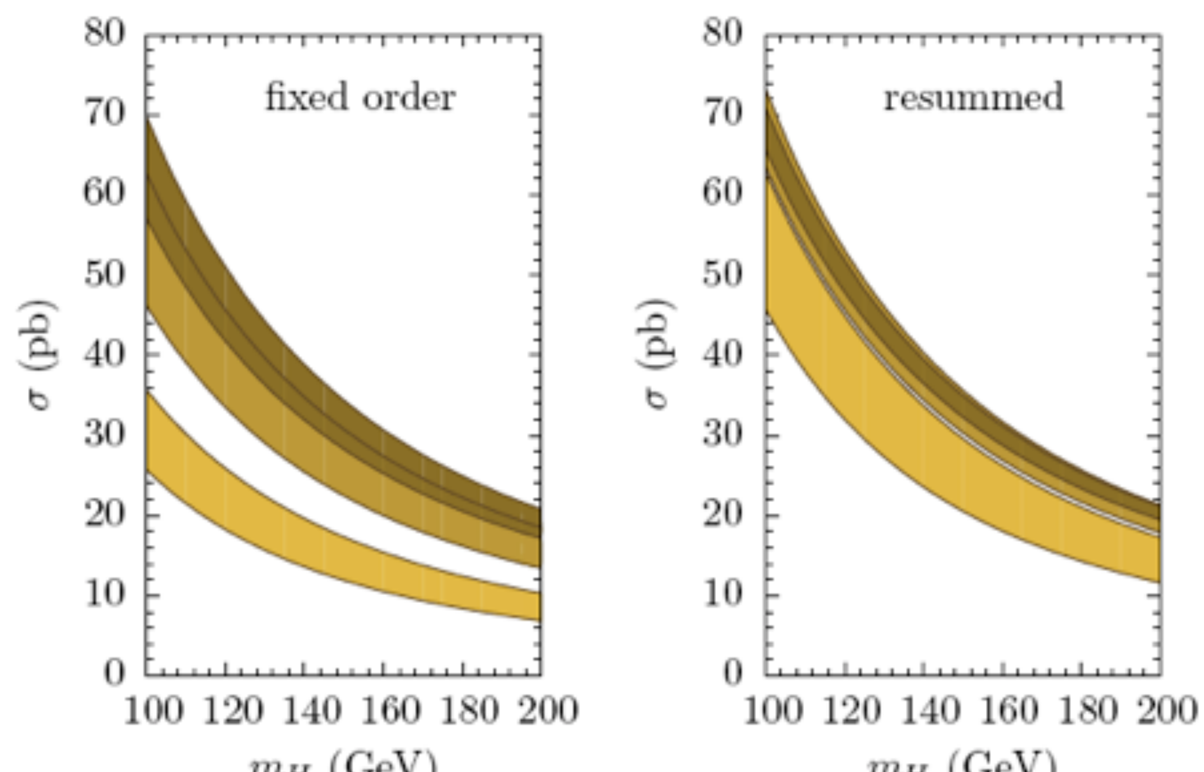
Logarithmic contributions from soft gluons have been resummed systematically to NNLL
Catani, de Florian, Grazzini, Nason 2003

The NNNLO logarithmic pieces have been confirmed by the computation of soft terms at this order by Moch, Vogt 2005 and Magnea, Laenen, 2005.

The added contribution to the fixed NNLO result is minimal when the scale is chosen properly.

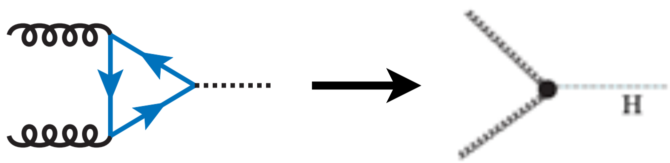
“RG-improved” predictions by Ahrens, Becher, Neubert, 2008, also agree at NNLO with fixed order (but uncertainties are unrealistically small).



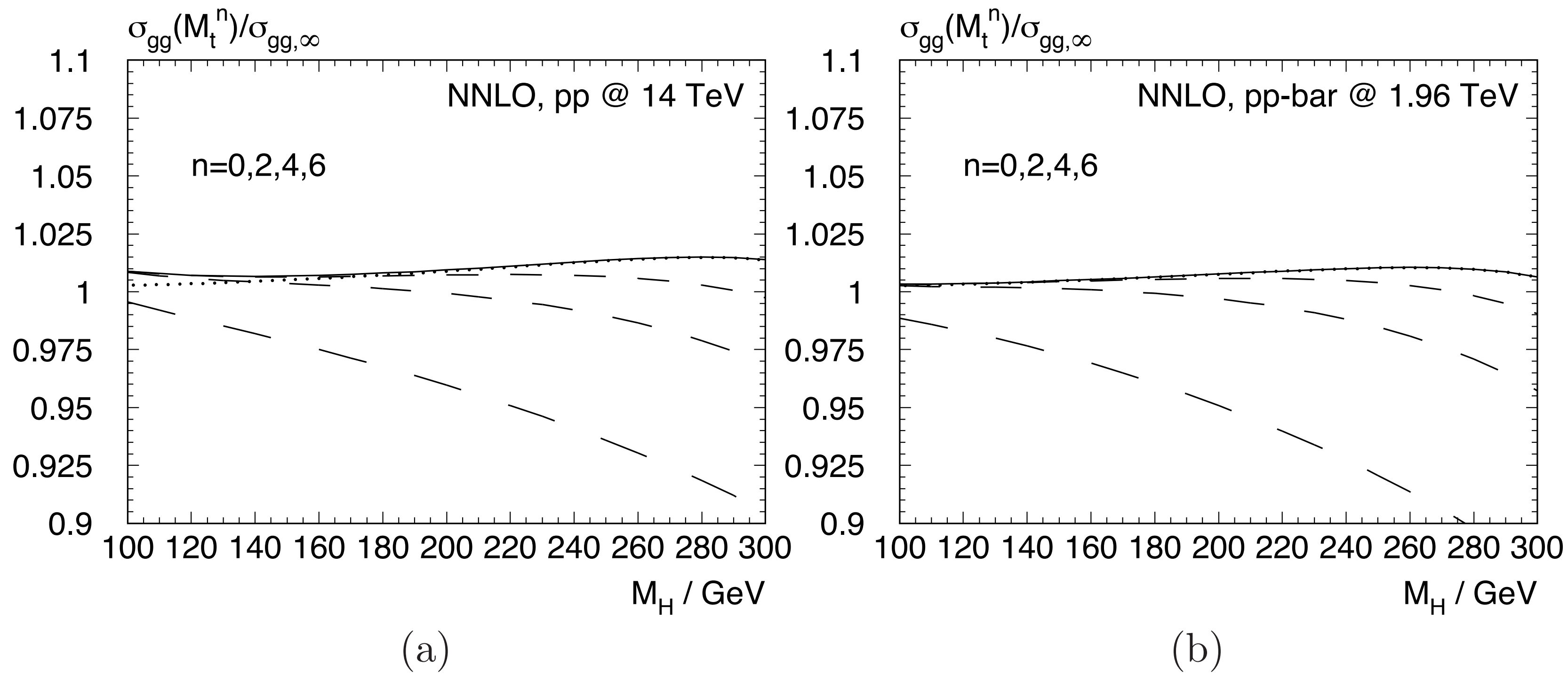


Heavy Quark EFT expansion

The approximation used for the NNLO part of the total cross section was believed to be valid also to the region above the top mass



It has been recently verified by explicit calculation of the subleading terms in the $1/m_t$ expansion that in the region 100-300 GeV the approximation is better than 0.5%
Harlander, Ozeren 2009
Pak, Rogal, Steinhauser 2009



A priori expected that the uncertainty due to HQEFT would be correcting the NNLO part that amounts to 20% of the total, and it would therefore be small.

iHixs

http://www.phys.ethz.ch/~pheno/ihixs/

ANASTASIOU, BUEHLER, HERZOG, AL

A new program for inclusive Higgs boson cross-section at hadron colliders.

Entirely revisited calculations at NLO QCD and EW. Cross checked many previous results.

A new and very reliable package (CHAPLIN) for harmonic polylogarithms at the heart of the calculation. BUEHLER, DUHR, 2011

Easily extendible to BSM models.

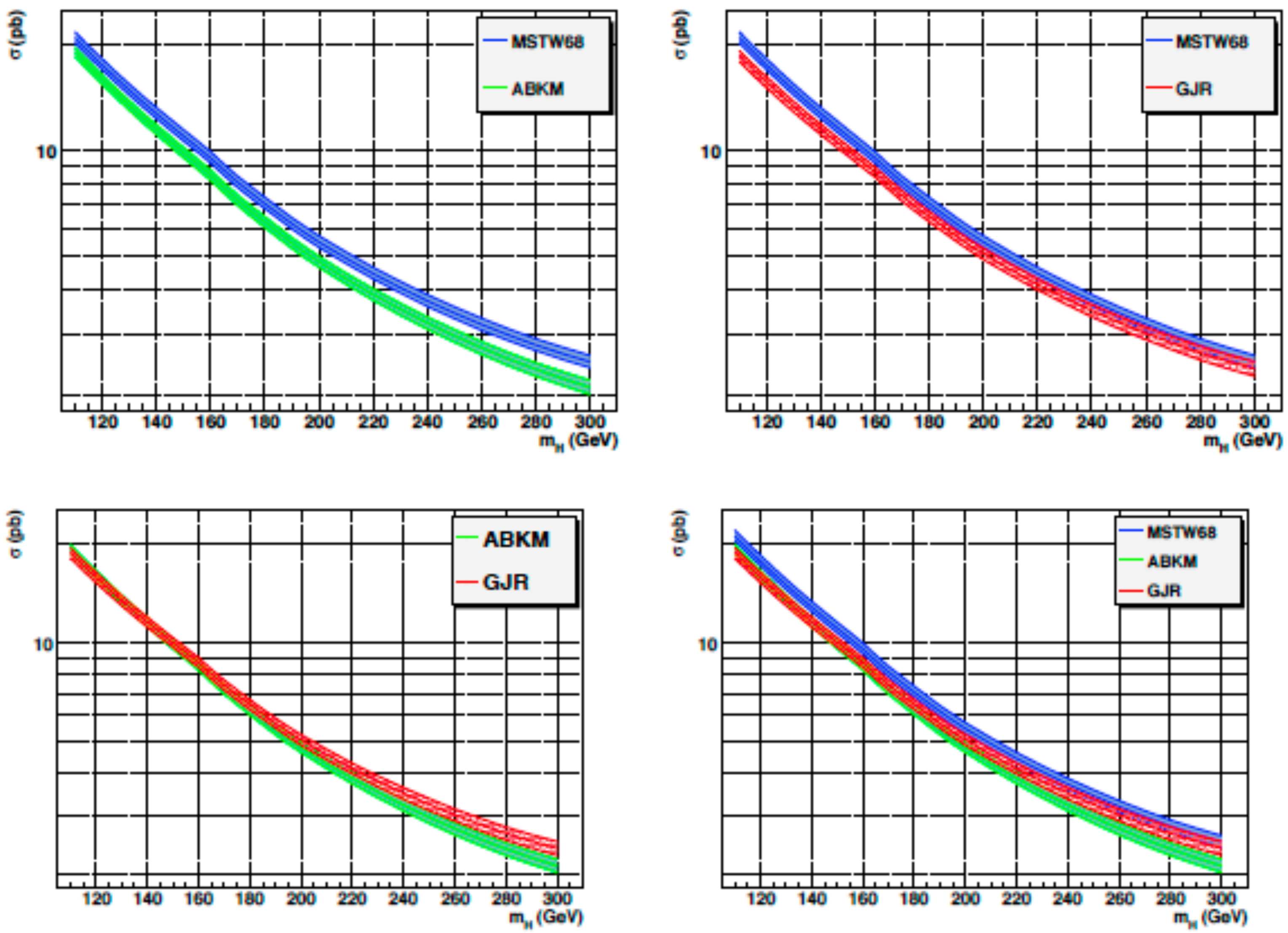
Easy to interface with Higgs total width and Branching Ratios in BSM models.

iHixs

http://www.phys.ethz.ch/~pheno/ihixs/

- Exact LO and NLO, retaining all quark mass effects at all channels.
- NNLO in improved HQET.
- Virtual EW corrections.
- Complete real electroweak corrections to H+j, including bg initial states.
- Finite Higgs width effects, in various schemes.
- LHAPDF support, uncertainties for all PDF sets.
- BSM wilson coefficients, and any number of extra heavy quarks.
- Top width effects.
- Extra production mode: bottom quark annihilation.

PDF uncertainty

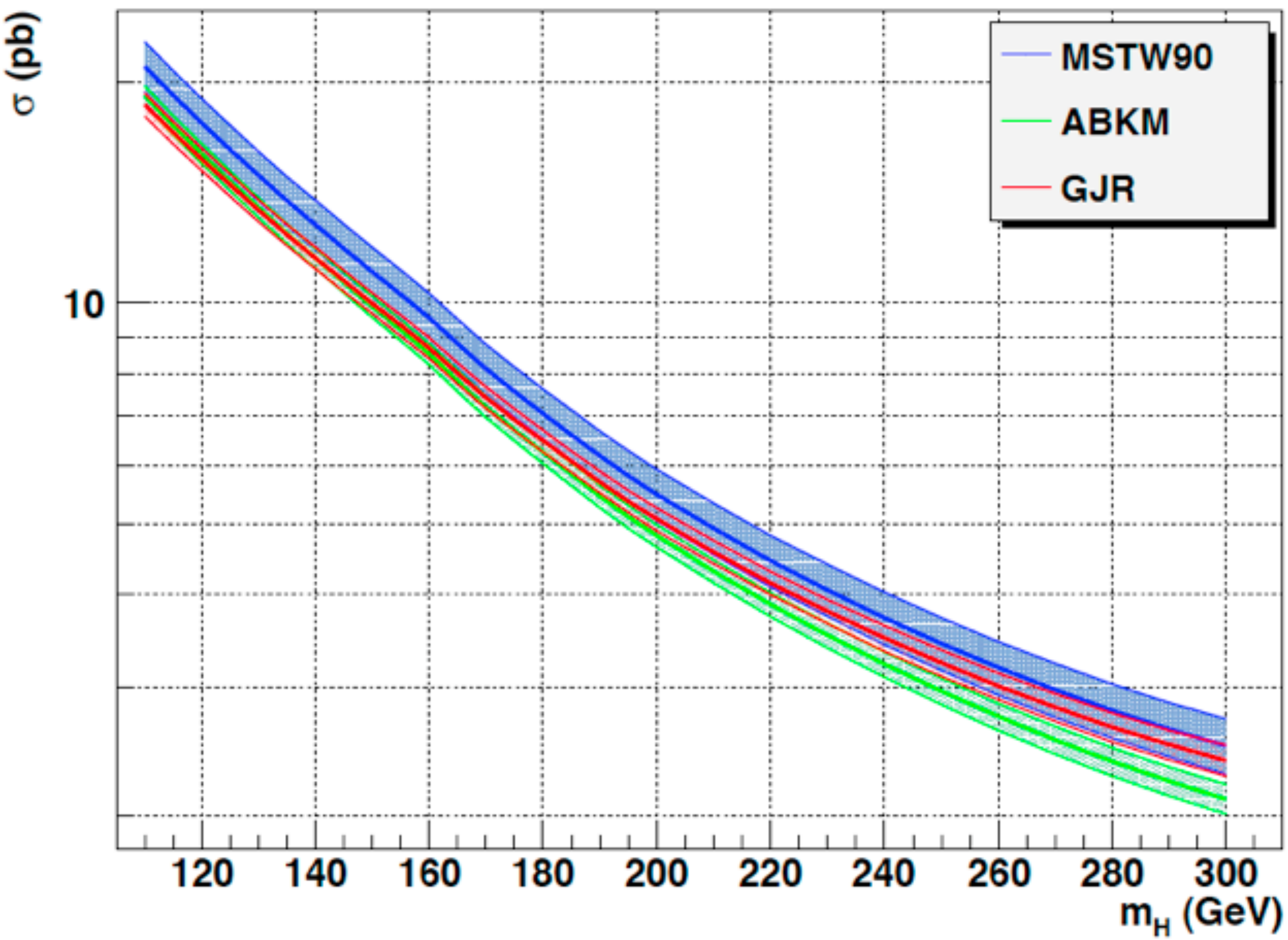


NNPDF uncertainty bands coming soon

Figure 3: The Higgs production cross section at NNLO with three different PDF sets and their 68%CL PDF+α_s uncertainty bands.

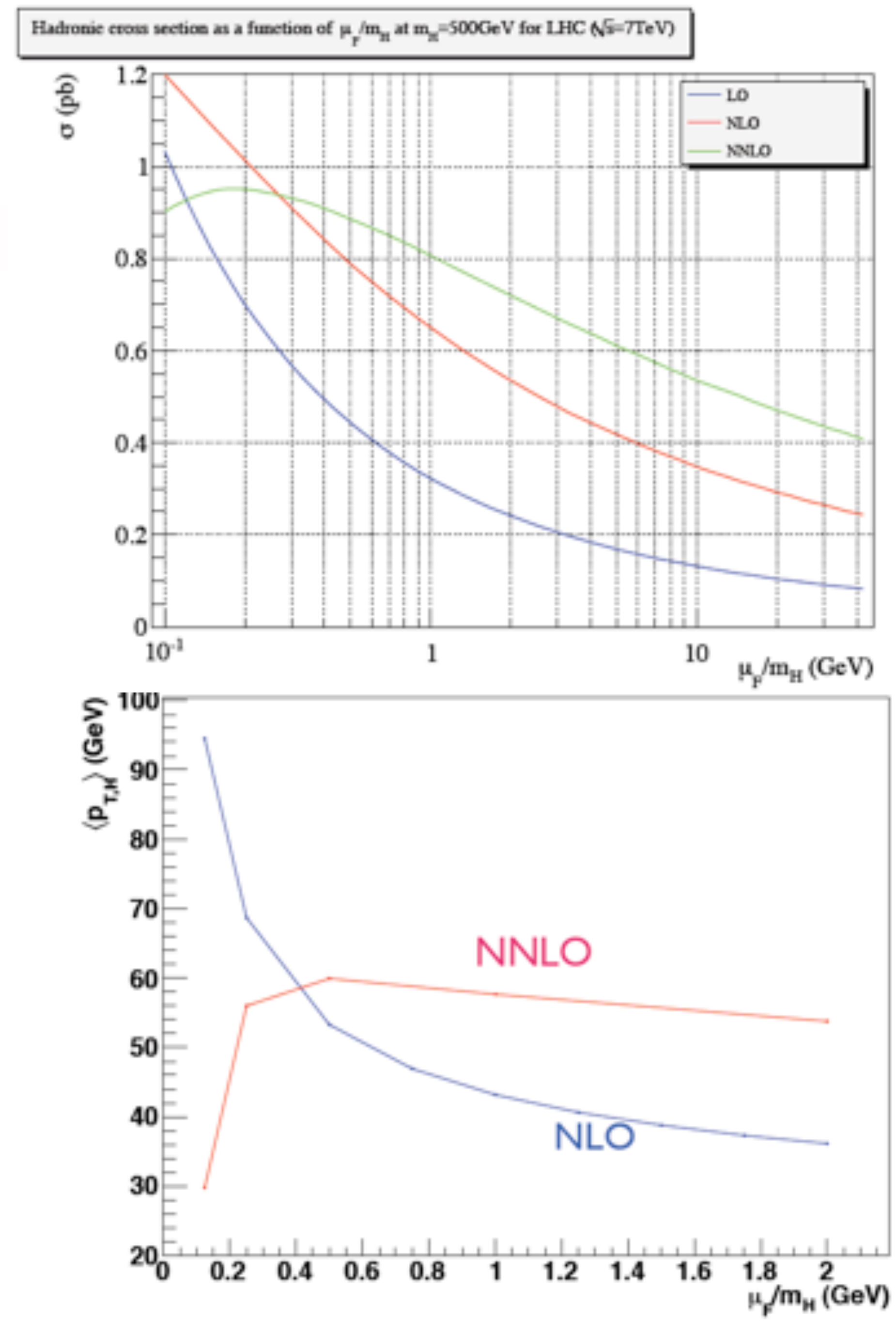
The predictions from the available NNLO PDF sets do NOT agree within their uncertainty bands

PDF uncertainty



The 90%CL of MSTW marginally agrees with ABKM and GJR
It is a good measure of PDF uncertainty.

Scales



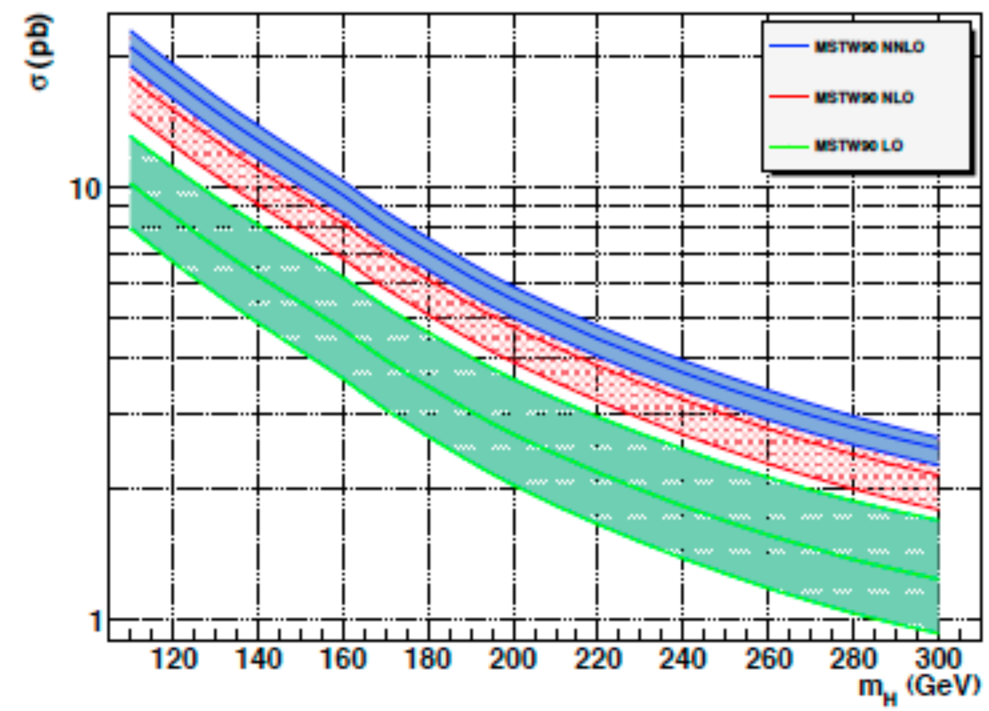
Traditionally m_H has been used as the central factorization and renormalization scale.

It has been recognized recently that $m_H/2$ captures the physics of Higgs production much better, and:

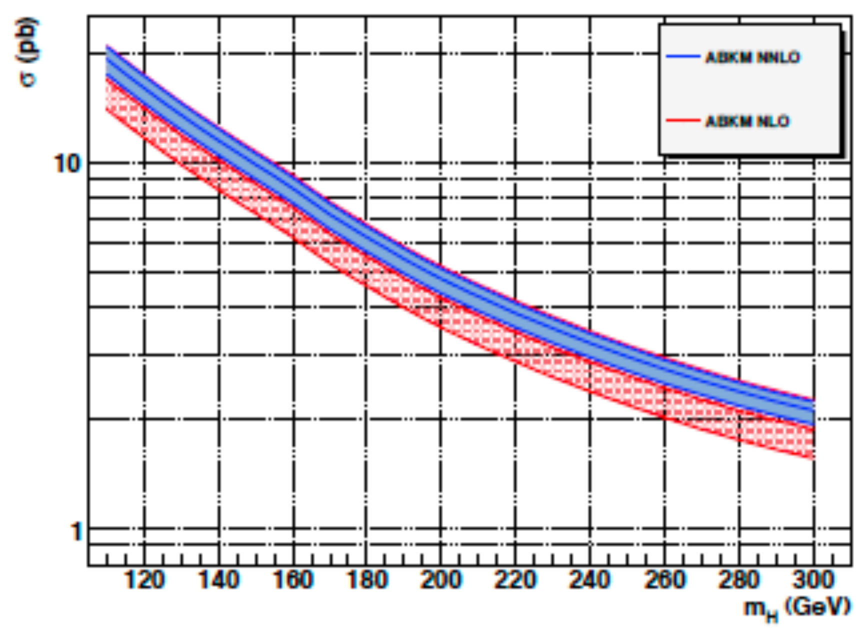
- leads to an uncertainty range that does not include too high, unphysical scales.
- improves the perturbative convergence
- minimizes resummation effects

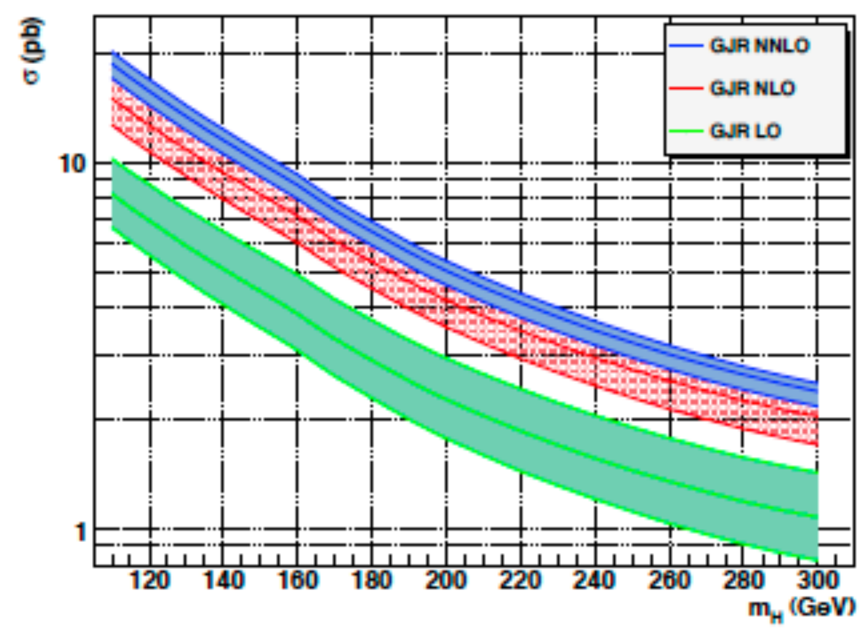
Scale uncertainty

Reasonable perturbative behaviour from NLO on, for all NNLO PDFs



NLO uncertainty band engulfs NNLO almost everywhere.





Good reasons to trust the NNLO uncertainty estimate for the inclusive cross section

Top quark width

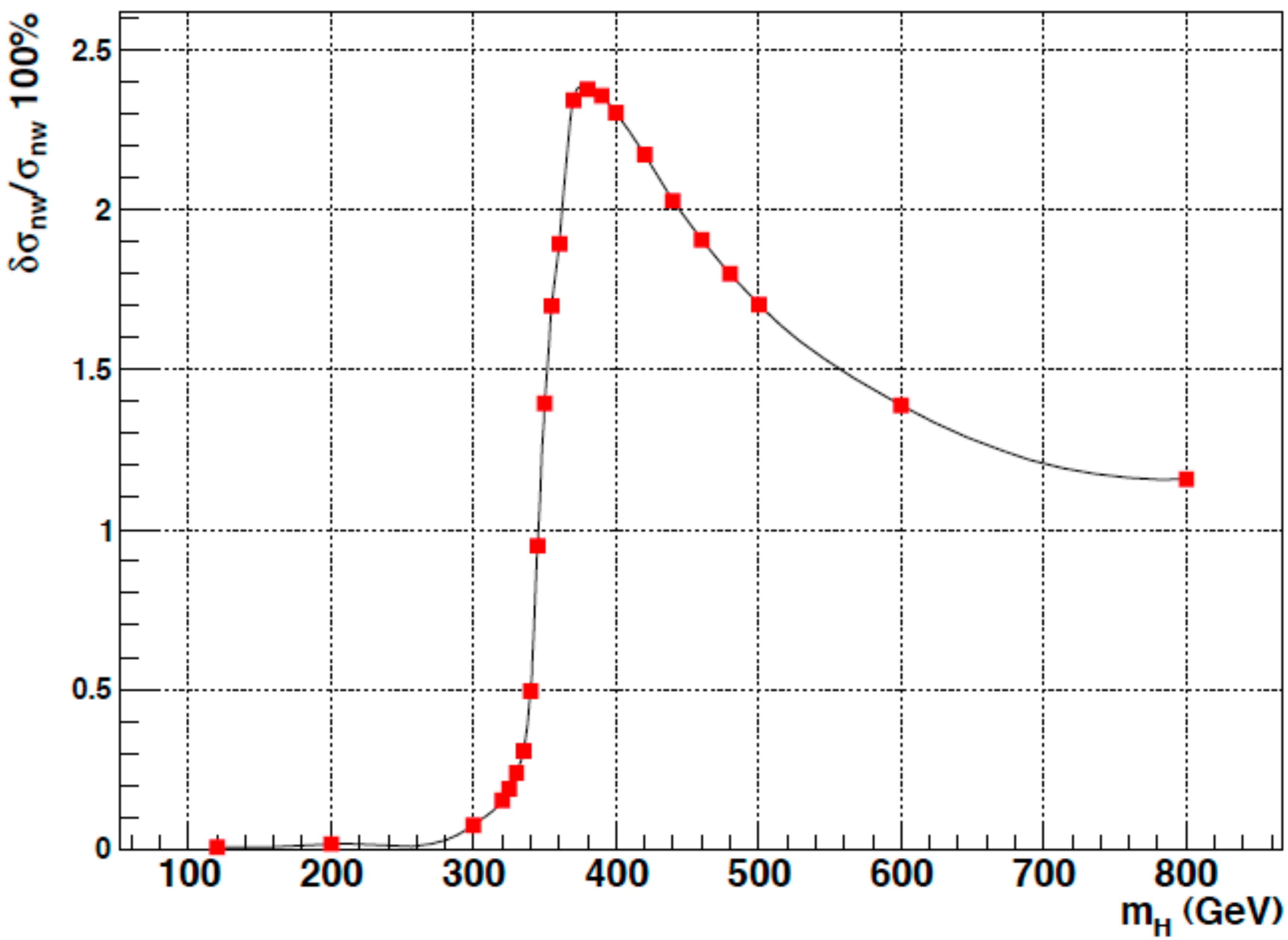
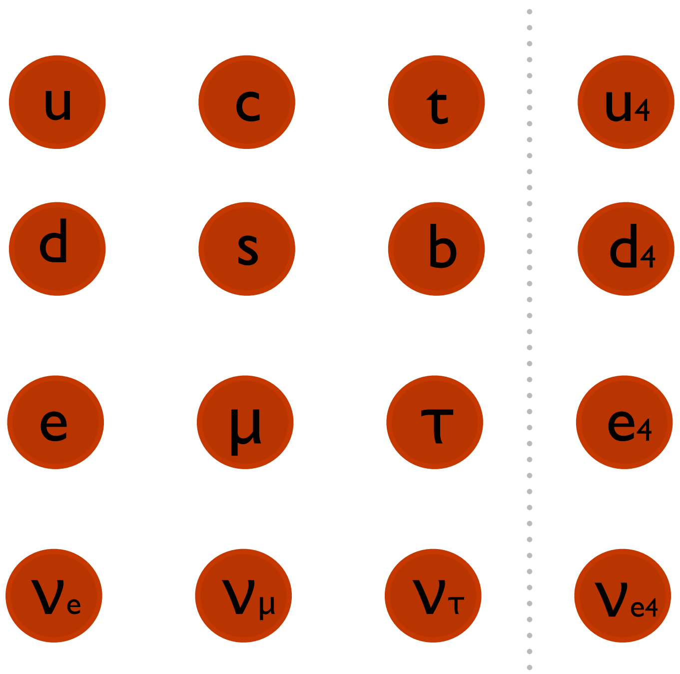


Figure 5: Relative difference $\delta\sigma_{nw}/\sigma_{nw} = \frac{\sigma - \sigma^*}{\sigma^*} \cdot 100\%$ of the cross section for the top quark with a real mass, σ^*, and in the complex mass scheme with $\Gamma_{top} = 2$ GeV.

BSM scenaria: SM4



$$\text{scenario 1: } m_{d_4} = 300\,\text{GeV}\,, \qquad \text{scenario 2: } m_{d_4} = 400\,\text{GeV}$$

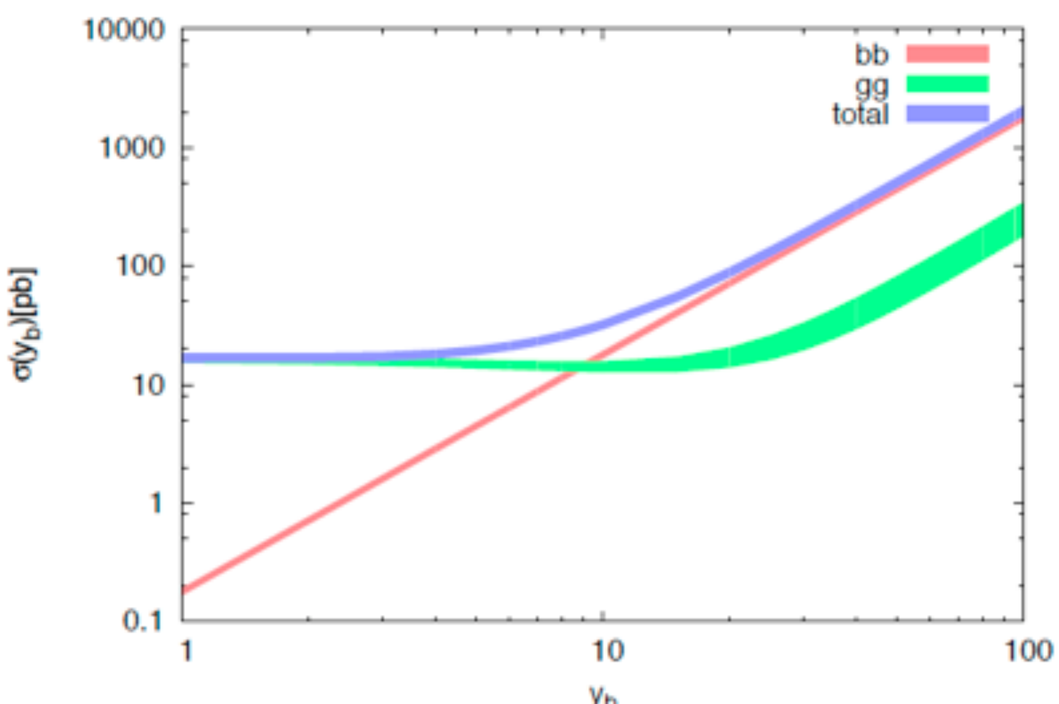
$$m_{u_4} - m_{d_4} = 50\,\text{GeV} + 10\,\text{GeV} \times \log\left(\frac{m_h}{115\,\text{GeV}}\right)\,\text{GeV}$$

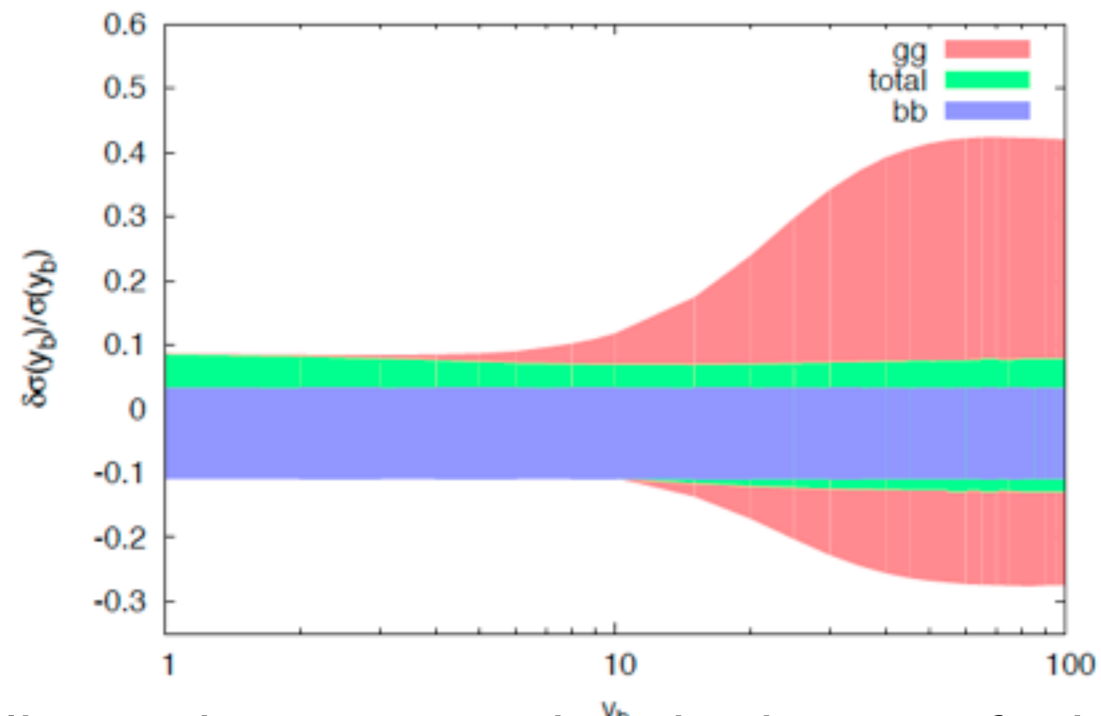
iHixs provides the most accurate SM4 predictions to date.
Very easy to interface with BSM decay BRs.
NO APPROXIMATIONS NECESSARY.
Experiments need to choose which precise model they want to exclude (inifinite masses for 4th generation lepton sector doesn't make sense)

$\sigma[pb]$	ABKM09	GJR	$\text{MSTW08}\vert_{68\%\text{CL}}$	$\text{MSTW08}\vert_{90\%\text{CL}}$
$m_h = 110\,\text{GeV}$	$167.59 \pm 3.0\%_{\text{pdf}}$	$162.78 \pm 3.6\%_{\text{pdf}}$	$183.41\ {}^{+4.0}_{-3.1}\ \%_{\text{pdf}}$	${}^{+7.9}_{-7.6}\ \%_{\text{pdf}}$
$m_h = 165\,\text{GeV}$	$66.130 \pm 3.3\%_{\text{pdf}}$	$67.713 \pm 3.3\%_{\text{pdf}}$	$74.221\ {}^{+4.0}_{-3.3}\ \%_{\text{pdf}}$	${}^{+7.9}_{-7.7}\ \%_{\text{pdf}}$
$m_h = 200\,\text{GeV}$	$40.634 \pm 3.6\%_{\text{pdf}}$	$42.867 \pm 3.5\%_{\text{pdf}}$	$46.306\ {}^{+4.1}_{-3.4}\ \%_{\text{pdf}}$	${}^{+8.1}_{-7.9}\ \%_{\text{pdf}}$
$m_h = 300\,\text{GeV}$	$14.768 \pm 4.7\%_{\text{pdf}}$	$16.786 \pm 5.0\%_{\text{pdf}}$	$17.541\ {}^{+4.3}_{-3.9}\ \%_{\text{pdf}}$	${}^{+8.8}_{-8.6}\ \%_{\text{pdf}}$

Table 2: A comparison for the gluon fusion cross-section in the "scenario 1" of the four-generation Standard Model with the three available NNLO pdf sets: ABKM09, GJR and MSTW08.

BSM scenaria: enhanced Y_b





In BSM models with enhanced Yukawa coupling to bottom quarks, the bottom fusion production process can become competitive with the ggF. Moreover, the b-quark contribution to ggF gets enhanced. It is only known to NLO, so the scale uncertainty is NLO level.

Morale: in BSM one should be careful before adapting NNLO SM uncertainties.

Heavy Higgs: lineshape and BW

Consider the process

$$pp \to ?? \to XX + \ldots$$

RESONANT

$$pp \to H + \ldots \to XX + \ldots$$

NON-RESONANT (PROMPT)

$$pp \to XX + \ldots$$

- Keeping only the resonant diagrams is justified (?) only in the low mass region.
- In high masses (>300-400 GeV) there are severe cancellations between resonant and non-resonant diagrams.
- In addition, the width of the Higgs boson grows (it gets equal to its mass at 1.1 TeV, in SM). This is a separate issue.

Heavy Higgs: lineshape and BW

- The resonant diagrams naively diverge.
- Dyson summation leads to a Breit-Wigner formula with a width that can be calculated perturbatively.
- This is already an approximation (diagrams that connect production and decay are ignored, the width has been expanded around the physical Higgs mass, etc).

$$\hat{\sigma}_{ij\to\{H_{\rm final}\}+X}(\hat{s},\mu_f) = \int_{Q_a^2}^{Q_b^2} dQ^2 \frac{Q\Gamma_H(Q)}{\pi} \frac{\hat{\sigma}_{ij\to H}(\hat{s},Q^2,\mu_f){\rm Br}_{H\to\{H_{\rm final}\}}(Q)}{(Q^2-m_H^2)^2+m_H^2\Gamma_H^2(m_H)}$$

But note the Q-dependence in width and BR!

Heavy Higgs: lineshape and BW

- For high Higgs masses the magnitude of signal-background interference cannot be neglected: contrary to the case of low Higgs masses, i.e. when higgs to diphoton is important, the resonance in high masses is very broad and hence the interference is non-negligible.

- In iHixs, we have implemented a variant of the simple Breit-Wigner, called Seymour scheme, in which the limiting behaviour of signal-background interference in the high energy regime is extrapolated to the region below 1 TeV. The limiting behaviour is deduced assuming that the Higgs boson unitarizes the WW scattering amplitude.

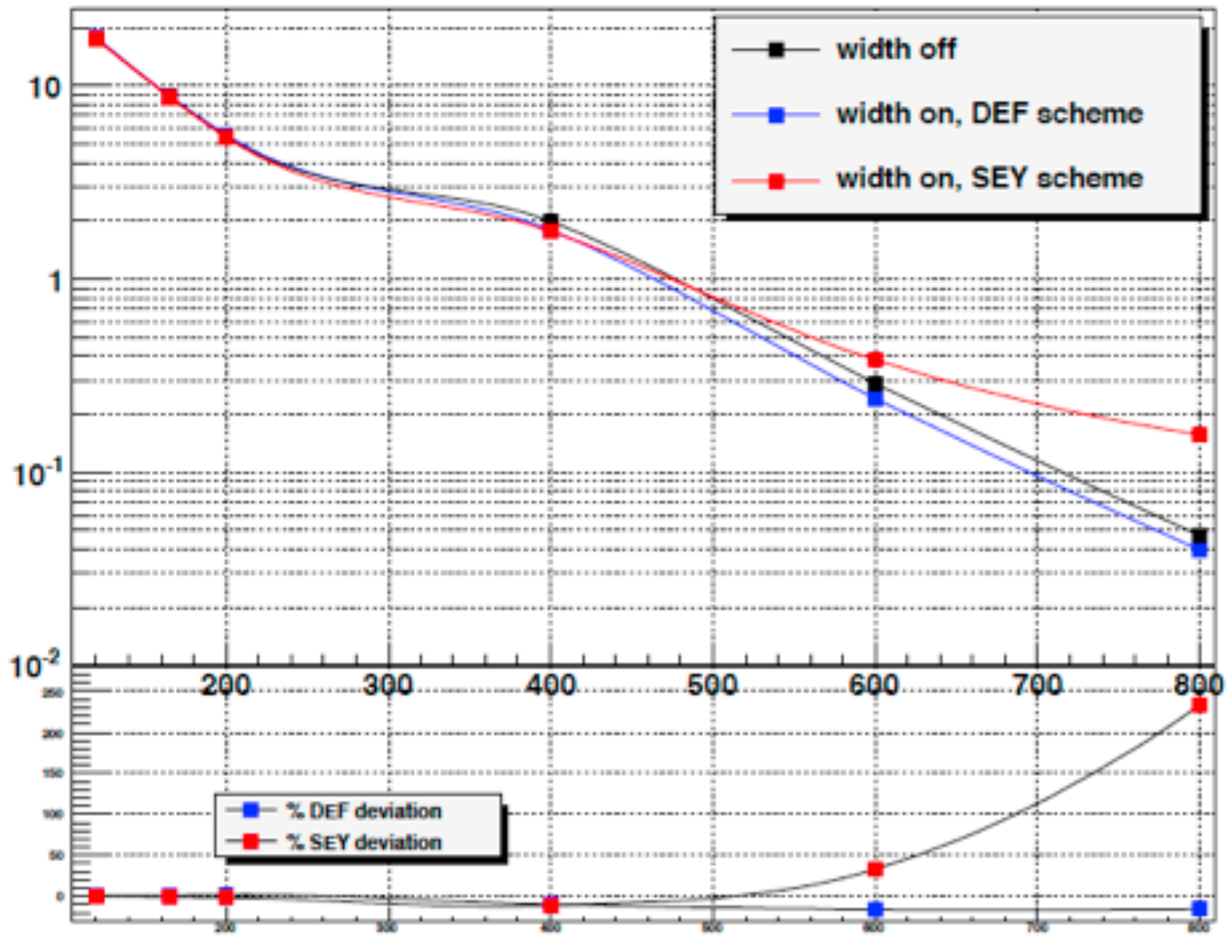
- This can be used as a diagnostic tool for cases when the signal-background interference becomes important.

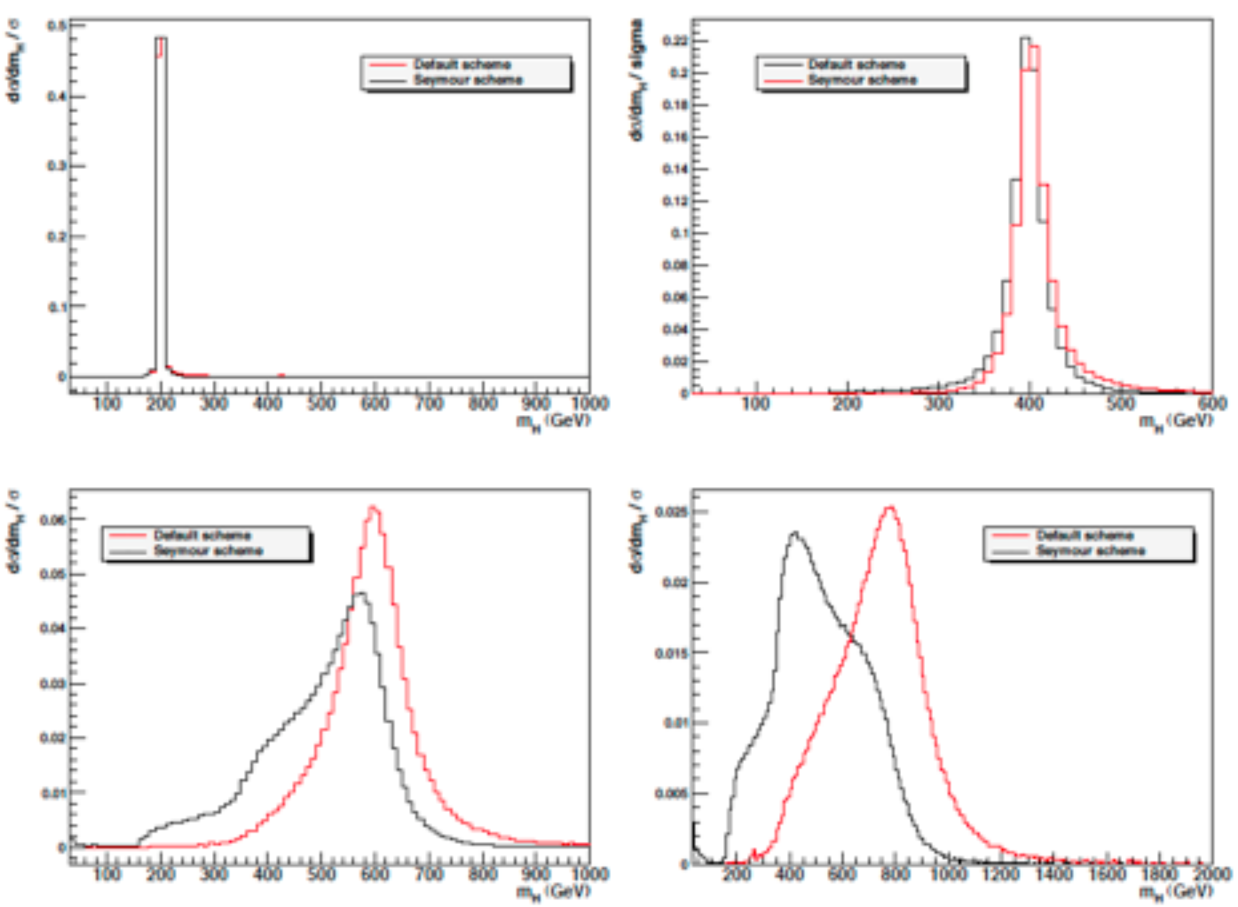
$$\frac{i}{\hat{s}-m_H^2} \to \frac{i\frac{m_H^2}{\hat{s}}}{\hat{s}-m_H^2+i\Gamma_H(m_H^2)\frac{\hat{s}}{m_H}}.$$

$$\hat{\sigma}_{ij\to\{H_{\rm final}\}+X}(\hat{s},\mu_f) = \int_{y_a}^{y_b} dy \frac{Q\Gamma_H(Q)}{m_H\Gamma(m_H)}\hat{\sigma}_{ij\to H}(\hat{s},Q^2,\mu_f)\mathrm{Br}_{H\to\{H_{\rm final}\}}(Q) \times f_{\rm seym}(Q,m_H),$$

$$f_{seym}(Q^2,m_H^2) \equiv \frac{m_H^4}{Q^4}\frac{\left(1-\frac{Q^2}{m_H^2}\right)^2+\delta^2}{\left(1-\frac{Q^2}{m_H^2}\right)^2+\delta^2\frac{Q^4}{m_H^4}}$$

Heavy Higgs: lineshape and BW





Heavy Higgs: lineshape and BW

- The problem of signal-background interference could be partly constrained with a restriction in the invariant mass of the Higgs boson in searches where this is possible, i.e the ZZ channel.
- However, due to the broadness of the Higgs resonance, a significant part of the signal is lost this way. Acceptances should then be estimated accordingly.

m_H	Γ_H	δQ	σ^{DEF}	$\sigma^{DEF;w}$	σ^{SEY}	$\sigma^{SEY;w}$
120	0.0038	5	17.66	17.56	17.57	17.56
165	0.2432	5	8.874	8.62	8.735	8.62
200	1.43	8	5.566	5.14	5.390	5.14
400	29.5	34	1.799	1.448	1.766	1.447
600	122	110	0.2409	0.1928	0.3819	0.2305
800	301	300	0.03982	0.03451	0.15683	0.07510

Heavy Higgs: lineshape and BW

- Interference effects can be non-negligible also in low masses: see paper by Campbell, Ellis, Williams 1107.5569
- A realistic study of interference effects from gg->WW
- The result is a 10% difference in the LO cross section for light Higgs (if cuts on the transverse mass are not applied)!
- Unfortunately higher order interference remains unknown (gg->WW at NLO is already at two loops).
- Unclear whether it is over- or under- conservative to rescale the NNLO cross section with the LO rescaling factor, as proposed.

PART 2

The WW experience

ANASTASIOU, DISSERTORI, STOECKLI, 2007

σ(fb)	LO	NLO	NNLO
$\mu = \frac{M_h}{2}$	152.63 ± 0.06	270.61 ± 0.25	301.23 ± 1.19
$\mu = 2M_h$	103.89 ± 0.04	199.76 ± 0.17	255.06 ± 0.81

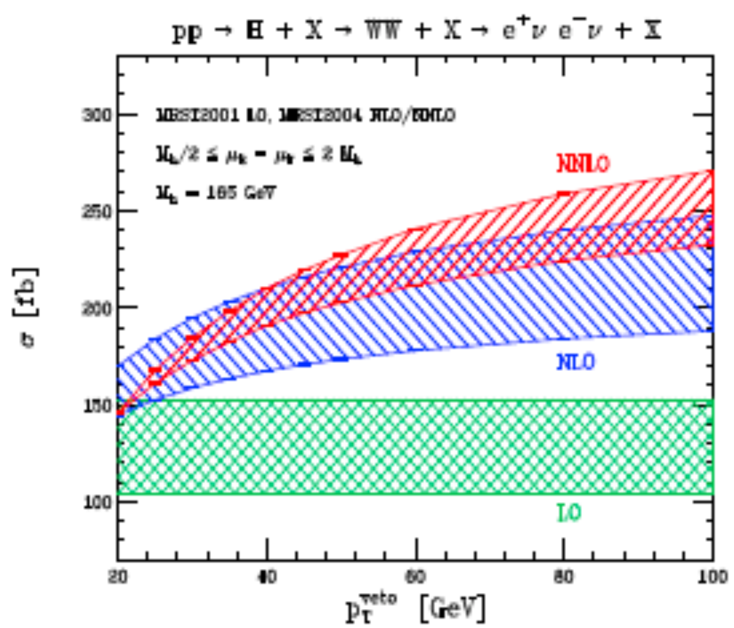
Table 1: The cross-section through NNLO with no experimental cuts applied.

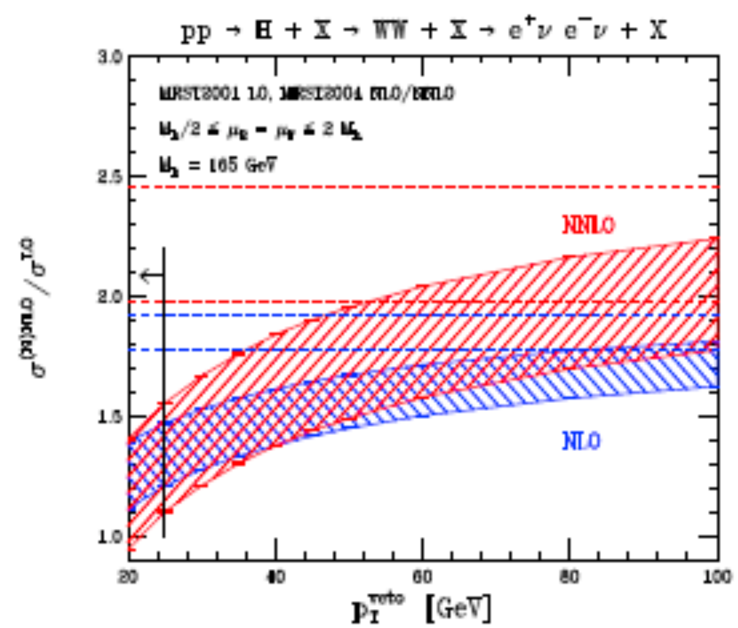
σ(fb)	LO	NLO	NNLO
$\mu = \frac{M_h}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = M_h$	17.413 ± 0.017	21.07 ± 0.11	18.75 ± 0.37
$\mu = 2M_h$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

Table 3: Cross-section through NNLO for the *signal cuts* of Section 3.

Before signal cuts

After signal cuts





Experimental cuts that discriminate signal from background might alter significantly the inclusive K-factors!

The WW experience

ANASTASIOU, DISSERTORI, STOECKLI, 2007

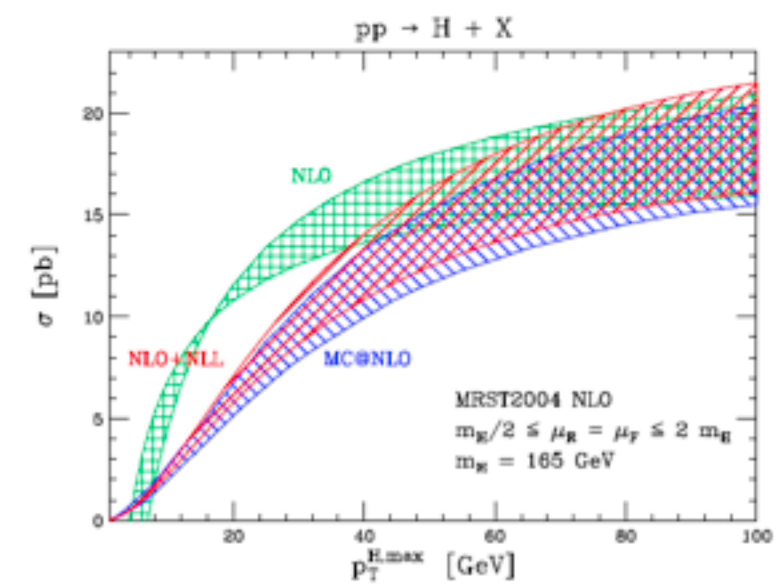
When rescaling parton showers with fixed order K-factors one needs to

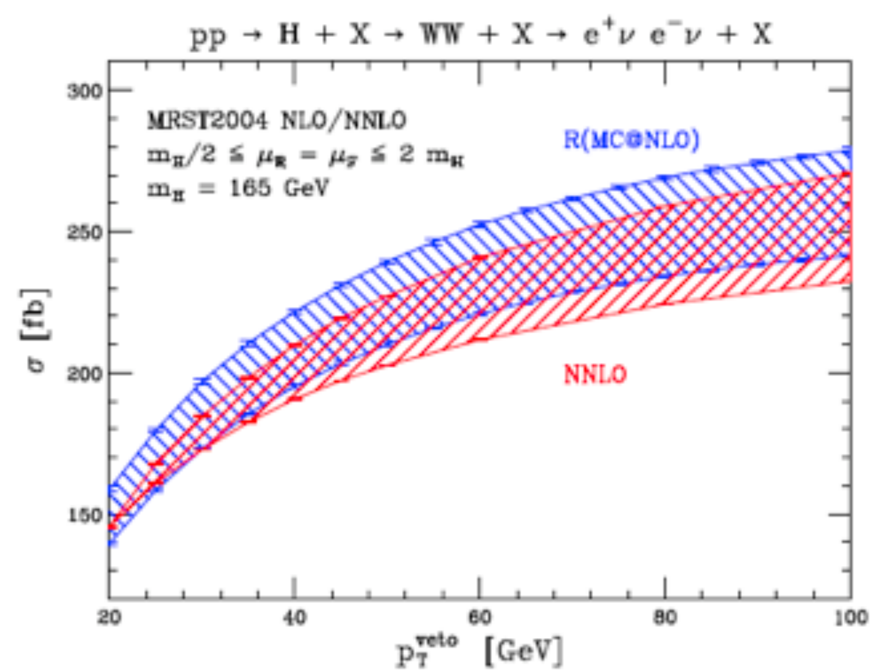
- calculate the K-factor with the experimental cuts applied, as opposed to using the inclusive K-factors.
- remember that fixed order LO has no extra jets and therefore 100% efficiency when a jet veto is applied, in contrast to a parton-shower.

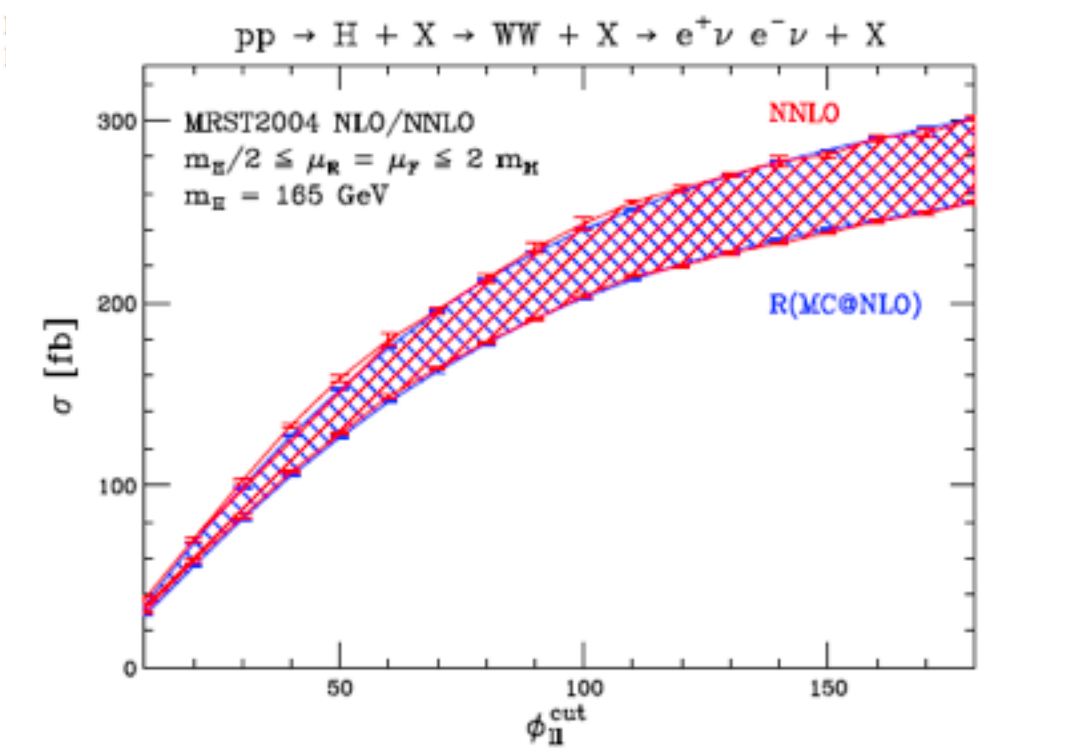
The WW experience

A series of studies (Anastasiou, Dissertori, Stoeckli, Webber, 2008) has shown that fixed order NNLO compares well with MC@NLO rescaled within the setup of the WW searches. This studies are now redone with the precise LHC set up.

The goal is to control as precisely as possible all sources of theoretical uncertainty.







Fully differential cross sections in ggF

For NNLO uncertainties on acceptances one has to use one of the two available tools below:

- HNNLO (Grazzini, Catani)
  - Heavy top limit, rescaled to exact LO
  - Includes H->ZZ -> eeμμ and H->ZZ->ee ee (with interferences)
- Fehip (Anastasiou, Melnikov, Petriello)
  - In the heavy top limit, rescaled to exact LO with tops.
  - semi-public code FeHiPro, that includes exact NLO mass dependence, all known EW effects, and improved HQEFT for NNLO. It also includes decays to H->ZZ->ee ee, H->ZZ -> eeμμ, as well as H->ZZ/WW -> llvv (although this interference is small).
- H->ZZ->llqq does not exist in any of the two codes.

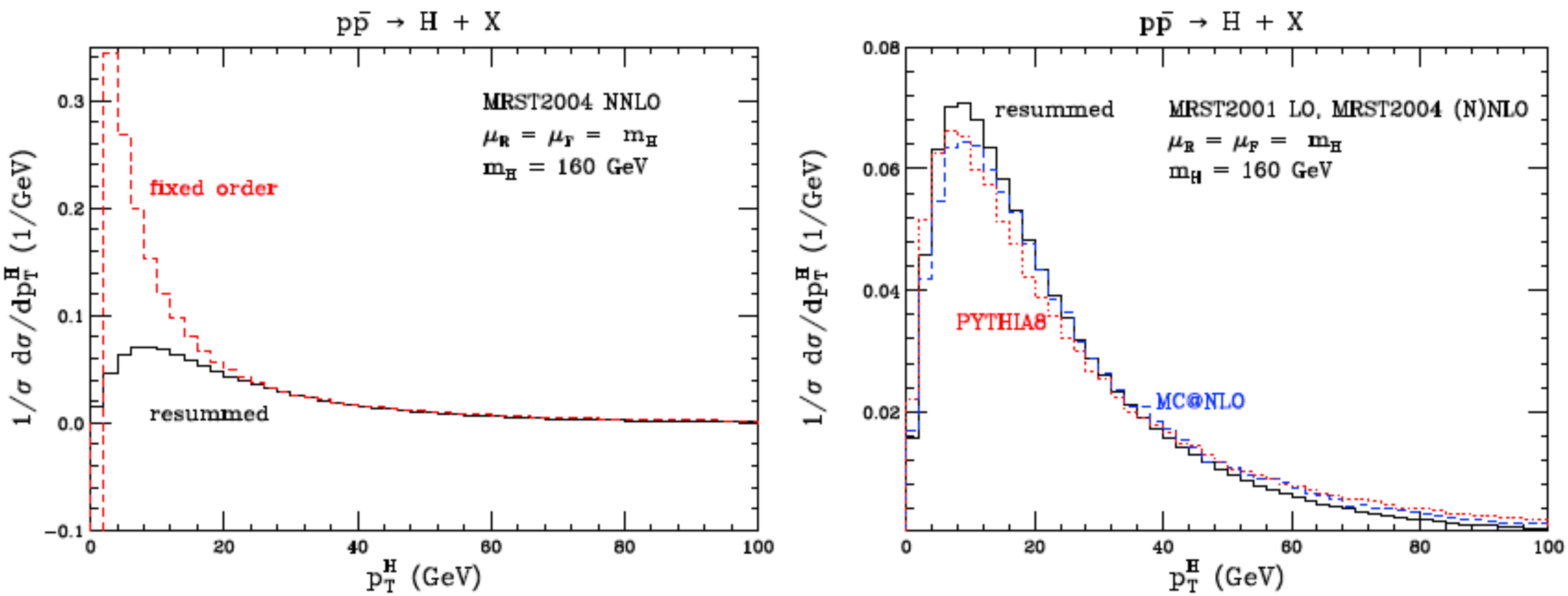
h->4f interferences

- Are included but only at LO in both HNNLO and FeHiPro.
- Also exist in Profecy4f, with NLO QCD and electroweak corrections.
- The effect of the latter is a few percent if the LO calculation is performed with a finite width for the vector bosons.
- This is the case for both HNNLO and FeHiPro.
- However, an interesting study would be to see whether in fully differential distributions, with the experimental cuts of CMS/ATLAS the QCD+EW corrections are enhanced (as is the case in ggF production withthe EW corrections to H+j).

signal-background interference in h->ZZ

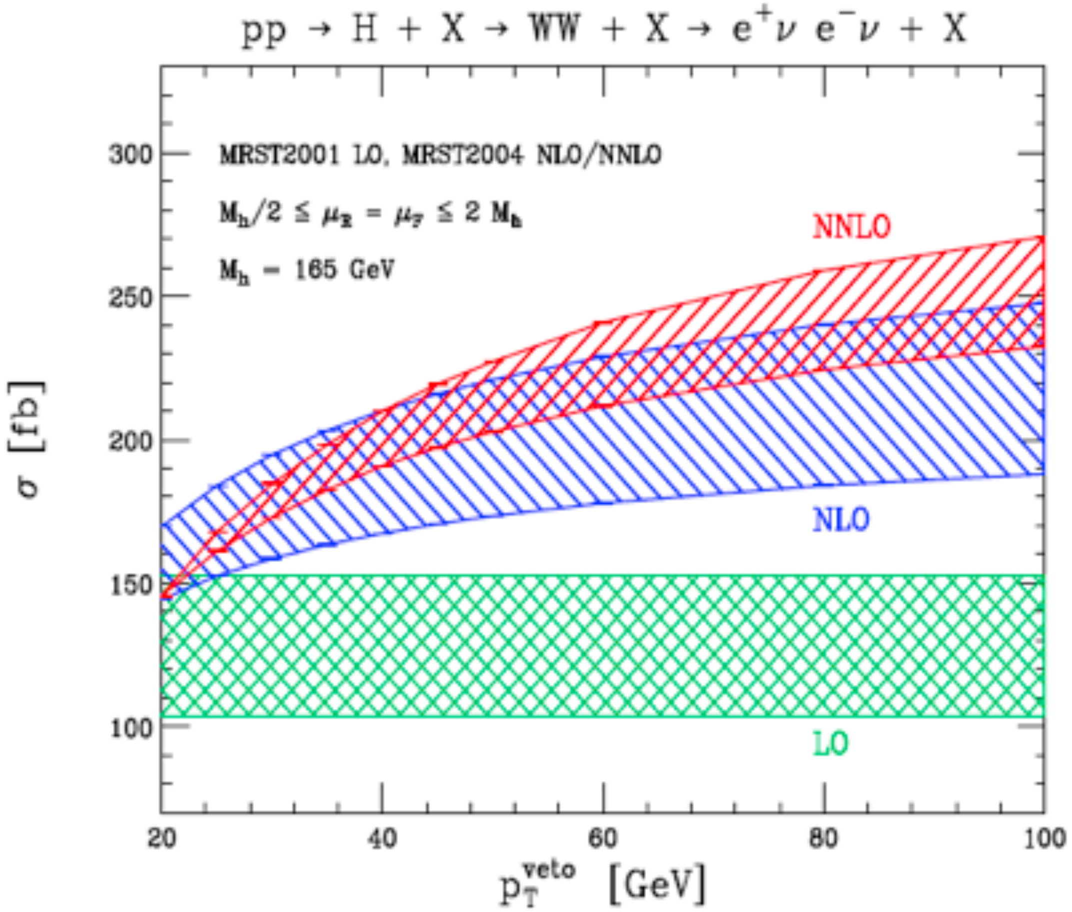
- There is a large increase to the qq channel in gluon fusion from qq->ZZ* signal background interference, but the qq channel is absolutely insignificant.
- It is entirely possible that gg->ZZ would also introduce an interference effect similar to that of gg->WW.

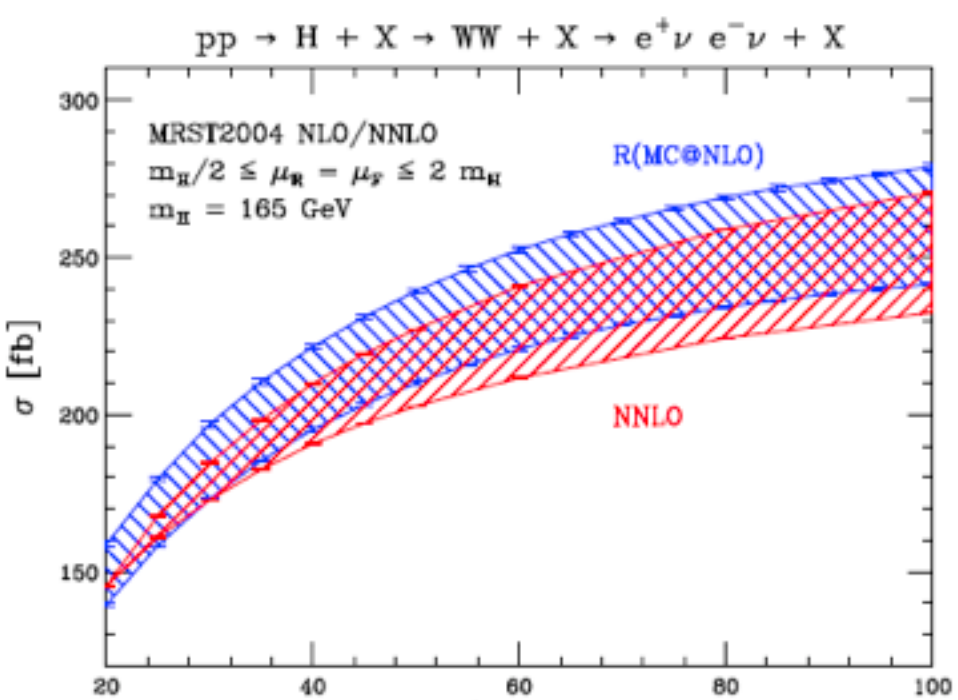
Higgs pT as discriminant



- Fixed order perturbation theory fails for pT < 20 GeV
- Resuming the soft gluon logarithmic contributions the distribution becomes smooth (see Catani, Grazzini).
- Parton showers (rescaled) agree with the resummed distribution.
- In the presence of jet vetos, one would need to resum soft gluon contributions also around the veto values.
- It is therefore best to either avoid pT as a discriminant, or use parton showers (MC@NLO) with the corresponding NLO uncertainty properly assigned.

Jet bin uncertainty





- Jet veto reduces drastically NNLO K-factors.
- This means that the bulk of NNL corrections come from hard real radiation.
- The logarithmic terms from soft gluon radiation are therefore likely to be small.
- It is reasonable to expect smaller uncertainties.
- But not vanishing ones! The vanishing of the scale uncertainty at 20 GeV is due to accidental cancellation.
- However, the central value of the jet veto acceptance is within the MC@NLO prediction and hence trustworthy.
- A more conservative estimate of the scale uncertainty, e.g. by varying the renormalization and factorization scale independently of each other, is the way to go.

The ZZ in the near future

- Intense collaboration between theorists and the experimental groups is desirable for both.
- That means detailed analysis of all kinematical distributions with the experimental cuts applied, both in NNLO fixed order Monte Carlos and in parton showers (that are eventually used in the analysis).
- It could also mean studies where multivariate analysis is interfaced with theory tools, like ANNs, BDTs or ME methods as discriminants.
- But the latter is only possible if we have access to the multivariate tools actually used by the experiments. This seems to be classified information currently.