The status of Higgs production cross sections

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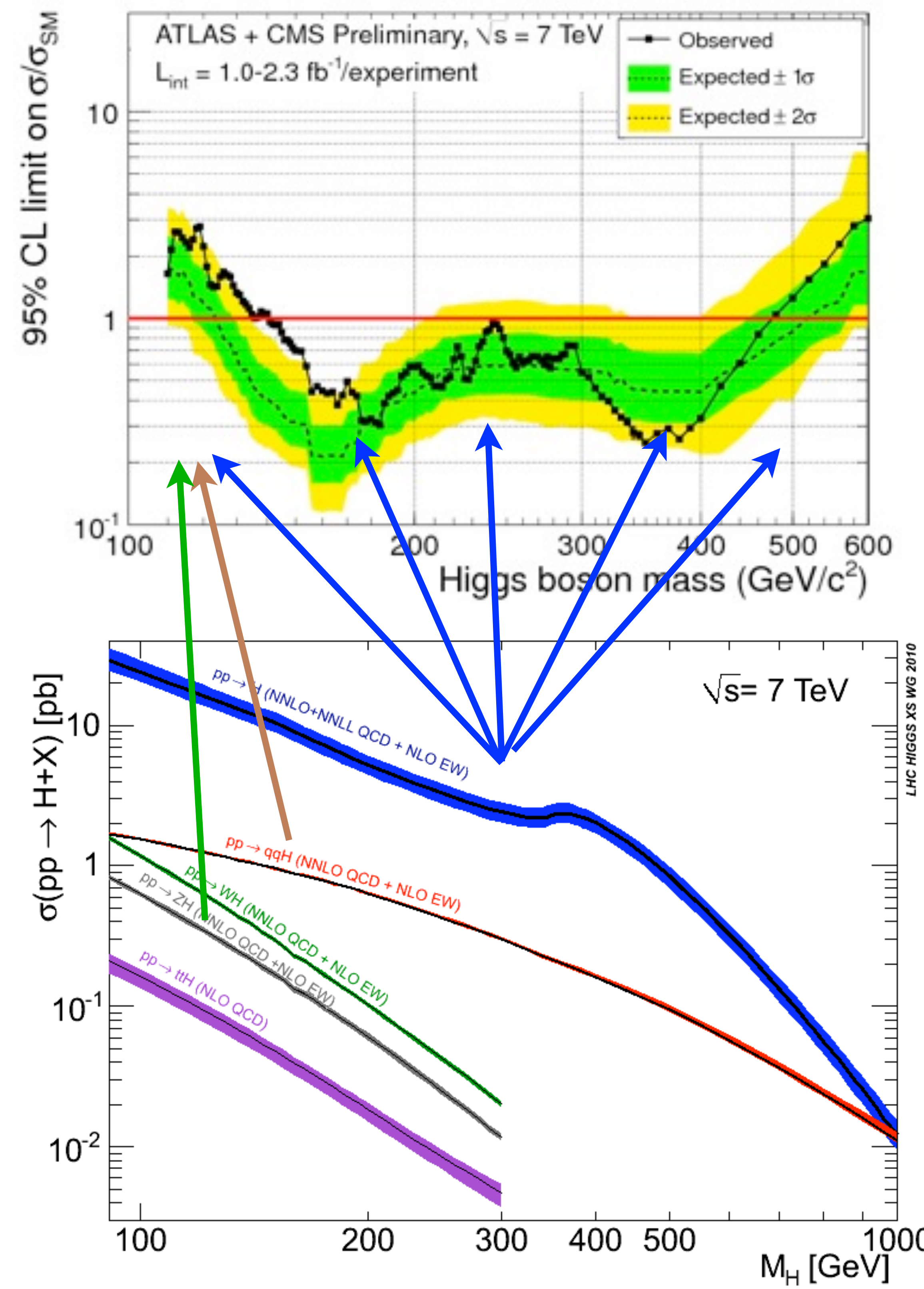
Introduction

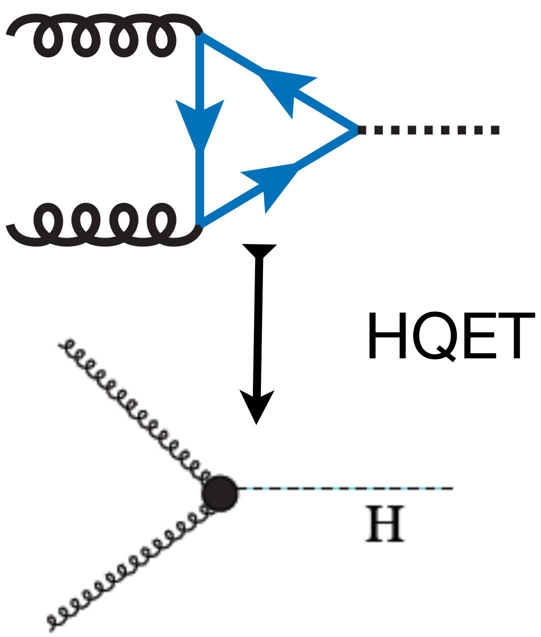
- The Higgs searches at the LHC are getting hot! The ‘thing’ must be around the corner!
- But they depend on theory input. How well do we know the production processes? What are the important signal observables and how well do we know them?
- Experiments use precise predictions on Higgs rates to reweigh the Monte Carlos and estimate the theory uncertainties.



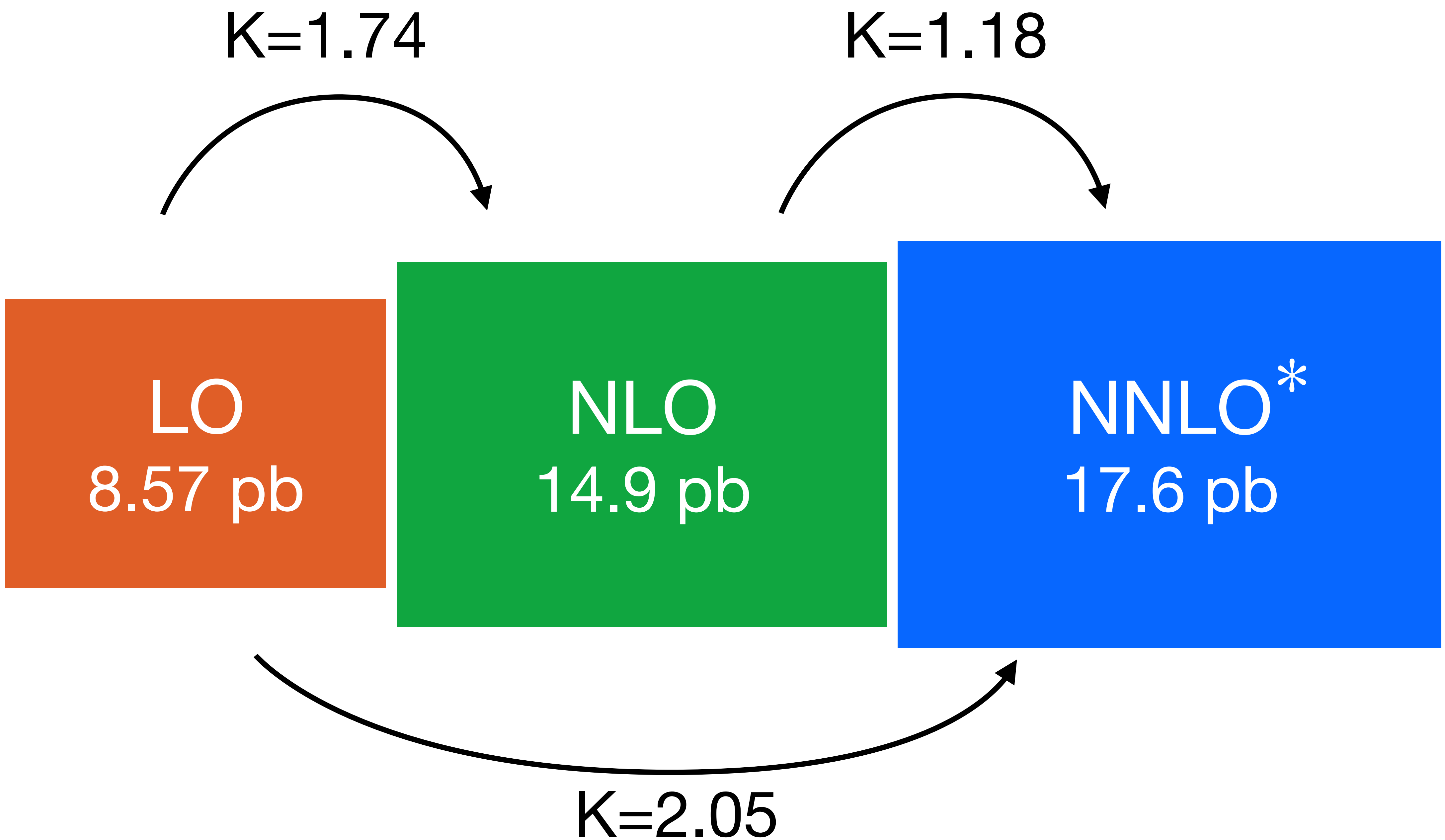
Gluon Fusion

Gluon fusion

- Inclusive cross section: a puzzle with many pieces, the result of the combined effort of many, many theorists for more than two decades.
- We now know:
  - NLO QCD corrections (exact, including top-bottom interference)
  - NNLO QCD corrections (in HQET),
  - subleading terms in the 1/m-top expansion
  - EW corrections
  - mixed QCD EW corrections
  - resummation to NNLL
  - soft terms from NNNLO.
- toolkit: mc@nlo, powheg (now with all mass effects retained at NLO, see Bagnaschi et al. 1111.2854), higlu, ihixs, HqT, HNNLO, Fehip.



Gluon fusion: basic numbers

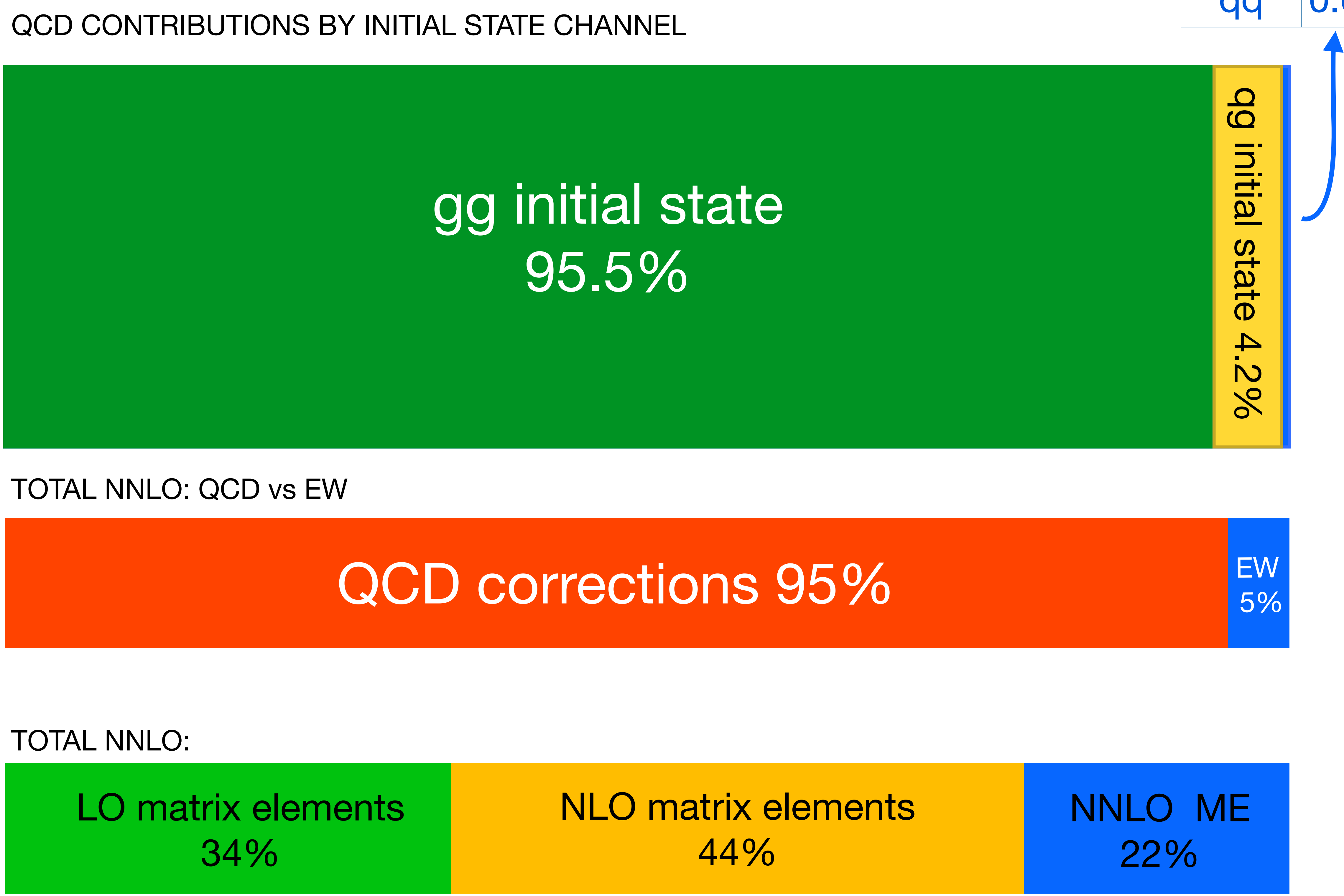


*NNLO is in the HQET, rescaled with the exact LO cross-section i.e. it doesn’t contain top-bottom interference. But this effect is estimated by the scale uncertainty.

@m_H=120 GeV

Gluon fusion: basic numbers

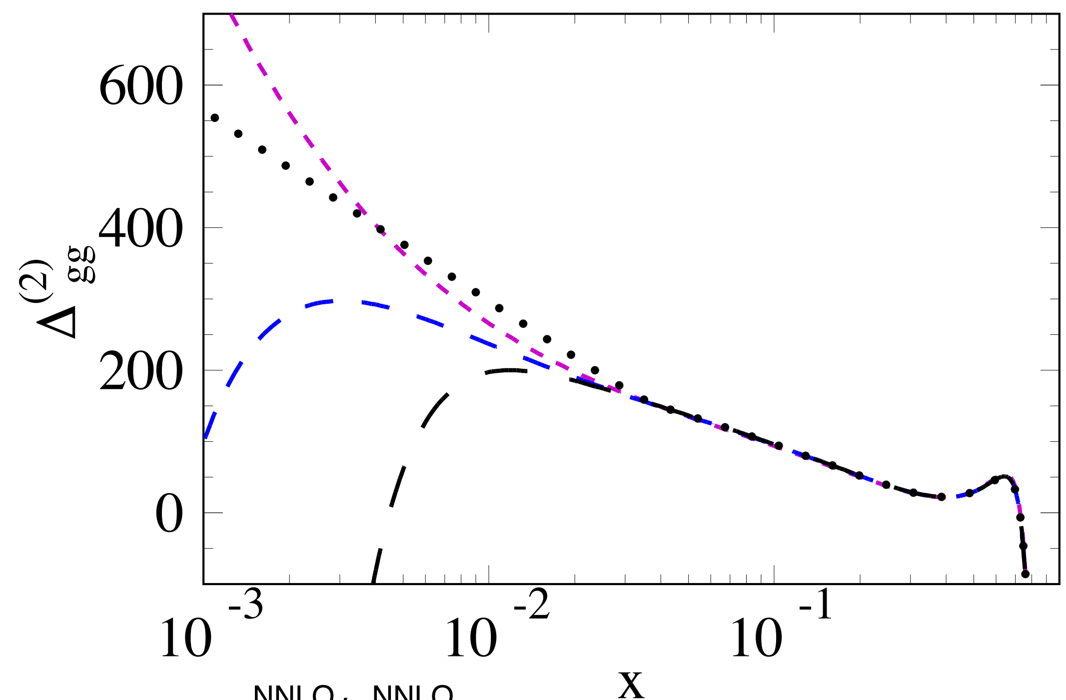
qq	0.16%
qq’	0.1%
qq	0.04%



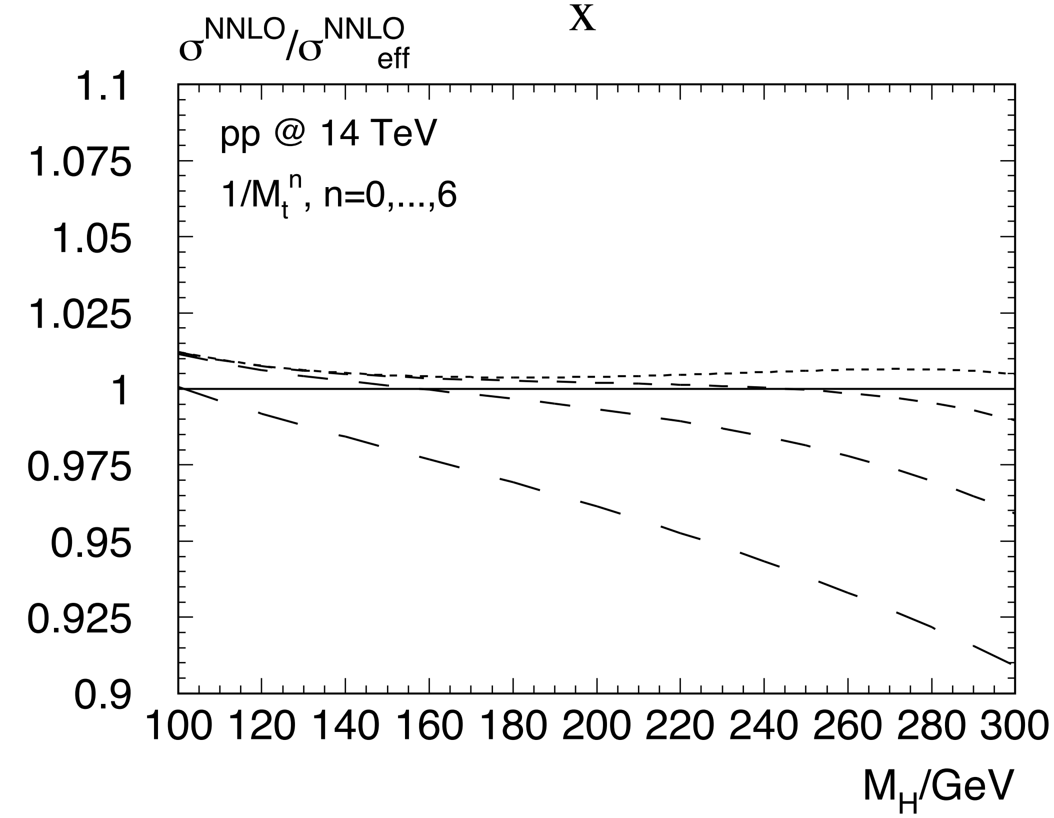
@m_H=120 GeV

Is HQET a valid approximation?

- The matrix elements within the HQET approximation have the wrong asymptotic behavior at the high energy limit. Marzani et al, 2008
- However it remains a very good approximation for low Higgs masses [100,300] GeV, because of the suppression of such kinematics by the PDFs.
- Two independent studies indicate that the uncertainty introduced due to the approximation is below the 1% limit for the low mass region. see Harlander et al. 2009-2010, Steinhauser et al. 2009.



Steinhauser et al. 2009



Harlander et al. 2009-2010

Resummed and soft contributions

- NNLL resummation adds aditional contributions. see Catani et al. 2003.
- Soft terms at NNNLO (gg initial state) have been calculated, in HQET, based on three-loop splitting function result. see Moch and Vogt 2005, Laenen and Magnea 2005
- SCET-type resummation by Ahrens et al. 0809.4283, results in very small scale uncertainty (~3%)
- Effects of NNLL fully simulated in fixed order NNLO with a low central scale.
- But to estimate the uncertainty of missing pieces by varying the scale on predictions that include higher order soft terms might be too optimistic.

LHC@14

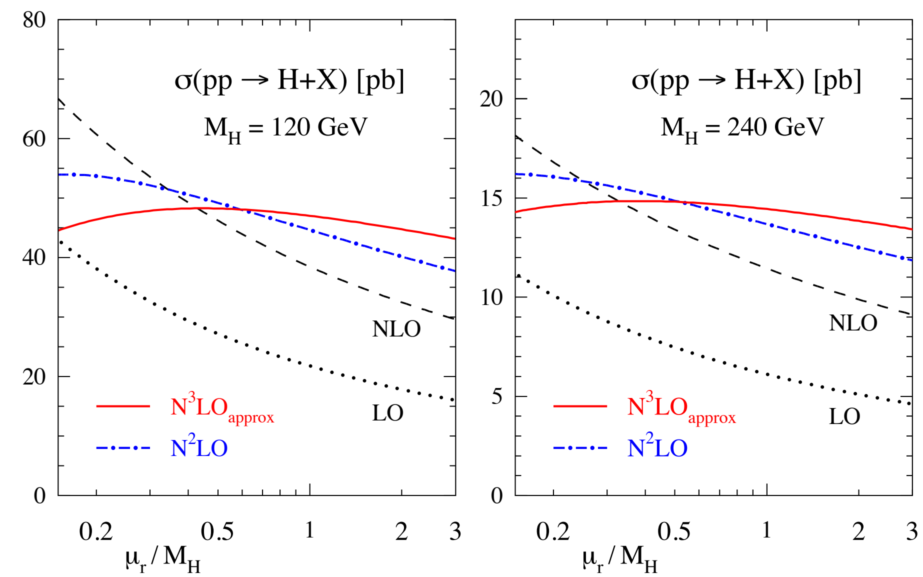
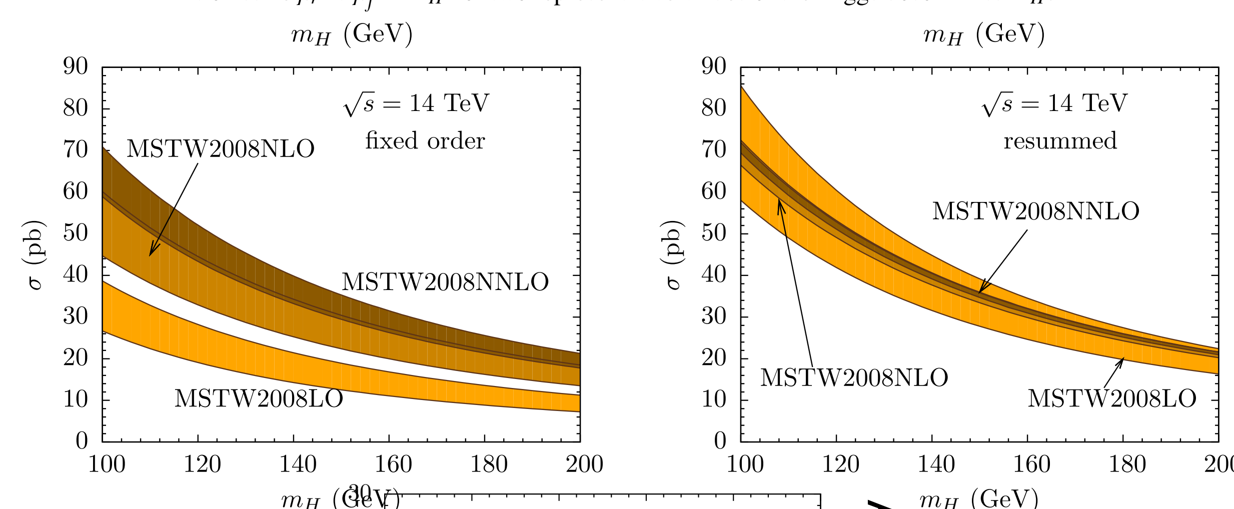
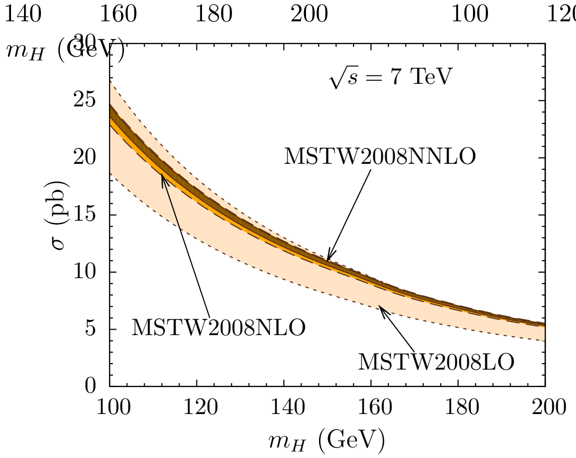


Figure 2: The dependence of the fixed-order predictions for the LHC cross section on the renormalization scale μ_r at $\mu_f = M_H$ for two representative values of the Higgs boson mass M_H.

Moch and Vogt 2005



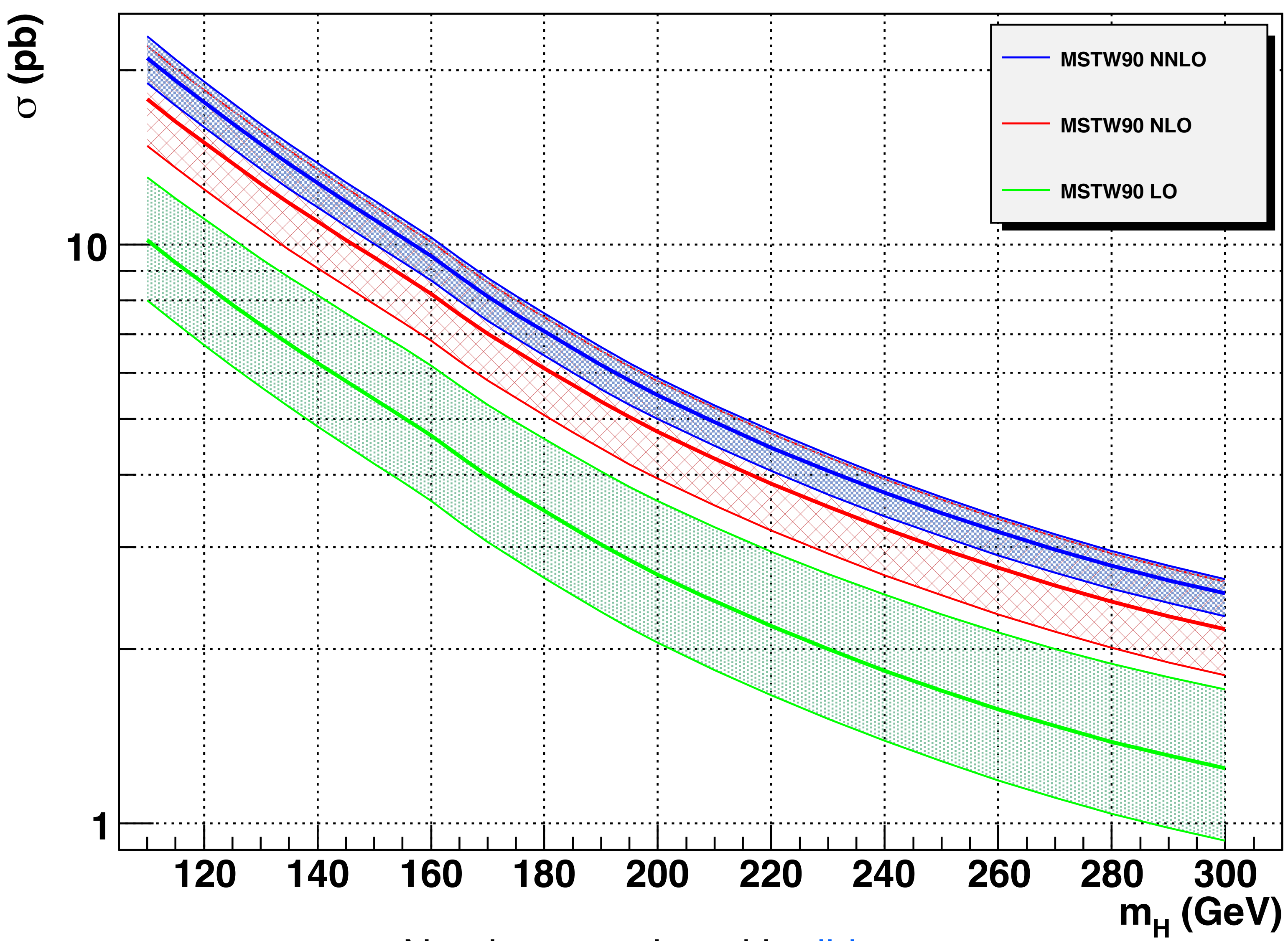
Ahrens et al. 2008



Ahrens et al. 2010

Scale uncertainty

Scale uncertainty @120GeV: +8.63%, -9.5%

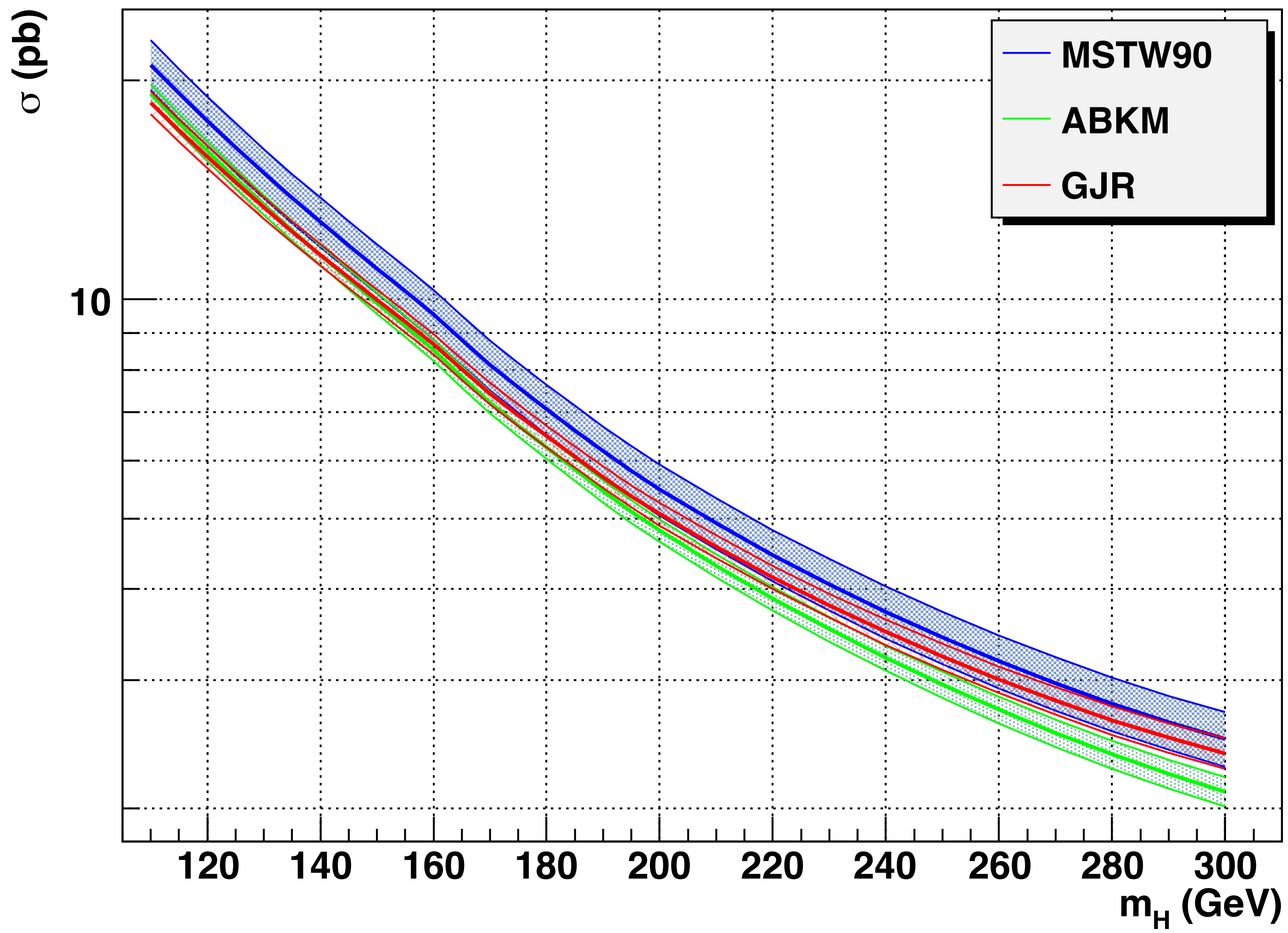


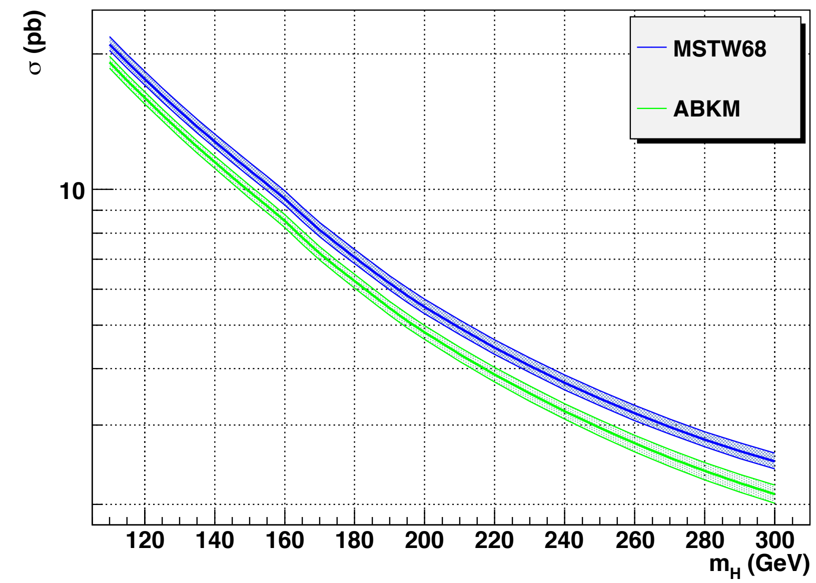
Numbers produced by ihixs
see Anastasiou, Buehler, Herzog, AL 1107.0683

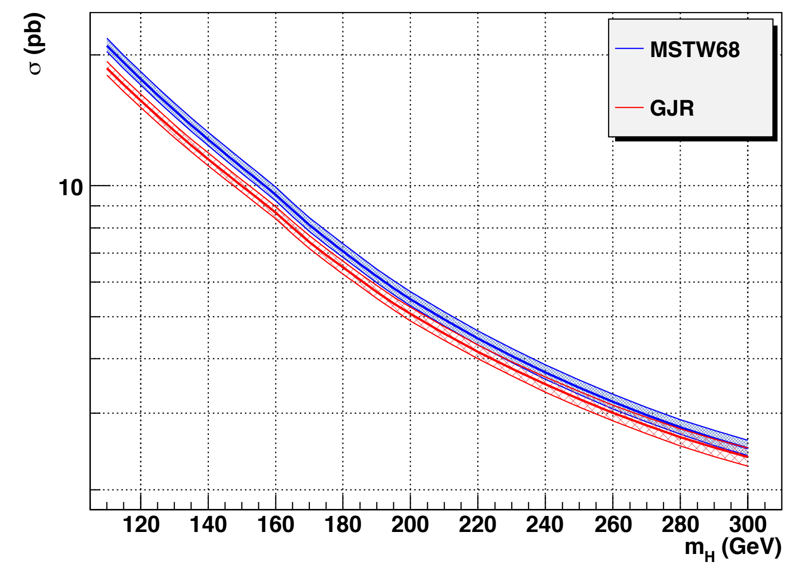
m_H	$\sigma(pb)$	$\%\delta^+_{PDF}$	$\%\delta^-_{PDF}$	$\%\delta^-_{\mu_F}$	$\%\delta^+_{\mu_F}$
110.0	21.04	4.05	-3.1	8.95	-9.6
115.0	19.22	4.05	-3.11	8.78	-9.55
120.0	17.7	4.05	-3.11	8.63	-9.5
125.0	16.3	4.04	-3.12	8.48	-9.46
130.0	15.04	4.04	-3.12	8.35	-9.42
135.0	13.92	4.03	-3.14	8.23	-9.37
140.0	12.93	4.04	-3.15	8.12	-9.34
145.0	12.03	4.03	-3.16	8.0	-9.32
150.0	11.22	4.04	-3.17	7.89	-9.28
155.0	10.49	4.05	-3.18	7.8	-9.25
160.0	9.77	4.04	-3.2	7.7	-9.22
165.0	8.87	4.05	-3.22	7.65	-9.2
170.0	8.23	4.05	-3.24	7.58	-9.17
175.0	7.69	4.05	-3.26	7.51	-9.15
180.0	7.2	4.06	-3.28	7.43	-9.13
185.0	6.69	4.06	-3.29	7.37	-9.13
190.0	6.26	4.07	-3.31	7.31	-9.12
195.0	5.89	4.07	-3.34	7.24	-9.1
200.0	5.57	4.07	-3.36	7.19	-9.06
210.0	5.01	4.09	-3.39	7.06	-9.02
220.0	4.54	4.1	-3.44	6.92	-8.99
230.0	4.14	4.11	-3.48	6.79	-8.96
240.0	3.8	4.12	-3.53	6.68	-8.91
250.0	3.5	4.14	-3.56	6.57	-8.85
260.0	3.25	4.13	-3.6	6.44	-8.84
270.0	3.04	4.17	-3.65	6.3	-8.79
280.0	2.85	4.18	-3.69	6.18	-8.74
290.0	2.7	4.19	-3.73	6.04	-8.65
300.0	2.57	4.21	-3.78	5.89	-8.58

PDF uncertainty (including a_s)

PDF uncertainty @120GeV: +7.8%, -7.2%

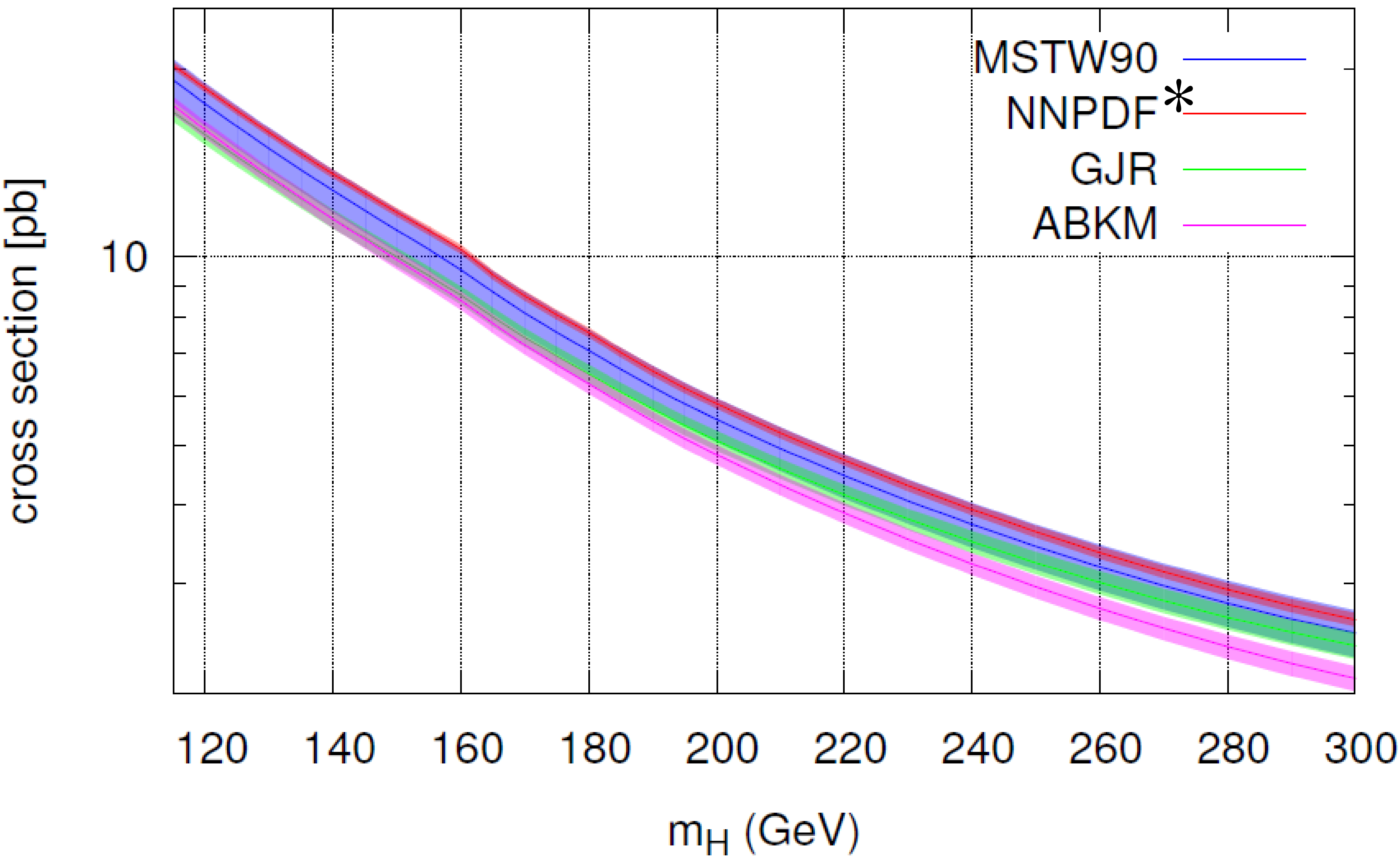






1-σ predictions using different PDF providers do not agree. Using MSTW90CL is a conservative choice that makes all bands (marginally) overlap.

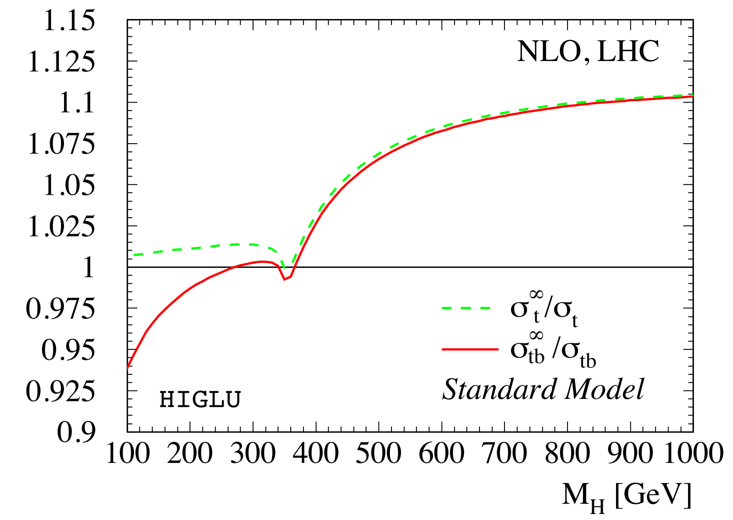
PDF uncertainties



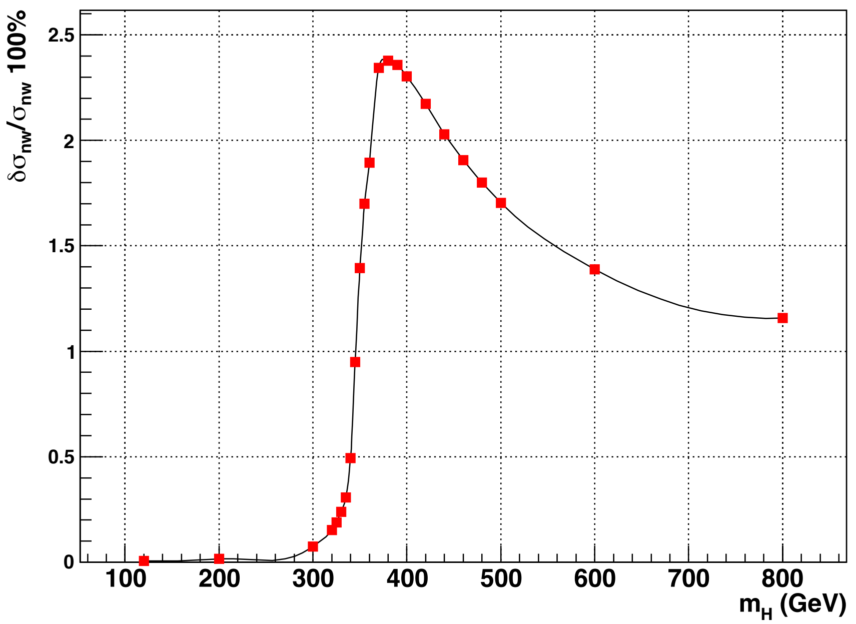
* NNPDFs uncertainty here doesn't include alpha strong variation

High mass cross sections (above 300)

- The HQET approximation is not guaranteed to be as good (but probably it is, it is better than 10% accurate at NLO, up to 1TeV)
- Top width effects rise to ~2-3%
- The narrow-resonance assumption is no longer good
- The signal+bg hypothesis includes signal-bg interference effects.
- They are only known to LO for H→WW decay channel in the low mass region (see Campbel, Ellis, Williams, 1107.5569). They can be up to -6% (@120) or +10%(@200 GeV) on the LO result, depending on cuts.



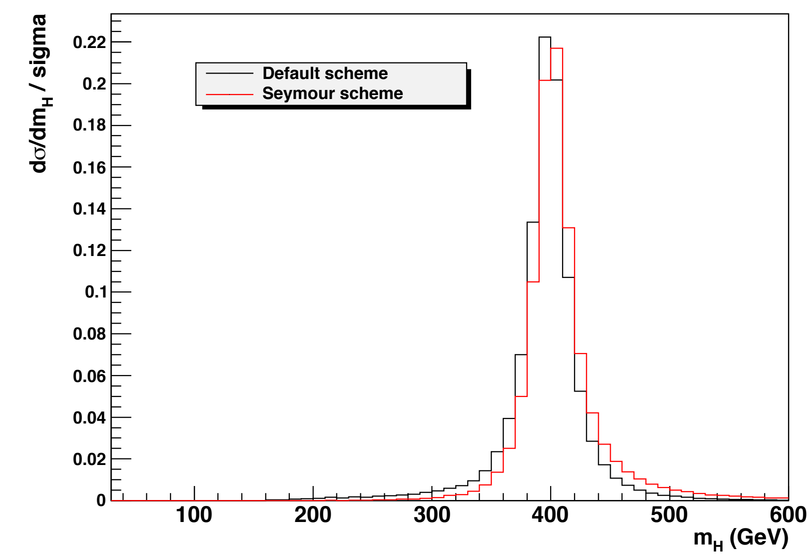
Harlander, 2003

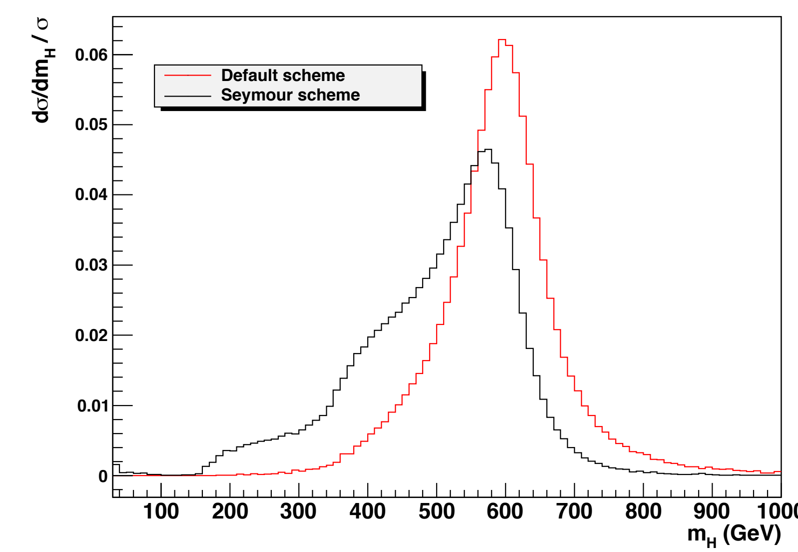


ihixs, 1107.0683

High mass cross sections (above 300)

- At high Higgs mass, the width of the Higgs becomes large.
- The zero width approximation ($\sigma_{production}$ x BR) is becoming increasingly bad.
- Moreover, the Higgs lineshape gets distorted by signal-background interference effects.
- These affect the cross section in a way we don't fully understand yet.
- There seems to be a tendency to neglect the problem both from experiments and from theorists.





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

Gluon fusion: beyond the SM

- Gluon fusion is sensitive to the presence of heavy colored particles that can circulate in the production loop, enhancing the rate.
- In the SM with a 4th fermionic generation the Higgs production cross-section is enhanced by a factor of ~9: easy to exclude. See Anastasiou et al, 1003.4677, 1103.3645, 1107.0683
- In most Composite Higgs models the Higgs production cross section is modified via modifications to the Yukawa couplings. ihixs can provide NNLO accuracy within any such model. For an example see Furlan 1106.4024.

Gluon fusion: the pT distribution

- Necessary ingredient as a discriminant variable in many MVA analysis.
- Very important in searches that focus on boosted configurations.
- In powheg and mc@nlo it is a LO observable.
- Validation against NLL+NNLO showed that the mc@nlo and Herwig describe well the pT distribution.
- Unknown whether the HQET approximation used at NNLO is valid at the high pT bins (which do not influence the total cross section).

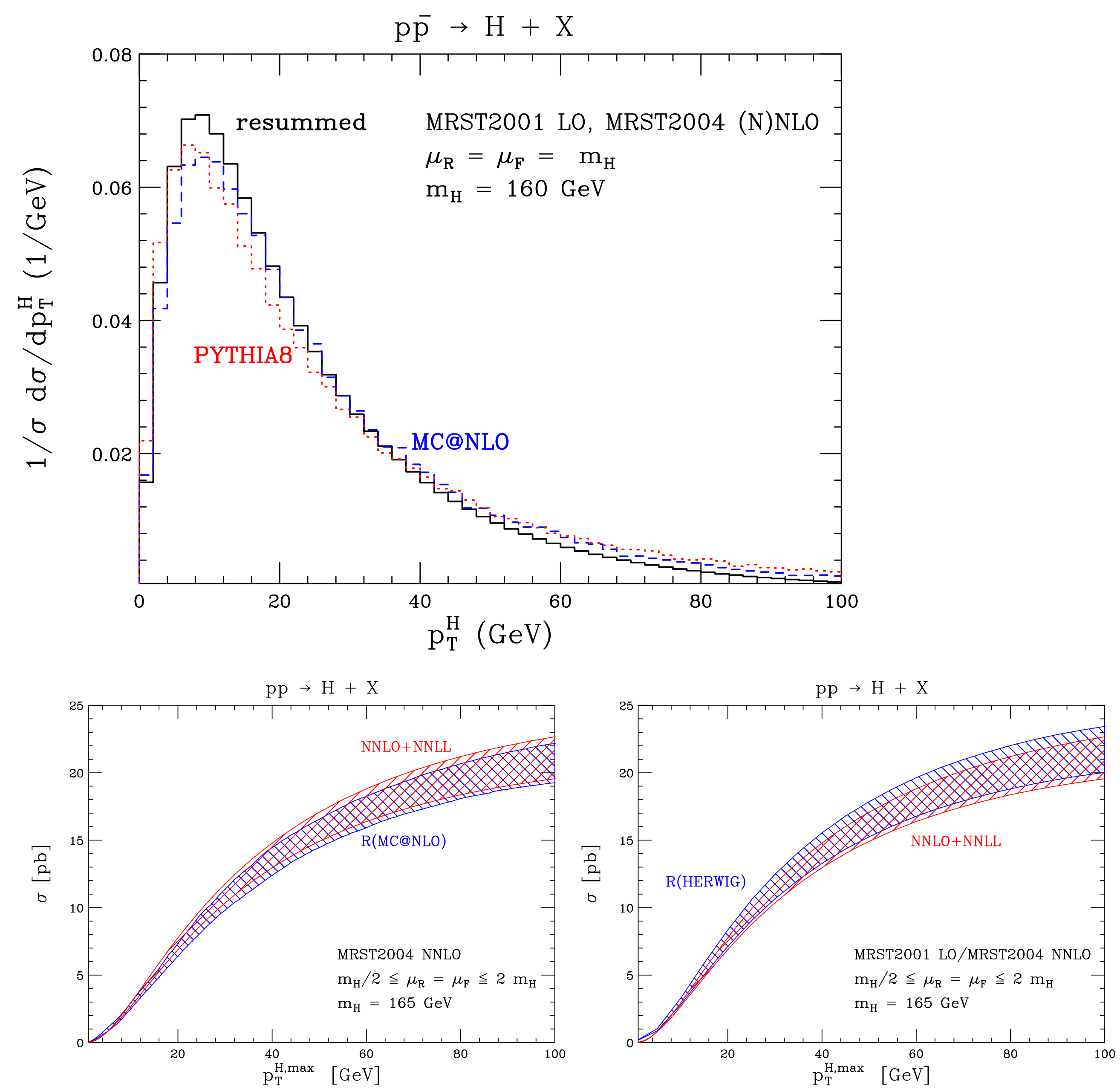
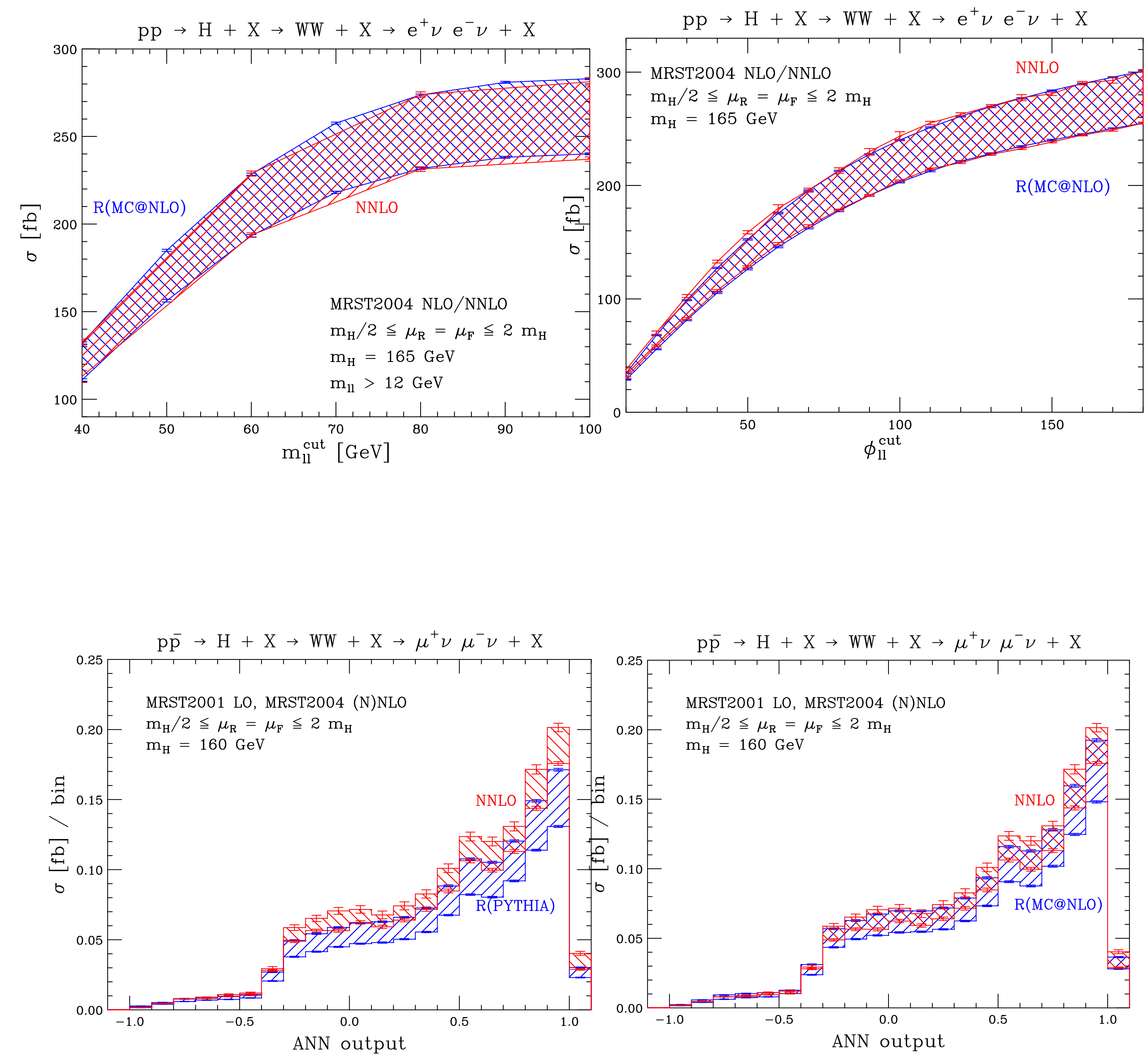


Figure 4: Cumulative cross-section for the Higgs transverse momentum distribution. The scaled MC@NLO and HERWIG spectra agree very well with the resummed NNLL spectrum [38].

Gluon fusion: other differential distributions

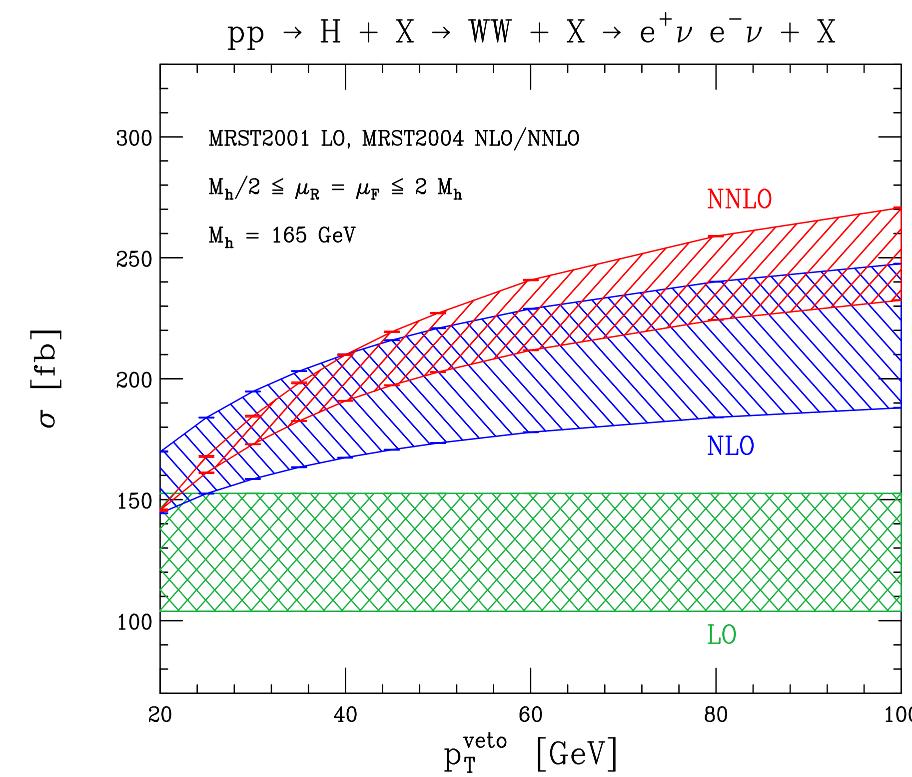
- Careful validation of Monte Carlo predictions for key differential distributions in a realistic experimental set-up has been achieved only for H→WW (see Anastasiou et al. 0801.2682) and earlier for H→γγ (Dissertori et al. hep-ph/0509130).
- The difference in the response of MVA tools between MCs and NNLO has only been explored in 0905.3529, for Tevatron.
- Producing the output of a trained ANN is no more difficult that any other distribution.



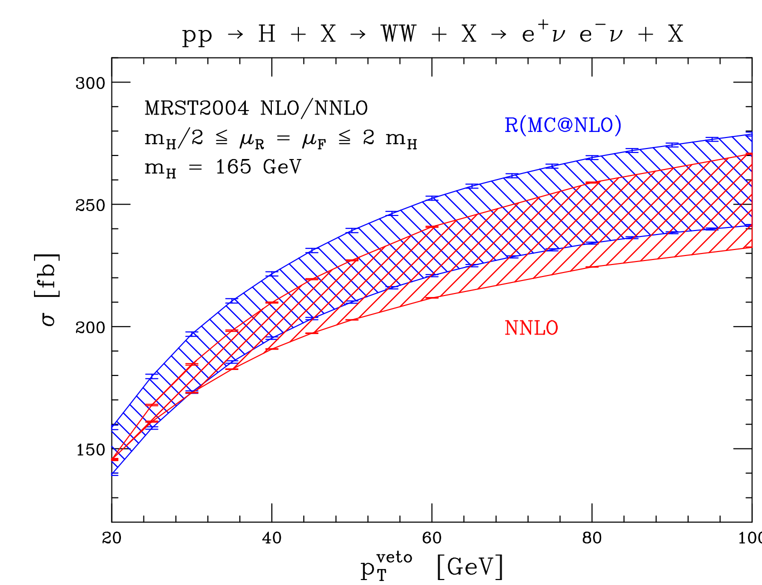
Anastasiou, Dissertori, Grazzini, Stoeckli, Weber 0905.3529 (for Tevatron)

Gluon fusion: jet bin uncertainties.

- It is useful to divide data in jet bins, when the background depends strongly on the number of jets. Done at H→WW, H→τ τ, H→bb in boosted configurations.
- The jet bins are defined by a ‘jet veto’: no further central jets with pT>p*.
- The presence of the veto affects the scale uncertainty.
- Worries have been raised that the fixed order prediction for the uncertainty might be artificially small.
- However, in the absence of resummation of soft gluon on the veto value, one can only estimate the uncertainty in fixed order and compare with parton showers (that resum those gluons naturally). In both fixed order and parton shower results the uncertainty on the *efficiency* is driven by that of the total cross section, i.e. the uncertainty on the 0-bin cross section is minimal.
- Allowing for unequal factorization and renormalization scales provides a slightly larger uncertainty (but still small).
- Other proposals include that of Stewart and Tackmann, where the uncertainty on the total cross section and the one with one or more jets in the presence of a veto, are considered uncorrelated. This implies that the pure uncertainty of the latter is dominated entirely by the presence of the veto, which is not fully justified. The procedure enlarges artificially the 0-bin uncertainty.



Anastasiou et al. 0707.2373 with Fehip



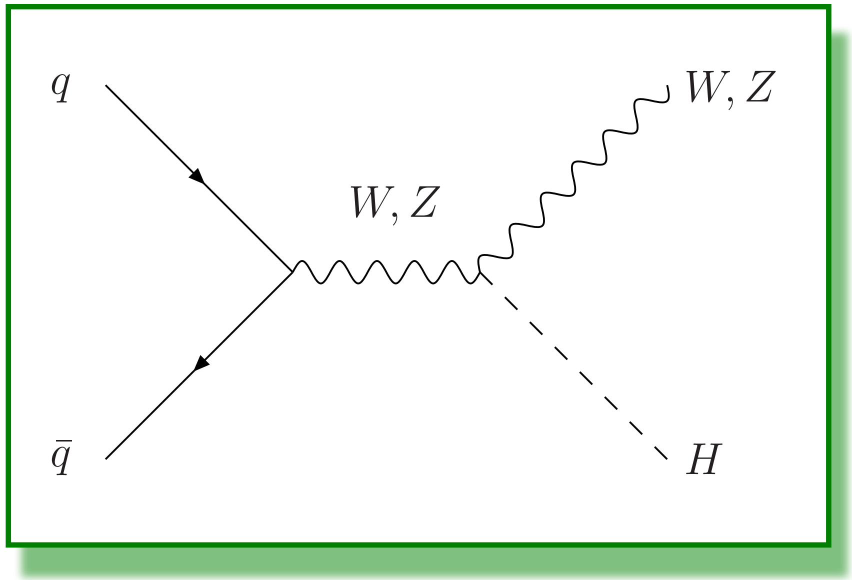
Anastasiou et al. 0801.2682

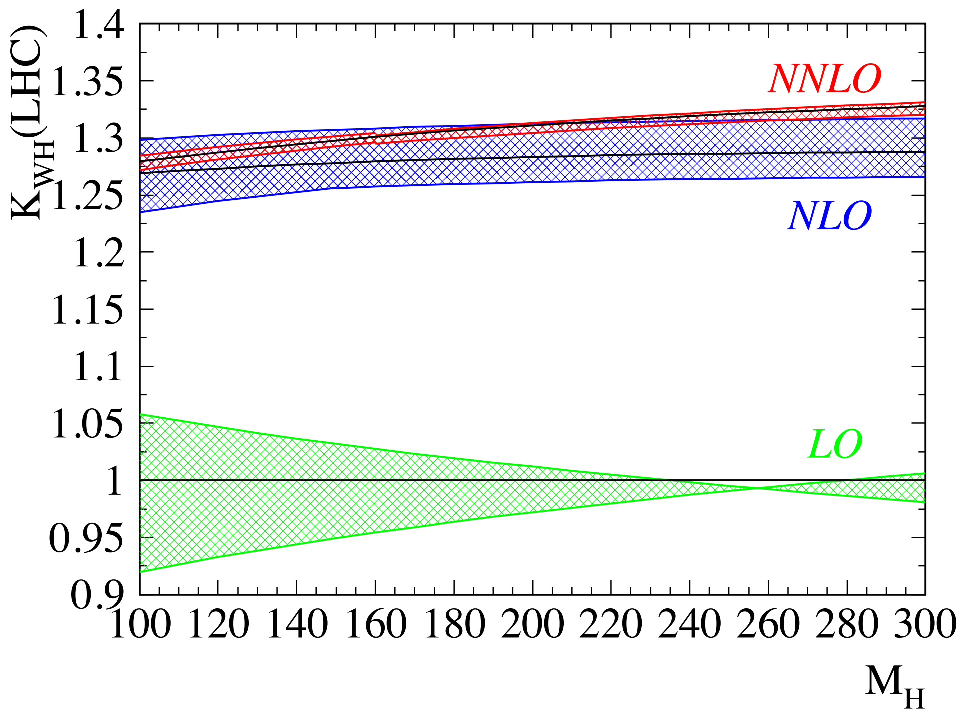
Figure 9: The Higgs production cross-section with a fixed-order computation (NNLO) and MC@NLO rescaled with an inclusive K-factor (R(MC@NLO)) when a veto on jets with $p_T > p_T^{\rm veto}$ at central rapidities $|\eta| < 2.5$ is applied.

Associated Production

Associated production

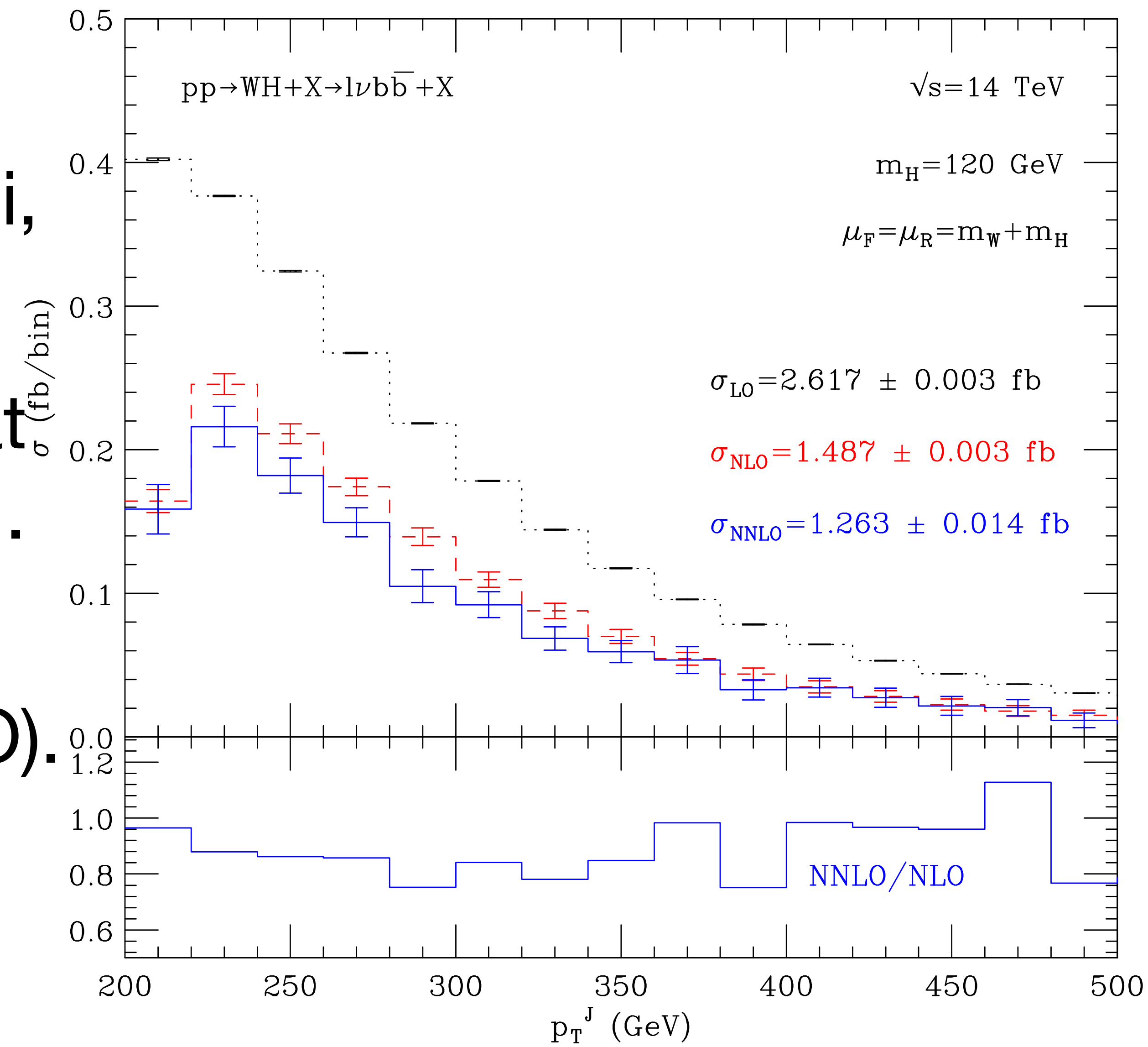
- Inclusive cross section known to NNLO. See Harlander, Djouadi, Brein, 2003
- Scale uncertainty reduced to ~3%
- K-factor: 1.27@NLO, 1.28@NNLO
- Very stable perturbative expansion.
- But was considered hopeless due to large backgrounds.
- The channel was resurrected by the boosted Higgs search strategy (see Butterworth et al, 2008) and is contributing to Higgs searches in the low mass region.
- main decay channel: the bbar.





Associated production

- The differential NNLO calculation to WH is now available. see Ferrera, Grazzini, Tramontano 1107.1164
- Ignoring box contributions that are expected to be small ~1%.
- With decays of W to leptons and of H to bottom quarks (LO).
- Following the cuts of the boosted search, including a veto on any additional jet with pT larger than 20GeV.

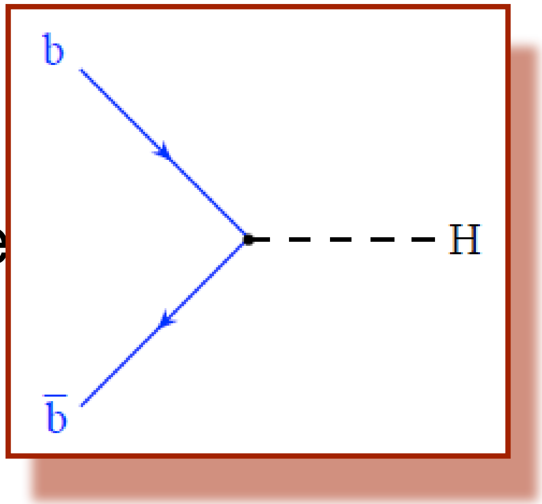


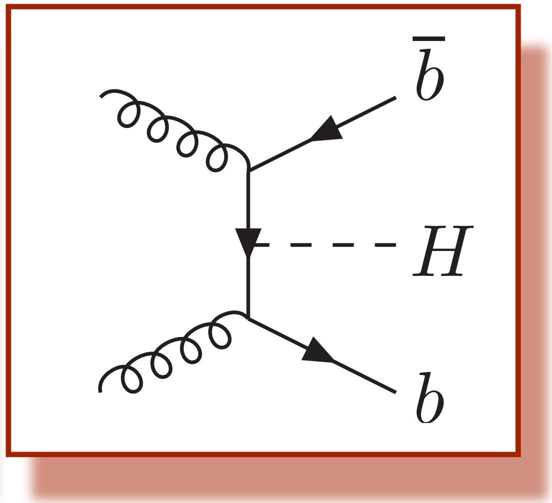
The reduction in the accepted cross section is due to the jet veto.

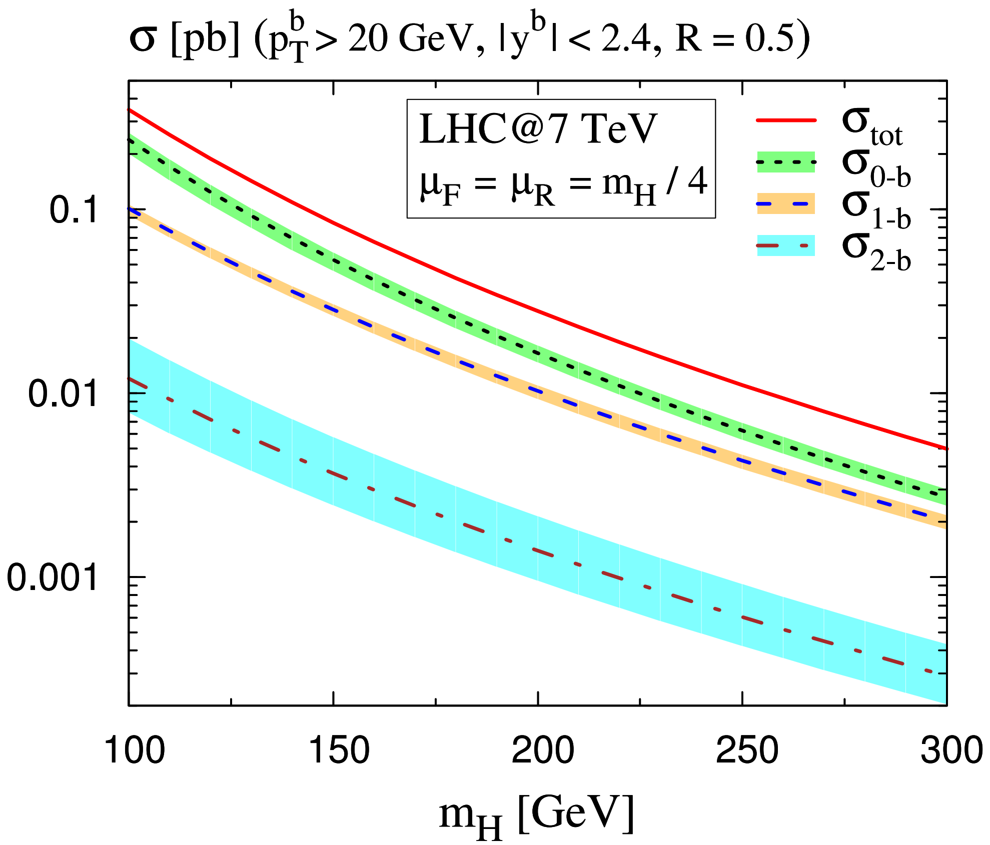
Bottom Annihilation

Bottom annihilation

- Indistinguishable from gluon fusion, but much smaller production rate (~1% of ggF).
- It could be enhanced in models with large bottom Yukawa.
- Inclusive cross section known to NNLO. See Harlander and Kilgore, hep-ph/0304035.
- Inclusive cross section available from bbh@nnlo (Harlander). Now also from ihixs (Anastasiou et al.) with arbitrary Yukawa couplings.
- First differential results: cross section for different jet bins. Harlander et al. 1111.2182

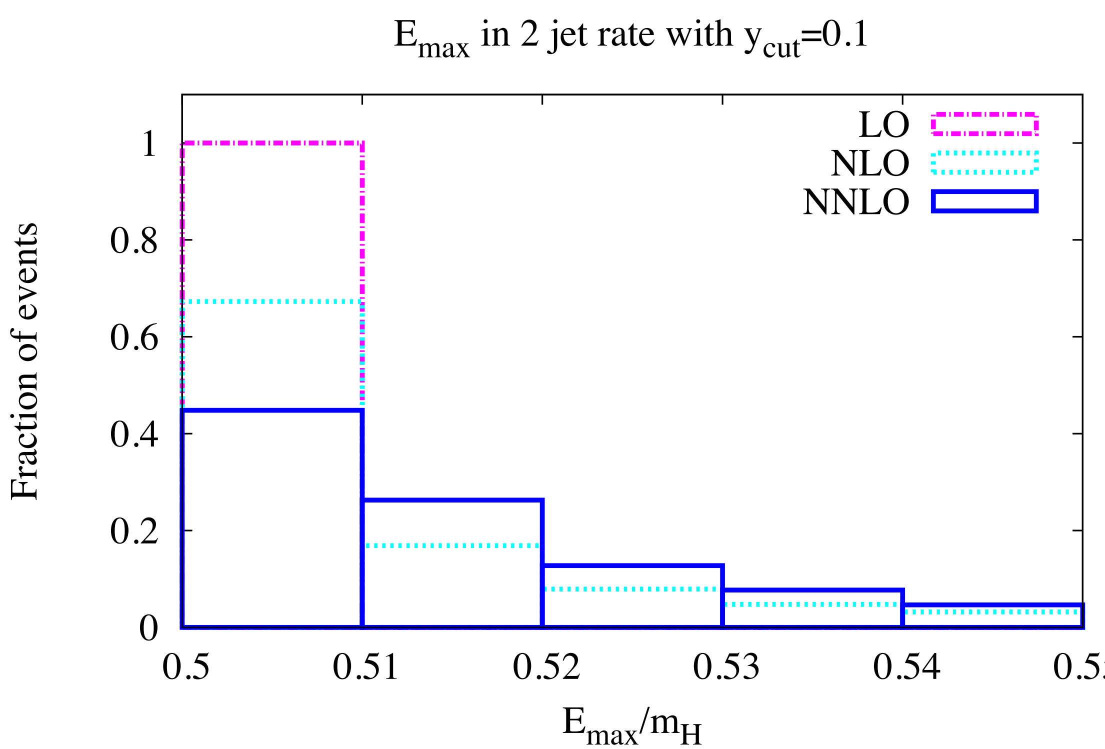






Bonus: the H→bb decay

- Useful for VH channel.
- Will, later on, give access to the bottom Yukawa coupling.
- Recently computed at differential NNLO using new subtraction technique. See Anastasiou, Herzog, AL 1110.2368
- Fully differential code will soon be available.
- Eager to combine it with differential calculation on VH.



The leading jet energy at the rest frame of H

conclusions / outlook

- We know pretty precisely the inclusive cross sections for all processes.
- The uncertainties from theory are still large for the all-important gluon fusion process (and it’s unlikely that they will shrink significantly anytime soon).
- There is still a lot to do in terms of differential quantities.
- Once the Higgs is (hopefully) found, we will still need to measure its properties and couplings. *That* is going to be a precision party!