Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Precise inclusive Higgs predictions using `iHixs`

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in collaboration with
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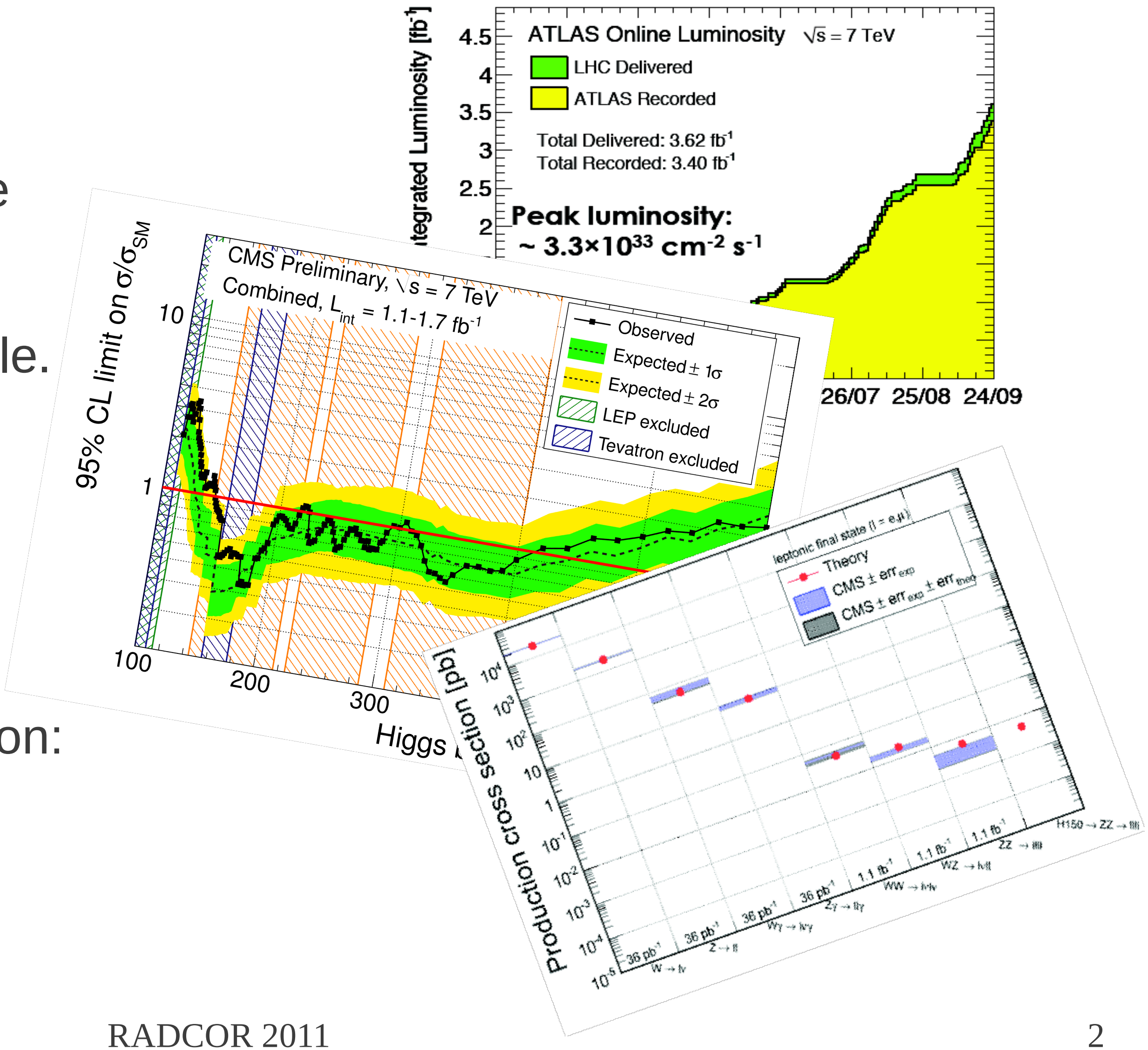
Mamallapuram, India

Motivation

- The LHC is operating impressively.
- Statistical uncertainties are improving and become comparable to theoretical uncertainties at the pb-scale.
- We need the best theory predictions we can get!

→ We tried to write to most complete code for inclusive single Higgs boson production:

iHixs



The `iHixs` code

- `iHixs` = "inclusive Higgs cross sections"
- Presented in arXiv:1107.0683
- Downloadable at

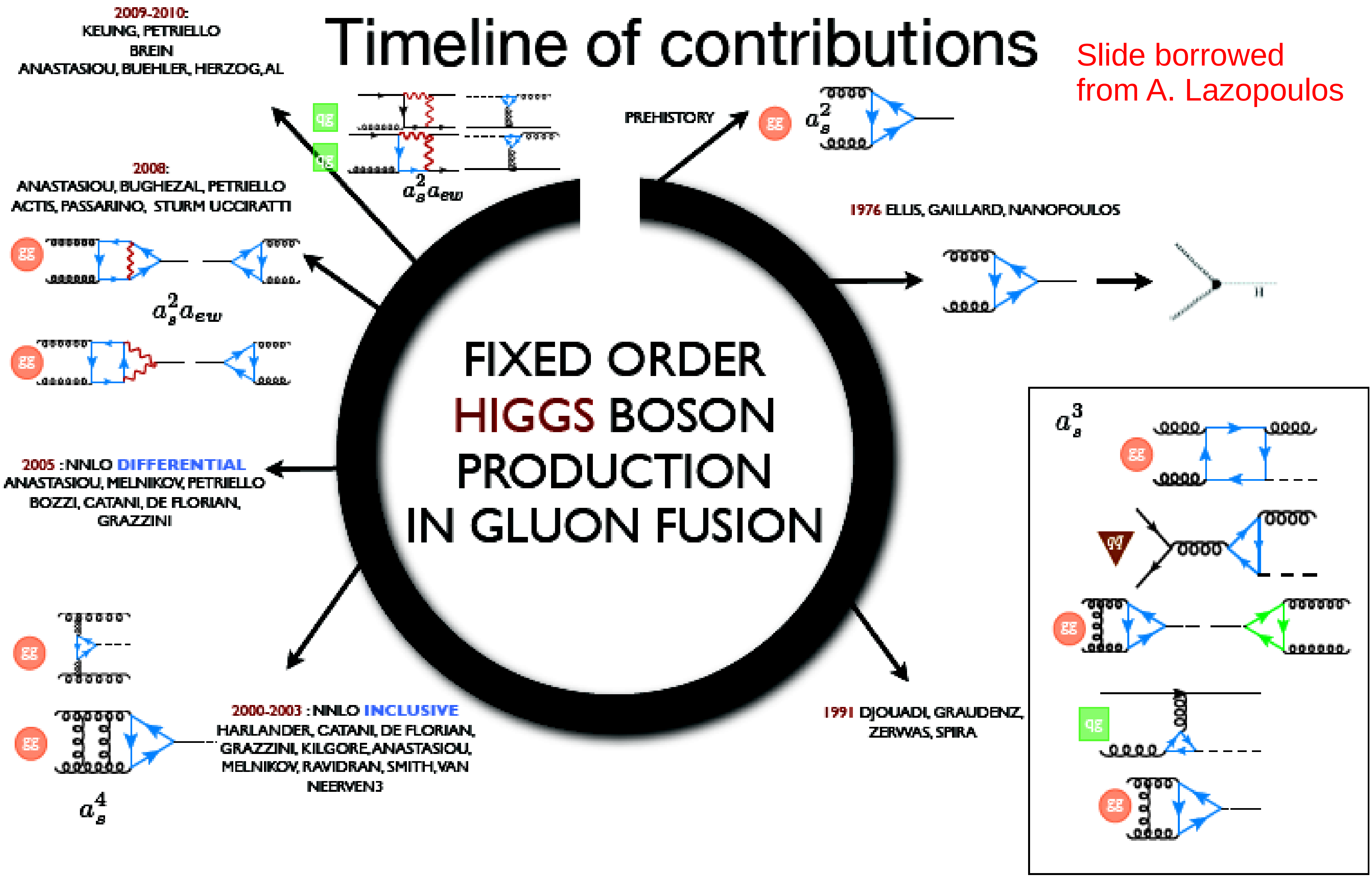
  http://www.phys.ethz.ch/~pheno/ihixs/

Features of the `iHixs` code

- Gluon fusion
- Bottom-quark fusion
- Higgs width effects
- Supports all NNLO PDF sets and calculates PDF uncertainties
- Extensible beyond SM

Timeline of contributions

Slide borrowed from A. Lazopoulos



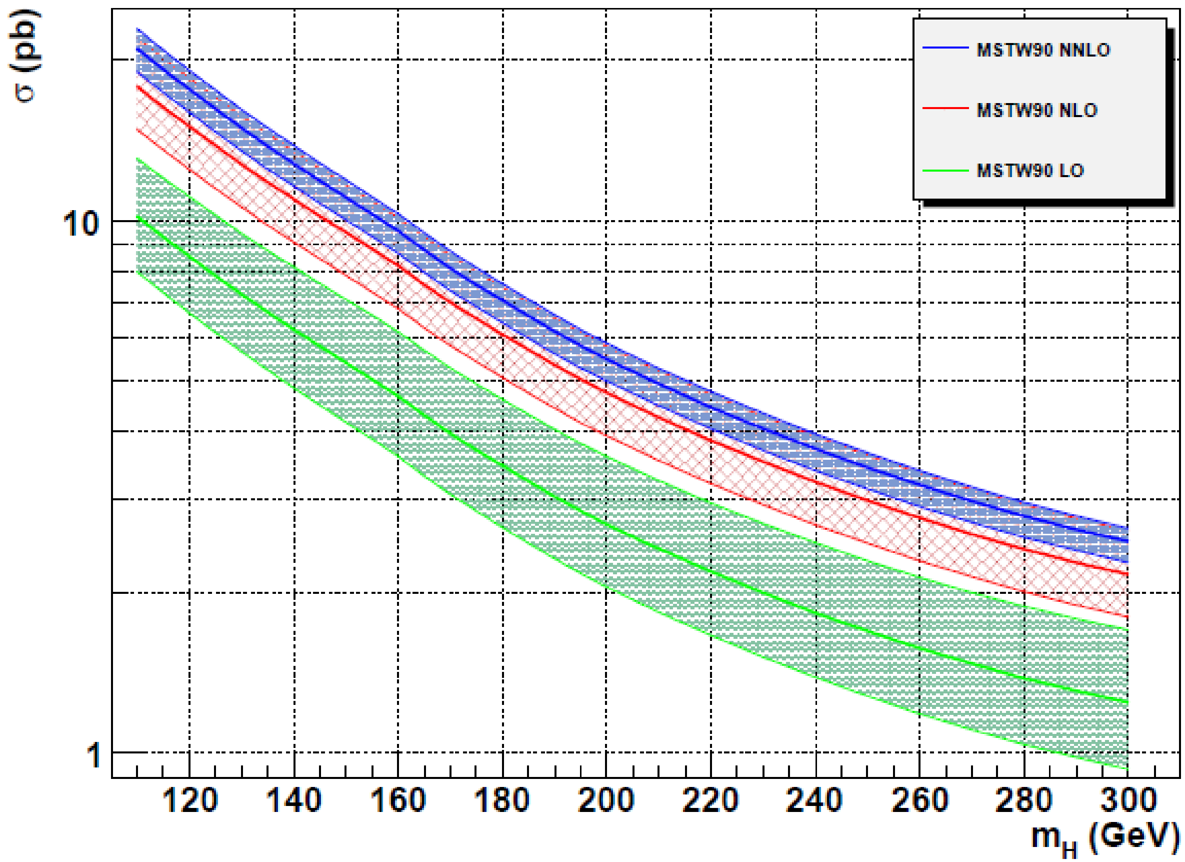
Gluon fusion in `iHixs`

- Main Higgs production channel at the LHC, main feature of `iHixs`
- Components:
  - LO contribution: heavy quark triangle.
  - NLO QCD corrections with exact mass dependence.
  - NNLO QCD corrections using HQET.
  - Two-loop electroweak corrections.
  - One-loop electroweak contributions to $q\bar{q} \to gh$ and $qg \to qh$.
  - Mixed QCD-electroweak corrections with light quarks.
- Almost all re-derived and checked against existing codes / limiting cases.

Including massive internal quarks

Gluon fusion in iHixs

- Decay options: $b\bar{b}$, WW, ZZ, γγ.
- Plot includes all known fixed-order corrections.
- Scale variations: $\mu/2 < m_H/2 < 2\,\mu$ with $\mu_R = \mu_F$
- Scales can be chosen separately.



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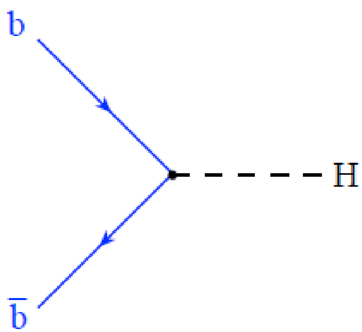
Bottom-quark fusion in `iHixs`

- Contributes to the same final state (single Higgs) in 5FS.
- Can be strongly enhanced in BSM scenarios (e.g. 2HDM)
  → Included in `iHixs`
- Components:
  - LO process and NLO QCD corrections.
    [Dicus, Willenbrock; Dicus, Stelzer, Sullivan, Willenbrock]

    NNLO QCD corrections. [Harlander, Kilgore]



- Matrix elements taken from arXiv:hep-ph/0304035v2.
- Re-derived factorisation- and renormalisation-scale dependence and checked vs. `bbh@nnlo` (Harlander)

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Higgs Width effects

- Most experimental and theoretical studies use the Narrow-Width-Approximation (NWA):

$$\hat{\sigma}_{ij\to\{H_{final}\}}\left(\hat{s},\mu_f\right) = \hat{\sigma}_{ij\to H}\left(\hat{s},m_H,\mu_f\right) \times BR_{H\to\{H_{final}\}}(Q=m_H)$$

- In `iHixs`, we implemented the actual integration over the Breit-Wigner distribution of the Higgs virtuality:

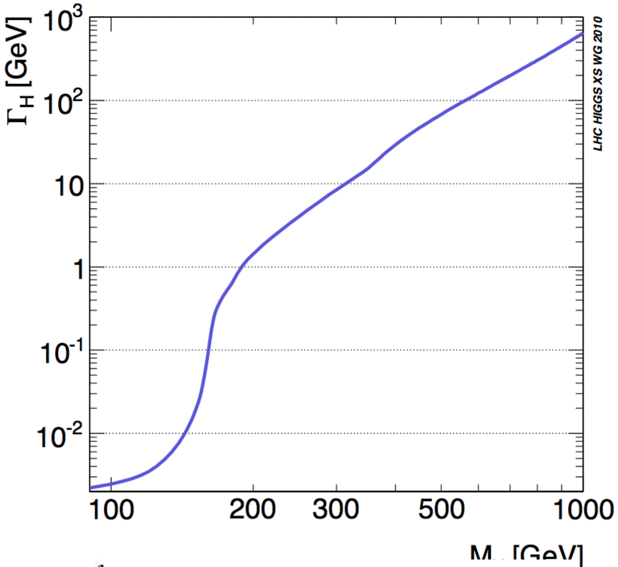
$$\hat{\sigma}_{ij\to\{H_{final}\}}\left(\hat{s},\mu_f\right) = \int_{Q_a^2}^{Q_b^2} dQ^2 \frac{Q\Gamma_H(Q)}{\pi} \frac{\hat{\sigma}_{ij\to H}(\hat{s},Q^2,\mu_f)\mathrm{Br}_{H\to\{H_{\mathrm{final}}\}}(Q)}{(Q^2-m_H^2)^2+m_H^2\Gamma_H^2(m_H)}$$

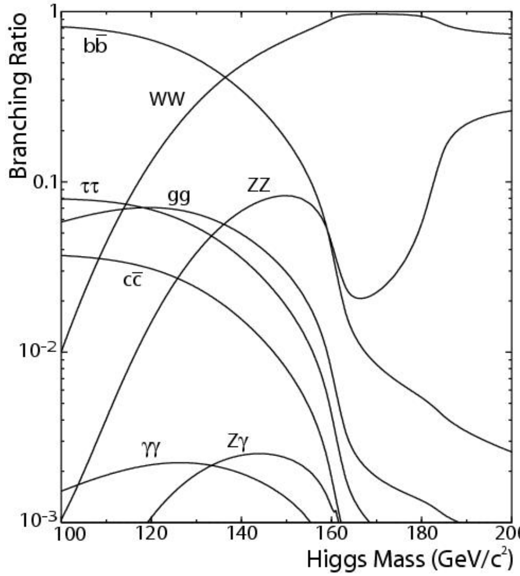
- Note that this involves the Higgs width and Branching ratios at any given Q in the integration range.
  → `iHixs` comes with a grid file containing this information for the SM.

Higgs Width effects

- The difference between the NWA and the BW-integration are of $O(\Gamma/m_H)$ for the inclusive cross section, which reaches the percent level at $m_H \approx 150$ GeV.

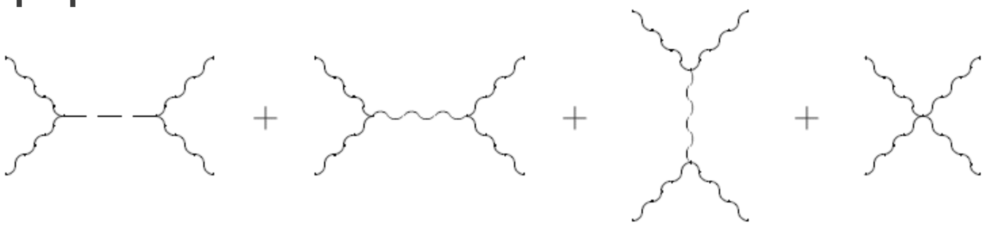
- $m_H > 450$ GeV: Higgs width exceeds 10% of its mass. → BW loses validity, Signal-Background interference becomes important.





Higgs Width effects

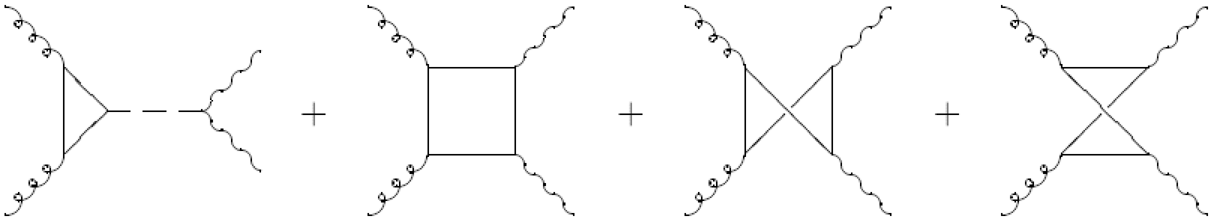
- “Fudge” way for SB-interference in VV final states: Employ the improved s-channel approximation (ISA) presented by M. Seymour in hep-ph/9505211.



- ISA resums the VV → VV 4-point function. The result interpolates between the BW-behaviour around the m_H resonance and unitarises the VV scattering in high-energy limit. It can be fully absorbed into a modified Higgs propagator:

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

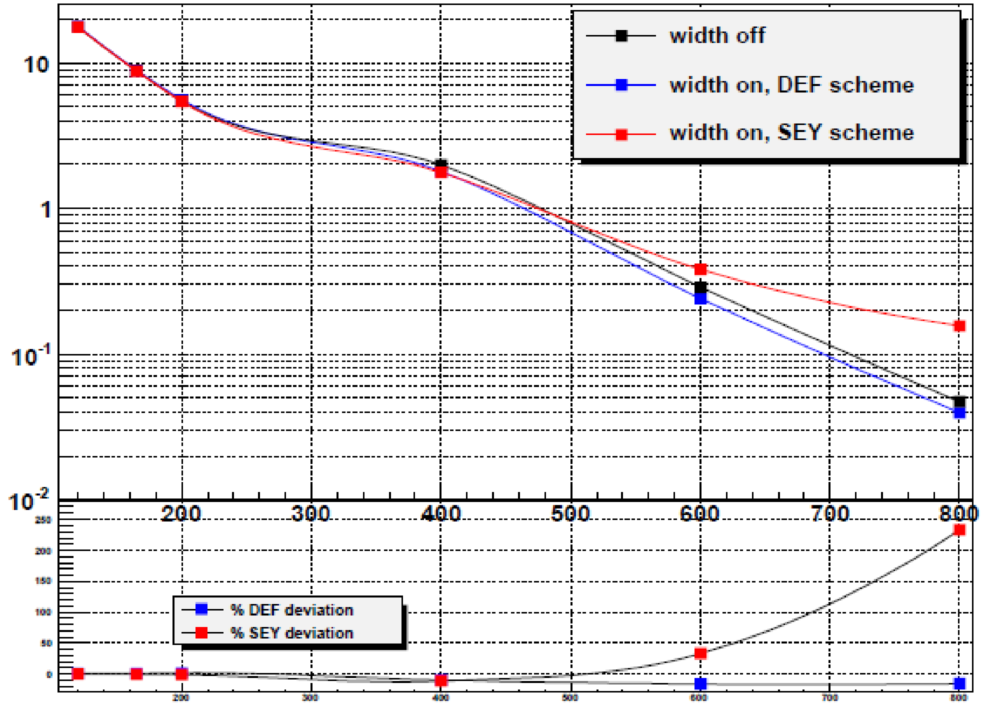
Higgs Width effects



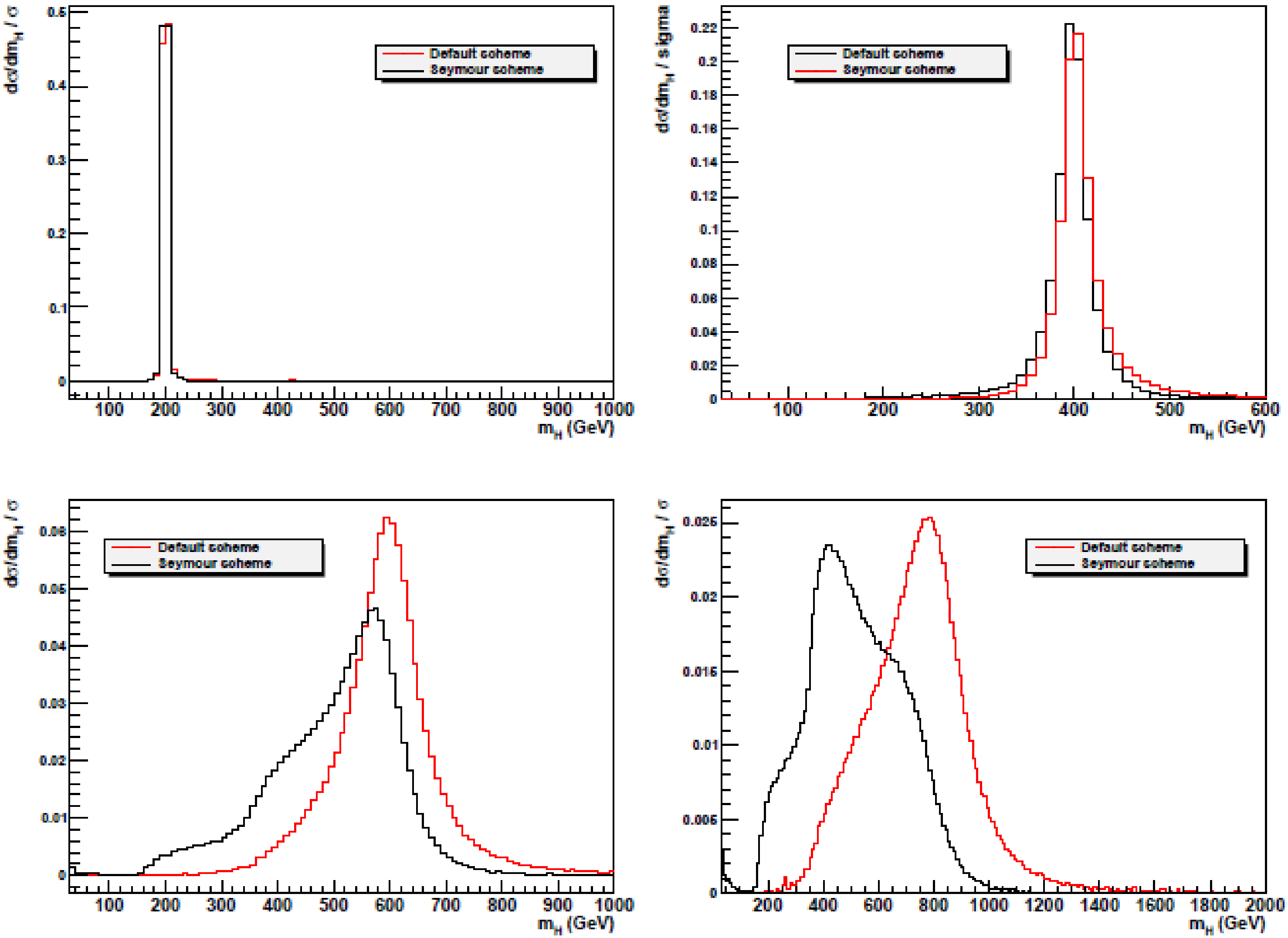
- $gg \to VV$ has the same structure as the $VV \to VV$ scattering.

  $\to$ The same approximation is applicable for the gluon fusion process.

- Width options in `iHixs`:
  - NWA
  - BW-integration
  - BW-integration with ISA

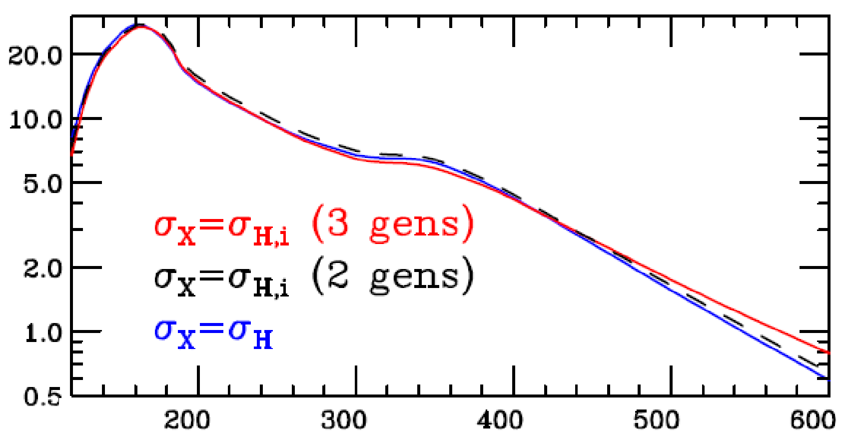


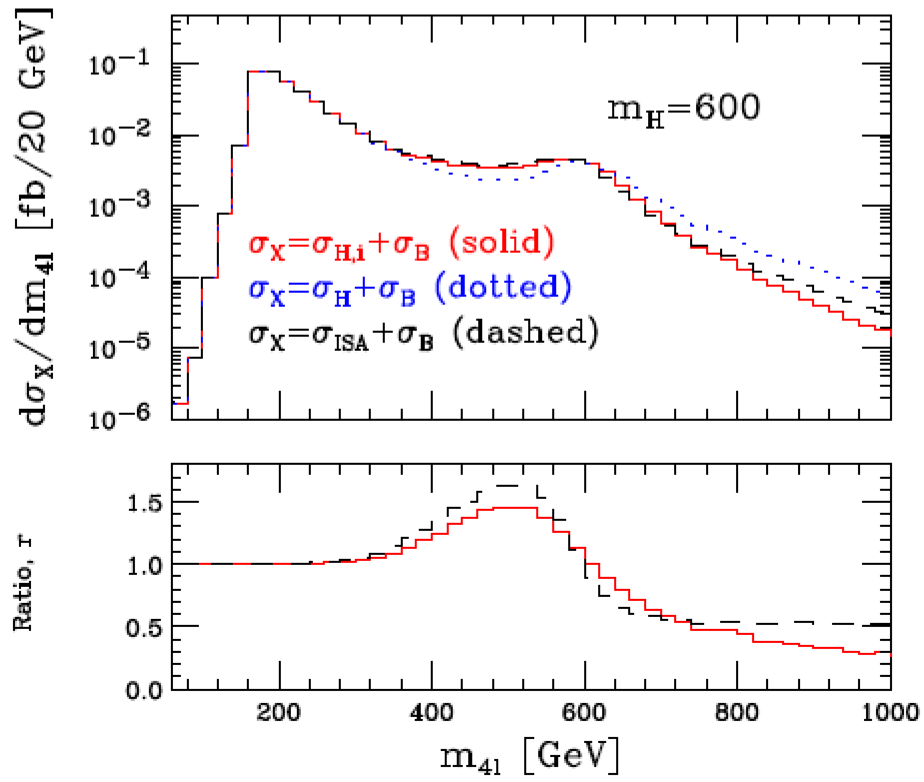
Higgs Width effects



Higgs Width effects

- arXiv:1107.5569 (Campbell, Ellis, Williams) compare their full calculation of the SB-interference with the ISA and find some agreement, esp. for high Higgs masses.





See also Talk by Nikolas Kauer!

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PDF comparison

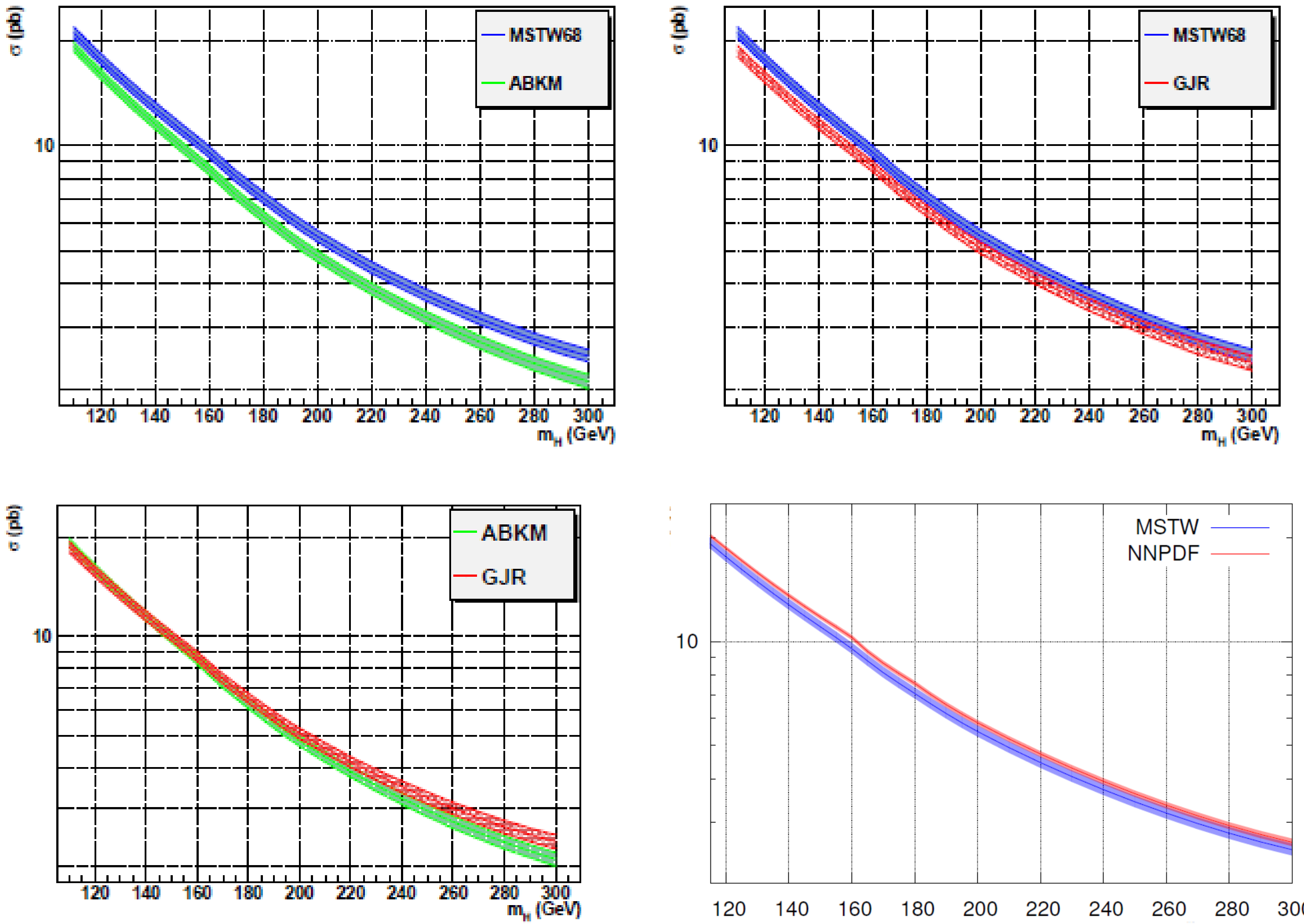
- `iHixs` supports all parton distribution providers that have sets using NNLO DGLAP evolution:

  MSTW2008, ABKM09, JR09, NNPDF21 NEW!

- Interfaced through the LHAPDF library [Whalley]. The value of α_S used in the run is fixed by the providers choice.

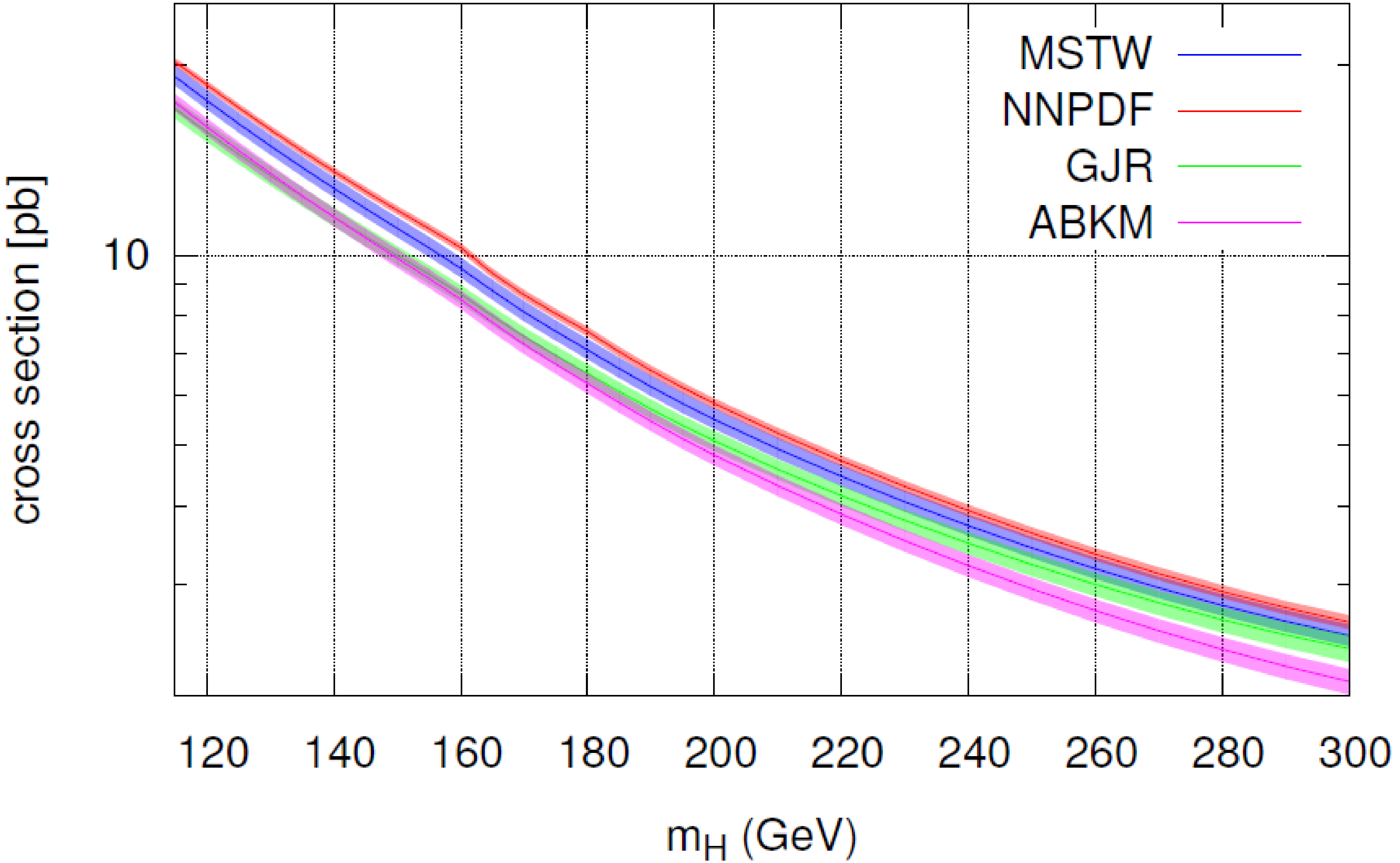
- PDF+α_S uncertainties are automatically calculated according to the providers prescription if the option is chosen.

PDF comparison: 68%-CL uncertainty bands

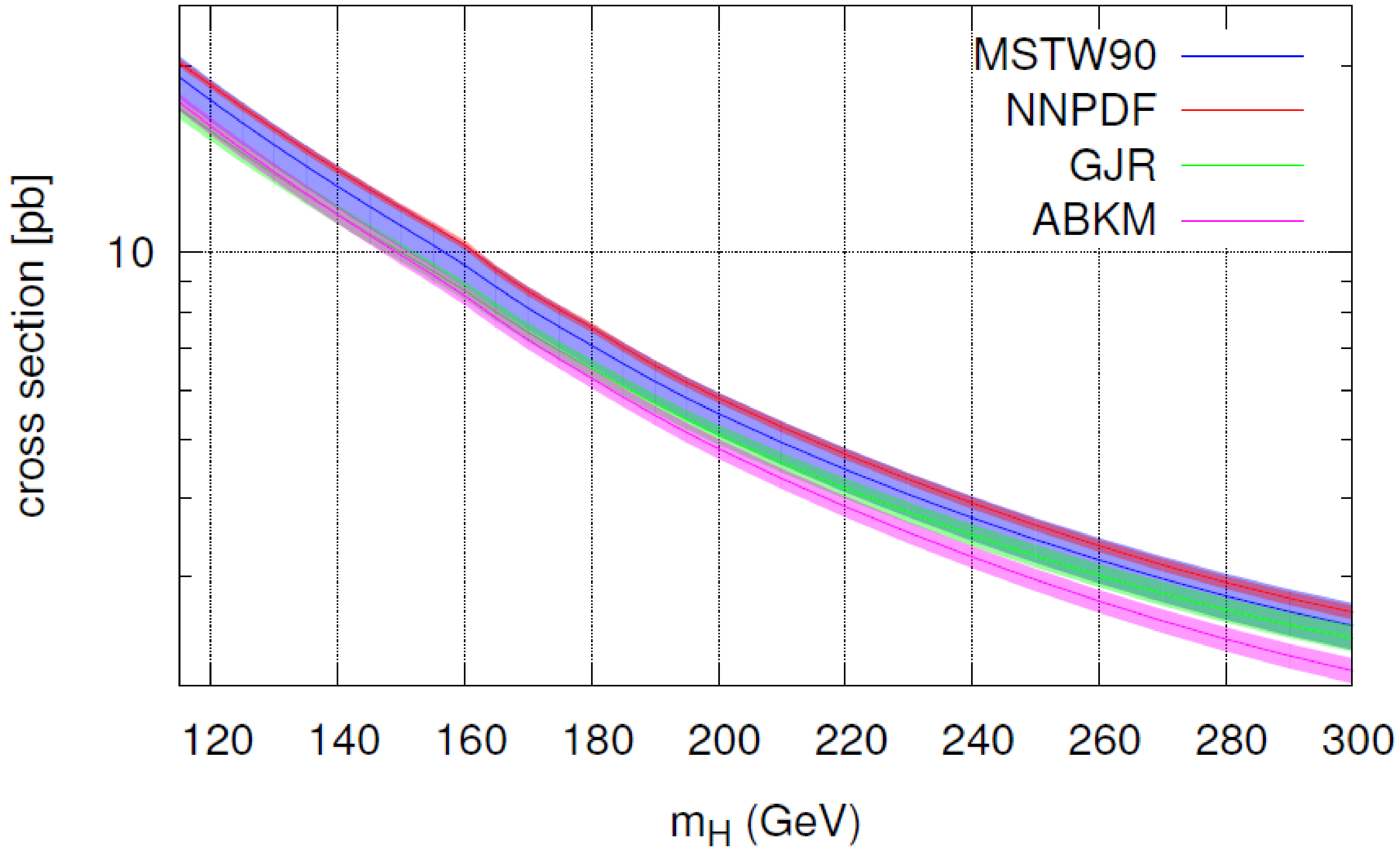


NEW!

PDF comparison: 68%-CL uncertainty bands



PDF comparison: 90%-CL uncertainty band



PDF comparison: 68%-CL uncertainty bands

- Uncertainty bands generally do not overlap → Prescriptions seem to underestimate the actual PDF uncertainty.
- The differences may stem from the choice of central α_S, since gluon fusion is very sensitive to that value and the inclusion of Tevatron jet-data in the fit. See 1105.5349 and 1106.5789.
- Using MSTW2008-90cl instead brings most bands to overlap with the MSTW one.
- Note that the NNPDF band is so narrow because it includes only the central α_S set, as the other sets are not available in the LHAPDF interface yet.

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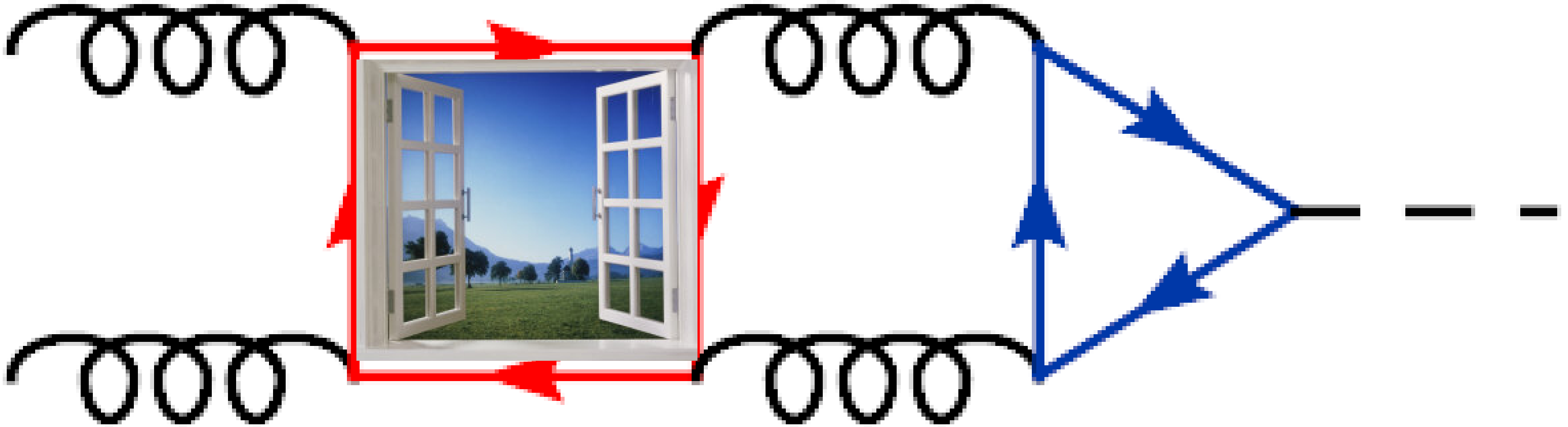
BSM capabilities of `iHixs`

- Gluon fusion cross section sensitive to heavy particles in loops.



A window to new physics!

BSM capabilities of `iHixs`

- Consistent treatment of arbitrary number of heavy quarks through NNLO.
  [Anastasiou, Boughezal, Furlan]
- Arbitrary Yukawa coupling strength for all heavy quarks.
  [Furlan]
- Arbitrary coupling strength for Higgs interactions with electroweak gauge bosons.
- Possibility to provide own grid file containing Higgs width and branching ratio information.
- Possibility to add completely arbitrary Wilson coefficient for the $H\,\mathrm{tr}\left(G_{\mu\nu}G^{\mu\nu}\right)$ operator. (with little effort)

BSM capabilities of iHixs

- Example 1: arXiv:1103.3645 (using a preliminary version of iHixs)

Higgs production cross-section in a Standard Model with four generations at the LHC

Charalampos Anastasiou[1], Stephan Buehler[1], Elisabetta Furlan[2] , Franz Herzog[1], Achilleas Lazopoulos[1]

- Considered two different SM4 scenarios.
- Provided the most precise Higgs production cross section estimate including PDF- and scale-uncertainties:

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

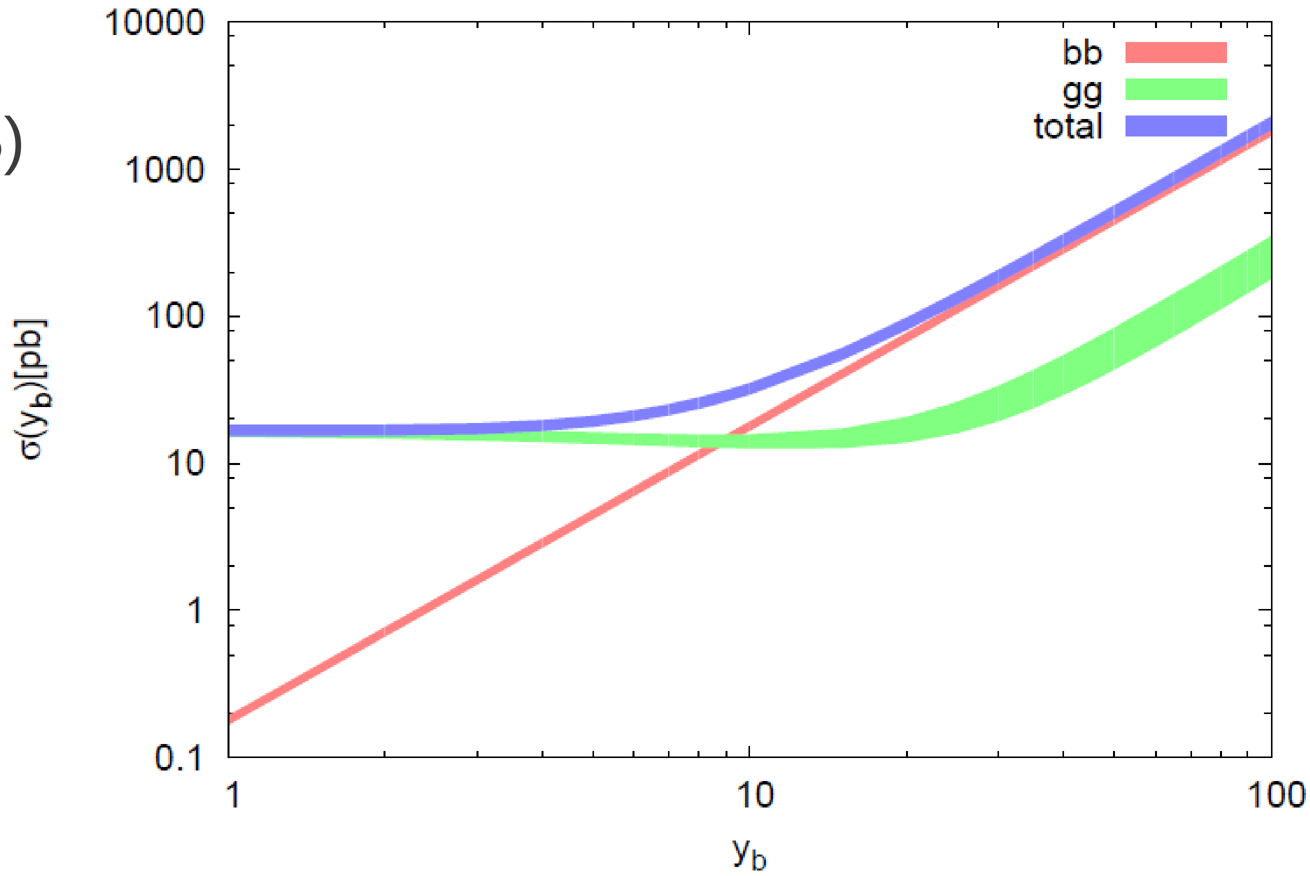
BSM capabilities of `iHixs`

- Example 2: Total single Higgs cross section in a generic model with enhanced Bottom Yukawa coupling:

$$i\,\frac{m_b}{v} \rightarrow i\,Y_b\,\frac{m_b}{v}$$

- Mimics large-tan(β) MSSM, general 2HDM, or other BSM models.

- $b\bar{b}$ channel surpassses gluon fusion for $Y_b > 10$.

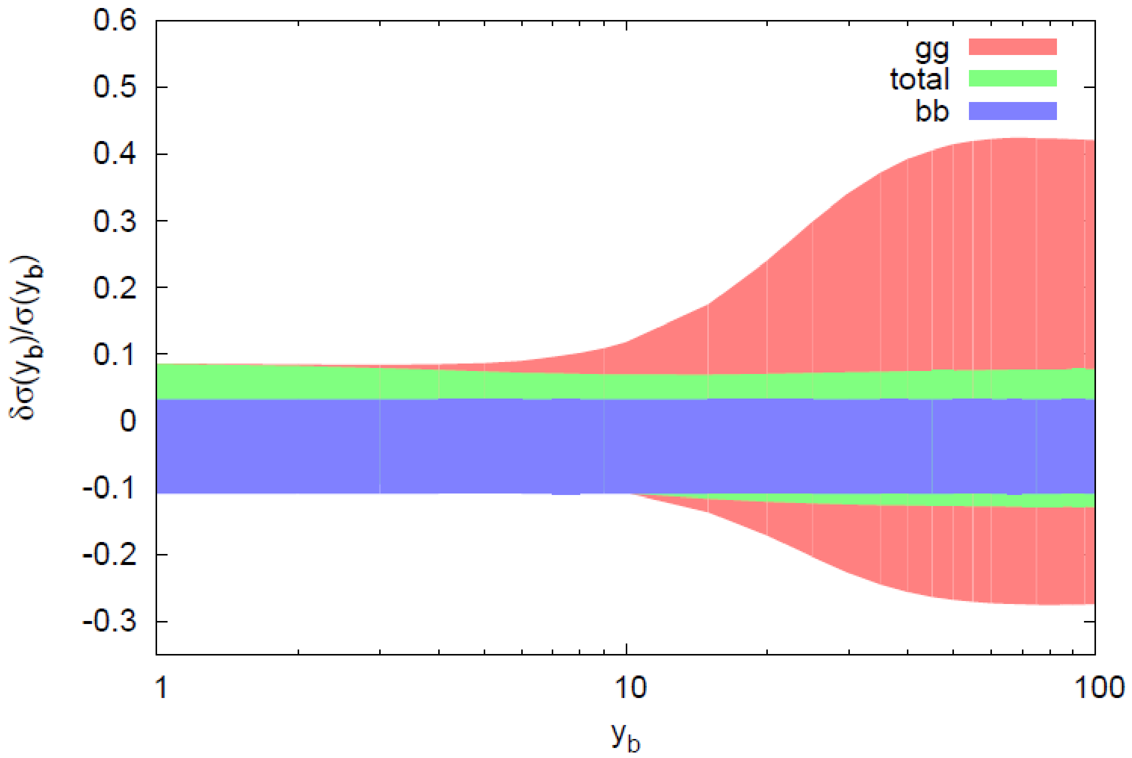


BSM capabilities of `iHixs`

- Example 2: Total single Higgs cross section in a generic model with enhanced Bottom Yukawa coupling:

$$i\,\frac{m_b}{v} \longrightarrow i\,Y_b\,\frac{m_b}{v}$$

- Gluon fusion: Scale uncertainty grows dramatically for large Values of Y_b.
- Reason: We “fall back” to NLO accuracy, since the b-quark is absent from the NNLO Wilson coefficient.



Summary

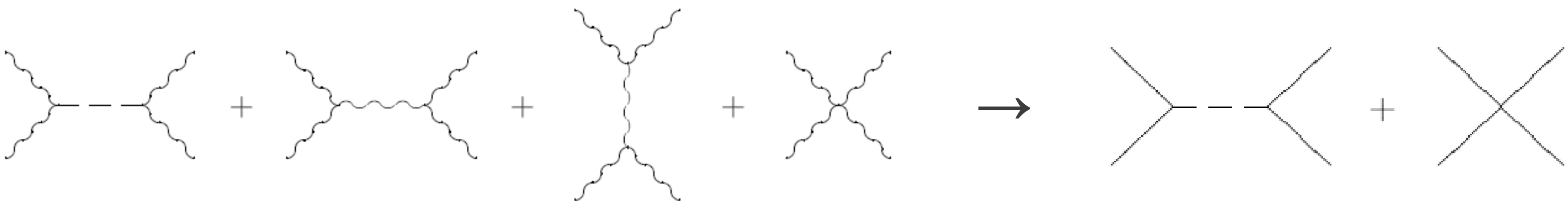
- `iHixs` provides the most precise numbers for inclusive Higgs production cross sections in the SM through gluon fusion that are available.
- Estimating all theoretical uncertainties is made easy by the automation of the pdf+α_S error for all NNLO pdf providers.
- Higgs width effects are built in with the choice of two different schemes.
- It is flexible enough to be used for BSM predictions.
- Please download and try it out, feedback is always appreciated!
  http://www.phys.ethz.ch/~pheno/ihixs/

Thank you for your attention,
enjoy the excursion to Kanchipuram!

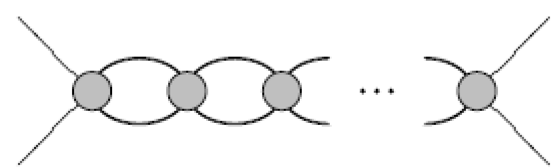
Backup

Higgs Width effects

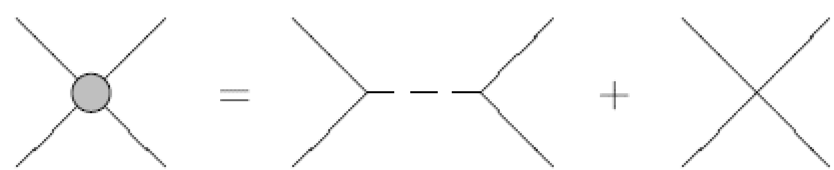
- Some more details on the derivation of the ISA:
  - Goldstone equivalence theorem is used:



  - The VV → VV amplitude looks like $i\mathcal{A} = \frac{-ig^2}{4m_W^2}\left\{\frac{s^2}{s-m_H^2} - s\right\}$
  - The resummed 4-point function is obtained by summing up all n-fold insertions of this amplitude:



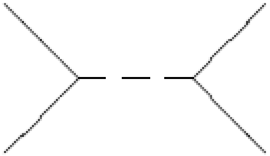
$$i\bar{\mathcal{A}} = \sum_{n=0}^{\infty}\left(\frac{3}{2}\frac{1}{16\pi}\int_{-s}^{0}\frac{dt}{s} i\mathcal{A}\right)^n i\mathcal{A}$$



Higgs Width effects

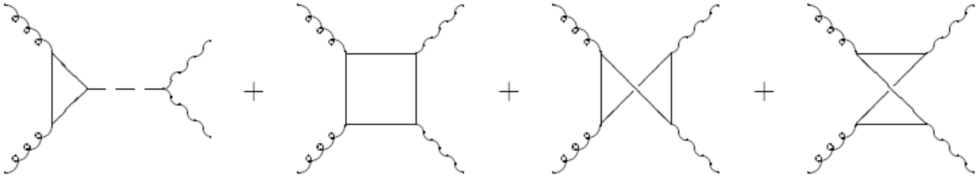
- Some more details on the derivation of the ISA:
  - $i\overline{A}$ is found to be $\frac{-ig^2 m_H^2}{4m_W^2} \frac{s}{s - m_H^2 + i\Gamma_H s/m_H}$
  - So when one replaces the Higgs propagator according to

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



one can just keep the diagram with the Higgs in the s-channel to get the full amplitude.

  - The gluon fusion amplitude is then found to be very similar:



$$= \frac{-ig^2 g_s^2}{m_W^2}\left\{\frac{s^2}{s - m_H^2} - s\right\} I(s)$$

with $I(s) = \frac{1}{2}\frac{m_q^2}{s}\left[\left(\log\frac{s}{m_q^2} - i\pi\right)^2 - 4\right]$ → The same prescription is applied

Higgs Width effects

- Furthermore, `iHixs` users can choose an invariant mass window which the produced Higgs boson must lie in. Final states of higher or lower virtuality will not be contributing
- Motivation behind this: For a relatively broad Higgs, experimentalists might miss out on a non-negligible fraction of the signal by applying too stringent cuts on the invariant mass of the final state particles, thus overestimating the NNLO K-factor.
- While in the SM, this only is relevant in the high-mass region, the effect can show up earlier in BSM models where the Higgs width becomes broad earlier.

m_H	Γ_H	δQ	K^{DEF}_{NNLO}	$K^{DEF;w}_{NNLO}$	K^{SEY}_{NNLO}	$K^{SEY;w}_{NNLO}$	K^{ZWA}_{NNLO}
120	0.0038	5	2.05	2.05	2.05	2.05	2.05
165	0.2432	5	2.02	2.03	2.016	2.04	2.033
200	1.43	8	2.00	2.03	2.023	2.03	2.027
400	29.5	34	1.90	1.94	1.94	1.95	1.95
600	122	110	1.66	1.66	1.87	1.72	1.64
800	301	300	1.63	1.59	2.07	1.77	1.54

Top width effects

- `iHixs` also allows for the quarks in the gluon fusion loops to have nonzero width. If the user chooses this option, the squared quark mass will be replaced by:

$$m_q^2 \to m_q \left(m_q - i\Gamma_q\right)$$

- This is absolutely straightforward, thanks to the `CHAPLIN` library [SB, Duhr], that allows for the evaluation of harmonic polylogarithms up to weight 4 for any complex argument.
- Adding a nonzero width for the top quark has negligible effects for Higgs masses below the $t\bar{t}$-threshold, but can arise to an enhancement of 2.4% on threshold and above.

Top width effects