“TOTAL HIGGS BOSON” CROSS-SECTION

CERN, May 2012
The case of a heavy Higgs boson

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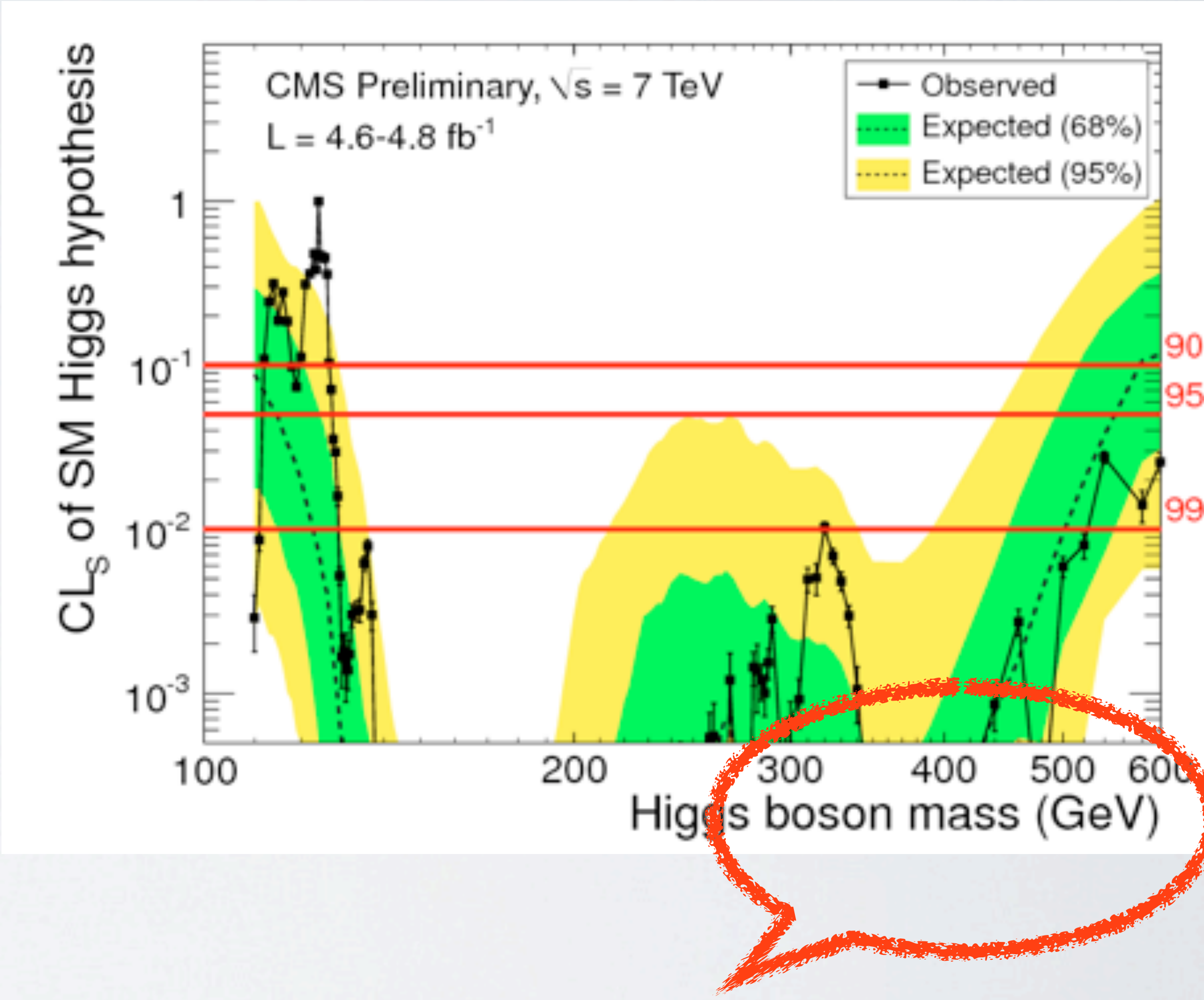
HIGGS BOSON SEARCHES

- Cover a large range of Standard Model "models" for varied values of the Higgs mass
- Not all of these models are favored by theory and previous data, which point strongly to a light Higgs boson.
- On the other hand, only ATLAS and CMS data can probe directly the existence of a heavy scalar with properties similar to the ones predicted in the Standard Model.
- Standard Model heavy Higgs boson searches may be used as an "easy to adapt" benchmark for spin-0 resonance searches in models that it may make more sense after a light SM Higgs boson has been discovered or excluded.



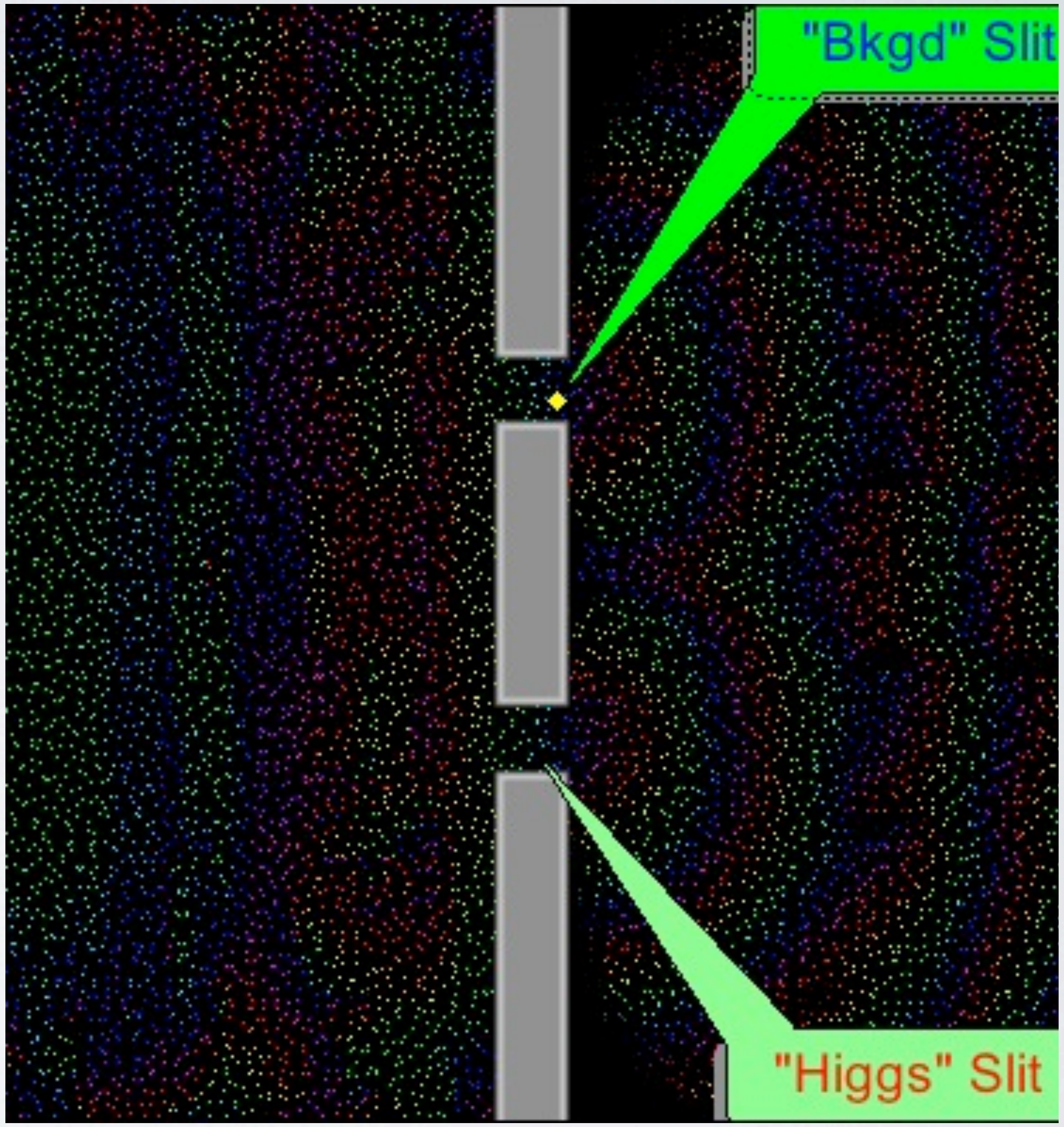
What are the SM predictions for measured cross-sections in the scenario of a heavy Higgs?

TOTAL CROSS-SECTION

- Can we condense, at least in practice, the SM predictions into:

$$\sigma_{total} \times \text{BR} \times \text{efficiency?}$$

- Experiments can prepare |in> states and measure the probability that they overlap with a certain final |out> state.
- The S-matrix <in|out> is constructed out of _stable_ particles. Unstable particles, such as a Higgs boson, propagate but cannot be in a final state.
- The "total Higgs cross-section" is _ill-defined_: more _experimentally_ than theoretically (in a theory calculations, one can select cleverly terms in the squared amplitude with s-channel Higgs propagators).



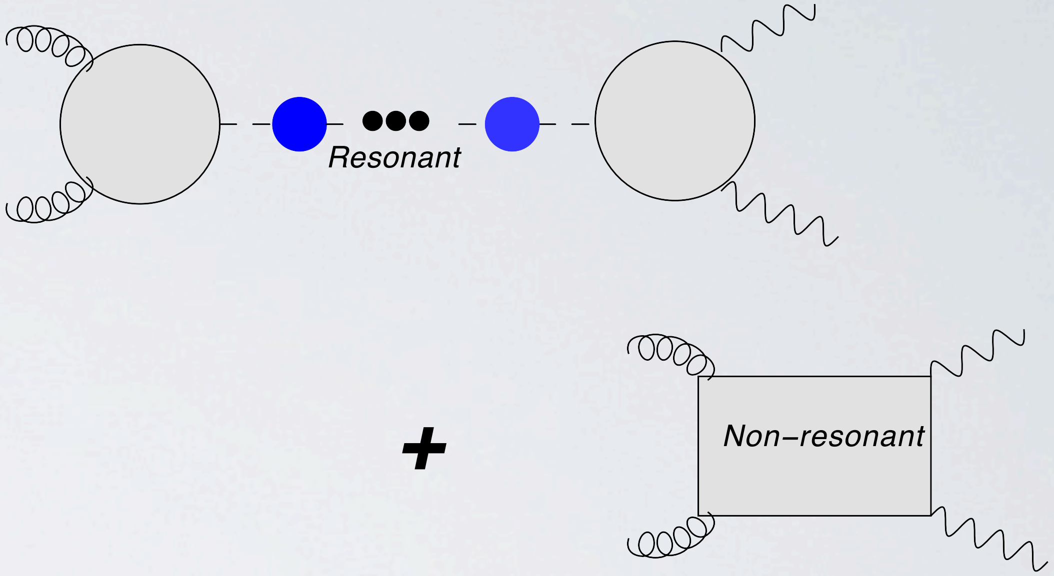
ATLAS/CMS

Interference is strong in ZZ and WW production at high invariant masses.

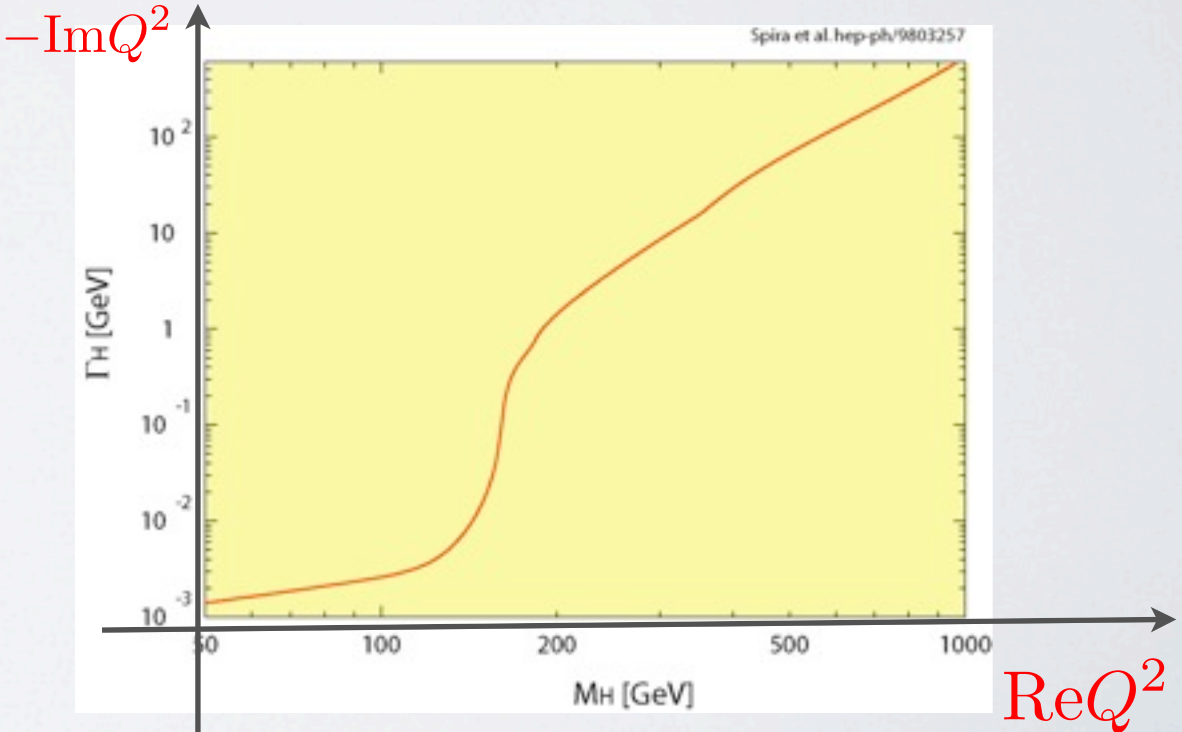
The "Higgs Slit" is not always safely bigger than the "Background Slit"!

POLES OF AMPLITUDES

- Amplitudes for WW,ZZ,… production have a pole due to the Higgs boson.
- The position of the pole is outside the physical region, for complex invariant masses of final state particles.
- Experiments measure squared probability amplitudes for real momenta.
- Still, the pole may influence strongly the value of the amplitude if it lies very close to the real axis (small width).
- The physical amplitude becomes increasingly insensitive to the complex pole by increasing the Higgs mass-width.



$$Q^2_{pole} = \mu_H^2 - i\gamma_H \mu_H$$



ATLAS/CMS

UNSTABLE PARTICLES AND PERTURBATION THEORY

Problem

- For zero couplings (no interactions) all particles are stable.
- For finite couplings, no matter how minute their value, particles may become unstable.
- Naive perturbation theory around the zero coupling limit cannot capture such a non-smooth transition

Solution

- Find a kinematic region where perturbation theory converges, for virtuality far away from the real part of the pole.
- Sum up at all orders in perturbation theory all "relevant" contributions which blow up as one approaches the pole region.
- Analytically continue the result to the pole region
- **Complications: Isolate "relevant only" contributions.** Impossible to sum everything at all orders in perturbation theory.
- Clumsy remnants can lead to loss of gauge invariance and unitarity.

THE FULL PROCESS

VECTOR BOSON PAIR PRODUCTION VIA GLUON FUSION

E.W.N. GLOVER and J.J. VAN DER BIJ
CERN, CH-1211 Geneva 23, Switzerland

Received 5 December 1988

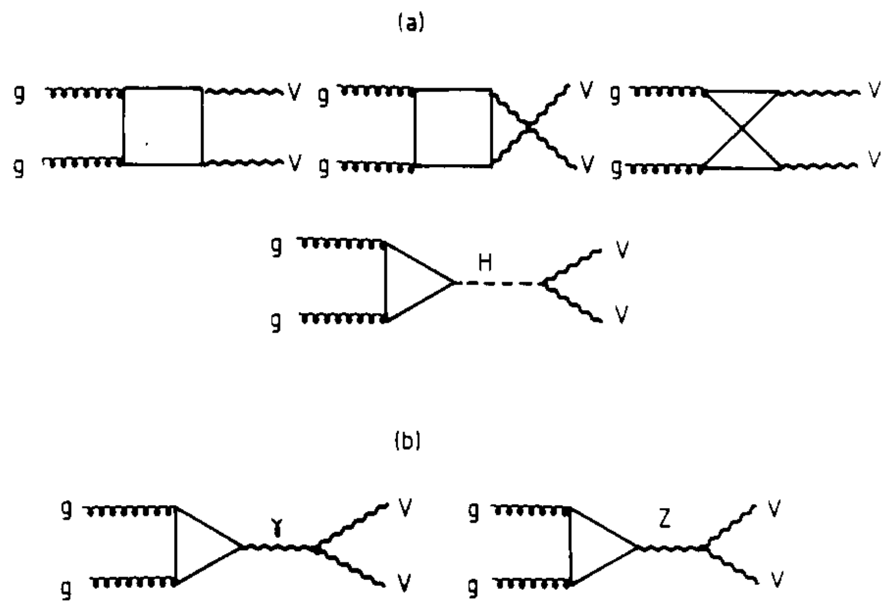


Fig. 1. Diagrams contributing to the process gg→VV, where V is either a Z or a W boson. The diagrams in fig. 1a contribute to ZZ and to WW production. Those in fig. 1b contribute only to WW production.

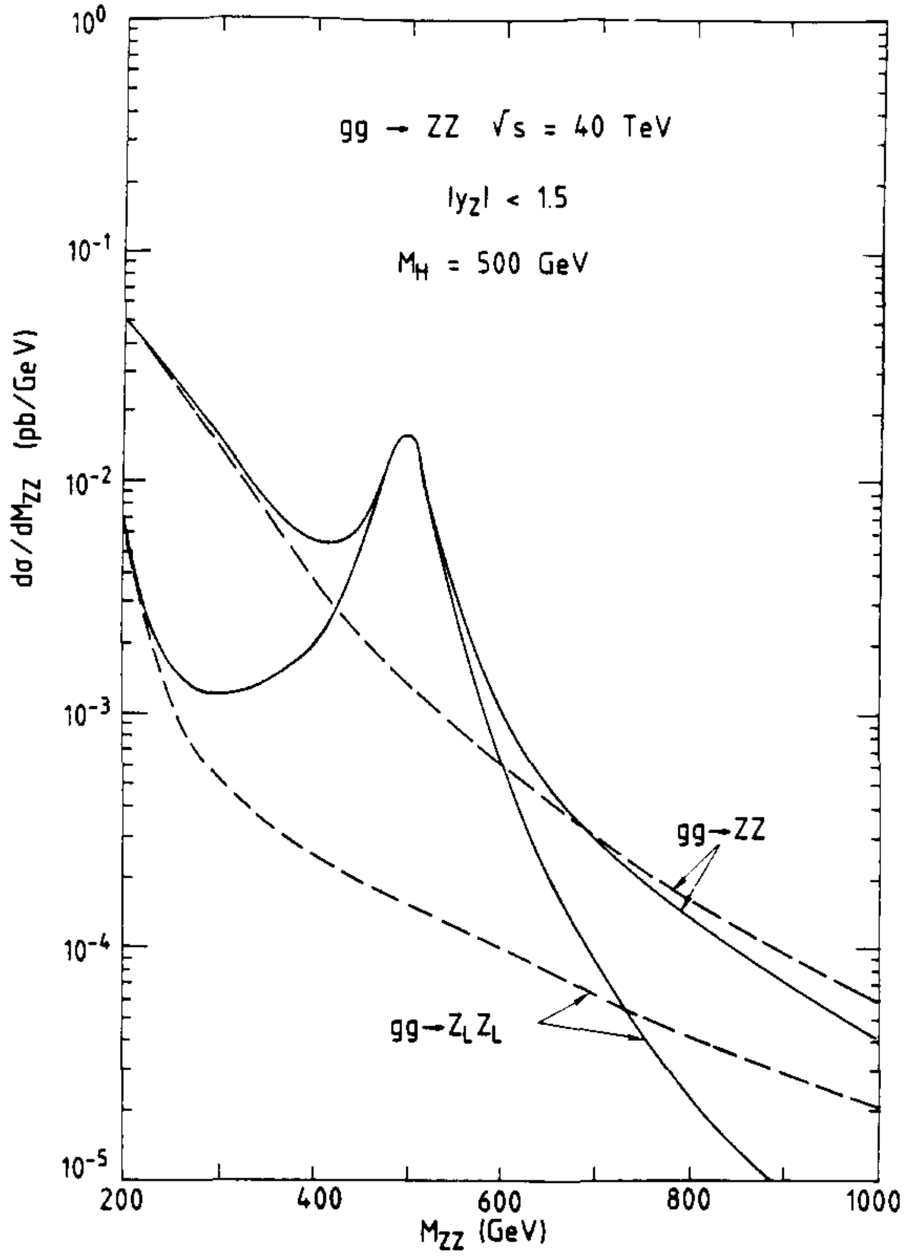
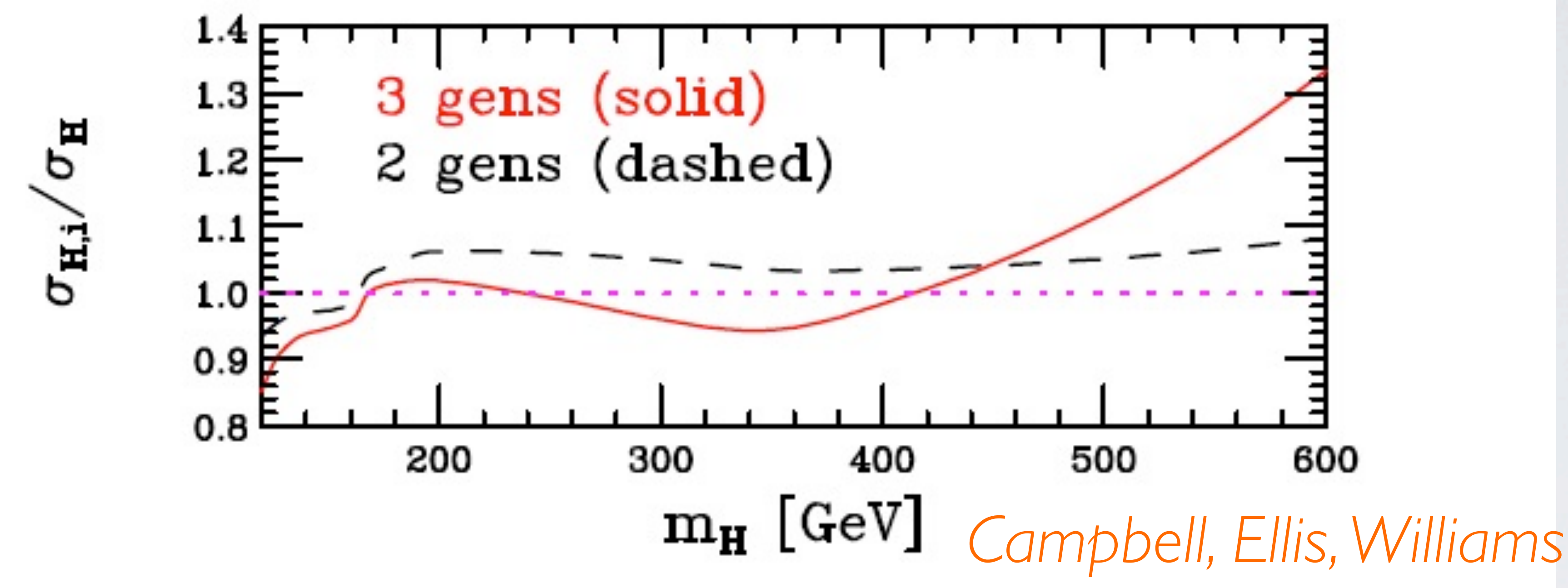


Fig. 3. The invariant mass distribution for gg→ZZ in pp collisions at $\sqrt{s}=40$ TeV. We took $m_t=100$ GeV and show curves both with a Higgs boson of mass $M_H=500$ GeV (solid lines) and without the Higgs boson (dashed lines). We show curves for longitudinally polarised Z boson pair production in addition to the sum over all Z boson polarisations. A rapidity cut on the Z bosons of $|y_Z<1.5$ has been applied.

For a large width, interference effects are large. We must compute the full process, assessing consistently the uncertainty due to higher order corrections. Not the first time that we are interested in this physics. Before LEP and when SSC was considered, the case of a large Higgs mass was very serious

HOW IMPORTANT IS THE INTERFERENCE?



Campbell, Ellis, Williams

- Interference effects rise fast for masses higher than 400 GeV.
- In the yet to be explored region above 600 GeV, interference is as important (or even more) as the "inclusive signal cross-section".
- No significant benefit of knowing NNLO QCD corrections for the signal cross-section when Mh=800 GeV.
- There should be equally important yet unknown QCD corrections for the interference and the irreducible background.
- There are important effects from the Higgs propagator and electroweak corrections.

CL**s** -METHOD WITH STRONG INTERFERENCE EFFECTS

discussed also by Dulat, Mistlberger

- The CLs method of ATLAS/CMS quantifies the solidity of our conclusions for a potential Higgs boson signal based on the likelihood ratio of two hypotheses:

$$\text{Hypothesis}(\mu) = \mu \times \sigma_{\text{HIGGS}} + \sigma_{BKGD}$$
$$\& \quad \text{Hypothesis}(0) = \sigma_{BKGD}$$

- This has to be modified to account for interference. For example,

$$\text{Hypothesis}(\mu) = \mu \times \sigma_{\text{HIGGS}} + \sqrt{\mu} \times \sigma_{\text{INTERF.}} + \sigma_{\text{BKGD}}$$

- Any artificial deformation which recovers the Standard Model prediction for mu=1 is good for excluding just the Standard Model hypothesis with exact SM couplings. Difficult to utilize exclusions plots for other models with different couplings.

- Better to use:

$$\text{Hypothesis}(\mu) = \sigma_{VV \text{ in } SM}\,(\text{Higgs coupling} \to \sqrt{\mu} \times \text{Higgs coupling})$$

- Accounts for cancelations due to interference and non-linearities at higher orders

CL**s** -METHOD AND THE NULL HYPOTHESIS

- The Standard Model Higgs boson plays a special role, taming the growth of cross-sections at high energies. Interference is negative.

- The typical null ***Hypothesis(0)*** of "background only" is large (and likely in need to receive non-perturbative or new-physics corrections) for the EWK boson-pair signatures which are searched experimentally.

- Glover and Seymour define the background for a Higgs signature in diboson production as the minimum of signal+background+interference for all Higgs masses. This corresponds to a zero value of the Higgs mass.

$$\mathrm{Hypothesis}_{\mathrm{Glover}}(0) = \min\{\sigma_{VV \text{ in } SM}\left(M_{\mathrm{Higgs}}\right), \quad \forall \quad M_{\mathrm{Higgs}}\}$$

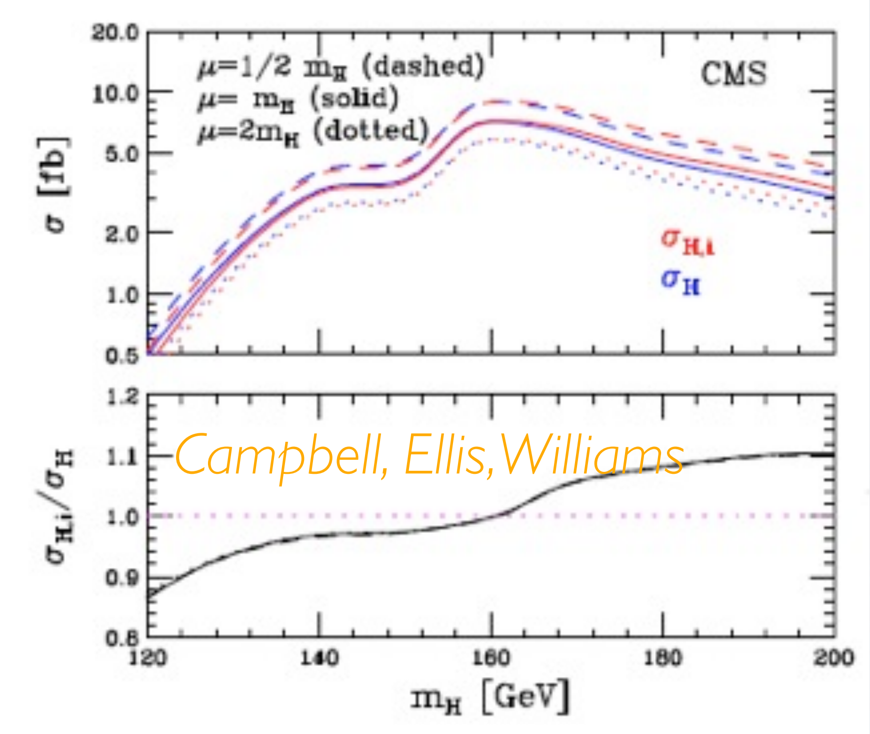
- As long as a SM-like light Higgs has not been discovered, we could also think about using

$$\mathrm{Hypothesis}(0) = \sigma_{VV \text{ in } SM}\left(M_{\mathrm{Higgs}}\right), \quad \text{for} \quad M_{\mathrm{Higgs}} \sim 125\mathrm{GeV}$$

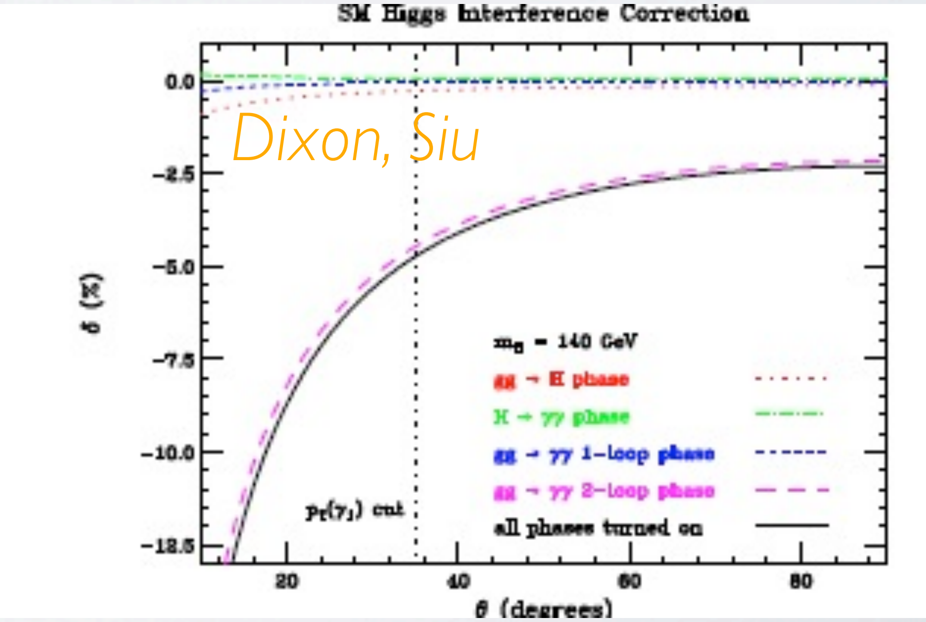
- Can be turned into a search for a second particle decaying into ZZ and WW if a light Higgs boson is discovered. Or, into an analysis of constraining the couplings of a light Higgs boson. A light Higgs may be a reality, but does it do its job at high invariant masses?

INTERFERENCE AT LOW HIGGS MASS

- Interference effects are not small enough to be ignored even at low masses.
- They are comparable to estimates of their uncertainties (e.g. N3LO QCD and electroweak effects)
- They have different efficiencies than the signal cross-sections.
- Sensitive to imaginary parts and phases: novel two-loop corrections.
- Appropriate to assign a conservatively large "K-factor" to destructive interference inspired by the large QCD corrections of the signal cross-section (as suggested by Campbell, Ellis, Williams)



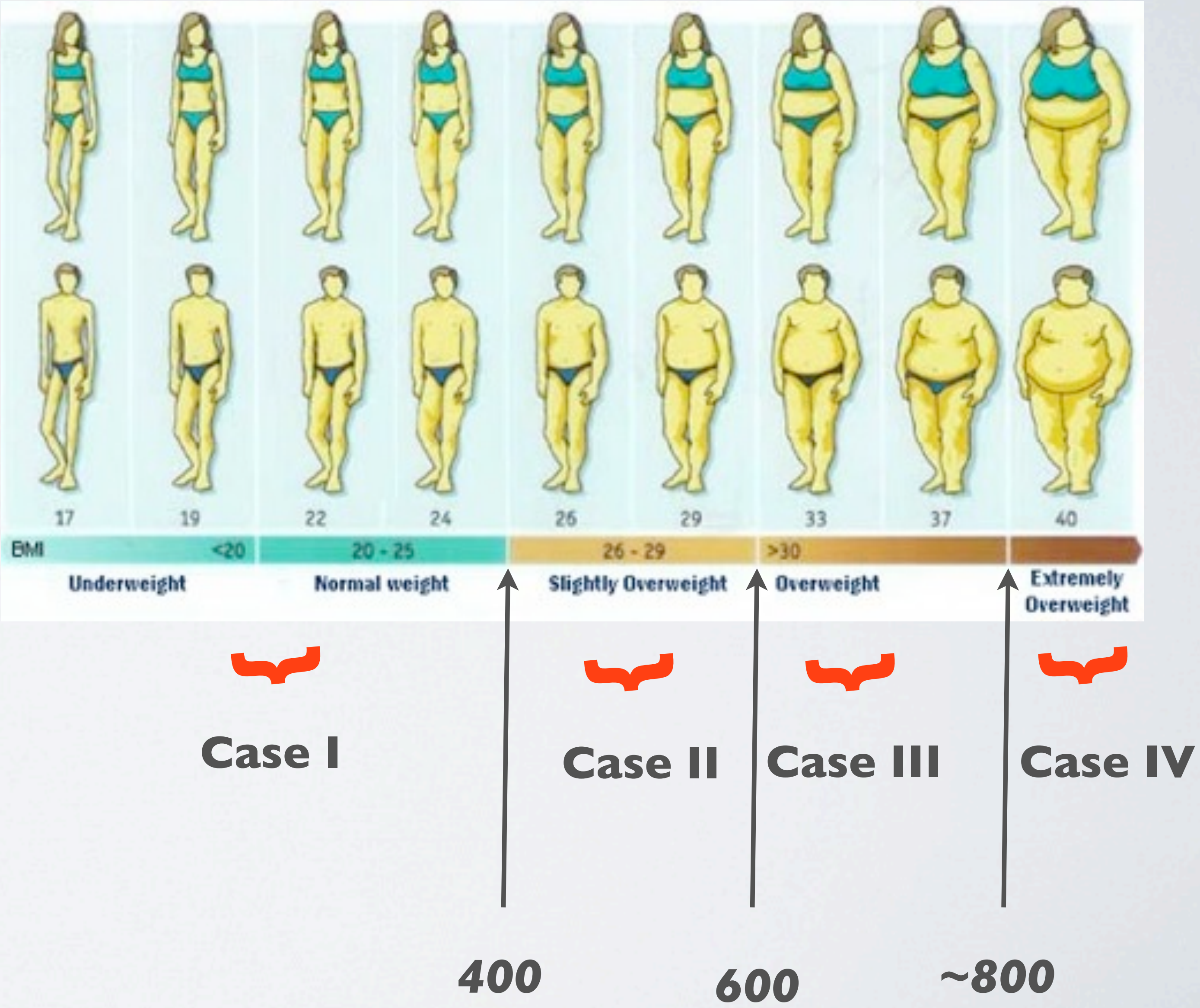
Campbell, Ellis, Williams



Dixon, Siu

THE “BMI” OF THE STANDARD MODEL HIGGS

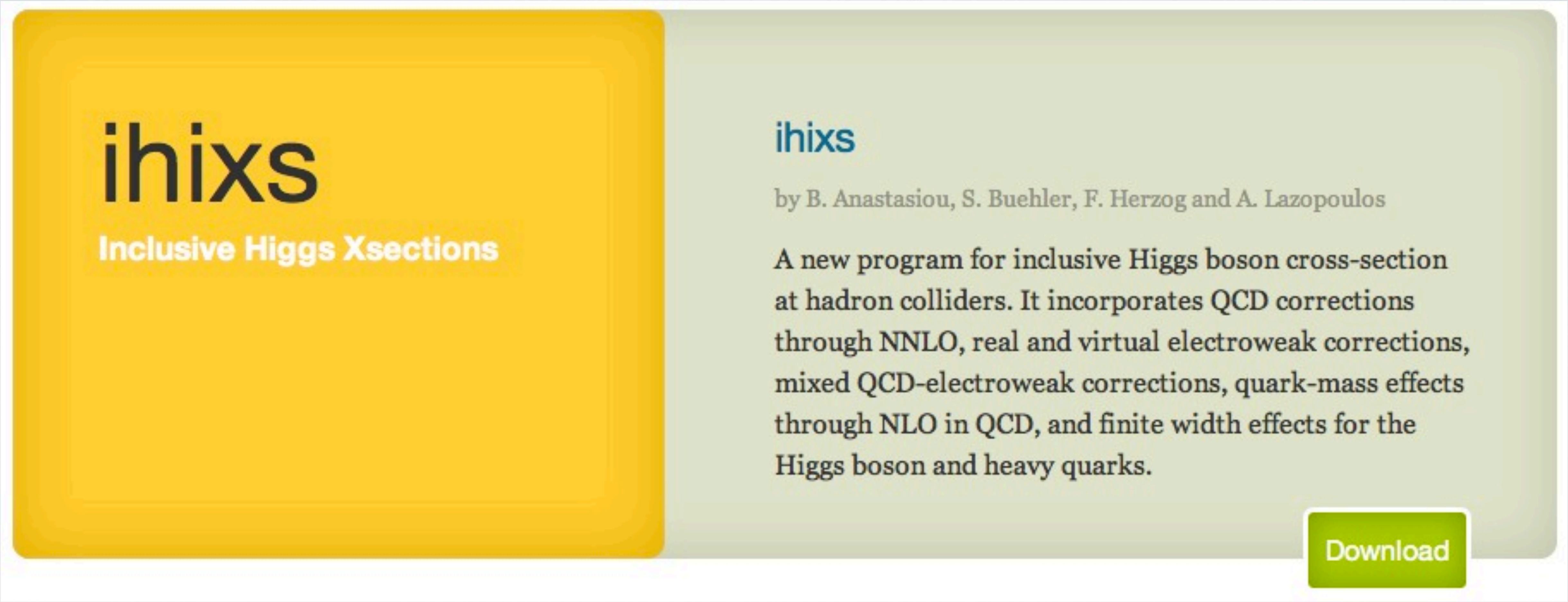
- Case I: Mhiggs < 400 GeV
- Case II: 400 GeV < Mhiggs < ~600 GeV
- Case III: ~600 GeV < Mhiggs < ~0.8-1 TeV
- Case IV: >~0.8-1 TeV



CASE I: LIGHT HIGGS

- Interference in gluon is small but non-negligible.
- It can be computed at leading order QCD in the ZZ,WW channel and NLO QCD in the diphoton channel.
- A factorization of the signal cross-section into production, propagation and decay, where all these components may be computed at differing highest attainable orders in perturbation theory, is well justified and accurate.
- The Higgs decay widths have been computed to very high orders (see the very impressive N4LO QCD calculations by Chetyrkin, Baikov and careful global studies paying attention to thresholds etc by Denner, Heinemeyer, Pulzak, Rebuzzi, Spira)
- For gluon fusion production, the cross-section has been computed to NNLO QCD, threshold resummed to NNLL in various ways, corrected with 2-loop electroweak and estimated ~3-loop electroweak corrections, and corrected with 2-loop and ~3loop finite quark mass effects.
- Perhaps one of the most exhaustively studied inclusive cross-section from the theory side (...large list of authors).
- Irreducible theoretical uncertainty of ~10% at the LHC, unless further calculations are performed at NNNLO.

INCLUSIVE HIGGS X-SECTION



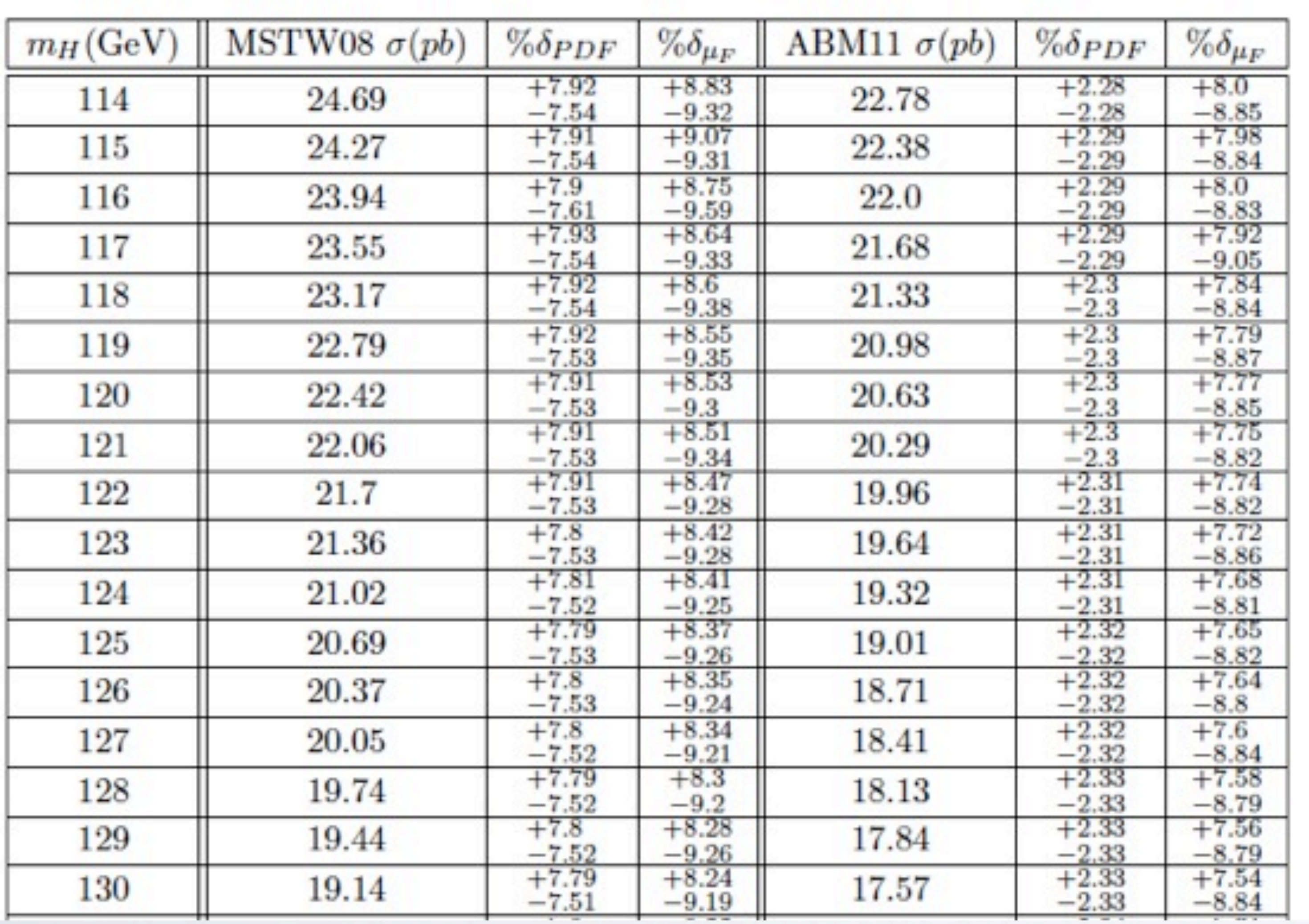
ihixs

by B. Anastasiou, S. Buehler, F. Herzog and A. Lazopoulos

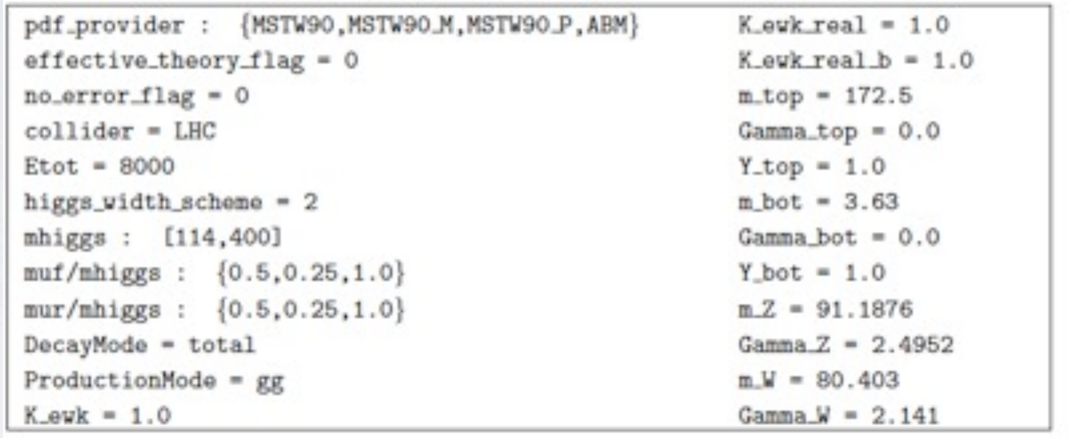
A new program for inclusive Higgs boson cross-section at hadron colliders. It incorporates QCD corrections through NNLO, real and virtual electroweak corrections, mixed QCD-electroweak corrections, quark-mass effects through NLO in QCD, and finite width effects for the Higgs boson and heavy quarks.

- Painstaking checking or recalculation of of virtually all higher order contributions to the cross-section
- Extending it to include consistently non-SM Yukawa couplings (3-loop Wilson coefficient by E. Furlan).
- A beautiful tool for studies of Higgs couplings. Currently relies on manual input or HDECAY for the width and branching ratios. Soon, it will perform an automated calculation of width+BRs in a "SM" with anomalous Higgs couplings.

PREDICTIONS AT 8 TEV



m_H(GeV)	MSTW08 $\sigma(pb)$	$\%\delta_{PDF}$	$\%\delta_{\mu_F}$	ABM11 $\sigma(pb)$	$\%\delta_{PDF}$	$\%\delta_{\mu_F}$
114	24.69	$^{+7.92}_{-7.54}$	$^{+8.83}_{-9.32}$	22.78	$^{+2.28}_{-2.28}$	$^{+8.0}_{-8.85}$
115	24.27	$^{+7.91}_{-7.54}$	$^{+9.07}_{-9.31}$	22.38	$^{+2.29}_{-2.29}$	$^{+7.98}_{-8.84}$
116	23.94	$^{+7.9}_{-7.61}$	$^{+8.75}_{-9.59}$	22.0	$^{+2.29}_{-2.29}$	$^{+8.0}_{-8.83}$
117	23.55	$^{+7.93}_{-7.54}$	$^{+8.64}_{-9.33}$	21.68	$^{+2.29}_{-2.29}$	$^{+7.92}_{-9.05}$
118	23.17	$^{+7.92}_{-7.54}$	$^{+8.6}_{-9.38}$	21.33	$^{+2.3}_{-2.3}$	$^{+7.84}_{-8.84}$
119	22.79	$^{+7.92}_{-7.53}$	$^{+8.55}_{-9.35}$	20.98	$^{+2.3}_{-2.3}$	$^{+7.79}_{-8.87}$
120	22.42	$^{+7.91}_{-7.53}$	$^{+8.53}_{-9.3}$	20.63	$^{+2.3}_{-2.3}$	$^{+7.77}_{-8.85}$
121	22.06	$^{+7.91}_{-7.53}$	$^{+8.51}_{-9.34}$	20.29	$^{+2.3}_{-2.3}$	$^{+7.75}_{-8.82}$
122	21.7	$^{+7.91}_{-7.53}$	$^{+8.47}_{-9.28}$	19.96	$^{+2.31}_{-2.31}$	$^{+7.74}_{-8.82}$
123	21.36	$^{+7.8}_{-7.53}$	$^{+8.42}_{-9.28}$	19.64	$^{+2.31}_{-2.31}$	$^{+7.72}_{-8.86}$
124	21.02	$^{+7.81}_{-7.52}$	$^{+8.41}_{-9.25}$	19.32	$^{+2.31}_{-2.31}$	$^{+7.68}_{-8.81}$
125	20.69	$^{+7.79}_{-7.53}$	$^{+8.37}_{-9.26}$	19.01	$^{+2.32}_{-2.32}$	$^{+7.65}_{-8.82}$
126	20.37	$^{+7.8}_{-7.53}$	$^{+8.35}_{-9.24}$	18.71	$^{+2.32}_{-2.32}$	$^{+7.64}_{-8.8}$
127	20.05	$^{+7.8}_{-7.52}$	$^{+8.34}_{-9.21}$	18.41	$^{+2.32}_{-2.32}$	$^{+7.6}_{-8.84}$
128	19.74	$^{+7.79}_{-7.52}$	$^{+8.3}_{-9.2}$	18.13	$^{+2.33}_{-2.33}$	$^{+7.58}_{-8.79}$
129	19.44	$^{+7.8}_{-7.52}$	$^{+8.28}_{-9.26}$	17.84	$^{+2.33}_{-2.33}$	$^{+7.56}_{-8.79}$
130	19.14	$^{+7.79}_{-7.51}$	$^{+8.24}_{-9.19}$	17.57	$^{+2.33}_{-2.33}$	$^{+7.54}_{-8.84}$



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pdf_provider :  {MSTW90,MSTW90_M,MSTW90_P,ABM}        K_ewk_real = 1.0
effective_theory_flag = 0                             K_ewk_real_b = 1.0
no_error_flag = 0                                     m_top = 172.5
collider = LHC                                        Gamma_top = 0.0
Etot = 8000                                           Y_top = 1.0
higgs_width_scheme = 2                                m_bot = 3.63
mhiggs :  [114,400]                                   Gamma_bot = 0.0
muf/mhiggs :  {0.5,0.25,1.0}                          Y_bot = 1.0
mur/mhiggs :  {0.5,0.25,1.0}                          m_Z = 91.1876
DecayMode = total                                     Gamma_Z = 2.4952
ProductionMode = gg                                   m_W = 80.403
K_ewk = 1.0                                           Gamma_W = 2.141
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Perturbative uncertainties estimated with scale variations

Uncertainty of parton densities

PDF UNCERTAINTIES

- Four NNLO pdf sets
- 68% confidence level uncertainties show discrepancies
- Situation can be ameliorated by adopting the 90%CL uncertainty of MSTW
- Still, ABM11 set is quite different
- ABM11 finds a lower value of alpha strong, relies on less data, but not yet shown to disagree with LHC data
- Difference with other pdfs is systematic. We do not try to reconcile it by enlarging further the pdf uncertainty. Instead, we provide a nominal prediction based on MSTW@90%CL and a typically lower prediction of ABM11

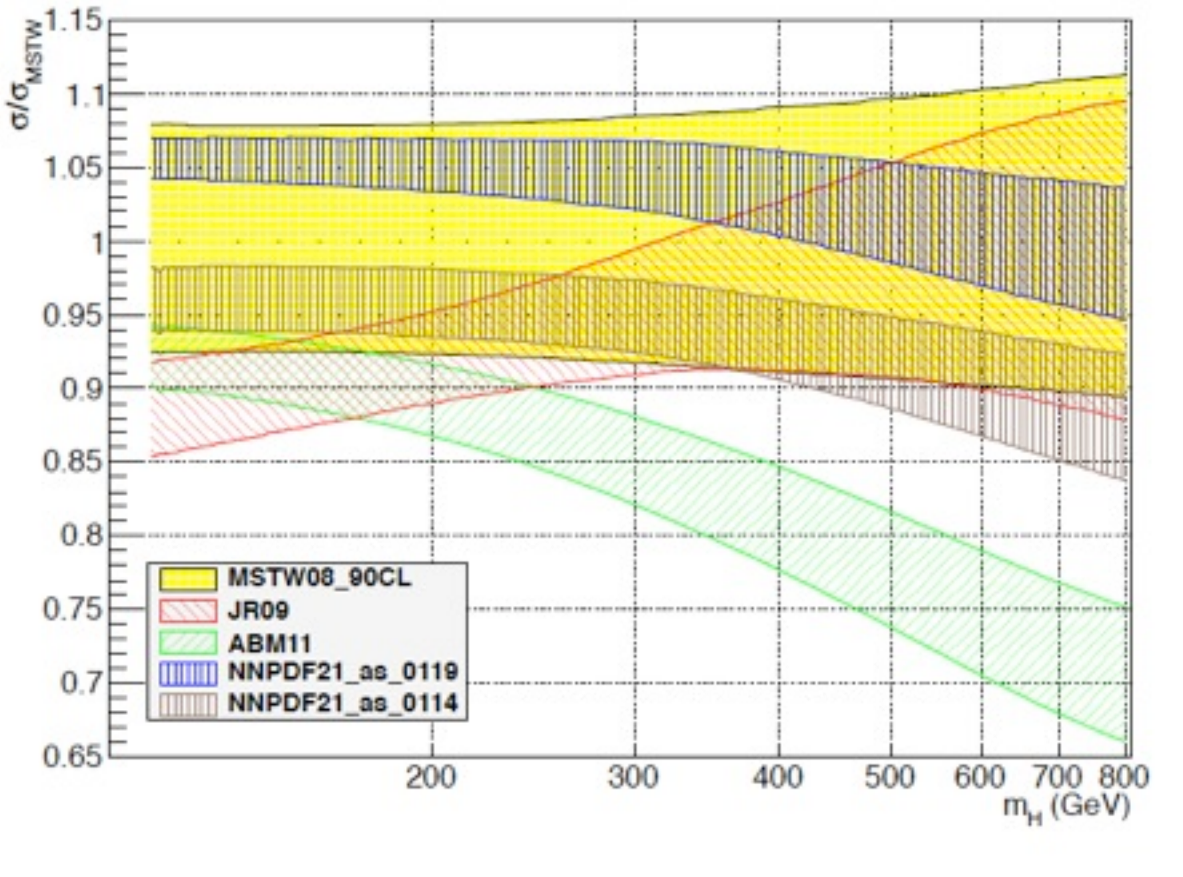
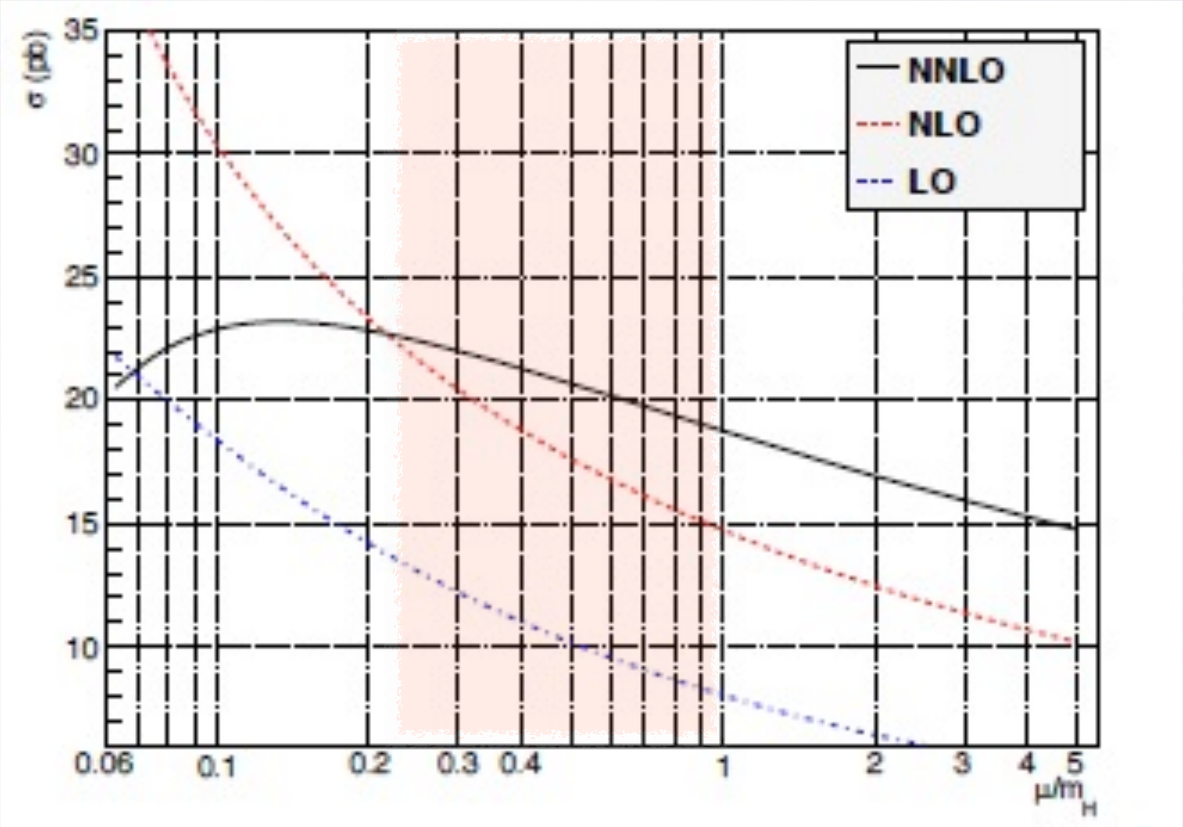
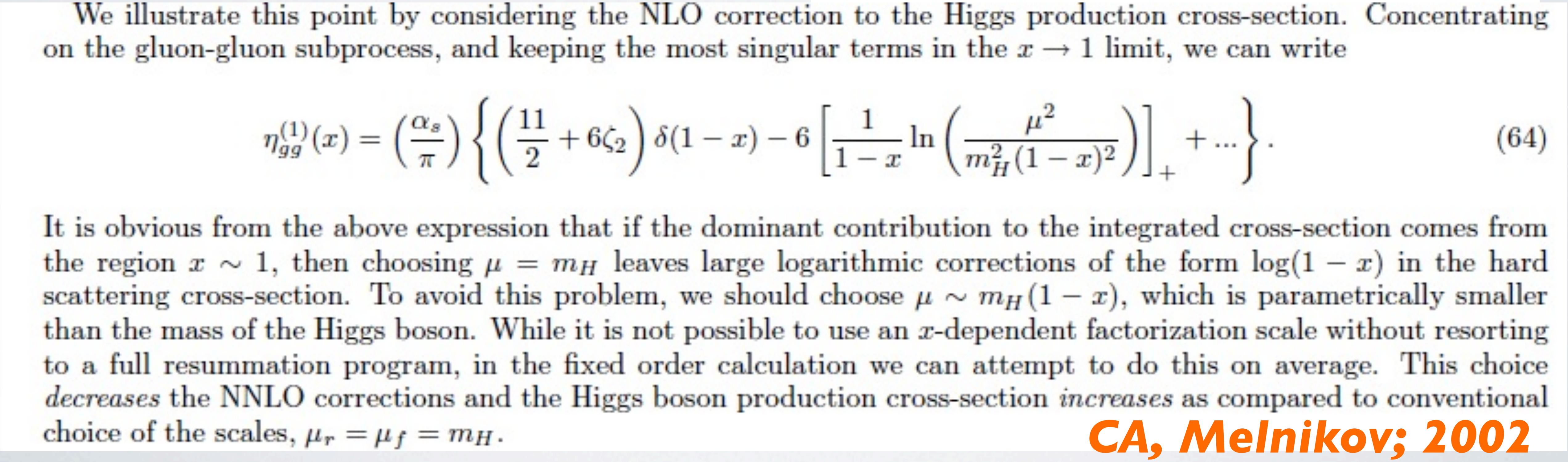


Figure 3: The uncertainty of the Higgs cross-section due to the parton distribution functions.

SCALE VARIATIONS

- We find that the perturbative series converges well for scales around half the Higgs mass
- We vary the scale in the interval [Mh/4, Mh]




We illustrate this point by considering the NLO correction to the Higgs production cross-section. Concentrating on the gluon-gluon subprocess, and keeping the most singular terms in the $x \to 1$ limit, we can write

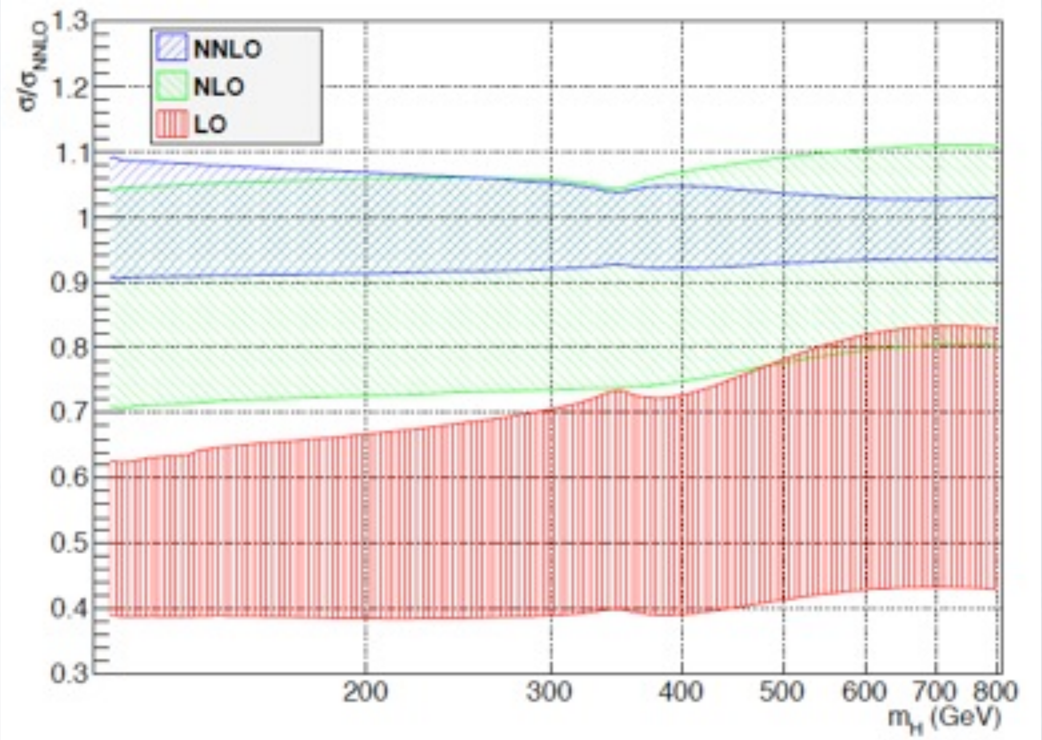
$$\eta_{gg}^{(1)}(x) = \left(\frac{\alpha_s}{\pi}\right)\left\{\left(\frac{11}{2}+6\zeta_2\right)\delta(1-x) - 6\left[\frac{1}{1-x}\ln\left(\frac{\mu^2}{m_H^2(1-x)^2}\right)\right]_+ + \ldots\right\}. \qquad (64)$$

It is obvious from the above expression that if the dominant contribution to the integrated cross-section comes from the region $x \sim 1$, then choosing $\mu = m_H$ leaves large logarithmic corrections of the form $\log(1-x)$ in the hard scattering cross-section. To avoid this problem, we should choose $\mu \sim m_H(1-x)$, which is parametrically smaller than the mass of the Higgs boson. While it is not possible to use an x-dependent factorization scale without resorting to a full resummation program, in the fixed order calculation we can attempt to do this on average. This choice *decreases* the NNLO corrections and the Higgs boson production cross-section *increases* as compared to conventional choice of the scales, $\mu_r = \mu_f = m_H$.

CA, Melnikov; 2002

THEORY ERROR PROPAGATION IN THE LIKELIHOOD DETERMINATION

- PDF uncertainties can be treated with Gaussian priors in the calculation of the likelihood.
- Perturbative uncertainties have no such statistical interpretation.
- Notice, for example, that the NNLO band lies at the upper extremity of the NLO band.
- A flat prior must be assigned to the pdf uncertainty.



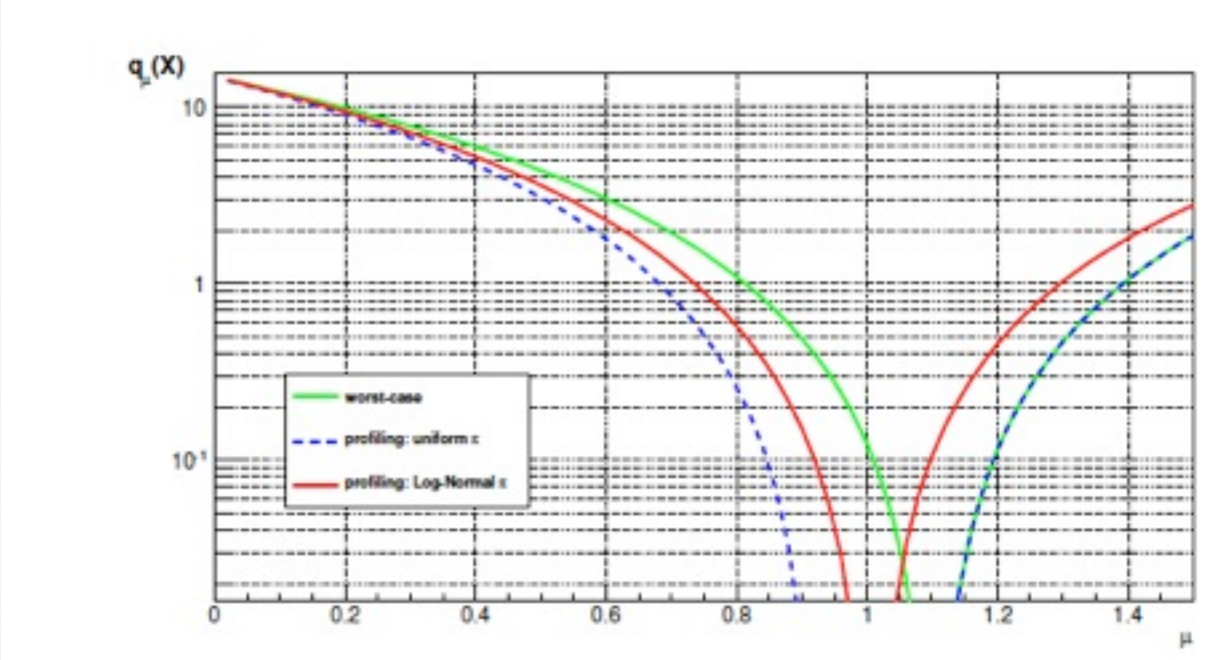
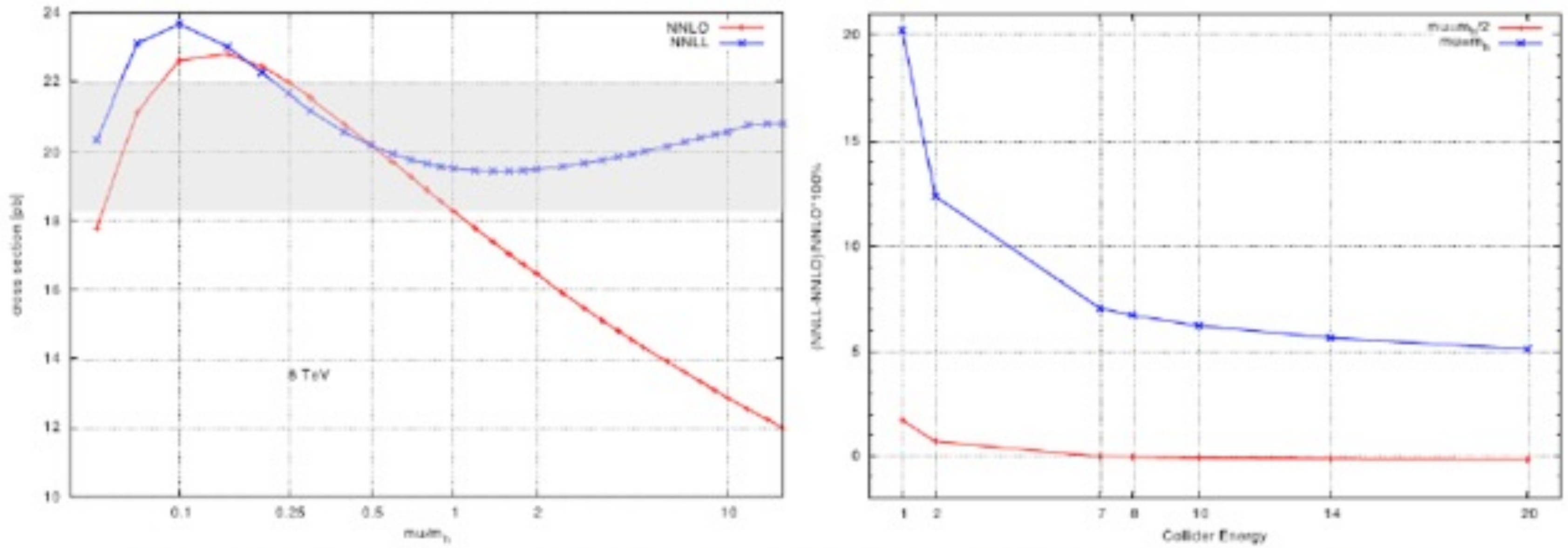


Figure 3. The test-statistic obtained with the worst-case (green) and the profiling method using a uniform (blue) or log-normal (red) likelihood $\pi(1|\hat{\rho}_\mu)$ as a function of μ. As one can see, the worst-case method and the profiling method with a flat π result in equal values for the test-statistic in the region $\mu > \mu'$. Consequently, the exclusion limits obtained from both methods are the same.

CHECKS AGAINST KNOWN BEYOND NNLO EFFECTS

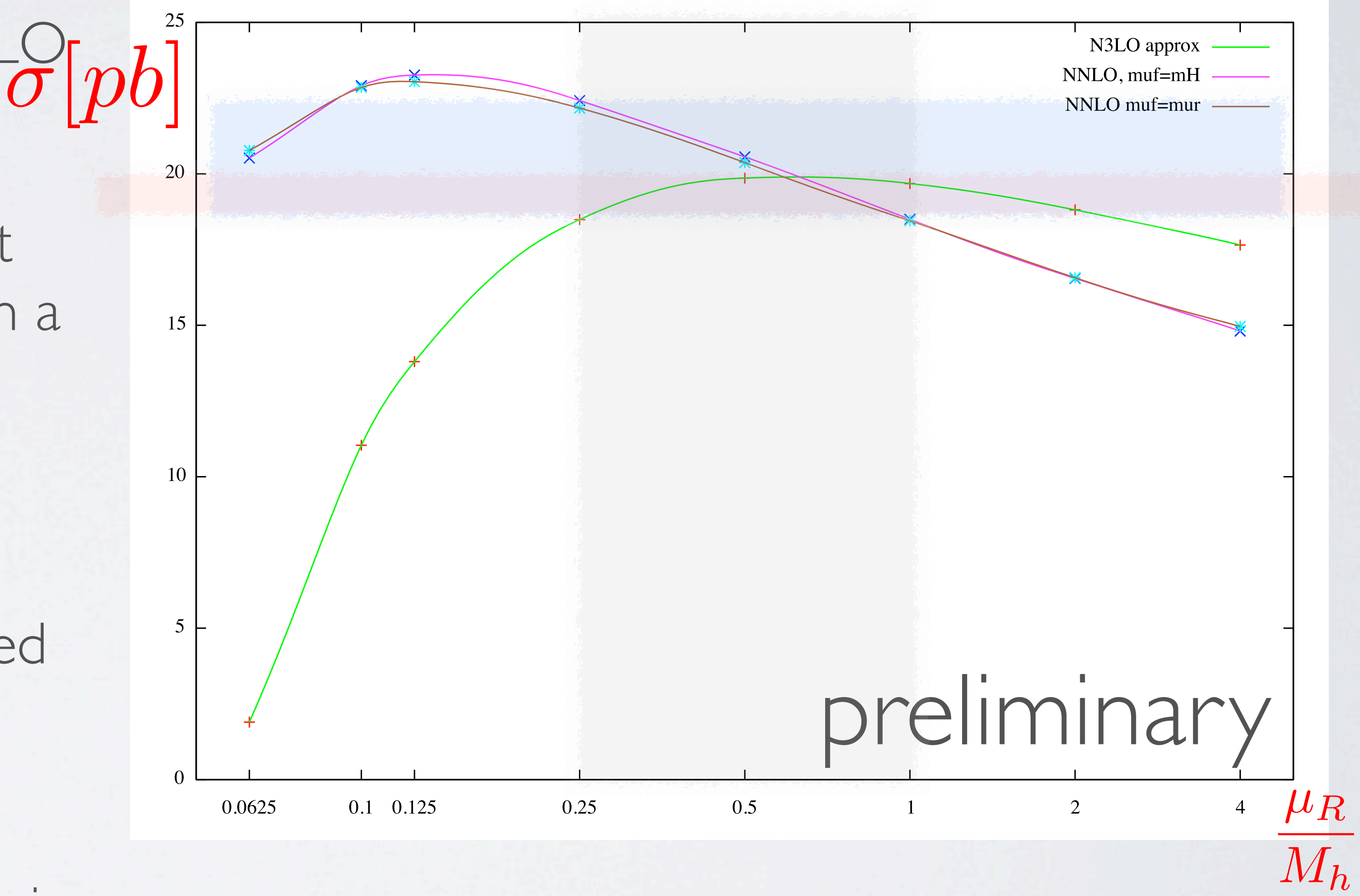


All numbers for these plots are calculated with the online calculator by M. Grazzini, see http://theory.fi.infn.it/grazzini/hcalculators.html

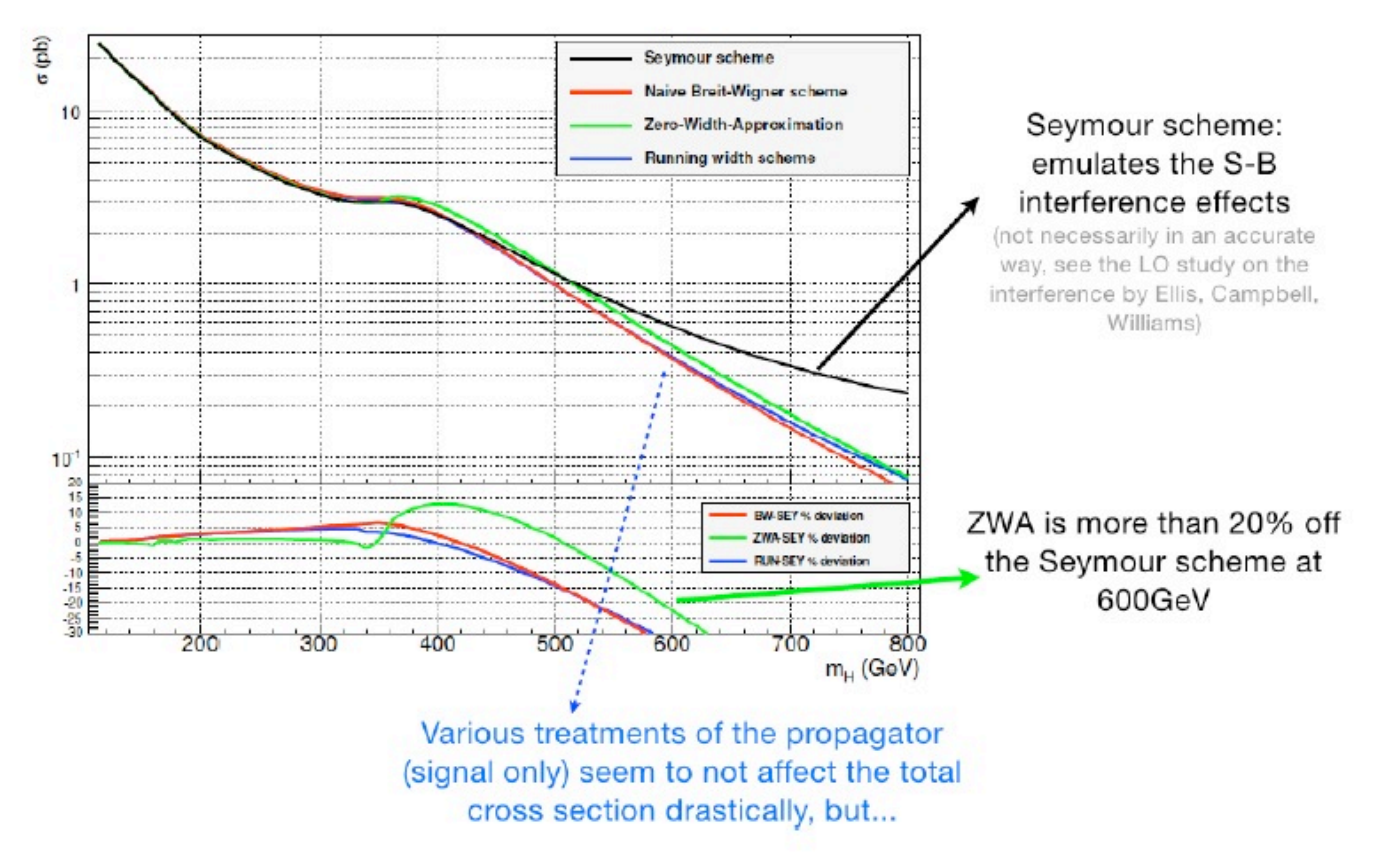
- We have compared NNLO vs NNLL resummation of Grazzini, de Florian.
- For low renormalization scales < Mh, the NNLL and NNLO results agree extremely well.
- For higher scales, outside our variation choices, NNLO keep decreasing monotonically but NNLL develops a minimum at around mu_R = Mh
- For our scale choice, NNLL and NNLO agree extremely well for a vast range of collider energies, from the Tevatron to beyond LHC energies.
- We notice that NNLO is virtually insensitive to variations of the factorization scale (~1%). NNLL is more sensitive (~5%). An interesting feature that we would like to investigate further.

APPROXIMATE N3LO

- We have just implemented the soft NNNLO contributions of Moch & Vogt in ihixs.
- These include all logarithmic corrections at this order which need to be regulated with a plus prescription.
- Such contributions are defined with an ambiguity of subleading integrable logarithmic contributions. Can only be fixed with a complete NNNLO computations.
- Adopting the same separation of soft and hard, as in the SVC approximation of Catani de Florian Grazzini. we find a consistent “NNNLOapprox”



IHIXS ALERT OF IMPORTANT NON-FACTORIZED EFFECTS



Seymour scheme: emulates the S-B interference effects

(not necessarily in an accurate way, see the LO study on the interference by Ellis, Campbell, Williams)

ZWA is more than 20% off the Seymour scheme at 600GeV

Various treatments of the propagator (signal only) seem to not affect the total cross section drastically, but...

WHY DO WE NOT PROVIDE “SIGNAL ONLY” INCLUSIVE CROSS-SECTIONS ABOVE 400 GEV?

- The distinction of resonant vs non-resonant is not diagrammatic. It is kinematic. (see Adrian’s talk)
- We shall do the separation carefully, expanding all diagrams in the amplitude of the full process in width/mass.
- The outcome depends on the final state...
- and the cuts designed to uncover such a wide resonance.

The king

$\sigma_{total} \times \mathrm{BR} \times \mathrm{efficiency}$

is dead...

“If there are certain pages ... which seem rather empty, that is merely to say that we have now sunk to a depth at which the restatement of the obvious is the first duty of intelligent men.”, George Orwell