Theory of the Higgs production in hadron collisions

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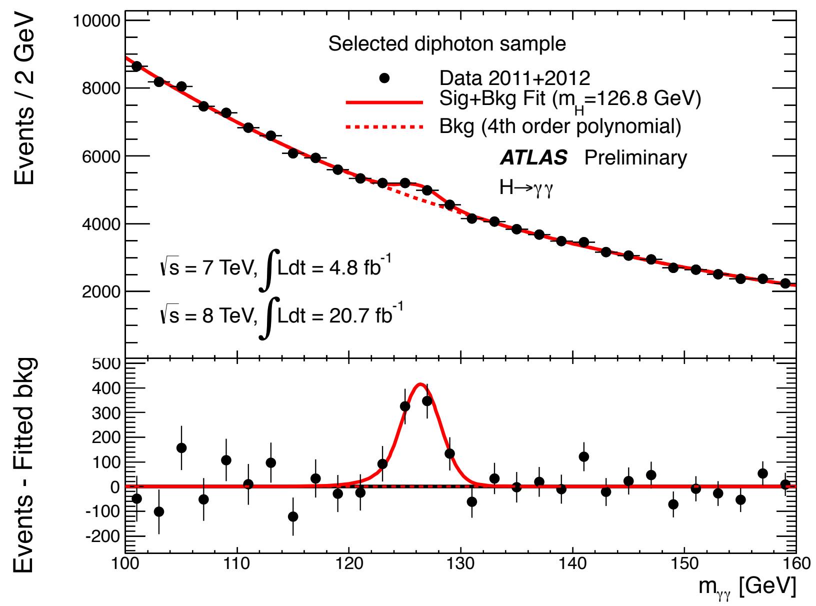
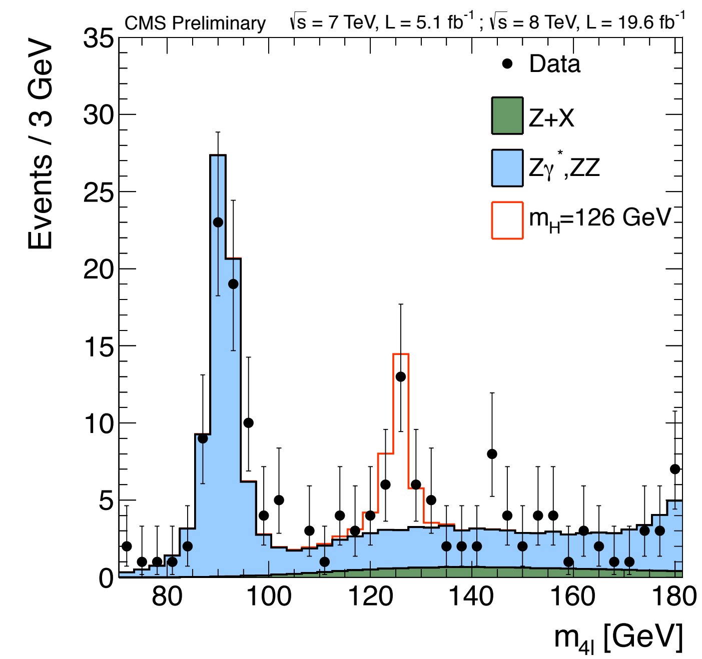
Higgs Hunting 2013

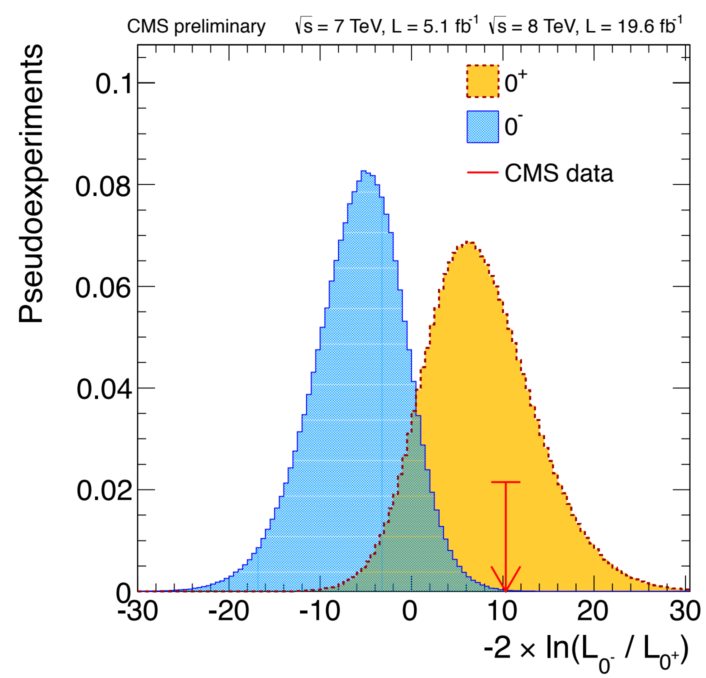
The discovery of the Higgs boson

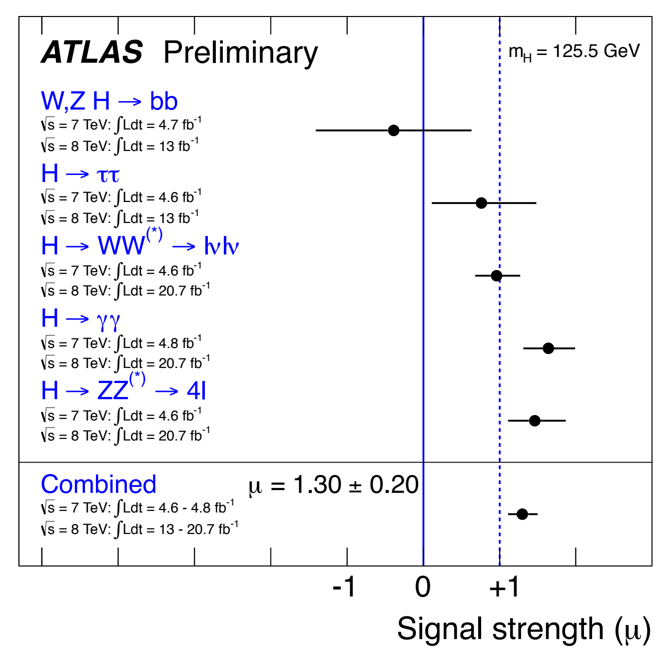
The discovery of the Higgs boson by CMS and ATLAS collaborations has rapidly turned into detailed studies of various properties of the new particle.

The Higgs boson signal







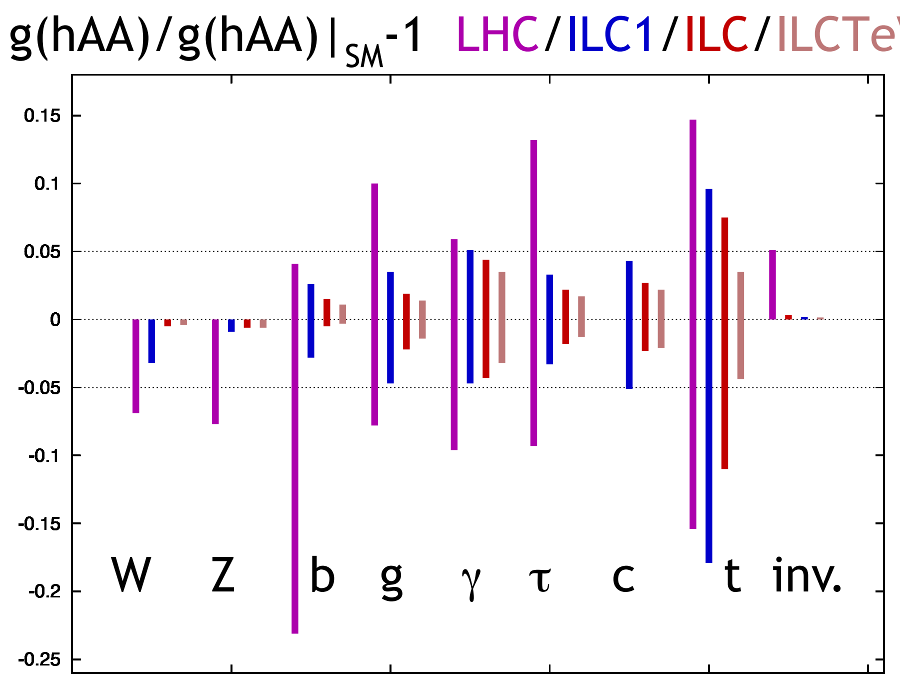


A common theme that comes out of these studies is that the new particle is very similar to the Standard Model Higgs boson. This implies that searches for BSM physics in Higgs production and decay will require good control of theoretical predictions within the SM and attention to subtle details.

The Higgs boson signal: precision target

To set a scale for what we want to achieve, let us recall that BSM physics at the TeV scale may change the Higgs couplings (and therefore Higgs production cross-sections) by a few percent:

$$g = g_{\rm SM}\left(1+\mathcal{O}\left(v^2/\mathrm{TeV}^2\right)\right)$$



Observable	Expected Error (experiment ⊕ theory)
LHC at 14 TeV with 300 fb^{-1}	
$\sigma(gg)\cdot BR(\gamma\gamma)$	$0.06 \oplus 0.13$
$\sigma(WW)\cdot BR(\gamma\gamma)$	$0.15 \oplus 0.10$
$\sigma(gg)\cdot BR(ZZ)$	$0.08 \oplus 0.08$
$\sigma(gg)\cdot BR(WW)$	$0.09 \oplus 0.11$
$\sigma(WW)\cdot BR(WW)$	$0.27 \oplus 0.10$
$\sigma(gg)\cdot BR(\tau^+\tau^-)$	$0.11 \oplus 0.13$
$\sigma(WW)\cdot BR(\tau^+\tau^-)$	$0.15 \oplus 0.10$
$\sigma(Wh)\cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Wh)\cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(Zh)\cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Zh)\cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(t\bar{t}h)\cdot BR(\gamma\gamma)$	$0.42 \oplus 0.10$
$\sigma(WW)\cdot BR(\text{invisible})$	$0.2 \oplus 0.24$

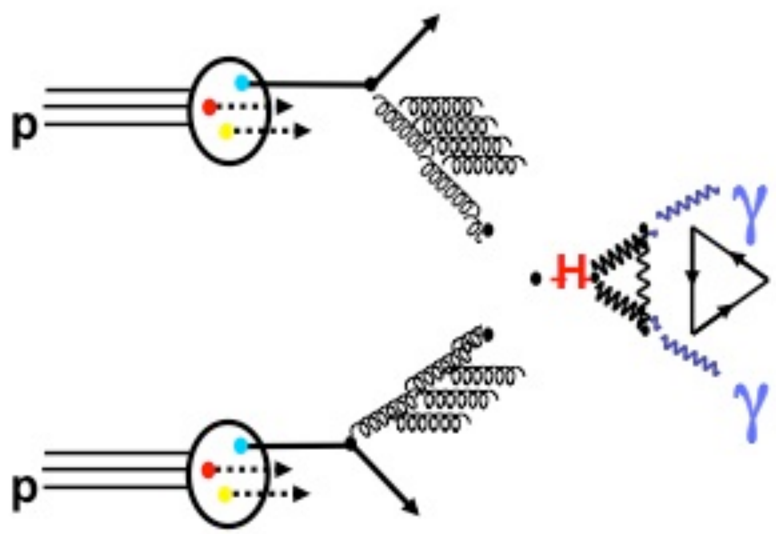
M. Peskin

The precision with which the Higgs couplings can be measured at the LHC are estimated to be in the range between 5 and 20 percent; with comparable contributions due to theoretical and experimental uncertainties. These numbers are not dramatically different from expected BSM effects. Therefore, it is important to keep focus on improving measurement techniques and theory predictions for major Higgs production processes at the LHC; by doing that we may, in fact, discover something interesting.

Theory of the Higgs production

Our understanding of Higgs boson production rates in hadron collisions is based on QCD factorization theorems. They imply that Higgs production at the LHC can be described in perturbative QCD and that theoretical predictions are systematically improvable without obvious showstoppers.

$$\sigma_{pp\to H} = \sum_{ij} \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \mathrm{d}\sigma_{ij\to H} \mathcal{F}_{\rm obs} \left(1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\right)$$



Perturbation theory is far from trivial. To obtain reliable description of various Higgs production processes in hadron collisions, we must understand

1) parton distribution functions;

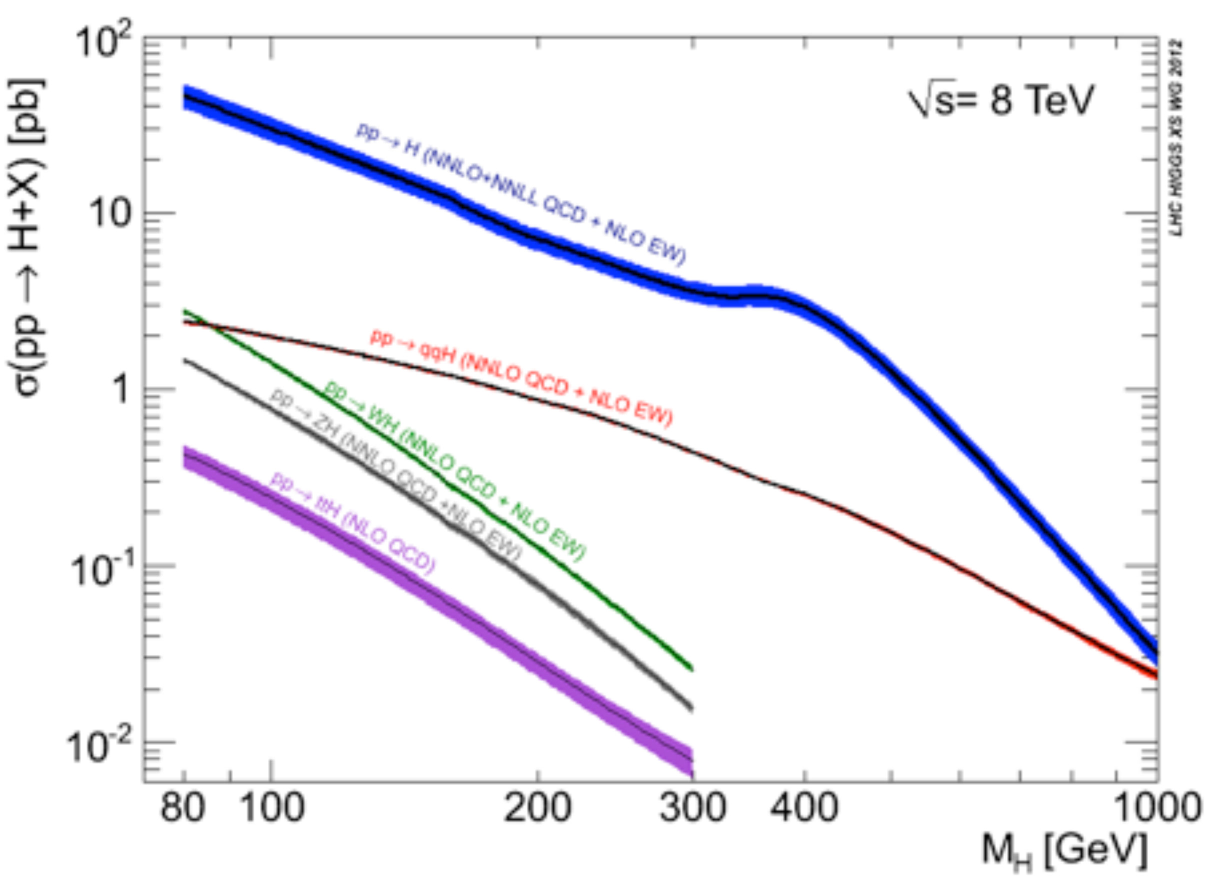
2) experimental realities (jets, jet vetoes, acceptancies);

3) higher-order QCD effects in partonic cross-sections.

It is important to stress that only by gaining full control over QCD, can we get access to interesting aspects of Higgs physics such as values of the couplings, the mass, the spin, the width, etc. This is the reason why perturbative QCD is so important for Higgs physics at the LHC

Theory of the Higgs production

Theory of the Higgs production is in a good shape: main Higgs production cross-sections are currently known to O(1-15) percent precision and existing tools often allow us to compute realistic observables.



Higgs cross-sections working group

Gluon fusion: NNLO QCD, (inlcusive and differential), NLO EW, QCD resummations, mixed EW-QCD, 1/mt corrections ; H+1j, H+2j @NLO

15%

Weak boson fusion: NNLO QCD (inclusive), NLO EW, WBF+1j @ NLO

$\sim 1\%$

Higgs Strahlung: NNLO QCD (differential), NLO EW, VH+1j @NLO

$\sim 1\%$

ttH production: NLO QCD, including matching to parton showers

$\sim 10\%$

Given the very advanced stage of the Higgs boson production theory, it is quite remarkable that the pace of progress accelerated after the Higgs discovery and we have witnessed very interesting developments in the past year. The goal of my talk is to summarize them.

Progress with understanding Higgs production

I think there are three main directions in current physics of the Higgs boson production:

1) search for subtle effects that could have been overlooked previously and may lead to either misinterpretation of the Higgs signal or help with better understanding Higgs properties;

2) application of high-level QCD theory (NNLO, resummations, SCET, merging, matching) to more exclusive processes and observables;

3) study exotic Higgs production options with an eye on the LHC future.

To illustrate these points, I will describes some examples of recent developments in Higgs production theory

1) estimates of the Higgs production cross-section in gluon fusion beyond NNLO;

2) Higgs pair production at the LHC beyond the infinite top mass limit;

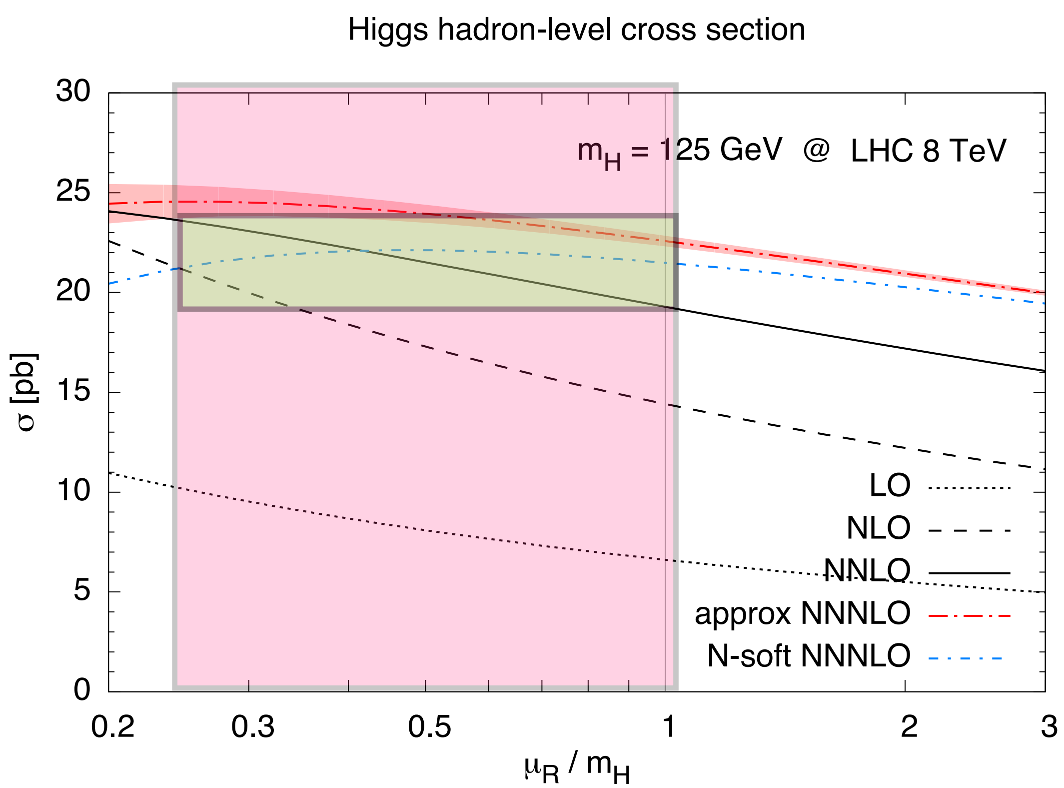
3) Higgs transverse momentum distribution and finite mass effects;

4) Higgs production with or without jets;

5) off-shell effects and signal - background interference in the Higgs production.

Higgs boson gluon fusion: inclusive cross-section

The gluon fusion Higgs production cross section is clearly one of the major elements in the Higgs program at the LHC. Its cross section is known to be strongly affected by higher order QCD effects. The current state-of-the art is the NNLO in QCD, so moving forward will require us to either compute or estimate the three-loop corrections.



R. Ball, M. Bonvini et al.

Earlier work by Catani, Grazzini, de Florian, Moch, Vogt, Becher and Neubert

Estimates of QCD corrections to Higgs production make use of universal enhancement mechanisms of fixed-order contributions such as soft and collinear emissions and BFKL-type behavior at high energy.

The most recent study claims the increase in the NNLO cross-section by 10-15 percent, depending on the original value of the renormalization and factorization scales, and a much better stability with respect to scale variation.

The new results are quite consistent with scale choices used in previous computations.
In particular, if $\mu = \frac{m_H}{2}$, the shift (8%) does not look dramatic when compared with previous uncertainty estimates (~ 10%). Nevertheless, the O(10) percent shift is, most-likely, to be expected and so uncertainty estimate in NNLO cross-section is to be taken seriously.

Higgs boson gluon fusion: inclusive cross-section

While approximate results are based on good understanding of physics relevant for Higgs production, and therefore look appealing, it is important to have them backed up by exact computations. Next step for the Higgs production in gluon fusion is N3LO... How far are we from getting it?

It may be that the three-loop computation is actually closer than it seems... Indeed, we now have

1) very powerful reduction algorithms of complicated Feynman integrals to master-integrals;

2) new ideas on how integrals can be computed. Three-loop predictions for Higgs decay to gluons and the three-loop result for the Hgg form-factor;

Smirnov, Henn, Duhr, Baikov, Chetyrkin, Lee, Gehrmann, Glover, Huber, Ikizleri, Studerius

4) two-loop approaches to real radiation (``reverse unitarity") combined with threshold expansion seem to hold up also at NNNLO;

Anastasiou, Duhr, Dulat, Mistlberger

5) complete computations of the scale dependence of NNNLO cross-sections from the known NNLO results and corresponding results for collinear renormalization terms

Hoschele, Hoff, Pak, Steinhauser, Ueda

Buehler, Lazopoulos

Higgs boson gluon fusion: inclusive cross-section

It is probably a safe bet that Higgs production in gluon fusion will be known through N3LO sooner, rather than later. This will be very important -- it will mean that we can turn a 60 percent NLO QCD correction into a few percent uncertainty and that Higgs physics at the LHC is becoming a truly precision physics.

However, it is important to remember that for any quantitative conclusion about the true size of these N3LO corrections, we need to understand gluon (and other) parton distribution functions at N3LO level.

It is difficult to imagine how this can be done in a self-consistent way. However, it is quite possible to see how this can be accomplished in the context of resummed calculations, primarily because resummations to high orders are available for a larger number of processes than the number of processes for which exact N3LO computations exist.

Determination of the PDF sets that can be used consistently with yet higher order predictions for Higgs production in gluon fusion is an important task that PDF fitting community should be aware of.

Higgs pair production at the LHC

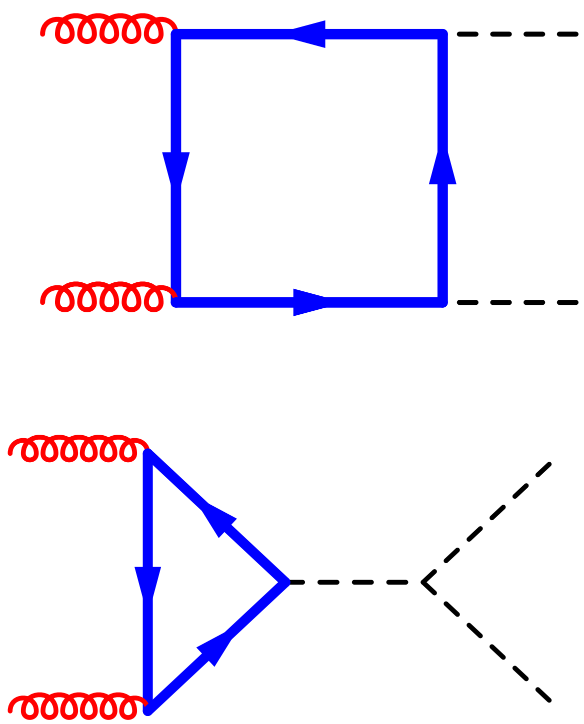
To what extent does the Higgs boson look Standard Model like? An answer to this question is very important for the future of high-energy physics program worldwide. Usually we address this question by focusing on Higgs couplings to other Standard Model particles.

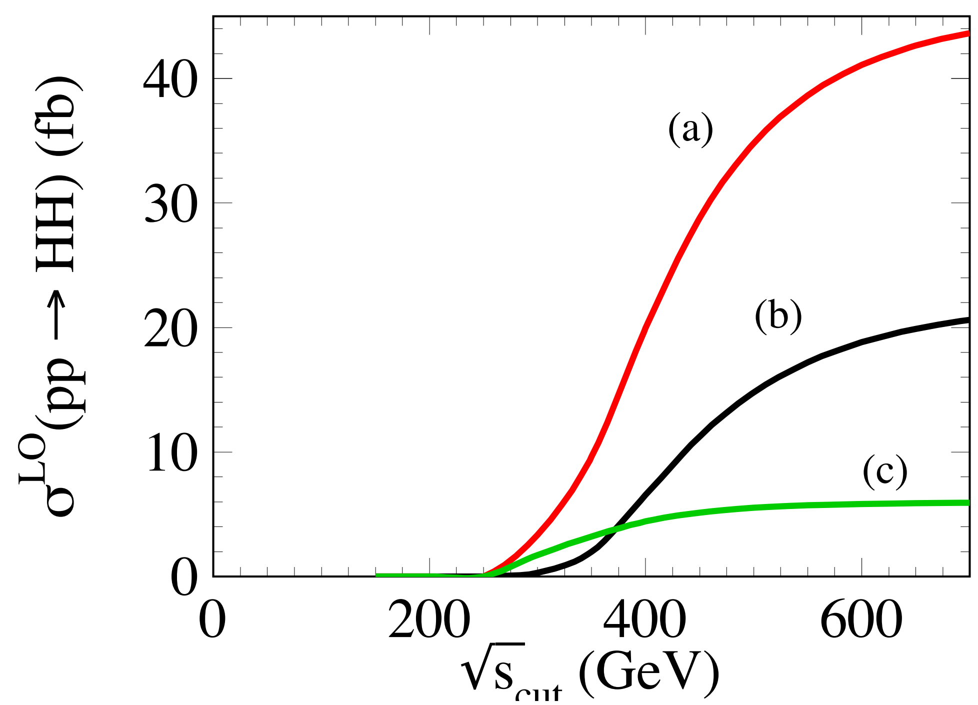
While it is important to do this with the utmost precision, it is also very exciting to test if the Higgs self-coupling exists and, if it does, is it the same as in the Standard Model. This is a difficult task, both experimentally and theoretically -- but it may be very rewarding. Indeed, by probing the Higgs coupling, we can measure the part of the Lagrangian that is directly responsible for EW symmetry breaking.

$$V(\varphi) = V(v) + \frac{V''}{2} h^2 + \frac{V'''}{6} h^3 + \ldots$$

The Higgs self-coupling can be explored using Higgs pair production at the LHC.

Baur, Plehn, Rainwater





Large destructive interference between box and triangle diagrams

Higgs pair production at the LHC

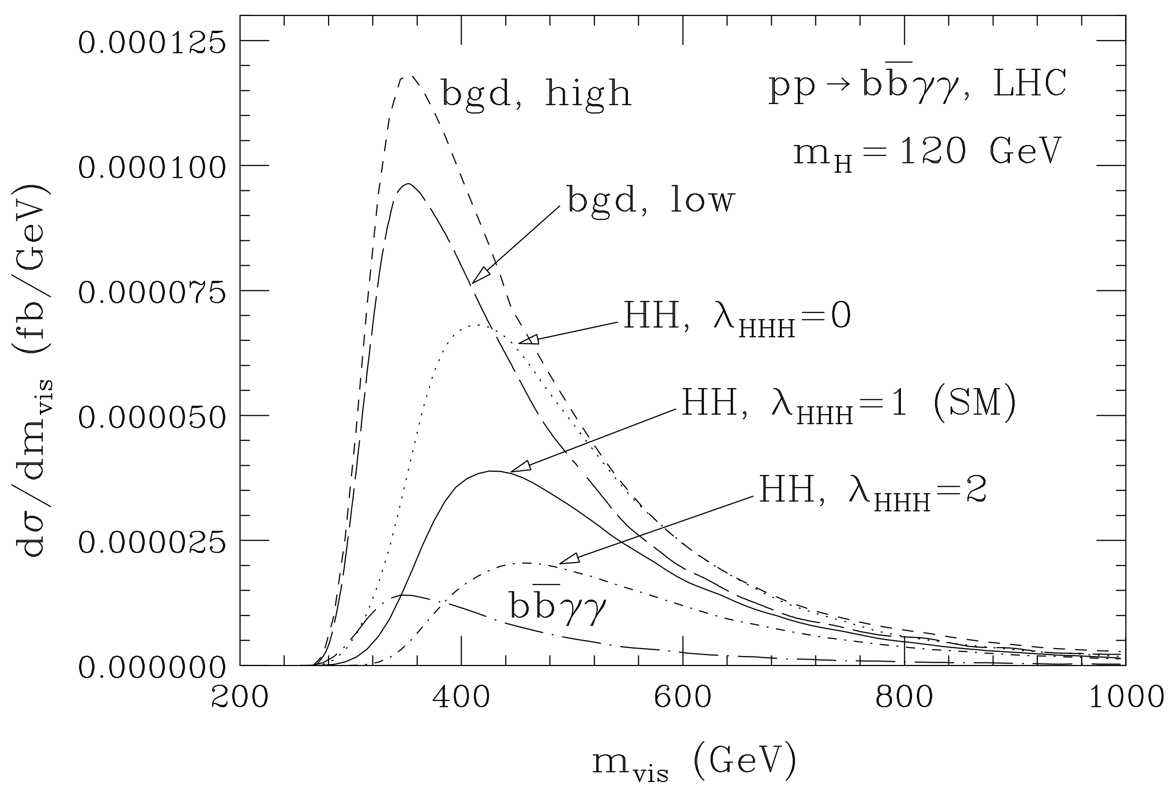
Measuring the Higgs boson self-coupling is difficult. Estimates of feasibility vary but it seems that a 30 percent self-coupling measurement is not unreasonable to expect. To achieve this, very high luminosity (3000/fb) is required.

Baur, Plehn, Rainwater; Baglio et al.; Goertz et al.; Dolan et al.

Reducible backgrounds (jets faking photons) dominate in $b\bar{b}\gamma\gamma$ channel, irreducible backgrounds are relatively minor problem.

Baur, Plehn, Rainwater

Major kinematic distributions for HH production should be controlled at the level of 10 percent, to achieve a 30 percent self-coupling measurement.



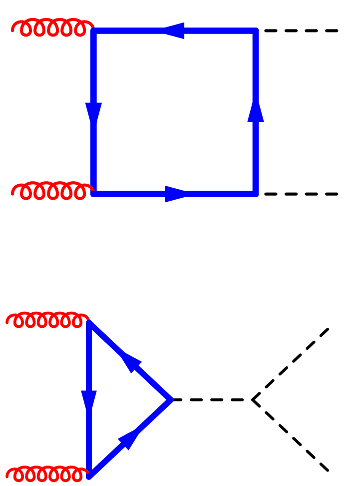
Baur, Plehn, Rainwater

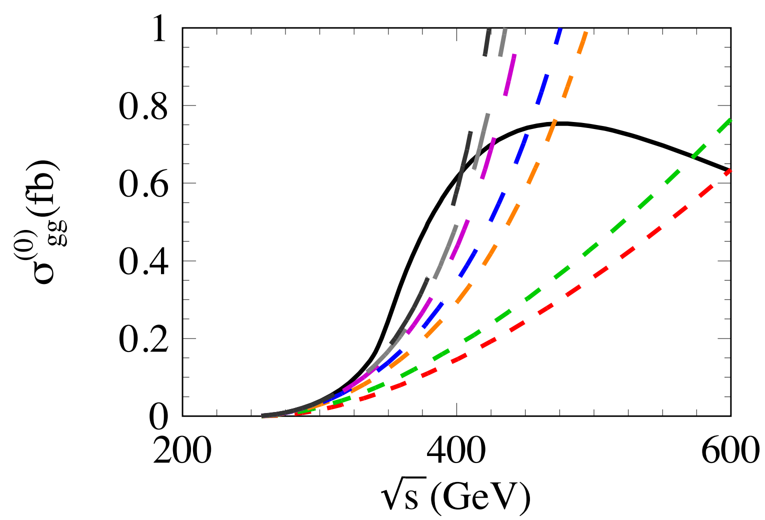
Higgs pair production at the LHC

It is difficult to achieve the required precision. Indeed, Higgs pair production suffers from large radiative corrections which, however, are only known in the approximation of infinitely heavy top quark.

Dawson, Dittmaier, Spira

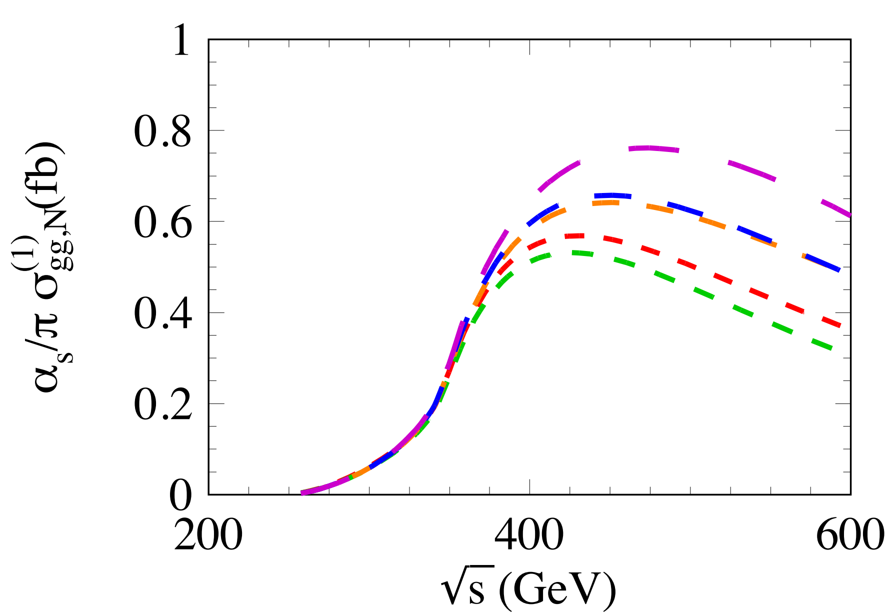
But, it is unclear how to use the large-Mt results in practice since exact leading order and large-Mt cross-sections show dramatically different behavior at relevant energies of colliding partons. Therefore, a high-priority question is to quantify the impact of finite-Mt corrections on the prediction for Higgs pair production cross-section. Can we estimate them? Are they small?





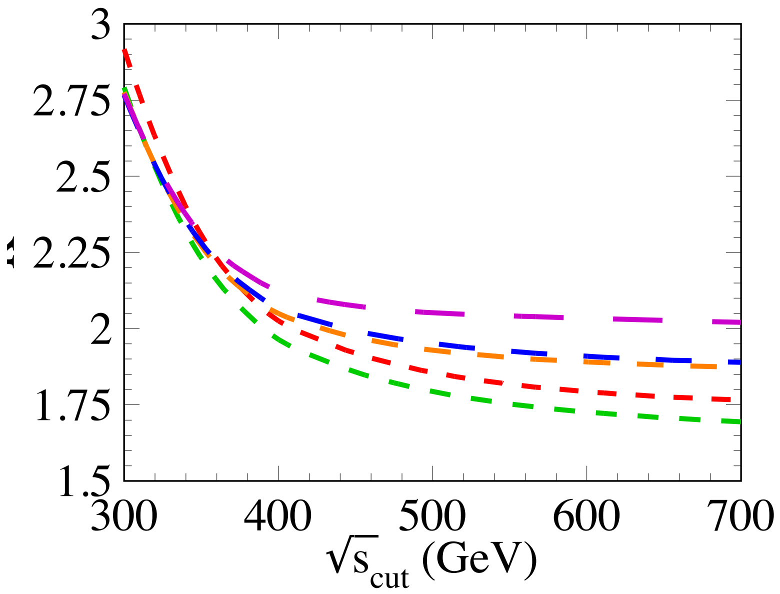
Grigo, Hoff, K.M., Steinhauser

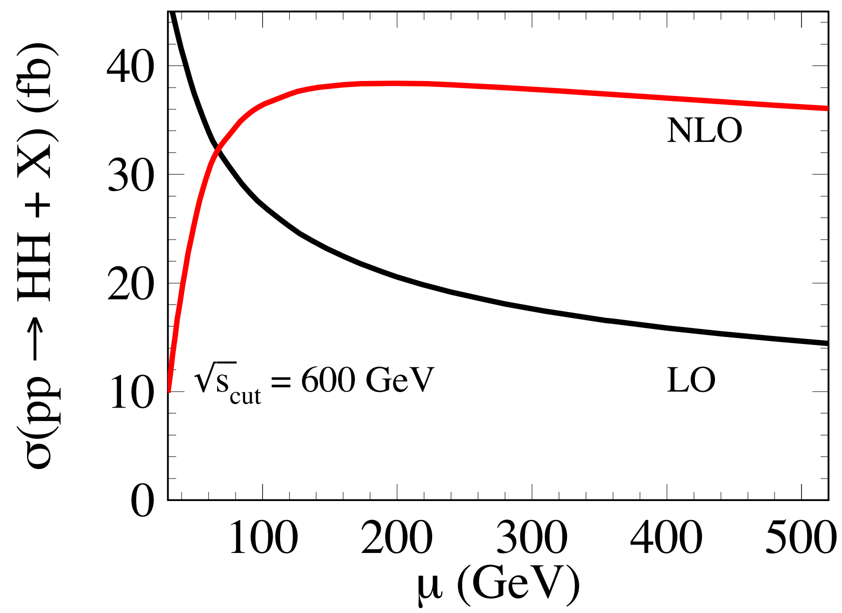
$$\sigma^{(1)}_{ij} = \sigma^{(0)}_{gg,\text{exact}} \Delta^N_{ij} \qquad \Delta^N_{ij} = \frac{\sigma^{(1)}_{ij,\text{exp}}}{\sigma^{(0)}_{gg,\text{exp}}} = \frac{\sum\limits_{n=0}^{N} c^{\text{NLO}}_{ij,n} \rho^n}{\sum\limits_{n=0}^{N} c^{\text{LO}}_{ij,n} \rho^n}$$



Taking ratios of expanded one- and two-loop results may help to extend cross-section estimates further into the region of large HH invariant masses; the reason for that is the dominance of soft emissions in large radiative effects in gluon fusion.

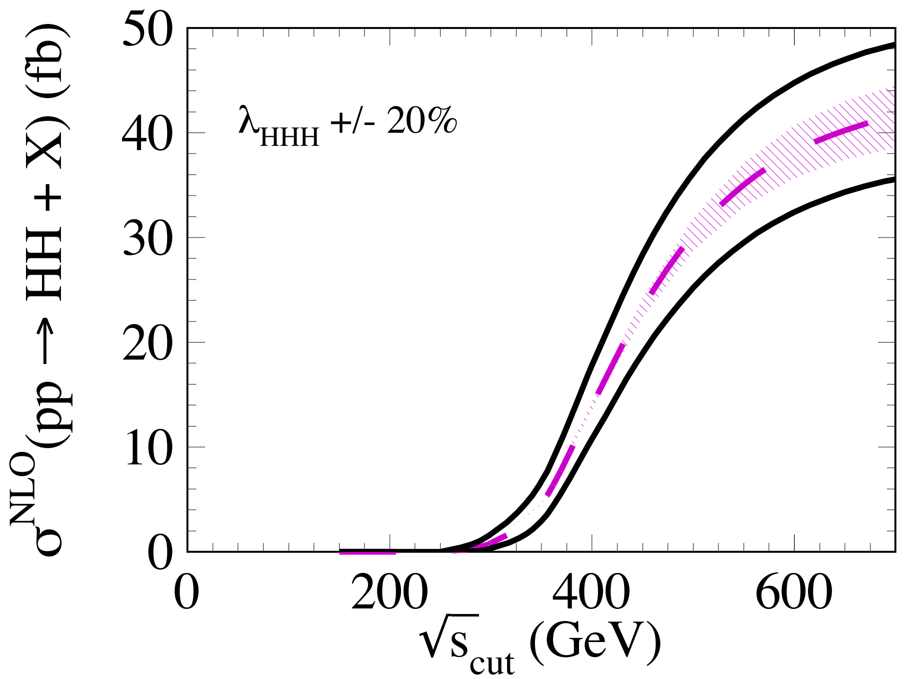
Higgs pair production at the LHC





K-factors change by about 10-15 percent when top-quark mass corrections are included

The scale dependence is significantly improved



These results show that infinite Mt approximation works reliably for total cross-section K-factor. This opens up a way to estimate NNLO QCD corrections to Higgs pair production. First (soft-virtual) results were recently obtained.

de Florian, Mazzitelli

The theory challenge now is to find a way to describe kinematic distributions with high precision. This is not possible with existing methods, so some ingenuity is required !

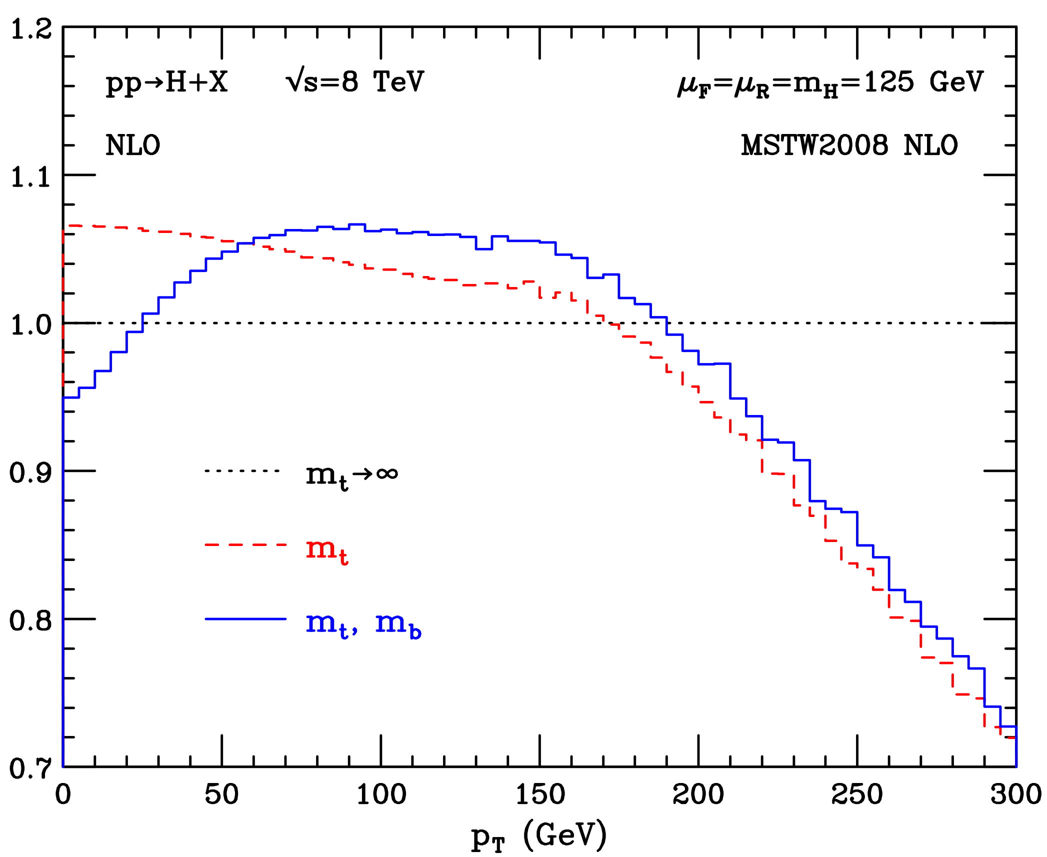
Sufficient control of the mass-dependent corrections to the cross-section, to detect 20 percent changes in the Higgs self-coupling

Grigo, Hoff, K.M., Steinhauser

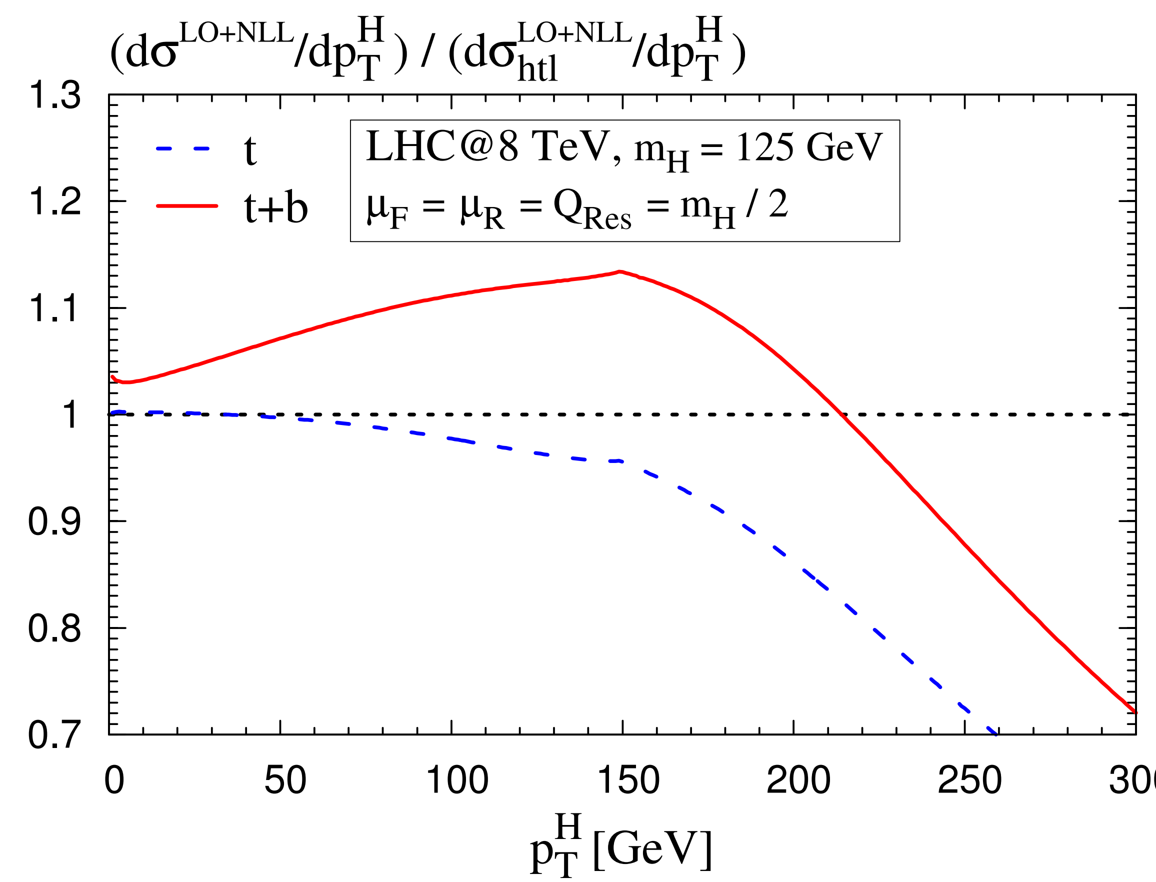
Mass effects in Higgs transverse momentum distribution

Many results on the Higgs production are derived in the approximation of the infinite top quark mass. There are many attempts to estimate the accuracy of this approximation for various observables and to understand better how finite quark mass effects can affect the Higgs production. Usually, one talks about top quark mass corrections, but recently there was an interesting discussion of b-quark contribution to Higgs transverse momentum distribution.

It is interesting that inclusion of the bottom quark loop to ggH vertex changes the shape of the distribution and creates large deviations from the infinite top mass limit at around 150 GeV. Why the Higgs transverse momentum -- where bottom contribution is important -- is so large?



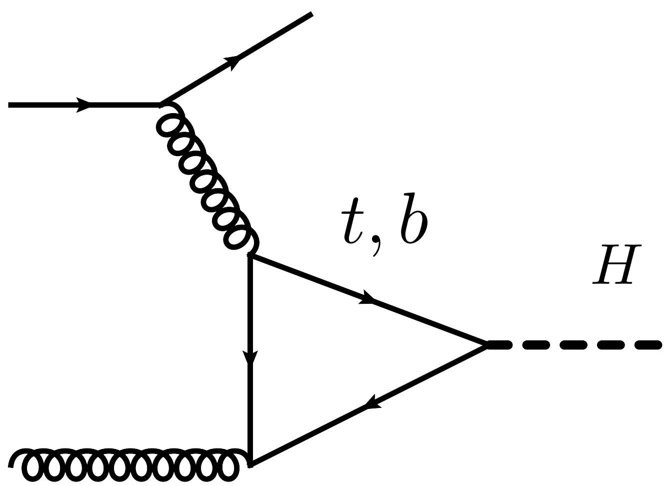
Grazzini, Sargsyan

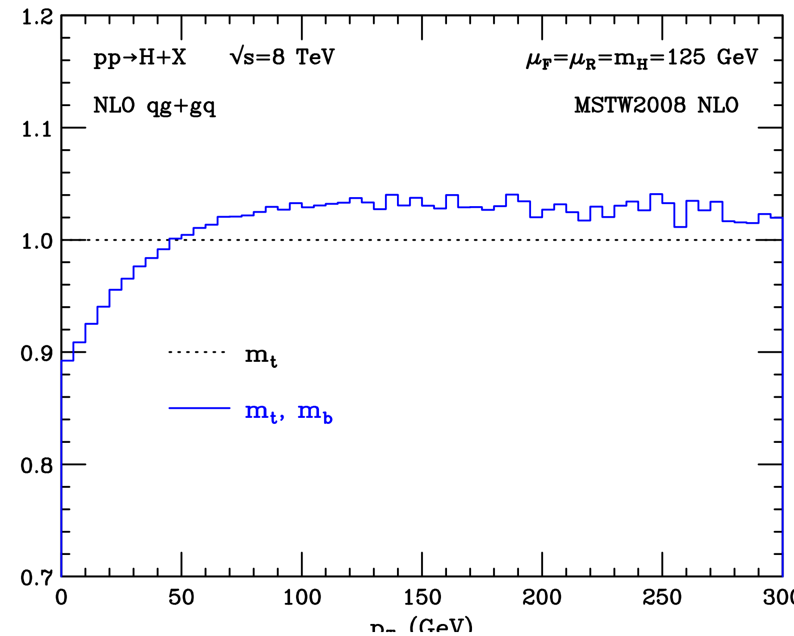


Mantler, Wiesemann

Mass effects in the transverse momentum distributions

Example from Grazzini, Sargsyan based on a paper by R.K. Ellis, Hinchliffe, Soldate, van der Bij





The b-quark loop affects the inclusive Higgs production cross-section by destructively interfering with the top loop, at low values of the Higgs transverse momentum. Once the Higgs transverse momentum increases, the b-quark loop contribution becomes smaller thereby reducing the the magnitude of negative interference and increasing the differential cross-section. Eventually, negative interference changes the sign and becomes positive.

$$|M_{qg\to qH}|^2 \sim \frac{m_h^2}{t}|A_5(s,t)|^2 \qquad A_5(s,0) = \frac{2}{3} - \frac{4m_b^2}{m_h^2}\ln^2\frac{m_h}{m_b} \approx 0.66 - 0.06$$

$$A_5(s,t)|_{m_b^2 \ll |t| \ll m_h^2} \approx \frac{2}{3} - \frac{4m_b^2}{m_h^2}\left(\ln^2\frac{m_h}{m_b} - \ln^2\frac{\sqrt{|t|}}{m_b}\right)$$

Anticipating discussion on the next slide, note additional double logarithmic contributions in the b-loop that are not accounted for in the standard transverse-momentum resummation

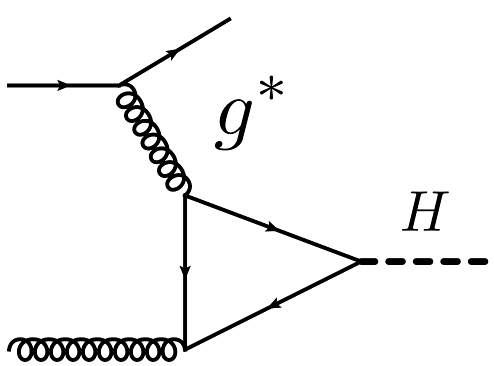
Mass effects in the transverse momentum distributions

Recent interest in finite mass effects in Higgs momentum distribution was related to heavy quark mass effects implementation in MC@NLO and POWHEG and the comparison between the two generators. The implementation and comparison produced somewhat counter-intuitive results (large b-quark effects at high transverse momenta) which were then scrutinized using analytic resummations.

Mantler, Wiesemann; Grazzini, Sarksyan

Resummation is performed by separating modes into ``soft'' and ``hard''. Hard modes go into Wilson coefficient, ``soft modes'' are dynamic. Hard and soft are separated by the factorization scale. The b-loop has an intrinsic scale given by its mass. It is not resolved only if the virtuality of the gluon is small compared to the b-quark mass. One can use different resummation scales for top and bottom loops to ensure correct behavior of ``re-summed'' radiation in the two cases.

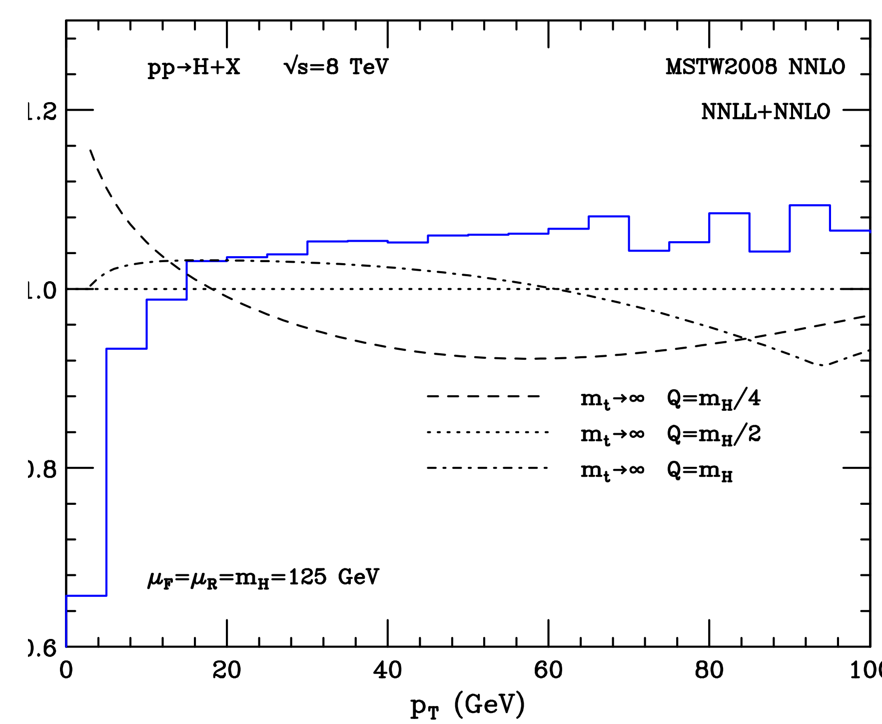
Grazzini, Sarksyan



$$\mathrm{d}\sigma_N(b) \sim \mathcal{H}_N(m_H, Q) \times e^{\mathcal{G}(\ln(Qb/b_0), Q)}$$

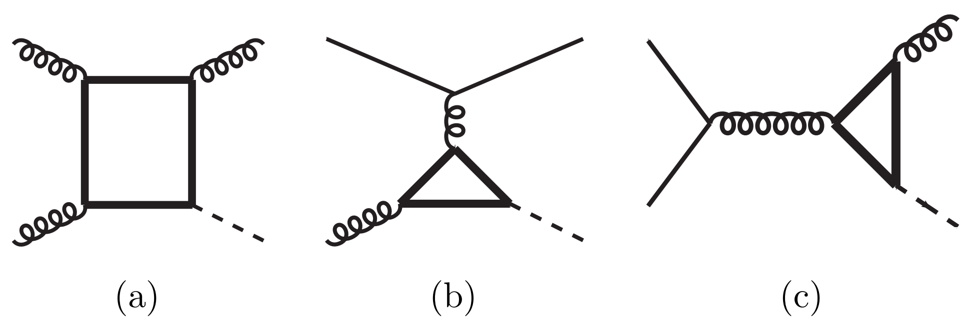
$$Q_t \sim m_H \qquad Q_b \sim m_b$$

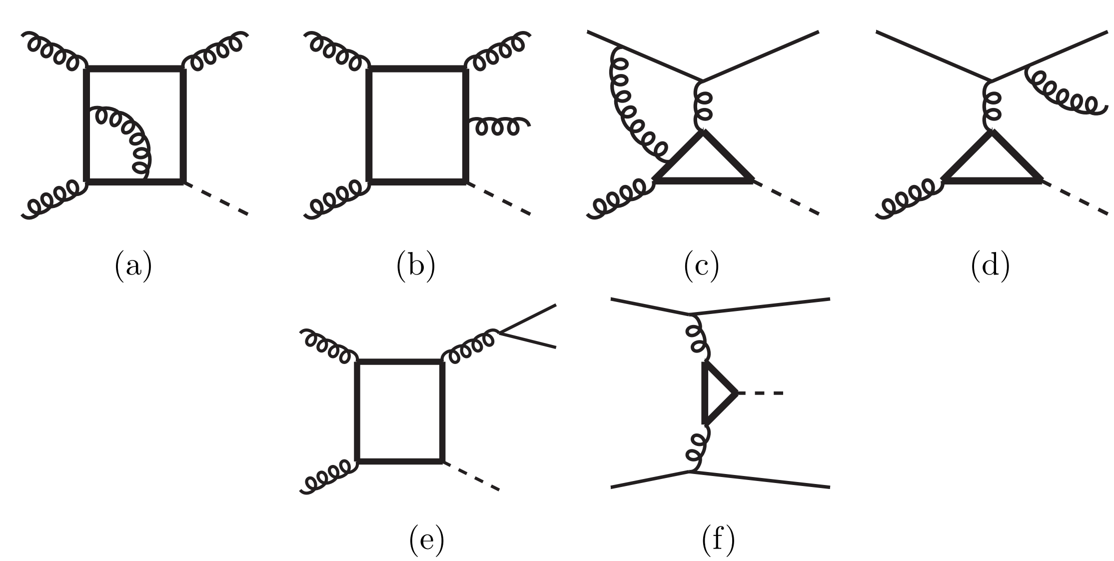
The effects are important at small transverse momenta and are comparable to the current uncertainties in NNLL +NNLO resummations for Higgs $p_\perp$ distribution.

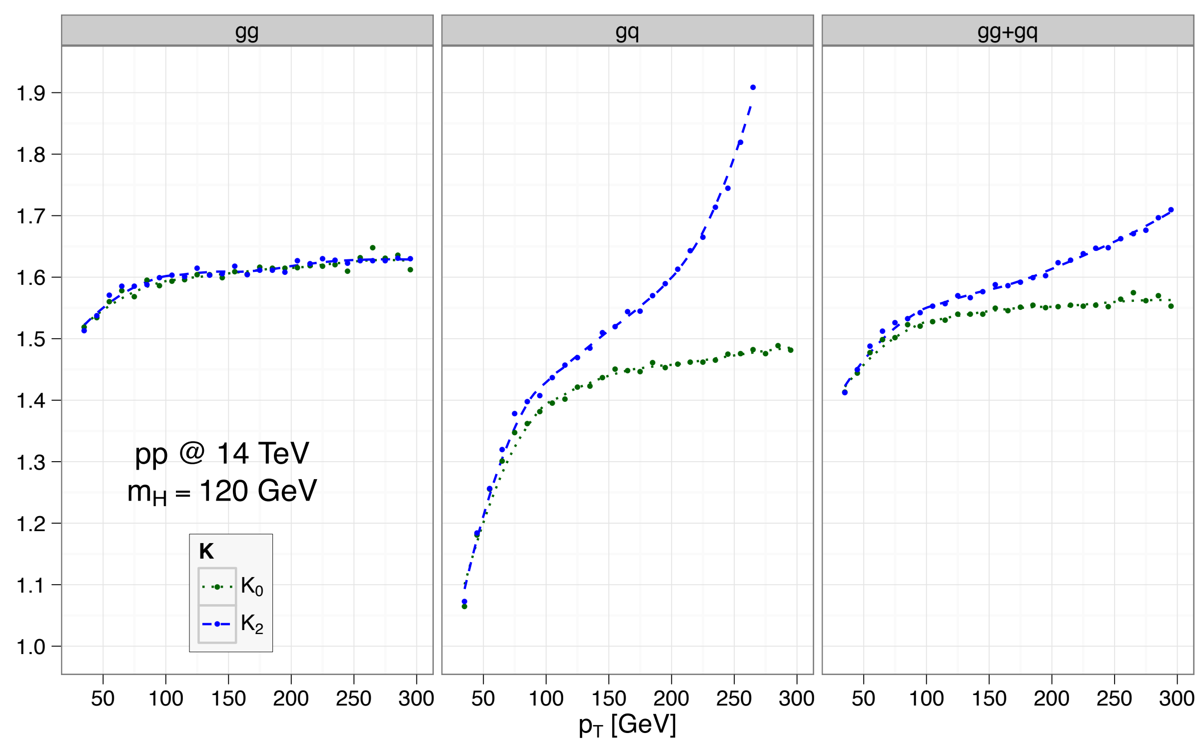


Top quark mass effects in Higgs production

The preceding discussion of Higgs transverse momentum is, strictly speaking, the leading-order one, albeit for finite values of quark masses. To improve on that, two-loop computations are required. This was recently done in the context of 1/mt expansion. The ratio of NLO to LO expanded differential cross-sections turned out to be stable against 1/mt expansion, especially in gg channel. A useful way to approach mass effects in more differential observables?







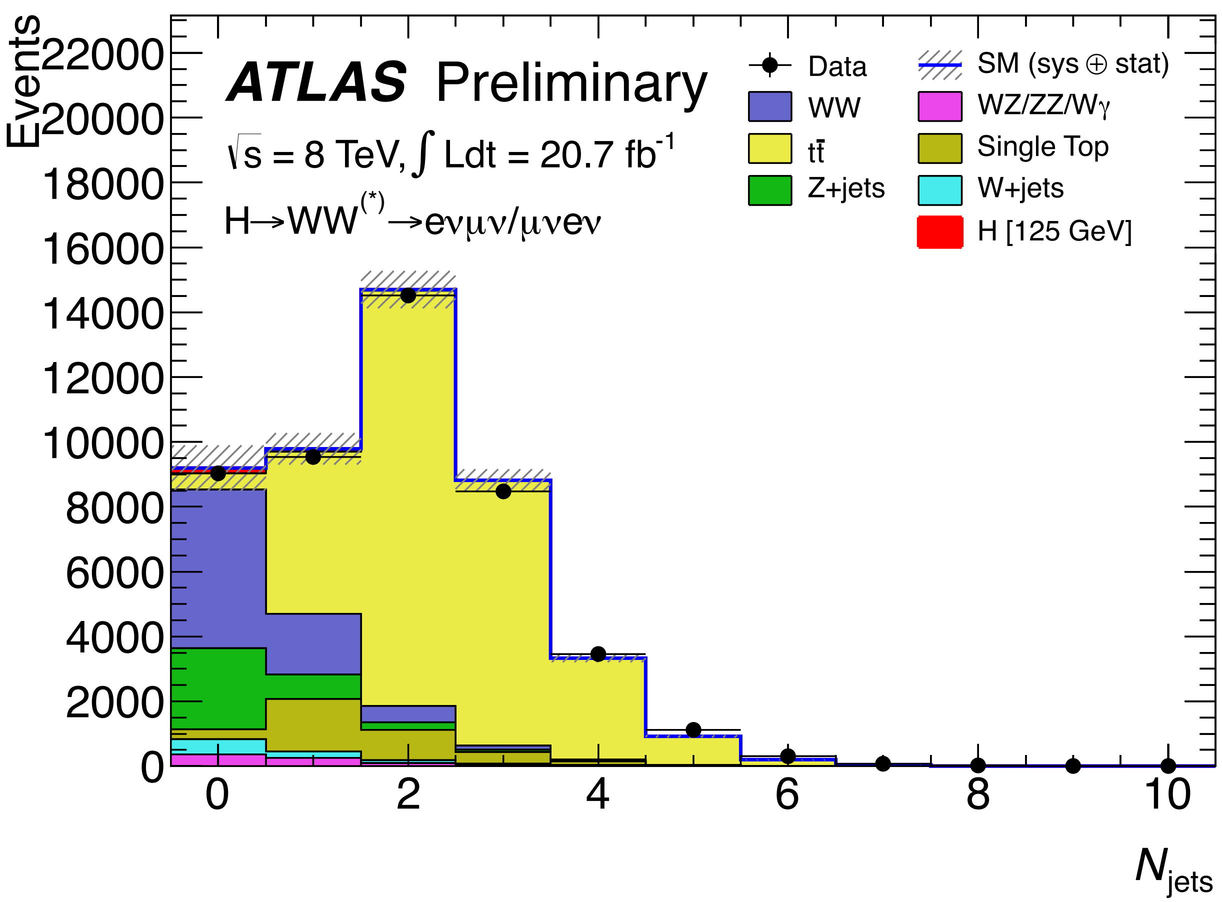
R. Harlander et al.

$$\rho = \frac{s}{m_t^2}$$

$$d\sigma^{(i)}(N) = \sum_{n=0}^{N} \rho^n d\sigma_n^{(i)}(N), \quad i = \mathrm{LO}, \mathrm{NLO}$$

$$K_N(p_\perp) = \frac{d\sigma^{\mathrm{NLO}}/p_\perp(N)}{d\sigma^{\mathrm{LO}}/\mathrm{d}p_\perp(N)}$$

Higgs production in association with jets



Experimental analyses of Higgs decays to W-bosons splits the Higgs signal according to jet multiplicities since backgrounds for H+0 jets, H+1 jet and H+2 jets are different.

Signal to background ratios in H+1 and H+2 jet bins are small -- signals are at best O(10) percent of the background.

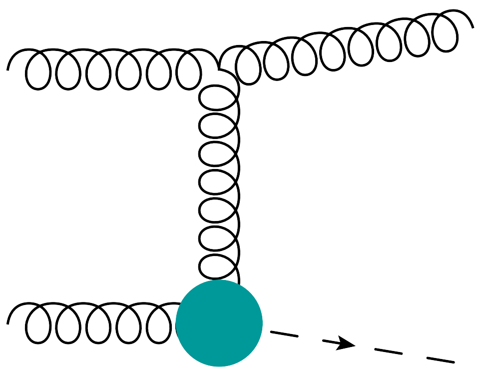
The significance of H+1jet is smaller, but not much smaller, than the significance of H+0 jets. With full LHC luminosity, 5 sigma significance can be reached for H+1jet process as alone.

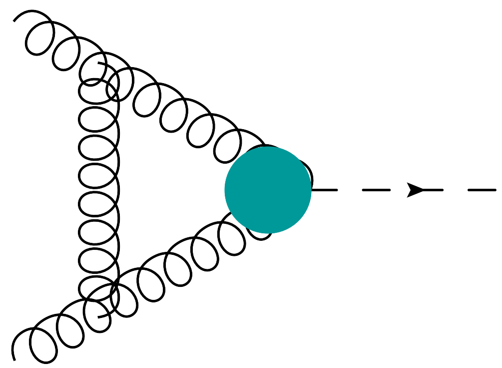
(a) $e\mu + \mu e$ channel

Selection	$N_{\rm obs}$	$N_{\rm bkg}$	$N_{\rm sig}$	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\rm jets}$
$N_{\rm jet} = 1$	9527	9460 ± 40	97 ± 1	1660 ± 10	270 ± 10	4980 ± 30	1600 ± 20	760 ± 20	195 ± 5
$N_{b\text{-jet}} = 0$	4320	4240 ± 30	85 ± 1	1460 ± 10	220 ± 10	1270 ± 10	460 ± 10	670 ± 10	160 ± 4
$Z \to \tau\tau$ veto	4138	4020 ± 30	84 ± 1	1420 ± 10	220 ± 10	1220 ± 10	440 ± 10	580 ± 10	155 ± 4
$m_{\ell\ell} < 50$	886	830 ± 10	63 ± 1	270 ± 4	69 ± 5	216 ± 6	80 ± 4	149 ± 5	46 ± 2
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	728	650 ± 10	59 ± 1	250 ± 4	60 ± 4	204 ± 6	76 ± 4	28 ± 3	34 ± 2

Higgs production in association with jets

Separating events into different jet-multiplicity bins may introduce instabilities into perturbative expansion. The reason can be an``incomplete'' cancellation of infra-red sensitivity of virtual and real corrections or sensitivity of an observable to soft/collinear emissions. The sum of the jet-vetoed cross-section and the 1-jet cross-section are not affected by the transverse momentum cut.





$$\sigma_{0j}^{R} \approx \sigma_B \frac{C_A \alpha_s}{\pi} \left(\frac{1}{\epsilon^2} - 2 \ln^2 \frac{p_\perp}{m_H} \right)$$

$$\sigma_{0j}^{V} \approx -\frac{C_A \alpha_s}{\pi \epsilon^2} \sigma_B$$

$$\sigma_{0j} \approx \sigma_B \left(1 - \frac{2 C_A \alpha_s}{\pi} \ln^2 \frac{p_\perp}{m_H} \right)$$

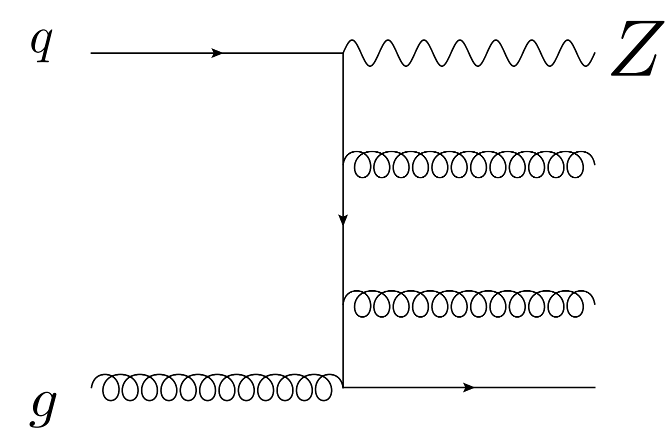
$$\sigma_{1j} \approx \sigma_B \frac{2 C_A \alpha_s}{\pi} \ln^2 \frac{p_\perp}{m_H}$$

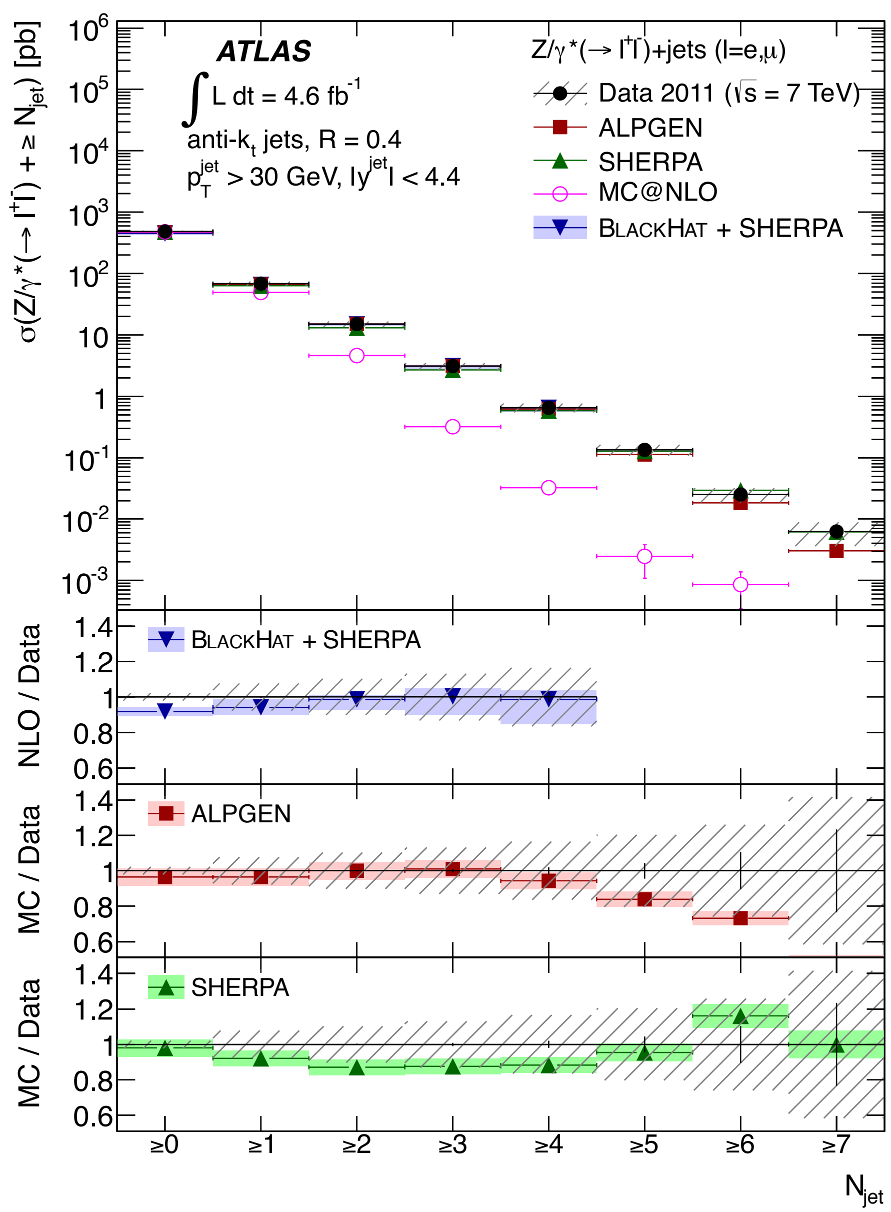
The standard argument is that jet-pt veto-dependent corrections are large and require resummations. But how large are they really? Numerically, for 30 GeV jet transverse momentum cut, the corrections may be significant but they are hardly overwhelming and, probably, can be cured by going to sufficiently high order in fixed-order perturbation theory. Note that this is exactly what happens in the inclusive Higgs production. Nevertheless, it is interesting to see if we have experimental indications that processes with jet-vetoes show worse perturbative behavior than the inclusive ones.

$$\frac{2 \alpha_s C_A}{\pi} \ln^2 \frac{125 \text{ GeV}}{30 \text{ GeV}} \sim 0.37$$

Higgs production in association with jets

Jet cross sections and jet-vetoed cross sections are two sides of the same coin. Jet cross sections for objects with electroweak-scale masses (Z-bosons) and 30 GeV jet transverse momentum cut are being measured at the LHC. There is no indication that perturbation theory breaks down.





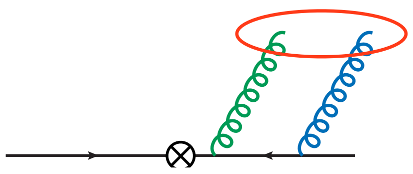
The important difference between Higgs and Z production is that color charges of colliding partons are smaller in Z-production than in the Higgs production -- radiative effects in Higgs production should be worse. But this difference is (somewhat, not completely) ameliorated if we go to Z+1j etc. Yet, even in Z+1 jet, fixed-order perturbation theory works well.

Higgs production with a jet veto

If the jet transverse momentum cut is small compared to the Higgs boson mass, $\alpha_s \ln^2 \frac{m_H}{p_\perp} \sim 1$ and Higgs production with a jet veto can be studied using resummation techniques. The current state of the art is NNLL resummation. The challenging part is the appearance of the jet-algorithm dependence at NNLL.

Soft-collinear logs

$R \gg p_\perp / m_H$

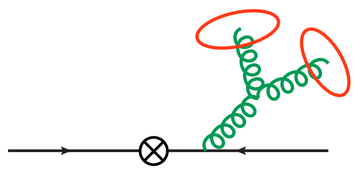


$$\delta\sigma \sim \left(\frac{\alpha_s C_A}{\pi}\right)^2 R^2 \ln \frac{m_H}{p_\perp}$$

Soft and collinear emissions are combined together by a jet algorithm

Clustering logs

$R \sim p_\perp / m_H$

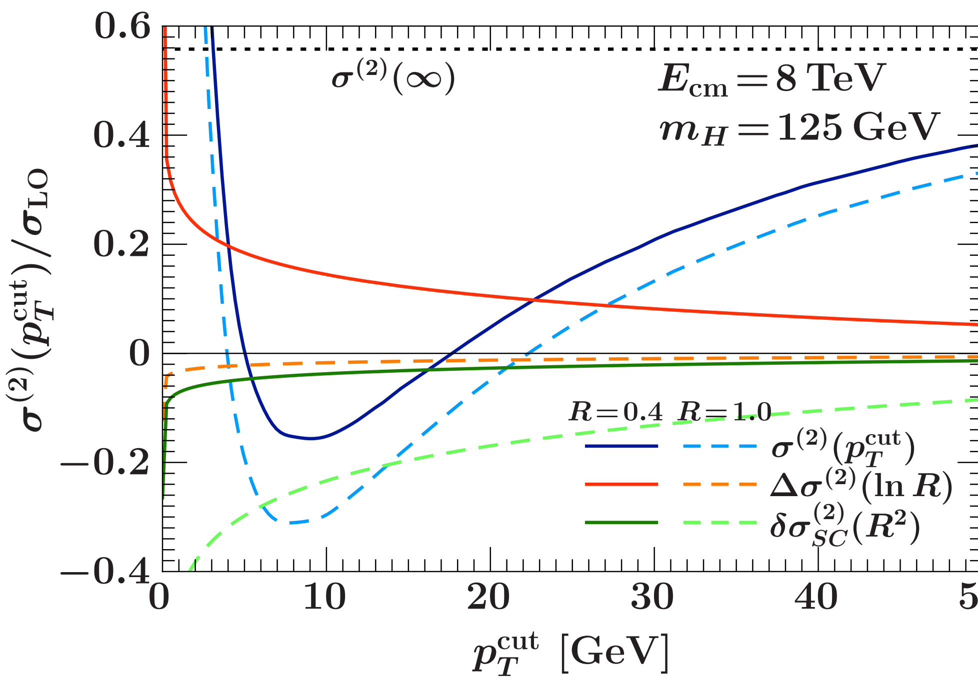


$$\delta\sigma \sim \left(\frac{\alpha_s C_A}{\pi}\right)^2 \ln R \ln \frac{m_H}{p_\perp}$$

Jet angular size regularizes collinear divergence for two independent emissons

At NNLL exact dependence of the resummed cross section on R is know. Banfi, Salam, Zanderighi

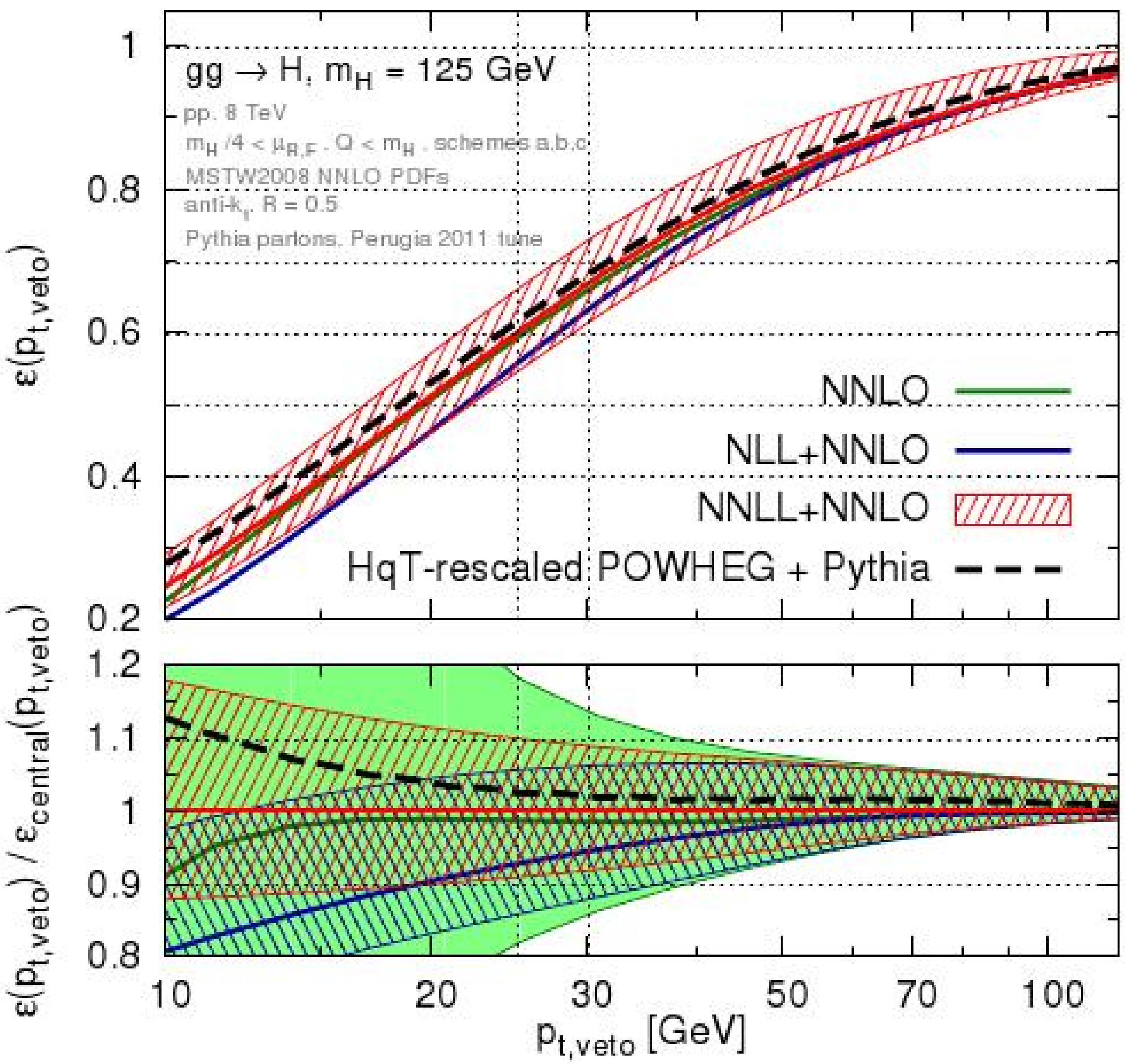
In practice, R~0.4; it is comparable to $p_\perp / m_H$ so that clustering logs appear to be relevant for phenomenology. Numerically, at NNLO, log(R)-dependent terms are about one half of the terms that are resummed. Does this mean that log(R) terms need to be resummed as well?



Tackman, Zuberi, Walsh

Higgs production with a jet veto

Current state-of-the-art computations allow us to predict ratios of the zero-jet to the inclusive cross-section with about ten percent accuracy. Relevance of the resummation changes dramatically in a small range of jet-veto momenta. Significant contribution to the uncertainty in efficiency is caused by a poor knowledge of H+1 jet production cross-section. To improve on this, we need NNLO QCD prediction for H+1 jet.



Banfi, Salam, Zanderighi

R	$p_{\mathrm{t,veto}}$	$\epsilon^{(7\ \mathrm{TeV})}$	$\sigma^{(7\ \mathrm{TeV})}_{\text{0-jet}}$	$\epsilon^{(8\ \mathrm{TeV})}$	$\sigma^{(8\ \mathrm{TeV})}_{\text{0-jet}}$
0.4	25	$0.63^{+0.07}_{-0.05}$	$9.6^{+1.3}_{-1.1}$	$0.61^{+0.07}_{-0.06}$	$12.0^{+1.6}_{-1.4}$
0.5	30	$0.68^{+0.06}_{-0.05}$	$10.4^{+1.2}_{-1.1}$	$0.67^{+0.06}_{-0.05}$	$13.0^{+1.5}_{-1.5}$
1.0	30	$0.64^{+0.03}_{-0.05}$	$9.8^{+0.8}_{-1.1}$	$0.63^{+0.04}_{-0.05}$	$12.2^{+1.1}_{-1.4}$

$$\epsilon = \frac{\sigma_{0,\mathrm{jet}}}{\sigma_{\mathrm{tot}}} = 1 - \frac{\sigma_{1,\mathrm{jet}}}{\sigma_{\mathrm{tot}}}$$

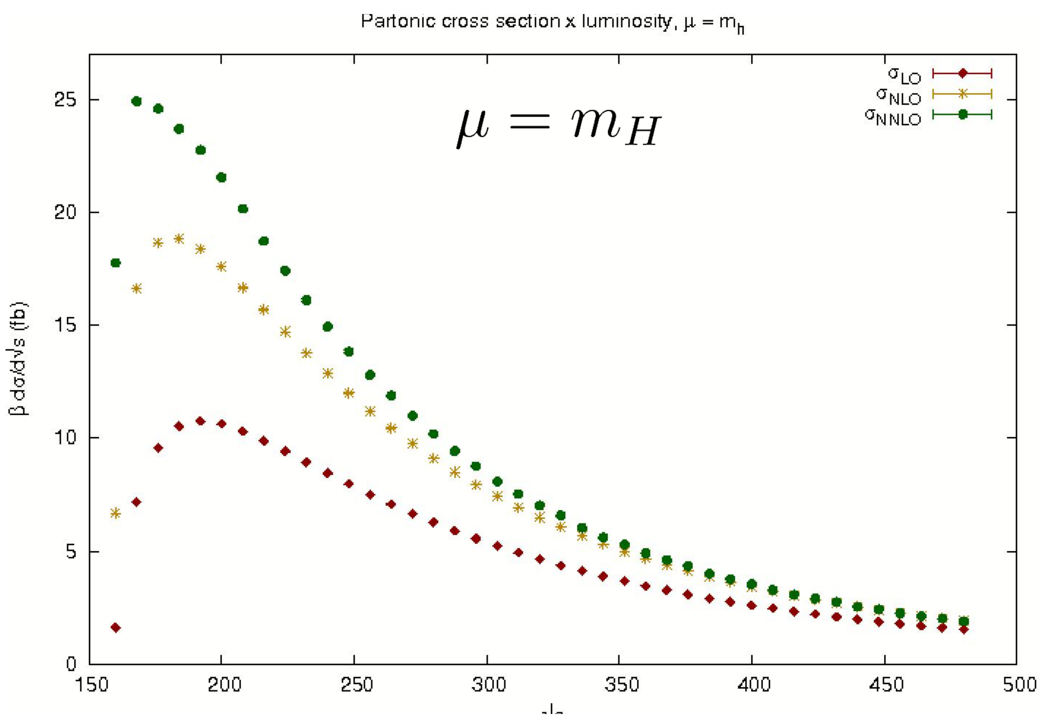
Also recent studies by Becher, Neubert; Stewart, Tackmann, Zuberi, Walsh

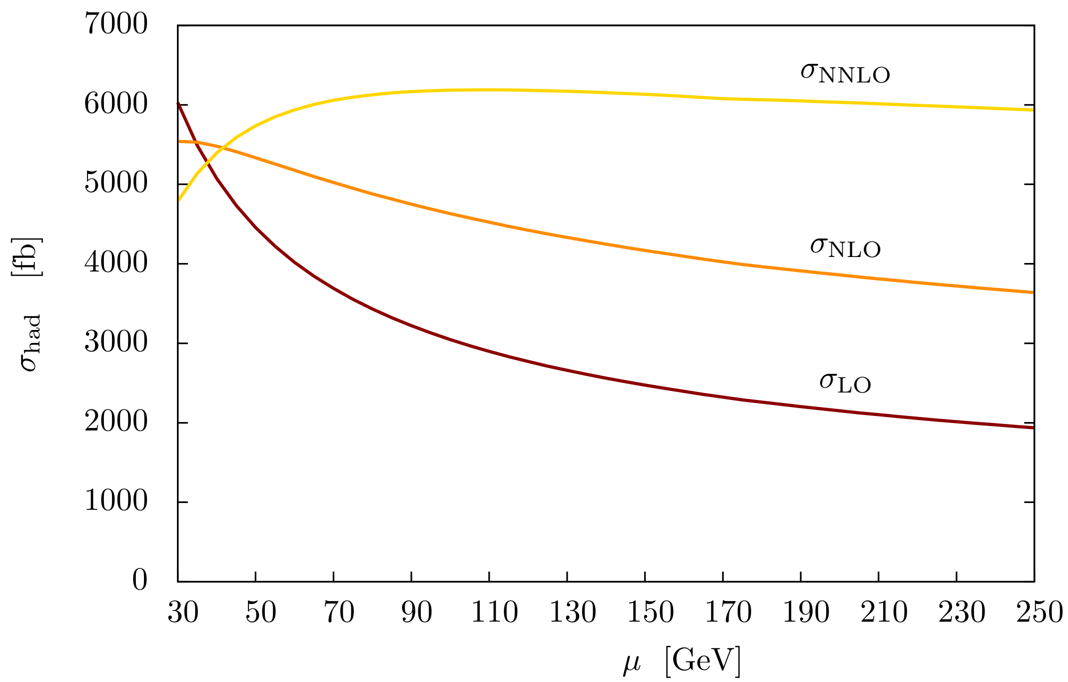
Higgs production in association with a jet

H+jet cross section at NNLO in QCD without light quarks was recently computed. Light quarks are important (30 percent at leading order) but one should not expect dramatic changes in the size of radiative corrections.

R. Bougezhal, F. Caola, K.M., F. Petriello, M. Schulze

Extremely challenging computation; one of the first NNLO QCD results for two-to-two scattering processes whose existence depends on the presence of a jet algorithm.





$$\sigma_{\rm LO}(pp \to Hj) = 2713^{+1216}_{-776} \text{ fb},$$
$$\sigma_{\rm NLO}(pp \to Hj) = 4377^{+760}_{-738} \text{ fb},$$
$$\sigma_{\rm NNLO}(pp \to Hj) = 6177^{-204}_{+242} \text{ fb}.$$

As expected, significant K-factors, strongly reduced O(3%) residual scale dependence.

Once light quarks are added, one can do interesting phenomenology including better understanding effects of the jet veto and true NNLO analysis of the Higgs transverse momentum distribution.

Higgs boson signals off the Higgs mass peak

Higgs boson is a narrow resonance in the Standard Model and, probably, even if the SM assumption is relaxed. Usually, narrow resonances can be studied almost independently of the background, even if the two have a potential to interfere.

Amazingly, this is not quite true in case of the Higgs boson where one can find interesting off-peak effects and effects related to signal-background interference. Usually, these effects are small and not very relevant in the Standard Model but they become very interesting in the BSM context.

I will discuss two topics in the context of off-peak / interference effects:

1) signal-background interference in Higgs decays to two photons and its impact on the Higgs boson mass measurement;

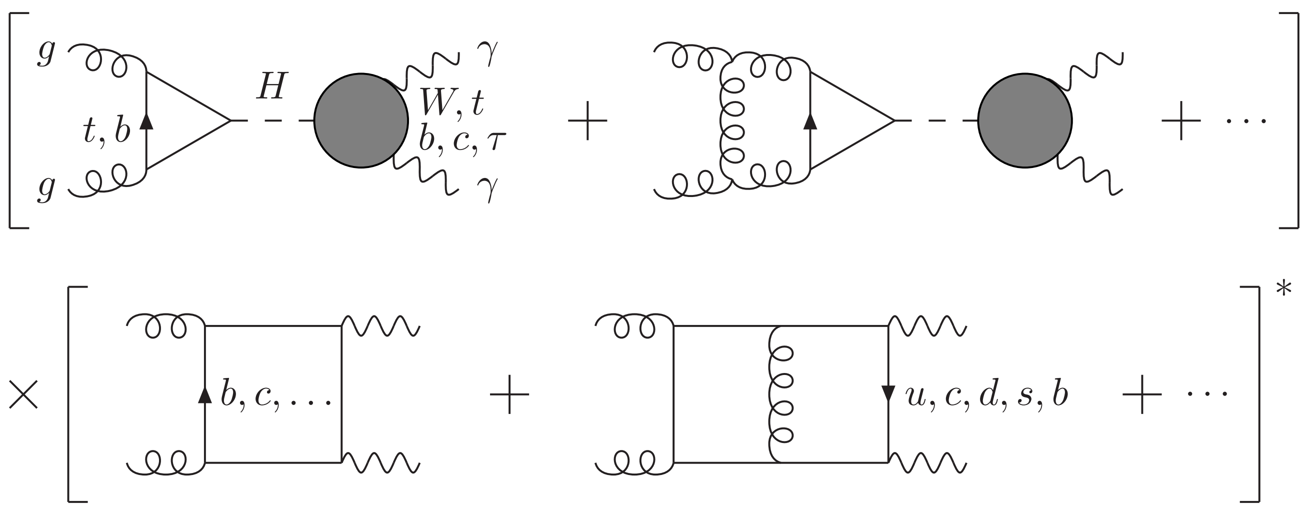
2) off-peak effects in $pp \to H \to ZZ$

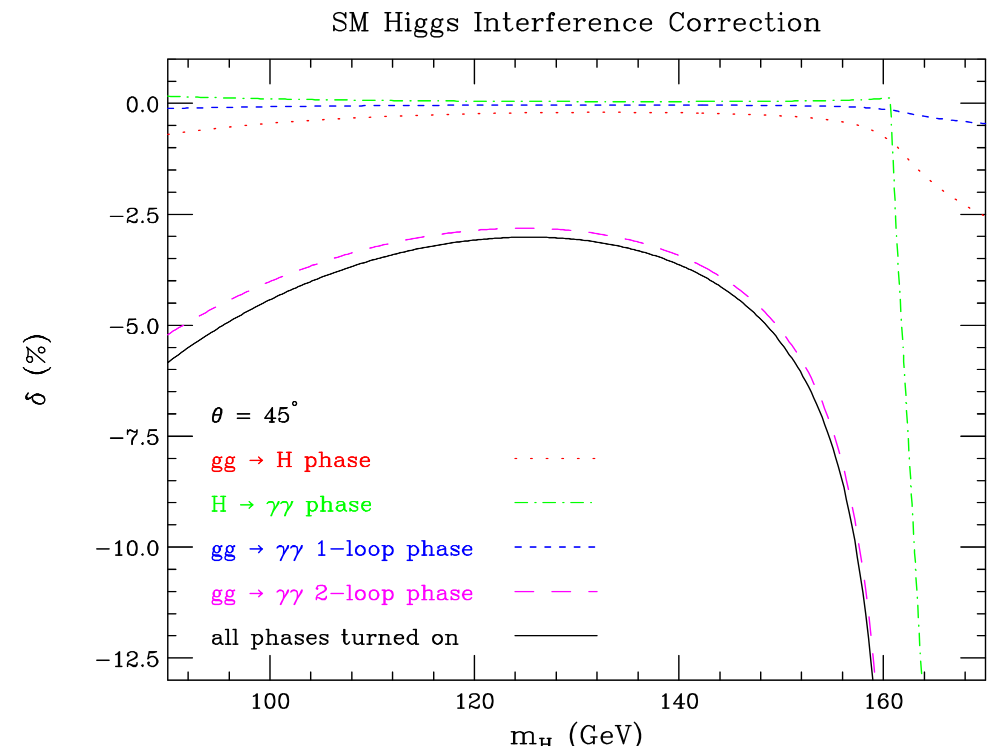
The good reason for off-peak Higgs physics to be of interest is that it can be used to constrain the Higgs boson width at the LHC.

Higgs boson signal-background interference

D. Dicus and S. Willenbrock

L. Dixon and S. Siu





$$\mathcal{A}_{gg\to\gamma\gamma} = \frac{-\mathcal{A}_{gg\to H}\mathcal{A}_{H\gamma\gamma}}{s - m_H^2 + i m_H \Gamma_H} + \mathcal{A}_{\rm cont}$$

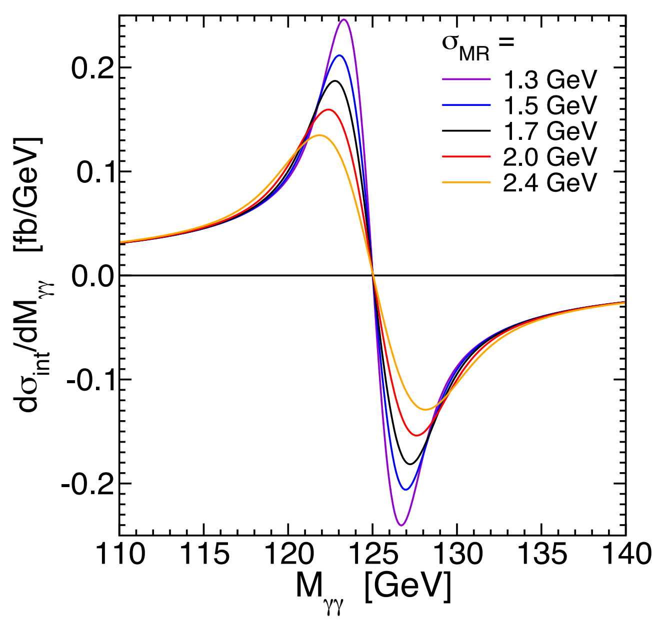
$$\delta\sigma_{gg\to H\to\gamma\gamma} \approx -2 m_H \Gamma_H \frac{{\rm Im}\left(\mathcal{A}_{gg\to H}\mathcal{A}_{H\to\gamma\gamma}\mathcal{A}^*_{\rm cont}\right)}{(s-m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\delta_{\rm naive} \approx \frac{\Gamma_H}{m_H}(4\pi)^2\frac{v^2}{m_H^2} \times 10 \sim 0.2$$

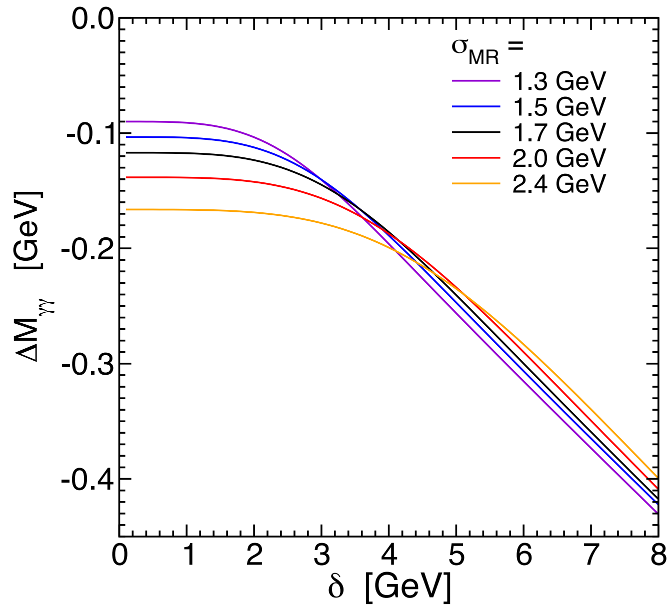
Since the Higgs boson is a a narrow particle, no significant impact of the interference on the production cross-section should be expected. On the other hand, the Higgs boson resonance amplitude is small (two-loop), so that large (one-loop) background amplitude can interfere. Naively, the interference can be as large as few tens of percent but -- by accident -- the effect is small, it changes the cross-section by about 2% for the Higgs boson with the mass 125 GeV.

Higgs boson signal-background interferences

An interesting effect of the interference is the shift in the measured value of the Higgs boson mass. This effect comes from the real part of the interference amplitude, anti-symmetric across the resonance peak. It impacts the mass measurement because of imperfect experimental resolution of the photon invariant mass that, in effect, forces us to define the mass through e.g. first moment of Breit-Wigner distribution. Interference leads to a downward shift in mass, proportional to either the size of the bin or experimental resolution. It was estimated to be close to -70 MeV and it is present even for an infinitely narrow resonance. The mass shift is small; it is comparable to the ultimate precision on the Higgs mass that can be reached at the LHC.



S. Martin



$$\Delta\left[\frac{d\sigma_{\gamma\gamma}}{ds_{\gamma\gamma}}\right] = -\frac{(s_{\gamma\gamma}-m_H^2)}{(s_{\gamma\gamma}-m_H^2)^2+m_H^2\Gamma_H^2} 2\mathrm{Re}\left[A_{ggH}A_{\gamma\gamma H}A^*_{cont}\right]$$

$$m_{\gamma\gamma} = \sqrt{s_{\gamma\gamma}}$$

$$\Delta\left[\frac{d\sigma_{\gamma\gamma}}{dm_{\gamma\gamma}}\right] \sim \frac{1}{m_{\gamma\gamma}}, \qquad m_{\gamma\gamma} \neq m_H$$

$$\langle m_{\gamma\gamma}\rangle = \frac{1}{N_\delta}\int_{m_{\rm peak}-\delta}^{m_{\rm peak}+\delta} dm_{\gamma\gamma} m_{\gamma\gamma}\frac{d\sigma}{dm_{\gamma\gamma}}$$

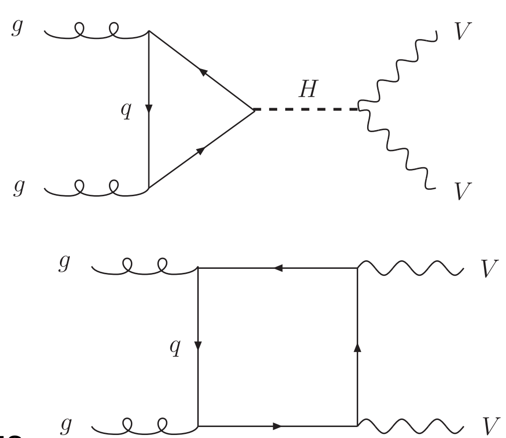
$$\Delta\langle m_{\gamma\gamma}\rangle = \frac{1}{N_\delta}\int_{m_{\rm peak}-\delta}^{m_{\rm peak}+\delta} dm_{\gamma\gamma}\, m_{\gamma\gamma}\Delta\left[\frac{d\sigma}{dm_{\gamma\gamma}}\right] \approx \int_{m_{\rm peak}-\delta}^{m_{\rm peak}+\delta} dm_{\gamma\gamma}\, m_{\gamma\gamma}\frac{1}{m_{\gamma\gamma}} \sim \delta \times \left(\frac{A_{ggH}A_{\gamma\gamma H}}{A_{\rm cont}}\right)$$

Studies of similar effects in the Higgs+jet channel showed very small impact on the Higgs boson mass measurement.

De. Florian, N. Fidanza et. al; S. Martin; Dixon and Li

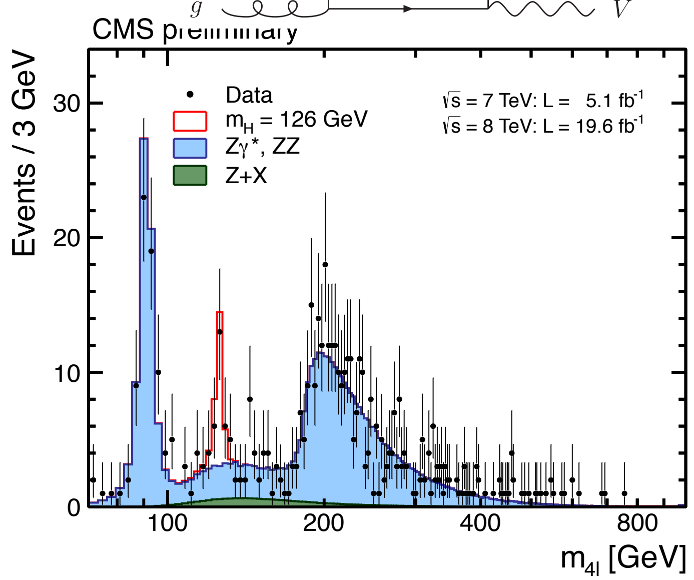
Off-shell effects in pp -> H -> ZZ

As pointed out by Kauer and Passarino, there are fairly large off-shell and interference effects in pp -> H -> ZZ. For example, using CMS cuts employed in the 4-lepton analysis, we estimate that off-shell production of the Higgs adds almost 20 percent compared to number of events in the peak and that the interference gives -50 percent compared to the number of events in the peak. These events are not in the Higgs mass peak -- and do not affect the analysis of the Higgs signal -- but, as a matter of fact, they are present at higher invariant masses.



Energy	$\sigma^{\mathrm{H}}_{\mathrm{peak}}$	$\sigma^{H}_{\mathrm{off}}$	$\sigma^{\mathrm{int}}_{\mathrm{off}}$
7 TeV	0.203	0.044	-0.1070
8 TeV	0.255	0.0613	-0.165
$N^{\mathrm{SM}}_{2e2\mu}$	9.8	1.73	-4.6
$N^{\mathrm{SM}}_{\mathrm{tot}}$	21.1	3.73	-9.91

F. Caola and K.M.



Fiducial leading order cross-sections for the peak, Higgs off-peak and the interference. Significant number of off-peak Higgs events is related to an enhanced behavior of the off-shell decay width of the Higgs boson to two real Z boson at large invariant masses

Kauer, Passarino

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{4l}^2} \sim \frac{\Gamma(H^* \to ZZ)}{M_{4l}^4} \qquad \Gamma(H^* \to ZZ) \sim M_{4l}^4$$

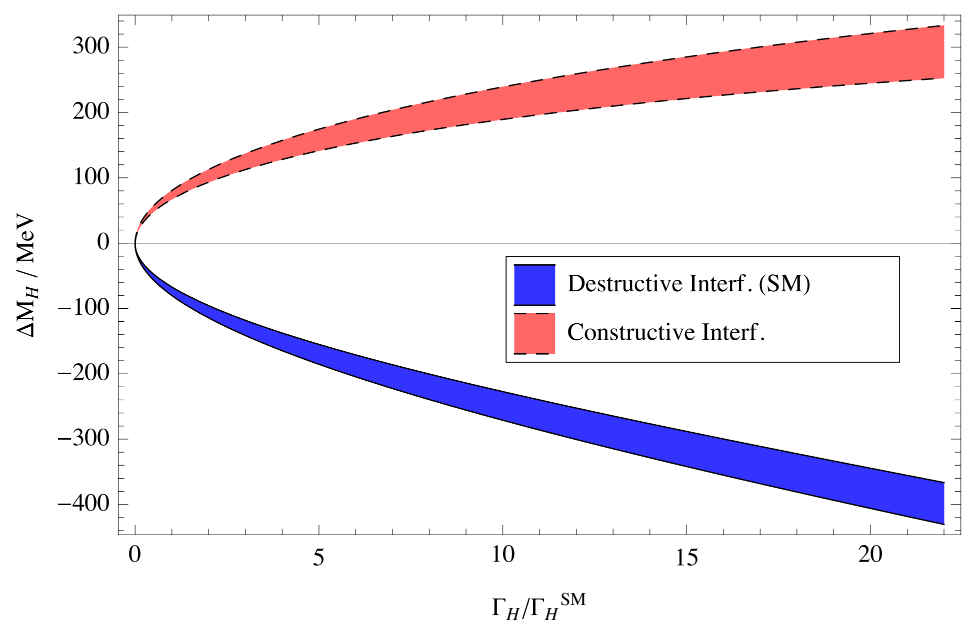
Total number of Higgs-related events off the peak is small compared to the number of expected background events(430) ; this means that in the SM the off-shell four-lepton contributions seems to be not very relevant.

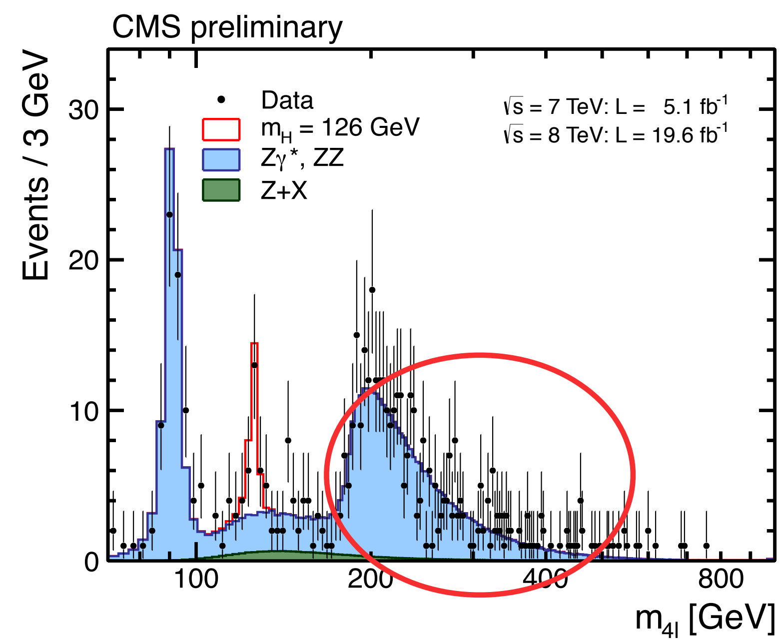
Off-shell effects and the Higgs width

An interesting physics use of these off-shell Higgs-related effects is a constraint on the Higgs couplings. Once Higgs couplings are constrained, the on-shell cross-sections provide the measurement of the Higgs total width.

Peak
$$\sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

Off-peak
$$\sigma_{i \to H^* \to f} \sim \frac{g_i^2 g_f^2}{m_{H^*}^4}$$





By measuring the apparent Higgs mass difference in ZZ and di-photon channels that is caused by signal-background interference in the di-photon channel, it is possible to constrain the Higgs width relative to its Standard Model value

Dixon and Li

In ZZ channel, the high-mass tail is sensitive to HZZ and Hgg couplings -- more events must appear there if couplings are signficiantly larger than in the SM. Theory estimates lead to the following 95% CL

$$\Gamma_H \leq 20.8\ \Gamma_{\rm SM} = 83.2\ {\rm MeV}$$

Caola, K.M.

Conclusions

Detailed exploration of the Higgs boson properties is in full swing. It relies on trustable predictions for Higgs production rates, provided by the theory community, that take realities of experimental event selection into account. We have wonderful tools that allow us to do this and we have added quite a number of interesting results to the Higgs production toolkit during this year. They include

1) estimates of N^3LO effects in Higgs production in gluon fusion and strong indications that exact computations are within reach;

2) understanding mass effects in Higgs pair production;

3) improved control of mass effects in Higgs transverse momentum distribution;

4) better understanding of the Higgs production cross-sections with jets or jet vetoes from both fixed order (NNLO QCD) and resummations;

5) appreciation of the off-shell Higgs signals, with interesting constraints on the Higgs width;

The pace of progress in understanding SM Higgs production has been remarkable. Our goal should be to significantly out-perform the metric set by the projected accuracy for Higgs couplings extractions with 300/fb. Given the pace of progress on the theory side that we saw in recent years, we are on the right track to achieve that goal.