Renormalization Group Improved Prediction for Higgs Production at Hadron Colliders

Li Lin Yang

Institut für Physik, Johannes Gutenberg-Universität Mainz

In collaboration with V. Ahrens, T. Becher and M. Neubert

arXiv:0808.3008 and arXiv:0809.4283

Pheno 09, Madison, Wisconsin
May 11, 2009

Outline

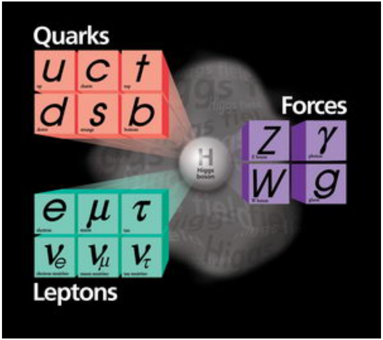
Higgs production at hadron colliders

Effective theory analysis

RG improved Predictions

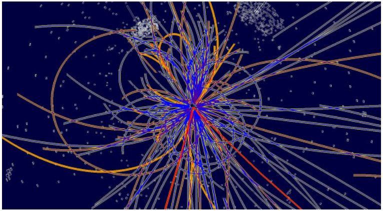
Summary

The Higgs boson in the Standard Model



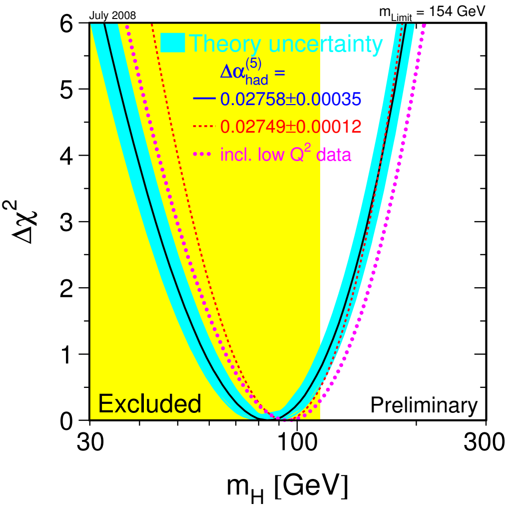
The "God" particle

- The minimal way to implement electroweak symmetry breaking
- Generates masses
- Still missing — one of the main reasons that we have the Large Hadron Collider now



CMS simulation of Higgs events

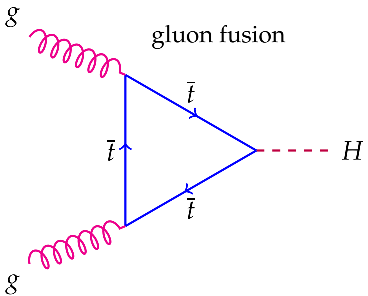
The mass of the Higgs boson

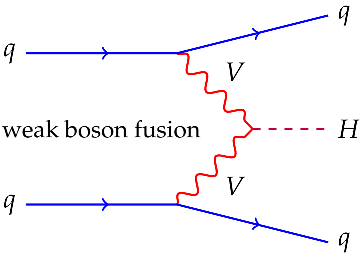


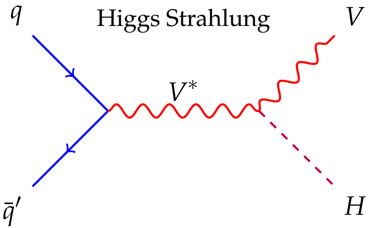
[Figure from the LEP EWWG]

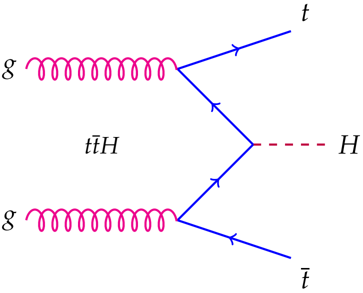
- Direct search limit:
  $m_H > 114$ GeV at 95%CL
- Electroweak global fit:
  $m_H < 154$ GeV at 95% CL
  or
  $m_H < 185$ GeV when combined

Higgs production at hadron colliders

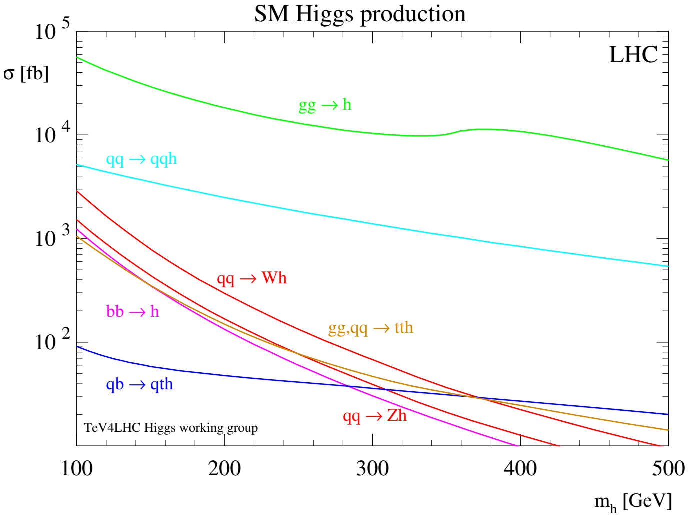








Cross sections at the LHC



[Figure from arXiv:hep-ph/0612172]

The gluon fusion channel

- Dominant production channel — important at the LHC
- One of the best theoretically studied process in perturbative QCD
  - NLO: [Dawson '91], [Djouadi, Spira and Zerwas '91]
  - NNLO: [Harlander and Kilgore '02], [Anastasiou and Melnikov '02], [Ravindran, Smith and van Neerven '03]
- Lessons from fixed-order calculations:
  - Corrections are large: at the LHC, NLO correction $\sim 70\%$, NNLO correction another 40%; at the Tevatron the corrections are even larger — bad convergence;
  - Scale uncertainties are not small ($\pm 15\%$) even at NNLO;
  - Higher order contributions are important!

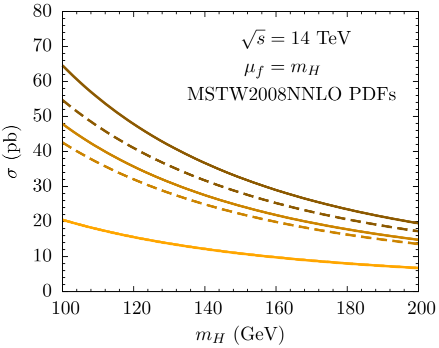
The threshold logarithms

One way to extend our ability to higher orders is resumming the threshold logs in the partonic cross section:

$$
\begin{aligned}
&C_{gg}(z, m_t, m_H, \mu_f) \equiv C(z, m_t, m_H, \mu_f) + \text{regular terms} \\
&= \delta(1-z) \\
&+ \frac{\alpha_s}{\pi}\left[6\left[\frac{1}{1-z}\ln\frac{m_H^2(1-z)^2}{\mu_f^2 z}\right]_+ + \delta(1-z)\left(\frac{11}{2}+2\pi^2\right) + \text{regular terms}\right] \\
&+ \left(\frac{\alpha_s}{\pi}\right)^2\left[9\left[\frac{1}{1-z}\ln^3\frac{m_H^2(1-z)^2}{\mu_f^2 z}\right]_+ + \cdots + \text{regular terms}\right] + \mathcal{O}(\alpha_s^3)
\end{aligned}
$$

The red terms are so called “threshold logs” or “leading singular terms” or “soft-virtual terms” which give the dominant contribution at partonic threshold $z = m_H^2/\hat{s} \to 1$.
How about the total hadronic cross section?

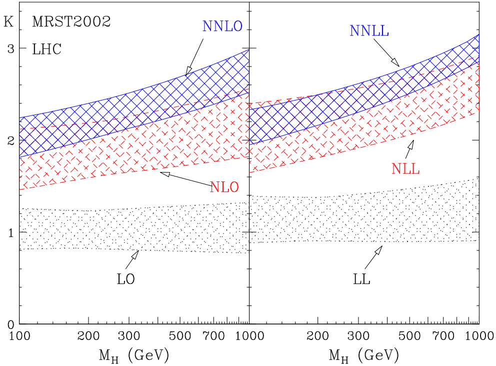
Leading singular terms dominate!



- It seems that the corrections at the hadronic level are still dominated by the leading singular terms (82% of NLO and 74% of NNLO for $m_H = 120$ GeV).
- Threshold resummation is expected to have huge numerical impact? However...

Threshold resummation

Such a resummation was carried out by Catani *et al.* in 2003 (recently updated by de Florian *et al.*)



[Figure from arXiv:hep-ph/0306211]

Threshold resummation does reduce the scale uncertainties but has NO improvement on convergence!

Confusing facts about the corrections

There are two facts which are very confusing:

- We know that we are far away from the threshold even after taking into account the enhancement from gluon luminosity, yet still the leading singular terms dominate the corrections
- Given the dominance of threshold logs, leading log resummation should have captured the most important contributions from all orders, and the remaining contributions should not be very large — However, this is not the case

To resolve these, let's take a closer look at the leading singular terms.

A closer look at the leading singular terms

- The leading singular terms at NLO is:

$$\frac{\alpha_s}{\pi}\left[6\left[\frac{1}{1-z}\ln\frac{m_H^2(1-z)^2}{\mu_f^2 z}\right]_+ + \delta(1-z)\left(\frac{11}{2}+2\pi^2\right)\right].$$

  These terms contribute 82% of the full NLO corrections for a 120 GeV Higgs at the LHC, however, of which only 12% comes from the first term (the “log term”) while 70% actually comes from the second term (the “delta term”).
- This is exactly the reason why threshold resummation does not improve the convergence: leading log resummation only captures the first term which is numerically small!
- So what can we do now? It seems impossible to predict the delta term at higher orders without actually calculating them. But...
- In the following, I will tackle the problem from an effective theory point of view. And in the procedure, we will see that we can actually predict “some” of the delta terms and resum them to all orders.

A closer look at the leading singular terms

- The leading singular terms at NLO is:

$$\frac{\alpha_s}{\pi}\left[6\left[\frac{1}{1-z}\ln\frac{m_H^2(1-z)^2}{\mu_f^2 z}\right]_+ + \delta(1-z)\left(\frac{11}{2}+2\pi^2\right)\right].$$

  These terms contribute 82% of the full NLO corrections for a 120 GeV Higgs at the LHC, however, of which only 12% comes from the first term (the "log term") while 70% actually comes from the second term (the "delta term").

- This is exactly the reason why threshold resummation does not improve the convergence: leading log resummation only captures the first term which is numerically small!
- So what can we do now? It seems impossible to predict the delta term at higher orders without actually calculating them. But...
- In the following, I will tackle the problem from an effective theory point of view. And in the procedure, we will see that we can actually predict "some" of the delta terms and resum them to all orders.

A closer look at the leading singular terms

- The leading singular terms at NLO is:

$$\frac{\alpha_s}{\pi}\left[6\left[\frac{1}{1-z}\ln\frac{m_H^2(1-z)^2}{\mu_f^2 z}\right]_+ + \delta(1-z)\left(\frac{11}{2}+2\pi^2\right)\right].$$

  These terms contribute 82% of the full NLO corrections for a 120 GeV Higgs at the LHC, however, of which only 12% comes from the first term (the "log term") while 70% actually comes from the second term (the "delta term").
- This is exactly the reason why threshold resummation does not improve the convergence: leading log resummation only captures the first term which is numerically small!
- So what can we do now? It seems impossible to predict the delta term at higher orders without actually calculating them. But...
- In the following, I will tackle the problem from an effective theory point of view. And in the procedure, we will see that we can actually predict "some" of the delta terms and resum them to all orders.

A closer look at the leading singular terms

- The leading singular terms at NLO is:

$$\frac{\alpha_s}{\pi}\left[6\left[\frac{1}{1-z}\ln\frac{m_H^2(1-z)^2}{\mu_f^2 z}\right]_+ + \delta(1-z)\left(\frac{11}{2}+2\pi^2\right)\right].$$

  These terms contribute 82% of the full NLO corrections for a 120 GeV Higgs at the LHC, however, of which only 12% comes from the first term (the “log term”) while 70% actually comes from the second term (the “delta term”).
- This is exactly the reason why threshold resummation does not improve the convergence: leading log resummation only captures the first term which is numerically small!
- So what can we do now? It seems impossible to predict the delta term at higher orders without actually calculating them. But...
- In the following, I will tackle the problem from an effective theory point of view. And in the procedure, we will see that we can actually predict “some” of the delta terms and resum them to all orders.

Strategy of effective theory

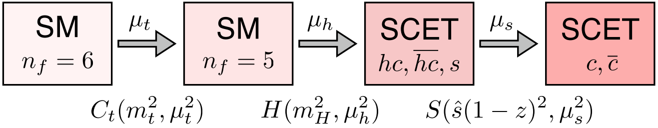
- The presence of double logs in the threshold region is due to the presence of two distinct energy scales:

$$Q_{\text{hard}} \sim m_H \gg Q_{\text{soft}} \sim \sqrt{\hat{s}}(1-z)$$

  The logarithms are actually $\ln(Q^2_{\text{hard}}/Q^2_{\text{soft}})$.
- Actually, there are more than two scales in this problem:

$$2m_t \gg \sqrt{\hat{s}} \sim m_H \gg \sqrt{\hat{s}}(1-z) \gg \Lambda_{\text{QCD}}$$

- The strategy of effective theory is: from high to low, integrating out one energy scale at a time, constructing successive effective theory which is valid below that scale



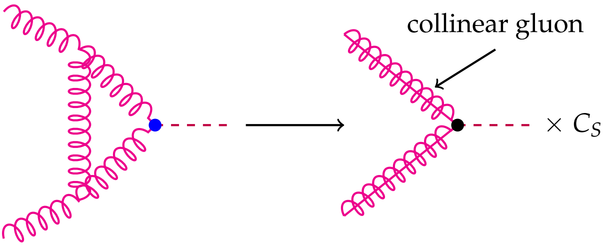
Factorization and resummation from effective theories

- The resulting factorization formula reads

$$\sigma = \sigma_0 \left[C_t(m_t^2, \mu^2)\right]^2 H(m_H^2, \mu^2) \times S(\hat{s}(1-z)^2, \mu^2) \otimes f_{g/N_1}(x_1, \mu) \otimes f_{g/N_2}(x_2, \mu)$$

  - Any single choice of μ^2 leads to large logs, especially double logs in the hard function H and the soft function S
  - Solution: Choose the appropriate renormalization scale for each function where it is perturbatively well-behaved. Then use RG evolution to connect the different scales.
    (This is what traditionally called “resummation”, while from the effective theory point of view, it is a “RG improvement”).
- I will concentrate on the hard function in the following, which is the main source of the large corrections we observed before.

The hard function



$$
\begin{aligned}
H(m_H^2,\mu^2) &= |C_S(-m_H^2 - i\epsilon, \mu^2)|^2 \\
&= 1 && \text{[LO]} \\
&\quad + \frac{\alpha_s(\mu^2)}{4\pi}\left[-6\ln^2\frac{m_H^2}{\mu^2} + 7\pi^2\right] && \text{[NLO]} \\
&\quad + \left(\frac{\alpha_s(\mu^2)}{4\pi}\right)^2\left[18\ln^4\frac{m_H^2}{\mu^2} + \frac{46}{3}\ln^3\frac{m_H^2}{\mu^2} + \cdots\right] && \text{[NNLO]}
\end{aligned}
$$

(valid for $\mu^2 > 0$)

Suppose that we want to choose $\mu \sim Q_{\text{soft}} \ll m_H$ to get rid of the logs in the soft function, then we have large logs in the hard function.

RG evolution of the hard function

The hard function obeys an evolution equation (valid for $\mu^2 > 0$)

$$\frac{d}{d\ln\mu} H(m_H^2, \mu^2) = 2\left[\Gamma^A_{\text{cusp}}(\alpha_s)\ln\frac{m_H^2}{\mu^2} + \gamma^S(\alpha_s)\right] H(m_H^2, \mu^2)$$

The solution is

$$H(m_H^2, \mu^2) = \exp\left[4S(\mu_h^2, \mu^2) - 2a_\Gamma(\mu_h^2, \mu^2)\ln\frac{m_H^2}{\mu_h^2} - 2a_{\gamma^S}(\mu_h^2, \mu^2)\right] H(m_H^2, \mu_h^2)$$

$$S(\nu^2, \mu^2) = -\int_{\alpha_s(\nu^2)}^{\alpha_s(\mu^2)} d\alpha \frac{\Gamma^A_{\text{cusp}}(\alpha)}{\beta(\alpha)} \int_{\alpha_s(\nu^2)}^{\alpha} \frac{d\alpha'}{\beta(\alpha')}, \quad a_\Gamma(\nu^2, \mu^2) = -\int_{\alpha_s(\nu^2)}^{\alpha_s(\mu^2)} d\alpha \frac{\Gamma^A_{\text{cusp}}(\alpha)}{\beta(\alpha)}$$

Now H can be evaluated at some hard scale μ_h for good convergence and then evolved down to some soft scale $\mu \sim Q_{\text{soft}}$ to match the soft function. This gives what we call
"Renormalization Group Improved (RGI) perturbation theory"

Note that the logs between μ_h and μ are resummed in the exponential evolution factor.

RG-Improved perturbation theory and resummation

RGI Pert. Theory	Log Approx.	$\Gamma^A_{\rm cusp}$	γ^S, ...	H, ...
LO	NLL	2-loop	1-loop	tree-level
NLO	NNLL	3-loop	2-loop	1-loop
NNLO	NNNLL	4-loop	3-loop	2-loop

Now let's see what happens when we want to evaluate the hard function at some soft scale $\mu \sim Q_{\rm soft}$ in RGI perturbation theory.

We use a "natural" choice $\mu_h^2 = m_H^2$, and re-expand the leading order expression in RGI perturbation theory in powers of $\alpha_s(\mu^2)$:

$$H(m_H^2, \mu^2) = \exp\left[4S(m_H^2, \mu^2) - 2a_{\gamma^S}(m_H^2, \mu^2)\right]_{\rm LO}$$

$$= 1 - \frac{\alpha_s(\mu^2)}{4\pi} 6 \ln^2 \frac{m_H^2}{\mu^2} + \left(\frac{\alpha_s(\mu^2)}{4\pi}\right)^2 \left[18 \ln^4 \frac{m_H^2}{\mu^2} + \frac{46}{3} \ln^3 \frac{m_H^2}{\mu^2} + \left(-\frac{302}{3} + 6\pi^2\right) \ln^2 \frac{m_H^2}{\mu^2}\right] + \cdots \quad \text{[RGI-LO]}$$

So indeed the RGI-LO expression sums infinite number of terms in fixed-order perturbation theory via the evolution factor.

RG-Improved perturbation theory and resummation

RGI Pert. Theory	Log Approx.	Γ^A_{cusp}	γ^S, ...	H, ...
LO	NLL	2-loop	1-loop	tree-level
NLO	NNLL	3-loop	2-loop	1-loop
NNLO	NNNLL	4-loop	3-loop	2-loop

Now let's see what happens when we want to evaluate the hard function at some soft scale $\mu \sim Q_{\text{soft}}$ in RGI perturbation theory. We use a "natural" choice $\mu_h^2 = m_H^2$, and re-expand the leading order expression in RGI perturbation theory in powers of $\alpha_s(\mu^2)$:

$$
\begin{aligned}
H(m_H^2, \mu^2) &= \exp\left[4S(m_H^2, \mu^2) - 2a_{\gamma^S}(m_H^2, \mu^2)\right]_{\text{LO}} \\
&= 1 - \frac{\alpha_s(\mu^2)}{4\pi} 6 \ln^2 \frac{m_H^2}{\mu^2} + \left(\frac{\alpha_s(\mu^2)}{4\pi}\right)^2 \left[18 \ln^4 \frac{m_H^2}{\mu^2}\right. \\
&\quad \left. + \frac{46}{3} \ln^3 \frac{m_H^2}{\mu^2} + \left(-\frac{302}{3} + 6\pi^2\right) \ln^2 \frac{m_H^2}{\mu^2}\right] + \cdots \quad \text{[RGI-LO]}
\end{aligned}
$$

So indeed the RGI-LO expression sums infinite number of terms in fixed-order perturbation theory via the evolution factor.

Is the choice $\mu_h^2 = m_H^2$ good enough?

Now the remaining question is whether or not $H(m_H^2, \mu_h^2)$ has good convergence for $\mu_h^2 \sim m_H^2$. For $m_H = 120$ GeV,

$$H(m_H^2, m_H^2) \approx 1 + 5.50\alpha_s(m_H^2) + 17.24\alpha_s^2(m_H^2) + \cdots$$
$$\approx 1 + 0.618 + 0.218 + \cdots$$

Not so good... But why?

We know $H(m_H^2, \mu^2) = |C_S(-m_H^2 - i\epsilon, \mu^2)|^2$, with

$$C_S(-m_H^2, \mu^2) = 1 + \frac{\alpha_s(\mu^2)}{4\pi}\left[-3\ln^2\frac{-m_H^2}{\mu^2} + \frac{\pi^2}{2}\right] + \cdots$$

The double logs leave behind π^2 terms for the choice $\mu^2 = m_H^2$, which will eventually contribute to the “delta term” we observed before —— maybe a better choice is $\mu^2 = -m_H^2 - i\epsilon$?

This requires evaluating the running $\alpha_s(\mu^2)$ at negative argument.

Is the choice $\mu_h^2 = m_H^2$ good enough?

Now the remaining question is whether or not $H(m_H^2, \mu_h^2)$ has good convergence for $\mu_h^2 \sim m_H^2$. For $m_H = 120$ GeV,

$$\begin{aligned} H(m_H^2, m_H^2) &\approx 1 + 5.50\alpha_s(m_H^2) + 17.24\alpha_s^2(m_H^2) + \cdots \\ &\approx 1 + 0.618 + 0.218 + \cdots \end{aligned}$$

Not so good... But why?

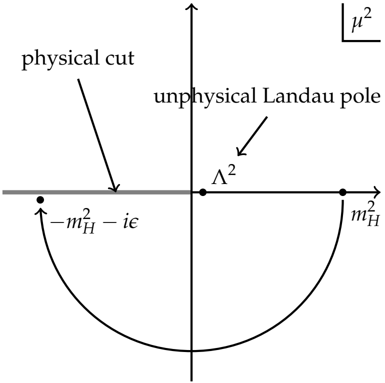
We know $H(m_H^2, \mu^2) = |C_S(-m_H^2 - i\epsilon, \mu^2)|^2$, with

$$C_S(-m_H^2, \mu^2) = 1 + \frac{\alpha_s(\mu^2)}{4\pi}\left[-3\ln^2\frac{-m_H^2}{\mu^2} + \frac{\pi^2}{2}\right] + \cdots$$

The double logs leave behind π^2 terms for the choice $\mu^2 = m_H^2$, which will eventually contribute to the "delta term" we observed before —— maybe a better choice is $\mu^2 = -m_H^2 - i\epsilon$?

This requires evaluating the running $\alpha_s(\mu^2)$ at negative argument.

Running of α_s in the complex μ^2 plane



$$\int_{\alpha_s(\mu^2)}^{\alpha_s(-\mu^2)} \frac{d\alpha}{\beta(\alpha)} = -\frac{i\pi}{2}$$

For $m_H = 120$ GeV

$$\alpha_s(m_H^2) \approx 0.112$$
$$\alpha_s(-m_H^2 - i\epsilon) \approx 0.107 + 0.024i$$

The "π^2 resummation"

Now we can evaluate

$$H(m_H^2, -m_H^2) = |C_S(-m_H^2, -m_H^2)|^2 \approx 1 + 0.0840 - 0.0015 + \cdots$$

Convergence much better!

And we use RG evolution to obtain

$$H(m_H^2, m_H^2) = \exp\left[2\mathrm{Re}\left(2S(-m_H^2, m_H^2) - a_{\gamma^S}(-m_H^2, m_H^2)\right)\right] H(m_H^2, -m_H^2)$$

Again we re-expand the leading order expression in RGI perturbation theory in powers of $\alpha_s(m_H^2)$:

$$H(m_H^2, m_H^2) = \exp\left[2\mathrm{Re}\left(2S(-m_H^2, m_H^2) - a_{\gamma^S}(-m_H^2, m_H^2)\right)\right]_{\mathrm{LO}}$$
$$= 1 + \frac{\alpha_s(m_H^2)}{4\pi} 6\pi^2 + \left(\frac{\alpha_s(m_H^2)}{4\pi}\right)^2 \left[12\pi^4 + \frac{302}{3}\pi^2\right] + \cdots$$

[RGI-LO]

Note that the π^2 terms are not chosen arbitrarily, but are generated automatically from RG evolution.

The "π^2 resummation"

Now we can evaluate

$$H(m_H^2, -m_H^2) = |C_S(-m_H^2, -m_H^2)|^2 \approx 1 + 0.0840 - 0.0015 + \cdots$$

Convergence much better!

And we use RG evolution to obtain

$$H(m_H^2, m_H^2) = \exp\left[2\mathrm{Re}\left(2S(-m_H^2, m_H^2) - a_{\gamma^S}(-m_H^2, m_H^2)\right)\right] H(m_H^2, -m_H^2)$$

Again we re-expand the leading order expression in RGI perturbation theory in powers of $\alpha_s(m_H^2)$:

$$\begin{aligned} H(m_H^2, m_H^2) &= \exp\left[2\mathrm{Re}\left(2S(-m_H^2, m_H^2) - a_{\gamma^S}(-m_H^2, m_H^2)\right)\right]_{\mathrm{LO}} \\ &= 1 + \frac{\alpha_s(m_H^2)}{4\pi} 6\pi^2 + \left(\frac{\alpha_s(m_H^2)}{4\pi}\right)^2 \left[12\pi^4 + \frac{302}{3}\pi^2\right] + \cdots \end{aligned}$$

[RGI-LO]

Note that the π^2 terms are not chosen arbitrarily, but are generated automatically from RG evolution.

Some additional remarks

I will not go into details for the other ingredients in the factorization formula, but a few remarks are deserved:

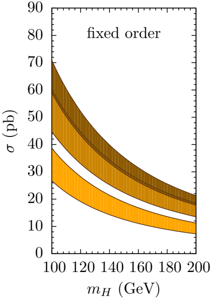
- We use a soft scale μ_s between two values μ_s^{I} and μ_s^{II} which are chosen to make the convolution of the soft function with the PDFs well behaved perturbatively. The ratio μ_s/μ_h characterizes the scale hierachy between the soft scale and the hard scale. In our case the ratio is close to $1/2$ — no large scale hierachy, and so no large logs.
- The RGE for the soft function is solved analytically in momentum space ([Becher and Neubert '06]), so the Landau pole problem in the traditional moment space approach is avoided.
- We define our final RG improved cross section with matching to fixed-order result:

$$\sigma^{\mathrm{RGI}} = \sigma^{\mathrm{resummed}}\Big|_{\mu_t,\mu_h,\mu_s,\mu_f} + \left(\sigma^{\mathrm{fixed\ order}}\Big|_{\mu_f} - \sigma^{\mathrm{resummed}}\Big|_{\mu_t=\mu_h=\mu_s=\mu_f} \right).$$

Predictions for the cross section

Comparison of uncertainties and convergence

LHC, MSTW2008 LO/NLO/NNLO PDF sets



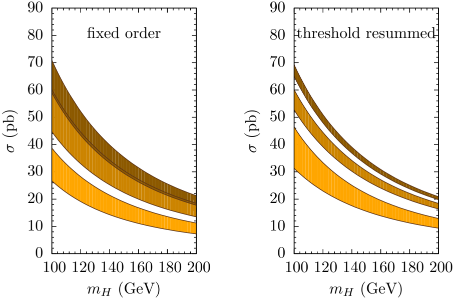
fixed order

$$m_H/2 < \mu_r = \mu_f < 2m_H$$

Predictions for the cross section

Comparison of uncertainties and convergence

LHC, MSTW2008 LO/NLO/NNLO PDF sets



threshold resummed

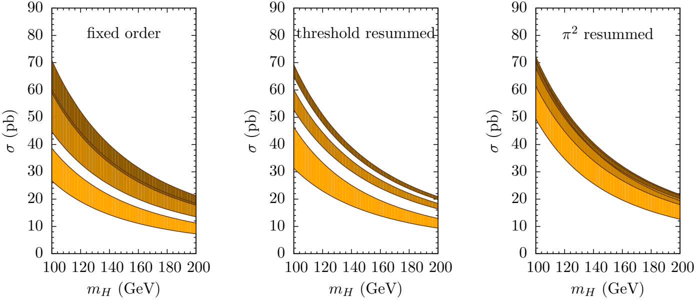
$$m_t/2 < \mu_t < 2m_t, \quad \mu_s^{II} < \mu_s < \mu_s^{I}$$

$$(m_H/2)^2 < \mu_h^2 < (2m_H)^2, \quad m_H/2 < \mu_f < 2m_H$$

Predictions for the cross section

Comparison of uncertainties and convergence

LHC, MSTW2008 LO/NLO/NNLO PDF sets



π^2 resummed

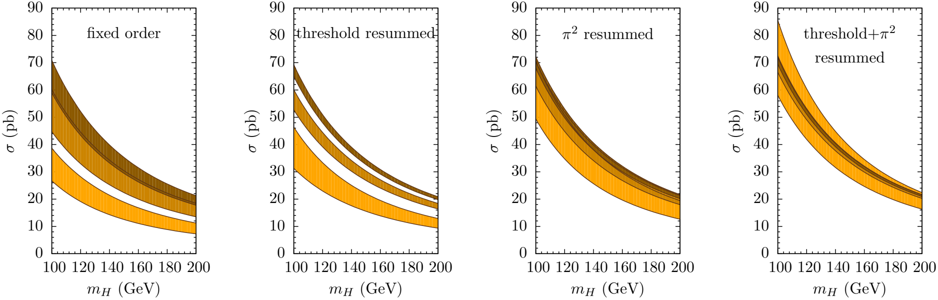
$$m_H/2 < \mu_t = \mu_s = \mu_f < 2m_H$$

$$\mu_h^2 = -\mu_f^2$$

Predictions for the cross section

Comparison of uncertainties and convergence

LHC, MSTW2008 LO/NLO/NNLO PDF sets



threshold + π^2 resummed

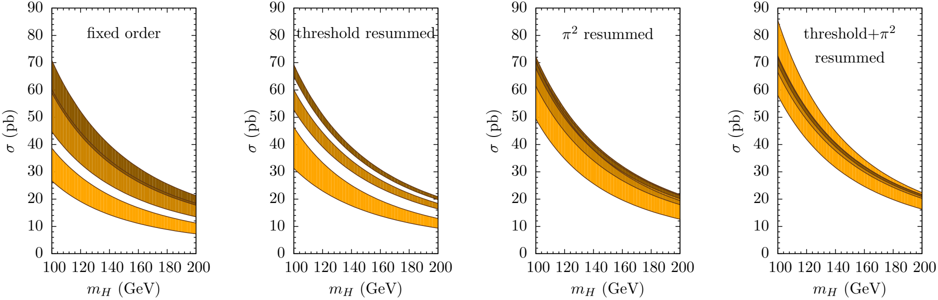
$$m_t/2 < \mu_t < 2m_t, \quad \mu_s^{II} < \mu_s < \mu_s^{I}$$

$$(m_H/2)^2 < -\mu_h^2 < (2m_H)^2, \quad m_H/2 < \mu_f < 2m_H$$

Predictions for the cross section

Comparison of uncertainties and convergence

LHC, MSTW2008 LO/NLO/NNLO PDF sets



- Resumming threshold logs reduces scale dependence, but does not improve convergence;
- Resumming π^2 leads to faster convergence and smaller scale dependence;
- When combining both effects, the K-factor is close to 1!

Summary

- The prediction for Higgs production in perturbative QCD has poor convergence. Also the scale dependence is still large even at NNLO.
- We performed an analysis of Higgs production near partonic threshold using effective field theory:
  - All matching scales are chosen properly to ensure the perturbative convergence of the corresponding quantities;
  - Especially a time-like hard scale $\mu_h^2 < 0$ is chosen to eliminate the π^2 terms associated with Sudakov double logs in the hard function;
  - Different scales are connected by renormalization group evolution, which sums certain terms in fixed-order perturbation theory to all orders.
- Numerically no large threshold logarithm is found. Threshold resummation reduces scale dependence but does not improve convergence of the cross section.
- On the other hand, we find large corrections from Sudakov π^2 terms, and the new choice $\mu_h^2 < 0$ significantly improves convergence and leads to more reliable predictions.

Summary

- The prediction for Higgs production in perturbative QCD has poor convergence. Also the scale dependence is still large even at NNLO.
- We performed an analysis of Higgs production near partonic threshold using effective field theory:
  - All matching scales are chosen properly to ensure the perturbative convergence of the corresponding quantities;
  - Especially a time-like hard scale $\mu_h^2 < 0$ is chosen to eliminate the π^2 terms associated with Sudakov double logs in the hard function;
  - Different scales are connected by renormalization group evolution, which sums certain terms in fixed-order perturbation theory to all orders.
- Numerically no large threshold logarithm is found. Threshold resummation reduces scale dependence but does not improve convergence of the cross section.
- On the other hand, we find large corrections from Sudakov π^2 terms, and the new choice $\mu_h^2 < 0$ significantly improves convergence and leads to more reliable predictions.

Summary

- The prediction for Higgs production in perturbative QCD has poor convergence. Also the scale dependence is still large even at NNLO.
- We performed an analysis of Higgs production near partonic threshold using effective field theory:
  - All matching scales are chosen properly to ensure the perturbative convergence of the corresponding quantities;
  - Especially a time-like hard scale $\mu_h^2 < 0$ is chosen to eliminate the π^2 terms associated with Sudakov double logs in the hard function;
  - Different scales are connected by renormalization group evolution, which sums certain terms in fixed-order perturbation theory to all orders.
- Numerically no large threshold logarithm is found. Threshold resummation reduces scale dependence but does not improve convergence of the cross section.
- On the other hand, we find large corrections from Sudakov π^2 terms, and the new choice $\mu_h^2 < 0$ significantly improves convergence and leads to more reliable predictions.

Summary

- The prediction for Higgs production in perturbative QCD has poor convergence. Also the scale dependence is still large even at NNLO.
- We performed an analysis of Higgs production near partonic threshold using effective field theory:
  - All matching scales are chosen properly to ensure the perturbative convergence of the corresponding quantities;
  - Especially a time-like hard scale $\mu_h^2 < 0$ is chosen to eliminate the π^2 terms associated with Sudakov double logs in the hard function;
  - Different scales are connected by renormalization group evolution, which sums certain terms in fixed-order perturbation theory to all orders.
- Numerically no large threshold logarithm is found. Threshold resummation reduces scale dependence but does not improve convergence of the cross section.
- On the other hand, we find large corrections from Sudakov π^2 terms, and the new choice $\mu_h^2 < 0$ significantly improves convergence and leads to more reliable predictions.