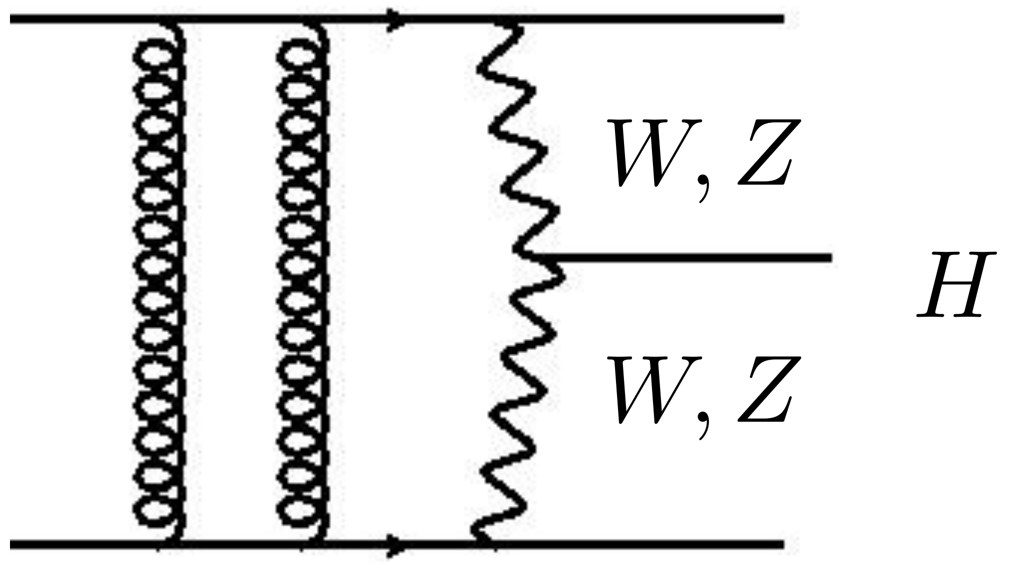
Karlsruher Institut für Technologie

Particle Physics Phenomenology after the Higgs Discovery

Higher order QCD effects in Higgs boson production in weak boson fusion

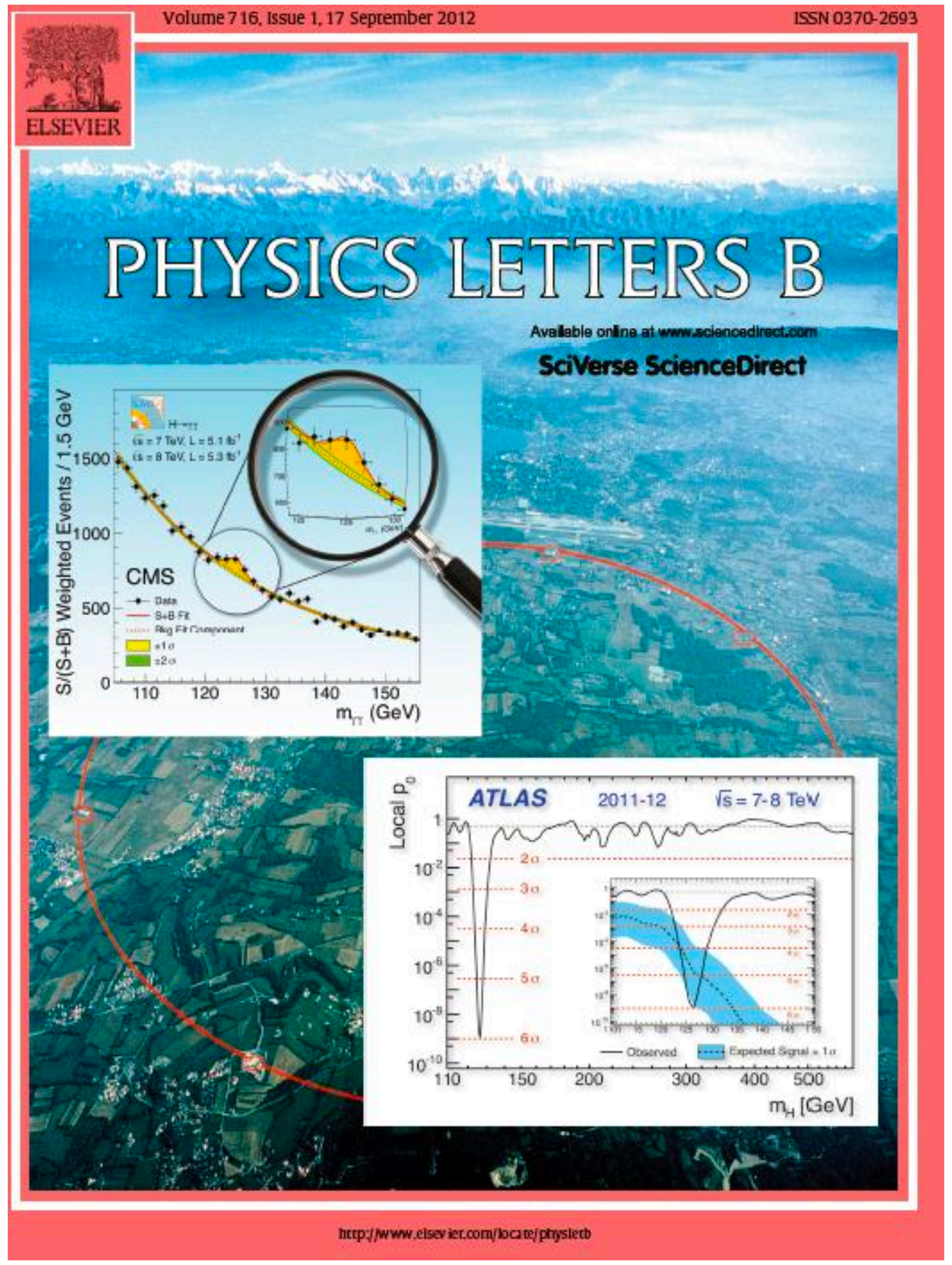
Kirill Melnikov

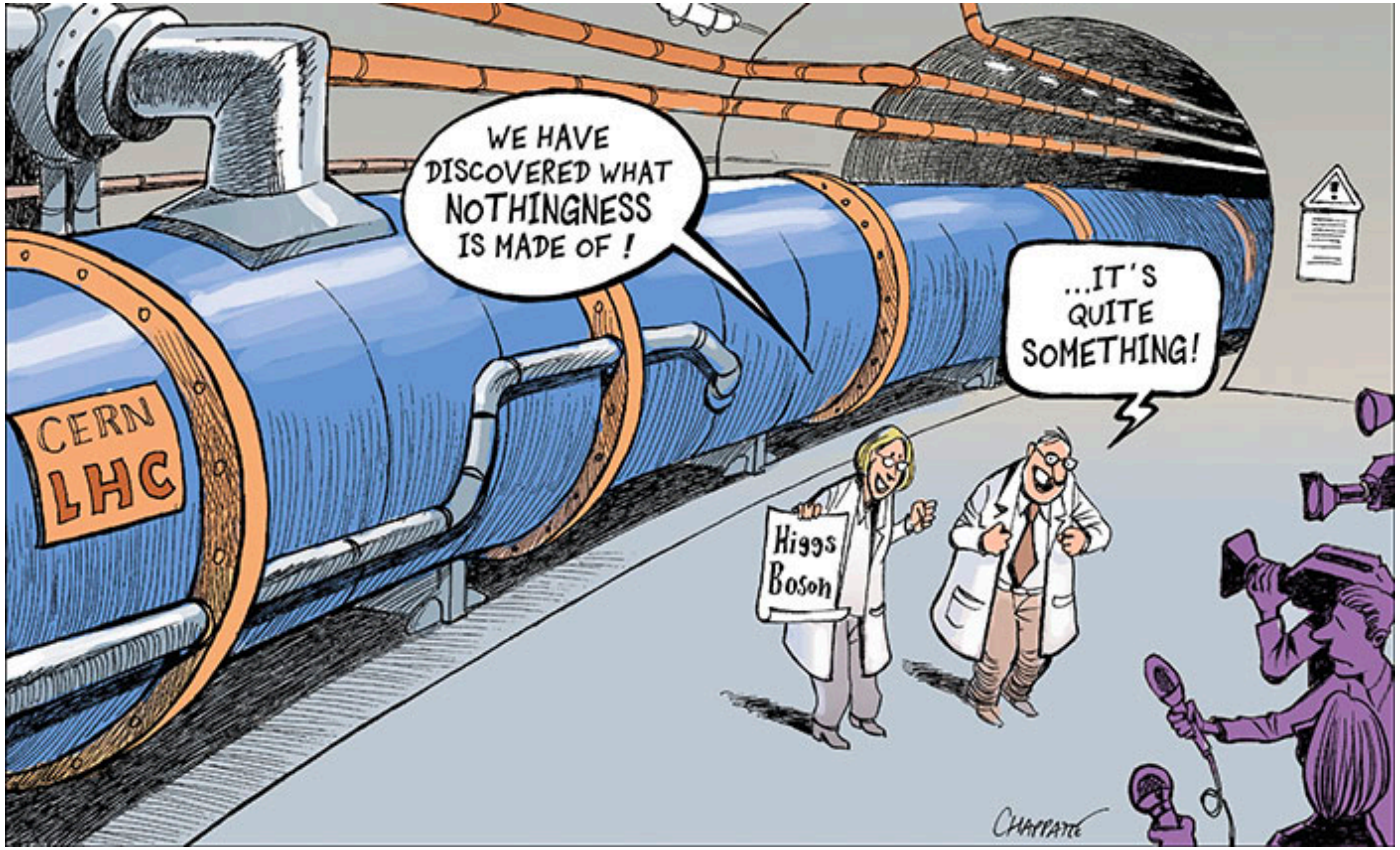
CRC 257 annual meeting; Siegen 06.10-08.10 2020



Higgs boson as a harbinger of new physics

Higgs boson discovery structurally completed the Standard Model and launched an era of the detailed exploration of this particle.



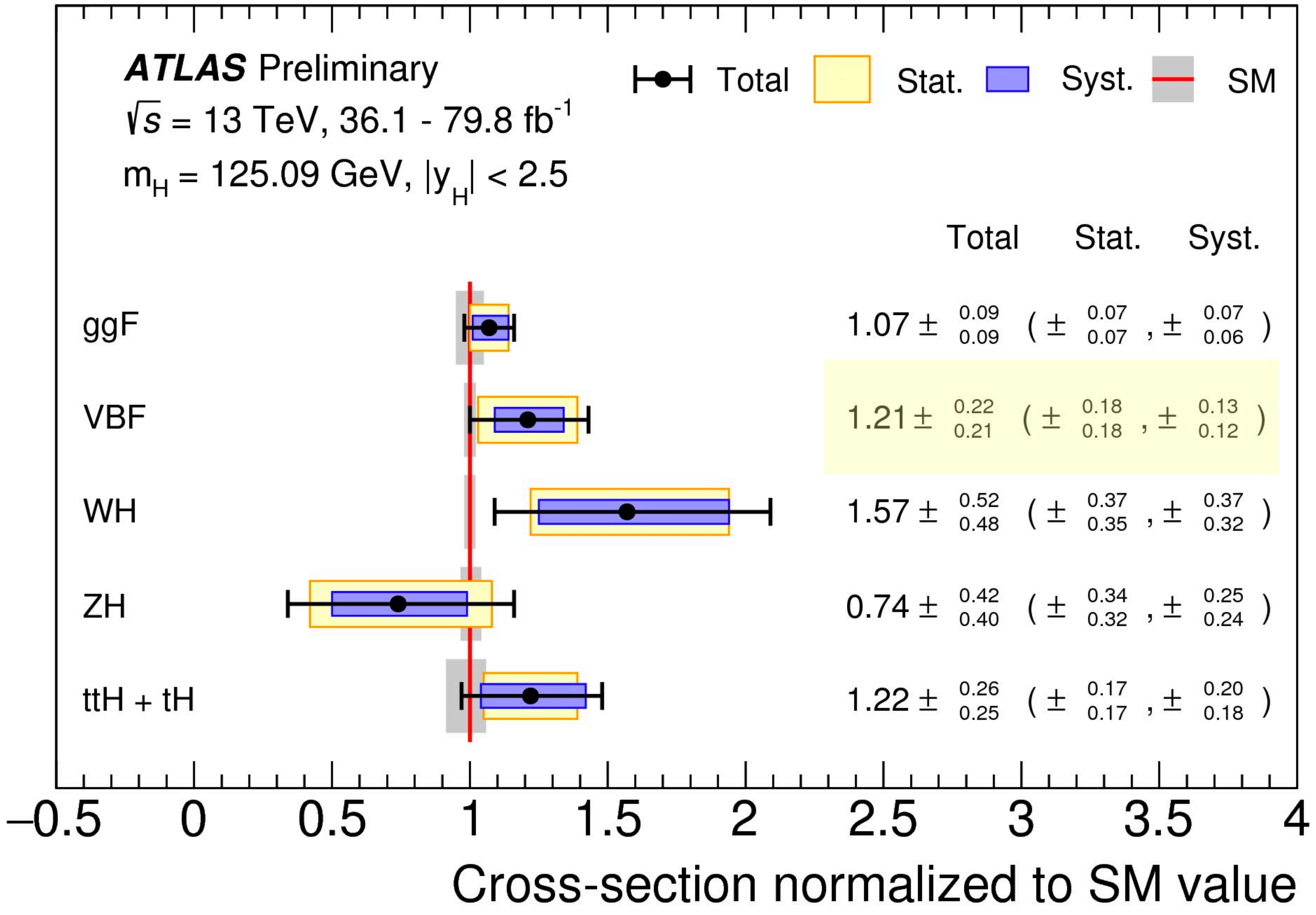


CERN Courier

Higgs boson properties are known but not quite

Higgs boson properties are very much consistent with the SM expectations. Nevertheless, there is still room for O(10-20) percent deviations even in the largest cross sections and the best known couplings.

Weak boson fusion cross sections are measured with about 20 percent precision; uncertainties are still dominated by statistics (note that analysed data sets are still incomplete).



Production process	Best fit value	Uncertainty	stat.	syst.
ggH	1.22	$^{+0.14}_{-0.12}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.12}_{-0.10}$ $\left(^{+0.09}_{-0.08}\right)$
VBF	0.73	$^{+0.30}_{-0.27}$ $\left(^{+0.29}_{-0.27}\right)$	$^{+0.24}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$
WH	2.18	$^{+0.58}_{-0.55}$ $\left(^{+0.53}_{-0.51}\right)$	$^{+0.46}_{-0.45}$ $\left(^{+0.43}_{-0.42}\right)$	$^{+0.34}_{-0.32}$ $\left(^{+0.30}_{-0.29}\right)$
ZH	0.87	$^{+0.44}_{-0.42}$ $\left(^{+0.43}_{-0.41}\right)$	$^{+0.39}_{-0.38}$ $\left(^{+0.38}_{-0.37}\right)$	$^{+0.20}_{-0.18}$ $\left(^{+0.19}_{-0.17}\right)$
ttH	1.18	$^{+0.30}_{-0.27}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.26}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$

CMS, 13 TeV, 36 fb^{-1}

Weak boson fusion

Higgs boson production in weak boson fusion (WBF) is interesting for several reasons:

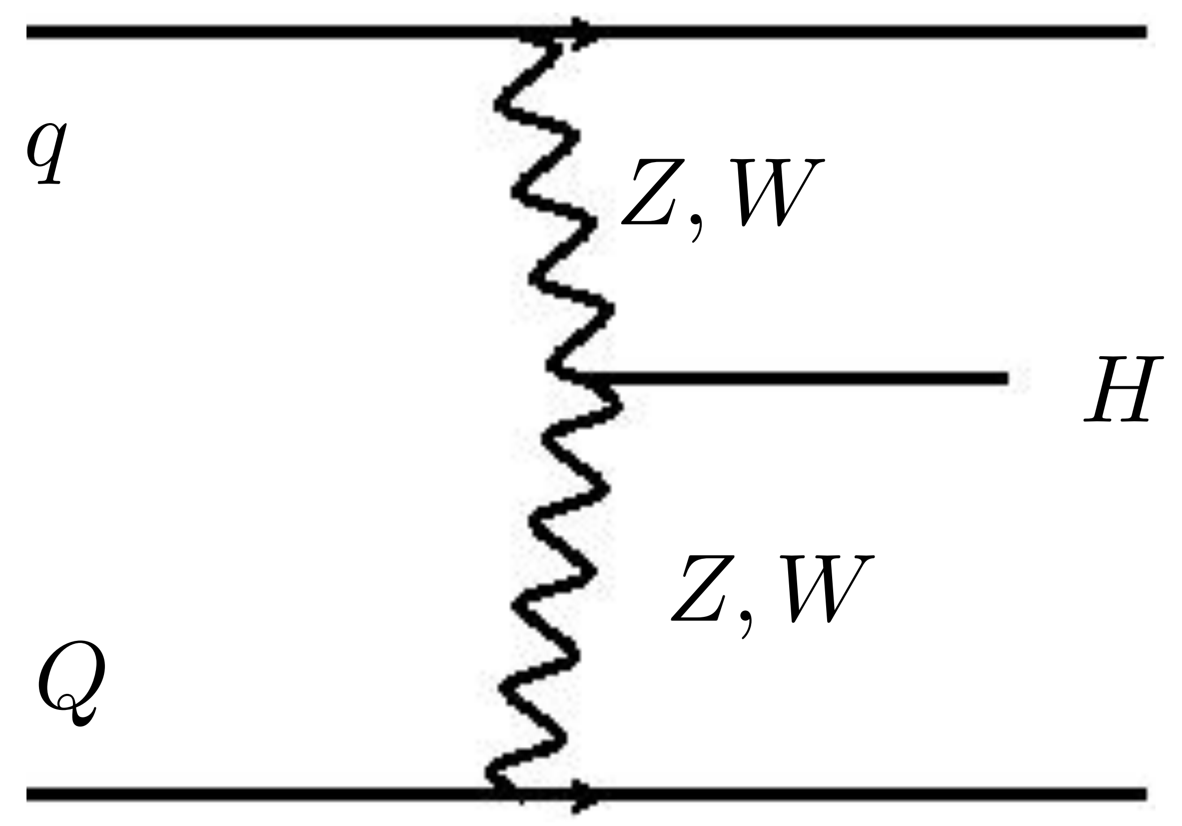
a) this process has a relatively large cross section;

b) the cross section depends on HWW and HZZ couplings that are fixed by Higgs quantum numbers, gauge invariance and the SM renormalizabilty requirements;

c) the process is sensitive to HVV anomalous couplings;

d) it provides useful signatures to study CP properties of the Higgs boson;

e) different Higgs boson decays can be studied.



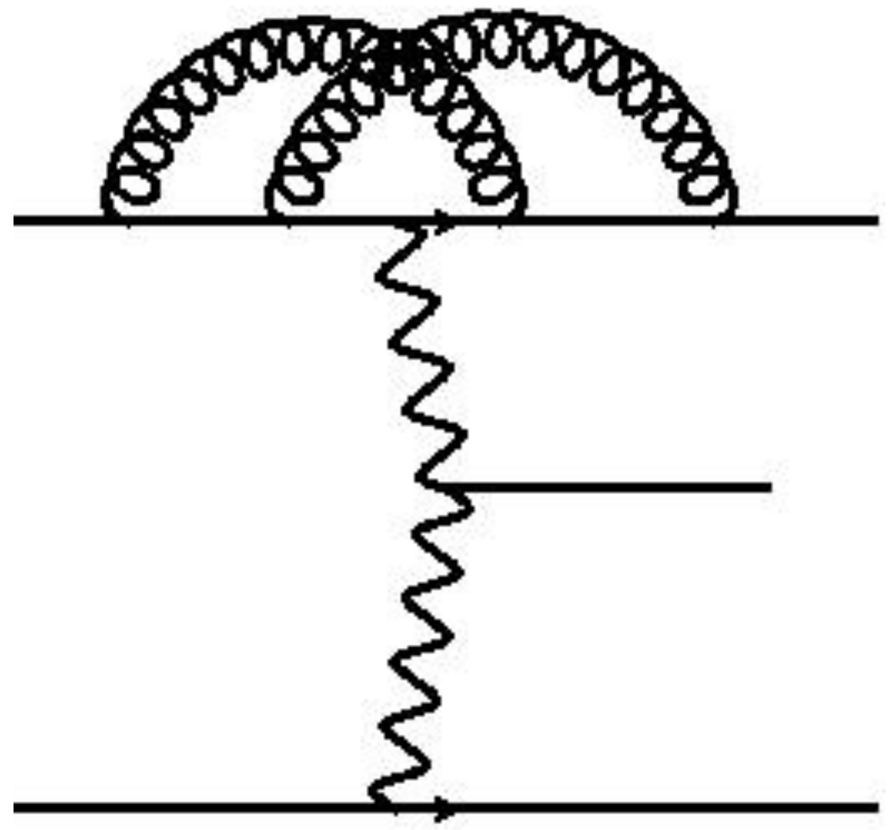
QCD corrections to weak boson fusion

We will focus on the QCD corrections to Higgs boson production in weak boson fusion; these corrections involve two distinct contributions:

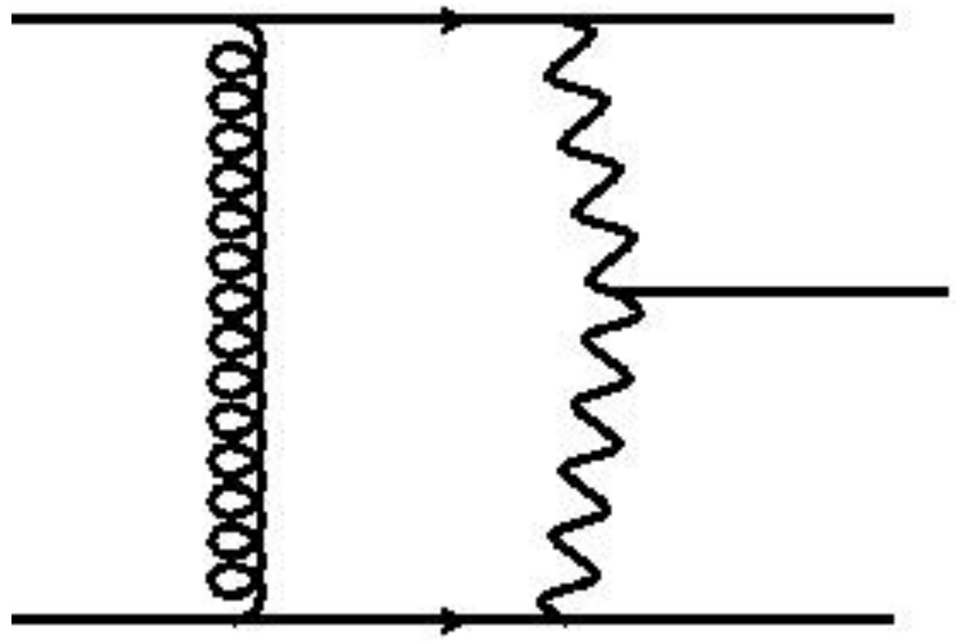
a) corrections to the same fermion line (factorizable);

b) interactions between two fermion lines (non-factorizable).

There are other contributions to WBF that do not fit into this template: the interference of the two fermion lines (e.g. uu -> Huu) or V*H production followed by the decay V* -> 2 jets). These contributions have been computed at leading and sometimes at next-to-leading order in the strong coupling constant and were found to be small (permille).



DIS-like, factorizable effects



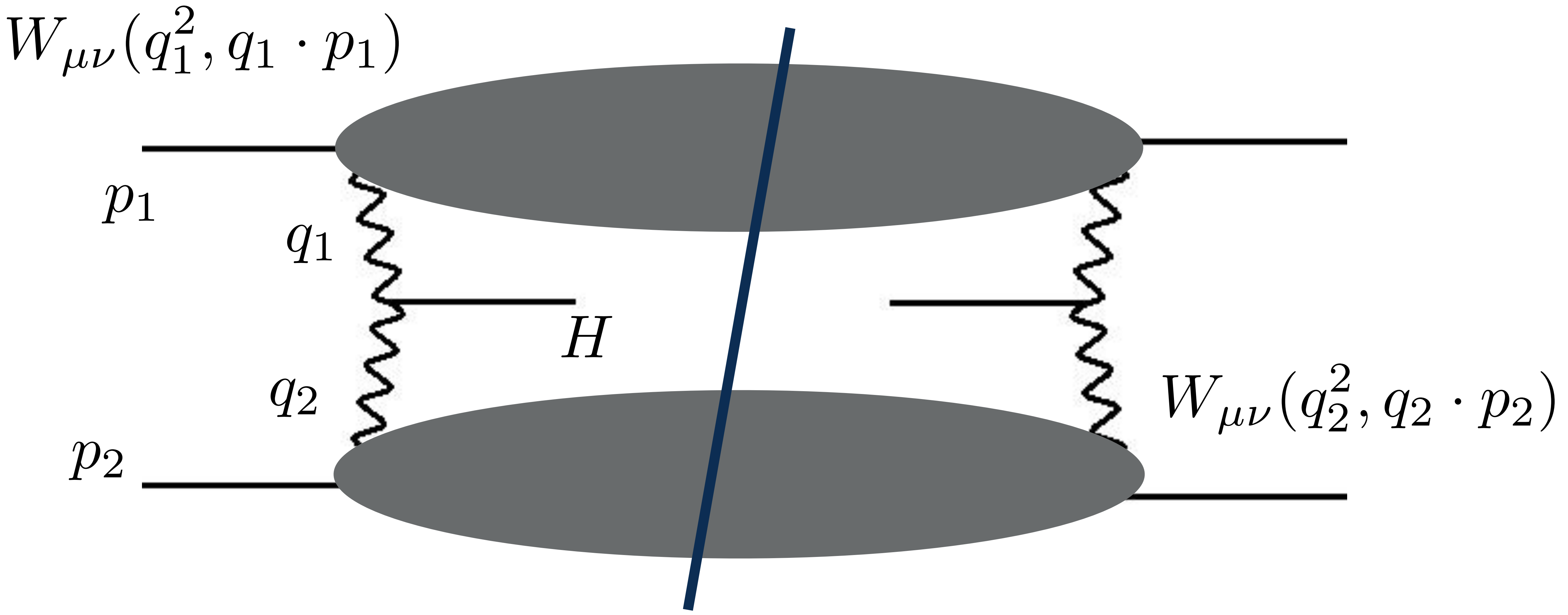
Non-factorizable corrections: cross-talk between two fermion lines

Factorizable QCD corrections to weak boson fusion

Factorizable corrections, integrated over kinematic variable of final state particles except the Higgs boson, can be described by DIS structure functions. If DIS structure functions are known to a particular order in pQCD, factorizable contributions to WBF can be computed through the same order.

Boltoni, Maltoni, Moch, Zaro;

$$W^{\mu\nu} = W_1(q^2, p\cdot q)\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + W_2(q^2, p\cdot q)\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2}q^\nu\right) - i\epsilon^{\mu\nu\alpha\beta}\frac{p^\alpha q^\beta}{2p\cdot q}W_3(q^2, p\cdot q)$$



$$\mathrm{d}\sigma_{\mathrm{VBF}} \sim \frac{(2\pi)^4\delta^{(4)}(q_1+q_2-p_H)\mathrm{d}^4q_1\mathrm{d}^4q_2}{(q_1^2-m_V^2)(q_2^2-m_V^2)} W^{\mu\nu}(q_1^2, q_1\cdot p_1)W^{\mu'\nu'}(q_2^2, q_2\cdot p_2)\mathcal{M}_{VV\to H}^{\mu\mu',\nu\nu'}\frac{\mathrm{d}^3p_H}{2E_H(2\pi)^3}$$

In practice, this has been done through N3LO QCD, since this is the perturbative order through which DIS structure functions are currently known.

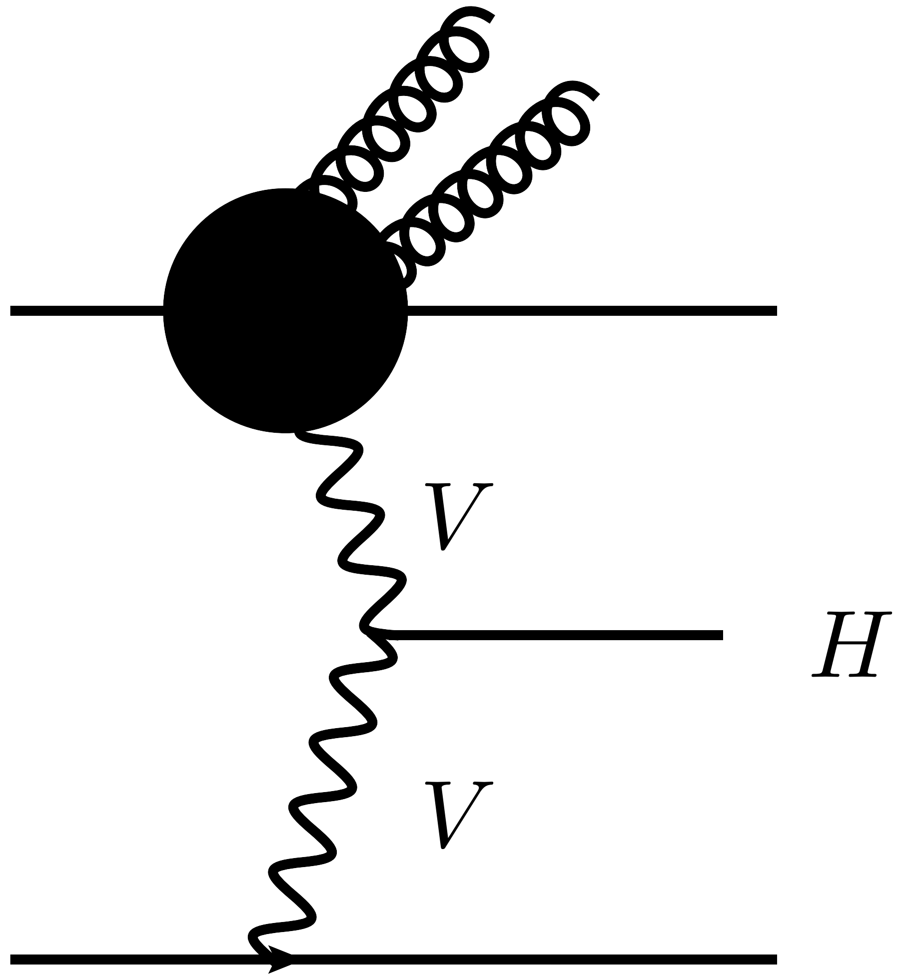
Karlberg, Dreyer

Factorizable QCD corrections to weak boson fusion

Within the structure functions approach, quite moderate QCD corrections to WBF were found (~3% at NLO, ~1% at NNLO, ~0.1 % at N3LO. However it is unclear to what extent some of these results are relevant for weak boson fusion process as studied at the LHC.

Indeed, the structure function approach involves integration over partons in the final state and does not allow us to impose constraints on QCD radiation. This is not ideal since WBF cuts are quite severe (the WBF cross section after cuts is only about 20 percent of the cross section without the WBF cuts) and involve forward tagging jets.

For this reason, it is important to perform a fully differential computation (even within the factorization approximation!) that accounts for WBF cuts on the tagging jets.



Typical WBF cuts

$$
\begin{gathered}
p_\perp^{j_{1,2}} > 25 \text{ GeV}, \quad |y_{j_{1,2}}| < 4.5, \\
\Delta y_{j_1,j_2} = 4.5, \quad m_{j_1,j_2} > 600 \text{ GeV}, \\
y_{j_1} y_{j_2} < 0, \quad \Delta R > 0.4
\end{gathered}
$$

Factorizable QCD corrections to WBF

A fully differential NNLO QCD computation within the DIS-approximation has been performed using two different methods: projection-to-Born and antenna subtraction.

It was observed that the QCD corrections to the total cross section with WBF cuts are larger, by almost a factor of 3, than the QCD corrections computed in the structure function approximation.

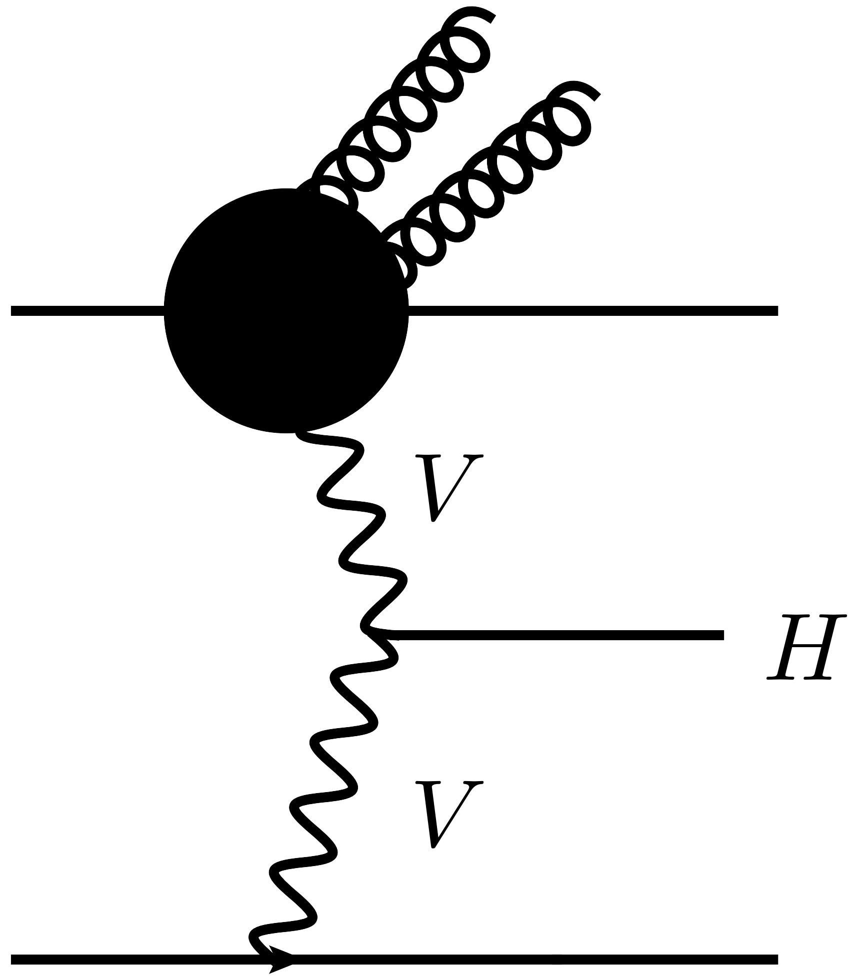
	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.844^{+0.008}_{-0.008}$

Cacciari, Dreyer, Karlberg, Salam, Zanderighi

Cruz-Martinez, Glover, Gehrmann, Huss

Factorizable QCD corrections to weak boson fusion

We are working on NNLO QCD fully-differential corrections within the so-called nested soft-collinear subtraction scheme. The first step — derivation of analytic formulas for subtraction terms etc. for deep inelastic scattering — has been completed. We are in the process of applying these results in the context of weak boson fusion.



$$\mathrm{d}\hat\sigma^{\rm NNLO}_{q,\rm ns} = \mathrm{d}\hat\sigma^{\rm NNLO}_{q,\rm ns,3j} + \mathrm{d}\hat\sigma^{\rm NNLO}_{q,\rm ns,2j} + \mathrm{d}\hat\sigma^{\rm NNLO}_{q,\rm ns,1j}$$

$$2s\cdot \mathrm{d}\hat\sigma^{\rm NNLO}_{q,\rm ns,3j} = \left\langle F^{s_r c_r}_{\rm LM,ns}(1,4,5,6)\right\rangle_\delta$$

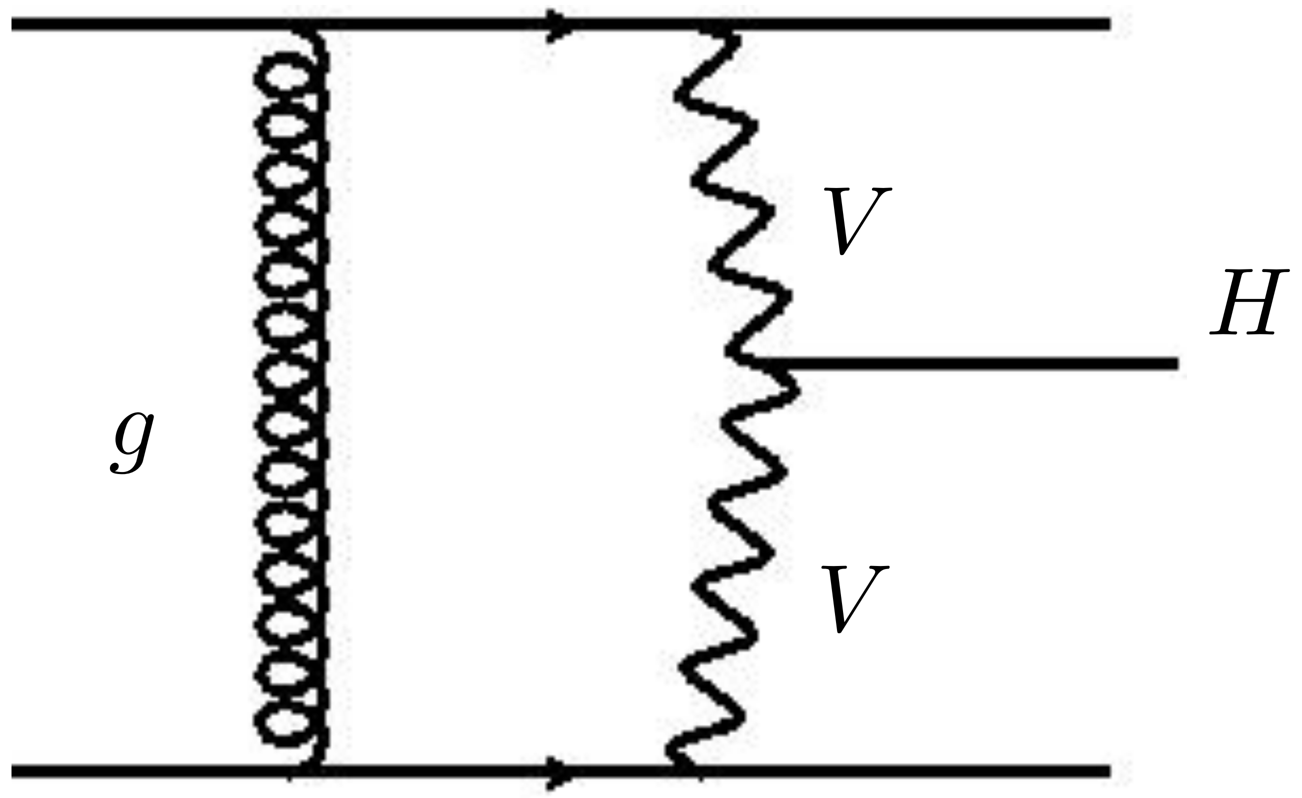
Asteriadis, Caola, K.M., Röntsch

$$\begin{aligned}
&\left\langle F^{s_r c_r}_{\rm LM,ns}(1,4,5,6)\right\rangle_\delta \\
&= \sum_{i\in[1,4]} \Bigg\langle \Big[\theta^{(a)}(I-C_{6i}) + \theta^{(b)}(I-C_{65}) + \theta^{(c)}(I-C_{5i}) + \theta^{(d)}(I-C_{65})\Big] \\
&\quad \times [df_5][df_6]\,(I-\mathbb{C}_i)\,w^{5i,6i}(I-S_6)(I-\mathbb{S})F_{\rm LM,ns}(1,4,5,6)\Bigg\rangle_\delta \\
&+ \sum_{(ij)\in[14,41]} \Bigg\langle \Big[(I-C_{5i})(I-C_{6j})\Big][df_5][df_6]\,(I-S_6)(I-\mathbb{S})F_{\rm LM,ns}(1,4,5,6)\Bigg\rangle_\delta
\end{aligned}$$

$$\begin{aligned}
&2s\cdot \mathrm{d}\hat\sigma^{\rm NNLO}_{q,\rm ns,1j} = \left\langle F^{\rm fin}_{\rm LVV}(1_q,4_q)\right\rangle_\delta + \left\langle F^{\rm fin}_{\rm LV^2}(1_q,4_q)\right\rangle_\delta \\
&+ \frac{\alpha_s(\mu)}{2\pi}\Bigg\{\int_0^1 \mathrm{d}z\,\left[\mathcal{P}'_{qq}(z) + \ln\left(\frac{4E_1^2}{\mu^2}\right)\hat P^{(0)}_{qq}(z)\right]\left\langle \frac{F^{\rm fin}_{\rm LV}(z\cdot 1_q,4_q)}{z}\right\rangle_\delta \\
&\quad + \left[2C_F\mathcal{S}^{E_{\max}}_{14} + \gamma'_q\right]\left\langle F^{\rm fin}_{\rm LV}(1_q,4_q)\right\rangle_\delta\Bigg\} + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2\Bigg\{\Bigg\langle\Bigg[\Delta_{\rm NS}(E_1,E_4,E_{\max},\eta_{14}) \qquad (3.69)\\
&\quad + C_F\left(\delta_{k_\perp,g}\left\langle r^\mu r^\nu\right\rangle_{\rho_5} - \delta_g\left\langle\Delta_{65}\right\rangle''_{S_5} + \tilde\gamma_q(E_4,E_{\max})\left\langle\Delta_{64}\right\rangle''_{S_5}\right)\Bigg]F_{\rm LM}(1_q,4_q)\Bigg\rangle_\delta \\
&\quad + \int_0^1 \mathrm{d}z\Bigg\langle\Bigg[C_F\tilde{\mathcal{P}}_{qq}(z,E_1,E_{\max})\left\langle\Delta_{61}\right\rangle''_{S_5} + \mathcal{T}_{\rm NS}(z,E_1,E_4,E_{\max},\eta_{14})\Bigg]\frac{F_{\rm LM}(z\cdot 1_q,4_q)}{z}\Bigg\rangle_\delta\Bigg\}.
\end{aligned}$$

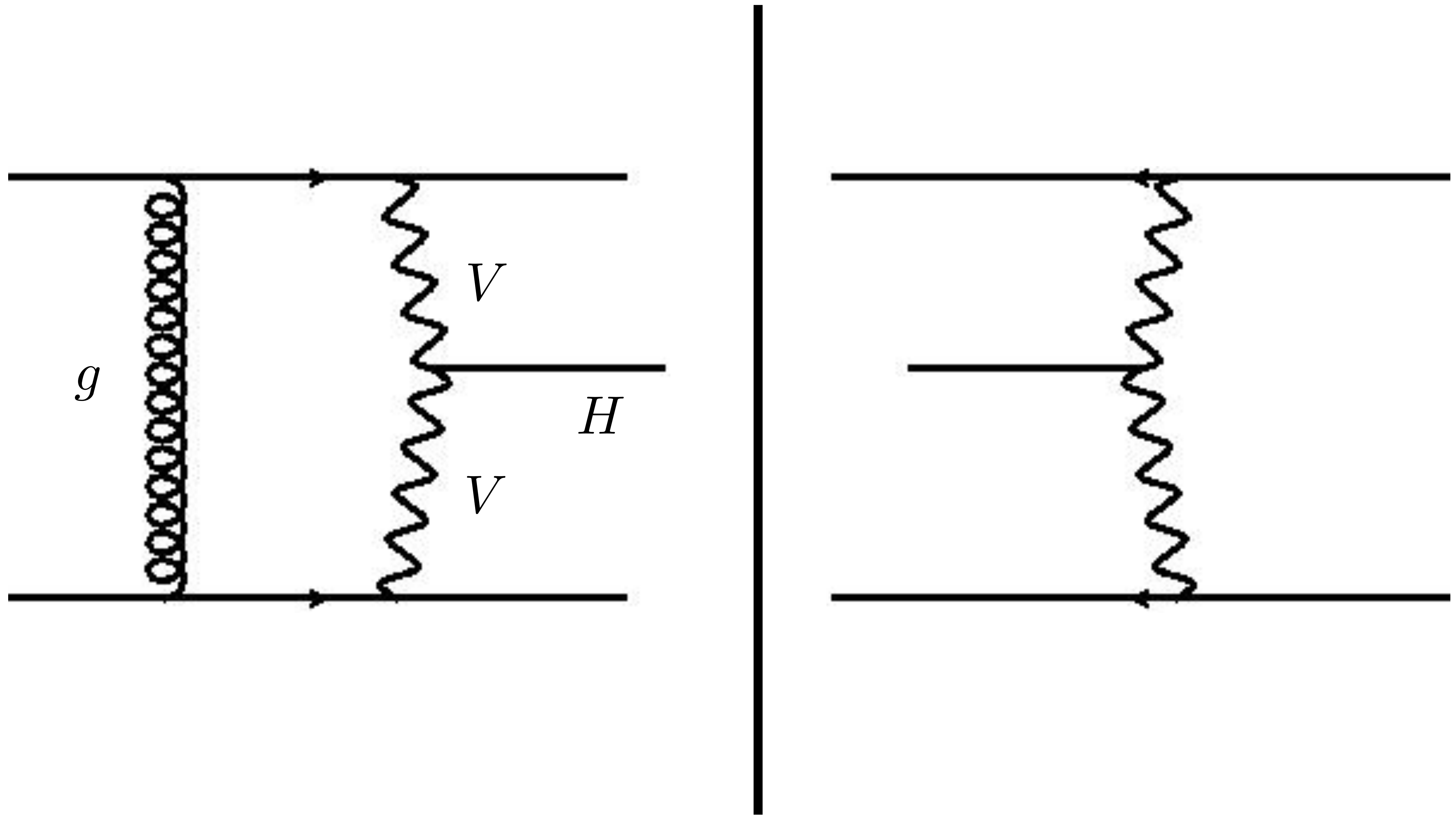
Non-factorizable contributions

It may appear that non-factorizable corrections contribute at next-to-leading order since the diagram below is definitely not zero.



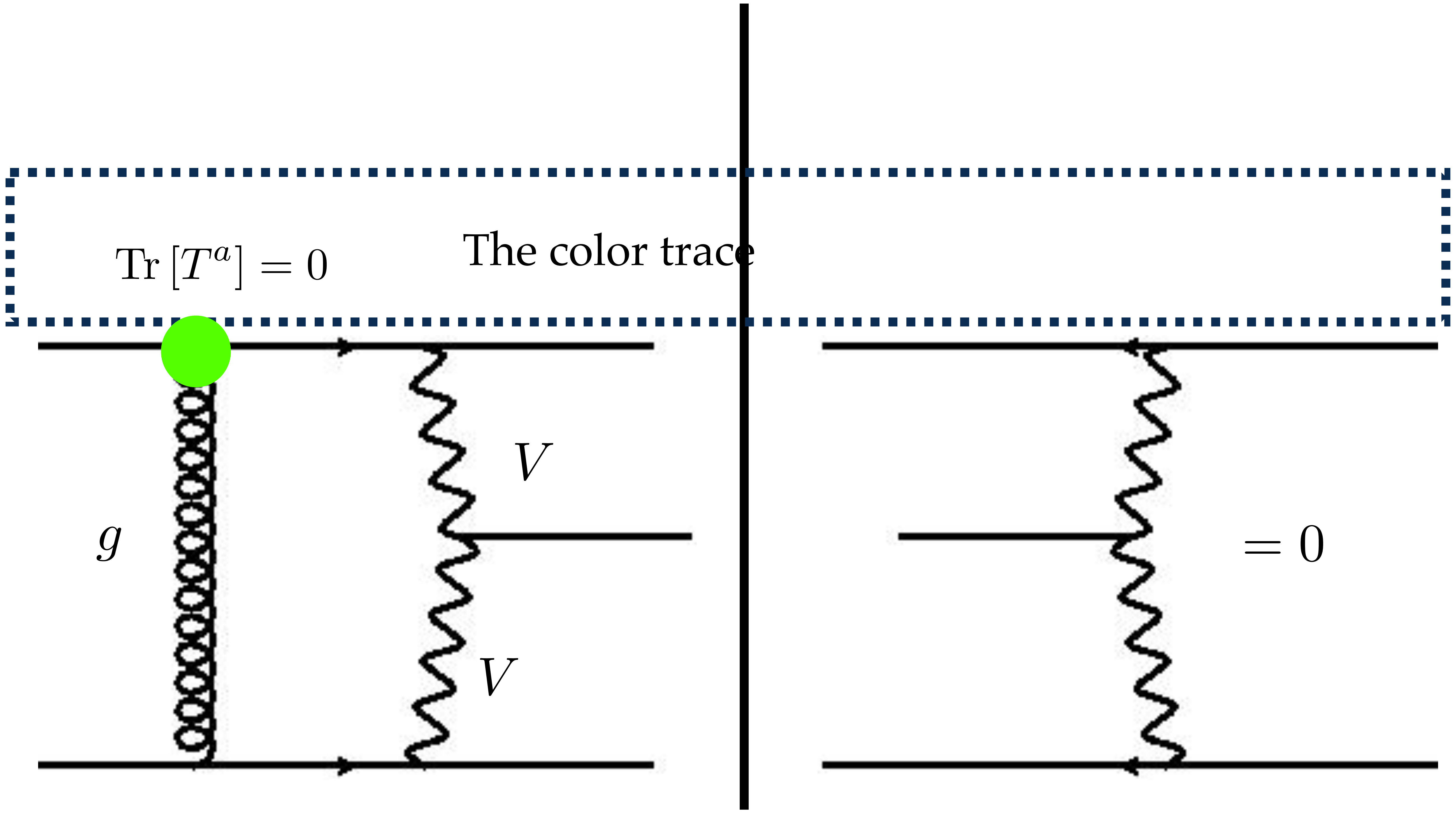
Non-factorizable contributions

However, the cross section requires interference of the one-loop amplitude with Born amplitude..



Non-factorizable contributions

…and this interference vanishes because of color conservation. Although we illustrate this for virtual contributions, it is clear that this is the feature of real-emission diagrams as well.



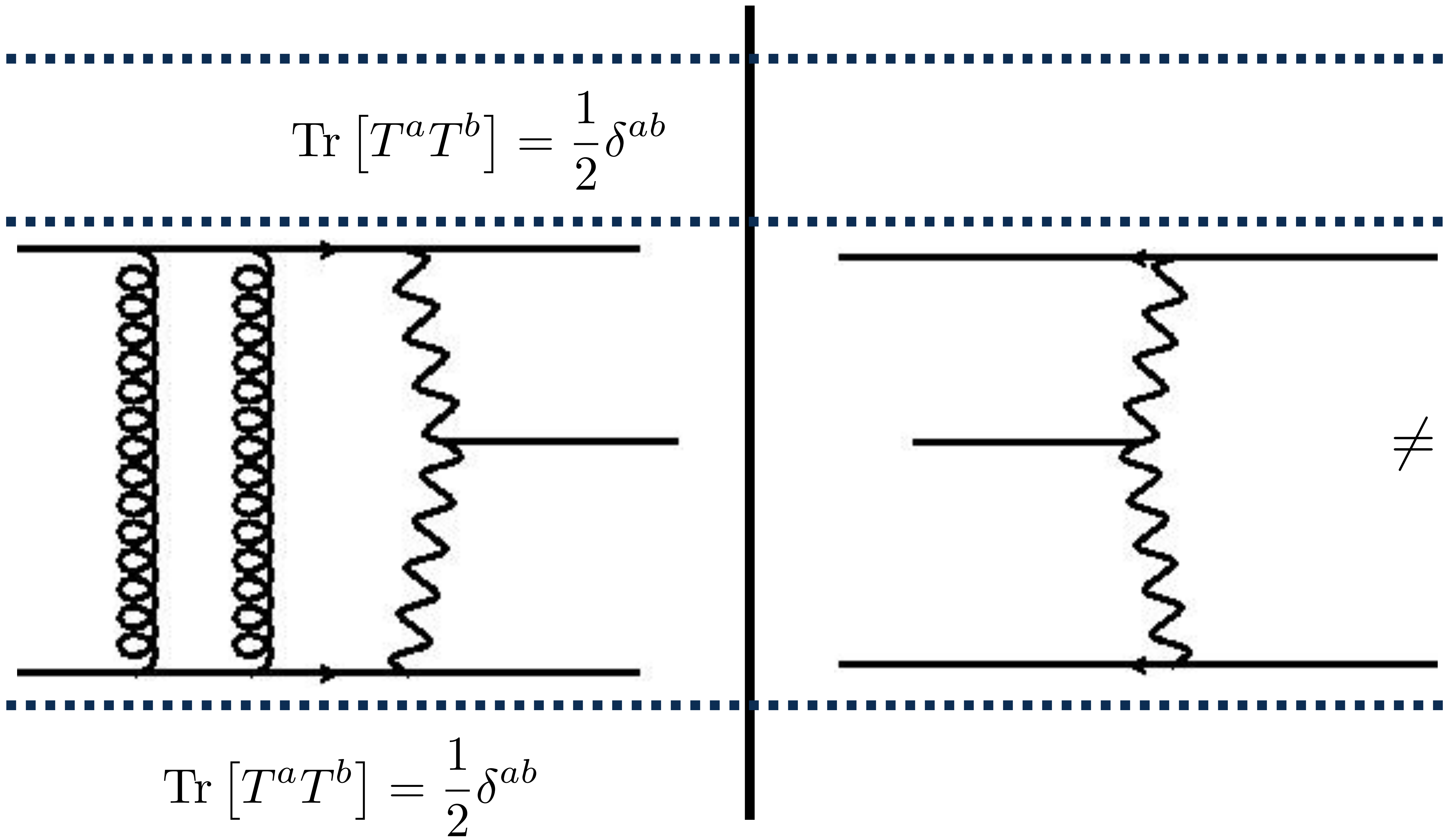
Non-factorizable contributions

At two loops, the situation changes. If the two gluons, exchanged between the quark lines, are in a color-singlet state, the non-factorizable contribution is non-vanishing. However, it is color-suppressed relative to factorizable contributions.

$$\mathrm{Tr}\left[T^a T^b\right] = \frac{1}{2}\delta^{ab}$$

$$\mathrm{fact}_{\mathrm{color}} = C_F^2 N_c^2 = \frac{(N_c^2-1)^2}{4}$$

$$\mathrm{non/fact}_{\mathrm{color}} = \frac{1}{4}\delta^{ab}\delta_{ab} = \frac{(N_c^2-1)}{4}$$



$$\neq 0$$

$$\mathrm{Tr}\left[T^a T^b\right] = \frac{1}{2}\delta^{ab}$$

$$\frac{\sigma_{\mathrm{non-fact}}}{\sigma_{\mathrm{VBF}}} \sim \alpha_s^2 \qquad \frac{\sigma_{\mathrm{non-fact}}}{\Delta\sigma_{\mathrm{VBF}}^{\mathrm{NNLO}}} \sim \frac{1}{N_c^2}$$

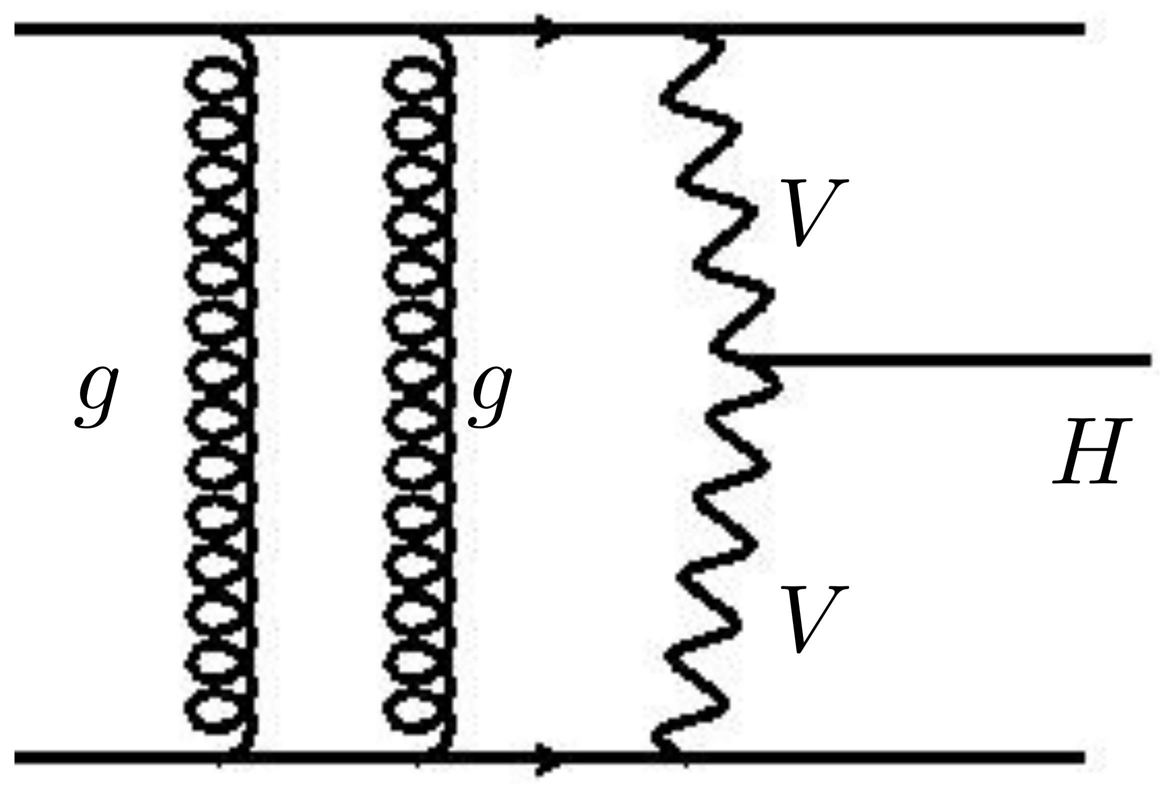
These estimates suggest that non-factorizable contributions should be below 1%. However, it was also argued that these contributions are further suppressed because they are kinematically disfavoured. As we will see, this feature is quite subtle.

Non-factorizable contributions

It is important to scrutinise these claims and to estimate the non-factorizable contributions in a convincing manner (we really do not have much experience with such effects).

Since such corrections are of a NNLO type, understanding them at a fully-differential level requires us to compute the double-virtual, real-virtual and double-real contributions. It is clear that the double-real and the real-virtual contributions can be managed since they are at most one-loop computations supplemented with NNLO subtraction schemes.

The double-virtual non-factorizable corrections are a problem since they require a two-loop five-point function with external (the Higgs) and internal (weak bosons) masses. It is impossible to compute such complicated diagrams/amplitudes using existing technology for multi-loop computations.



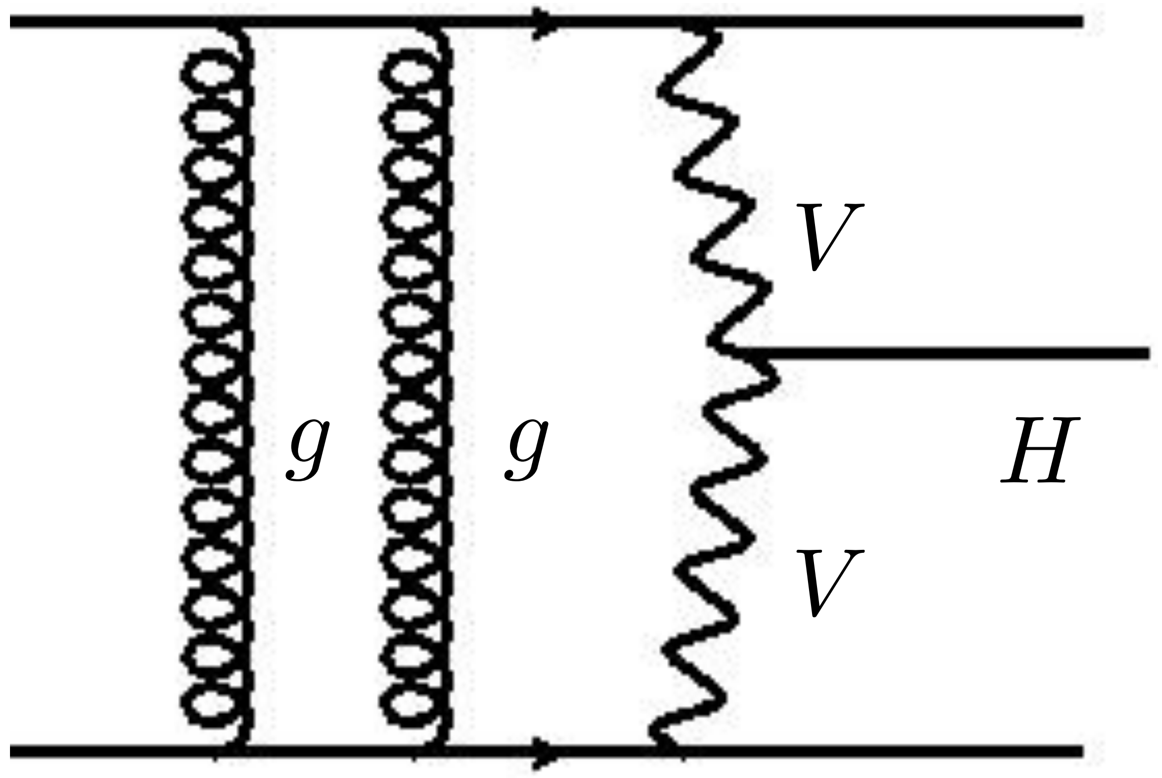
Non-factorizable contributions

However, the weak boson fusion kinematics is particular…

Indeed, we have two jets flying in the opposite directions with relatively small transverse momenta and very high energies. We also have rapidity gap between the jets and between the jets and the Higgs. In other words, jets are energetic and forward/backward and all (jet and Higgs) transverse momenta are comparable and (fairly) small.

Is it possible to construct an expansion of the virtual amplitudes by taking into account the smallness of jets transverse momenta relative to their energies?

Penin, K.M.



$$p_\perp^{j_1,j_2} > 25\ \mathrm{GeV}, \quad |y_{j_1,j)2}| < 4.5$$
$$|y_{j_1} - y_{j_2}| > 4.5, \quad m_{j_1 j_2} > 600\ \mathrm{GeV}$$

Non-factorizable contributions

The answer to this question is affirmative. In fact, the leading term in the required expansion is known as the high-energy scattering (Regge) limit.

Penin, K.M.

We will only need the abelian version of the Regge limit that was extensively studied in the early days of physics at electron-positron colliders.

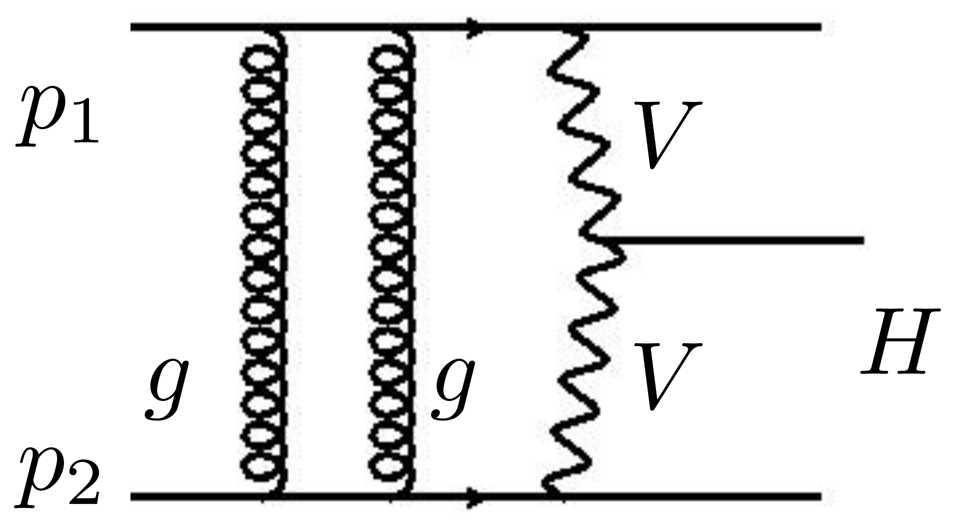
Sudakov, Lipatov, Gribov, Cheng, Wu, Chang, Ma

Translated to QCD language, these studies imply that virtual gluons are ``soft'' so that leading high-energy asymptotic is obtained by employing the following approximations:

1) use eikonal propagators for quark lines: $\dfrac{1}{2pk + i0}$ $\qquad k = \alpha p_1 + \beta p_2 + k_\perp$

2) use eikonal couplings of quarks to gluons: $-2ie\, p_\mu$

3) neglect longitudinal momenta components in gluon and vector boson propagators: $\dfrac{1}{k^2} \to -\dfrac{1}{k_\perp^2}$

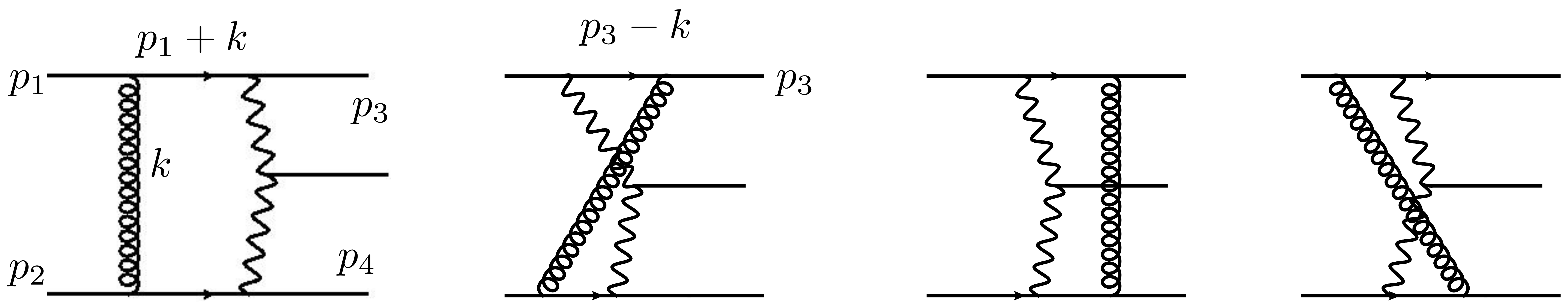


$$p_\perp^{j_1,j_2} > 25\ \text{GeV}, \quad |y_{j_1,j)2}| < 4.5$$
$$|y_{j_1} - y_{j_2}| > 4.5, \quad m_{j_1 j_2} > 600\ \text{GeV}$$

Non-factorizable contributions

Since we only need the interference of the two-loop amplitude with the leading order amplitude, the sum over colors makes the contribution abelian, i.e. QED-like. This effective abelianization, together with the eikonal approximation, makes one- and two-loop computations quite simple.

Corrections are enhanced by an additional factor π.



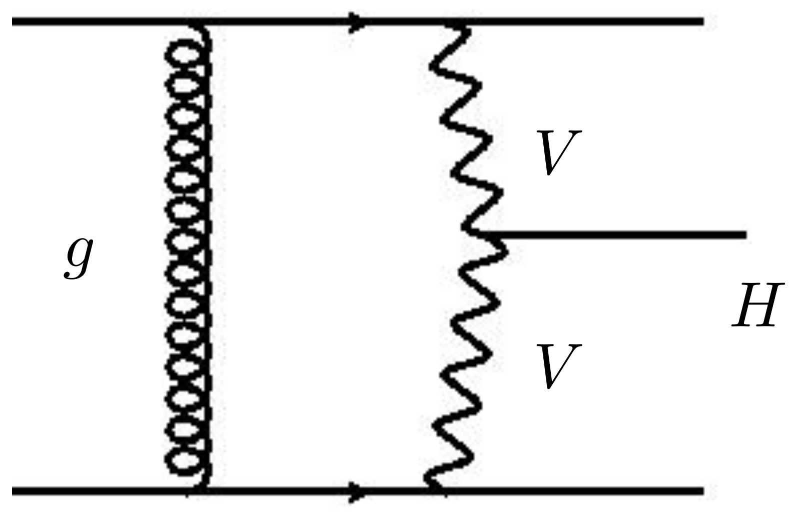
$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k_\perp^2} \frac{1}{(k_\perp - q_{3,\perp})^2 + M_V^2} \frac{1}{(k_\perp + q_{4,\perp})^2 + M_V^2} \left[\frac{1}{2p_1k + i0} + \frac{1}{-2p_3k + i0}\right] \left[\frac{1}{-2p_2k + i0} + \frac{1}{2p_4k + i0}\right]$$

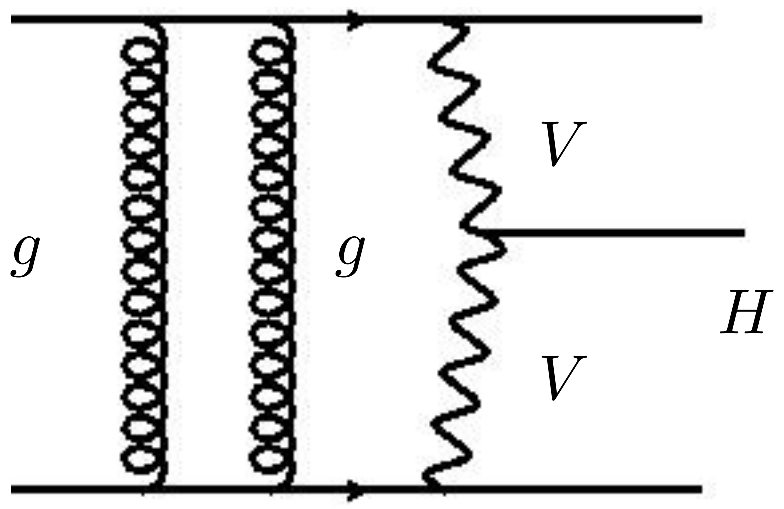
$$\lim_{p_3 \to p_1} \left[\frac{1}{2p_1k + i0} - \frac{1}{-2p_3k + i0}\right] = -\frac{2i\pi}{s}\delta(\beta) \qquad \lim_{p_4 \to p_2} \left[\frac{1}{-2p_2k + i0} + \frac{1}{2p_4k + i0}\right] = -\frac{2i\pi}{s}\delta(\alpha)$$

$$k = \alpha p_1 + \beta p_2 + k_\perp \qquad d^4k = \frac{s}{2}\, d\alpha\, d\beta\, d^2k_\perp$$

Non-factorizable contributions

A very similar computation can be done for the two-loop amplitude. Upon integrating over longitudinal loop momenta fractions, we obtain the following results for the one- and two-loop eikonal amplitudes. The results are infra-red divergent; we introduce the gluon mass to regulate these divergences. Note that the one-loop amplitude is pure imaginary.





$$\left|\frac{p_\perp}{\sqrt{s}}\right| \ll 1.$$

$$\mathcal{M}^{(1)} = i\tilde{\alpha}_s \chi^{(1)}(\boldsymbol{q}_3, \boldsymbol{q}_4)\mathcal{M}^{(0)}$$

$$\chi^{(1)}(\boldsymbol{q}_3, \boldsymbol{q}_4) = \frac{1}{\pi}\int \frac{\mathrm{d}^2\boldsymbol{k}}{\boldsymbol{k}^2+\lambda^2} \times \frac{\boldsymbol{q}_3^2+M_V^2}{(\boldsymbol{k}-\boldsymbol{q}_3)^2+M_V^2}\,\frac{\boldsymbol{q}_4^2+M_V^2}{(\boldsymbol{k}+\boldsymbol{q}_4)^2+M_V^2},$$

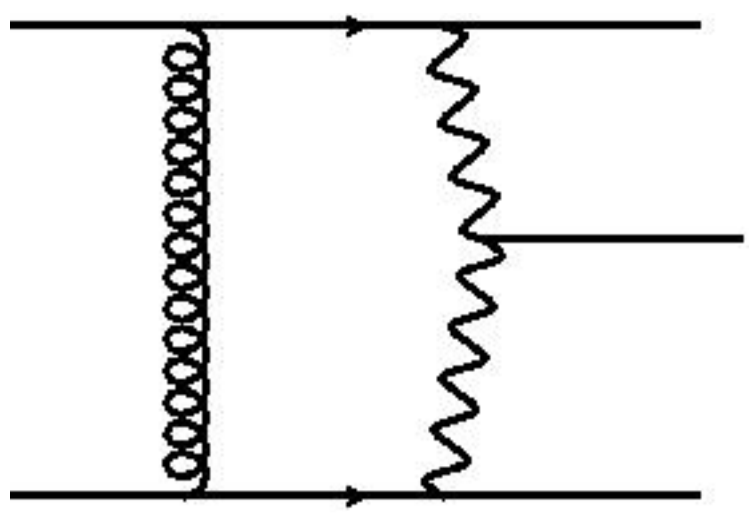
Color projection has been taken; this one-loop contribution is meant to be used in the NNLO contribution only.

$$\mathcal{M}^{(2)} = -\frac{\tilde{\alpha}_s^2}{2!}\chi^{(2)}(\boldsymbol{q}_3, \boldsymbol{q}_4)\mathcal{M}^{(0)}$$

$$\tilde{\alpha}_s = \left[\frac{N_c^2-1}{4N_c^2}\right]^{1/2}\alpha_s$$

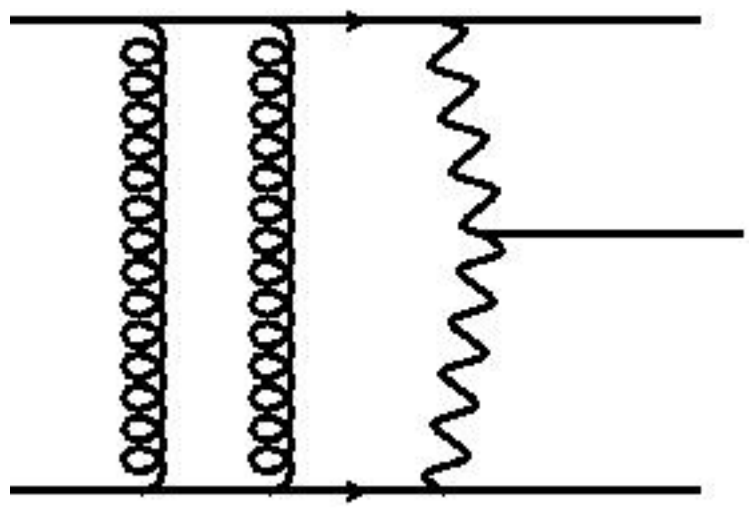
$$\chi^{(2)}(\boldsymbol{q}_3, \boldsymbol{q}_4) = \frac{1}{\pi^2}\int \left(\prod_{i=1}^{2}\frac{\mathrm{d}^2\boldsymbol{k}_i}{\boldsymbol{k}_i^2+\lambda^2}\right) \times \frac{\boldsymbol{q}_3^2+M_V^2}{(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{q}_3)^2+M_V^2}\,\frac{\boldsymbol{q}_4^2+M_V^2}{(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{q}_4)^2+M_V^2}$$

Non-factorizable contributions



$$\chi^{(1)} = \frac{1}{\pi}\int \frac{\mathrm{d}^2\mathbf{k}}{\mathbf{k}^2+\lambda^2} \times \frac{\mathbf{q}_3^2+M_V^2}{(\mathbf{k}-\mathbf{q}_3)^2+M_V^2}\,\frac{\mathbf{q}_4^2+M_V^2}{(\mathbf{k}+\mathbf{q}_3)^2+M_V^2}$$

$$\chi^{(1)} = -\ln\left(\frac{\lambda^2}{M_V^2}\right) + f^{(1)}(\boldsymbol{q}_3, \boldsymbol{q}_4, M_V^2)$$



$$\chi^{(2)} = \frac{1}{\pi^2}\int \prod_{i=1}^{2} \frac{\mathrm{d}^2\mathbf{k}_i}{\mathbf{k}_i^2+\lambda^2} \times \frac{\mathbf{q}_3^2+M_V^2}{(\mathbf{k}_1+\mathbf{k}_2-\mathbf{q}_3)^2+M_V^2}\,\frac{\mathbf{q}_4^2+M_V^2}{(\mathbf{k}_1+\mathbf{k}_2+\mathbf{q}_4)^2+M_V^2}$$

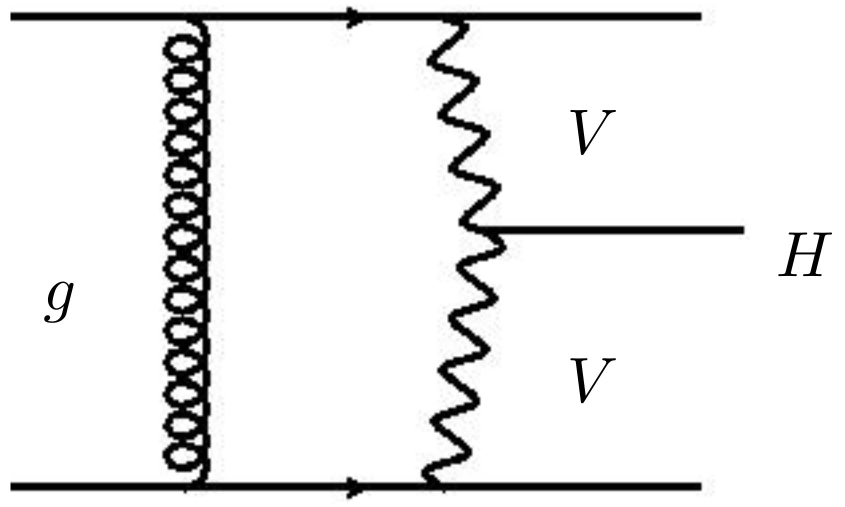
$$\chi^{(2)} = \ln^2\left(\frac{\lambda^2}{M_V^2}\right) - 2\ln\left(\frac{\lambda^2}{M_V^2}\right) f^{(1)}(\boldsymbol{q}_3, \boldsymbol{q}_4, M_V^2) + f^{(2)}(\boldsymbol{q}_3, \boldsymbol{q}_4, M_V^2)$$

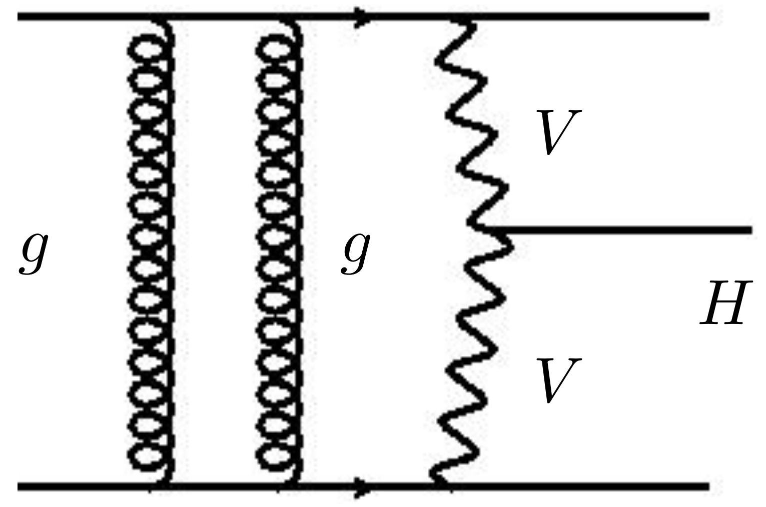
The infrared divergences that appear in non-factorizable contributions exponentiate into a Coulomb (Glauber) phase and cancel on their own, without any reference to real emission contributions.

$$\mathcal{M} = \mathcal{M}_0\, e^{-i\tilde{\alpha}_s \ln\frac{\lambda^2}{M_V^2}}\left[1 + i\tilde{\alpha}_s f^{(1)} - \frac{\tilde{\alpha}_s^2}{2} f^{(2)} + \ldots\right].$$

Non-factorizable contributions

The final result is given by the sum of the one-loop amplitude squared and the interference of the two-loop and tree amplitudes. In this combination, the dependence on the gluon mass (i.e. infra-red sensitivity) cancels out. Hence, we obtain a physical result that does not require us to account for real emissions.





$$\mathrm{d}\sigma_{\mathrm{nf}}^{\mathrm{NNLO}} = \left(\frac{N_c^2-1}{4N_c^2}\right)\alpha_s^2\,\chi_{\mathrm{nf}}\,\mathrm{d}\sigma^{\mathrm{LO}}$$

$$\chi_{\mathrm{nf}}(\boldsymbol{q}_3,\boldsymbol{q}_4) = [f^{(1)}(\boldsymbol{q}_3,\boldsymbol{q}_4)]^2 - f^{(2)}(\boldsymbol{q}_3,\boldsymbol{q}_4)$$

$$r_1 = \boldsymbol{q}_3^2\,x + \boldsymbol{q}_4^2\,(1-x) - \boldsymbol{q}_H^2\,x(1-x)\,,$$
$$r_2 = \boldsymbol{q}_H^2\,x(1-x) + M_V^2\,,$$
$$r_{12} = r_1 + r_2\,,$$
$$\Delta_i = \boldsymbol{q}_i^2 + M_V^2\,.$$

$$f^{(1)} = \int_0^1 \mathrm{d}x\,\frac{\Delta_3\Delta_4}{r_{12}^2}\left[\ln\left(\frac{r_{12}^2}{r_2 M_V^2}\right) + \frac{r_1-r_2}{r_2}\right],$$

$$f^{(2)} = \int_0^1 \mathrm{d}x\,\frac{\Delta_3\Delta_4}{r_{12}^2}\left[\left(\ln\left(\frac{r_{12}^2}{r_2 M_V^2}\right) + \frac{r_1-r_2}{r_2}\right)^2 - \ln^2\left(\frac{r_{12}}{r_2}\right) - \frac{2r_{12}}{r_2}\ln\left(\frac{r_{12}}{r_2}\right) - 2\,\mathrm{Li}_2\left(\frac{r_1}{r_{12}}\right) - \left(\frac{r_1-r_2}{r_2}\right)^2 + \frac{\pi^2}{3}\right],$$

Fiducial cross section: the set up

Non-factorizable corrections to fiducial WBF cross section computed with cuts shown below are found to be small -0.4 percent. However, they are larger than N3LO factorizable corrections (computed and estimated).

Factorizable corrections	$\sigma^{(\text{no cuts})}$ [pb]		$\sigma^{(\text{VBF cuts})}$ [pb]	
LO	$4.032^{+0.057}_{-0.069}$		$0.957^{+0.066}_{-0.059}$	
NLO	$3.929^{+0.024}_{-0.023}$	-2.6%	$0.876^{+0.008}_{-0.018}$	-8.4%
NNLO	$3.888^{+0.016}_{-0.012}$	-1%	$0.844^{+0.008}_{-0.008}$	-3.6%

$$p_\perp^{j_1,j_2} > 25 \text{ GeV}, \quad |y_{j_1,j)2}| < 4.5$$
$$|y_{j_1} - y_{j_2}| > 4.5, \quad m_{j_1 j_2} > 600 \text{ GeV}$$

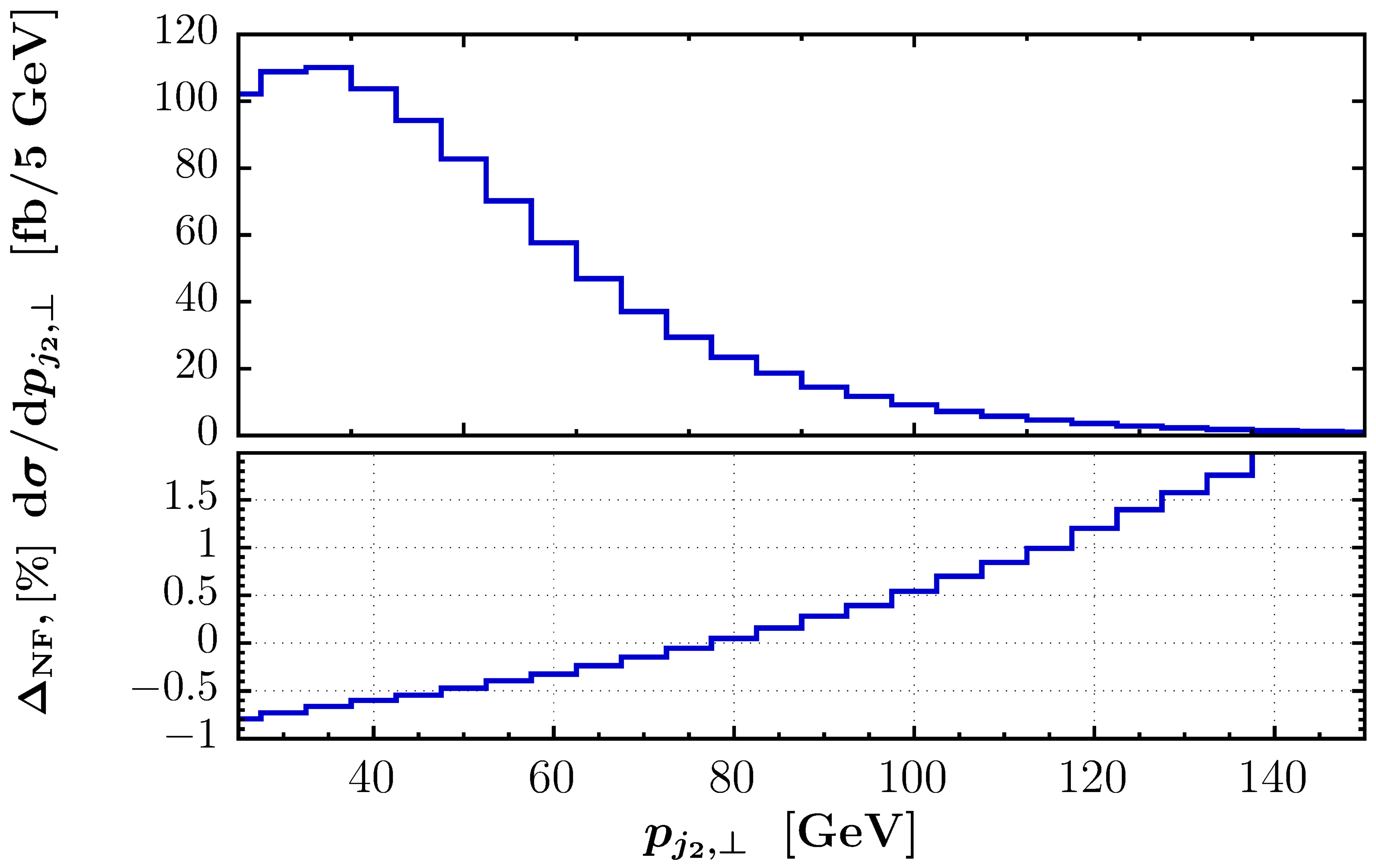
Cacciari, Dreyer, Karlberg, Salam, Zanderighi

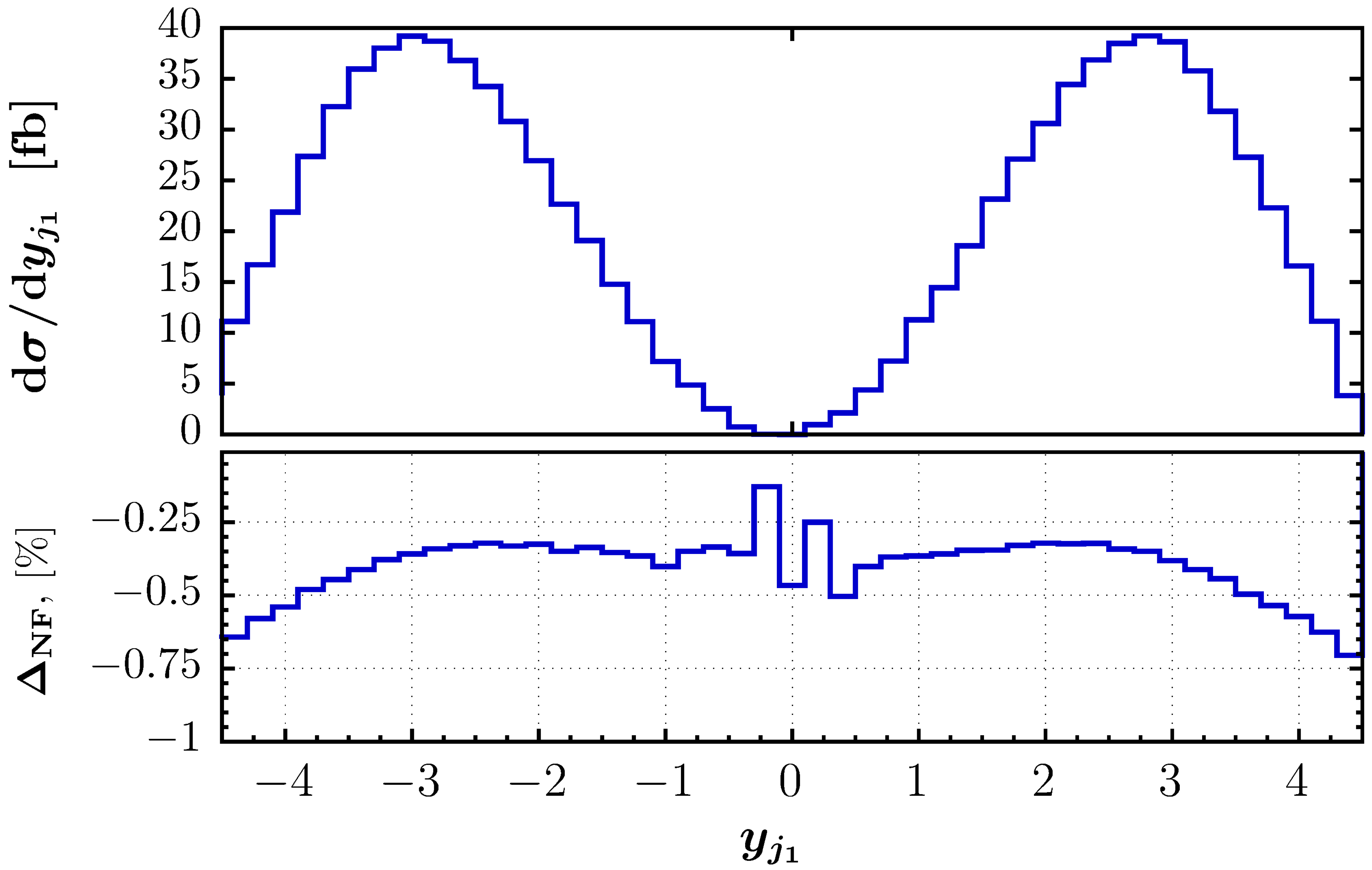
$$\mu_F = \left[\frac{m_H}{2} \sqrt{\frac{m_H^2}{4} + p_{\perp,H}^2} \right]^{1/2}$$

$$\mu_R = \sqrt{p_{\perp,j_1} p_{\perp,j_2}}$$

PDF set: NNPDF 3.0

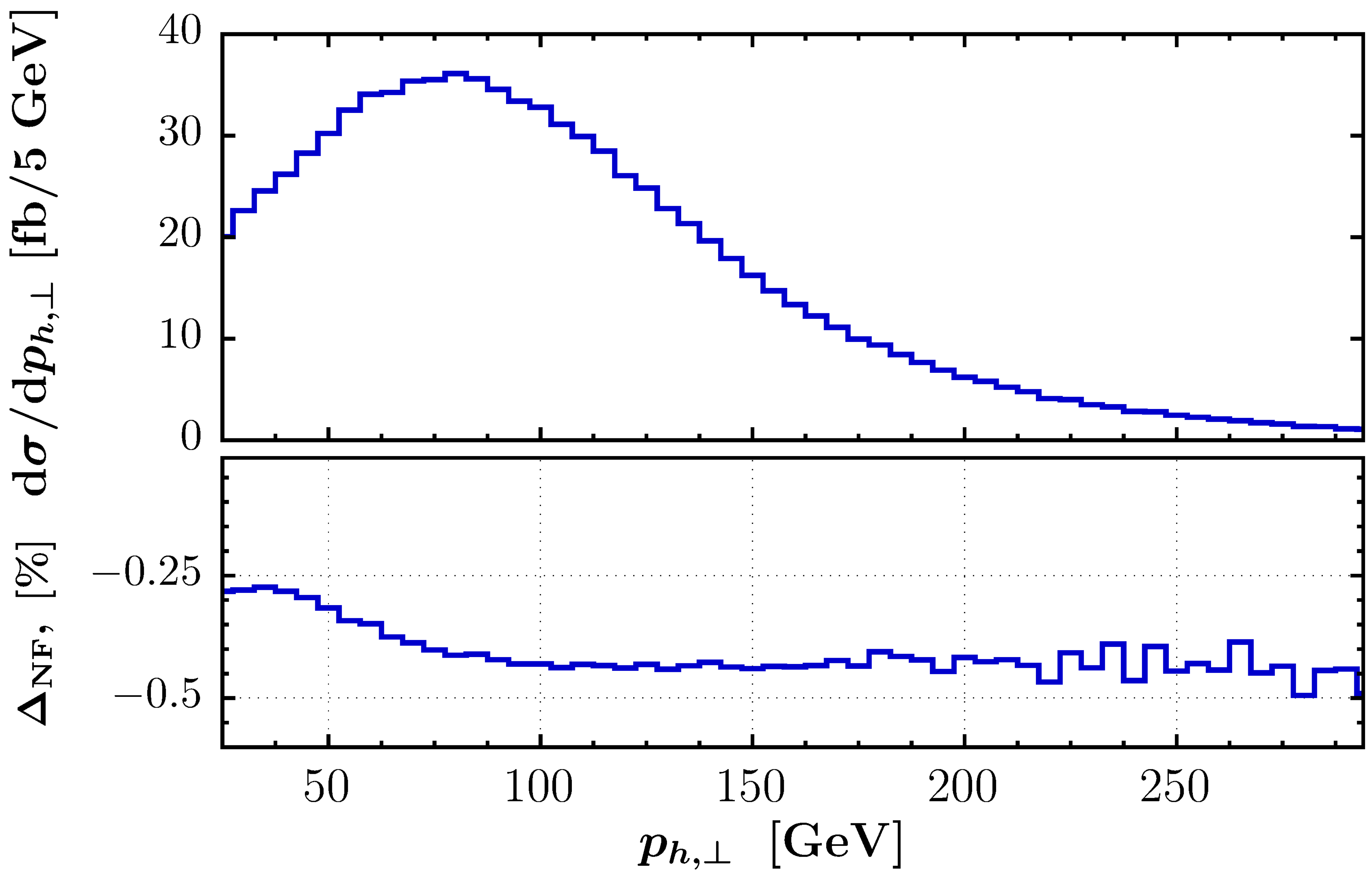
Kinematic distirbutions: non-factorizable corrections

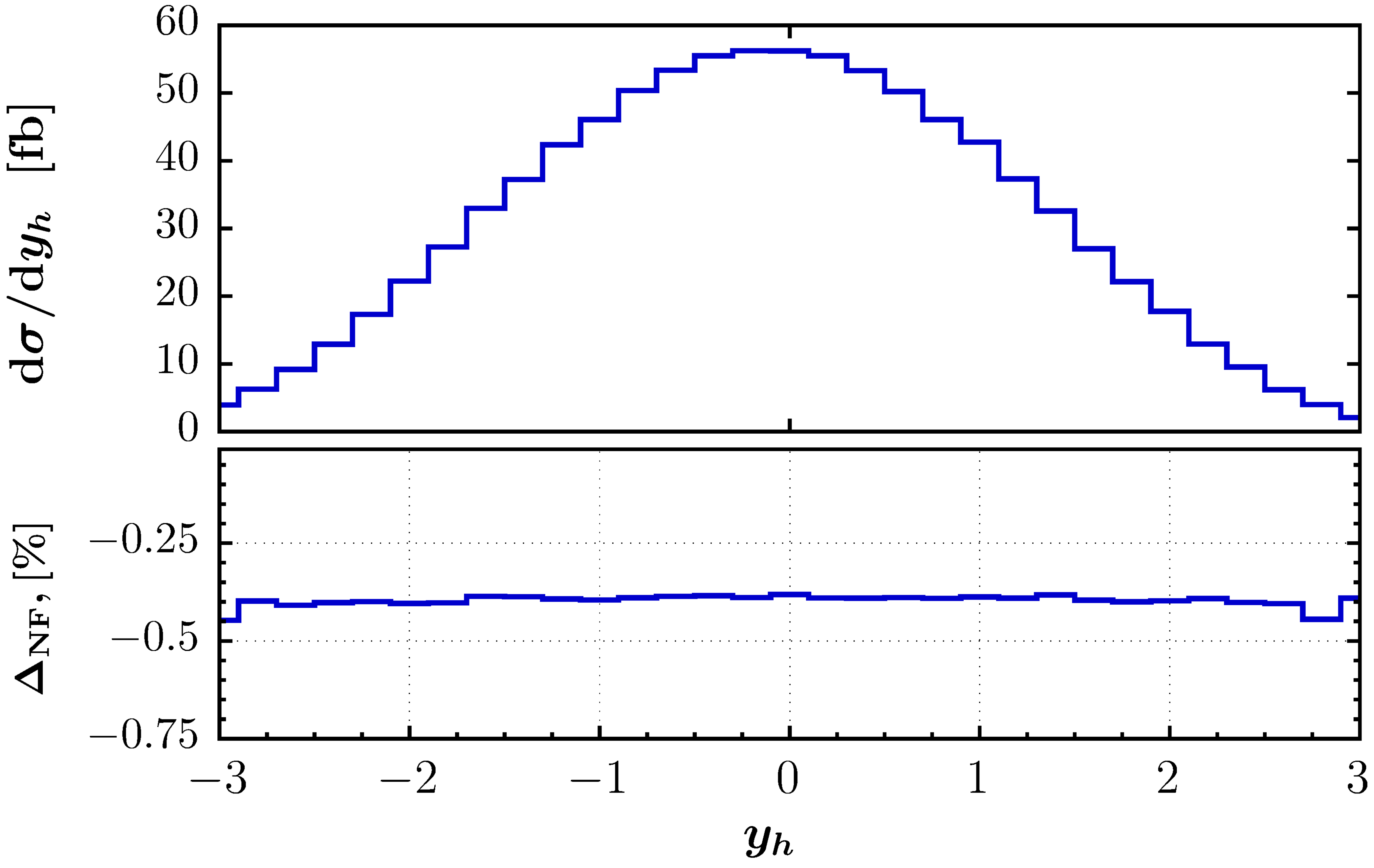




Percent level non-factorizable effects in kinematic distributions; corrections to transverse momentum distribution of a second jet change from negative to positive.

Kinematic distirbutions: non-factorizable corrections





Corrections to the Higgs boson transverse momentum and rapidity distributions are much less volatile… Both are about half a percent. The non-factorizable corrections to the cross section with WBF cuts are quite similar.

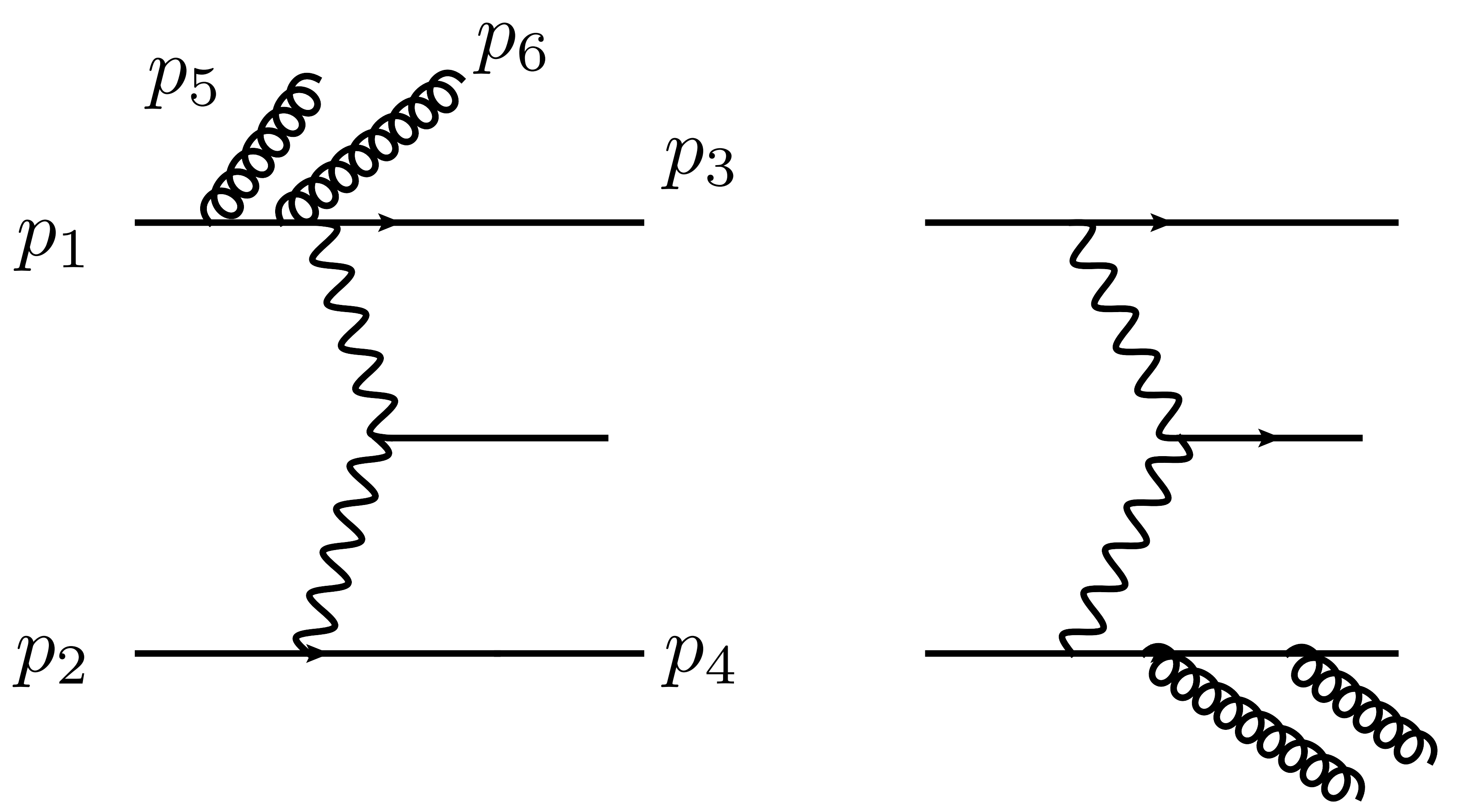
Non-factorizable corrections beyond eikonal approximation

Eikonal approximation (forward scattering) gives us the Coulomb phase; that is why the infra-red singularities cancel on their own. Because of the difference between a gluon and two weak bosons fusing into the Higgs boson, the result is different from zero.

Other effects, e.g. real emissions, require going beyond the forward scattering limit in computing both virtual and real emission contributions.

$$\lim_{p_5,p_6\to 0} |\mathcal{M}(1_q,2_Q,3_q,4_Q)|^2_{\rm nf} = (N_c^2-1){\rm Eik}_{\rm nf}(p_5){\rm Eik}_{\rm nf}(p_6)\ \mathcal{A}_0^2(1,2,3,4)$$

$${\rm Eik}(p) = \sum_{i\in[1,3];j\in[2,4]} \lambda_{ij} \frac{p_i p_j}{(p_i p)(p_j p)} \qquad \lambda_{ij} = \begin{cases} 1 & i,j \text{ both incoming or outgoing} \\ -1 & \text{otherwise} \end{cases}$$



Summary

We discussed higher order QCD corrections to Higgs production in the weak boson fusion process. These corrections can be divided into factorizable (single fermion line, DIS-like) and non-factorizable (two lines involved).

Factorizable corrections: derived simple formulas for fully-differential NNLO contributions to DIS; we are in the process of assembling NNLO QCD corrections to WBF.

Non-factorizable corrections: first-ever careful estimate of such effects in the context of the LHC physics.

- they appear at next-to-next-to-leading order for the first time; two-loop five-point functions ! However, thanks to WBF kinematic, they can be studied in high-energy (eikonal) approximation;
- they are colour-suppressed but π - enhanced; their origin is related to the Coulomb (Glauber) phase;
- these corrections can reach a percent level in WBF kinematic distributions and can be strongly kinematic-dependent; they change the fiducial WBF cross section by O(-0.5) percent;
- they appear to be equally if not more important than factorizable N3LO corrections;
- they can not be estimated using parton showers, even approximately.