Karlsruher Institut für Technologie

Particle Physics Phenomenology
after the Higgs Discovery

Higgs boson physics with higher order QCD corrections within Higgs Effective Field Theory

Kirill Melnikov

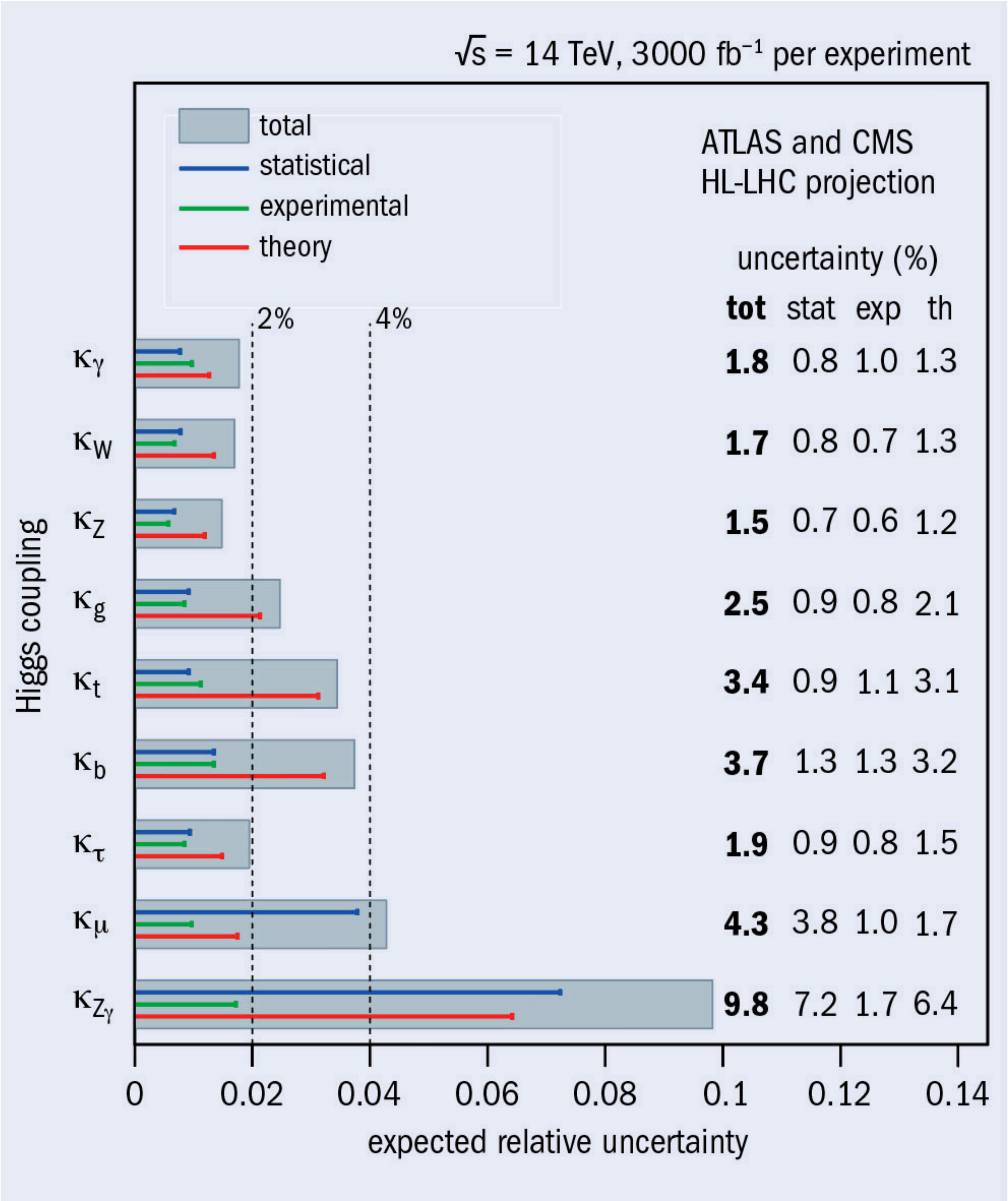
CRC 257 annual meeting; Siegen 06.10-08.10 2020

Higgs physics

Higgs boson properties are expected to be studied in great detail during Run III and at HL-LHC.

Information about Higgs couplings and quantum numbers is obtained from kinematic distributions of Higgs decay products and any particles produced along with Higgs bosons.

Such kinematic distributions are affected by both radiative corrections and modified couplings or higher-dimensional operators (BSM Physics).



Higgs physics

We would like to combine precise fully-differential description of Higgs production and decay processes with anomalous couplings / effects of higher-dimensional operators.

This requires two things:

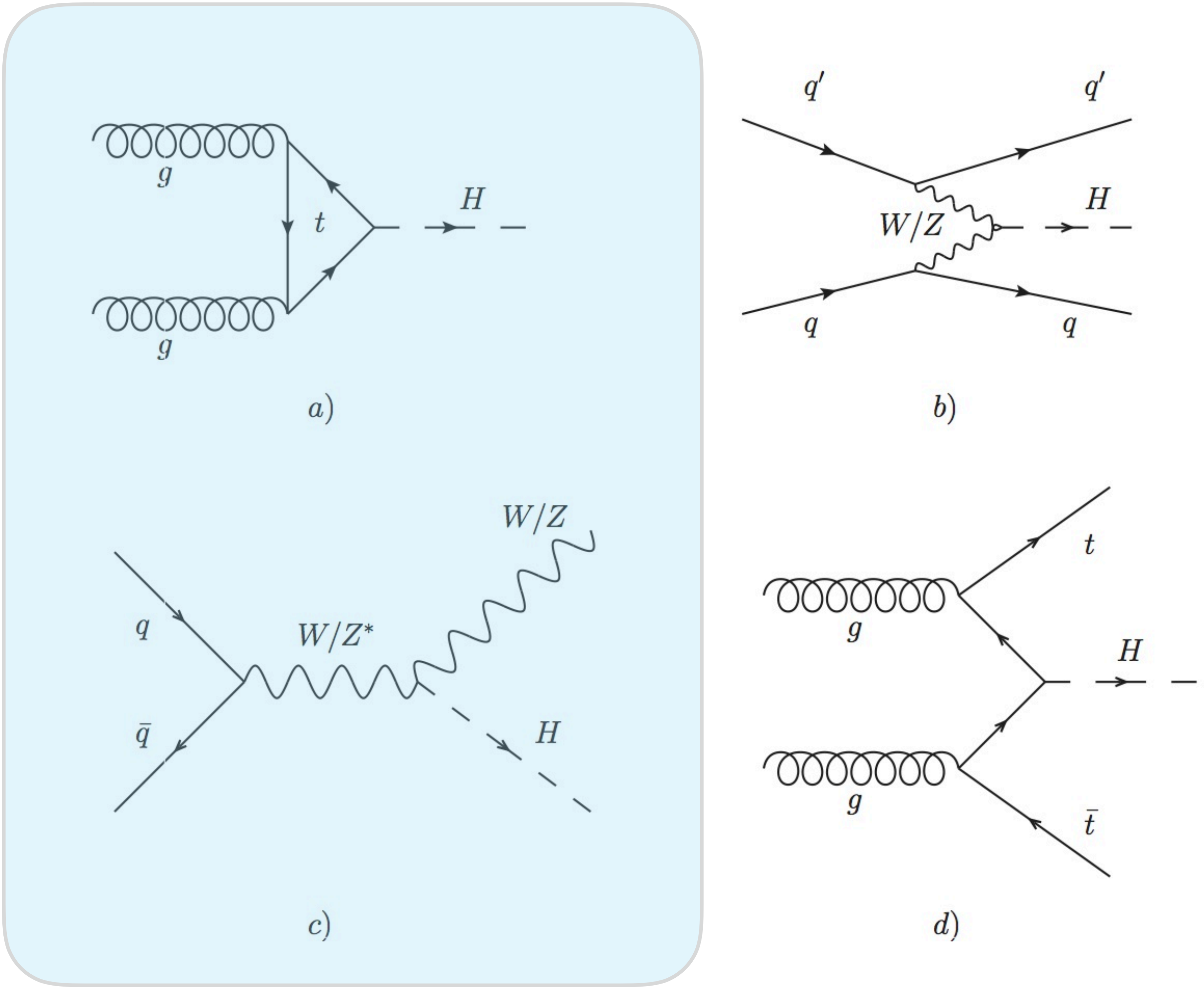
1) simple, general, realistic and efficient ways to describe fully-differential NNLO QCD corrections to basic Higgs production processes;

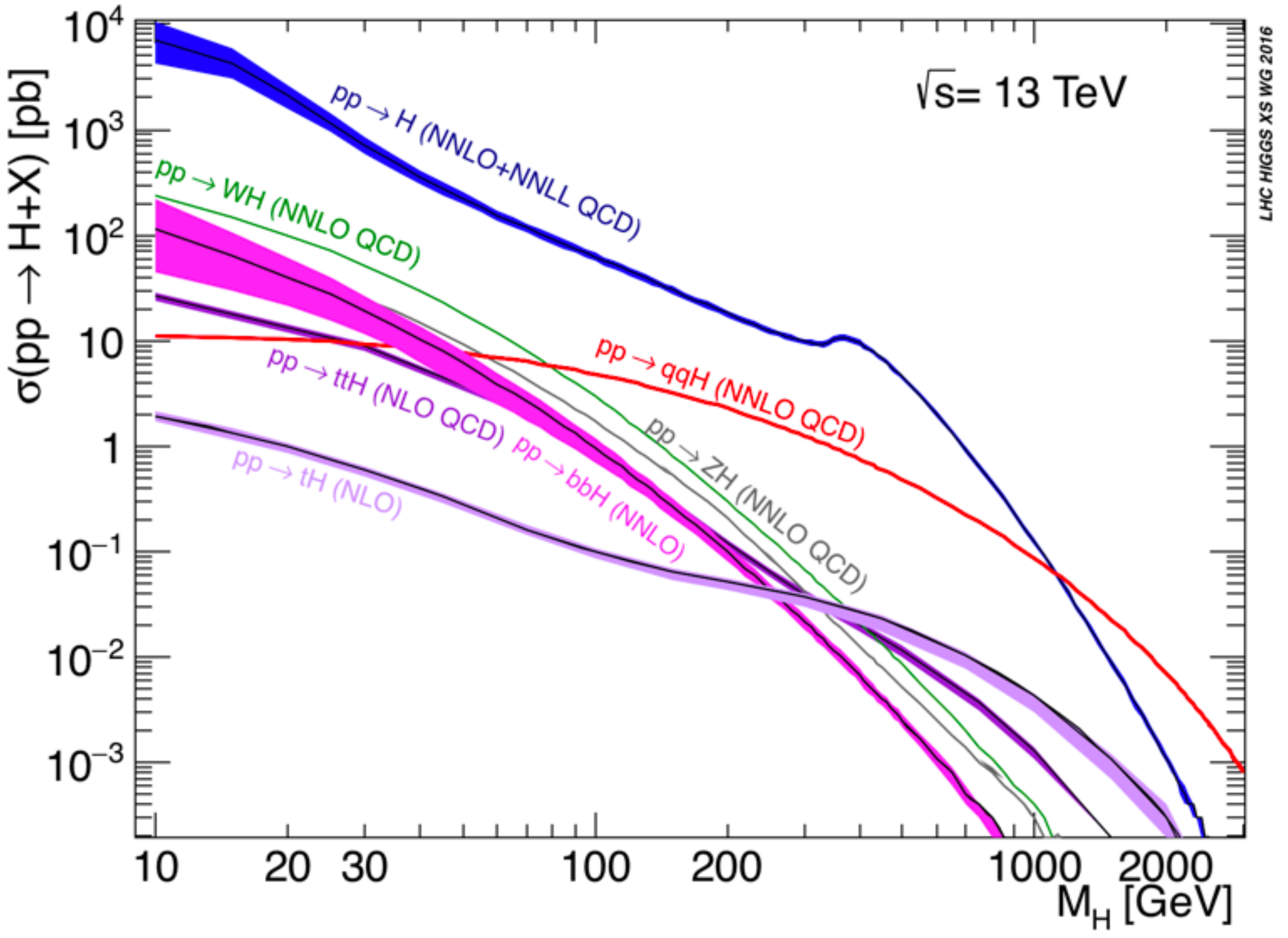
2) scattering amplitudes that accommodate SMEFT effects.

We are not there yet with either 1) and 2) but I will give you a few examples of how we move (or plan to move) forward.

Higgs boson production

A number of Higgs boson production processes can be explored at the LHC. Also, Higgs boson decays into different final states can be studied.

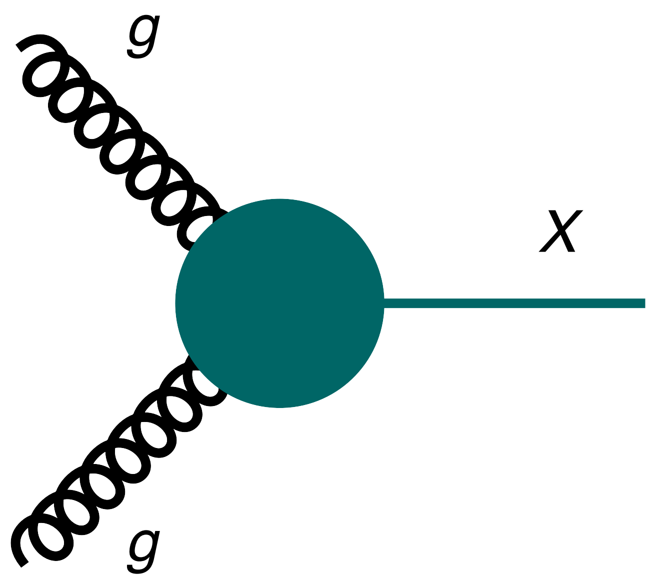




NNLO QCD corrections to color singlet production

Simple formulas exist for NNLO QCD color-singlet production (H,VH, HH etc.). These formulas contain unspecified four-dimensional hard matrix elements for higher-multiplicity partonic processes and finite remainders of loop corrections. Hence, they can be used (almost) verbatim if hard matrix elements change.

Caola, Melnikov, Röntsch



$$
\begin{aligned}
\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{\mathrm{virt}_{12},gg} = & \Big\langle F^{\mathrm{fin}}_{\mathrm{LVV},gg}(1,2) + F^{\mathrm{fin}}_{\mathrm{LV}^2,gg}(1,2) + \frac{\alpha_s(\mu)}{2\pi}\left[\frac{2\pi^2}{3}C_A - 2\gamma_g \ln\left(\frac{\mu^2}{s}\right)\right] \times \\
& F^{\mathrm{fin}}_{\mathrm{LV},gg}(1,2)\Big\rangle + \frac{\alpha_s(\mu)}{2\pi}\int_0^1 dz \left[\mathcal{P}'_{gg}(z) - \ln\left(\frac{\mu^2}{s}\right)\hat{P}^{(0)}_{gg,R}(z)\right] \times \\
& \left\langle \frac{F^{\mathrm{fin}}_{\mathrm{LV},gg}(z\cdot 1,2) + F^{\mathrm{fin}}_{\mathrm{LV},gg}(1,z\cdot 2)}{z}\right\rangle .
\end{aligned}
$$

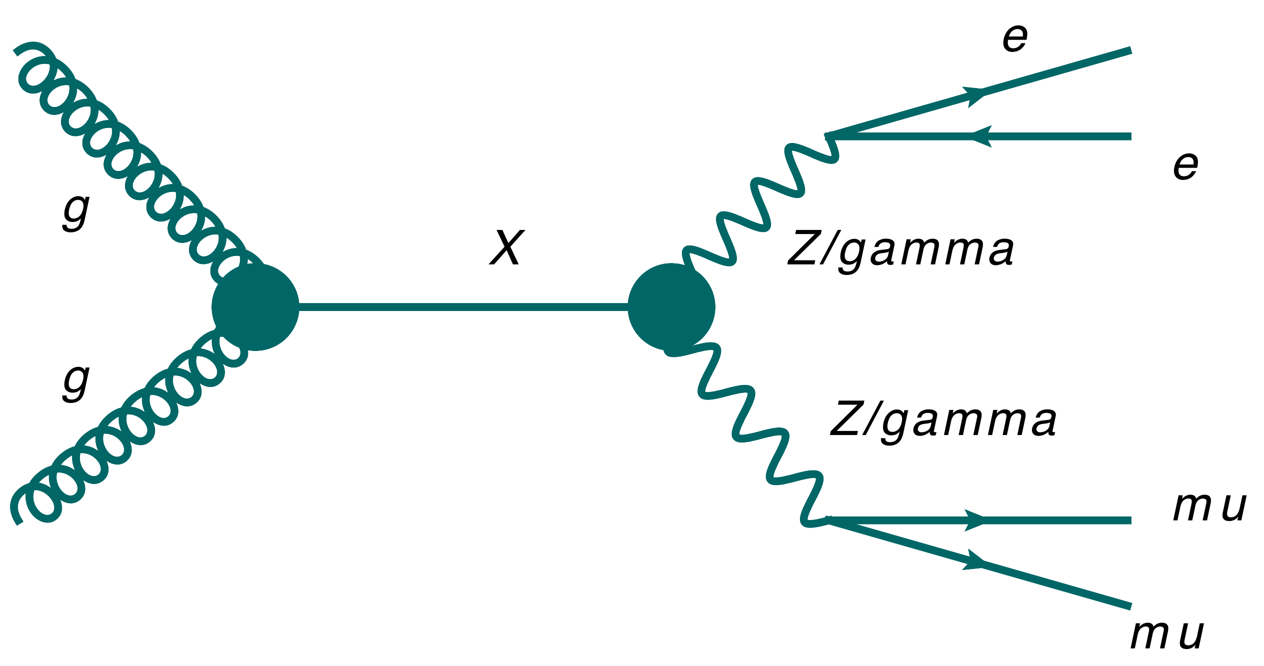
$$
\begin{aligned}
\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{(1,2),gg} = & \Big\langle F_{\mathrm{LM}}(1,2)\Big\rangle \times \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 \Bigg\{ C_A^2 \Bigg[\frac{739}{81} + \frac{4}{3}\ln 2 + \frac{187\pi^2}{54} - 2\ln^2(2) \\
& + \frac{11}{9}\pi^2 \ln 2 - \frac{407}{36}\zeta_3 + \frac{13\pi^4}{144} + \frac{\pi^2}{6}\ln^2 2 - \frac{\ln^4 2}{6} - \frac{7}{2}\zeta_3 \ln 2 \\
& - 4\mathrm{Li}_4\left(\frac{1}{2}\right) - \ln\left(\frac{\mu^2}{s}\right)\left(\frac{37}{6} + \frac{11\pi^2}{8} + 23\zeta_3\right) + \ln^2\left(\frac{\mu^2}{s}\right)\left(\frac{121}{36} - \frac{2\pi^2}{3}\right)\Bigg] \\
& + C_A n_f \Bigg[-\frac{214}{81} - \frac{227}{216}\pi^2 - \frac{4}{3}\ln 2 - \frac{2}{9}\pi^2 \ln 2 + 2\ln^2 2 + \frac{37}{18}\zeta_3 \\
& + \ln\left(\frac{\mu^2}{s}\right)\left(\frac{94}{27} + \frac{\pi^2}{4}\right) - \frac{11}{9}\ln\left(\frac{\mu^2}{s}\right)^2 \Bigg] \\
& + n_f^2 \left[\frac{11\pi^2}{108} - \frac{10}{27}\ln\left(\frac{\mu^2}{s}\right) + \frac{1}{9}\ln^2\left(\frac{\mu^2}{s}\right)\right] \\
& + \Theta_{bd}\left[C_A^2\left(-\frac{131}{36} + \frac{11}{3}\ln 2 + \frac{\pi^2}{3}\right) + C_A n_f\left(\frac{23}{36} - \frac{2}{3}\ln 2\right)\right]\Bigg\}.
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{1245,gg} = & \sum_{(ij)\in dc} \Big\langle \Big[(I - C_{5j})(I - C_{4i})\Big]\left[I - \mathbb{S}\right]\left[I - S_5\right] \times \\
& \times [df_4][df_5] w^{4i,5j} F_{\mathrm{LM},gg}(1,2,4,5)\Big\rangle \\
& + \sum_{i\in tc}\Big\langle \Big[\theta^{(a)}\left[I - \mathbb{C}_i\right]\left[I - C_{5i}\right] + \theta^{(b)}\left[I - \mathbb{C}_i\right]\left[I - C_{45}\right] \\
& + \theta^{(c)}\left[I - \mathbb{C}_i\right]\left[I - C_{4i}\right] + \theta^{(d)}\left[I - \mathbb{C}_i\right]\left[I - C_{45}\right]\Big] \\
& \times \left[I - \mathbb{S}\right]\left[I - S_5\right][df_4][df_5] w^{4i,5i} F_{\mathrm{LM},gg}(1,2,4,5)\Big\rangle
\end{aligned}
$$

Mixed parity Higgs boson production at LHC

Independence of NNLO QCD corrections on hard matrix elements allows one to consider exotic cases, e.g. production/ decay of mixed parity Higgs bosons at the LHC.

Jaquier, Röntsch



$$pp \to X_{H/A} \to Z/\gamma^* Z/\gamma^* \to e^+e^-\mu^+\mu^-$$

$$L_{\rm eff} = -\frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}G^{\mu\nu} + s_\alpha \kappa_{Agg} G_{\mu\nu}\tilde{G}^{\mu\nu}\right] X + c_\alpha \kappa_{\rm SM}\frac{g_{HZZ}}{2} Z_\mu Z^\mu X - \frac{1}{4\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] X$$

$$g_{Hgg} = -\frac{\alpha_s}{3\pi v}, \quad g_{Agg} = \frac{\alpha_s}{2\pi v} \quad c_\alpha = \cos\alpha, \quad s_\alpha = \sin\alpha$$

	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]	$\sigma^{\rm NNLO}$ [pb]
$c_\alpha = 1$	$15.13^{-14\%}_{+16\%}$	$34.81^{-14\%}_{+20\%}$	$43.85^{-9\%}_{+9\%}$
$c_\alpha = 0$	$34.04^{-14\%}_{+16\%}$	$79.01^{-15\%}_{+20\%}$	$99.46^{-9\%}_{+9\%}$
$c_\alpha = \sqrt{1/2}$	$24.59^{-14\%}_{+16\%}$	$56.91^{-15\%}_{+20\%}$	$71.66^{-9\%}_{+9\%}$

Inclusive cross sections, no decays — no interference of scalar and pseudoscalar components.

$$\sigma_{\rm mixed} \sim c_\alpha^2 \sigma_+ + s_\alpha^2 \sigma_-$$

	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]	$\sigma^{\rm NNLO}$ [ab]
$c_\alpha = 1$	$10.6^{-14\%}_{+15\%}$	$23.5^{-14\%}_{+19\%}$	$29.1^{-8\%}_{+8\%}$
$c_\alpha = 0$	$0.0151^{-14\%}_{+15\%}$	$0.0344^{-14\%}_{+19\%}$	$0.0428^{-8\%}_{+8\%}$
$c_\alpha = \sqrt{1/2}$	$8.61^{-14\%}_{+15\%}$	$19.2^{-14\%}_{+19\%}$	$23.7^{-8\%}_{+8\%}$
$c_\alpha = 0.6$	$9.95^{-14\%}_{+15\%}$	$22.4^{-14\%}_{+19\%}$	$27.7^{+8\%}_{-8\%}$

When parity-violating decays are included, there appears an interplay between parity-even and parity-odd production/decay mechanisms.

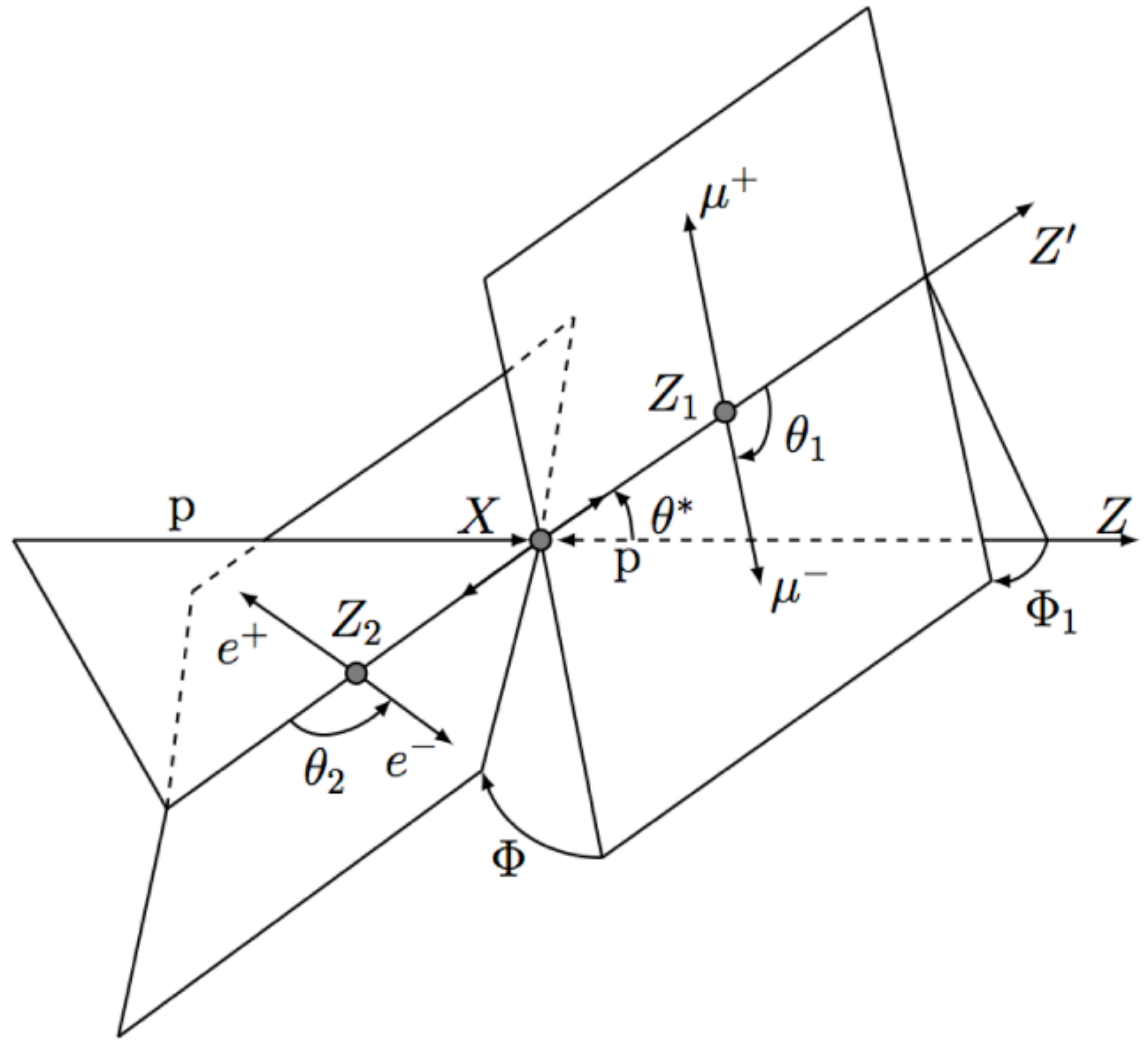
Mixed parity Higgs boson production at LHC

Angular distributions of leptons are important for the analysis of mixed parity case.

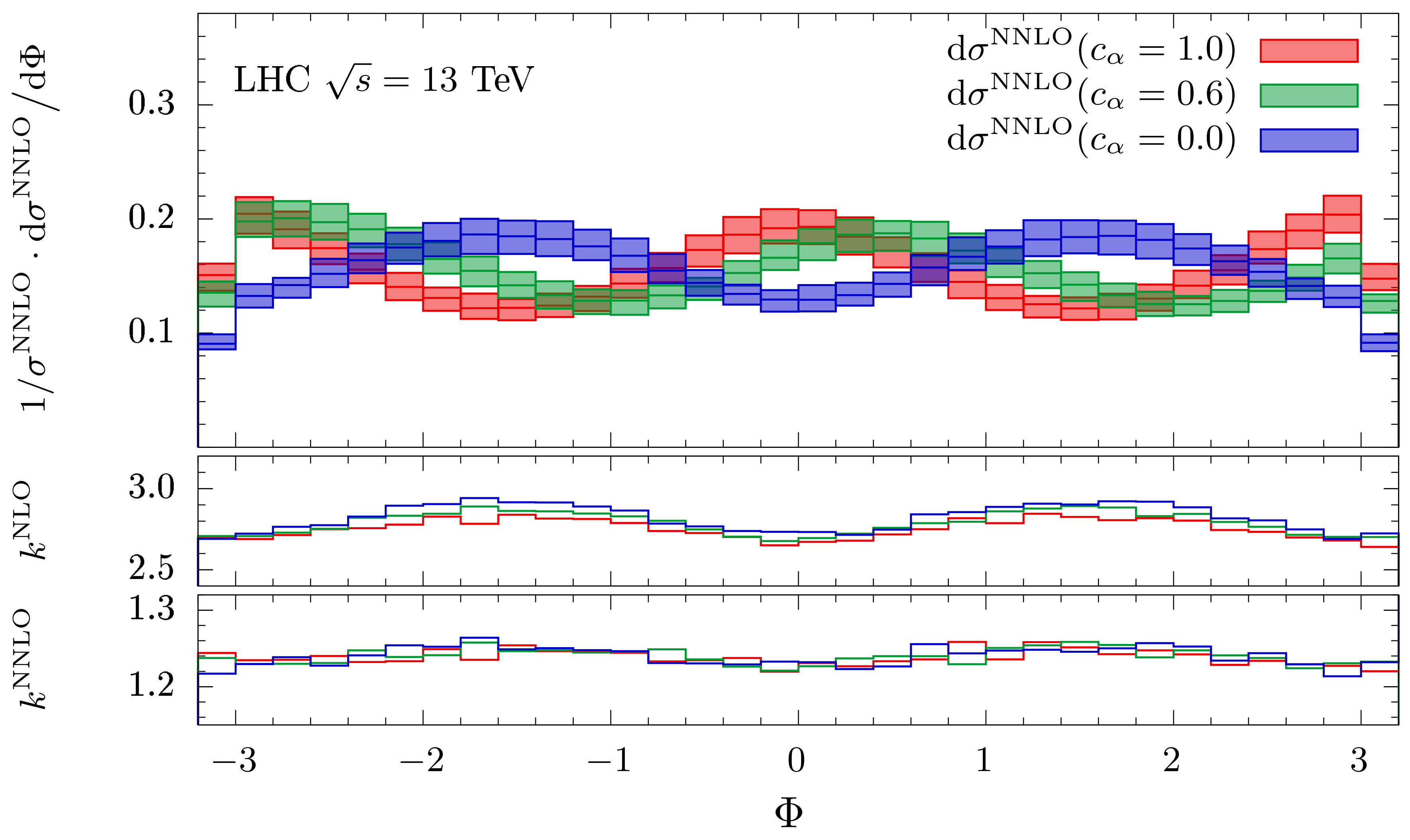
Gao, Gritsan, Guo, K.M., Schulze, Tran

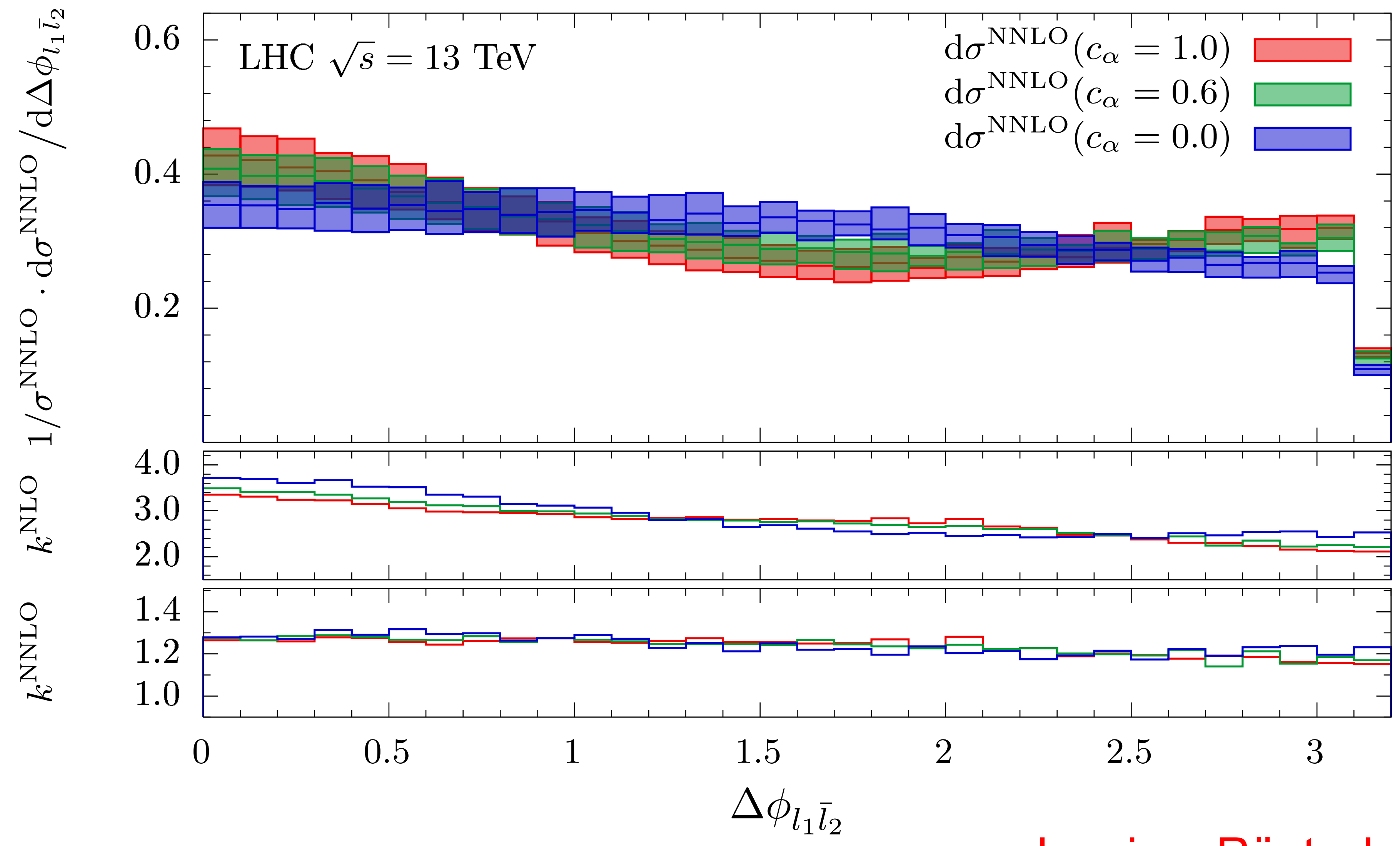
Theoretical predictions of these quantities can now be extended to NNLO QCD — helpful for constraining small(er) admixtures of pseudoscalar component.

We observe rather flat NNLO K-factors and reduced scale dependence.



$$pp \to X_{H/A} \to Z/\gamma^* Z/\gamma^* \to e^+e^-\mu^+\mu^-$$



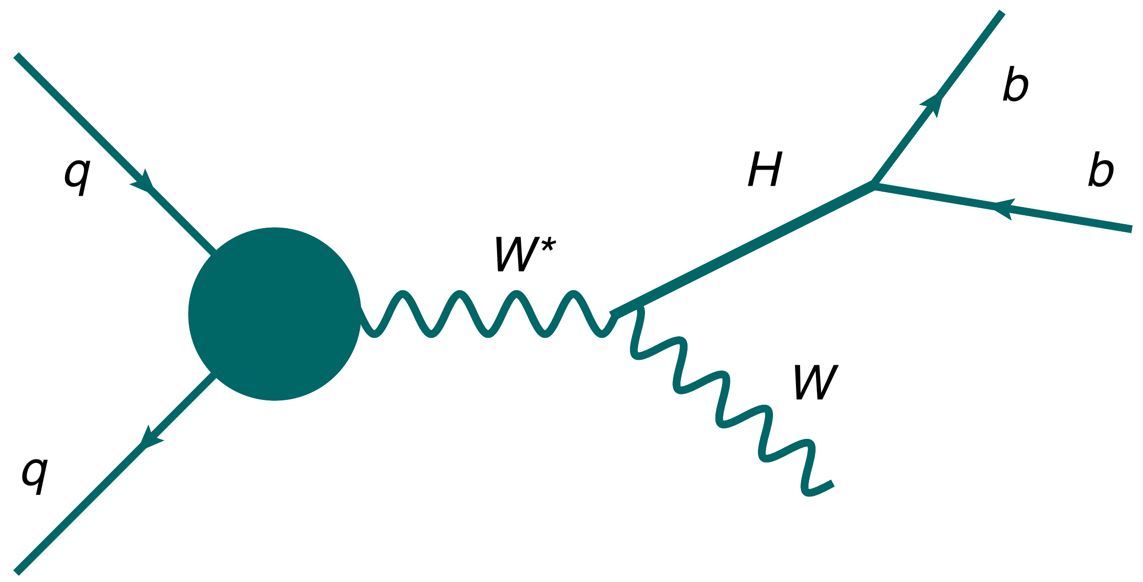


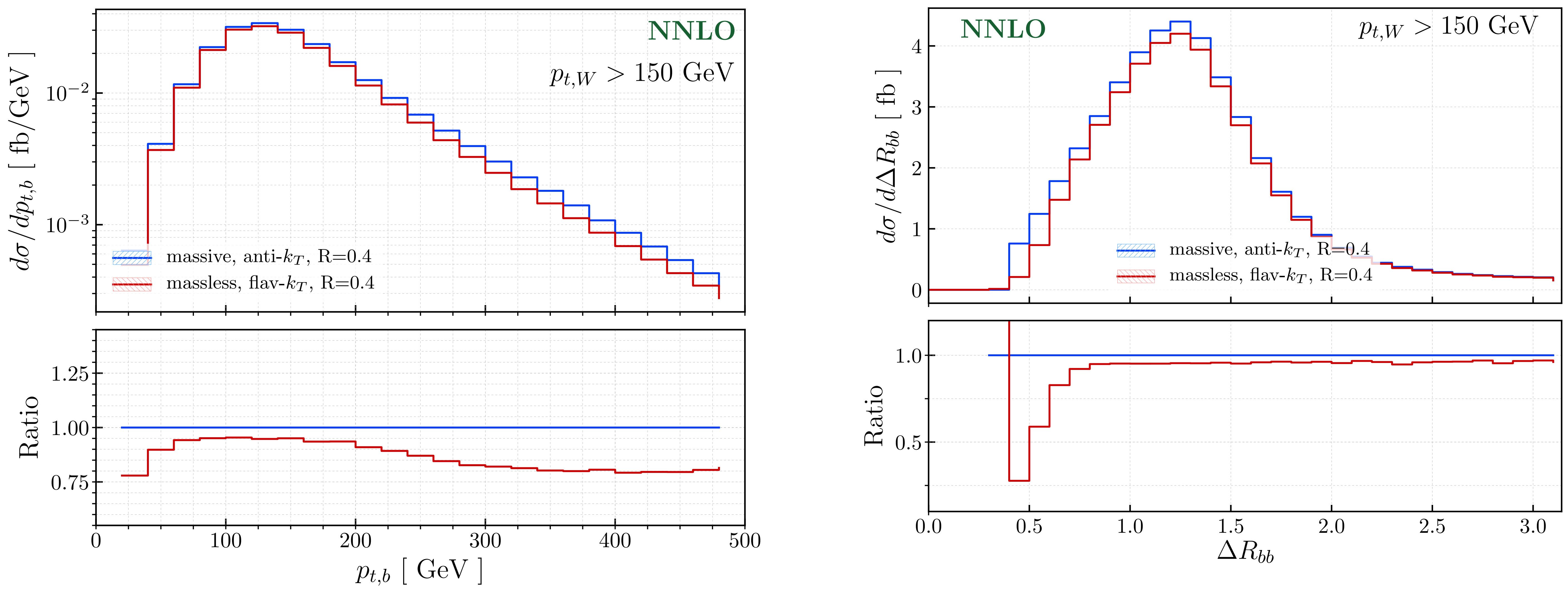
Jaquier, Röntsch

Associated production WH

We can use NNLO QCD formulas derived in the context of color-singlet production to describe pp ➔ WH process. However, in case of associated production, Higgs decays to two b-quarks are studied experimentally. Higgs decays need to be described in pQCD as well.

Another problematic aspect is whether to work with massless or massive b-quarks; massive quarks are important for a (quasi)realistic identification of b-jets.





NNLO QCD corrections to massless H->bb decays and combination with WH production.

Caola, K.M., Röntsch

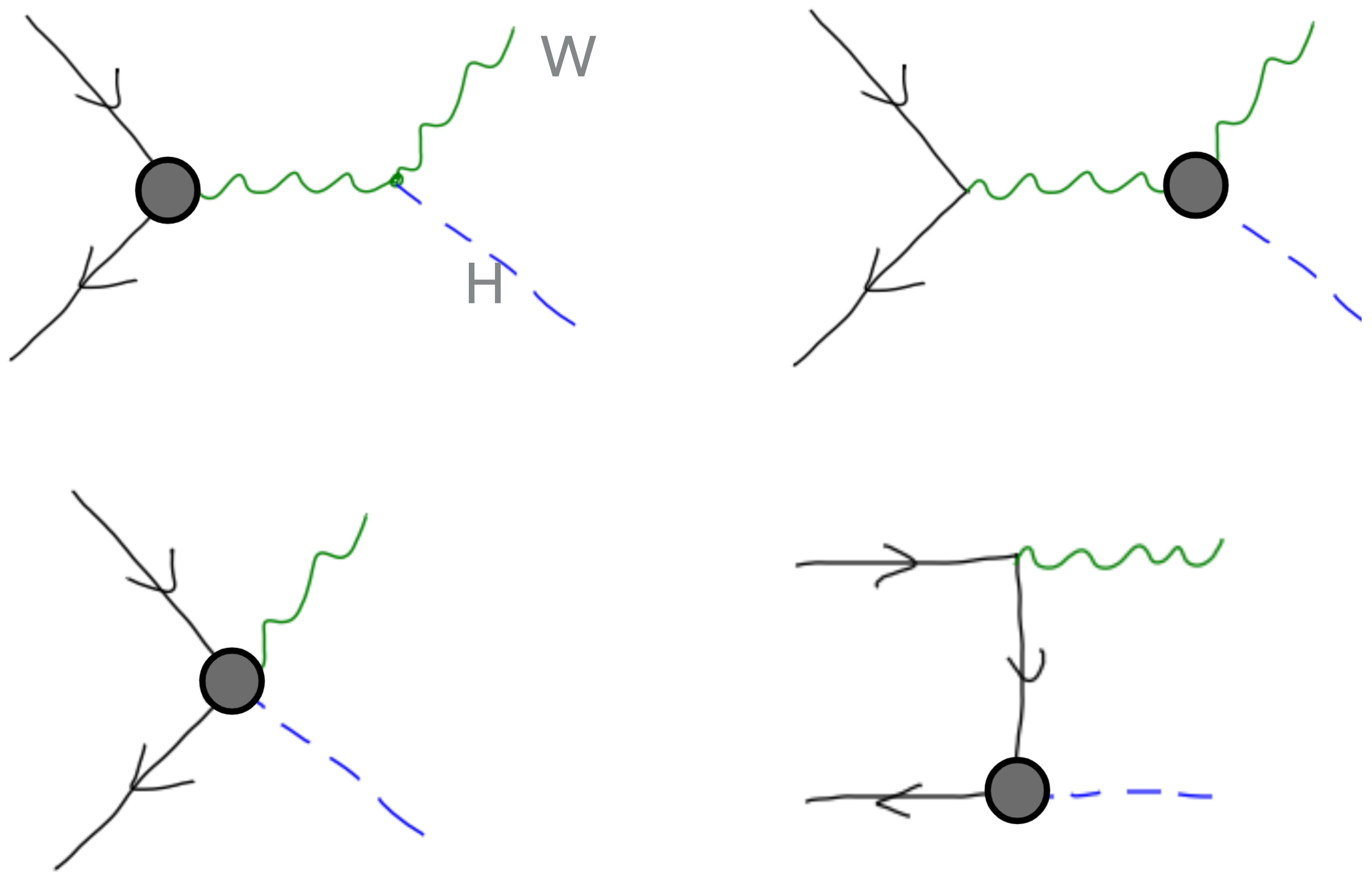
NNLO QCD corrections to massive H->bb decays and combination with WH production.

Behring, Bizon Behring, Bizon; Caola, K.M. , Röntsch

Differences between massive and massless computations can be sizable; this isn't a matter of mass effects per se but of a jet algorithms.

Associated production WH

The above results provide state of the art description of fully-differential associated WH production and decay. It is simple, realistic and modular.   We plan to combine the NNLO QCD computations of the associated production with contributions from higher-dimensional operators / anomalous couplings to pp -> WH(bb) production process.



- Calculate WH amplitudes in SMEFT through NNLO.
- Implement them into existing SM code for NNLO WH.
- Include SMEFT also for decays.
- Study effect of various operators on kinematic quantities.
- Make the code accessible to experimentalists.
- Move on to other Higgs production process.

R. Harlander, previous (2019). CRC meeting

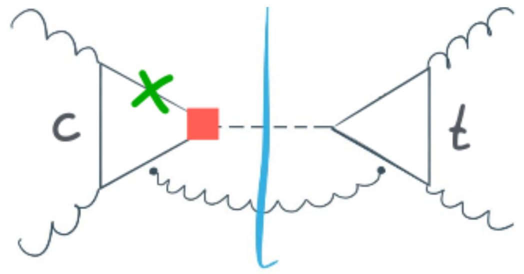
Musings on charm-Yukawa measurement at the LHC

Studies of Higgs couplings to fermions is an important part of the program of studying the Higgs particle. Higgs coupling to third generation fermions and to muons have been measured.

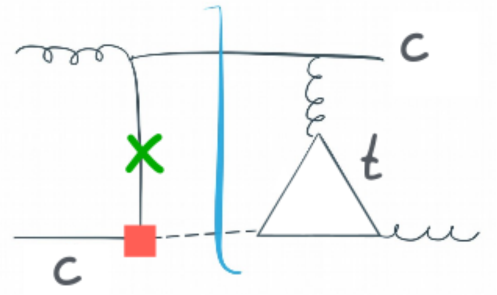
It is interesting to measure/understand to what extent the charm Yukawa coupling is canonical.

Different ways to do that were suggested:

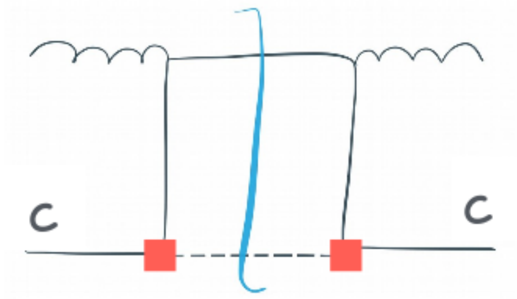
1) Exclusive Higgs decays to $c\bar{c}$ mesons and a photon;
2) Higgs + charm associated production;
3) Higgs kinematic distributions (e.g. transverse momentum, rapidity etc.).



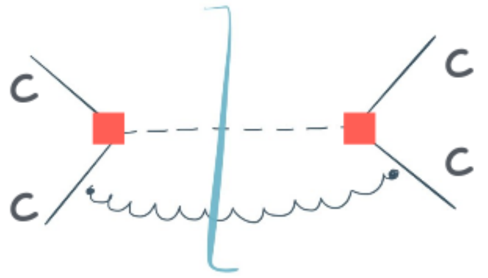
$$\sim \alpha_s^3 \, y_c \, m_c \, \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$



$$\sim \alpha_s \alpha_s^2 \, y_c \, m_c \qquad (= 0 \text{ in 4, 5 flavour scheme})$$



$$\sim \alpha_s \alpha_s \, y_c^2$$



$$\sim \alpha_s^2 \alpha_s \, y_c^2$$

chirality flip

extra powers of α_s from charm PDF
[Sullivan, Nadolsky: hep-ph/0111358]

Talk by F. Bishara, SM@LHC 2019

Musings on charm-Yukawa measurement at the LHC

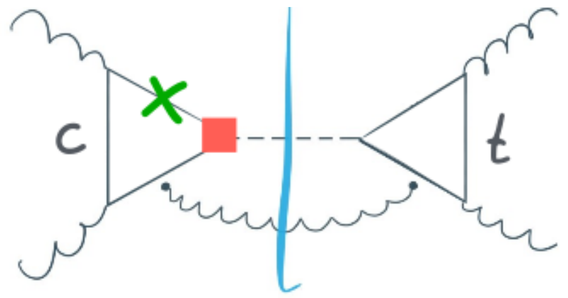
Studies of Higgs couplings to fermions is an important part of the program of studying the Higgs particle. Higgs coupling to third generation fermions and to muons have been measured.

It is interesting to measure/understand to what extent the charm Yukawa coupling is canonical.

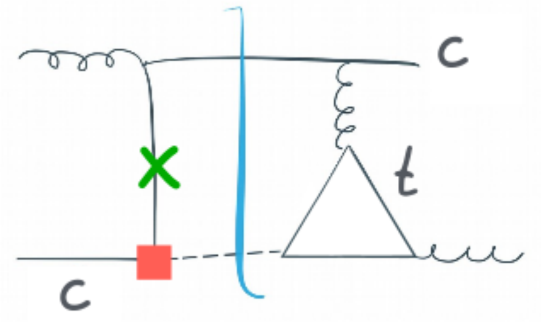
Needs helicity flip — requires massive charm quarks.

Different ways to do that were suggested:

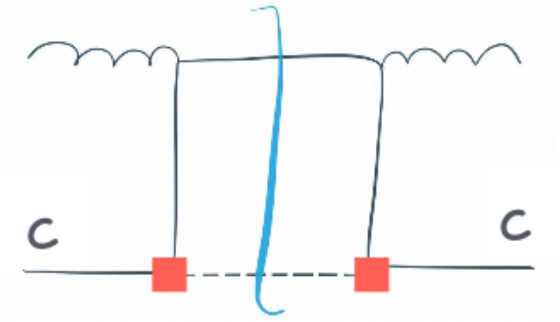
1) Exclusive Higgs decays to cc mesons and a photon;
2) Higgs + charm associated production;
3) Higgs differential distributions (e.g. transverse momentum, rapidity etc.).



$$\sim \alpha_s^3 y_c m_c \ln^2\left(\frac{p_T^2}{m_c^2}\right)$$



$$\sim \alpha_s \alpha_s^2 y_c m_c \quad (=0 \text{ in 4, 5 flavour scheme})$$



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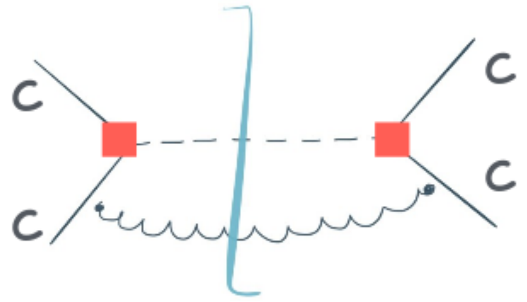


$$\sim \alpha_s^2 \alpha_s y_c^2$$

chirality flip

extra powers of α_s from charm PDF

[Sullivan, Nadolsky: hep-ph/0111358]

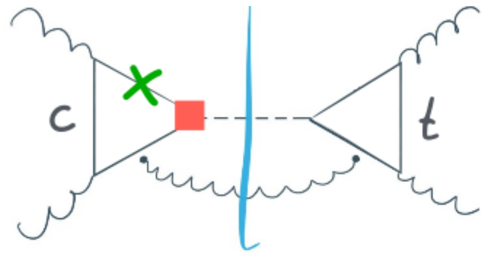
Talk by F. Bishara, SM@LHC 2019

Musings on charm-Yukawa measurement at the LHC

The calculation can be performed at leading order: start with massive charm quarks, compute the interference, take the limit of the vanishing charm mass and only keep first non-vanishing term. The results are shown below.

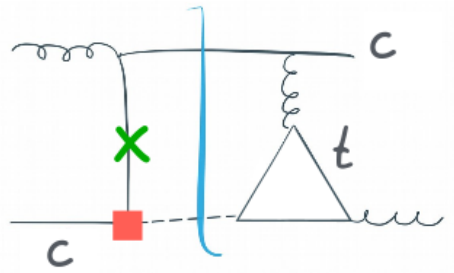
$$\sigma^{\rm int}_{H+c} = -4.4 \text{ fb} \left(\frac{m_c^y}{1.3 \text{ GeV}}\right)\left(\frac{m_c^{\rm flip}}{1.3 \text{ GeV}}\right)\left(\frac{\lambda_{Hgg}}{\lambda^{\rm LO}_{Hgg}}\right)$$

$$\sigma^{y}_{H+c} = 65.7 \text{ fb} \left(\frac{m_c^y}{1.3 \text{ GeV}}\right)^2$$

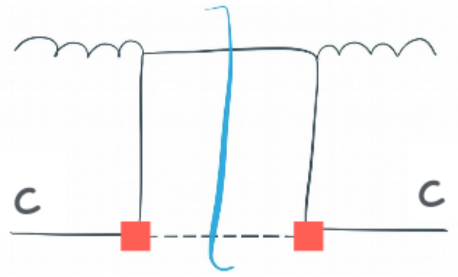


$\sim \alpha_s^3 y_c m_c \ln^2\left(\frac{p_T^2}{m_c^2}\right)$

?



$\sim \alpha_s \alpha_s^2 y_c m_c$ $(= 0$ in 4, 5 flavour scheme)



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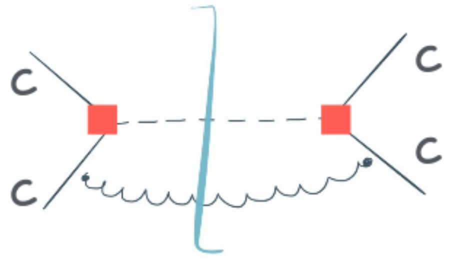


$\sim \alpha_s^2 \alpha_s y_c^2$

chirality flip

extra powers of α_s from charm PDF

[Sullivan, Nadolsky: hep-ph/0111358]

How reliable are these estimates? Some possible sources of ambiguities and large effects are shown explicitly.

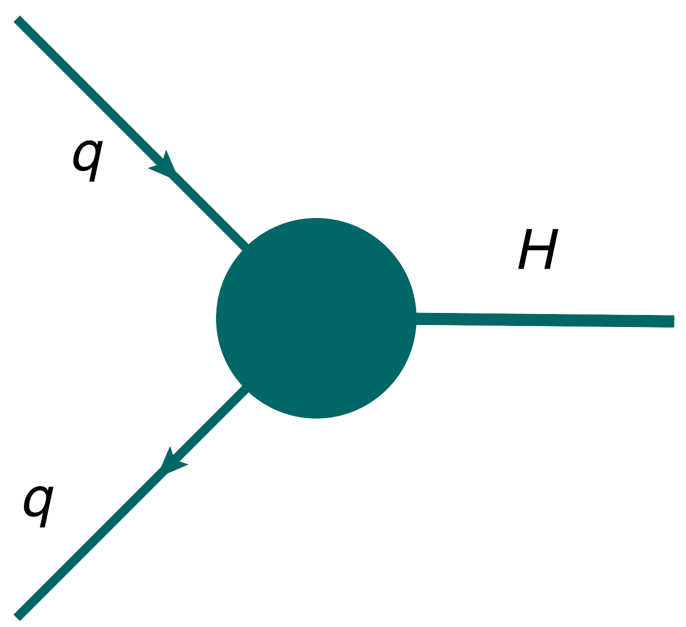
Need NLO QCD to provide better estimates and take care of large effects. Can the same approach where massless computation is the limit of a massive one also work at NLO? Is it reasonable to expect that in this case all charm mass logarithms disappear from the inclusive prediction?

Talk by F. Bishara, SM@LHC 2019

Work in progress with Bizon and Quarroz

Musings on charm-Yukawa measurement at the LHC

Apart from mass insertions required to get non-vanishing result for the interference, mass plays a role of a collinear regulator. For processes without helicity flip, it is possible to remove all mass logarithms from hard processes by performing finite PDF renormalisation (since appropriate matrix elements exhibit standard collinear factorization pattern) and expressing results in terms of MSbar-renormalised Yukawa coupling, if appropriate.



$$\lim_{p_3||p_1} |\mathcal{M}(1_c, 2_{\bar{c}}, 3_g)|^2 \to g_s^2 \left[\frac{P_{qq}(z)}{z(p_1p_3)} - \frac{C_F m_c^2}{(p_1p_3)^2} \right] |\mathcal{M}(z1_c, 2_{\bar{c}})|^2$$

$$\sigma^{\rm massless}_{c\bar{c}\to H} = \sigma^{\rm massive}_{c\bar{c}\to H} \Big|_{m_c \to 0}$$

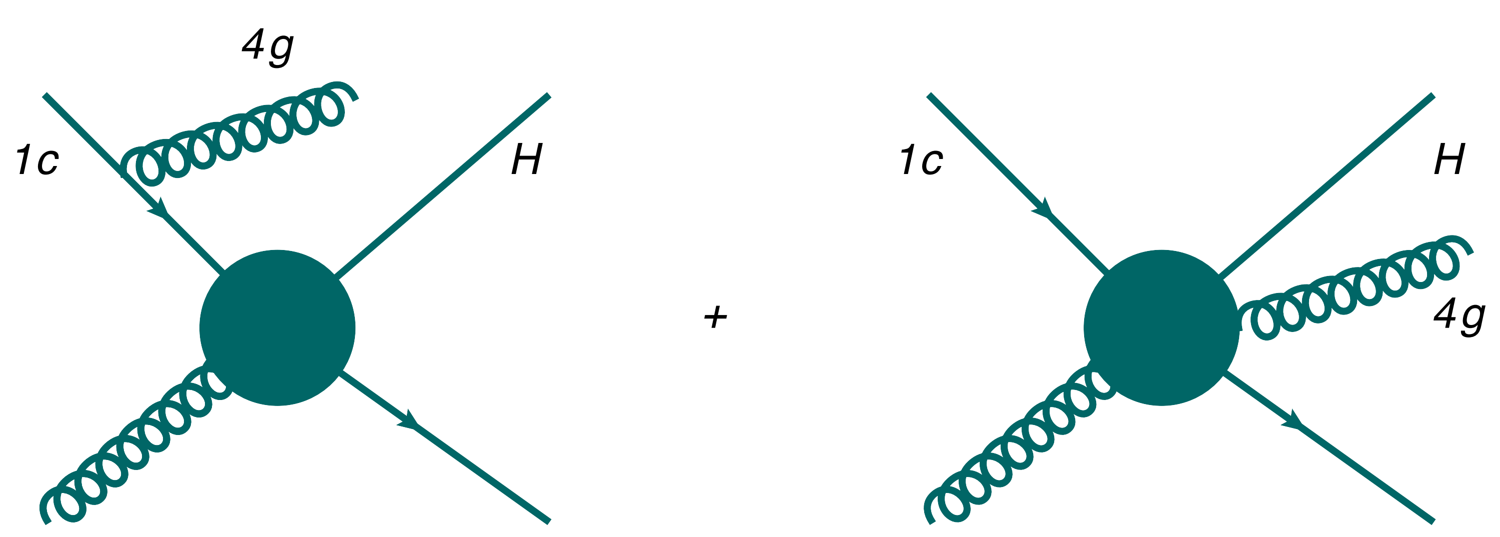
$$\boxed{f_m = f_{\overline{\rm MS}}(\mu) + \frac{\alpha_s(\mu)}{2\pi}\left(-\ln\frac{\mu^2}{m_c^2}\, P^{\rm AP}_{\rm qq} + F^{\rm fin}_{qq} \right) \otimes f_{\rm MS}(\mu)}$$

$$P^{\rm AP}_{qq} = C_F \left[\frac{1+z^2}{1-z} \right]_+$$

$$F^{\rm fin}_{qq} = C_F \left[\frac{1+z^2}{1-z} \right]_+ + 2C_F \left[\frac{(1+z^2)\ln(1-z)}{1-z} \right]_+ - C_F\left(2 - \frac{3}{2}\zeta_2 \right)$$

Musings on charm-Yukawa measurement at the LHC

However, for the interference contribution — as the consequence of the required helicity flip — the standard factorization pattern breaks down.



$$\lim_{p_4||p_1} \mathrm{Int}\left[|\mathcal{M}(1_c, 2_{\bar{c}}, 3_c, 4_g)|^2\right] \to g_s^2 \left[\frac{P_{qq}(z)}{z(p_1p_4)} - \frac{C_F m_c^2}{(p_1p_4)^2}\right] \mathrm{Int}\left[|\mathcal{M}(z1_c, 2_g; 3_c)|^2\right]$$
$$- \frac{C_F m_c (1-z)}{z(p_1p_4)} \mathrm{Int}\left[\mathrm{Tr}\left[A_{\mathrm{sing}} A^{c,+}_{\mathrm{sing}}(z1_c, 2_g; 3_c)\right]\right]$$
$$+ g_s C_F \frac{(1-z)m_c}{2p_1p_4} \mathrm{Int}\left[\mathrm{Tr}\left[\hat{p}_1 A_{\mathrm{sing}}(z1_c, 2_g; 3_c) A^{+}_{\mathrm{fin}}(1_c, 2_g, 3_c, (1-z)1_g) + \mathrm{h.c.}\right]\right]$$

$$\mathcal{M} = \mathcal{M}_{\mathrm{sing}} + \mathcal{M}_{\mathrm{fin}}$$

The above result reflects the fact that the mass insertion can occur in many places, including in singular propagator. This violates canonical factorization formula for quasi-collinear singularities.

Also, the quasi-collinear singularity depends on the full 2->3 amplitude albeit in the collinear limit. This feature

Musings on charm-Yukawa measurement at the LHC

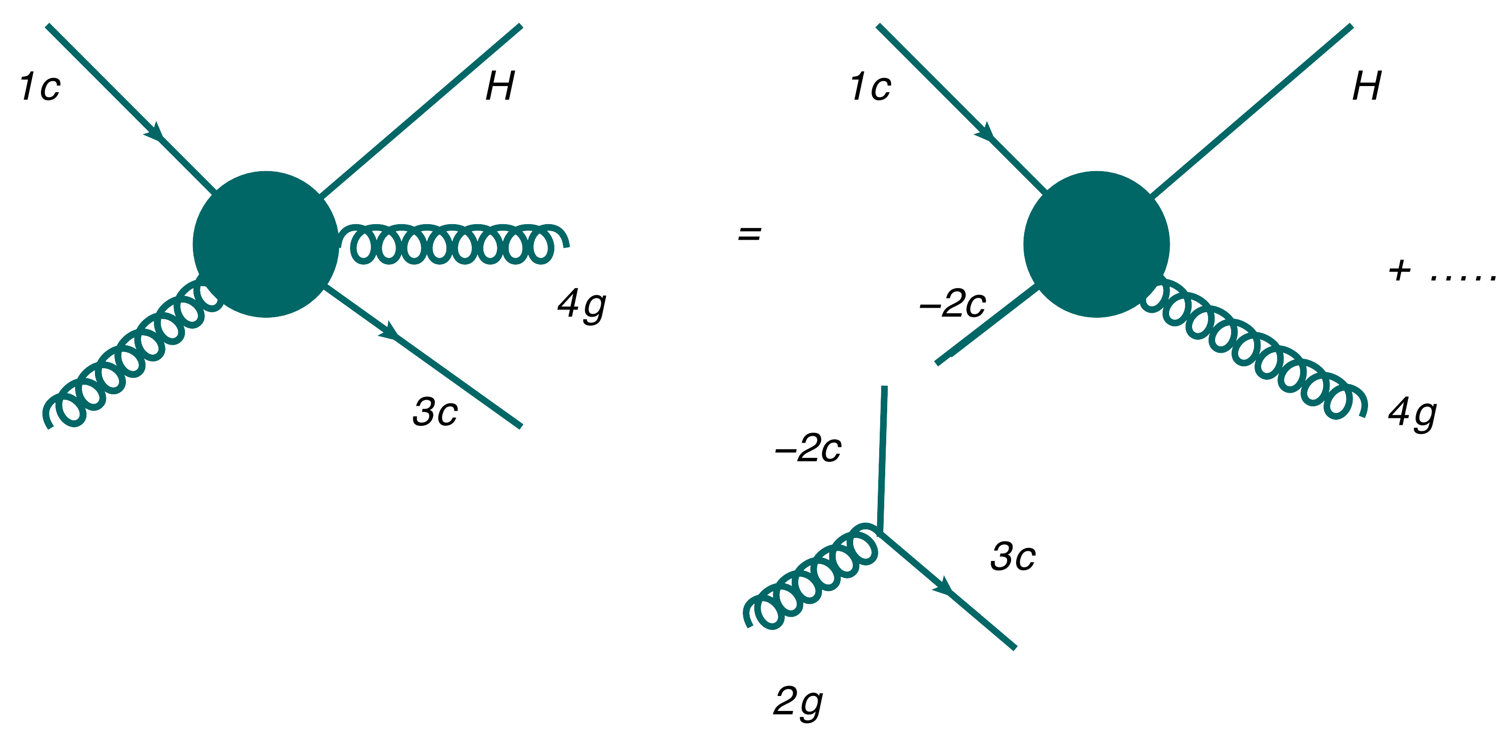
Similarly, the interference exhibits soft quark (quasi) singularities. This implies that flavour of a jet ceases to be infra-red safe quantity in a sense of log(m_c) sensitivity, if a mass insertion is accounted for. To protect us again soft-quark singularities, we plan to cut on the transverse momentum of a charm even if it is clustered into a charm jet.

$$\mathcal{M}(1_c, 2_g; 3_c, 4_g) = \bar{u}(p_3)\; A \quad \to \quad \mathrm{Tr}\left((\hat{p}_3 + m_c) A A^+ \right).$$

A mass term in the density matrix is the only source of soft quark singularities.

$$\mathcal{M}(1_c, 2_g; 3_{\bar{c}}, 4_g) = \mathcal{M}_y(1_c, 2_g; 3_{\bar{c}}, 4_g) + \mathcal{M}_{g^2}(1_c, 2_g; 3_{\bar{c}}, 4_g).$$

$$\lim_{p_3 \to 0} \mathcal{M}_y(1_c, 2_g; 3_{\bar{c}}, 4_g) = g_s t^{a2}_{i_3 i_f} \frac{\bar{u}_3 \hat{\epsilon}_2 v_2^{(\lambda)}}{2 p_2 p_3} \mathcal{M}_y \left(1_c, 2_{\bar{c}}^{\lambda, i_f}; 4_g \right)$$
$$+ g_s t^{a4}_{i_3 i_f} \frac{\bar{u}_3 \hat{\epsilon}_4^* u_4^{(\lambda)}}{2 p_3 p_4} \mathcal{M}_y \left(1_c, 2_g; 4_c^{\lambda, i_f} \right),$$
$$\lim_{p_3 \to 0} \mathcal{M}_{g^2}(1_c, 2_g; 3_{\bar{c}}, 4_g) = g_s t^{a_g}_{i_3 i_1} \frac{\bar{u}_3 \gamma_\mu u_1}{2 p_1 p_3} \mathcal{M}_{g^2} \left(1_g^{a_g, \mu}, 2_g; 4_g \right)$$
$$+ g_s t^{a4}_{i_3 i_f} \frac{\bar{u}_3 \hat{\epsilon}_4^* u_4^{(\lambda)}}{2 p_3 p_4} \mathcal{M}_{g^2} \left(1_c, 2_g; 4_c^{\lambda, i_f} \right) + g_s t^{a2}_{i_3 i_f} \frac{\bar{u}_3 \hat{\epsilon}_2 v_2^{(\lambda)}}{2 p_2 p_3} \mathcal{M}_{g^2} \left(1_c, 2_{\bar{c}}^{\lambda, i_f}; 4_g \right),$$



Soft quark factorization

Musings on charm-Yukawa measurement at the LHC

With soft quark singularities argued away, the remaining singularities can be subtracted even if factorization formulas for quasi-collinear ones are not always canonical. The end result is a fairly standard NLO computation with non-standard subtraction terms.

All subtraction terms are designed in such a way that m_c -> 0 limit is smooth. Logarithms of the charm quark mass appear explicitly in integrated subtraction terms and in one-loop virtual corrections.

We are in the process of putting everything together…

$$\sigma^{\rm int}_{H+c} = -4.4 \text{ fb} \left(\frac{m_c^y}{1.3 \text{ GeV}} \right) \left(\frac{m_c^{\rm flip}}{1.3 \text{ GeV}} \right) \left(\frac{\lambda_{Hgg}}{\lambda_{Hgg}^{\rm LO}} \right) \quad \left(1 + ? \, \frac{C_F \alpha_s}{2\pi} \ln^2 \frac{m_H}{m_c} + ... \right)$$

Conclusions

The goal of this project is to provide description of Higgs boson production processes that combines QCD effects with SMEFT effects, ideally accounting for NNLO QCD corrections.

This requires process-independent understanding of NNLO QCD fully-differential subtraction terms. This has now been accomplished for color-singlet production processes and decays of the Higgs boson to massive b-quarks.

These results provide the necessary QCD ingredients for the analysis of associated production pp -> WH(bb) process also when corrections to the decay are included. Need SMEFT amplitudes for these processes.

As a proof of principle: NNLO QCD corrections to the production of mixed parity Higgs boson with decays to four lepton pairs.

Study of interference effects (Hcc & HGG) for Higgs-charm Yukawa coupling determination in an wassociated H+charm production process.

The interference vanishes for massless charm quarks since helicity flip is needed.

Interesting QCD effects — helicity flip leads to deviations from canonical factorization pattern of mass singularities (soft quarks, incomplete collinear decoupling etc.). Work on estimating QCD corrections in progress.