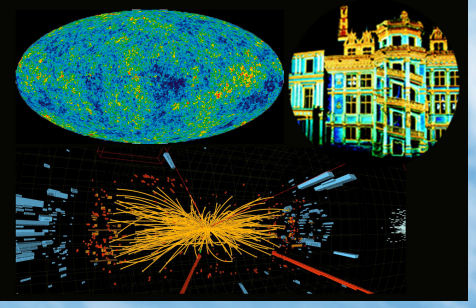

Electroweak Corrections in Higgs Physics

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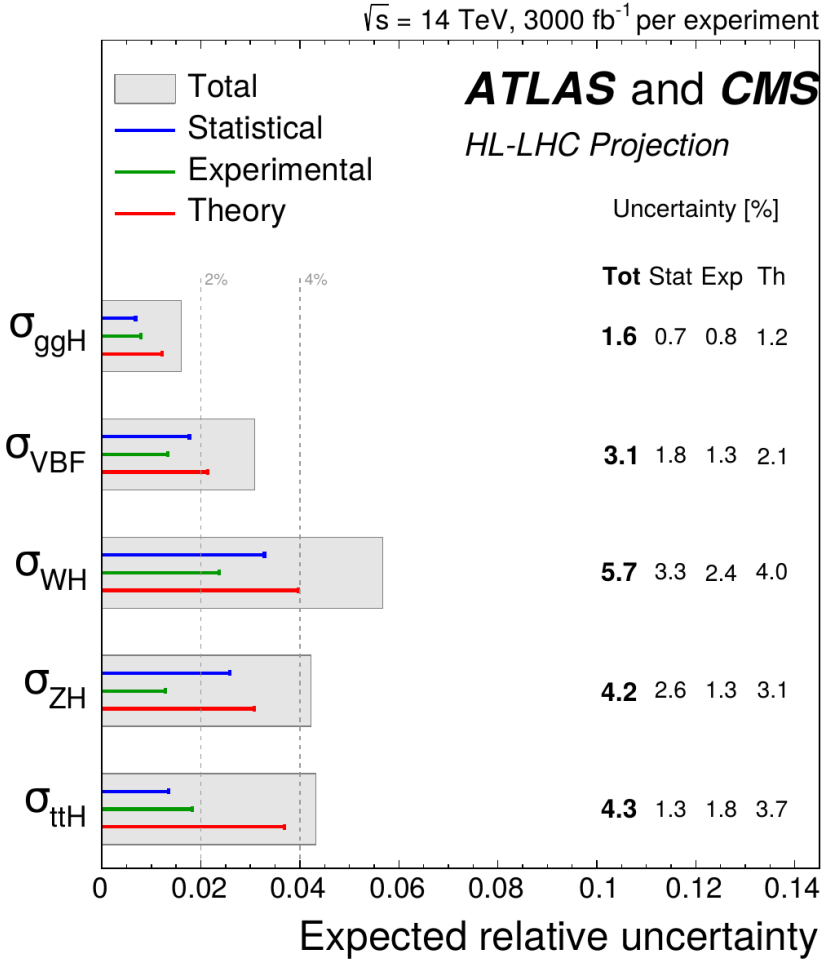
Motivation

State of the Art Overview: Physics of the HL-LHC Working Group et al.:

1902.00134



- High Luminosity phase of the LHC will reduce experimental uncertainties
- Predictions dominated my theoretical uncertainties
- Higher order and sub-dominant effects have to be computed

Higgs Production at LHC

State of the Art Overview: Physics of the HL-LHC Working Group et al.:

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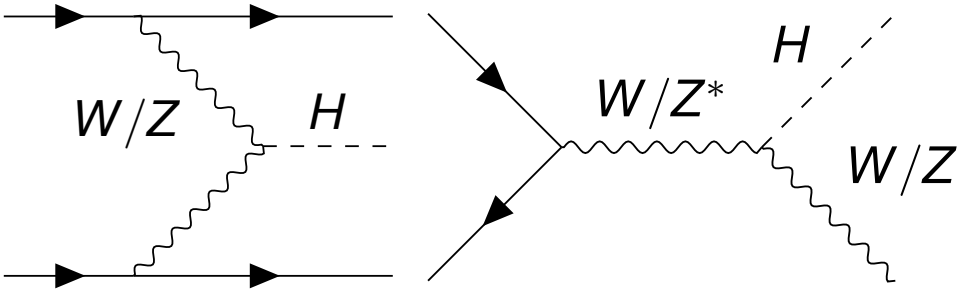

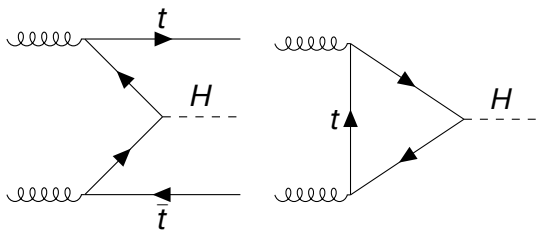

VBF and VH:

- Information about $SU(2)_L$
- Weak contributions:
  - Triple gauge interactions accessible
  - Radiated bosons: Large corrections in the high-energy tail (Sudakov logarithms)

Higgs Production at LHC

State of the Art Overview: Physics of the HL-LHC Working Group et al.:

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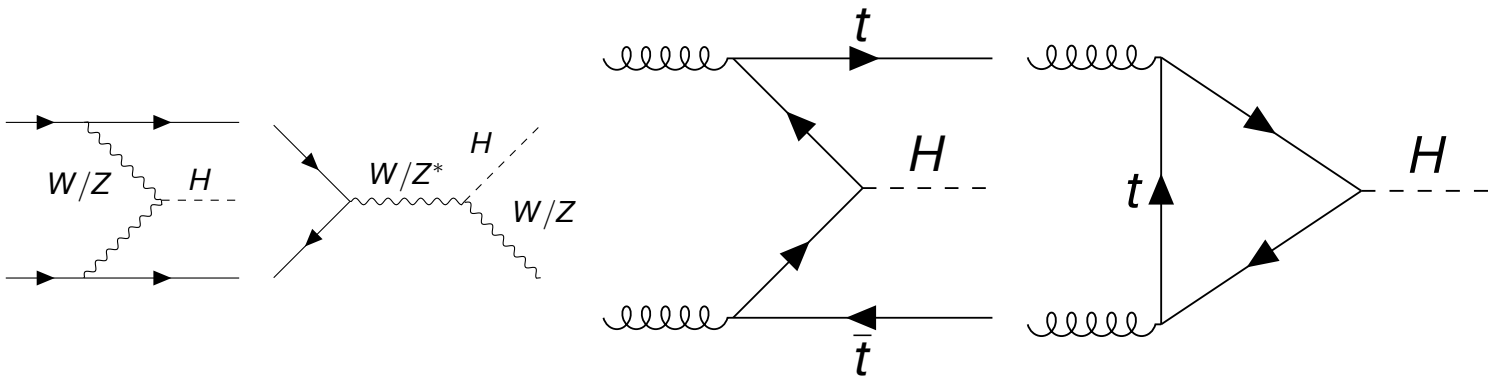


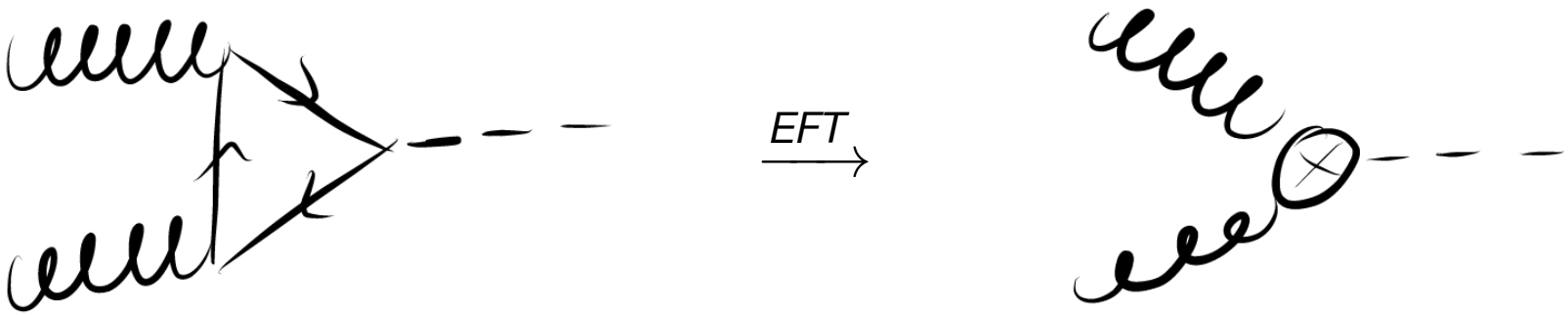
$Ht\bar{t}$ and ggF:

- Information about y_t
- $Ht\bar{t}$: theoretical challenging
  - Major uncertainty: NNLO-QCD
- ggF: QCD extremely well understood
  - EW-correction become relevant

Infinite Top Mass

The process that we are looking at is EW corrections to the Higgs production via gluon fusion, computed in the infinite top mass limit.

Effective theory:



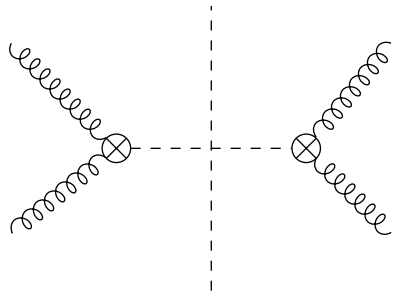
- Remove one loop!
- Work with 5 massless flavors
- Good approximation: $\delta_t^{NNLO} \sim 0.7\%$

Reminder: $\sigma_{gg\to H}$ in EFT

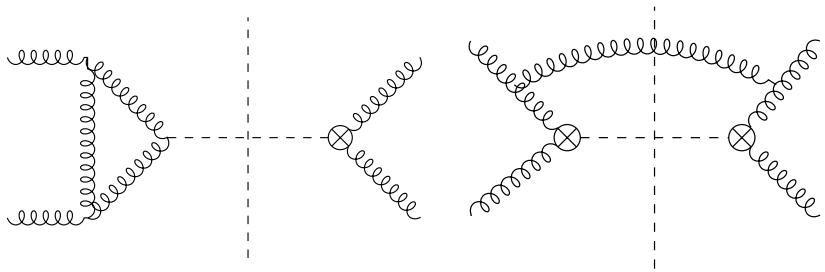
Pure QCD EFT:

(C. Anastasiou et al.: 1602.00695, B. Mistlberger: 1802.00833, F. Dulat et al.: 1802.00827)

- LO $\propto \alpha_s^2\alpha$: $\sigma^{\text{LO}}_{\text{rEFT}} = 16.00\text{pb} \propto$



- NLO $\propto \alpha_s^3\alpha$: $\sigma^{\text{NLO}}_{\text{rEFT}} = 20.84\text{pb} \propto$

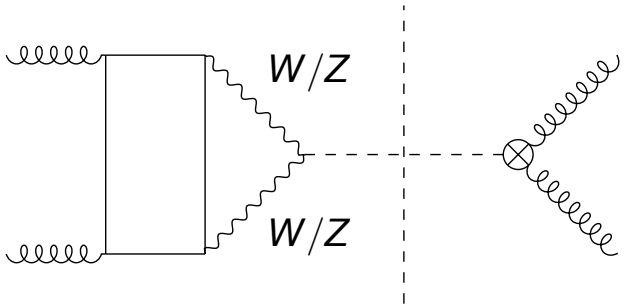


- NNLO $\propto \alpha_s^4\alpha$: $\sigma^{\text{NNLO}}_{\text{rEFT}} = 9.56\text{pb}$
- N^{3}LO $\propto \alpha_s^5\alpha$: $\sigma^{\text{N3LO}}_{\text{rEFT}} = 1.49\text{pb}$

Slow Convergence

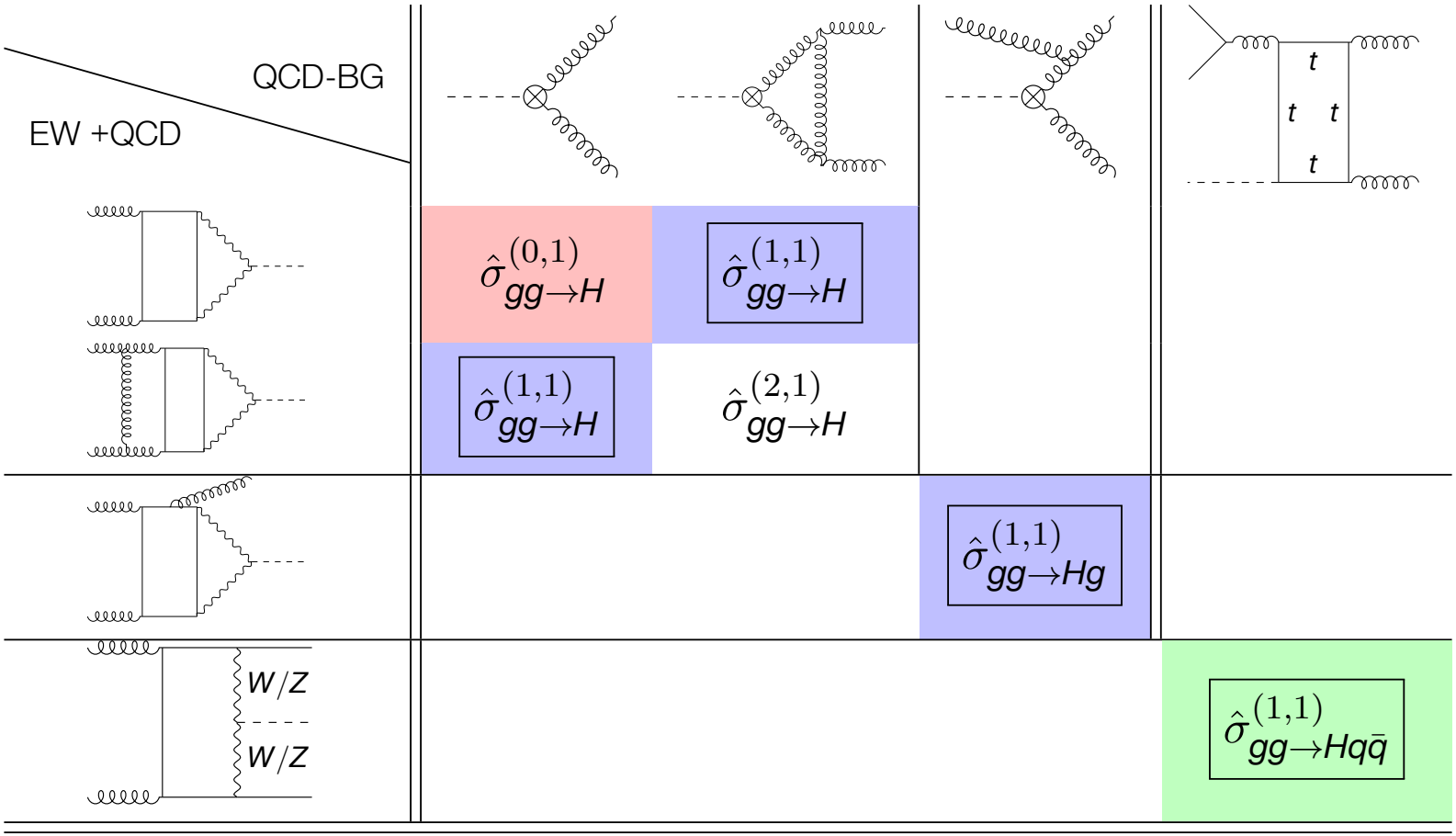
Reminder: $\sigma_{gg\to H}$ in EFT

- **Elektroweak contributions:**
  - "LO:" $\propto \alpha_s^2\alpha^2$



  - Start at 2-loops
  - Involve weak boson masses ($\leftrightarrow$ massless QCD)
    (computed in: U. Aglietti et al.: HEP-PH/0404071)
  - $\sigma^{\alpha_s^2\alpha^2}_{gg\to H} = 0.83$ pb (almost similar size as $\sigma^{\text{N3LO}}_{\text{rEFT}}$)
- **Do we need higher orders?** If pattern of QCD continues, yes!
  - Naive expectation (factorization): $\sigma^{\alpha_s^2\alpha^2}_{gg\to H} \sim \sigma^{\alpha_s^3\alpha^2}_{gg\to H}$

"Mixed Corrections" in ggF: $\sigma^{(m,n)}_{pp\to H+X} \propto \alpha_s^{m+2}\alpha^{n+1}$



Factorization Hypothesis

Fact: Exact computation often too hard.

Factorization Hypothesis:
NLO mixed QCD-EW~NLO QCD×LO EW

Assumptions:

- Most of the QCD and EW corrections are dominated by:
  - (universal) soft effects (factorize LO)

Task: Compute sensible multiplicative constant (k-factor)

Factorization Hypothesis

Factorization Hypothesis:

NLO mixed QCD-EW~NLO QCD×LO EW

Task: Compute sensible multiplicative constant (k-factor)

Used in $\sigma_{gg\to H}$: "Infinite Boson Mass Approximation"

(C. Anastasiou et al.: 0811.3458)

- Consider unphysical limit: $m_{W/Z} \gg m_H$

Factorization

$$\text{Estimate: } \hat{\sigma}^{(1,1)}_{\text{EXACT}} \approx \frac{\hat{\sigma}^{(1,1)}_{m_{W/Z}\gg m_H}}{\hat{\sigma}^{(1,0)}_{m_{W/Z}\gg m_H}} \hat{\sigma}^{(0,1)}_{\text{EXACT}}$$

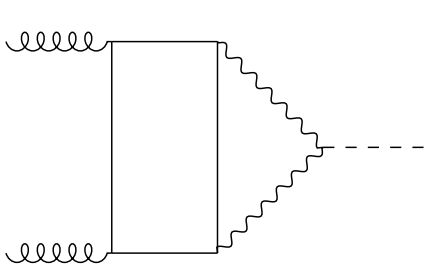
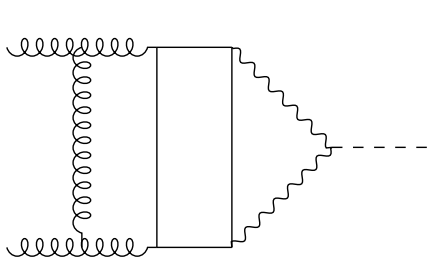
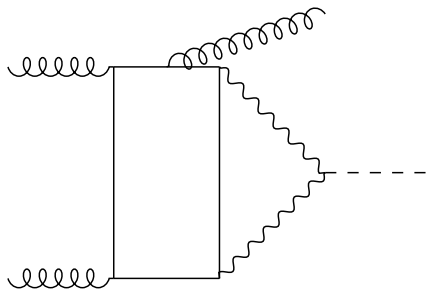
$$\text{Result: } \sigma^{(1,1)}_{\text{EXACT}} \approx 1.77 \text{ pb}$$

- Cross-section increase of $\sigma^{NLO}_{QCD} = 33.24$ pb by 5.32% $(\pm 1\%)$

Mixed Corrections Today: Exact?

They involve:

- Massive 2-loop to order ε^2
- Massive 3-loop (one scale)
- Massive 2-loop (three scales)

×			
Status	✓ (2017)	✓ (2017)	✗ (2018, planar ones)
	M. Bonetti et al.: 1610.05497	M. Bonetti et al.: 1711.11113	M. Becchetti et al.: 1810.05138

Mixed Corrections Updates:

Soft Gluon Approximation

(M. Bonetti et al.: 1801.10403)

- Take physical masses and exact virtuals
- Captures hard virtual contributions exactly
- Real radiation treated in soft limit: $\propto \alpha_s \eta_{gg}^{fact} \mathrm{d}\hat{\sigma}^{(0,1)}_{\mathrm{EXACT}}$
- η_{gg}^{fact}: Universal Eikonal factor

$$\begin{aligned} \textbf{Result:} \quad & \sigma^{(1,1)}_{\text{soft-gluon}} \approx 1.6 - 2 \text{ pb} \\ \text{Remember:} \quad & \sigma^{(1,1)}_{m_{W/Z} \gg m_H} = 1.77 \text{ pb} \end{aligned}$$

- Agreement of very different approximations

Mixed Corrections Updates:

Small Boson Mass Approximaten

(C. Anastasiou et al.: 1811.11211)

- Consider limit: $m_{W/Z} \ll m_H$
- Consequence: Same master integrals as in N^3LO
- Complete treatment of non-factorizable contributions:
  - They are numerically small (non-trivial)

Mixed Corrections Updates:

Small Boson Mass Approximaten

(C. Anastasiou et al.: 1811.11211)

- Consider limit: $m_{W/Z} \ll m_H$
- Consequence: Same master integrals as in N^3LO
- Complete treatment of non-factorizable contributions:
  - They are numerically small (non-trivial)

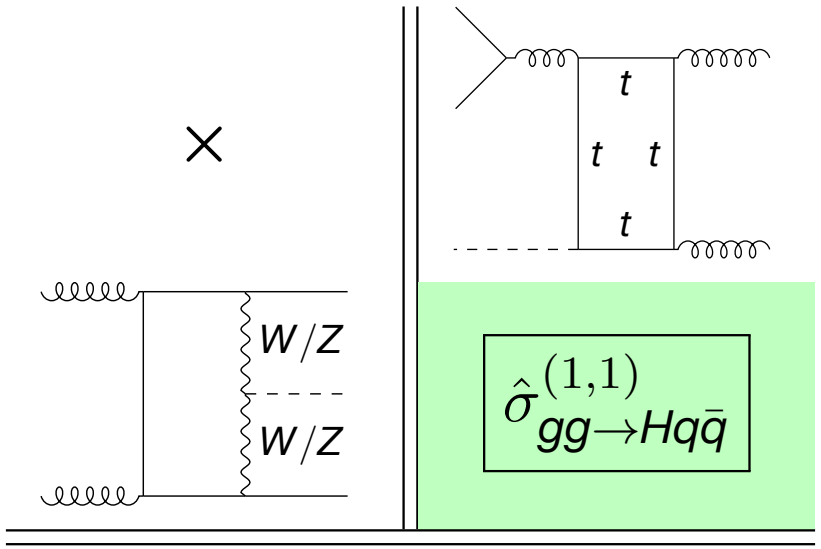
Factorization Holds!

Results:

$$\sigma^{(1,1)}_{m_{W/Z} \ll m_H} = 1.96 \text{ pb}$$
$$\sigma^{(1,1)}_{\text{soft-gluon}} \approx 1.6 - 2 \text{ pb}$$
$$\sigma^{(1,1)}_{m_{W/Z} \gg m_H} = 1.77 \text{ pb}$$

- Agreement of **all** available approximations
- Factorizable contribution seem dominant

Mixed Corrections: Non-Factorizable Contributions

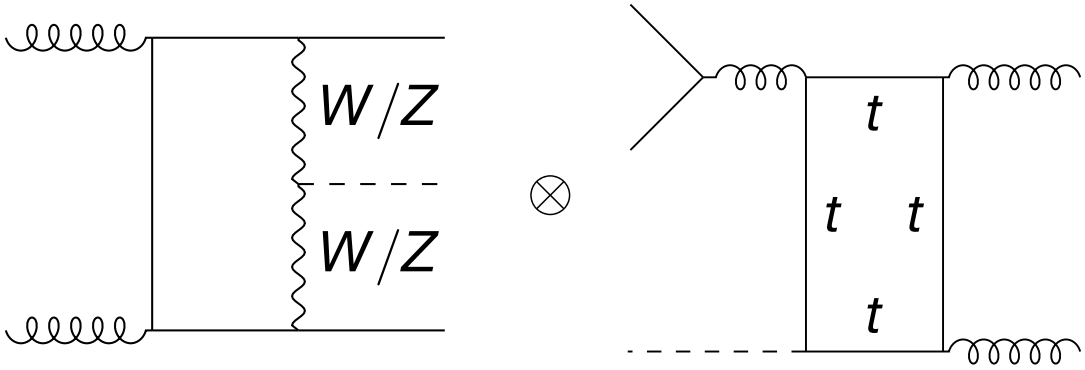


$gg \to Hq\bar{q}$: (V. Hirschi et al.: 1902.10167, similar computation in R. V. Harlander et al.: 0801.3355)

- Gluon induced and $\mathcal{O}\left(\alpha_s^3\alpha\right)$ (as before)
- Inherently non-factorizable
- For $m_{W/Z} \gg m_H$: Mass supressed
- For $m_{W/Z}$ physical: Maybe kinematic supression?

Mixed Corrections: Non-Factorizable Contributions

$$\mathcal{M}_{gg\to Hq\bar{q}} \propto 2\,\mathrm{Re}\sum$$



$gg \to Hq\bar{q}$: **Details of Computation**

- Interference of sub-processes needs flexibility
- Matrix elements $\mathcal{M}$: Fully Analytic and **MadLoop**
  (V. Hirschi et al.: 1103.0621)
- NLO-subtraction: "MadN^{k}LO" (private implementation of colourful)
  (G. Somogyi: 0903.1218)

Mixed Corrections: Irrelevant Contributions

cross section interferences	[fb]
$\sigma^{(\alpha_s^3\alpha^2)}_{gg\to Hq\bar{q}}$	11.93 ± 0.04
$\sigma^{(\alpha_s^3\alpha^2)}_{gg\to Hb\bar{b}}$	-5.94 ± 0.03
$\sigma^{(\alpha_s^2\alpha^2)}_{qg\to Hq} + \sigma^{(\alpha_s^2\alpha^2)}_{\bar{q}g\to H\bar{q}}$	-163.9 ± 0.1
$\sigma^{(\alpha_s^2\alpha^2)}_{bg\to Hb} + \sigma^{(\alpha_s^2\alpha^2)}_{\bar{b}g\to H\bar{b}}$	20.95 ± 0.04

- All cross-sections $\mathcal{O}(\text{fb})$
- No enhancement for $p_T^H > 400$ GeV
- Irrelevant for Higgs production in ggF

Factorization Still Holds!

Conclusion

- High precision theoretical predictions make higher order EW-corrections relevant
- Loop induced corrections are highly non-trivial to compute
- The here presented results reassure: The factorization hypothesis yields a good approximation of EW-corrections in ggF
- Full control over EW in ggF will require one more 2-loop computation

Conclusion

- High precision theoretical predictions make higher order EW-corrections relevant
- Loop induced corrections are highly non-trivial to compute
- The here presented results reassure: The factorization hypothesis yields a good approximation of EW-corrections in ggF
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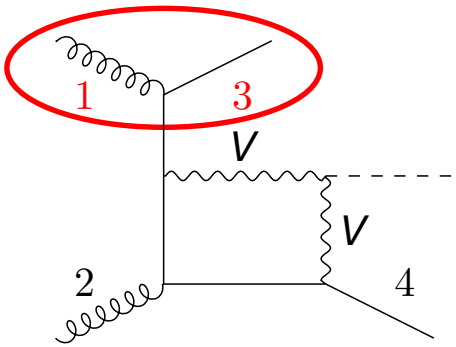
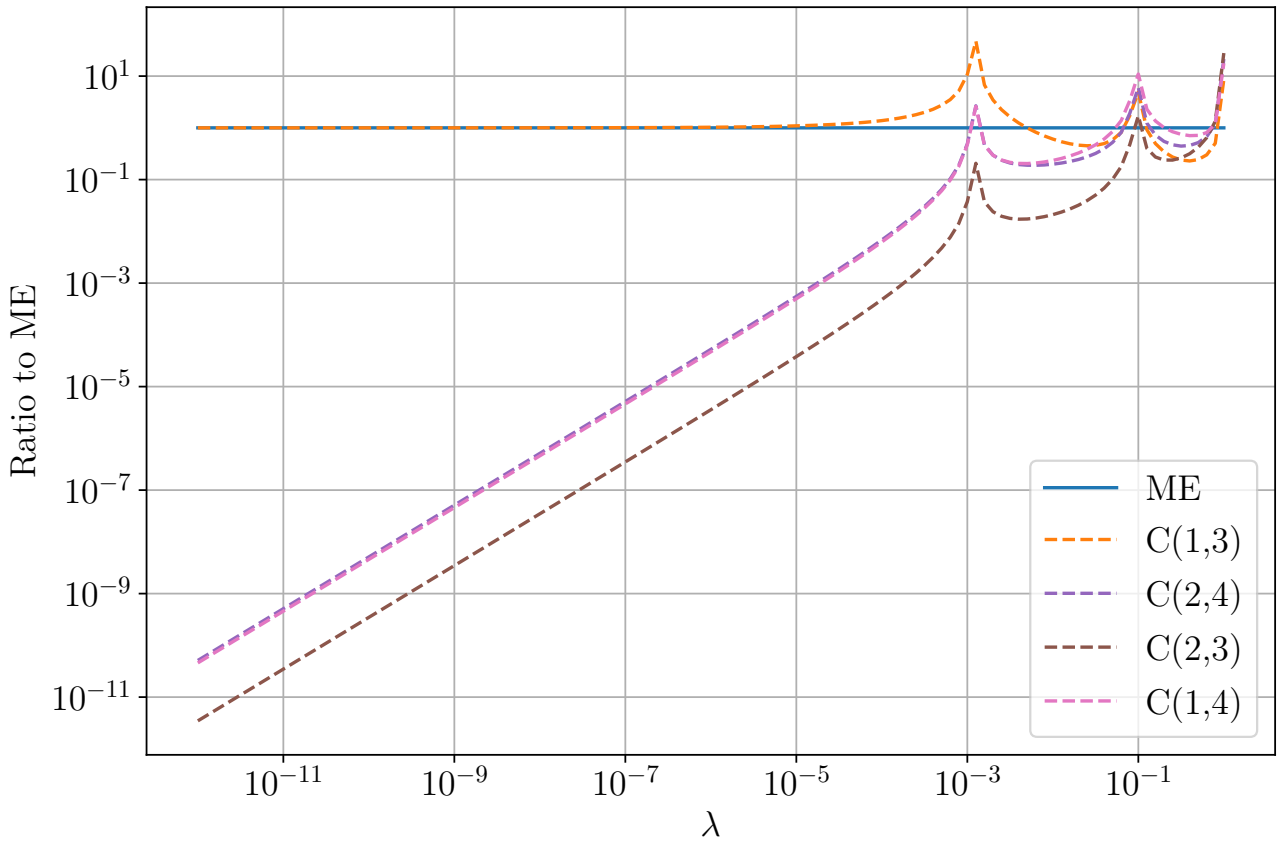
Thank you!

Subtraction in $gg \to Hq\bar{q}$



- $\mathcal{M} \propto 1/\lambda$
- $\lambda = 10^{-12}$:
  $p_T : \mathcal{O}(\text{MeV})$



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