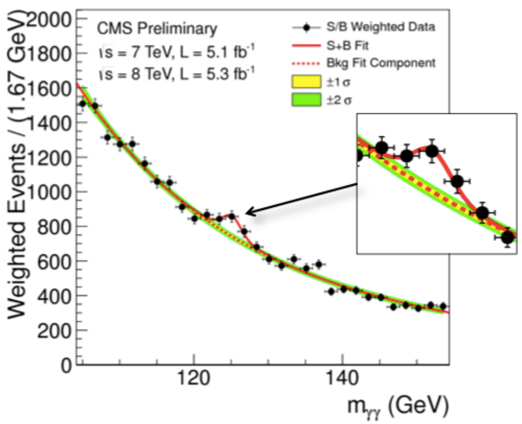
Higgs Boson Pair Production at NNLO in the EFT

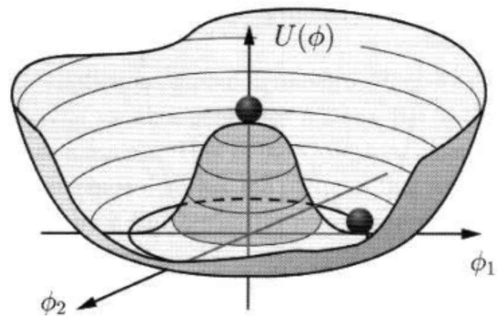
Javier Mazzitelli - *Universidad de Buenos Aires*

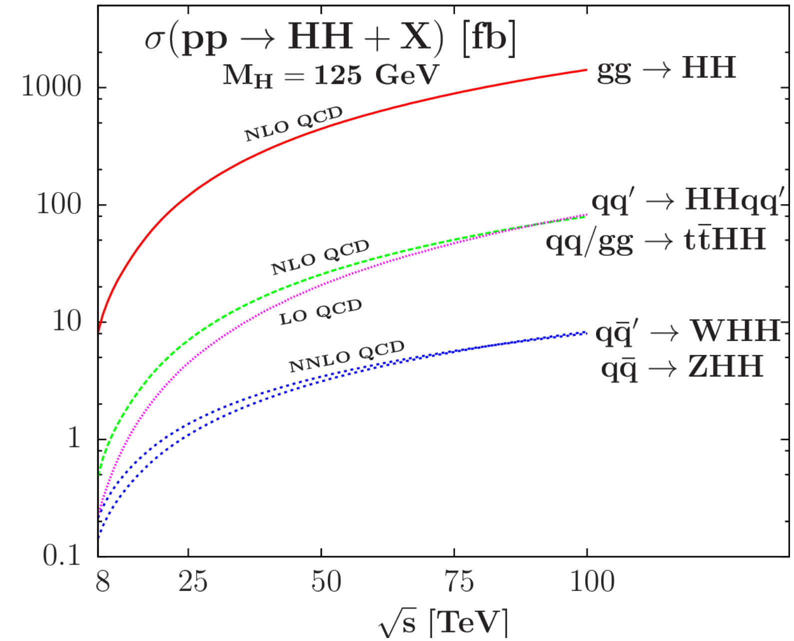
in collaboration with **Daniel de Florian**

HH subgroup meeting – October 2014, CERN

Motivation







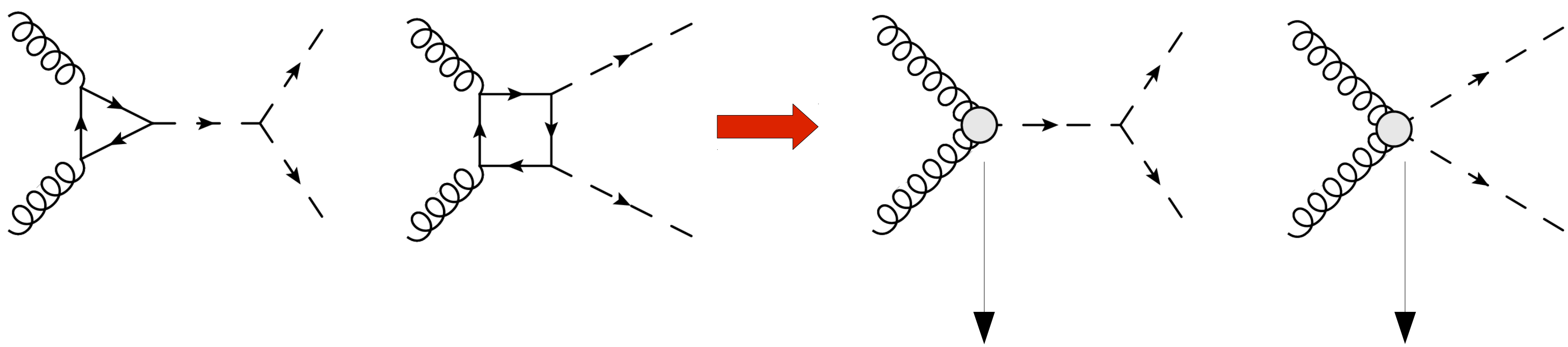
- **Why computing HH production via gluon fusion at NNLO in the EFT?**
  - Gluon fusion is the main HH production channel
  - NLO corrections in the EFT are large
    K factor close to 2
    Large theoretical uncertainties
  - We need to improve both precision and accuracy of the prediction
    Finite top mass effects at NLO
    NNLO in the EFT

Calculation in the EFT

- **Calculation is much simpler! Loop induced in the full theory, tree level in the EFT**

Leading Order

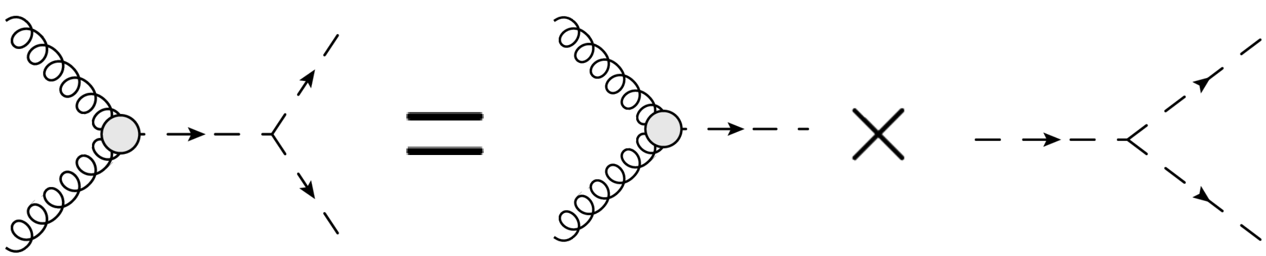
Full Theory (1-loop) | Eff. Theory (tree level)



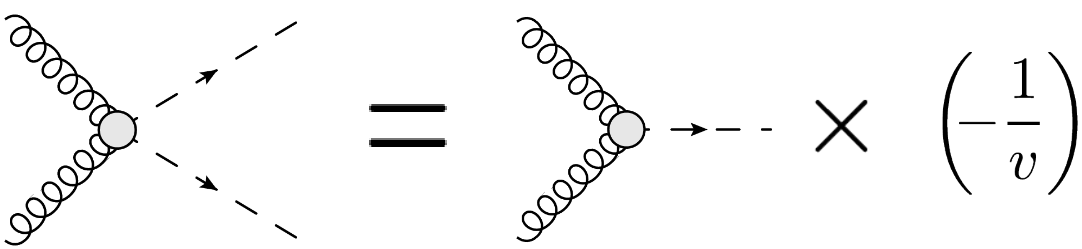
- **Even more, the vertices have the same structure!**

$$\mathcal{L}_{ggH} \propto G_{\mu\nu}G^{\mu\nu} H/v \qquad \mathcal{L}_{ggHH} \propto G_{\mu\nu}G^{\mu\nu} (H/v)^2$$

- **We don't need to calculate those diagrams again: use the single Higgs case**



(1)

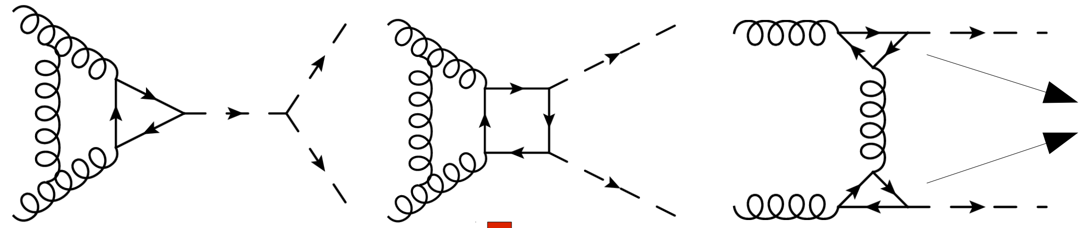


(2)

- **These relations also hold at higher orders, in a diagram by diagram basis**

Calculation in the EFT – virtual corrections

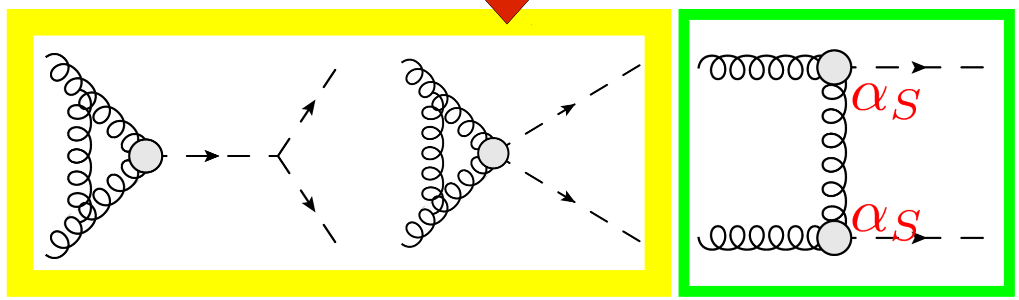
Full theory



Two heavy quark loops

NLO
virtual corrections

Eff. theory



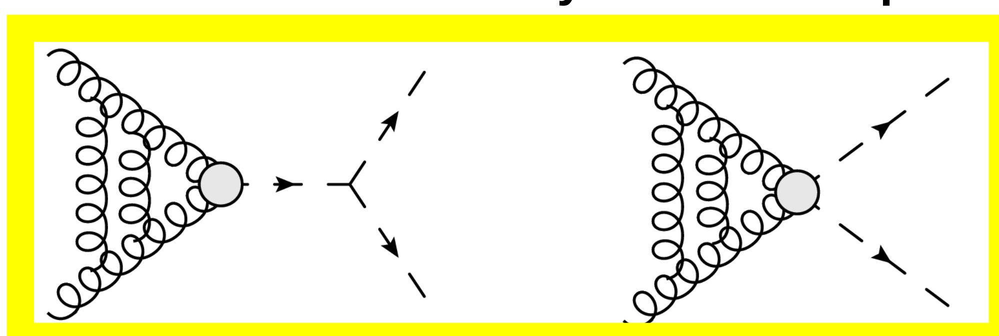
Proportional to the gluon form factor

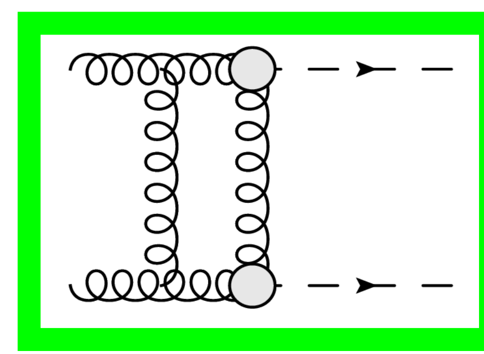
“New” contribution
Tree level at NLO

- **For the NNLO virtual corrections we only need to compute one-loop diagrams**

NNLO
virtual corrections

Eff. theory





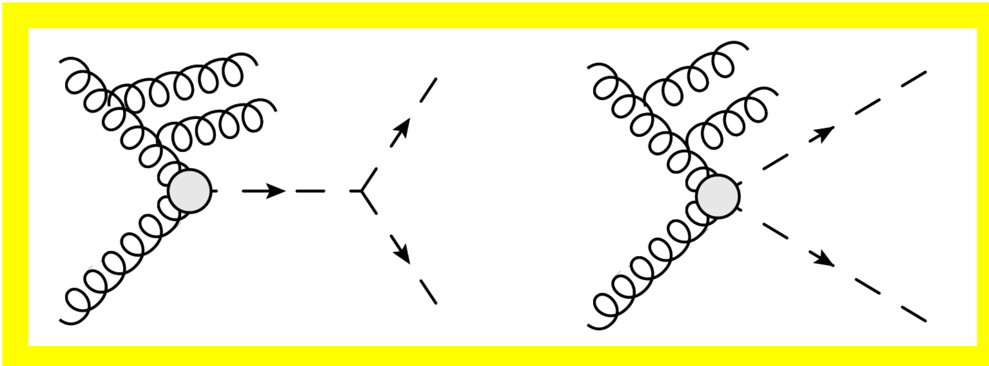
Proportional to the two-loop gluon form factor

“New” contribution
One-loop at NNLO

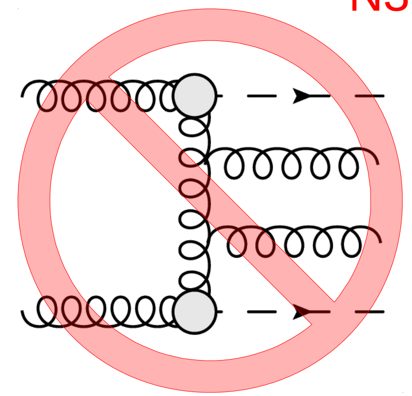
- **Reduction into master integrals using FIRE**

Calculation in the EFT – real corrections

- **Double real emission:**

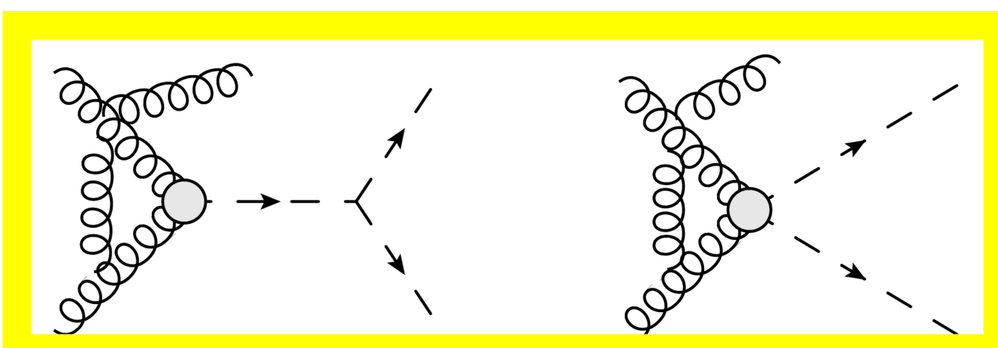


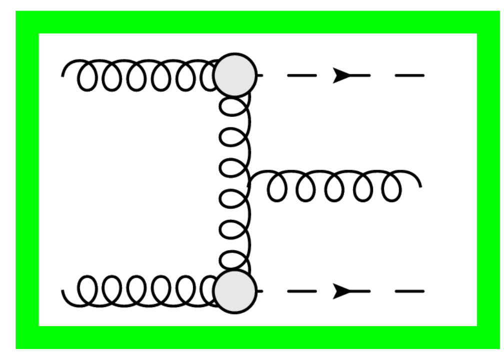
N3LO contribution



- Everything can be taken from the single Higgs results

- **Single real emission at “one-loop”:**





- Single soft and collinear divergencies at tree level: we use FKS subtraction

Calculation in the EFT – in short:

- We split the calculation: $Q^2 \frac{d\hat{\sigma}}{dQ^2} = \hat{\sigma}^a + \hat{\sigma}^b$

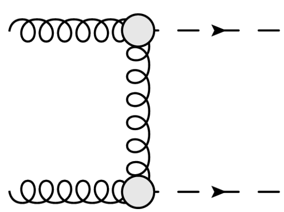
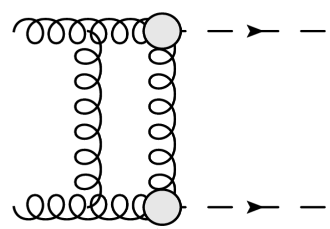
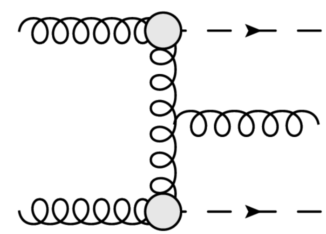
Single-Higgs like

New topologies with two effective vertices

$$\hat{\sigma}^a_{ij} = \hat{\sigma}_{LO} \left\{ \eta^{(0)}_{ij} + \left(\frac{\alpha_S}{\pi}\right) \eta^{(1)}_{ij} + \left(\frac{\alpha_S}{\pi}\right)^2 \left[\eta^{(2)}_{ij} + \underbrace{\delta_{ig}\delta_{jg}\delta(1-z) \frac{2\mathrm{Re}(C_{LO})}{|C_{LO}|^2} (C_H^{(2)} - C_{HH}^{(2)})} \right] \right\}$$

Known coefficients from single Higgs XS

Differences in the second order corrections to the effective vertex (Grigo et al., 1408.2422)

$\hat{\sigma}^b =$  $+$  and 

Starting at NLO

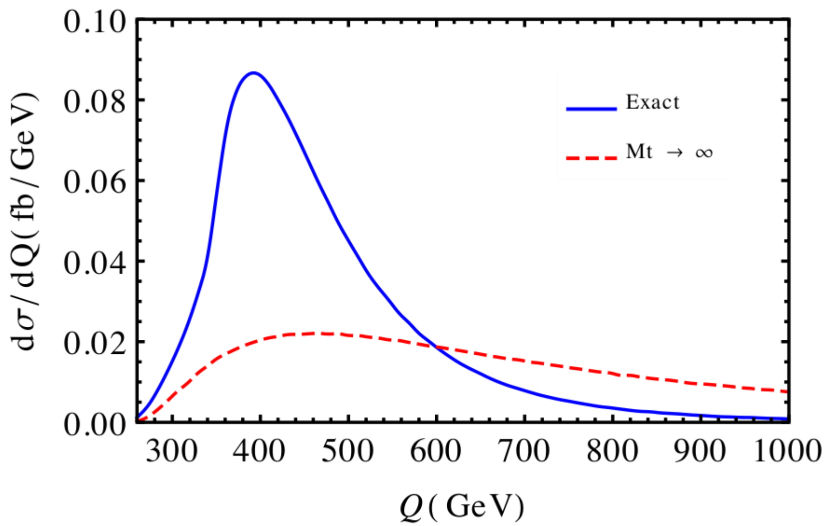
Reduced to MIs

FKS subtraction

- The “new” contributions are essentially a NLO calculation of a 2 $\rightarrow$ 2 process

Top mass effects

- **Is the EFT calculation reliable?**



- Worse than in the single Higgs case (larger inv. mass)
- Not reliable for distributions
- Underestimation of the total XS at LO of O(20%)

- **Should be more reliable to compute the QCD corrections**
  - Corrections are dominated by initial state soft radiation, not sensitive to the vertex structure
  - Usual procedure: compute the corrections in the EFT and normalize by the exact LO

- **First step: validate it at NLO**

Exact NLO not available

Grigo et al. +10%
1305.7340

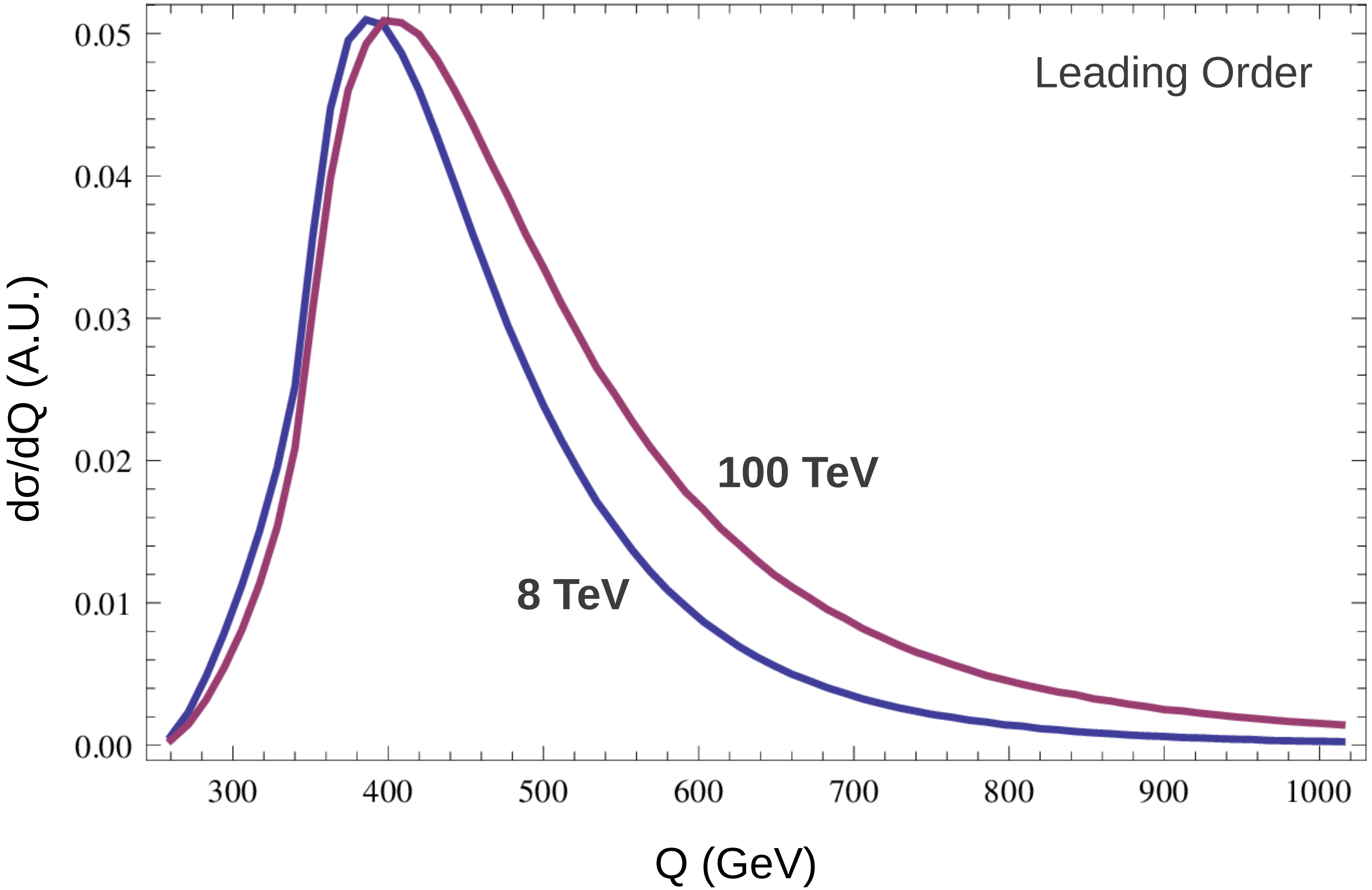
Maltoni et al. -10%
1408.6542

~±20% effect in the NLO contribution

O(5%) in the NNLO XS?

Top mass effects

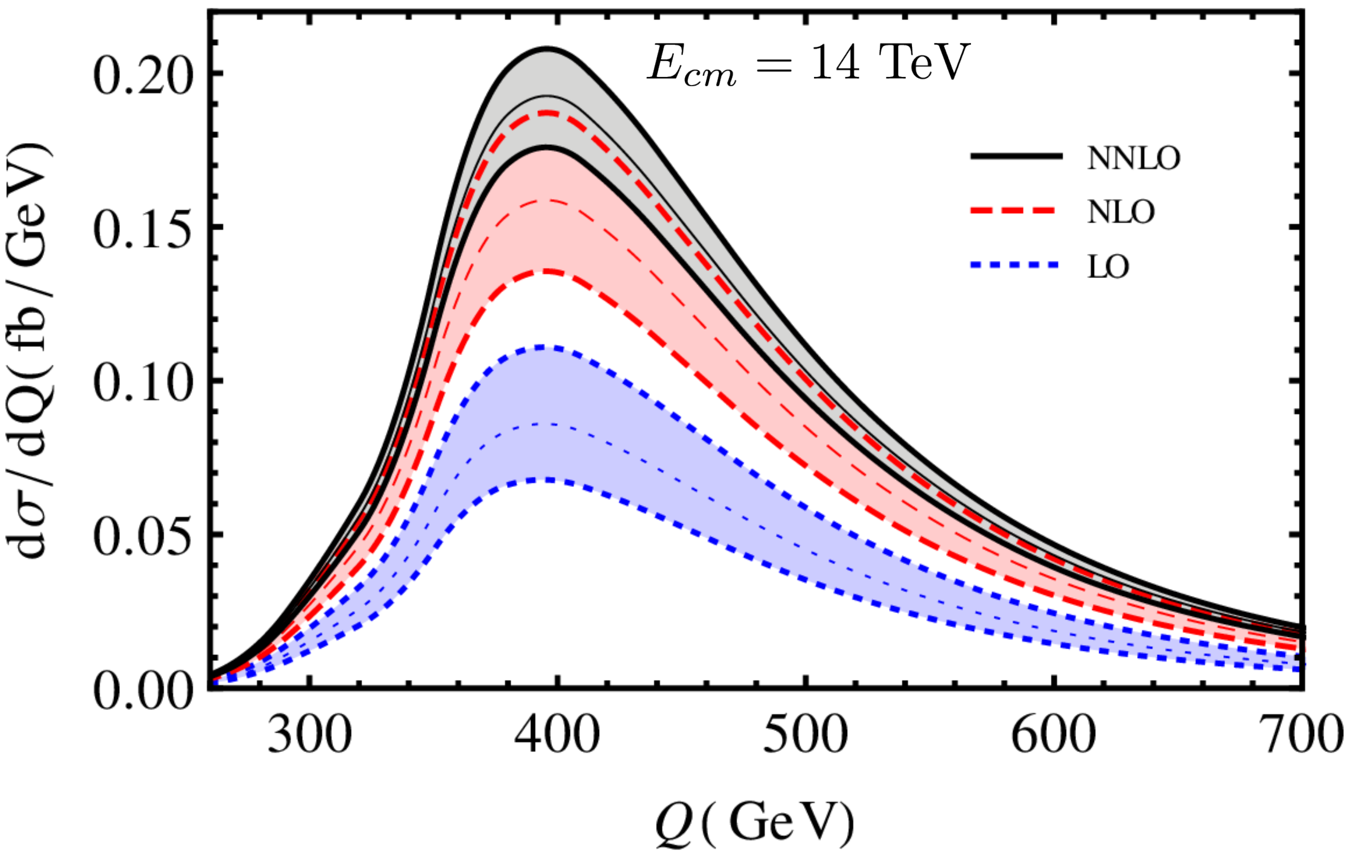
- The previous estimation is for E_{cm}=14 TeV
- The quality of the approximation should decrease with the collider energy



- There is a (moderate) shift towards higher invariant masses as we increase E_{cm}

Numerical results for the LHC

- Central value $\mu_F = \mu_R = Q$ (Higgs pair inv. Mass), and $M_H = 126 \text{ GeV}$
- Scale variation: $0.5Q \leq \mu_F, \mu_R \leq 2Q$ with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$
- MSTW08 parton distributions and QCD coupling
- Exact LO top and bottom-mass dependence normalization



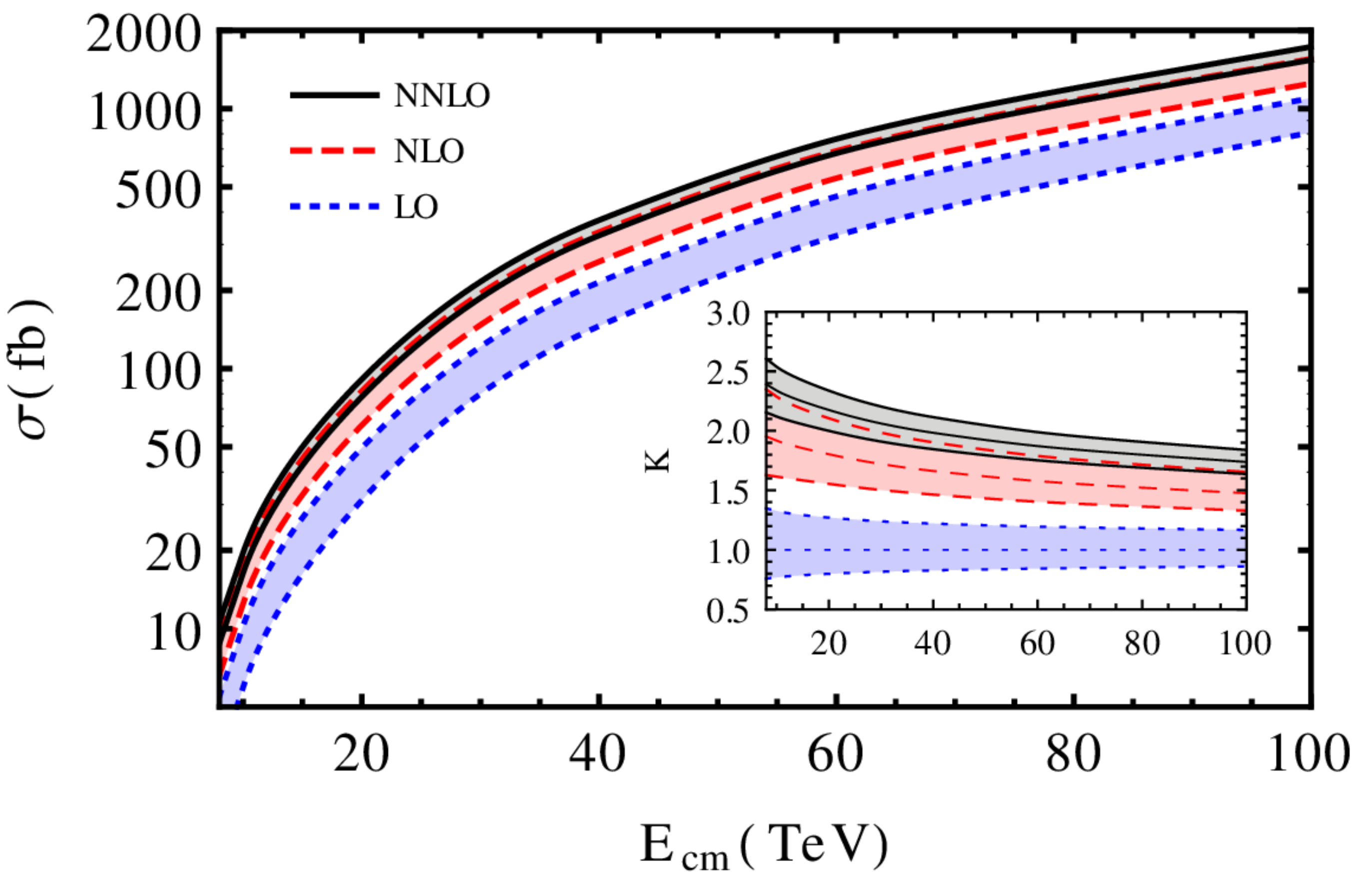
- Overlap between NLO and NNLO bands
- K factor approx. constant $K_{\text{NNLO}} = 2.3$

  $\sim 20\%$ increase w.r.t. NLO
- $\pm 8\%$ scale uncertainty

  (2 times smaller than NLO)

Numerical results for the LHC

- Central value $\mu_F = \mu_R = Q$ (Higgs pair inv. Mass), and $M_H = 126\ \mathrm{GeV}$
- Scale variation: $0.5Q \leq \mu_F, \mu_R \leq 2Q$ with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$
- MSTW08 parton distributions and QCD coupling
- Exact LO top and bottom-mass dependence normalization



- Overlap between NLO and NNLO bands
- K factor smaller as the center of mass energy increases
- Substantial reduction of the scale uncertainty

Numerical results for the LHC

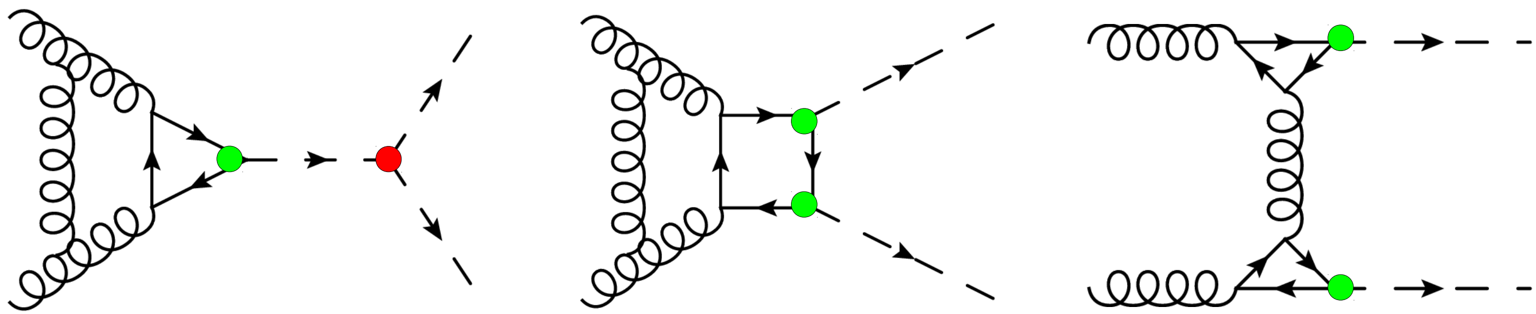
- To estimate the size of the missing higher orders → Scale variation
- Uncertainties in the PDFs and QCD coupling determination → 90% C.L. MSTW08 sets

E_{cm}	8 TeV	14 TeV	33 TeV	100 TeV
σ_{NNLO}	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$	$+7.0-7.4$	$+5.9-5.8$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.5-2.6$	$+2.3-2.6$
PDF+α_S [%]	$+9.3-8.8$	$+7.2-7.1$	$+6.0-6.0$	$+5.8-6.0$

- Total scale uncertainty drops from 19% (8TeV) to 12% (100TeV)
- Also non-perturbative uncertainties drop as E_{cm} increases
- Pert. and non pert. unc. are of the same order
- Uncertainty coming from the use of the EFT is not included!

Numerical results for the LHC

- How does the K factor behave in near-SM scenarii?
  - Trilinear coupling λ
  - Top yukawa coupling y_t



EFT: Single Higgs like — “New” contribution

- In principle not trivial because of the different contributions
- We found that dependence is almost negligible for a large range of the parameters

$$\lambda/\lambda_{SM} \in [-10; 20] \qquad y_t/y_{t,SM} \in [0.5; 2.5]$$

Numerical results for the LHC

- **Soft-virtual approximation:**

Consists in considering only soft radiation in the real corrections

↕

Keep only the plus distributions and delta functions (calculation is much simpler)

- **Why should it work?**

Gluon PDFs prefer low values of x → Threshold production

In the HH production case:

- Overestimates the total NNLO result by less than a 2%
- Better than in the single Higgs case (larger inv. Mass, closer to the threshold)

- Next step in the EFT: N3LO cross section in the SV approx

Conclusions

- We computed the NNLO corrections to the inclusive Higgs pair production XS for the gluon fusion production channel.
- We worked within the large top-mass approximation (normalizing our results with the exact LO).
- We found an increase of ~20% w.r.t. the NLO prediction (E_{cm}=14TeV).
- The scale uncertainty is substantially reduced (~17%), and we found an overlap with the previous order result.
- Finite top-mass effects still have to be analyzed at NLO.
- If at NLO the effect on the total XS is of O(10%) at 14 TeV, at NNLO we can expect them to be of O(5%)

Thanks!