Higgs Pair Production at the LHC

Marina Billoni[1,2]

in collaboration with S. Dittmaier[1,2] and A. Mück[3]

[1]Albert-Ludwigs-Universität, Freiburg

[2]Max-Planck-Institut für Physik, München

[3]RWTH Aachen

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Outline

Introduction

Why Higgs Pairs?

Discovery of a neutral scalar particle at the CERN Large Hadron Collider:

SM Higgs Boson $\mathcal{H}$?

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$\longrightarrow$ Determination of the properties and experimental reconstruction of the Higgs potential:

$$V(\mathcal{H}) = \frac{1}{2} M_{\mathcal{H}}^2 \mathcal{H}^2 + \lambda_{\mathcal{H}\mathcal{H}\mathcal{H}} \mathcal{H}^3 + \frac{1}{4} \lambda_{\mathcal{H}\mathcal{H}\mathcal{H}\mathcal{H}} \mathcal{H}^4$$

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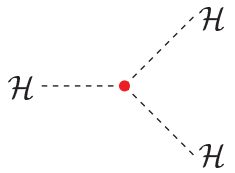

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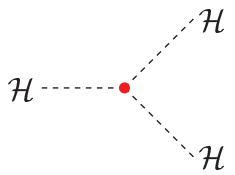
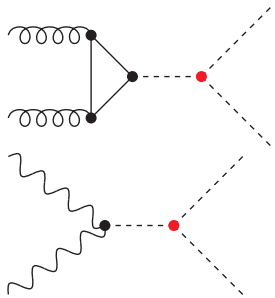


Production mechanisms at the LHC

- Gluon–Gluon Fusion $g\ g \rightarrow \mathcal{H}\ \mathcal{H}$ (NLO QCD known approx.) Dawson, Dittmaier, Spira '98
- Vector-Boson Fusion $V\ V \rightarrow \mathcal{H}\ \mathcal{H}$ (NLO QCD known) Figy '08
- Higgs-strahlung $q\ \bar{q}' \rightarrow \mathcal{H}\ \mathcal{H}\ V$



This Work

Aim: Calculation of NLO QCD corrections to the following processes

SM

$p\,p \to \mathcal{H}\,\mathcal{H}\,Z$
$p\,p \to \mathcal{H}\,\mathcal{H}\,W^+$
$p\,p \to \mathcal{H}\,\mathcal{H}\,W^-$

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \mathcal{H} + i\phi^0) \end{pmatrix},$$

$M_{\mathcal{H}} = ?$

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MSSM

$$H_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_1 + \phi_1 - \mathrm{i}\chi_1) \\ -\phi_1^- \end{pmatrix}, H_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2 + \mathrm{i}\chi_2) \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \mathbf{R}(\alpha) \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \mathbf{R}(\alpha) = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix},$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \mathbf{R}(\beta) \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}, \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \mathbf{R}(\beta) \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1} = ?,\ M_A = ?,\ \alpha = \mathrm{F}(\tan\beta, M_A, M_W, M_Z, \dots)$$

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$p\,p \to h\,h\,V$
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$p\,p \to H\,H\,V$
$p\,p \to A\,A\,V$
$(+\text{etc.})$

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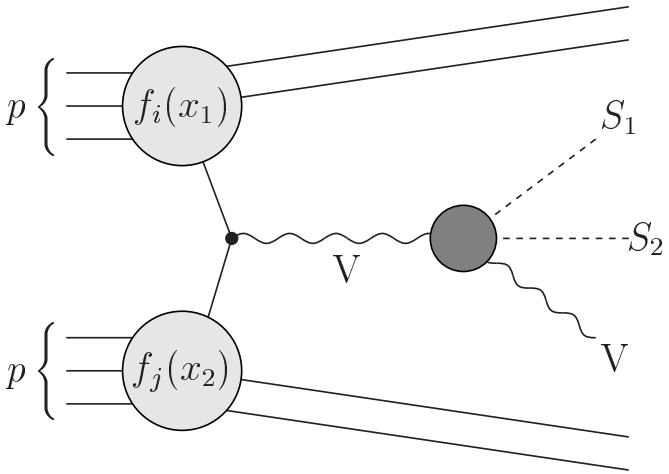
Hadronic Cross Section



$$\{S_1\, S_2\} = \{\mathcal{H}\,\mathcal{H},\ h\,h,\ h\,H, H\,H,\ A\,A\},$$

$$V = \{Z, W^+, W^-\}$$

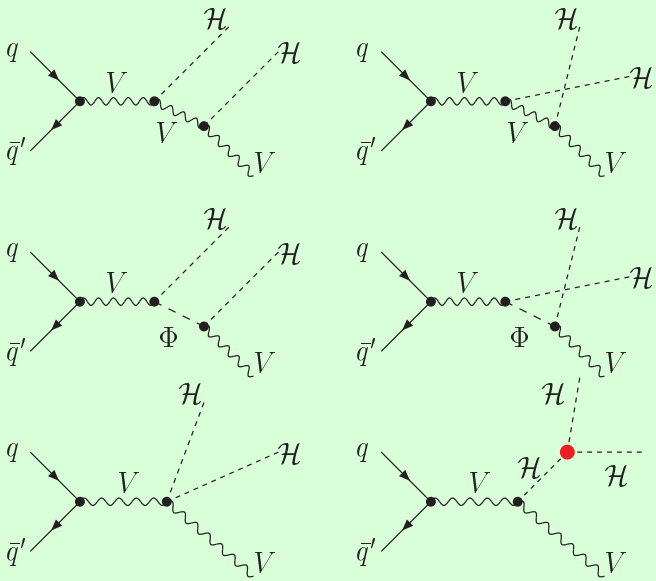
QCD-improved Parton model

- QCD factorization $\longrightarrow$ Redefinition of parton densities to absorb collinear initial-state singularities

$$\sigma(P_1, P_2) = \sum_{i,j} \int_0^1 dx_1 dx_2\, f_i(x_1, \mu_F)\, f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu_R), \mu_F).$$

Feynman Diagrams at LO

SM: $q\,\bar{q}' \to \mathcal{H}\,\mathcal{H}\,V$



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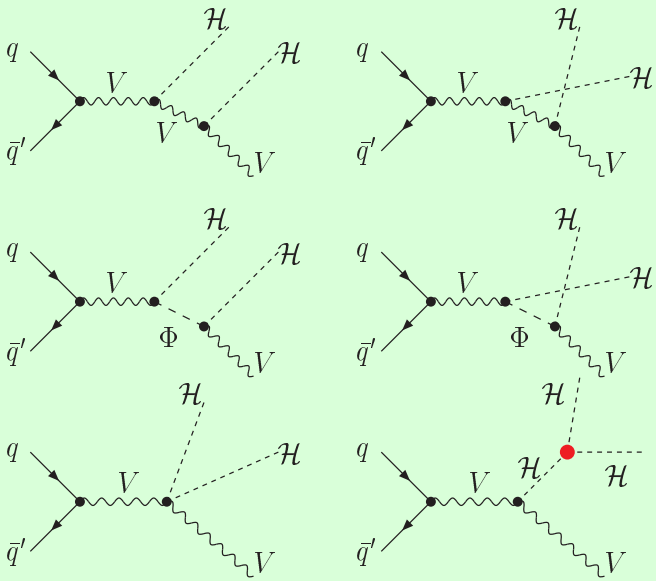

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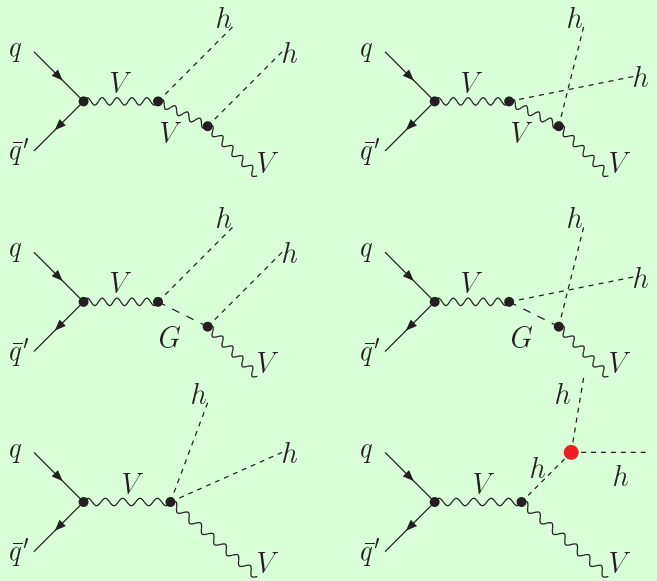

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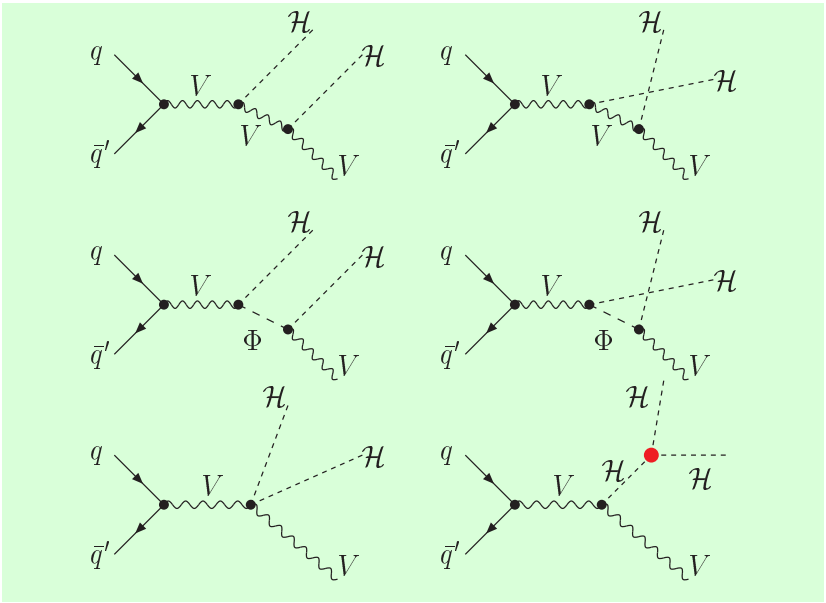

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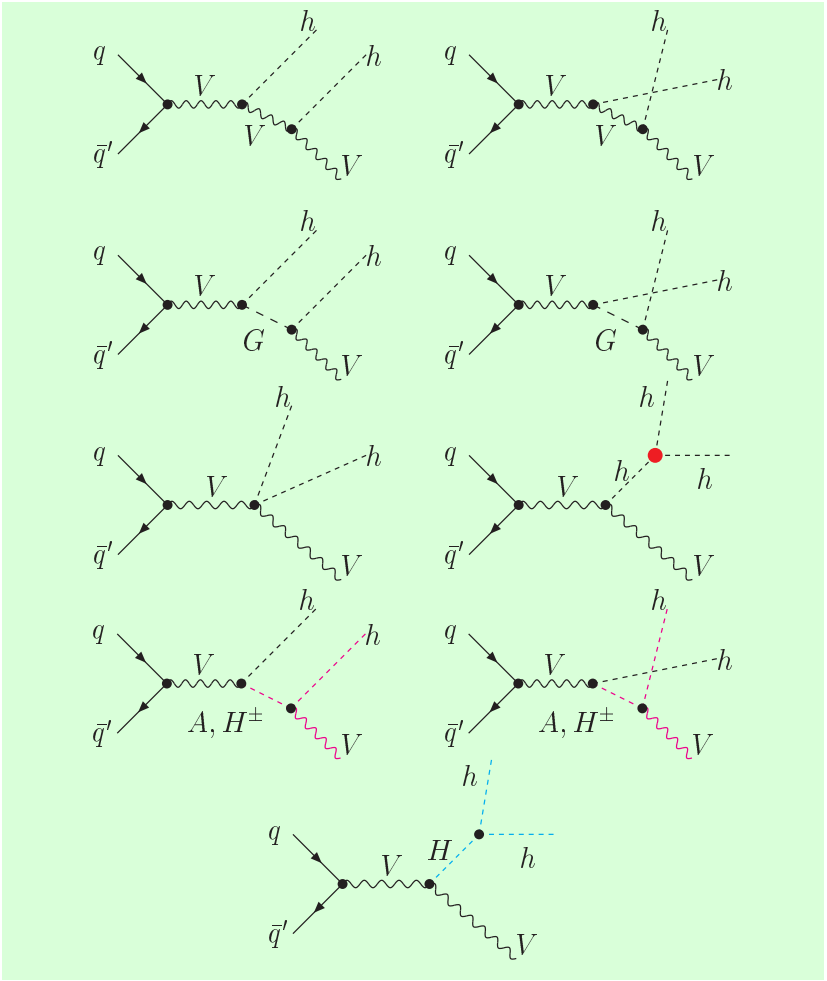


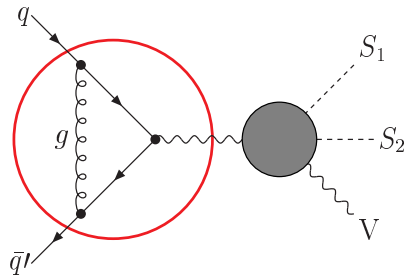
Possible resonances in the MSSM:

- $A \to h\,Z, \quad H^{\pm} \to h\,W^{\pm}$
- $H \to h\,h$

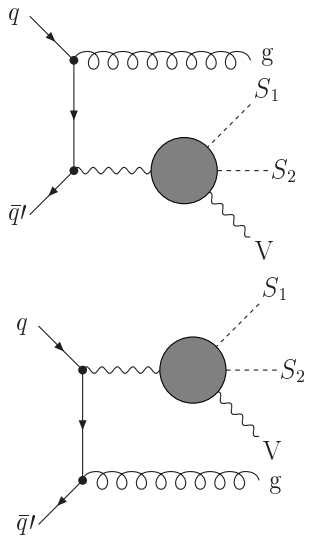
Next-to-leading order QCD corrections

$$\sigma_{NLO} = \sigma_{LO} + \sigma_{virt} + \sigma_{real}$$

Virtual corrections



Real corrections



Next-to-leading order QCD corrections

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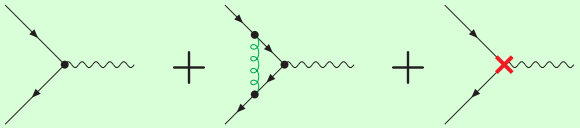
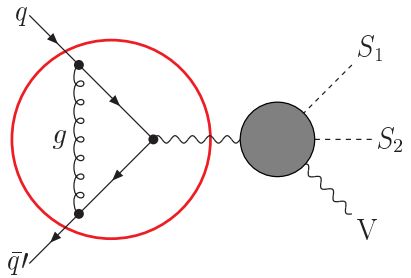
Virtual corrections

Calculation of the renormalized vertex function

$\hat{\Gamma}_\mu =$  $\propto \gamma_\mu (1 + F + \delta F)$

$\sigma_{virt} = \delta_{virt} \cdot \sigma_{Born}, \quad \delta_{virt} = 2\,Re(F + \delta F)$ UV finite !



$\frac{1}{\epsilon}$, $\ln m_g$, $\ln m$

Singularities:

- UV $\longrightarrow$ D-dim. $\epsilon = \frac{4-D}{2}$
- soft $\longrightarrow$ infinitesimal gluon mass m_g
- collinear $\longrightarrow$ small quark masses m

$\longrightarrow \delta_{virt} =$ UV finite (after renormalization)

Next-to-leading order QCD corrections

$$\sigma_{NLO} = \sigma_{LO} + \sigma_{virt} + \sigma_{soft} + \sigma_{coll} + \sigma_{hard}$$

Virtual corrections

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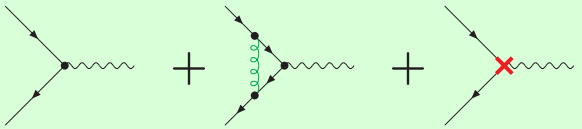
$\hat{\Gamma}_\mu =$  $\propto \gamma_\mu (1 + F + \delta F)$

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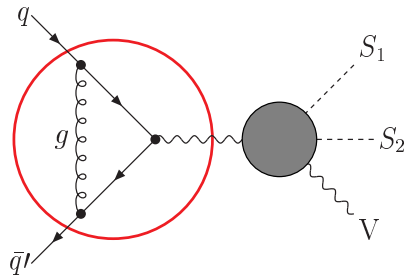


$\frac{1}{\epsilon}$, $\ln m_g$, $\ln m$

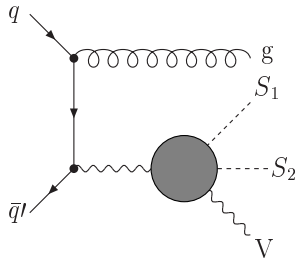
Real corrections

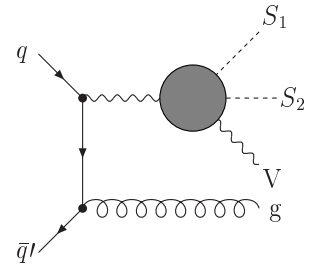
→ **Phase Space Slicing**: ΔE, $\Delta\Theta$

Soft region: $0 < m_g < E_g < \Delta E \ll \sqrt{\hat{s}}$

Collinear region: $E_g > \Delta E$, $\theta_{qg} < \Delta\Theta \ll 1$

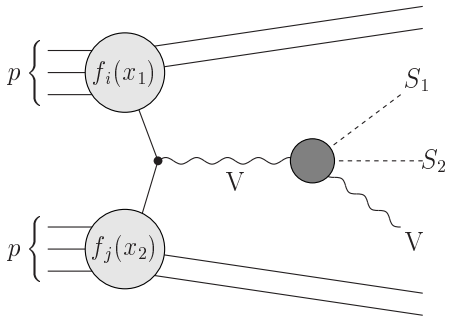
Hard non-collinear region: $E_g > \Delta E$, $\theta_{qg} > \Delta\Theta$





$$\sigma_{virt} + \sigma_{soft} + \sigma_{coll} \propto \underbrace{\int_0^1 dz\, \ln m\, P_{qq}(z)\, \sigma_{Born}(z\hat{s})}_{\text{absorbed into PDFs !}} + \textbf{finite}$$

Drell-Yan like process

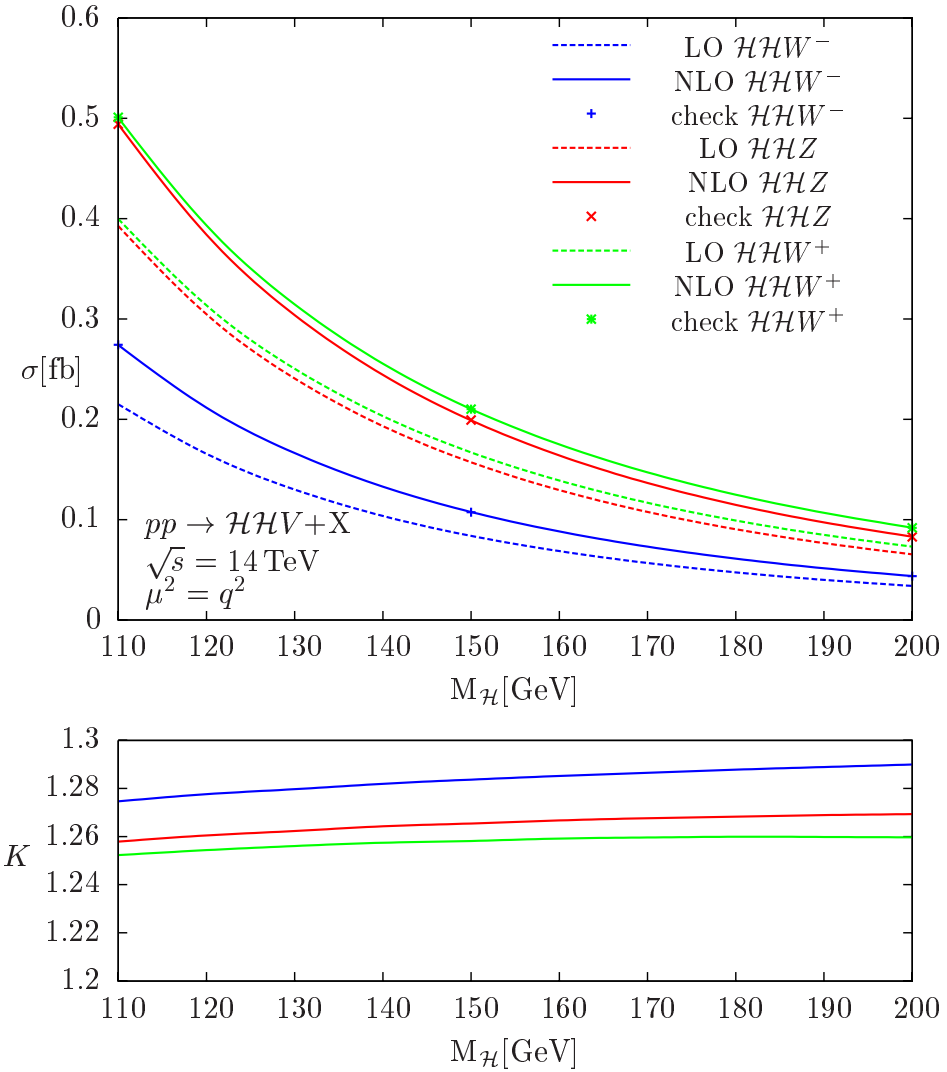


Hamberg, van Neerven, Matsuura '91

$$\sigma^{S_1 S_2 V}_{NLO}(s) = \int_0^1 dx_1 \int_0^1 dx_2 \int_0^1 dx \; \hat{\sigma}^{S_1 S_2 V}_{Born}(q^2)$$
$$\times \left\{ \sum_{q,q'} (f_{\bar{q}}(x_1, \mu_F^2) f_{q'}(x_2, \mu_F^2) + f_{\bar{q}}(x_2, \mu_F^2) f_{q'}(x_1, \mu_F^2)) \right.$$
$$\left[\Delta^{(0)}_{\bar{q}q}(x) + \Delta^{1}_{\bar{q}q}(x) - \frac{\alpha_S}{\pi} \ln\left(\frac{\mu_F^2}{q^2}\right) [P_{qq}(x)]_+ \right]$$
$$+ \sum_q [f_g(x_1, \mu_F^2)(f_q(x_2, \mu_F^2) + f_{\bar{q}}(x_2, \mu_F^2)) + x_1 \leftrightarrow x_2]$$
$$\left. \left[\Delta_{qg}(x) - \frac{\alpha_S}{2\pi} \ln\left(\frac{\mu_F^2}{q^2}\right) P_{gq}(x) \right] \right\}$$

internal check

SM Results: Cross section as a function of the SM-Higgs mass

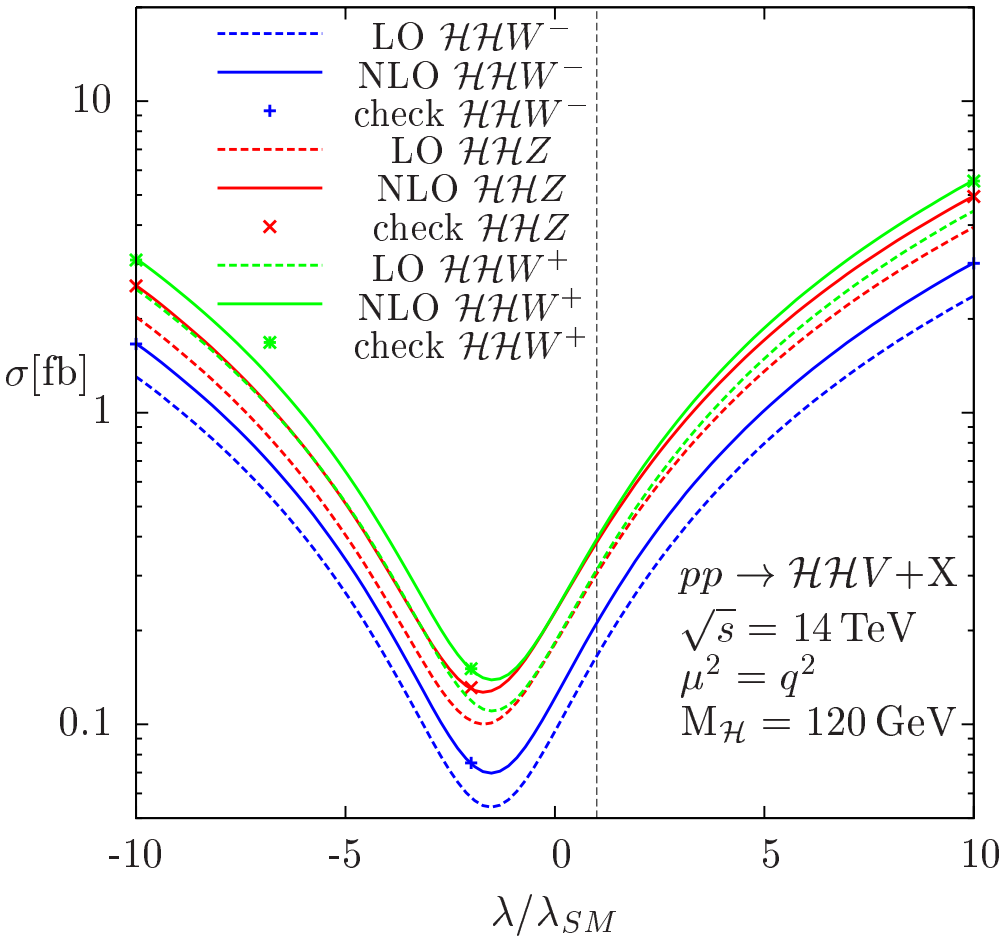


$$q = k_{S_1 S_2 V}$$

$$\sigma \sim \mathcal{O}(0.1\,\text{fb})$$

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} \sim 1.25$$

SM Results: Impact of non-standard triple $\mathcal{H}$ coupling λ



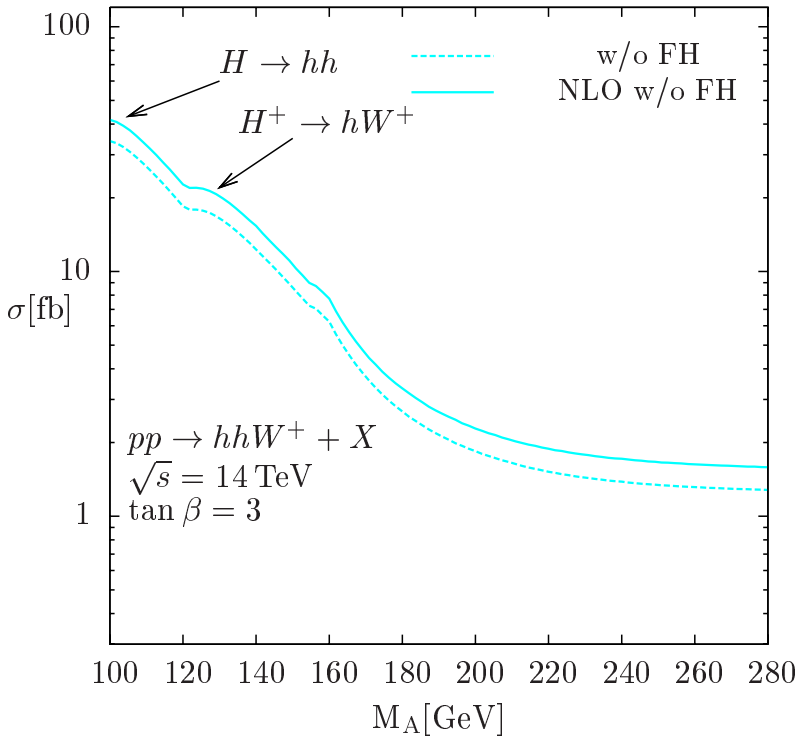
High sensitivity:

$$\frac{\Delta\lambda}{\lambda_{\mathrm{SM}}} = \pm 100\%$$

$$\rightarrow \frac{\Delta\sigma}{\sigma} \sim \pm 40\%$$

MSSM Results Example: $p\,p \to h\,h\,W^+ + X$

- SPS1a, $\tan\beta = 3,\ 30$; $M_A = 100 - 300\,\mathrm{GeV}$



- only tree-level masses and couplings

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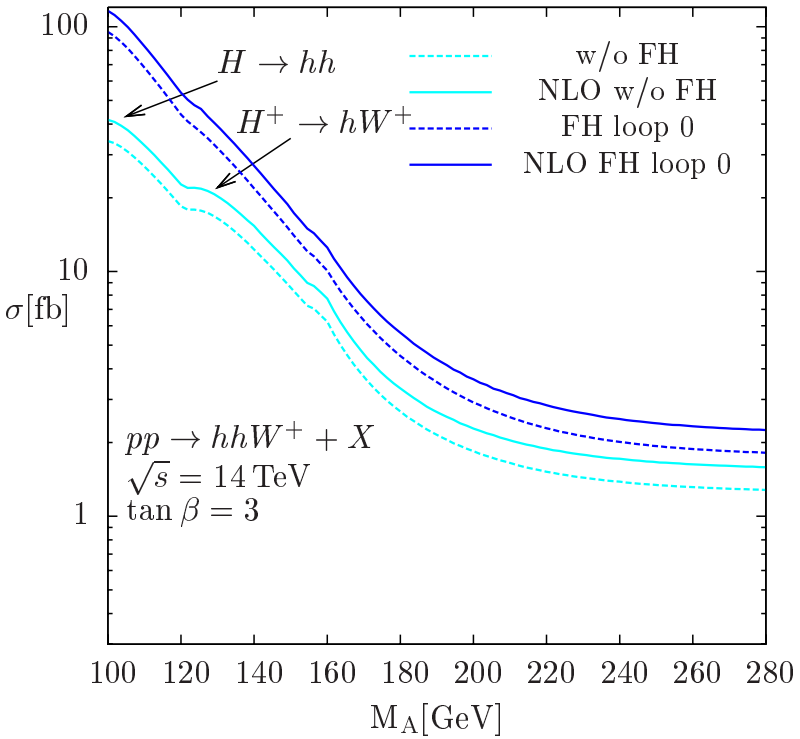

- only tree-level masses and couplings
- `FH loop=0`: loop-improved triple Higgs couplings

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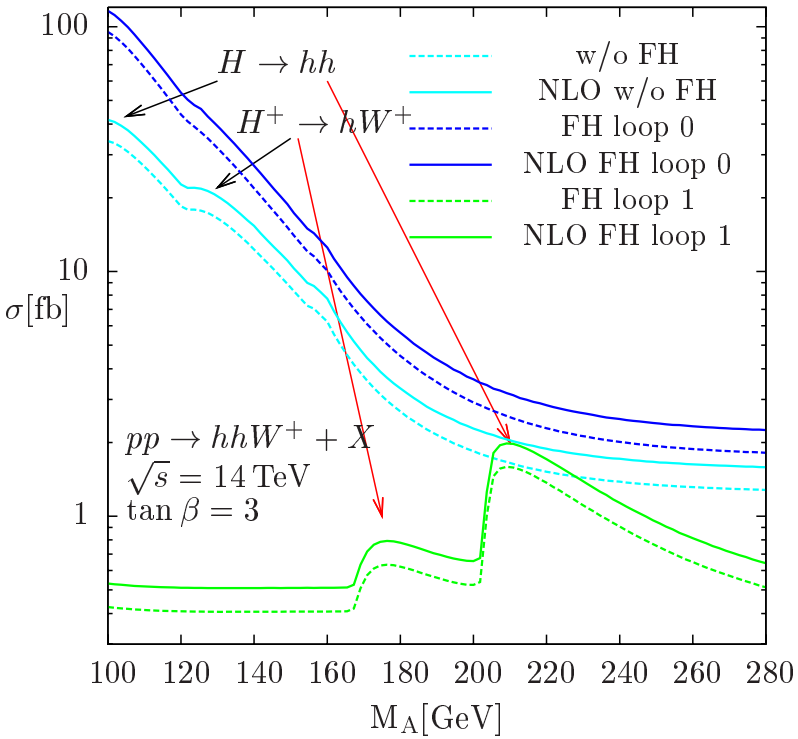

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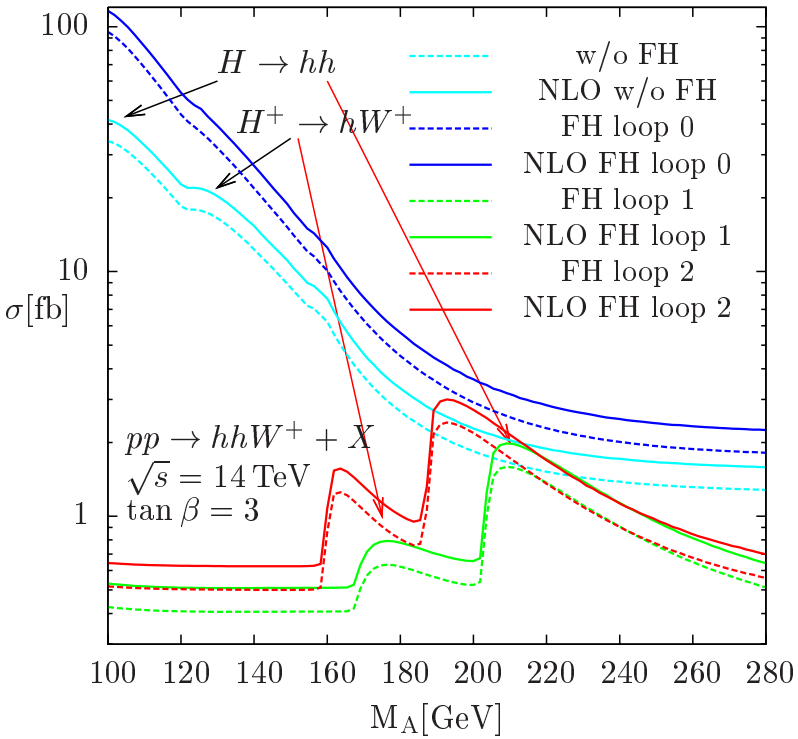

- only tree-level masses and couplings
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- `FH loop=1`: 1-loop improved masses and couplings
- `FH loop=2`: 2-loop improved masses and couplings

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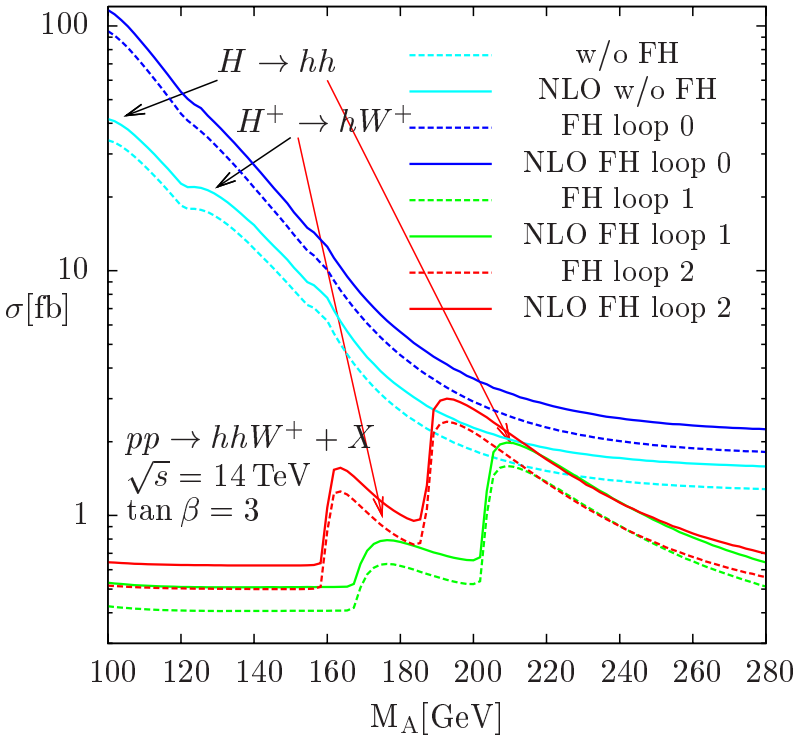
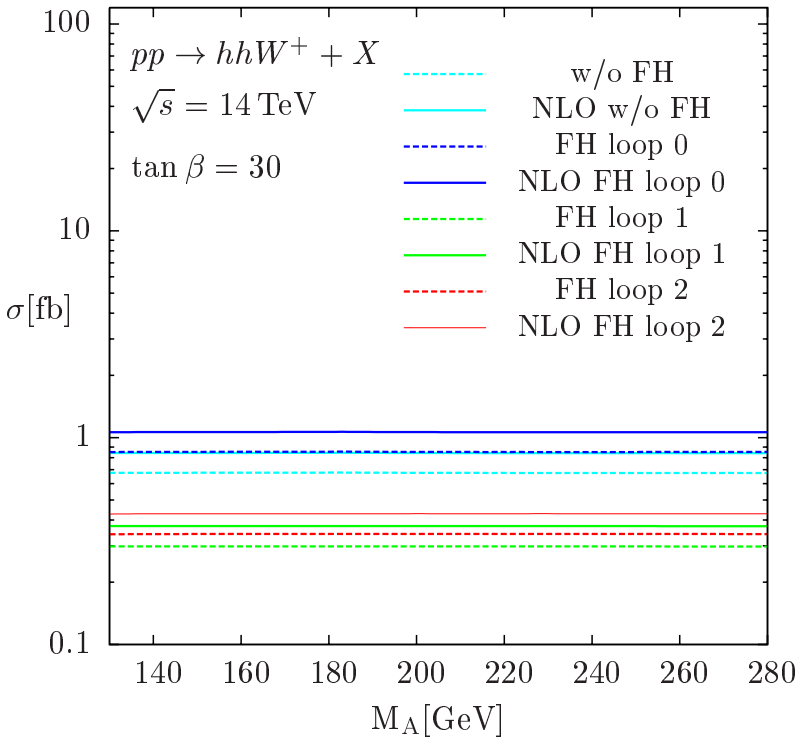
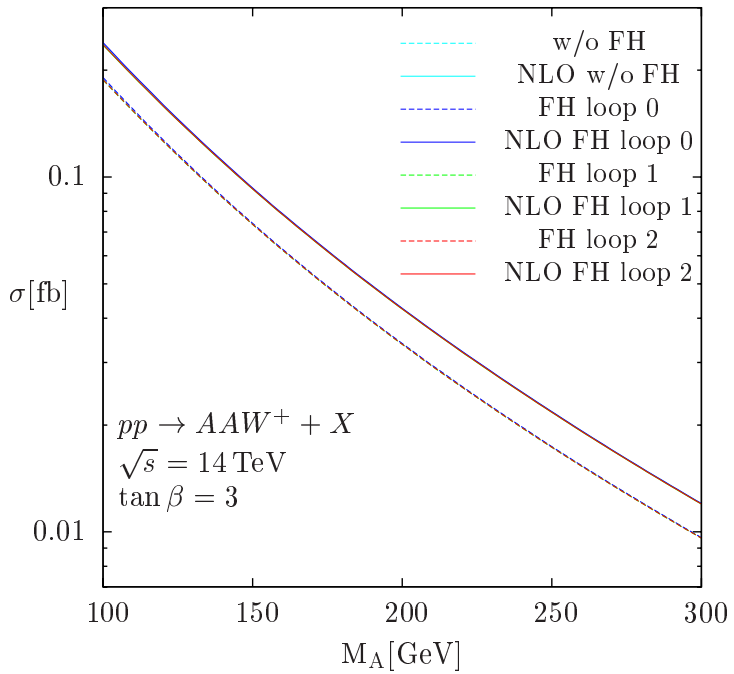
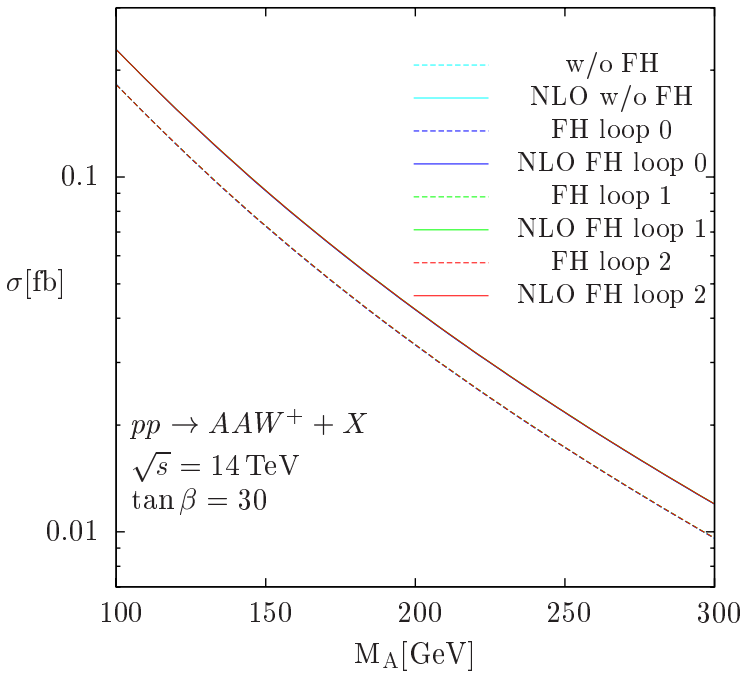




MSSM Results

Example: $p\,p \to A\,A\,W^+ + X$





Conclusion

Results

- 25% QCD corrections to Born cross sections in the SM and MSSM
- SM processes
  small cross sections < 1 fb
  but: high sensitivity to the 3-Higgs coupling λ
- MSSM processes
  - **with** resonances: $p\,p \to \{h\,h,\ h\,H\}\,V$
    cross sections > 1 fb
    strong dependence on loop-improved couplings and masses
    $\to$ smaller cross sections
    strong dependence on $\tan\beta$
  - **without** resonances: $p\,p \to \{H\,H,\ A\,A\}\,V$
    small cross sections < 1 fb

Outlook

Measurability at the LHC $\to$ compare signals to backgrounds