Higgs pair production via VBF at hadron colliders up to QCD NNLO

报告人：凌刘生
合作者：马文淦，张仁友，李伟华等
中国科大高能物理唯象实验室

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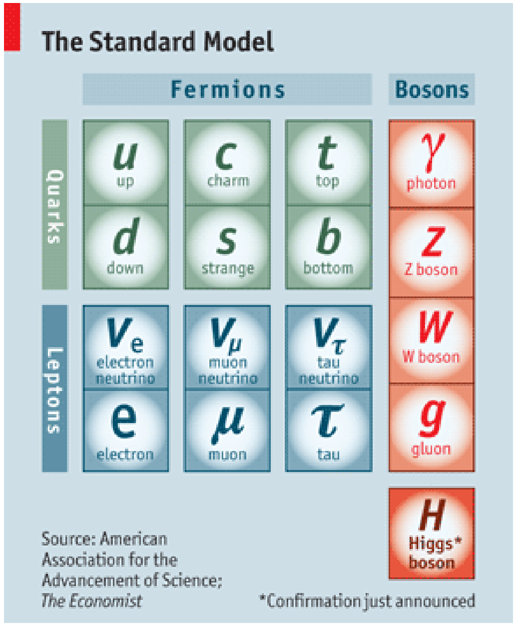
1. Motivation

- 2012, both the ATLAS and CMS collaboration have observed Higgs boson.



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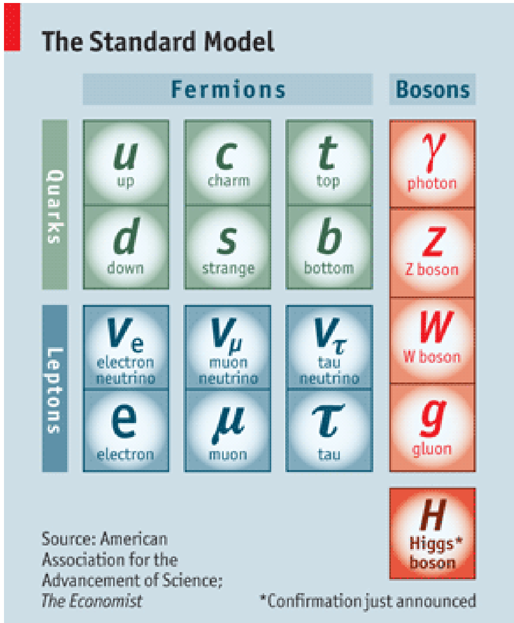

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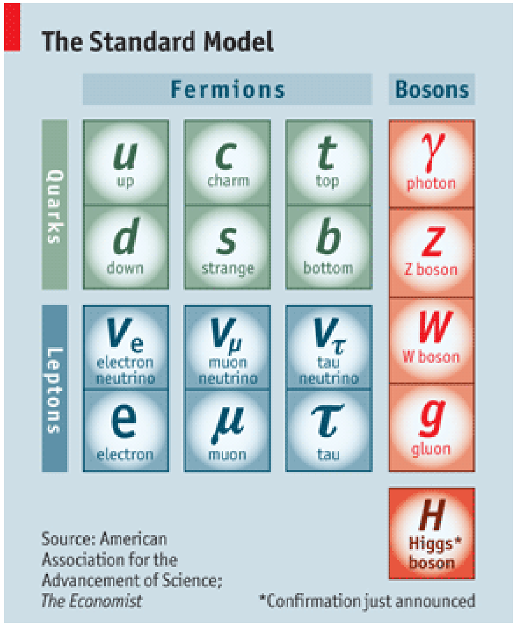


- It is the beginning and there are a lot of things that have to be done:

Higgs → spin, parity

Higgs → coupling → to fermions

coupling → to gauge bosons

coupling → self-coupling (untested so far)

- Higgs boson self-coupling in SM

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4.$$

$\lambda v H^3$ ↓ triple Higgs self-coupling

$\frac{\lambda}{4} H^4$ ↓ quartic Higgs self-coupling

- Higgs boson self-coupling in SM

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 .$$

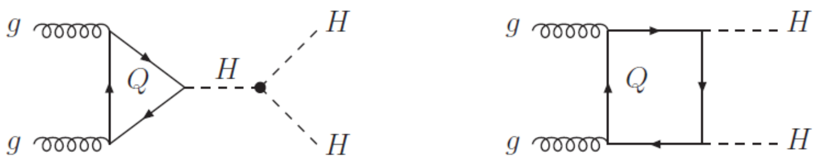
triple Higgs self-coupling　　quartic Higgs self-coupling

Higgs pair production　　require large luminosity

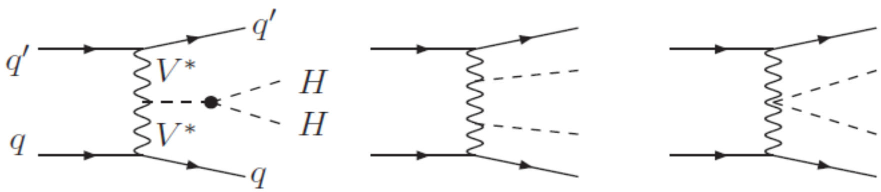
Triple Higgs production　　seriously challenging

2. The four main Higgs pair production channels at LHC

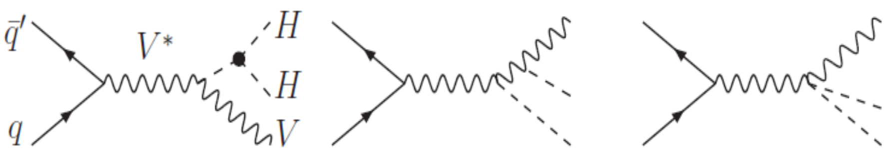
(1) gluon-gluon fusion



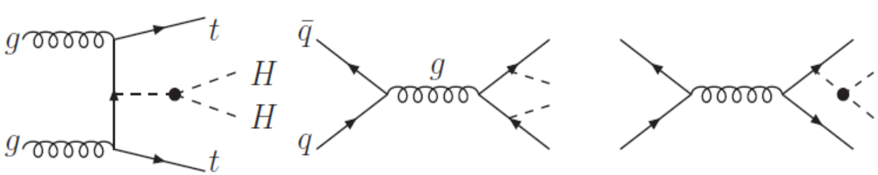
(2) vector boson fusion (VBF)



(3) double Higgs-strahlung



(4) associated production with top-quarks



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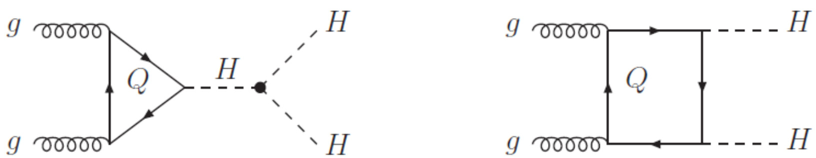
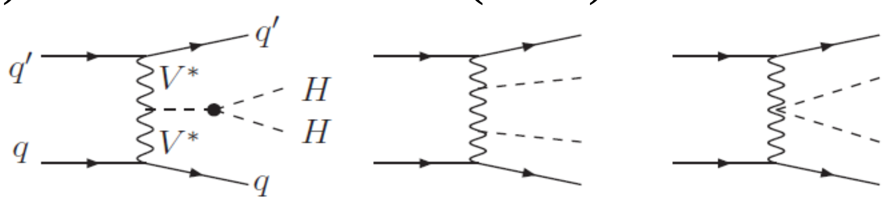


(2) vector boson fusion (VBF) →

- yields the second largest cross section.
- shows a clear experimental signature.



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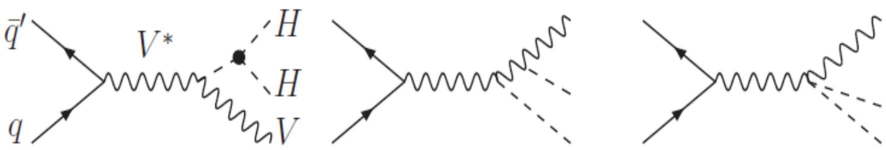
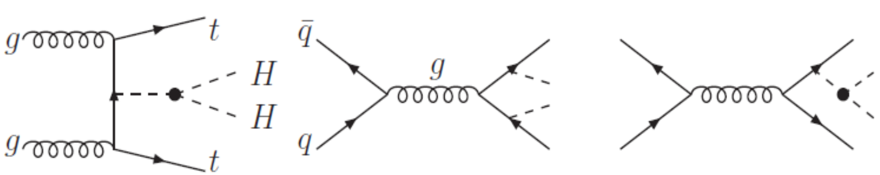


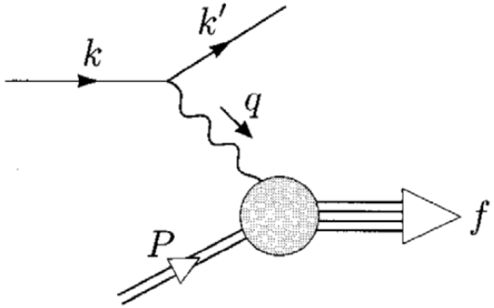
(4) associated production with top-quarks



3. The VBF Higgs pair production up to QCD NNLO in SM

3.1 Calculation setup

- deep-inelastic scattering (DIS) and structure function approach



$$e(k)+H(P)\rightarrow e(k')+f$$

deep-inelastic scattering

$$d\sigma=\frac{1}{F}C\frac{1}{\left(Q^2+M^2\right)^2}L^{\mu\nu}W_{\mu\nu}dPS$$

$$\left(V=\gamma/W/Z\Rightarrow C=e^4/(\frac{g}{2})^4/(\frac{g}{2\cos\theta_W})^4\right)$$

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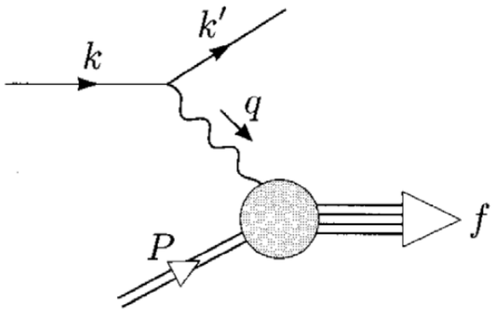


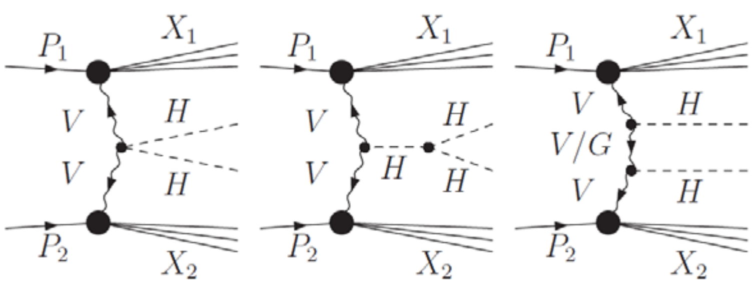
$$e(k) + H(P) \rightarrow e(k') + f$$

deep-inelastic scattering

$$d\sigma = \frac{1}{F} C \frac{1}{\left(Q^2 + M^2\right)^2} L^{\mu\nu} W_{\mu\nu} dPS$$

$$\left(V = \gamma / W / Z \Rightarrow C = e^4 / (\frac{g}{2})^4 / (\frac{g}{2\cos\theta_W})^4 \right)$$

- VBF process can be viewed as the double DIS



VBF Higgs pair production process at the hadron collider

Then we have $$d\sigma = \sum_{V=Z,W} d\sigma_V,$$

$$d\sigma_V = \frac{G_F^2 M_V^4}{S(Q_1^2 + M_V^2)^2 (Q_2^2 + M_V^2)^2} W_{\mu\upsilon}(x_1, Q_1^2) \mathcal{M}_V^{\mu\rho} \mathcal{M}_V^{*\nu\sigma} W_{\rho\sigma}(x_2, Q_2^2) dPS.$$

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Where

$$W_{\mu\nu}(x_i, Q_i^2) = (-g_{\mu\nu} + \frac{q_{i\mu} q_{i\nu}}{q_i^2}) F_1(x_i, Q_i^2) + \frac{\hat{P}_{i\mu} \hat{P}_{i\nu}}{P_i \cdot q_i} F_2(x_i, Q_i^2) + i\varepsilon_{\mu\nu\alpha\beta} \frac{P_i^\alpha q_i^\beta}{2 P_i \cdot q_i} F_3(x_i, Q_i^2),$$

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$F_j(x_i, Q_i^2)(j = 1,2,3)$ are the usual DIS structure functions.

$$F_j(x_i, Q_i^2) = \frac{1}{k} \sum_i PDF_i \otimes C_{ij}$$

In the NNLO calculation, we need the NNLO PDF and NNLO Wilson coefficient functions.

3.2 Numerical results

- The scale uncertainty, PDF uncertainty and α_s uncertainty.

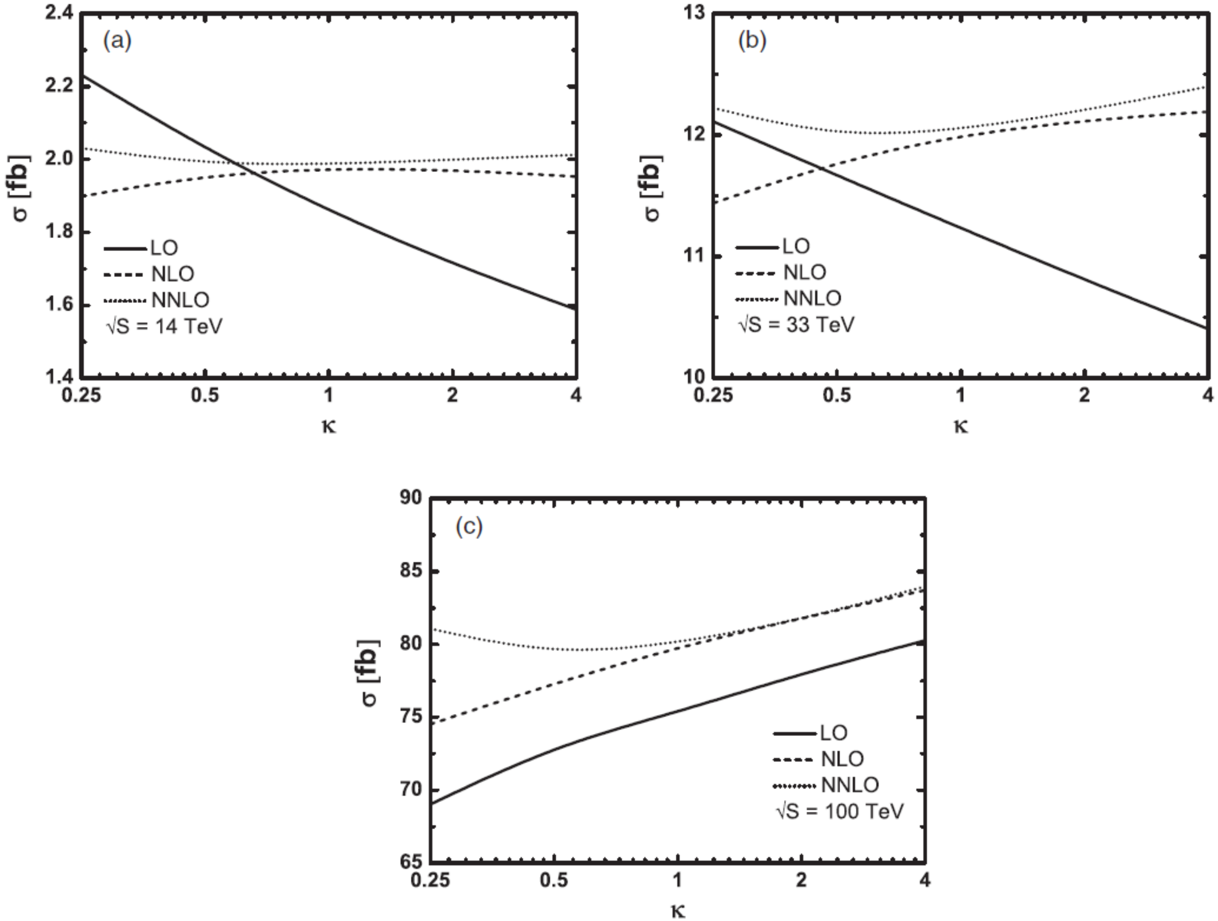

Figure 1: The scale dependence of the total cross section

The scale uncertainty of σ_{NNLO} is much smaller than the corresponding ones of σ_{NLO} and σ_{LO} .

$\sqrt{S}$	LO [fb]	NLO [fb]	NNLO [fb]
14 TeV	$1.858^{+0.374}_{-0.270}$	$1.976^{+0}_{-0.078}$	$1.986^{+0.045}_{-0}$
33 TeV	$11.234^{+0.878}_{-0.830}$	$12.002^{+0.190}_{-0.562}$	$12.041^{+0.359}_{-0.060}$
100 TeV	$75.36^{+4.91}_{-6.34}$	$79.82^{+3.92}_{-5.26}$	$80.05^{+3.92}_{-0.80}$

Table 1: The central values of total cross section and the errors due to scale uncertainty.

α_s

$\sqrt{S}$	LO [fb]	NLO [fb]	NNLO [fb]
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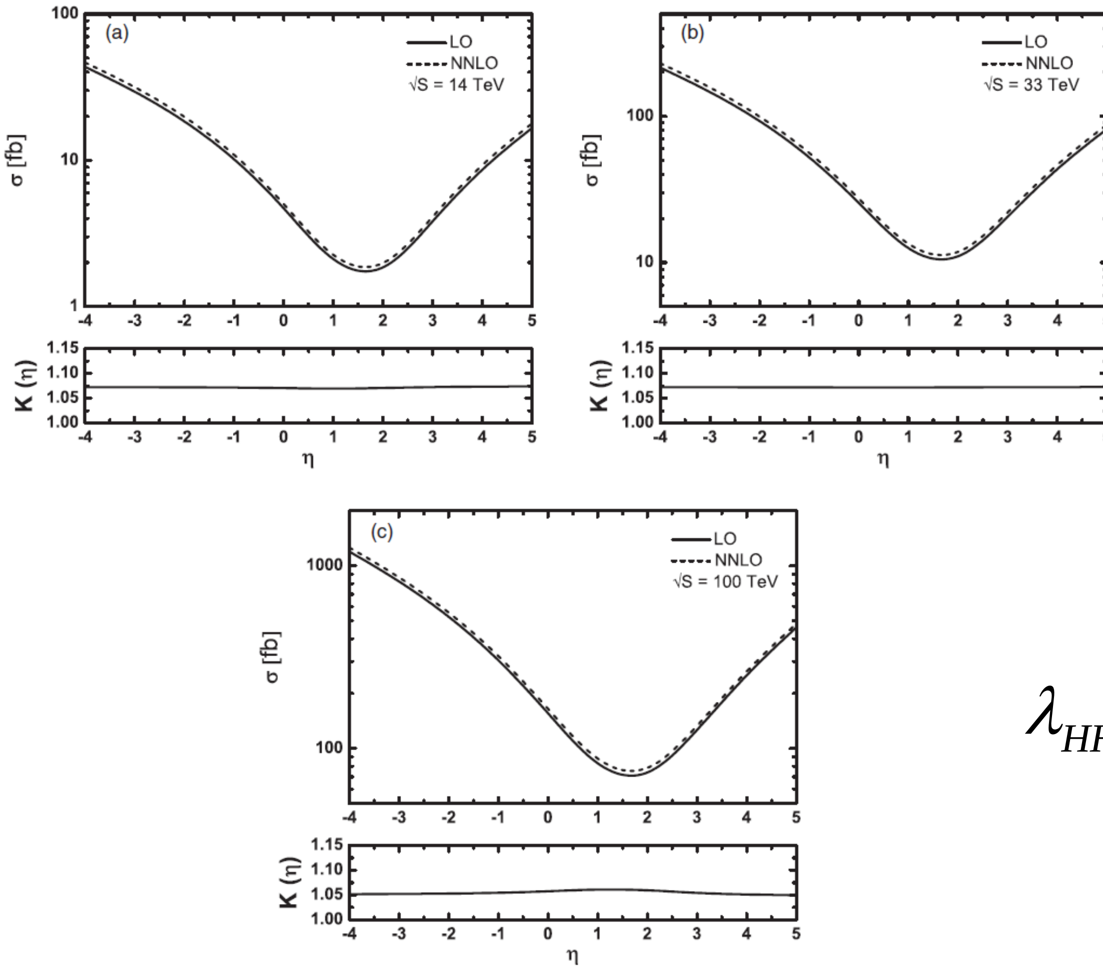
PDF sets	$\sqrt{S} = 14\ TeV$ [fb]	$\sqrt{S} = 33\ TeV$ [fb]	$\sqrt{S} = 100\ TeV$ [fb]
ABM11	$2.048^{+0.020+0.003}_{-0.014-0.004}$	$12.475^{+0.113+0.038}_{-0.071-0.038}$	$83.20^{+0.68+0.259}_{-0.63-0.234}$
CT10	$2.023^{+0.039+0.001}_{-0.037-0.001}$	$12.255^{+0.210+0.022}_{-0.201-0.013}$	$81.74^{+1.28+0.255}_{-1.48-0.288}$
HERA1.5	$2.013^{+0.051+0.004}_{-0.044-0.006}$	$12.136^{+0.269+0.022}_{-0.232-0.030}$	$80.45^{+1.27+0.145}_{-1.41-0.159}$
MSTW2008	$1.986^{+0.047+0.001}_{-0.034-0.001}$	$12.041^{+0.240+0.018}_{-0.184-0.025}$	$80.05^{+1.33+0.246}_{-1.17-0.309}$
NNPDF2.3	$1.981^{+0.044+0.002}_{-0.045-0.007}$	$11.987^{+0.221+0.047}_{-0.249-0.080}$	$79.97^{+1.38+0.487}_{-1.67-0.749}$

Table 2: The NNLO QCD corrected total cross sections and the 68% C.L. PDF uncertainties (the first error) and α_s uncertainties (the second error).

- The sensitivity of total cross sections to the trilinear Higgs self-coupling strength.



$$\lambda_{HHH} = \eta \lambda_{HHH}^{SM}$$

Figure 2: The dependence of the total cross section on self-coupling parameter η.

The total cross sections are strongly dependent on the parameter η.

4. The VBF Higgs pair production in 2HDM

- The 2HDM is built by adding a complex scalar doublet to the SM field content.

  2HDM: Two-Higgs-Doublet Model

$$\begin{aligned} V(\Phi_1,\Phi_2) &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &\quad +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] \end{aligned}$$

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&\quad +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right]
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Five scalar particles: $h^0, H^0, A^0, H^\pm$

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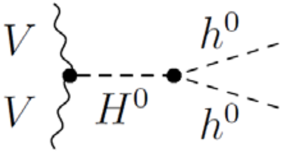
Five scalar particles: $h^0, H^0, A^0, H^\pm$

We focus on the light Higgs pair production via VBF:

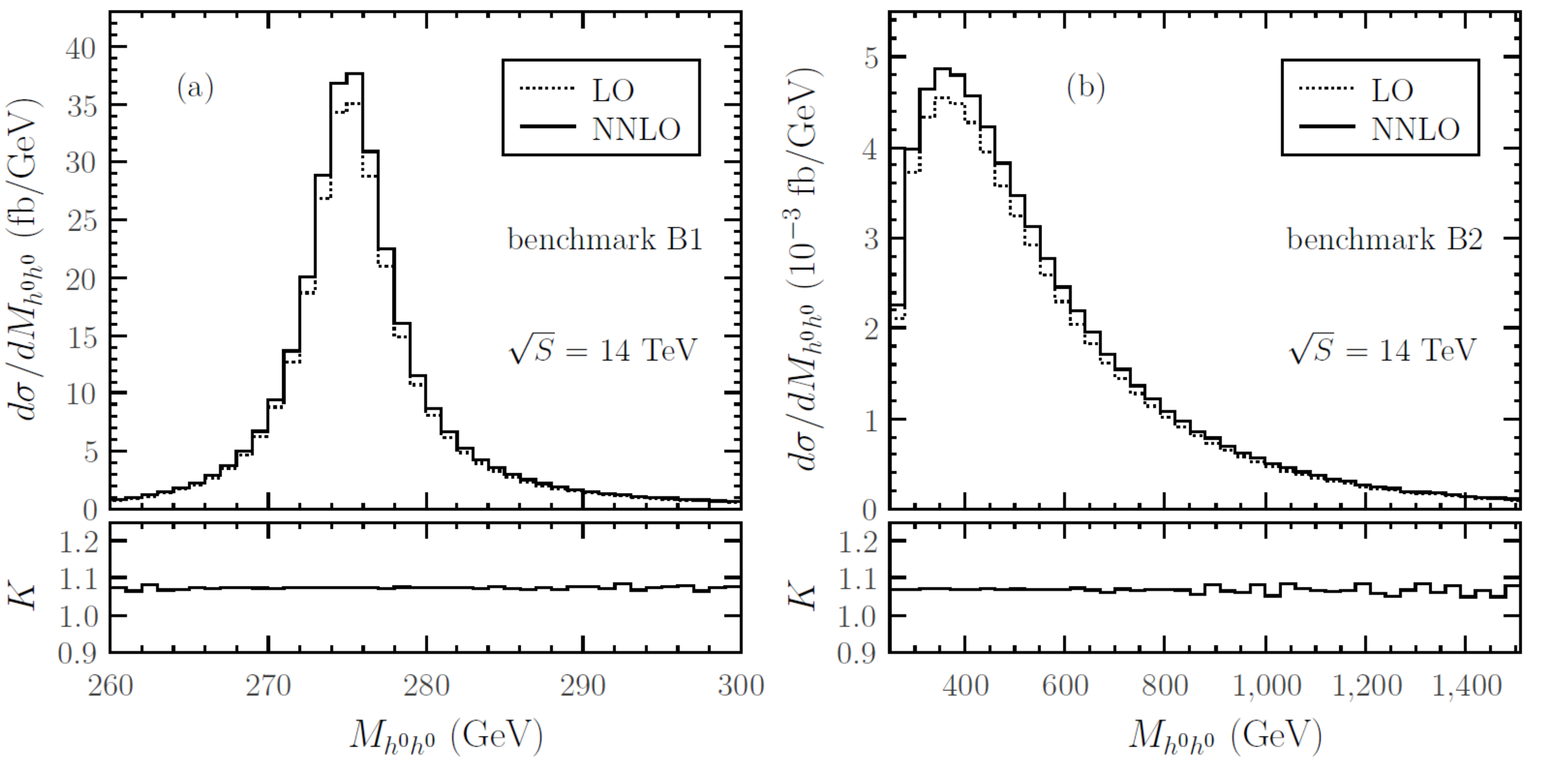
$$pp \xrightarrow{VBF} jh^0h^0j$$

Resonance:



- Numerical results

	$\sin(\beta-\alpha)$	$\tan\beta$	m_{h^0} (GeV)	m_{H^0} (GeV)	m_{A^0} (GeV)	$m_{H^\pm}$ (GeV)
B1	0.6	2	126	275	600	600
B2	1	1.5	126	160	380	420



Thank you！