NNLO differential calculation from soft-collinear effective theory: Vhh production at hadron colliders

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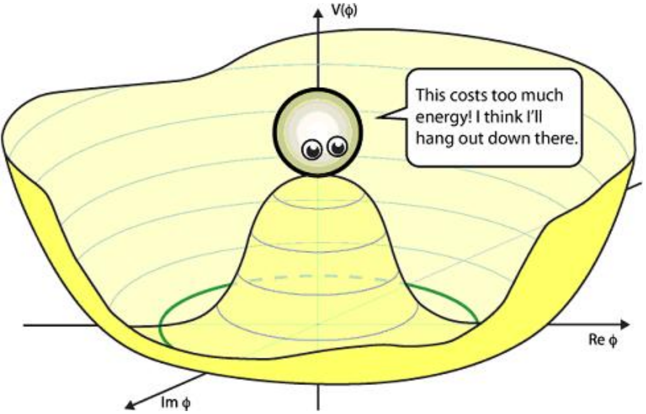
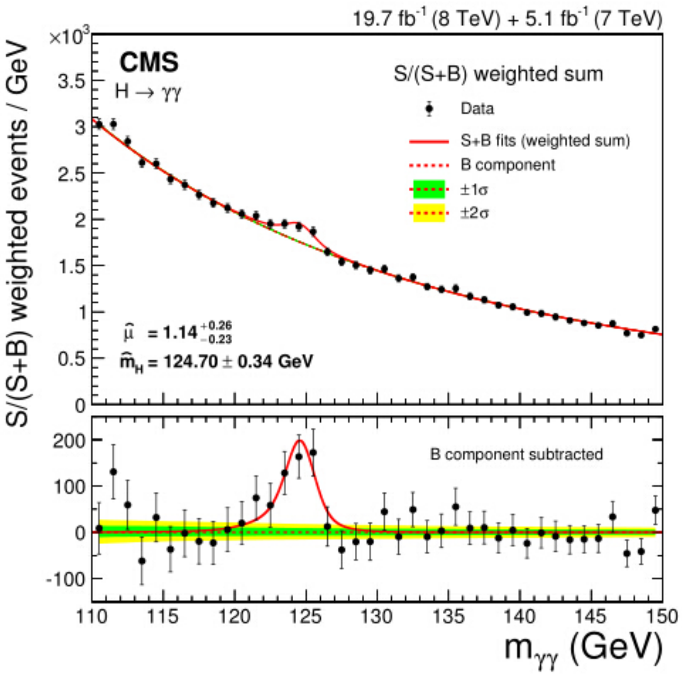
in collaboration with C.S. Li, H.T. Li, arXiv:1607.06382, 1710.02464

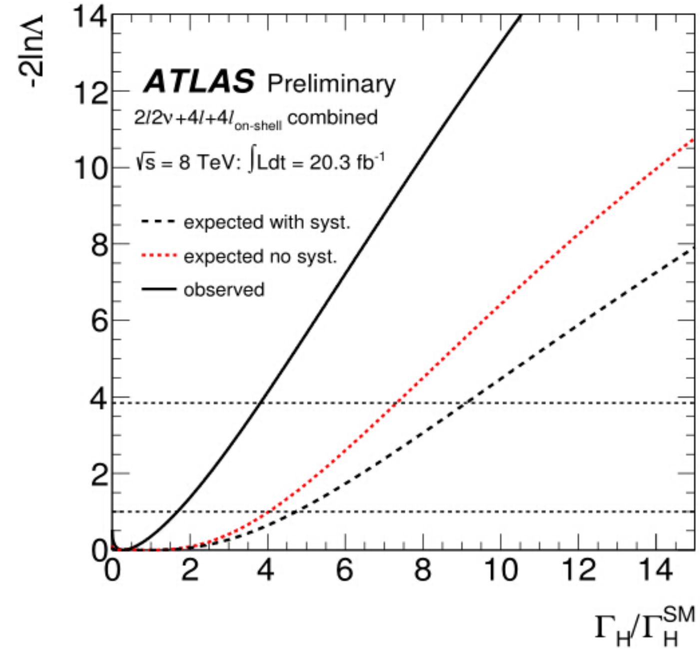
May 1st

Loops and Legs 2018



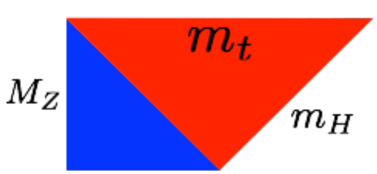
Higgs mass and width





EW fit: 94_{-24}^{+29} GeV

Triviality & stability: (130, 180)GeV

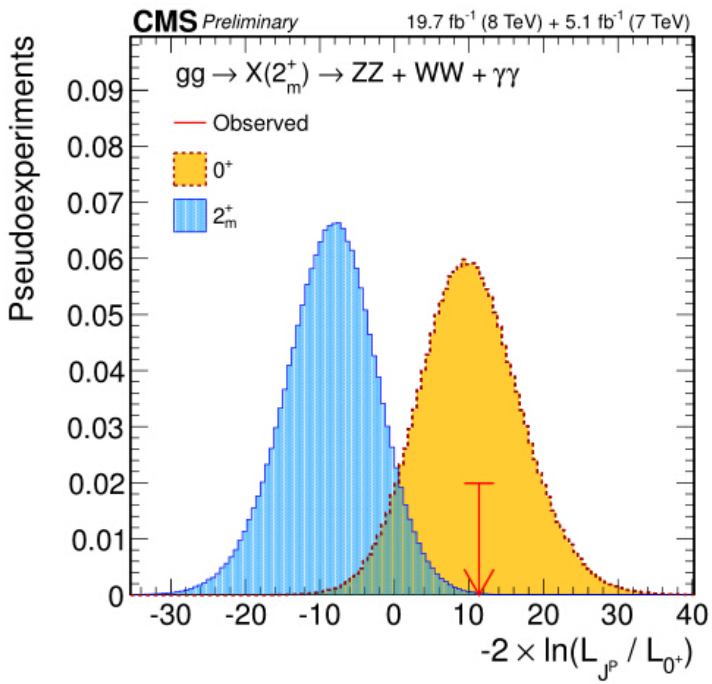


$$\sigma_{peak}^{sig} \propto \frac{g_i^2 g_f^2}{\Gamma_h}$$

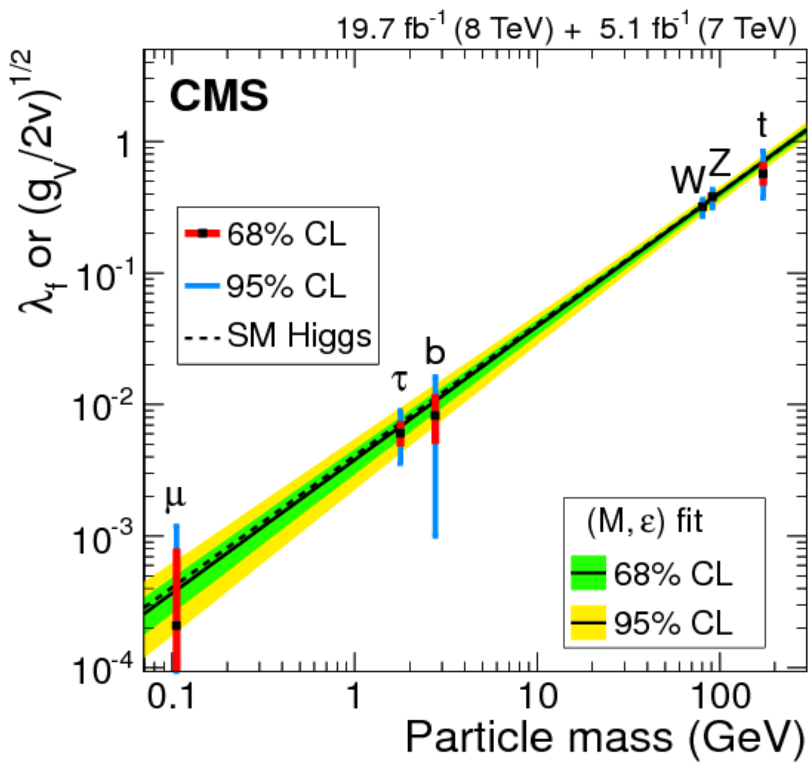
Caola, Melnikov '13

$$\sigma_{off}^{sig} \propto g_i^2 g_f^2 \qquad \sigma_{off}^{int} \propto g_i \; g_f$$

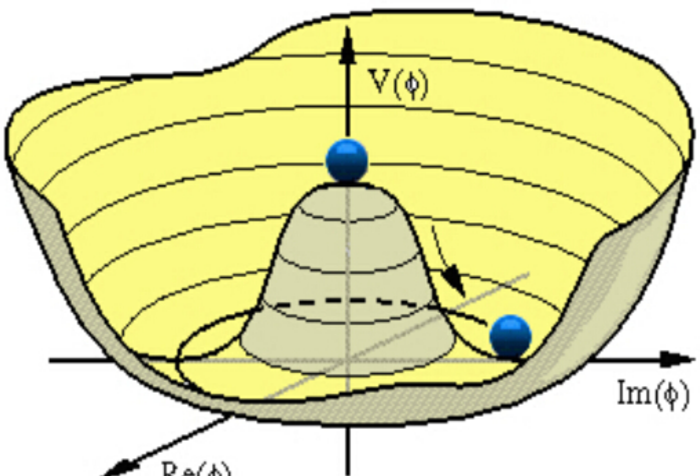
Higgs spin, CP and couplings



CP-even spin 0 hypothesis strongly preferred.
No significant deviations from SM couplings.
Data up to now are consistent with a SM Higgs boson.



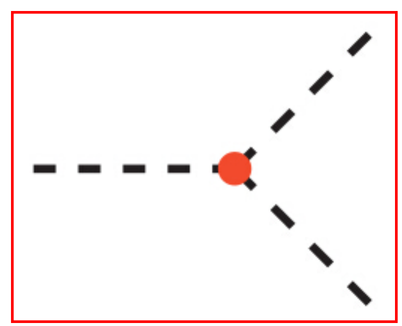
Higgs potential



$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

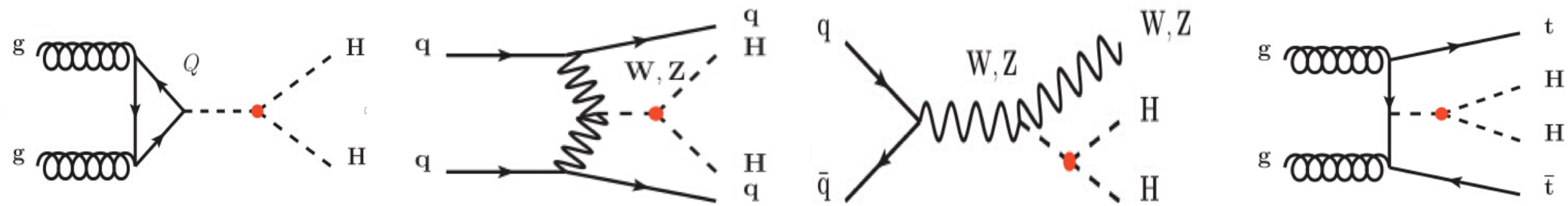
$$M_H = \sqrt{2}m = \sqrt{2\lambda}v$$

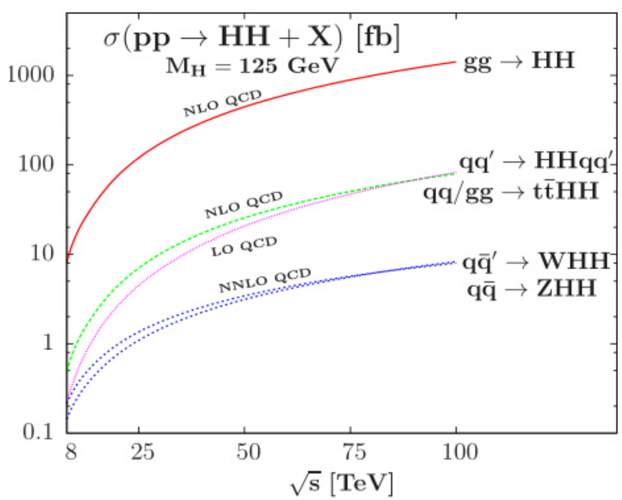
$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{\mathbf{M_H^2}}{\mathbf{v}}\mathbf{H^3} + \frac{1}{8}\frac{M_H^2}{v^2}H^4$$

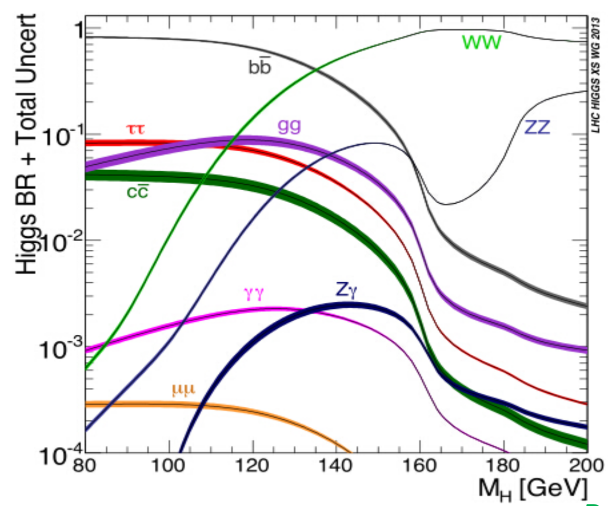


In some new physics models, the trilinear Higgs self-coupling may change by O(100)%, while the couplings with gauge bosons and fermions are still in agreement with SM.

Higgs pair productions







$b\bar{b}WW$

$b\bar{b}\gamma\gamma$

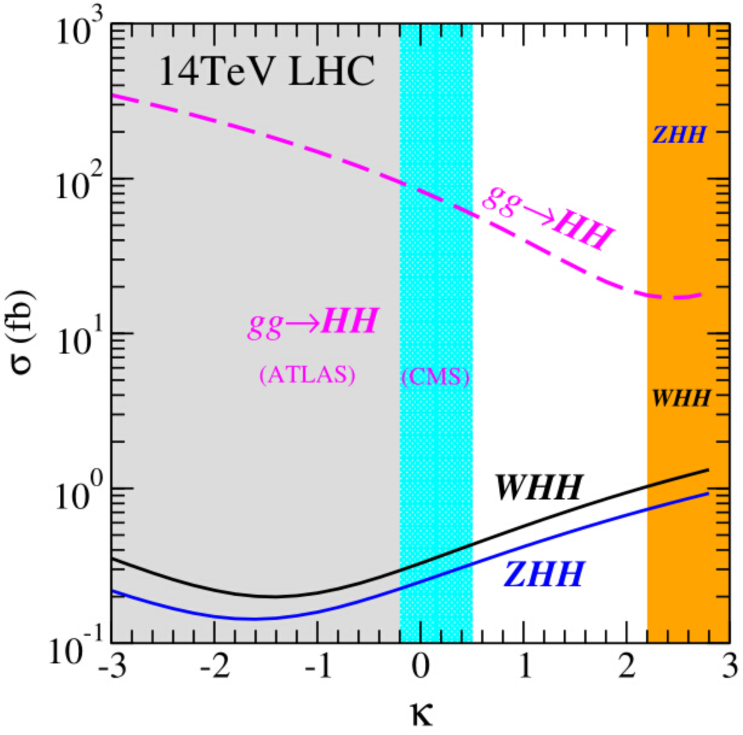
$b\bar{b}\tau\bar{\tau}$

VBF

$t\bar{t}HH$

Baur, Plehn, and Rainwater '04,
Dolan, Englert, and Spannowsky '12,
Papaefstathiou, Yang, and Zurita '13,
Liu and Zhang '14,
………

Sensitivity of different channels



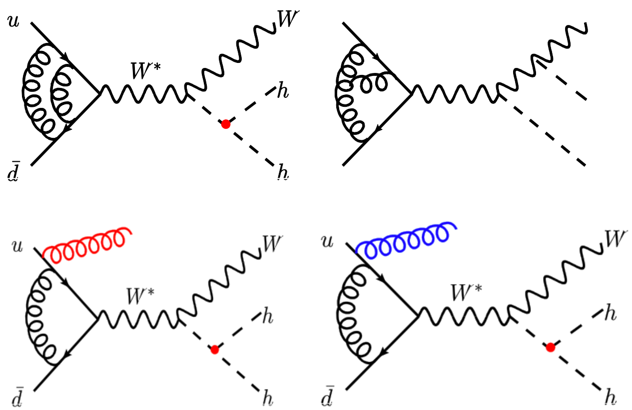
$$\sigma(W^{\pm}HH) \times \mathrm{BR}(W^{\pm} \to \ell^{\pm}\nu_{\ell}, HH \to b\bar{b}b\bar{b}) = 0.042\mathrm{fb},$$
$$\sigma(ZHH) \times \mathrm{BR}(Z \to \nu\bar{\nu}, HH \to b\bar{b}b\bar{b}) = 0.028\mathrm{fb},$$
$$\sigma(gg \to HH) \times \mathrm{BR}(HH \to \gamma\gamma b\bar{b}) = 0.053\mathrm{fb},$$

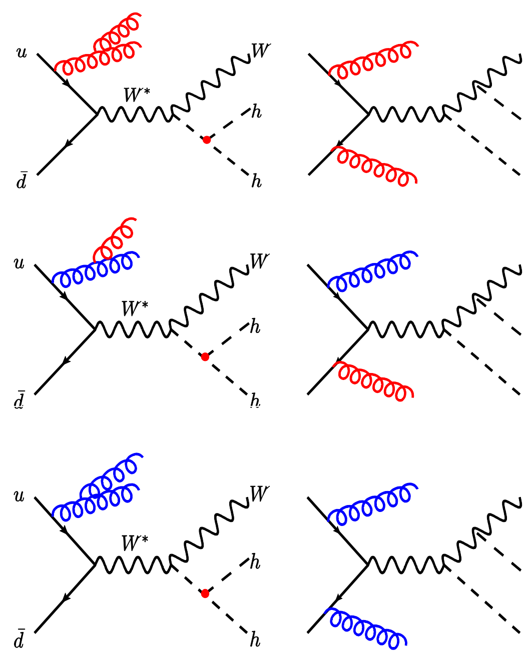
The different channels are complementary to each other and deserve discussion on the same footing.

Qing-Hong Cao, Yandong Liu, Bin Yan,arXiv:1511.03311

NNLO prediction for $pp \rightarrow Vhh$

$$\left.\frac{d\sigma_3}{d\Phi_3 dy}\right|_{\text{NNLO}} = \underbrace{\int_0^{q_T^{\text{cut}}} dq_T \frac{d\sigma_3}{d\Phi_3 dy dq_T}}_{\text{SCET}} + \underbrace{\int_{q_T^{\text{cut}}}^{q_T^{\text{max}}} dq_T \frac{d\sigma_{3+j}}{d\Phi_3 dy dq_T}}_{\text{NLO calculations}}$$





The others with $q_T > q_T^{cut}$

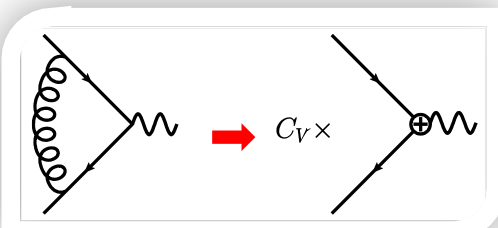
Black: virtual
Red: soft
Blue: collinear

NNLO prediction for $pp \to Vhh$

$$\left.\frac{d\sigma_3}{d\Phi_3 dy}\right|_{\rm NNLO} = \underbrace{\int_0^{q_T^{\rm cut}} dq_T \frac{d\sigma_3}{d\Phi_3 dy dq_T}}_{\rm SCET} + \underbrace{\int_{q_T^{\rm cut}}^{q_T^{\rm max}} dq_T \frac{d\sigma_{3+j}}{d\Phi_3 dy dq_T}}_{\text{NLO calculations}}$$

$$\frac{d\sigma}{dq_T^2 dy} = \frac{1}{2s}\sum_{i,j=q\bar{q}g}\int_{\zeta_1}^1 \frac{dz_1}{z_1}\int_{\zeta_2}^1 \frac{dz_2}{z_2}\int d\Phi_3 H_{q\bar{q}}(M,\mu) f_{i/N_1}(\zeta_1/z_1,\mu) f_{j/N_2}(\zeta_1/z_2,\mu) C_{q\bar{q}\leftarrow ij}(z_1,z_2,q_T,M,\mu) + \mathcal{O}\left(\frac{q_T^2}{M^2}\right)$$

Becher, Neubert, Wilhelm, \`11



Becher, Neubert, Xu, \`07

NNLO:

$$C_F\left(\frac{\alpha_s}{4\pi}\right)^2 \left[C_F H_F + C_A H_A + T_F n_f H_f\right]$$

$$H_F = \frac{L^4}{2} - 3L^3 + \left(\frac{25}{2} - \frac{\pi^2}{6}\right)L^2 + \left(-\frac{45}{2} - \frac{3\pi^2}{2} + 24\zeta_3\right)L + \frac{255}{8} + \frac{7\pi^2}{2} - \frac{83\pi^4}{360}$$

$$H_A = \frac{11}{9}L^3 + \left(-\frac{233}{18} + \frac{\pi^2}{3}\right)L^2 + \left(\frac{2545}{54} + \frac{11\pi^2}{9} - 26\zeta_3\right)L - \frac{51157}{648} - \frac{337\pi^2}{108} + \frac{11\pi^4}{45} + \frac{313}{9}\zeta_3,$$

$$H_f = -\frac{4}{9}L^3 + \frac{38}{9}L^2 + \left(-\frac{418}{27} - \frac{4\pi^2}{9}\right)L + \frac{4085}{162} + \frac{23\pi^2}{27} + \frac{4}{9}\zeta_3,$$

$$\frac{d}{d\ln\mu}C_V(-M^2,\mu) = \left[\Gamma_{\rm cusp}^F(\alpha_s)\ln\frac{-M^2}{\mu^2} + 2\gamma^q(\alpha_s)\right]C_V(-M^2,\mu)$$

$$C_V(-M^2,\mu) = 1 + \frac{C_F\alpha_s(\mu)}{4\pi}\left(-L^2 + 3L - 8 + \frac{\pi^2}{6}\right)$$

NNLO prediction for $pp \to Vhh$

$$\frac{d\sigma_3}{d\Phi_3 dy}\bigg|_{\text{NNLO}} = \underbrace{\int_0^{q_T^{\text{cut}}} dq_T \frac{d\sigma_3}{d\Phi_3 dy dq_T}}_{\text{SCET}} + \underbrace{\int_{q_T^{\text{cut}}}^{q_T^{\max}} dq_T \frac{d\sigma_{3+j}}{d\Phi_3 dy dq_T}}_{\text{NLO calculations}}$$

$$\frac{d\sigma}{dq_T^2 dy} = \frac{1}{2s} \sum_{i,j=q\bar{q}g} \int_{\zeta_1}^1 \frac{dz_1}{z_1} \int_{\zeta_2}^1 \frac{dz_2}{z_2} \int d\Phi_3 H_{q\bar{q}}(M,\mu) f_{i/N_1}(\zeta_1/z_1,\mu) f_{j/N_2}(\zeta_1/z_2,\mu) C_{q\bar{q}\leftarrow ij}(z_1,z_2,q_T,M,\mu) + \mathcal{O}\left(\frac{q_T^2}{M^2}\right)$$

Parton Distribution Function

$$C_{q\bar{q}\to Whh}(z_1,z_2,q_T,M,\mu) = \frac{1}{4\pi}\int d^2x_\perp e^{-ix_\perp\cdot q_\perp} \left(\frac{x_T^2 M^2}{b_0^2}\right)^{F_{q\bar{q}}(x_T^2,\mu)} I_{q\leftarrow i}(z_1,L_\perp,\alpha_s) I_{\bar{q}\leftarrow j}(z_1,L_\perp,\alpha_s)$$

$$B_{i/N}(\xi,x_T^2,\mu) = \sum_j \int_\xi^1 \frac{dz}{z} I_{i\leftarrow j}(z,x_T^2,\mu)\,\phi_{j/N}(\xi/z,\mu) + \mathcal{O}(\Lambda_{\text{QCD}}^2\, x_T^2)$$

NNLO: Gehrmann, Luebbert and Yang, Phys.Rev.Lett.109.242003; JHEP, 06(2014)155

NNLO prediction for $pp \to Vhh$

$$\frac{d\sigma_3}{d\Phi_3 dy}\bigg|_{\rm NNLO} = \underbrace{\int_0^{q_T^{\rm cut}} dq_T \frac{d\sigma_3}{d\Phi_3 dy dq_T}}_{\rm SCET} + \underbrace{\int_{q_T^{\rm cut}}^{q_T^{\rm max}} dq_T \frac{d\sigma_{3+j}}{d\Phi_3 dy dq_T}}_{\rm NLO\ calculations}$$

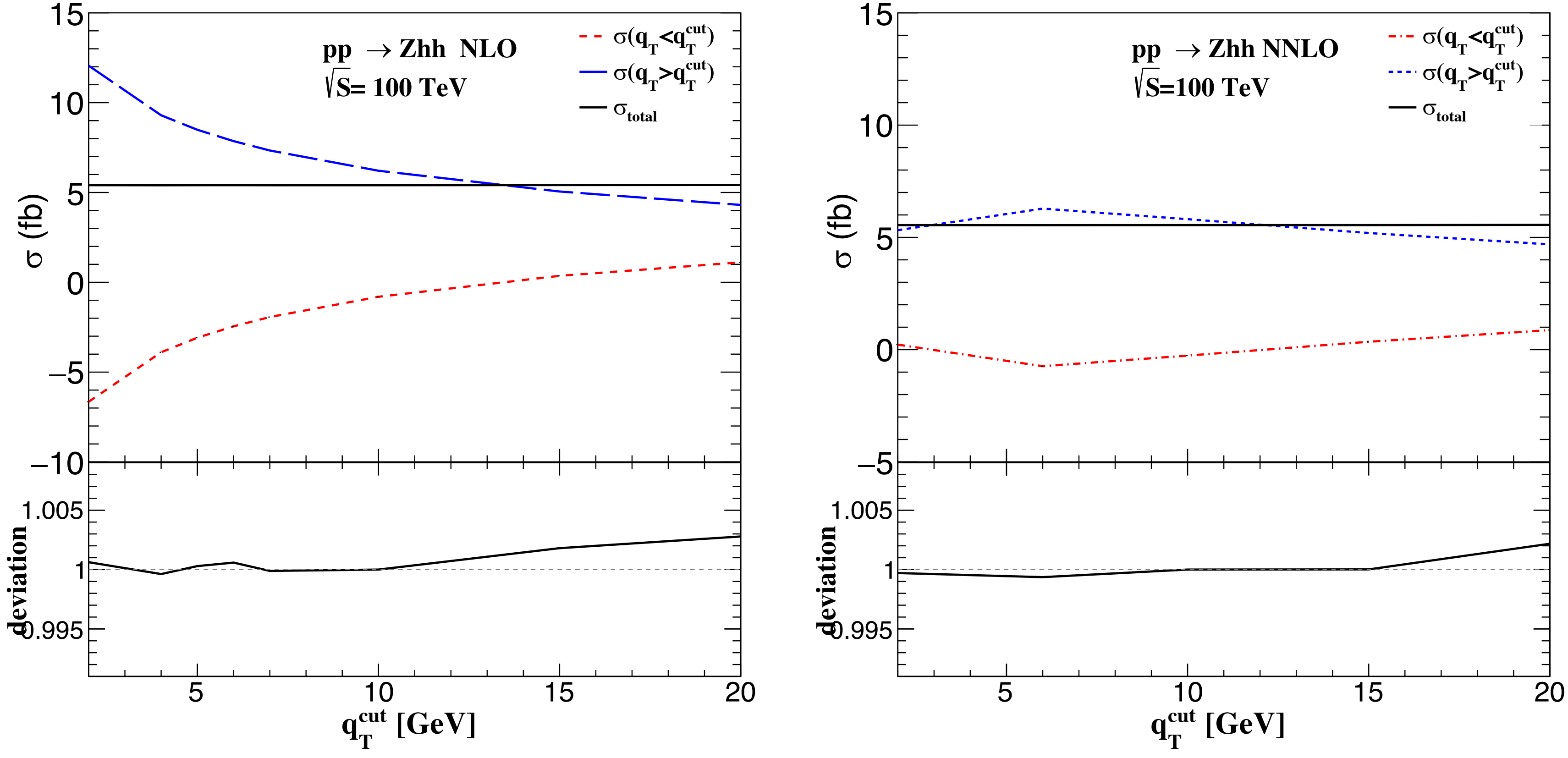
$$\frac{d\sigma}{dq_T^2 dy} = \frac{1}{2s} \sum_{i,j=q\bar{q}g} \int_{\zeta_1}^1 \frac{dz_1}{z_1} \int_{\zeta_2}^1 \frac{dz_2}{z_2} \int d\Phi_3 H_{q\bar{q}}(M,\mu)$$
$$f_{i/N_1}(\zeta_1/z_1,\mu) f_{j/N_2}(\zeta_1/z_2,\mu) C_{q\bar{q}\leftarrow ij}(z_1,z_2,q_T,M,\mu)$$

$$C_{q\bar{q}\to Whh}(z_1,z_2,q_T,M,\mu) = \frac{1}{4\pi}\int d^2x_\perp e^{-ix_\perp\cdot q_\perp}\left(\frac{x_T^2 M^2}{b_0^2}\right)^{F_{q\bar{q}}(x_T^2,\mu)} I_{q\leftarrow i}(z_1,L_\perp,\alpha_s) I_{\bar{q}\leftarrow j}(z_1,L_\perp,\alpha_s),$$

MadGraph5_aMC@NLO

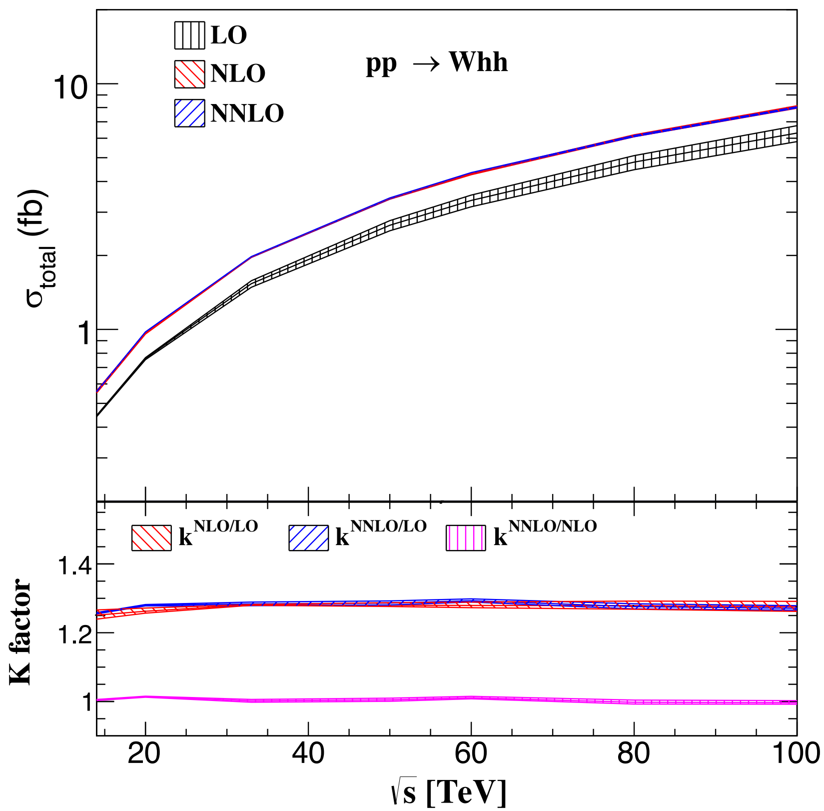
No jet algorithm

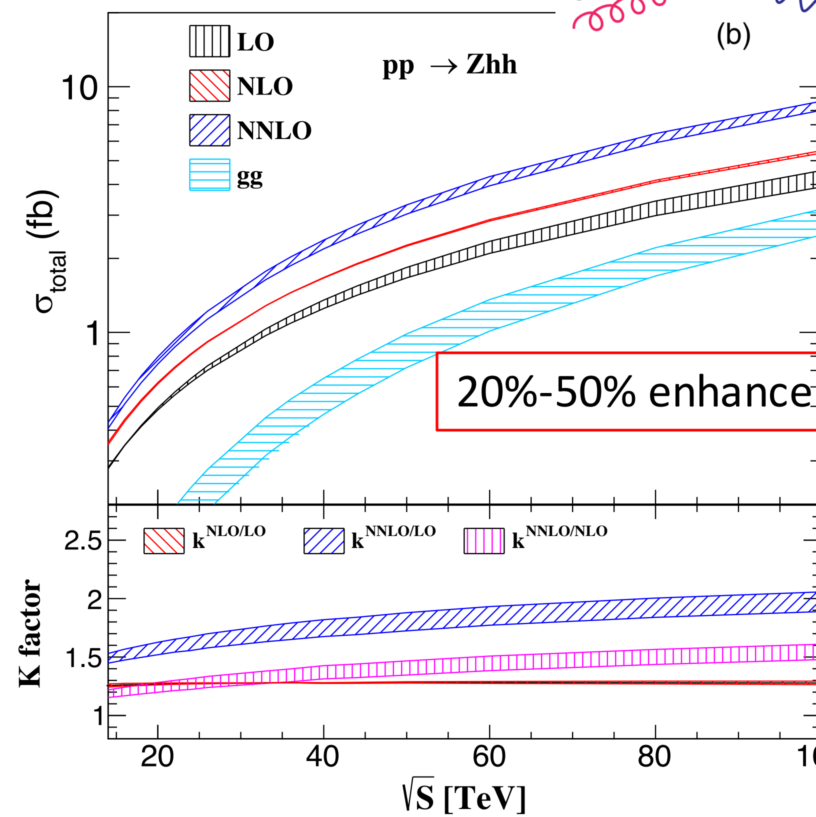
Check cutoff independence

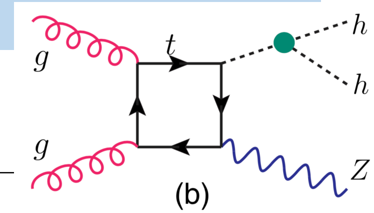


Monte Carlo integration uncertainty: <0.2%; Power correction ~0.04%

Total cross sections



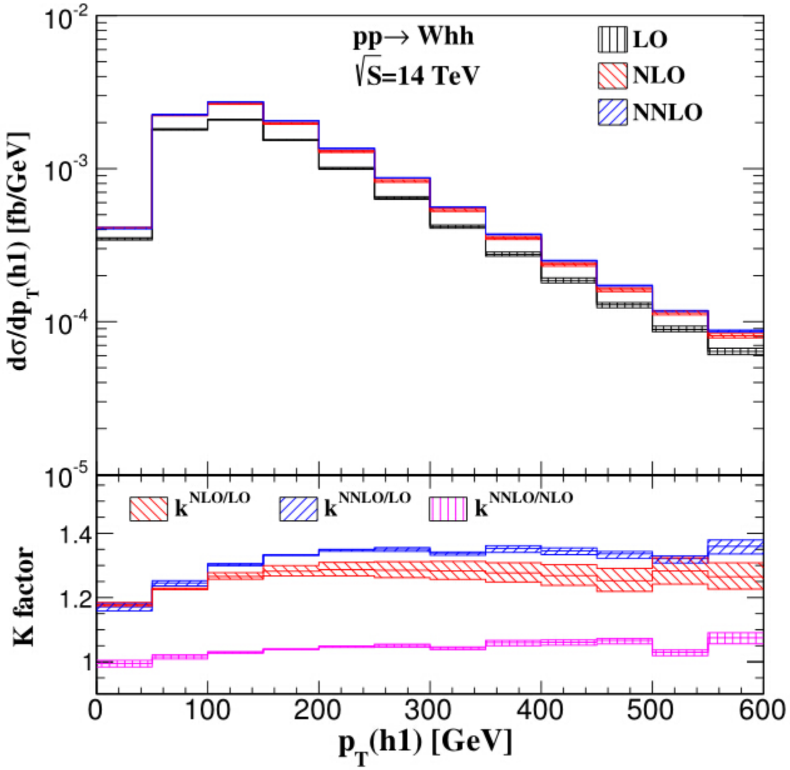


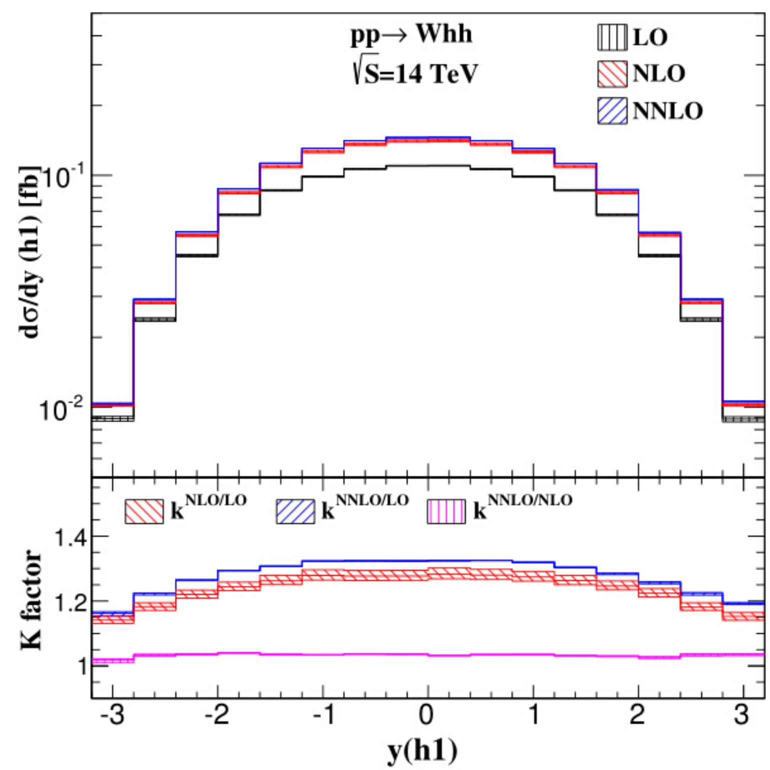


20%-50% enhancement

Agree with previous total xs in JHEP04(2013)151

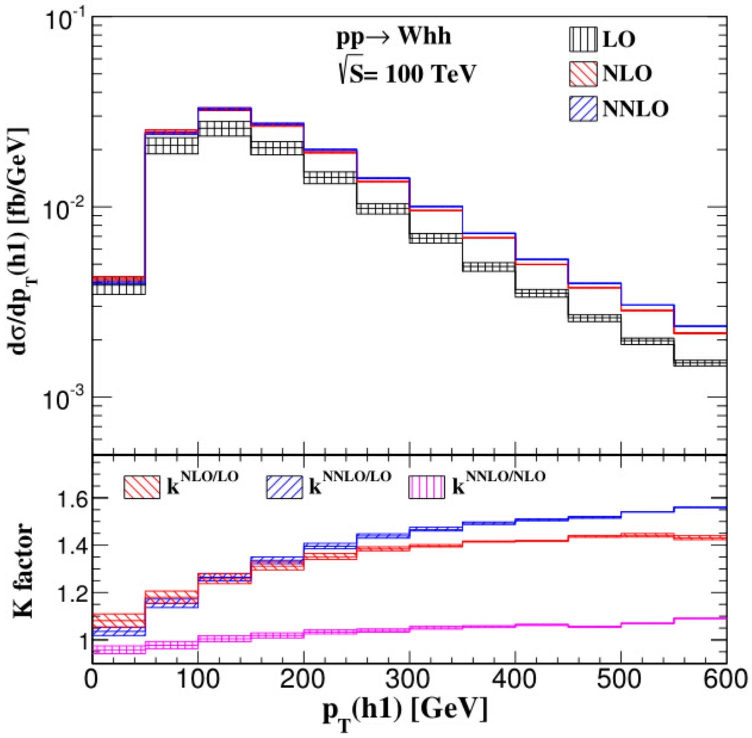
Kinematic distributions (Whh)

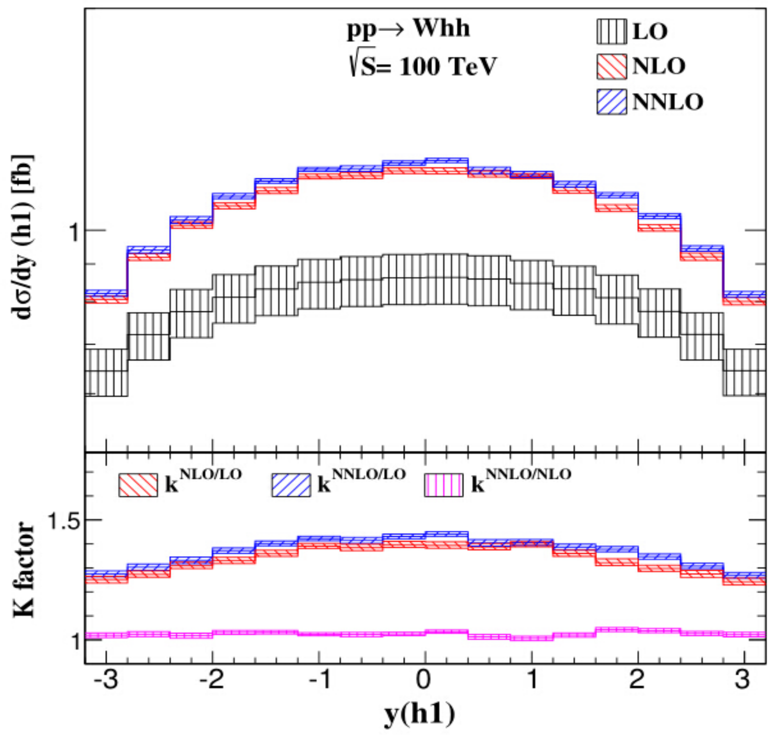




NNLO vs. NLO: Shapes almost unchanged, but scale uncertainties reduced

Kinematic distributions (Whh)





NNLO effects are more significant in the larger pT regions

Cross sections after cuts (Whh)

$\sigma\ [fb]$	boosted region	jet veto
LO	$0.271^{+3.0\%}_{-3.5\%}$	$6.30^{+7.1\%}_{-7.7\%}$
NLO	$0.360^{+0.5\%}_{-0.1\%}$	$3.76^{+6.3\%}_{-5.7\%}$
NNLO	$0.382^{+0.7\%}_{-0.5\%}$	$3.04^{+2.7\%}_{-2.2\%}$
$K^{\mathrm{NLO/LO}}$	1.33	0.60
$K^{\mathrm{NNLO/LO}}$	1.41	0.48
$K^{\mathrm{NNLO/NLO}}$	1.06	0.81

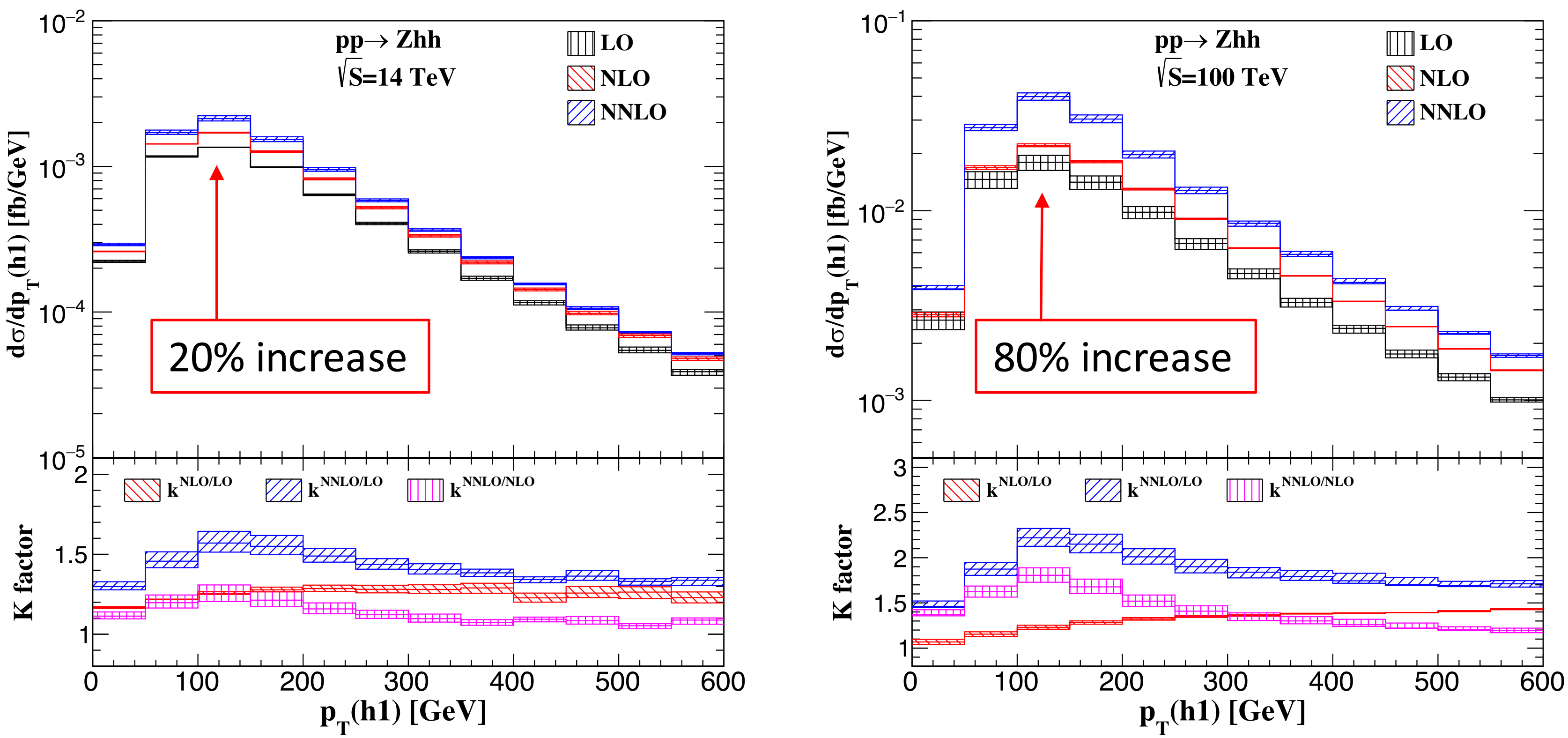
Boosted region:

$p_T(W) > 200$ GeV, $|y(W)| < 2.4$,
$p_T(h) > 200$ GeV, $|y(h)| < 2.4$

Jet veto:

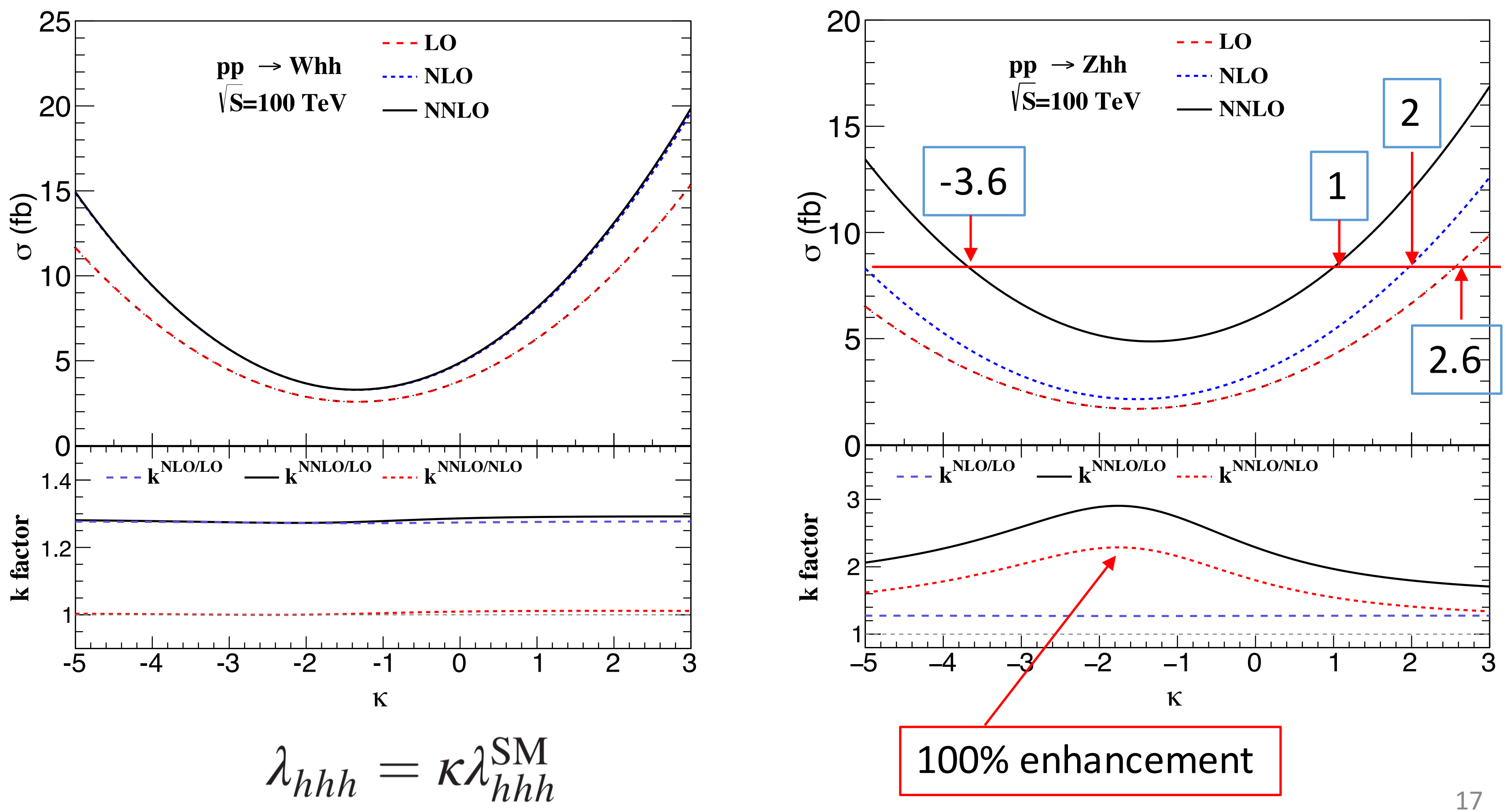
$p_T(\mathrm{jet}) > 30$ GeV
$|\eta(\mathrm{jet})| < 3.5$
$R = 0.7$

Kinematic distributions (Zhh)



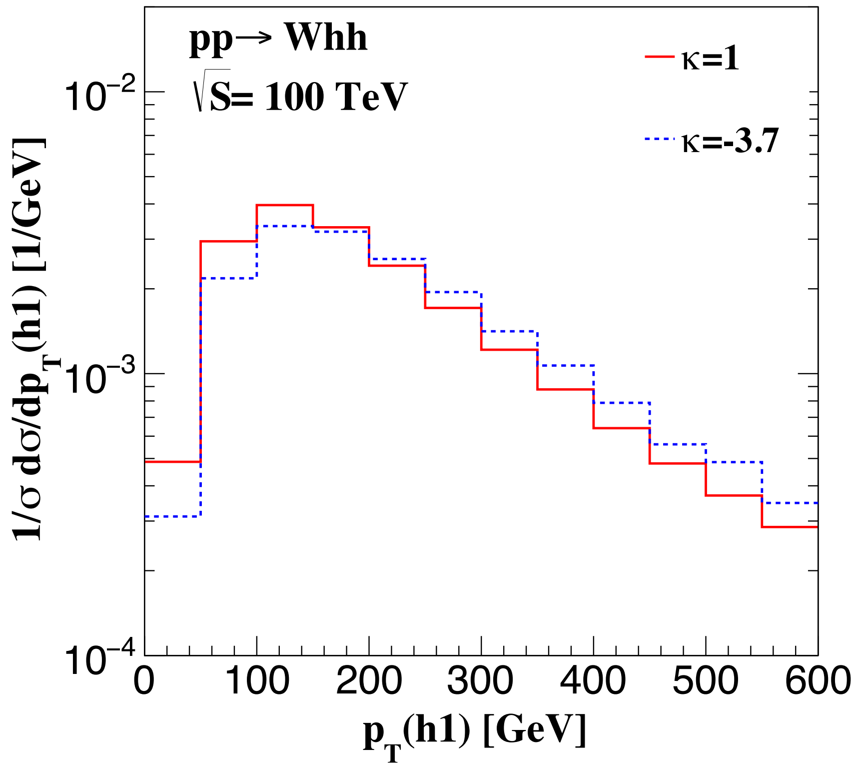
Shapes are changed

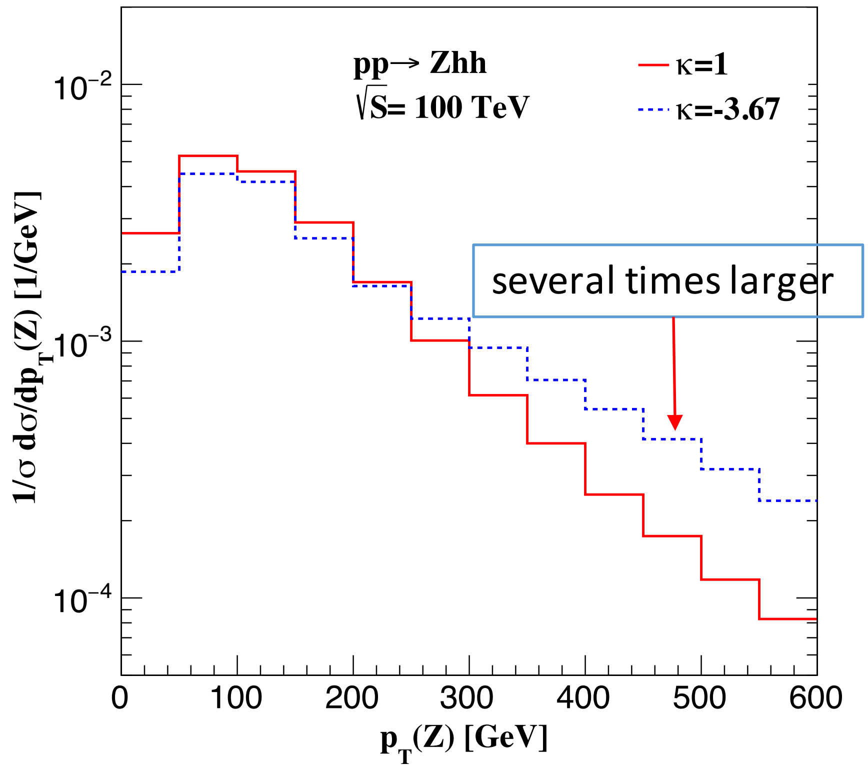
Dependence on the self-coupling



$$\lambda_{hhh} = \kappa \lambda_{hhh}^{\rm SM}$$

Break the degeneracy

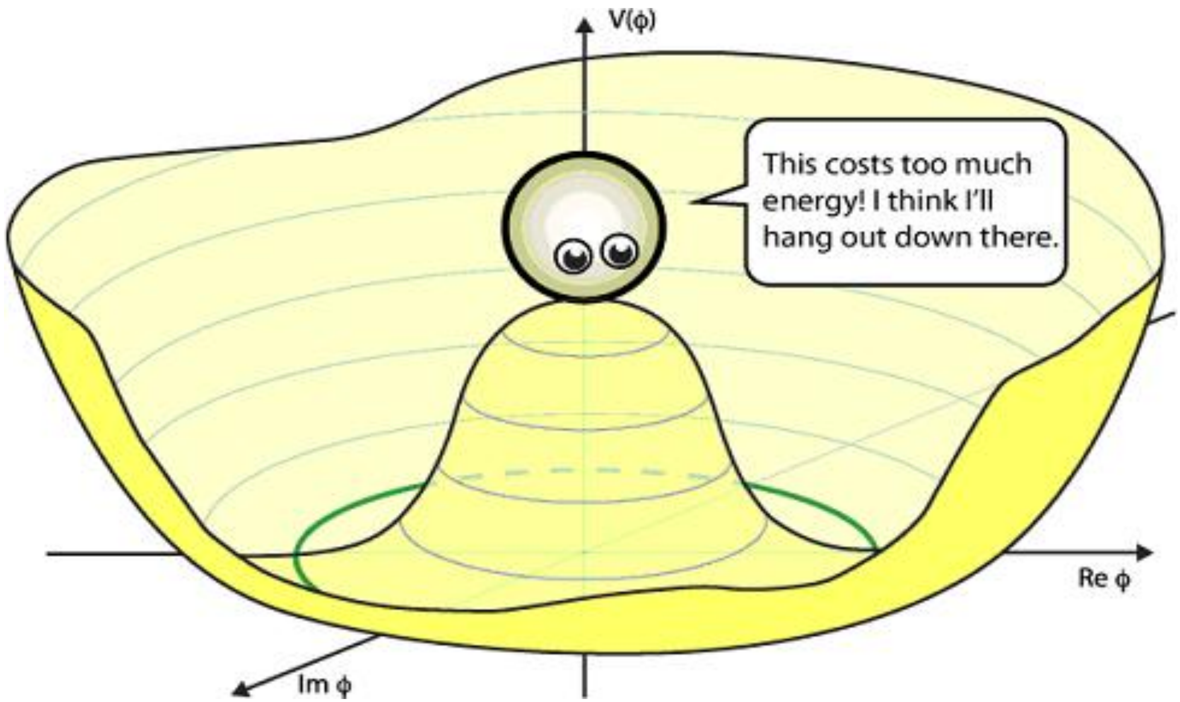




Conclusions

- We present the QCD NNLO prediction on the total cross section and kinematic distributions of Vhh productions based on q_T subtraction.
- For Whh production, the NNLO effects reduce the scale uncertainties significantly, and are sizable for jet-vetoed cross section.
- For Zhh production, the NNLO effects enhance the NLO total cross sections by a factor of 1.2–1.5, and change the shape of NLO kinematic distributions. The impact on the extraction of the self-coupling from experiments is significant.
- These theoretical results can be utilized in future experimental analysis.

Thank You!


V(ϕ)
This costs too much energy! I think I'll hang out down there.
Re ϕ
Im ϕ