Measuring the Higgs Trilinear and Quartic Couplings at the LHC

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Measuring the Higgs Trilinear and Quartic Higgs Couplings at the LHC

Dicus, Kao, and Willenbrock, Phys. Lett. B203 (1988).
Dawson, Kao, and Wang, Phys.Rev. D75 (2007); Phys.Rev. D77 (2008).
Dicus, Kao, and Repko, Phys. Rev. D92 (2015); Phys. Rev. D93 (2016).

- Introduction
- Higgs Pair Production: Gluon Fusion and Bottom Fusion
- The Trilinear Higgs Coupling(s)
- The Discovery Potential of Higgs Pairs at the LHC
- Associated Production of Higgs Pairs and Triple Higgs
- Conclusions

Introduction

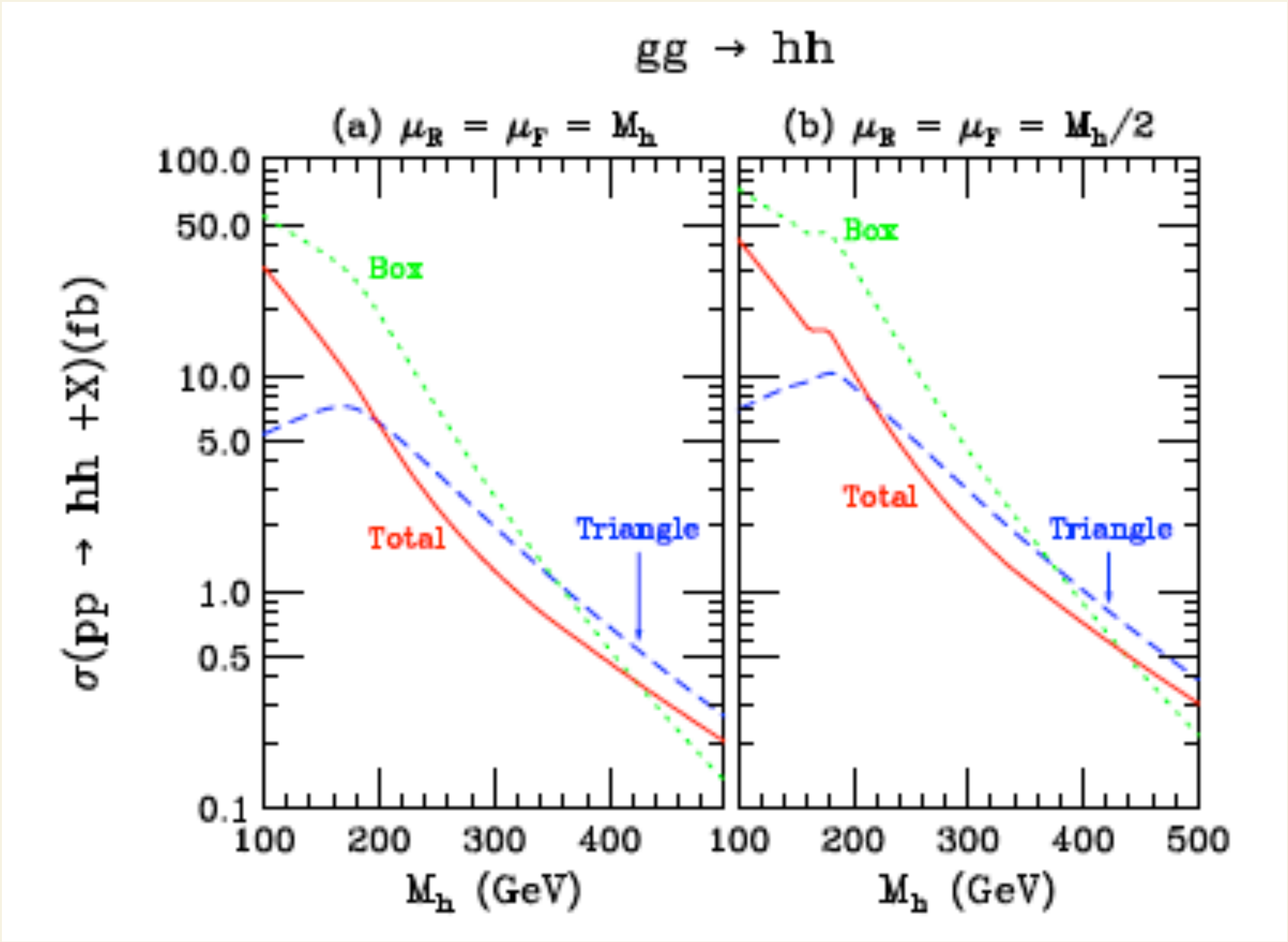
- Thus far the results from the LHC indicate that the couplings of the Higgs boson to other particles are consistent with the Standard Model.
- But the ultimate test as to whether this particle is the SM Higgs boson will be the trilinear Higgs coupling that appears in Higgs pair production.
- There are uncertainties in the factorization and renormalization scales as well as variations in the parton distribution functions.

Higgs Pairs Production from Gluon Fusion

Dicus, Kao, and Willenbrock, Phys. Lett. **B203** (1988) 457;
Glover and van der Bij, Nucl. Phys. **B309** (1988) 282.

- For a light Higgs boson with $M_H < 500$ GeV, the dominant source of Higgs boson pair production is gluon fusion through both triangle and box diagrams.
- The triangle diagram involves the Higgs self-coupling while the box diagrams don't.
- For a heavy Higgs boson with $M_H \sim 1$ TeV, vector boson fusion can become significant.

Higgs Pairs Production from Gluon Fusion



Higgs Pair Production from Gluon Fusion

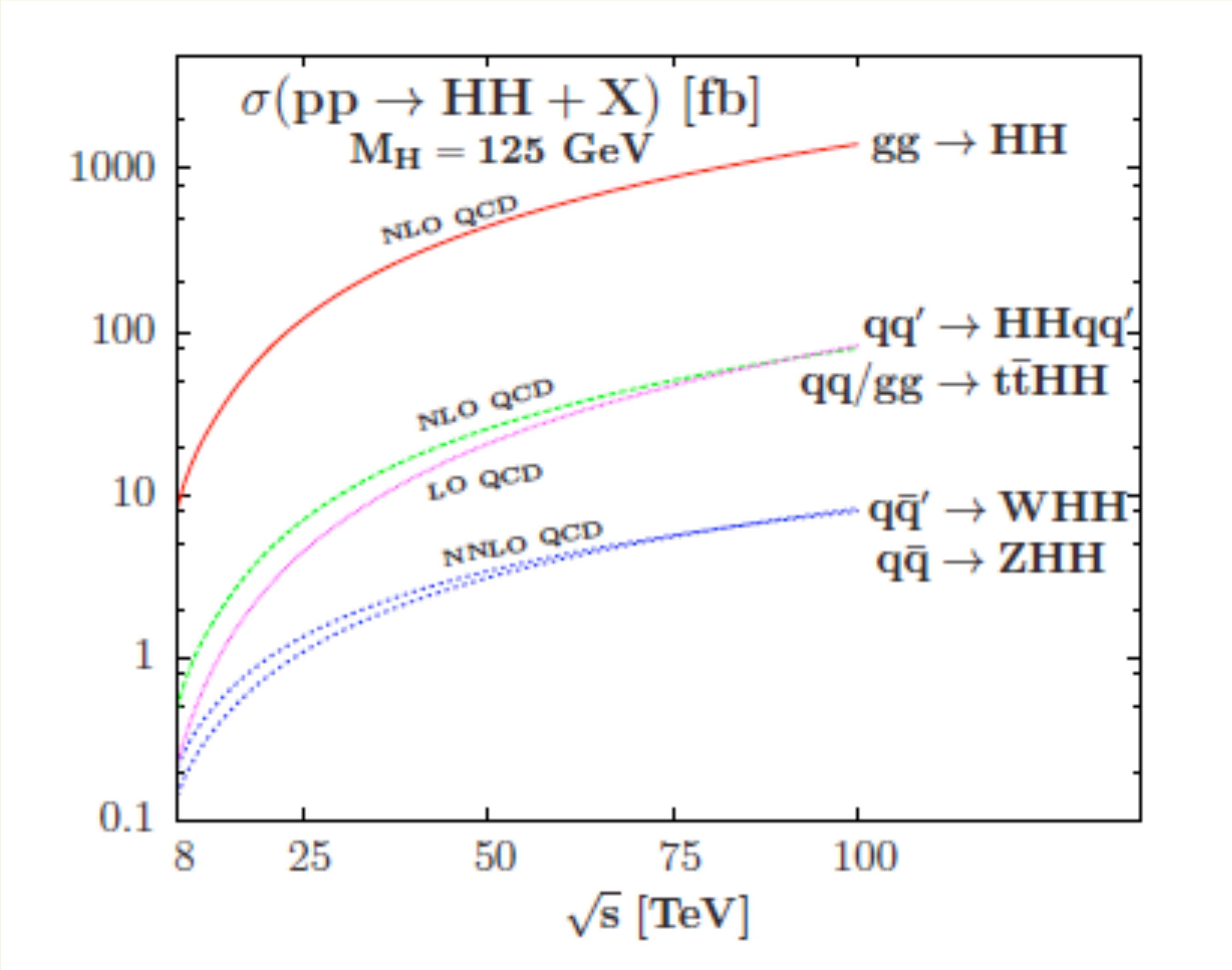
- Li and Voloshin, PRD 89, 013012 (2014); Dawson, Ismail and Low, PRD 91, no. 11, 115008 (2015).
- NLO: Plehn, Spira, and Zerwas, NPB 479 (1996) 46; NPB531 (1998) 655(E); Dawson, Dittmaier, and Spira, PRD 58 (1998) 115012; Jin, Li, Li, Liu and Oakes, PRD 71 (2005) 095004; Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, and Spira, JHEP 1304 (2013) 151; Grigo, Hoff, Melnikov and Steinhauser, NPB 875 (2013) 1.
- NNLO: de Florian and Mazzitelli, Phys. Rev. Lett. 111 (2013) 201801.
- MSSM: Belyaev, Drees, Eboli, Mizukoshi and Novaes, PRD 60 (1999) 075008; Bendezu and Kniehl, PRD 64 (2001) 035006.
- A General Potential and a Non-perturbative Higgs Model: Haba, Kaneta, Mimura and Tsedenbalji, PRD 89 (2014) no.1, 015018.

Discovery Channels of Higgs Pairs

- bbττ, bbγγ, bbWW, bbbb:
  U. Baur, T. Plehn, and D. L. Rainwater, PRD 67 (2003) 033003; PRD 69 (2004) 053004; Dib, Rosenfeld, Zerwekh, JHEP 0605 (2006) 074; Grober and Muhlleitner, JHEP 1106 (2011) 020; Dolan, Englert, Spannowsky JHEP 1210 (2012) 112; Barr, Dolan, Englert, Spannowsky PLB 728 (2014) 308; Papaefstathiou, Yang and Zurita, PRD 87 (2013) 011301; Goertz, Papaefstathiou, Yang and Zurita, JHEP 1306 (2013) 016.

Higgs Pair Production in Hadron Collisions

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira, JHEP **1304** (2013) 151.



NNLO Higgs Pair Production at Hadron Colliders

de Florian and Mazzitelli, Phys. Rev. Lett. **111** (2013) 201801.

$$\sigma_{\rm LO} = 17.8^{+5.3}_{-3.8}\ \text{fb}, \quad \sigma_{\rm NLO} = 33.2^{+5.9}_{-4.9}\ \text{fb},$$
$$\sigma_{\rm NNLO} = 40.2^{+3.2}_{-3.5}\ \text{fb}, \qquad (18)$$

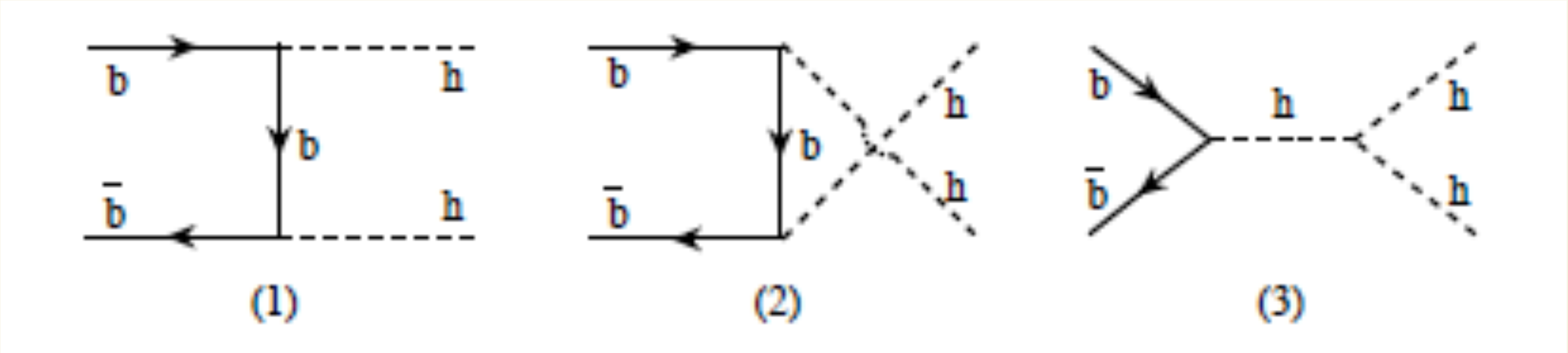
$E_{\rm c.m.}$	8 TeV	14 TeV	33 TeV	100 TeV
$\sigma_{\rm NNLO}$	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0 - 9.8$	$+8.0 - 8.7$	$+7.0 - 7.4$	$+5.9 - 5.8$
PDF [%]	$+6.0 - 6.1$	$+4.0 - 4.0$	$+2.5 - 2.6$	$+2.3 - 2.6$
PDF + α_S [%]	$+9.3 - 8.8$	$+7.2 - 7.1$	$+6.0 - 6.0$	$+5.8 - 6.0$

Higgs Pair Production via Bottom Quark Fusion

- In the Standard Model, bottom quark fusion is almost negligible for Higgs pair production.
- In two Higgs doublet models with Type II Yukawa interactions, the Hbb coupling is enhanced by a large value of tanβ. Thus for $\tan\beta > 7$, bottom quark fusion makes dominant contribution.
- The physical process is gg to bbHH.
- However, it is a good approximation to calculate bb to HH if no associate b quarks are tagged.

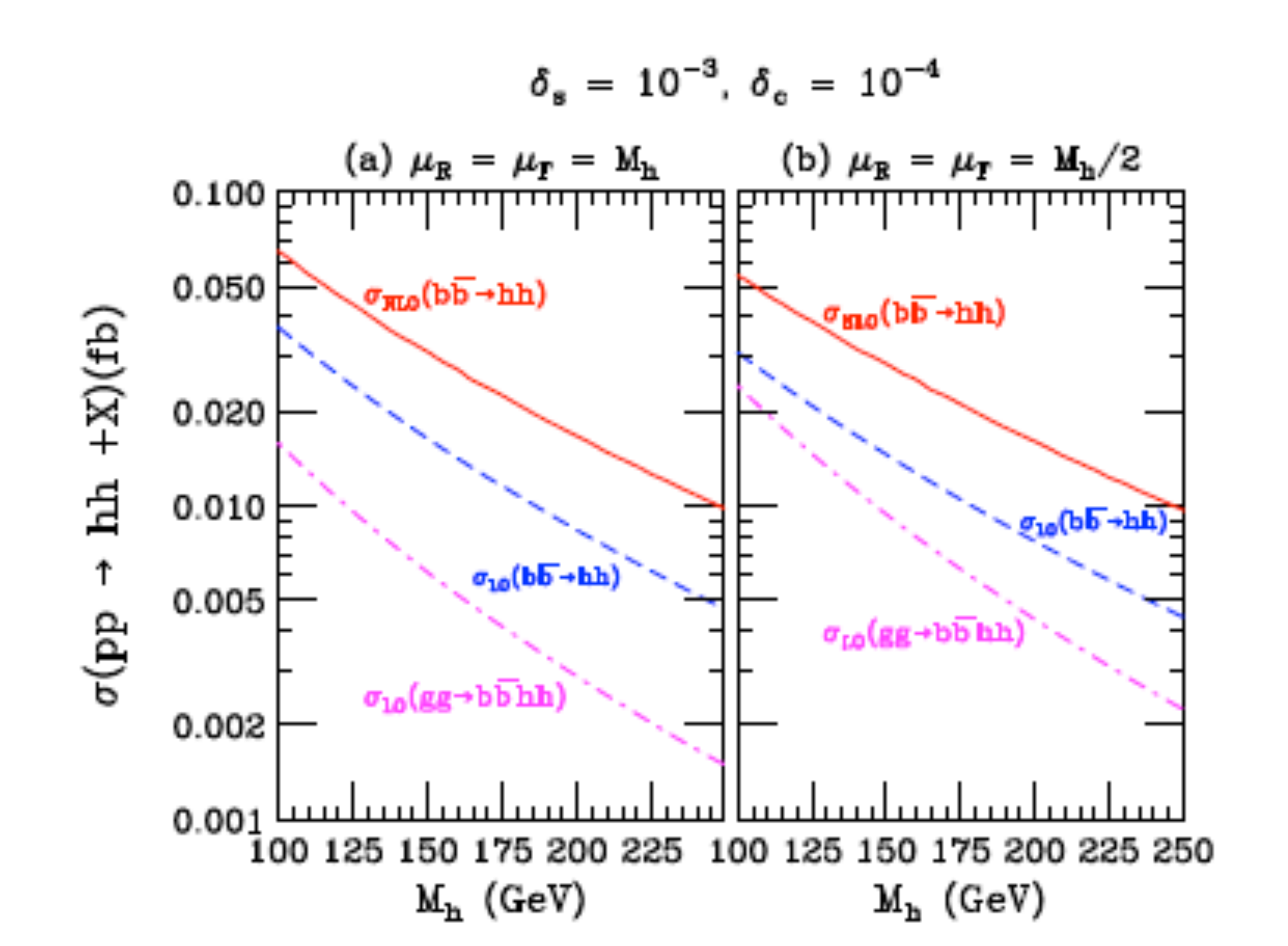
Higgs Pair Production via Bottom Quark Fusion

Dawson, Kao, Wang and Williams, Phys. Rev. D **75** (2007) 013007;
Dawson, Kao and Wang, Phys. Rev. D **77** (2008) 113005.



Higgs Pair Production via Bottom Quark Fusion

Dawson, Kao, Wang and Williams, Phys. Rev. **D75** (2007) 013007.

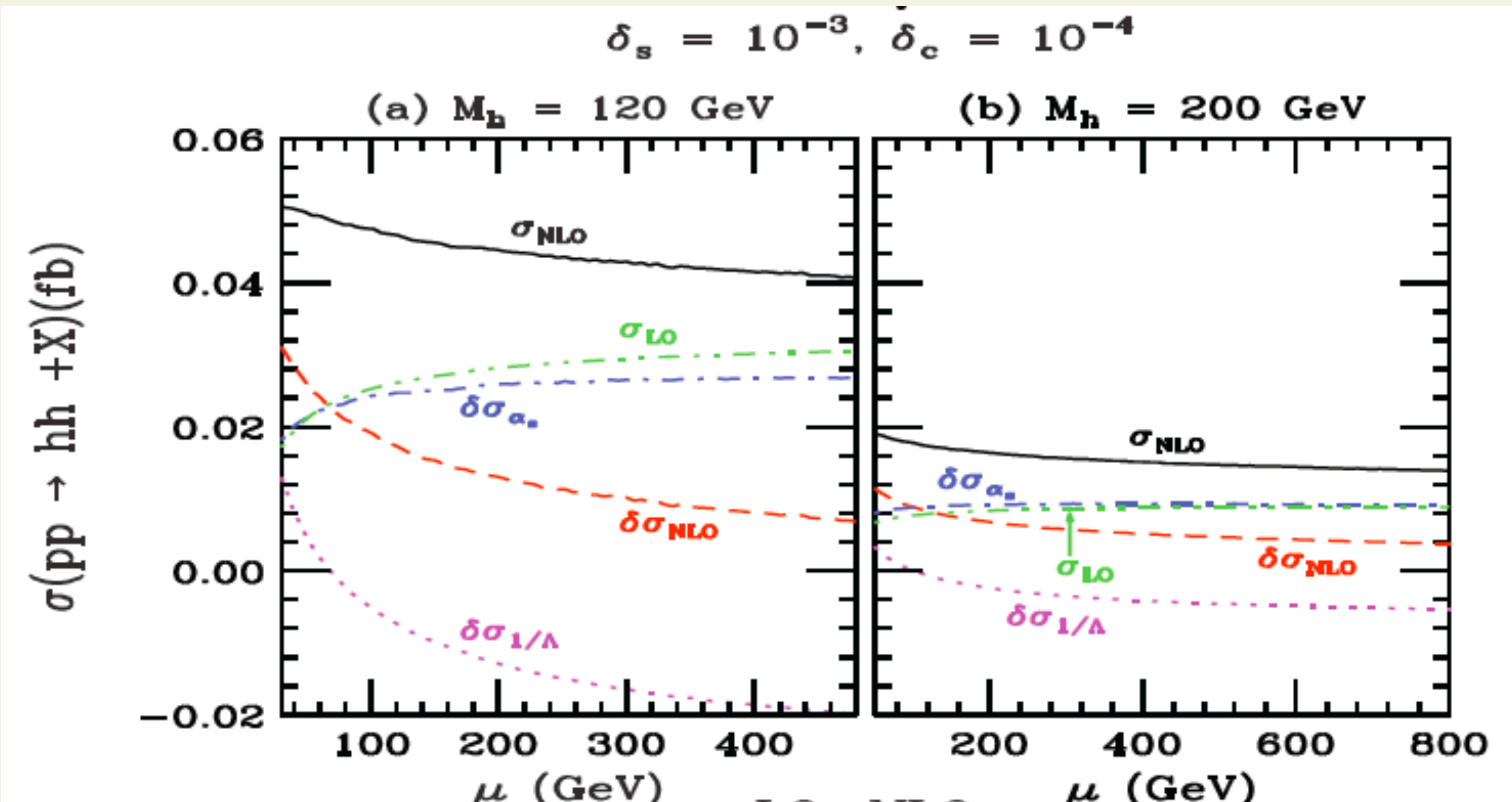


QCD CORRECTIONS TO bb → h h

Dawson, Kao, Wang and Williams, Phys. Rev. **D75** (2007) 013007.

- **Next-to-Leading Order Corrections**
- α_s **Corrections: Real Emission, bb → hhg**
- α_s **Corrections: Virtual Correction**
- **1/Λ Corrections: bg → bhh [Λ = ln (m_h/m_b)]**
- **gg → bbhh Cross Section ($1/\Lambda^2$)**

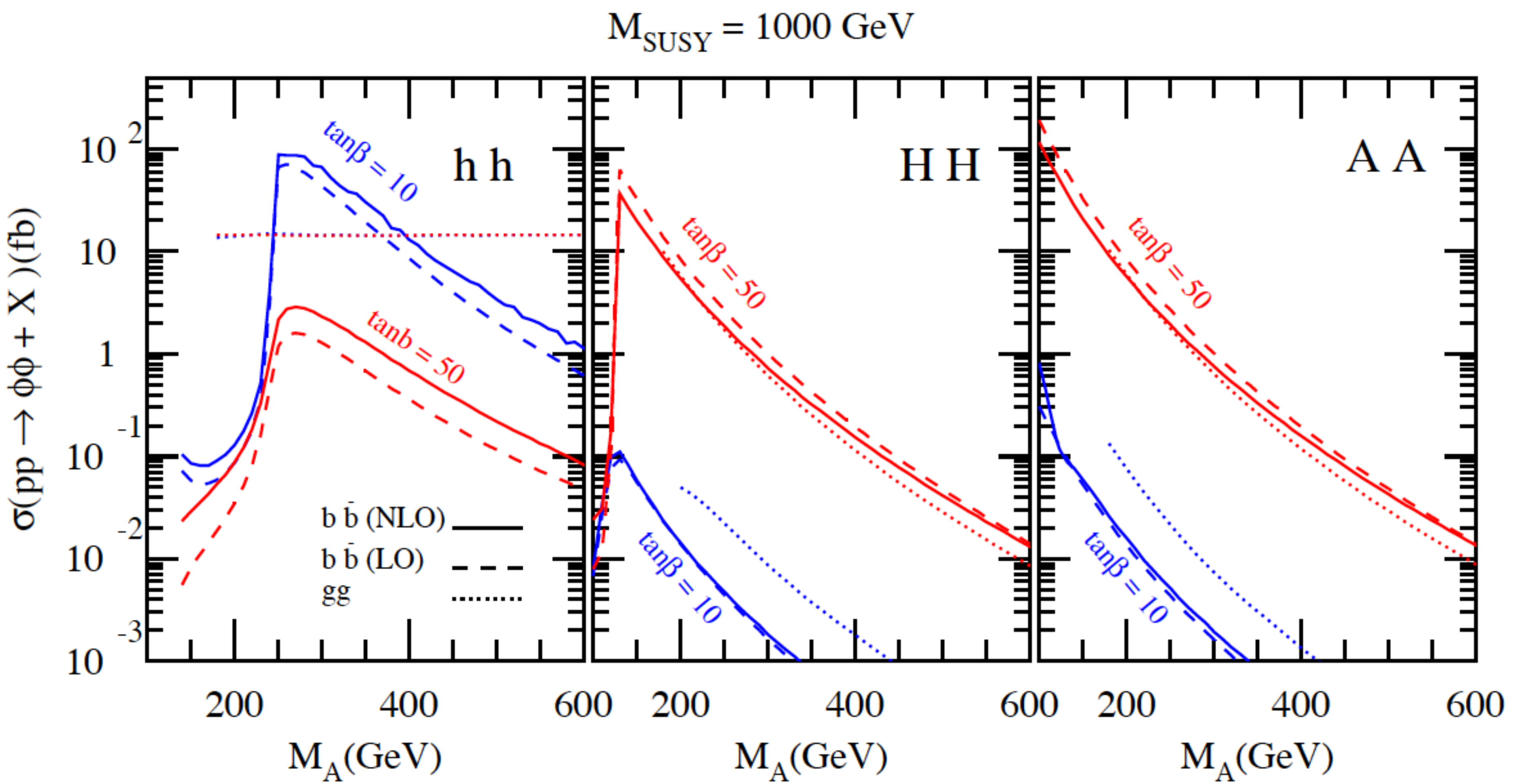
NLO Corrections to bb → h h



$$K = \frac{\mathrm{LO} + \mathrm{NLO}}{\mathrm{LO}} \sim 1.5$$

NLO Corrections to bb → ϕϕ in MSSM

Dawson, Kao, and Wang, Phys.Rev. D77 (2008).



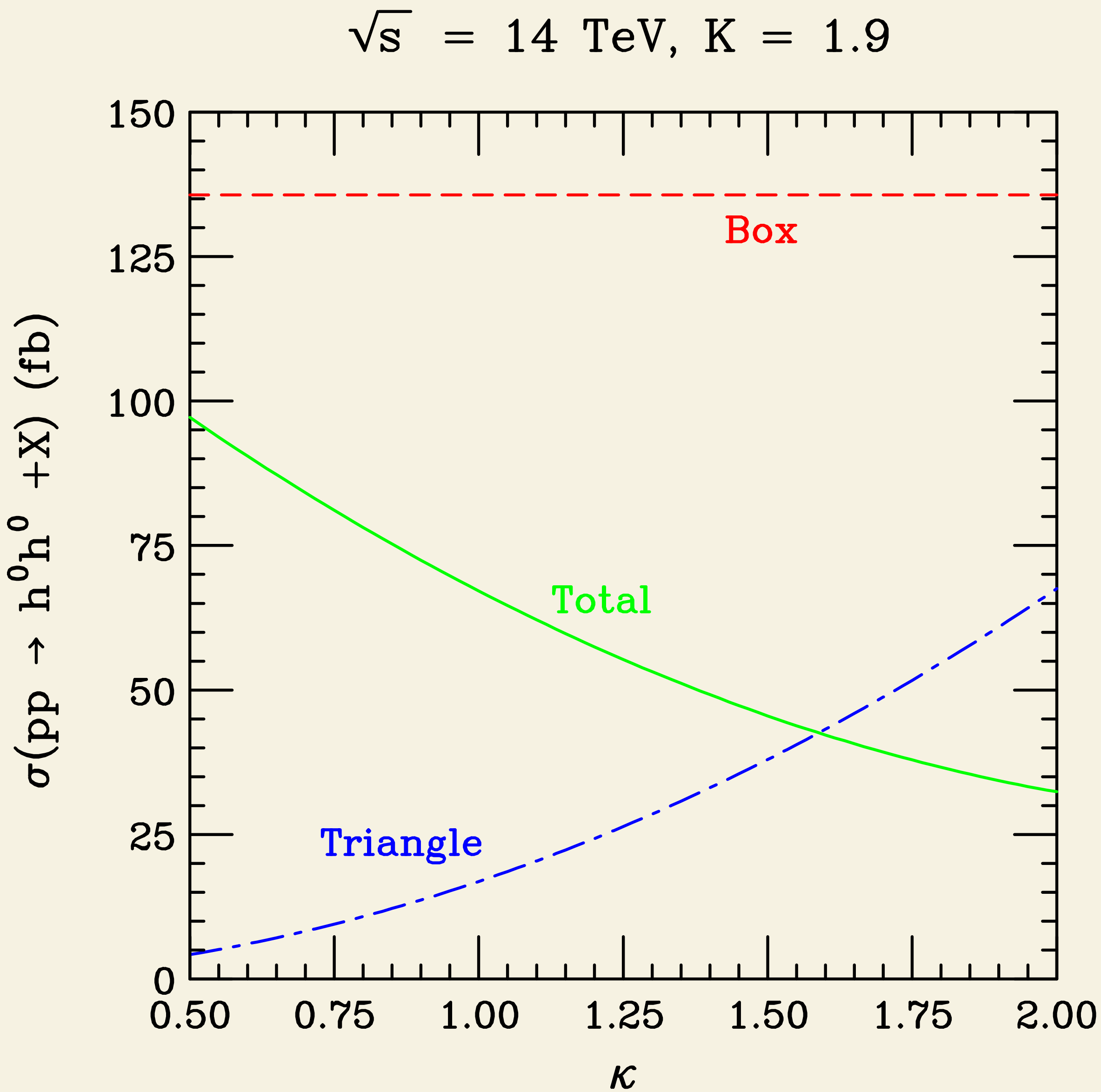
The Trilinear Higgs Coupling(s)

- Higgs pair production from gluon fusion involves ttH and HHH couplings.
- The box and triangle diagrams are separately gauge invariant so we can vary the two couplings independently by introducing parameters κ_t and κ or κ_H ,

$$t\bar{t}H \; : \quad -\frac{m_t}{v}\, k_t$$

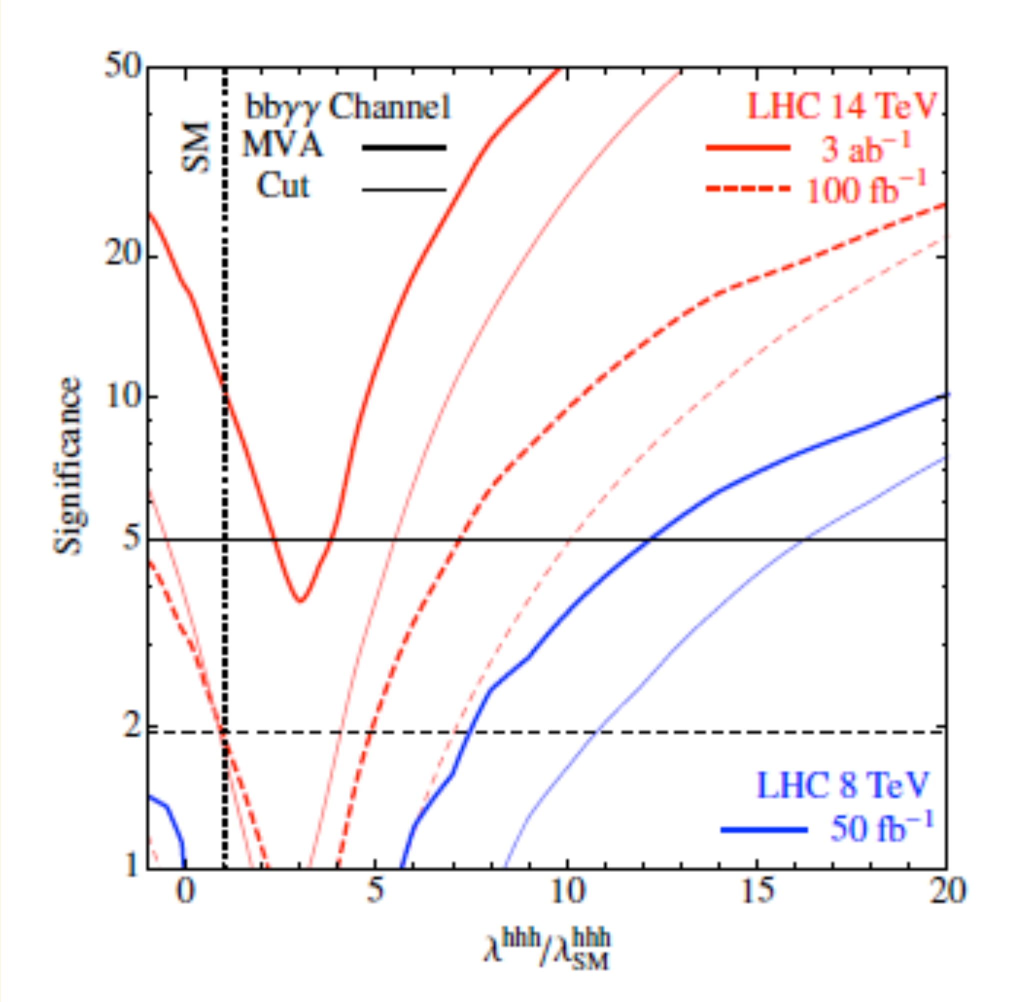
$$HHH \; : \quad -\frac{3\,M_H^2}{v}\kappa$$

Effects of kappa with κ > 0



The Discovery Potential of Higgs Pairs

Barger, Everett, Jackson, Shaughnessy, PLB 728 (2014) 433.



Conclusions

Barger, Everett, Jackson, Shaughnessy, Phys. Lett. B728 (2014) 433;
Goertz, Papaefstathiou, Yang and Zurita, JHEP 1306 (2013) 016;
de Lima, Papaefstathiou, Spannowsky, JHEP 1408 (2014) 030.

- The $bb\gamma\gamma$, $bb\tau\tau$, bbWW and bbbb final states are promising channels to measure the Higgs trilinear coupling(s) at the LHC.
- LHC data at 7–8 TeV should probe large deviations of λ_{hhh} from the SM ($\kappa_h > 7.5$ at 95% C.L.).
- At the LHC with a CM energy of 14 TeV and an integrated luminosity of 3 ab^{-1}, ATLAS and CMS will be able to measure λ_{hhh} within 20%–40% uncertainty.

Interference in Higgs Pair Production

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

$$\lambda = \frac{m_H^2}{2v^2}$$

$$\sigma_{TOT} = \sigma_T + \sigma_B = 2\cos(\alpha_I)\sqrt{\sigma_T \sigma_B}$$

pp to HH +X

$\sqrt{s}$ (TeV)	$\sigma_B(fb)$	$\sigma_T(fb)$	$\sigma_{TOT}(fb)$	$\cos(\alpha_I)$
8	9.06	1.34	4.11	-0.902
12	26.0	3.62	12.2	-0.899
13	31.6	4.36	14.9	-0.898
14	37.8	5.16	17.9	-0.898
33	243.	30.3	120.	-0.893
60	760.	89.8	383.	-0.893
100	1900.	212.	965.	-0.904

ud to ud HH

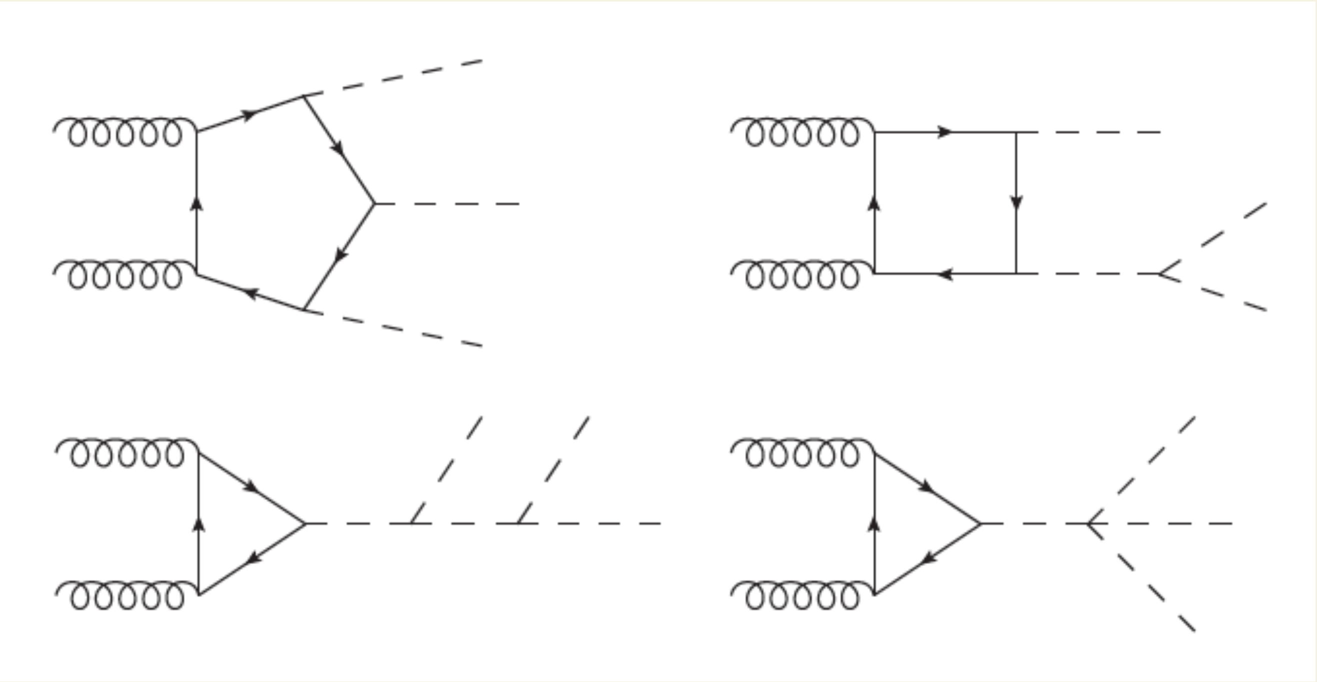
$\sqrt{s}$ (TeV)	σ_B	σ_T	σ_{TOT}	$\cos(\alpha_I)$
8	0.404	0.128	0.141	-0.860
12	0.997	0.295	0.377	-0.844
13	1.18	0.344	0.452	-0.841
14	1.36	0.394	0.530	-0.836
33	6.24	1.60	2.76	-0.804
60	15.6	3.72	7.32	-0.788
100	32.2	7.36	15.8	-0.772

Associated Production with Top Pair

$\sqrt{s}$ (TeV)	σ_B	σ_T	σ_{TOT}	$\cos(\alpha_I)$
8	6.47×10^{-2}	1.96×10^{-3}	8.56×10^{-2}	0.841
12	0.178	5.47×10^{-3}	0.235	0.826
13	0.212	6.54×10^{-3}	0.280	0.825
14	0.249	7.68×10^{-3}	0.328	0.815
33	1.19	3.75×10^{-2}	1.56	0.788
60	2.98	9.51×10^{-2}	3.89	0.765
100	6.15	0.197	8.04	0.769

Production of Triple Higgs Bosons

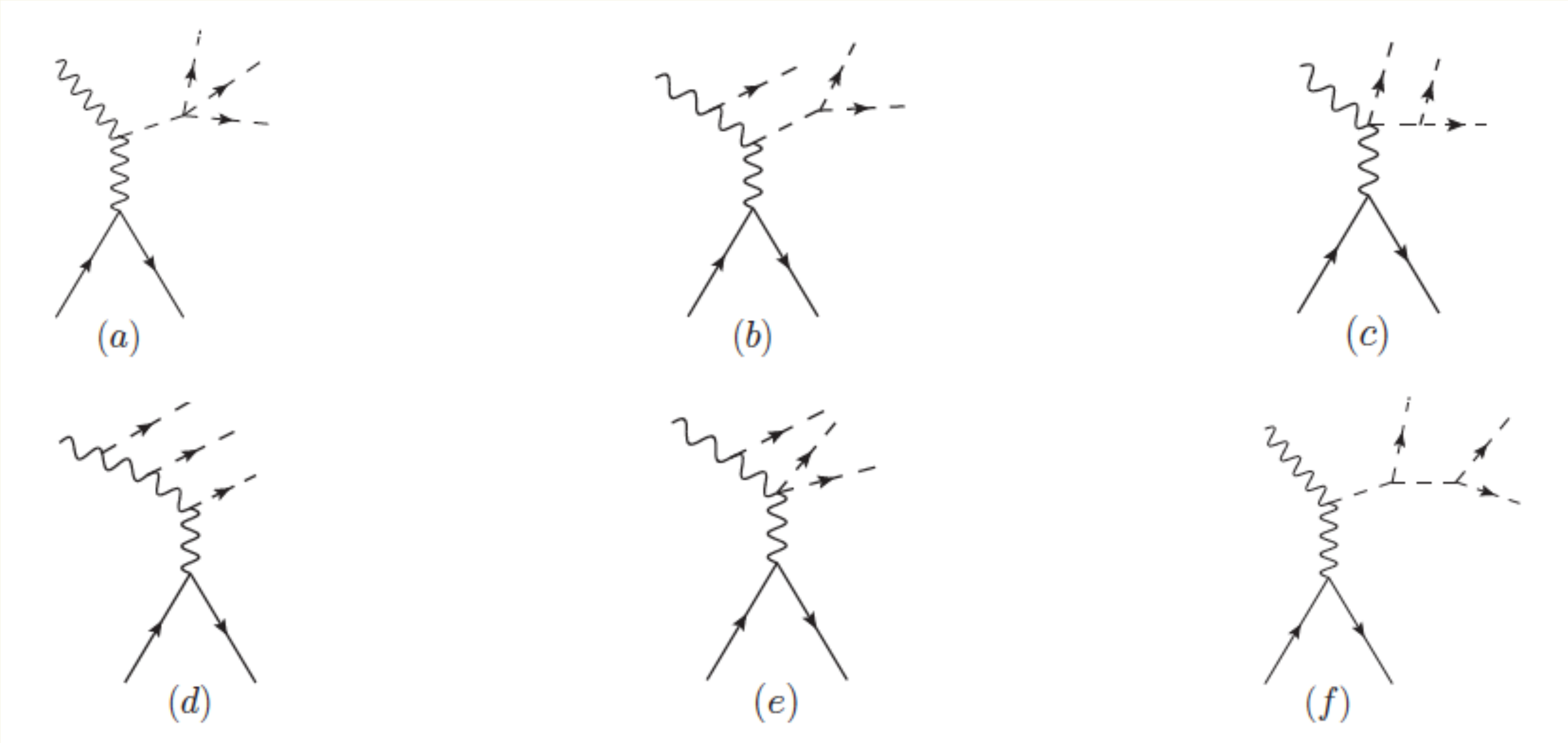
Maltoni, Vryonidou and Zaro, JHEP 1411 (2014) 079.



$\sigma(HHH)$ [fb]	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33$ TeV	$\sqrt{s} = 100$ TeV
LO FT	$0.0557\ ^{+34.5+2.5\%}_{-24.0-2.7\%}$	$0.438\ ^{+26.8+1.5\%}_{+20.0-2.0\%}$	$3.78\ ^{+24.1+0.9\%}_{-18.7-1.7\%}$
NLO $\mathrm{FT}_{\mathrm{approx}}$	$0.0894^{+16.5+2.5\%}_{-14.6-3.2\%}$	$0.677\ ^{+14.5+1.4\%}_{-13.4-1.7\%}$	$5.09\ ^{+13.5+1.0\%}_{-12.7-1.3\%}$

Associated Triple Higgs Boson Production

Dicus, Repko and Kao, Phys.Rev. D93 (2016) no.11, 113003.



Cancellation of High Energy Behavior

- Let us consider the matrix element as
  $\mathcal{M} = f\bar{v}(p_2)\gamma_\mu(g_V + g_A\gamma_5)u(p_1)X^{\mu\nu}\epsilon_\nu(p)$
- The spinor factor goes as E^1.
- $X^{\mu\nu}$ has two or three Z propagators, some goes as E^0.
- The longitudinal Z polarization vector goes as E^1.
- We have explicitly implemented cancellation of energy dependence by proper grouping of terms.

σ(pp to ZHHH +X) in fb

$\sqrt{s}$	σ_{44}	σ_{3333}	σ_{433}	σ_{40}	σ_{330}	σ_{43}	σ_{0}	σ_{333}	σ_{30}	σ_{33}	σ_{TOT}
8	$4.72\ 10^{-7}$	$1.20\ 10^{-6}$	$1.43\ 10^{-6}$	$2.38\ 10^{-6}$	$3.38\ 10^{-6}$	$6.03\ 10^{-6}$	$7.69\ 10^{-6}$	$9.01\ 10^{-6}$	$3.05\ 10^{-5}$	$3.60\ 10^{-5}$	$9.80\ 10^{-5}$
13	$1.57\ 10^{-6}$	$3.61\ 10^{-6}$	$4.47\ 10^{-6}$	$6.94\ 10^{-6}$	$9.31\ 10^{-6}$	$1.80\ 10^{-5}$	$2.32\ 10^{-5}$	$2.55\ 10^{-5}$	$9.05\ 10^{-5}$	$1.09\ 10^{-4}$	$2.92\ 10^{-4}$
14	$1.85\ 10^{-6}$	$4.21\ 10^{-6}$	$5.22\ 10^{-6}$	$8.01\ 10^{-6}$	$1.07\ 10^{-5}$	$2.08\ 10^{-5}$	$2.70\ 10^{-5}$	$2.94\ 10^{-5}$	$1.05\ 10^{-4}$	$1.27\ 10^{-4}$	$3.39\ 10^{-4}$
33	$9.37\ 10^{-6}$	$1.90\ 10^{-5}$	$2.46\ 10^{-5}$	$3.47\ 10^{-5}$	$4.38\ 10^{-5}$	$9.24\ 10^{-5}$	$1.23\ 10^{-4}$	$1.24\ 10^{-4}$	$4.64\ 10^{-4}$	$5.84\ 10^{-4}$	$1.52\ 10^{-3}$
60	$2.43\ 10^{-5}$	$4.67\ 10^{-5}$	$6.16\ 10^{-5}$	$8.41\ 10^{-5}$	$1.04\ 10^{-4}$	$2.26\ 10^{-4}$	$3.06\ 10^{-4}$	$2.97\ 10^{-4}$	$1.14\ 10^{-3}$	$1.45\ 10^{-3}$	$3.74\ 10^{-3}$
100	$5.15\ 10^{-5}$	$9.55\ 10^{-5}$	$1.27\ 10^{-4}$	$1.70\ 10^{-4}$	$2.07\ 10^{-4}$	$4.61\ 10^{-4}$	$6.26\ 10^{-4}$	$5.96\ 10^{-4}$	$2.31\ 10^{-3}$	$2.97\ 10^{-3}$	$7.62\ 10^{-3}$

σ(pp to WHHH +X) in fb

$\sqrt{s}$	σ_{44}	σ_{3333}	σ_{433}	σ_{40}	σ_{330}	σ_{43}	σ_{0}	σ_{333}	σ_{30}	σ_{33}	σ_{TOT}
8	$6.58\ 10^{-7}$	$1.63\ 10^{-6}$	$1.96\ 10^{-6}$	$2.27\ 10^{-6}$	$3.17\ 10^{-6}$	$7.26\ 10^{-6}$	$6.14\ 10^{-6}$	$1.07\ 10^{-5}$	$2.87\ 10^{-5}$	$4.16\ 10^{-5}$	$1.04\ 10^{-4}$
13	$2.03\ 10^{-6}$	$4.53\ 10^{-6}$	$5.65\ 10^{-6}$	$6.00\ 10^{-6}$	$7.96\ 10^{-6}$	$1.99\ 10^{-5}$	$1.70\ 10^{-5}$	$2.78\ 10^{-5}$	$7.79\ 10^{-5}$	$1.17\ 10^{-4}$	$2.85\ 10^{-4}$
14	$2.36\ 10^{-6}$	$5.19\ 10^{-6}$	$6.52\ 10^{-6}$	$6.58\ 10^{-6}$	$9.02\ 10^{-6}$	$2.28\ 10^{-5}$	$1.96\ 10^{-5}$	$3.16\ 10^{-5}$	$8.93\ 10^{-5}$	$1.34\ 10^{-4}$	$3.27\ 10^{-4}$
33	$1.08\ 10^{-5}$	$2.12\ 10^{-5}$	$2.78\ 10^{-5}$	$2.66\ 10^{-5}$	$3.34\ 10^{-5}$	$9.15\ 10^{-5}$	$8.08\ 10^{-5}$	$1.21\ 10^{-4}$	$3.55\ 10^{-4}$	$5.54\ 10^{-4}$	$1.32\ 10^{-3}$
60	$2.66\ 10^{-5}$	$5.01\ 10^{-5}$	$6.65\ 10^{-5}$	$6.13\ 10^{-5}$	$7.56\ 10^{-5}$	$2.13\ 10^{-4}$	$1.91\ 10^{-4}$	$2.77\ 10^{-4}$	$8.29\ 10^{-4}$	$1.31\ 10^{-3}$	$3.10\ 10^{-3}$
100	$5.43\ 10^{-5}$	$9.95\ 10^{-5}$	$1.33\ 10^{-4}$	$1.20\ 10^{-4}$	$1.64\ 10^{-4}$	$4.21\ 10^{-4}$	$3.81\ 10^{-4}$	$5.40\ 10^{-4}$	$1.63\ 10^{-3}$	$2.62\ 10^{-3}$	$6.14\ 10^{-3}$

Summary for Triple Higgs Production

- In general the problem of determining κ_4 will be very difficult.
- Similar conclusions have been reached by Binoth, Karg, Kauer, and Ruckl (2006) and others for the gluon fusion process.

Bonus

Loop Integrals

- Scalar Integrals: ’t Hooft and Veltman (1979)
- Tensor Integrals: Passarino and Veltman (1979)
- FF: G.J. van Oldenborgh (1990)
- LOOP: Dicus and Kao (1990)
- LoopTools: Hahn and Perez-Victoria (1999)
- BlackHat: Bern, Dixon, and Kosower et al. (2013)

Decoupling Limit of General 2HDMs