In search of the Higgs trilinear coupling: double and single Higgs processes

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30/10/2018

Based mainly on R. Bonciani, G. Degrassi, PPG, R. Gröber; arXiv:1806.1156
G. Degrassi, P.P.G, F. Maltoni, D. Pagani; arXiv:1607.0425
G. Degrassi, M. Fedele, P.P.G; arXiv:1702.01737

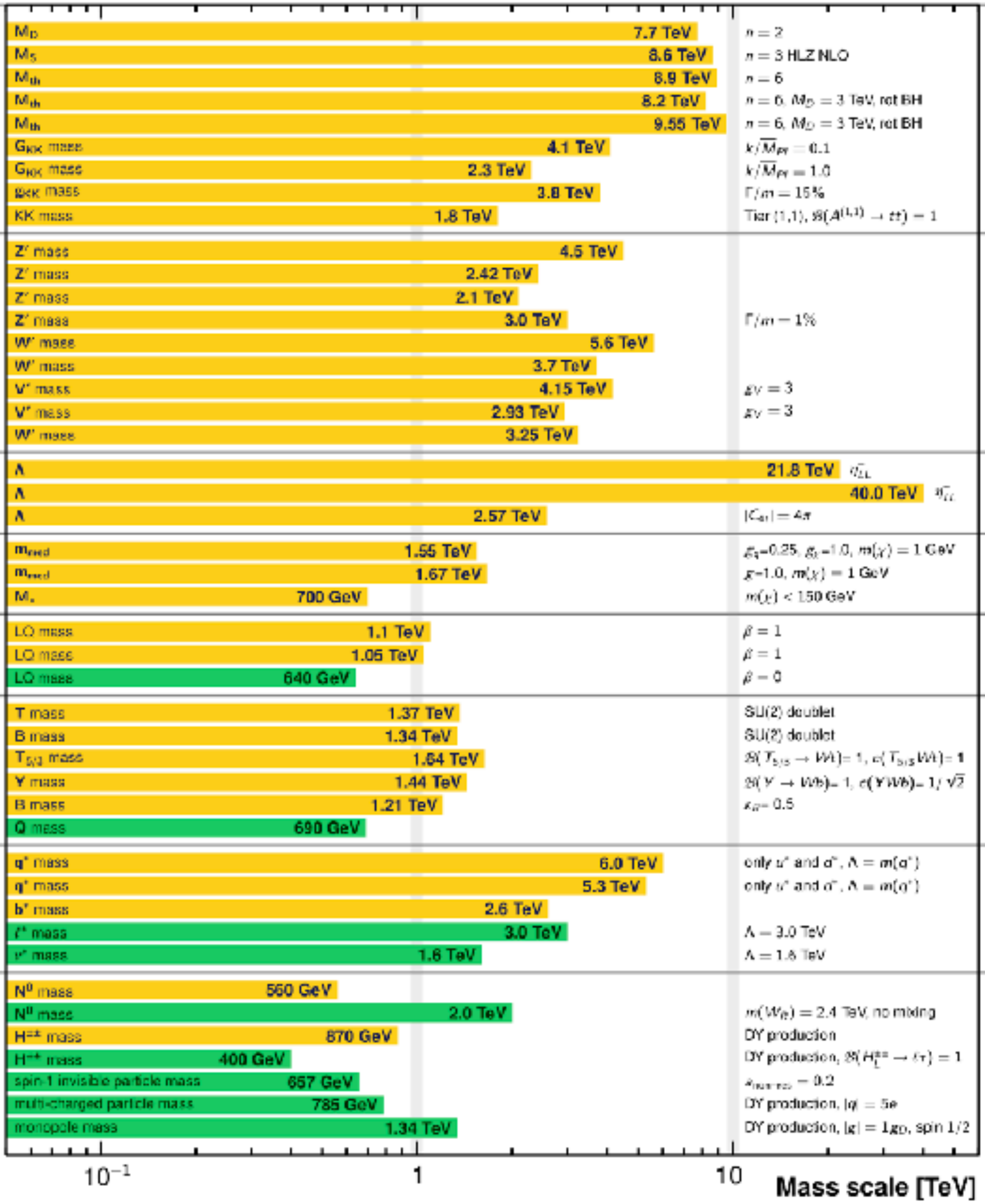
Discovery of the Higgs Boson!

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

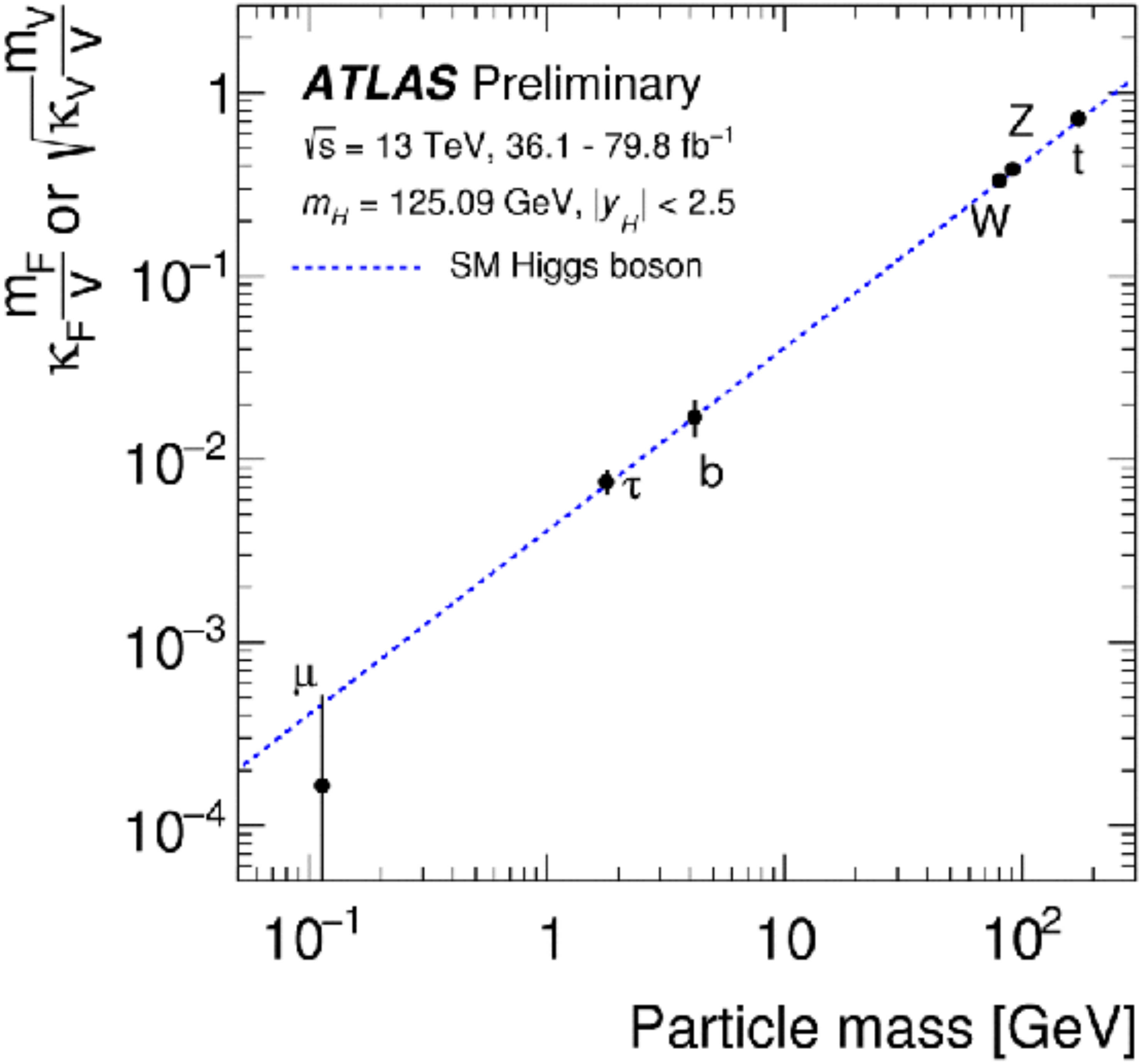


	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z′ mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z′ mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z′ mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z′ mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	79.8	🟨 W′ mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	🟨 W′ mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	79.8	🟨 V′ mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V′ mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	🟨 W′ mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.0 TeV η_{LL}^-		1707.02424
	CI $tttt$	$\geq 1\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $T_{5/3}T_{5/3} \mid T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb) = 1$, $c(YWb) = 1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	$0\ e, \mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-XXX
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	🟨 N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2,3,4\ e, \mu$ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s} = 8$ TeV 🟨 $\sqrt{s} = 13$ TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).



The Higgs appears to be quite standard (?)

$$\mathscr{L}_{\phi} = (y\bar{\psi}\psi\phi + h.c.) + |D_{\mu}\phi|^2 + V(\phi)$$

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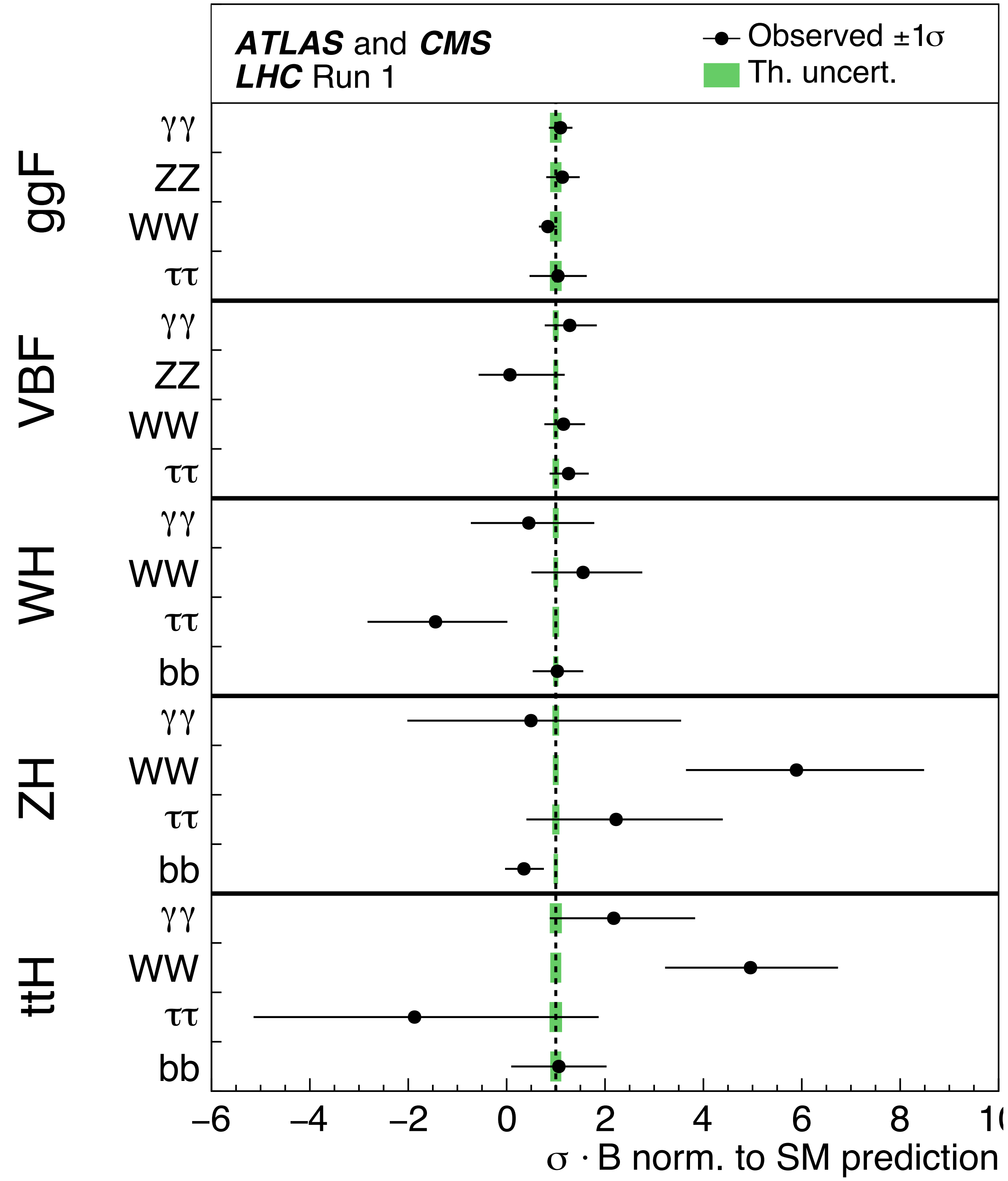
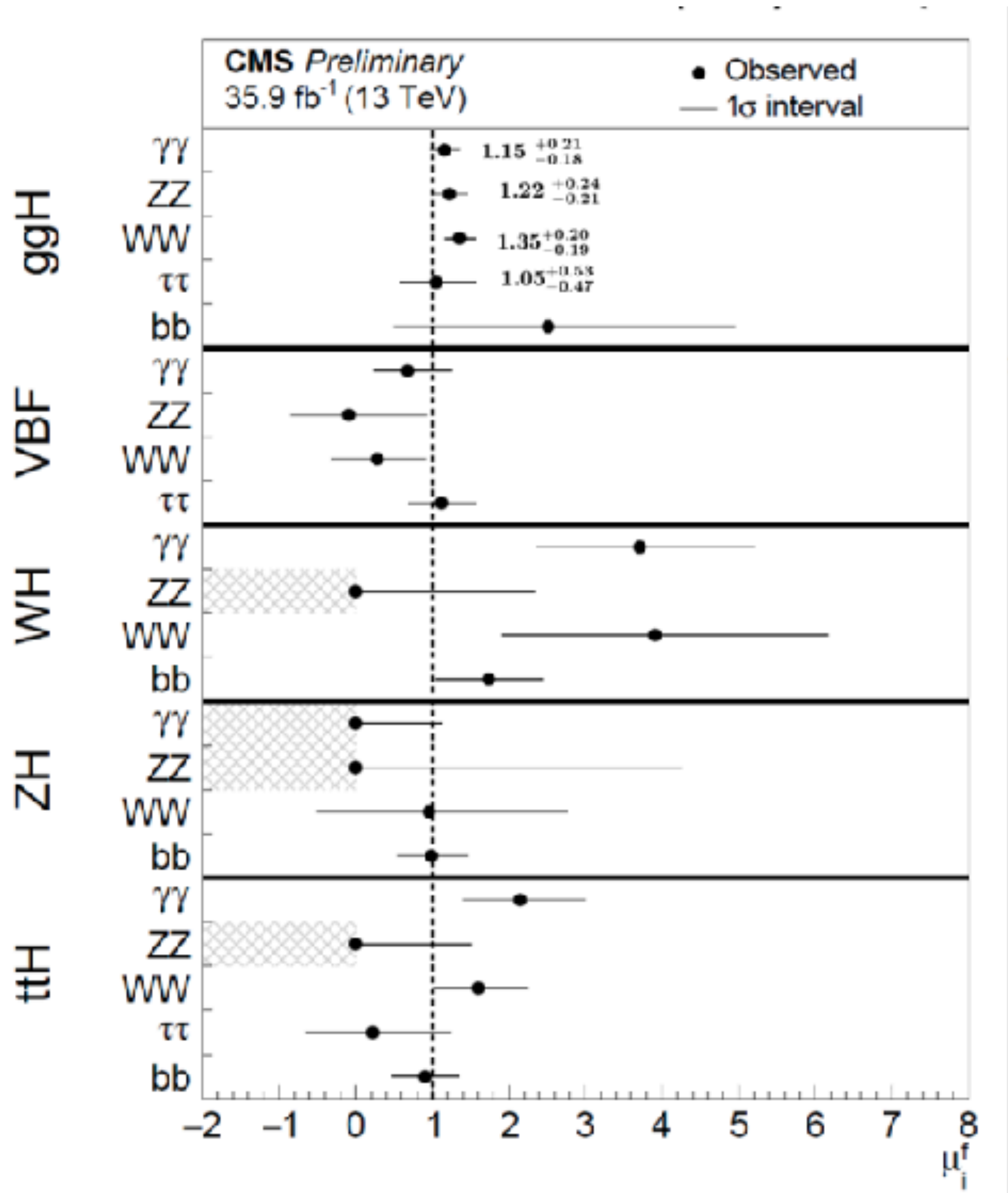
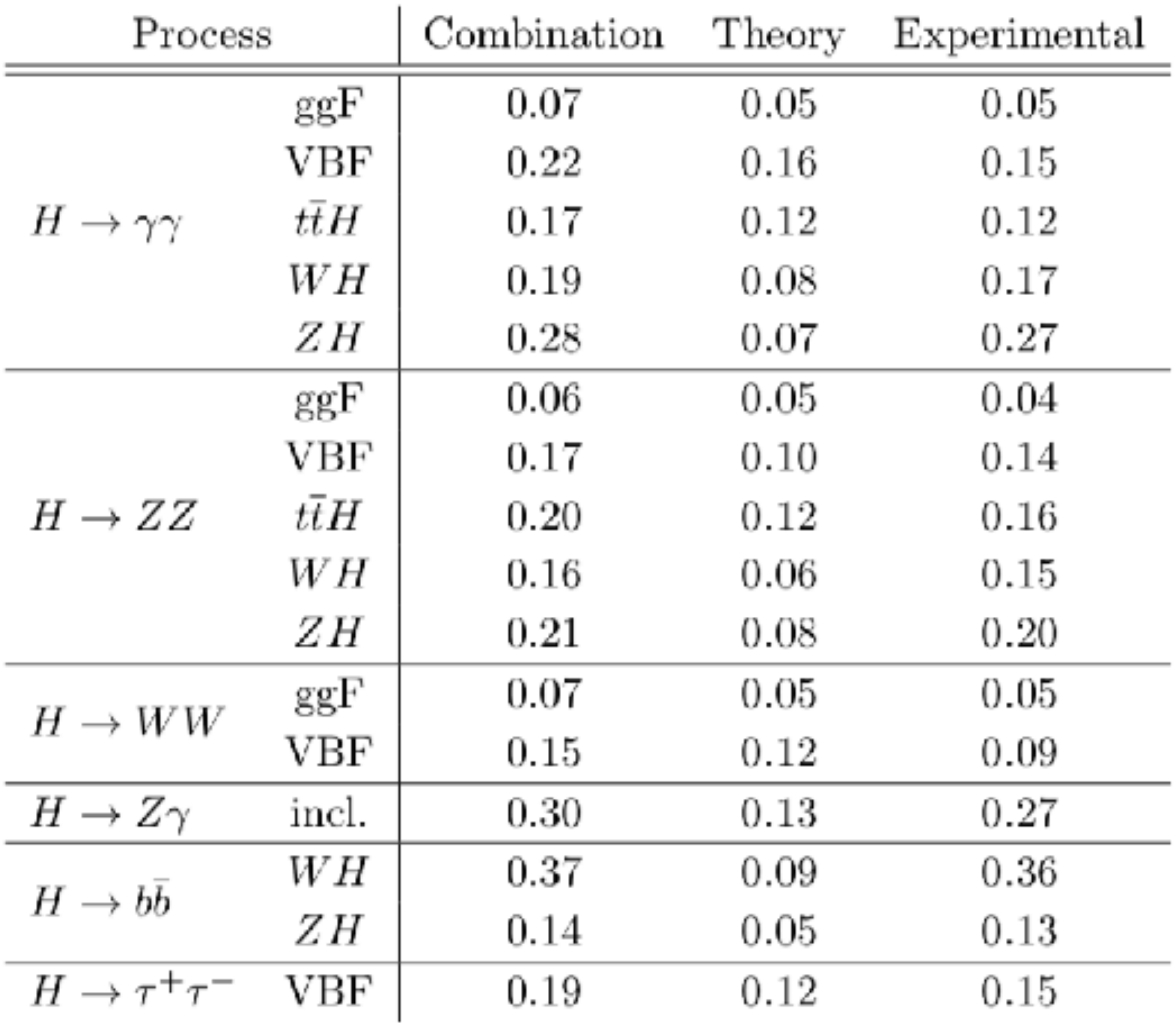




$$\mathscr{L}_{\phi} = \boxed{(y\bar{\psi}\psi\phi + h.c.) + |D_{\mu}\phi|^{2}} + V(\phi)$$



Process		Combination	Theory	Experimental
$H \to \gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H \to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H \to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
$H \to Z\gamma$	incl.	0.30	0.13	0.27
$H \to b\bar{b}$	WH	0.37	0.09	0.36
	ZH	0.14	0.05	0.13
$H \to \tau^+\tau^-$	VBF	0.19	0.12	0.15

Estimated precisions at HL-LHC

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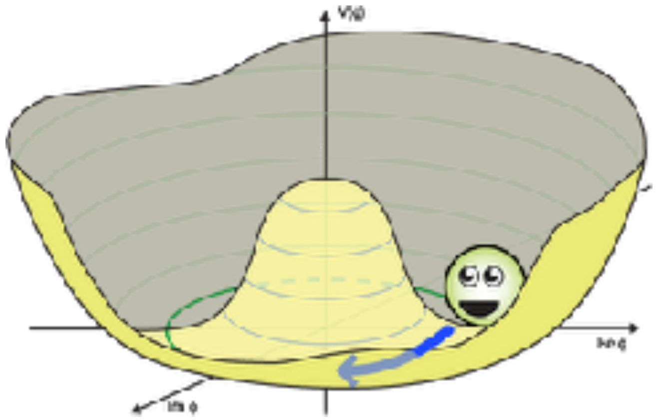
$$\mathscr{L}_{\phi} = (y\bar{\psi}\psi\phi + h.c.) + |D_{\mu}\phi|^{2} + \boxed{V(\phi)}$$

Measuring the Higgs potential

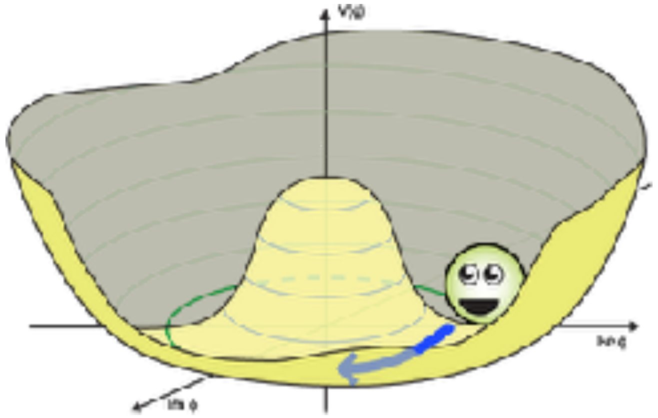
$$\mathscr{L}_{\phi} = (y\bar{\psi}\psi\phi + h.c.) + |D_{\mu}\phi|^2 + \boxed{V(\phi)}$$



$$V(\phi) = -\mu^2\phi^{\dagger}\phi + \lambda(\phi^{\dagger}\phi)^2$$

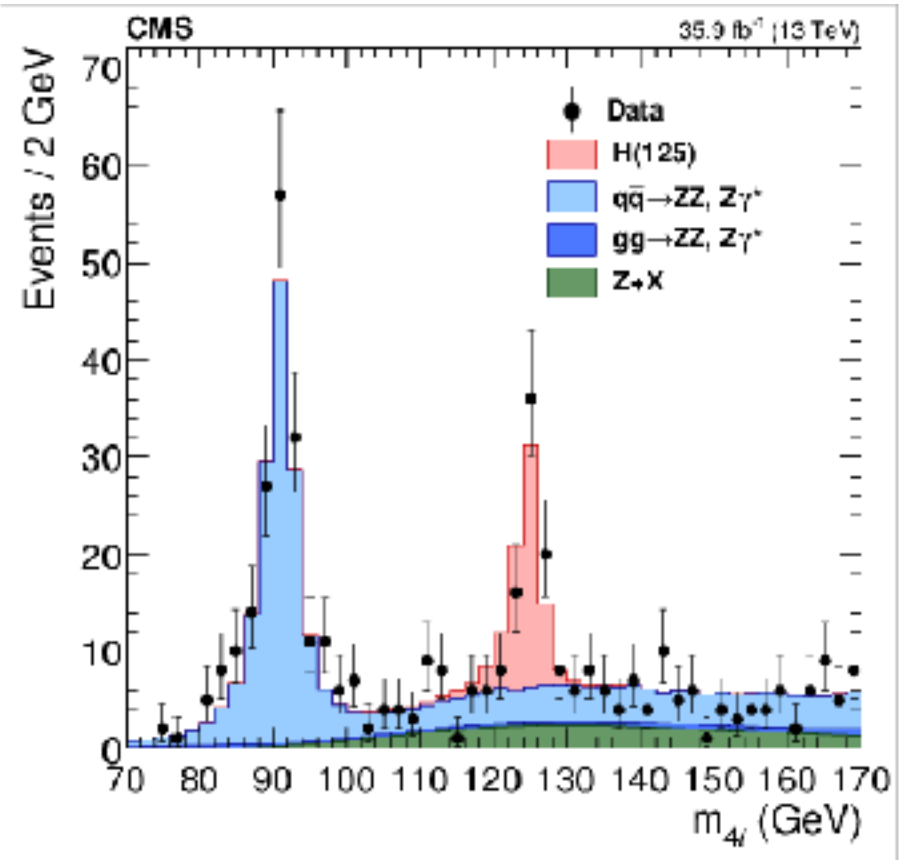
$$V(H) = \frac{1}{2}M_H^2H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

$$\mathscr{L}_\phi = (y\bar{\psi}\psi\phi + h.c.) + |D_\mu\phi|^2 + \boxed{V(\phi)}$$

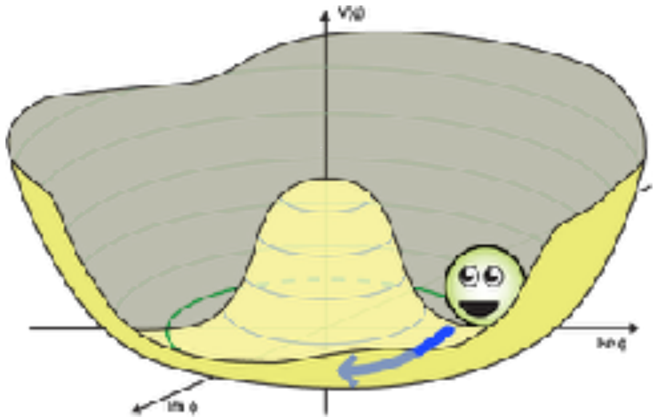


known

$$V(H) = \frac{1}{2}M_H^2 H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$



$$\mathscr{L}_\phi = (y\bar{\psi}\psi\phi + h.c.) + |D_\mu \phi|^2 + \boxed{V(\phi)}$$



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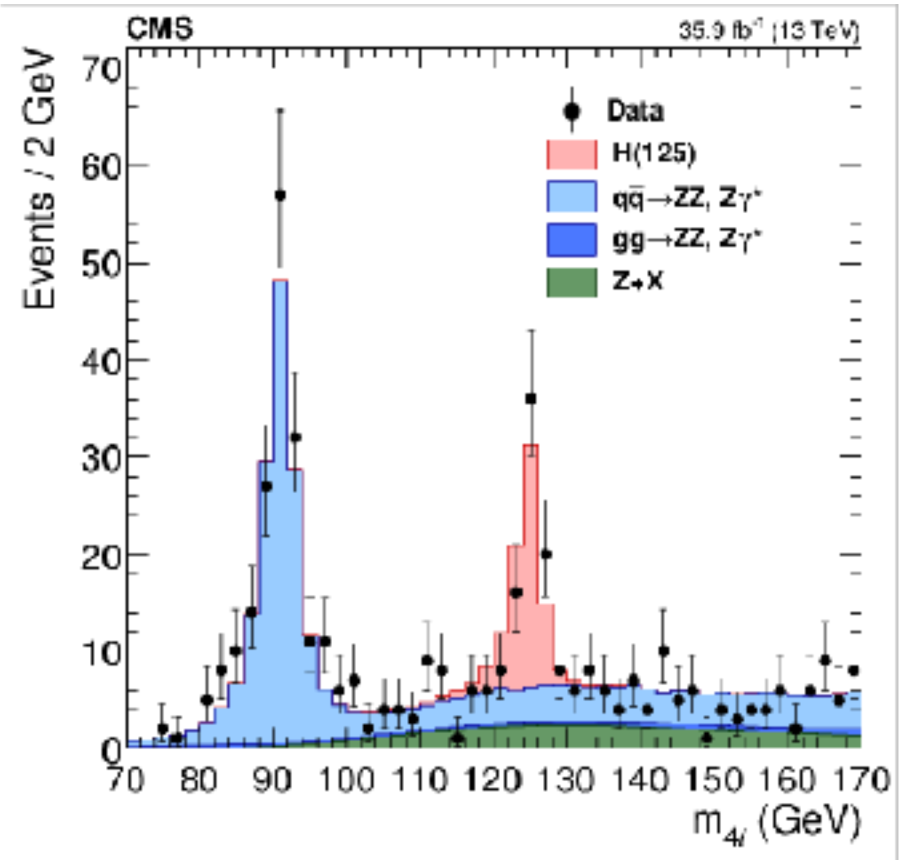
$$\sqrt{\frac{1}{2G_\mu}}$$



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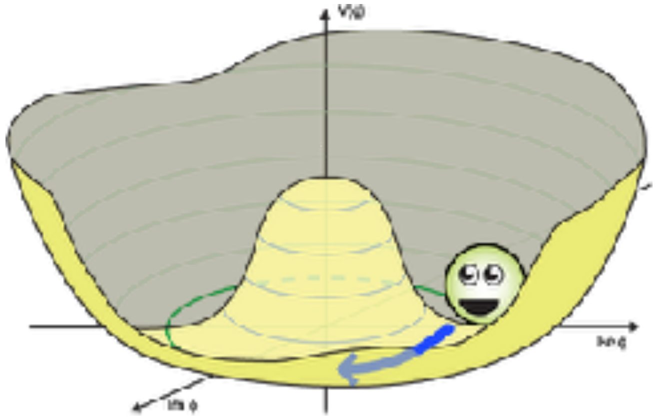

$$V(H) = \frac{1}{2}M_H^2H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

From double Higgs production

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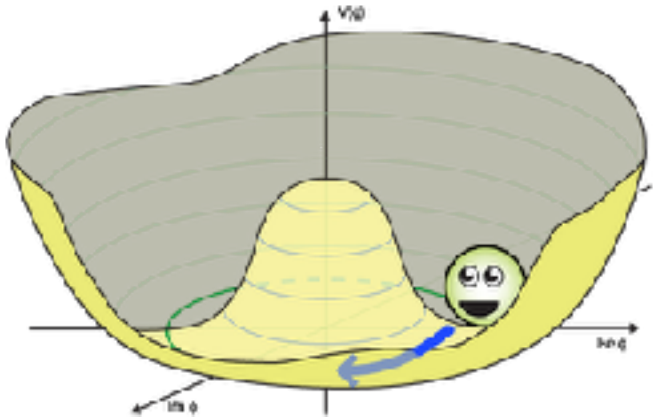

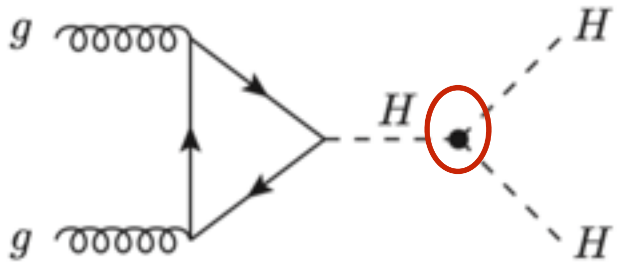

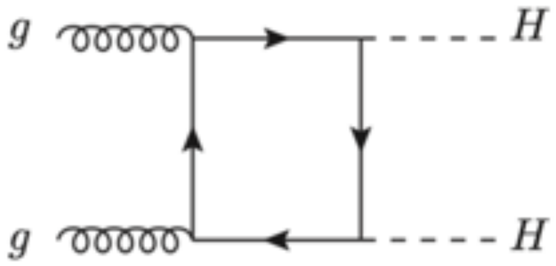

$$V(H) = \frac{1}{2}M_H^2H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

From double Higgs production $\sigma(gg \to HH) \sim 35$ fb

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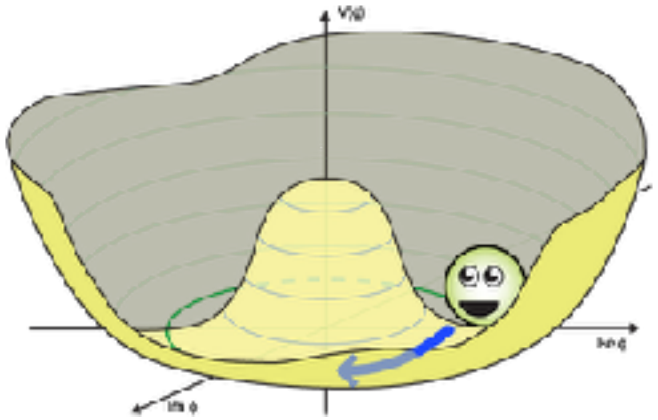

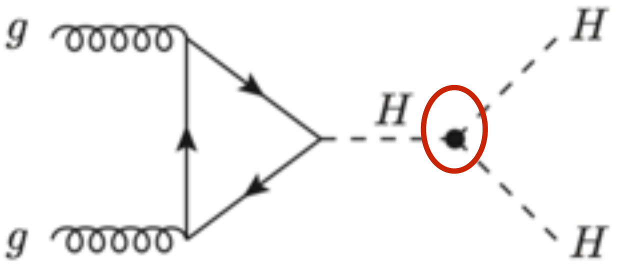

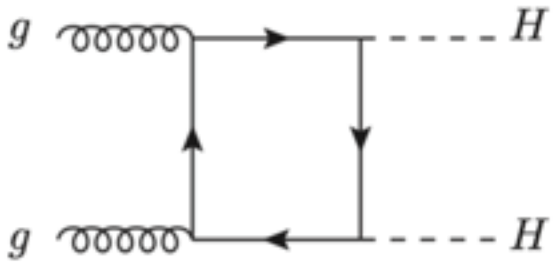

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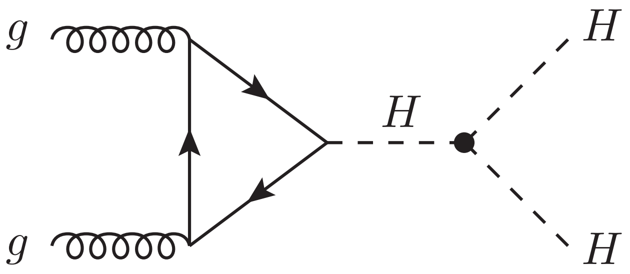
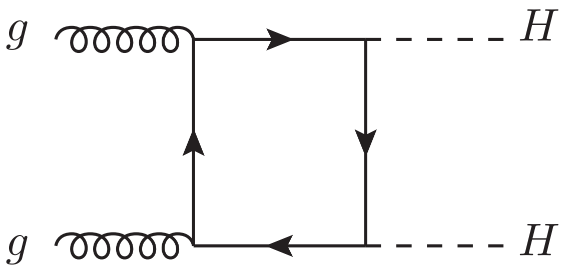
From triple Higgs production $\sigma(gg \to HHH) \sim 0.1$ fb



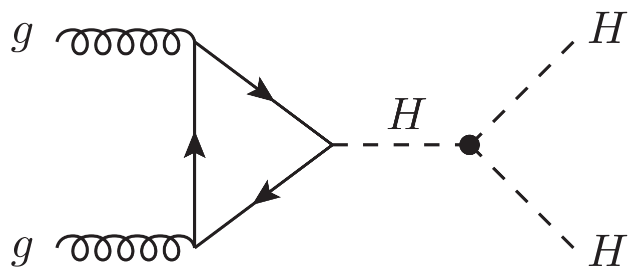


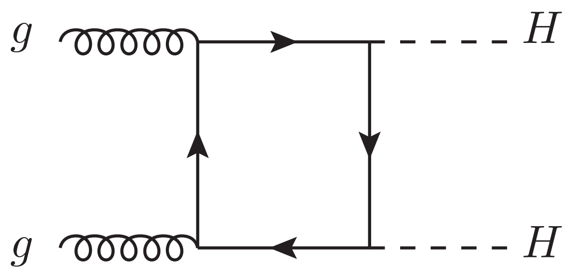
Very small cross section:
- Heavier final state.
- Additional weak coupling.
- Destructive interference

13 TeV

$$gg \to H \sim 40000\,\mathrm{fb}$$

$$gg \to HH \sim 30\,\mathrm{fb}$$





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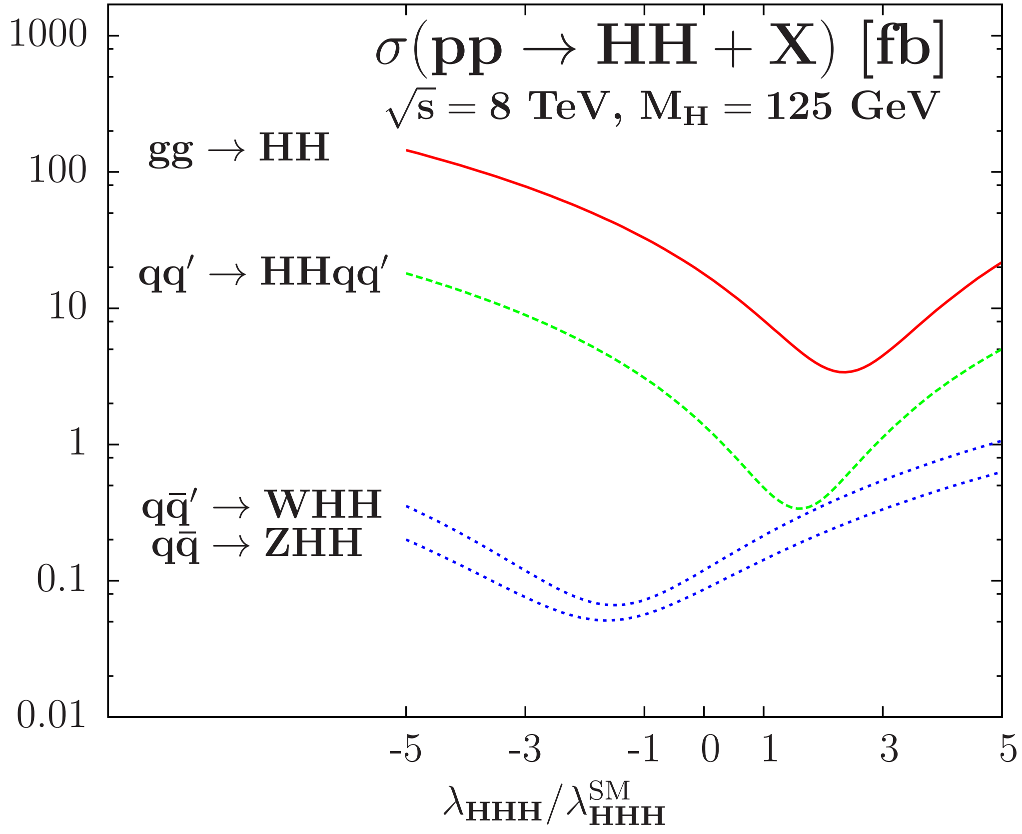
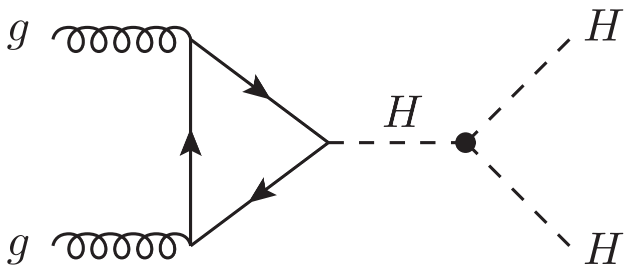
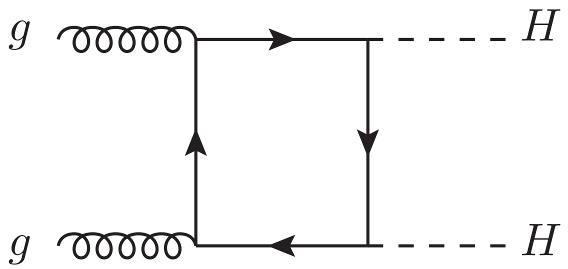


$$V_{H^3} = \lambda_3 v H^3 \equiv \kappa_\lambda \lambda_3^{\mathrm{SM}} v H^3$$





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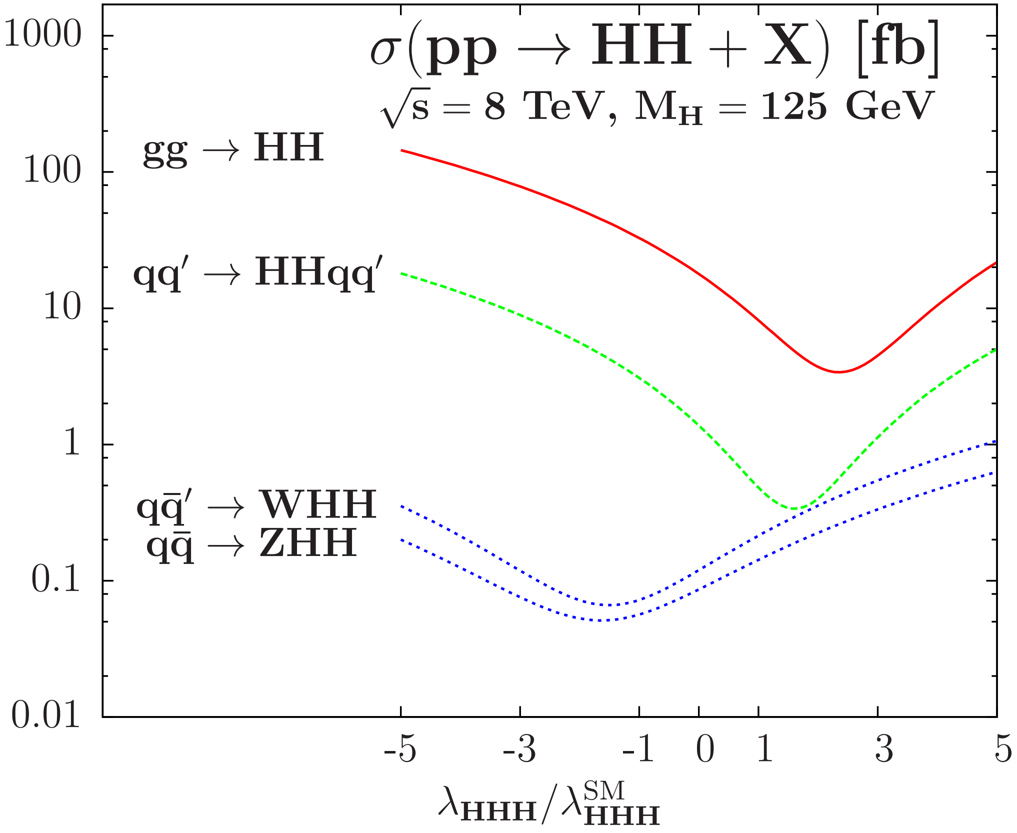
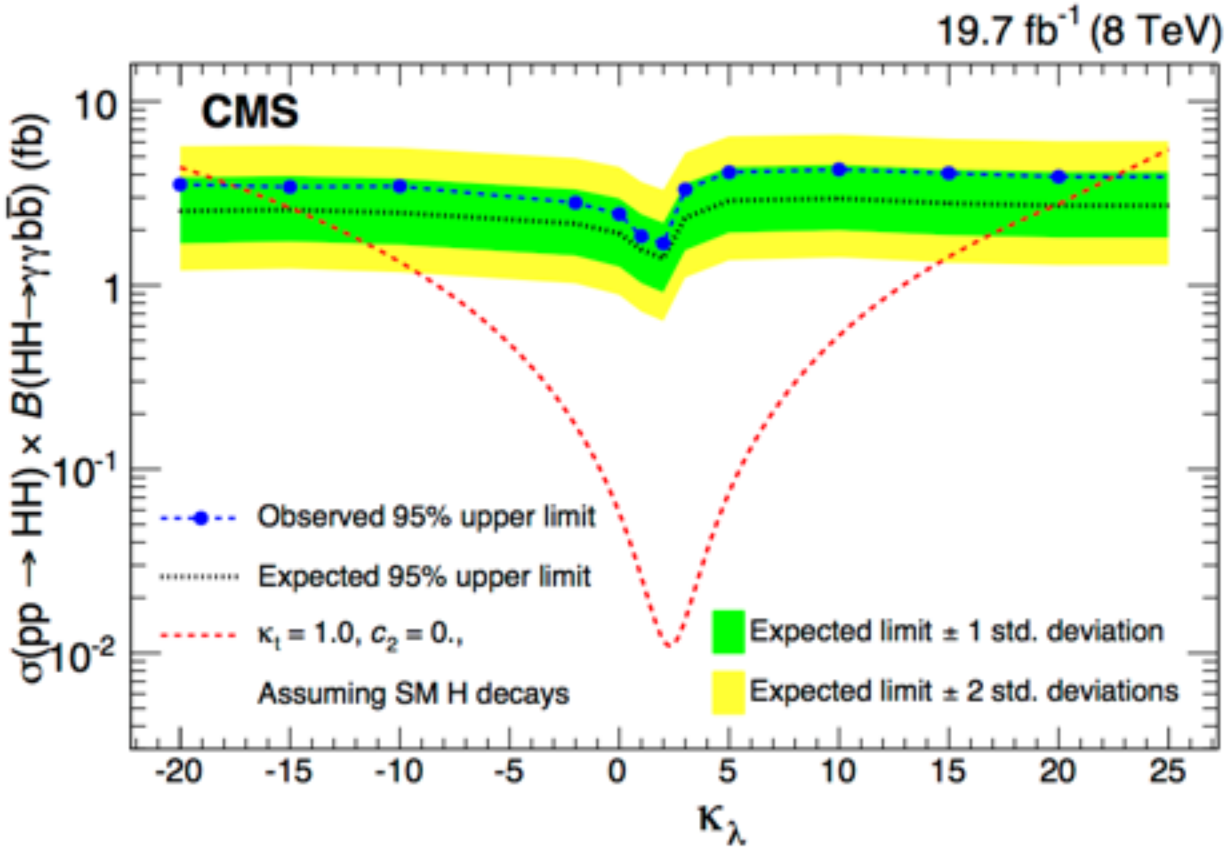
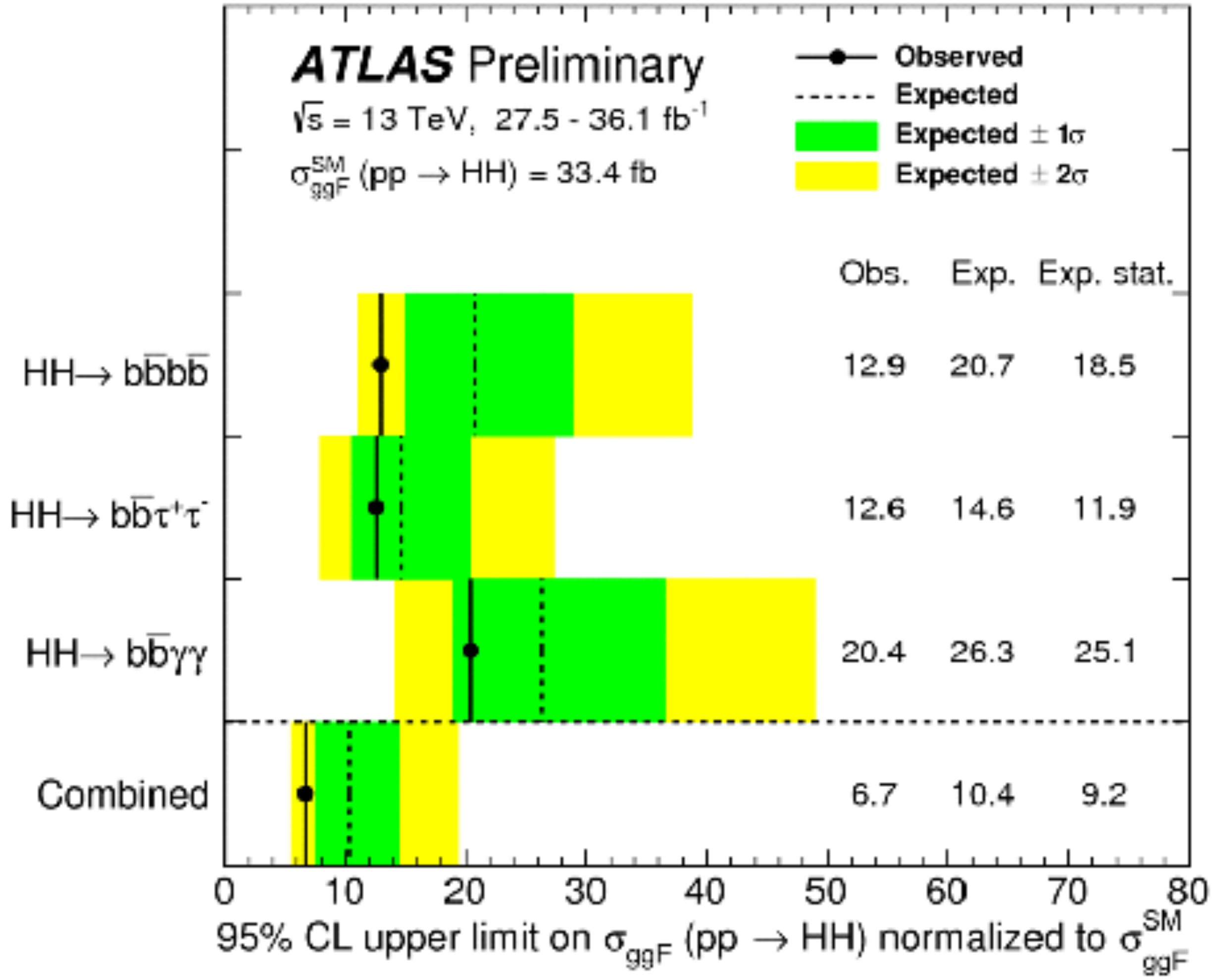




Current limits on Double Higgs production



	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}b\bar{b}$	12.9	20.7	18.5
HH→ $b\bar{b}\tau^+\tau^-$	12.6	14.6	11.9
HH→ $b\bar{b}\gamma\gamma$	20.4	26.3	25.1
Combined	6.7	10.4	9.2

Best channels

$$HH \to bb\gamma\gamma$$

Clean, small BR

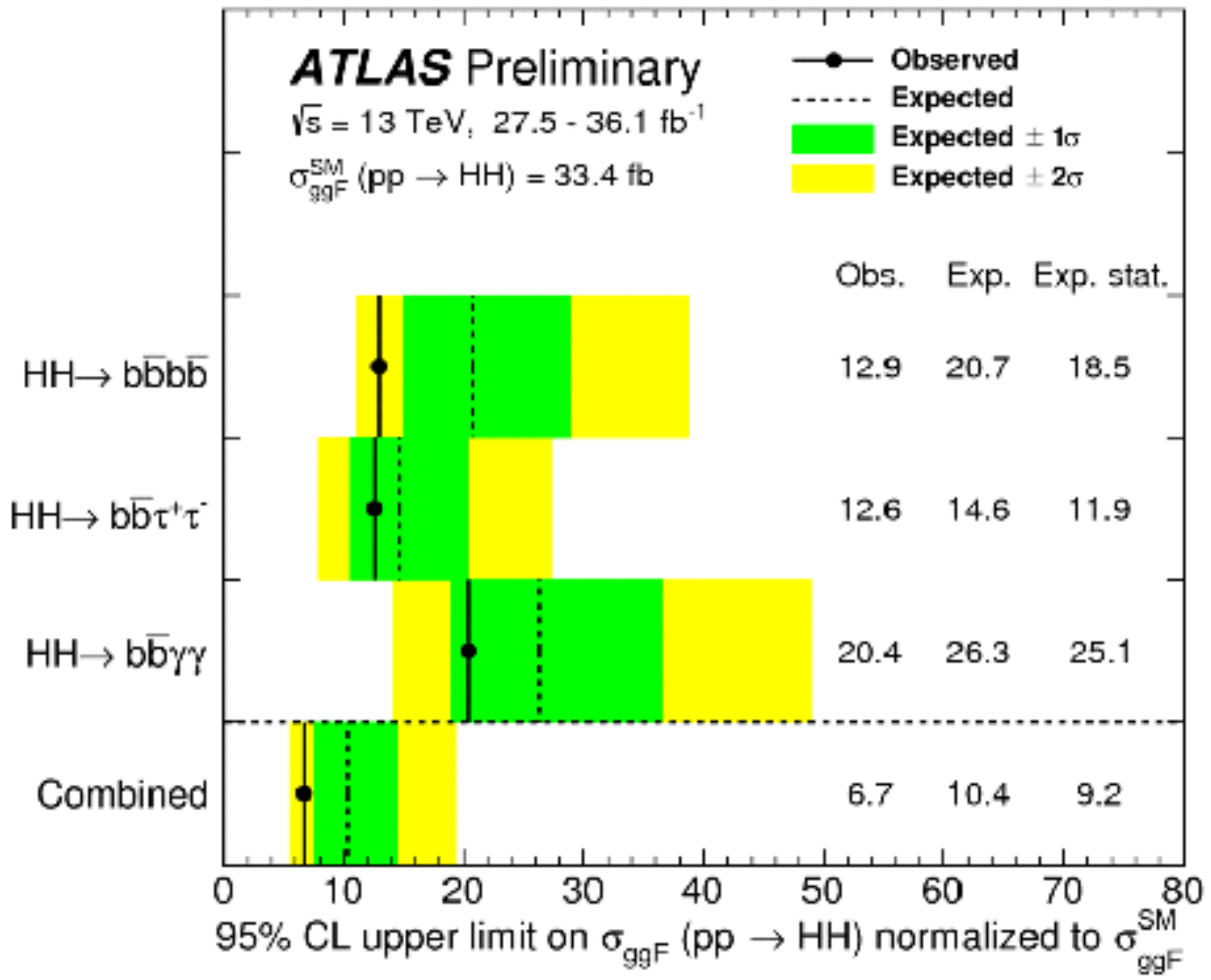
$$HH \to bb\tau\tau$$

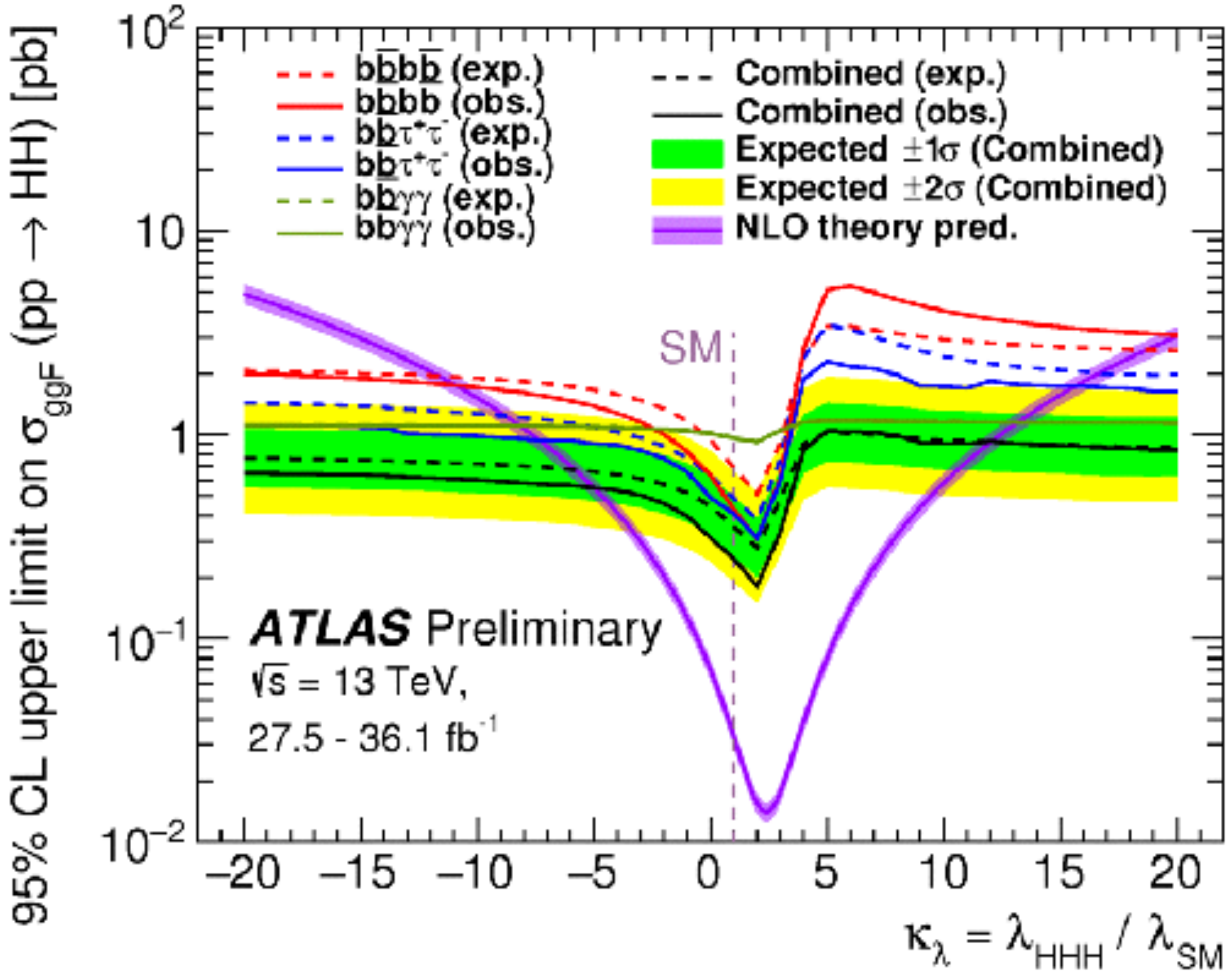
Less clean, larger BR

$$HH \to bbbb$$

Very difficult, largest BR

Current limits on Double Higgs production





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(QCD) NLO fully known only numerically

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert and Zirke, (16)

- Total cross section including the full top-quark dependence.
- One phase-space point ~ 2 hours per node
- 16 dual NVIDIA Tesla K20X GPGPU nodes.

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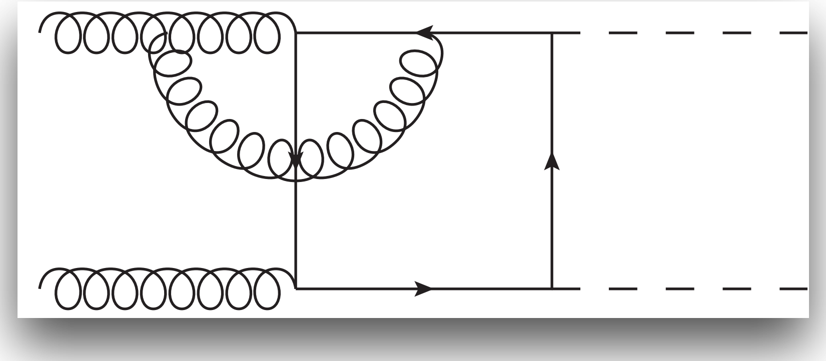
Where is the problem?

Too many scales (3)



Approaches to an analytical approximation of NLO

HEFT $(m_t \to \infty)$

Dawson, Dittmaier, Spira (98)

$\sqrt{\hat{s}} \lesssim 350\,\text{GeV}$

Large Top Mass expansion $\left(\frac{1}{m_t^2}\right)^n$

Grigo, Hoff, Melnikov, Steinhauser (13)

Degrassi, Giardino, Groeber (16)

Improves the HEFT

High Energy expansion $(m_t)^n$

Davies, Mishima, Steinhauser, Wellmann (18)

$\sqrt{\hat{s}} \gtrsim 750\,\text{GeV}$

Large Top Mass expansion $\left(\frac{1}{m_t^2}\right)^n$

Grigo, Hoff, Melnikov, Steinhauser (13)

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High Energy expansion $(m_t)^n$

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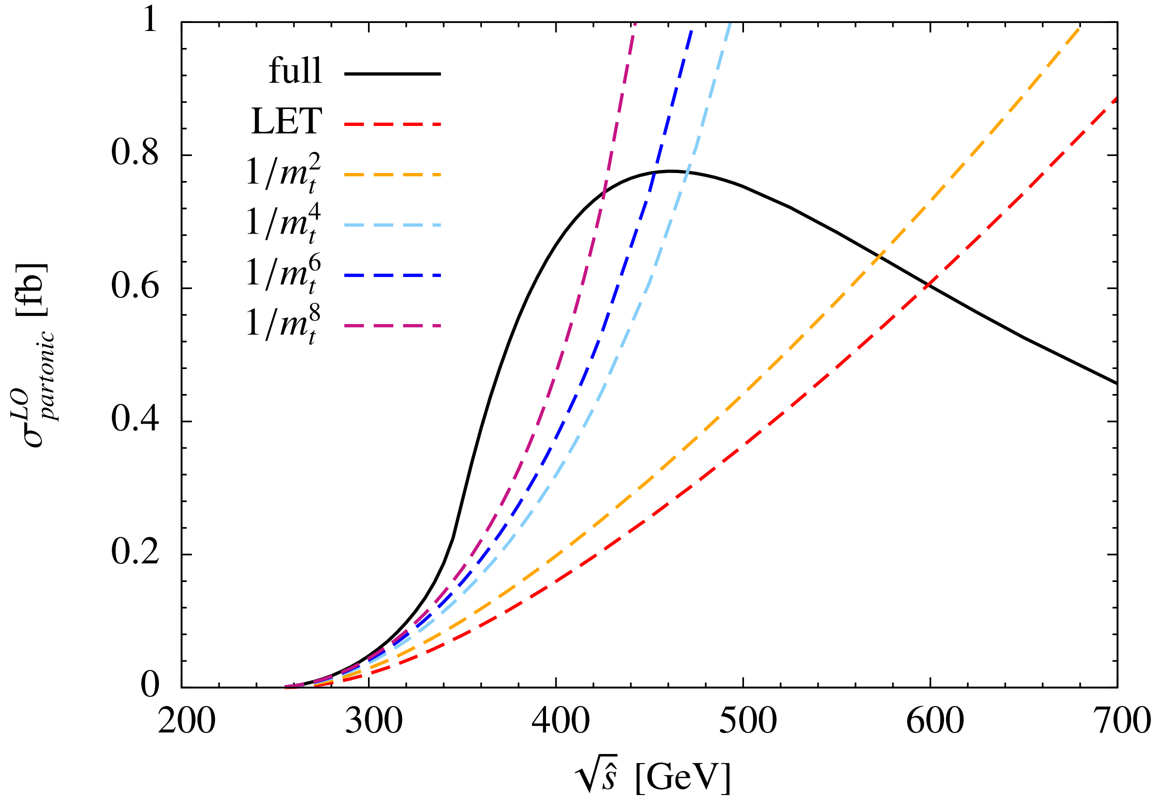

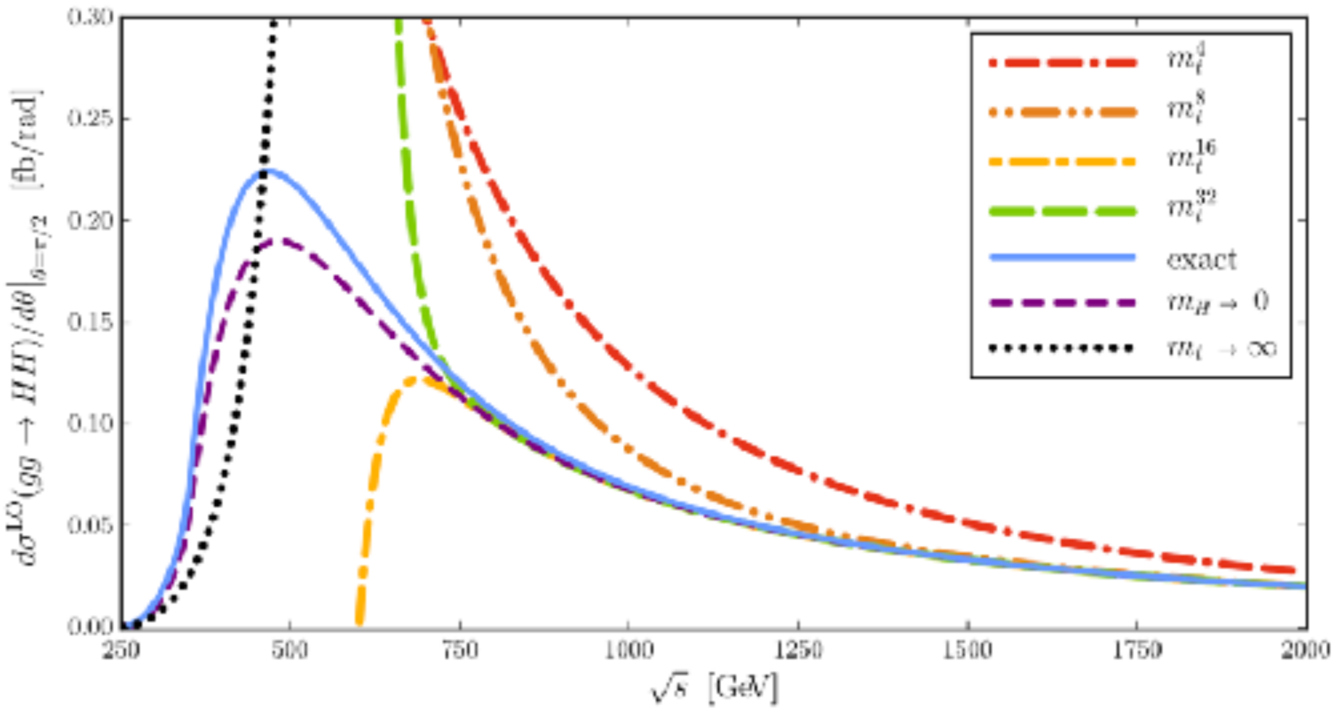

Region $350\,\text{GeV} \lesssim \sqrt{\hat{s}} \lesssim 750\,\text{GeV}$ not covered!!

Large Top Mass expansion $\left(\frac{1}{m_t^2}\right)^n$

Grigo, Hoff, Melnikov, Steinhauser (13)

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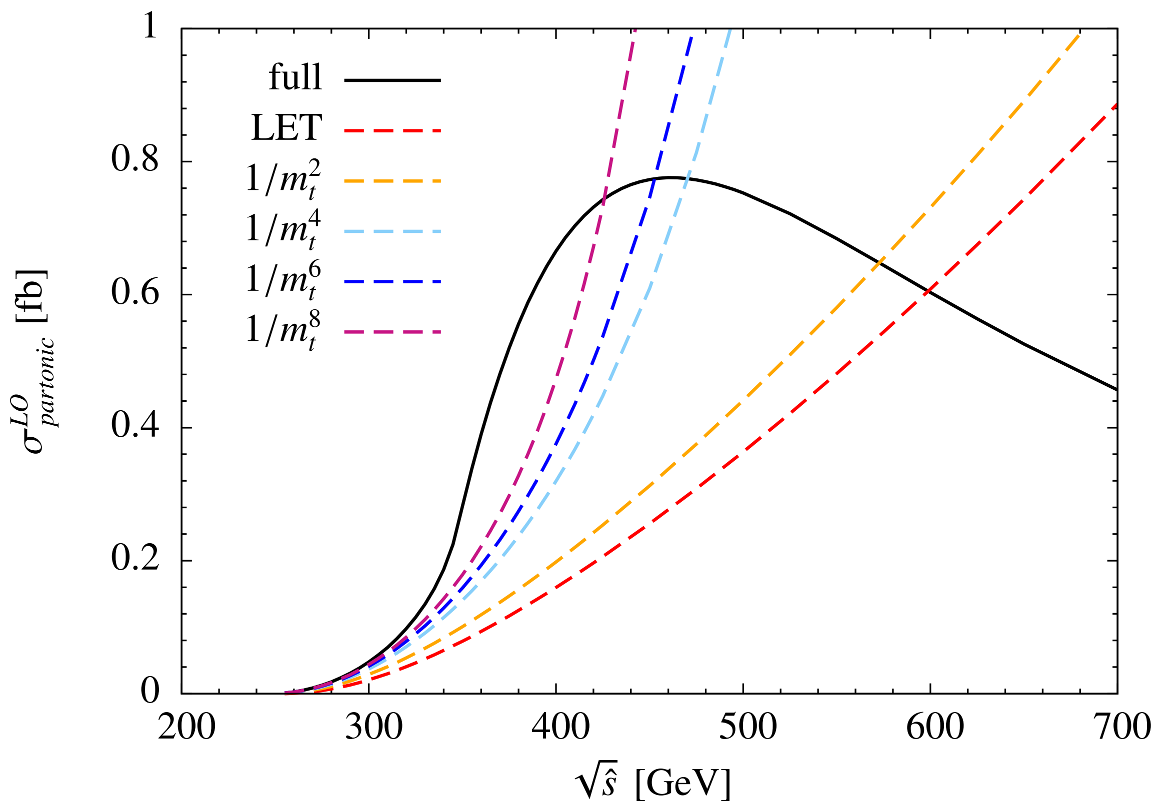

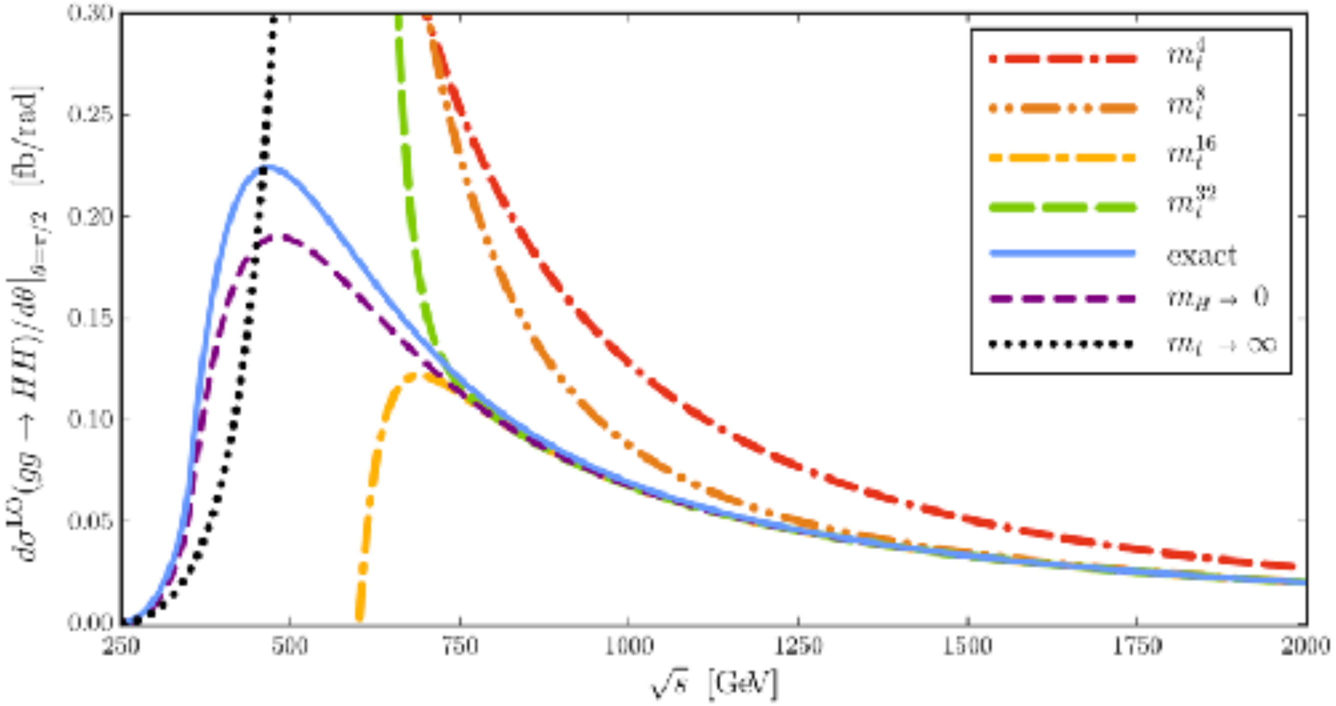

Region $350\,\text{GeV} \lesssim \sqrt{\hat{s}} \lesssim 750\,\text{GeV}$ not covered!!

~95% of hadronic cross section (13 TeV LHC)

Three scales: $\boxed{\frac{m_t^2}{\hat{s}}, \frac{p_T^2}{\hat{s}}, \frac{m_H^2}{\hat{s}}}$

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$\ll 1$ always true

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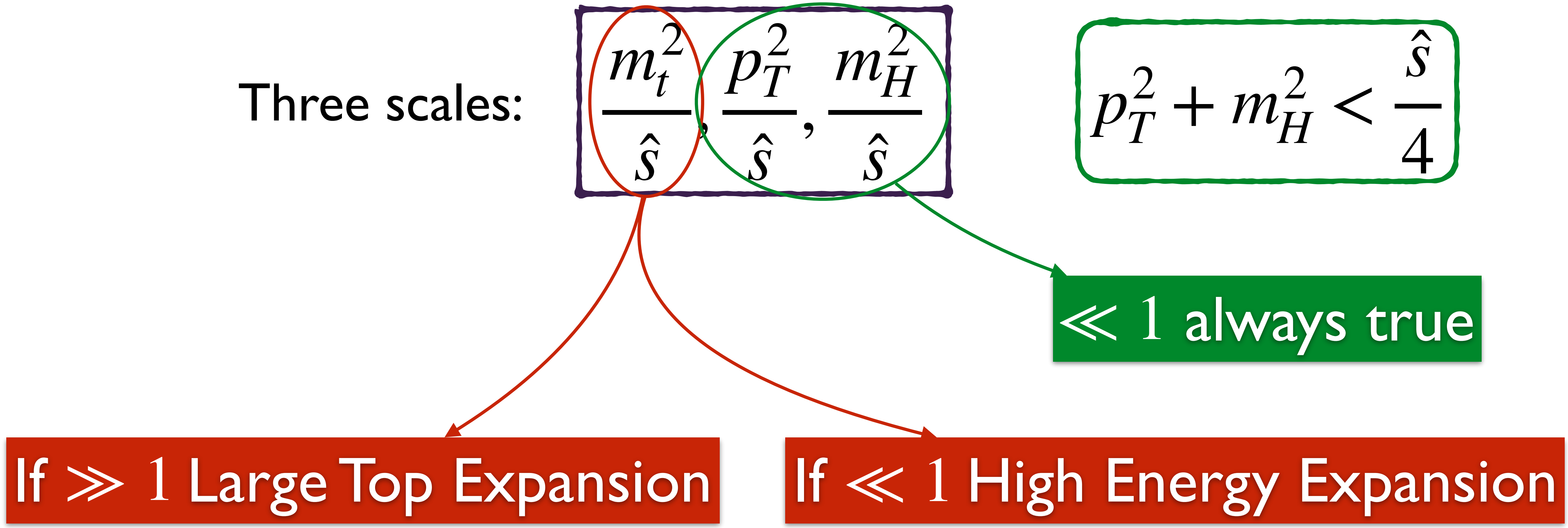
If $\gg 1$ Large Top Expansion



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If $\gg 1$ Large Top Expansion

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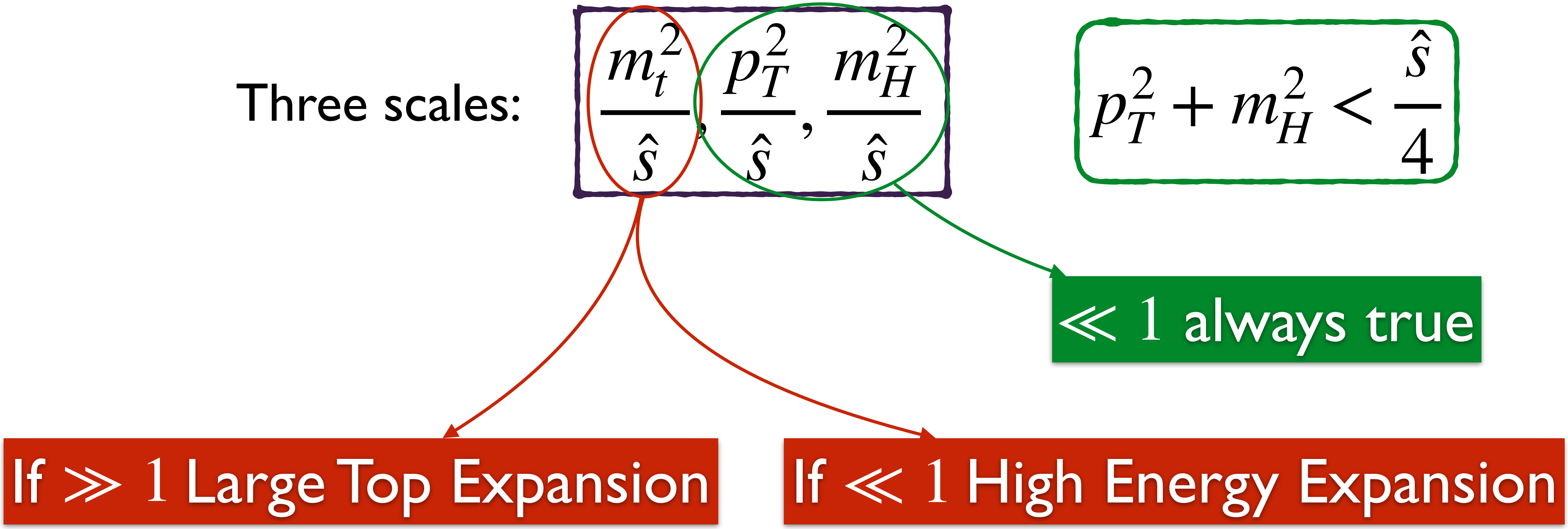

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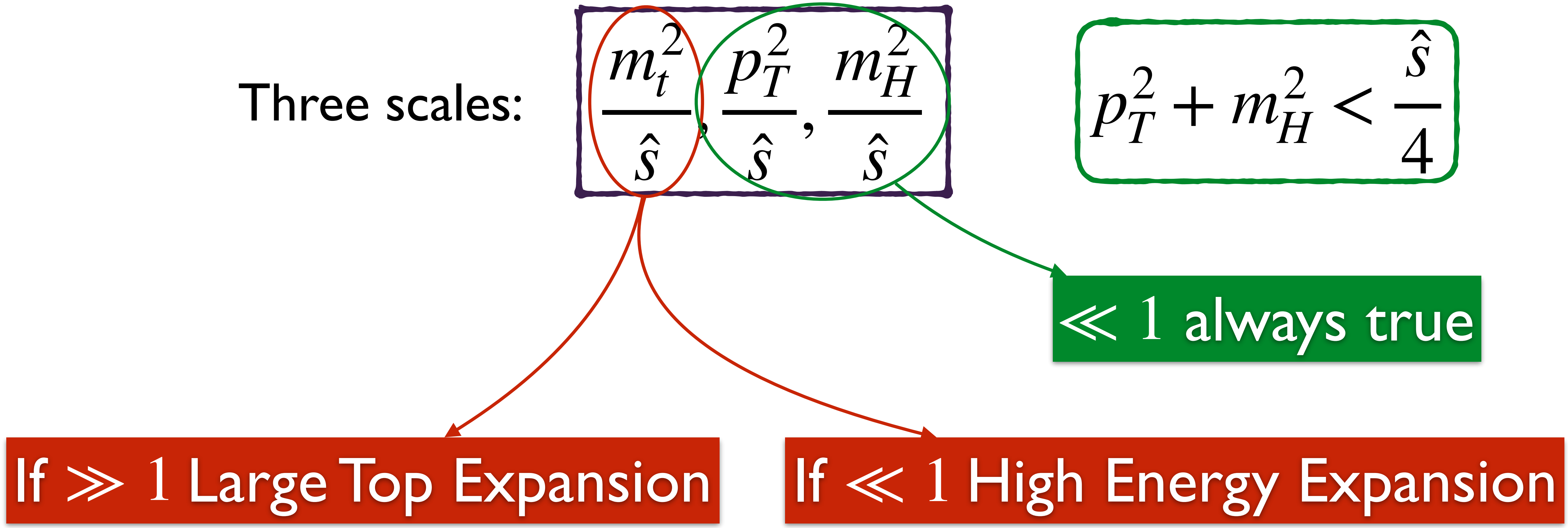
If $\gg 1$ Large Top Expansion

If $\ll 1$ High Energy Expansion

We can try to keep $m_t^2/\hat{s}$ arbitrary and expand on p_T^2 and m_H^2



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If $\gg 1$ Large Top Expansion

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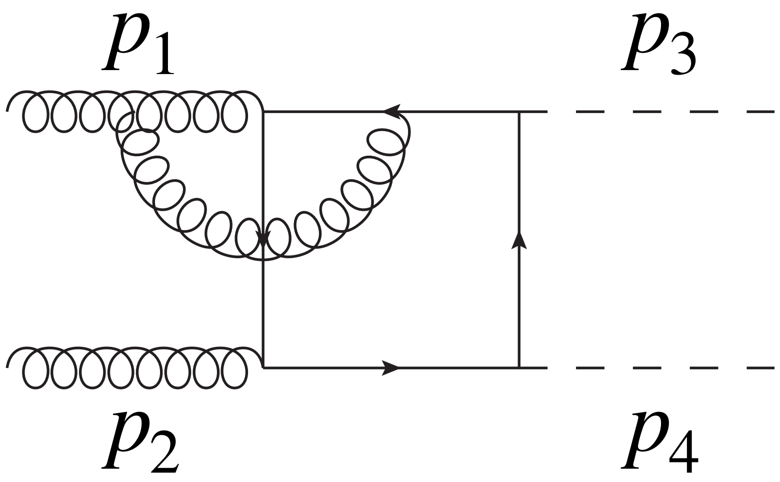
We can try to keep $m_t^2/\hat{s}$ arbitrary and expand on p_T^2 and m_H^2

Problem: amplitudes do not depend directly on p_T^2



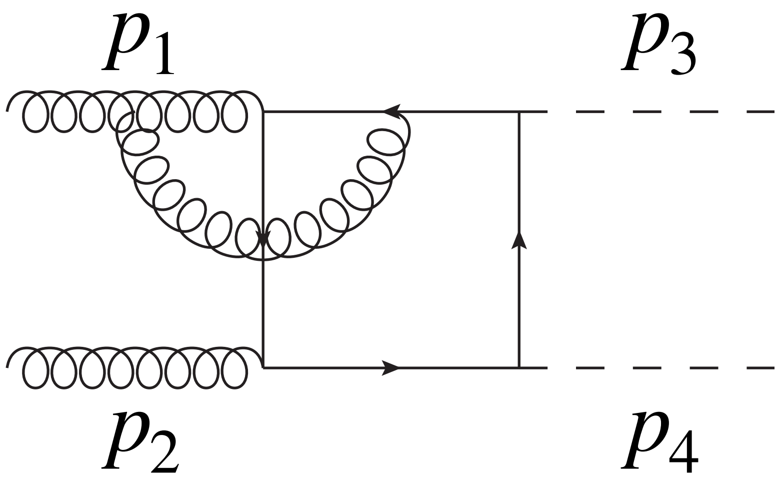
$$\hat{s} = (p_1 + p_2)^2 \qquad \hat{t} = (p_1 + p_3)^2$$

$$\hat{u} = (p_2 + p_3)^2$$

We can use

$$\boxed{\hat{t} \sim 0 \Rightarrow p_T^2 \sim 0}$$

$$p_T^2 = \frac{\hat{t}\hat{u} - m_H^4}{\hat{s}}$$



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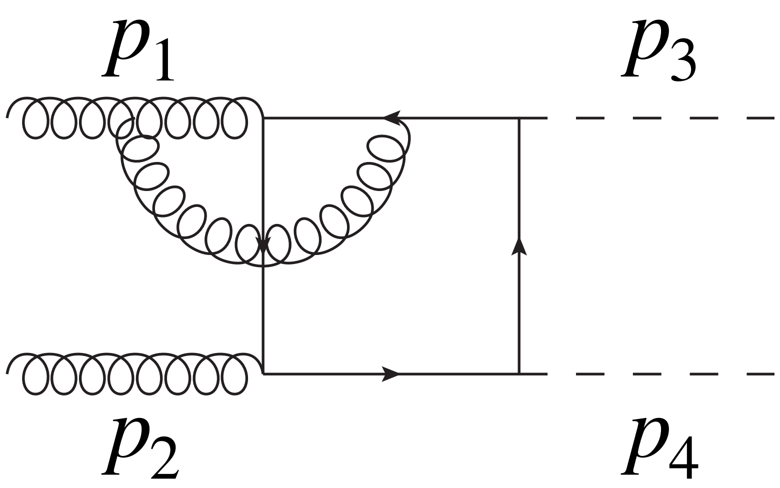
N.B. $\boxed{p_T^2 \sim 0 \not\Rightarrow \hat{t} \sim 0}$

$$\begin{tikzcd} & \hat{t} \sim 0\,, \hat{u} \sim -\hat{s} \\ p_T^2 \sim 0 \arrow[ur, bend right] \arrow[dr, bend left] & \\ & \hat{u} \sim 0\,, \hat{t} \sim -\hat{s} \end{tikzcd}$$



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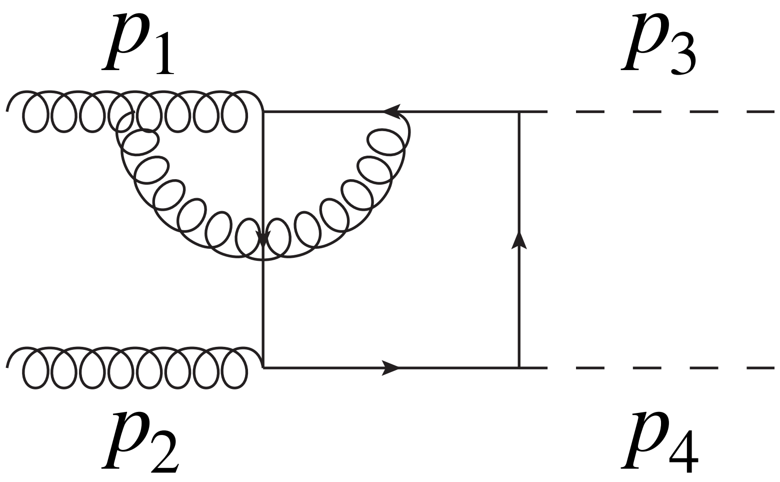
Symmetry!



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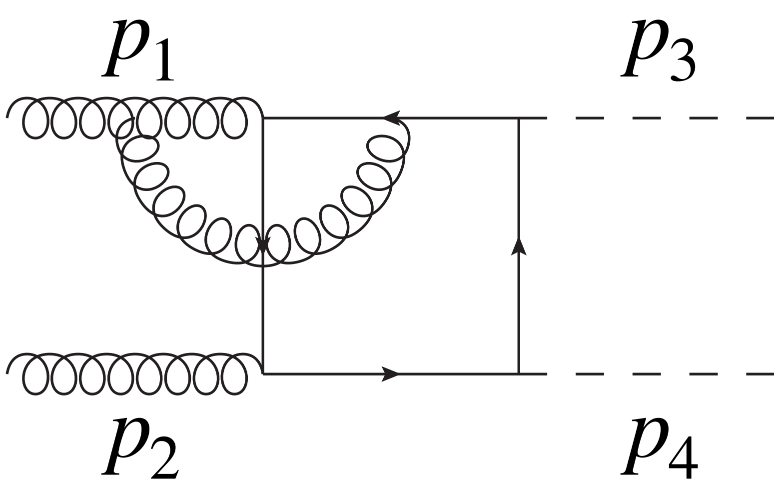
$$\boxed{\sigma \propto \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t}\,\mathscr{G}(\hat{t}) \sim \int_{\hat{t}_-}^{\hat{t}_m} d\hat{t}\,\mathscr{G}(\hat{t} \sim 0) + \int_{\hat{t}_m}^{\hat{t}_+} d\hat{t}\,\mathscr{G}(\hat{t} \sim -\hat{s}) = \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t}\,\mathscr{G}(\hat{t} \sim 0)}$$



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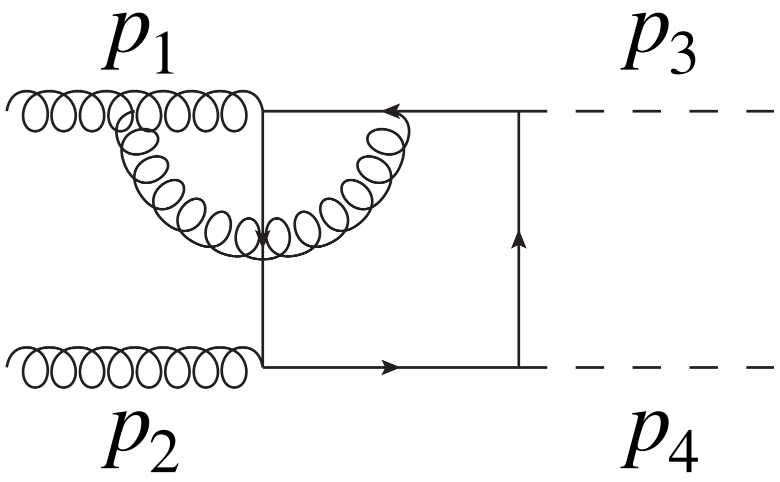
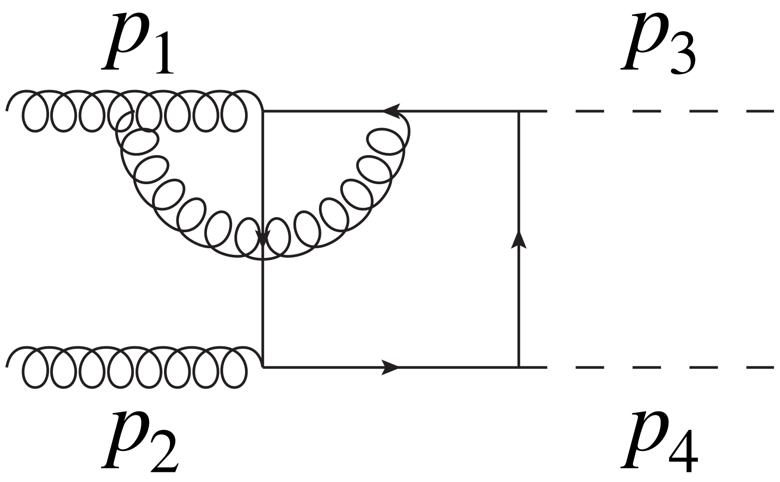


(Momenta are incoming)

Let’s define

$$\boxed{r^\mu = p_1^\mu + p_3^\mu}$$



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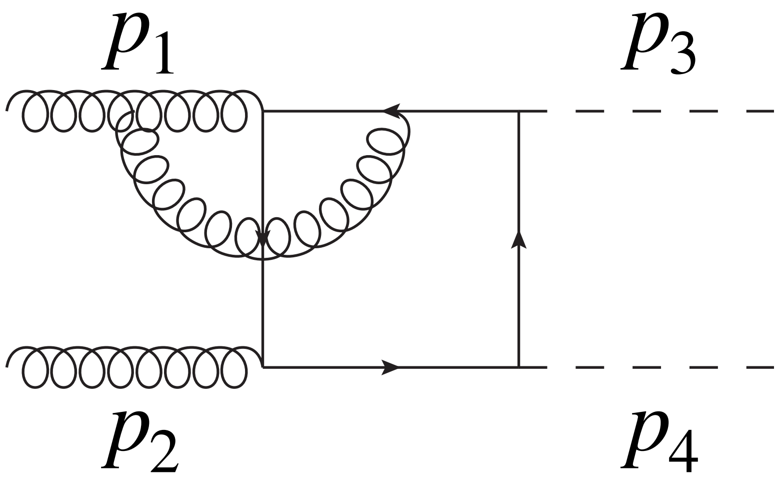

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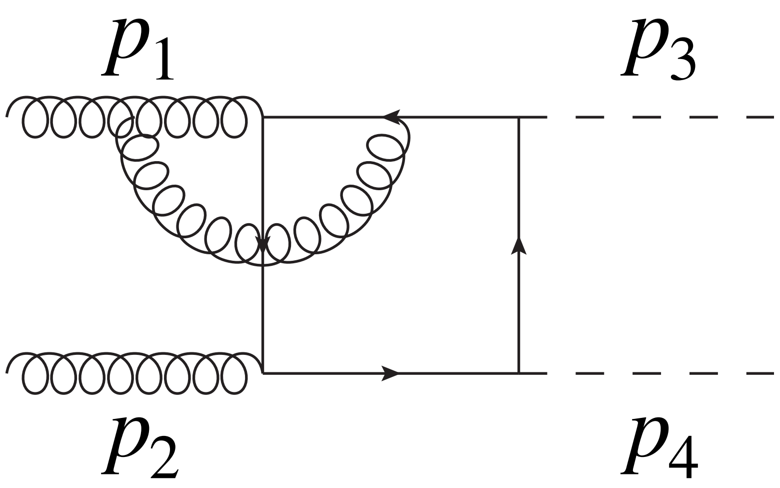
$$r^\mu = \frac{\hat{t} - m_H^2}{\hat{s}}(p_2 - p_1)^\mu + r_\perp^\mu$$



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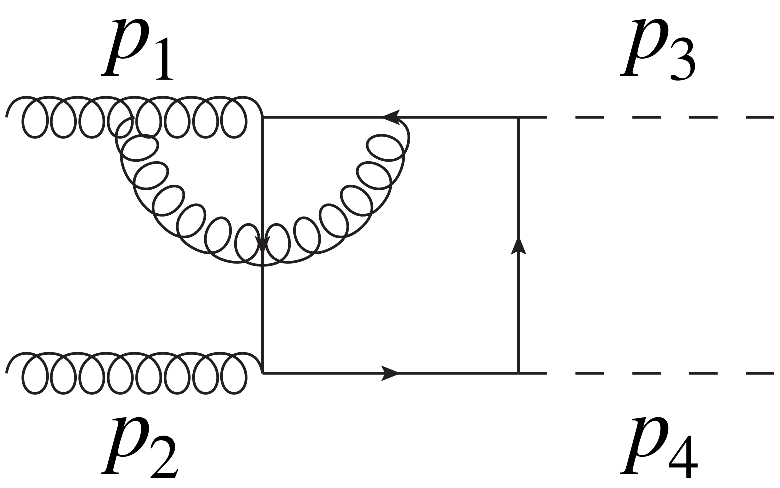

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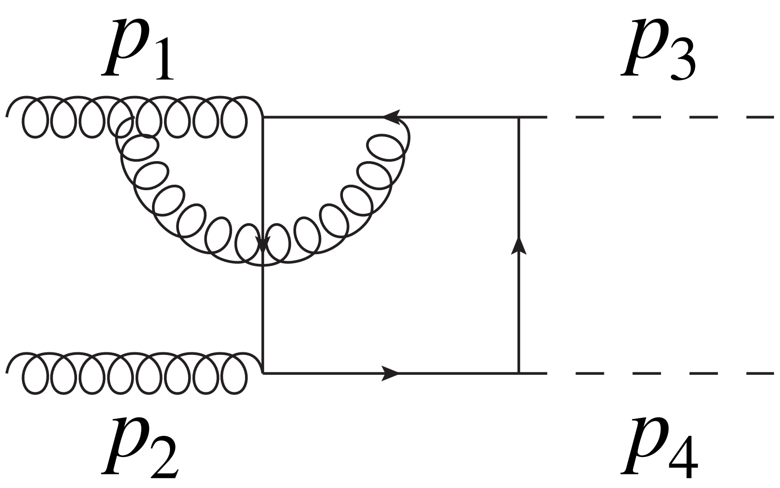

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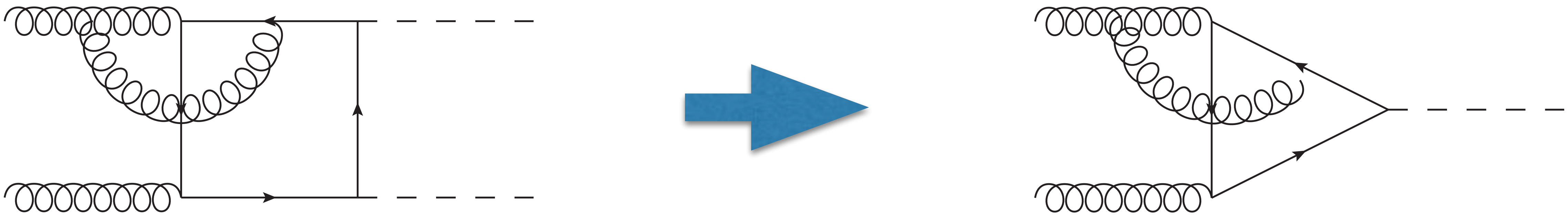


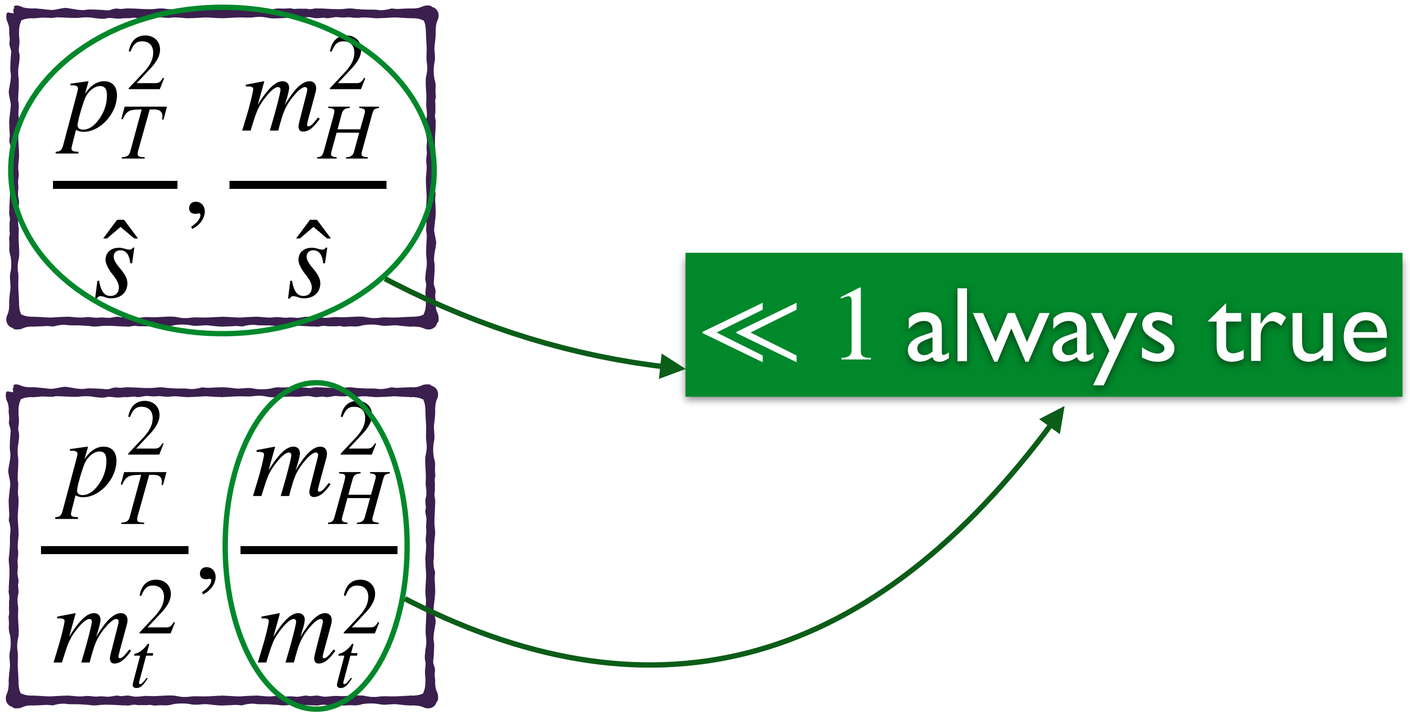
$$\boxed{\frac{p_T^2}{\hat{s}}, \frac{m_H^2}{\hat{s}}}$$

$$\boxed{\frac{p_T^2}{\hat{s}}, \frac{m_H^2}{\hat{s}}} \longrightarrow \ll 1 \text{ always true}$$

$$\boxed{\frac{p_T^2}{\hat{s}}, \frac{m_H^2}{\hat{s}}}$$

$\ll 1$ always true

$$\boxed{\frac{p_T^2}{m_t^2}, \frac{m_H^2}{m_t^2}}$$



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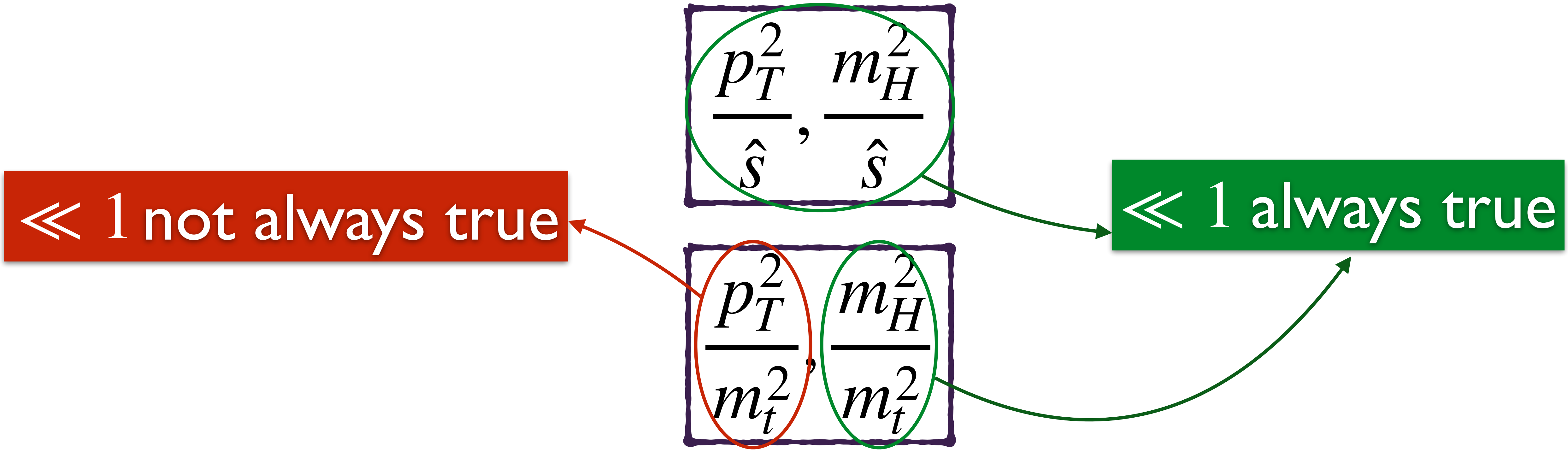
$\ll 1$ always true



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$$\frac{p_T^2}{m_t^2}, \frac{m_H^2}{m_t^2}$$

$\ll 1$ not always true

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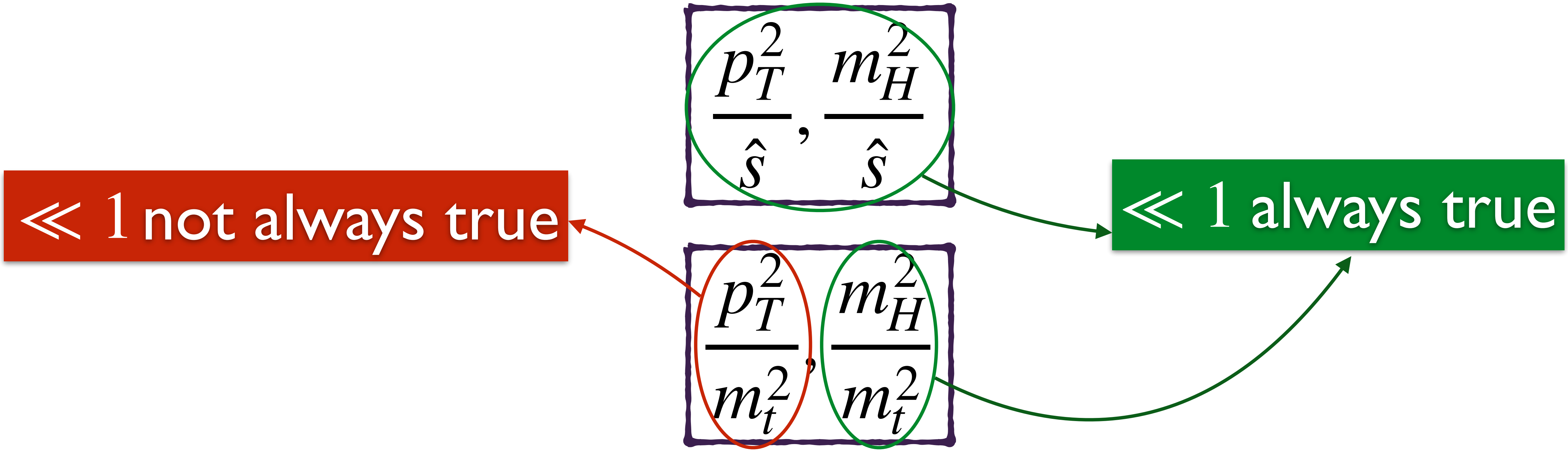

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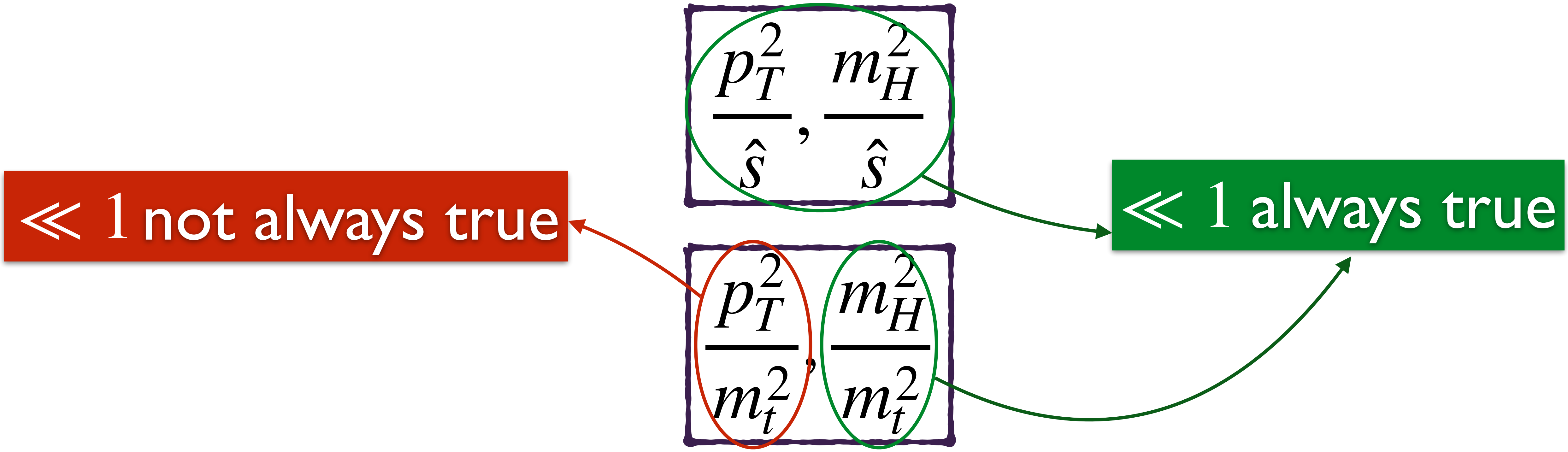
$\ll 1$ always true

$\Delta\sigma$ — $\hat{s}$	$4m_t^2$	$6m_t^2$	$8m_t^2$	$12m_t^2$	$16m_t^2$	$32m_t^2$
$p_T^0 \times 10^{-1}$	6.2	4.4	3.2	1.8	1.0	0.3
$p_T^2 \times 10^{-2}$	8.5	4.4	1.1	2.4	5.1	33.2
$p_T^4 \times 10^{-2}$	1.3	0.1	0.4	0.2	0.9	2.8
$p_T^6 \times 10^{-3}$	2.3	0.9	1.0	0.1	3.5	450



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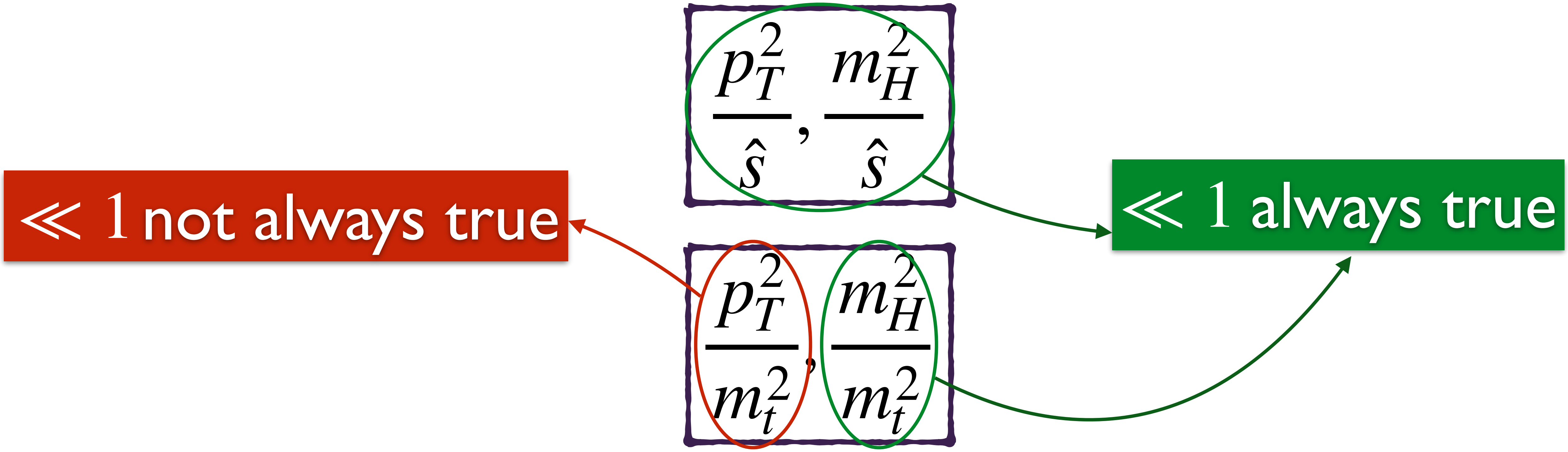
It starts diverging around

$$\sqrt{\hat{s}} \lesssim 500 - 600\, GeV$$

$$\hat{t}_m \lesssim 4m_T^2$$



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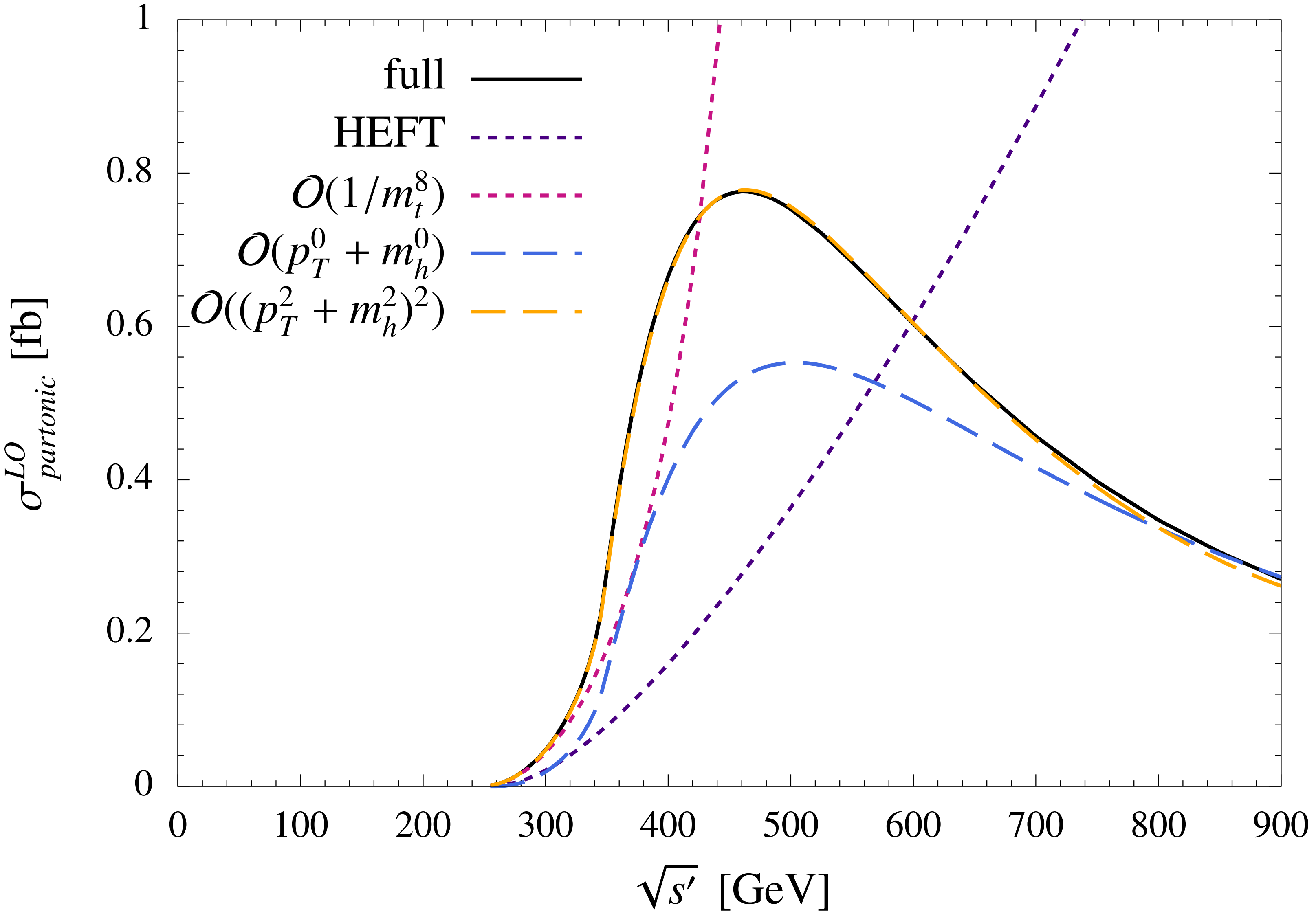
It starts diverging around

$$\sqrt{\hat{s}} \lesssim 500 - 600\, GeV$$

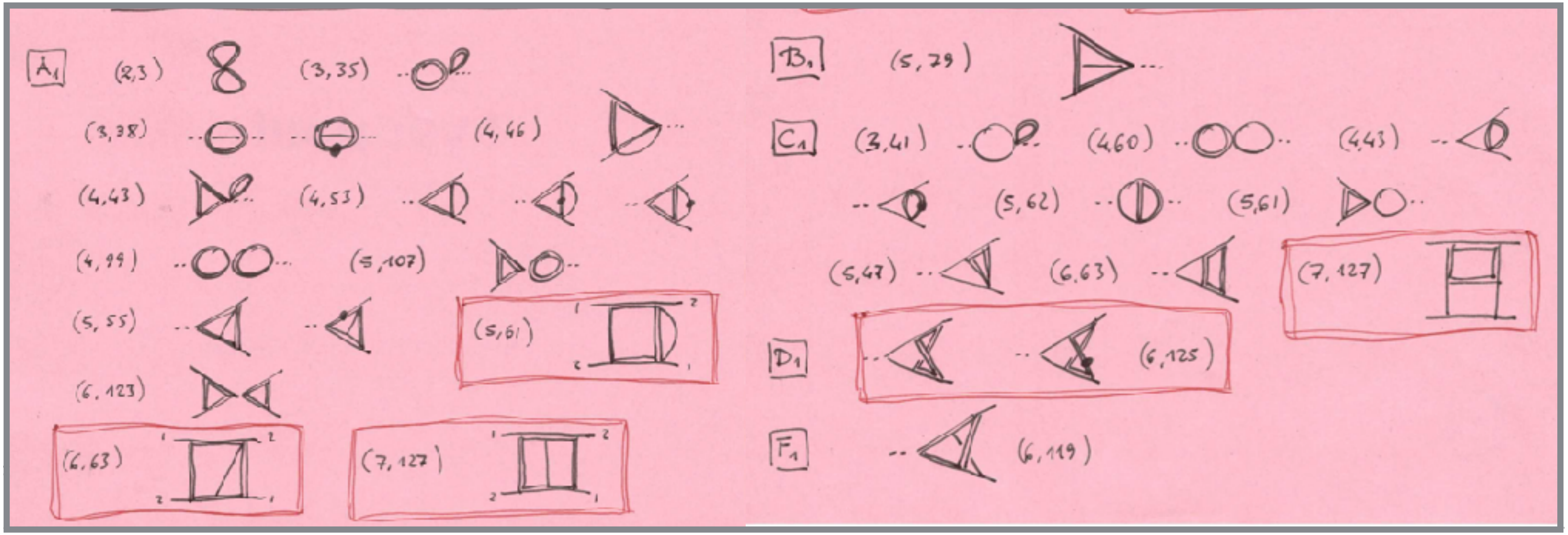
$$\hat{t}_m \lesssim 4m_T^2$$

Good approximation up to $\sqrt{\hat{s}} \lesssim 800 - 900\, GeV$!



The middle region is perfectly covered!

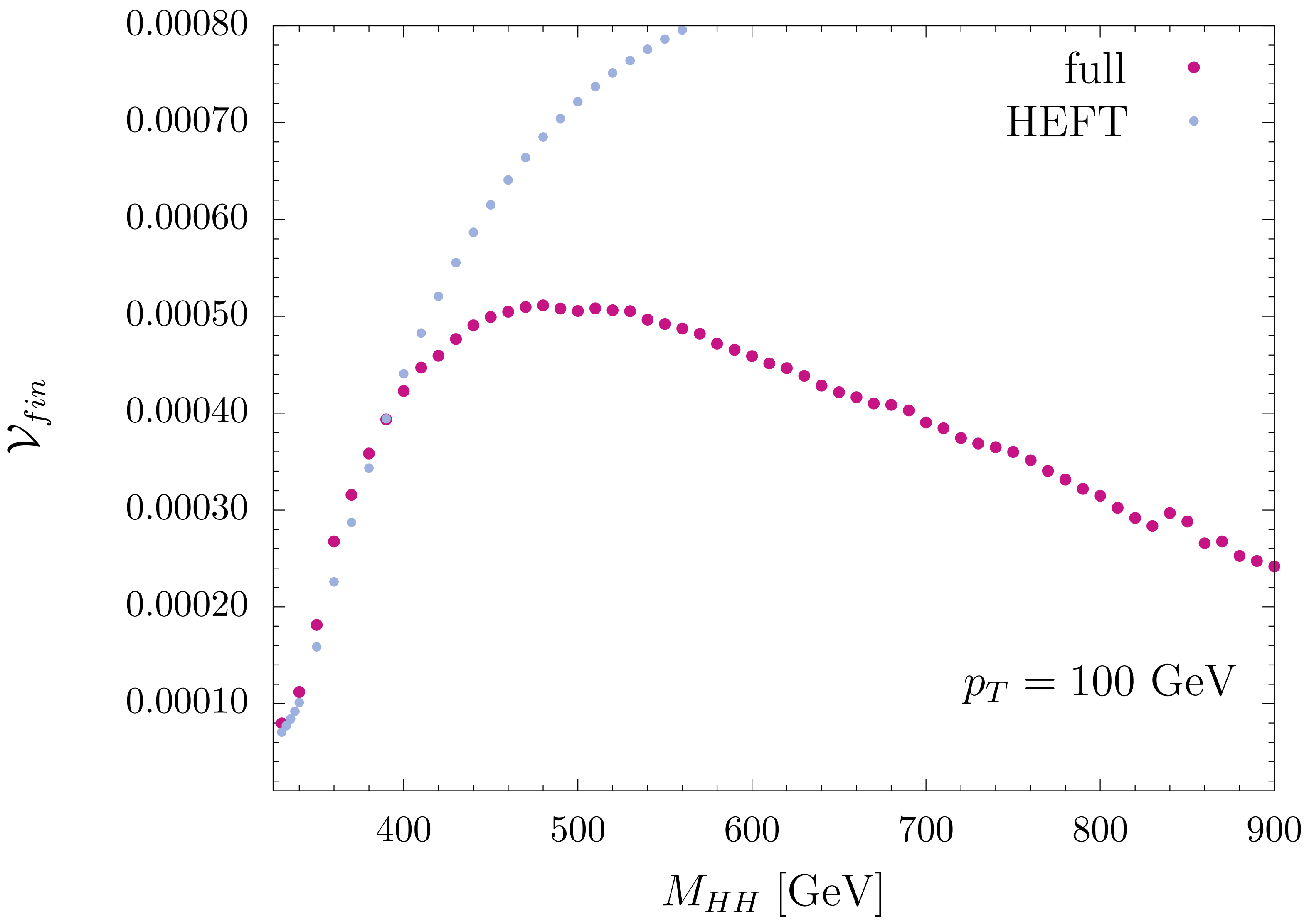
We did the expansion at the amplitude level and then reduced



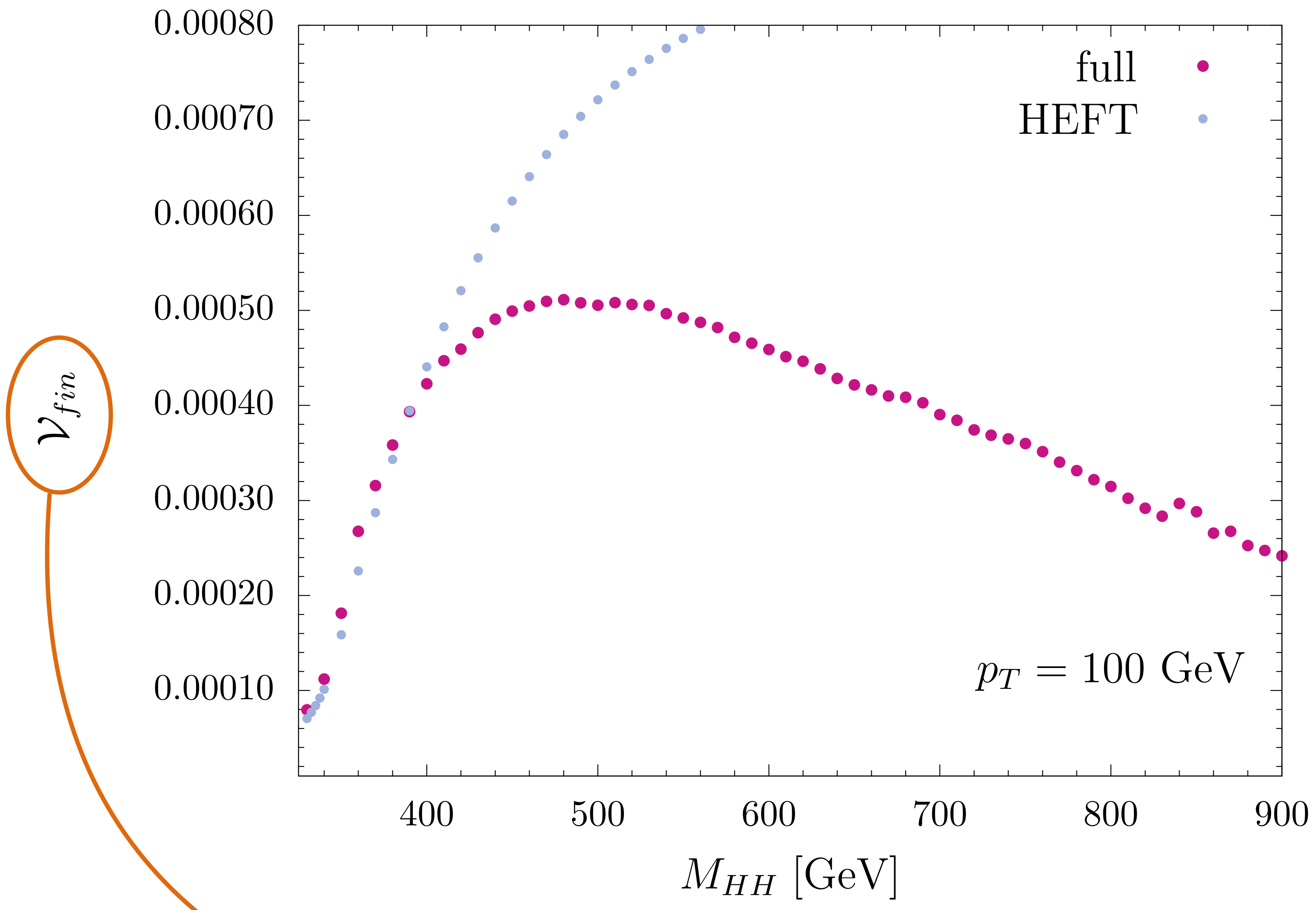
~50 MI known (recomputed in forward kinematics)

Nearly all expressed in terms of HPL

Higgs pair production at NLO

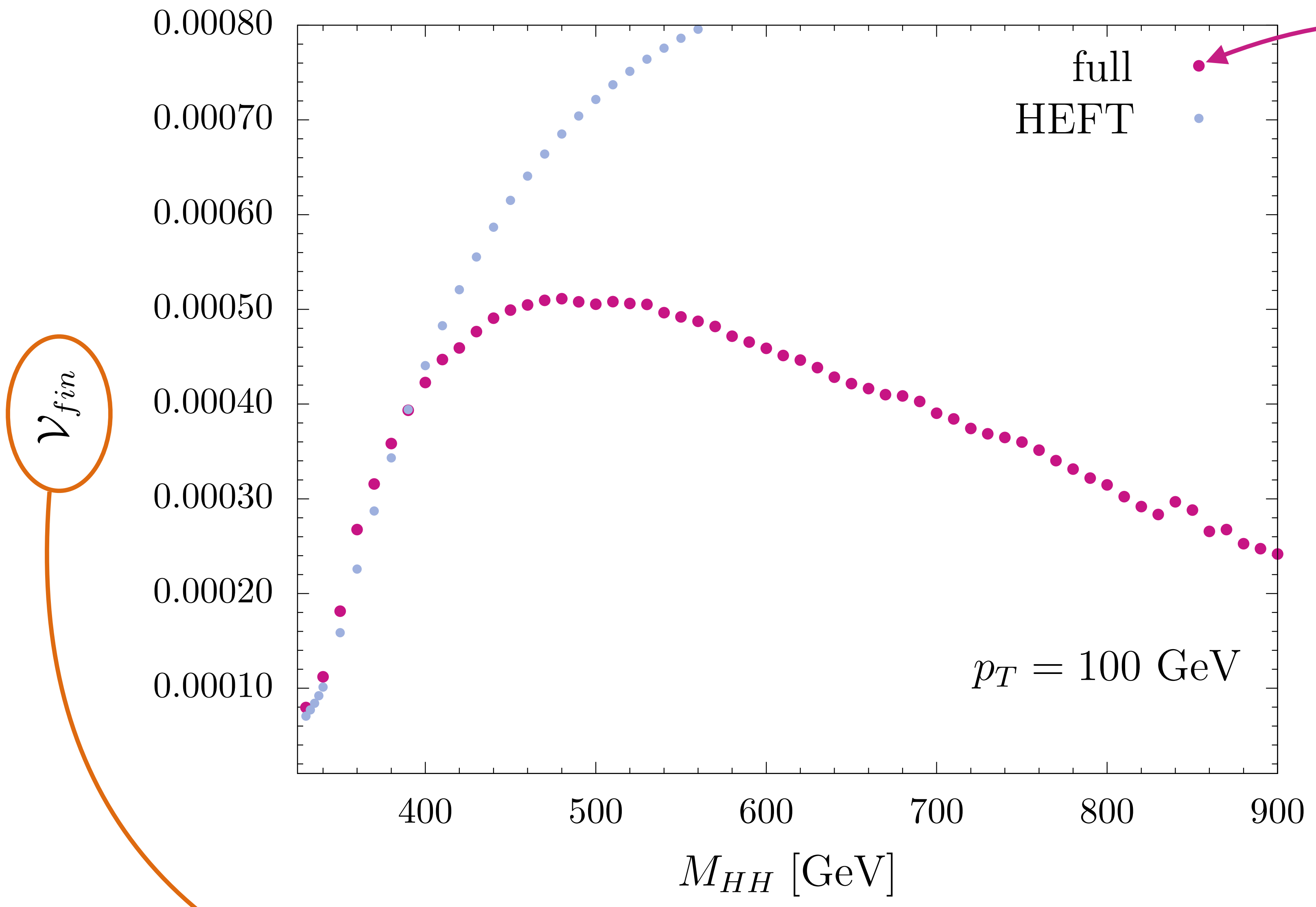


Grid and the interpolation function provided by G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni, and E. Vryonidou (17)



Finite part of the virtual correction

Grid and the interpolation function provided by G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni, and E. Vryonidou (17)



Full Numerical result

Finite part of the virtual correction

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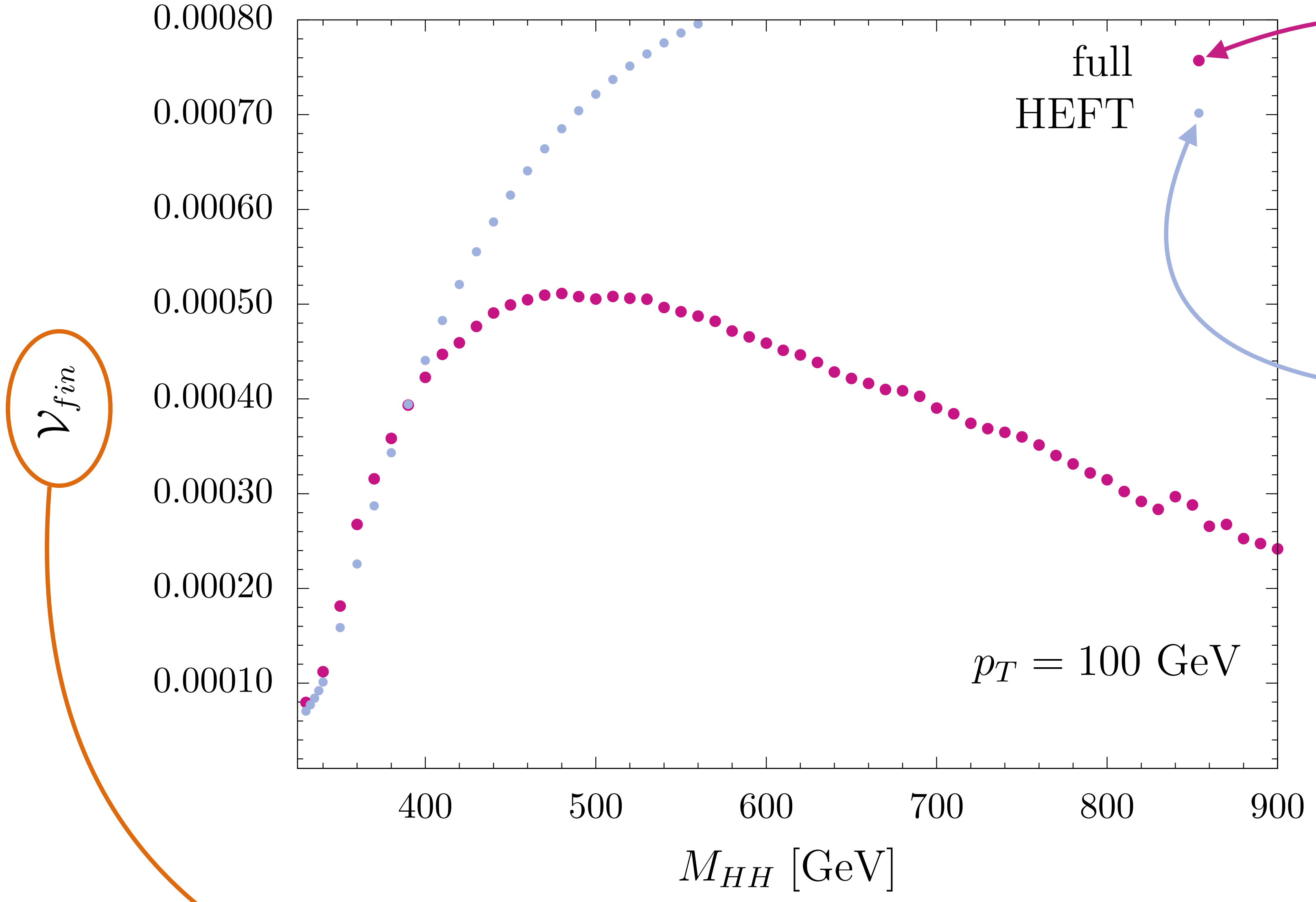

Full Numerical result

HEFT approximation

HEFT is good enough for low-energy region

Finite part of the virtual correction

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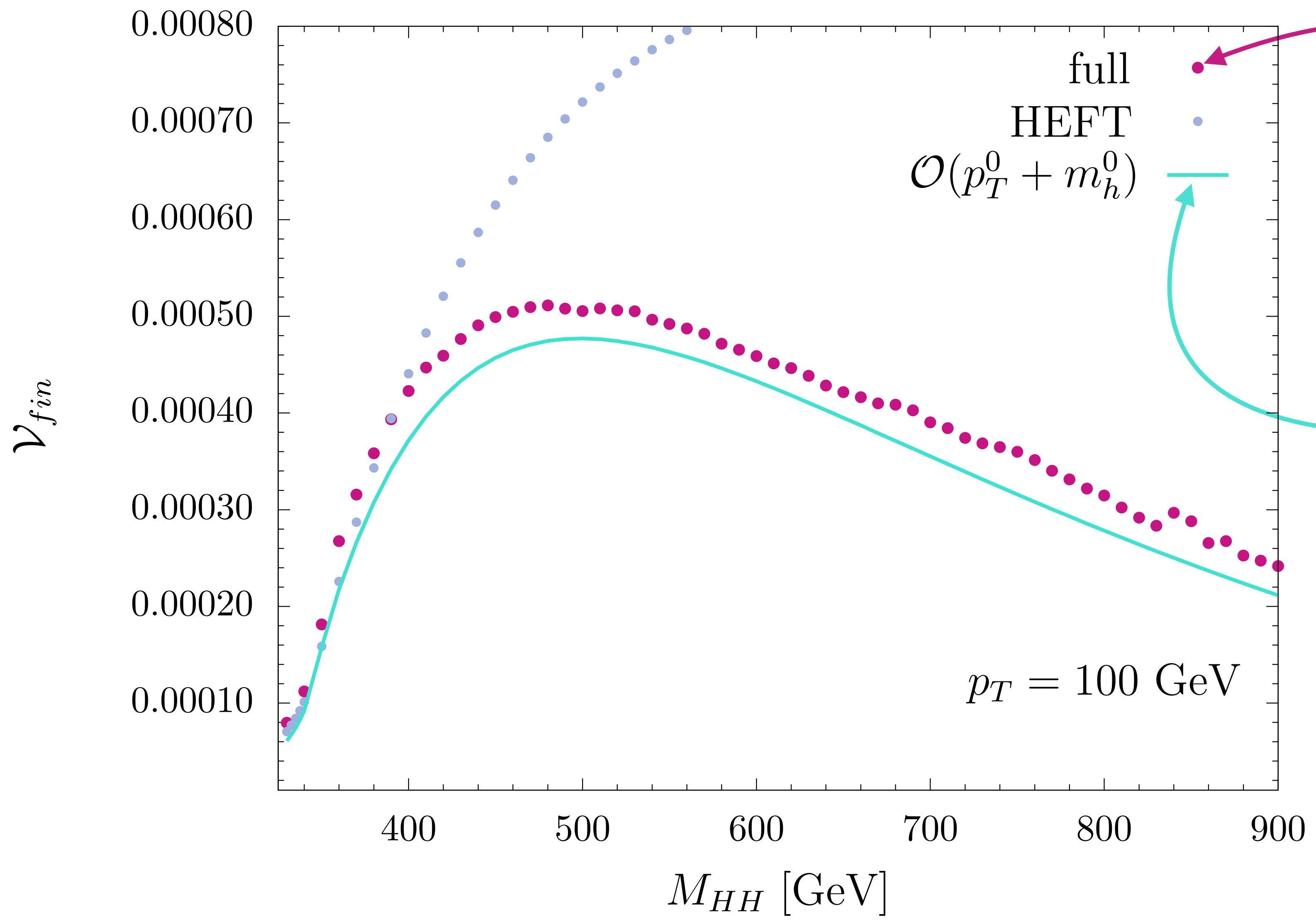
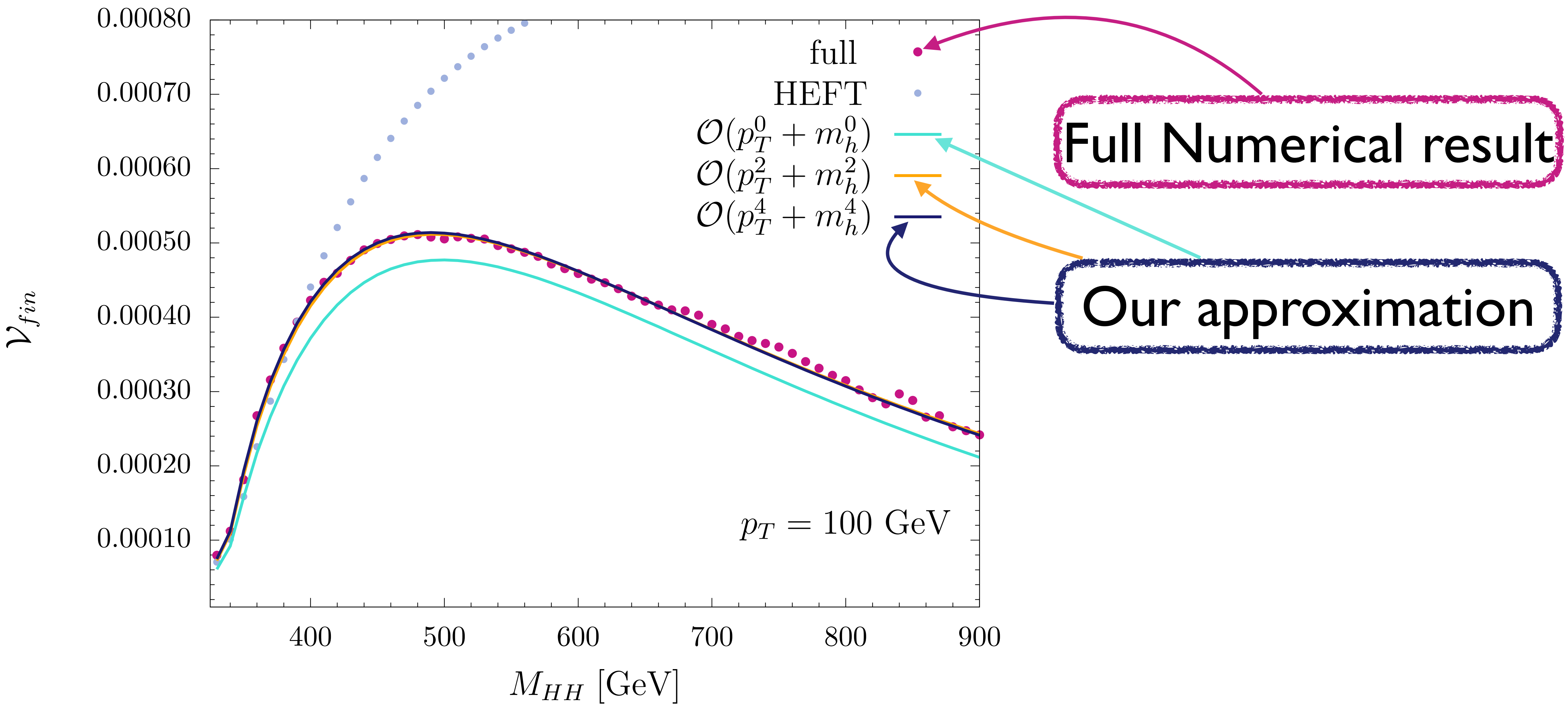


Full Numerical result

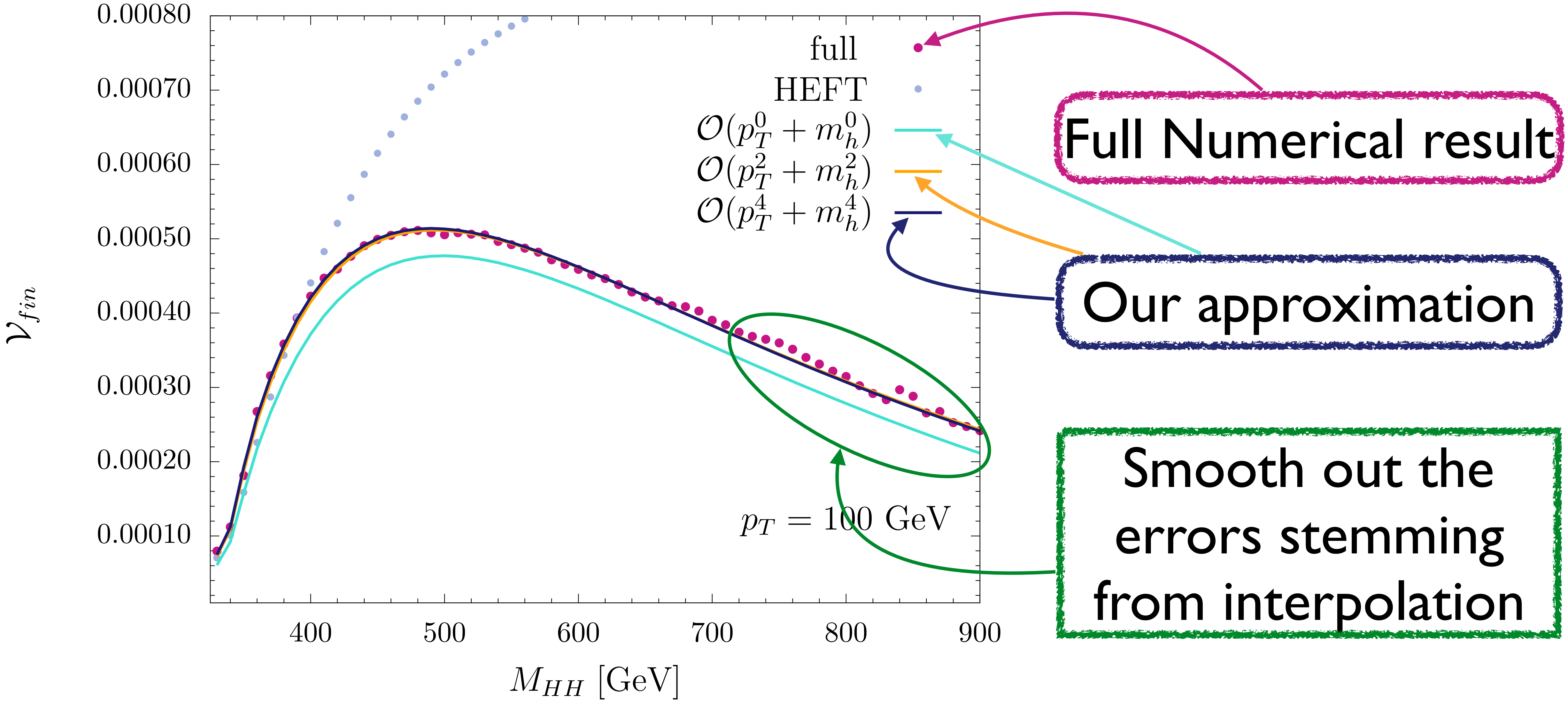
Our approximation

Approximation good already at order $\mathcal{O}(p_T^0)$



Full Numerical result

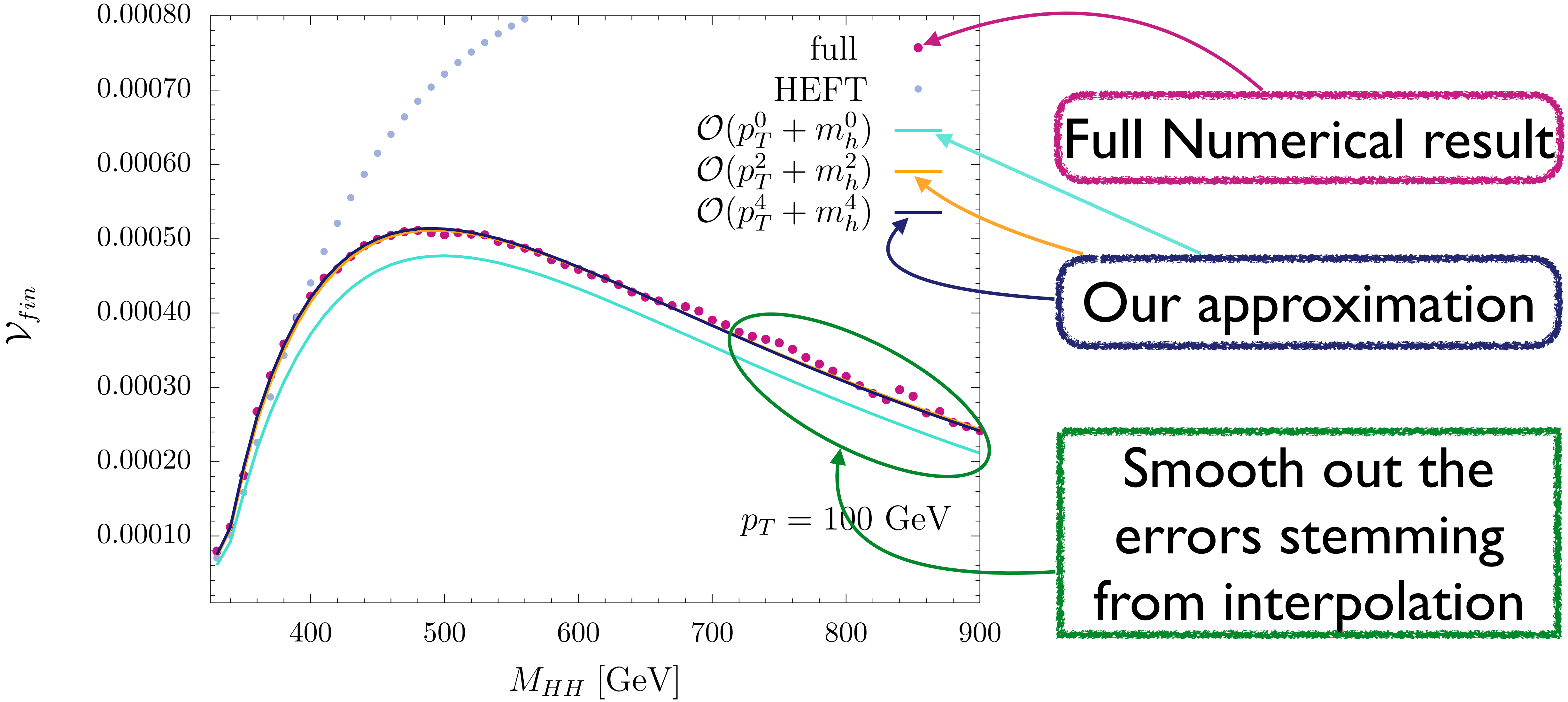
Our approximation



Full Numerical result

Our approximation

Smooth out the errors stemming from interpolation



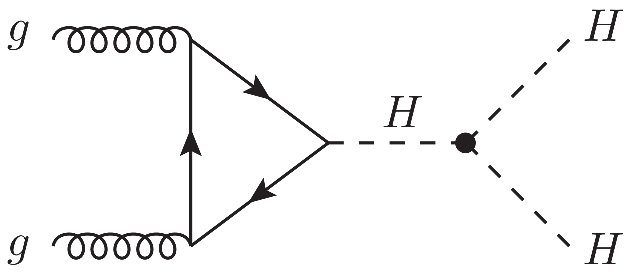
Full Numerical result

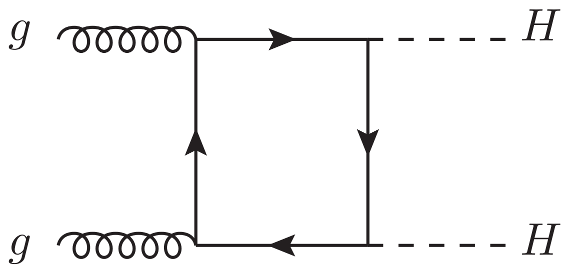
Our approximation

Smooth out the errors stemming from interpolation

1 phase-space point: ~4 seconds on a MacBook Air

In search of the Higgs trilinear coupling





Very small cross section:

- Heavier final state.
- Additional weak coupling.
- Destructive interference

13 TeV

$$gg \to H \sim 40000\,\mathrm{fb}$$
$$gg \to HH \sim 30\,\mathrm{fb}$$

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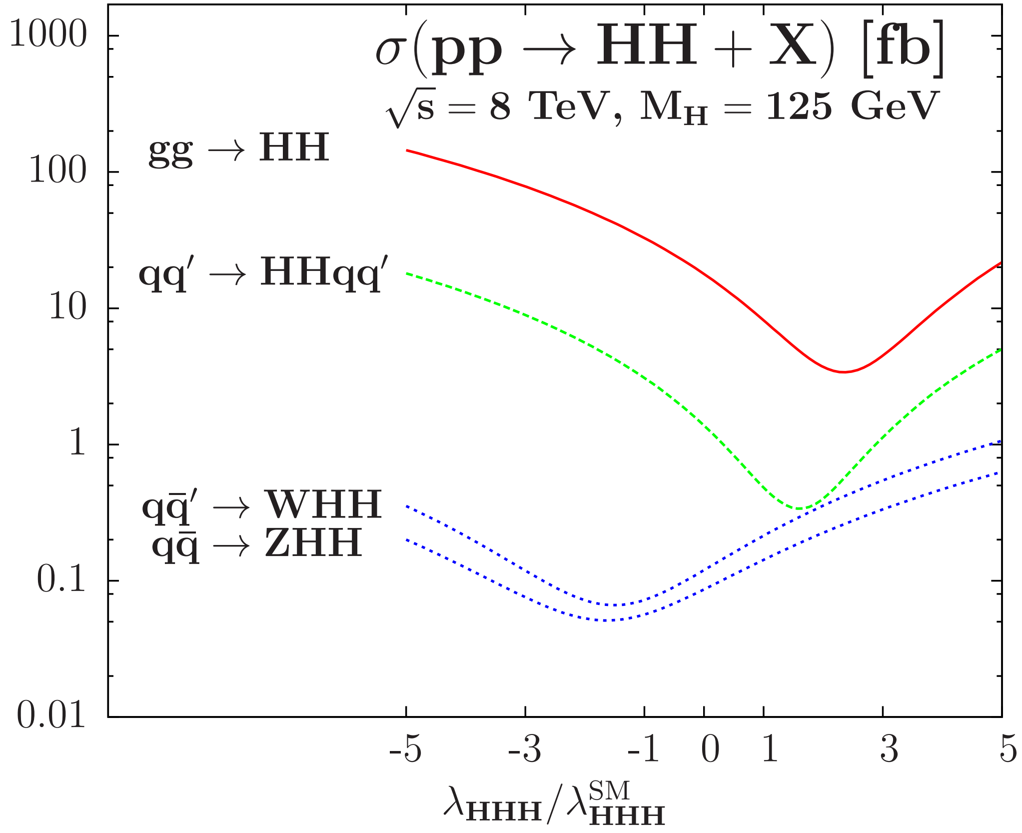
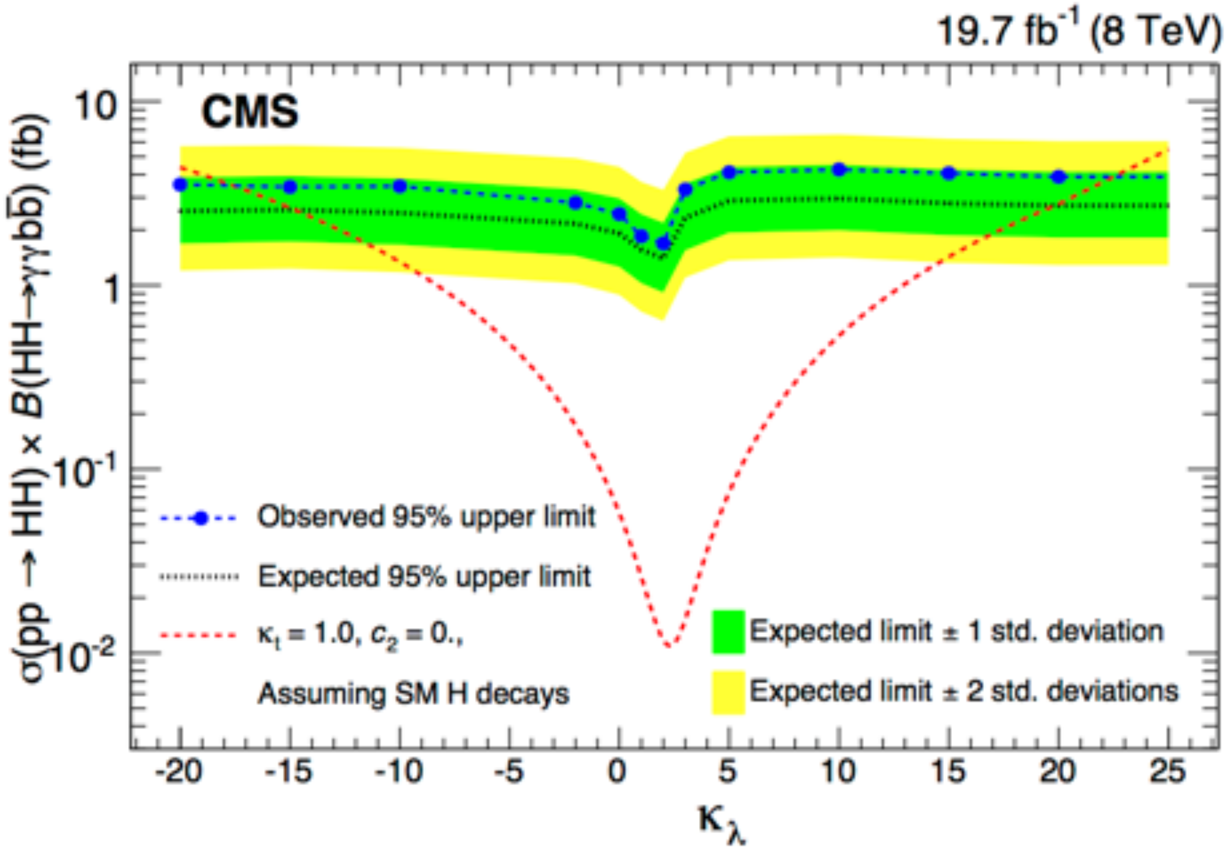
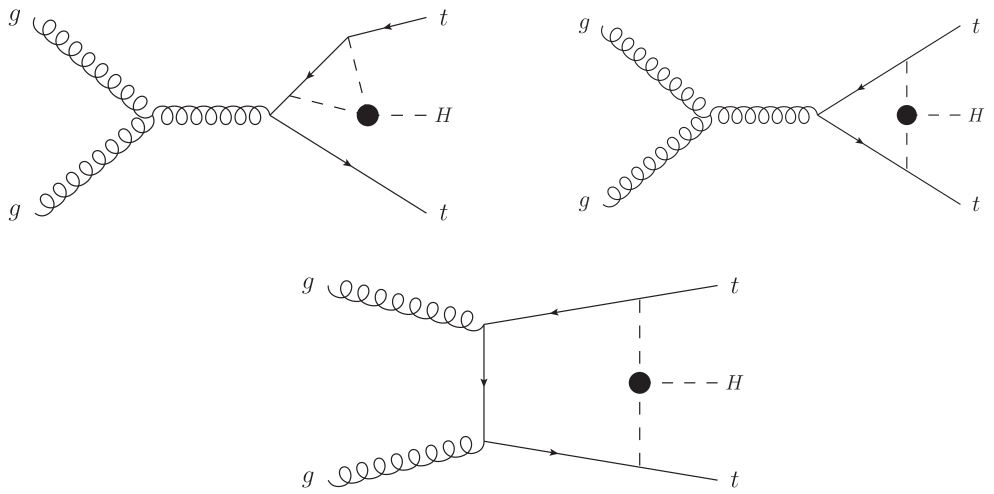
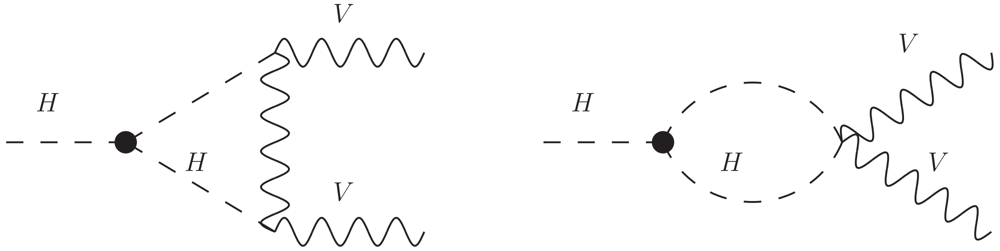




The trilinear appears at NLO in Single Higgs processes.

$$V_{H^3} = \lambda_3 v H^3 \equiv \kappa_\lambda \lambda_3^{\mathrm{SM}} v H^3$$





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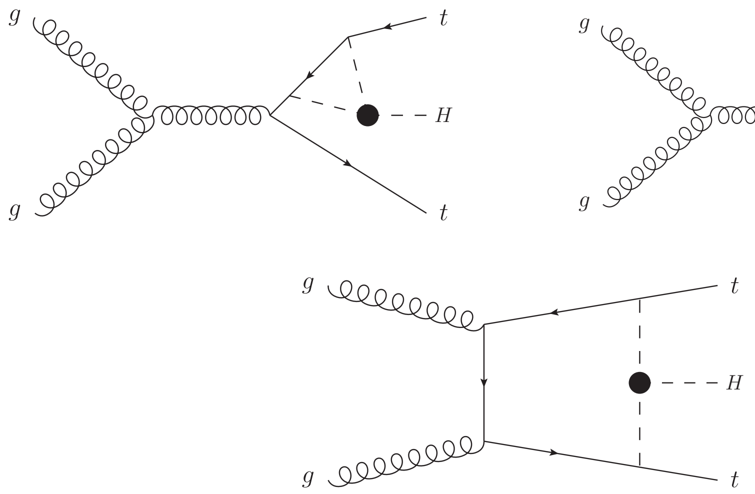

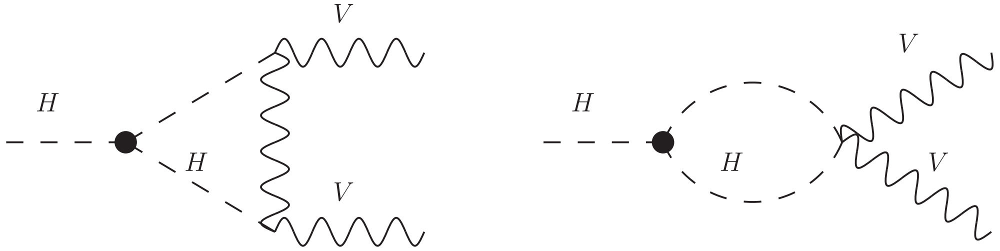

Due to the presence of different Loop structures these contributions cannot be captured by a local rescaling.

For similar ideas:
M. McCullough Phys. Rev. D90 (2014), no. 1 015001
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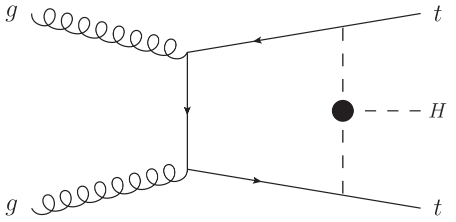

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Working assumption: only the trilinear is modified

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$$\Sigma_{NLO} = Z_H \Sigma_{LO}(1 + \kappa_\lambda C_1)$$

Contains QCD corrections

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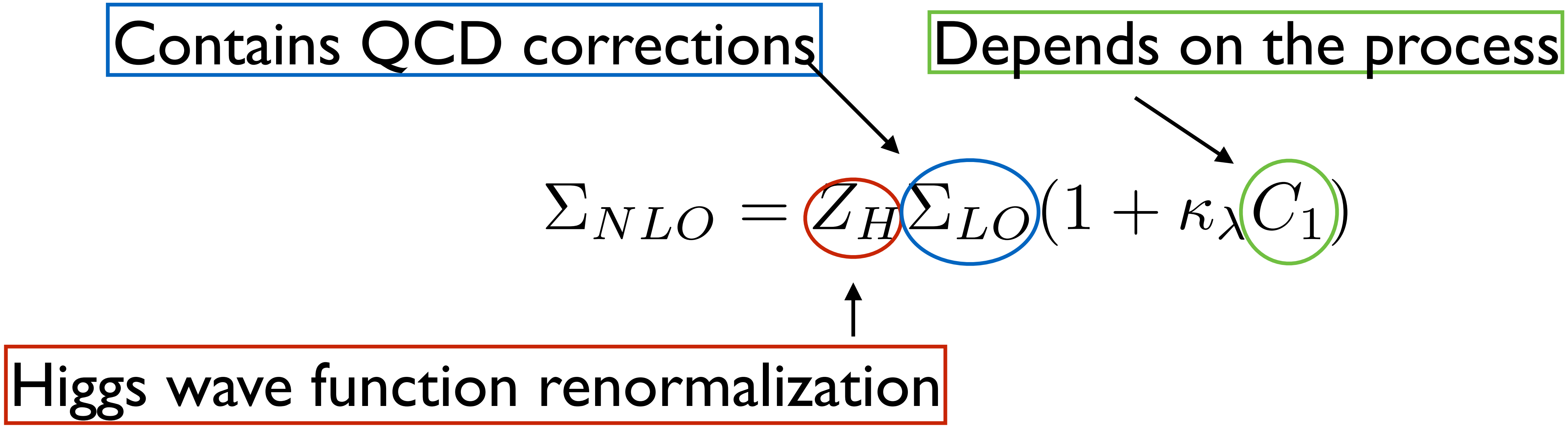

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Higgs wave function renormalization

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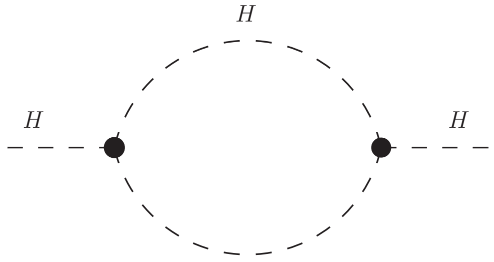

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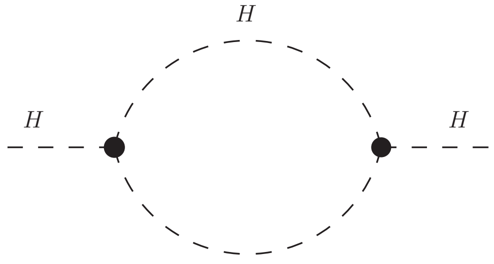

The range of validity of our calculation is $\boxed{|\kappa_\lambda| \lesssim 20}$

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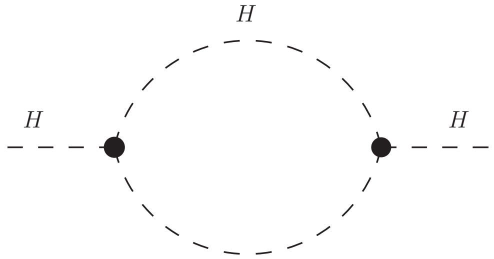

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$$C_1 = \frac{\int 2\Re(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM}})}{\int |\mathcal{M}^0|^2}$$

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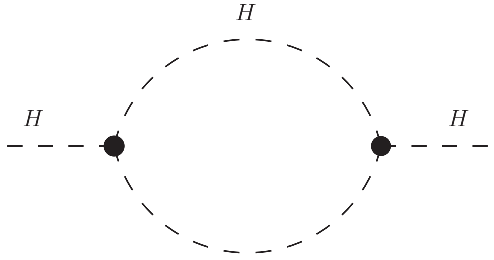

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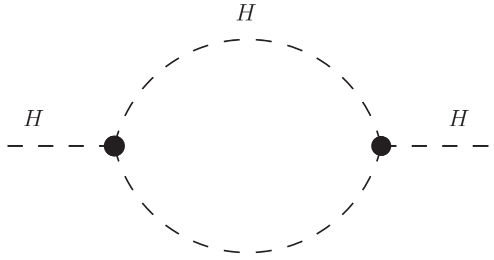

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Amplitudes at LO and NLO

Contains QCD corrections

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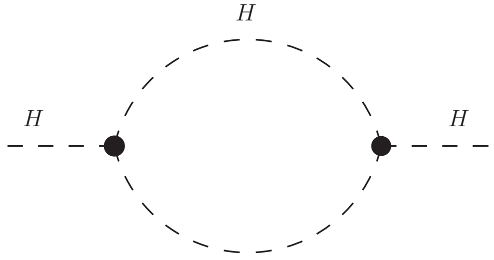

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Amplitudes at LO and NLO

Depends on kinematics

What does it mean to calculate corrections in κ-framework?

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$$\xi = \varphi^+\varphi^- + \frac{1}{2}\varphi_0^2$$

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Correlation between modifications

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$$\boxed{\frac{m_H^2}{2v}k_\lambda}$$

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Quartic does not contribute. κ-framework equivalent to EFT

(For the calculations presented here)

What kind of physics are we looking for?

Unitary conditions for $HH \to HH$ → $|\kappa_\lambda| \lesssim 6$

Di Luzio Gröber Spannowsky(13)

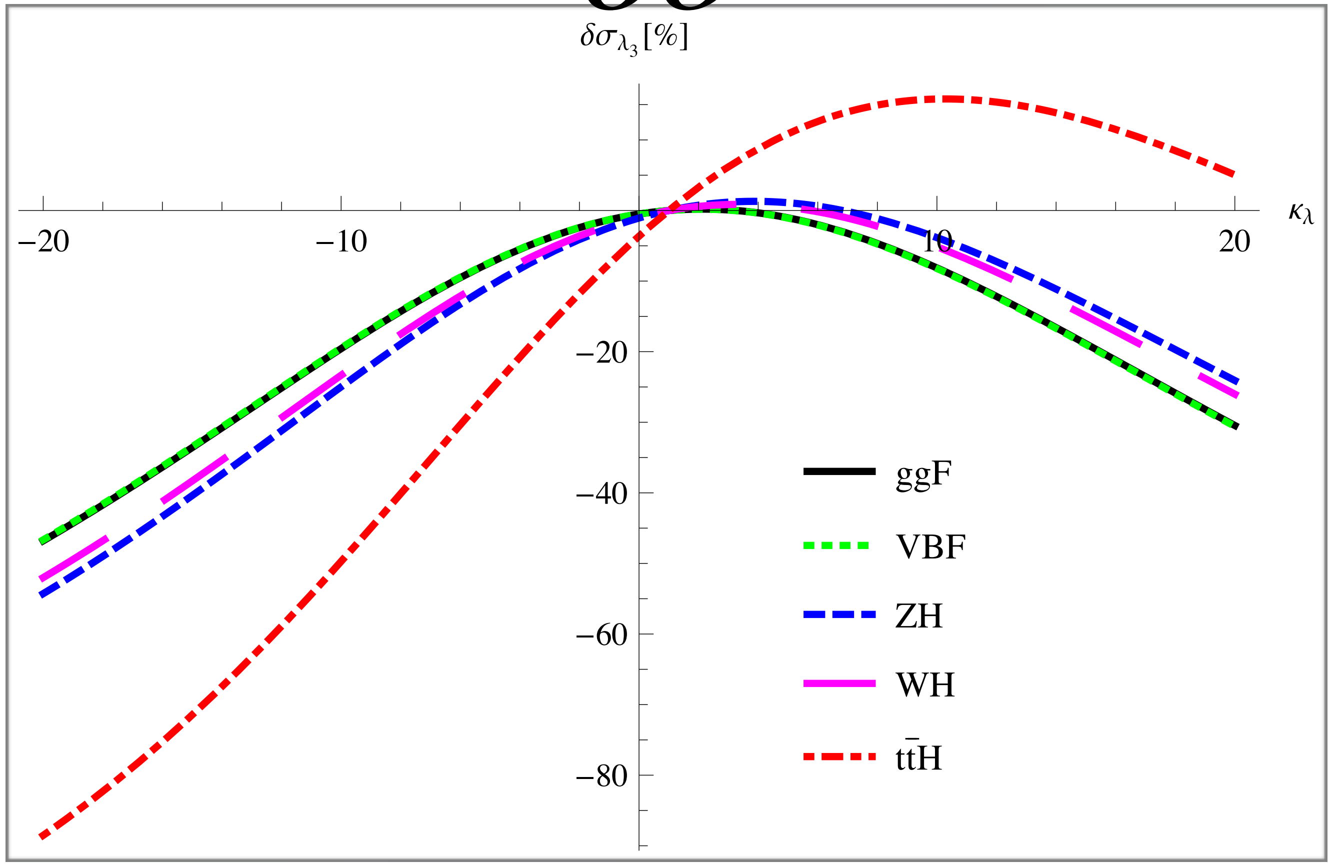
Higgs portal + tuning → $|\kappa_\lambda| \lesssim 6$

Di Vita et al (17)

Unitary conditions for $V_L V_L \to V_L V_L H^n$ → $|\kappa_\lambda| \lesssim 10$

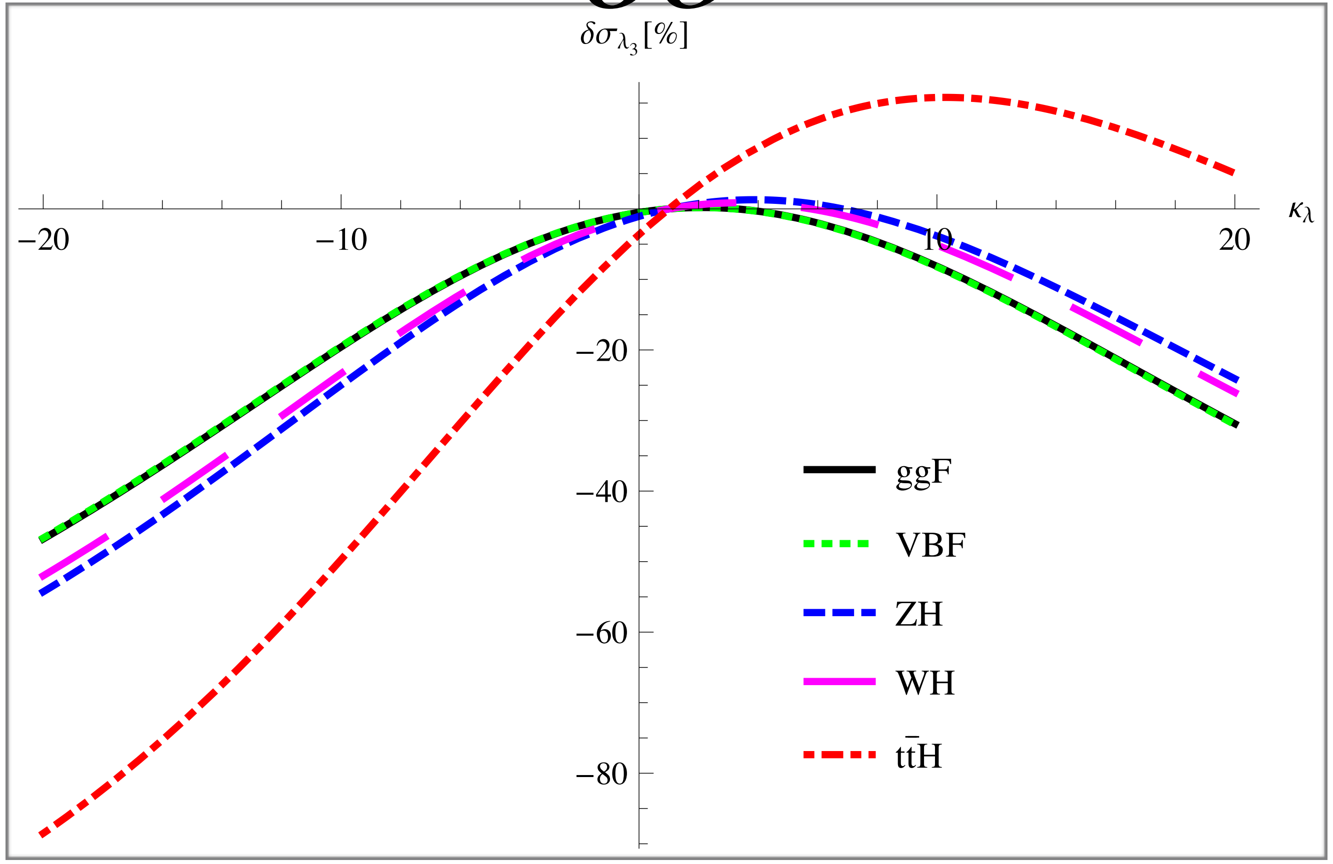
Falkowski Rattazzi

$\delta\sigma$



$\delta\sigma_{\lambda_3}[\%]$
κ_λ
−20
−10
10
20
−20
−40
−60
−80
ggF
VBF
ZH
WH
$t\bar{t}H$

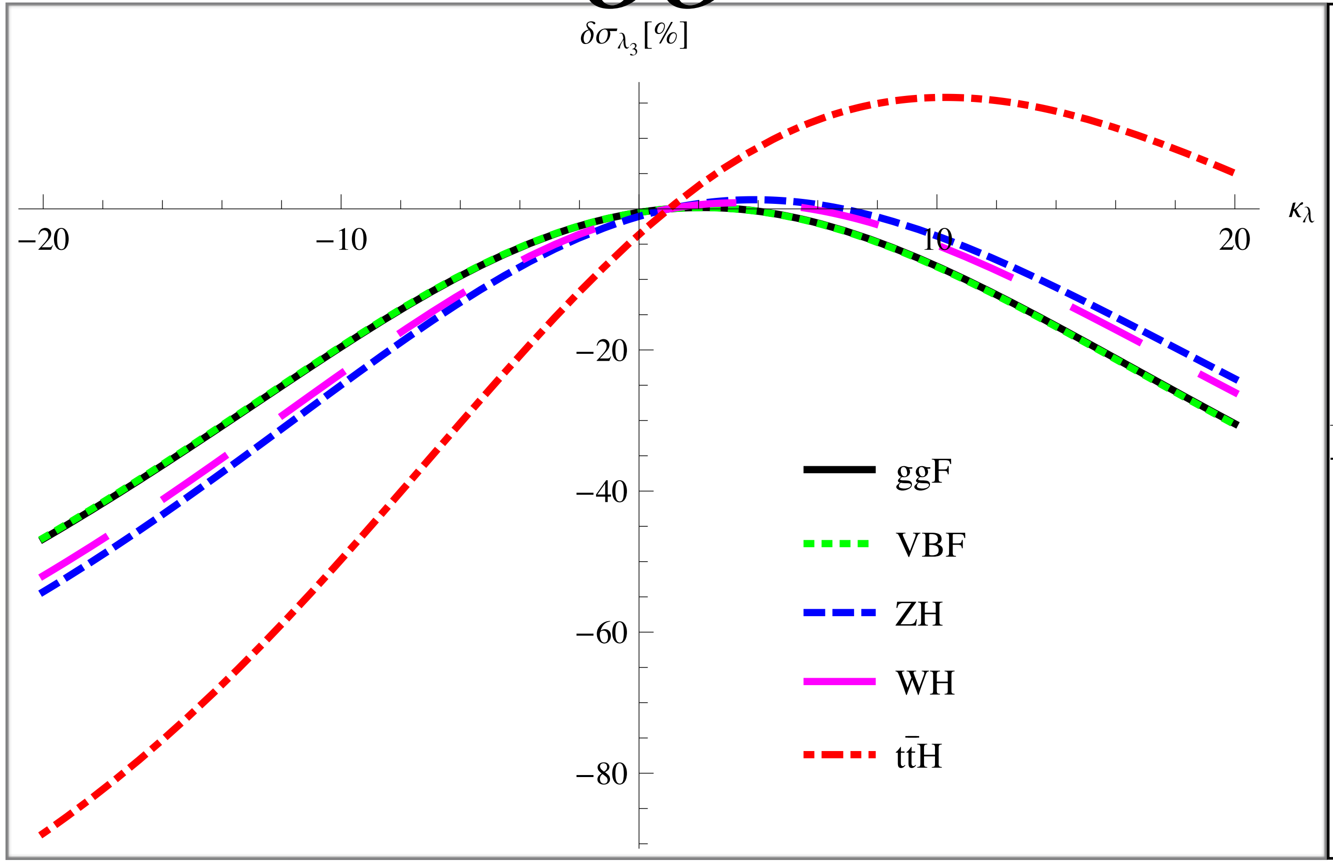
$\delta\sigma$



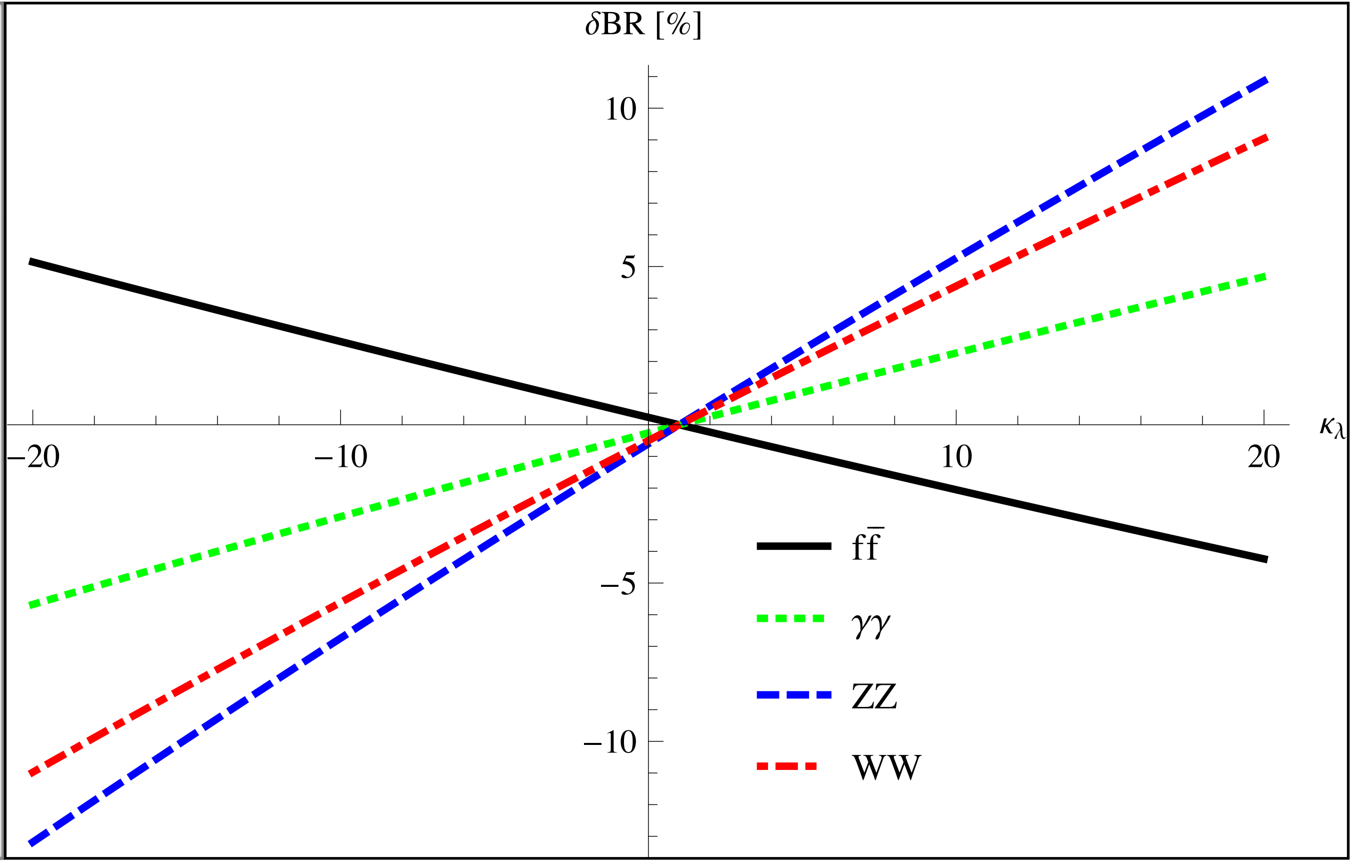
$t\bar{t}H$ receives sizeable positive corrections.

All the other receive very small positive corrections

$\delta\sigma$



δBR



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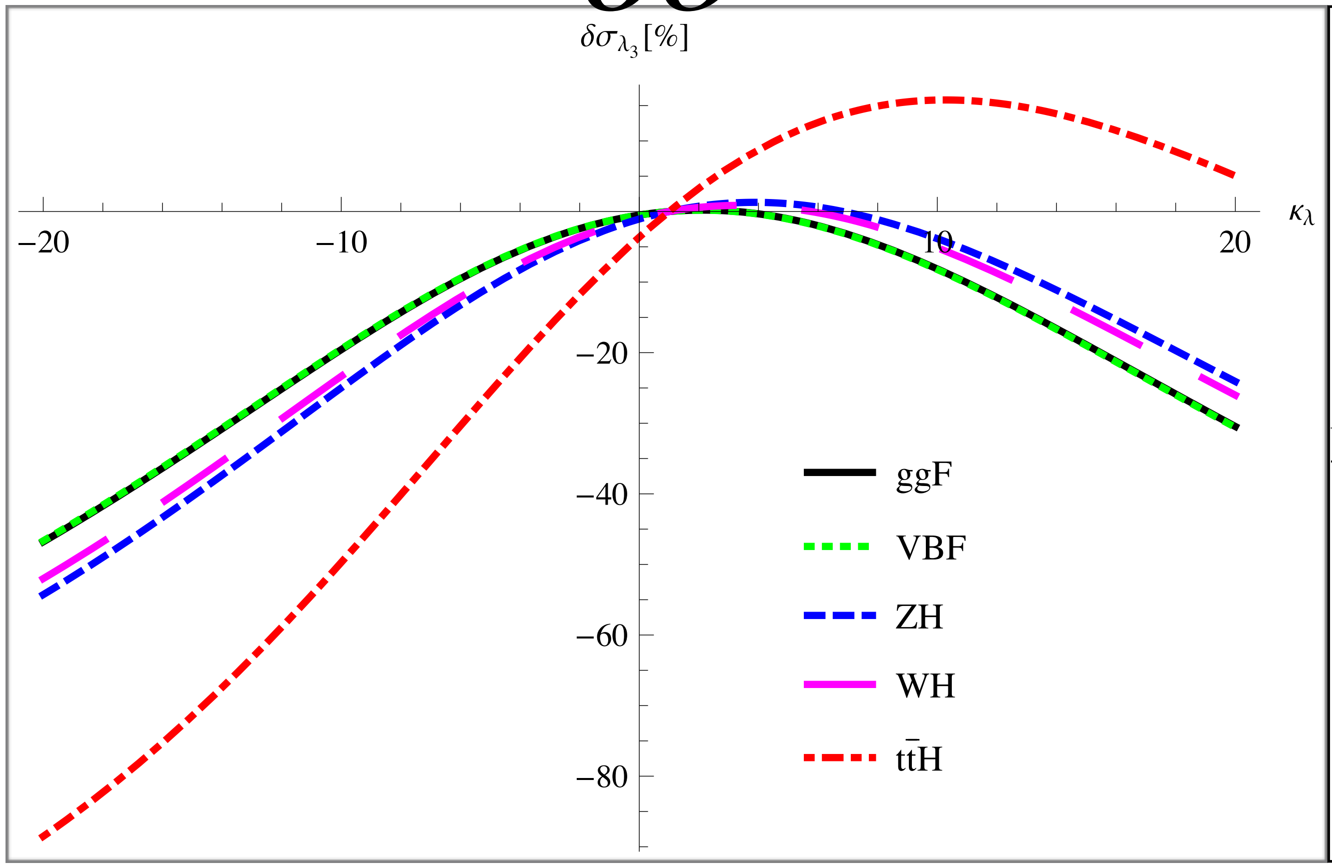

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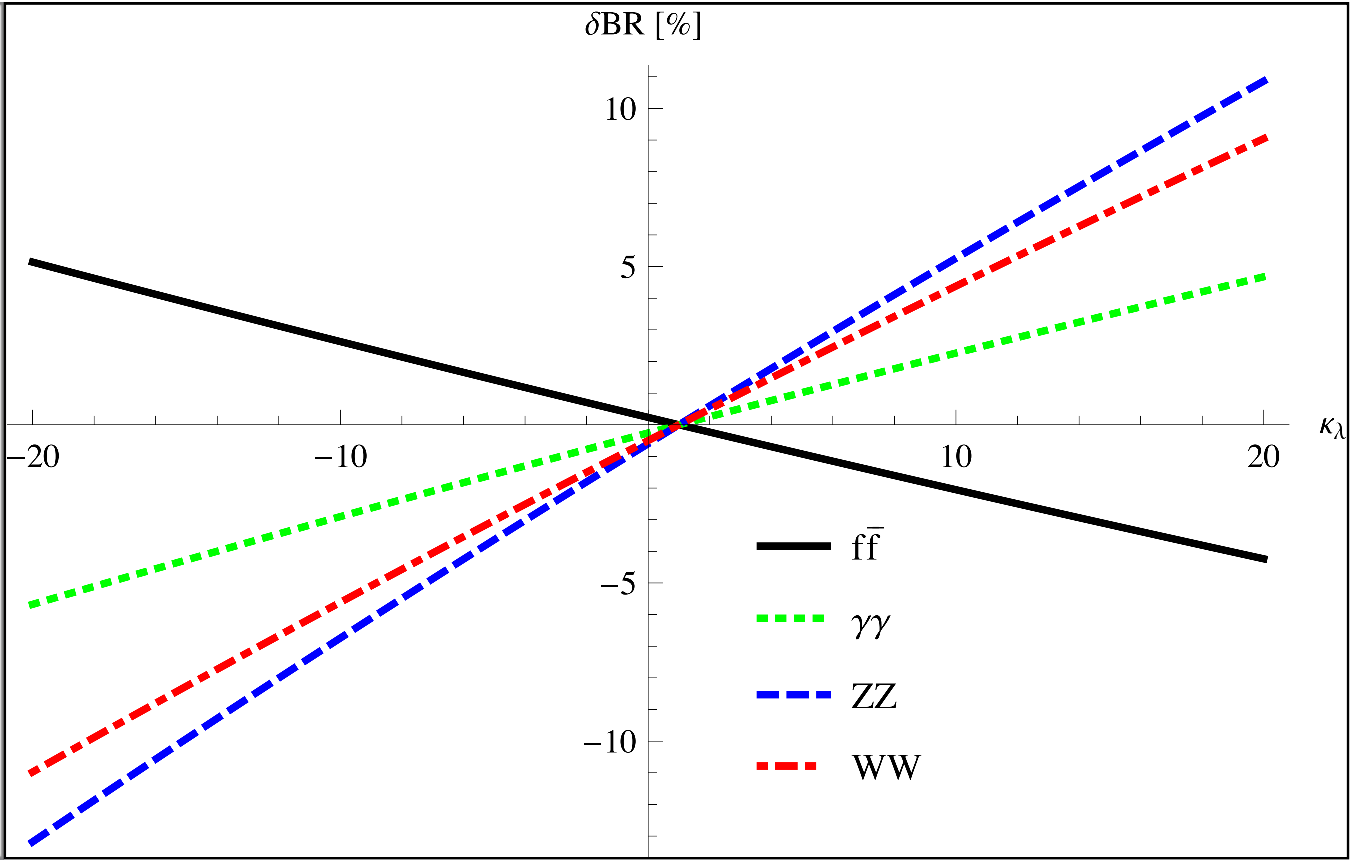
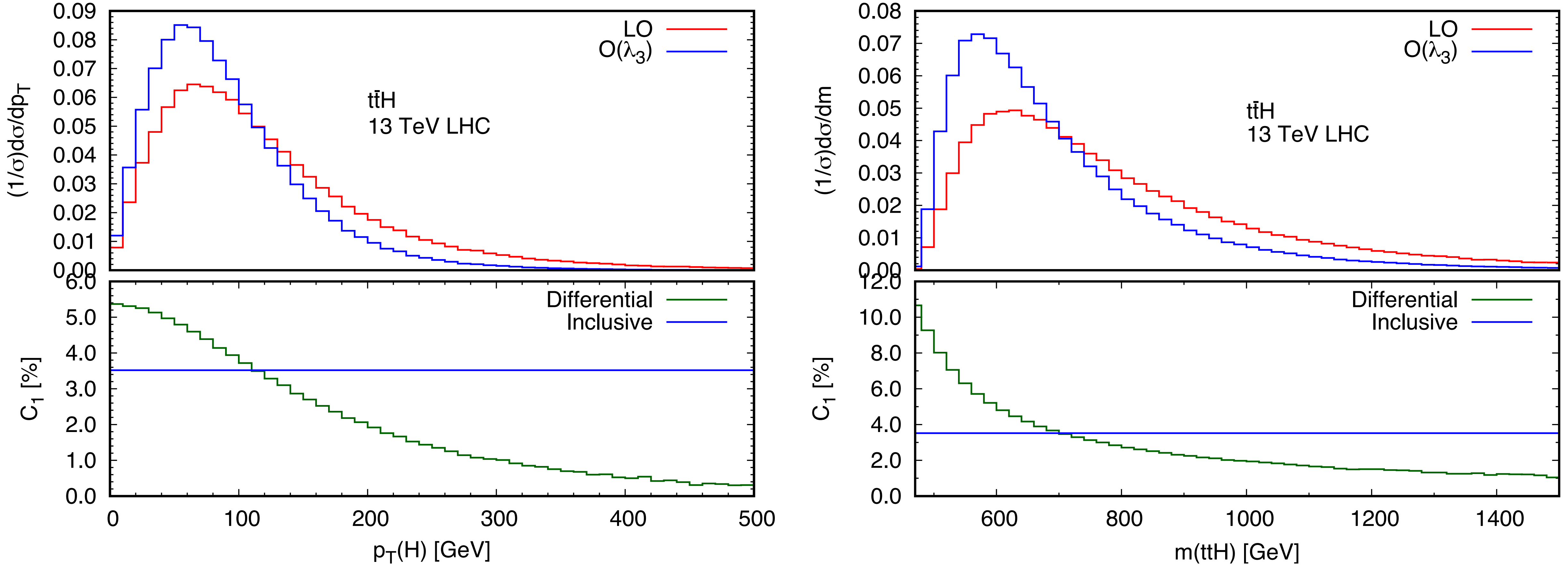


Quadratic dependence on κ cancels in the ratio.

In the range close to the SM, the decays are more sensitive to κ than the production processes

Further information can be extracted from differential distribution



F. Maltoni, D. Pagani, A.Shivaji, X. Zhao (17)

Large effects at the threshold

Another source of information: P.O.

$$m_W^2 = \frac{\hat{\rho}\, m_Z^2}{2}\left\{1 + \left[1 - \frac{4\hat{A}^2}{m_Z^2\hat{\rho}}(1 + \Delta\hat{r}_W)\right]^{1/2}\right\}$$

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$$\hat{\rho} \sim \frac{A_{ZZ}(M_Z^2)}{m_Z^2} - \frac{A_{WW}(M_W^2)}{m_W^2} + \ldots \qquad \Delta\hat{r}_W \sim \frac{A_{WW}(M_W^2)}{m_W^2} - \frac{A_{WW}(0)}{m_W^2} + \ldots$$

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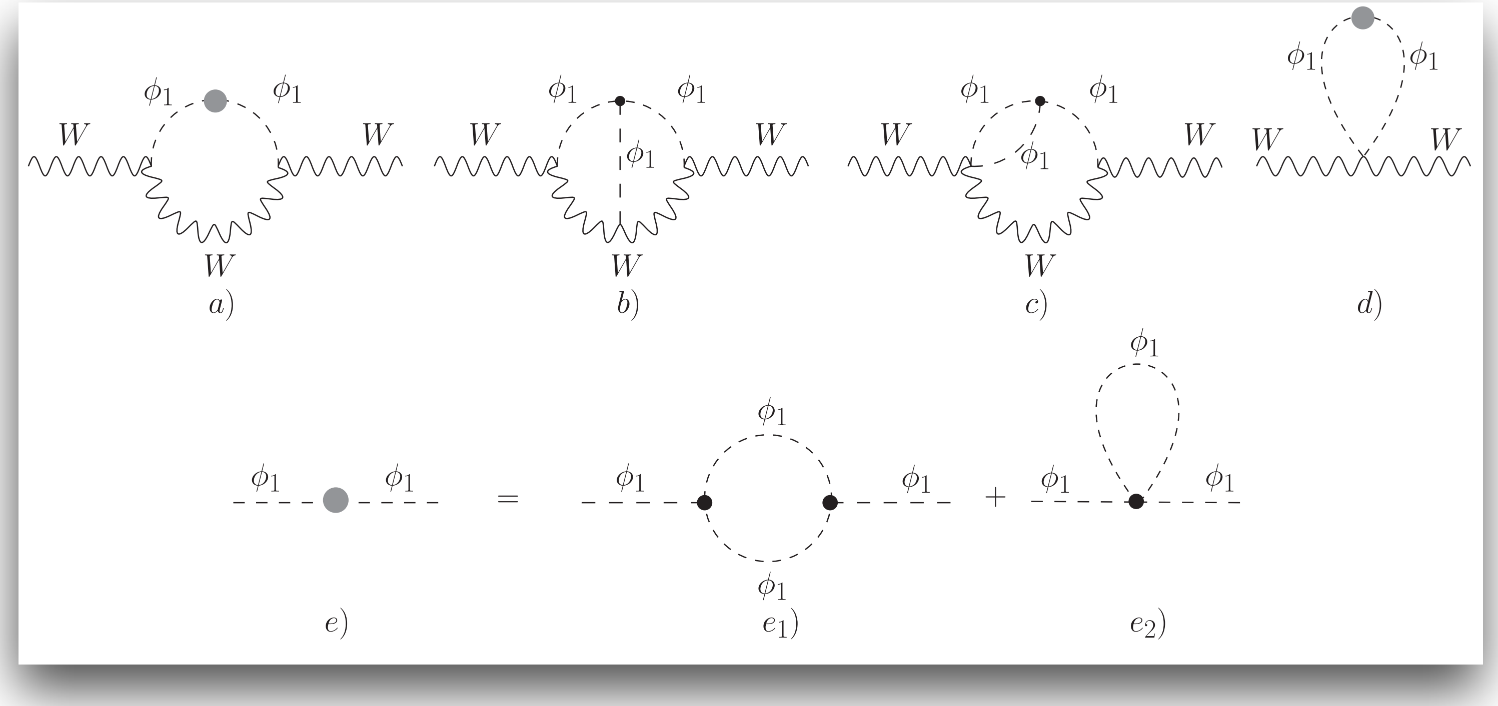

Two loops dependence on κ

Constraints on trilinear coupling

- Run I (7-8 TeV):
  - ATLAS and CMS: $\mathcal{O}(\pm(15-20))$
  - Our constraint using ggF+VBF: $\kappa_\lambda > -14.3$
  - Our constraint using ggF+VBF+EW: $-13.3 < \kappa_\lambda < 20.0$
- Future capabilities (3000 fb^{-1}):
  - ATLAS constraint: $-1.3 < \kappa_\lambda < 8.7$
  - Our result: $-2.8 < \kappa_\lambda < 7.9$

Constraints on trilinear coupling

Higgs Pair Production

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Single Higgs Production

Constraints on trilinear coupling

Data from JHEP 1608 (2016) 045

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PDG2016

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Using arXiv:1312.4974

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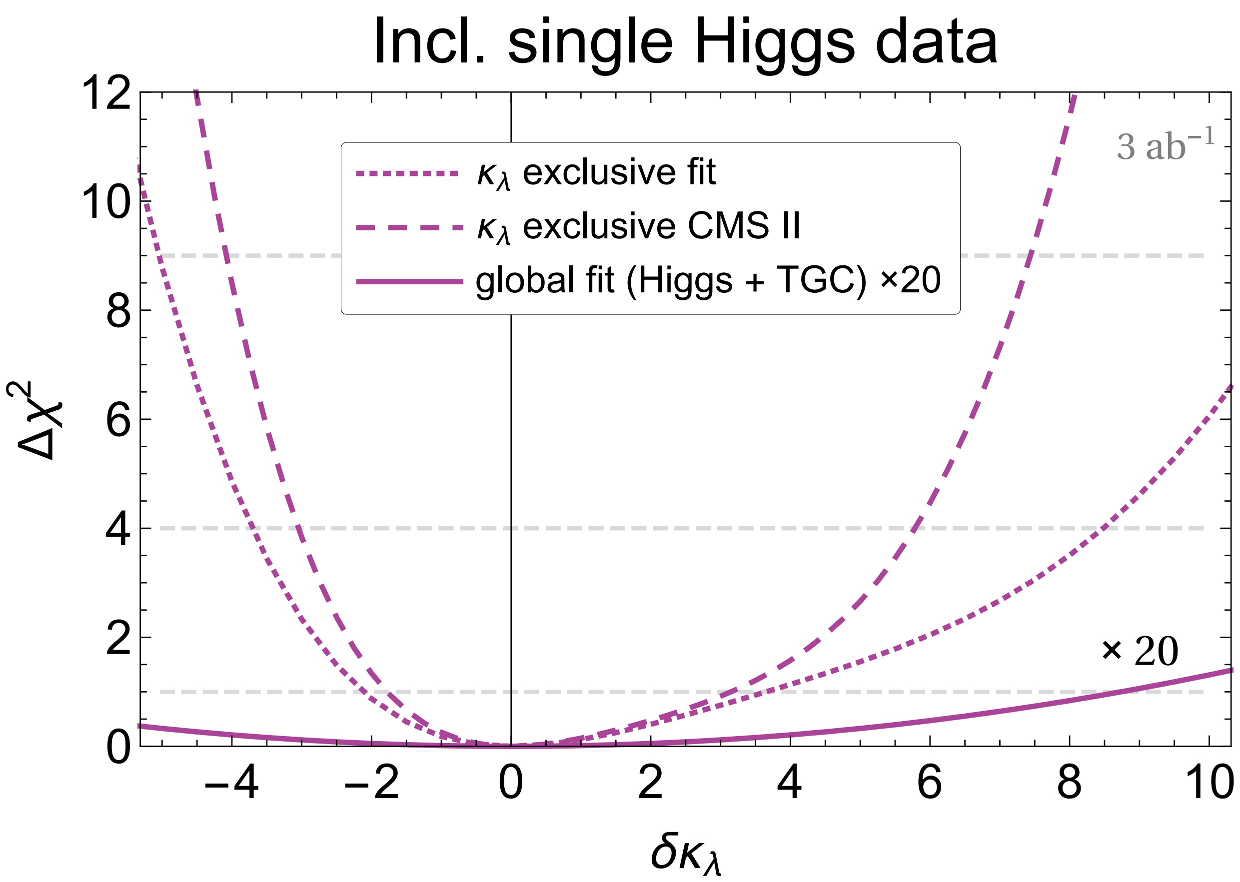
At higher luminosities we can relax our assumptions

JHEP 1709 (2017) 069



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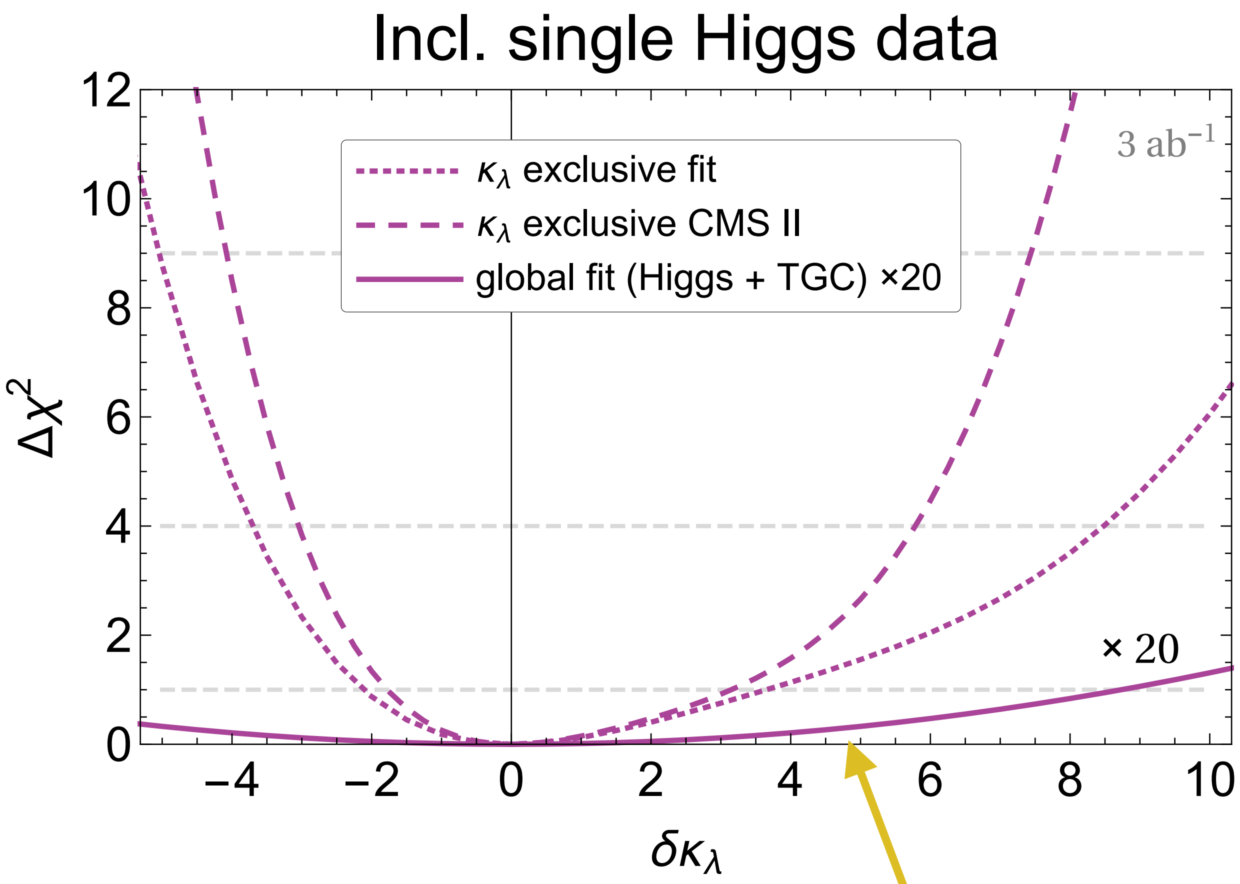
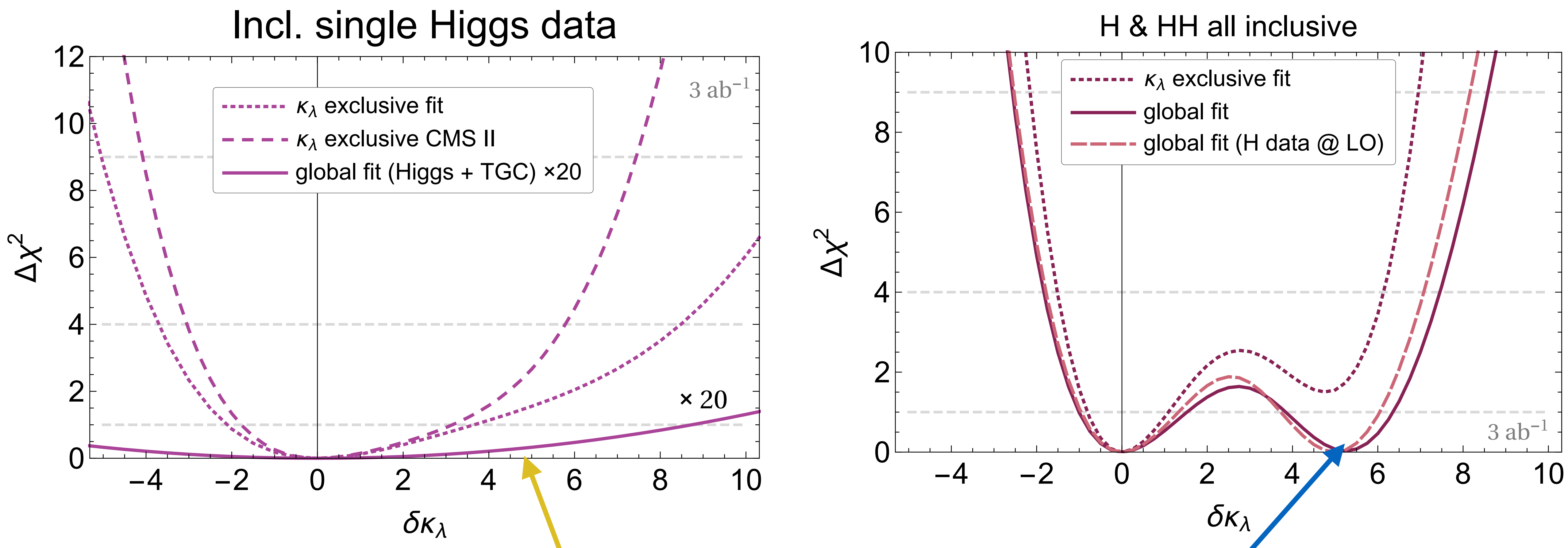
JHEP 1709 (2017) 069



Degeneracy due to global fit (flat direction)

At higher luminosities we can relax our assumptions

JHEP 1709 (2017) 069

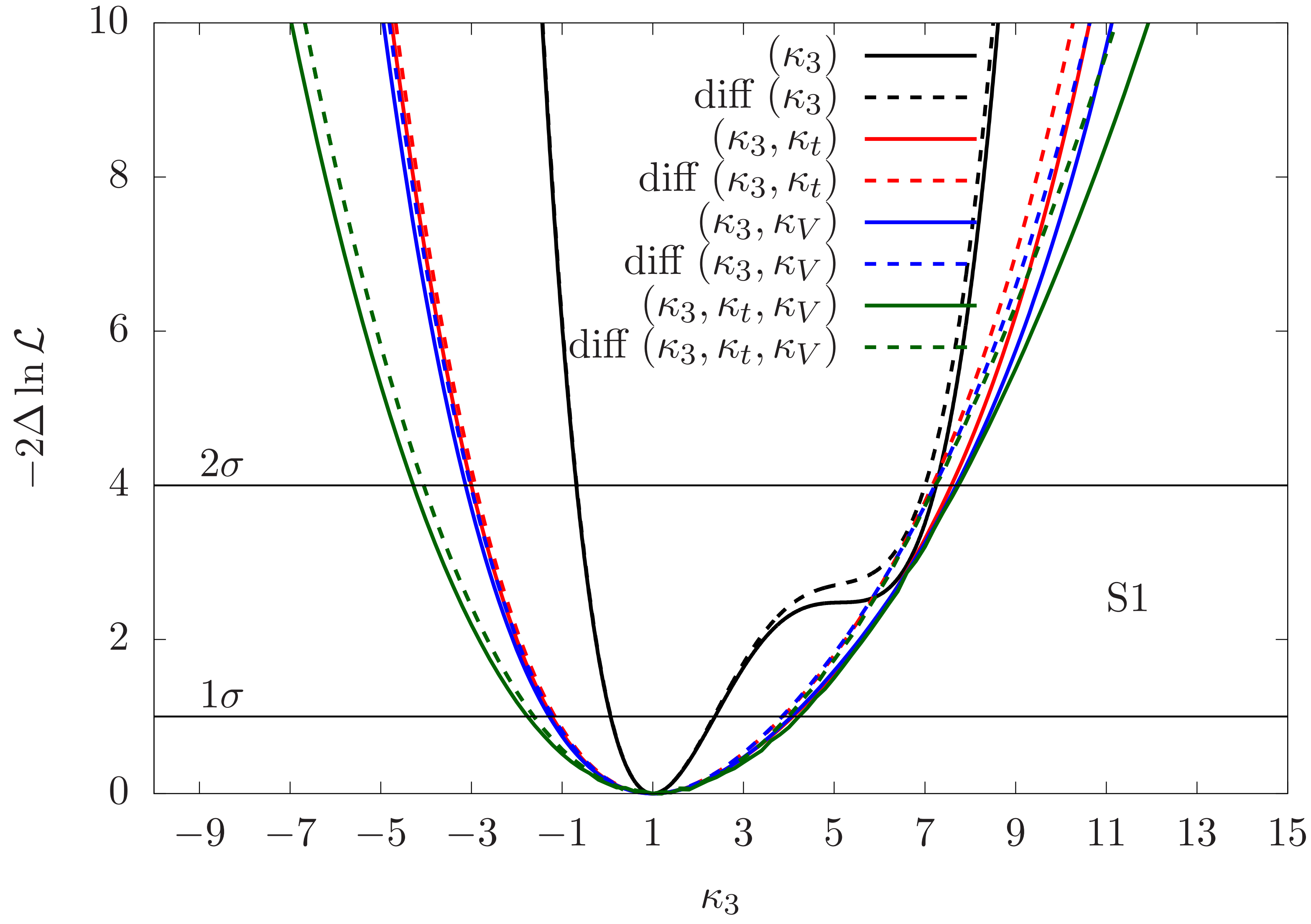


Degeneracy due to global fit (flat direction)

Solved by double Higgs

It is sensible to consider a smaller set of anomalous couplings

F. Maltoni, D. Pagani, A.Shivaji, X. Zhao (17)



Constrains relaxed for κ<1

Nearly unaltered for κ>1

- We proposed a new way to approach the calculation of Higgs pair production through gluon fusion at NLO.
- The method is based on the expansion for small transverse momentum.
- Possibility to apply the method to other 2to2 processes.
- The Higgs trilinear coupling can be investigated from single Higgs processes.
- Compared to Higgs pair production, the bounds obtained are competitive and complementary.
- This approach is model dependent,
    - however the condition for the other couplings to be SM can be lifted.

Thank you!

Olena Shmahalo/Quanta Magazine