Precise theoretical predictions for Higgs processes

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Higgs potential and BSM opportunity
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Higgs boson

A cornerstone of the SM is the EWSB proposed fifty years ago by Higgs, Englert, Guralnik, Hagen and Kibble to generate the weak vector boson masses in a way that is minimal and respects the requirements of renormalizability and unitarity. The Higgs boson, as the remaining degree of freedom of the doublet scalar field, was a prediction of this mechanism.

The only sector of the SM that has not yet been probed in a satisfactory way is the scalar sector.

Given its large mass, the discovery and study of its properties rely on the high energy colliders.

Precise theoretical predictions

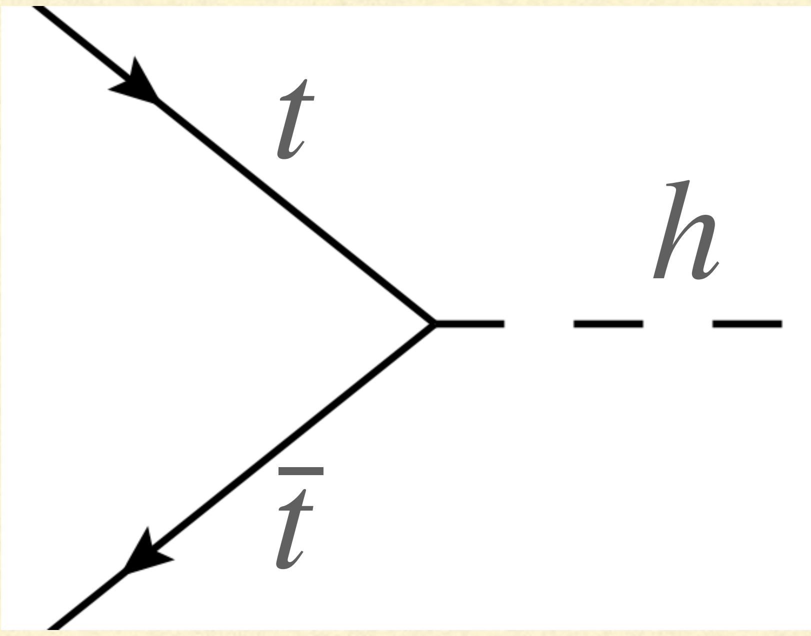
The current measurements indicate that a possible New Physics, if any, leaves subtle imprints below TeV scale. The theoretical predictions need to be precise enough to tell apart New Physics effects from the uncertainties of MC simulations.

The theoretical uncertainties may come from missing higher orders for hard scattering, large logarithms that could spoil the convergence of the perturbative series, simulation of parton showers and hadronization, fitting of parton densities. I will focus on the recent progresses in the first two parts due to the limit of my expertise and time.

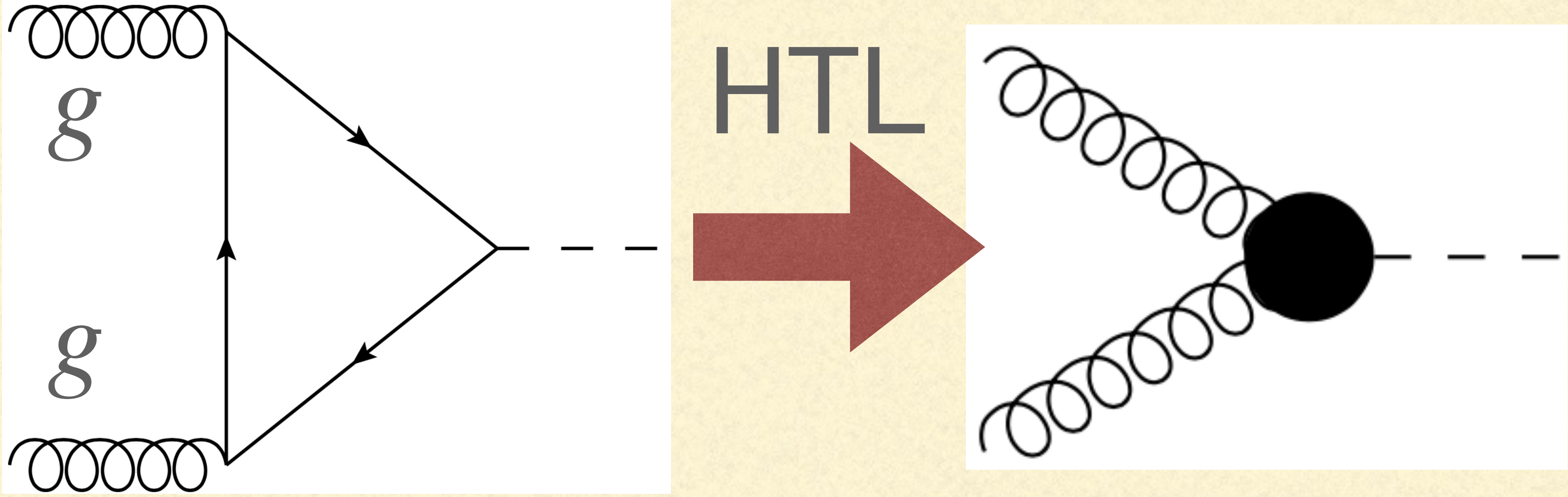
Higgs processes at the LHC

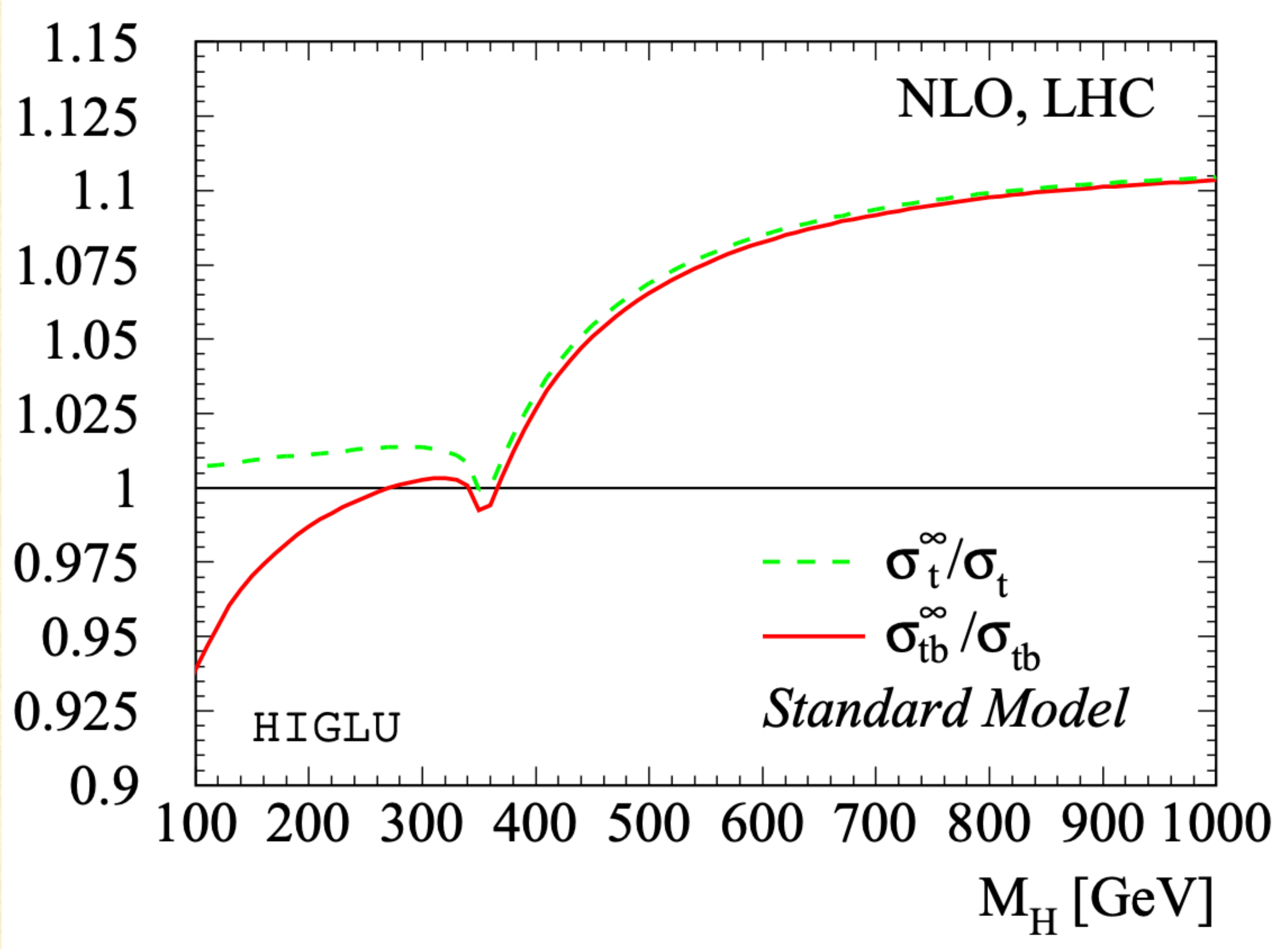
The discovery of the Higgs boson is a quantum effect.

Ideal process:



Real process:



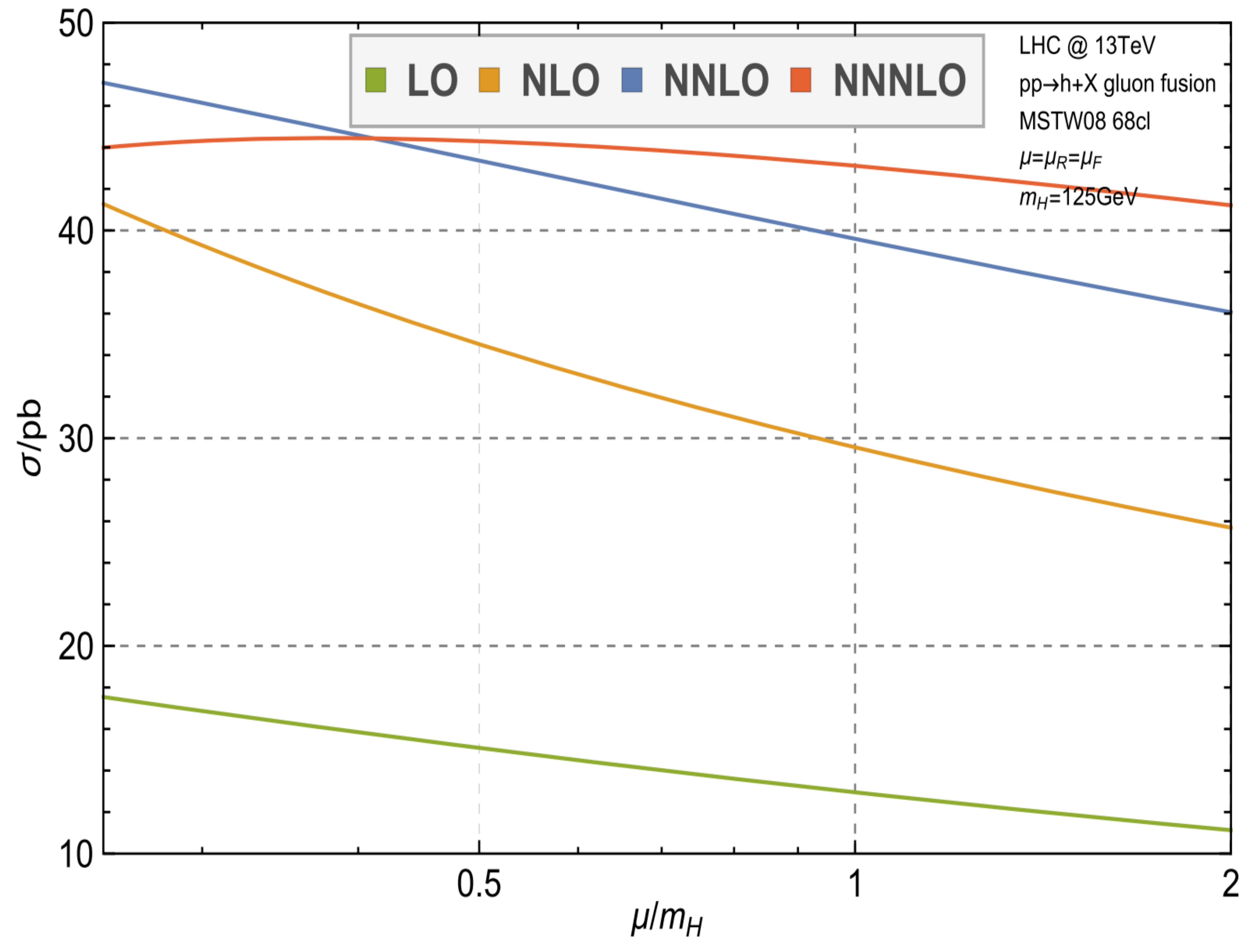


The approximation looks good at $m_H \sim 125$ GeV with an accuracy below 1%.

The bottom quark effects are around -5%.

Harlander, 0311005

Higgs production: first N3LO XS at a hadron collider



Anastasiou et al, PRL 114,212001(2015)

Quota of different corrections

Anastasiou et al, JHEP05(2016)058

48.58 pb =	16.00 pb	(+32.9%)	(LO, rEFT)
	+ 20.84 pb	(+42.9%)	(NLO, rEFT)
	− 2.05 pb	(−4.2%)	((t, b, c), exact NLO)
	+ 9.56 pb	(+19.7%)	(NNLO, rEFT)
	+ 0.34 pb	(+0.7%)	(NNLO, $1/m_t$)
	+ 2.40 pb	(+4.9%)	(EW, QCD-EW)
	+ 1.49 pb	(+3.1%)	(N^3LO, rEFT)

Quota of theoretical uncert.

$$^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

scale
AP
EW
1/mt
b,c

vs. Exp of H via di-photon

127 ± 7 (stat.) ± 7 (syst.) fb

ATLAS-CONF-2020-026

Higgs production: finite mt effect at NNLO

Why does the infinite mt limit work well? The partonic c.m. energy can be larger than mt.

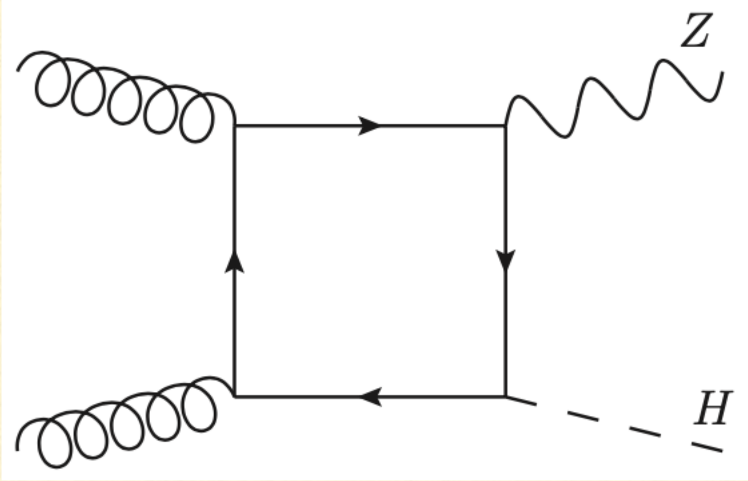
channel	$\sigma^{\rm NNLO}_{\rm HEFT}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\rm NNLO}_{\rm exact}-\sigma^{\rm NNLO}_{\rm HEFT})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\rm NNLO}_{\rm exact}/\sigma^{\rm NNLO}_{\rm HEFT}-1)$ [%]
		$\sqrt{s}=8\,\mathrm{TeV}$		
gg	$7.39+8.58+3.88$	$+0.0353$	$+0.0879\pm0.0005$	$+0.62$
qg	$0.55+0.26$	-0.1397	-0.0021 ± 0.0005	-18
qq	$0.01+0.04$	$+0.0171$	-0.0191 ± 0.0002	-4
total	$7.39+9.15+4.18$	-0.0873	$+0.0667\pm0.0007$	-0.10
		$\sqrt{s}=13\,\mathrm{TeV}$		
gg	$16.30+19.64+8.76$	$+0.0345$	$+0.2431\pm0.0020$	$+0.62$
qg	$1.49+0.84$	-0.3696	-0.0115 ± 0.0010	-16
qq	$0.02+0.10$	$+0.0322$	-0.0501 ± 0.0006	-15
total	$16.30+21.15+9.79$	-0.3029	$+0.1815\pm0.0023$	-0.26

The bottom quark contribution is readily obtained.

Czakon, Harlander, Klappert, Niggetiedt, 2105.04436

Higgs production with Z

HZ production has been used to measure the Hbb coupling.
It is of Drell-Yan type, but the gluon fusion contributes from NNLO.



$\mu_r = \mu_f$	$\sigma^{gg}_{\rm LO}$	$\sigma^{gg}_{\rm NLO}$	$\sigma^{\text{no } gg}_{pp\to ZH}$	$\sigma_{pp\to ZH}$	$\sigma^{gg,m_t\to\infty}_{\rm NLO}$	$\sigma^{m_t\to\infty}_{pp\to ZH}$
$M_{ZH}/3$	73.56(7)	129.4(3)	784.0(7)	913.4(7)	133.6(6)	917.6(9)
M_{ZH}	51.03(5)	101.7(2)	781.1(7)	882.9(7)	106.0(4)	887.2(8)
$3M_{ZH}$	36.62(4)	80.4(2)	780.7(8)	861.1(8)	84.0(3)	864.8(9)

Oneloop squared ~ 50% of NLO

Twoloop: Expansion in mZ, mH

Exact mt: reduce x-sec by 5%

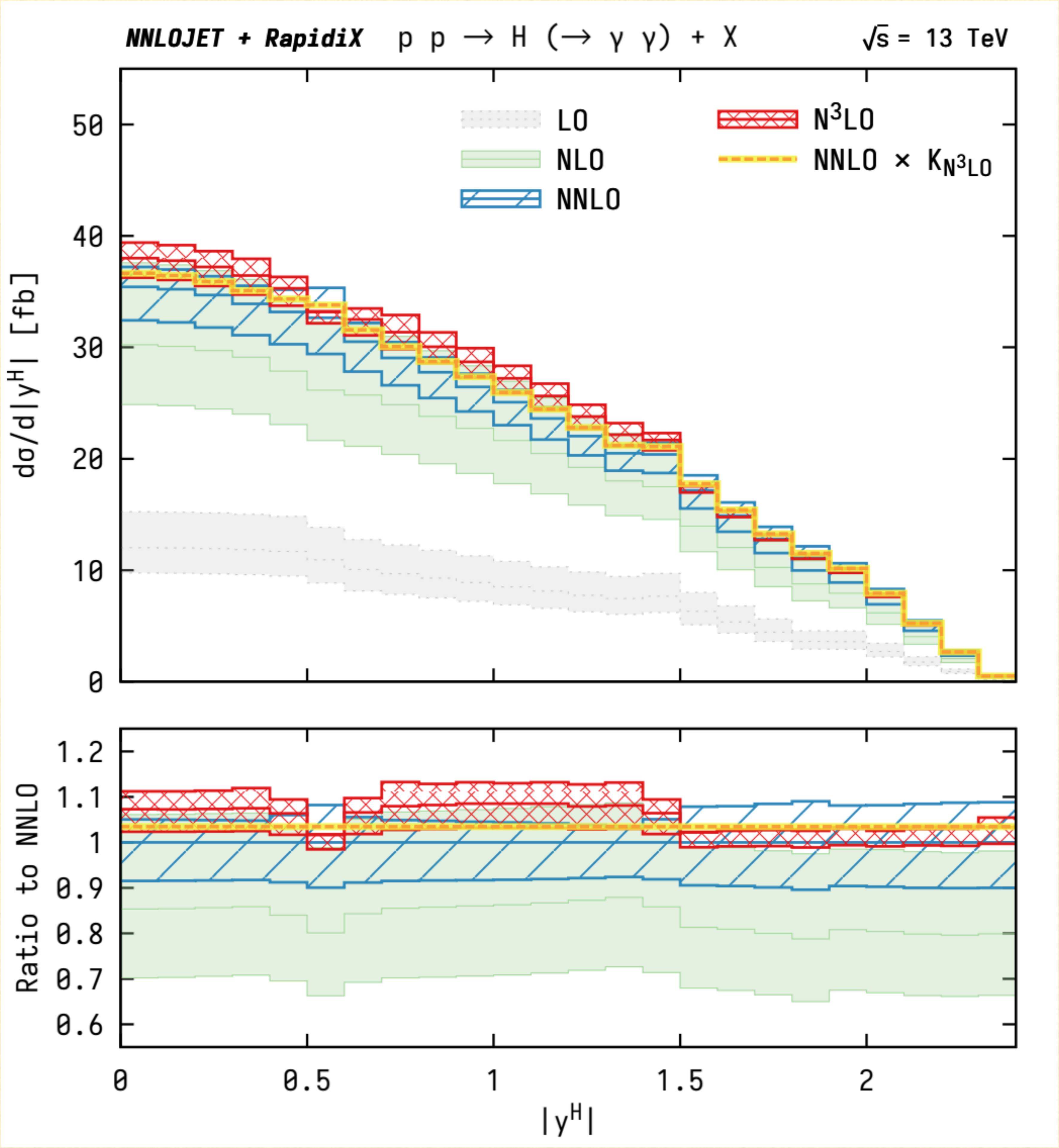
The NLO correction is ~100% for gg channel, and improves the total ZH x-sec by 6%.
The final scale uncertainties are ~3%.

See Guoxing's talk.

Wang, Xu, Xu, Yang, 2107.08206

Higgs rapidity distribution

Fully differential predictions require special treatment for the cancellation of infrared singularities.



$$\frac{d\sigma_F^{N^kLO}}{d\mathcal{O}} = \left(\frac{d\sigma_{F+\mathrm{jet}}^{N^{(k-1)}LO}}{d\mathcal{O}} - \frac{d\sigma_{F+\mathrm{jet}}^{N^{(k-1)}LO}}{d\widetilde{\mathcal{O}}} \right) + \frac{d\sigma_F^{N^kLO}}{d\widetilde{\mathcal{O}}}$$

Lower orders | Subtraction term | Born-like higher orders

Fiducial cuts

$$p_T^{\gamma_1} > 0.35 \times m_{\gamma\gamma}, \qquad p_T^{\gamma_2} > 0.25 \times m_{\gamma\gamma},$$
$$|\eta^\gamma| < 2.37 \ \text{ excluding } \ 1.37 < |\eta^\gamma| < 1.52,$$

The distribution at the central region is larger than expected from inclusive K-factor.

Uncertainties are larger than inclusive x-sec.

Chen et al, PRL127,072002(2021)

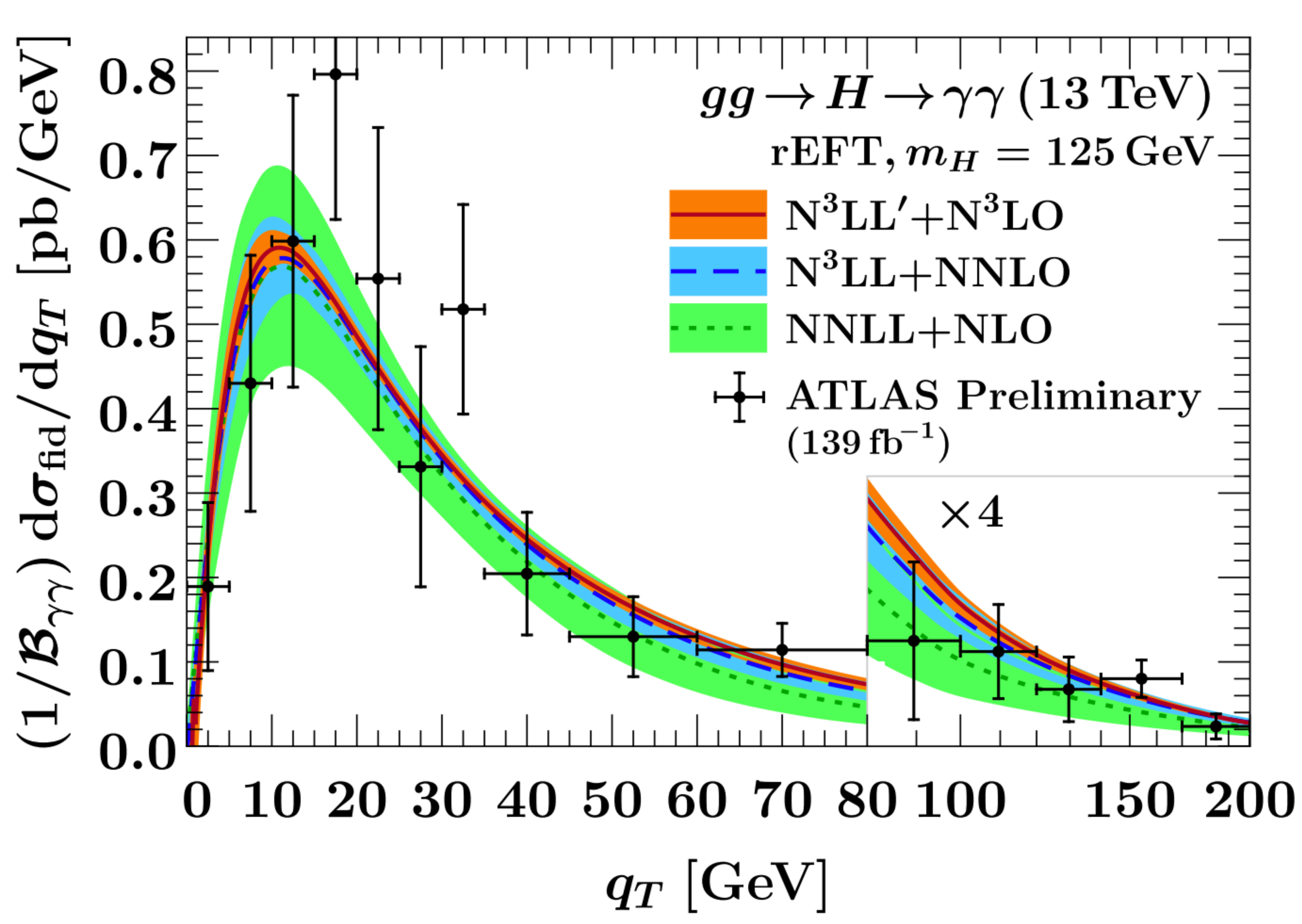
Higgs pT spectrum

$$\frac{d\sigma}{dq_T} = \frac{d\sigma^{\mathrm{sing}}}{dq_T} + \frac{d\sigma^{\mathrm{nons}}}{dq_T}$$

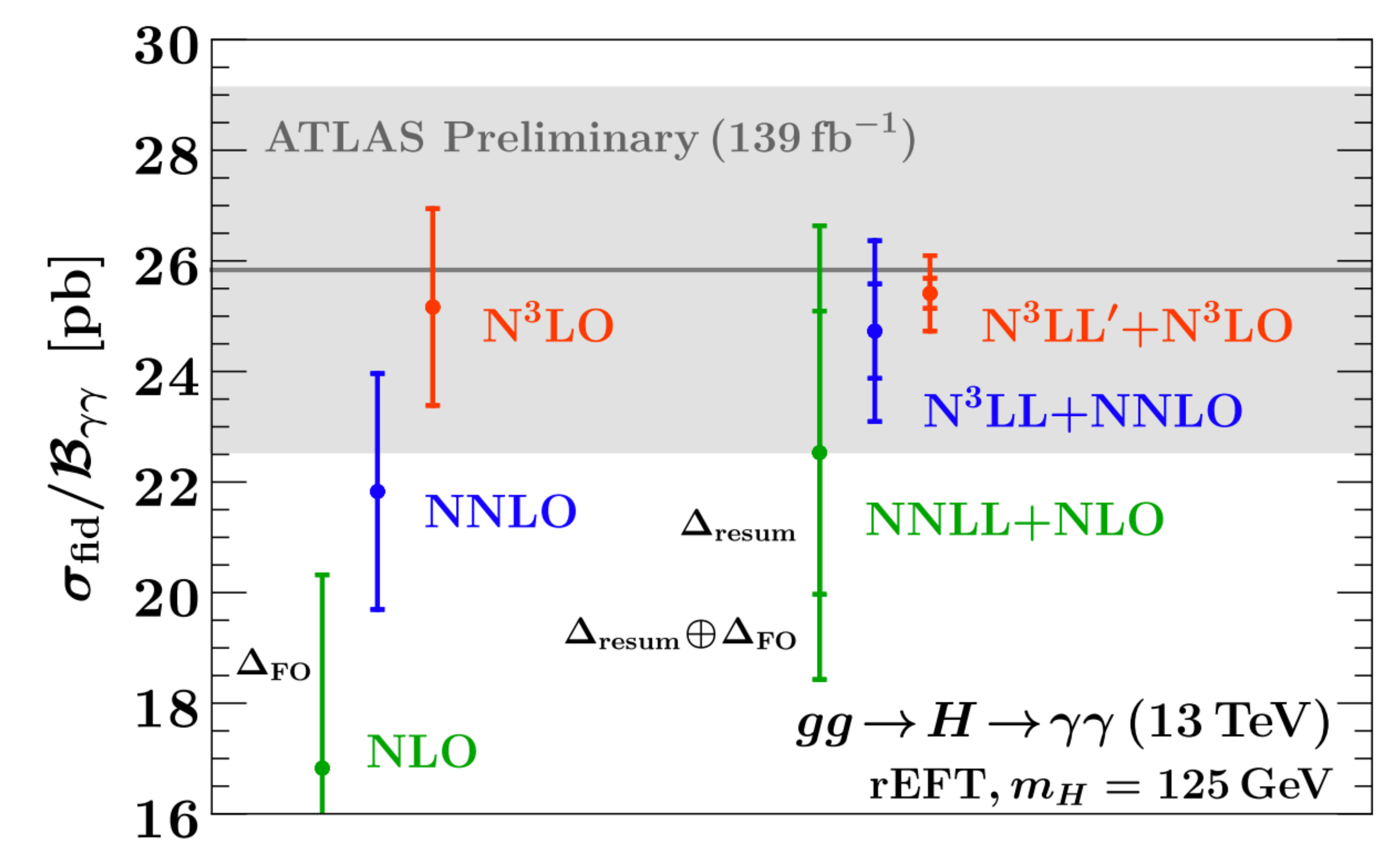
Excellent perturbative convergence

Soft-collinear effective theory

NNLOjet

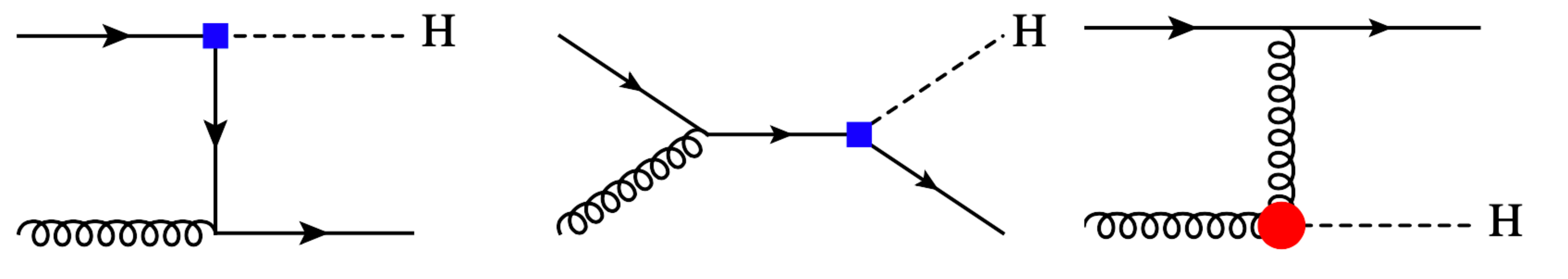


Fiducial x-sec.



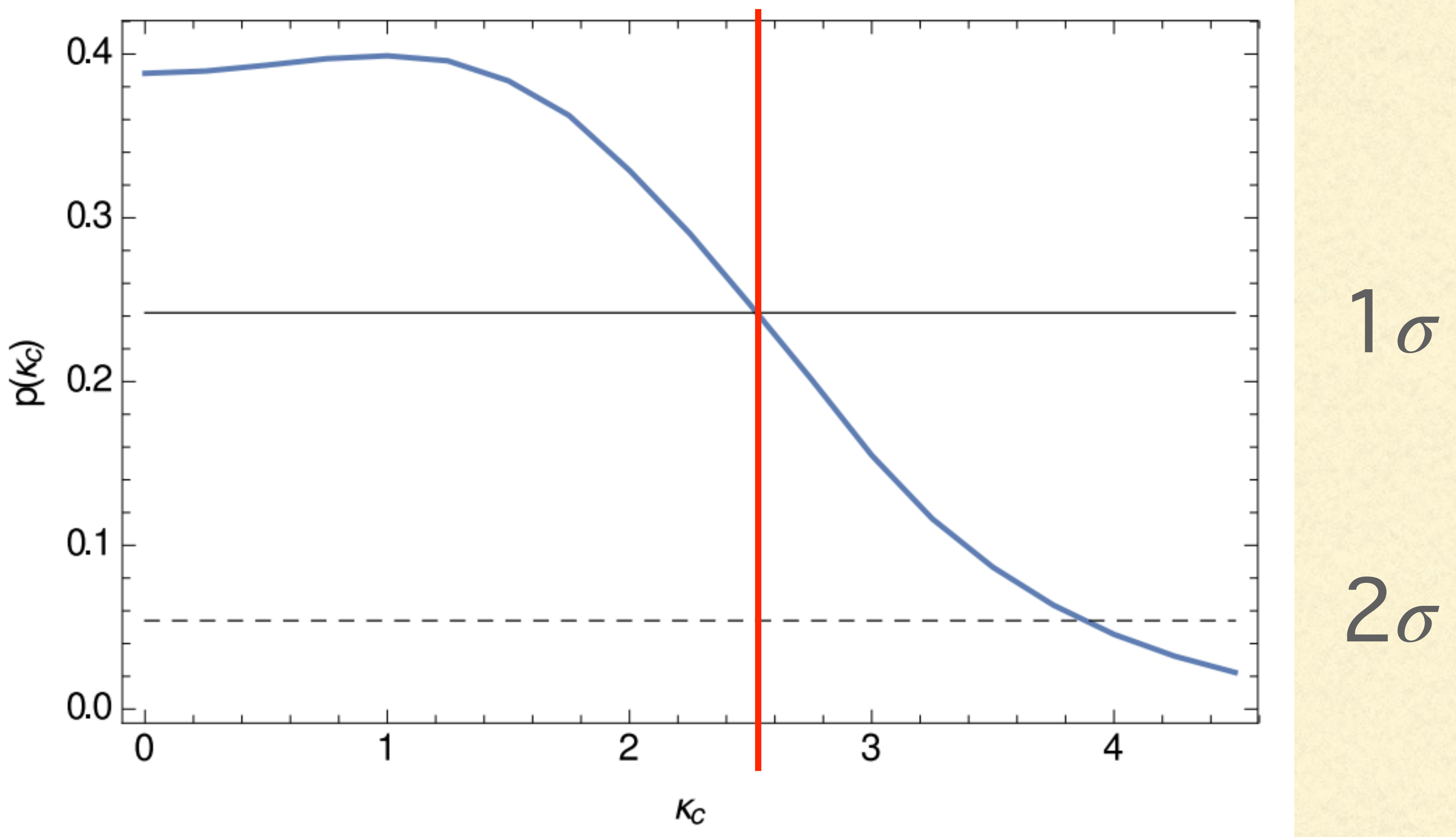
Billis et al, PRL127,072001(2021)

Higgs production with a c-jet



(a) Yukawa coupling (b) Effective ggH vertex

$$\sigma_{Hc} \sim g_{\rm Yuk}^2\ \tilde{\sigma}_1 + g_{ggH}^2\ \tilde{\sigma}_2 + g_{\rm Yuk} g_{ggH}\ \tilde{\sigma}_{\rm Int}$$



Brivio, Goertz, Isidori, PRL115,211801(2015)

The interference vanishes if one uses $m_c = 0$

Keeping non-vanishing m_c is non-trivial

$$f_a^{(m)} = \hat{O}_{ab} \otimes f_b^{\overline{\rm MS}}$$

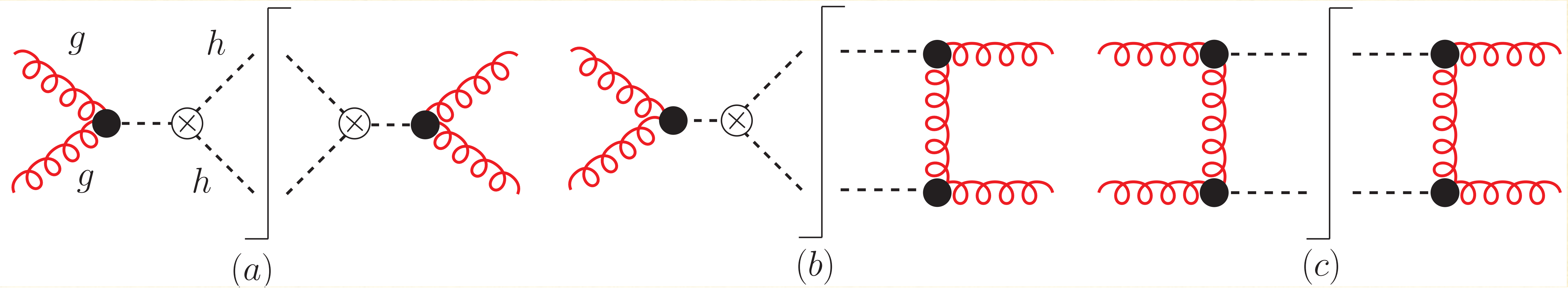
$\downarrow$

Contain $\ln \frac{\mu}{m_c}$

$\Delta\sigma^{\rm NLO}$ [fb]	cg	cq	gg	cc	$c\bar{c}$	PDF	sum
const	−1.63	0.13	2.33	0.01	−0.01	0.11	0.94
L	2.23	–	−6.33	−0.04	0.01	1.66	−2.47
L^2	−0.06	–	2.66	0.01	−0.08	–	2.52
total	0.54	0.13	−1.34	−0.02	−0.08	1.76	1.00

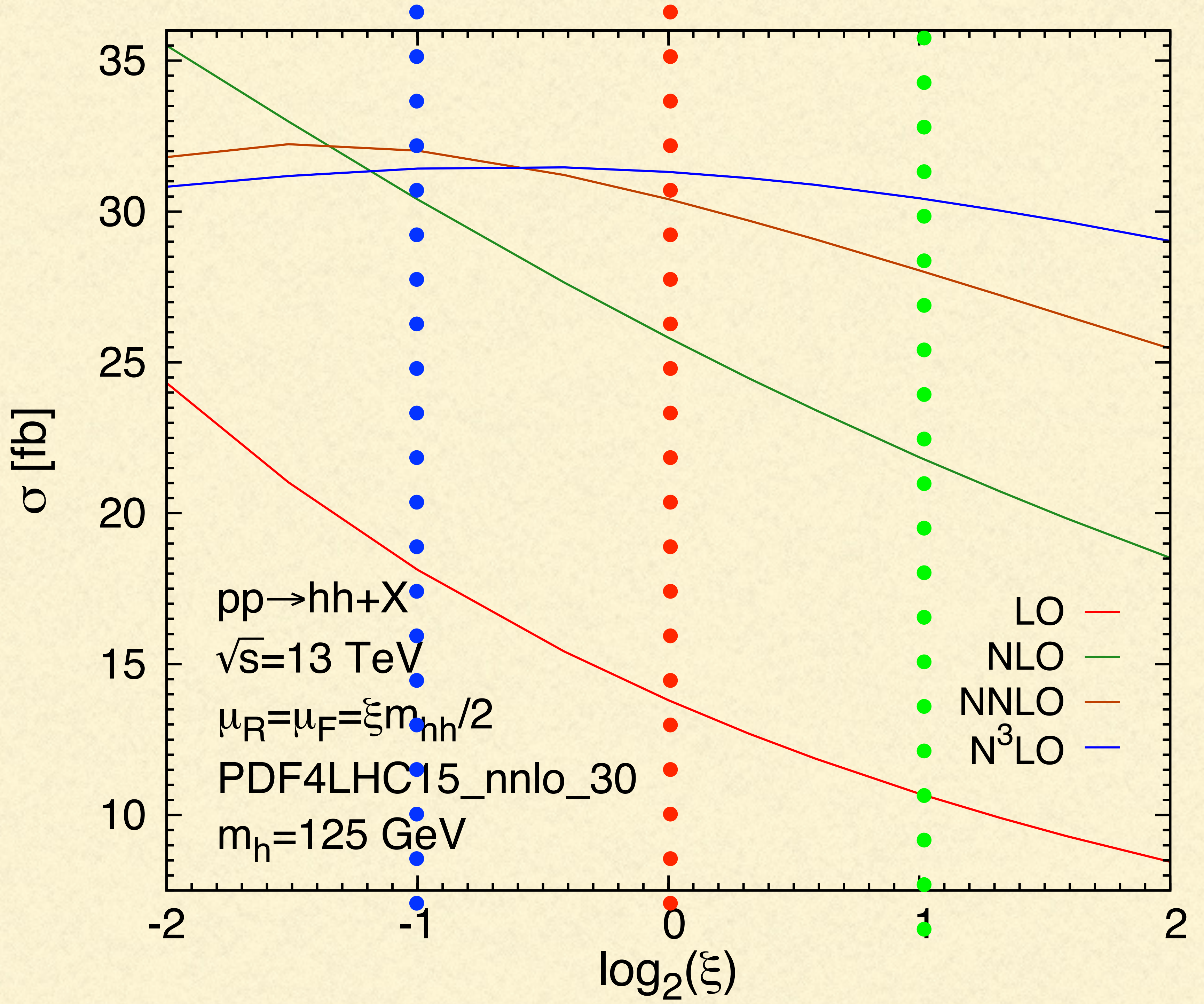
Bizon, Melnikov, Quarroz JHEP06(2021)107

Higgs pair production



	LO	NLO	NNLO	N^3LO
Total	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
a	LO_a	NLO_a	$NNLO_a$	N^3LO_a
	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
b	–	LO_b	NLO_b	$NNLO_b$
	0	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
c	–	–	LO_c	NLO_c
	0	0	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$

order \ $\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^3LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4438^{+0.51\%}_{-1.8\%}$



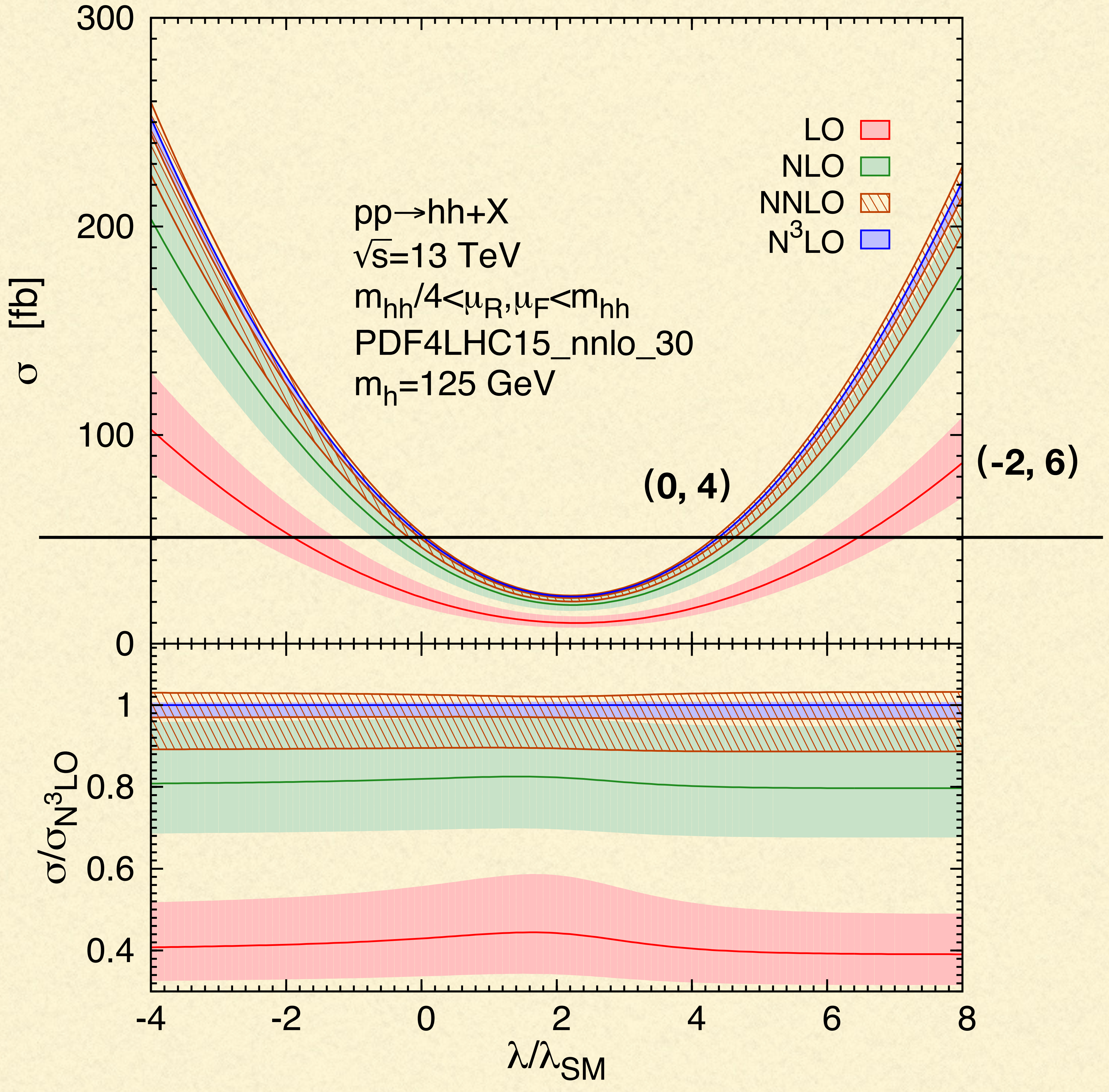
NLO/LO=1.87, NNLO/NLO=1.18,NNNLO/NNLO=1.03

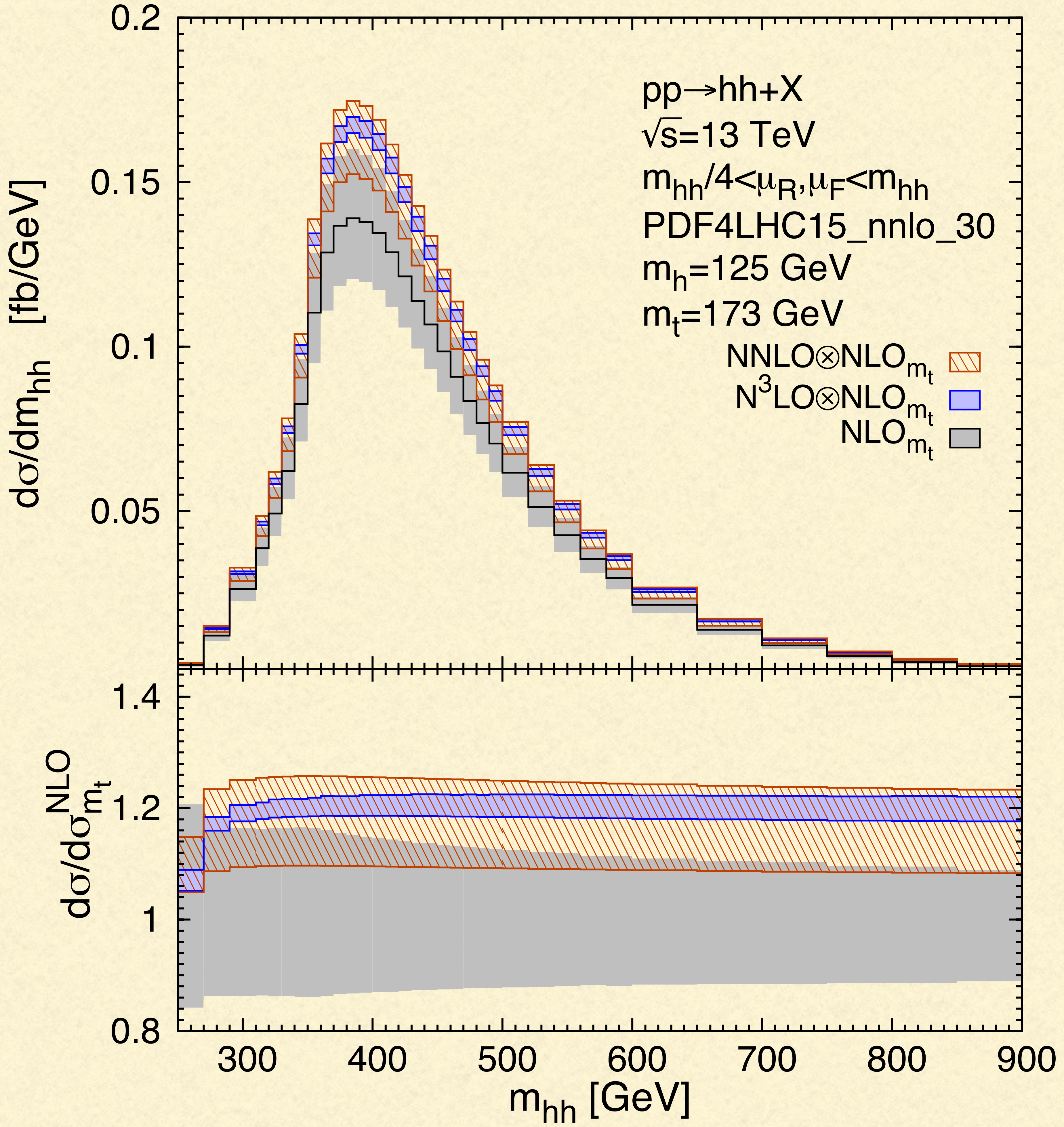
Different scale choices may change these values.

Scale uncert indicate size of missing higher orders.

Chen, Li, Shao, JW, Phys.Lett.B,803,135292, JHEP,03(2020)072

Higgs pair production





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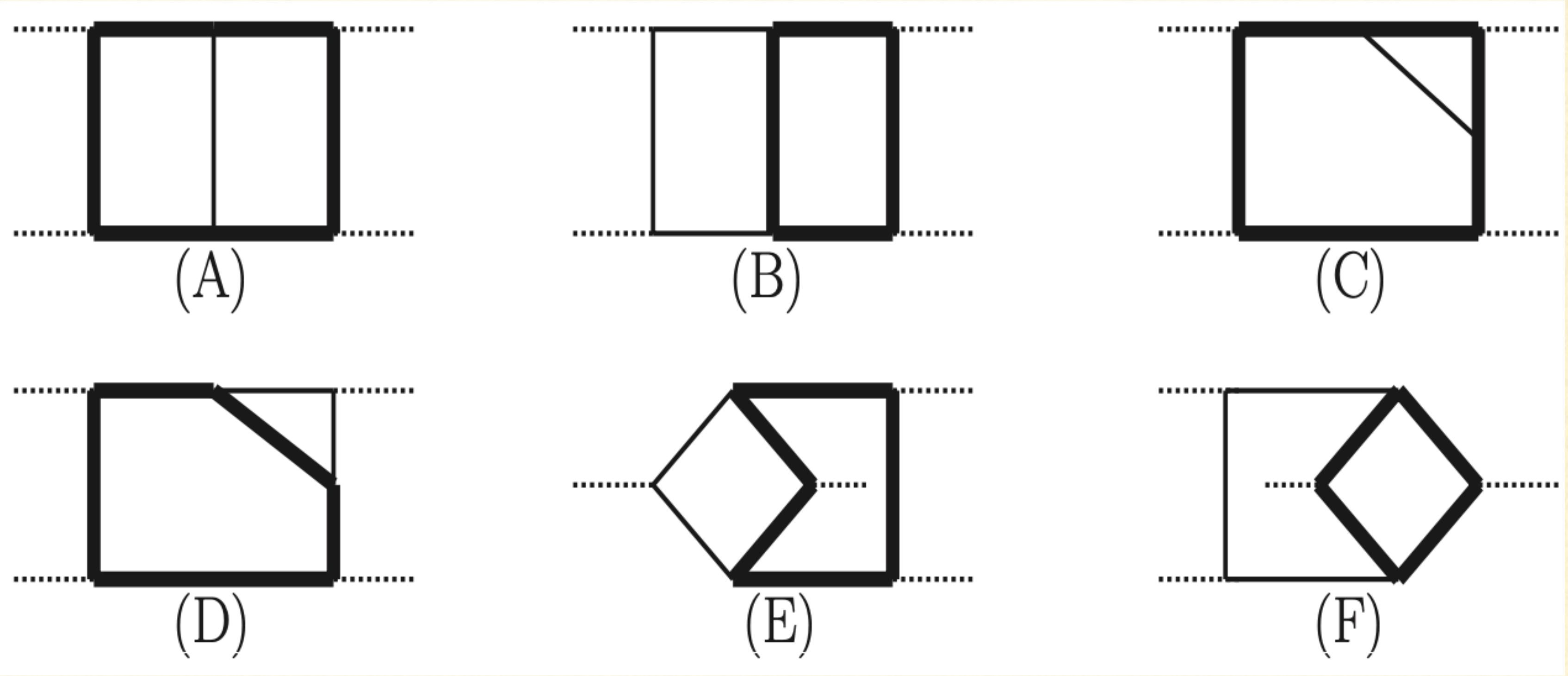


$$F^{(1)}_{i,\text{box}}(\hat{s},\hat{t}_1,m_t^2,m_H^2) = \sum_{n=0}^{\infty} \frac{(m_H^2)^n}{n!}\left[\frac{\partial^n F^{(1)}_{i,\text{box}}}{\partial(m_H^2)^n}\right]_{m_H^2=0}$$

$$\partial_{m_H^2} = \frac{\hat{u}_1 p_1^\mu + \hat{t}_1 p_2^\mu + \hat{s} p_3^\mu}{2m_H^2\hat{s} - 2\hat{t}_1\hat{u}_1}\,\partial_{p_3^\mu}$$

29, 32, 37, 27, 54, 36 master integrals

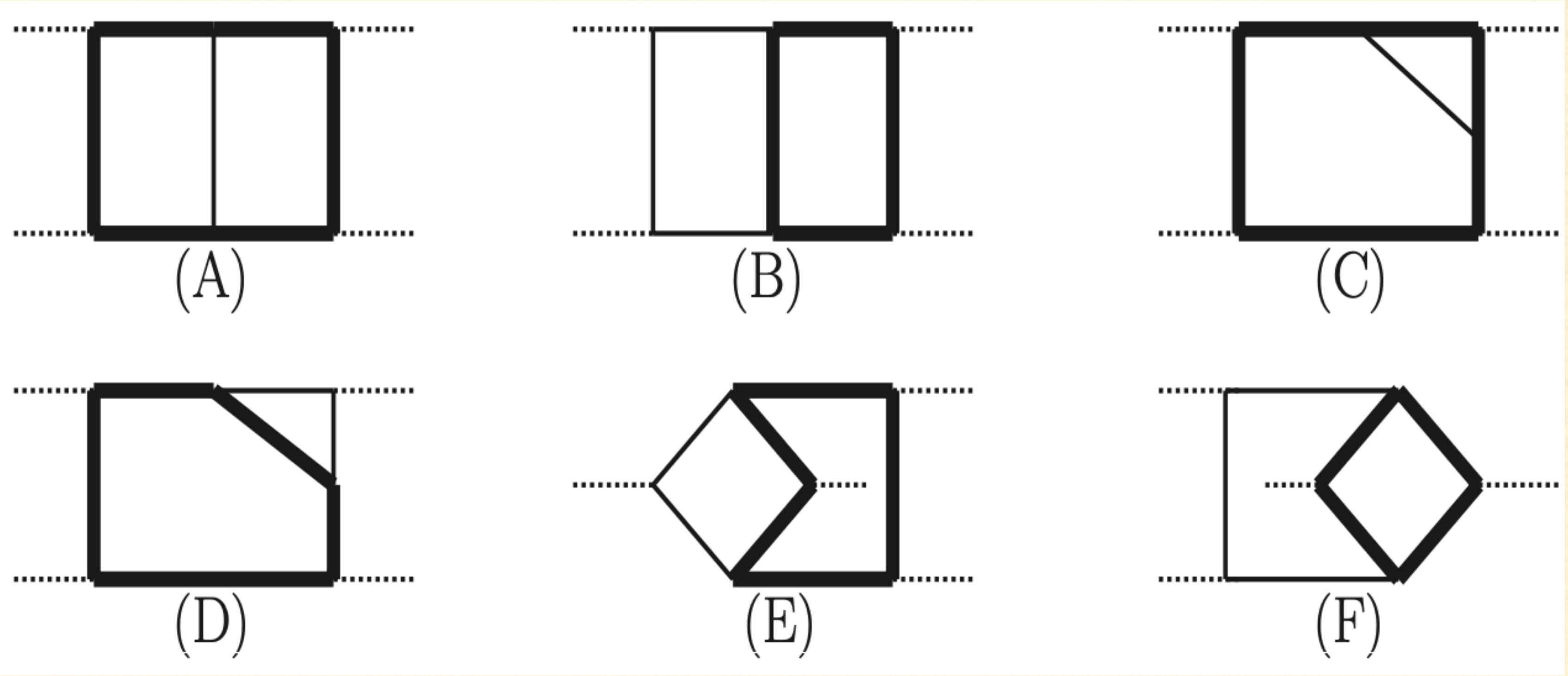
For numerical calculation, using generalized polylogarithms,

or its integration, or the integrals over elliptic integrarls.

The accuracy can be systematically improved, though O(m_H^4) seems enough.

Wang, Wang, Xu, Xu, Yang, 2010.15649

Higgs pair production



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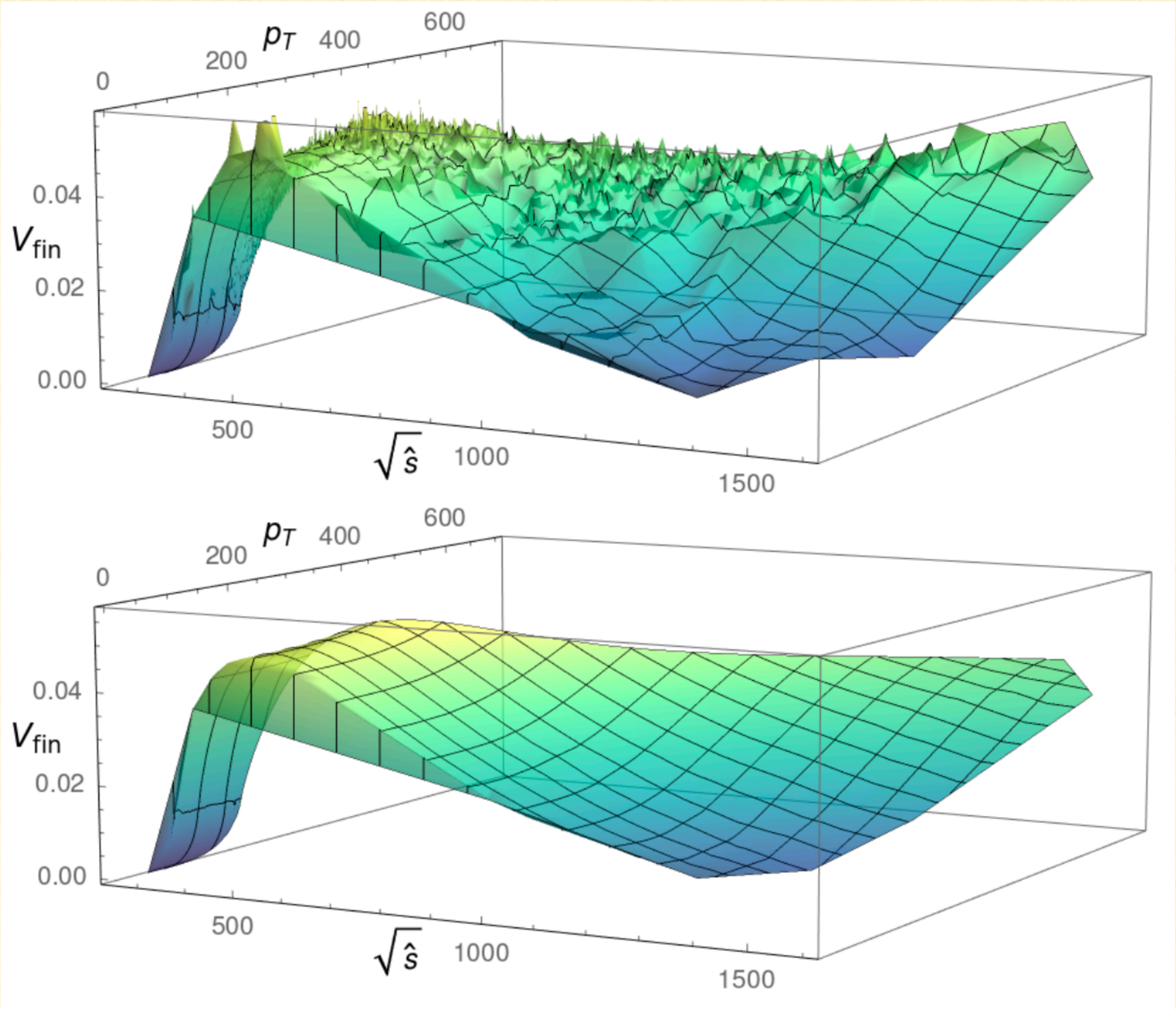

7 GPU hours

For numerical calculation, using generalized polylogarithms,

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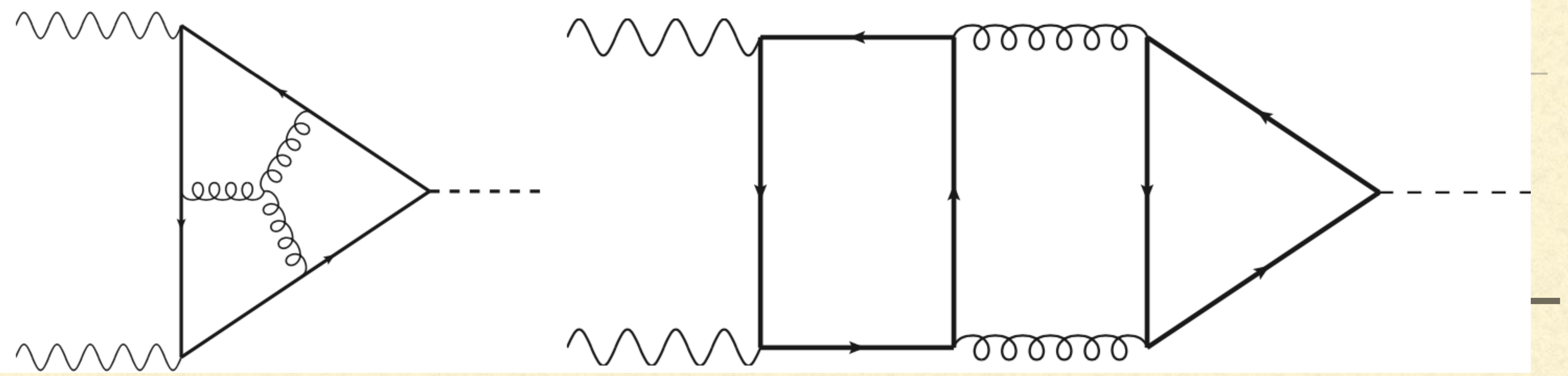
The accuracy can be systematically improved, though O(m_H^4) seems enough.

10 seconds of one CPU

Wang, Wang, Xu, Xu, Yang, 2010.15649

Higgs decay to di-photon



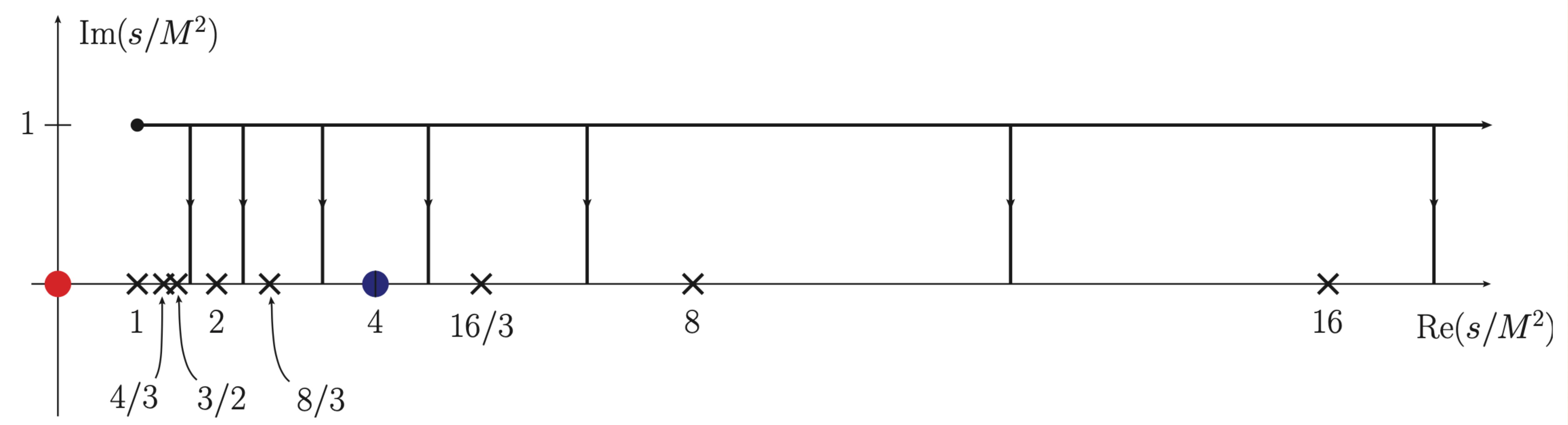
$$\mathcal{C}^{(2)} = \mathcal{C}^{(2,0)} + n_h\,\mathcal{C}^{(2,1)} + n_l\,\mathcal{C}^{(2,2)} + \sum_{k=1}^{n_l}\left(\frac{Q_k}{Q_q}\right)^2 \mathcal{C}^{(2,3)}$$

Gluon web   Heavy loop   Light loop

Method:

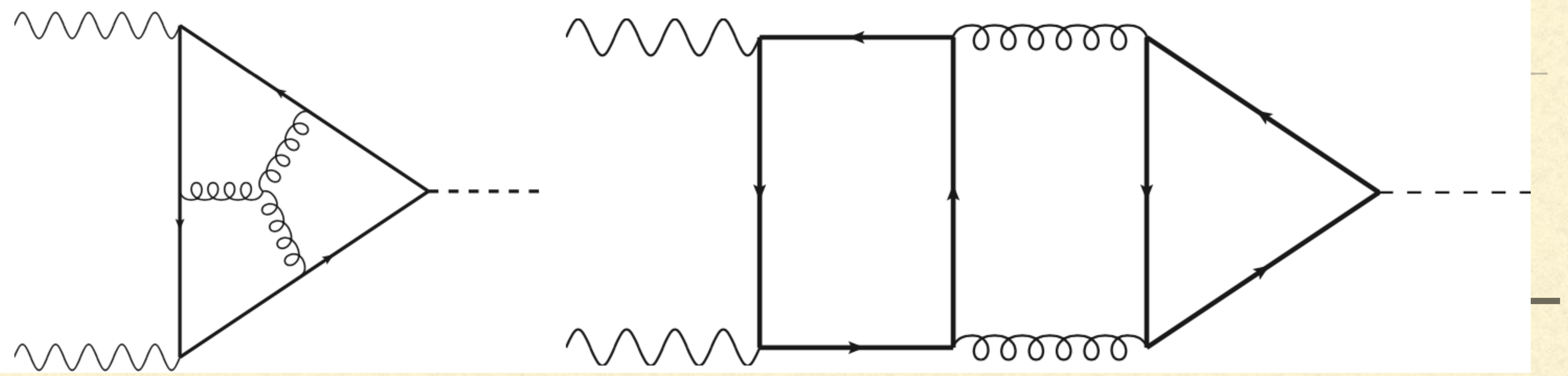
$$\frac{\mathrm{d}M_i(z,\epsilon)}{\mathrm{d}z} \equiv \sum_j A_{ij}(z,\epsilon)\,M_j(z,\epsilon)$$

$$\frac{\mathrm{d}I_k(z)}{\mathrm{d}z} \equiv \sum_l B_{kl}(z)\,I_l(z)$$



Czakon, Niggetiedt, JHEP05(2020)149, JHEP04(2021)196

Higgs decay to di-photon



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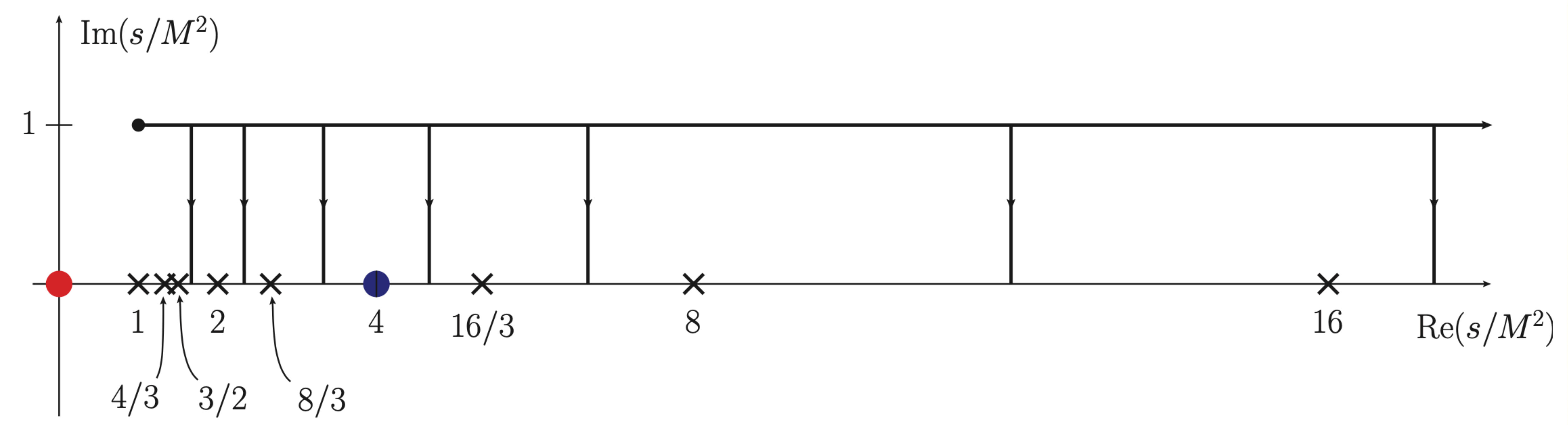

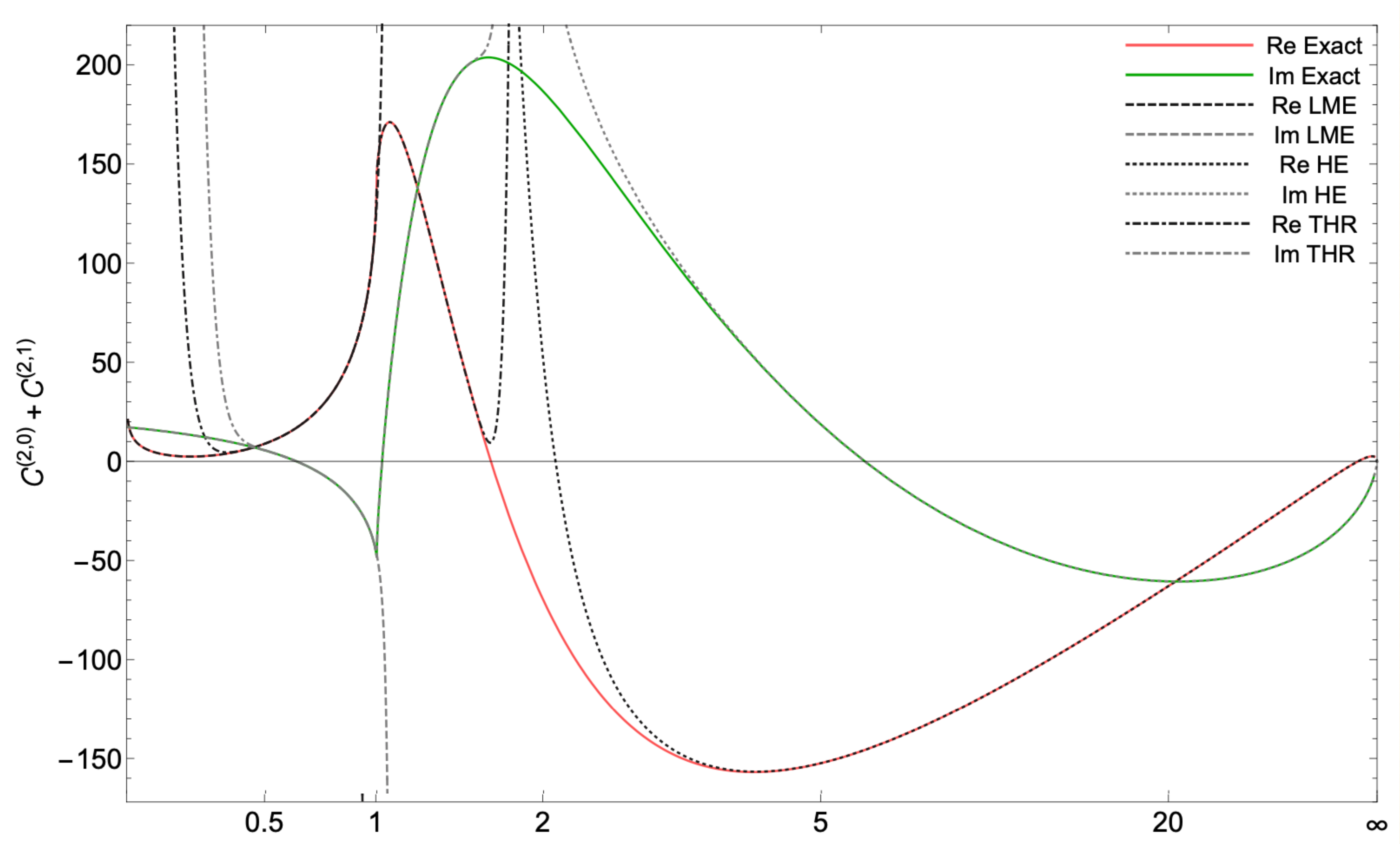

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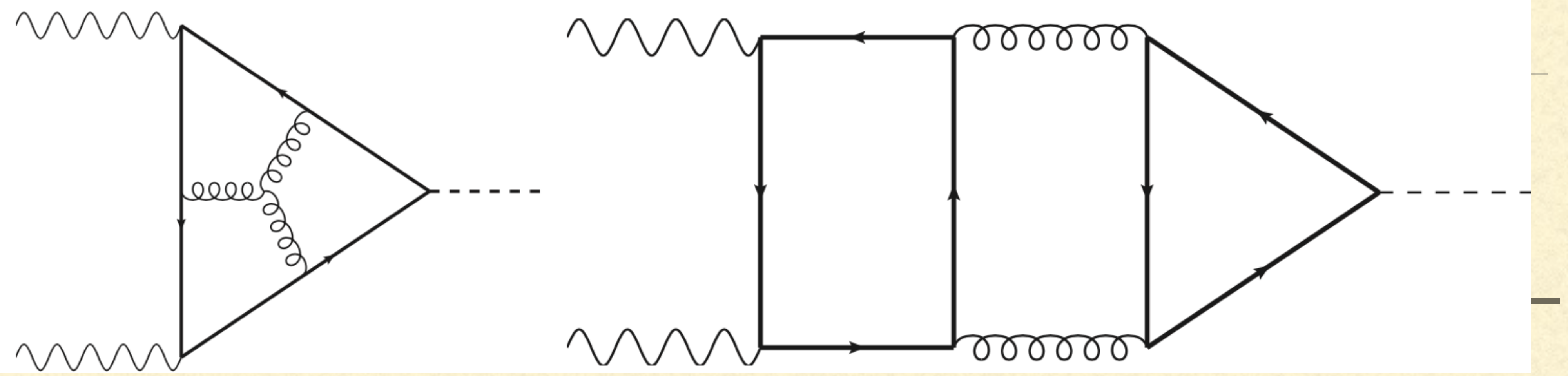

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Gluon web Heavy loop Light loop

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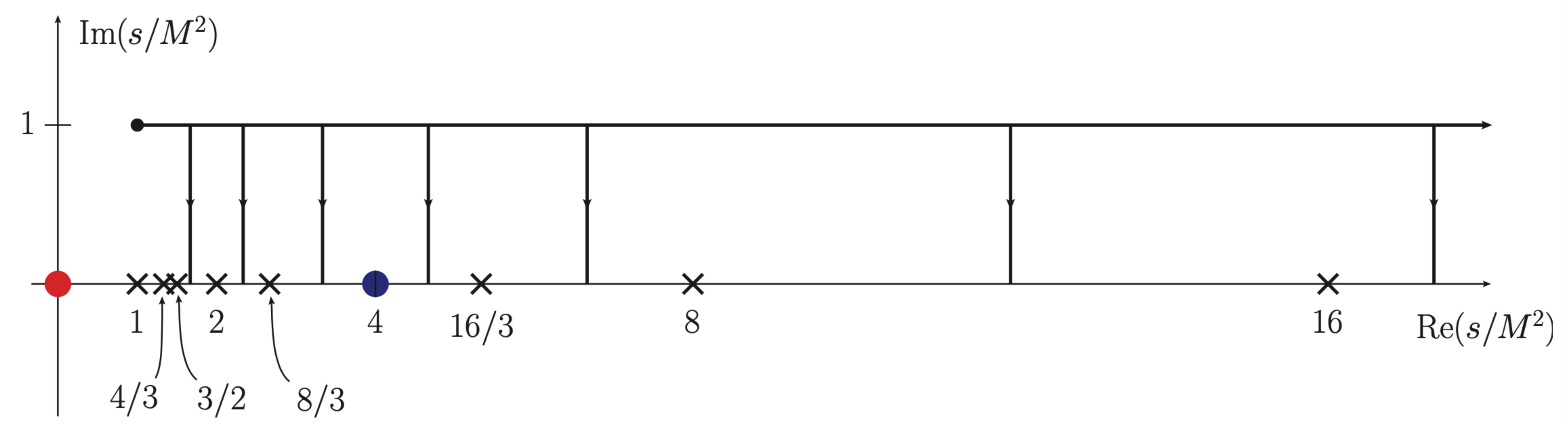
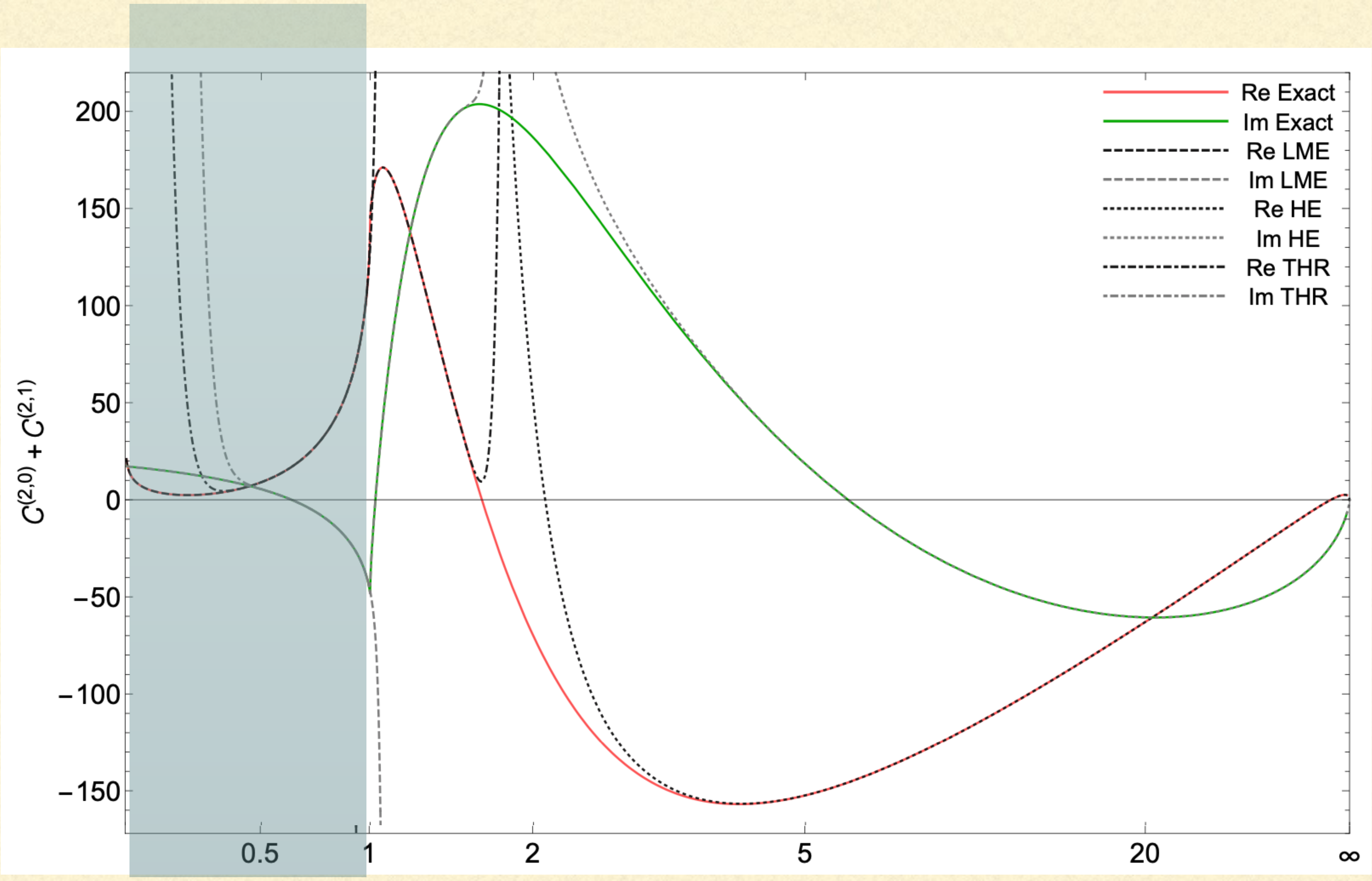
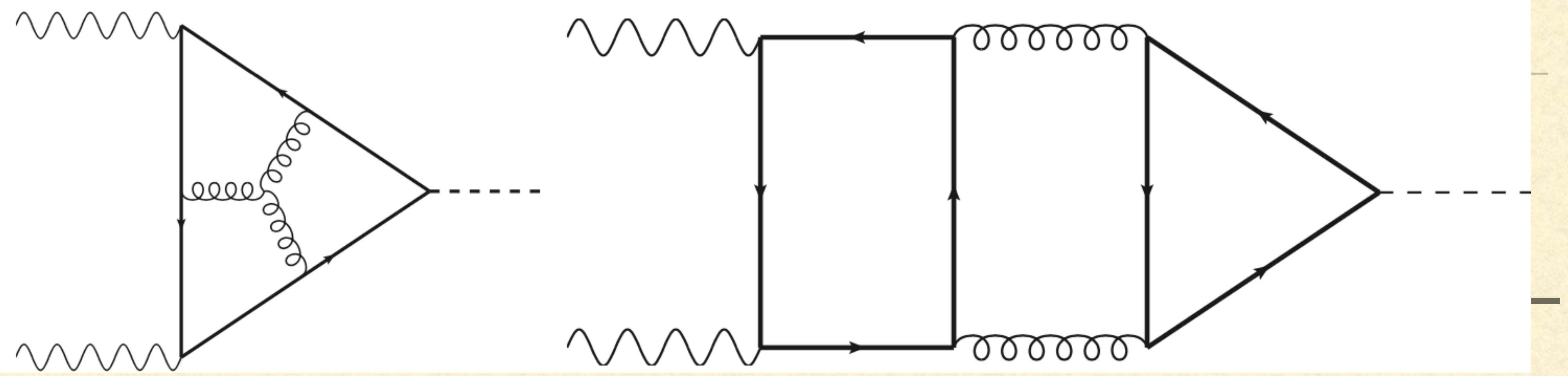




Large mass

Czakon, Niggetiedt, JHEP05(2020)149, JHEP04(2021)196

Higgs decay to di-photon



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Gluon web Heavy loop Light loop

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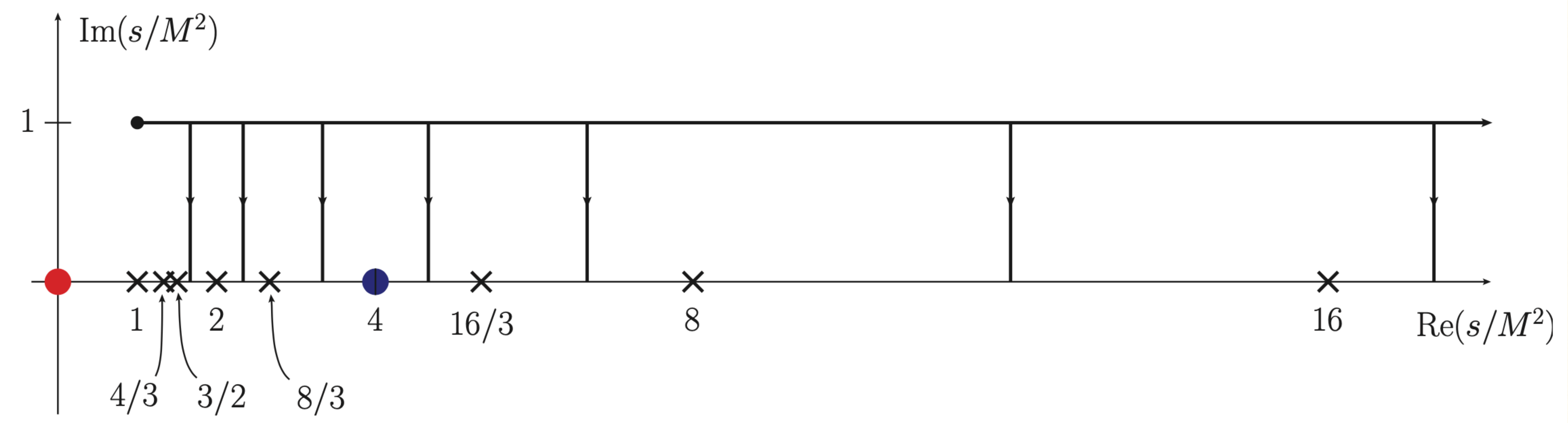
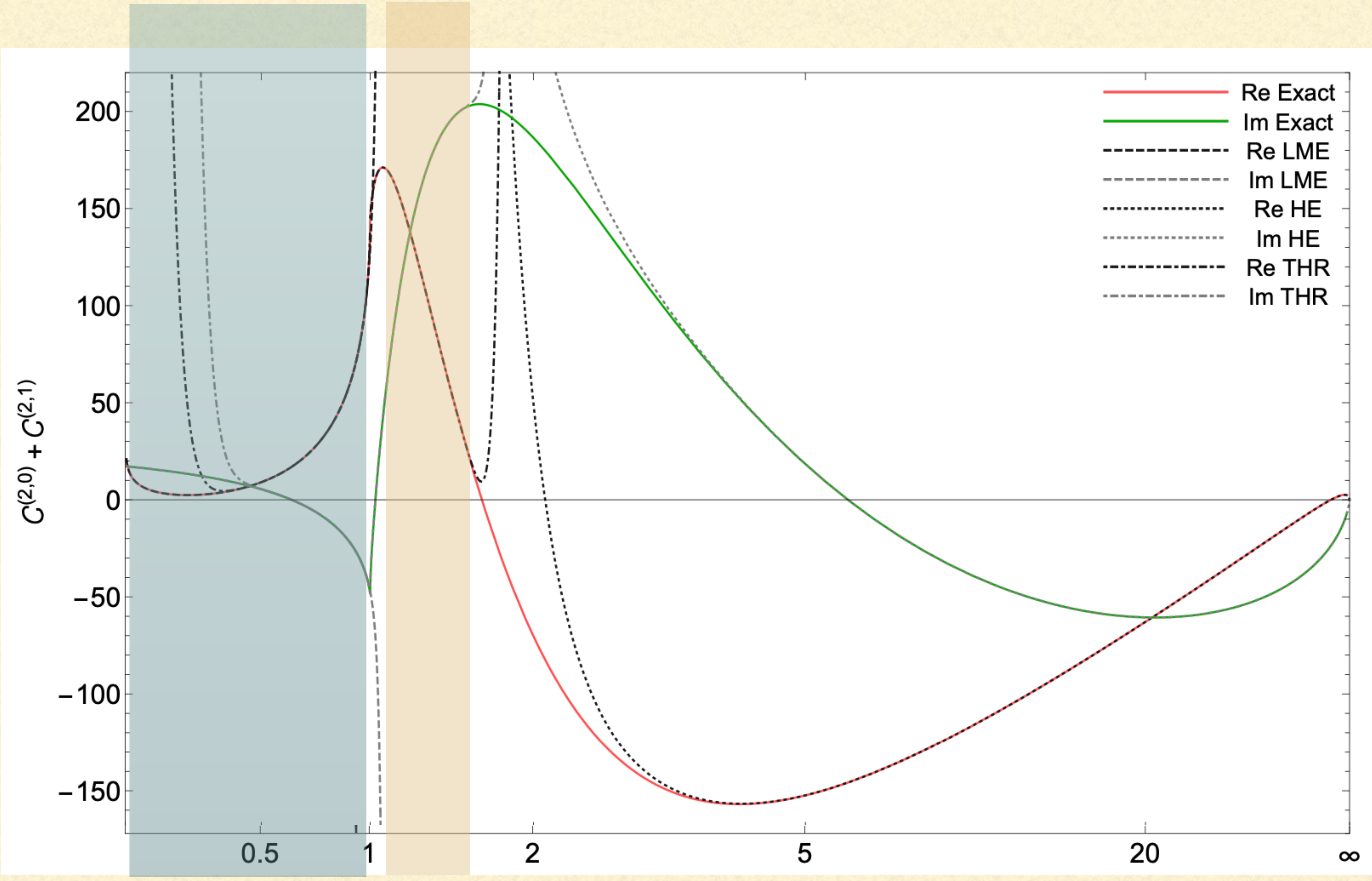
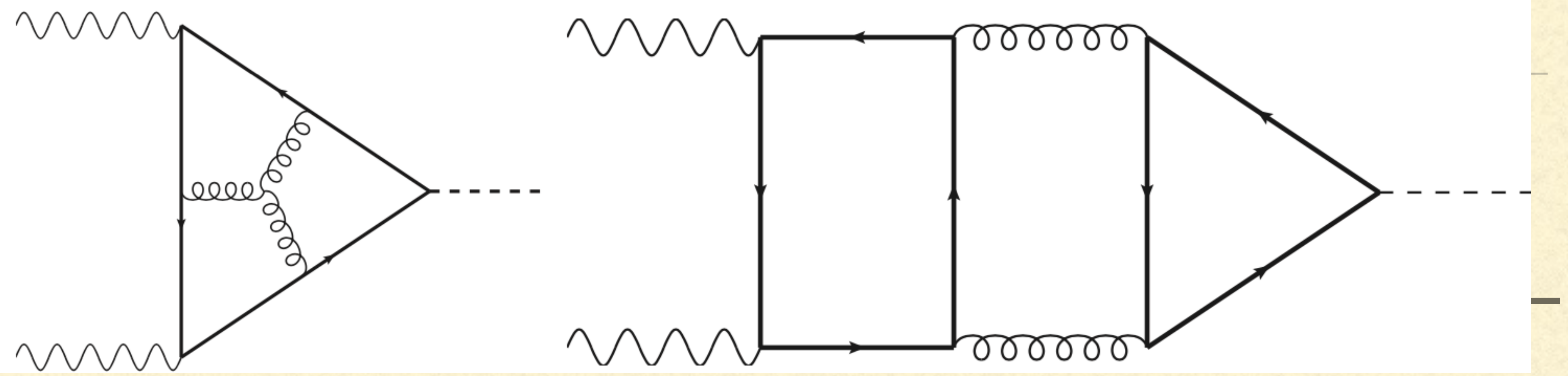




Large mass Threshold

Czakon, Niggetiedt, JHEP05(2020)149, JHEP04(2021)196

Higgs decay to di-photon



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Gluon web Heavy loop Light loop

Method:

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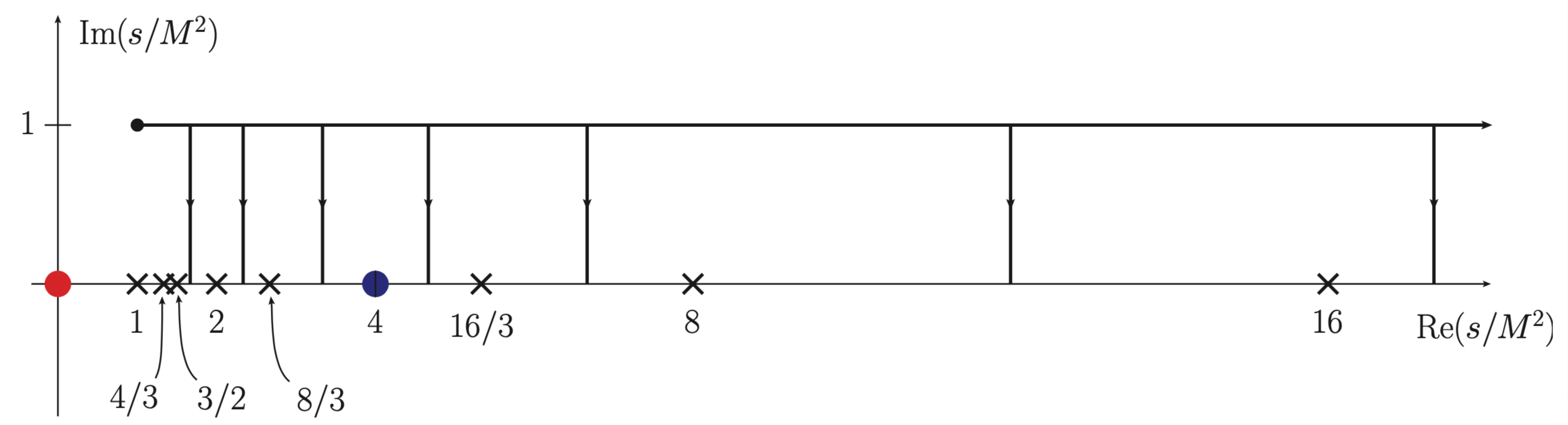

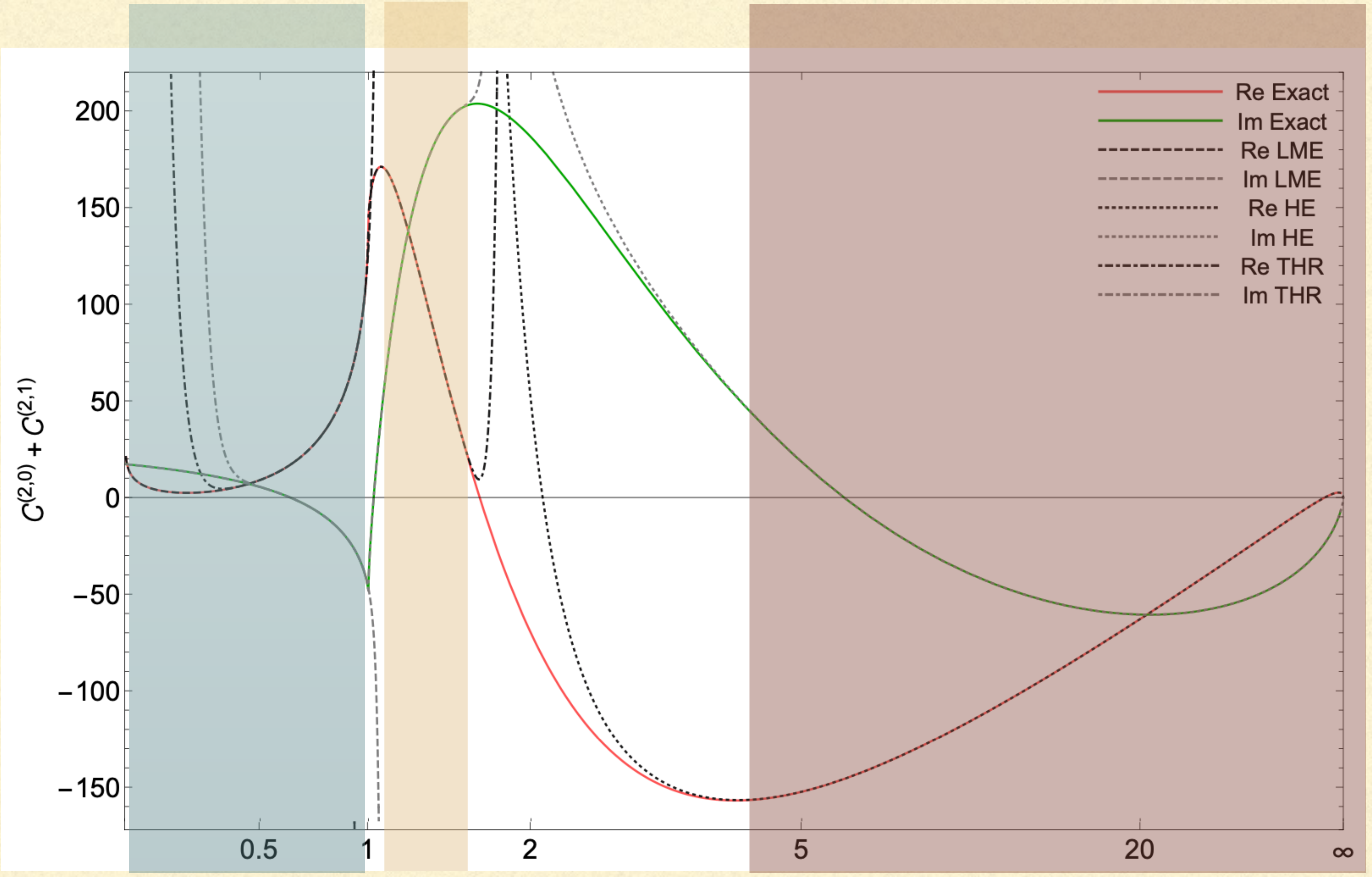

Large mass Threshold Small mass

Analytic Method: Prausa, Usovitsch, JHEP03(2021)127

Czakon, Niggetiedt, JHEP05(2020)149, JHEP04(2021)196

Higgs decay to fermions

The $h \to f\bar{f}$ decays allows measurement of Yukawa interactions and put constrains on NP.
SMEFT offers a model-independent framework for analyses of the NP effects.

Dimension-6 operators

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
Q_{HG}	$H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\tilde{G}}$	$H^\dagger H \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{dG}	$g_s(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$

LO bb width

$$\bar{\Gamma}^{(4,0)} = \frac{N_c m_h \bar{m}_b^2 \beta^3}{8\pi v_T^2},$$

$$\bar{\Gamma}^{(6,0)} = \left(2C_{\rm H,kin} - \frac{\sqrt{2} v_T^3}{\bar{m}_b} C_{bH}\right)\bar{\Gamma}^{(4,0)}.$$

NLO decay width

$$\frac{\bar{\Gamma}}{\rm MeV} = \kappa^{\rm QCD}\left\{2.22\left[1 + 2\left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2 \tilde{C}_{H,\rm kin}\right] - 258\left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2 \tilde{C}_{bH}\right\} + \left(\frac{v_T}{\Lambda_{\rm NP}}\right)^2 (1.55\tilde{C}_{bG} + 6.88\tilde{C}_{HG}) + \cdots,$$

1.2

Missing in LO

Cullen, Gauld, Pecjak, Scott, PRD94,074045(2016),JHEP08(2019)173, JHEP04(2021)196

Higgs decay to fermions

The $h \to f\bar{f}$ decays allows measurement of Yukawa interactions and put constrains on NP.
SMEFT offers a model-independent framework for analyses of the NP effects.

Dimension-6 operators

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
Q_{HG}	$H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\tilde{G}}$	$H^\dagger H \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$
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Consider EW part:

$$\Delta^{\rm LO}(m_H) = 1 + \frac{(\overline{v}^{(\ell)})^2}{\Lambda_{\rm NP}^2}\left[3.74\tilde{C}_{HWB} + 2.00\tilde{C}_{H\Box} - 1.41\frac{\overline{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}_{bH} + 1.24\tilde{C}_{HD}\right]$$

Cullen, Gauld, Pecjak, Scott, PRD94,074045(2016),JHEP08(2019)173, JHEP04(2021)196

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	SM	$\tilde{C}_{HWB}$	$\tilde{C}_{H\Box}$	$\tilde{C}_{bH}$	$\tilde{C}_{HD}$
NLO QCD-QED	18.2%	17.9%	18.2%	18.2%	18.2%
NLO large-m_t	−3.1%	−4.6%	3.2%	3.5%	−9.0%
NLO remainder	−2.2%	−1.9%	−1.2 %	0.6%	−2.0%
NLO correction	12.9%	11.3%	20.2%	22.3%	7.1%

Cullen, Gauld, Pecjak, Scott, PRD94,074045(2016),JHEP08(2019)173, JHEP04(2021)196

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At NLO, 12 more operators will contribute.

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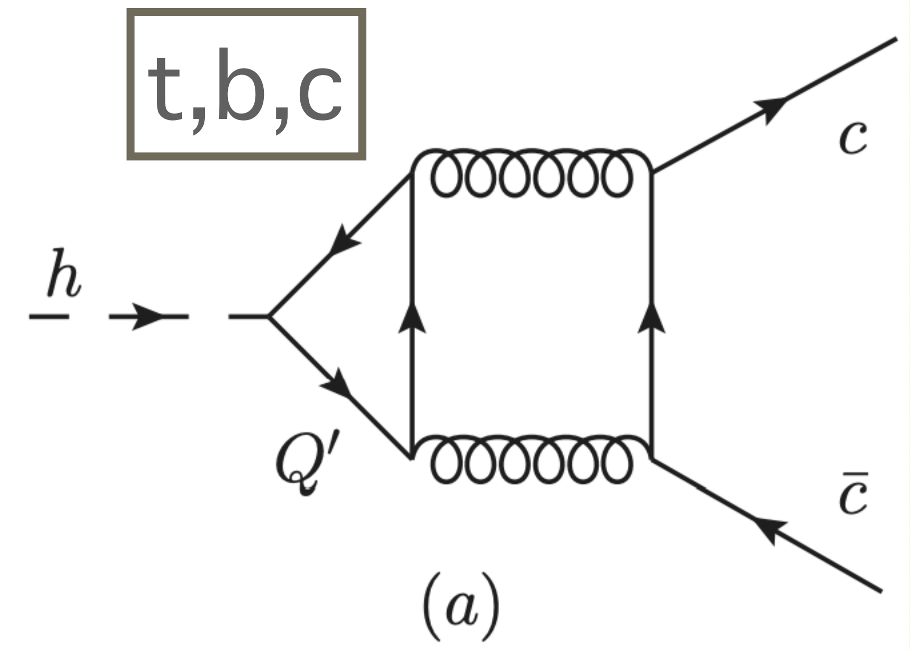
Higgs decay to fermions

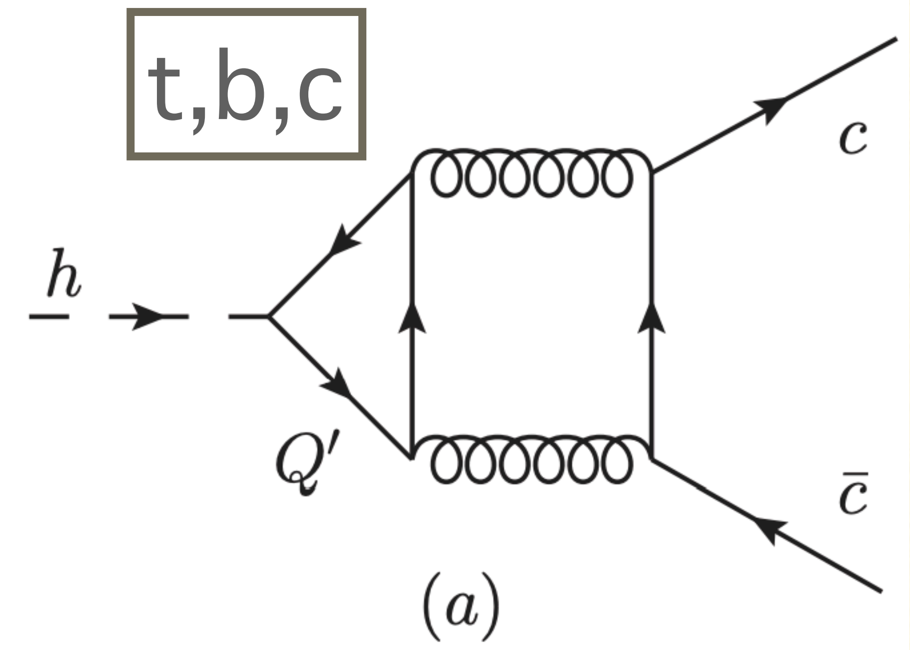
Li, Li, Lu, Si, CPC45(2021)093105

Higgs decay to fermions



Li, Li, Lu, Si, CPC45(2021)093105

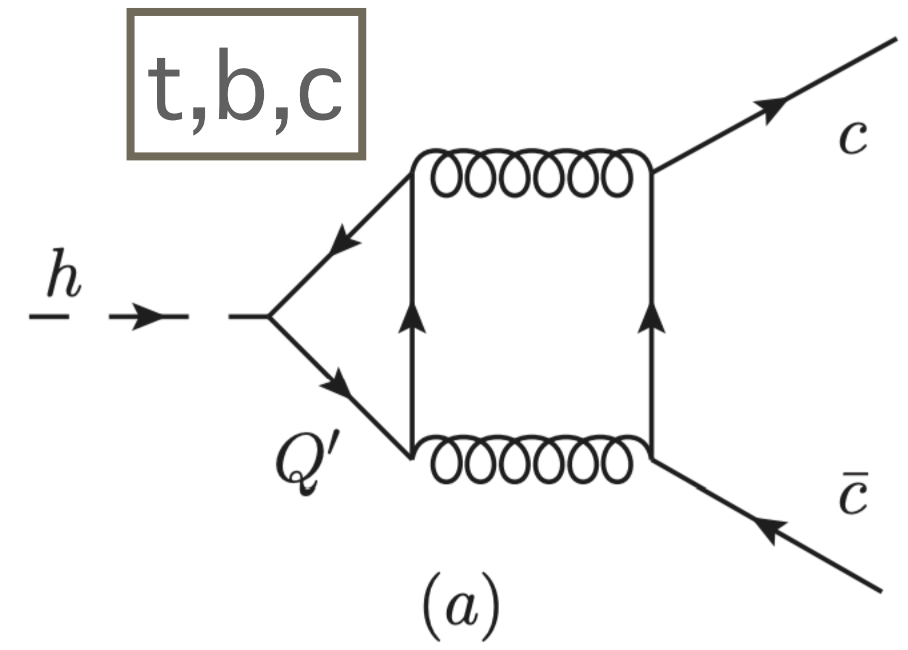
Higgs decay to fermions



$\tilde{\Gamma}_b^{FS}$ [MeV]	$\tilde{\Gamma}_t^{FS}$ [MeV]	$\tilde{\Gamma}_{c\bar{c}c\bar{c}}$ [MeV]	$\tilde{\Gamma}_{b\bar{b}c\bar{c}}$ [MeV]
-0.0482	0.7411	0.4262	3.4495

Li, Li, Lu, Si, CPC45(2021)093105

Higgs decay to fermions



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Small

Li, Li, Lu, Si, CPC45(2021)093105

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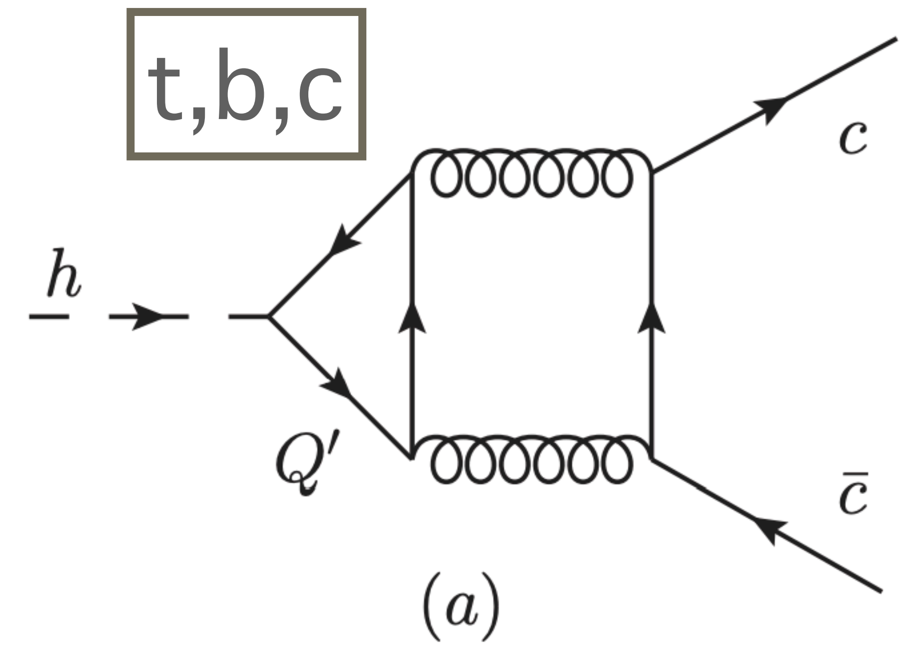

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Small

Flavor singlet: ~ 4%

Li, Li, Lu, Si, CPC45(2021)093105

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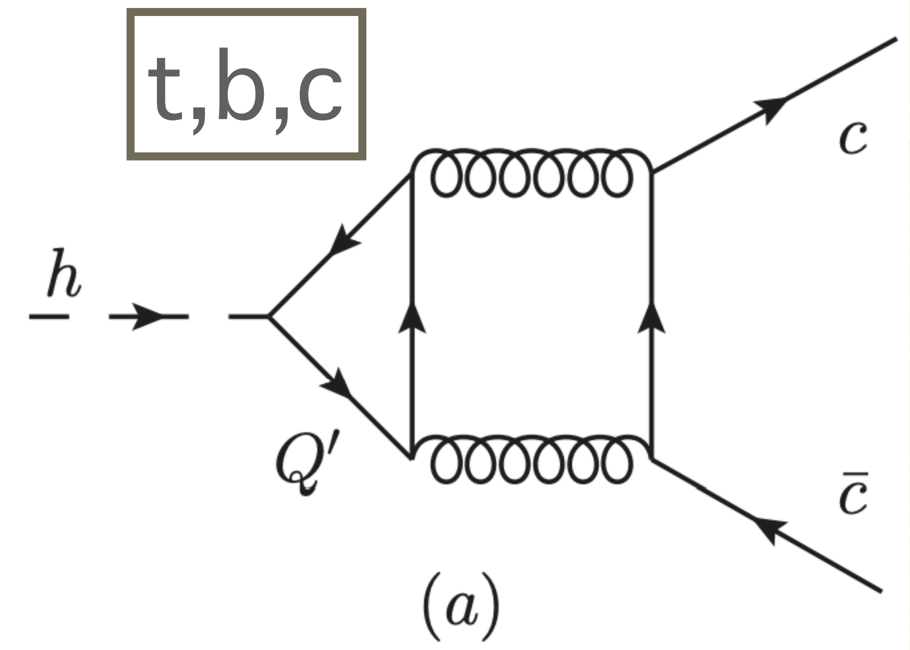

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Li, Li, Lu, Si, CPC45(2021)093105

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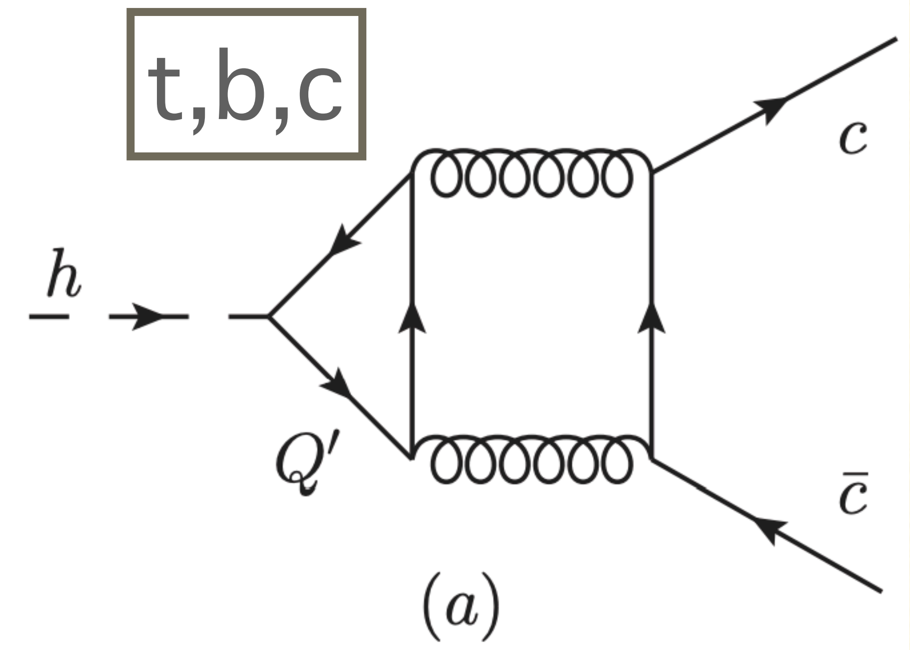

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	$\mu = m_h/2$	$\mu = m_h$	$\mu = 2m_h$
$\overline{\Gamma}_{LO}^{c\bar{c}}$[MeV]	0.1033	0.0916	0.0823
$\overline{\Gamma}_{NLO}^{c\bar{c}}$[MeV]	0.1153	0.1103	0.1049
$\overline{\Gamma}_{NNLO}^{c\bar{c}}$[MeV]	0.1162	0.1148	0.1125

Li, Li, Lu, Si, CPC45(2021)093105

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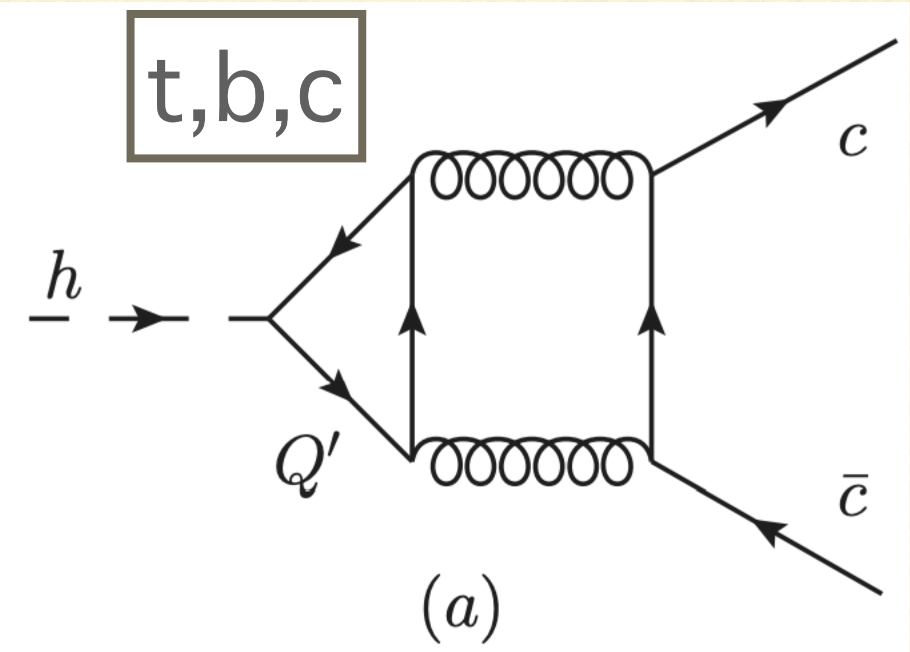

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NNLO QCD + NLO EW

	$\mu = m_h/2$	$\mu = m_h$	$\mu = 2m_h$
$\Gamma^{c\bar{c}}_{total}$ [MeV]	0.1165	0.1151	0.1129
$\Gamma^{b\bar{b}}_{total}$ [MeV]	2.4248	2.3990	2.3533
$\Gamma^{b\bar{b}}_{total}/\Gamma^{c\bar{c}}_{total}$	20.8137	20.8427	20.8441

Li, Li, Lu, Si, CPC45(2021)093105

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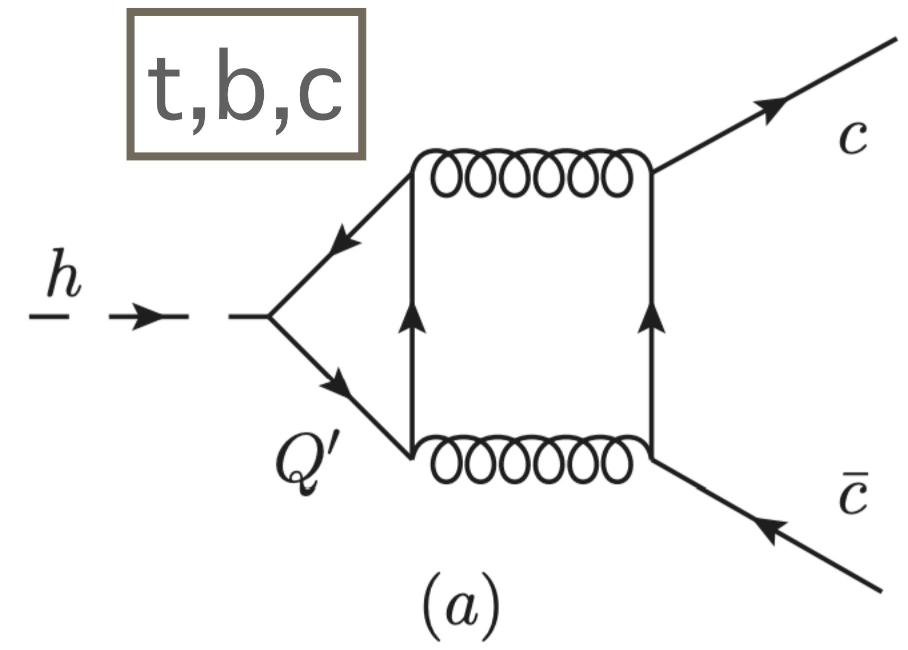

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In VH production channel, 1.5×10^5 $H \to b\bar{b}$ events and 2.8×10^4 $H \to c\bar{c}$ events, with 300 fb^{-1} int. lumi.

Li, Li, Lu, Si, CPC45(2021)093105

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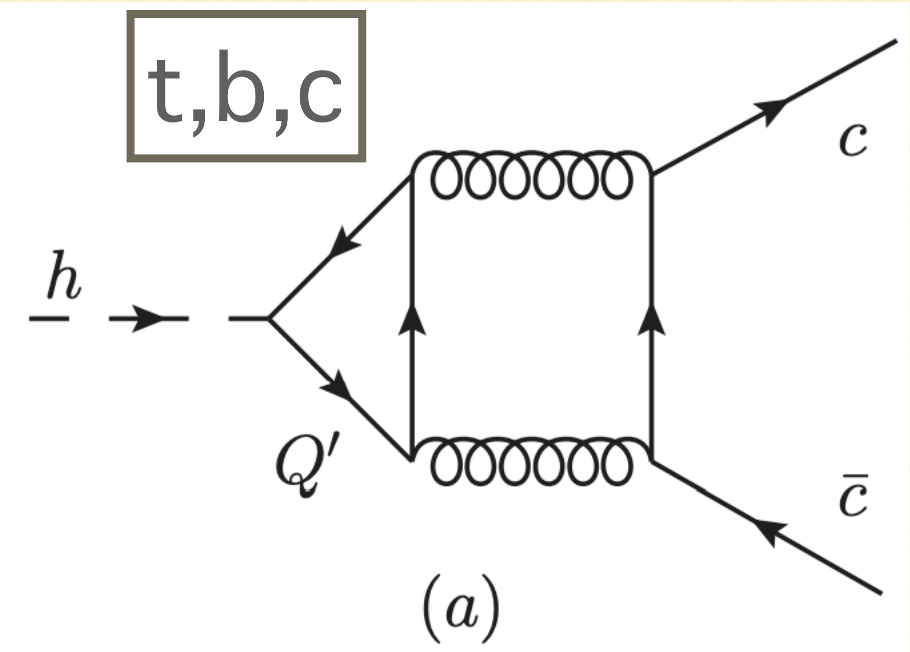

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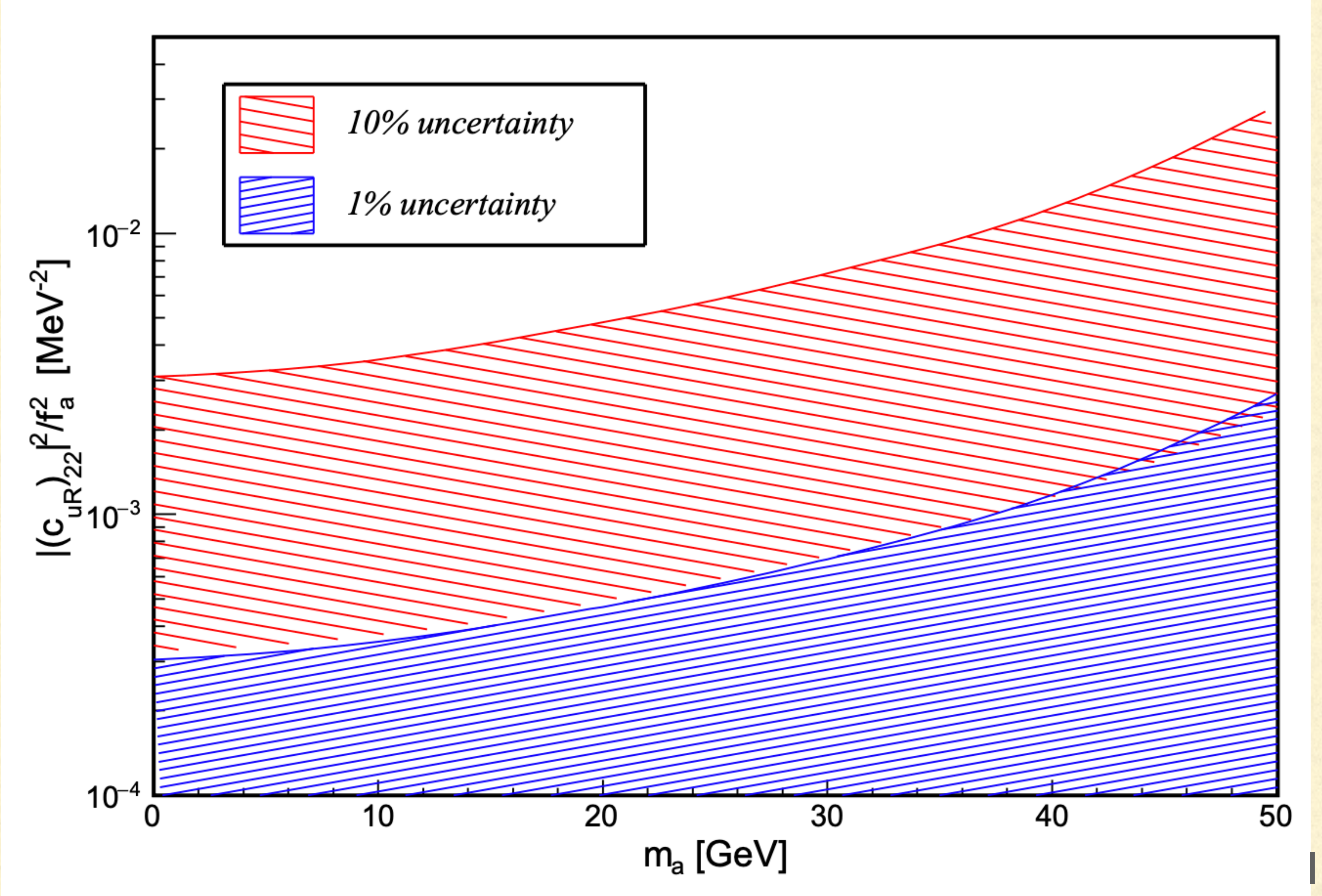
Constraints on ALP

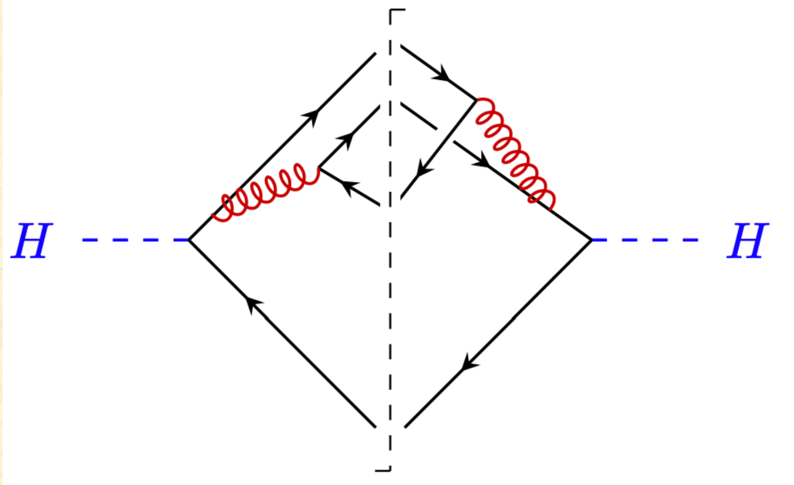


Li, Li, Lu, Si, CPC45(2021)093105

Higgs decay: Energy-Energy correlator

Higgs EEC is a novel event shape variable that can be measured by reconstructing 4-vectors of the final state particles originating from hadronic Higgs decays.

$$\frac{1}{\Gamma_{\text{tot}}}\frac{d\Sigma_H(\chi)}{d\cos\chi} = \sum_{a,b}\int \frac{2E_aE_b}{m_H^2}\,\delta(\cos\theta_{ab}-\cos\chi)\,d\Gamma_{a+b+X}$$



Gao, Shtabovenko,Yang, JHEP02(2021)210

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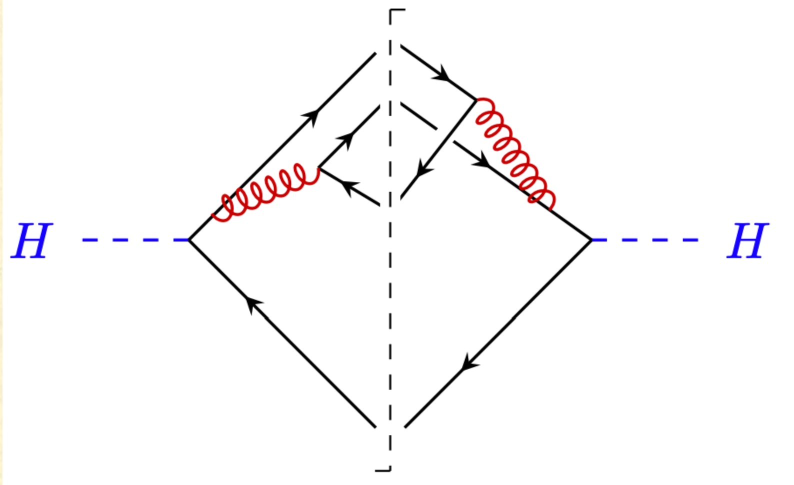

$$
\begin{aligned}
g_1^{(1)} &= \log(1-z)\,, \\
g_2^{(1)} &= \log(z)\,, \\
g_1^{(2)} &= 2(\mathrm{Li}_2(z)+\zeta_2)+\log^2(1-z)\,, \\
g_2^{(2)} &= \mathrm{Li}_2(1-z)-\mathrm{Li}_2(z)\,, \\
g_3^{(2)} &= -2\,\mathrm{Li}_2\left(-\sqrt{z}\right)+2\,\mathrm{Li}_2\left(\sqrt{z}\right)+\log\left(\frac{1-\sqrt{z}}{1+\sqrt{z}}\right)\log(z)\,, \\
g_4^{(2)} &= \zeta_2\,, \\
g_1^{(3)} &= -6\left[\mathrm{Li}_3\left(-\frac{z}{1-z}\right)-\zeta_3\right]-\log\left(\frac{z}{1-z}\right)\left(2(\mathrm{Li}_2(z)+\zeta_2)+\log^2(1-z)\right)\,, \\
g_2^{(3)} &= -12\left[\mathrm{Li}_3(z)+\mathrm{Li}_3\left(-\frac{z}{1-z}\right)\right]+6\,\mathrm{Li}_2(z)\log(1-z)+\log^3(1-z)\,, \\
g_3^{(3)} &= 6\log(1-z)\left(\mathrm{Li}_2(z)-\zeta_2\right)-12\,\mathrm{Li}_3(z)+\log^3(1-z)\,, \\
g_4^{(3)} &= \mathrm{Li}_3\left(-\frac{z}{1-z}\right)-3\,\zeta_2\log(z)+8\,\zeta_3\,, \\
g_5^{(3)} &= -8\left[\mathrm{Li}_3\left(-\frac{\sqrt{z}}{1-\sqrt{z}}\right)+\mathrm{Li}_3\left(\frac{\sqrt{z}}{1+\sqrt{z}}\right)\right]+2\mathrm{Li}_3\left(-\frac{z}{1-z}\right)+4\zeta_2\log(1-z) \\
&\quad +\log\left(\frac{1-z}{z}\right)\log^2\left(\frac{1+\sqrt{z}}{1-\sqrt{z}}\right)\,.
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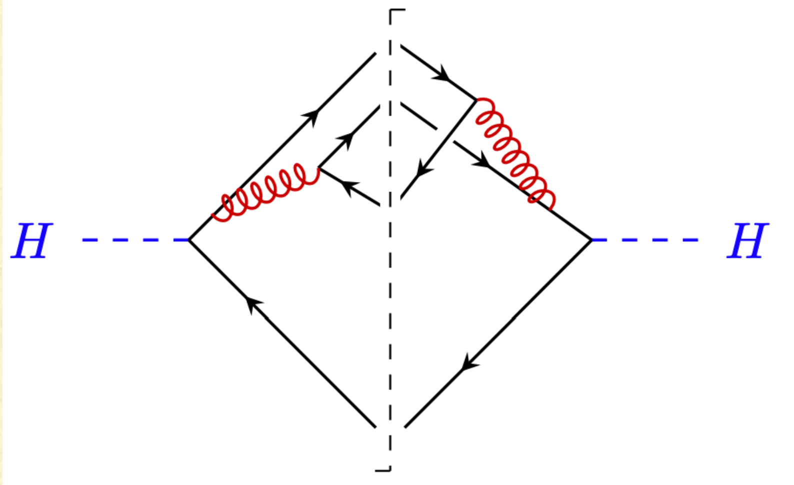

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\end{aligned}
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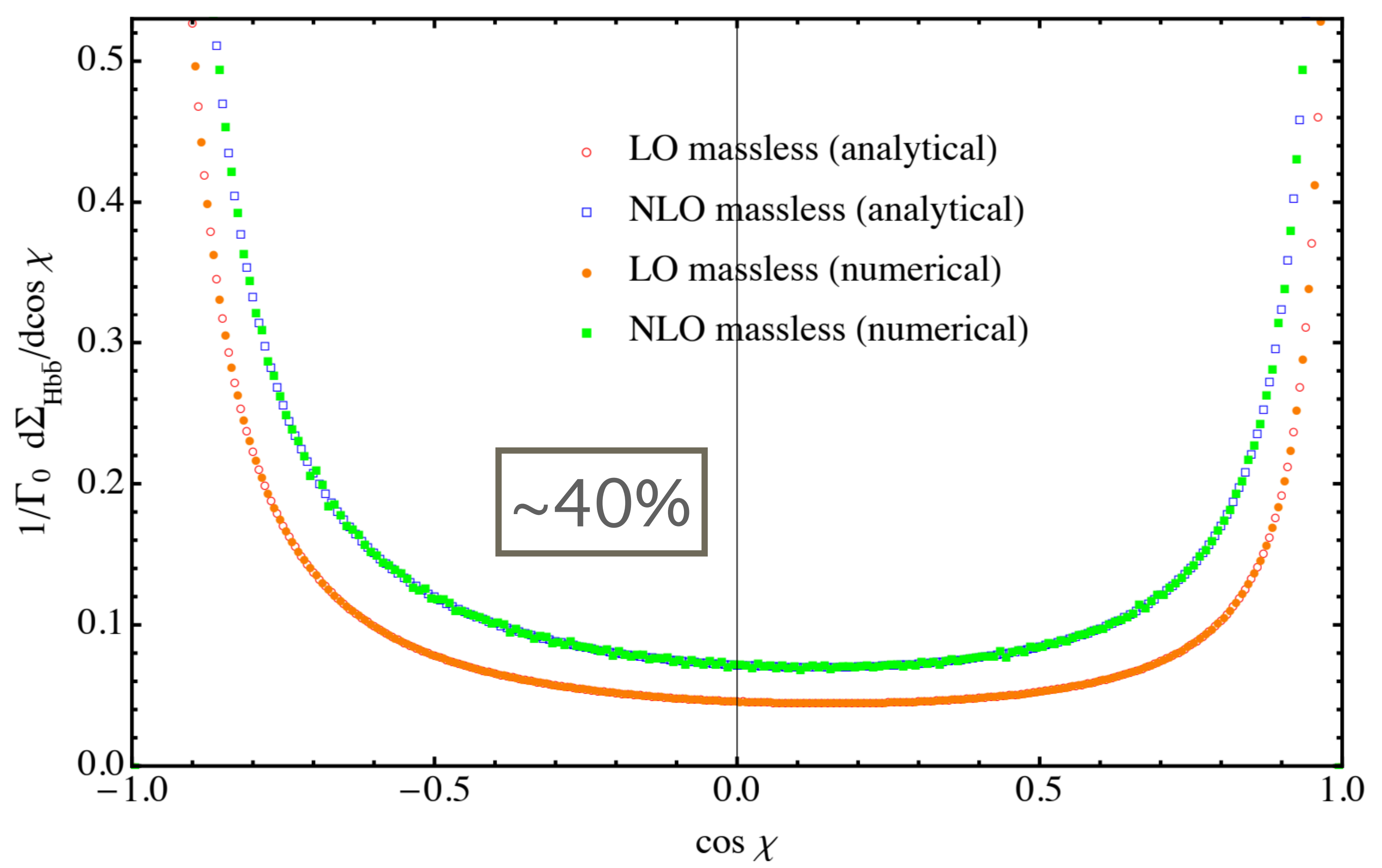

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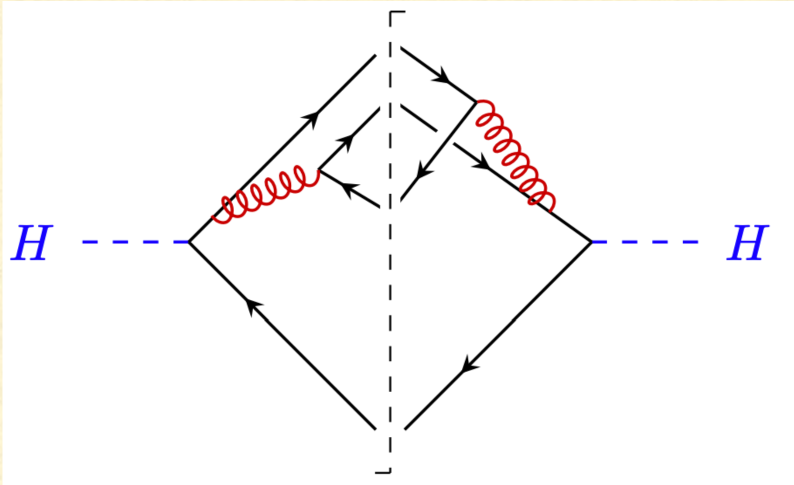

Parton shower & hadronization effects are significant

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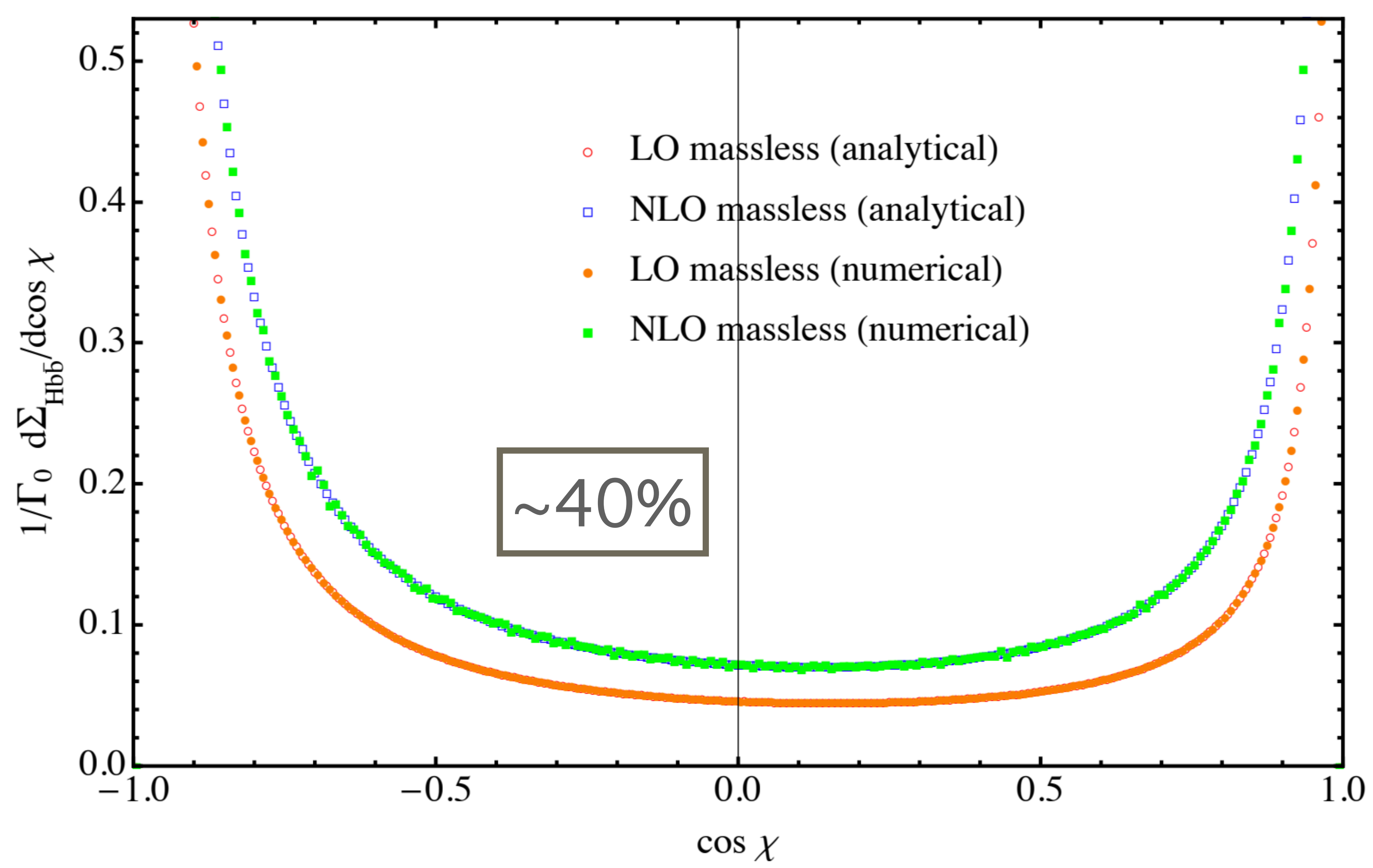
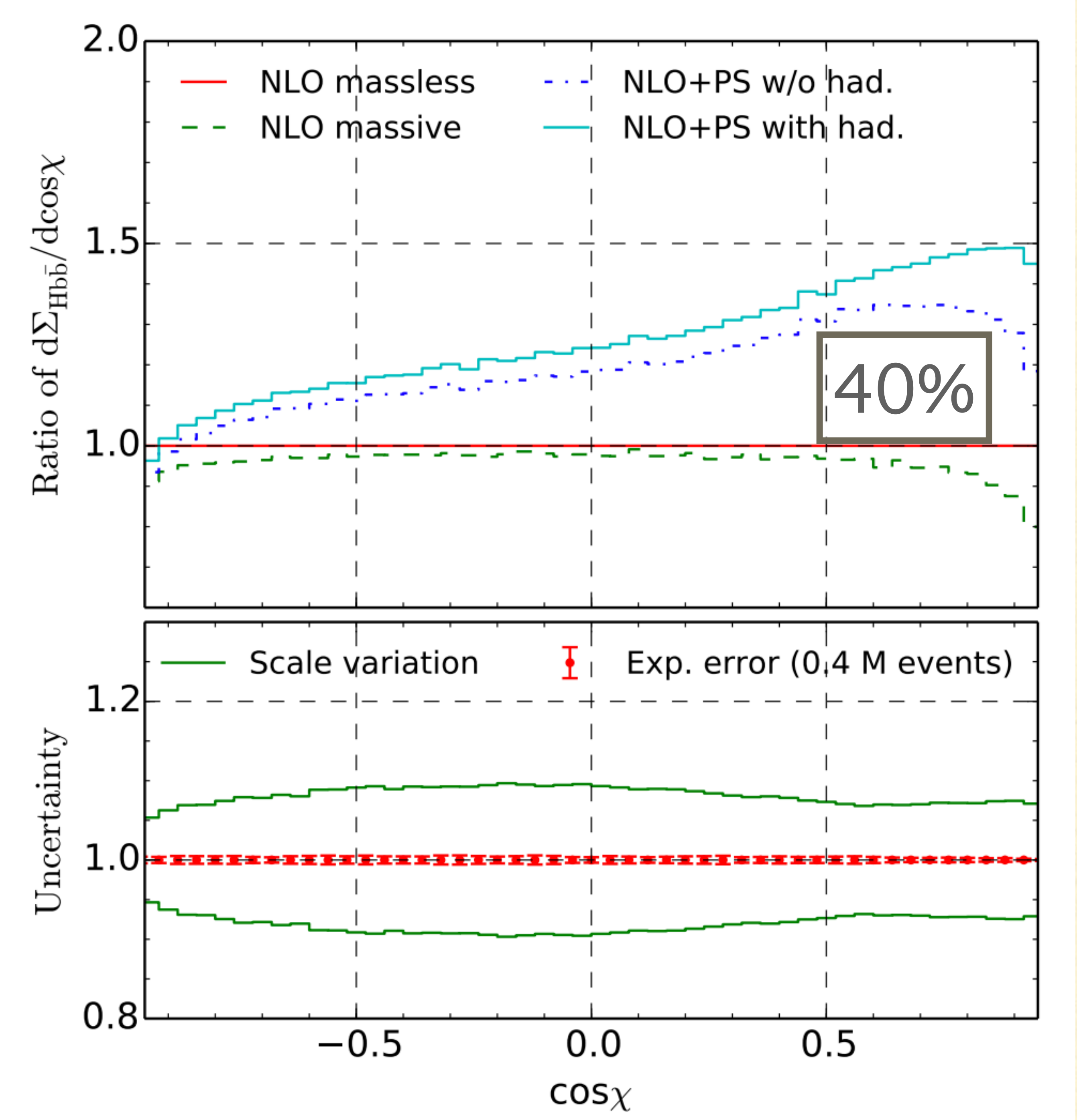
g_1^{(2)} &= 2(\mathrm{Li}_2(z)+\zeta_2)+\log^2(1-z)\,,\\
g_2^{(2)} &= \mathrm{Li}_2(1-z)-\mathrm{Li}_2(z)\,,\\
g_3^{(2)} &= -2\,\mathrm{Li}_2\left(-\sqrt{z}\right)+2\,\mathrm{Li}_2\left(\sqrt{z}\right)+\log\left(\frac{1-\sqrt{z}}{1+\sqrt{z}}\right)\log(z)\,,\\
g_4^{(2)} &= \zeta_2\,,\\
g_1^{(3)} &= -6\left[\mathrm{Li}_3\left(-\frac{z}{1-z}\right)-\zeta_3\right]-\log\left(\frac{z}{1-z}\right)\left(2(\mathrm{Li}_2(z)+\zeta_2)+\log^2(1-z)\right)\,,\\
g_2^{(3)} &= -12\left[\mathrm{Li}_3(z)+\mathrm{Li}_3\left(-\frac{z}{1-z}\right)\right]+6\,\mathrm{Li}_2(z)\log(1-z)+\log^3(1-z)\,,\\
g_3^{(3)} &= 6\log(1-z)\left(\mathrm{Li}_2(z)-\zeta_2\right)-12\,\mathrm{Li}_3(z)+\log^3(1-z)\,,\\
g_4^{(3)} &= \mathrm{Li}_3\left(-\frac{z}{1-z}\right)-3\,\zeta_2\log(z)+8\,\zeta_3\,,\\
g_5^{(3)} &= -8\left[\mathrm{Li}_3\left(-\frac{\sqrt{z}}{1-\sqrt{z}}\right)+\mathrm{Li}_3\left(\frac{\sqrt{z}}{1+\sqrt{z}}\right)\right]+2\mathrm{Li}_3\left(-\frac{z}{1-z}\right)+4\zeta_2\log(1-z)\\
&\quad+\log\left(\frac{1-z}{z}\right)\log^2\left(\frac{1+\sqrt{z}}{1-\sqrt{z}}\right)\,.
\end{aligned}$$





Gao, Shtabovenko, Yang, JHEP02(2021)210

Summary

The Higgs boson has been discovered over nine years.

Measurements of Higgs processes have reached percent level.

Precision is the key to a discovery of NP.

Interplay between theory and experiments may boost discovery.

Thank you for your attention!