浙江大學
ZHEJIANG UNIVERSITY

Efficient NLO computation for gg->HH/ZH with top quark mass dependence

G. Wang, Wang, Xu, Xu, Yang, arXiv:2010.15649

G. Wang, Xu, Xu, Yang, arXiv:2107.08206

Guoxing Wang

09/16/2021

Catalog

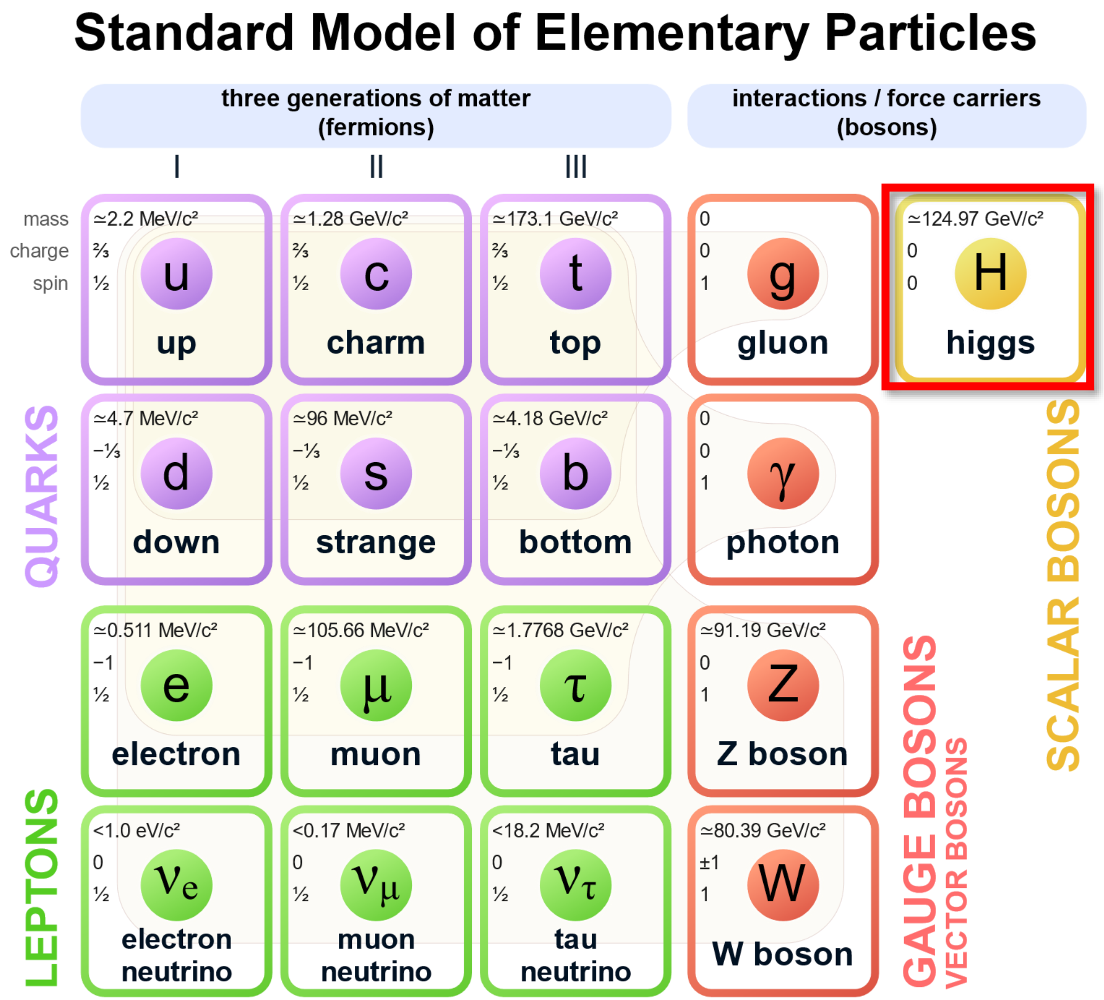
- Introduction to Higgs physics.
- HH and ZH production.
- Calculation of the amplitudes.
- Numeric calculation and discussions.
- Summary and outlook.

Basic facts about Higgs

- Large mass: $m_H \sim 125\ \mathrm{GeV}$
- Small width: $\Gamma_H \sim 5\ \mathrm{MeV}$
- EWSB: Fermion mass origin
  Hierarchy problem
  Vacuum stability
- Interactions:

$$g_{Hf\bar{f}},\ g_{HVV},\ g_{HHVV}$$

$$g_{HHH},\ g_{HHHH}$$

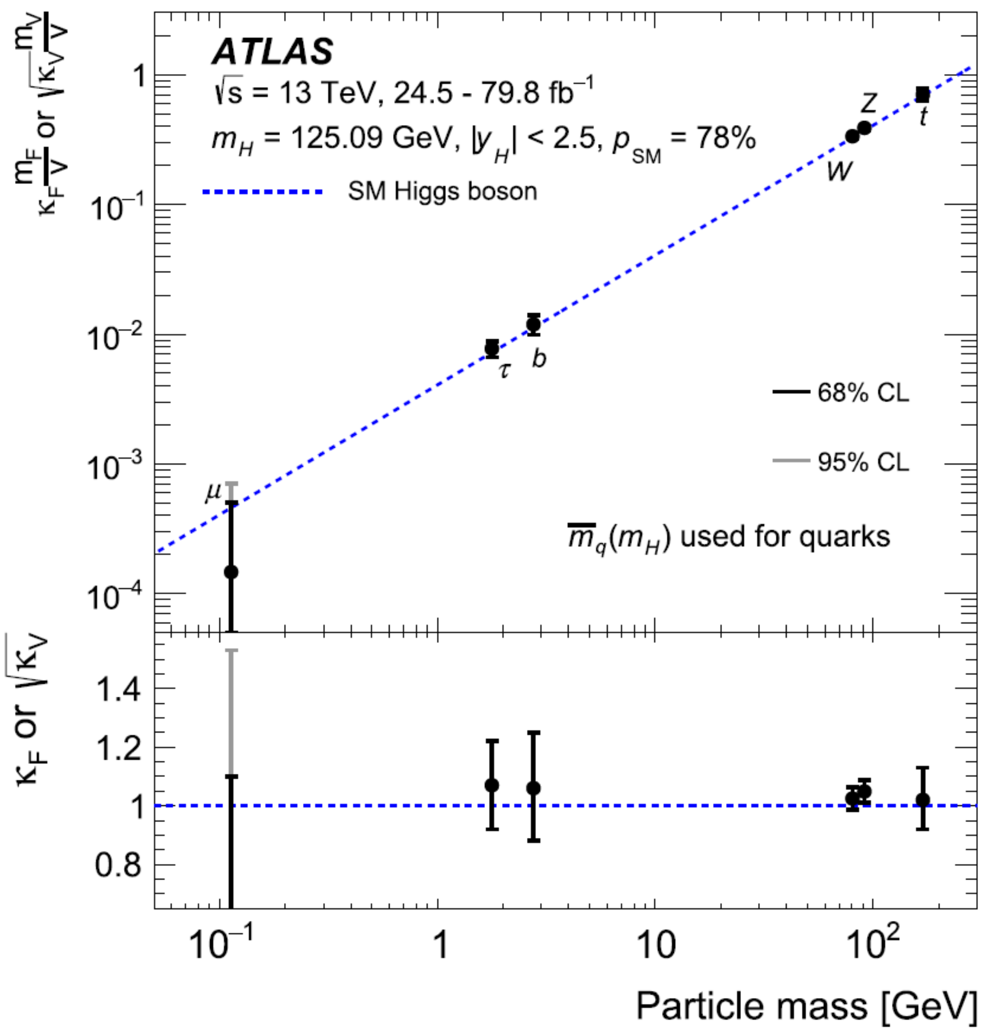


Basic facts about Higgs

- Large mass: $m_H \sim 125\ \text{GeV}$
- Small width: $\Gamma_H \sim 5\ \text{MeV}$
- EWSB: Fermion mass origin
  Hierarchy problem
  Vacuum stability
- Interactions:

$$g_{Hf\bar{f}},\ g_{HVV},\ g_{HHVV}$$

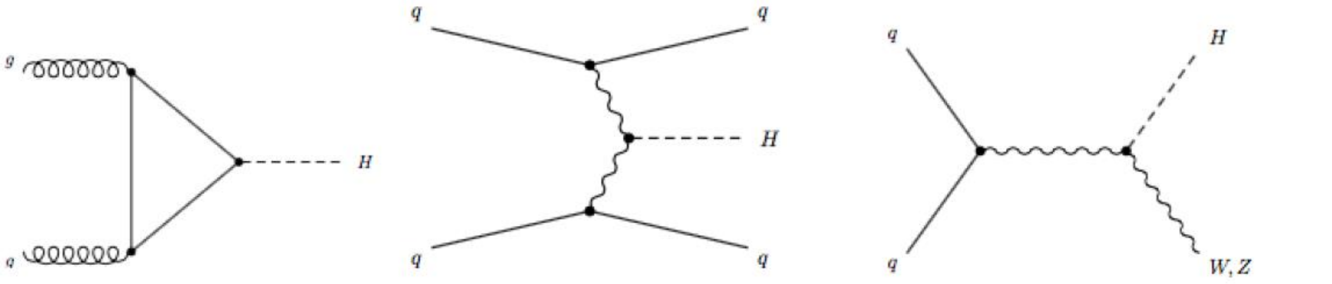
$$g_{HHH},\ g_{HHHH}$$



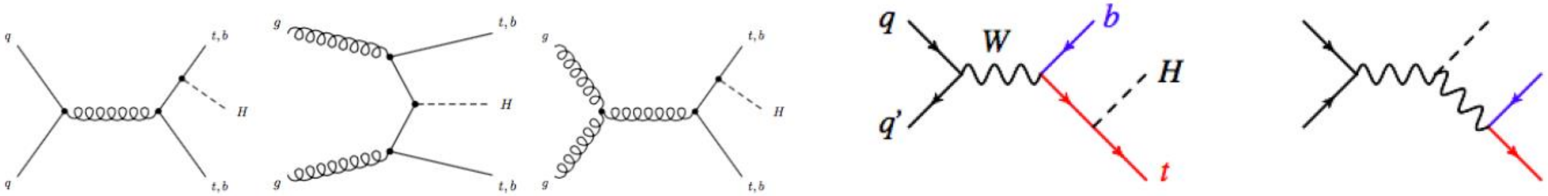
ATLAS: 1909.02845

Basic facts about Higgs

- Large mass: $m_H \sim 125\ \mathrm{GeV}$
- Small width: $\Gamma_H \sim 5\ \mathrm{MeV}$
- EWSB: Fermion mass origin
  Hierarchy problem
  Vacuum stability
- Interactions:
  $g_{Hf\bar{f}},\ g_{HVV},\ g_{HHVV}$
  $g_{HHH},\ g_{HHHH}$
- Production:



$gg \to H$ | Vector boson fusion | Associated $V + H$ production



$\bar{t}t + H$ production | s-channel diagrams for $t + H$ production

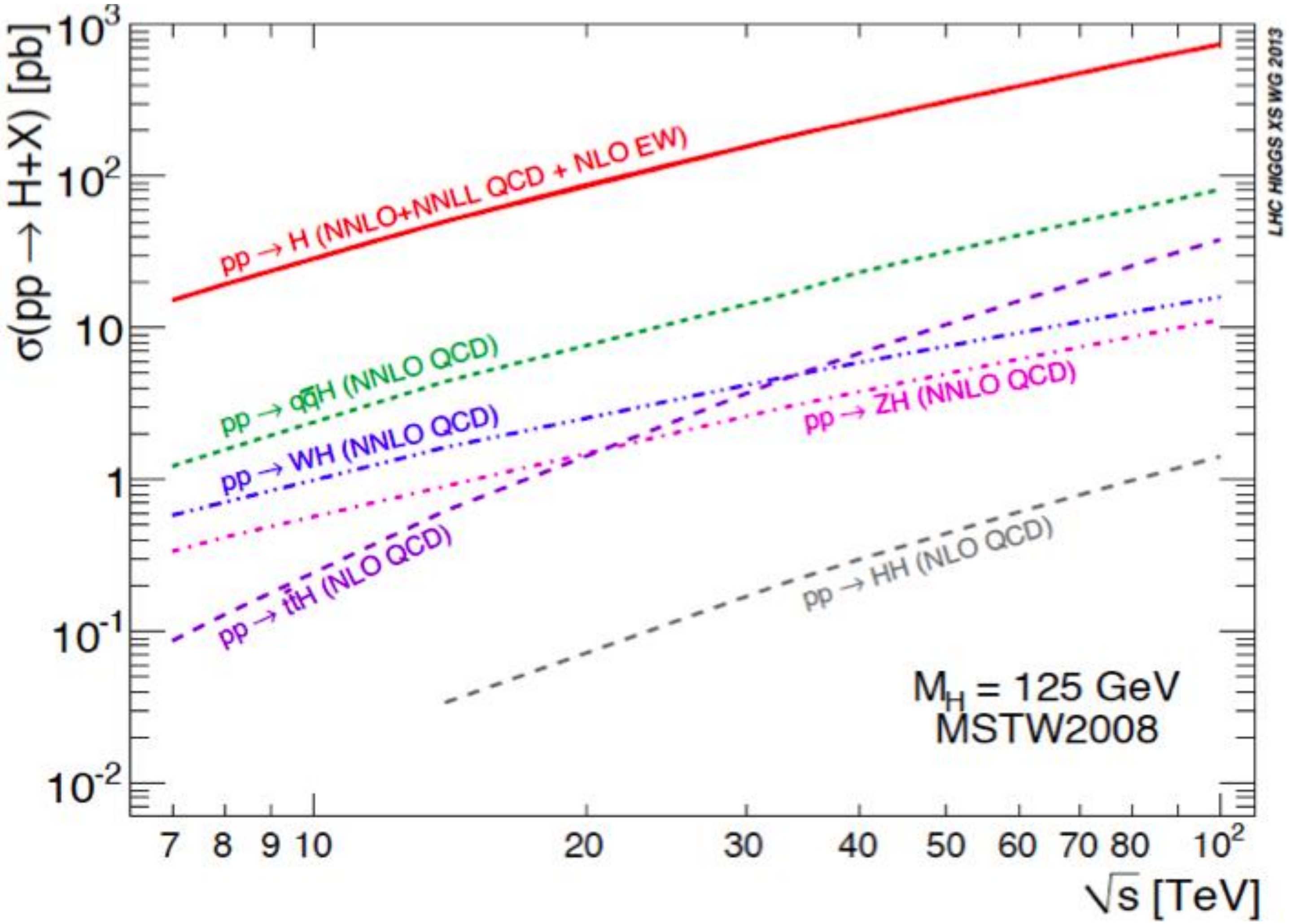
J. Ellis: 1702.05436

Basic facts about Higgs

- Large mass: $m_H \sim 125\ \text{GeV}$
- Small width: $\Gamma_H \sim 5\ \text{MeV}$
- EWSB: Fermion mass origin
  Hierarchy problem
  Vacuum stability
- Interactions:

  $g_{Hf\bar{f}},\ g_{HVV},\ g_{HHVV}$

  $g_{HHH},\ g_{HHHH}$
- Production:



R. Contino et al: 1606.09408

Basic facts about Higgs

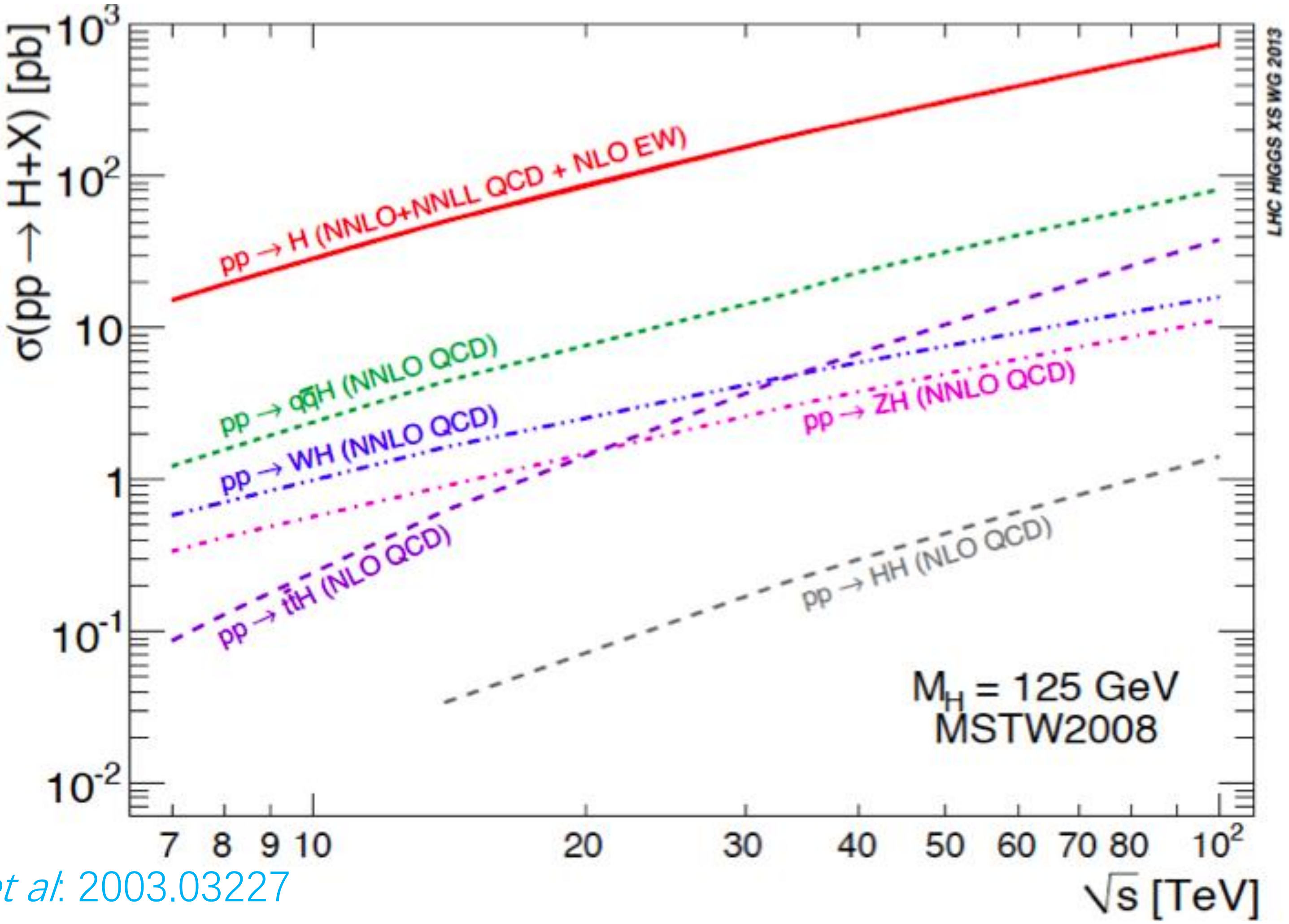
- Large mass: $m_H \sim 125\ \text{GeV}$
- Small width: $\Gamma_H \sim 5\ \text{MeV}$
- EWSB: Fermion mass origin
  Hierarchy problem
  Vacuum stability
- Interactions:

$$g_{Hf\bar{f}},\ g_{HVV},\ g_{HHVV}$$

$$g_{HHH},\ g_{HHHH}$$

- Production:

$$\sigma_{HH} \sim 30\ \text{fb}\ \ @13\,\text{TeV LHC}$$
$$\sigma_{HHH} \sim\ \ 6\ \text{fb}\ \ @100\,\text{TeV LHC}$$



J. Baglio *et al*: 2003.03227

D. Florian *et al*: 1912.02760

R. Contino *et al*: 1606.09408

Basic facts about Higgs

- Large mass: $m_H \sim 125\ \text{GeV}$
- Small width: $\Gamma_H \sim 5\ \text{MeV}$
- EWSB: Fermion mass origin
  Hierarchy problem
  Vacuum stability
- Interactions:

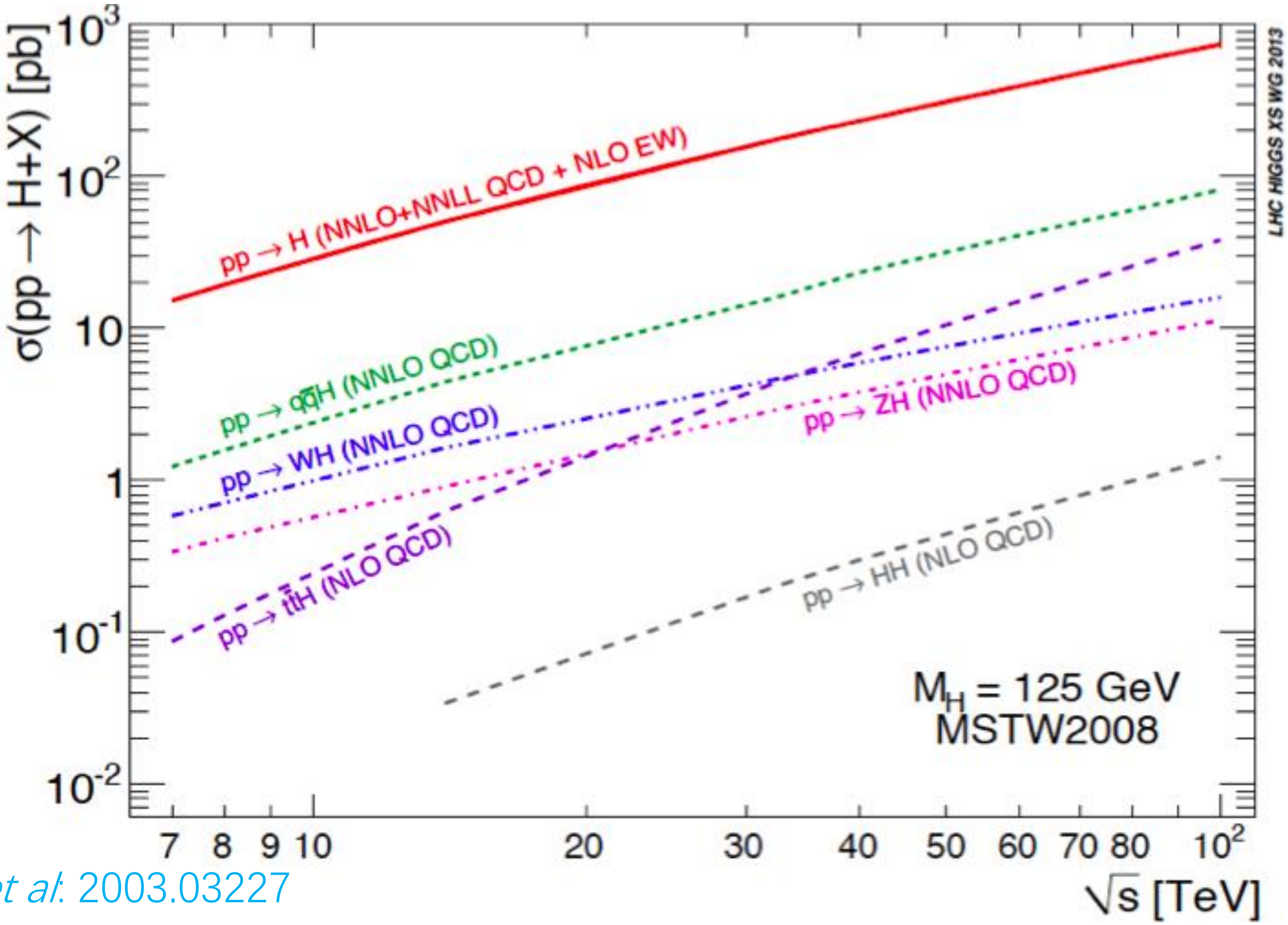
HH and *ZH* $\quad g_{Hf\bar{f}},\ g_{HVV} \quad g_{HHVV}$

$\quad g_{HHH},\ g_{HHHH}$

- Production and decay:

$\sigma_{HH} \sim 30\ \text{fb} \quad @14\text{TeV LHC}$

$\sigma_{ZH} \sim 900\ \text{fb} \quad @14\text{TeV LHC}$



J. Baglio *et al*: 2003.03227

O. Breina, *et al*: 1111.0761

R. Contino *et al*: 1606.09408

HH and ZH production

HH production

ZH production

- LO:

E. Glover, *et al.* Nucl. Phys. B 309, 282(1988)
T. Plehn, *et al.* Nucl. Phys. B 479, 46 (1996)

B. A. Kniehl, Phys. Rev. D 42 (1990) 2253

- NLO: absence of full analytic results
  - Numeric results

SecDec/pySecDec

e.g. S. Borowka, *et al.* 1604.06447
J. Baglio, *et al.* 2003.03227

L. Chen , *et al.* 2011.12325

  - Approx. analytic results:

$1/m_t$, p_T , $1/\hat{s}$ expansion

e.g. S. Dawson, *et al.* hep-ph/9805244
R. Bonciani, *et al.* 1806.11564
J. Davies, *et al.* 1811.05489

e.g. L. Altenkamp, *et al.* 1211.5015
L. Alasfar, *et al.* 2103.06225
J. Davies, *et al.* 2011.12314

HH and ZH production

HH production

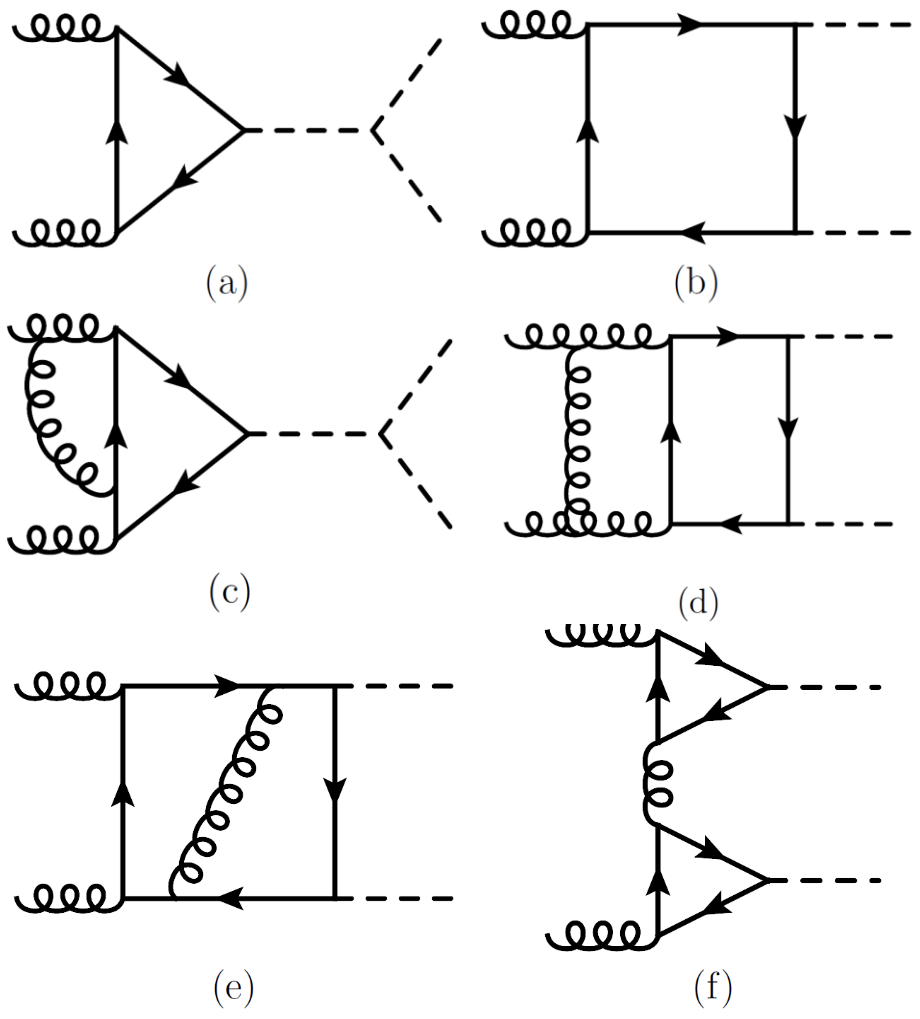
- NLO: absence of full analytic results
  - Combination of former results: high-energy expansion & sector decomposition via Padé approx.

J.Davies , *et al.* 1907.06408

Small external mass expansion

$$m_H^2/m_t^2\,,\ m_H^2/\hat{s}\,,\ m_H^2/\hat{t}_1$$

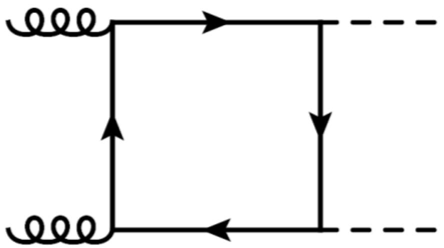
X. Xu, L. L. Yang. 1810.12002
G. Wang, Y. Wang, X. Xu, Y. Xu, L. L. Yang, 2010.15649



J. Davies, *et al*, 1907.06408

Calculation of the amplitudes

Set up



- Partonic process: $g_a^\mu(p_1) + g_b^\nu(p_2) \to H(p_3) + H(p_4)$
- Mandelstam variables: $\hat{s} = (p_1 + p_2)^2,\ \hat{t}_1 = (p_1 - p_3)^2 - m_H^2,$
  $\hat{u}_1 = (p_2 - p_3)^2 - m_H^2 = -\hat{s} - \hat{t}_1$
- Amplitude: $\mathcal{M}_{ab}^{\mu\nu} = \frac{G_F}{\sqrt{2}} \frac{\alpha_s}{2\pi} \hat{s}\, \delta_{ab} \left[A_1^{\mu\nu} F_1 + A_2^{\mu\nu} F_2\right],$

$$A_1^{\mu\nu} = g^{\mu\nu} - \frac{2p_1^\nu\, p_2^\mu}{\hat{s}},$$

T. Plehn, *et al.* hep-ph/9603205

- Projection operators:

$$A_2^{\mu\nu} = g^{\mu\nu} + \frac{2m_H^2\, p_1^\nu\, p_2^\mu + 2\hat{s} p_3^\mu\, p_3^\nu + 2\,\hat{u}_1\, p_1^\nu\, p_3^\mu + 2\,\hat{t}_1\, p_2^\mu\, p_3^\nu}{p_T^2\, \hat{s}},$$

$$P_1^{\mu\nu} = \frac{A_1^{\mu\nu}(d-2) - A_2^{\mu\nu}(d-4)}{4(d-3)}, \quad P_2^{\mu\nu} = \frac{A_2^{\mu\nu}(d-2) - A_1^{\mu\nu}(d-4)}{4(d-3)}.$$

Calculation of the amplitudes

Set up

J. Davies, *et al*, 1907.06408

- Form factor: $F_i\left(\hat{s},\hat{t}_1,m_t^2,m_H^2\right) = F_i^{(0)} + \frac{\alpha_s}{\pi} F_i^{(1)} + \mathcal{O}(\alpha_s^2)\,.$

UV & IR divergences

- Finite part:

$$\tilde{F}_i^{(1)} = F_i^{(1),\mathrm{ren}} - K_g^{(1)} F_i^{(0)} - \beta_0 F_i^{(0)} \log\left(\frac{\mu^2}{-\hat{s}}\right),$$

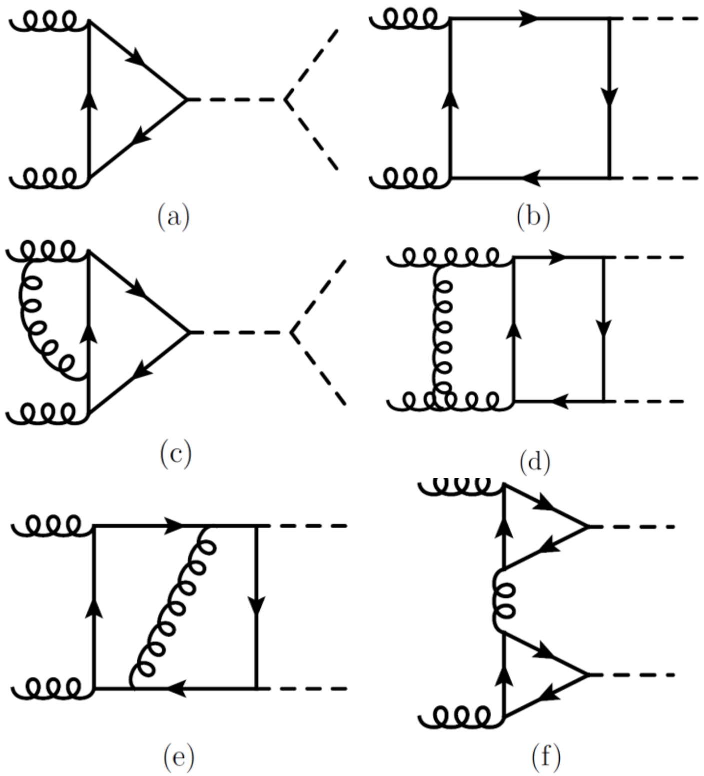
S. Catani, hep-ph/9802439

- Two-loop virtual corrections:

$$\mathcal{V}_{\mathrm{fin}} = \frac{1}{16\pi^2}\frac{G_F^2 \hat{s}^2}{64}(C_0 + C_1)$$

$$C_0 = \left[|F_1^{(0)}|^2 + |F_2^{(0)}|^2\right] C_A \left(\pi^2 - \log^2\frac{\mu^2}{\hat{s}}\right),$$

$$C_1 = 4\,\Re\left[F_1^{(0)}\tilde{F}_1^{(1)*} + F_2^{(0)}\tilde{F}_2^{(1)*}\right].$$



Calculation of the amplitudes

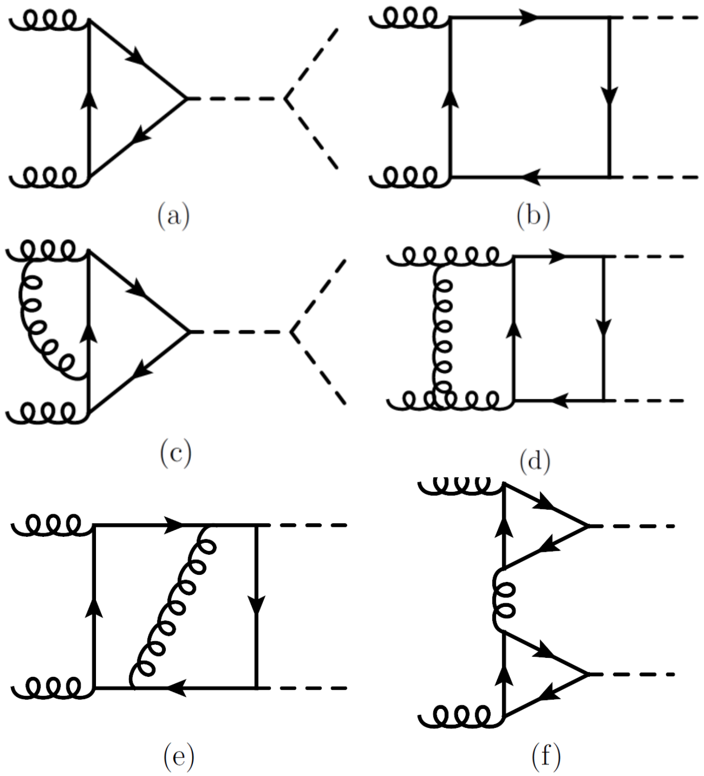
Expansion

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

UV & IR divergences

- Integrand level:

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



$$\{k_1^2 - m_t^2,\ (k_1+p_1)^2 - m_t^2,\ (k_1+p_1+p_2)^2 - m_t^2,\ (k_1+k_2)^2,$$
$$k_2^2 - m_t^2,\ (k_2-p_3)^2 - m_t^2,\ (k_2-p_1-p_2)^2 - m_t^2\}$$

Calculation of the amplitudes

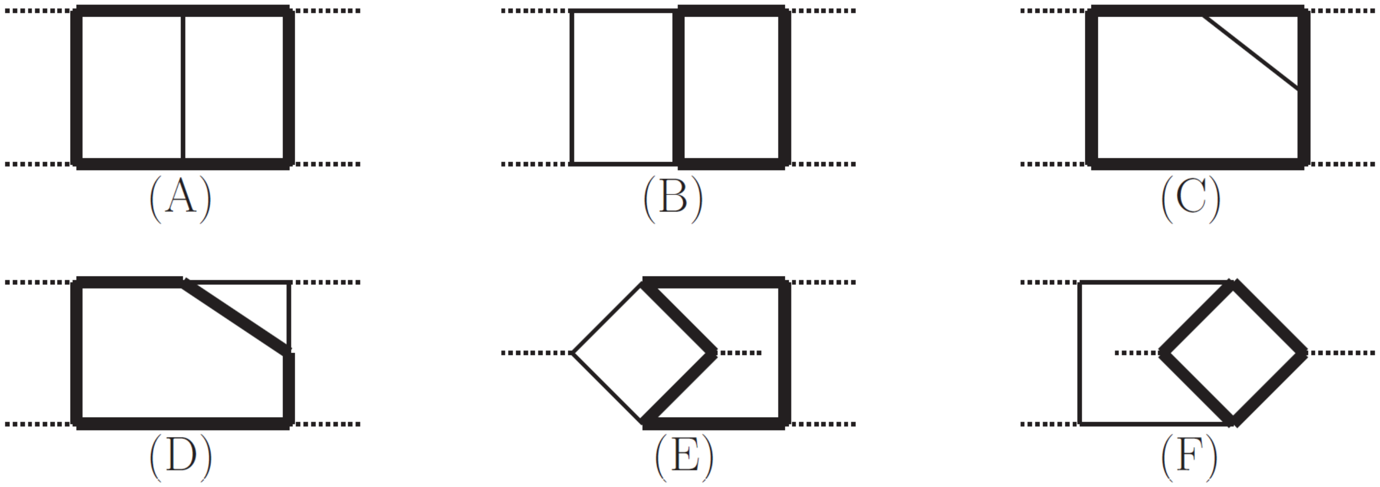
Expansion

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

UV & IR divergences

- Integrand level:

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



S. Caron-Huot, *et al.* 1404.2922
M. Becchetti, *et al.* 1712.02537

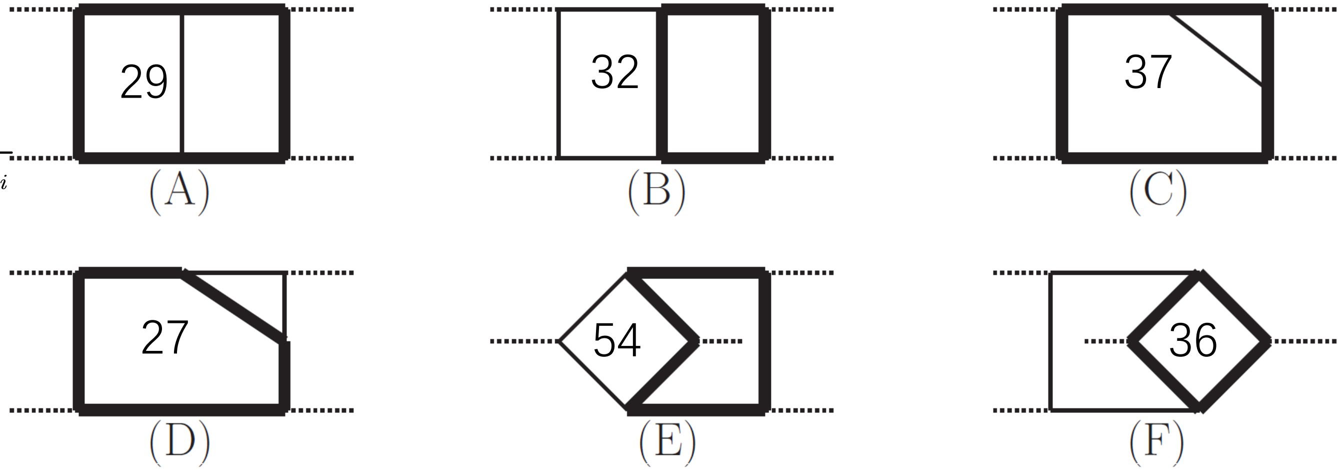
X. Xu, L. L. Yang. 1810.12002

Calculation of the amplitudes

- Topology, e.g. $\{k_1^2-m_t^2,\ (k_1+p_1)^2-m_t^2,\ (k_1+p_1+p_2)^2-m_t^2,\ (k_1+k_2)^2,\ k_2^2-m_t^2,$
$(k_2-p_3)^2-m_t^2,\ (k_2-p_1-p_2)^2-m_t^2,\ (k_2-p_1)^2-m_t^2,\ (k_1+p_3)^2-m_t^2\}$

- Master integrals:

$$I_{\{a_i\}}(\hat{s},\hat{t}_1,m_t^2,d)=\mathcal{C}\int\frac{d^dk}{(2\pi)^d}\frac{d^dk}{(2\pi)^d}\prod_{i=1}^{9}\frac{1}{D_i^{a_i}}$$



- Differential equations:

$$d\vec{f}(\vec{x},\epsilon)=dA(\vec{x},\epsilon)\vec{f}(\vec{x},\epsilon)$$

- Canonical form: $d\vec{g}(\vec{x},\epsilon)=\epsilon\, dB(\vec{x})\vec{g}(\vec{x},\epsilon)$ J. Henn, 1304.1806 $\vec{g}(\vec{x},\epsilon)=\hat{T}(\vec{x},\epsilon)\vec{f}(\vec{x},\epsilon)$

or $d\vec{h}(\vec{x},\epsilon)=[\epsilon\, dB_1(\vec{x})+dB_0(\vec{x})]\vec{h}(\vec{x},\epsilon)$ $\vec{h}(\vec{x},\epsilon)=\hat{T}'(\vec{x},\epsilon)\vec{f}(\vec{x},\epsilon)$

Calculation of the amplitudes

- Canonical form: $d\vec{g}(\vec{x},\epsilon)=\epsilon\, dB(\vec{x})\,\vec{g}(\vec{x},\epsilon)$
- d-log form: $d\vec{g}(\vec{x},\epsilon)=\epsilon\sum_k B_k\, d\log\alpha_k(\vec{x})\,\vec{g}(\vec{x},\epsilon)$

  B_k is constant matrix,

  α_k is called a letter
- Solution: $\vec{g}(\vec{x},\epsilon)=\mathcal{P}\exp\left[\epsilon\int_{\vec{x}_0}^{\vec{x}}\sum_k B_k\, d\log\alpha_k(\vec{x})\right]\vec{g}_0(\vec{x}_0,\epsilon)$
- Square root: $\{\sqrt{1+a},\sqrt{1+a+b},\sqrt{a+b},\sqrt{16a+(4+b)^2}\}$ $\quad\{a,b\}\subset\{u,v,\frac{uv}{u+v}\}$

$$u=-\frac{4m_t}{\hat{s}},\quad v=-\frac{4m_t}{\hat{t}_1}$$

M. Besier, *et al*, 1809.10983

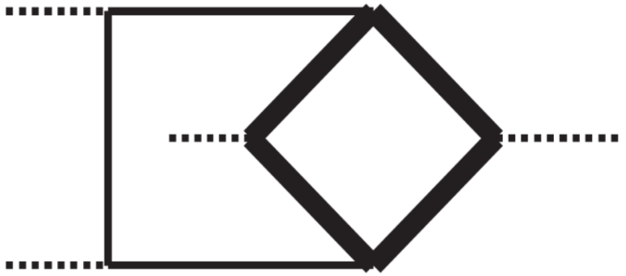
$$G(a_1,\cdots a_n;z)=\int_0^z\frac{dt}{t-a_1}G(a_2,\cdots a_n;t)$$

A. Goncharov, 1105.2076

Calculation of the amplitudes

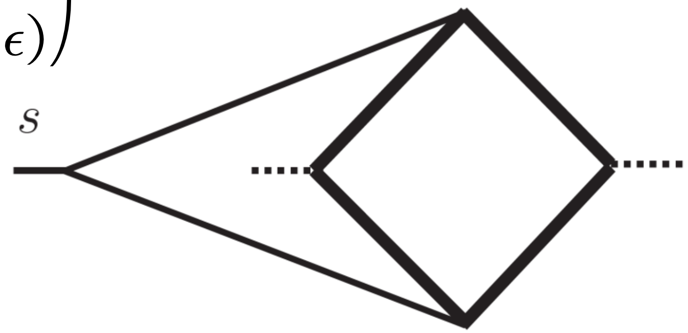
- $d\vec{h}(\vec{x},\epsilon) = [dB_0(\vec{x}) + \epsilon\, dB_1(\vec{x})]\vec{h}(\vec{x},\epsilon)$

$$\{(k_1-p_1)^2,\ k_1^2,\ (k_1+p_2)^2,\ (k_1+k_2-p_1)^2-m_t^2,\ k_2^2-m_t^2,$$
$$(k_2-p_3)^2-m_t^2,\ (k_1+k_2+p_2-p_3)^2-m_t^2,\ (k_1-p_3)^2,\ (k_2-p_1)^2-m_t^2\}$$



(F)

sub-topology



- DEs: $\frac{d}{du}\begin{pmatrix} h_1(u,\epsilon) \\ h_2(u,\epsilon) \end{pmatrix} = \left[\tilde{B}_0(u) + \epsilon \tilde{B}_1(u)\right]\begin{pmatrix} h_1(u,\epsilon) \\ h_2(u,\epsilon) \end{pmatrix} + \tilde{C}(u,\epsilon)\begin{pmatrix} k_1(u,\epsilon) \\ k_2(u,\epsilon) \end{pmatrix}$

$$\tilde{B}_0(u) = \begin{pmatrix} 0 & \frac{4}{u} \\ \frac{1}{4(1-4u)} & \frac{4}{1-4u} \end{pmatrix}$$

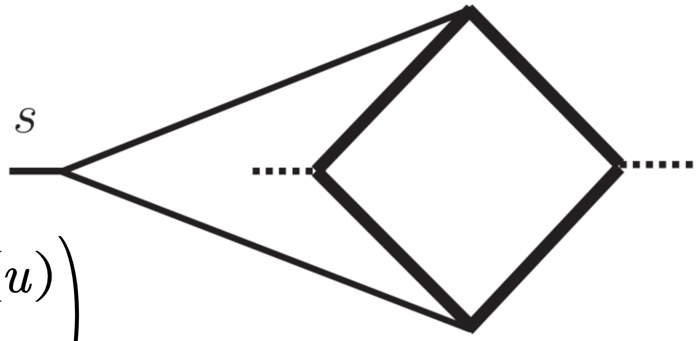
- Homogeneous part:

$$\frac{d}{du}\begin{pmatrix} H_1^{(n)}(u) \\ H_2^{(n)}(u) \end{pmatrix} = \tilde{B}_0(u)\begin{pmatrix} H_1^{(n)}(u) \\ H_2^{(n)}(u) \end{pmatrix}$$

A. Manteuffel, *et al*, 1701.05905

Calculation of the amplitudes

- $$\frac{d}{du}\begin{pmatrix} H_1^{(n)}(u) \\ H_2^{(n)}(u) \end{pmatrix} = \tilde{B}_0(u)\begin{pmatrix} H_1^{(n)}(u) \\ H_2^{(n)}(u) \end{pmatrix}$$

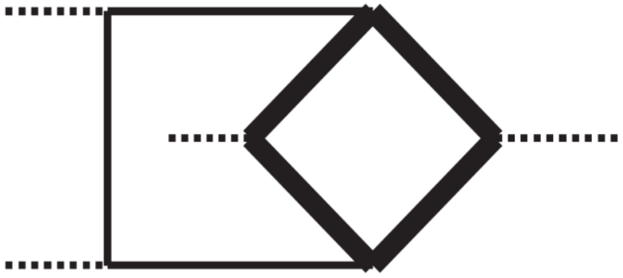


$$G(u) = \begin{pmatrix} I_1(u) & J_1(u) \\ I_2(u) & J_2(u) \end{pmatrix} \xrightarrow{\text{transform}} \begin{pmatrix} H_1^{(n)}(u) \\ H_2^{(n)}(u) \end{pmatrix} = G(u)\begin{pmatrix} \tilde{H}_1^{(n)}(u) \\ \tilde{H}_2^{(n)}(u) \end{pmatrix}$$

- New DEs: $$\frac{d}{du}\begin{pmatrix} \tilde{H}_1^{(n)}(u) \\ \tilde{H}_2^{(n)}(u) \end{pmatrix} = G^{-1}(u)\tilde{B}_1(u)G(u)\begin{pmatrix} \tilde{H}_1^{(n-1)}(u) \\ \tilde{H}_2^{(n-1)}(u) \end{pmatrix} + G^{-1}(u)\begin{pmatrix} \tilde{k}_1^{(n)}(u) \\ \tilde{k}_2^{(n)}(u) \end{pmatrix}$$

Can be solved as usual !

- Top-topology: $$d\tilde{B}'_0 = \begin{pmatrix} 0 & \star & \star & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \star & \star \\ 0 & 0 & \star & 0 \end{pmatrix}$$



(F)

Calculation of the amplitudes

ZH production

- Partonic process: $g_a^\alpha(p_1) + g_b^\beta(p_2) \to Z^\mu(p_3) + H(p_4)$

$$A_1^{\alpha\beta\mu}(p_1,p_2,p_3) = \frac{\hat{s}}{2}\epsilon^{\alpha\beta\mu\rho}p_{2\rho} - p_2^\alpha\epsilon^{\beta\mu\rho\sigma}p_{1\rho}p_{2\sigma}\,,$$

$$A_2^{\alpha\beta\mu}(p_1,p_2,p_3) = -\frac{\hat{s}}{2}\epsilon^{\alpha\beta\mu\rho}p_{1\rho} + p_1^\beta\epsilon^{\alpha\mu\rho\sigma}p_{1\rho}p_{2\sigma}\,,$$

$$A_3^{\alpha\beta\mu}(p_1,p_2,p_3) = -\left(p_3^\alpha + \frac{\hat{t}_1}{\hat{s}}p_2^\alpha\right)\epsilon^{\beta\mu\rho\sigma}p_{2\rho}p_{1\sigma}\,,$$

$$A_4^{\alpha\beta\mu}(p_1,p_2,p_3) = -\left(p_3^\beta + \frac{m_H^2 - m_Z^2 - \hat{s} - \hat{t}_1}{\hat{s}}p_1^\beta\right)\epsilon^{\alpha\mu\rho\sigma}p_{1\rho}p_{2\sigma}\,,$$

$$A_5^{\alpha\beta\mu}(p_1,p_2,p_3) = \left(p_3^\alpha + \frac{\hat{t}_1}{\hat{s}}p_2^\alpha\right)\epsilon^{\beta\mu\rho\sigma}p_{2\rho}p_{3\sigma}\,,$$

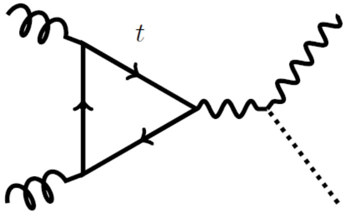
$$A_6^{\alpha\beta\mu}(p_1,p_2,p_3) = \left(p_3^\beta + \frac{m_H^2 - m_Z^2 - \hat{s} - \hat{t}_1}{\hat{s}}p_1^\beta\right)\epsilon^{\alpha\mu\rho\sigma}p_{1\rho}p_{3\sigma}\,,$$

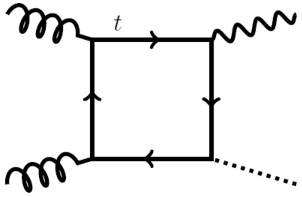
$$A_7^{\alpha\beta\mu}(p_1,p_2,p_3) = -\frac{\hat{s}}{2}\epsilon^{\alpha\beta\mu\rho}p_{3\rho} + p_2^\alpha\epsilon^{\beta\mu\rho\sigma}p_{1\rho}p_{3\sigma} - p_1^\beta\epsilon^{\alpha\mu\rho\sigma}p_{2\rho}p_{3\sigma} - g^{\alpha\beta}\epsilon^{\mu\rho\sigma\tau}p_{1\rho}p_{2\sigma}p_{3\tau}\,,$$

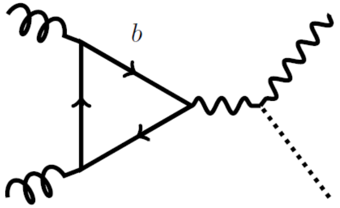
B. A. Kniehl, Phys. Rev. D 42 (1990) 2253

$$\bar{\psi}\gamma^\mu\gamma_5\psi \to i\frac{\epsilon^{\mu\rho\sigma\tau}}{3!}\bar{\psi}\gamma_\rho\gamma_\sigma\gamma_\tau\psi$$

S. A. Larin, hep-ph/9302240

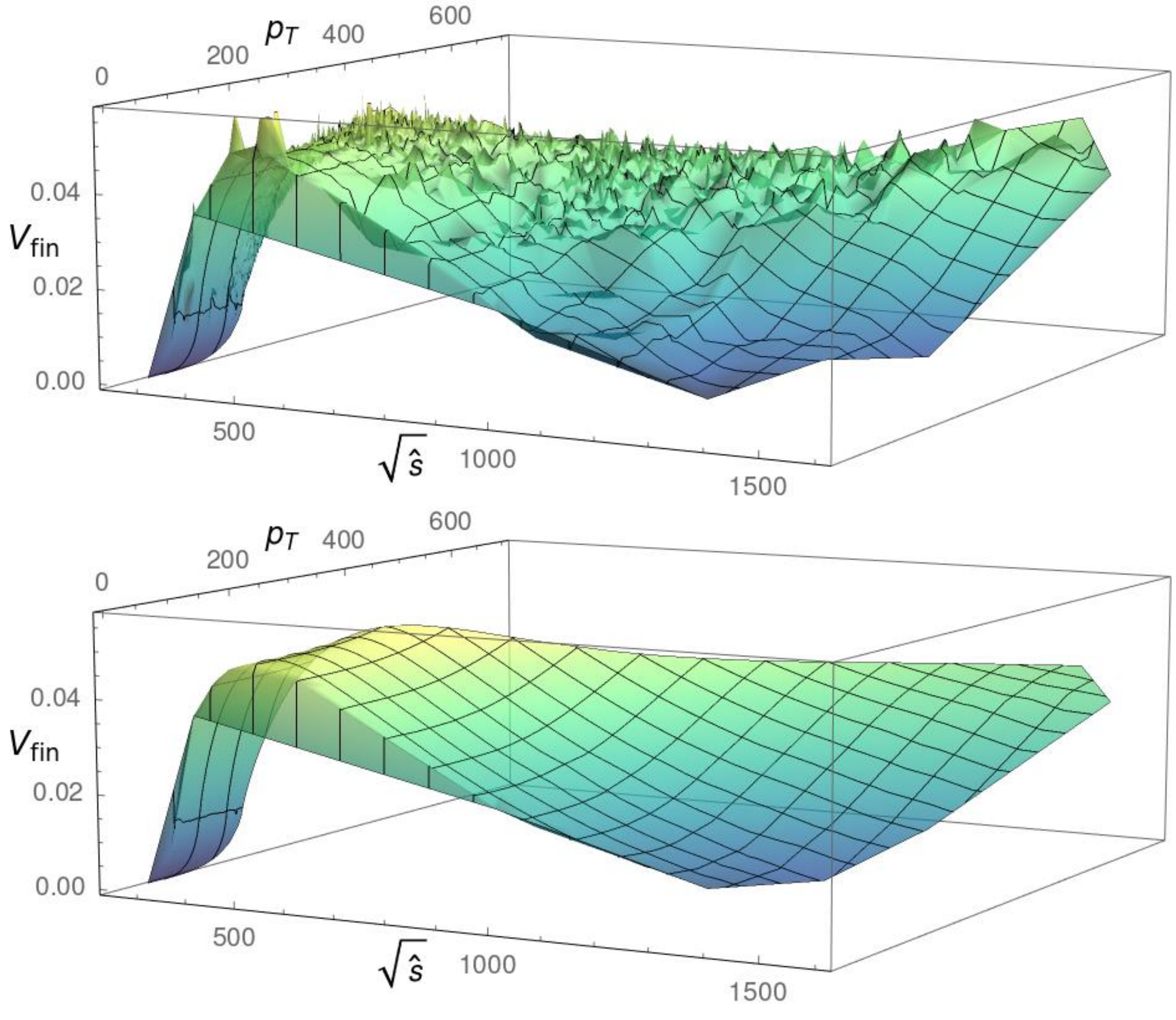






J. Davies, *et al.* 2011.12314

Validation of small mass expansion (HH)



$$\mathcal{V}_{\text{fin}} = \frac{1}{16\pi^2}\frac{G_F^2\hat{s}^2}{64}(C_0 + C_1)$$

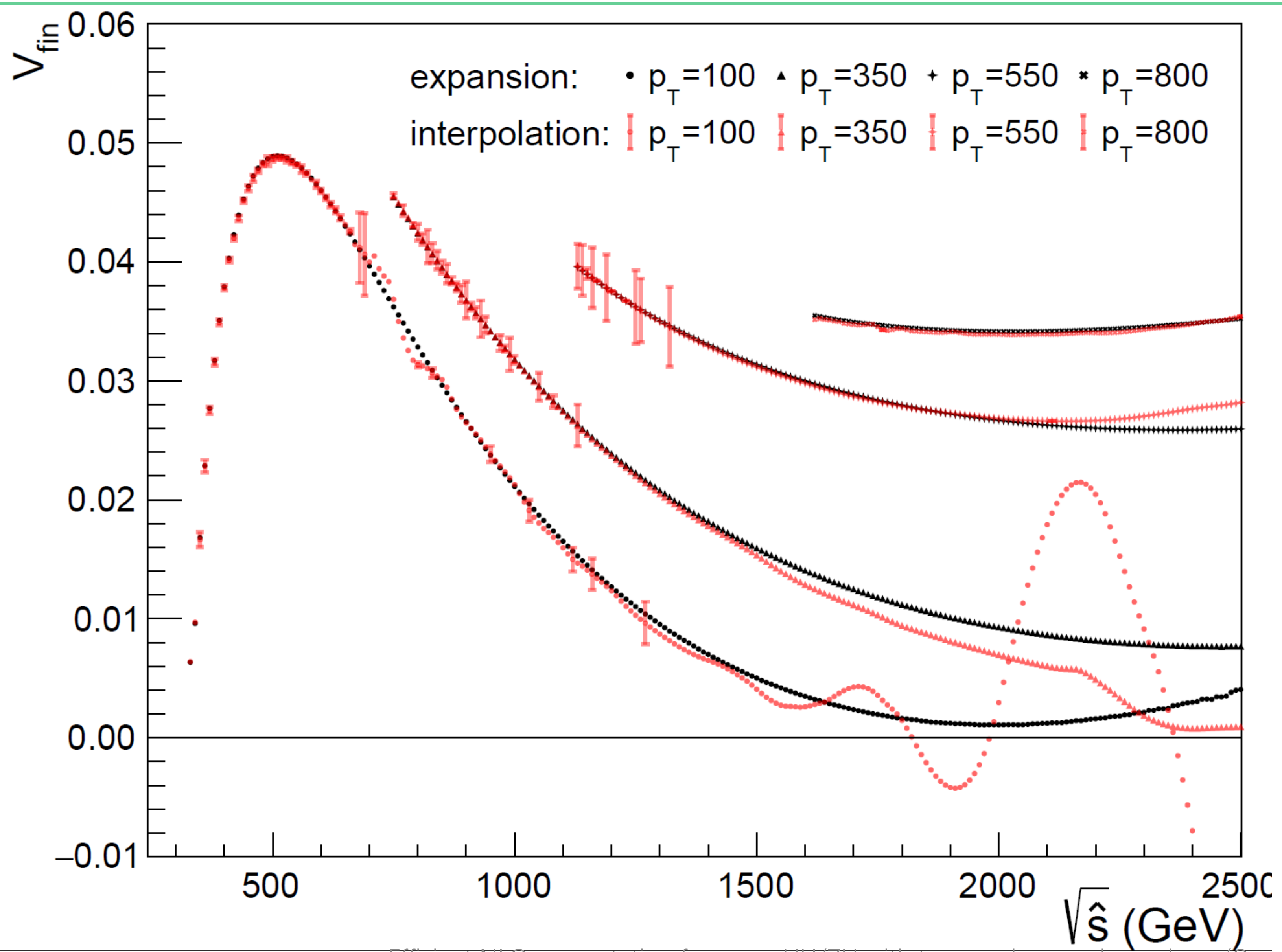
$$C_0 = \left[|F_1^{(0)}|^2 + |F_2^{(0)}|^2\right] C_A \left(\pi^2 - \log^2\frac{\mu^2}{\hat{s}}\right),$$

$$C_1 = 4\,\Re\left[F_1^{(0)}\tilde{F}_1^{(1)*} + F_2^{(0)}\tilde{F}_2^{(1)*}\right].$$

The upper plot uses the results from the grid file of [J. Davies, *et al*, 1907.06408]

while the lower one uses our results with the small-mass expansion up to $\mathcal{O}(m_H^4)$

Validation of small mass expansion (HH)



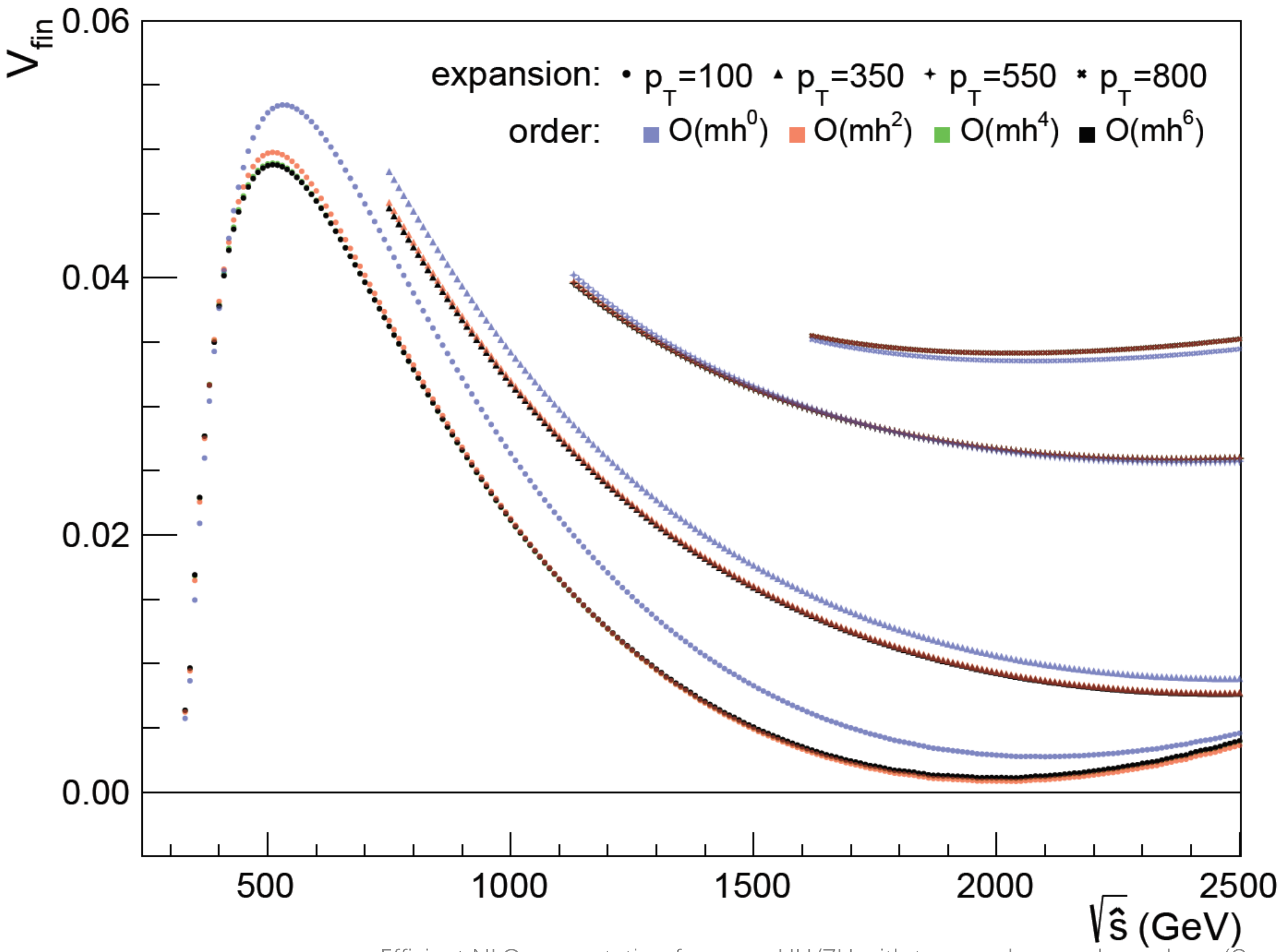
The black curves are obtained from our results with the small-mass expansion up to $\mathcal{O}(m_H^4)$, while the red ones are obtained using the interpolation code associated with

[J. Davies, *et al*, 1907.06408]

~7 GPGPU hours vs. ~10 seconds for one CPU core per phase-space point

S. Borowka. 1604.06447

Validation of small mass expansion (HH)



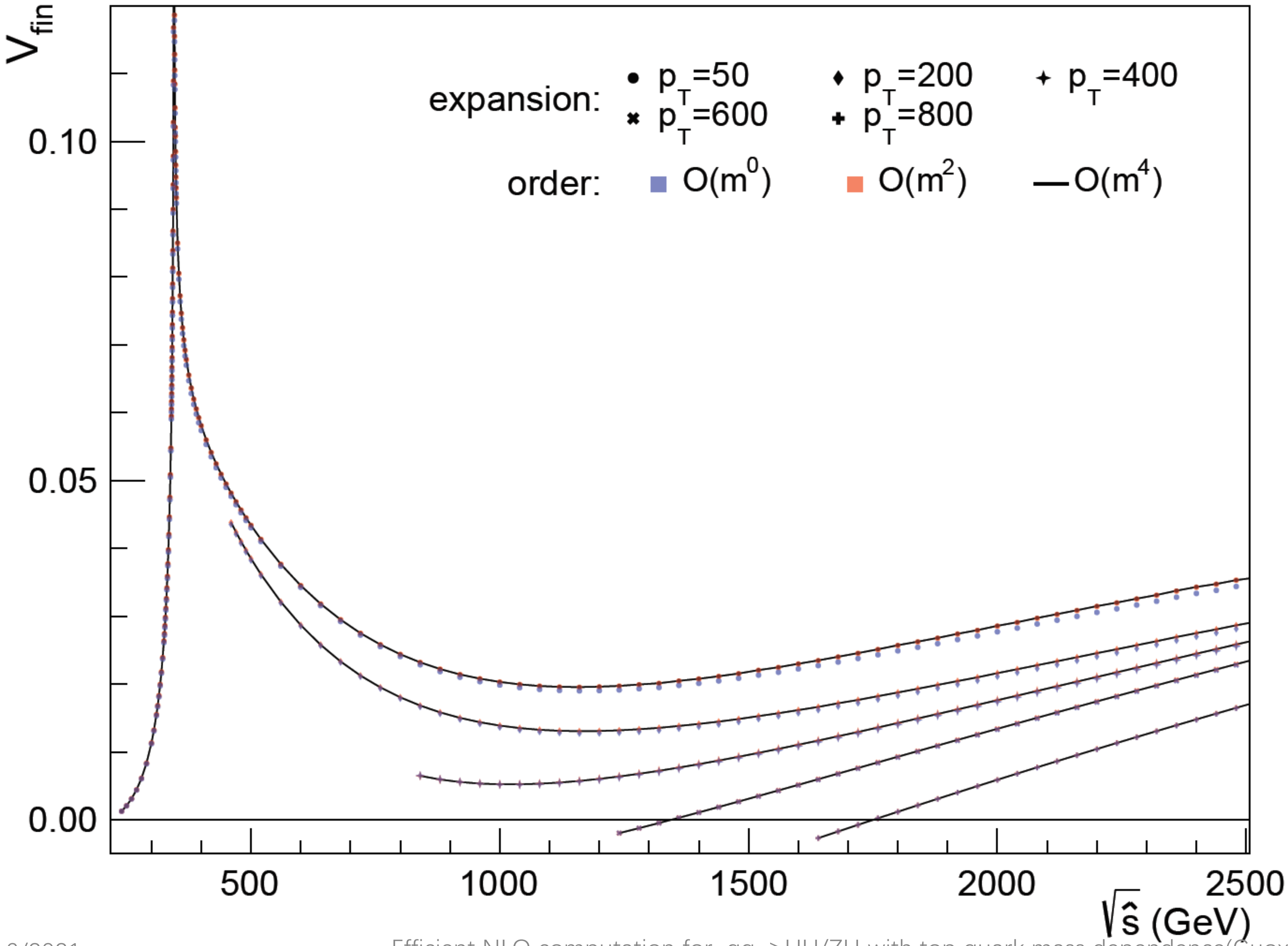
$\mathcal{V}_{\text{fin}}$ as a function of $\sqrt{\hat{s}}$ computed with the small-mass expansion up to $\mathcal{O}(m_H^0)$ (blue), $\mathcal{O}(m_H^2)$ (red), $\mathcal{O}(m_H^4)$ (green) and $\mathcal{O}(m_H^6)$ (black) for several values of p_T.

Validation of small mass expansion (HH)

$\hat{s}/m_t^2$	$\hat{t}/m_t^2$	$\mathcal{V}_{\text{fin}}$			
		$\mathcal{O}(m_H^0)$	$\mathcal{O}(m_H^2)$	$\mathcal{O}(m_H^4)$	$\mathcal{O}(m_H^6)$
3.2443043708235	−1.0734638644799	0.00280453	0.00307065	0.00312913	0.00313992
4.2027119591110	−1.2278481146799	0.0177979	0.0194677	0.0198132	0.0198753
8.8545981095756	−2.8396961750008	0.0541052	0.0517787	0.0510048	0.0508705
79.129243688545	−19.843014115015	0.0349780	0.0351603	0.0351405	0.0351394
115.01243983627	−27.092080482688	0.0338849	0.0343846	0.0343842	0.0343840

The finite part of the virtual corrections computed at several orders in the small-mass expansion for five representative phase-space points.

Validation of small mass expansion (ZH)



$\mathcal{V}_{\text{fin}}$ as a function of $\sqrt{\hat{s}}$ computed with the small-mass expansion up to $\mathcal{O}(m^0)$ (blue), $\mathcal{O}(m^2)$ (red), and $\mathcal{O}(m^4)$ (black) for several values of p_T.

$$-\eta_{\alpha\rho}\,\eta_{\beta\sigma}\left(\eta_{\mu\nu}-\frac{p_{3\mu}p_{3\nu}}{m_Z^2}\right)$$

Validation of small mass expansion (ZH)

$\hat{s}/m_t^2$	$\hat{u}/m_t^2$	$\mathcal{V}'_{\text{fin}}$			
		pySecDec	$\mathcal{O}(m^0)$	$\mathcal{O}(m^2)$	$\mathcal{O}(m^4)$
1.707133657190554	−0.441203767016323	35.429092(6)	35.9823	35.5530	35.4478
3.876056604162662	−1.616287256345735	4339.045(1)	4319.37	4336.63	4338.73
4.130574250302561	−1.750372271104745	6912.361(3)	6870.47	6906.92	6911.64
4.130574250302561	−2.595461551488002	6981.09(2)	6979.28	6980.14	6980.85
134.514205209356 4	−70.341259433051 49	−153.9(4)	−154.543	−154.458	−154.460
134.5142052093564	−105.1770655376327	527(4)	524.585	525.958	525.965

The column labelled pySecDec contains results from [L. Chen, *et al*, 2011.12325], while those labelled $\mathcal{O}(m^n)$ come from our small mass expansion.

Total cross section (ZH)

$\mu_r = \mu_f$	σ^{gg}_{LO}	σ^{gg}_{NLO}	$\sigma^{\text{no }gg}_{pp\to ZH}$	$\sigma_{pp\to ZH}$	$\sigma^{gg,m_t\to\infty}_{\text{NLO}}$	$\sigma^{m_t\to\infty}_{pp\to ZH}$
$M_{ZH}/3$	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)

Total cross section @13TeV LHC

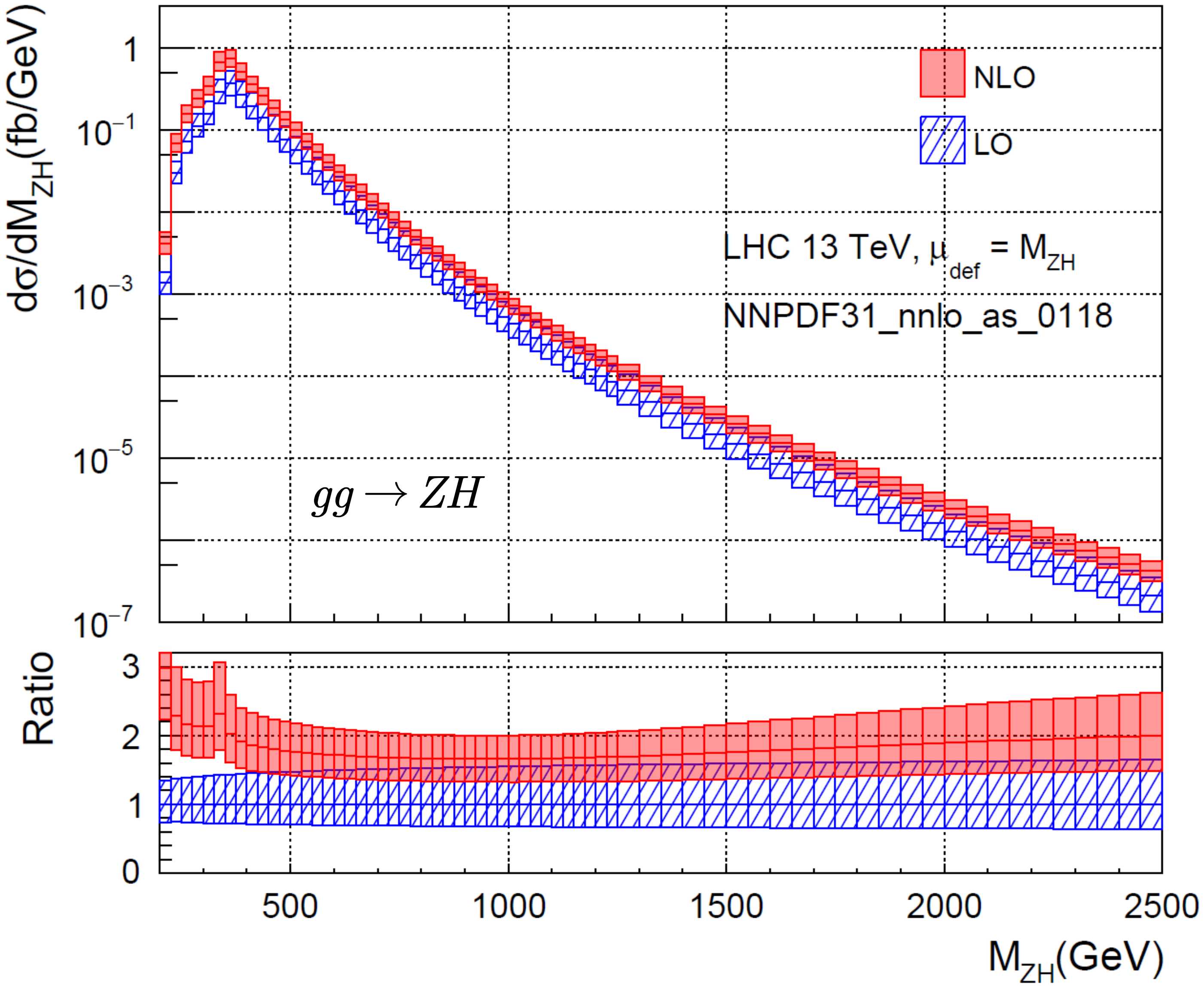
$\mu_r = \mu_f$	σ^{gg}_{LO}	σ^{gg}_{NLO}	$\sigma^{\text{no }gg}_{pp\to ZH}$	$\sigma_{pp\to ZH}$	$\sigma^{gg,m_t\to\infty}_{\text{NLO}}$	$\sigma^{m_t\to\infty}_{pp\to ZH}$
$m_{ZH}/3$	310.5(3)	551(1)	2106(2)	2658(2)	568(3)	2675(3)
m_{ZH}	233.7(2)	451(1)	2104(2)	2555(2)	476(2)	2579(3)
$3m_{ZH}$	179.0(2)	373(1)	2113(2)	2485(2)	396(2)	2509(3)

Total cross section @27TeV HE-LHC

Exact top-quark mass dependence[2105.04436]

Combine results from vh@nnlo [1210.5347, 1802.04817]

Differential cross section (ZH)



Summary and outlook

- Our method is based on a series expansion in terms of the small mass m_H and m_Z : precision and efficiency
- We present the state-of-the-art fixed-order predictions for the total cross sections of ZH production.
- We show the representative M_{ZH} differential distribution and further phenomenologically interesting results will be presented in the future.
- Our method can also be implemented for other $2 \to 2$ processes with a heavy quark loop: $gg \to ZZ,\ gg \to Hj$

Summary and outlook

- Our method is based on a series expansion in terms of the small mass m_H and m_Z : precision and efficiency
- We present the state-of-the-art fixed-order predictions for the total cross sections of ZH production.
- We show the representative M_{ZH} differential distribution and further phenomenologically interesting results will be presented in the future.
- Our method can also be implemented for other $2 \to 2$ processes with a heavy quark loop: $gg \to ZZ,\ gg \to Hj$

Thanks

Example 3

- Expansion by Subgraphs: $I(m^2,0,q^2;2,1;d)=\mathcal{C}\int\frac{d^dl}{(2\pi)^d}\frac{1}{(l^2-m^2+i\varepsilon)^2[(l+q)^2+i\varepsilon]}$

$$\left\{\frac{1}{(l+q)^2}\right\}=\frac{1}{q^2}+\frac{-l^2-2q\cdot l}{(q^2)^2}+\frac{(-l^2-2q\cdot l)^2}{(q^2)^3}+\cdots$$

$$\left\{\frac{1}{(l^2-m^2)^2}\right\}=\frac{1}{(l^2)^2}+\frac{2m^2}{(l^2)^3}+\frac{3(m^2)^2}{(l^2)^4}+\cdots$$

$$I=\mathcal{C}\int\frac{d^dl}{(2\pi)^d}\frac{1}{(l^2-m^2+i\varepsilon)^2}\left\{\frac{1}{(l+q)^2+i\varepsilon}\right\}+\left\{\frac{1}{(l^2-m^2+i\varepsilon)^2}\right\}\frac{1}{(l+q)^2+i\varepsilon}$$

$$I=-\Gamma(1+\epsilon)\int_0^1 d\xi\,\frac{\xi^{-\epsilon}}{[-q^2(1-\xi)+m^2-i\varepsilon]^{1+\epsilon}}$$

$$I=-\frac{1}{q^2}\ln\left(\frac{m^2}{m^2-q^2}\right)$$

$$I=-\frac{1}{q^2}\frac{\Gamma^2(1-\epsilon)\Gamma(\epsilon)}{(q^2)^\epsilon\Gamma(1-2\epsilon)}\left(1+2\epsilon\frac{m^2}{q^2}+\cdots\right)+\frac{1}{q^2}\frac{\Gamma(\epsilon)}{(m^2)^\epsilon}\left(1+\frac{\epsilon}{1+\epsilon}\frac{m^2}{q^2}+\cdots\right)$$