NLO electroweak corrections to $gg \to HH$

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Based on [JHEP 08 (2022) 259] & [JHEP 10 (2023) 033]

Karlsruher Institut für Technologie

Young Scientists Meeting - Siegen

Institute for Theoretical Particle Physics

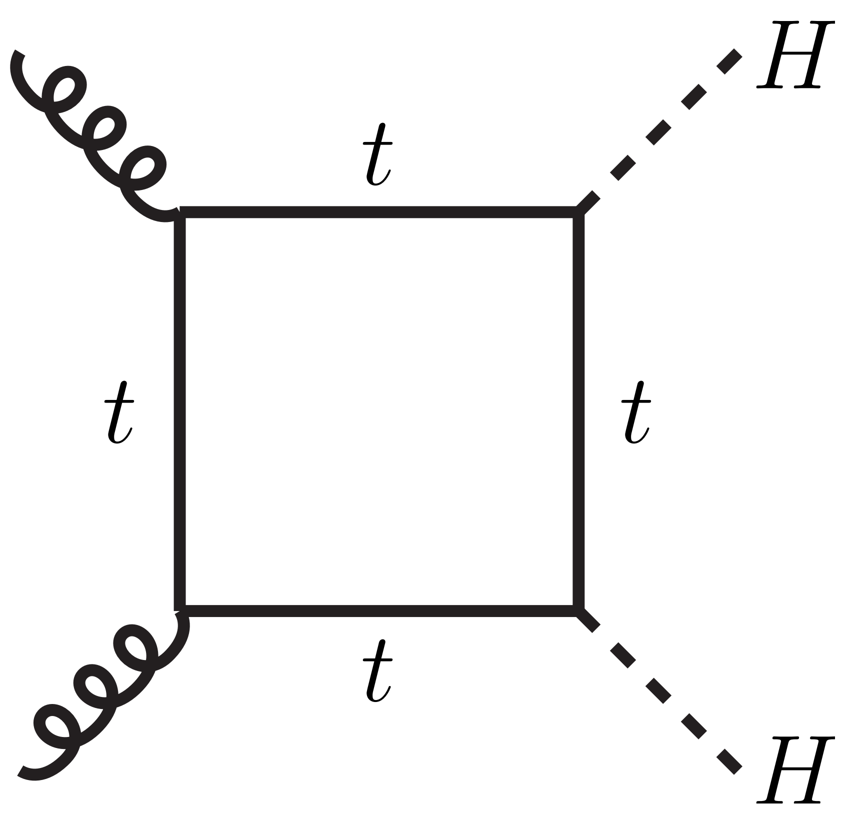
Motivation: Higgs self-coupling

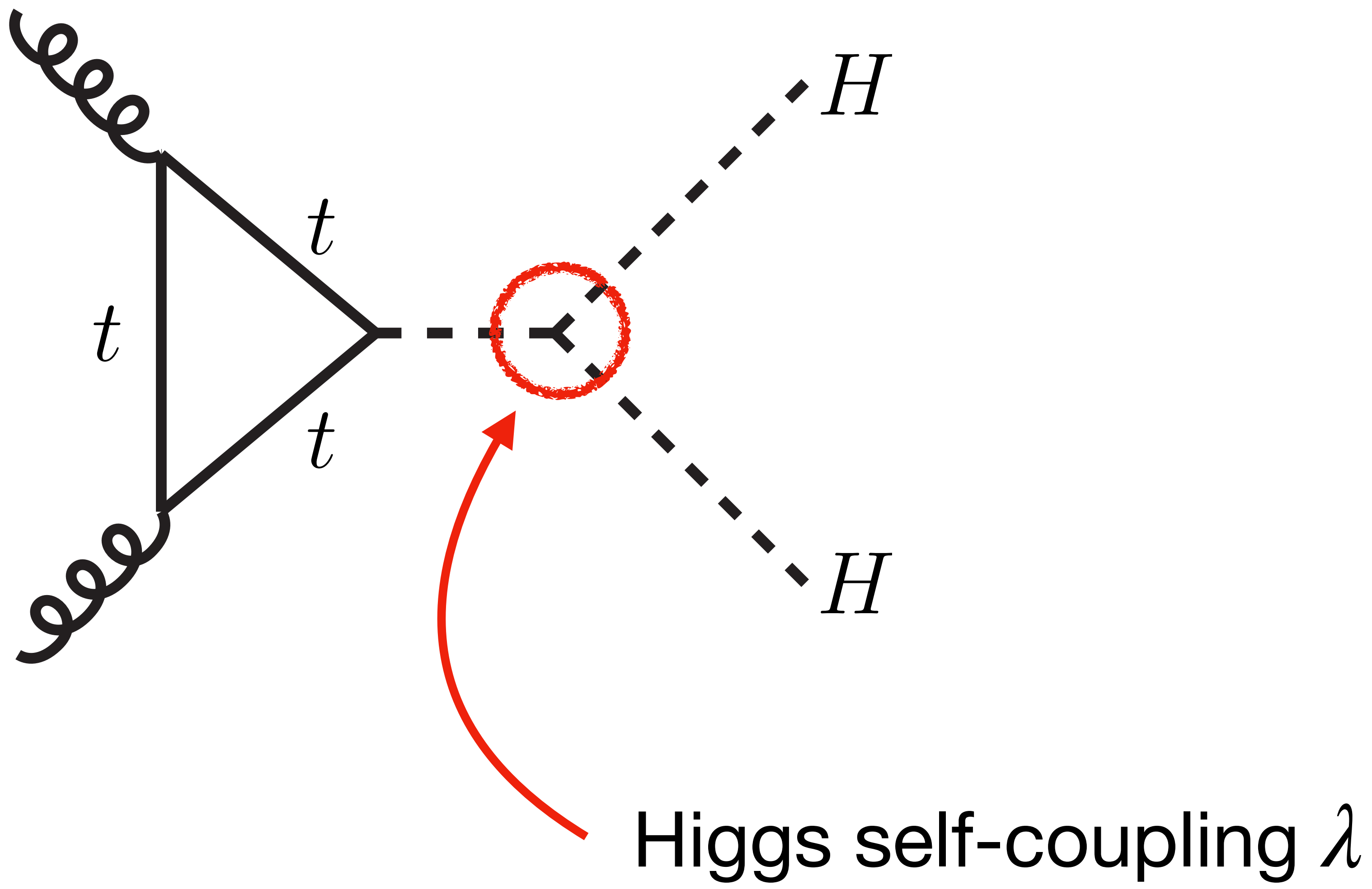
- Probe Higgs self-coupling in pair productions, and compare with the Standard Model value

  $\lambda = m_H^2/(2v^2) \approx 0.13$ in the Higgs potential

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

- Gluon-fusion channel dominates Higgs pair production at LHC





Overview of QCD and EW calculations

- **NLO QCD corrections with full m_t-dependence are known**
  - Expansion-by-Region & Numerical approaches [Borowka, Geiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke, 16'], [Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher, 18'], [Daoson, Dittmaier, Spira, 98'], [Grigo, Hoff, Melnikov, Steinhauser, 13'], [Degrassi, Giardino, Gröber, 16', and Bonciani, 18'], [Gröber, Maier, Raum, 17'], [Davies, Mishima, Steinhauser, Wellmann, 18', 19'], [Xu, Yang, 18', and Wang, Xu, 20'], [Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, Wellmann, 19'], [Bellafronte, Degrassi, Giardino, Gröber, Vitti, 22']

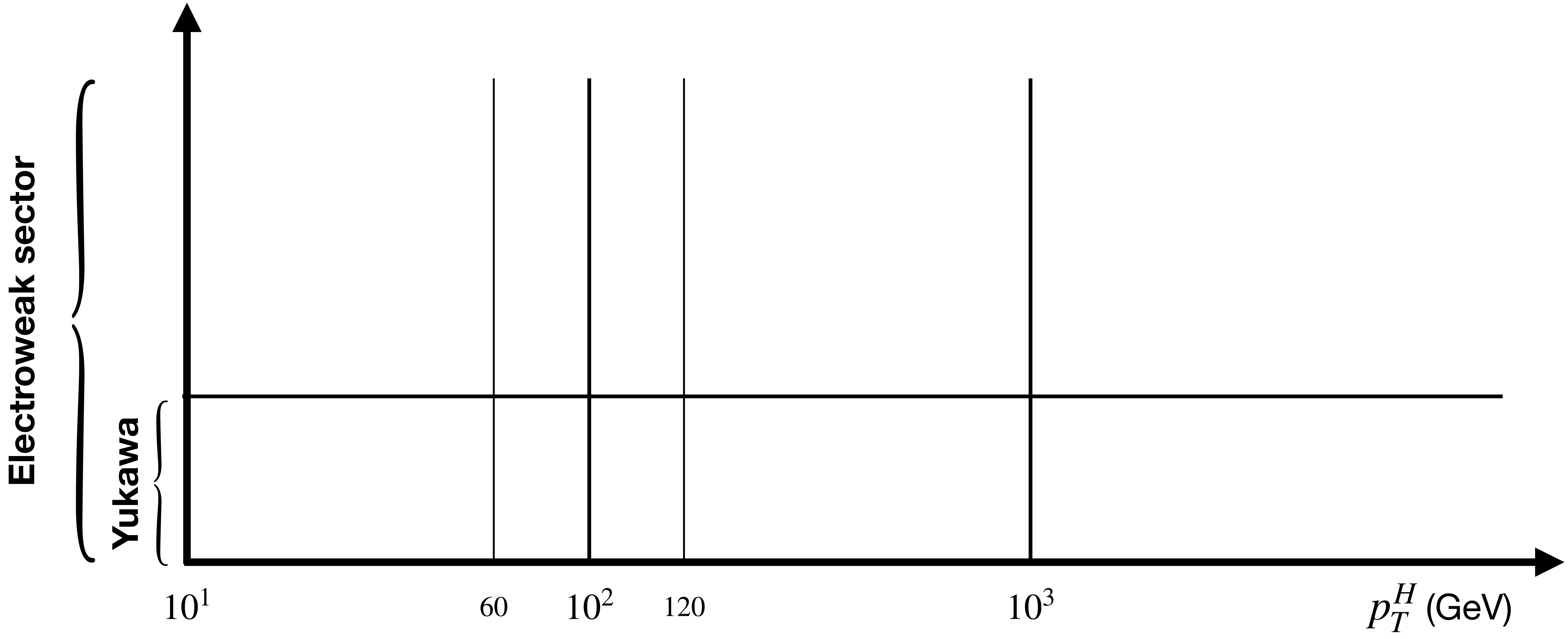
- **NNLO and N^{3}LO QCD corrections are available in large-m_t limit / expansion**
  - At NNLO [de Florian, Mazzitelli, 13'], [Grigo, Melnikov, Steinhauser, 14' and Hoff, 15'], [Davies, Herren, Mishima, Steinhauser, 19', 21'], [Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli, 18']
  - At N^{3}LO [Spira, 16'], [Gerlach, Herren, Steinhauser, 18'], [Banerjee, Borowka, Dhabi, Gehrmann, Ravindran, 18'], [Chen, Li, Chao, Wang, 19']

- **NLO EW corrections become available recently in**
  - Higgs self-coupling corrections [Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao, 19']
  - Yukawa-top corrections in high-energy expansion [Davies, Mishima, Schönwald, Steinhauser, Zhang, 22'] and large-m_t limit [Mühlleitner, Schlenk, Spira, 22']
  - Full EW corrections in large-m_t expansion [Davies, Schönwald, Steinhauser, Zhang, 23']

This talk

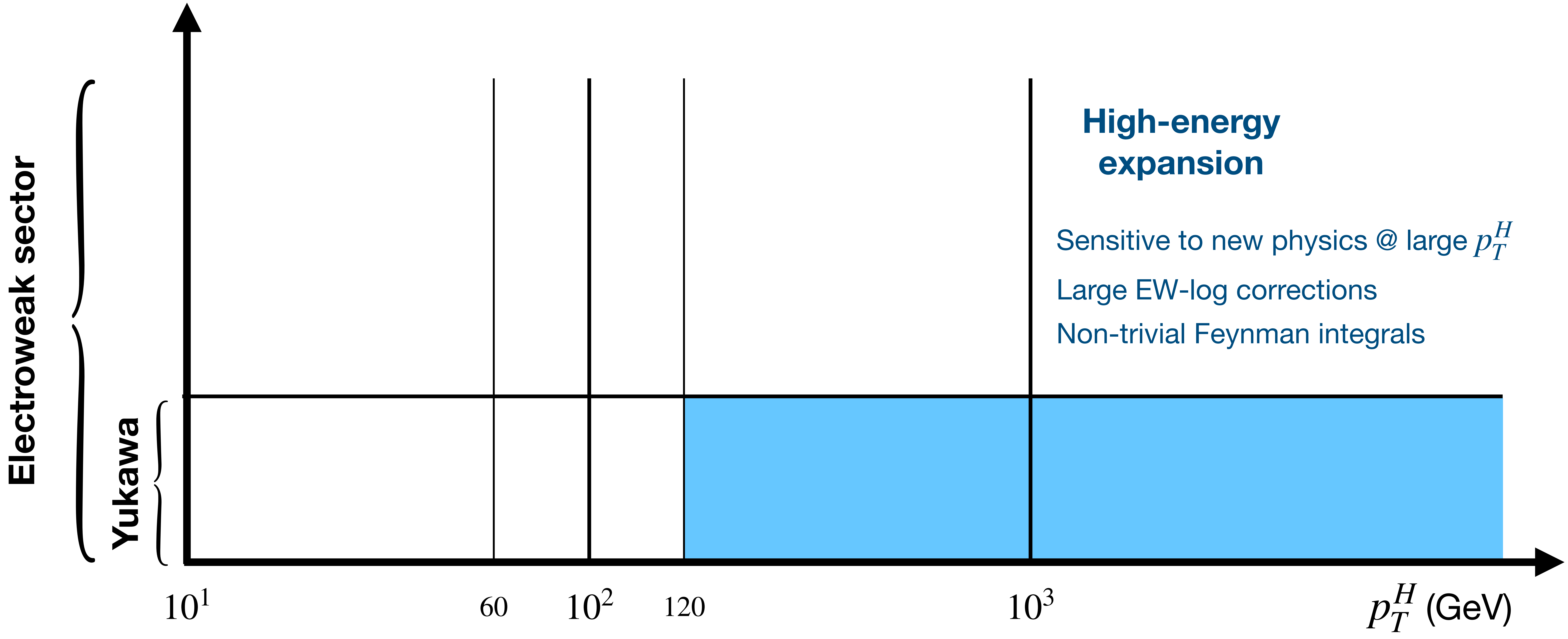
Recent NLO EW calculations

JHEP 08 (2022) 259 & JHEP 10 (2023) 033



Recent NLO EW calculations

JHEP 08 (2022) 259 & JHEP 10 (2023) 033



Recent NLO EW calculations

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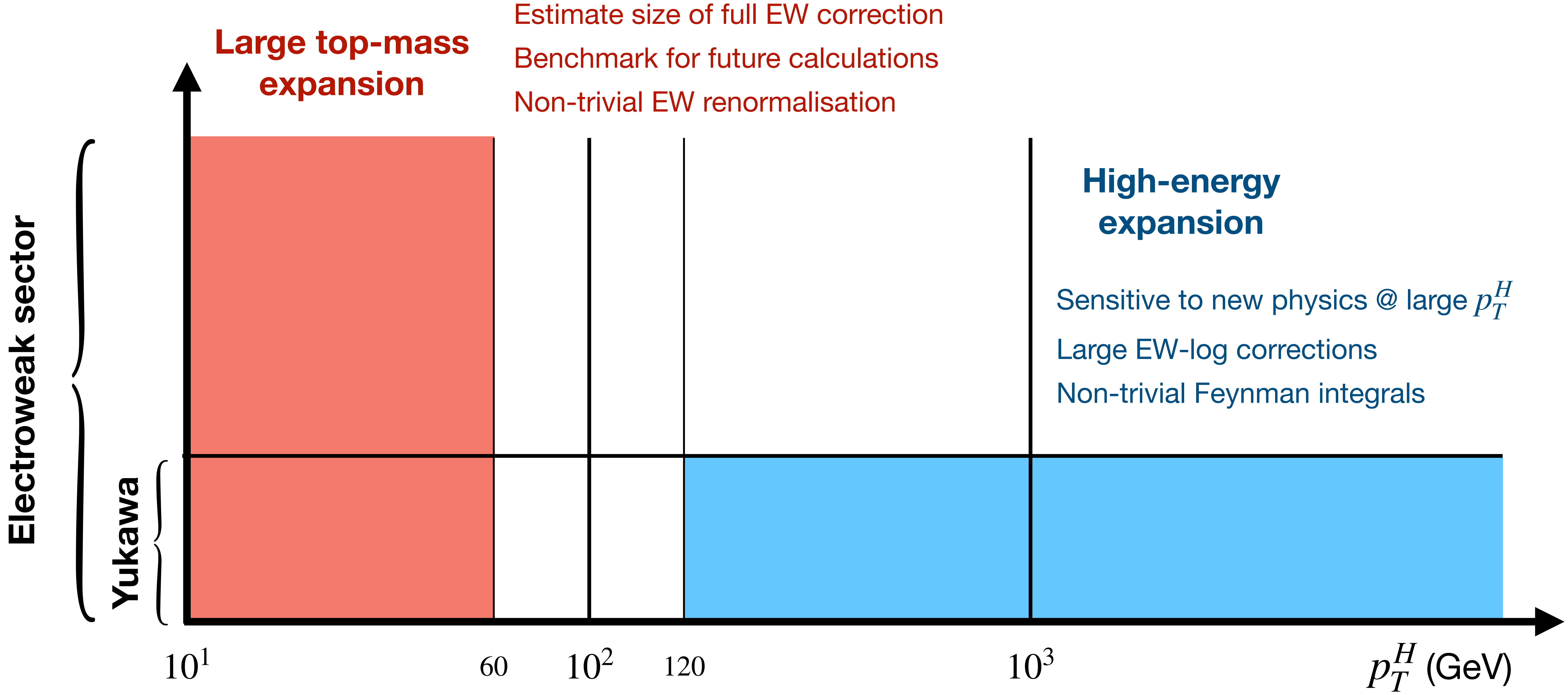
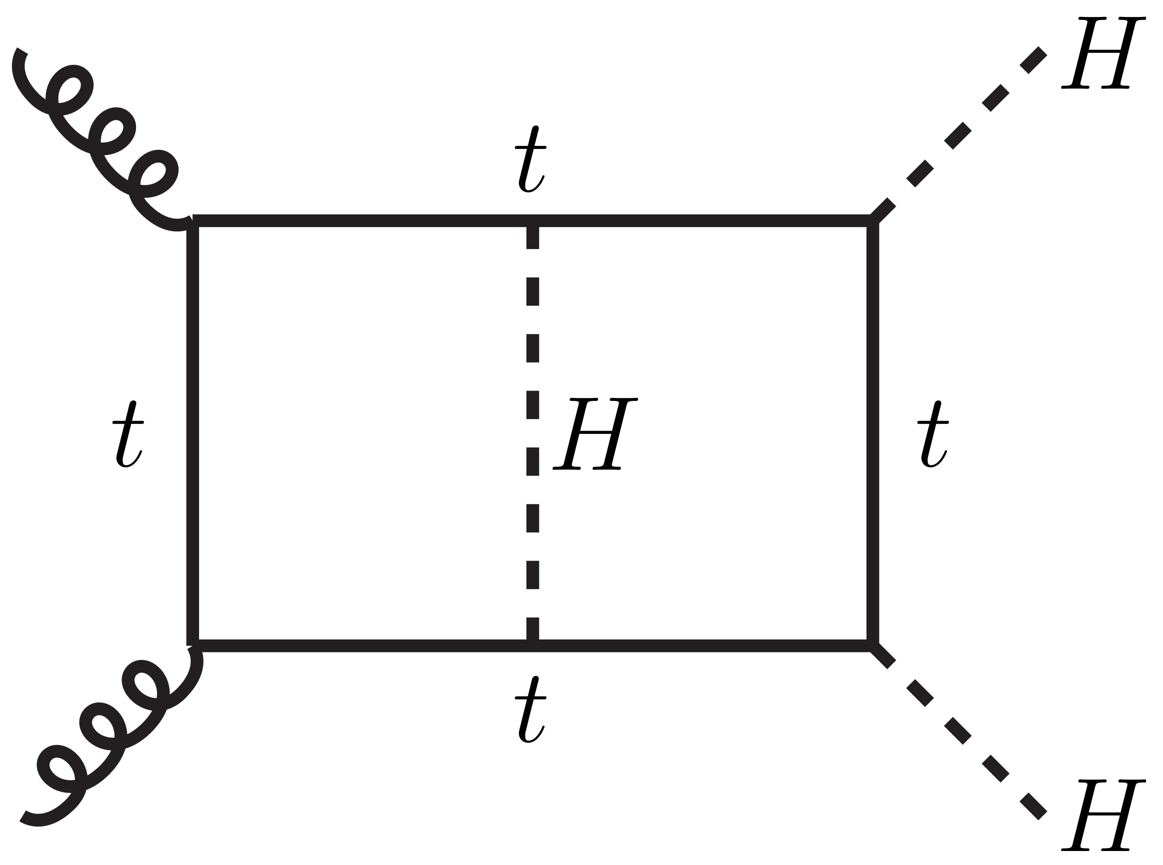


Part 1: Leading Yukawa corrections

[Davies, Mishima, Schönwald, Steinhauser, **Zhang**, ***JHEP 08 (2022) 259***]

- Sample two-loop diagrams contributing to leading Yukawa-top corrections $\sim \alpha_s y_t^4$



- Yukawa-top corrections are **not small**, $y_t^2 = \dfrac{\alpha\, m_t^2}{2\sin^2\theta_w\, m_W{}^2}$

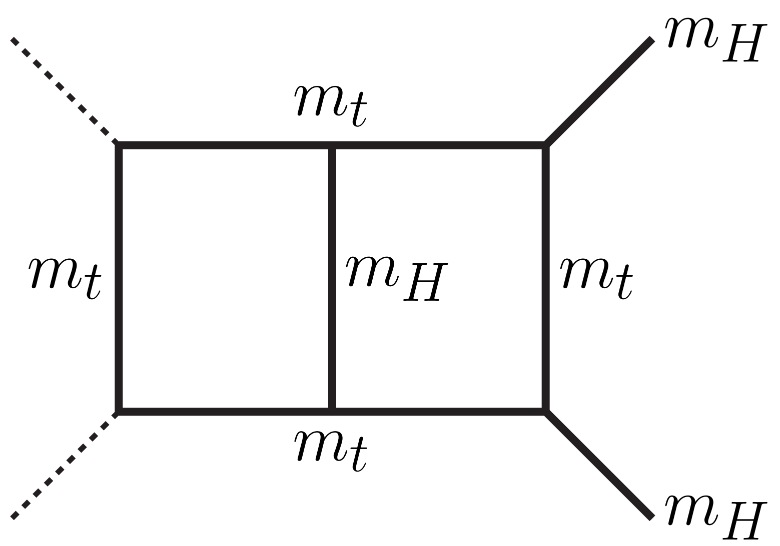
- **Aim:** analytic high-energy expansion in $p_T^H \geq 120\,\mathrm{GeV}$ region

Analytic high-energy expansion to $\mathcal{O}(m_t^{120})$

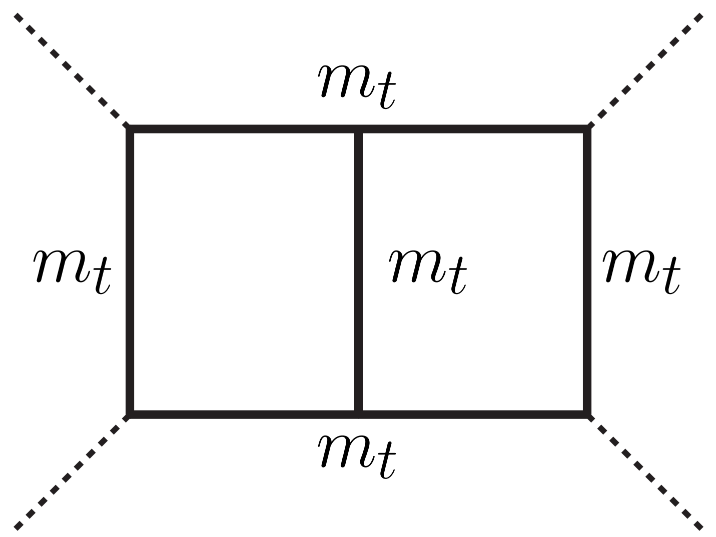
1. **Expansion hierarchy:** $\left\{s,t \gg m_t^2 \approx \left(m_H^{\text{int}}\right)^2 \gg \left(m_H^{\text{ext}}\right)^2\right\}$ or $\left\{s,t \gg m_t^2 \gg \left(m_H^{\text{int}}\right)^2, \left(m_H^{\text{ext}}\right)^2\right\}$

   Expand and compute by **`qgraf`** [Nogueira], **`q2e&exp`** [Harlander, Seidensticker, Steinhauser], **`LiteRed`** [Lee], **`FORM`** [Vermaseren]

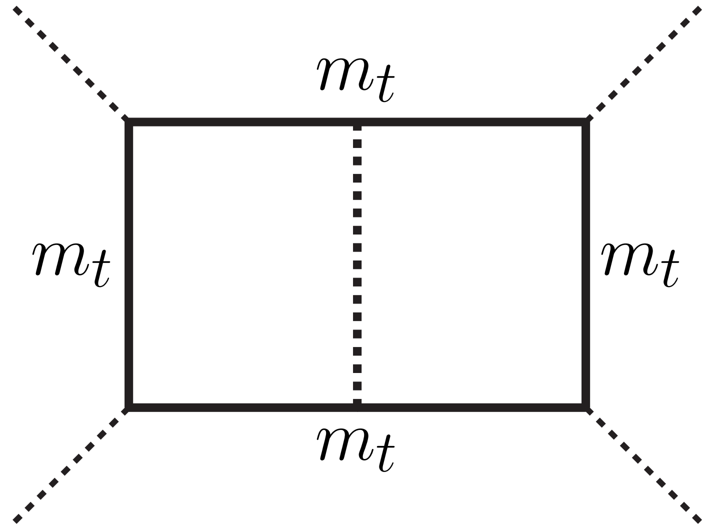
scalar master integral



kinematic invariants s, t



$s,t \gg m_t^2 \approx \left(m_H^{\text{int}}\right)^2 \gg \left(m_H^{\text{ext}}\right)^2$



$s,t \gg m_t^2 \gg \left(m_H^{\text{int}}\right)^2, \left(m_H^{\text{ext}}\right)^2$

Analytic techniques: Asymptotic expansions -> Differential equations -> Mellin-Barnes integrals

Analytic high-energy expansion to $\mathcal{O}(m_t^{120})$

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2. **System of differential equations for 140 Master Integrals** from IBP reduction with `LiteRed` [Lee], `FIRE6 and ImproveMasters.m` [Chukharev, Smirnov[2]]

$$\frac{\partial}{\partial\left(m_t^2\right)}\mathbf{I} = M(s, t, m_t^2, \epsilon)\,\mathbf{I} \quad \text{with} \quad \mathbf{I} = \left(\mathcal{I}_1, \ldots, \mathcal{I}_{140}\right)^T$$

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3. Plug in **power-log ansatz** for each master integral

$$\mathcal{I}_n = \sum_{i=-2}^{0} \sum_{j=-1}^{60} \sum_{k=0}^{i+4} C_{(n)}^{ijk}(s,t)\,\epsilon^i \left(m_t^2\right)^j \log^k(m_t^2)$$

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Novel Math. method & Automated algorithm

4. Solve **boundary master integrals in asymptotic limit $m_t \to 0$** with Mellin-Barnes method by `AsyInt` [Schönwald, **Zhang**] with help of `MB.m` [Czakon], `HarmonicSums.m` [Ablinger], `Sigma.m and EvaluateMultiSums.m` [Schneider]

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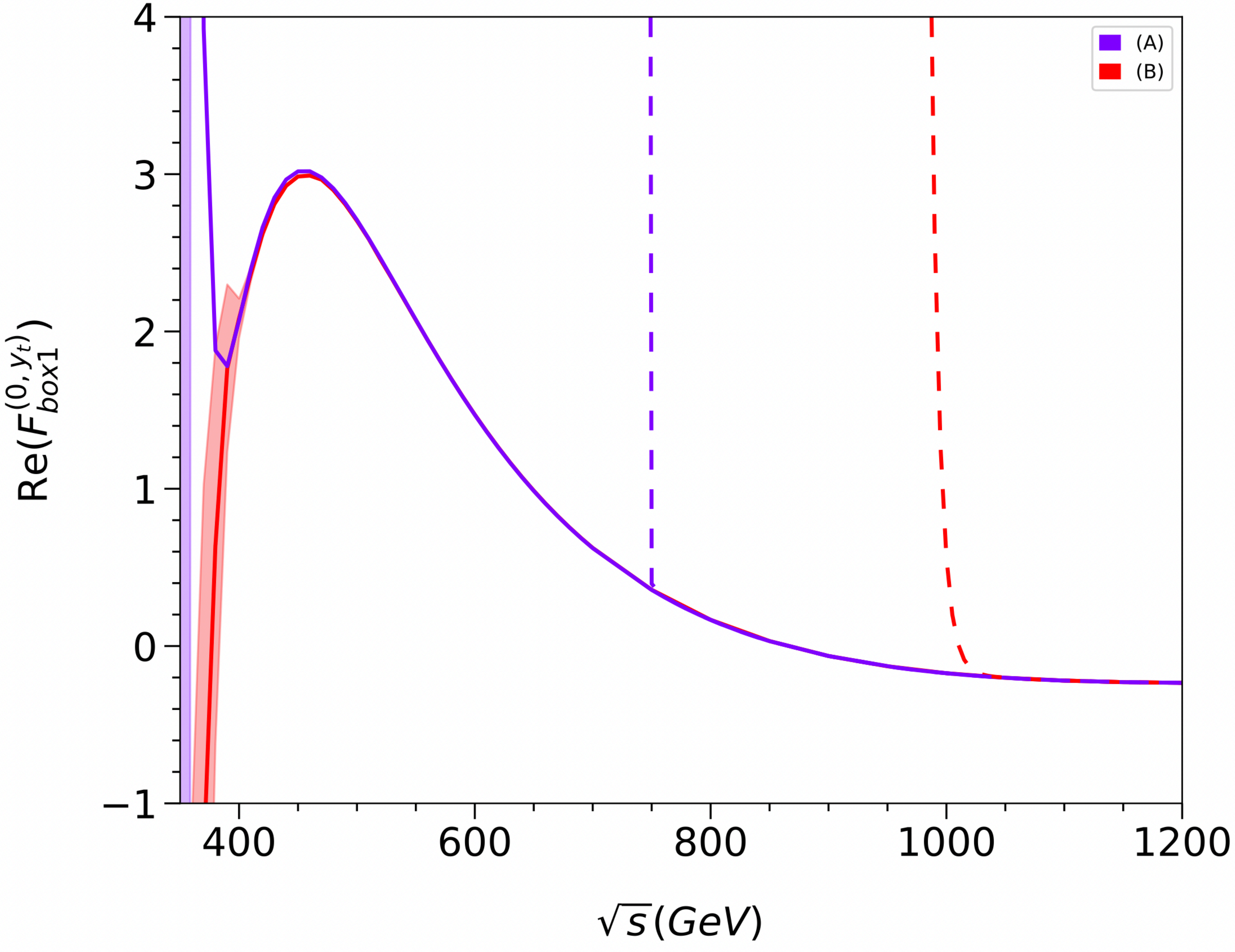
5. Apply Padé approximations at the level of form factors as a **precision tool**

$$\mathcal{F}^N = \lim_{x\to 1}\sum_{i=0}^{N} f_i\,(m_t^2)^i\,x^i \qquad \Rightarrow \qquad \mathcal{F}^N = \lim_{x\to 1}\frac{a_0 + a_1 x + \ldots + a_n x^n}{1 + b_1 x + \ldots + b_m x^m} = \lim_{x\to 1}\,[n/m](x)$$

Form factors for $gg \to HH$ with fixed scattering angle

[Davies, Mishima, Schönwald, Steinhauser, **Zhang**, ***JHEP 08 (2022) 259***]



$$\mathscr{A}^{\mu\nu} = T_1^{\mu\nu}\,\mathscr{F}_1 + T_2^{\mu\nu}\,\mathscr{F}_2^{\mu\nu}$$

Scattering angle: $\theta = \dfrac{\pi}{2}$

Solid color lines: Padé improved results using MIs from $\mathcal{O}(m_t^{116})$ in two expansion approaches

Dashed color lines: Naive expansions at high energies to $\mathcal{O}(m_t^{116})$

Form factors for $gg \to HH$ with fixed scattering angle

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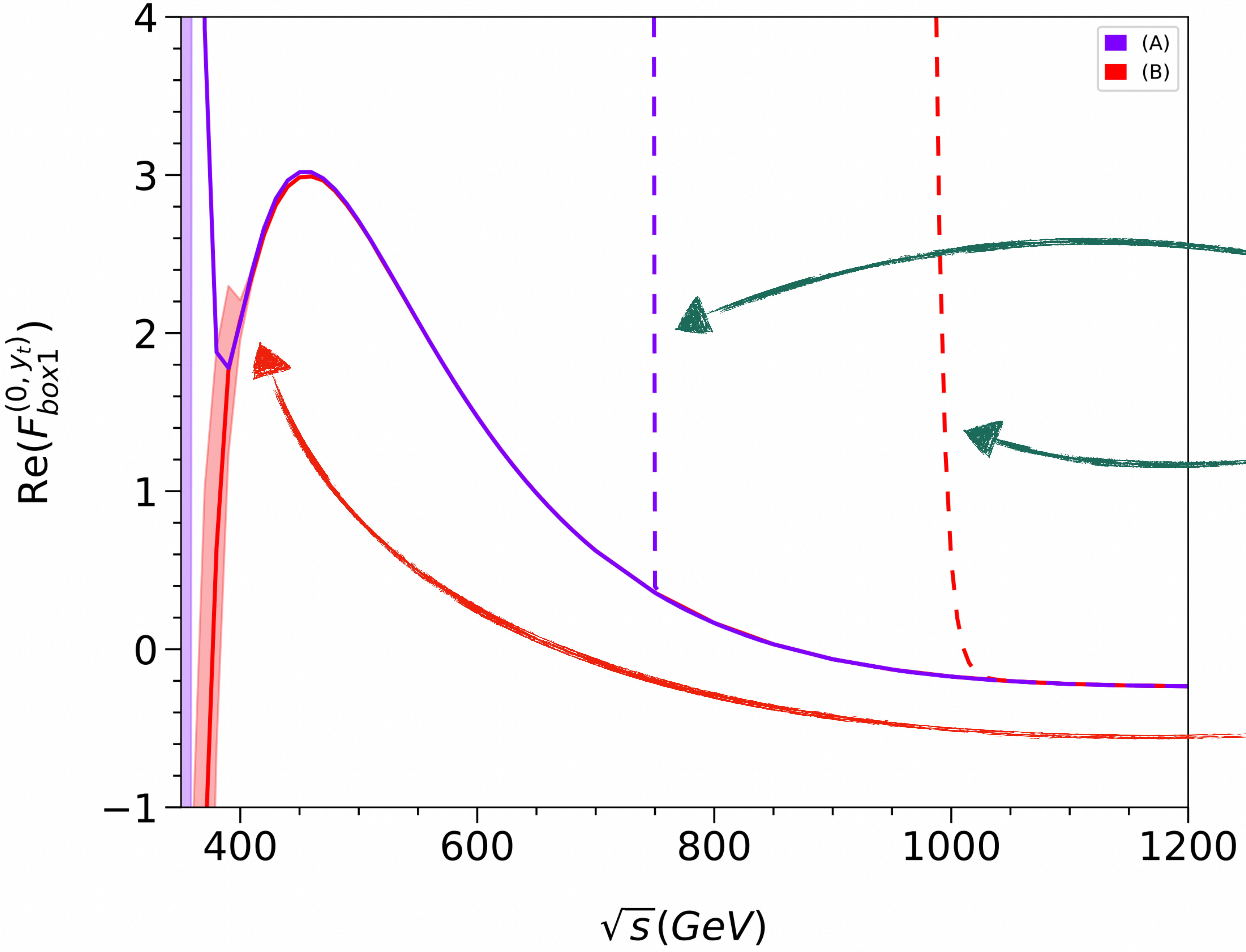

$$\mathscr{A}^{\mu\nu} = T_1^{\mu\nu}\,\mathscr{F}_1 + T_2^{\mu\nu}\,\mathscr{F}_2^{\mu\nu}$$

Scattering angle: $\theta = \dfrac{\pi}{2}$

Naive high-energy expansions starts to diverge at $\sqrt{s} \approx 700$ & 1000 GeV

$$\mathscr{F}^{58} = \lim_{x\to 1} \sum_{i=0}^{58} f_i\,(m_t^2)^i\,x^i$$

Padé improved high-energy expansions converge even at $\sqrt{s} \approx 400$ GeV

$$\mathscr{F}^{58} = \lim_{x\to 1} \frac{a_0 + a_1 x + \ldots + a_n x^n}{1 + b_1 x + \ldots + b_m x^m} = \lim_{x\to 1} [n/m](x)$$

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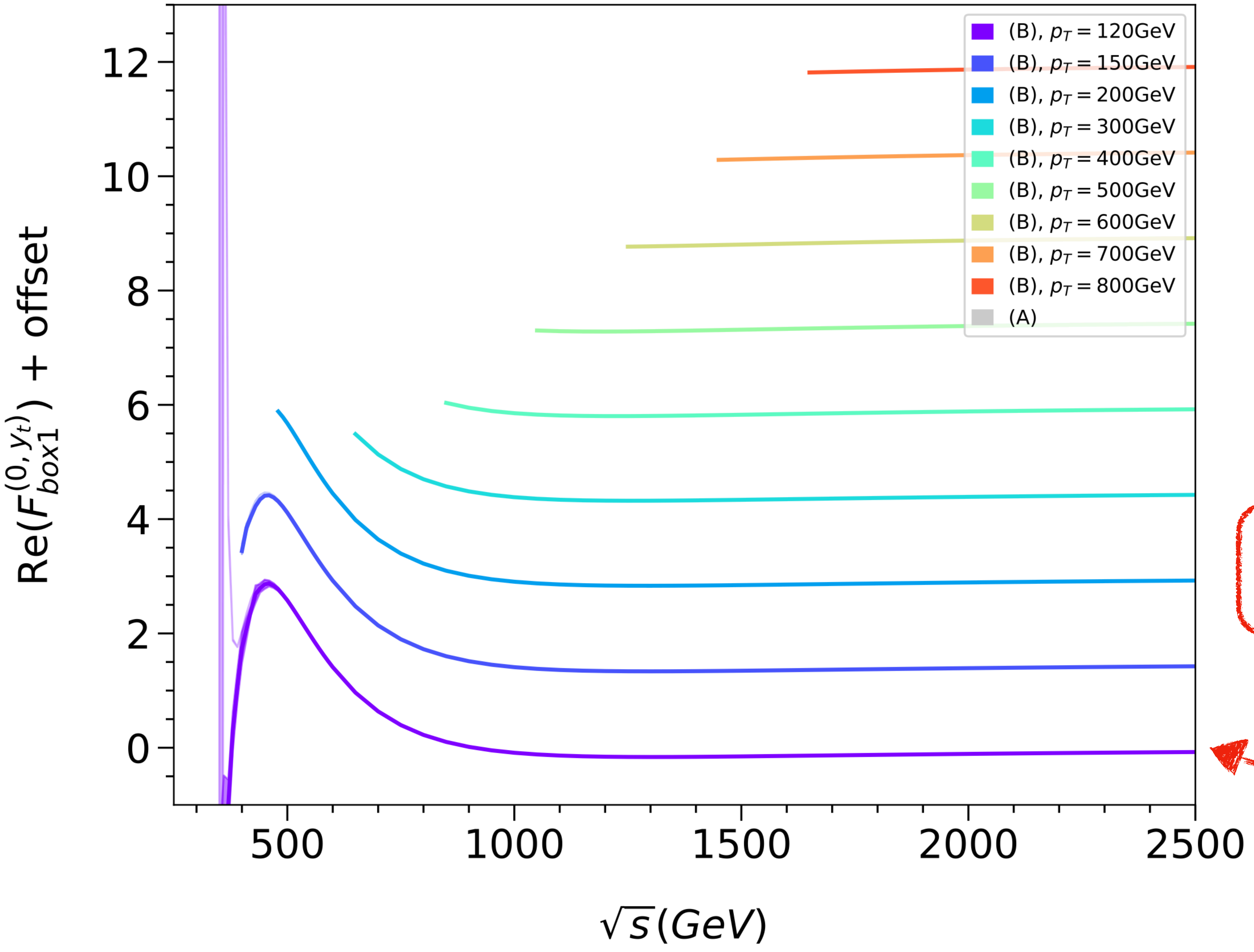
Dashed color lines: Naive expansions at high energies to $\mathscr{O}(m_t^{116})$

Form factors for $gg \to HH$ with various fixed p_T^H

[Davies, Mishima, Schönwald, Steinhauser, **Zhang**, ***JHEP 08 (2022) 259***]



$$\mathscr{A}^{\mu\nu} = T_1^{\mu\nu}\,\mathscr{F}_1 + T_2^{\mu\nu}\,\mathscr{F}_2^{\mu\nu}$$

$$p_T^H = \sqrt{\frac{u\,t - m_H^4}{s}}$$

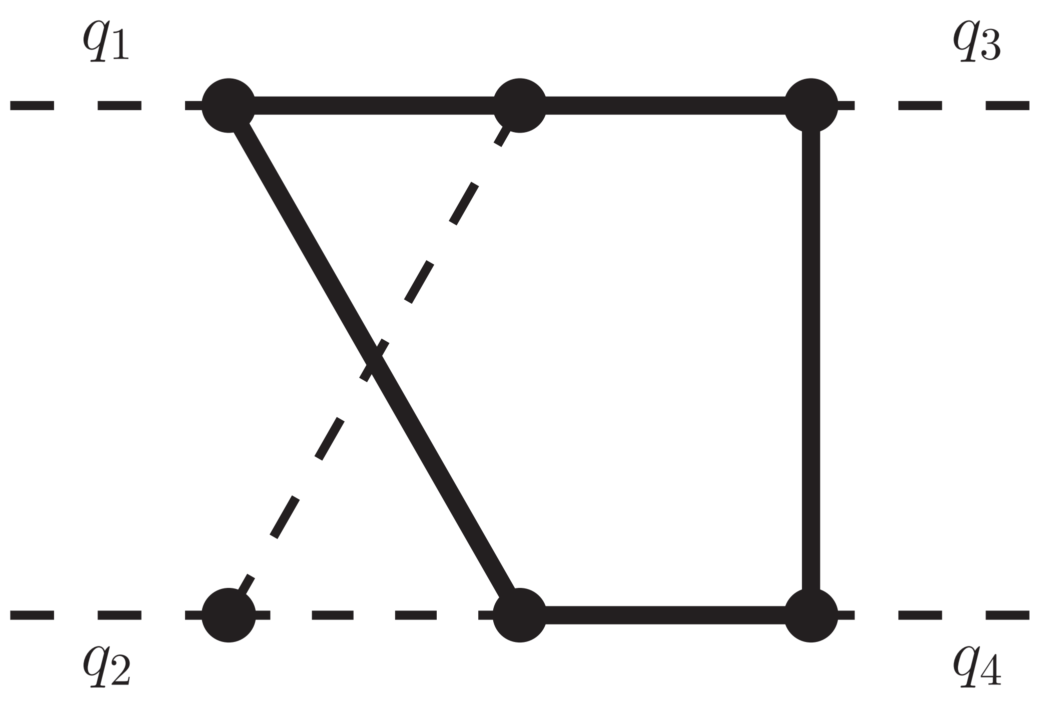
Padé improved high energy expansions converge even at $p_T^H = 120$ GeV

Color lines: Padé improved equal-mass δ expansions in $m_t^2 \approx \left(m_H^{\rm int}\right)^2$ using MIs from $\mathcal{O}(m_t^{116})$

Grey lines: Coincide with colourful lines (two approaches agree)

Padé improved integral for $gg \to HH$ in t-expansion

[Davies, Mishima, Schönwald, Steinhauser, ***JHEP 06 (2023) 063***]



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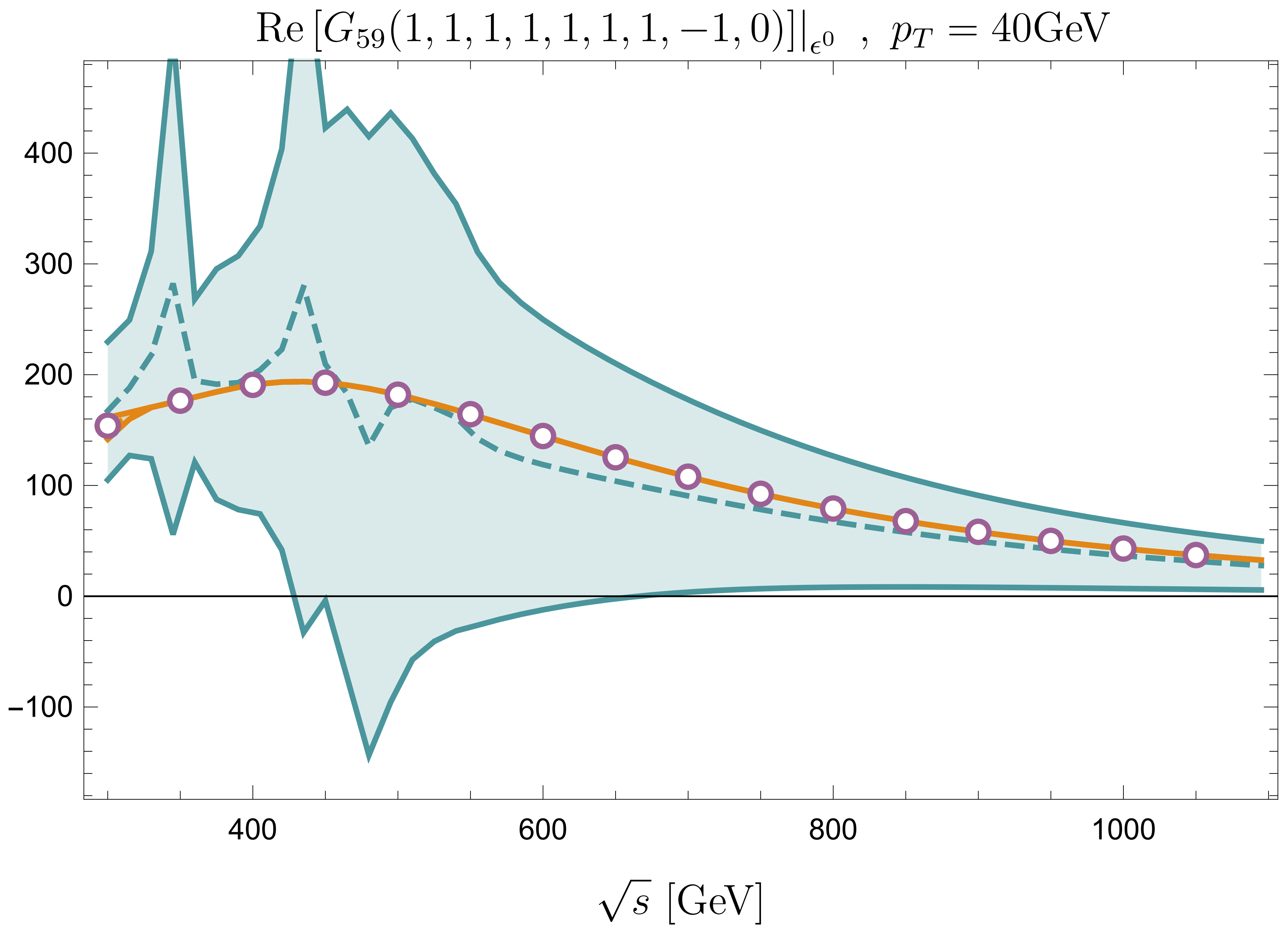
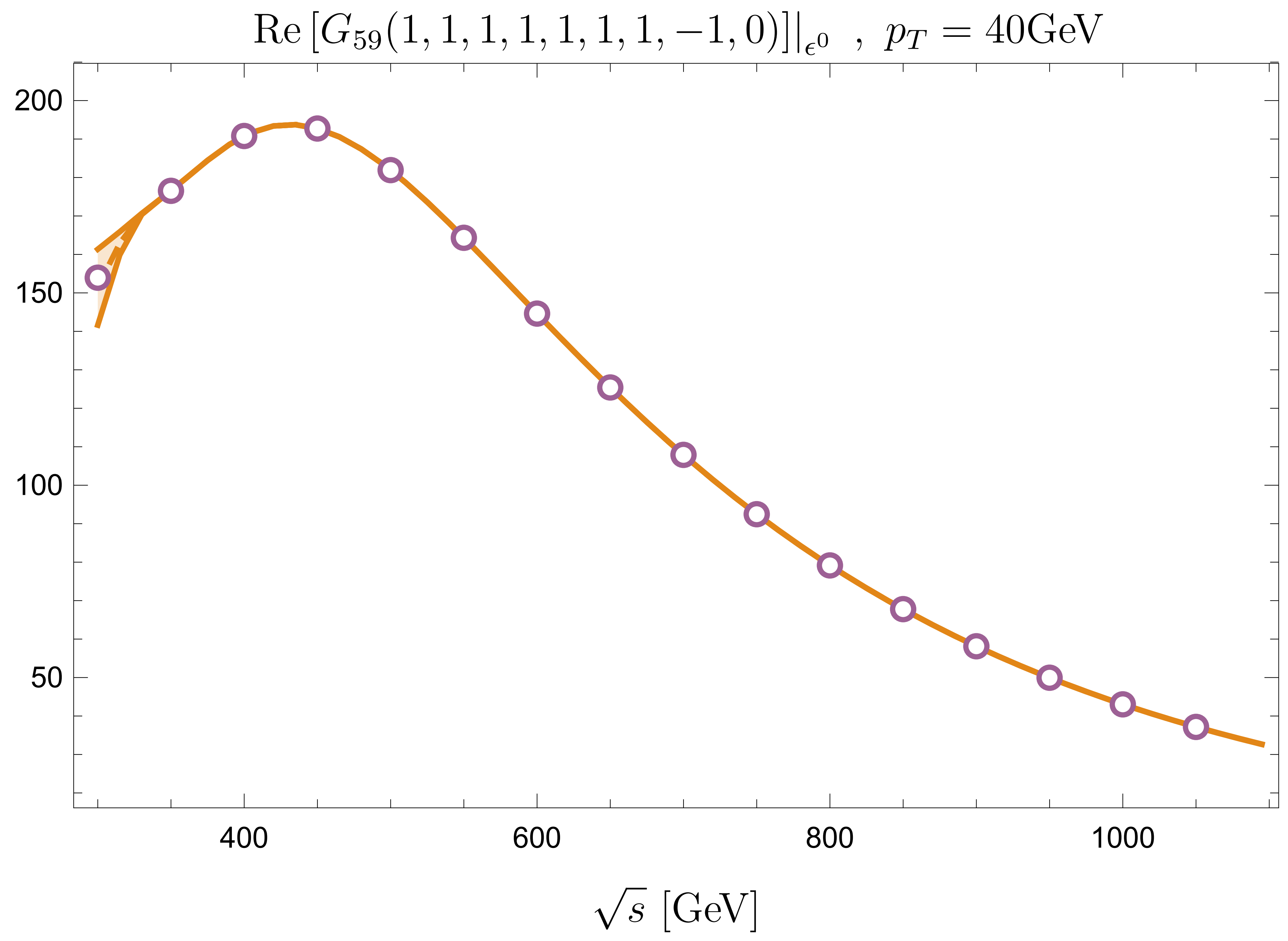


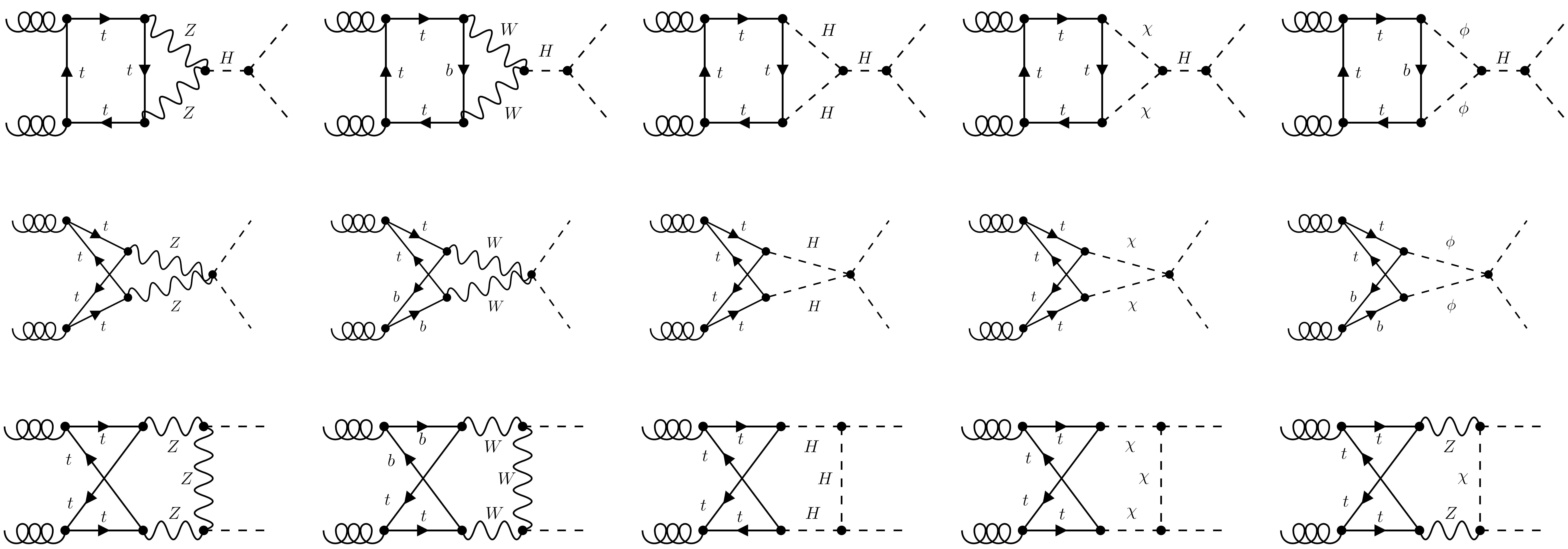


Padé(14, 16) Padé(49, 56) FIESTA

Part 2: Full EW corrections in large-m_t limit

[Davies, Schönwald, Steinhauser, **Zhang**, ***JHEP* 10 (2023) 033**]

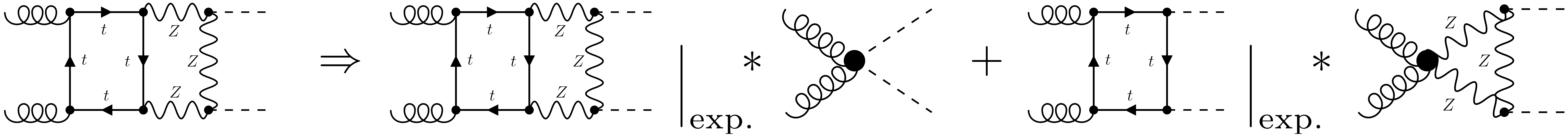
- Sample two-loop diagrams involving SM fields: $\{t, b, H, \gamma, Z, W^{\pm}, \chi, \phi^{\pm}\}$ and ghosts: $\{u^{\gamma}, u^{Z}, u^{\pm}\}$



- **Aim:** analytic large-m_t expansion in $\sqrt{s} \leq 300\,\mathrm{GeV}$ region

Large-m_t expansion and EW renormalisation

- Expansion hierarchy: $m_t^2 \gg \xi_W m_W^2, \xi_Z m_Z^2 \gg s, t, m_H^2, m_W^2, m_Z^2$
- Expand and calculate in **general R_ξ gauge** with **`qgraf`** [Nogueira], **`tapir`** [Gerlach, Herren, Lang], **`q2e&exp`** [Harlander, Seidensticker, Steinhauser], **`FORM`** [Vermaseren], **`LiteRed`** [Lee], **`MATAD`** [Steinhauser]



Large-m_t expansion and EW renormalisation

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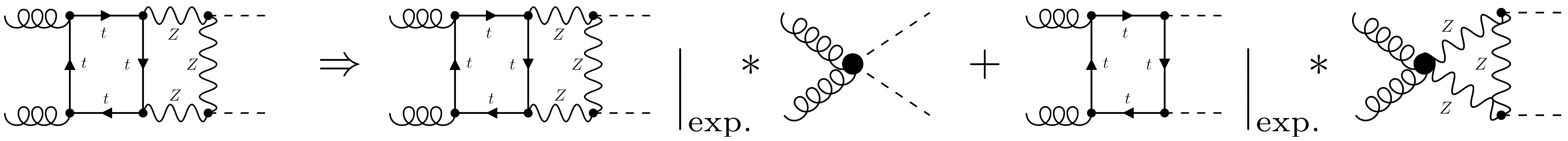


- **On-Shell renormalise** input parameters $\{e, m_W, m_Z, m_t, m_H\}$ and external Higgs fields in G_μ scheme

  $\Rightarrow \xi_W, \xi_Z$ cancel completely $\Rightarrow$ gauge invariant results

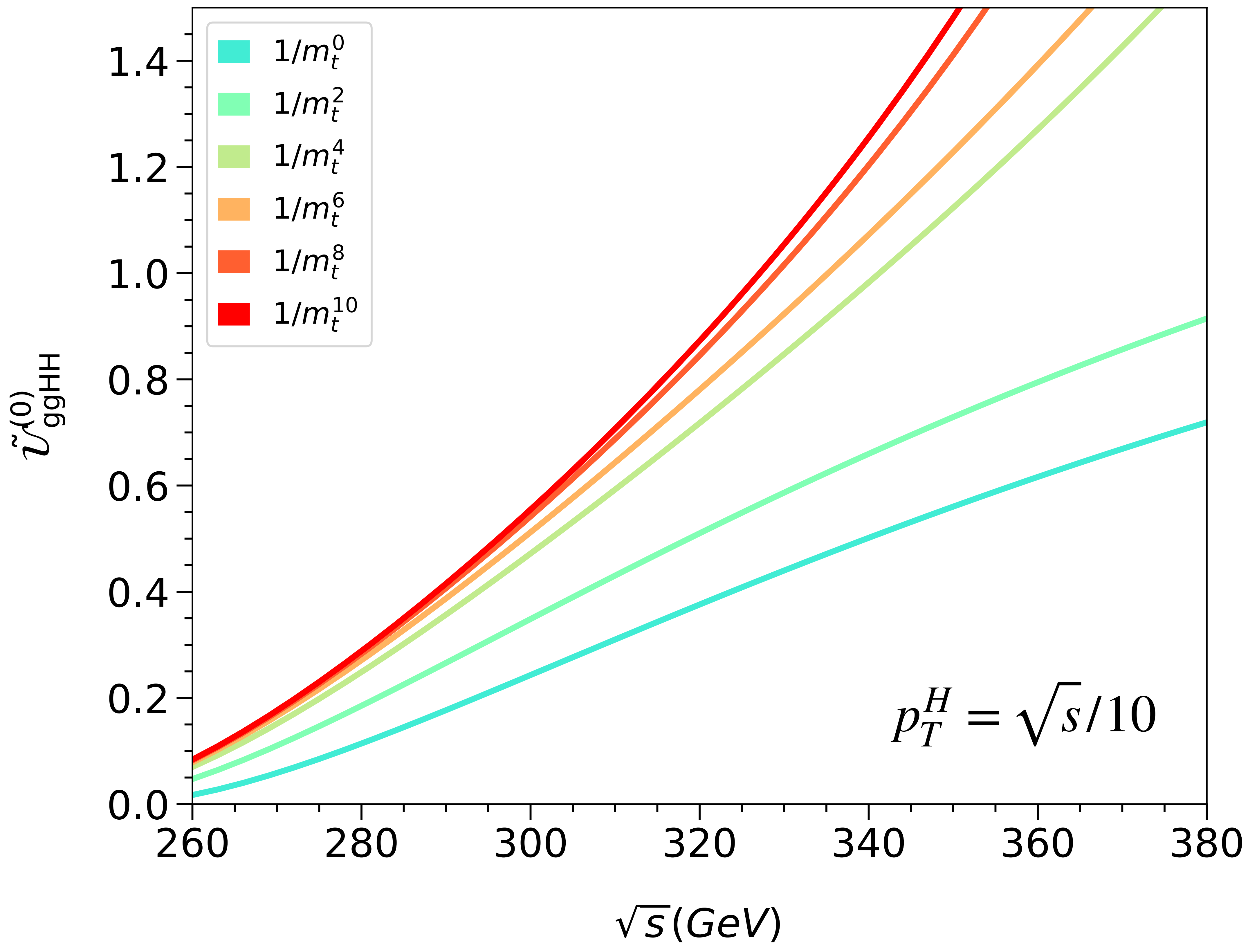
  $\Rightarrow \mu^2$ cancel completely $\Rightarrow$ renormalisation scale independent

Matrix elements for $gg \to HH$ @ LO

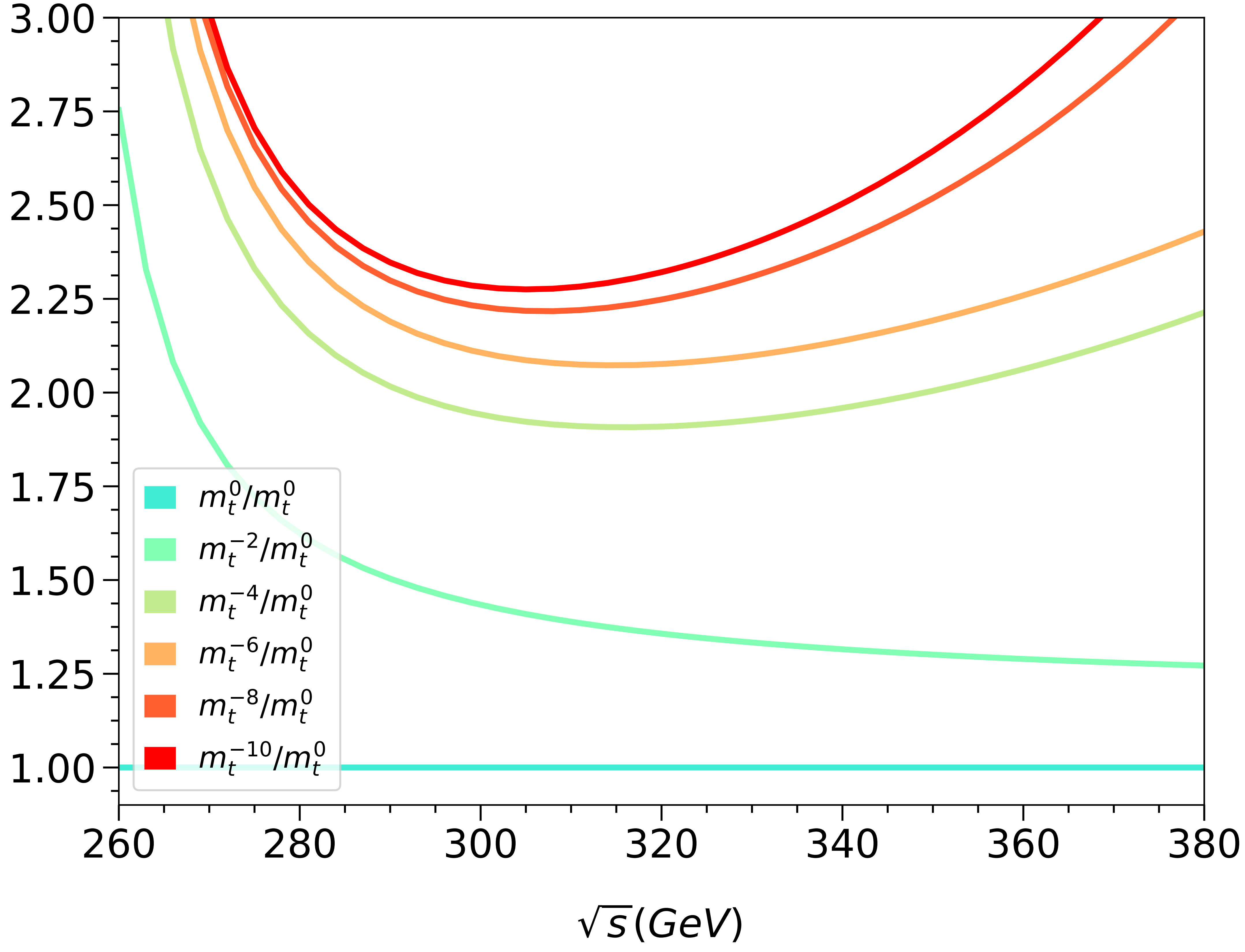
[Davies, Schönwald, Steinhauser, **Zhang**, ***JHEP 10 (2023) 033***]

$$\mathscr{M} = \frac{1}{8^2\, 2^2} \sum_{\text{col}} \sum_{\text{pol}} |\mathscr{A}|^2 = \frac{1}{16} \left(X_0^{\text{ggHH}}\, s\right)^2 \tilde{U}_{\text{ggHH}}$$

$$\tilde{\mathscr{U}}_{\text{ggHH}} = \tilde{\mathscr{U}}^{(0)}_{\text{ggHH}} + \frac{\alpha}{\pi} \tilde{\mathscr{U}}^{(0,1)}_{\text{ggHH}}$$



$\tilde{U}_{\text{ggHH}}$ plot up to different expansion order $1/m_t^n$



$\tilde{U}_{\text{ggHH}}$ **convergence** plot normalised to m_t^0

Good convergence observed

Matrix elements for $gg \to HH$ @ NLO EW

[Davies, Schönwald, Steinhauser, **Zhang**, ***JHEP 10 (2023) 033***]

$$\mathscr{M} = \frac{1}{8^2\,2^2}\sum_{\text{col}}\sum_{\text{pol}}|\mathscr{A}|^2 = \frac{1}{16}\left(X_0^{\text{ggHH}}\,s\right)^2\tilde{U}_{\text{ggHH}}$$

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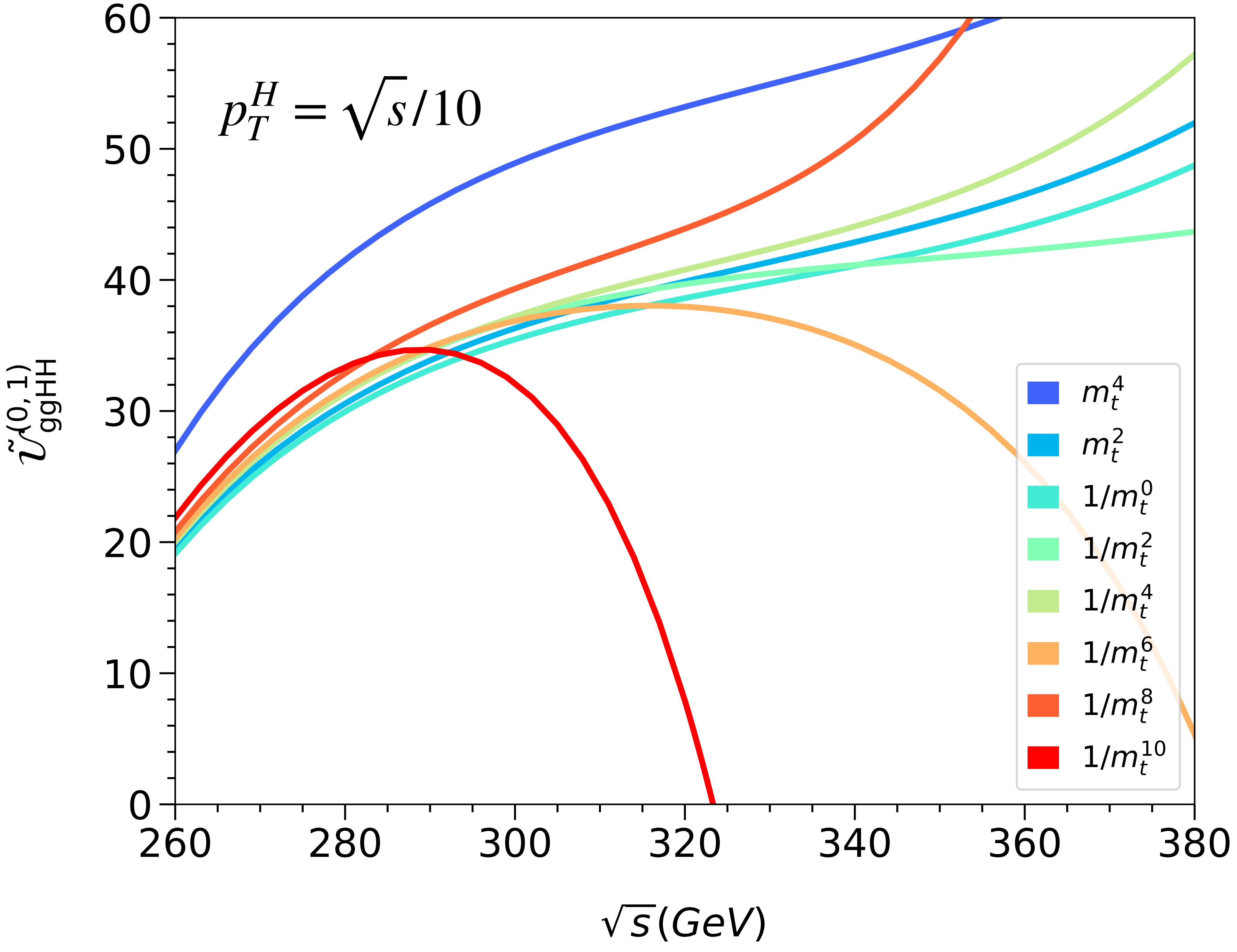
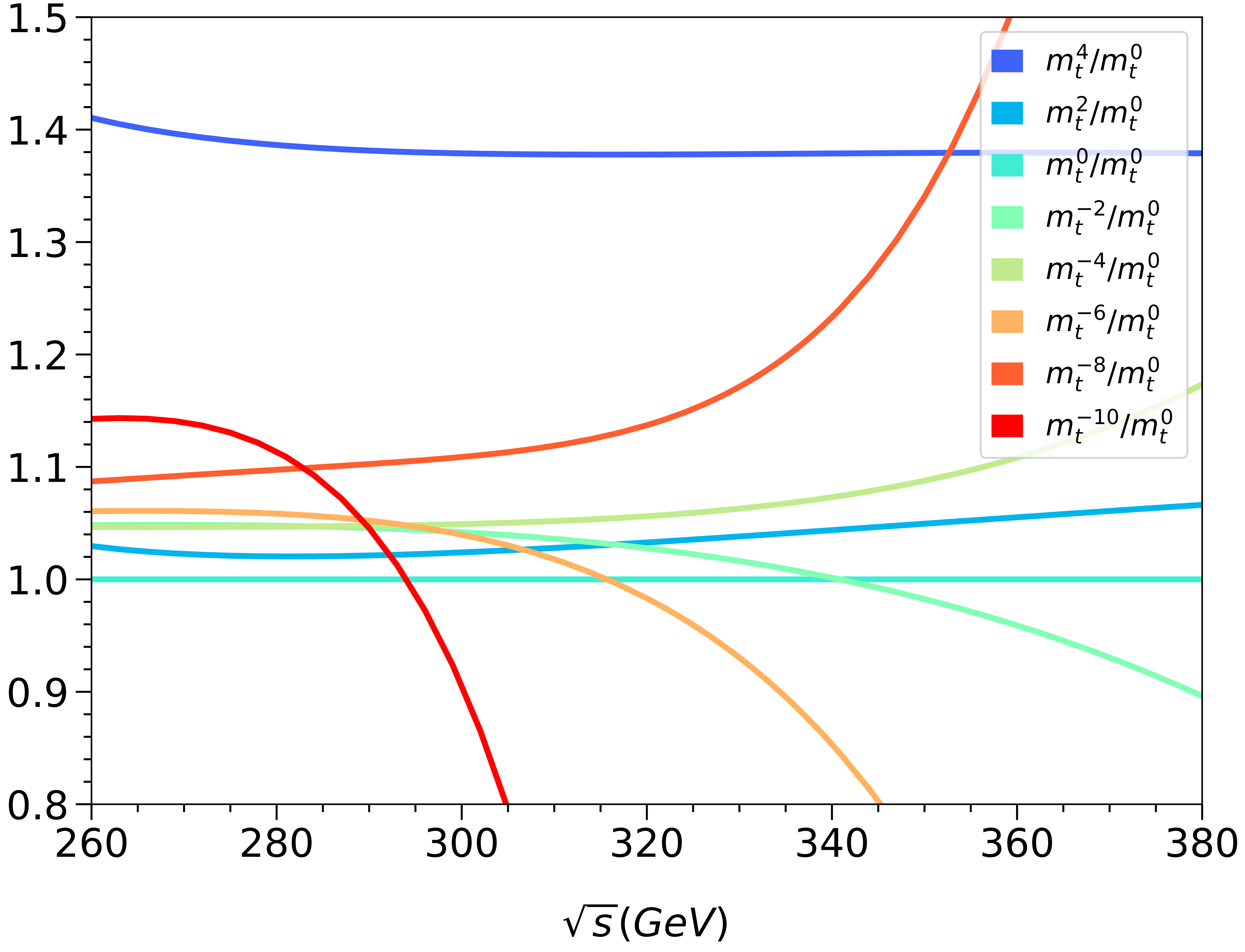


$\tilde{U}_{\text{ggHH}}$ plot up to different expansion order $1/m_t^n$



$\tilde{U}_{\text{ggHH}}$ **convergence** plot normalised to m_t^0

Convergence not good, but estimation of size of EW corrections are correct

Matrix elements for $gg \to HH$ @ NLO EW

[Davies, Schönwald, Steinhauser, **Zhang**, ***JHEP 10 (2023) 033***]

$$\mathcal{M} = \frac{1}{8^2\, 2^2} \sum_{\mathrm{col}} \sum_{\mathrm{pol}} |\mathcal{A}|^2 = \frac{1}{16} \left(X_0^{\mathrm{ggHH}} s\right)^2 \tilde{U}_{\mathrm{ggHH}}$$

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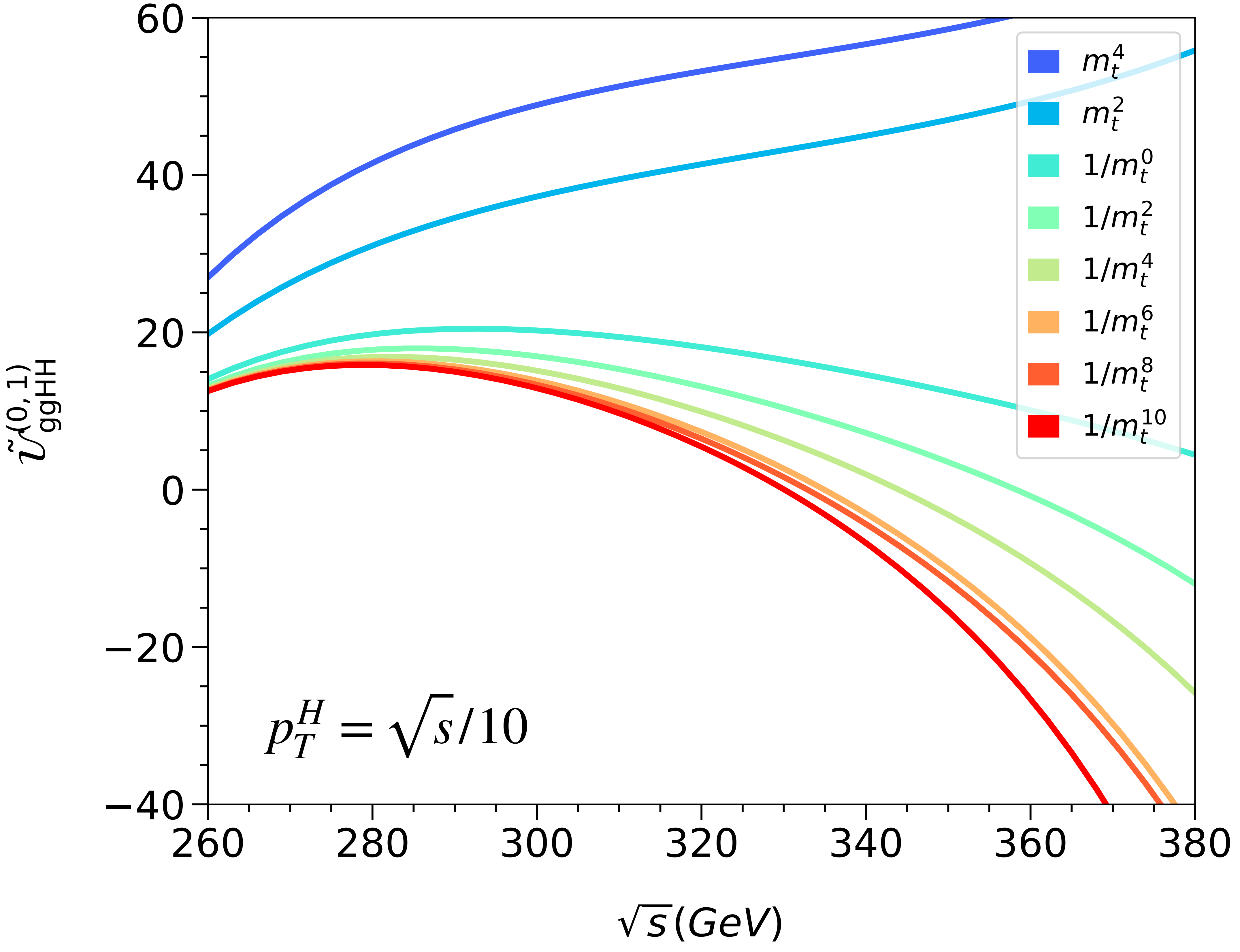
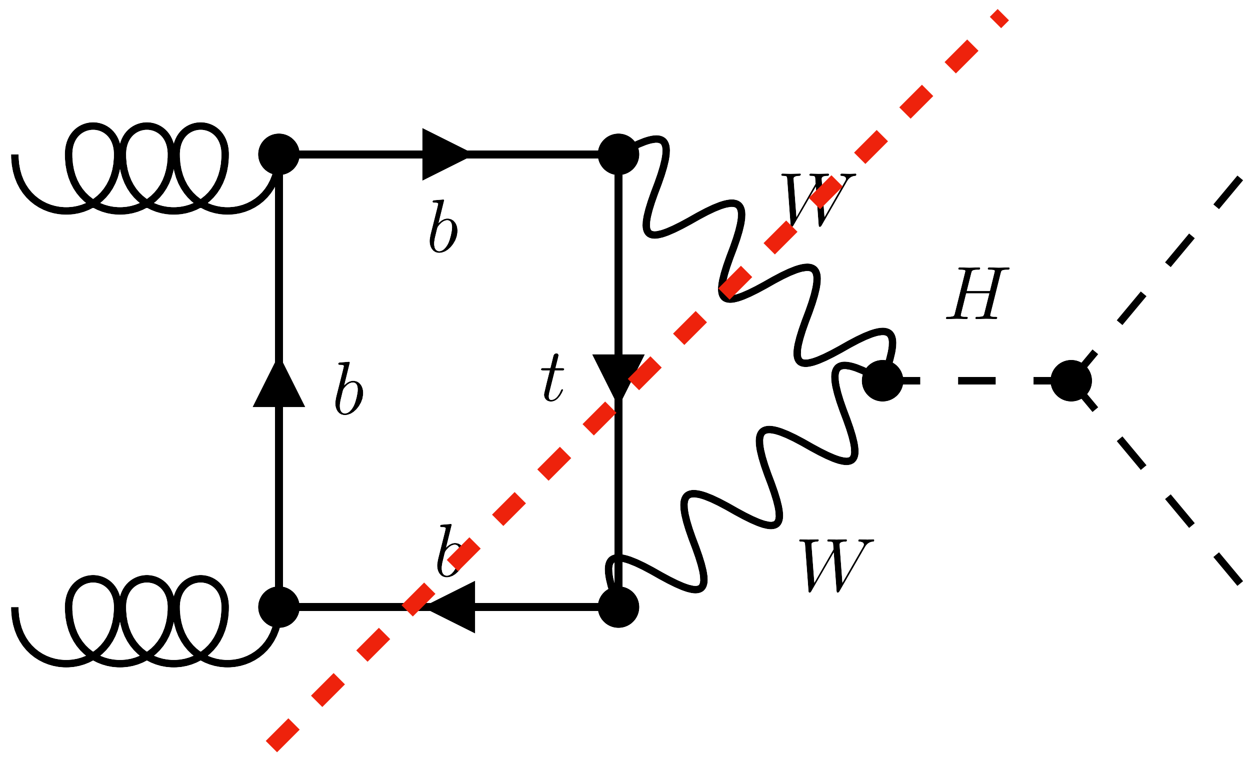


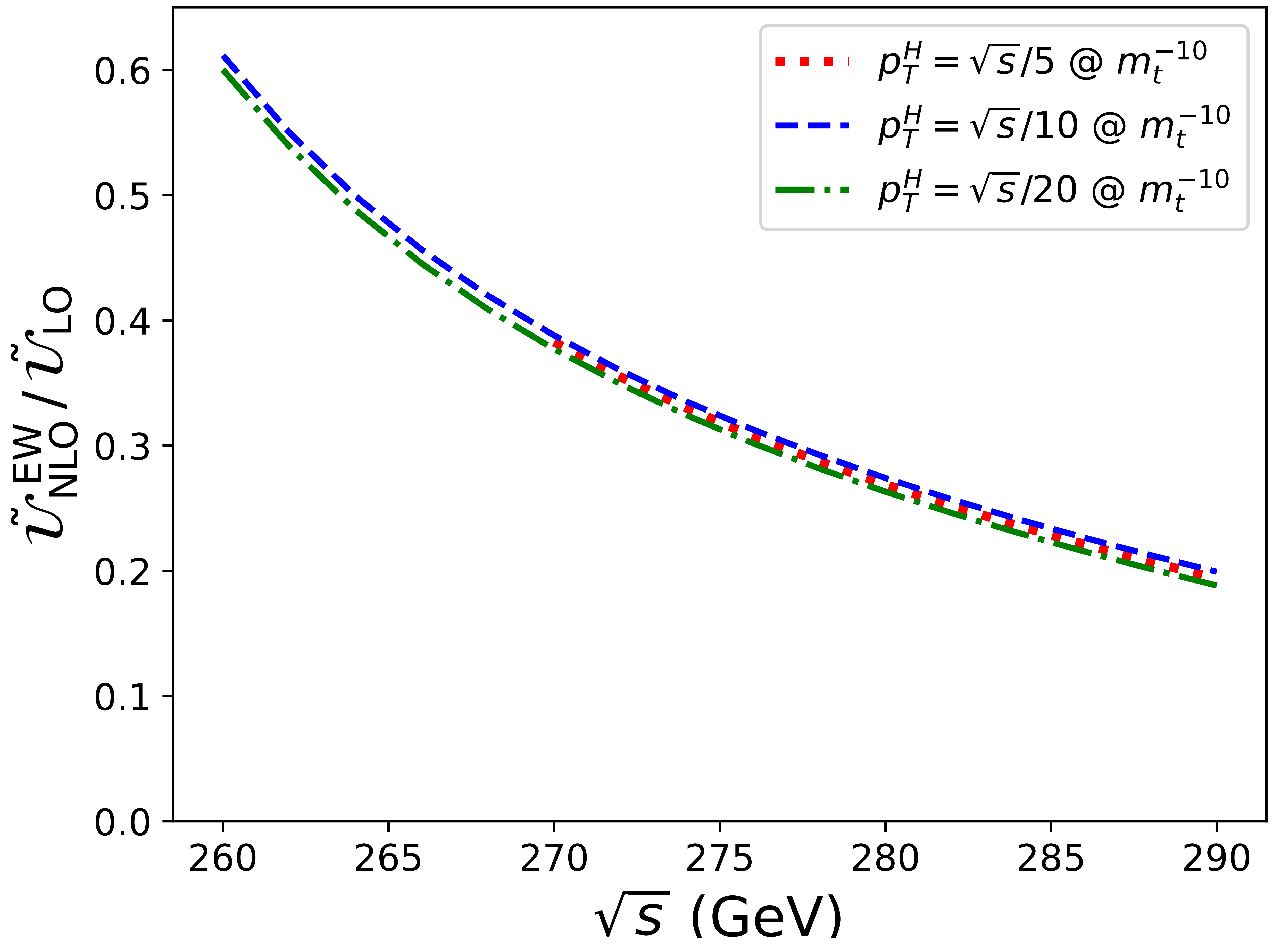
$\tilde{U}_{\mathrm{ggHH}}$ plot up to different expansion order $1/m_t^n$



Cut through W-t-b worsen convergence at $m_t + m_b + m_W \approx 250\,\mathrm{GeV}$

Good convergence restored by excluding W-t-b contributions

Ratio plot of matrix elements for NLO EW / LO



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$$\tilde{\mathscr{U}}_{\rm ggHH} = \tilde{\mathscr{U}}^{(0)}_{\rm ggHH} + \frac{\alpha}{\pi} \tilde{\mathscr{U}}^{(0,1)}_{\rm ggHH}$$

$$\frac{\tilde{\mathscr{U}}^{\rm EW}_{\rm NLO}}{\tilde{\mathscr{U}}_{\rm LO}} = \frac{\alpha}{\pi} \frac{\tilde{\mathscr{U}}^{(0,1)}_{\rm ggHH}}{\tilde{\mathscr{U}}^{(0)}_{\rm ggHH}}$$

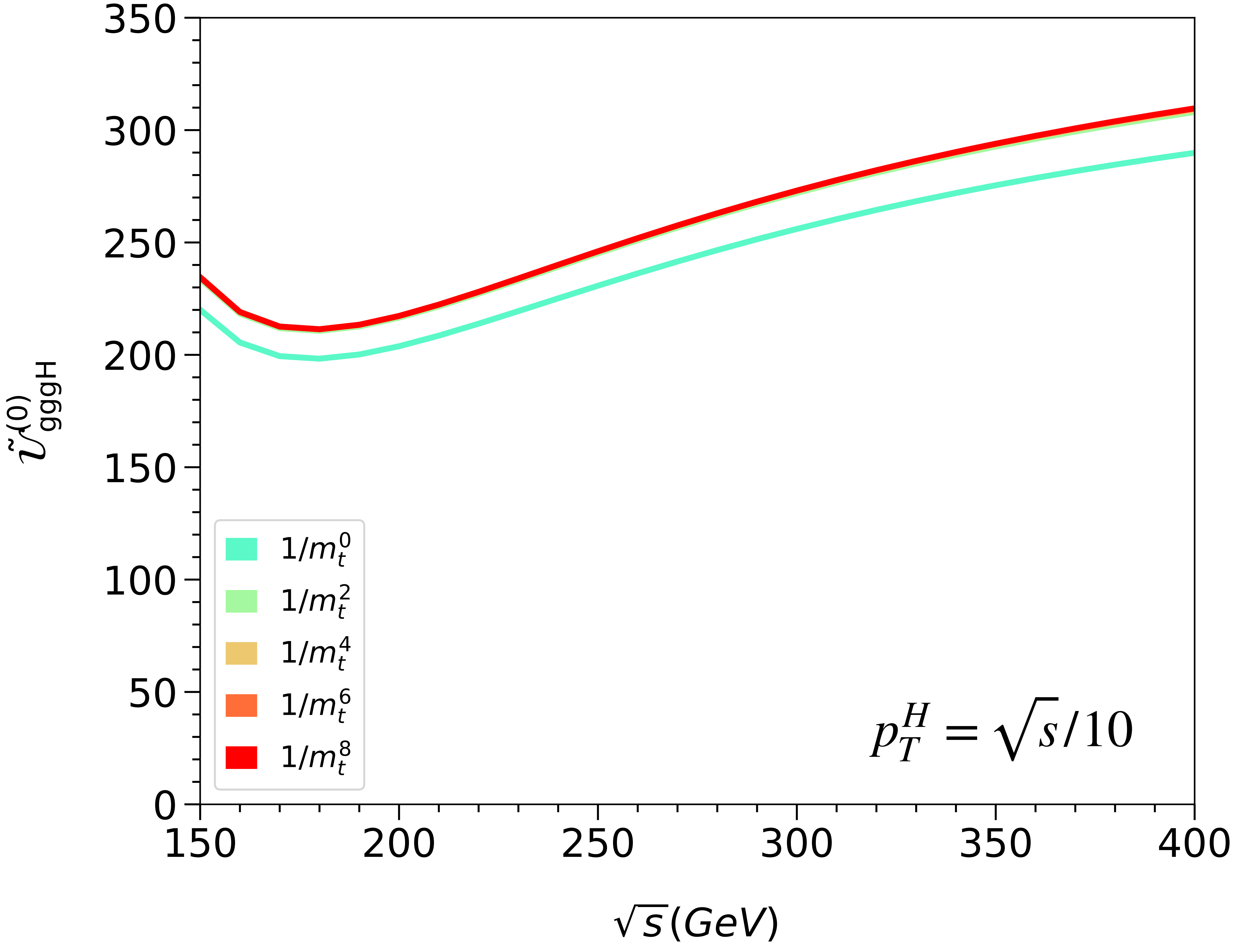
- Size of NLO EW corrections (positive) can easily reach $\geq 20\,\%$ w.r.t. LO at low-energy region
- EW effects are expected to be even larger in high-energy region (stay tuned to our future papers)

Matrix elements for H+jet $(gg \to gH)$ @ NLO QCD

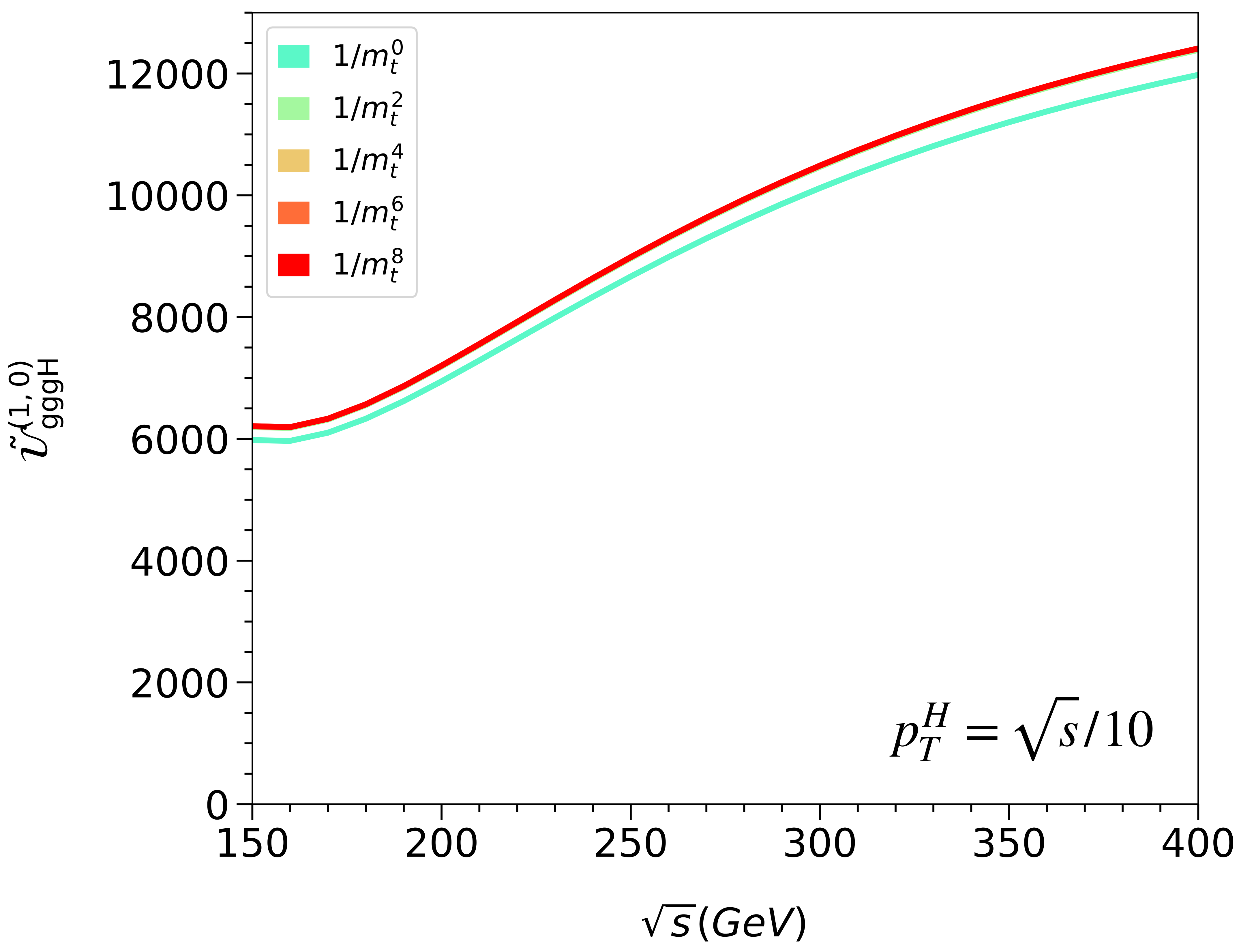
[Davies, Schönwald, Steinhauser, **Zhang**, ***arXiv: 2308.01355***]

$$\mathcal{M} = \frac{1}{8^2\,2^2}\sum_{\text{col}}\sum_{\text{pol}}|\mathcal{A}|^2 = \frac{3}{32}\left(X_0^{\text{gggH}}\right)^2 s\,\tilde{U}_{\text{gggH}}$$

$$\tilde{\mathcal{U}}_{\text{gggH}} = \tilde{\mathcal{U}}^{(0)}_{\text{gggH}} + \frac{\alpha_s(\mu)}{\pi}\tilde{\mathcal{U}}^{(1,0)}_{\text{gggH}} + \frac{\alpha}{\pi}\tilde{\mathcal{U}}^{(0,1)}_{\text{gggH}}$$



$\tilde{U}_{\text{gggH}}$ plot @ LO



$\tilde{U}_{\text{gggH}}$ plot @ **NLO QCD**

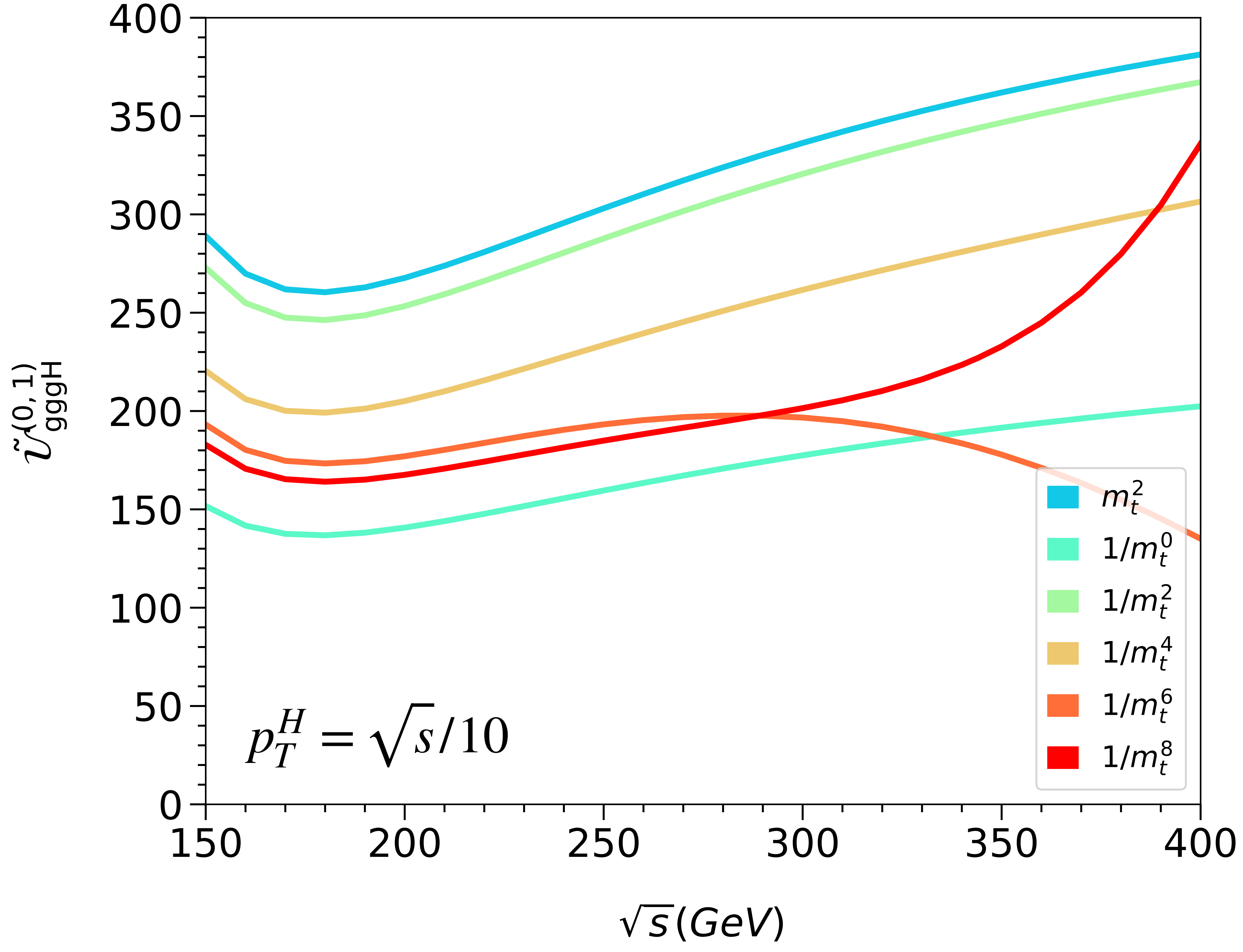
Rapid convergence observed

Matrix elements for H+jet $(gg \to gH)$ @ NLO EW

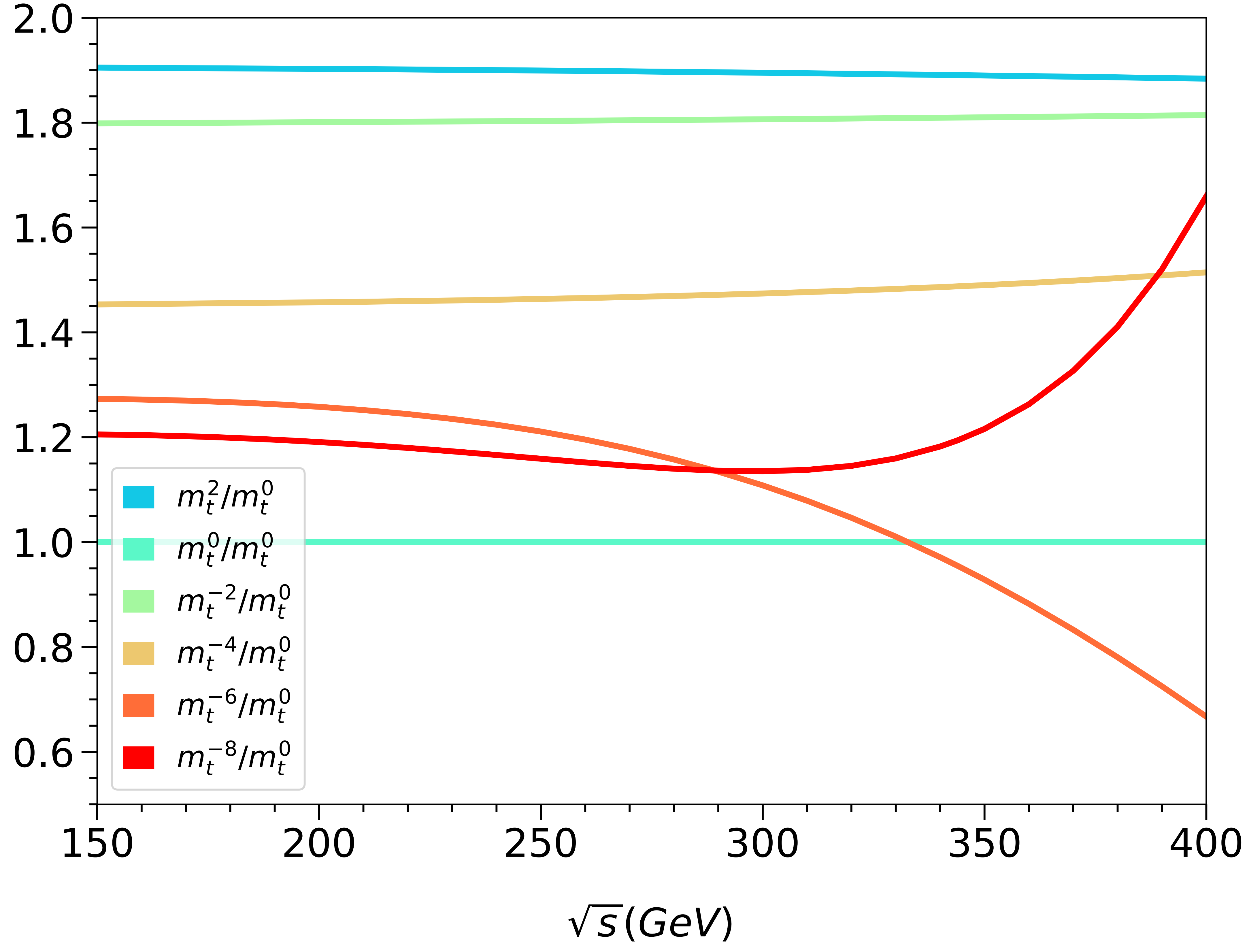
[Davies, Schönwald, Steinhauser, **Zhang**, ***arXiv: 2308.01355***]

$$\mathcal{M} = \frac{1}{8^2\,2^2}\sum_{\text{col}}\sum_{\text{pol}}|\mathcal{A}|^2 = \frac{3}{32}\left(X_0^{\text{gggH}}\right)^2 s\,\tilde{U}_{\text{gggH}}$$

$$\tilde{\mathcal{U}}_{\text{gggH}} = \tilde{\mathcal{U}}^{(0)}_{\text{gggH}} + \frac{\alpha_s(\mu)}{\pi}\tilde{\mathcal{U}}^{(1,0)}_{\text{gggH}} + \frac{\alpha}{\pi}\tilde{\mathcal{U}}^{(0,1)}_{\text{gggH}}$$



$\tilde{U}_{\text{gggH}}$ plot @ **NLO EW**



$\tilde{U}_{\text{gggH}}$ **convergence** plot normalised to m_t^0

Good convergence observed, but corrections are small

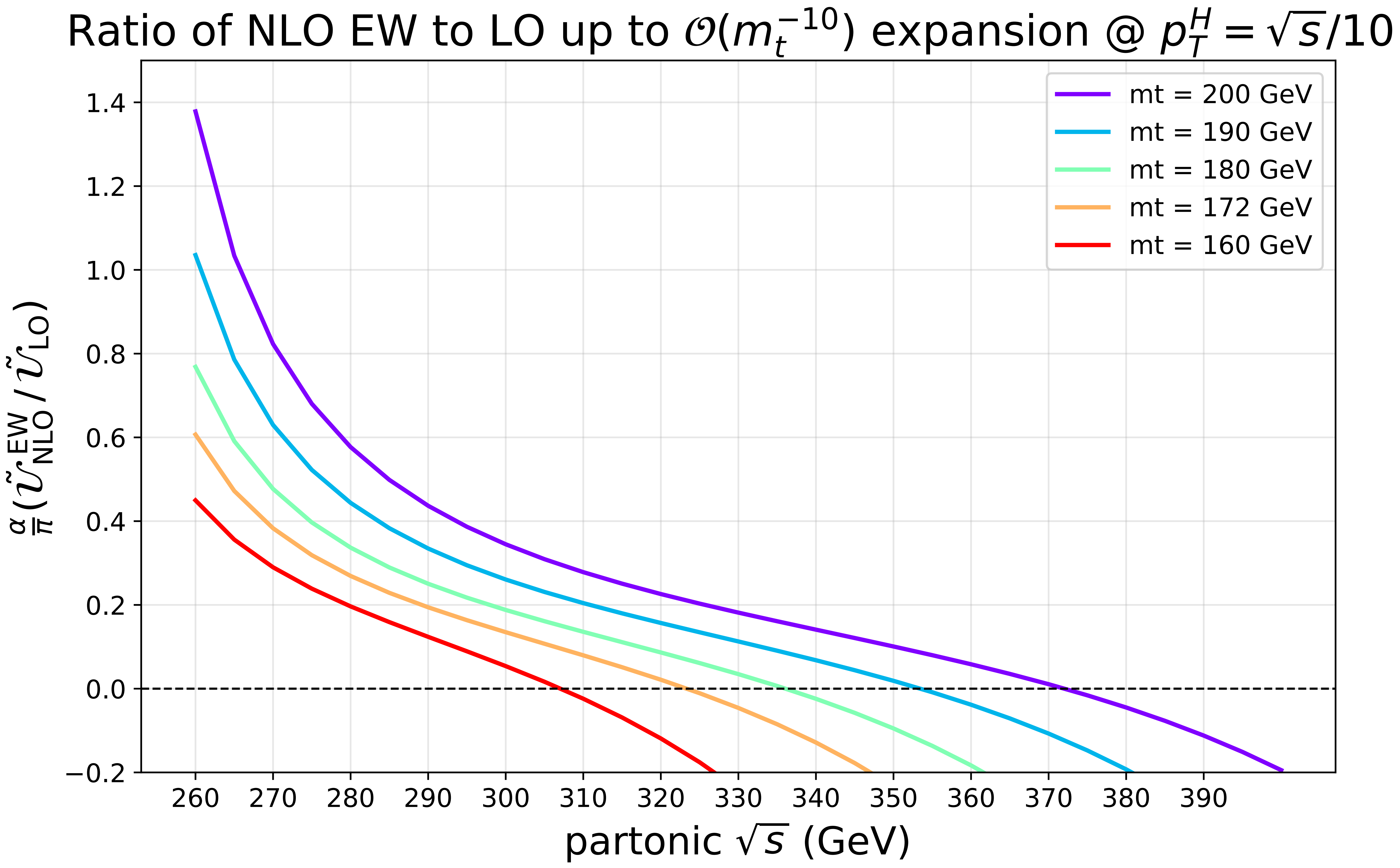
Conclusions and outlook

JHEP 08 (2022) 259 & JHEP 10 (2023) 033

- We analytically compute **NLO leading Yukawa corrections** to $gg \to HH$ in high-energy expansion
  - Two expansion approaches for challenging massive two-loop four-point integrals
  - Padé improved approximations yield **precise results for $p_T^H > 120$ GeV**
- We analytically compute **full NLO EW corrections** to $gg \to HH$ in large-m_t expansion
  - Estimation of EW corrections can reach **a few tens of percent (positive)** w.r.t LO in this region
- We also consider **full NLO EW corrections** to $gg \to gH$ in large-m_t expansion
  - Good convergence observed, but corrections are small
- Future work: complete NLO EW corrections to $gg \to HH$ in whole phase space region by including t-expansion.

Backup Slides

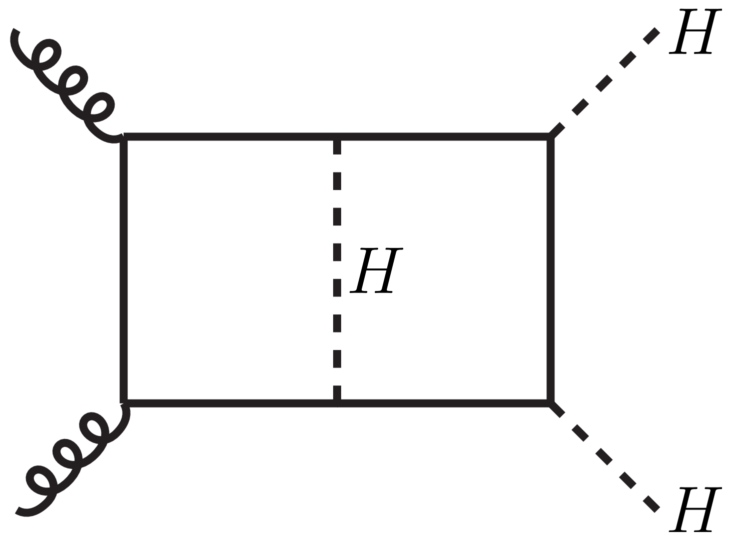
Ratio plot of matrix elements for NLO EW / LO



- Size estimation of NLO EW corrections by varying numerical values of m_t

Analytic high-energy expansion

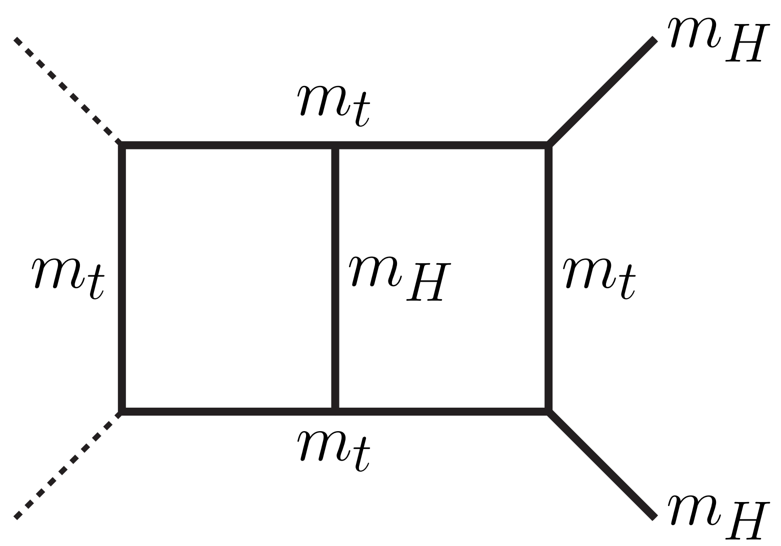
How?



kinematic invariants

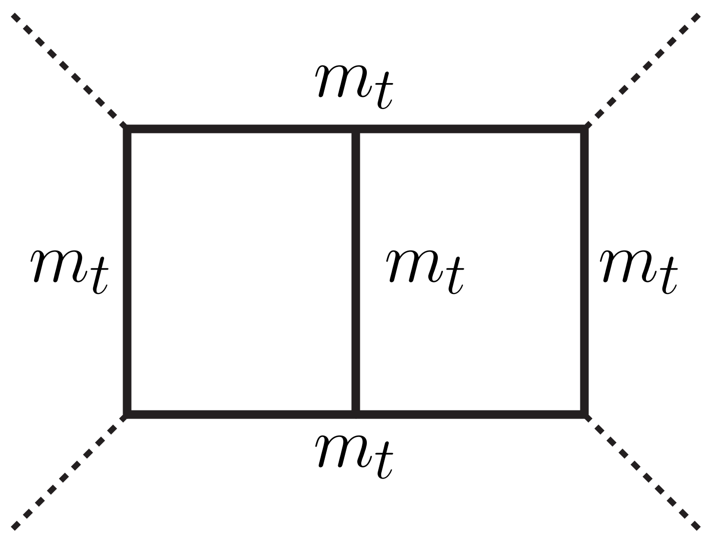
$$s = (q_1 + q_2)^2$$
$$t = (q_1 + q_3)^2$$
$$u = (q_2 + q_3)^2$$

scalar master integral (MI)



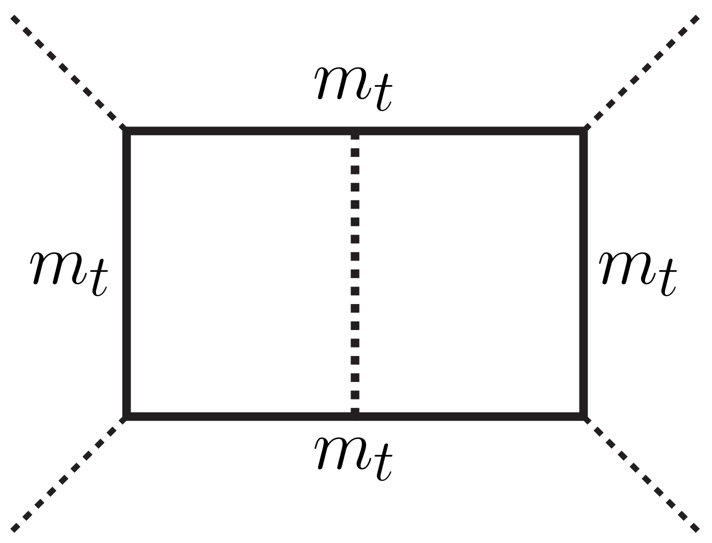
solid line: massive
dashed line: massless

two expansions



$$s, t \gg m_t^2 \approx \left(m_H^{\text{int}}\right)^2 \gg \left(m_H^{\text{ext}}\right)^2$$

- general to full EW corrections
- need entire new family of MIs

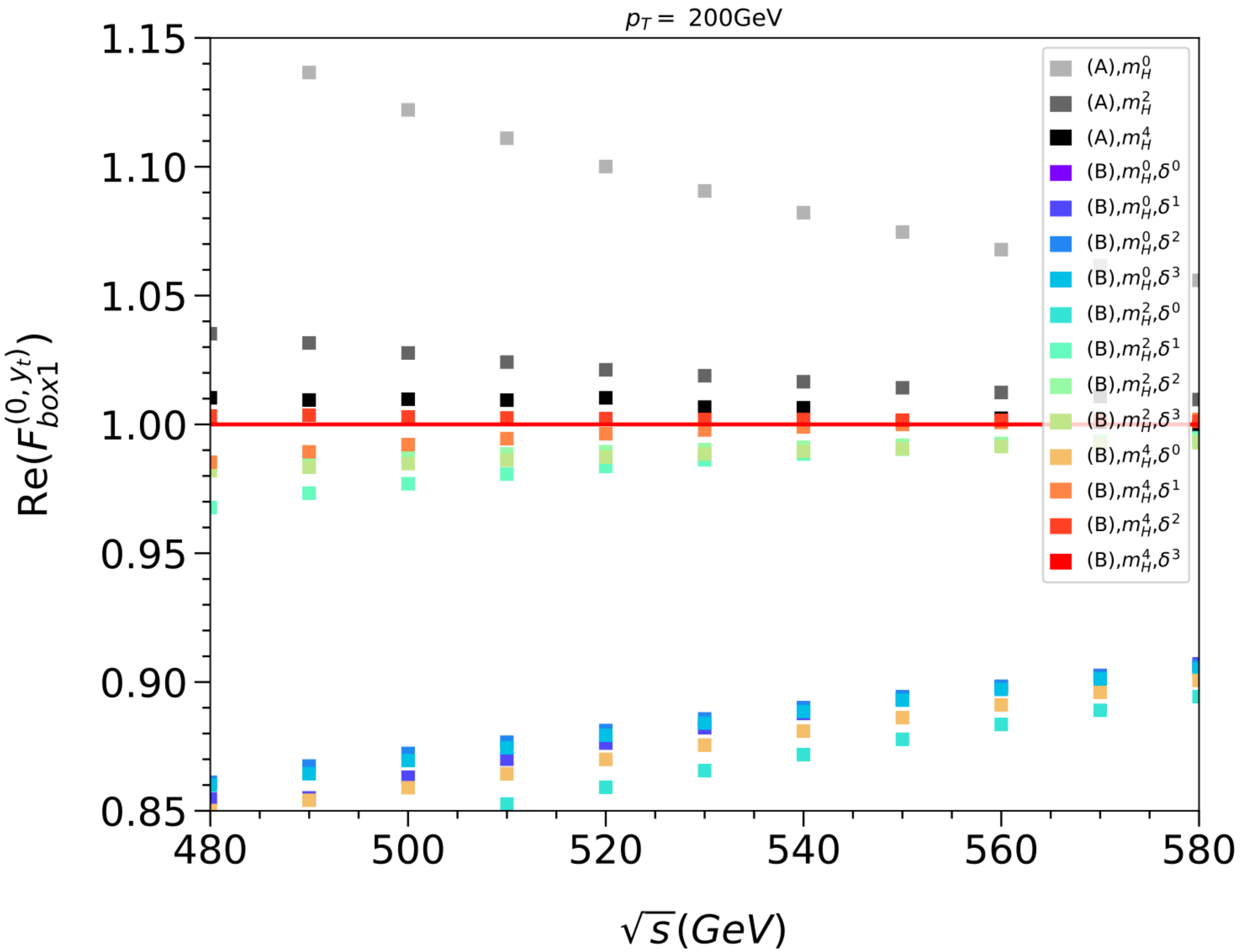


$$s, t \gg m_t^2 \gg \left(m_H^{\text{int}}\right)^2, \left(m_H^{\text{ext}}\right)^2$$

- reduce to known QCD MIs
- non-trivial to full EW corrections

Convergence of expansions for $gg \to HH$ form factors

[Davies, Mishima, Schönwald, Steinhauser, **Zhang**, ***JHEP 08 (2022) 259***]



$$\mathscr{A}^{\mu\nu} = T_1^{\mu\nu}\,\mathscr{F}_{\mathrm{box1}} + T_2^{\mu\nu}\,\mathscr{F}^{\mu\nu}_{\mathrm{box2}}$$

The benchmark is expansion at $\mathcal{O}\left(m^4_{H(\mathrm{ext})}, \delta^3, m_t^{116}\right)$.

$$\delta = 1 - \frac{m_H^{(\mathrm{int})}}{m_t}$$

Color points: Convergence plot of different expansion orders by ratios to the benchmark at fixed $p_T^H = 200$ GeV.