Analytic electroweak corrections to di-Higgs and Higgs+jet production

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Based on [JHEP 08 (2022) 259] & [JHEP 10 (2023) 033] & [2407.05787] & [2407.12107]

Karlsruher Institut für Technologie

ICHEP 2024 — Prague

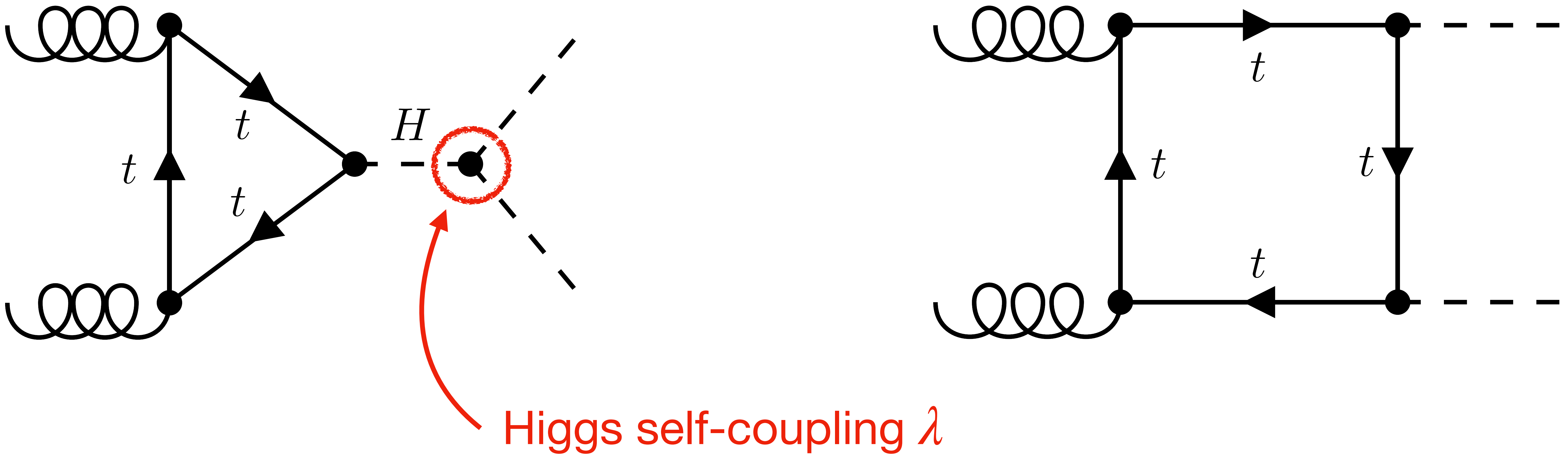
Institute for Theoretical Particle Physics

Motivation: probe Higgs self-coupling

- Probe Higgs self-coupling in Higgs 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 boson pair production (key process at HL-LHC)

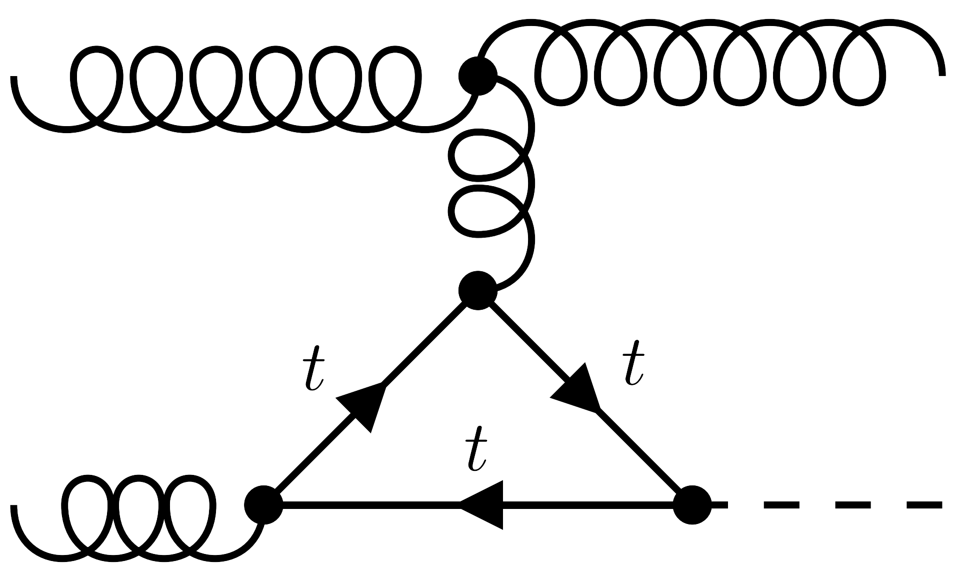


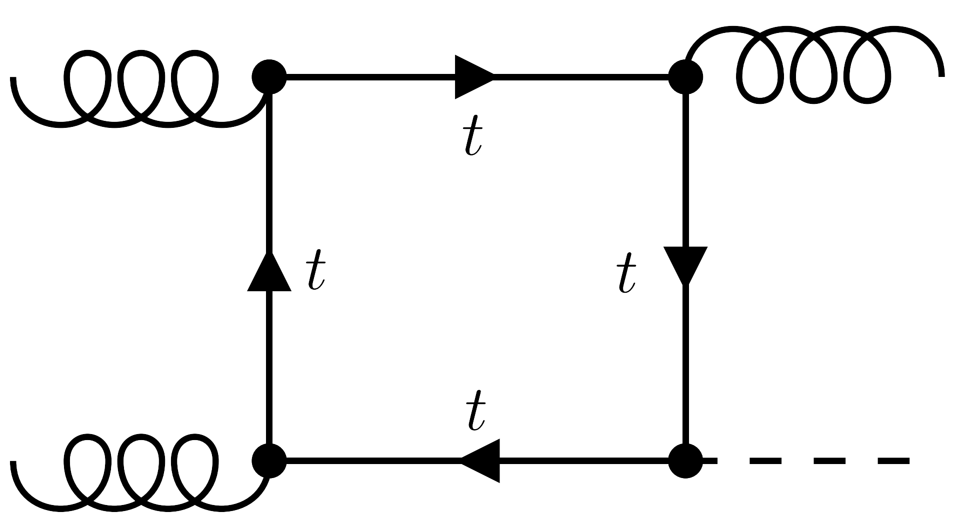
New Physics opportunity?

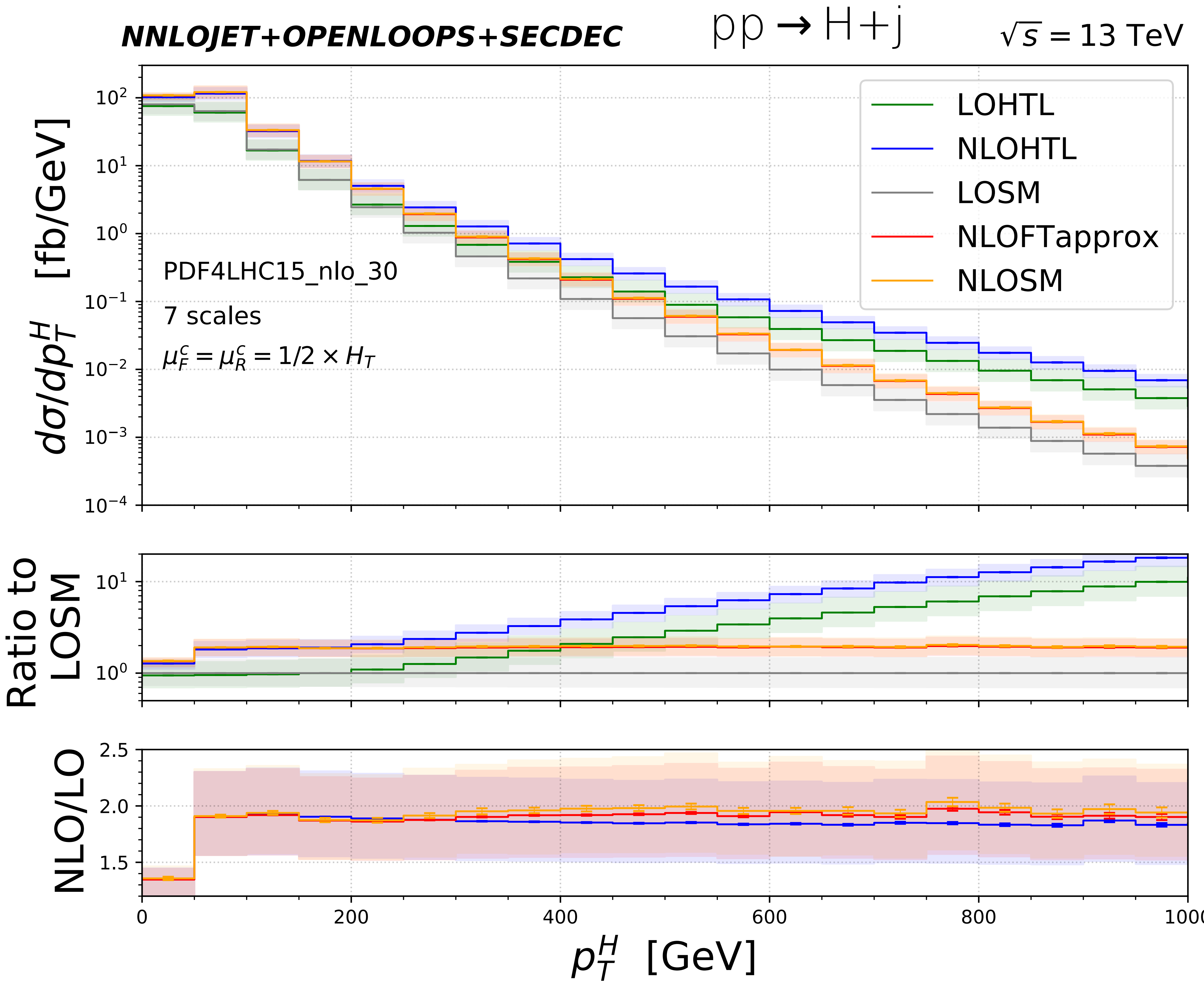
[Iguro, Kitahara, Omura, **Zhang**, ***Phys.Rev.D 107 (2023) 7, 075017***]

Motivation of Higgs+jet: study p_T^H spectrum

- Dominant channel for Higgs boson production with large transversal momentum p_T^H at LHC







p_T^H spectrum:
crucial for studying
Higgs boson properties

NLOSM ⇒ NLO QCD with top-mass dependence

Precise Higgs + 2 jets @ NLO QCD also available → [Chen, Huss, Jones, Kerner, Lang, Lindert, **Zhang**, *JHEP 03 (2022) 096*]

Overview of EW calculations

Analytical approach

$gg \to HH$

- Yukawa-top corrections in high-energy expansion [Davies, Mishima, Schönwald, Steinhauser, **Zhang**, 22']
- Yukawa-top corrections in large-m_t limit [Mühlleitner, Schlenk, Spira, 22']
- Full top-induced EW corrections in large-m_t expansion [Davies, Schönwald, Steinhauser, **Zhang**, 23']
- Factorizable EW corrections [Davies, Schönwald, Steinhauser, **Zhang**, 24']

$gg \to Hg$

- Mixed QCD-EW correction (fully analytic) [Bonetti, Panzer, Smirnov, Tancredi, 20']
- Higgs self-coupling corrections in large-m_t expansion [Gao, Shen, Wang, Yang, Zhou, 23']
- Full top-induced EW corrections in large-m_t expansion [Davies, Schönwald, Steinhauser, **Zhang**, 23']

Numerical approach

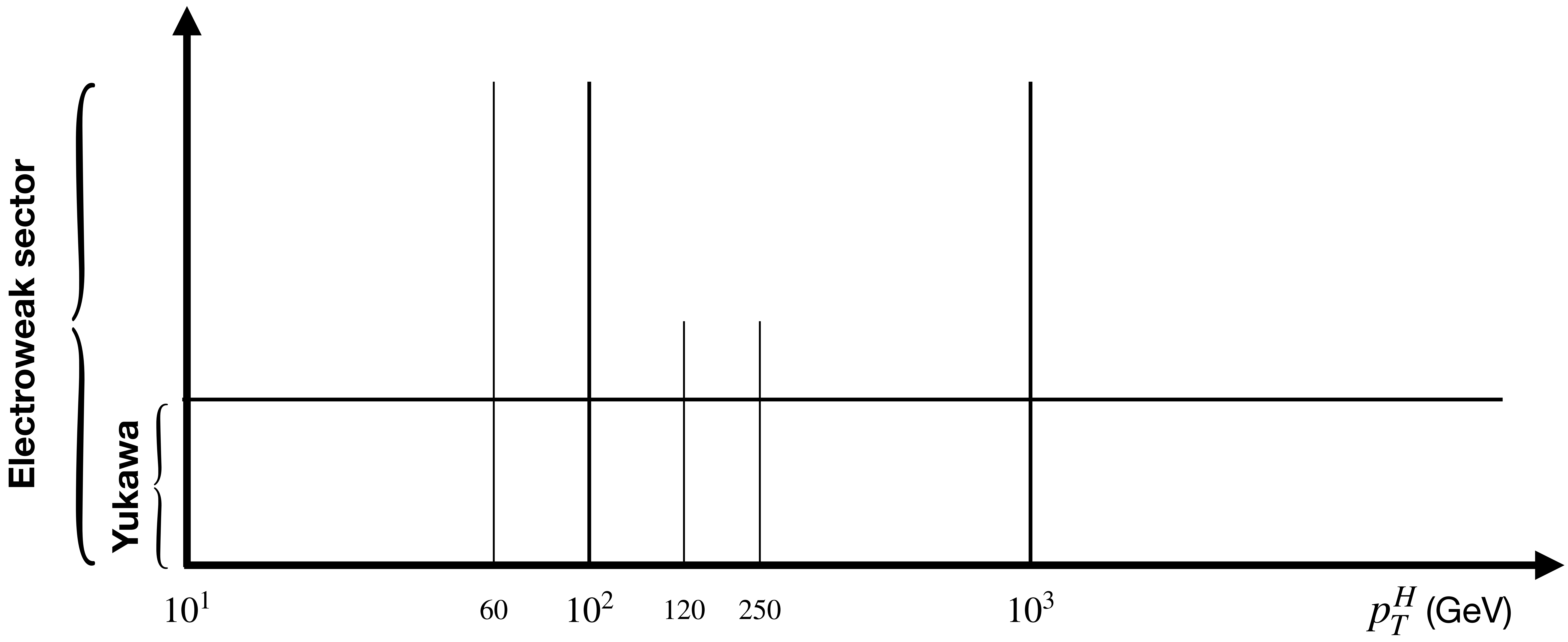
$gg \to HH$

- Higgs self-coupling corrections with SecDec [Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao, 19']
- Full EW corrections with AMFlow [Bi, Huang, Huang, Ma, Yu, 24']
- Yukawa and Higgs self-coupling corrections with SecDec [Heinrich, Jones, Kerner, Stone, Vestner, 24]

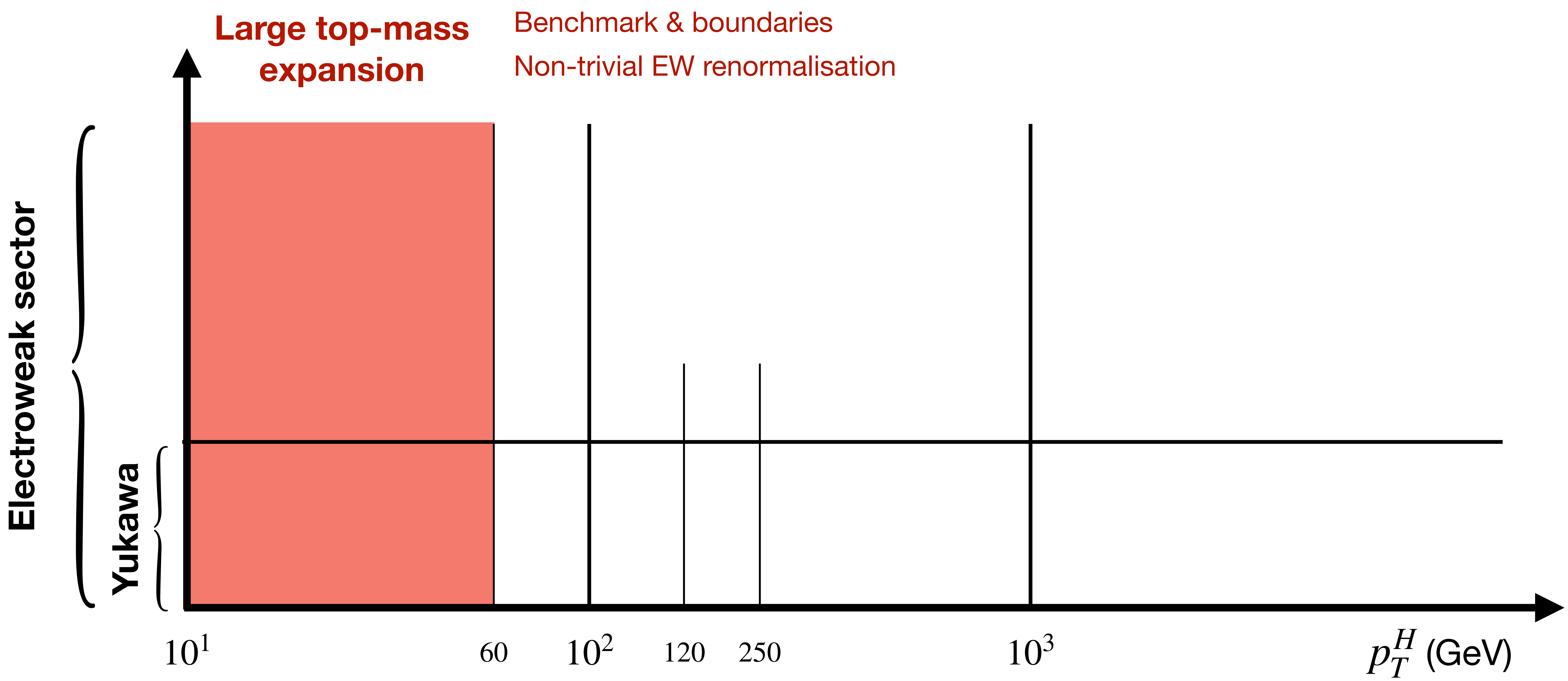
[See talk by Matthias Steinhauser for QCD corrections to di-Higgs]

This talk: analytic expansion in large-mass, forward scattering, and high-energy kinematics

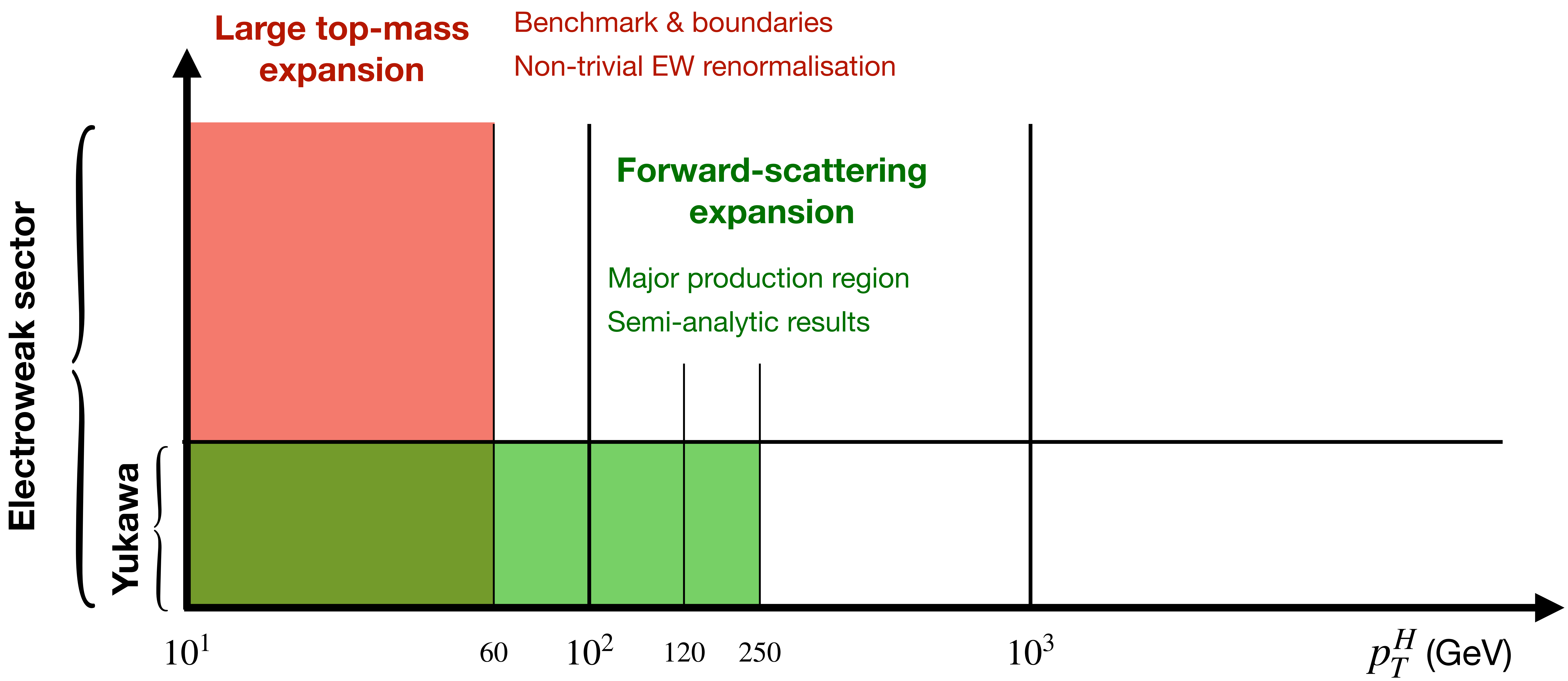
Expansions of two-loop EW corrections



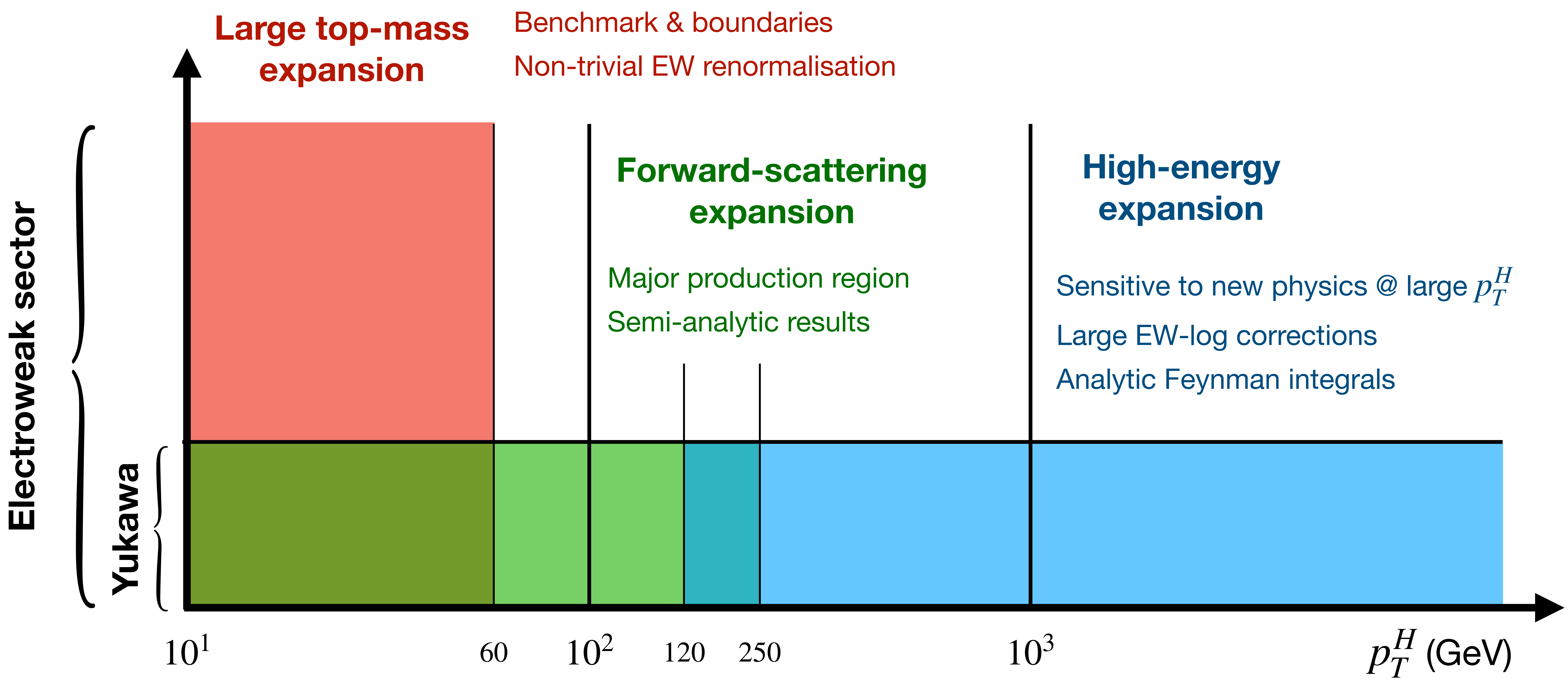
Expansions of two-loop EW corrections



Expansions of two-loop EW corrections

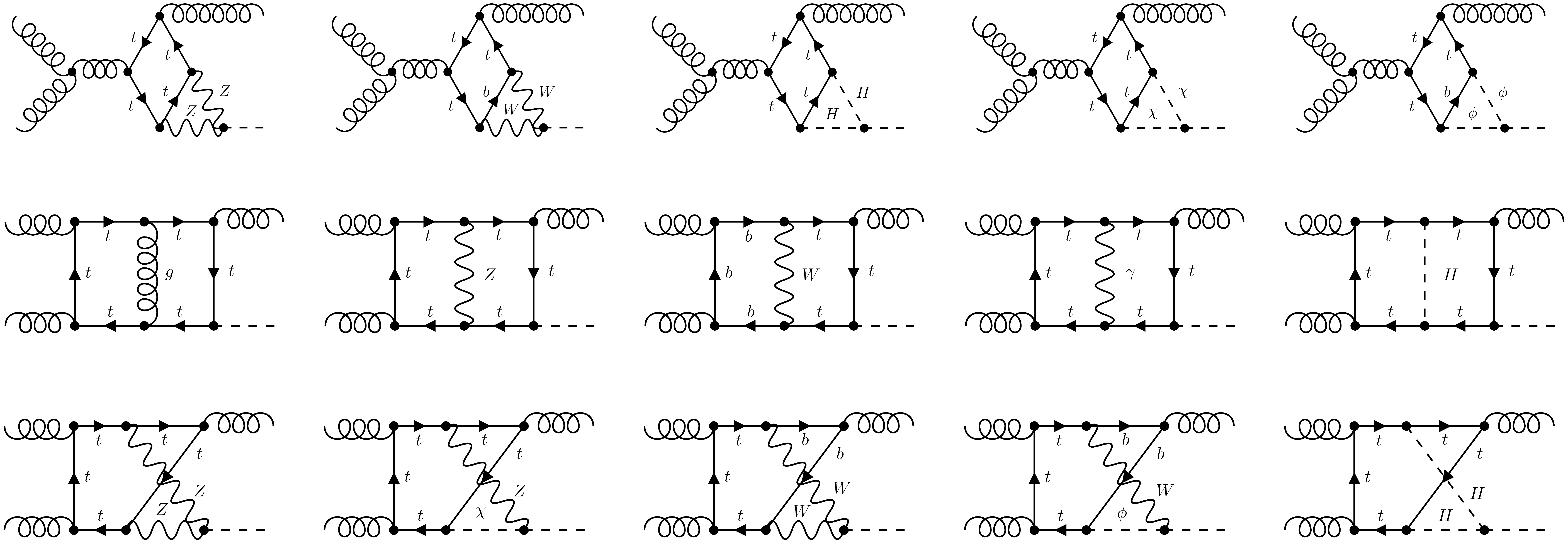


Expansions of two-loop EW corrections



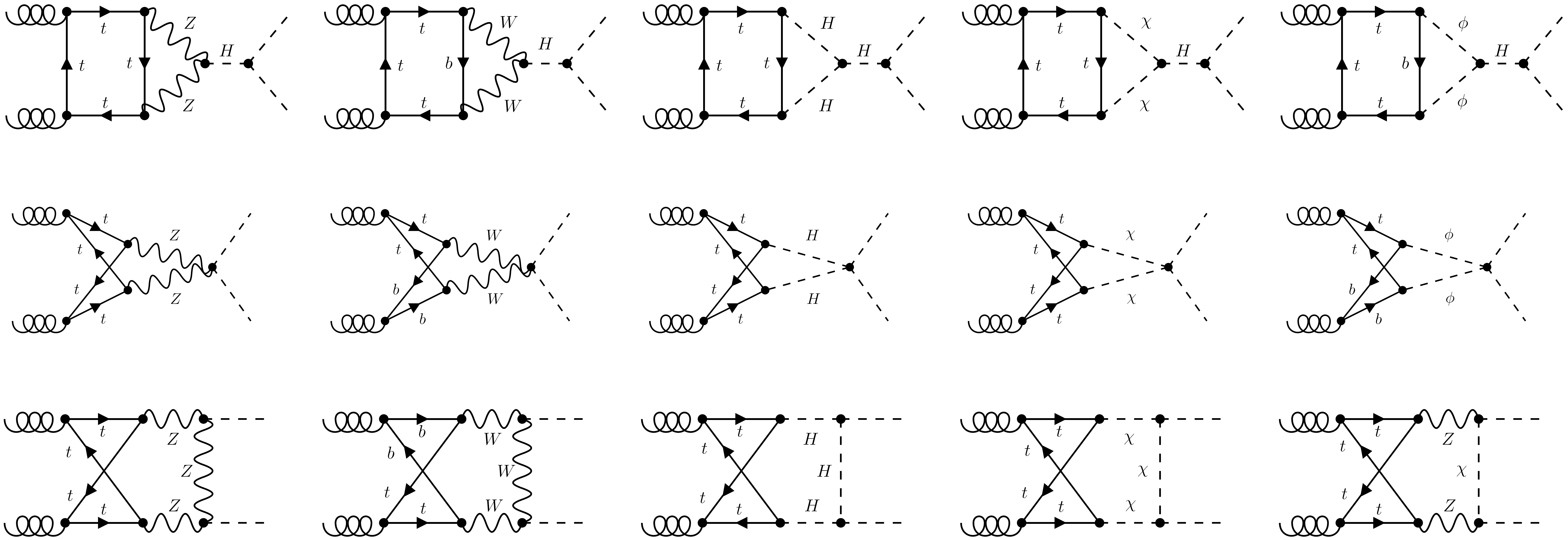
Two-loop EW diagrams with top-quark (H+jet)

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



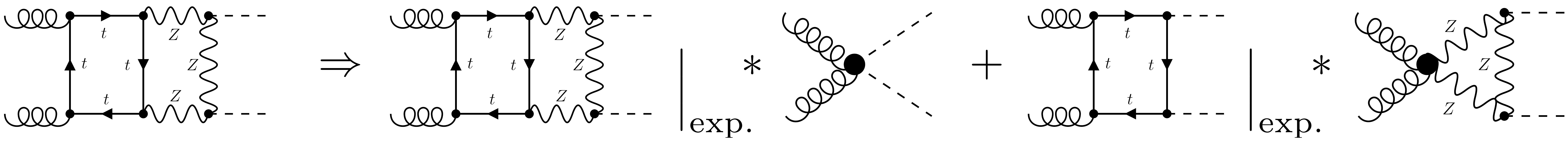
Two-loop EW diagrams with top-quark (HH)

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



Large-m_t expansion and EW renormalisation

- Expansion hierarchy: $m_t^2 \gg s, t, m_H^2, m_W^2, m_Z^2$
- Expand and calculate in **general R_ξ gauge** with large gauge fixing parameters $\xi_Z, \xi_W \gg 1$



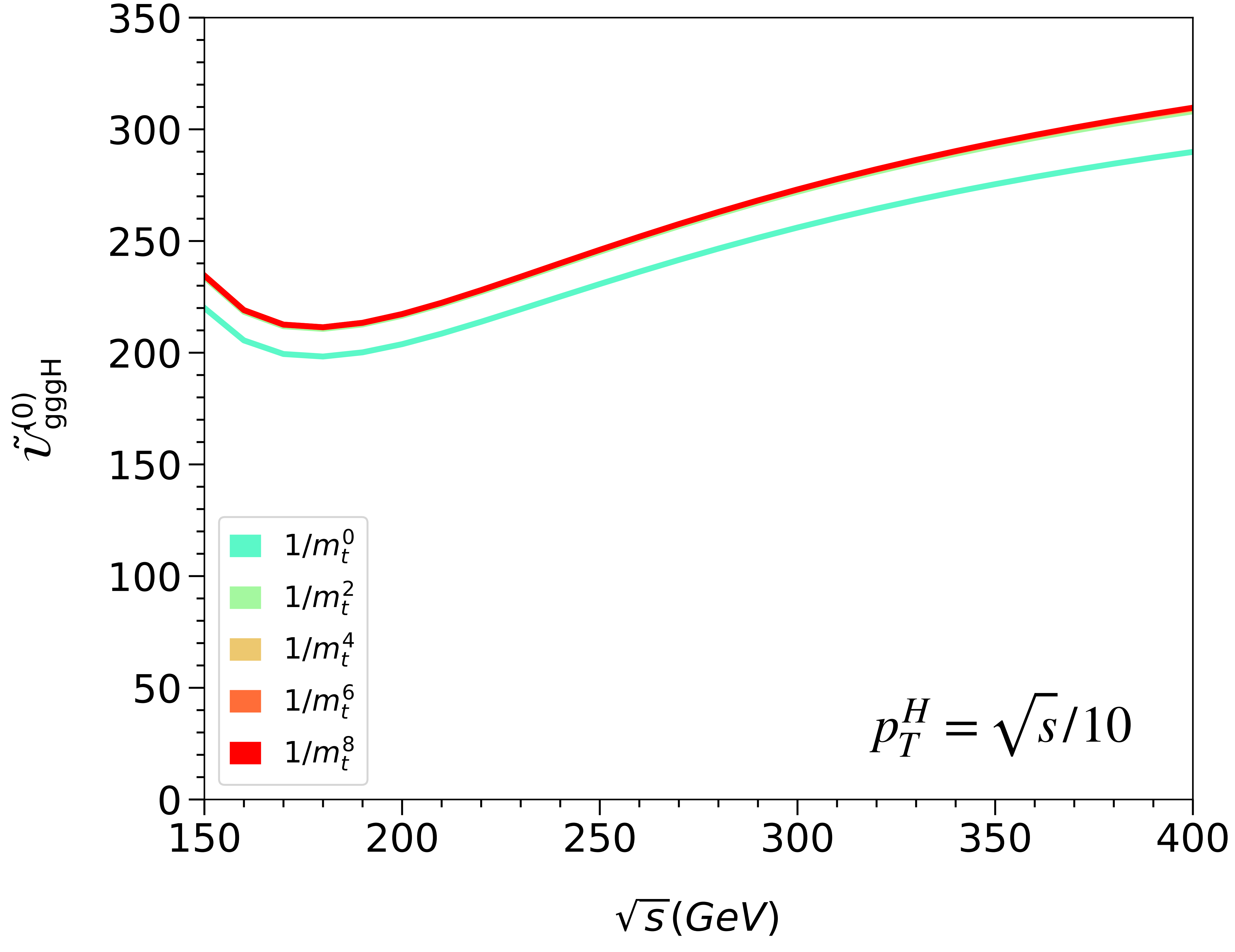
- **On-Shell renormalise** input parameters $\{e, m_W, m_Z, m_t, m_H\}$ in G_μ scheme
- ξ_W, ξ_Z **cancel** after external Higgs **fields OS renormalisation**

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

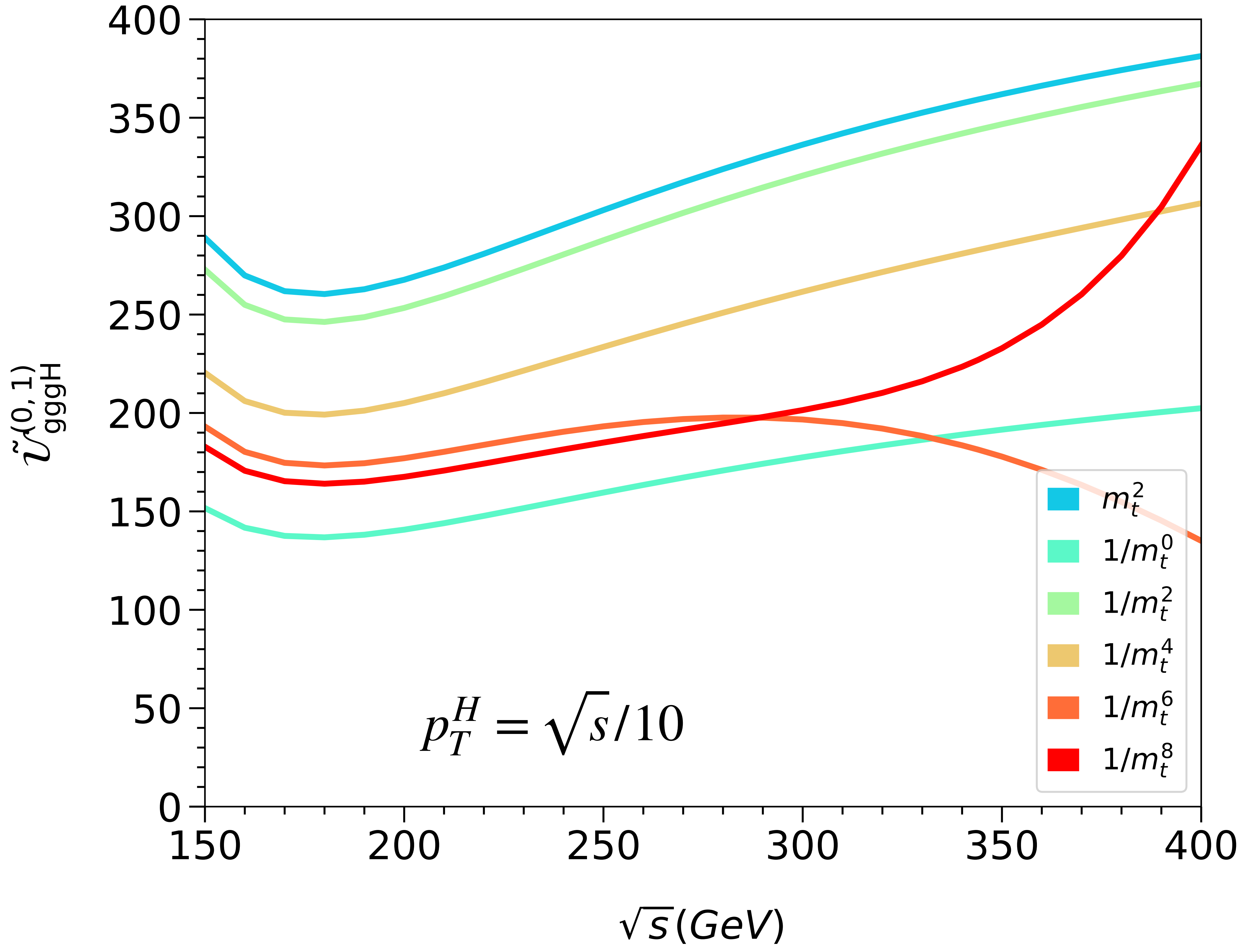
[Davies, Schönwald, Steinhauser, **Zhang**, ***JHEP 10 (2023) 033***]

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

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



$\tilde{\mathscr{U}}^{(0)}_{\text{gggH}}$ plot @ **LO**



$\tilde{\mathscr{U}}^{(0,1)}_{\text{gggH}}$ plot @ **NLO EW**

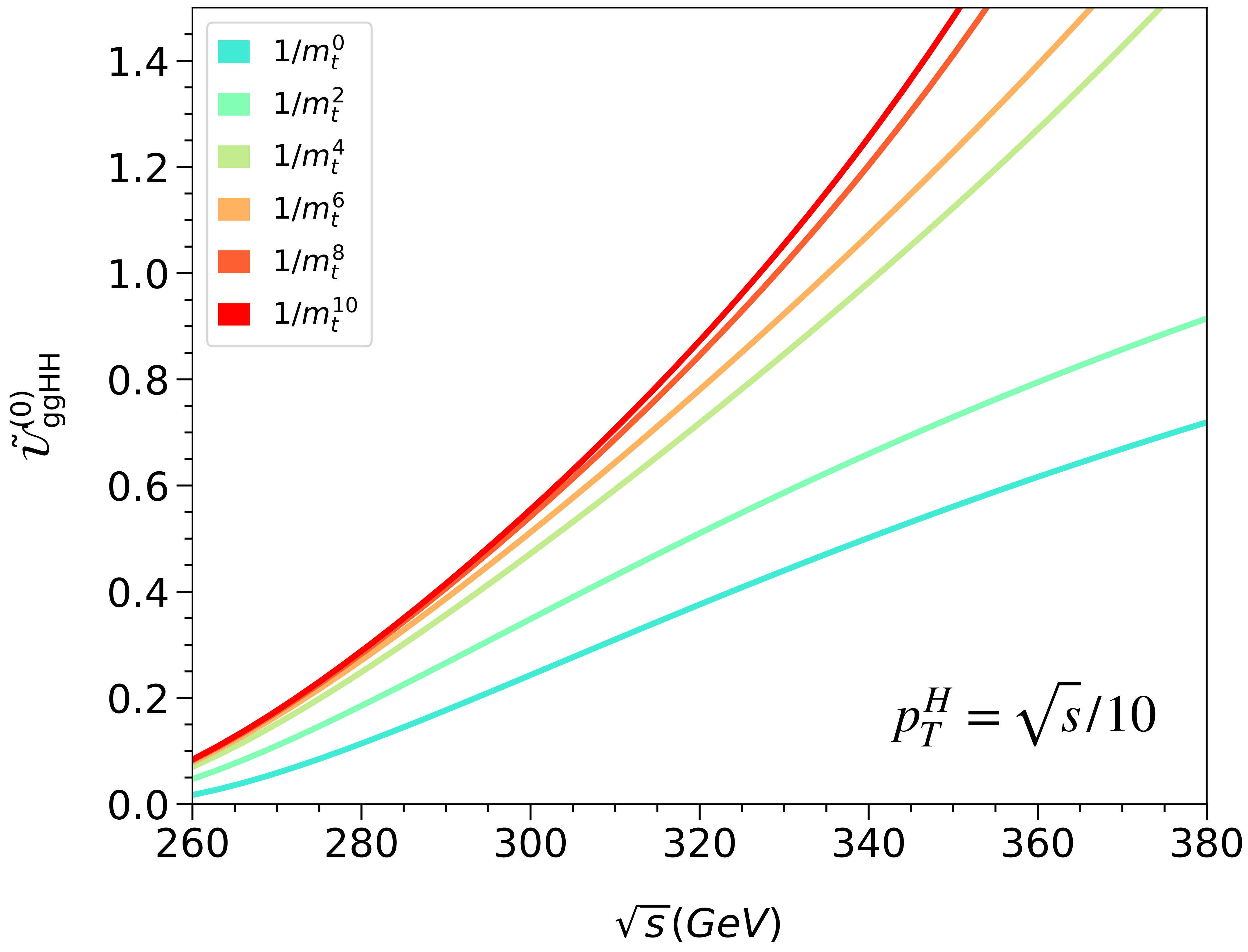
Good convergence observed, corrections are small $\lesssim \mathcal{O}(1\%)$

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

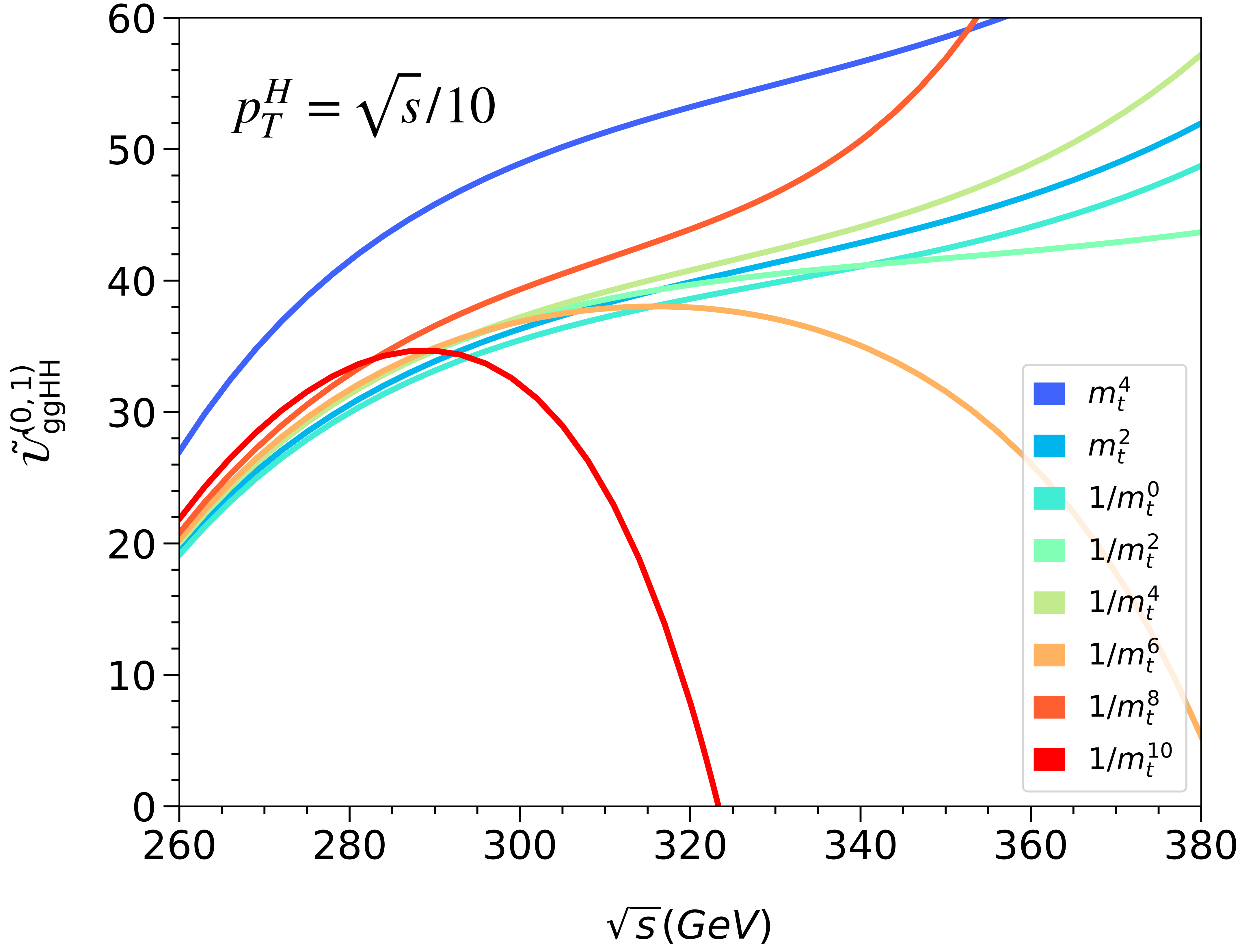
[Davies, Schönwald, Steinhauser, **Zhang**, ***JHEP 10 (2023) 033***]

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

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



$\tilde{\mathscr{U}}^{(0)}_{\text{ggHH}}$ @ **LO**



$\tilde{\mathscr{U}}^{(0,1)}_{\text{ggHH}}$ plot up @ **NLO EW**

Not very good convergence at NLO, but serve as boundaries to forward scattering expansion

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

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

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

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

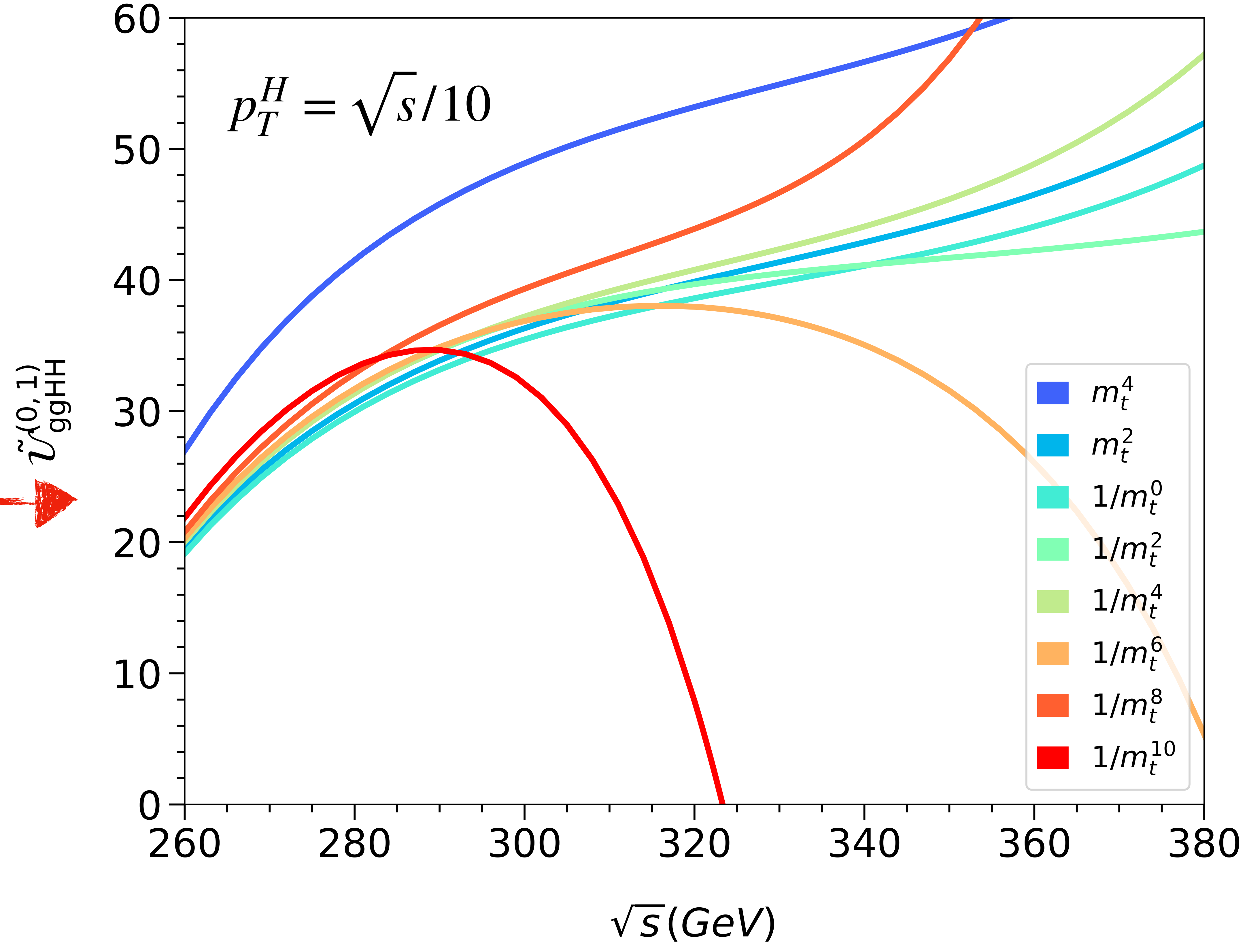
Famous di-Higgs destructive interference (vanishing ME at production threshold in HTL) is **lifted**

3-loop QCD corrections also **lifts** this destructive interference

[Grigo, Melnikov, Steinhauser, 14']

Large EW (Yukawa) corrections found near production threshold by several groups

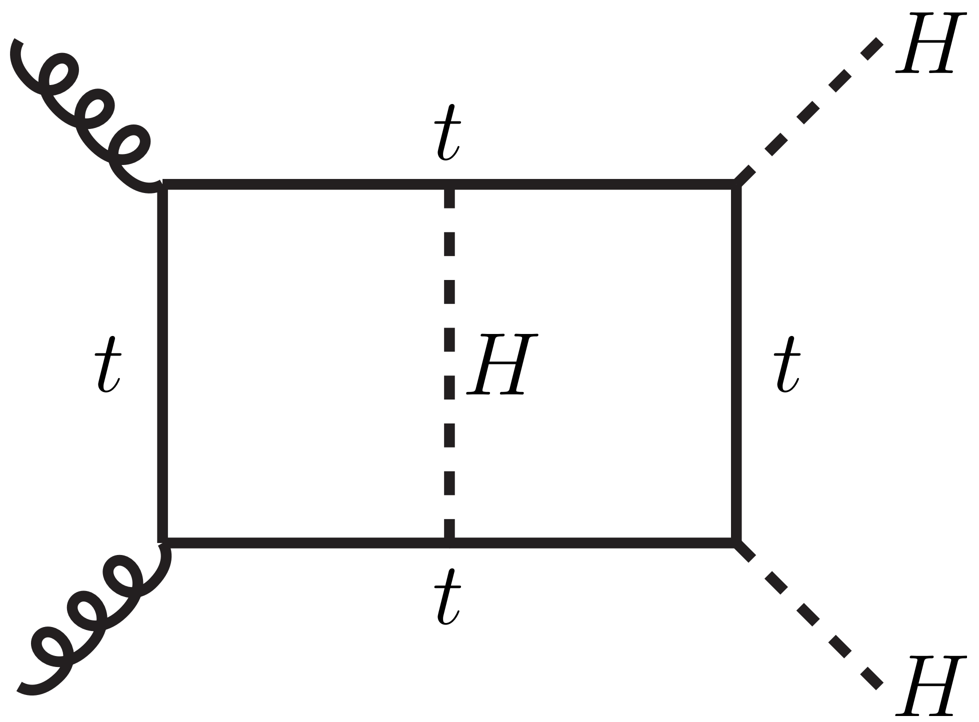
[Mühlleitner, Schlenk, Spira, 22']
[Bi, Huang, Huang, Ma, Yu, 24']
[Heinrich, Jones, Kerner, Stone, Vestner, 24]



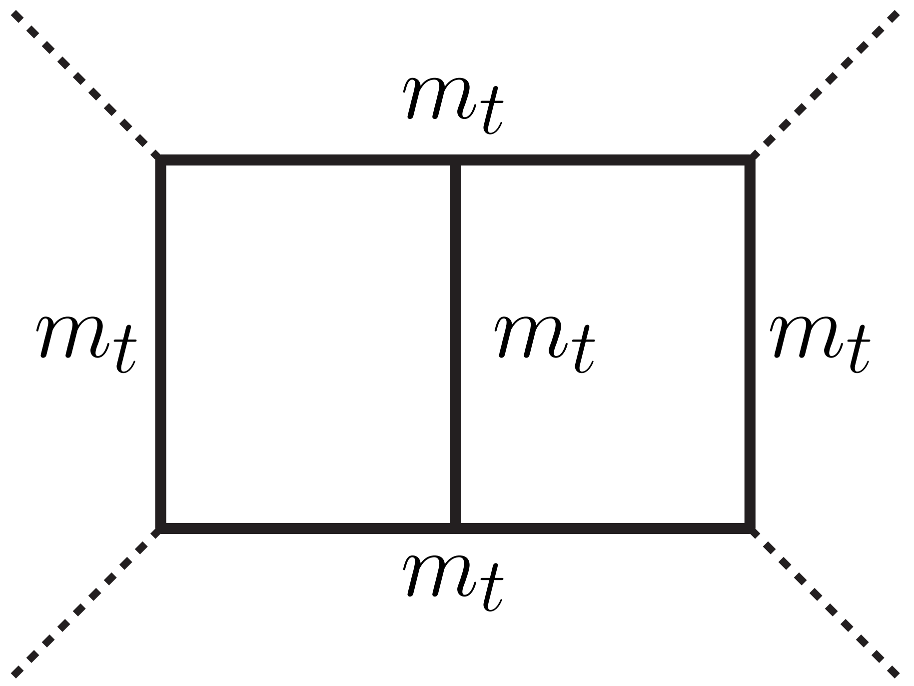
$\tilde{\mathscr{U}}^{(0,1)}_{\text{ggHH}}$ plot up @ **NLO EW**

Beyond large-m_t expansion @ NLO Yukawa $\mathcal{O}(\alpha_s y_t^4)$

- Sample two-loop diagrams and expansion strategy



scalar master integral



Taylor expansion in internal mass difference
and external Higgs mass

Use boundary conditions from large-m_t limit

$s, m_t^2 \gg$ t or u

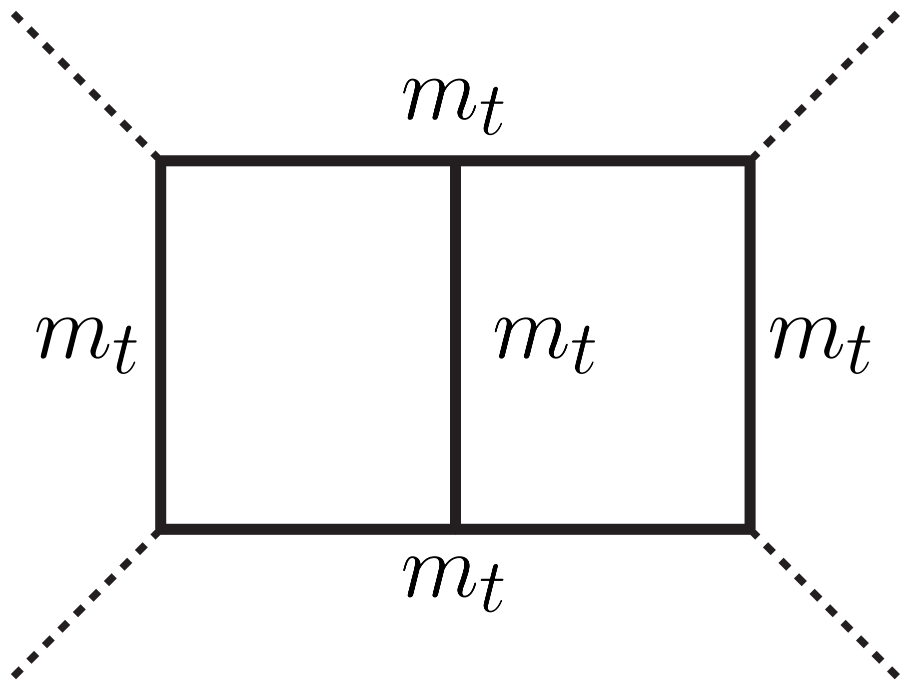
Forward scattering expansion

[See talk by M. Steinhauser]

$s, t, u \gg m_t^2$

High-energy expansion

High energy expansion @ NLO Yukawa



1. **Asymptotic expansion:** $s, t \gg m_t^2$

2. **System of differential equations for 140 Master Integrals** from IBP reduction [**Kira**]

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

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

$$\mathcal{I}_n = \sum C_{(n)}^{ijk}(s,t)\,\epsilon^i\,\left[m_t^2\right]^j\left[\log(m_t^2)\right]^k$$

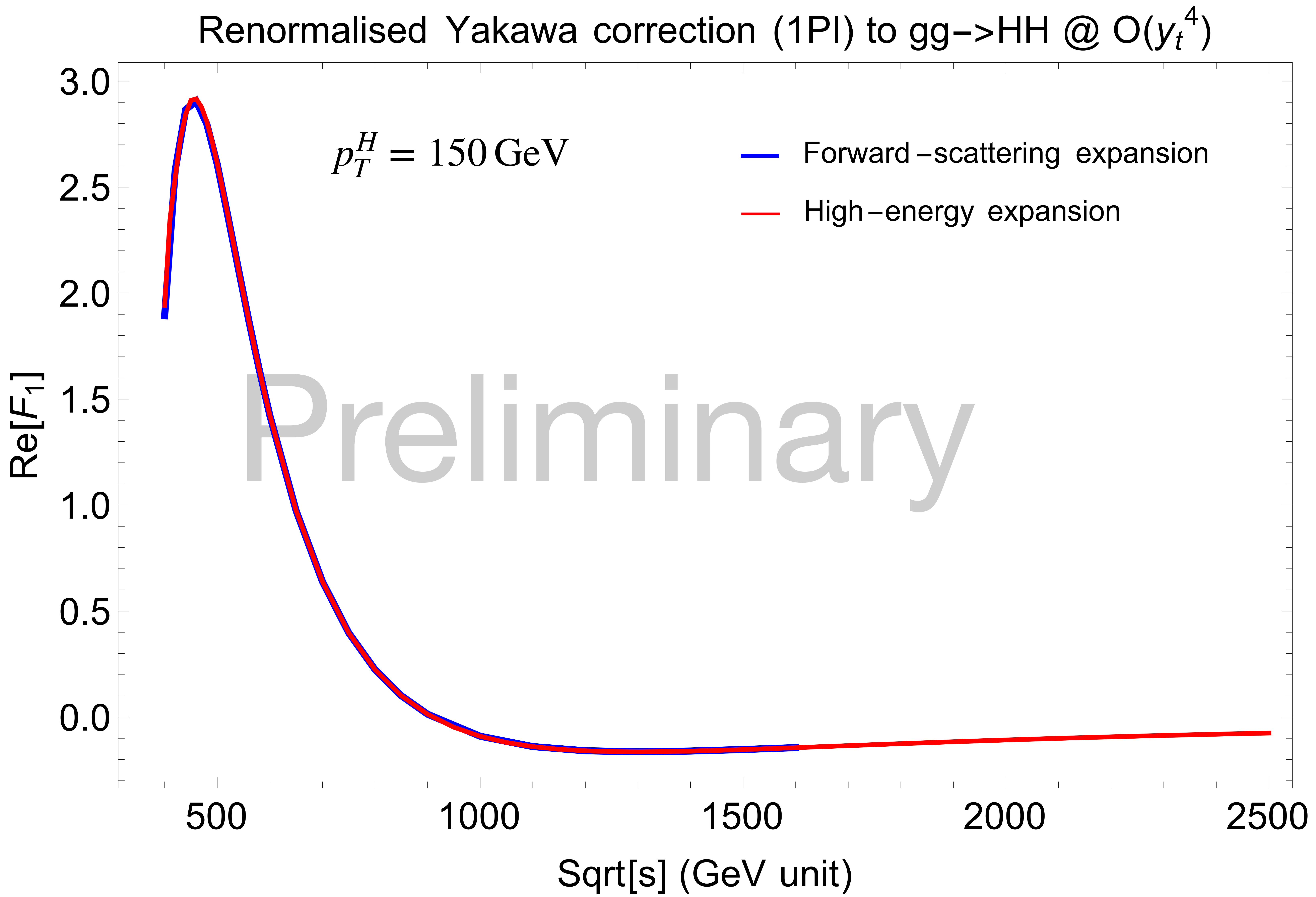
Released today in *[2407.12107]*

4. Solve **boundary master integrals in $m_t^2/s \to 0$ to higher orders** with Mellin-Barnes method by **AsyInt** [Zhang]

   with help of **asy.m** [Smirnov], **MB.m** [Czakon], **HarmonicSums.m** and **Sigma.m** [Ablinger, Schneider]

5. Apply **Padé approximations** to $\mathcal{O}(m_t^{120})$ expansion terms at the level of form factors as a **precision tool**

Combination of F.S. and H.E. expansions @ NLO Yukawa



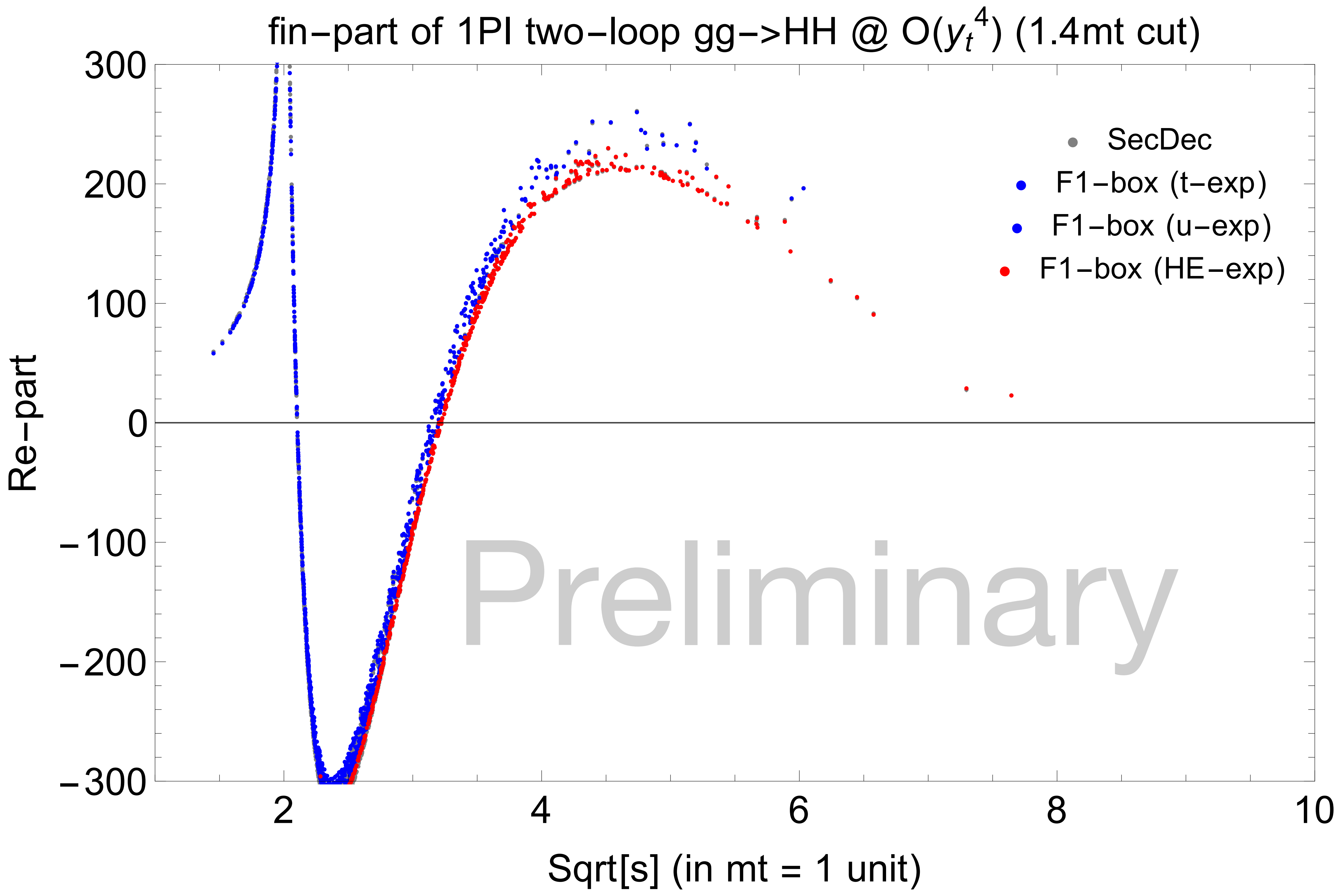
$$\mathscr{A}^{\mu\nu} = T_1^{\mu\nu}\mathscr{F}_1 + T_2^{\mu\nu}\mathscr{F}_2^{\mu\nu}$$

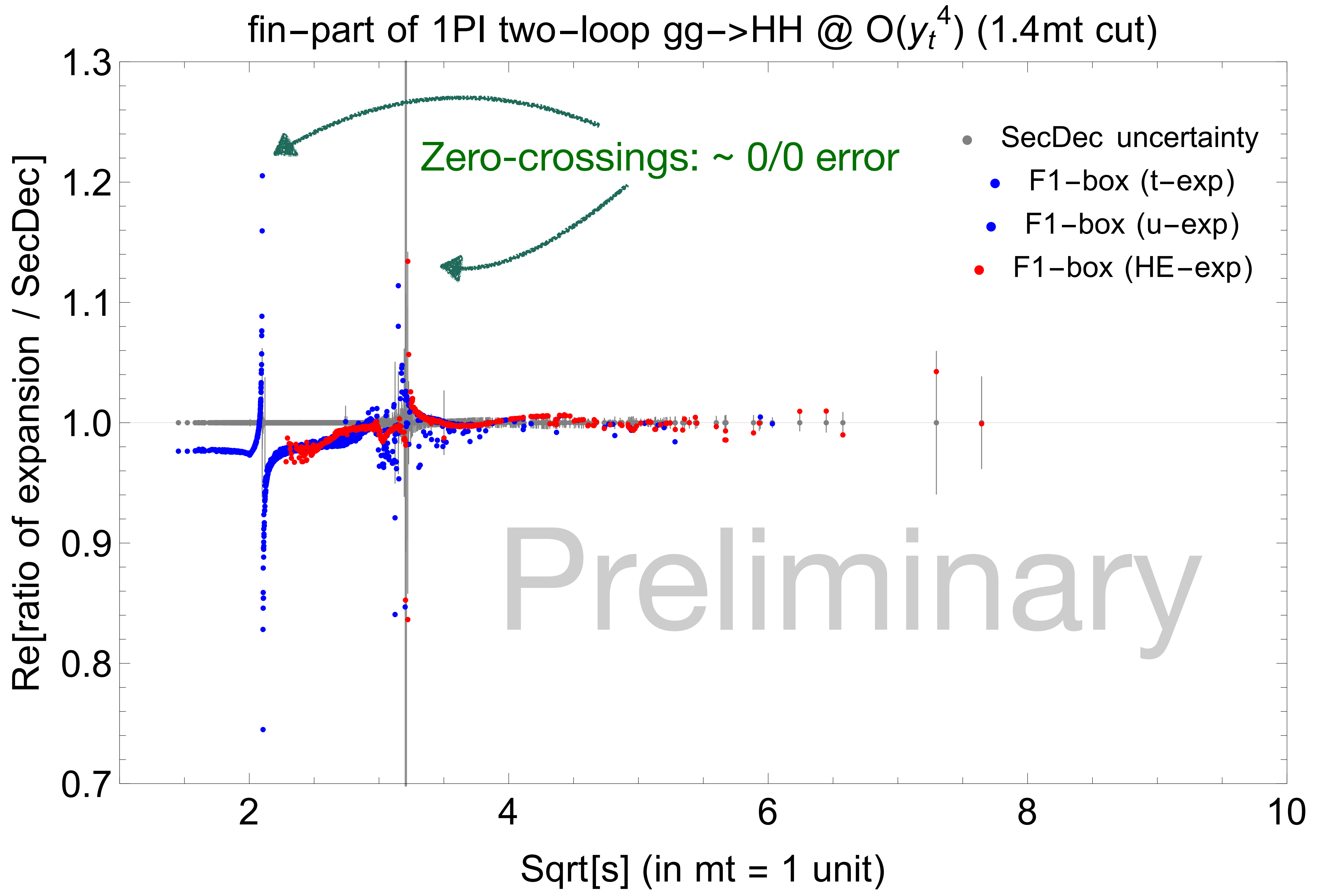
$$p_T^H = \sqrt{\frac{u\,t - m_H^4}{s}}$$

Highest available expansion terms are used

Comparison to SecDec numerical results @ NLO Yukawa

Finite part of bare two-loop form factor comparison to SecDec group
[Heinrich, Jones, Kerne, Stone, Vestner, 2407.04653]





High-energy expansion agree perfectly with SecDec results

Forward-scattering expansion agree within 2% level with SecDec near production threshold
(more expansion terms under computing)

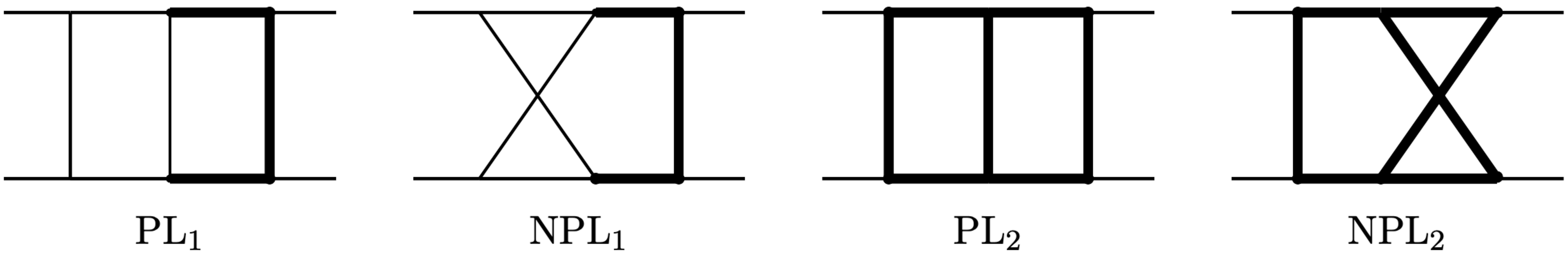
AsyInt

by Hantian Zhang — *hep-ph [2407.12107]*

For analytic calculations of massive two-loop four-point integrals at high energies

Download at: https://gitlab.com/asyint/asyint-public

Sample Feynman diagrams calculated by AsyInt



Sample planar and non-planar diagrams. Thick lines denote massive propagators

leading H.E. terms to ϵ-finite part
@ $\mathcal{O}(1/m)$ and $\mathcal{O}(m^0)$

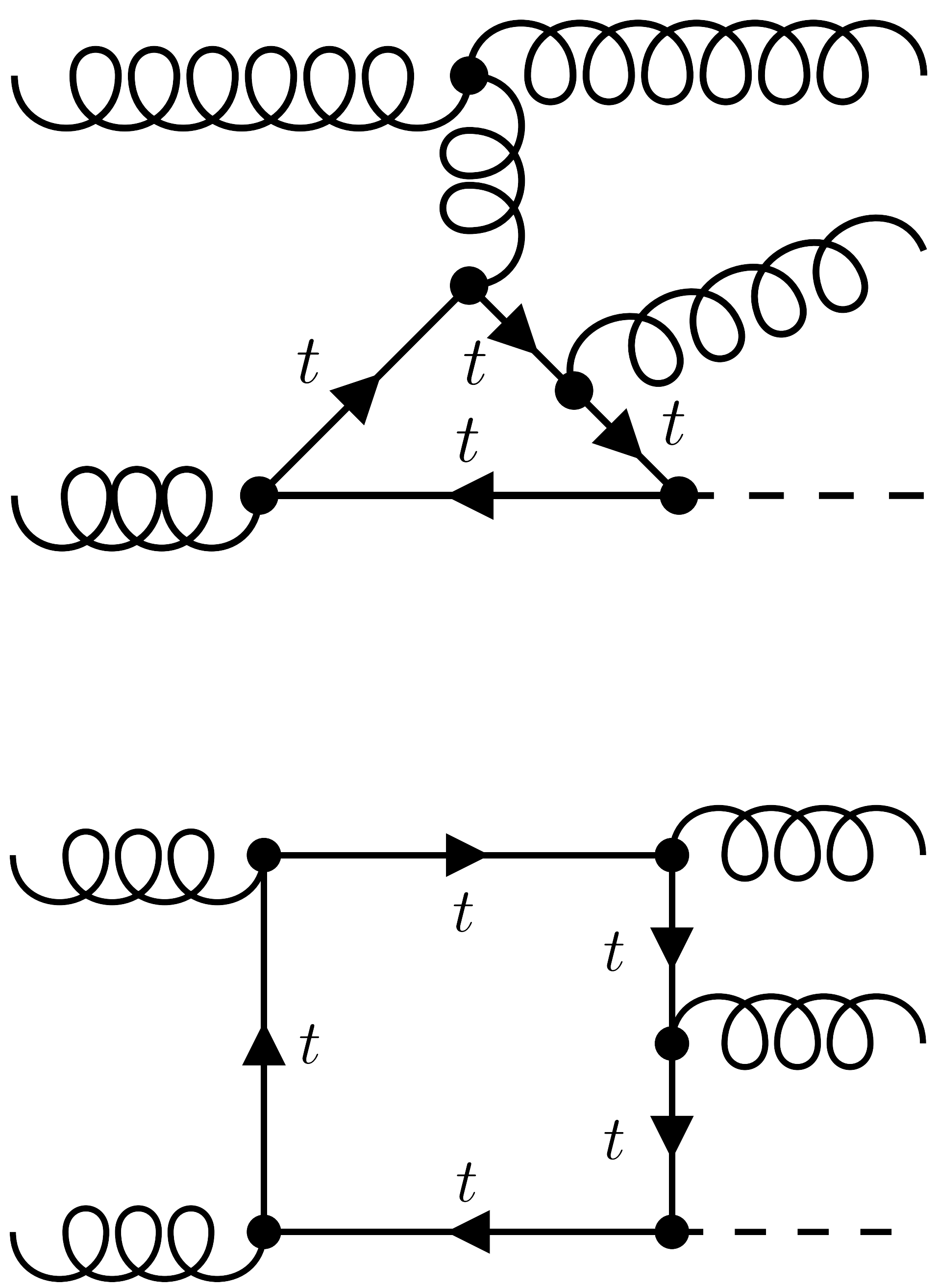
Conclusions

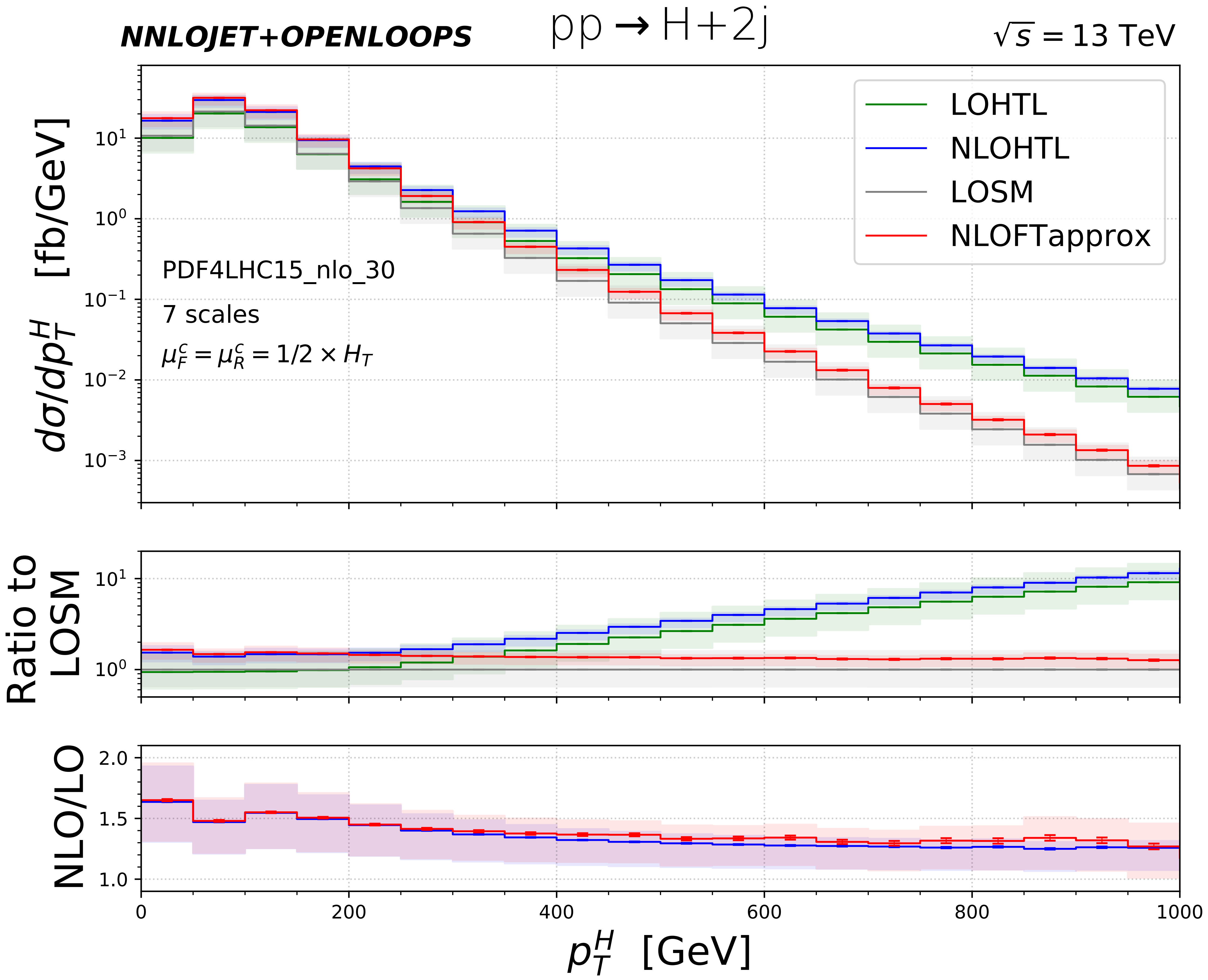
- We compute **NLO leading Yukawa corrections** to $gg \to HH$ in **forward-scattering expansion** and **high-energy expansion** *[JHEP 08 (2022) 259]*
  - Precise (semi)-analytic results for the whole phase space
  - Cross-checked with SecDec group's numerical results
- We compute **full top-induced NLO EW corrections** to $gg \to HH$ and $gg \to gH$ in large-m_t expansion *[JHEP 10 (2023) 033]*
- We also compute factorisable EW corrections to $gg \to HH$ analytically *[2407.05787]*
- **AsyInt** released in *[2407.12107]*
  - Toolbox for analytic calculations of massive two-loop four-point Feynman integrals at high energies

Backup Slides

Higgs+2 jets @ NLO QCD

- Dominant channel for Higgs boson production with large transversal momentum p_T^H at LHC





p_T^H spectrum: crucial for studying Higgs boson properties

NLOSM ⇒ NLO QCD with top-mass dependence

First NLO Higgs + 2 jets calculation with top-mass dependence

[Chen, Huss, Jones, Kerner, Lang, Lindert, **Zhang**, ***JHEP 03 (2022) 096***]

Forward scattering expansion @ NLO Yukawa

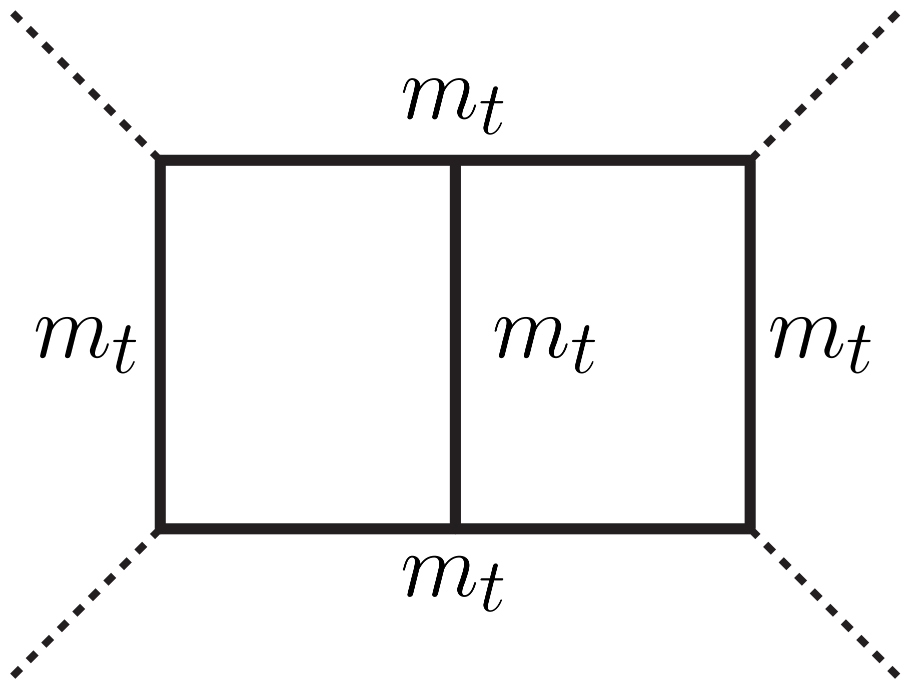
1. **Taylor expansion in $t \to 0$:** t-series expressed in terms of MIs $I(s, m_t^2)$

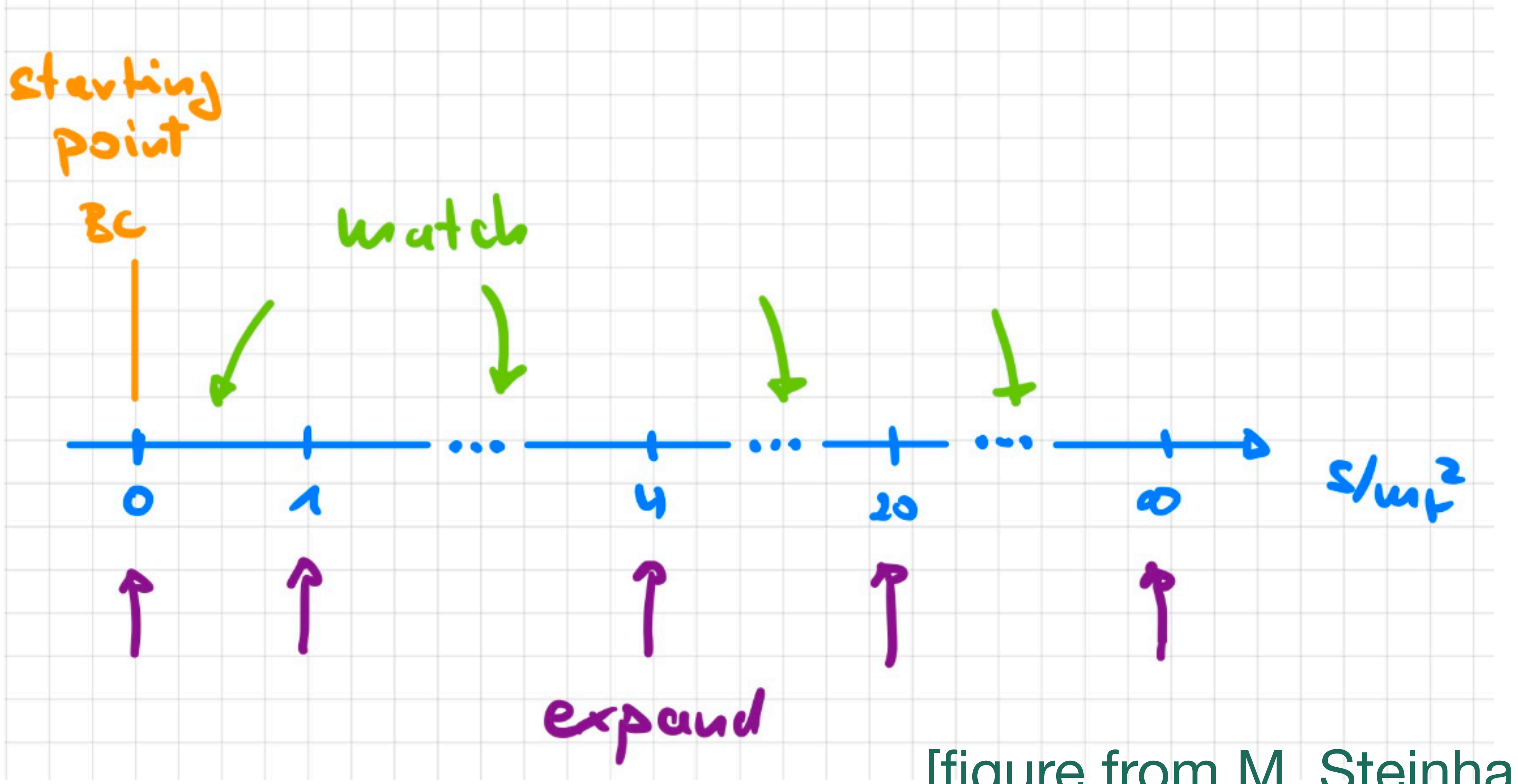
   [Davies, Mishima, Schönwald, Steinhauser, 23']

2. Compute boundary conditions at $s/m_t^2 \to 0$ limit

3. Use **"Expand and match" method** evolve $I(s, m_t^2)$ towards $s/m_t^2 \to \infty$

   through differential equations [Fael, Lange, Schönwald, Steinhauser,21',22']



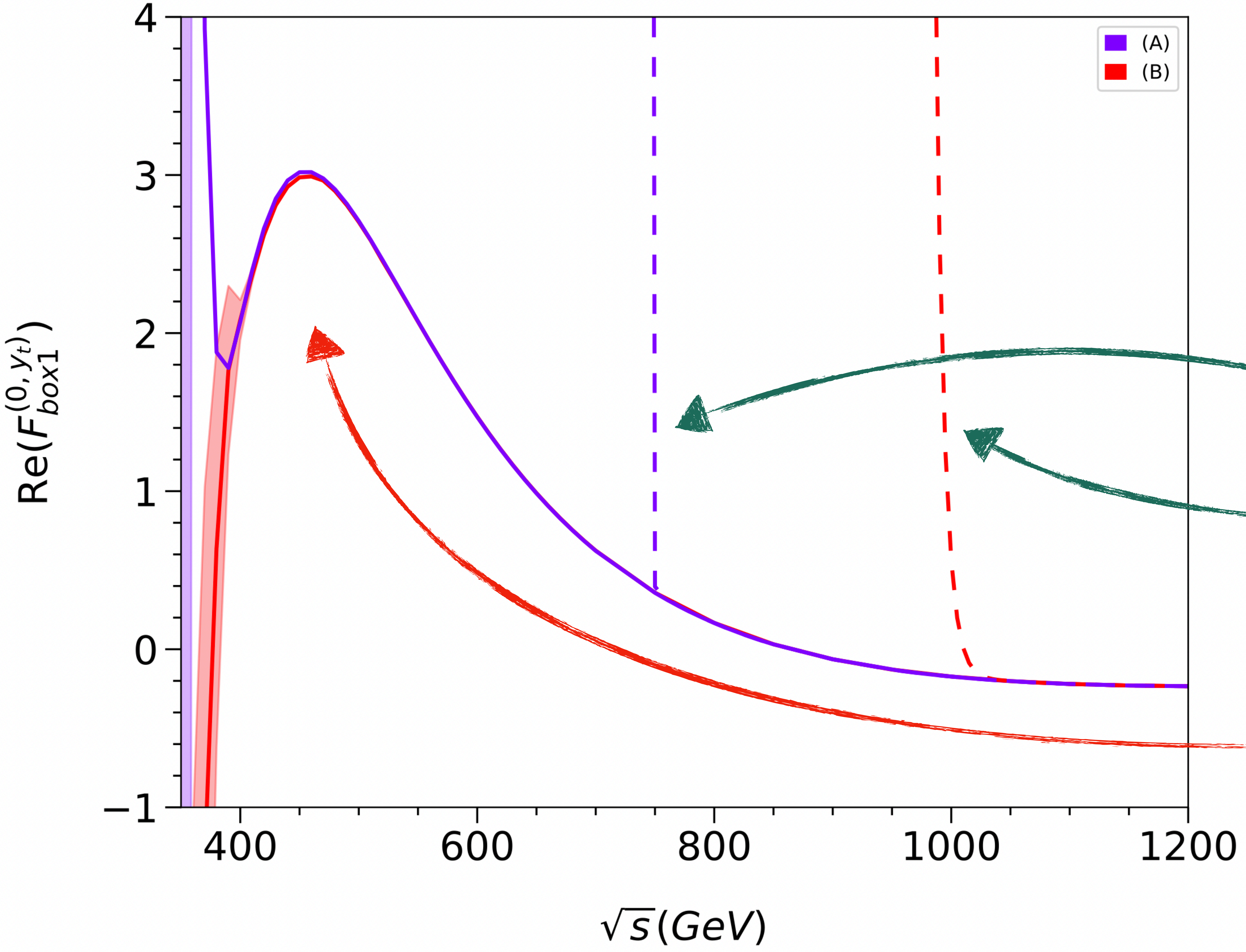


[figure from M. Steinhauser]

[See talk by M. Steinhauser for more details]

High energy expansion @ NLO Yukawa

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



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

Fixed scattering angle: $\theta = \dfrac{\pi}{2}$

Two internal-mass expansion approaches (A,B)
(see backups)

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

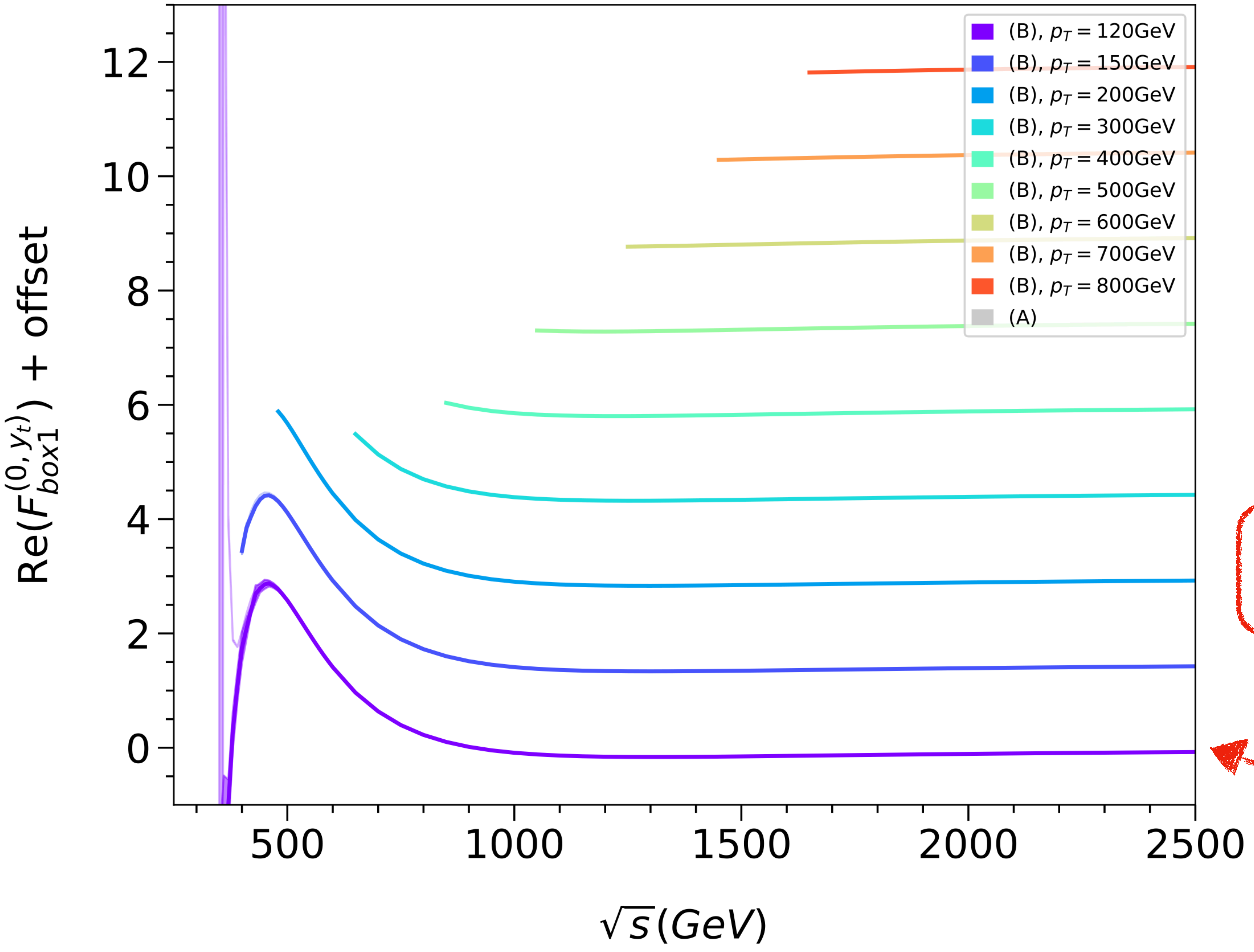
Padé improved high-energy expansions converge even at $\sqrt{s} \approx 500$ GeV

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 $\mathcal{O}(m_t^{116})$

High energy expansion @ NLO Yukawa

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



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

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

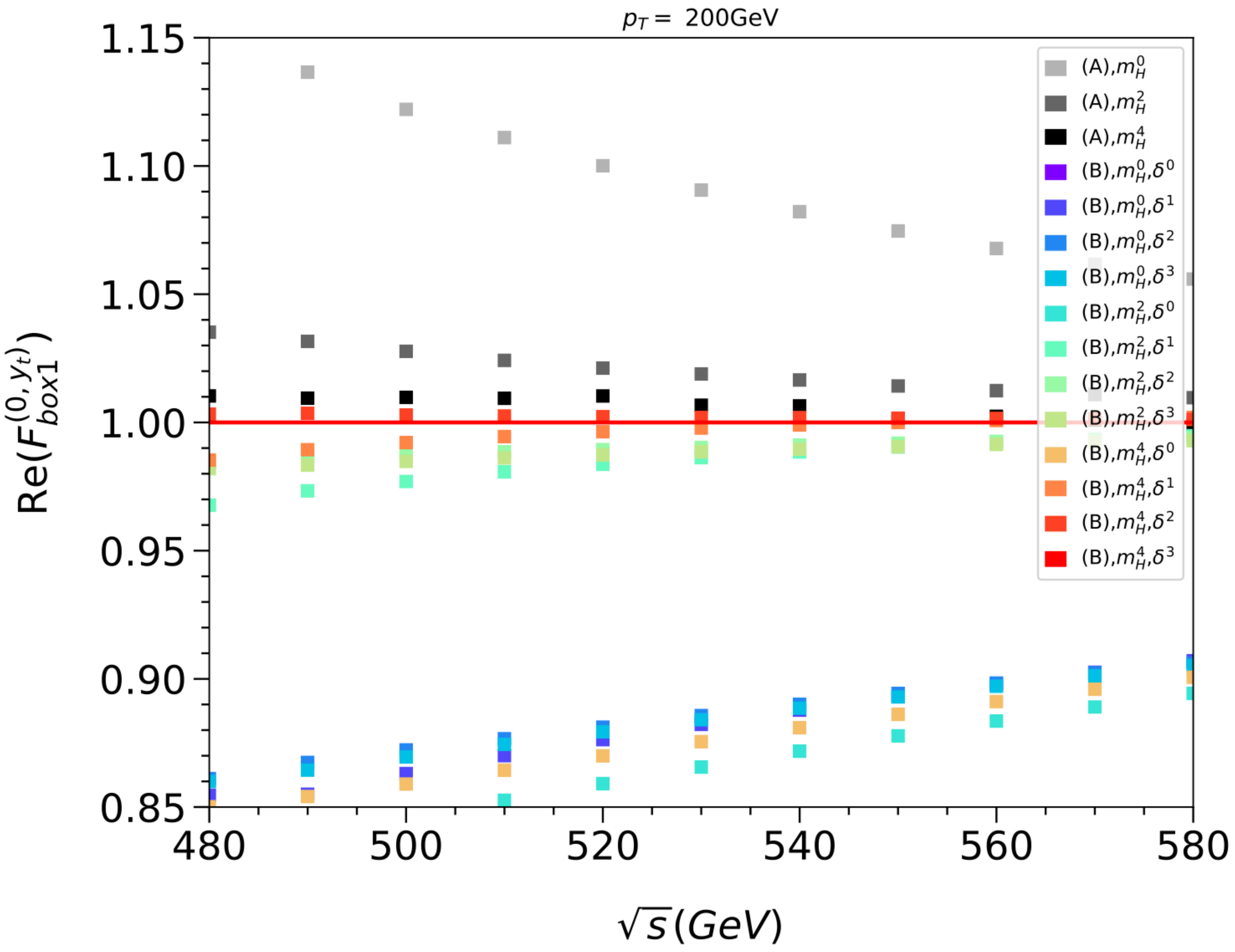
Padé improved high energy expansions converge even at $p_T^H = 120$ GeV

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

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

Convergence of H.E. expansions for $gg \to HH$ form factors

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



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

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

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

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