# Electroweak corrections for within and beyond the SM

**Hantian Zhang**

CERN

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MARIE CURIE ACTIONS

# Can we observe New Physics through EW corrections at EW scale?

**Yes, BSM particles enter loops by virtue of perturbative QFT**

**Search at a high-precision $e^+e^-$ collider: FCC-ee**

➡️ "Chasing the Two-Higgs-Doublet Model via Electroweak Corrections at $e^+e^-$ Colliders"
[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, Phys.Rev.Lett. 136 (2026) 081801]

# What kind of new physics?

**Is Higgs boson the unique scalar field of nature?** ➡️ **Search for additional scalars**

Actively searched model
Scalar sector is less constrained

Provide strong first-order phase transition
for baryogenesis and gravitational wave

Low-energy scalar sector of SUSY models

**2HDM**

**Two-Higgs Doublet Model**

Potential dark matter candidates

**Simple, yet phenomenologically rich**

Hints from flavour anomalies in $R_D$ and $R_{D^{(*)}}$

[Blanke, Iguro, **Zhang**, JHEP 06 (2022) 043]

Hints from electroweak-scale excesses at the LHC

First paper of our “Chasing the 2HDM” series:
[Iguro, Kitahara, Omura, **Zhang**, Phys.Rev.D 107 (2023) 075017]

# How to search?

**From a precision physicist perspective:**

**Bottom-Up: Assume $\Lambda_{\rm BSM} \gg \sqrt{s}$ ➡️ EFT @ NLO / high-dim operator ➡️ Matching to UV models**

**Top-Down: Select UV models ➡️ Precision phenomenology @ NLO / NNLO**

**are theoretically almost equivalent** (up to $\Lambda_{\rm BSM} \gg \sqrt{s}$ and renormalization scheme difference)

Experimentally, two approaches are different, but the gap may become small in the AI era

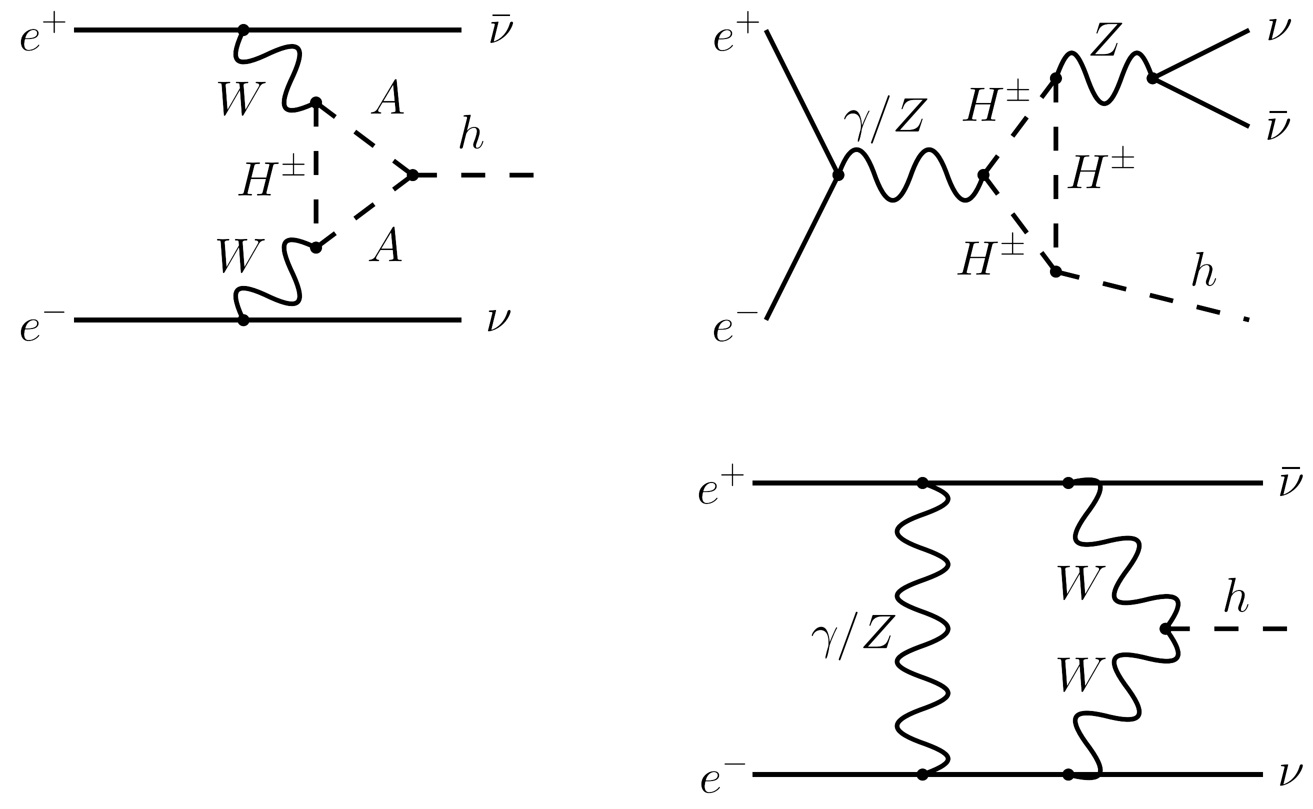
For Bottom-Up, $\kappa$-framework is not sufficient for high-precision measurements

➡️ **SMEFT / HEFT / Higgs Pseudo-Observables**

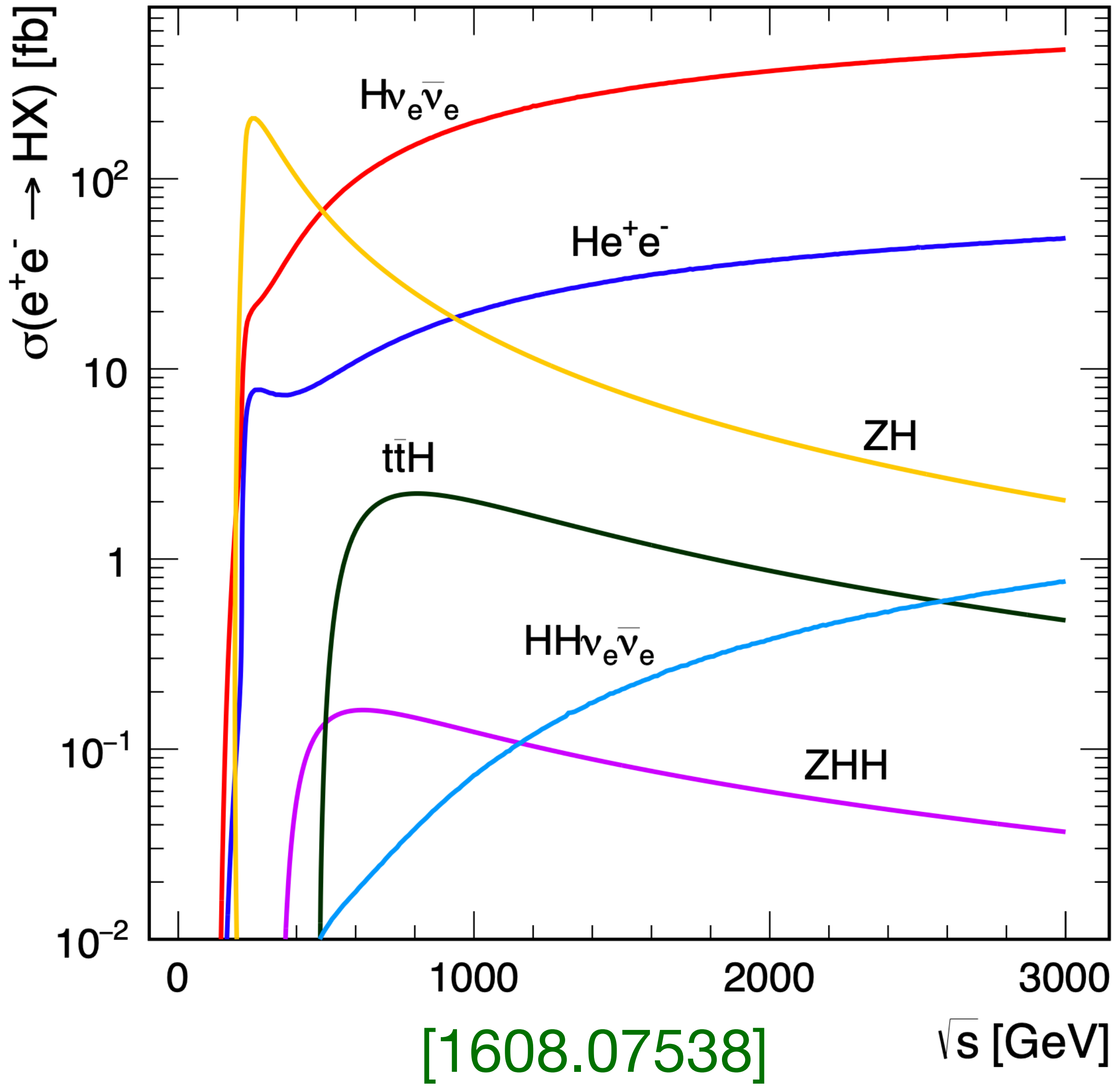
HiggsPO: [Grejlo, Isidori, Lindert, Marzocca, **Zhang**, Eur.Phys.J.C 77 (2017) 12, 838 & Section 3.1 of LHC Higgs Working Group YR4]

# Where to search?

## “Dynamical” single Higgs production $e^+e^- \to h\,\nu\bar{\nu}$




- NLO EW corrections are significant and can **enhance new physics signals**
- Key production channel at higher energies, e.g., $\sqrt{s} \geq 365$ GeV
- **Good perturbative convergence**, away from production threshold
  - NNLO and beyond-NLO ISR corrections are small
  - Ideal for probing New Physics which requires only NLO EW in BSM
- Contain $Zh$ and $WW$-fusion channels ➡️ study Higgs dynamics




[1608.07538]

# Computational framework for $e^+e^- \to h\nu\bar{\nu}$

Widely-used one-loop amplitude provider in NNLO community

**OpenLoops2**

Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, **Zhang**, Zoller
Eur.Phys.J.C 79 (2019) 866

**OpenLoops algorithm + On-the-fly reduction + analytic expansion**

General-purpose Monte Carlo generator

**Whizard**

Kilian, Ohl, Reuter
Eur.Phys.J.C 71 (2011) 1742

One-loop amplitude provider with BSM models

**Recola2**

Denner, Lang, Uccirati
Comput.Phys.Commun. 224 (2018)

For this study $e^+e^- \to h\,\nu\bar{\nu}$:
FKS subtraction
Massive electron beam set up
ISR effect is included in NLO real corrections
ISR beyond NLO is $\sim 0.2\,\%$ for $\sqrt{s} \geq 365$ GeV

Cross checks to [Denner, Dittmaier, Roth, Weber, 03'] for $e^+e^- \to h\,\nu\bar{\nu}$ in SM
to HAWK [Denner, Dittmaier, Kallwait, Mück, 14'] for $pp \to h\,\mu^+\nu_\mu$ in 2HDM

# Total cross sections (benchmark point)

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, Phys.Rev.Lett. 136 (2026) 081801]

## Type I 2HDM

Benchmark point: $m_H = m_{H^\pm} = 400$ GeV, $m_A = 435$ GeV, $c_{\beta\alpha} = 0.037$, $t_\beta = 1.88$, $\lambda_5 = -2.54$

| | $\sqrt{s} = 365\,\mathrm{GeV}$ | | $\sqrt{s} = 550\,\mathrm{GeV}$ | |
|---|---|---|---|---|
| | LO [fb] | NLO EW [fb] | LO [fb] | NLO EW [fb] |
| SM | 55.79 | 52.44(1) | 97.82(1) | 88.45(2) |
| 2HDM | 55.71 | 51.45(1) | 97.67(1) | 86.59(2) |
| Rel.Diff. | −0.1% | −1.9% | −0.2% | −2.1% |
| 2HDM (aligned) | 55.79 | 51.58(1) | 97.81(1) | 86.83(2) |
| Rel.Diff. | 0.0% | −1.7% | 0.0% | −1.8% |

Renormalization scheme:
$G_\mu$ for SM, on-shell for 2HDM
mixing angles, $\overline{\mathrm{MS}}$ for $\lambda_5$

Estimated missing higher-order effect $\sim 0.3\,\%$ from NNLO mixed QCD-EW corrections in $G_\mu$ scheme
[Wang, Yang, Zhou, 21; Sun, Feng Jia, Sang, 17']
and ISR effect beyond NLO
[Denner, Dittmaier, Roth, Weber, 03']

Total cross sections for $e^+e^- \to h\,\nu\bar{\nu}$ in SM and 2DHM benchmark without cuts.
Alignment limit is $\cos(\beta - \alpha) = 0$

**Sizable NLO effects even in alignment limit**

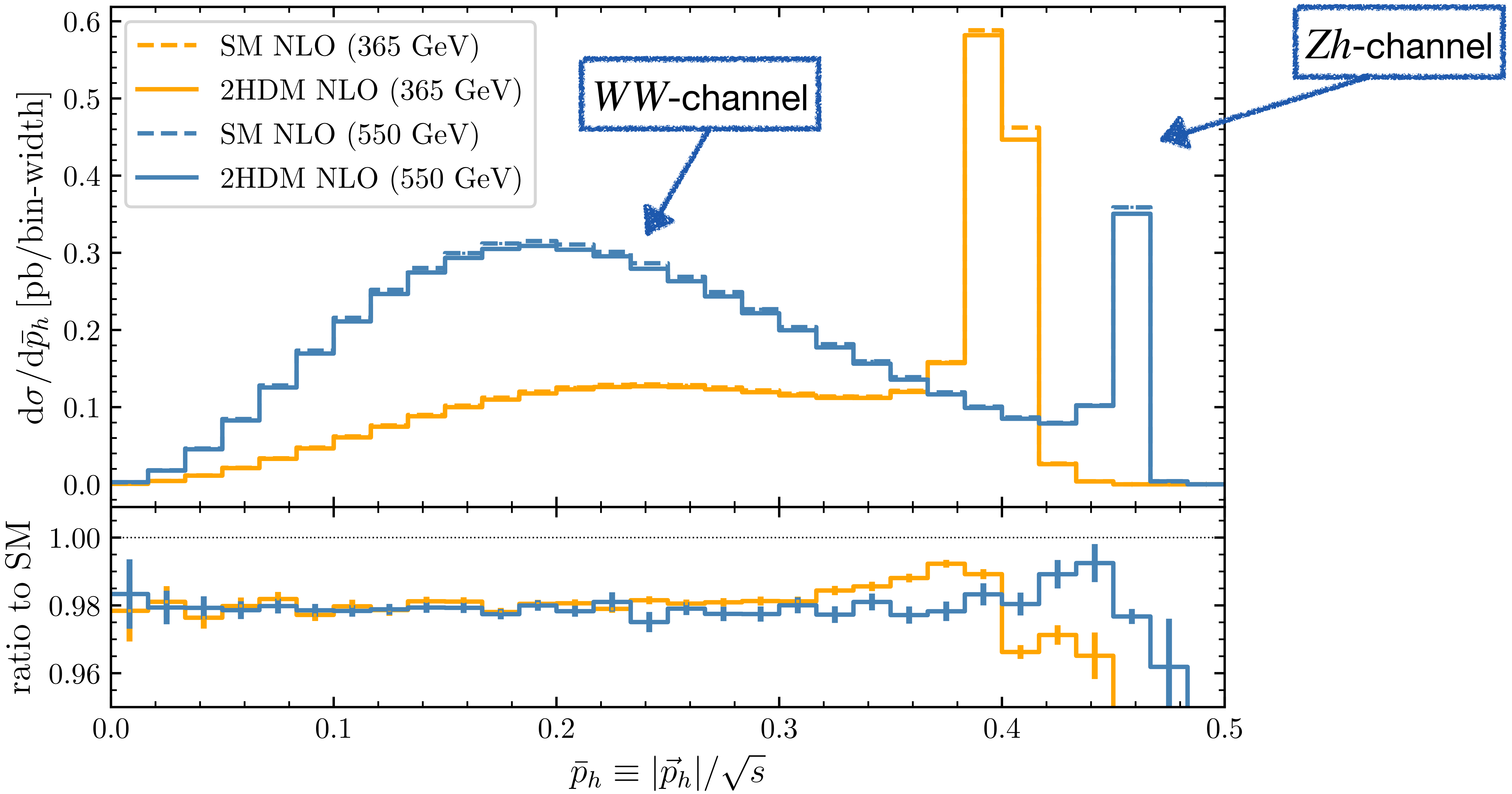
Experimental uncertainties are estimated to
$\sim 0.6\,\%$ for $\sqrt{s} = 365$ GeV
$\sim 0.3\,\%$ for $\sqrt{s} = 550$ GeV
[Linear Collider Vision, 2503.19983]

# Differential cross sections (benchmark point)

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, Phys.Rev.Lett. 136 (2026) 081801]

## Type I 2HDM

Benchmark point: $m_H = m_{H^\pm} = 400$ GeV, $m_A = 435$ GeV, $c_{\beta\alpha} = 0.037$, $t_\beta = 1.88$, $\lambda_5 = -2.54$




Differential cross sections at NLO as a function of normalised Higgs three-momentum

**Disentangle $Zh$ and $WW$ channels, allow simultaneous probes for $hZZ$ and $hWW$ vertices**

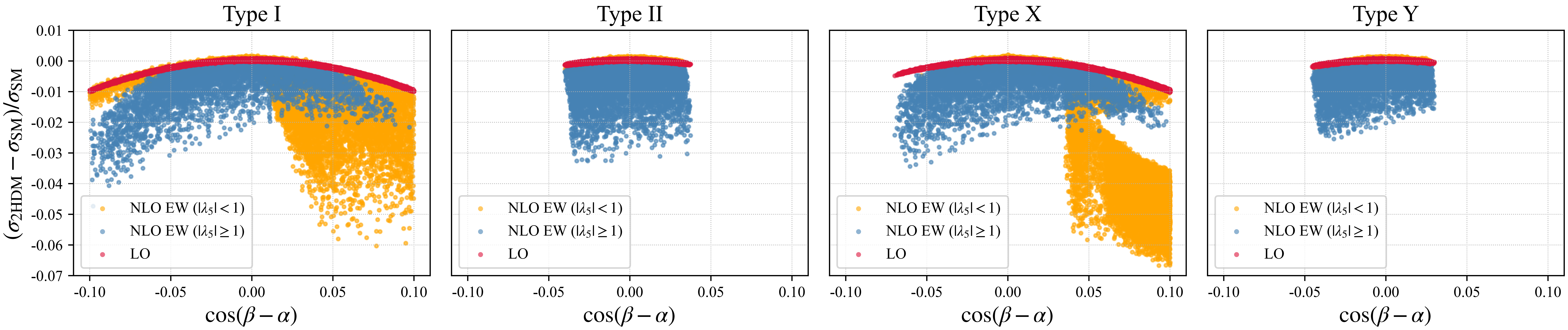
# Comprehensive sensitivity analysis at $\sqrt{s} = 365$ GeV

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, Phys.Rev.Lett. 136 (2026) 081801]

**160 000 allowed parameter points** from **ScannerS** and **HiggsTools** (assuming $m_\phi \equiv m_H = m_{H^\pm} = m_A$) for type I, II, X, Y 2HDMs

Maximal theory uncertainty in $(\sigma_{\mathrm{2HDM}} - \sigma_{\mathrm{SM}})$ is estimated to $0.7\,\%$

Reference scheme: $G_\mu$ for SM, on-shell for 2HDM mixing angles, $\overline{\mathrm{MS}}$ for $\lambda_5$




Relative differences between 2HDM and SM predictions in $c_{\beta\alpha}$-plane at $\sqrt{s} = 365$ GeV at LO (red) and NLO (orange for $|\lambda_5| < 1$, blue for $|\lambda_5| > 1$)

A combined (th+exp) maximal uncertainty is estimated to be $0.92\,\%$

Precise model-type discrimination requires NNLO EW in 2HDM and permille level experimental measurement

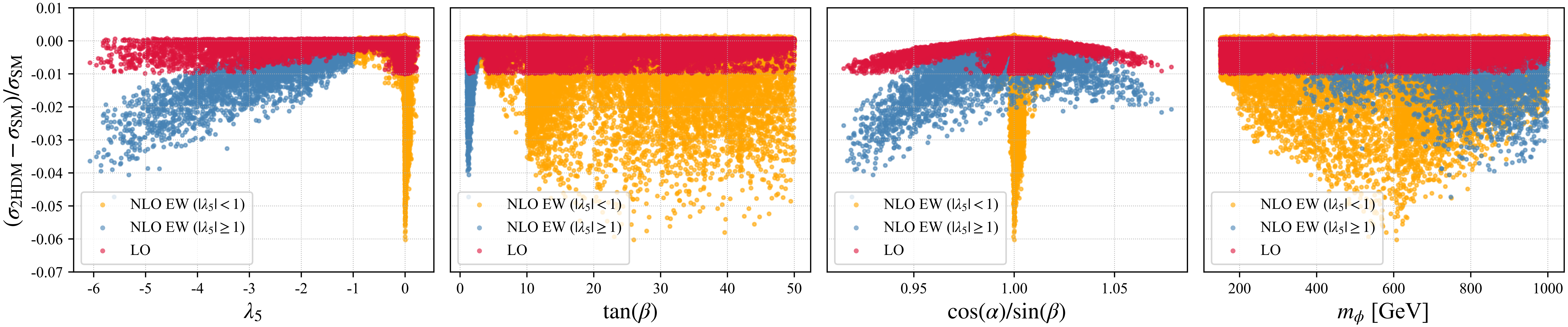
# Type I 2HDM sensitivity analysis at $\sqrt{s} = 365$ GeV

[Bredt, Banno, Höfer, Iguro, Kilian, Ma, Reuter, **Zhang**, Phys.Rev.Lett. 136 (2026) 081801]

**Type I 2HDM analysis with 30 000 allowed parameter points** (assuming $m_\phi \equiv m_H = m_{H^\pm} = m_A$)

Maximal theory uncertainty in $(\sigma_{\rm 2HDM} - \sigma_{\rm SM})$ is estimated to $0.7\,\%$

Reference scheme: $G_\mu$ for SM, on-shell for 2HDM mixing angles, $\overline{\rm MS}$ for $\lambda_5$




Type I 2HDM predictions at $\sqrt{s} = 365$ GeV at LO (red) and NLO (orange for $|\lambda_5| < 1$, blue for $|\lambda_5| > 1$) for $|c_{\beta\alpha}| < 0.1$

A combined (th+exp) maximal uncertainty is estimated to be $0.92\,\%$

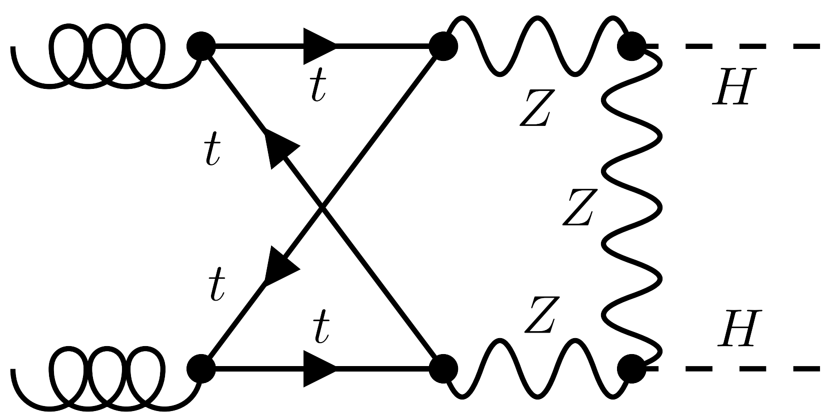
# Can we compute two-loop EW corrections analytically?

## Yes, e.g. Higgs pair production

### Large-mass expansion

Davies, Schönwald, Steinhauser, Zhang

JHEP 10 (2023) 033




### High-energy expansion

Davies, Schönwald, Steinhauser, Zhang

JHEP 08 (2022) 259

JHEP 04 (2025) 193

2603.08789

&

Zhang, JHEP 09 (2024) 069

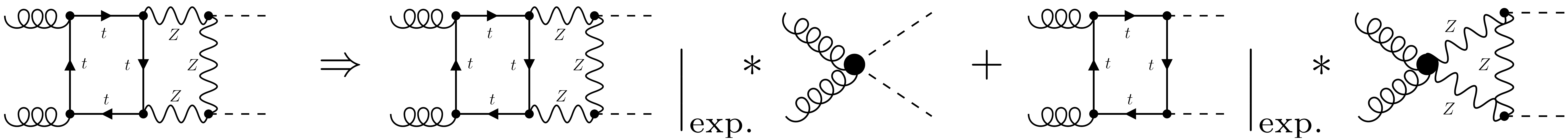
**Applicable to low-energy experiments and BSM physics @ FCC-ee**

**For SM @ LHC**

# Large-$m_t$ expansion and EW renormalisation

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

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

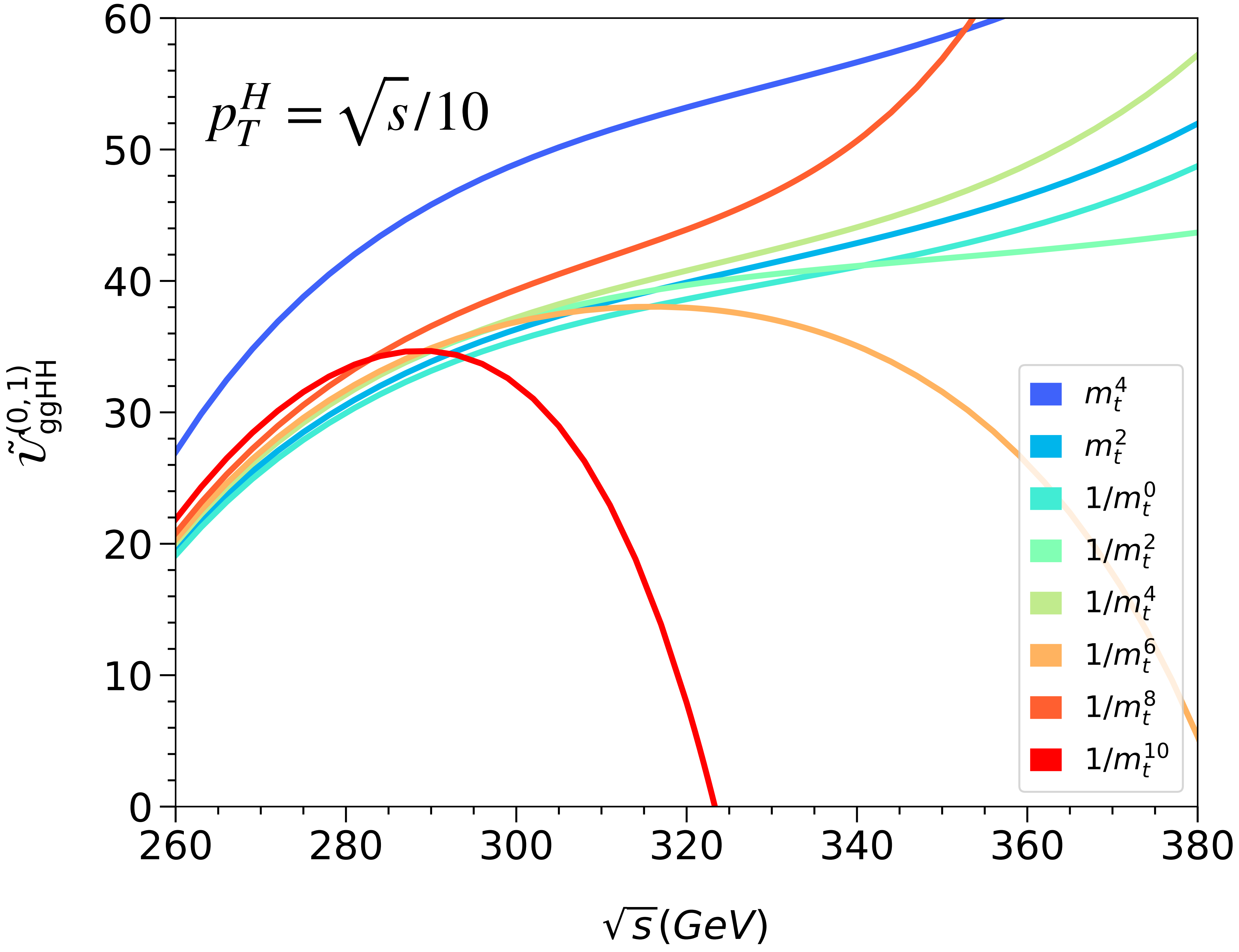



- **On-Shell renormalise** input parameters $\{e, m_W, m_Z, m_t, m_H\}$ in $G_\mu$ scheme
- $\xi_W, \xi_Z$ **cancel** after external Higgs **fields OS renormalisation**

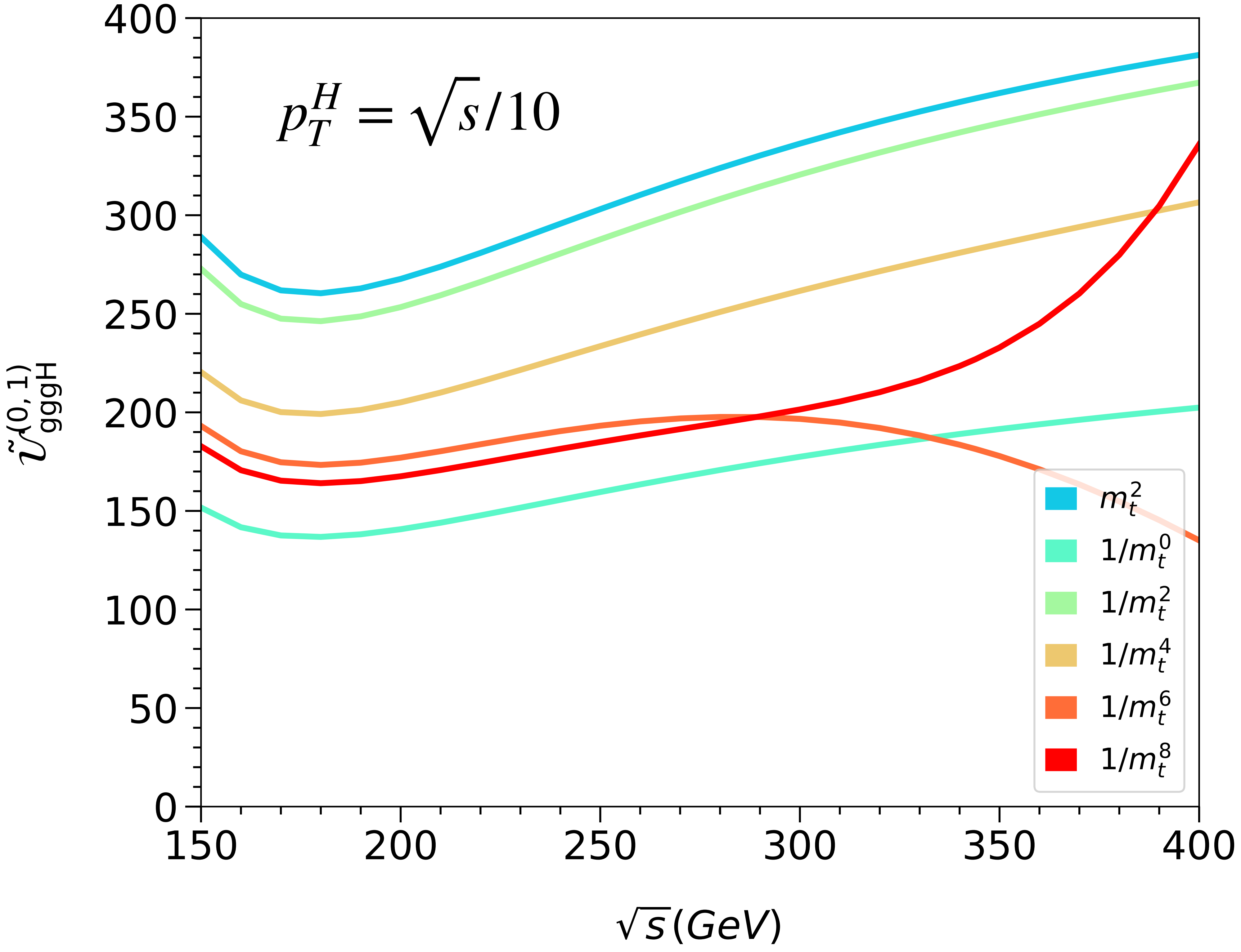
# Large-$m_t$ expansion to $gg \to HH$ and $gg \to Hg$

$$\mathcal{M} = X_0 \sum_{\text{col}} \sum_{\text{pol}} |\mathcal{A}|^2 \propto \tilde{\mathcal{U}}^{(0)}_{\text{HH/H+j}} + \frac{\alpha}{\pi} \tilde{\mathcal{U}}^{(0,1)}_{\text{HH/H+j}}$$

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




$\tilde{\mathcal{U}}^{(0,1)}_{\text{HH}}$ plot up @ NLO EW

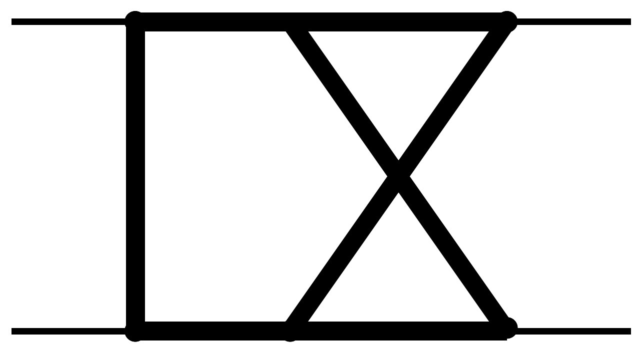



$\tilde{\mathcal{U}}^{(0,1)}_{\text{H+j}}$ plot @ NLO EW

Large-$m_t$ expansion works perfectly for NNLO mixed QCD-EW corrections for $e^+e^- \to ZH$ for $\sqrt{s} < 300GeV$

[Gong, Li, Xu, Yang, Zhao, Phys.Rev.D 95 (2017) 9, 093003]
[Wang, Xu, Yang, Phys.Rev.D 100 (2019) 7, 071502]

# Roadmap for analytic EW at high energies



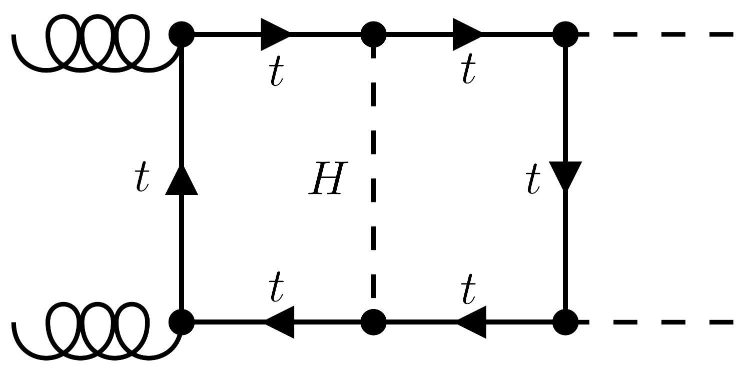
**AsyInt** toolbox for
master integrals (MIs) in high-energy limit

[**Zhang**, JHEP 09 (2024) 069 ]

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

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

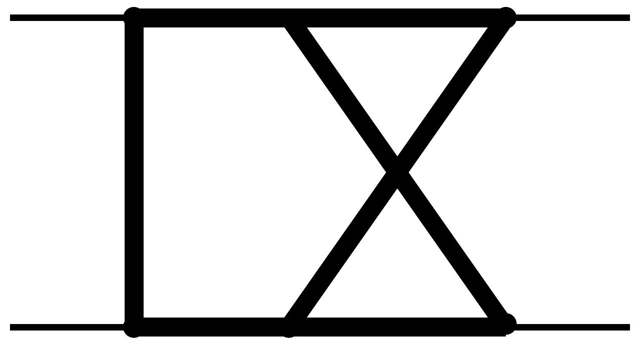
First attempt on leading
Yukawa corrections




**Recent (semi)-analytic EW calculations**

- Two-loop logarithmic (Sudakov) EW corrections in **OpenLoops** for V+jets [Lindert, Mai, 2604.14320]
- Mixed QCD-EW corrections to Drell-Yan, e.g. [Bonciani et al. 2106.11953, Buccioni et al., 2203.11237]

# Roadmap for analytic EW at high energies



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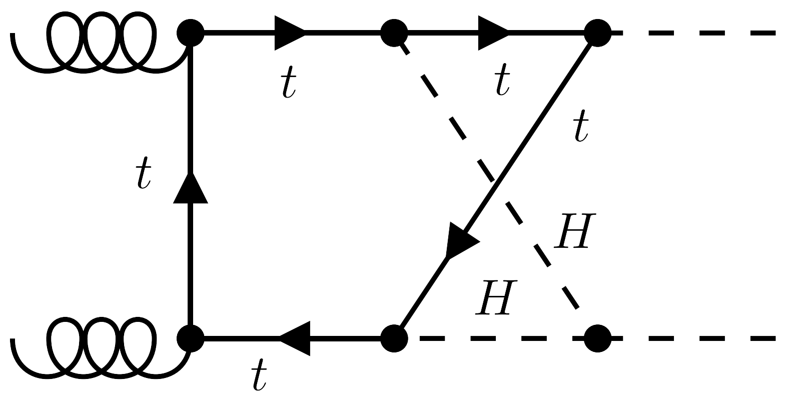


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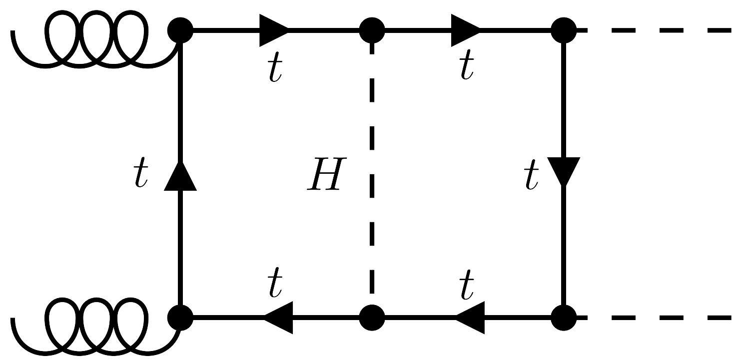
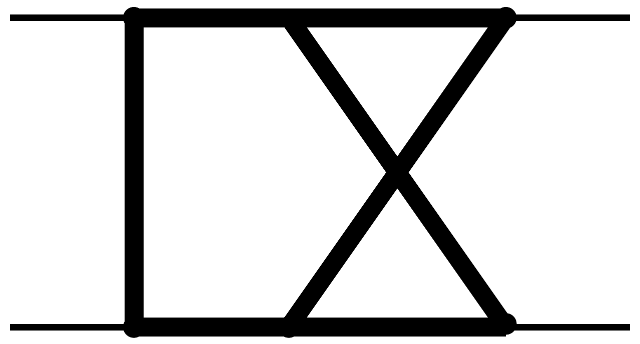



Full set of MIs in deep high-energy expansion
&
Yukawa and Higgs self-coupling corrections

[Davies, Schönwald, Steinhauser, **Zhang**,
JHEP 04 (2025) 193]

# Roadmap for analytic EW at high energies



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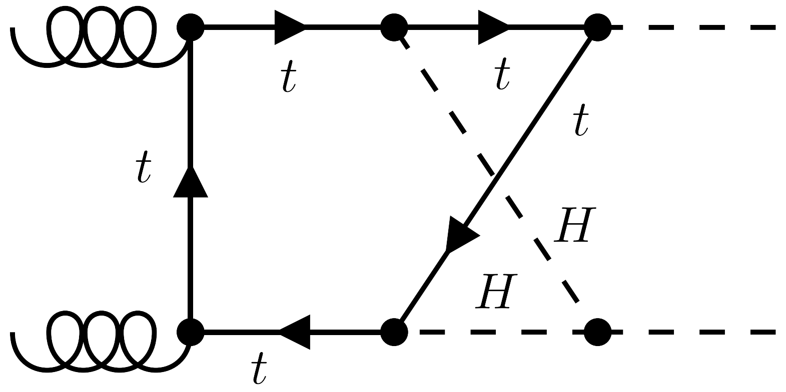


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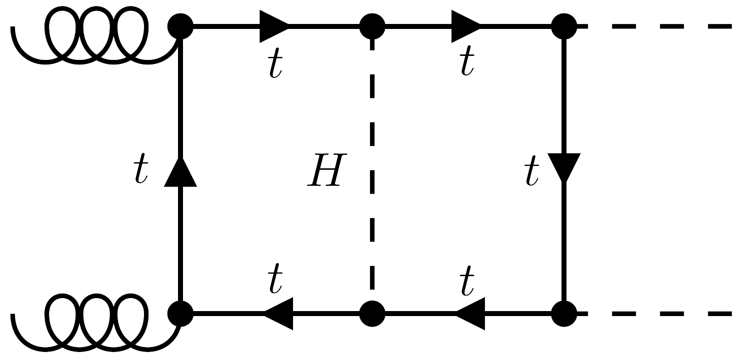
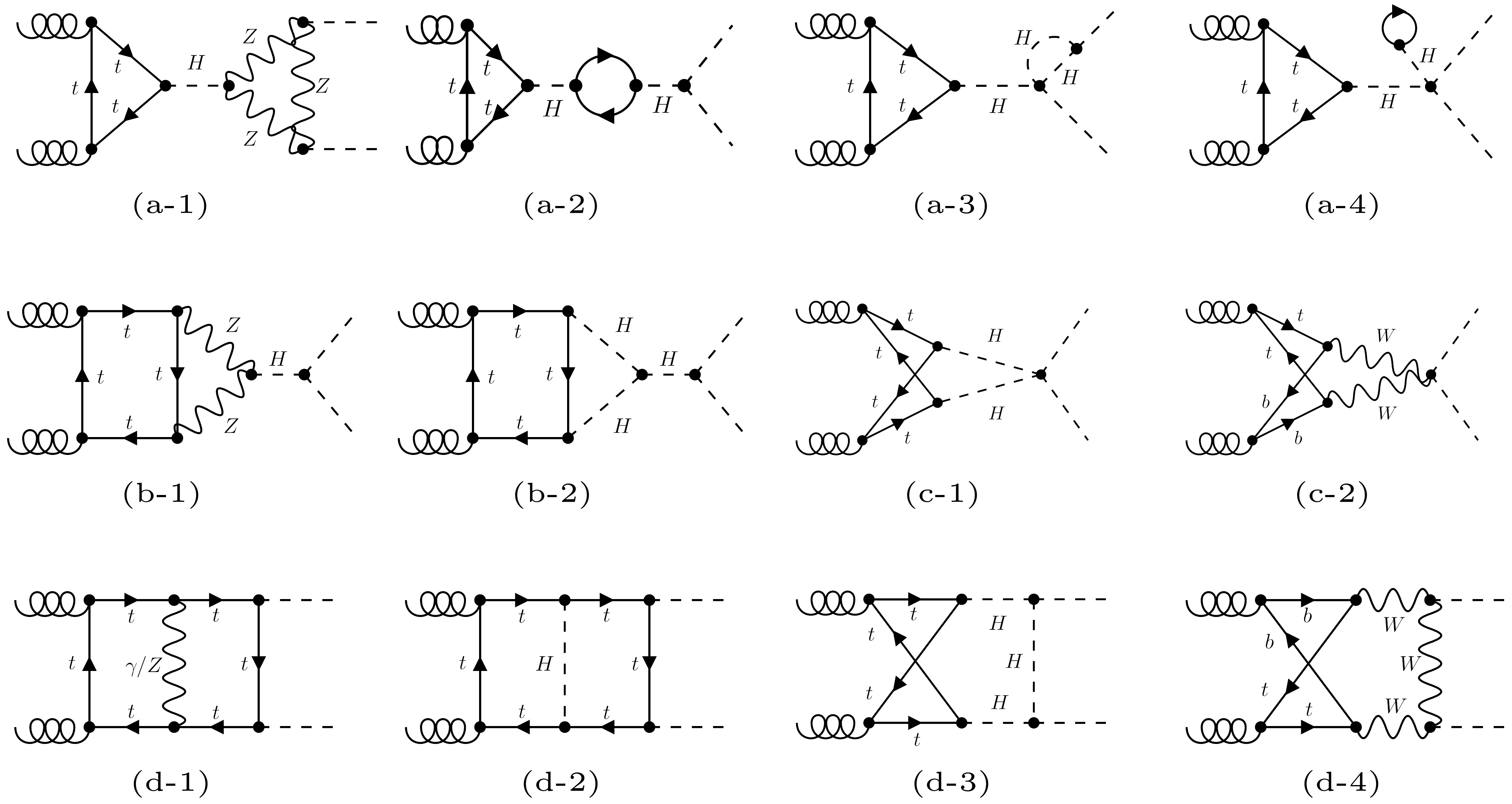


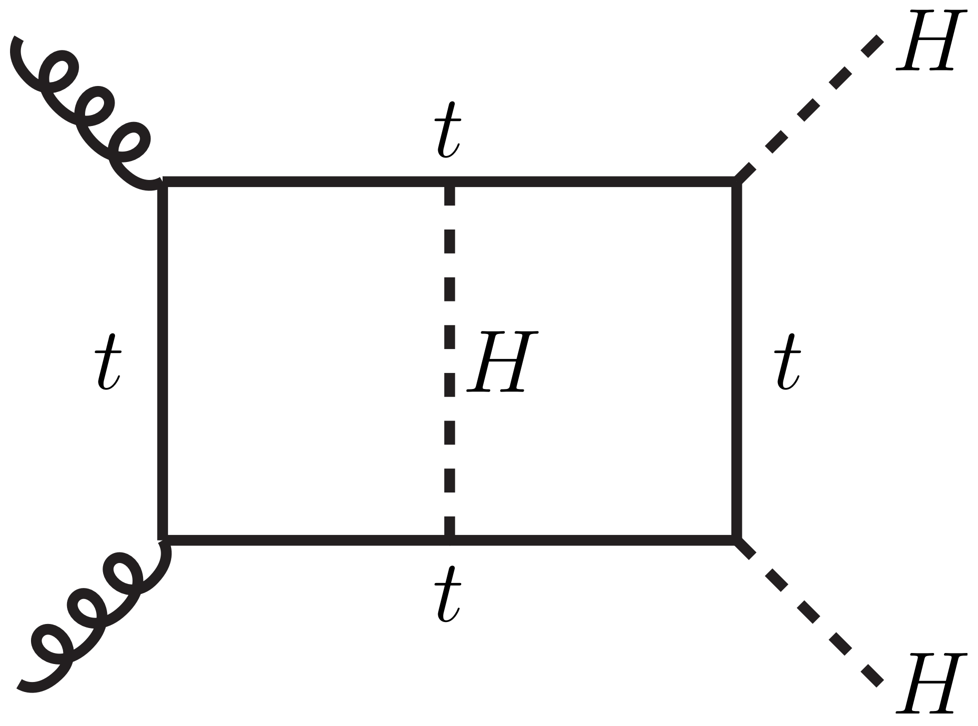



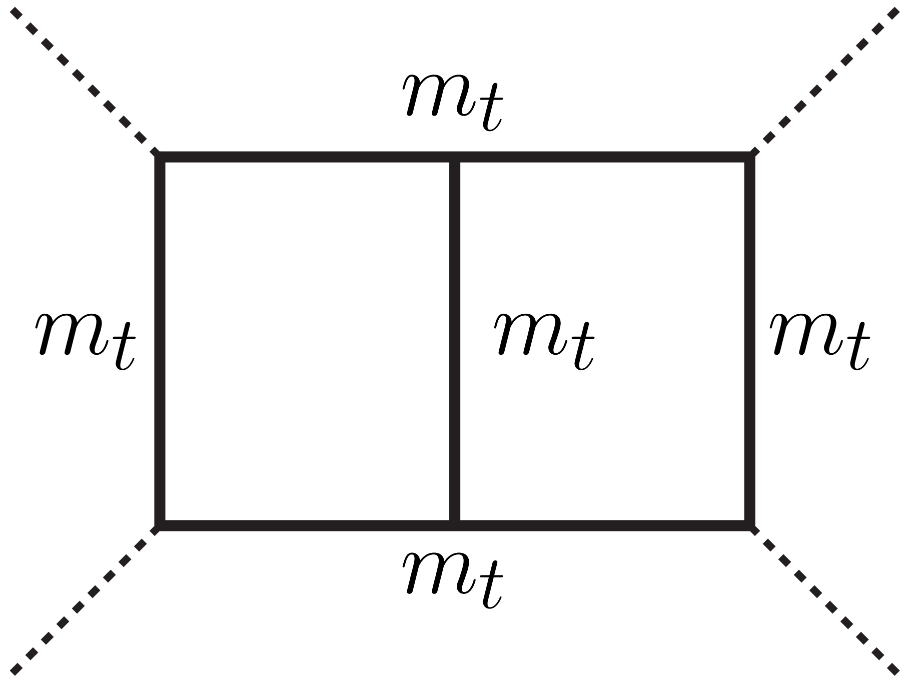

[Davies, Schönwald, Steinhauser, **Zhang**,
2603.08789]

Full top-quark contribution at NLO EW

# Expansion strategies at high energies

- At high energies, SM masses are of a similar order: $m_t^2 \approx m_W^2, m_Z^2, m_H^2 \ll s, |t|$
- Two **Taylor expansions**: equal-internal-mass and small-external-mass expansions




$s, t \gg m_t^2$

**High-energy expansion**

$$\delta_X = 1 - \frac{m_X}{m_t}, \quad X = H, W, Z$$

# High energy expansion of master integrals

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

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

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

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

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

4. Solve **boundary master integrals** in $m_t^2/s \to 0$ to higher orders in $m_t^2$ and $\epsilon$ using **AsyInt**

# AsyInt toolkit I: generate MB-integral representations

- Two-loop Feynman integral with $n$ propagators and $k$ numerators

$$\mathcal{I}_{n,k} = \int \prod_{j=1}^{2} \mathrm{d}l_j \, \frac{N_1^{\lambda_1} \cdots N_k^{\lambda_k}}{D_1^{1+\delta_1} \cdots D_n^{1+\delta_n}}$$

$\delta_i$: additional regulators and shifts for dotted propagators (e.g. $\delta_i \to \delta_i + 1$)

`GenerateInput / GenerateInputNum`

**Hard region**

**Massless integrals**

**Asymptotic regions**

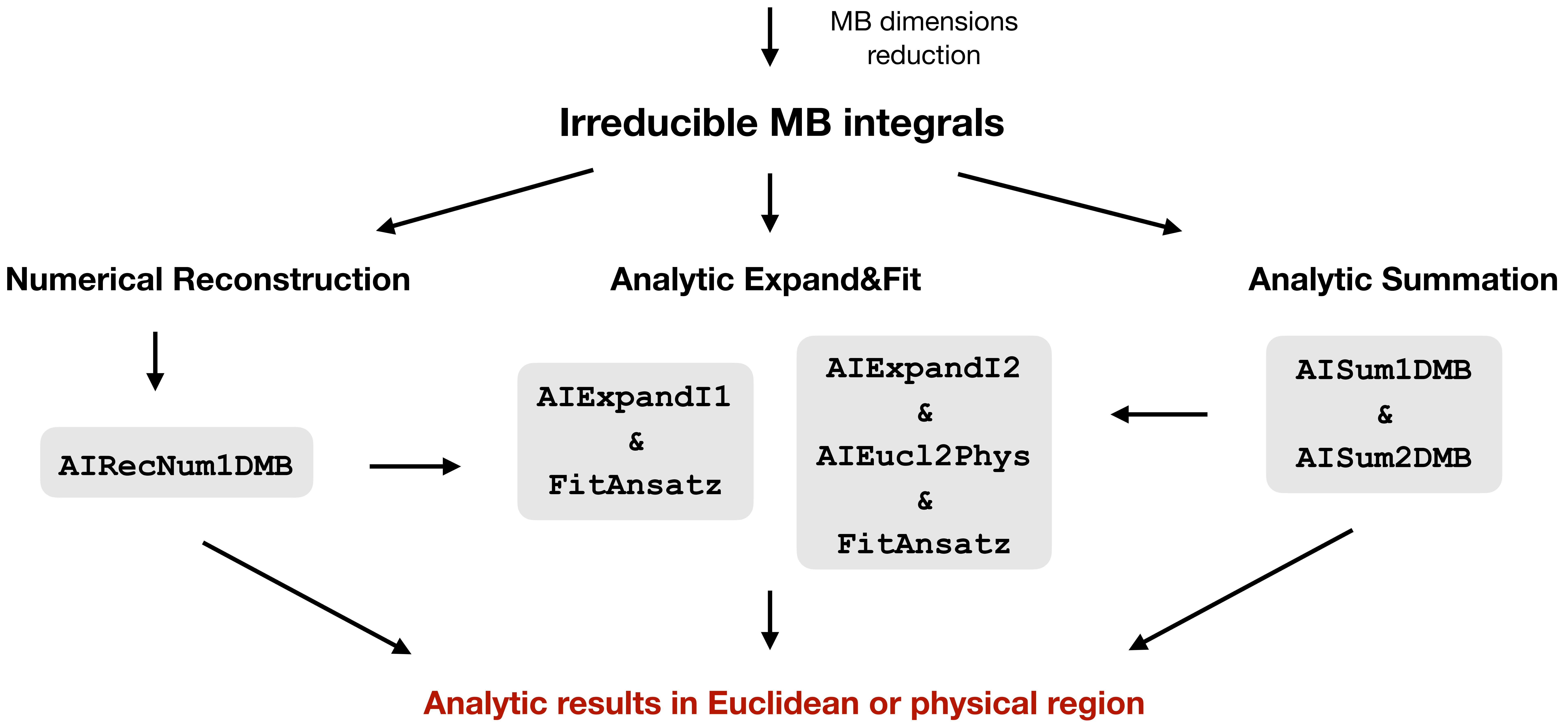
`AlphaRepForTempInt`

**Template integrals**

`AsyExp2MB / AsyExpNum2MB`

**Mellin-Barnes integrals to higher orders in $m_t$ and $\epsilon$**

# AsyInt toolkit II: solve MB integrals

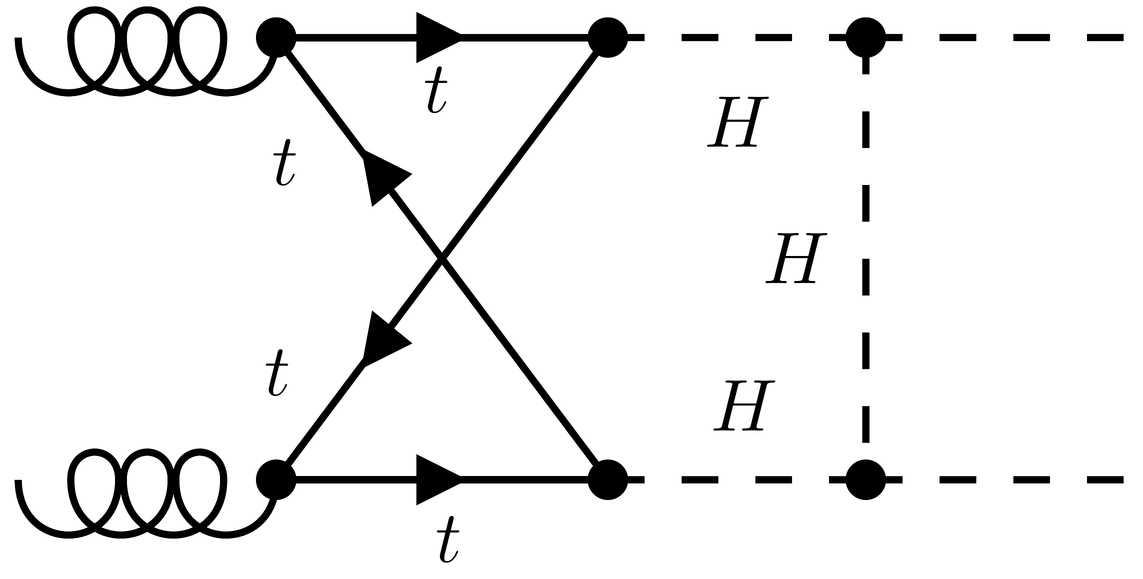



Expand&Fit for complicated irreducible MB integrals

(type-1): 2-dim 1-scale MB integrals with non-vanishing arc contributions

(type-2): 2-dim 2-scale MB integrals

# Comparison of Yukawa and Higgs self-coupling corrections

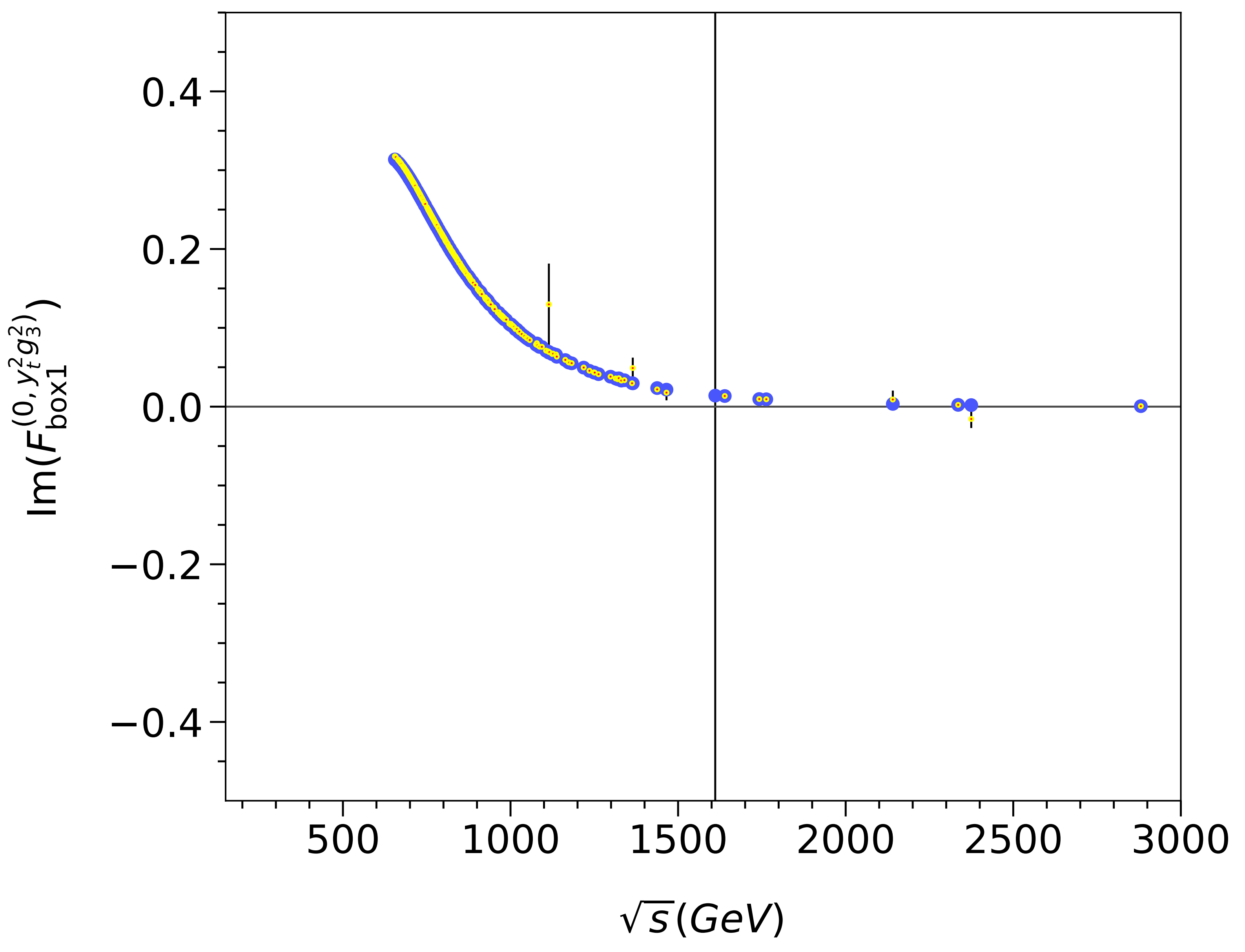



[Davies, Schönwald, Steinhauser, **Zhang**, JHEP 04 (2025) 193]

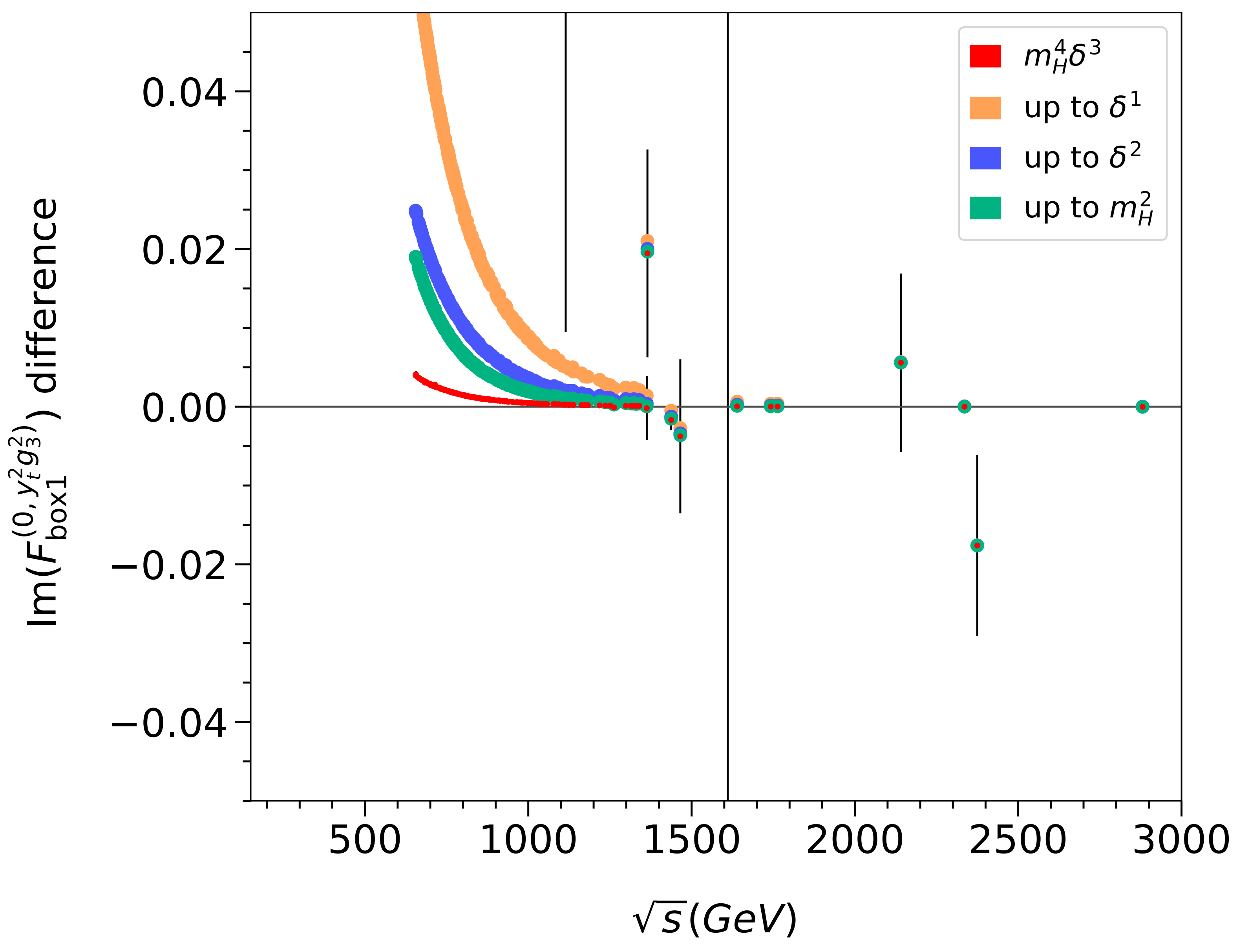
Comparison to numerical results from SecDec group - $y_t^2\,\lambda^2$ (bare) form factor

[Heinrich, Jones, Kerne, Stone, Vestner, JHEP 11 (2024) 040]

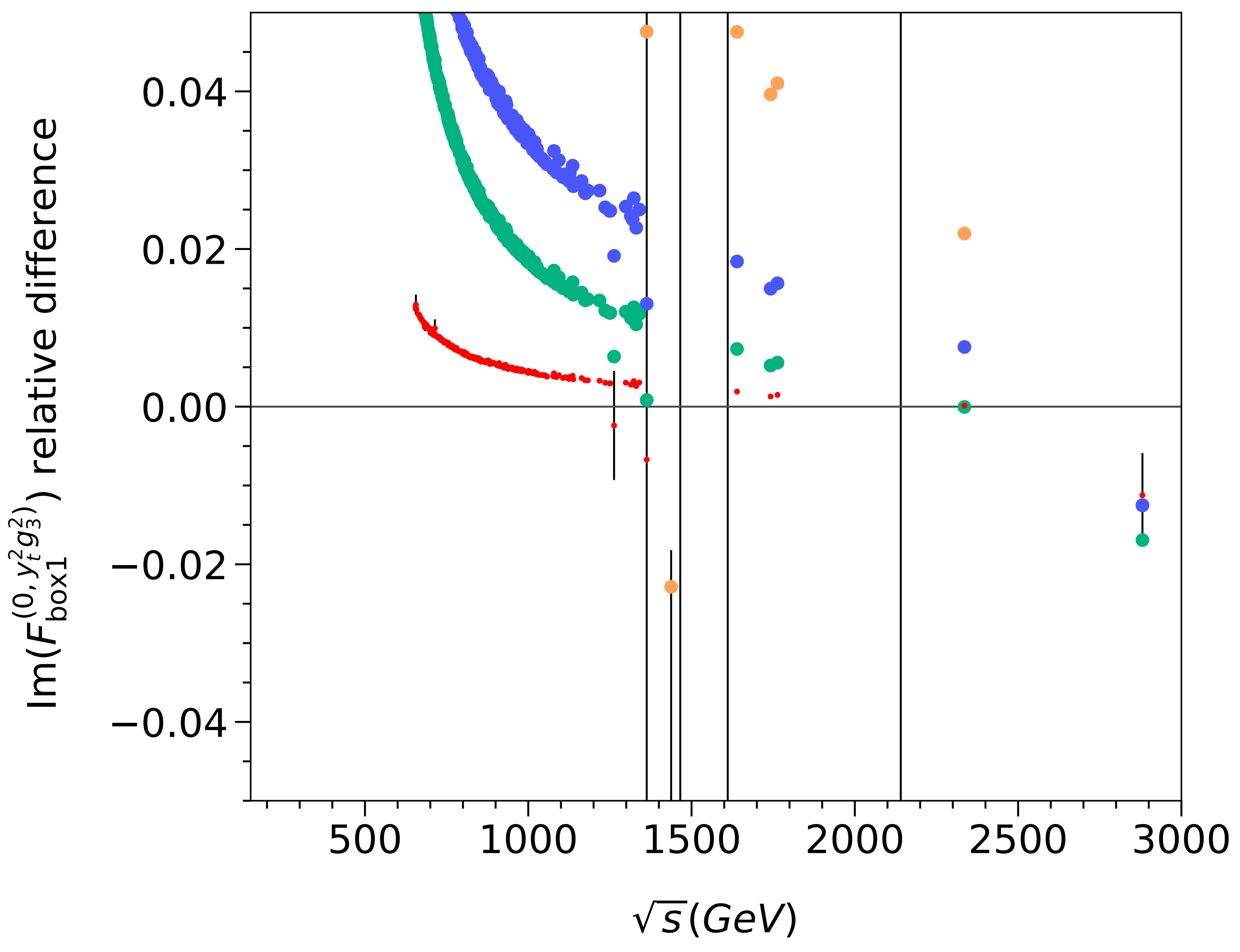
Note the expansion is only up to $\delta^3$ order ($\delta = 1 - m_H/m_t$) for this comparison




$F_{\text{box}}^{(y_t^2\,\lambda^2)}$ form factor




Absolute difference




Relative difference

# Analytic EW results - form factors

[Davies, Schönwald, Steinhauser, **Zhang**, 2603.08789]

**Perturbative QCD and EW expansion:** $F = F^{(0)} + \frac{\alpha_s(\mu)}{\pi} F^{(1,0)} + \frac{\alpha}{\pi} F^{(0,1)} + \cdots$

Central EW mass scale $m_{EW} := m_t$

**Deep high-energy expansion:** $F = \sum_{n=-4}^{108} \sum_{i=0}^{2} \sum_{k_W=0}^{4} \sum_{k_Z=0}^{4} \sum_{k_H=0}^{4} c_{ni}^{k_W k_Z k_H} \, m_t^n \, (m_H^{\text{ext}})^{2i} \, \delta_W^{k_W} \, \delta_Z^{k_Z} \, \delta_H^{k_H}$ , with $\delta_X = 1 - \frac{m_X}{m_t}$

- **In the $m_t \to 0$ and $m_H = 0$ limits**, one-loop box form factors are

$$l_{ms} = \log\left(\frac{m_t^2}{s}\right) + i\pi\,,\ l_{ts} = \log\left(-\frac{t}{s}\right) + i\pi\,,\ l_{1ts} = \log\left(1 + \frac{t}{s}\right) + i\pi\,,\ c_{\rm w} = \frac{m_W}{m_Z}$$

$$F^{(0)}_{\text{box1}} = \frac{8\,m_t^2}{s} + \mathcal{O}\left(\frac{m_t^4}{s^2}, \frac{m_H^2}{s}\right)$$

$$F^{(0)}_{\text{box2}} = \frac{2m_t^2}{st(s+t)}\left[-l_{1ts}^2(s+t)^2 - l_{ts}^2 t^2 - \pi^2(s^2 + 2st + 2t^2)\right] + \mathcal{O}\left(\frac{m_t^4}{s^2}, \frac{m_H^2}{s}\right)$$

- Two-loop box form factors are

$$F^{(0,1)}_{\text{box1}} = \frac{m_W^4}{s^2 c_{\rm w}^6 s_{\rm w}^2}\left[l_{ms}^2 \frac{36c_{\rm w}^6 + 32c_{\rm w}^4 - 40c_{\rm w}^2 + 17}{36}\left(l_{1ts}^2 + l_{ts}^2 - 2l_{1ts}l_{ts} + \pi^2 - 4\right)\right] + \cdots$$

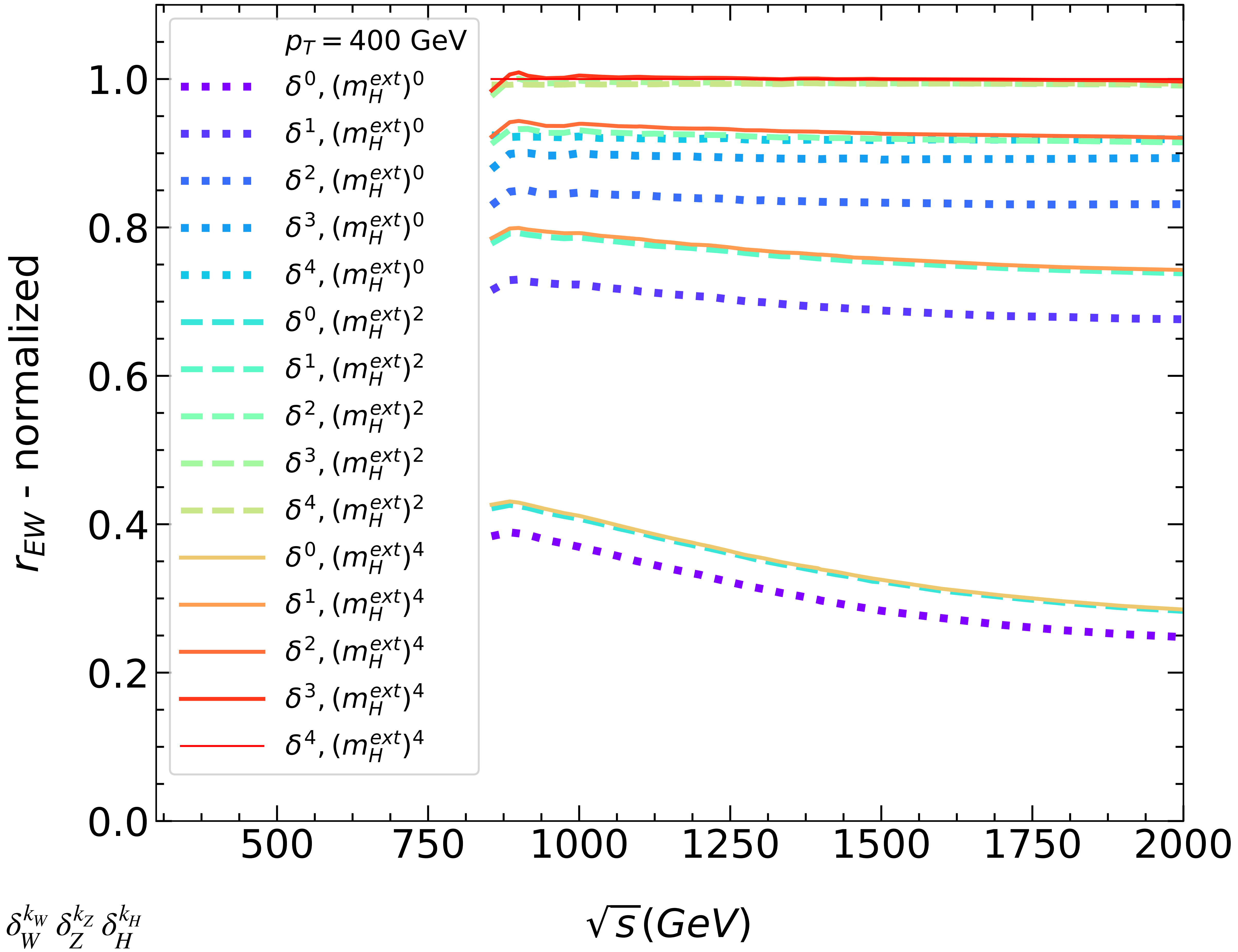
$$F^{(0,1)}_{\text{box2}} = \frac{m_W^4}{s^2 c_{\rm w}^6 s_{\rm w}^2}\left[l_{ms}^3 \frac{36c_{\rm w}^6 + 32c_{\rm w}^4 - 40c_{\rm w}^2 + 17}{27} + l_{ms}^2\left(-\frac{2}{9}\,\delta_Z\,(32c_{\rm w}^4 - 40c_{\rm w}^2 + 17) - 8\,\delta_W\, c_{\rm w}^6 + \cdots\right)\right] + \cdots$$

$gg \to HH$ at NLO EW contains several coupling structures
Logarithmic / power corrections in different limits
can be obtained from the ancillary file
https://www.ttp.kit.edu/preprints/2026/ttp26-006

# Analytic EW results - convergence

[Davies, Schönwald, Steinhauser, **Zhang**, 2603.08789]

$r_{\mathrm{EW}} = \frac{\alpha}{\pi}\frac{\mathcal{U}^{(0,1)}}{\mathcal{U}^{(0)}}$ in perturbative expansion of squared matrix element $|\mathcal{M}|^2 = \bar{X}_0\left(\mathcal{U}^{(0)} + \frac{\alpha_s}{\pi}\mathcal{U}^{(1,0)} + \frac{\alpha}{\pi}\mathcal{U}^{(0,1)} + \cdots\right)$




We estimate a conservative $1\,\%$ uncertainty due to truncation of higher-order $\delta, m_H$ expansion

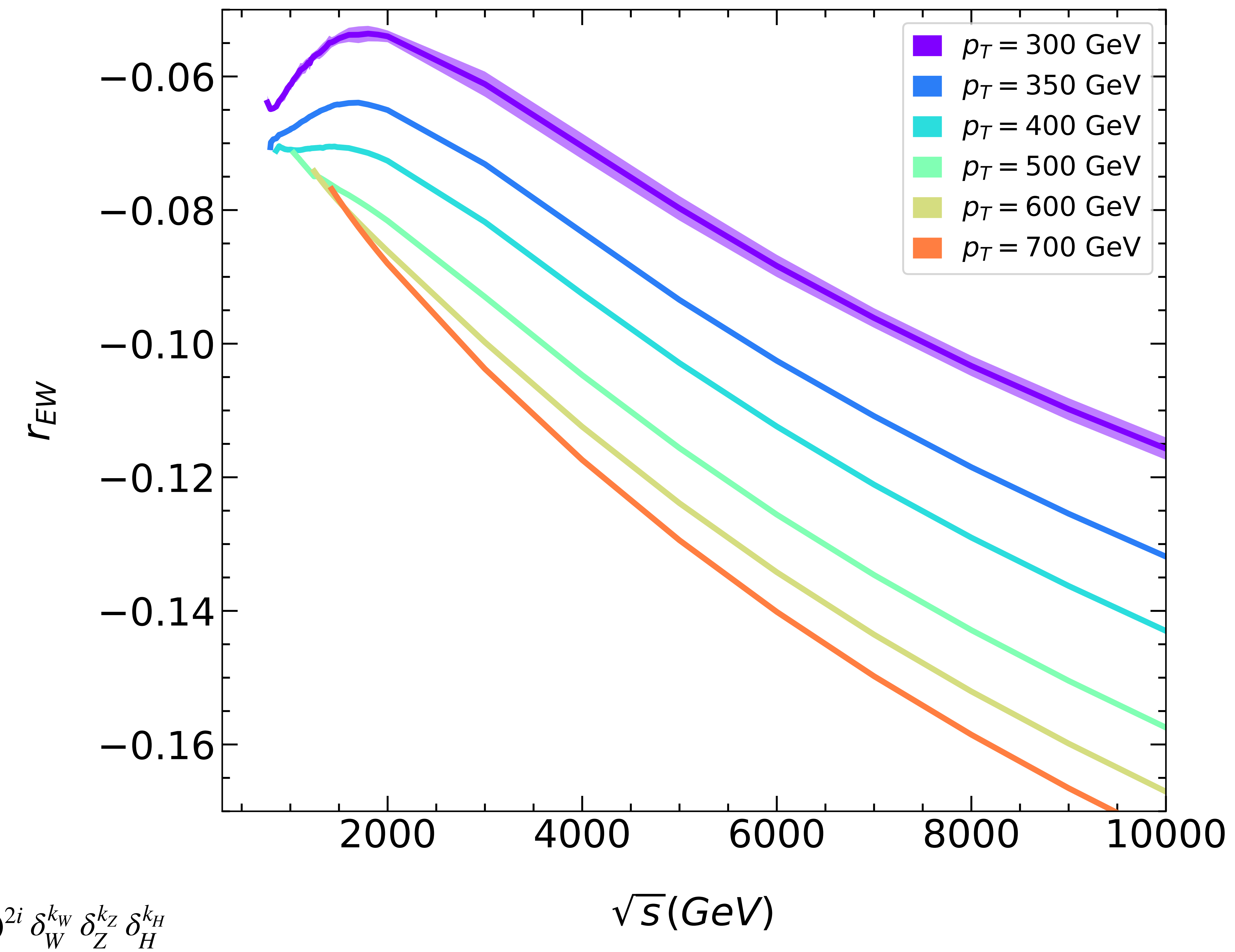
**Deep high-energy expansion:**

$$F = \sum_{n=-4}^{108}\sum_{i=0}^{2}\sum_{k_W=0}^{4}\sum_{k_Z=0}^{4}\sum_{k_H=0}^{4} c_{ni}^{k_W k_Z k_H}\, m_t^n\, (m_H^{\mathrm{ext}})^{2i}\, \delta_W^{k_W}\, \delta_Z^{k_Z}\, \delta_H^{k_H}$$

# Analytic EW results - partonic K factor

[Davies, Schönwald, Steinhauser, **Zhang**, 2603.08789]

$r_{\rm EW} = \dfrac{\alpha}{\pi}\dfrac{\mathscr{U}^{(0,1)}}{\mathscr{U}^{(0)}}$ in perturbative expansion of squared matrix element $|\mathscr{M}|^2 = \bar{X}_0\left(\mathscr{U}^{(0)} + \dfrac{\alpha_s}{\pi}\mathscr{U}^{(1,0)} + \dfrac{\alpha}{\pi}\mathscr{U}^{(0,1)} + \cdots\right)$




NLO EW corrections from top-quark contribution is of **the order of $-10\,\%$ at high energies**

Padé approximation uncertainty band only visible at $p_T = 300$ GeV (Padé used for $m_t/\sqrt{s}$ expansion)

**Deep high-energy expansion:**

$$F = \sum_{n=-4}^{108}\sum_{i=0}^{2}\sum_{k_W=0}^{4}\sum_{k_Z=0}^{4}\sum_{k_H=0}^{4} c_{ni}^{k_W k_Z k_H}\, m_t^n\, (m_H^{\rm ext})^{2i}\, \delta_W^{k_W}\, \delta_Z^{k_Z}\, \delta_H^{k_H}$$

# Summary

- **Analytic two-loop EW machinery for $2 \to 2$ processes at high & low energies**
  - A technical roadmap developed for MIs and amplitudes calculations at high energies [JHEP 08 (2022) 259, JHEP 04 (2025) 193]
    - NLO EW corrections to Higgs pair production at high energies [2603.08789]
    - **AsyInt** toolbox for MIs at high energies public available [JHEP 09 (2024) 069]
  - Large-mass expansion demonstrated for $gg \to HH$ and $gg \to Hg$ [JHEP 10 (2023) 033]
    - Applicable to precision NNLO BSM physics @ FCC-ee
    - Importance of BSM effects at NLO EW demonstrated @ FCC-ee [Phys.Rev.Lett. 136 (2026) 8, 081801]
- **Precision EW Studies can help New Physics Searches** [Phys.Rev.Lett. 136 (2026) 081801]
  - NLO EW is necessary for BSM phenomenology at FCC-ee
  - EW corrections are powerful probe to explore extended Higgs sector in $e^+e^- \to h\nu\bar{\nu}$