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the European Union

Higher order calculations for $gg \rightarrow ZH$

Warsaw Theory Seminar, 2026

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Warsaw, April 23, 2026

CERN

Based on: [JHEP 02 (2026) 191; JHEP 03 (2026) 200; Davies, KS, Steinhauser, Stremmer, arXiv:2603.15762]

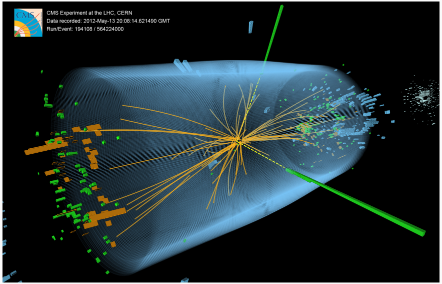
Outline

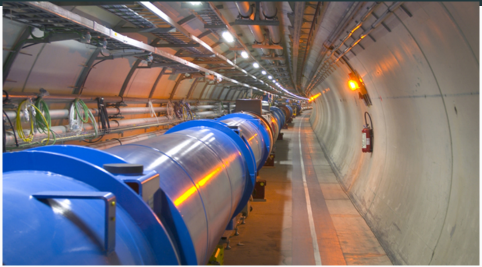
Introduction

High Energy Particle Physics

Questions:

- What is matter made of?
- How do particles interact with each other?





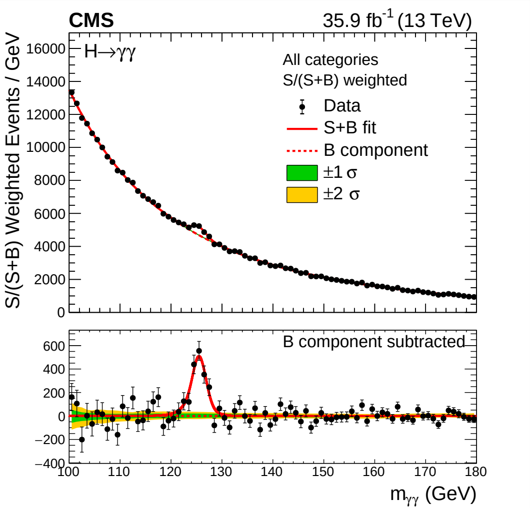
Tools:

- Scattering particles on each other.
- Collider experiments:
    - LHC at CERN (Geneva)
    - SuperKEKB at KEK (Tsukuba)
    - ...

→ **Standard Model of Particle Physics** $SU_{\mathrm{C}}(3) \times SU_{\mathrm{L}}(2) \times U_{\mathrm{Y}}(1)$

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathrm{i}\overline{\psi}_i \not{D}\psi_i + \psi_i y_{ij}\psi_j\phi + \mathrm{h.c.} + |D_\mu\phi|^2 - V(\phi)}$$

LHC – Higgs Discovery



[CMS, PLB 805 (2020)]

- 2012: Discovery of the Higgs boson.

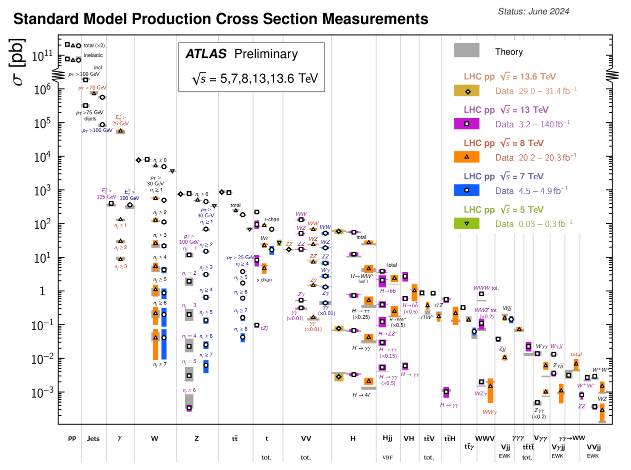
$$\boxed{m_H = 125.20 \pm 0.11\ \text{GeV}}$$ [PDG '25]

- Standard Model is completed:
  → All particles have been detected experimentally.
- **Questions:**
  - Are there more resonances/particles?
  - Do all particles interact like we predict?

LHC – Precision Program

In general good agreement between data and SM expectations:

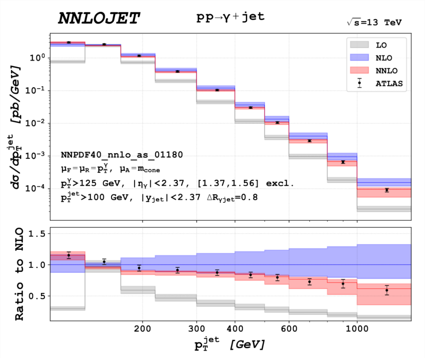
- No evidence of additional resonances/particles.
- A lot of different observables spanning several orders of magnitude agree with theory predictions.



Why Precision?

- The SM cannot explain several observations:
  - gravity
  - baryon asymmetry of the universe
  - dark matter and energy
  - …
- No evidence of physics beyond the SM yet.
- More and more precise data from LHC (High-Luminosity LHC in the future).
- **Some hints:**
  - some flavor observables
  - $g-2$ of the muon
  - W mass measurement of CDF

  $\rightarrow$ all under scrutiny



[Chen, Gehrmann, Glover, Höfer, Huss, Schürmann '22]

$\Rightarrow$ If new particles are heavy or weakly coupled, we can search for small deviations in data.

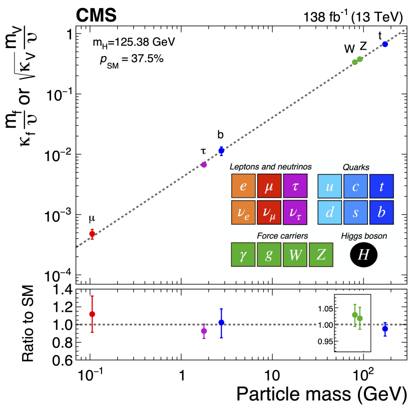
Is the Higgs boson SM like?

- What are the properties of the SM Higgs boson?
    - Spin 0
    - coupling strength is proportional to the mass of the other particle
    - has very constrained self-interactions
    - ...
- Standard Model Higgs potential:

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

with $\lambda = m_H^2/(2v^2) \approx 0.13$

- $-0.71 < \lambda/\lambda_{SM} < 6.1$ [Atlas + CMS '26]
- $-1.7 < \lambda/\lambda_{SM} < 6.6$ [Atlas '25]



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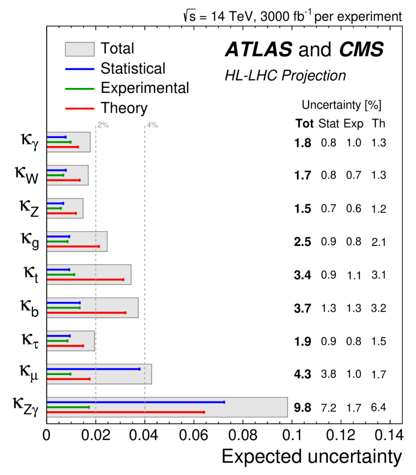
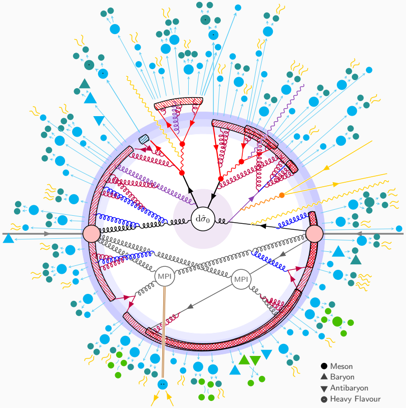
- HL projection: 20% uncertainty on λ



High Energy Particle Physics – Theory

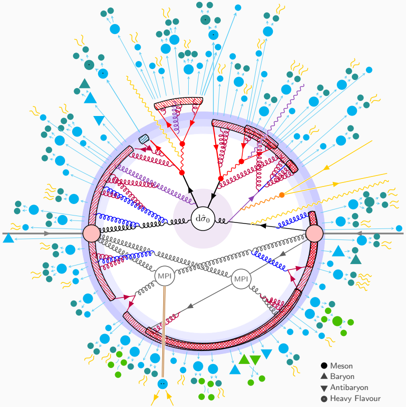


[PYTHIA 8.3 manual '22]

Theoretical predictions at hadron colliders are challenging:

- protons are not elementary particles
- QCD is strongly coupled at small energies
- only hadrons are measured in the experiments

High Energy Particle Physics – Theory



[PYTHIA 8.3 manual '22]

Theoretical predictions at hadron colliders are challenging:

- factorization (proton → parton)
- hard scattering
- parton shower
- hadronisation

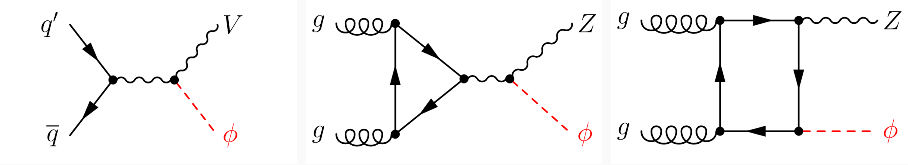
Factorize physics at different energy scales:

$$\boxed{d\sigma = \underbrace{\int dx_1 \int dx_2\, f_i(x_1) \otimes f_j(x_2)}_{\text{parton distributions}} \otimes d\hat{\sigma}_{ij} + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q^2}\right)}$$

Partonic hard scattering $d\hat{\sigma}_{ij}$ can be calculated perturbatively.

Why *ZH* production?

- *ZH* production is important for the $H \to b\bar{b}$ measurement
  - $Z \to l\bar{l}$ can be used for background suppression
  - main contribution in observation of $H \to b\bar{b}$ bt ATLAS and CMS in 2018
- different production channels for *ZH*:



- Drell-Yan like topologies (left) are known up to N3LO [Bagli, Duhr, Mistelberger, Szafron '22] :

  $\Rightarrow 1 - 2\%$ effect

- Gluon fusion enters suppressed in α_s, but still has sizable contributions:

$$\frac{\sigma(gg \to ZH)}{\sigma(pp \to ZH)} \sim 13\%$$

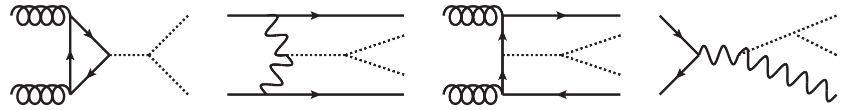
Why *HH* production?

Standard Model prediction:

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

with $\lambda = m_H^2/(2v^2) \sim 0.13$

- *HH* production is the most promising way to measure the Higgs self-coupling.
- different production channels for *HH*:



- Gluon fusion is the dominant production channel for *HH* production:

$$\frac{\sigma(gg \to HH)}{\sigma(pp \to HH)} \sim 90\%$$

- Feynman diagrams very similar to *ZH* production in gluon fusion.

Higher order calculations

Typical Workflow

- Calculate all Feynman diagrams contributing to the process of interest:

$$\boxed{\mathrm{d}\hat{\sigma} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}} + \alpha_s \cdot \mathrm{d}\hat{\sigma}^{\mathrm{NLO}} + \alpha_s^2 \cdot \mathrm{d}\hat{\sigma}^{\mathrm{NNLO}} + \alpha_s^3 \cdot \mathrm{d}\hat{\sigma}^{\mathrm{N3LO}} + \ldots}$$

- At higher orders also real radiation has to be taken into account to cancel infrared singularities (Kinoshita-Lee-Nauenberg theorem):

$$\boxed{\mathrm{d}\hat{\sigma}_0^{\mathrm{NLO}} = \int_n \mathrm{d}\hat{\sigma}_0^{\mathrm{NLO,V}} + \int_{n+1} \mathrm{d}\hat{\sigma}_0^{\mathrm{NLO,R}} = \int_n \left(\mathrm{d}\hat{\sigma}_0^{\mathrm{NLO,V}} + \int_1 \mathrm{d}\hat{\sigma}^{\mathrm{S}} \right) + \int_{n+1} \left(\mathrm{d}\hat{\sigma}_0^{\mathrm{NLO,R}} - \mathrm{d}\hat{\sigma}^{\mathrm{S}} \right)}$$

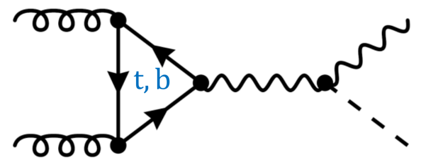
- Feynman integrals can be reduced a small set of master integrals: [Tkachov '81, Chetyrkin '81]

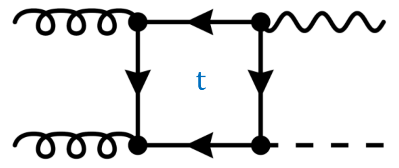
$$\boxed{\int \frac{\mathrm{d}^D k}{i\pi^{D/2}} \frac{\partial}{\partial k^\mu} \left[l^\mu f(k) \right] = 0}$$

- We can derive and solve differential equations in order to find solutions of the master integrals: [Kotikov '91]

$$\mathrm{d}\vec{M} = \left[\sum_{i,j} A_{s_{ij}} \mathrm{d}s_{ij} + \sum_k A_{m_k^2} \mathrm{d}m_k^2 \right] \cdot \vec{M}$$

$gg \to ZH$ – technical challenges





- Exact LO (1-loop) result known for a long time [Discus, Kao '88; Kniehl '90]
- Only axial coupling of $Zf\bar{f}$ vertex contributes
  - Sum over mass-degenerate quark families vanishes
  - Only contribution from t, b inside loop
- For boxes we have to compute 2-loop Feynman integrals with many scales:

$$\boxed{\epsilon, s, t, m_t, m_H, m_Z}$$

  - Very challenging analytic calculation.
  - No fully analytic result available (yet).

$gg \to ZH$ – NLO calculations

- large-m_t expansion [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke '13; Hasselhuhn, Luthe, Steinhauser '17]
- numerical integration with pySecDec [Chen, Heinrich, Jones, Kerner, Klappert, Schlenk '21]
- small-mass expansion with numerical integration [Wang, Xu, Xu, Yang '22]
- high-energy expansion [Davies, Mishima, Steinhauser '21]
- small-p_T expansion [Alasfar, Degrassi, Giardino, Gröber, Vitti '21]

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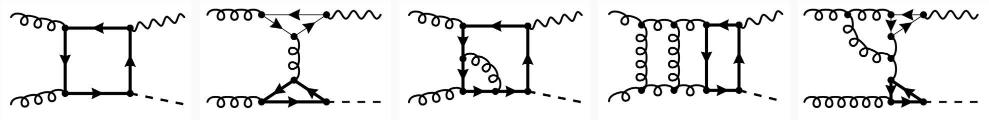
- small-p_T expansion [Alasfar, Degrassi, Giardino, Gröber, Vitti '21]
- deep high-energy and small-t expansion [Davies, Grau, KS, Steinhauser, Stremmer '25]
- large-m_t expansion at NNLO [Davies, Grau, KS, Steinhauser, Stremmer '25]

$gg \to ZH$ – Set-up

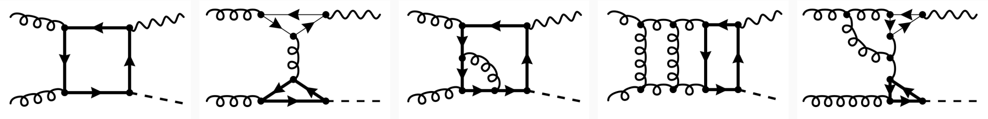


We calculate the amplitude for $\boxed{g(q_1) + g(q_2) \to Z(-q_3) + H(-q_4)}$:

$$A(q_1, q_2, q_3) = i\delta_{ab} \frac{\sqrt{2} G_F m_Z}{s} \frac{\alpha_s(\mu)}{\pi} A^{\mu\nu\rho}(q_1, q_2, q_3) \epsilon^a_\mu(q_1) \epsilon^b_\nu(q_2) \epsilon^*_\rho(q_3),$$

- We use on-shell kinematics: $q_1^2 = q_2^2 = 0,\ q_3^2 = m_Z^2,\ q_4^2 = m_H^2$
- The Mandelstam variables are: $(q_1 + q_2)^2 = s,\ (q_1 + q_3)^2 = t,\ (q_1 + q_4)^2 = u$
- The transverse momentum of the final-state particles is: $\boxed{p_T^2 = (ut - m_Z^2 m_H^2)/s}$
- We compute the form factor F_1,..., F_4 by projection.

$gg \to ZH$ – Set-up



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$$
\boxed{
\begin{aligned}
&A^{\mu\nu\rho}(q_1, q_2, q_3) = \\
&\Bigg\{ \left(\frac{s}{2} \varepsilon^{\mu\nu\rho\alpha} q_{2\alpha} - q_2^\mu \varepsilon^{\nu\rho\alpha\beta} q_{1\alpha} q_{2\beta} \right) F_1(t,u) - \left(\frac{s}{2} \varepsilon^{\mu\nu\rho\alpha} q_{1\alpha} - q_1^\nu \varepsilon^{\mu\rho\alpha\beta} q_{1\alpha} q_{2\beta} \right) F_1(u,t) \\
&+ \left(q_3^\mu + \frac{m_Z^2 - t}{s} q_2^\mu \right) \varepsilon^{\nu\rho\alpha\beta} q_{2\alpha} \left[q_{1\beta} F_2(t,u) + q_{3\beta} F_3(t,u) \right] + \left(q_3^\nu + \frac{m_Z^2 - u}{s} q_1^\nu \right) \varepsilon^{\mu\rho\alpha\beta} q_{1\alpha} \left[q_{2\beta} F_2(u,t) + q_{3\beta} F_3(u,t) \right] \\
&+ \left(\frac{s}{2} \varepsilon^{\mu\nu\rho\alpha} q_{3\alpha} - q_2^\mu \varepsilon^{\nu\rho\alpha\beta} q_{1\alpha} q_{3\beta} + q_1^\nu \varepsilon^{\mu\rho\alpha\beta} q_{2\alpha} q_{3\beta} + g^{\mu\nu} \varepsilon^{\rho\alpha\beta\gamma} q_{1\alpha} q_{2\beta} q_{3\gamma} \right) F_4(t,u) \Bigg\}.
\end{aligned}
}
$$

- We use on-shell kinematics: $q_1^2 = q_2^2 = 0,\ q_3^2 = m_Z^2,\ q_4^2 = m_H^2$
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- The transverse momentum of the final-state particles is: $\boxed{p_T^2 = (ut - m_Z^2 m_H^2)/s}$
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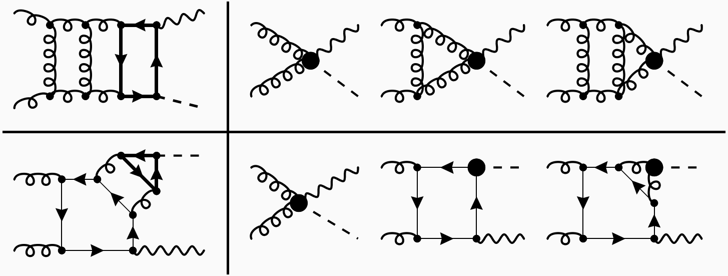
Large mass expansion – Technique



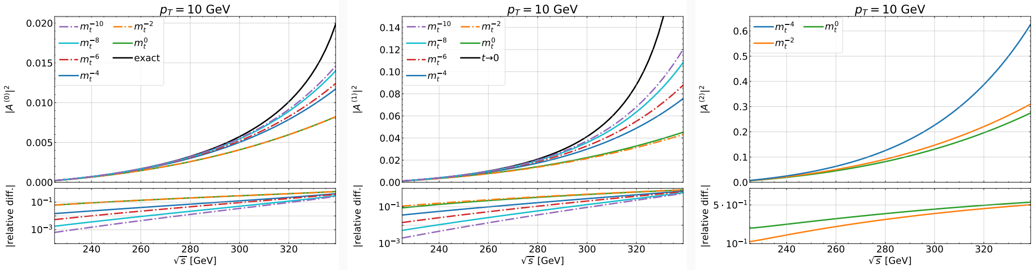
- The large m_t expansion is the 'simplest' approximation we can apply.
- The leading term of the expansion can be described by a simple effective field theory:

$$\boxed{\mathcal{L}_{\text{int}} \sim H\, G_{\mu\nu}\, G^{\mu\nu}}$$

- The expansion is based on expansion-by-region [Beneke, Smirnov '97] :
  - The loop momenta can either scale hard $k_i \sim m_t$, or soft $k_i \sim 1$
  - The amplitude factorizes in $m \geq 1$ loop massive tadpoles and $m - l$ loop box integrals, with massless internal lines only.
  - Master integrals for the virtual corrections are known up to three loop. [Gehrmann, von Manteuffel, Tancredi '15]

$\Rightarrow$ We pushed the expansion to $O(m_t^{-4})$: analytic expression of $O(10)$ Mb

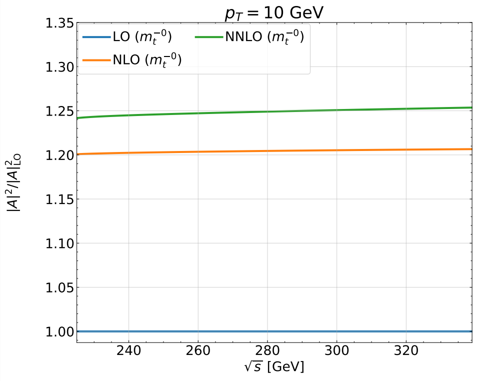
Large mass expansion – Results

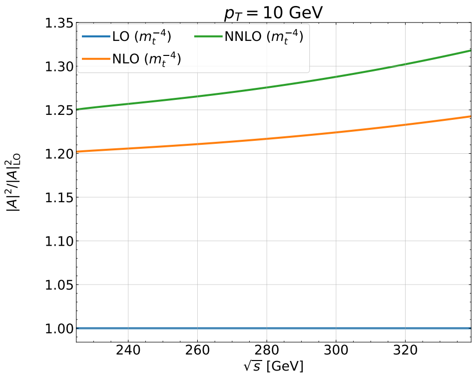


- Good convergence up to $\boxed{\sqrt{s} \sim 2m_t = 340\text{GeV}}$

⇒ Different expansion necessary to cover the full phase space.

Large mass expansion – Results





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$\Rightarrow$ Different expansion necessary to cover the full phase space.

High-Energy Expansion

Seek an expansion where $s, |t| > m_t^2 > m_H^2, m_Z^2$ [Davies, Mishima, Steinhauser, Wellmann '18-'19]

1. Form factors in terms of scalar Feynman integrals: $I(m_H^2, m_Z^2, m_t^2, s, t, \epsilon)$
2. Taylor expand for $m_H^2, m_Z^2 \to 0$ (with `LiteRed`): [Lee '14]

$$\boxed{I(m_H^2, m_Z^2, m_t^2, s, t, \epsilon) = I(0, 0, m_t^2, s, t, \epsilon) + m_{H/Z}^2 I'(0, 0, m_t^2, s, t, \epsilon) + \ldots}$$

3. IBP reduce to master integrals: $J(0, 0, m_t^{,} s, t, \epsilon)$ (`FIRE`, `Kira`) [Smirnov '15]
   [Klappert, Lange, Maierhöfer, Usovitsch '21]
4. Determine MIs as an expansion around $m_t \to 0$:

$$\boxed{J(0, 0, m_t^2, s, t, \epsilon) = \sum_{i,j,k} C_{ijk}(s, t) \epsilon^i (m_t^2)^j \log(m_t^2)^k}$$

- Insert ansatz into differential equation → linear equations for c_{ijk}.
- Compute boundary conditions with expansion-by-regions.

High-Energy Expansion – Calculation of boundary conditions

- We start with the Schwinger parametrization of the integrals:

$$\boxed{I = \int_0^\infty \left(\prod_{i=1}^{n} d\alpha_i \frac{\alpha_i^{\delta_i}}{\Gamma(1+\delta_1)} \right) \mathcal{U}^{-d/2} e^{-\mathcal{F}/\mathcal{U}} \,,}$$

  with the Symanzik polynomials $\mathcal{U}$ and $\mathcal{F}$.
- We use expansion-by-regions and reveal the different regions with `asy.m` [Pak, Smirnov '11] .
- In the high-energy limit: $\boxed{s, |t| \sim 1 \,,\; m_t^2 \sim \xi}$, we find 13 regions.
  - One hard region, where the master integrals are known. [Smirnov, Veretin '00; Bern, Sixon, Smirnov '05]
  - 12 'soft' regions, where the α parameters scale differently in ξ.
- We calculate the expansion using Mellin-Barnes techniques.

Calculation of boundary conditions – Results

- We obtain analytic results for 161 (QCD), 168(28) (electroweak) master integrals.
- The final result can be expressed via harmonic polylogarithms [Remiddi, Vermaseren '99] .

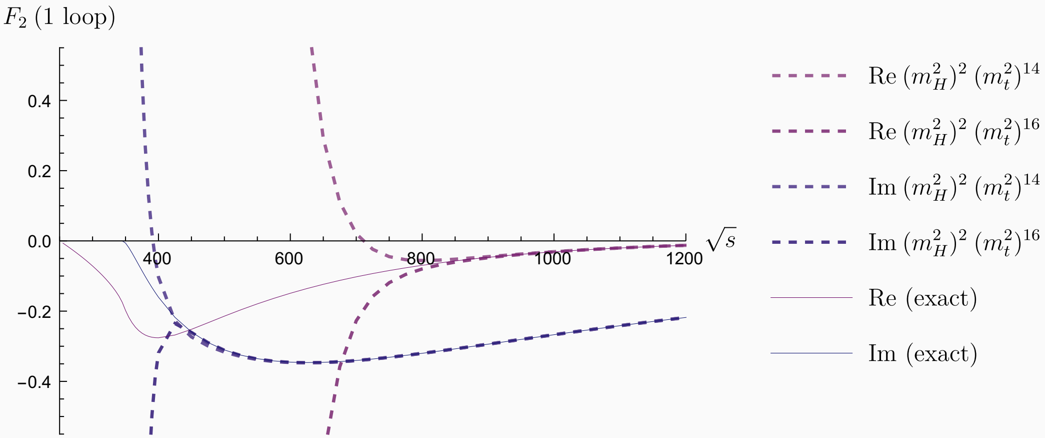
$$H_0(-t/s), H_1(-t/s), H_{0,1}(-t/s), H_{0,0,1}(-t/s),$$
$$H_{0,1,1}(-t/s), H_{0,0,0,1}(-t/s), H_{0,0,1,1}(-t/s), H_{0,1,1,1}(-t/s)$$

and transcendental numbers

$$\pi,\ \ln(3),\ \sqrt{3},\ \zeta_2,\ \zeta_3,\ \psi^{(1)}(1/3),\ \mathrm{Im}(\mathrm{Li}_3(i/\sqrt{3})),\ K^2(\frac{1}{2}-\frac{\sqrt{3}}{4}),\ E^2(\frac{1}{2}-\frac{\sqrt{3}}{4})\ .$$

- All master integrals are computed up to $\mathcal{O}(m_t^{120})$.

High-Energy Expansion: LO comparison



High-Energy Expansion: Padé approximants

The expansion diverges for $\sqrt{s} \lesssim 750\,\text{GeV}$.

The convergence can be improved by making use of Padé approximants:

- Approximate a function using a rational polynomial:

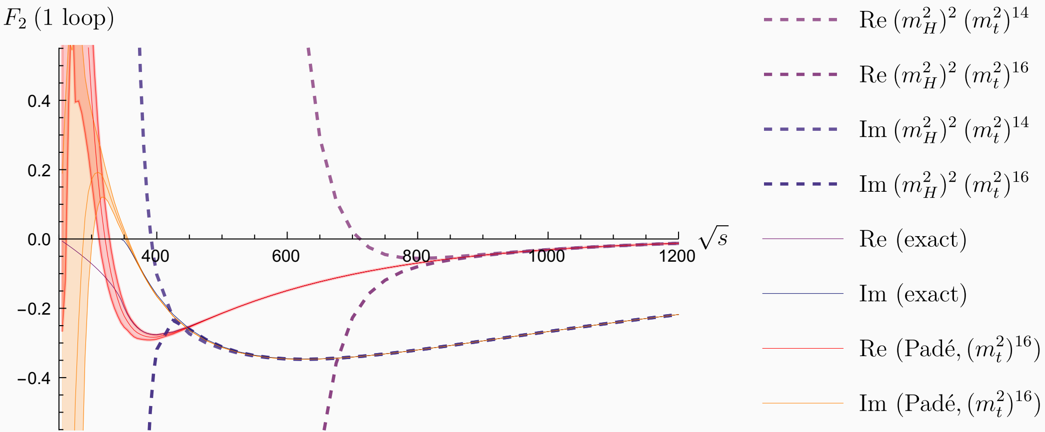
$$\boxed{f(x) \approx [n/m](x) = \frac{a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n}{1 + b_1 x + b_2 x^2 + \cdots + b_m x^m}\,,}$$

where the coefficients a_i, b_j are fixed by the series expansion of $f(x)$.

Compute a set of approximants (various choices of n, m):

- combine to give a central value and error estimate
- deeper expansions $\Rightarrow$ larger $n + m$ $\Rightarrow$ smaller error
- expansions to m_t^{120} allows for very high-order approximants

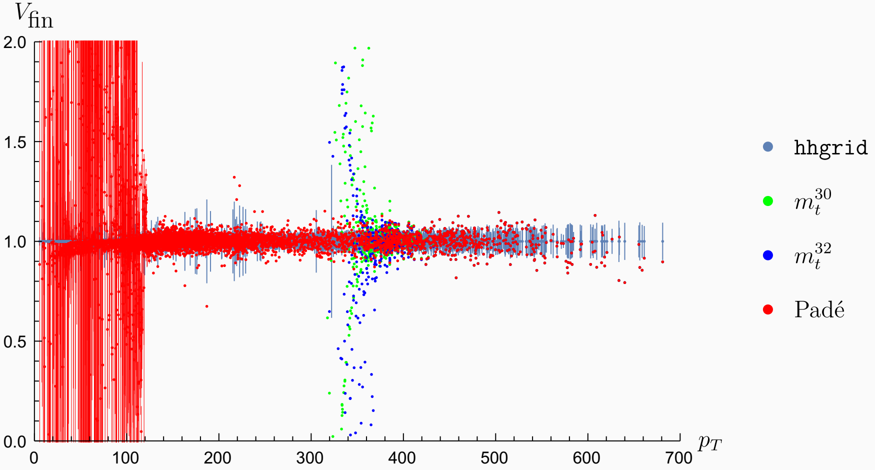
High-Energy Expansion: Padé approximants



High-Energy Expansion: V_{fin}

Comparison with `hhgrid`: [https://github.com/mppmu/hhgrid]

- interpolation grid of 6320 points evaluated numerically by `pySecDec`
- grid points normalized to `hhgrid` as function of p_T:

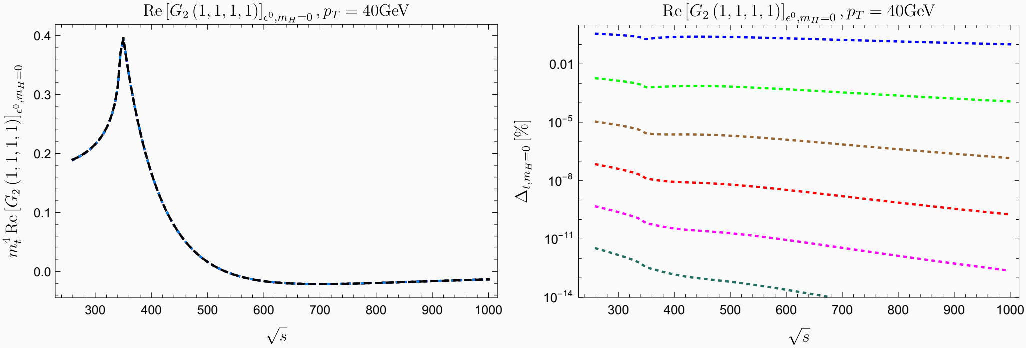


Small-t Expansion

As for high-energy expansion, first expand around $m_H \to 0$.

Then two possible (and finally equivalent) approaches:

1. Take the IBP-reduced amplitude of the high-energy expansion:
    - expand the master integrals around $t \to 0$ instead of $m_t \to 0$
2. Expand the unreduced amplitude around $q_3 \to -q_1$ $(t \to 0)$:
    - IBP reduce to new master integrals which only depend on ϵ, s, m_t
    - this approach can be applied at NNLO, but only to restricted expansion depth



Small-t Expansion: Evaluation of the MIs

“Semi-analytic” determination of the $t \to 0$ MIs: [Fael, Lange, Schönwald, Steinhauser ‘21]

1. Establish system of DEs for the MIs, w.r.t. $\hat{s} = s/m_t^2$.
2. Expand around $\hat{s} = 0$:
    - insert ansatz into DE: $J(\epsilon, \hat{s} = 0) = \sum_{i,j} c_{ijk}\, \epsilon^i\, \hat{s}^j \ln^k(\hat{s})$
    - determine minimal set of c_{ijk} (`Kira`+`FireFly`)
    - evaluate minimal boundary constants analytically (in the large-mass expansion)
3. Expand around a new point $\hat{s} = \hat{s}_0$ (repeat the above, modify ansatz).
4. Match the expansions (numerically) at a point where they both converge.

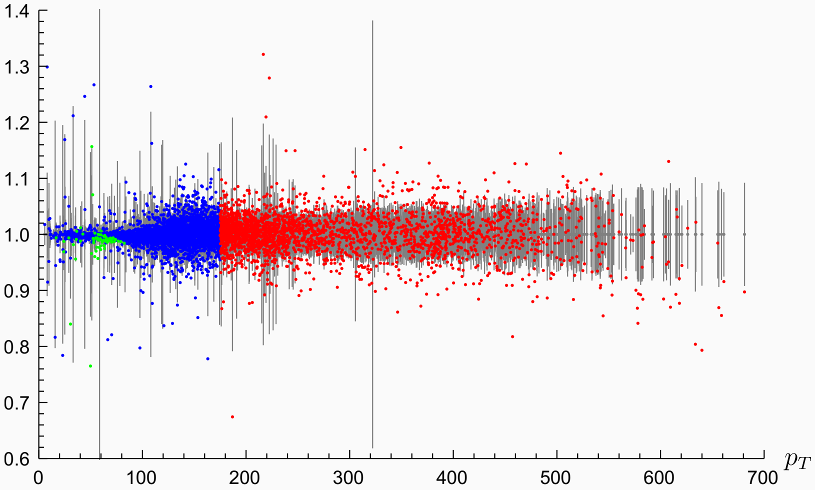
Here we have such “semi-analytic” expansions for the MIs at:

$$\hat{s} = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 16, 20, 25, 30, 40, 50, \infty\}$$

HE and $t \to 0$ Combination: "V_{fin}"

Comparison with `hhgrid`: [[https://github.com/mppmu/hhgrid]]

- merge both results, switch at $p_T = 175$ GeV.



● `pySecDec`

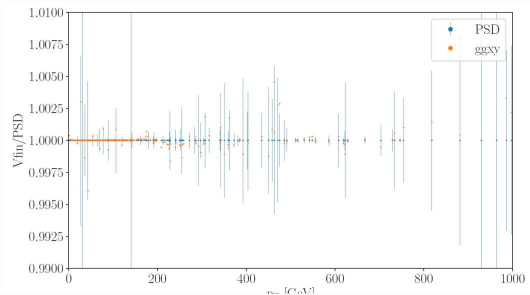
● small-t

● high-en.

● LME

Public implementation `ggxy`

- The results for the form factors are implemented in the public library `ggxy`: `https://gitlab.com/ggxy/ggxy-release`
    - Implementation is validated against results in the literature (where available):



[Chen, Heinrich, Jones, Kerner, Klappert, Schlenk '21]

- At NLO new partonic processes at 1-loop order: $\boxed{gg \to ZHg,\; qg \to ZHq,\; q\bar{q} \to ZHg}$
    - Implemented with the packages Recola, Collier, CutTools and OneLOop

[Actis, Denner, Hofer, Lang, Scharf, Uccirati '17; Denner, Dittmaier, Hofer '17; Ossolo, Papadopoulos, Pittau '09; Hameren '11]

⇒ fast evaluation of NLO corrections for $gg \to ZH$ with full flexibility of input parameters

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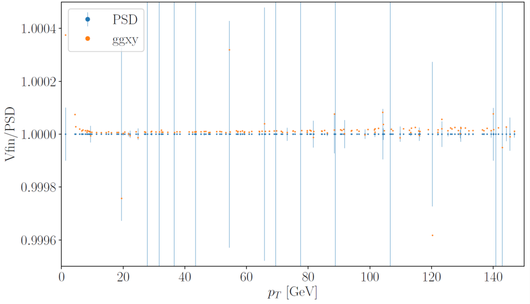

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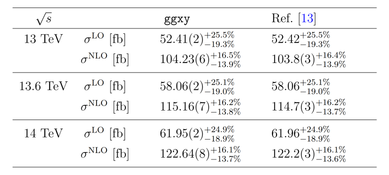
⇒ fast evaluation of NLO corrections for $gg \to ZH$ with full flexibility of input parameters

Cross section – $gg \to ZH$

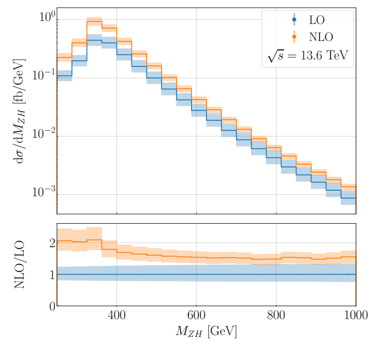
- NLO QCD corrections are large:

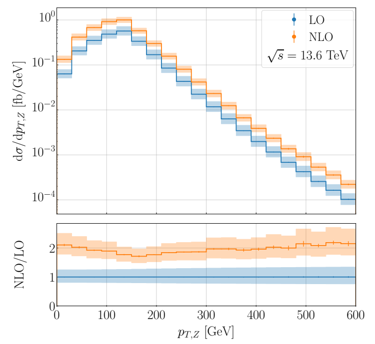
  K-factor ~ 2

- Scale uncertainty reduced, but not negligible.



$\sqrt{s}$		ggxy	Ref. [13]
13 TeV	σ^{LO} [fb]	$52.41(2)^{+25.5\%}_{-19.3\%}$	$52.42^{+25.5\%}_{-19.3\%}$
	σ^{NLO} [fb]	$104.23(6)^{+16.5\%}_{-13.9\%}$	$103.8(3)^{+16.4\%}_{-13.9\%}$
13.6 TeV	σ^{LO} [fb]	$58.06(2)^{+25.1\%}_{-19.0\%}$	$58.06^{+25.1\%}_{-19.0\%}$
	σ^{NLO} [fb]	$115.16(7)^{+16.2\%}_{-13.8\%}$	$114.7(3)^{+16.2\%}_{-13.7\%}$
14 TeV	σ^{LO} [fb]	$61.95(2)^{+24.9\%}_{-18.9\%}$	$61.96^{+24.9\%}_{-18.9\%}$
	σ^{NLO} [fb]	$122.64(8)^{+16.1\%}_{-13.7\%}$	$122.2(3)^{+16.1\%}_{-13.6\%}$



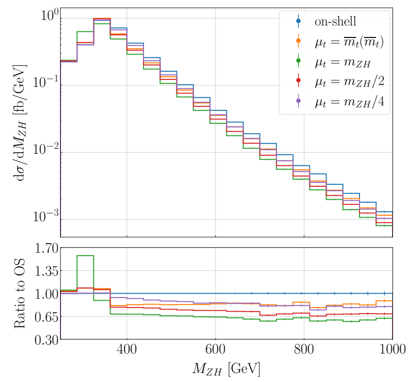


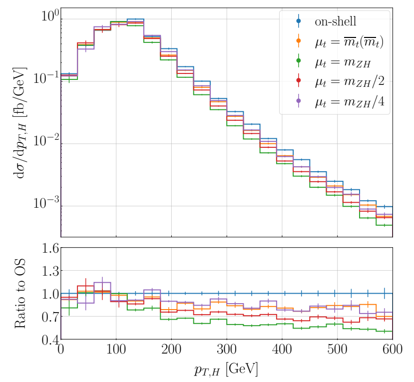
Total cross section – Top quark renormalization scheme

- The top quark mass can be renormalized in different schemes:

$$\boxed{m_t^{\mathrm{OS}} = \bar{m}_t(\mu_t)\left(1+\frac{\alpha_s(\mu_r)}{4\pi}\left\{4+3\ln\left(\frac{\mu_t^2}{\bar{m}_t(\mu_t)^2}\right)\right\}+\ldots\right)}$$

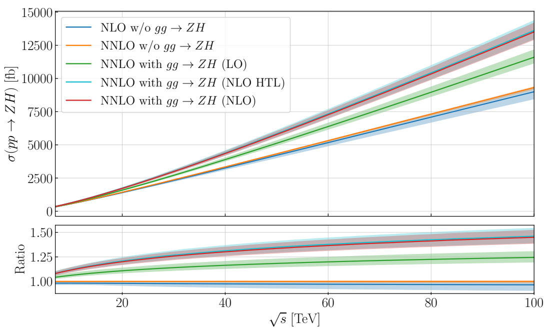
- The flexibility of `ggxy` allows for a change of all input parameters.
- We see large scheme uncertainties due to the top quark mass.

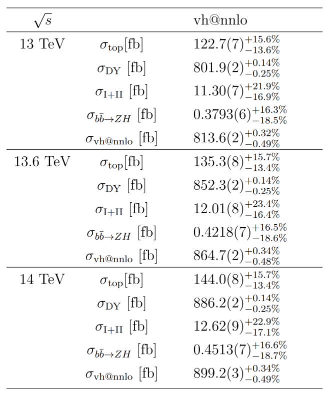




Total cross section – Including Drell-Yan like contributions

- $gg \to ZH$ introduces large scale uncertainties
- $gg \to ZH$ becomes more important at high energies
  $\Rightarrow$ boosted analysis
- large-m_t reproduces total cross-section at the $1-2\%$ level
  - same order of magnitude as N3LO Drell-Yan
  - calculate NNLO large-m_t completely

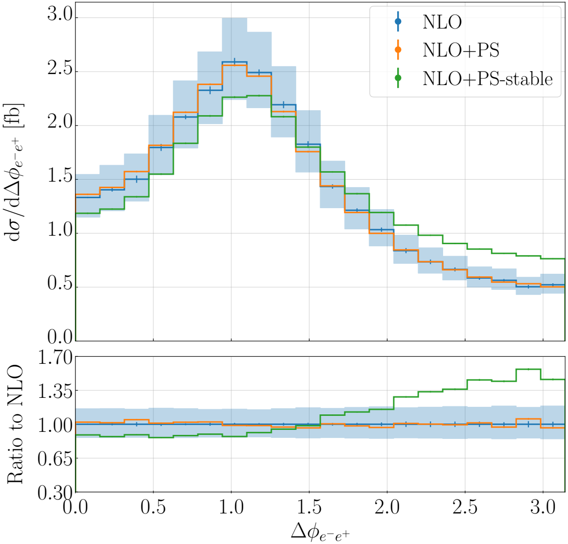




$\sqrt{s}$		vh@nnlo
13 TeV	σ_{top}[fb]	$122.7(7)^{+15.6\%}_{-13.6\%}$
	σ_{DY} [fb]	$801.9(2)^{+0.14\%}_{-0.25\%}$
	$\sigma_{\text{I+II}}$ [fb]	$11.30(7)^{+21.9\%}_{-16.9\%}$
	$\sigma_{b\bar{b}\to ZH}$ [fb]	$0.3793(6)^{+16.3\%}_{-18.5\%}$
	$\sigma_{\text{vh@nnlo}}$ [fb]	$813.6(2)^{+0.32\%}_{-0.49\%}$
13.6 TeV	σ_{top}[fb]	$135.3(8)^{+15.7\%}_{-13.4\%}$
	σ_{DY} [fb]	$852.3(2)^{+0.14\%}_{-0.25\%}$
	$\sigma_{\text{I+II}}$ [fb]	$12.01(8)^{+23.4\%}_{-16.4\%}$
	$\sigma_{b\bar{b}\to ZH}$ [fb]	$0.4218(7)^{+16.5\%}_{-18.6\%}$
	$\sigma_{\text{vh@nnlo}}$ [fb]	$864.7(2)^{+0.34\%}_{-0.48\%}$
14 TeV	σ_{top}[fb]	$144.0(8)^{+15.7\%}_{-13.4\%}$
	σ_{DY} [fb]	$886.2(2)^{+0.14\%}_{-0.25\%}$
	$\sigma_{\text{I+II}}$ [fb]	$12.62(9)^{+22.9\%}_{-17.1\%}$
	$\sigma_{b\bar{b}\to ZH}$ [fb]	$0.4513(7)^{+16.6\%}_{-18.7\%}$
	$\sigma_{\text{vh@nnlo}}$ [fb]	$899.2(3)^{+0.34\%}_{-0.49\%}$

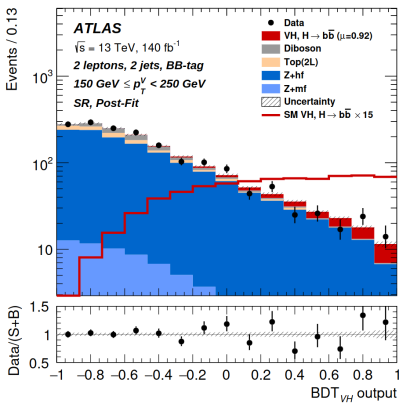
Total cross section – Including the leptonic decay

- ggxy is linked to the Monte-Carlo event generator POWHEG to allow also for the matching to parton shower.
- The Z boson decays further into a $\ell^+\ell^-$ pair $\Rightarrow$ spin correlations between the Z boson and the leptons are important



Experimental status

- ATLAS analysis of $pp \to VH$ [JHEP 04 (2025) 075]
- Extract information on Higgs-bottom(charm) interaction.
- Statistical and systematic uncertainties have the same magnitude.
- Theoretical systematics dominated by signal modelling $\Rightarrow$ inclusion of higher order results will improve this in the future



$$\mu_{VH}^{bb} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\,(\text{Stat.})^{+0.13}_{-0.11}\,(\text{Syst.}),$$

$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{Stat.})^{+3.7}_{-3.5}\,(\text{Syst.}).$$

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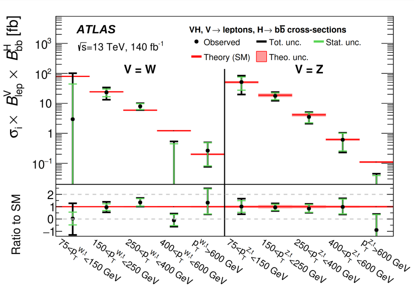

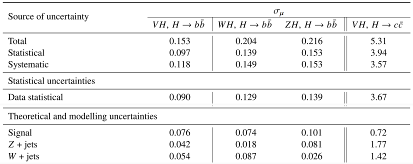

Source of uncertainty	σ_μ			
	$VH, H \to b\bar{b}$	$WH, H \to b\bar{b}$	$ZH, H \to b\bar{b}$	$VH, H \to c\bar{c}$
Total	0.153	0.204	0.216	5.31
Statistical	0.097	0.139	0.153	3.94
Systematic	0.118	0.149	0.153	3.57
Statistical uncertainties				
Data statistical	0.090	0.129	0.139	3.67
Theoretical and modelling uncertainties				
Signal	0.076	0.074	0.101	0.72
Z + jets	0.042	0.018	0.081	1.77
W + jets	0.054	0.087	0.026	1.42

Conclusions and Outlook

Conclusions and Outlook

Conclusions:

- $pp \to ZH$ is an important channel to measure the Higgs-bottom coupling.
- The production channel $gg \to ZH$ is suppressed in α_s but important.
- We have implemented the 2-loop corrections to $gg \to ZH$ with analytical expansions:
  - coverage of the full phase space
  - fast evaluation
  - already successfully applied for double Higgs production
- We have implemented NLO QCD QCD corrections to $gg \to ZH$ in c++ library ggxy:
  - input parameters such as masses and top mass renormalization scheme can be chosen freely
  - we provide leptonic decays of the Z boson: $Z \to \ell^+\ell^-$, $Z \to \nu_\ell \bar{\nu}_\ell$
  - useful to directly compute hadronic cross sections or as a matrix element provider for MC programs like POWHEG

Conclusions and Outlook

Outlook:

- The approach can be used for other important signatures at the LHC like $gg \to ZZ$.
- We are working on including EW corrections to $gg \to HH$ and later $gg \to ZH$.
- A complete NNLO computation for $gg \to ZH$ in the large-m_t limit might be useful for the total cross-section.
- Reduction of top mass scheme will require a full NNLO calculation.

Thank You!

Calculation of boundary conditions – Example

- E.g. we find:

$$\boxed{I_3 = m_t^{-4\epsilon+2} \int \frac{dz_1}{2\pi i} \frac{\Gamma\left[-z_1, z_1-\epsilon+2, -z_1+\epsilon-1, z_1+1, z_1+1, z_1+\epsilon\right]}{\Gamma\left[2-\epsilon, 2z_1+2\right]}}$$

- We use `MB` [Czakon '05] for the analytic continuation in ϵ:

$$I_3 = m_t^{-4\epsilon+2} e^{-2\epsilon\gamma_E} \left(-\frac{3}{2\epsilon^2} - \frac{9}{2\epsilon} - \frac{21}{2} - \frac{5\pi^2}{12} + I^{(MB)} + \mathcal{O}(\epsilon) \right)$$

with the remaining integral

$$I^{(MB)} = \int_{-1/7-i\infty}^{-1/7+i\infty} \frac{dz_1}{2\pi i} \frac{\Gamma\left[-z_1-1, -z_1, z_1, z_1+1, z_1+1, z_1+2\right]}{\Gamma\left[2z_1+2\right]}$$

Calculation of boundary conditions – Example

- We can close the contour to the right and sim the residues at $\boxed{z_1 = 0, 1, 2, \ldots}$:

$$I^{(MB)} = \int\limits_{-1/7-i\infty}^{-1/7+i\infty} \frac{dz_1}{2\pi i} \frac{\Gamma\left[-z_1-1, -z_1, z_1, z_1+1, z_1+1, z_1+2\right]}{\Gamma\left[2z_1+2\right]}$$

$$= 4 + \frac{\pi^2}{6} + 2\sum_{k=0}^{\infty} \binom{2k+1}{k}^{-1} \frac{(4k^2+8k+3)\left[S_1(k) - S_1(2k)\right] - 4(k+1)}{(2k+1)(2k+2)(2k+3)^3}$$

- Summation over residues can be done analytically with `HarmonicSums` [Ablinger et al. '10-] , `Sigma` and `EvaluateMultiSums` [Schneider et al. '07-] .
- The (inverse) binomial sums we encounter sum to generalized iterated integrals and special constants, e.g.:

$$\boxed{\sum_{k=0}^{\infty} x^k \binom{2k+1}{k}^{-1} \frac{1}{3+2k} = \frac{2}{x\sqrt{(4-x)x}} \int\limits_0^x dt \sqrt{(4-t)t} - 1 \overset{x\to 1}{=} \frac{4\pi}{3\sqrt{3}} - 2}$$

Calculation of boundary conditions – Example

- Non-planar master integrals also have regions which scale in odd powers of m_t.
- Here elliptic constants appear:

$$
\begin{aligned}
c_Z &= \int_0^\infty \int_0^\infty \frac{\mathrm{d}\alpha_1\,\mathrm{d}\alpha_2}{\sqrt{\alpha_1\,\alpha_2\,(\alpha_1+\alpha_2+1)\,(\alpha_2\alpha_1+\alpha_1+\alpha_2)}} \\
&= \sum_{k=0}^{\infty} \frac{\Gamma^4(k+1/2)}{\pi\Gamma^2(k+1)\Gamma(2k+1)} \Big(8\log(2)+6S_{-1}(2k)\Big) \\
&= 4\sqrt{3}\,K^2\left(\frac{1}{2}-\frac{\sqrt{3}}{4}\right) \\
&= 17.69503190845430976423422874725504875106205943863 7\ldots
\end{aligned}
$$

- We were able to determine these constants utilizing `HarmonicSums` and the `PSLQ` algorithm.