$gg \to ZH$: Theory Status and Prospects

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The problem with $gg \to ZH$

VH Production at the LHC

Karlsruhe Institute of Technology

$pp \to VH$ is the most sensitive process to $H \to b\bar{b}$ [ATLAS-2007.02873, CMS-1808.08242]

- Work in progress on $H \to c\bar{c}$
  [ATLAS-2201.11428, CMS-2205.0555]
- Probe of VVH coupling
- Larger scale uncertainties in *ZH*

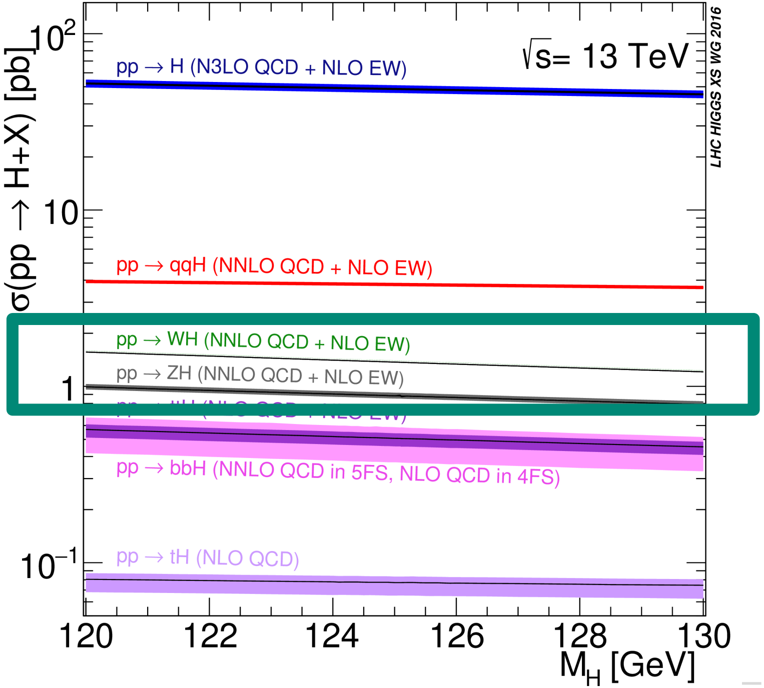
$pp \to WH$

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	1.358	$^{+0.51}_{-0.51}$	1.35
14	1.498	$^{+0.51}_{-0.51}$	1.35
27	3.397	$^{+0.29}_{-0.72}$	1.37

$pp \to ZH$

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.880	$^{+3.50}_{-2.68}$	1.65
14	0.981	$^{+3.61}_{-2.94}$	1.90
27	2.463	$^{+5.42}_{-4.00}$	2.24

[Cepeda et al. - 1902.00134]



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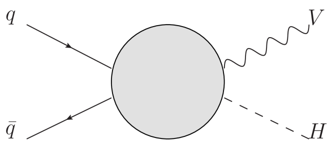
- Probe of VVH coupling

- Partonic channels

$pp \to W^+H$



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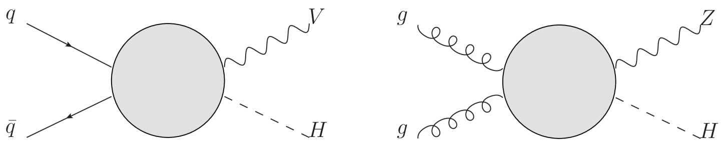
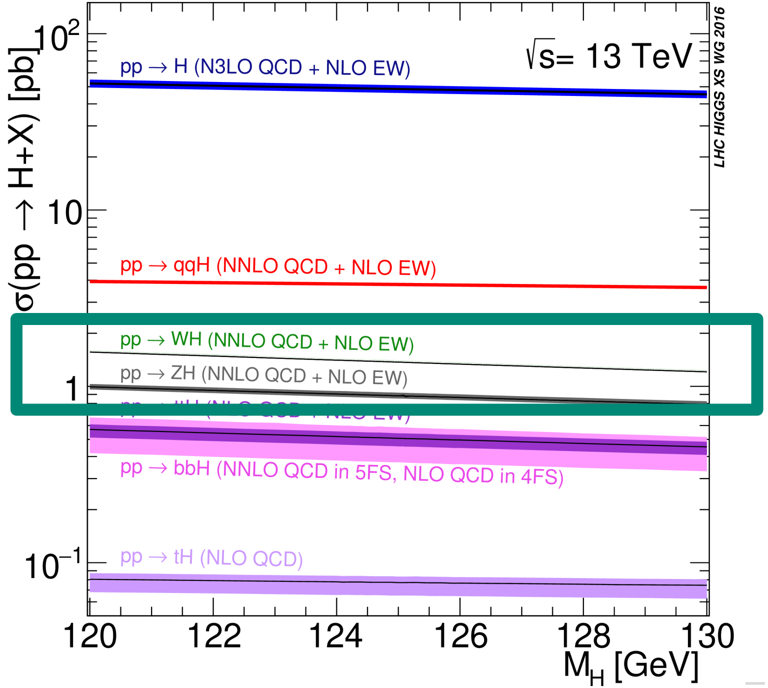


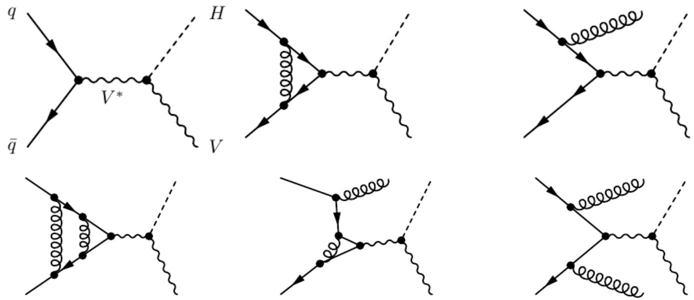


Theoretical Predictions for $pp \to ZH$

LO: quark-initiated tree-level contribution

QCD effects: mainly due to Drell-Yan (DY) production followed by $Z^* \to ZH$ decay

- **Drell-Yan**

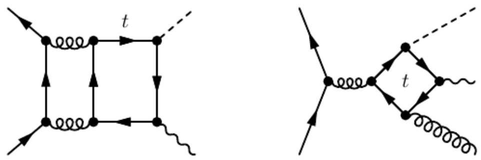


- Known through N3LO (+30% wrt LO)

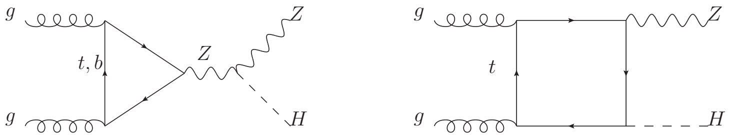
  [Han, Willenbrock ('91) ; Hamberg, van Neerven, Matsuura ('92) ; Brein, Djouadi, Harlander – 0307206; Baglio, Duhr, Mistlberger, Szafron - 2209.06138]

- **Non Drell-Yan - quark-initiated** O(1%) wrt LO

  [Brein, Harlander, Wiesemann, Zirke - 1111.0761]



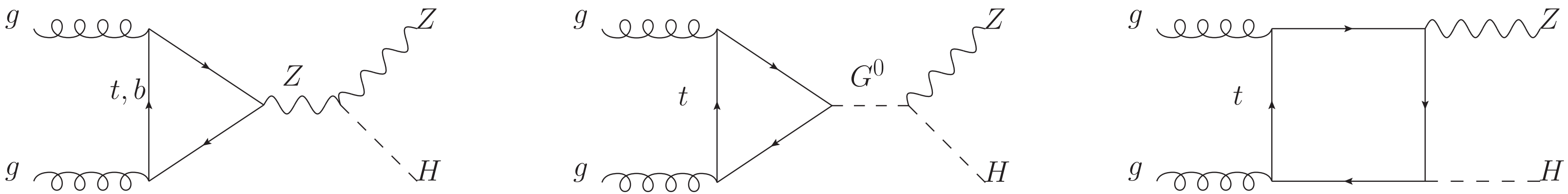
- **Non Drell-Yan - gluon-initiated**



EW corrections: known through NLO (-(5-10%) wrt LO)

[Dittmaier et al. - 1211.5015]

$gg \to ZH$ @ LO



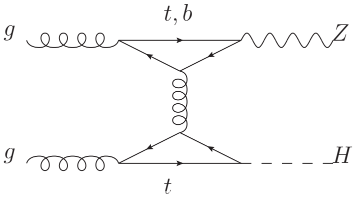
- Top-quark loops give dominant contribution [Kniehl ('90) - Dicus, Kao ('88)]
- O(α_s^2) correction to $\sigma(pp \to ZH)$
- NNLO suppression wrt to $q\bar{q} \to ZH$ compensated by larger gluon luminosity
- Contributes to ~ 6% of $\sigma(pp \to ZH)$ for $\sqrt{s} = 14$ TeV
- Only LO included in MC → scale variation leads to **25%** relative uncertainties

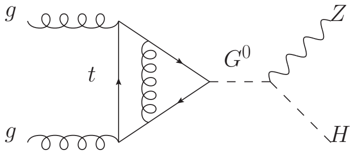
$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.123	$^{+24.9}_{-18.8}$	4.37
14	0.145	$^{+24.3}_{-19.6}$	7.47
27	0.526	$^{+25.3}_{-18.5}$	5.85

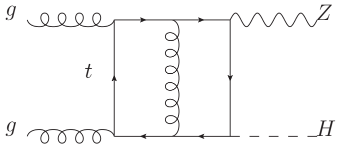
[Cepeda et al. - 1902.00134]

$gg \to ZH$ @ NLO in QCD - Ingredients

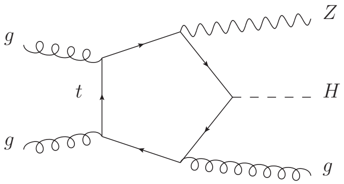
Virtual corrections (2→2, two loops) - interference with LO

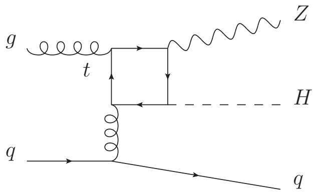


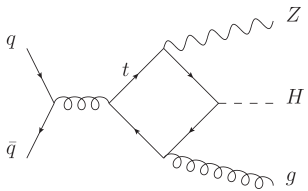




Real emission (2→3, one loop) - squared amplitudes

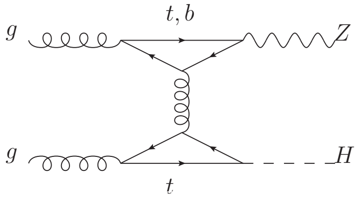


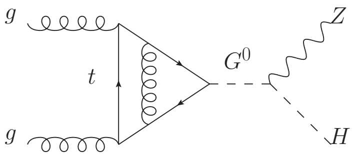


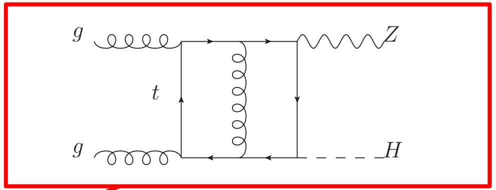


$gg \to ZH$ @ NLO in QCD - Ingredients

Virtual corrections ($2 \to 2$, two loops) - interference with LO







Main problem in the NLO calculation

Multi-scale (m_Z, m_H, m_t, s, t) two-loop box integrals

No full analytic results

Two-loop Massive Boxes for *gg*→*ZH*

Numerical Evaluation [Chen, Heinrich, Jones, Kerner, Klappert, Schlenk - 2011.12325]

- Exact results
- Demanding in terms of computing resources and time
- Issues with flexibility

Analytic Approximations: exploit **hierarchies** of masses/kinematic invariants

- Reduce the number of scales in Feynman integrals
- Proliferation of integrals
- Restricted to specific phase-space regions

- Limit $m_t \to \infty$
  [Altenkamp, Dittmaier, Harlander, Rzehak, Zirke - 1211.50]
- Large mass expansion
  [Hasselhuhn, Luthe, Steinhauser - 1611.05881]
- High-energy expansion: $m_Z^2, m_H^2 \ll m_t^2 \ll \hat{s}, \hat{t}$
  [Davies, Mishima, Steinhauser - 2011.12314]
- Small-mass expansion: $m_Z, m_H \to 0$
  [Wang, Xu, Xu, Yang - 2107.08206]
- pT expansion: $m_Z^2, m_H^2, p_T^2 \ll m_t^2, \hat{s}$
  [Alasfar, Degrassi, Giardino Groeber, MV – 2103.06225]

Latest Complete NLO Predictions

- Small-mass expansion [Wang, Xu, Xu, Yang - 2107.08206]

Virtual corrections

I. Expansion in $m_Z, m_H \to 0$ limit
II. Elliptic integrals evaluated numerically

Real emission

- Automated evaluation with GoSam [Cullen et al. - 1404.7096]

- Sector decomposition ⊕ High-Energy expansion [Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]

Virtual corrections

- pySecDec for $p_T < 200\,\mathrm{GeV}$
- HE exp for $p_T > 200\,\mathrm{GeV}$

Real emission

- GoSam & in-house C++ code

- pT expansion ⊕ High-Energy expansion [Degrassi, Gröber, MV, Zhao - 2205.02769]

Virtual corrections

- pT exp for $|\hat{t}| < 4m_t^2$
- HE exp for $|\hat{t}| > 4m_t^2$

Real emission

- RECOLA2 [Denner, Lang, Uccirati - 1711.07388]
- MadGraph5 [Alwall et al. - 1405.0301]

Comparing Validity Ranges

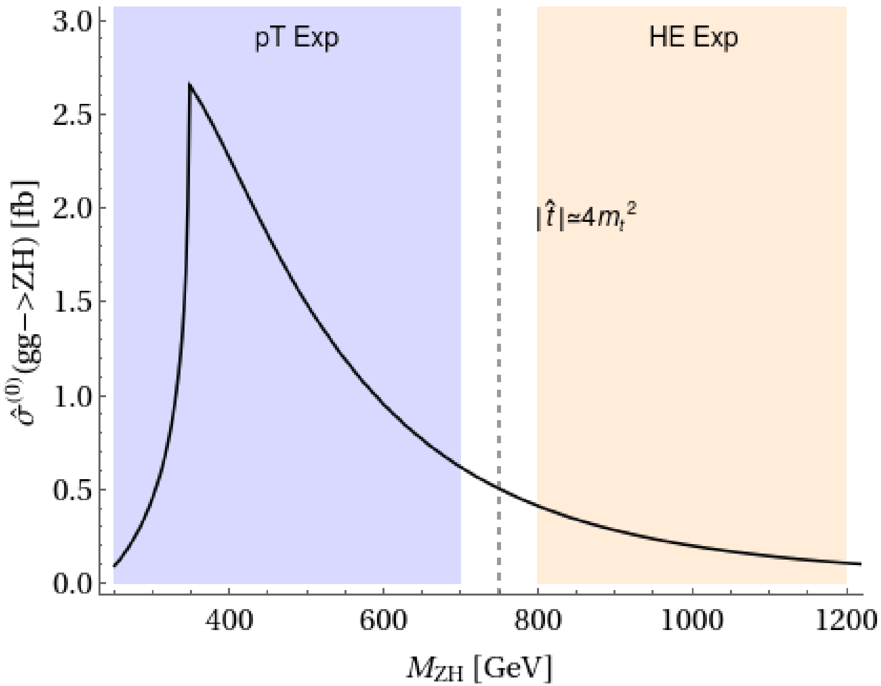
- p_T exp: valid for

$$p_T^2 \lesssim 4m_t^2$$

or

$$|\hat{t}| \lesssim 4m_t^2$$

[Alasfar, Degrassi, Giardino Groeber, MV – 2103.06225]



- High-Energy exp:

$$|\hat{t}| \gtrsim 4m_t^2$$

[Davies, Mishima, Steinhauser - 2011.12314]

The two expansions can be combined

(Needed refinement using Padé approximants)

[Bellafronte, Degrassi, Giardino, Gröber, MV -2103.06225]

- Accuracy at % level or below $\Rightarrow$ OK for phenomenology
- Evaluation time for a phase-space point below 0.1 *s* $\Rightarrow$ suitable for Monte Carlo

Results

$gg \to ZH$ @ NLO QCD – Inclusive Cross Section

Karlsruhe Institute of Technology

[Wang, Xu, Xu, Yang - 2107.08206]

$\sqrt{s} = 13\text{TeV}$

$\mu_r = \mu_f$	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)

[Chen et al. - 2204.05225]

$\mu_r = \mu_f = M_{ZH}$

$\sqrt{s}$	LO [fb]	NLO [fb]
13 TeV	$52.42^{+25.5\%}_{-19.3\%}$	$103.8(3)^{+16.4\%}_{-13.9\%}$
13.6 TeV	$58.06^{+25.1\%}_{-19.0\%}$	$114.7(3)^{+16.2\%}_{-13.7\%}$
14 TeV	$61.96^{+24.9\%}_{-18.9\%}$	$122.2(3)^{+16.1\%}_{-13.6\%}$

- General agreement between the three results when same inputs are adopted

[Degrassi, Gröber, MV, Zhao - 2205.02769]

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Top-mass scheme	LO [fb]	$\sigma_{LO}/\sigma^{OS}_{LO}$	NLO [fb]	$\sigma_{NLO}/\sigma^{OS}_{NLO}$	$K = \sigma_{NLO}/\sigma_{LO}$
On-Shell	$64.01^{+27.2\%}_{-20.3\%}$	—	$118.6^{+16.7\%}_{-14.1\%}$	—	1.85
$\overline{\text{MS}}, \mu_t = M_{ZH}/4$	$59.40^{+27.1\%}_{-20.2\%}$	0.928	$113.3^{+17.4\%}_{-14.5\%}$	0.955	1.91
$\overline{\text{MS}}, \mu_t = m_t^{\overline{\text{MS}}}(m_t^{\overline{\text{MS}}})$	$57.95^{+26.9\%}_{-20.1\%}$	0.905	$111.7^{+17.7\%}_{-14.6\%}$	0.942	1.93
$\overline{\text{MS}}, \mu_t = M_{ZH}/2$	$54.22^{+26.8\%}_{-20.0\%}$	0.847	$107.9^{+18.4\%}_{-15.0\%}$	0.910	1.99
$\overline{\text{MS}}, \mu_t = M_{ZH}$	$49.23^{+26.6\%}_{-19.9\%}$	0.769	$103.3^{+19.6\%}_{-15.6\%}$	0.871	2.10

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- NLO corrections are the same size as LO

[Degrassi, Gröber, MV, Zhao - 2205.02769]

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- Scale uncertainties reduced by ~30% wrt LO

[Degrassi, Gröber, MV, Zhao - 2205.02769]

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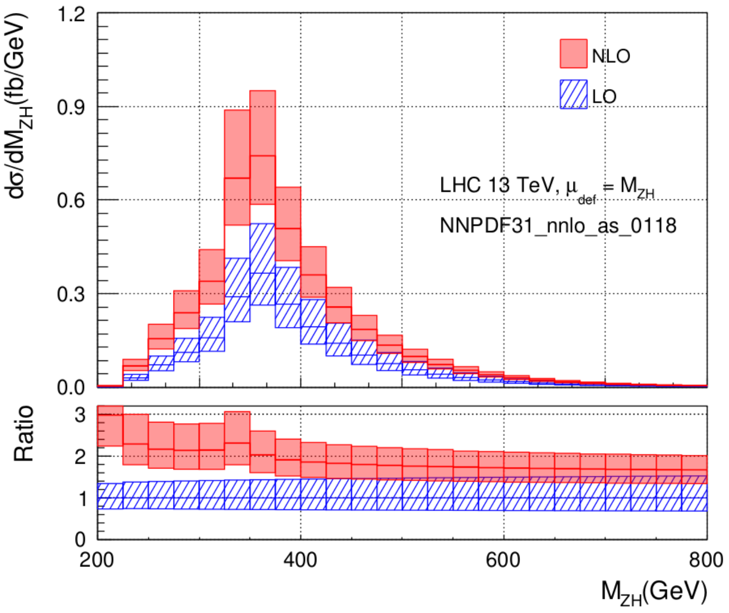
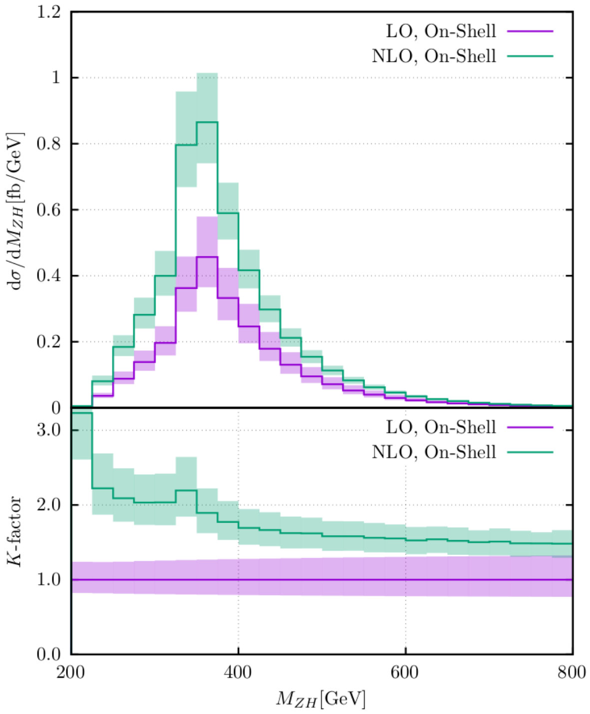
Invariant-Mass Distribution

- K-factor not flat in the low-energy region



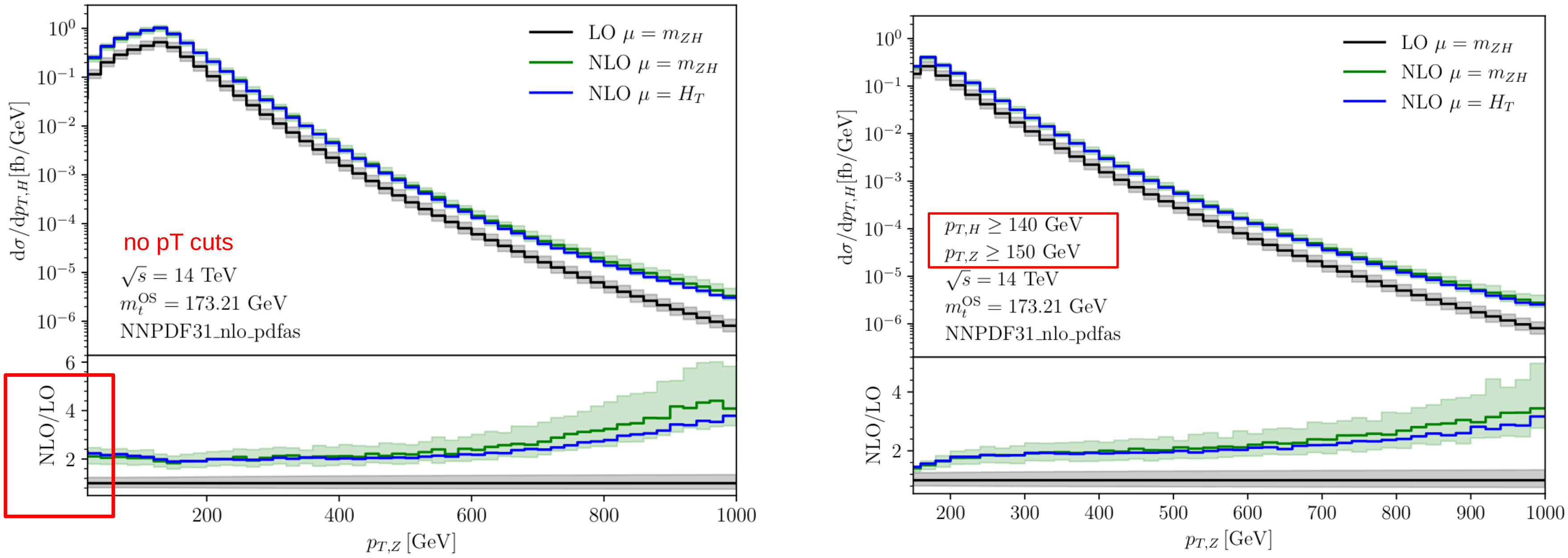


[Wang, Xu, Xu, Yang - 2107.08206]

[Degrassi, Gröber, MV, Zhao - 2205.02769]

High-Energy Tails I – pT Distributions

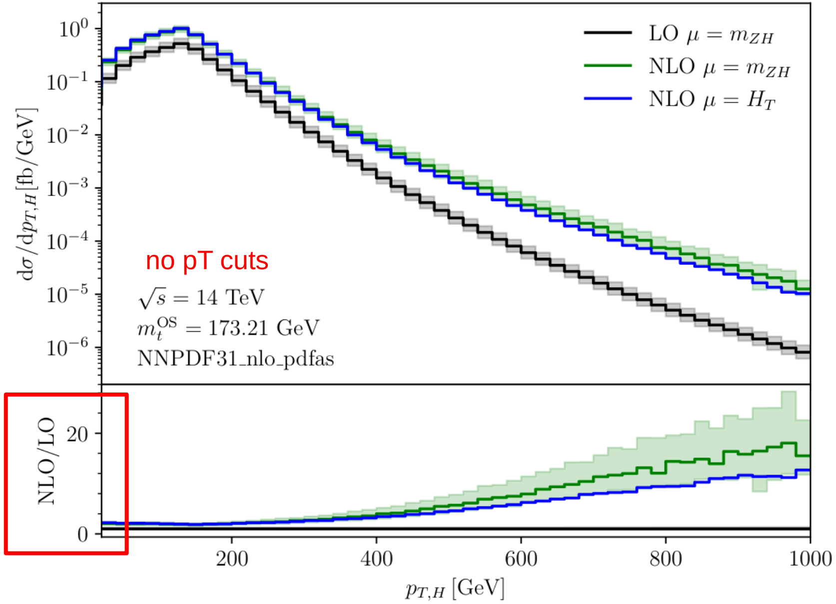
- K-factor increasing for $p_{T,Z} > 600\,\mathrm{GeV}$
- Not very sensitive to pT cuts

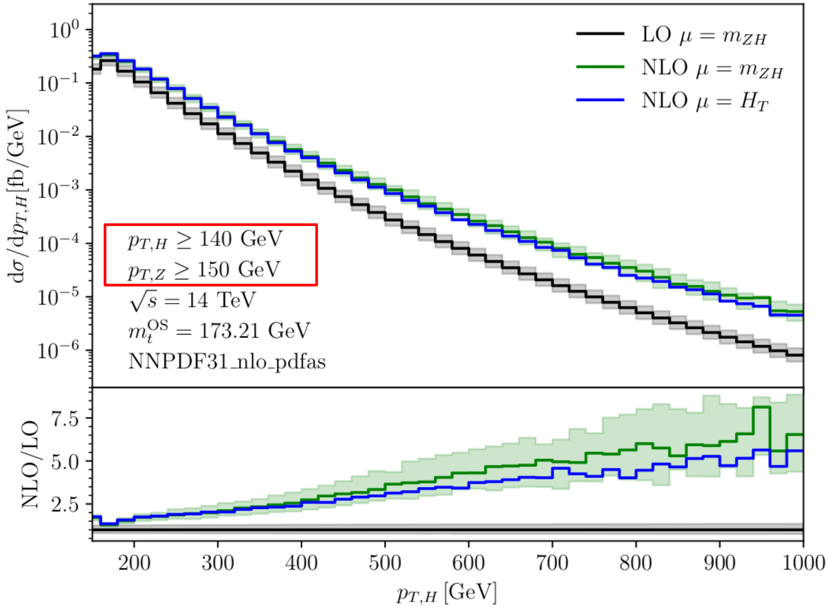


[Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]

High-Energy Tails I – pT Distributions

- Very large NLO corrections for $p_{T,H} > 400\,\mathrm{GeV}$
- Still K-factor of ~5 after pT cuts



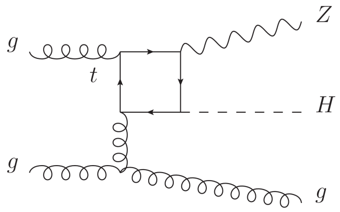


[Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]

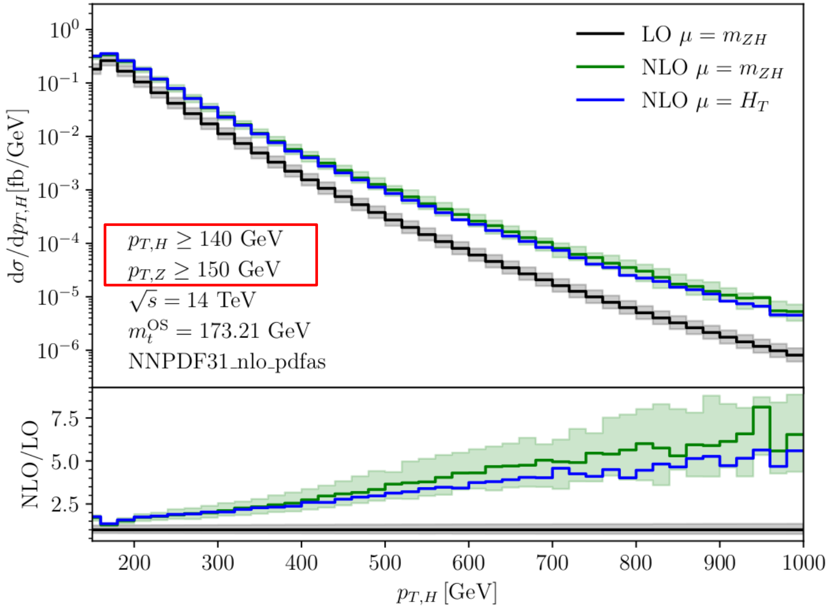
High-Energy Tails I – pT Distributions

- Very large NLO corrections for $p_{T,H} > 400\,\mathrm{GeV}$
- Still K-factor of ~5 after pT cuts

- The pT cuts remove 2→3 configurations with a hard jet and a soft Z
- These are very likely in the high-energy region



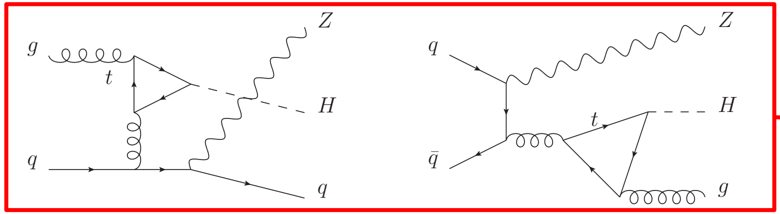
Observed in [Hespel, Maltoni, Vryonidou -1503.01656]



[Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser - 2204.05225]

High-Energy Tails II – Z Radiation

- K-factor rapidly increasing for $M_{ZH} > 1\,\mathrm{TeV}$
- Effect due to real-emission diagrams where the *Z* is radiated from an open fermion line
- Not included in [Wang, Xu, Xu, Yang - 2107.08206] [Chen et al. - 2204.05225] (can be attributed to DY process)



Dominant

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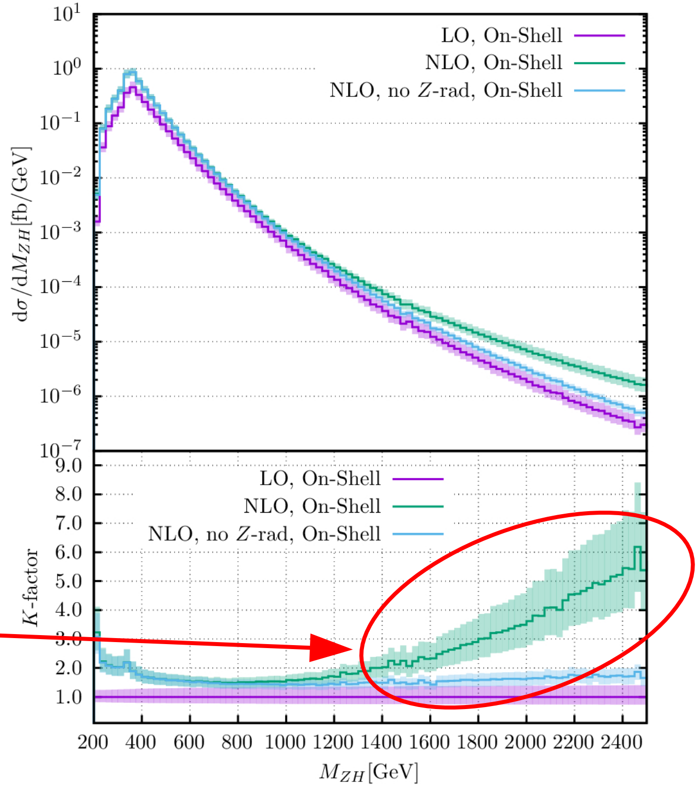
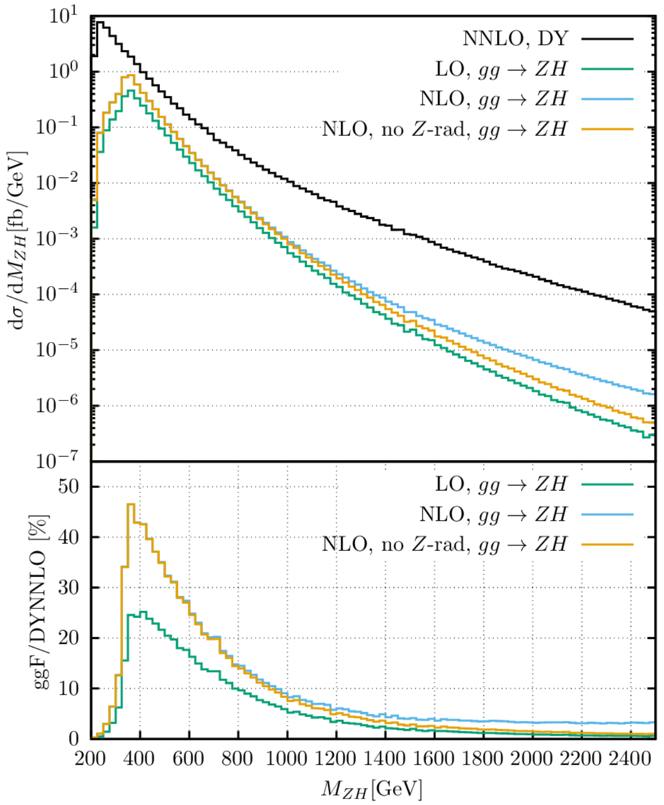


[Degrassi, Gröber, MV, Zhao - 2205.02769]

$gg \to ZH$ @ NLO vs Drell-Yan contribution

- $gg \to ZH$ is almost 50% of DY near $M_{ZH} \sim 2\,m_t$
- Because of Z-radiated diagrams the gg contribution falls off as rapidly as the DY one (ratio constant at ~ 2%)
- DY obtained using **vh@nnlo**
  [Harlander et al - 1802.04817]



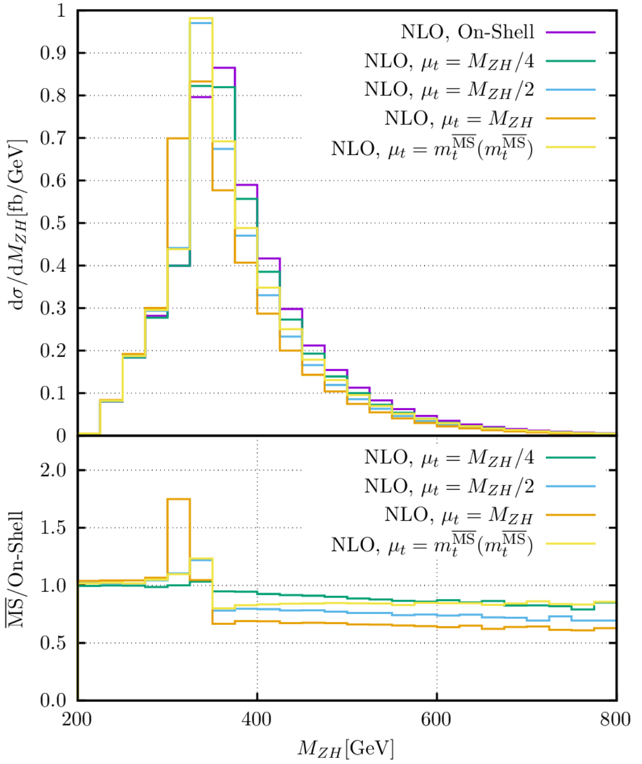
[Degrassi, Gröber, MV, Zhao - 2205.02769]

Top Mass Scheme Uncertainty

- Envelope of deviations of $\overline{\text{MS}}$ schemes wrt OS result
  Same method already used for HH production
  [Baglio et al. - 1811.05692, 2003.03227]
- Uncertainty sensitive to the binning of top-pair threshold peak

Avoid overestimate of uncertainty

Bin Width [GeV]	LO	NLO
1	$64.01^{+15.6\%}_{-35.9\%}$	$118.6^{+17.2\%}_{-27.0\%}$
5	$64.01^{+15.3\%}_{-35.6\%}$	$118.6^{+14.7\%}_{-24.9\%}$
25	$64.01^{+14.0\%}_{-33.1\%}$	$118.6^{+10.9\%}_{-20.8\%}$
100	$64.01^{+2.0\%}_{-25.3\%}$	$118.6^{+0.6\%}_{-13.7\%}$
∞	$64.01^{+0\%}_{-23.1\%}$	$118.6^{+0\%}_{-12.9\%}$



- Top-mass uncertainty ~ scale uncertainty
- Agreement with [Chen et al. - 2204.05225] for $M_{ZH} > 400\,\text{GeV}$

[Degrassi, Gröber, MV, Zhao - 2205.02769]

Conclusions

- Three (almost) independent predictions are in good agreement
- $gg \to ZH$ receives large NLO QCD corrections
- Enhanced importance wrt $qq \to ZH$ in differential distributions
- Combinations of different approaches (numerical, expansions…) crucial for virtual corrections

Outlook

- Agree on a unified prediction - work in progress from [Chen et al. - 2204.05225] [Degrassi, Gröber, MV, Zhao - 2205.02769]
- Improve understanding of high-energy tails of distributions
- Understand better top-mass scheme uncertainties
- Computation of NNLO QCD corrections may be desirable for complete control over scale uncertainties

Thank you for your attention

Backup

pT Expansion - Calculation Overview

1. Generation of Feynman diagrams - O(100 diags) (FeynArts [Hahn - 0012260])

2. Lorentz decomposition of the amplitude: **projectors** and **scalar form factors** (FeynCalc [Mertig et al. ('91) ; Shtabovenko et al. - 1601.01167]): contractions, Dirac traces...

$$\mathcal{A}_{\mu\nu\rho} = \sum_{i=1}^{6} \mathcal{P}^{(i)}_{\mu\nu\rho} F^{(i)} \qquad F^{(i)} = \sum_{i=1}^{n} C^{(i)}\ I^{(i)}(\hat{s}, \hat{t}, m_Z^2, m_H^2, m_t^2)$$

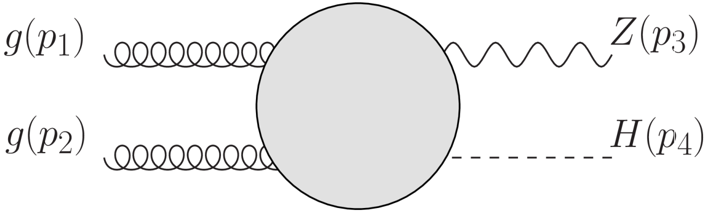
3. Expansion of the form factors in the limit of small pT

4. Decomposition of scalar integrals using integration-by-parts (IBP) identities (LiteRed [Lee - 1310.1145])

5. Evaluation of master integrals

Steps implemented in **Mathematica** code on a **desktop machine**

pT Expansion - Details



- We assume the limit of a **forward kinematics**

$$(p_1 + p_3)^2 \to 0 \Leftrightarrow \hat{t} \to 0 \Rightarrow p_T \to 0$$

- Then Taylor-expand the form factors in the ratios

$$\frac{m_H^2}{\hat{s}}, \frac{m_Z^2}{\hat{s}}, \frac{p_T^2}{\hat{s}} \ll 1 \qquad \frac{p_T^2}{4m_t^2} \ll 1$$

Expansion at integrand level

- Now scalar loop integrals depend on fewer scales

$$I(\hat{s}, \hat{t}, m_Z^2, m_H^2, m_t^2) \to I'(\hat{s}, \hat{t}, m_t^2)$$

- The new scalar integrals are decomposed in MIs using IBP relations
- The MIs depend on the ratio $\hat{s}/m_t^2 \Rightarrow$ **only one scale**

$$I(\hat{s}, \hat{t}, m_Z^2, m_H^2, m_t^2) \to I'(\hat{s}, \hat{t}, m_t^2) \to \mathrm{MI}(\hat{s}/m_t^2)$$

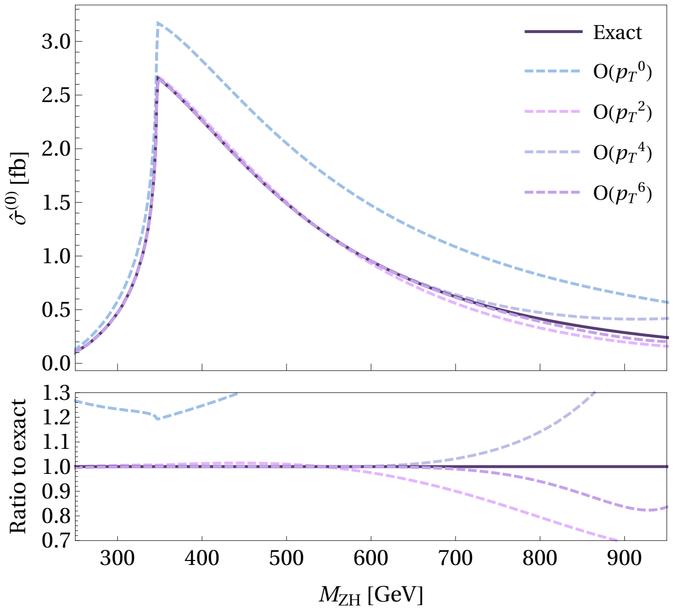
- 52 MIs already known in the literature
  SAME MIs FOR $gg \to HH$, $gg \to ZH$, $gg \to ZZ$

pT Expansion - LO Validation

- Three orders sufficient for very good accuracy
- Reliable results for $M_{ZH} \lesssim 700 \text{ GeV}$
- For $M_{ZH} \gtrsim 700 \text{ GeV}$ the assumption

$$p_T^2 \ll 4m_t^2$$

  can be violated $\Rightarrow$ the p_T expansion **diverges**



Merging pT and HE Expansions at NLO

Karlsruhe Institute of Technology

Improve the convergence of a series expansion by matching the coefficients of the **Pade approximant** [m/n] [e.g. Fleisher, Tarasov ('94)]

$$f(x) \overset{x\to 0}{\simeq} c_0 + c_1 x + \cdots + c_q x^q \qquad f(x) \simeq [m/n](x) = \frac{a_0 + a_1 x + \cdots + a_m x^m}{1 + b_1 x + \cdots + b_n x^n} \quad (q = m+n)$$

[Bellafronte, Degrassi, Giardino, Gröber, MV -2103.06225]

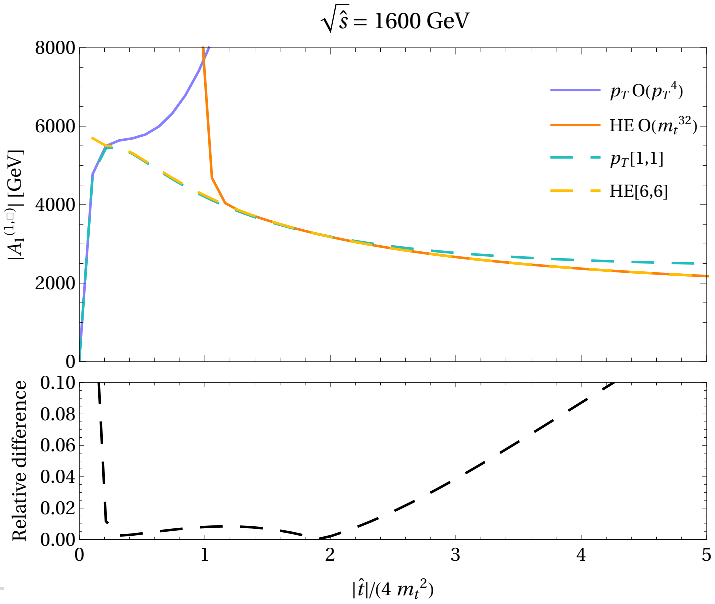
- For each FF we merged the following results

  - pT exp improved by [1/1] Padé

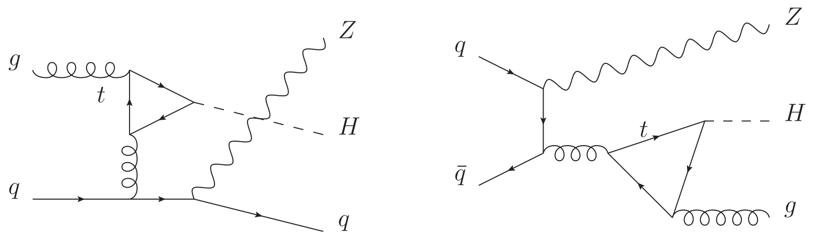
  - HE exp improved by [6/6] Padé

- Padé results are stable and comparable in the region $|\hat{t}| \sim 4 m_t^2 \rightarrow$ can switch without loss of accuracy (% level or below)

- Evaluation time for a phase-space point below 0.1 $s \Rightarrow$ suitable for Monte Carlo

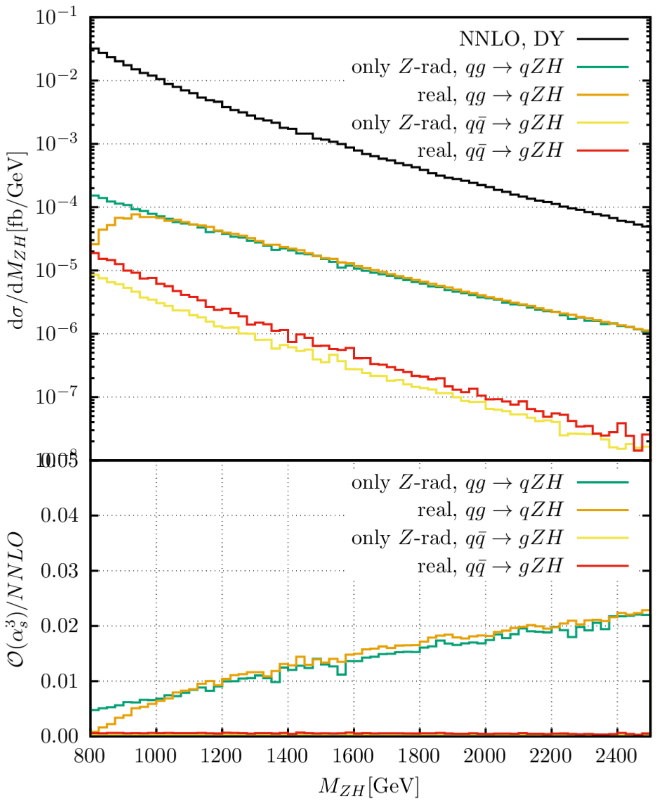


High-Energy Tails II – Z Radiation



In the high-energy tail (M_{ZH} > 1 TeV)

- **qg → ZHq channel**
  - Z-radiated diagrams dominate
  - Non-negligible contribution (up to 2% wrt DY)
- **$q\bar{q}$ → ZHg channel**
  - Z-radiated diagrams dominate
  - Negligible (PDF suppression)



[Degrassi, Gröber, MV, Zhao - 2205.02769]

Master Integrals – pT Expansion

- 50 MIs expressed in terms of Generalized Polylogarithms (GPLs)

  [Bonciani, Mastrolia, Remiddi ('03) - Aglietti et al. ('06) - Anastasiou et al. ('06) - Caron-Huot, Henn ('14) - Becchetti, Bonciani ('17) - Bonciani, Degrassi, Vicini ('10)]

- Two elliptic integrals [von Manteuffel, Tancredi ('17)]

  Semi-analytical evaluation implemented in FORTRAN routine

  [Bonciani, Degrassi, Giardino, Gröber ('18)]