Top-Quark Loops for Precision Higgs Physics

Marco Vitti (Karlsruhe Institute of Technology, TTP and IAP)

TUM/MPP Collider Phenomenology Seminar, Munich, 24 Jul 2024

Outline

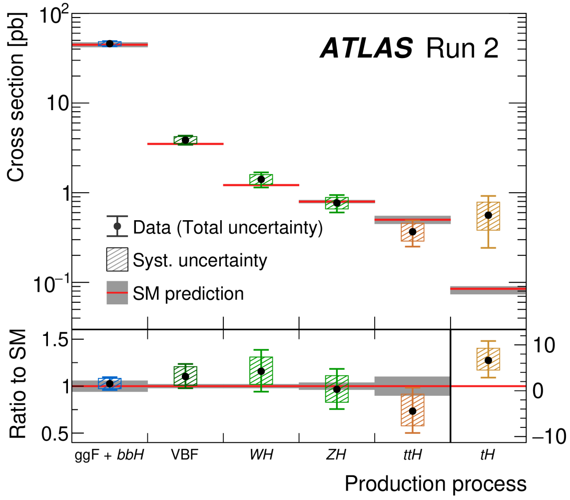
1. Precision Higgs physics at the LHC
2. Challenge: $2\to2$ with massive loops
3. Example: top-mediated $gg\to ZZ$ @NLO QCD
4. Towards NNLO QCD...
5. Conclusions

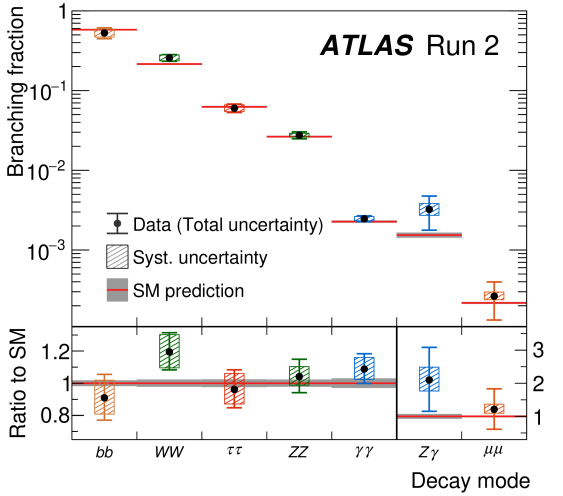
Higgs Physics at the LHC

Does the discovered Higgs boson behave as the SM predicts?

What we know after Run2 $(139\ \mathrm{fb}^{-1})$

- CP-even scalar
- Mass measured with **permille** precision
- Production and decay channels all compatible with SM predictions
- Experimental uncertainties in the 10-20% range





[ATLAS-2207.00092]

Higgs Physics at the LHC

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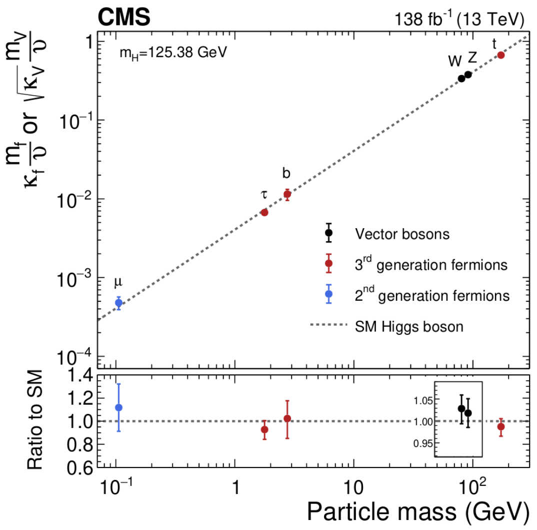
Does the discovered Higgs boson behave as the SM predicts?

$$V(h) = \frac{m_H^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

What we still don't know

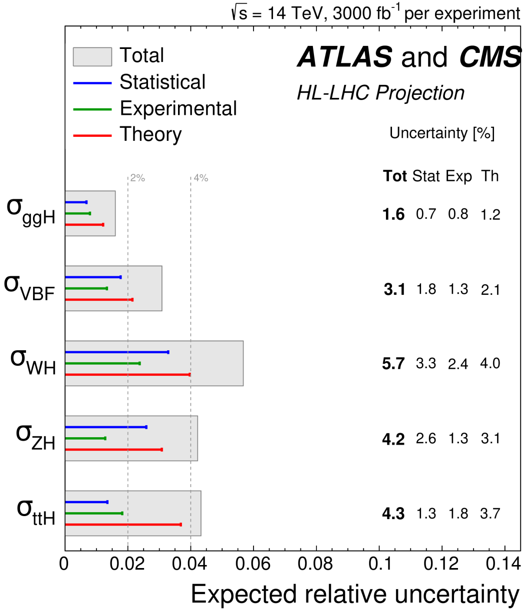
- Shape of the Higgs potential
- Yukawa couplings of first and second generation
- Higgs total decay width
- ...

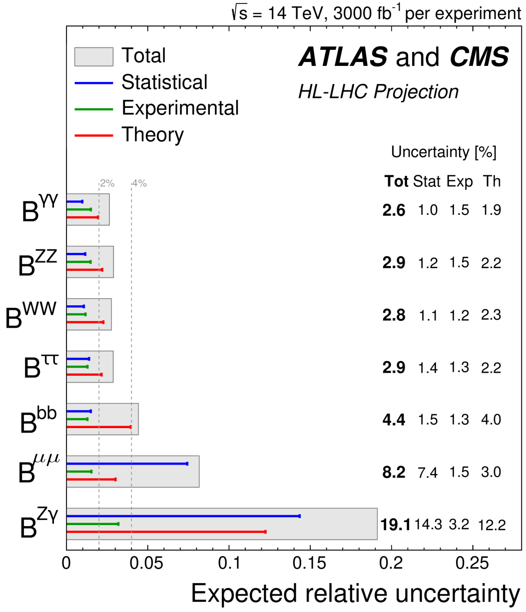


[CMS - 2207.00043]

Projections for High-Luminosity LHC

- Systematic uncertainties will play a very important role





[Cepeda et al. - 1902.00134]

- Theory uncertainties need to be reduced $\Rightarrow$ Improve predictions within the SM

Theory goal : **percent precision**

(Some) Theory Uncertainties

- Parametric uncertainties
- PDF determination
- Matching with parton showers

[THIS TALK]

- Missing higher orders in perturbative calculations
  Conventionally estimated by varying renormalization and factorization scales

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, \mu_F) f_j(x_2, \mu_F) \; \hat{\sigma}_{ij}(x_1, x_2, Q, \mu_F, \mu_R) + \mathcal{O}(\Lambda_{QCD}/Q)$$

$$\hat{\sigma}_{ij}(\mu_F, \mu_R) = \alpha_S^k(\mu_R) \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)}(\mu_F, \mu_R) \alpha_S^m(\mu_R)$$

Where to Look for Improvements?

Karlsruhe Institute of Technology

Les Houches precision wishlist [Huss et al. - 2207.02122]

Table 1. Precision wish list: Higgs boson final states. $\mathrm{N}^x\mathrm{LO}^{(\mathrm{VBF}*)}_{\mathrm{QCD}}$ means a calculation using the structure function approximation. $V = W, Z$.

Process	Known	Desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO}^{(t)}_{\mathrm{QCD}}$ $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO}^{(b,c)}_{\mathrm{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO^{(VBF*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO^{(VBF*)}_{QCD}}$ $\mathrm{NNLO^{(VBF)}_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NLO}^{(t,b)}_{gg\to HZ}$	
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HH + 2j$	$\mathrm{N^3LO^{(VBF*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

Table 3. Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

Process	Known	Desired
$pp \to V$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+\,\mathrm{NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$

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$pp \to H+j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
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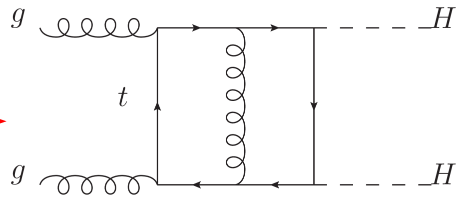
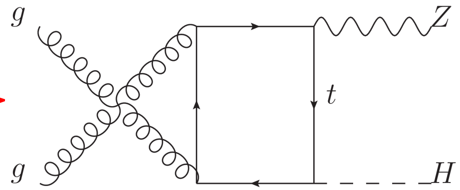
$pp \to V+b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV'+1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV'+2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$

Diboson Production (*gg*-initiated)

Process	Known	Desired
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$



Process	Known	Desired
$pp \to VH$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NLO}^{(t,b)}_{gg \to HZ}$	



Process	Known	Desired
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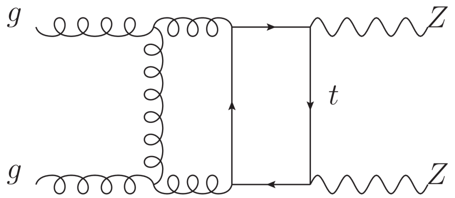


Typically receive large QCD corrections!

Multi-scale (m_t, s, t, m_{ext}) two-loop integrals

No full analytic results available

Two-loop Boxes with Massive Lines

Numerical Evaluation (Sector Decomposition)

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

[Borowka et al. - 1604.06447]
[Chen et al. - 2011.12325]
[Agarwal et al. - 2011.15113]

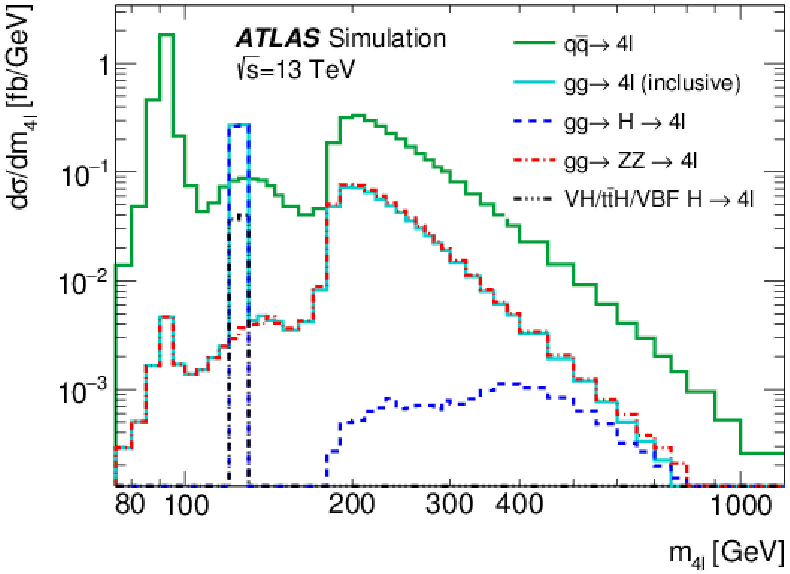
Analytic Approximations: exploit **hierarchies** of masses/kinematic invariants

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

- Limit $m_t \to \infty$
  [Dawson et al. - 9805244]
  [Altenkamp et al. - 1211.50]
  [Dowling, Melnikov – 1503.01274; Caola, et al. – 1605.04610]
- Large mass expansion (LME)
  [Grigo, Hoff, Steinhauser - 1508.00909]
  [Hasselhuhn, Luthe, Steinhauser - 1611.05881]
- High-energy expansion: $m_{\text{ext}}^2 \ll m_t^2 \ll \hat{s}, \hat{t}$
  [Davies, Mishima, Steinhauser, Wellmann - 2002.05558]
  [Davies, Mishima, Steinhauser – 2011.12314]
  [Davies, Mishima, Steinhauser, Wellmann - 2002.05558]
- Small-mass expansion: $m_{\text{ext}} \to 0$
  [Wang et al. - 2010.15649]
  [Wang, Xu, Xu, Yang - 2107.08206]
- pT expansion: $m_{\text{ext}}^2, p_T^2 \ll m_t^2, \hat{s}$
  [Bonciani, Degrassi, Giardino, Gröber - 1806.11564]
  [Alasfar, Degrassi, Giardino Groeber, MV – 2103.06225]
  [Degrassi, Gröber, MV - 2404.15113]

$pp \to ZZ$ at the LHC

- Probe of EW theory: polarisation measurements, “golden channel” for Higgs production
- Indirect access to Higgs width [Kauer, Passarino – 1206.4803] [Caola, Melnikov – 1307.4935] [Campbell, Ellis, Williams - 1311.3589]



[ATLAS – 1902.05892]

Compare on-shell and off-shell signal strengths

$$\mu_{\text{on}} = \frac{\kappa^2_{ggh}(m_h)\kappa^2_{hZZ}(m_h)}{\Gamma_h/\Gamma_h^{\text{SM}}}$$

$$\mu_{\text{off}} = \kappa^2_{ggh}(m_{ZZ})\kappa^2_{hZZ}(m_{ZZ})$$

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\text{MeV}$$

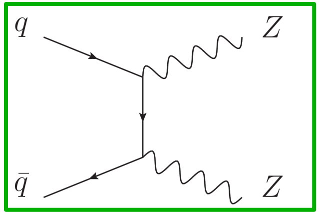
[CMS - 2202.06923]

$$\Gamma_H = 4.5^{+3.3}_{-2.5}\text{MeV}$$

[ATLAS - 2304.01532]

Accurate theoretical predictions needed in both regions!

Theoretical Predictions



Dominant contribution

NNLO QCD

[Brown, Mikaelian – ('79); Ohnemus, Owens - ('91); Mele, Nason, Ridolfi - ('91); Cascioli et al. - 1405.2219; Heinrich et al. - 1710.06294; Gehrmann et al. - 1404.4853; Caola et al. - 1408.6409; Gehrmann et al. - 1503.04812; Grazzini et al. - 1507.06257; Kallweit, Wiesemann - 1806.05941]

NLO EW

[Bierweiler et al. – 1305.5402; Baglio, Ninh, Weber – 1307.4331; Chiesa et al. - 2005.12146]

$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(1)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.09(2)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+7.0\%$	$+8.6\%$
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ggNLO$_{gg}$	$1.4787(4)^{+15.9\%}_{-13.1\%}$	$3.626(1)^{+15.2\%}_{-12.7\%}$	$+86.3\%$	$+80.8\%$
ggNLO	$1.3892(4)^{+15.4\%}_{-13.6\%}$	$3.425(1)^{+13.9\%}_{-12.0\%}$	$+75.1\%$	$+70.8\%$
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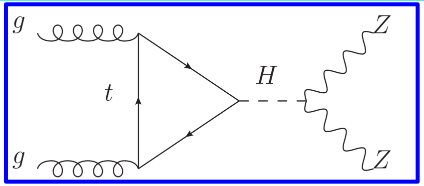
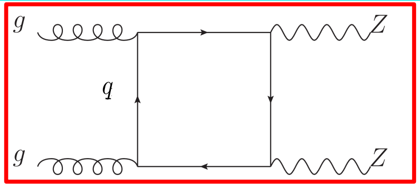
NNLO	$12.88(2)^{+2.8\%}_{-2.2\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	$+14.0\%$	$+18.7\%$
nNNLO	$13.48(2)^{+2.6\%}_{-2.3\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	$+19.3\%$	$+25.8\%$

[Grazzini, Kallweit, Wiesemann, Yook - 1811.09593]

Theoretical Predictions





LO loop-induced (α_s^2 correction)

[Dicus, Kao, Repko – ('87); Glover, Van der Bij – ('89)]

Contributes to ~10% of hadronic xsec

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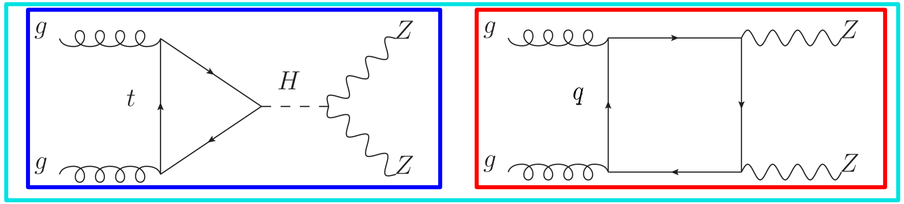
Theoretical Predictions



LO loop-induced (α_s^2 correction)

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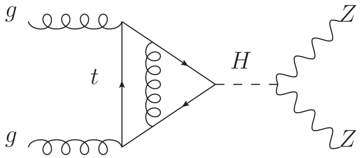
Virtual NLO QCD

Higgs-mediated

[Spira et al. - 9504378 ; Aglietti et al. - 0611266 ;
Harlander, Kant - 0509189; Anastasiou et al. - 0611236]



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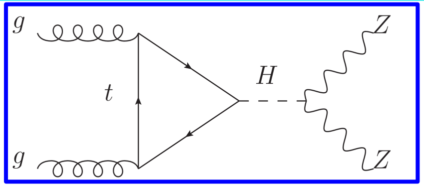

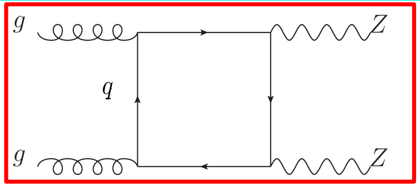

LO loop-induced (α_s^2 correction)

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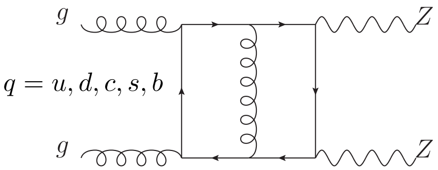
Virtual NLO QCD

Non-resonant (light quarks)

[von Manteuffel, Tancredi – 1503.08835;
Caola et al. - 1509.06734]



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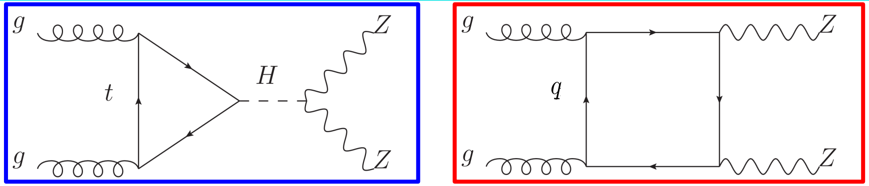
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.09(2)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+7.0\%$	$+8.6\%$
	σ [fb]		$\sigma/\sigma_{\rm ggLO} - 1$	
ggLO	$0.79355(6)^{+28.2\%}_{-20.9\%}$	$2.0052(1)^{+23.5\%}_{-17.9\%}$	0%	0%
ggNLO$_{gg}$	$1.4787(4)^{+15.9\%}_{-13.1\%}$	$3.626(1)^{+15.2\%}_{-12.7\%}$	$+86.3\%$	$+80.8\%$
ggNLO	$1.3892(4)^{+15.4\%}_{-13.6\%}$	$3.425(1)^{+13.9\%}_{-12.0\%}$	$+75.1\%$	$+70.8\%$
	σ [fb]		$\sigma/\sigma_{\rm NLO} - 1$	
NNLO	$12.88(2)^{+2.8\%}_{-2.2\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	$+14.0\%$	$+18.7\%$
nNNLO	$13.48(2)^{+2.6\%}_{-2.3\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	$+19.3\%$	$+25.8\%$

[Grazzini, Kallweit, Wiesemann, Yook - 1811.09593]

Theoretical Predictions



LO loop-induced (α_s^2 correction)

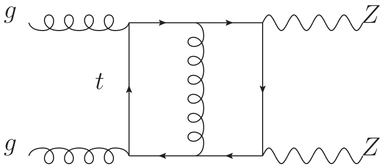
[Dicus, Kao, Repko – ('87); Glover, Van der Bij – ('89)]

Contributes to ~10% of hadronic xsec

Virtual NLO QCD

Non-resonant (top quark)

No exact results in full analytic form



$$\Rightarrow I(\hat{s}, \hat{t}, m_Z^2, m_t^2)$$

$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(1)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
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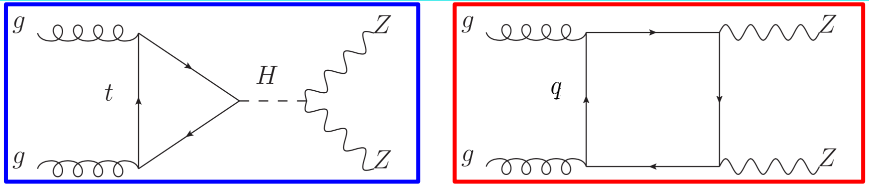
[Grazzini, Kallweit, Wiesemann, Yook - 1811.09593]

Theoretical Predictions



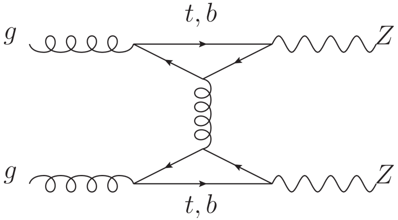
LO loop-induced (α_s^2 correction)

[Dicus, Kao, Repko – (‘87); Glover, Van der Bij – (‘89)]

Contributes to ~10% of hadronic xsec

Virtual NLO QCD

Double-Triangle diagrams
(Standard one-loop techniques)



$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
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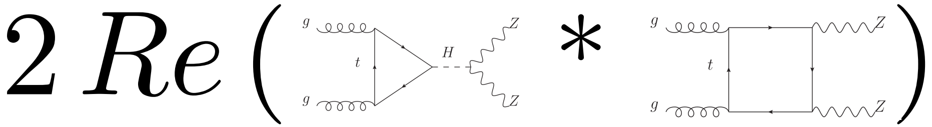
[Grazzini, Kallweit, Wiesemann, Yook - 1811.09593]

Importance of Top-Quark Effects

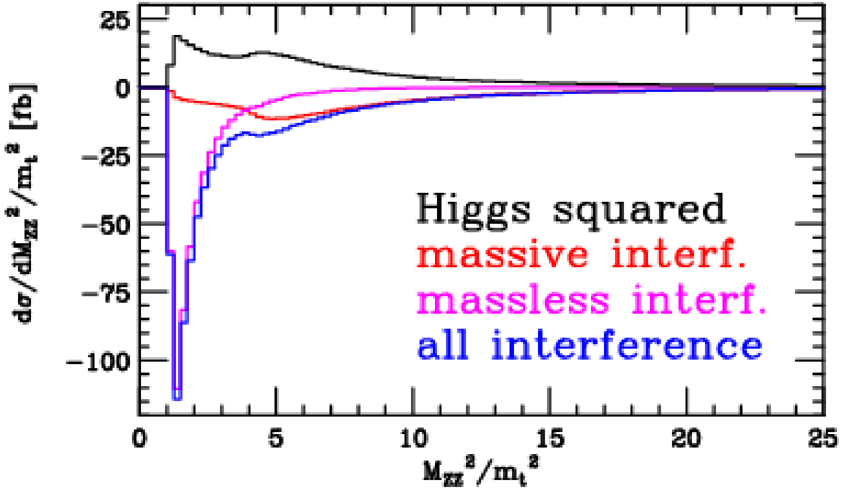


- Dominant contribution to Higgs-mediated/nonresonant interference for large invariant masses
- Exact numerical results available

  [Agarwal, Jones, von Manteuffel - 2011.15113 ; Brønnum-Hansen, Wang – 2101.12095]

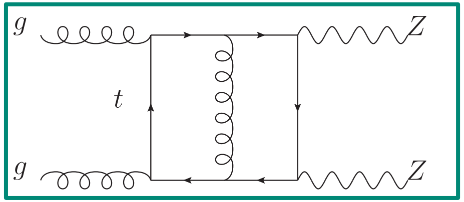
- Large effects found also at NLO QCD

  [Agarwal, Jones, Kerner, von Manteuffel - 2404.05684]



[Campbell et al. - 1605.01380]

Analytic Approximations



- Limit $m_t \to \infty$
  [Dowling, Melnikov – 1503.01274; Caola, et al. – 1605.04610]

- Large mass expansion (LME)
  [Campbell et al. - 1605.01380; Gröber, Maier, Rauh – 1908.04061]

- High-energy expansion: $m_Z^2 \ll m_t^2 \ll \hat{s}, \hat{t}$
  [Davies, Mishima, Steinhauser, Wellmann - 2002.05558]

This talk: pT expansion $m_Z^2, p_T^2 \ll m_t^2, \hat{s}$ [Degrassi, Gröber, MV - 2404.15113]

Previously applied to

$gg \to HH$ [Bonciani, Degrassi, Giardino, Gröber - 1806.11564]

$gg \to ZH$ [Alasfar, Degrassi, Giardino, Gröber, MV - 2103.06225]

pT Expansion - Calculation Overview

Karlsruhe Institute of Technology

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

2. Lorentz decomposition of the amplitude: contractions, Dirac traces... (FeynCalc [Shtabovenko et al. - 2001.04407])

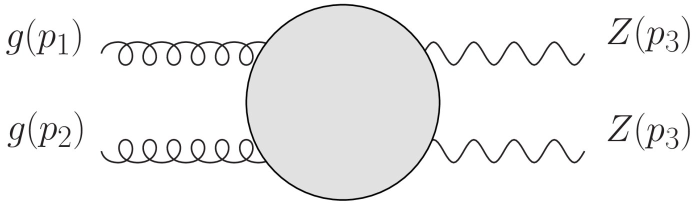
$$\mathcal{A}_{\mu\nu\rho\sigma} = \sum_{i=1}^{16} \mathcal{P}^{(i)}_{\mu\nu\rho\sigma}\, A^{(i)} \qquad A^{(i)} = \sum_{i=1}^{n} C^{(i)}\, I^{(i)}(\hat{s}, \hat{t}, m_Z^2, m_t^2)$$

3. Expansion of form factors in the limit of small p_T, m_Z (Mathematica)

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

5. Evaluation of master integrals

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

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

Expansion at integrand level

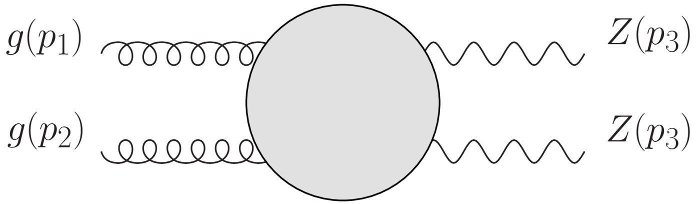
- After tensor + IBP reduction

$$\mathcal{A}_i = \mathcal{N}(p_T^2, m_Z^2) \sum_{N=0}^{\infty} \sum_{i+j=N} c_{ij}(\hat{s}/m_t^2)(p_T^2)^i (m_Z^2)^j$$

- The MIs depend on the ratio $\hat{s}/m_t^2 \Rightarrow$ **single-scale integrals!**

$$I(\hat{s}, p_T^2, m_Z^2, m_t^2) \to \mathrm{MI}(\hat{s}/mt^2)$$

pT Expansion - Example



1) Consider a **one-loop** box integral

$$\int d^D q \; \frac{(q^2)^{n_1}(q\cdot p_1)^{n_2}(q\cdot p_2)^{n_3}(q\cdot p_3)^{n_4}}{(q^2-m_t^2)[(q+p_2)^2-m_t^2][(q-p_1-p_3)^2-m_t^2][(q-p_1)^2-m_t^2]}$$

2) Focus on the p3-dependent part; explicit transverse momentum (Sudakov)

$$\frac{(q\cdot p_3)^{n_4}}{[(q-p_1-p_3)^2-m_t^2]}$$

$$p_3^\mu = -p_1^\mu - \frac{t'}{s'}(p_1-p_2)^\mu + r_\perp^\mu$$

$$r_\perp^2 = -p_T^2 \qquad \frac{t'}{s'} = -\frac{1}{2}\left\{1-\sqrt{1-2\frac{p_T^2+m_Z^2}{s'}}\right\}$$

3) In the forward limit $p_3^\mu \simeq -p_1^\mu$

$$\int d^D q \; \frac{(q^2)^{n_1}(q\cdot p_1)^{n_2'}(q\cdot p_2)^{n_3'}(q\cdot r_\perp)^{n_4'}}{(q^2-m_t^2)^{l_1}[(q+p_2)^2-m_t^2][(q-p_1)^2-m_t^2]}$$

4) Tensor + IBP reduction $\rightarrow$ Dependence on $r_\perp$ removed

pT Expansion - Two-Loop Master Integrals

- 52 MIs: same basis for $gg \to HH$, $gg \to ZH$

- 50 MIs expressed in terms of Generalized Harmonic Polylogarithms

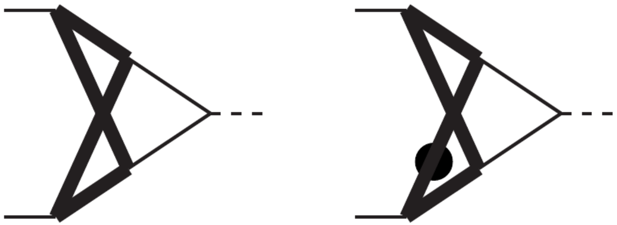
  [Bonciani, Mastrolia, Remiddi ('03) - Aglietti et al. ('06) - Anastasiou et al. ('06) - Caron-Huot, Henn ('14) - Becchetti, Bonciani ('17) - Bonciani, Degrassi, Vicini ('10)]

  Evaluated using handyG [Naterop, Signer, Ulrich - 1909.01656]

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

  Re-evaluated using expansion of differential equations (semi-analytical)

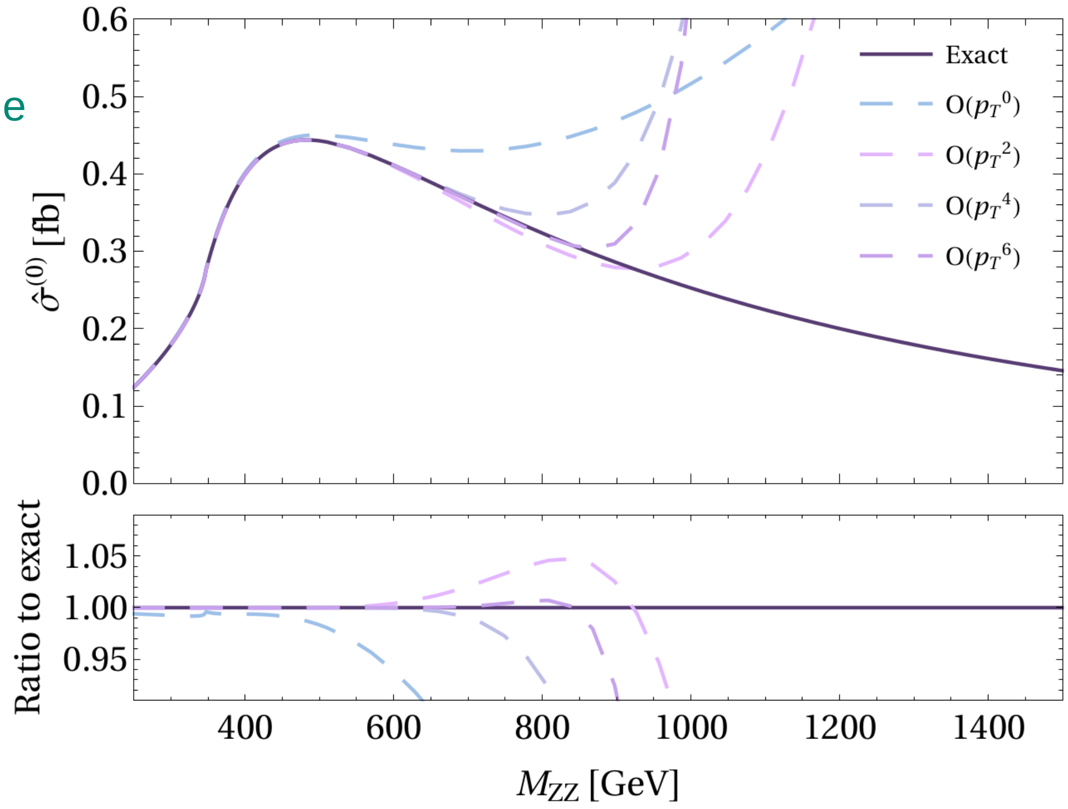
  Implemented in FORTRAN routine [Bonciani, Degrassi, Giardino, Gröber - 1812.02698]



Validation at LO

- Three orders sufficient for permille accuracy

- For $M_{ZZ} \gtrsim 700\ \mathrm{GeV}$ the assumption $p_T^2 \ll 4m_t^2$ can be violated in a significant part of the phase space



Complementing Phase-Space Coverage

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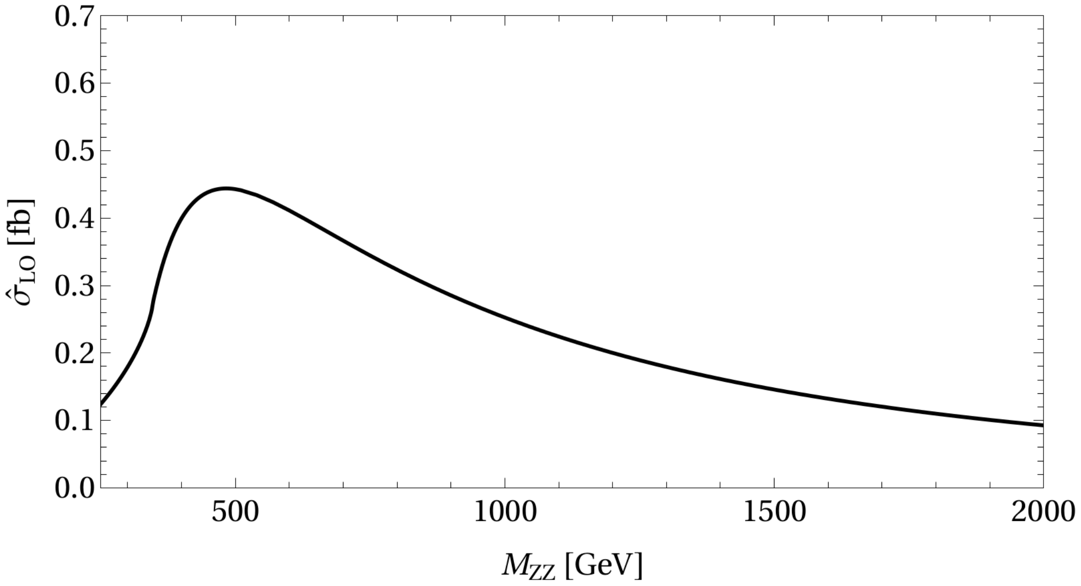
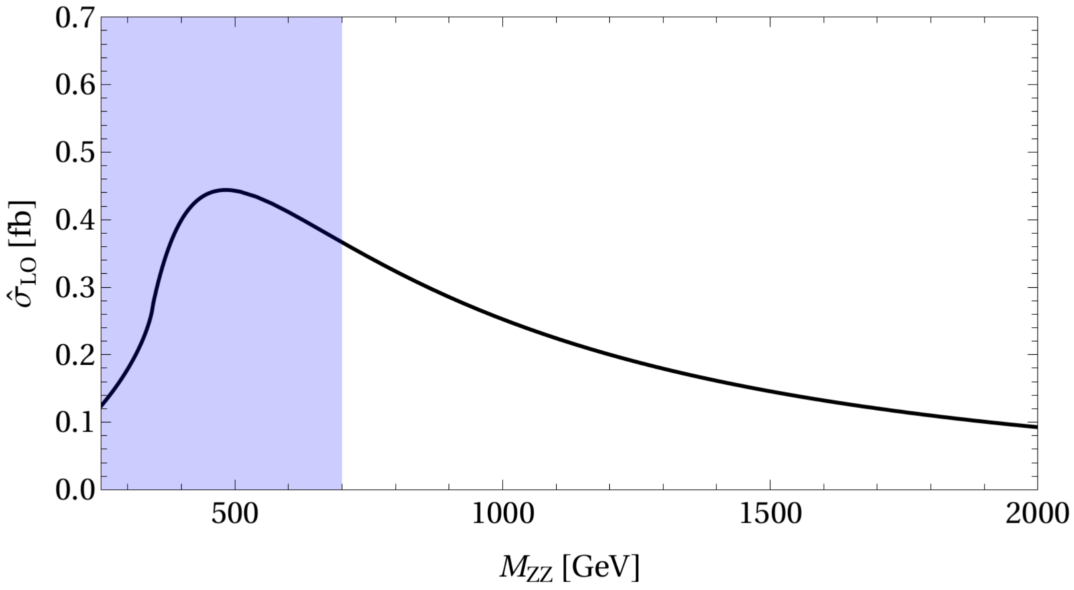


Complementing Phase-Space Coverage

- p_T exp

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



Complementing Phase-Space Coverage

- p_T exp

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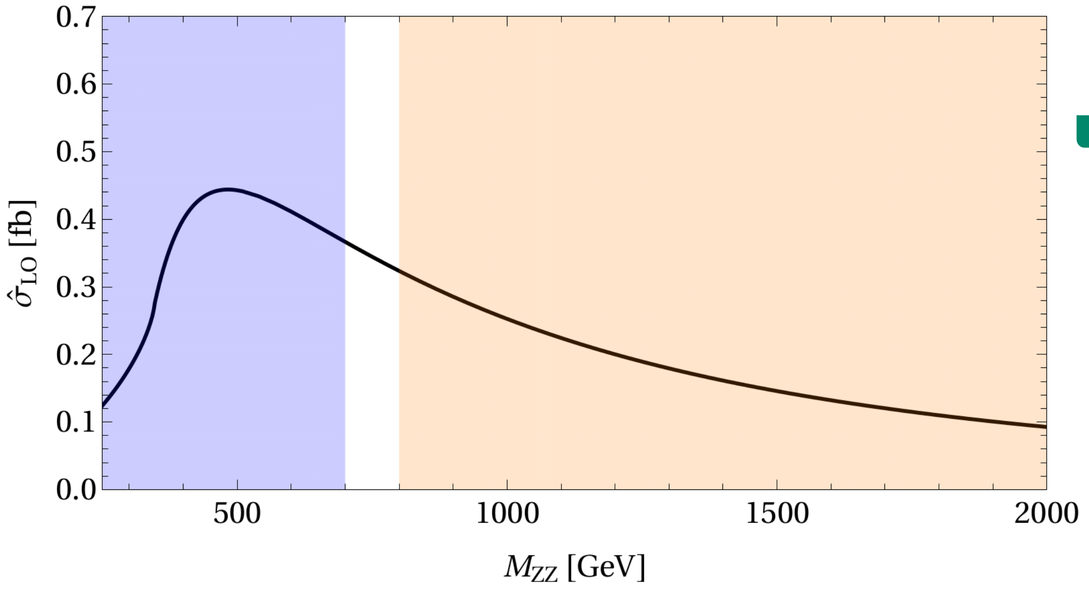


- High-Energy exp:

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

[Davies, Mishima, Steinhauser, Wellmann - 2002.05558]

The two expansions can be combined

Needed refinement using Padé approximants

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

See also [Davies, Mishima, Schönwald, Steinhauser - 2302.01356]

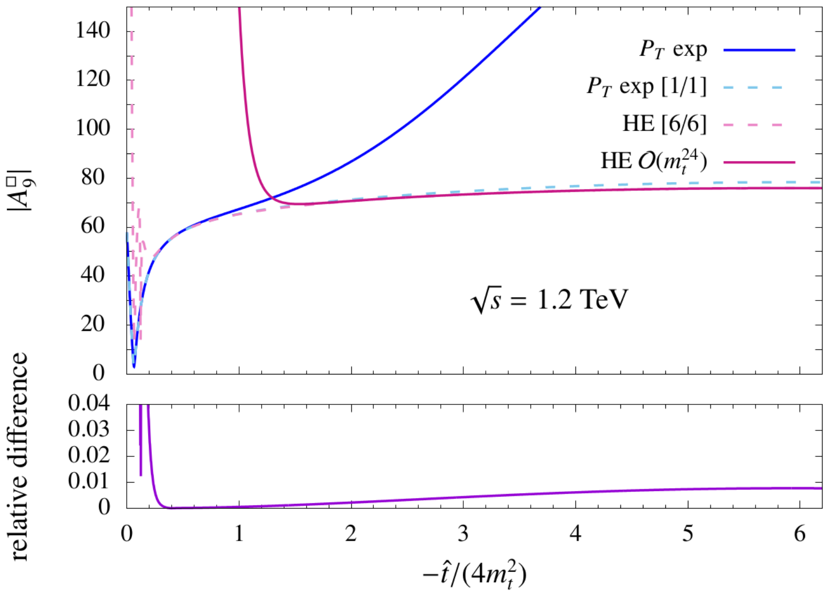
Merging pT and HE Expansions at NLO

Karlsruhe Institute of Technology

Improve the convergence of a series expansion by matching the coefficients of the **Padé approximant [m/n]** [e.g. Fleisher, Tarasov ('94) - Campbell et al. - 1605.01380]

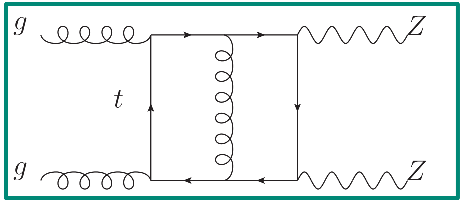
$$f(x) \overset{x\to 0}{\simeq} c_0 + c_1 x + \cdots + c_q x^q \qquad f(x) \simeq [m/n](x) = \frac{a_0 + a_1 x + \cdots + a_m x^m}{1 + b_1 x + \cdots + b_n x^n} \quad (q = m+n)$$

- For each FF we merged the following results
  - pT exp improved by [1/1] Padé
  - HE exp improved by [6/6] Padé
    [Davies, Mishima, Steinhauser, Wellmann - 2002.05558]
- Padé results are stable and comparable in the region $|\hat{t}| \sim 4 m_t^2$ → can switch without loss of accuracy
- Evaluation time for a phase-space point below 0.1 *s* ⇒ suitable for Monte Carlo



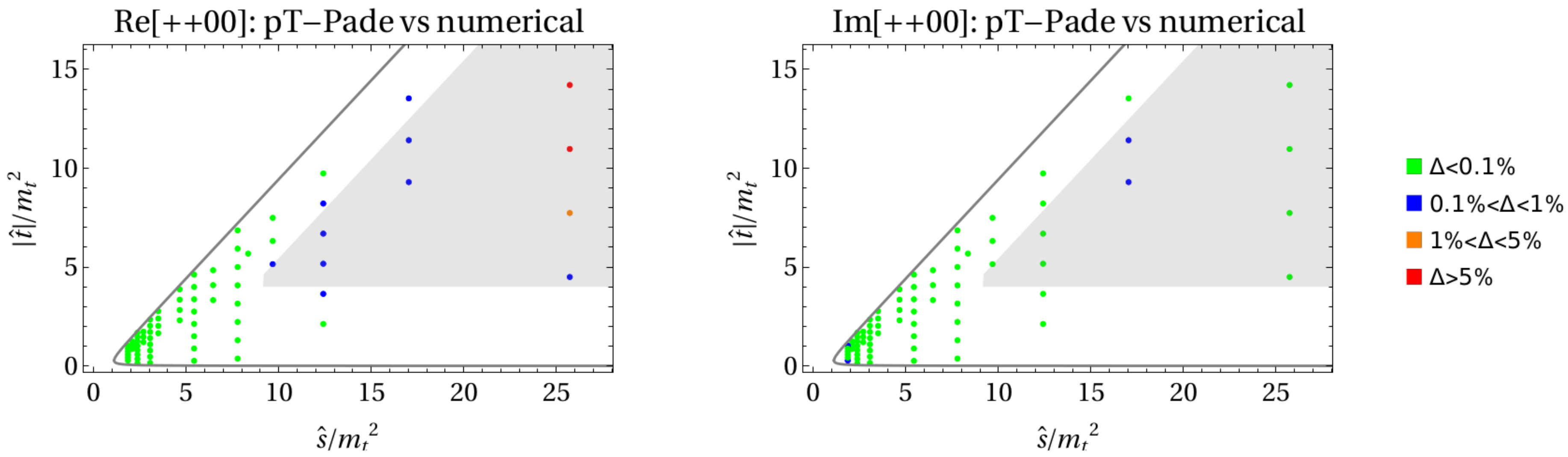
[Degrassi, Gröber, MV - 2404.15113]

Comparing with Numerical Results



Comparison with helicity amplitudes of [Agarwal, Jones, von Manteuffel - 2011.15113]

$$\mathcal{M}^{\text{fin}}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} = \left(\frac{\alpha_s}{2\pi}\right)\mathcal{M}^{(1)}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + \left(\frac{\alpha_s}{2\pi}\right)^2 \mathcal{M}^{(2)}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + \mathcal{O}(\alpha_s^3)$$



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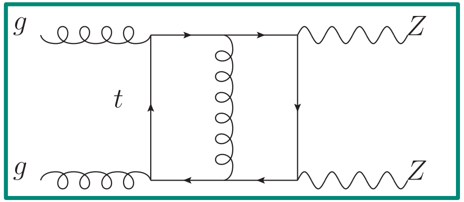

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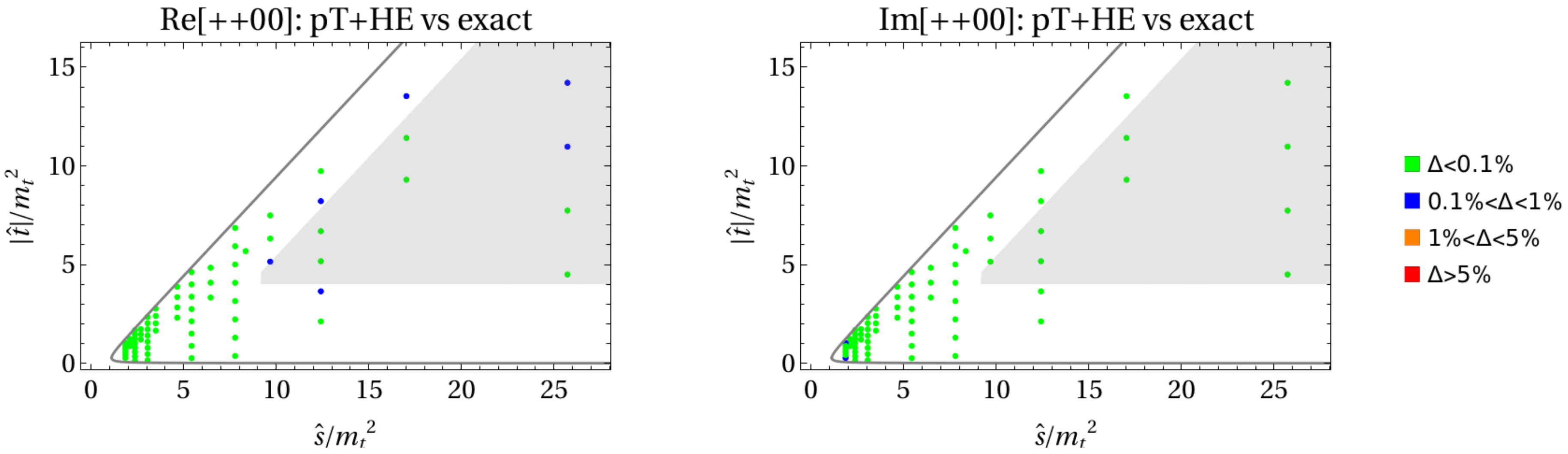


Results

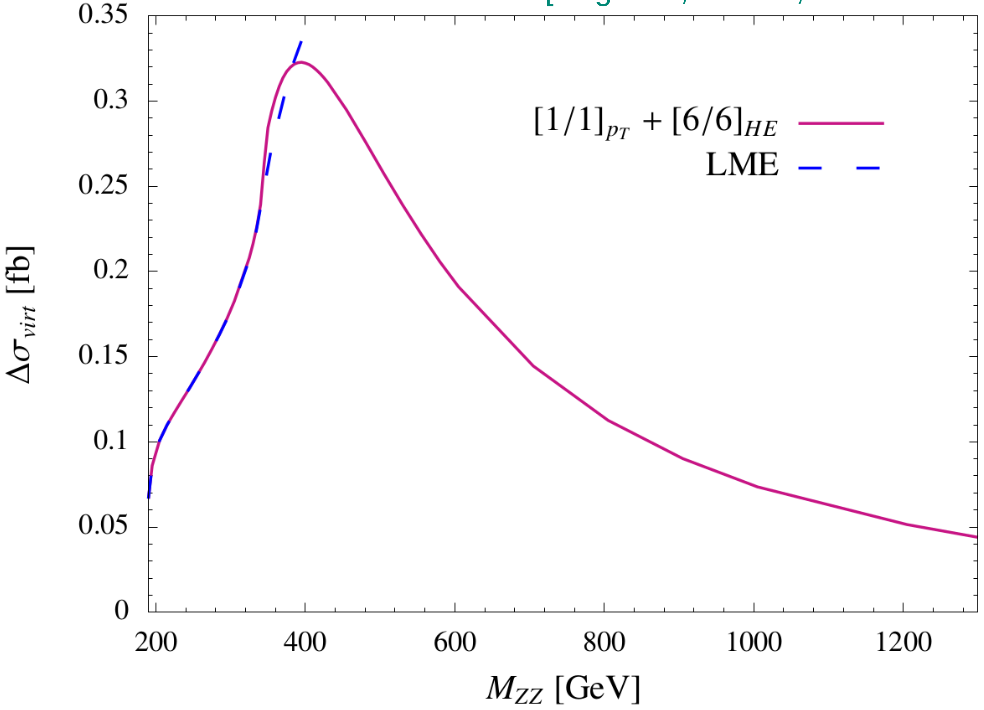
$$\mathcal{V}_{\text{fin}} = \frac{G_F^2 m_Z^4}{16}\left(\frac{\alpha_s}{\pi}\right)^2 \left\{\sum_i \left|\mathcal{A}_i^{(0)}\right|^2 \frac{C_A}{2}\left(\pi^2 - \log^2\left(\frac{\mu_R^2}{\hat{s}}\right)\right) + 2\sum_i \text{Re}\left[\mathcal{A}_i^{(0)}\left(\mathcal{A}_i^{(1)}\right)^*\right]\right\}$$

[Degrassi, Gröber, MV - 2404.15113]

$$\Delta\sigma_{\text{virt}} = \int_{\hat{t}^-}^{\hat{t}^+} d\hat{t}\,\frac{1}{2}\frac{1}{16\pi\hat{s}^2}\left(\frac{\alpha_s}{\pi}\right)\mathcal{V}_{\text{fin}}(\hat{t})$$

$$\mathcal{A}_i^{(0)} = \mathcal{A}_i^{(0,\triangle)} + \mathcal{A}_i^{(0,\square)}$$

$$\mathcal{A}_i^{(1)} = \mathcal{A}_i^{(1,\triangle)} + \mathcal{A}_i^{(1,\square)} + \mathcal{A}_i^{(1,\bowtie)}$$

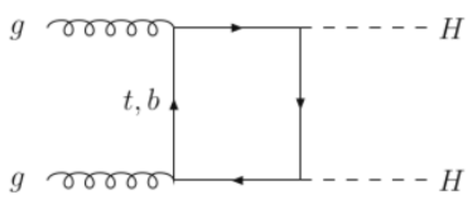


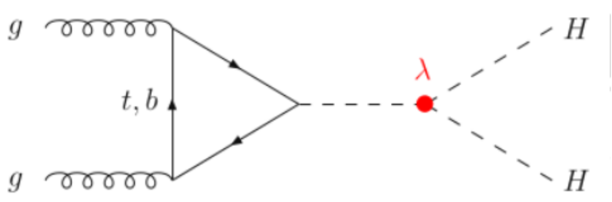
LME from
[Davies, Mishima, Steinhauser, Wellmann - 2002.05558]

Going to NNLO QCD...

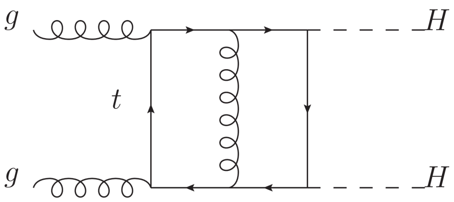
- Consider a "simpler" case: $gg \to HH$

  (2 FFs, scalar identical final particles)
- Best chance to measure λ_3 at LHC





- Two loop boxes are a problem again

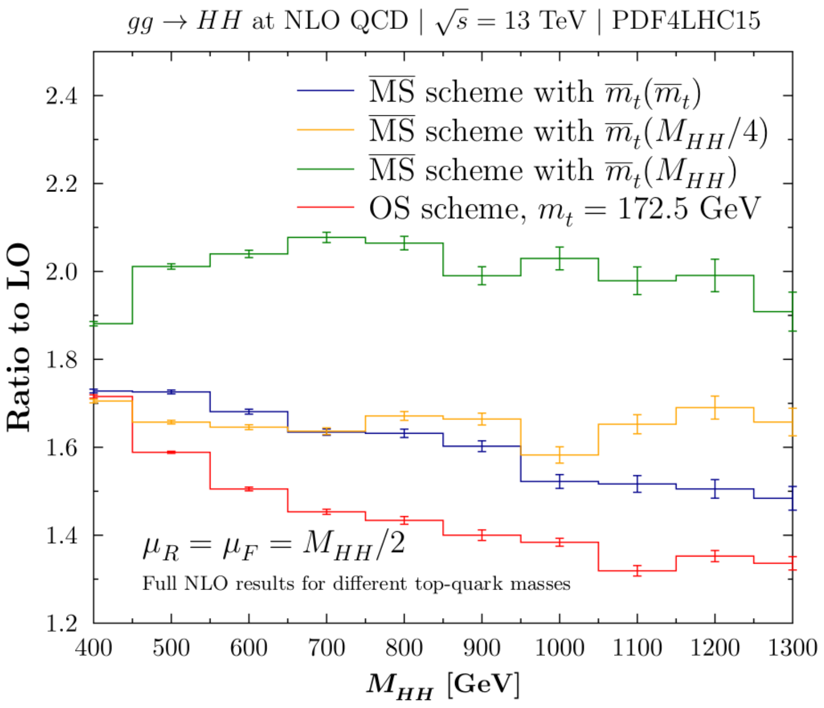


Going to NNLO QCD...

- Consider a “simpler” case: $gg \to HH$

  (2 FFs, scalar identical final particles)
- Best chance to measure λ_3 at LHC

- Large uncertainty at NLO, due to choice of renormalization scheme and scale for the top mass
- NNLO would still be desirable

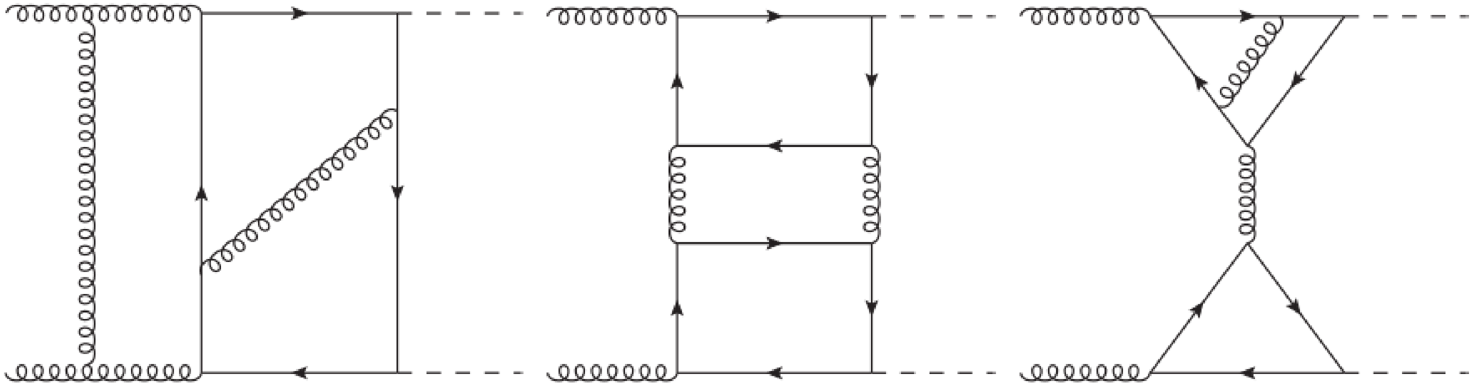


[Baglio et al. - 2008.11626]

Going to NNLO QCD...

Can we use the forward expansion for higher orders?

- Classes of three loop diagrams



Going to NNLO QCD...

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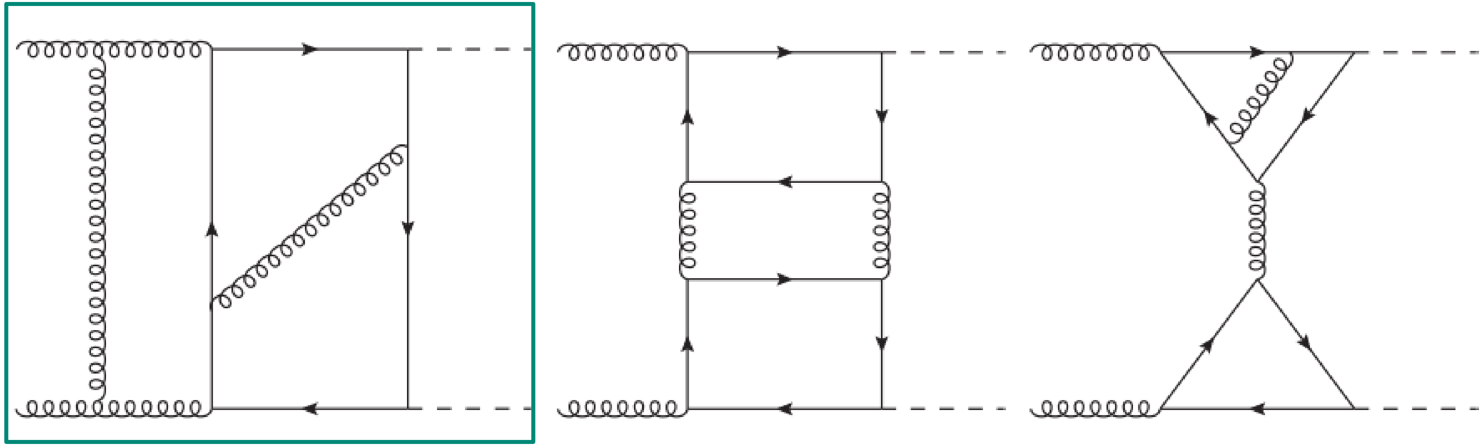


Conceptually yes

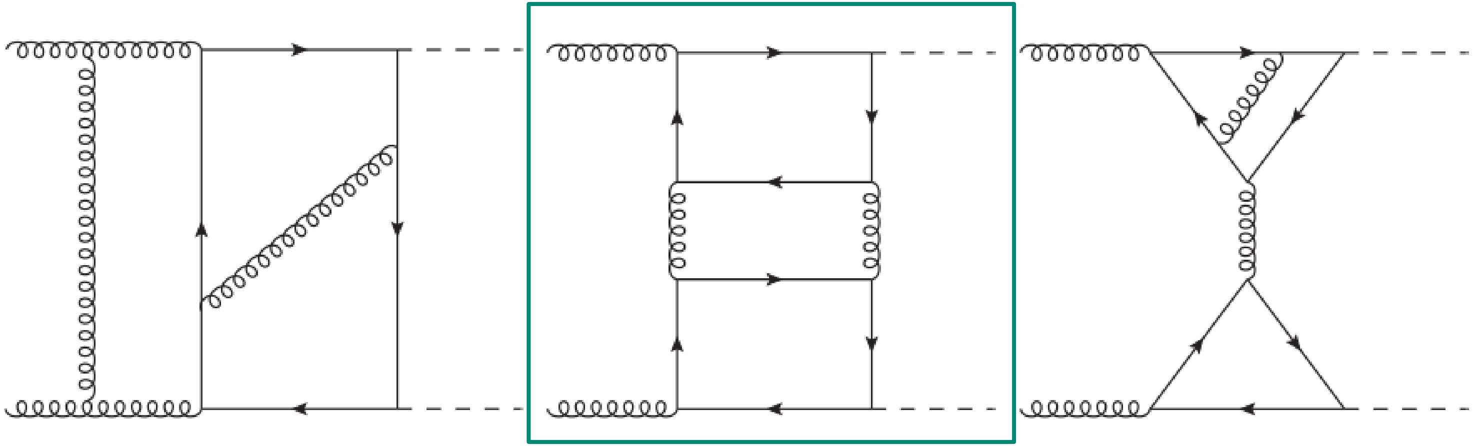
Practical implementation promising for the $t \to 0$ expansion $\{t^0, m_H^0\}$

[Davies, Schönwald, Steinhauser 2307.04796]

Going to NNLO QCD...

Can we use the forward expansion for higher orders?

- Classes of three loop diagrams

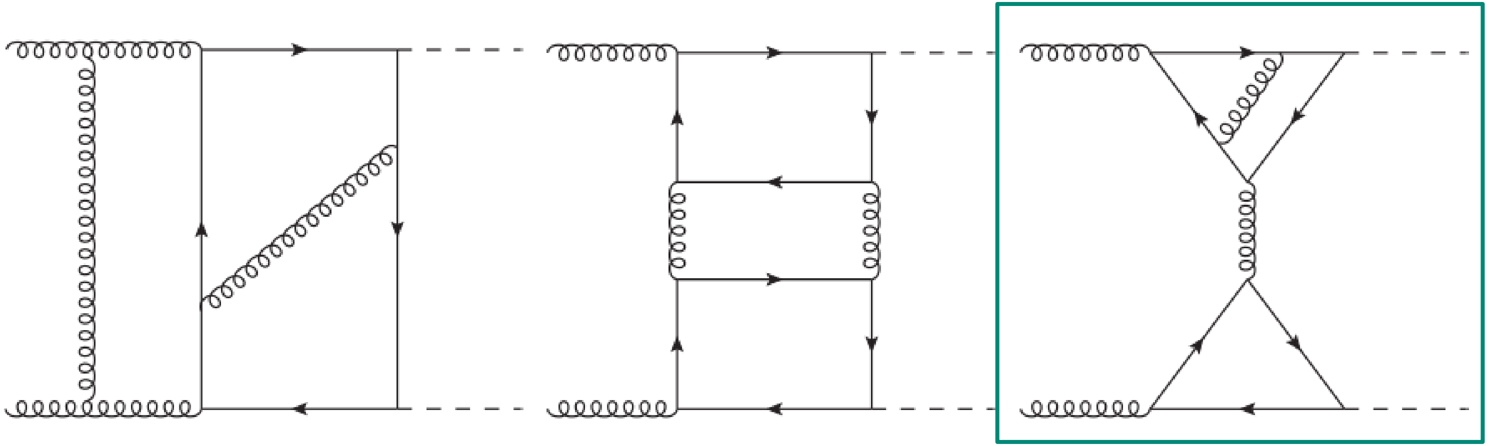


More involved due to t-channel cuts
through massless lines
$\Rightarrow$ A Taylor expansion is not sufficient

Going to NNLO QCD...

Can we use the forward expansion for higher orders?

- Classes of three loop diagrams

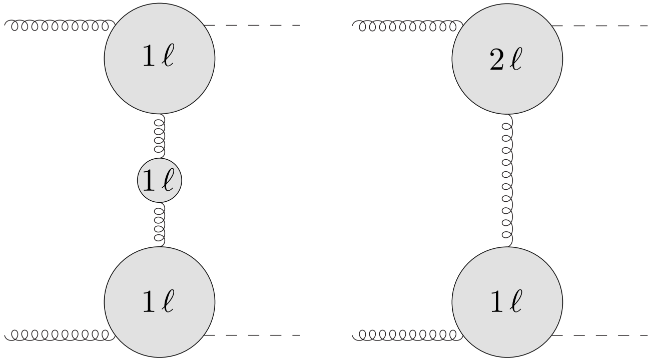


Start by studying the 1PR piece

1PR Contribution to *gg*→*HH* @ 3 Loops

[Davies, Schönwald, Steinhauser, MV - 2405.20372]

$$\mathcal{M}^{ab} = \varepsilon_{1,\mu}\varepsilon_{2,\nu}\mathcal{M}^{\mu\nu,ab} = \varepsilon_{1,\mu}\varepsilon_{2,\nu}\delta^{ab}X_0 s\,(F_1 A_1^{\mu\nu} + F_2 A_2^{\mu\nu})$$

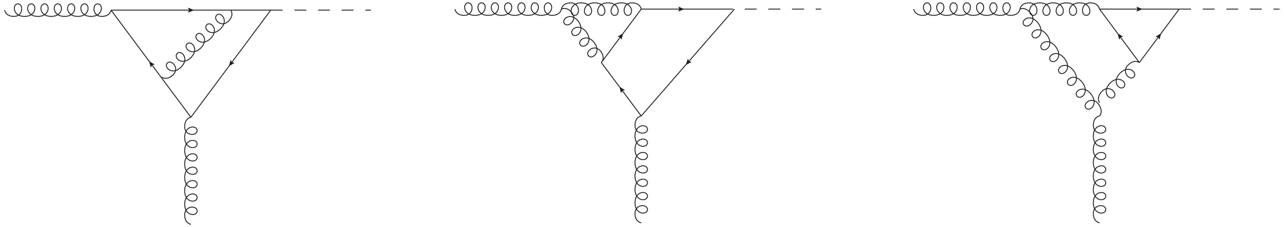


Goal: compute $F_1^{(3\ell,\ 1\mathrm{PR})}$ $F_2^{(3\ell,\ 1\mathrm{PR})}$

Approach: construct the *gg*→*HH* form factors from the 1PI gg*H subamplitudes

$$\mathcal{V}^{\alpha\beta}(q_s, q_2) = F_a\ g^{\alpha\beta}(q_s\cdot q_2) + F_b\ q_s^\alpha q_2^\beta + F_c\ q_2^\alpha q_s^\beta + F_d\ q_s^\alpha q_s^\beta + F_e\ q_2^\alpha q_2^\beta$$

$$q_2^2 = 0, q_s^2 \neq 0$$
$$m_H \neq 0$$

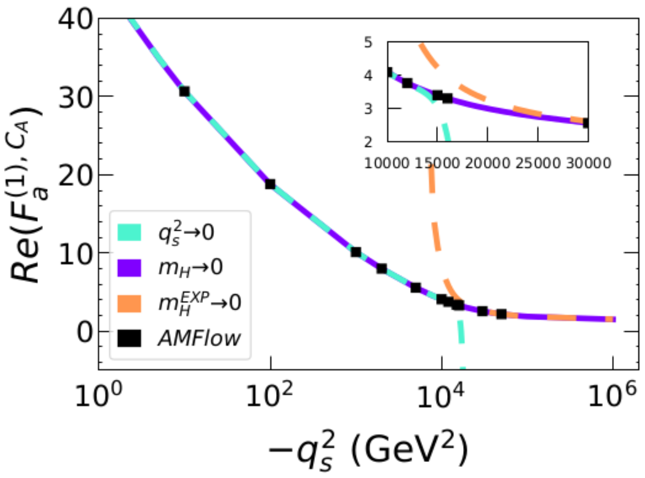


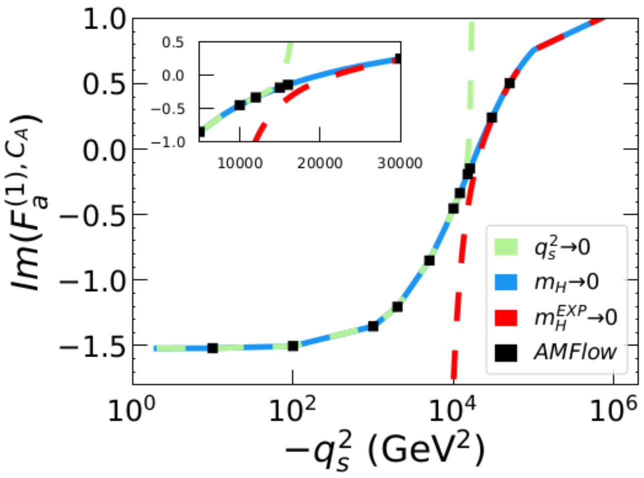
1PR Contribution to $gg \to HH$ @ 3 Loops

Expansion by regions [Beneke, Smirnov ('98)]

- $m_H^2 \ll q_s^2, m_t^2$
- $q_s^2 \ll m_H^2, m_t^2$

- Use expanded MIs but keep coefficients exact ($m_H \to 0$)
- Results checked with AMFlow [Liu, Ma - 2201.11669]





Conclusions

- Top loops are crucial for precision Higgs physics
- At two-loops, an important class of *gg*-initiated diboson processes can be approximated (semi-)analytically using a combination of a forward expansion and a high-energy expansion
- Results are fast and precise over the complete phase space

Outlook

- Going to 3 loops is not straightforward $\Rightarrow$ use asymptotic expansions?
- Looking for new combinations of expansions to cover a significant part of the phase space

- “You can’t ~~always~~ for now get what you want”

- But if you try sometime / you might find / you get what you need (for phenomenology)

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Thank you for your attention

Backup

VH Production at the LHC

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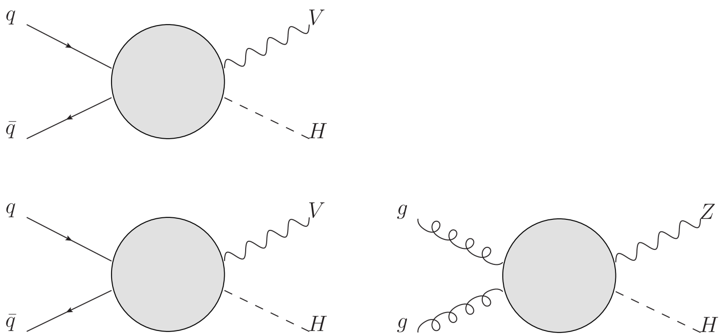
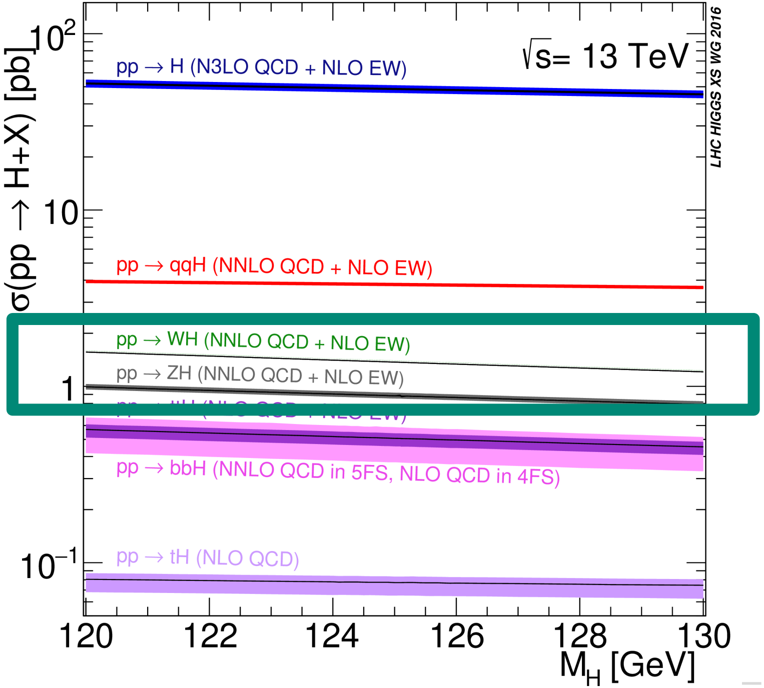
$pp \to VH$ is the most sensitive process to $H \to b\bar{b}$ [ATLAS-2007.02873, CMS-1808.08242]

- Work in progress on $H \to c\bar{c}$
  [ATLAS-2201.11428, CMS-2205.0555]
- Probe of VVH coupling
- Partonic channels

$pp \to WH$

$pp \to ZH$





VH Production at the LHC

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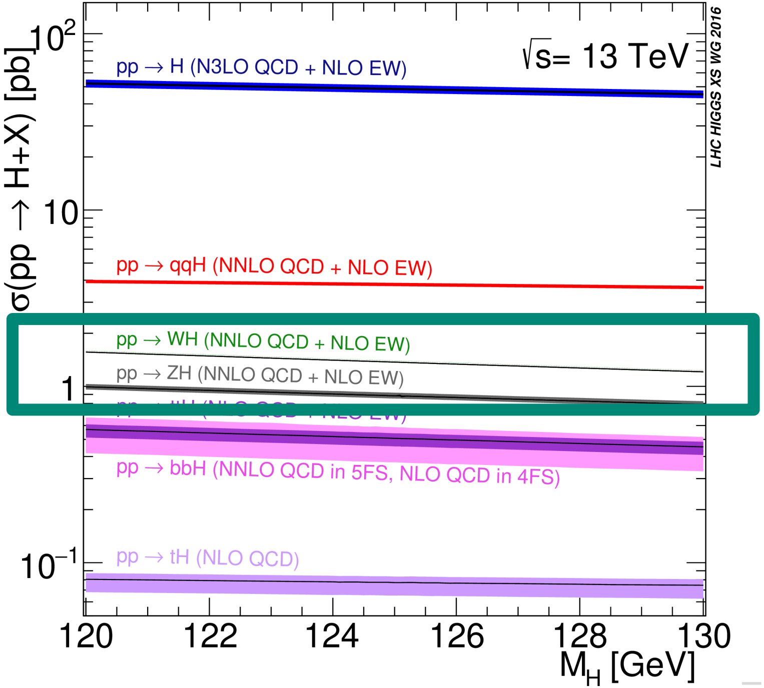


- Larger scale uncertainties in *ZH*

$pp \to WH$

$\sqrt{s}$ [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]

$gg \rightarrow ZH$ @ NLO QCD

Inclusive cross section

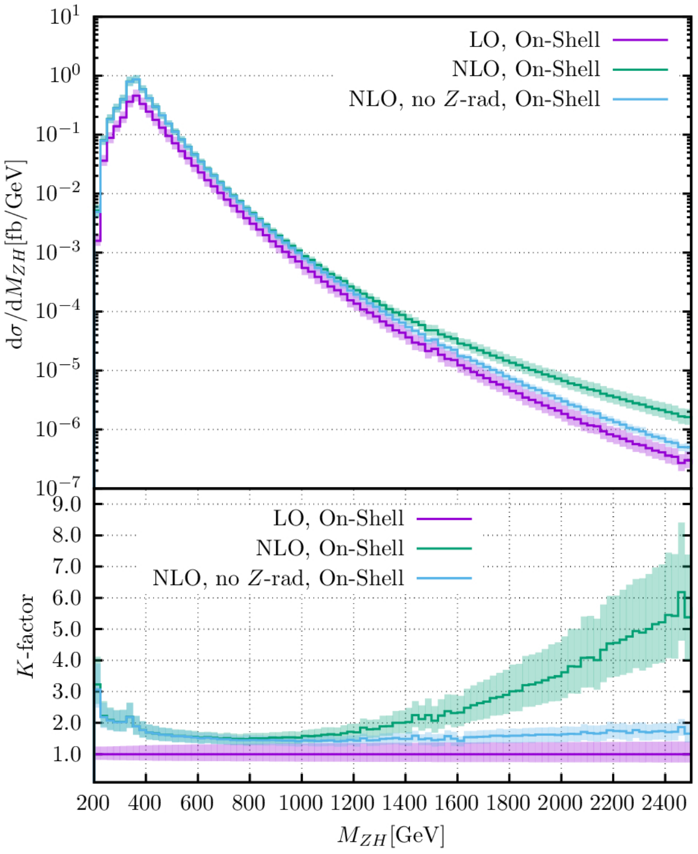
$$\sqrt{s} = 13\text{TeV}$$
$$\mu_r = \mu_f = M_{ZH}/2$$

Top-mass scheme	LO [fb]	$\sigma_{LO}/\sigma_{LO}^{OS}$	NLO [fb]	$\sigma_{NLO}/\sigma_{NLO}^{OS}$	$K = \sigma_{NLO}/\sigma_{LO}$
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

- NLO corrections are the same size as LO (K~2)
- Scale uncertainties reduced by 30% wrt LO

Invariant-mass distribution

- K-factor is not flat over M_{ZH} range
- Large NLO enhancement in the high-energy tail ($M_{ZH} > 1\,\text{TeV}$)



[Degrassi, Gröber, MV, Zhao - 2205.02769]

$gg \to ZH$ @ NLO QCD

Inclusive cross section

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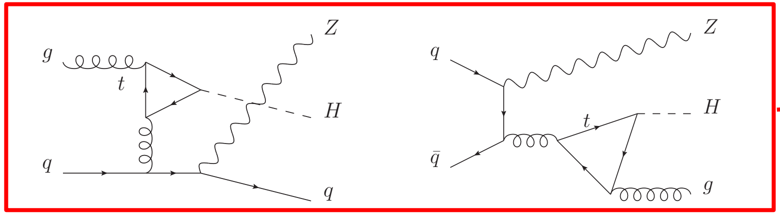
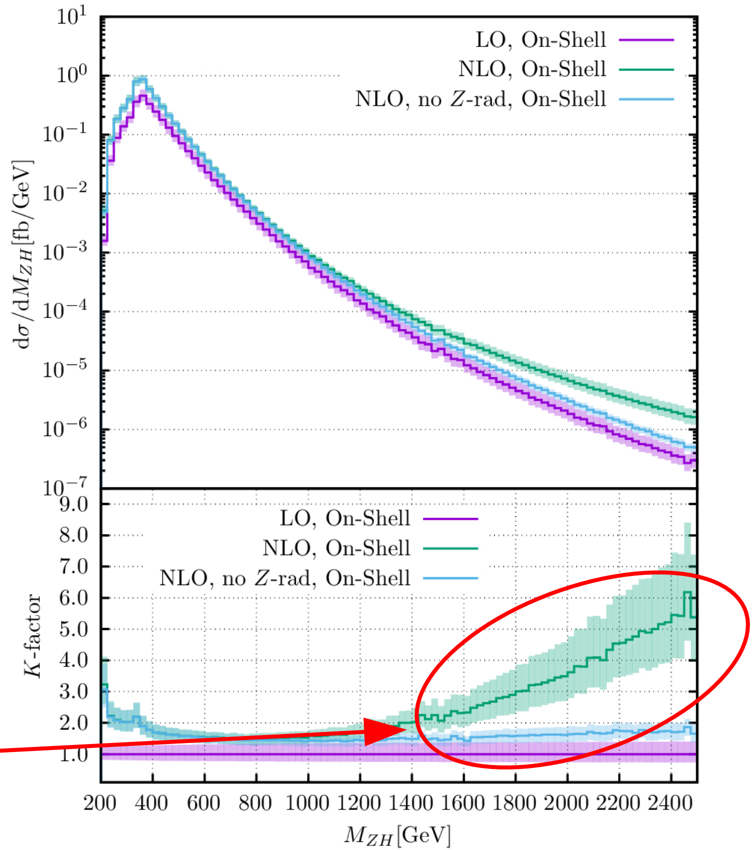
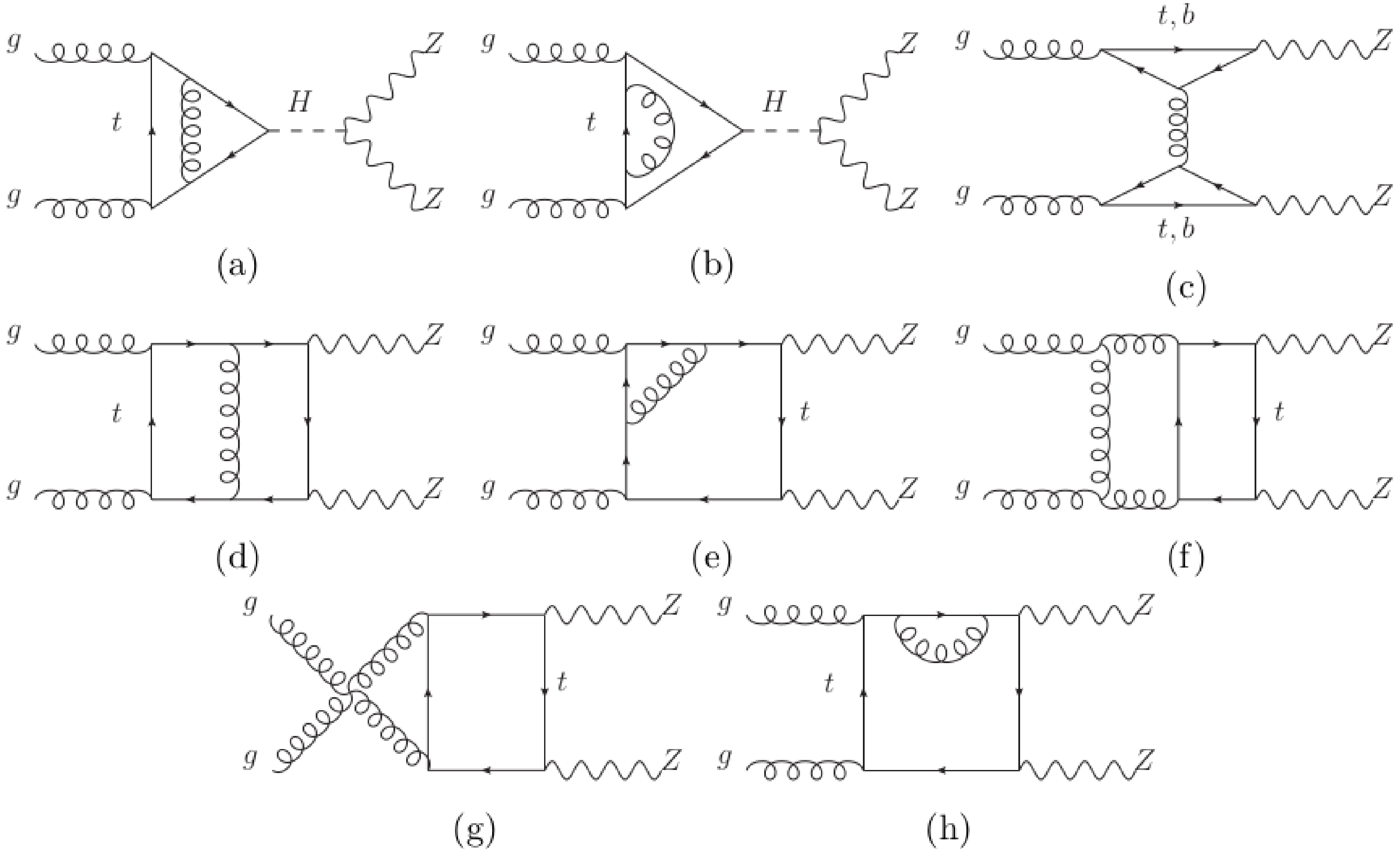


Dominant

PDF suppressed



[Degrassi, Gröber, MV, Zhao - 2205.02769]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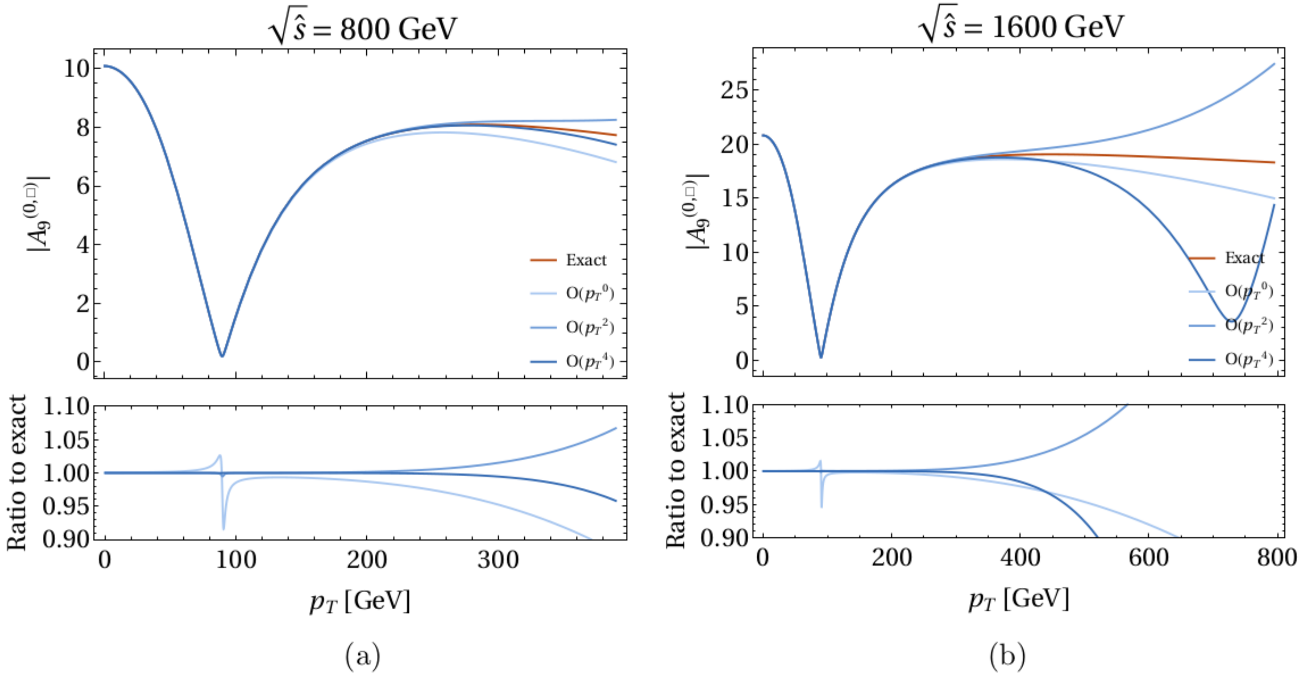

Figure 3: Absolute value of the form factor $\mathcal{A}_9^{(0,\square)}$ for moderate (a) and high (b) partonic centre-of-mass energies as a function of the transverse momentum. The exact result and the results obtained at various orders in the p_T expansion are shown.

1PR Contribution to *gg*→*HH* @ 3 Loops: Strategy

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1. Generation of diagrams with qgraf [Nogueira, ‘93]
2. Manipulation with Tapir [Gerlach, Herren, Lang - 2201.05618], q2e/exp [Harlander, Seidensticker Steinhauser – ‘97], FORM [Ruijl, Ueda, Vermaseren - 1707.06453]
3. IBP reduction (KIRA [Klappert, Lange, Maierhöfer, Usovitsch - 2008.06494])
4. The MIs can be expanded for $m_H \to 0$ (LiteRed [Lee - 1310.1145])
5. Results mapped onto single-scale “forward” topologies [Davies, Mishima, Schönwald, Steinhauser - 2302.01356]
6. Evaluated semi-analytically using “expand-and-match” approach [Fael, Lange, Schönwald, Steinhauser – 2106.05296; 2202.05276]

- Two-loop: results in agreement with [Degrassi, Giardino, Gröber – 1603.00385]
- Three-loop: agreement with LME result of [Davies, Steinhauser - 1909.01361]