Summary of precision Higgs calculations

Raoul Röntsch

Higgs 2024
Uppsala, Sweden
4 November 2024

Preamble

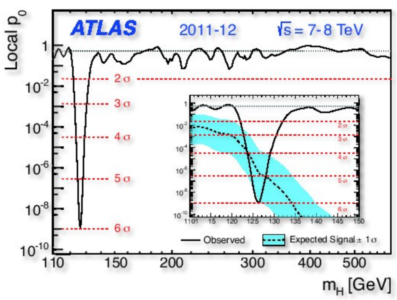
Summarizing ~ 12 months of hard work done by dozens of theorists in 20 minutes is an impossible task.

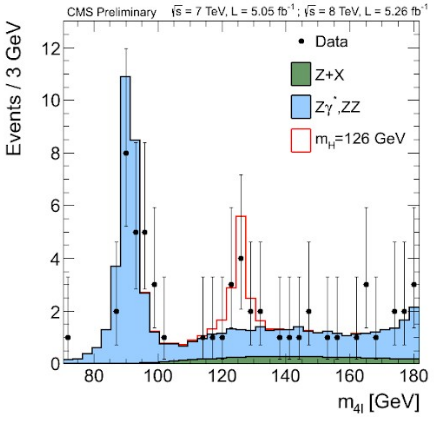
I have tried to highlight results that have appeared since ~ Higgs 2023 (and indicate these as NEW) and especially those that will be presented at this workshop.

My apologies if I've left something (or someone) out!

The Road to Precision Higgs Physics

The now-famous discovery in 2012...





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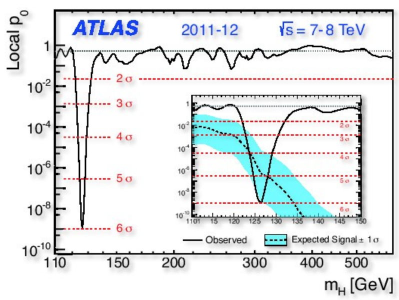

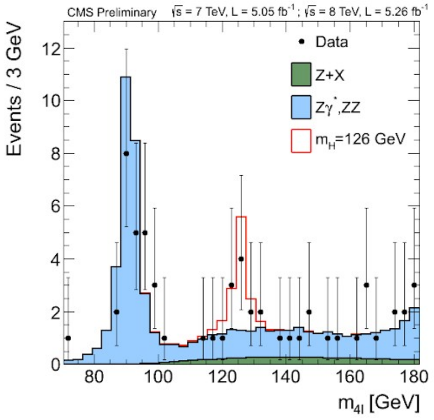

… was only the beginning!

The Higgs completes the SM, but that doesn't mean our work is complete!

The Road to Precision Higgs Physics

We have a new particle to explore:

- Source of EWSB
- First fundamental scalar (?)
- New coupling structure (Yukawa interactions)
- Deep connections to fate of the universe
- Bridge to New Physics?

We need to understand:

- Its properties
  (mass, width, spin, CP properties, ...)
- Its couplings to other particles
- Its self-couplings (i.e. form of potential)
- …

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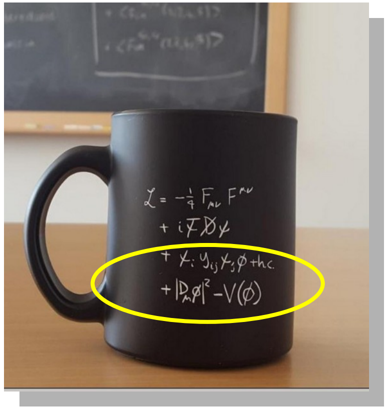

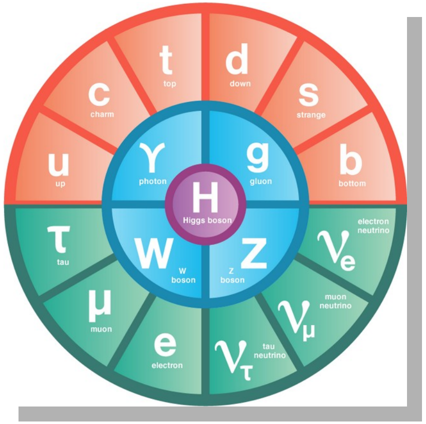

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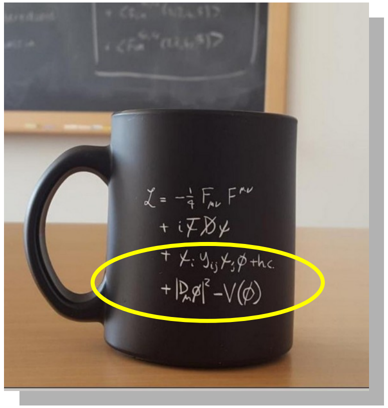

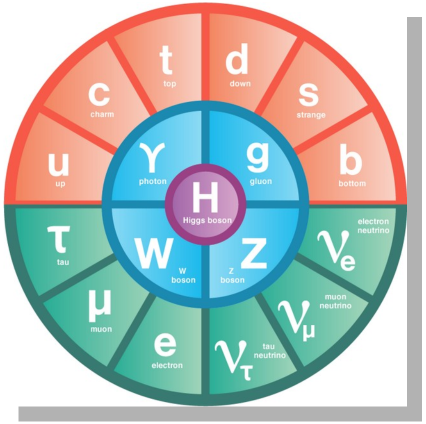

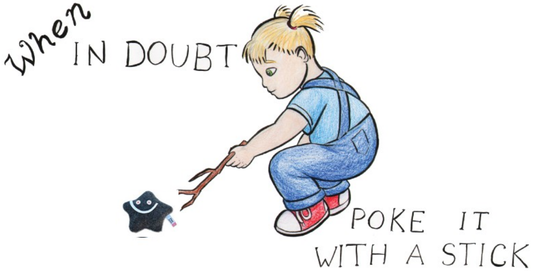

Image: G. C. Katz, CCL

The Road to Precision Higgs Physics

The LHC : a very powerful stick

“Speak quietly and carry a big stick.”

- Theodore Roosevelt

The Road to Precision Higgs Physics

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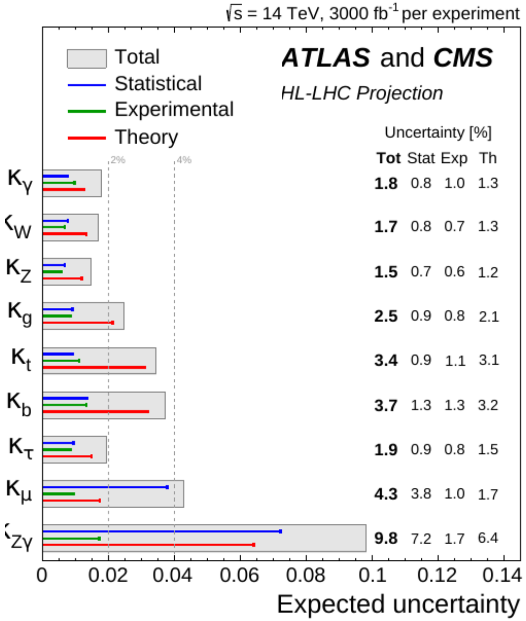
… and a (surprisingly) sharp one!



Percent-level precision on Higgs couplings by the end of the HL-LHC

"Except for rare decays, the overall uncertainties will be dominated bythe theoretical systematics, with a precision close to percent level."

- Report on *Physics Potential of the HL-LHC*, submitted to CERN Council

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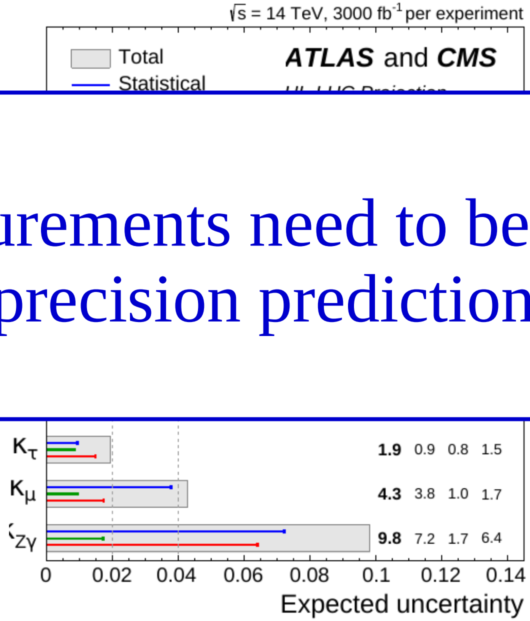

Precision measurements need to be confronted with precision predictions

P…cent-level precision …ggs couplings by …d of the HL-LHC

“… or rare decays, the overall …ties will be dominated bythe …l systematics, with a precision …percent level.”

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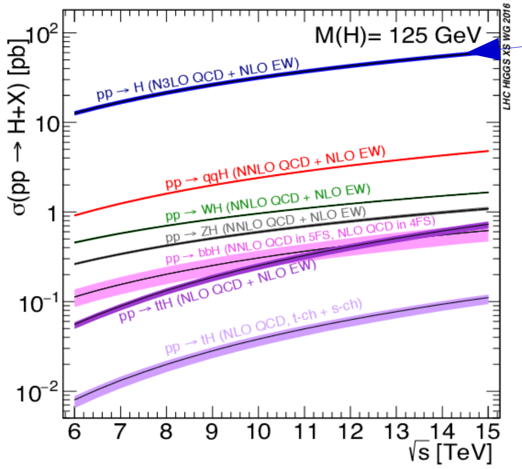
Outline

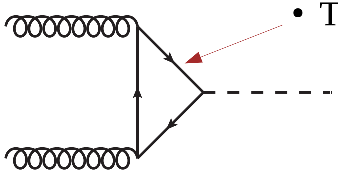
- Higgs production in gluon fusion
- Higgs + jet
- Electroweak Higgs production
- $t\bar{t}H$ production
- Di-Higgs Production

Gluon Fusion

Gluon fusion

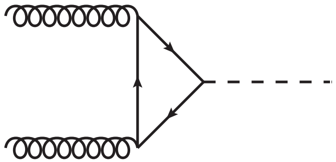


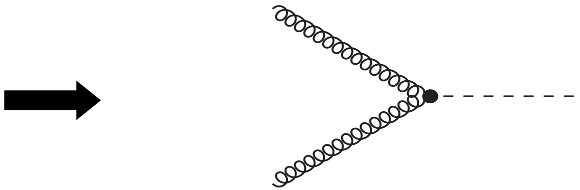
- Largest production cross section
  (~ 87% of Higgs production at LHC come from GF)
- Loop-induced process



- Top quarks dominate in loop

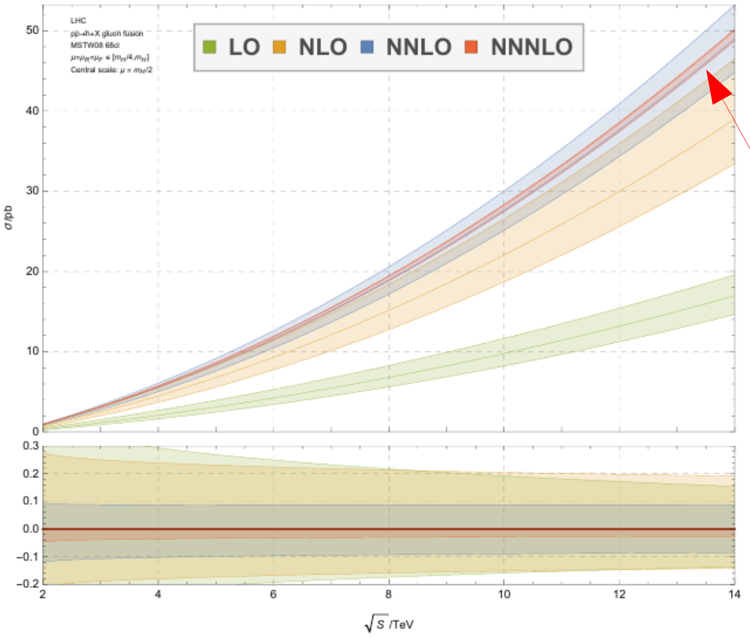
- **H**eavy **T**op **L**imit $m_t \to \infty$





$\sim HG_{\mu\nu,a}G^{\mu\nu,a}$

Gluon fusion: Using the Heavy Top Limit



[Anastasiou et al, ‘15]

- Very large QCD corrections – higher order calculations are essential.

  ($K_{NLO} \sim 2$)

- N3LO result within scale uncertainty bands at NNLO:

  ➡ Perturbative expansion under control from NNLO.

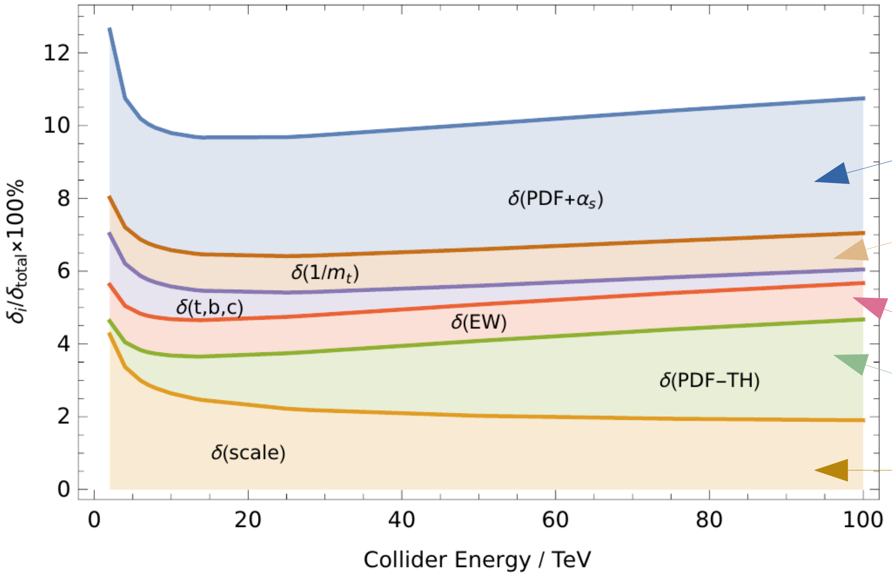
- N3LO scale uncertainty ~ few percent

[NLO: Dawson ‘91; Graudenz, Spira, Zerwas ‘93; + Djouadi ‘95]

[NNLO: Anastasiou, Melnikov ‘02; Harlander, Kilgore ‘02; Ravindran, Smith, v. Neerven ‘03]

[N3LO: Anastasiou et al ‘15, ‘16; Mistlberger ‘18]

Gluon Fusion: Sources of Uncertainties



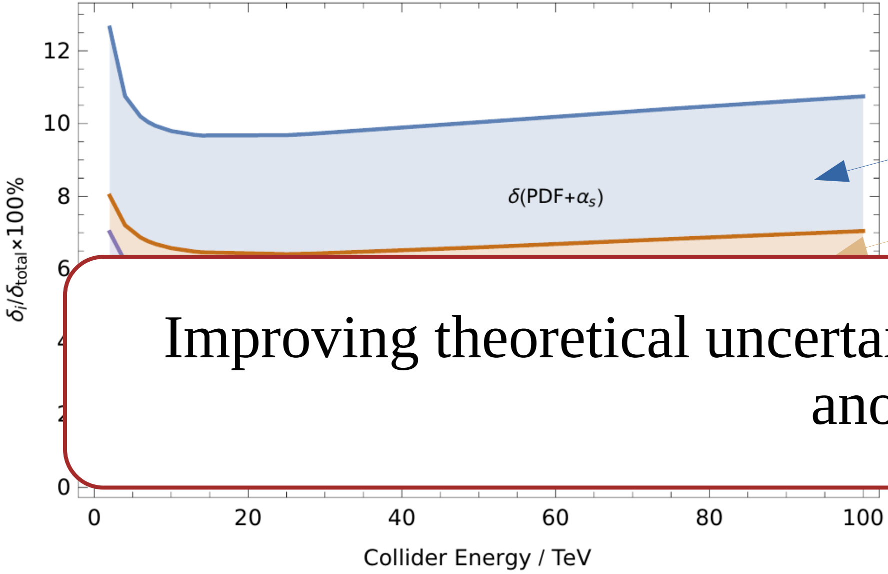
[Mistlberger, Dulat, Lazopoulos '18]

Sources of theoretical uncertainty:

- α_s determination
- Top mass effects
- Other quark mass effects
- EW corrections
- Pdf detemination
- Missing higher-order QCD corrections

All roughly the same size

Gluon Fusion: Sources of Uncertainties



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Sources of theoretical uncertainty:

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Improving theoretical uncertainty is no longer just a case of "add another N"

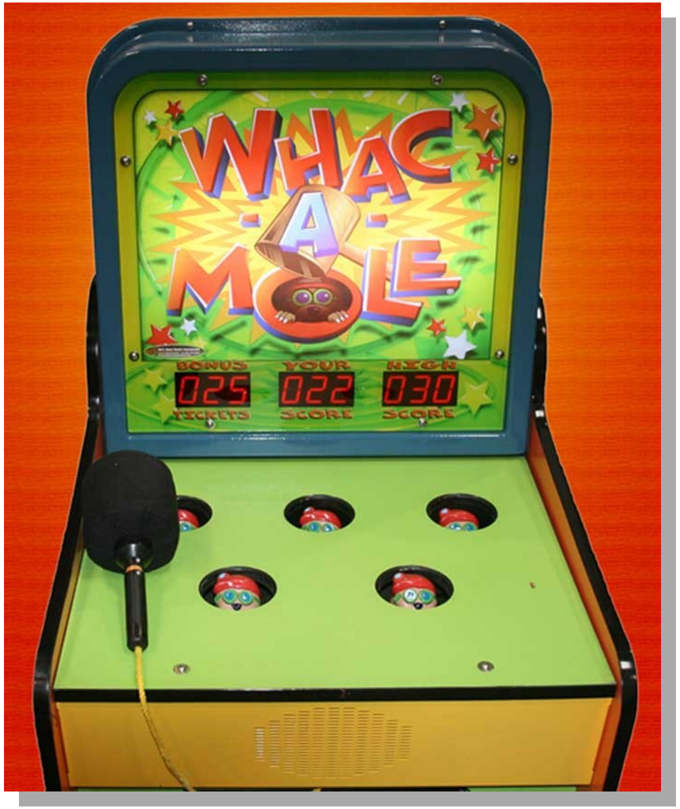
All roughly the same size

Gluon fusion

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

Gluon fusion



With a small apology to Peter Skands for re-appropriating his metaphor.

Beyond the Heavy Top Limit

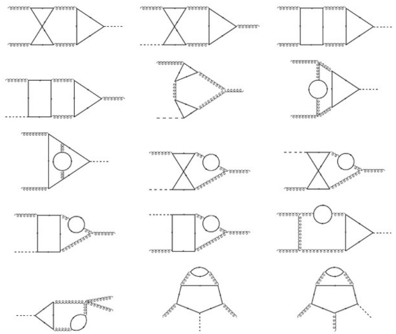
- **H**eavy **E**ffective **F**ield **T**heory: QCD corrections are (approximately) independent of value of top mass

  ➡ Include top mass effects by rescaling HTL results according to exact LO cross section.

$$\mathrm{d}\sigma_{\mathrm{HEFT}}^{(N^nLO)} = \frac{\mathrm{d}\sigma_{\mathrm{exact}}}{\mathrm{d}\sigma_{\mathrm{HTL}}}\,\mathrm{d}\sigma_{\mathrm{HTL}}^{(N^nLO)}$$

- Exact (finite top mass) results known to NNLO
- Requires 3-loop H + 2 parton and 2-loop H + 3 parton amplitudes.
- Reduce cross section by -0.32% relative to HEFT (at 13 TeV)

[Czakon, Niggetiedt '20;
Czakon, Harlander, Klappert, Niggetiedt '21]



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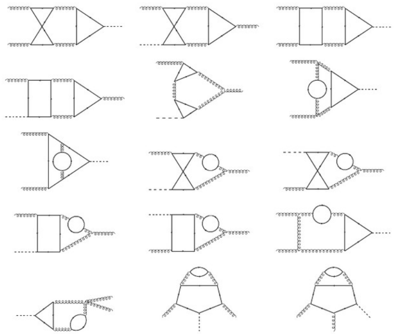
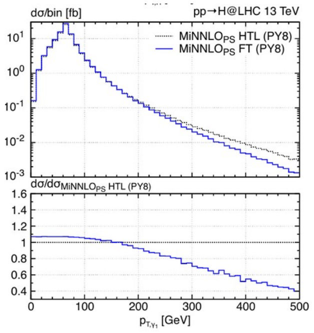


Matched to PS with MiNNLO$_{\mathrm{PS}}$

[Niggetiedt, Wiesemann ‘24]

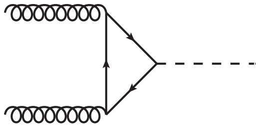


Gluon Fusion: It's not all about tops

- Other quarks in the loop suppressed by m_q^2/m_H^2 but enhanced by $\log^2(m_q^2/m_H^2)$
- Biggest contribution is interference with top quark loops.

Computed to NNLO QCD

[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '23]



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			$\sqrt{s} = 13.6$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+17.47$	–	-2.117	-1.311	
LO	$17.47^{+4.67}_{-3.32}$	–	$-2.12^{+0.40}_{-0.57}$	$-1.31^{+0.31}_{-0.47}$	-12
$\mathcal{O}(\alpha_s^3)$	$+22.76$	-0.338	$-0.464(1)$	$-0.659(1)$	
NLO	$40.23^{+9.07}_{-6.77}$	$-0.338^{+0.11}_{-0.18}$	$-2.58^{+0.20}_{-0.12}$	$-1.97^{+0.28}_{-0.28}$	$-6.4^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+10.47$	$+0.162(1)$	$+0.464(9)$	$+0.022(6)$	
NNLO	$50.70^{+4.53}_{-5.14}$	$-0.176(1)^{+0.14}_{-0.03}$	$-2.12(1)^{+0.33}_{-0.16}$	$-1.95(1)^{+0.09}_{-0.03}$	$-4.2^{+0.9}_{-0.8}$

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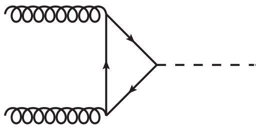
[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '23]



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- Interference effect ~ -12%
- QCD corrections ~ 2 %
- NLO and NNLO have opposite sign

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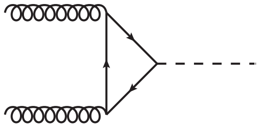

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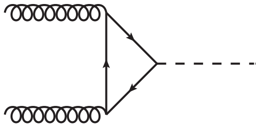
- $\overline{\text{MS}}$ renormalization of Yukawa coupling gives smaller contribution...
- And better behaved perturbative expansion.

Gluon Fusion: It's not all about tops

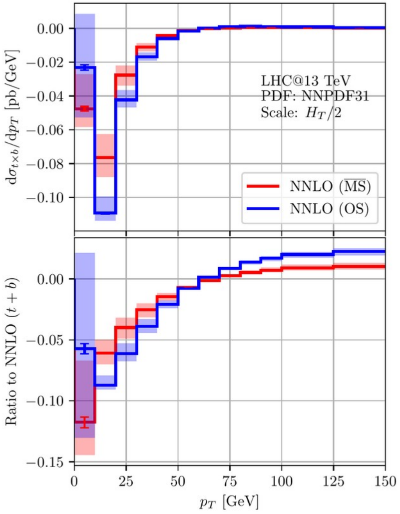
- Additional inconsistency: bottom quarks treated as massive inside loop, massless inside proton (5FS). Better to use 4FS?
- Impact of $\overline{\text{MS}}$ versus onshell renormalization for bottom mass? For top mass? Compared to impact of 5FS versus 4FS? Compared to impact of finite top masses?



- NEW Comprehensive study at NNLO QCD

[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '23]

Order	$\sigma_{t\times b}$ [pb]			
	$\sqrt{s} = 13$ TeV			
	5FS $m_t = 173.06$ GeV $\overline{m}_b(\overline{m}_b) = 4.18$ GeV	5FS $m_t = 173.06$ GeV $m_b = 4.78$ GeV	5FS $m_t(m_t) = 162.7$ GeV $\overline{m}_b(\overline{m}_b) = 4.18$ GeV	4FS $m_t = 173.06$ GeV $\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	-1.11	-1.98	-1.12	-1.15
LO	$-1.11^{+0.28}_{-0.43}$	$-1.98^{+0.38}_{-0.53}$	$-1.12^{+0.28}_{-0.42}$	$-1.15^{+0.29}_{-0.45}$
$\mathcal{O}(\alpha_s^3)$	-0.65	-0.44	-0.64	-0.66
NLO	$-1.76^{+0.27}_{-0.28}$	$-2.42^{+0.19}_{-0.12}$	$-1.76^{+0.27}_{-0.28}$	$-1.81^{+0.28}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.02$	$+0.43$	-0.02	-0.02
NNLO	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$	$-1.78(1)^{+0.15}_{-0.03}$	$-1.83(2)^{+0.14}_{-0.03}$

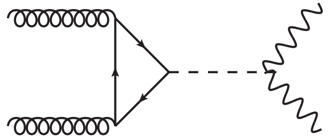


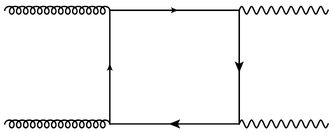
→ Talk by Tom Schellenberger

Gluon Fusion: Offshell Production

Offshell production $p_H^2 \gg m_H^2$ allows us to probe unitarizing behavior of Higgs and constrain Higgs width

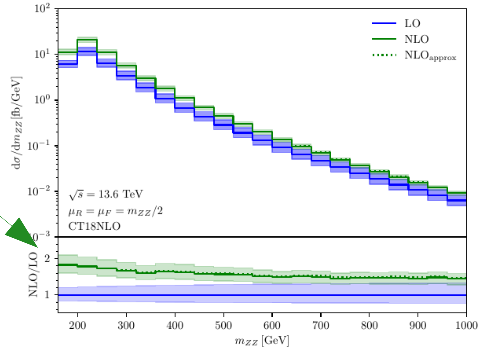
Need to account for signal, background and their interference.





Two-loop amplitudes for $gg \to ZZ$ known [Agarwal, Jones, v. Manteuffel ‘20; Brønnum-Hansen, Chen ‘20, ‘21]

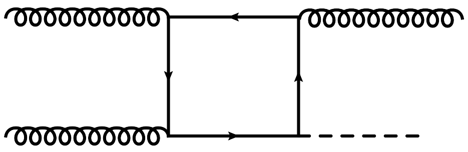
- NLO QCD corrections to $gg \to ZZ$
  [Agarwal, Jones, Kerner, v. Manteuffel ‘24]
  - ➡ Reweighting of massless amplitudes seems to work very well



- Soft-virtual NLO QCD corrections to interference in $gg \to Z\gamma$
  [Buccioni et al, ‘23]

Higgs + Jet

Higgs + Jet



Can probe what happens inside loop

- Light quark Yukawa couplings
- NP effects
- …

[Bishara, Haisch, Monni, Re '16 ; Soreq, Zhu, Zupan '16 ; ...]

- NNLO in HTL
  - HTL not valid for $p_{T,H} \gtrsim m_t$

[Chen, Gehrmann, Glover, Jaquier, '14; + Cruz-Martinez '16; Boughezal, Caola, Melnikov, Petriello, Schulze '15; Boughezal, Focke, Giele, Liu, Petriello '15; Caola, Melnikov, Schulze '15; Campbell, Ellis, Seth '19]

- Top-bottom interference at NLO

[Lindert, Melnikov, Tancredi, Wever '17]

- NLO including top mass effects

[Jones, Kerner, Luisoni '18; Kudashkin, Lindert, Melnikov, Wever '18; Neumann '18]

- Top and bottom mass effects

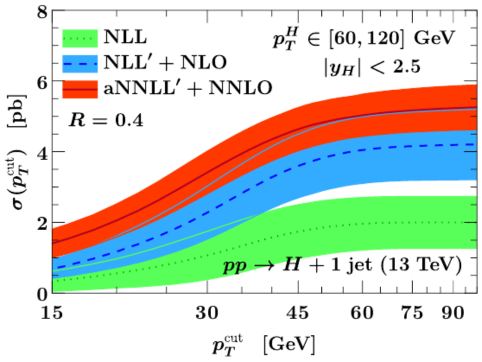
[Bonciani et al, '22]

Higgs + Jet: Resummations

Jet vetos introduce large logarithms ~ $\log(p_T^{\mathrm{veto}}/m_H)$ which spoil perturbative convergence and must be resummed

- Jet veto resummation at (approximate)NNLL'+NLO computed for STXS bins

  [Cal, Lim, Scott, Tackmann, Waalewijn '24]



Semi-hard regime (large rapidity gap) induces ~ $\log(s/Q^2)$

- Resummed using BFKL

- Resummation to NLL/NLO$^+$ in hybrid factorization approach

  [Celiberto, Papa, '20; Celiberto, Delle Rose, Fucilla, Gatto, Papa '24]

$$\underbrace{d\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)}_{\text{NLL/NLO}^- \text{ POWHEG+JETHAD}} = \underbrace{d\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\text{NLO POWHEG w/o PS}} + \underbrace{\underbrace{d\sigma^{\mathrm{NLL^-}}(\Delta Y, \varphi, s)}_{\text{NLL}^- \text{ resum (HyF)}} - \underbrace{\Delta d\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)}_{\text{NLL}^- \text{ expanded at NLO}}}_{\text{NLL}^- \text{ JETHAD w/o NLO}^- \text{ double counting}} .$$

→ Talk by Francesco Celiberto

H+J: New Physics + QCD effects

Full NLO QCD corrections combined with NP parametrized in HEFT Lagrangian

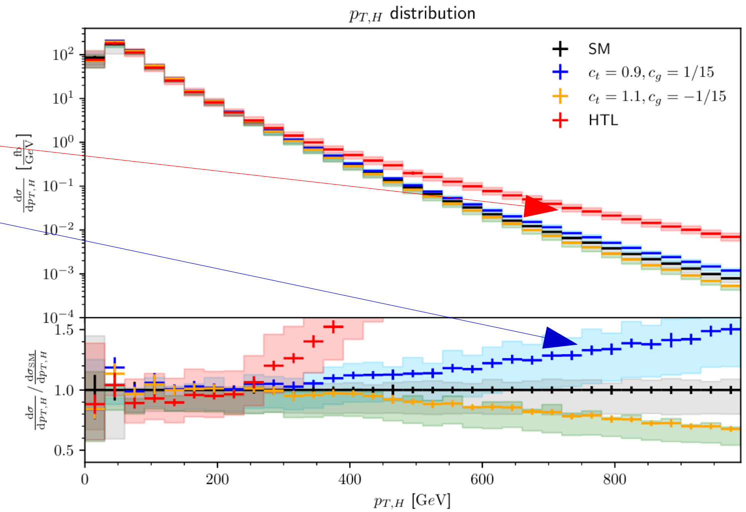
[Aveleira, Heinrich, Kerner, Kunz '24]

$$\mathcal{L} \supset -c_t\, m_t \frac{H}{v} \bar{t}t + \frac{\alpha_s}{8\pi} c_g \frac{H}{v} G^a_{\mu\nu} G^{a,\mu\nu} \,.$$

NP integrated out → effective vertex

Rescale top Yukawa

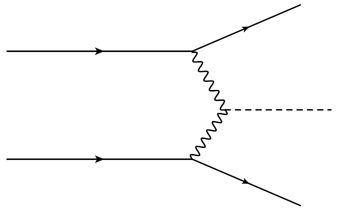
- HTL overshoots in tail
- NP effects can also enhance tail
- Delicate interplay between NP effects and higher-order corrections



→ Talk by Benjamin Aveleira

Vector Boson Fusion

Vector boson fusion



- Direct coupling to EW bosons
- Distinctive signature:
  - forward jets in opposite hemispheres
  - little hadronic activity at central rapidities

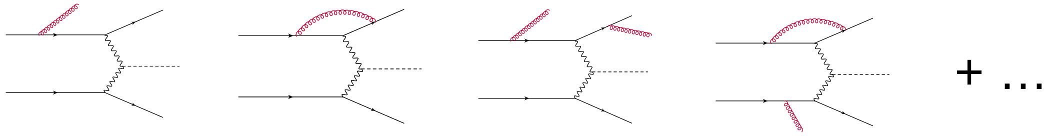
VBF cuts:

$$m_{j_1 j_2} > 600\ \mathrm{GeV},\ \Delta y_{j_1 j_2} > 4.5,\ y_{j_1} y_{j_2} < 0$$

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

"Double-DIS approximation" for QCD corrections:

- Radiation connecting quark lines is zero at NLO, color-suppressed at NNLO.



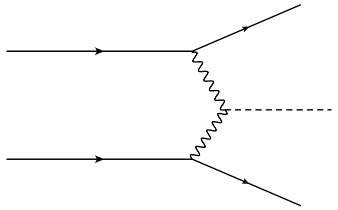
- Fully differential at NNLO QCD (VBF cuts):
  - NNLO corrections at 1%-5% level
  - Residual scale uncertainties ~ 1%

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15;
Cruz-Martinez, Gehrmann, Glover, Huss '18; Asteriadis, Caola, Melnikov, RR '21]

- Inclusive cross section known to N3LO QCD
  - Corrections ~ 2%, within NNLO scale uncertainty bounds
  - Residual scale uncertainties ~ 1%-2%

[Dreyer, Karlberg '16]

Vector boson fusion



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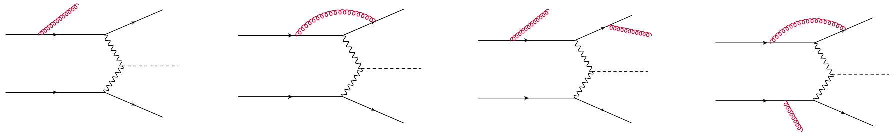

+ …

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m, Zanderighi '15;
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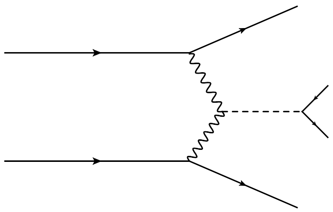
Perturbative QCD corrections appear to be well-controlled

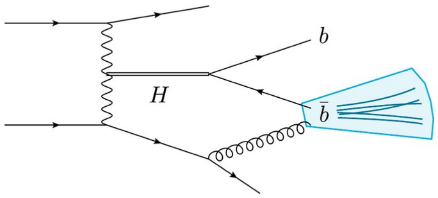
Vector boson fusion + Higgs decay



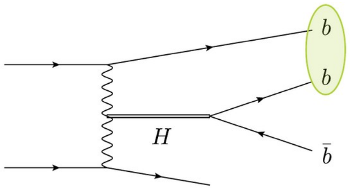
VBF + $H \to b\bar{b}$ decay:

- B-tagged jets in central region – can access bottom quark Yukawa.
- Higgs is a narrow-width scalar $\to$ production and decay factorize and can be treated separately: VBF at NNLO, $H \to b\bar{b}$ at LO.

[Asteriadis, Caola, Melnikov, RR '21]



Jet-clustering breaks factorization



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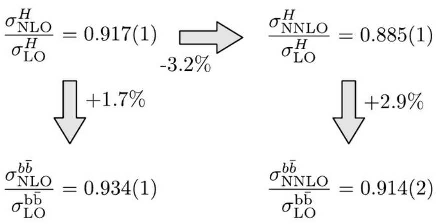


[From talk by K. Asteriadis at "Past, present, and future of VBF" workshop, 20/10/2022]

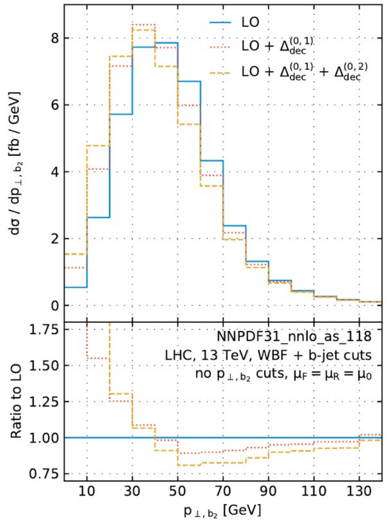
Impact of including decay comparable to NNLO corrections

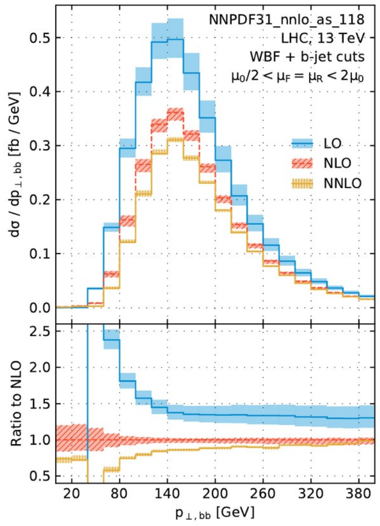
Vector boson fusion + Higgs decay

- NNLO in production and decay:

[Asteriadis, Behring, Melnikov, Novikov, RR '24]

  - Large impact: corrections in decay reduce fiducial cross section by 7% at NLO and 7% at NNLO (poor perturbative convergence)
  - Interplay of cuts on b-tagged jets and corrections to decay





→ Talk by Ivan Novikov

Vector boson fusion: non-factorizable effects

Two-loop non-factorizable corrections computed in eikonal expansion $(p_{T,j}/\sqrt{s})$

- Color-suppressed but enhanced by Glauber phase → 0.5%-1% corrections

  [Liu, Melnikov, Penin '19; Dreyer, Karlberg, Tancredi '20]

- Other non-factorizable contributions at NNLO (real-real and real-virtual) negligible [Asteriadis, Brønnum-Hansen, Melnikov '23]
- Sub-leading eikonal effects ~ 20% of leading eikonal contribution [Long, Melnikov, Quarroz '23]
- $\mathcal{O}(\beta_0 \alpha_s^3)$ corrections ~ 20% of leading eikonal and reduce scale uncertainty on eikonal to ~ 5% [Brønnum-Hansen, Long, Melnikov '23]

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Non-factorizable effects under control

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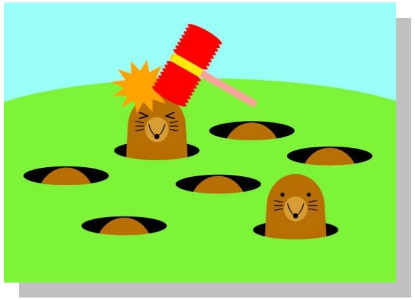

$t\bar{t}H$ production

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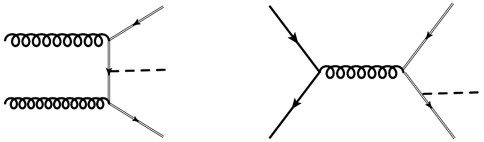
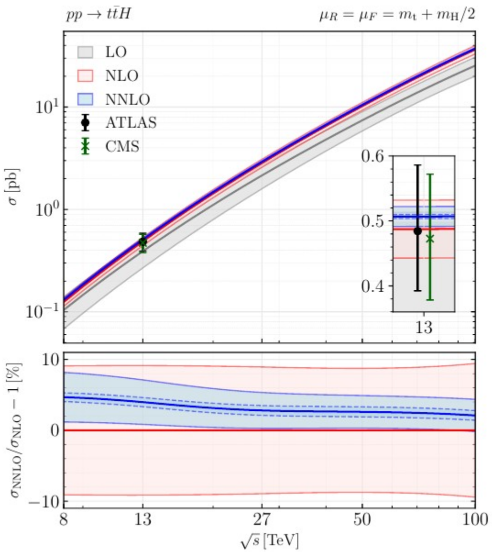
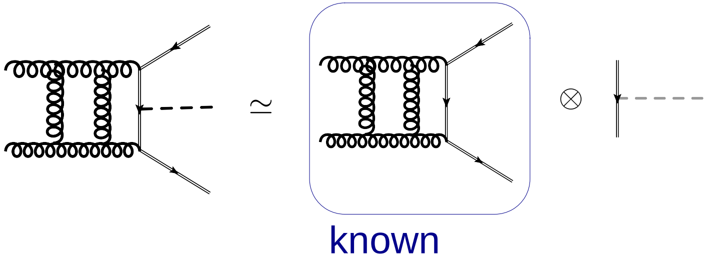


Direct access to top Yukawa



- NNLO two-loop amplitudes are extremely challenging ($2 \to 3$ process with 7 scales)
- Soft-Higgs approximation [Catani et al , '22]



- Rescale LO amplitude

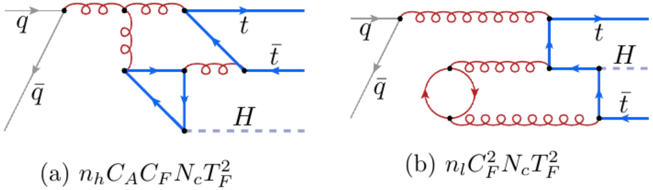
- (Approximate) NNLO QCD corrections ~ 4%
- Residual scale uncertainty ~ 3%,
- Approximation uncertainty ~ 0.5%

$t\bar{t}H$ production: Towards two-loop amplitudes

- NEW Amplitudes computed in boosted limit (top and Higgs approximately massless) [Wang, Xia, Yang, Ye ‘24]

Recent progress towards full two-loop amplitude:

- NEW Master integrals for leading color amplitudes [Febres Cordero et al ‘23]
- NEW One-loop $gg \to t\bar{t}H$ amplitude at $\mathcal{O}(\epsilon^2)$ [Buccioni, Kreer, Liu, Tancredi ‘23]
- NEW Nf-dependent contributions computed numerically [Agarwal et al ‘24]

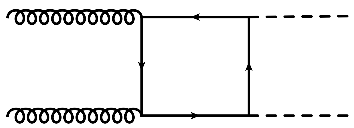


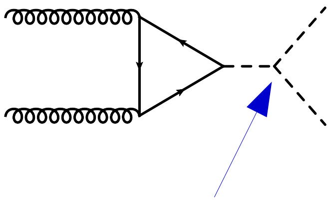
+ ….

→ Talk by Anton Olsson

Di-Higgs Production

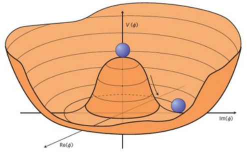
Di-Higgs Production





$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

$$\lambda_{HHH} = 6\lambda v = 3\frac{m_H^2}{v}$$



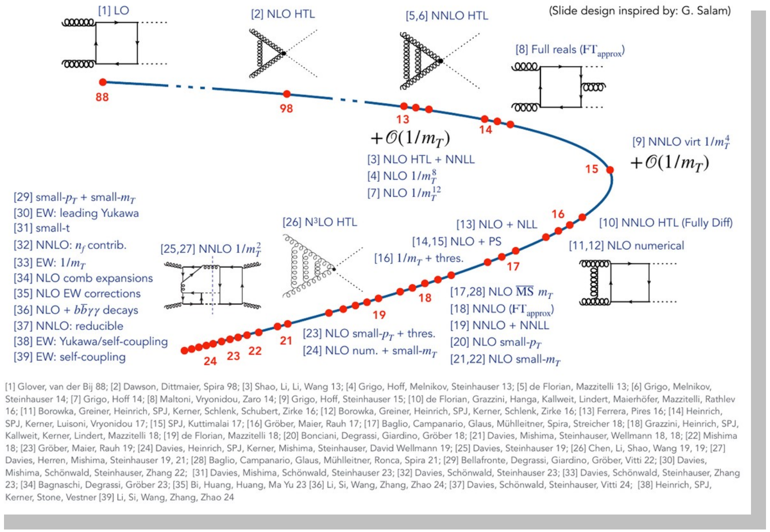
- Direct access to Higgs self-coupling → Higgs potential

- NLO QCD corrections increase cross section by ~ 60%-70%
- Residual scale uncertainty ~ 10%-15%
- Top mass definition uncertainty as high as 20%

  [Borowka et al, '16, '16; Baglio et al '18; '20]

- NNLO QCD results unavailable, but numerous approximations + matching to resummation/PS

Including $HH \to b\bar{b}\gamma\gamma$ at NLO [Li, Si, Wang, Zhang, Zhao '24]

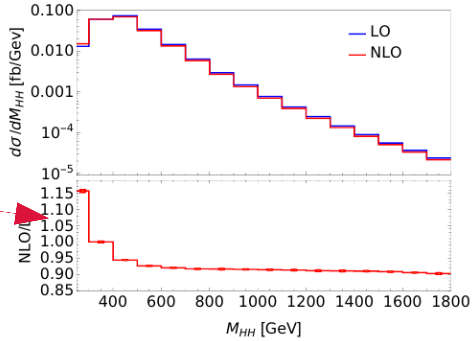


[Slide from S. Jones, Higgs Hunting 2024]

Di-Higgs Production: EW corrections

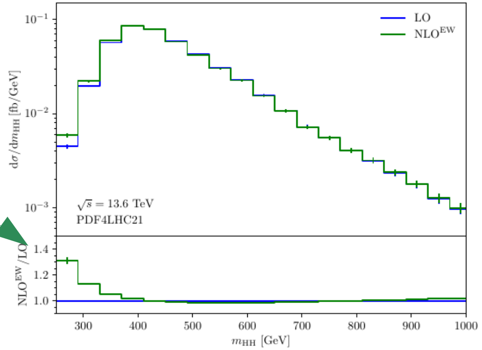
NEW NLO EW corrections computed [Bi, Huang, Huang, Ma, Yu '23]

- Decrease cross section by ~ 5%
- Stronger shape change in invariant mass and transverse momentum distributions



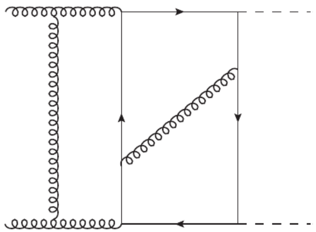
NEW Partial NLO EW corrections [Heinrich, Jones, Kerner, Stone, Vestner '24]

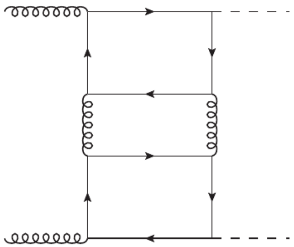
- Corrections involving top Yukawa and Higgs self-interaction
- Larger impact on shapes of distributions compared to full EW corrections



→ See talk by Augustin Vestner

Di-Higgs: Towards full NNLO QCD





Higgs may couple to same quark loop or different loops

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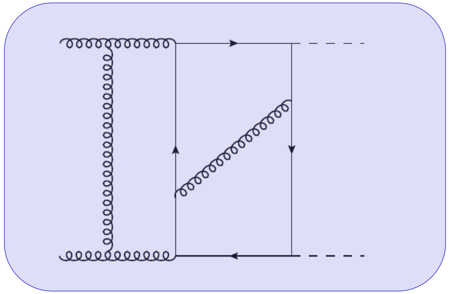

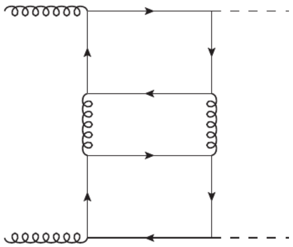

Known for $t = 0, m_H = 0$

[Davies, Schönwald, Steinhauser '23]

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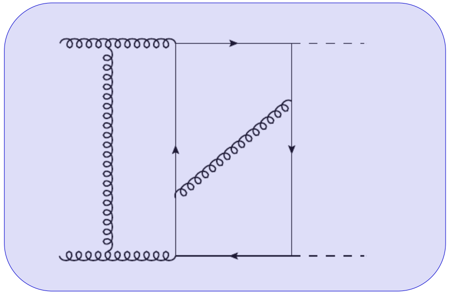

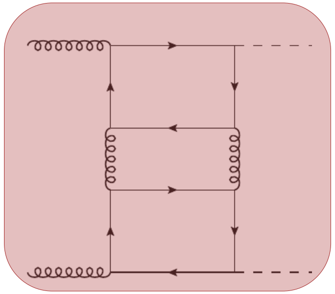

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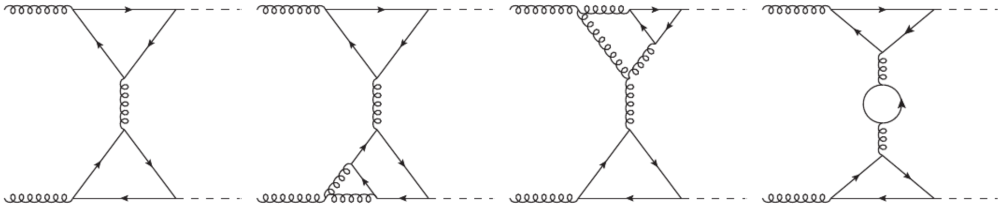
Higgs may couple to same quark loop or different loops

Reducible contributions computed [Davies, Schönwald, Steinhauser, Vitti '24]



→ Talk by Marco Vitti

Smörgåsbord

Many other interesting and important topics:

- Progress towards N4LO gluon fusion
- Impact of aN3LO pdfs on gluon fusion
- Progress towards N3LO in $H+j$ (HTL)
- Mixing between VH with hadronic Higgs decay and VBF at NLO QCD+EW
- Progress towards $t\bar{t}H$ fully differential at NNLO
- Parton shower uncertainties in VBF
- Interference effects in diphoton production and Higgs width
- Higgs decays
- ...

Conclusions

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Good luck!

THANK YOU FOR YOUR ATTENTION

QUESTIONS?