Higgs Hunting 2024, Orsay, France

23 September 2024

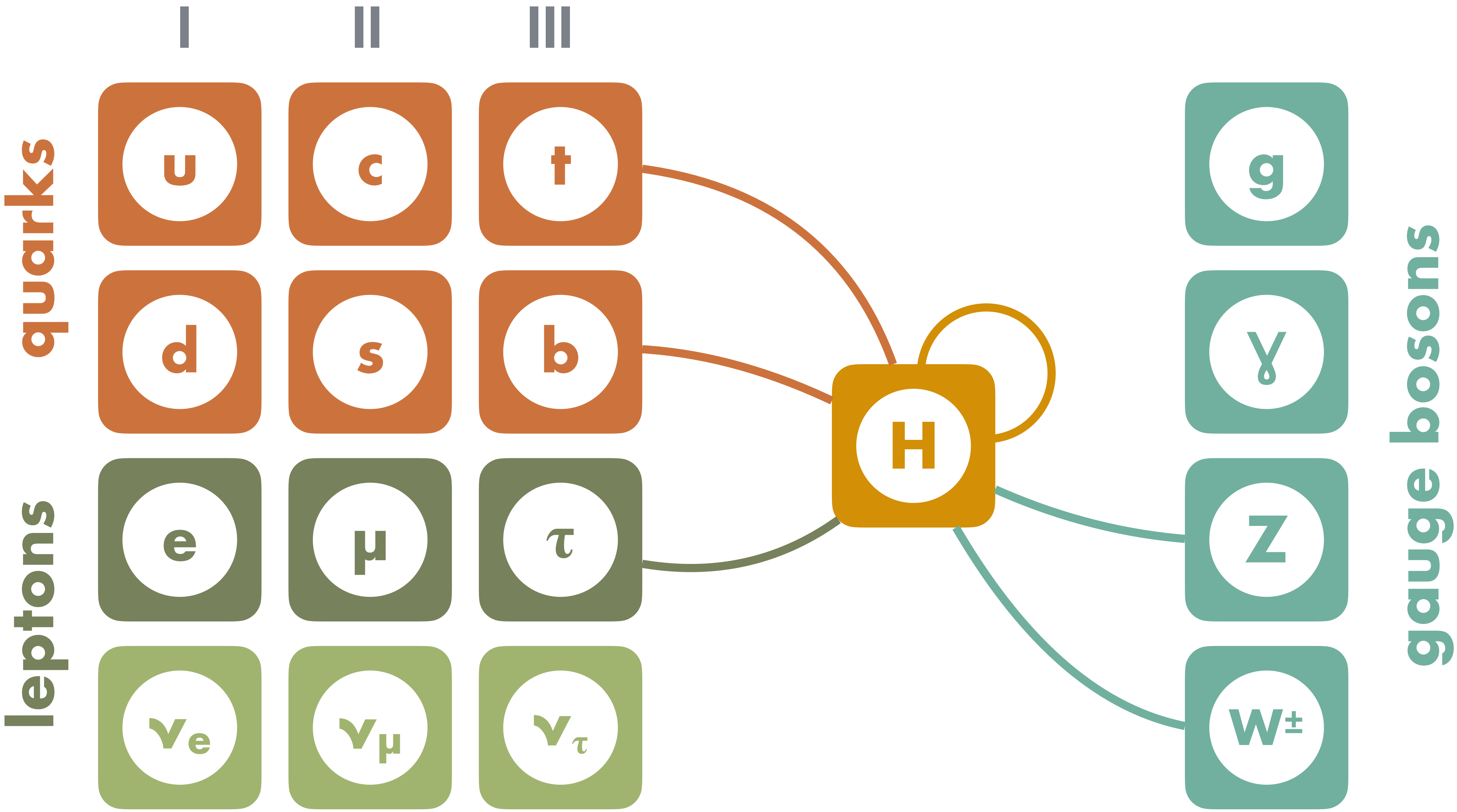
Higgs production:
A theory overview

Stephen Jones

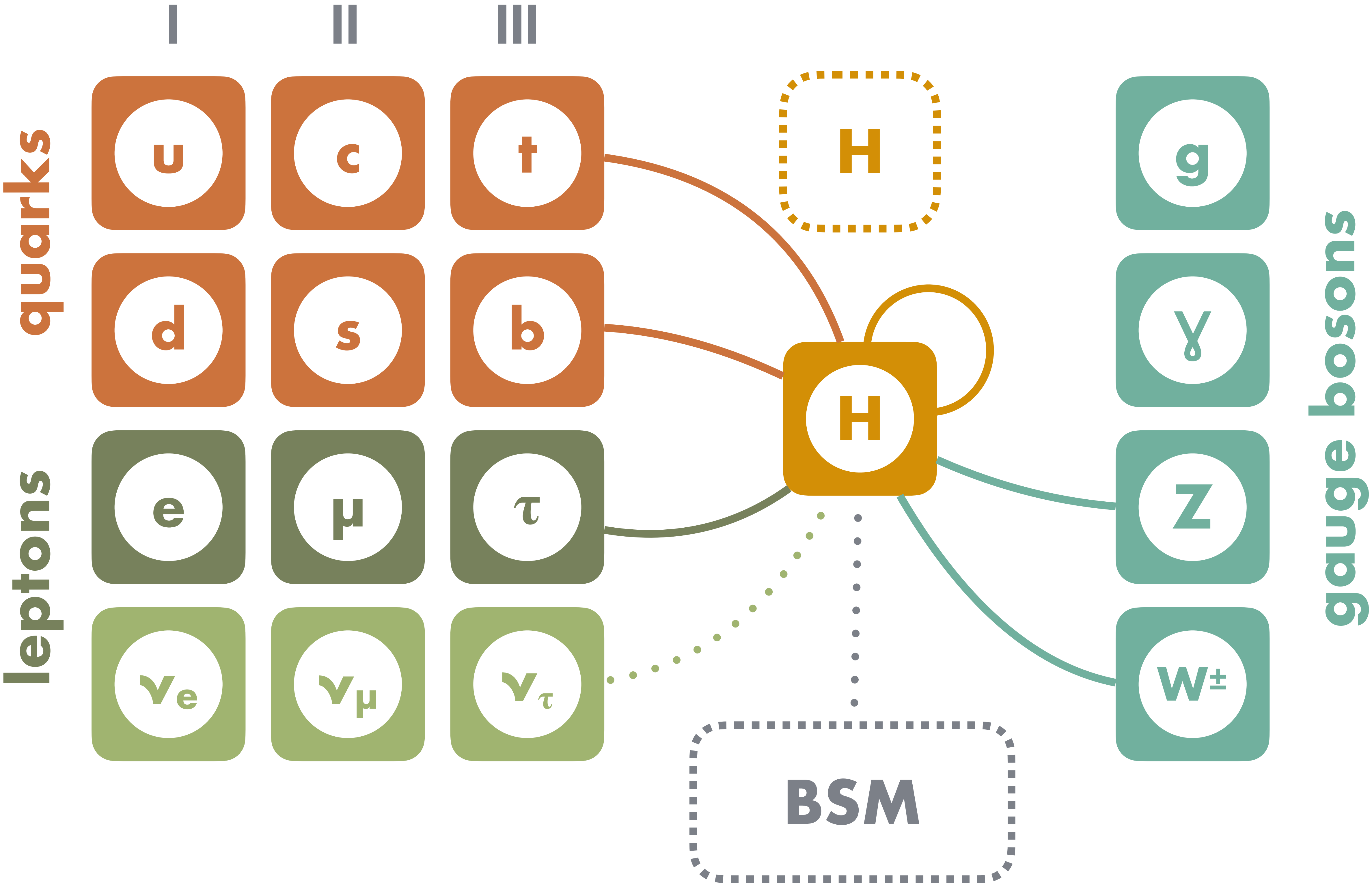
IPPP Durham / Royal Society URF

Photo: Chris Karidis on Unsplash

The Standard Model

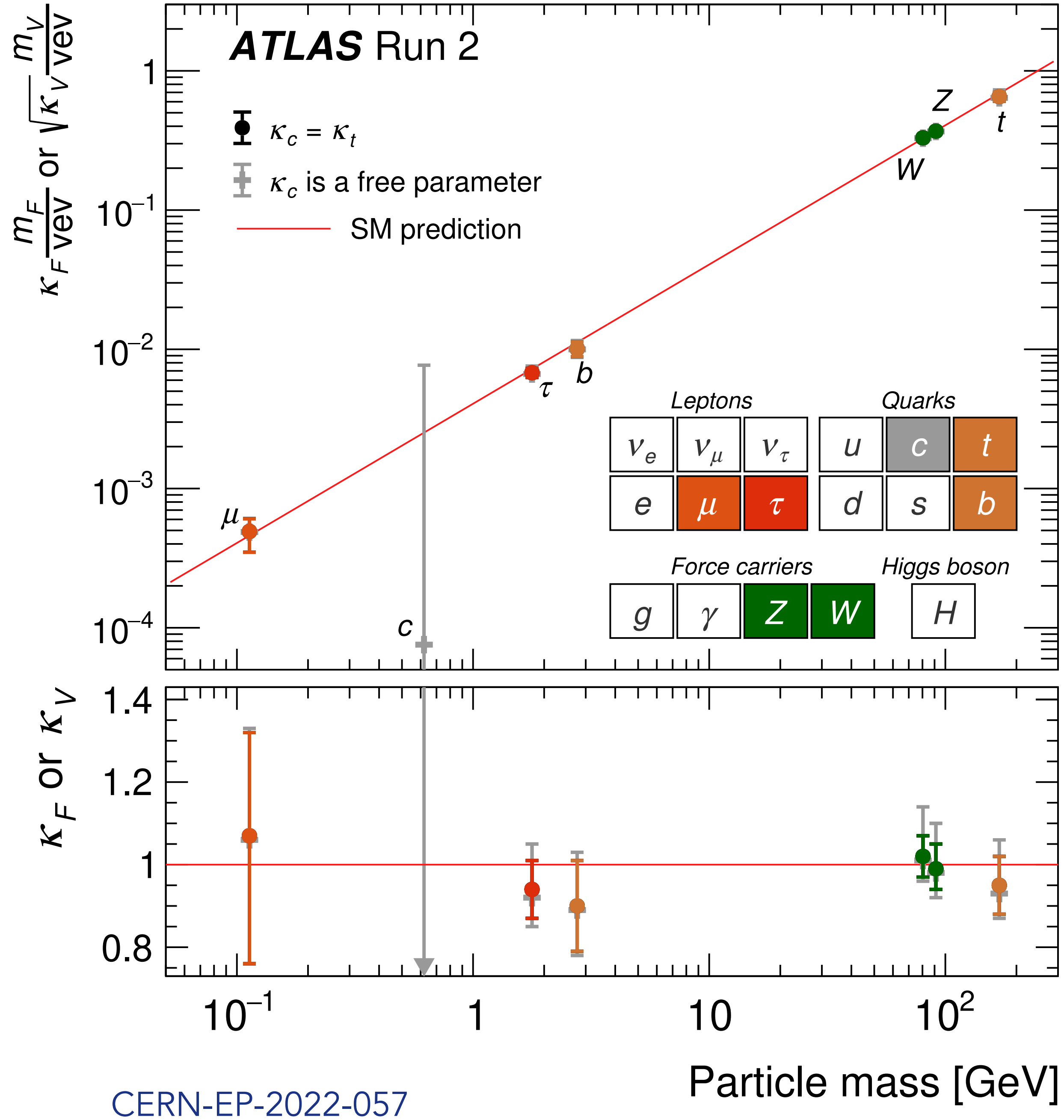


The Standard Model and Beyond



Higgs Couplings

The Higgs sector continues to yield impressive fundamental discoveries



CERN-EP-2022-057

2018 ($t\bar{t}H$): First direct observation of top-quark Yukawa coupling

CMS 1804.02610/ ATLAS 1806.00425
CMS 2407.10896/ ATLAS 2407.10904

2020 ($H \rightarrow \mu\mu$): First direct evidence that Higgs field is responsible for mass of 2nd gen. leptons

CMS 2009.04363 / ATLAS 2007.07830

2022 ($H \rightarrow c\bar{c}$): First hints that Higgs field is responsible for mass of 2nd gen. quarks

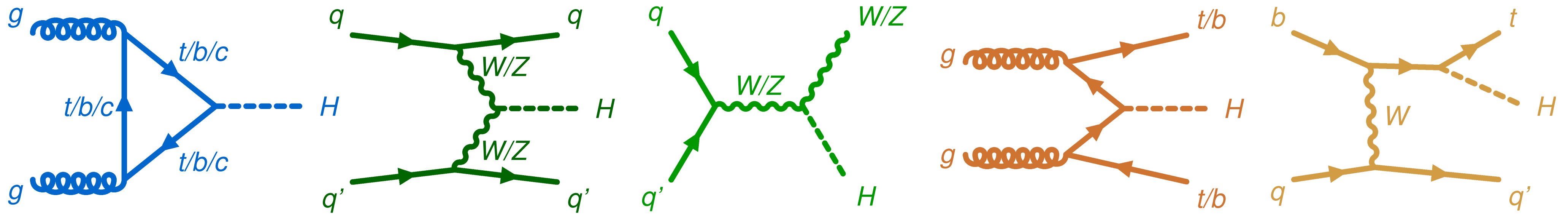
CMS 2205.05550 / ATLAS 2201.11428
ATLAS-CONF-2024-010

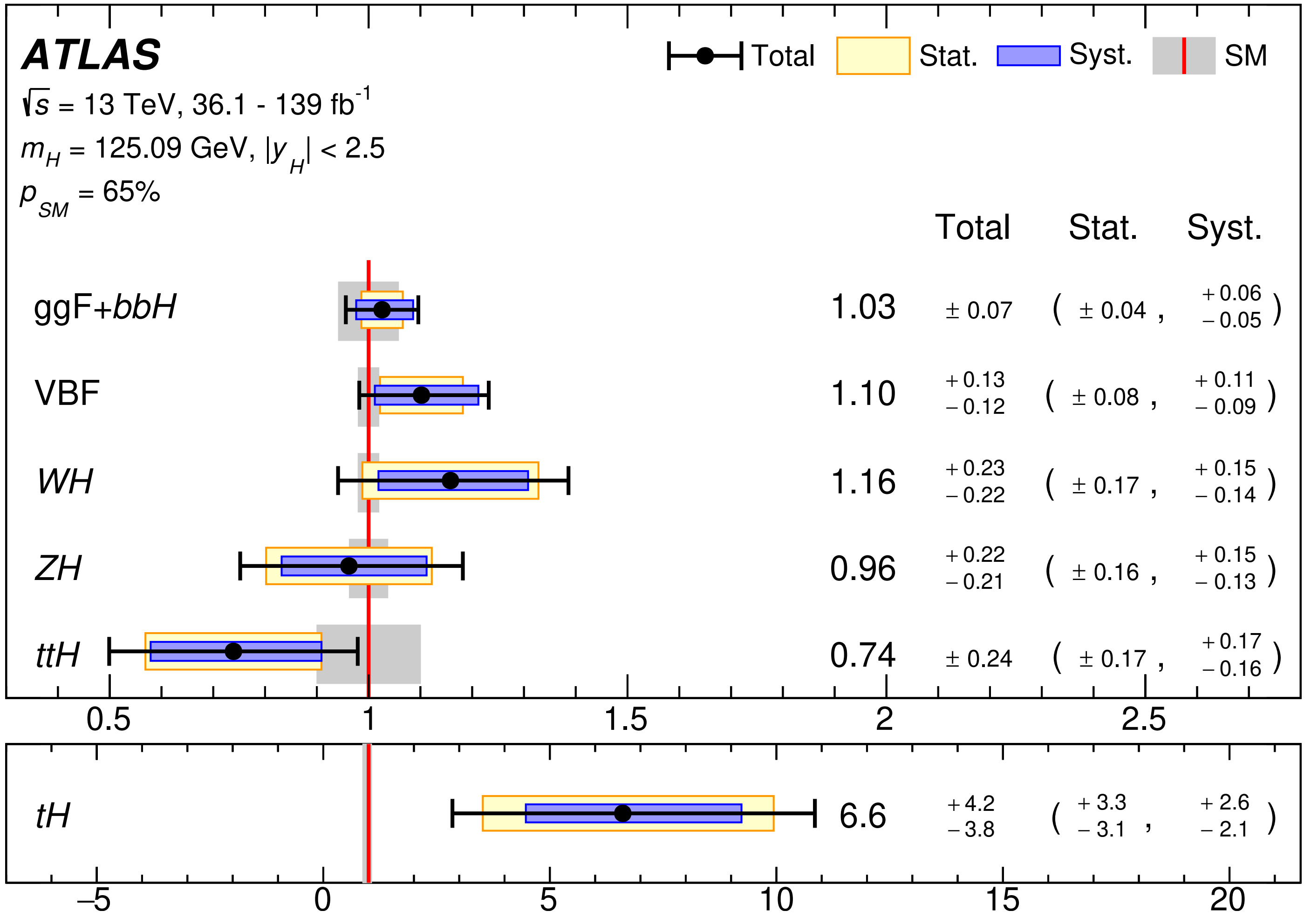
2024 (Sign HWW/HZZ): Exclude $\lambda_{WZ} = \kappa_W/\kappa_Z < 0$ using WH via VBF

CMS 2405.16566

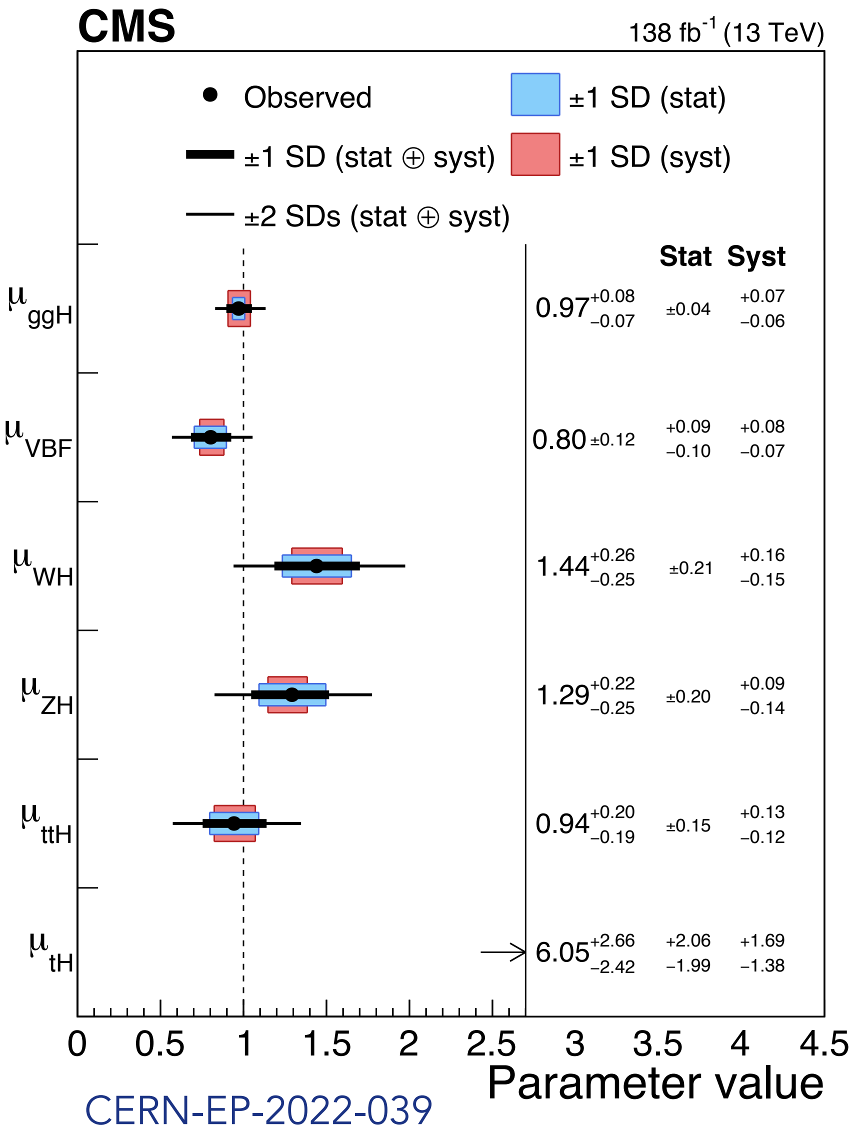
Higgs Precision Era

In Run 2 we have entered the era of precision Higgs physics…



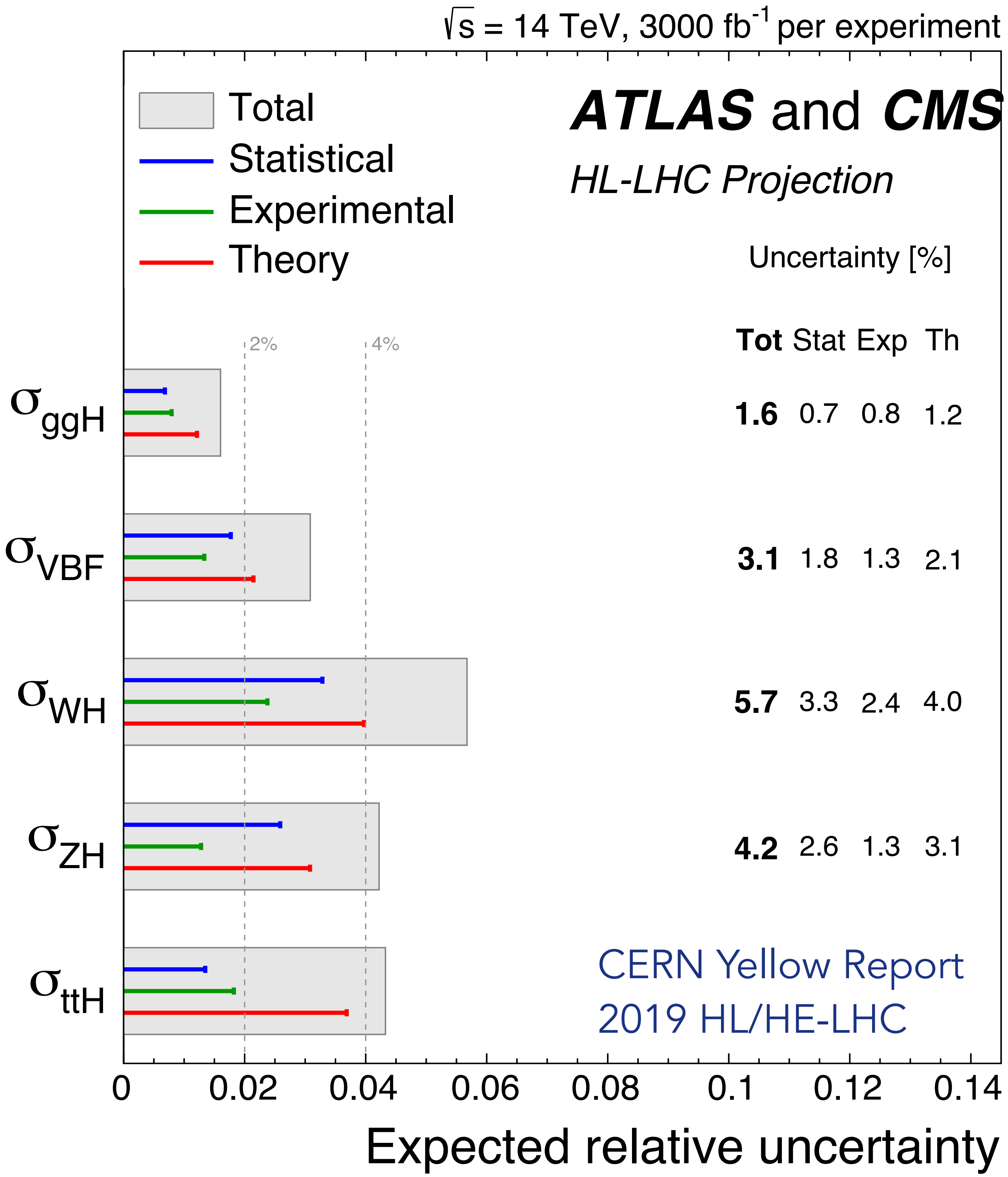


CERN-EP-2022-057



CERN-EP-2022-039

Upcoming Experiments



CERN Yellow Report 2019 HL/HE-LHC

HiLumi HL-LHC PROJECT

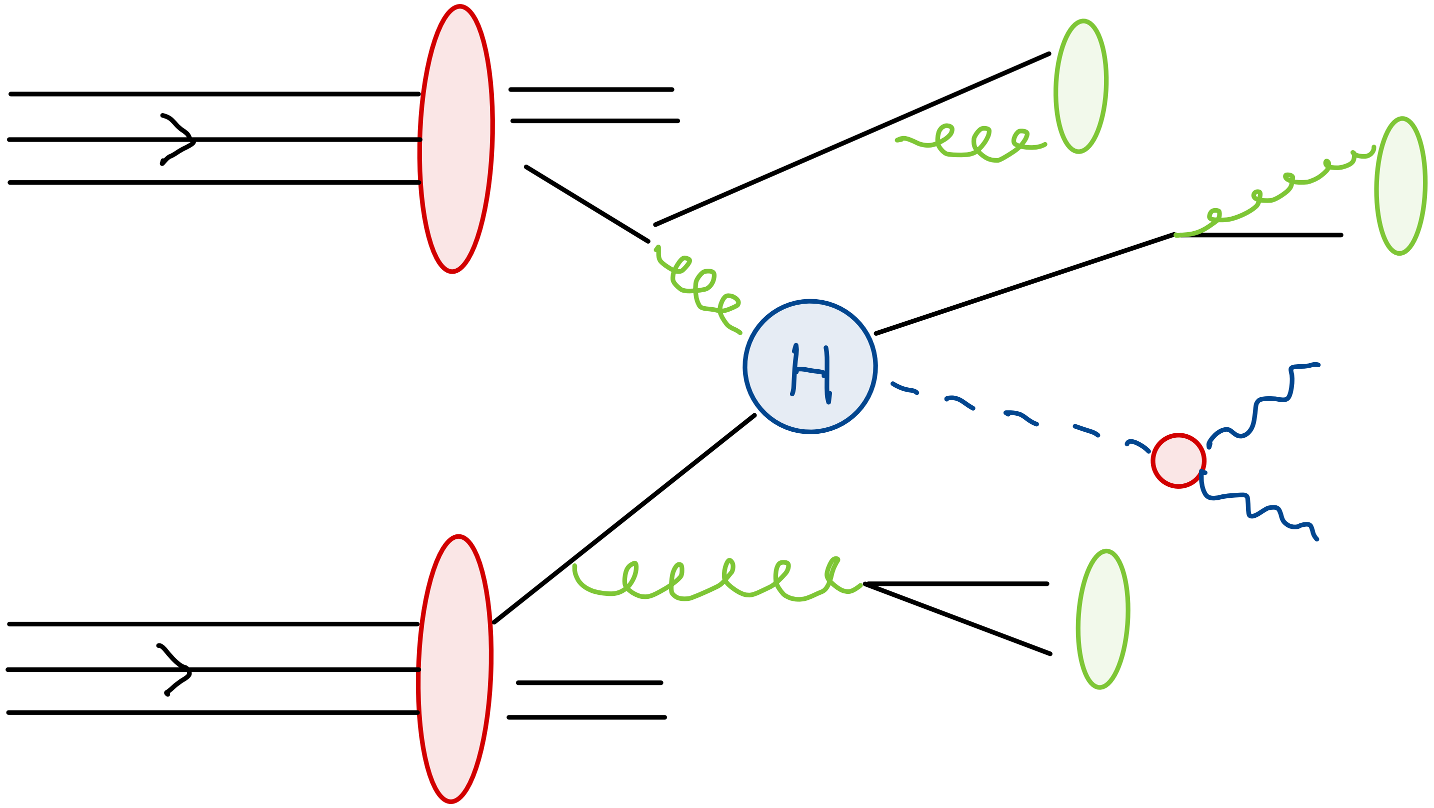
HL-LHC construction underway
~10x integrated luminosity of LHC (LHC 0.3 ab^{-1}, HL-LHC: 3 ab^{-1})

1) Experimental projection is pessimistic considering current performance

2) Plot shown assumes reduction by factor 2 of today's uncertainties

Theory uncertainty is expected to dominate HL-LHC Higgs physics

Improving Precision



- Parton Shower
- Resummation
- Hadronisation
- Underlying Event

$$d\sigma = \int dx_a dx_b f_a(x_a) f_b(x_b) d\hat{\sigma}_{ab}(x_a, x_b) F_J + \mathcal{O}\left((\Lambda/Q)^m\right)$$

Parton Distribution Functions (PDFs)

Hard Scattering Matrix Element

Non-perturbative effects ~ few %

With $\alpha_s \sim 0.1$, expect: NLO ~ 10% correction, NNLO ~ 1% correction

Higgs channels are important exceptions, receive much larger corrections!

Improving Precision

- Parton Shower
- Resummation
- Hadronisation
- Underlying Event

$$\mathrm{d}\sigma = \int \mathrm{d}x_a \mathrm{d}x \quad \Lambda/Q)^m)$$

Parton Distrib
Functions (PD

erturbative
s ~ few %

With $\alpha_s \sim 0.1$, expec correction

Higgs channels are i rger corrections!

Outline

Gluon Fusion

Impact of quark mass effects

aN3LO PDFs

Quest towards N4LO

Signal-background Interference

Boosted Production

Anomalous couplings

Towards N3LO

Vector Boson Fusion

Non-factorisable contributions

Parton Shower Uncertainties

NNLO with Production and Decay

ttH Production

Results at NNLO

Massive 2-loop Amplitudes

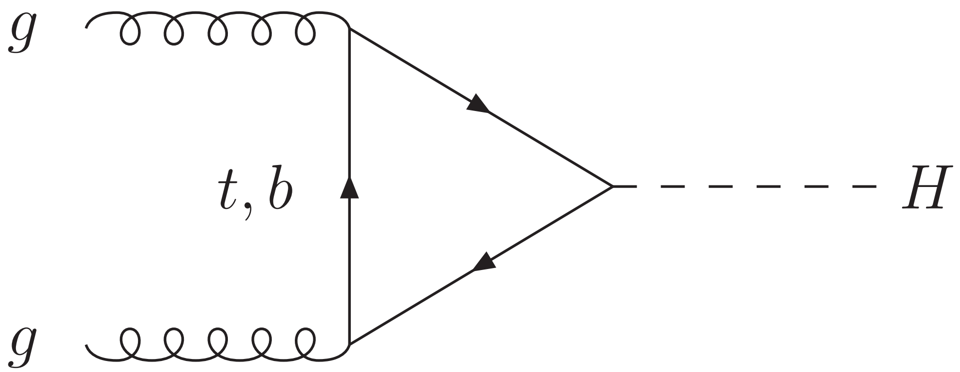
HH Production

Overview

EW Corrections

*All of these areas are very active, apologies for my very biased topic selection

Gluon Fusion

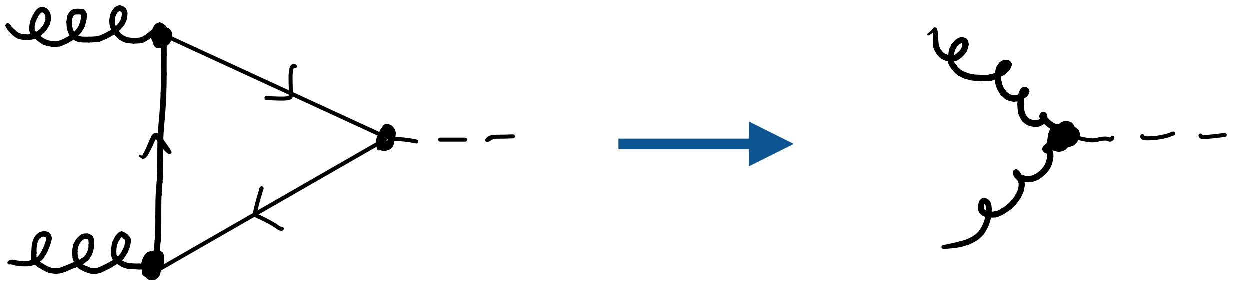


A Useful Approximation: Heavy Top Limit

Heavy Top Limit (HTL): integrate out top quarks ($m_T \to \infty$)

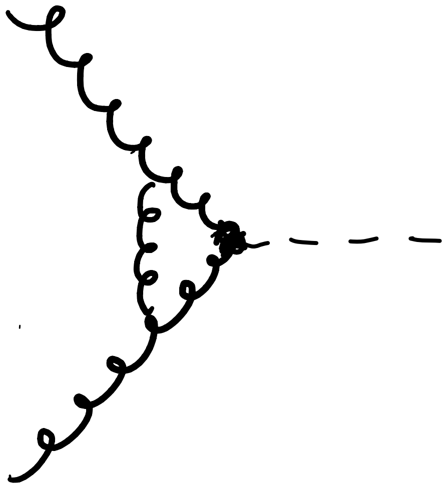
Introduces couplings c_h & c_{hh} between gluons and Higgs

Removes dependence on m_T and decreases the number of loops by 1



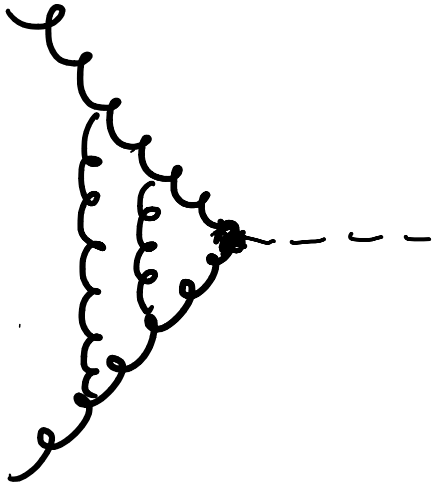
HTL valid for $\sqrt{\hat{s}} \ll 2m_T$

NLO



$\mathrm{NLO/LO} \approx 2.3$

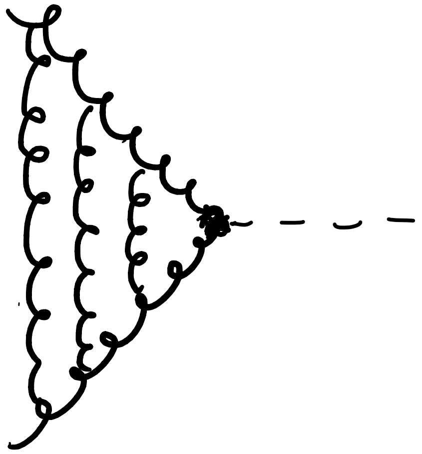
NNLO



$\mathrm{NNLO/NLO} \approx 1.3$

Anastasiou, Melnikov 02; Harlander, Kilgore 02; Ravindran, Smith, van Neerven 03;

N³LO



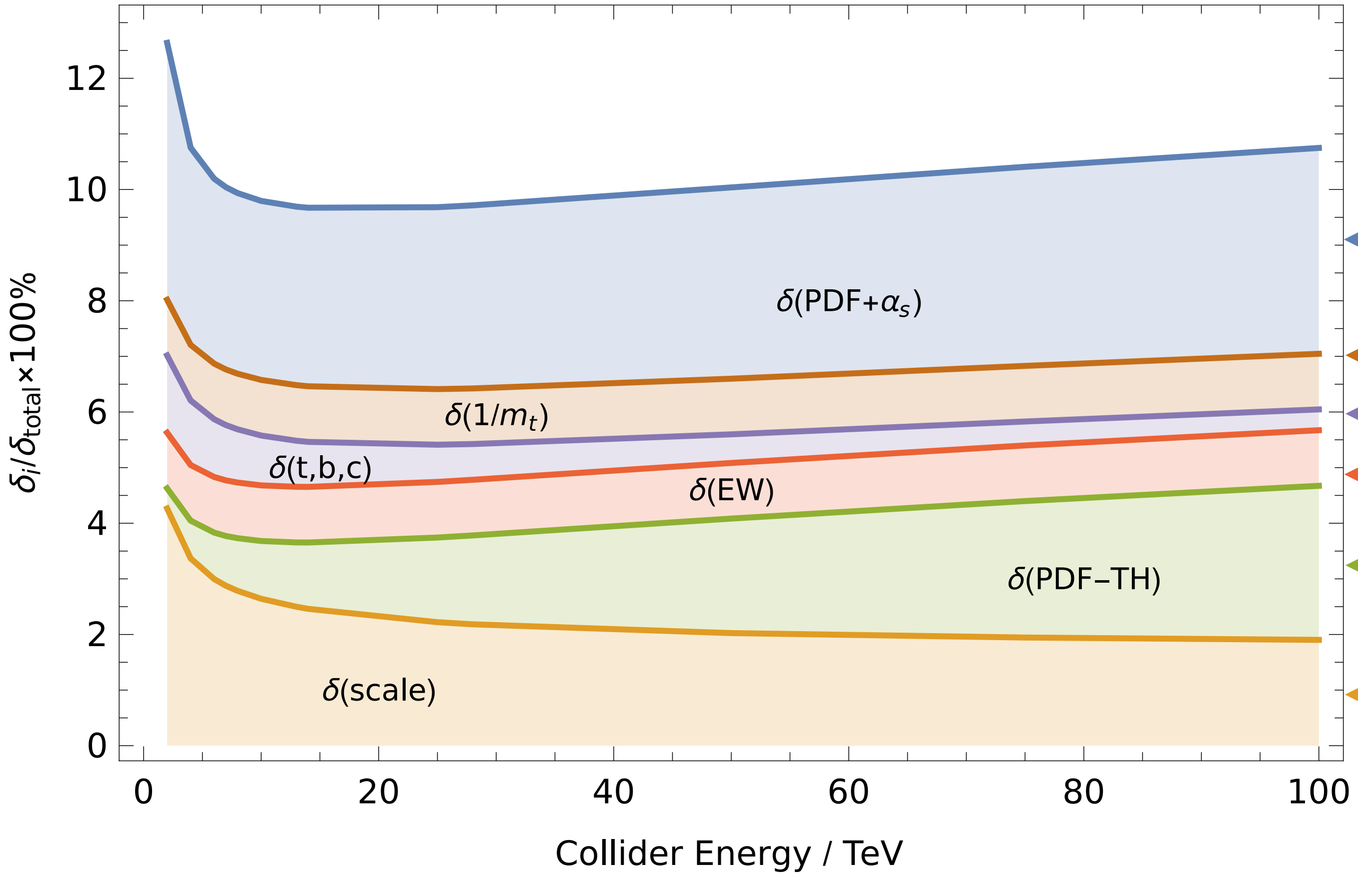
$\mathrm{N^3LO/NNLO} \approx 1.03$

Anastasiou, Duhr, Dulat, (Furlan), (Gehrmann), Herzog, Mistlberger 16; Mistlberger 18;

Gluon Fusion: Error Budget

2018 Error Budget

Dulat, Lazopoulos, Mistlberger 18



More data, better α_s deter.

NNLO top-quark mass dep.

NNLO b,c mass dep. + interferences

Mixed QCD-EW corrections

Missing N^3LO PDFs

Missing N^4LO

Progress

$\delta(1/m_t)$: Now known to NNLO — Czakon, Niggetiedt 20; Czakon, Harlander, Klappert, Niggetiedt 21

$\delta(t, b, c)$: Now known to NNLO — Niggetiedt, Usovitsch 23; Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 23

$\delta(\text{EW})$: gg known, reduced from ~1% to 0.6% — Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20; + Bonetti, Panzer, Smirnov, Tancredi, Melnikov, …

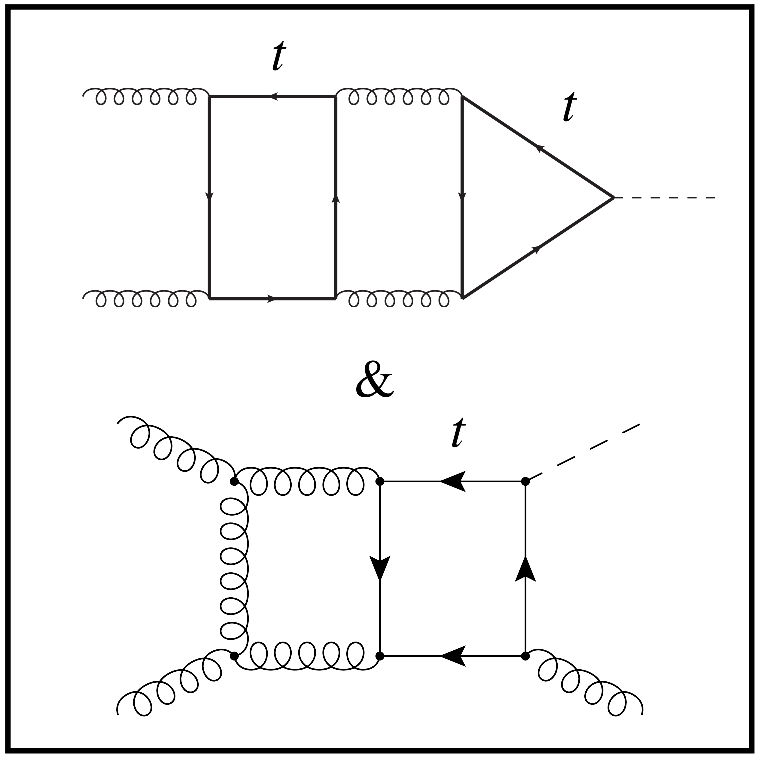
$\delta(\text{PDF} - \text{TH})$: Progress but uncertainty persists — McGowan, Cridge, Harland-Lang, Thorne 22; NNPDF 24

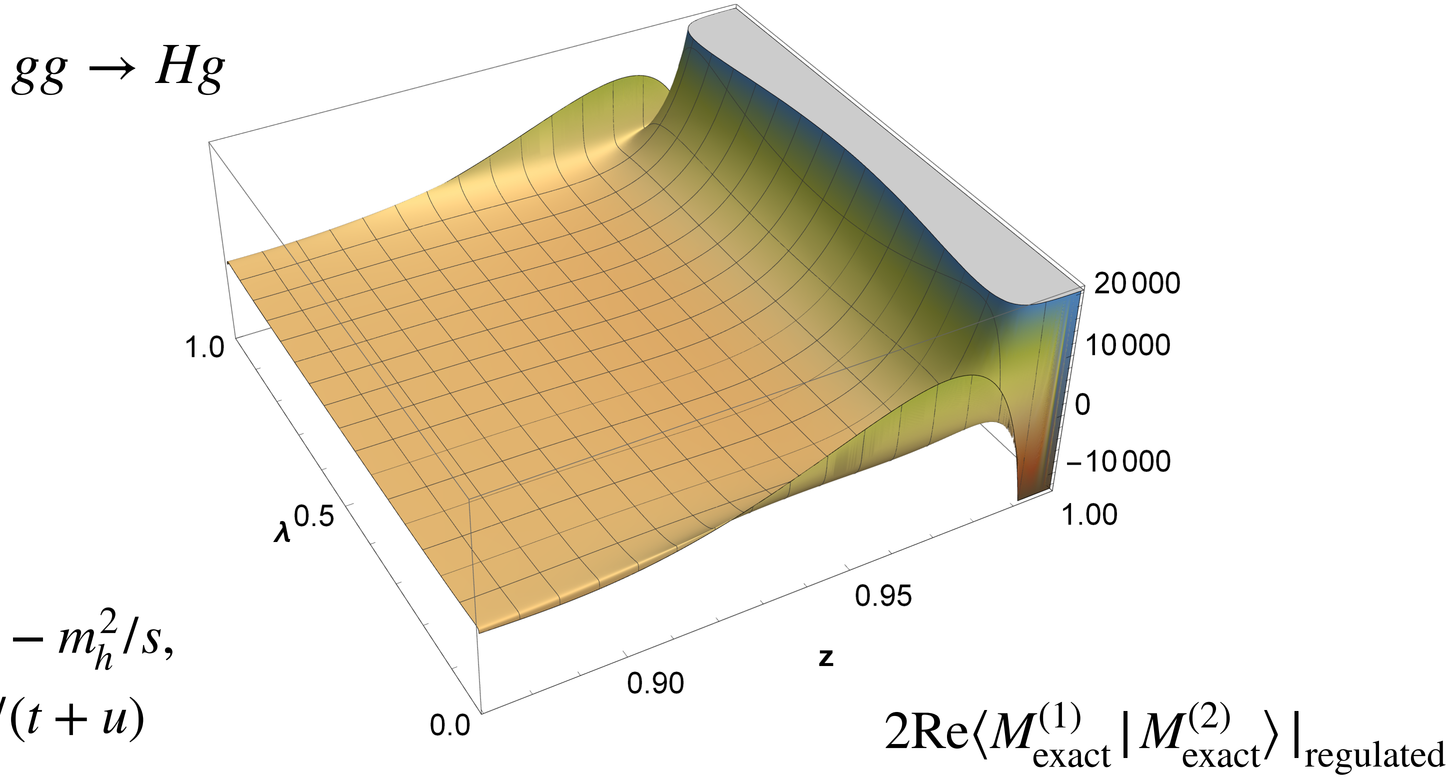
$\delta(\text{scale})$: Some ingredients known — Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser 22

$\delta(1/m_t)$: NNLO with Top Mass Dependence

H @ 3-loop & HJ @ 2-loop with m_t using numerical solution of differential equations

Czakon, Niggetiedt 20;
Czakon, Harlander, Klappert, Niggetiedt 21





$z = 1 - m_h^2/s$,
$\lambda = t/(t+u)$

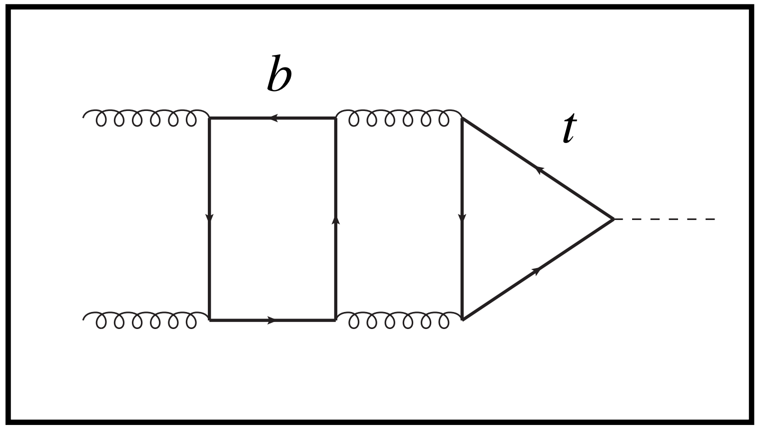
Decreases σ_{tot} by $-0.32\,\%$ @ 13 TeV compared to heavy top limit (HTL)

Intricate interplay between mass effects gg $(+0.62\%)$, qg (-18%), qq (-15%)
Complete NNLO results obtained using STRIPPER framework

$\delta(t, b, c)$: NNLO with Top/Bottom Mass Dependence

H @ 3-loop with two different quark masses m_t and m_b in the on-shell quark mass scheme

Niggetiedt, Usovitsch 23
Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 23



3-loop integrals computed using asymptotic expansions & AMFlow

Liu, Ma, Wang 17; Liu, Ma 22, 22;

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}\,(Y_{b,\overline{\text{MS}}})$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
			$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	-1.223	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	$-1.22^{+0.29}_{-0.44}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	$-0.623(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-1.85^{+0.26}_{-0.26}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	$+0.019(5)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-1.83(1)^{+0.08}_{-0.03}$	$-4.2^{+0.9}_{-0.8}$

Very large decrease of σ_{tot} by $-4.2\,\%$ @ 13 TeV compared to heavy top limit (HTL)

Results sensitive to the choice of renormalization scheme for the Yukawa coupling (on-shell vs $\overline{\text{MS}}$), with the on-shell scheme receiving large perturbative corrections

$\delta(t,b,c)$: NNLO with Top/Bottom Mass Dependence

H @ 3-loop with two different quark masses m_t and m_b in the $\overline{\mathrm{MS}}$ mass scheme

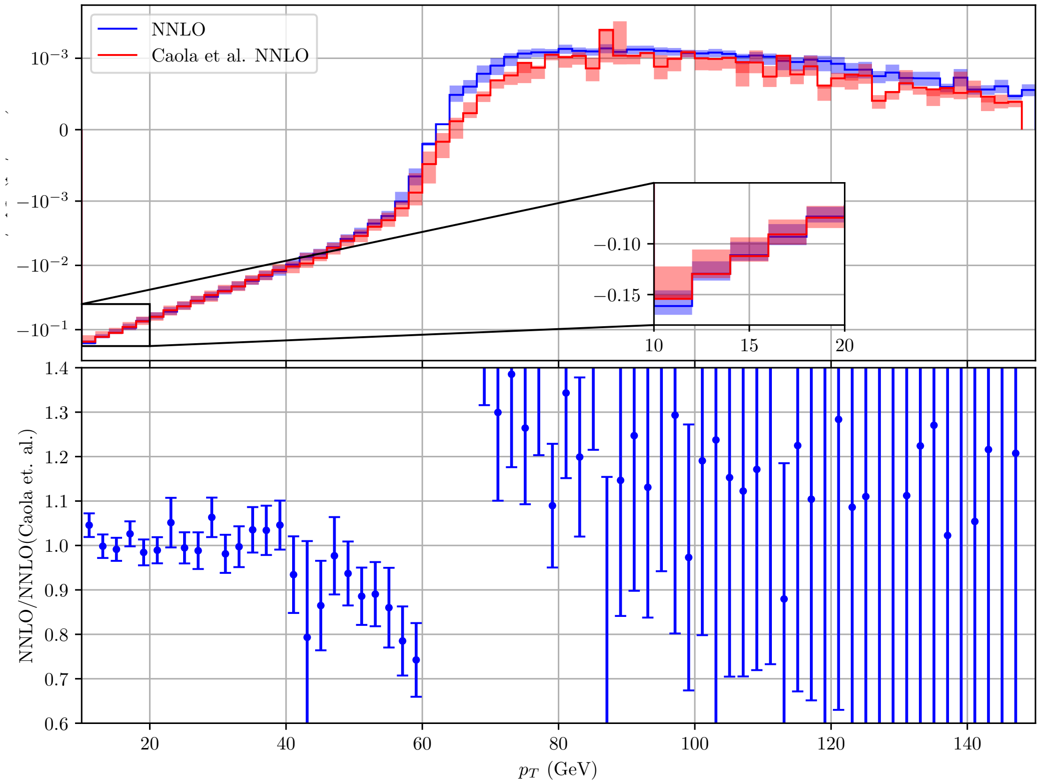
Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 23

Order	$(\sigma_t^{\overline{\mathrm{MS}}} - \sigma_t^{\mathrm{OS}})$ [pb]
	$\sqrt{s} = 13$ TeV
$\mathcal{O}(\alpha_s^2)$	-0.04
LO	$-0.04^{+0.12}_{-0.17}$
$\mathcal{O}(\alpha_s^3)$	$+0.02$
NLO	$-0.02^{+0.14}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.01$
NNLO	$-0.01^{+0.12}_{-0.24}$

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	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$	$-1.78(1)^{+0.15}_{-0.03}$	$-1.83(2)^{+0.14}_{-0.03}$

For $m_h = 125$ GeV, mass scheme uncertainty for m_t is very small

Perturbative corrections to top-bottom interference much more stable in $\overline{\mathrm{MS}}$



Can study also t/b interference effects on Higgs p_T spectrum

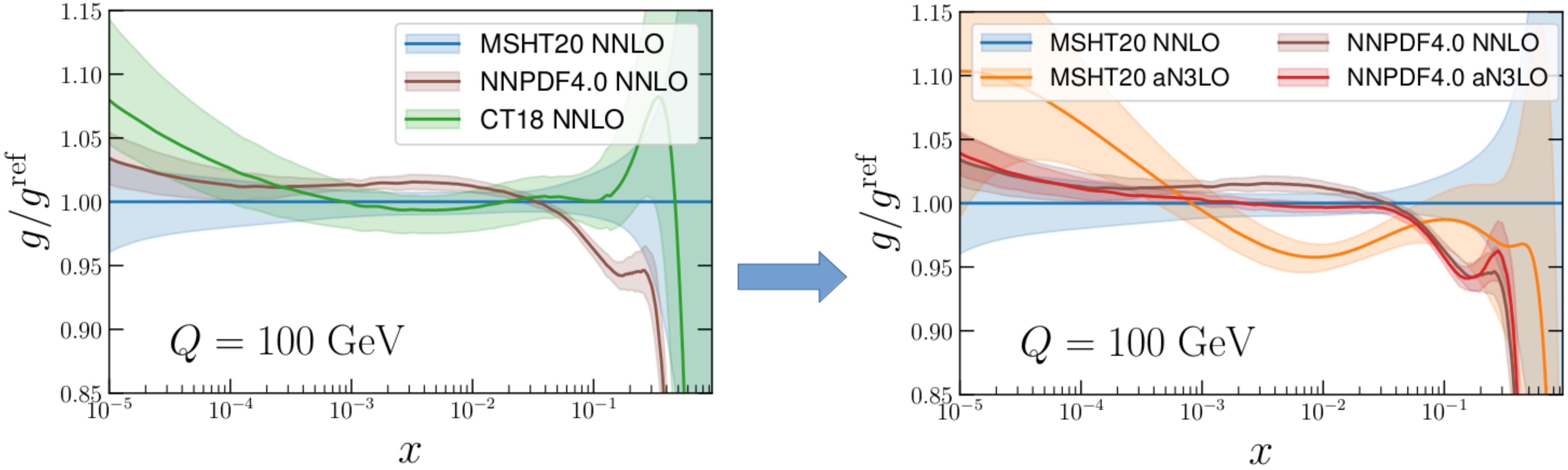
Previous approximation with HTL m_t and $m_b \sim 0$ works well for $p_T \lesssim 40$ GeV

Caola, Lindert, Melnikov, Monni, Tancredi, Wever 18

aN^3LO PDFs

Two global fit groups have now produced approximate N3LO PDFs

McGowan, Cridge, Harland-Lang, Thorne 22; NNPDF 24



Significant impact for gluon PDF & Higgs production (MSHT -5%, NNPDF -2%)

Ingredients

Splitting Functions	@ 4-loop: moments $N \leq 20$ now known Falcioni, Herzog, Moch, Pelloni, Vogt 23, 24, TA; Gehrmann, von Manteuffel, Sotnikov, Yang 23
Transition Matrix Elements	@ 3-loop: now known except 2-mass $A_{Qg}^{(3)}$ Ablinger, Behring, Blümlein, De Freitas, von Manteuffel, Schneider, Schönwald et al, 14-24;
DIS Coefficient Functions	@ 3-loop: light flavour, high-Q^2, low-Q^2 Catani, Ciafaloni, Hautmann 91; Laenen, Moch 98; Vermaseren, Vogt, Moch 05
Hadronic Cross-Sections	@ N3LO: relatively little known

Estimate for PDF-TH & aN^{3}LO PDFs

numbers for $\sqrt{s} = 13.6\,\mathrm{TeV}$ & $M_\mathrm{H} = 125.09\,\mathrm{GeV}$

Higgs WG baseline:

$$\delta(\text{PDF-TH}) = \pm\frac{1}{2}\left|\sigma^{(2),\ \text{EFT, NNLO}}_{PP\to H+X} - \sigma^{(2),\ \text{EFT, NLO}}_{PP\to H+X}\right|$$

PDF4LHC21 — no NLO set available

⇒ switch to PDF4LHC15 *just* for δ(PDF-TH) estimate

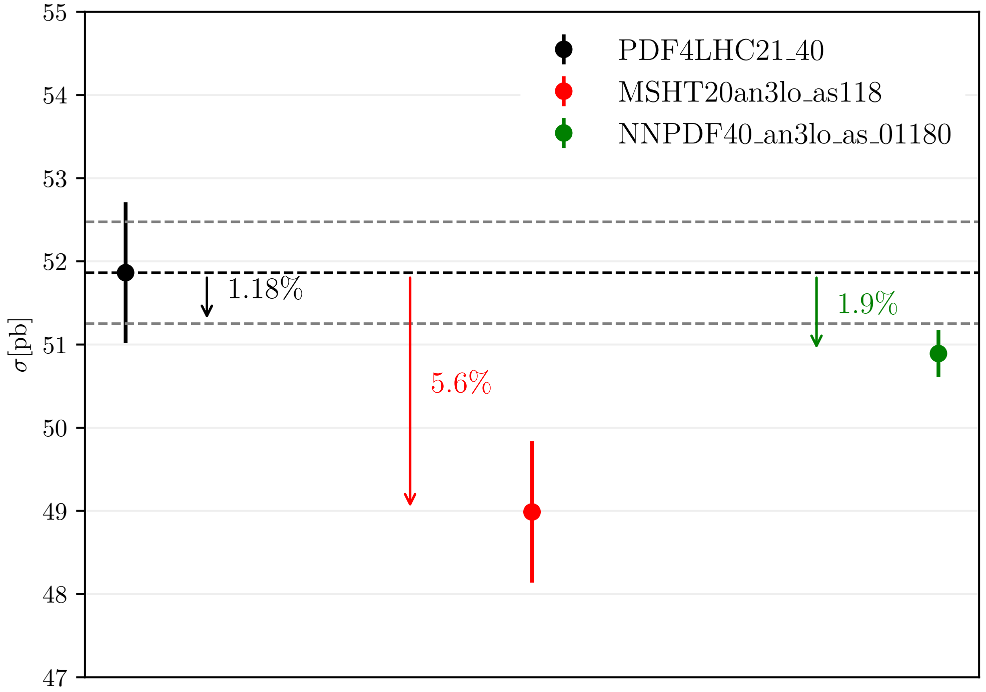
↪ PDF4LHC15 $\pm 1.18\,\%$

Robust w.r.t. PDF var.

↪ MSHT20	$\pm 1.43\,\%$
↪ CT18	$\pm 1.03\,\%$
↪ NNPDF3.1	$\pm 0.92\,\%$
↪ NNPDF4	$\pm 0.18\,\%$

Alternative 1:

$$\delta(\text{PDF}-\text{TH}) = |\,\sigma^{(3),\text{EFT,aN3LO}}_{PP\to H+X} - \sigma^{(3),\text{EFT,NNLO}}_{PP\to H+X}\,|$$



Error bars: δ(PDF)

Alternative 2:

Use aN3LO PDF uncertainties (include MHOUs)

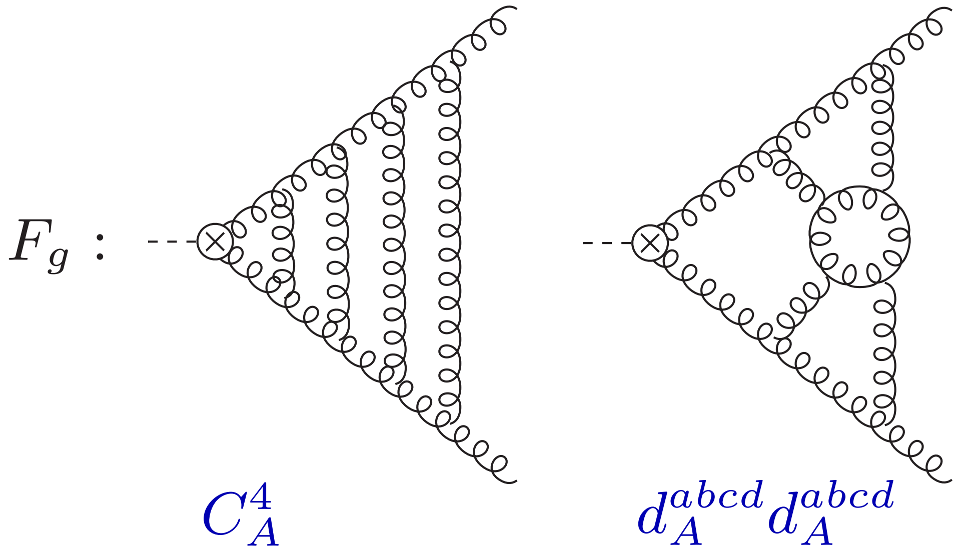
To the extent we can trust the new aN3LO PDFs, they seem to indicate that the $\delta(\text{PDF}-\text{TH})$ uncertainty was underestimated in previous Higgs WG updates

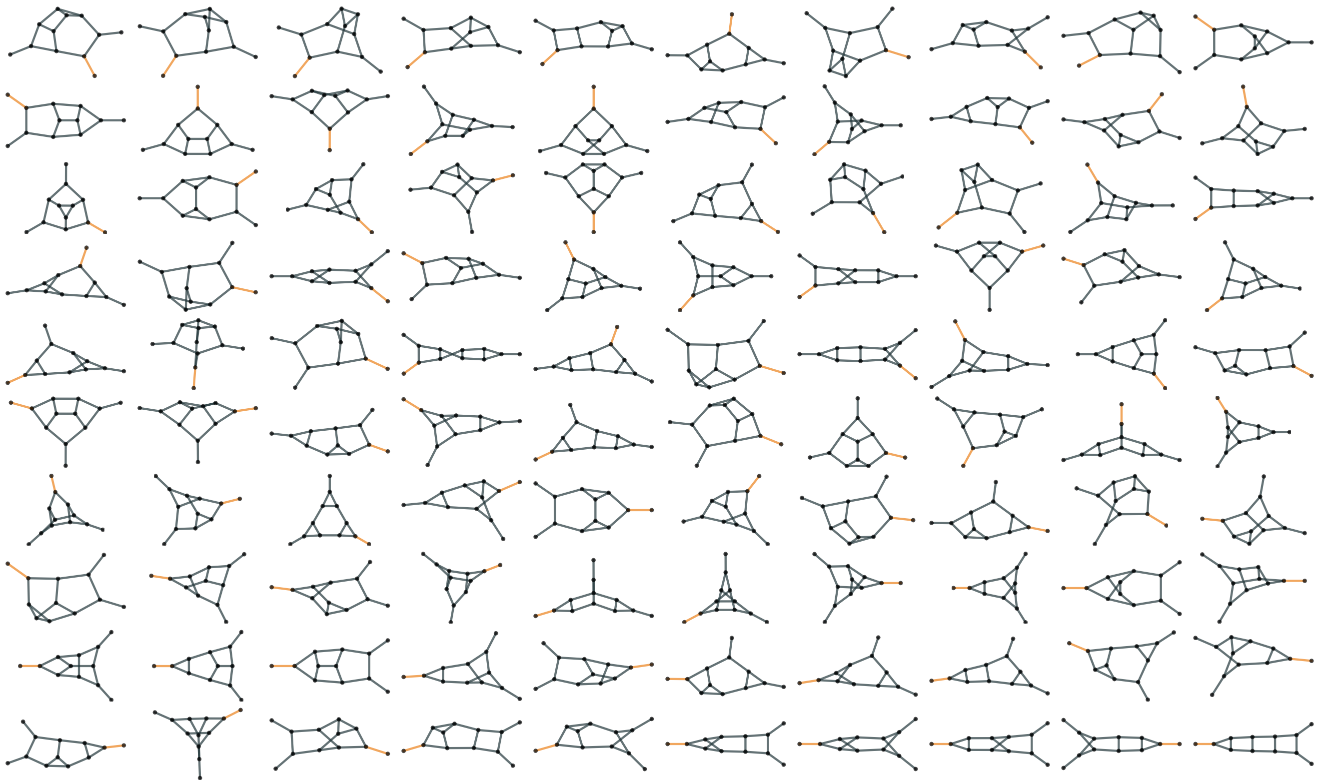
Anticipated Theory Results

Towards N4LO Higgs Production

Gluon Form Factor known @ $\mathrm{N^4LO}$ (Virtual Contribution) + 4-loop Master Integrals

Lee, von Manteuffel, Schabinger, Smirnov, Smirnov, Steinhauser 22, 23;





Obtaining real-virtual contribution will be very considerable work

Soft-Virtual Approx: $+0.2 - 2.7\,\%$ @ 14 TeV vs $\delta(\mathrm{scale}) \sim^{+2.5}_{-0.3}\,\%$ @ $\mathrm{N^3LO}$

Das, Moch, Vogt 20;

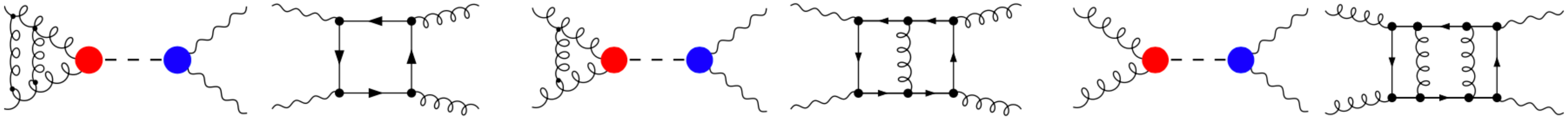
Signal-background Interference

Signal-background interference can be used in $H \to \gamma\gamma$ to place model-dependent bounds on Γ_H by lifting degeneracy on couplings and width

Martin 12; Dixon, Li 13; Campbell, Carena, Harnik, Liu 17

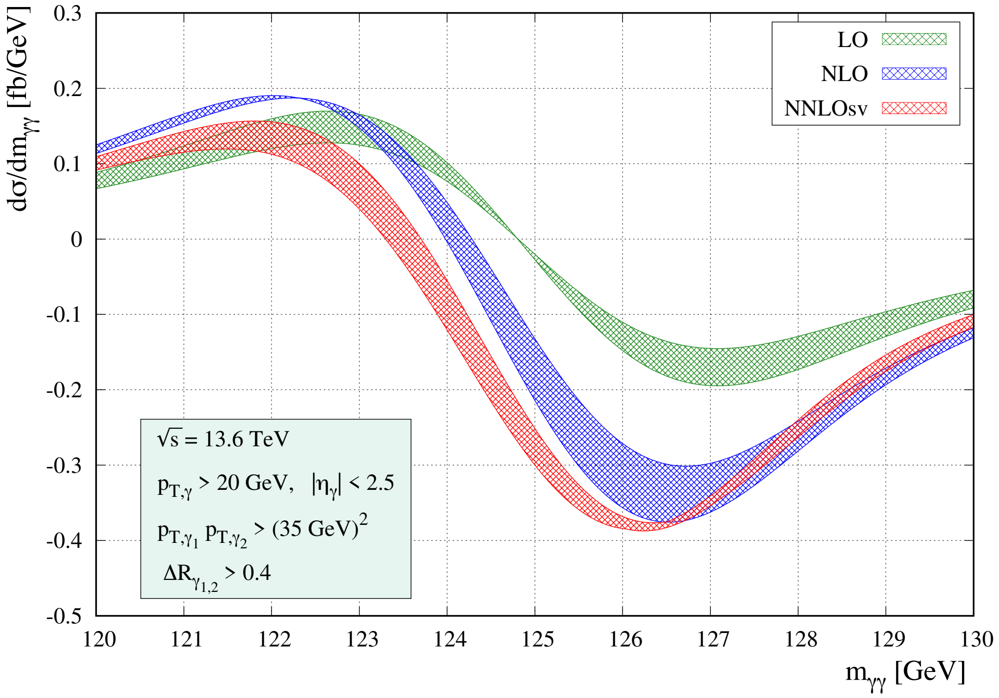
Calculation of $gg \to \gamma\gamma$ @ NNLO allows computation of interference @ NNLO

Bargiela, Caola, von Manteuffel, Tancredi 21 + Buccioni, Devoto 22



NNLO corrections sizeable

- ↪ Mass shift less pronounced
- ↪ Destructive interference enhanced
- ↪ -1.7% decrease of total cross section



Interference effects for $gg \to Z\gamma$ @ NLO also recently calculated

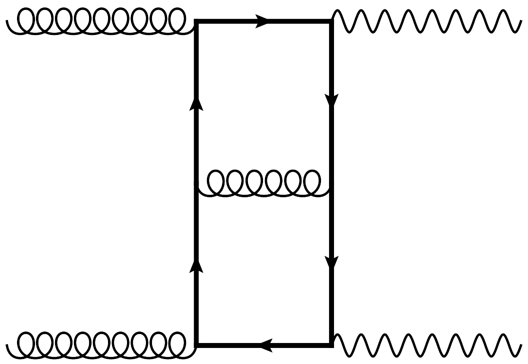
Buccioni, Devoto, Djouadi, Ellis, Quevillon, Tancredi 23

→Talk of Federico

ZZ Production via Gluon Fusion

Process $gg \rightarrow ZZ$ gives indirect constraints on **Higgs width** via off-shell production and constrains **Anomalous Couplings** ($t\bar{t}Z$ & triple gauge), **BSM Searches**

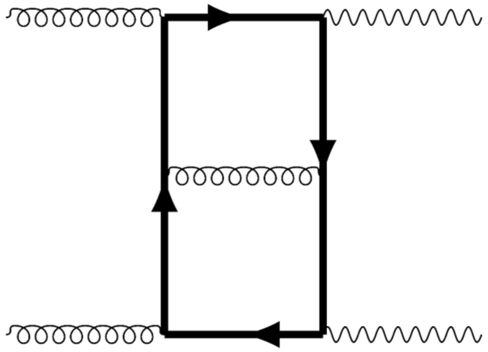
Loop-induced at LO, NLO calculation challenging (2-loops)



Class $\mathbf{A}_l$

Z bosons couple to same massless fermion line

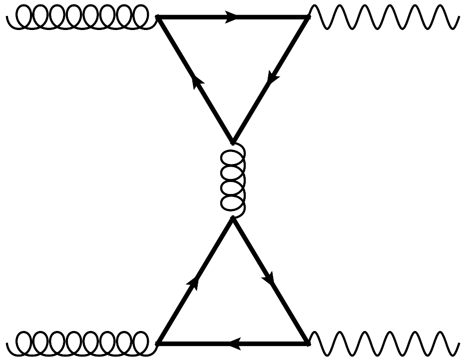
von Manteuffel, Tancredi 15



Class $\mathbf{A}_h$

Z bosons couple to same massive fermion line

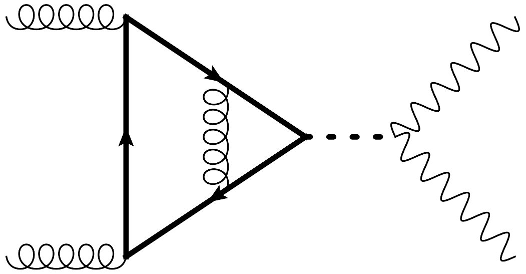
Agarwal, SPJ, von Manteuffel 20
Brønnum-Hansen, Wang 21
Degrassi, Gröber, Vitti 24



Class B

Z bosons couple to different fermion lines

Campbell, Ellis, Czakon, Kirchner 16



Class C

Z bosons couple to Higgs boson

Djouadi, Spira, Zerwas 91

ZZ Production NLO QCD Corrections

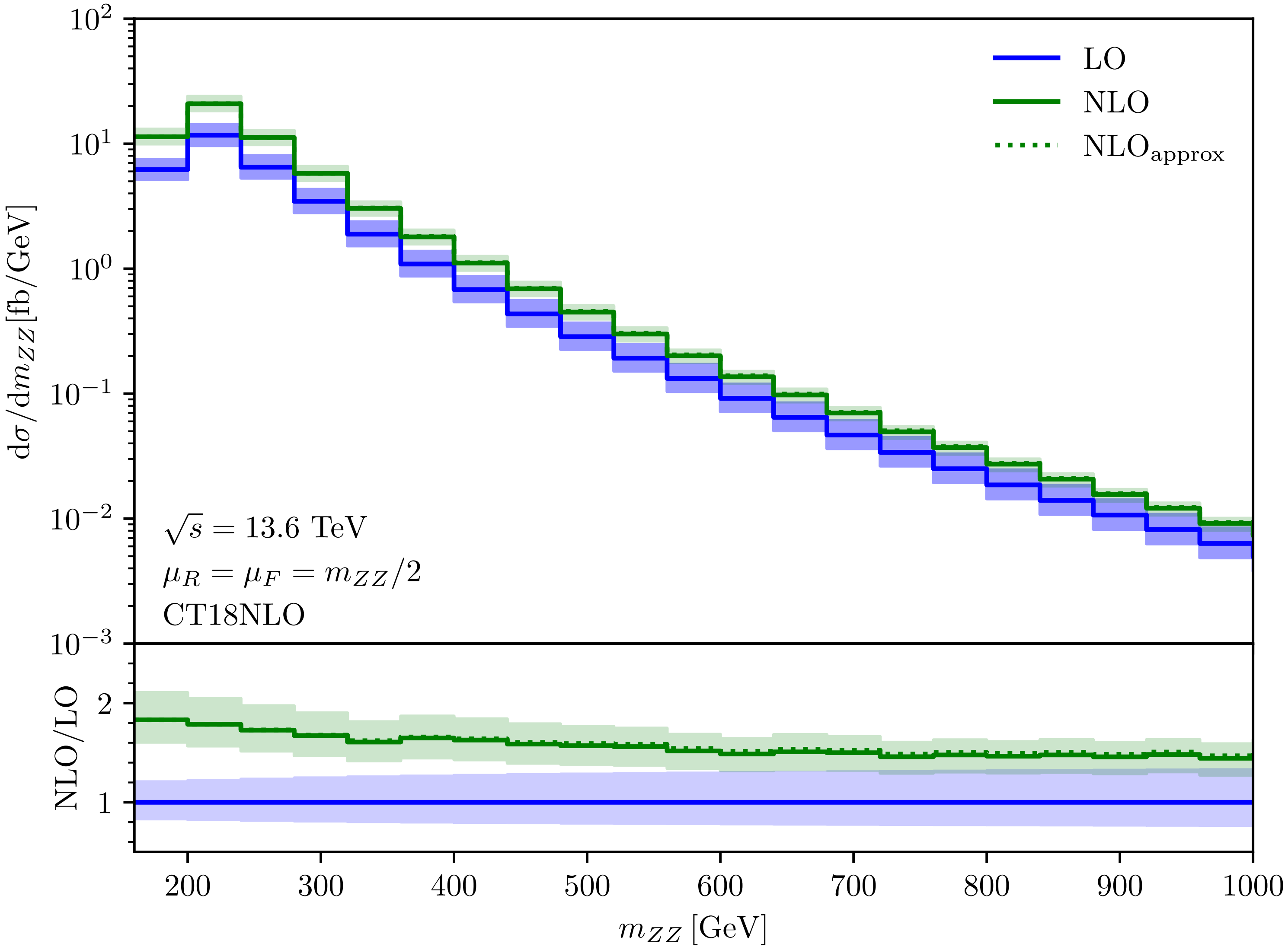
Putting all classes together: complete NLO corrections are large, K-factor ~ 1.7

NLO corrections reduce the scale uncertainties significantly

$$\sigma_{\mathrm{LO}} = 1316^{+23.0\%}_{-18.0\%}\,\mathrm{fb}$$

$$\sigma_{\mathrm{NLO}} = 2275(12)^{+14.0\%}_{-12.0\%}\,\mathrm{fb}$$

Approximation obtained by applying the massless K-factor to the massive born agrees well within the scale uncertainty, also for the invariant mass distribution

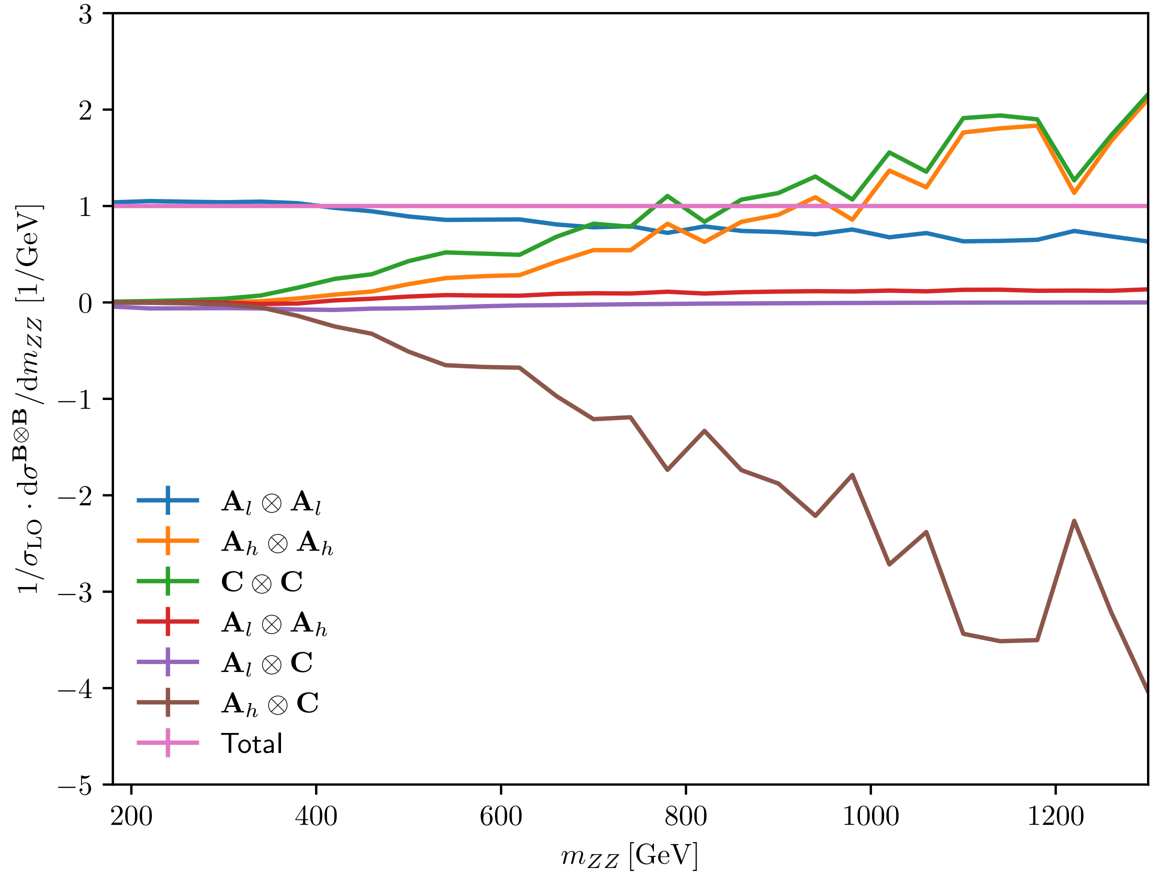


Agarwal, SPJ, Kerner, von Manteuffel 24

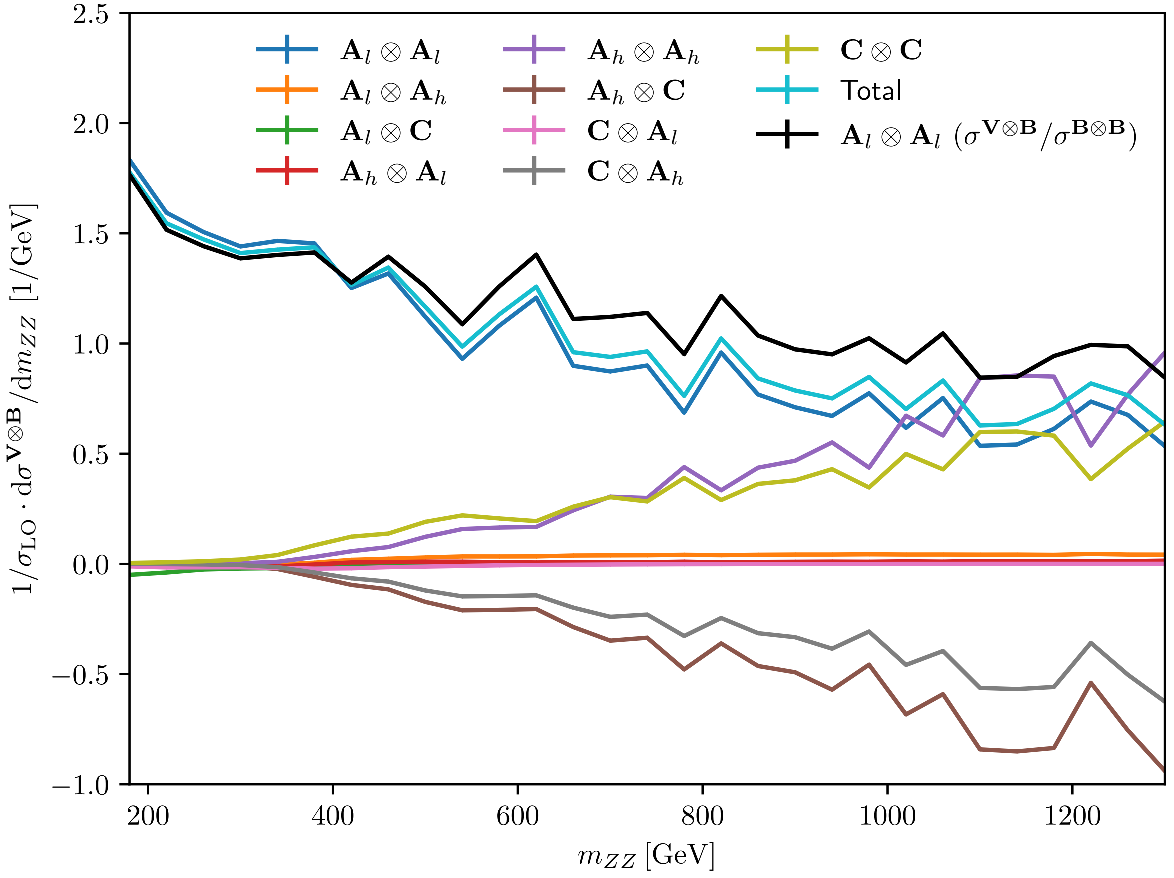
ZZ Production Channel Breakdown

Can examine the interference patterns of **Class A+B+C**

Born



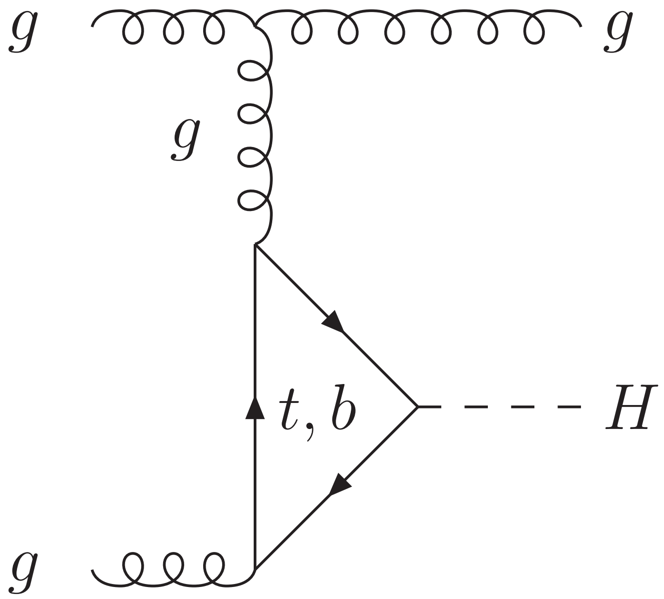
Born-Virtual



Observe the unitarizing behaviour of the massive & Higgs-mediated amplitudes

Above ~ $2m_t$ significant destructive interference between $\mathbf{A}_h$ and $\mathbf{C}$ @ LO and NLO

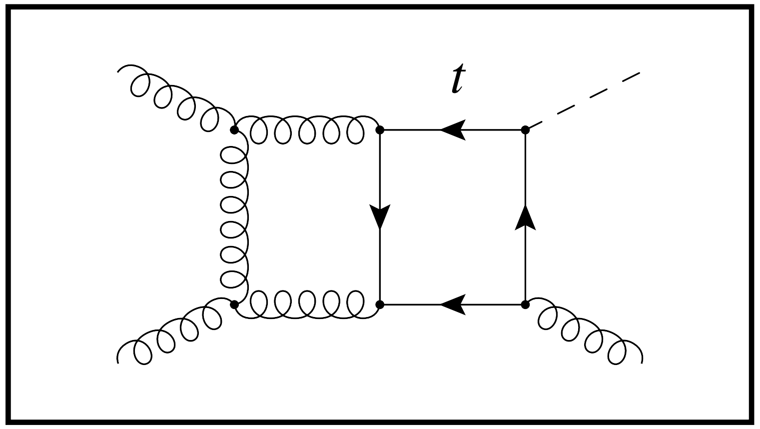
Boosted Higgs



Anomalous Couplings with Top Mass Dependence

HJ production known to NLO including m_t

Kudashkin, (Lindert), Melnikov, Wever 17, (18); SPJ, Kerner, Luisoni 18, 21; Neumann 18; Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22;



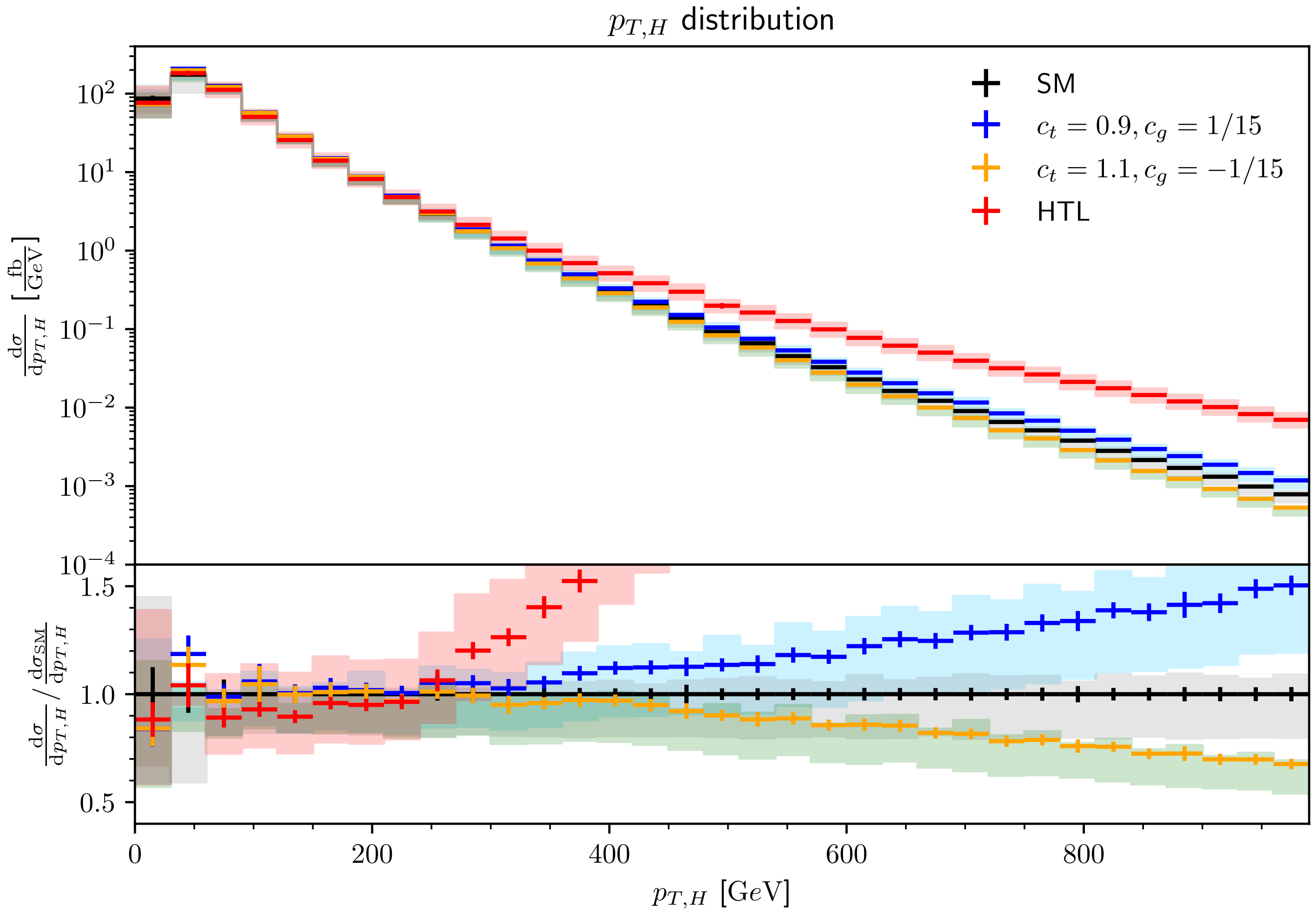
Recent study of impact of anomalous top-Yukawa (c_t) and Higgs-gluon contact interactions (c_g) in HEFT

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

Found scenarios where BSM effects only exceed scale uncertainty for boosted Higgs $p_T > 600$ GeV

NLO K-factor ~1.7 in SM, varies by $\mathcal{O}(30\%)$ as (c_t, c_g) changed

Use of HTL can hide new physics



Campillo Aveleira, Heinrich, Kerner, Kunz 24

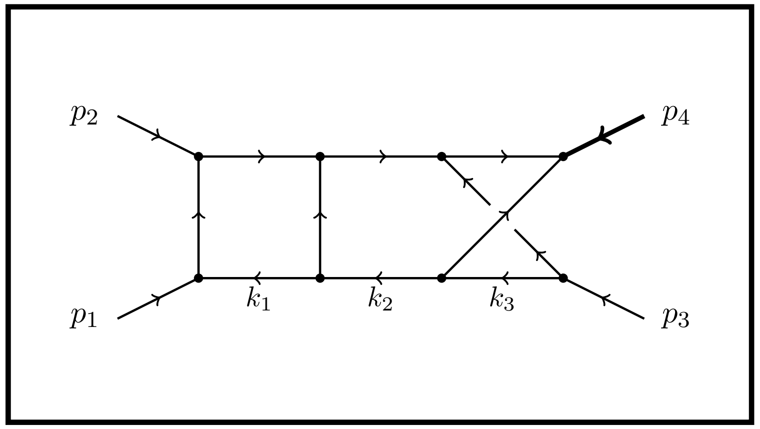
Towards N3LO in the HTL

Impressive work ongoing to push Higgs plus Jet production to N3LO in the HTL

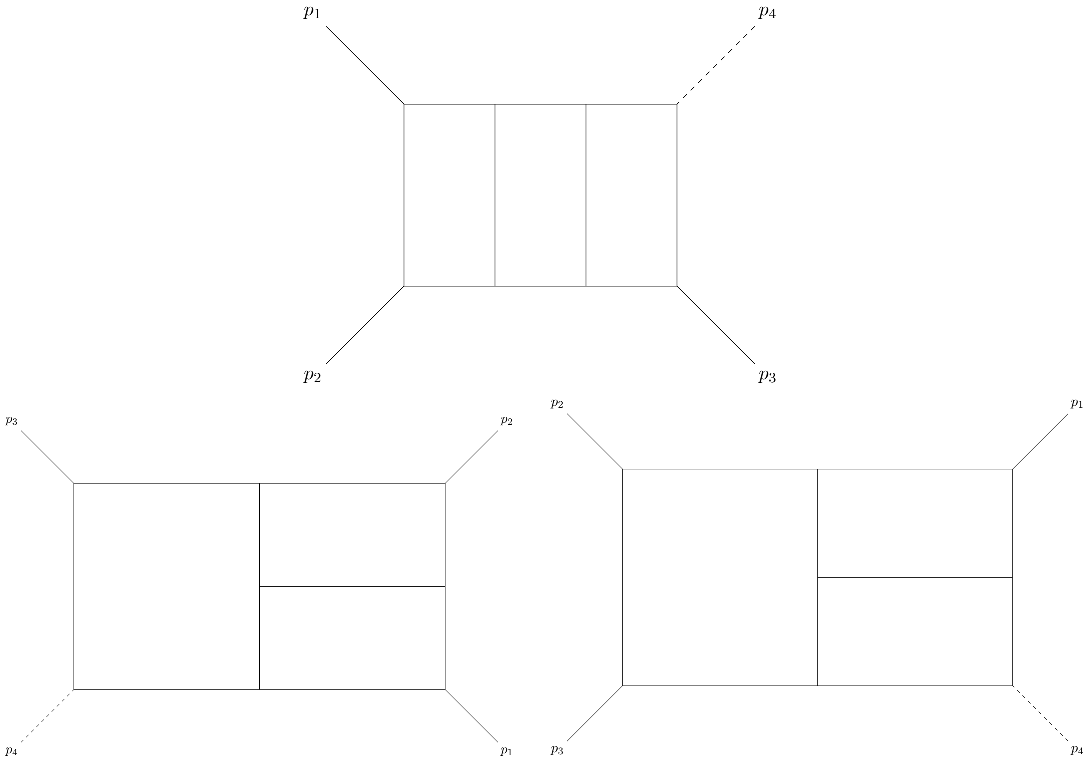
Describes Higgs-p_T spectrum below top threshold

$H \to ggg, H \to q\bar{q}g$ @ 2-loop to $\mathcal{O}(\epsilon^2)$ canonical basis

Gehrmann, Jakubčík, Carlo Mella, Syrrakos, Tancredi 23

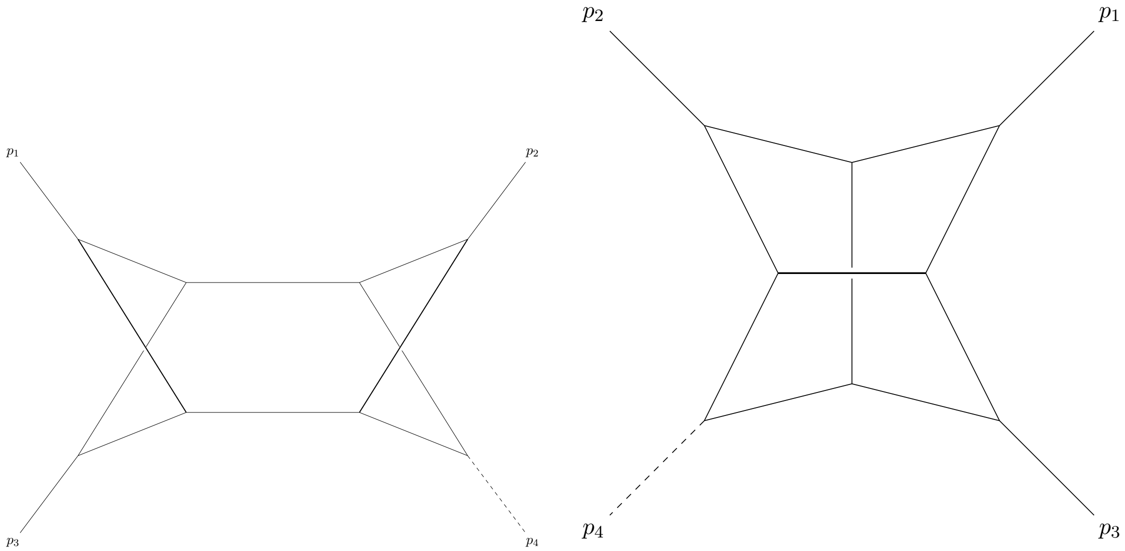


Planar master integrals known



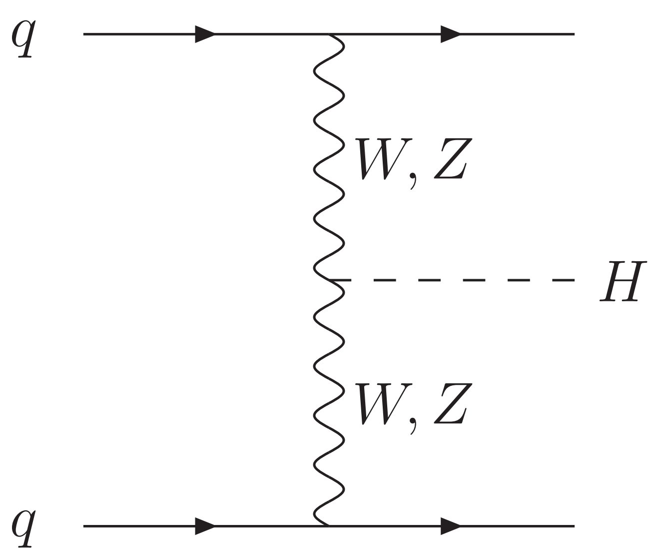
Di Vita, Mastrolia, Schubert, Yundin 14; Canko, Syrrakos 20, 21;

Progress with challenging non-planars



Henn, Lim, Torres Bobadilla 23; Syrrakos, Canko 23; Aliaj, Papathanasiou 24; Carlo Mella 24

Vector Boson Fusion (VBF)

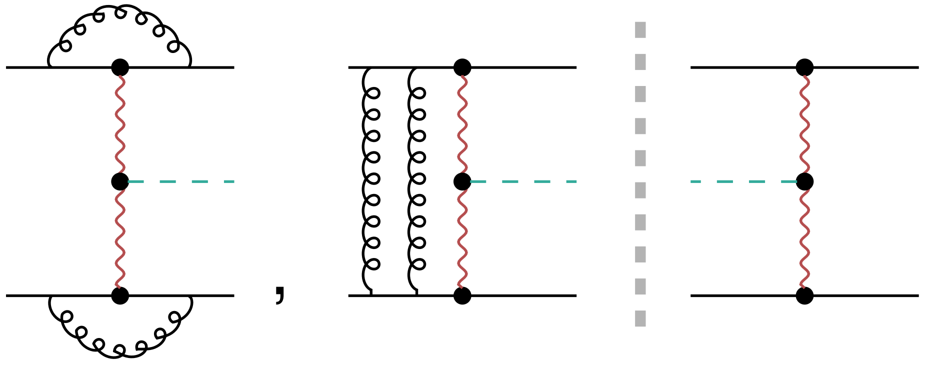


Non-Factorisable Corrections

Factorisable contributions are known to N3LO inclusive/ NNLO differential

Dreyer, Karlberg 16; Bolzoni, Maltoni, Moch, Zaro 10, 12; Cacciari, Dreyer, Karlberg, Salam, Zanderighi 15; Cruz-Martinez, Gehrmann, Glover, Huss 18; Asteriadis, Caola, Melnikov, Röntsch 22, 23

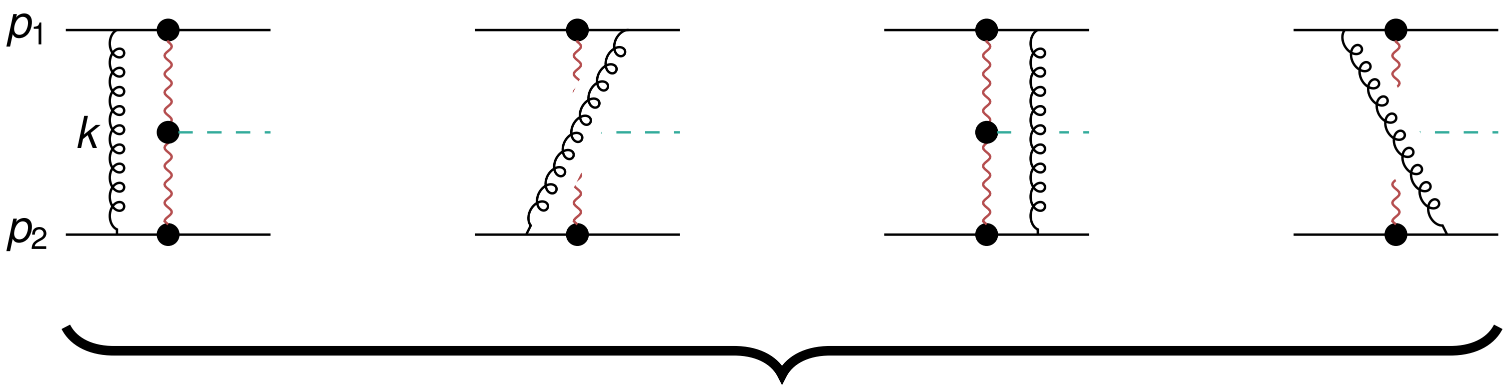
Non-factorisable contributions are **colour suppressed**



$$\Longrightarrow \frac{(N_c^2-1)^2}{4}, \quad \frac{(N_c^2-1)}{4}$$

However, (soft/eikonal approximation) it was found they are π^2 **enhanced**

Liu, Melnikov, Penin 19



$$\left[\frac{1}{2p_1k+i0}+\frac{1}{-2p_1k+i0}\right]\left[\frac{1}{-2p_2k+i0}+\frac{1}{2p_2k+i0}\right] \Longrightarrow \pi^2$$

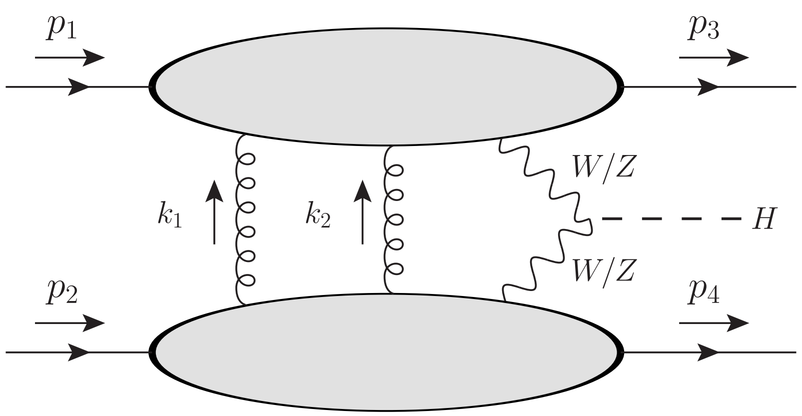
Figures: Ming-Ming Long (20th LHCHWG Meeting)

Non-Factorisable Corrections (II)

NNLO non-factorisable contribution computed beyond the eikonal approximation

Brønnum-Hansen, Long, Melnikov, Juvin-Quarroz 23, 23;

Used expansion-by-regions in forward limit, $\mathbf{p}_{3,\perp}^2/s \sim \mathbf{p}_{4,\perp}^2/s \sim \lambda$



$$k_1 = \alpha_1 p_1 + \beta_1 p_2 + k_{1,\perp}, \quad \frac{\mathrm{d}^d k_1}{(2\pi)^d} = -\frac{s}{2} \frac{\mathrm{d}\alpha_1}{2\pi i} \frac{\mathrm{d}\beta_1}{2\pi i} \frac{\mathrm{d}^{d-2}\mathbf{k}_{1,\perp}}{(2\pi)^{d-2}}$$

	α_1	β_1	$\mathbf{k}_{1,\perp}$	$\mathcal{M}_1$
G	λ	λ	$\sqrt{\lambda}$	-2
G-S	λ	$\sqrt{\lambda}$	$\sqrt{\lambda}$	-3/2
S	$\sqrt{\lambda}$	$\sqrt{\lambda}$	$\sqrt{\lambda}$	-1
C	1	λ	$\sqrt{\lambda}$	0
H	1	1	1	0

Only Glauber/ Mixed @ next-to-leading power

Sub-eikonal correction about 20% of eikonal correction

Result: NNLO non-factorisable contribution similar in size to N3LO correction

	$\sigma^{(13\text{ TeV})}$ [pb]	$\sigma^{(14\text{ TeV})}$ [pb]	$\sigma^{(100\text{ TeV})}$ [pb]
LO	$4.099^{+0.051}_{-0.067}$	$4.647^{+0.037}_{-0.058}$	$77.17^{+6.45}_{-7.29}$
NLO	$3.970^{+0.025}_{-0.023}$	$4.497^{+0.032}_{-0.027}$	$73.90^{+1.73}_{-1.94}$
NNLO	$3.932^{+0.015}_{-0.010}$	$4.452^{+0.018}_{-0.012}$	$72.44^{+0.53}_{-0.40}$
N3LO	$3.928^{+0.005}_{-0.001}$	$4.448^{+0.006}_{-0.001}$	$72.34^{+0.11}_{-0.02}$

+

$$\sigma_{\mathrm{LO}}^{\mathrm{non-fac}} = -2.97^{+0.52}_{-0.69}\ \mathrm{fb}$$

$$\sigma_{\mathrm{NLO}}^{\mathrm{non-fac}} = -3.20^{+0.14}_{-0.01}\ \mathrm{fb}$$

Figures/Tables: Ming-Ming Long (20th LHCHWG Meeting)

VBF Parton Shower Uncertainties

Parton shower uncertainties dominate the theory uncertainty for VBF

↪ Currently ±15% on inclusive measurement, will limit interpretation in Run 3

↪ Not clear if Pythia dipole vs Herwig 7 captures true uncertainty

Several studies completed:

NNLO QCD vs NLO+PS

Good agreement theoretically

Less so for experimental PS studies (underlying event? hadronisation? tuning vs recoil scheme?)

Buckley et al. 21

NLL PanScales showers

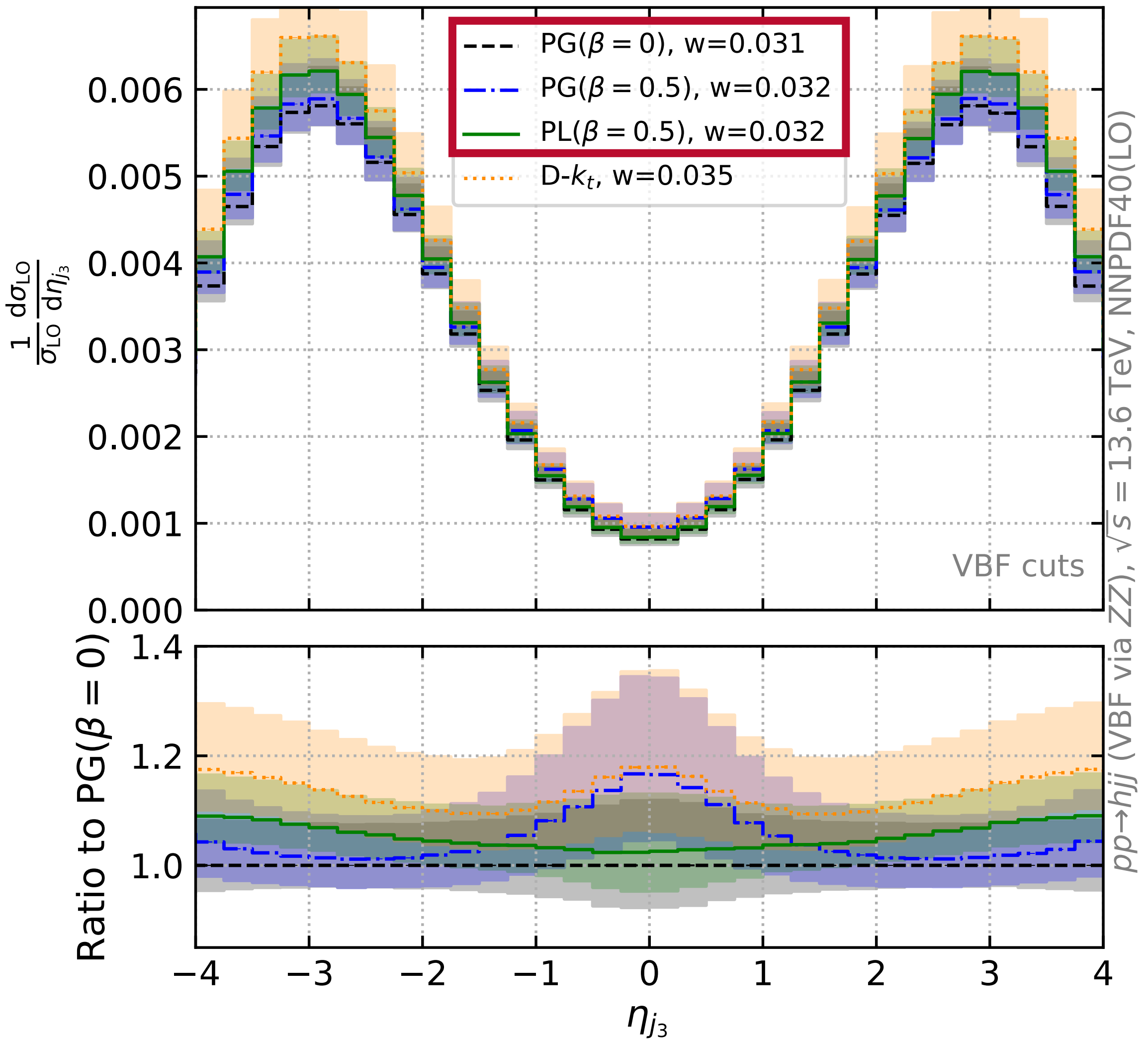
LL vs NLL differ by ~15% for 3rd jet (within scale var.)

van Beekveld, Ferrario Ravasio 23

NLO EW+PS recently available

Jäger, Scheller 22

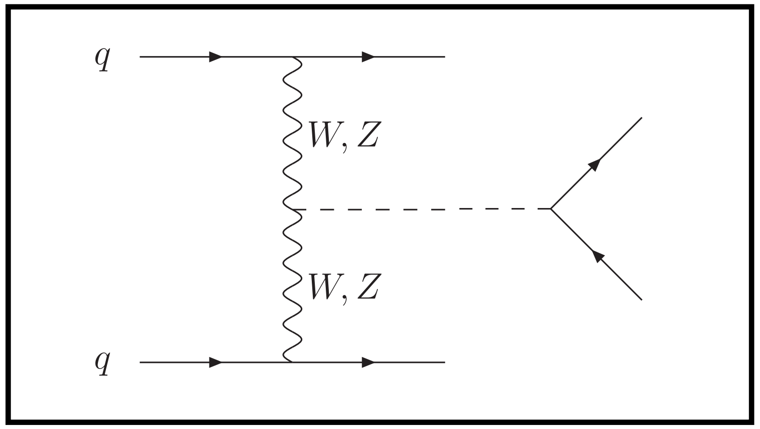
NLL

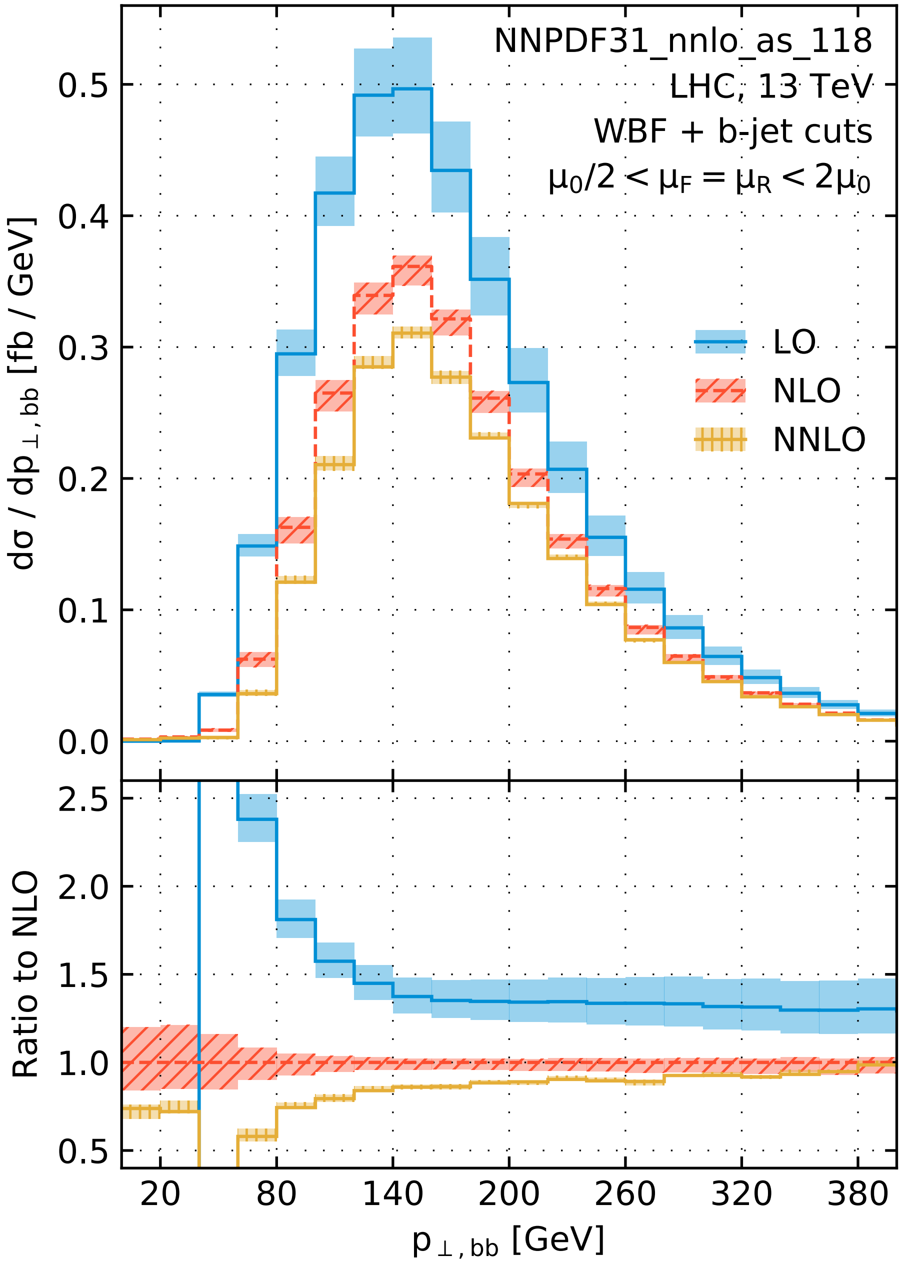


VBF with $H \to b\bar{b}$ Decay

NNLO accurate predictions of VBF: $pp \to H(\to b\bar{b})jj$
Including corrections to both production and decay

Asteriadis, Behring, Melnikov, Novikov, Röntsch 24





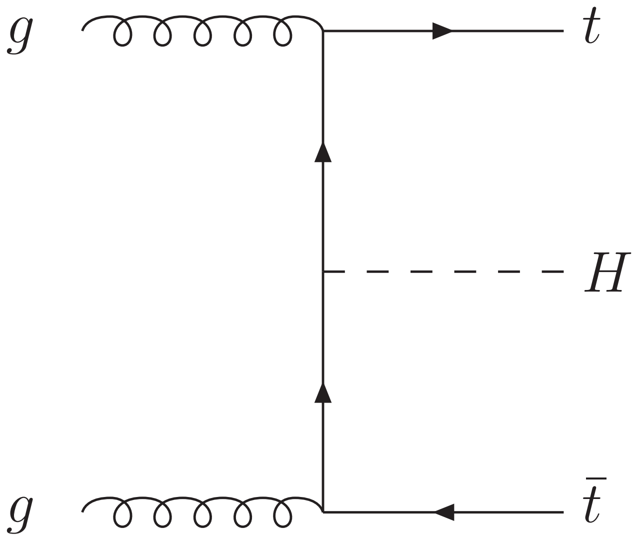
QCD corrections very sensitive to the b-jet cuts especially transverse momentum

Recent ATLAS/CMS cuts give large pert. corr.
Anti-k_t $R = 0.4$, $|y_b| < 2.5$, $p_{T,b} > 65$ GeV
+ WBF (2 jets $p_{T,j} > 25$ GeV, $m_{jj} > 600$ GeV)

$$\sigma^{\mathrm{LO}} = 75.6^{-5.6}_{+6.5}\,\mathrm{fb}\,,$$
$$\sigma^{\mathrm{NLO}} = 52.4^{+1.5}_{-2.6}\,\mathrm{fb}\,,$$
$$\sigma^{\mathrm{NNLO}} = 44.6^{+0.9}_{-0.6}\,\mathrm{fb}\,,$$

Corrections of -40% relative to LO, outside LO ~9% and NLO ~5% uncertainty estimates

$t\bar{t}H$ Production



Soft-Higgs Approximation

The 2-loop virtual matrix elements for $t\bar{t}H$ are extremely challenging to compute:
↪ $2 \to 3$ process involving two additional scales (m_t, m_h)

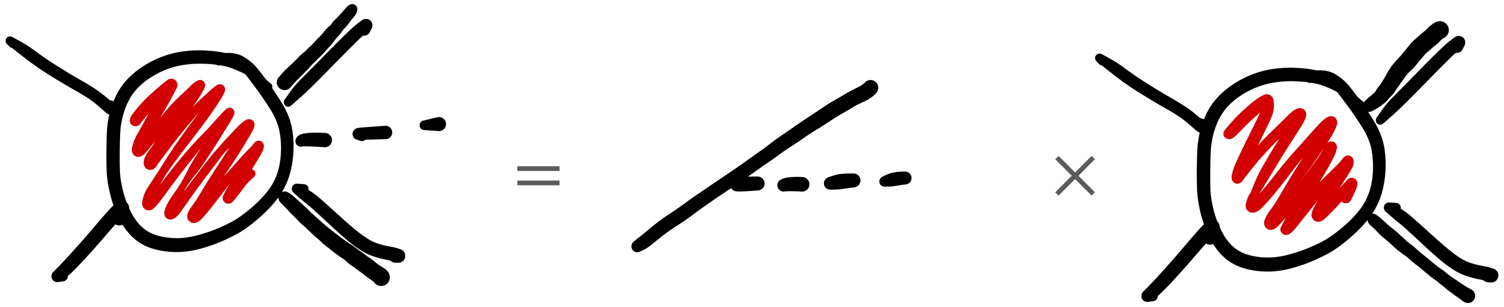
Idea

Soft-Higgs boson emission from on-shell top quarks gives soft singularity

$$\lim_{k\to 0}\,[(p+k)^2 - m_t^2]^{-1} \to [(p^2 - m_t^2)]^{-1}, \quad p^2 = m_t^2$$

Can derive **factorisation formula** from eikonal approx/low energy theorem (emission from highly off-shell propagators not captured)

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 22

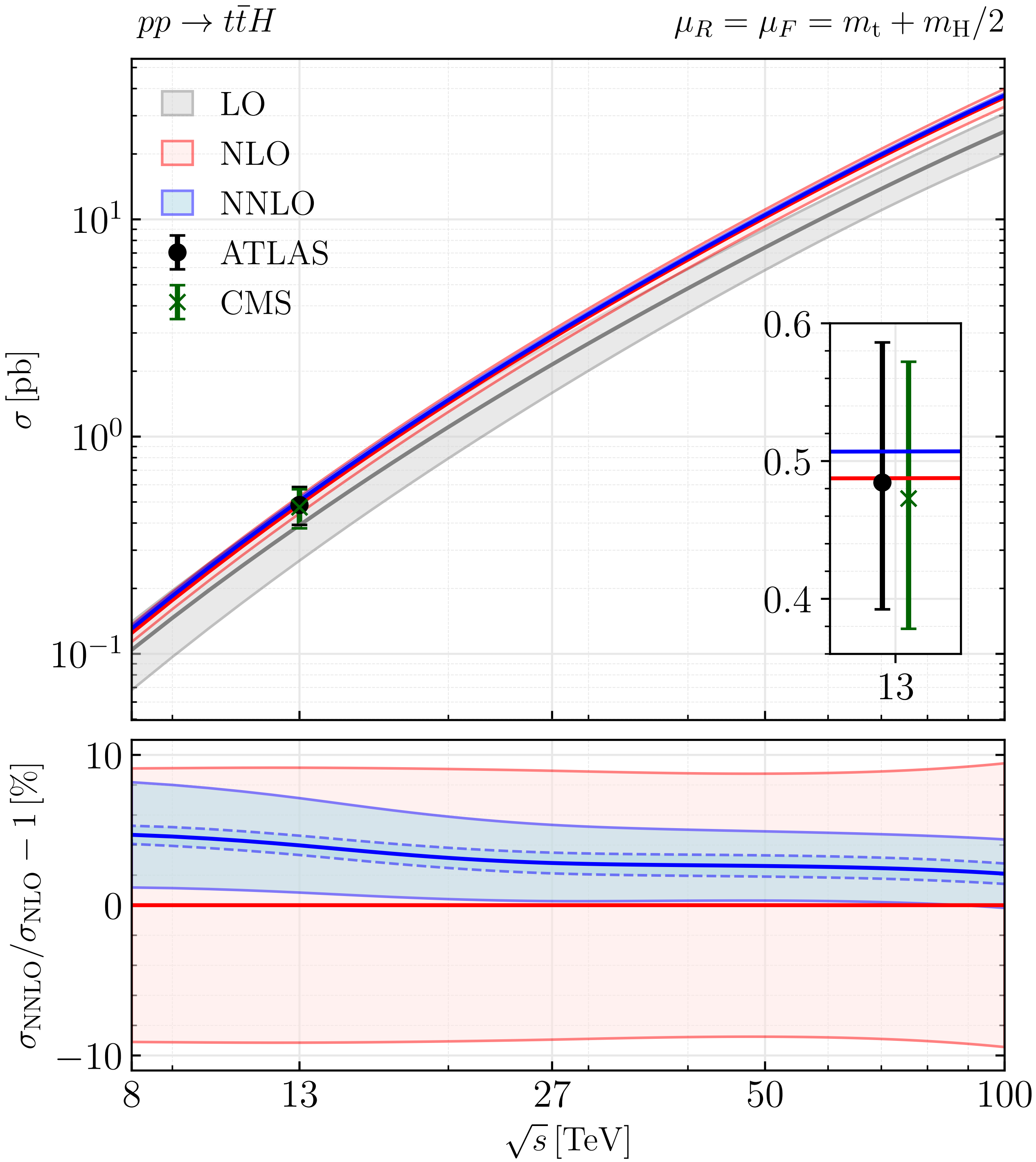


$$\mathcal{M}_{q\bar{q}'\to t\bar{t}H}\big(\{p_i\},k\big) \simeq F\big(\alpha_S(\mu_R);m_t/\mu_R\big)\,\frac{m_t}{v}\sum_{i=3,4}\frac{m_t}{p_i\cdot k}\mathcal{M}_{q\bar{q}'\to t\bar{t}}\big(\{p_i\}\big)$$

Figure: Simone Devoto
(QCD@LHC 2023)

$t\bar{t}H$ @ Approximate NNLO

Use $c\bar{c} \to t\bar{t}$ $(c = q, g)$ amplitudes + $Q\overline{Q}F$ generalisation of q_T subtraction



σ [pb]	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 100$ TeV
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)\,^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 22

NNLO +4% @ 13 TeV

Significant reduction of scale uncertainties

Soft approximation uncertainty estimated to be significantly smaller than scale uncertainty (using NLO)

Massification

Massification Obtain massive amplitudes from massless amplitudes up to power corrections $\mathcal{O}(m^2/Q^2)$ Penin 06; Moch, Mitov 07; Becher, Melnikov 07; Engel et al 19; Wang, Xia, Yang, Ye 23;

$$|\mathcal{M}^{(m)}\rangle = \prod_i \left(Z_{[i]}^{(m|0)}\left(\frac{m^2}{\mu^2}, \alpha_s, \epsilon\right) \right)^{1/2} \mathbf{S}\left(\frac{m^2}{\mu^2}, \frac{m^2}{s_{ij}}, \alpha_s, \epsilon\right) |\mathcal{M}\rangle$$

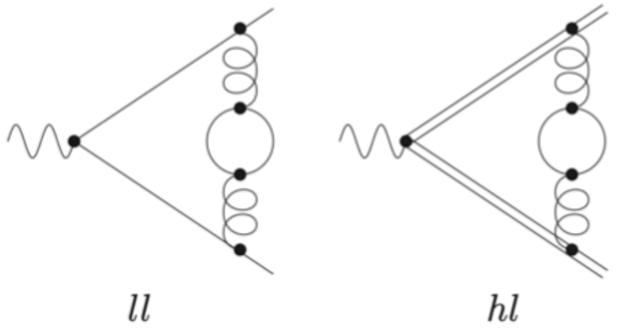
External quark contribution

Dress external quarks with mass

Mass screens collinear singularities

Ratio of FFs $\mathcal{F}^{Q\bar{Q}\to F}/\mathcal{F}^{q\bar{q}\to F}$

Universal & perturbatively computable

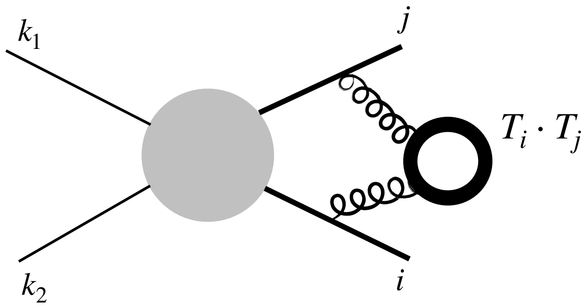


Soft contribution

Account for heavy quark loops

Starts at 2-loops

Process dependent

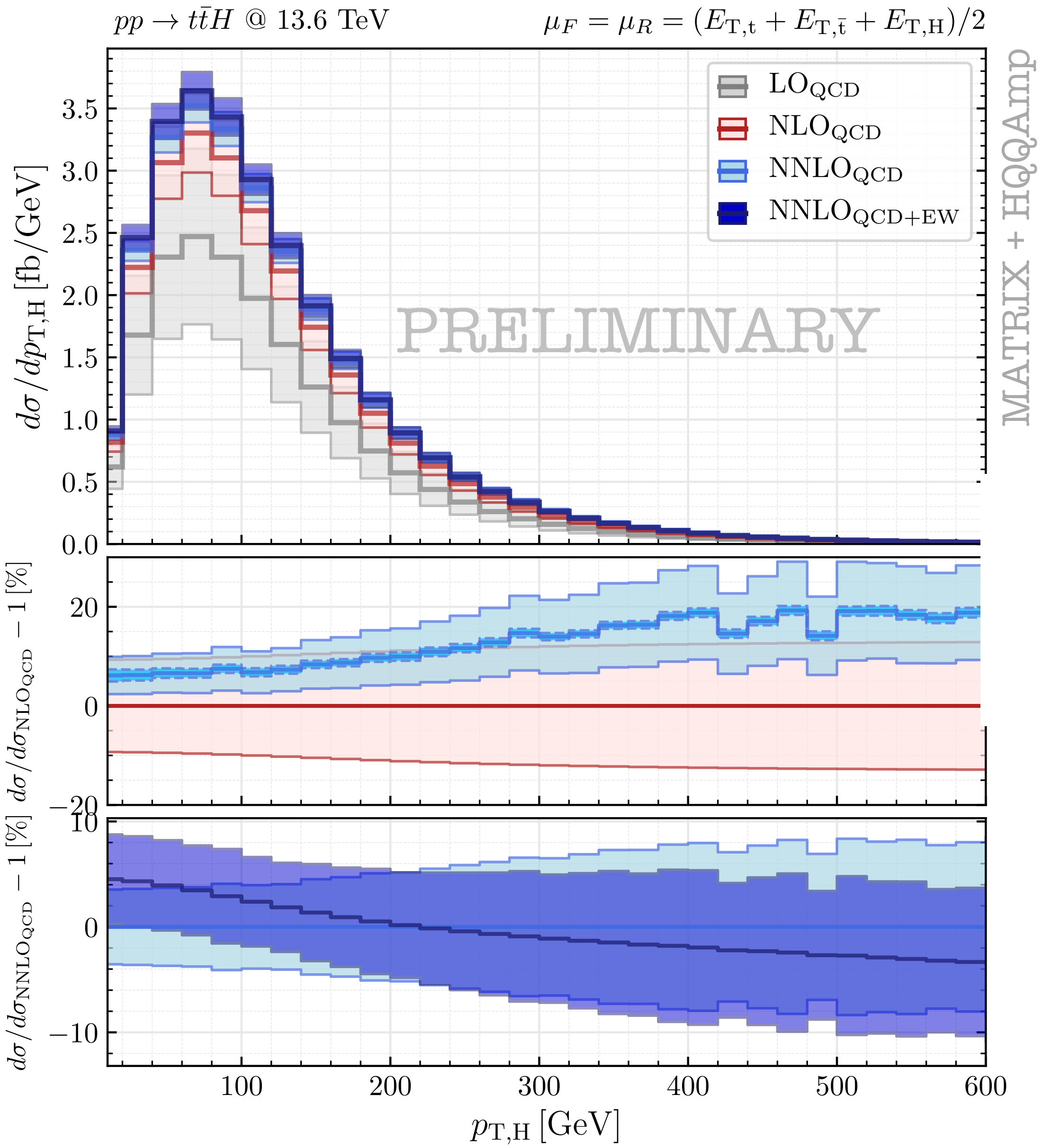


Also require mapping from massless ↔ massive momenta

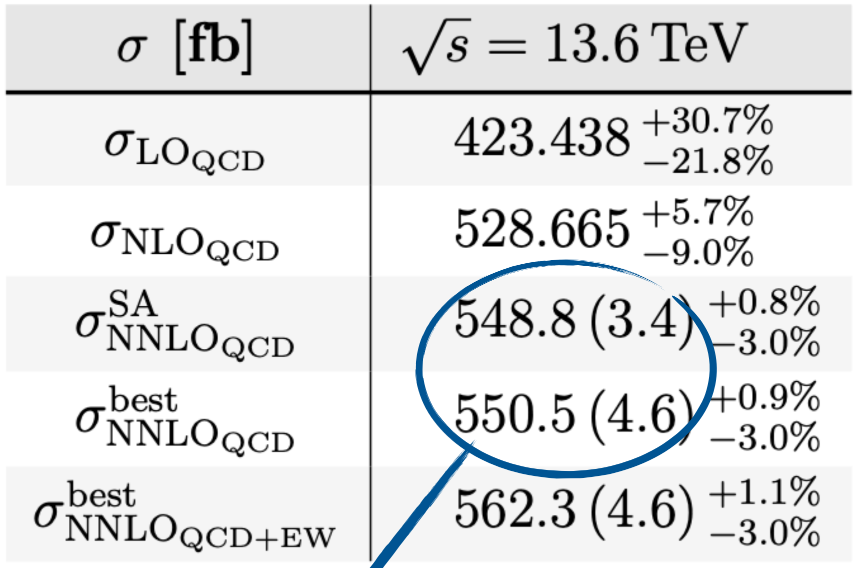
$t\bar{t}H$ @ Approximate NNLO Differential

Differential predictions possible by combining soft-Higgs approximation with massification of $pp \to Hq\bar{q}$ amplitudes (with $m_q = 0$)

Wang, Xia, Yang, Ye 24; Devoto, Grazzini, Kallweit, Mazzitelli, Savoini (WIP); Badger, Hartanto, Kryś, Zoia 21



Slide: Chiara Savoini (HP2 2024)



σ [fb]	$\sqrt{s} = 13.6$ TeV
$\sigma_{\mathrm{LO_{QCD}}}$	$423.438\,^{+30.7\%}_{-21.8\%}$
$\sigma_{\mathrm{NLO_{QCD}}}$	$528.665\,^{+5.7\%}_{-9.0\%}$
$\sigma^{\mathrm{SA}}_{\mathrm{NNLO_{QCD}}}$	$548.8\,(3.4)\,^{+0.8\%}_{-3.0\%}$
$\sigma^{\mathrm{best}}_{\mathrm{NNLO_{QCD}}}$	$550.5\,(4.6)\,^{+0.9\%}_{-3.0\%}$
$\sigma^{\mathrm{best}}_{\mathrm{NNLO_{QCD+EW}}}$	$562.3\,(4.6)\,^{+1.1\%}_{-3.0\%}$

NNLO QCD predictions based on the soft-approximated and "best" double virtual are **fully compatible**: difference of 0.3 %

- the **systematic uncertainty** based on the refined prescription is **slightly larger**: $\mathcal{O}(0.8\%)$ instead of $\mathcal{O}(0.6\%)$ of the NNLO cross section

2-loop Amplitudes for $t\bar{t}H$

Significant progress in directly computing the 2-loop virtual amplitudes

↪ 5-point amplitude, 5 variables + 2 masses

Leading N_c contribution to n_l part of $pp \to t\bar{t}H$ obtained analytically/series exp.

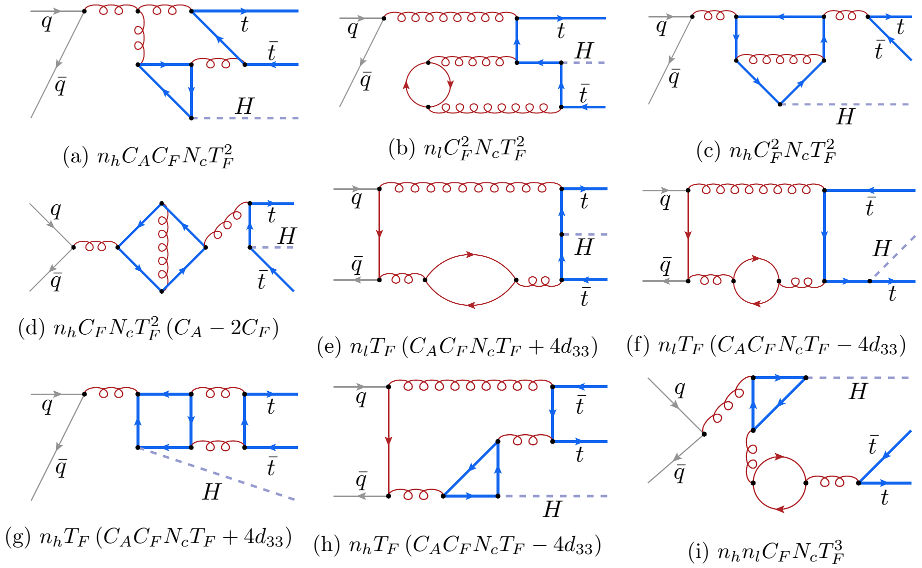
↪ ϵ-factorised form

↪ 127 master integrals, up to 7 per sector

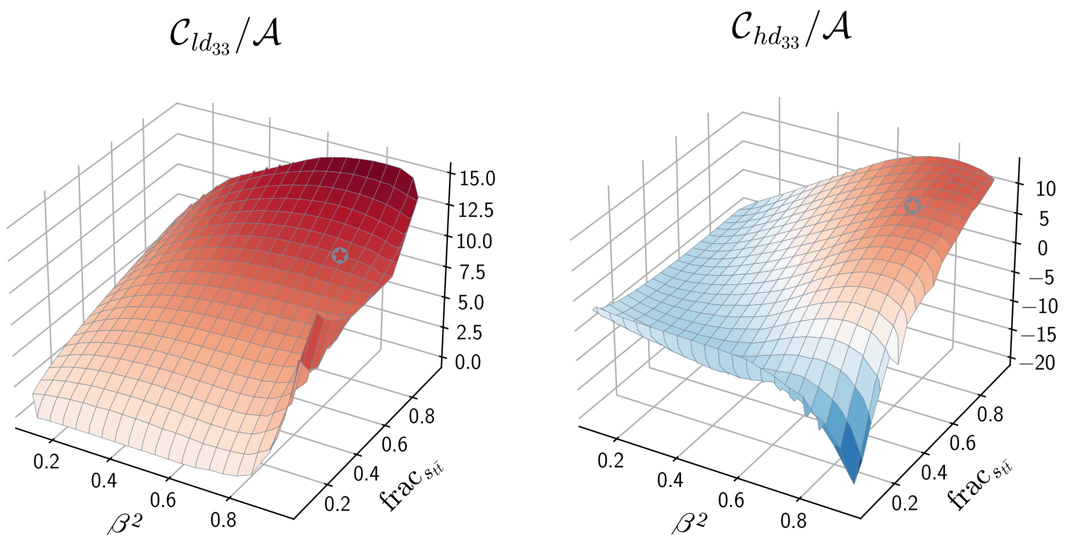
Cordero, Figueiredo, Kraus, Page, Reina 23

The n_l and n_h parts of $q\bar{q} \to t\bar{t}H$ obtained numerically

↪ 831 master integrals, up to 8 per sector



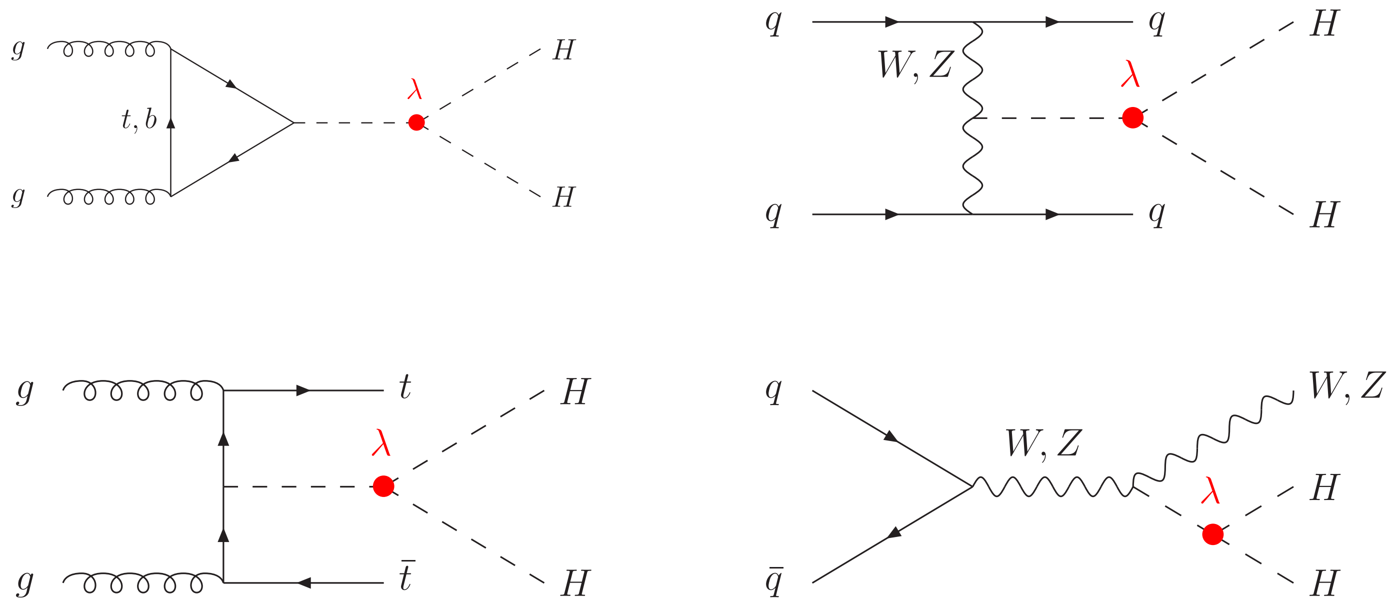
(a) $n_h C_A C_F N_c T_F^2$
(b) $n_l C_F^2 N_c T_F^2$
(c) $n_h C_F^2 N_c T_F^2$
(d) $n_h C_F N_c T_F^2 (C_A - 2C_F)$
(e) $n_l T_F (C_A C_F N_c T_F + 4d_{33})$
(f) $n_l T_F (C_A C_F N_c T_F - 4d_{33})$
(g) $n_h T_F (C_A C_F N_c T_F + 4d_{33})$
(h) $n_h T_F (C_A C_F N_c T_F - 4d_{33})$
(i) $n_h n_l C_F N_c T_F^3$



Agarwal, Heinrich, SPJ, Kerner, Klein, Lang, Magerya, Olsson 24

Next challenges: non-N_f amplitude, integrating over phase-space (non-trivial)

HH Production



$$\sigma(pp \to HH) \sim \frac{\sigma(pp \to H)}{1000}$$

→Talk of Ramona

HH: Why Measure it?

$$\mathcal{L} \supset -V(\phi), \quad V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

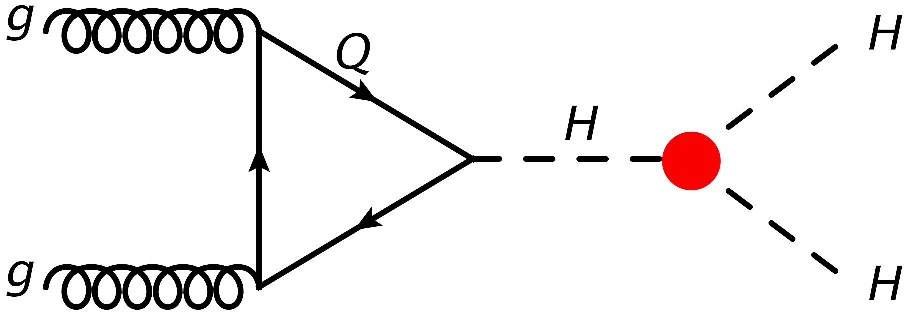
EW symmetry breaking

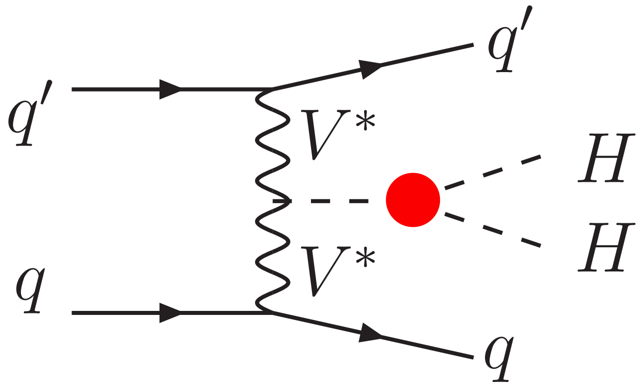
$$\mu^2 = \lambda v^2$$
$$m_H^2 = 2\lambda v^2$$

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

SM: self-couplings
determined by m_H, v

EXP: need measurements
to confirm/refute this

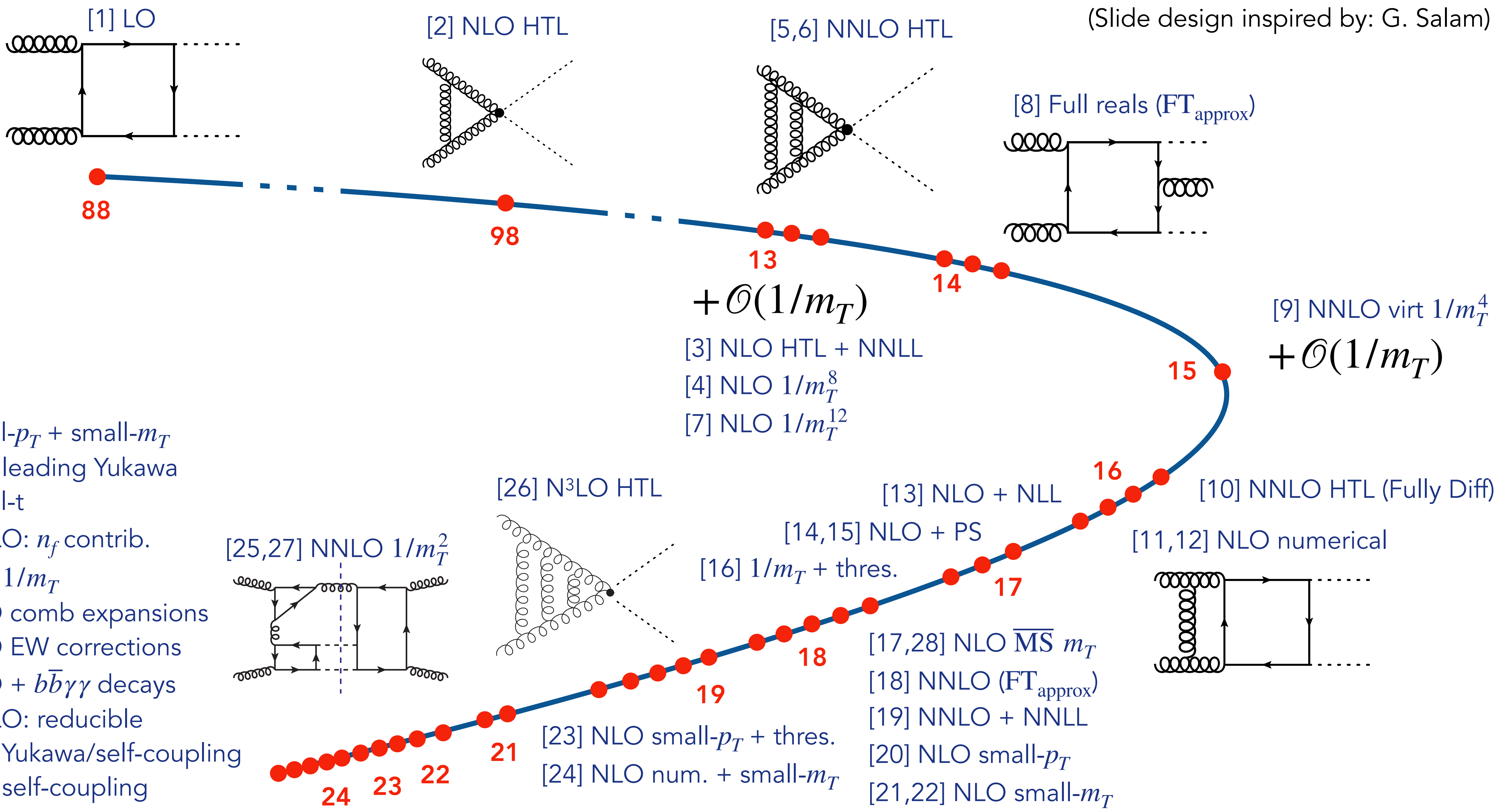




$$+t\bar{t}HH$$
$$+VHH$$
$$+H\ \mathrm{(EW)}$$

Overview

(Slide design inspired by: G. Salam)



[1] LO

[2] NLO HTL

[5,6] NNLO HTL

[8] Full reals ($\mathbf{FT}_{\text{approx}}$)

$+\mathcal{O}(1/m_T)$

[3] NLO HTL + NNLL

[4] NLO $1/m_T^8$

[7] NLO $1/m_T^{12}$

[9] NNLO virt $1/m_T^4$

$+\mathcal{O}(1/m_T)$

[10] NNLO HTL (Fully Diff)

[11,12] NLO numerical

[13] NLO + NLL

[14,15] NLO + PS

[16] $1/m_T$ + thres.

[17,28] NLO $\overline{\text{MS}}$ m_T

[18] NNLO ($\mathbf{FT}_{\text{approx}}$)

[19] NNLO + NNLL

[20] NLO small-p_T

[21,22] NLO small-m_T

[23] NLO small-p_T + thres.

[24] NLO num. + small-m_T

[26] N^{3}LO HTL

[25,27] NNLO $1/m_T^2$

[29] small-p_T + small-m_T
[30] EW: leading Yukawa
[31] small-t
[32] NNLO: n_f contrib.
[33] EW: $1/m_T$
[34] NLO comb expansions
[35] NLO EW corrections
[36] NLO + $b\bar{b}\gamma\gamma$ decays
[37] NNLO: reducible
[38] EW: Yukawa/self-coupling
[39] EW: self-coupling

[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagnaschi, Degrassi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23 [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, SPJ, Kerner, Stone, Vestner [39] Li, Si, Wang, Zhang, Zhao 24

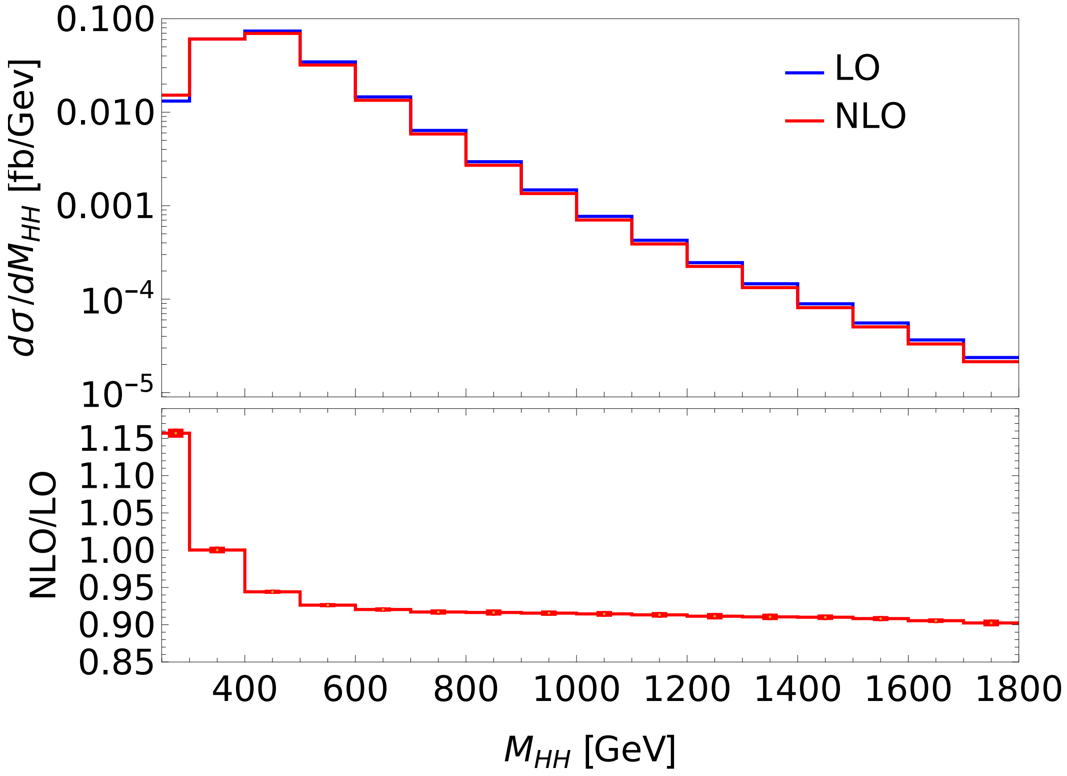
EW Corrections

Interesting to explore the impact of EW corrections (±5 % for off-shell Higgs)

Actis, Passarino, Sturm, Uccirati 08

Full EW Corrections

Recently computed using AMFlow

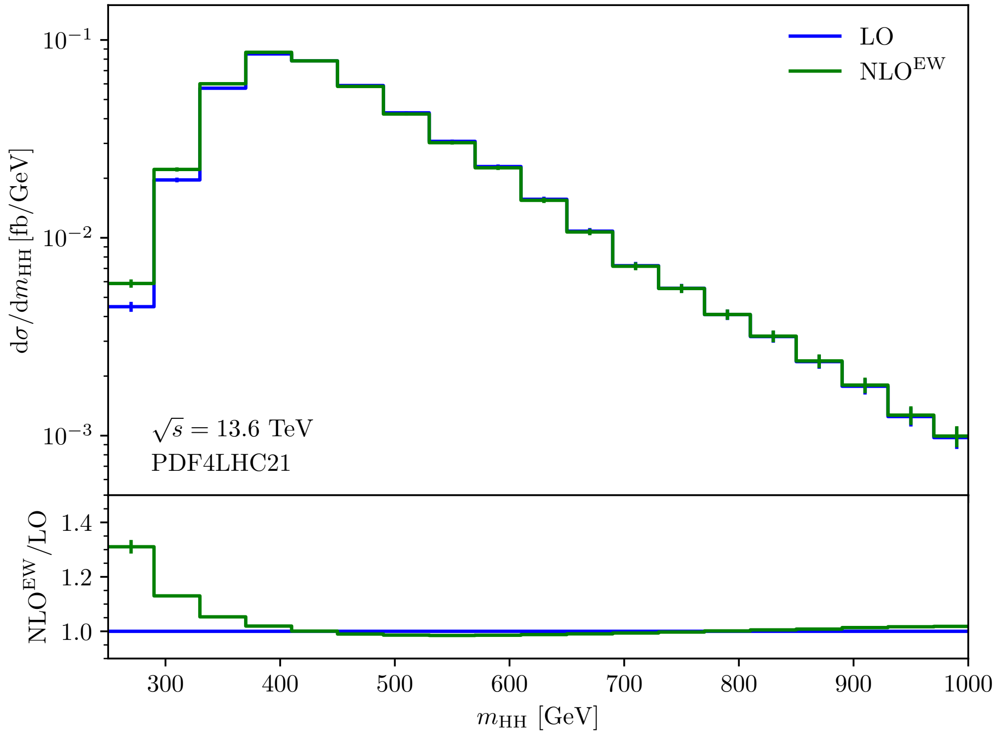


- ↪ -4% on total cross section
- ↪ +15% near production threshold
- ↪ -10% at high energy (Sudakov-like)

Bi, Huang, Huang, Ma, Yu 23

Partial EW Corrections ($y_t, \lambda_3, \lambda_4$)

Obtained using pySecDec



- ↪ +1% on total cross section
- ↪ +30% near production threshold

Can be adapted for EFT analyses

Heinrich, SPJ, Kerner, Stone, Vestner 24

EW corrections modify distributions and bounds in the SM & EFT frameworks

Conclusion

Higgs Sector

The Higgs boson allows us to explore the heart of the Standard Model

$$\mathscr{L} = \ldots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge Interactions

Yukawa Interactions

fermion masses ↔ flavour

Higgs Potential

self-coupling ↔
vacuum stability

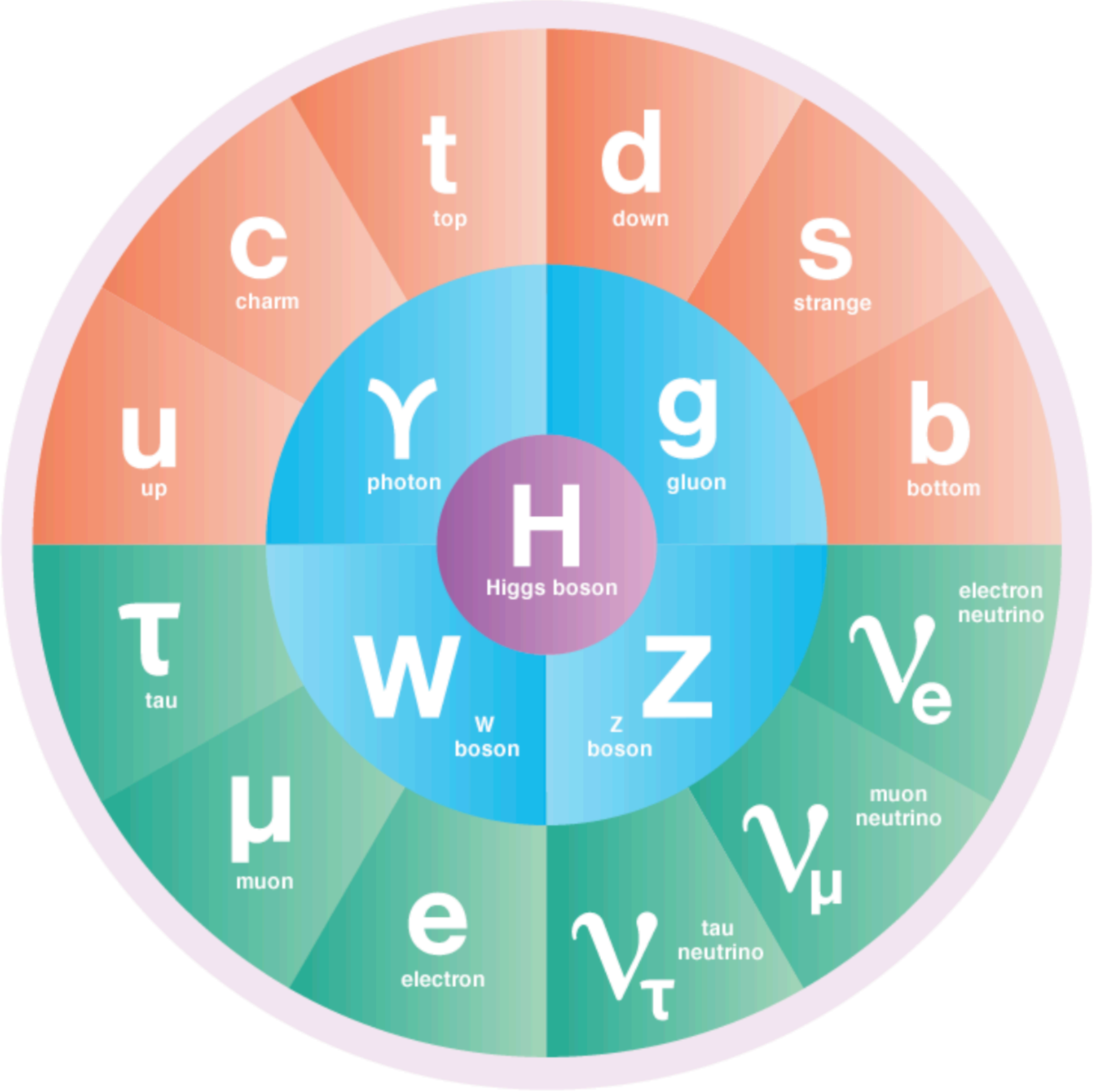


Image: Symmetry Magazine

Outlook

The precision program promises critically important fundamental discoveries

- ↪ Couplings to 2nd generation
- ↪ Boosted/high-energy behaviour
- ↪ Higgs self-coupling $\Longrightarrow$ Higgs potential
- ↪ BSM constraints …

Has significant potential to uncover something completely new and unexpected

Be determined …

Persevere …

Outlook

The precision program promises critically important fundamental discoveries

- ↪ Couplings to 2nd generation
- ↪ Boosted/high-energy behaviour
- ↪ Higgs self-coupling $\Longrightarrow$ Higgs potential
- ↪ BSM constraints …

Has significant potential to uncover something completely new and unexpected

Be determined …

Persevere …

Be prepared

Thank you for listening