Higgs-Maxwell Workshop 2023

15 February 2023

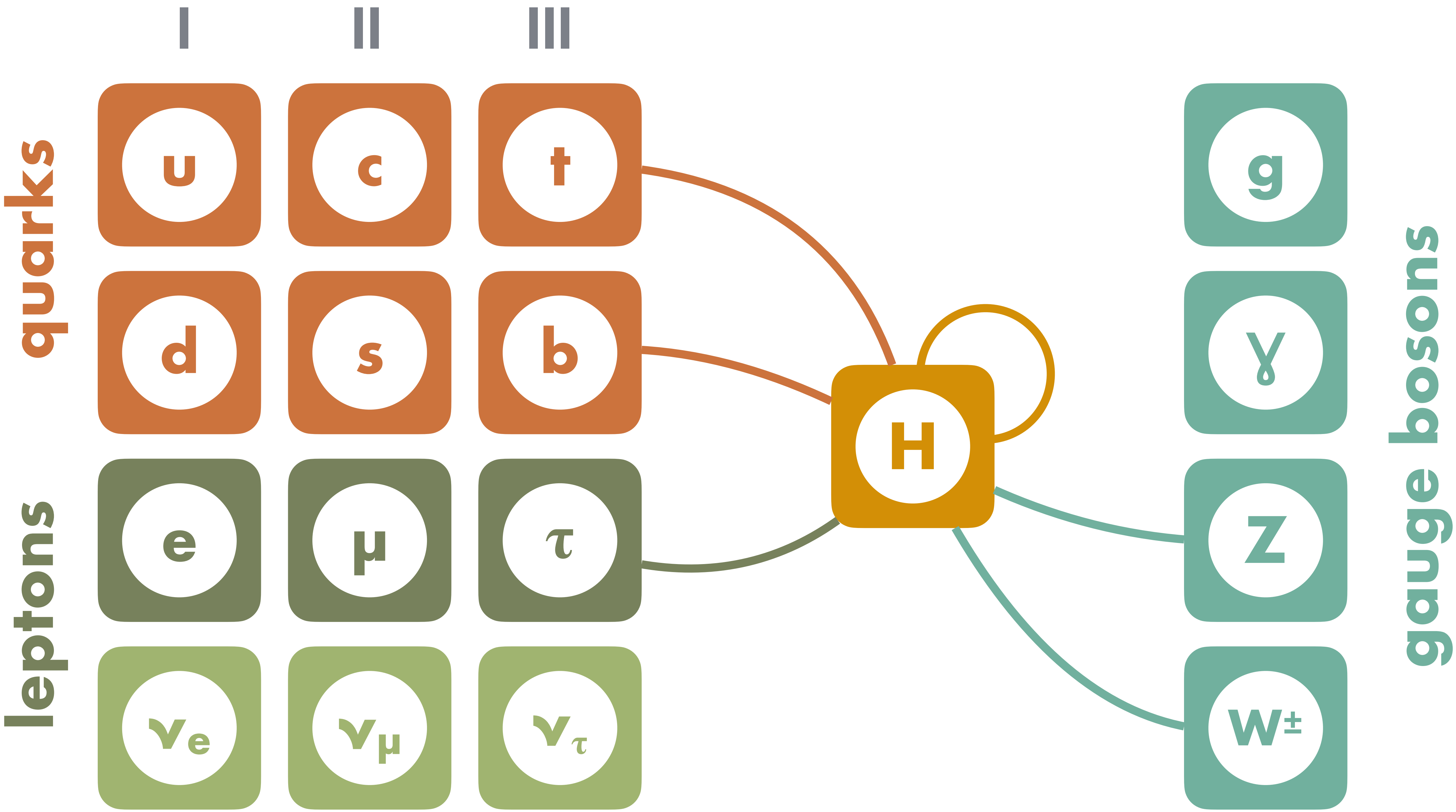
Precision Physics for Single and Multi-Higgs Boson Production

Stephen Jones
IPPP Durham / Royal Society URF

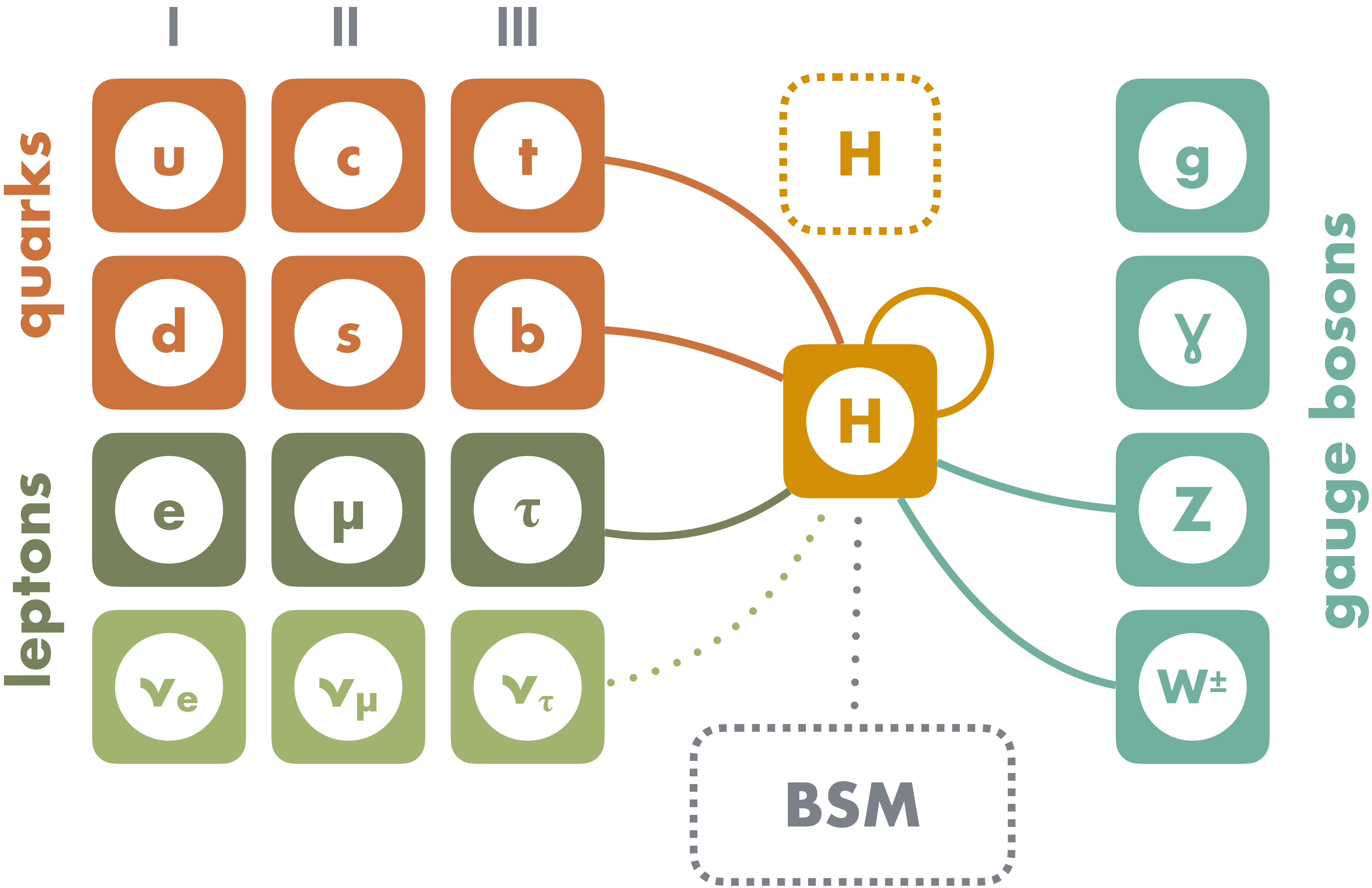
Durham University

THE ROYAL SOCIETY

The Standard Model

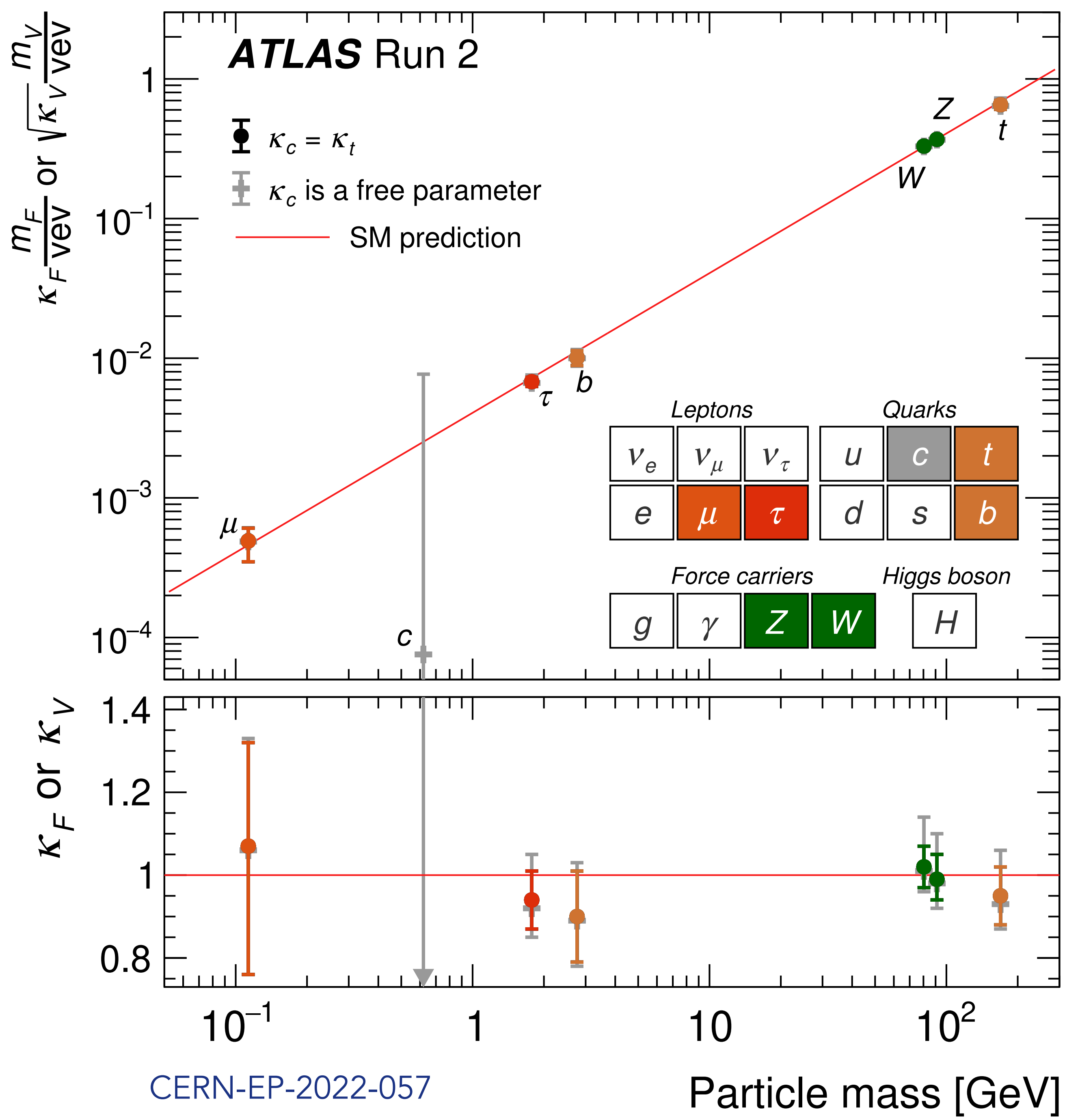


The Standard Model and Beyond



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

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

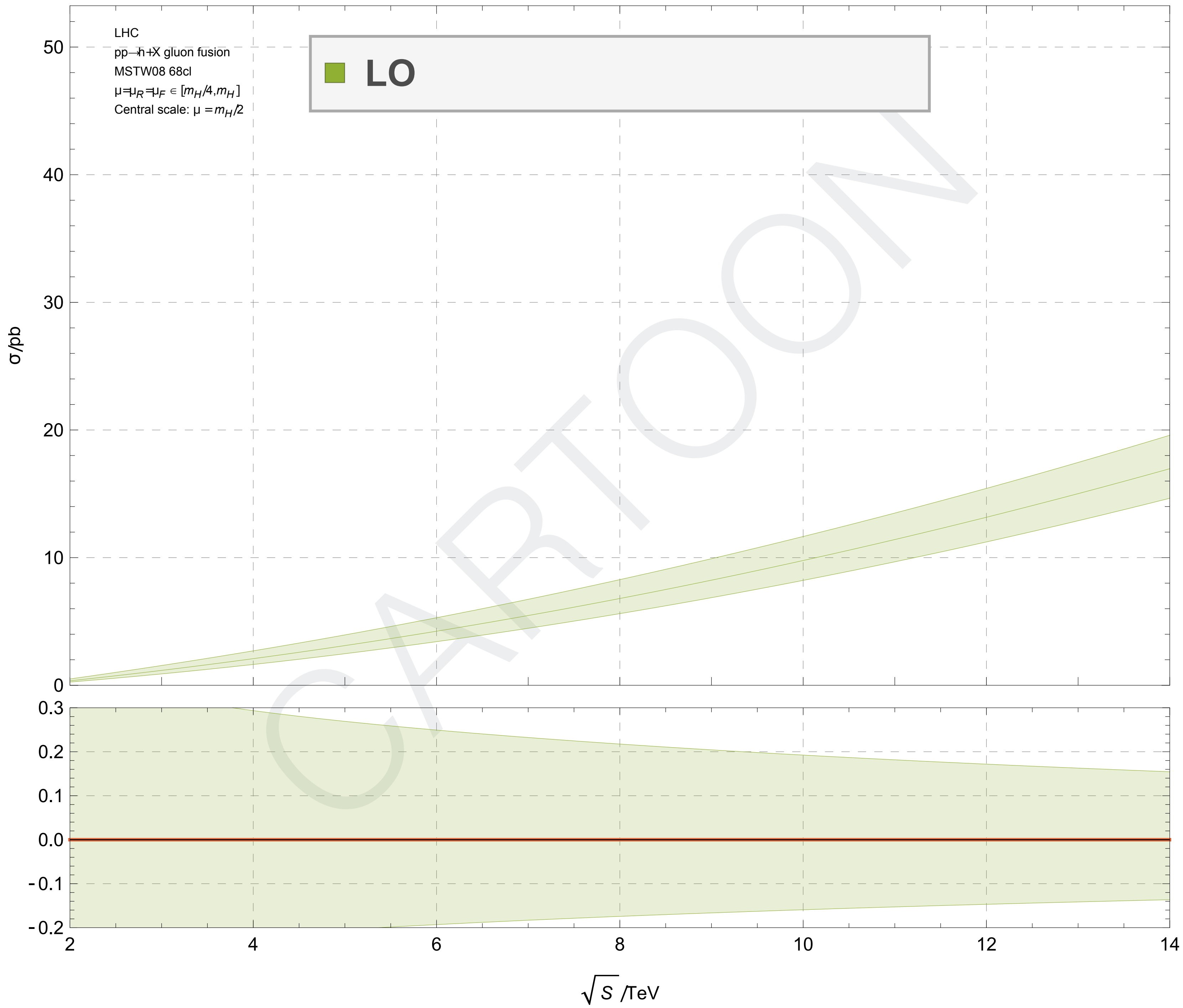
CMS 2009.04363 / ATLAS 2007.07830

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

CMS 2205.05550 / ATLAS 2201.11428

Cartoon: How Important is Precision?

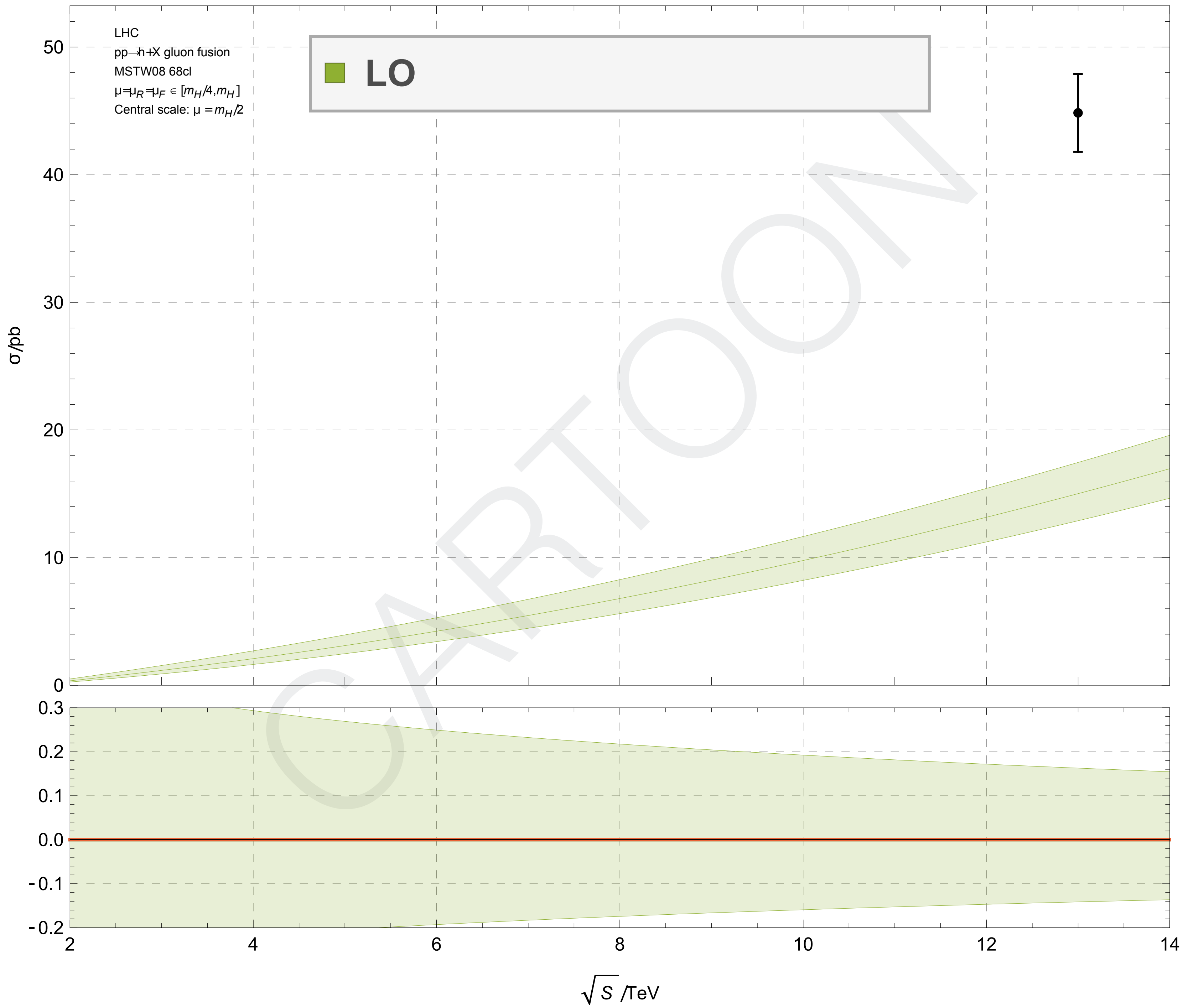
Imagine we had current experimental results for $gg \to H$, but only LO theory…



*Warning: just a cartoon, don't trust data/theory from this plot!

Cartoon: How Important is Precision?

Imagine we had current experimental results for $gg \to H$, but only LO theory…

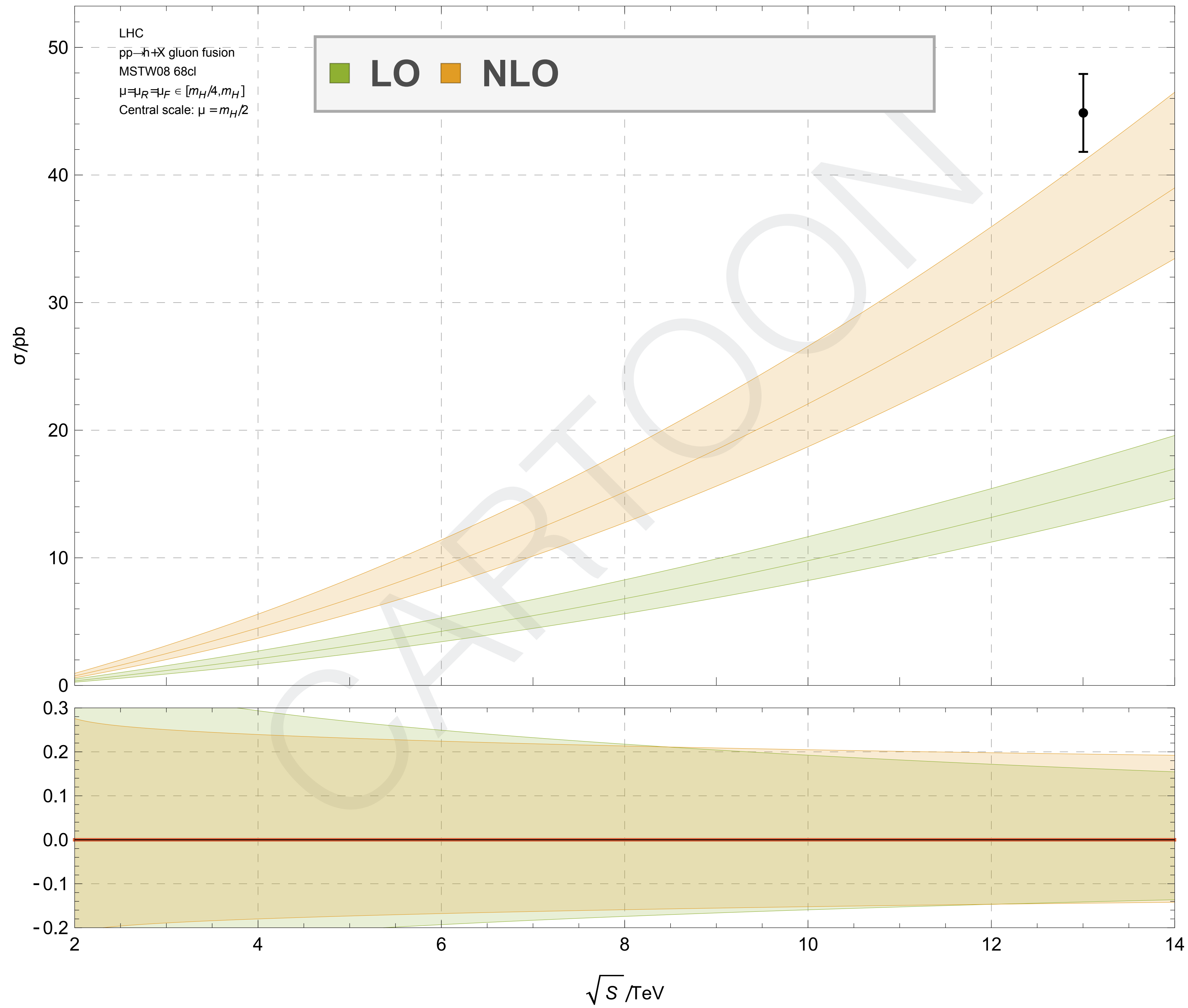


``ATLAS-CONF-2021-053''

*Warning: just a cartoon, don't trust data/theory from this plot!

Cartoon: How Important is Precision?

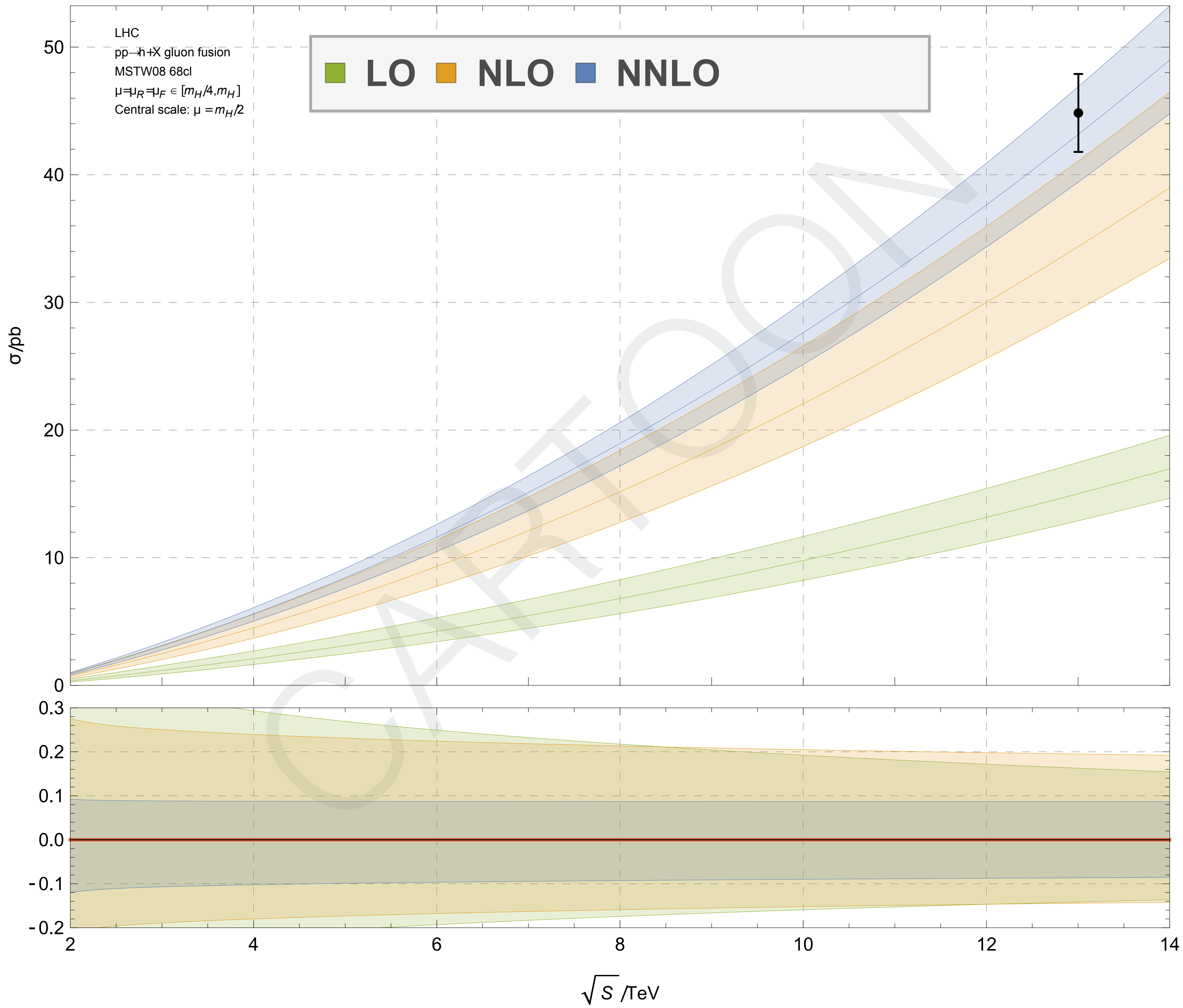
Imagine we had current experimental results for $gg \to H$, but only NLO theory…



*Warning: just a cartoon, don't trust data/theory from this plot!

Cartoon: How Important is Precision?

Much better with NNLO theory, but theory uncertainty is still quite large…

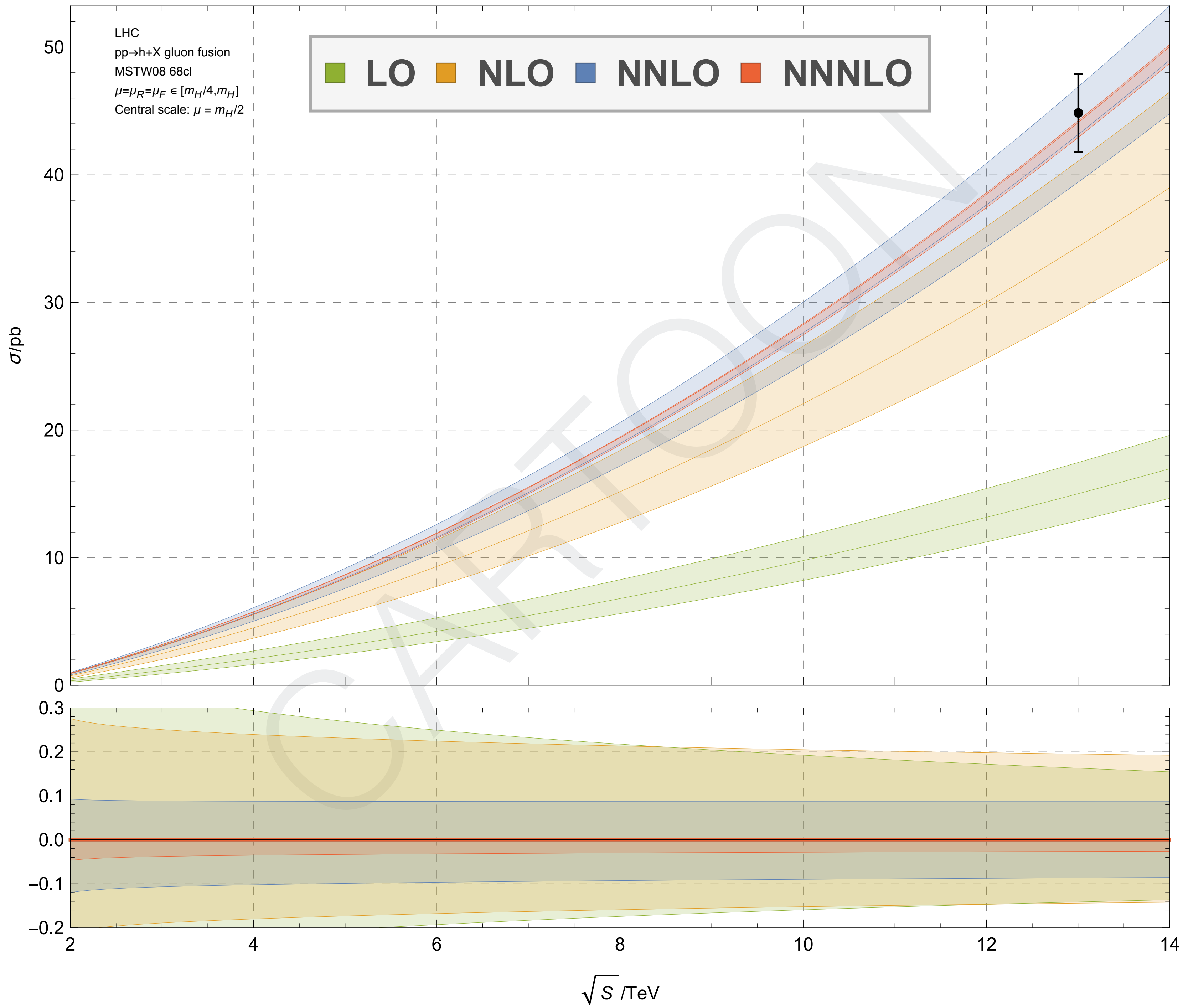


Anastasiou, Melnikov 02; Harlander, Kilgore 02; Ravindran, Smith, van Neerven 03;

*Warning: just a cartoon, don't trust data/theory from this plot!

Cartoon: How Important is Precision?

Reality: we actually have N^{3}LO theory, beautiful example of precision @ LHC



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

*Warning: just a cartoon, don't trust data/theory from this plot!

Cartoon 2: How Important is Precision?

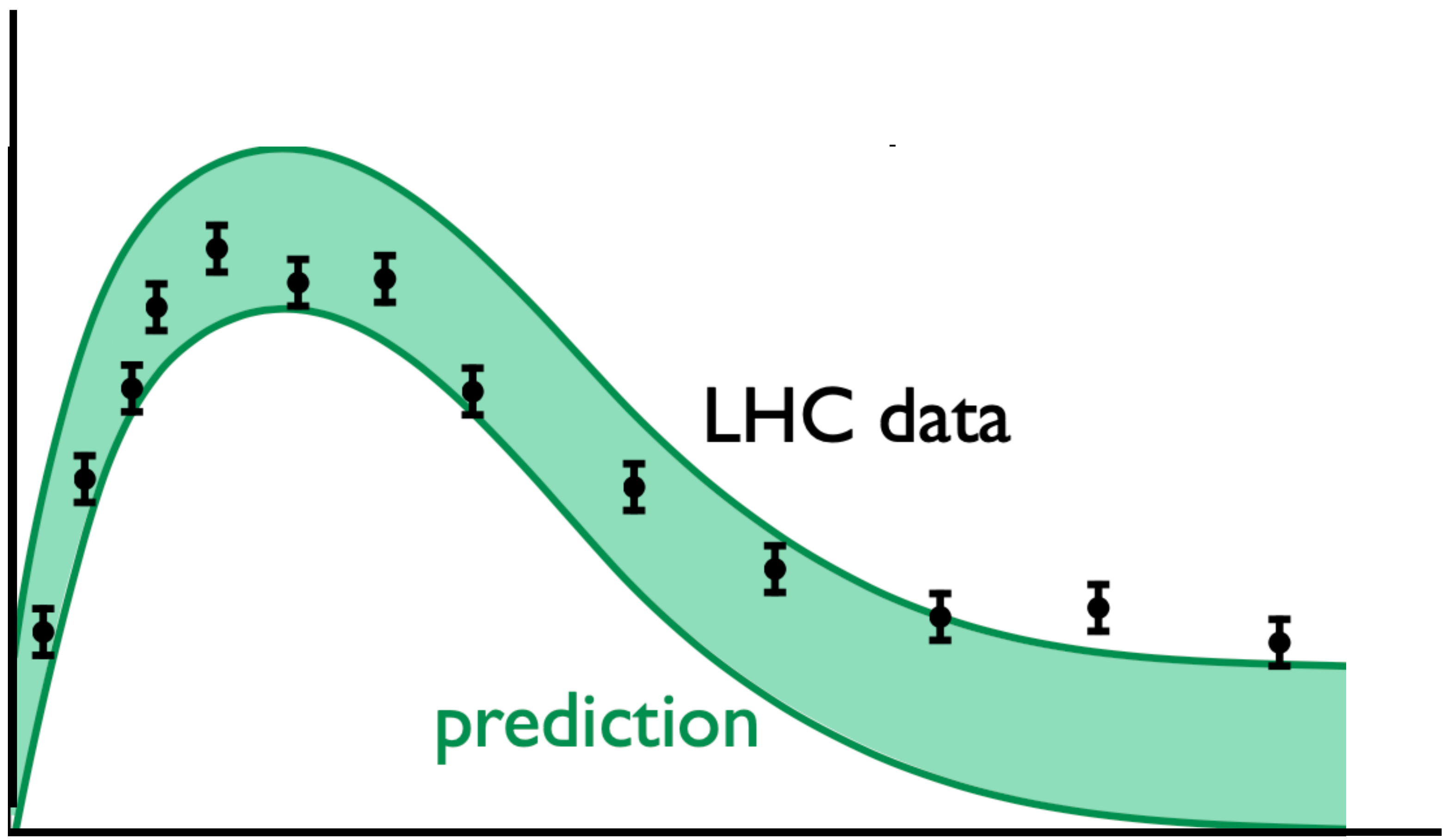


Figure: G. Zanderighi / M. Wiesemann

Cartoon 2: How Important is Precision?

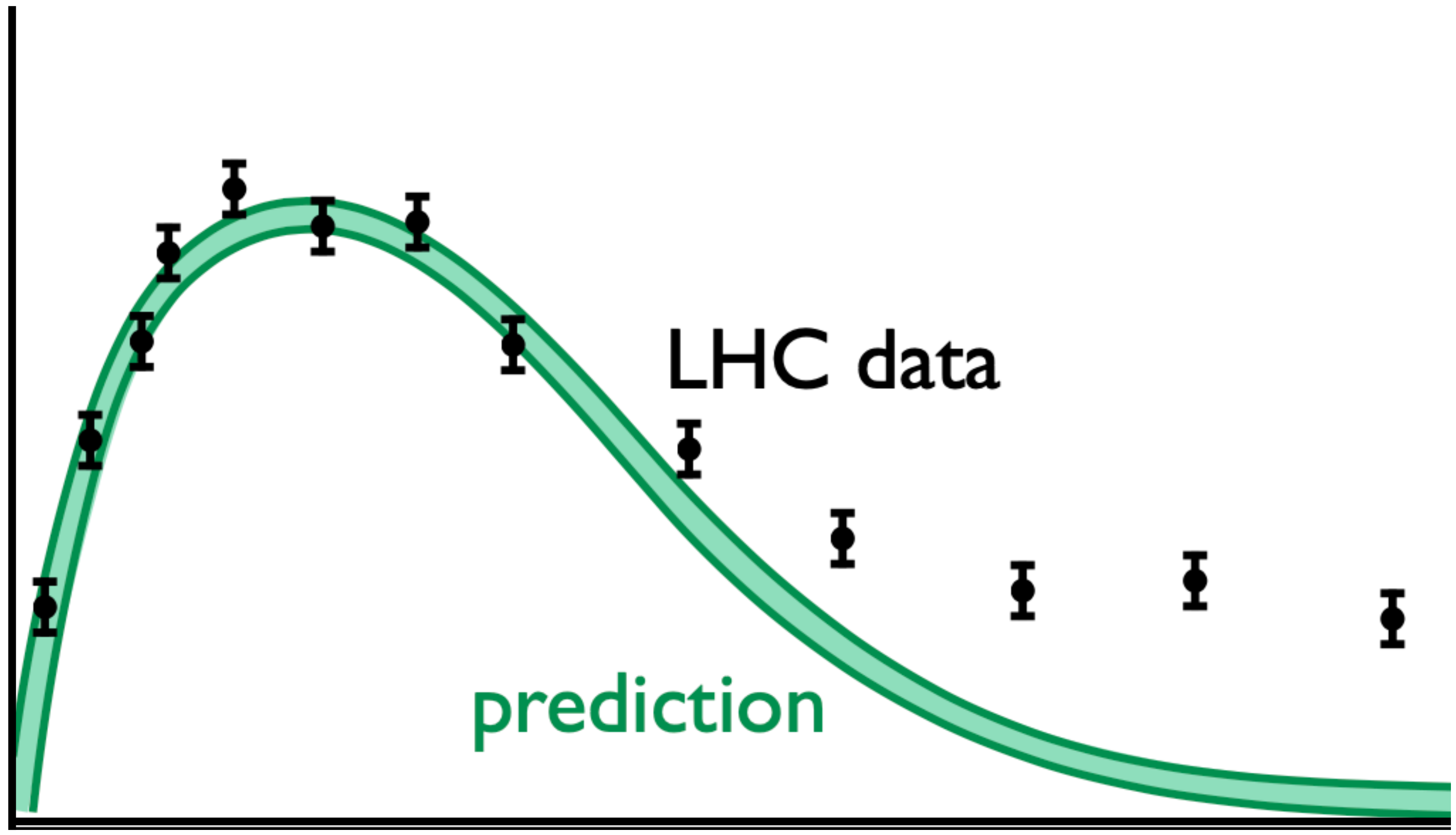


Figure: G. Zanderighi / M. Wiesemann

Cartoon 2: How Important is Precision?

Precision theory can enhance the discovery potential of our experiments!

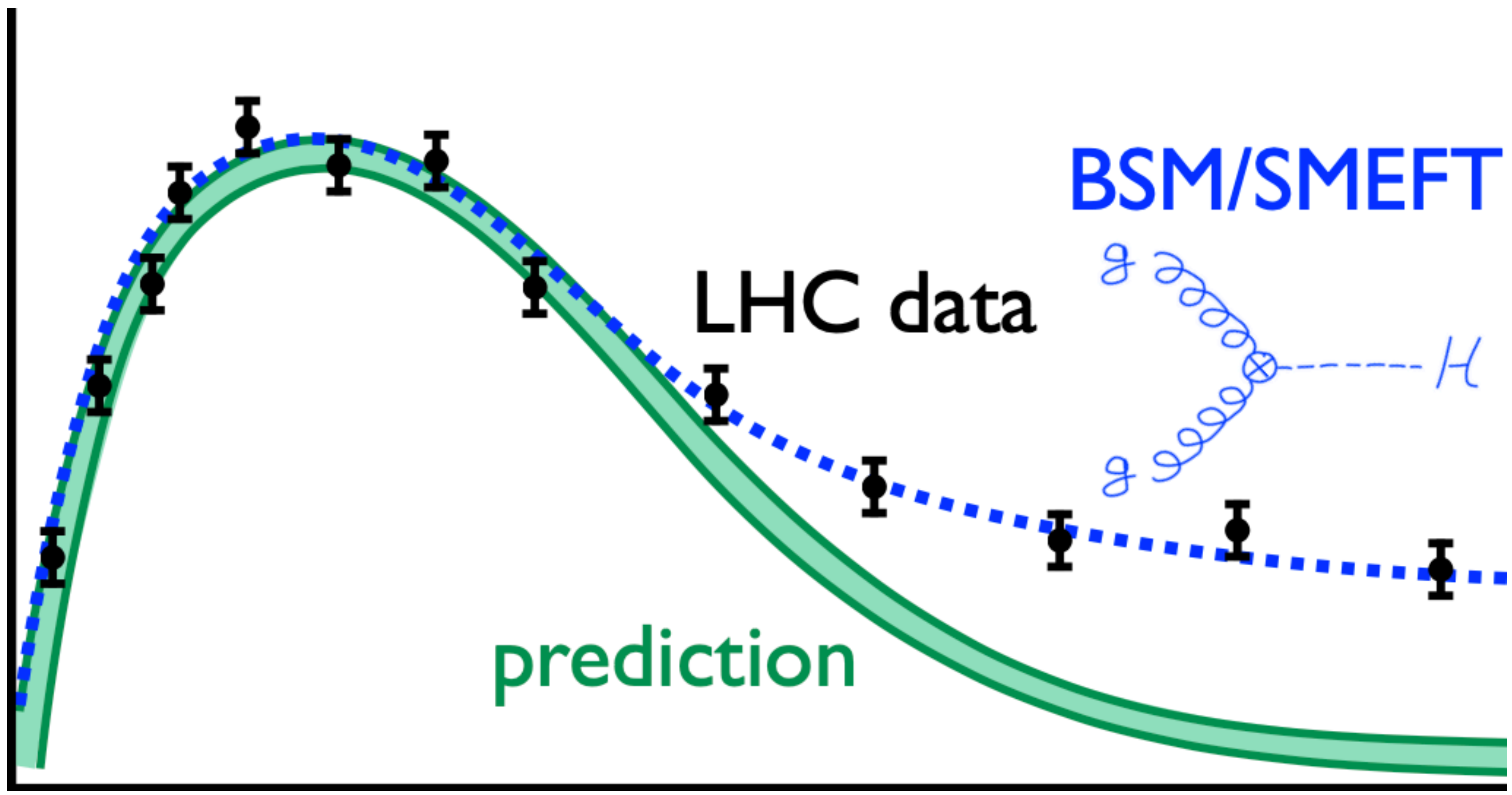
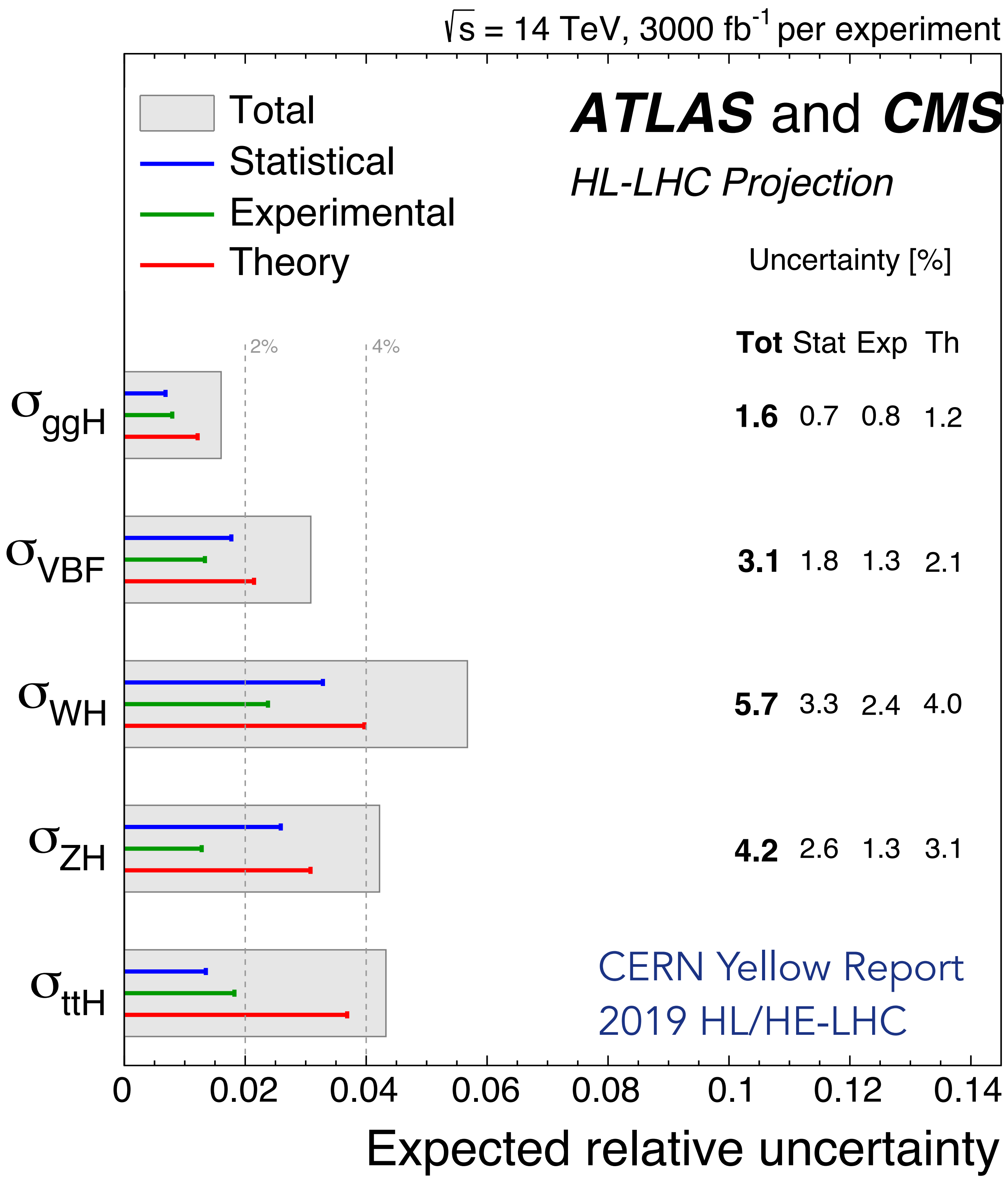


Figure: G. Zanderighi / M. Wiesemann

Upcoming Experiments: Precision



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

→ See next talk! (Harald Fox)

Outline

Higgs Boson Production

Gluon Fusion

Theory uncertainties in gluon fusion

Boosted Higgs boson production & the top-quark mass

ZH Production

Impact of the gluon channel

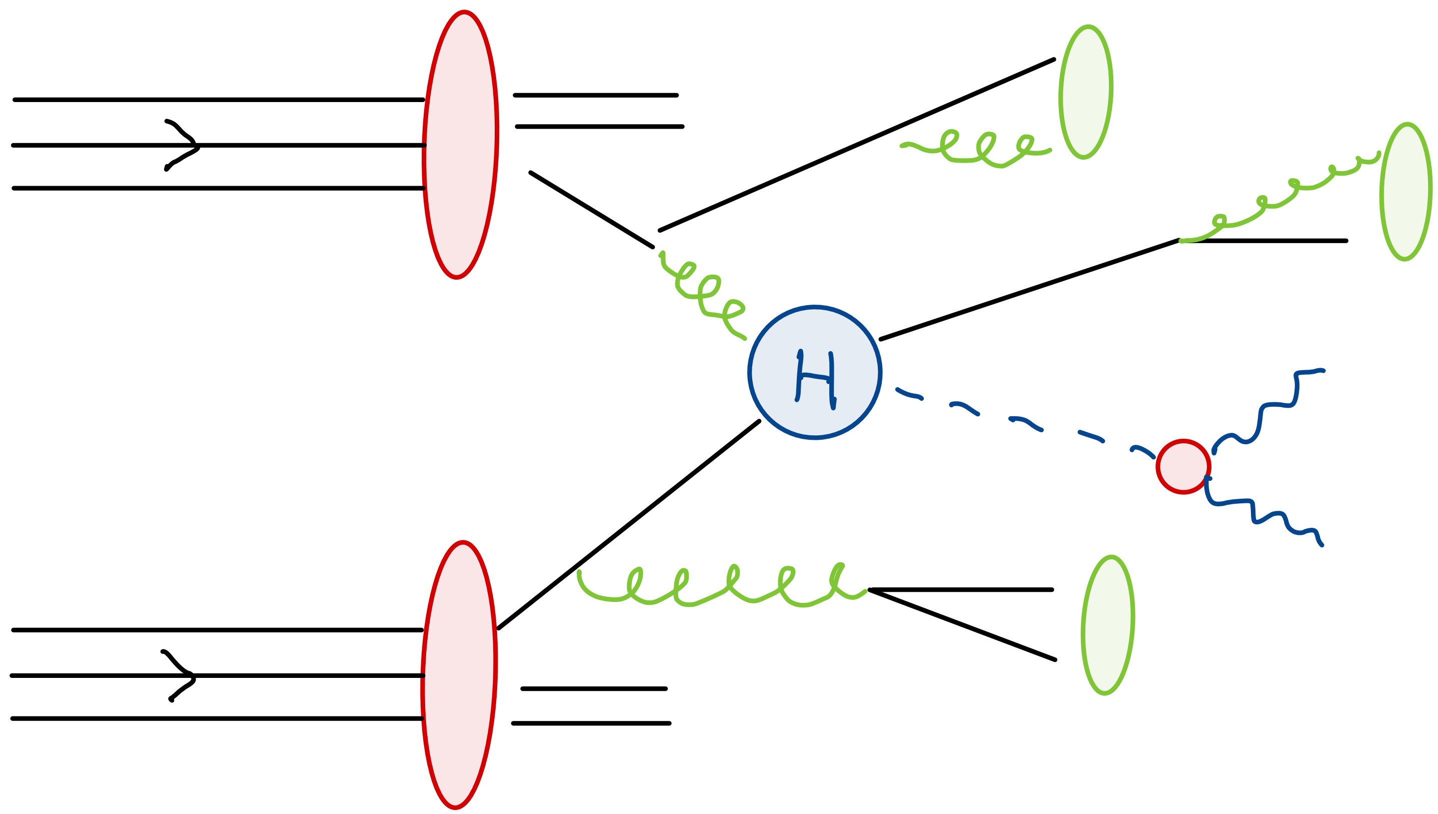
Remaining uncertainties and open questions

Di-Higgs Boson Production

Current status and open questions

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

How do we Improve Precision?



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

Parton Distribution Functions (PDFs)

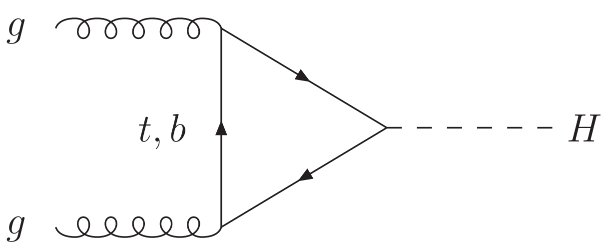
Hard Scattering Matrix Element

Non-perturbative effects ~ few %

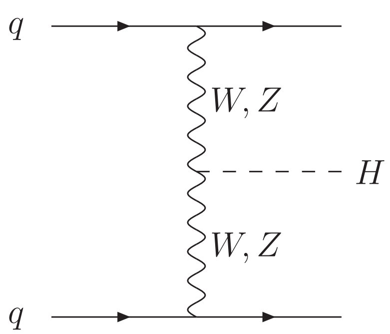
Higgs Production & Decay

σ [pb] @ 13 TeV

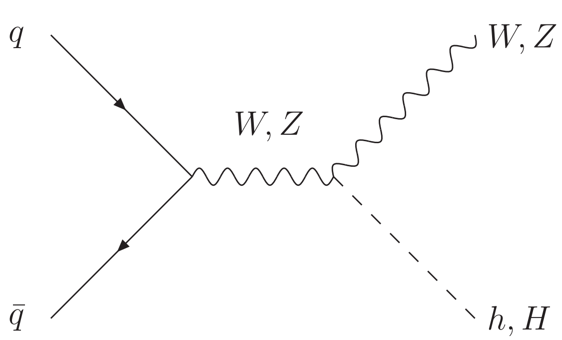
Higgs in 140 fb^{-1}



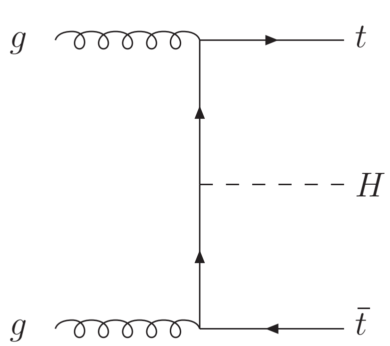
49 pb / 6.9M



3.8 pb / 520k

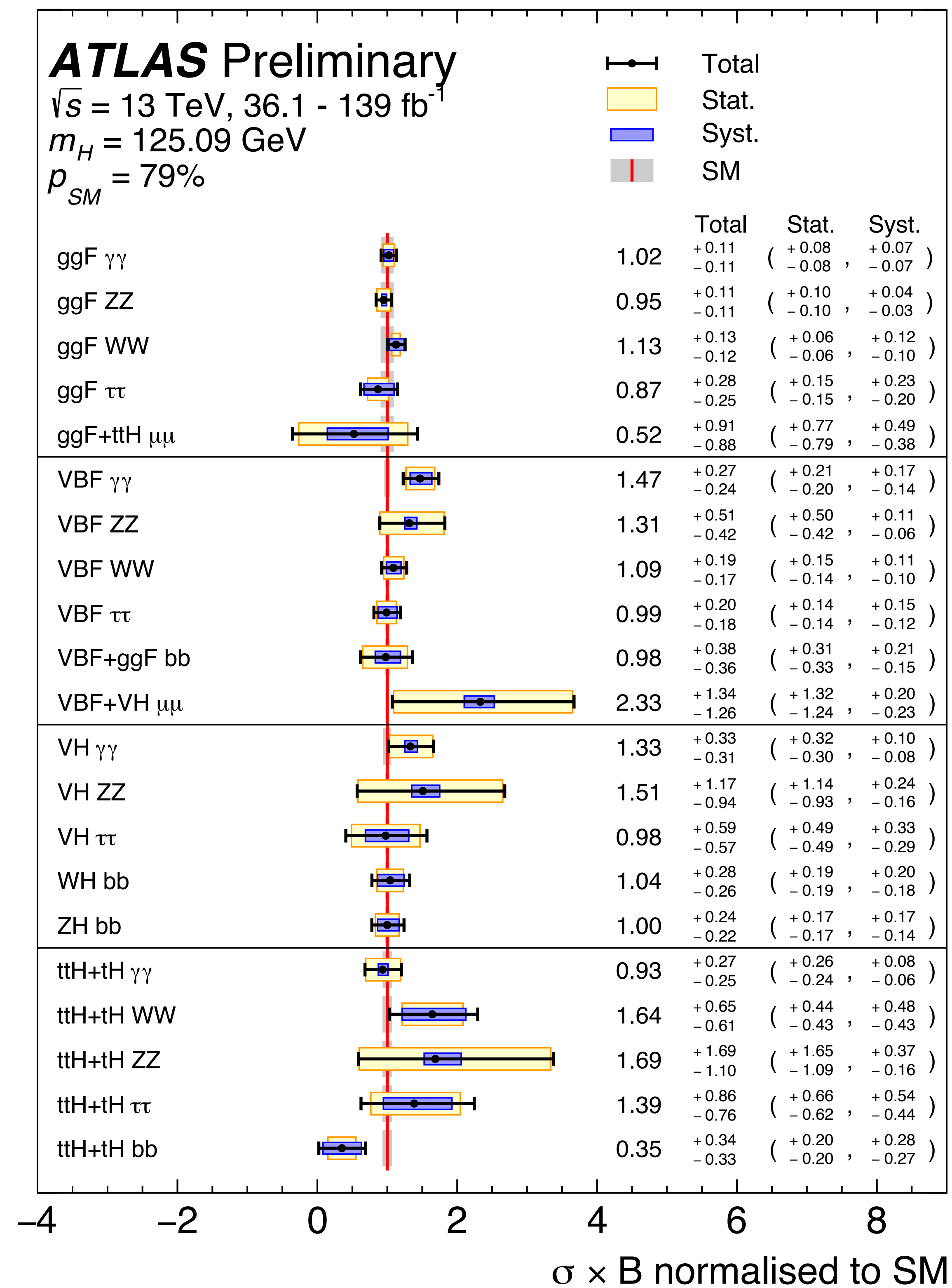


2.3 pb / 320k

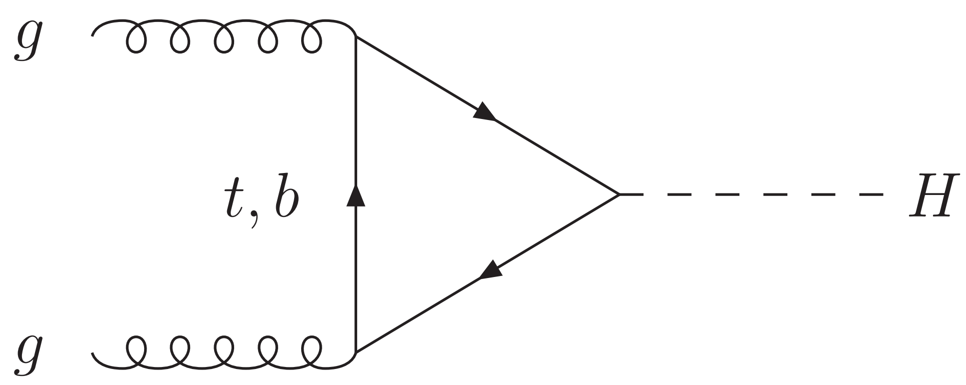


0.5 pb / 70k

ATLAS-CONF-2021-053



Gluon Fusion

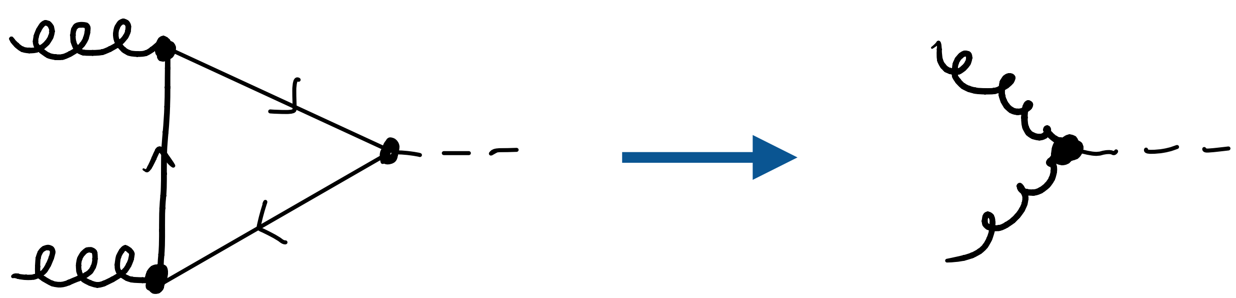


A Useful Approximation: Heavy Top Limit

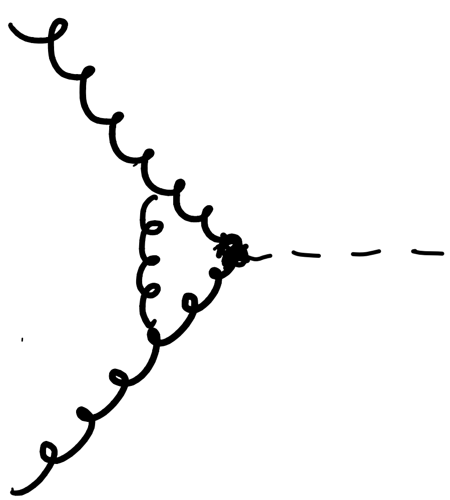
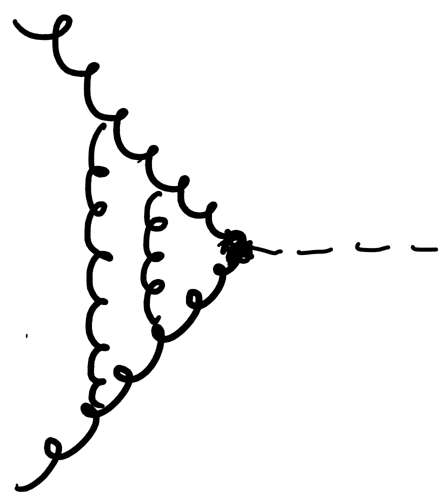
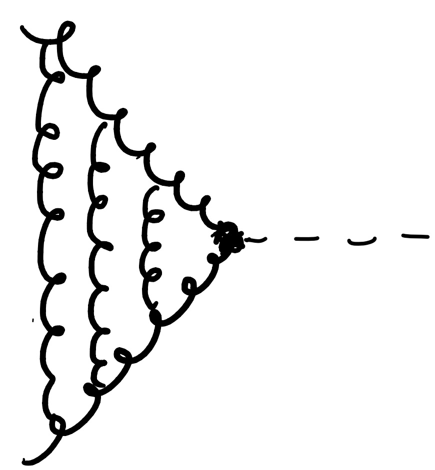
Heavy Top Limit (HTL): integrate out top quarks ($m_T \to \infty$)

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

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



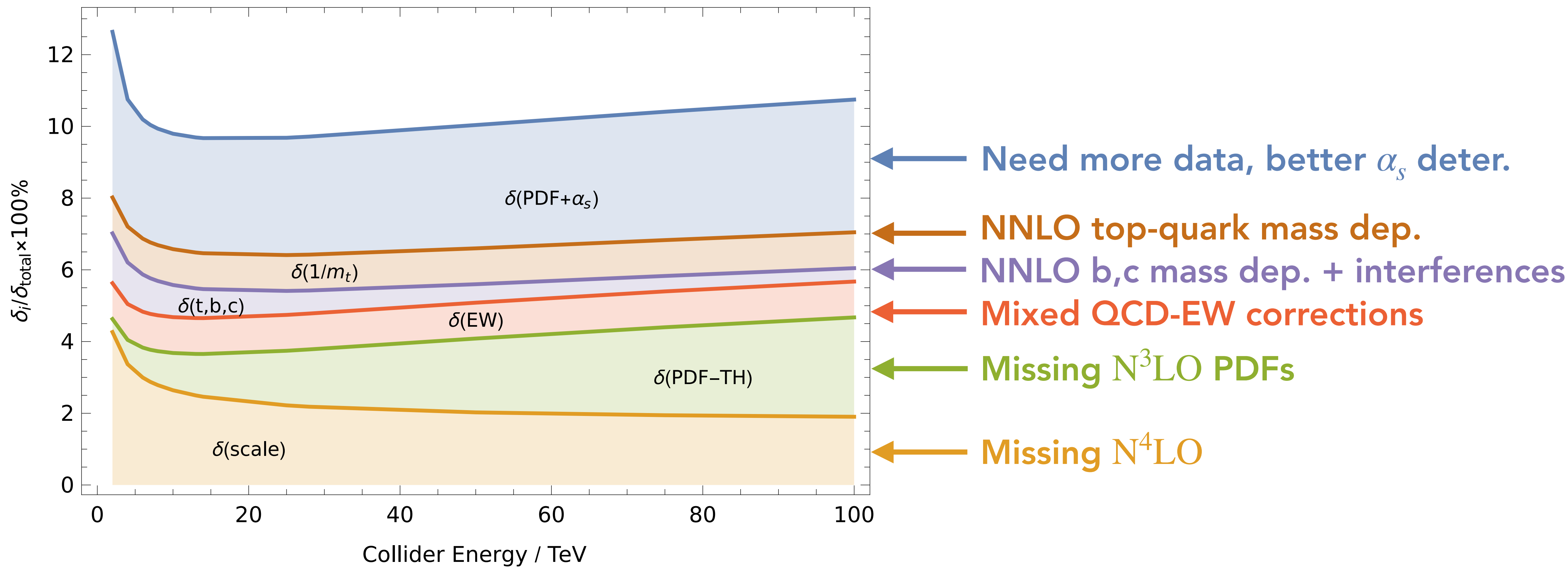
HTL valid for $\sqrt{\hat{s}} \ll 2m_T$

NLO	NNLO	N³LO
		
$\mathrm{NLO/LO} \approx 2.3$	$\mathrm{NNLO/NLO} \approx 1.3$	$\mathrm{N^3LO/NNLO} \approx 1.03$
	Anastasiou, Melnikov 02; Harlander, Kilgore 02; Ravindran, Smith, van Neerven 03;	Anastasiou, Duhr, Dulat, (Furlan), (Gehrmann), Herzog, Mistlberger 16; Mistlberger 18;

Gluon Fusion: Error Budget

2018 Error Budget

Dulat, Lazopoulos, Mistlberger 18



Progress

$\delta(1/m_t)$: Known to NNLO, removed — Czakon, Harlander, Klappert, Niggetiedt 21

$\delta(t,b,c)$: Challenging but possible

$\delta(\text{EW})$: 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

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

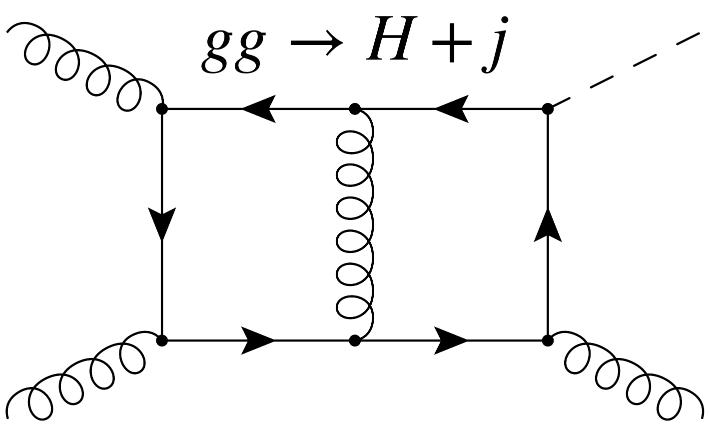
Boosted Higgs: NLO H+jet

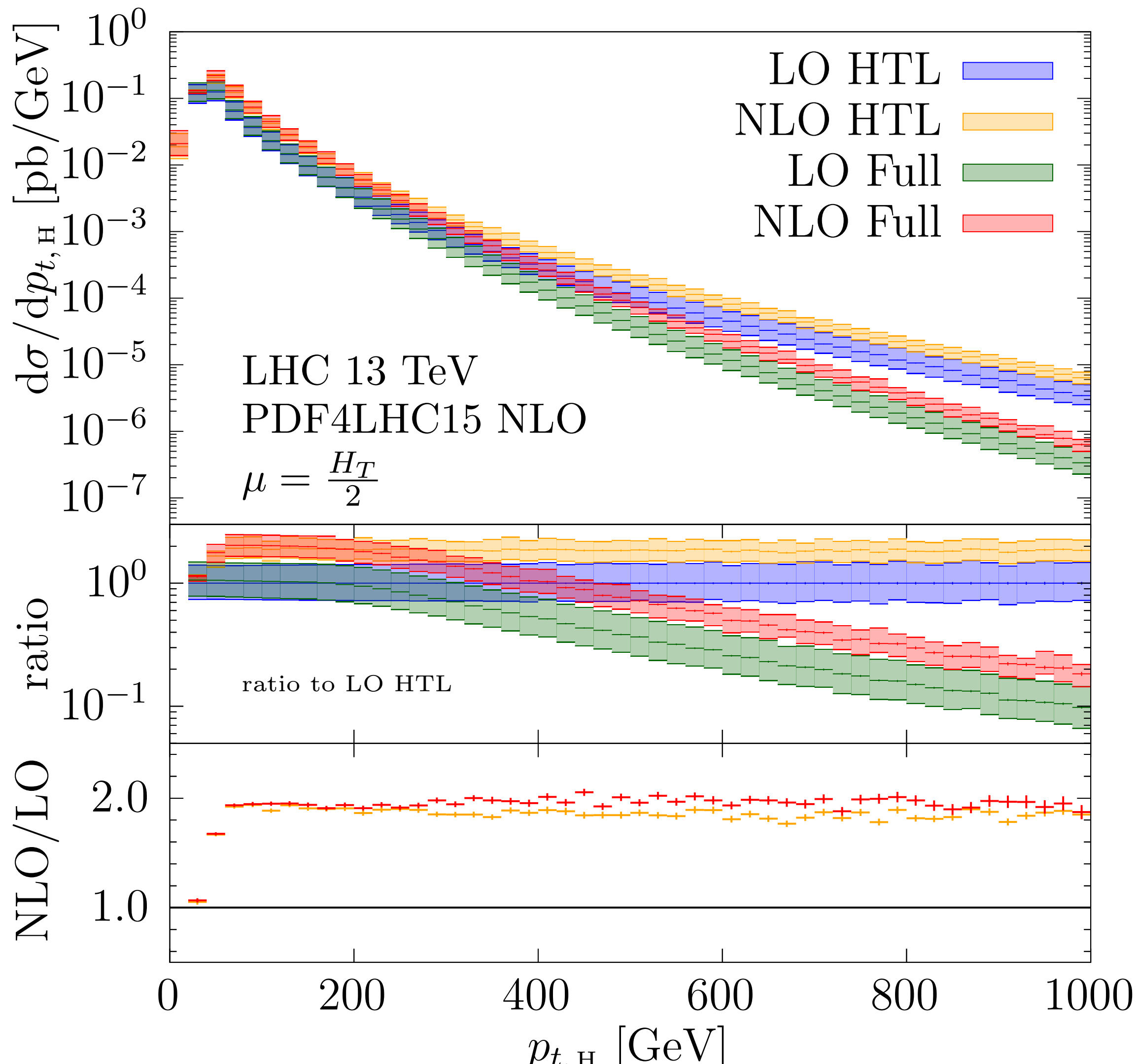
To attack $\delta(1/m_T)$ need amplitudes with m_T included

$pp \to Hjj$ @ LO (1-loop)

$pp \to Hj$ @ NLO (2-loop)

$pp \to H$ @ NNLO (3-loop)





SPJ, Kerner, Luisoni 18, 21

The *ppHj* amplitude is itself interesting

Predicts **boosted** (high-p_T) Higgs

Challenging calculation (s, t, m_H, m_T) completed with various techniques:

Small m_T approximation

Kudashkin, (Lindert), Melnikov, Wever 17, (18); Neumann 18;

Numerical evaluation of integrals

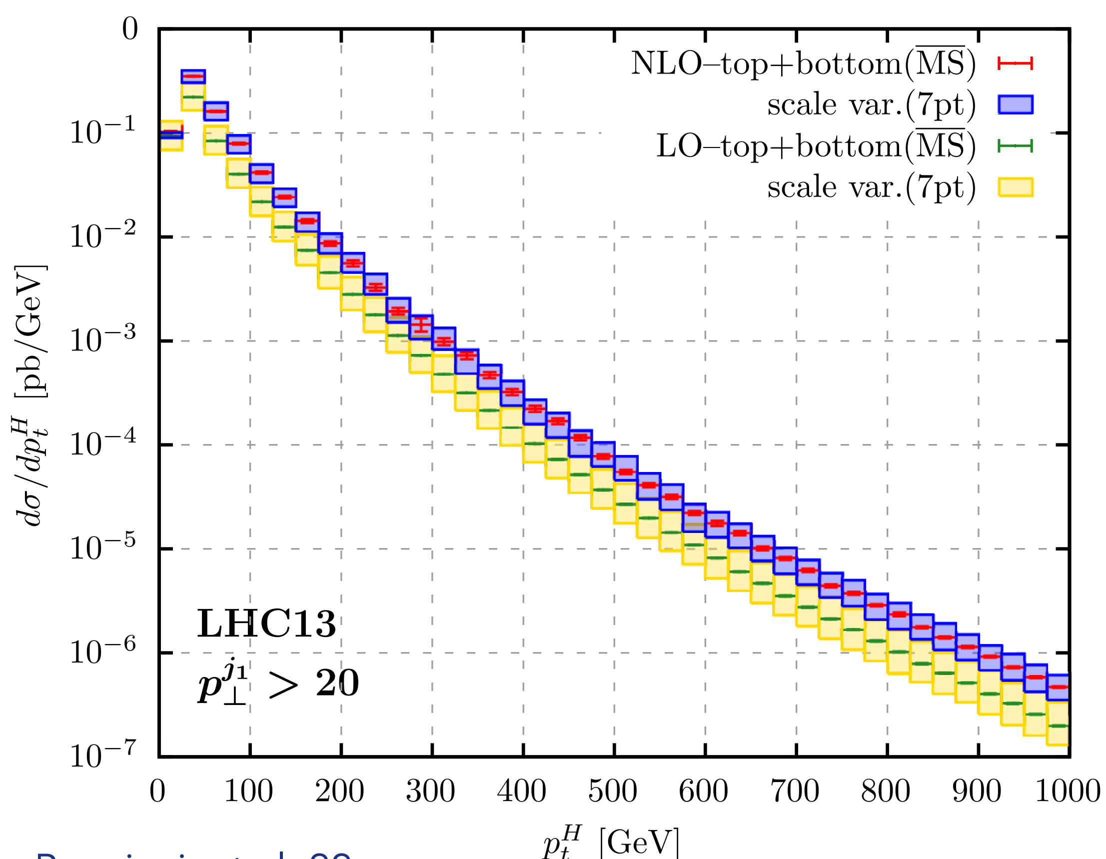
SPJ, Kerner, Luisoni 18, 21

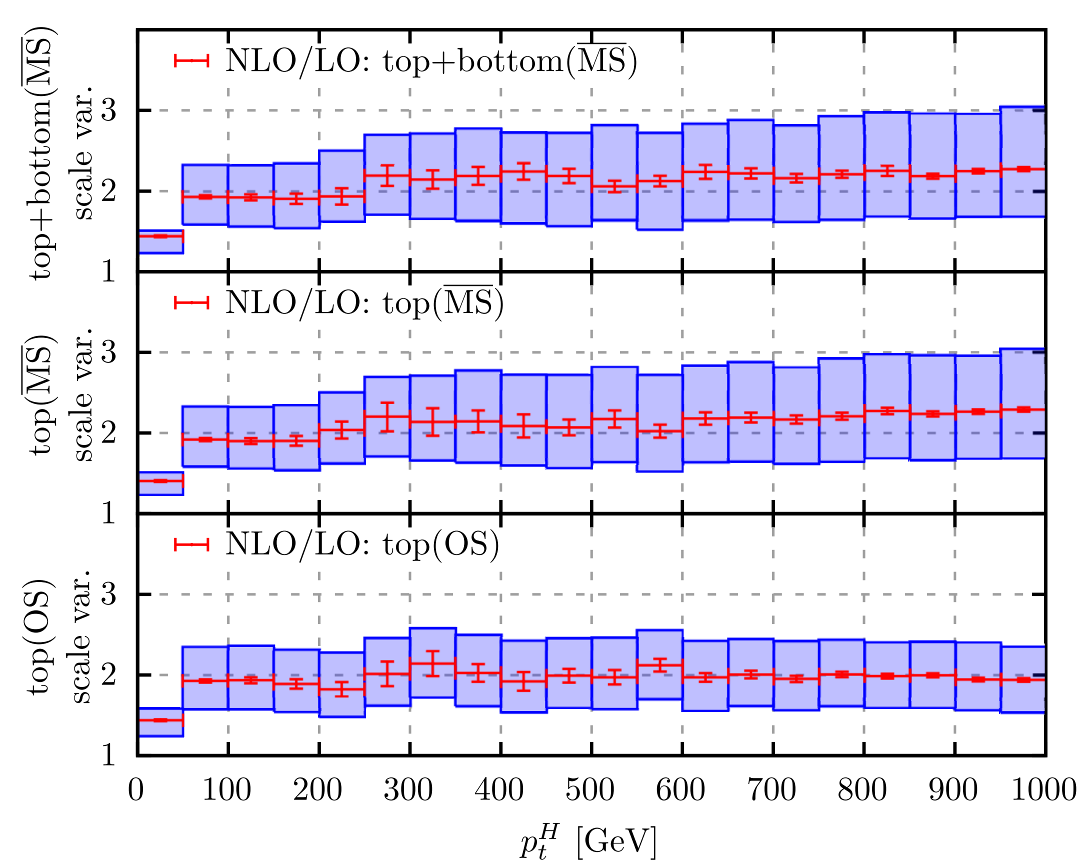
The HTL alone is a very poor approximation of the large-p_T behaviour

Boosted Higgs: NLO H+jet

Recently, $pp \to Hj$ was calculated including full m_B, m_T dependence using the series expansion of differential equations

Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22;





Bonciani, et al. 22

Confirm earlier results that indicated NLO corrections are large $K_{\mathrm{NLO/LO}} \approx 2$

Bottom and top/bottom interference effects relevant only for low-p_T

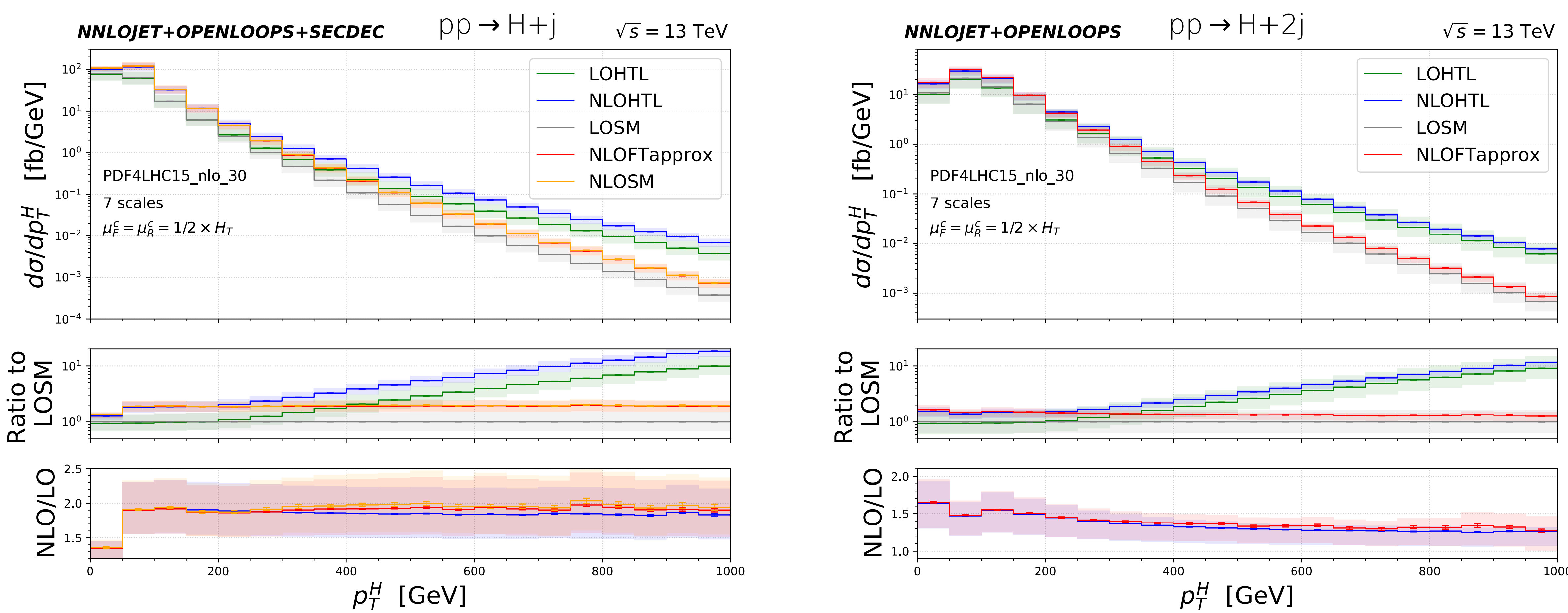
Result very flexible: allows quark masses to be renormalised in different schemes

Boosted Higgs: NLO H+2jet

Interestingly, a particular approximation ($\mathbf{FT}_{\text{approx}}$) works quite well for H+j

Use exact Born + Reals

Approximate 2-loop Virtuals with $|\mathcal{M}_4^2(m_t, \mu_R^2; \{p\})|^2 \to |\mathcal{M}_4^1(\infty, \mu_R^2; \{p\})|^2 \dfrac{|\mathcal{M}_4^1(m_t; \{p\})|^2}{|\mathcal{M}_4^0(\infty; \{p\})|^2}$

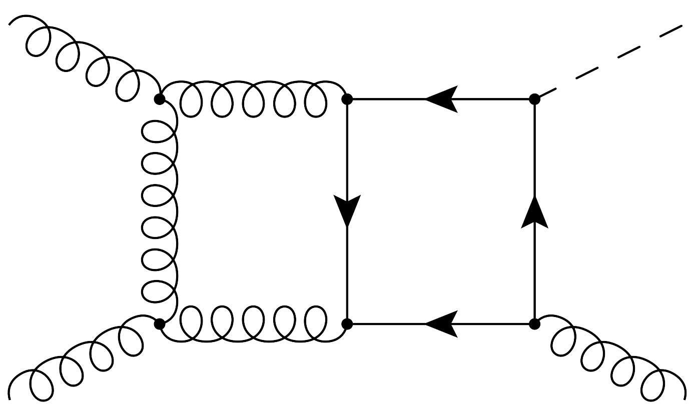


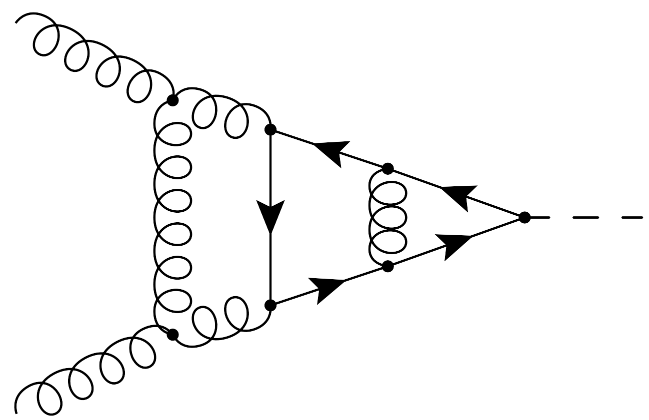
Chen, Huss, SPJ, Kerner, Lang, Lindert, Zhang 21

Assuming approximation works similarly well for higher jet multiplicity, can produce improved H+2j predictions just by computing full reals

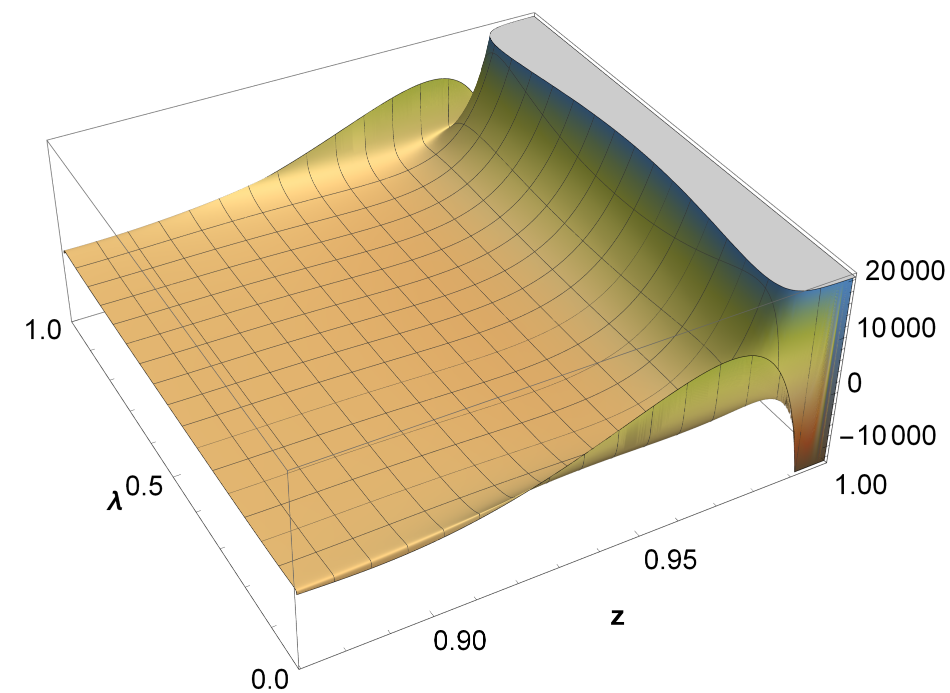
Gluon Fusion: NNLO with Full top-quark Mass

Returning to the $\delta(1/m_T)$ uncertainty in $gg \to H$





$gg \to Hg$



$2\mathrm{Re}\langle M^{(1)}_{\mathrm{exact}} | M^{(2)}_{\mathrm{exact}} \rangle |_{\mathrm{regulated}}$

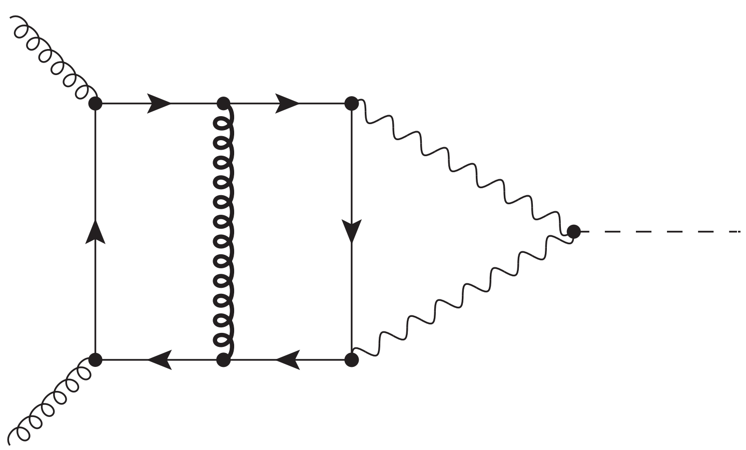
H+j @ 2-loop & H @ 3-loop with m_T using numerical solution of differential equations

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

Decreases σ_{tot} by $-0.26\,\%$ @ 13 TeV compared to heavy top limit (HTL)

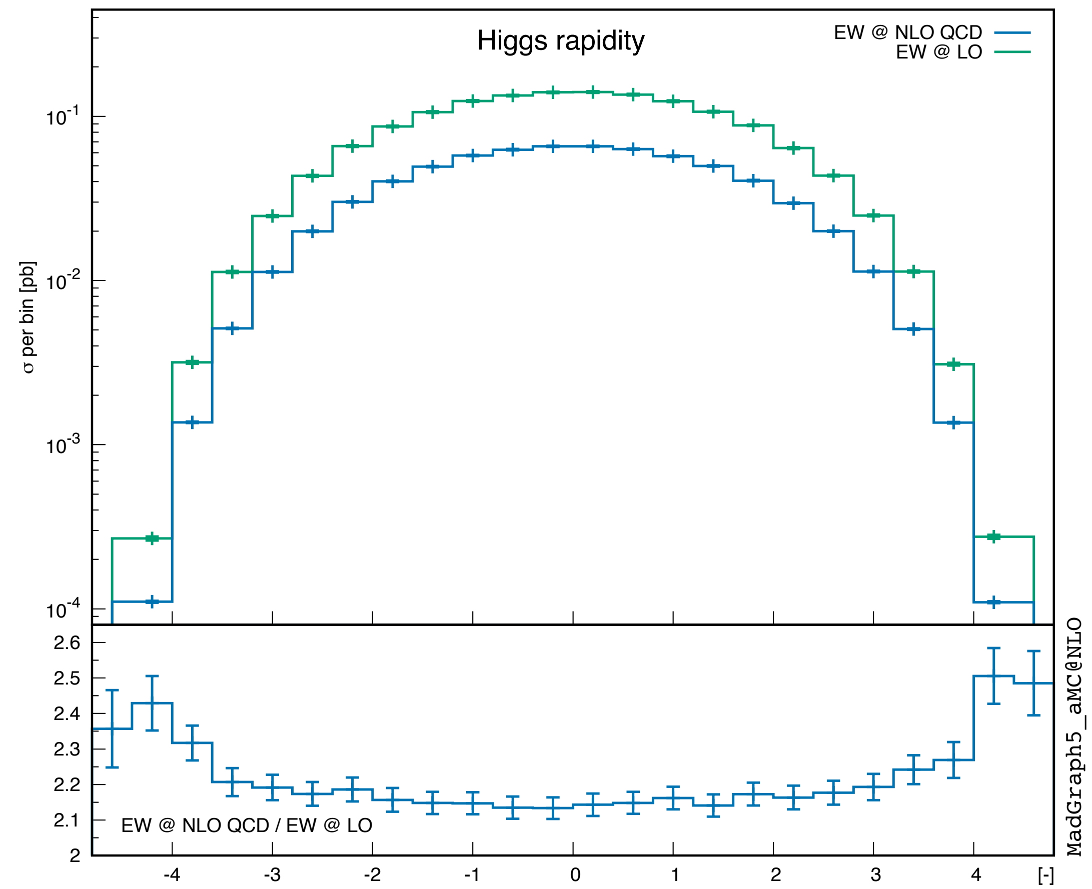
Intricate interplay between mass effects $gg\ (+0.62\%), qg\ (-16\%), qq\ (-15\%)$
Complete NNLO results obtained using STRIPPER framework

Gluon Fusion: Mixed QCD-EW Corrections



Challenging calculations

Bonetti, Melnikov, Tancredi 17
Bonetti, Panzer, Smirnov, Tancredi 20



Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20

Increases σ_{tot} by $+5.1\,\%$ @ 13 TeV, reduces residual uncertainty $\delta(\text{EW}) \sim 0.6\,\%$

Favouring factorisation of EW corrections: $\sigma = \sigma_{\text{LO}}\,(1+\delta_{\text{QCD}}) \times (1+\delta_{\text{EWK}})$

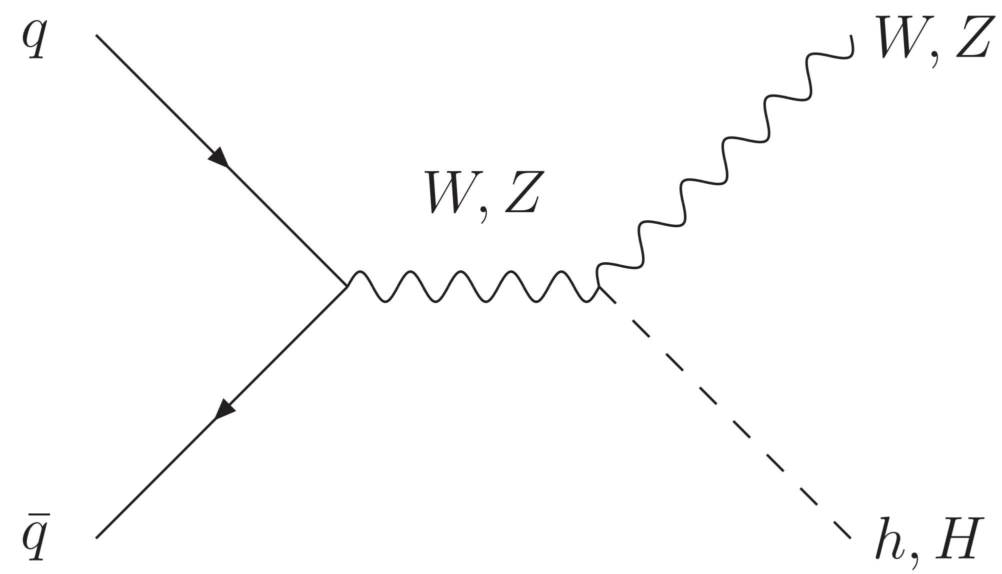
Compatible with previous estimates:

Soft approx: $+5.4\,\%$,
Bonetti, Melnikov, Tancredi 18;

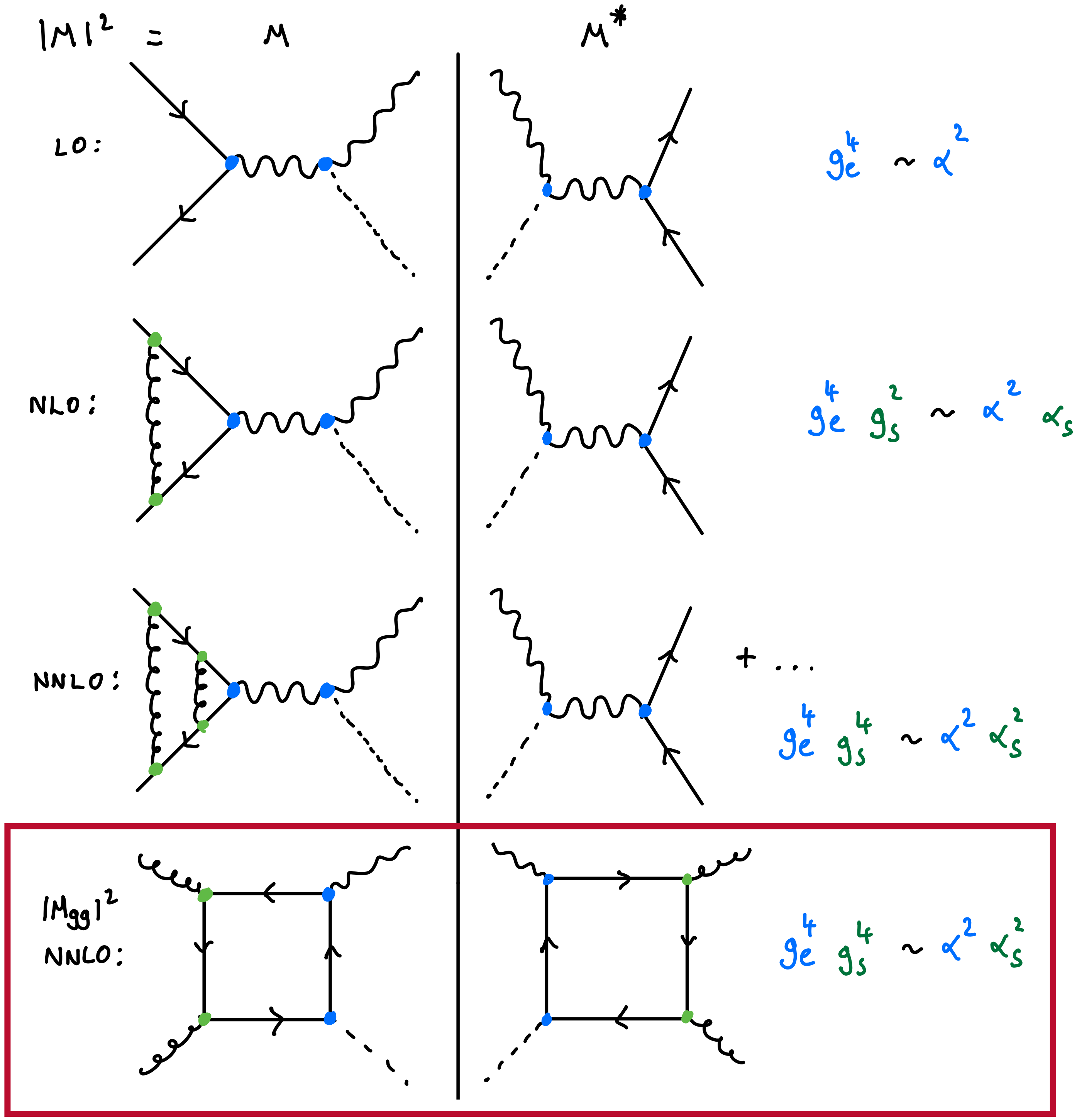
$M_H \ll M_V : +5.2\,\%$,
Anastasiou, Boughezal, Petriello 09;

$M_H \gg M_V : +5.4\,\%$
Anastasiou, Del Duca, Furlan, Mistlberger, Moriello, Schweitzer, Specchia 19

ZH Production



$pp \to ZH$: Role of $ggZH$ Channel



Drell-Yan-like contribution recently computed @ N^{3}LO

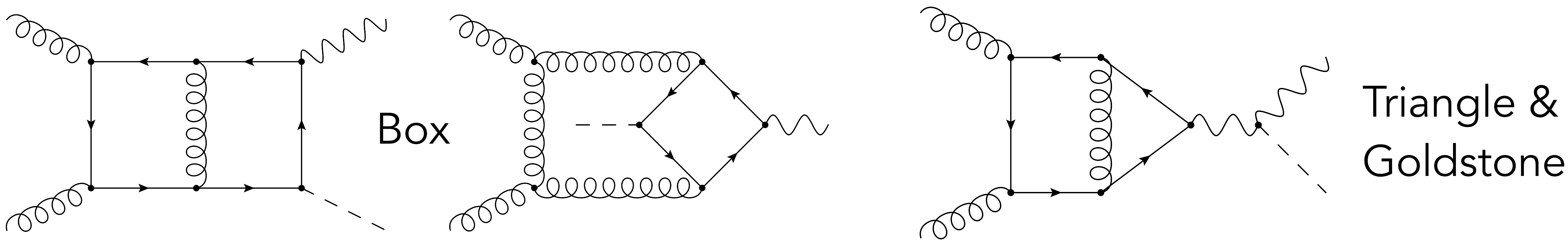
Baglio, Duhr, Mistlberger, Szafron 22

Gluon channel contributes to $pp \to ZH$ @ NNLO

1) ~10% of the total cross section at LHC (due to large gluon luminosity)
2) Has large uncertainty >100%
3) A dominant TH uncertainty on ZH analyses

This motivates calculating $ggZH$ @ NLO (2-loop)

$gg \to ZH$: 2-loop Virtual Amplitude



A challenging calculation (s, t, m_H, m_T, m_Z), completed with various techniques

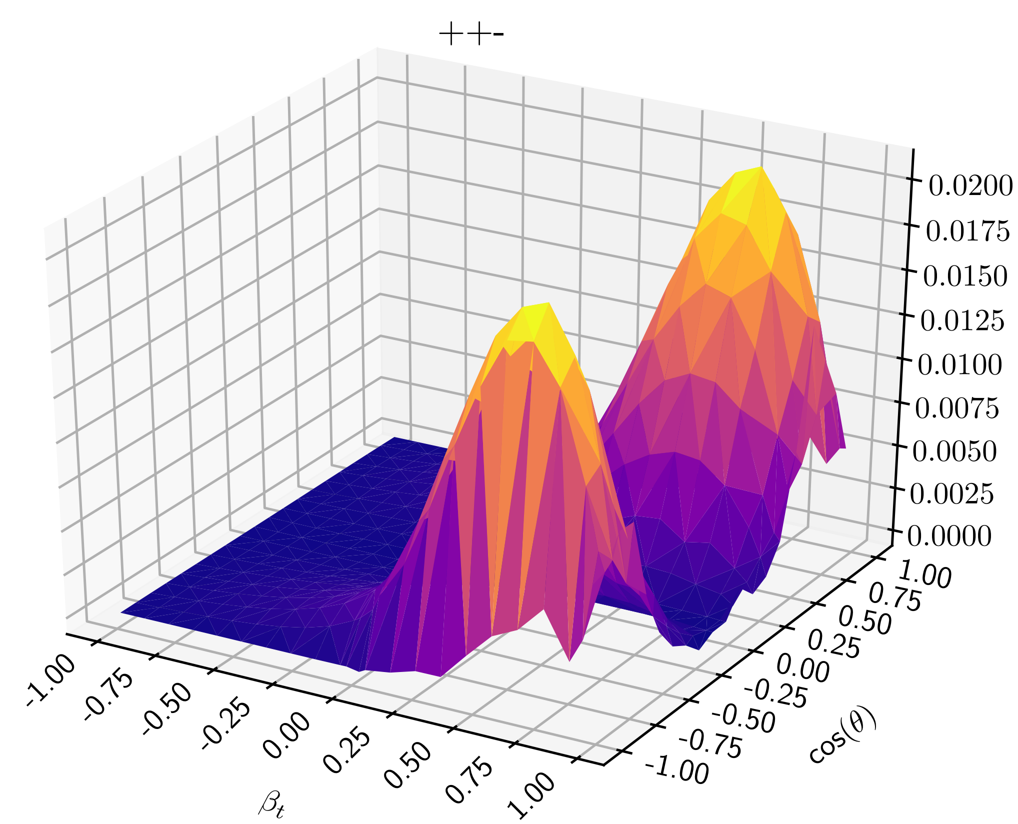
(Small m_Z, m_H) Wang, Xu, Xu, Yang 21; (Small m_T & $1/m_T$ Expansions) Davies, Mishima, Steinhauser 20; (Numerical) Chen, Heinrich, SPJ, Kerner, Klappert, Schlenk 20; (p_T & $1/m_T$ Expansions) Alasfar, Degrassi, Giardino, Gröber, Vitti 21; Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; Degrassi, Gröber, Vitti, Zhao 22; (Small m_T & Numerical) Chen, Davies, Heinrich, SPJ, Kerner, Mishima, Schlenk, Steinhauser 22

Our full result has 452 ``master integrals'' and ~5GB amplitude

Using (IBP) relations between the integrals we found a much simpler ~1GB expression for amplitude

Largest coefficient (double-tadpole) 150 MB → 5 MB

Chen, Heinrich, SPJ, Kerner, Klappert, Schlenk 20;



Aside: Evaluating Feynman Integrals

One of the biggest challenges for processes like this is computing the integrals

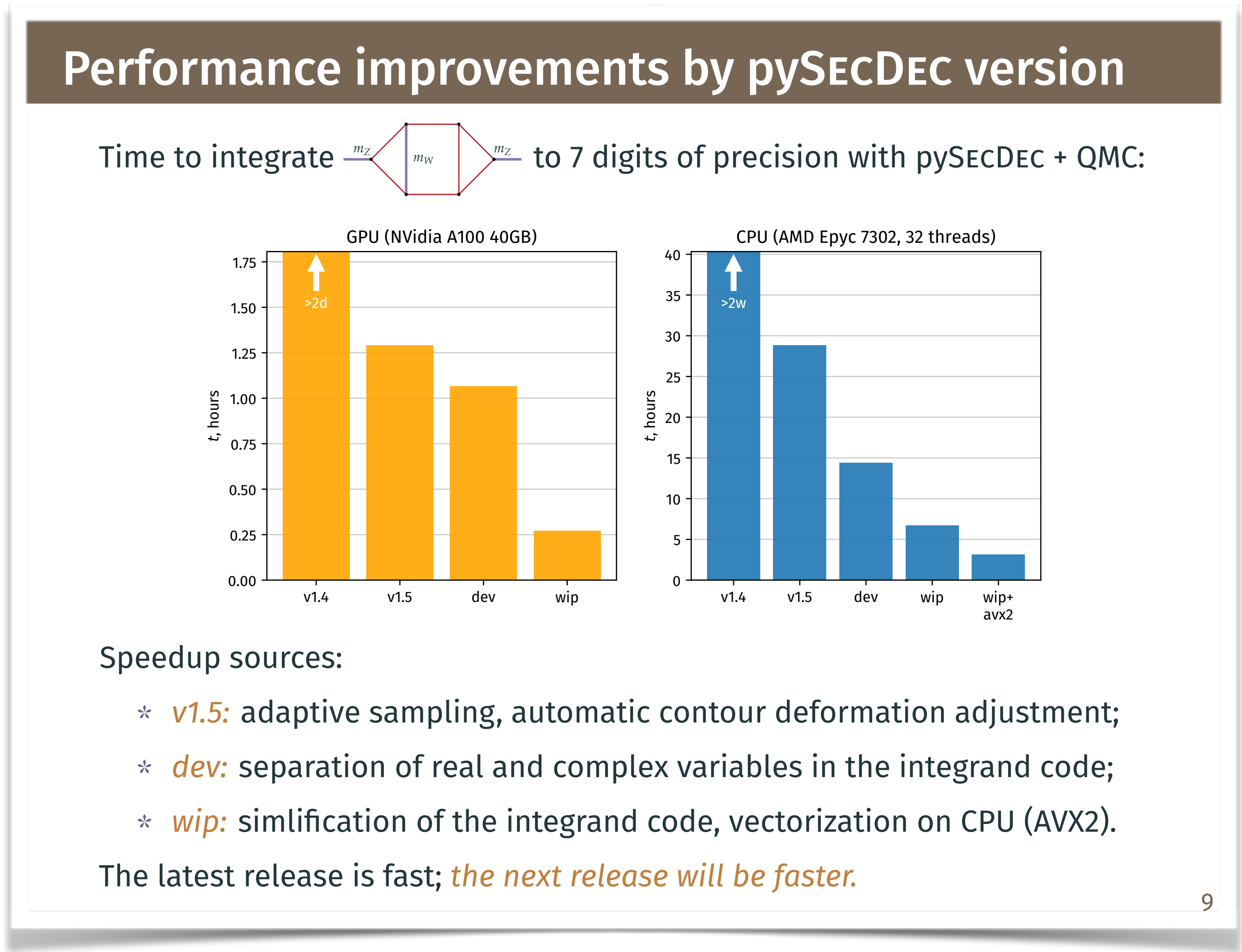
We evaluate them numerically on CPUs & GPUs using **pySecDec**

Try it now at: https://github.com/gudrunhe/secdec

Previous update (v1.5):
Expansion by Regions & Amplitude Evaluation

Heinrich, Jahn, SPJ, Kerner, Langer, Magerya, Põldaru, Schlenk, Villa 21

Upcoming (wip->v1.6):
Significant speed improvements, flexible amplitude input, smaller generated code, …



Vitaly Magerya (Loops & Legs 2022)

$gg \to ZH$: Results

Putting all pieces together (Born + reals + virtual) can obtain full NLO results

Chen, Davies, Heinrich, SPJ, Kerner, Mishima, Schlenk, Steinhauser 22

Total Cross-section

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

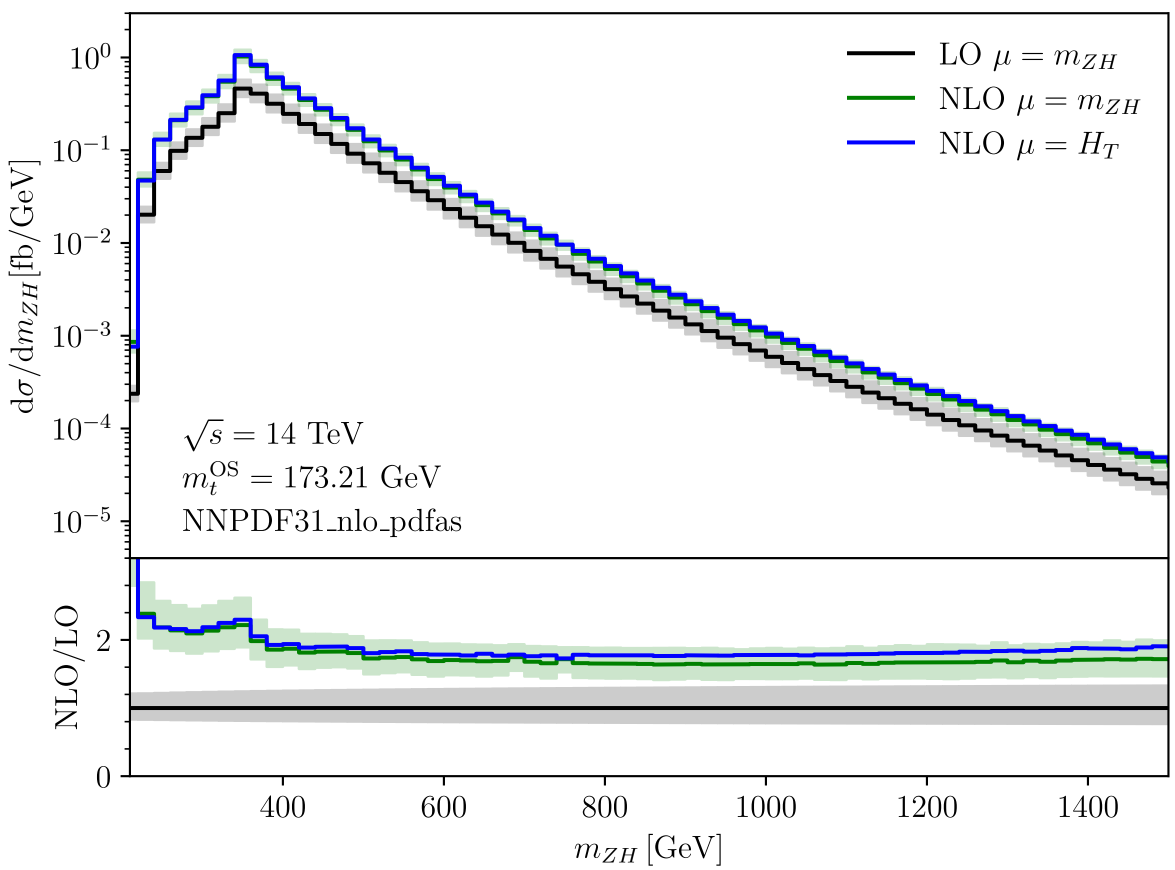
NNPDF31_nlo_pdfas

$m_t^{\mathrm{OS}} = 173.21$ GeV

$\mu = m_{ZH}$

$\mu_{R,F} \in \left[\frac{\mu}{2}, 2\mu\right]$ (7 – point)

Invariant Mass



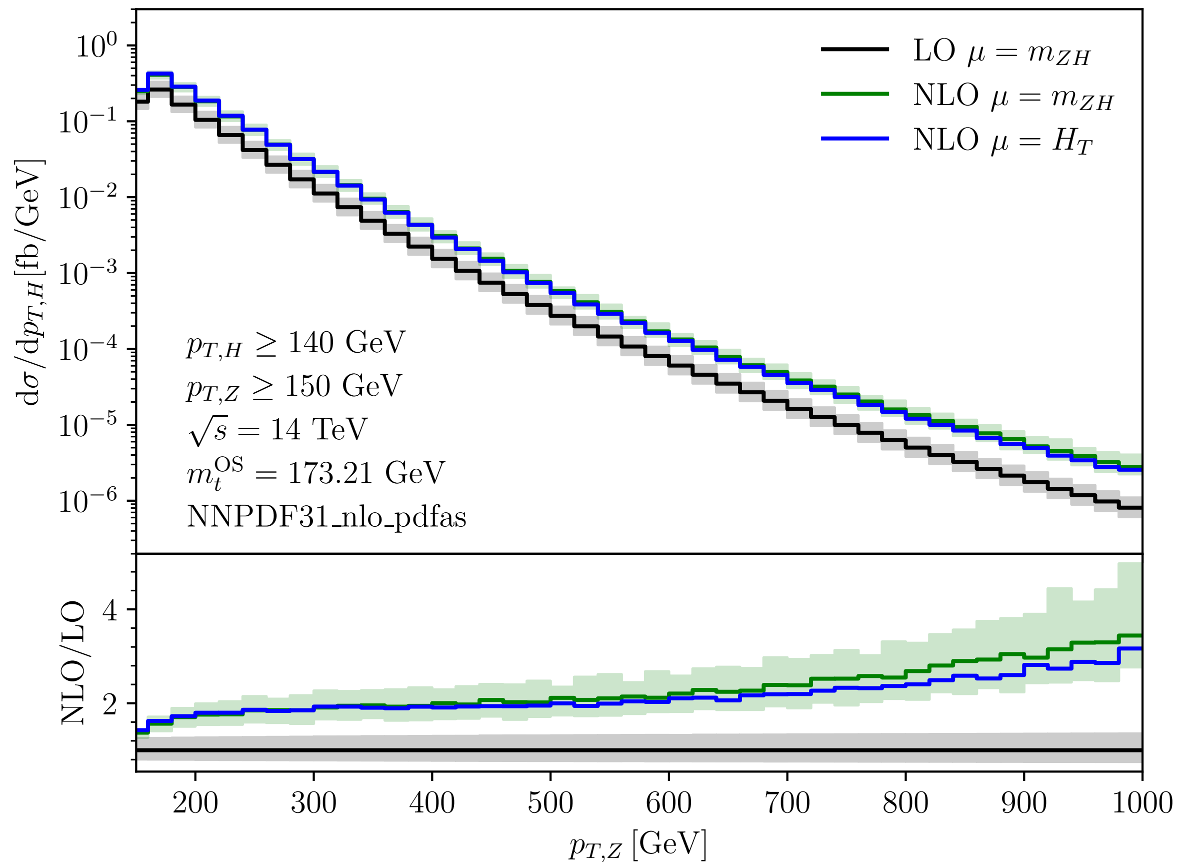
NLO corrections are large and lie outside the usual LO scale uncertainties

NLO/LO somewhat* flat except at production & top thresholds

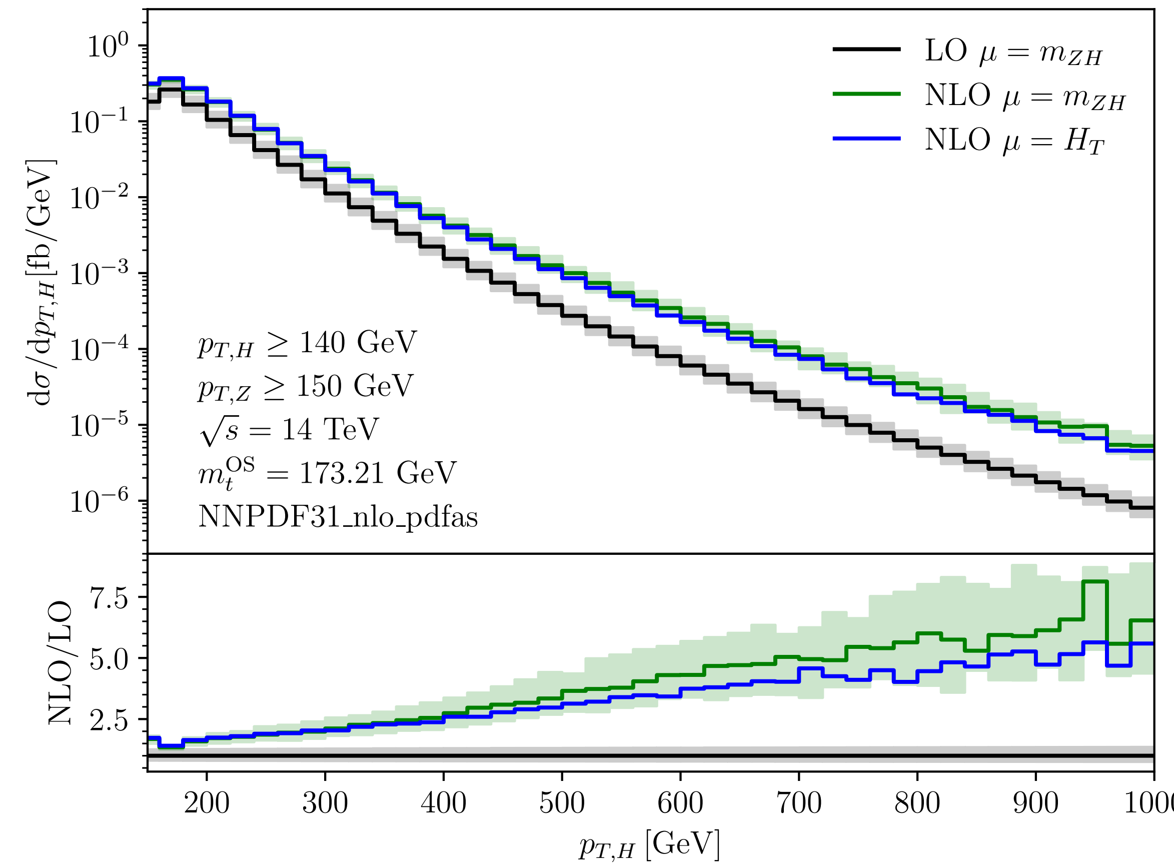
*Starts to rise above ~1 TeV (also depends on what real diagrams are included)

$gg \to ZH$: Transverse Momentum

Z Transverse Momentum



H Transverse Momentum



Z p_T : **Large** NLO corrections, rising sharply at large $p_{T,Z}$

H p_T : **Extremely** large NLO corrections, rising very sharply at large $p_{T,H}$

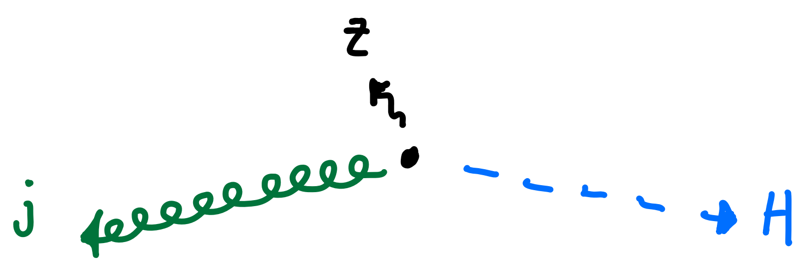
Placing cuts on soft Z or H emission slightly tames growth

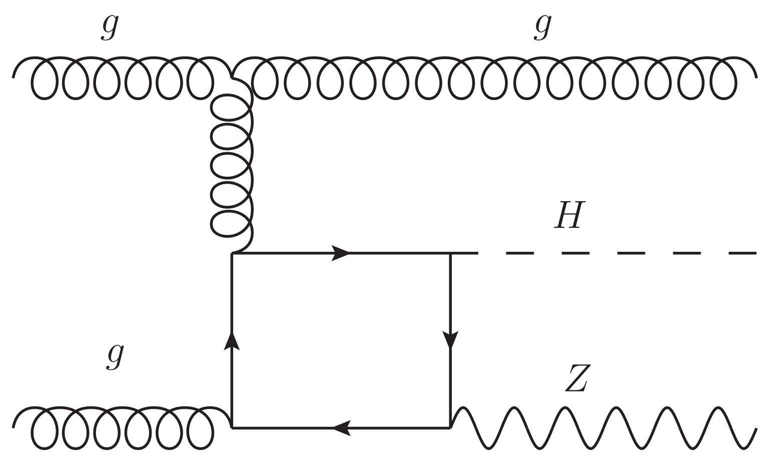
Radiating an additional jet opens up an important new region of phase-space
Very important to include higher order corrections in this region

$gg \to ZH$: Z vs H

The different behaviour of $p_{T,Z}$ and $p_{T,H}$ was observed previously in $gg \to ZH + j$

Hespel, Maltoni, Vryonidou 15; Les Houches 19





Traced to configurations where Higgs recoils against a hard jet, with a soft Z

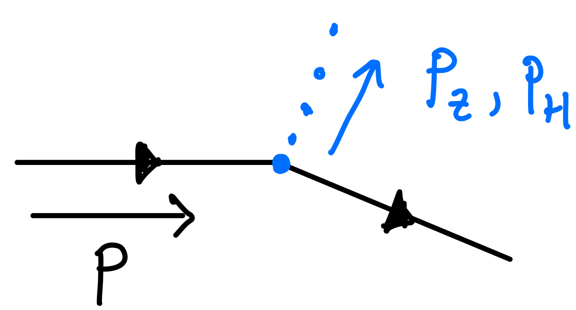
Maltoni et al. attributed this to t-channel gluon exchange

One observation

If we apply an eikonal approximation to such diagrams, the enhancement of soft Z bosons can be understood

$$\text{(Soft } Z \text{ emission)} : \frac{p^\mu}{p \cdot p_Z}$$

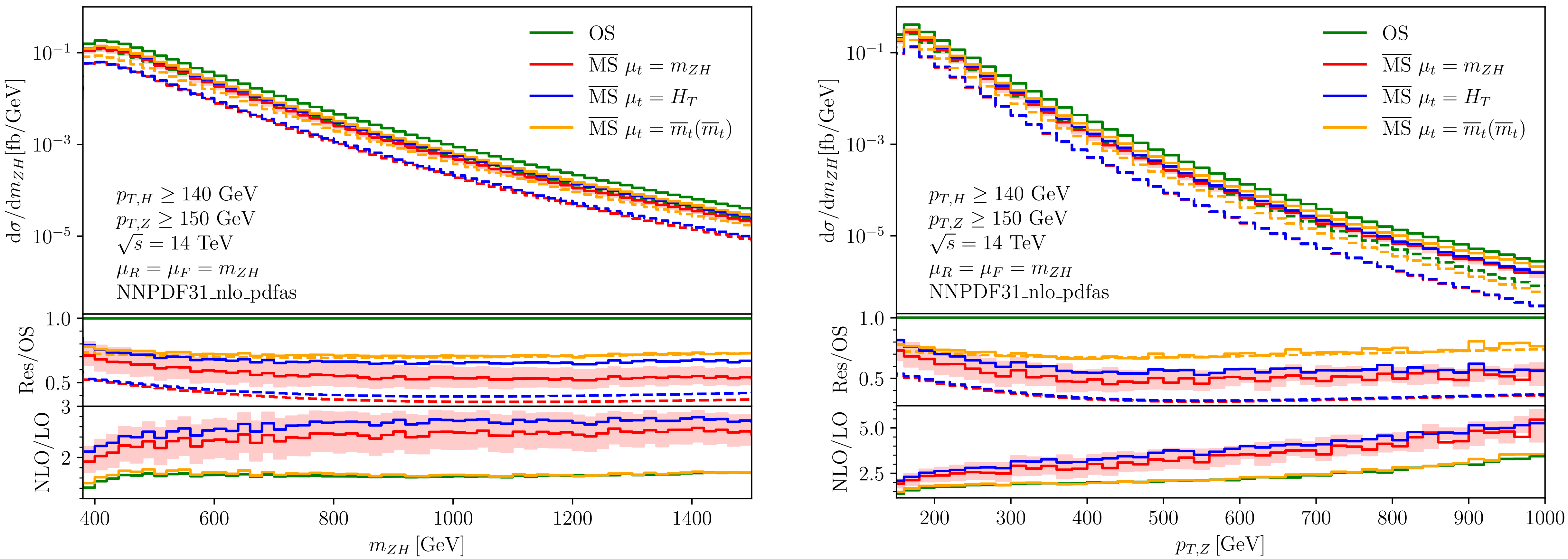
$$\text{(Soft } H \text{ emission)} : \frac{m_t}{p \cdot p_H}$$



Ratio for large radiator (transverse) momentum $\sim p_T / m_t \gg 1$

$gg \to ZH$: Mass Scheme Uncertainty

OS to $\overline{\mathrm{MS}}$ mass conversion: $m_t \to \overline{m}_t(\mu_t)\,[1 + \frac{\alpha_s}{4\pi} C_F \left\{4 + 3\log\left(\mu_t^2/\overline{m}_t^2(\mu_t)\right)\right\}]$



Observations @ $m_{ZH} = 1$ TeV

Large difference between different schemes

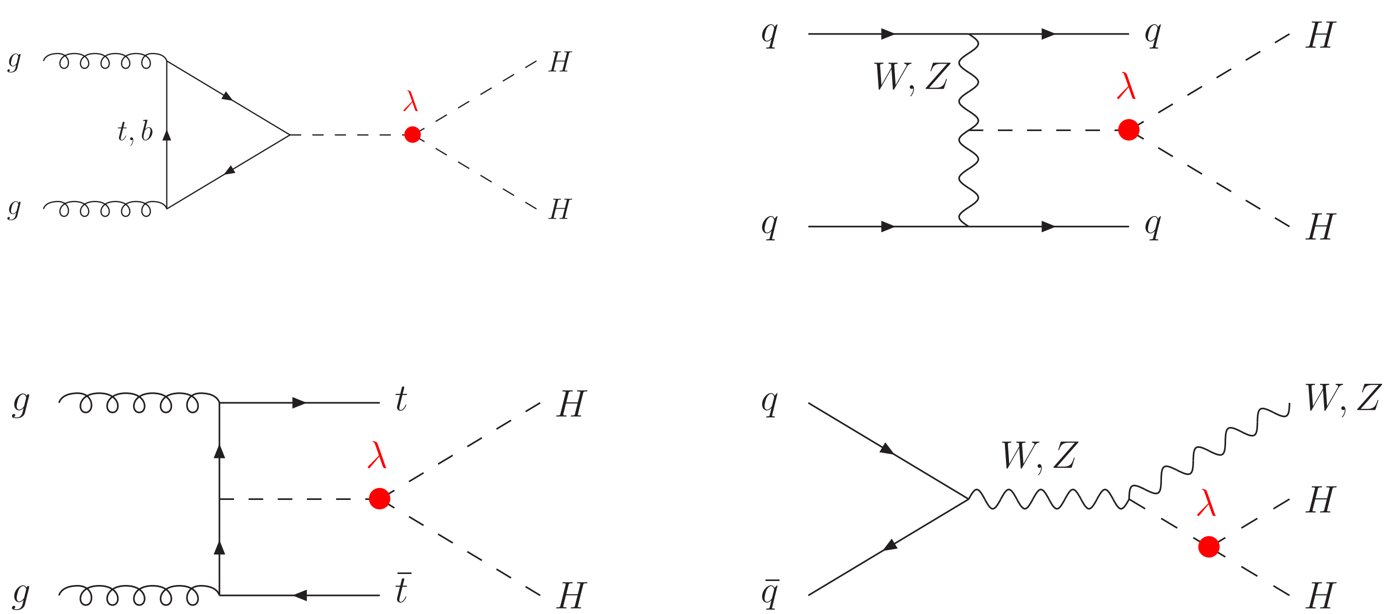
- LO: OS result ~2.9x $\overline{\mathrm{MS}}$ result
- NLO: Difference reduced ~1.9x

If taken as a theoretical uncertainty, this is larger than the scale uncertainty!

Such mass scheme uncertainties show up in other processes (e.g. HH, H*, HJ)

Baglio, Campanario, Glaus, Mühlleitner, (+Ronca) Spira, Streicher 18, (20); SPJ, Spira (Les Houches 19)

HH Production



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

HH: Why Measure it?

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

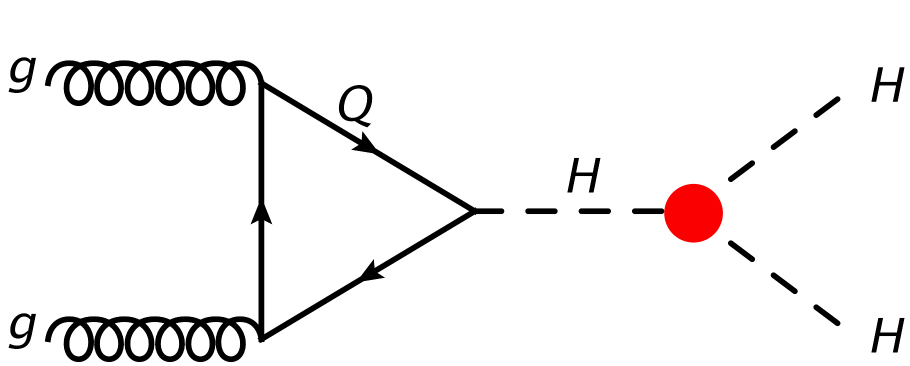
EW symmetry breaking

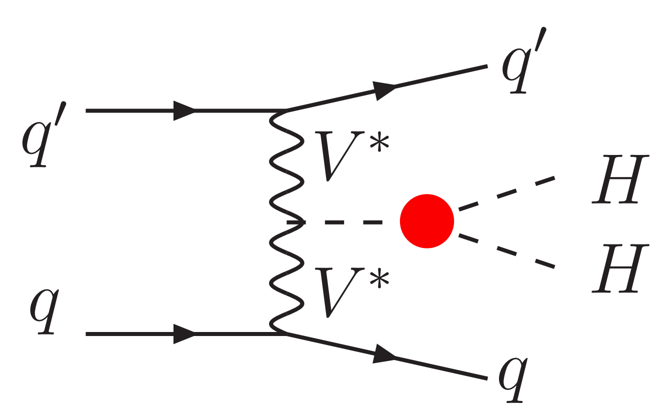
$$\mu^2 = \lambda v^2$$
$$m_H^2 = 2\lambda v^2$$

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

SM: self-couplings determined by m_H, v

EXP: need measurements to confirm/refute this





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

HH: Experimental Bounds

Very impressive experimental results

Combining 3 decay channels

+ using H and HH information

CERN-EP-2022-149

$$\mu_{HH} < 2.4 \ @ \ 95\,\%\,cl$$
$$-0.4 < \kappa_\lambda < 6.3 \ @ \ 95\,\%\,cl$$

HL-LHC projection

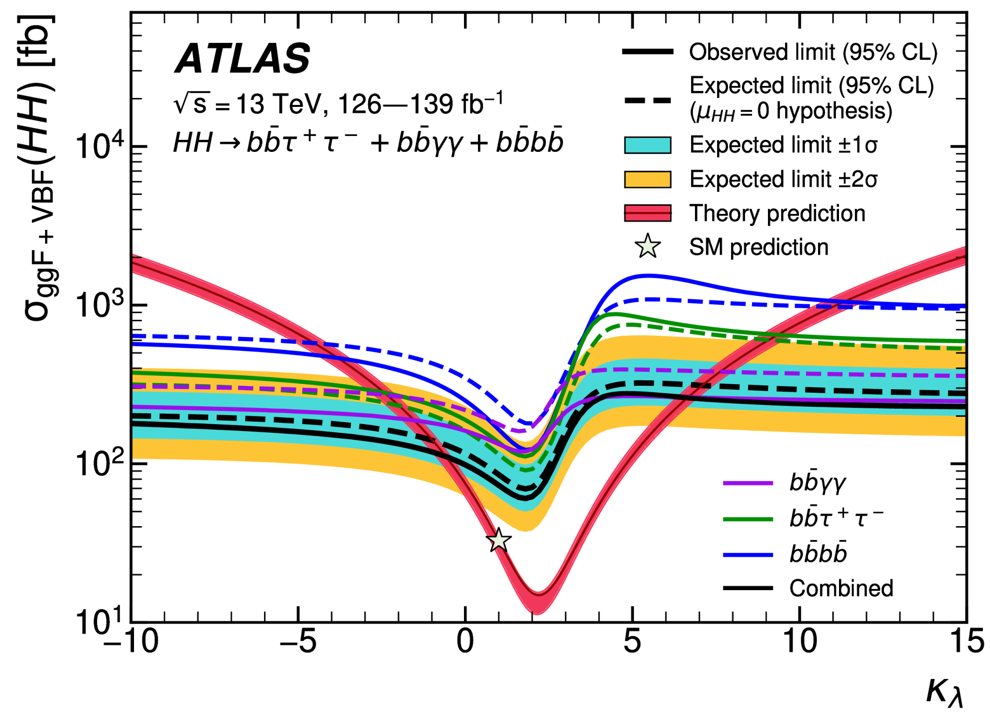
Using HH data from 3 channels

Assuming TH uncertainty is halved

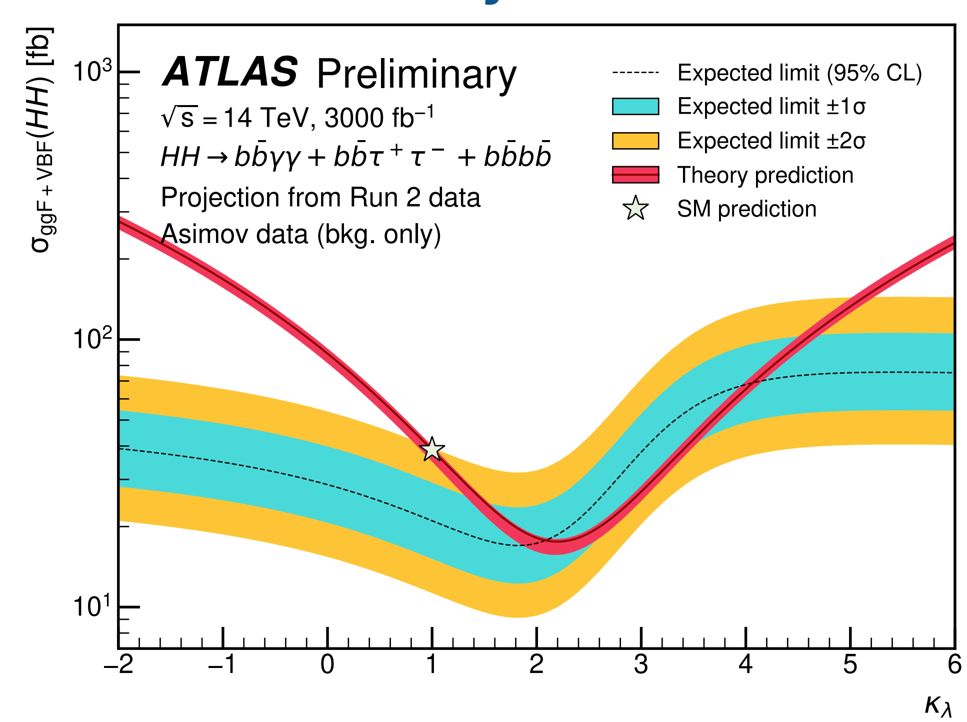
ATL-PHYS-PUB-2022-053

$$\mu_{HH} < 0.55 \ @ \ 95\,\%\,cl$$
$$0 < \kappa_\lambda < 2.5 \ @ \ 95\,\%\,cl$$

Current

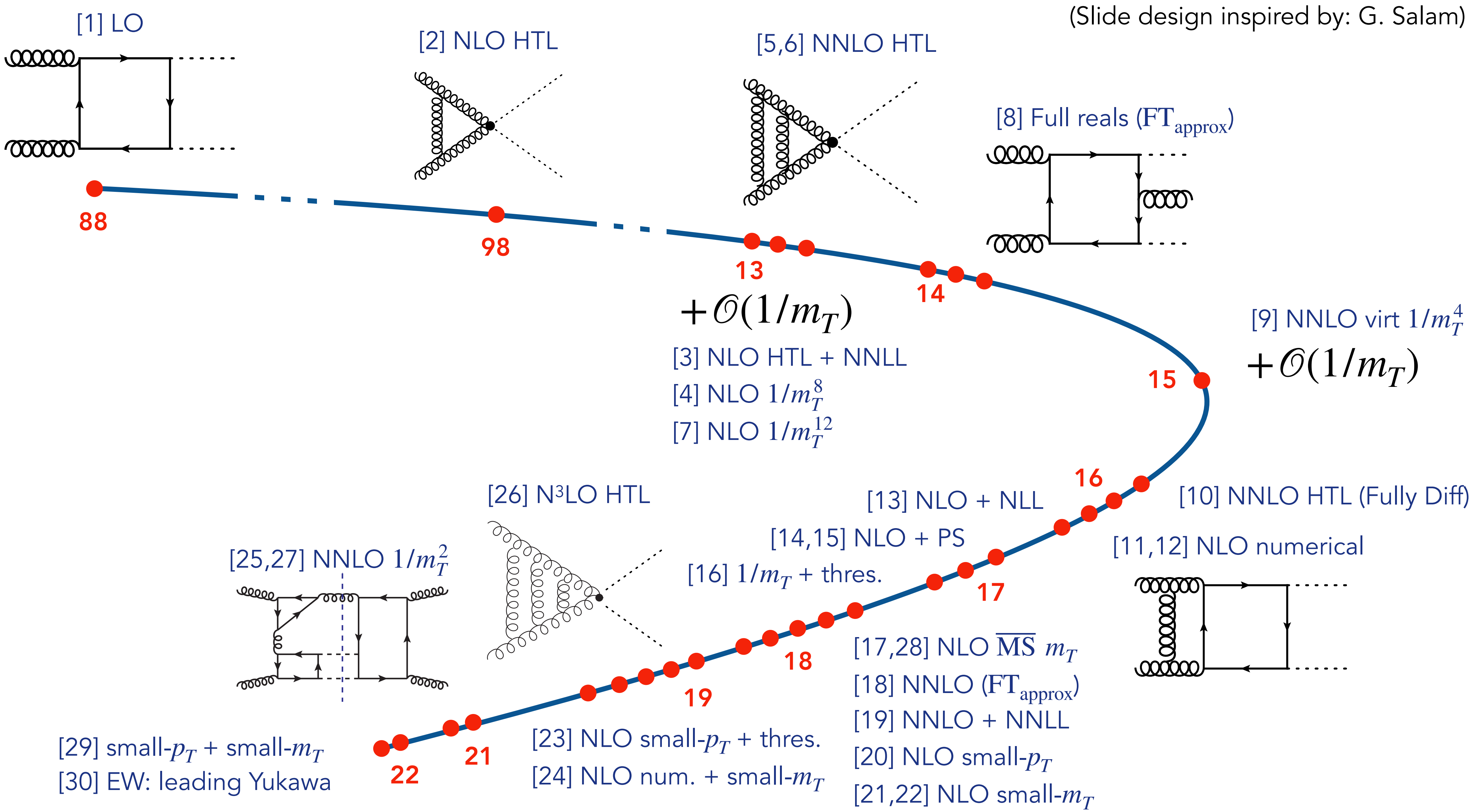


HL-LHC Projection



HH: Theory History

(Slide design inspired by: G. Salam)

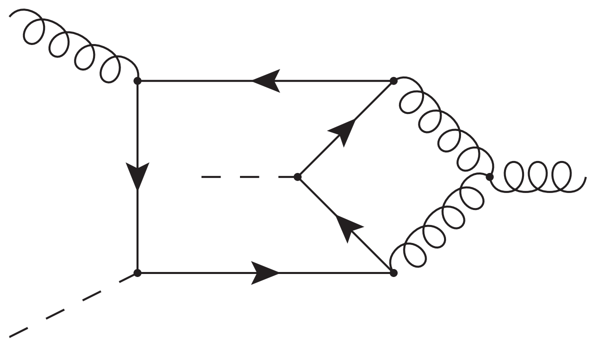


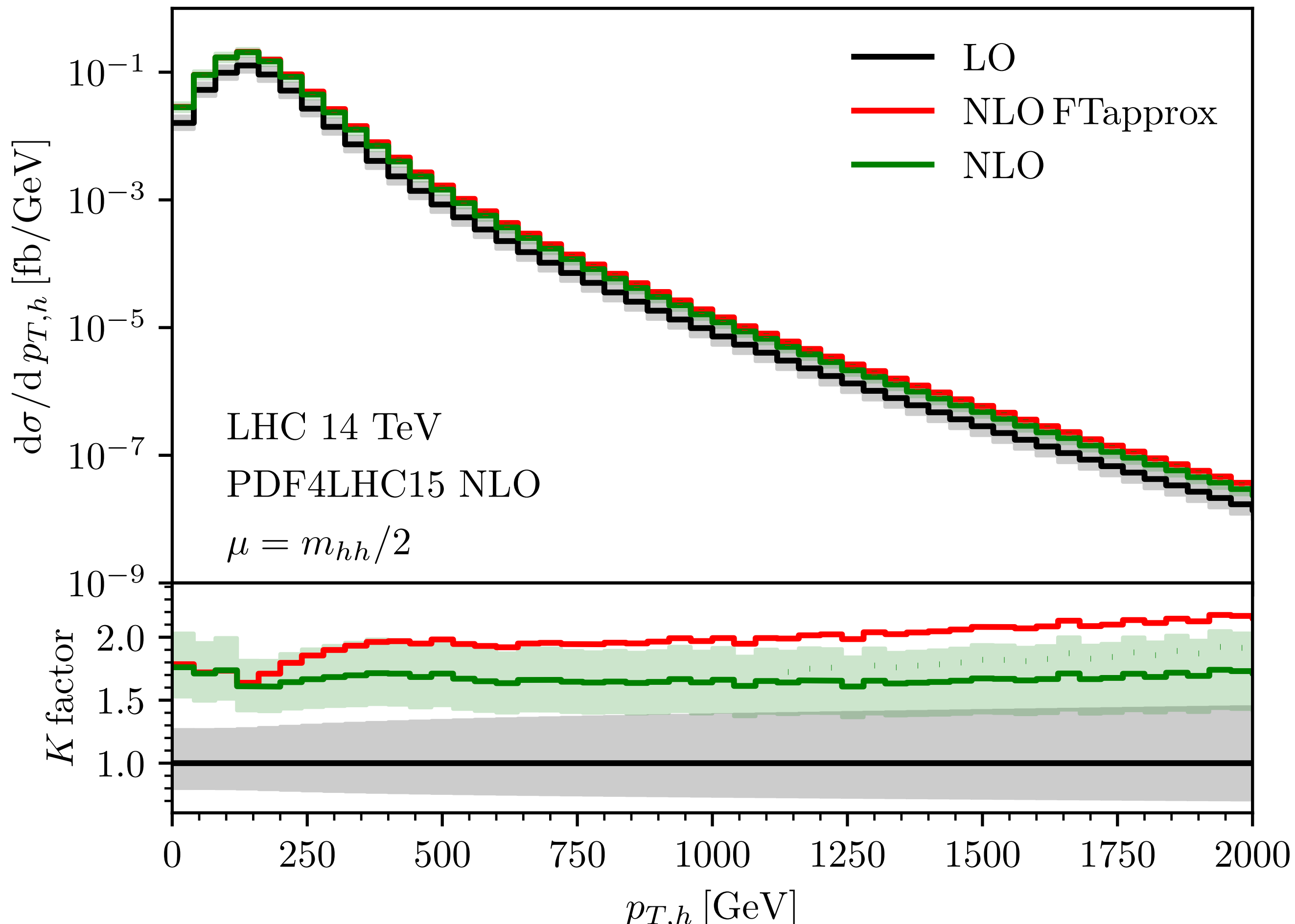
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, 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;

HH: NLO

Results including m_T are known up to NLO

(Numerical) Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18;
(Small m_T) Davies, Mishima, Steinhauser, Wellmann 18, 18;
(Numerical & Small m_T) Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, Wellmann 19





Davies et al. 19

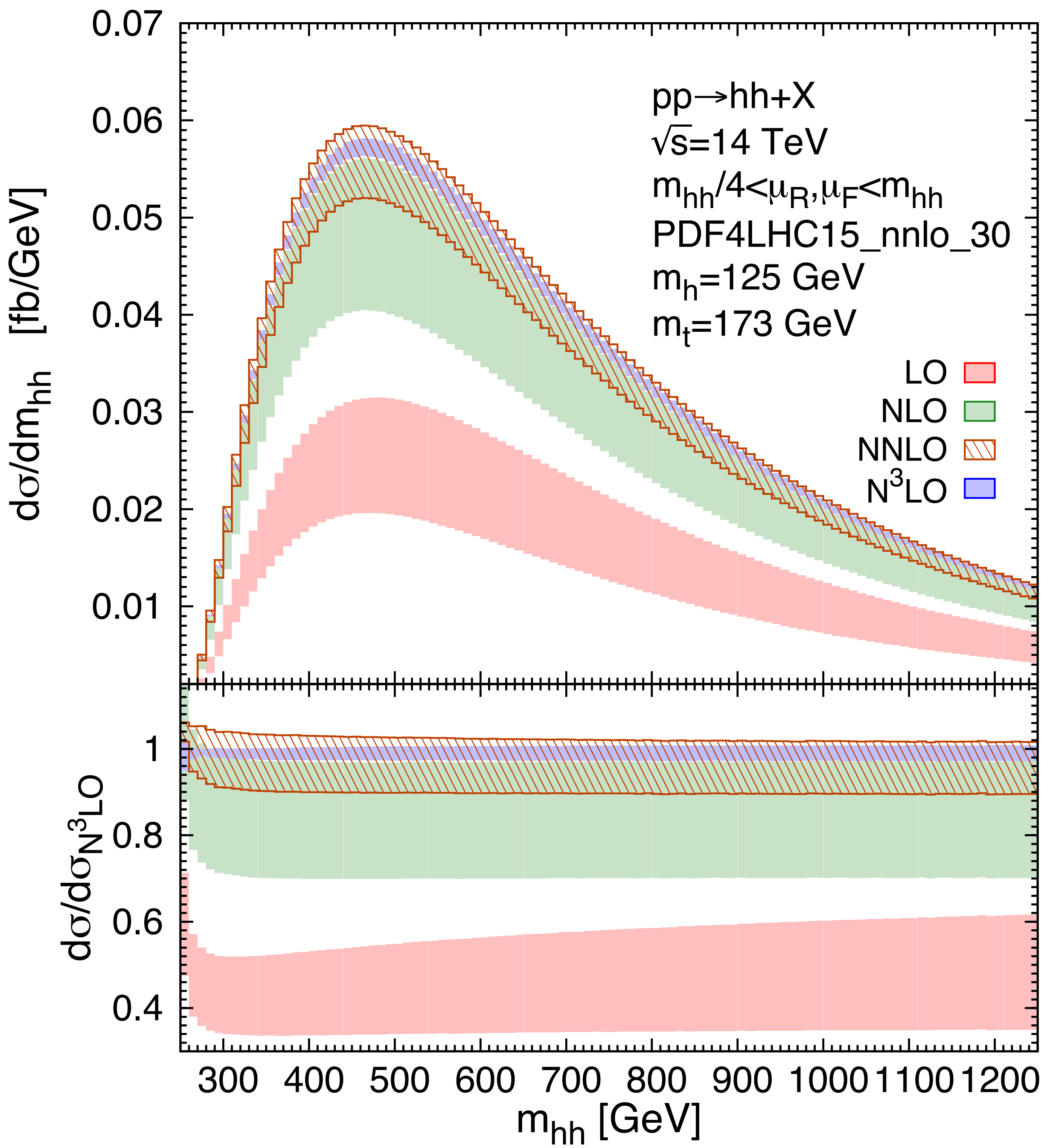
For HH production:

The NLO corrections are again large NLO/LO ≈ 1.7 and scale uncertainties ~halved

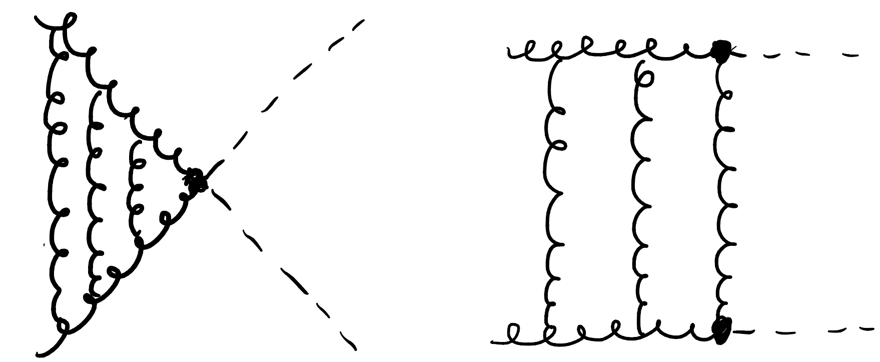
$\mathrm{FT}_{\mathrm{approx}}$ does not work so well above the the top-quark threshold

This is exactly the sort of situation depicted in our ``Cartoon 2''

HH: N³LO Heavy Top Limit



Chen, Li, Shao, Wang 19



Ingredients: N³LO H calculation

Anastasiou, Duhr, Dulat, Herzog, Mistlberger 15; Dulat, Lazopoulos, Mistlberger 18

\+ 2-loop 4-point functions

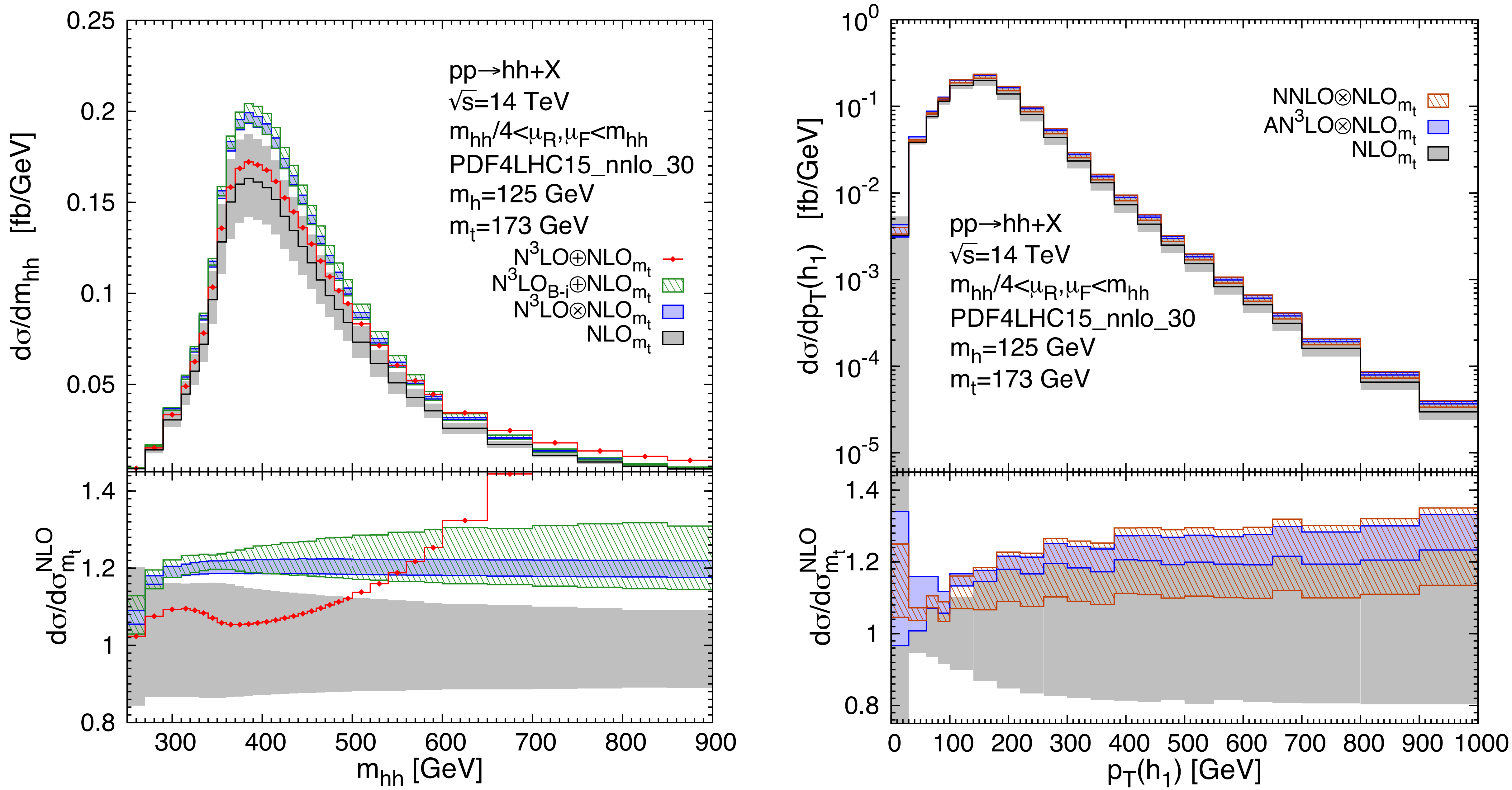
Banerjee, Borowka, Dhani, Gehrmann, Ravindran 18

order \ $\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^3LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4438^{+0.51\%}_{-1.8\%}$

Very mild scale dependence

HH: Beyond HTL @ N³LO

Top quark mass effects included in N³LO HTL (up to NLO)



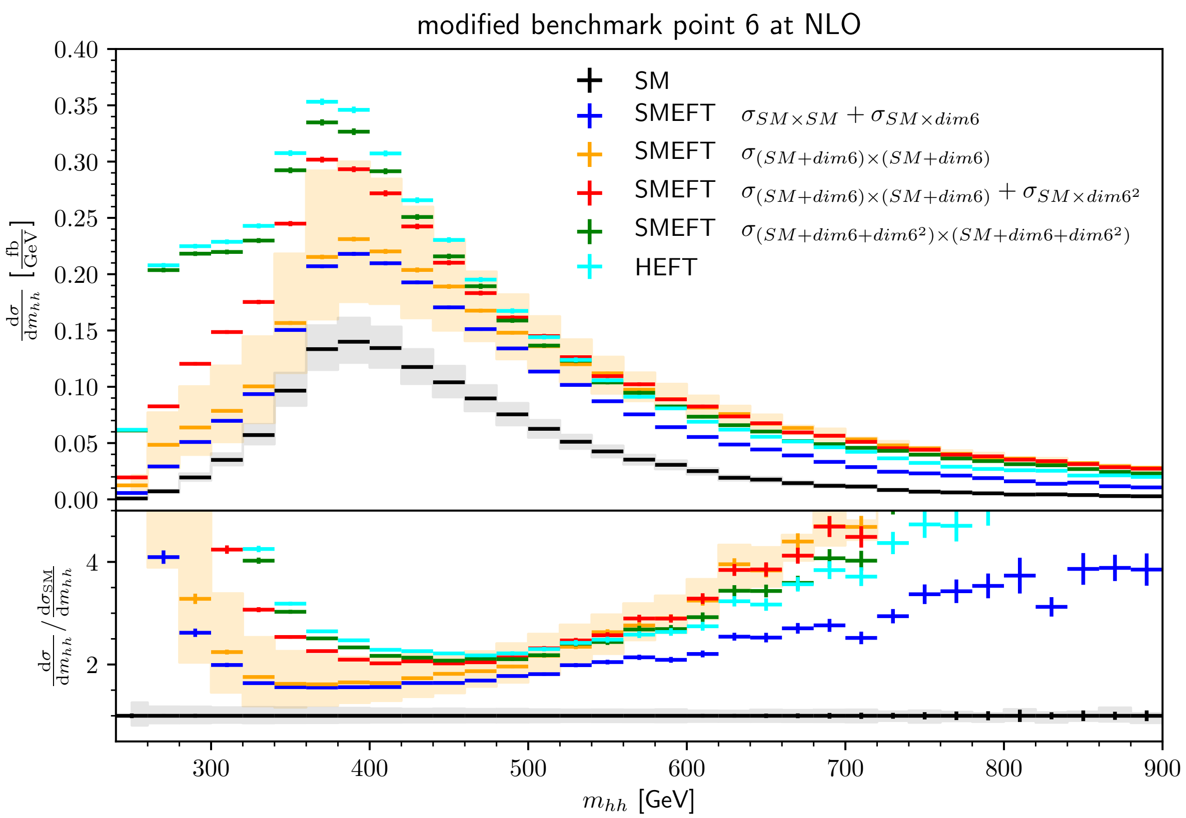
Chen, Li, Shao, Wang 19

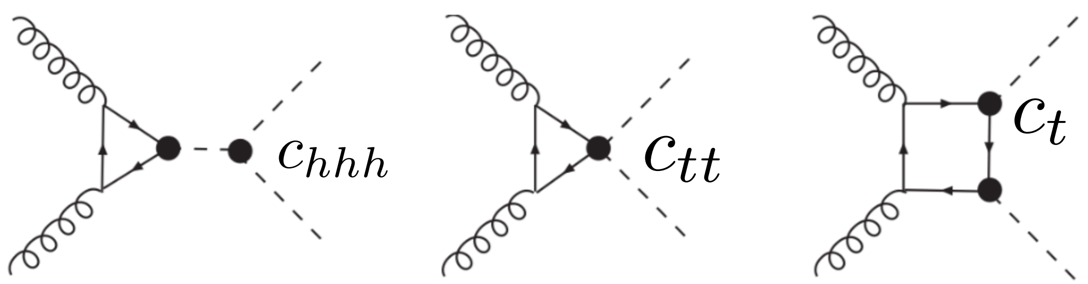
Results agree with NNLO result but with smaller scale uncertainty

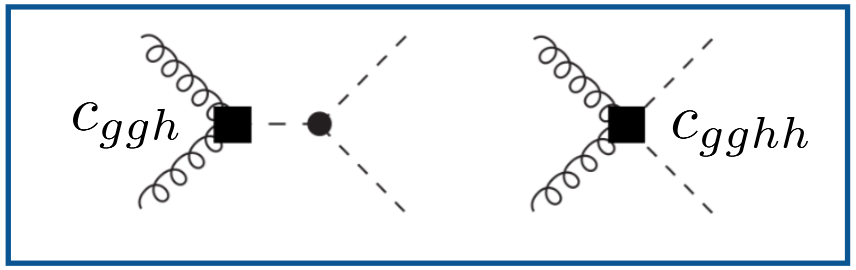
Results recently computed at N³LO + N³LL Ajjath, Shao 22

HH: EFT

Can leverage SM calculations @ NLO (NNLO,…) to compute also EFT results
(… though EFTs can be tricky HEFT/SMEFT, O_6/O_6^2, O_8, …)







Related in SMEFT

EFT results available in various approximations:

NLO (HEFT) Buchalla, Capozi, Celis, Heinrich, Scyboz 18;
+ PS Heinrich, SPJ, Kerner, Scyboz 20;
NLO + NNLO’ de Florian, Fabre, Heinrich, Mazzitelli, Scyboz 21
NLO (SMEFT) Heinrich, Lang, Scyboz 22;

HH: Mass Scheme Uncertainty

Comparing $gg \to HH$ and $gg \to ZH$ we see a different high-energy behaviour

$$A_i^{\text{fin}} = a_s A_i^{(0),\text{fin}} + a_s^2 A_i^{(1),\text{fin}} + \mathcal{O}(a_s^3) \quad \text{with} \;\; a_s = \alpha_s/4\pi$$

HH Davies, Mishima, Steinhauser, Wellmann 18; Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher 20

$$A_i^{(0)} \sim m_t^2 f_i(s,t)$$

$$A_i^{(1)} \sim 6 C_F A_i^{(0)} \log\left[\frac{m_t^2}{s}\right]$$

LO: m_t^2 from y_t^2

NLO: leading $\log(m_t^2)$ from mass c.t.

ZH Davies, Mishima, Steinhauser 20

$$A_i^{(0)} \sim m_t^2 f_i(s,t) \;\; \log^2\left[\frac{m_t^2}{s}\right]$$

$$A_i^{(1)} \sim \frac{(C_A - C_F)}{6} A_i^{(0)} \;\; \log^2\left[\frac{m_t^2}{s}\right]$$

LO: one m_t from y_t

NLO: leading $\log(m_t^2)$ not coming from mass c.t. (C_A)

Would be interesting to further understand these structures, similar power-suppressed mass logarithms were studied in single H Liu, Modi, Penin 22; Liu, Neubert, Schnubel, Wang 22

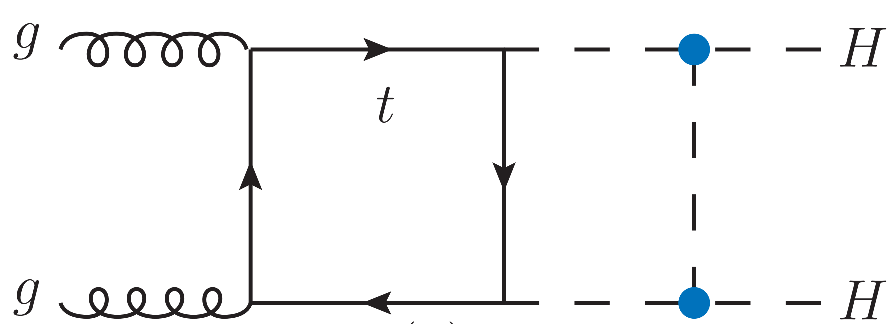
HH: EW Corrections

It is also interesting to explore the impact of EW corrections (in single Higgs for off-shell Higgs have $\pm 5\,\%$ impact) Actis, Passarino, Sturm, Uccirati 08

Richer structure in the SM and much richer structure in the context of EFT

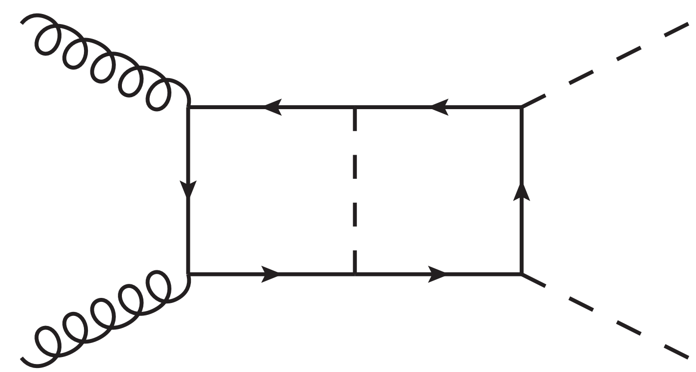
Partial 2-loop EW corrections known:

Involving λ_3 and λ_4



Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao 18

Leading top-Yukawa contributions



(Small m_T) Davies, Mishima, Schönwald, Steinhauser, Zhang 22
+ (EFT approach) Mühlleitner, Schlenk, Spira 22

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

Summary

Great progress in theory precision over the last few years

Uncertainties beyond scale variations are becoming increasingly relevant

Still plenty to do if you are bored!

See: Les Houches Wishlist 21

Thank you for listening

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

Backup

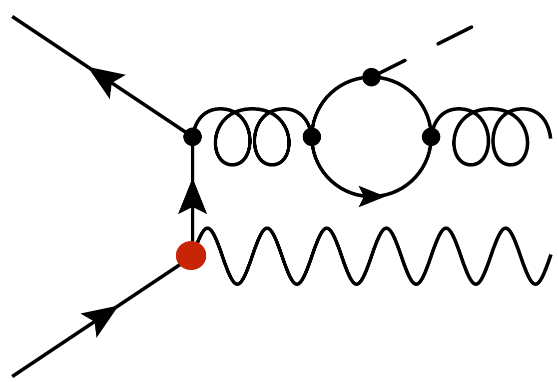
$gg \to ZH$: Real Emission Diagrams

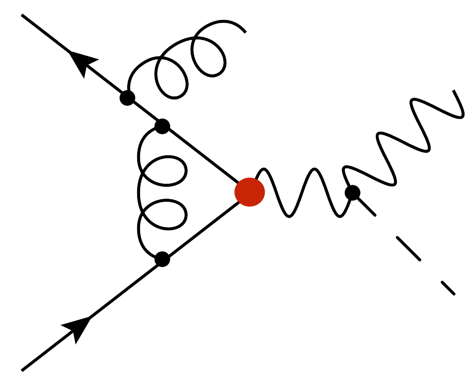
There is some **freedom** regarding which real diagrams we include in gg vs $q\bar{q}$

Must be careful not to double count when combining all channels for $pp \to ZH$

Our reals are evaluated using **GoSam** Cullen et al. 11,14

Diagrams excluded in our work





Left class of diagrams: separately UV/IR finite & gauge invariant

Previously studied in detail See e.g. Brein, Harlander, Wiesemann, Zirke 12

Right class of diagrams: belongs to real corrections to Drell-Yan (i.e. $q\bar{q}$)

Included in DY calculations

Brein, Djouadi, Harlander 03;
Ferrera, Grazzini, Tramontano 14;
See also: Kumara, Mandal, Ravindran 14

HH: Mass Scheme Uncertainty

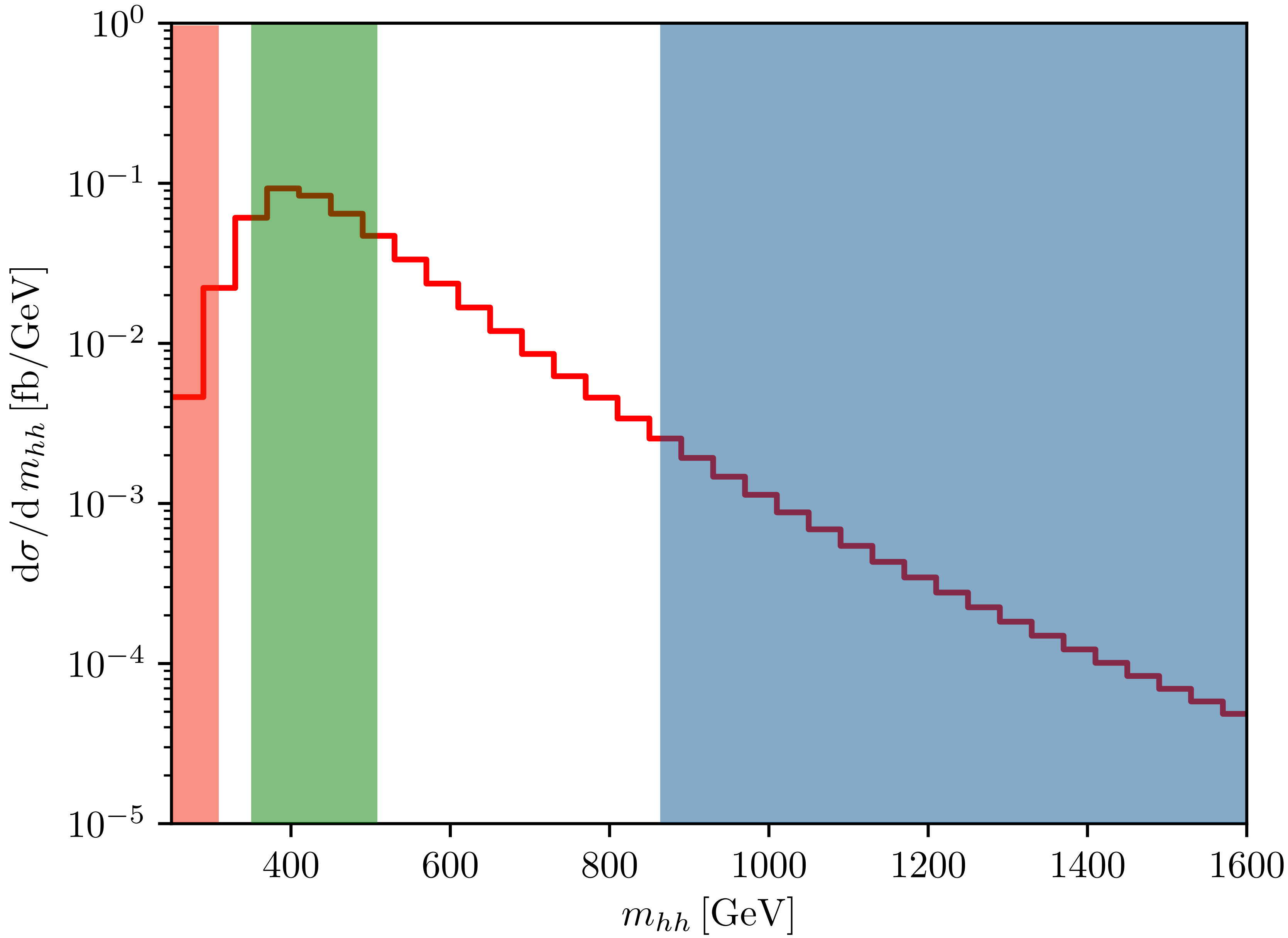
Combination of scale (μ_R, μ_F) and top mass scheme (OS / $\overline{\mathrm{MS}}$) studied
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 20

If we wish to take the **envelope** of the predictions as the uncertainty, then the two uncertainties should be added **linearly** (validated at NLO)

Scale (μ_R, μ_F)		**NLO Mass Scheme Unc.**		**Proposed Combination**
$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+3.0\%}_{-7.7\%}$ fb,		$\kappa_\lambda = -10: \quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%}$ fb,		$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+13\%}_{-14\%}$ fb,
$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+2.7\%}_{-7.5\%}$ fb,		$\kappa_\lambda = -5: \quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%}$ fb,		$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+13\%}_{-15\%}$ fb,
$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+2.5\%}_{-6.7\%}$ fb,		$\kappa_\lambda = -1: \quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%}$ fb,		$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+11\%}_{-16\%}$ fb,
$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+2.4\%}_{-6.1\%}$ fb,		$\kappa_\lambda = 0: \quad \sigma_{tot} = 61.22(6)^{+6\%}_{-12\%}$ fb,		$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+8\%}_{-18\%}$ fb,
$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+2.2\%}_{-5.0\%}$ fb,	+	$\kappa_\lambda = 1: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}$ fb,	=	$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}$ fb,
$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+2.1\%}_{-4.9\%}$ fb,		$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.2(1)^{+1\%}_{-23\%}$ fb,		$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+3\%}_{-28\%}$ fb,
$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+2.3\%}_{-5.1\%}$ fb,		$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 12.7(1)^{+4\%}_{-22\%}$ fb,		$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+6\%}_{-27\%}$ fb,
$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+2.7\%}_{-7.3\%}$ fb,		$\kappa_\lambda = 3: \quad \sigma_{tot} = 17.6(1)^{+9\%}_{-15\%}$ fb,		$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+12\%}_{-22\%}$ fb,
$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+4.9\%}_{-8.8\%}$ fb,		$\kappa_\lambda = 5: \quad \sigma_{tot} = 83.2(3)^{+13\%}_{-4\%}$ fb,		$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+18\%}_{-13\%}$ fb,
$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+4.2\%}_{-8.5\%}$ fb		$\kappa_\lambda = 10: \quad \sigma_{tot} = 579(1)^{+12\%}_{-4\%}$ fb		$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+16\%}_{-13\%}$ fb

@13 TeV

Tackling Mass Scheme Uncertainties



Low invariant mass:
expand in $1/m_t^2$
known to NNLO
Grigo, Hoff, Steinhauser 15;

Around Peak:
threshold expansion
Gröber, Maier, Rauh 17

High energy:
small-m_t expansion
known at NLO
Davies, Mishima, Steinhauser, Wellmann 18, 19

Options:

1) Try to understand structure of mass logarithms
2) Keep calculating
3) Other ideas (?)