Higgs physics: recent developments

Gudrun Heinrich
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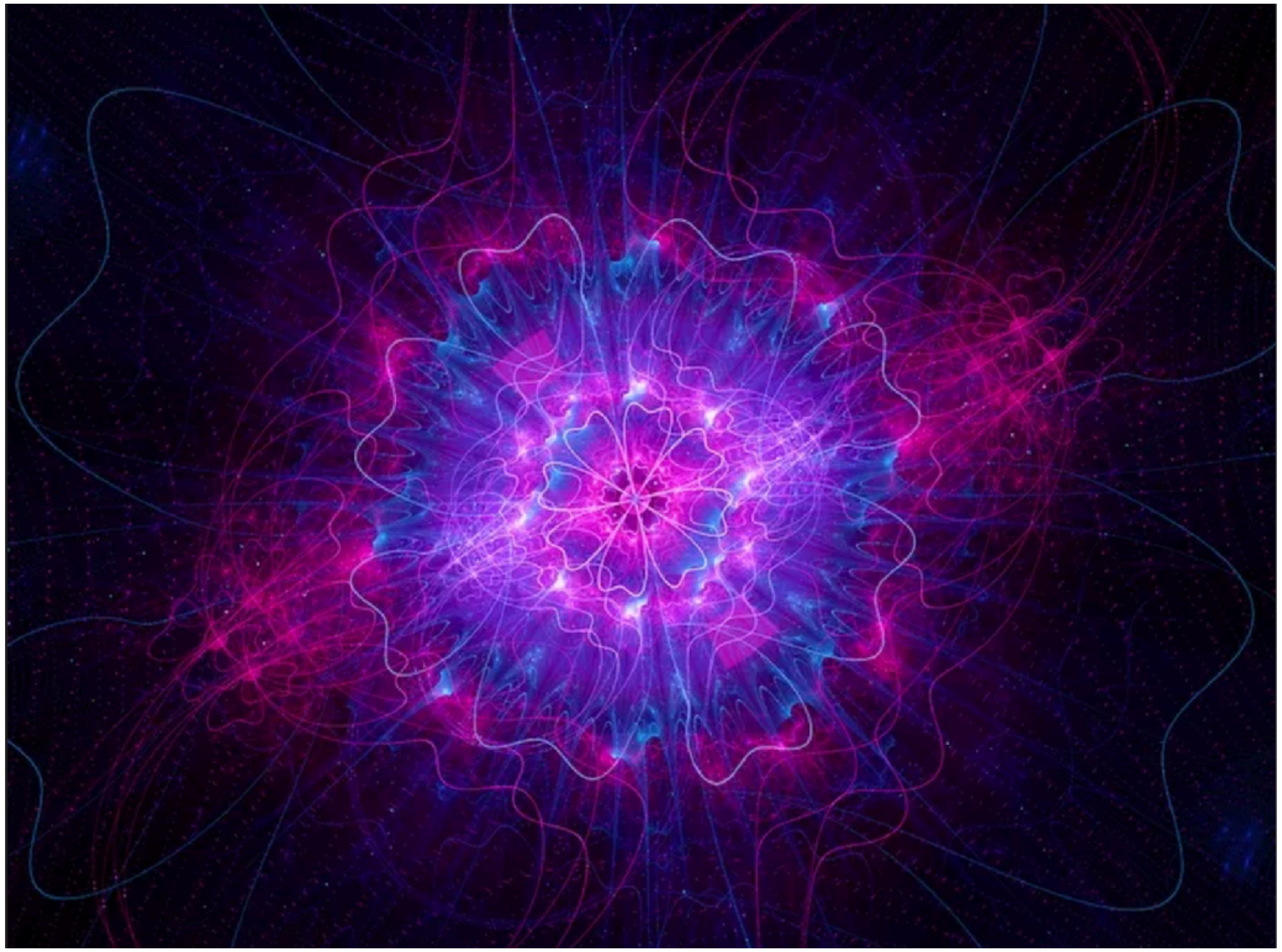
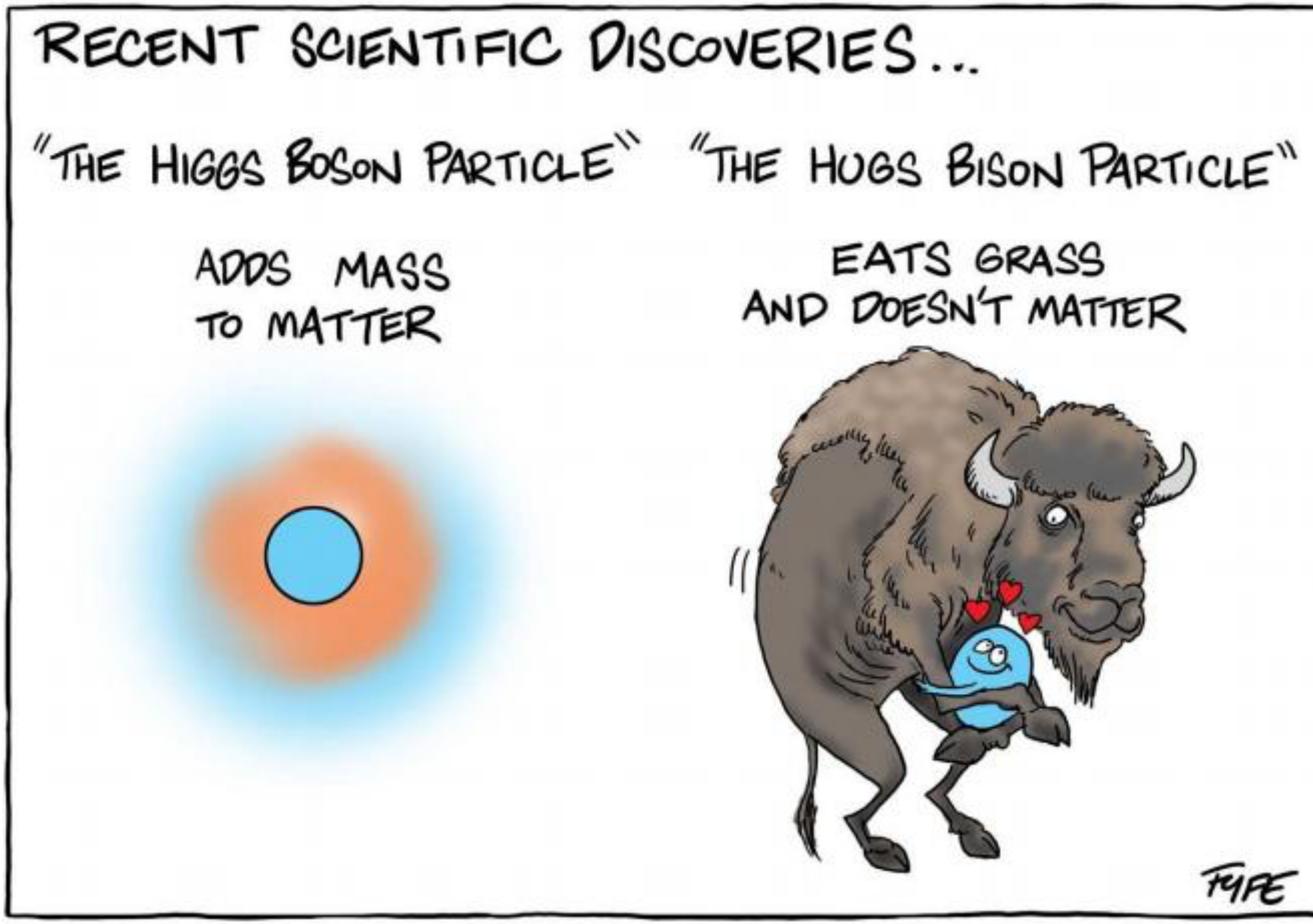


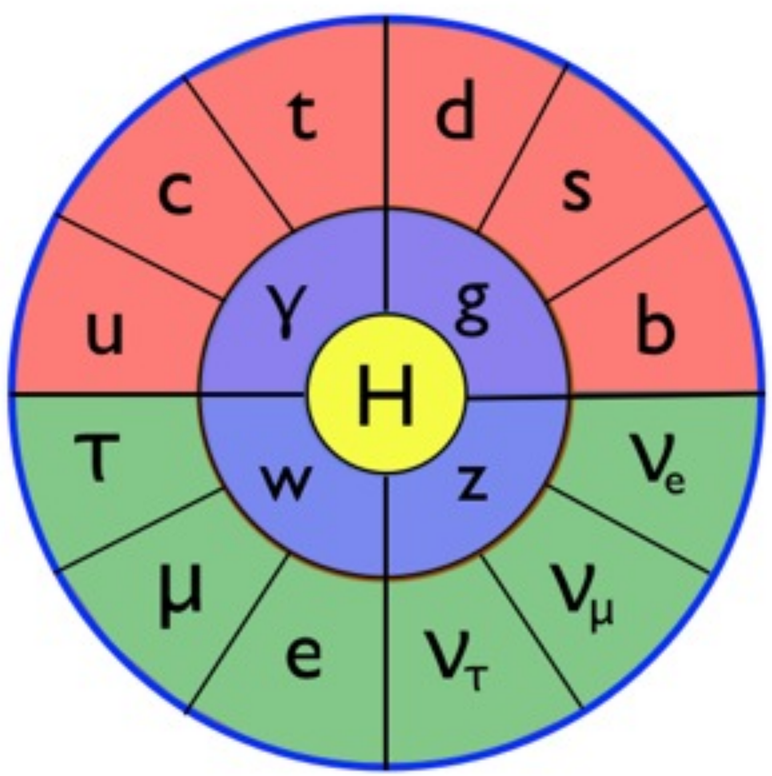
an artists's view of
the Higgs boson
Sakkmesterke
Shutterstock.com

Dipartimento di Fisica e Astronomia, Padova, 16.12.2020

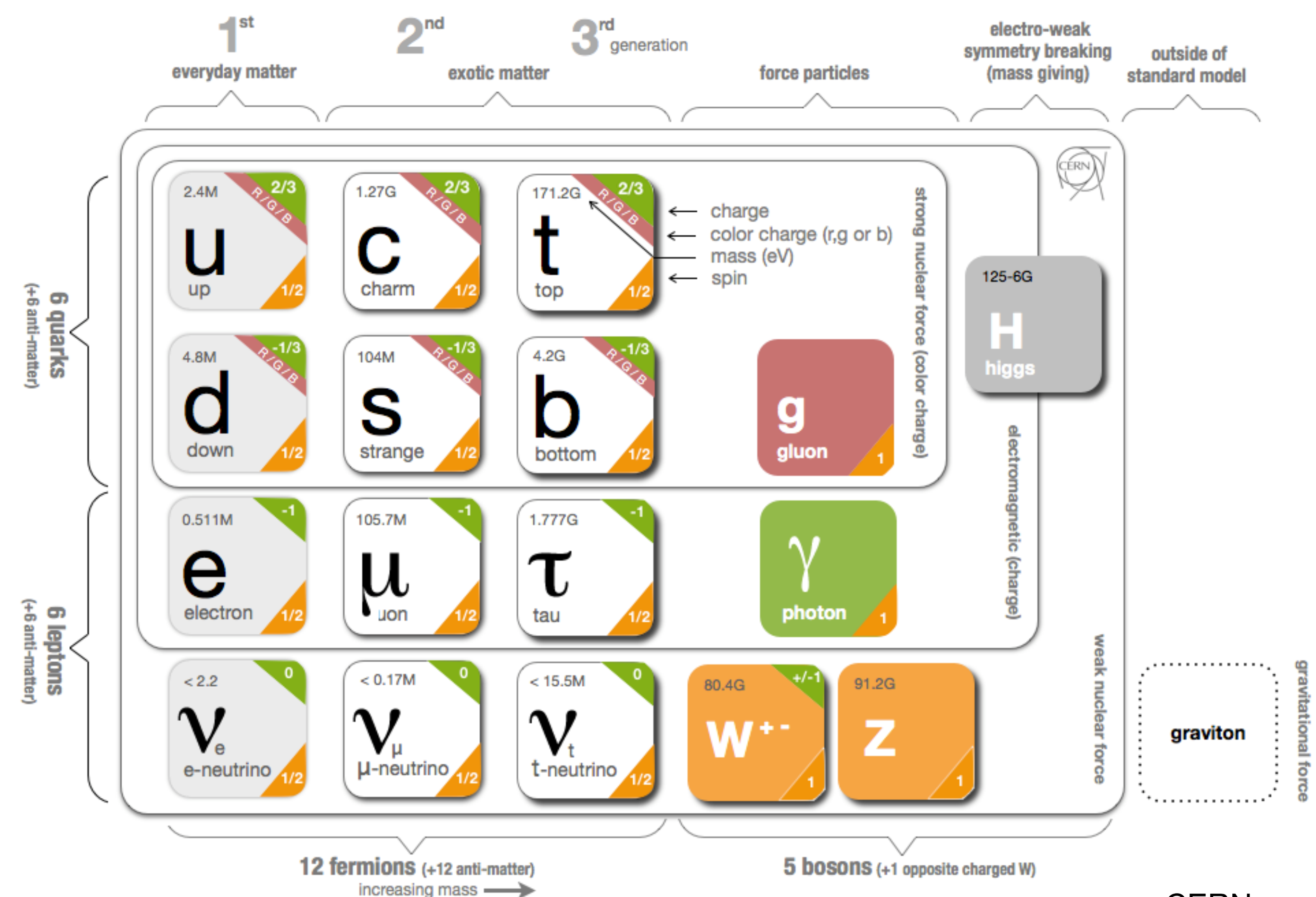
Karlsruhe Institute of Technology


RECENT SCIENTIFIC DISCOVERIES...
"THE HIGGS BOSON PARTICLE"
"THE HUGS BISON PARTICLE"
ADDS MASS TO MATTER
EATS GRASS AND DOESN'T MATTER
FYFE

Role of the Higgs boson



source: stanford.edu



source: CERN

the Higgs boson is central:

provides mass to all elementary particles (including itself)

or:

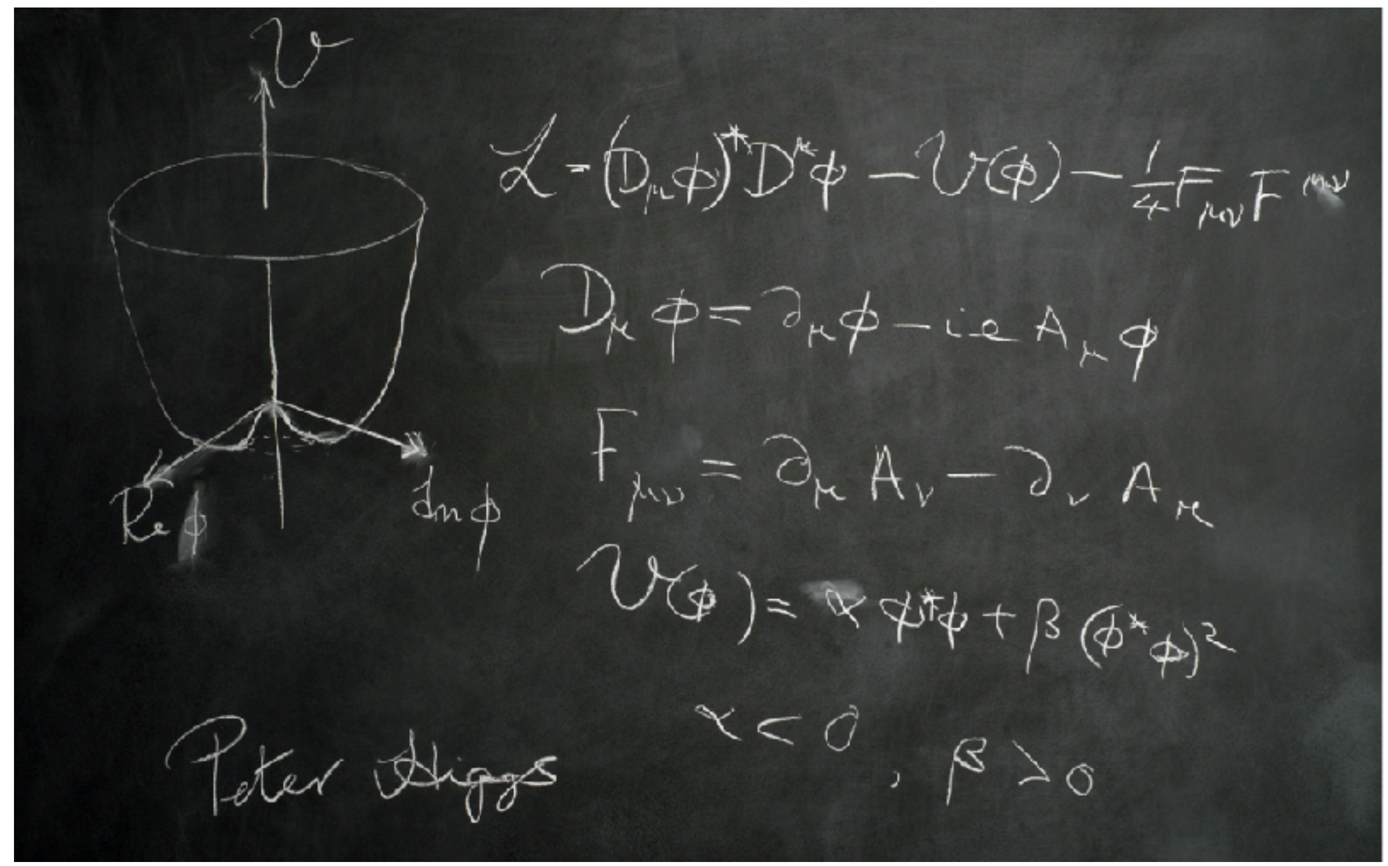
it suggests the picture is incomplete

Higgs-related questions

- Higgs properties (mass, CP, width)
- couplings to vector bosons and fermions → flavour physics
  neutrino masses
- Higgs potential (self-couplings)
- Higgs and the Universe
  (meta-stability, baryogengesis, portal to dark matter, …)
- the only elementary scalar? compositeness?

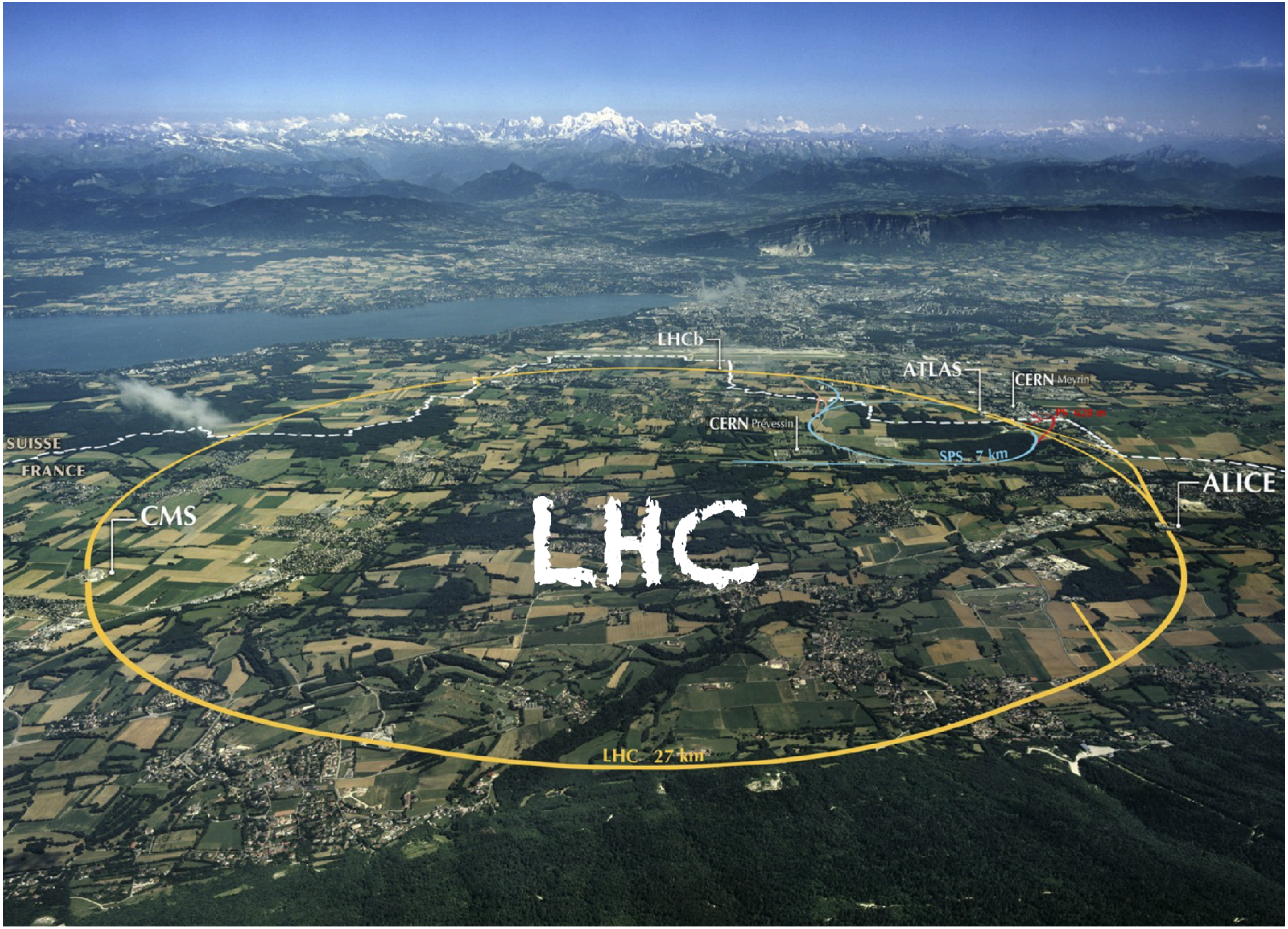
The Higgs sector might be a window to physics at higher scales

Higgs Sector

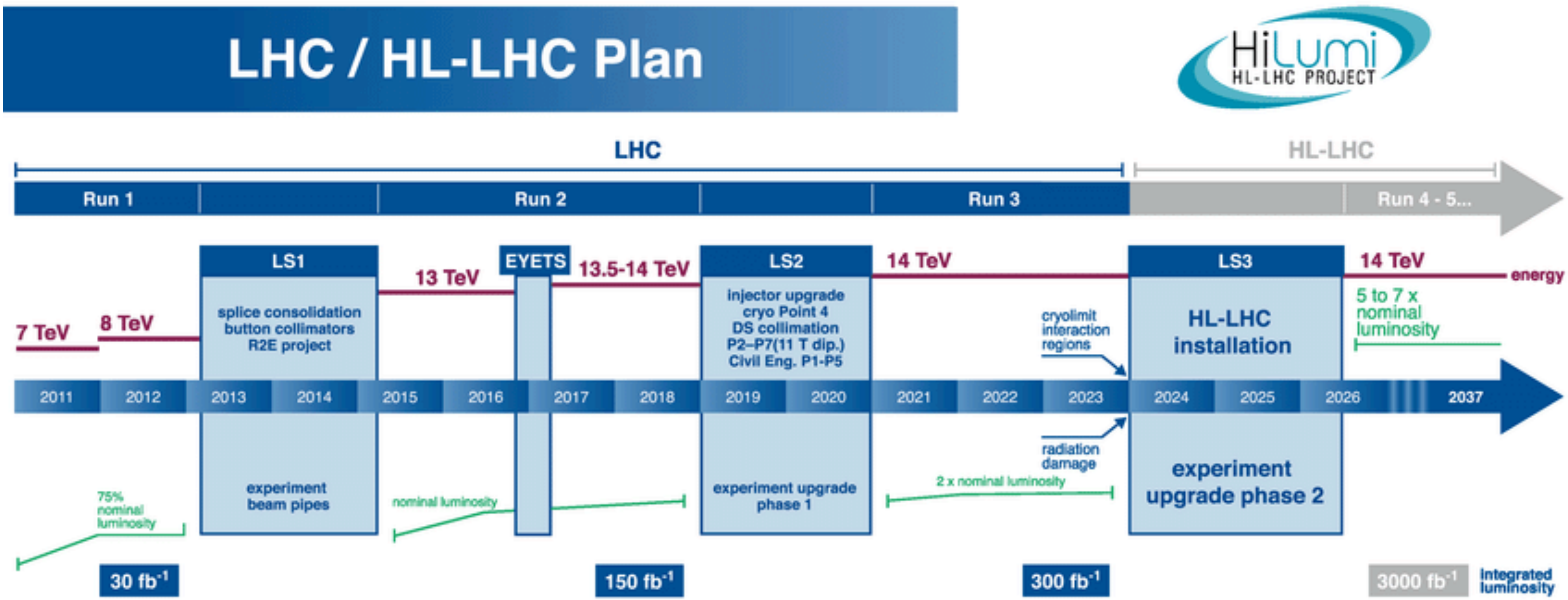


Large Hadron Collider

Large Hadron Collider



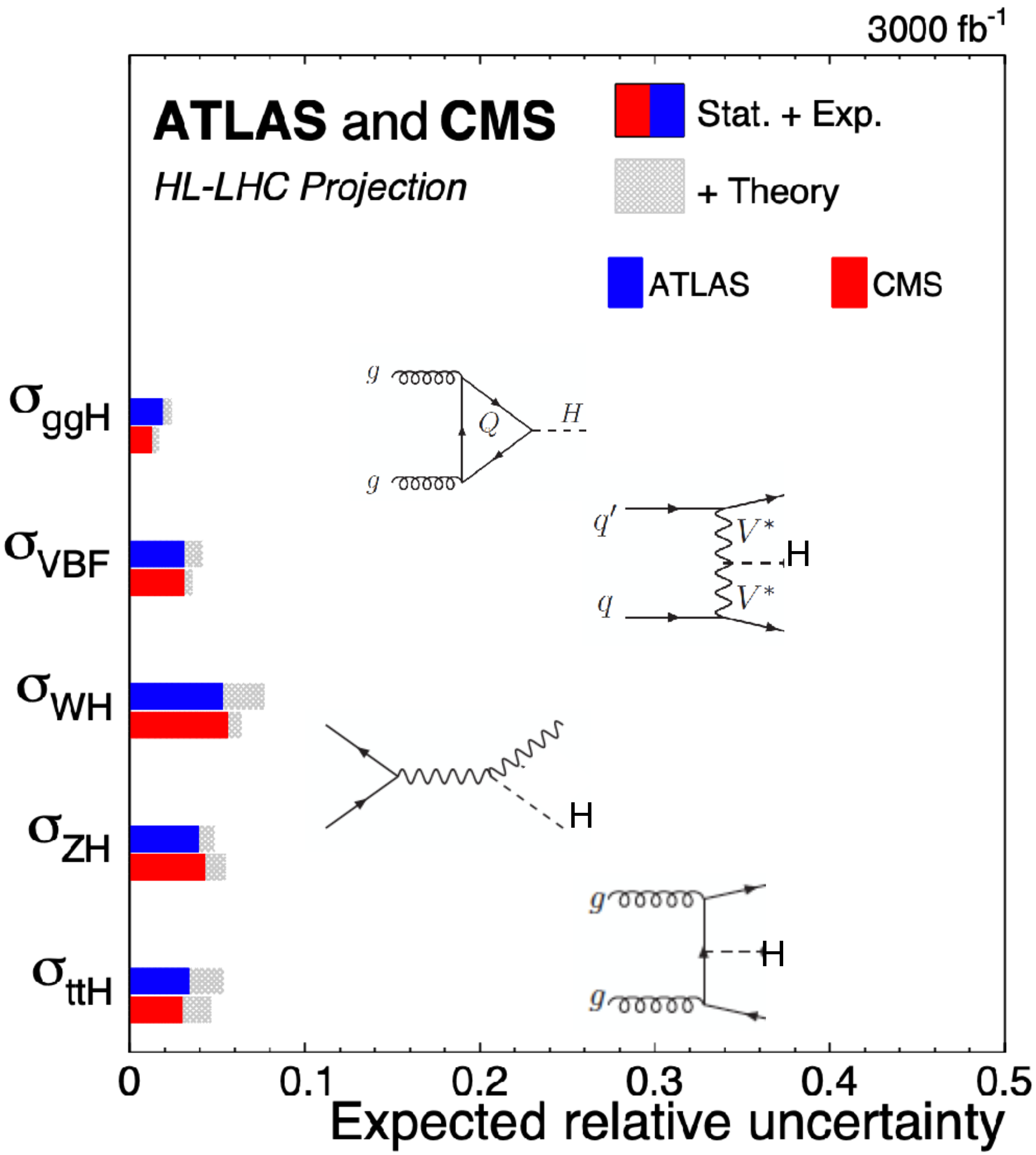
High-Luminosity LHC

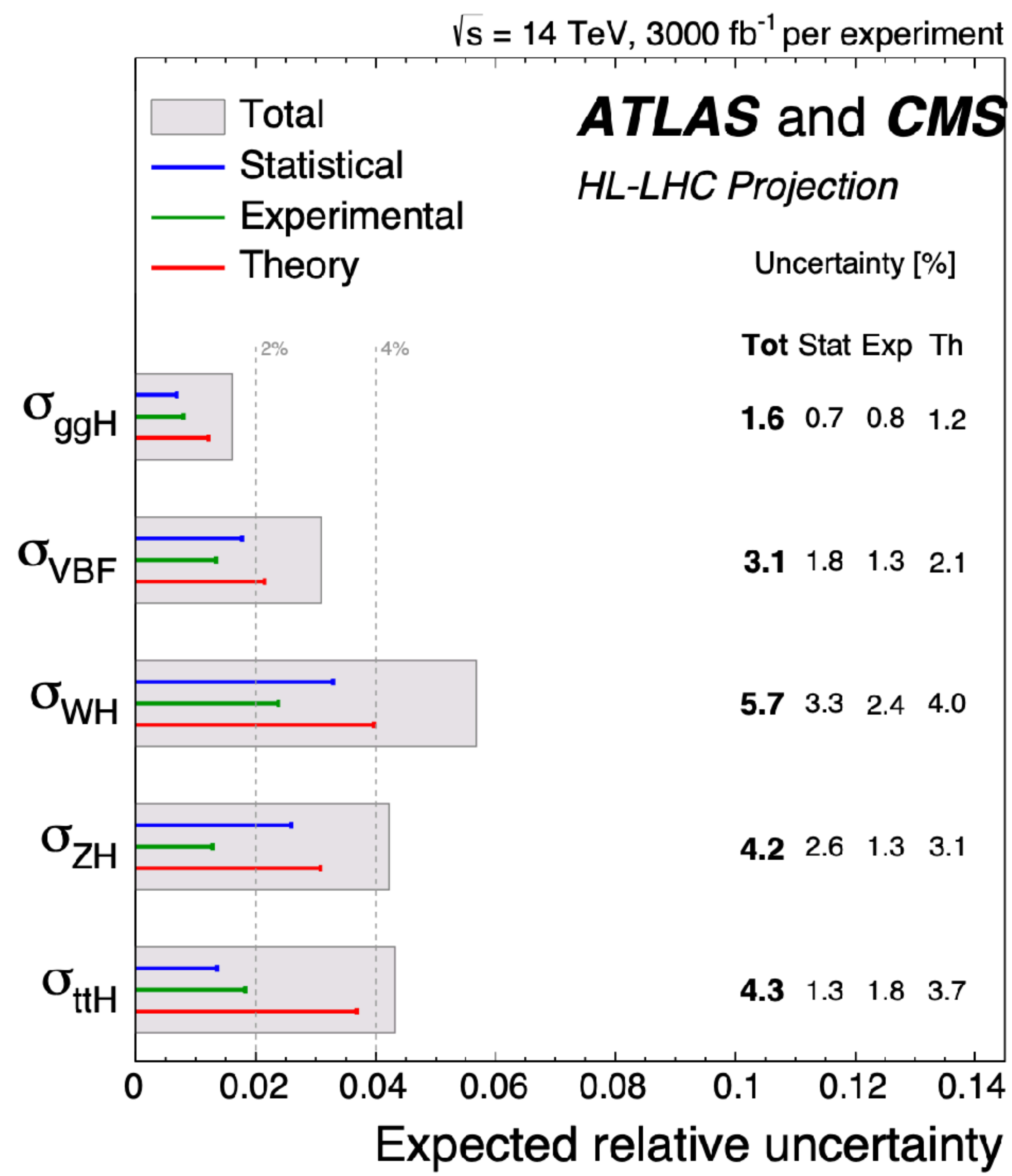


Luminosity

reaction rate $R = L \cdot \sigma(E)$ ← cross section

Higgs boson production: expected precision

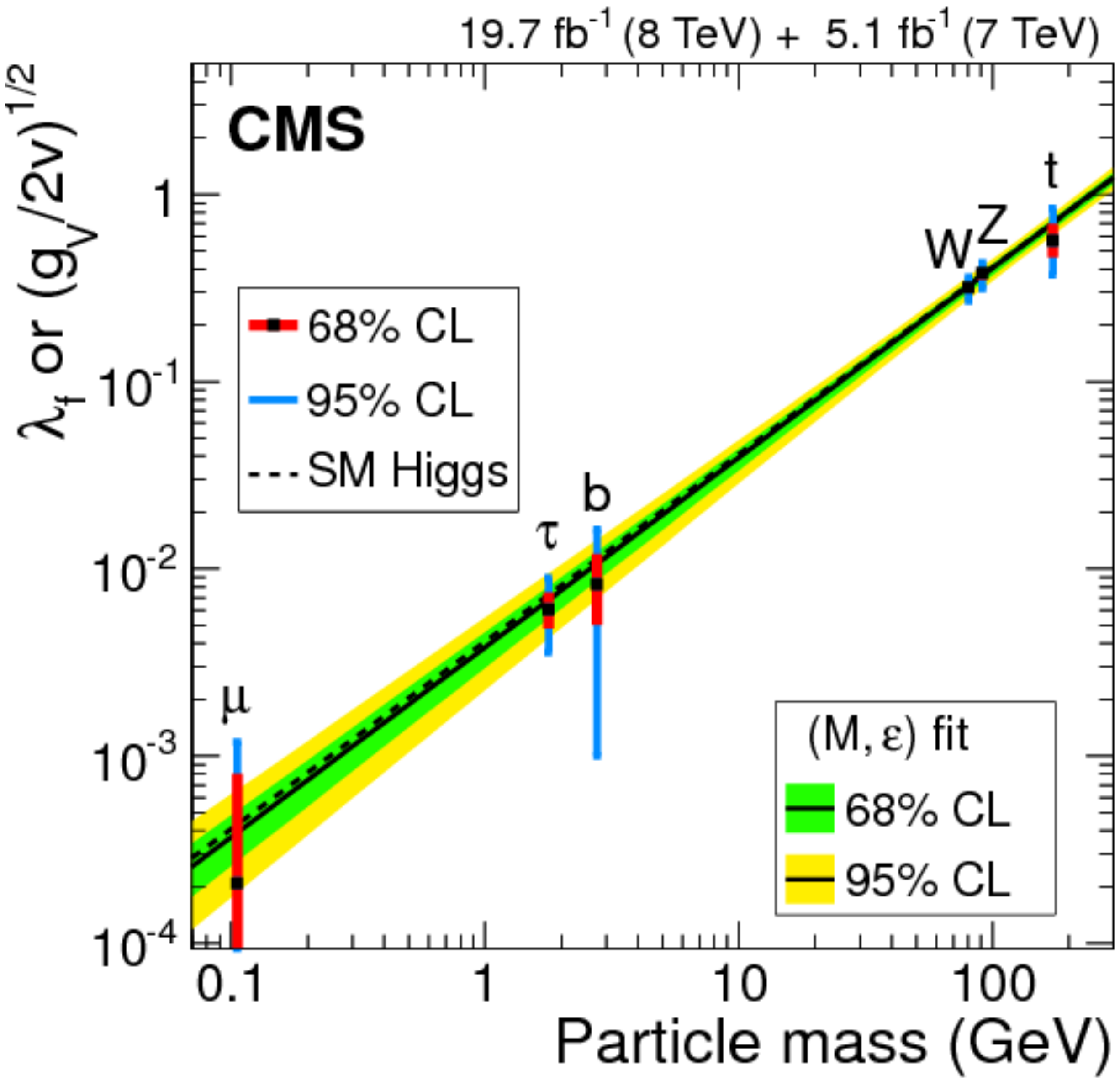




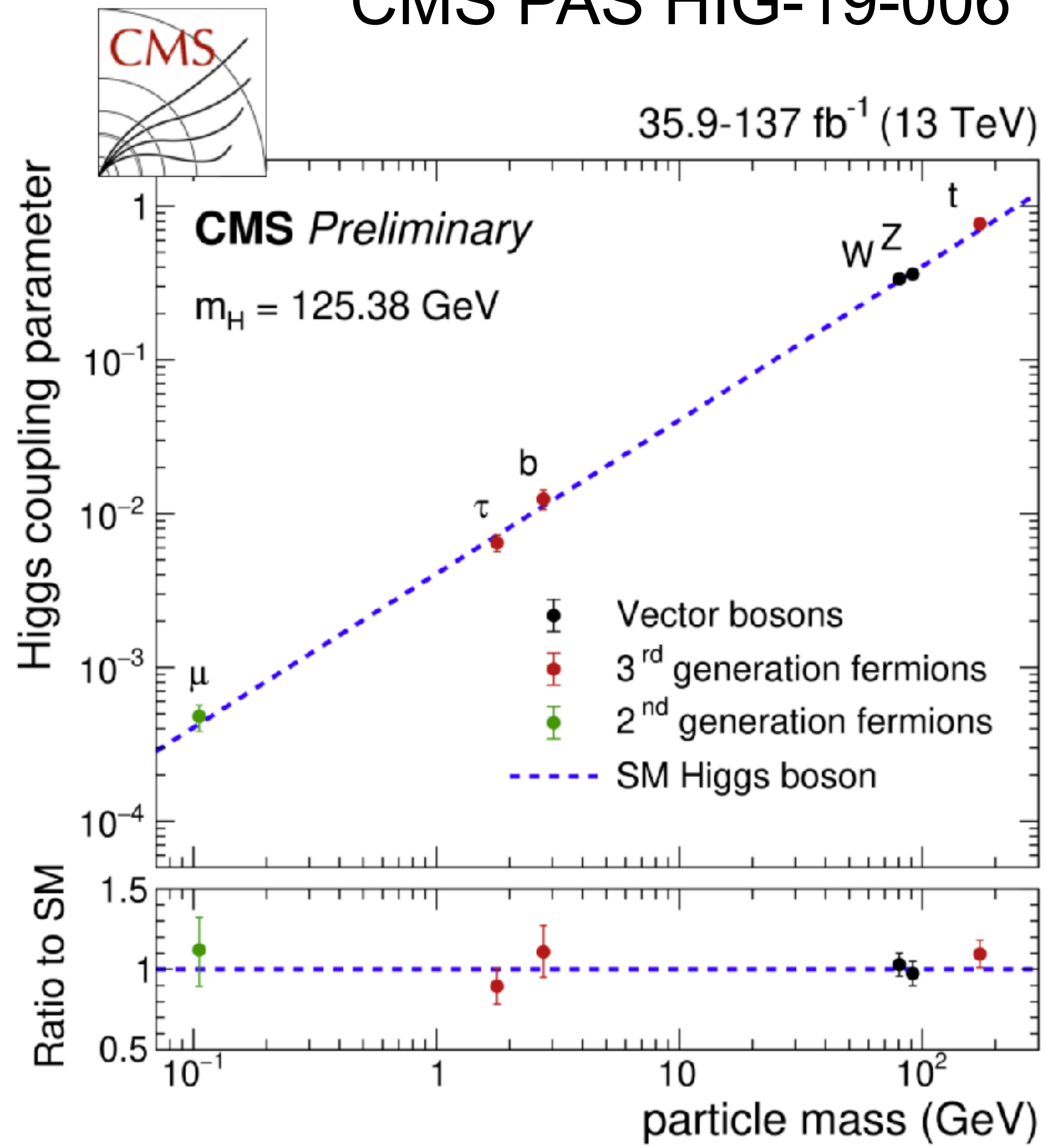
HL-HE CERN Yellow Report, 1902.00134

Higgs couplings

Run I



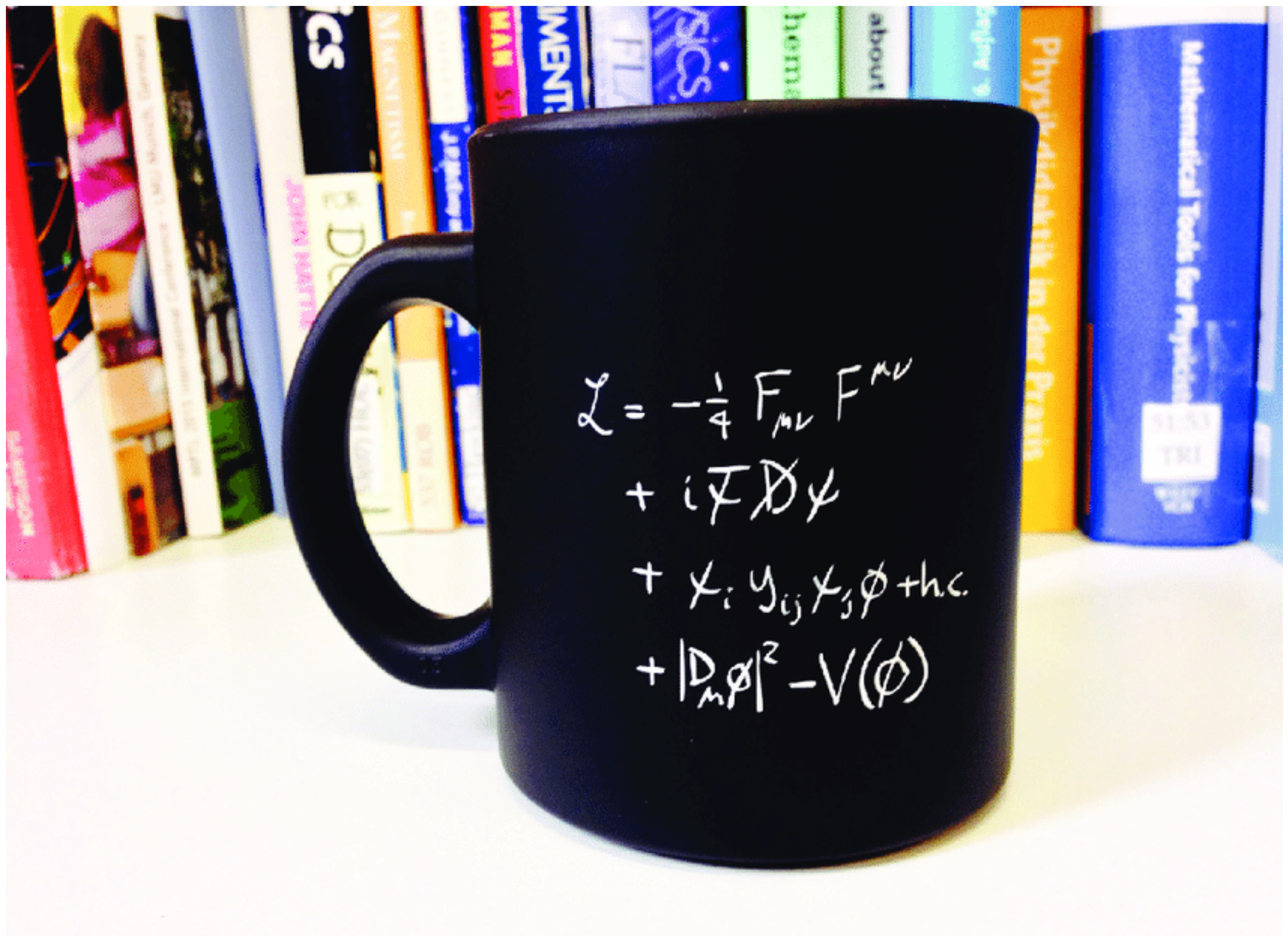
CMS PAS HIG-19-006



H?

enormous experimental progress

The Standard Model
~~in a nutshell~~ on a mug



where are the interactions with the gauge bosons?

$$D_\mu = \partial_\mu - igW_\mu^a \tau^a - ig' B_\mu Y - ig_s G_\mu^a T^a$$

Higgs sector

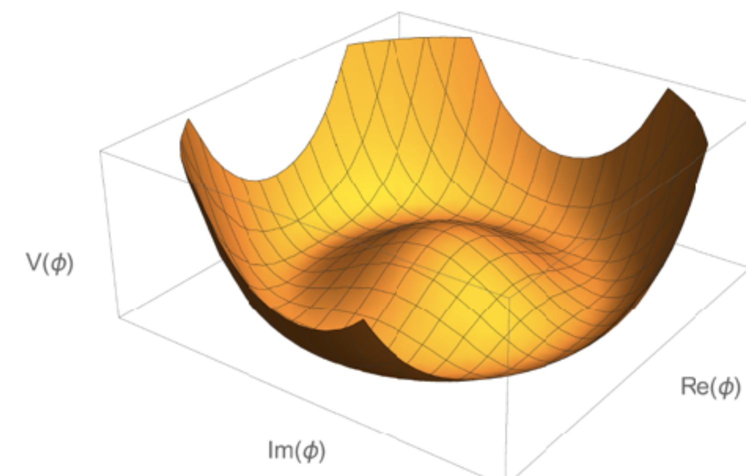
the assumption $$V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_3 \end{pmatrix}$$

$$\langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

↓ spontaneous symmetry breaking

$$V(h) \sim \frac{1}{2}\underbrace{(2v^2\lambda)}_{m_h^2}\, h^2 + v\lambda\, h^3 + \frac{\lambda}{8}\, h^4$$



the elegant $$(D_\mu\Phi)^\dagger(D^\mu\Phi) \rightarrow \quad M_{W^\pm} = \frac{v}{2}g\,, \; M_Z = \frac{v}{2}\sqrt{g^2 + g'^2}$$

the ugly $$\mathcal{L}_{\rm Yuk} = -Y^e_{ij}\bar{L}^i\Phi e^j_R - Y^d_{ij}\bar{Q}^i\Phi d^j_R - Y^u_{ij}\bar{Q}^i\Phi^c u^j_R + \text{h.c.}$$

$m_i \sim y_i \cdot v$ ad hoc mass hierarchies

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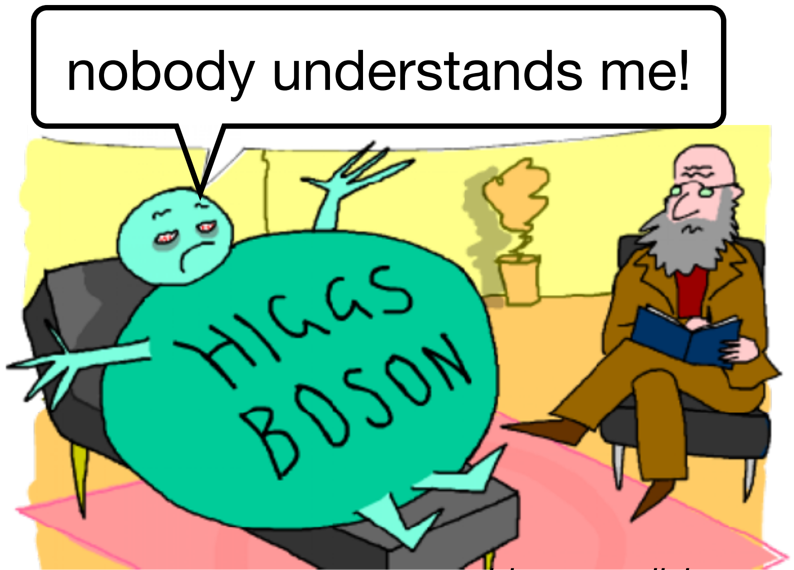
Higgs sector



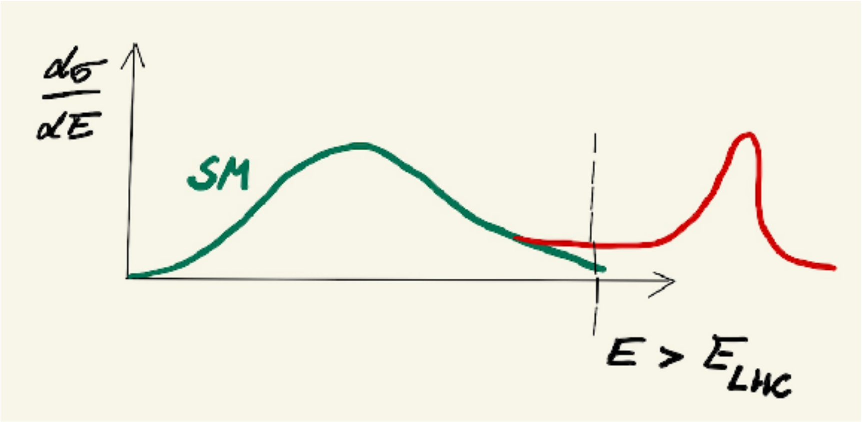
blog.gymglish.com

we are just at the beginning …

How can we learn more?

- precision measurements (and -calculations)
  - test specific BSM models
  - EFT parametrisations of new physics effects

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d=6}^{\infty} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$



$$\Rightarrow \quad (\sigma \times BR) = (\sigma \times BR)_{\text{SM}} (1 + \Delta)$$

for typical energy scale E of measurement: $\Delta \sim \left(\frac{E}{\Lambda}\right)^2$

The SM as an effective field theory

$$\Delta \sim \left(\frac{E}{\Lambda}\right)^2$$

example Higgs production: typical energy scale $E \sim v = 0.25\,\mathrm{TeV}$

$$\Rightarrow \Delta \sim (0.25)^2 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \sim 0.06 \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

$\Rightarrow$ to generate $\gtrsim$ 1% deviations need $\Lambda \lesssim 2.5\,\mathrm{TeV}$

boosted Higgs, tails of distributions: $E \sim 1\,\mathrm{TeV}$

$\Rightarrow$ with $\Lambda = 2.5\,\mathrm{TeV}$ we achieve $\Delta = 1/(2.5)^2 \simeq 16\%$

$\Rightarrow$ off-shell measurements, tails of distributions very important!

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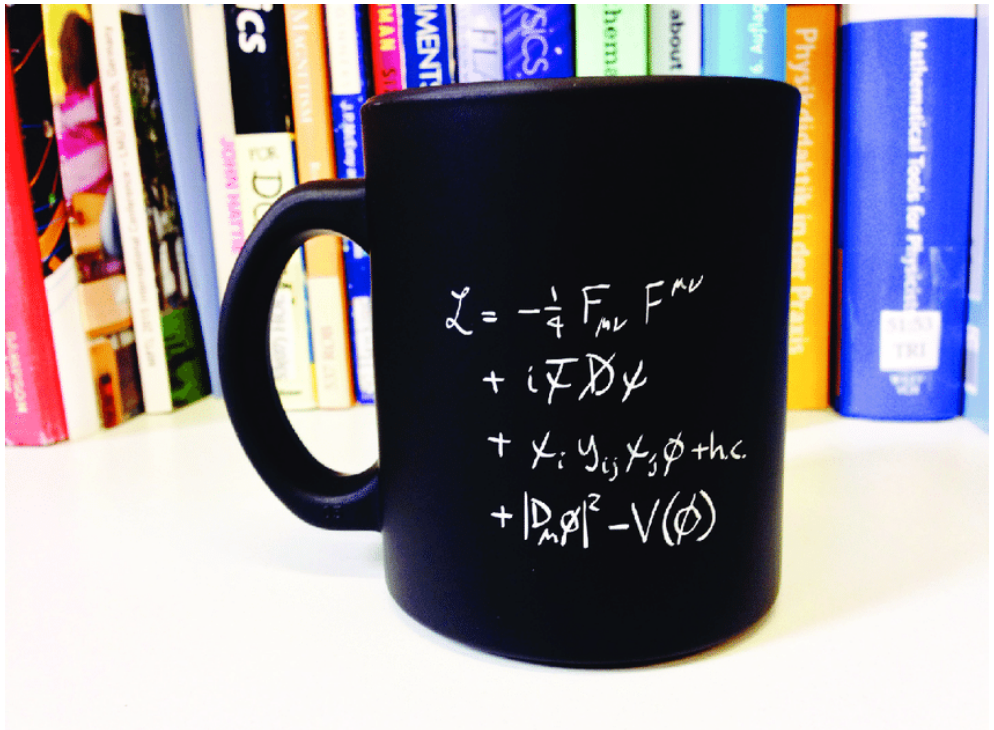
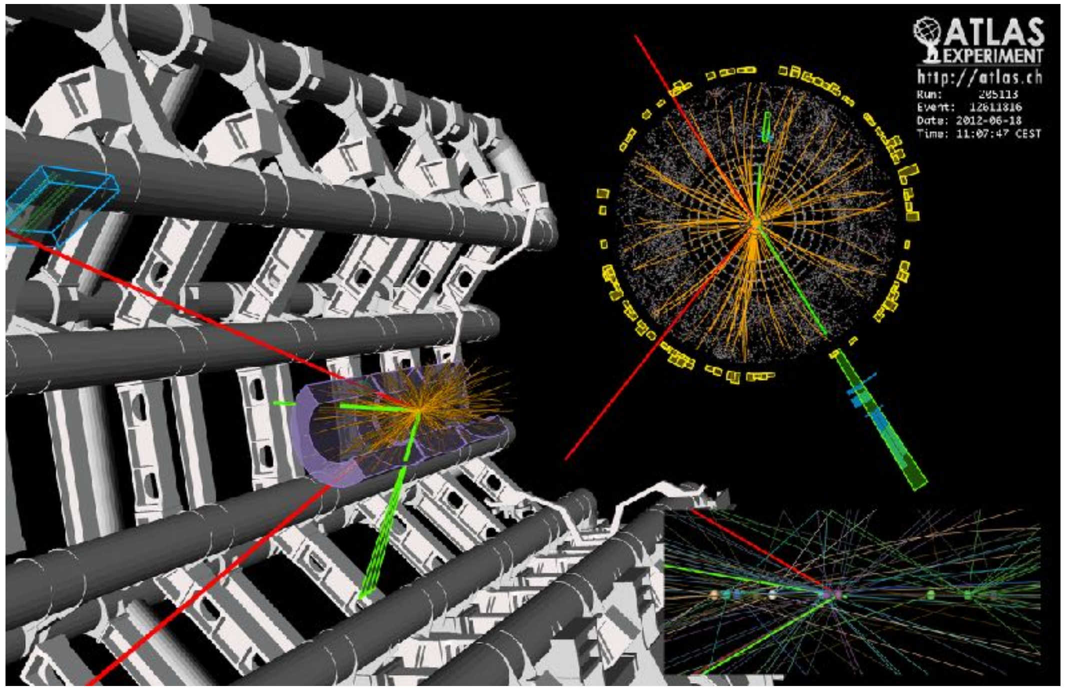
Precision phenomenology in the Higgs sector

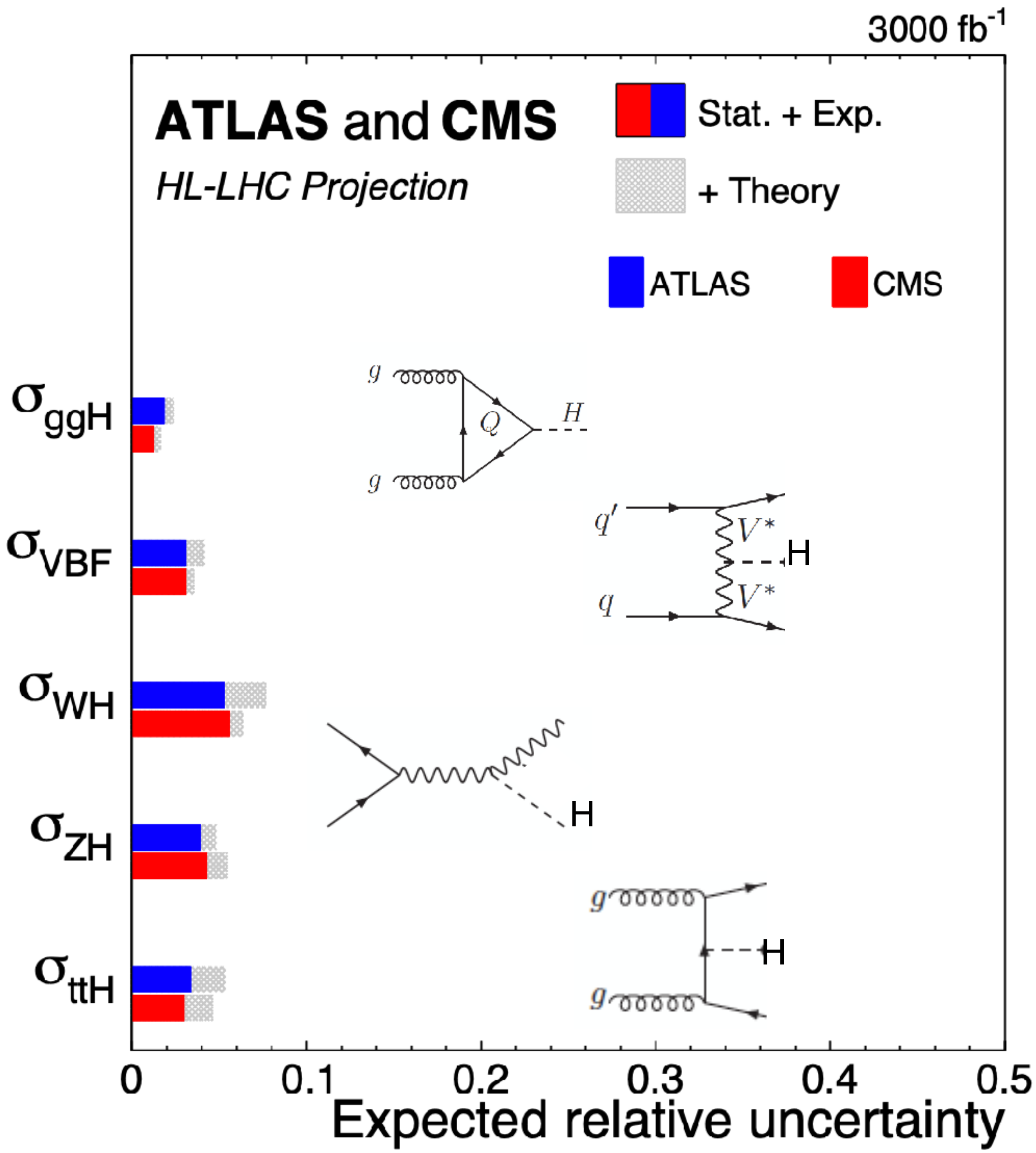


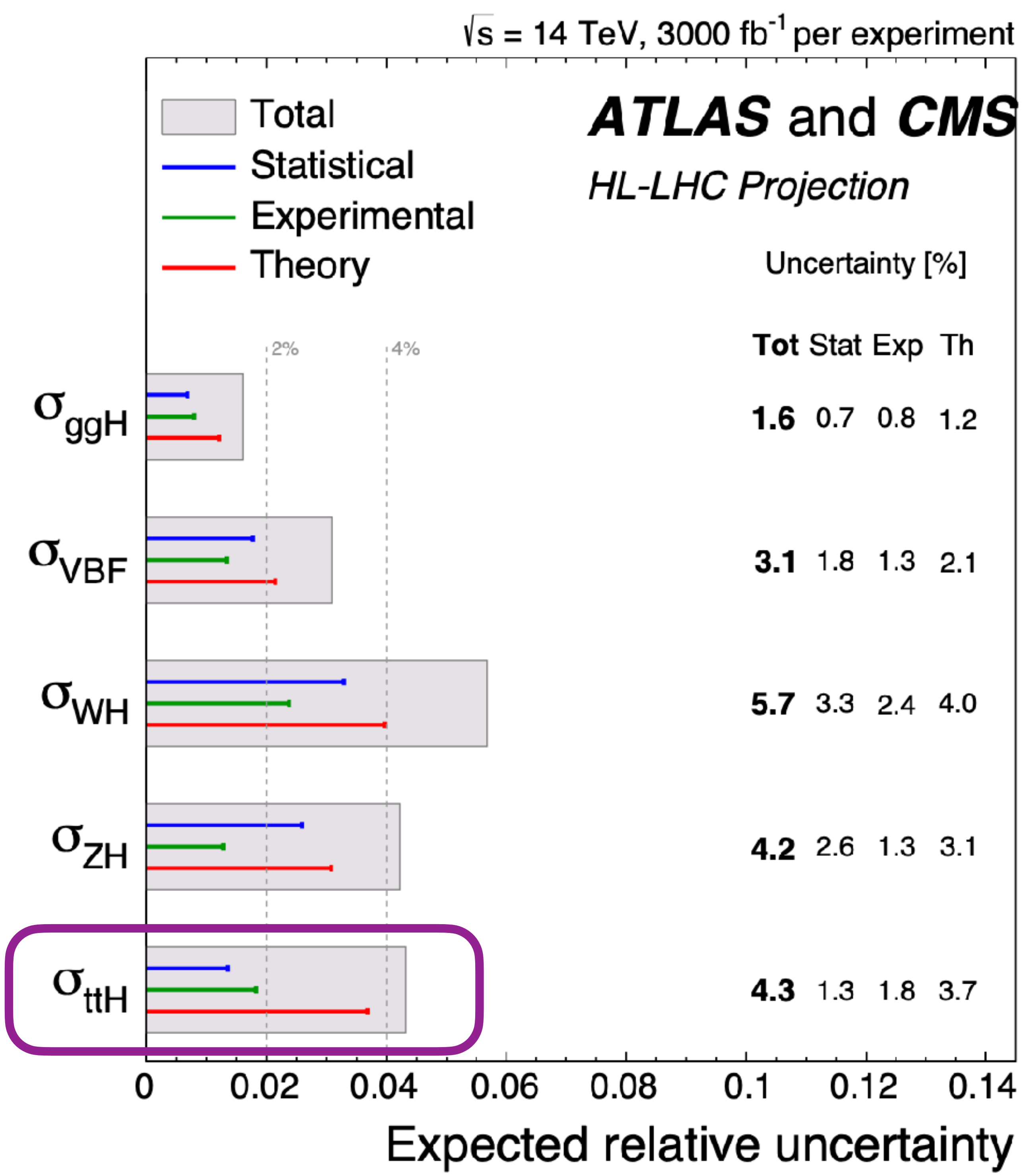
models,
simulations

verify/falsify models,
provide bounds,
new phenomena



Higgs boson production: expected uncertainties

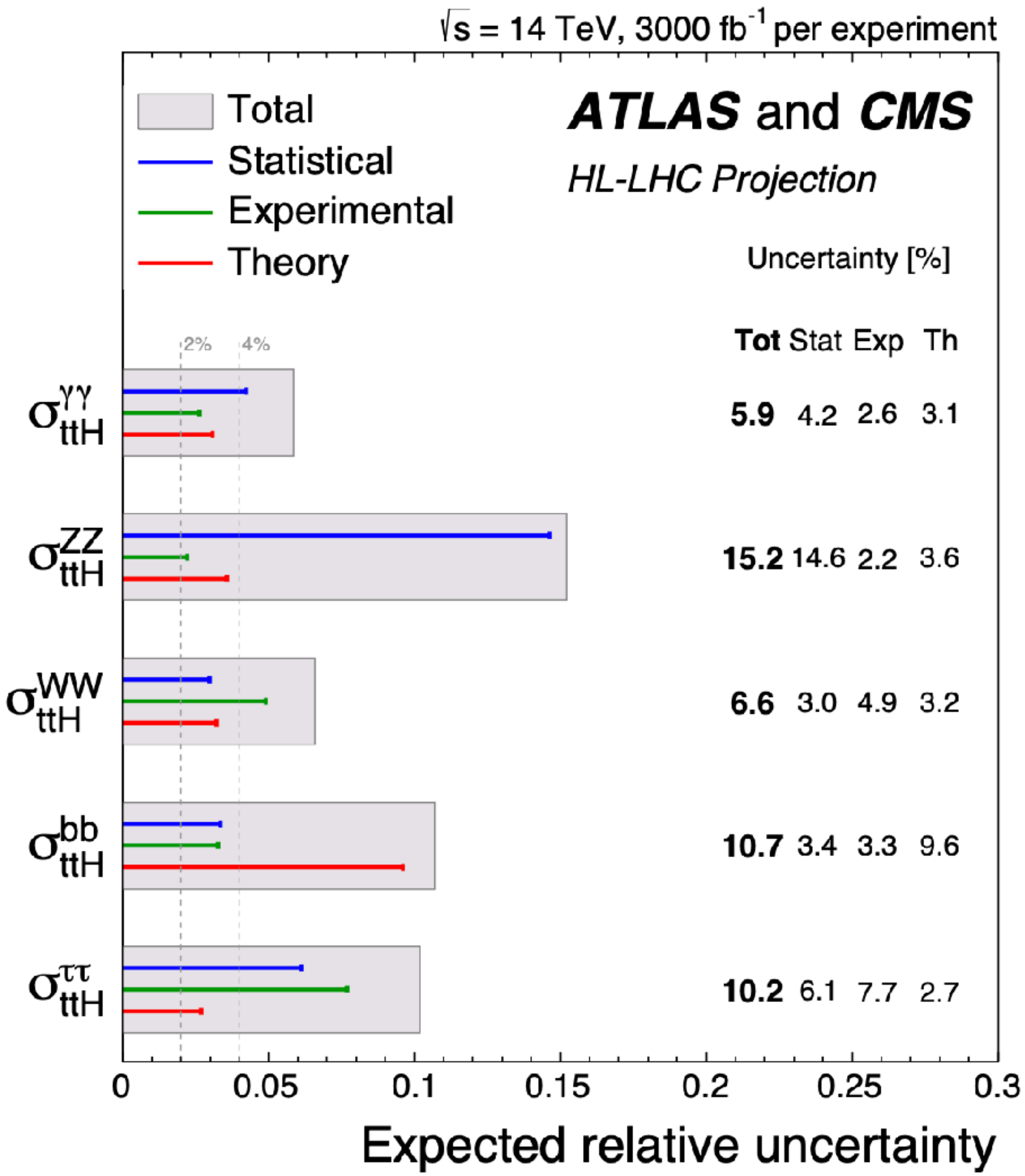




HL-HE CERN YR, 1902.00134

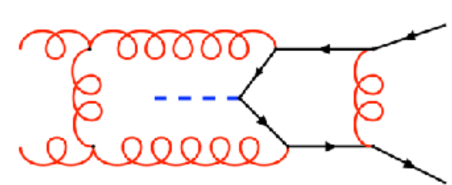
expected uncertainties

$t\bar{t}H$ production channel in more detail, including decay modes:



uncertainties depend significantly on the decay mode!

- need good control of Monte Carlo uncertainties
- modelling of backgrounds very important
- NNLO very hard
  (5-point process with massive propagators)



$$\hat{\sigma} = \alpha_s^k(\mu)\left[\hat{\sigma}^{\mathrm{LO}} + \alpha_s(\mu)\,\hat{\sigma}^{\mathrm{NLO}}(\mu) + \alpha_s^2(\mu)\,\hat{\sigma}^{\mathrm{NNLO}}(\mu) + \dots\right.$$

fixed order precision frontier

N3LO available for:

gluon fusion Higgs, bbH, Drell-Yan, VBF H, VBF HH, gluon fusion HH

	Drell-Yan	gluon fusion Higgs
LO	1970	1978
NLO	1978-80	1991 (HTL) 1995 (full mt)
NNLO	1991	2002 (HTL) 2009-2020 (mass effects)
N3LO	2020 Duhr, Dulat, Mistlberger	2015 (HTL, threshold exp.) Anastasiou, Duhr, Dulat, Herzog, Mistlberger 2018 (HTL) Mistlberger 2020 Das, Moch, Vogt partial N4LO

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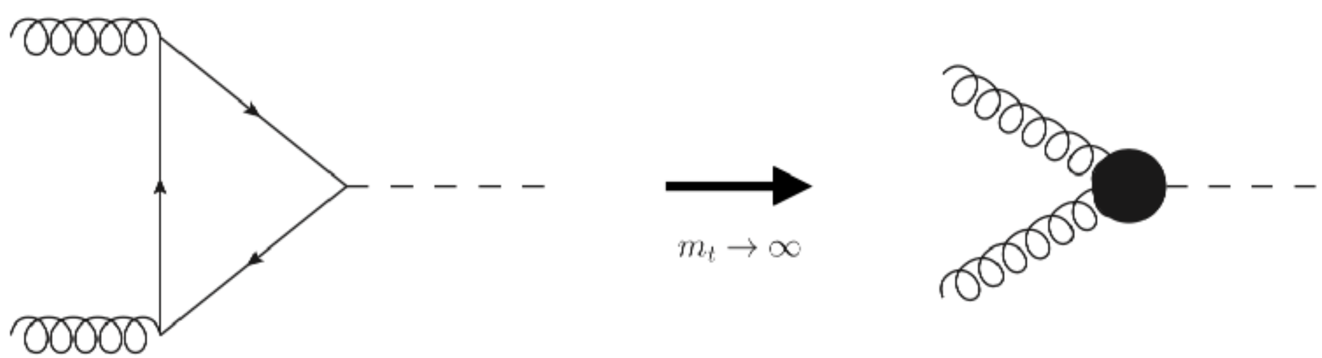
aside: heavy top limit

- Higgs production in gluon fusion:

  leading order already contains one loop

  (same for HH, HJ, HZ, … in gluon fusion)

- many calculations of high perturbative order use “heavy top limit” (HTL)



- good approximation for inclusive Higgs production if rescaled with full Born

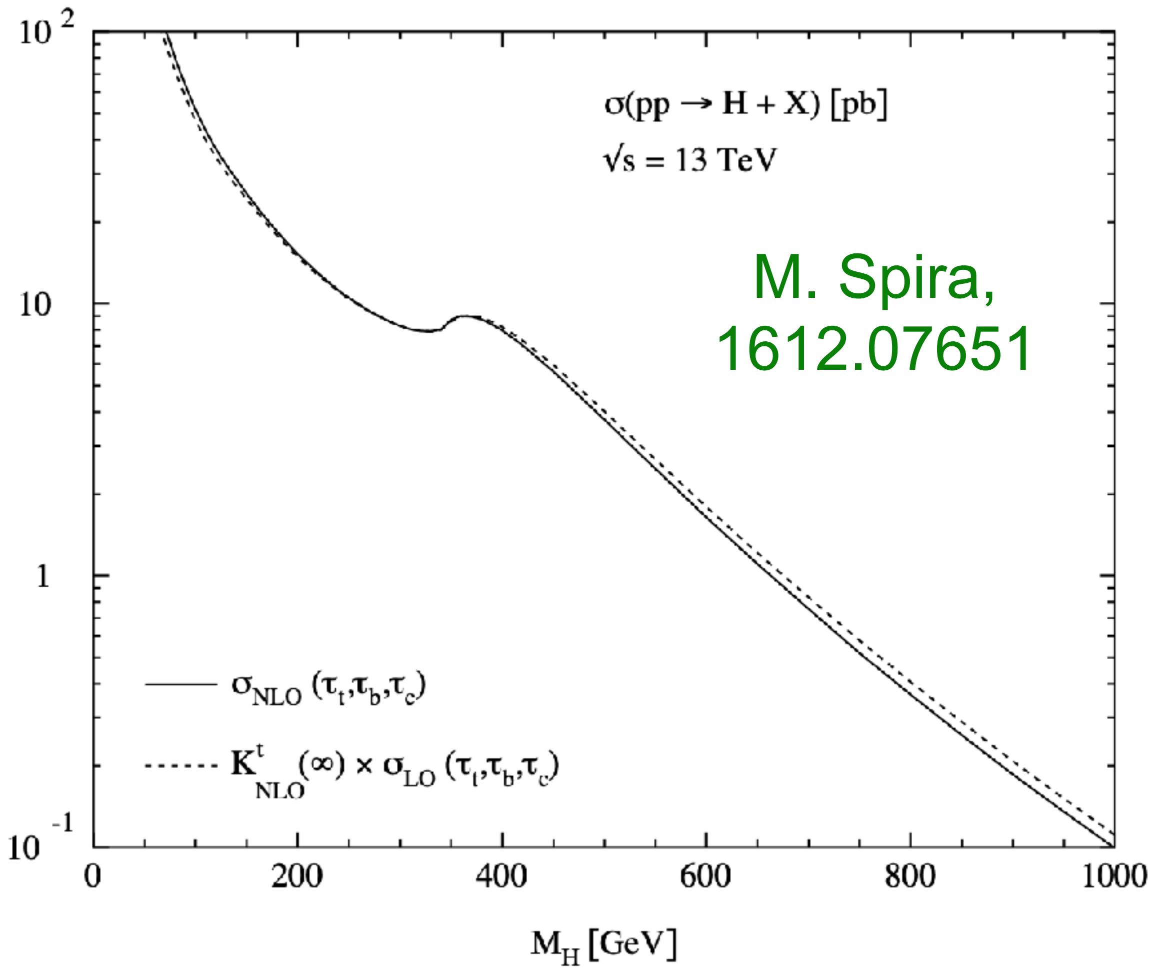
- not justified if top loops can be resolved (e.g. high energy tails of distributions)

  (in fact only justified below threshold, $E \lesssim 2m_t$)

  example HH production: only valid for $250\,\mathrm{GeV} \leq m_{HH} \lesssim 350\,\mathrm{GeV}$

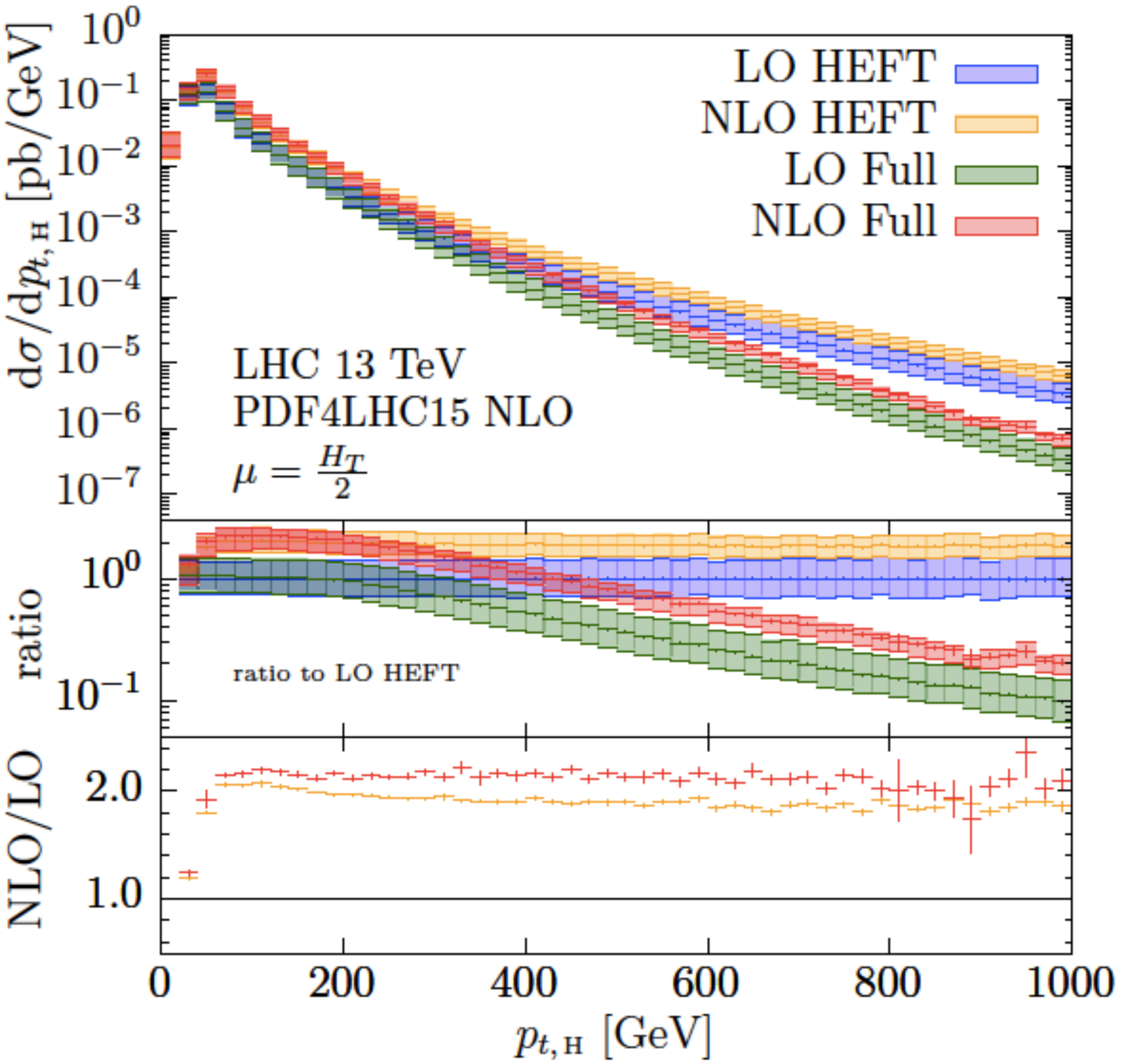
heavy top limit

inclusive Higgs production



"Born-improved" NLO HTL

Higgs+jet production



Jones, Kerner, Luisoni '18

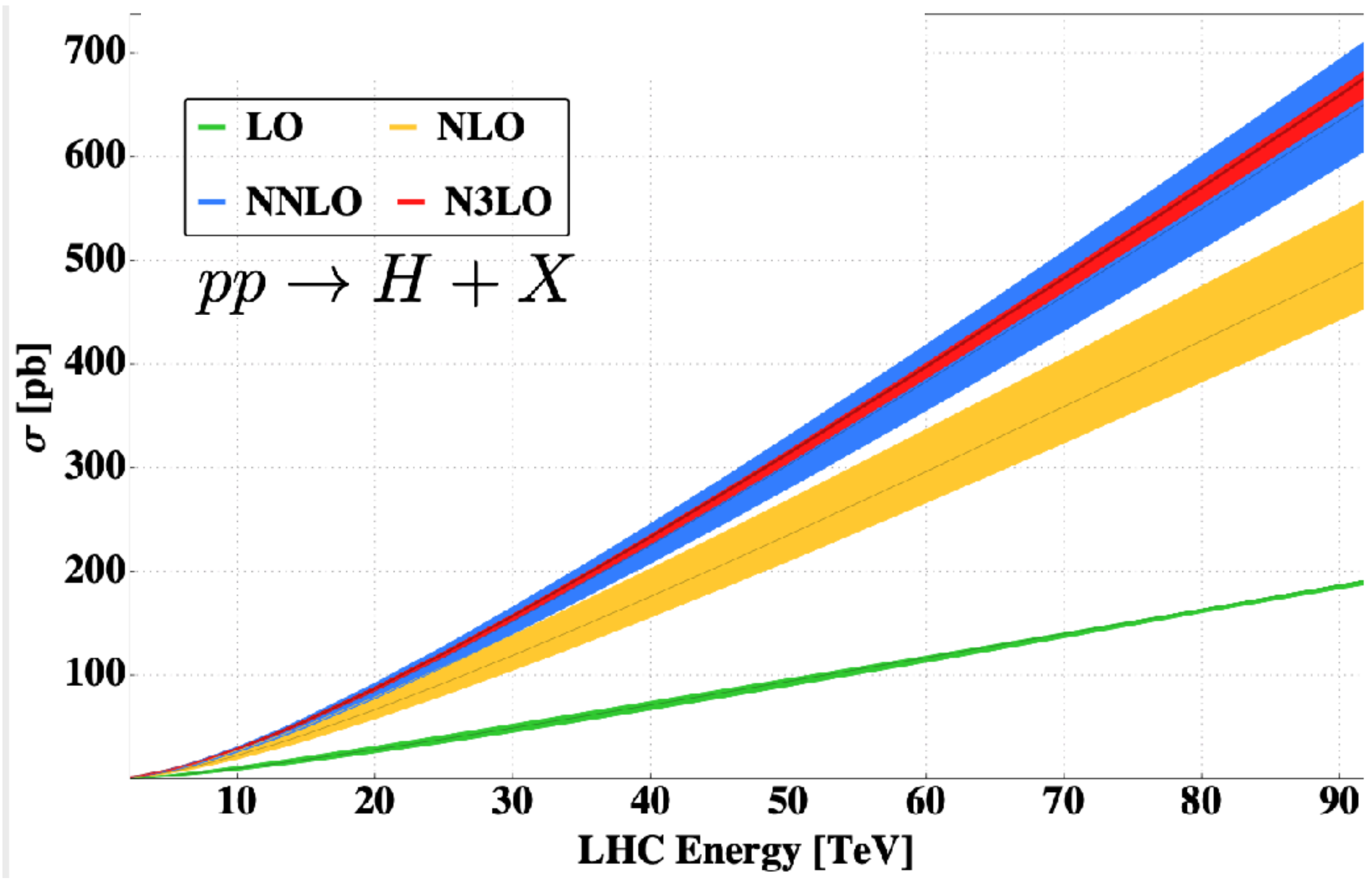
("HEFT"=HTL)

fixed order precision frontier

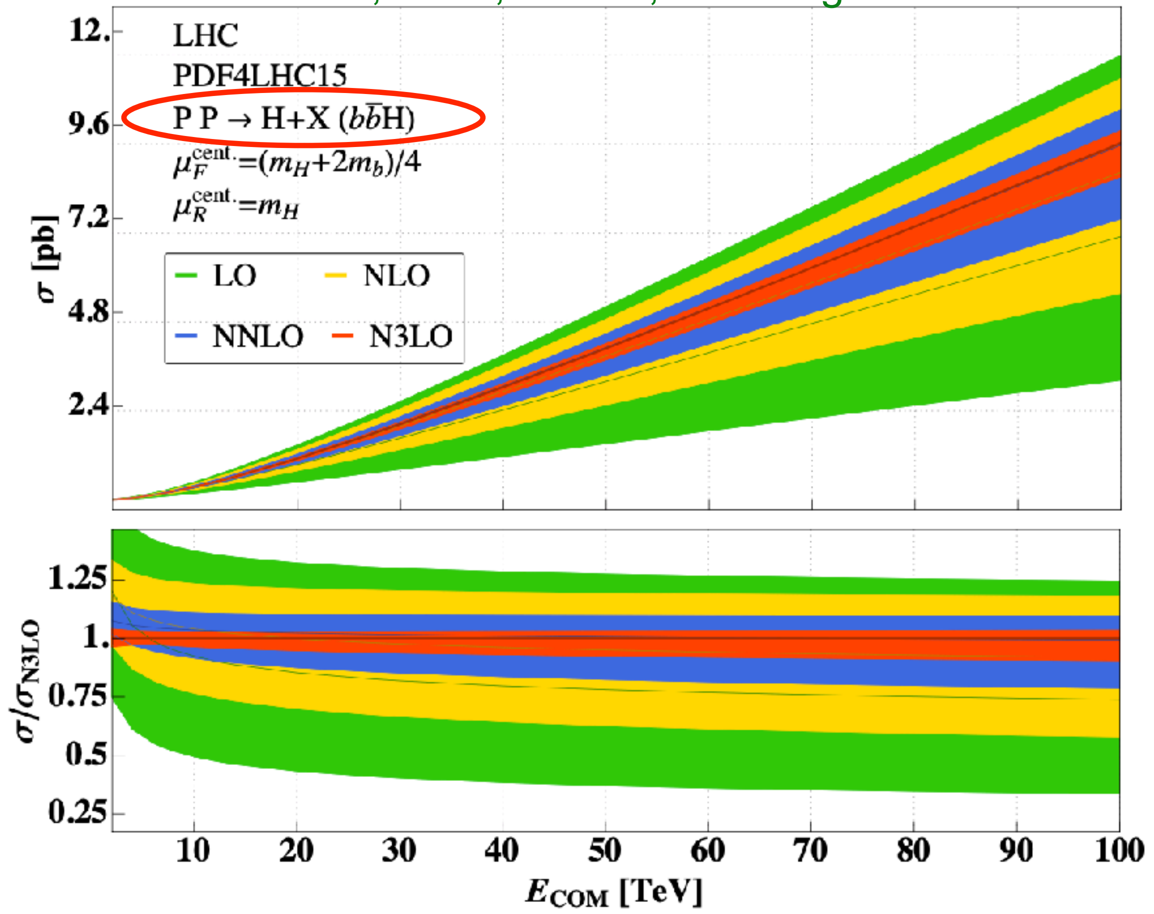
	VBF Higgs	Higgs pairs gluon fusion
LO	1979	1988
NLO	1992 (structure func.approx.) 2003 (full)	1998 (HTL) 2016 (full mt)
NNLO	2015	2013 (HTL) 2013-2020 (mass effects)
N3LO	2016 Dreyer, Karlberg (VBF HH 2018)	2019 (HTL+mass effects) Chen, Li, Shao, Wang

precision frontier

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ‘15



Duhr, Dulat, Hirschi, Mistlberger ‘20



shift of focus:

at N3LO scale uncertainties under control, but need to address

- QCDxEW corrections
- massive quarks at higher orders
- PDF, α_s uncertainties, non-perturbative effects
- parton shower uncertainties

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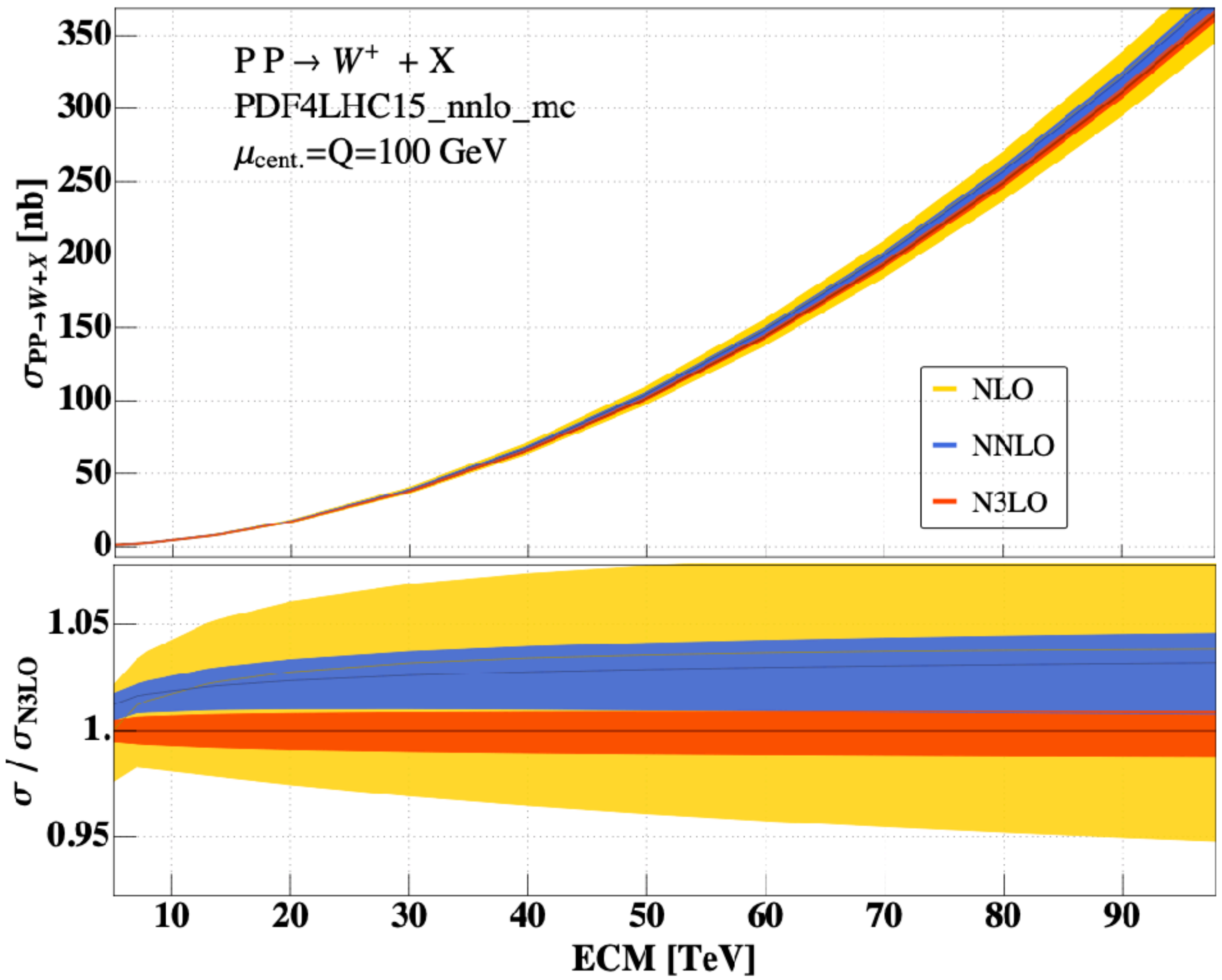
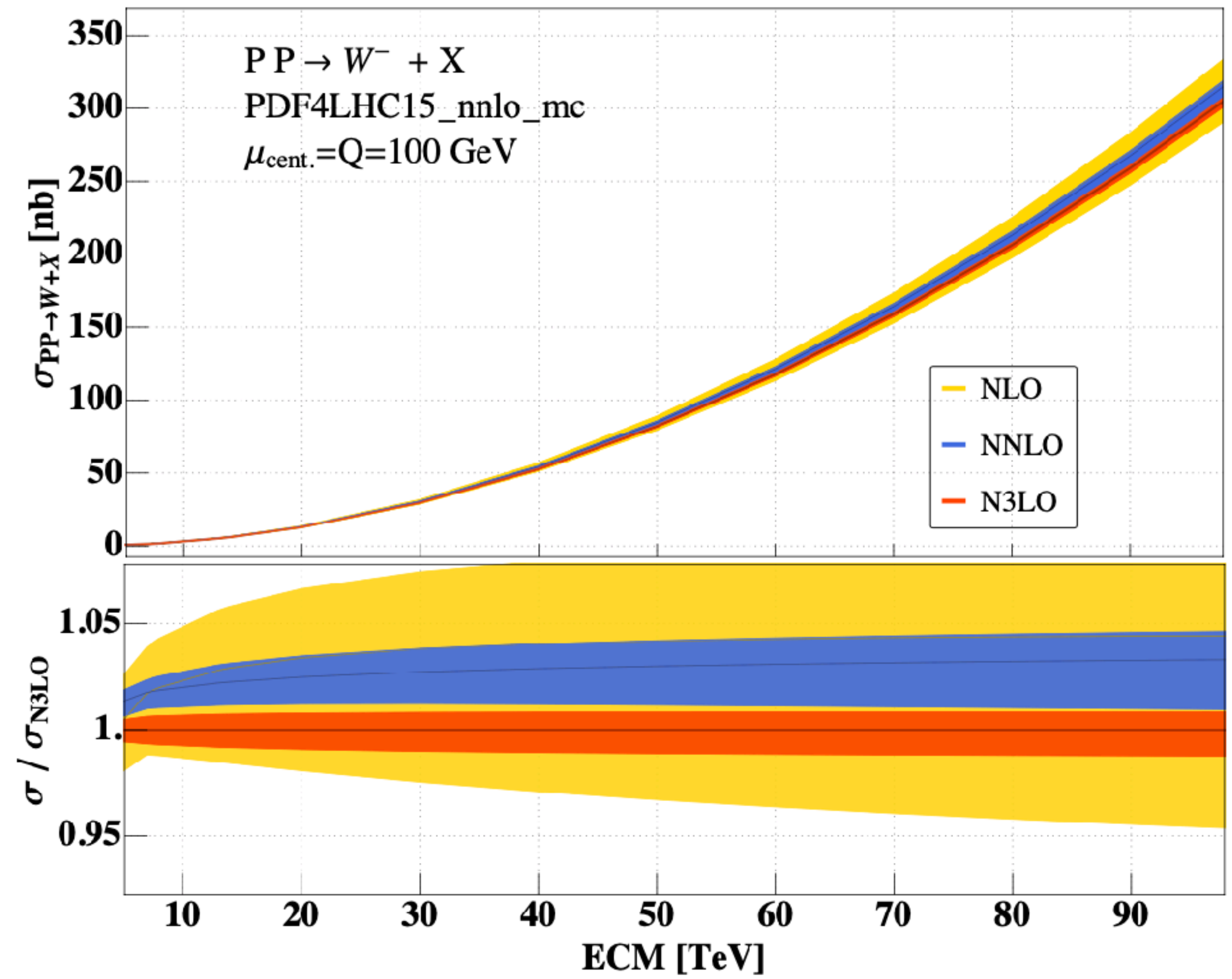
W-boson production

Duhr, Dulat, Mistlberger ‘20





N3LO uncertainty band not within NNLO band

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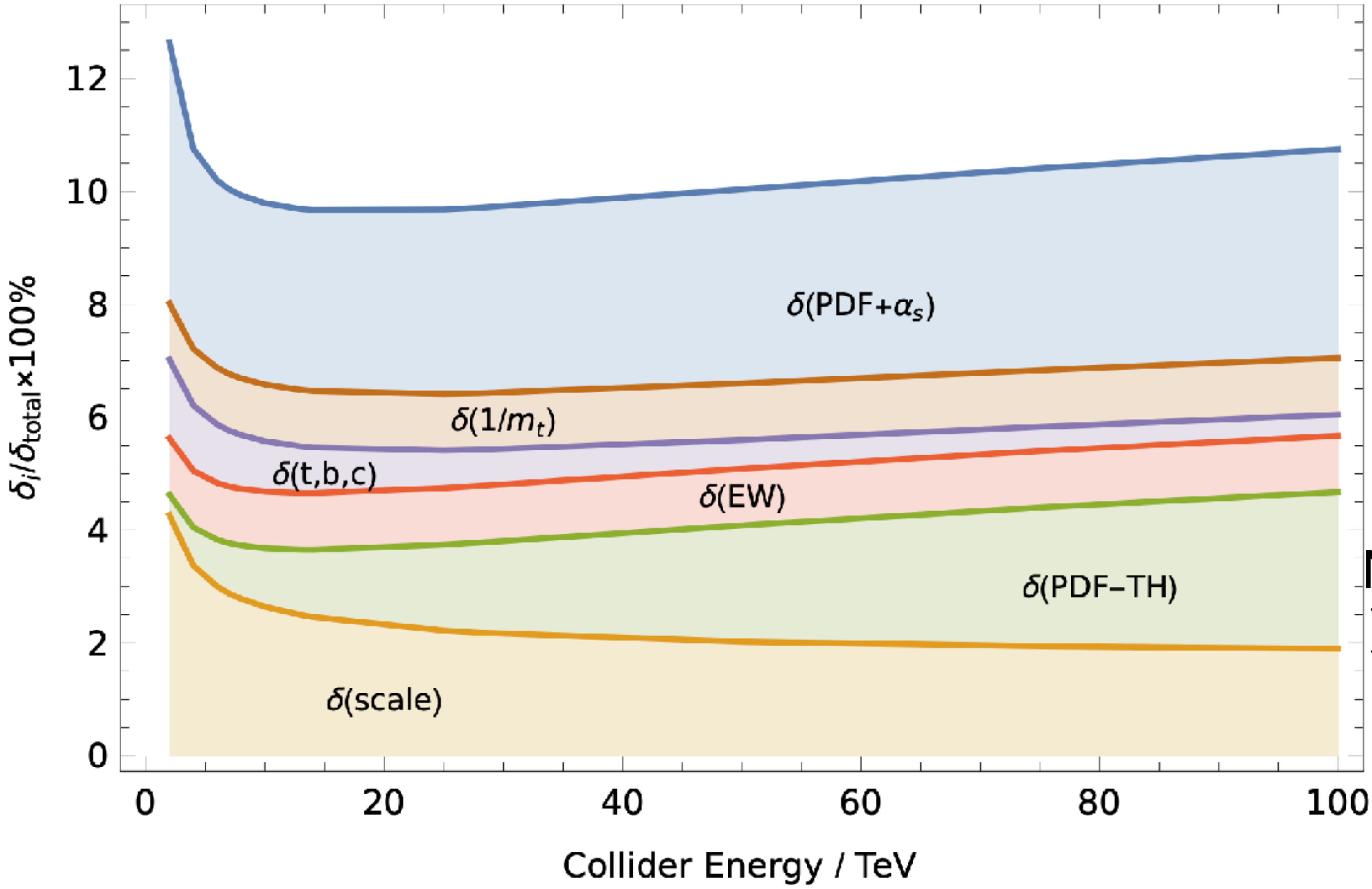
H in gluon fusion: uncertainties

$\delta(\text{scale})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
$^{+0.10}_{-1.15}$ pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb	$\pm$ 0.89 pb	$^{+1.25}_{-1.26}$ pb
$^{+0.21\%}_{-2.37\%}$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$	$\pm 1.85\%$	$^{+2.59\%}_{-2.62\%}$

2009.00516

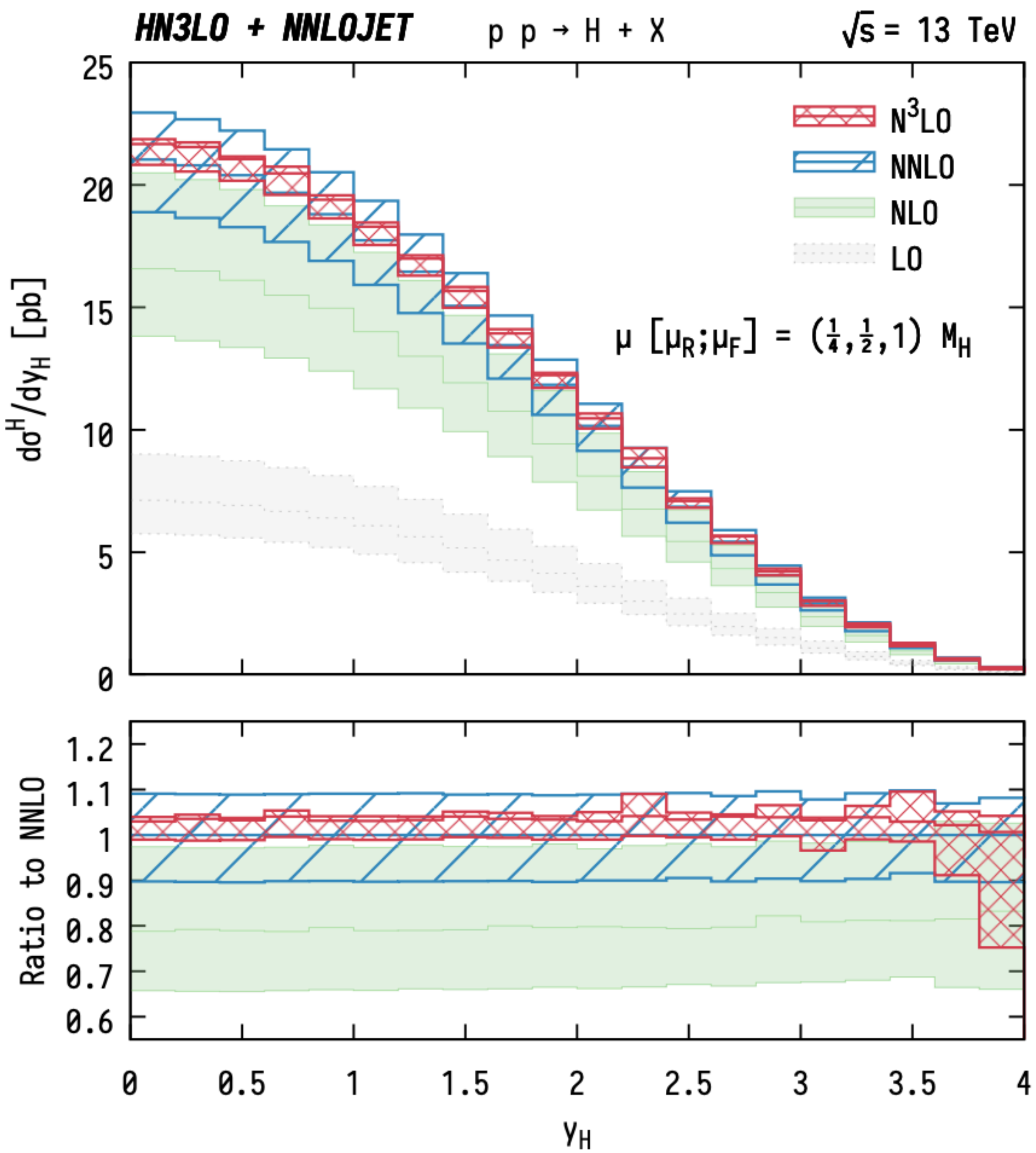
scale uncertainties no longer the dominant uncertainties



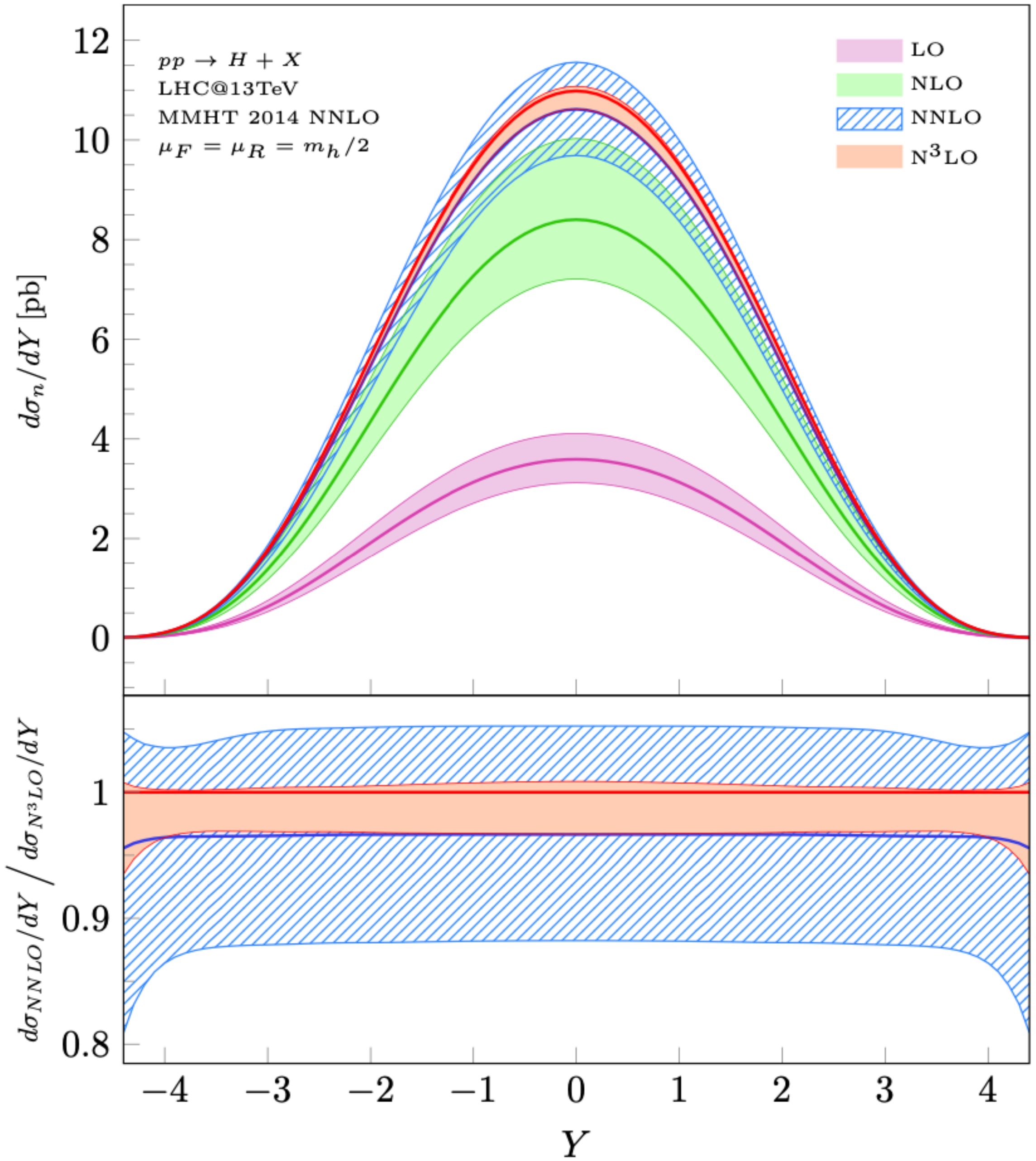
NNLO PDFs with $\text{N}^3\text{LO}\ \sigma$

1902.00134

differential N3LO results



Cieri, Chen, Gehrmann, Glover, Huss
1807.11501



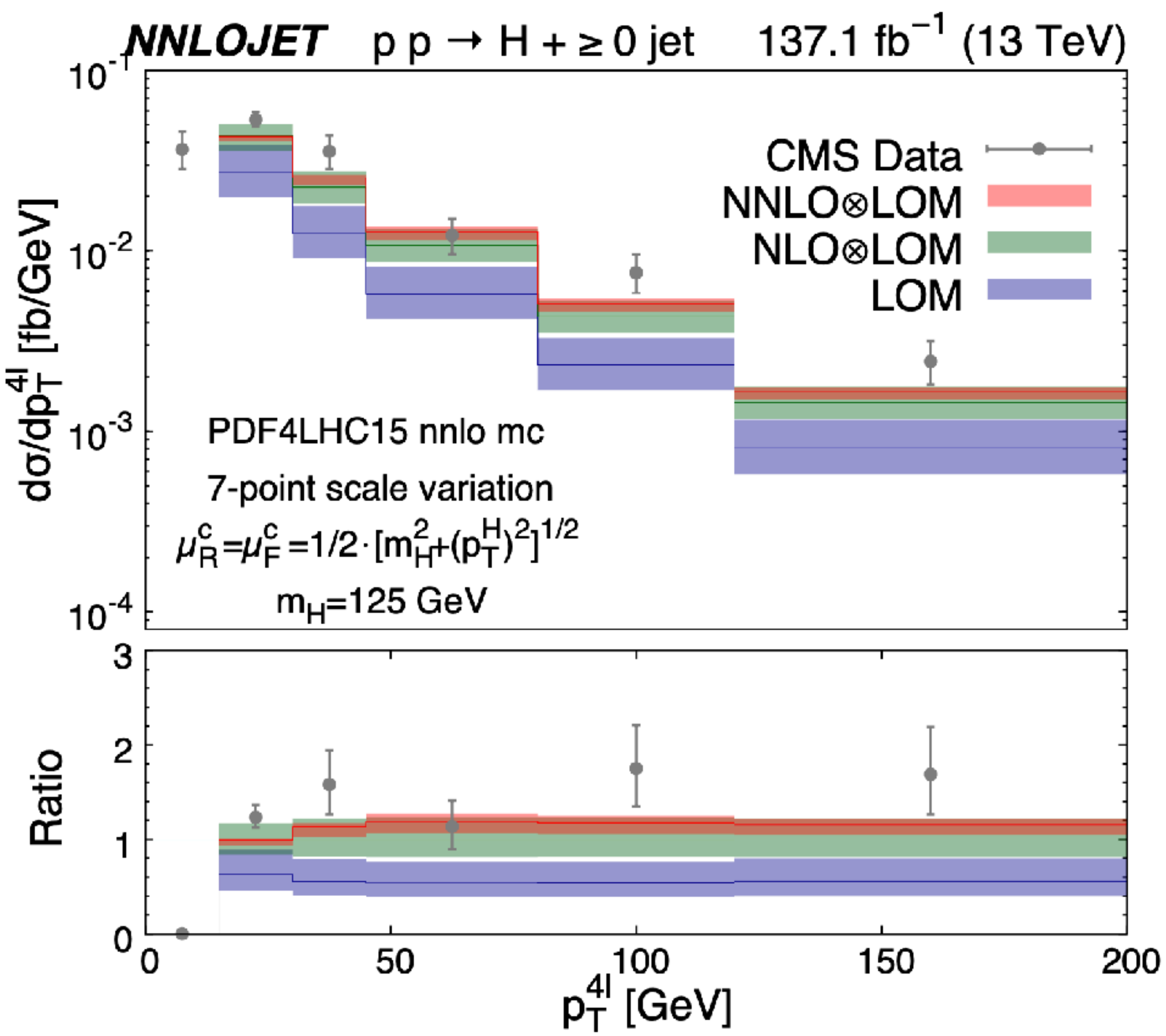
Dulat, Mistlberger, Pelloni
1810.09462

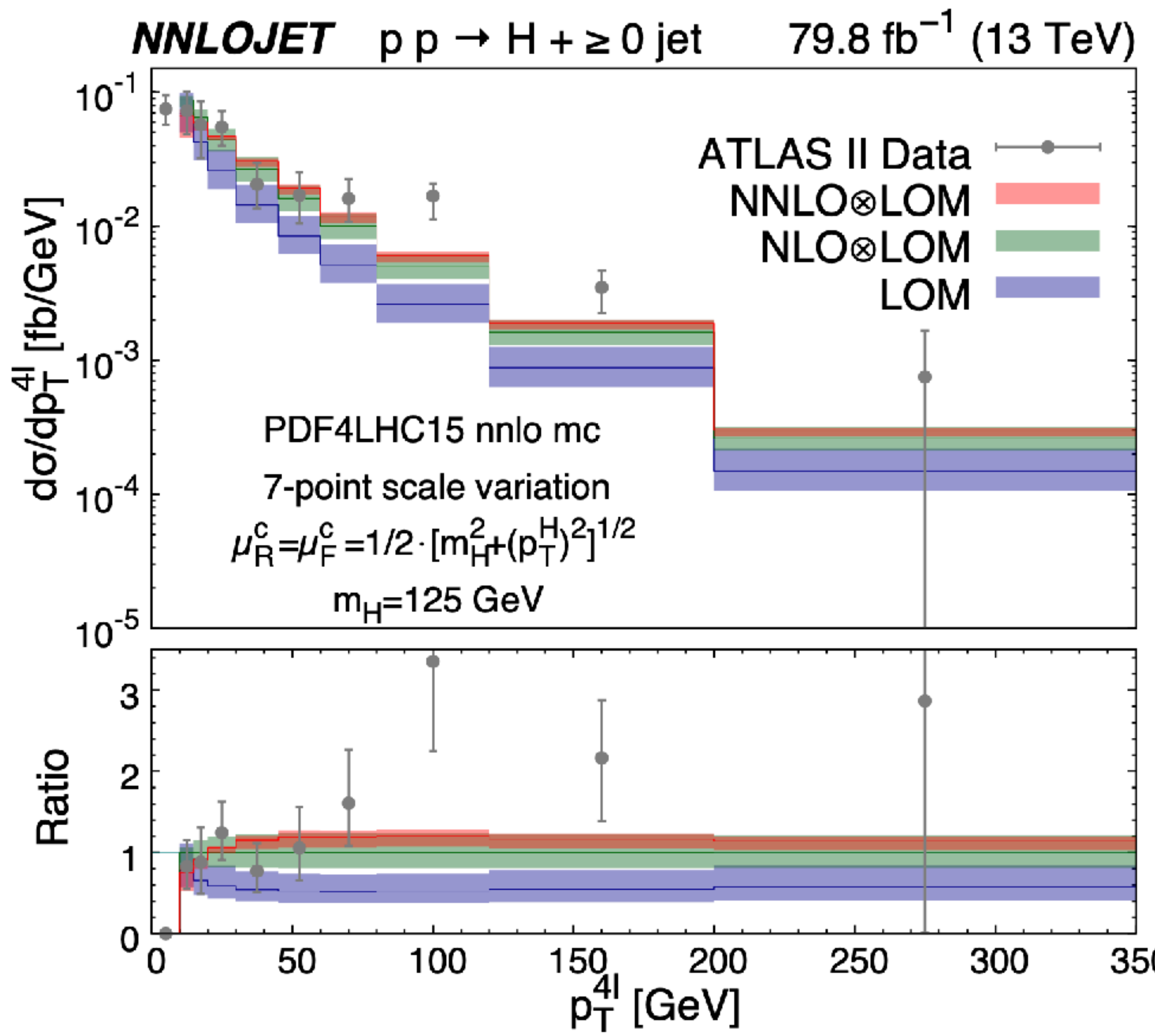
scale uncertainties reduced by more than 50% w.r.t. NNLO

gluon fusion H NNLO differential results

$$pp \to H + \leq 1\,j \to 4l + \leq 1\,j$$

Chen, Gehrmann, Glover, Huss
1905.13738
NNLOJET



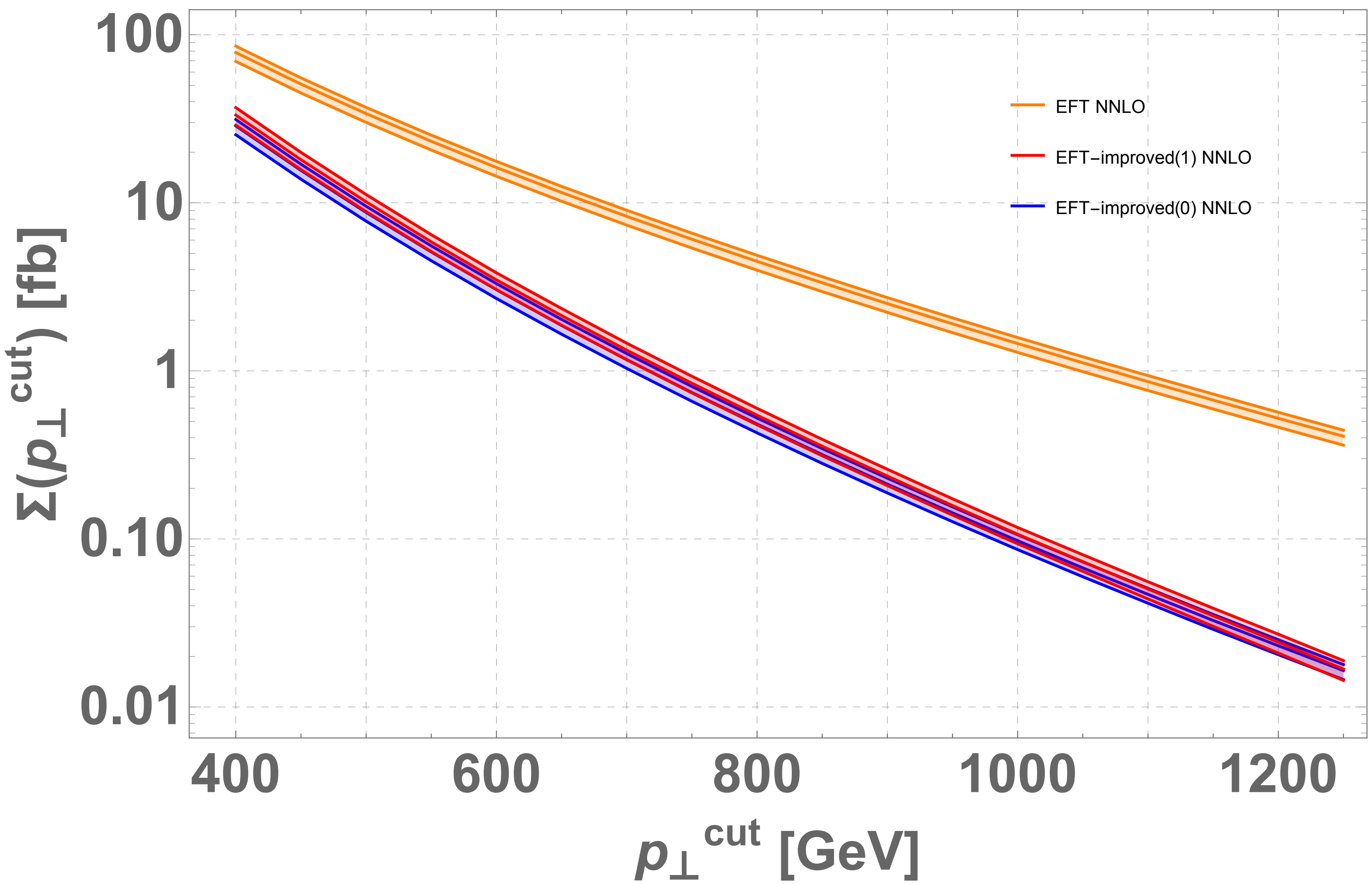


study of perturbative stability of lepton acceptance cuts

large-pT Higgs + jet production

combine NNLO (HTL) with NLO (full m_t)   (not unique)

$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) \equiv \frac{\Sigma^{\text{SM, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})}\, \Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$



7-point scale variations

red curve also contains estimated δ_{m_t} (on-shell top mass scheme)

Becker et al. 2005.07762

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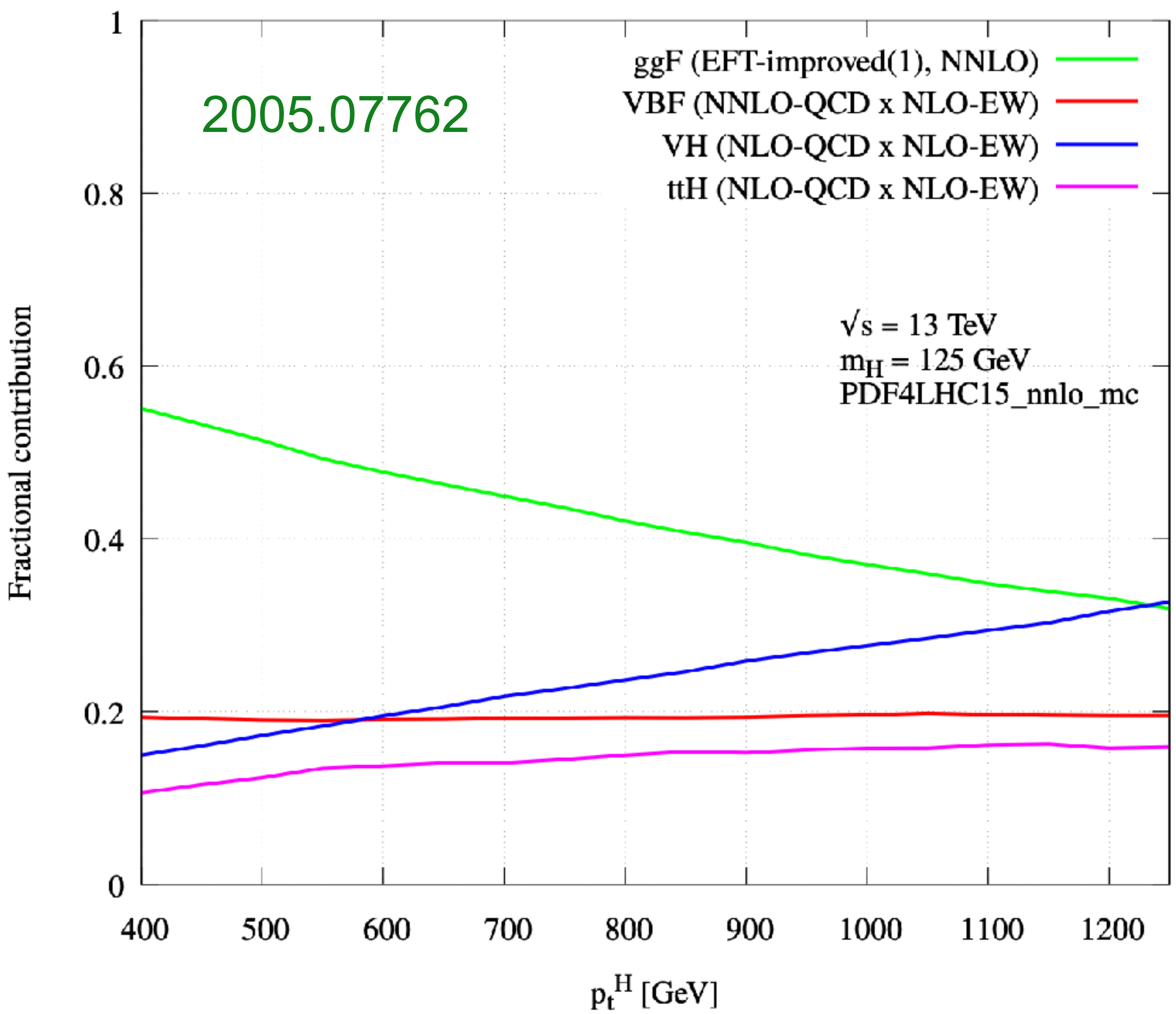
large-pT Higgs + jet production

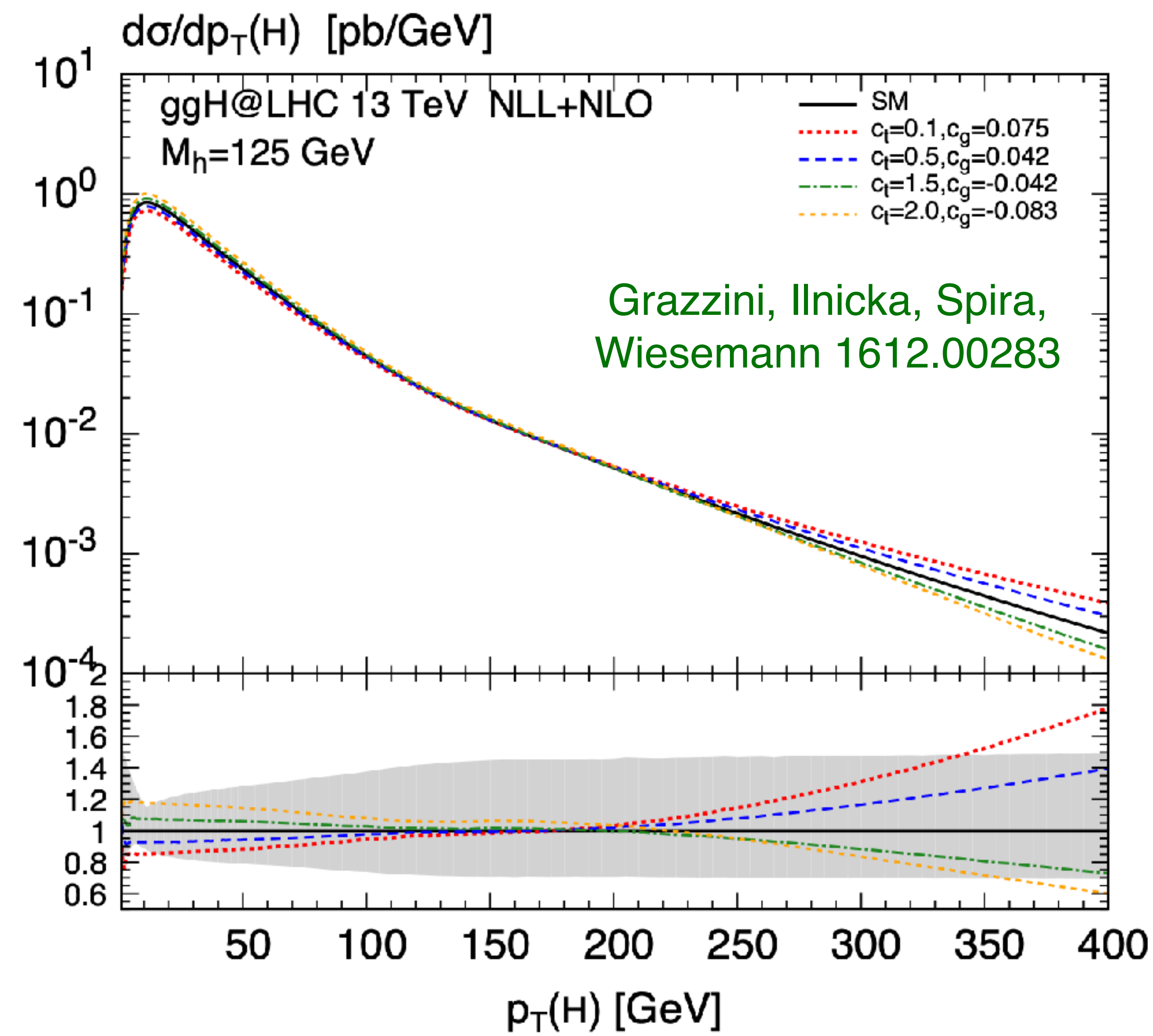
Becker et al. 2005.07762

$p_\perp^{\text{cut}}$	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	HJ-MINLO [fb]	MG5_MC@NLO [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$18.1^{+10.8\%}_{-12.8\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

reasonable agreement with state-of-the art generators
within (large) uncertainties

large-pT Higgs + jet production





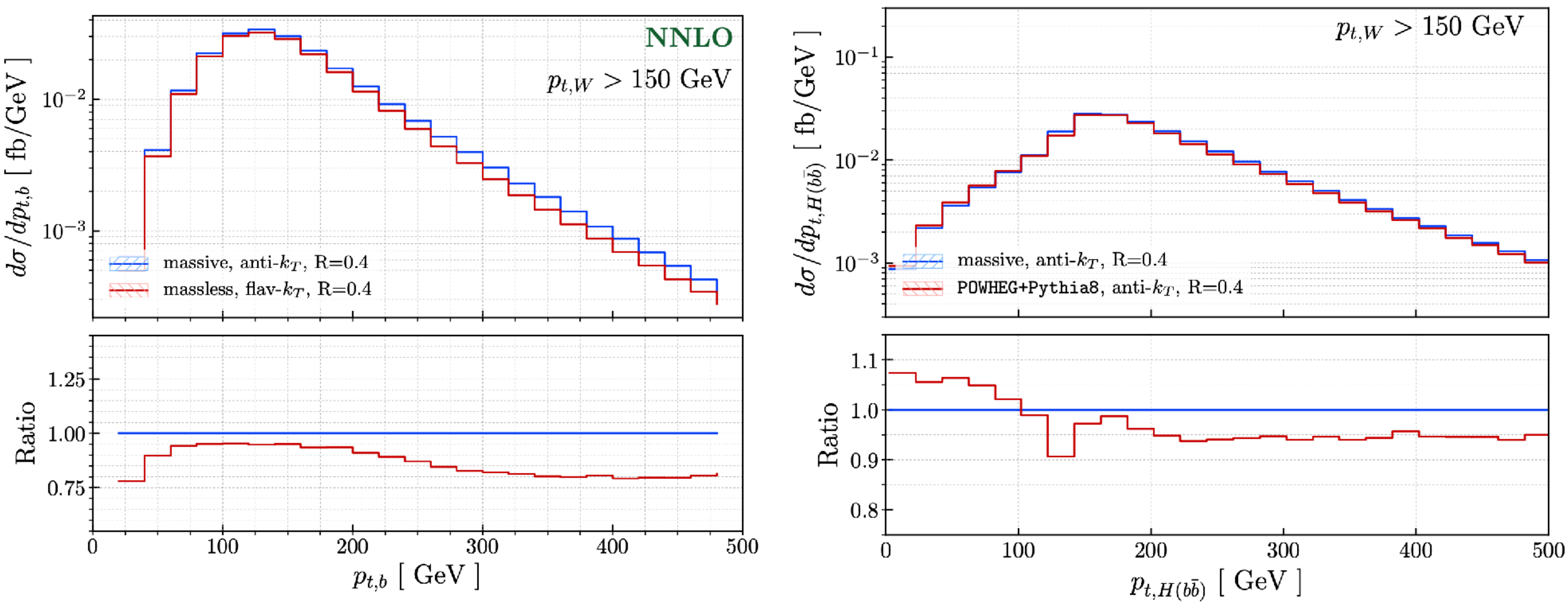
other channels gain importance at large pT, in particular VH

effects of anomalous couplings mostly at high pT

vector bosons associated production

WH production at NNLO with $H \to b\bar{b}$ with massive b-quarks

Behring, Bizon, Caola, Melnikov, Röntsch 2003.08321



significant differences between

massive and massless case and NNLO vs NLO+PS

The Higgs Potential

SM: $V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$

↓ EW symmetry breaking

$$\frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$

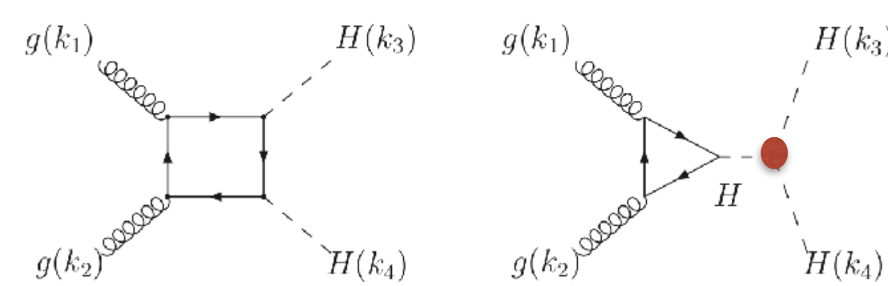
λ_{3h} completely determined in the SM

exp: $-3.3 \leq \lambda_{3h}/\lambda_{\mathrm{SM}} \leq 8.5$

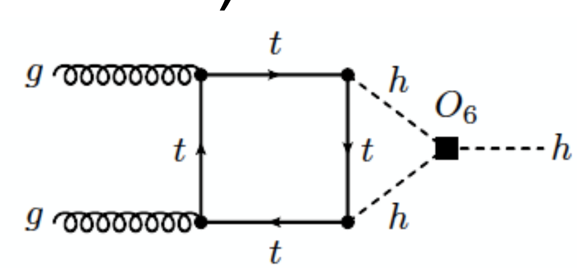
2011.12373

- is it really of this form?
- how large (or small) can the triple Higgs coupling be?

try to get information from

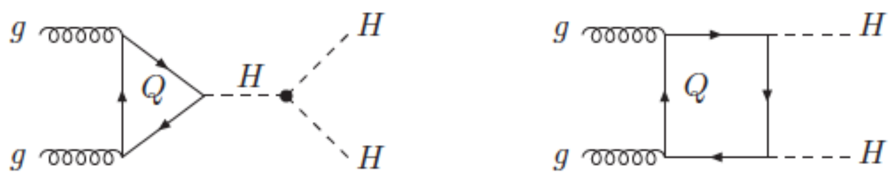


- non-resonant HH production (direct measurement)
- indirect constraints (e.g. from single H)

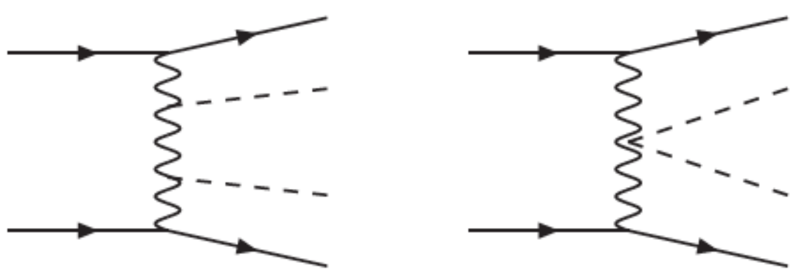


HH production channels

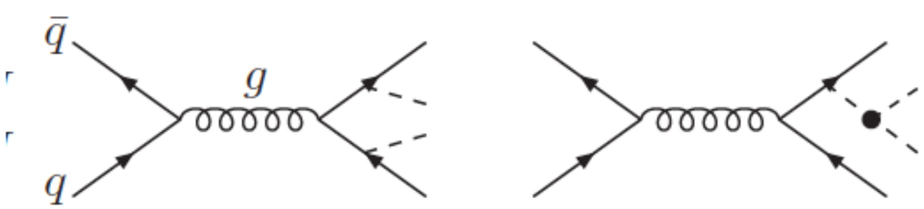
- gluon fusion



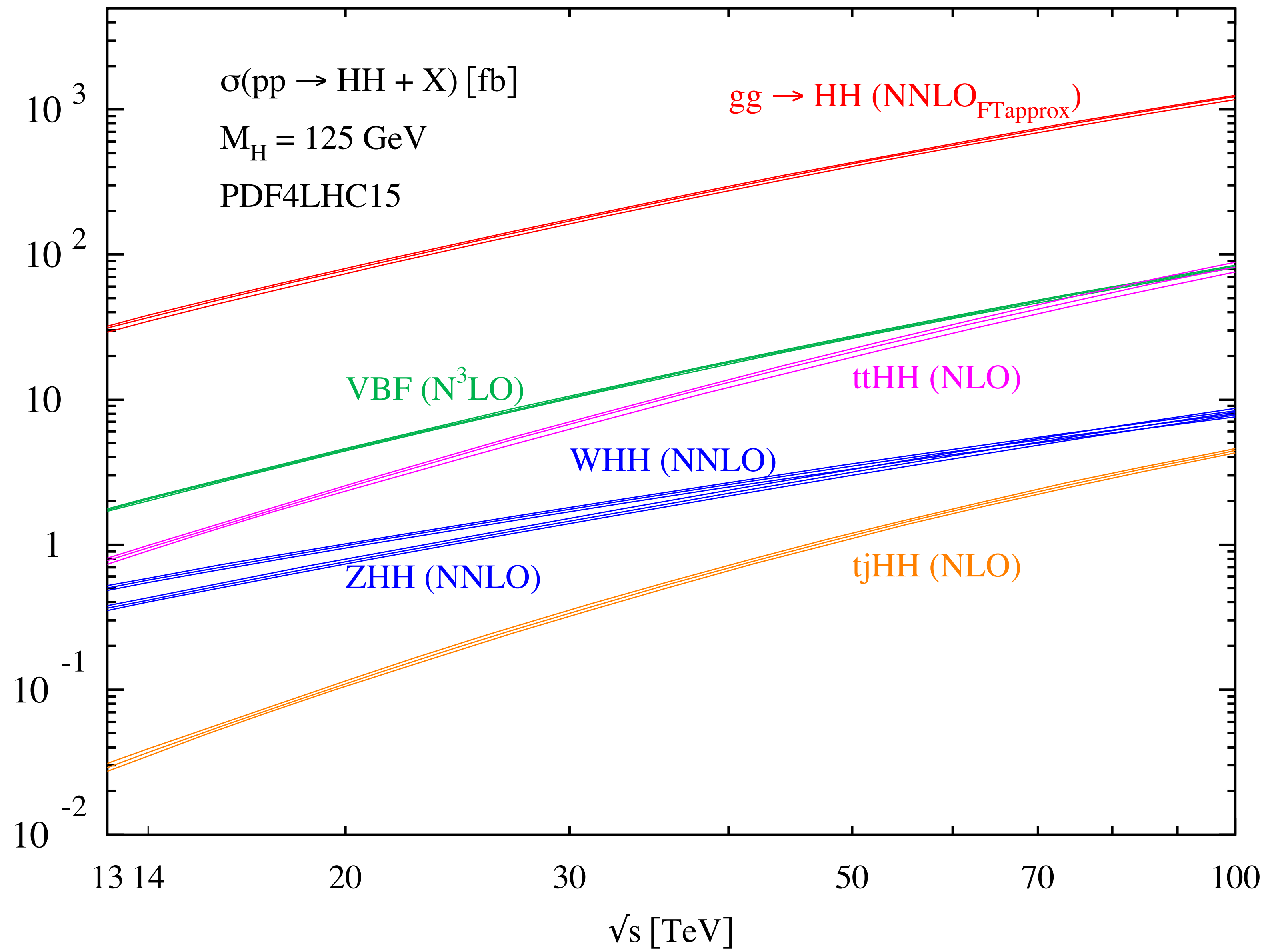
- vector boson fusion



- top-quark associated



- Higgs-strahlung



LHC Higgs WG YR4
1610.07922

$$\sigma_{ggHH} \sim 10^{-3}\,\sigma_{ggH}$$

Higgs boson pair production in gluon fusion

current status:

N3LO: Chen, Li, Shao, Wang '19 (HTL with mt effects)

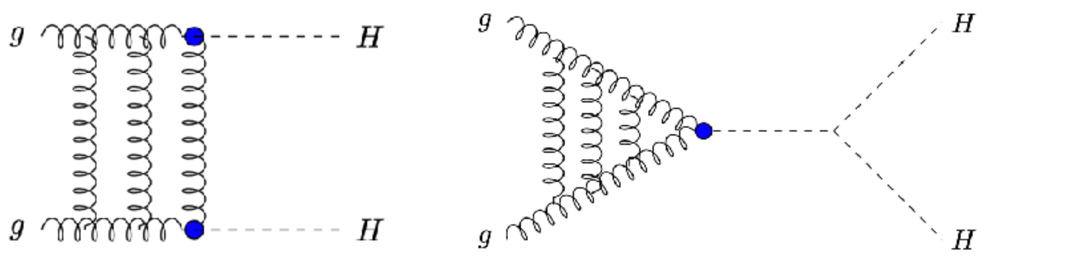


image: S. Borowka

NNLO: De Florian, Mazzitelli '13
Grigo, Melnikov, Steinhauser '14

$\mathrm{NNLO_{FTapprox}}$
current recommendation of LHC Higgs Working Group

Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

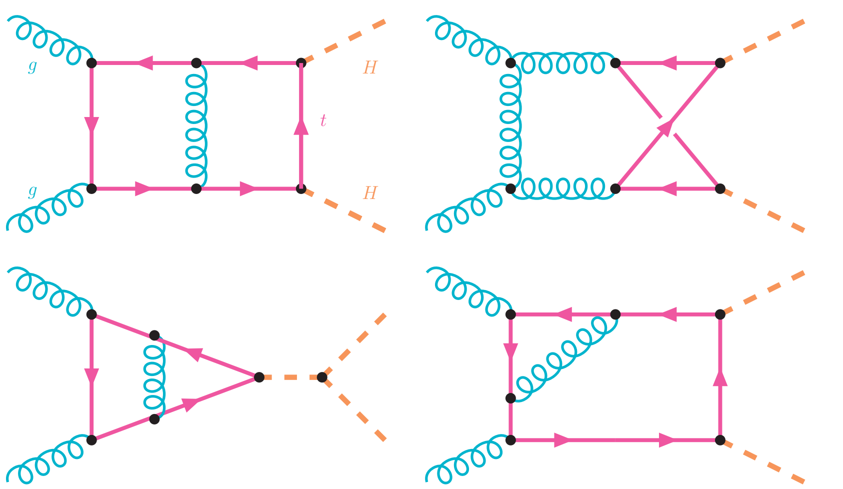


image: S. Jones

NLO full m_t

Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16

Baglio, Campanario, Glaus Mühlleitner, Spira, Streicher '18

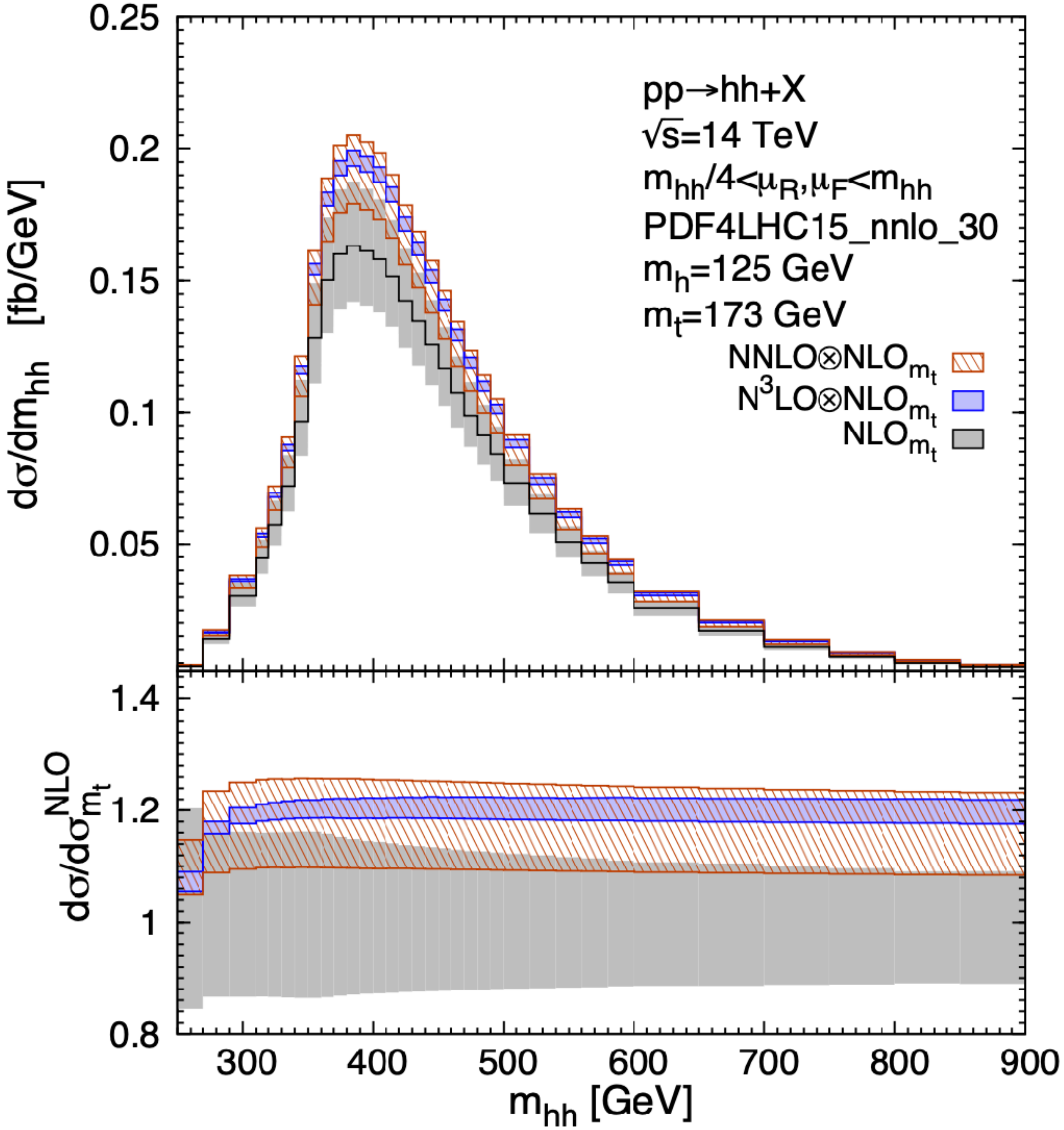
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

Baglio, Campanario, Glaus Mühlleitner, Ronca, Spira 2008.11626

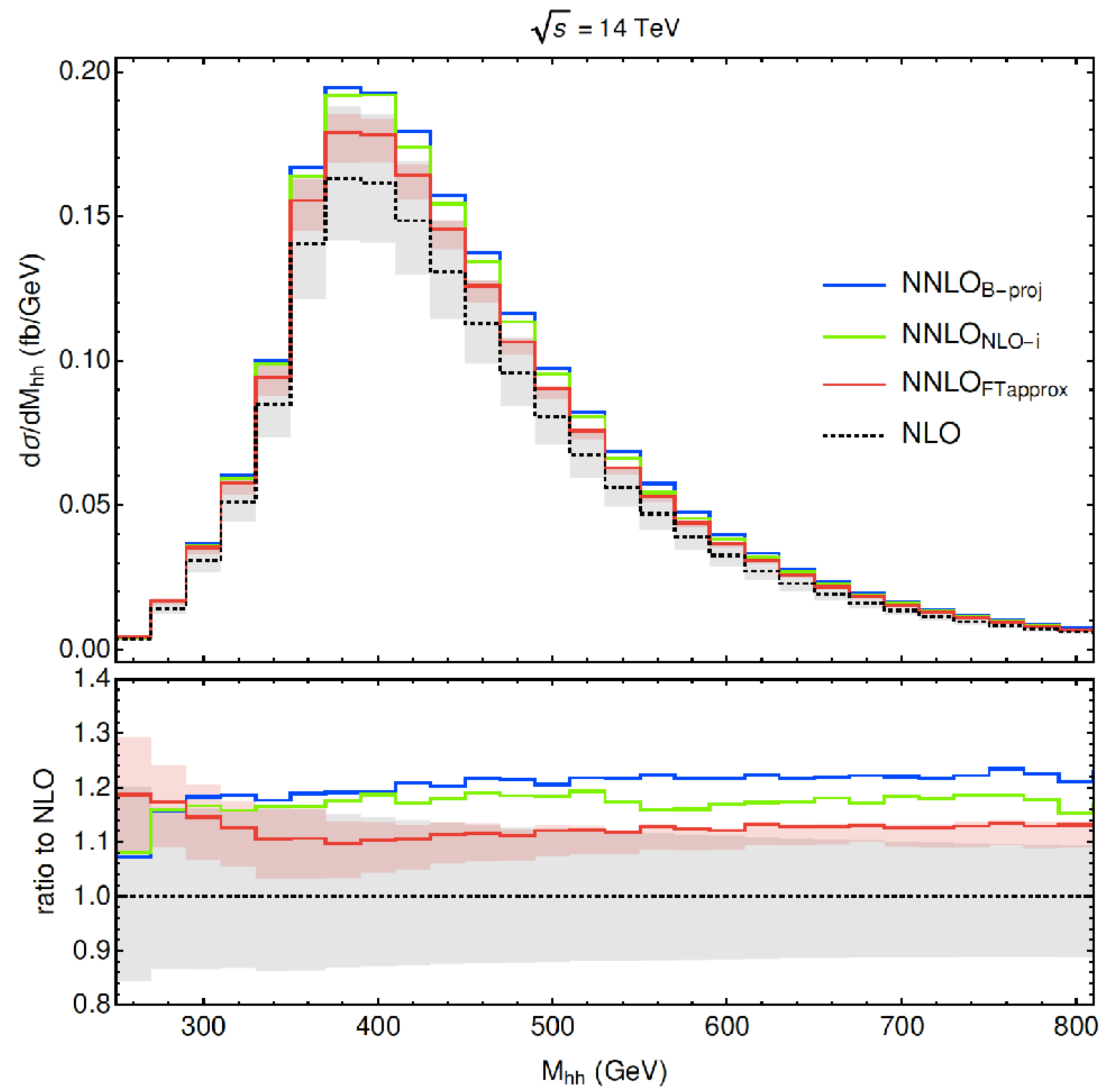
Higgs boson pair production in gluon fusion

Chen, Li, Shao, Wang 1912.13001



$\sqrt{s} = 14$ TeV

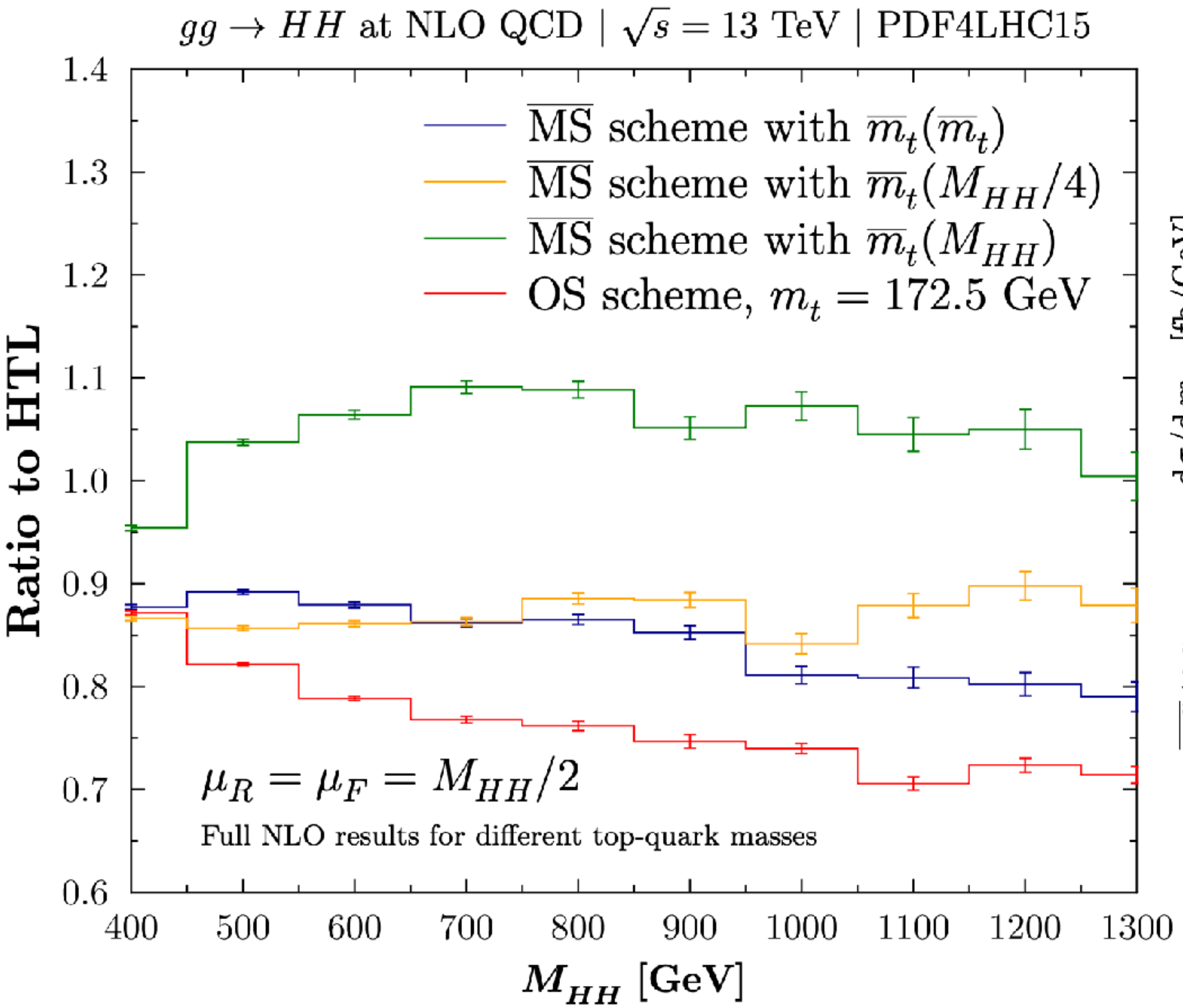
Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli 1803.02463

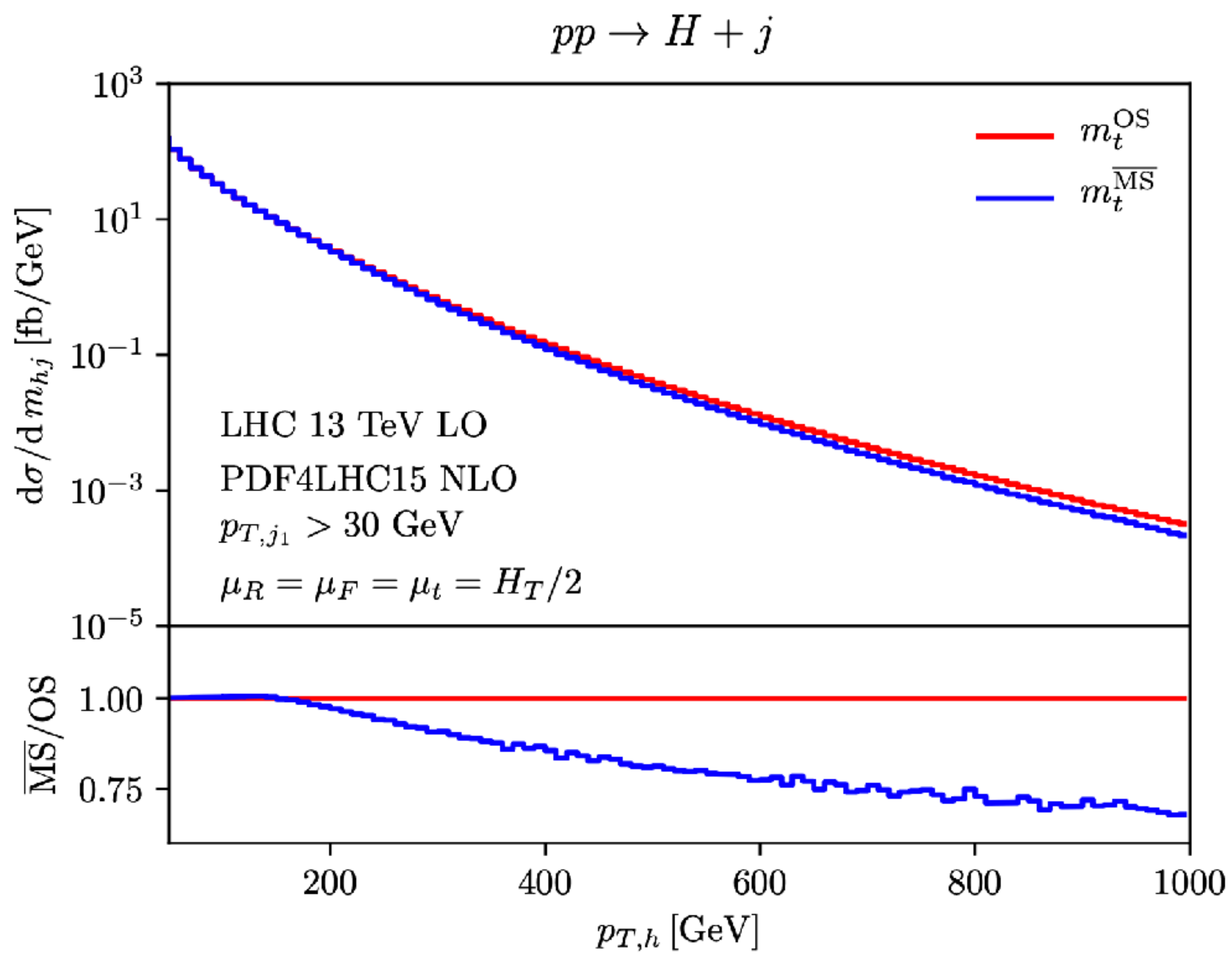


scheme dependence

$$\overline{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + K_2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3}$$

relation between pole mass and $\overline{\text{MS}}$ mass





Baglio, Campanario, Glaus Mühlleitner, Ronca, Spira 2003.03227, 2008.11626

also present in other loop induced processes

Jones, Spira Les Houches 2019

HH at NLO within EFT

SMEFT:

$$\Delta\mathcal{L}_{\rm dim6} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3 + \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\,G^a_{\mu\nu}G^{a\mu\nu}$$

HEFT (non-linear EFT):

$$\Delta\mathcal{L}_{d\chi\leq 4} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

SMEFT relations: $c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u\,, \quad c_{tt} = -\frac{\bar{c}_H + 3\bar{c}_u}{2}\,, \quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6\,,$

$$c_{ggh} = 2c_{gghh} = 128\pi^2\bar{c}_g\,.$$

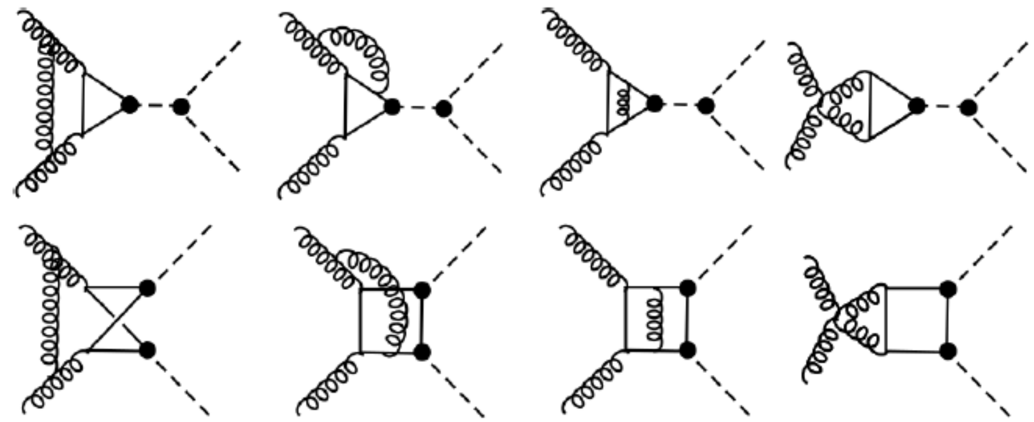
NLO QCD corrections

Buchalla, Capozi, Celis, GH, Scyboz ‘18

Example diagrams

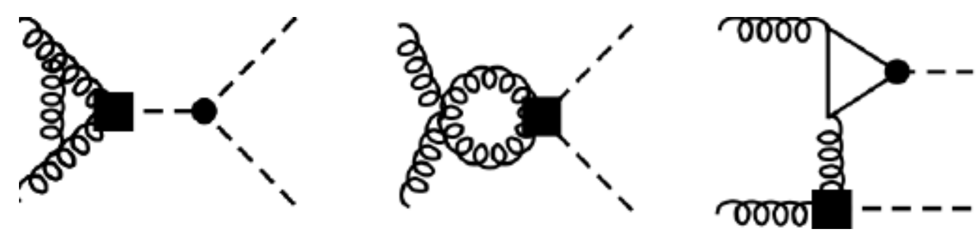
virtual corrections:

more loops



2-loop SM-like

Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke ’16

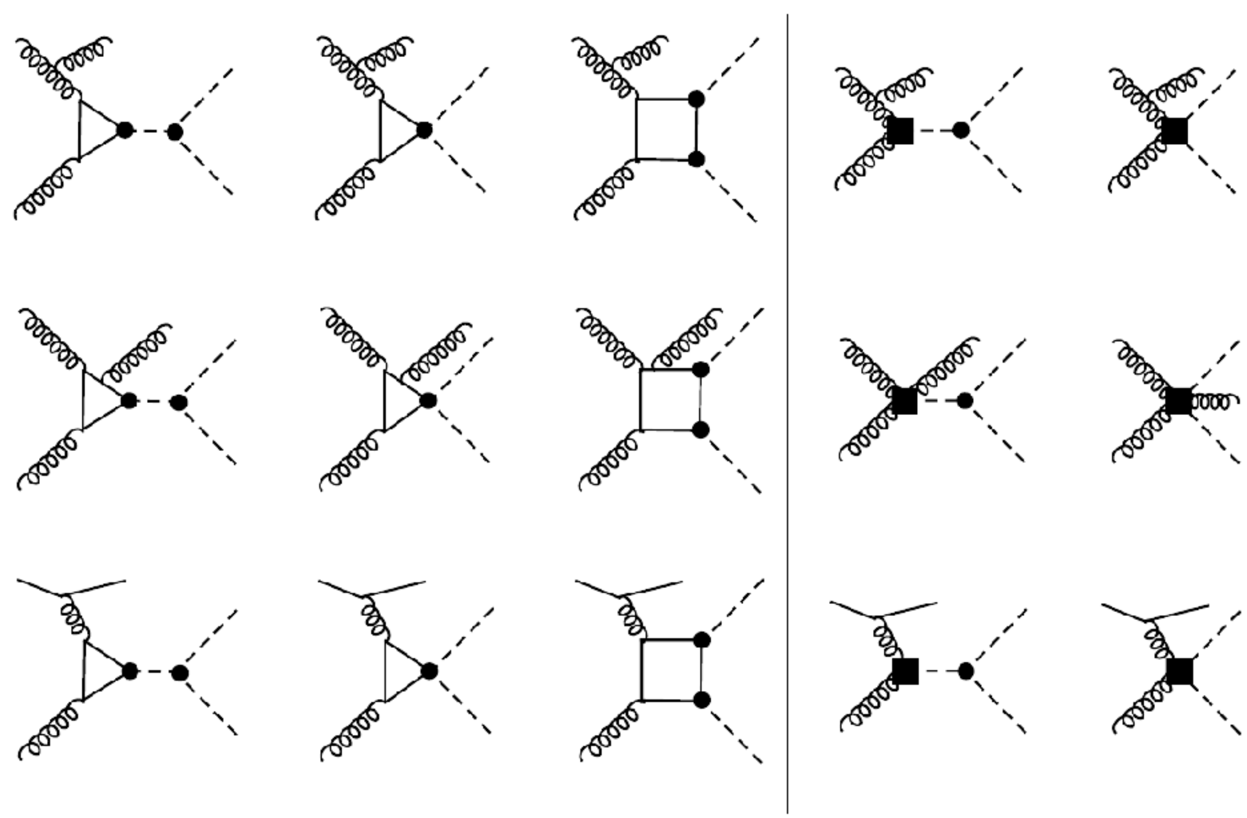


1-loop EFT

real corrections:

more legs

5-point 1-loop diagrams | tree diagrams $\propto c_{ggh}$, c_{gghh}



HH K-factors

K-factors as functions of the BSM couplings

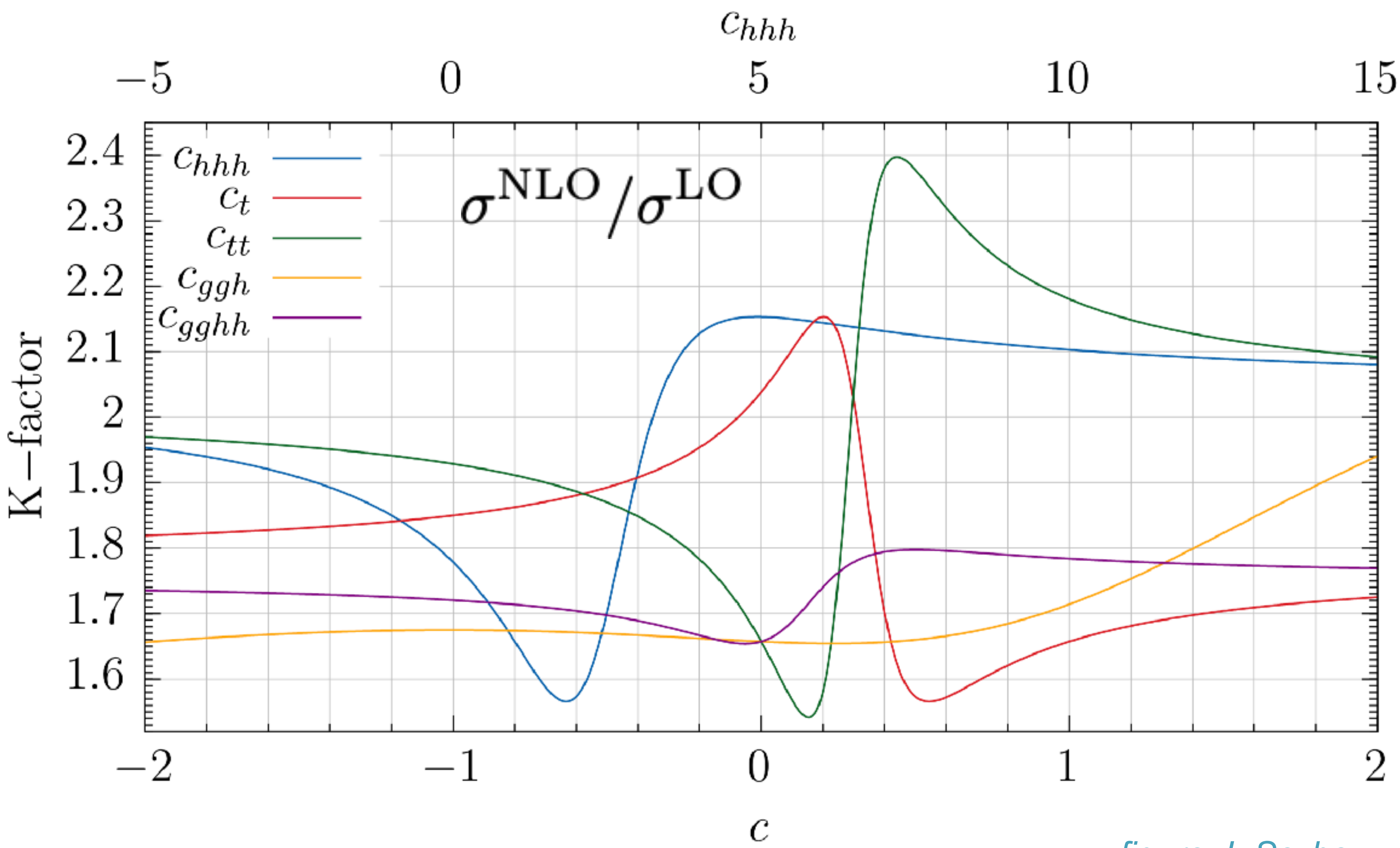


figure: L.Scyboz

vary substantially (much less variation in heavy top limit)

HH full NLO MC tool

- Monte Carlo program (within Powheg-Box) to produce full NLO results for Higgs pair production in gluon fusion

GH, Jones, Kerner, Luisoni, Scyboz 2006.16887,1903.08137

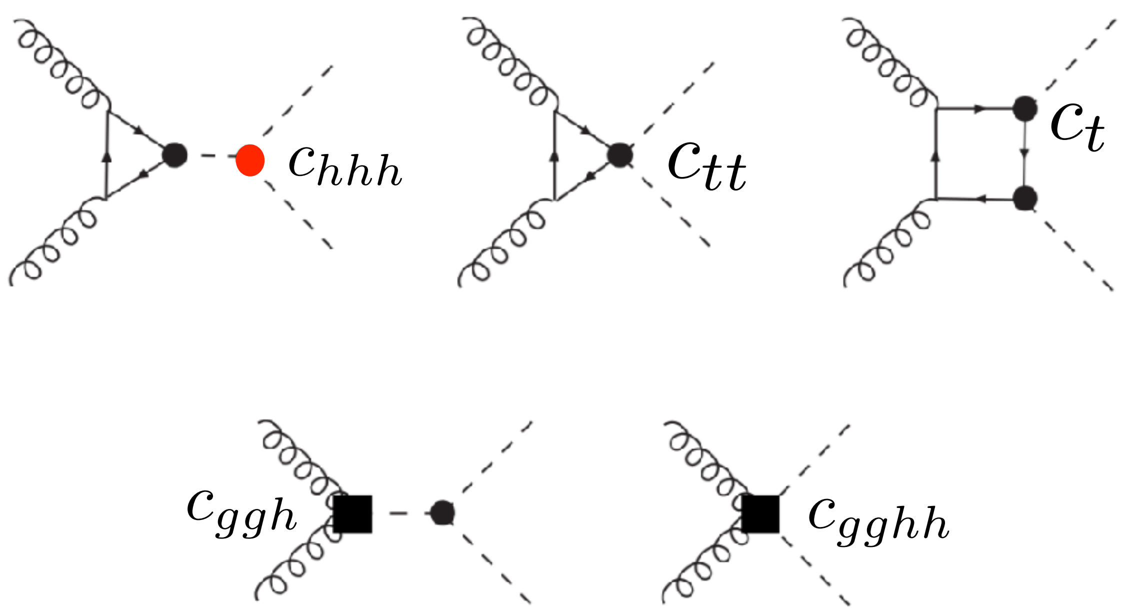
http://powhegbox.mib.infn.it/User-Process-V2/ggHH

- interface to Pythia and two different Herwig parton showers

- 5 anomalous couplings

$c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}$

can be varied by the user



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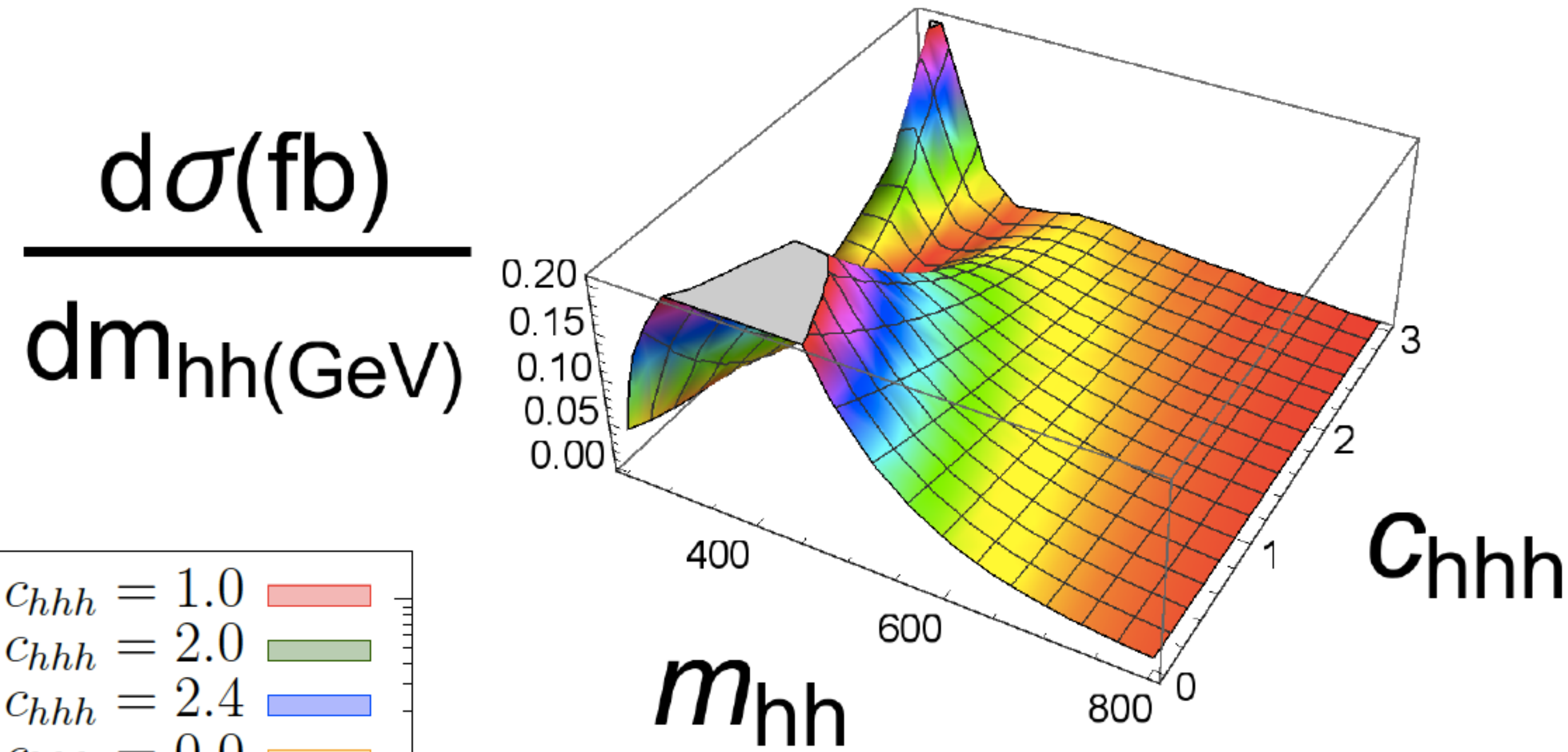
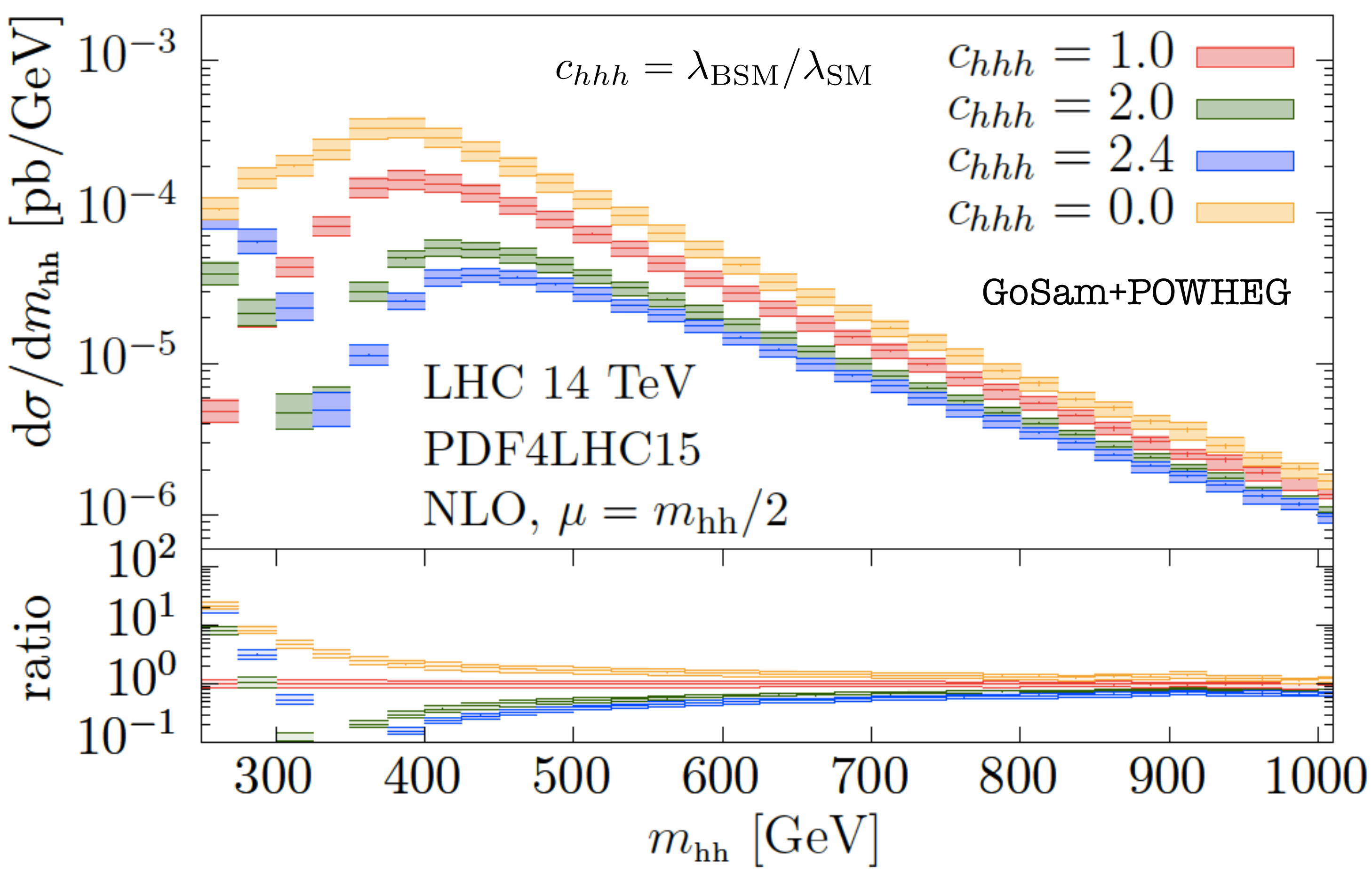
HH invariant mass with variation of the self-coupling

$$m_{hh} = (p_{h_1} + p_{h_2})^2$$





dip in m_{hh} distribution

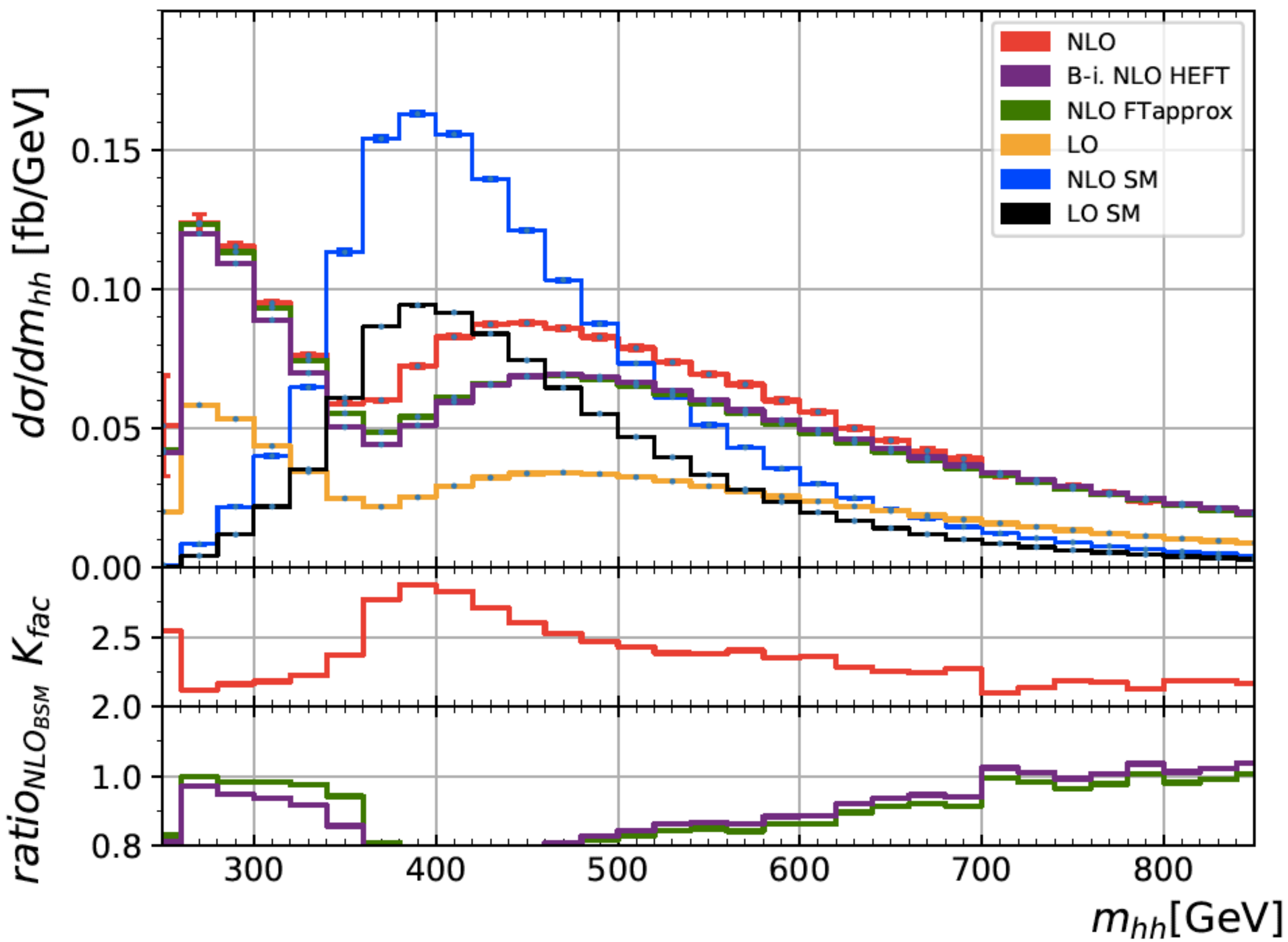
at 350 GeV for c_{hhh} ~ 2.4

due to maximal destructive interference

bands: 3-point scale variations

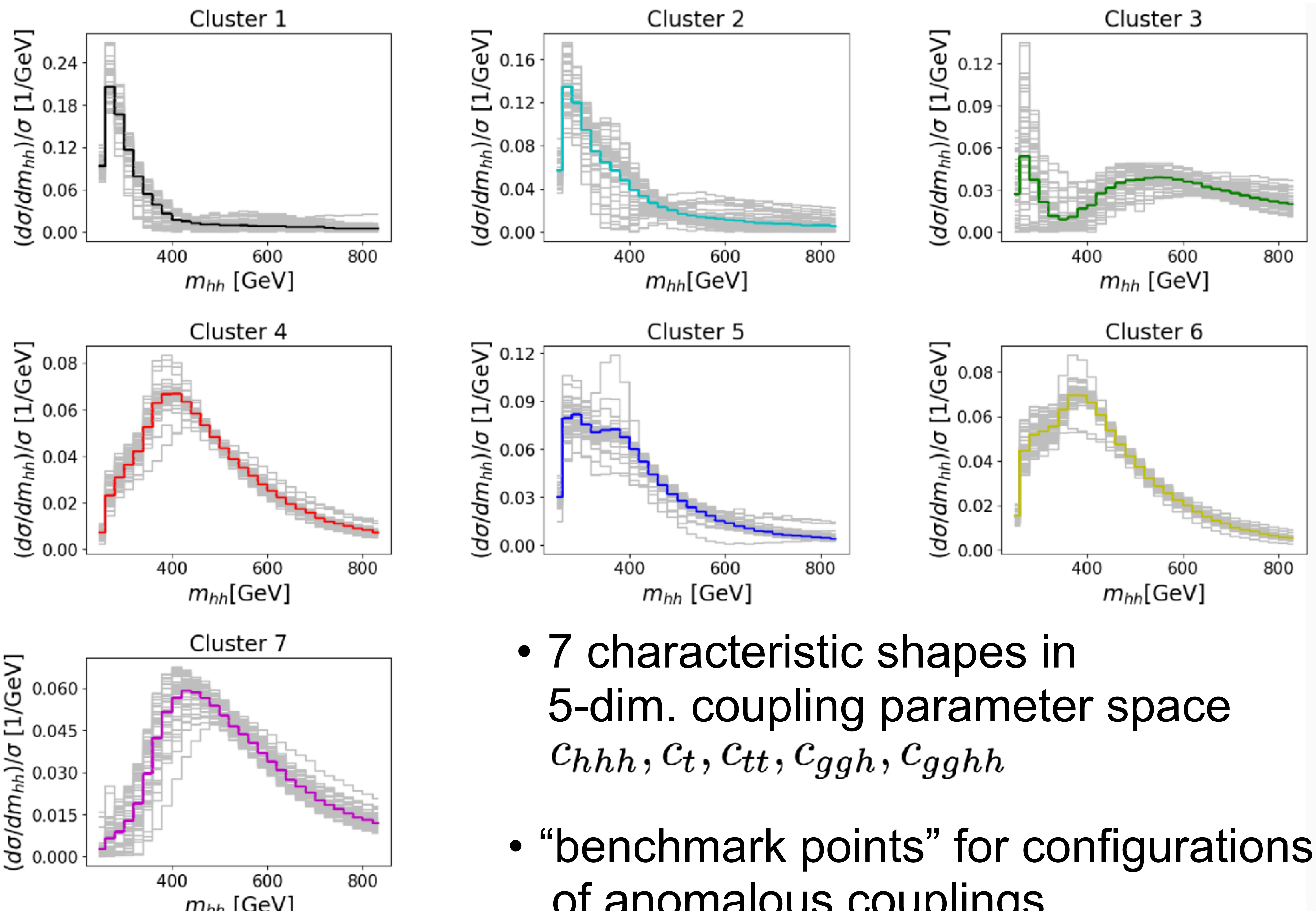
m_{hh} shape analysis

$$c_{hhh} = 1, c_t = 1, c_{tt} = 0.5, c_{ggh} = 4/15, c_{gghh} = 0$$



dip, even though $c_{hhh} = 1, c_t = 1$

m_{hh} shape analysis

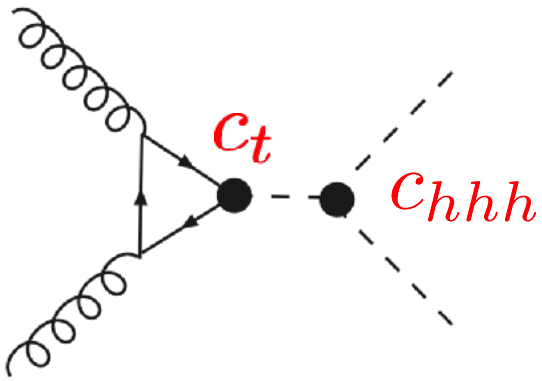


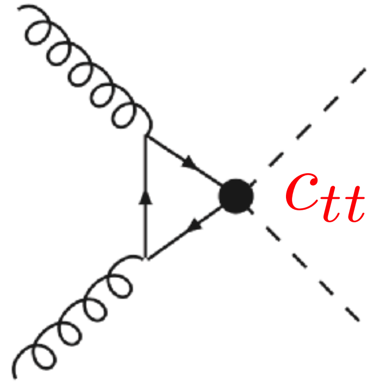
- 7 characteristic shapes in 5-dim. coupling parameter space $c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}$

- “benchmark points” for configurations of anomalous couplings

- based on autoencoder and K-means clustering M. Capozi, GH 1908.08932

m_{hh} shape analysis

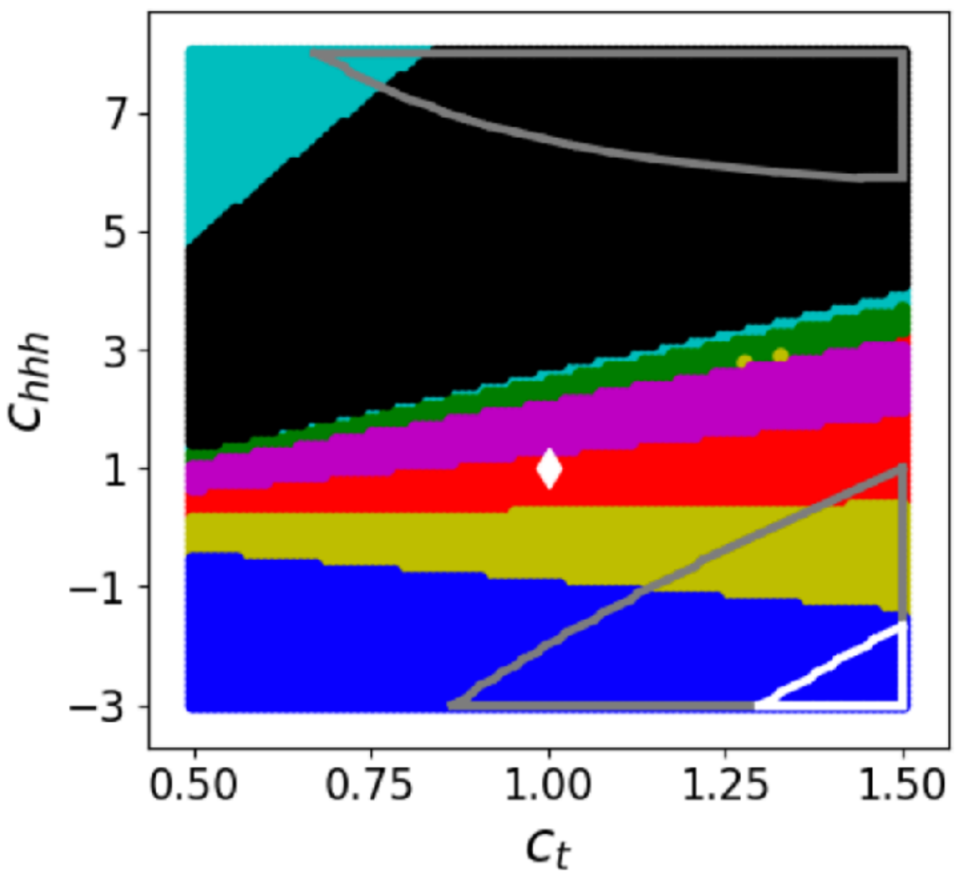


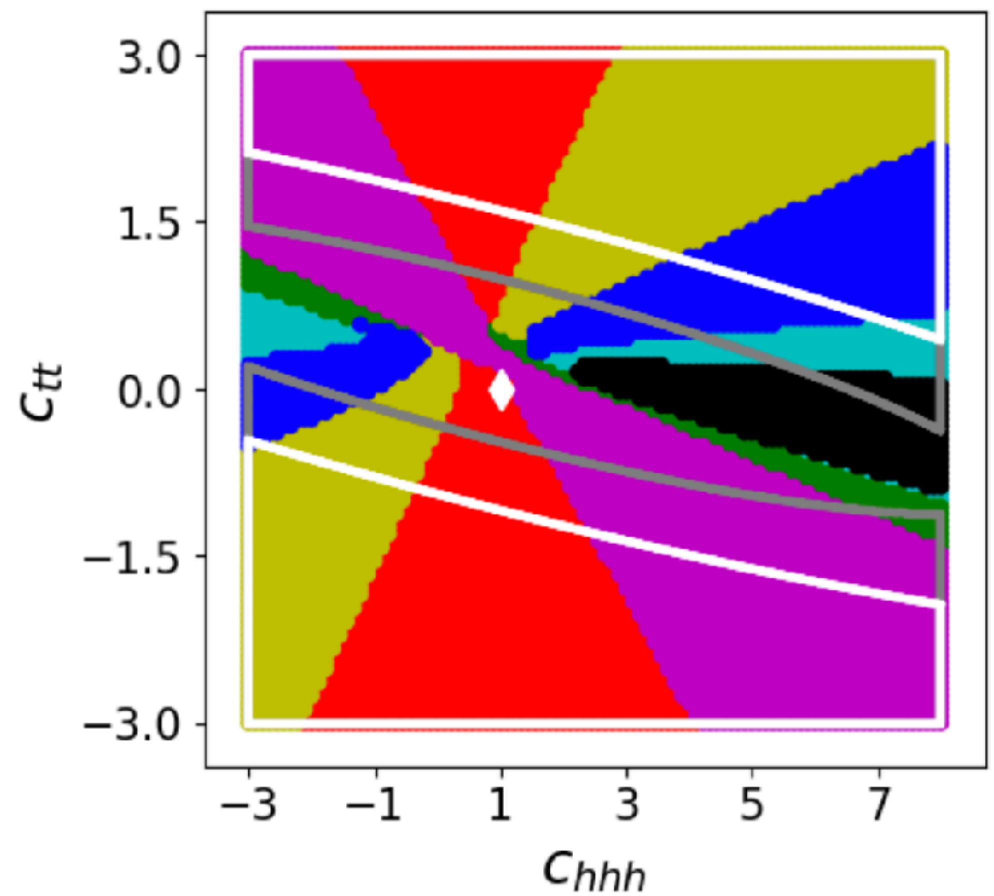


red: SM-like,

magenta: enhanced tail,

black: enhanced low m_{hh}





silver lines: limits on total cross section

$$\sigma^{HH}_{\max} = 6.9 \times \sigma_{SM}$$

c_{hhh} and c_{tt} have strong influence on shape

c_{tt} enhances total cross section

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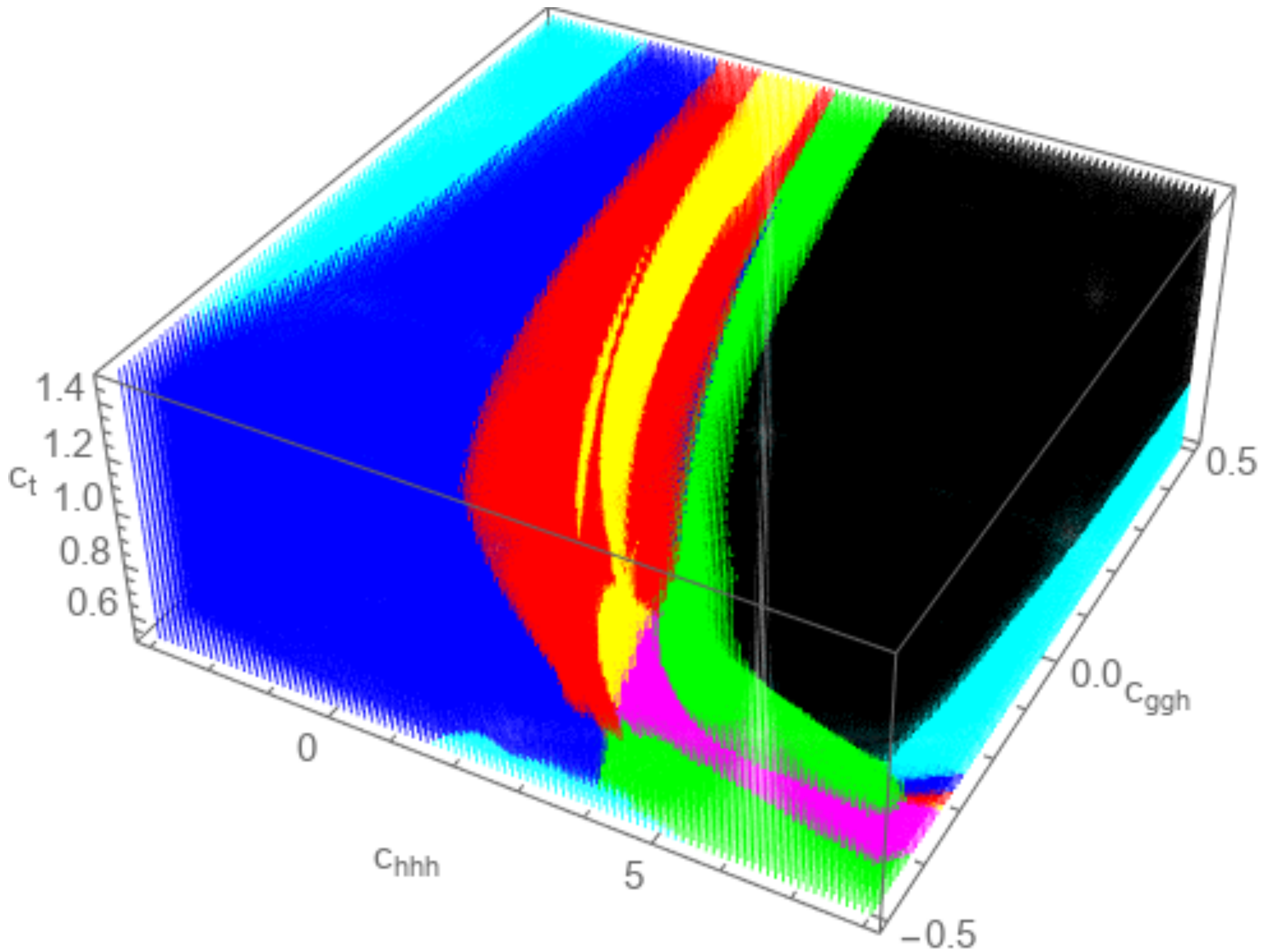
shape analysis



red: SM-like shape

yellow: SM-like with shoulder left of peak

green: second local maximum above $m_{hh} \simeq 2m_t$

blue: close-by double peaks or shoulder right

black: enhanced low m_{hh}

used $c_{gghh} = 0.5 c_{ggh}$ and $c_{tt} = 0.05 c_t$

(simulation of SMEFT situation)

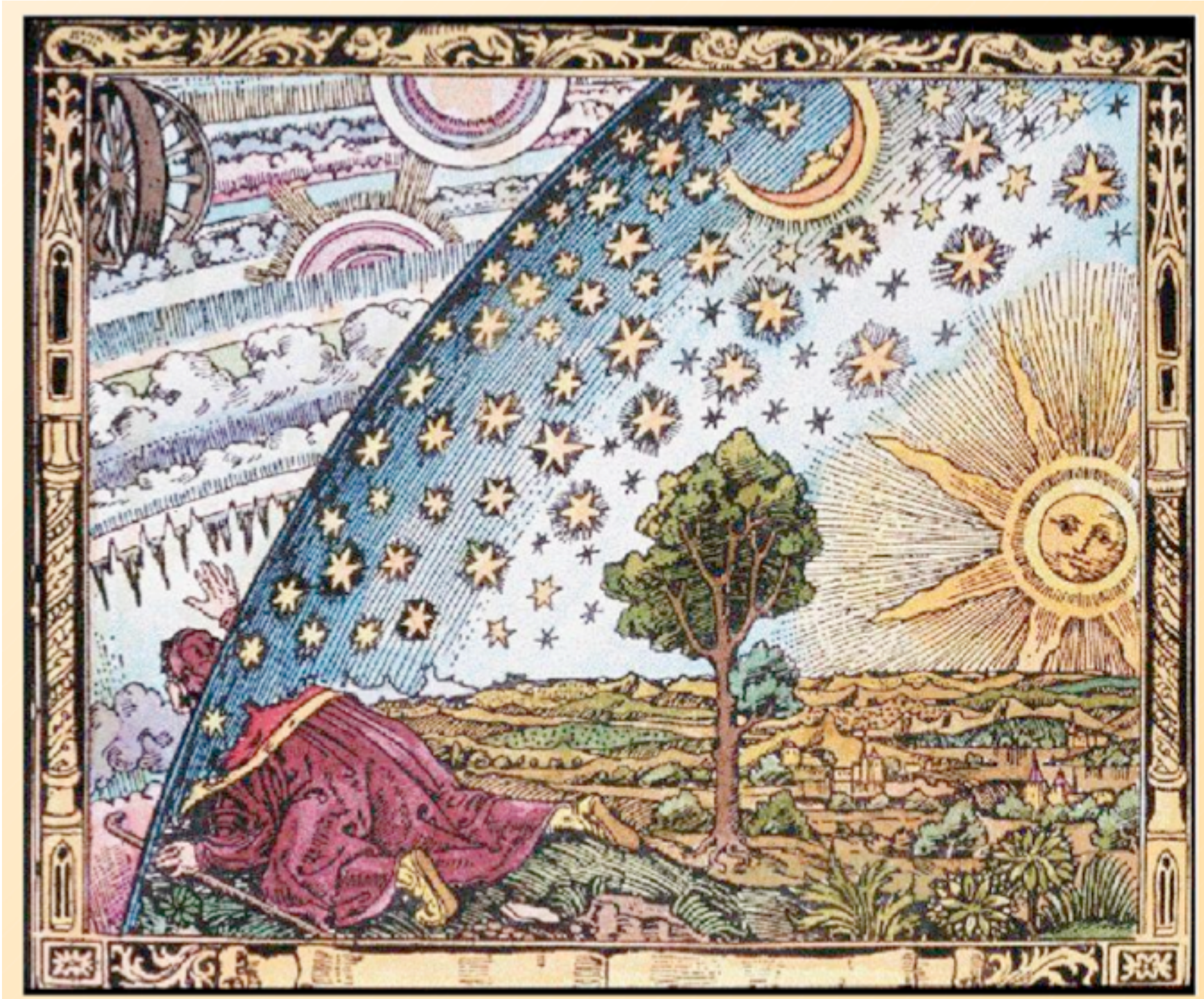
- enhanced low m_{hh} region not possible for SM value of c_{hhh}

Summary

- the Higgs sector might offer windows to new physics
- precision is the key at current energies
- great progress in precision calculations

  for some processes scale uncertainties no longer the dominant uncertainties

- current main challenges:
  - mass effects
  - mixed EW-QCD corrections
  - $2 \to 3$ processes at NNLO
  - reduce PDF, α_s-uncertainties
  - NNLO+PS/analytic resummation
  - BSM, EFT + higher orders



BACKUP SLIDES

Two EFT frameworks

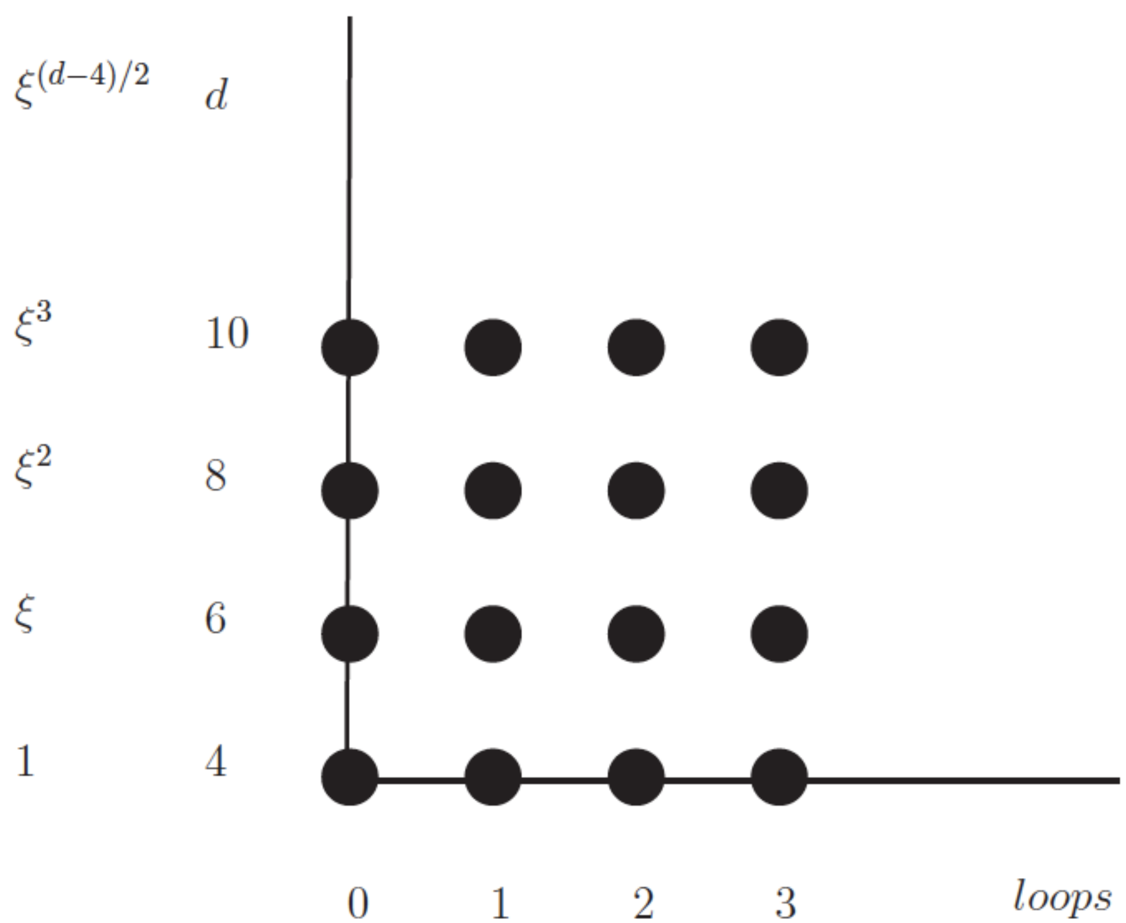
HEFT (EWChL): “loop expansion”

based on chiral dimension $d_\chi = 2L + 2$ L: “Loop”

with $d_\chi(A_\mu, \varphi, h) = 0, \;\; d_\chi(\partial, \bar\psi\psi, g, y) = 1$

expansion in canonical dimension $1/\Lambda^2$

SMEFT



loop expansion

HEFT

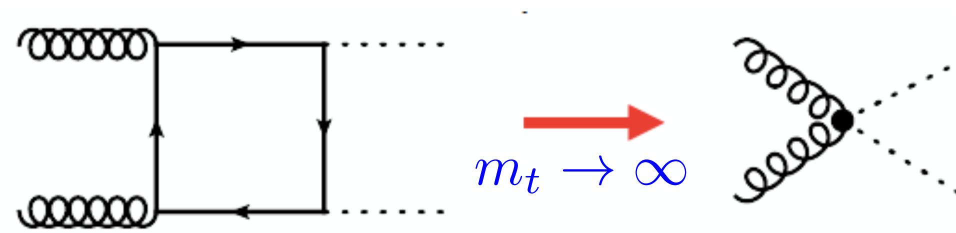
figure: G.Buchalla

Invariant mass of the Higgs boson pair

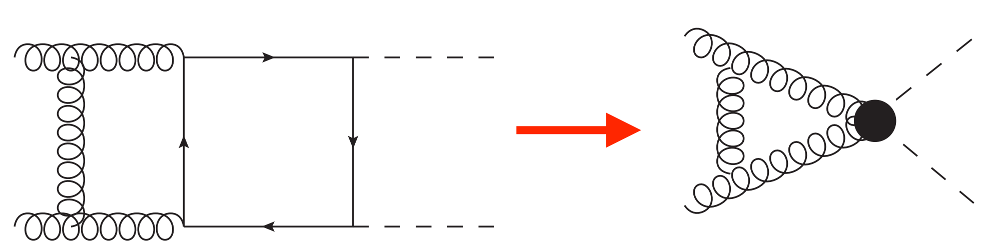
Observable: $m_{hh}^2 = (p_{h_1} + p_{h_2})^2$

approximations:

- $m_t \to \infty$ limit (HEFT):
  ("Higgs Effective Field Theory")



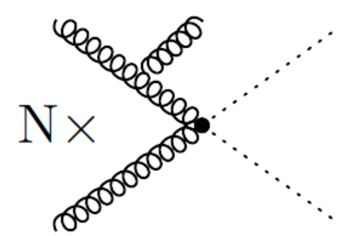
Leading Order (LO)



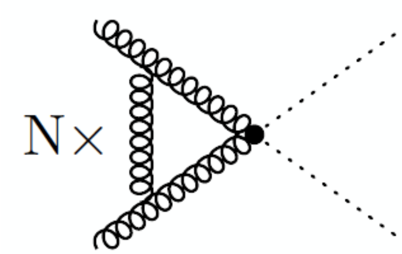
Next-to-Leading Order (NLO)

- Born-improved HEFT:

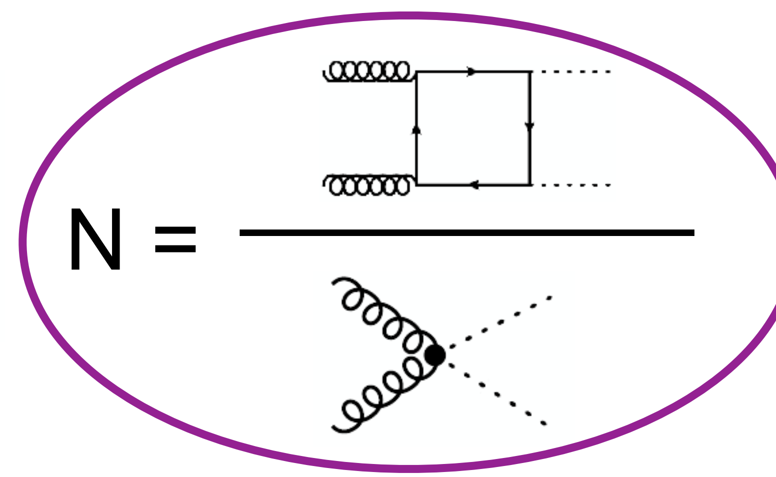
$$d\sigma^{\rm NLO}_{m_t\to\infty} \times \frac{d\sigma^{\rm LO}(m_t)}{d\sigma^{\rm LO}_{m_t\to\infty}}$$



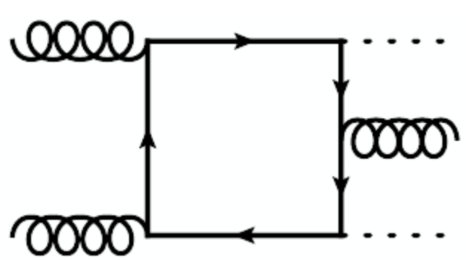
NLO real

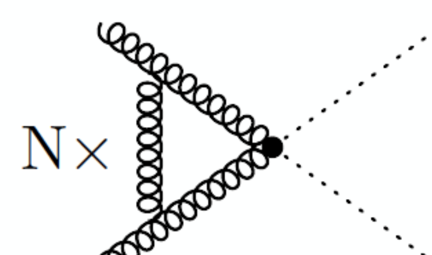


NLO virtual



- FTapprox:





NLO real:
full m_t-dependence

NLO virtual:
Born-improved HEFT