

# Collider Physics at the Precision Frontier



PARTICLE PHYSICS  
**How physicists are probing the Higgs boson 10 years after its discovery**

The famous particle may point to cracks in the standard model and new physics beyond

Physicists are searching for surprises in the properties and behavior of the Higgs boson. Anything unexpected might point to new physics.

NICOLLE R. FULLER/SAYOSTUDIO

<https://www.sciencenews.org/article/higgs-boson-particle-physics-standard-model-discovery-anniversary>

**Gudrun Heinrich**

*Institute for Theoretical Physics,  
Karlsruhe Institute of Technology*

**HET Seminar**

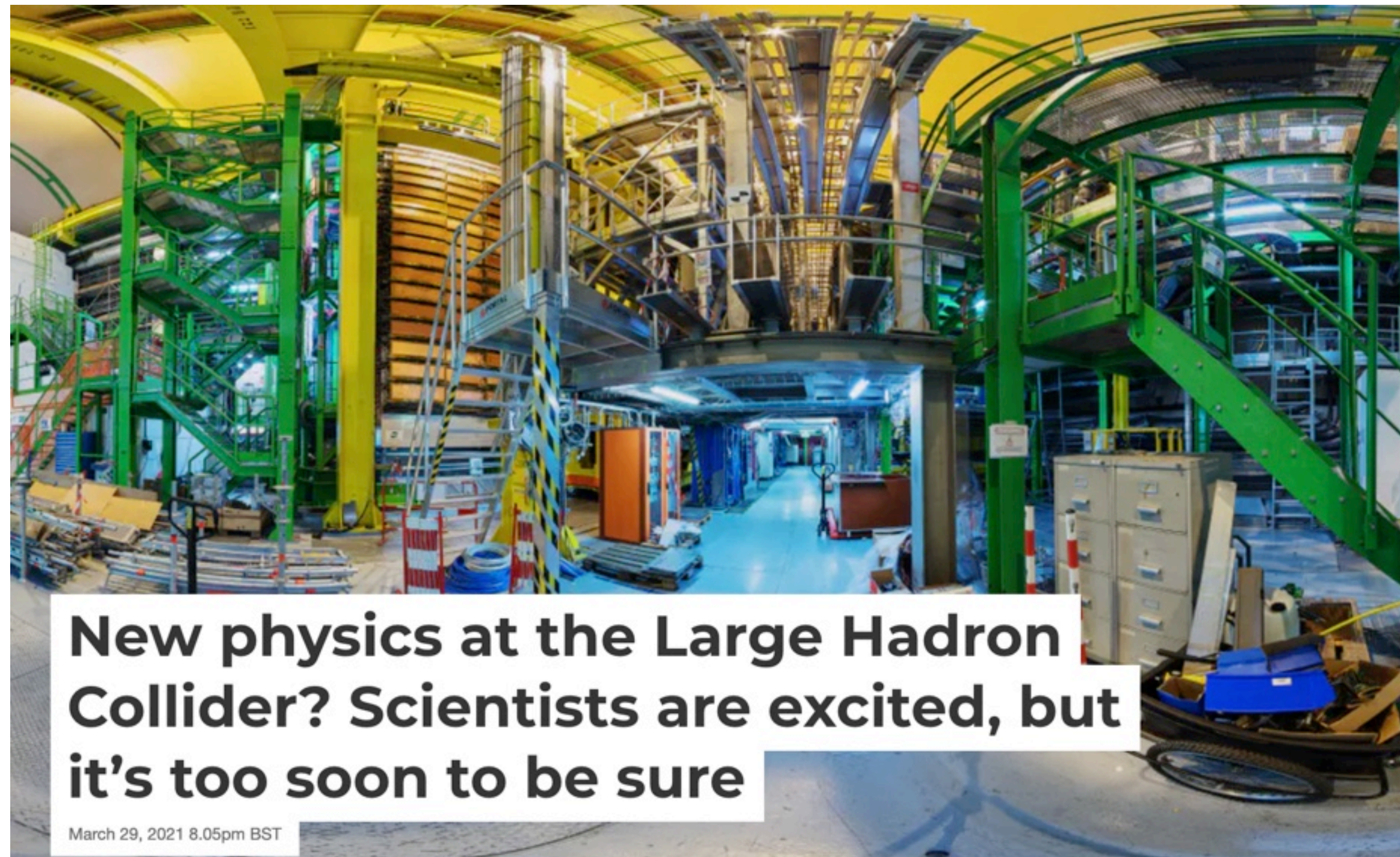
**Brookhaven National Laboratory**

*July 21, 2022*

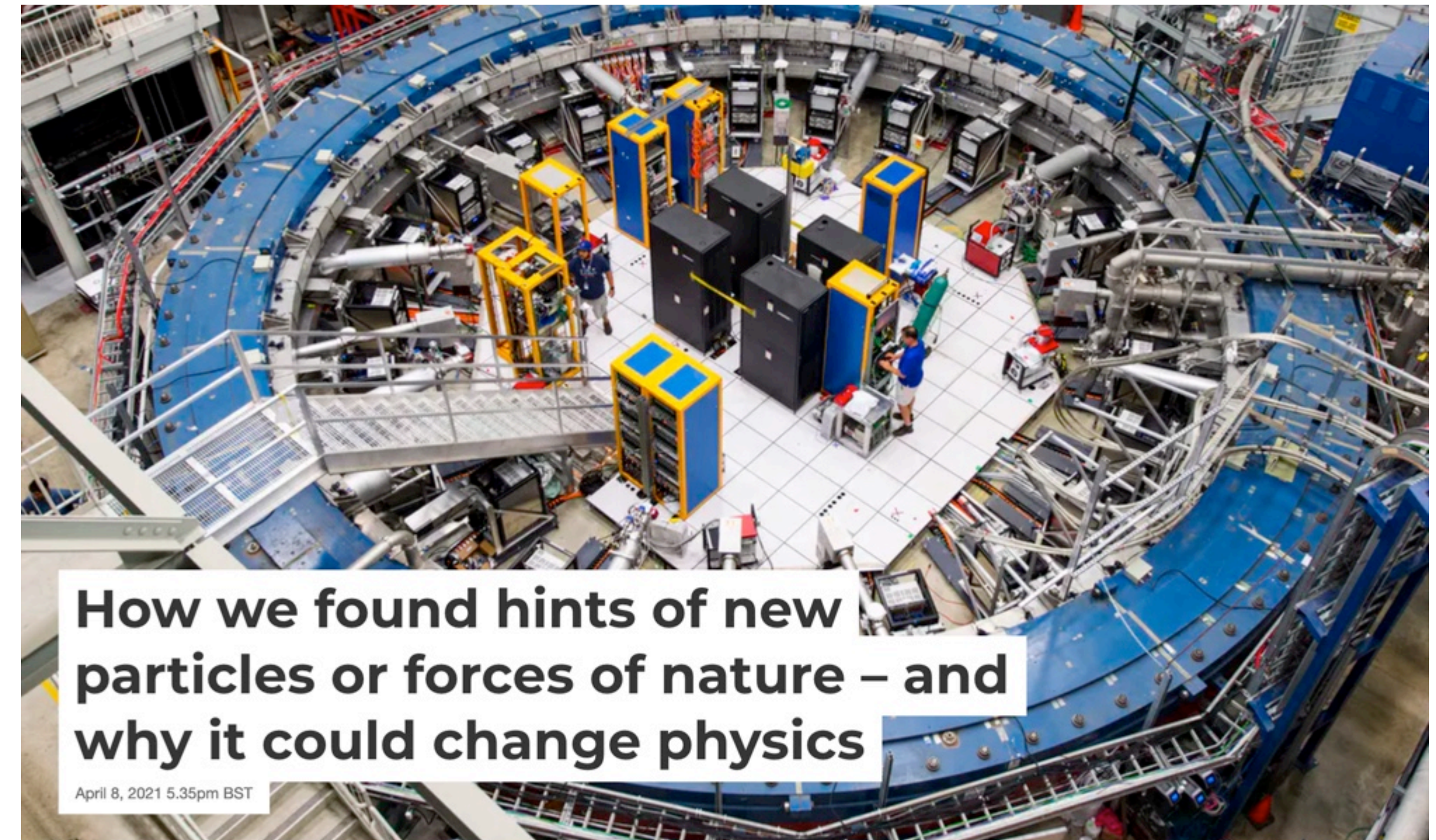


# Motivation

**The Standard Model of Particle Physics  
is unlikely to be the end of the story**



LHCb (CERN)



The muon experiment. Reidar Hahn/Fermilab

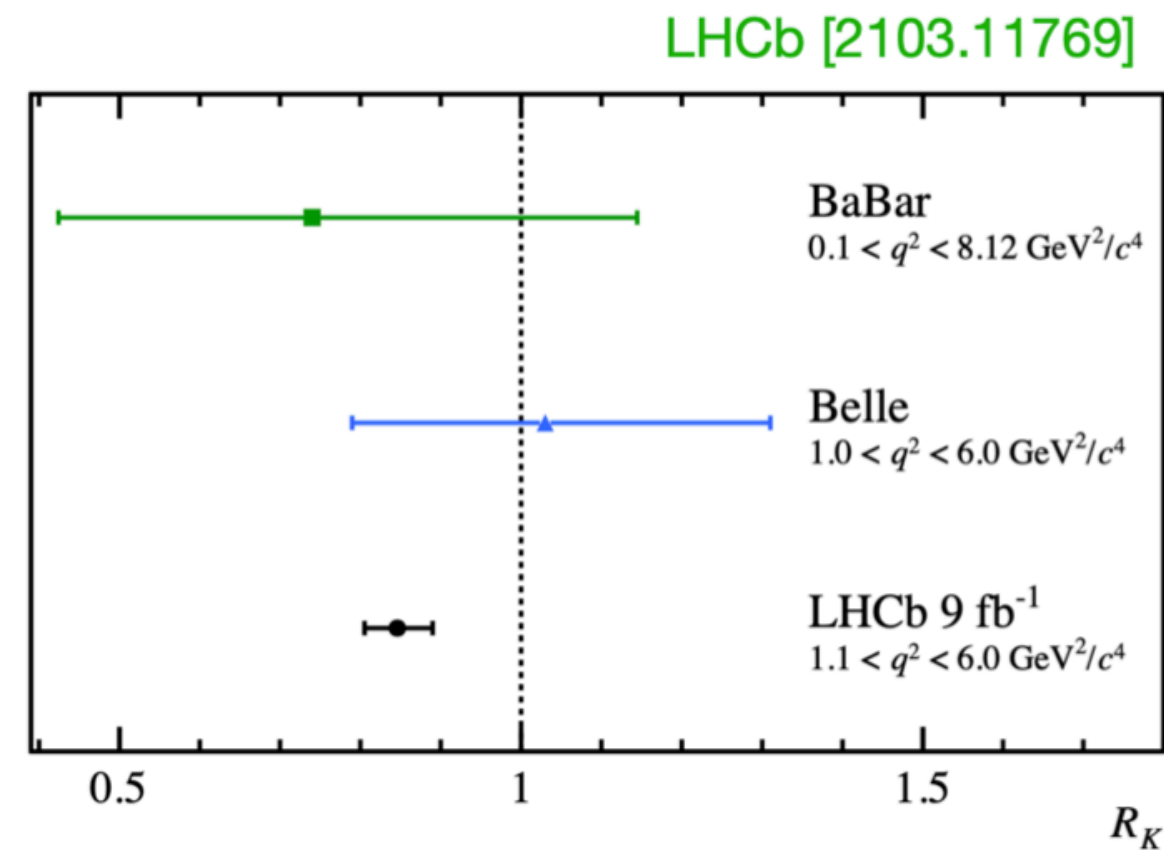
muon anomalous magnetic moment measurement  
(Fermilab)



# Motivation

Exciting new experimental value of  $R_K$

$$R_H \equiv \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow He^+e^-)}{dq^2} dq^2}$$

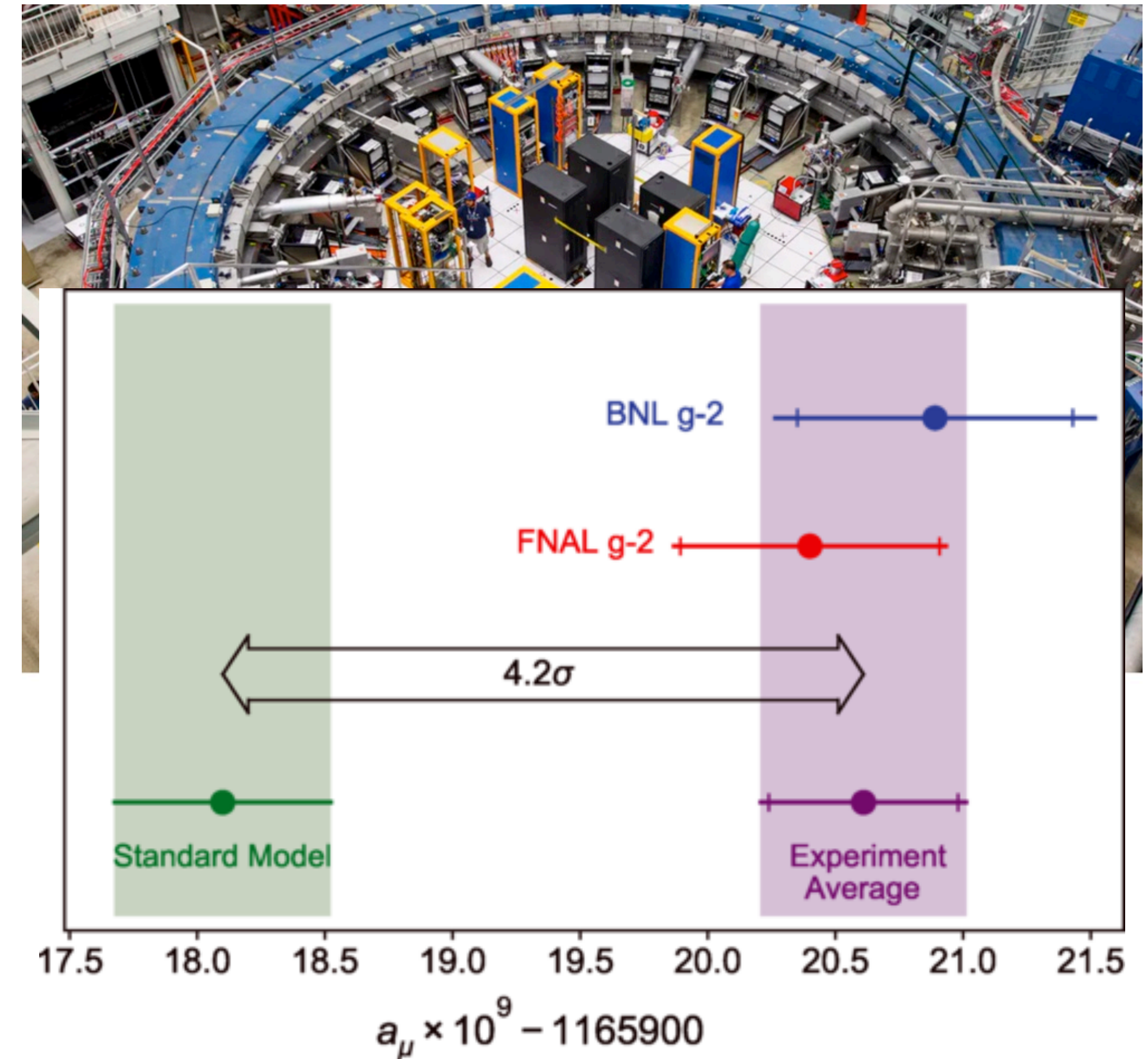


$$R_K^{\text{LHCb}} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

+ Likelihood

⇒ 3.1σ !!

M. Alguero, Moriond 2021





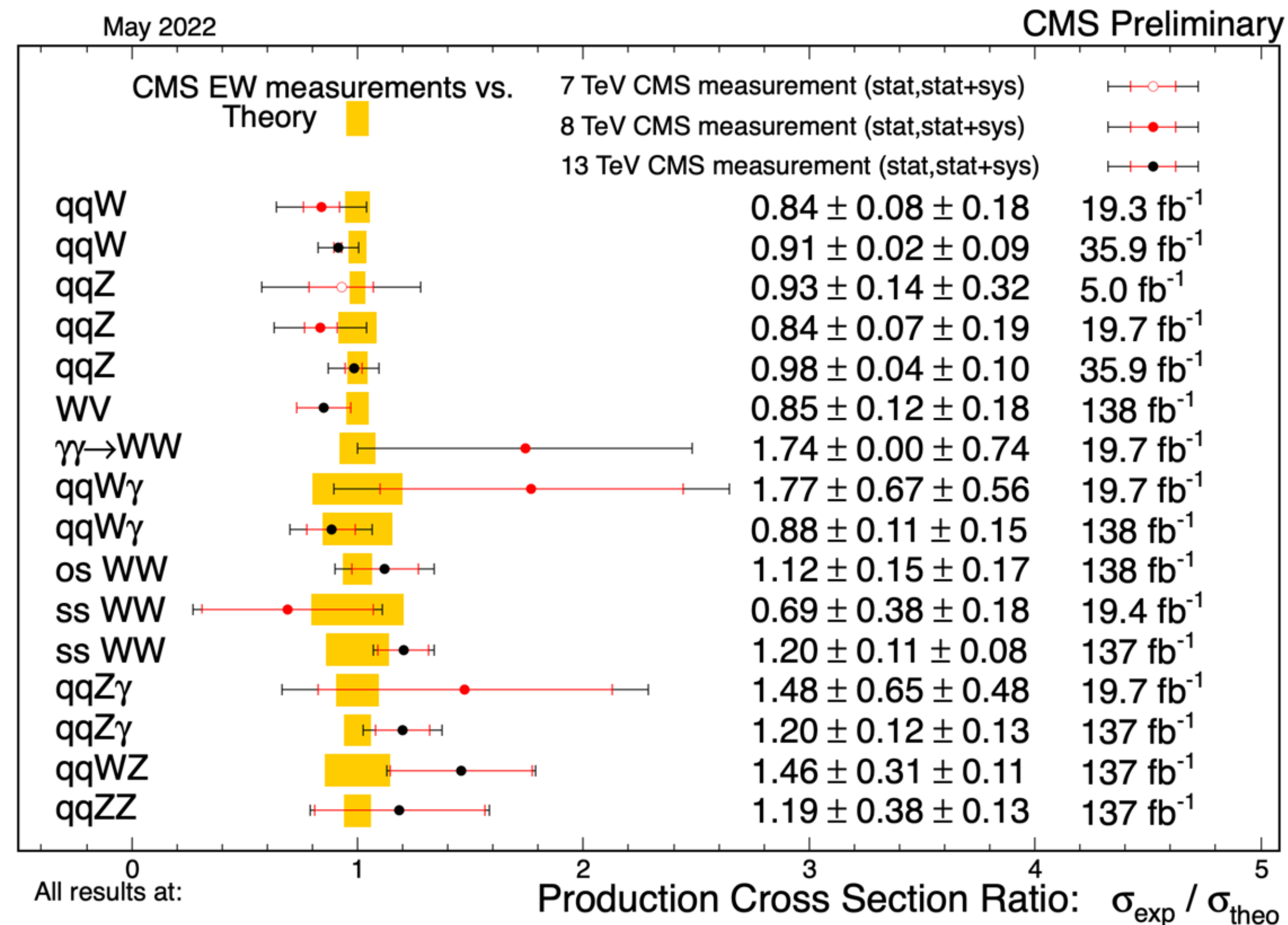
# Current high energy frontier





# Current high energy frontier

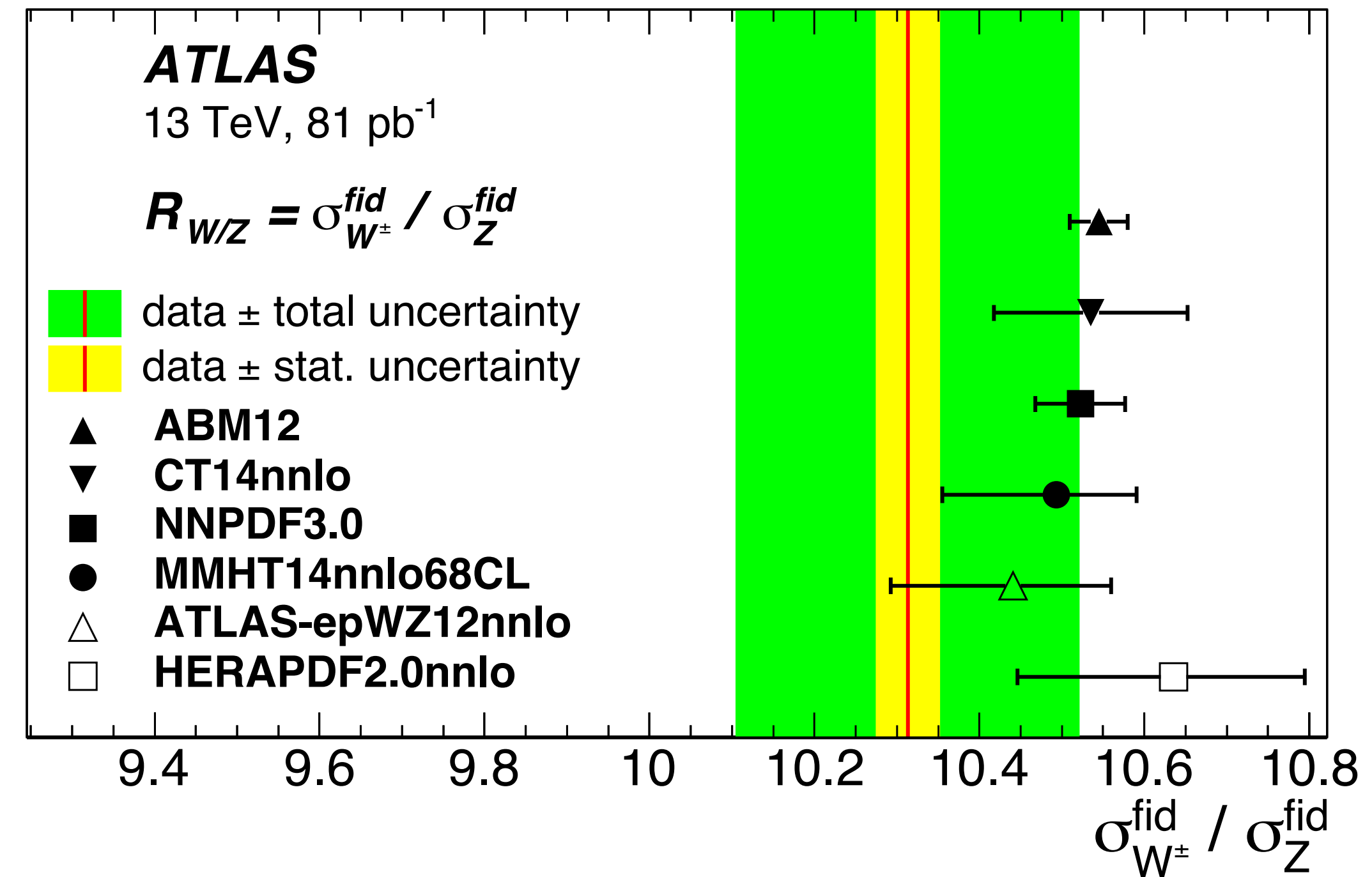
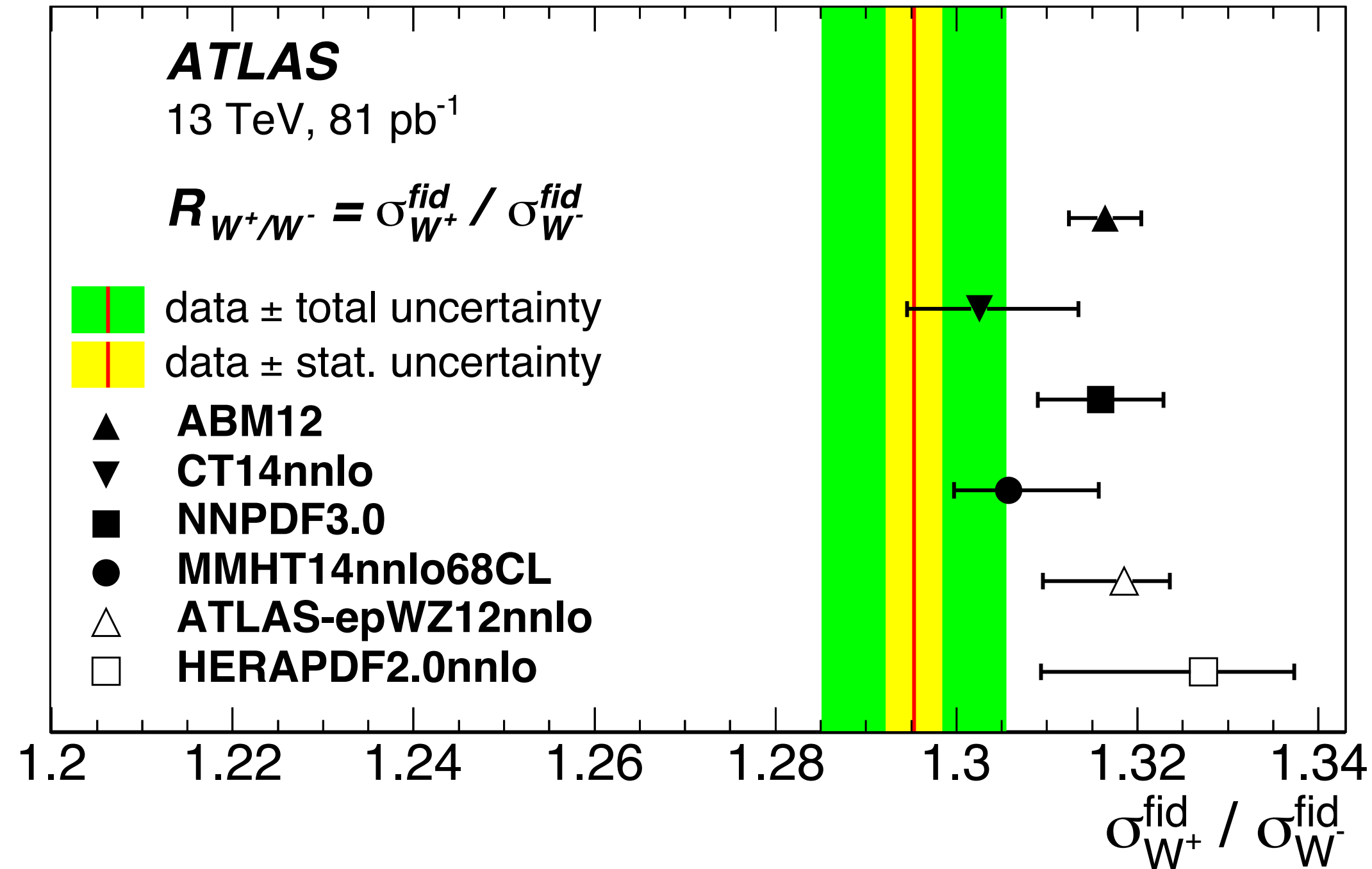
- at the current energy frontier, no hints of new physics (?)



- however, this is a question of **precision**



# The need for precise predictions



1603.09222

large spread in theory predictions based on different parton distribution functions

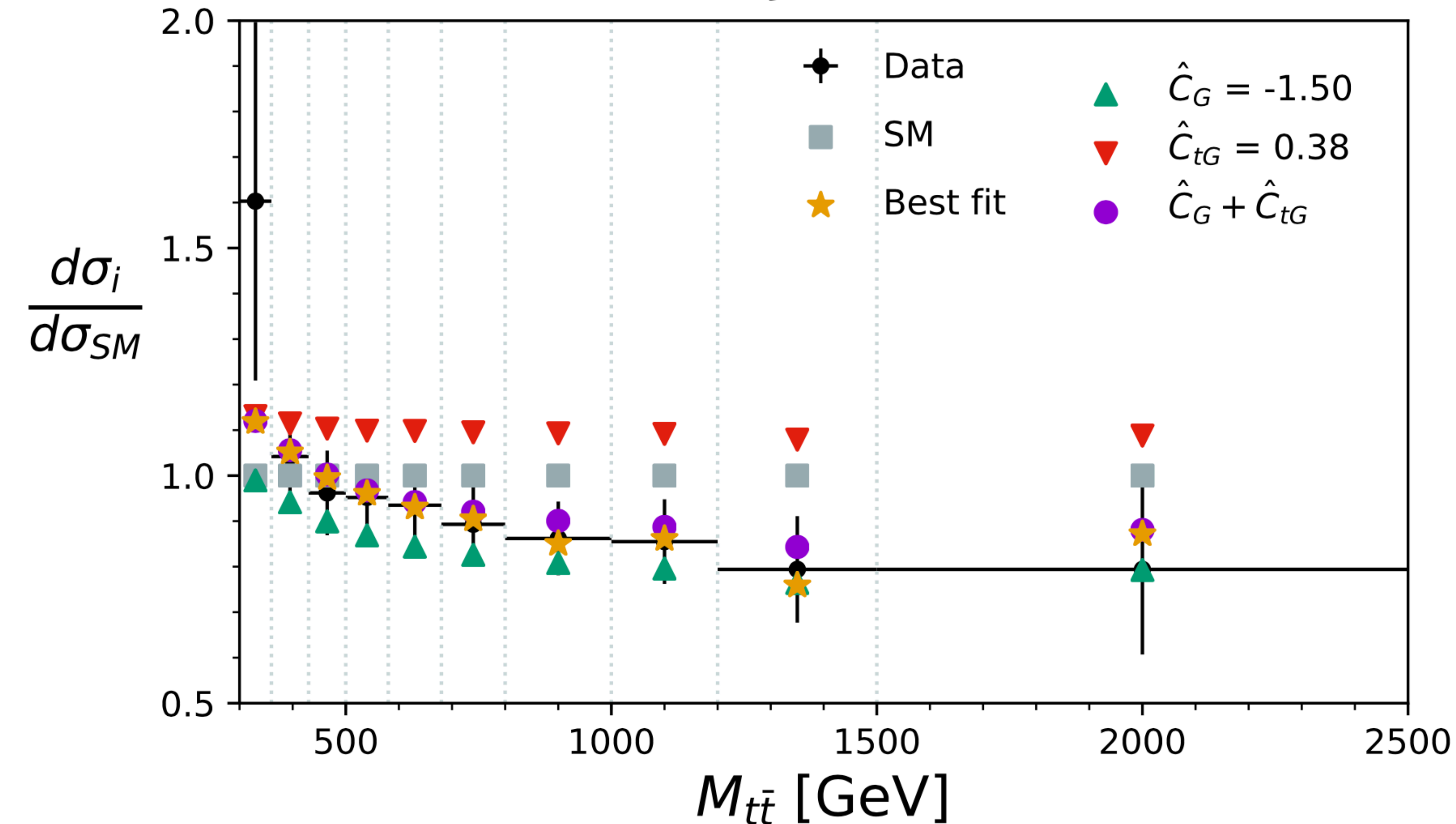
**note:** very recent results on approximate N3LO PDFs! (MSHT20 aN3LO)

McGowan, Cridge, Harland-Lang, Thorne, 2207.04739



# EFT parametrisation of new physics effects

## CMS $t\bar{t}(\text{l+jets})$ , 13 TeV



top quark pairs at large invariant mass

best fit includes anomalous couplings

J. Ellis, Madigan, Mimasu, Sanz, You  
2012.02779

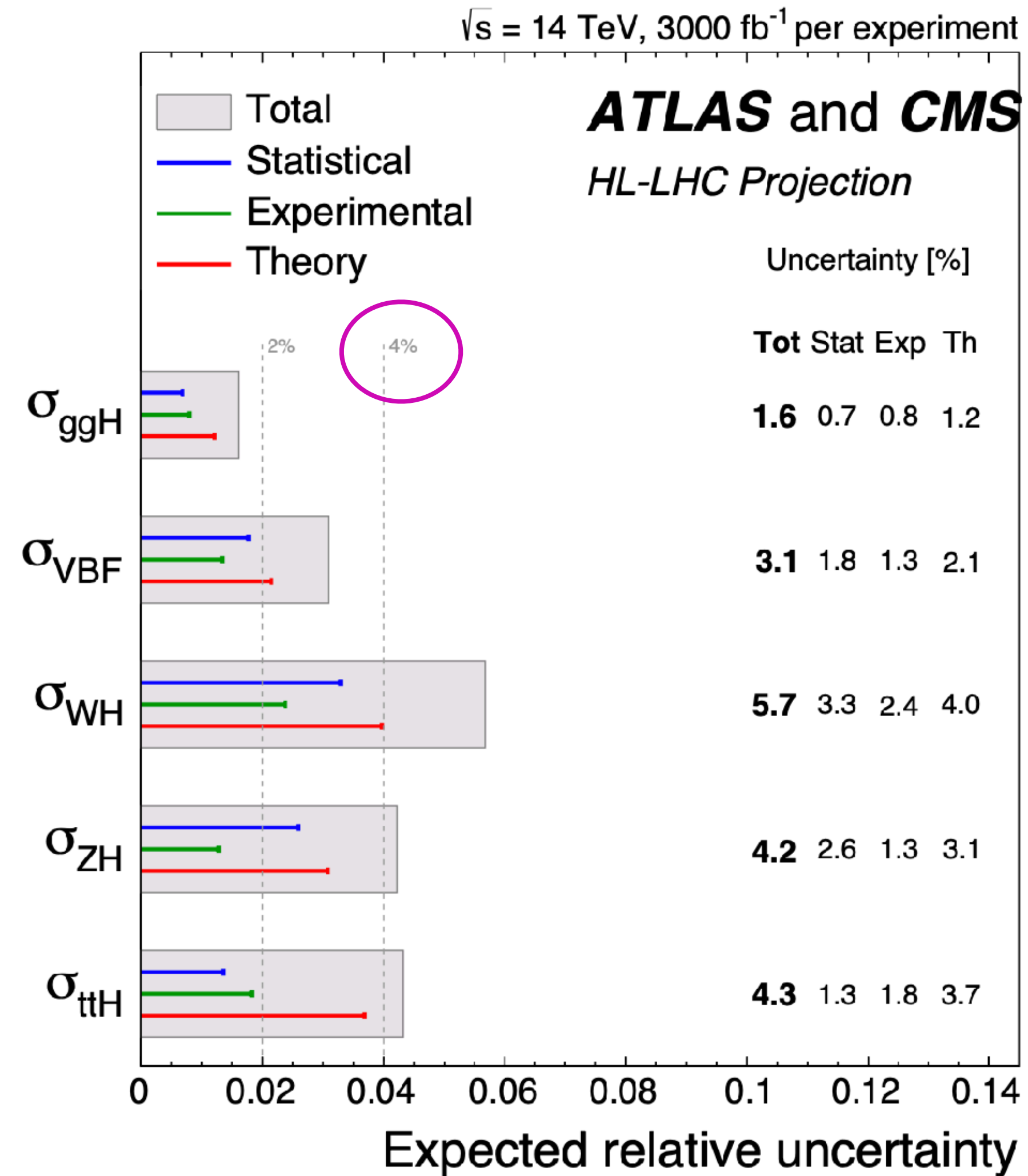
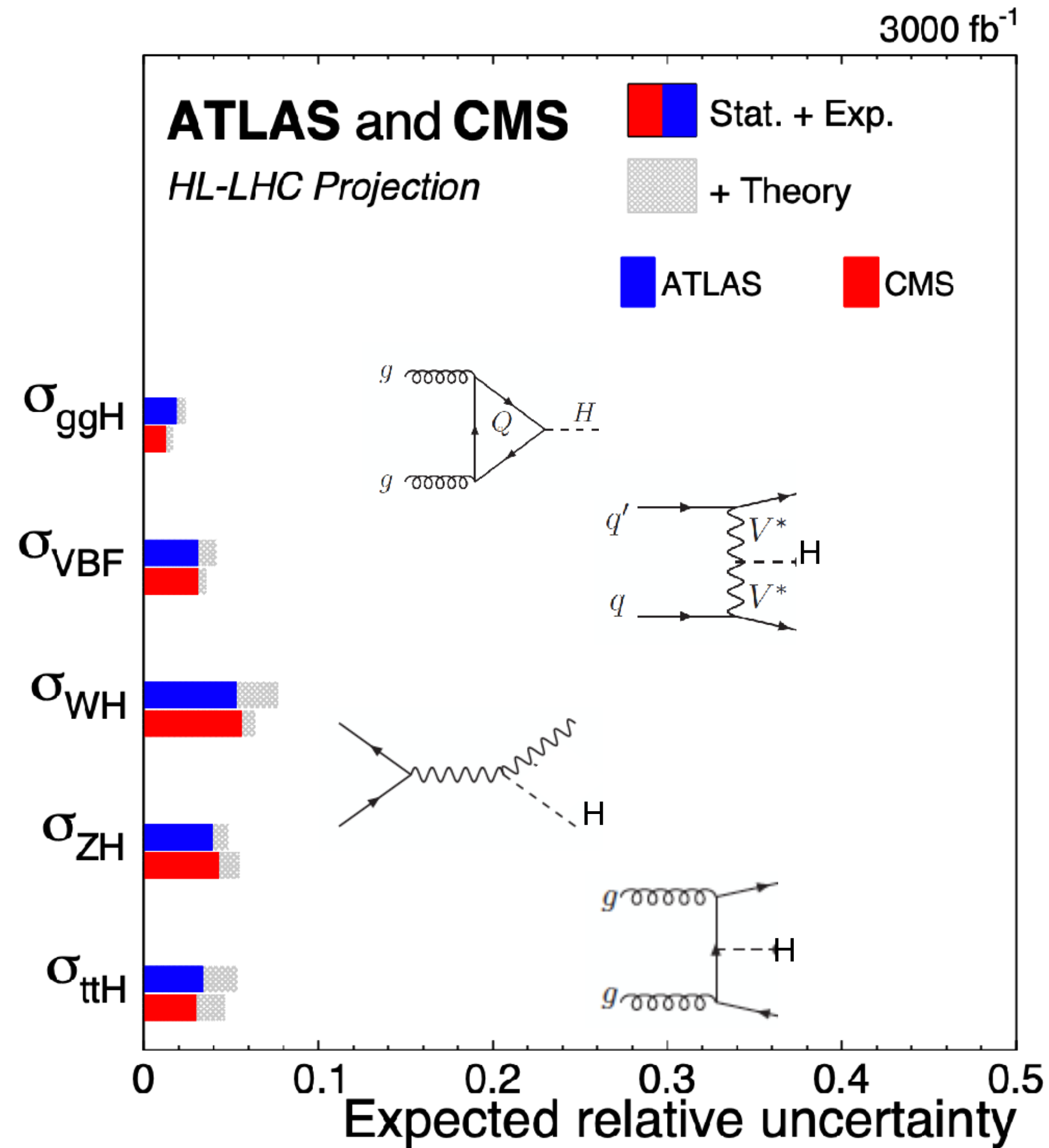


# High-Luminosity LHC





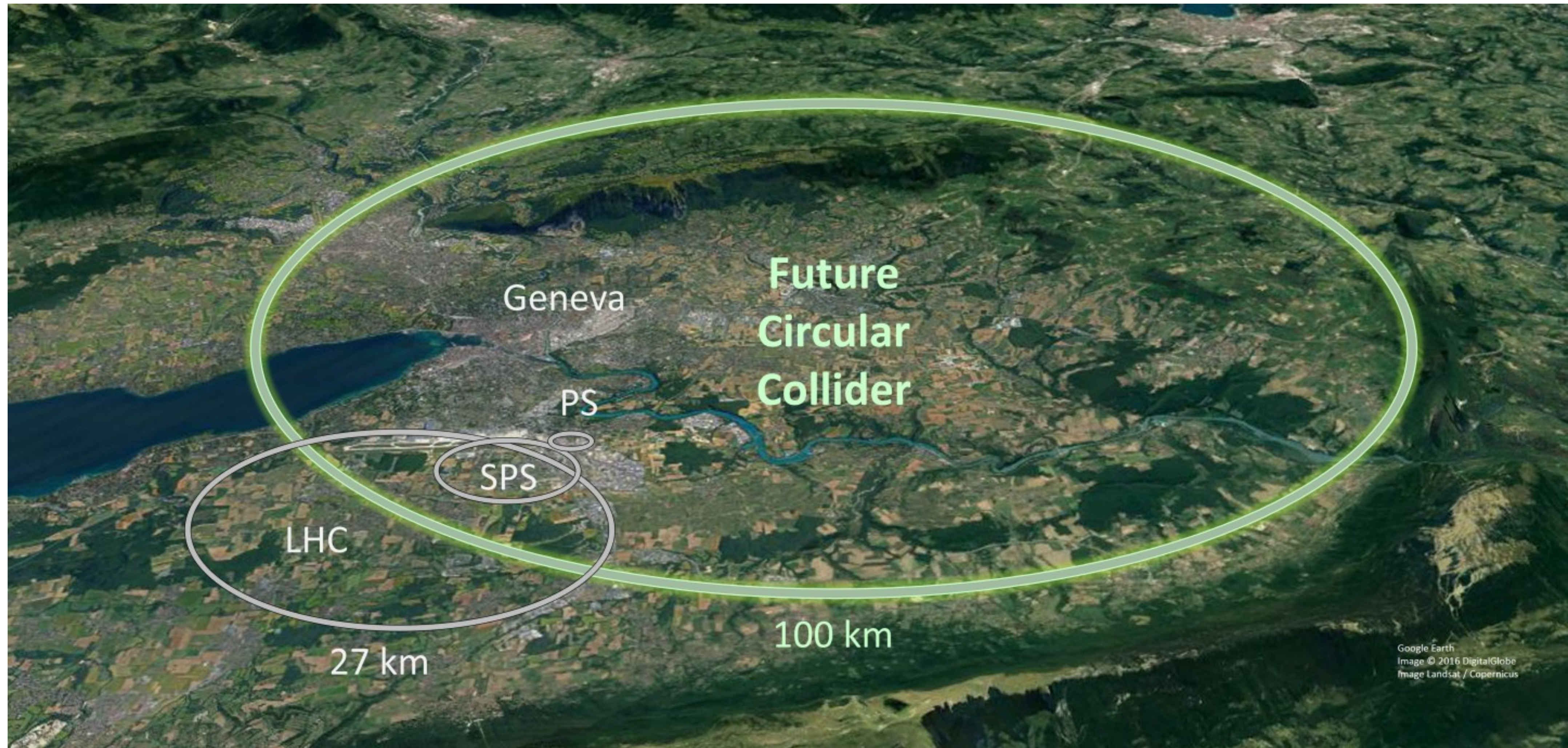
# Higgs production at HL-LHC: expected precision



HL-HE CERN Yellow Report,  
1902.00134



# Science (no) fiction?





# Low-luminosity LHC



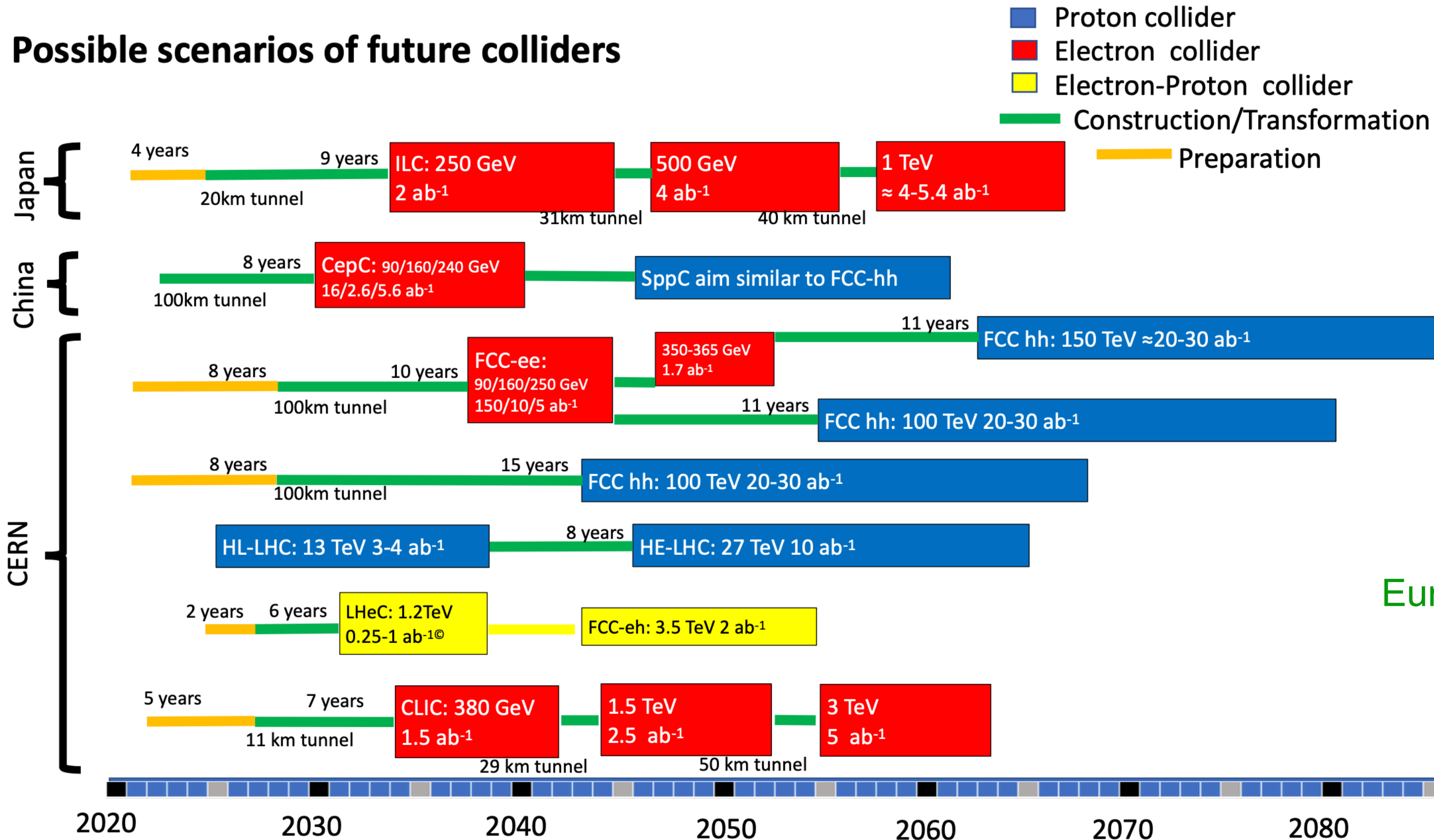
POSTER DESIGN: PETER REID (peter.reid@ed.ac.uk)

SUSSP 2009



# Future collider plans

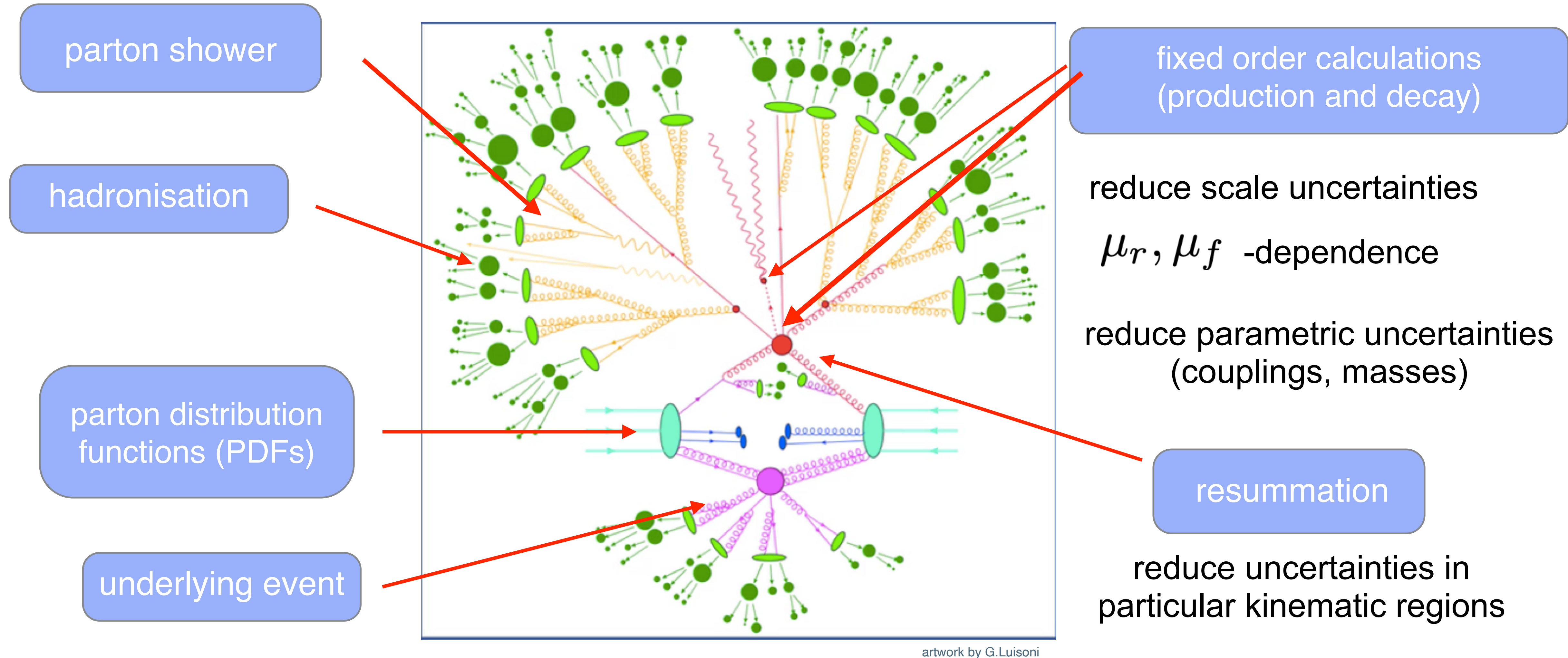
## Possible scenarios of future colliders



Ursula Bassler,  
European Strategy Meeting  
Granada, May 2019



# How to increase the precision of the predictions?





# Perturbation theory

$$\begin{array}{ccccccc}
 & \text{leading order} & & \text{next-to-leading order} & & \text{next-to-next-to-leading order} & \\
 & \downarrow & & \downarrow & & \downarrow & \\
 \sigma = \alpha_s^k \left( \sigma^{LO} + \alpha_s \sigma^{NLO} + \alpha_s^2 \sigma^{NNLO} + \dots \right) \\
 \alpha_s(M_Z) \simeq 0.118 & & \mathcal{O}(10\%) & & \mathcal{O}(1\%) & & 
 \end{array}$$

electroweak corrections:  $\alpha/\alpha_s \approx 0.1 \Rightarrow$  smaller, but beware of large terms like  $\log \left( \frac{M_Z^2}{\hat{s}} \right)$

**scale dependence:** due to truncation of perturbative series  $\longrightarrow$  measure of missing higher orders

$$\sigma = \alpha_s^k(\mu_r) \left( \sigma^{LO}(\mu_f) + \alpha_s(\mu_r) \sigma^{NLO}(\mu_r, \mu_f) + \alpha_s^2(\mu_r) \sigma^{NNLO}(\mu_r, \mu_f) + \dots \right)$$

$\uparrow$   
renormalisation scale
 $\uparrow$   
factorisation scale



# Higher orders in perturbation theory

example pp to 2 jets: subprocess contributing at parton level:  $gg \rightarrow gg$

LO

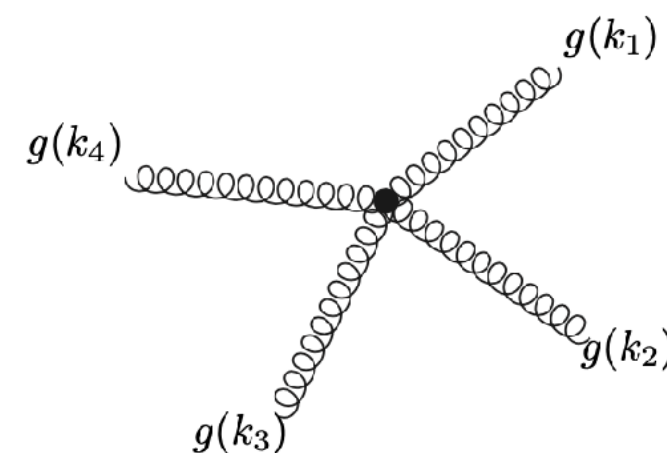


Diagram 1

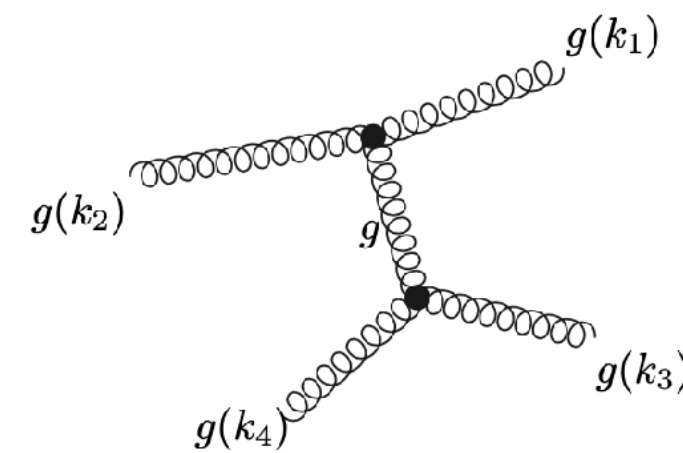
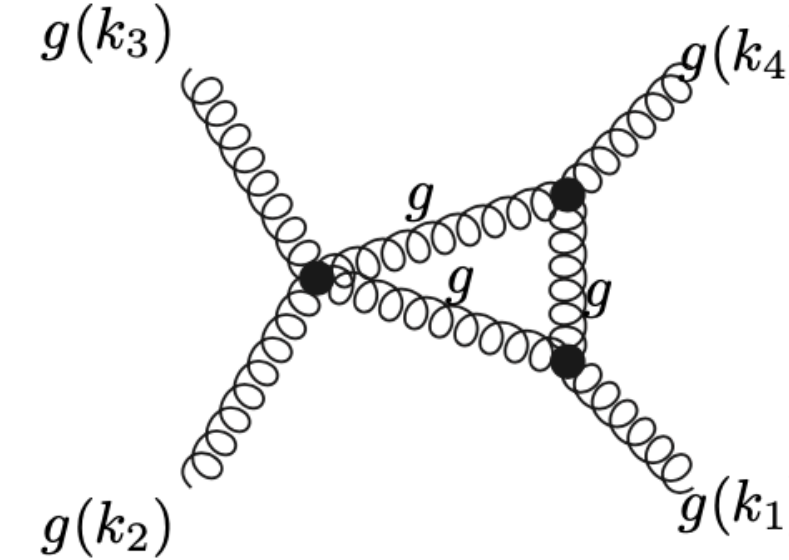
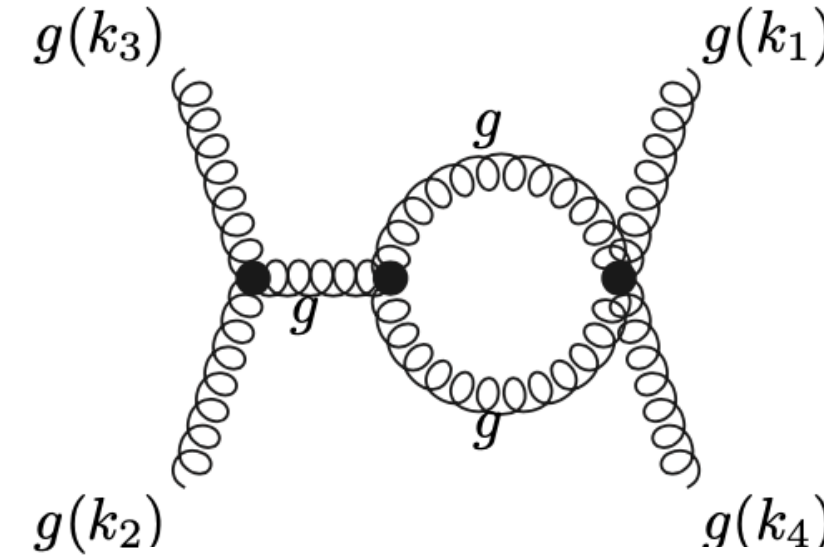
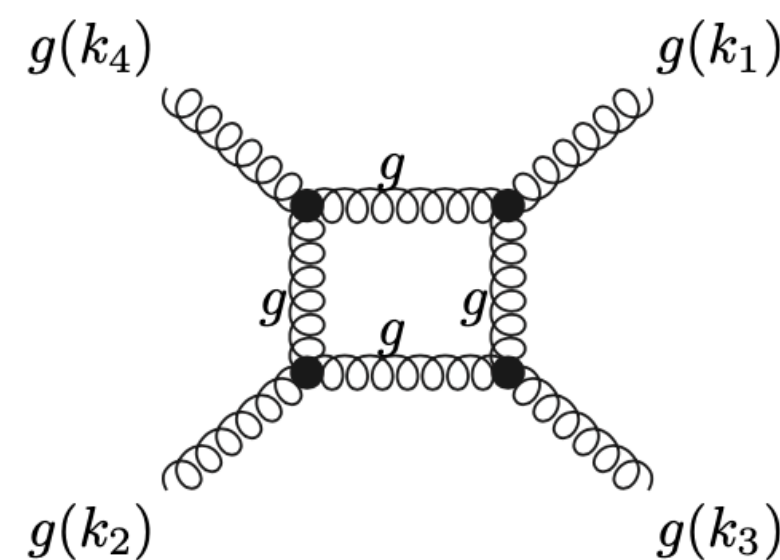


Diagram 2

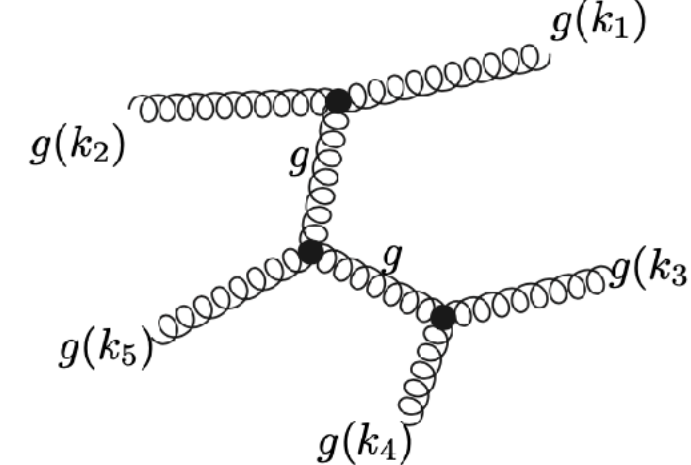
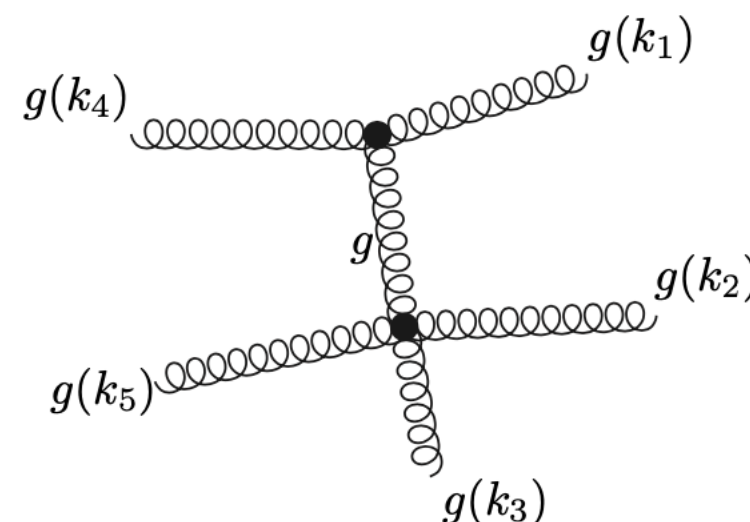
+ permutations (4 diagrams)

NLO virtual



+ ... (60 loop diagrams)

NLO real

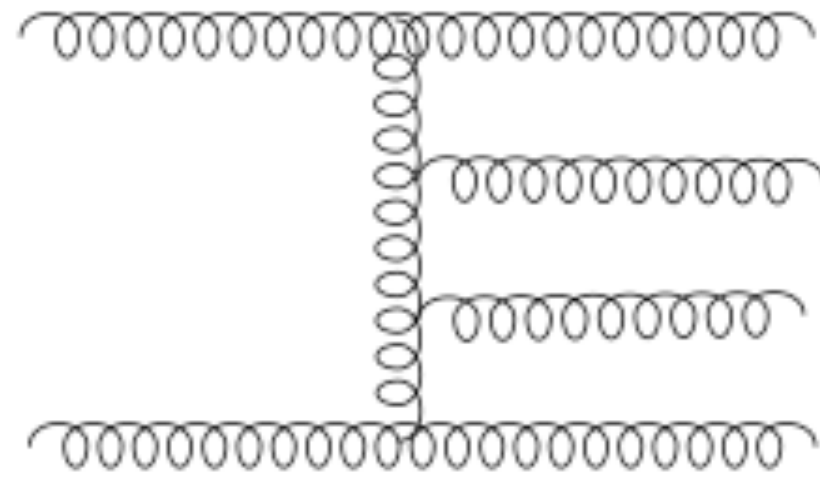


+ ... (25 diagrams)



# Higher orders in perturbation theory

example NNLO:

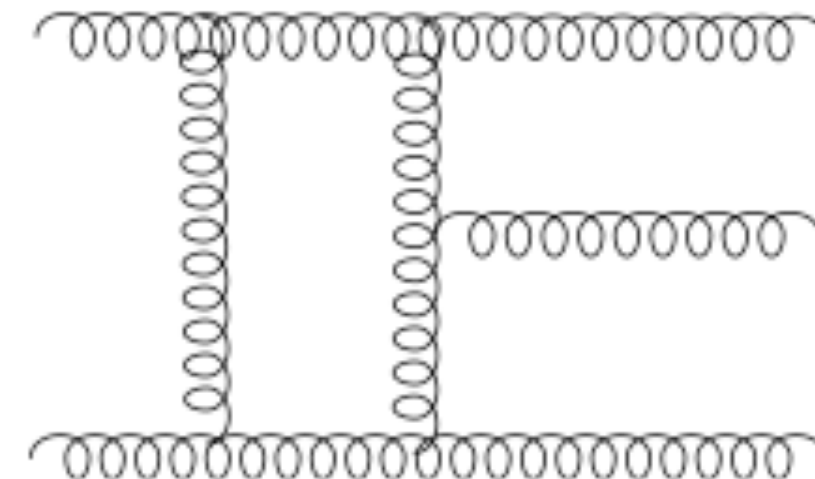


double real



implicit IR poles  
(phase space integration)

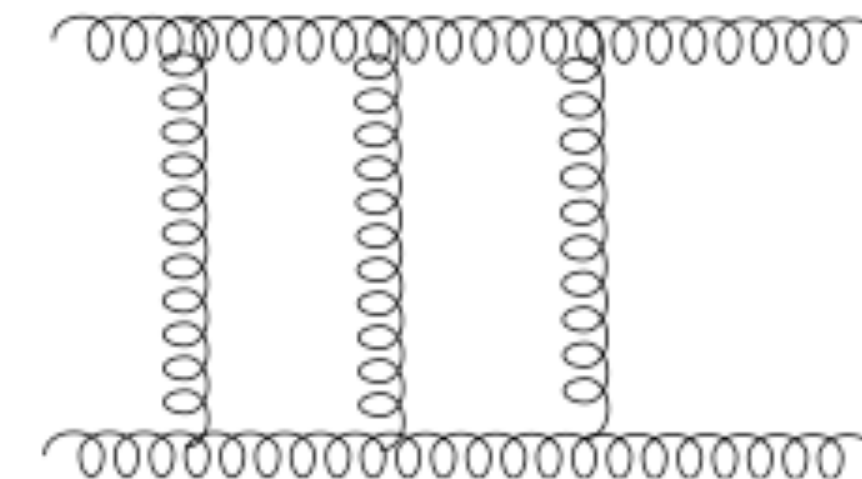
bottlenecks: IR subtraction



1-loop virtual  
⊗ single real



explicit and implicit poles



2-loop virtual



explicit poles  $1/\epsilon^{2L}$  ( $D = 4 - 2\epsilon$ )

(multi)-loop integrals

**current frontiers:**

- NNLO automation
- N3LO coloured

- 2 loops, 4 legs with several mass scales
- 2 loops, 5 legs
- more than 2 loops



# Highlights

Higgs Threshold Exp.

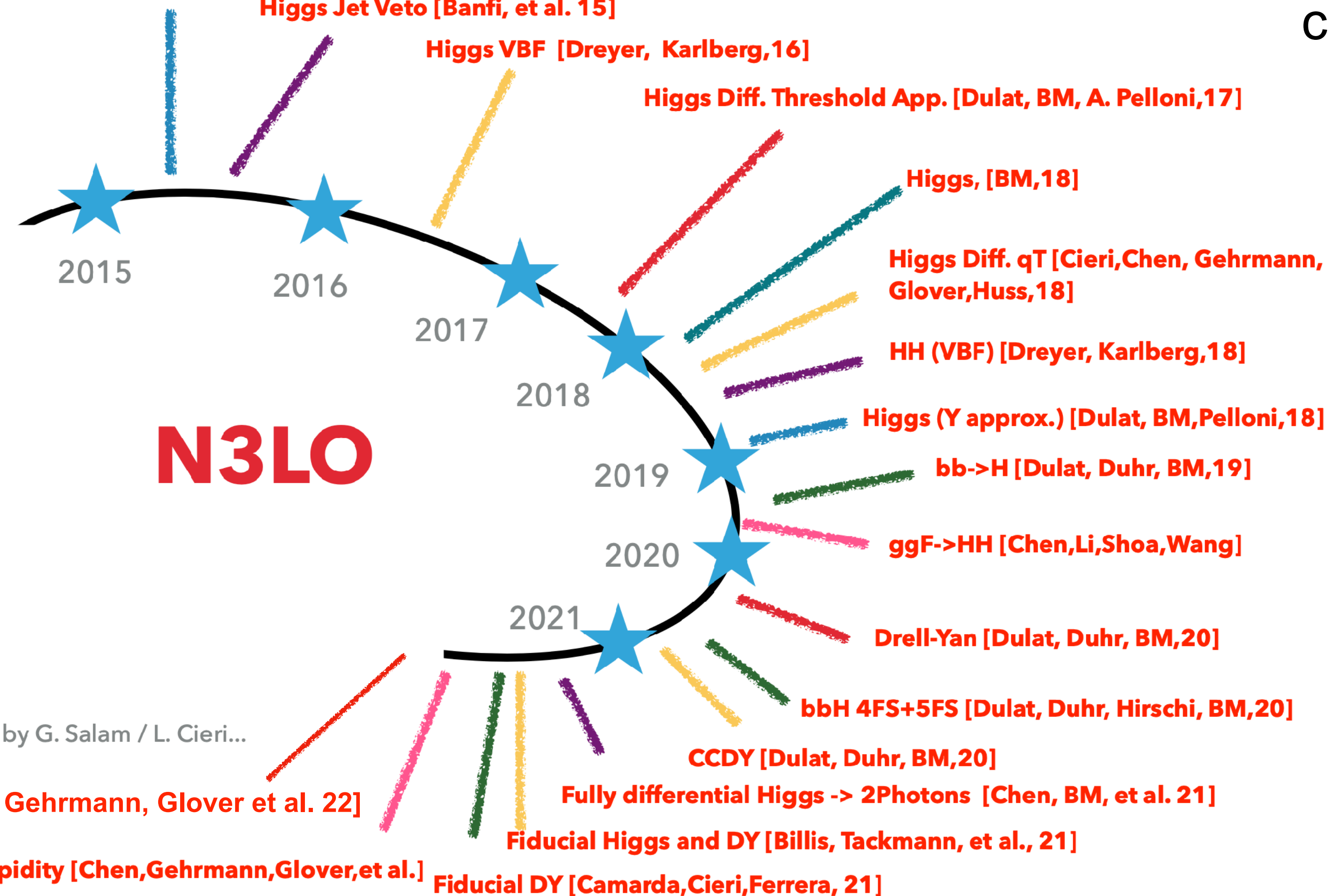
[Anastasiou, Duhr, Dulat, Herzog, BM, 15]

Higgs Jet Veto [Banfi, et al. 15]

Higgs VBF [Dreyer, Karlberg, 16]

Higgs Diff. Threshold App. [Dulat, BM, A. Pelloni, 17]

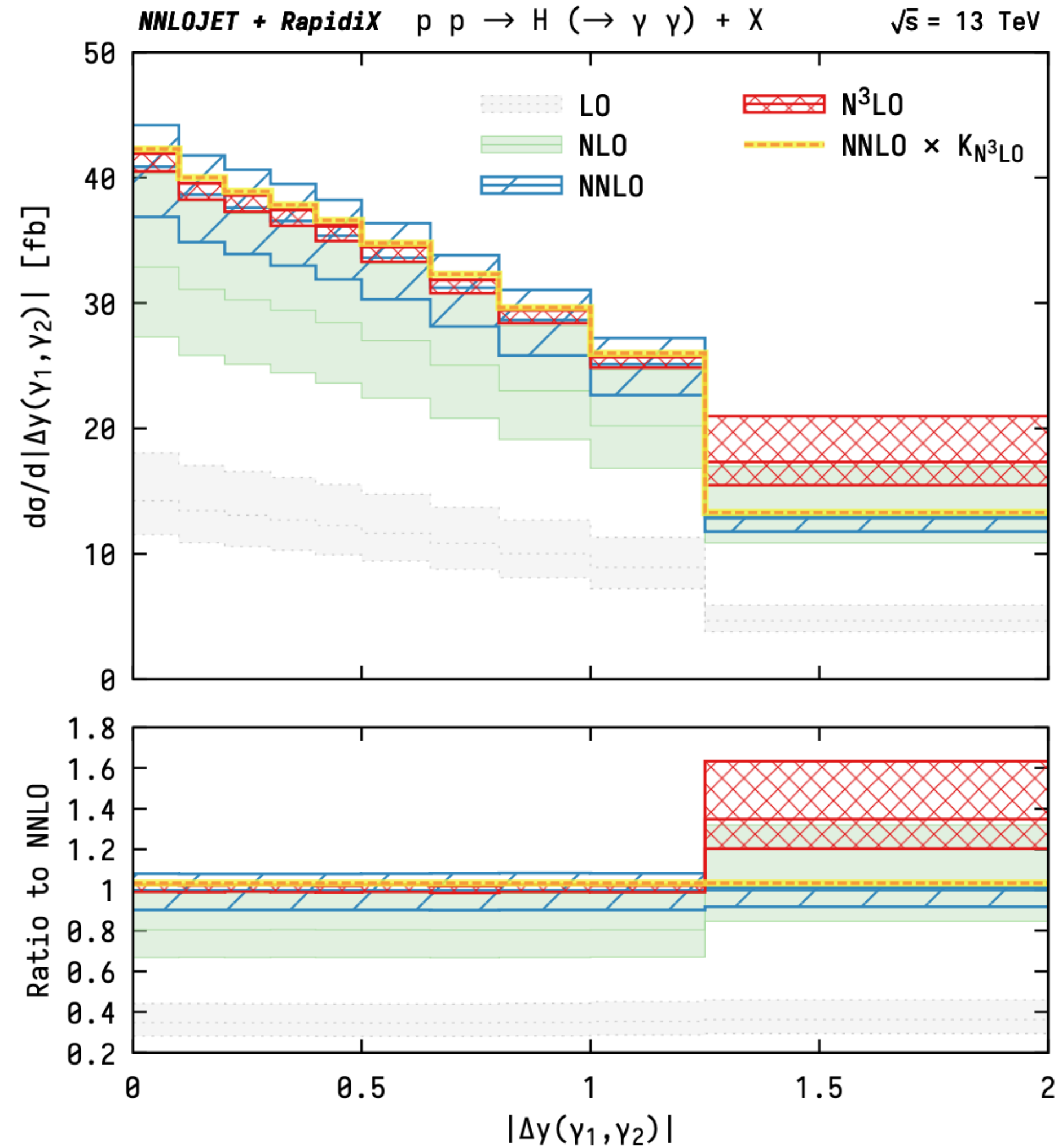
colour singlet final state particles  
(H, Z, W)



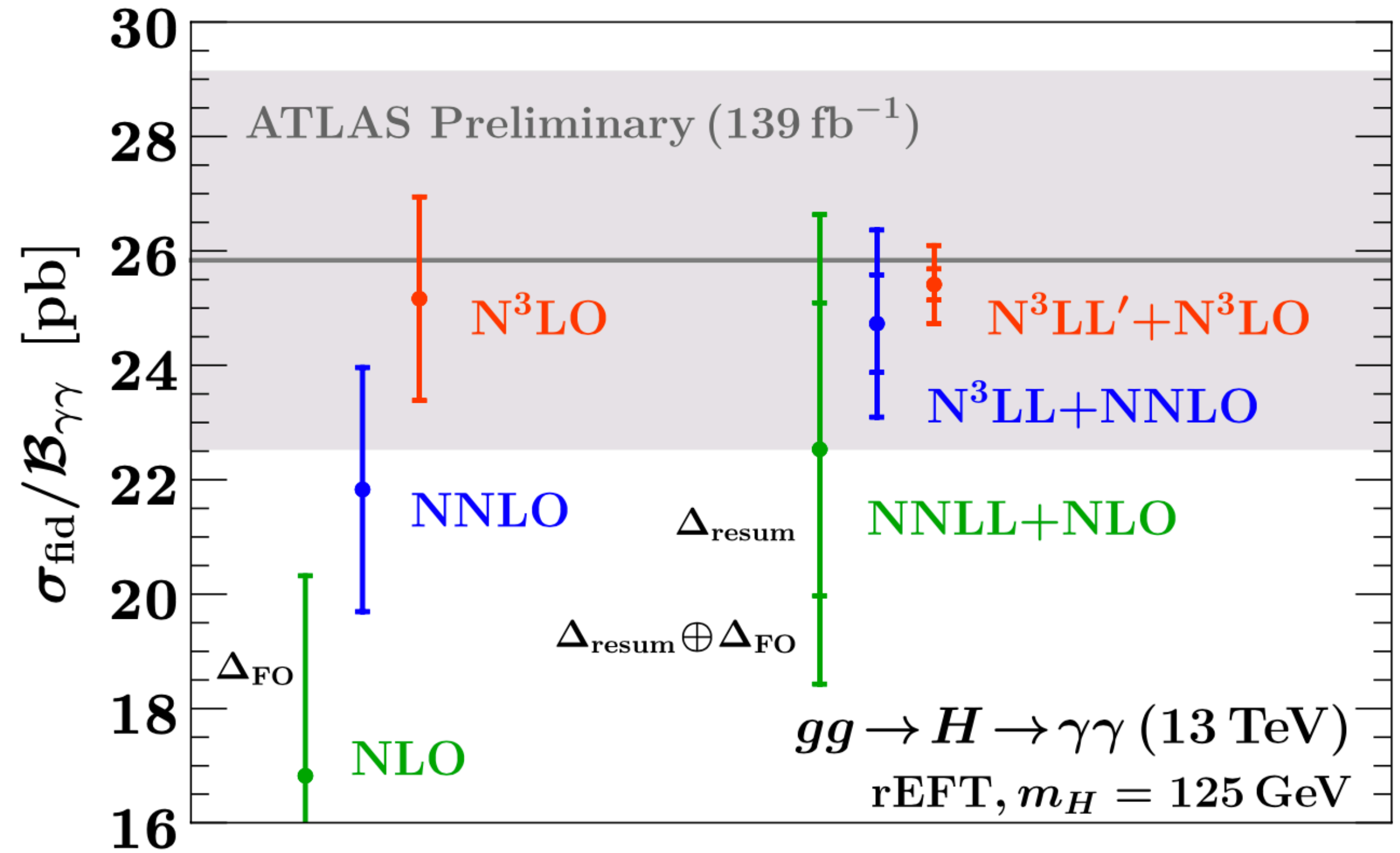
Bernhard Mistlberger, Amplitudes 2021



# ggH@N3LO fiducial



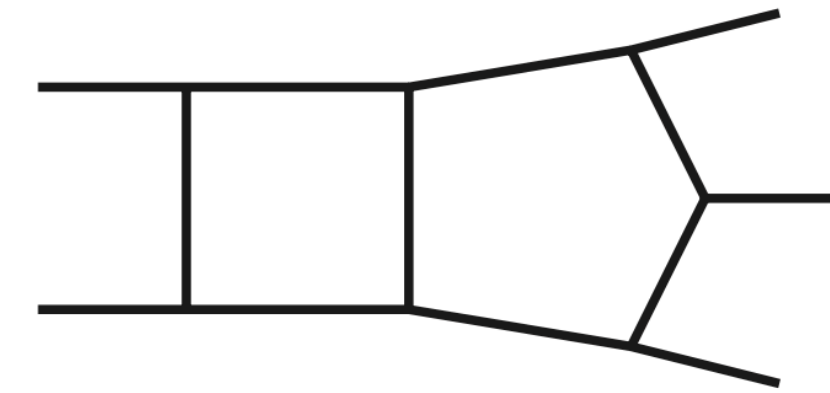
Chen, Gehrmann, Glover, Huss,  
Mistlberger, Pelloni, 2102.07607



Billis, Dehnadi, Ebert, Michel,  
Tackmann, 2102.08039



# Loop integrals: status 2-loop 5-point



massless:

$$pp \rightarrow \gamma\gamma\gamma$$

*Abreu, Page, Pascual, Sotnikov '20 (leading color amplitudes)*

*Chawdry, Czakon, Mitov, Poncelet '20 (leading color, full xs)*

*Kallweit, Sotnikov, Wiesemann '20 (leading color, full xs)*

$$pp \rightarrow \gamma\gamma j$$

*Chawdry, Czakon, Mitov, Poncelet '21 (leading color, full xs)*

*Agarwal, Buccioni, Manteuffel, Tancredi '21 (full color, amplitudes)*

$$gg \rightarrow \gamma\gamma g$$

*Badger, Brønnum-Hansen, Chicherin, Gehrmann, Hartanto '21 (amp)*

*Badger, Gehrmann, Marcoli, Moodie '21 (full xs)*

$$pp \rightarrow jjj$$

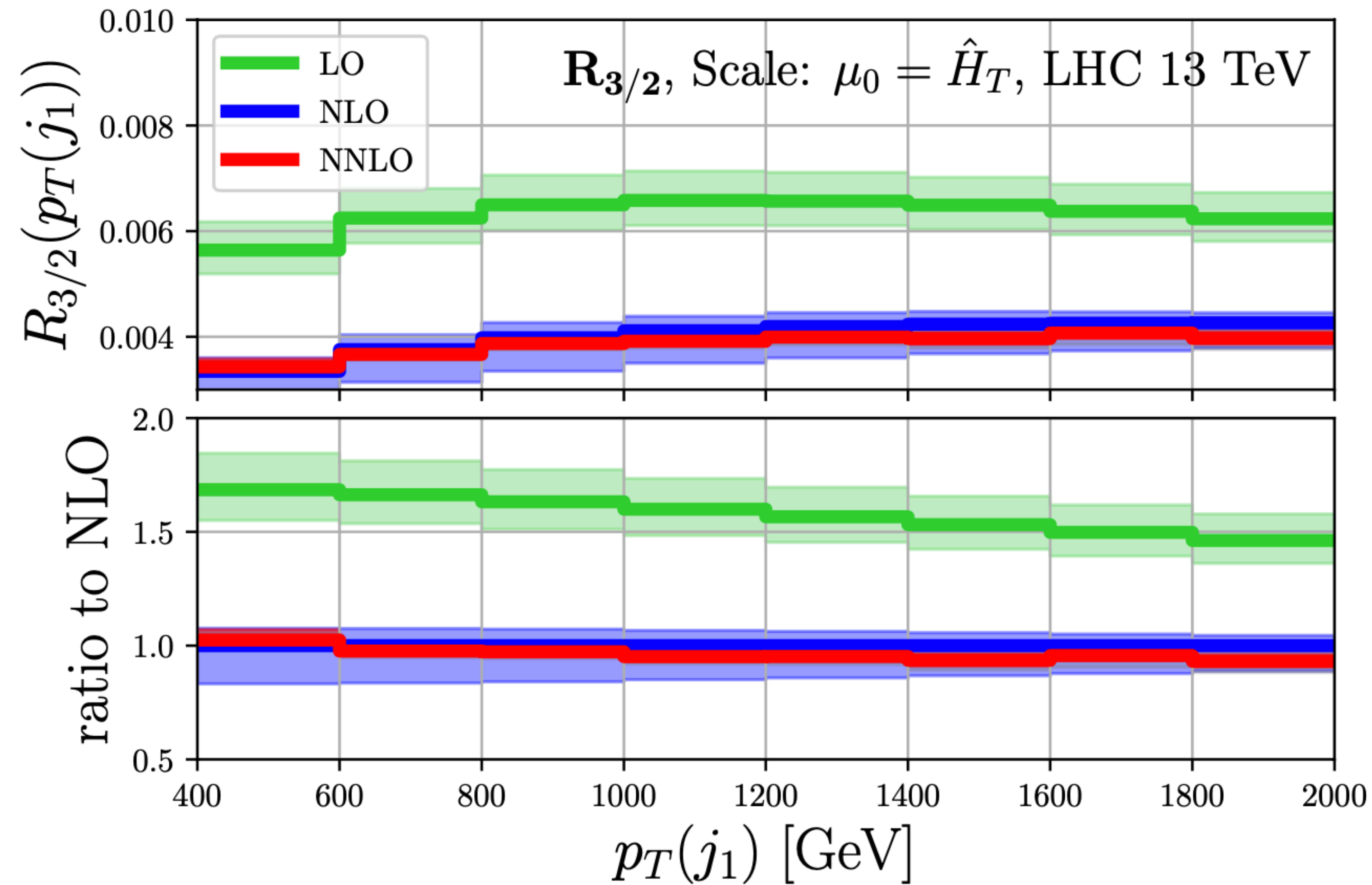
*Abreu, Febres Cordero, Ita, Page, Sotnikov '21 (leading color amp)*

*Czakon, Mitov, Poncelet '21 (full xs)*

important tool: pentagon functions in C++ *Chicherin, Sotnikov '21*



# 3-jet production at NNLO

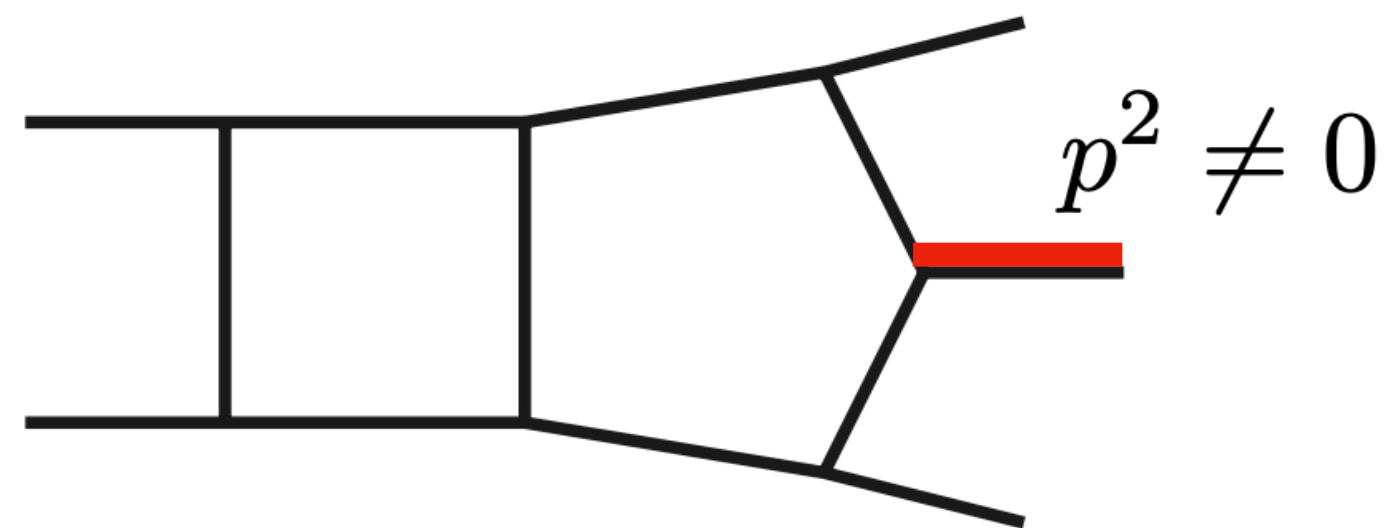


3-jet/2-jet ratio

*Czakon, Mitov, Poncelet '21*



# 2-loop 5-point (one off-shell leg)



*Abreu, Ita, Moriello, Page, Tschernow '20 (planar)*

*Canko, Papadopoulos, Syrrakos '21 (planar, analytic)*

$W + 4$  partons

*Badger, Brønnum-Hansen, Hartanto, Peraro '19 (planar, num. unitarity)*

*Abreu, Febres Cordero, Ita, Klinkert, Page, Sotnikov '21 (leading color)*

$pp \rightarrow W^+ b \bar{b}$

*Badger, Hartanto, Zoia '21; Hartanto, Poncelet, Popescu, Zoia '22*

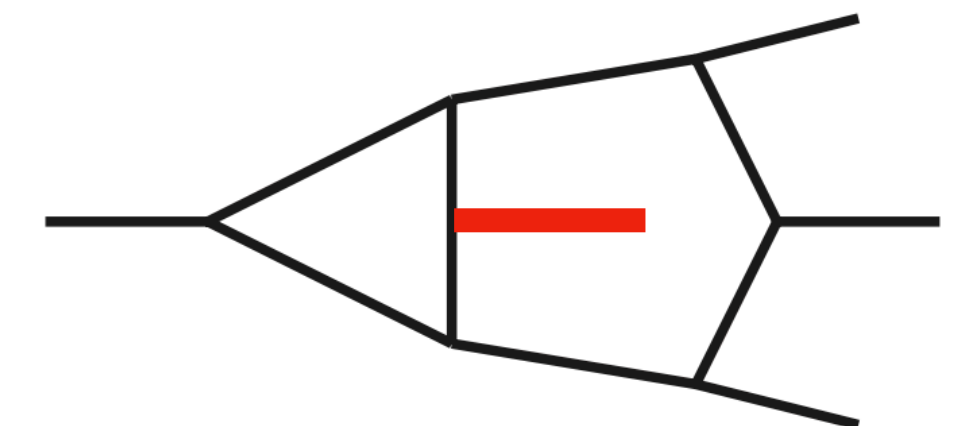
$pp \rightarrow b \bar{b} H$

*Badger, Hartanto, Krys, Zoia '21 (leading colour)*

**non-planar:**

*Abreu, Ita, Page, Tschernov '21*

*Liu, Ma '21*





# 2-loop 4-point with massive propagators

(semi-)numerically:

$$pp \rightarrow t\bar{t}$$

*Czakon, Mitov '13*

$$pp \rightarrow HH$$

*Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16*

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

$$pp \rightarrow Hj$$

*Jones, Kerner, Luisoni '18; Frellesvig, Hidding et al. '19;*

*Czakon, Harlander, Klappert, Niggetiedt '20; Bonciani, Del Duca, Frellesvig, Hidding, et al. 2206.10490*

$$pp \rightarrow HZ$$

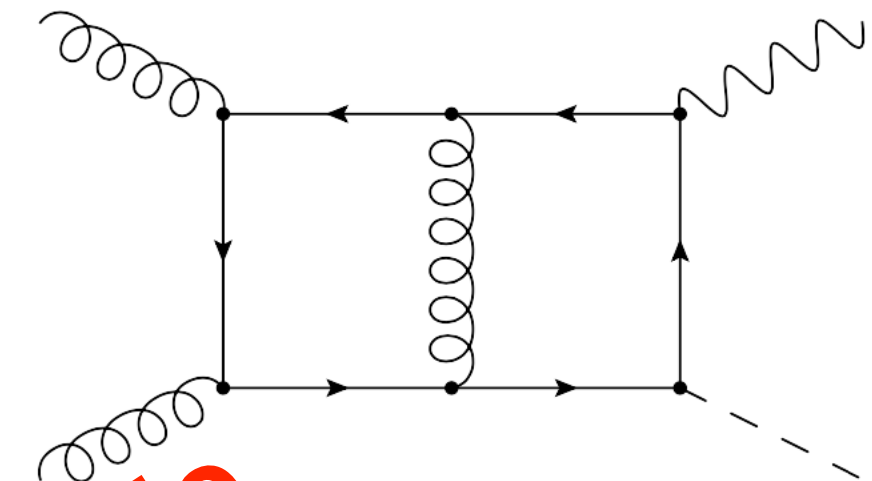
*Chen, GH, Jones, Kerner, Klappert, Schlenk '20*

$$pp \rightarrow W^+W^-$$

*Brønnum-Hansen, Wang '20*

$$pp \rightarrow ZZ$$

*Agarwal, Jones, Manteuffel '20; Brønnum-Hansen, Wang '21*



no complete analytic expressions available



# Pro's and con's analytic/numerical

|                                     | analytic              | numerical                  |
|-------------------------------------|-----------------------|----------------------------|
| pole cancellation                   | exact                 | with numerical uncertainty |
| fast evaluation                     | mostly                | depends                    |
| control of integrable singularities | analytic continuation | less straightforward       |
| extension to more scales/loops      | difficult             | promising                  |
| automation                          | difficult             | less difficult             |

often a combination can be beneficial,  
e.g. high energy limit analytically  
*Davies et al. 1907.06408*

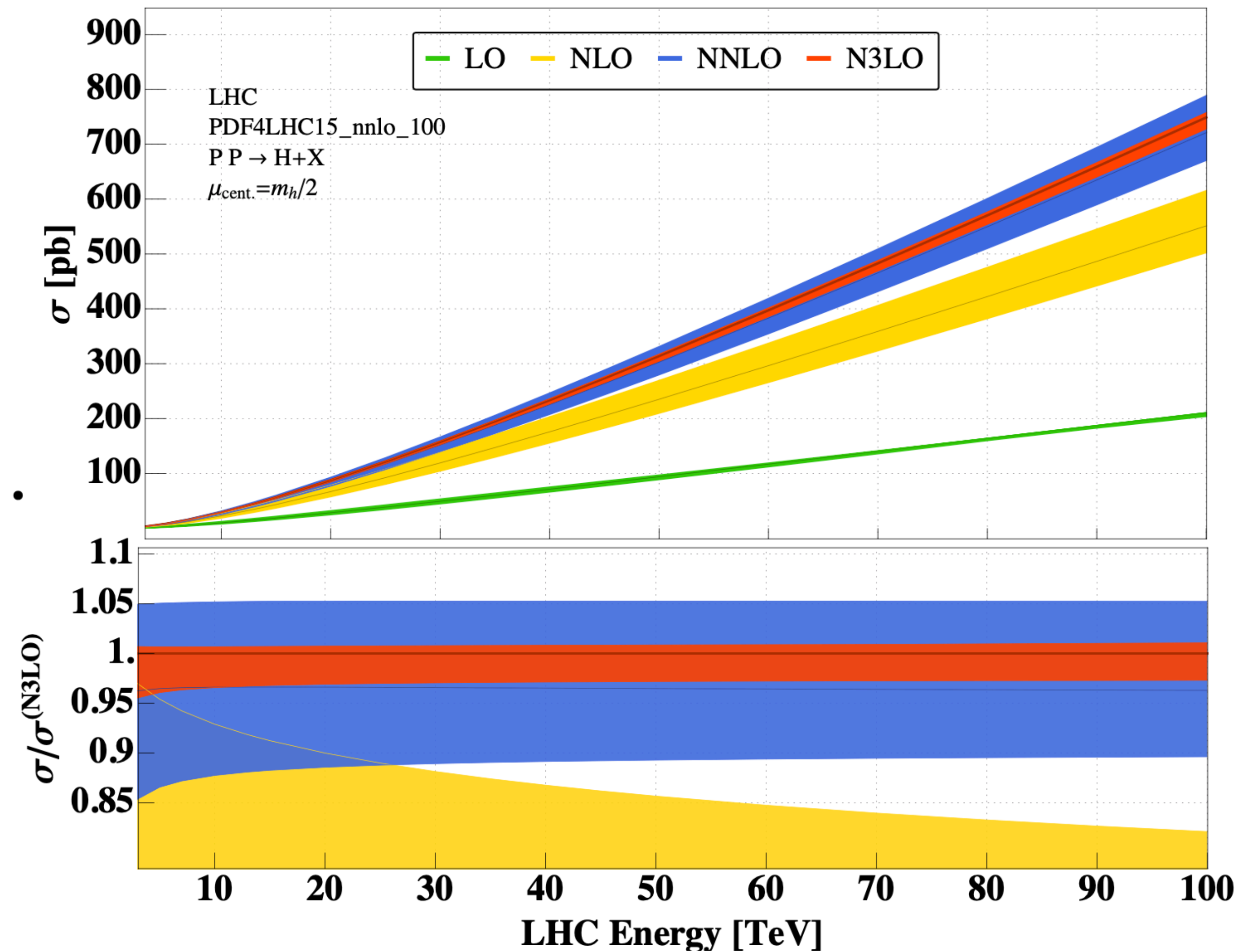


# Precision: the next challenges

- scale uncertainties: how well do they estimate missing higher orders?
  - depends on choice of central scales, modes of variation, contributing partonic channels, ...
- electroweak corrections, mixed QCD-EW
- PDFs
- quark mass-related uncertainties: neglected masses, different renormalisation schemes
- need for resummation in certain kinematic regions
- parton shower uncertainties
- Effective Field Theories: truncation uncertainties, validity range



# Scale uncertainties: Higgs production in gluon fusion

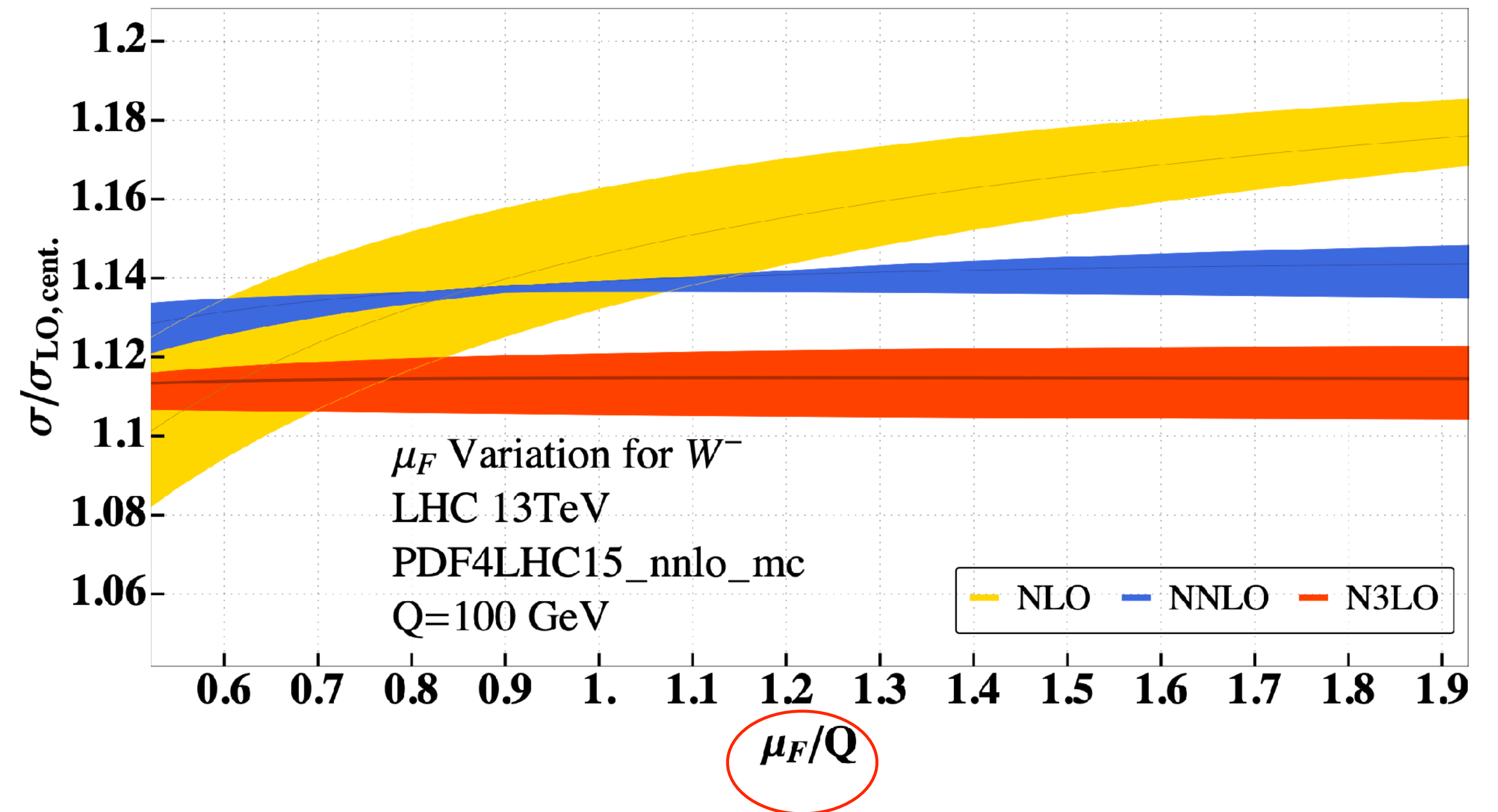
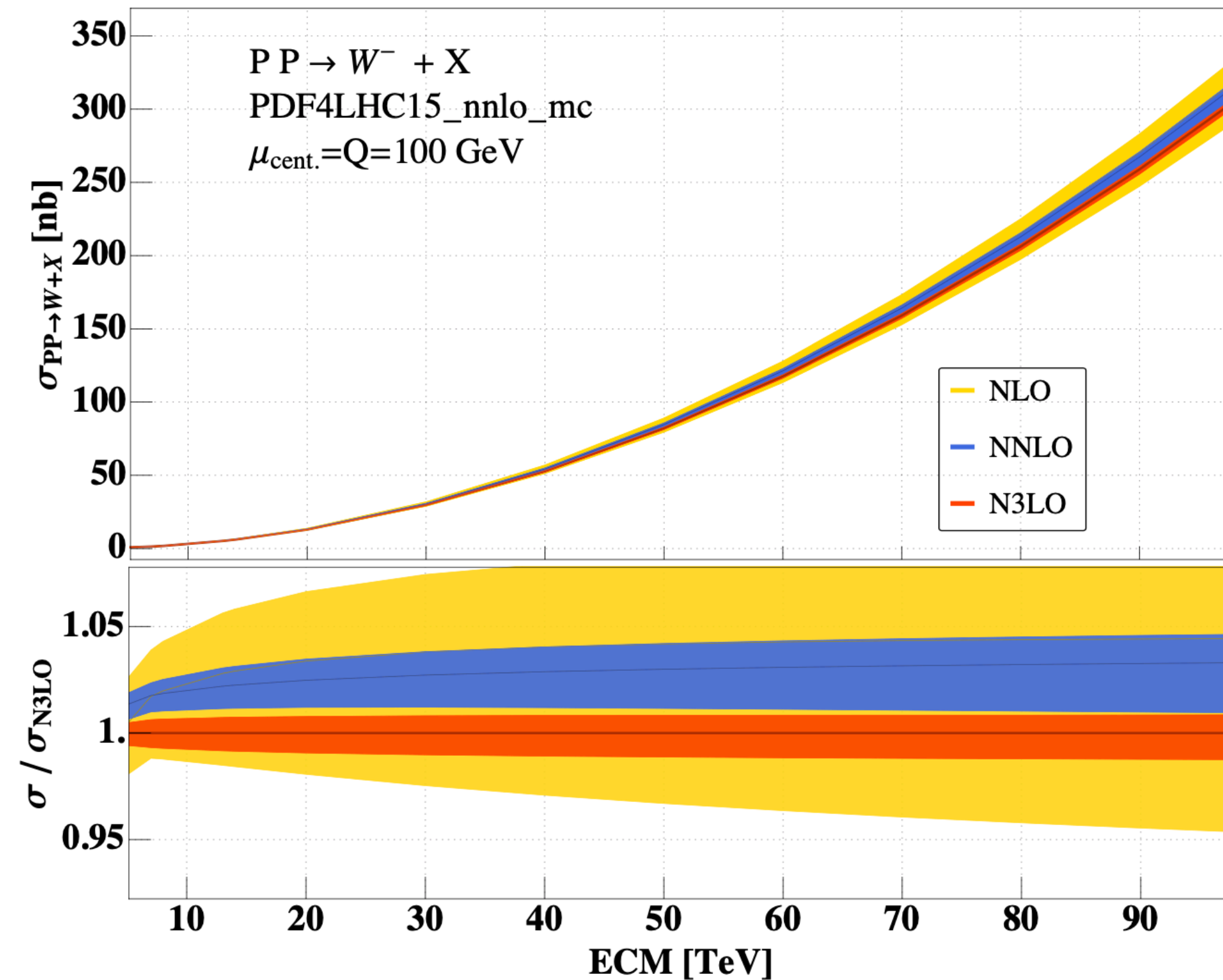


B. Mistlberger '18



# Scale uncertainties: Drell-Yan (W-production)

Duhr, Dulat, Mistlberger '20



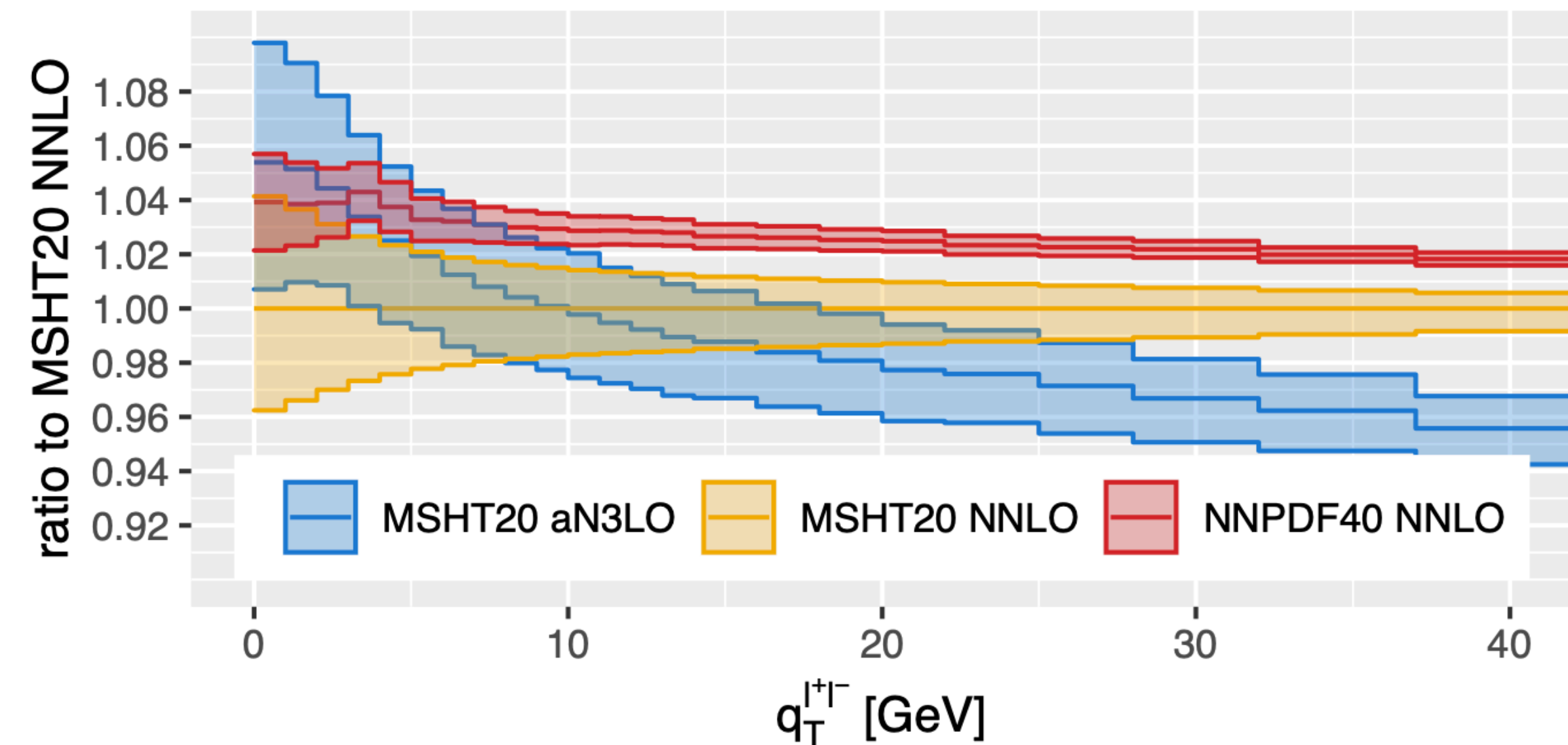
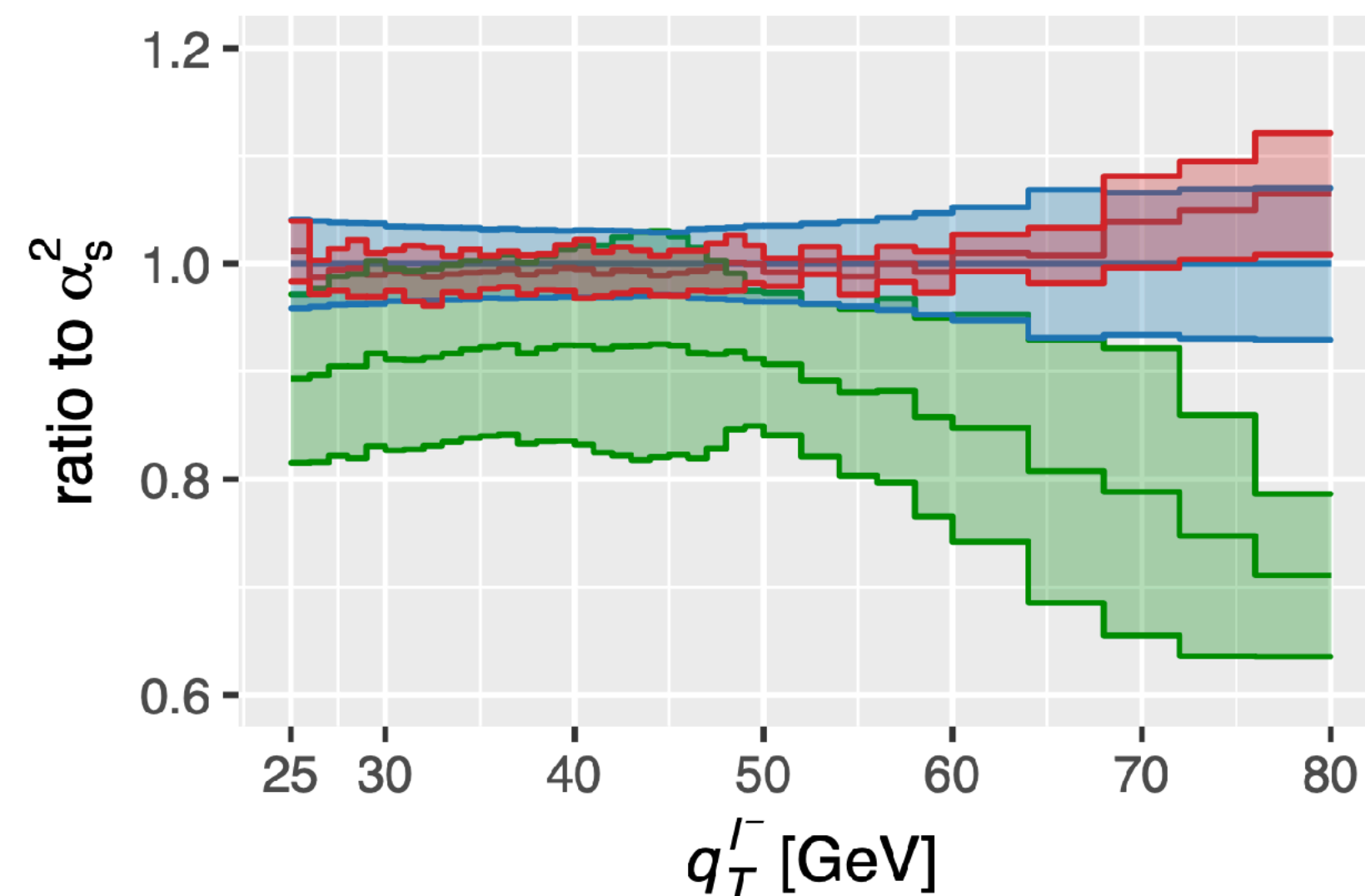
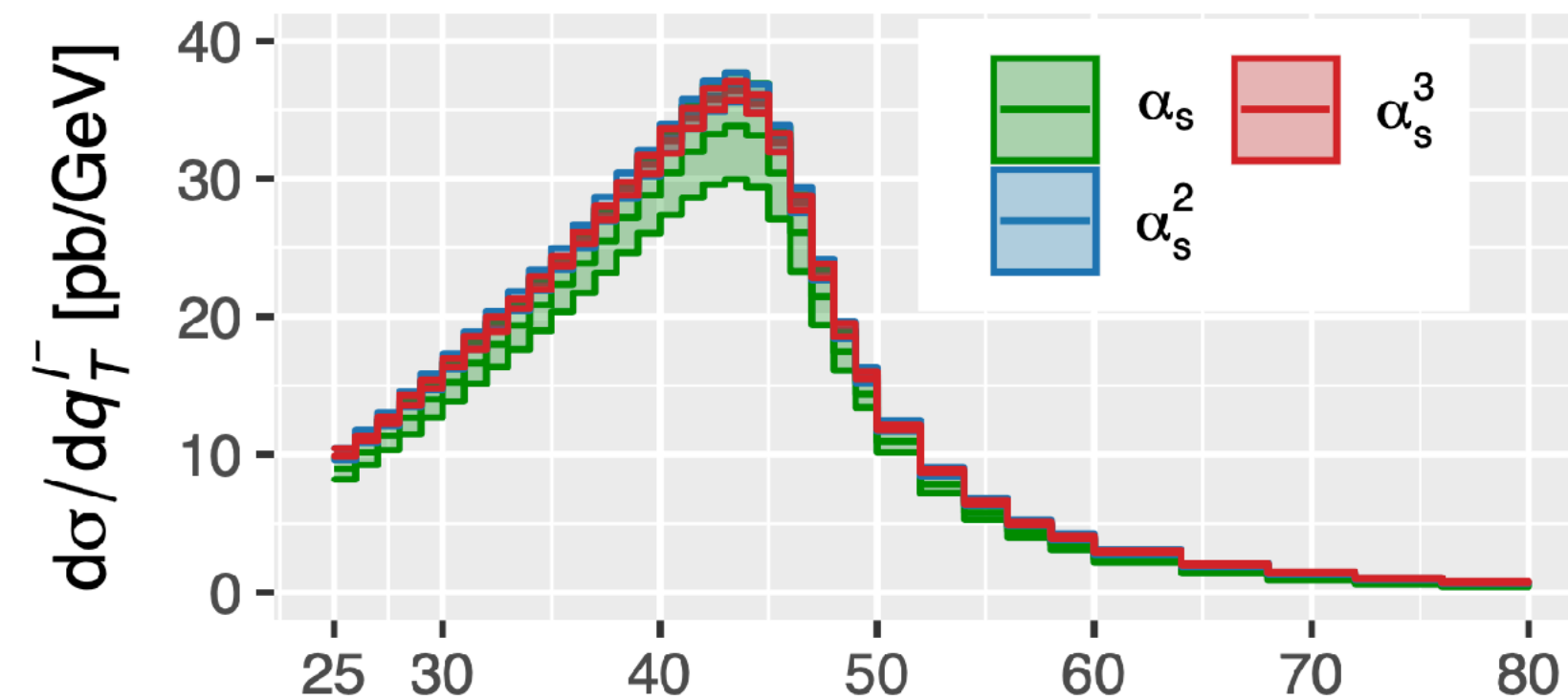
NNLO  $\mu_F$ -scale uncertainty bands do not properly reflect the uncertainty



# Scale uncertainties: Drell-Yan (Z-production)

N4LL+N3LO

Neumann, Campbell 2207.07056



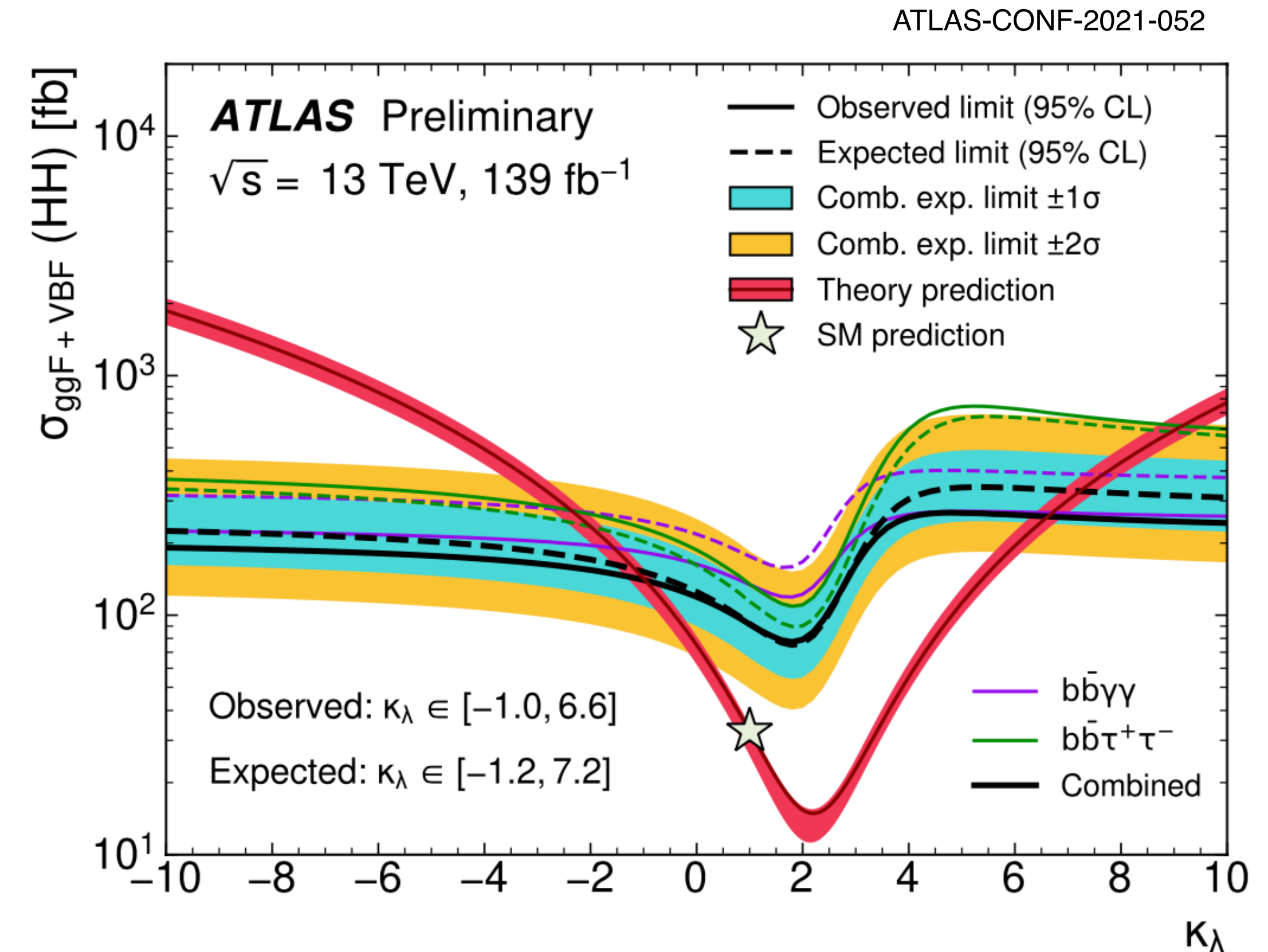
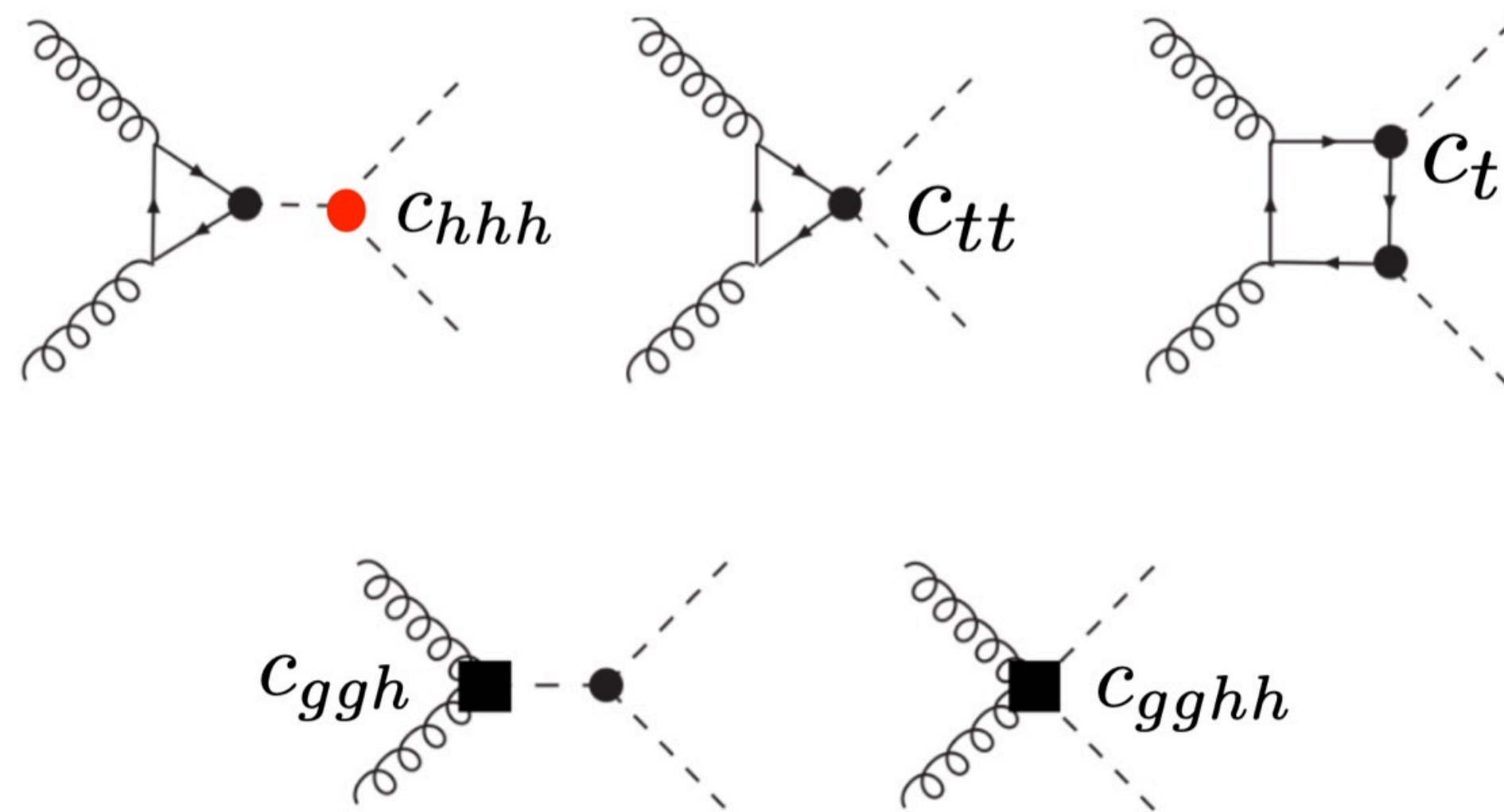
(approximate) N3LO PDFs introduce shape change



# Higgs boson pair production

- prime process to explore the Higgs potential (Higgs boson trilinear coupling)
- if trilinear coupling different from SM, other couplings are likely to be non-SM as well

→ EFT parametrisation by extra operators



$$\kappa_\lambda \equiv c_{hhh} = \lambda/\lambda_{SM}$$



# Effective Field Theory expansion schemes

## SMEFT (Standard Model Effective Field Theory):

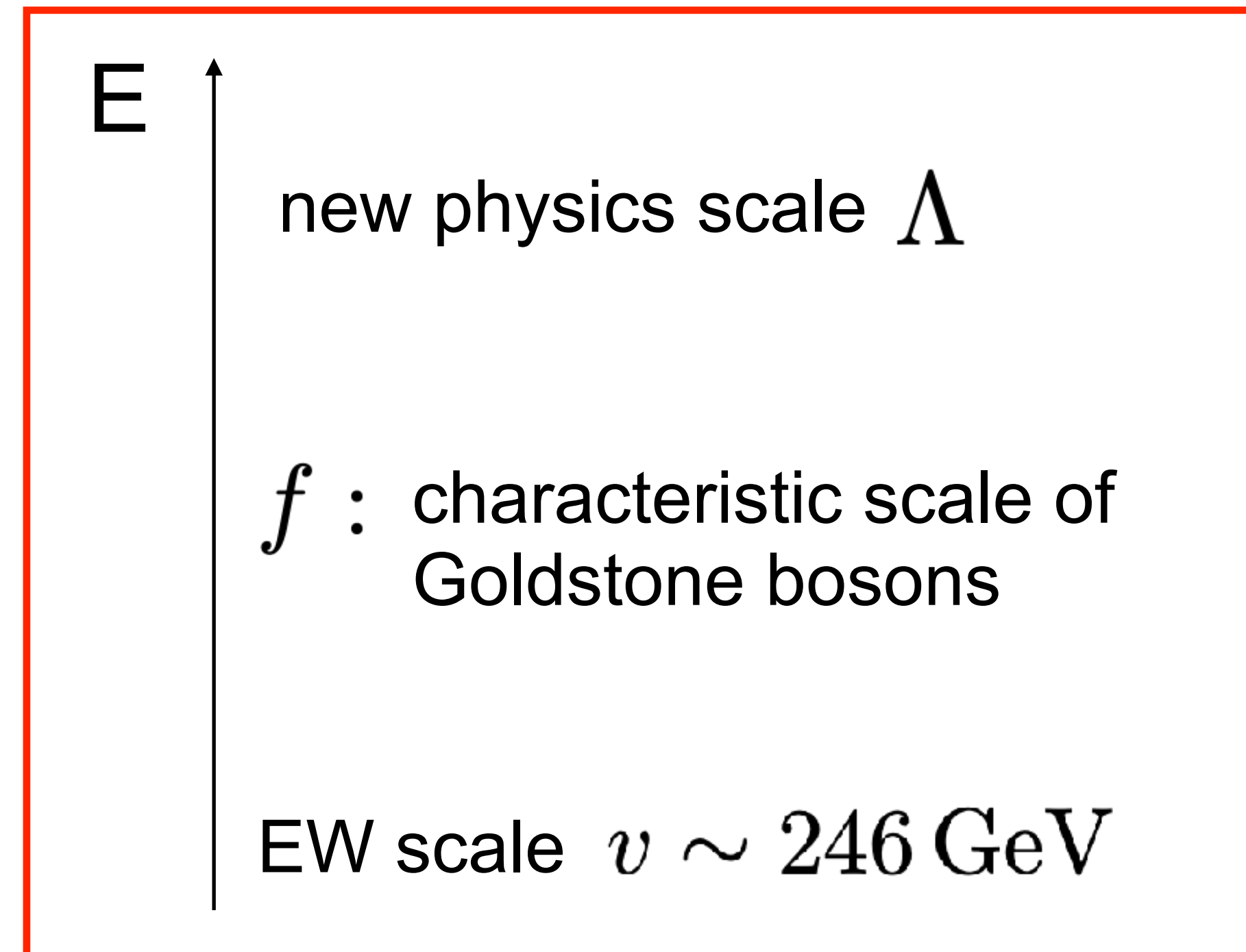
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{\text{dim6}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

canonical dimension counting

## HEFT (Higgs Effective Field Theory):

$$\mathcal{L}_{\text{HEFT}} = \mathcal{L}_2 + \sum_{L=1}^{\infty} \sum_i \left( \frac{1}{16\pi^2} \right)^L c_i^{(L)} \mathcal{O}_i^{(L)}$$

counting of loop orders, expansion parameter:  $f^2/\Lambda^2 \approx 1/(16\pi^2)$   
(similar to chiral perturbation theory)





# HEFT and SMEFT

- **HEFT:** Goldstone sector has a symmetry  $SU(2)_L \times SU(2)_R$  (chiral)  
which is broken to  $SU(2)_{L+R}$  (“custodial symmetry”, protects the rho-parameter)
- physical Higgs field  $h(x)$  is  $SU(2)_L \times U(1)_Y$  **singlet** (cf. non-linear sigma-model)  
→ Lagrangian can contain polynomials  

$$\sum_n c_n \left(\frac{h}{v}\right)^n$$
with no a priori relation among the  $c_n$
- UV completion can be strongly coupled  
**model examples:** composite H, H-dilaton, conformal H, induced EWSB, ...
- **SMEFT:** Higgs field  $\Phi(x)$  is complex doublet, transforms linearly under  $SU(2) \times U(1)$



# Lagrangians relevant for HH production

## SMEFT:

$$\Delta\mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2} (\phi^\dagger \phi) \Box (\phi^\dagger \phi) + \frac{C_{HD}}{\Lambda^2} (\phi^\dagger D_\mu \phi)^* (\phi^\dagger D^\mu \phi) + \frac{C_H}{\Lambda^2} (\phi^\dagger \phi)^3$$

$$+ \left( \frac{C_{uH}}{\Lambda^2} \phi^\dagger \phi \bar{q}_L \phi^c t_R + h.c. \right) + \frac{C_{HG}}{\Lambda^2} \phi^\dagger \phi G_{\mu\nu}^a G^{\mu\nu,a}$$

(Warsaw basis)

Grzadkowski et al. 1008.4884

**HEFT:** Feruglio '93; Grinstein, Trott '07; Contino et al. '10; Buchalla et al. '13, '18

$$\mathcal{L} \supset -m_t \left( c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t} t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left( c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G_{\mu\nu}^a G^{a,\mu\nu}$$

NLO with full top quark mass dependence implemented in

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

ggHH: GH, Jones, Kerner, Luisoni, Scyboz 2006.16877

**new:** ggHH\_SMEFT: GH, Lang, Scyboz 2204.13045



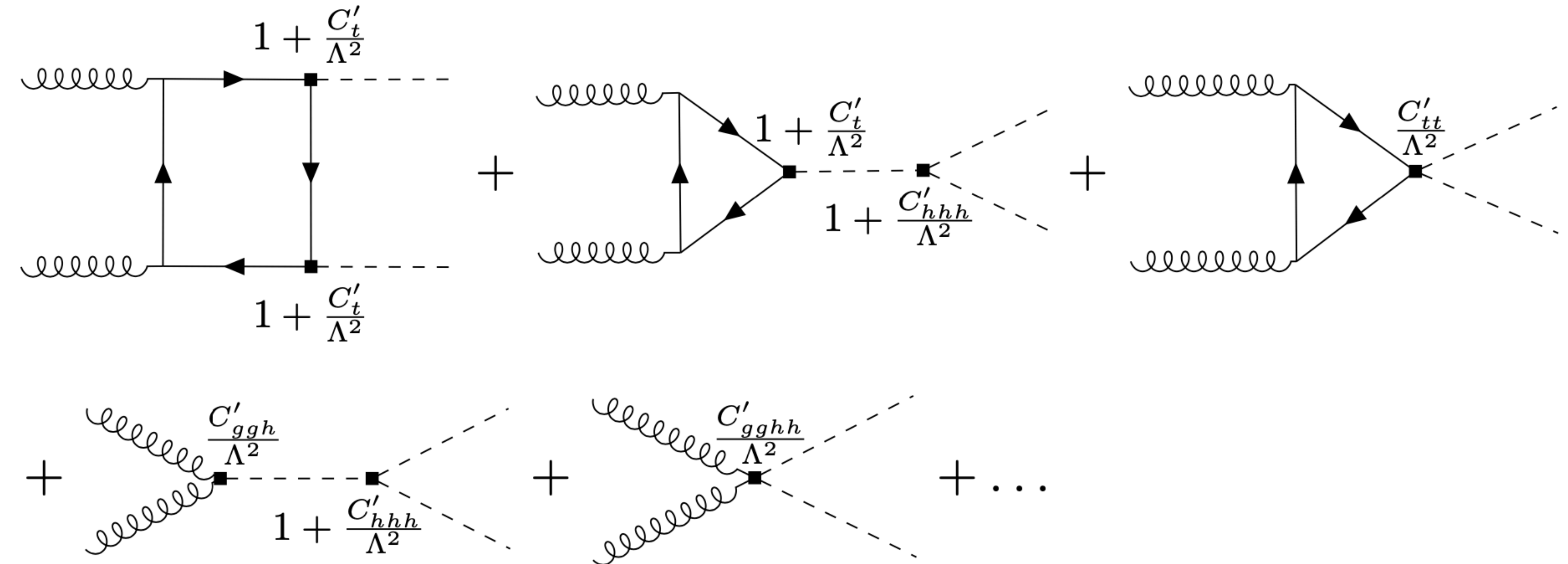
# Lagrangians relevant for HH production

naive translation (comparing coefficients at Lagrangian level):

| HEFT       | Warsaw                                                                                            |
|------------|---------------------------------------------------------------------------------------------------|
| $c_{hhh}$  | $1 - 2 \frac{v^2}{\Lambda^2} \frac{v^2}{m_h^2} C_H + 3 \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$    |
| $c_t$      | $1 + \frac{v^2}{\Lambda^2} C_{H,\text{kin}} - \frac{v^2}{\Lambda^2} \frac{v}{\sqrt{2}m_t} C_{uH}$ |
| $c_{tt}$   | $-\frac{v^2}{\Lambda^2} \frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$  |
| $c_{ggh}$  | $\frac{v^2}{\Lambda^2} \frac{8\pi}{\alpha_s} C_{HG}$                                              |
| $c_{gggh}$ | $\frac{v^2}{\Lambda^2} \frac{4\pi}{\alpha_s} C_{HG}$                                              |

$$C_{H,\text{kin}} = C_{H,\square} - \frac{1}{4} C_{HD}$$

# SMEFT truncation

$$\mathcal{M} =$$


$$= \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{single ins.}} + \mathcal{M}_{\text{double ins.}}$$

terms  $\sim 1/\Lambda^4$  same order as dim 8 operators (which are not included)



# SMEFT at amplitude squared level

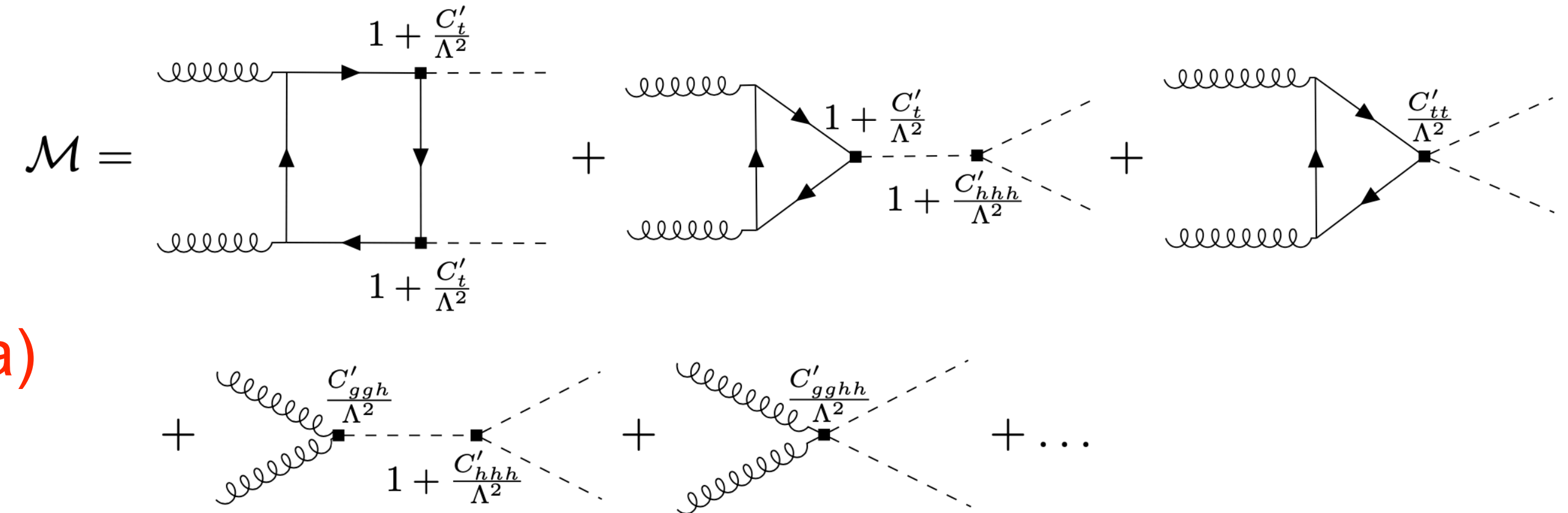
truncation options:

$$\sigma = \sigma_{\text{SM}} + \frac{1}{\Lambda^2} \sigma_{\text{SM}} \times \text{single ins.} \quad (a)$$

$$+ \frac{1}{\Lambda^4} \sigma_{\text{single ins.}} \times \text{single ins.} \quad (b)$$

$$+ \frac{1}{\Lambda^4} \sigma_{\text{SM}} \times \text{double ins.} \quad (c)$$

$$+ \frac{1}{\Lambda^6} \sigma_{\text{single ins.}} \times \text{double ins.} + \frac{1}{\Lambda^8} \sigma_{\text{double ins.}} \times \text{double ins.} \quad (d)$$



# SMEFT at amplitude squared level

4 options:

$$\sigma \simeq \left\{ \begin{array}{ll} \sigma_{\text{SM}} + \sigma_{\text{SM} \times \text{dim6}} & \text{(a)} \\ \sigma_{(\text{SM} + \text{dim6}) \times (\text{SM} + \text{dim6})} & \text{(b)} \\ \sigma_{(\text{SM} + \text{dim6}) \times (\text{SM} + \text{dim6})} + \sigma_{\text{SM} \times \text{dim6}^2} & \text{(c)} \\ \sigma_{(\text{SM} + \text{dim6} + \text{dim6}^2) \times (\text{SM} + \text{dim6} + \text{dim6}^2)} & \text{(d)} \end{array} \right.$$

(a): “linearised dim 6” (first order of expansion in  $1/\Lambda^2$  at cross section level)

(b): “quadratic dim 6” (first order of expansion in  $1/\Lambda^2$  at amplitude level, then squared)

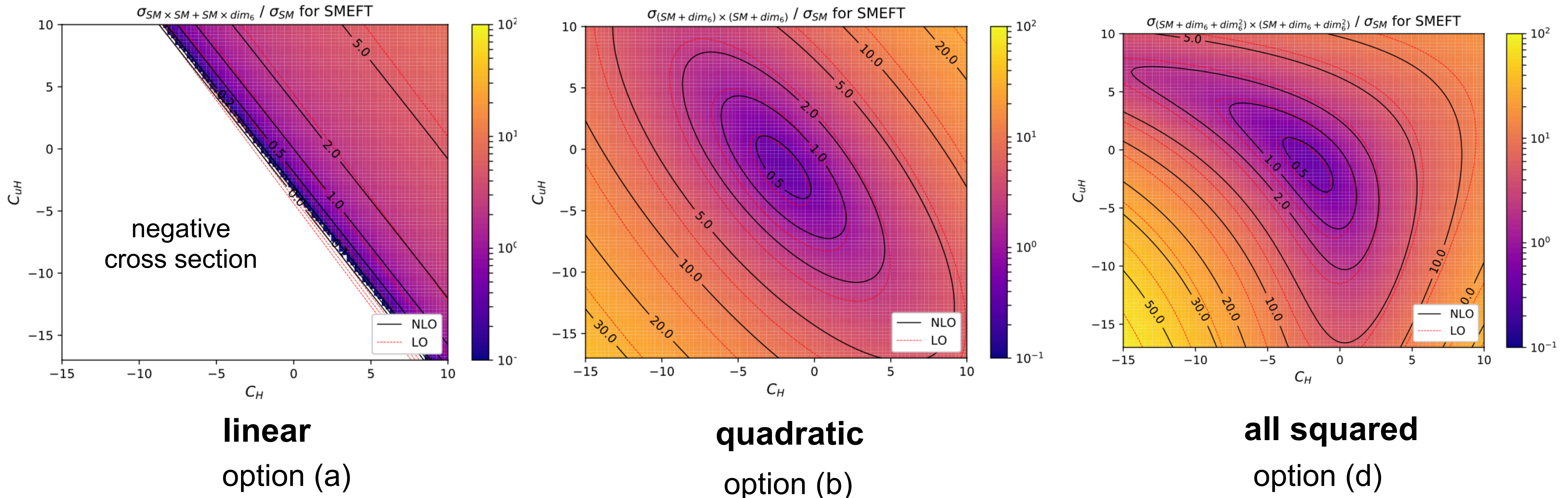
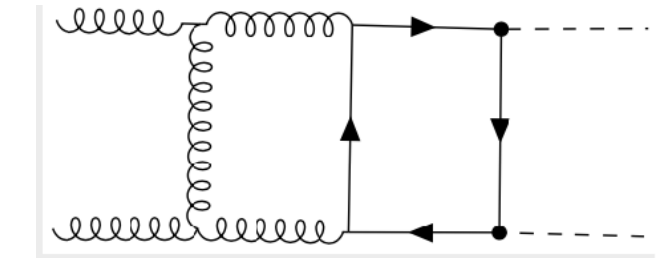
(c): include all terms  $\mathcal{O}(1/\Lambda^4)$  coming from  $\text{dim6}^2$  and double operator insertions

(d): would correspond to HEFT except for treatment of  $\alpha_s$



# Results: total HH cross section

note: **full NLO QCD corrections** building on Borowka, Greiner, GH, Jones, Kerner, et al. '16

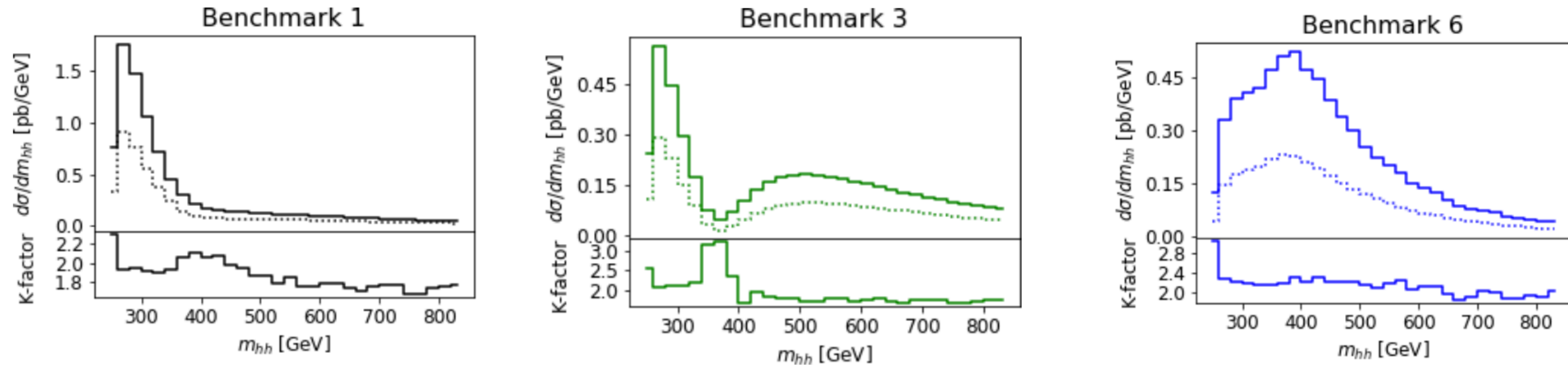


flat directions very different for different truncation options

figures: Jannis Lang

# Results at benchmark points

consider benchmark points characteristic for a certain mHH **shape**



Capozi, GH,  
1908.08923

| benchmark<br>(* = modified) | $c_{hhh}$ | $c_t$ | $c_{tt}$       | $c_{ggh}$ | $c_{gghh}$ |
|-----------------------------|-----------|-------|----------------|-----------|------------|
| SM                          | 1         | 1     | 0              | 0         | 0          |
| 1*                          | 5.105     | 1.1   | 0              | 0         | 0          |
| 3*                          | 2.21      | 1.05  | $-\frac{1}{3}$ | 0.5       | 0.25*      |
| 6*                          | -0.684    | 0.9   | $-\frac{1}{6}$ | 0.5       | 0.25       |

- benchmark 1: enhanced low mHH
- benchmark 3: dip
- benchmark 6: SM-like except for shoulder left of peak

modified: to fulfil SMEFT relation  $c_{ggh} = 2c_{gghh}$

new benchmarks fulfilling current constraints:  
Ludovic Scyboz



# Results: total HH cross sections

quadratic dim-6

linearised dim-6

| benchmark                 | $\sigma_{\text{NLO}}[\text{fb}]$<br>option (b) | K-factor<br>option (b) | ratio to SM<br>option (b) | $\sigma_{\text{NLO}}[\text{fb}]$<br>option (a) | $\sigma_{\text{NLO}}[\text{fb}]$<br>HEFT |
|---------------------------|------------------------------------------------|------------------------|---------------------------|------------------------------------------------|------------------------------------------|
| SM                        | $27.94^{+13.7\%}_{-12.8\%}$                    | 1.67                   | 1                         | -                                              | -                                        |
| $\Lambda = 1 \text{ TeV}$ |                                                |                        |                           |                                                |                                          |
| 1                         | $74.29^{+19.8\%}_{-15.6\%}$                    | 2.13                   | 2.66                      | -61.17                                         | 94.32                                    |
| 3                         | $69.20^{+11.7\%}_{-10.3\%}$                    | 1.82                   | 2.47                      | 29.64                                          | 72.43                                    |
| 6                         | $72.51^{+20.6\%}_{-16.4\%}$                    | 1.90                   | 2.60                      | 52.89                                          | 91.40                                    |
| $\Lambda = 2 \text{ TeV}$ |                                                |                        |                           |                                                |                                          |
| 1                         | $14.03^{+12.0\%}_{-11.9\%}$                    | 1.56                   | 0.502                     | 5.58                                           | -                                        |
| 3                         | $30.81^{+16.0\%}_{-14.4\%}$                    | 1.71                   | 1.10                      | 28.35                                          | -                                        |
| 6                         | $35.39^{+17.5\%}_{-15.2\%}$                    | 1.76                   | 1.27                      | 34.18                                          | -                                        |

# Naive translation at Lagrangian level:

| benchmark<br>(* = modified) | $c_{hhhh}$ | $c_t$ | $c_{tt}$       | $c_{ggh}$ | $c_{gghh}$ | $C_{H,\text{kin}}$ | $C_H$ | $C_{uH}$ | $C_{HG}$ | $\Lambda$ |
|-----------------------------|------------|-------|----------------|-----------|------------|--------------------|-------|----------|----------|-----------|
| SM                          | 1          | 1     | 0              | 0         | 0          | 0                  | 0     | 0        | 0        | 1 TeV     |
| 1*                          | 5.105      | 1.1   | 0              | 0         | 0          | 4.95               | -6.81 | 3.28     | 0        | 1 TeV     |
| 3*                          | 2.21       | 1.05  | $-\frac{1}{3}$ | 0.5       | 0.25*      | 13.5               | 2.64  | 12.6     | 0.0387   | 1 TeV     |
| 6*                          | -0.684     | 0.9   | $-\frac{1}{6}$ | 0.5       | 0.25       | 0.561              | 3.80  | 2.20     | 0.0387   | 1 TeV     |

| HEFT       | Warsaw                                                                                            |
|------------|---------------------------------------------------------------------------------------------------|
| $c_{hhhh}$ | $1 - 2 \frac{v^2}{\Lambda^2} \frac{v^2}{m_h^2} C_H + 3 \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$    |
| $c_t$      | $1 + \frac{v^2}{\Lambda^2} C_{H,\text{kin}} - \frac{v^2}{\Lambda^2} \frac{v}{\sqrt{2}m_t} C_{uH}$ |
| $c_{tt}$   | $-\frac{v^2}{\Lambda^2} \frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$  |
| $c_{ggh}$  | $\frac{v^2}{\Lambda^2} \frac{8\pi}{\alpha_s} C_{HG}$                                              |
| $c_{gghh}$ | $\frac{v^2}{\Lambda^2} \frac{4\pi}{\alpha_s} C_{HG}$                                              |

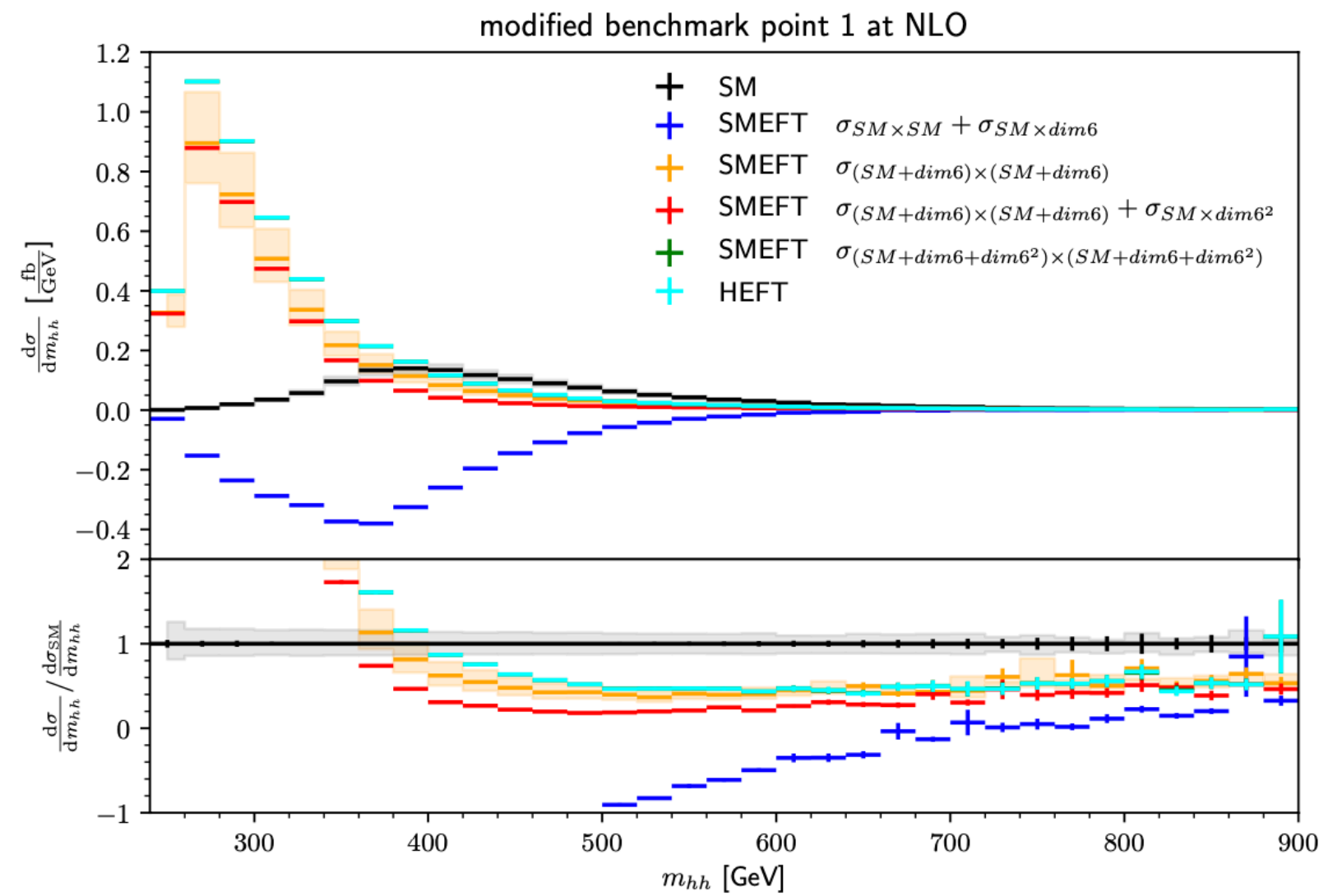
$E^2 \frac{|C_i|}{\Lambda^2} \ll 1$  **not fulfilled** for  $\Lambda \simeq 1 \text{ TeV}$   
 and  $E \simeq m_{hh}$  up to  $\sim 1 \text{ TeV}$



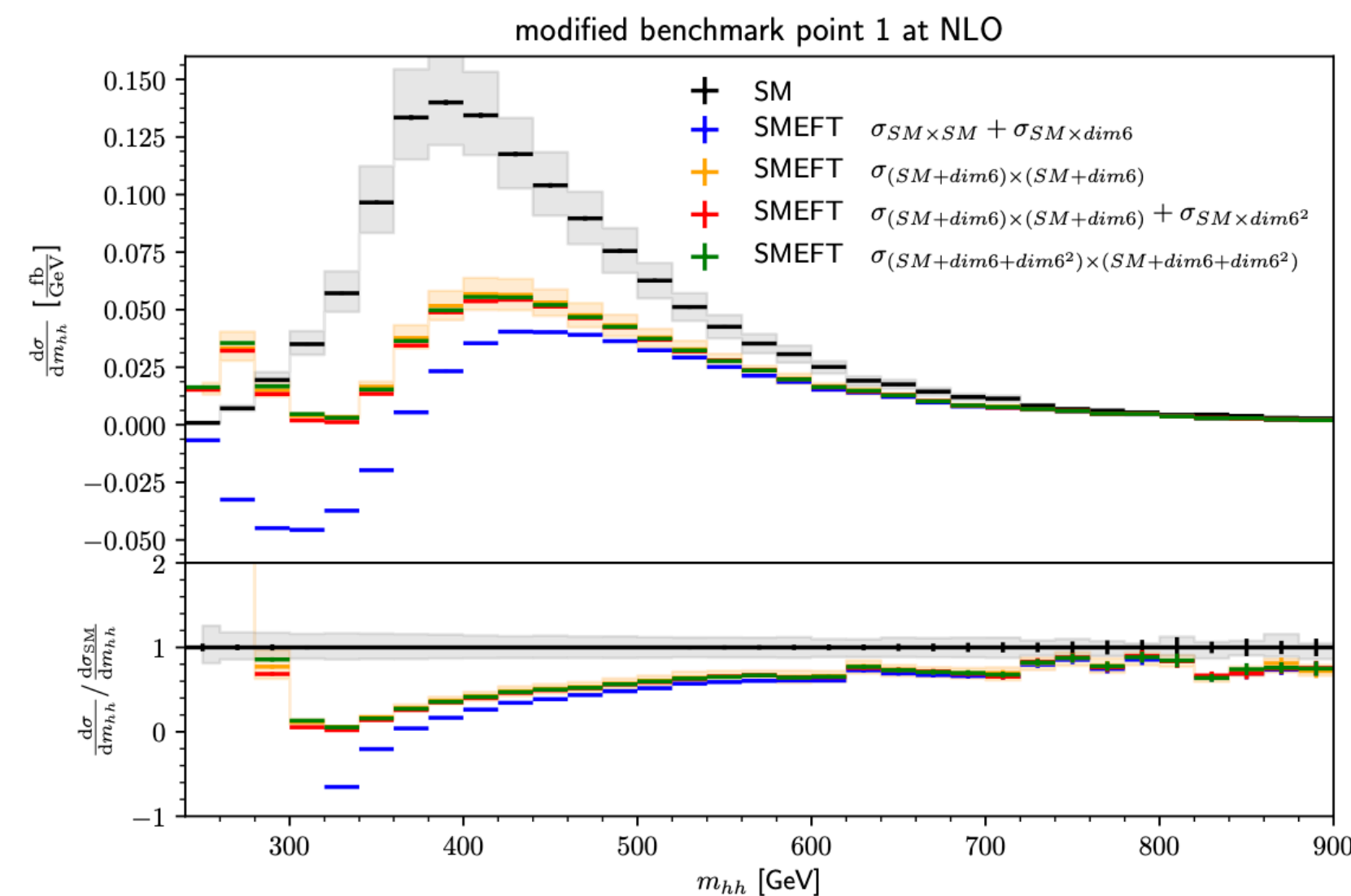
# Higgs boson pair invariant mass spectrum

benchmark point 1

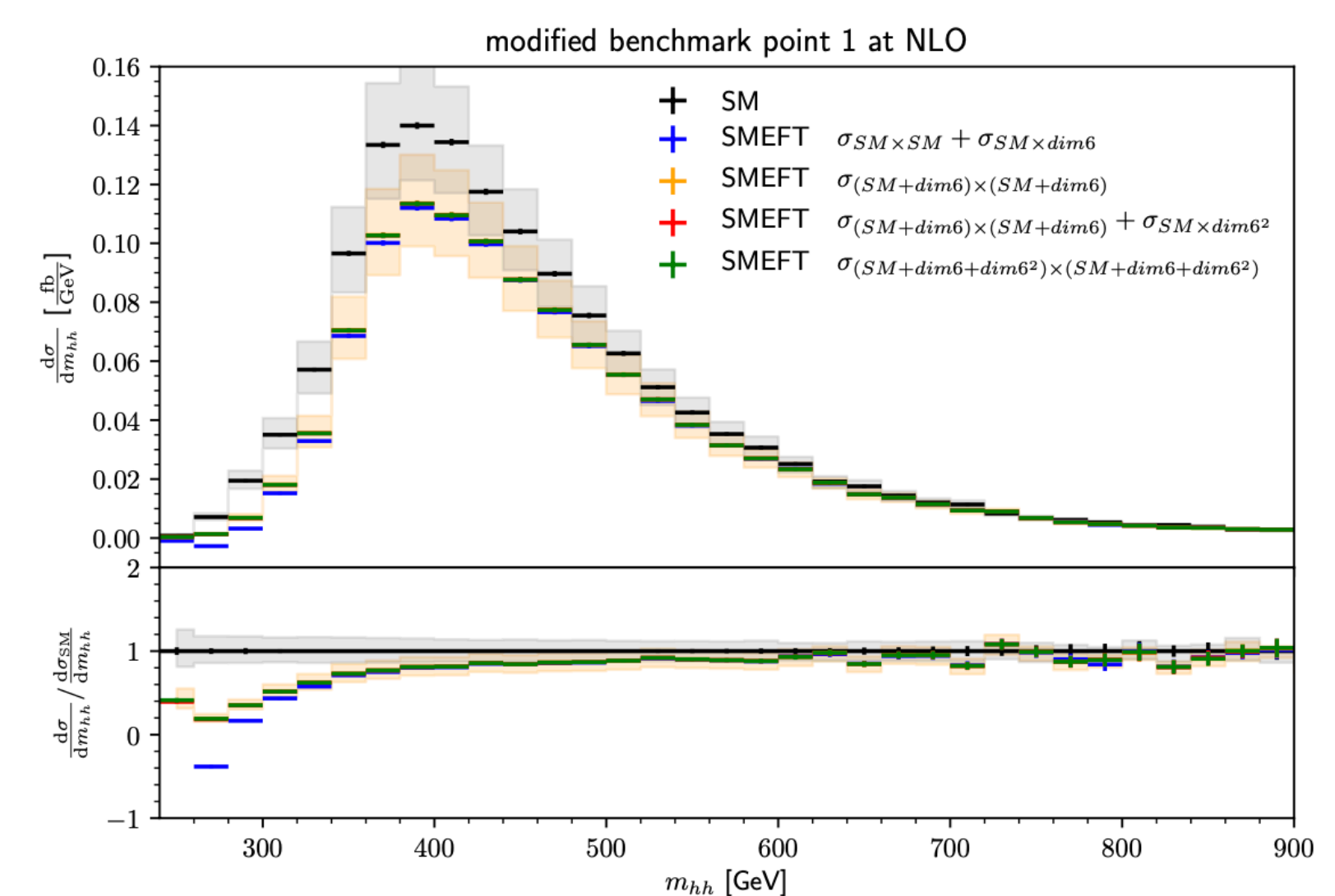
figures: Jannis Lang



$\Lambda = 1 \text{ TeV}$



$\Lambda = 2 \text{ TeV}$



$\Lambda = 4 \text{ TeV}$

linear dim6: negative cross sections

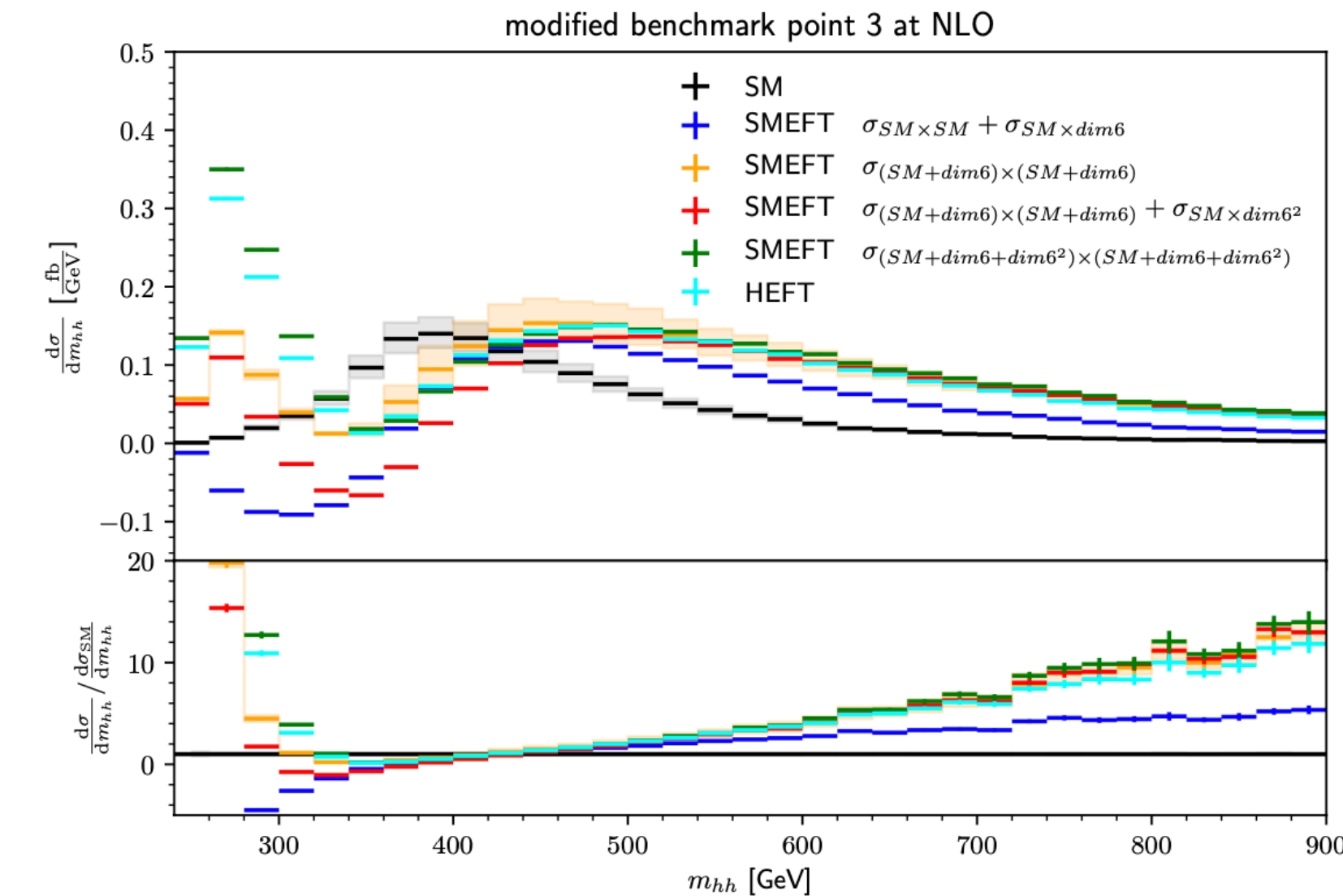
shape changes as  $\Lambda$  is increased (obviously, approaching SM shape)

→ for low values of  $\Lambda$ : parameter point valid in HEFT can be **invalid** in SMEFT

# Higgs boson pair invariant mass spectrum

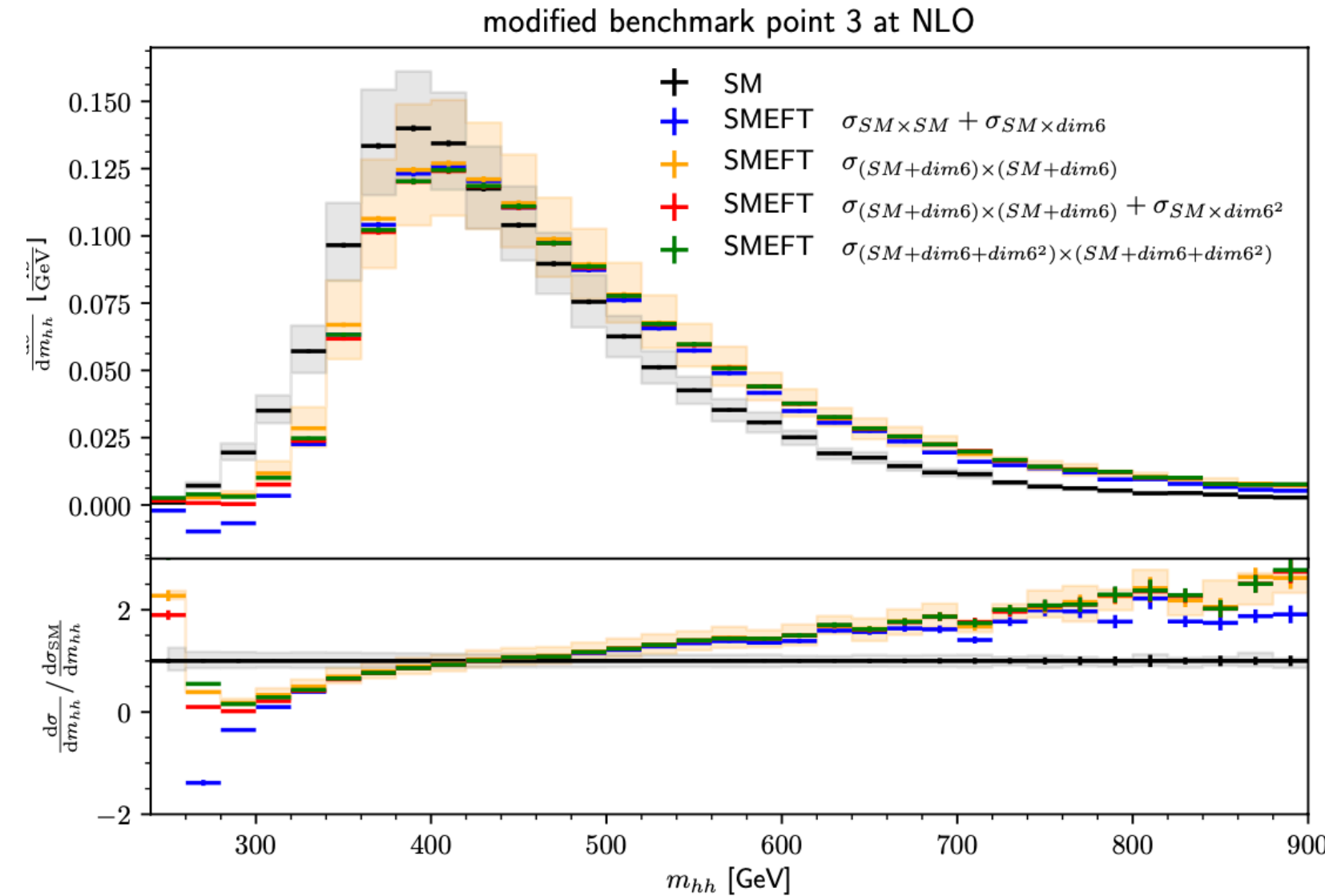
figures: Jannis Lang

benchmark point 3



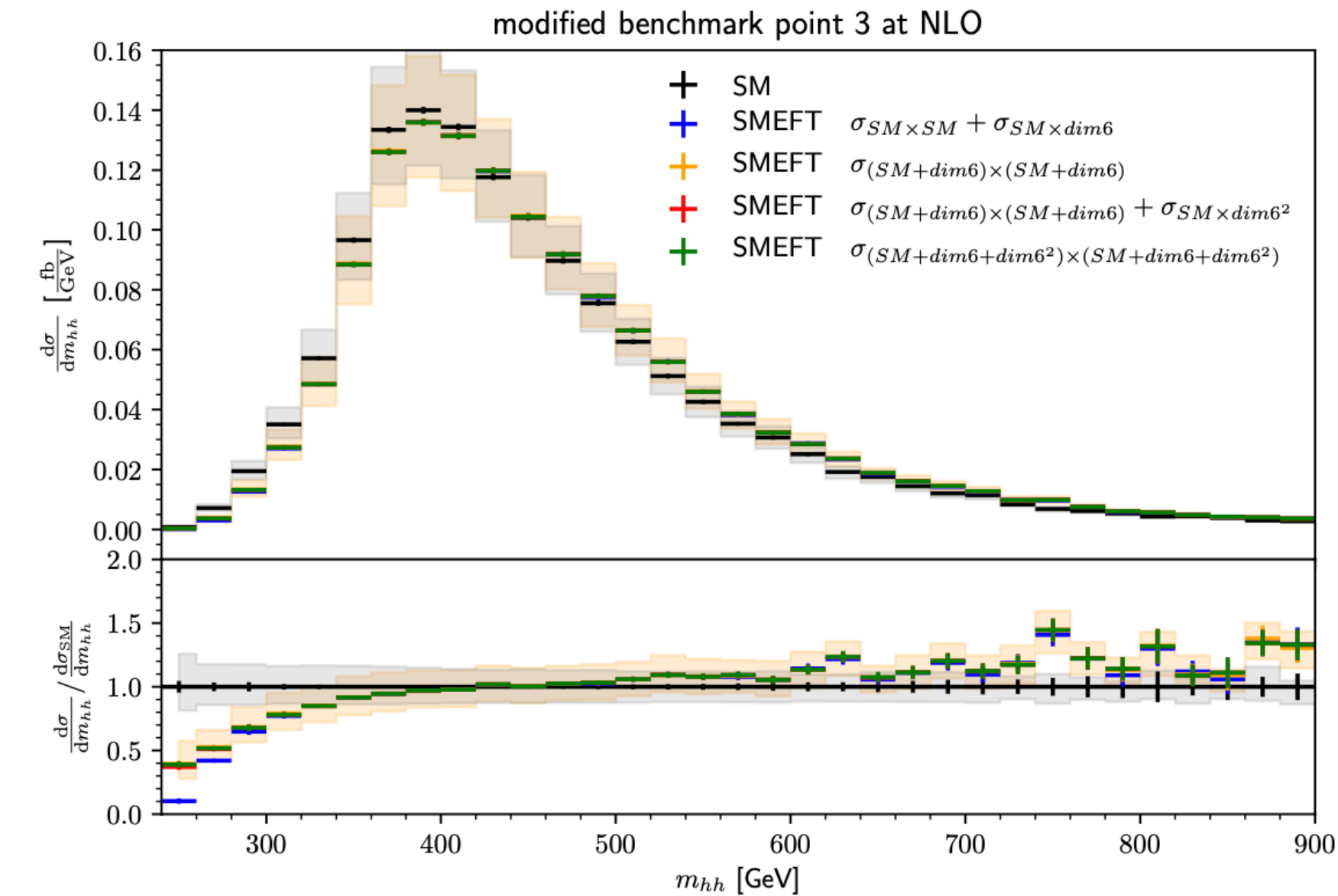
$\Lambda = 1 \text{ TeV}$

double operator insertions  
have large effect



$\Lambda = 2 \text{ TeV}$

distinguishable from SM  
within NLO uncertainties



$\Lambda = 4 \text{ TeV}$

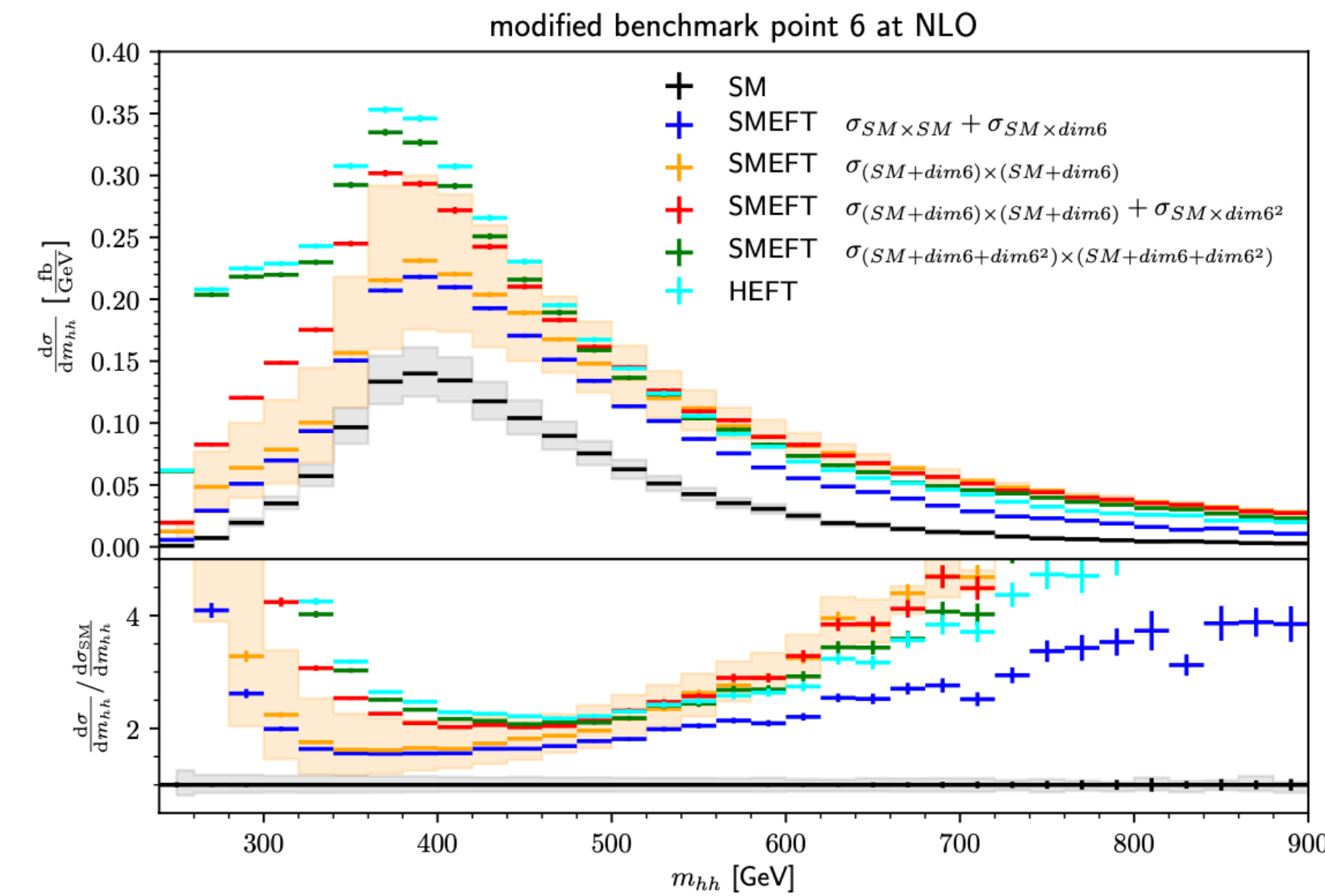
can be distinguished from SM  
in low  $m_{HH}$  region



# Higgs boson pair invariant mass spectrum

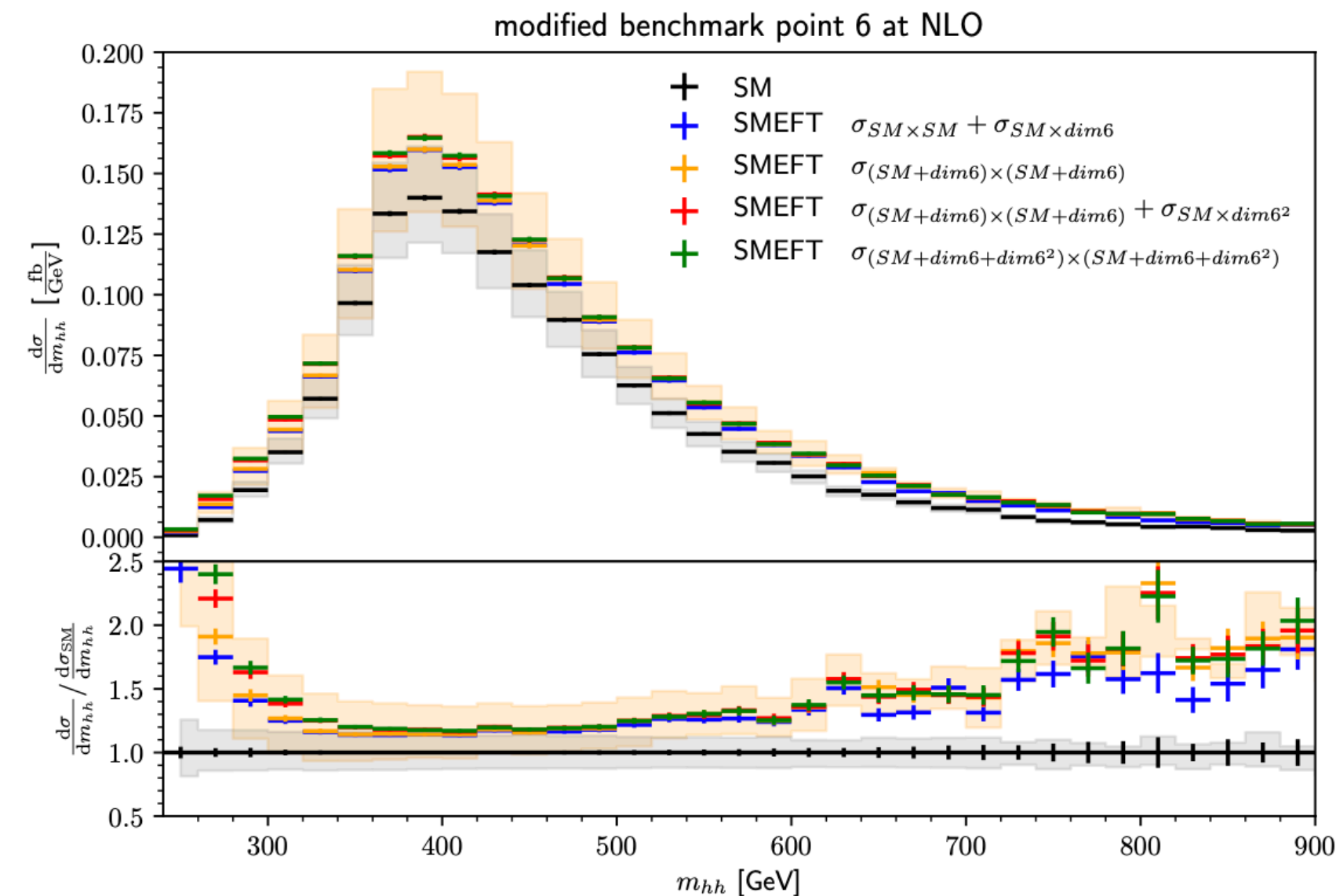
figures: Jannis Lang

benchmark point 6



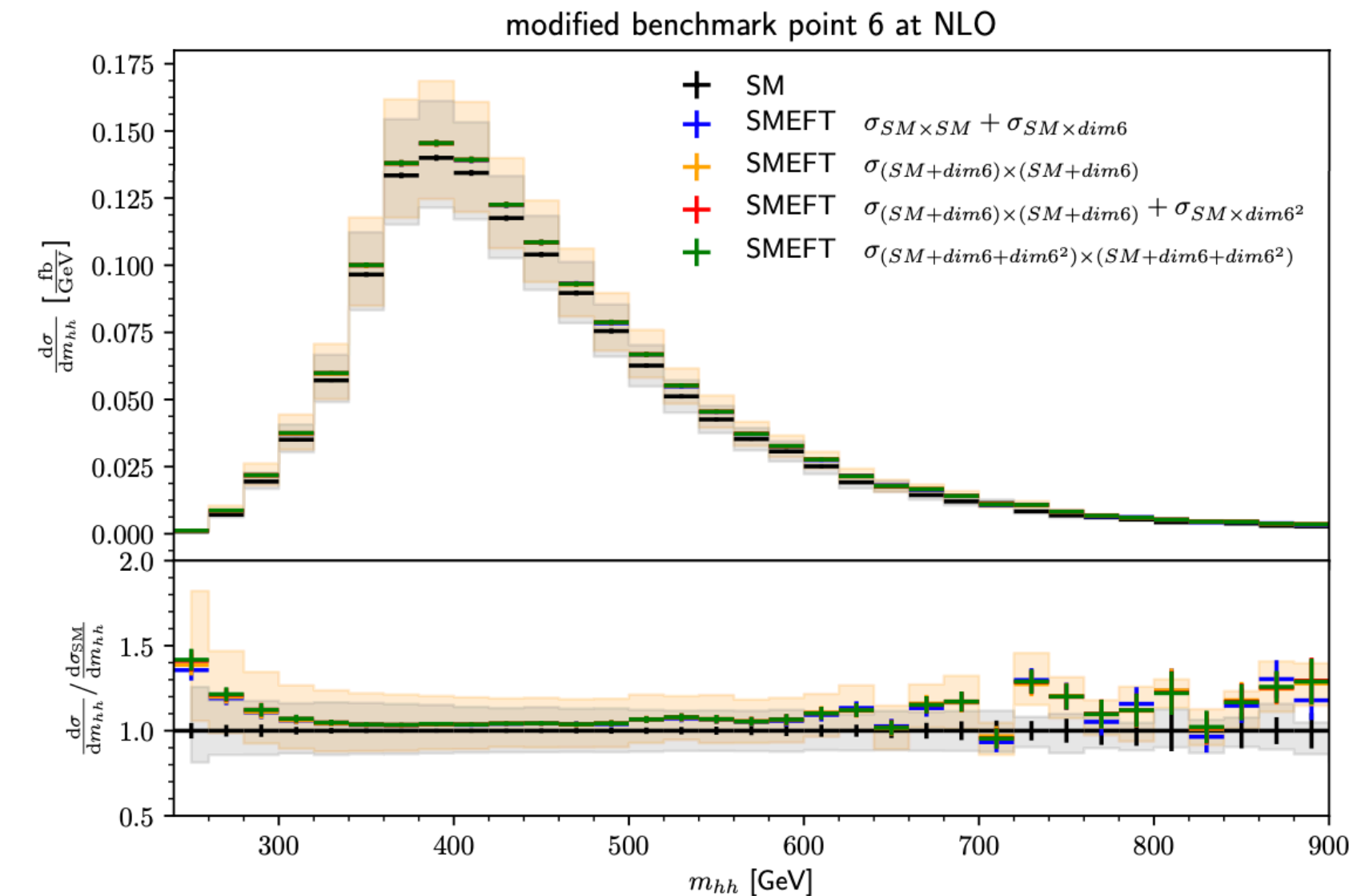
$\Lambda = 1 \text{ TeV}$

difference between green and cyan  
only running of  $\alpha_s$



$\Lambda = 2 \text{ TeV}$

shoulder left gone



$\Lambda = 4 \text{ TeV}$

can hardly be distinguished from SM  
within NLO scale uncertainties

# Summary & Outlook

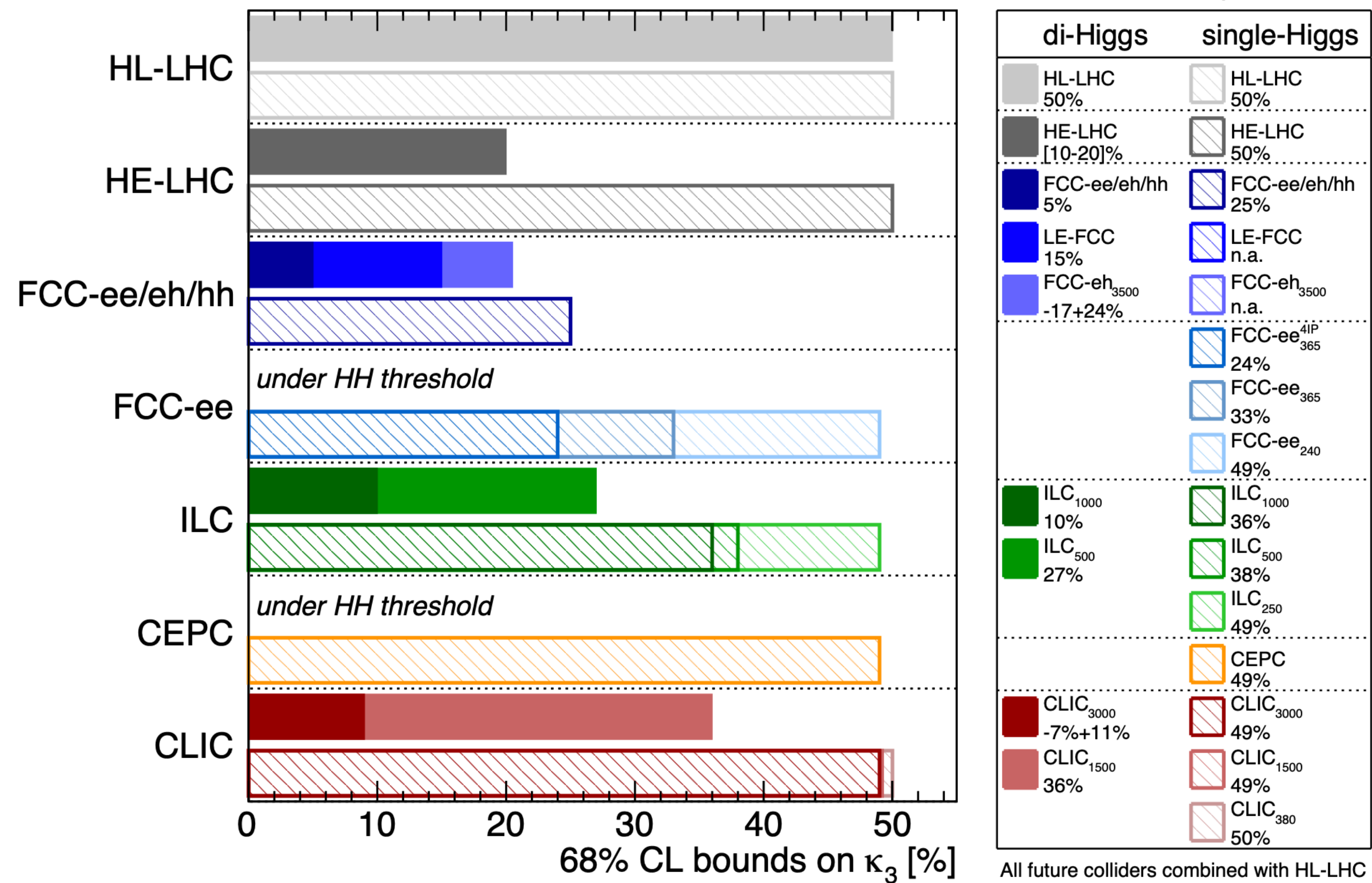
- Indirect signs of New Physics: precision is the key
- full NLO QCD results within SMEFT available for  $gg \rightarrow HH$   
([ggHH\\_SMEFT](#), Powheg-Box-V2)
- allows study of truncation effects and comparison to HEFT
- naive translation from HEFT to SMEFT can lead out of SMEFT validity range
- scenarios that are described well by SMEFT are often not distinguishable from SM within the scale uncertainties

*Thank you for your attention!*



# Higgs-boson self coupling

Higgs@FC WG September 2019

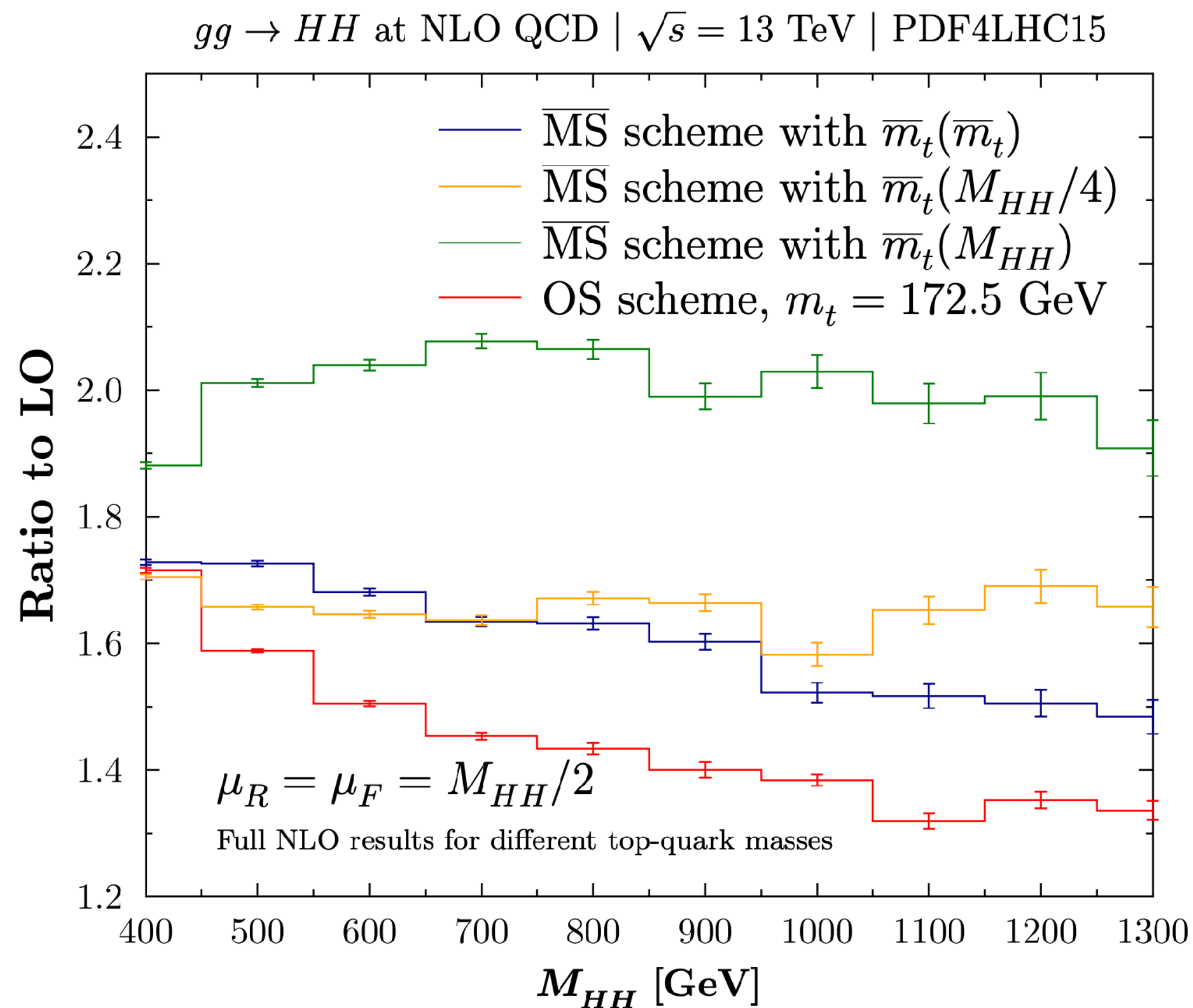


European Strategy Physics Briefing Book 1910.11775

# Top quark mass renormalisation scheme uncertainties

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

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



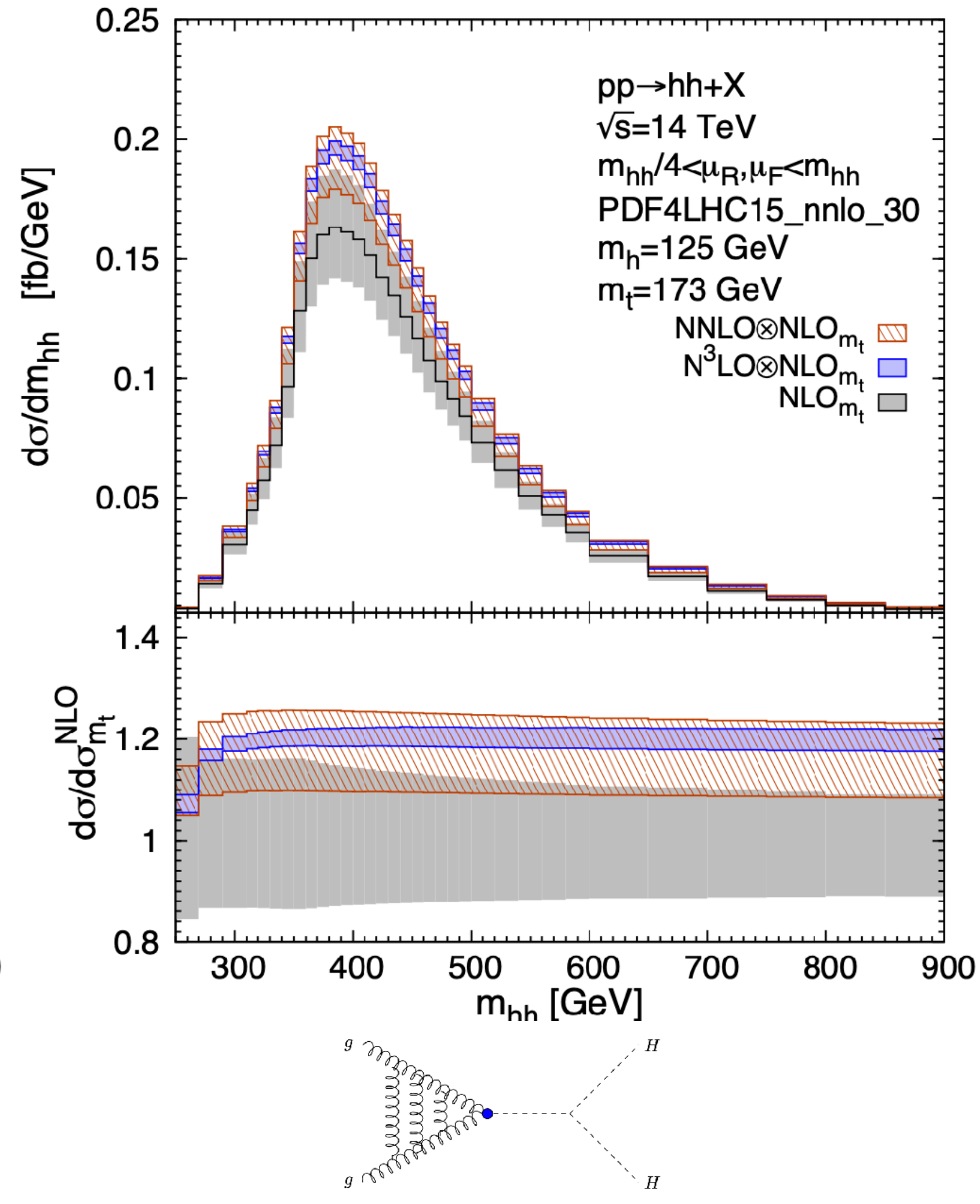
Baglio, Campanario, Glaus Mühlleitner,  
Ronca, Spira 2003.03227, 2008.11626

also present in other heavy quark  
loop induced processes

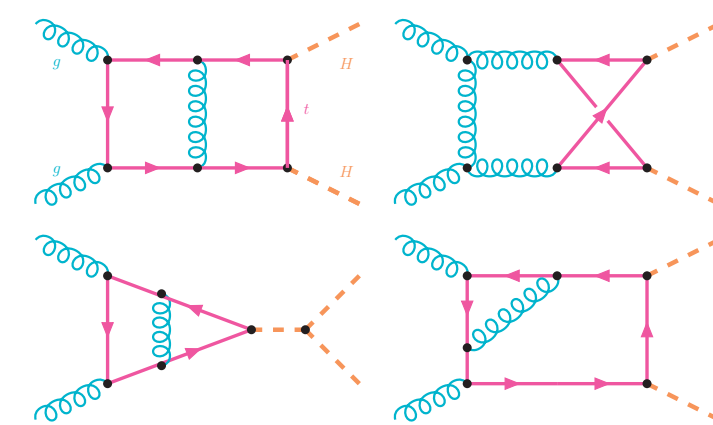
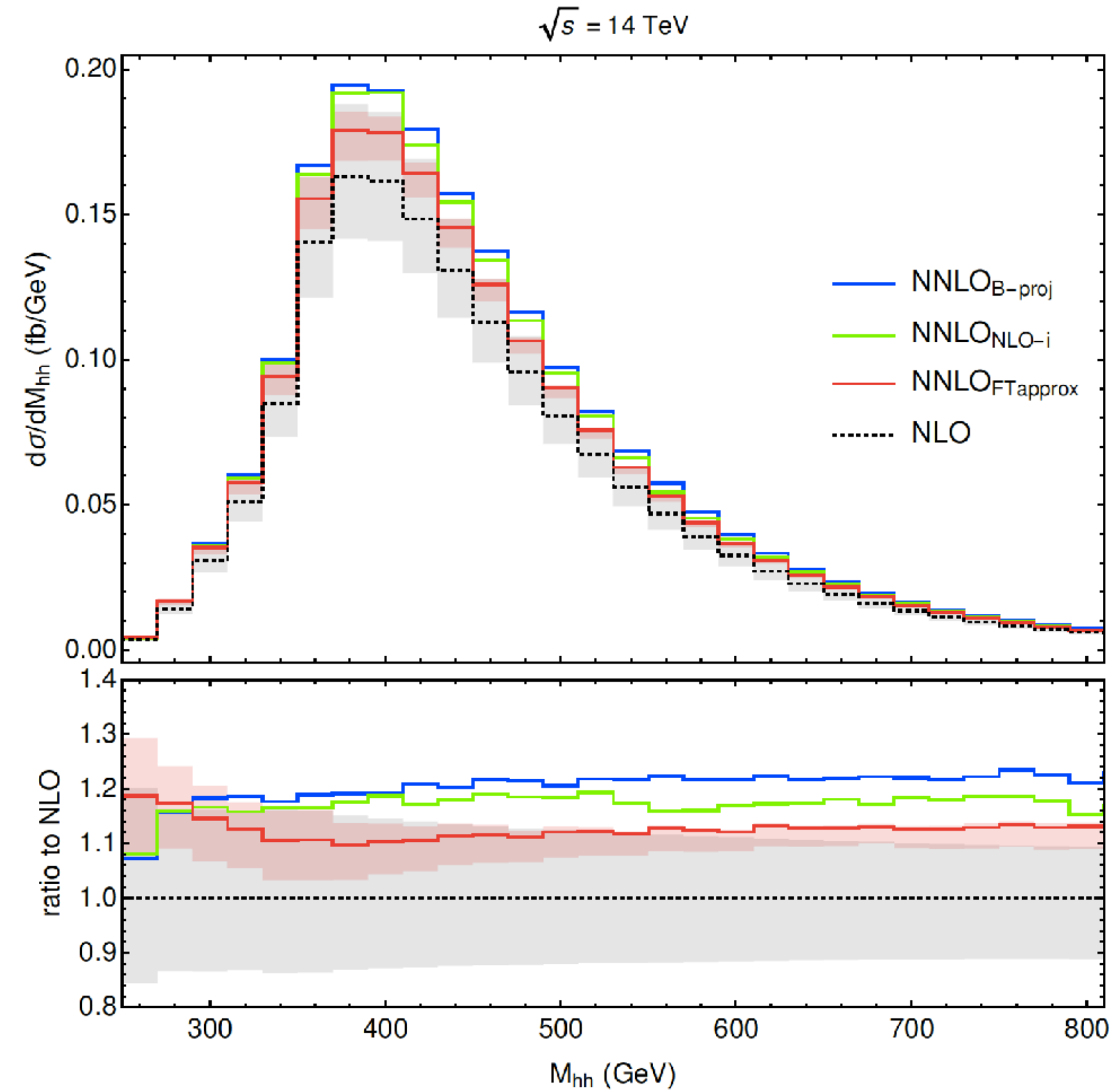


# Highest perturbative orders (SM)

Chen, Li, Shao, Wang 1912.13001

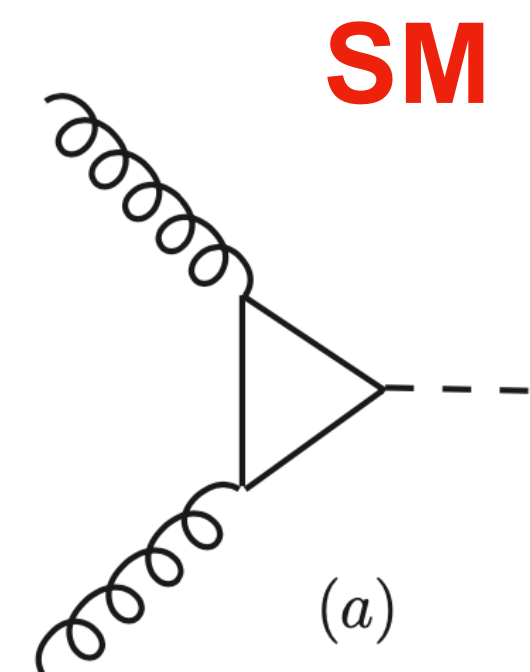


Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli 1803.02463

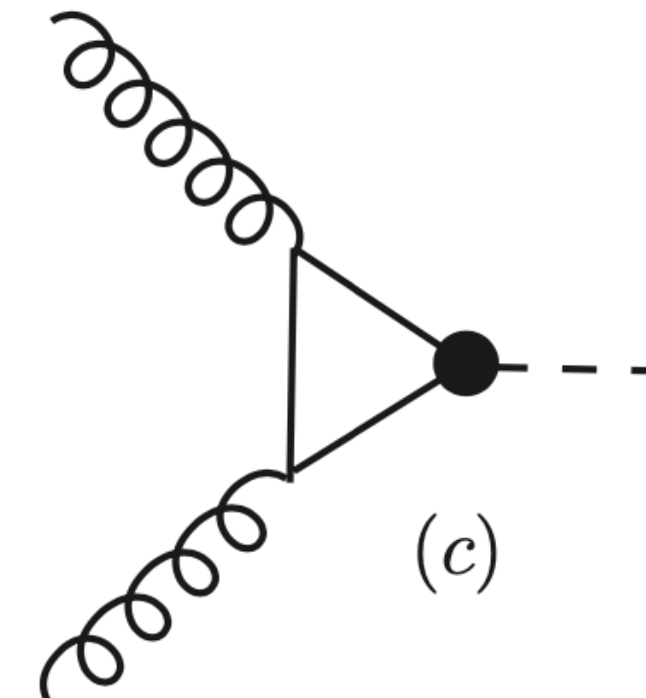
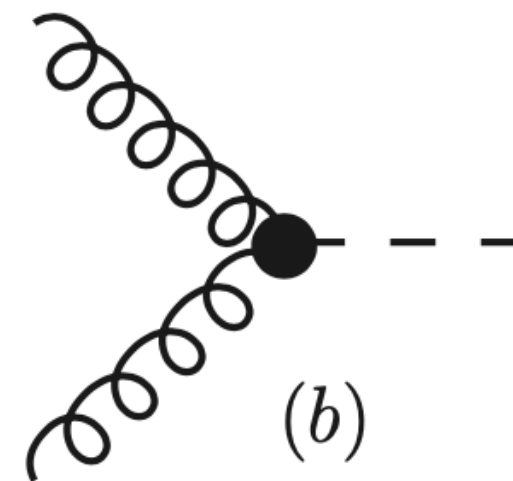


# Loop counting matters in SMEFT

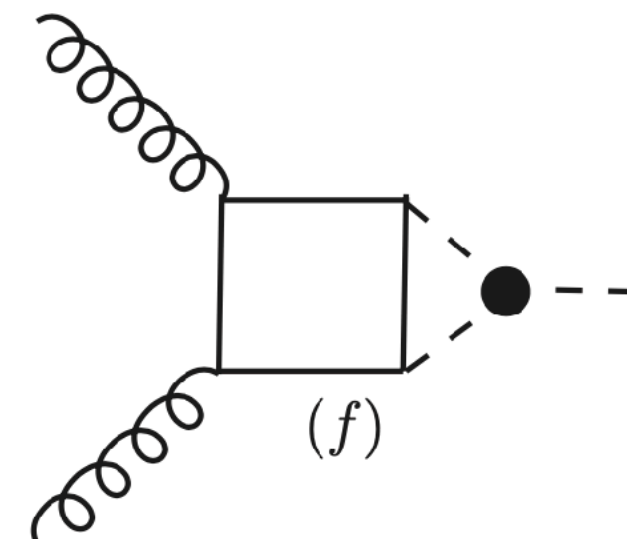
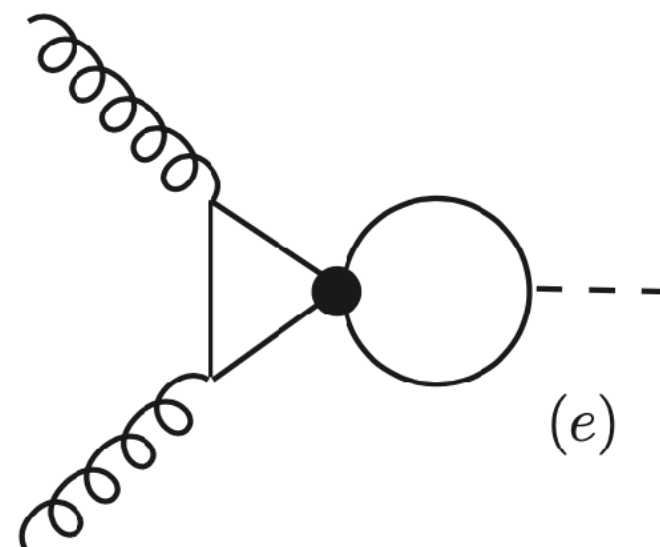
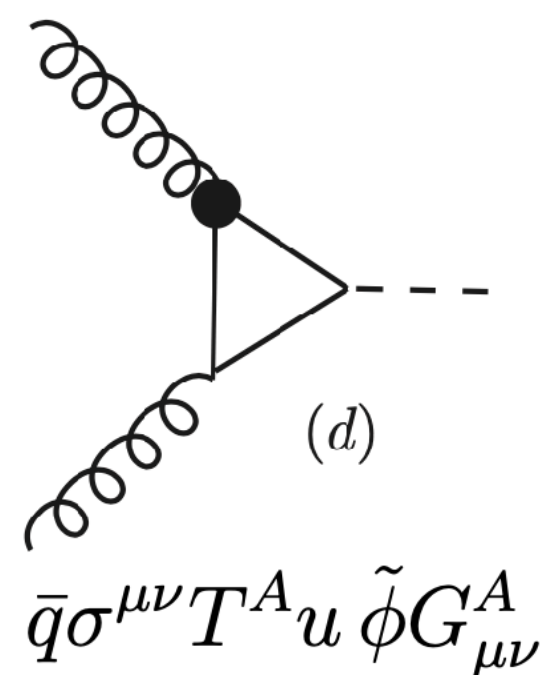
example single Higgs production    Buchalla, GH, Müller-Salditt, Pandler, arXiv:2204.11808



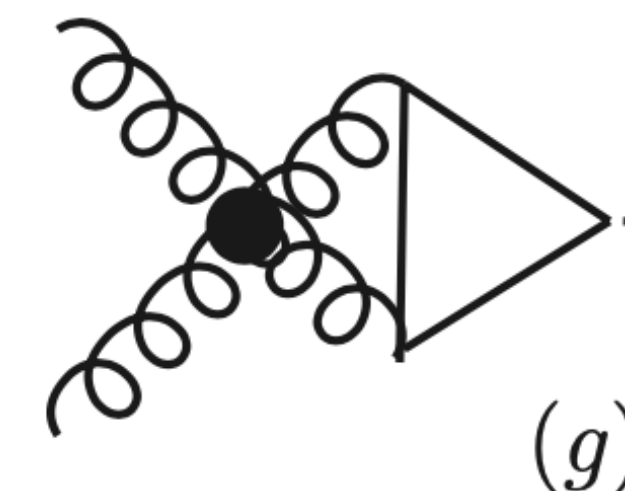
$$\frac{1}{16\pi^2}$$



$$\frac{1}{\Lambda^2} \frac{1}{16\pi^2}$$



$$\frac{1}{\Lambda^2} \frac{1}{(16\pi^2)^2}$$



$$\frac{1}{\Lambda^2} \frac{1}{(16\pi^2)^3}$$

$$Q_G = f^{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$$

if only canonical dimension is counted, (b) - (g) would all contribute at the same order (dim 6) !