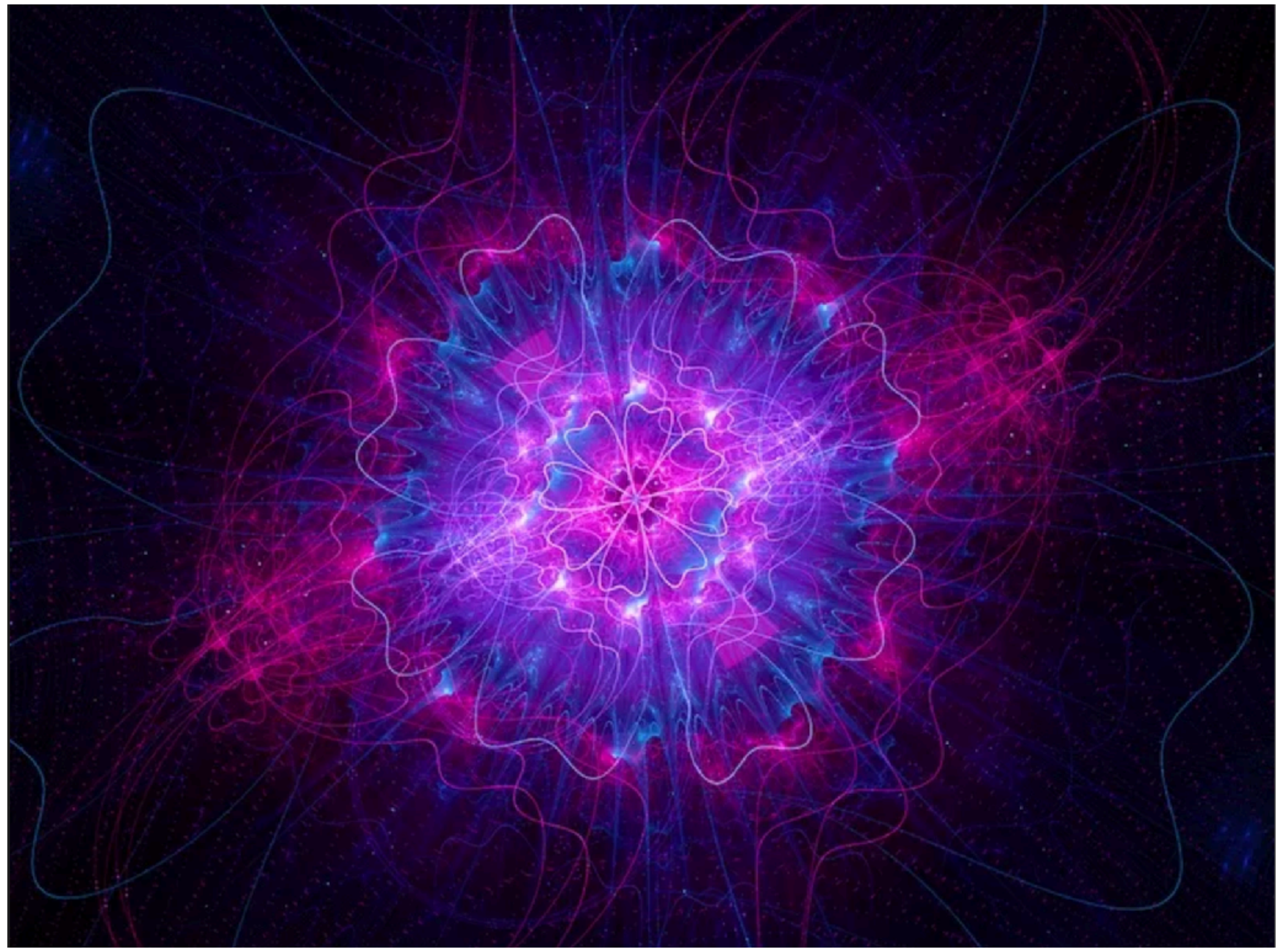
Collider Physics at the Precision Frontier:

The Higgs sector under scrutiny



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

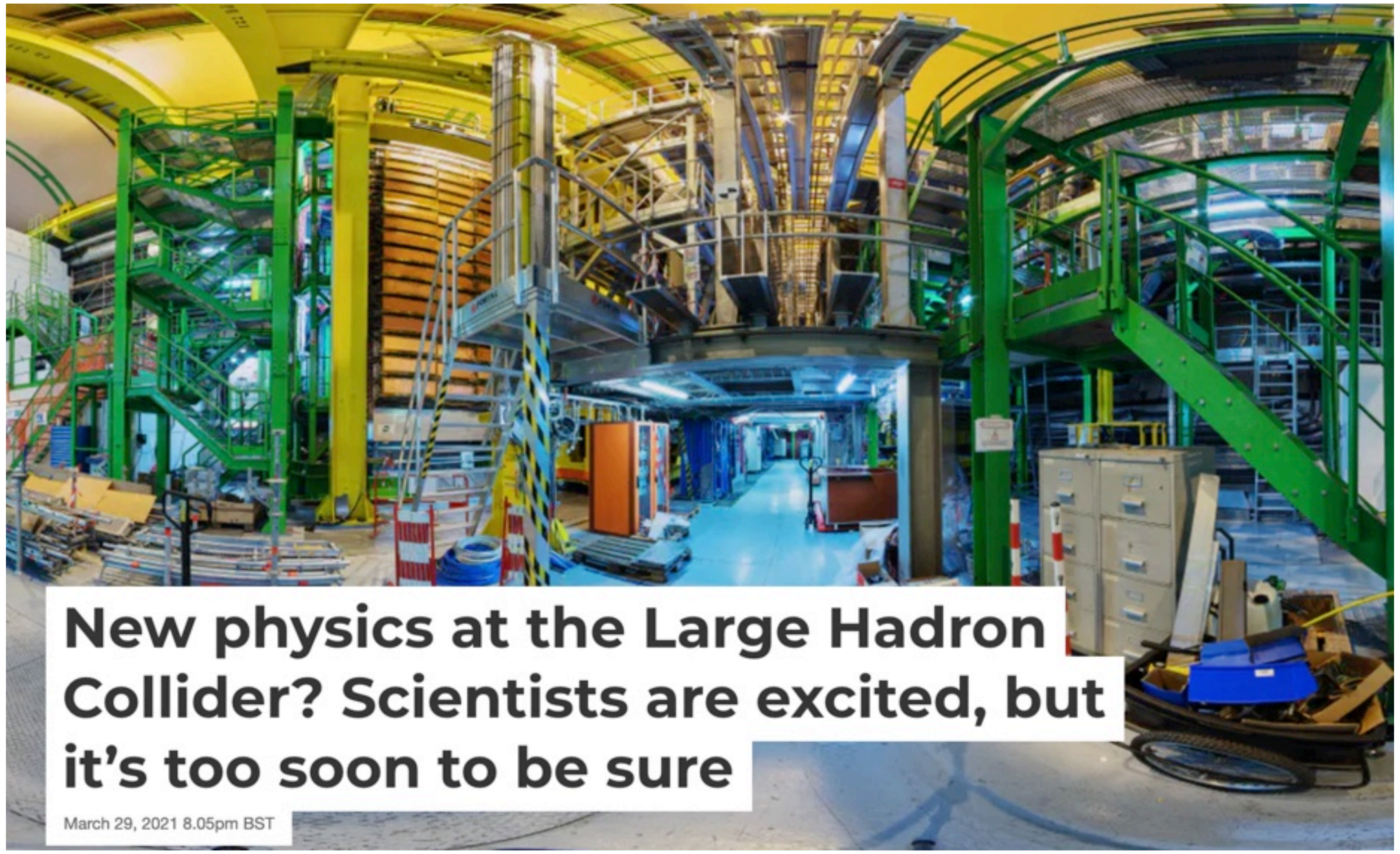
Gudrun Heinrich
Institute for Theoretical Physics,
Karlsruhe Institute of Technology

Particle Physics Seminar
Universität Wien

April 5, 2022

Motivation

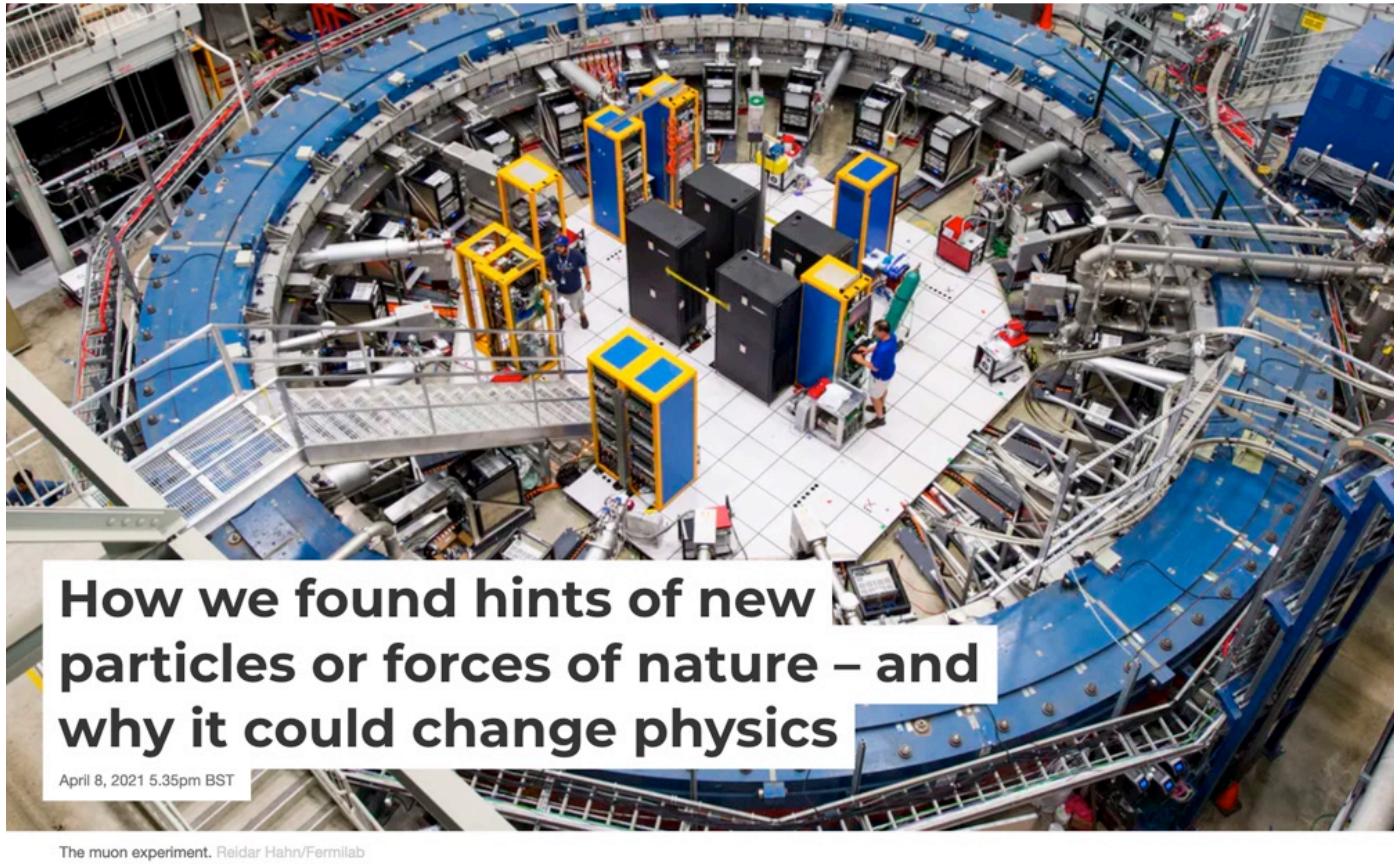
The Standard Model of Particle Physics is unlikely to be the end of the story



New physics at the Large Hadron Collider? Scientists are excited, but it's too soon to be sure

March 29, 2021 8.05pm BST

LHCb (CERN)



How we found hints of new particles or forces of nature – and why it could change physics

April 8, 2021 5.35pm BST

The muon experiment. Reidar Hahn/Fermilab

muon anomalous magnetic moment measurement (Fermilab)

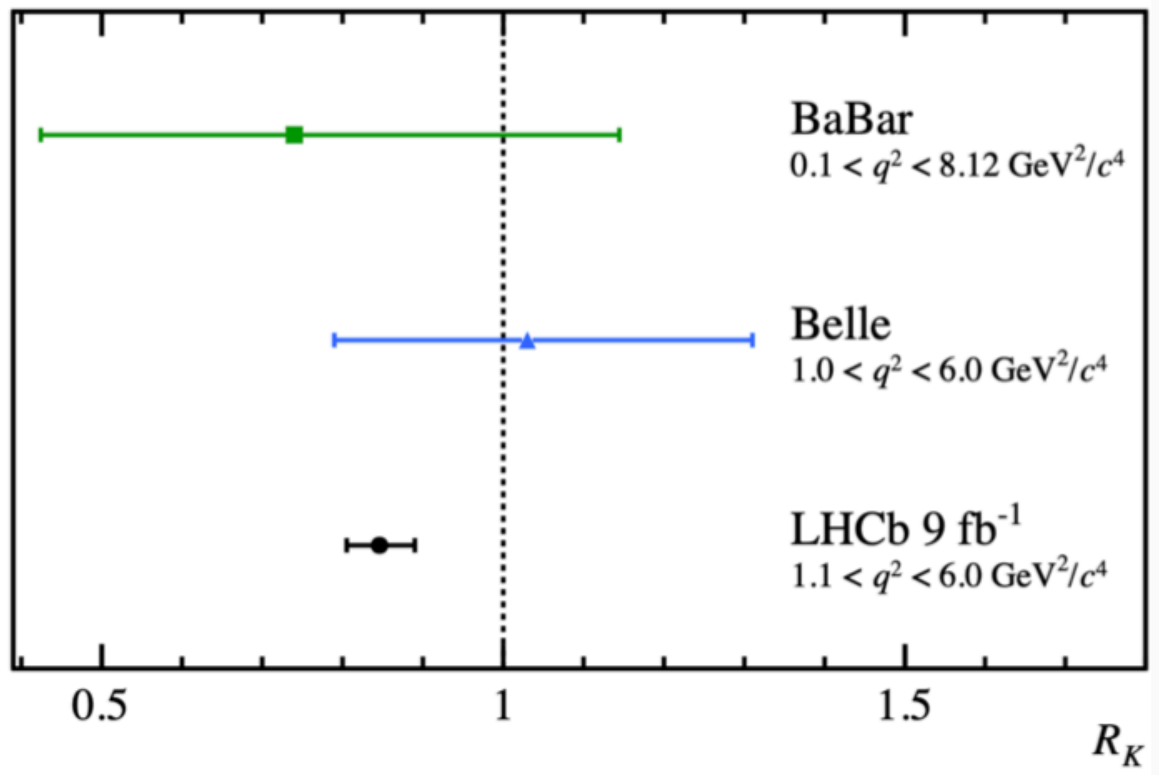
theconversation.com

Motivation

Exciting new experimental value of R_K

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(B\to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

LHCb [2103.11769]



M. Alguero, Moriond 2021

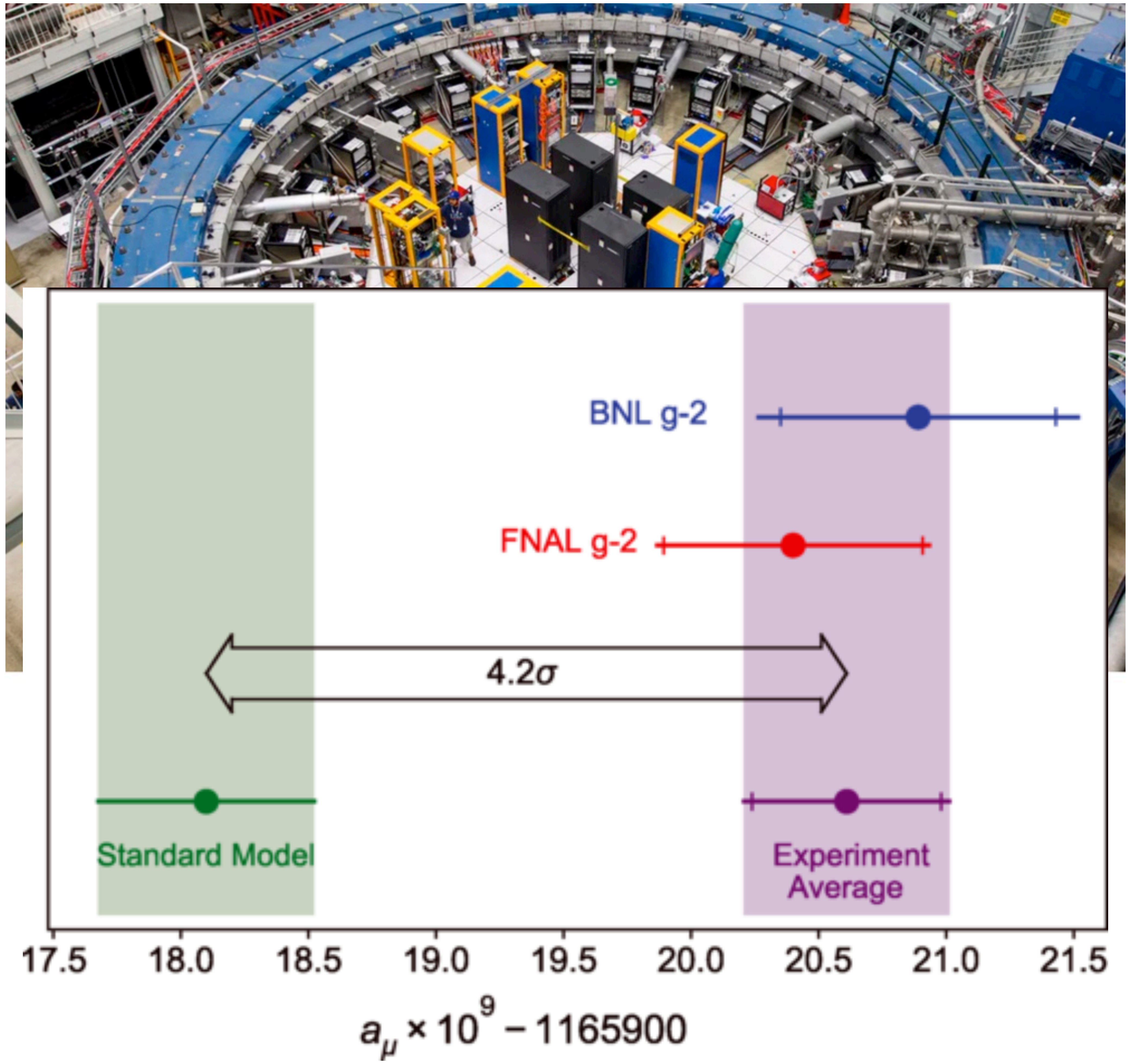
$$R_K^{\mathrm{LHCb}} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

+ Likelihood

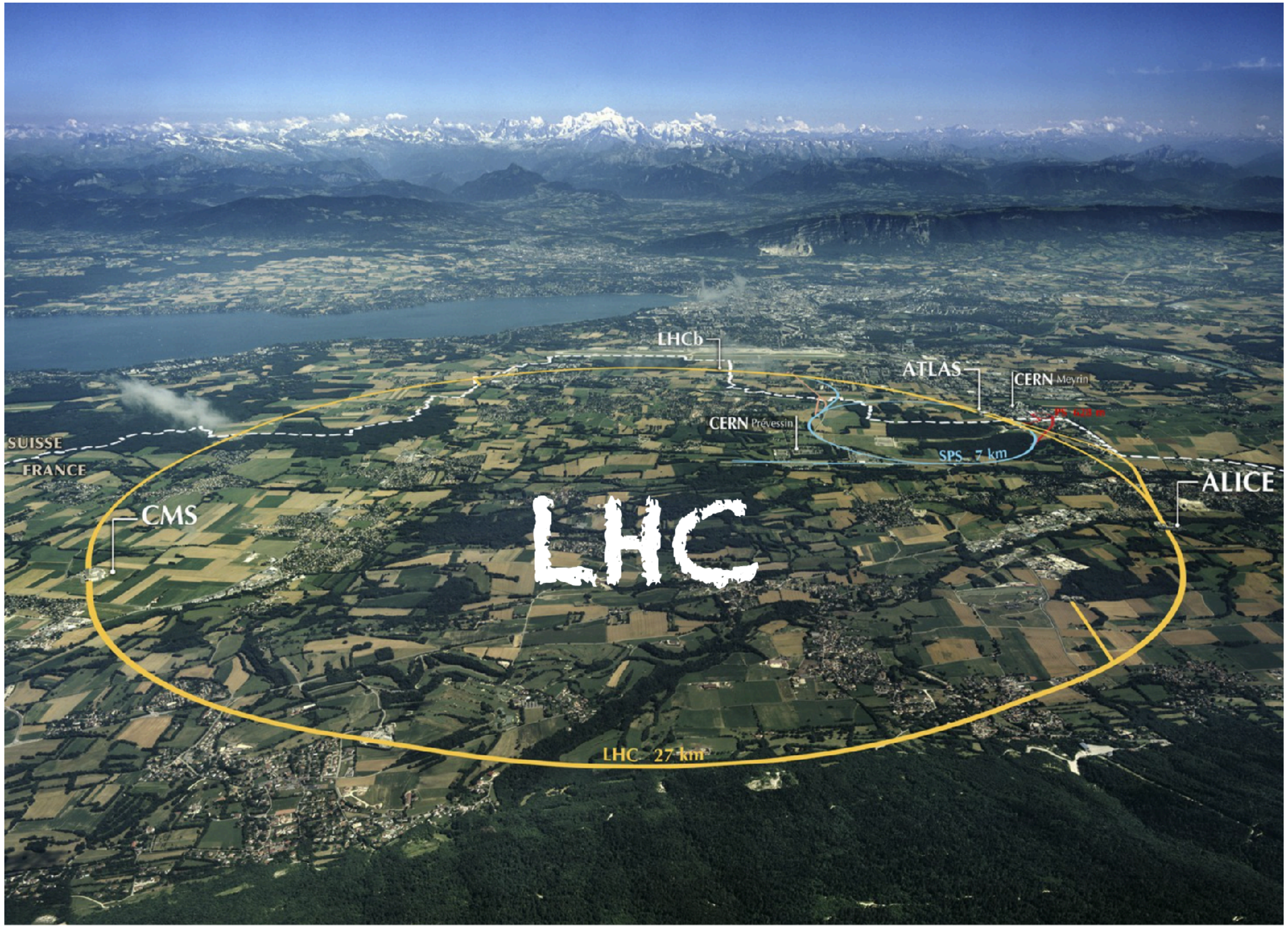
⇨ $\boxed{3.1\sigma}$! !

New physics at the Large Hadron Collider? Scientists are excited, but it's too soon to be sure

March 29, 2021 8.05pm BST



Current high energy frontier

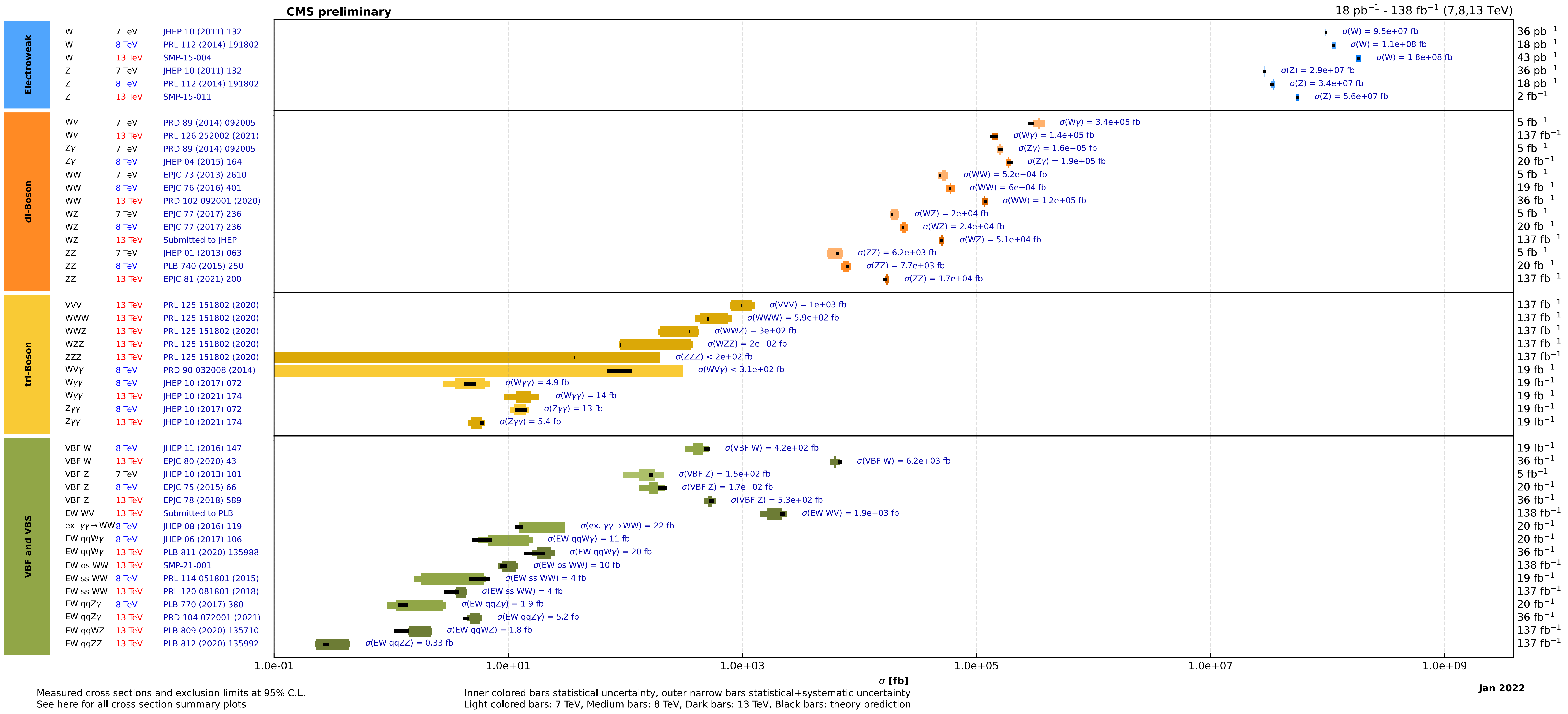


Current high energy frontier

Karlsruhe Institute of Technology

- at current energy frontier, no hints of new physics

Overview of CMS cross section results

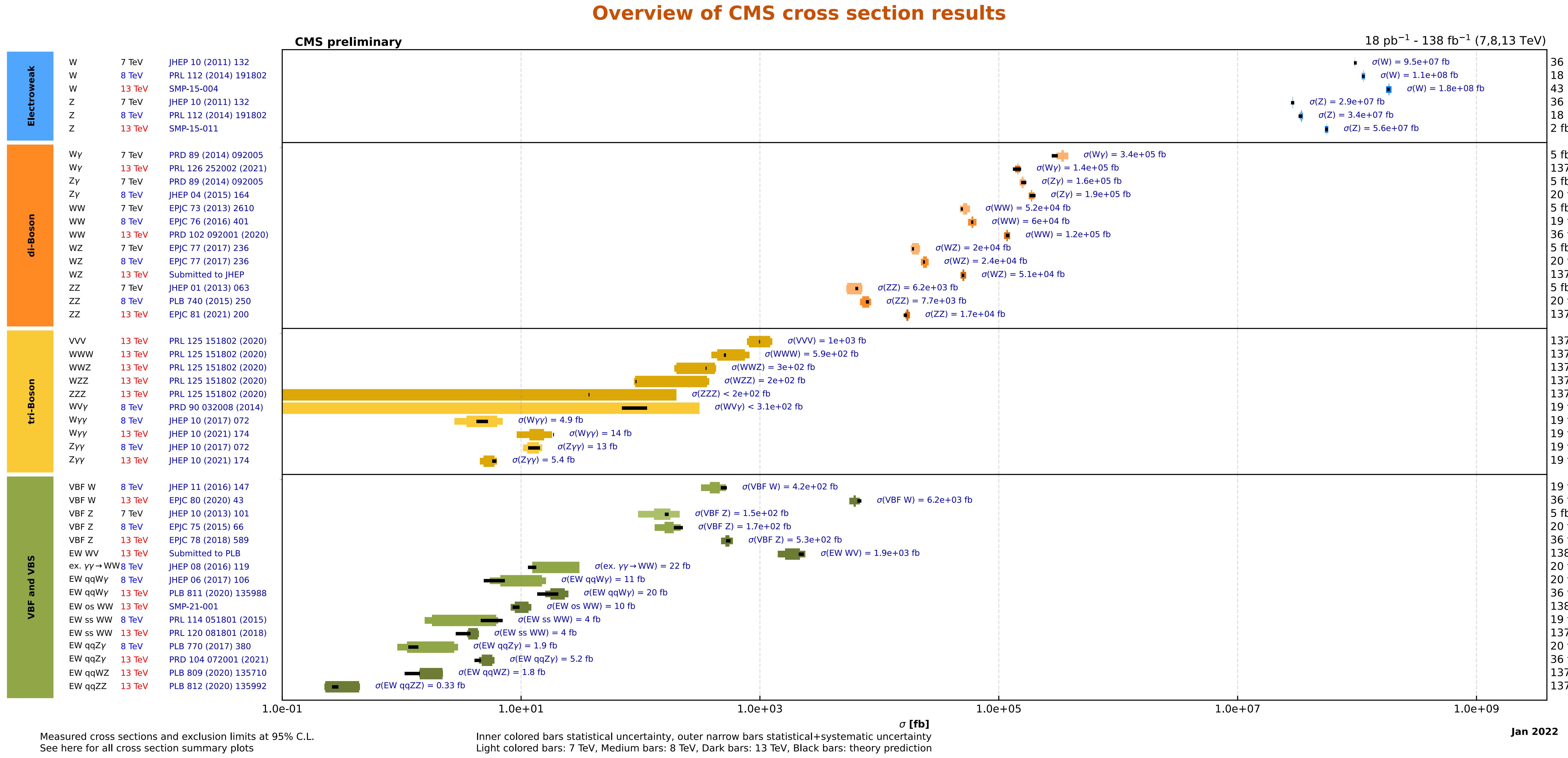


Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

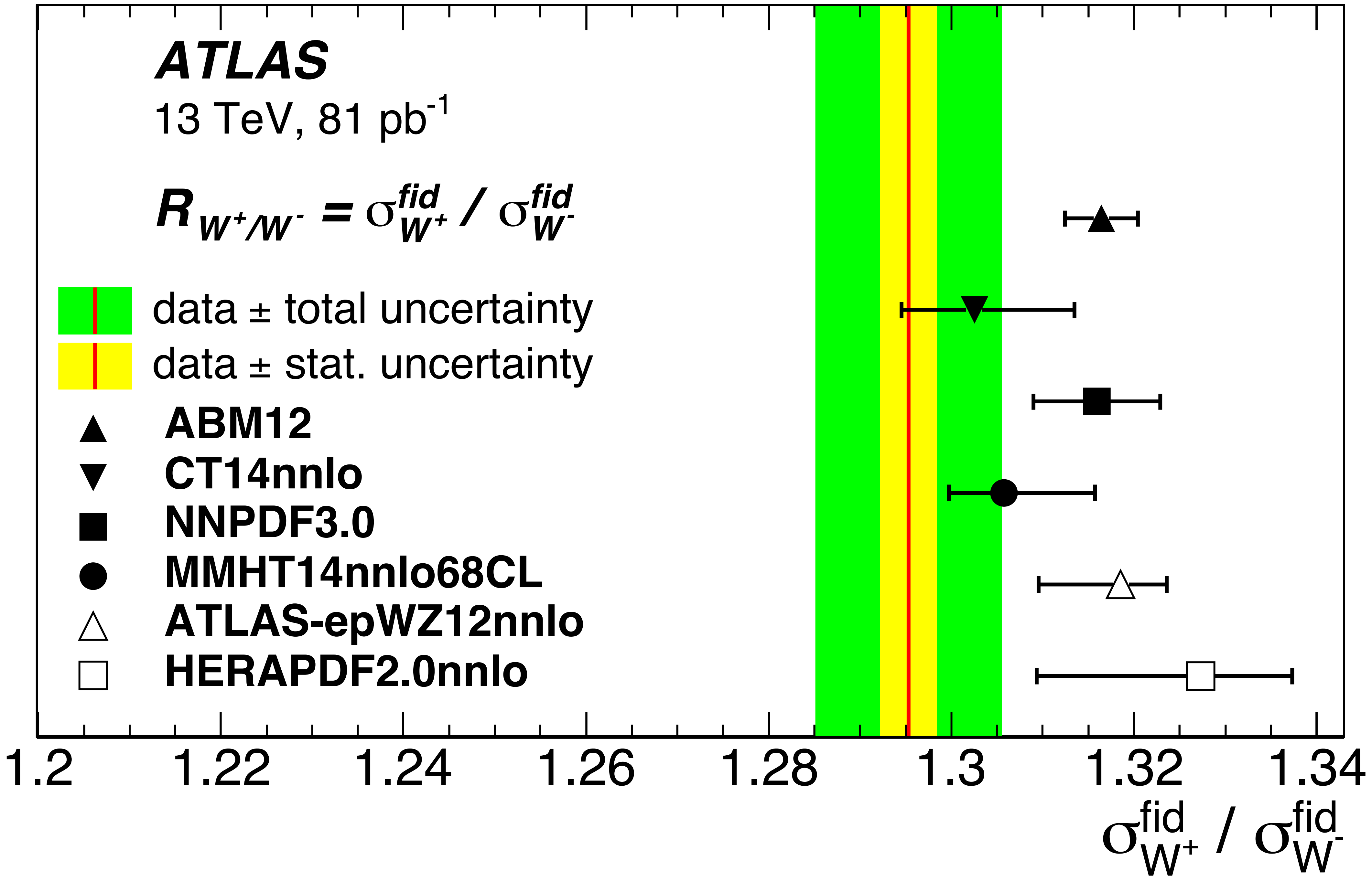
Current high energy frontier

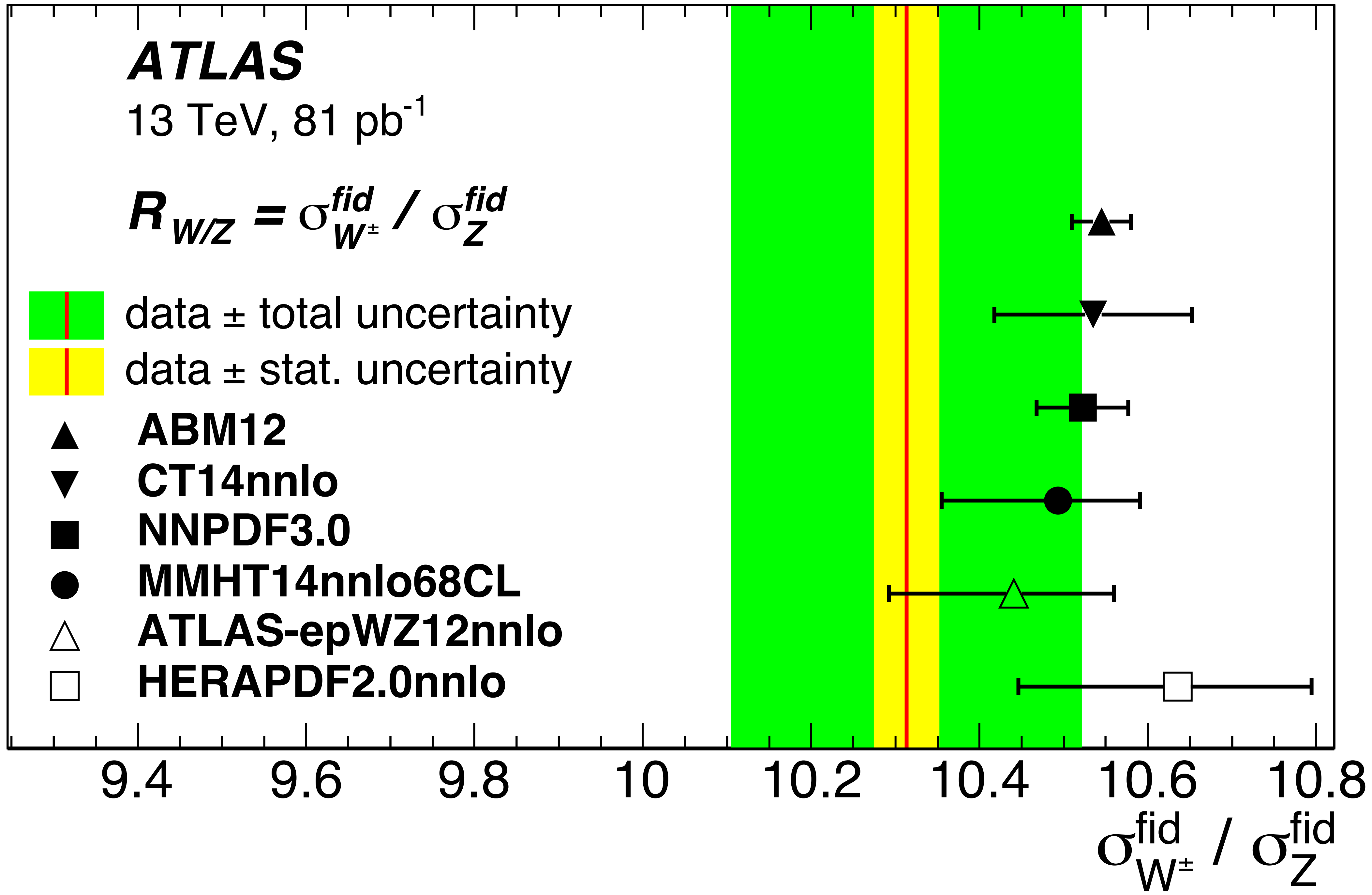
- at current energy frontier, no hints of new physics



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

The need for precise predictions

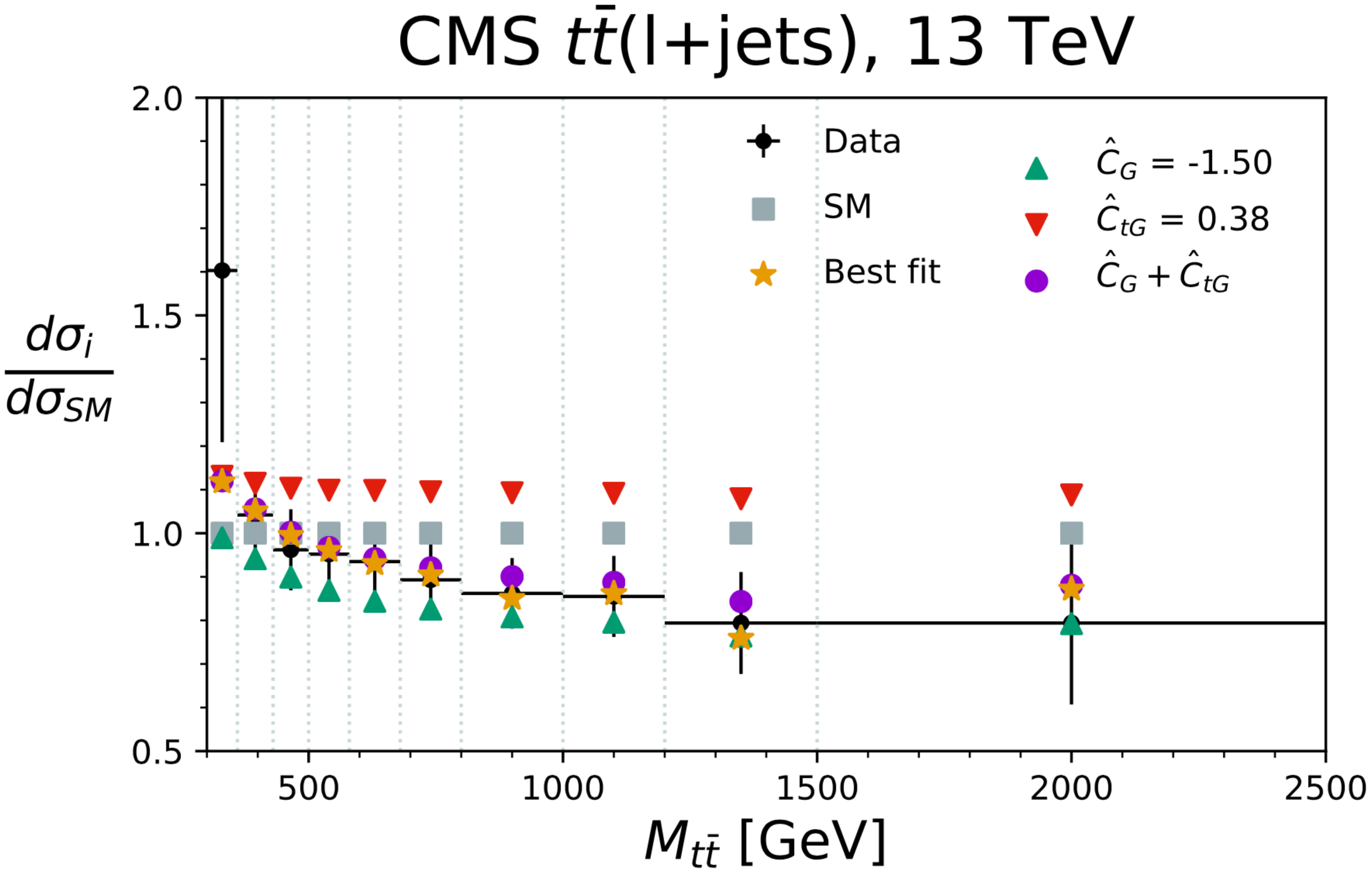




1603.09222

large spread in theory predictions based on different parton distribution functions

EFT parametrisation of new physics effects



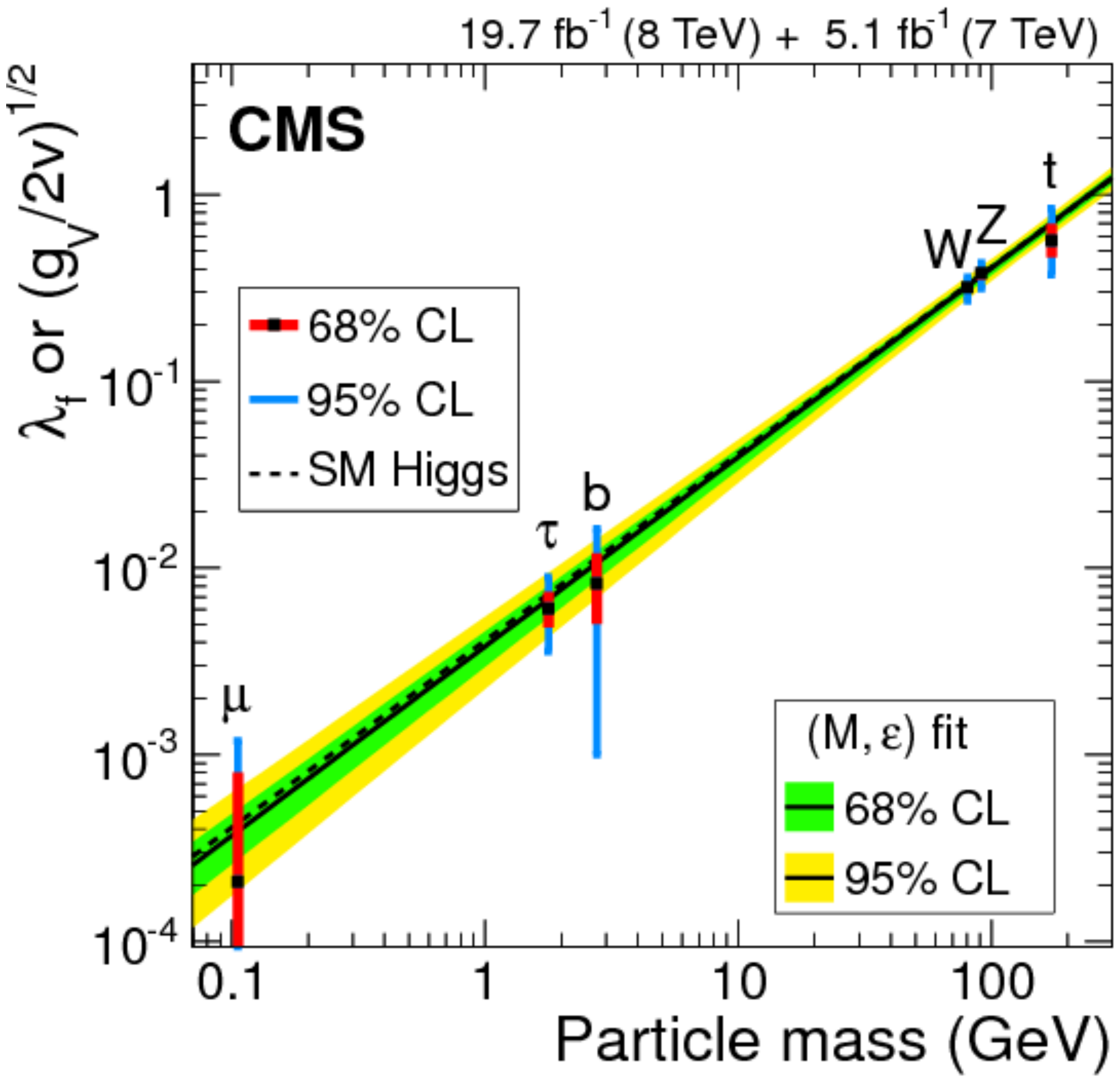
top quark pairs at large invariant mass

best fit includes anomalous couplings

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

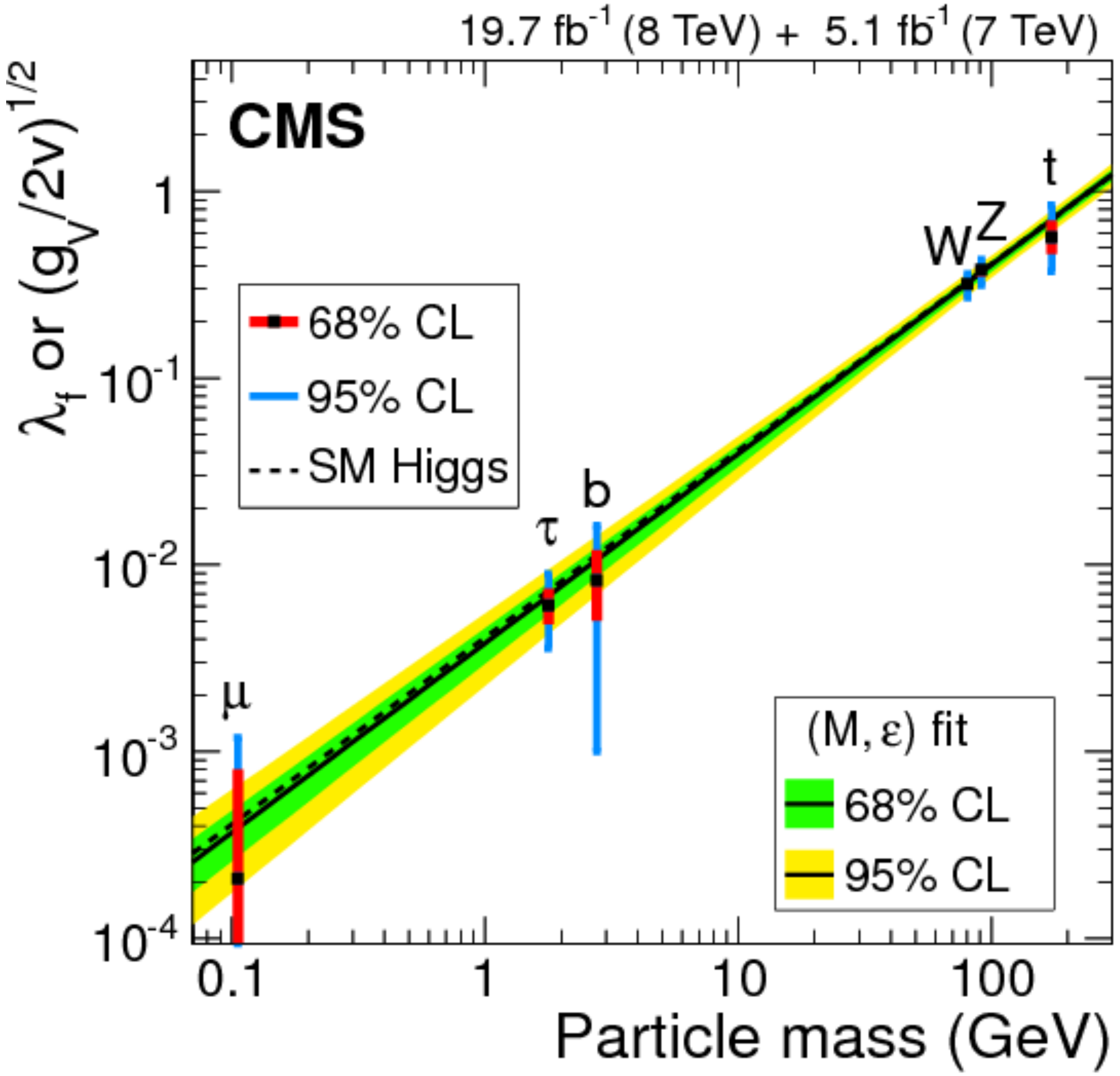
Higgs couplings

Run I

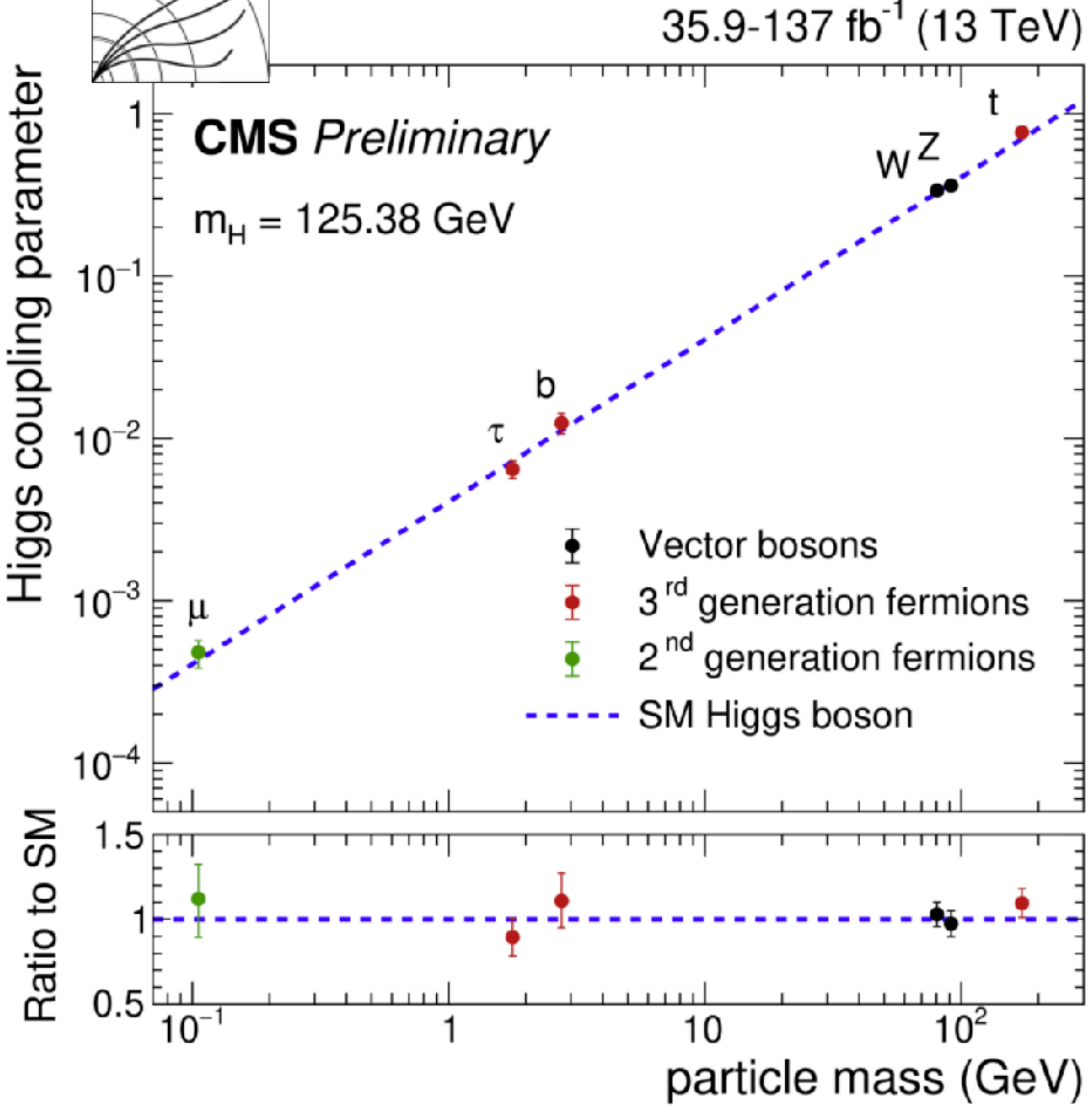


Higgs couplings

Run I



CMS PAS HIG-19-006



H?

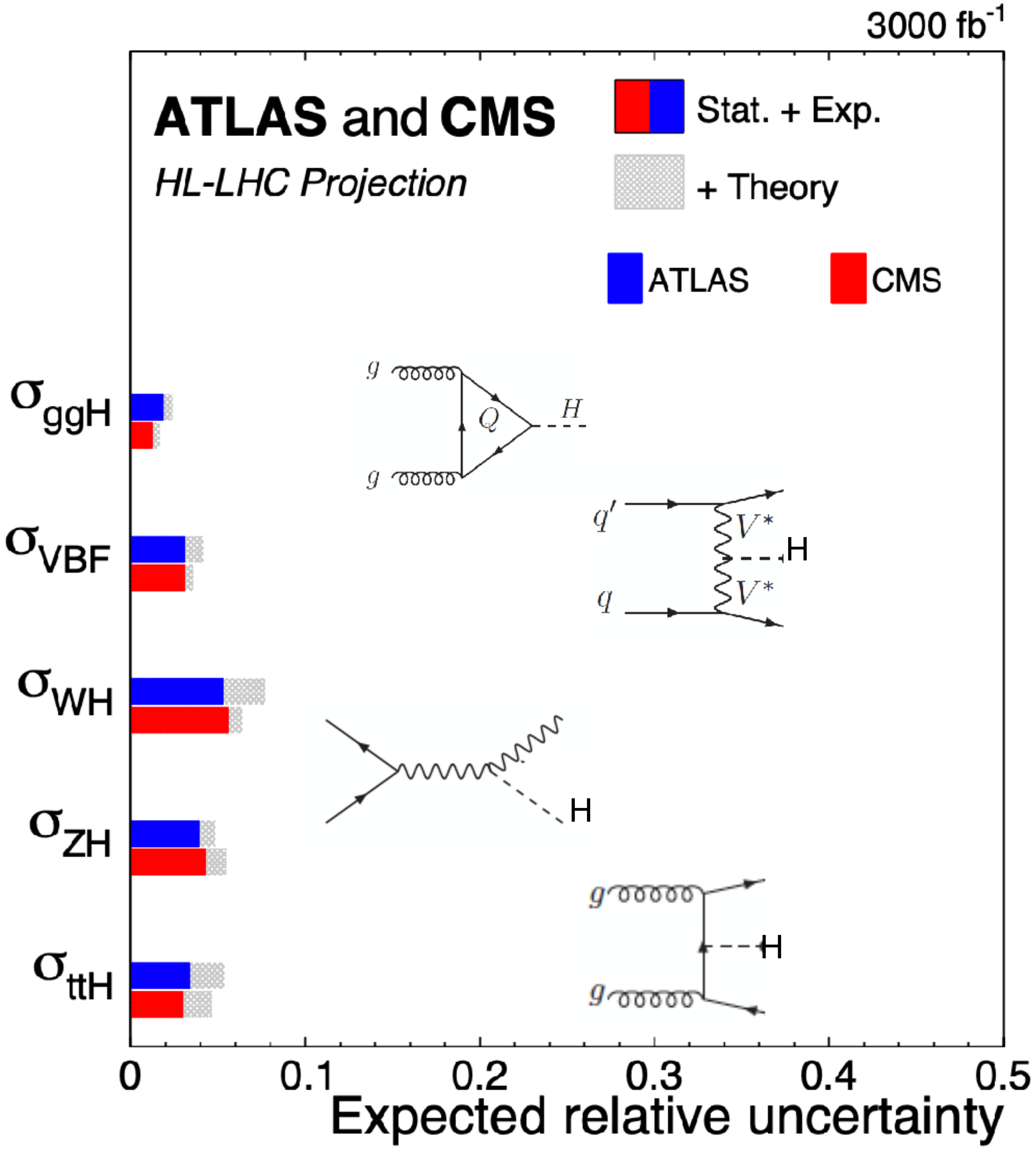
enormous experimental progress

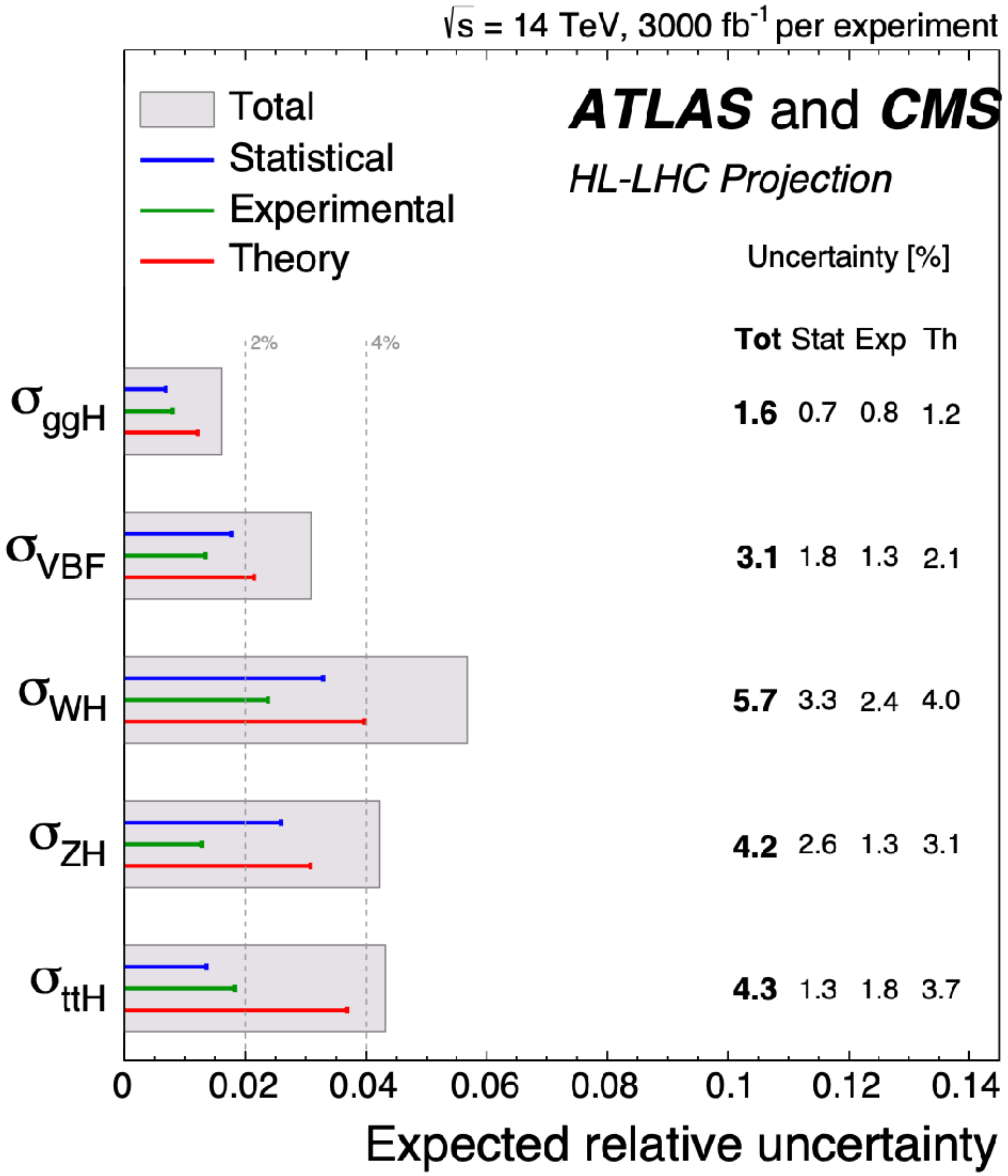
High-Luminosity LHC

rate $$R = L \cdot \sigma(s)$$

Low-luminosity LHC

Higgs production at HL-LHC: expected precision



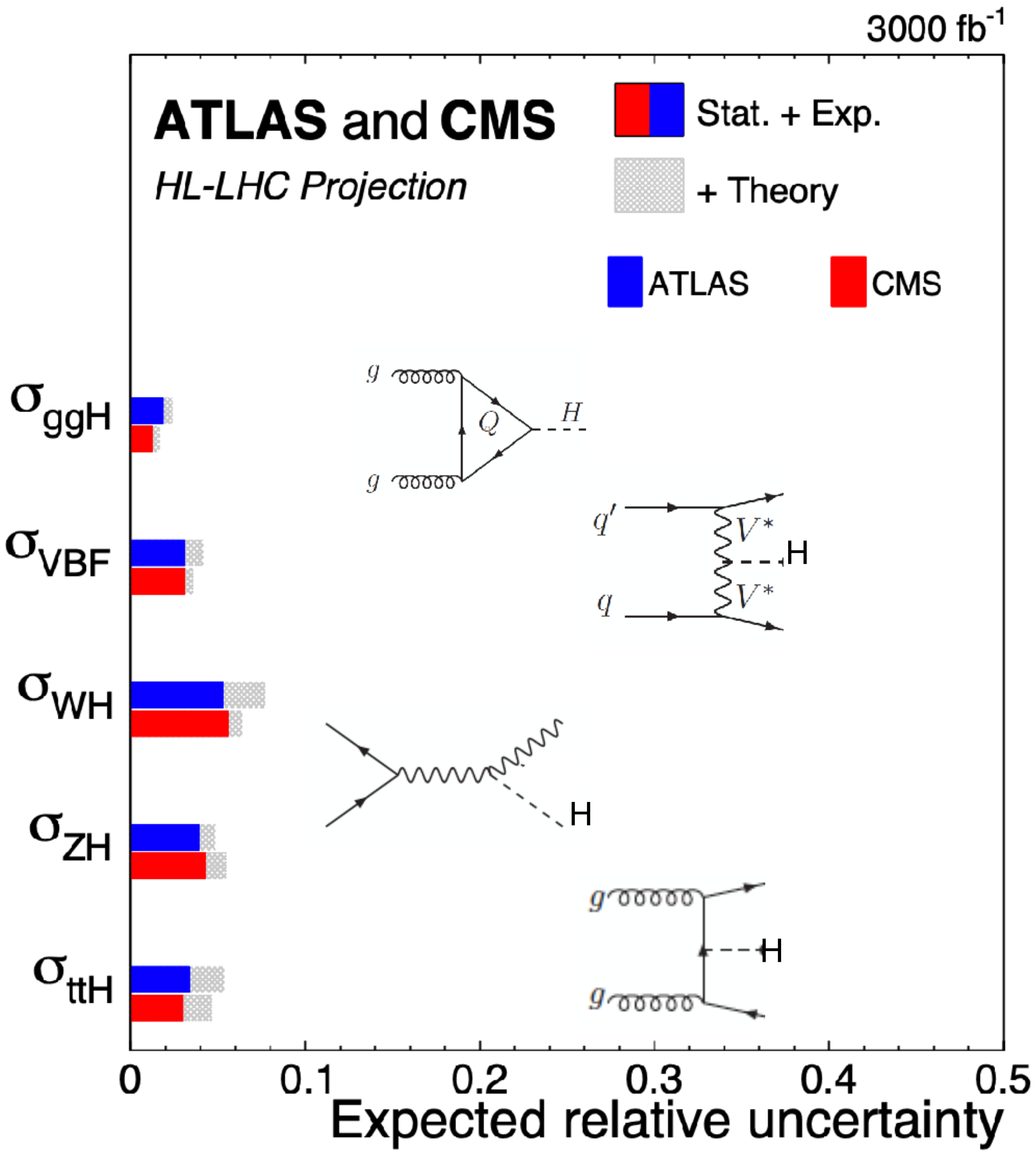


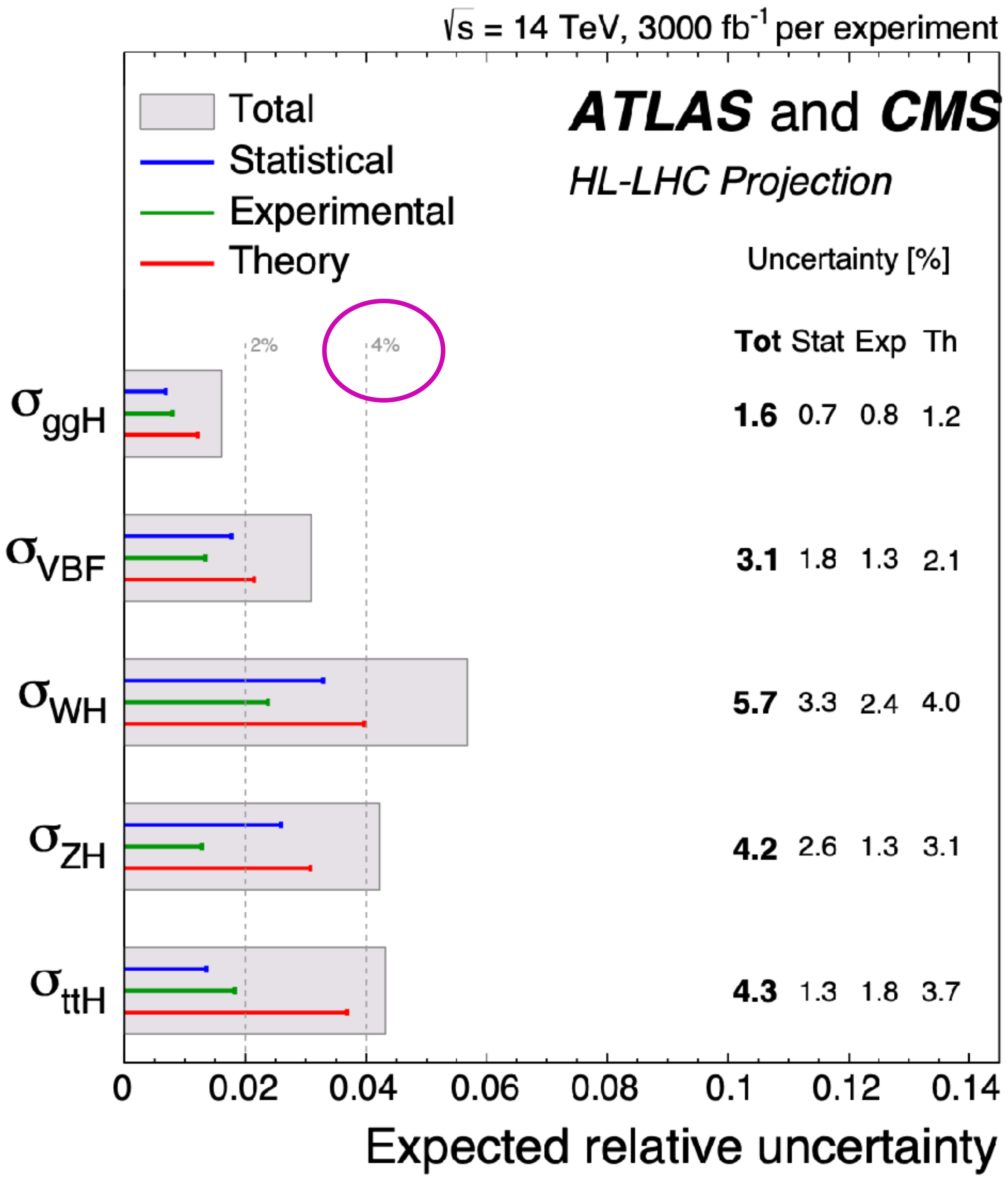
Uncertainty [%]

	Tot	Stat	Exp	Th
σ_{ggH}	**1.6**	0.7	0.8	1.2
σ_{VBF}	**3.1**	1.8	1.3	2.1
σ_{WH}	**5.7**	3.3	2.4	4.0
σ_{ZH}	**4.2**	2.6	1.3	3.1
σ_{ttH}	**4.3**	1.3	1.8	3.7

HL-HE CERN Yellow Report,
1902.00134

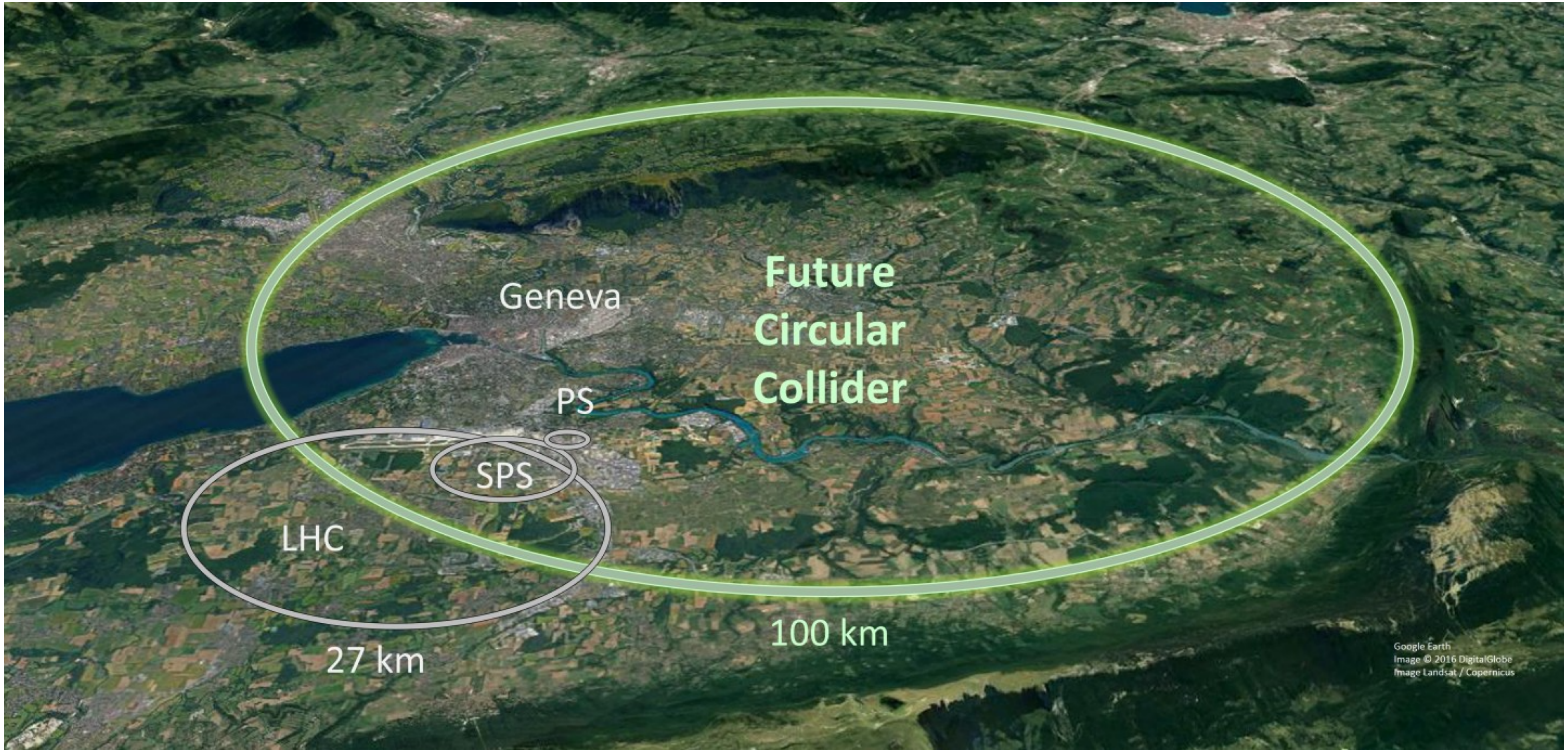
Higgs production at HL-LHC: expected precision





HL-HE CERN Yellow Report,
1902.00134

Science (no) fiction?

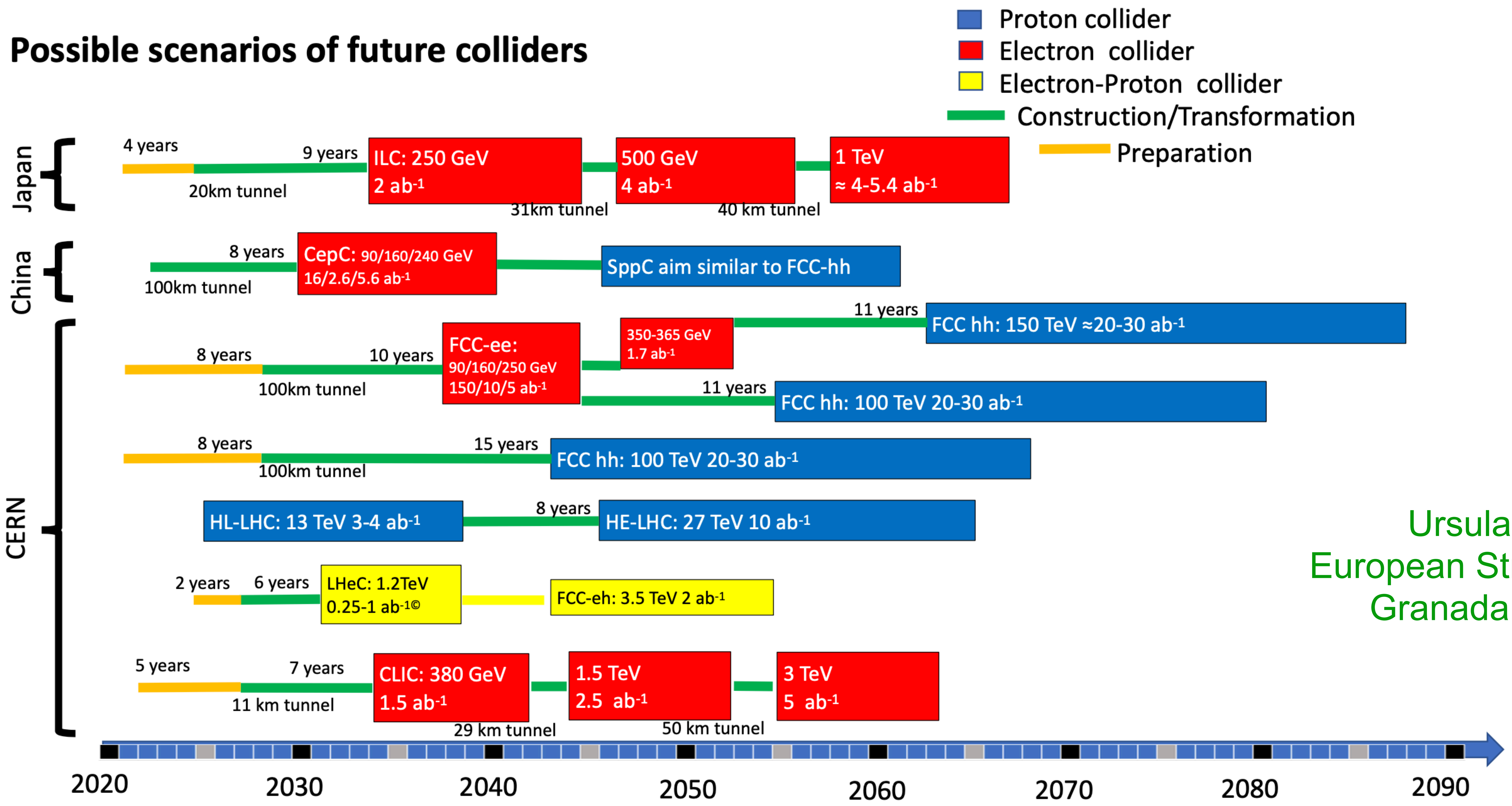


Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

Future collider plans

Karlsruhe Institute of Technology

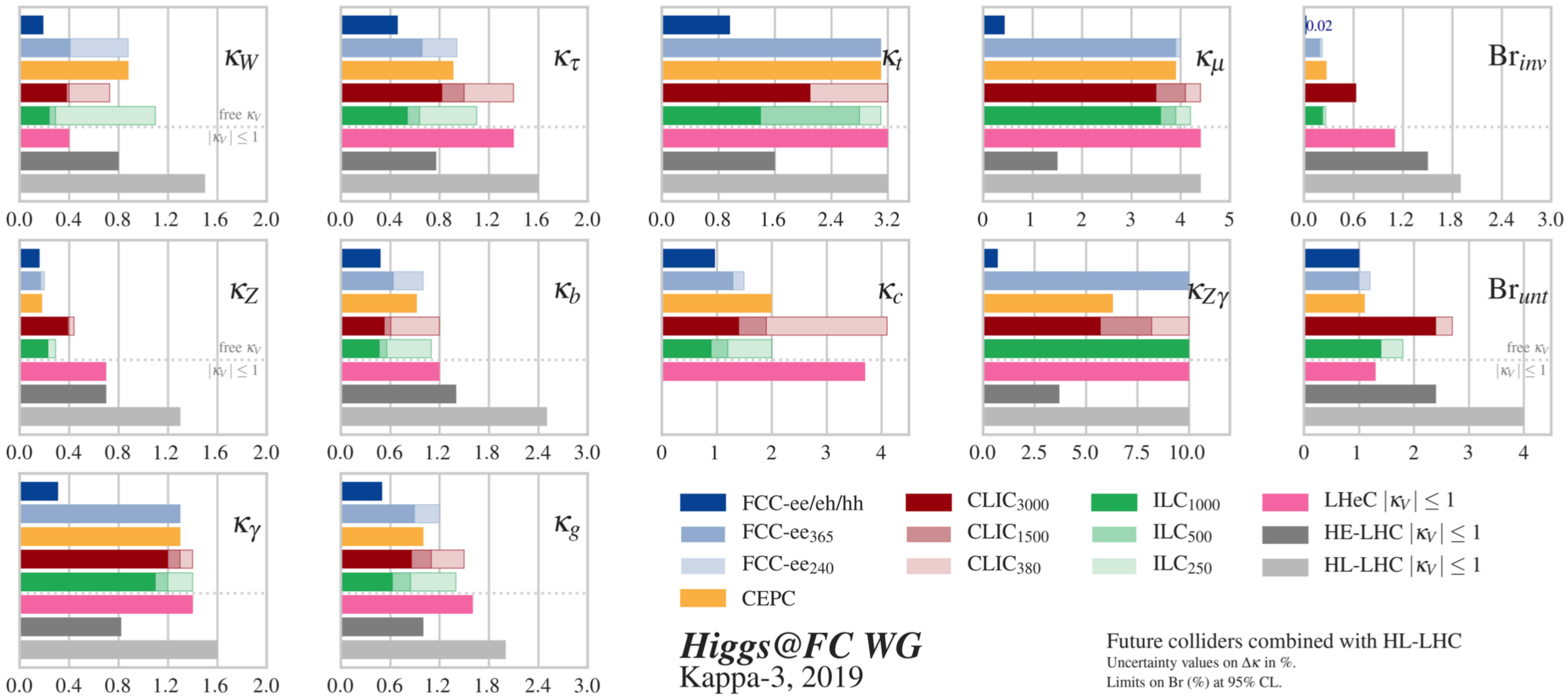
Possible scenarios of future colliders



🟦 Proton collider
🟥 Electron collider
🟨 Electron-Proton collider
Construction/Transformation
Preparation

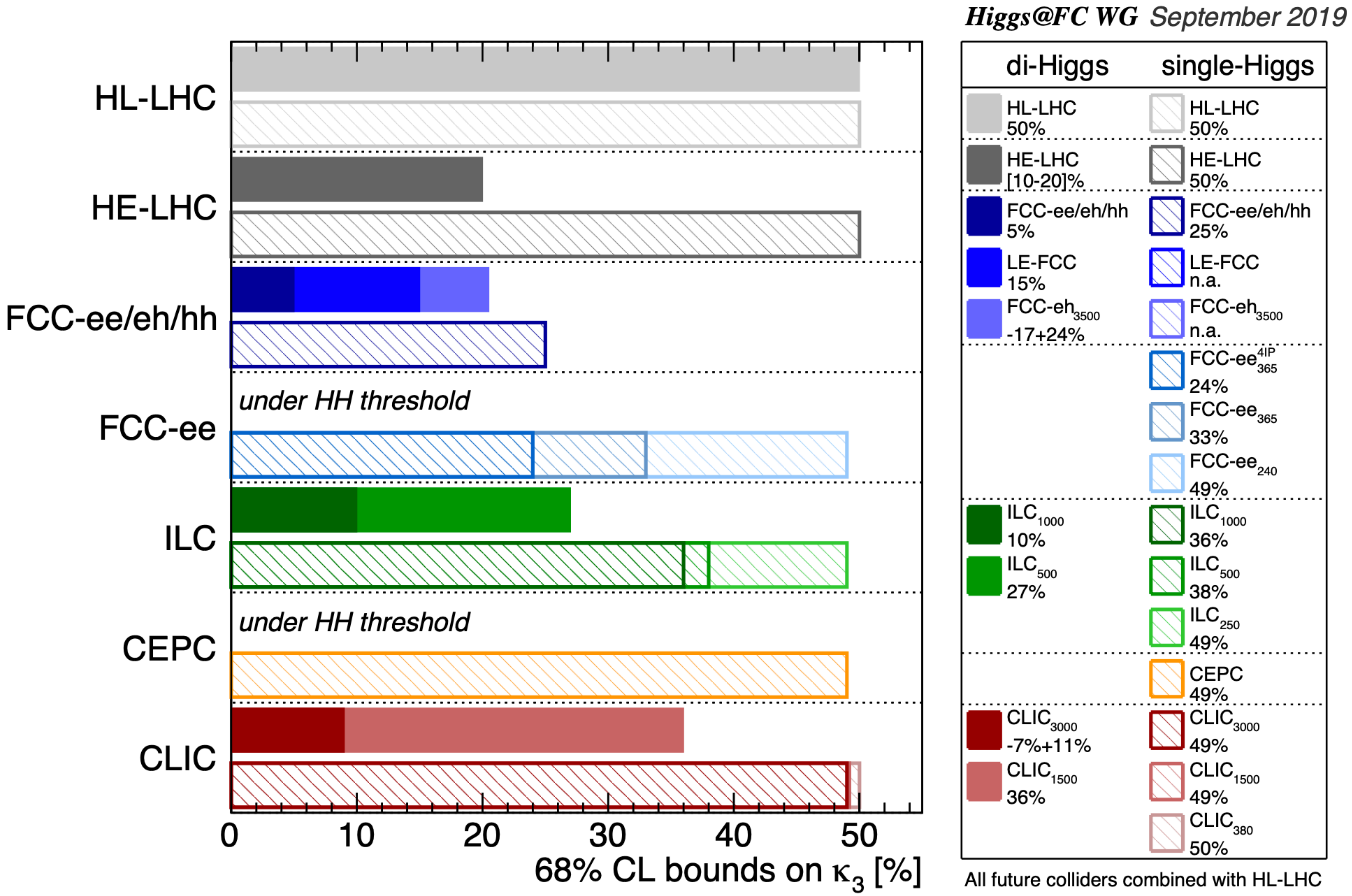
Ursula Bassler,
European Strategy Meeting
Granada, May 2019

Higgs couplings at future colliders



European Strategy Physics Briefing Book 1910.11775

Higgs-boson self coupling



European Strategy Physics Briefing Book 1910.11775

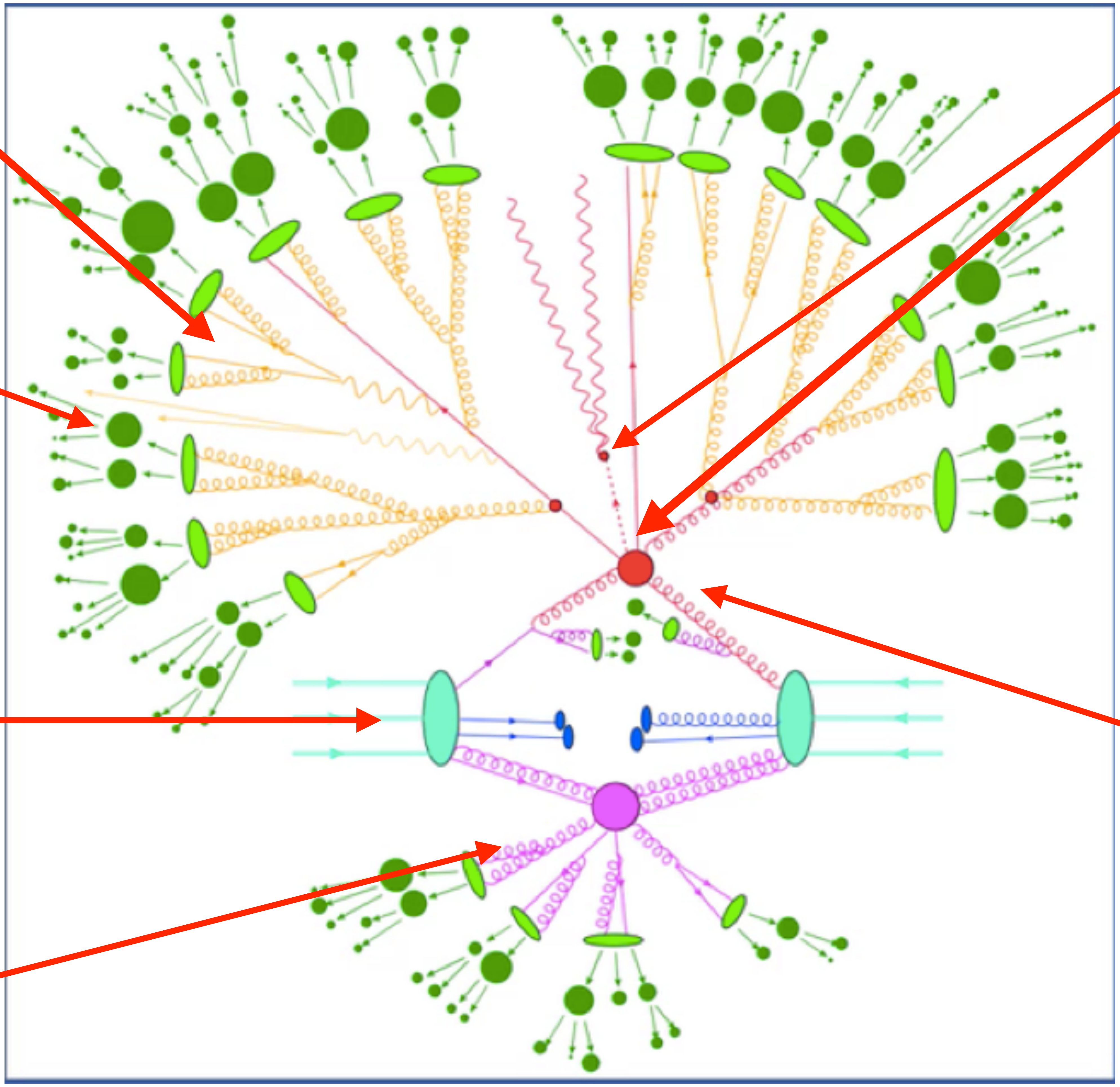
How to increase the precision of the predictions?

parton shower

hadronisation

parton distribution functions (PDFs)

underlying event



artwork by G.Luisoni

fixed order calculations (production and decay)

reduce scale uncertainties

μ_r, μ_f -dependence

reduce parametric uncertainties (couplings, masses)

resummation

reduce uncertainties in particular kinematic regions

Perturbation theory

leading order ↓ next-to-leading order ↓ next-to-next-to-leading order ↓

$$\sigma = \alpha_s^k \left(\sigma^{LO} + \alpha_s \sigma^{NLO} + \alpha_s^2 \sigma^{NNLO} + \ldots\right)$$

$\alpha_s(M_Z) \simeq 0.118$ $\mathcal{O}(10\%)$ $\mathcal{O}(1\%)$

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 ⟶ measure of missing higher orders

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

↑ renormalisation scale ↑ factorisation scale

Higher orders in perturbation theory

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

LO

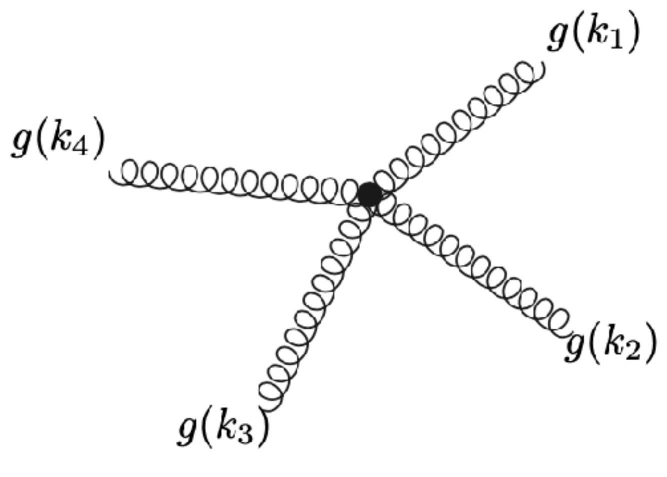


Diagram 1

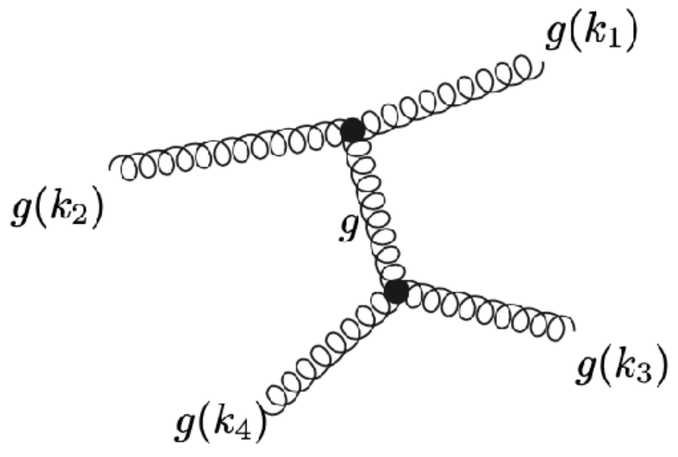
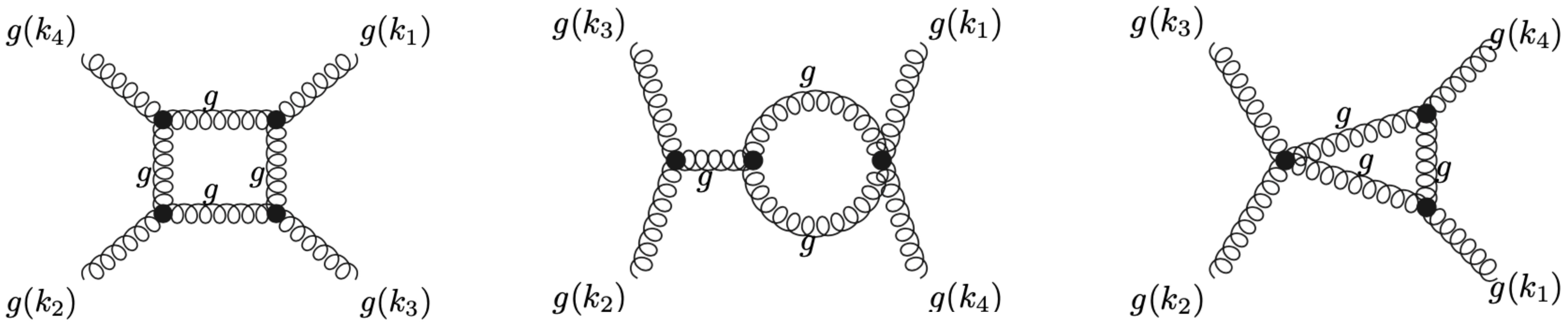


Diagram 2

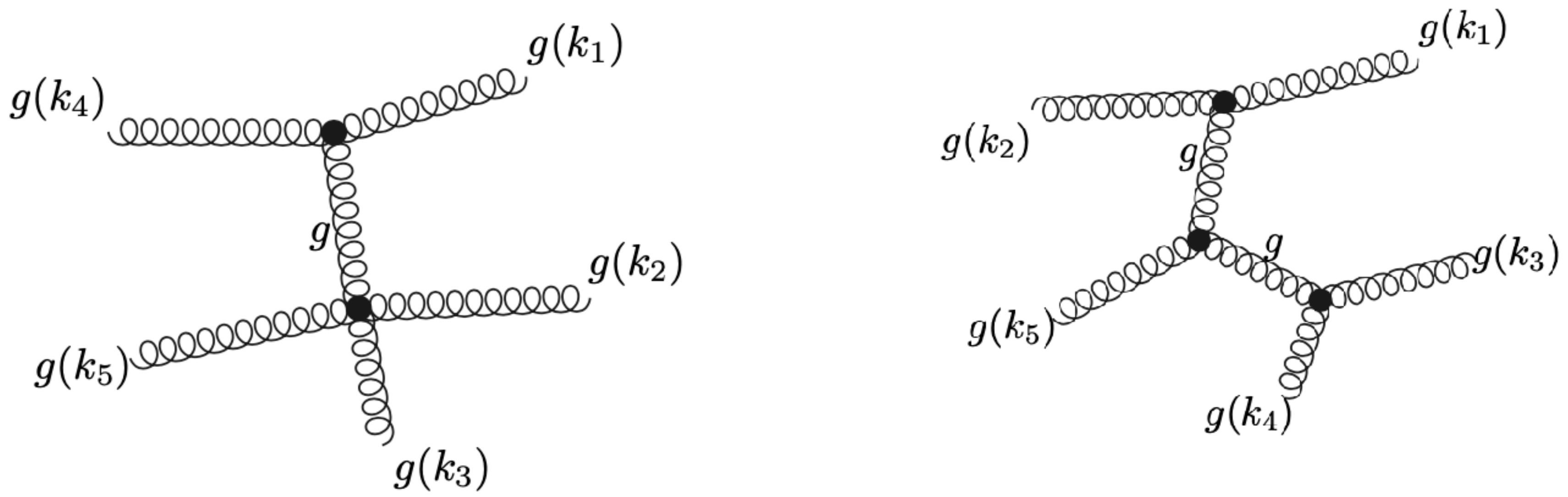
+ permutations (4 diagrams)

NLO virtual



+ … (60 loop diagrams)

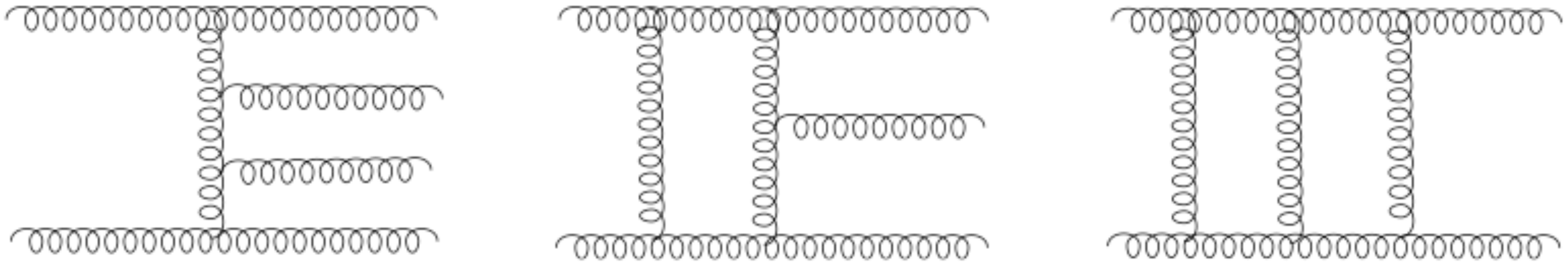
NLO real



+ … (25 diagrams)

Higher orders in perturbation theory

example NNLO:



double real

↓

implicit IR poles
(phase space integration)

1-loop virtual
$\otimes$ single real

↓

explicit and implicit poles

2-loop virtual

↓

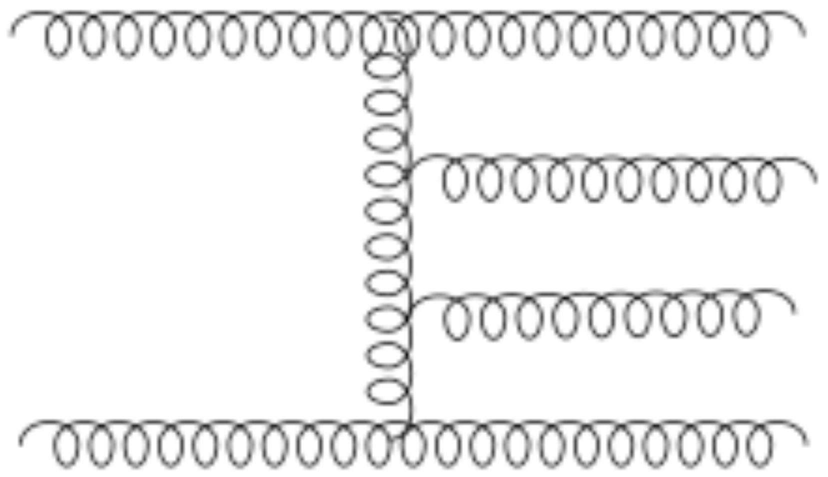
explicit poles $1/\epsilon^{2L}$ $\quad (D = 4 - 2\epsilon)$

bottlenecks: IR subtraction

(multi)-loop integrals

Higher orders in perturbation theory

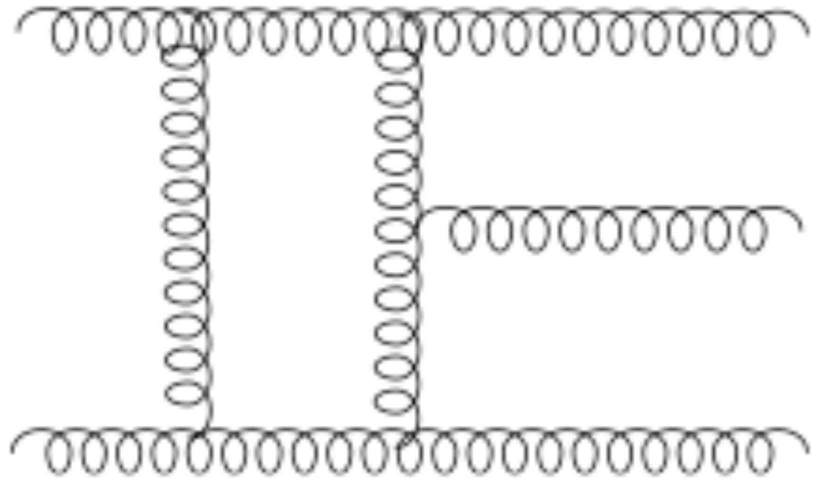
example NNLO:



double real

↓

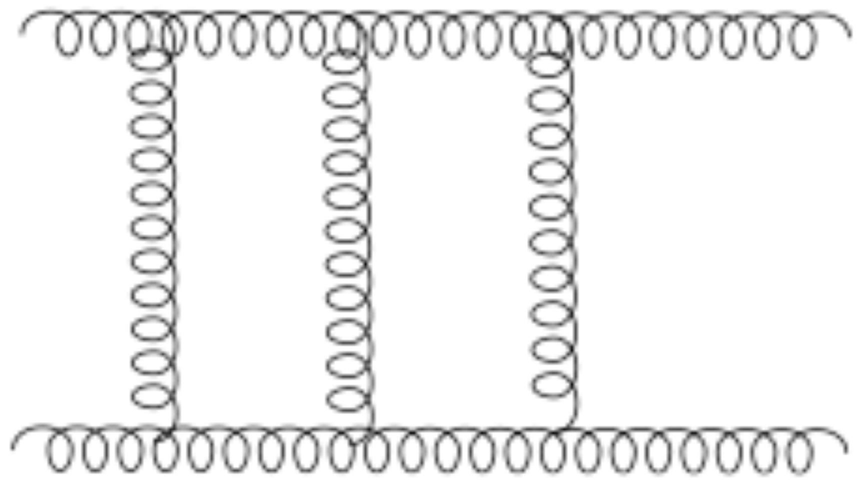
implicit IR poles
(phase space integration)



1-loop virtual
⊗ single real

↓

explicit and implicit poles



2-loop virtual

↓

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

bottlenecks: IR subtraction (multi)-loop integrals

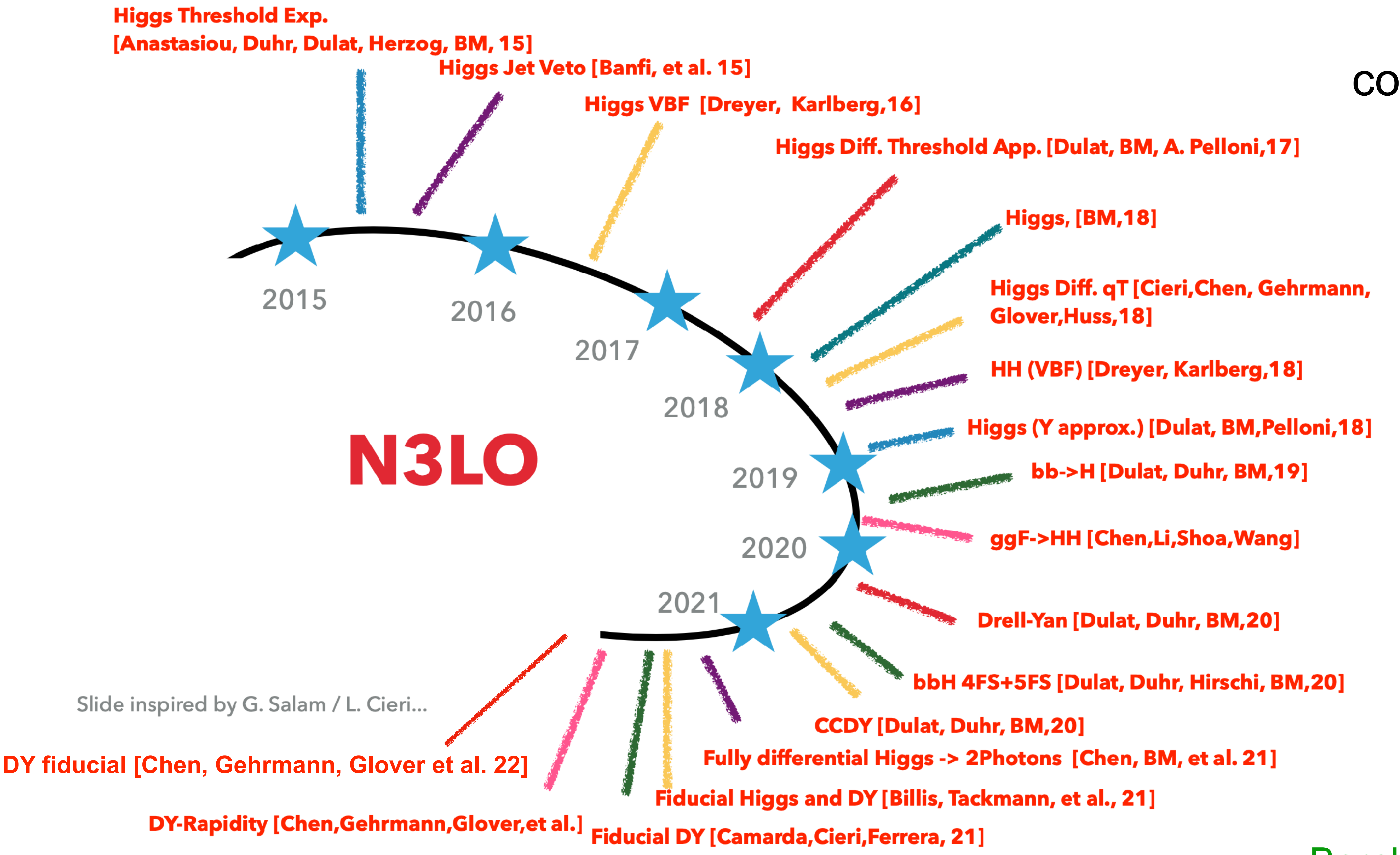
current frontiers:

- NNLO automation
- N3LO coloured

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

Highlights

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



N3LO

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]

Higgs, [BM,18]

Higgs Diff. qT [Cieri,Chen, Gehrmann, Glover,Huss,18]

HH (VBF) [Dreyer, Karlberg,18]

Higgs (Y approx.) [Dulat, BM,Pelloni,18]

bb->H [Dulat, Duhr, BM,19]

ggF->HH [Chen,Li,Shoa,Wang]

Drell-Yan [Dulat, Duhr, BM,20]

bbH 4FS+5FS [Dulat, Duhr, Hirschi, BM,20]

CCDY [Dulat, Duhr, BM,20]

Fully differential Higgs -> 2Photons [Chen, BM, et al. 21]

Fiducial Higgs and DY [Billis, Tackmann, et al., 21]

Fiducial DY [Camarda,Cieri,Ferrera, 21]

DY-Rapidity [Chen,Gehrmann,Glover,et al.]

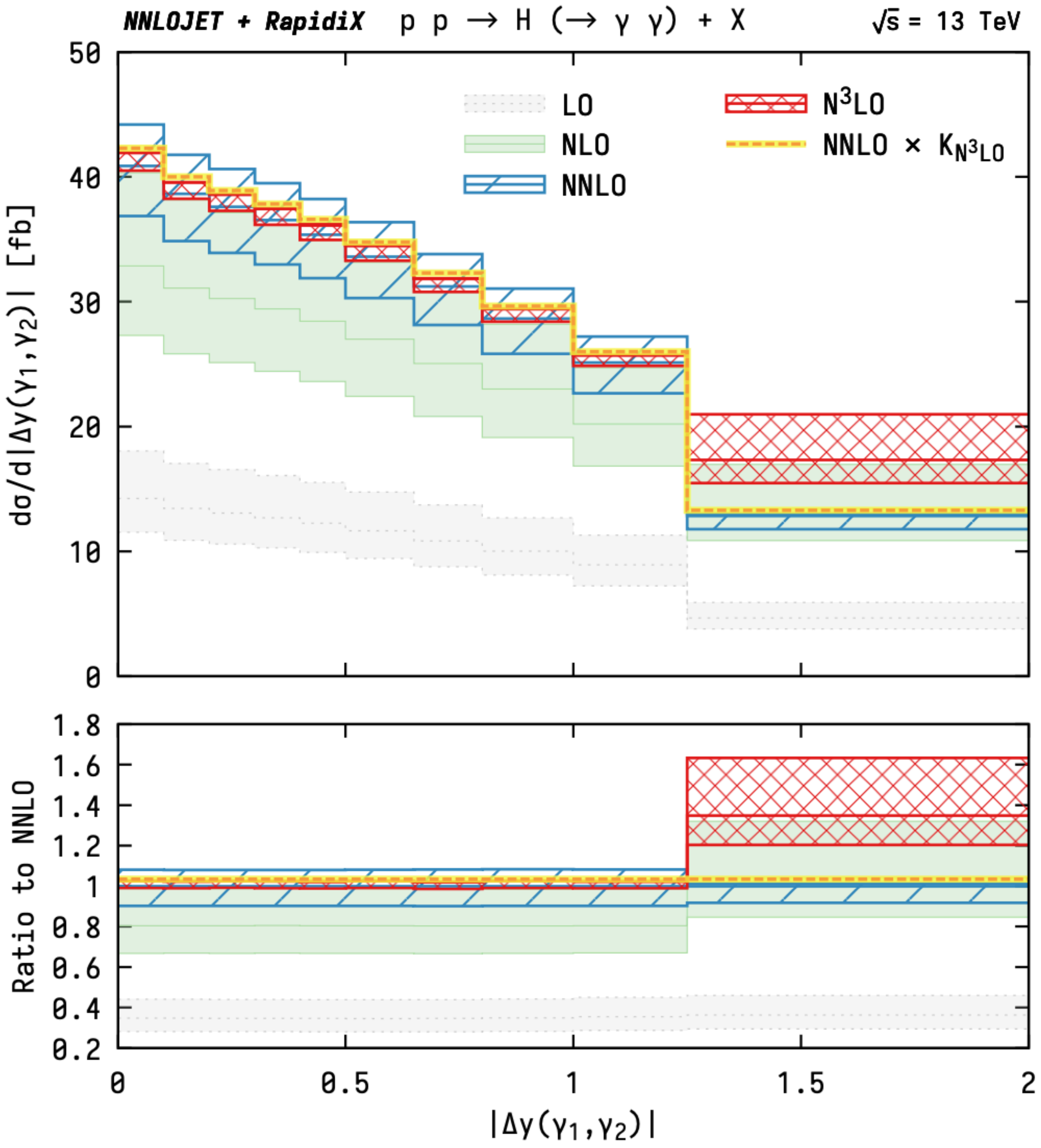
DY fiducial [Chen, Gehrmann, Glover et al. 22]

Slide inspired by G. Salam / L. Cieri...

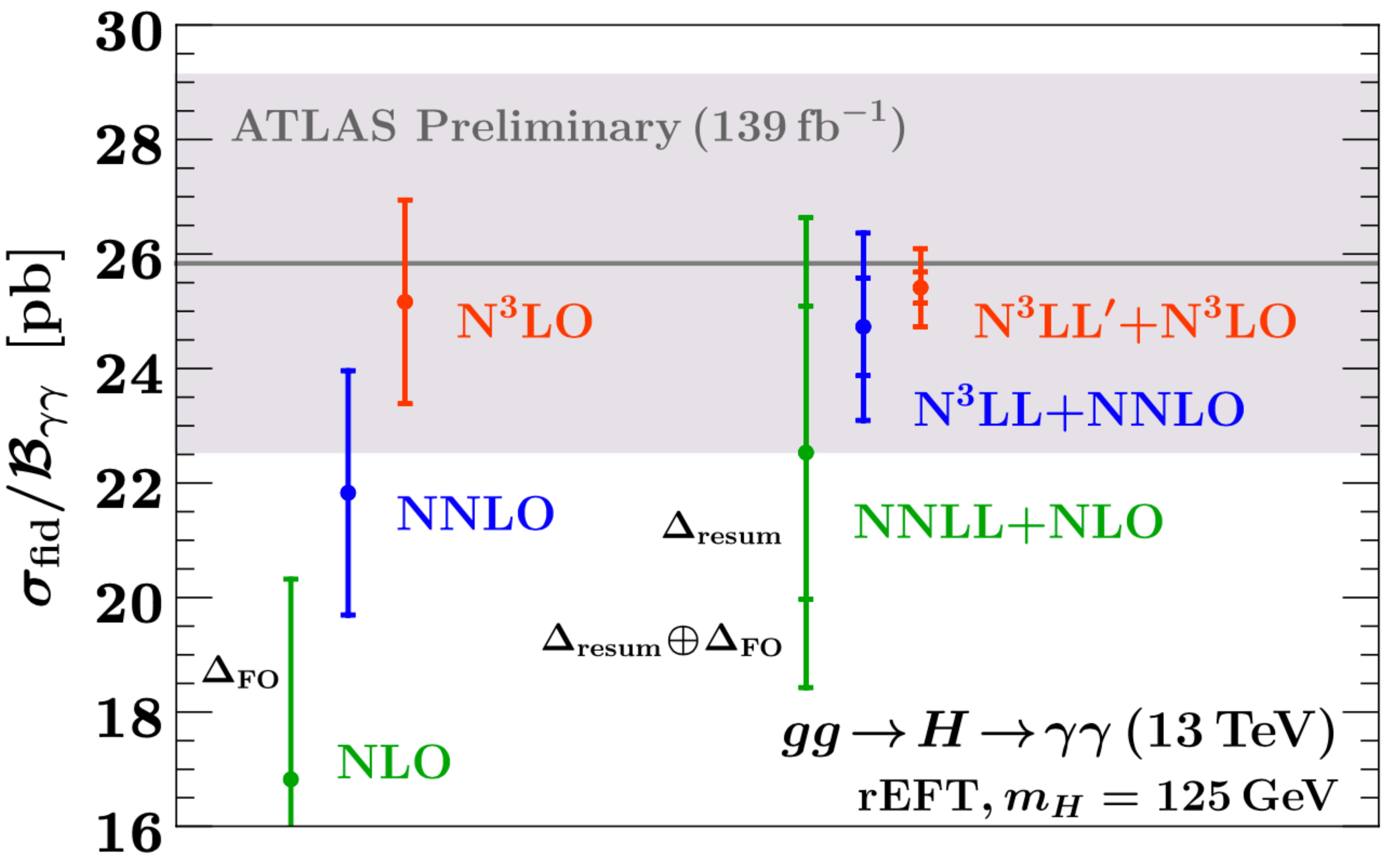
going more and more differential

Bernhard Mistlberger, Amplitudes 2021

ggH@N3LO fiducial

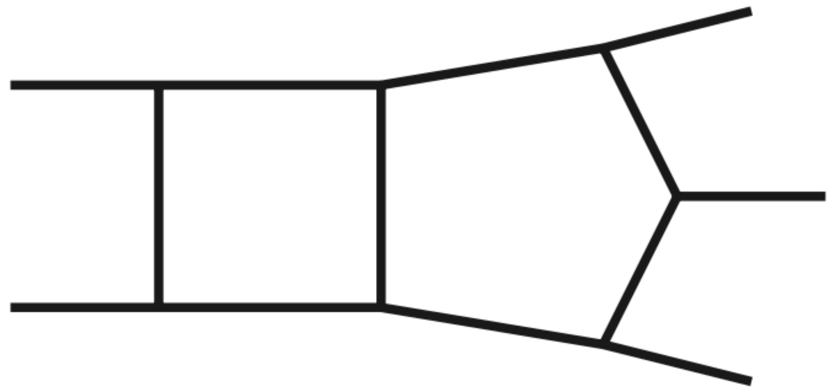


Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607



Billis, Dehnadi, Ebert, Michel, Tackmann, 2102.08039

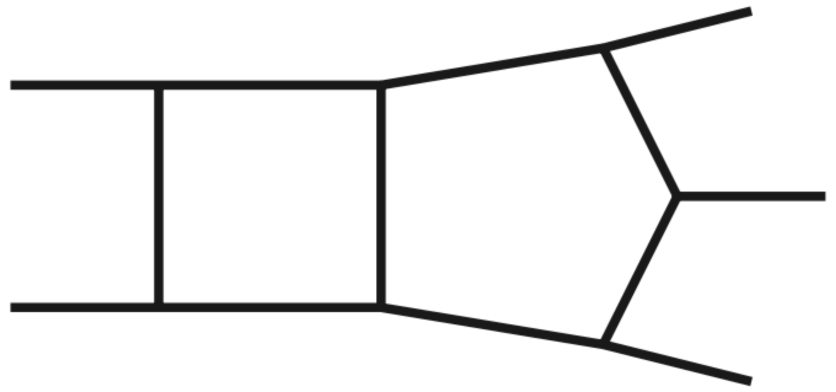
Loop integrals: status 2-loop 5-point



massless:

$pp \to \gamma\gamma\gamma$	*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)*
$pp \to \gamma\gamma j$	*Chawdry, Czakon, Mitov, Poncelet '21 (leading color, full xs)* *Agarwal, Buccioni, Manteuffel, Tancredi '21 (full color, amplitudes)*
$gg \to \gamma\gamma g$	*Badger, Brønnum-Hansen, Chicherin, Gehrmann, Hartanto '21 (amp)* *Badger, Gehrmann, Marcoli, Moodie '21 (full xs)*
$pp \to jjj$	*Abreu, Febres Cordero, Ita, Page, Sotnikov '21 (leading color amp)* *Czakon, Mitov, Poncelet '21 (full xs)*

Loop integrals: status 2-loop 5-point



massless:

$pp \to \gamma\gamma\gamma$ 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)

$pp \to \gamma\gamma j$ Chawdry, Czakon, Mitov, Poncelet '21 (leading color, full xs)

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

$gg \to \gamma\gamma g$ Badger, Brønnum-Hansen, Chicherin, Gehrmann, Hartanto '21 (amp)

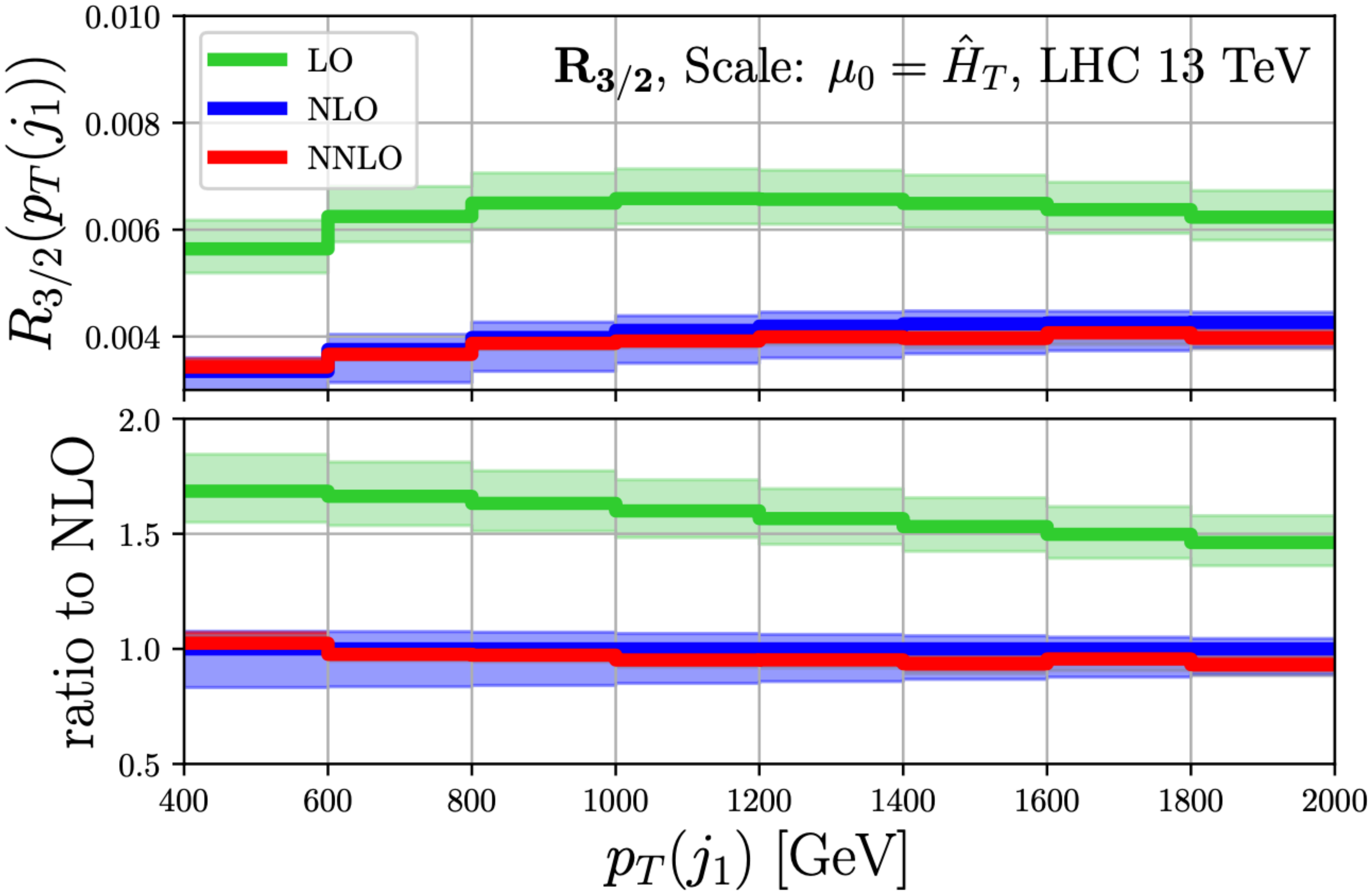
Badger, Gehrmann, Marcoli, Moodie '21 (full xs)

$pp \to jjj$ 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

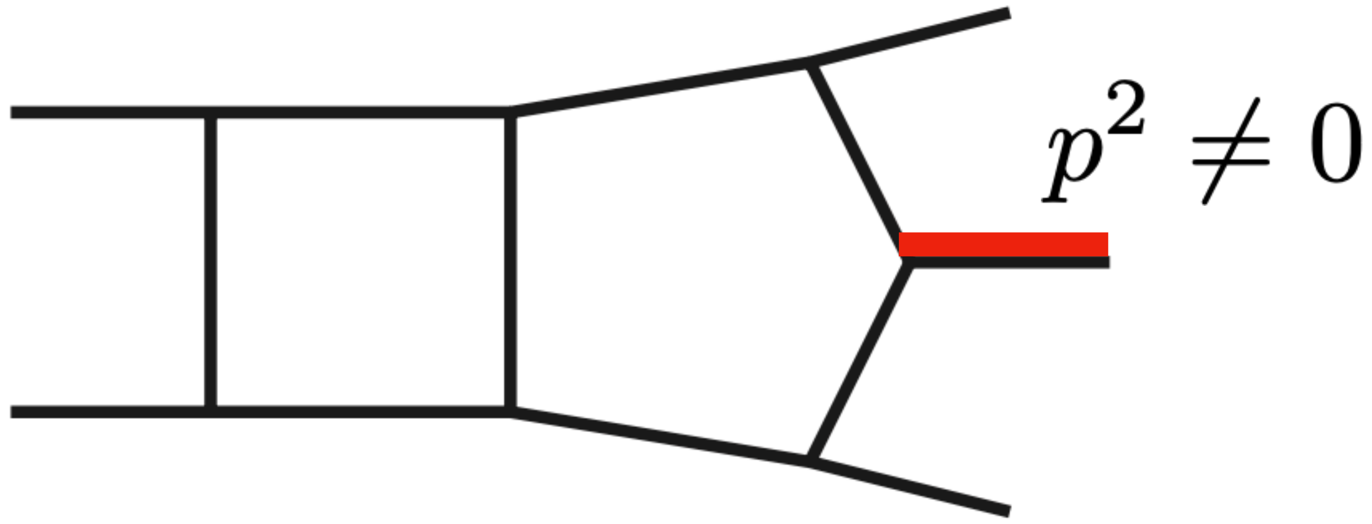
3-jet production at NNLO



3-jet/2-jet ratio

Czakon, Mitov, Poncelet ’21

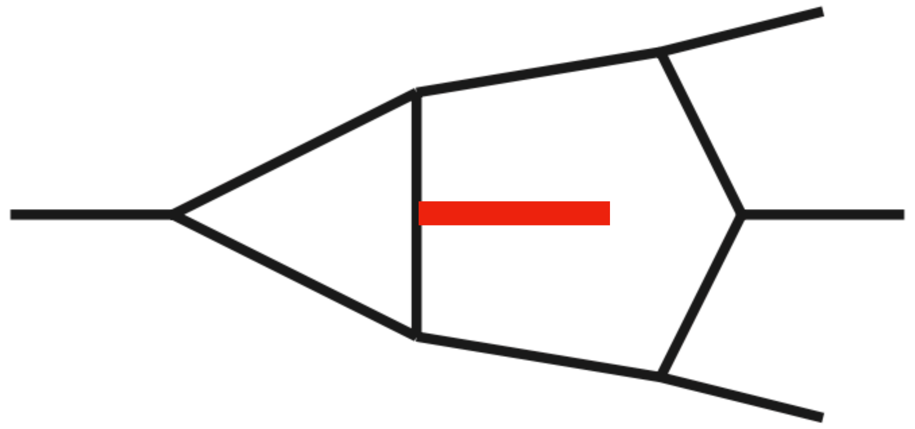
2-loop 5-point (one off-shell leg)



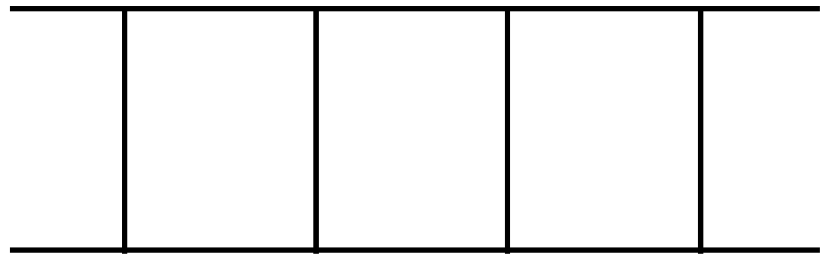
Abreu, Ita, Moriello, Page, Tschernow ’20 (planar)

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)
$u\bar{d} \to W^+ b\bar{b}$	*Badger, Hartanto, Zoia ’21 (planar, analytic)*
$pp \to b\bar{b}H$	*Badger, Hartanto, Krys, Zoia ’21 (leading colour)*
non-planar:	*Abreu, Ita, Page, Tschernov ’21*
	Liu, Ma ’21



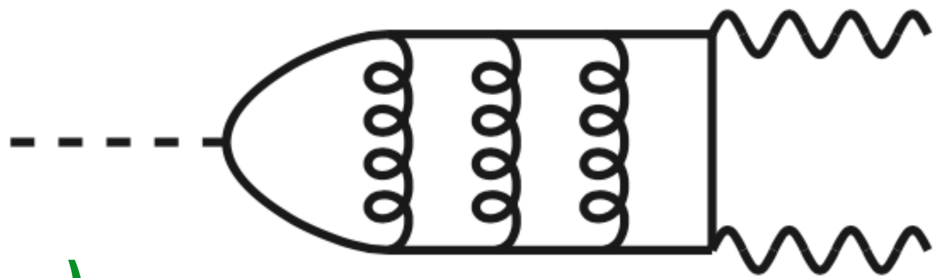
3-loop 4-point



$pp \to \gamma\gamma$ Caola, Manteuffel, Tancredi ’20

$q\bar{q} \to q\bar{q}$ Caola, Chakraborti, Gambuti, Manteuffel, Tancredi ’21

4-loop 3-point



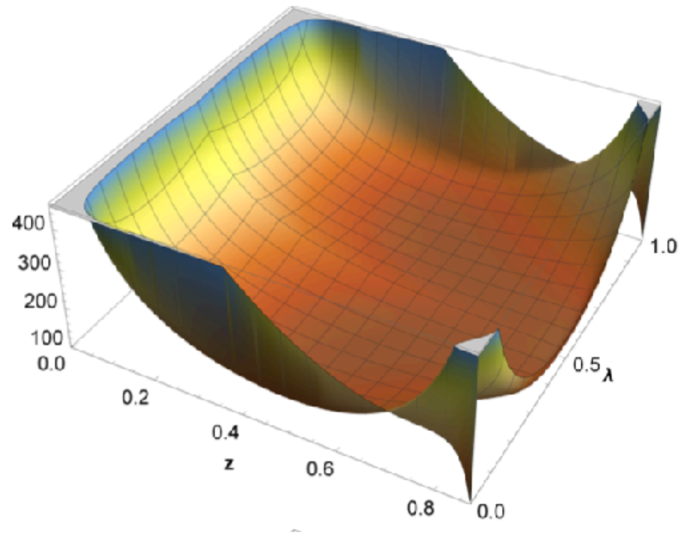
$H \to \gamma\gamma$ Davies, Herren ’21 (large mt-expansion)

form factors, e.g. $\gamma^\star \to q\bar{q}$ Agarwal, Manteuffel, Panzer, Schabinger ’21
Lee, Manteuffel, Schabinger, Smirnov^2 ’21, …

3-loop 3-point with *massive* propagators

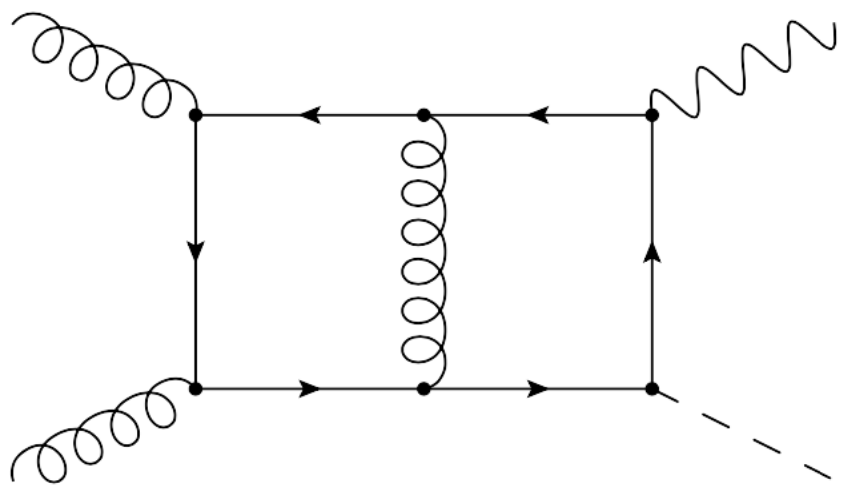
$gg \to H$ Czakon, Harlander, Klappert, Niggetiedt ’21 (full cross section)

semi-numerically



2-loop 4-point with massive propagators

numerically:



$pp \to t\bar{t}$ Czakon, Mitov '13

$pp \to HH$ Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16

Baglio, Campanario, Glaus, Mühlleitner, Spira '18

$pp \to Hj$ Jones, Kerner, Luisoni '18

$pp \to W^+W^-$ Brønnum-Hansen, Wang '20

$pp \to HZ$ Chen, GH, Jones, Kerner, Klappert, Schlenk '20

$pp \to ZZ$ Agarwal, Jones, Manteuffel '20

2-loop 4-point with massive propagators

analytically: $H + j$ full set of master integrals *Frellesvig et al. ’19*

mixed QCD-EW corrections to Higgs production *Bechetti et al. ‘20*

mixed QCD-EW corrections to Drell-Yan *Heller, von Manteuffel et al. ’19, ‘20*
Bonciani et al. ‘21
Buccioni, Caola, Chawdhry et al. ‘22

2-loop 4-fermion scattering in QED *Bonciani et al. ‘21*
Banerjee et al. ’20, ‘21

$\vdots$

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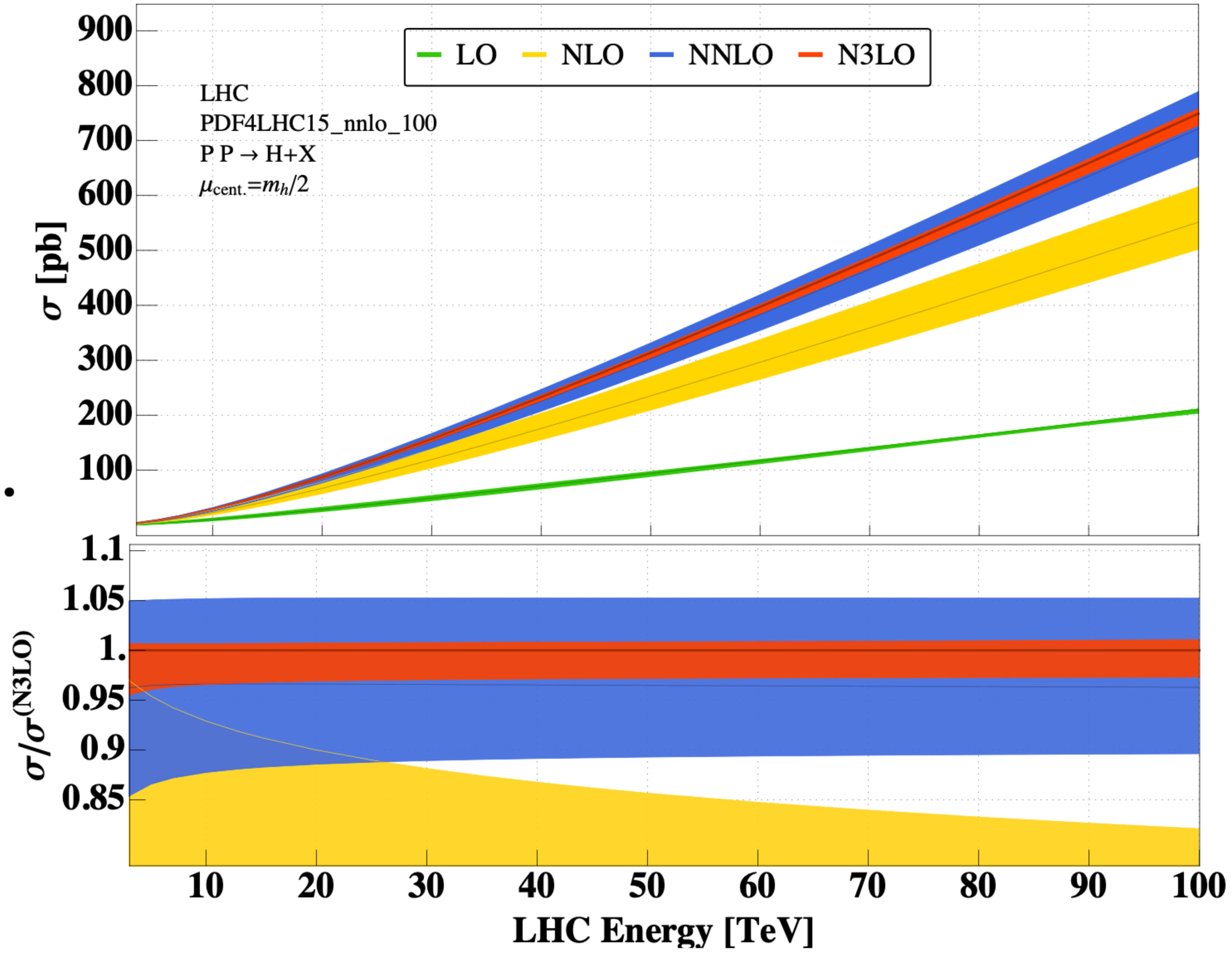
often a combination can be beneficial,
e.g. high energy limit analytically
Davies et al. 1907.06408

The Next Challenges

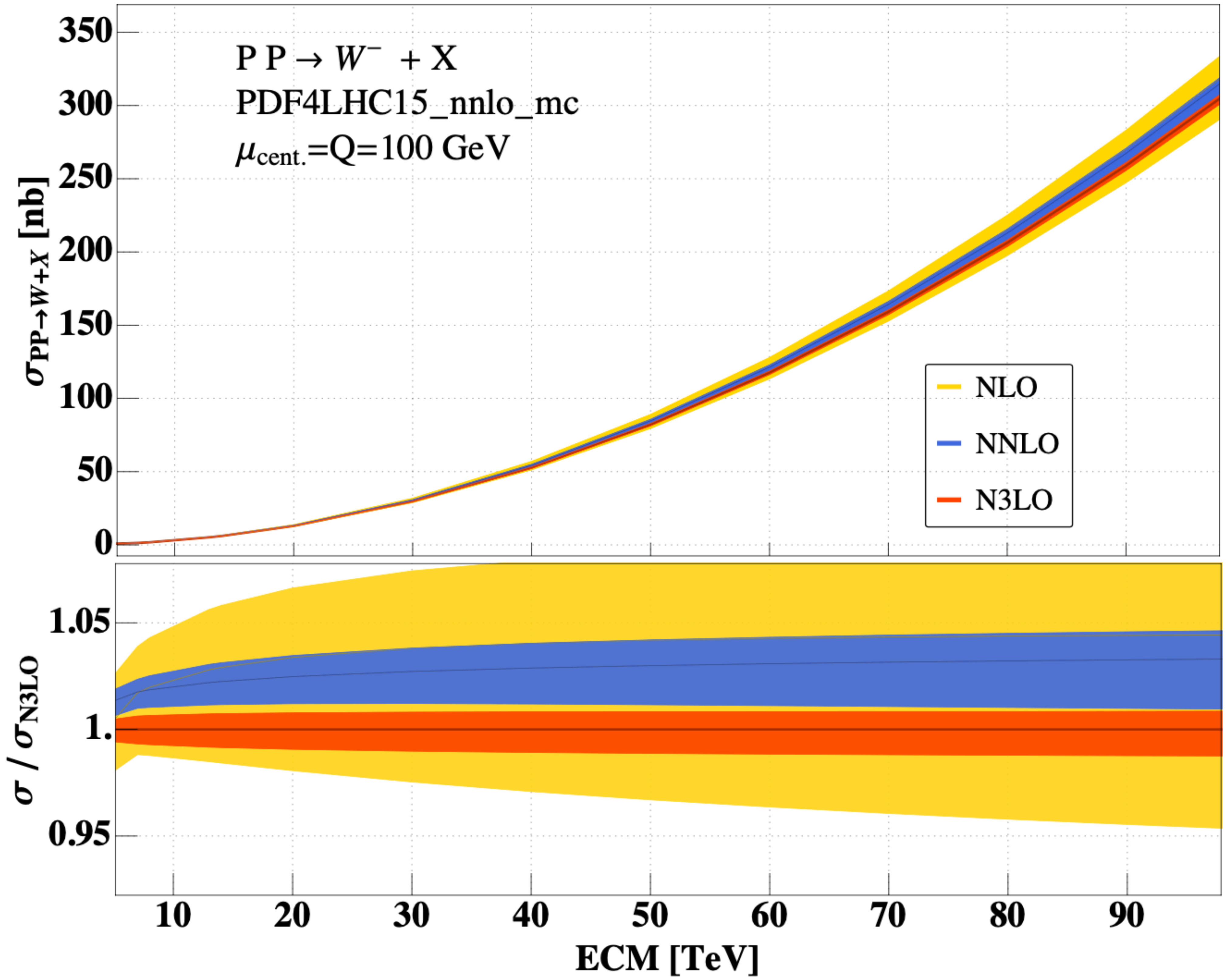
- scale uncertainties: how well do they estimate missing higher orders?
  - depends on choice of central scales, modes of variation, contributing partonic channels, …
- electroweak corrections, mixed QCD-EW
- PDFs
- quark mass-related uncertainties: neglected masses, different renormalisation schemes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

Scale uncertainties: Higgs production in gluon fusion



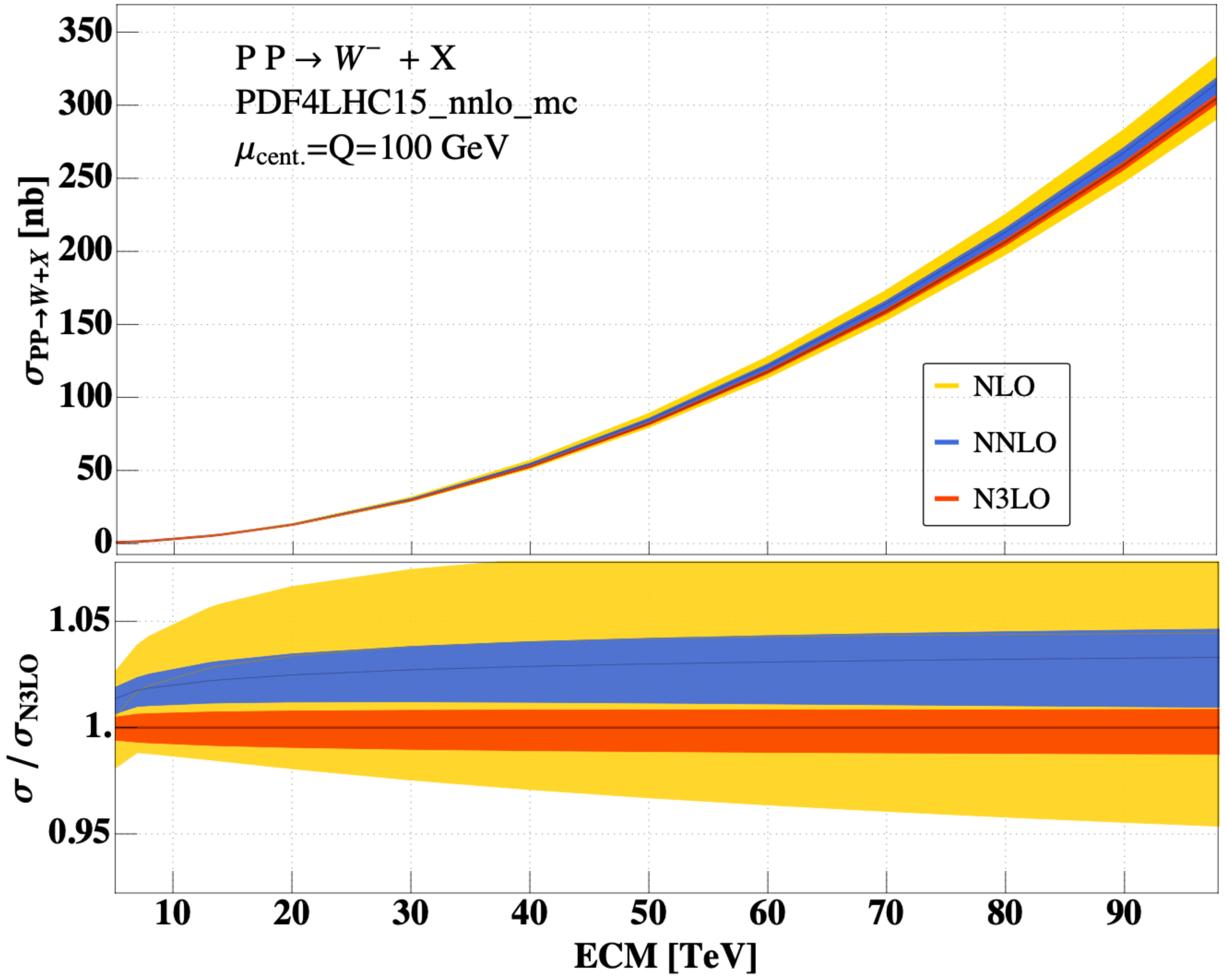
B. Mistlberger ‘18

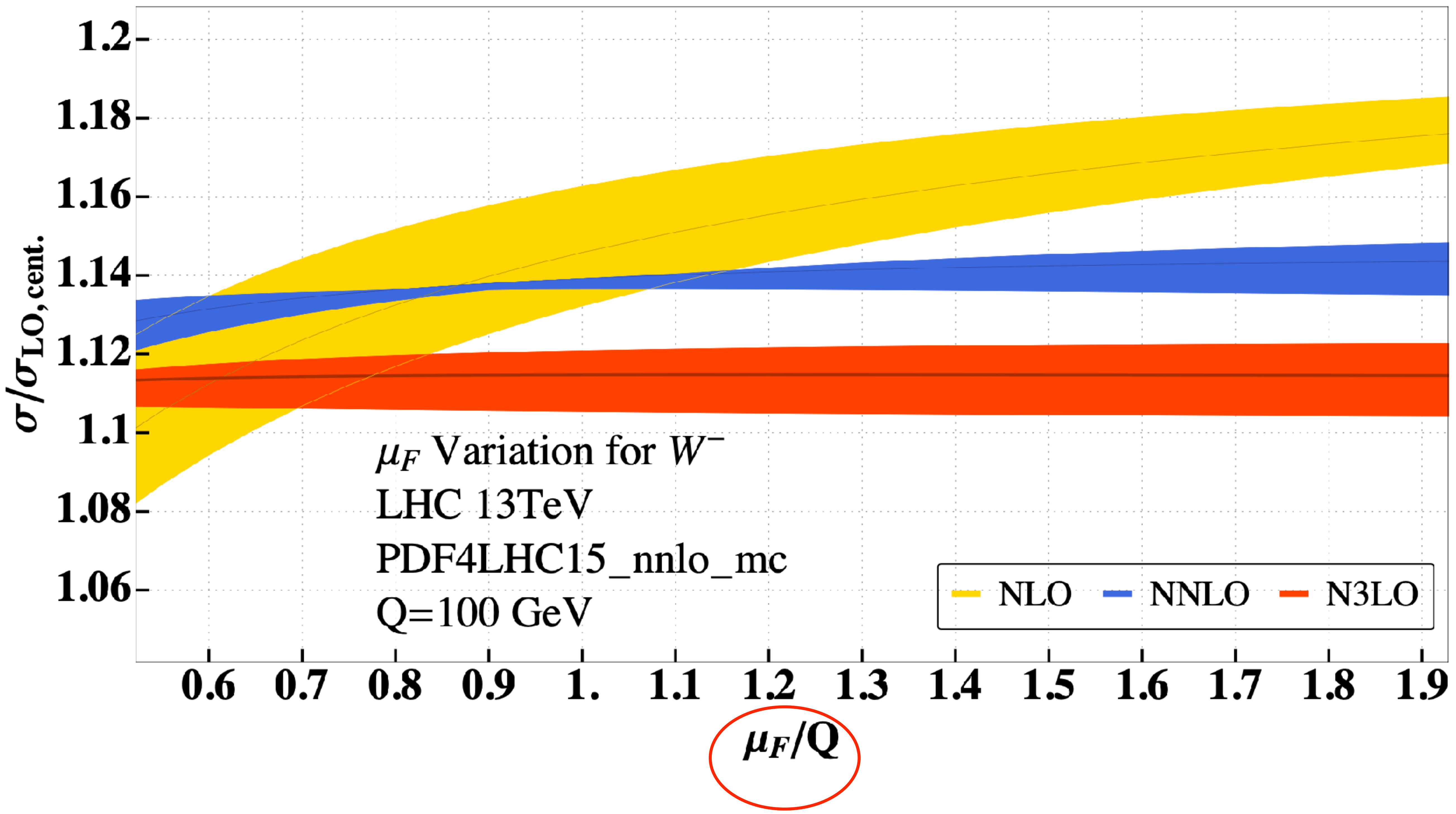
Scale uncertainties: Drell-Yan (W-production)



Scale uncertainties: Drell-Yan (W-production)

Duhr, Dulat, Mistlberger ‘20



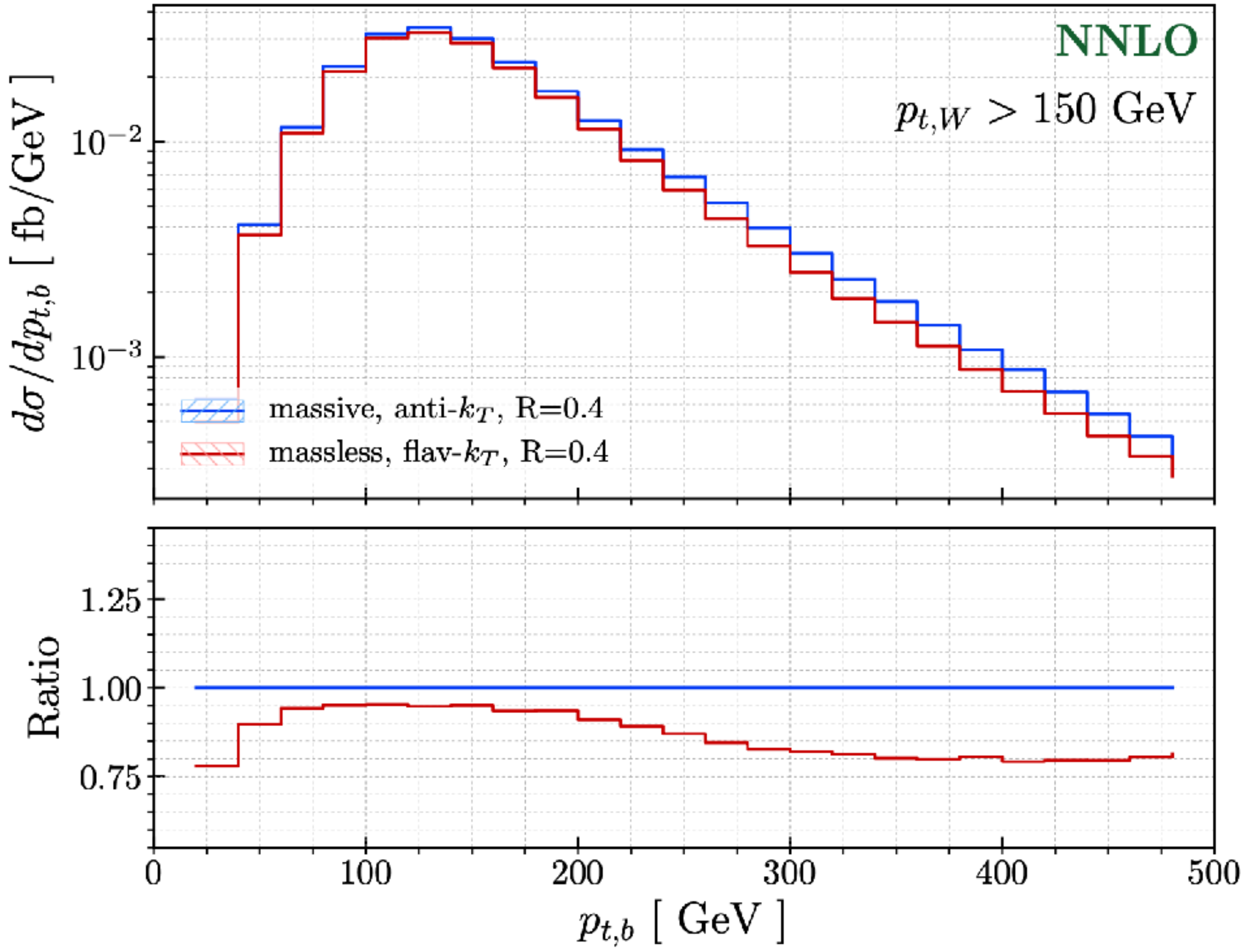


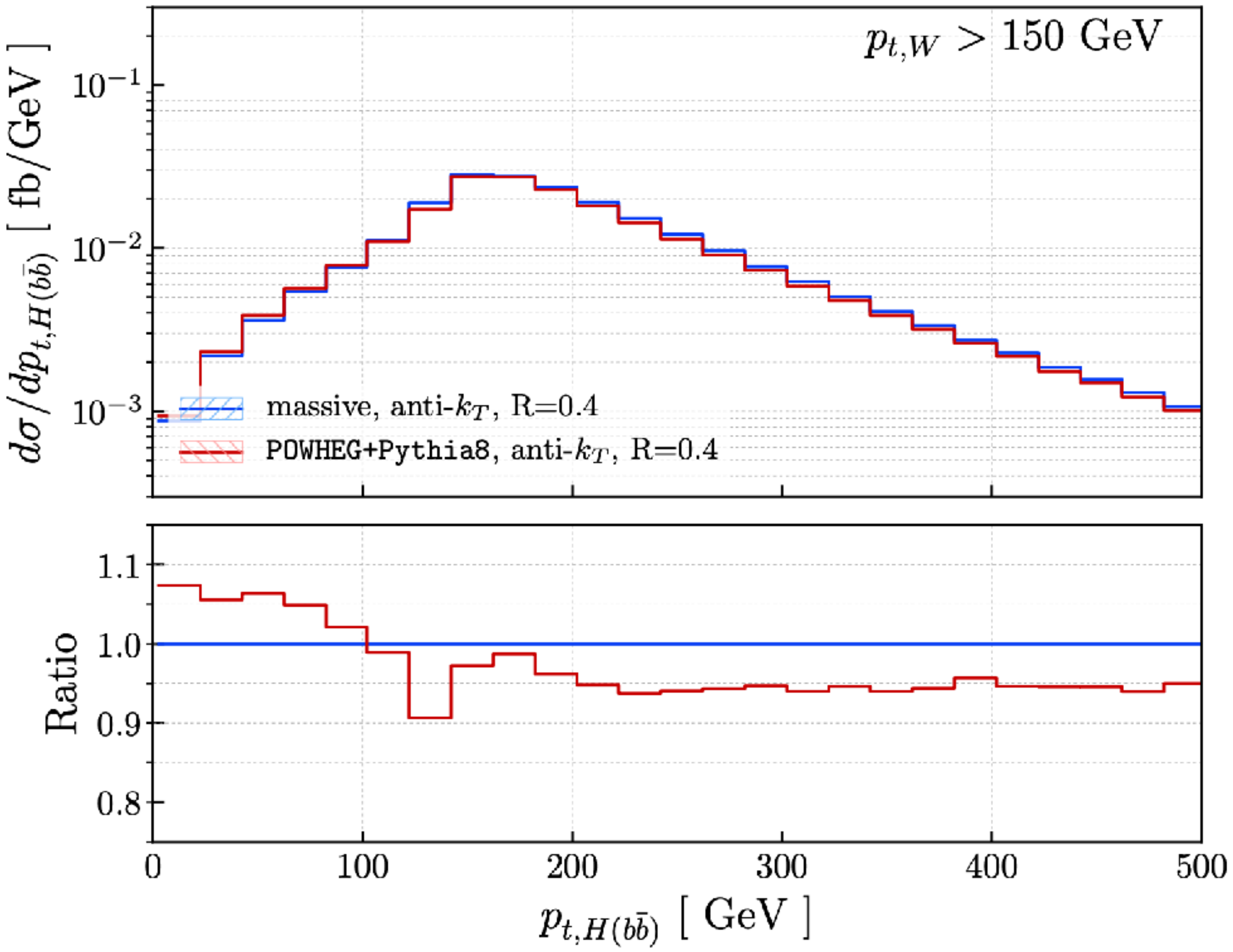
NNLO μ_F-scale uncertainty bands do not properly reflect the uncertainty

Mass effects, parton shower uncertainties

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

Behring, Bizon, Caola, Melnikov, Röntsch 2003.08321

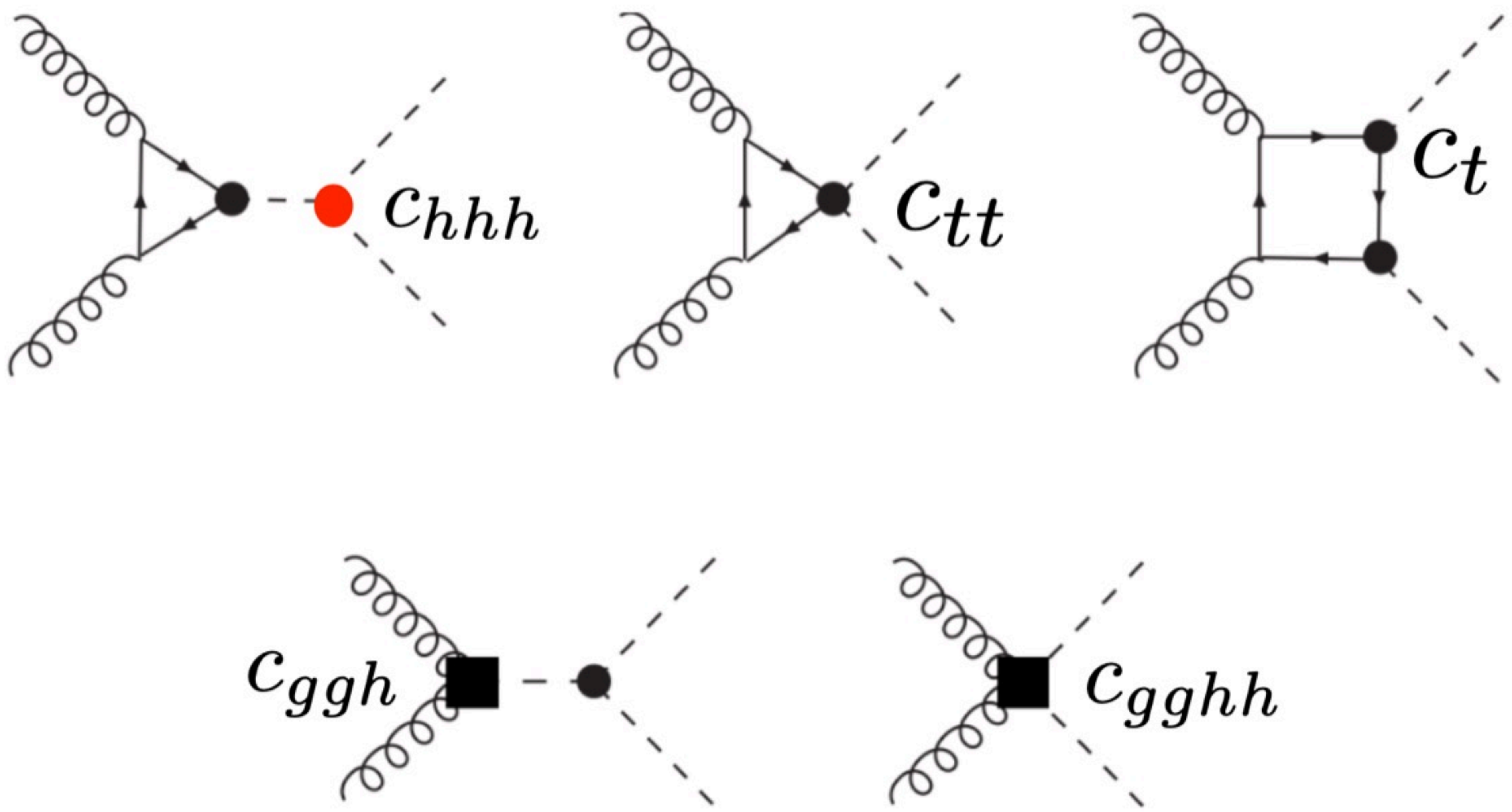


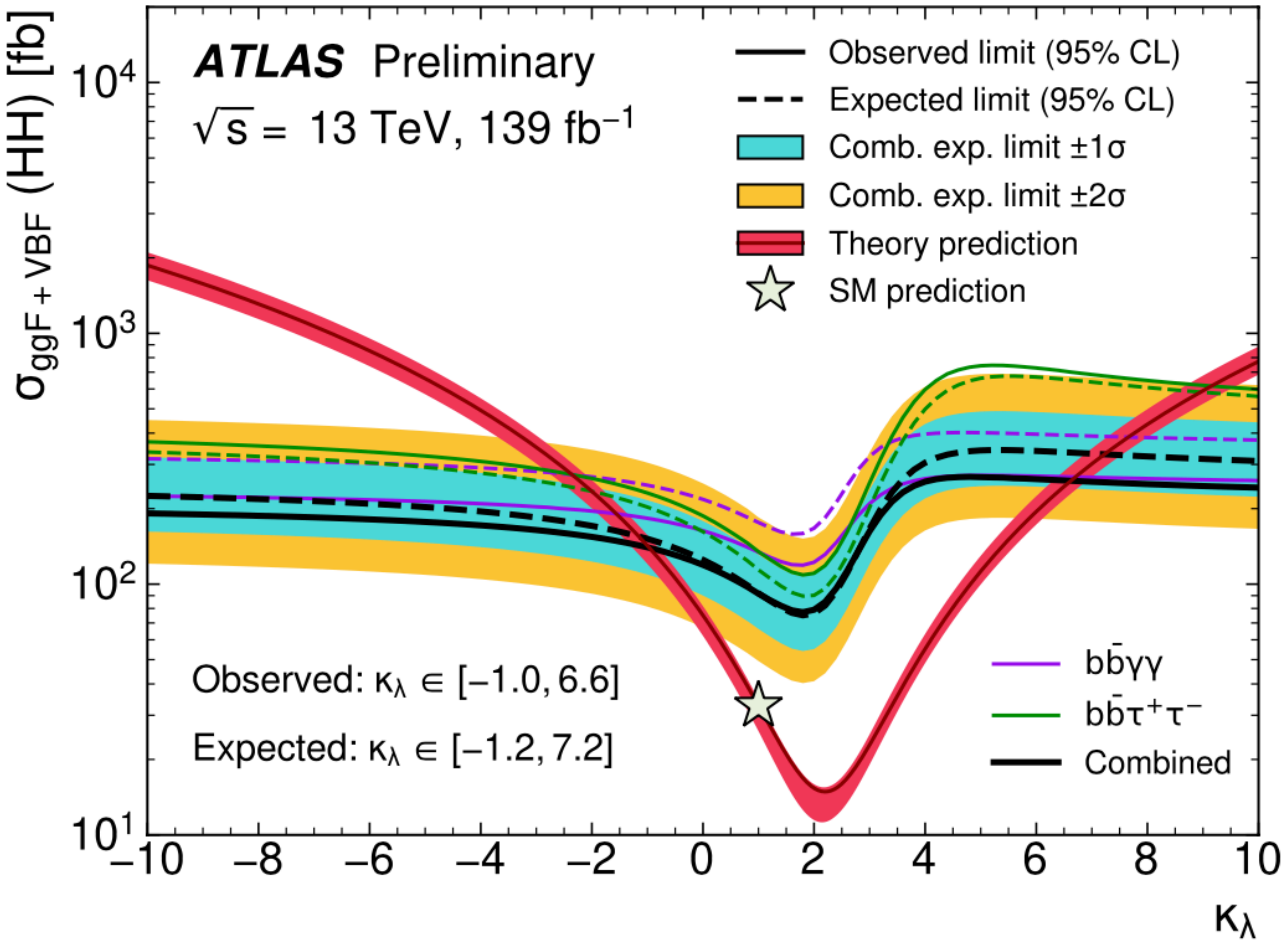


significant differences between massive and massless case and NNLO vs NLO+PS

Exploring the Higgs potential

through Higgs boson pair production in gluon fusion





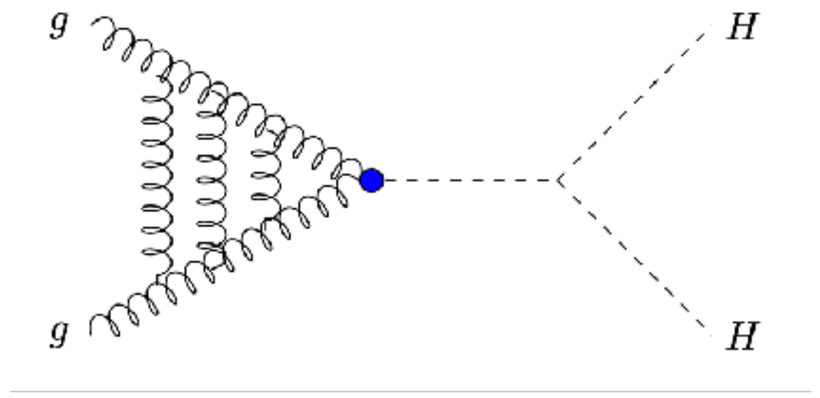
$$\mathcal{L} \supset -m_t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3+\frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v}+c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

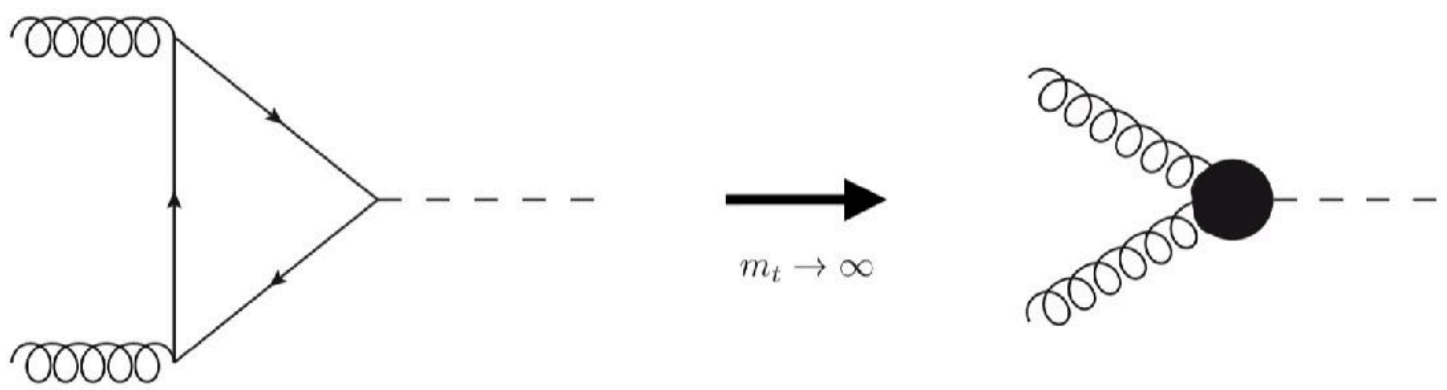
$$\kappa_\lambda \equiv c_{hhh}$$

description of unknown interactions at high energies through Effective Field Theory

Standard Model: $c_{tt} = 0, c_{ggh} = 0, c_{gghh} = 0$

Higher order corrections: SM





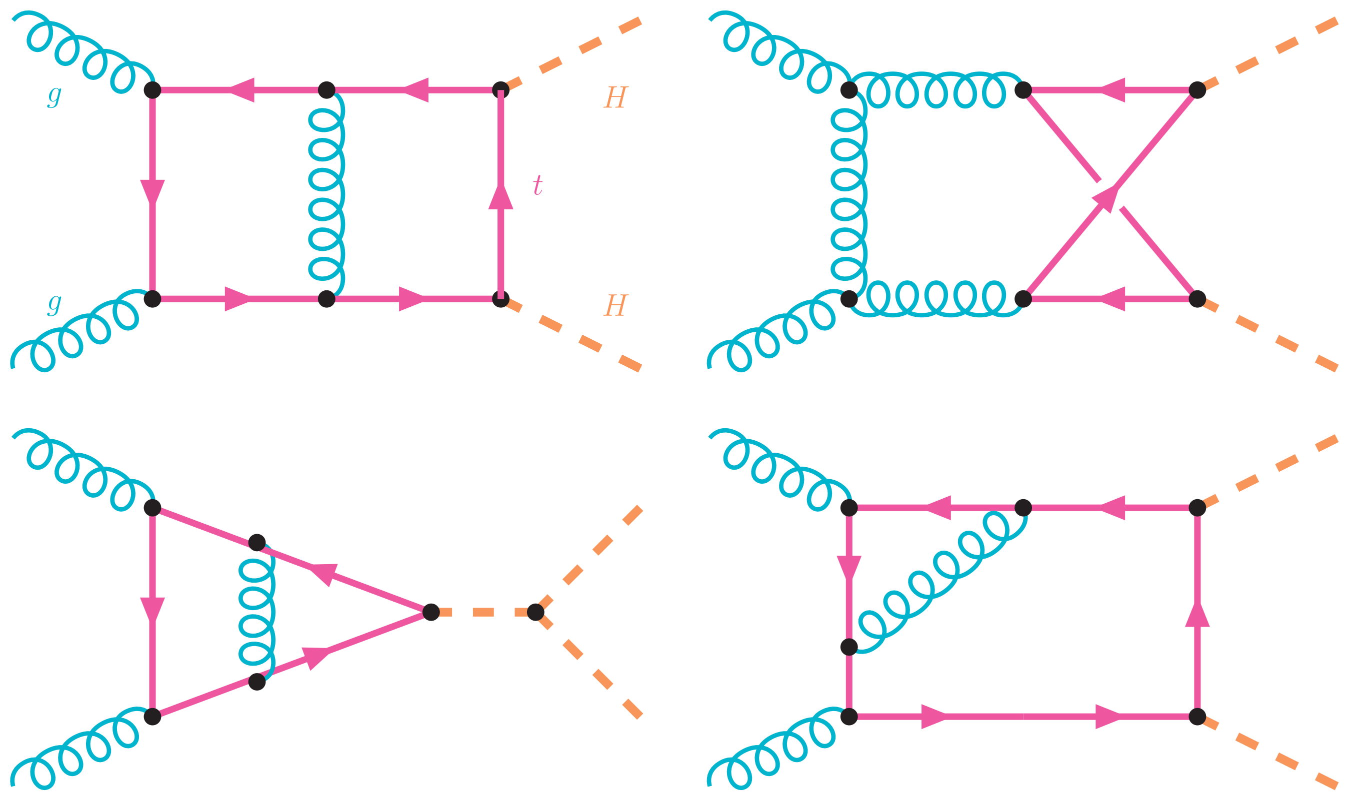
heavy top limit (HTL)

N3LO: Chen, Li, Shao, Wang ’19
(HTL with top mass effects)

NNLO: De Florian, Mazzitelli ’13
Grigo, Melnikov, Steinhauser ‘14

$\mathrm{NNLO}_{\mathrm{FTapprox}}$ Grazzini, Kallweit, GH, Jones,
Kerner, Lindert, Mazzitelli ‘18

inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$



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 ’18, ‘20

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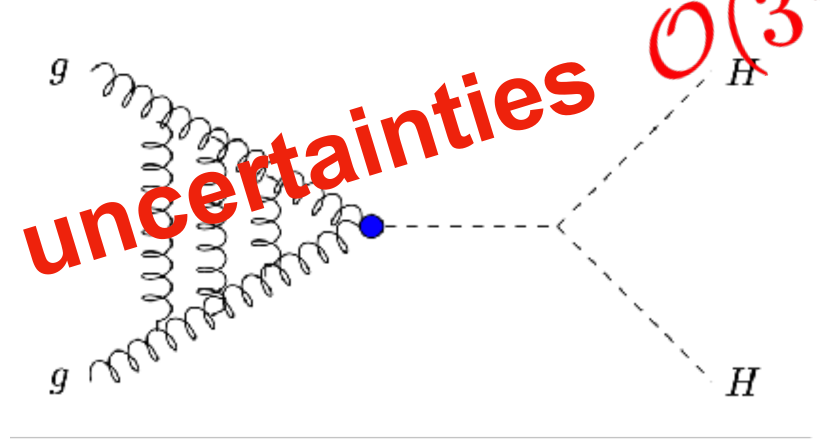
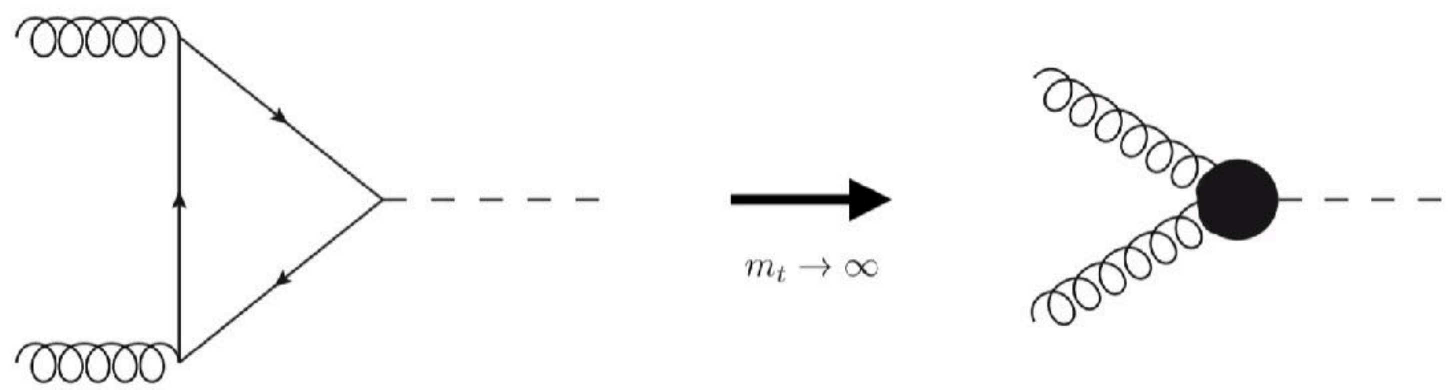


scale uncertainties $\mathcal{O}(3\%)$

NNLO: De Florian, Mazzitelli ’13
Grigo, Melnikov, Steinhauser ‘14



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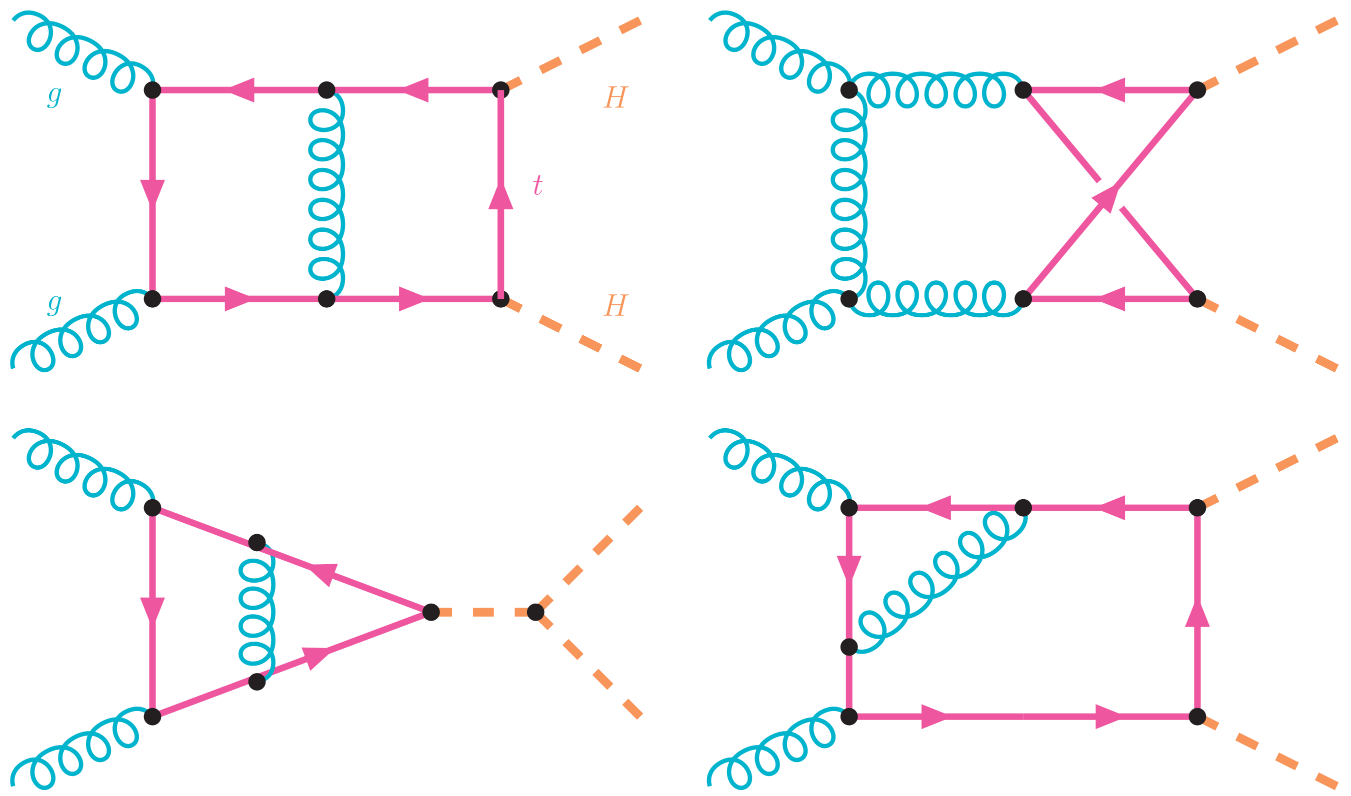

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Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ‘20

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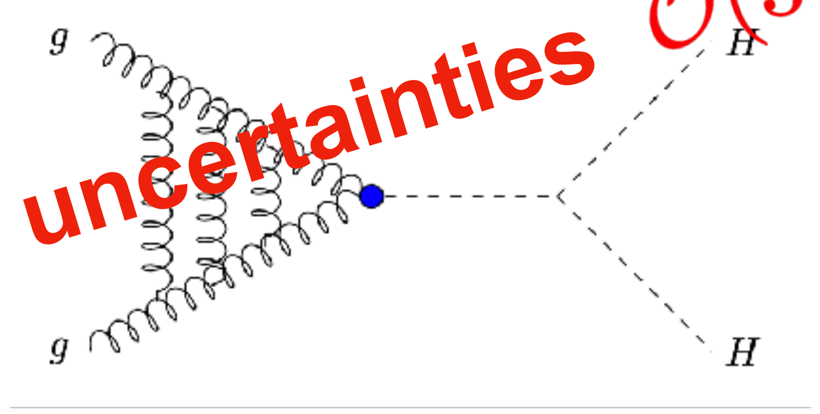

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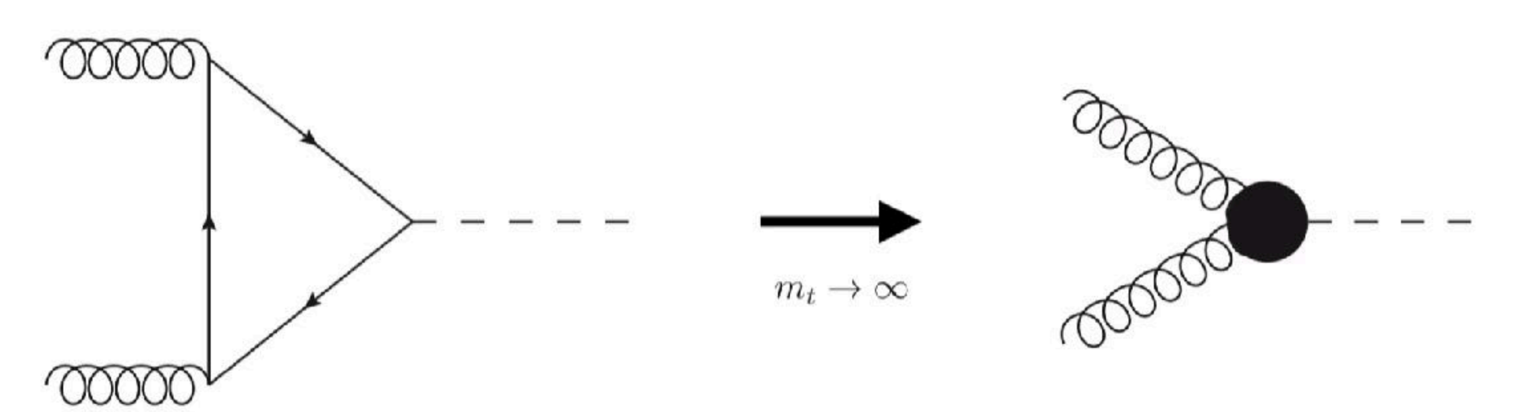

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residual missing top mass effects estimated to $\mathcal{O}(5\%)$

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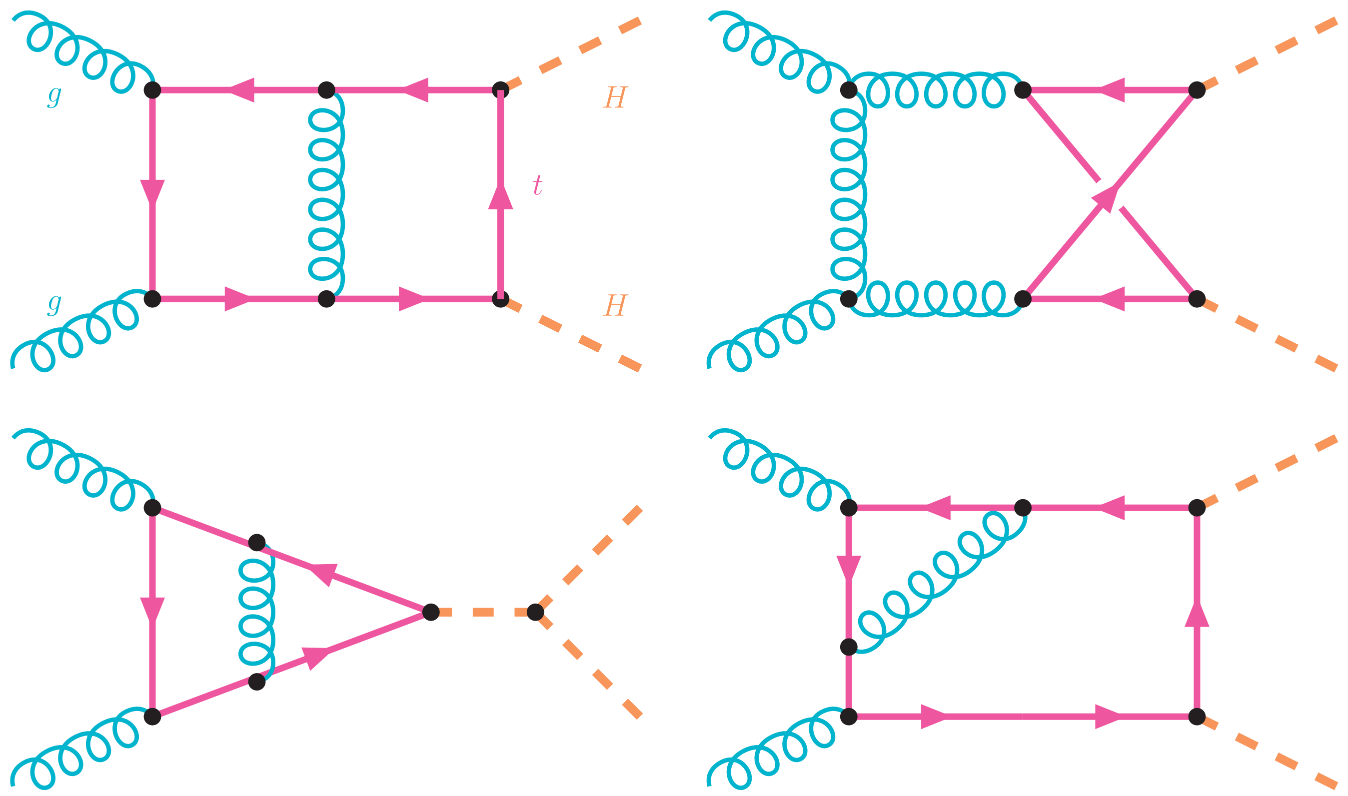
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann ‘19



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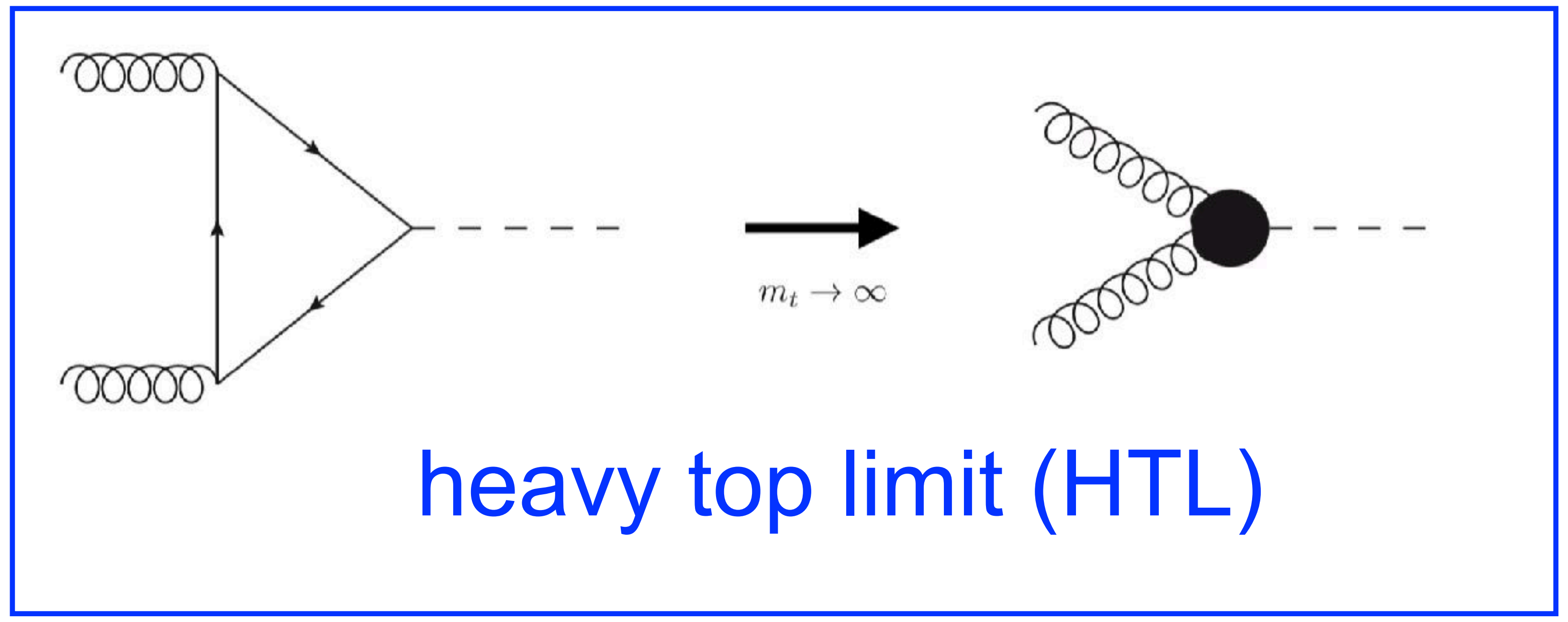
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ‘20

Higher order corrections: SM



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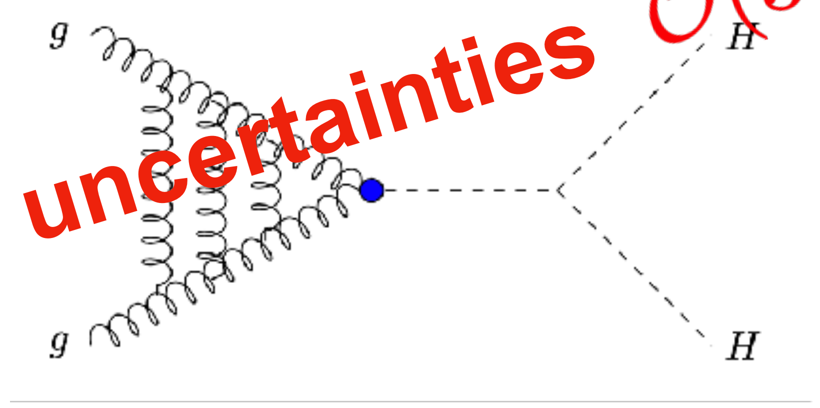

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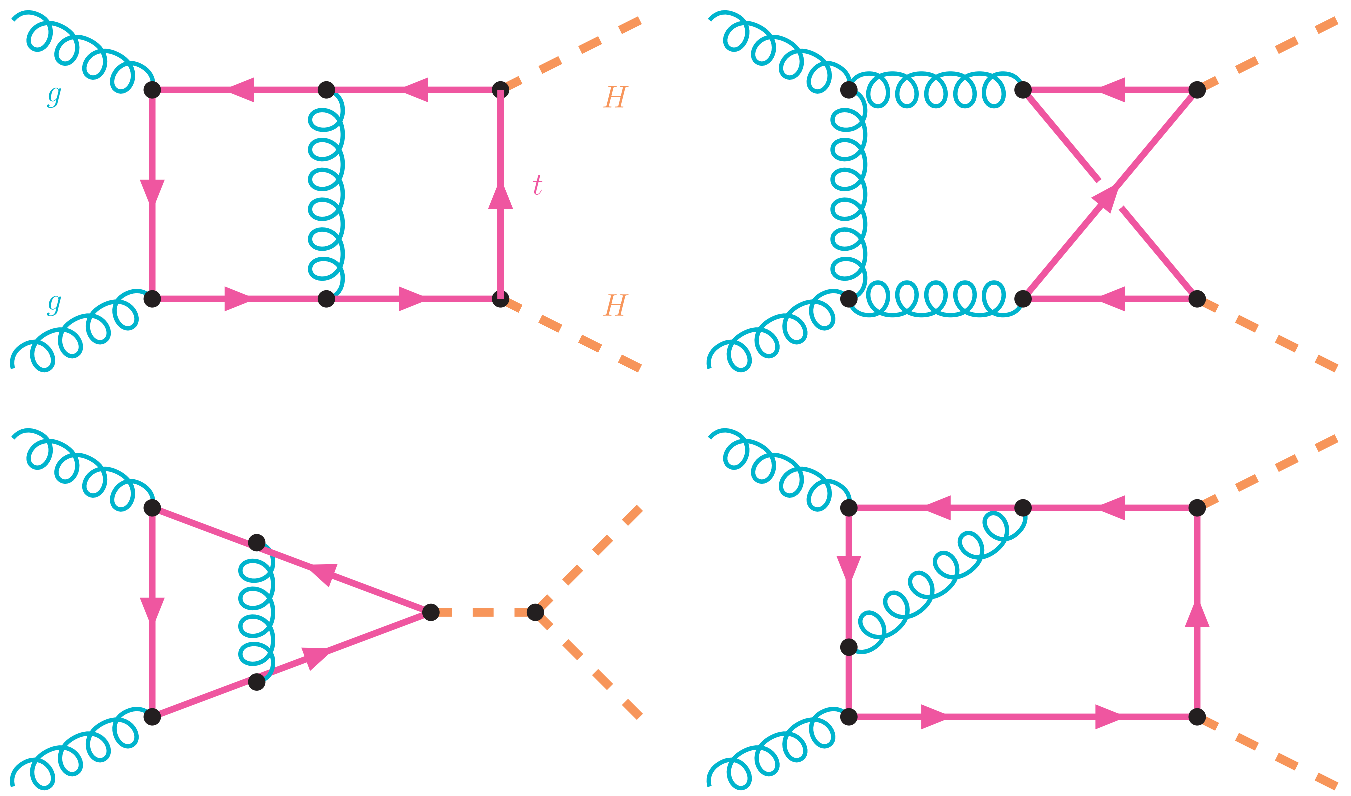


top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

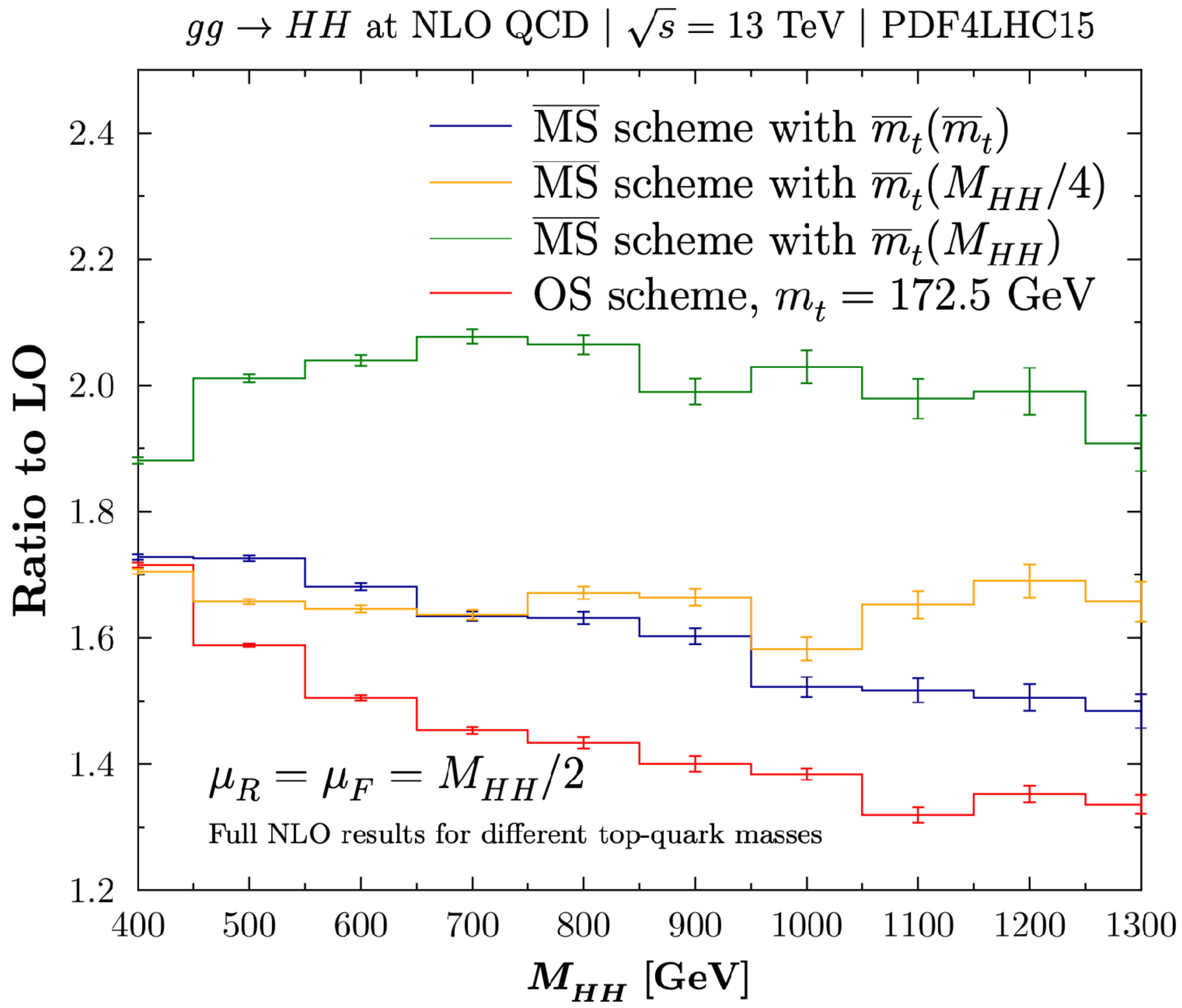
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ‘20

uncertainty due to top mass scheme $\mathcal{O}(20\%)$

Top quark mass renormalisation scheme uncertainties

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

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

Effective Field Theory expansion schemes

SMEFT (Standard Model Effective Field Theory):

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

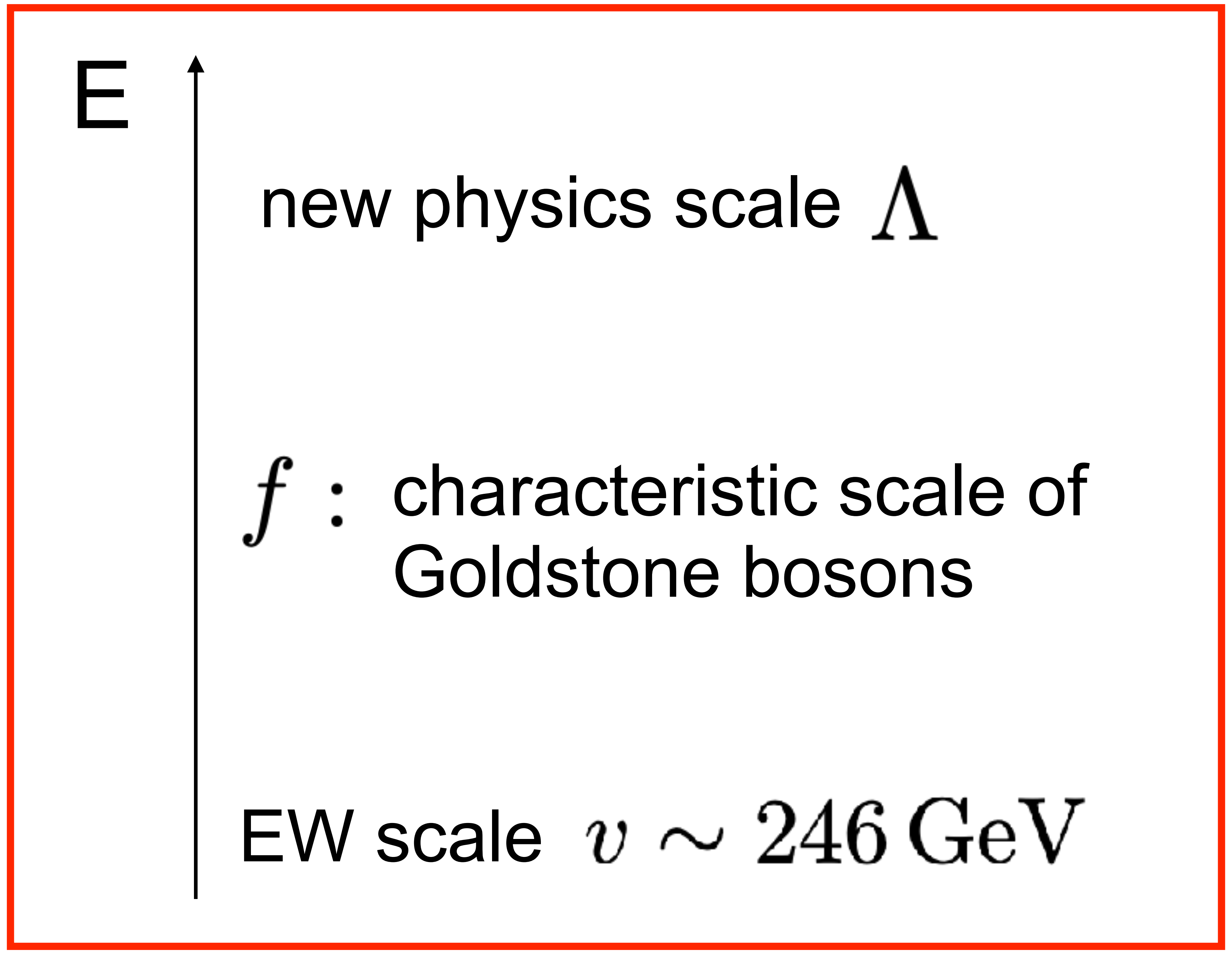
canonical dimension counting

HEFT (Higgs Effective Field Theory):

$$\mathcal{L}_{HEFT} = \mathcal{L}_0 + \sum_{L=1}^{\infty}\sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} O_i^{(L)}$$

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

(similar to chiral perturbation theory)



E

new physics scale Λ

f : characteristic scale of Goldstone bosons

EW scale $v \sim 246\,\mathrm{GeV}$

Lagrangians relevant for HH production

SMEFT:

$$\Delta\mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 + \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\phi^c t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a}$$

(Warsaw basis)

Grzadkowski et al. 1008.4884

HEFT:

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

Buchalla et al. '13, '18

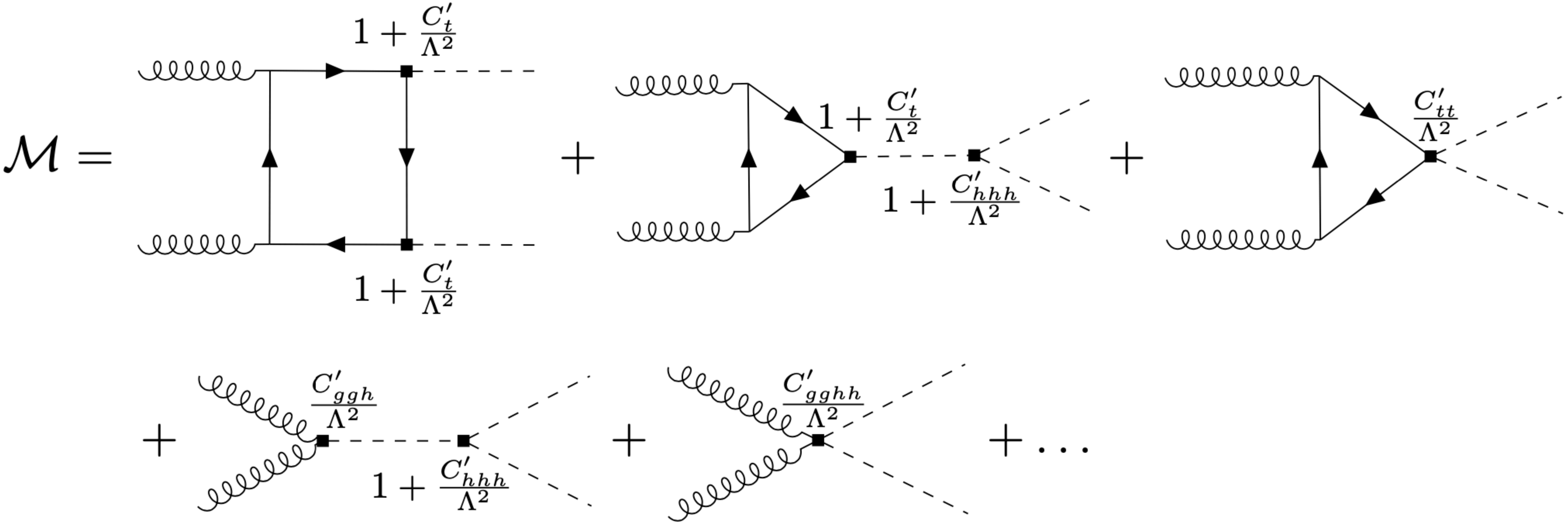
Lagrangians relevant for HH production

coupling relations at Lagrangian level:

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

$$C_{H,\mathrm{kin}}=C_{H,\Box}-\frac{1}{4}C_{HD}$$

SMEFT double operator insertions



$$= \mathcal{M}_{\rm SM} + \mathcal{M}_{\rm dim6} + \mathcal{M}_{\rm dim6^2}$$

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

SMEFT at amplitude squared level

4 possibilities:

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

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

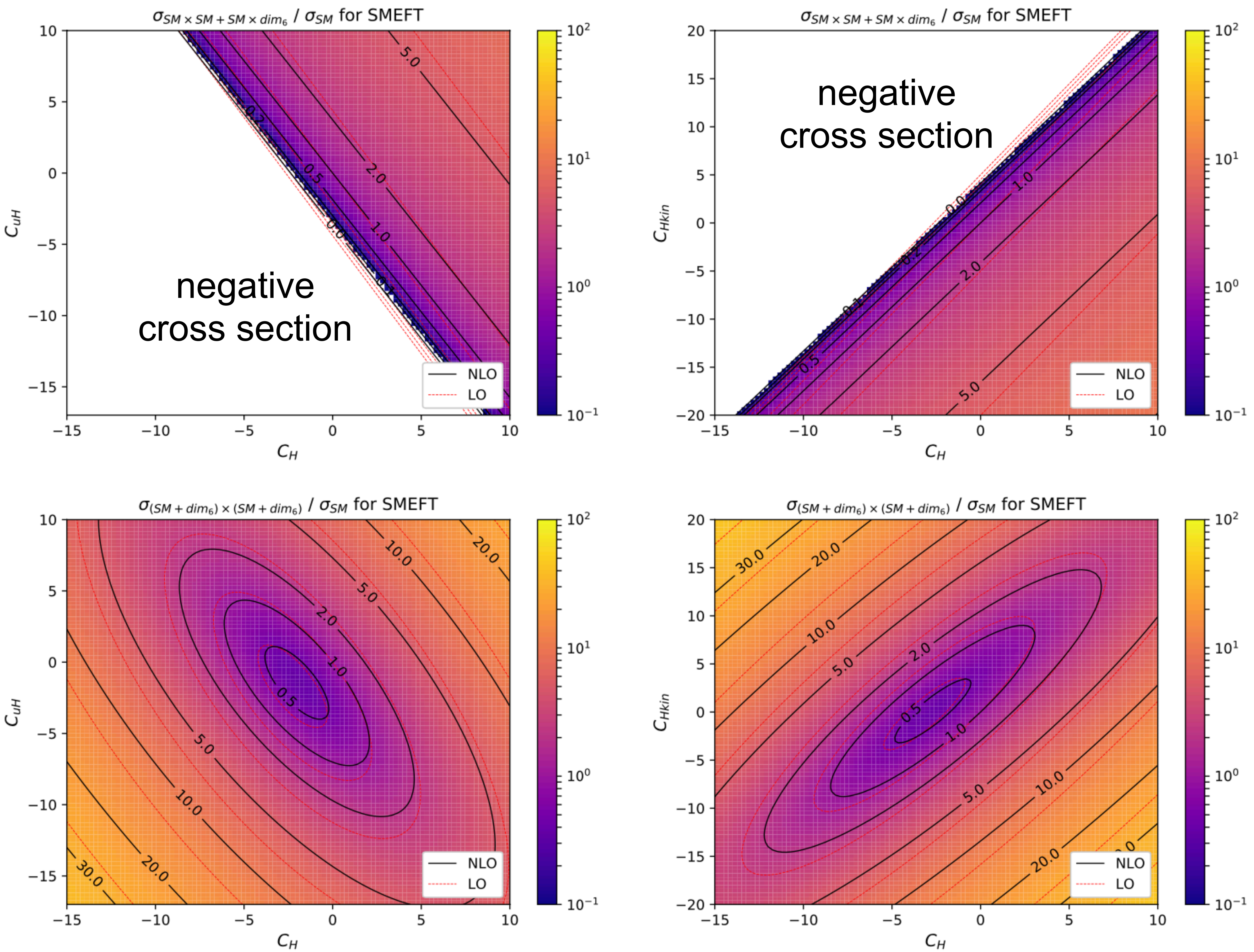
(b): “quadratic dim 6” (first order of expansion in $1/\Lambda^2$ at amplitude level)

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

(d): would correspond to HEFT except for treatment of α_s

Total HH cross section

flat directions very different in linear versus quadratic dim 6



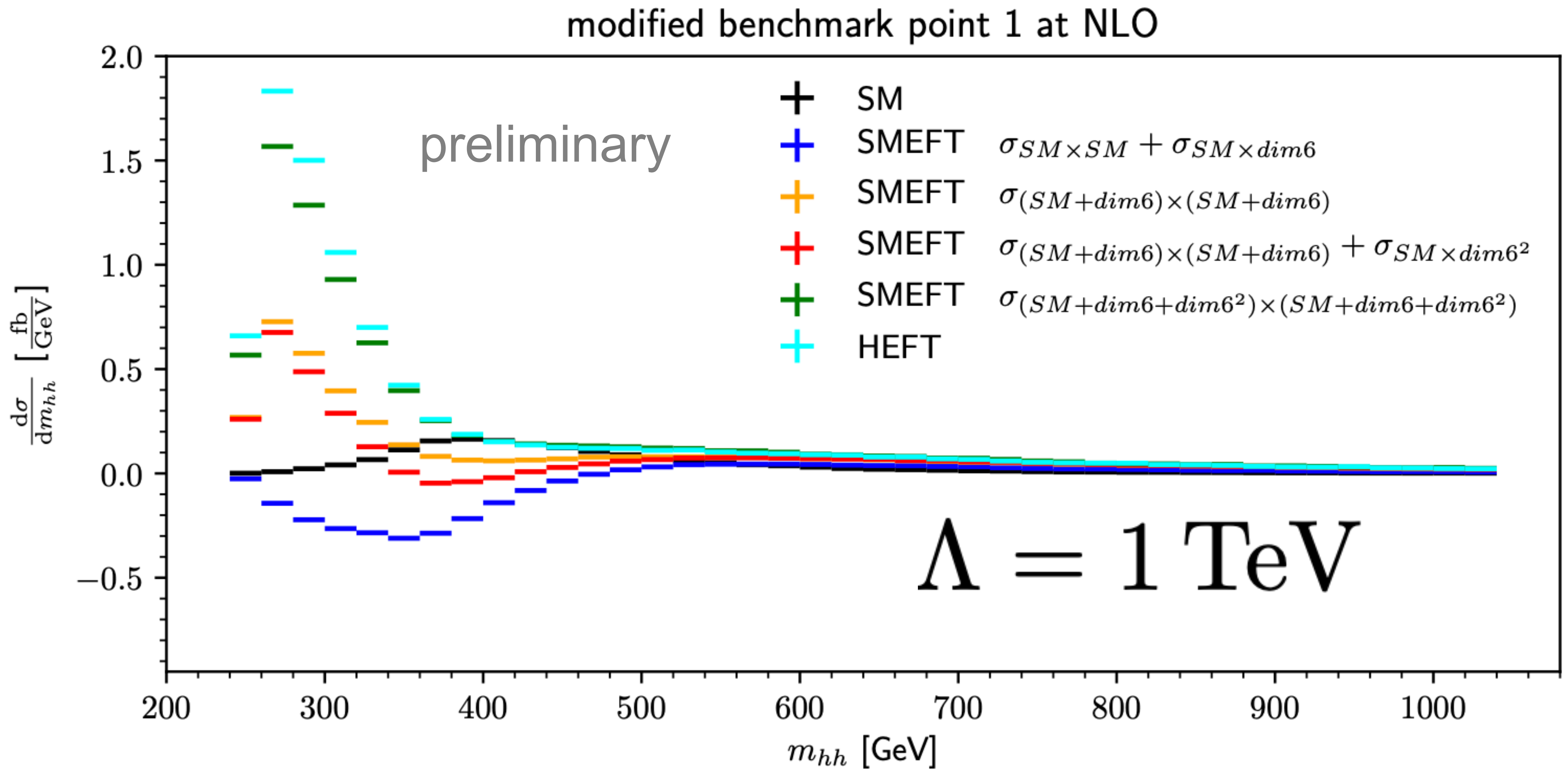
linear

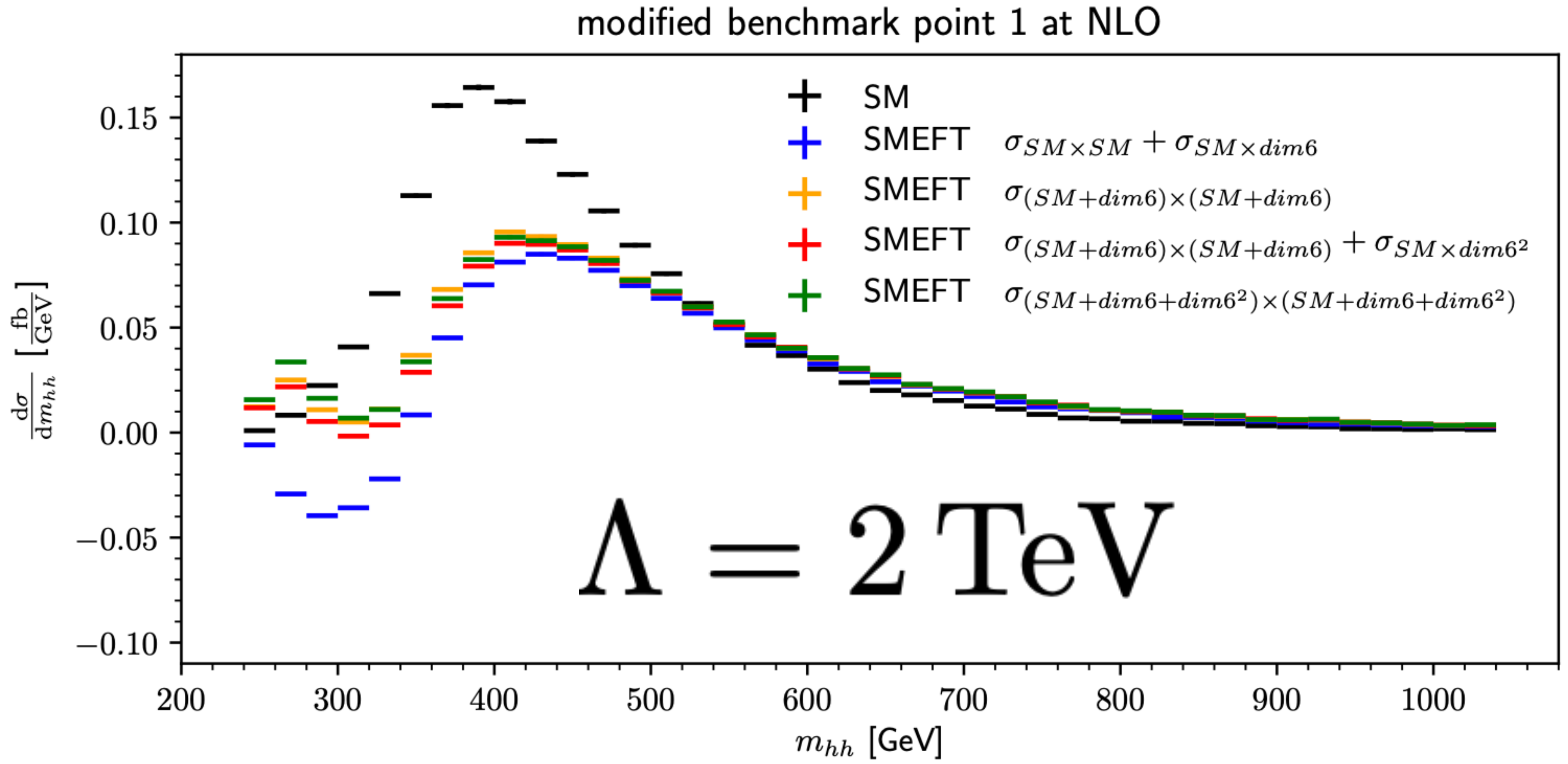
quadratic

figures: Jannis Lang

Higgs boson pair invariant mass spectrum

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	3.94	0.94	$-\frac{1}{3}$	0.5	0.25*
6*	5.68	0.83	$\frac{1}{3}$	-0.5	-0.25*


modified benchmark point 1 at NLO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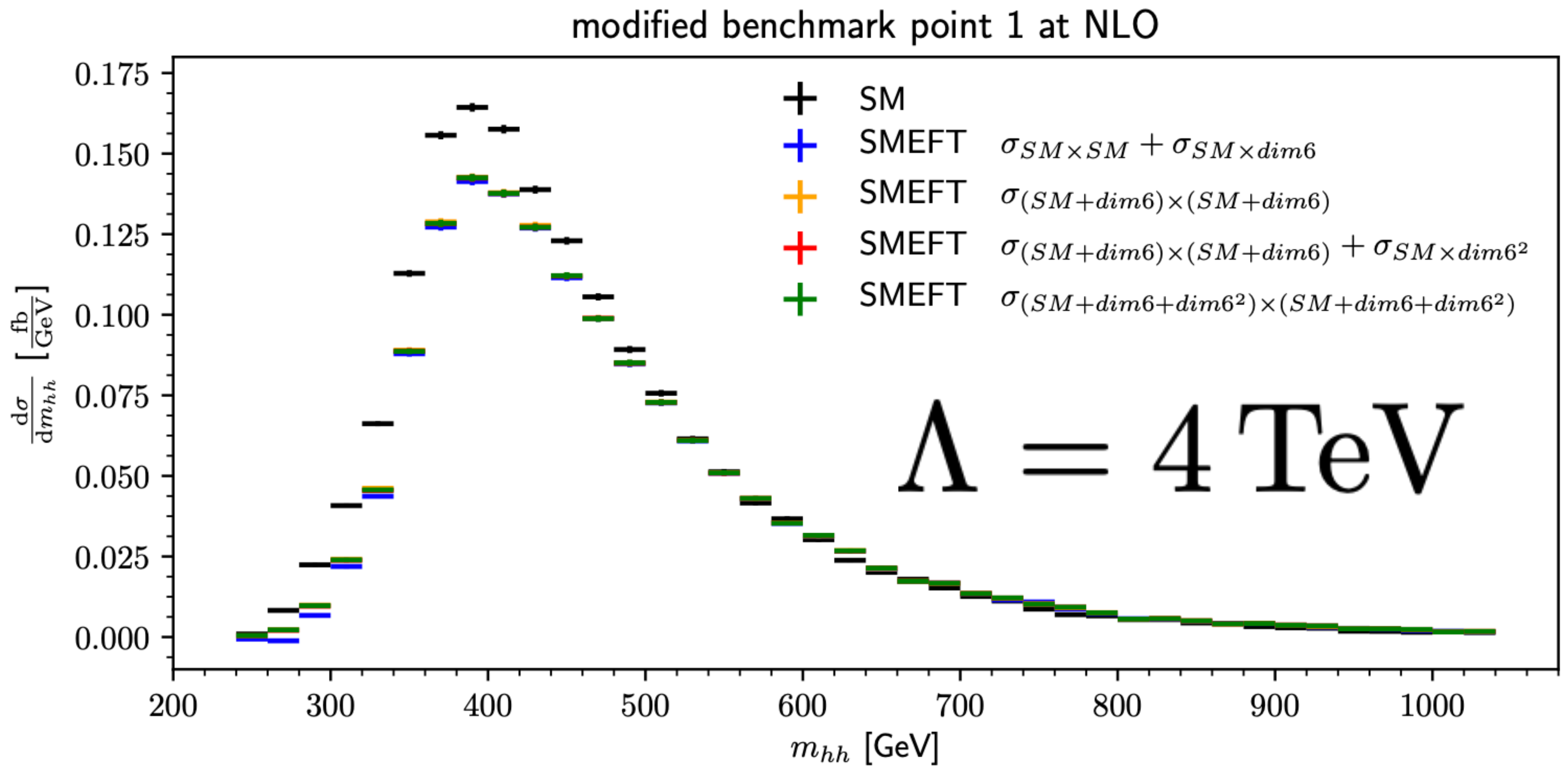
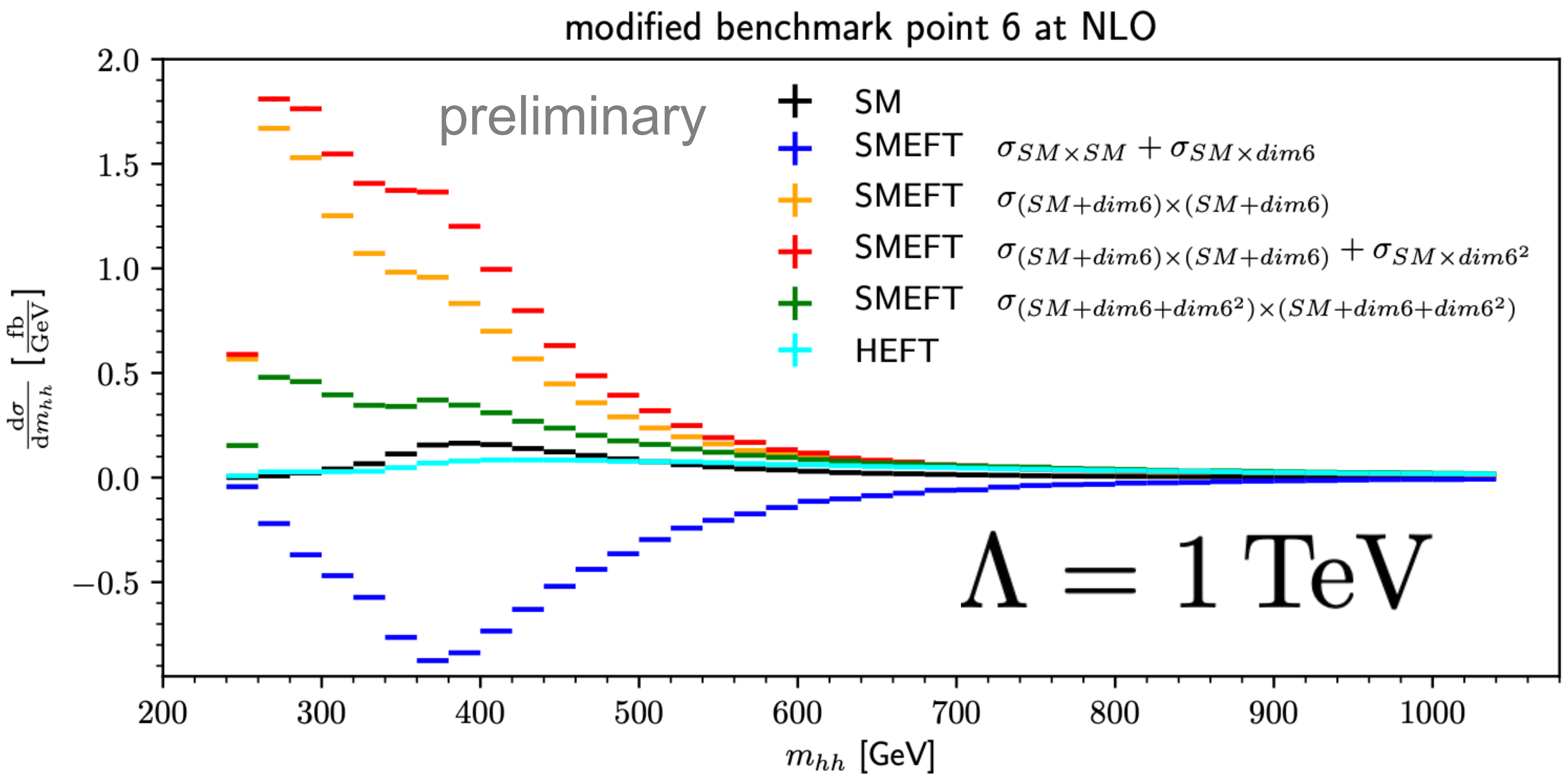
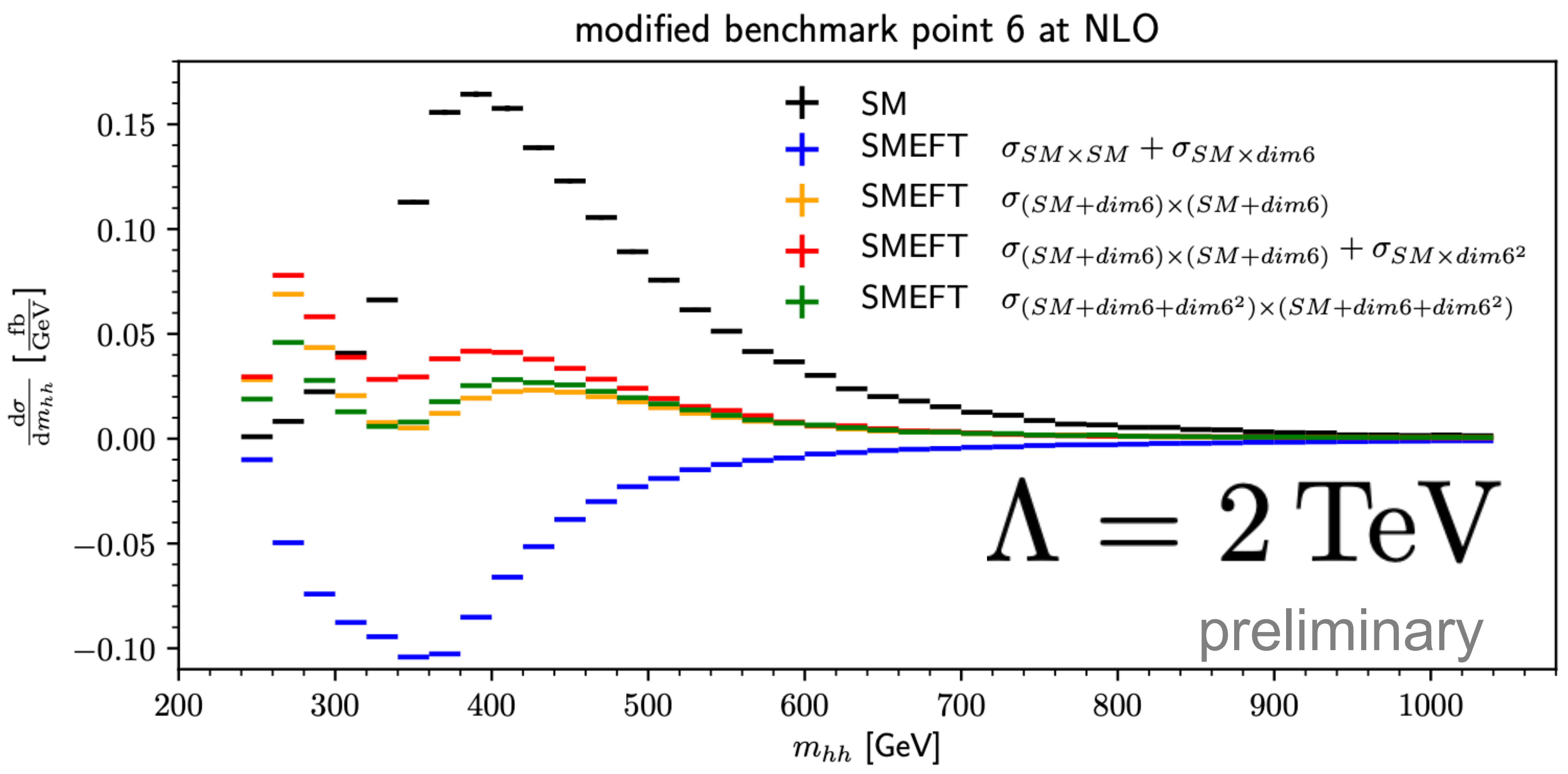

modified benchmark point 1 at NLO

figures: Jannis Lang

Higgs boson pair invariant mass spectrum


modified benchmark point 6 at NLO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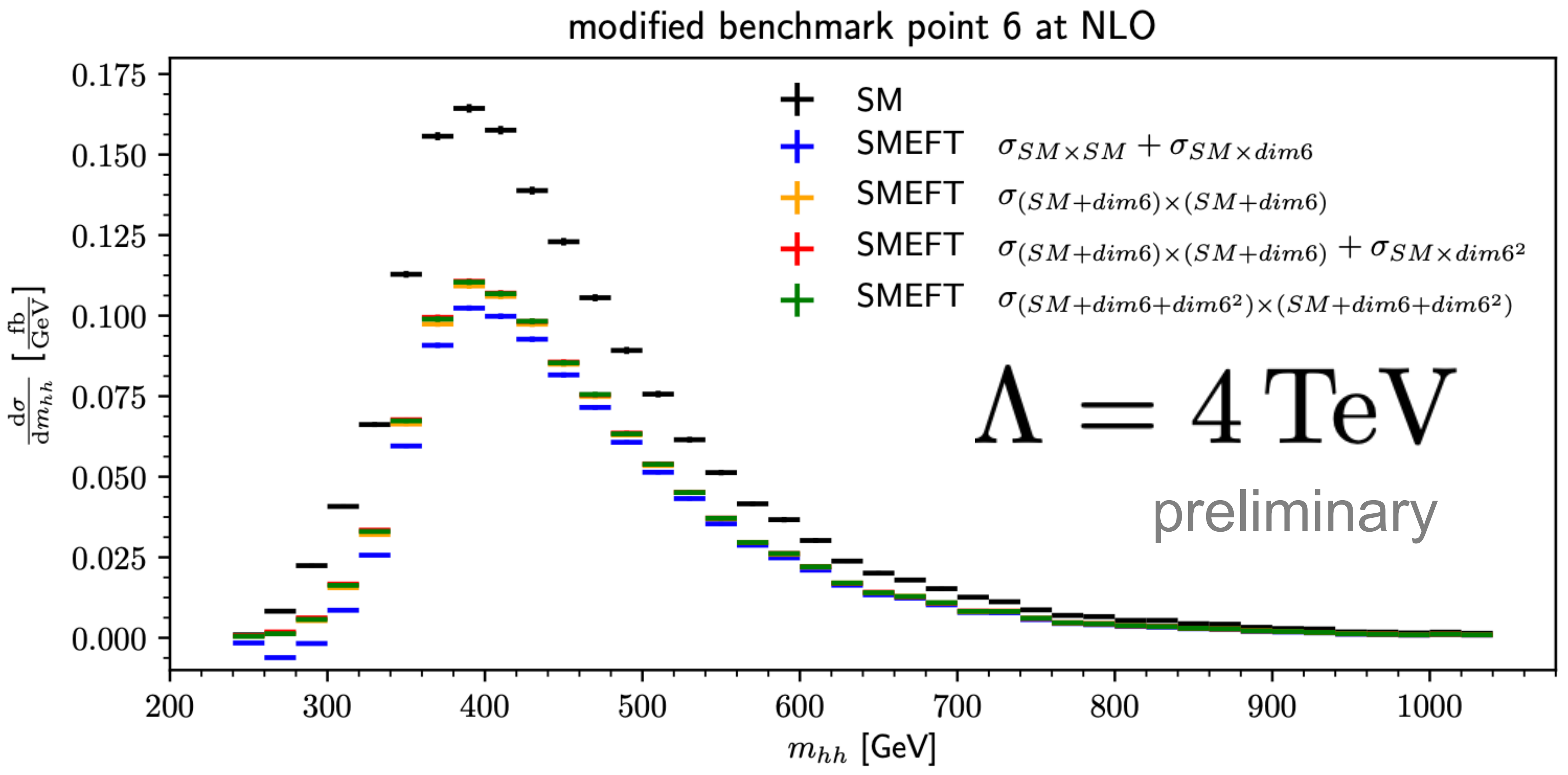
modified benchmark point 6 at NLO

significant differences, delicate interference patterns

parameter point valid in HEFT invalid in SMEFT

figures: Jannis Lang

Summary & Outlook

- Indirect signs of New Physics: precision is the key
- Increasing the precision at the percent level has many facets:

  missing higher orders (QCD/EW), parton shower uncertainties, PDFs,
  heavy quark mass effects/scheme dependence, non-perturbative effects, …
- Testable hypotheses of New Physics:
  - Concrete models -> model dependence
  - Effective field theories -> dependence on counting scheme, truncation, unitarity

Summary & Outlook

Karlsruhe Institute of Technology

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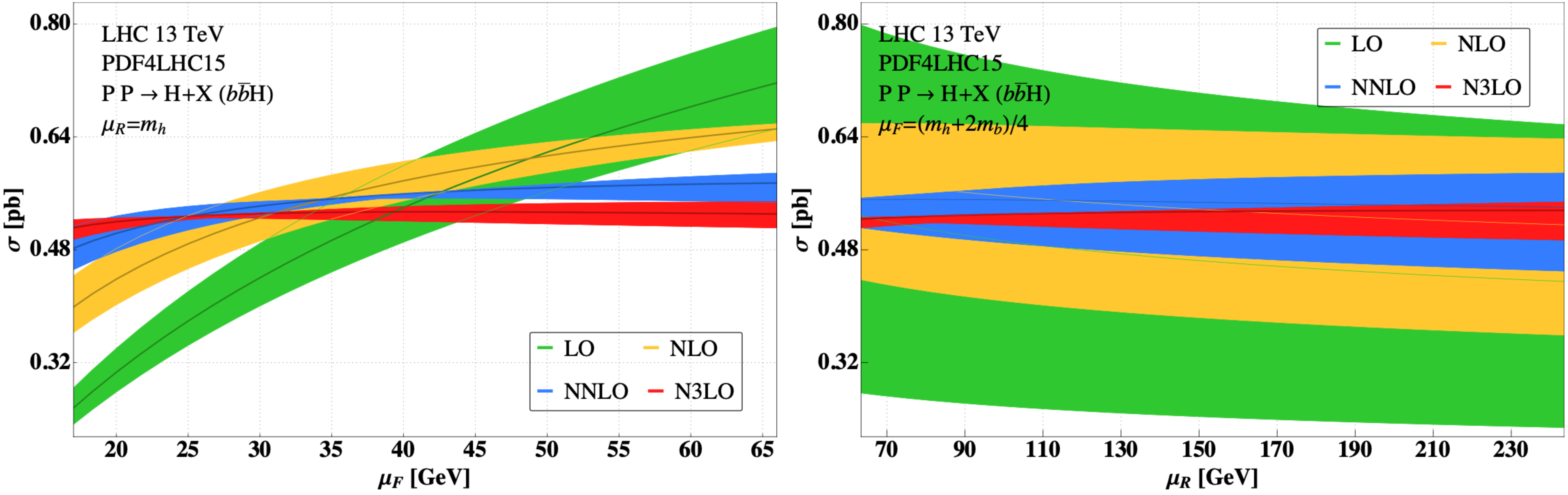
joint efforts needed to work on all the different aspects!

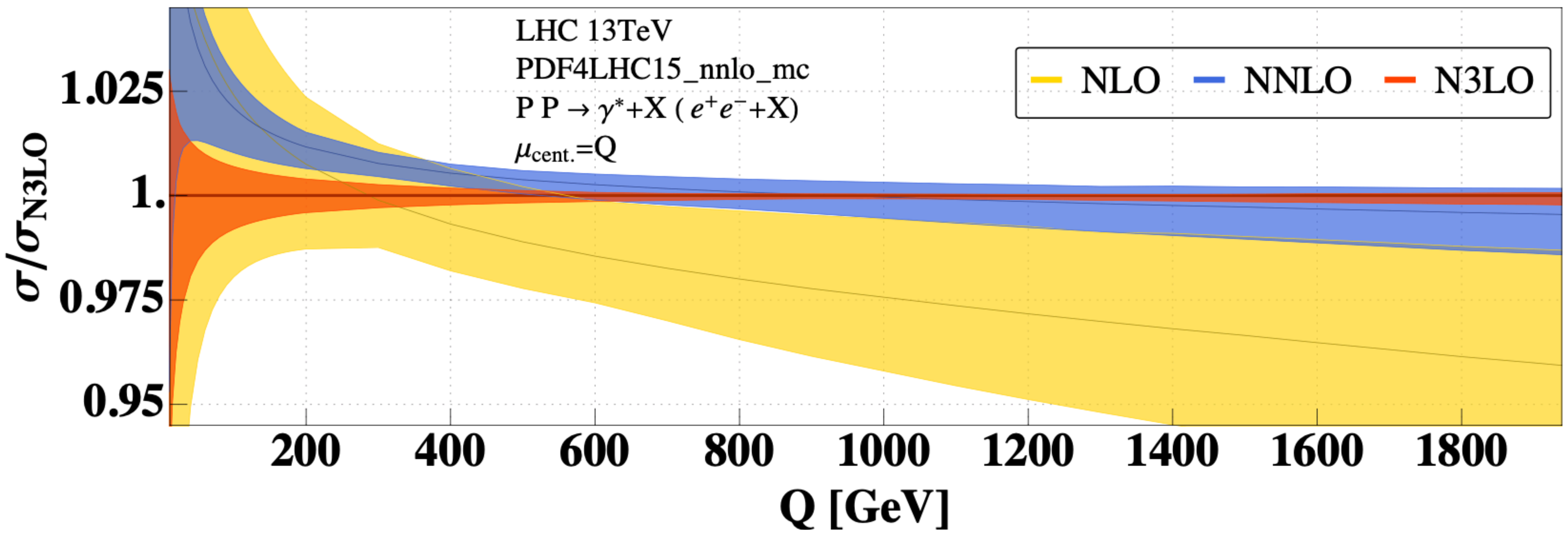
efinger-consulting.de

bbH

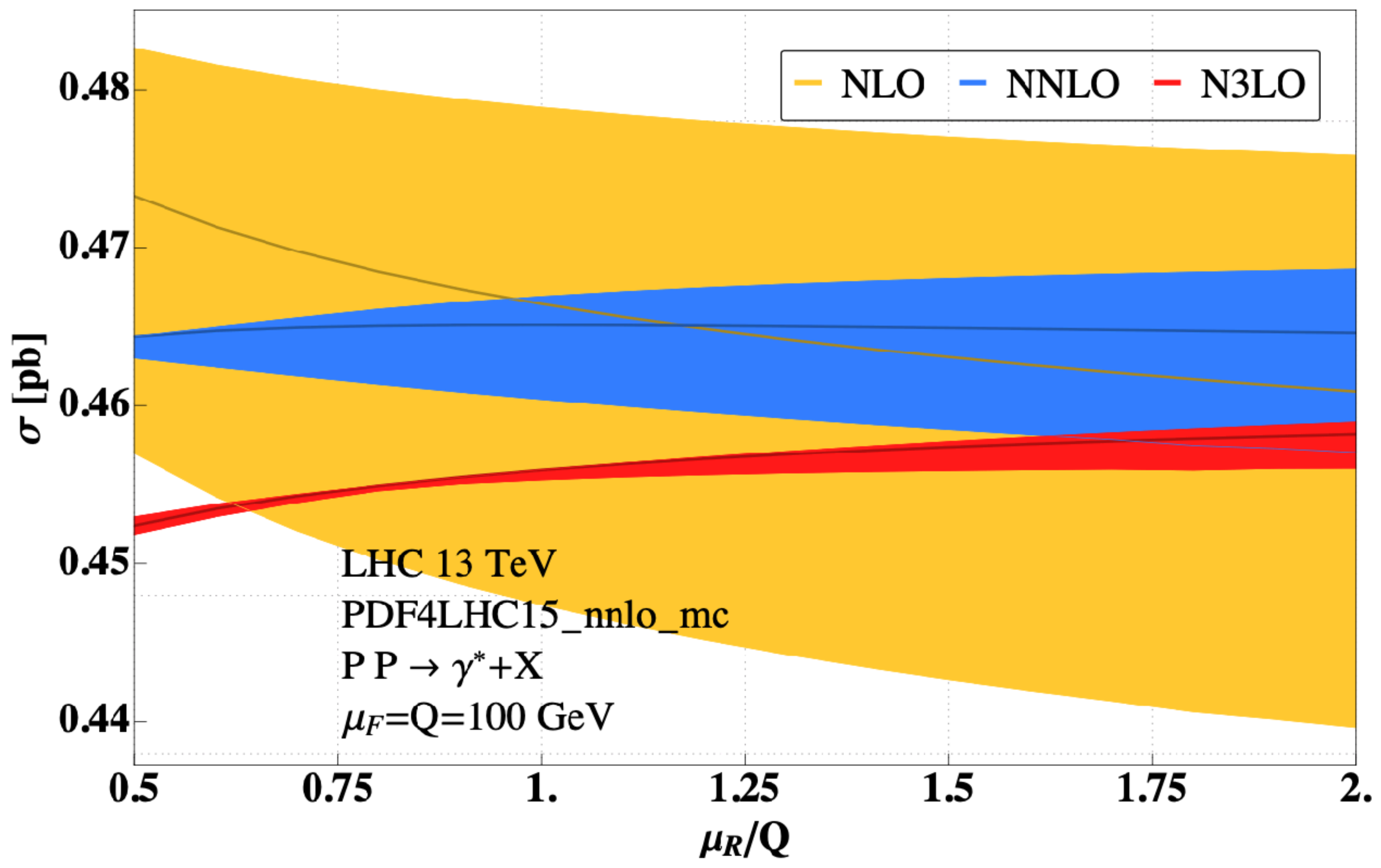


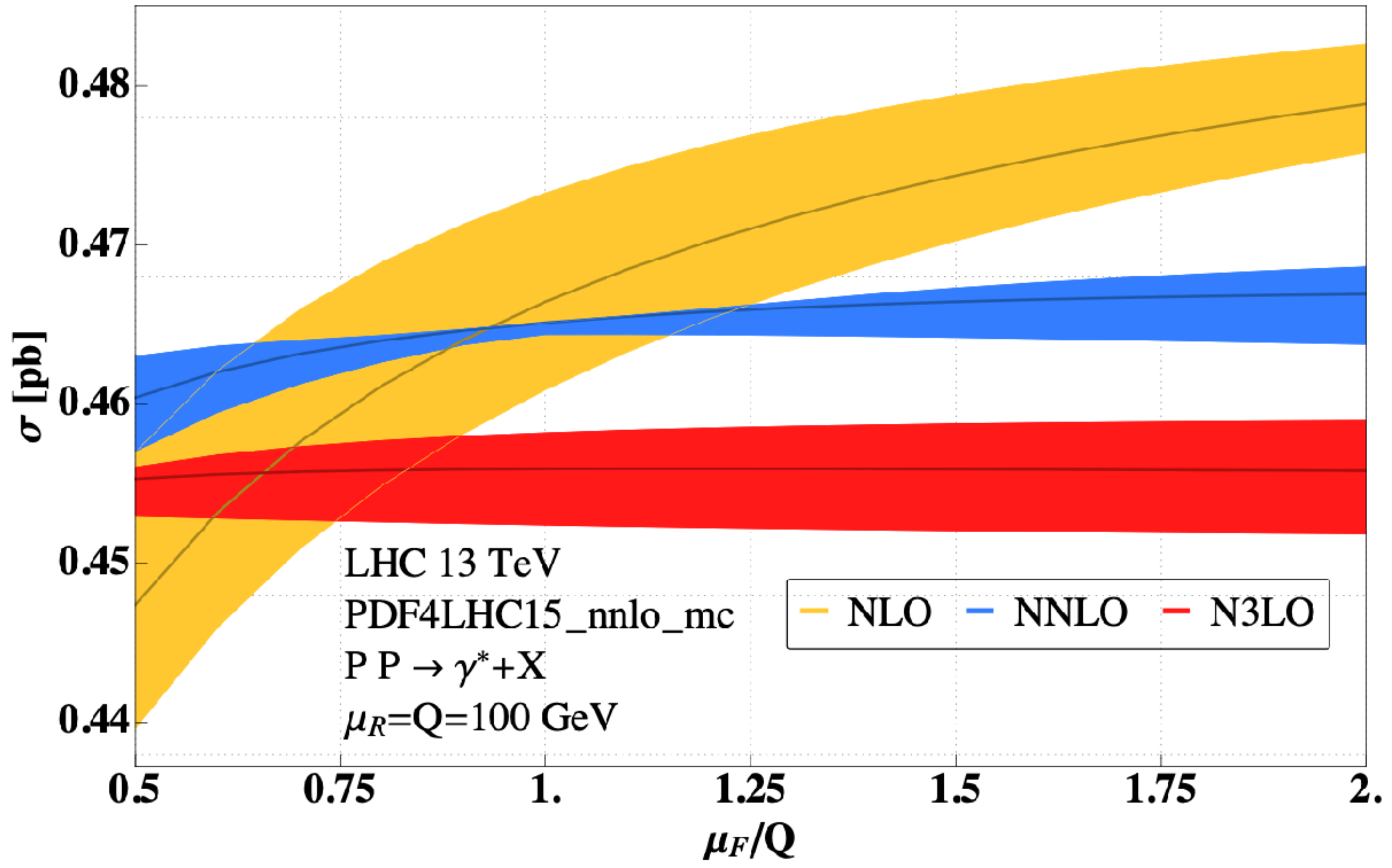
LHC 13 TeV
PDF4LHC15
P P → H+X ($b\bar{b}$H)
μ_R=m_h
0.80
0.64
0.48
0.32
σ [pb]
20
25
30
35
40
45
50
55
60
65
μ_F [GeV]
LO
NLO
NNLO
N3LO
LHC 13 TeV
PDF4LHC15
P P → H+X ($b\bar{b}$H)
μ_F=(m_h+2m_b)/4
70
90
110
130
150
170
190
210
230
μ_R [GeV]

Drell-Yan (NC)



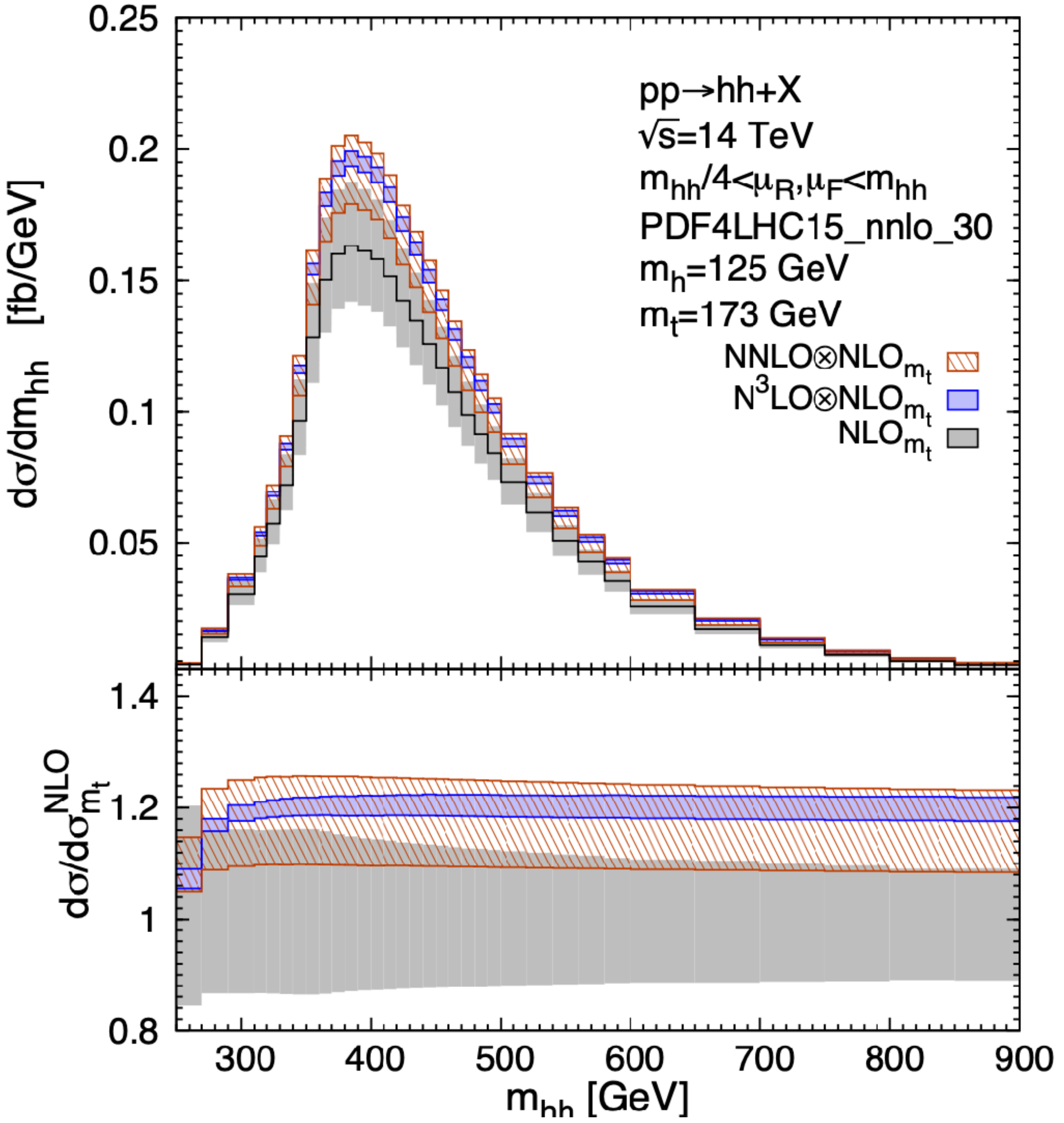
Duhr, Dulat, Mistlberger
2001.07717

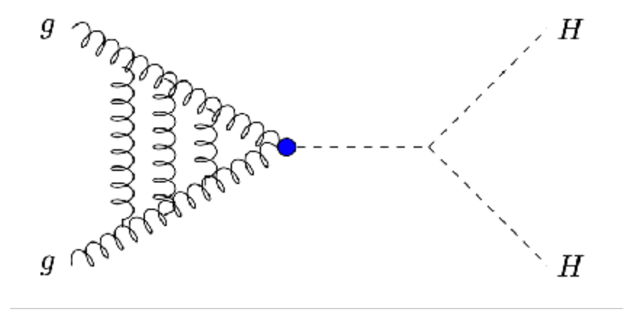




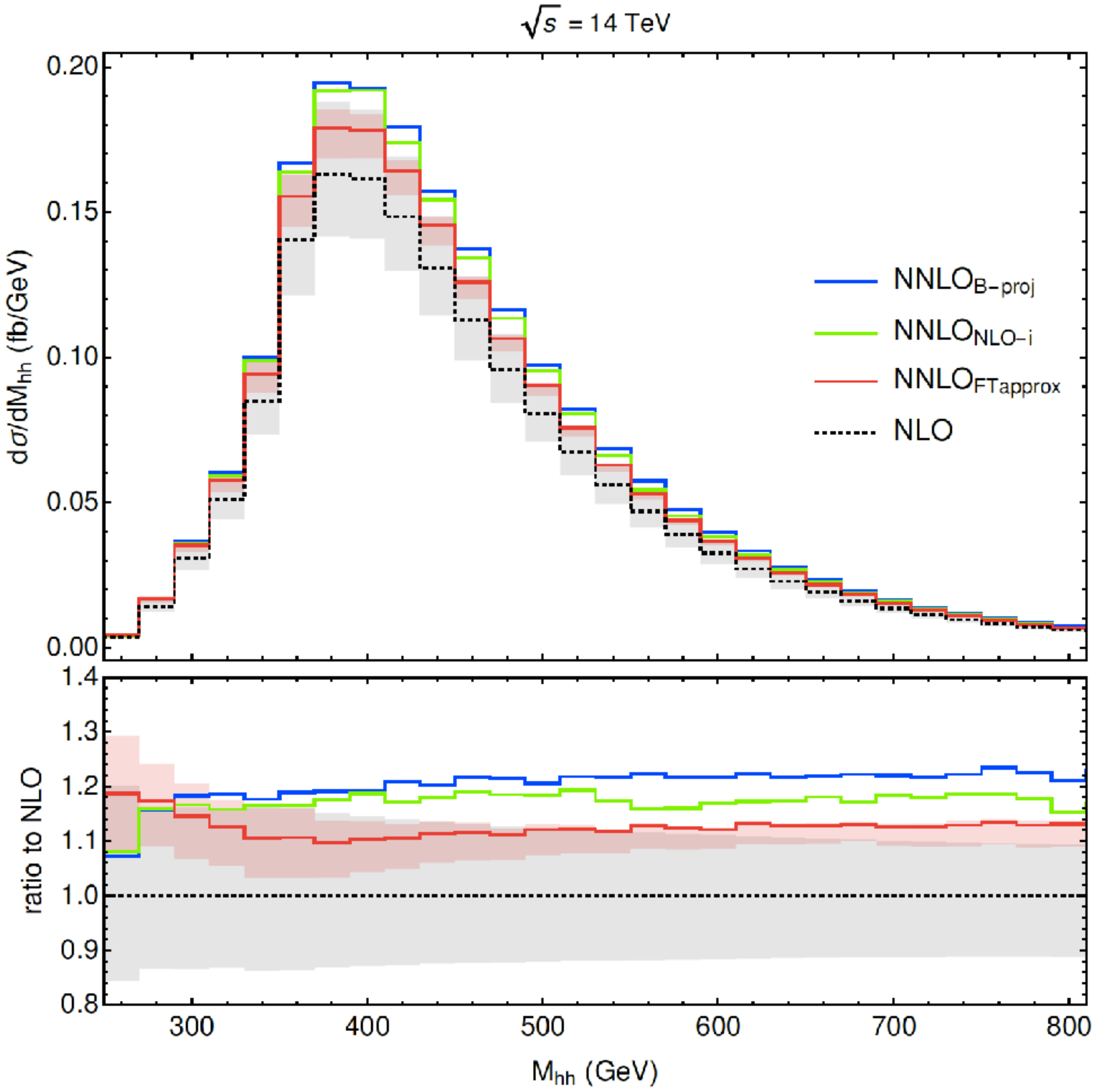
Highest perturbative orders (SM)

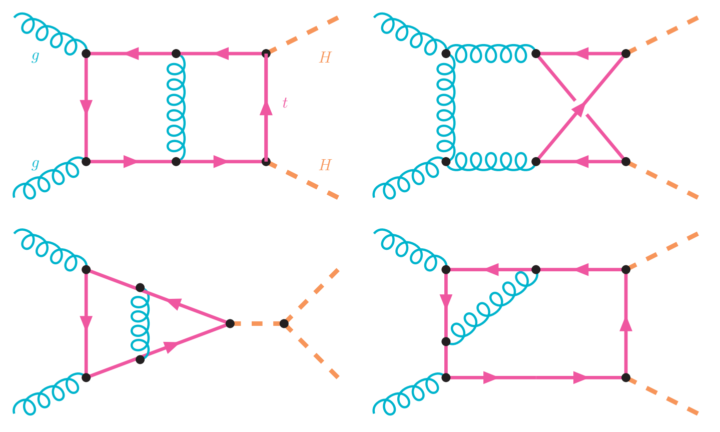
Chen, Li, Shao, Wang 1912.13001





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





Counting schemes

HEFT (EWChL): “loop expansion”

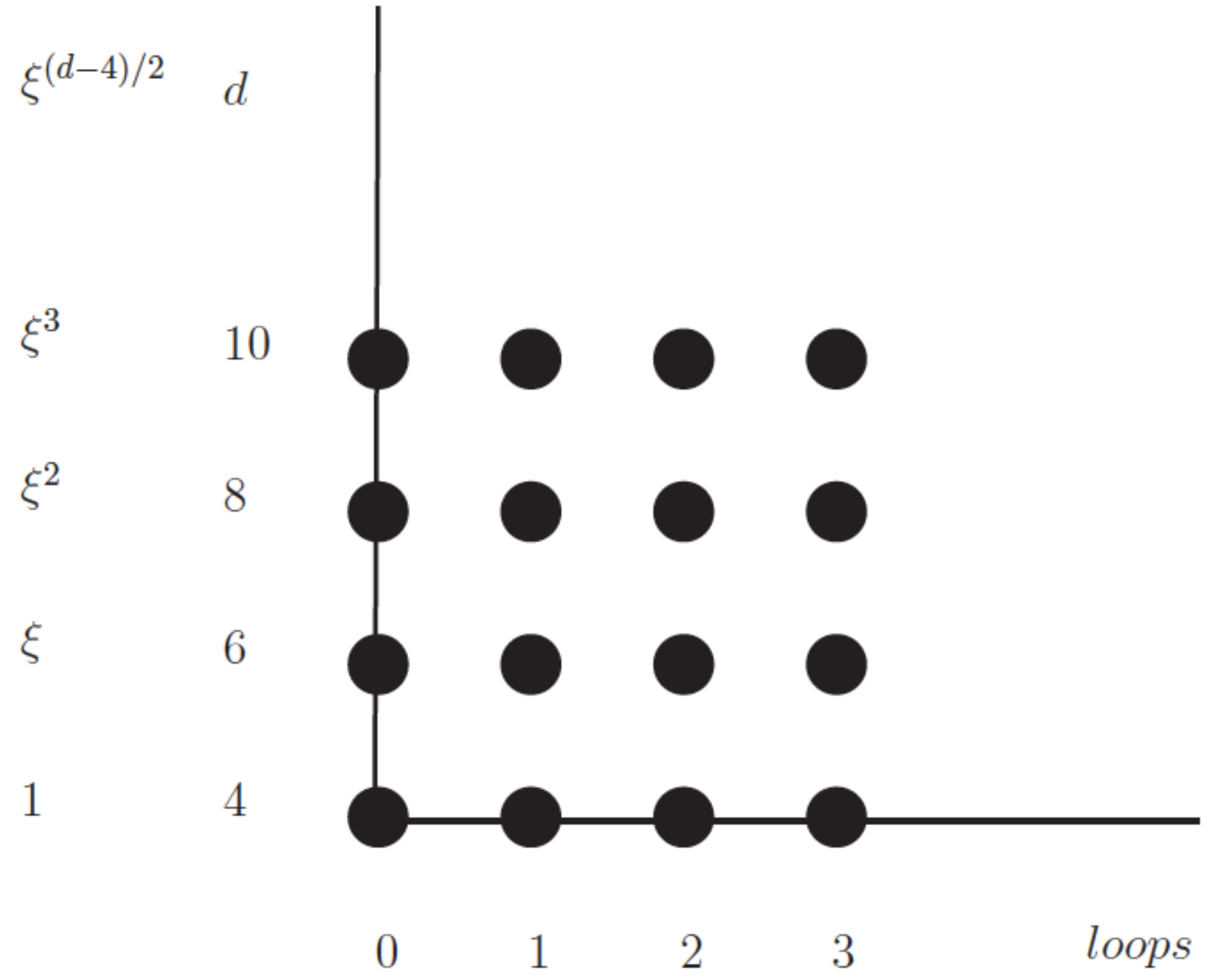
based on chiral dimension $d_\chi = 2L + 2$ L: “Loop”

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

$\xi = v^2/f^2$

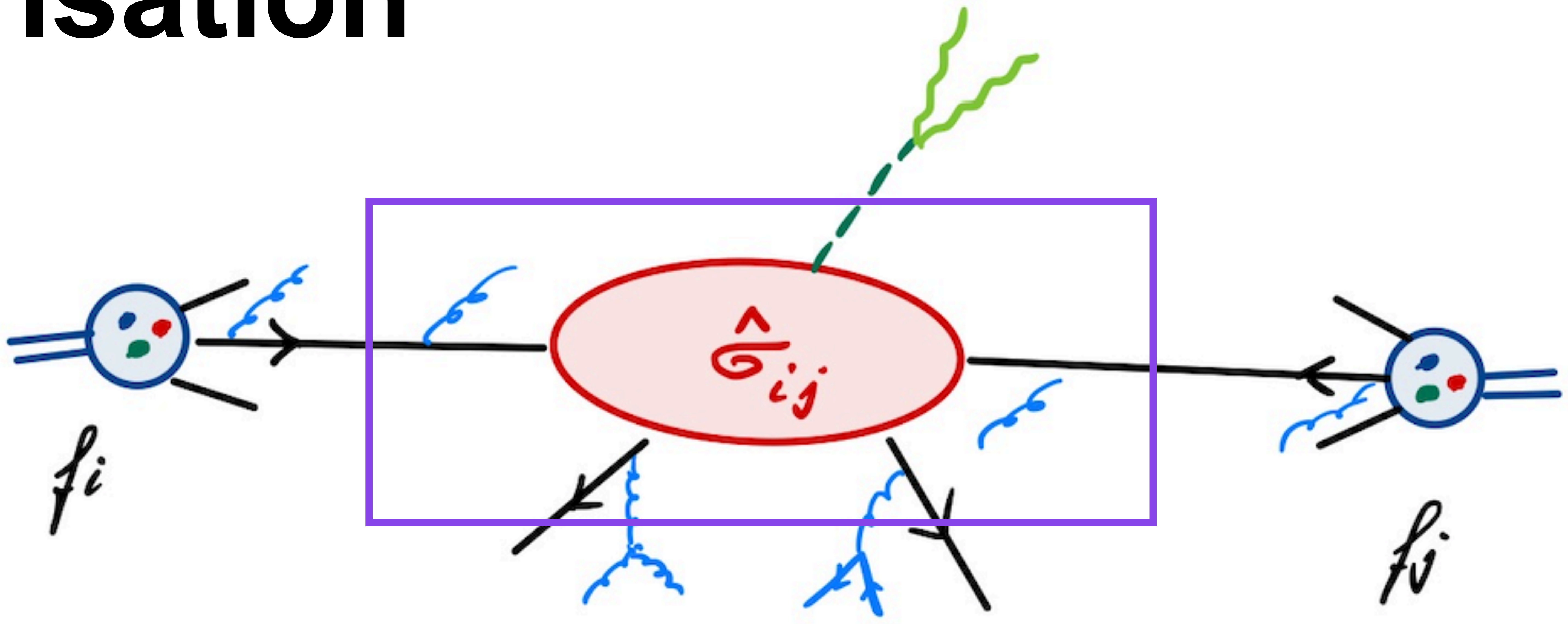


loop expansion

HEFT

figure: G.Buchalla

Factorisation



renormalisation scale

factorisation scale

$$d\sigma_{pp\to H+X} = \sum_{i,j}\int_0^1 dx_1\, f_{i/p_a}(x_1,\alpha_s,\mu_f)\int_0^1 dx_2\, f_{j/p_b}(x_2,\alpha_s,\mu_f)\; d\hat{\sigma}_{ij\to H+X}(x_1,x_2,\alpha_s,\mu_r,\mu_f) + \mathcal{O}\left(\frac{\Lambda}{Q}\right)^p$$

parton distribution functions
(PDFs)

partonic cross section

non-perturbative

perturbative