Karlsruhe Institute of Technology

# Collider Physics at the Precision Frontier

**Gudrun Heinrich** *Institute for Theoretical Physics*


## KSETA plenary workshop

*Durbach, September 27, 2021*

# Motivation

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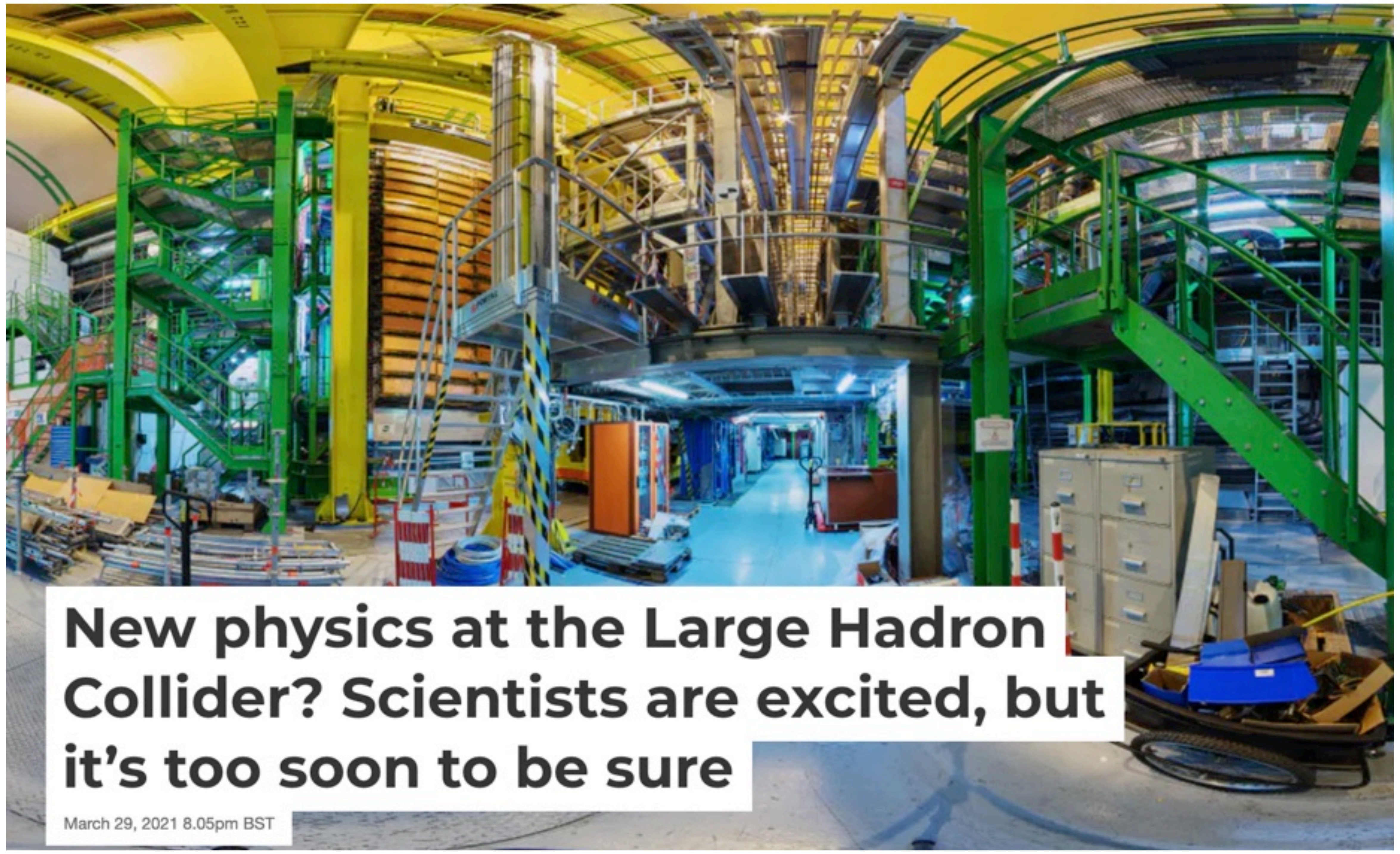
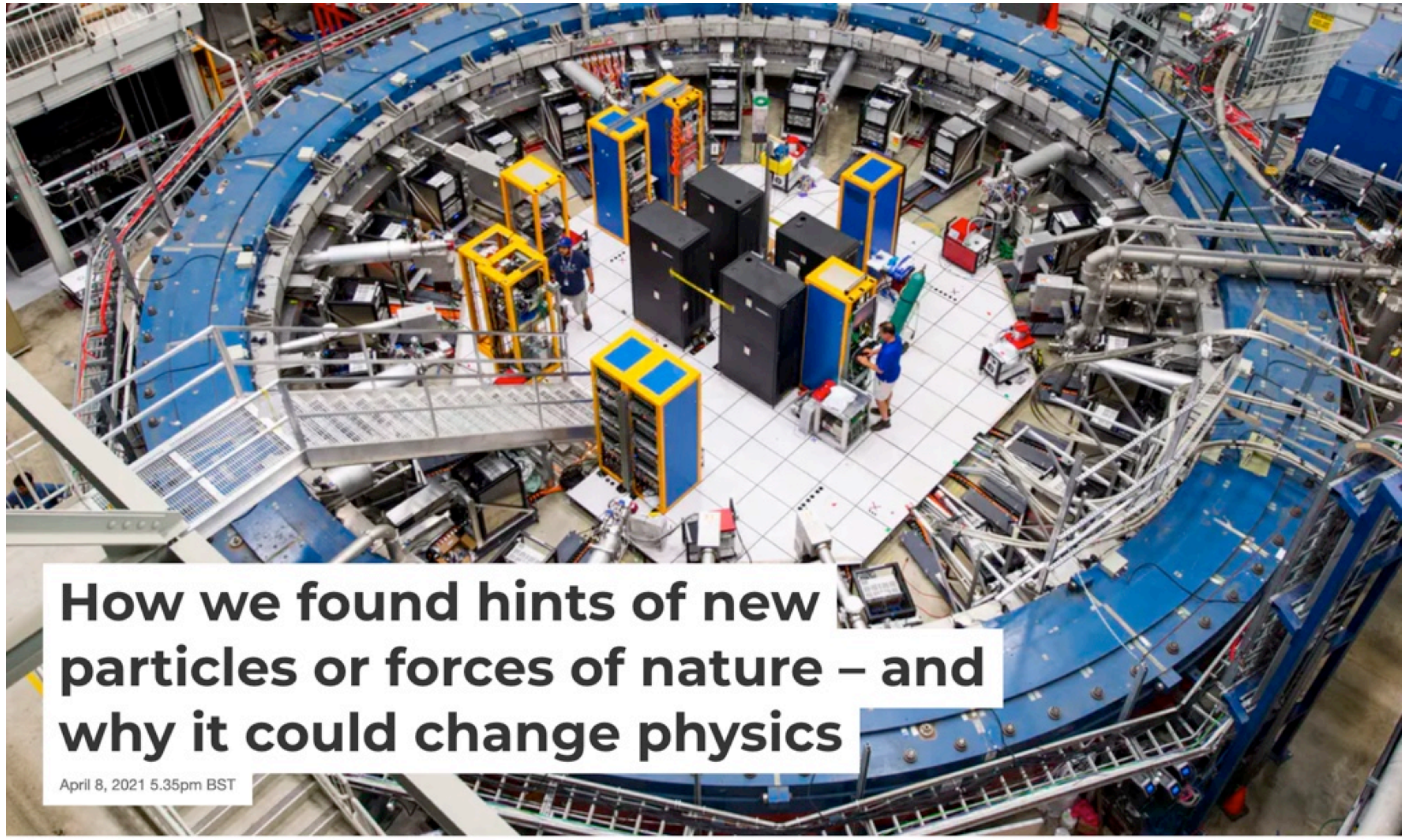
**The Standard Model of Particle Physics is unlikely to be the end of the story**




LHCb (CERN)




The muon experiment. Reidar Hahn/Fermilab

muon anomalous magnetic moment measurement (Fermilab)

theconversation.com

# Motivation

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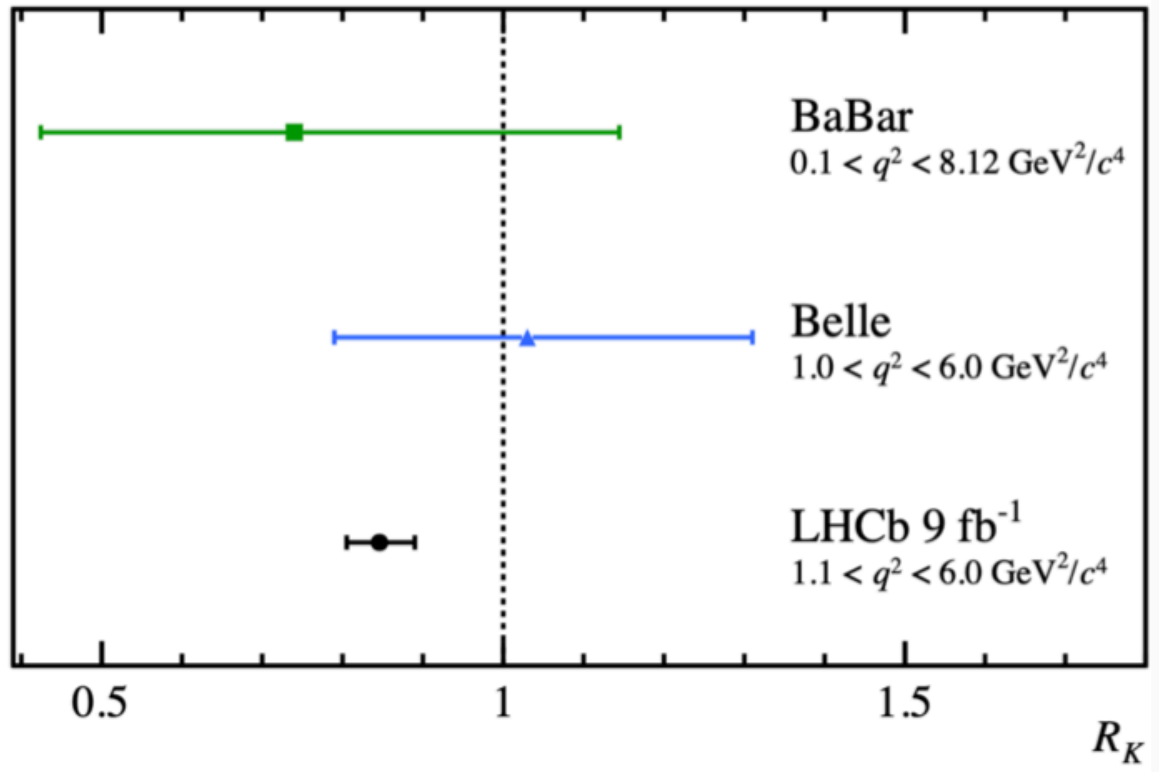
**Exciting new experimental value of $R_K$**

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

LHCb [2103.11769]

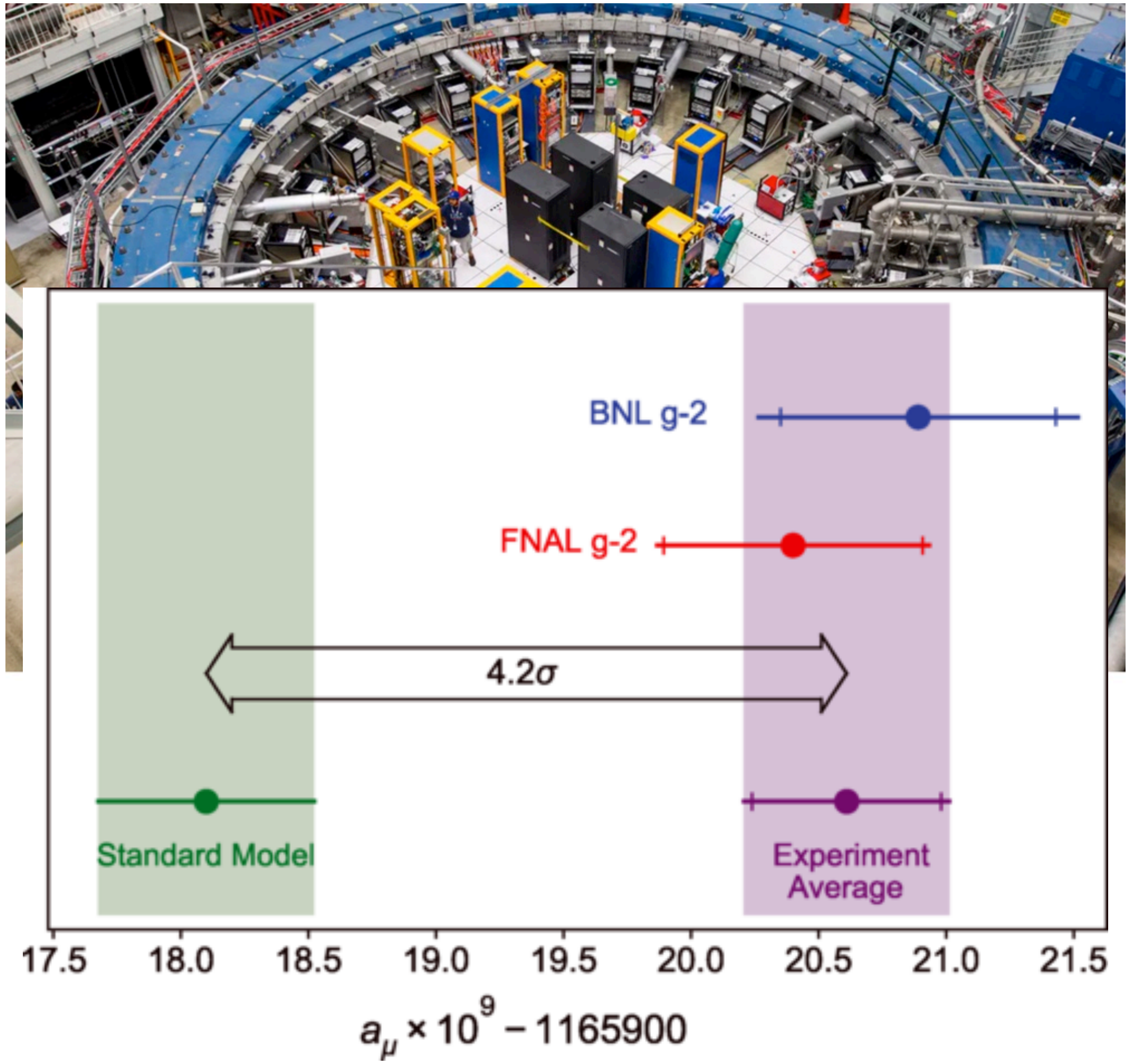



M. Alguero, Moriond 2021

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

+ Likelihood

$\Rightarrow$ $3.1\sigma$ !!

# Current high energy frontier

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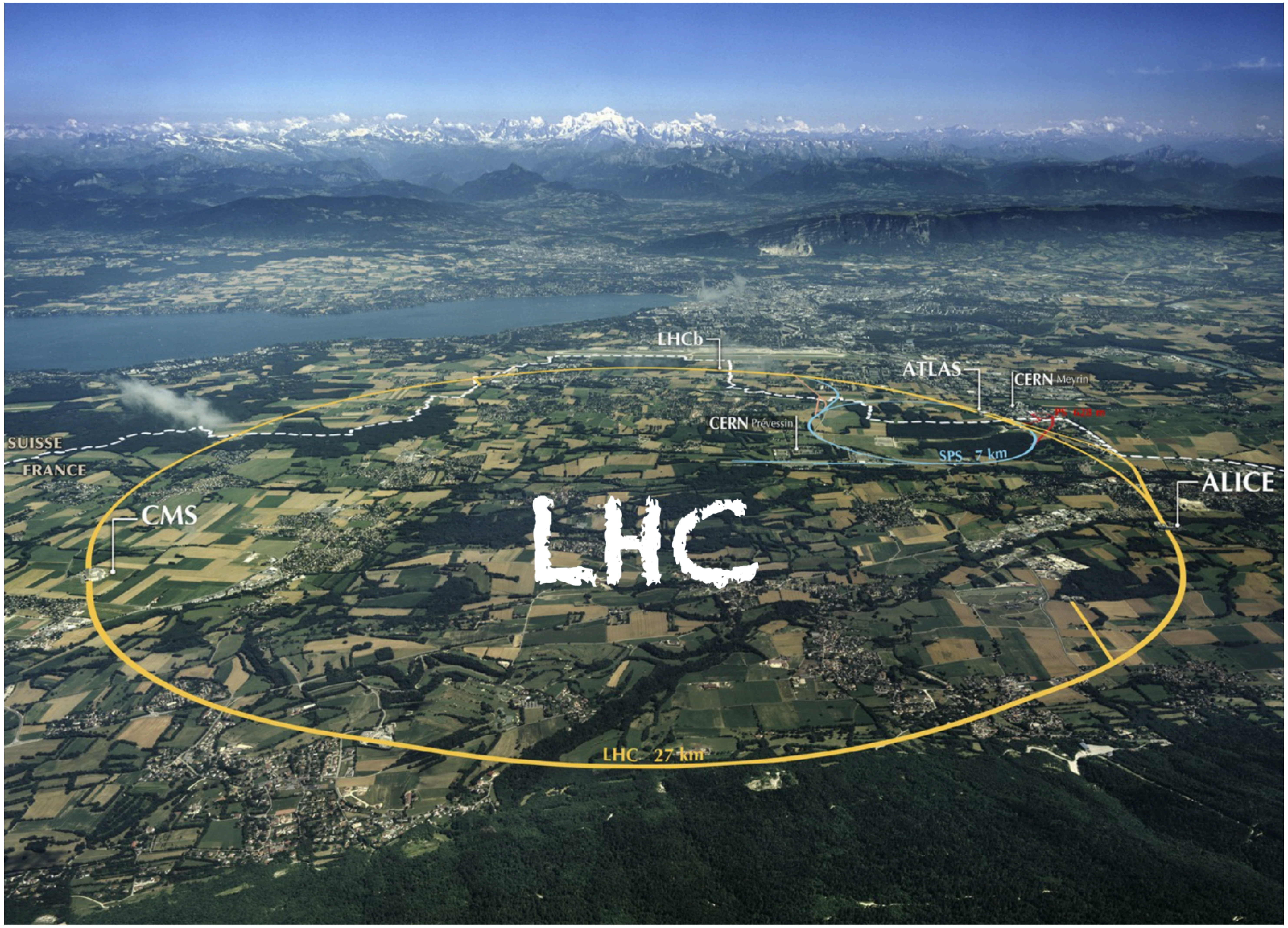
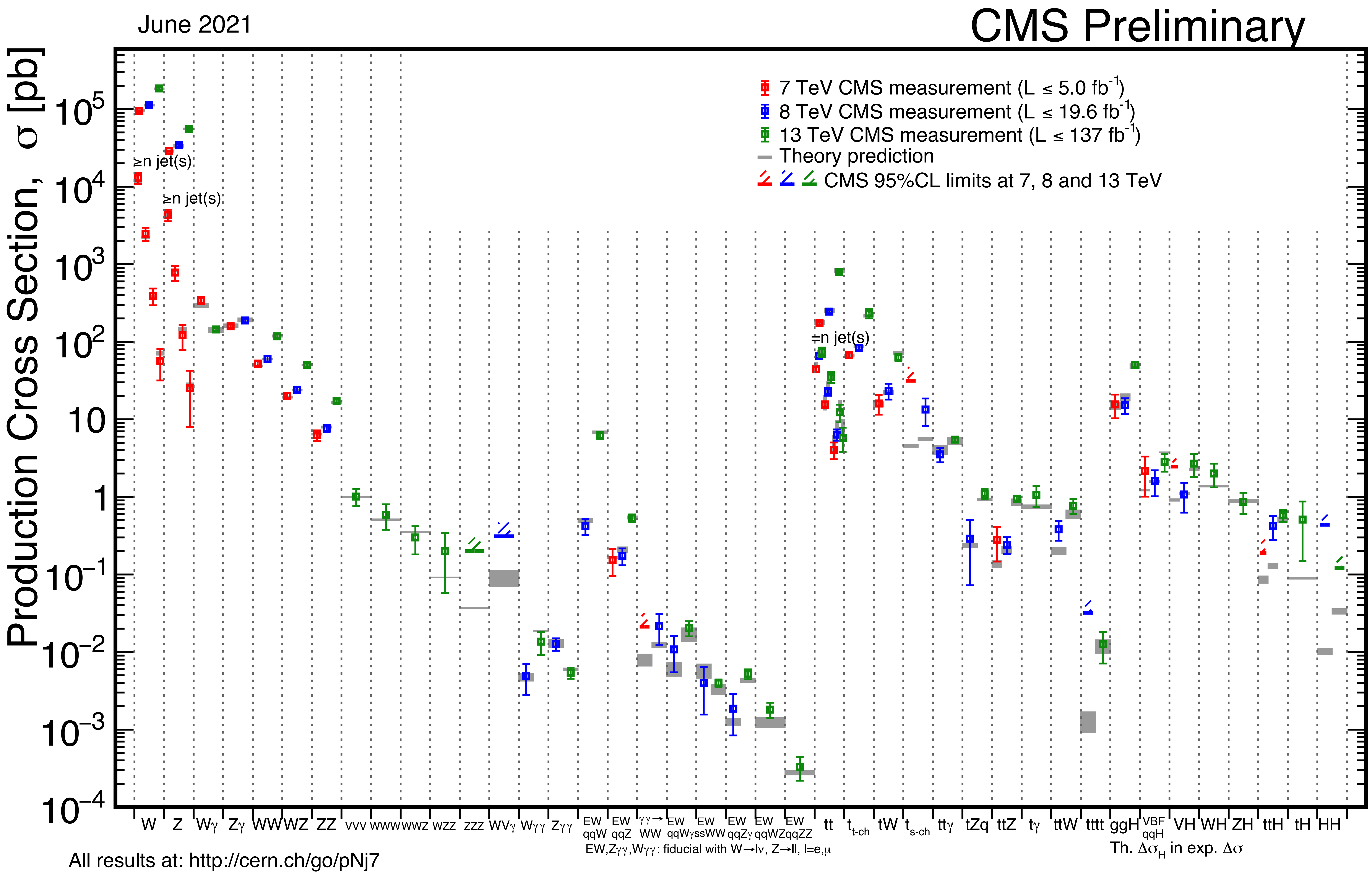
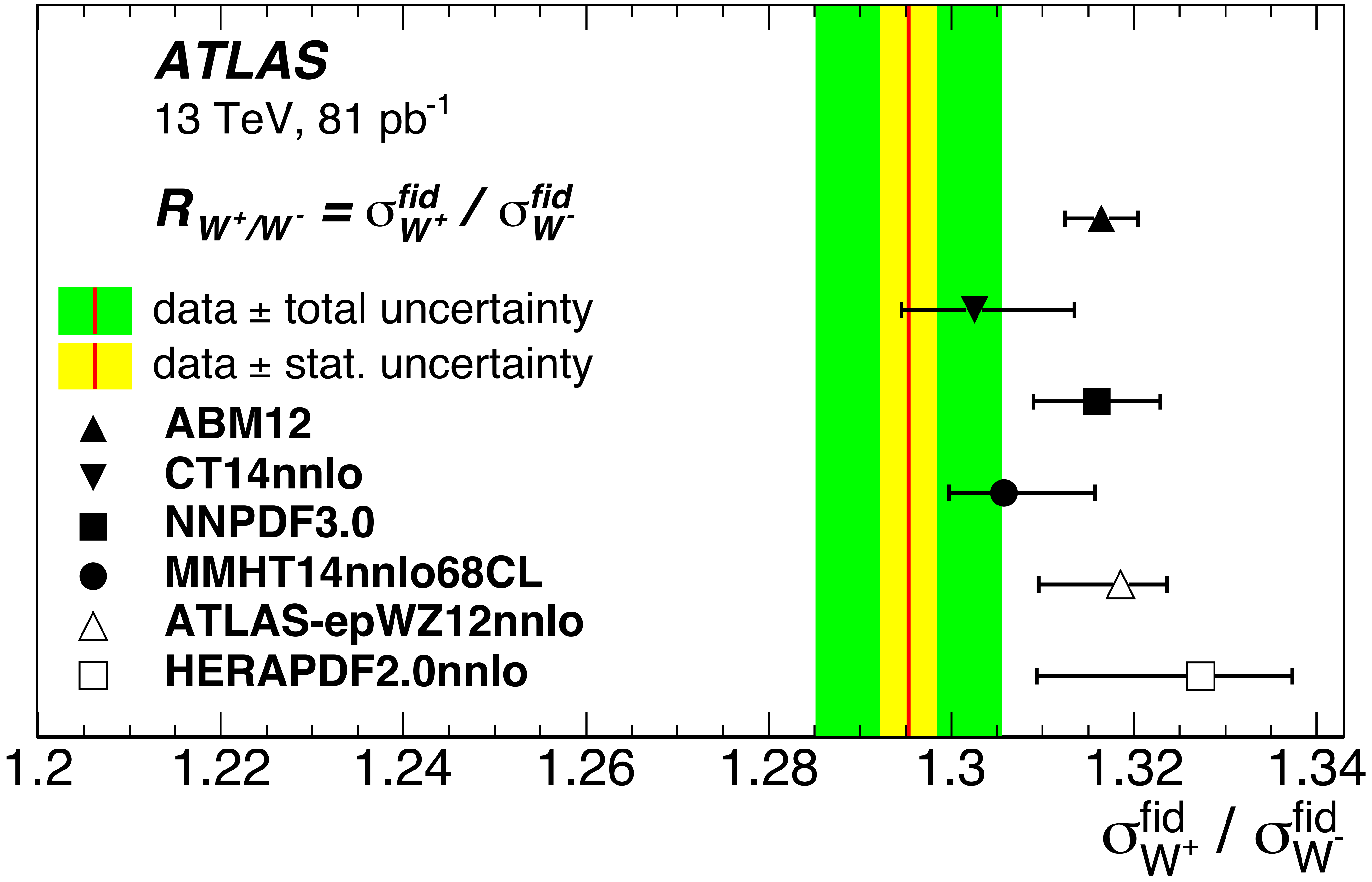


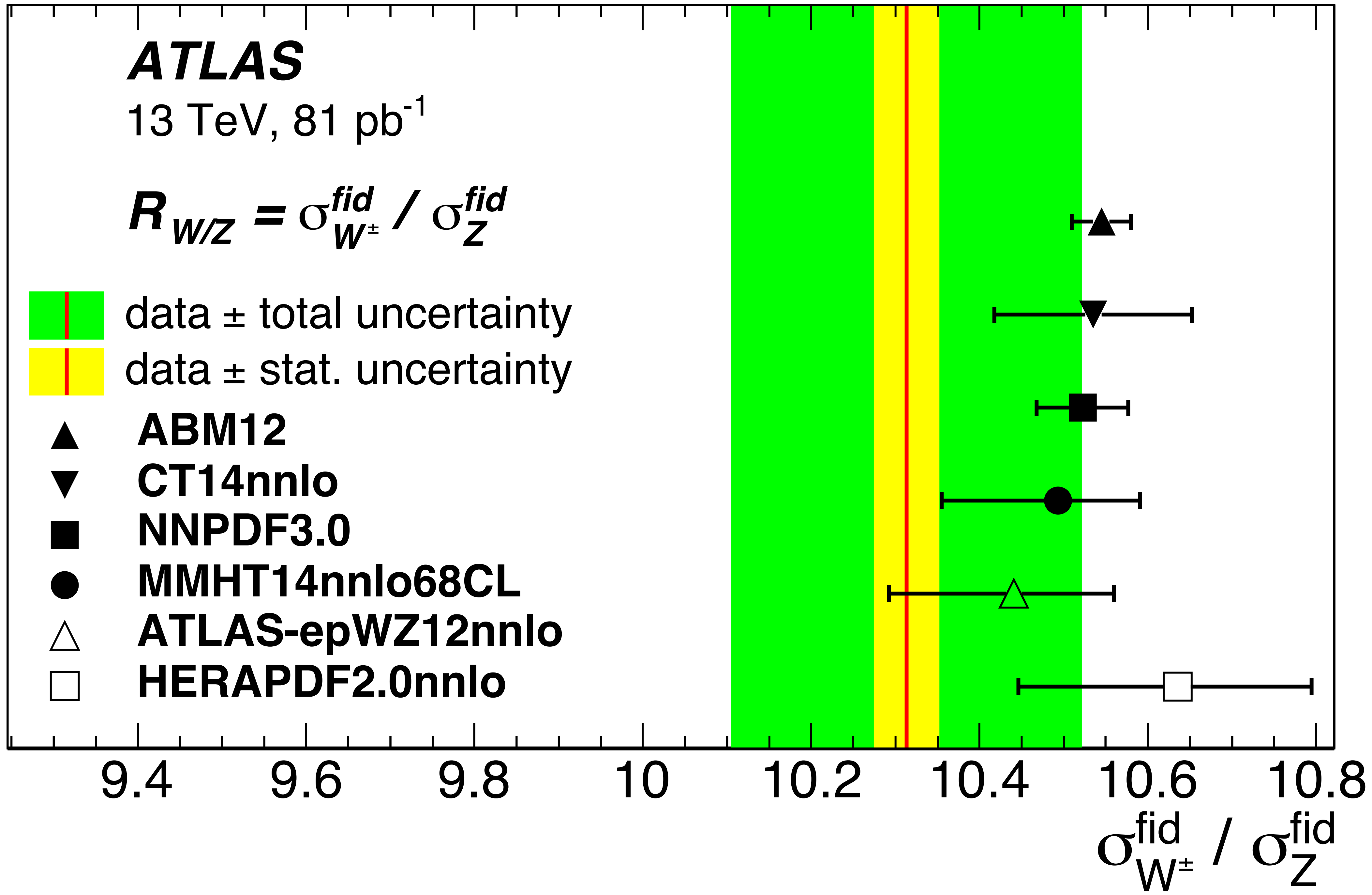
# Current high energy frontier

- at the current energy frontier, no hints of new physics
- however, this is a question of **precision**



# The need for precise predictions

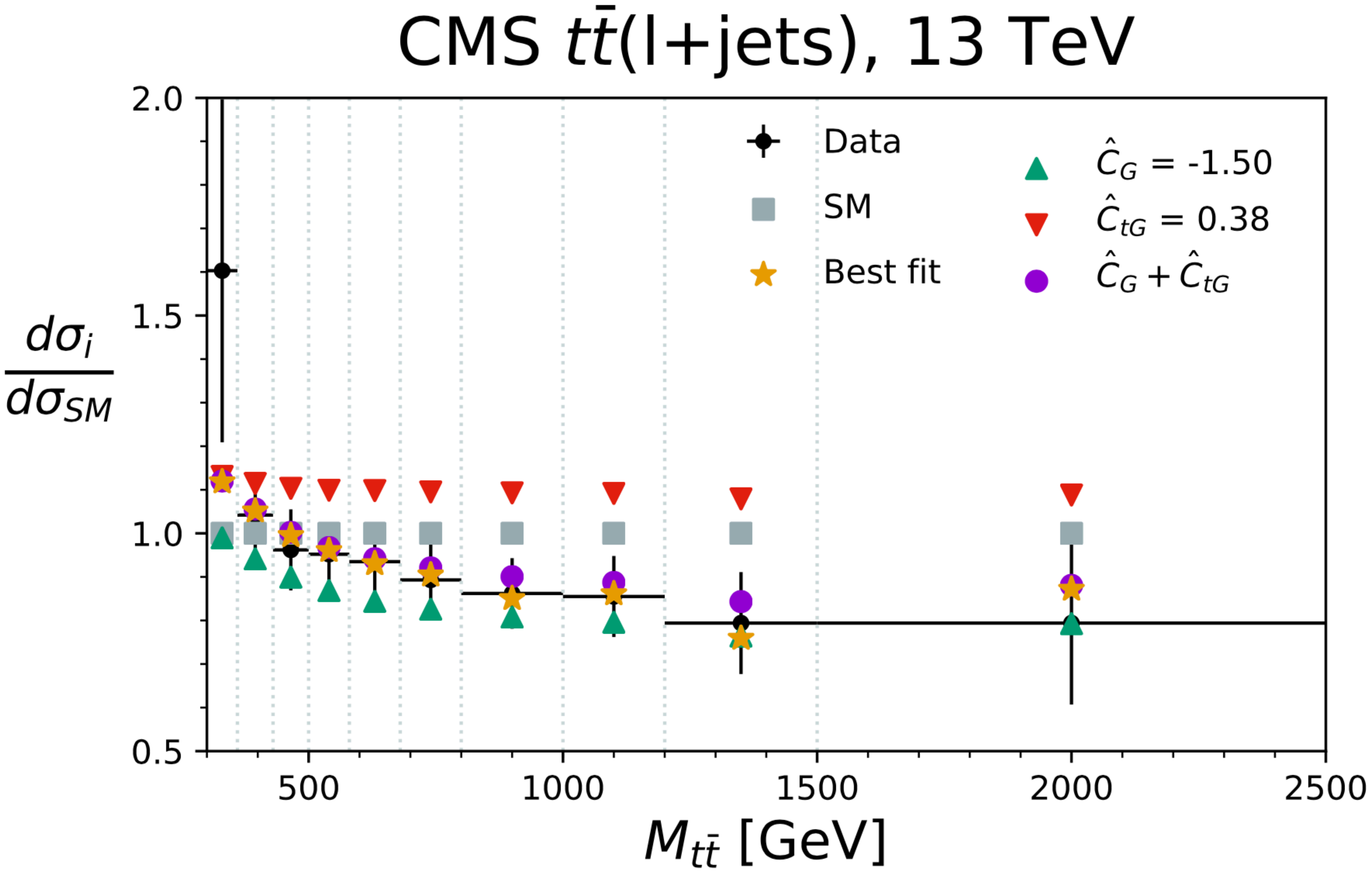



1603.09222

large spread in theory predictions based on different parton distribution functions

# EFT parametrisation of new physics effects



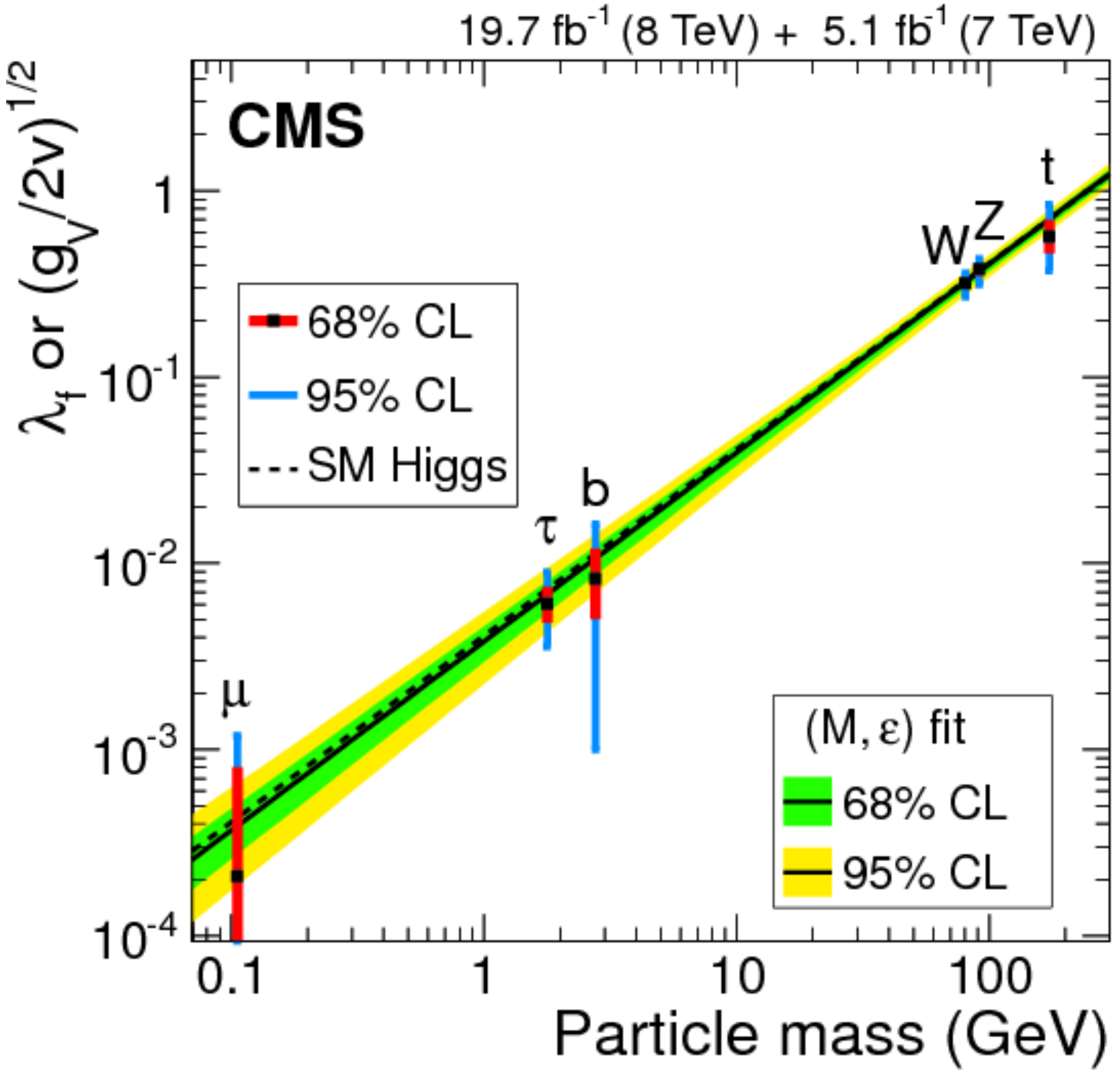

top quark pairs at large invariant mass

best fit includes anomalous couplings

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

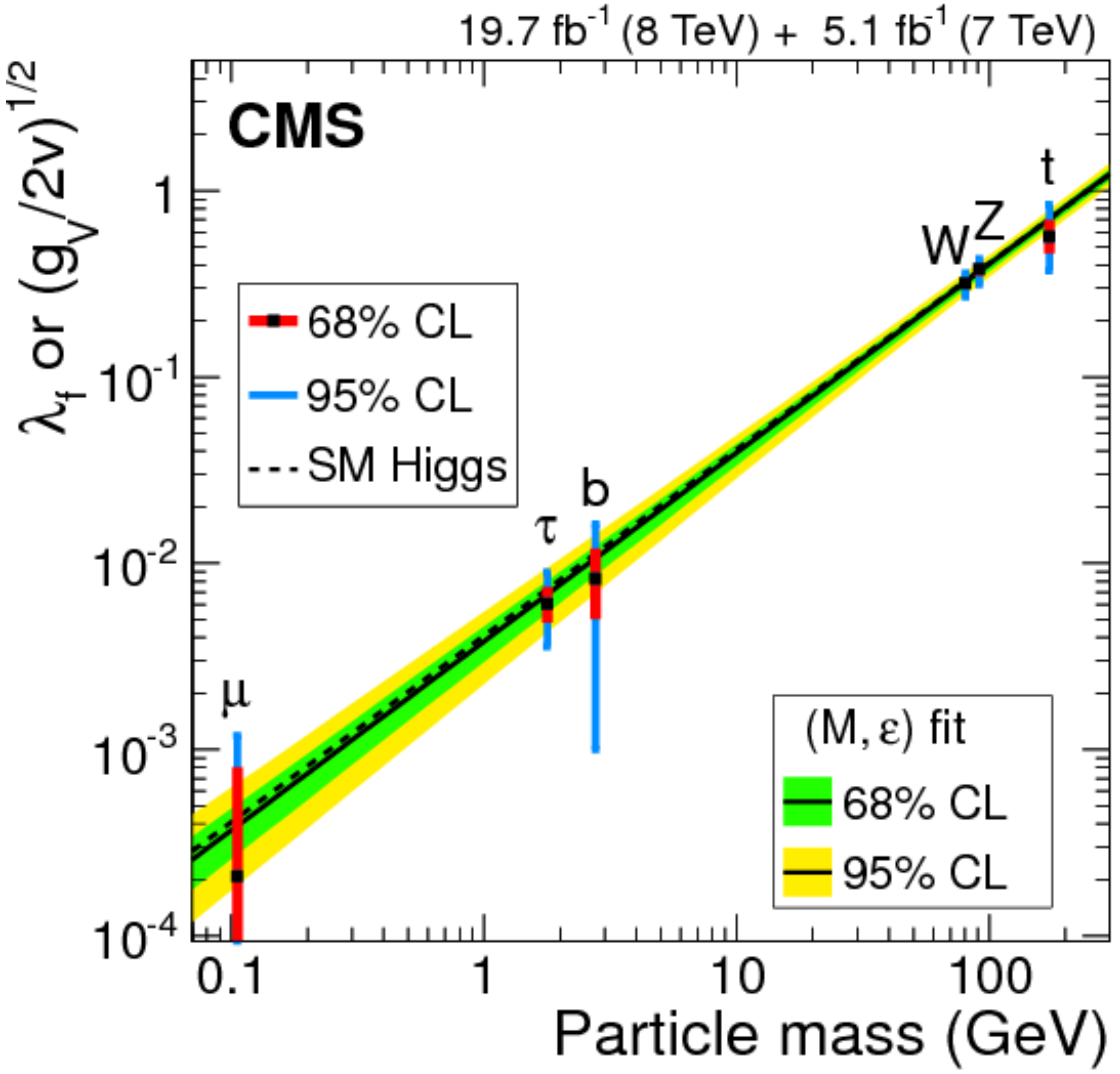
# Higgs couplings

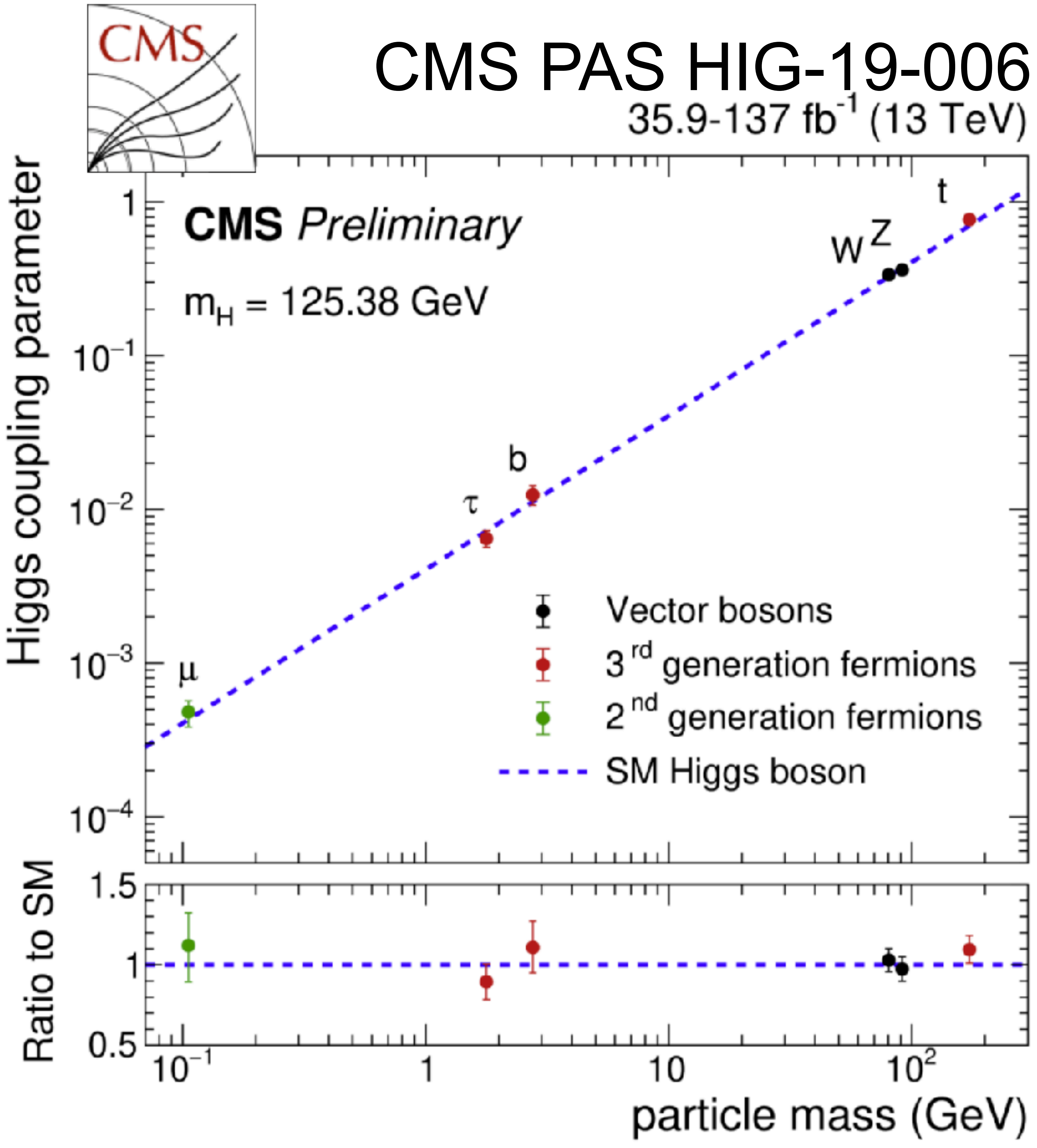
Run I



# Higgs couplings

Run I




H?

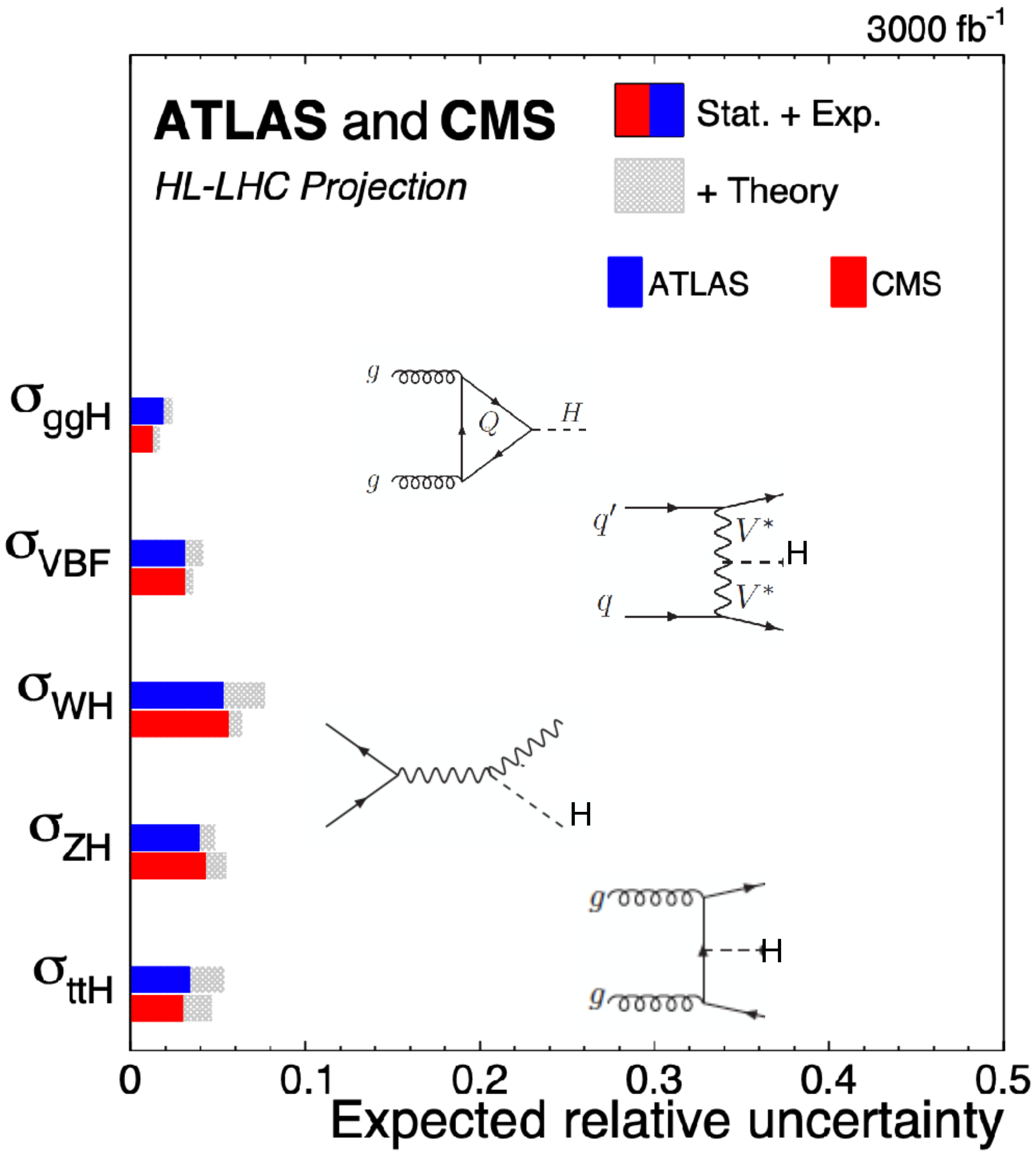
**enormous experimental progress**

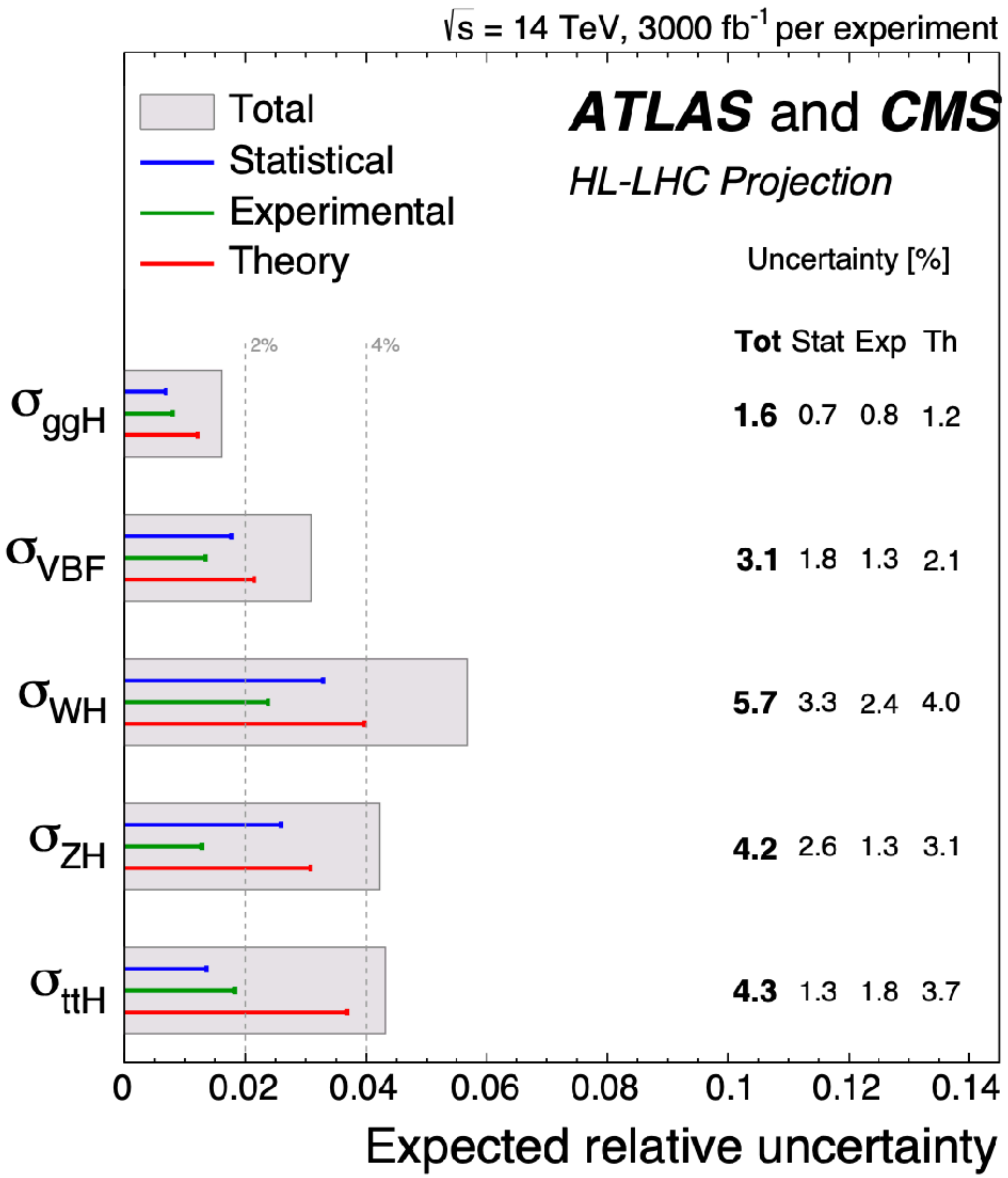
# High-Luminosity LHC


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

# Low-luminosity LHC

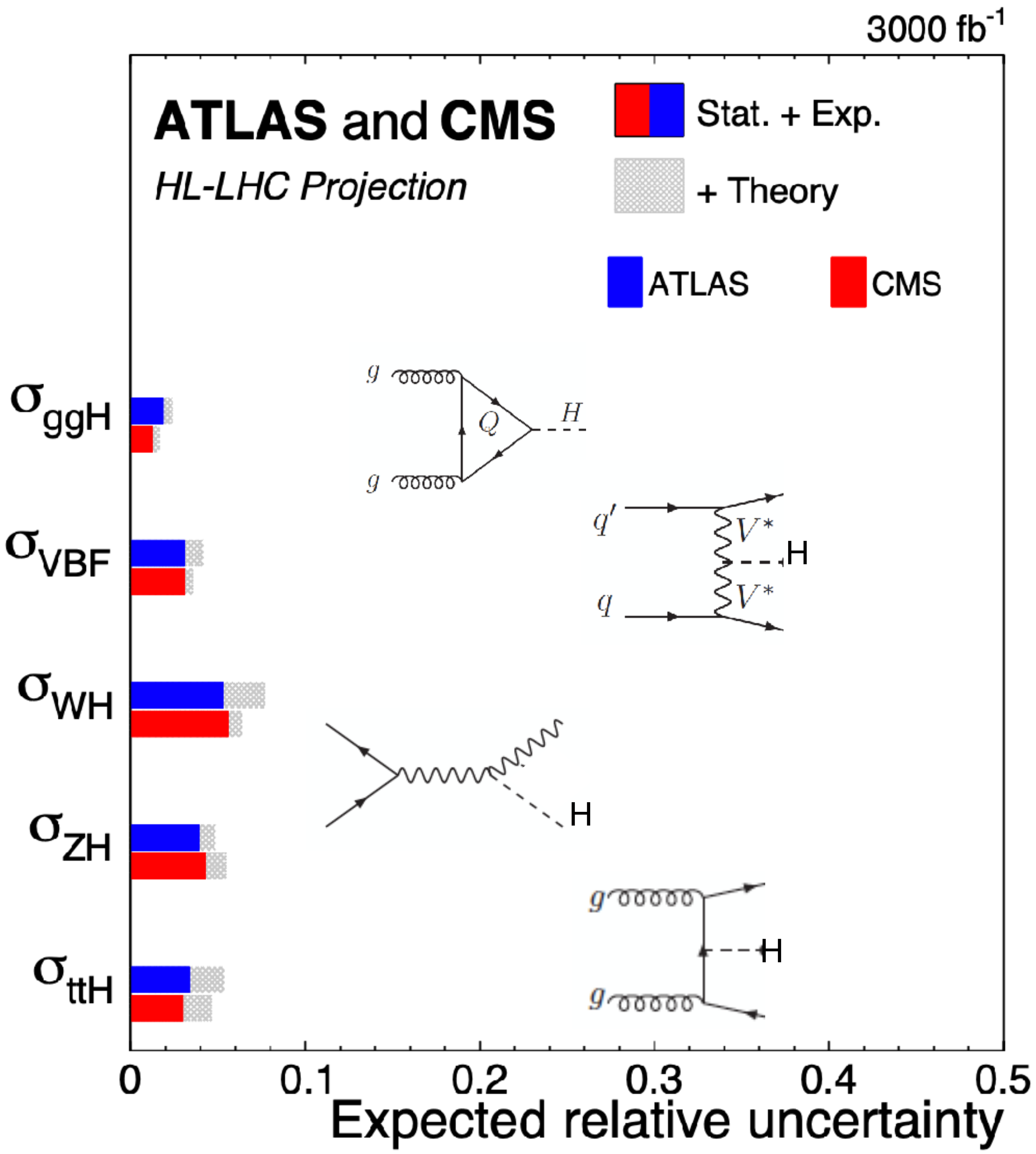
# Higgs production at HL-LHC: expected precision

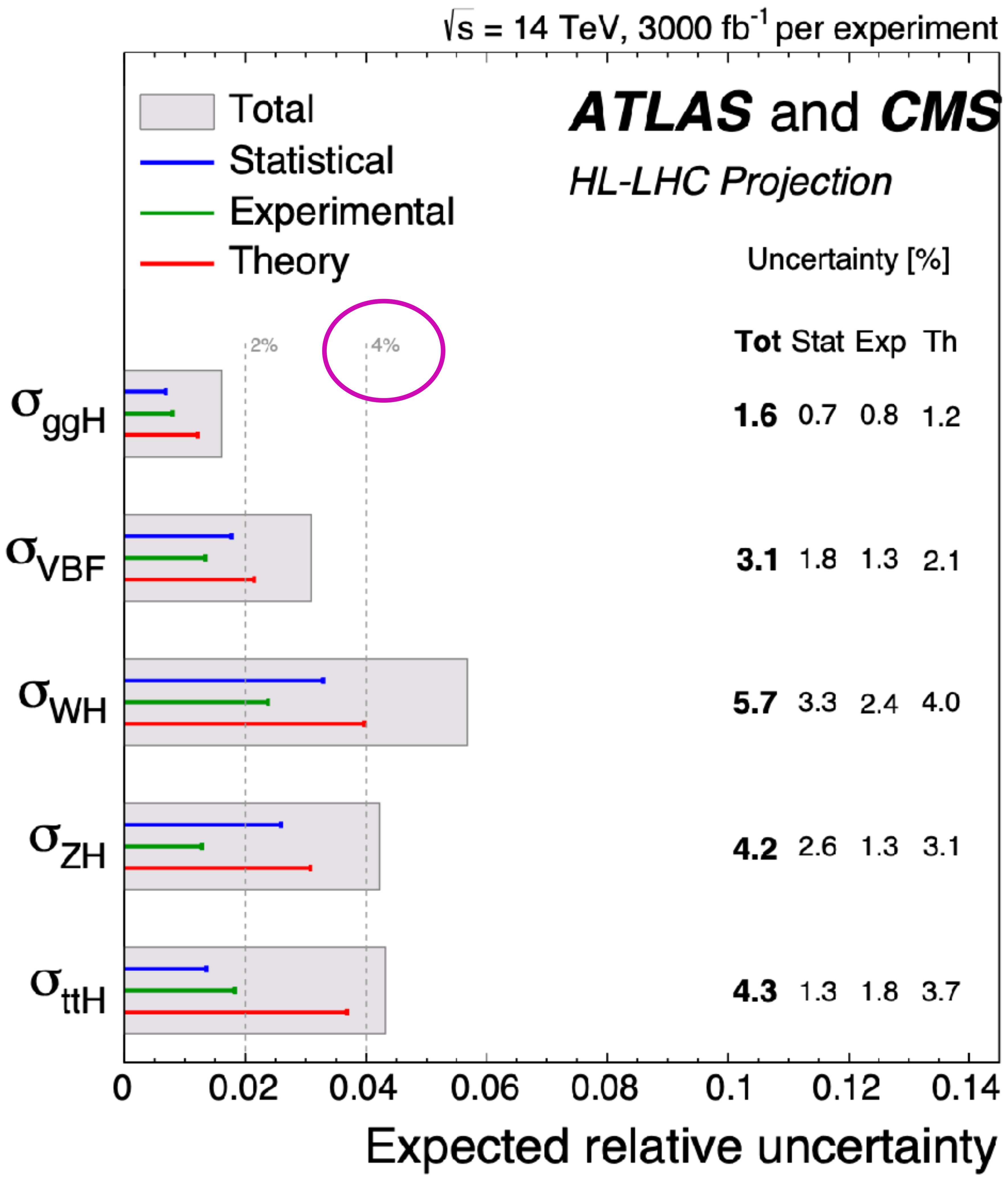



HL-HE CERN Yellow Report,
1902.00134

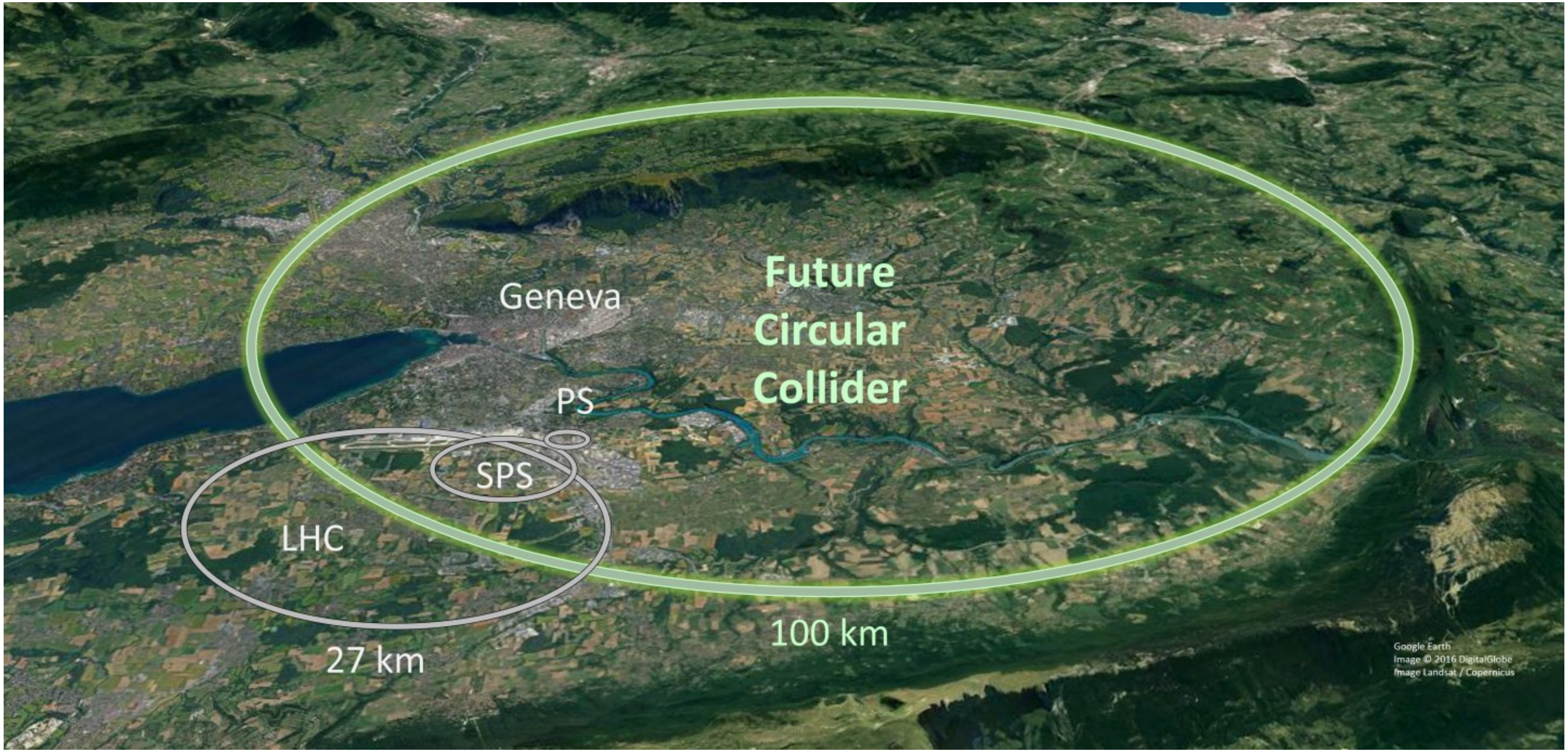
# Higgs production at HL-LHC: expected precision




HL-HE CERN Yellow Report, 1902.00134

# Science (no) fiction?



# Future collider plans

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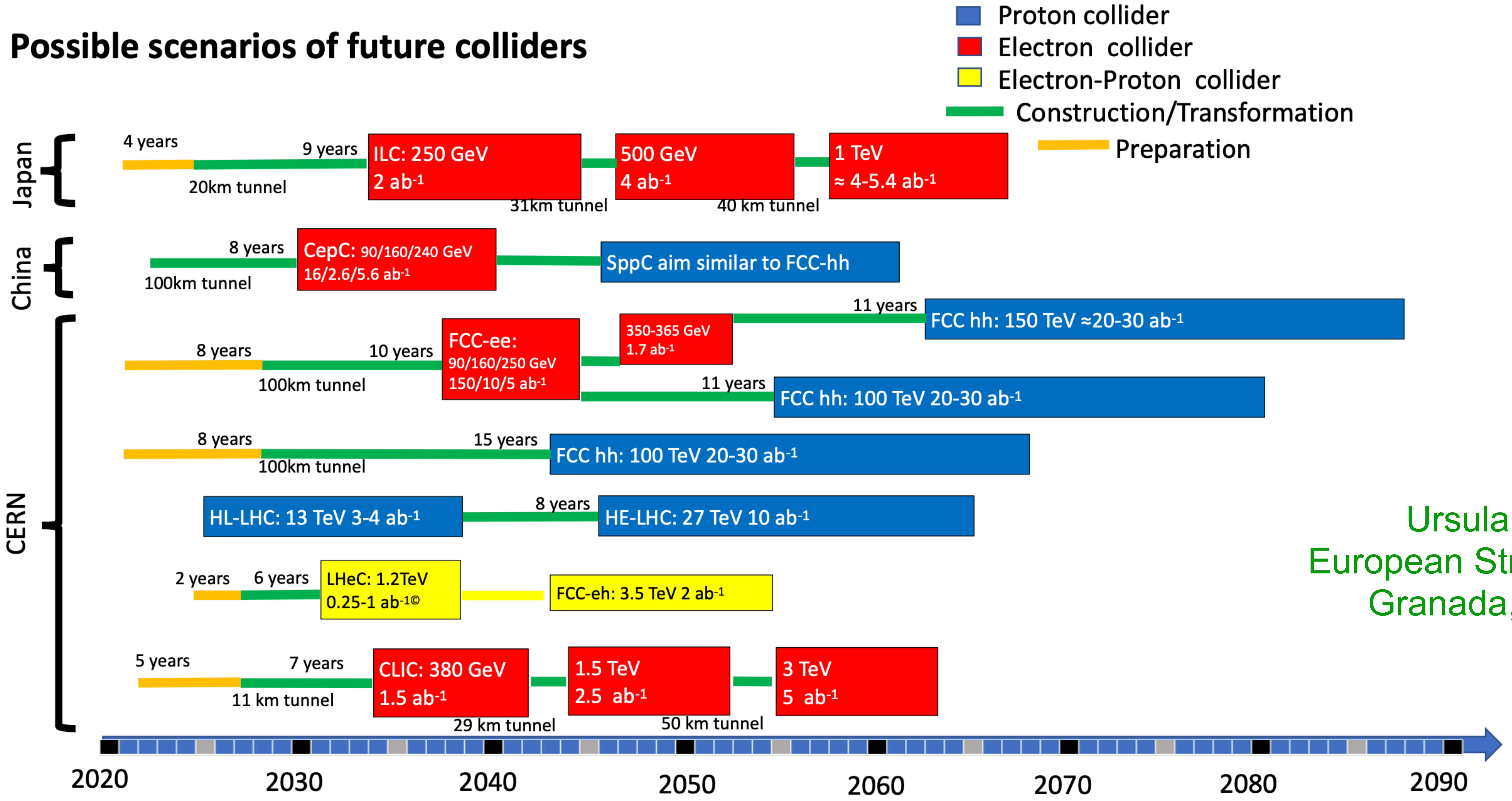
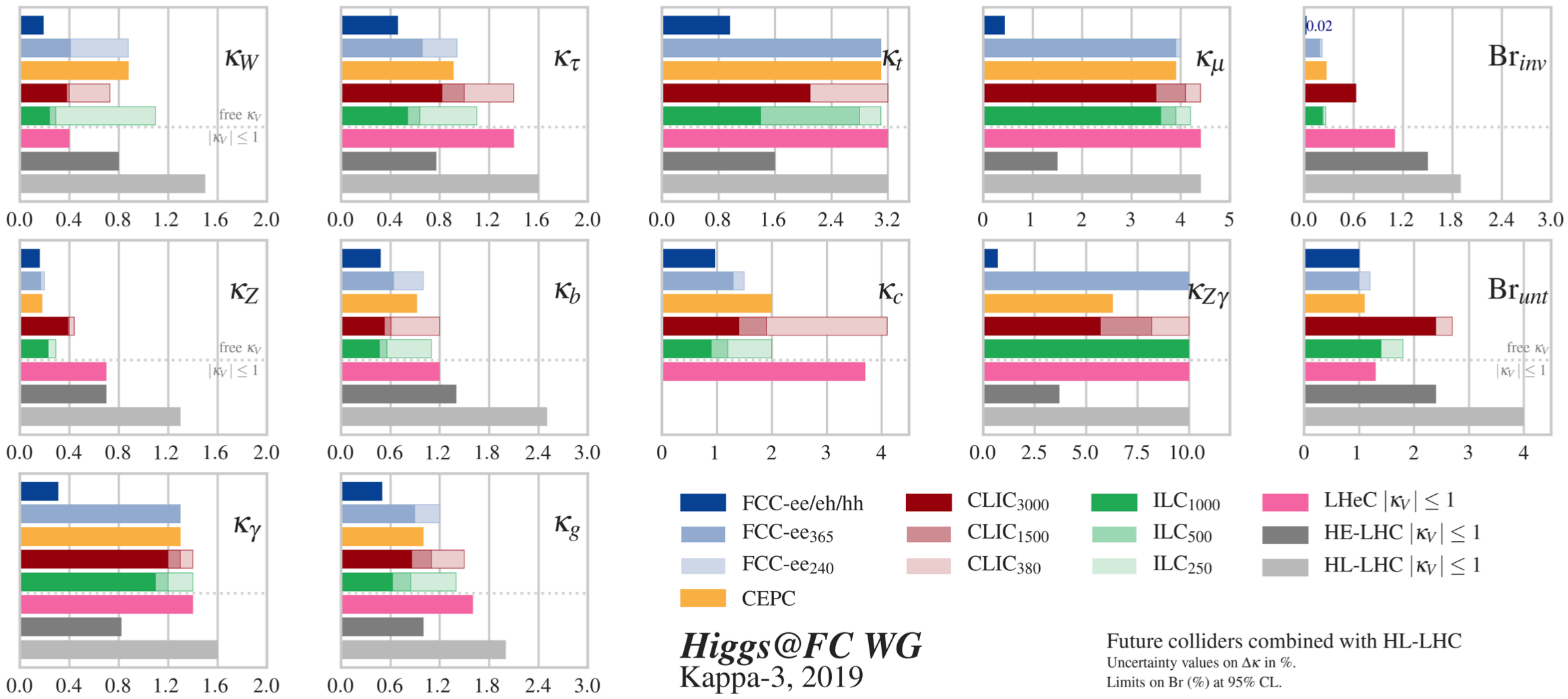


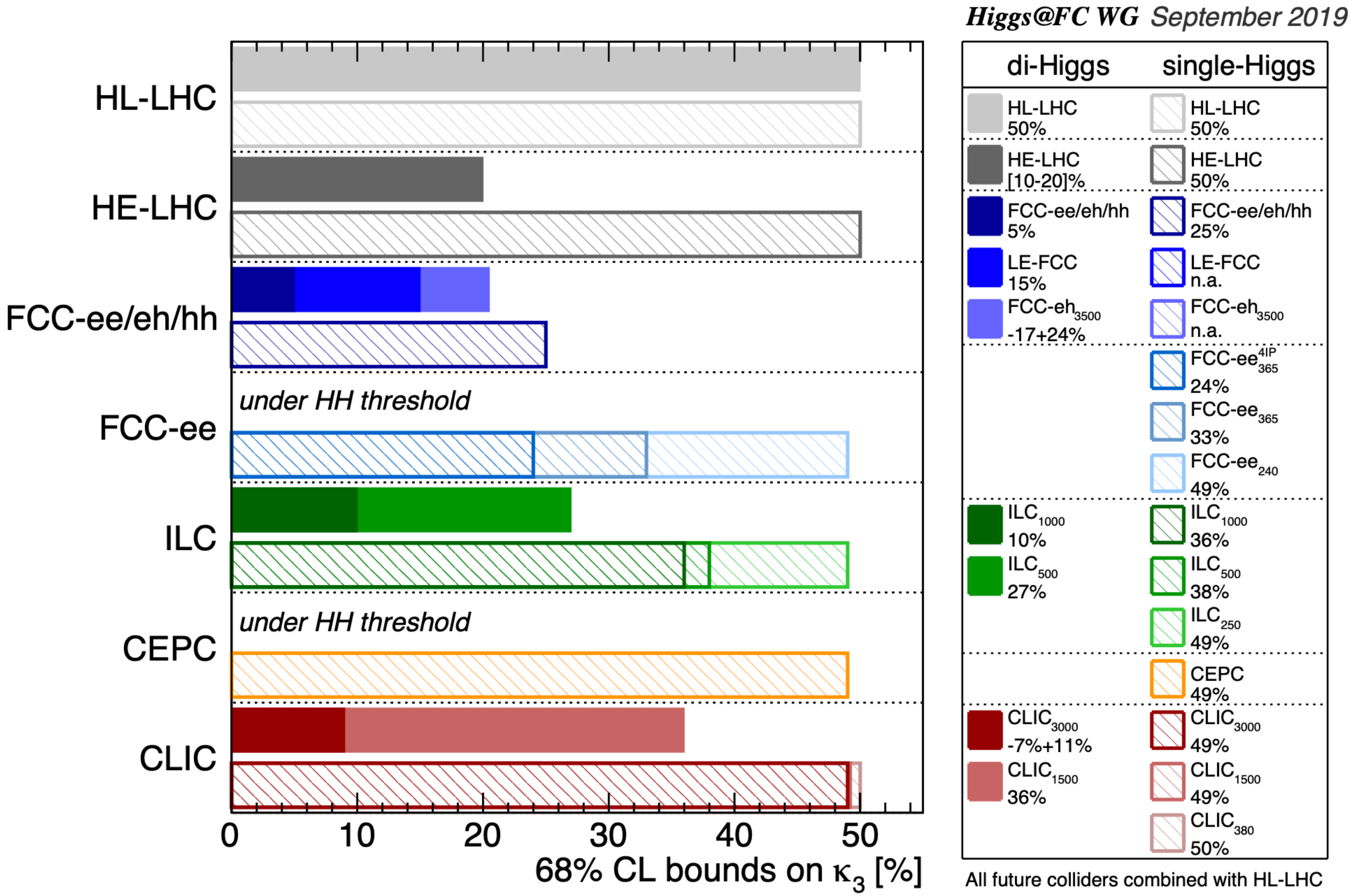

Ursula Bassler,
European Strategy Meeting
Granada, May 2019

# Higgs couplings at future colliders




European Strategy Physics Briefing Book 1910.11775

# Higgs-boson self coupling




European Strategy Physics Briefing Book 1910.11775

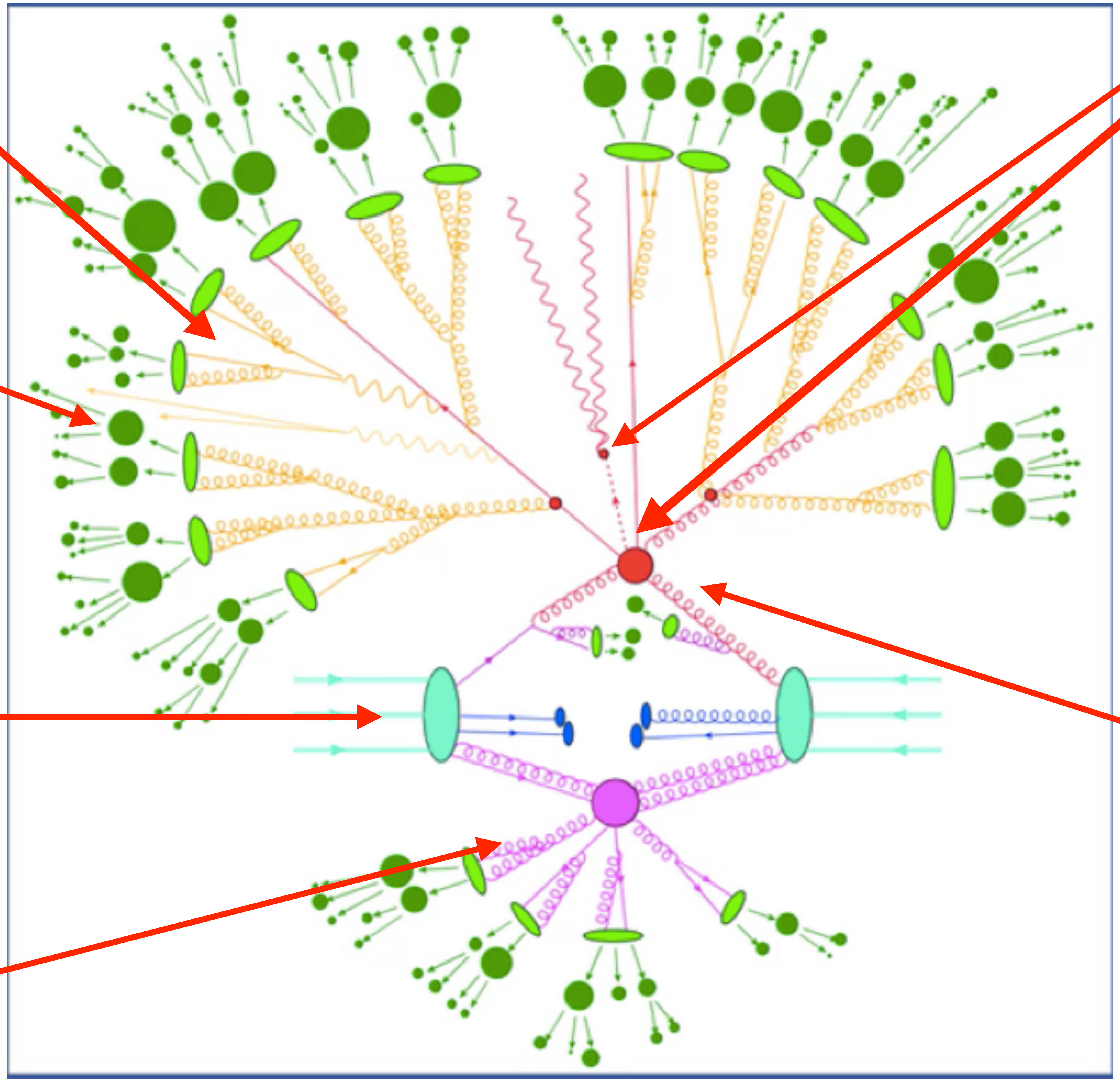
# How to increase the precision of the predictions?

parton shower

hadronisation

parton distribution functions (PDFs)

underlying event



artwork by G.Luisoni

fixed order calculations (production and decay)

reduce scale uncertainties

$\mu_r, \mu_f$ -dependence

reduce parametric uncertainties (couplings, masses)

resummation

reduce uncertainties in particular kinematic regions

# Perturbation theory

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leading order — next-to-leading order — next-to-next-to-leading order

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

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

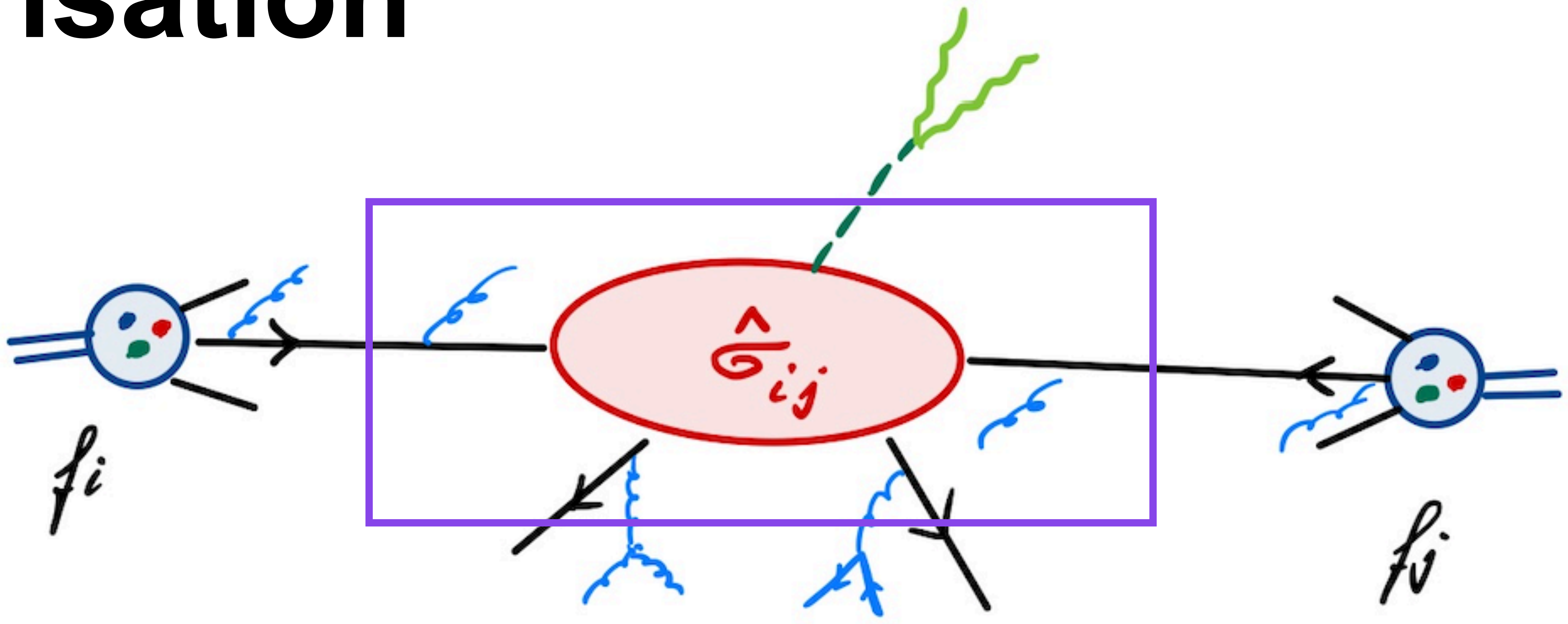
electroweak corrections: $\alpha/\alpha_s \approx 0.1 \Rightarrow$ smaller, but beware of large terms like $\log\left(\frac{M_Z^2}{\hat{s}}\right)$

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

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

renormalisation scale ($\mu_r$) — factorisation scale ($\mu_f$)

# 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

# Higher orders in perturbation theory

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

LO

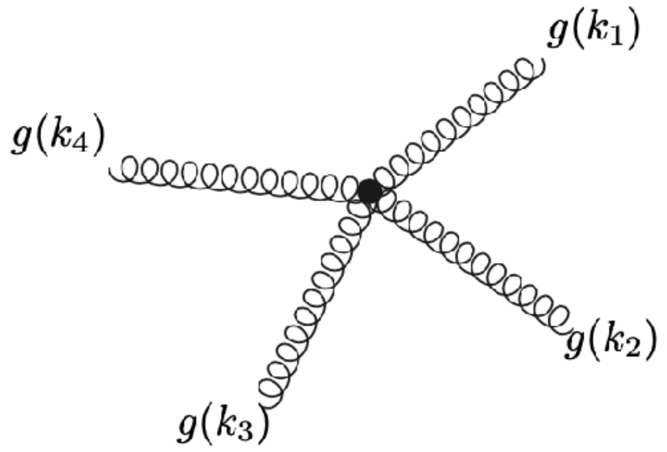



*Diagram 1*

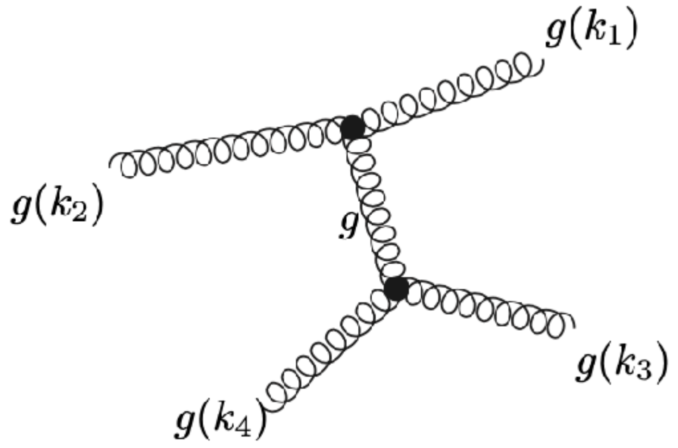
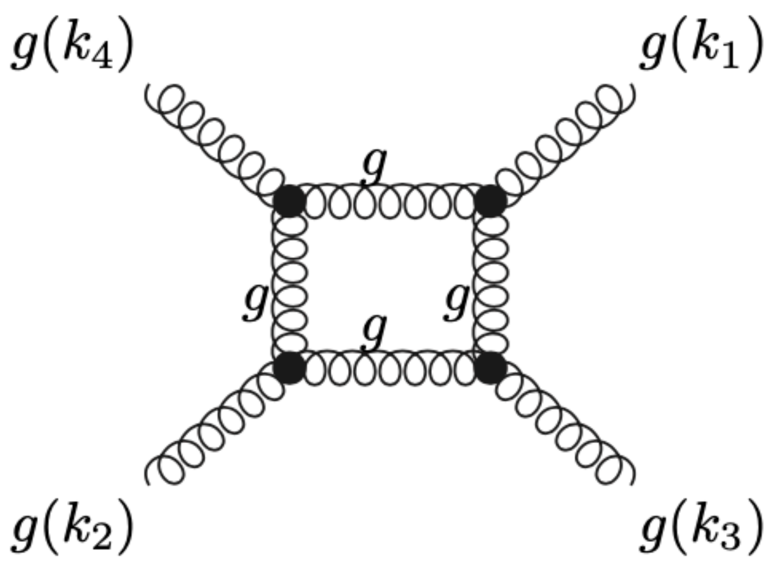
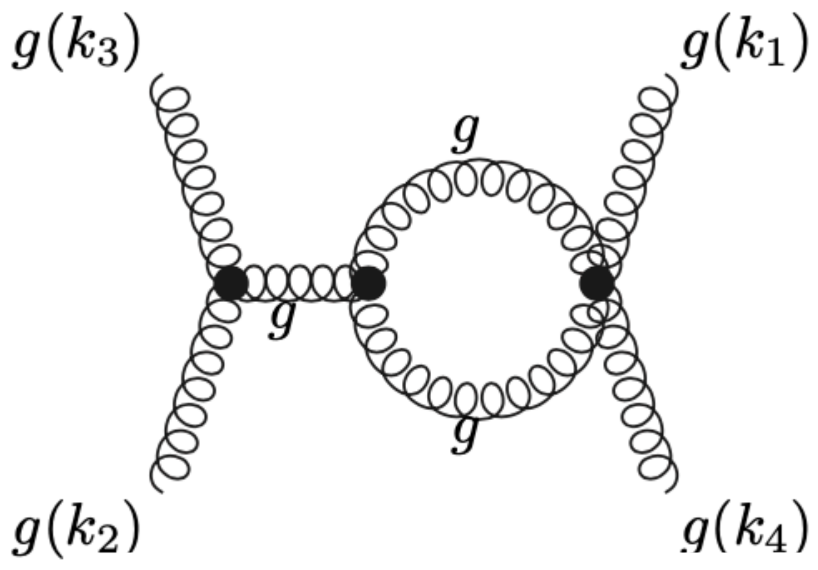


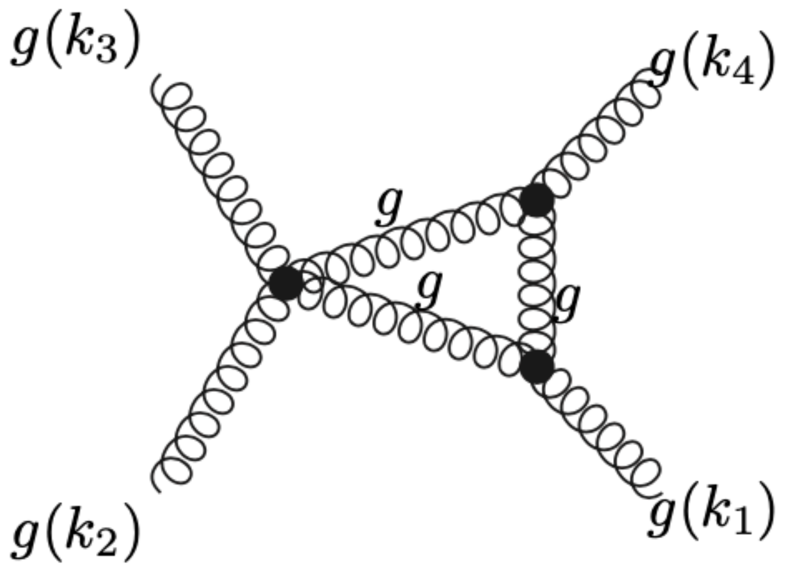

*Diagram 2*

+ permutations (4 diagrams)

NLO virtual

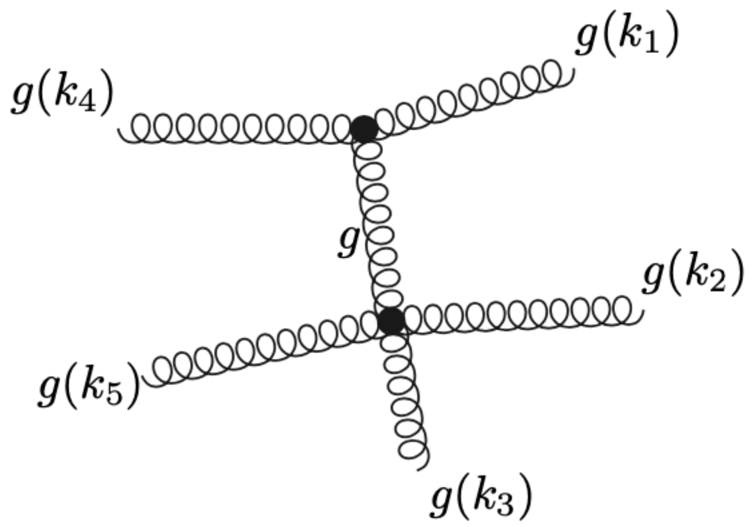


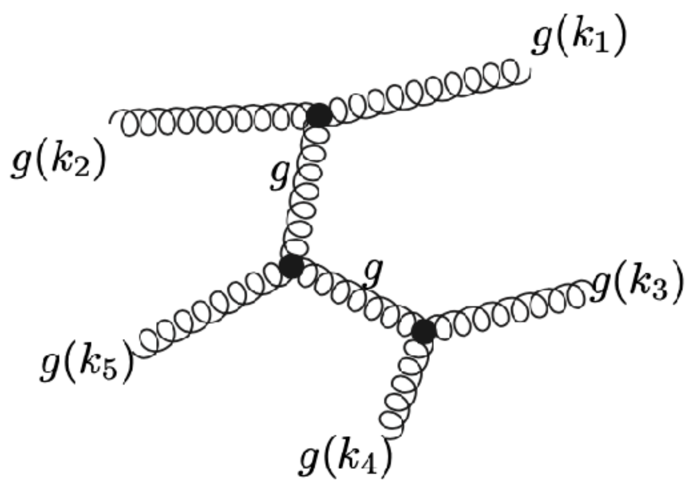




+ … (60 loop diagrams)

NLO real




+ … (25 diagrams)

# Higher orders in perturbation theory

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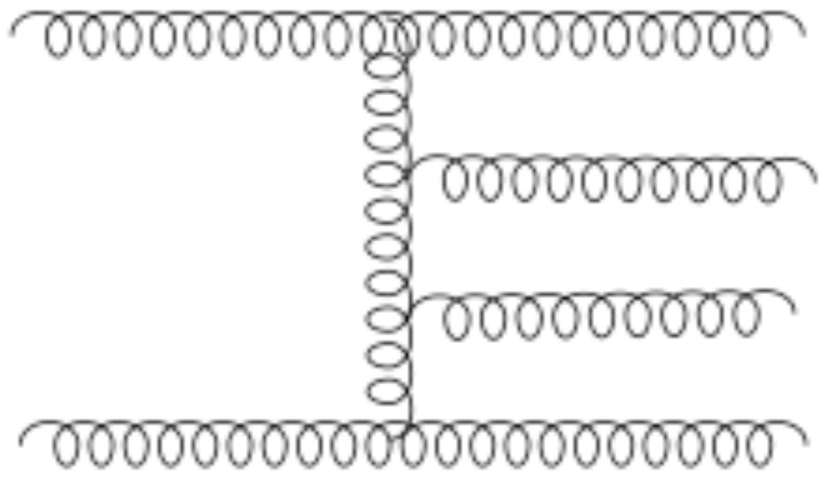
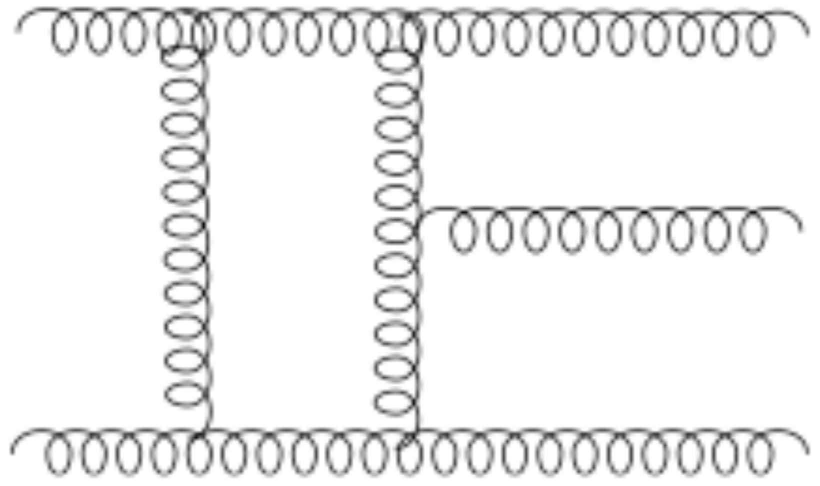
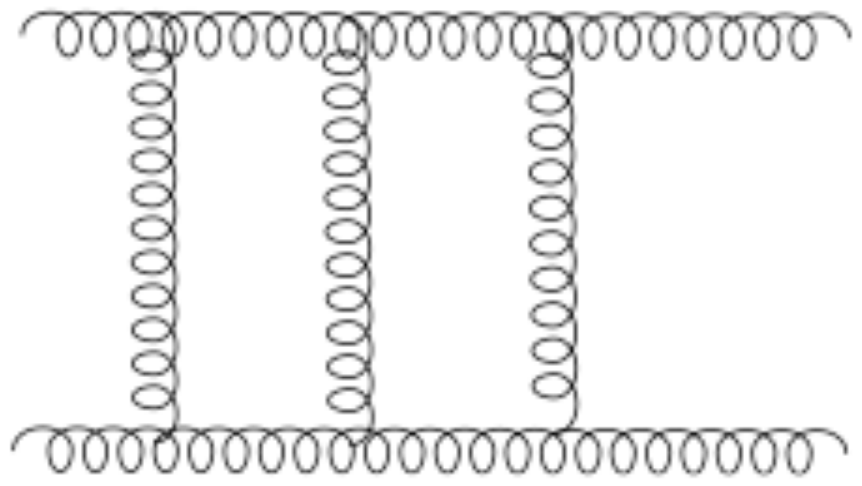
example NNLO:







double real | 1-loop virtual $\otimes$ single real | 2-loop virtual

↓ implicit IR poles (phase space integration)

↓ explicit and implicit poles

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

bottlenecks: IR subtraction (multi)-loop integrals

# Higher orders in perturbation theory

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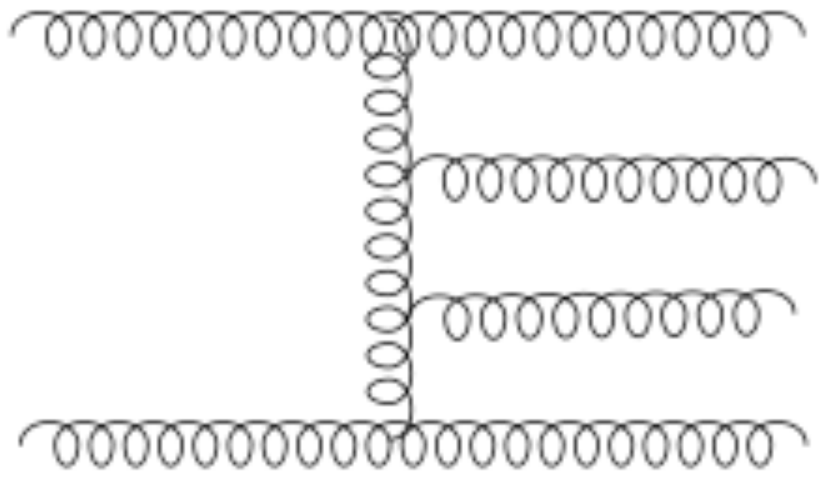
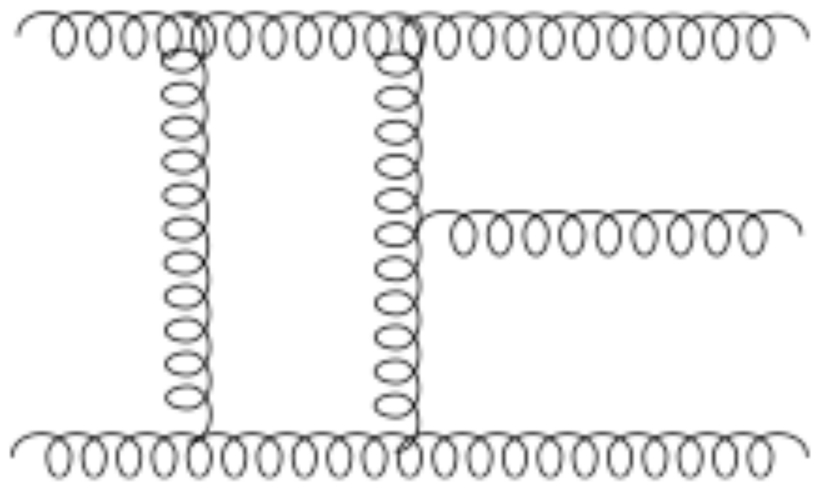
example NNLO:



double real

↓

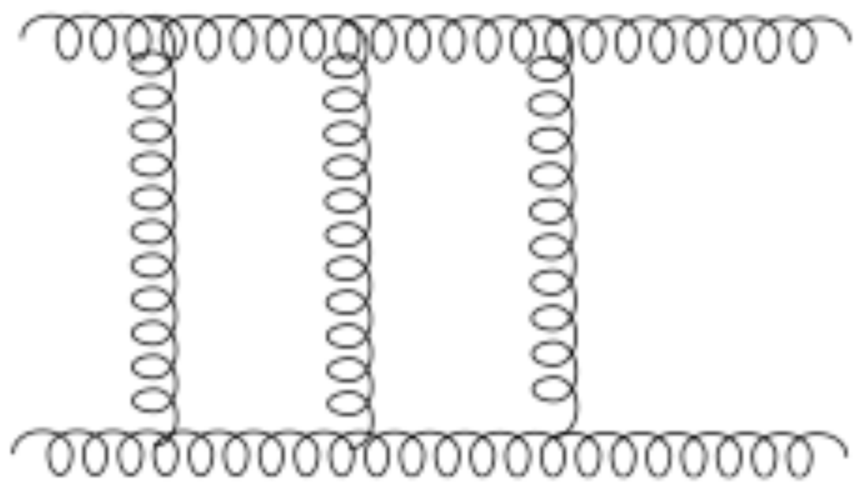
implicit IR poles
(phase space integration)



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

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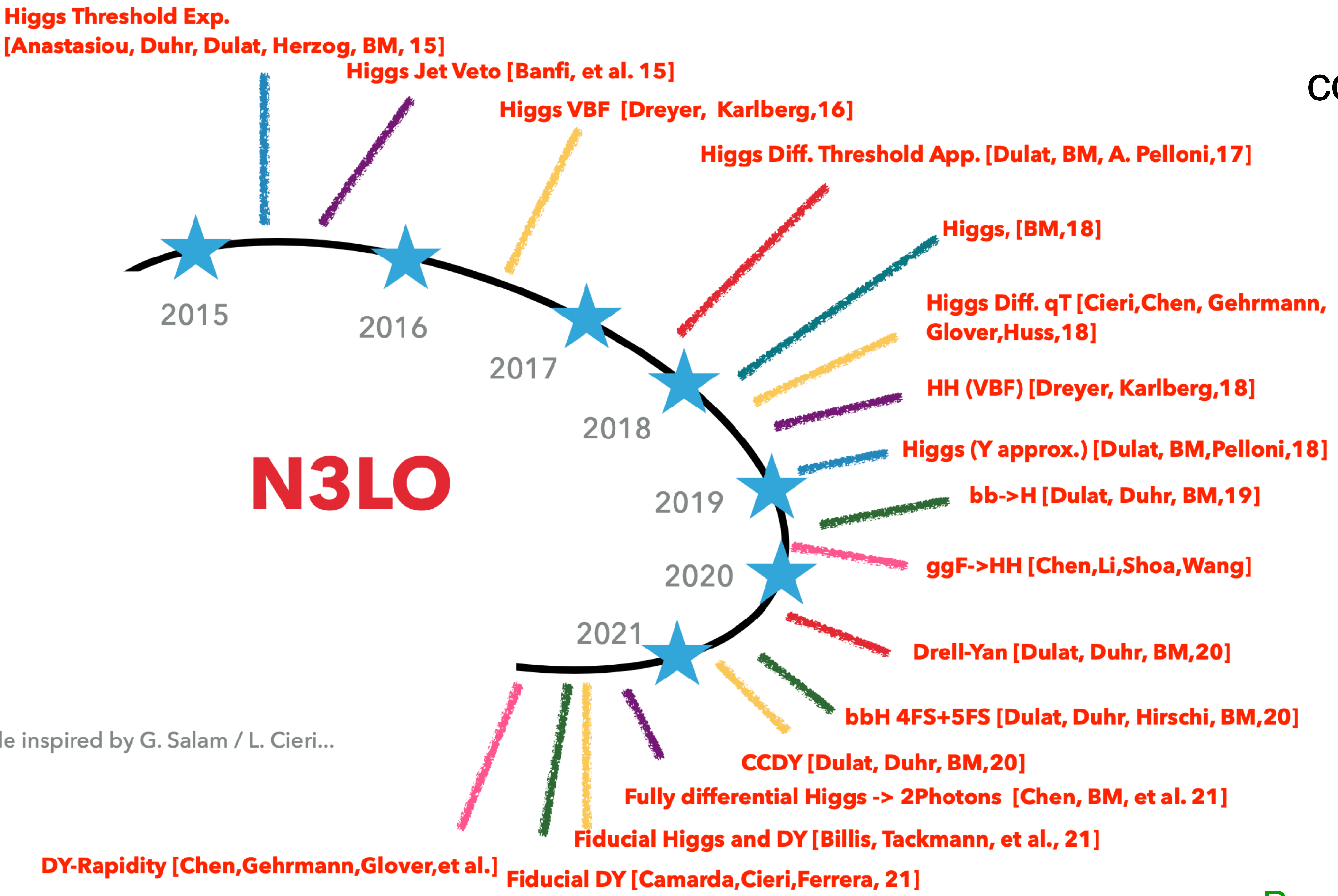
colour singlet final state particles
(H, Z, W)

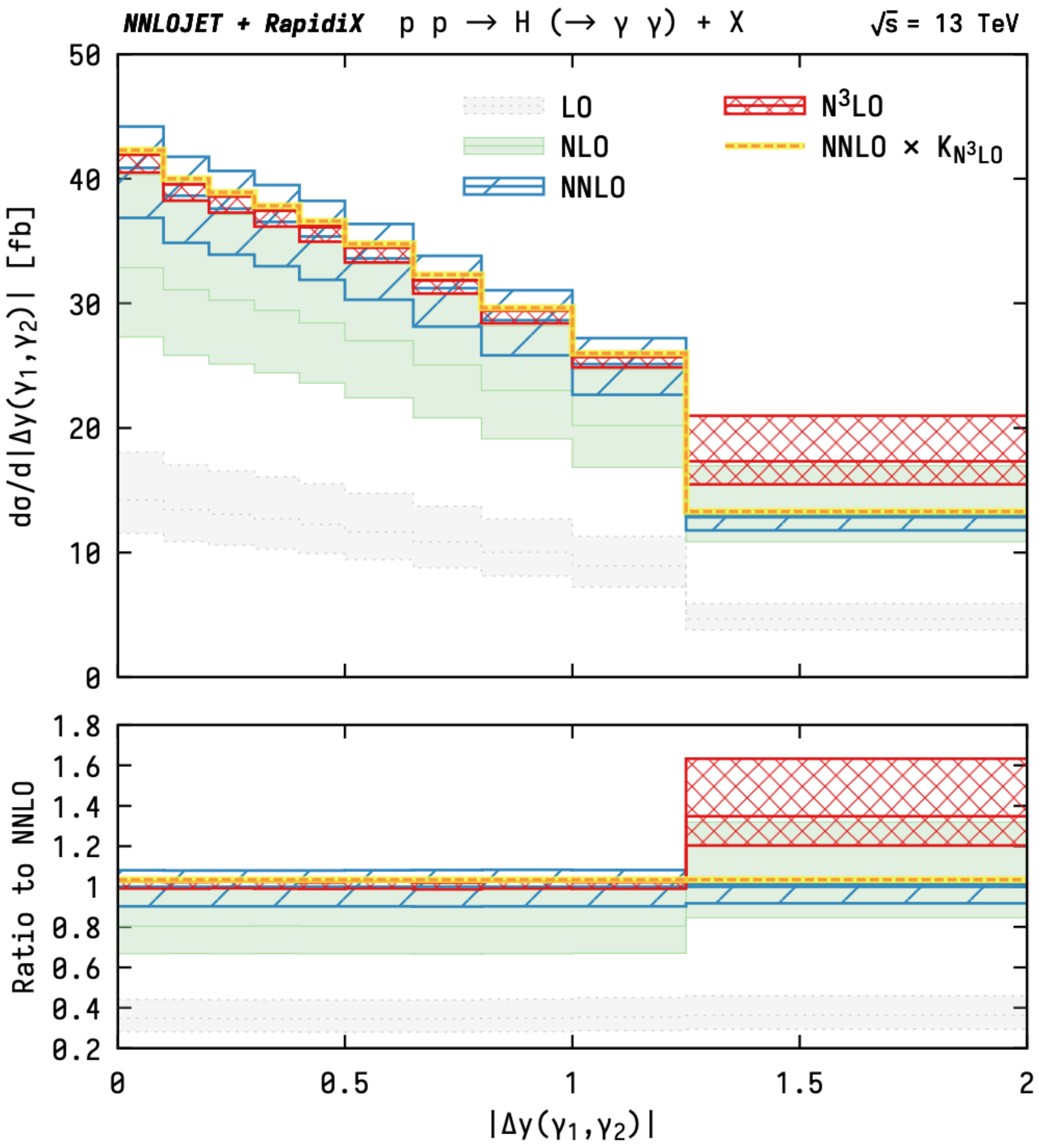



Slide inspired by G. Salam / L. Cieri...

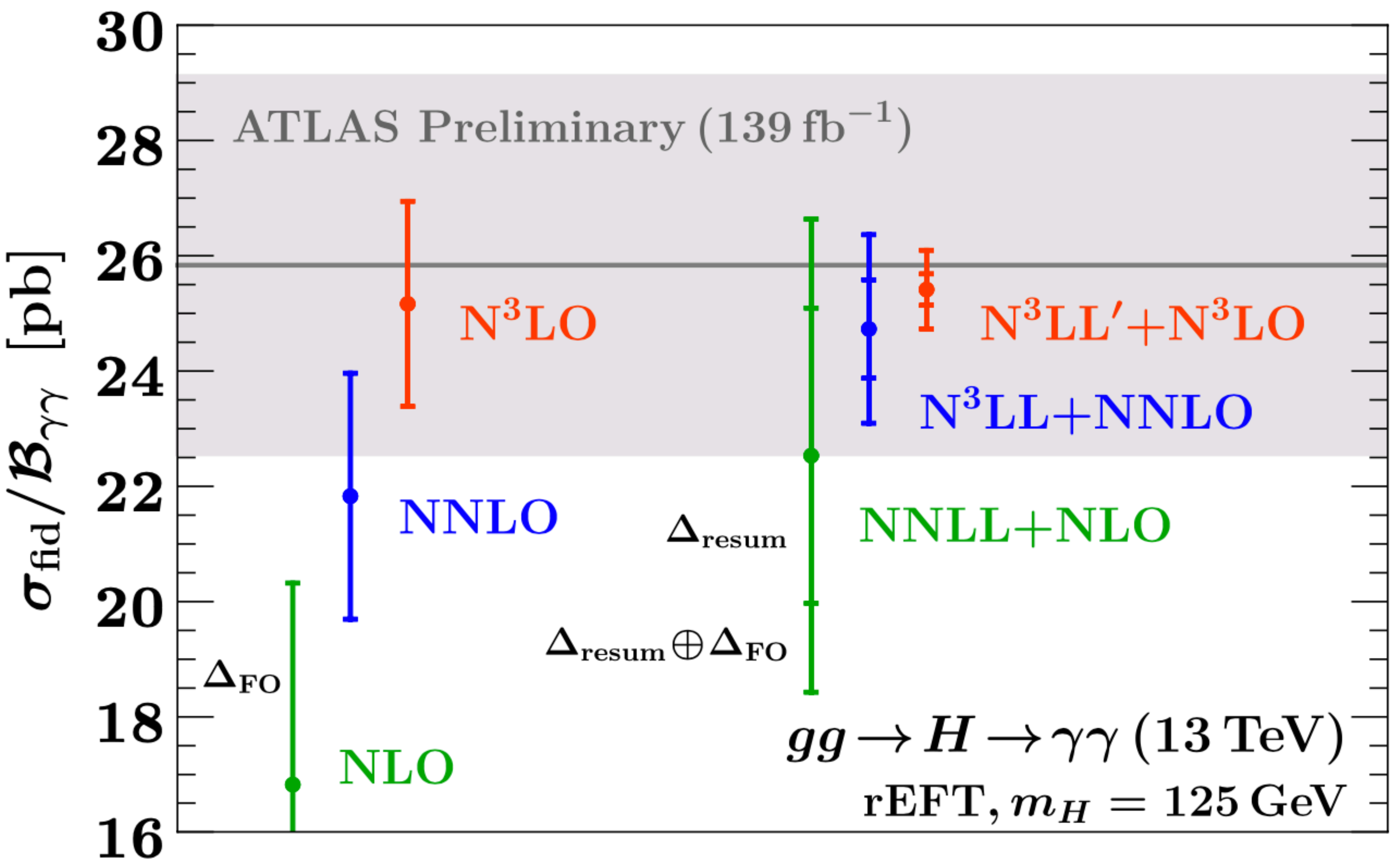
going more and more differential

Bernhard Mistlberger, Amplitudes 2021

# ggH@N3LO fiducial

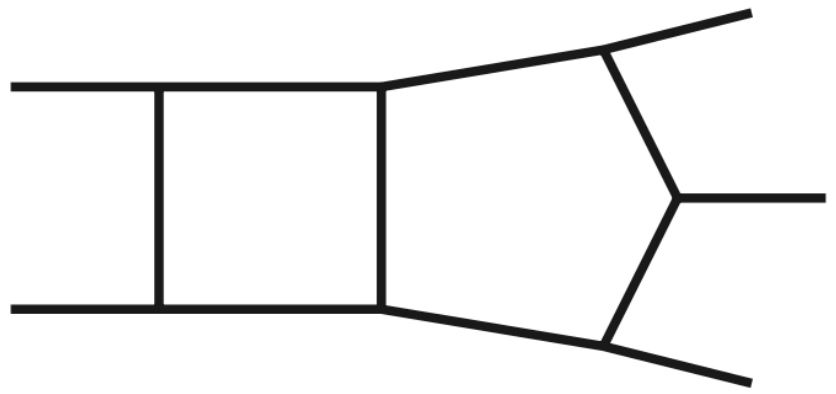



Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607




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)

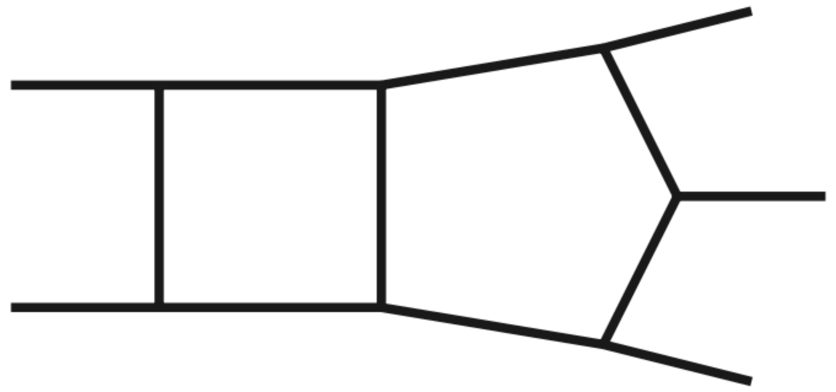
$gg \to \gamma\gamma g$ — Badger, Brønnum-Hansen, Chicherin, Gehrmann, Hartanto '21 (amp)

Badger, Gehrmann, Marcoli, Moodie today (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



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

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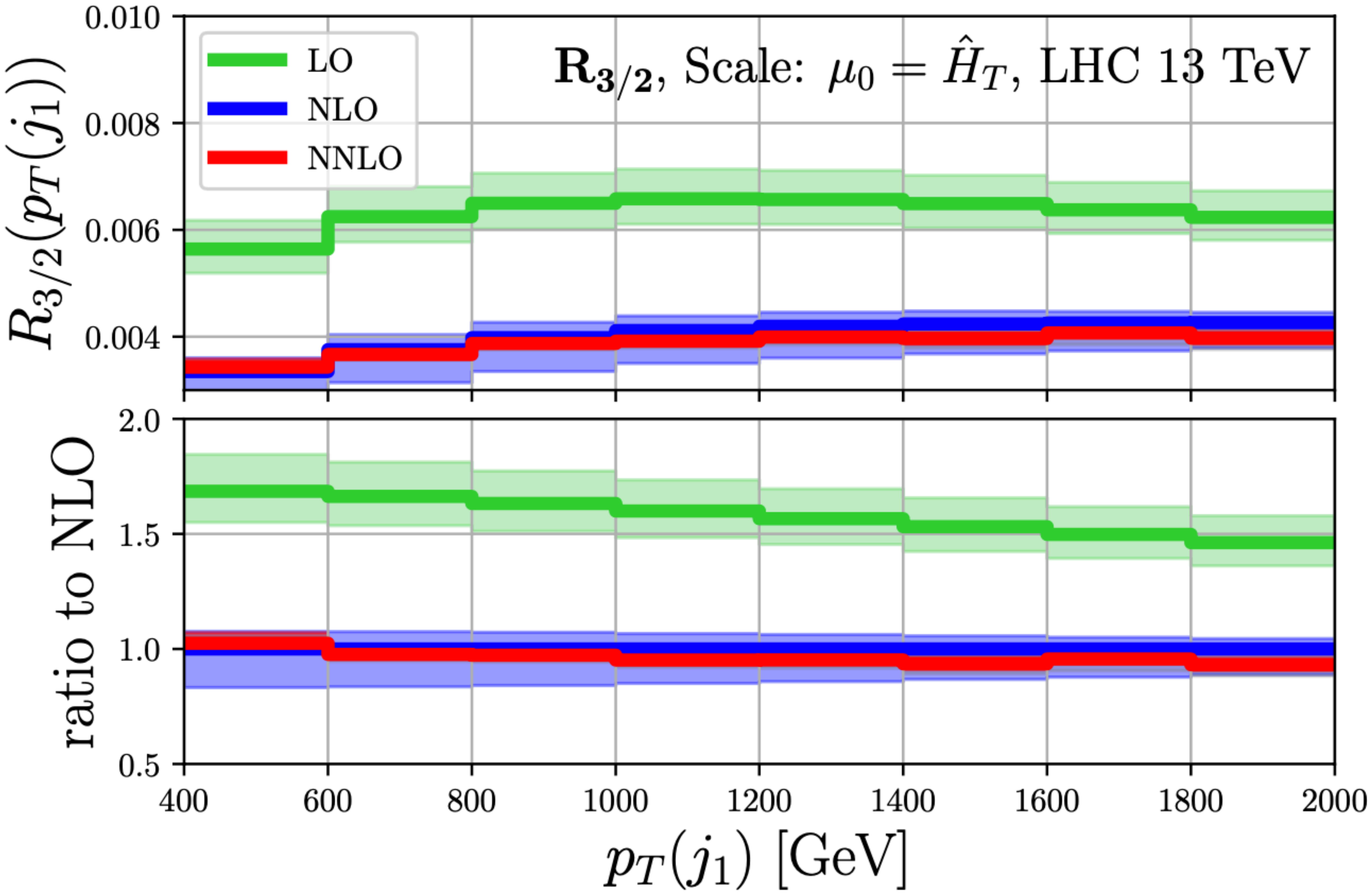
$pp \to jjj$

*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*

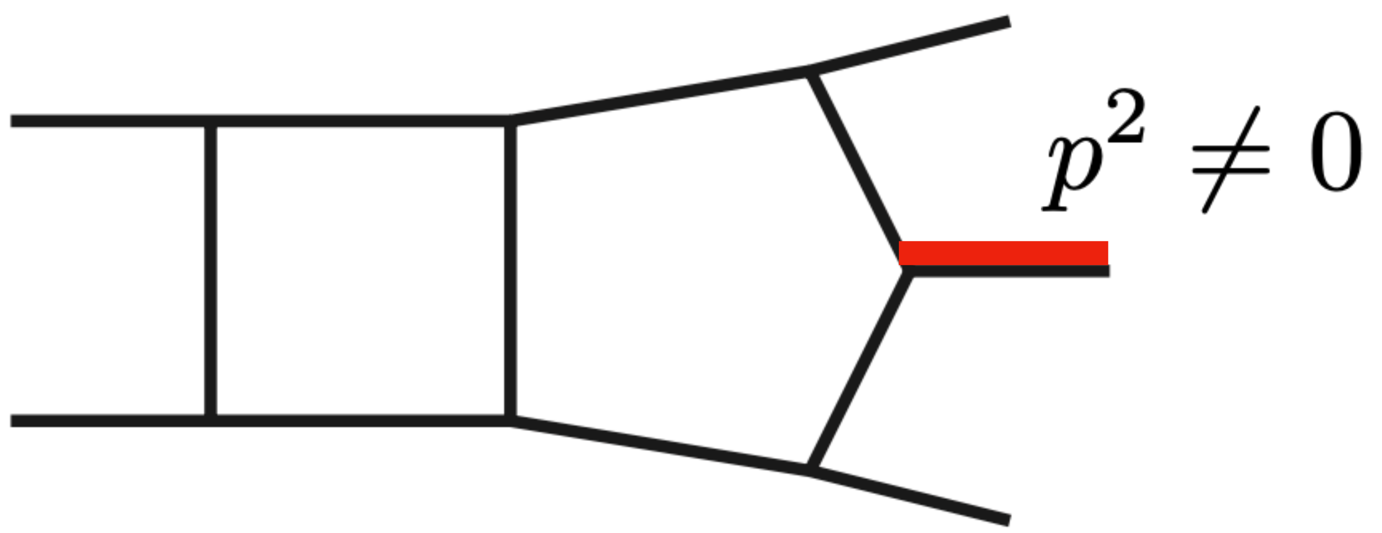
# 3-jet production at NNLO




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)*

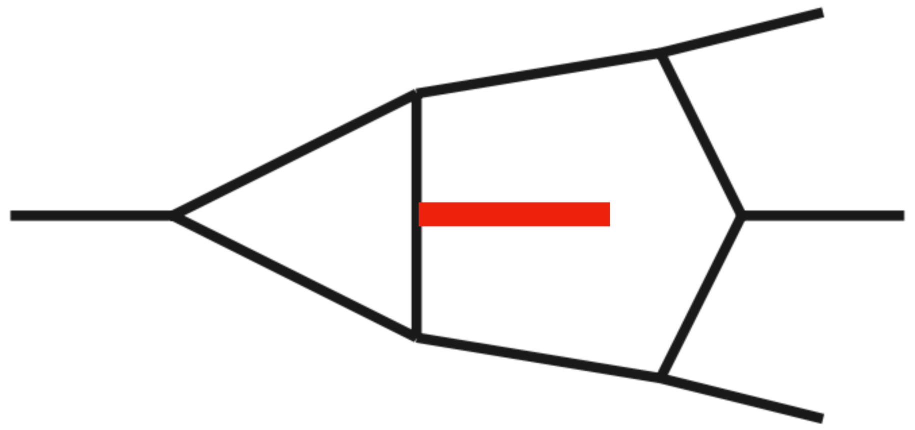
W + 4 partons *Badger, Brønnum-Hansen, Hartanto, Peraro ’19 (planar, num. unitarity)*

$u\bar{d} \to W^+ b\bar{b}$ *Badger, Hartanto, Zoia ’21 (planar, analytic)*

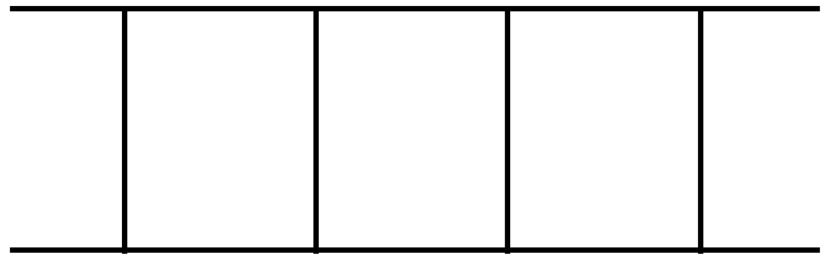
$pp \to b\bar{b}H$ *Badger, Hartanto, Krys, Zoia ’21 (leading colour)*

**non-planar:** *Abreu, Ita, Page, Tschernnov ’21*

*Liu, Ma ’21*



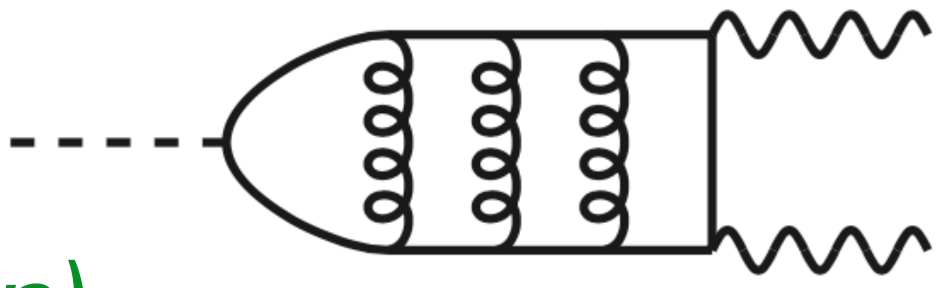
# 3-loop 4-point



$pp \to \gamma\gamma$ *Caola, Manteuffel, Tancredi '20*

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

# 4-loop 3-point



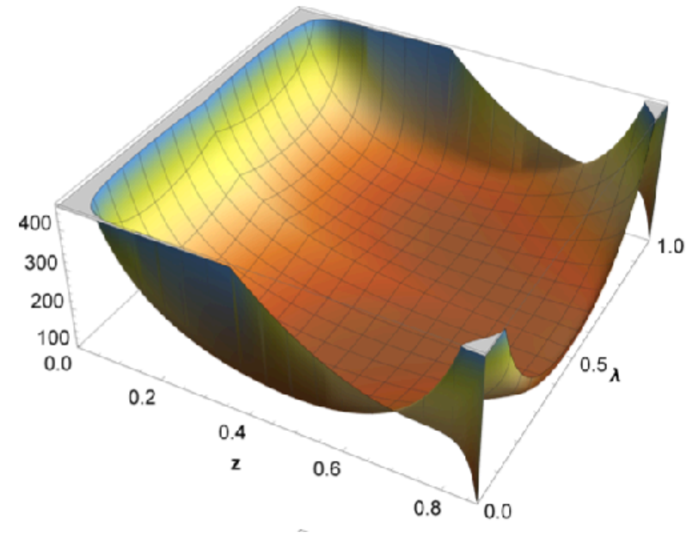
$H \to \gamma\gamma$ *Davies, Herren '21 (large mt-expansion)*

form factors $\gamma^\star \to q\bar{q}$ *Agarwal, Manteuffel, Panzer, Schabinger '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

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**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. ‘20*
*Bonciani et al. ‘21*

2-loop 4-fermion scattering in QED *Bonciani et al. ‘21*

*Banerjee et al. ’20, ‘21*

$\vdots$

# 2-loop 4-point with massive propagators

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**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* |

# 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 |

# Pro's and con's analytic/numerical

| | analytic | numerical |
|---|---|---|
| pole cancellation | exact | with numerical uncertainty |
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often a combination can be beneficial,
e.g. high energy limit analytically
Davies et al. '19

# Pro's and con's analytic/numerical

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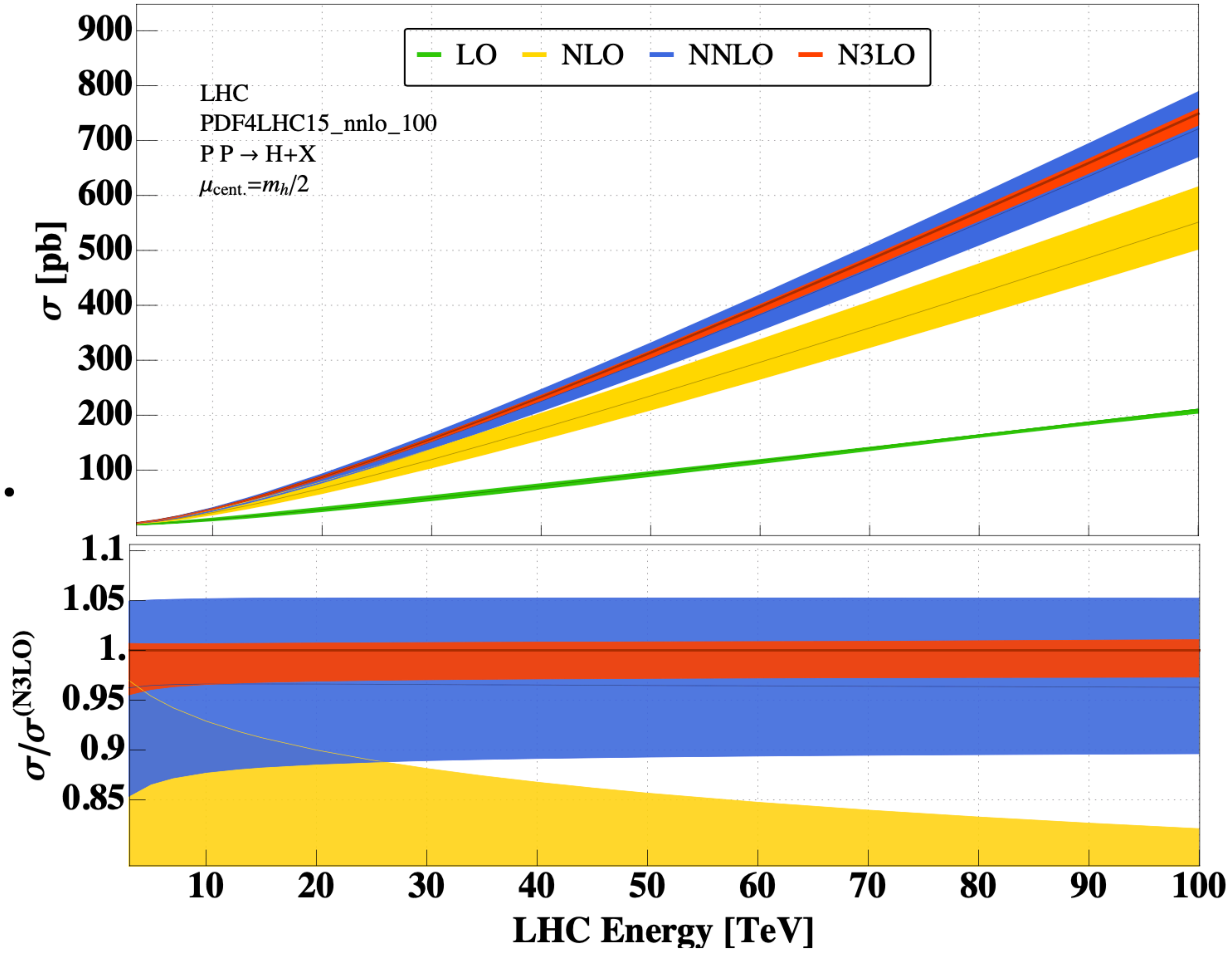
| control of integrable singularities | analytic continuation | less straightforward |
| extension to more scales/loops | difficult | promising |
| automation | difficult | less difficult |

often a combination can be beneficial,
e.g. high energy limit analytically
Davies et al. '19

# The Next Challenges

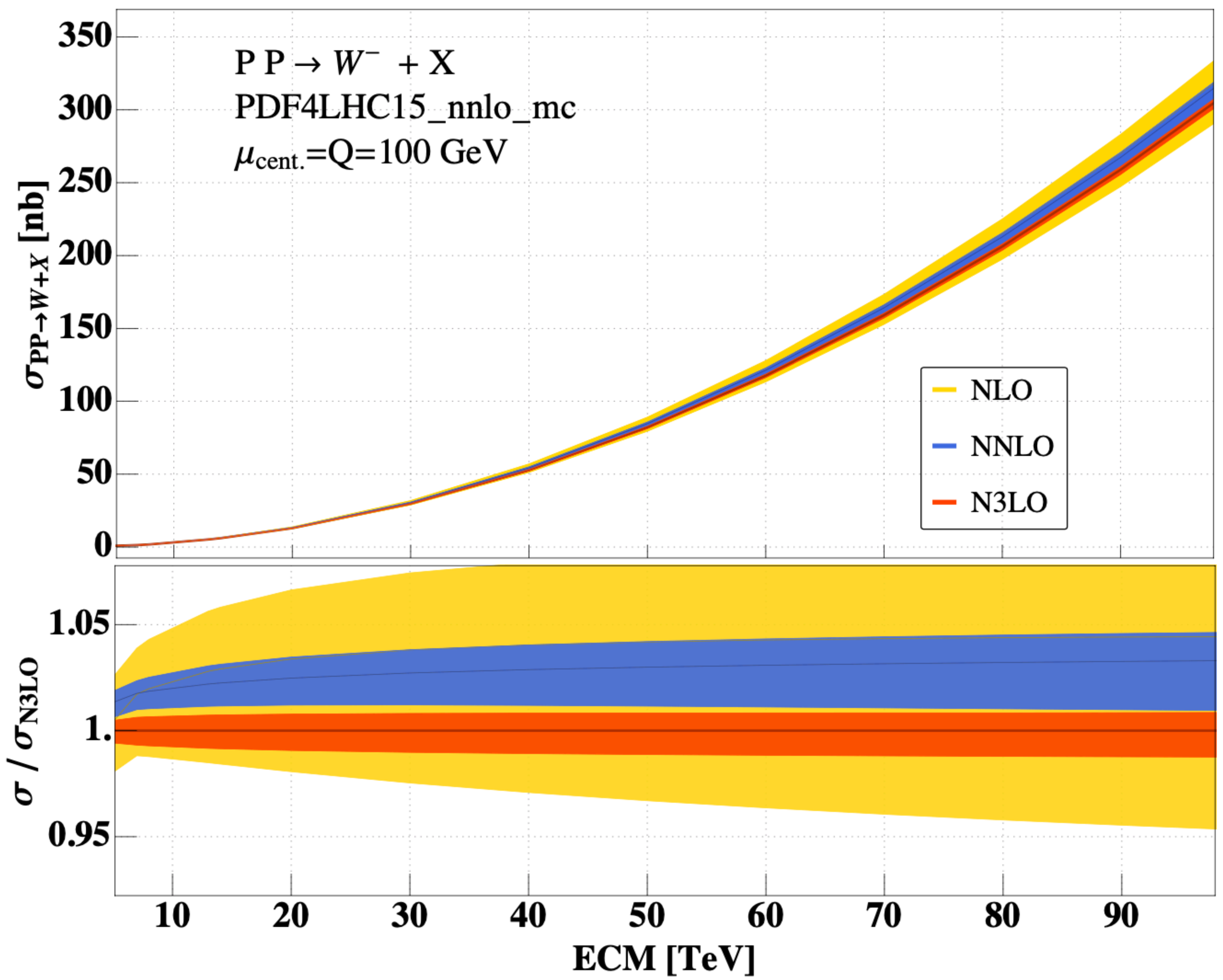
- scale uncertainties: how well do they estimate missing higher orders?
  - depends on choice of central scales, modes of variation, contributing partonic channels, …
- electroweak corrections, mixed QCD-EW
- PDFs
- quark mass-related uncertainties: neglected masses, different renormalisation schemes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

# Scale uncertainties: Higgs production in gluon fusion



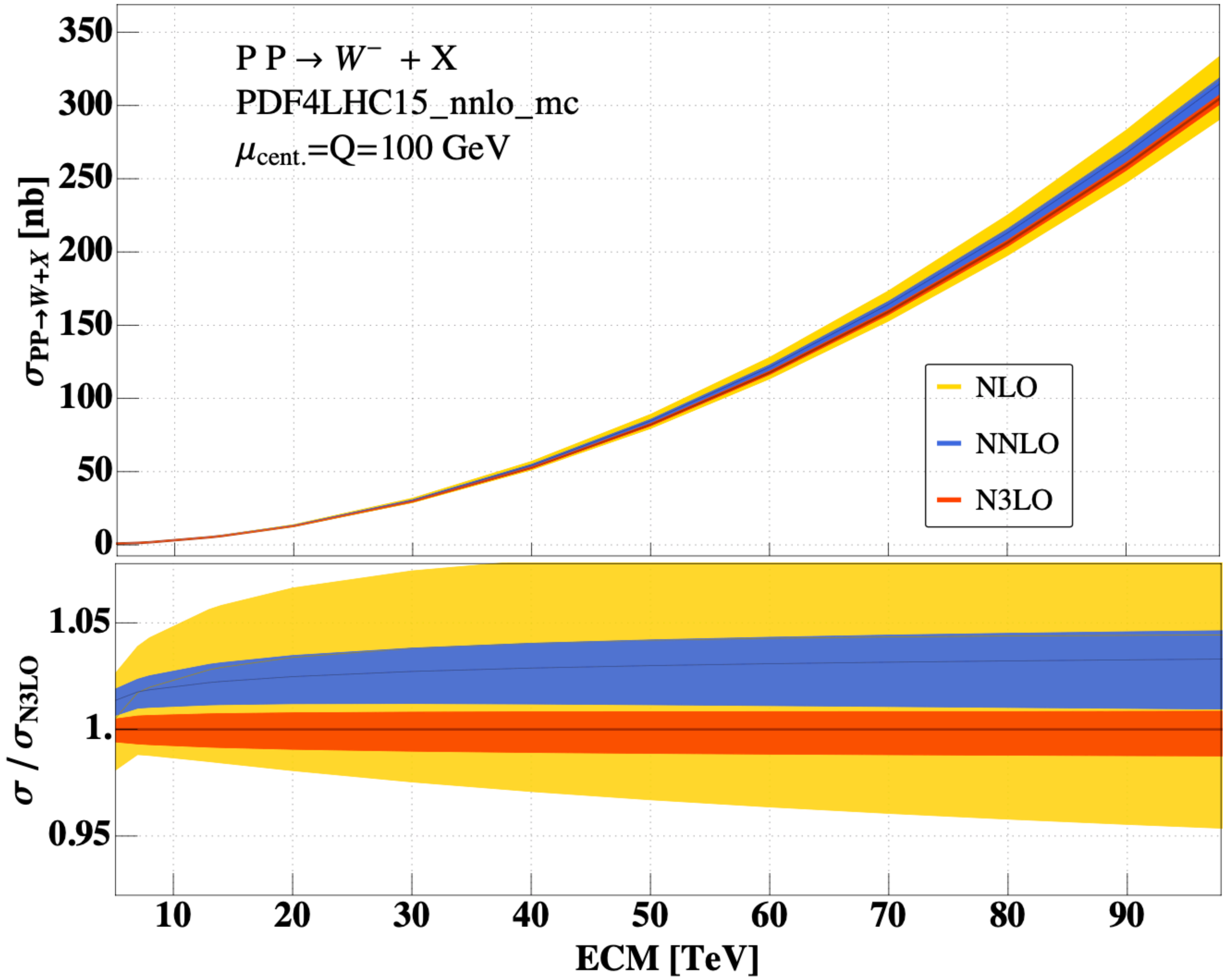

B. Mistlberger '18

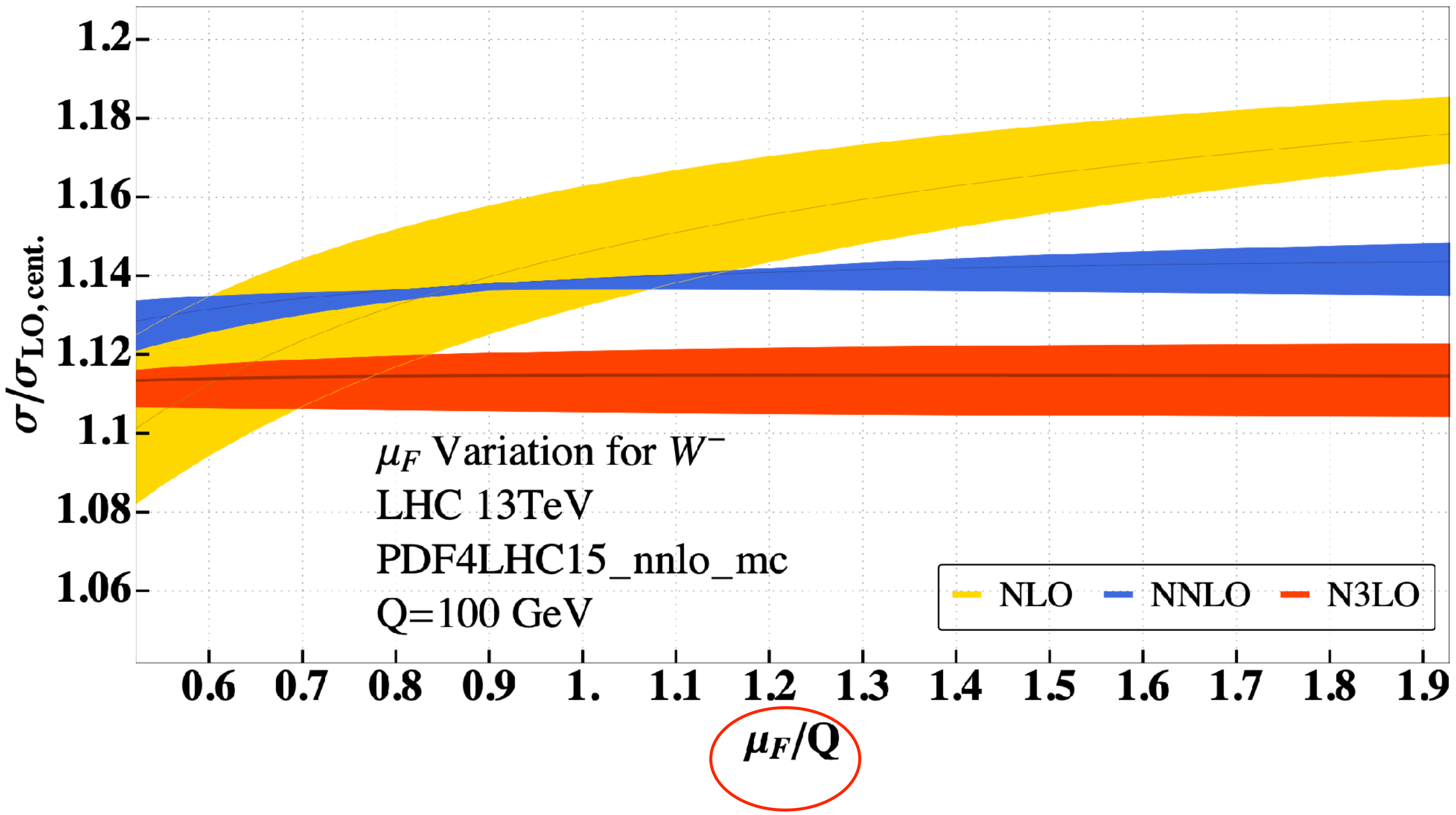
# Scale uncertainties: Drell-Yan (W-production)



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

Duhr, Dulat, Mistlberger ‘20



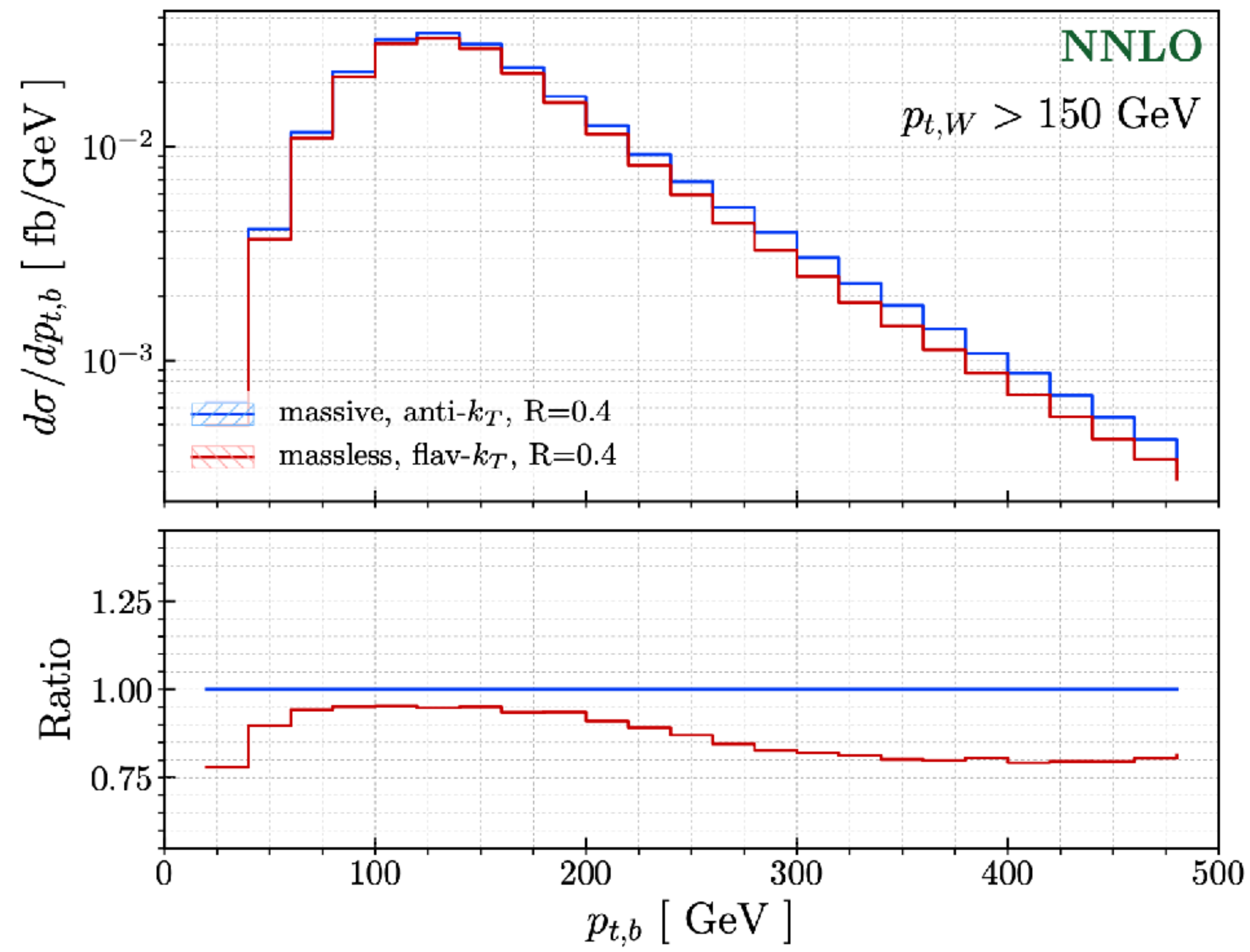



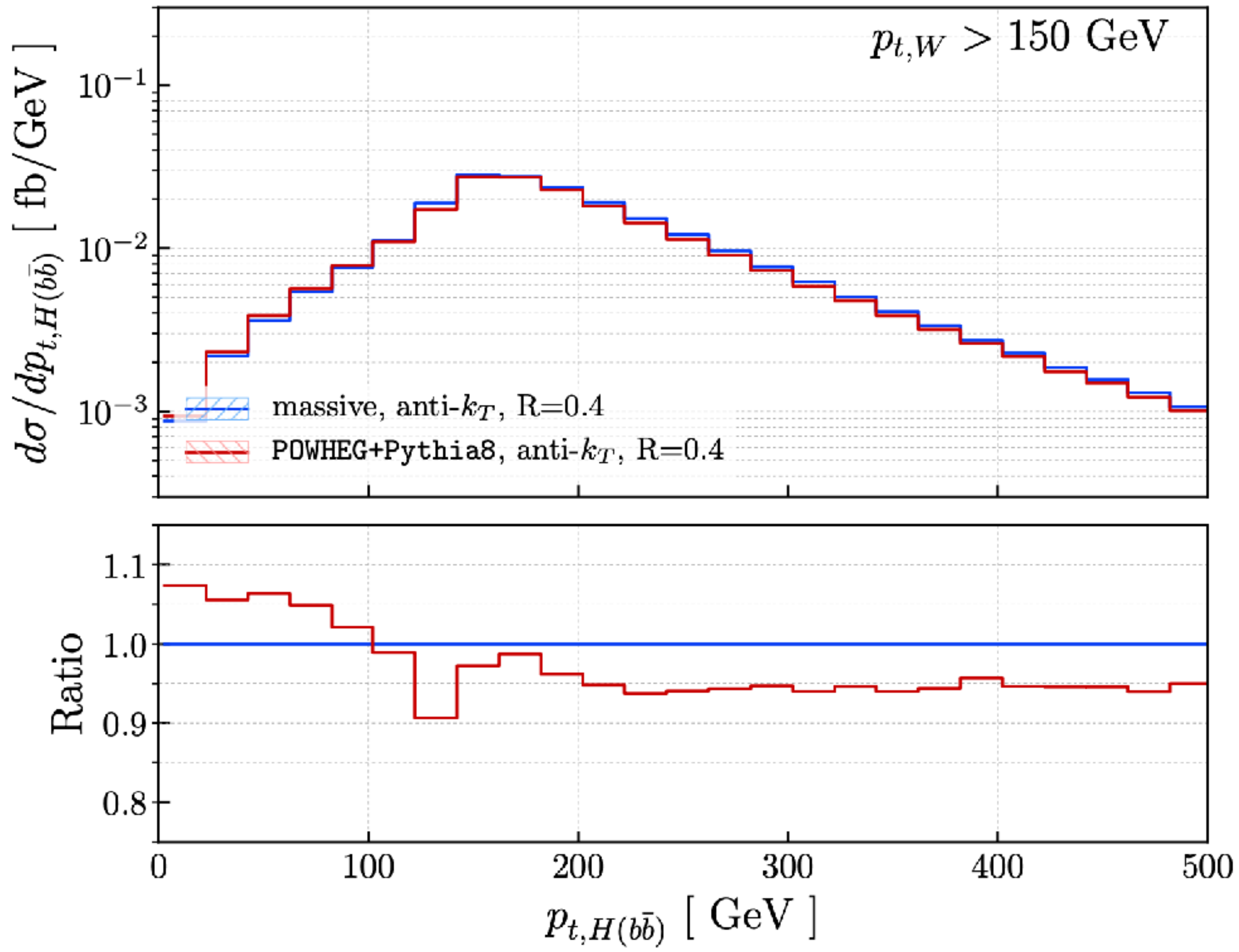

NNLO $\mu_F$-scale uncertainty bands do not properly reflect the uncertainty

# 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

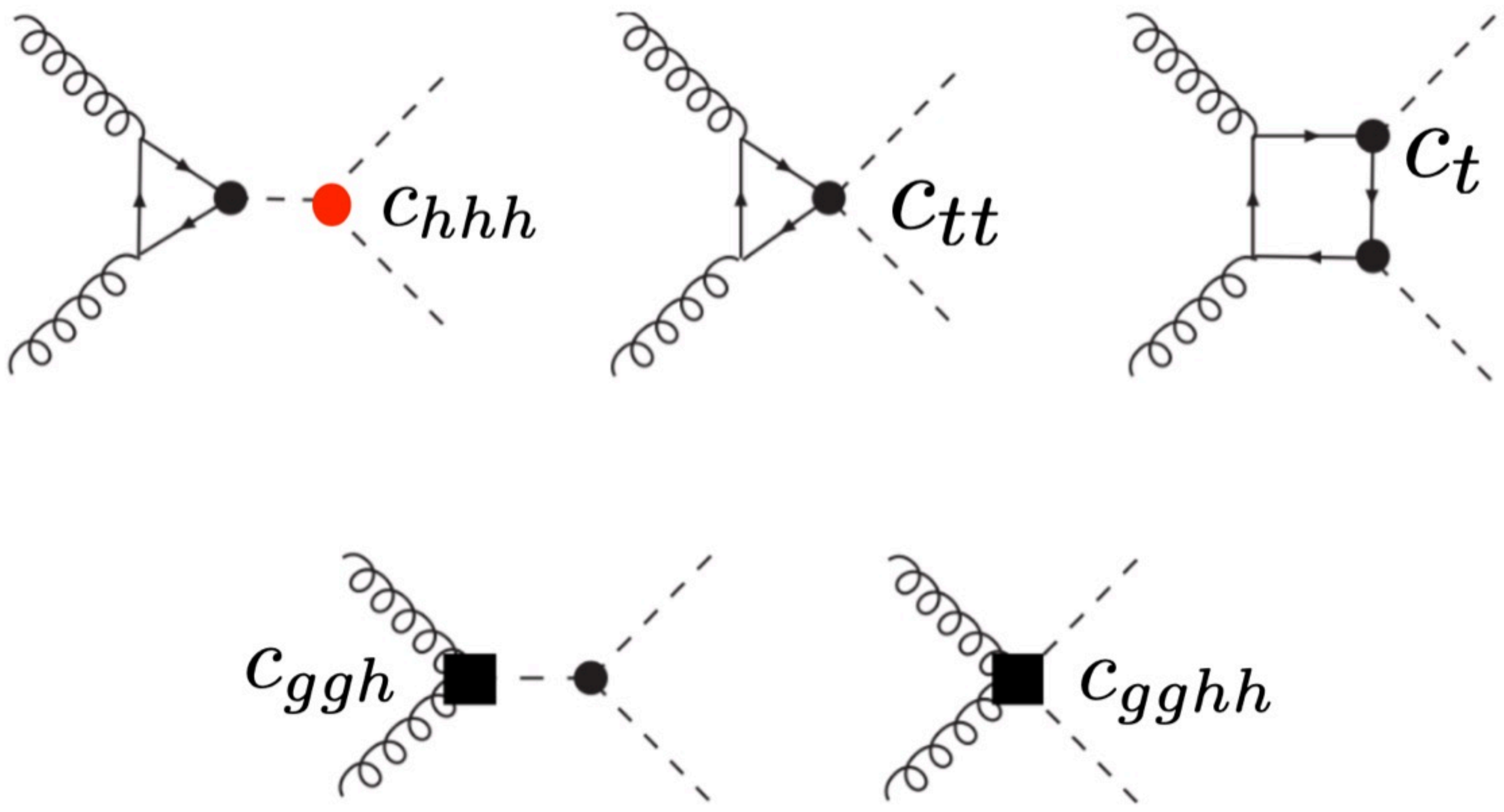


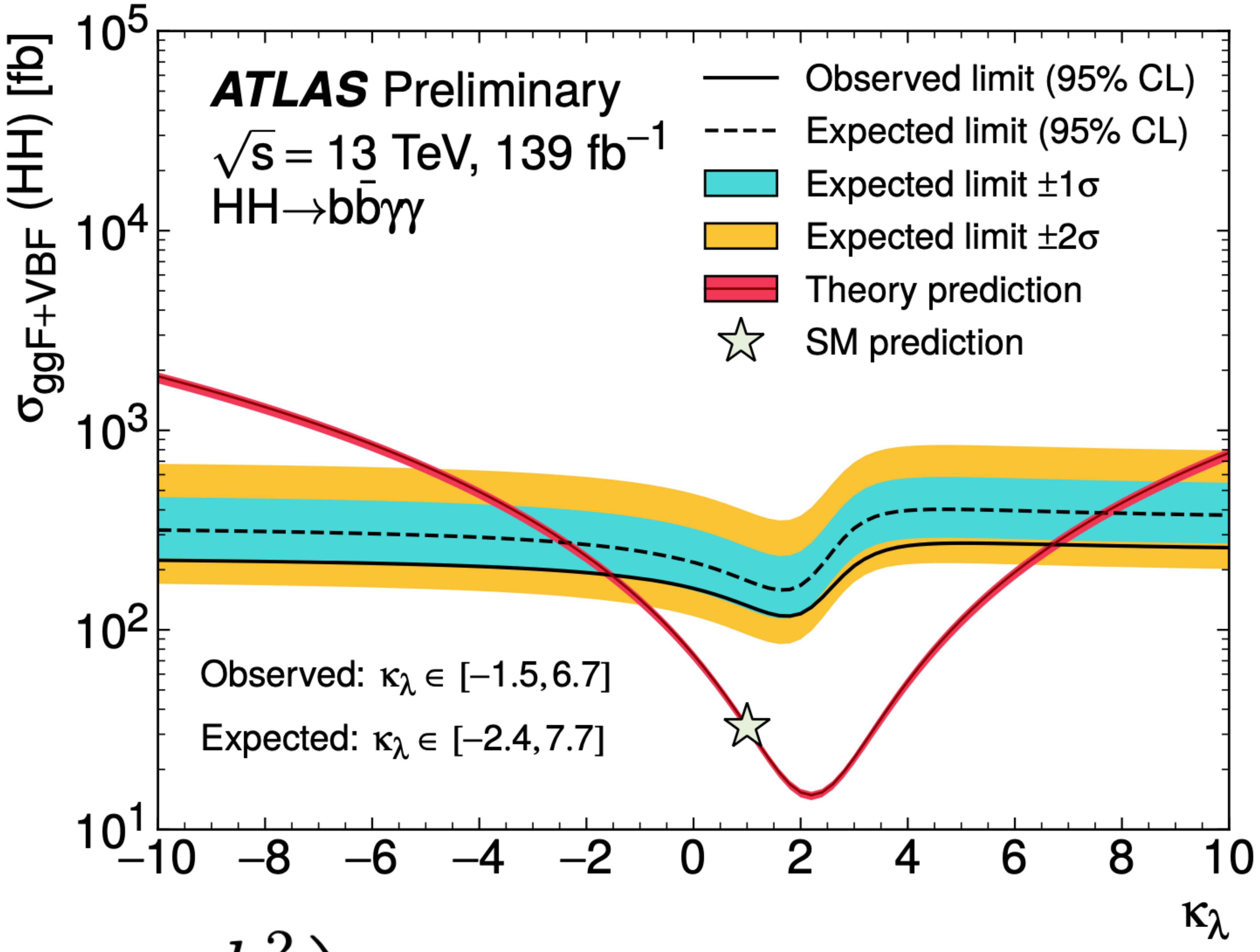

significant differences between massive and massless case and NNLO vs NLO+PS

# Exploring the Higgs potential

through Higgs boson pair production in gluon fusion




ATLAS-CONF-2021-016




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

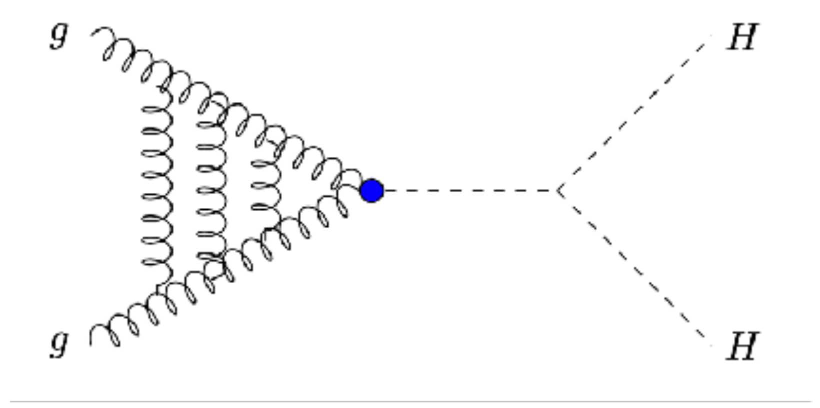
$$\kappa_\lambda \equiv c_{hhh}$$

description of unknown interactions at high energies through Effective Field Theory

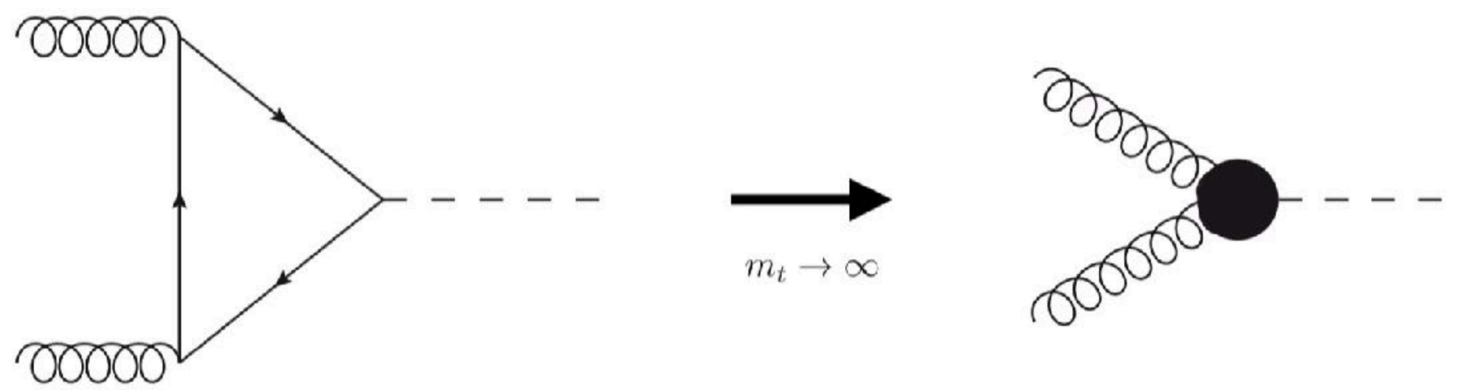
Standard Model: $c_{tt} = 0, c_{ggh} = 0, c_{gghh} = 0$

# Higher order corrections: SM

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




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



heavy top limit (HTL)

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

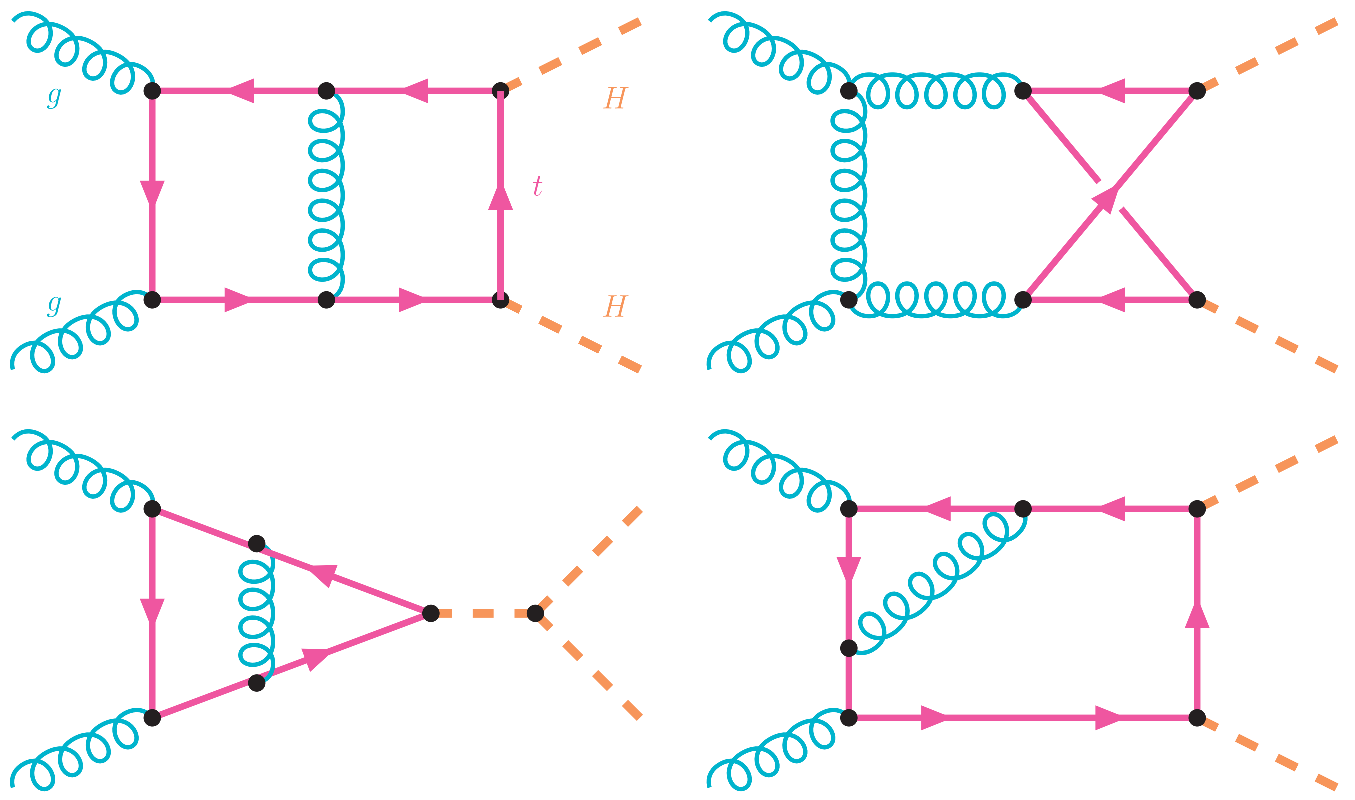
inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$

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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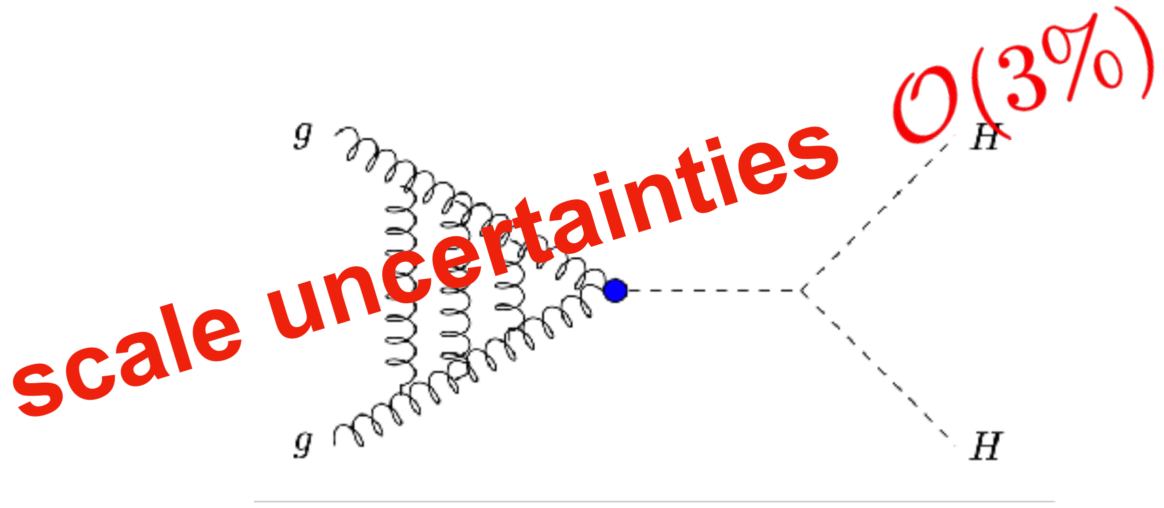


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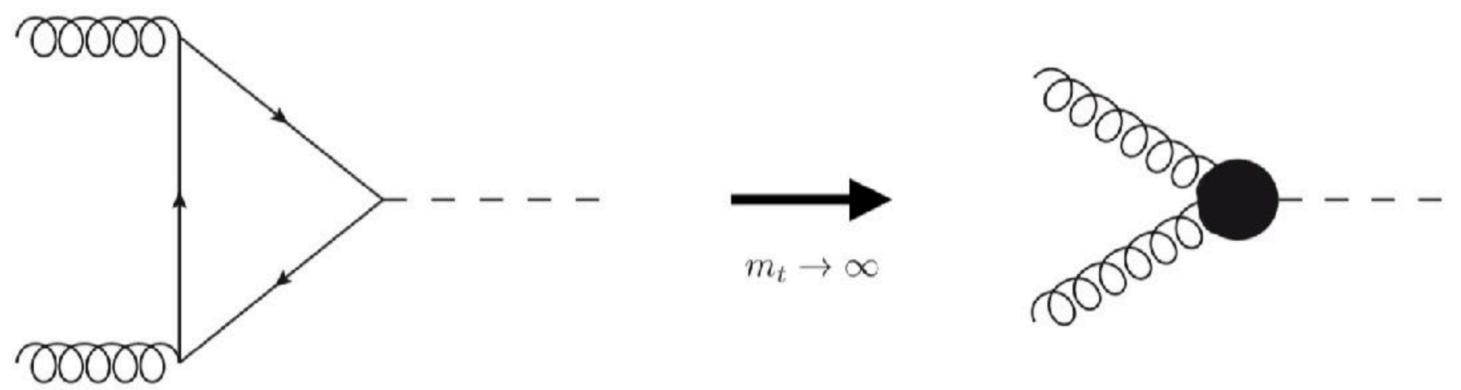


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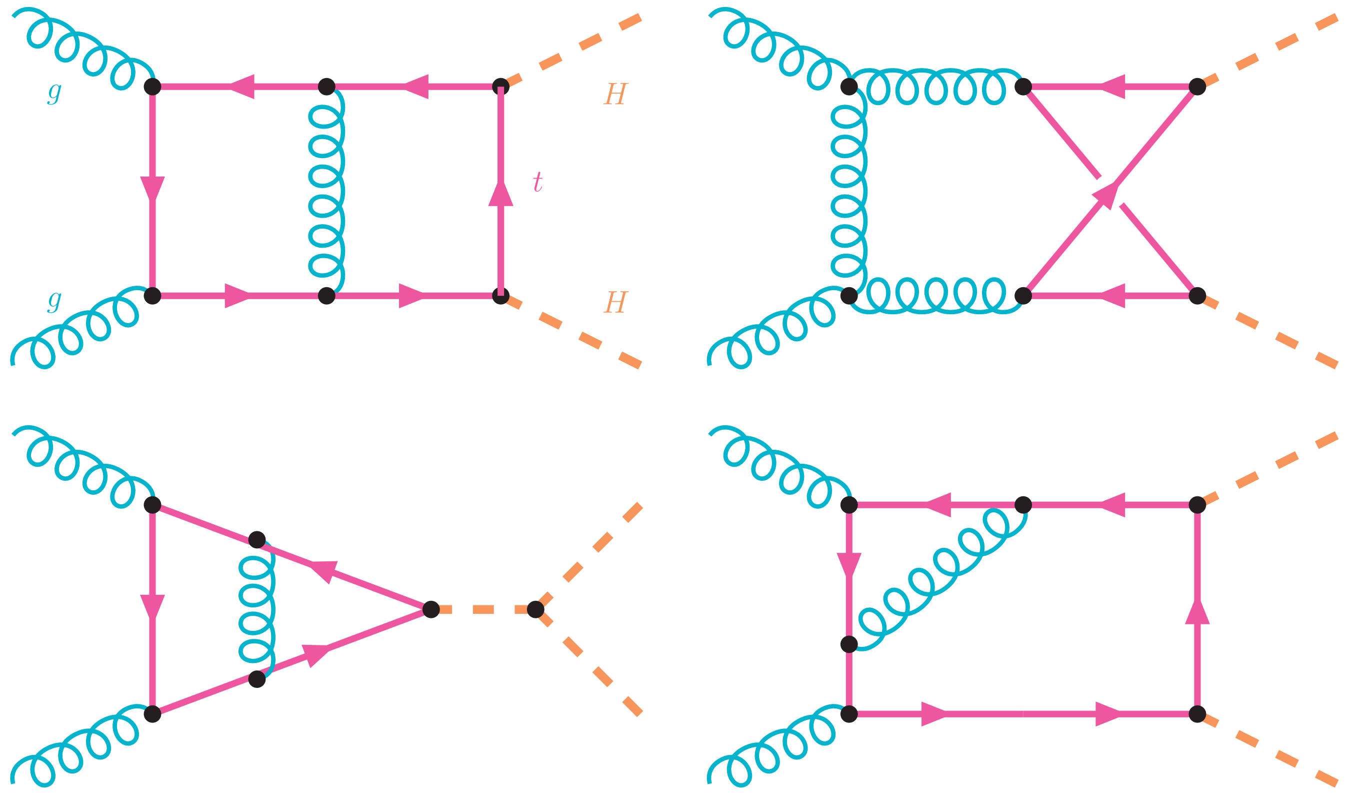


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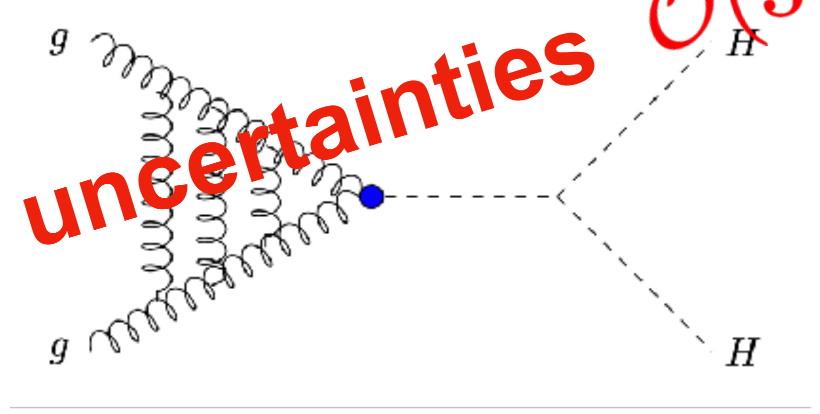
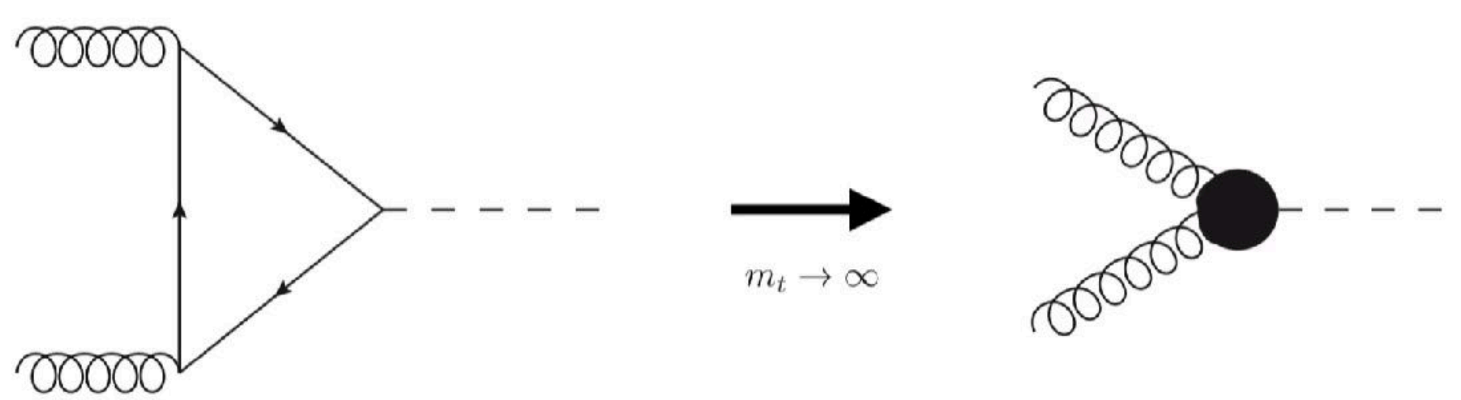
# Higher order corrections: SM

Karlsruhe Institute of Technology

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

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

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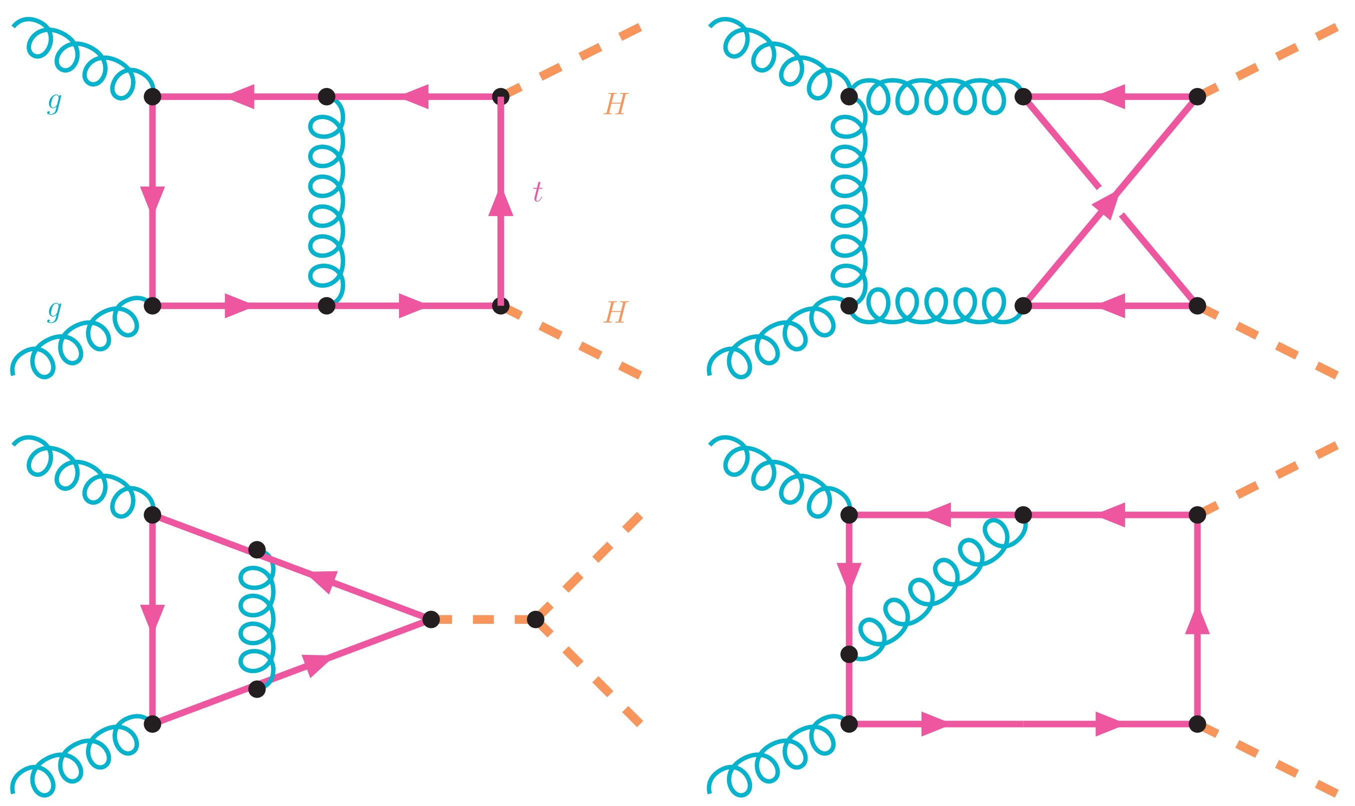
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann ‘19

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

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

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Karlsruhe Institute of Technology

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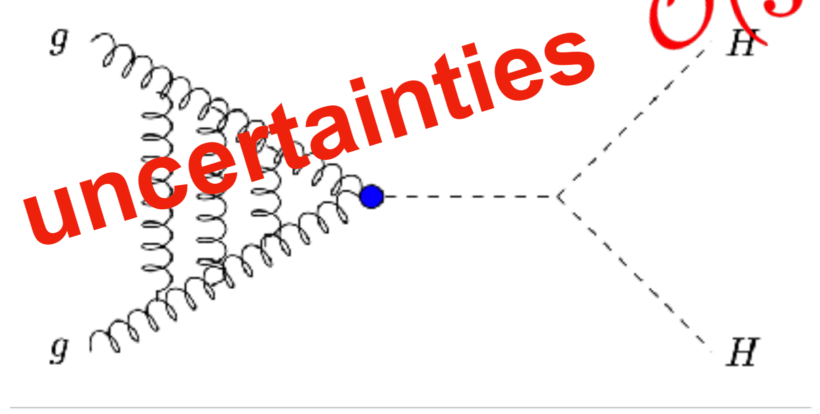


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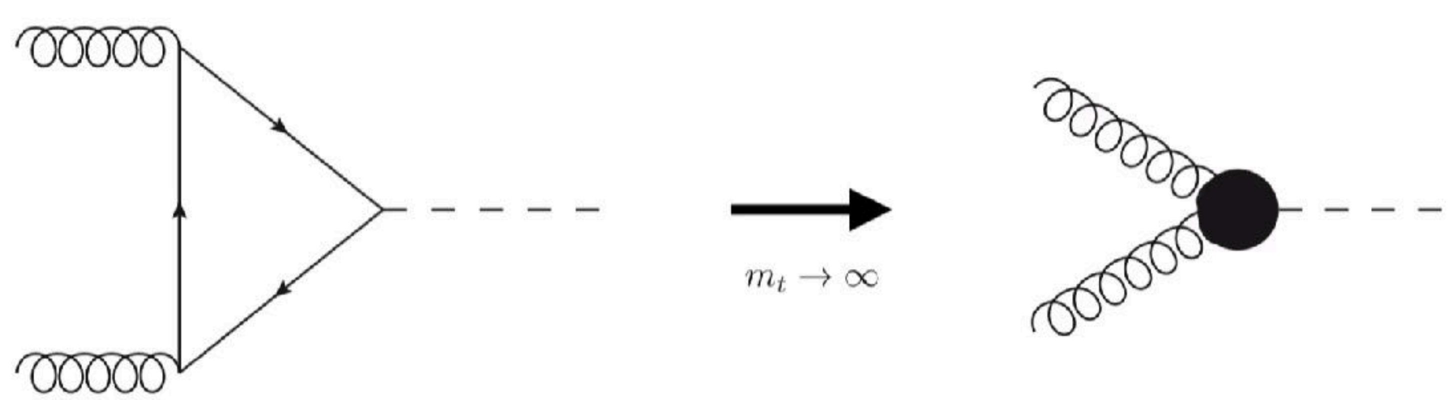


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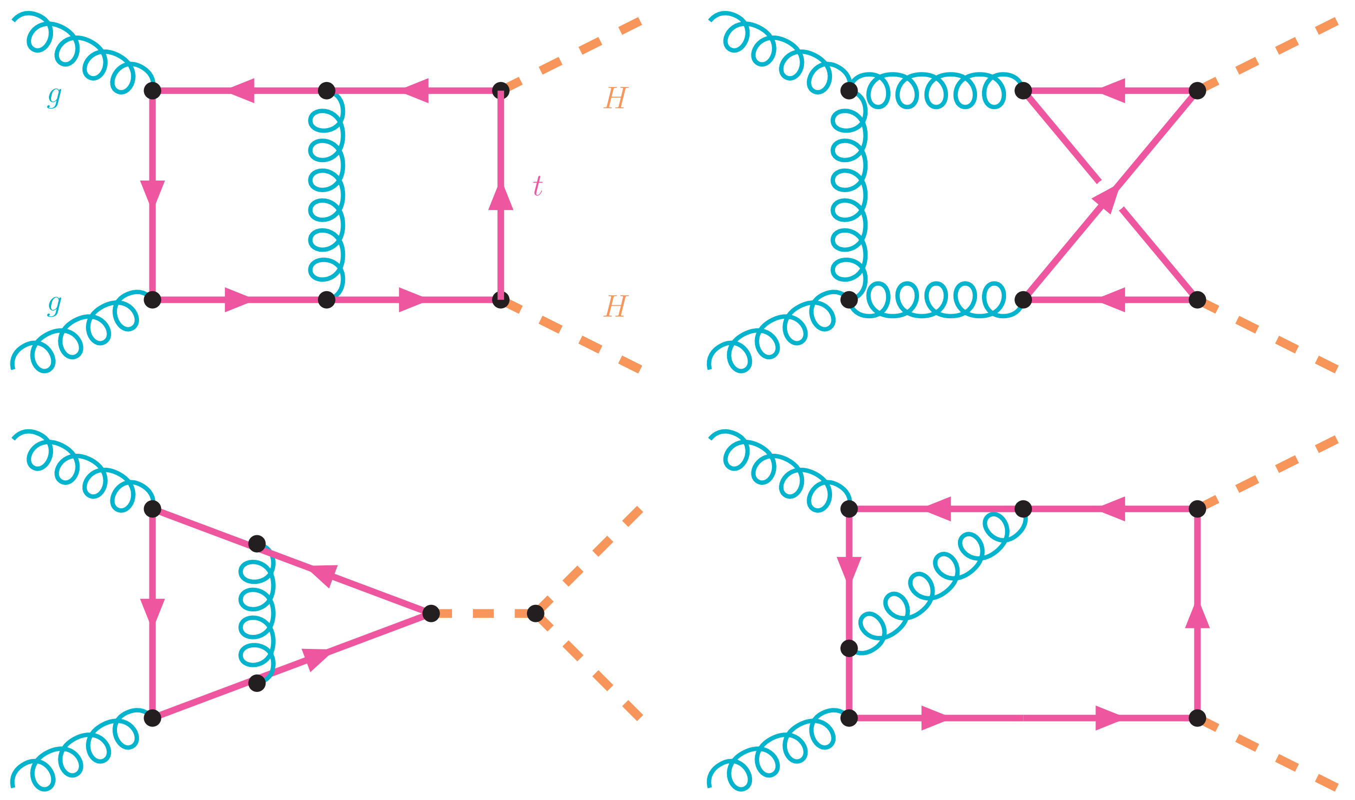


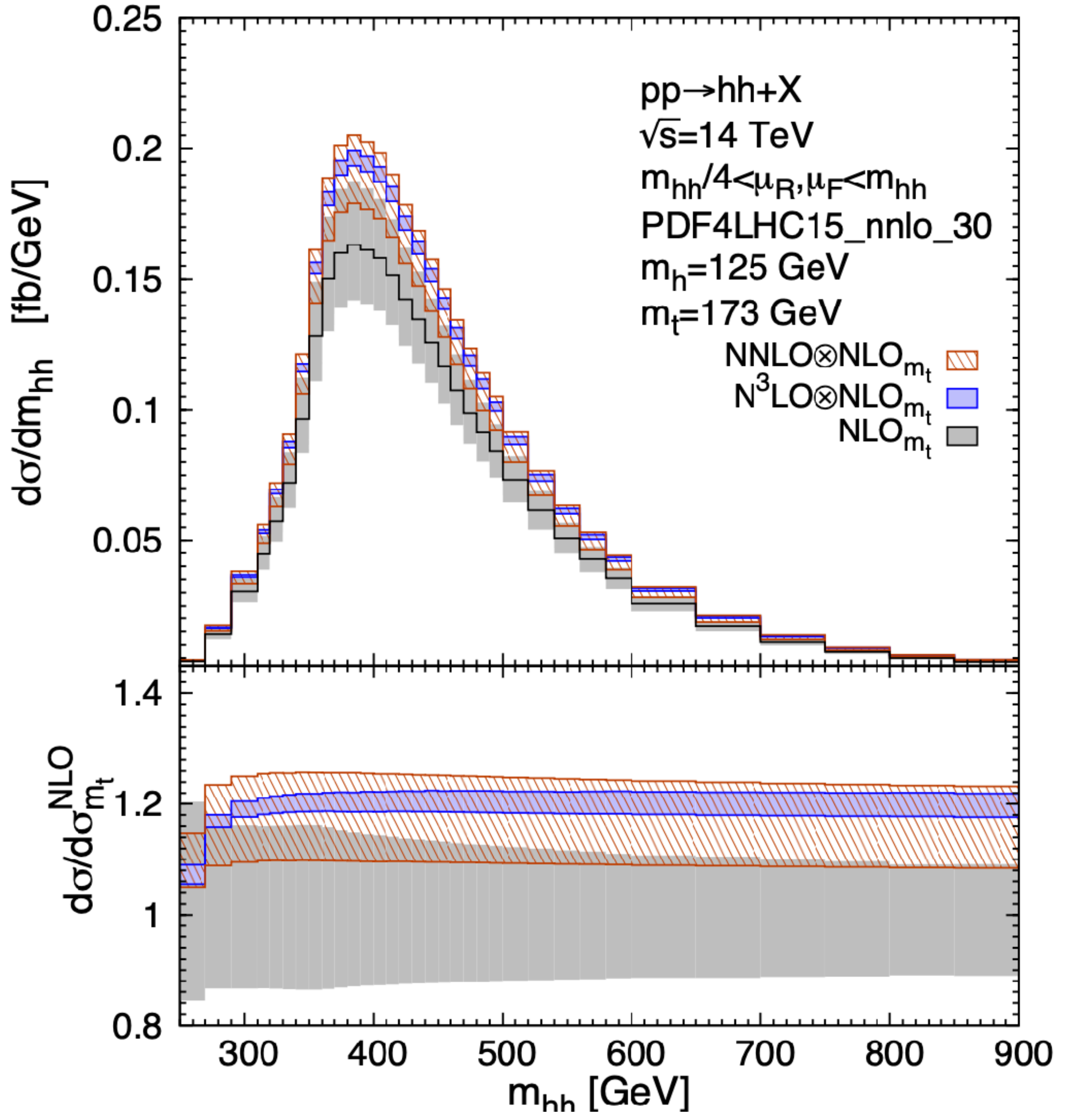

top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

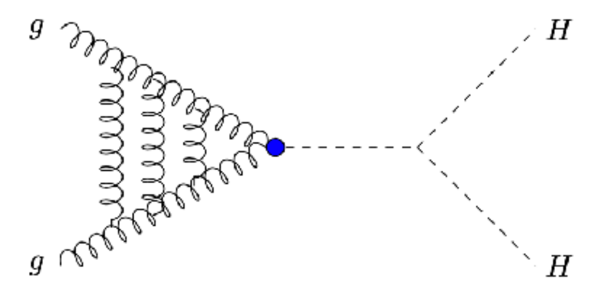
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ‘20

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

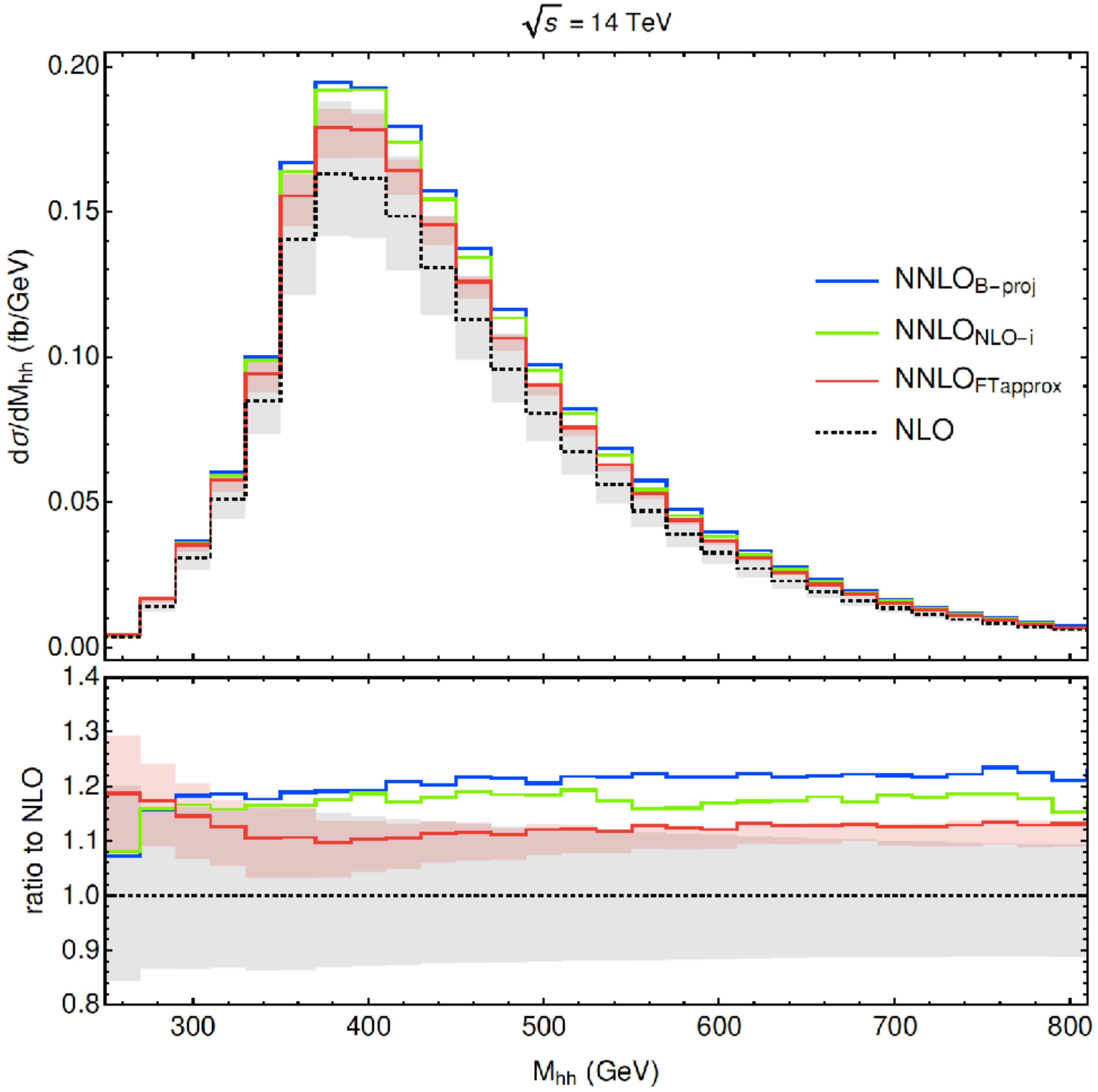
# Highest perturbative orders (SM)

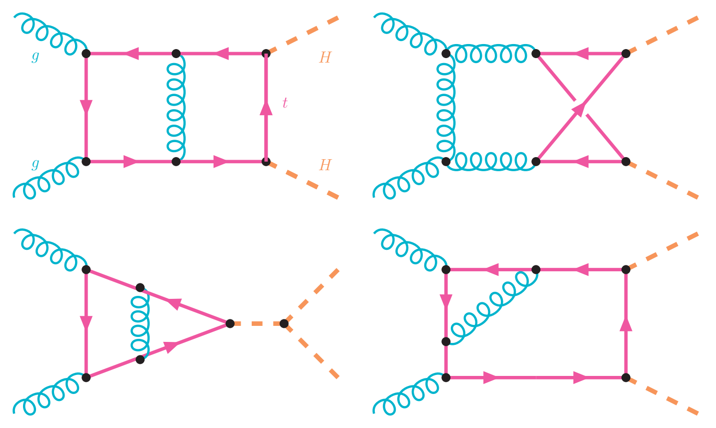
Chen, Li, Shao, Wang 1912.13001




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

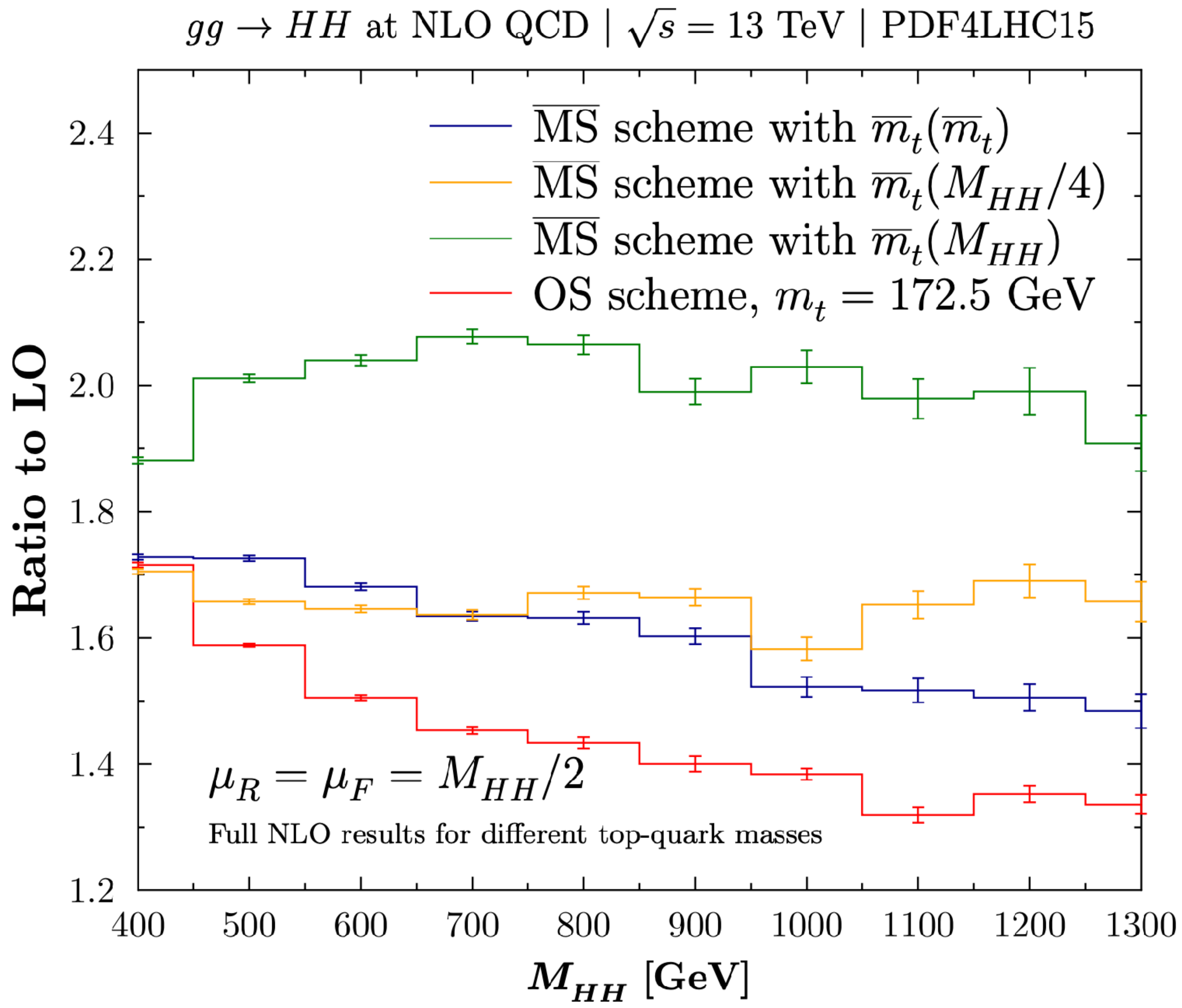


# Top quark mass renormalisation scheme uncertainties

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

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

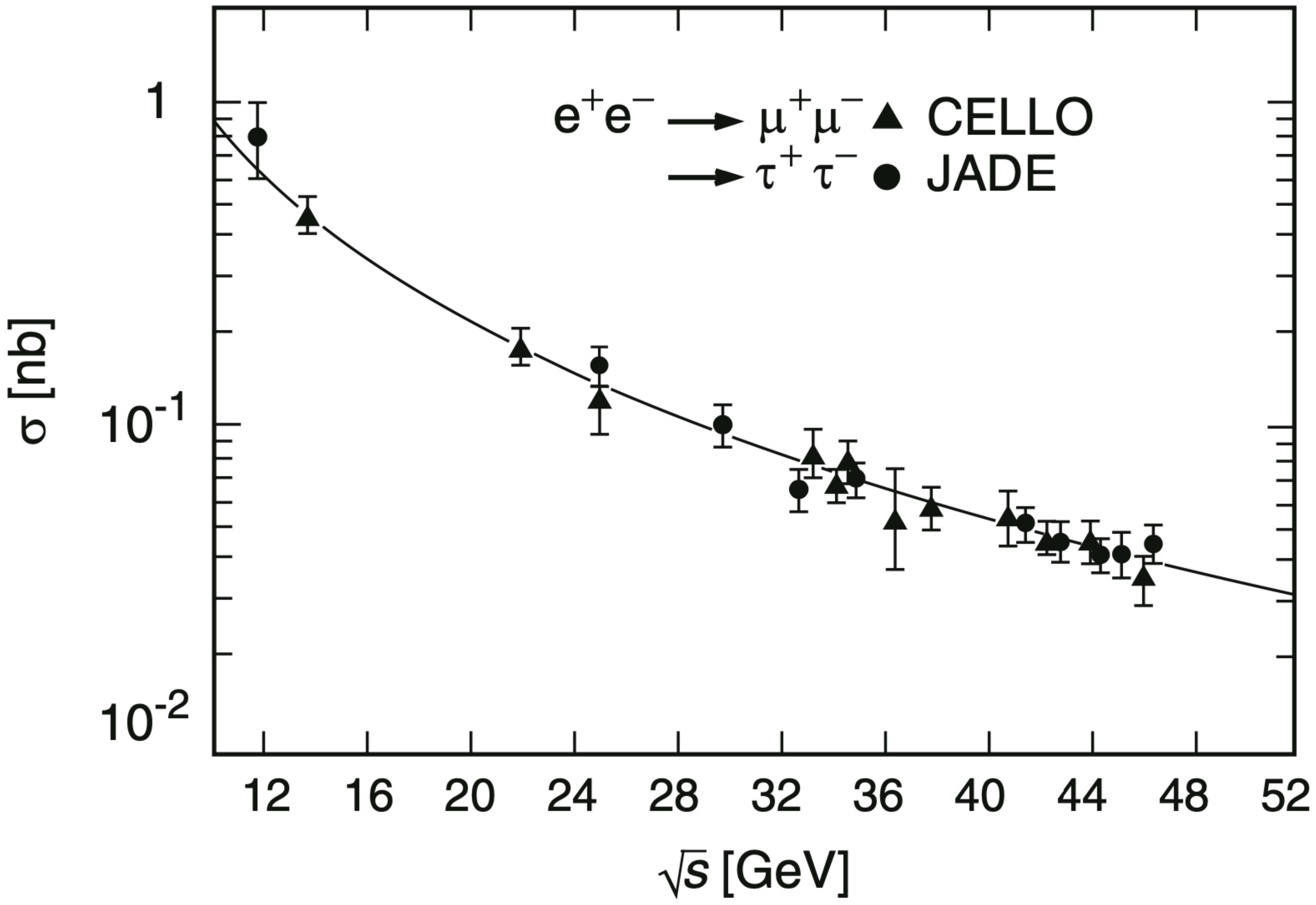
# Effective Field Theory parametrisation of New Physics

Karlsruhe Institute of Technology

"Standard Model Effective Field Theory" (SMEFT)

# Effective Field Theory parametrisation of New Physics

“Standard Model Effective Field Theory” (SMEFT)

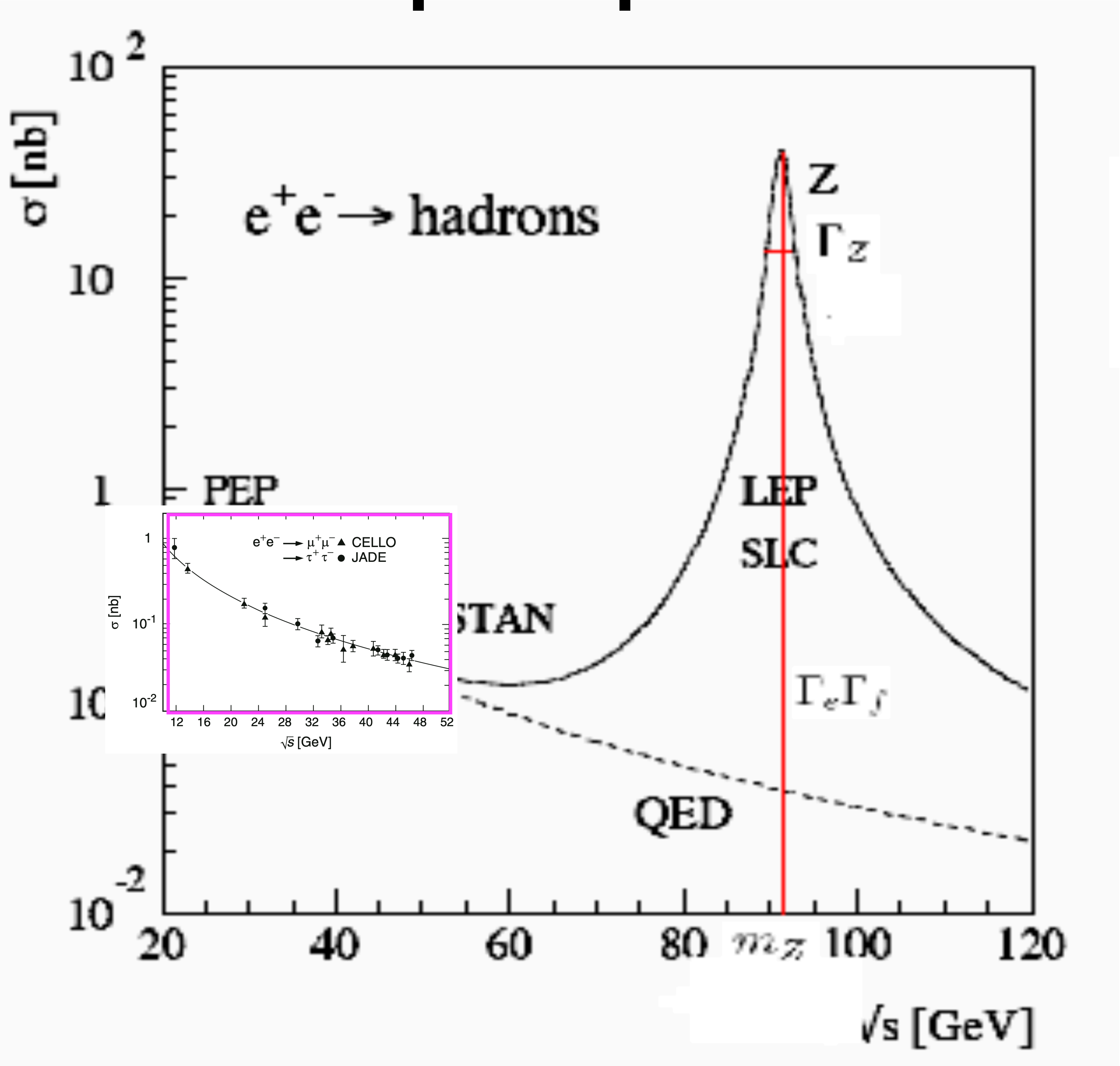


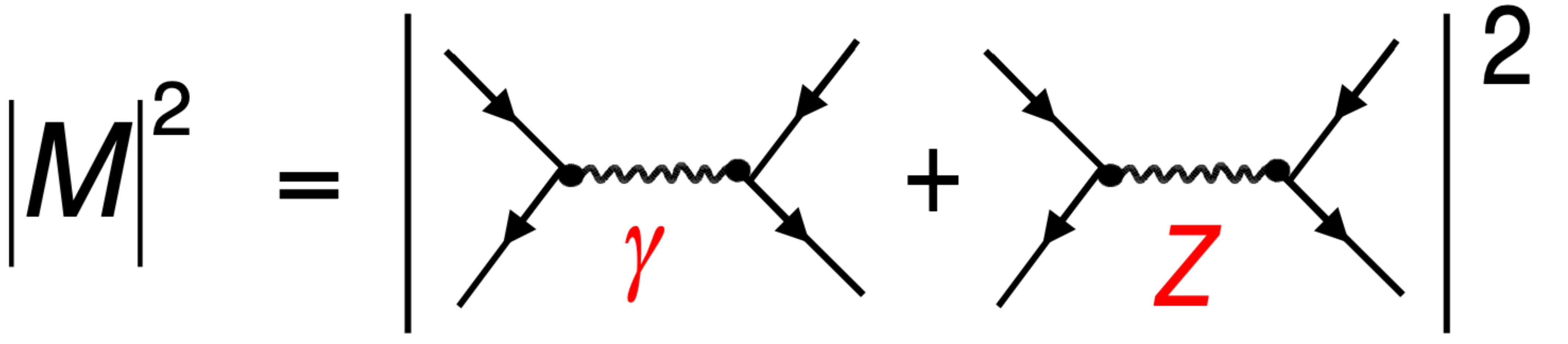

## QEFT (QED-Effective Field Theory)

tests of QED about 40 years ago …

$$\sigma \sim 1/s$$

# More complete picture



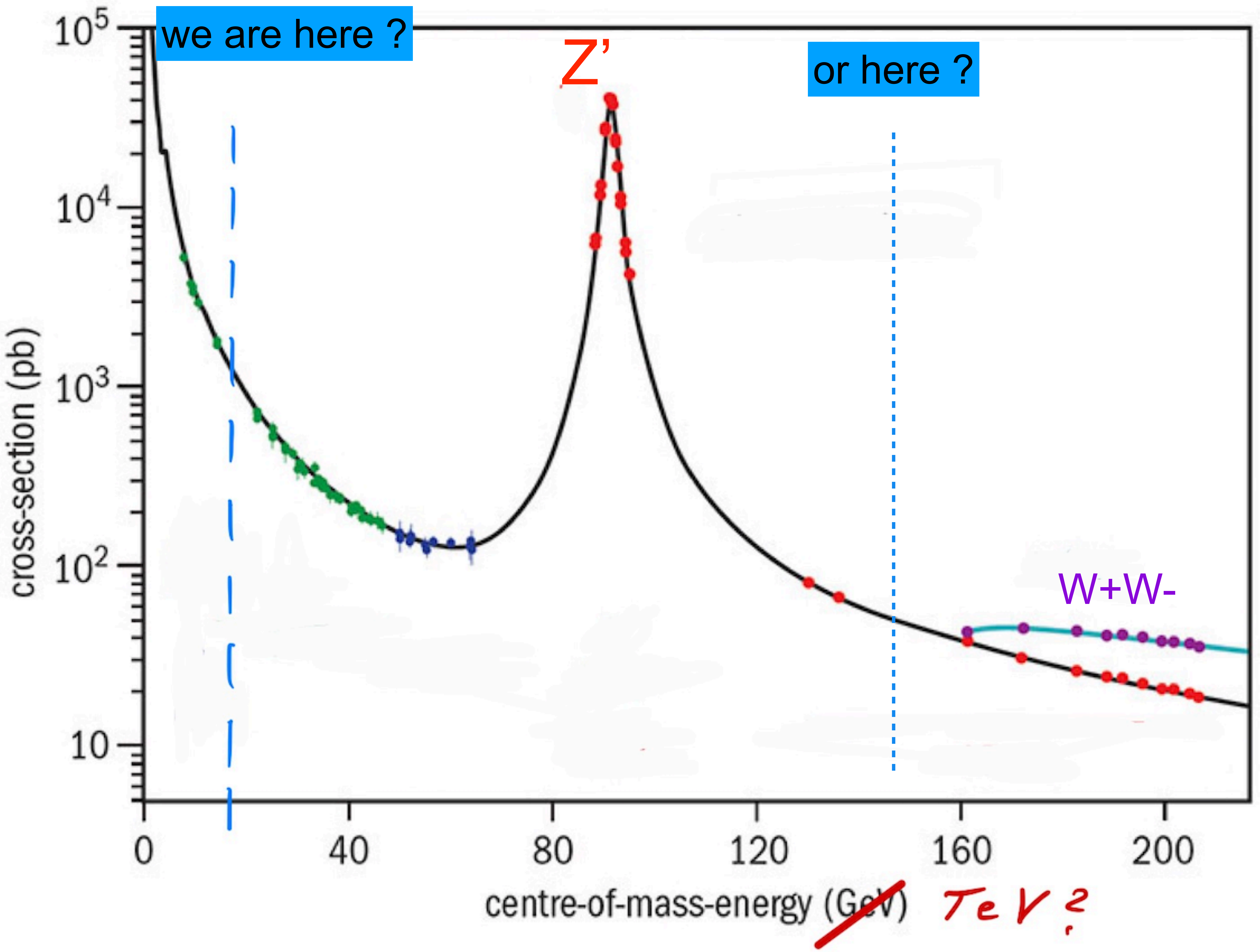




$M \sim 1/q^2$ $\qquad$ $M \sim 1/[q^2 - m_Z^2 + i m_Z \Gamma_Z]$

↓

$M \sim 1/m_Z^2$ for $q^2 \ll m_Z^2$

# Low energy picture



# Effective Field Theory expansion schemes

Karlsruhe Institute of Technology

## SMEFT (Standard Model Effective Field Theory):

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

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 $\Lambda$

$f$ : characteristic scale of Goldstone bosons

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

# Lagrangians relevant for HH production

Karlsruhe Institute of Technology

## SMEFT:

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

$$\bar{c}_i = C_i^{(6)}\frac{v^2}{\Lambda^2}$$

(SILH basis/Warsaw)

Giudice et al. hep-ph/0703164

Grzadkowski et al. 1008.4884

Gröber et al. 1504.06577

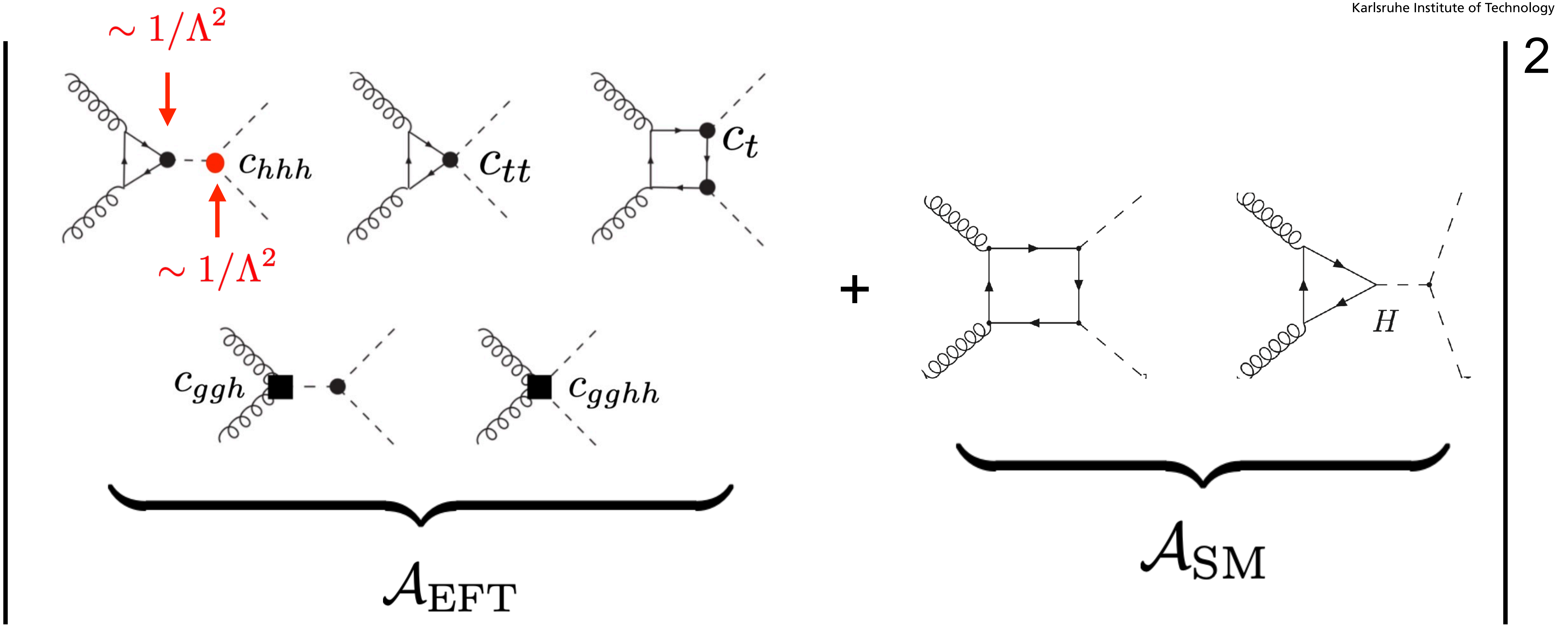
## HEFT:

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

coupling relations at Lagrangian level: $c_t = 1 - \bar{c}_H/2 - \bar{c}_u$ , $c_{tt} = -(\bar{c}_H + 3\bar{c}_u)/2$

$$c_{ggh} = 2\,c_{gghh} = 128\pi^2\bar{c}_g\ ,\quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$$

# SMEFT at amplitude squared level



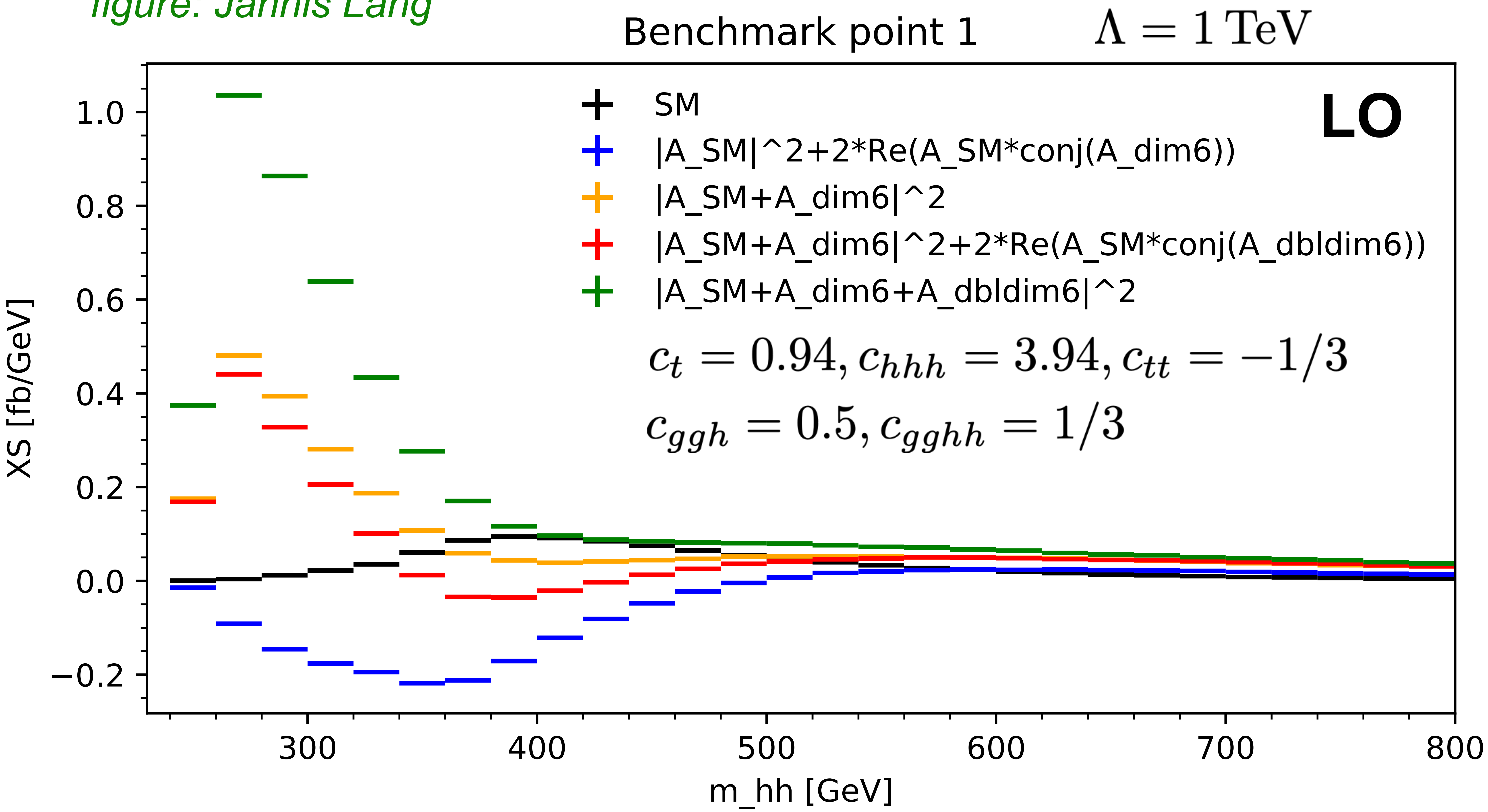

terms $\sim 1/\Lambda^4$ same order as dim 8 operators (which are not included)

# SMEFT at amplitude squared level

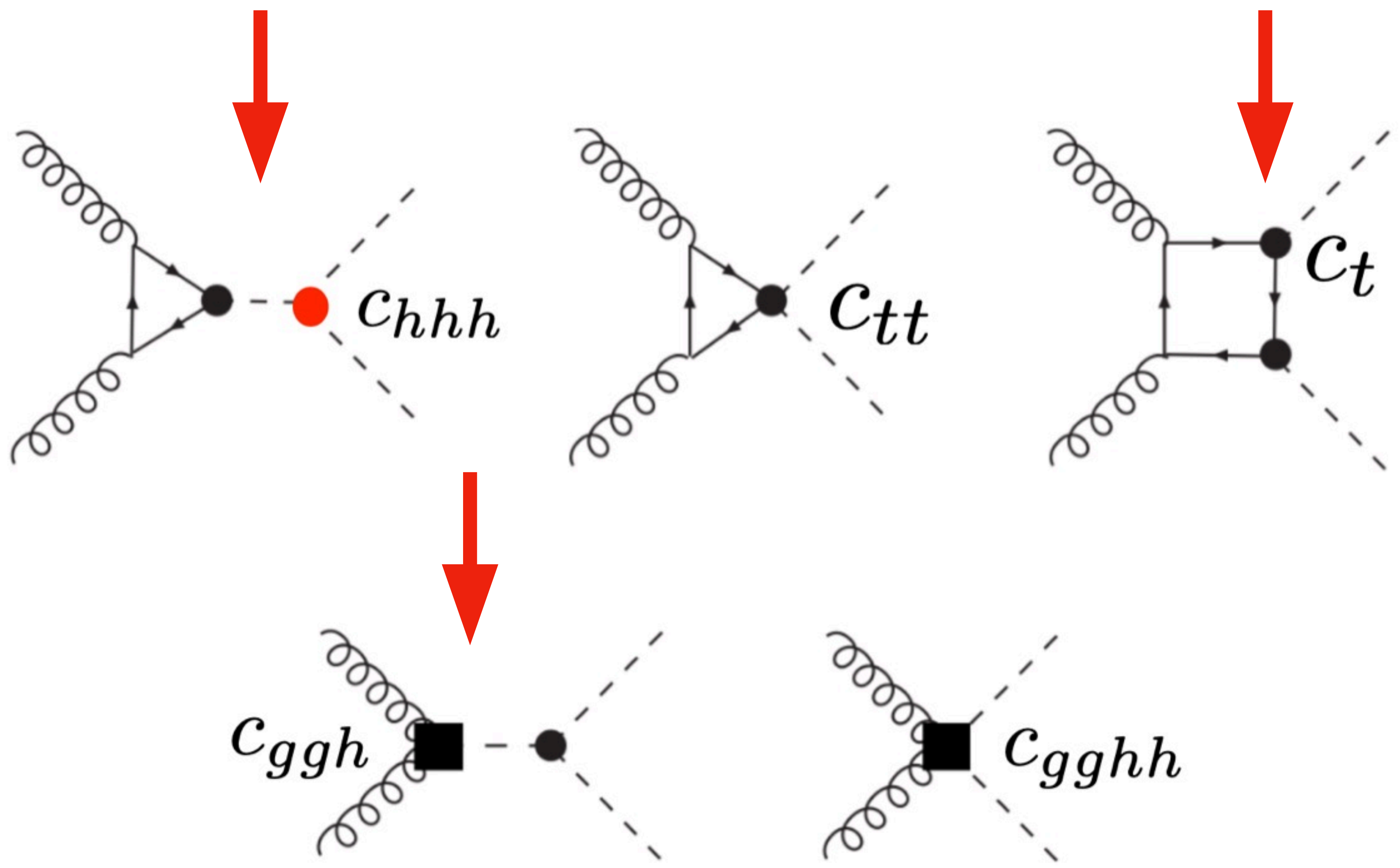
canonical dimension counting ⟶ how to treat |dim6|^2 versus dim8 ?

⟶ how to treat double operator insertions?

*figure: Jannis Lang*




two operators in one diagram



# Summary & Outlook

Karlsruhe Institute of Technology

- 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

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  - Effective field theories -> dependence on counting scheme, truncation, unitarity

efinger-consulting.de

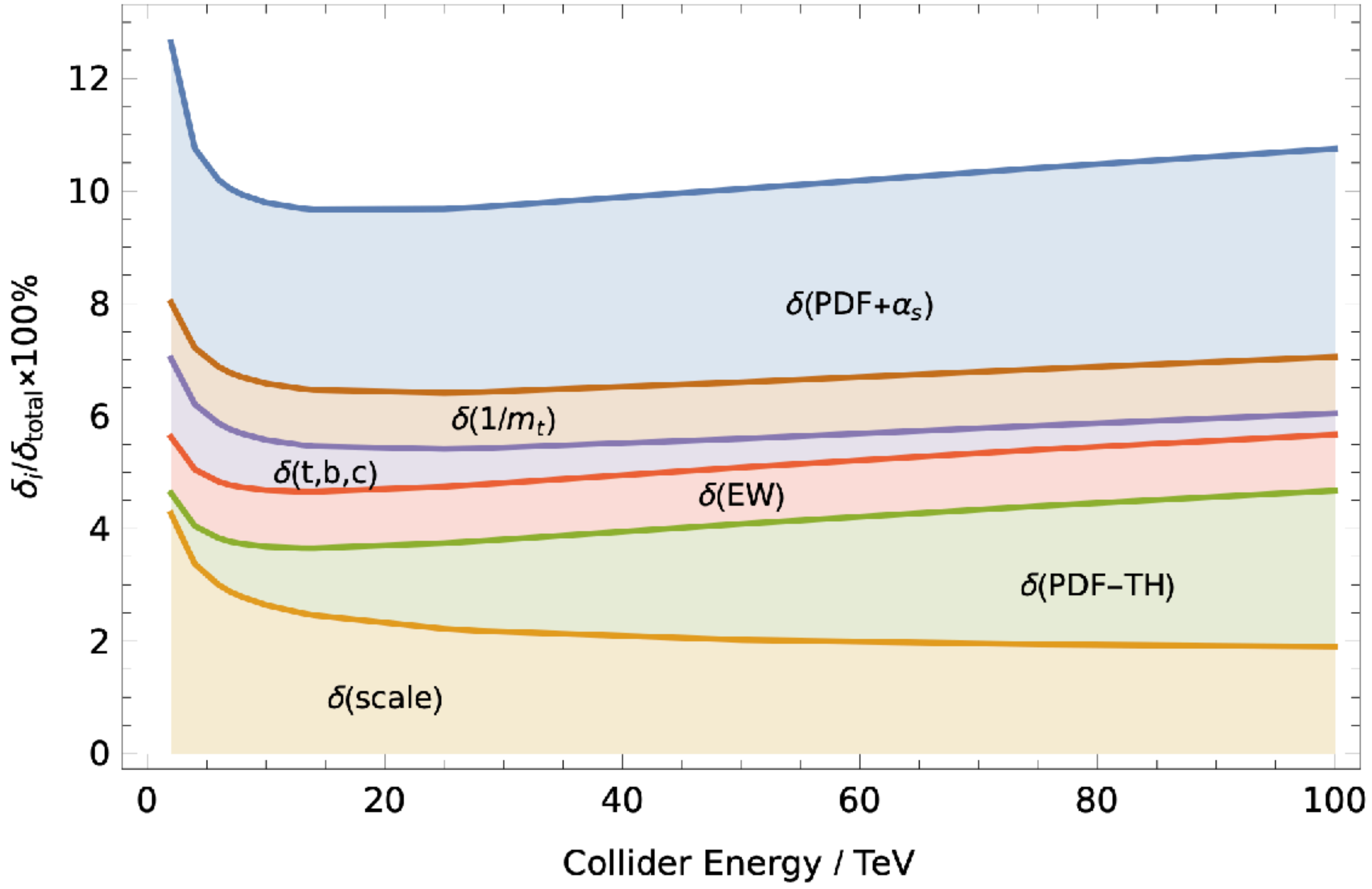
joint efforts needed to work on all the different aspects!

# Higgs production 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 | $\pm 0.56$ pb | $\pm 0.49$ pb | $\pm 0.40$ pb | $\pm 0.49$ pb | $\pm$ 0.89 pb | $^{+1.25}_{-1.26}$ pb |
| $^{+0.21\%}_{-2.37\%}$ | $\pm 1.16\%$ | $\pm 1\%$ | $\pm 0.83\%$ | $\pm 1\%$ | $\pm 1.85\%$ | $^{+2.59\%}_{-2.62\%}$ |

scale uncertainties no longer the dominant uncertainties

2009.00516

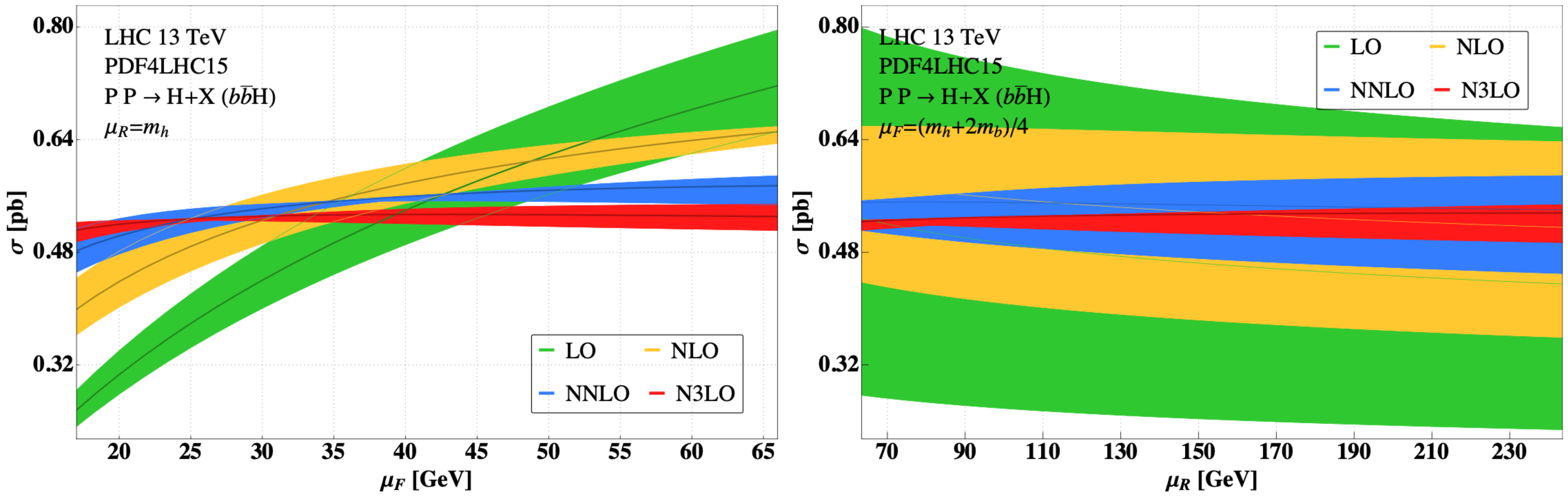



NNLO PDFs with
$\text{N}^3\text{LO}\ \sigma$

1902.00134

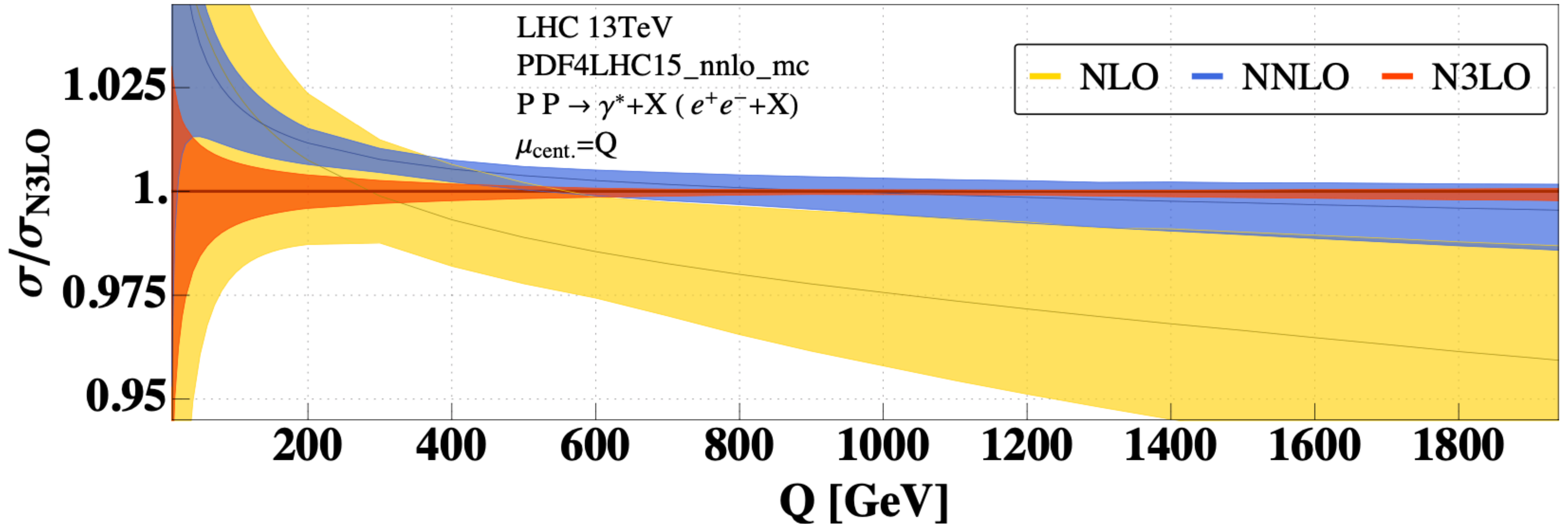
# bbH

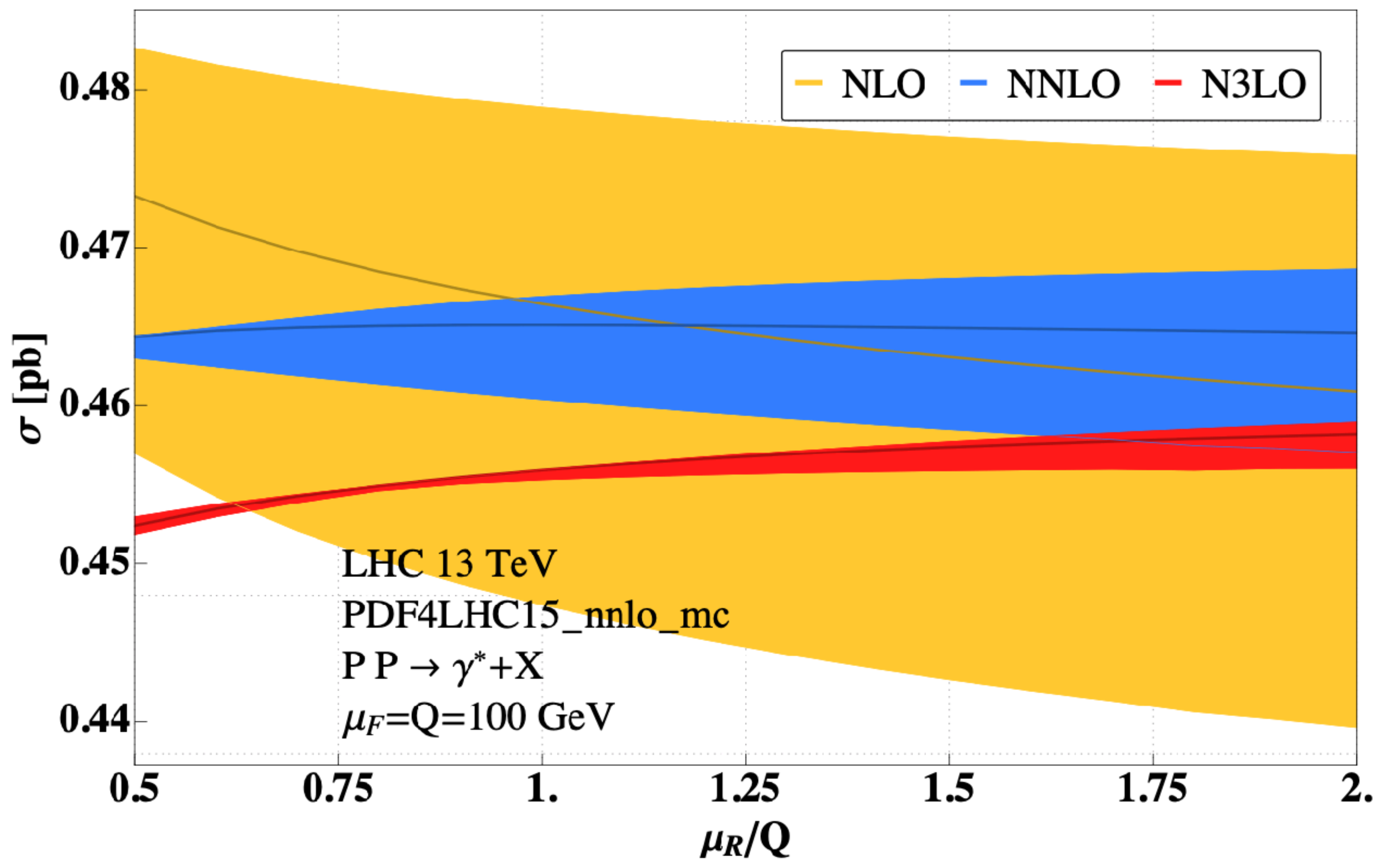
Karlsruhe Institute of Technology

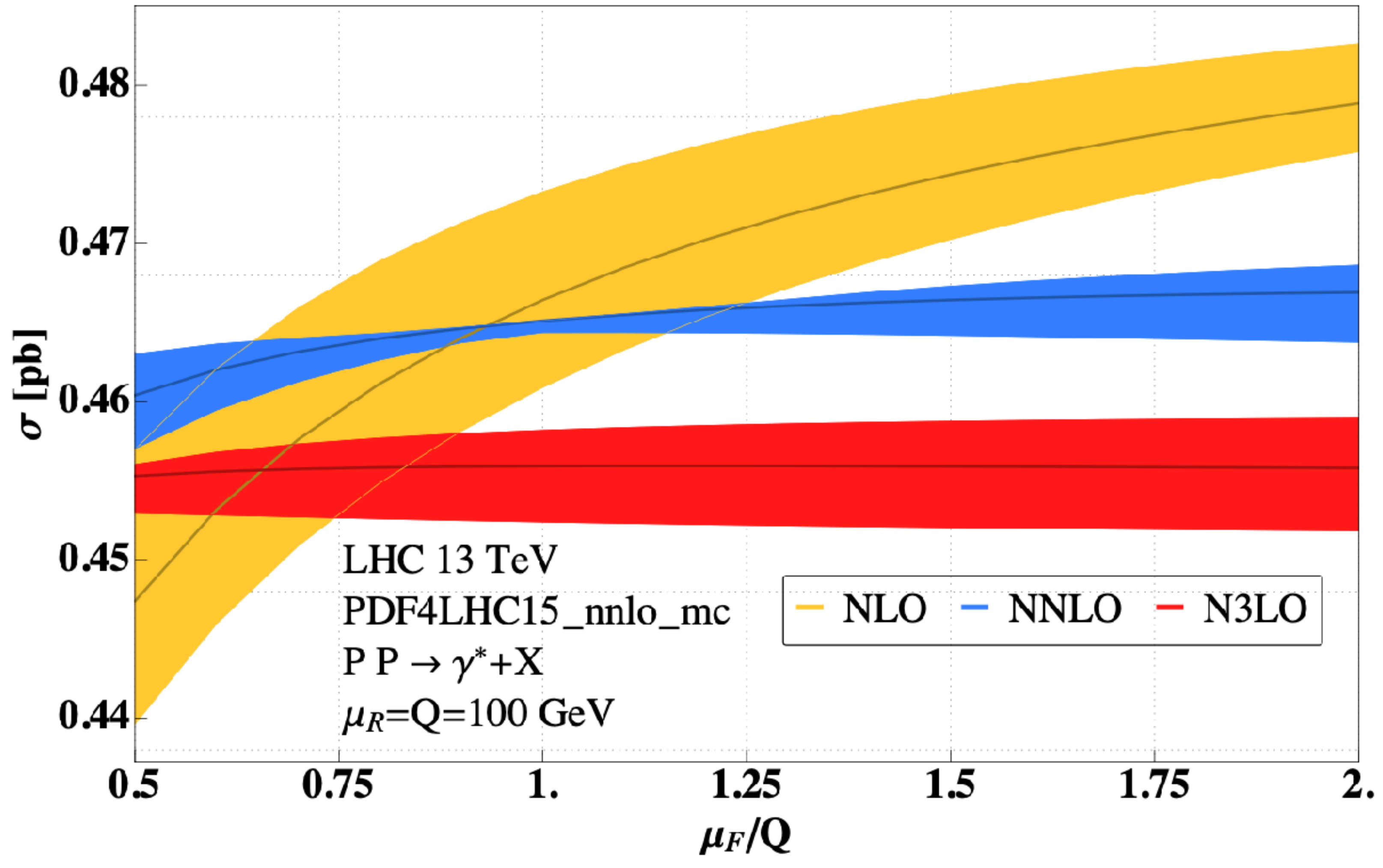


# Drell-Yan (NC)

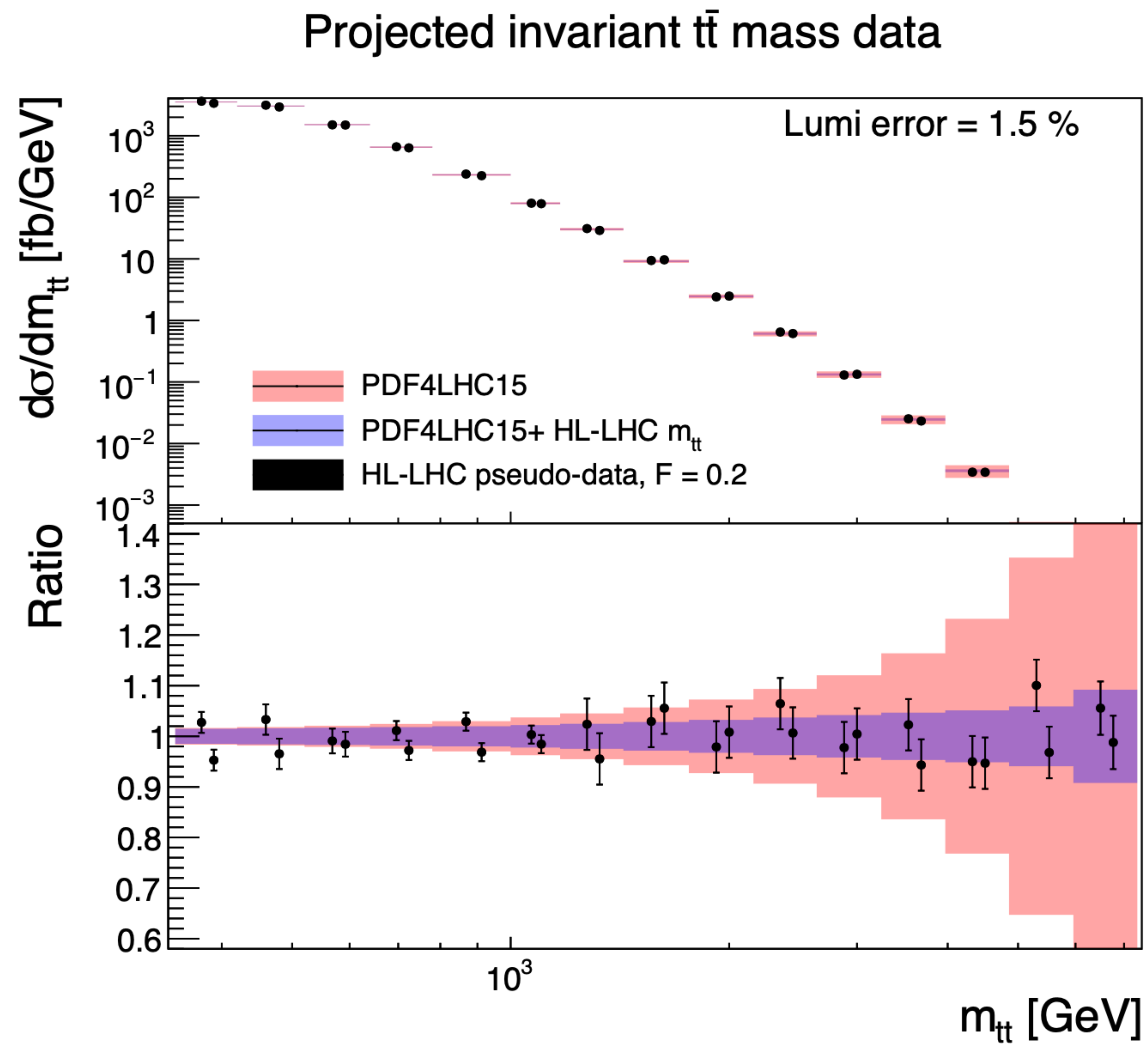
Duhr, Dulat, Mistlberger
2001.07717



# PDFs




R. Khalek et al, 1810.03639

# 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

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

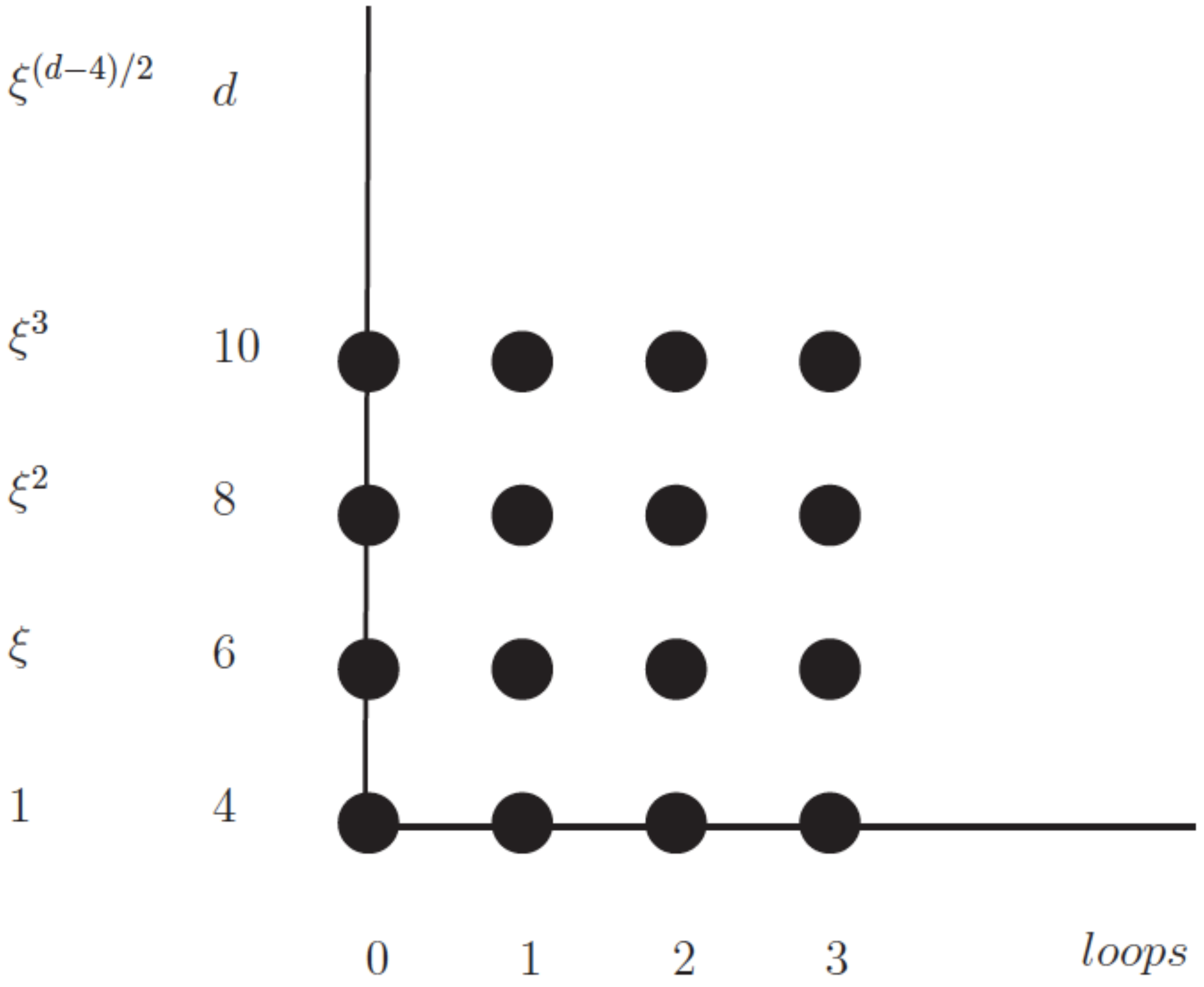



*figure: G.Buchalla*

loop expansion

HEFT