Karlsruhe Institute of Technology

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Precision calculations in the Higgs sector

foto: Wikimedia

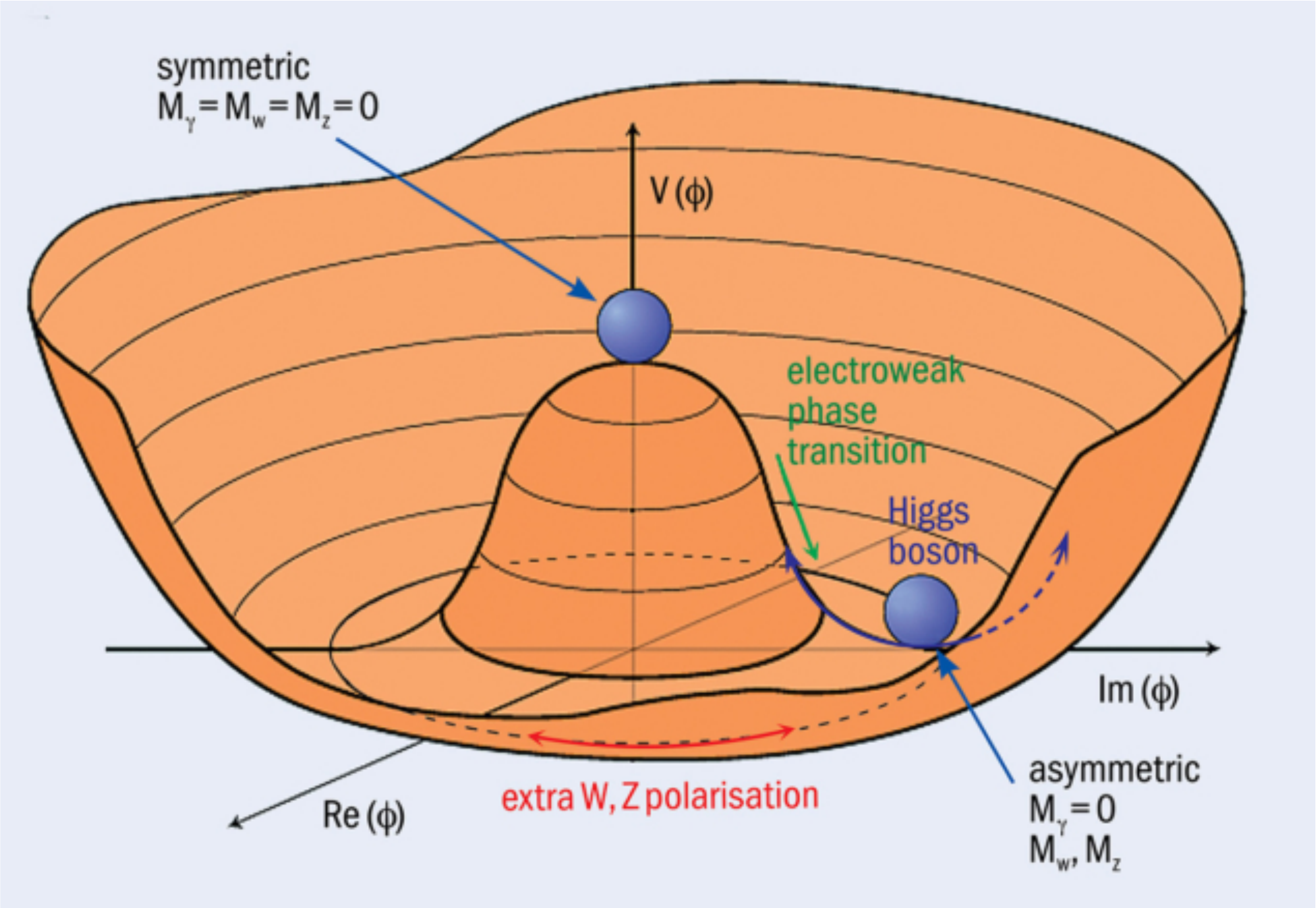
Gudrun Heinrich

Institute for Theoretical Physics
Karlsruhe Institute of Technology

QCD@LHC, Freiburg

October 8, 2024

Higgs bosons

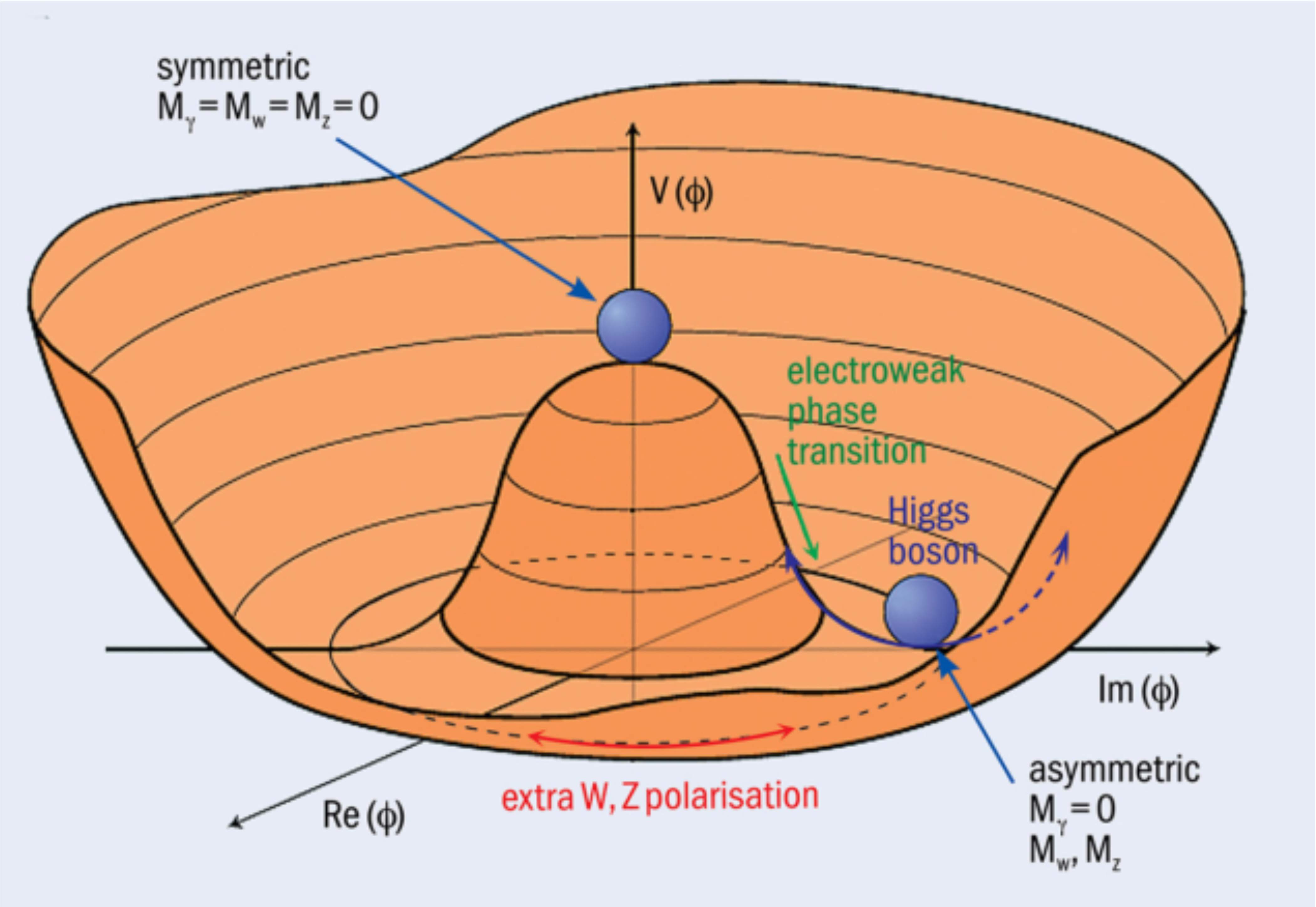


J. Ellis, M. Neubauer, CERN Courier

“We think we have it”

(Rolf Heuer 2012)

Higgs bosons

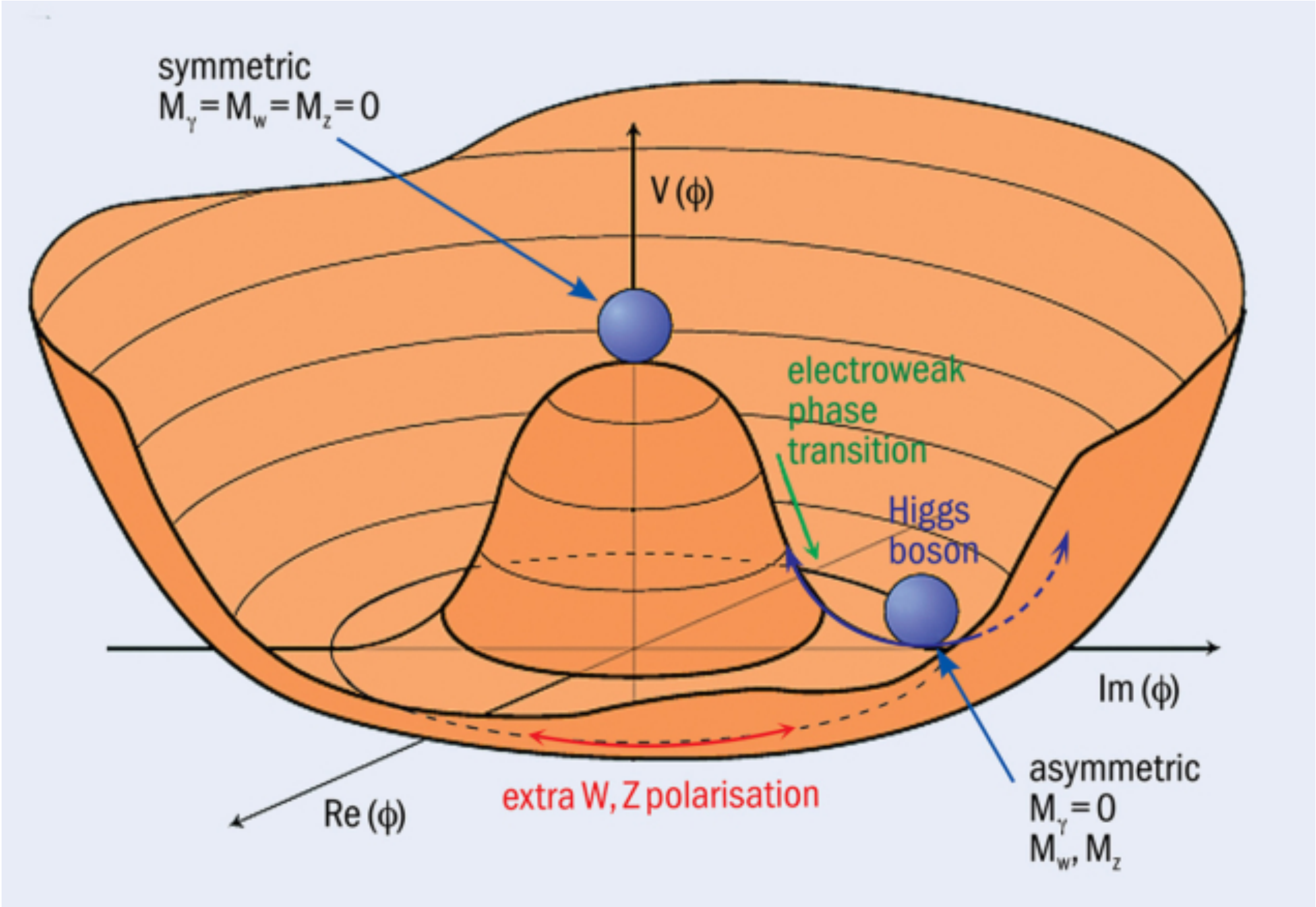


J. Ellis, M. Neubauer, CERN Courier

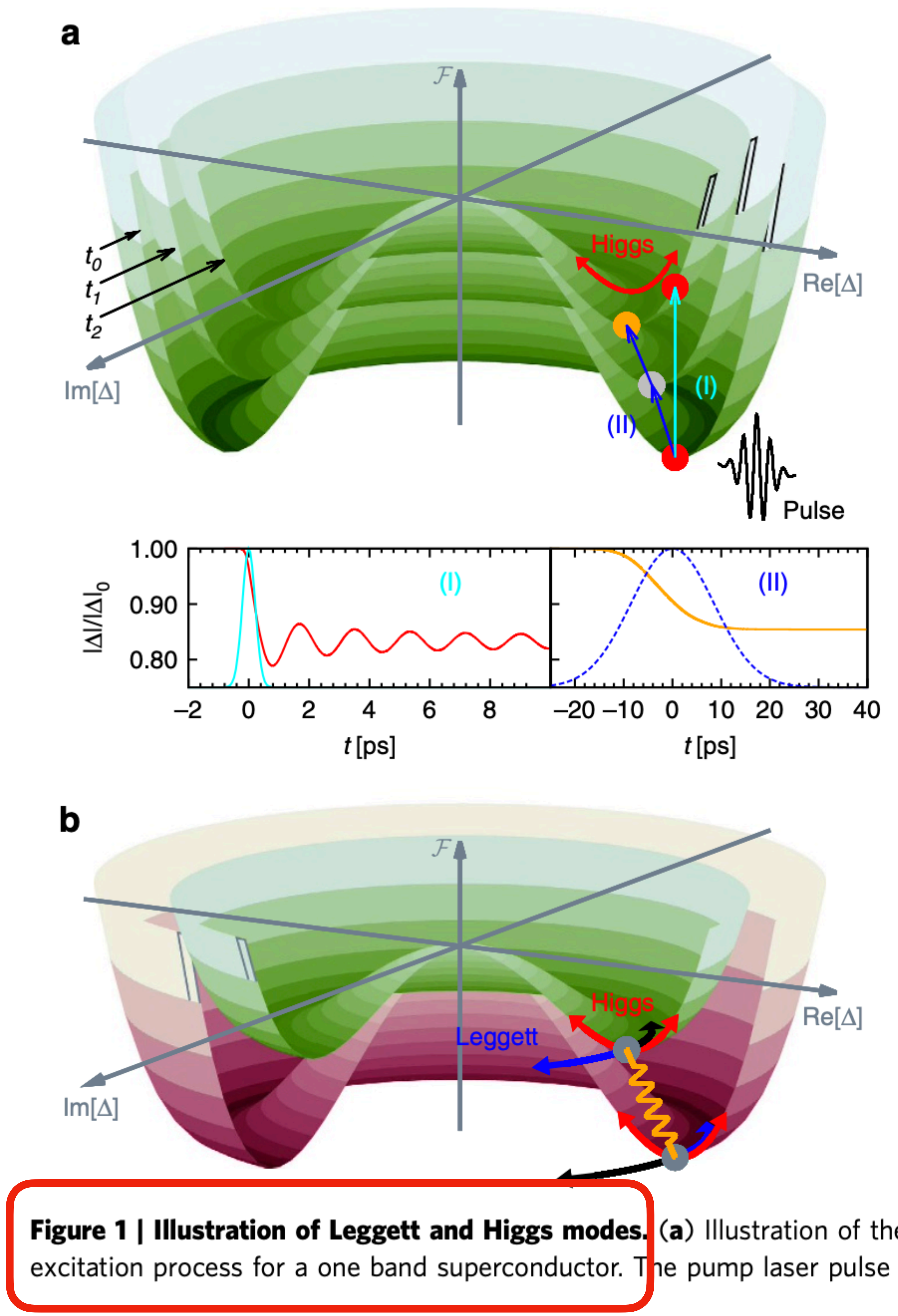
“We think we have it” … but it is not the only one …

(Rolf Heuer 2012)

Higgs bosons



J. Ellis, M. Neubauer, CERN Courier



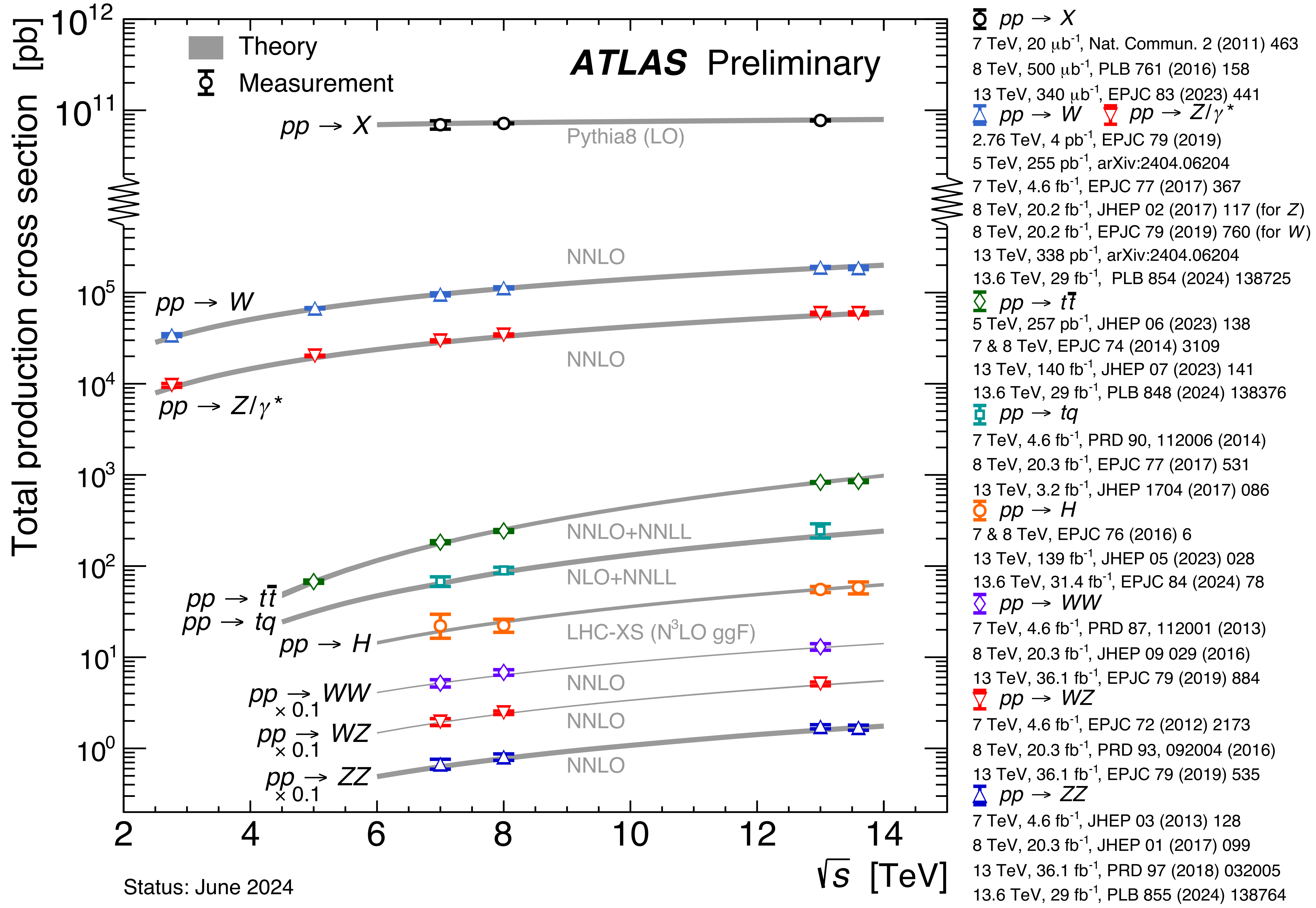
H. Krull et al., Nature Communications 7:11921, 2016

"We think we have it" … but it is not the only one …

(Rolf Heuer 2012)

The LHC as a precision hadron collider

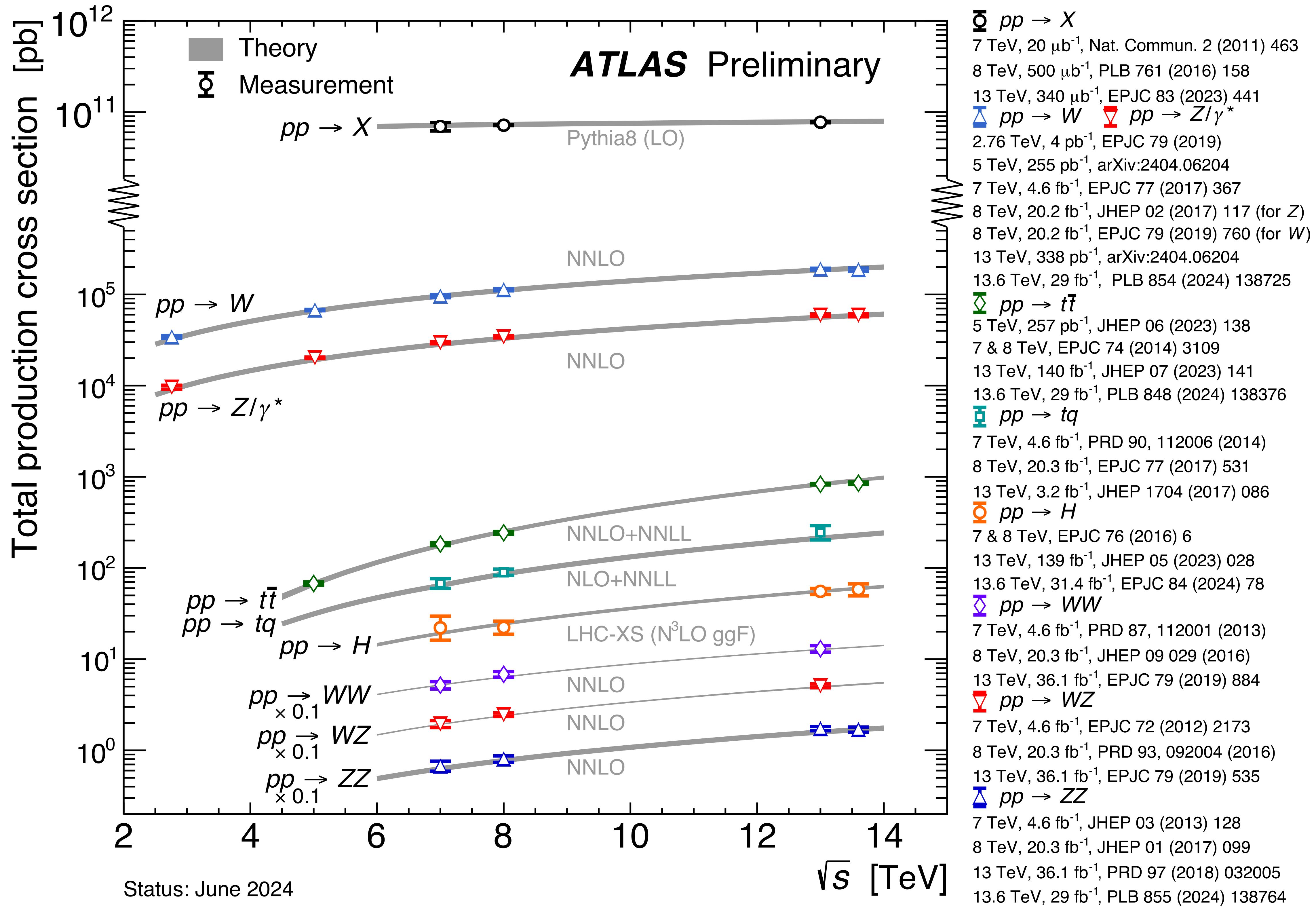
ATL-PHYS-PUB-2024-011

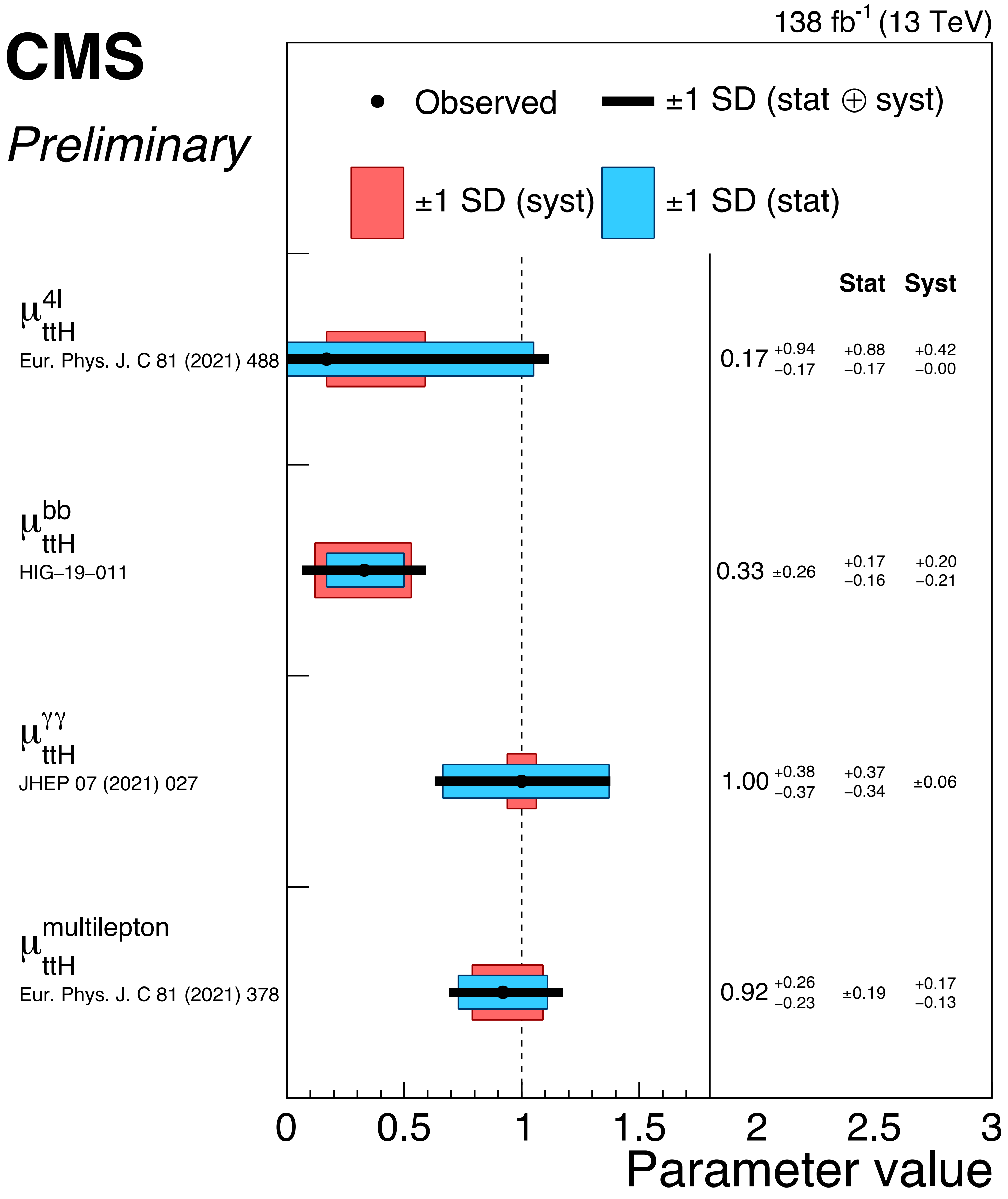


- good news: predictions mostly at NNLO (or higher)

The LHC as a precision hadron collider

ATL-PHYS-PUB-2024-011





2207.00043 (Nature)

- good news: predictions mostly at NNLO (or higher)
- bad (?) news: need higher precision in both data and predictions to clearly identify deviations from the SM

The LHC as a precision hadron collider

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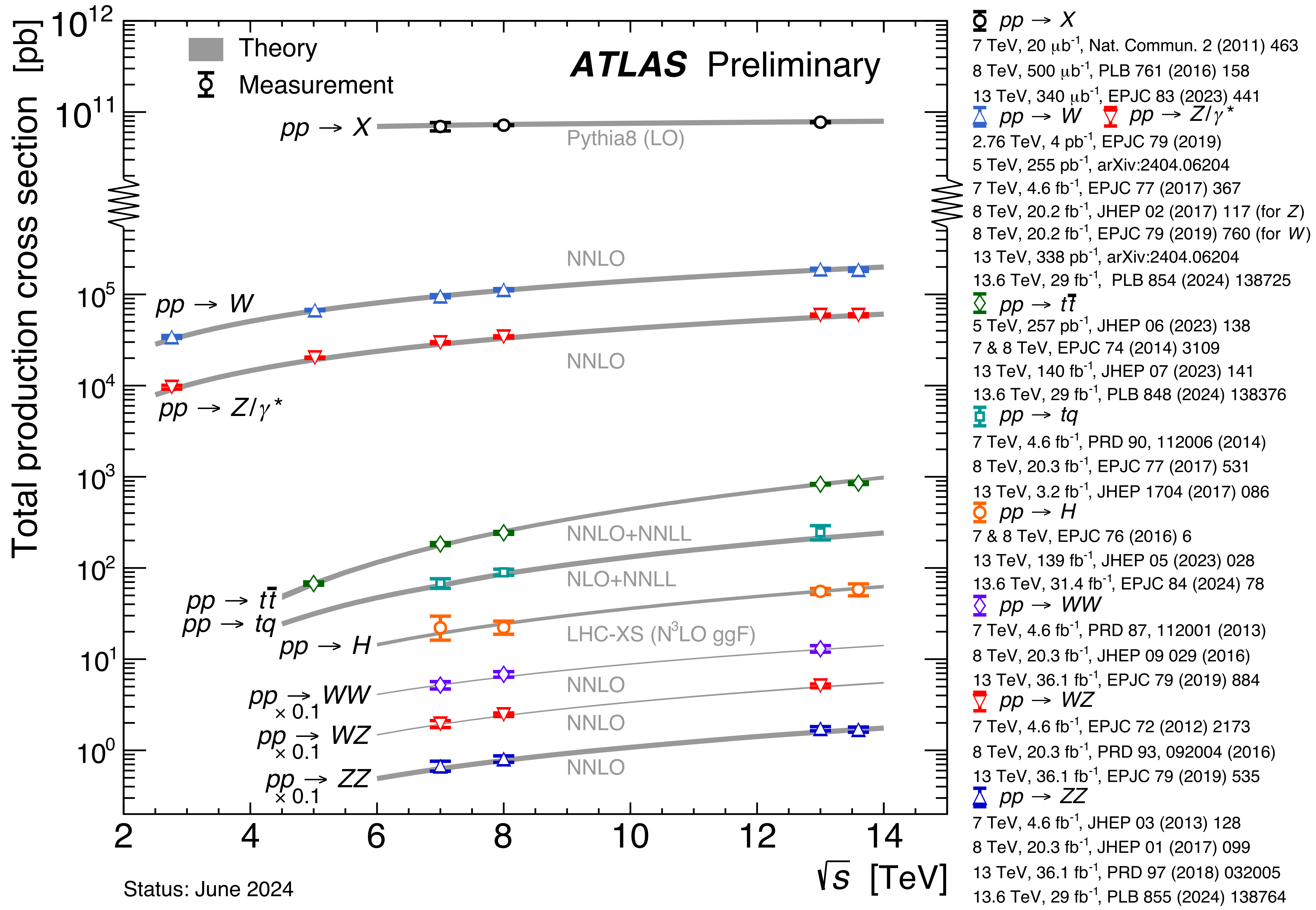
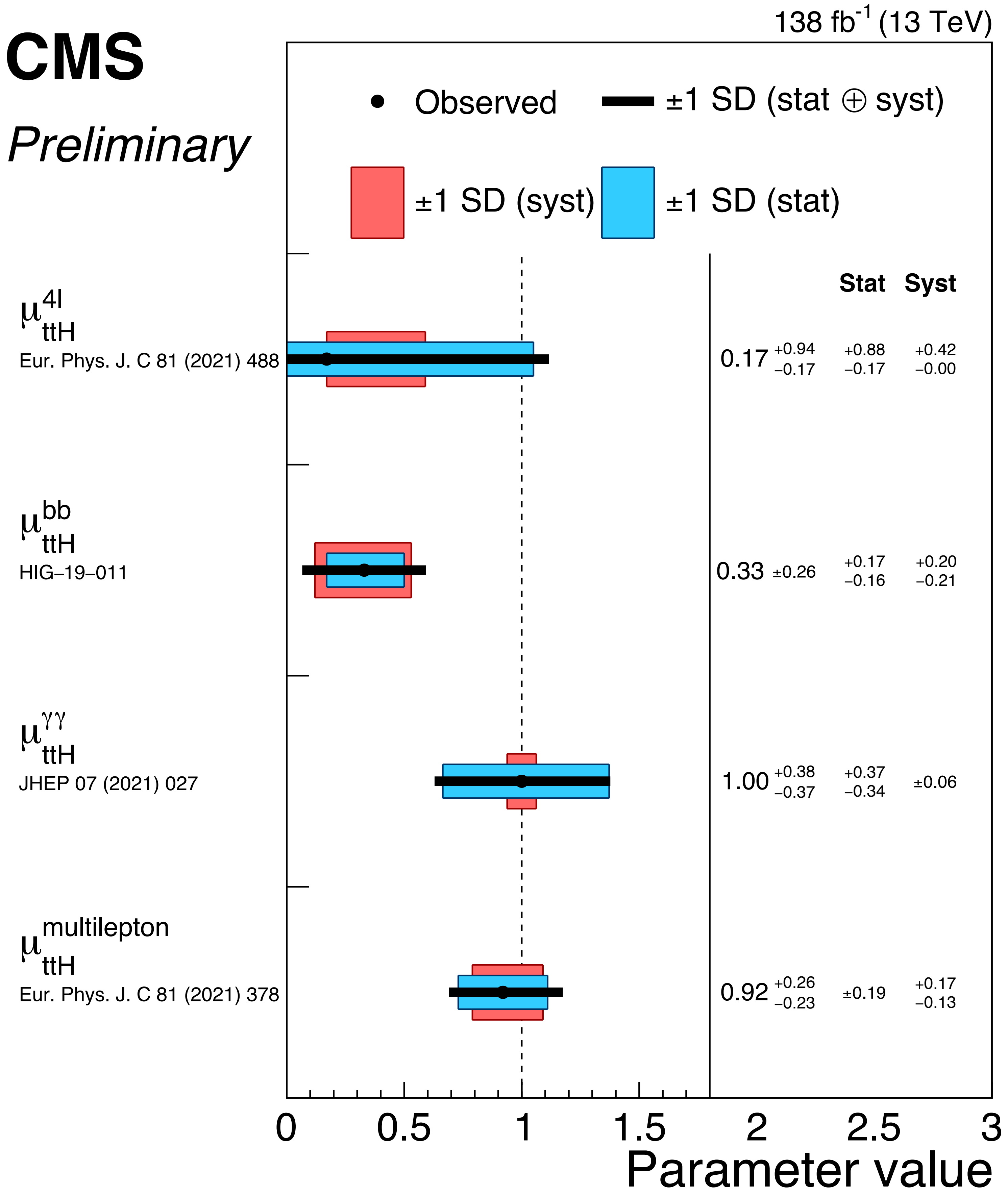
ATL-PHYS-PUB-2024-011





2207.00043 (Nature)

- good news: predictions mostly at NNLO (or higher)
- bad (?) news: need higher precision in both data and predictions to clearly identify deviations from the SM
- HL-LHC will decrease statistical uncertainties substantially ⟶ prime time for precision calculations!

Beyond total cross sections

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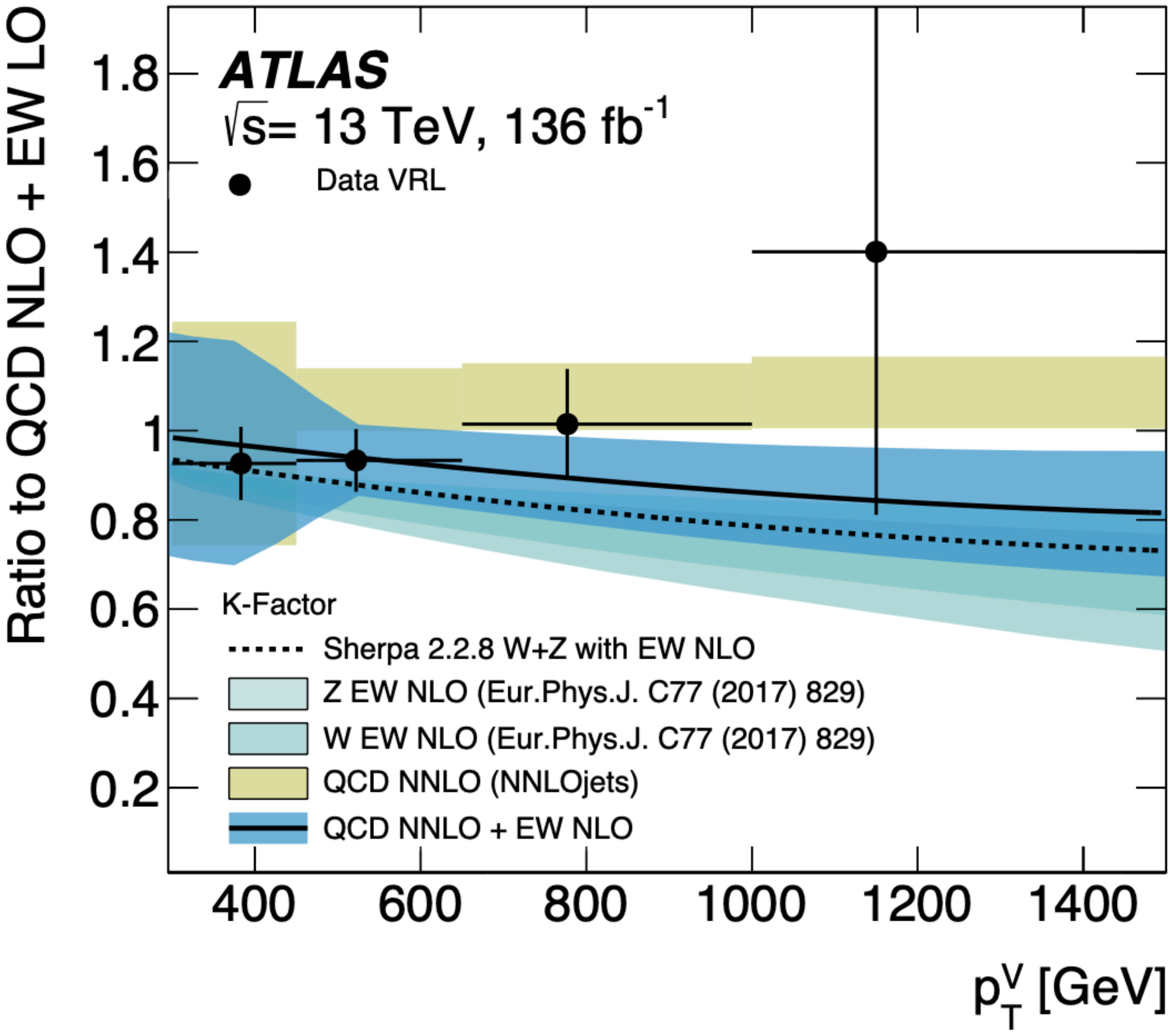
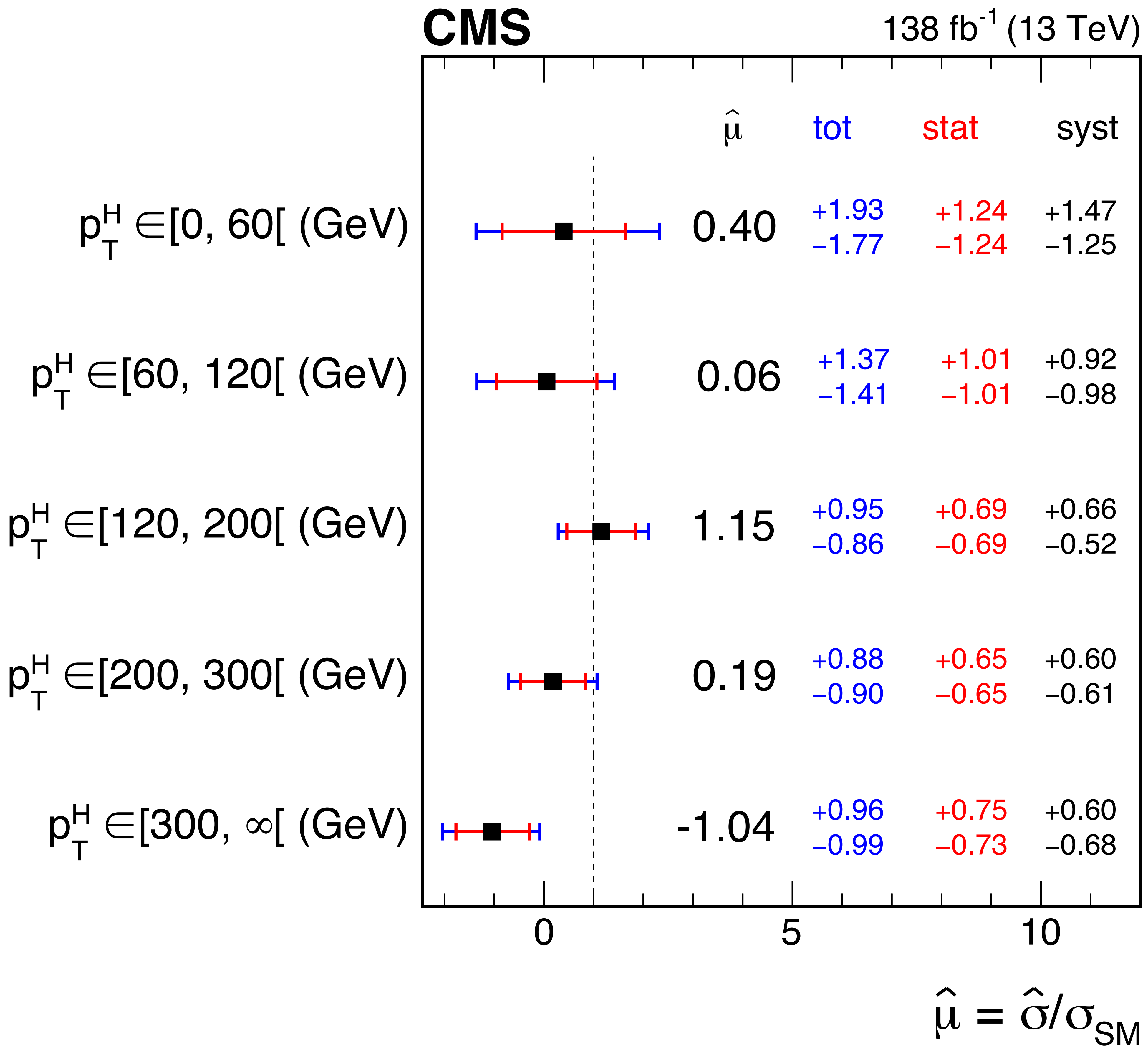


2111.08340



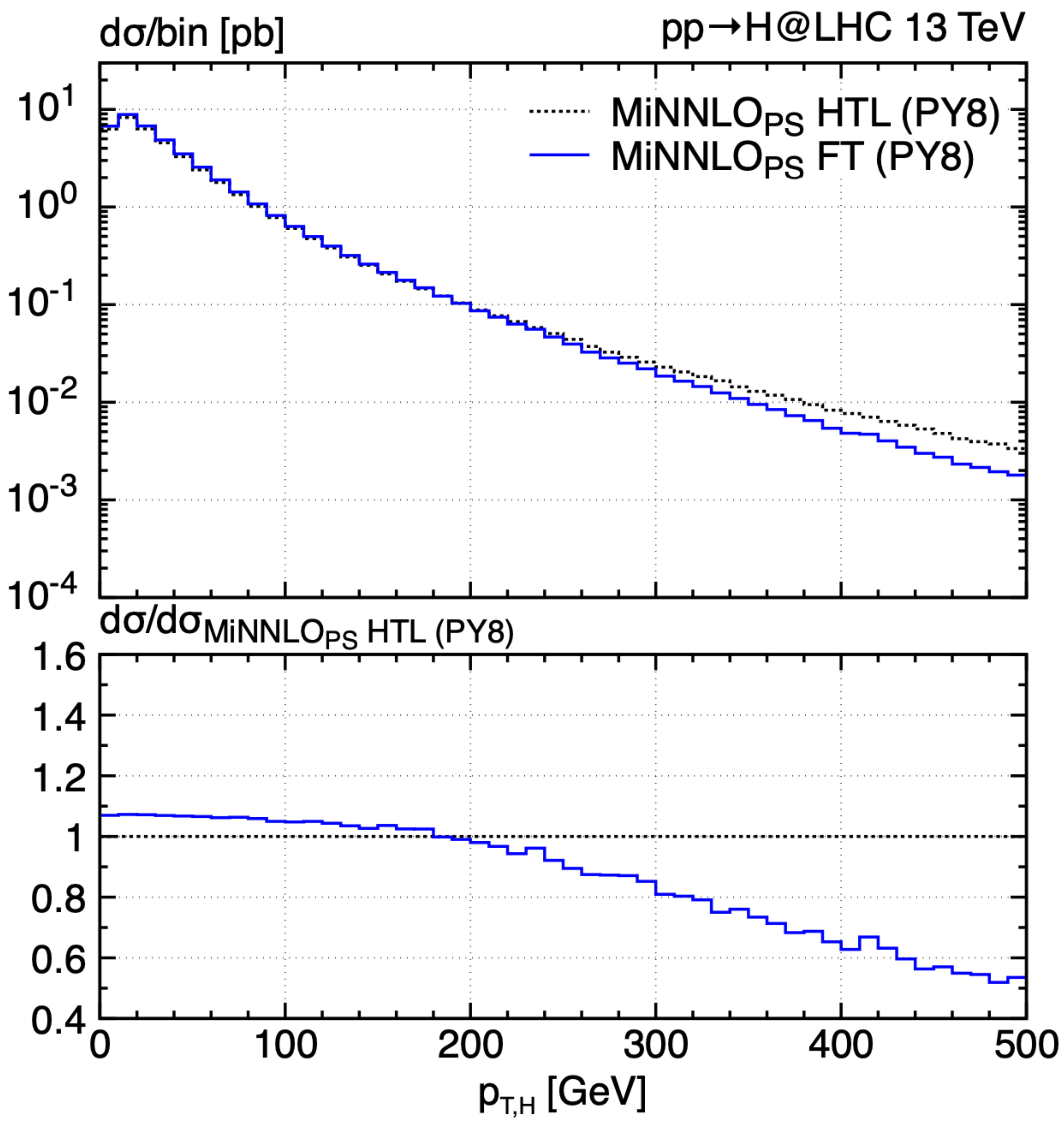
CERN-EP-2024-179

more differential information than total cross section is important

Outline

- focus on recent results in:
  - gluon fusion Higgs production
  - Higgs + jet production
  - VBF Higgs production
  - ttH production
  - Higgs boson pair production in gluon fusion
- not covered: VH, tH, bbH, couplings to 2nd generation, HHH, …
- apologies for the biased and incomplete selection

Higgs production at NNLO+PS

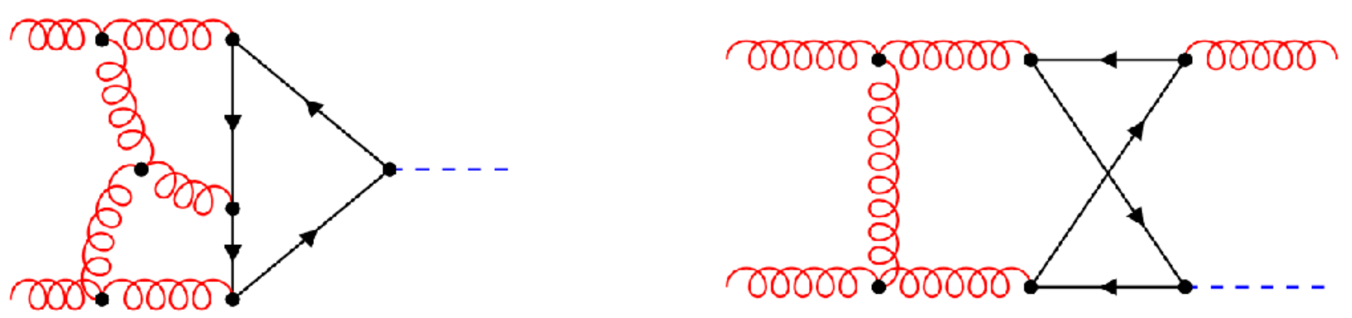


Niggetiedt, Wiesemann 2407.01354

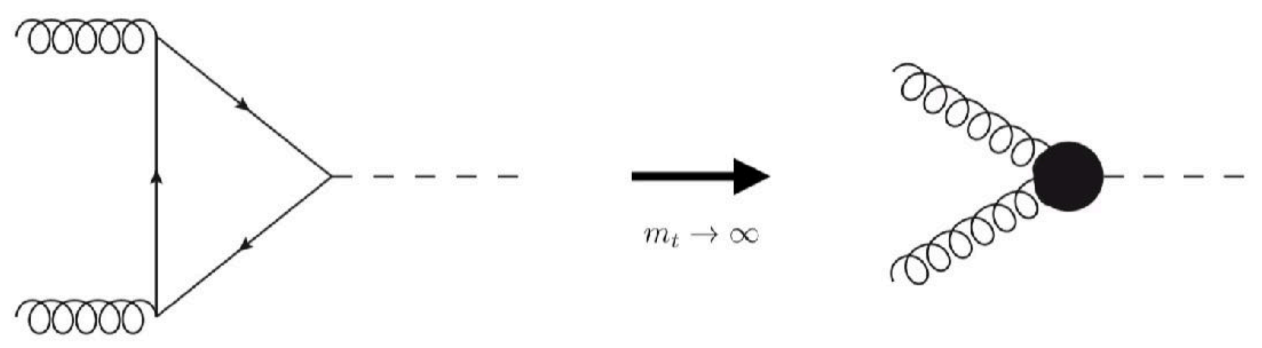
includes gg -> H up to 3 loops and

pp -> H+jet up to two loops with full top mass dependence

Czakon, Harlander, Klappert, Niggetiedt '20



uses MiNNLO_PS Monni, Nason, Re, Wiesemann, Zanderighi 1908.06987



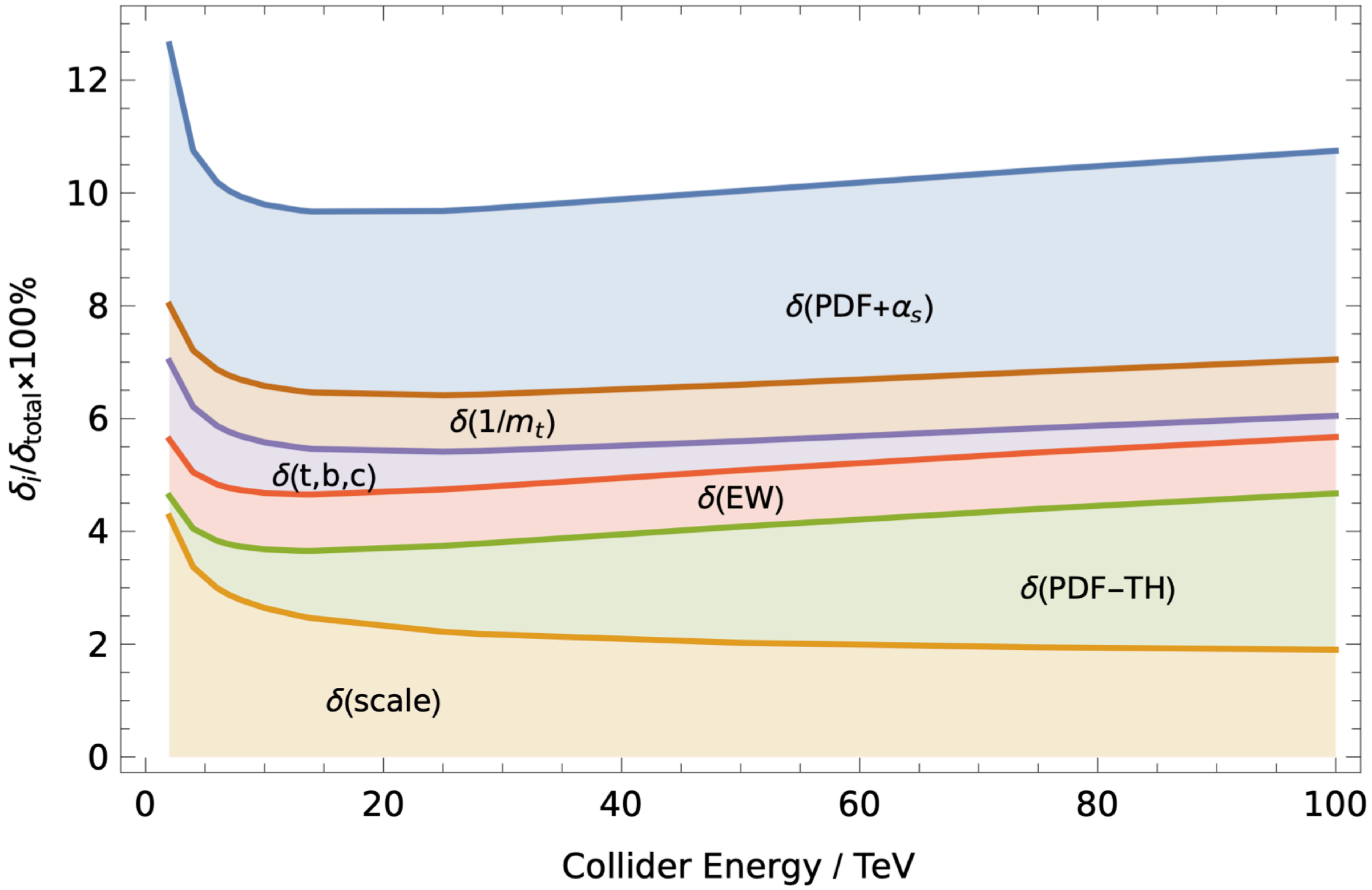
heavy top limit (HTL)

more than 40% difference between full theory (FT)
and heavy top limit (HTL) in tail of pT,H distribution

Higgs production in gluon fusion

uncertainty budget 6 years ago

Dulat, Lazopoulos, Mistlberger ’18
N3LO in heavy top limit



see PDF sessions and talk by Valentina Guglielmi

basically removed (NNLO with full top mass)

Czakon, Harlander, Klappert, Niggetiedt ‘20

Higgs production in gluon fusion

uncertainty budget 6 years ago

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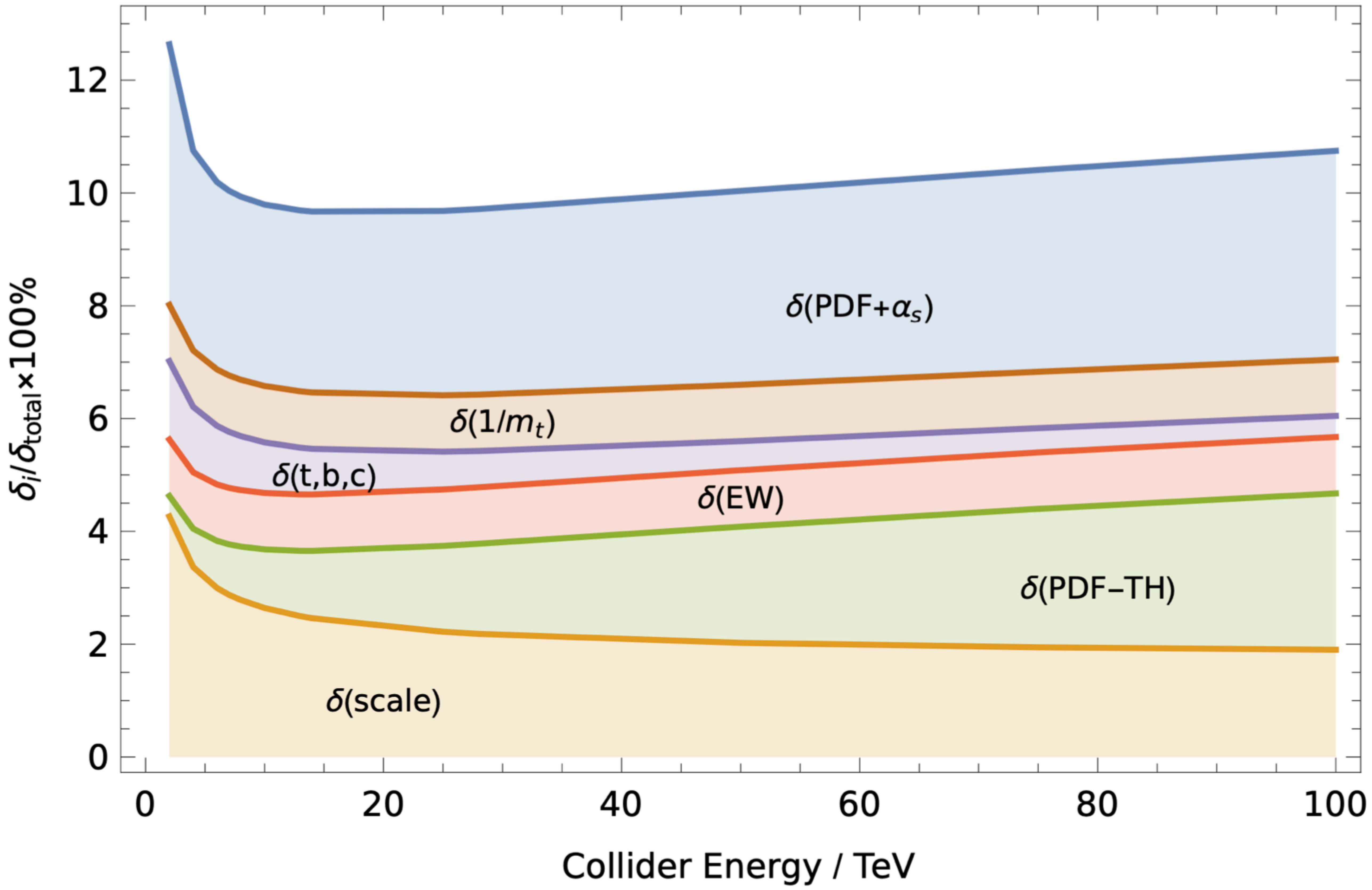

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t-b interference at NNLO calculated recently

Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger ’23, ‘24

Higgs production in gluon fusion

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uncertainty budget 6 years ago

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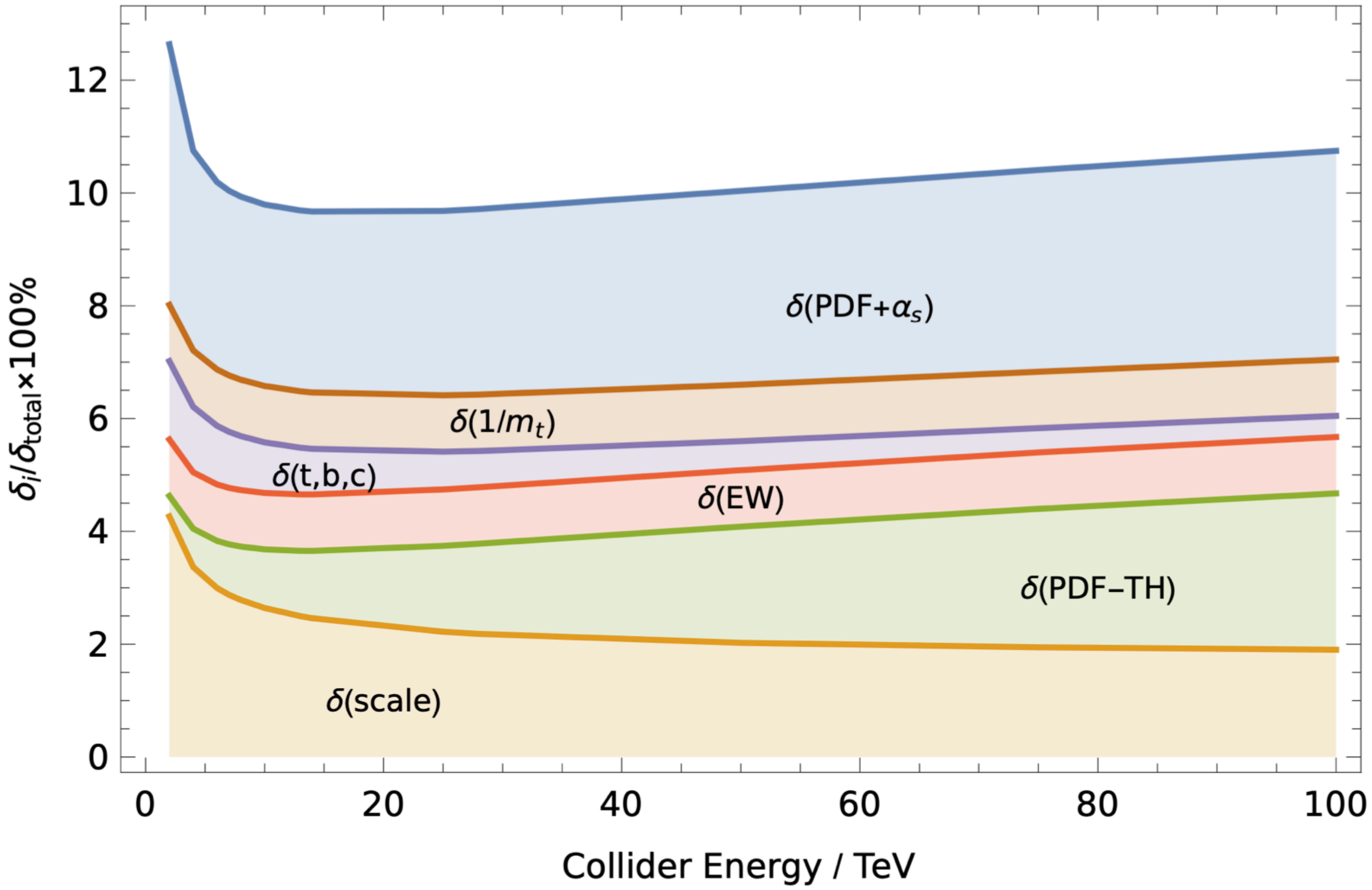

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t-b interference at NNLO calculated recently
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reduced to 0.6%
Bechetti et al ’20, ’21, Bonetti et al ’18, ’20, ‘22

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uncertainty budget 6 years ago

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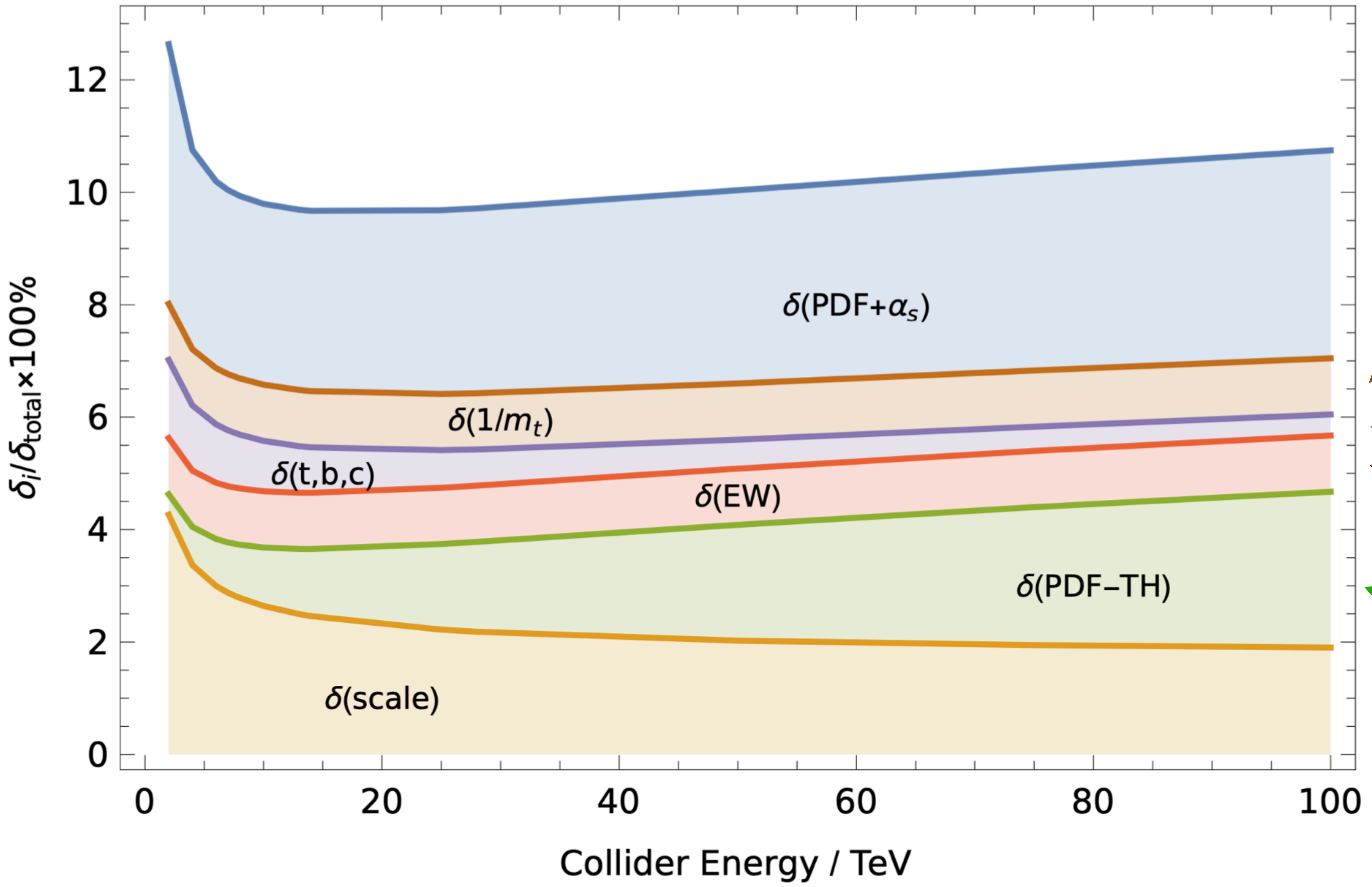

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mismatch between PDF (NNLO) and ME (N3LO)
towards N3LO PDFs: MSHT 2207.04739, NNPDF4.0 2402.18635, Cooper-Sarkar et al. 2406.16188, Falcioni et al 2302.07593, Guan et al. 2408.03019, Gehrmann, Manteuffel, Sotnikov, Yang '23, '24

Higgs production in gluon fusion

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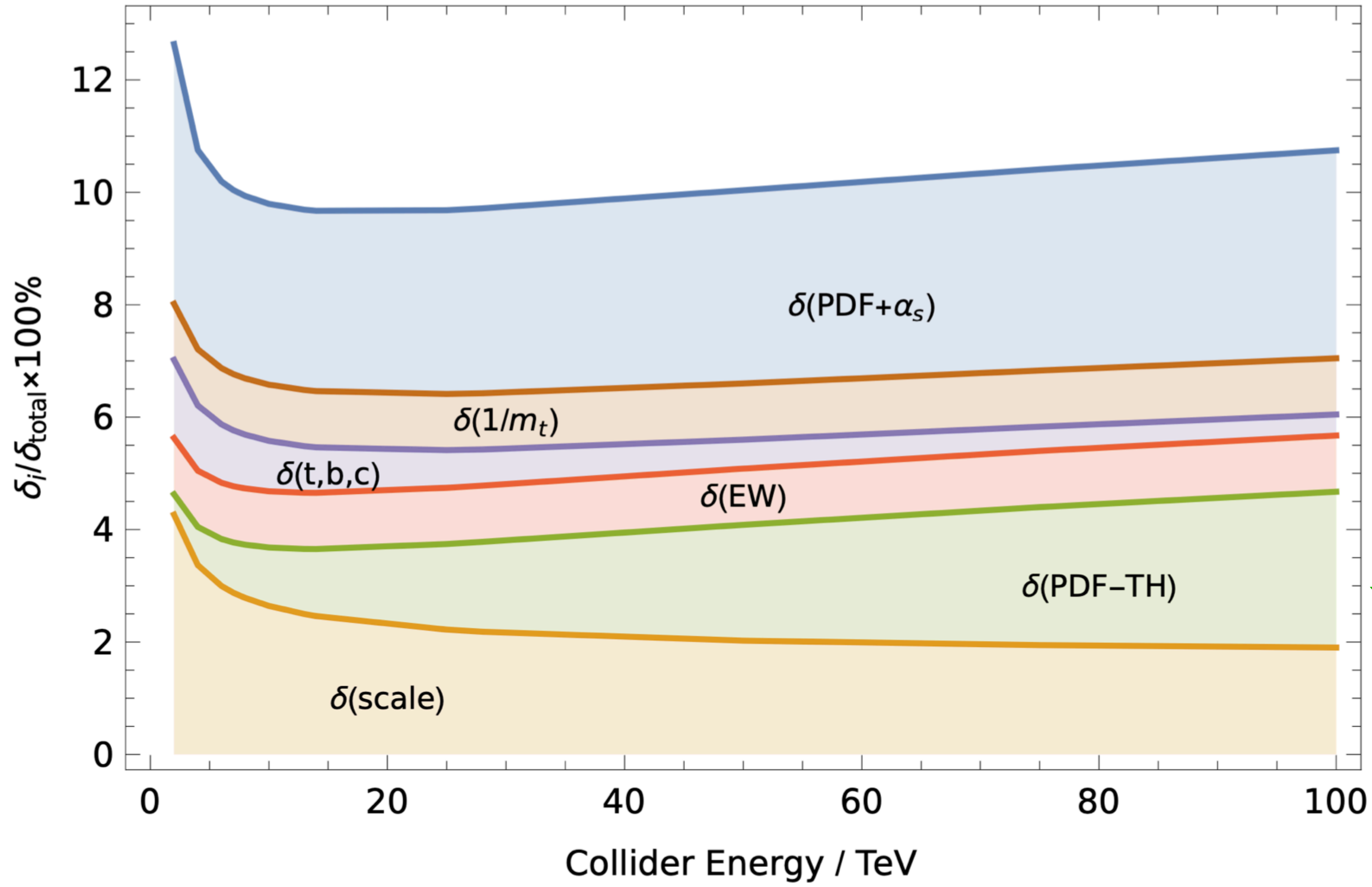
uncertainty budget 6 years ago   Dulat, Lazopoulos, Mistlberger '18
N3LO in heavy top limit



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N4LO soft-virtual approx. Das, Moch, Vogt '20;
4-loop form factor Lee, Manteuffel, Schabinger, Smirnov, Smirnov Steinhauser '22,'23

approximate N3LO PDFs

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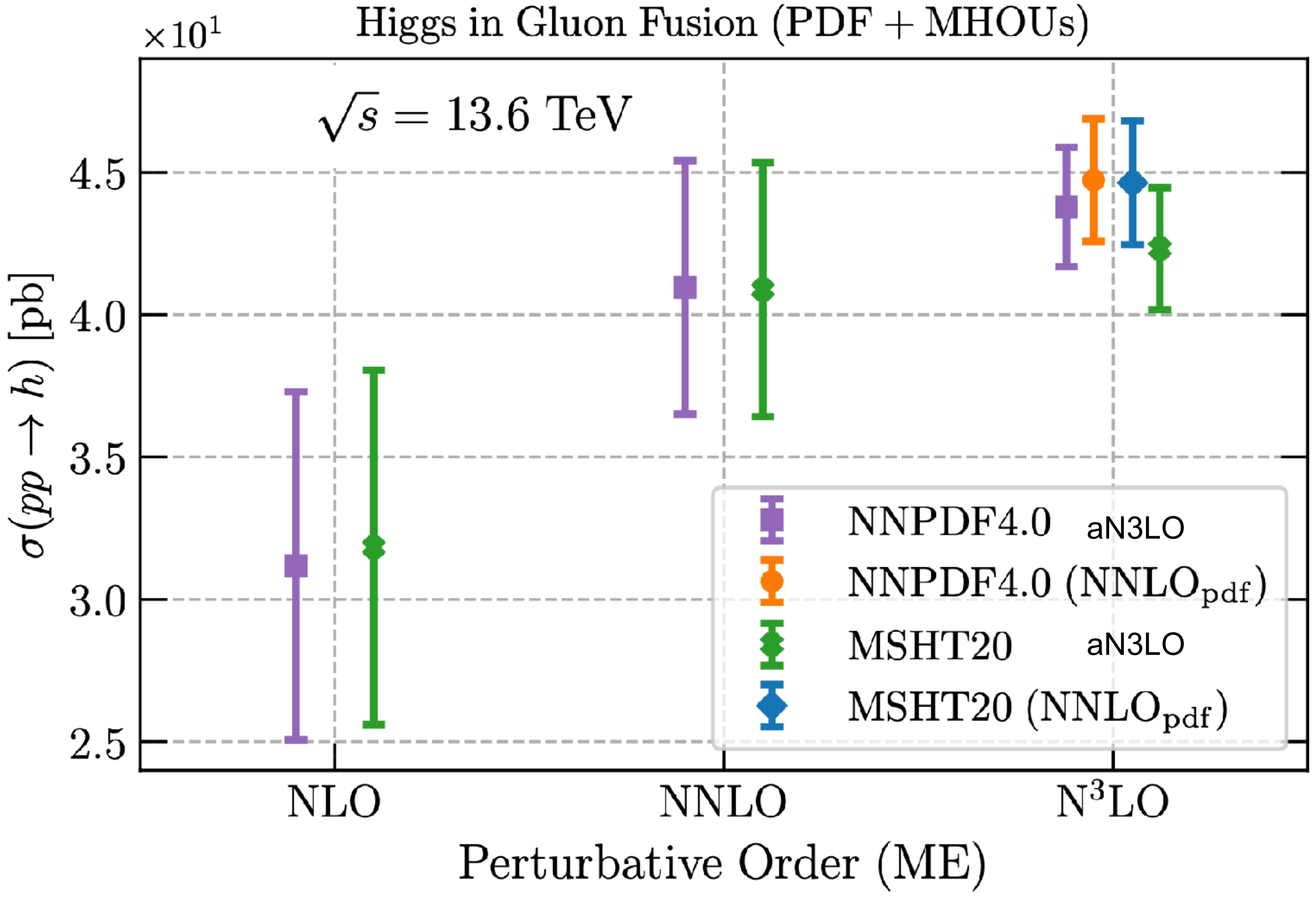
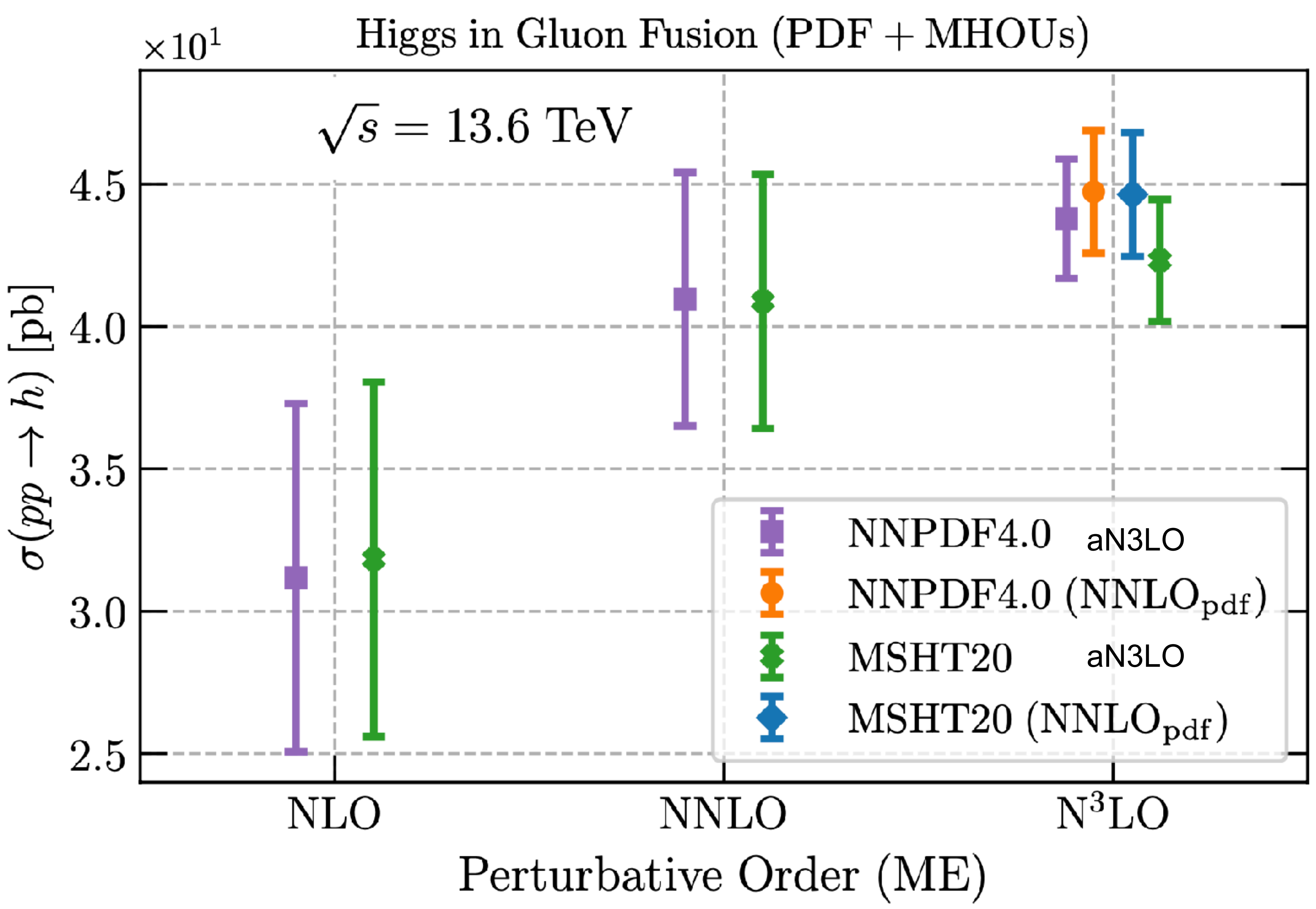


NNPDF collaboration, 2402.18635

ggF: reasonable agreement with different PDF sets

approximate N3LO PDFs



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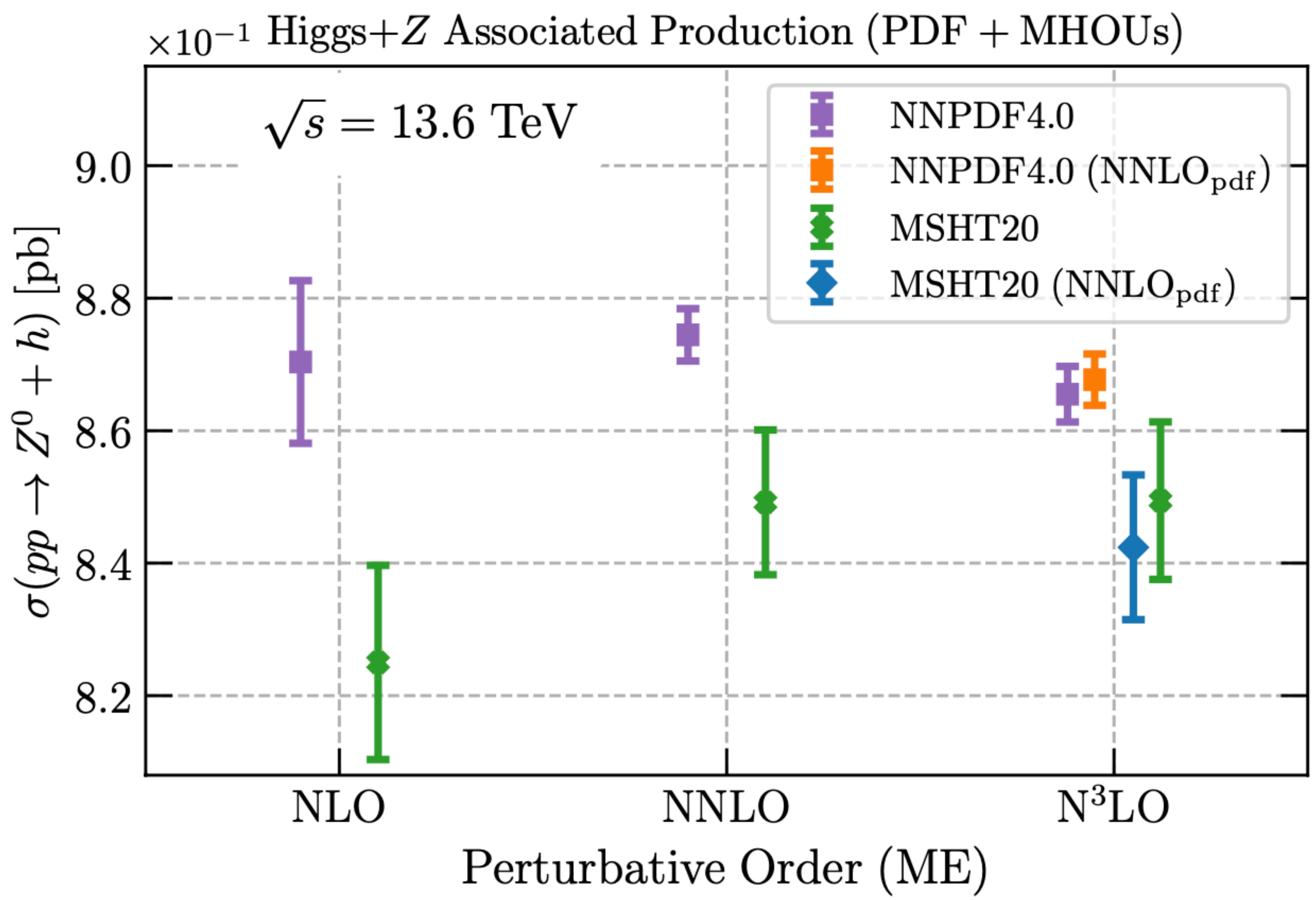

ggF: reasonable agreement with different PDF sets

less so for H+Z production

approximate N3LO PDFs

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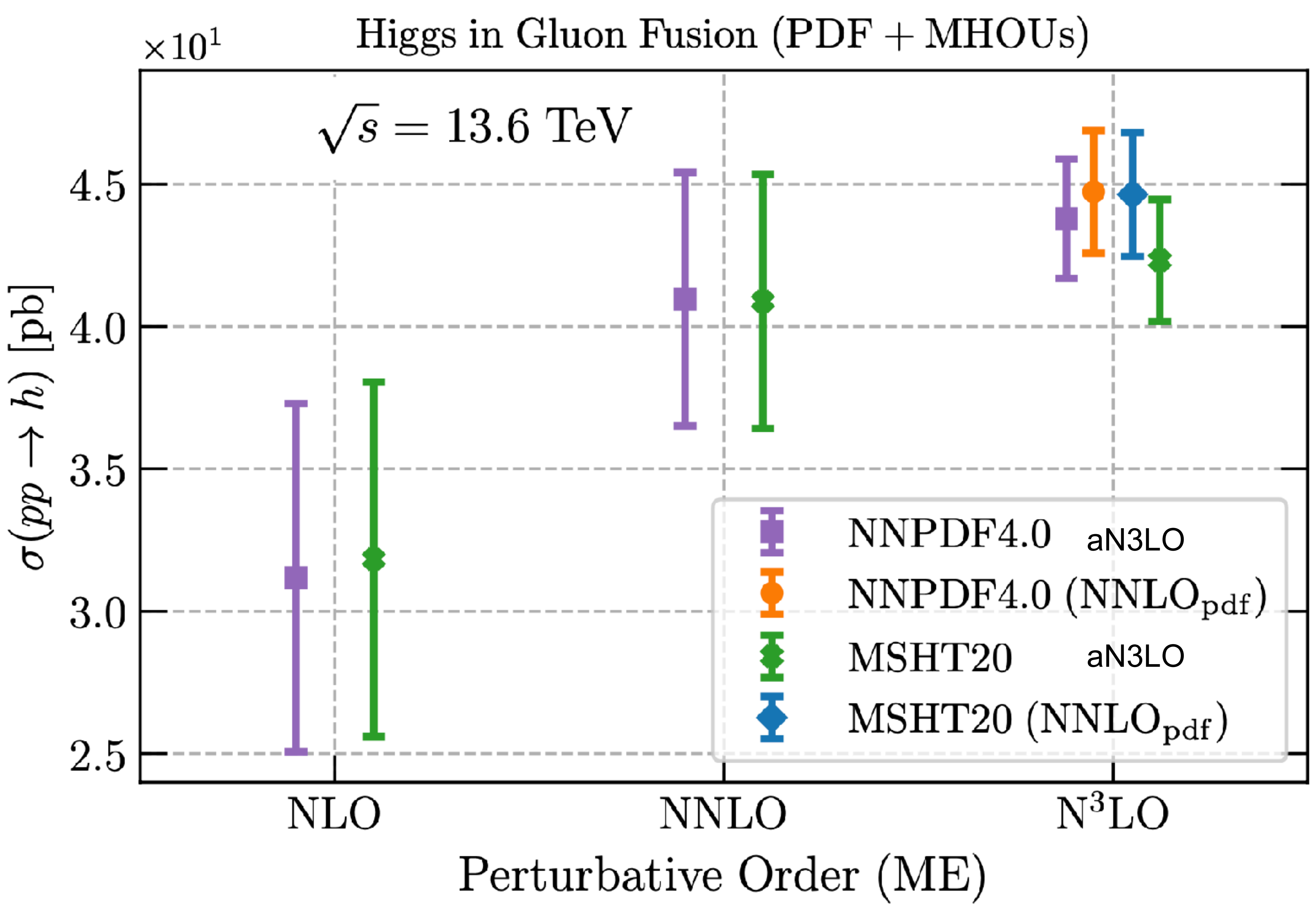
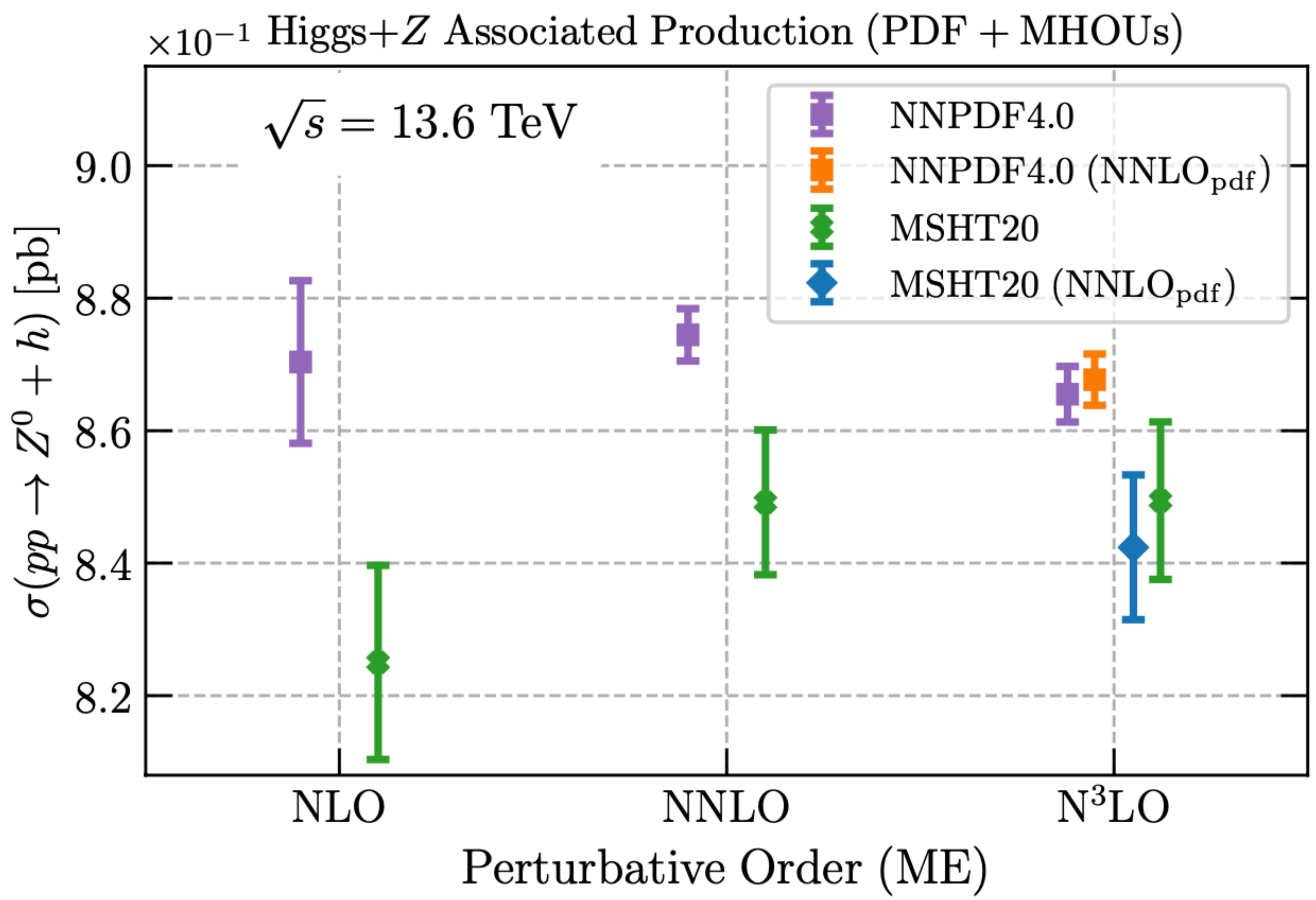


NNPDF collaboration, 2402.18635



ggF: reasonable agreement with different PDF sets

less so for H+Z production

see talks by Tongzhi Yang, Sven Moch, and PDF sessions Tuesday and Thursday

Higgs production in gluon fusion

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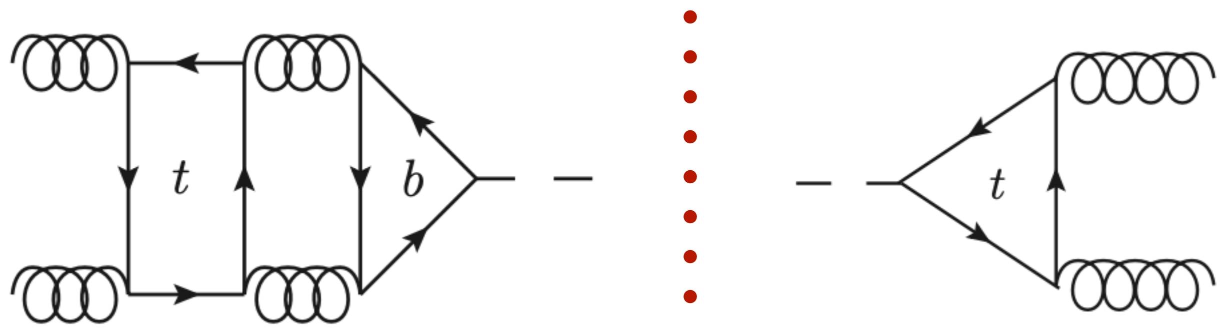
new: top-bottom interference effects at NNLO



Pietrulewicz, Stahlhofen 2302.06623

Niggetiedt, Usowitsch 2312.05297 (3-loop form factor with 3 mass scales)

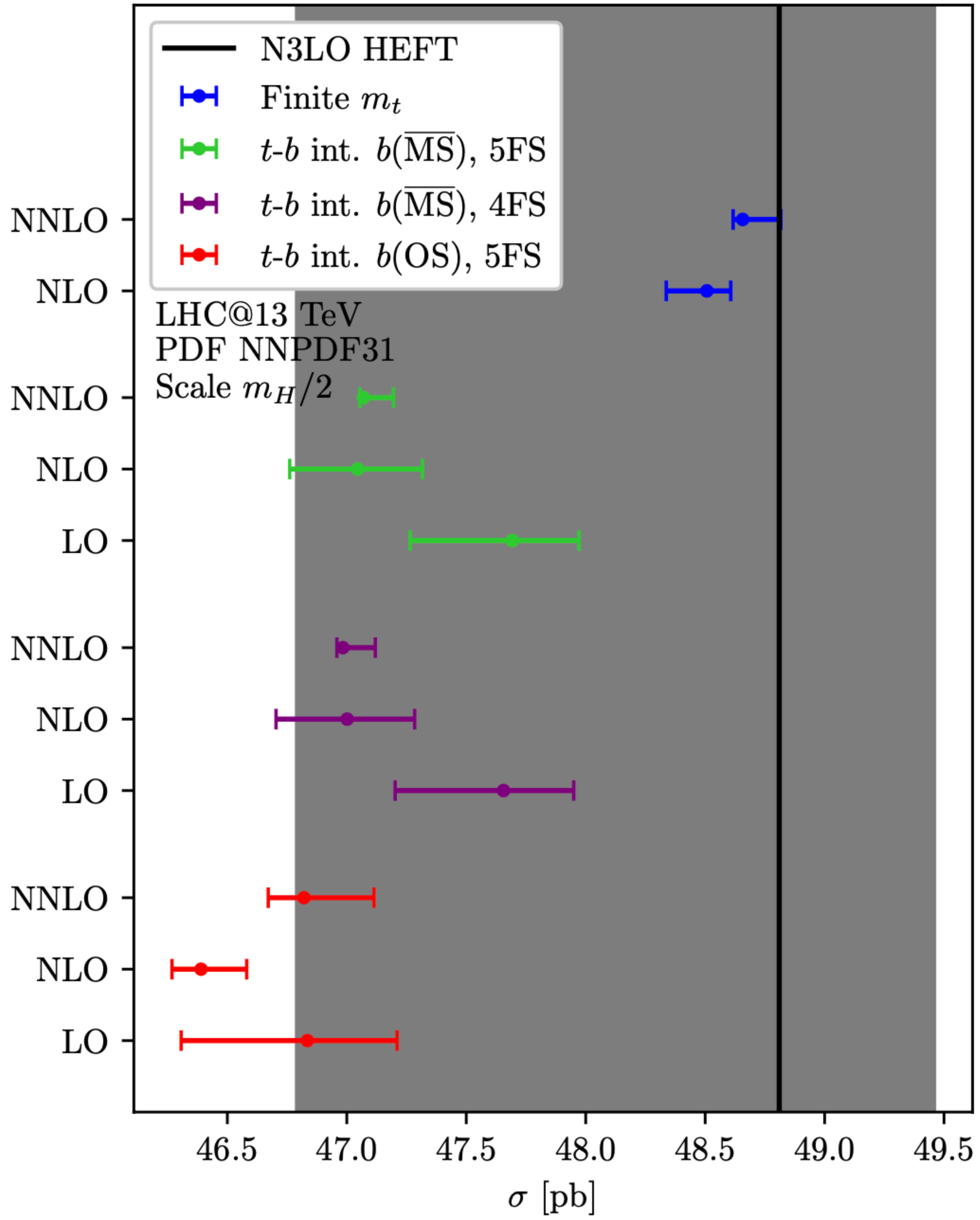
Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 2312.09896 (t-b interference), 2407.12413 (OS vs MSbar, 4FS/5FS)

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
$\sqrt{s} = 13$ TeV				
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

M. Niggetiedt, HP2 2024

t-b interference effect larger than pure top mass effect, also larger than NLO scale uncertainties

on-shell versus MSbar scheme



Tom Schellenberger, P3H YS Meeting 2024

- better perturbative convergence for b in $\overline{\text{MS}}$ scheme
- difference between 4 flavour scheme and 5 flavour scheme rather small

(HEFT here means heavy top limit, rescaled with full LO)

Higgs+jet (with mass dependence)

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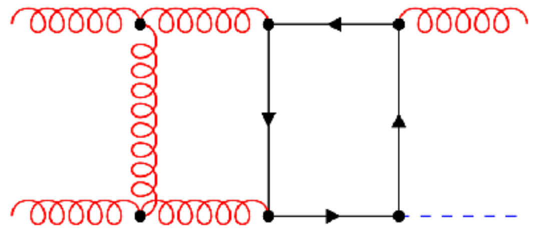
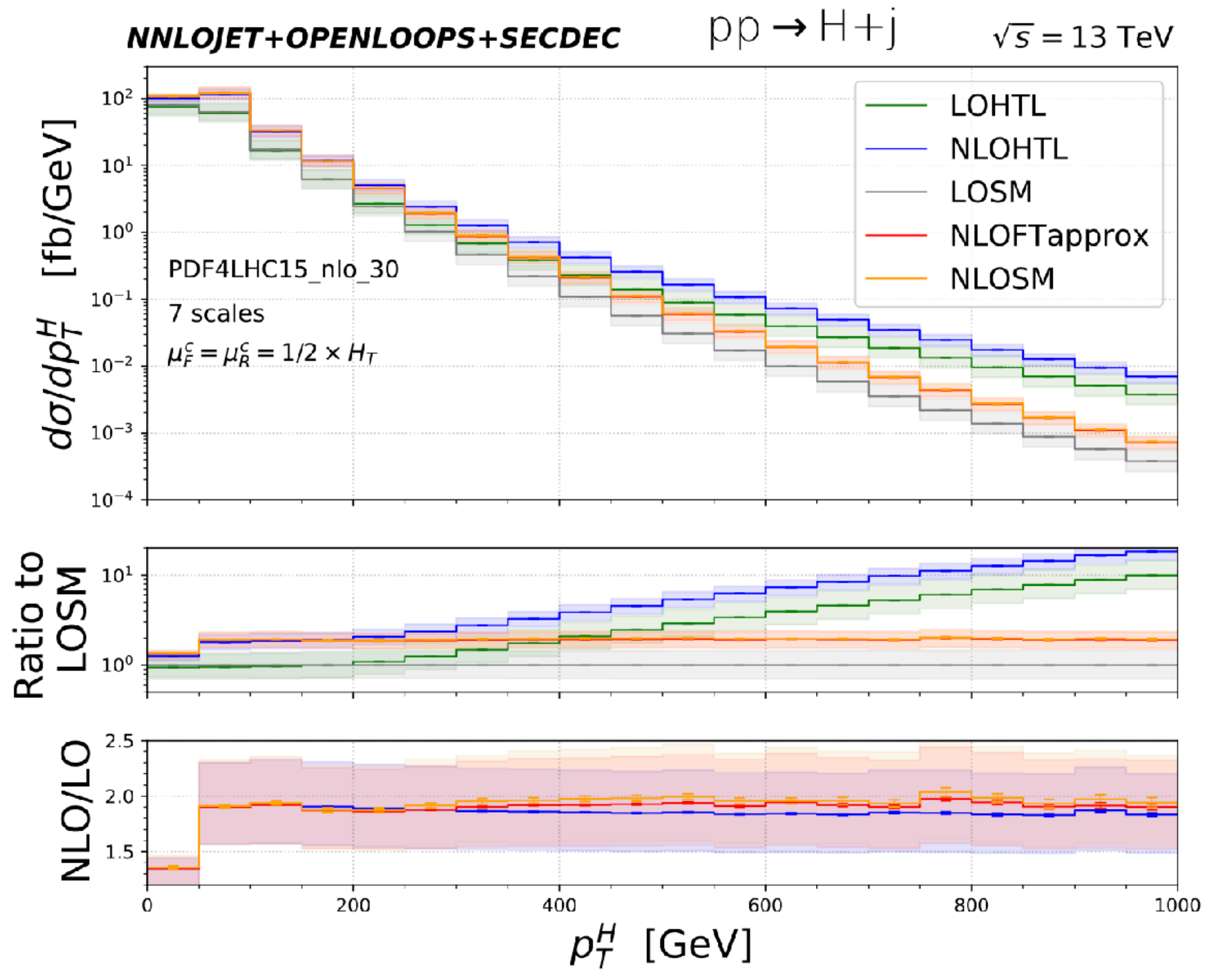


- NLO QCD (numerically) Jones, Kerner, Luisoni 1802.00349
- boosted Higgs, NLO QCD+NNLO HTL, generators Becker, Caola et al. (HXSWG note) 2005.07762, SciPost 2024
- top mass effects in H+jet and H+2jets Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang 2110.06953
- NLO QCD including bottom mass: Bonciani, Del Duca, Frellesvig, Hidding, Hirschi 2206.10490; Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 2312.09896, 2407.12413 (ingredient of ggH NNLO)
- EW corrections to ggHg in the large-mt limit: Davies, Schönwald, Steinhauser, Zhang 2308.01355

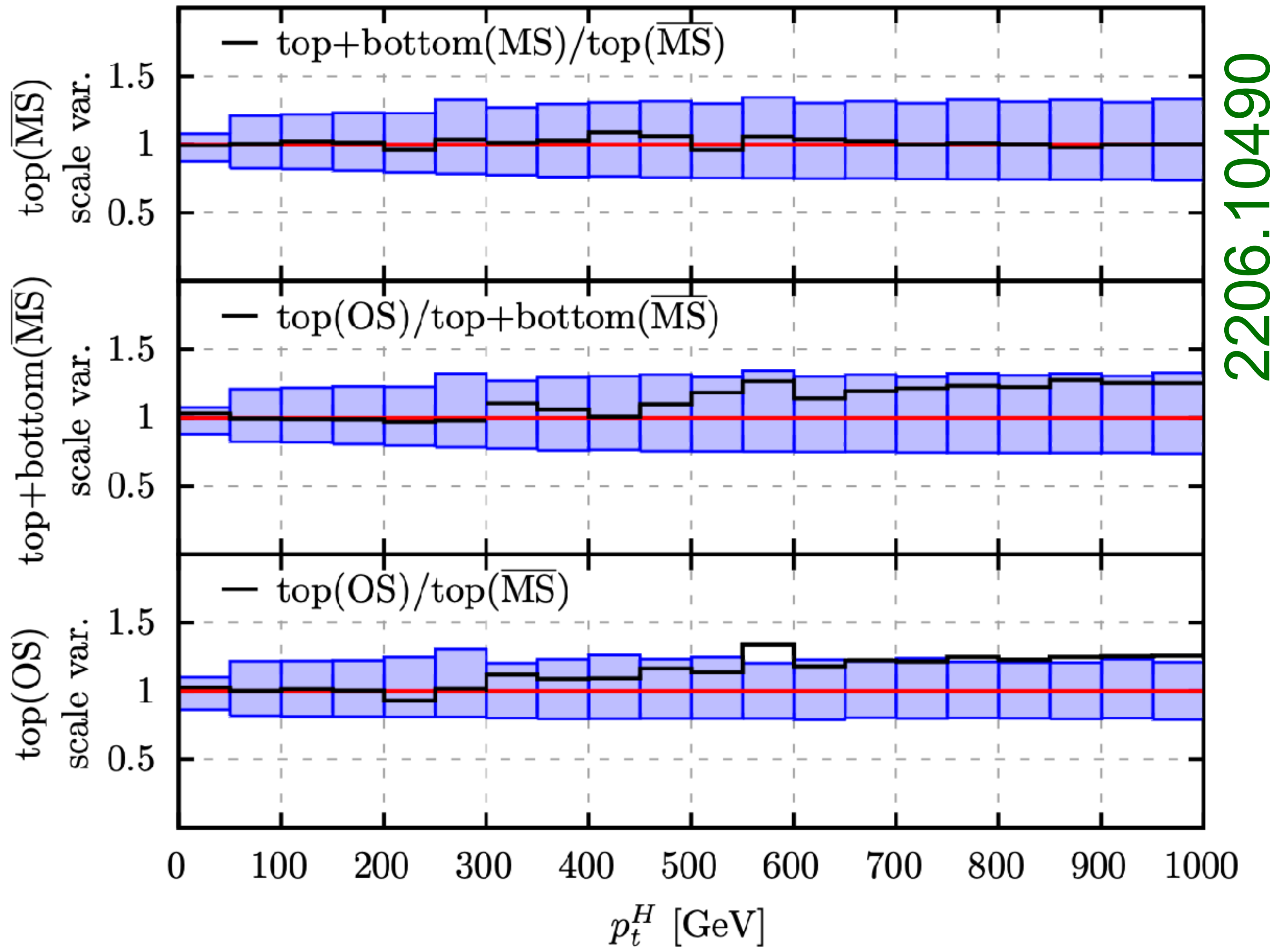
2110.06953



- large difference to heavy top limit at large pT,H
- full NLO and FTapprox (virtual part in HTL) very similar

  will this also be true for H+2j ?

- difference top on-shell vs MSbar starts to exceed scale uncertainties at large pT,H

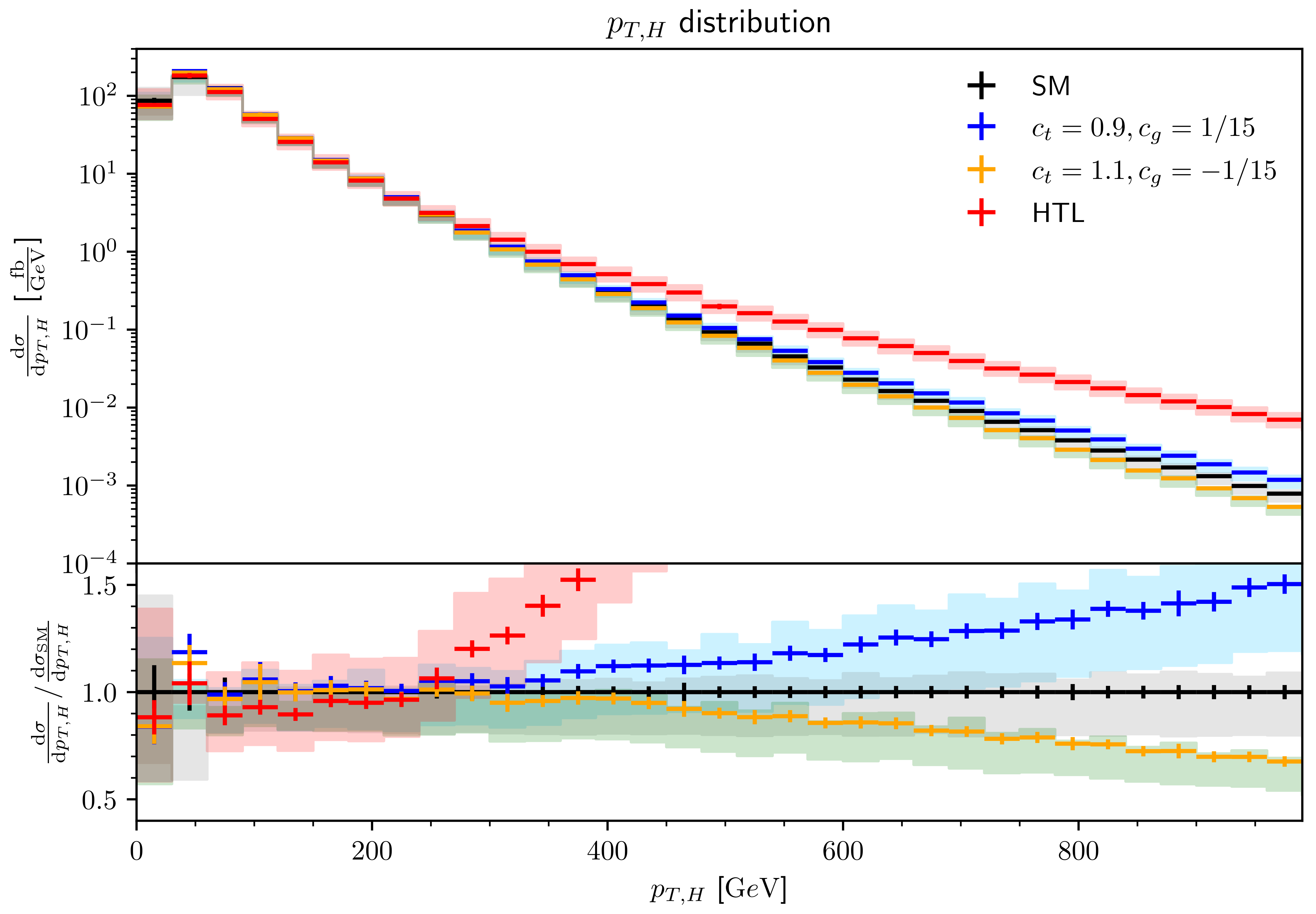


2206.10490

boosted Higgs at NLO with anomalous couplings

Campillo, GH, Kerner, Kunz 2409.05728 (based on SM NLO calculation of Jones, Kerner, Luisoni '18)

NLO with full top mass including anomalous couplings

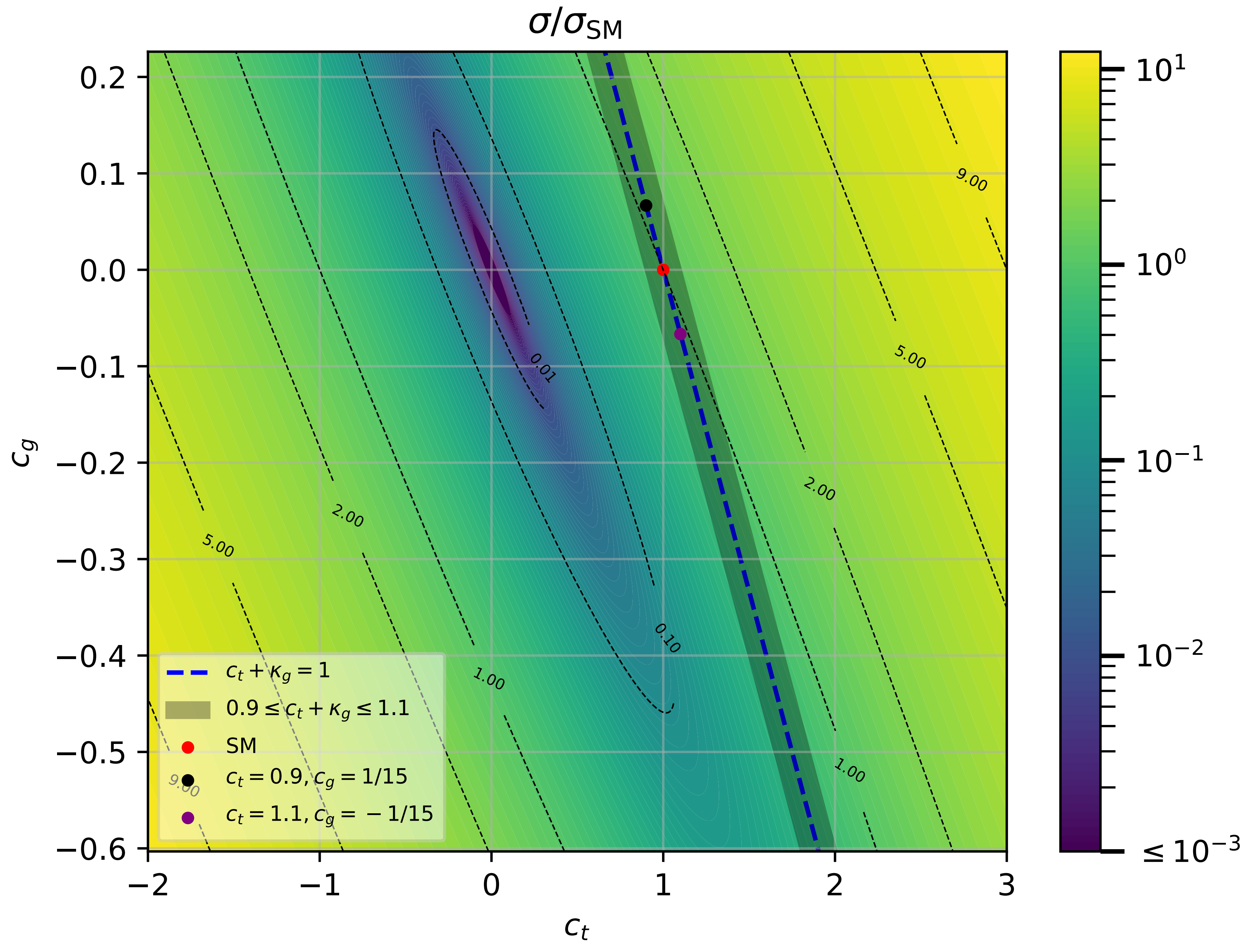


effects of ct, cg exceed scale uncertainties at large pT,H

$p_{T,H}$ cut [GeV]	σ_{EFT}/σ_{SM} LO	NLO
200	1.021 ± 0.002	1.02 ± 0.02
400	1.118 ± 0.007	1.11 ± 0.01
600	1.251 ± 0.012	1.23 ± 0.01
800	1.407 ± 0.016	1.37 ± 0.02

$(c_t, c_g) = (0.9, 1/15)$

40% effect for highly boosted Higgs



Towards N3LO Higgs+jet production in the HTL

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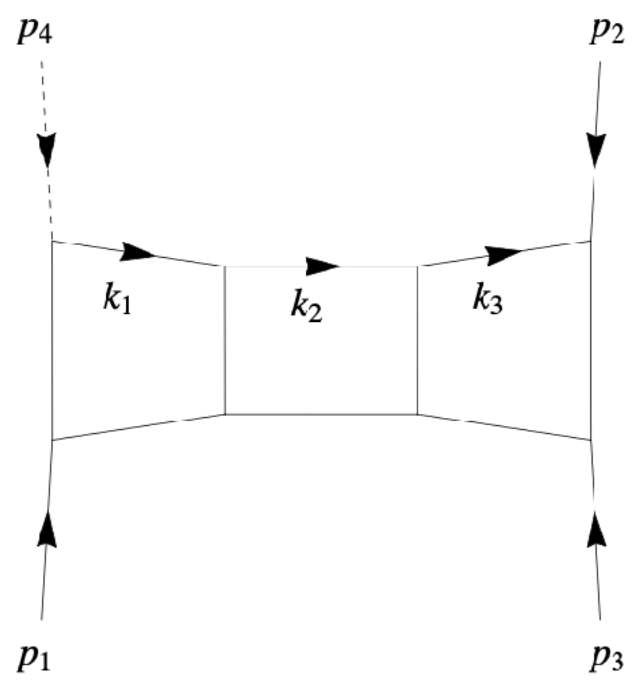
- **at NLO scale uncertainties are ~15%**
- **at NNLO in the HTL still O(10%) uncertainties**
- **also addresses N3LO V+jet production**



planar diagrams:

Di Vita, Mastrolia, Schubert, Yundin ’14;
Canko, Syrrakos ’21,

Gehrmann, Jakubcik, Mella, Syrrakos, Tancredi 2307.15405

NNLO to higher order in epsilon

Gehrmann, Jakubcik, Mella, Syrrakos, Tancredi 2301.10849

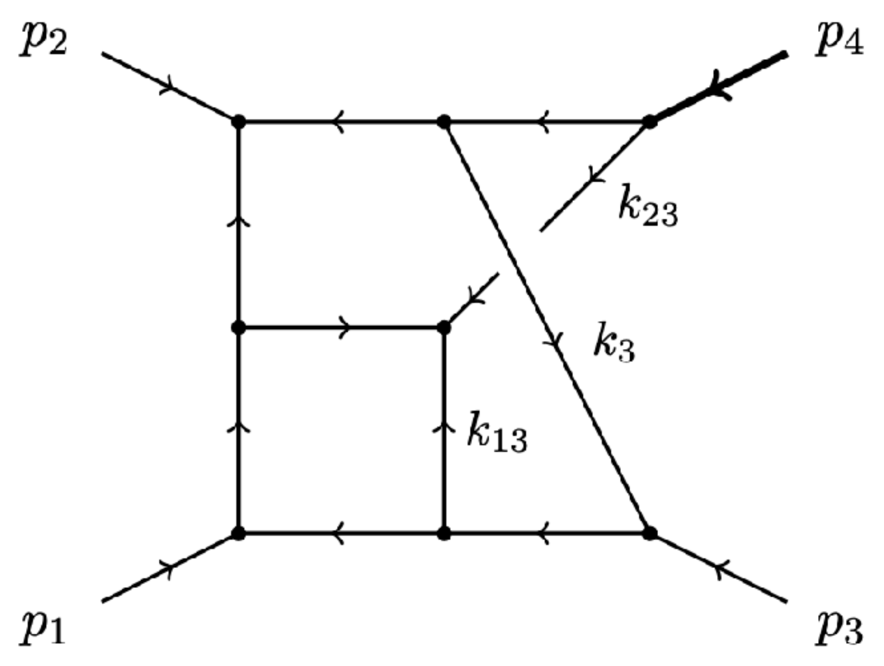
non-planar diagrams:

Henn, Lim, Torres-Bobadilla ‘23

Syrrakos, Canko ‘23

Aliaj, Papathanasiou ‘24

Cesare Carlo Mella, Loops&Legs 2024



see talk by Lorenzo Tancredi

VBF Higgs production

Asteriadis, Behring, Melnikov, Novikov, Röntsch 2407.09363

NNLO corrections to both, production and decay $H \to b\bar{b}$

large negative corrections, depending on pT cuts on b-jets

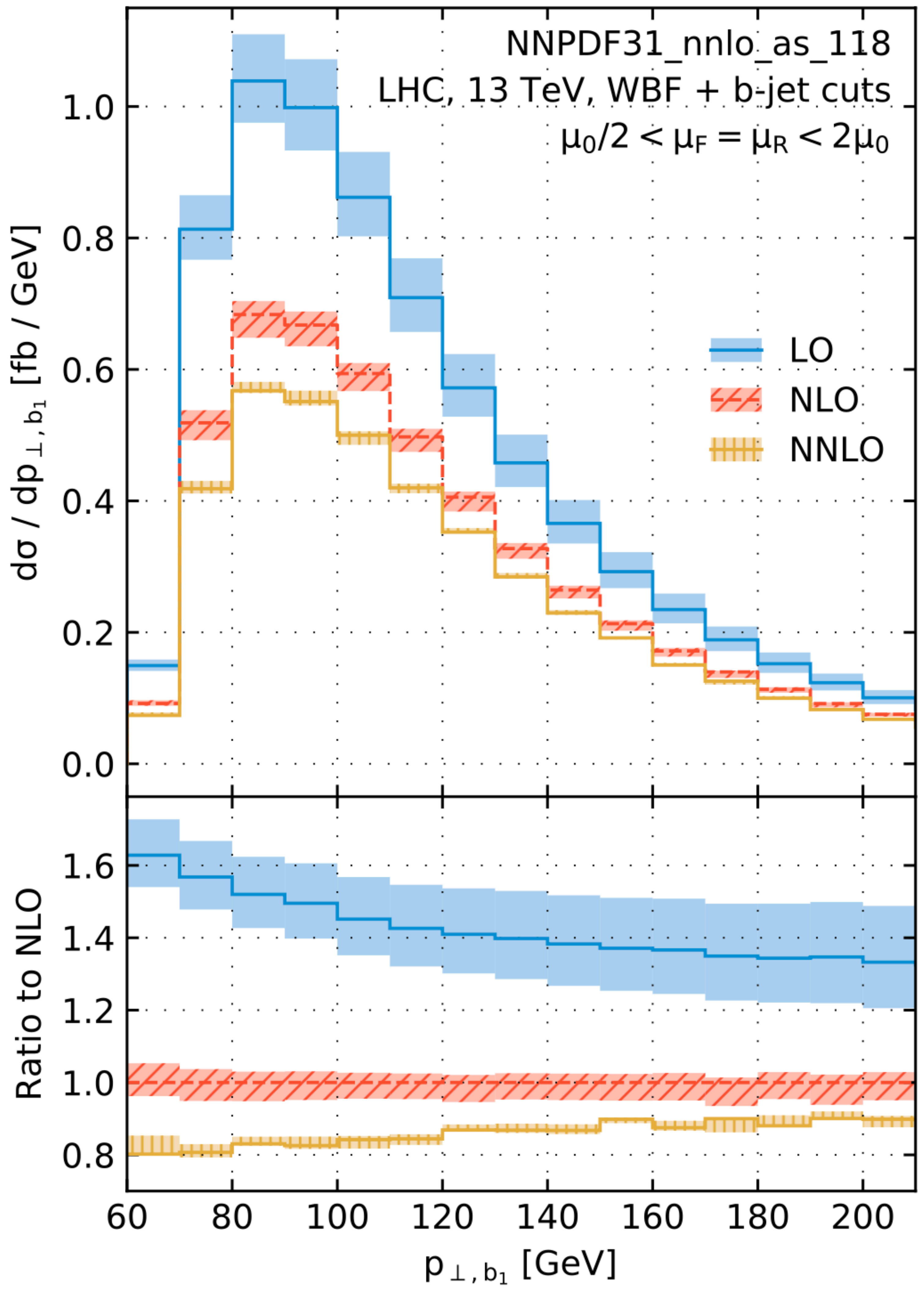
scale variation $^{2\mu_0}_{\mu_0/2}$ in WBF

$$\sigma^{\rm LO} = 75.6^{-5.6}_{+6.5}\,{\rm fb} \qquad (\pm 9\%)$$

$$\sigma^{\rm NLO} = 52.4^{+1.5}_{-2.6}\,{\rm fb} \;\; (\text{-}31\%\pm 3\%)$$

$$\sigma^{\rm NNLO} = 44.6^{+0.9}_{-0.6}\,{\rm fb} \;\; (\text{-}10\%\pm 1\%)$$

Ivan Novikov, P3H YS Meeting '24



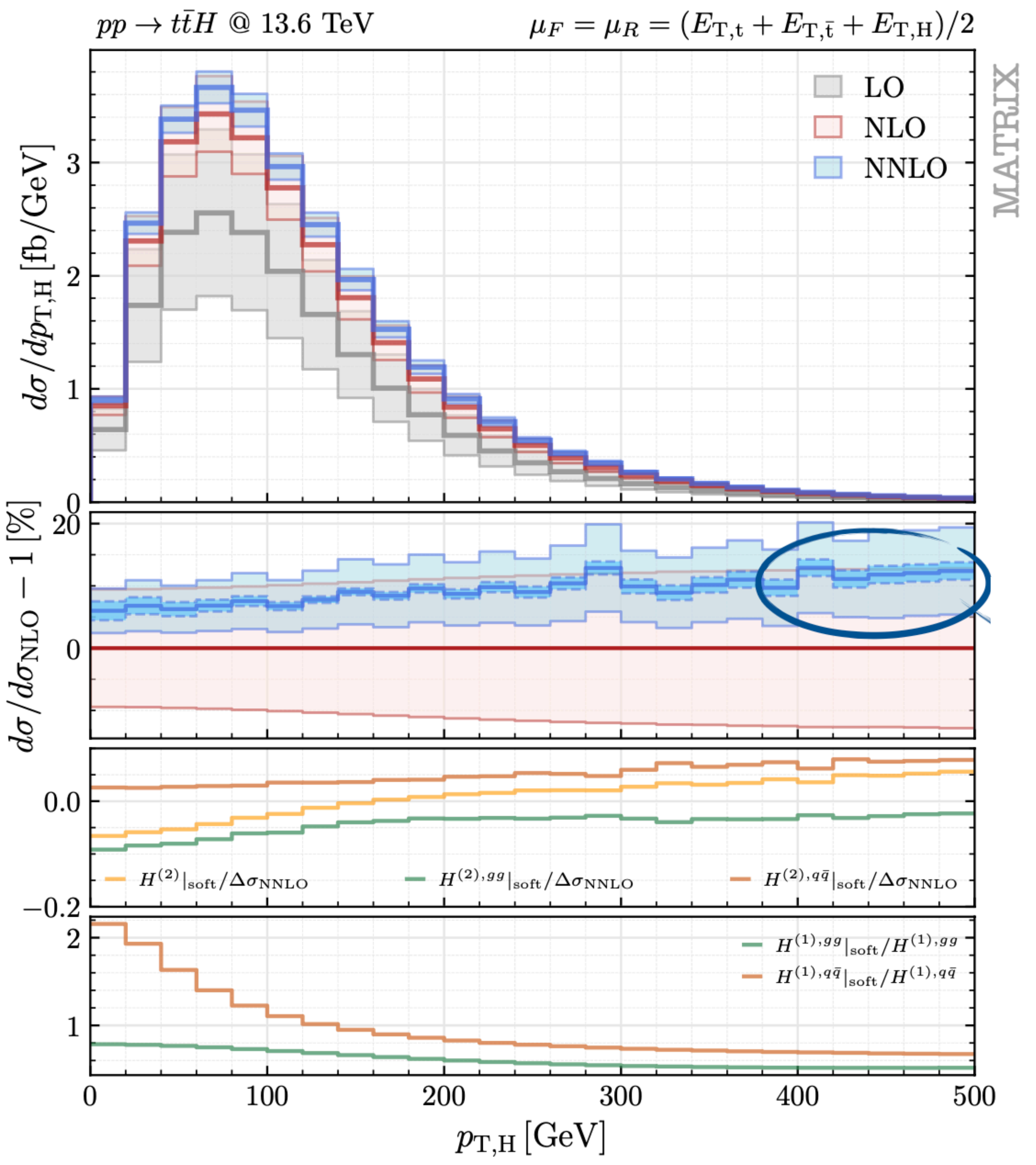
ttH production

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savioni ’22, ‘24

first differential NNLO results

4% increase at NNLO, reduction of scale uncertainties

σ [pb]	$\sqrt{s} = 13\,\text{TeV}$	$\sqrt{s} = 100\,\text{TeV}$
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$



Chiara Savioni, HP2 2024

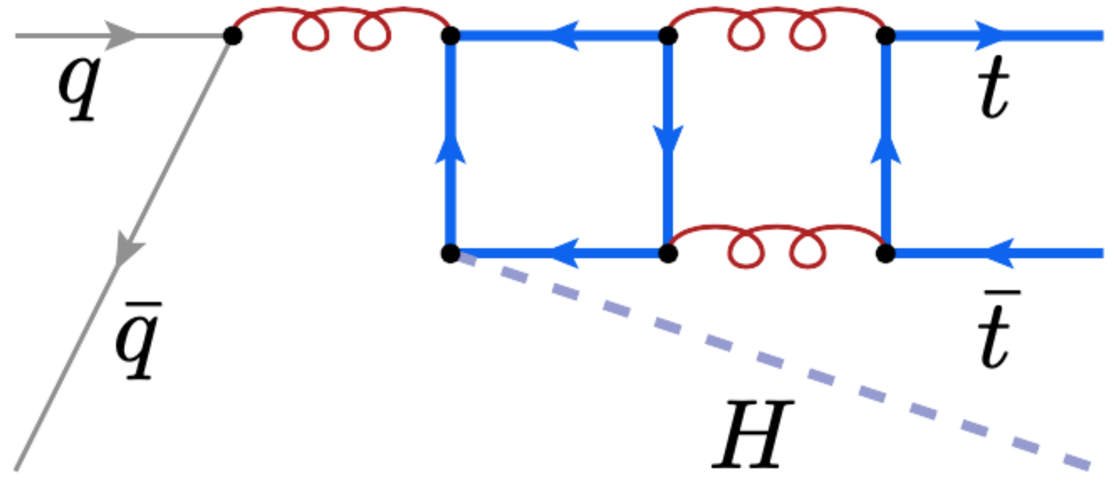
- soft approximation + “massification” for 2-loop virtual amplitude
- uncertainty due to approximate 2-loop amplitude estimated to ~1% for total cross section
- can be larger in tail of pT,H distribution (at NLO ~8%)

2-loop pentagon amplitudes

Results for massless 5-point amplitudes are known, physical results with 1 off-shell leg also exist

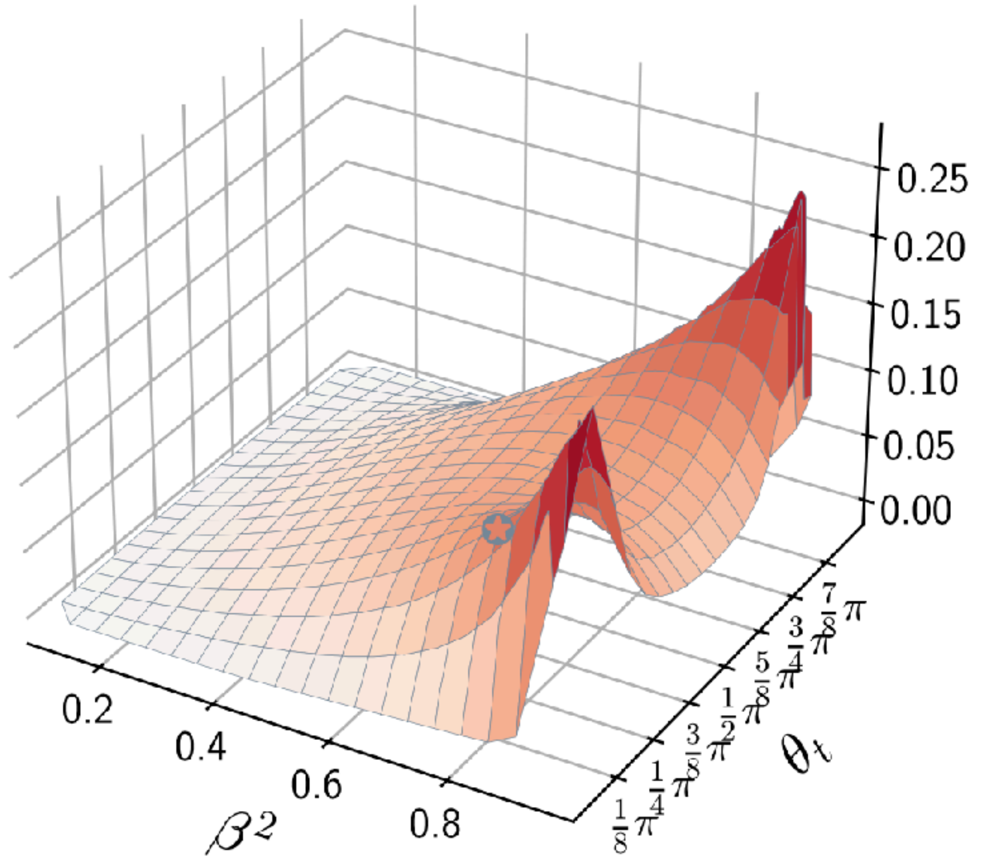
Abreu, Agarwal, Badger, Becchetti, Caola, Chicherin, Chawdry, Czakon, De Laurentis, Gambuti, Gehrmann, Hartanto, Henn, Ita, Kallweit, Klinkert, Krys, Lo Presti, Page, Peraro, Poncelet, Ma, Manteuffel, Mazzitelli, Mitov, Sotnikov, Tancredi, Wiesemann, Zhang, Zoia, …

2-loop 5-point amplitudes: 5 kinematic scales, for ttH in addition 2 masses



ttH @2-loops partial results:

- t -> H fragmentation functions Brancaccio, Czakon, Generet, Krämer, Mück, 2106.06516
- infrared pole coefficients Chen, Ma, Wang, Yang, Ye, 2202.02913
- leading colour contributions to amplitudes with light-quark loops Febres Cordero, Figueiredo, Kraus, Page, Reina, 2312.08131
- 1-loop to order eps^2 Buccioni, Kreer, Liu, Tancredi, 2312.10013
- high-energy limit, numerically Wang, Xia, Yang, Ye, 2402.00431
- Nf-part in quark channel, numerically Agarwal, GH, Jones, Kerner, Klein, Lang, Magerya, Olsson, 2402.03301



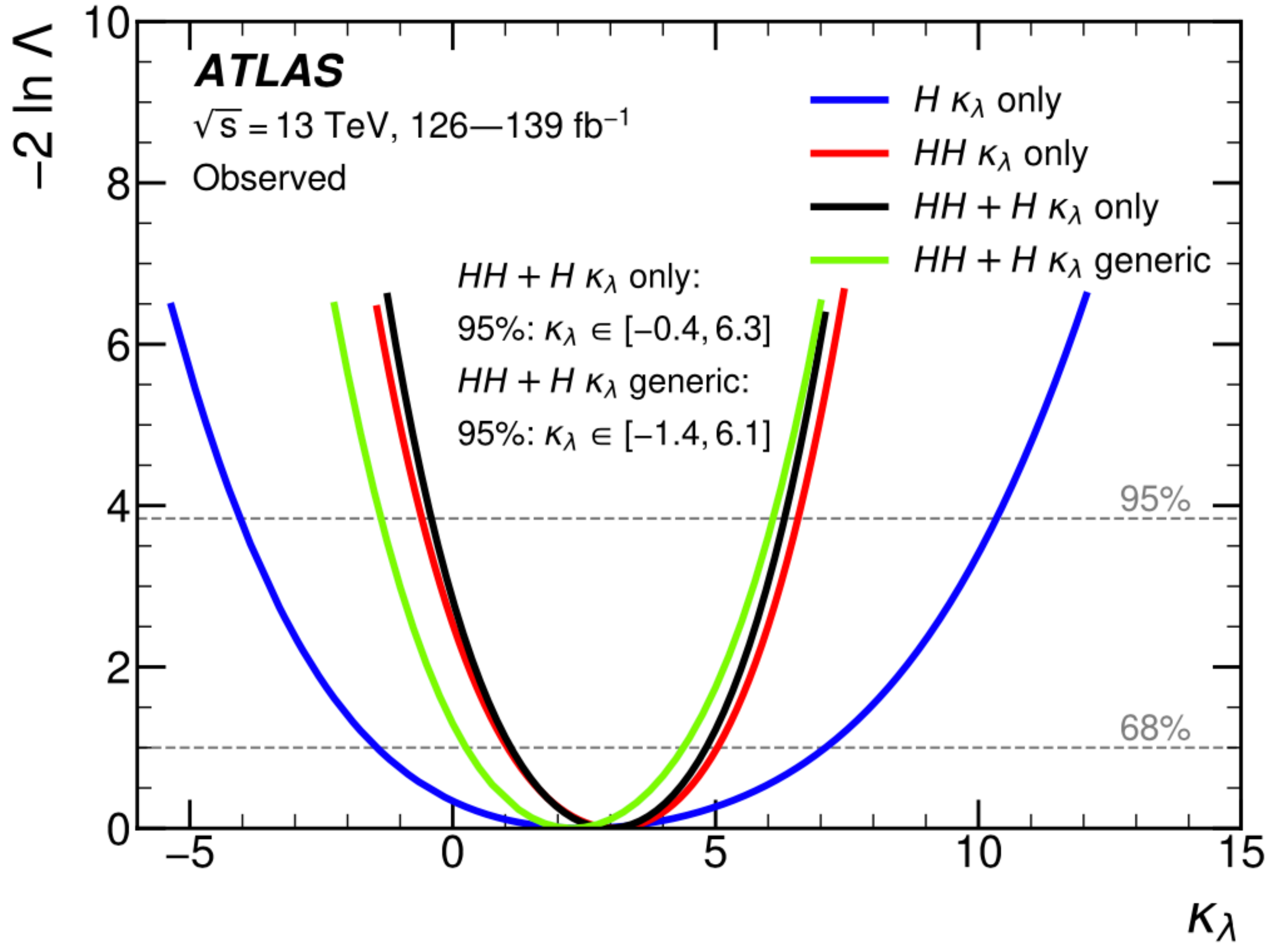
talk by Vitaly Magerya this afternoon

Higgs boson pair production

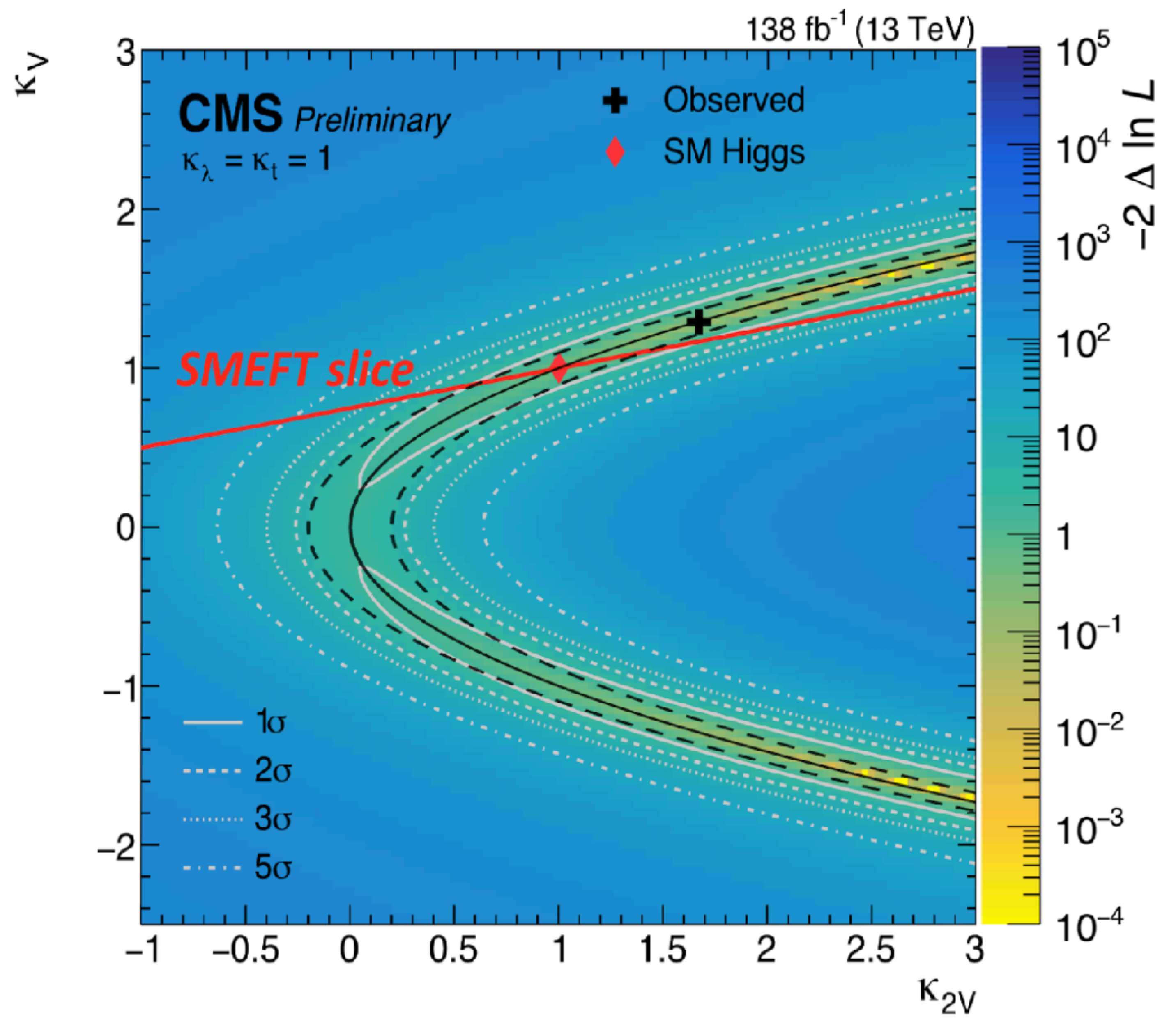
prime process to explore the Higgs potential

at energies much larger than the electroweak scale: $V(\Phi) = \ ?$

after EW symmetry breaking: $V(h) \sim \frac{1}{2}\underbrace{(2v^2\lambda)}_{m_h^2}\, h^2 + v\lambda\, h^3 + \frac{\lambda}{8}\, h^4 \quad + \ldots ?$

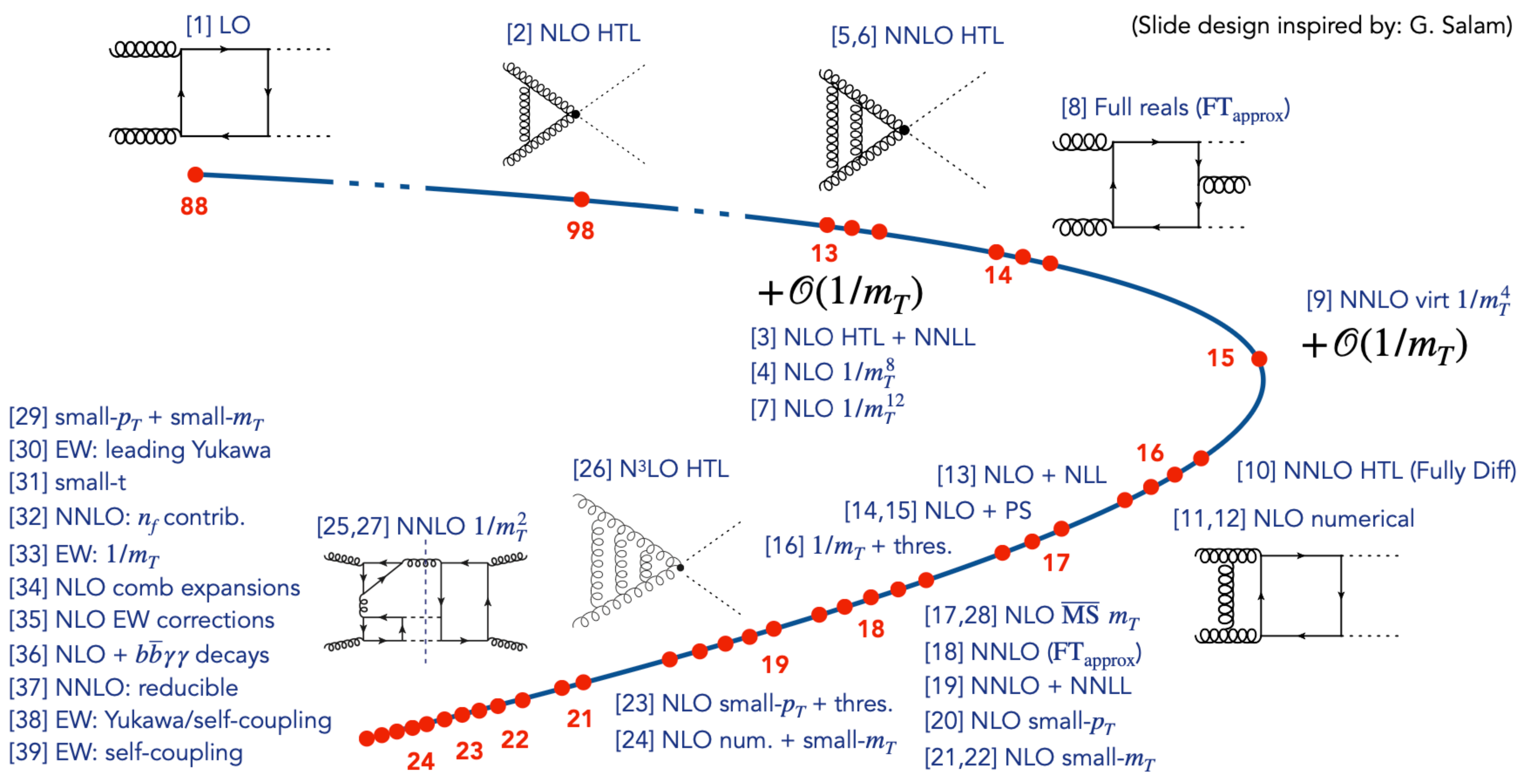


[2211.01216]



[2205.06667]

Overview

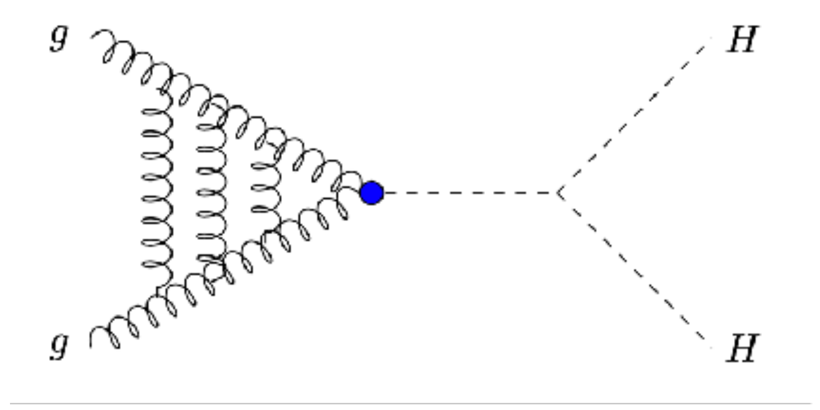


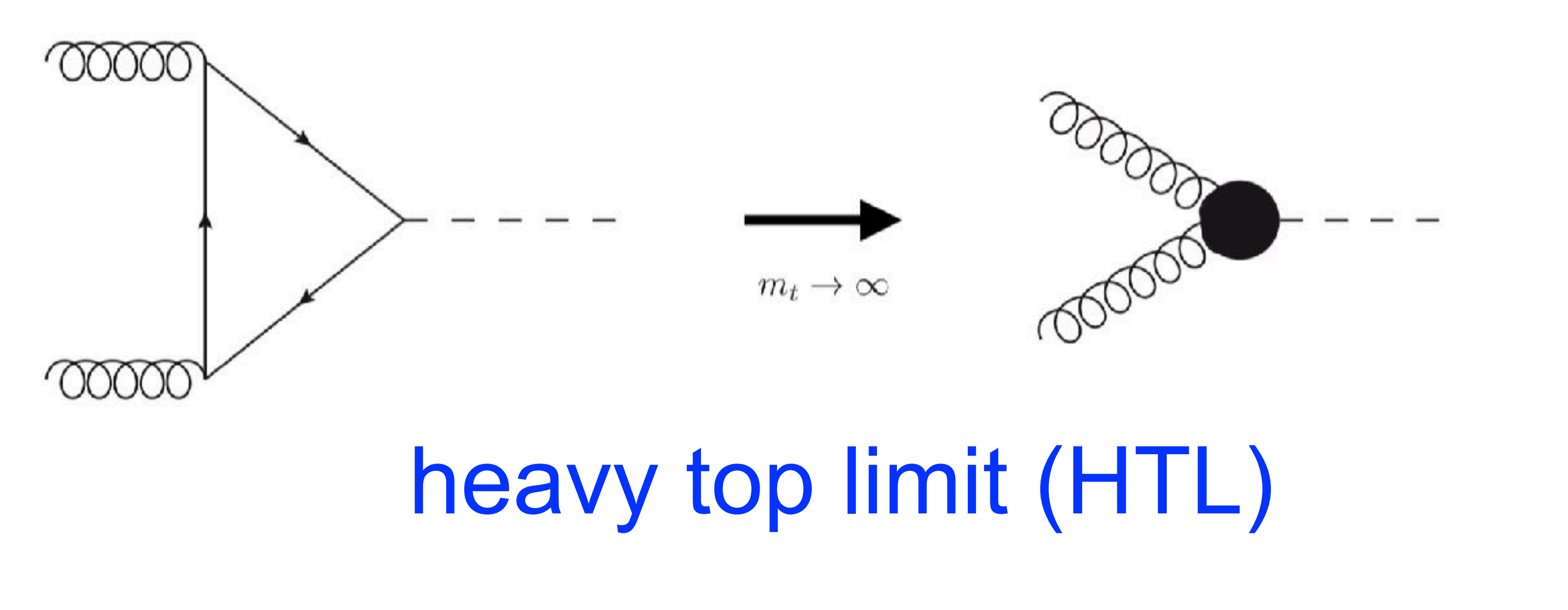
Stephen Jones
Higgs Hunting 2024

[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagnaschi, Degrassi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23 [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, SPJ, Kerner, Stone, Vestner [39] Li, Si, Wang, Zhang, Zhao 24

ggHH: higher order QCD corrections in the SM

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





N3LO$_{(HTL)}$+N3LL: Ajjath, Shao ‘22

NNLO$_{(HTL)}$: De Florian, Mazzitelli ’13
Grigo, Melnikov, Steinhauser ‘14

NNLO$_{(HTL)}$+Geneva PS: Alioli, Billis, Broggio et al.’22

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

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

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

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

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

Bagnaschi, Degrassi, Gröber ’23

ggHH: higher order QCD corrections in the SM

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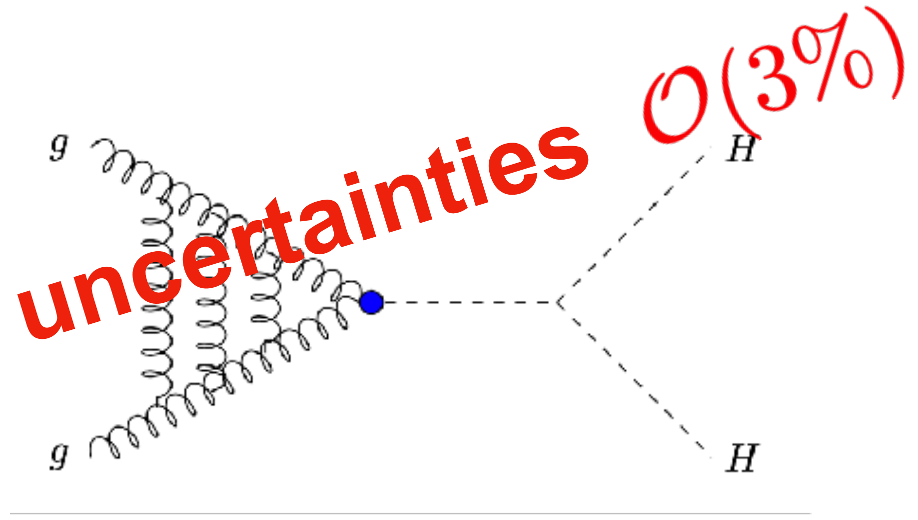

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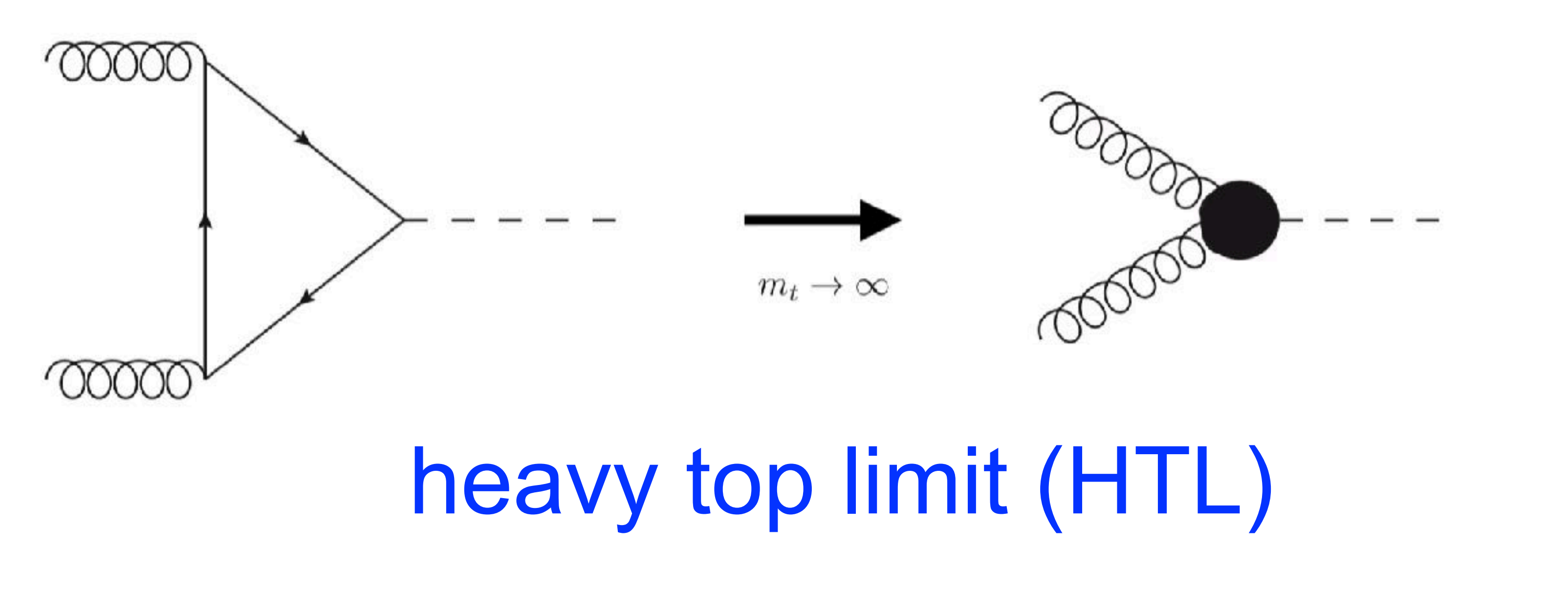

NLO full m_t

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

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ggHH: higher order QCD corrections in the SM

Karlsruhe Institute of Technology

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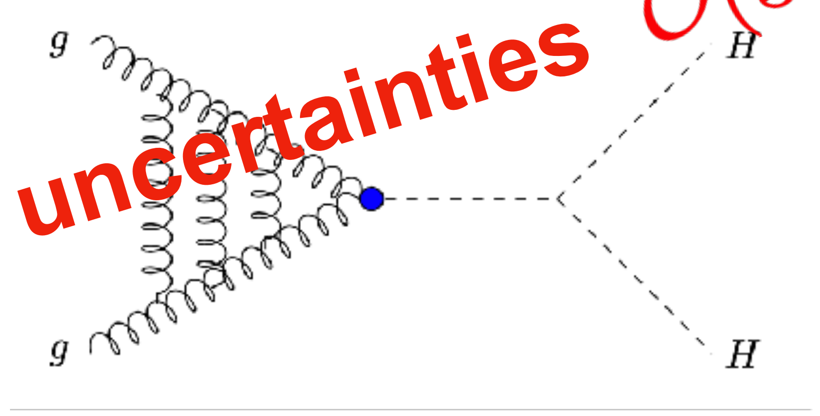
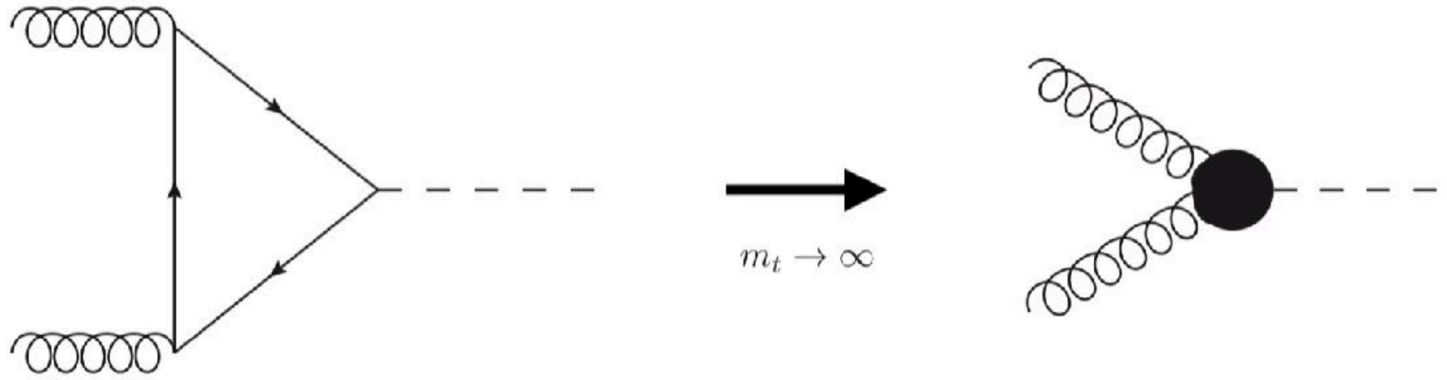
N3LO(HTL)+N3LL: Ajjath, Shao '22



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

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

NNLO(HTL)+Geneva PS: Alioli, Billis, Broggio et al.'22



heavy top limit (HTL)

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

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

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

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

Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20

Bagnaschi, Degrassi, Gröber '23

ggHH: higher order QCD corrections in the SM

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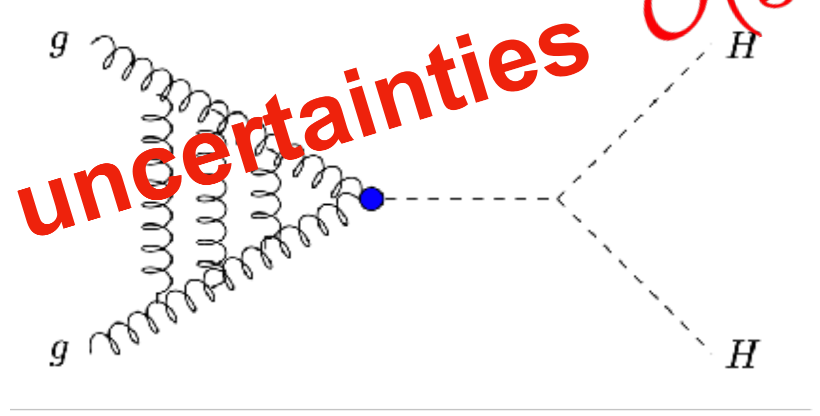
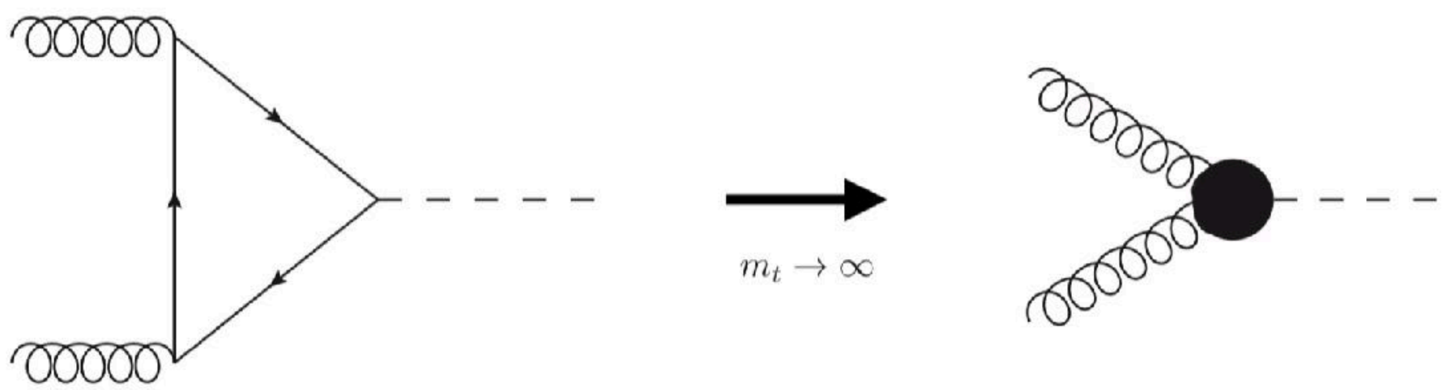
NNLO(HTL)+Geneva PS: Alioli, Billis, Broggio et al.'22



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



heavy top limit (HTL)

NLO full m_t

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

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

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

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

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

Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20

Bagnaschi, Degrassi, Gröber '23

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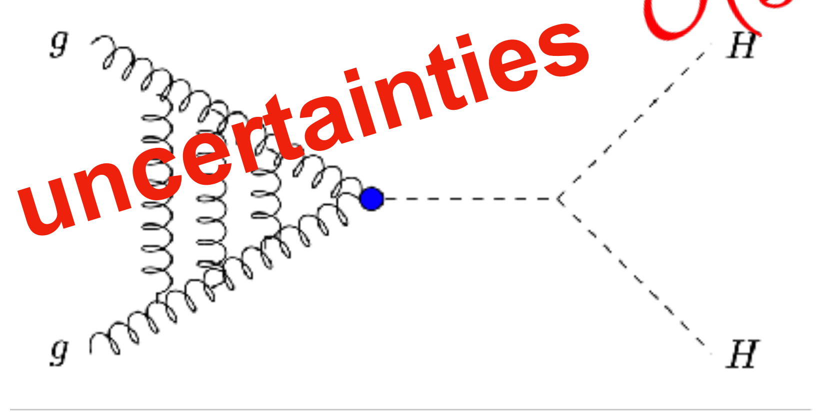
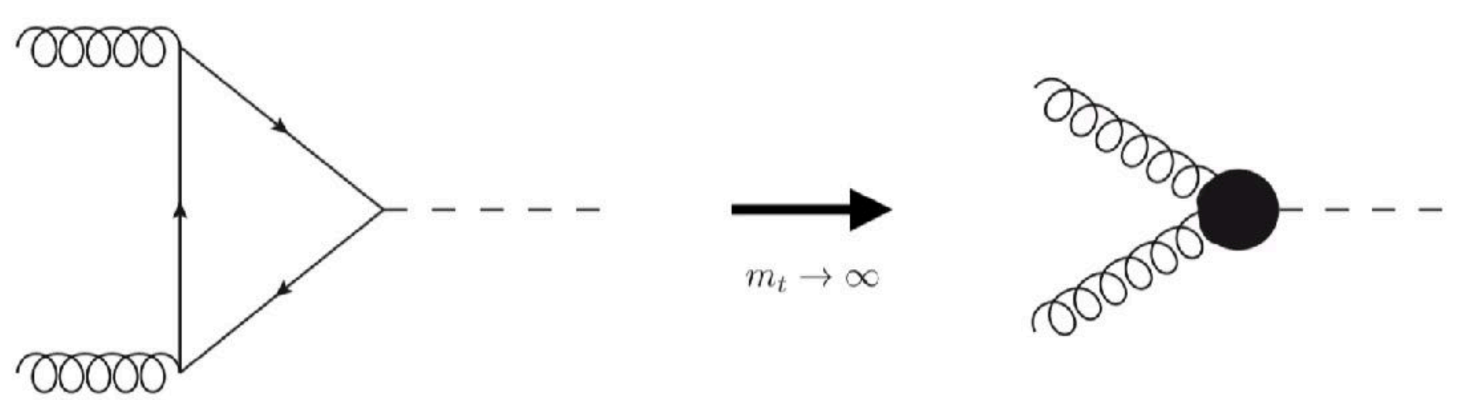
NNLO(HTL)+Geneva PS: Alioli, Billis, Broggio et al.’22



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



heavy top limit (HTL)

NLO full m_t

Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. ‘16
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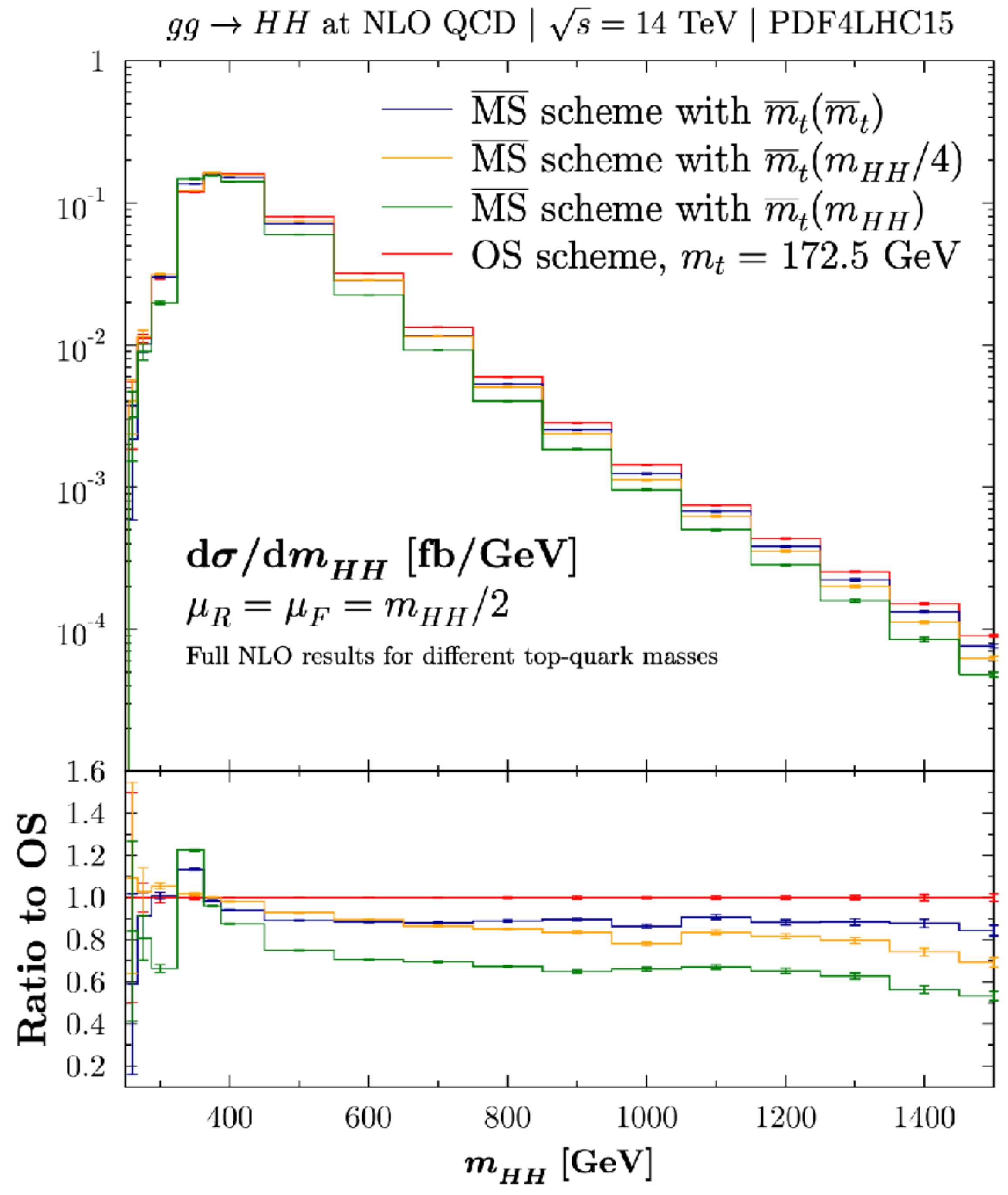
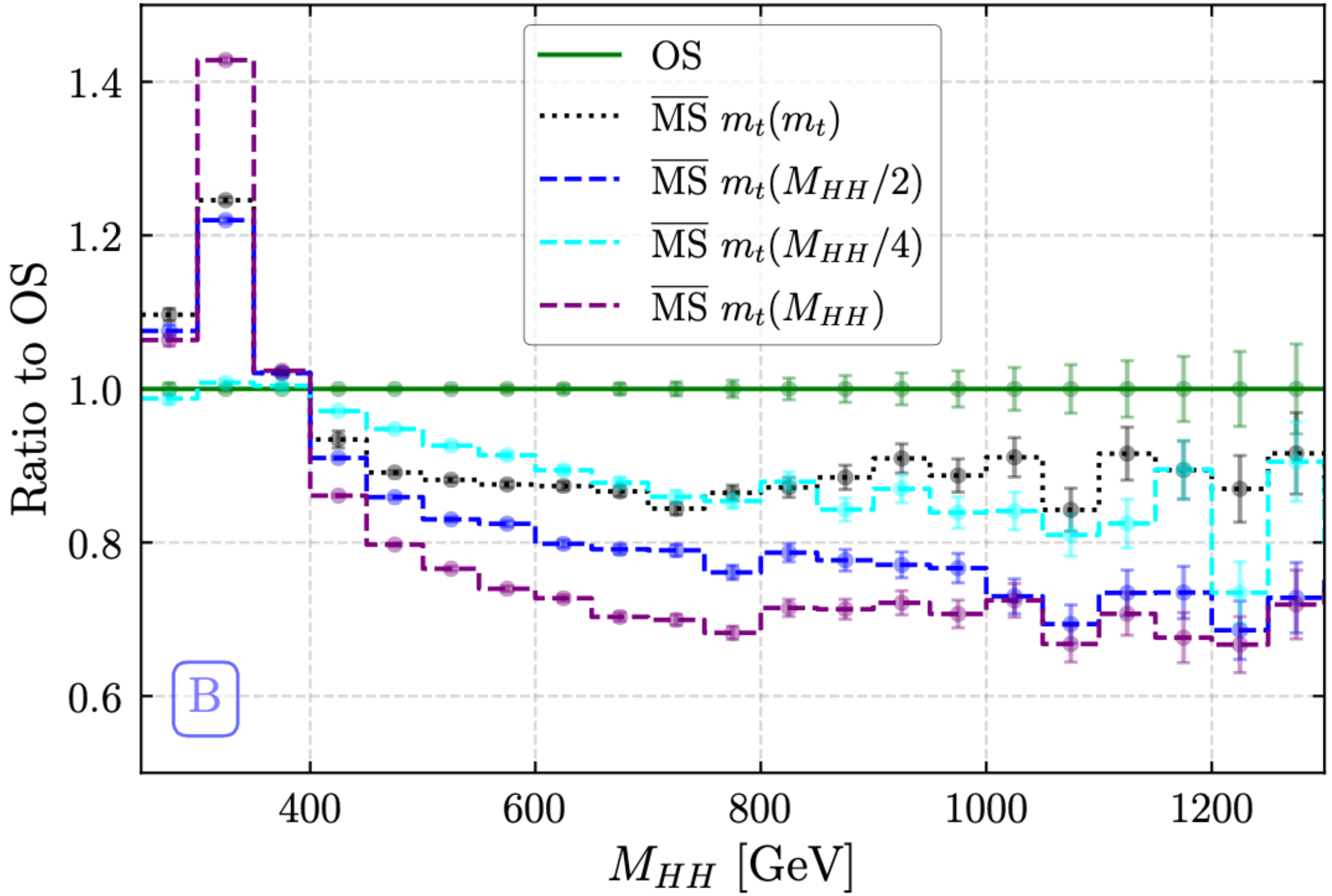
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ‘20
Bagnaschi, Degrassi, Gröber ’23

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



Baglio et al, 2003.03227

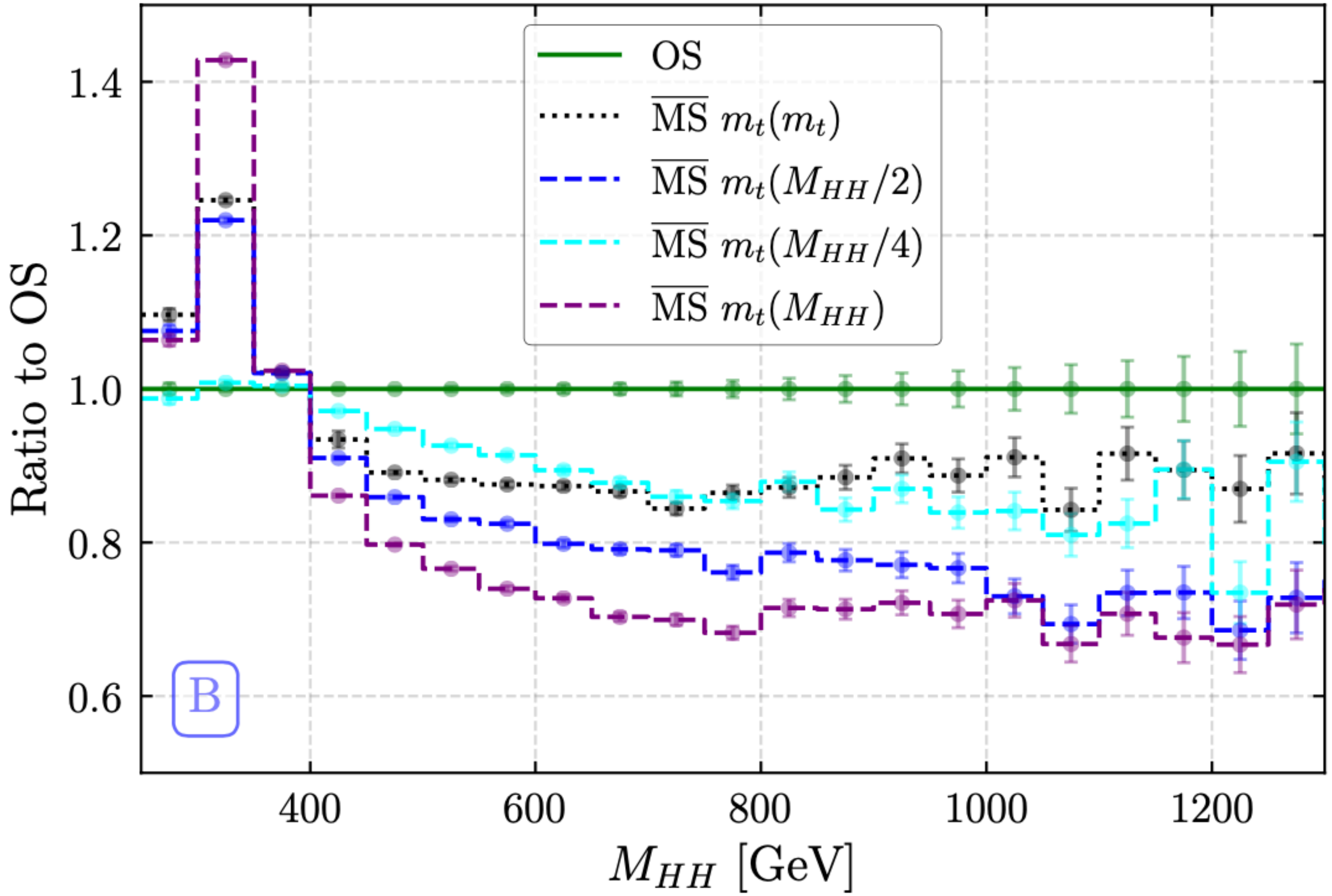
scheme uncertainties (top mass)



Bagnaschi, Degrassi, Gröber 2309.10525

PDF + α_s uncertainties ~ 2.3%

scheme uncertainties (top mass)



Bagnaschi, Degrassi, Gröber 2309.10525

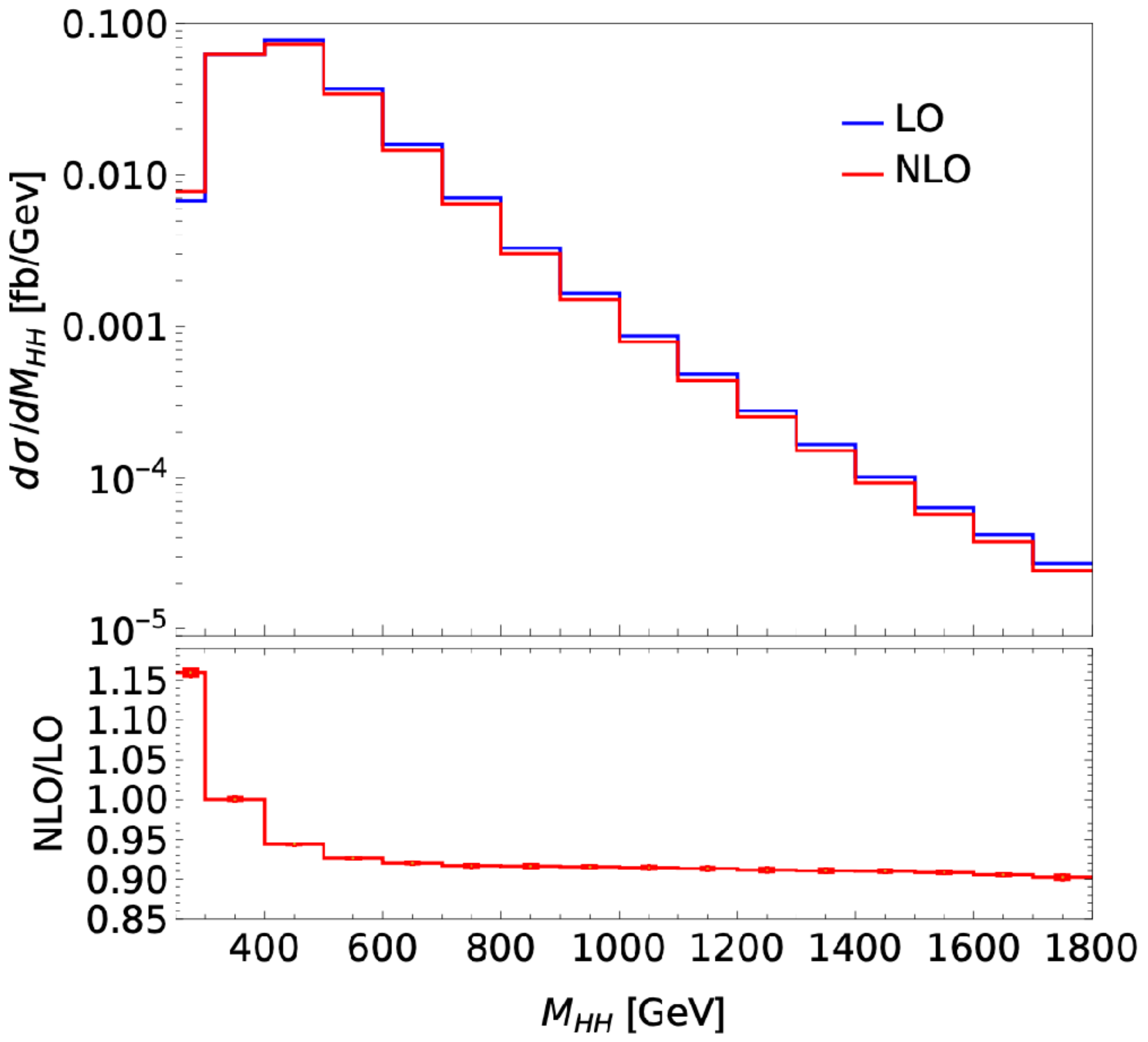
PDF + α_s uncertainties ~ 2.3%

top mass scheme uncertainty currently largest uncertainty in Higgs boson pair production

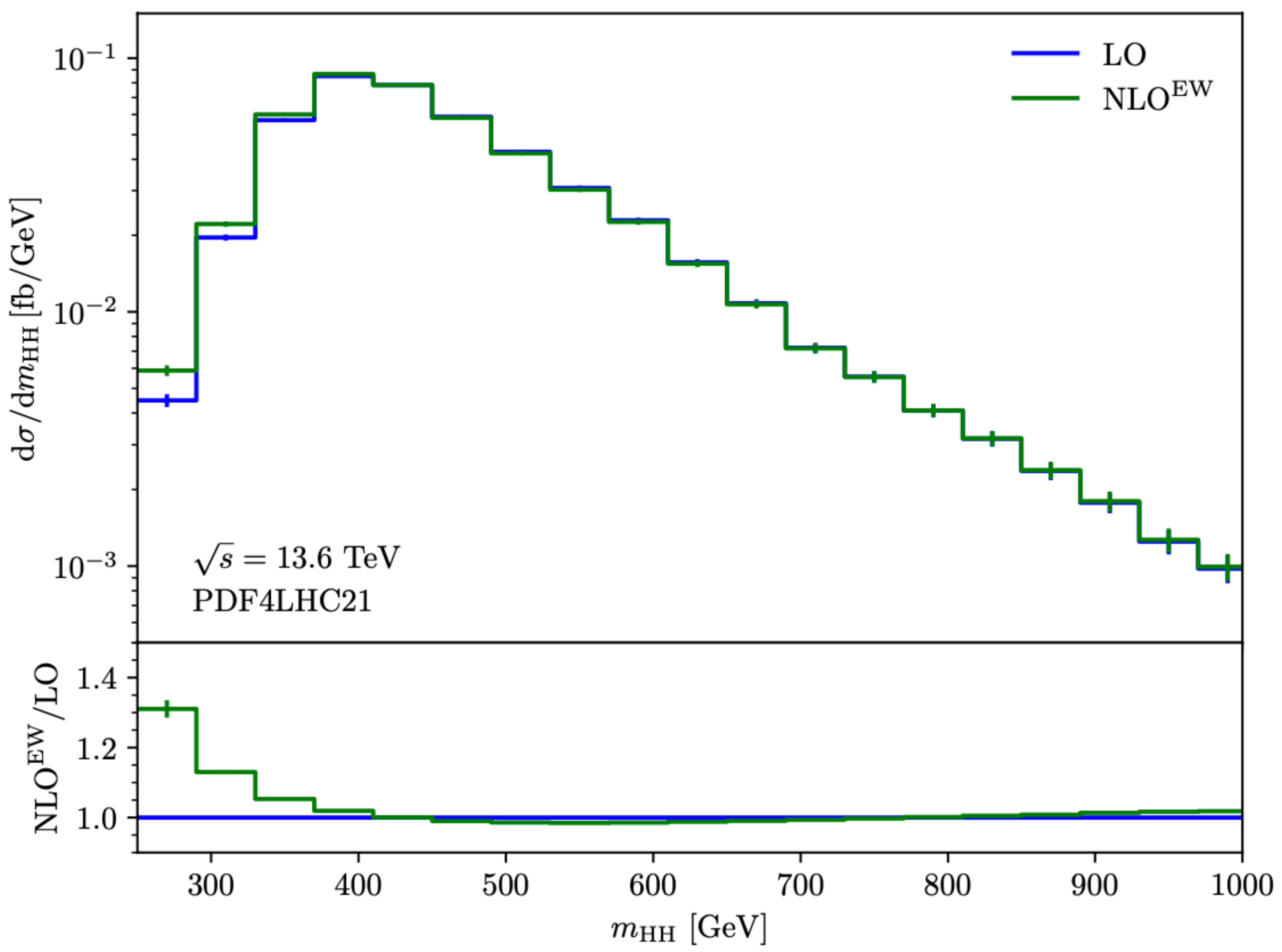
NLO electroweak corrections to ggHH

Karlsruhe Institute of Technology

full EW: Bi, Huang, Huang, Ma, Yu ’23



Yukawa- and Higgs self-coupling type corrections:



GH, Jones, Kerner, Stone, Vestner ‘24

see also

heavy top limit, high energy expansion

Davies, Mishima, Schönwald, Steinhauser, Zhang ‘22

Yukawa coupling corrections in (partial) HTL

Mühlleitner, Schlenk, Spira ’22

full EW in large-mt expansion ‘23
\+ factorisable contributions ‘24

Davies, Schönwald, Steinhauser, Zhang

cancellations between gauge-boson and Yukawa-type corrections

see talks by Huai-Min Yu,
Johannes Braaten

partial EW corrections, with coupling modifiers:

Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao ’18; Bizon, Haisch, Rottoli ’18, ’24

Summary & outlook

- The Higgs boson is our youngest particle (time since discovery) and the most peculiar particle (the only elementary scalar so far)
- Precision calculations are necessary to identify deviations from the SM predictions as new physics and to make the case for future colliders;
  in addition we keep learning about the structure of Quantum Field Theories
- Technical frontiers are 2-loop 5-point with several mass scales, 3-loop 4-point … (loops+legs+masses >=7), combining QCD corrections with EW corrections, EW schemes, treatment of heavy quarks (e.g. mass renormalisation schemes), parton shower matching beyond NLO, power corrections, PDFs, … lots of progress!
- Conceptual frontiers are …

Guess what's under the fog from the features peaking out of the fog …