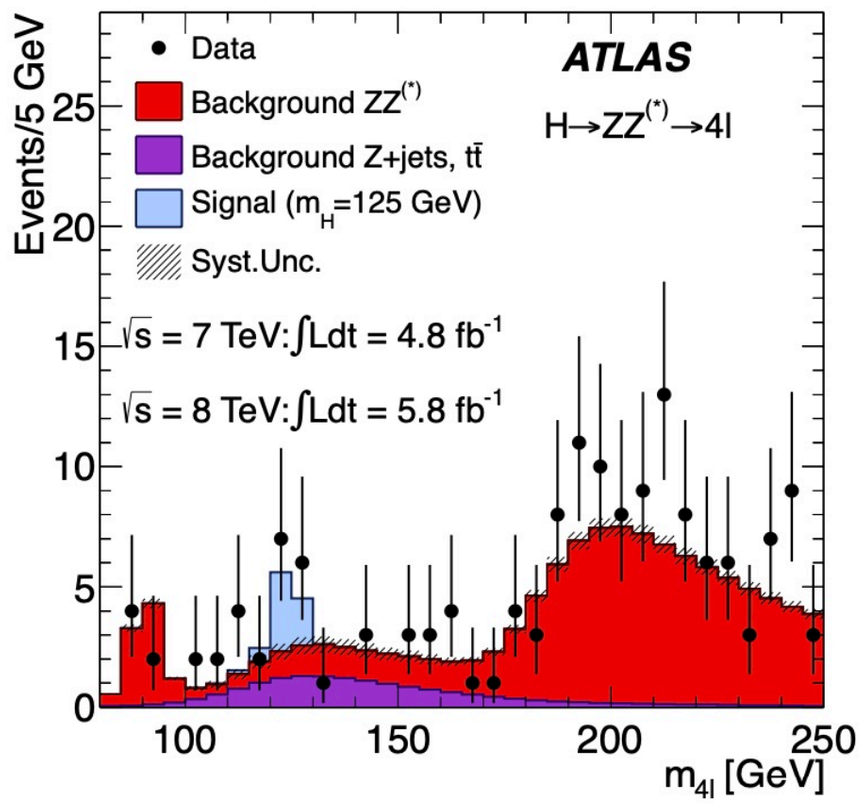
The importance of the accuracy of theoretical predictions

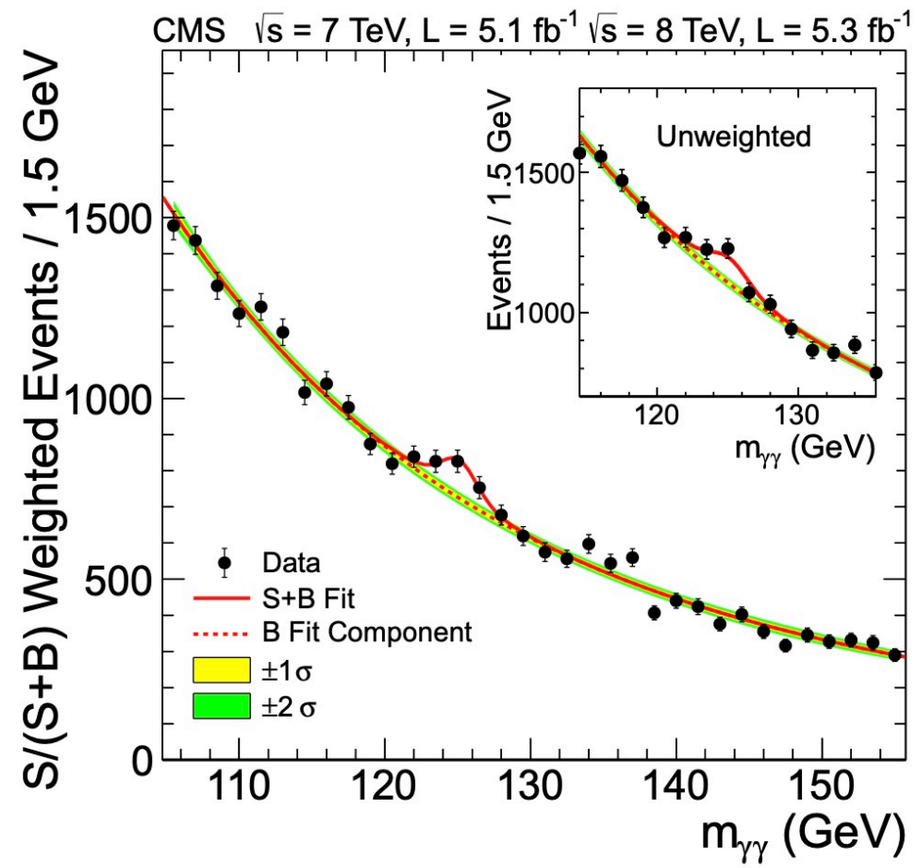
Massimiliano Grazzini
University of Zurich

Higgs10 Symposium, CERN, July 4th 2022

Preamble

The Higgs boson discovery happens by measuring an excess of events in the $\gamma\gamma$ and 4-lepton channels: accurate theory predictions play little role here



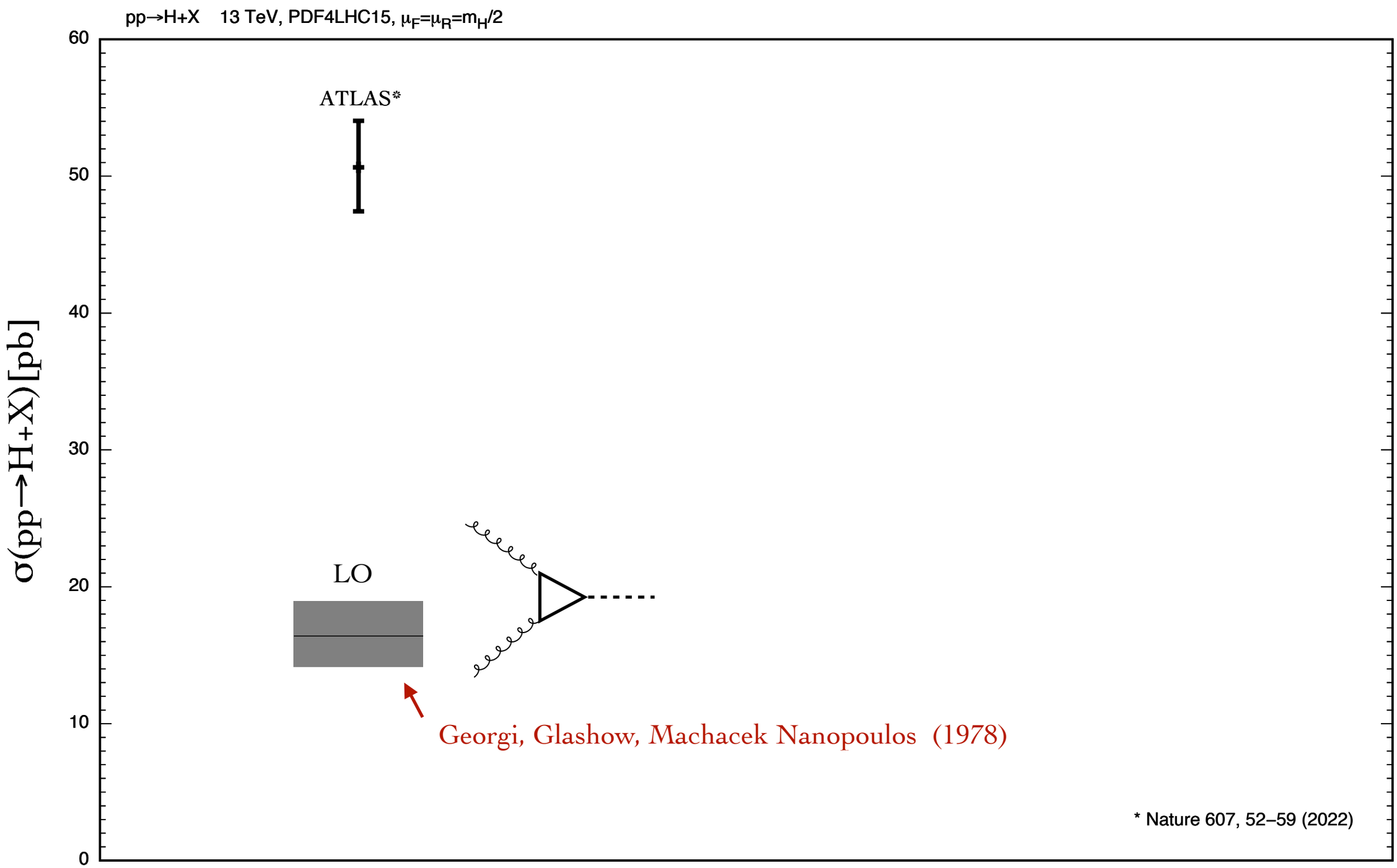


Landau-Yang theorem: $\gamma\gamma$ decay already rules out the spin-1 possibility

➡ Spin-0 quickly appears to be the most natural possibility

Significant decay fractions to ZZ and WW: very likely to have significant CP-even component

ggF inclusive rate…



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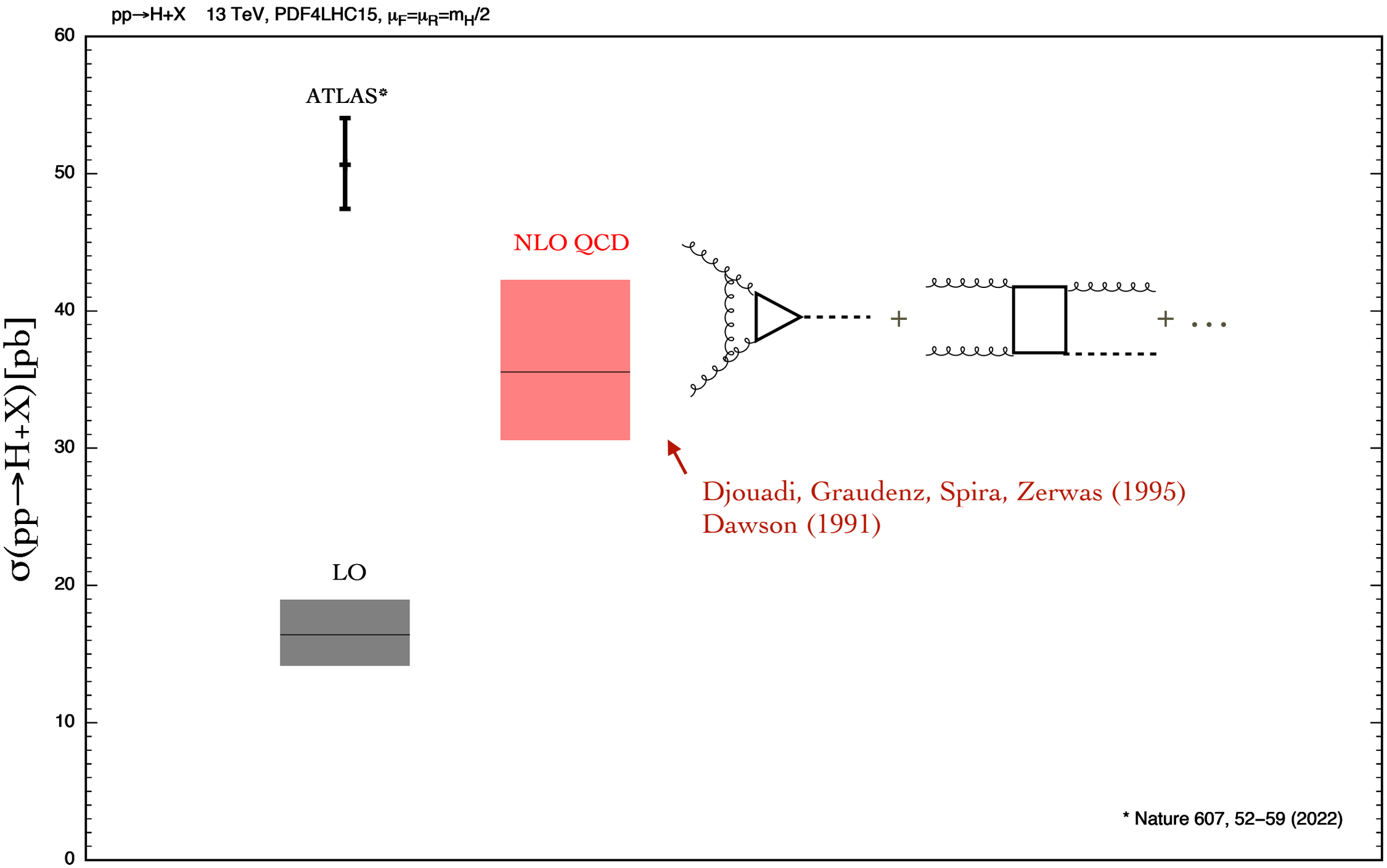
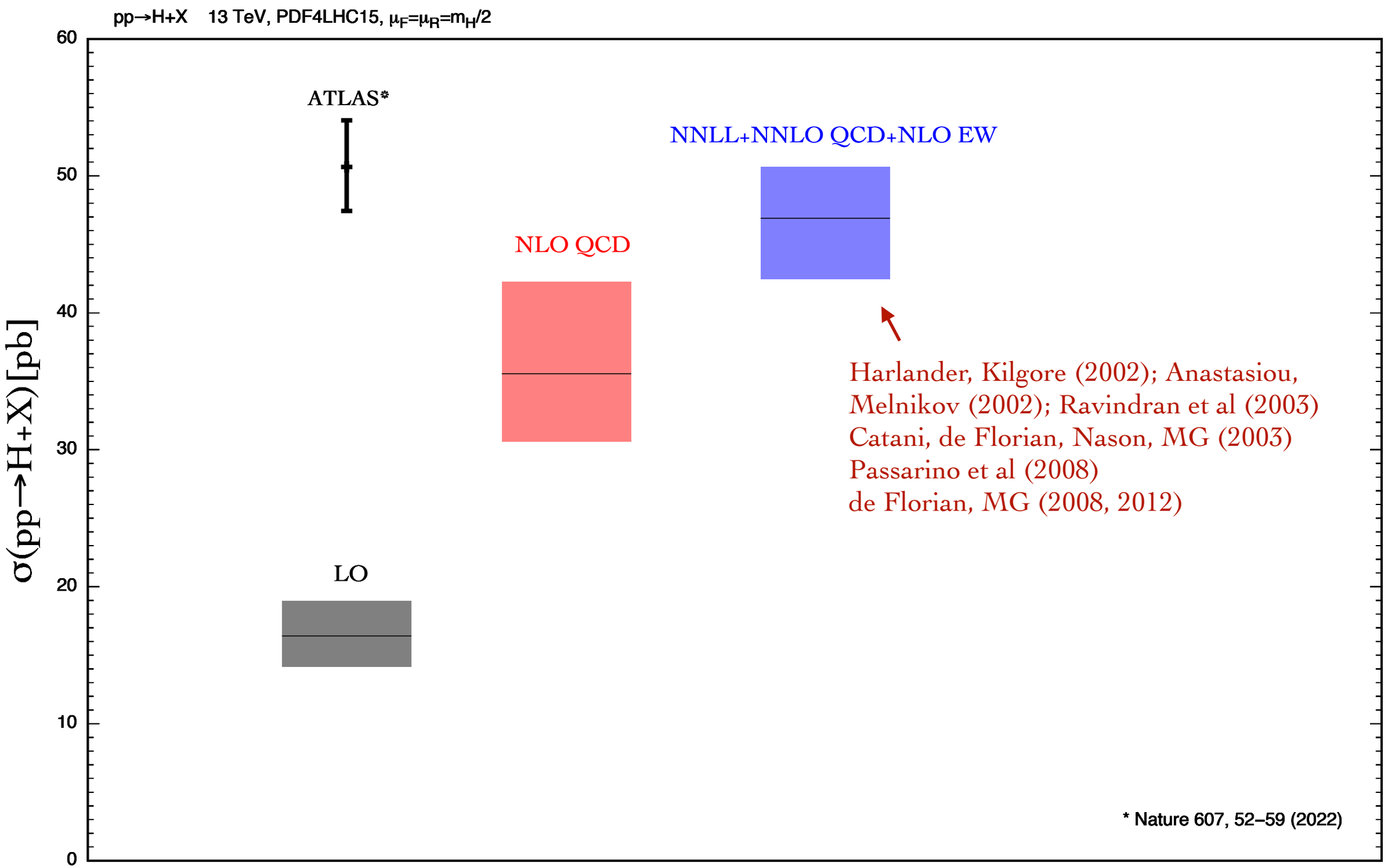


ggF inclusive rate…



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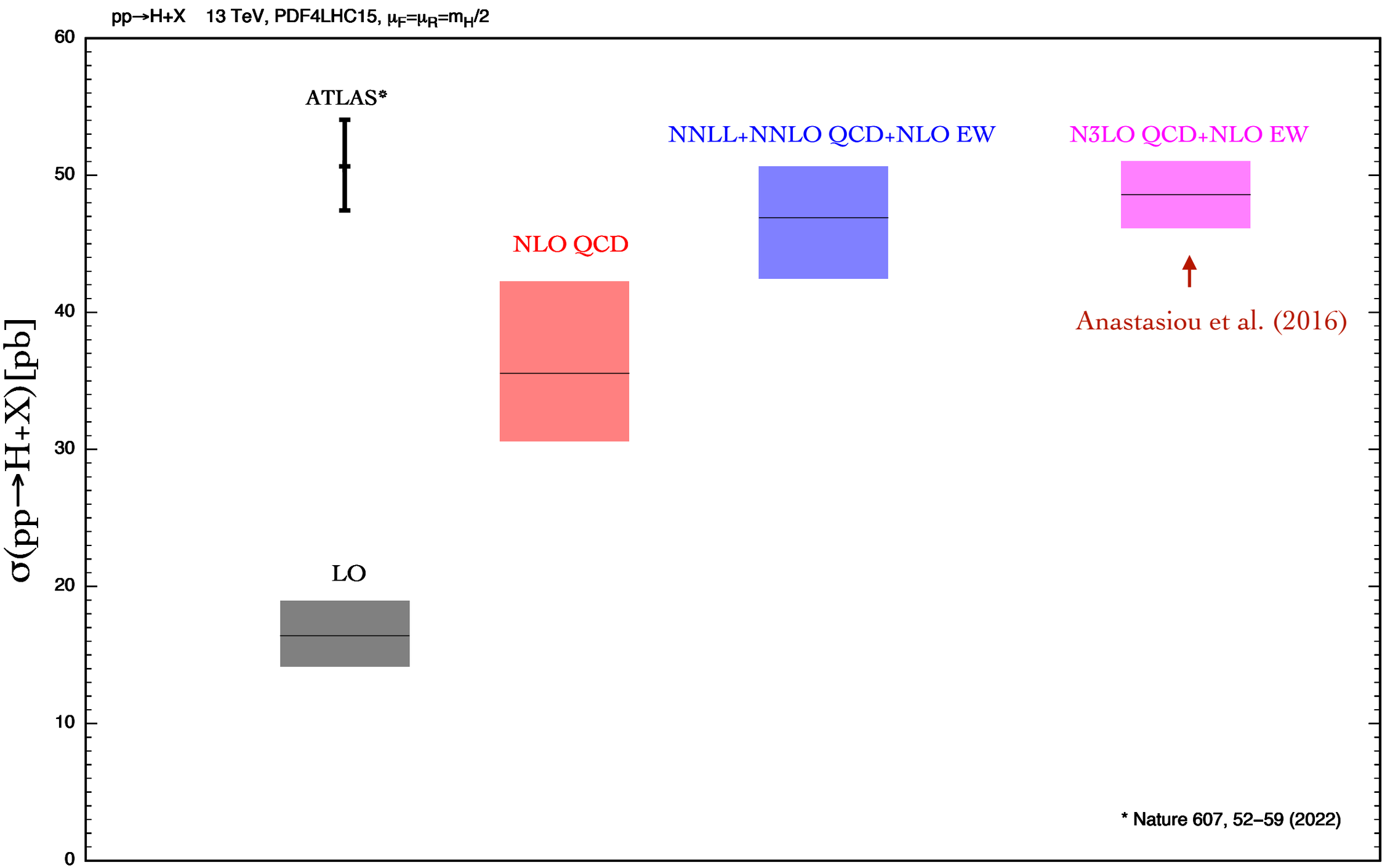
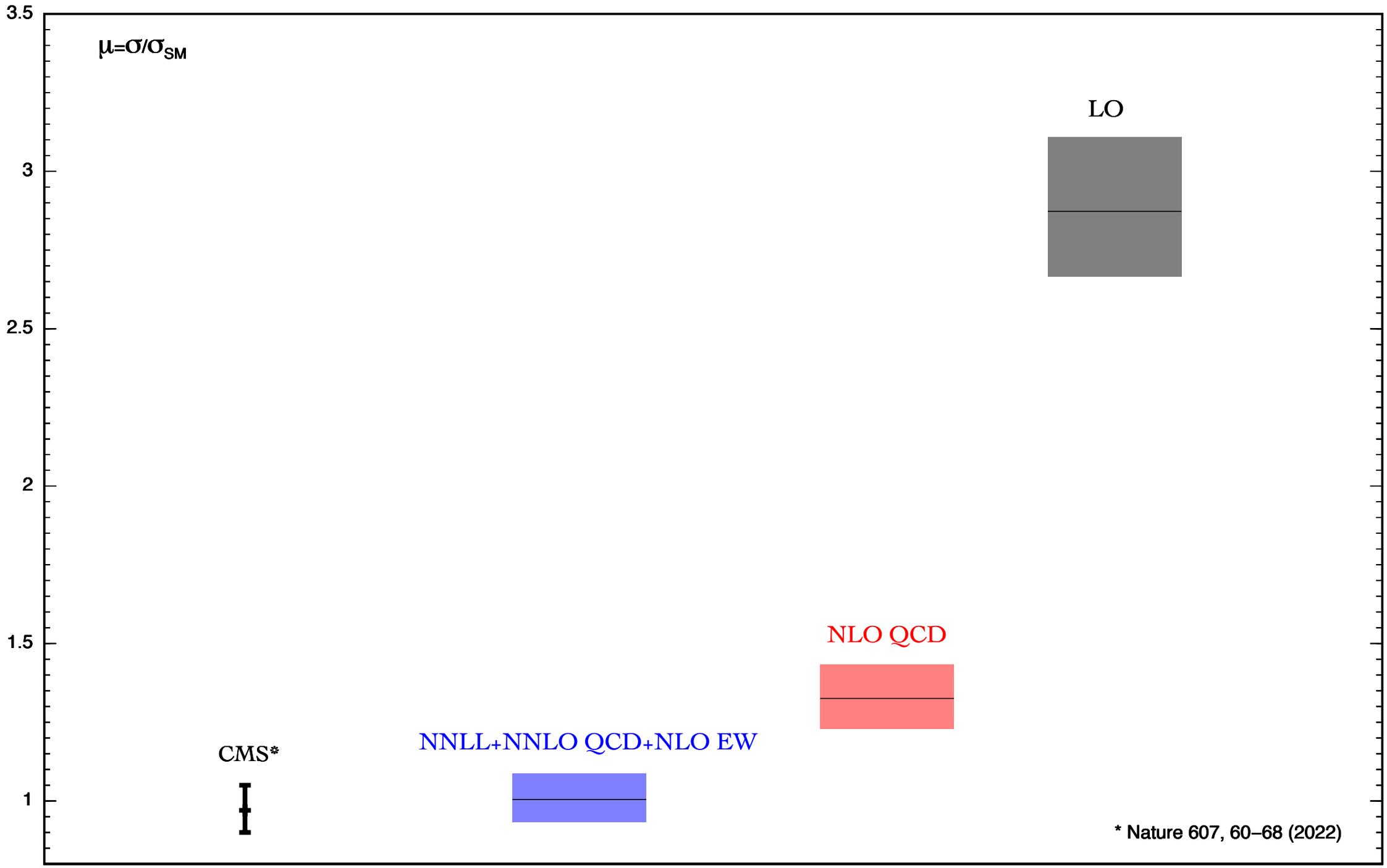


…or signal strength



Looking ahead

Current analyses based on N³LO QCD+NLO EW predictions

$\sigma_{ggH} = 48.58 \pm 3.2\,\%\,(\mathrm{PDF} + \alpha_S) \pm 3.9\,\%\,(\mathrm{TH})$ pb

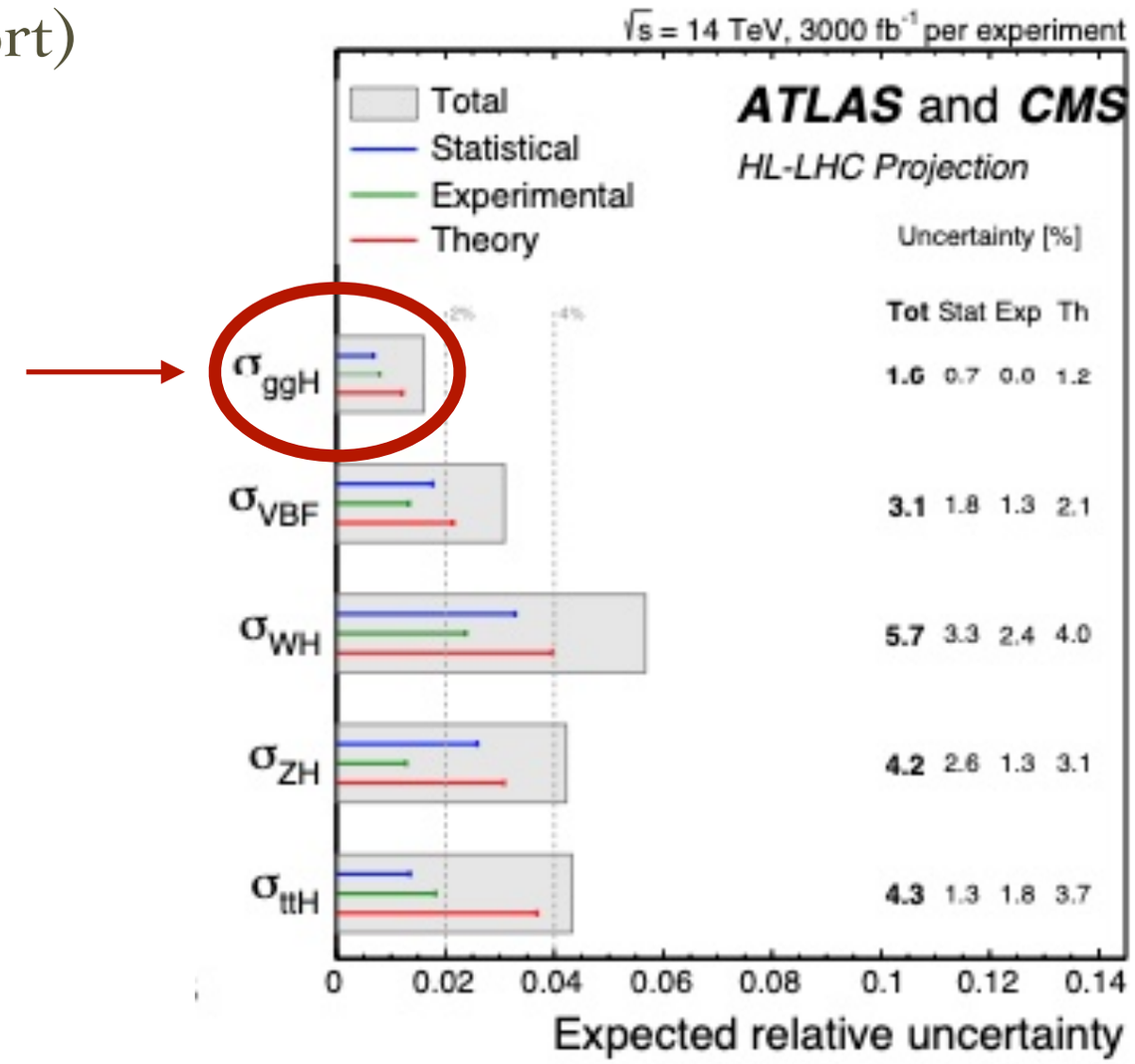
HXSWG YR4 result based on Anastasiou et al (2016)

Constructed from linear combination of theory uncertainties and finally converted to Gaussian dividing by $\sqrt{3}$

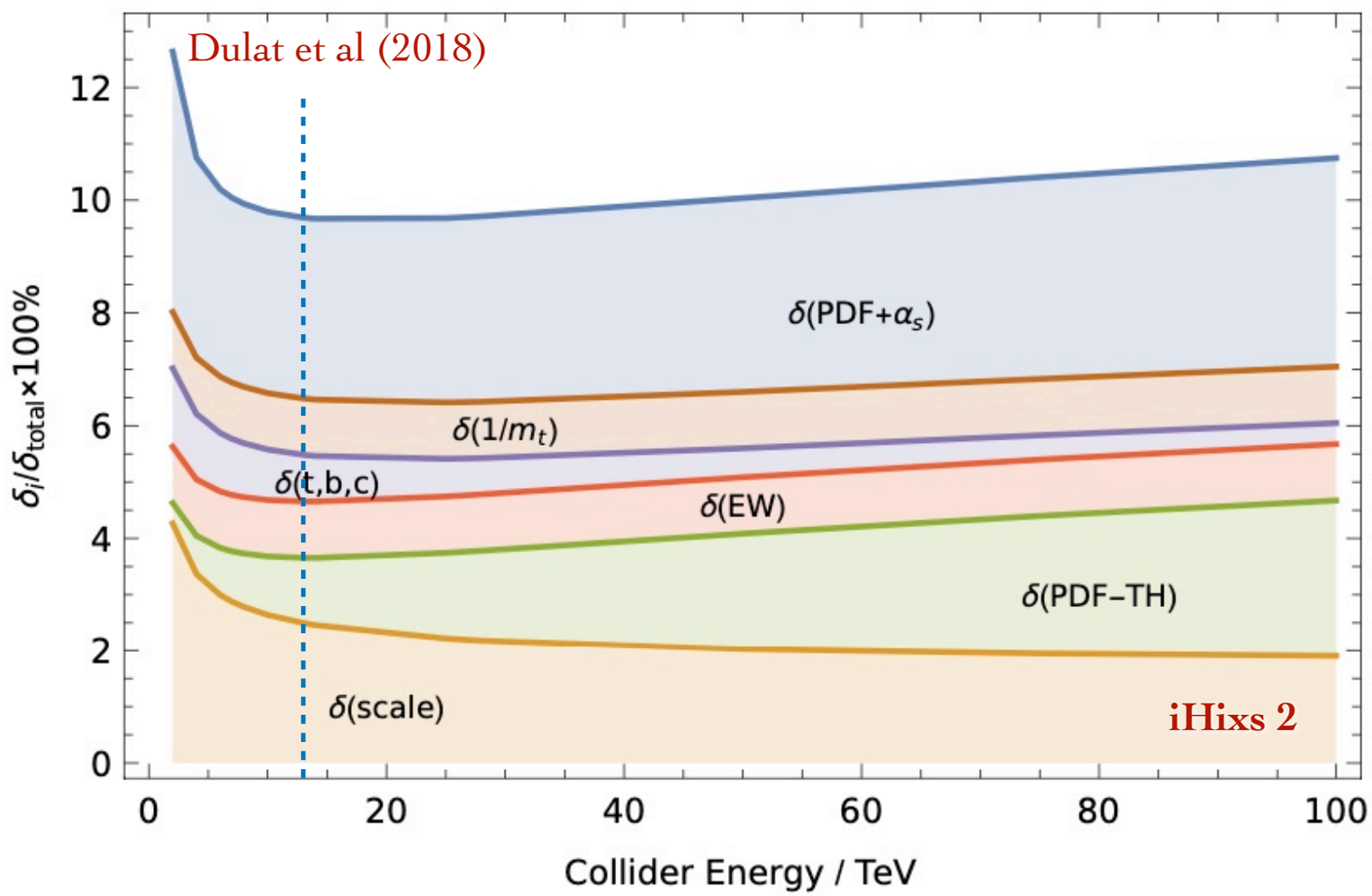
plus minor updates (see HL-HE report)

HL projections anticipate $\mathcal{O}(2\%)$ uncertainties and assume theory uncertainties halved !

Will theory keep up ?

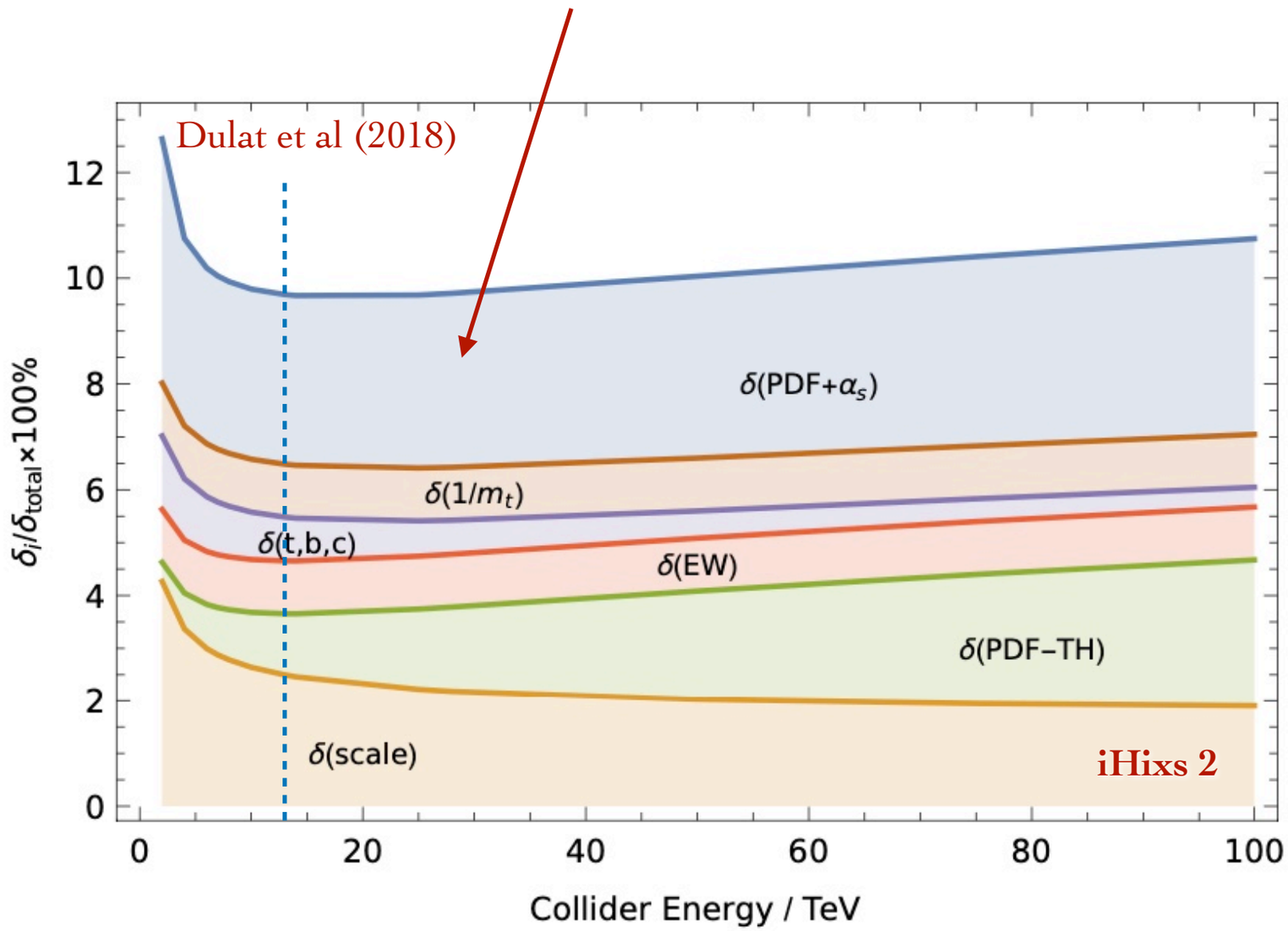


Uncertainty budget



Uncertainty budget

PDF uncertainty essentially unchanged from PDF4LHC15 to PDF4LHC21: still ±1.8 % :
note that using NNPDF4.0 would lead to ±0.75 % *



*from iHixs

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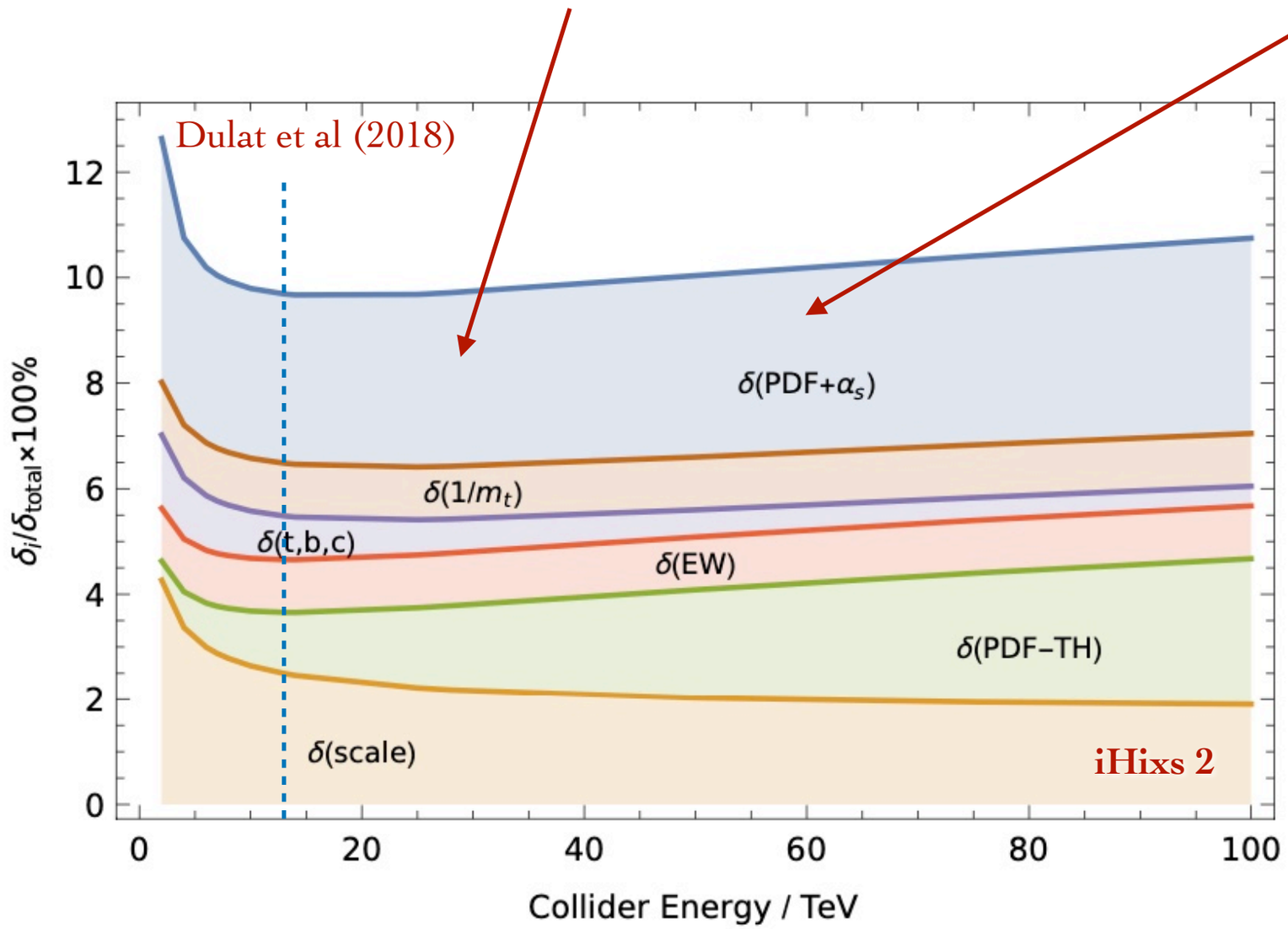

$\sigma_{gg\to H} \sim \alpha_s^2(1 + \ldots.)$

$\alpha_s = 0.118 \pm 0.001$ leads to $\mathcal{O}(2\%)$ uncertainty on σ_{ggH}

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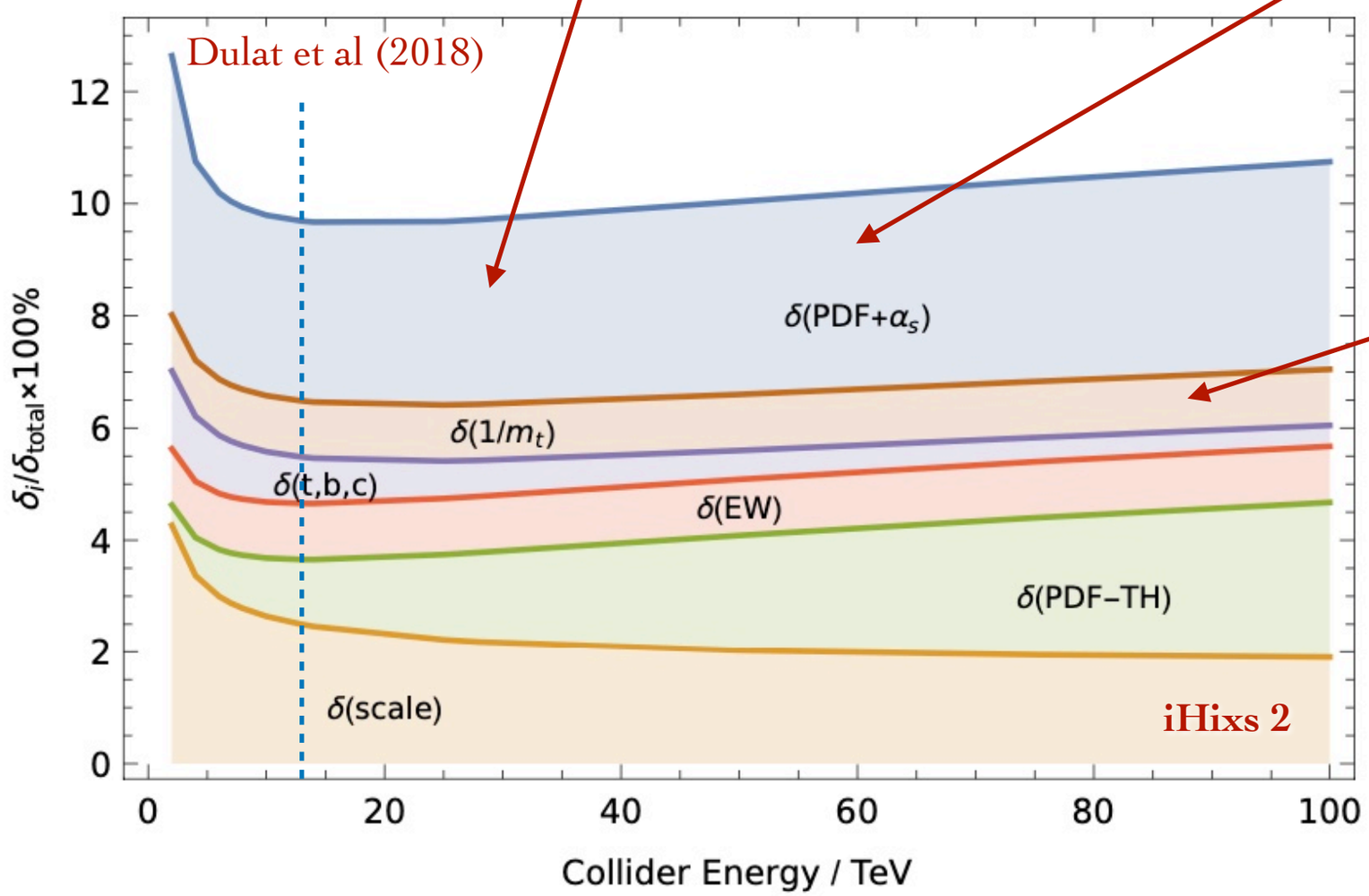

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Eliminated through exact NNLO calculation

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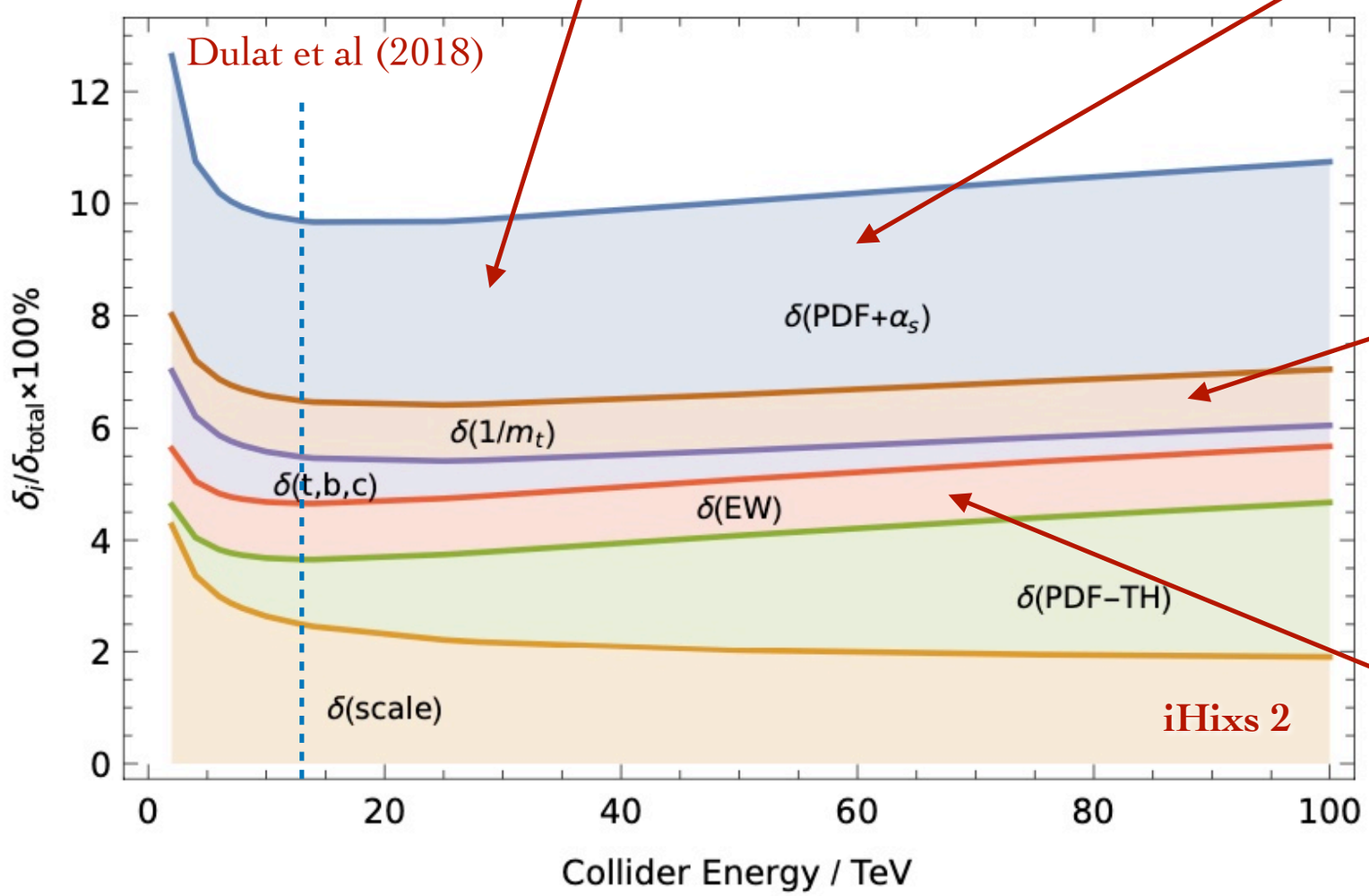

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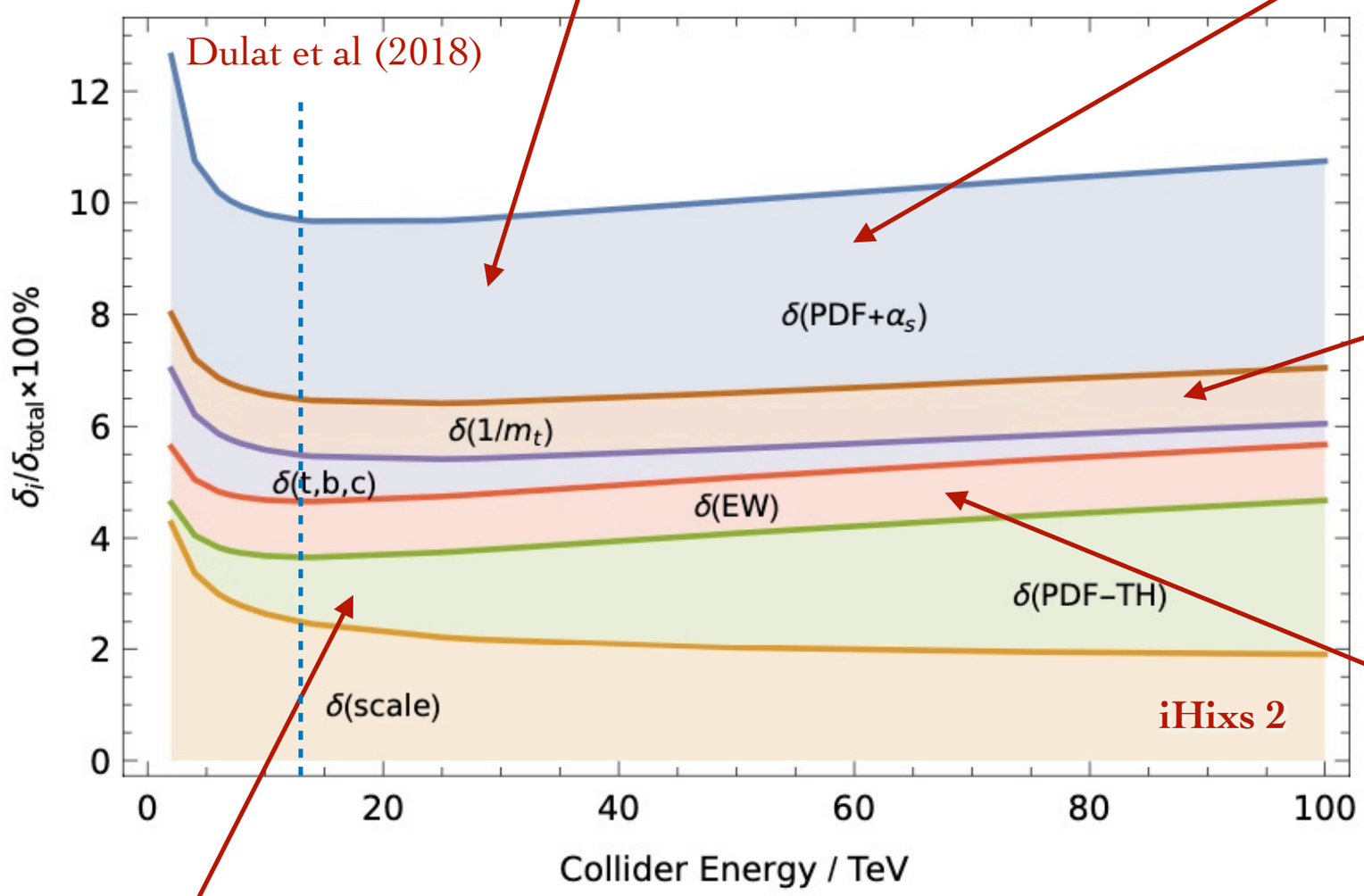

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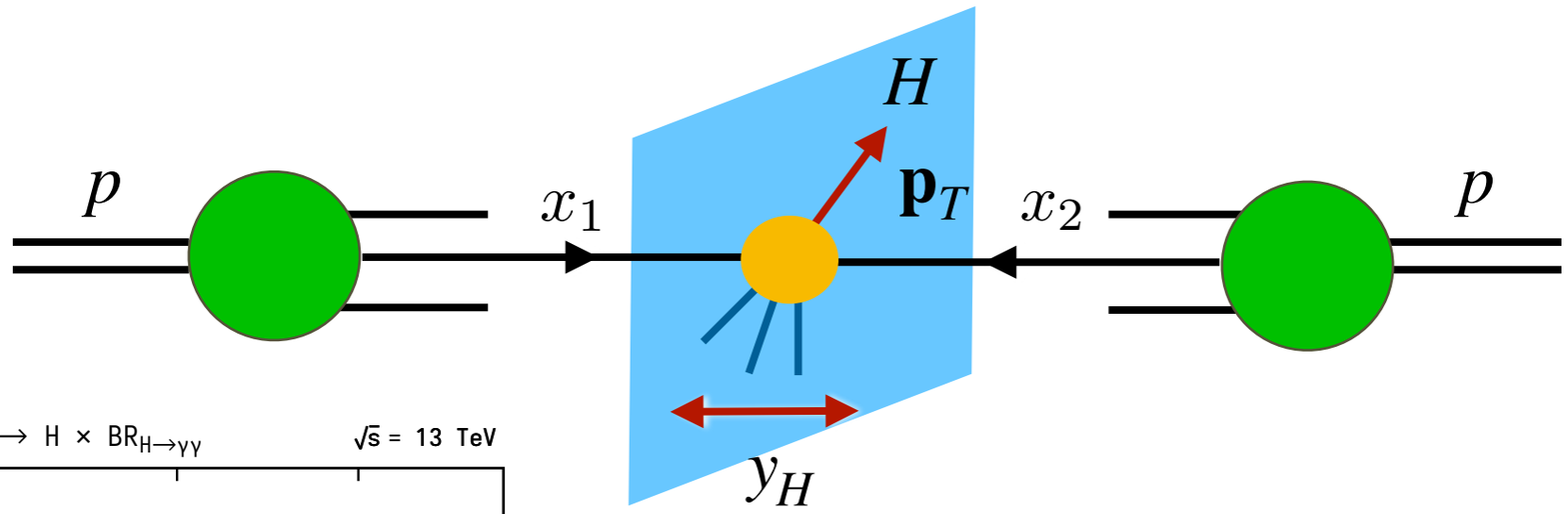
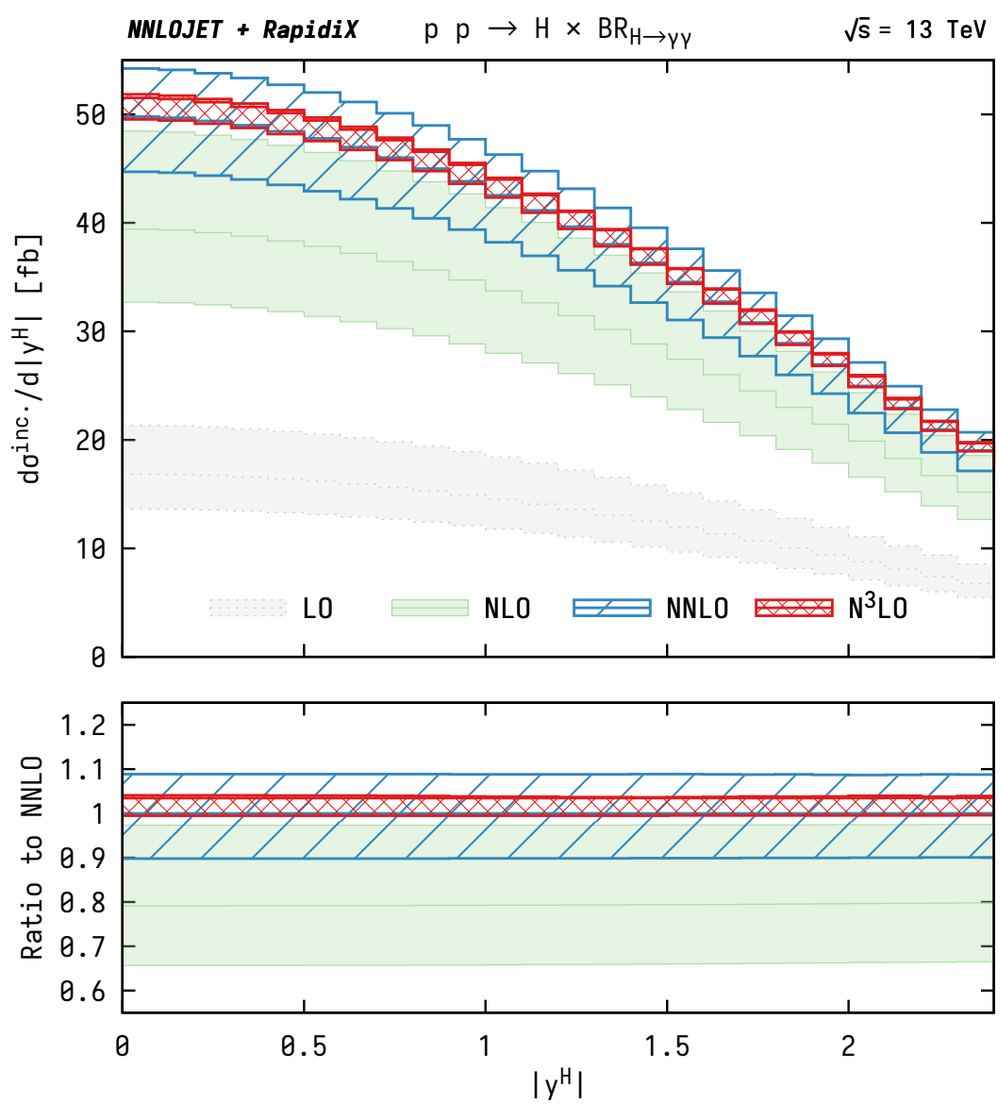
Requires N³LO PDFs (and thus 4-loop splitting functions)

*from iHixs

Going differential

Higgs production kinematics identified by rapidity and transverse momentum





The shape of the rapidity distribution is mostly determined by PDFs

Rapidity distribution now known at N^{3}LO

Chen, Gehrmann, Glover, Huss,Mistlberger Pelloni (2021); Dulat, Mistlberger, Pelloni (2018)

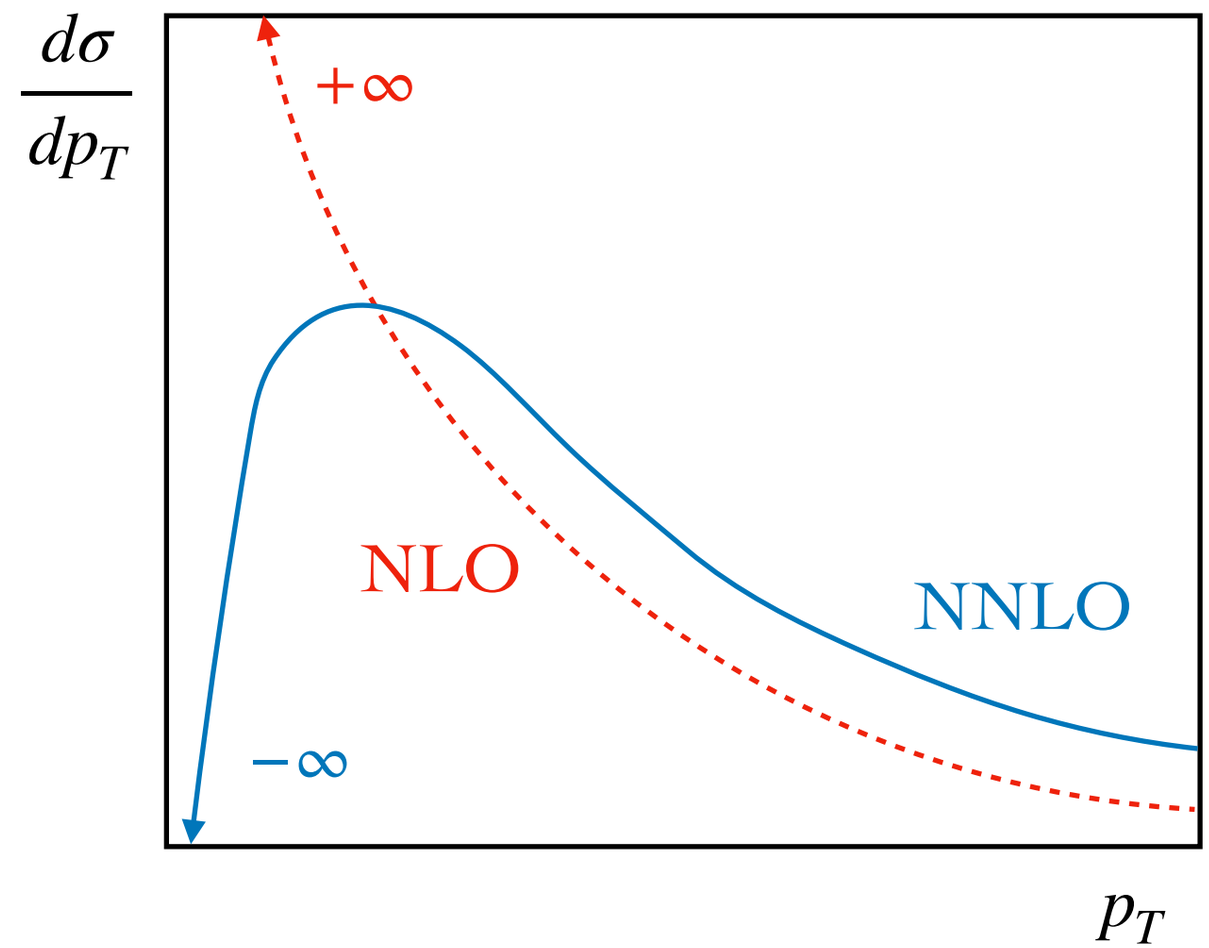
Inclusive K-factor completely flat

Effect of radiative corrections mainly encoded in the p_T spectrum

The p_T spectrum

The p_T spectrum gives us information on the hardness of the QCD radiation accompanying the Higgs boson but its precise shape cannot be computed by using fixed order perturbation theory

When $p_T \ll m_H$ multiparton emission needs to be accounted for through all order resummation



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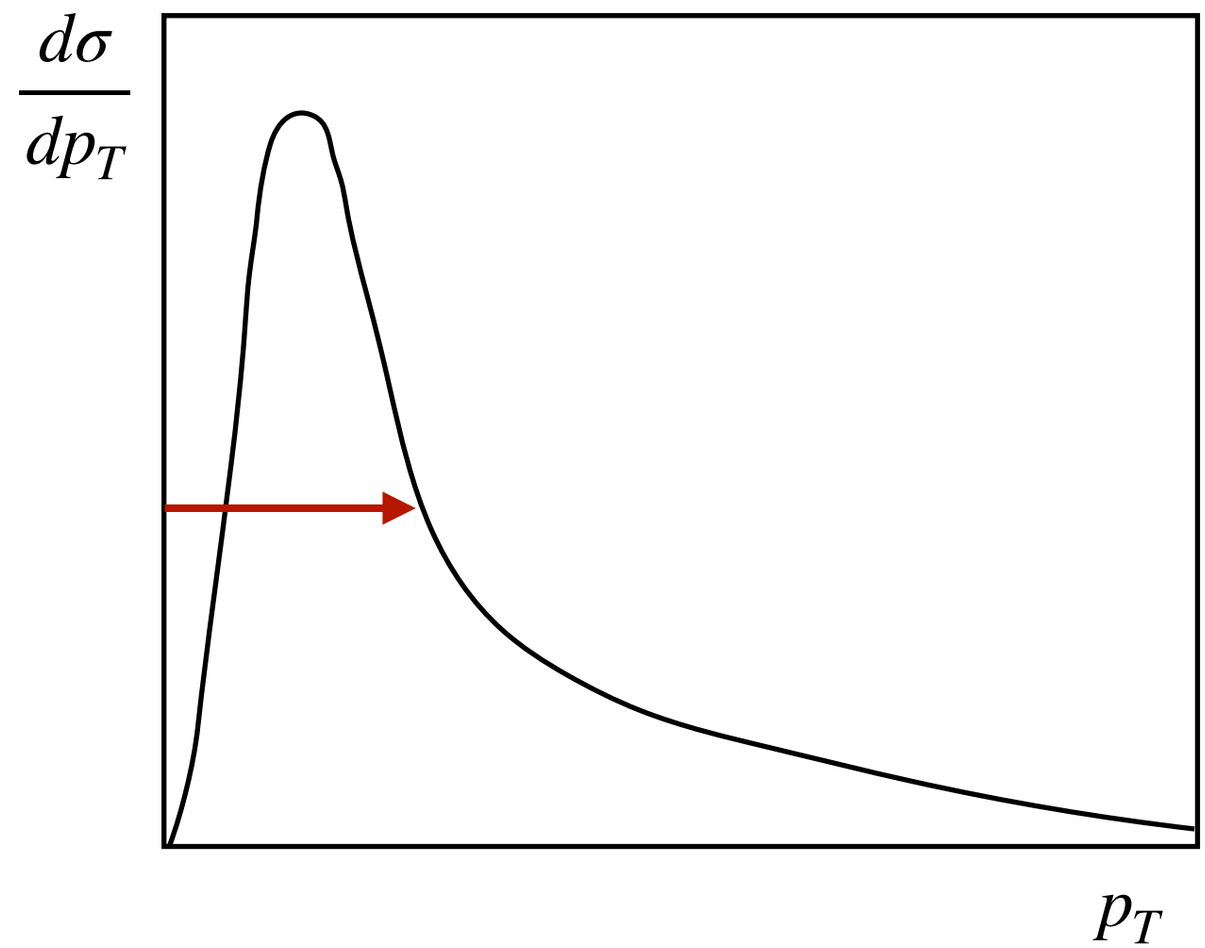
Effectively performed by Parton Showers but with limited logarithmic accuracy*



*to be improved with recent advances in Parton Showers

Salam et al, PanScales project

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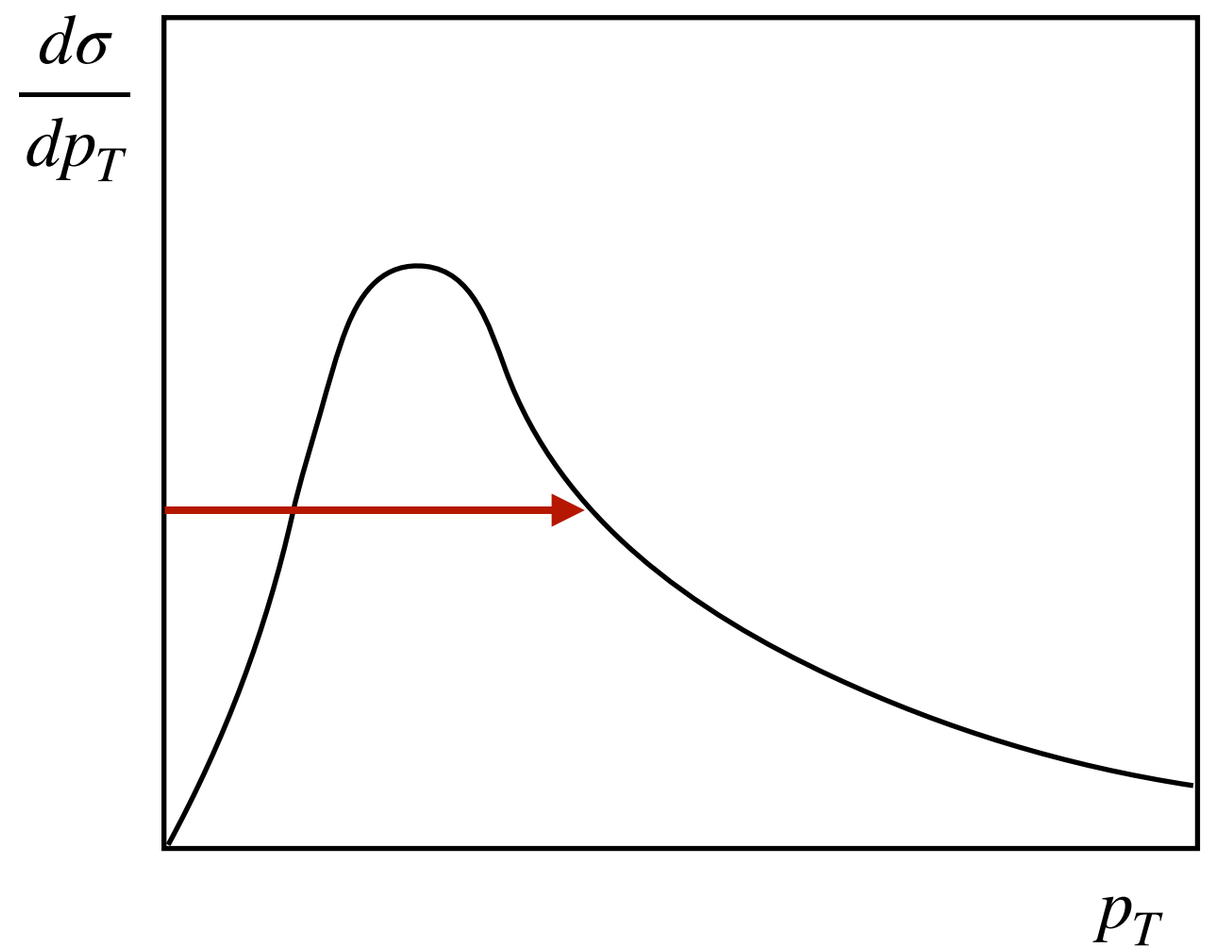
Different NLO matching prescription (e.g. MC@NLO vs POWHEG) may lead to different shapes



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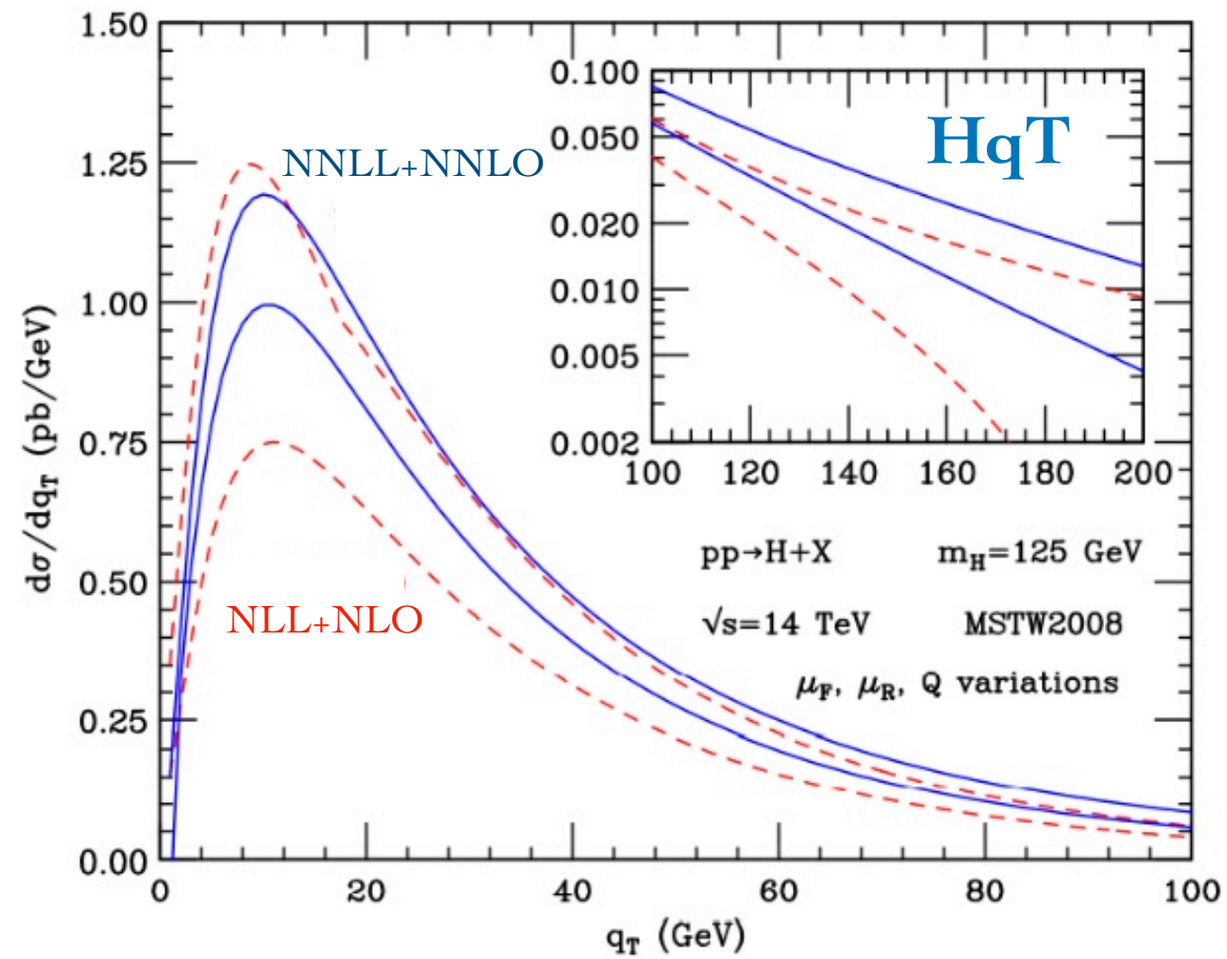
The availability of accurate predictions for differential distributions and for the spectrum played a twofold important role

- Help shaping analysis strategies



Bozzi, Catani, de Florian, MG (2005)

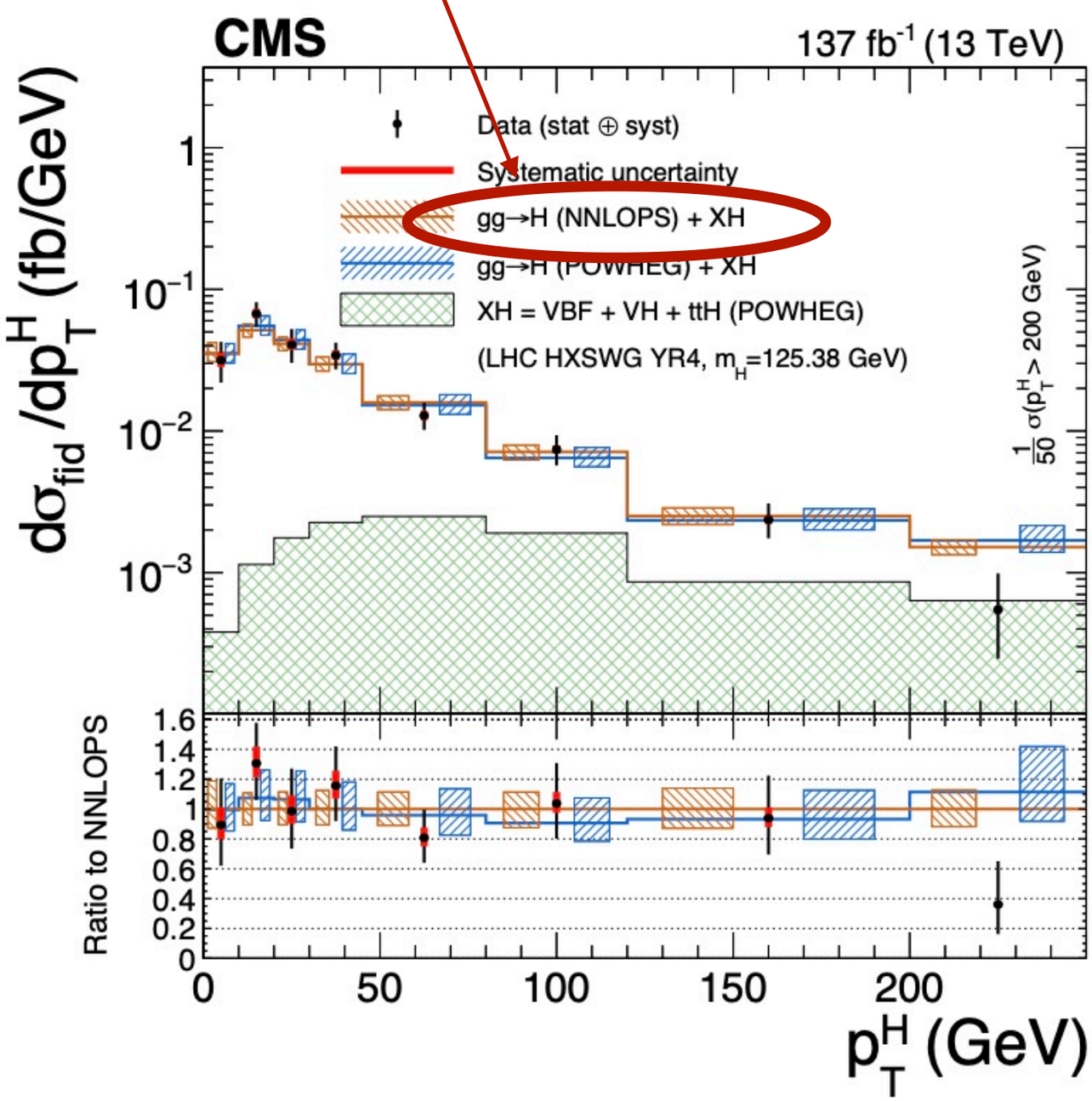
- Pave the way to the deployment of NNLO accurate Monte Carlo event generators which are nowadays routinely used in the analyses

Hamilton, Nason, Oleari, Zanderighi (2012)
Hamilton, Nason, Re, Zanderighi (2013)

Current status

default MC: MiNLO+reweighting of the rapidity distribution to HNNLO

Hamilton, Nason, Re, Zanderighi (2013)



Used by CMS to reweight POWHEG sample

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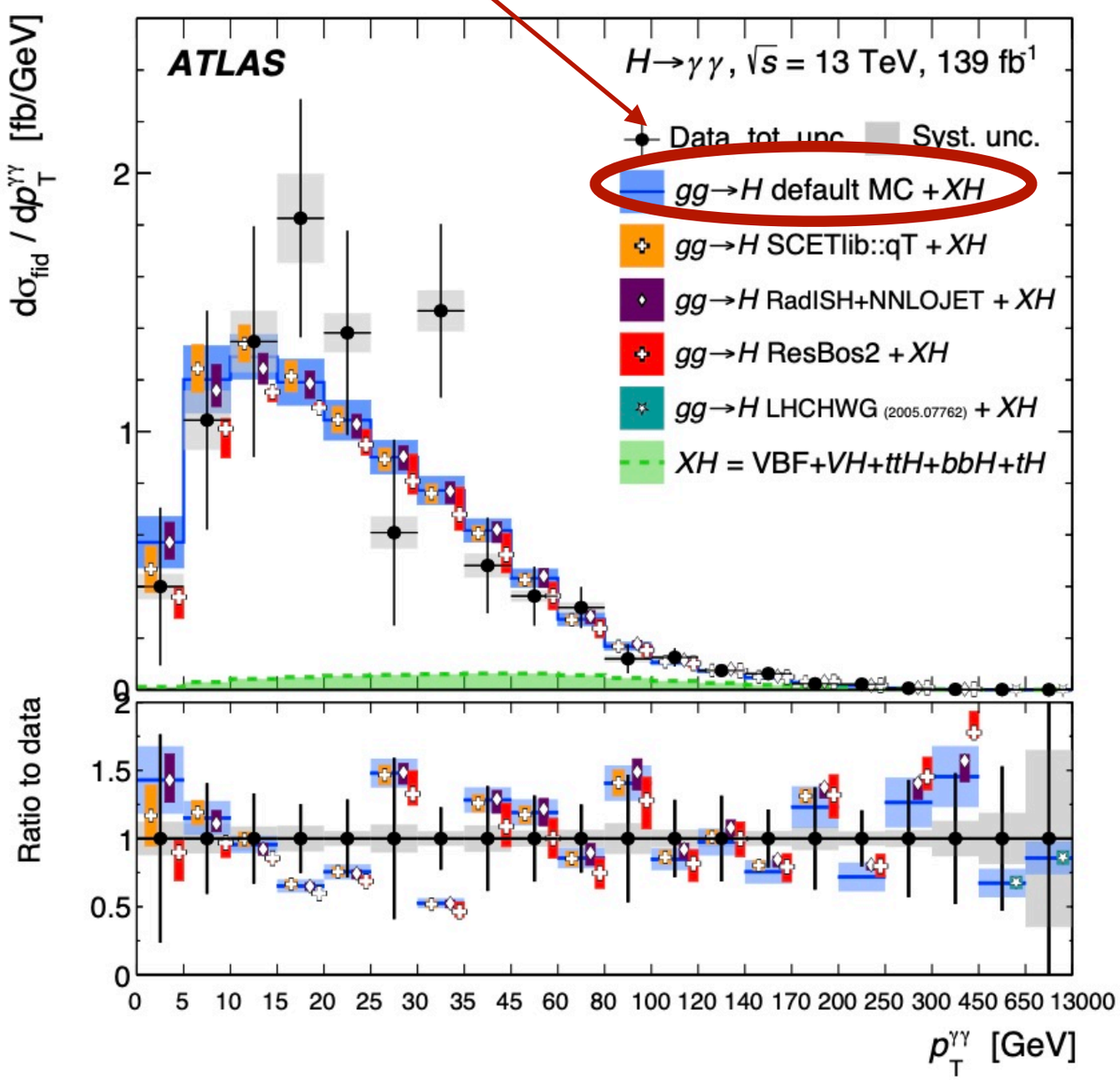

….and by ATLAS as default MC for ggF

To be eventually replaced by MiNNLOPS (no reweighting)

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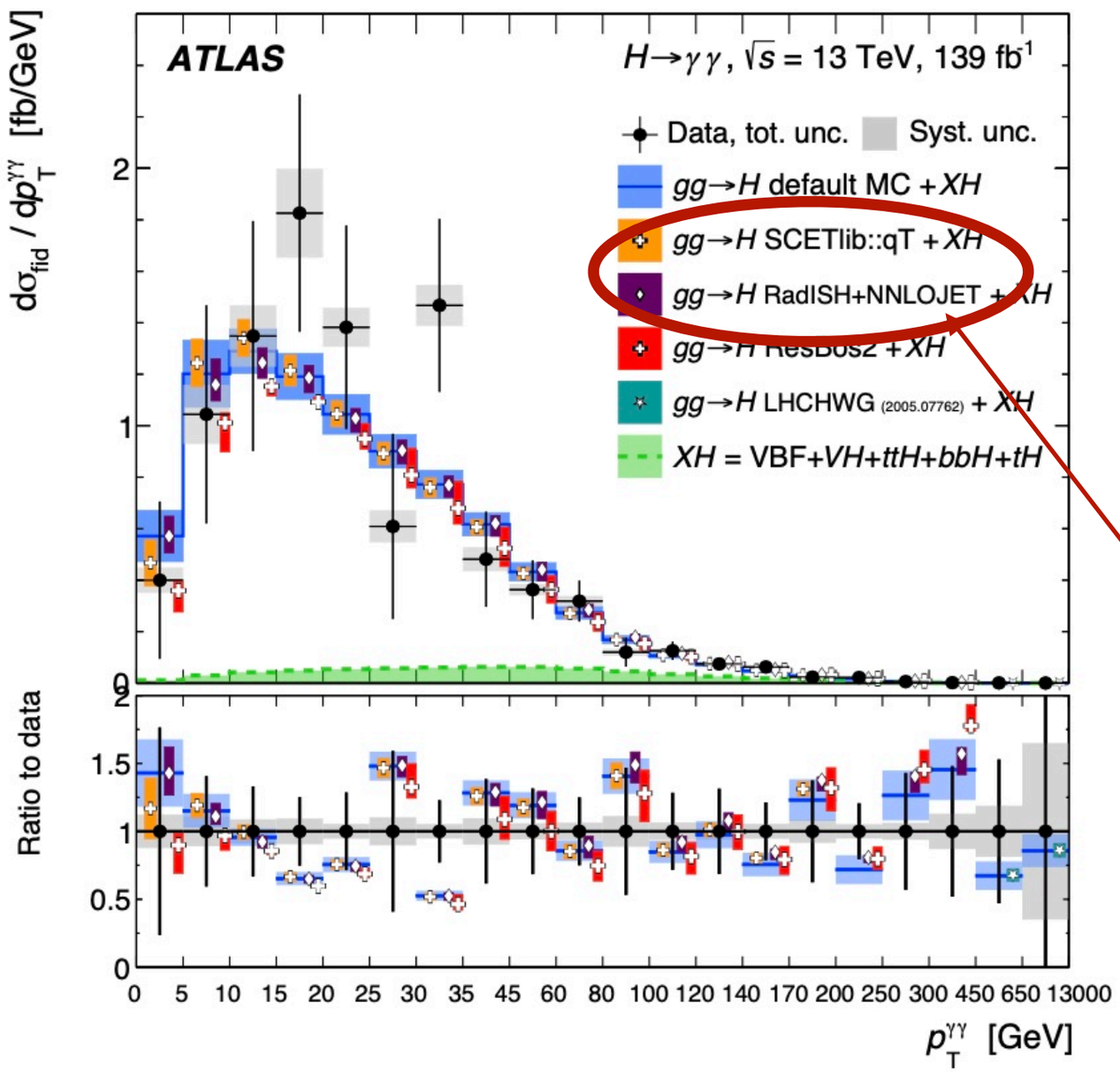

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In nice agreement with most advanced resummed computations*….

Billis, Dehnadi, Ebert, Michel, Tackmann (2021)
Re, Rottoli, Torrielli (2021)
Chen et al (2016)

*made possible by recent evaluation of "beam functions" at N³LO

Luo, Yang, Zhu, Zhu (2019)
Ebert, Mistlberger, Vita (2020)

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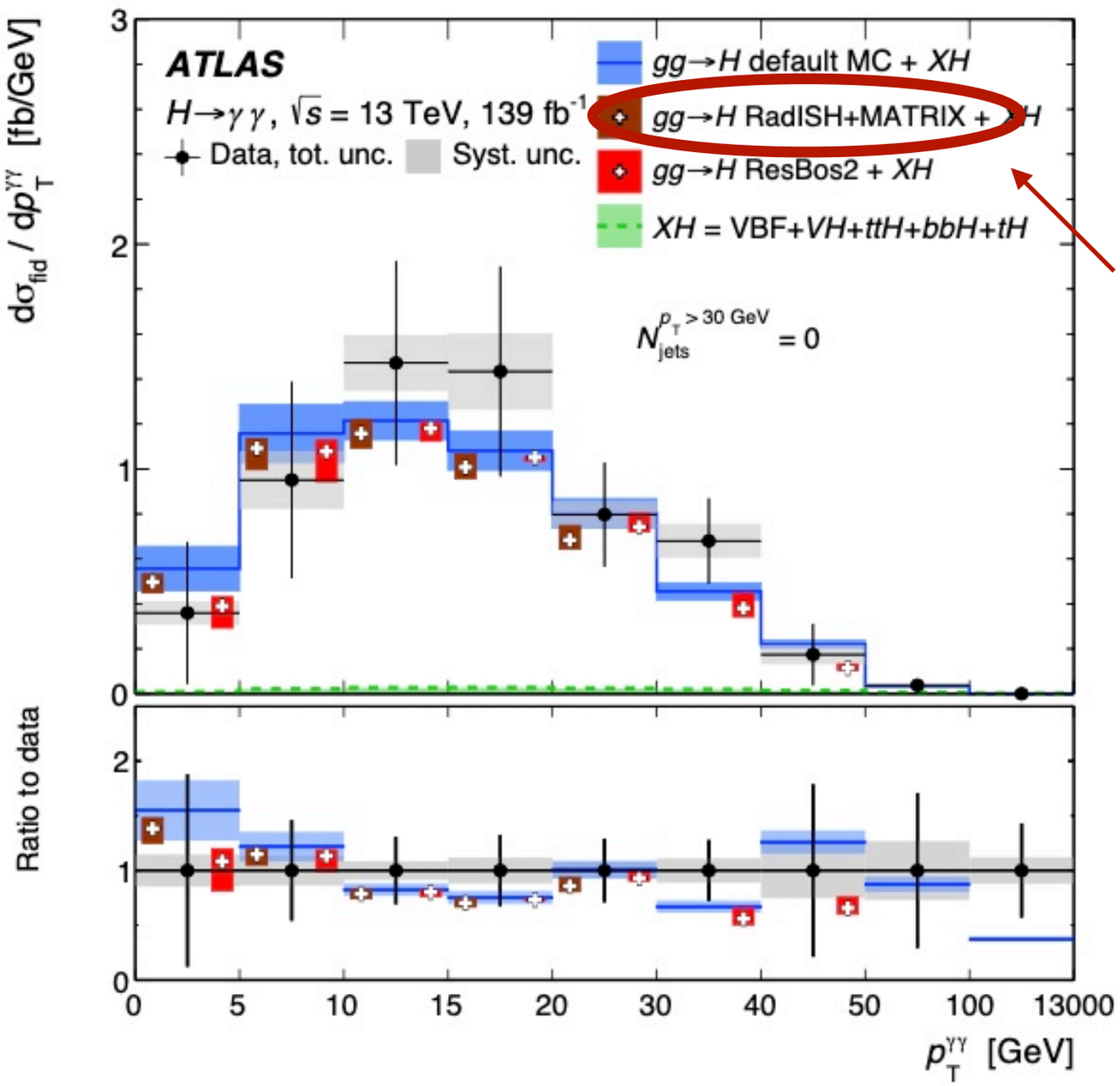
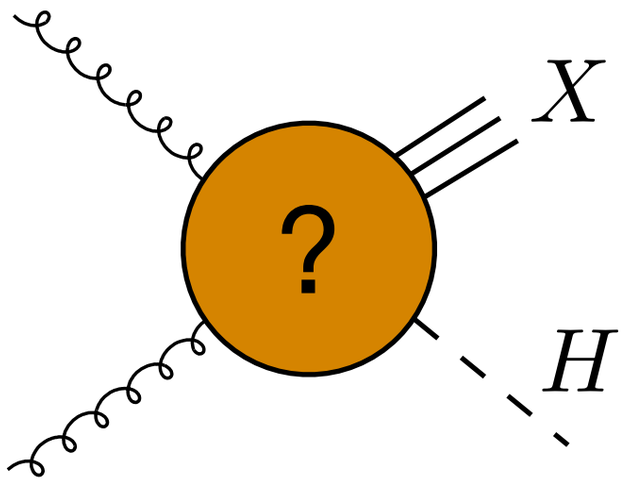


…and, when a jet veto is applied also with double differential resummations of p_T and p_T^{veto}

Monni, Rottoli, Torrielli (2019)
Kallweit, Re, Rottoli, Wiesemann (2020)

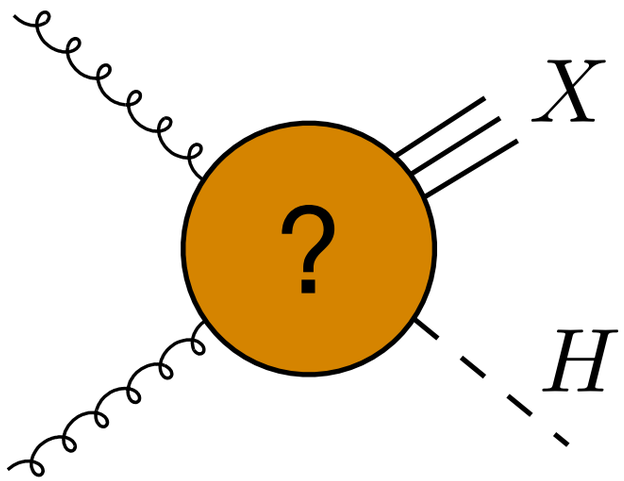
High p_T



Higgs production at high-p_T can be useful to test New Physics scenarios

New Physics could change the high-p_T spectrum mildly affecting the inclusive rates

High p_T



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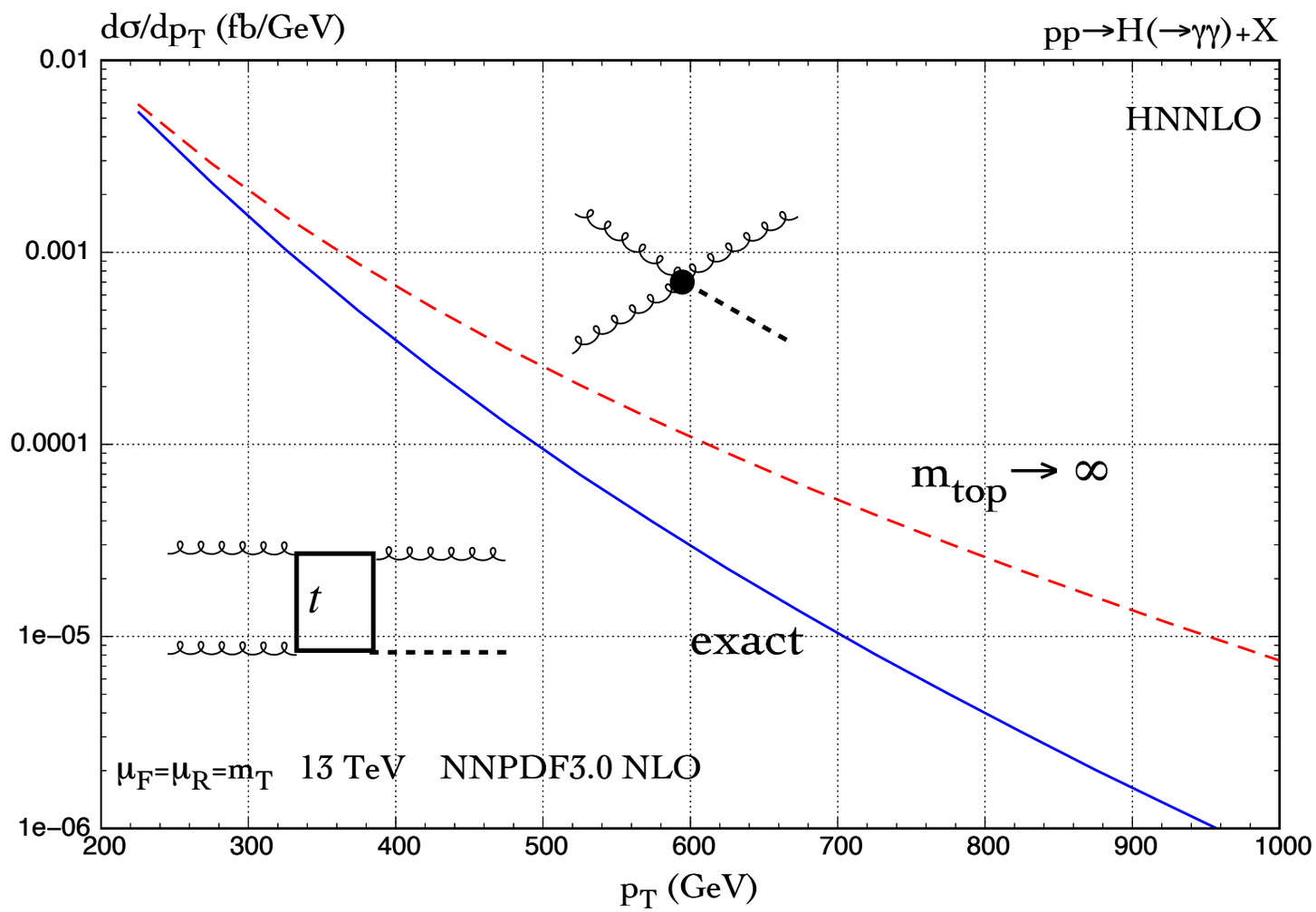
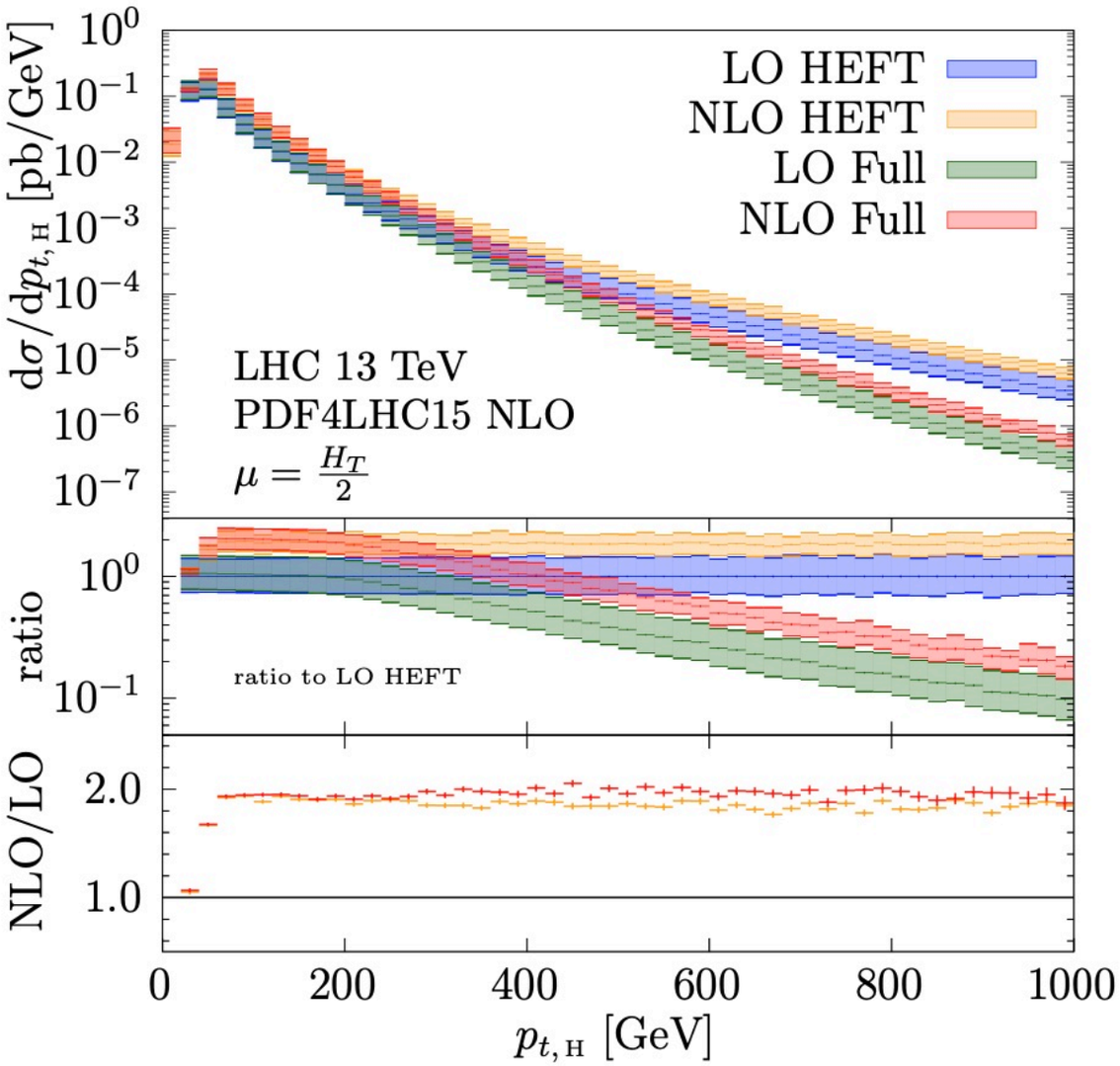


Up to recently predictions beyond LO only available in the large-m_t limit

De Florian, Kunszt, MG (1999)
Glosser, Schmidt (2002)
Ravindran, Smith , van Neerven (2002)

Mass effects lead to huge differences at large p_T

High p_T



Combined with NNLO in EFT

Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier (2016)
Boughezal et al (2015)

→ accurate predictions for boosted analyses

Exact NLO calculation requires 2-loop amplitudes with different mass scales: completed numerically

Jones, Kerner, Luisoni (2018)
Chen, Huss, Jones, Kerner, Lang Lindert, Zhang (2021)

Trick used: $m_H^2/m_{top}^2 = 12/23$

→ eliminates one scale

K-factor remarkably close to the one obtained in the large-m_{top} limit

Consistent with approximate result valid at large p_T

Lindert et al (2018)

$p_\perp^{cut}$	$\mathrm{NNLO}^{\mathrm{approximate}}_{\mathrm{quad.unc.}}$ [fb]	$\mathrm{NNLO}^{\mathrm{approximate}}_{\mathrm{lin.unc.}}$ [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$33.3^{+15.1\%}_{-17.4\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	$23.0^{+14.9\%}_{-17.2\%}$
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LHCHXSWG-2019-002

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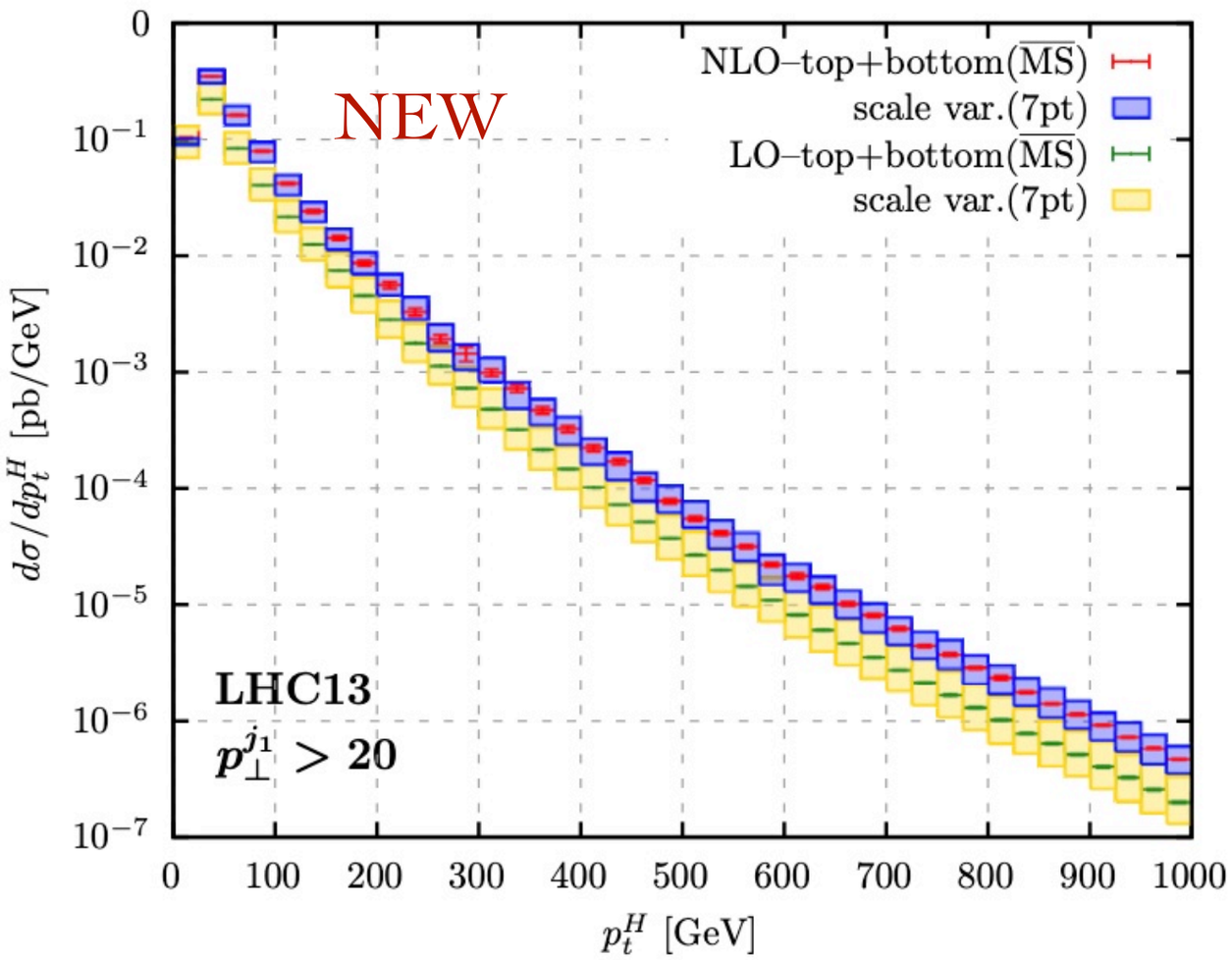

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Now extended to include exact dependence on quark and bottom masses

Bonciani et al (2022)

Includes uncertainties from heavy-quark mass scheme

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LHCHXSWG-2019-002

Off-shell Higgs

For the process $i \to H \to j$ the on-shell cross section is $\sigma_{\text{on-shell}} = (g_i g_j)^2/\Gamma_H$: impossible to study Higgs couplings and width separately

Off-shell Higgs production allows us to break this degeneracy and a measurement of $\sigma_{\text{on-shell}}/\sigma_{\text{off-shell}}$ provides an indirect way to constrain the width (assuming the couplings are independent on the scale)

Caola, Melnikov (2013)

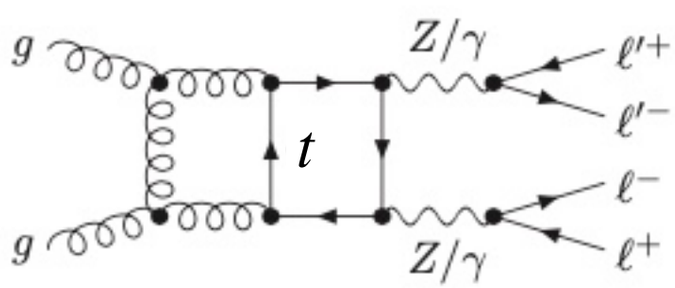
Possible handle on BSM effects

Azatov et al, LHCHWG-2022-001

Off-shell measurements rely on good knowledge of SM predictions

Contribution of top-quark loops to the signal background interference are important at high invariant masses….

M.Dowling, K.Melnikov (2015)



…but known only for on-shell vector bosons

Agarwal, Jones, von Manteuffel (2020); Brønnum-Hansen, Chen (2020,2021)

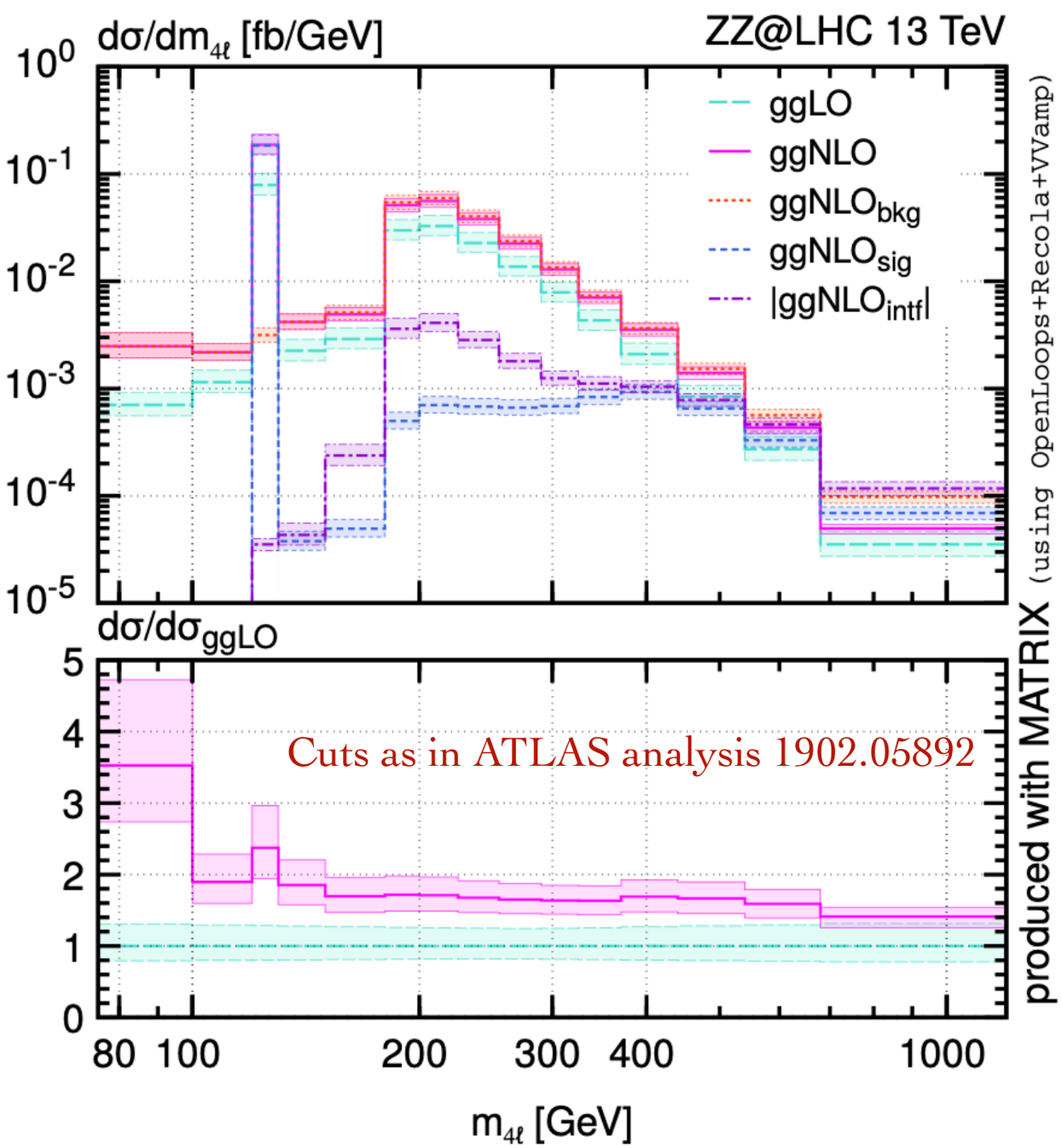
NLO corrections computed in different approximations

Campbell, Czakon, Ellis, Kirchner (2016)
Caola, Dowling, Melnikov, Röntsch, Tancredi (2016)

Matched to Parton Shower

Alioli, Ferrario Ravasio, Lindert, Röntsch (2021)

Off-shell Higgs

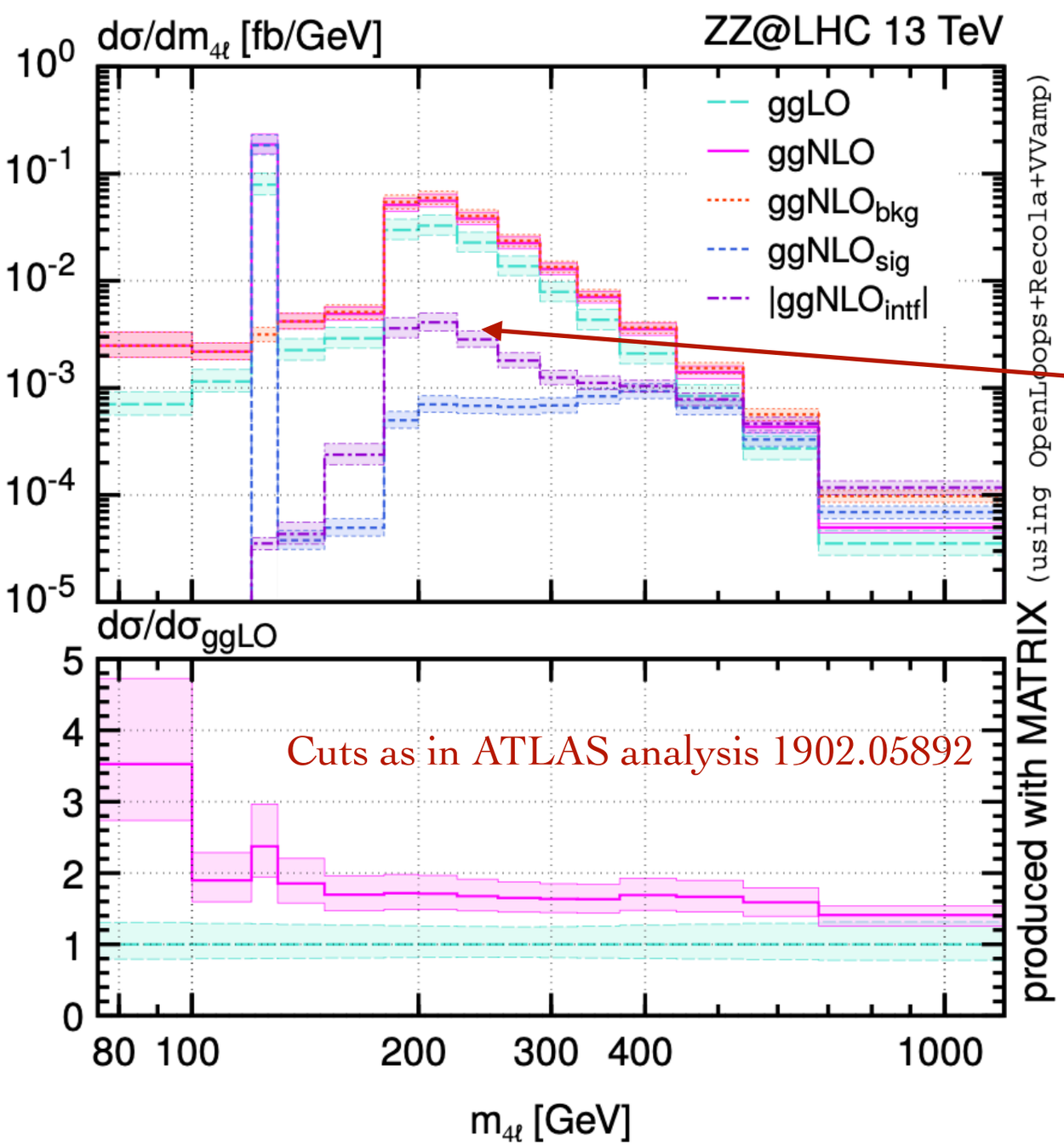


NLO corrections to the gg channel accounting for signal, background and interference*

Kallweit, Wiesemann, Yook, MG (2021)

*Use tree and one-loop amplitudes from Recola and Openloops, two-loop amplitudes from VVAMP + reweighing for massive top loops in $gg \to 4l$

Off-shell Higgs



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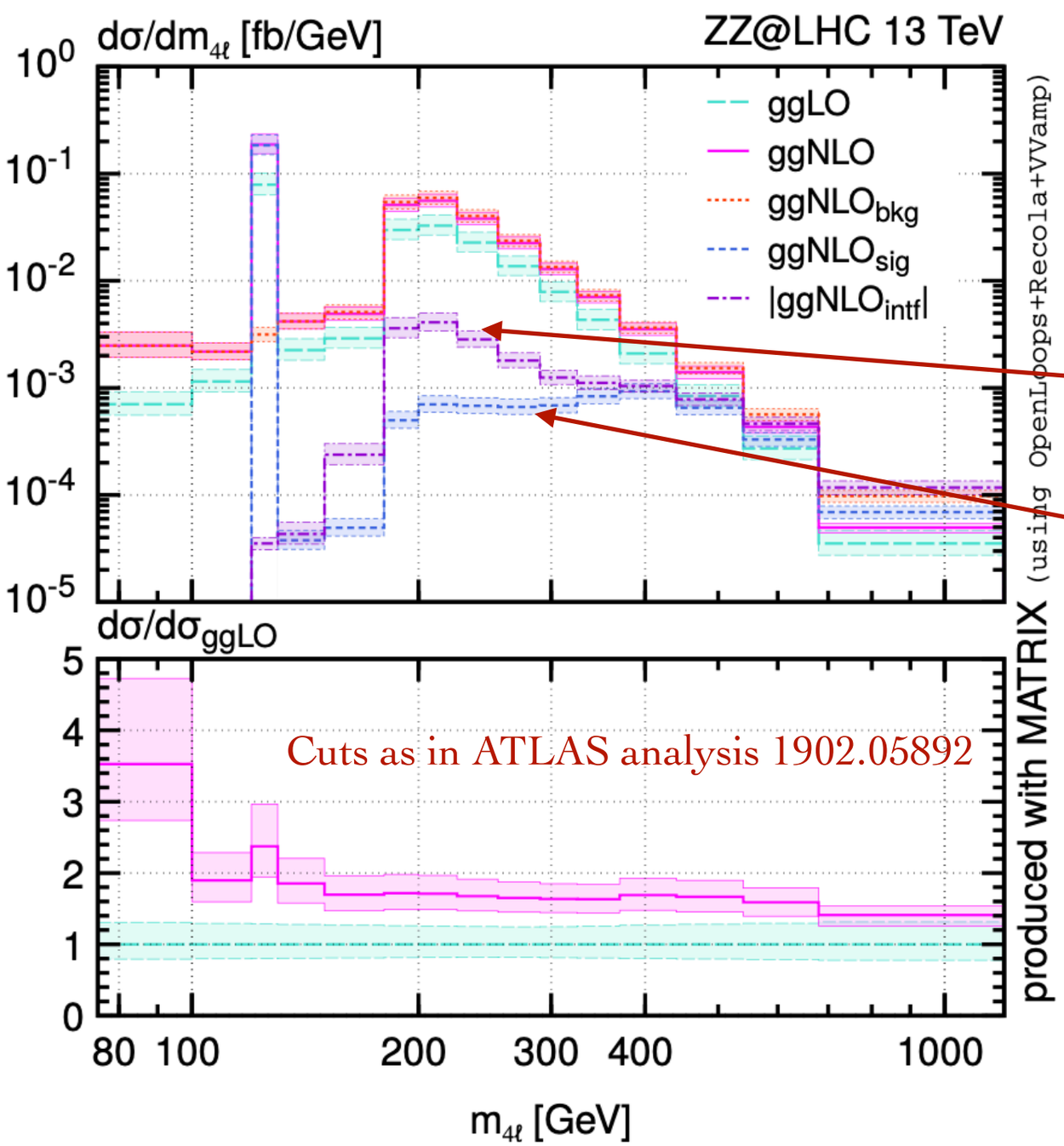

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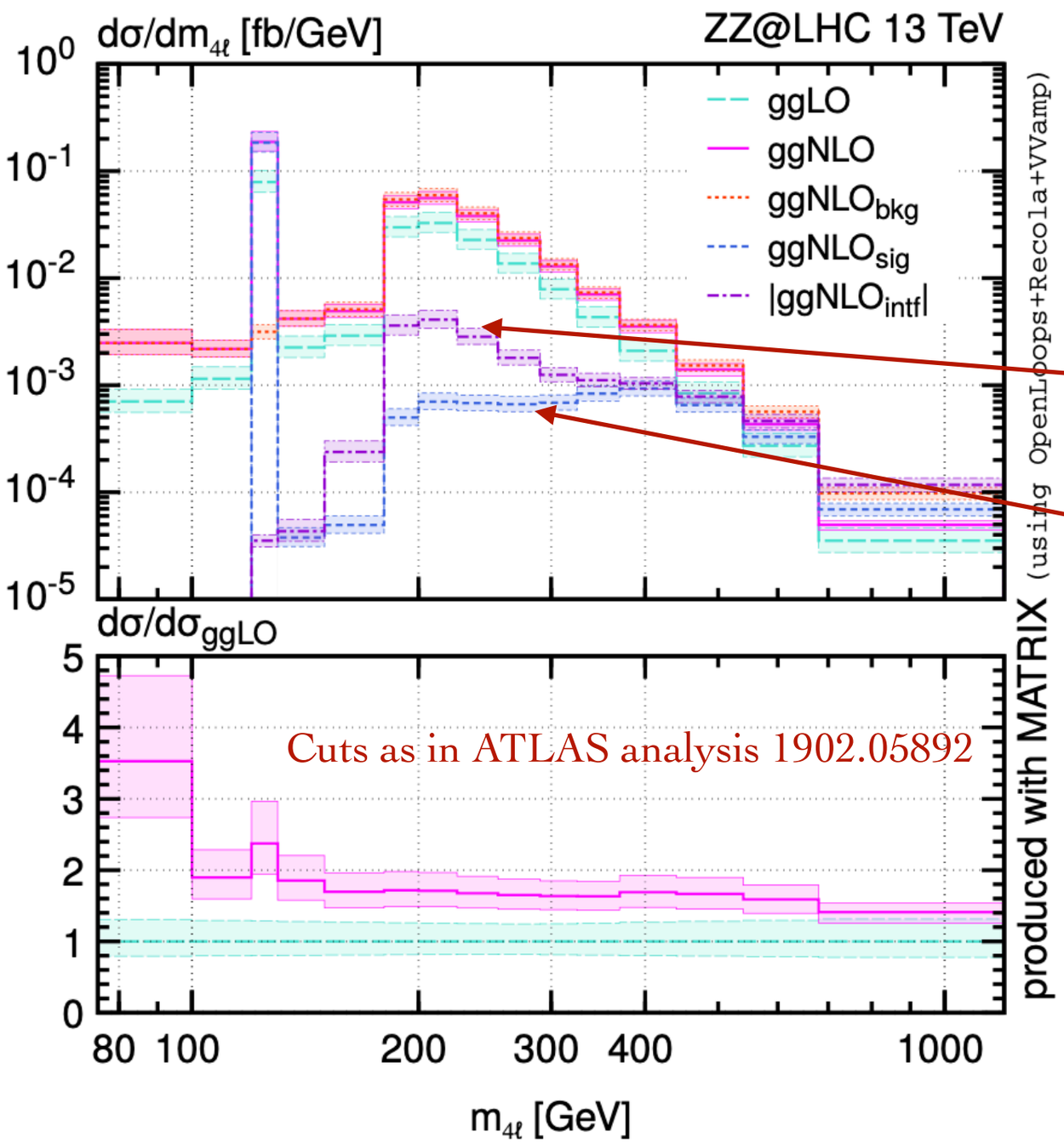
Off-shell Higgs



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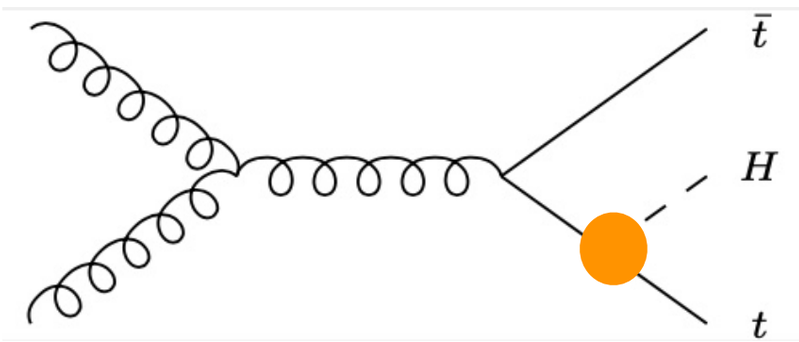
To be implemented in the public generator MATRIX which already includes all the massive diboson processes at NNLO QCD+NLO EW

Kallweit, Wiesemann, MG (2017)
Kallweit, Lindert, Pozzorini, Wiesemann, MG (2019)

*Use tree and one-loop amplitudes from Recola and Openloops, two-loop amplitudes from VVAMP + reweighing for massive top loops in $gg \to 4l$

ttH



Directly sensitive to the ttH Yukawa coupling

Current predictions based on NLO QCD+EW (+ resummations) and affected by $\mathcal{O}(7-8\%)$ uncertainty

NNLO QCD needed to bring theory uncertainty down to the $\mathcal{O}(2\%)$ level expected

First step completed by evaluation of the contribution of the off-diagonal partonic channels

Catani, Fabre,Kallweit, MG(2020)

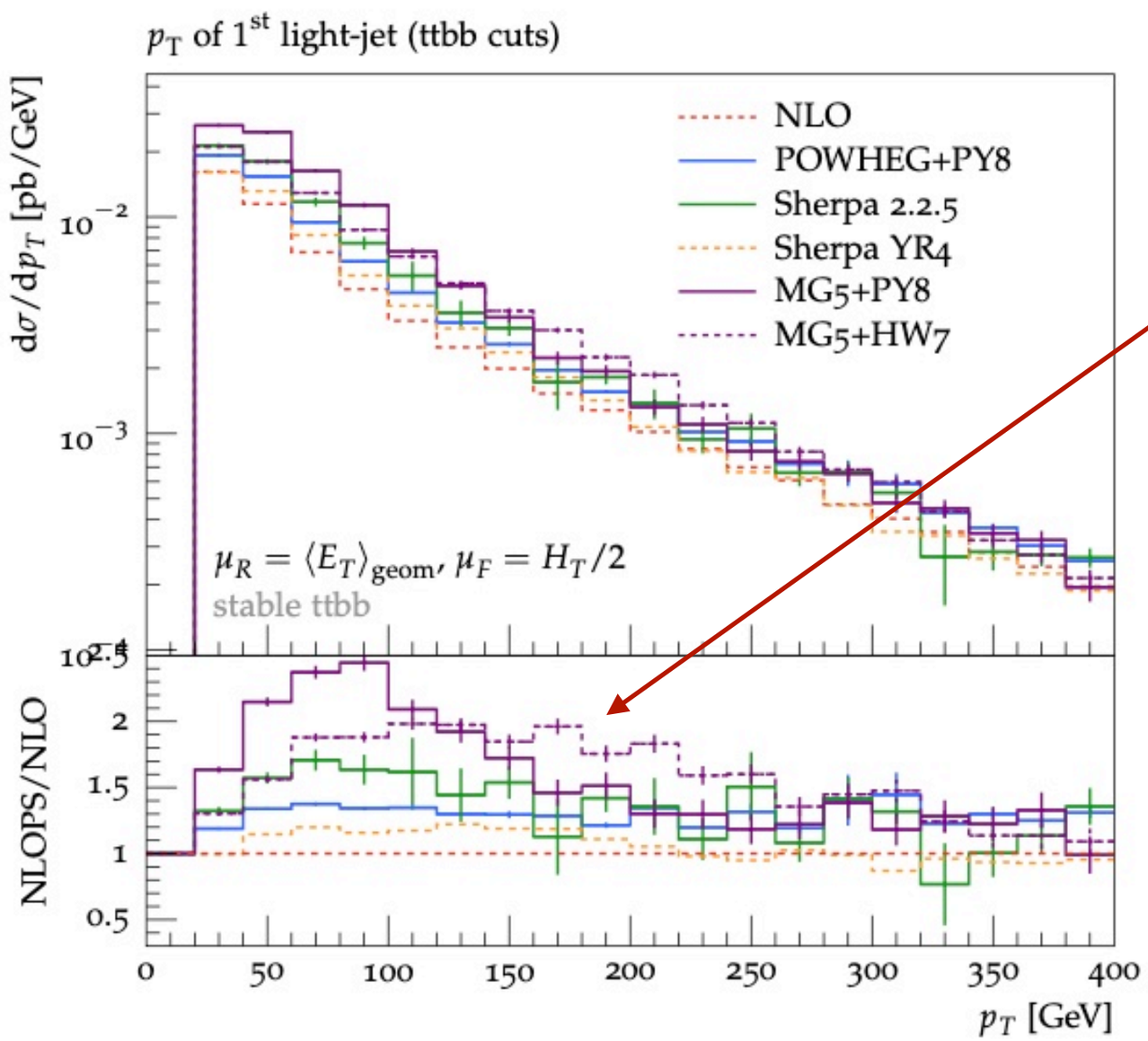
Missing ingredients are the two-loop $gg \to t\bar{t}H$ and $q\bar{q} \to t\bar{t}H$ amplitudes

Massive $2 \to 3$ amplitudes: at the frontier of current techniques (new classes of functions, really charting a new territory…)

Theory modelling

Accuracy in theory predictions is also crucial for the Monte Carlo tools used in the analyses, particularly when background modelling is difficult

Example: $t\bar{t}b\bar{b}$ background to $t\bar{t}H$ with $H \to b\bar{b}$



$\mathcal{O}(100\%)$ differences in p_T of the first light jet

Their origin can be traced back to the large NLOPS effect wrt NLO

Understanding these issues is crucial to assess theory systematics

S.Pozzorini, talk given at HXSWG ttH/tH subgroup meeting, October 2020

Theory modelling

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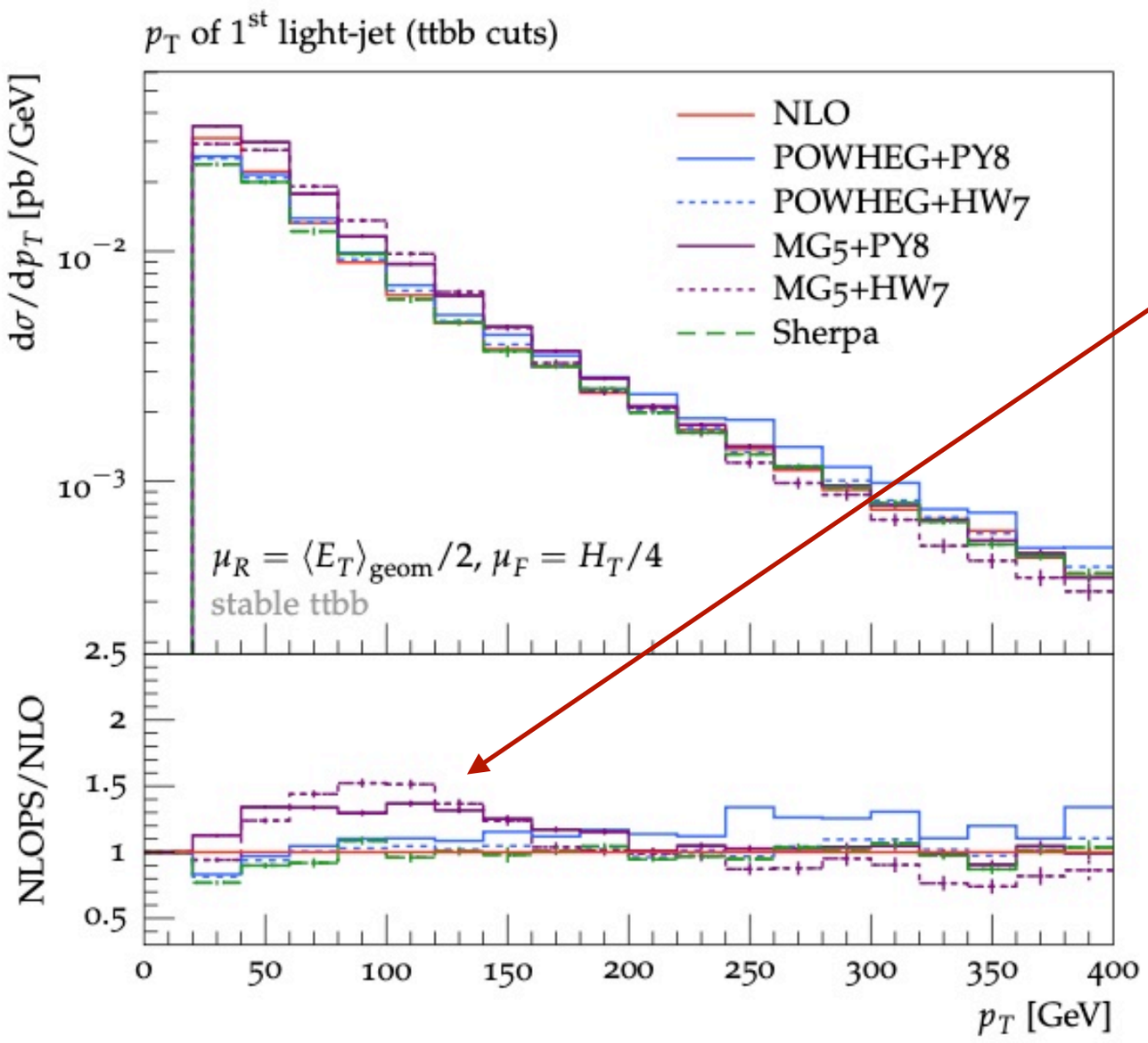


Reduction of default scale significantly reduces the spread between different predictions

Supported by explicit NLO computation of $t\bar{t}b\bar{b}j$

Buccioni, Kallweit, Pozzorini, Zoller (2019)

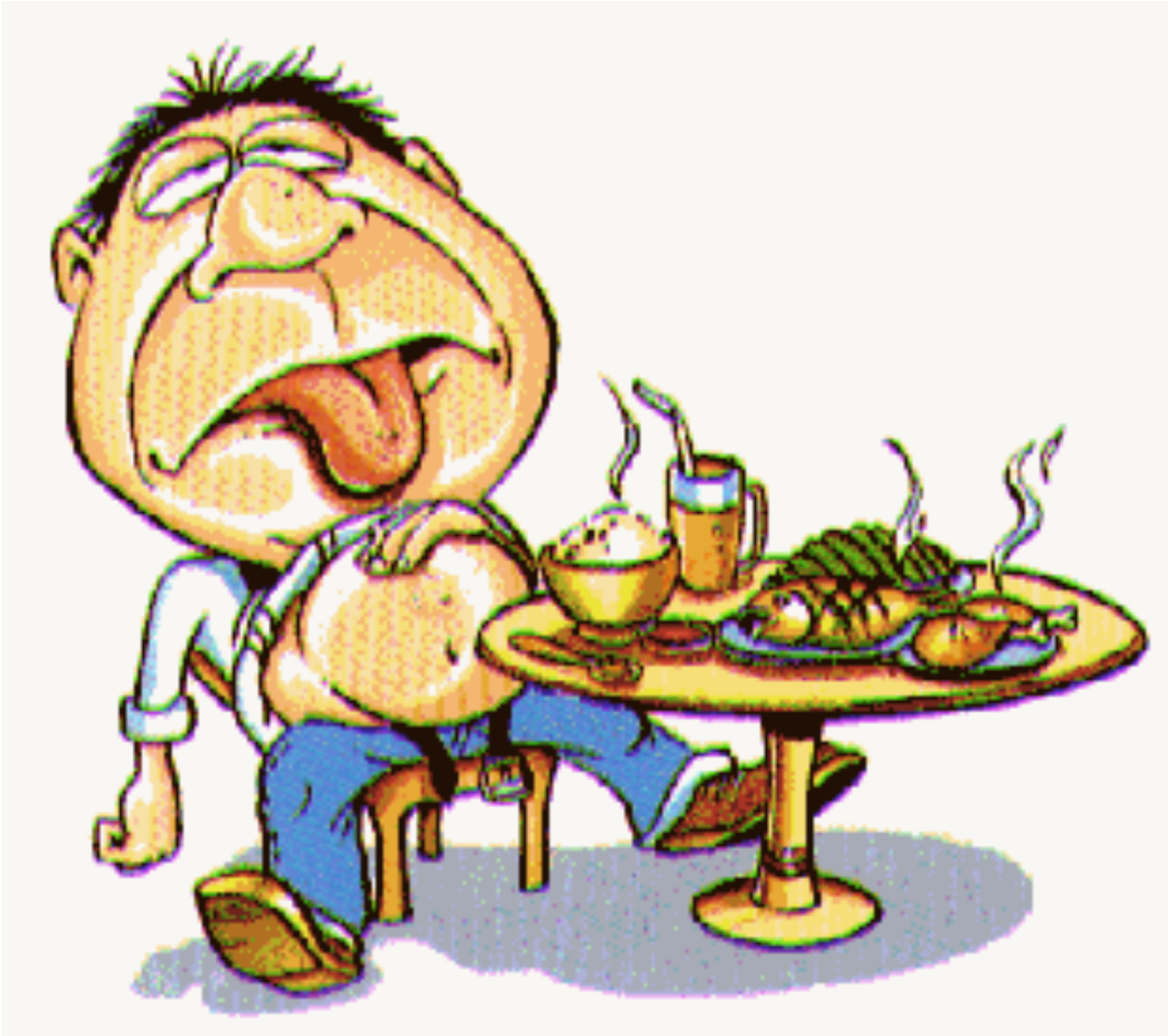
Ongoing studies within the Higgs WG

S.Pozzorini, talk given at HXSWG ttH/tH subgroup meeting, October 2020

Summary and Outlook

- The discovery of the Higgs boson marked a milestone in particle physics
- The enormous body of accurate theory predictions allowed us first to characterise the newly discovered resonance, comparing the theoretical predictions with measurements of increasing accuracy, finally allowing us to clearly identify it with the SM Higgs boson
- Theory predictions can be eventually deployed into more precise Monte Carlo tools that can be directly used in the analyses, thereby reducing extrapolation uncertainties
- Up to now only about 5 % of the expected data set has been analysed: theory accuracy will be even more important to make the best of the HL LHC data especially in the case in which no evidence of new physics will show up
- The HXSWG (now Higgs WG) has been crucial to review the progress of the various theory groups, moderate the ensuing discussions and to transform the results into recommendations to be used in the experimental analyses: it should continue to have such crucial role in the future

Thanks for your attention!

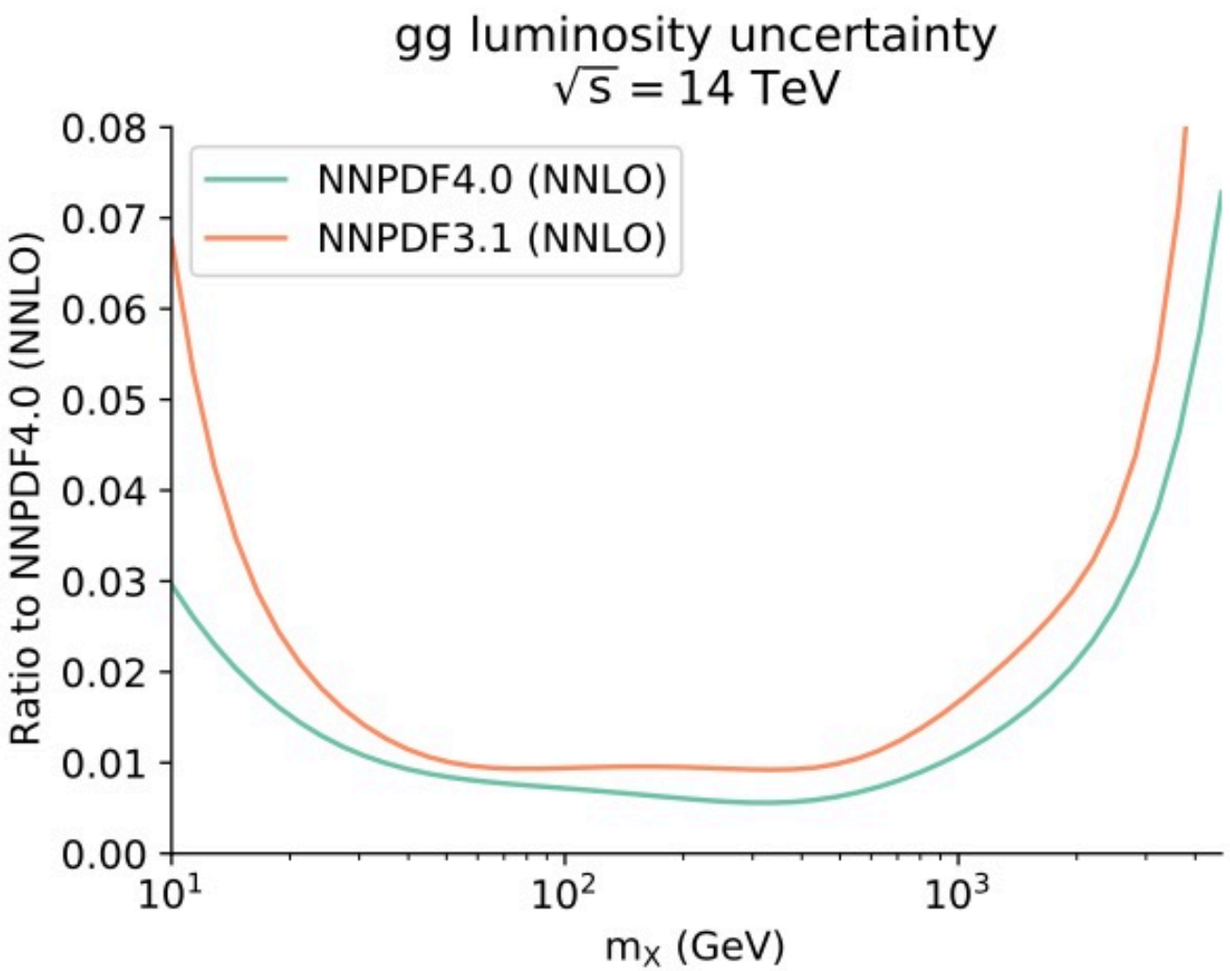


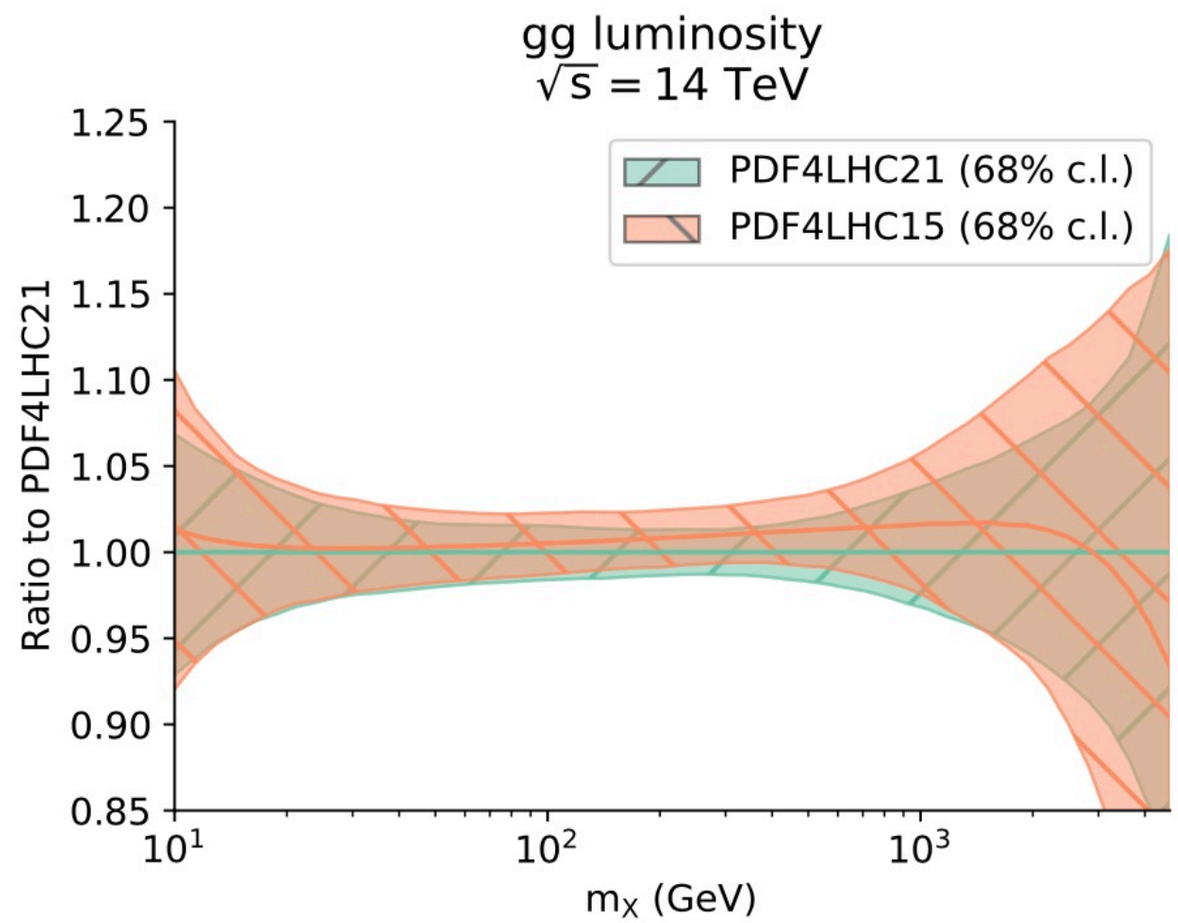
How a theorist feels trying to catch up with the beautiful ATLAS and CMS results in the last years....

...and more to come !

Backup slides

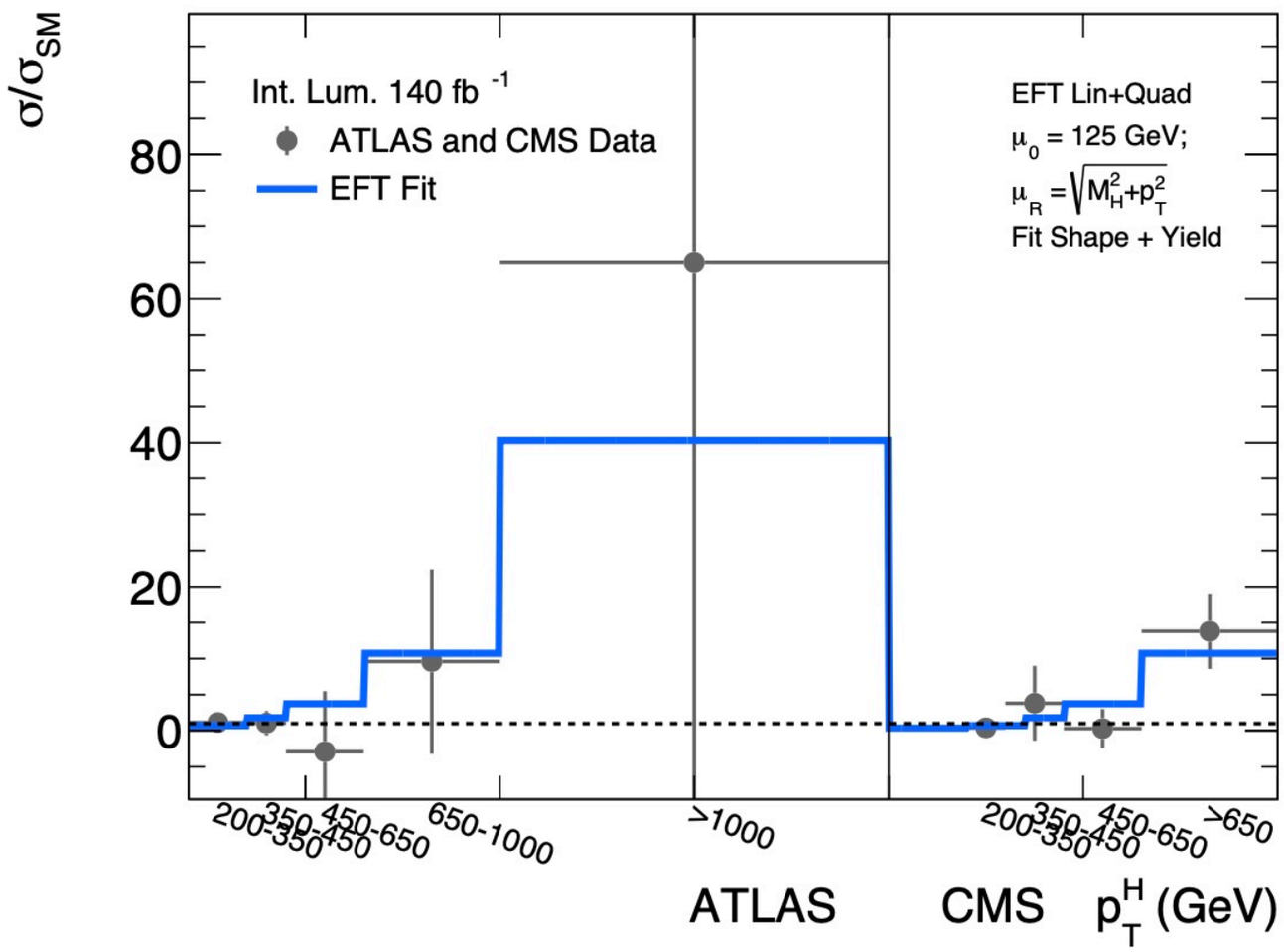
PDF uncertainties

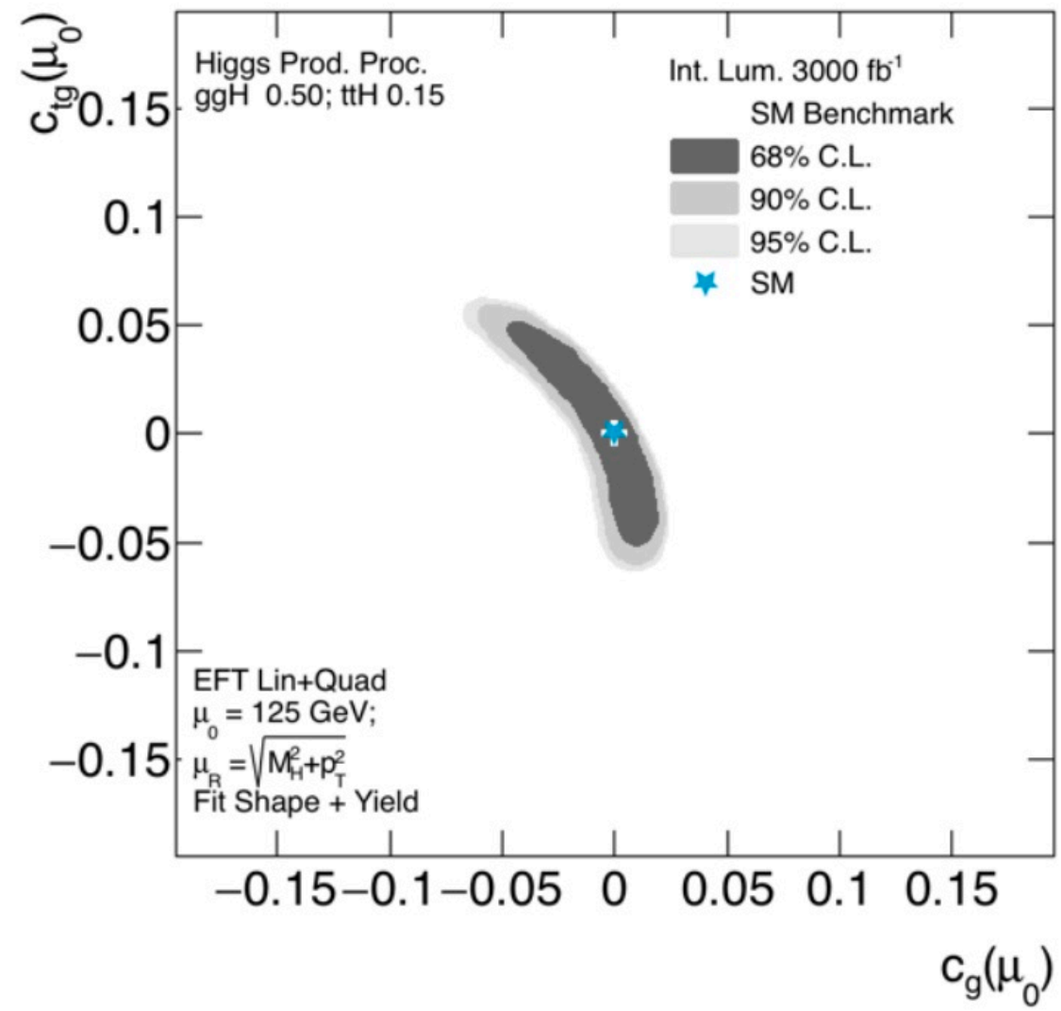




High p_T

Accurate predictions at high p_T will allow us to disentangle possible new physics effects in an EFT framework





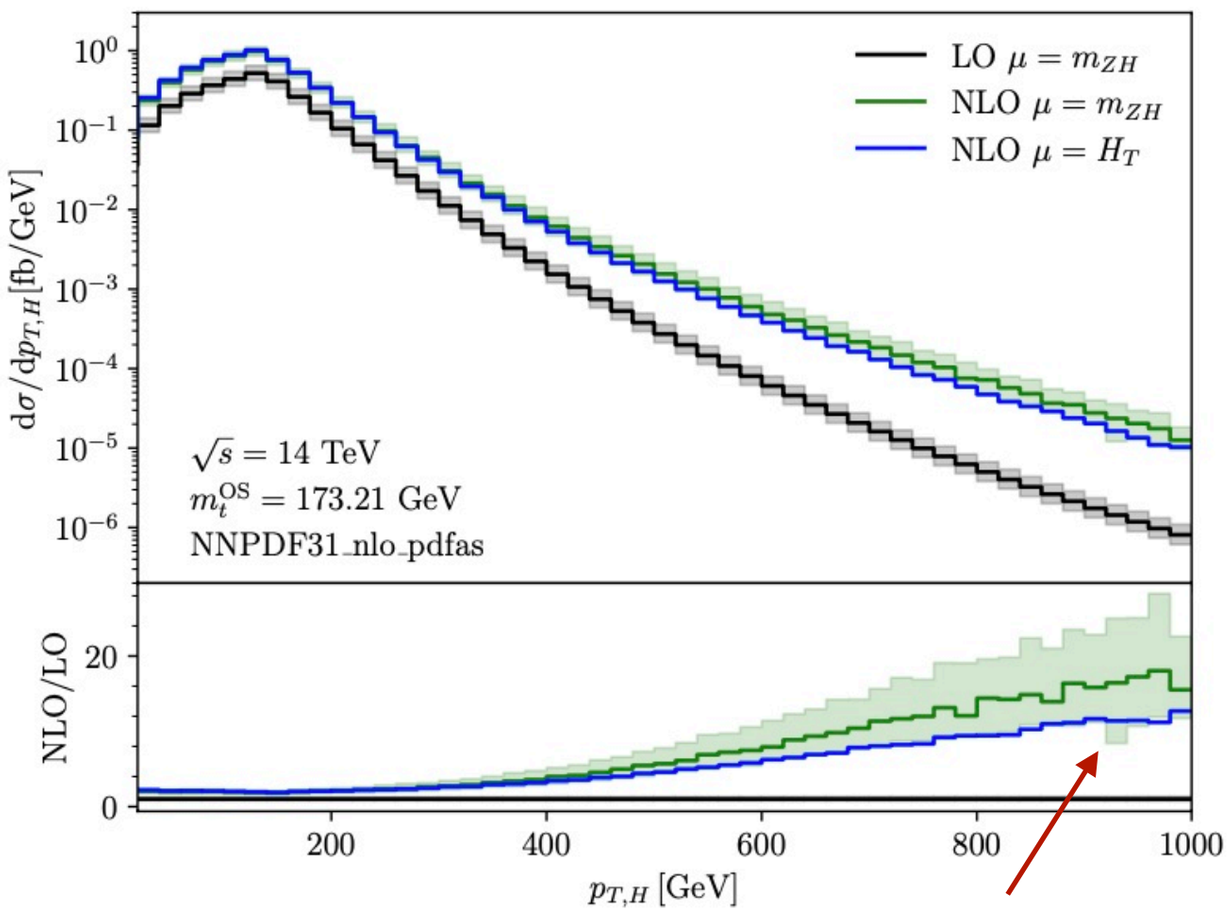
Battaglia, Spira, Wiesemann, MG (2021)

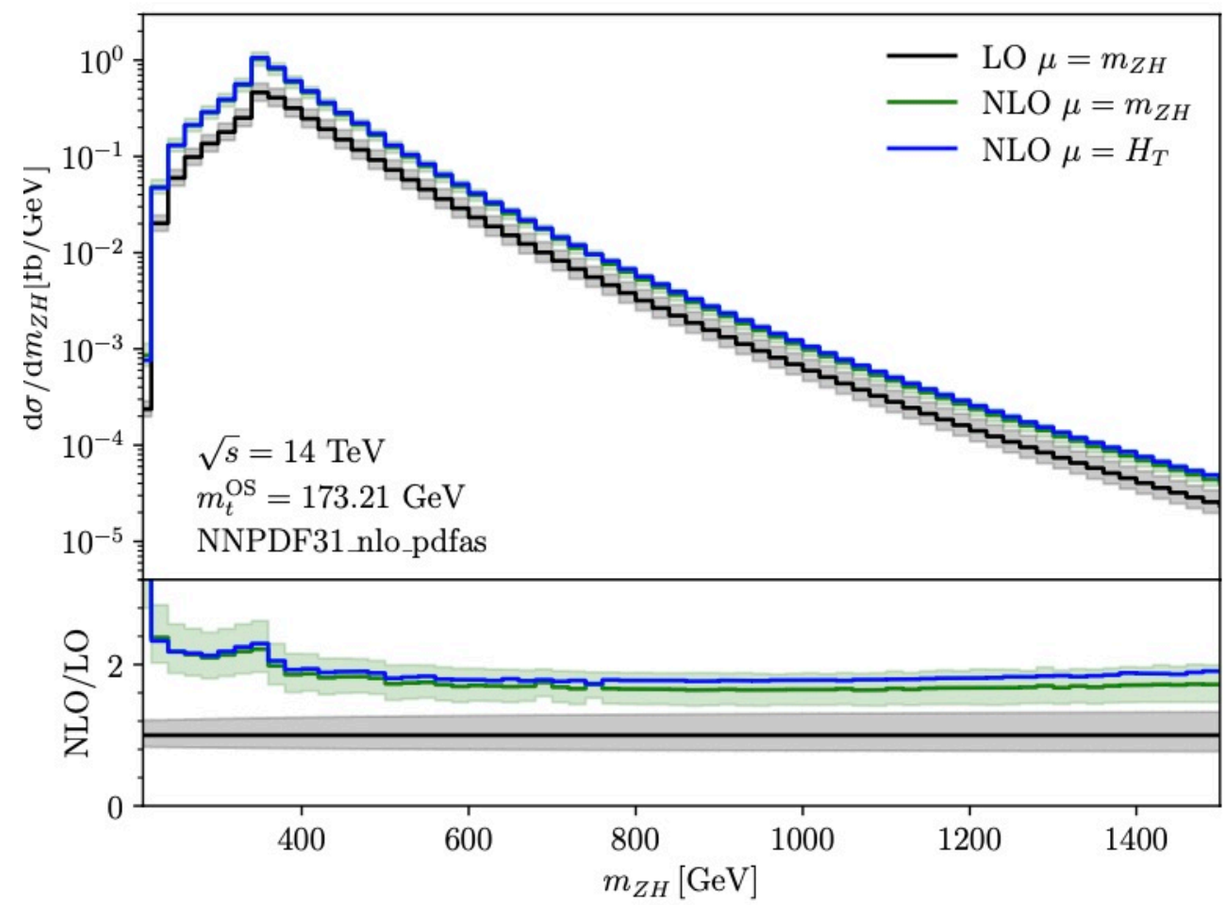
VH

Signal modelling was one of the main limitations to VH(bb) precision measurements

$gg \to ZH$ contribution (formally NNLO) becomes crucial in the boosted region: recently evaluated at NLO Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser (2022)

Uses $m_Z^2/m_t^2 = 23/83$ and $m_H^2/m_t^2 = 12/23$ to reduce number of scales





"giant K-factor"

Cross section in agreement with previous computation in a large m_t expansion

Wang, Xu, Xu, Yang (2021)