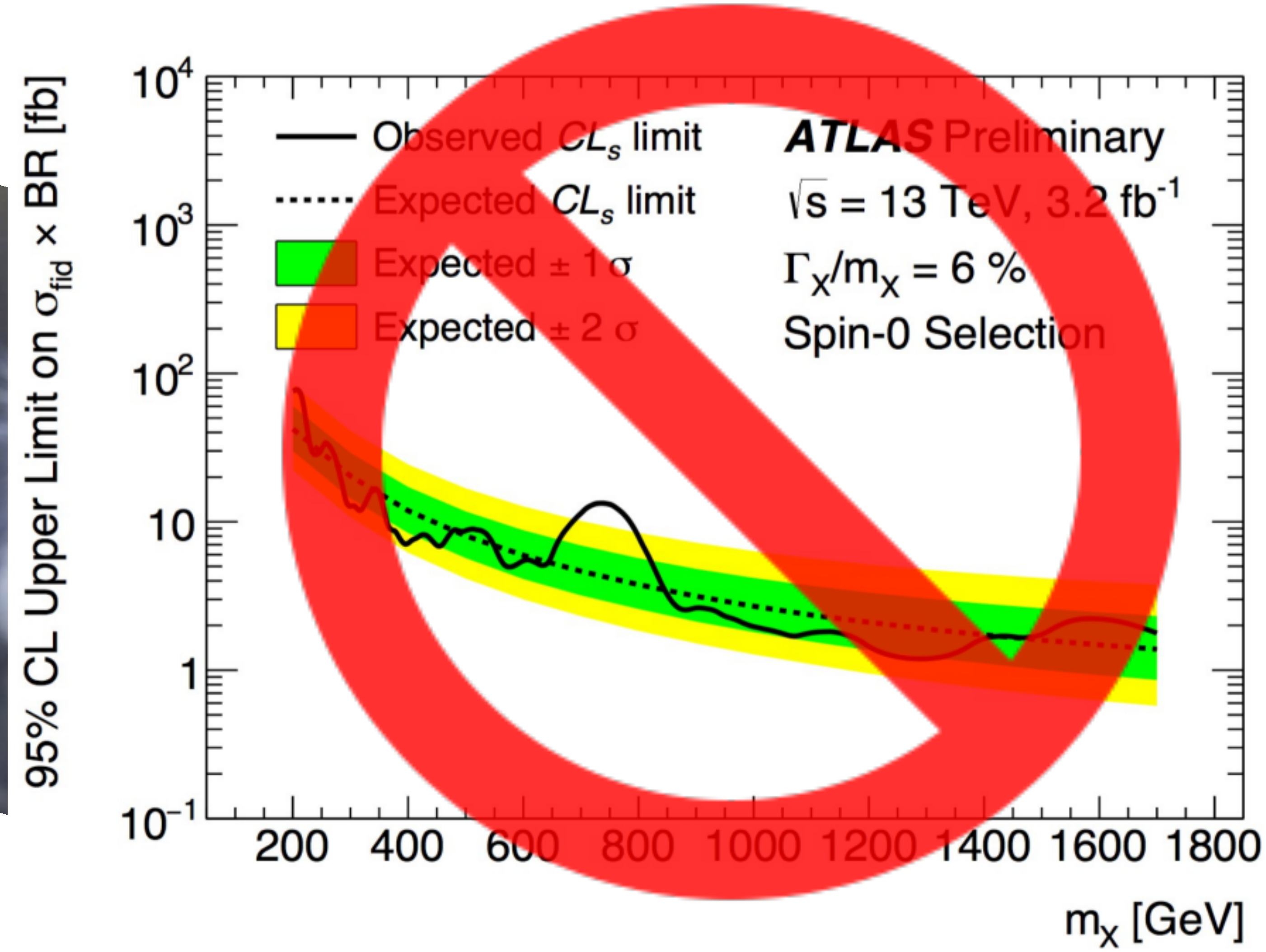
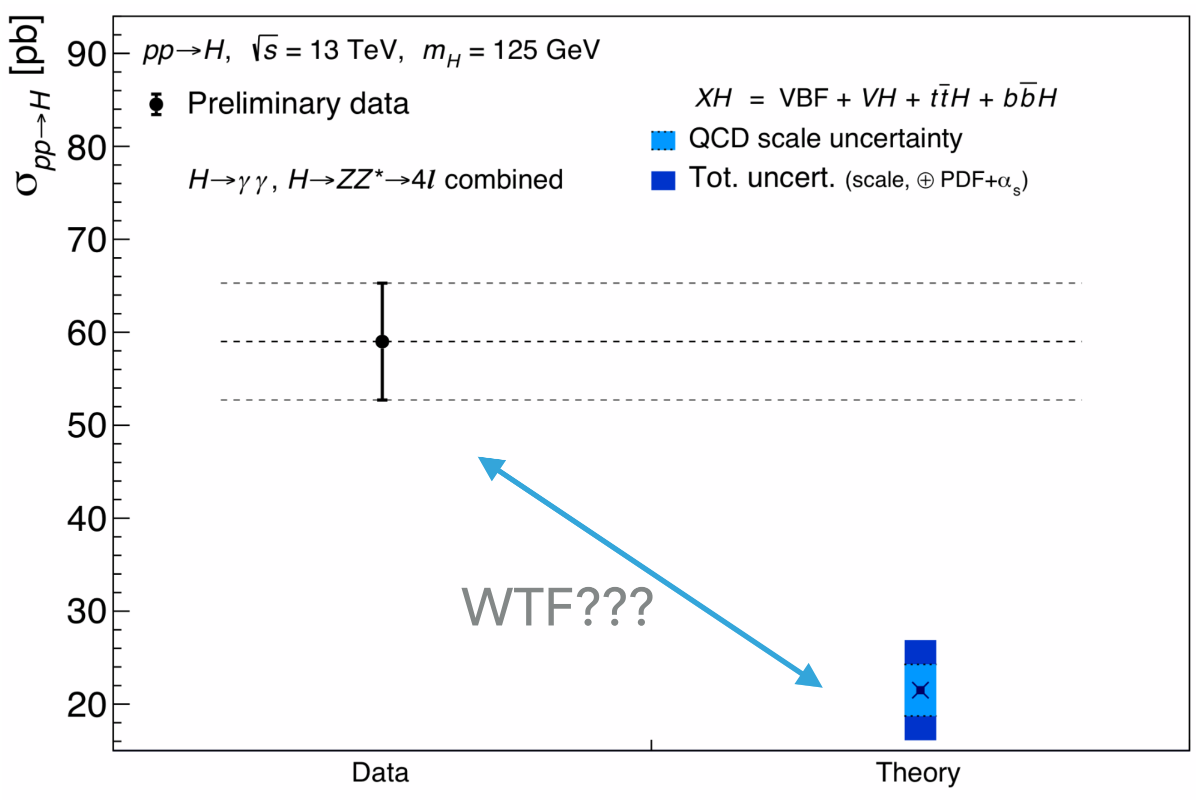
CLEVELAND 6/5/18

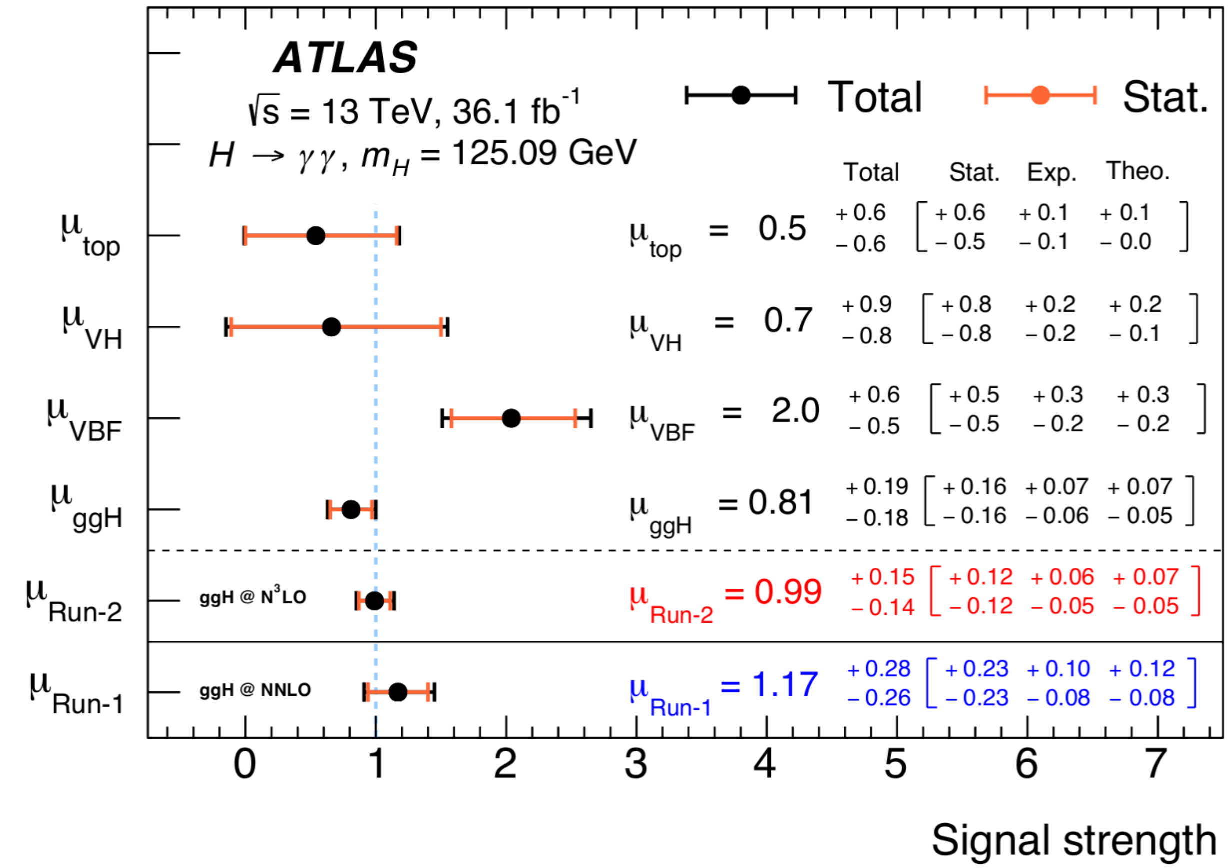
FALKO DULAT

PRECISION HIGGS PHYSICS

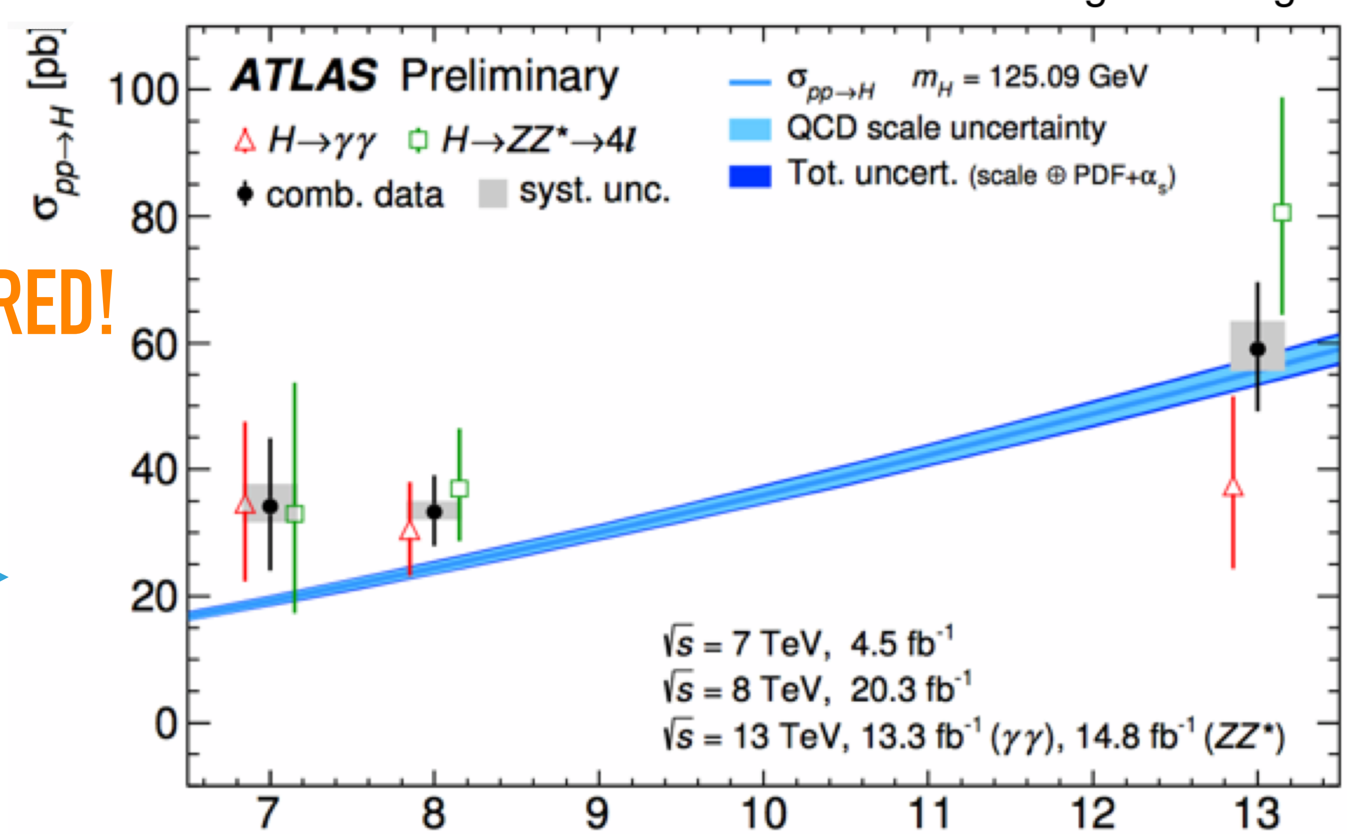


WHAT IS THE UV COMPLETION OF THE STANDARD MODEL?

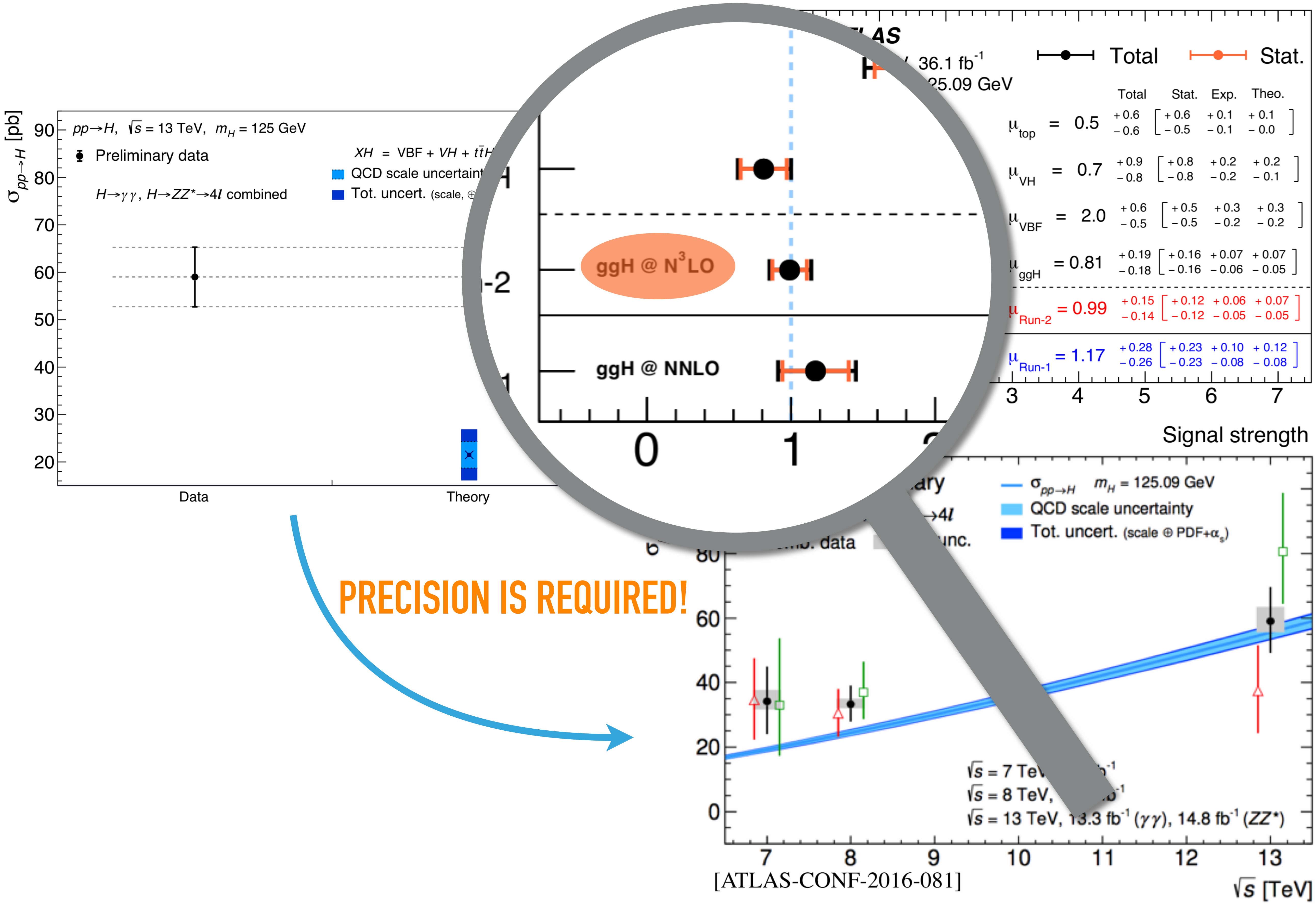




PRECISION IS REQUIRED!



[ATLAS-CONF-2016-081]



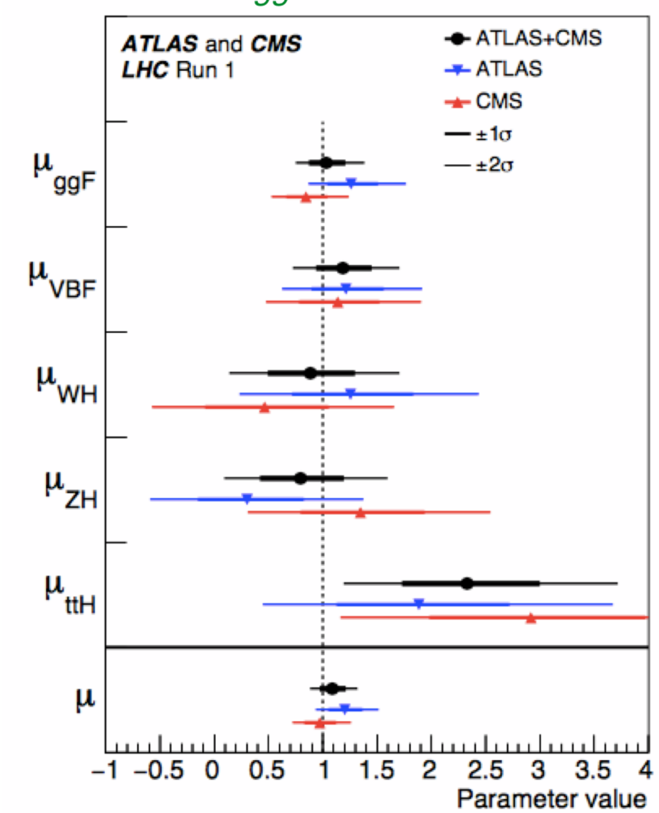
pp→H, √s = 13 TeV, m_H = 125 GeV
Preliminary data
H→γγ, H→ZZ*→4l combined
XH = VBF + VH + ttH
QCD scale uncertaint
Tot. uncert. (scale, ⊕
σ_pp→H [pb]
Data
Theory
36.1 fb-1
25.09 GeV
Total
Stat.
Total Stat. Exp. Theo.
μ_top = 0.5 +0.6 −0.6 [+0.6 −0.5 +0.1 −0.1 +0.1 −0.0]
μ_VH = 0.7 +0.9 −0.8 [+0.8 −0.8 +0.2 −0.2 +0.2 −0.1]
μ_VBF = 2.0 +0.6 −0.5 [+0.5 −0.5 +0.3 −0.2 +0.3 −0.2]
μ_ggH = 0.81 +0.19 −0.18 [+0.16 −0.16 +0.07 −0.06 +0.07 −0.05]
μ_Run-2 = 0.99 +0.15 −0.14 [+0.12 −0.12 +0.06 −0.05 +0.07 −0.05]
μ_Run-1 = 1.17 +0.28 −0.26 [+0.23 −0.23 +0.10 −0.08 +0.12 −0.08]
ggH @ N3LO
ggH @ NNLO
Signal strength
σ_pp→H m_H = 125.09 GeV
QCD scale uncertainty
Tot. uncert. (scale ⊕ PDF+α_s)
√s = 13 TeV, 13.3 fb-1 (γγ), 14.8 fb-1 (ZZ*)
√s [TeV]
[ATLAS-CONF-2016-081]
PRECISION IS REQUIRED!

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$

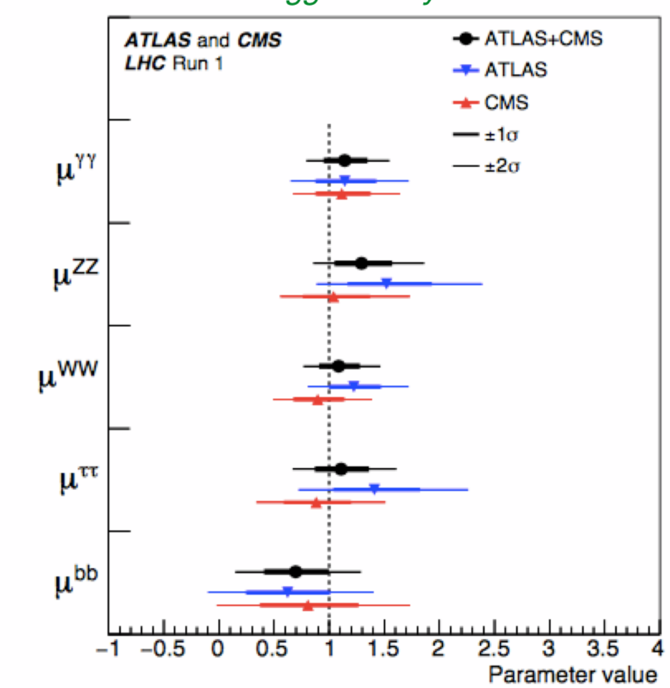
$$\mu^f = \frac{B^f}{(B^f)_{SM}}$$

Guindon '16

Higgs Production



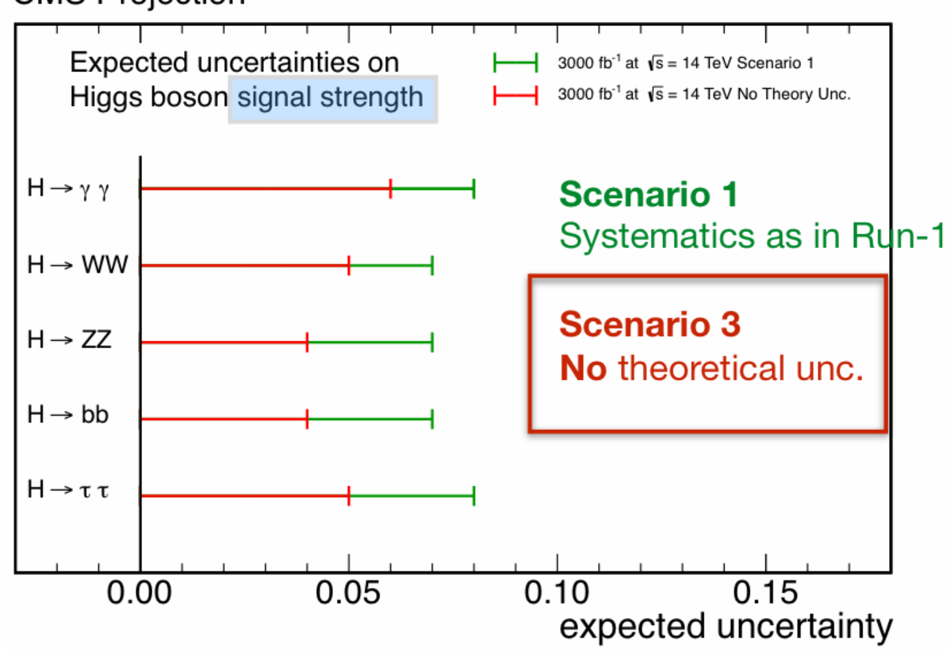
Higgs Decay



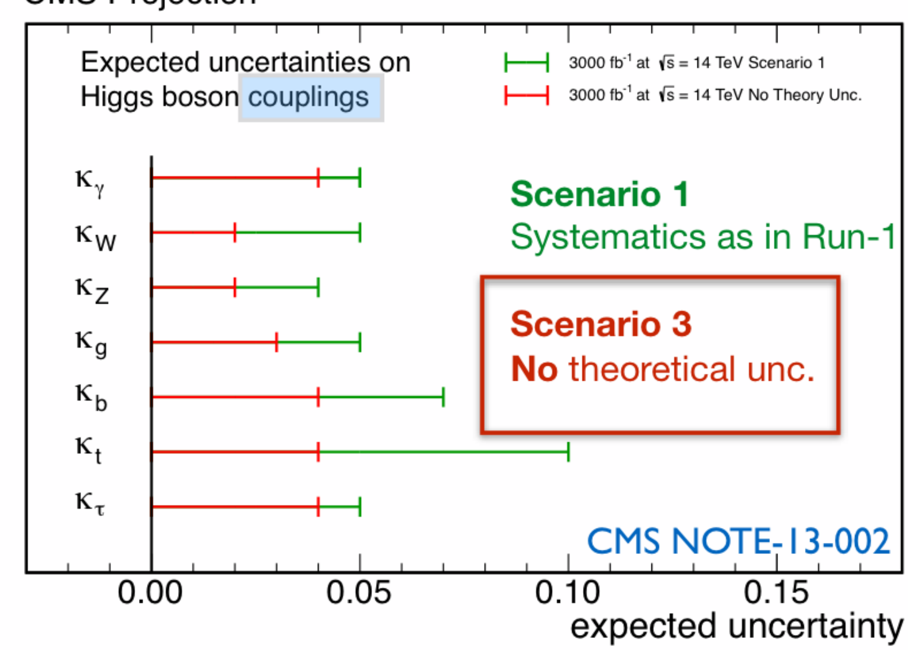
- *Production signal strengths assuming SM decay BR*
- *B signal strengths assuming SM production*

PROJECTION

CMS Projection



CMS Projection

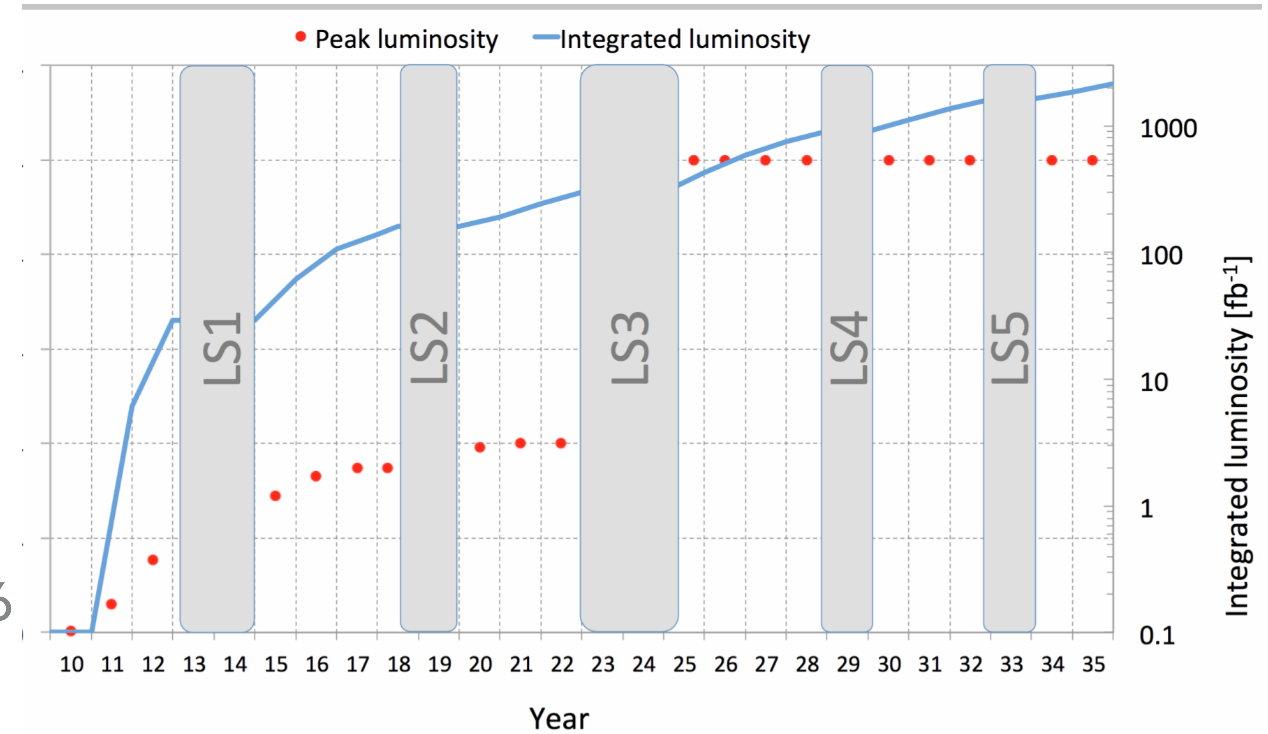


- Current status for Higgs production at the LHC (ATLAS)

$$\mu_{\rm ggH} = 0.81\,^{+0.19}_{-0.18} = 0.81\ \pm 0.16\,(\text{stat.})\,^{+0.07}_{-0.06}\,(\text{exp.})\,^{+0.07}_{-0.05}\,(\text{theo.})$$
$$\mu_{\rm VBF} = 2.0\,^{+0.6}_{-0.5} = 2.0\ \pm 0.5\,(\text{stat.})\,^{+0.3}_{-0.2}\,(\text{exp.})\,^{+0.3}_{-0.2}\,(\text{theo.})$$
$$\mu_{\rm VH} = 0.7\,^{+0.9}_{-0.8} = 0.7\ \pm 0.8\,(\text{stat.})\,^{+0.2}_{-0.2}\,(\text{exp.})\,^{+0.2}_{-0.1}\,(\text{theo.})$$
$$\mu_{\rm top} = 0.5\,^{+0.6}_{-0.6} = 0.5\,^{+0.6}_{-0.5}\,(\text{stat.})\,^{+0.1}_{-0.1}\,(\text{exp.})\,^{+0.1}_{-0.0}\,(\text{theo.})$$

arXiv:1802.04146

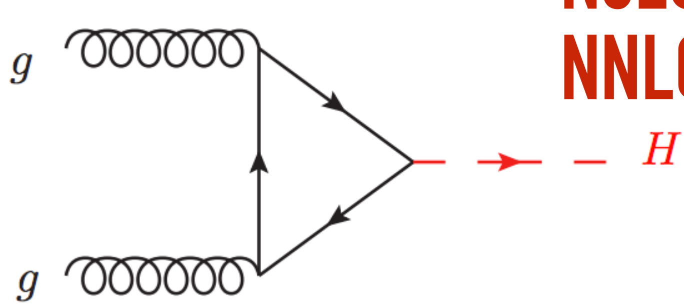
- Experimental uncertainties are getting close to the theoretical uncertainties
- New physics might modify the standard model at the % level
- Precision calculations (and generators) are needed



LHC AS A PRECISION MACHINE

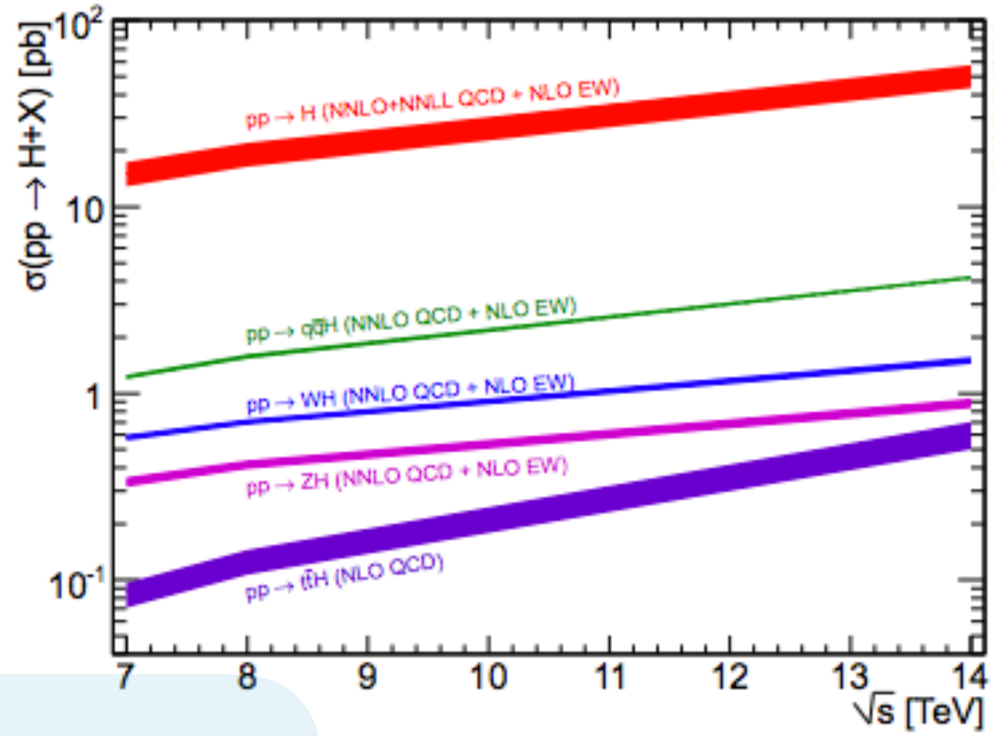
$$\mathcal{O}\left(\frac{Q^2}{(1TeV)^2}\right) \sim \%$$

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s}$ = 13 TeV	Order of calculation of σ
ggH	Powheg NNLOPS	Pythia8	PDF4LHC15	48.52	N^{3}LO(QCD)+NLO(EW)
VBF	Powheg-Box	Pythia8	PDF4LHC15	3.78	NNLO(QCD)+NLO(EW)
WH	Powheg-Box	Pythia8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}' \to ZH$	Powheg-Box	Pythia8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg \to ZH$	Powheg-Box	Pythia8	PDF4LHC15	0.12	NLO+NLL(QCD)
$t\bar{t}H$	MG5_aMC@NLO	Pythia8	NNPDF3.0	0.51	NLO(QCD)+NLO(EW)
$b\bar{b}H$	MG5_aMC@NLO	Pythia8	CT10	0.49	5FS(NNLO)+4FS(NLO)
t-channel tH	MG5_aMC@NLO	Pythia8	CT10	0.07	4FS(LO)
W-associated tH	MG5_aMC@NLO	Herwig++	CT10	0.02	5FS(NLO)
$\gamma\gamma$	Sherpa	Sherpa	CT10		
$V\gamma\gamma$	Sherpa	Sherpa	CT10		

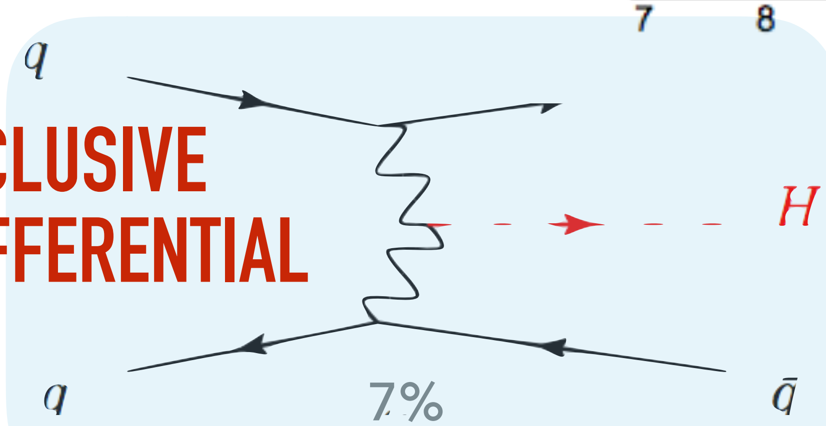


87%

N3LO INCLUSIVE
NNLO DIFFERENTIAL



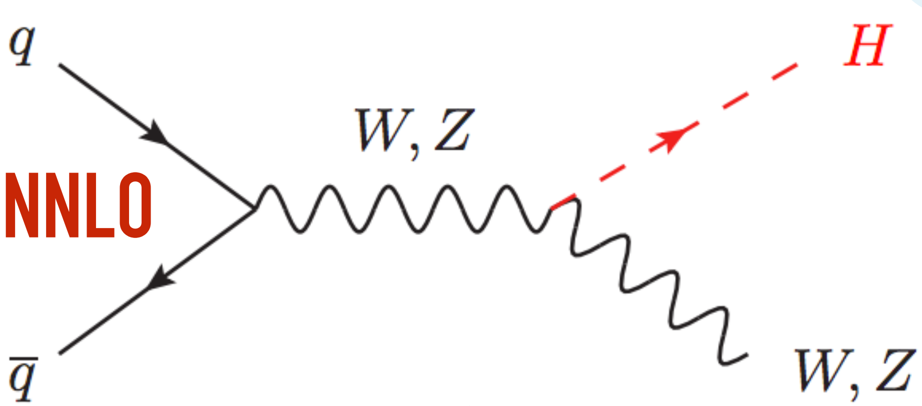
N3LO INCLUSIVE
NNLO DIFFERENTIAL



7%

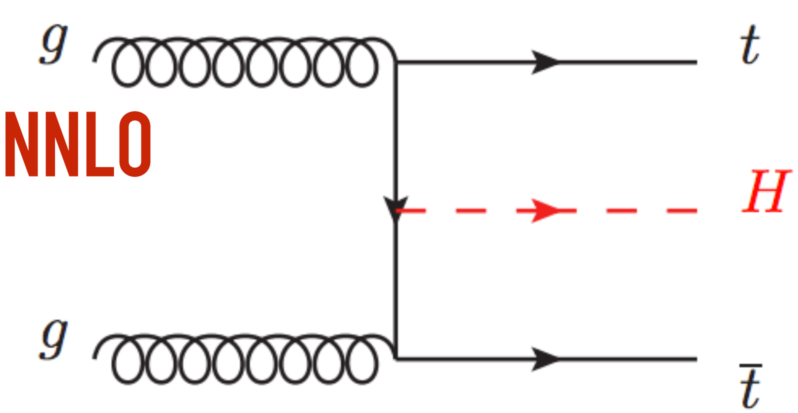
LHC@14TEV

NNLO



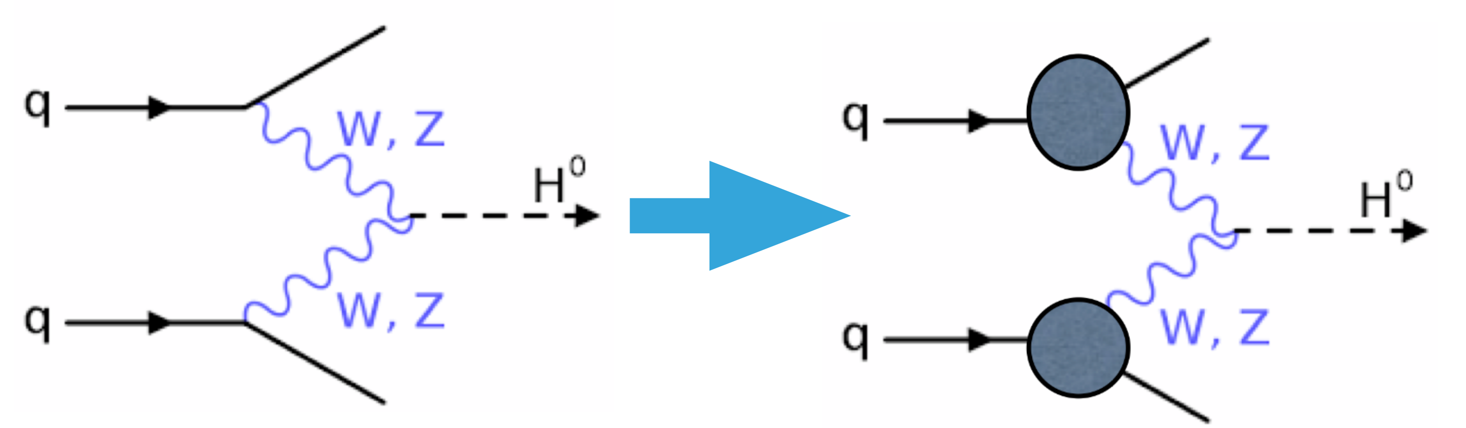
3%

NNLO



1%

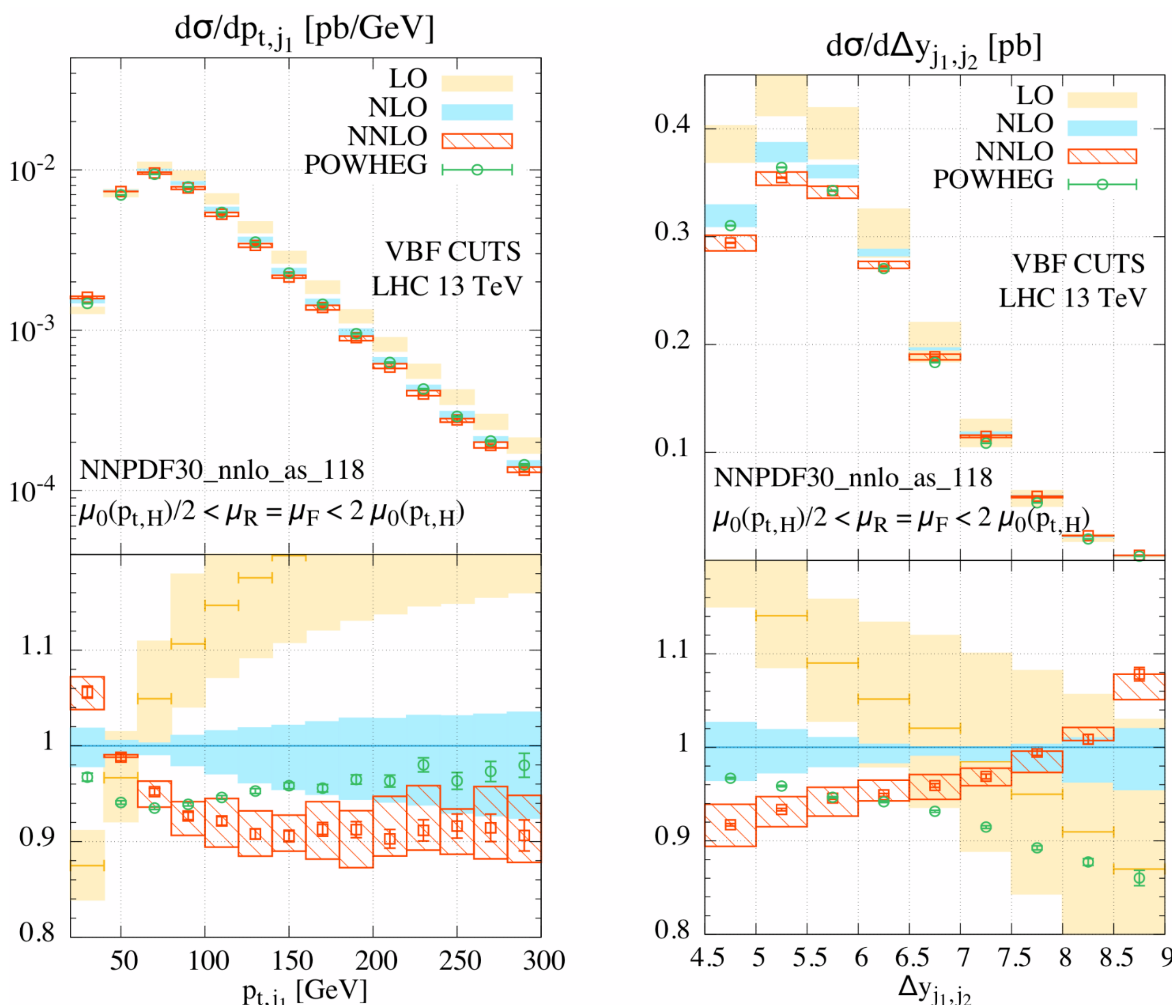
- Small corrections to the inclusive cross section (~5% NLO, ~3% NNLO, ~0.1% N3LO)



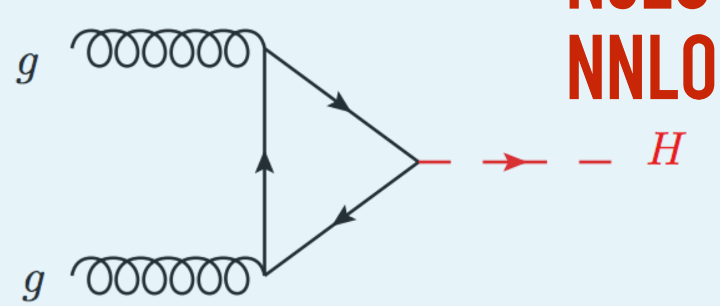
- Sizeable (~6-10%) corrections to fiducial cross sections

	$\sigma^{\rm nocuts}$[pb]	$\sigma^{\rm VBF\ cuts}$[pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

$$p_\perp^{j_{1,2}} > 25 \text{ GeV}, \quad |y_{j_{1,2}}| < 4.5,$$
$$\Delta y_{j_1,j_2} = 4.5, \quad m_{j_1,j_2} > 600 \text{ GeV},$$
$$y_{j_1} y_{j_2} < 0, \quad \Delta R > 0.4$$

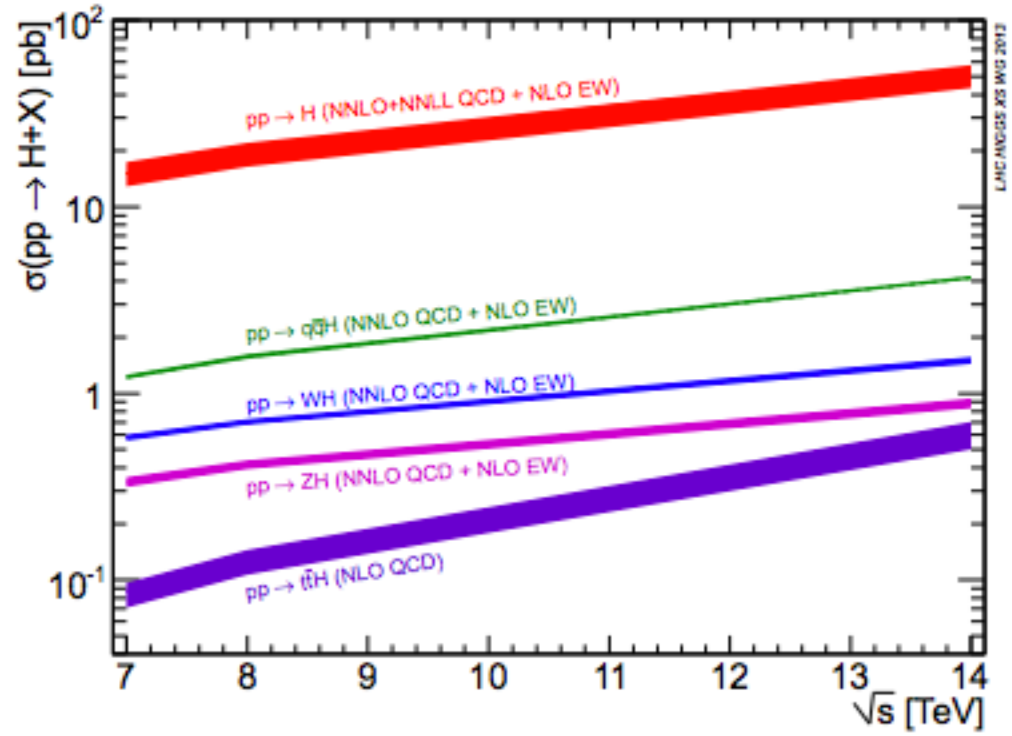


[Bolzoni, Maltoni, Moch, Zaro; Cacciari, Dreyer, Karlberg, Salam, Zanderighi; Dreyer, Karlberg]

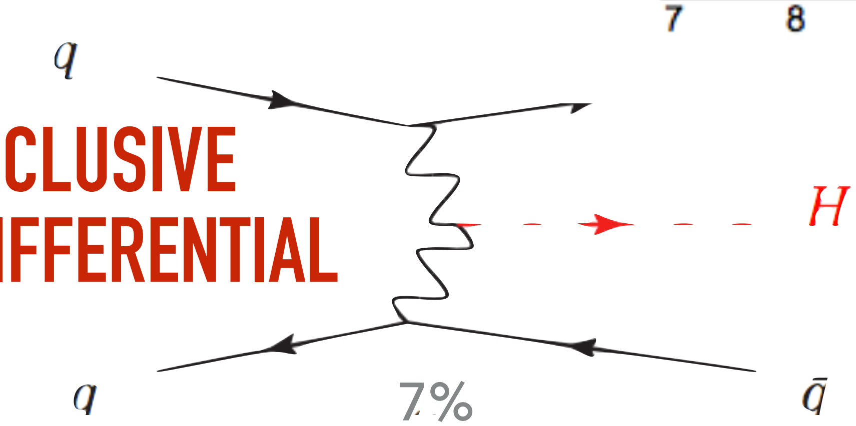


87%

N3LO INCLUSIVE
NNLO DIFFERENTIAL



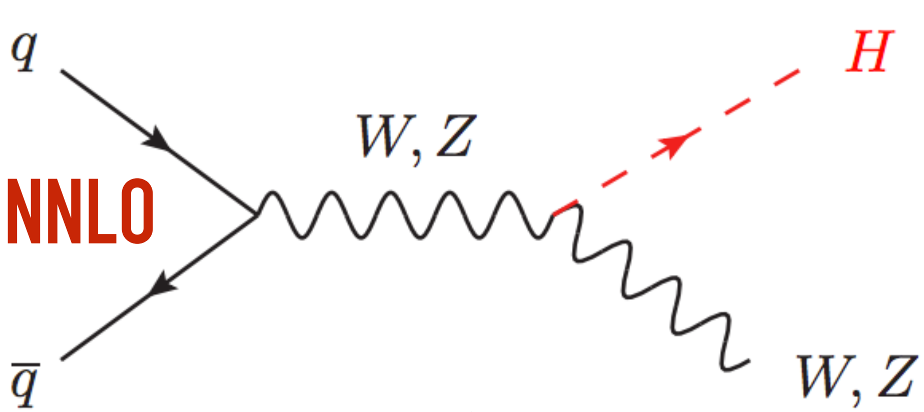
N3LO INCLUSIVE
NNLO DIFFERENTIAL



7%

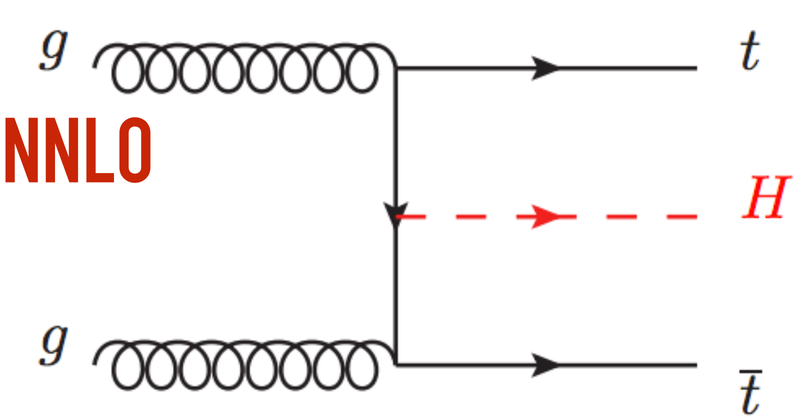
LHC@14TEV

NNLO



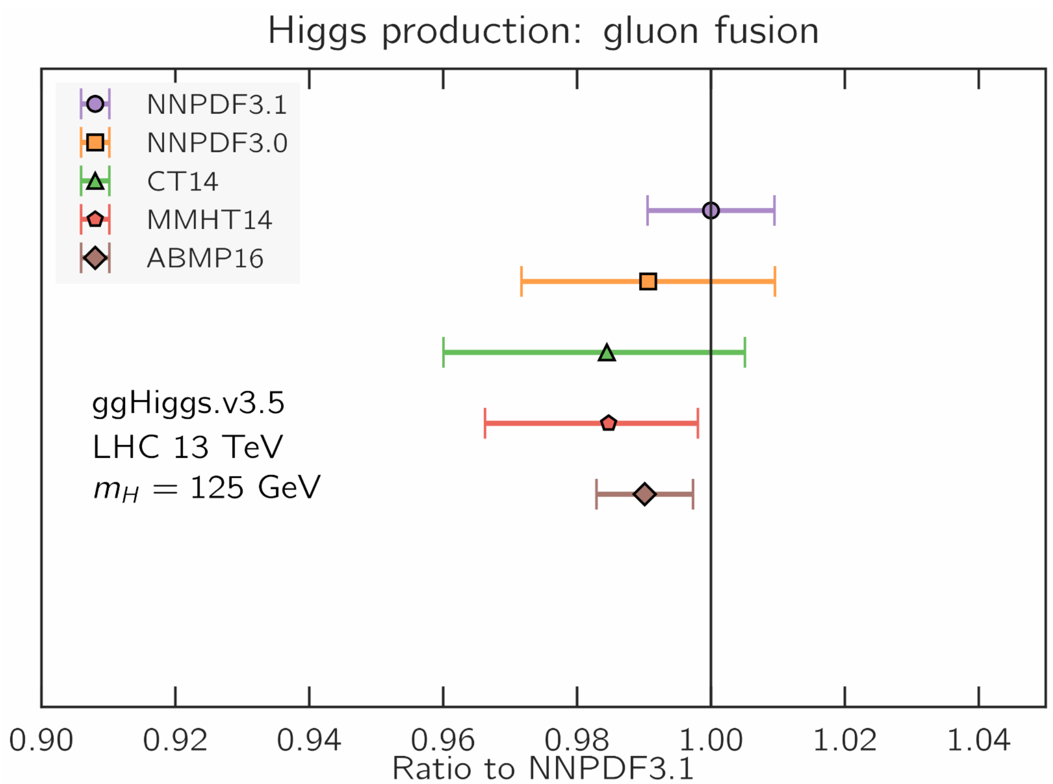
3%

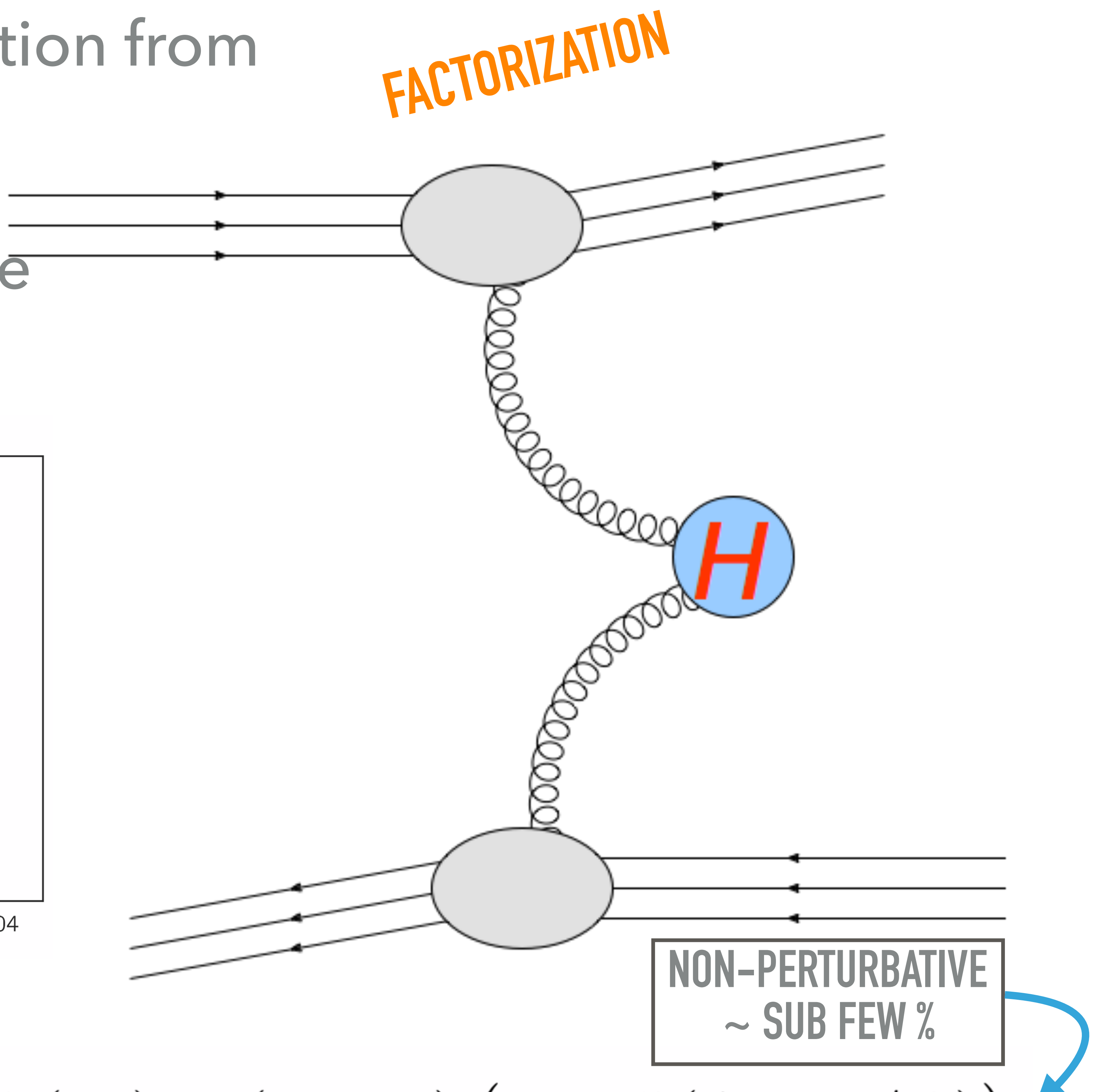
NNLO



1%

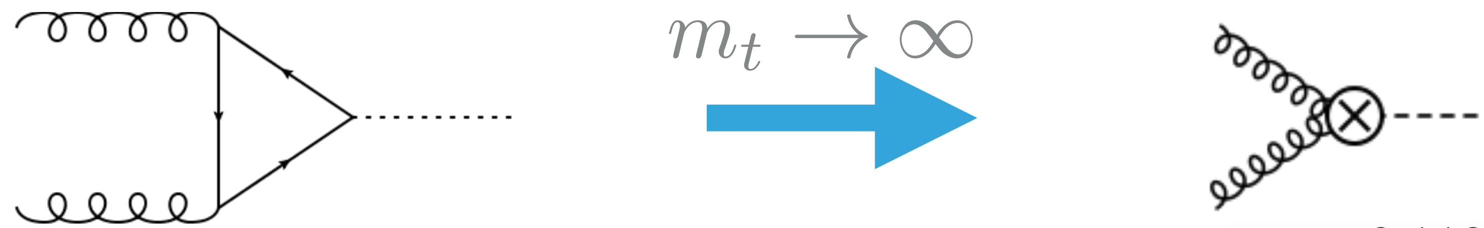
- Separate Higgs production from proton description
- Measure PDFs, compute partonic cross sections





$$\sigma = \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1, x_2) \left(1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q)\right)$$

- Compute dominant contribution at the LHC in fixed order perturbation theory
- Very successful for inclusive cross section
- Perturbative series stabilizes at N3LO

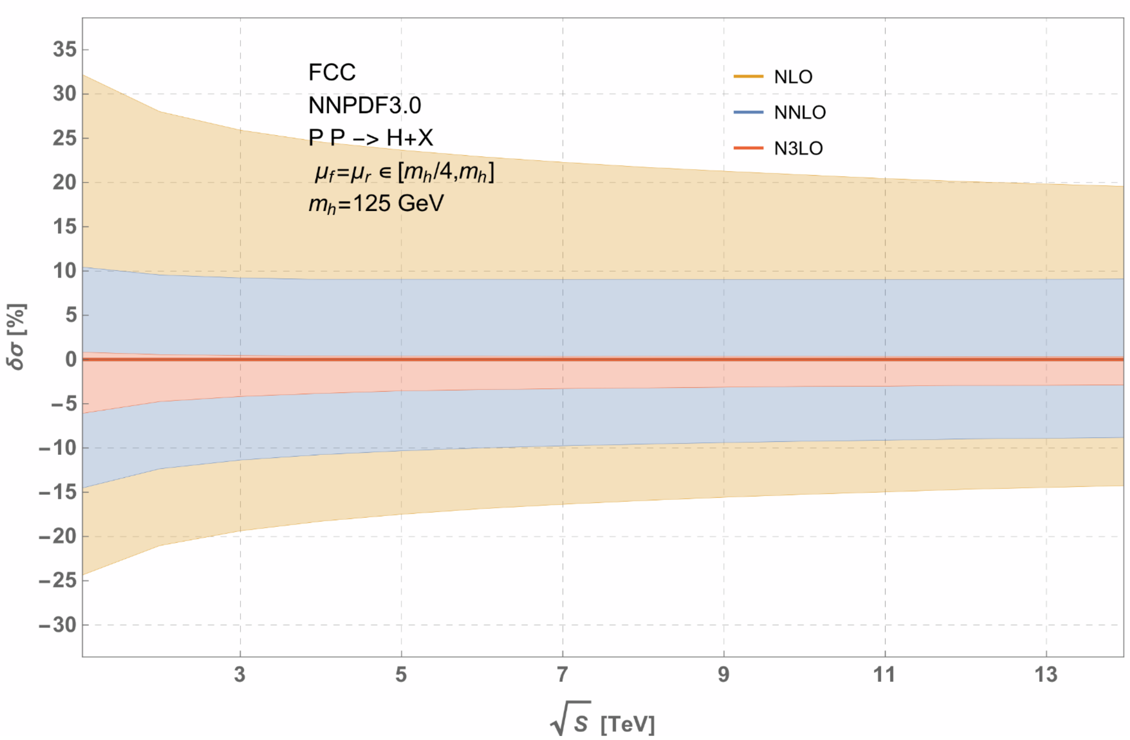


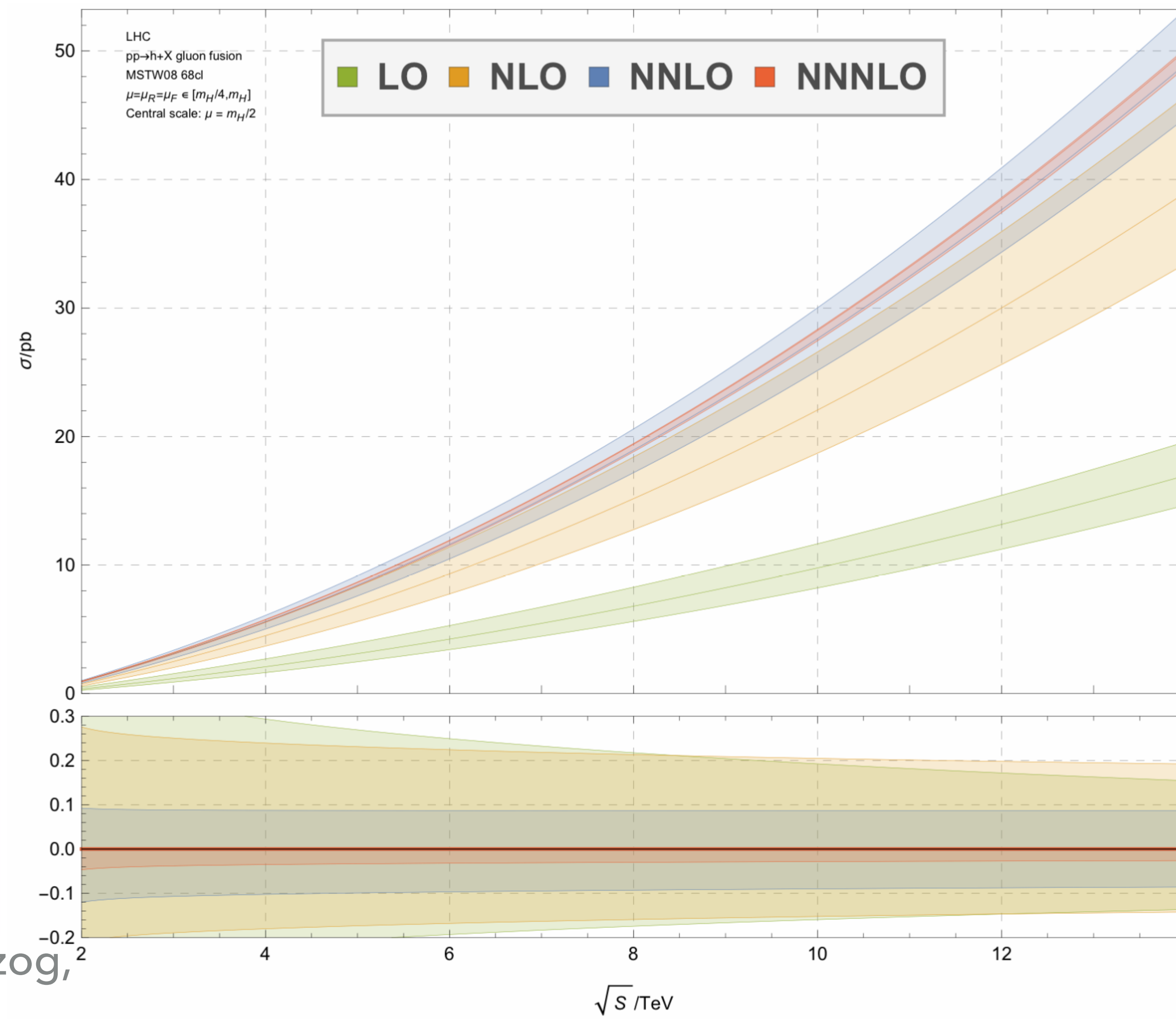
$m_t \to \infty$

$\alpha_S = 0.1181 \pm 1\%$

$$\hat{\sigma} = \alpha_s^2 \sigma^{\text{LO}} + \alpha_s^3 \sigma^{\text{NLO}} + \alpha_s^4 \sigma^{\text{NNLO}} + \alpha_s^5 \sigma^{\text{N3LO}}$$

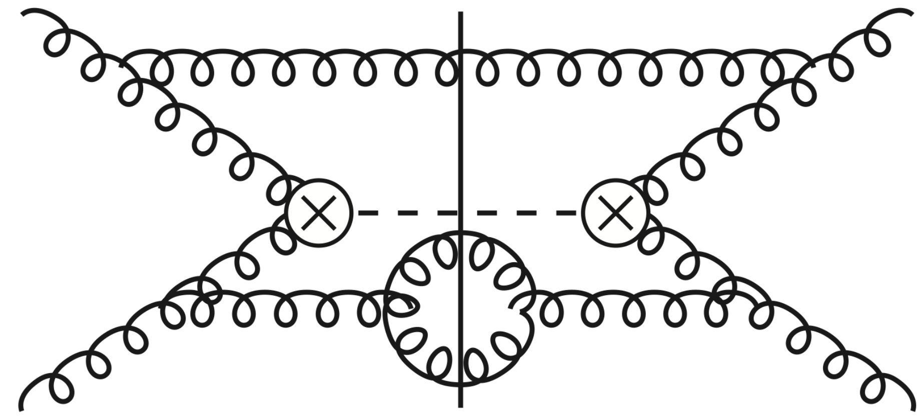
✓ ✓ ✓ ✓



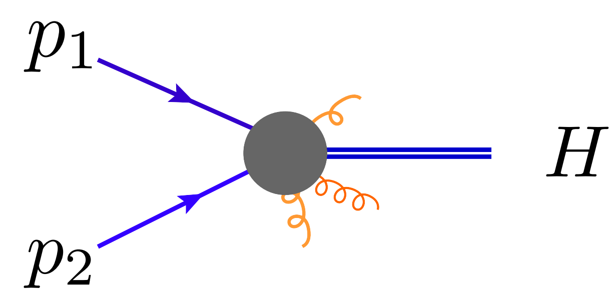


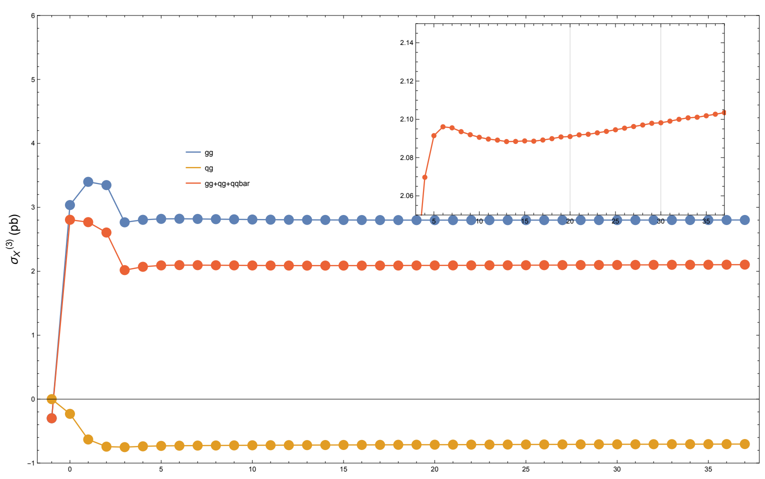
[Anastasiou, Duhr, FD, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger; Mistlberger]

- N3LO calculations are difficult
- Many complicated (analytic) integrals
- First step: threshold expansion

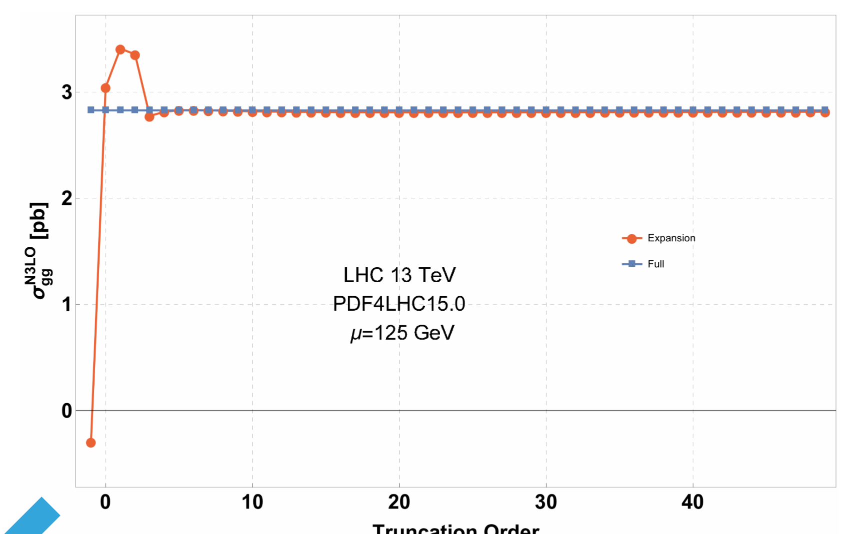


$$\bar{z} \simeq 1 \Leftrightarrow s \simeq m_h^2$$





[Mistlberger]



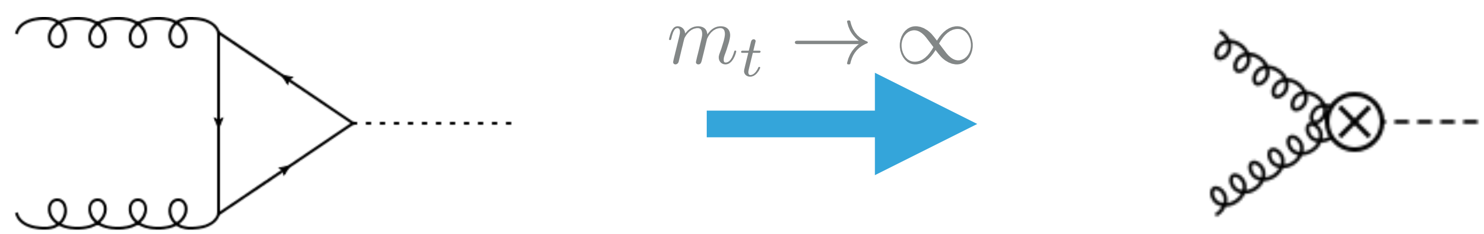
$$\hat{\sigma} = \sum_{n=-1}^{37} \bar{z}^n \eta_n$$

$$\hat{\sigma} = \hat{\sigma}(\bar{z})$$

iHixs 2.0

github.com/dulatf/ihixs

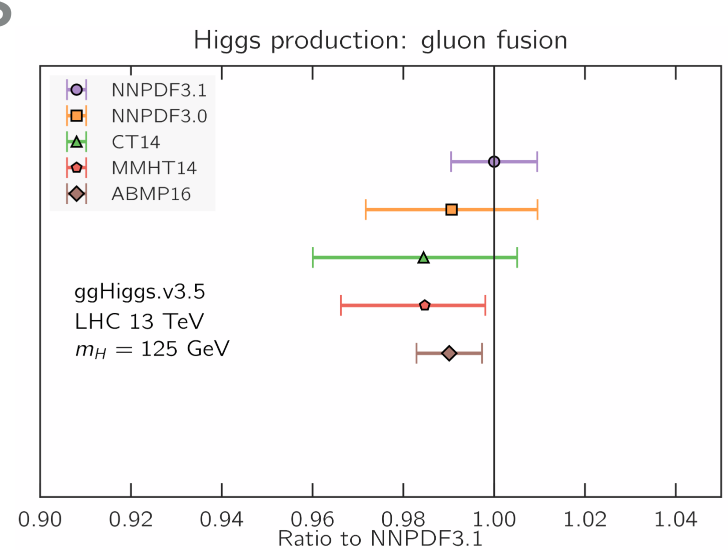
[FD, Lazopoulos, Mistlberger]

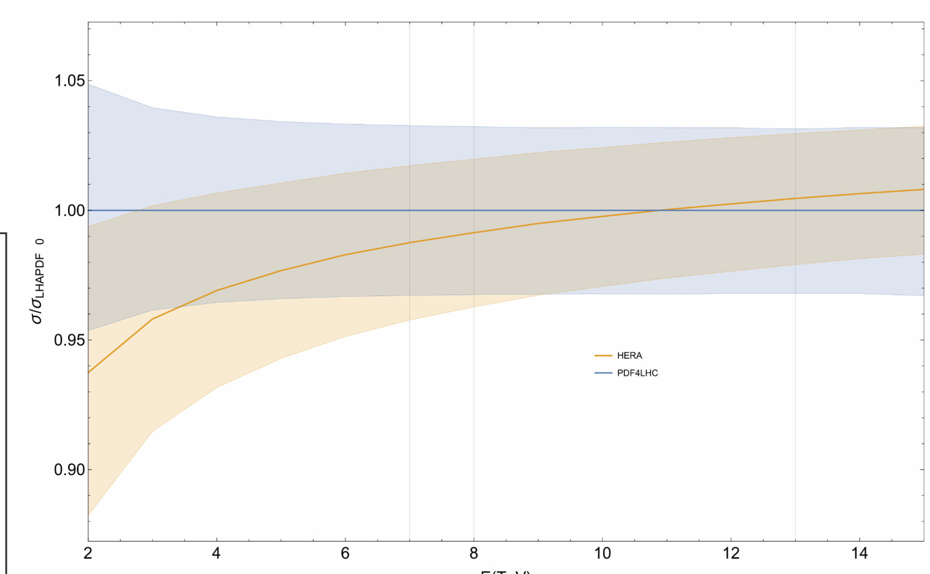


$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

- LHC precision requires effects beyond pure QCD
- Mass effects, electroweak corrections
- PDF uncertainties

$$\begin{aligned}
48.58\,\text{pb} = {} & \ 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& +20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& -\ \ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c),\ \text{exact NLO}) \\
& +\ \ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& +\ \ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO},\ 1/m_t) \\
& +\ \ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
& +\ \ 1.49\,\text{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

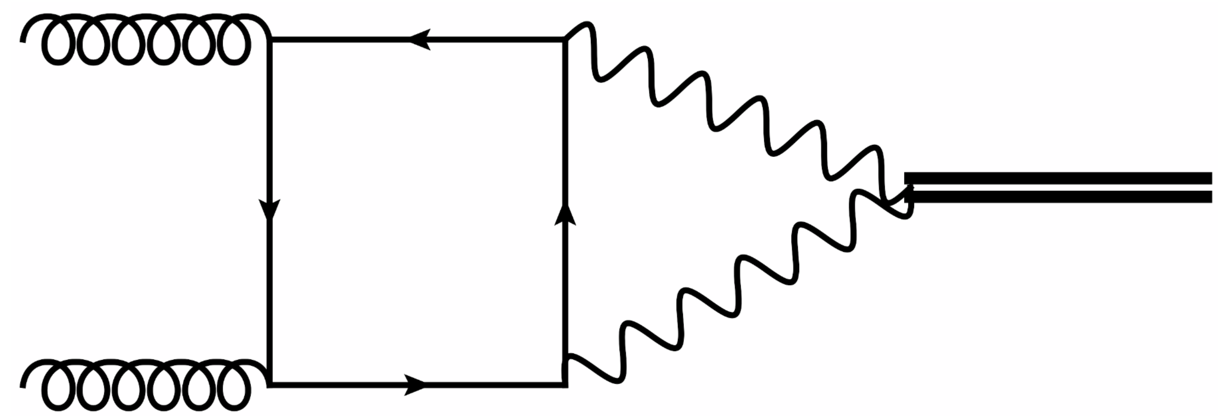




[Anastasiou, Duhr, FD, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger]

- Factorized EWK corrections ~5%

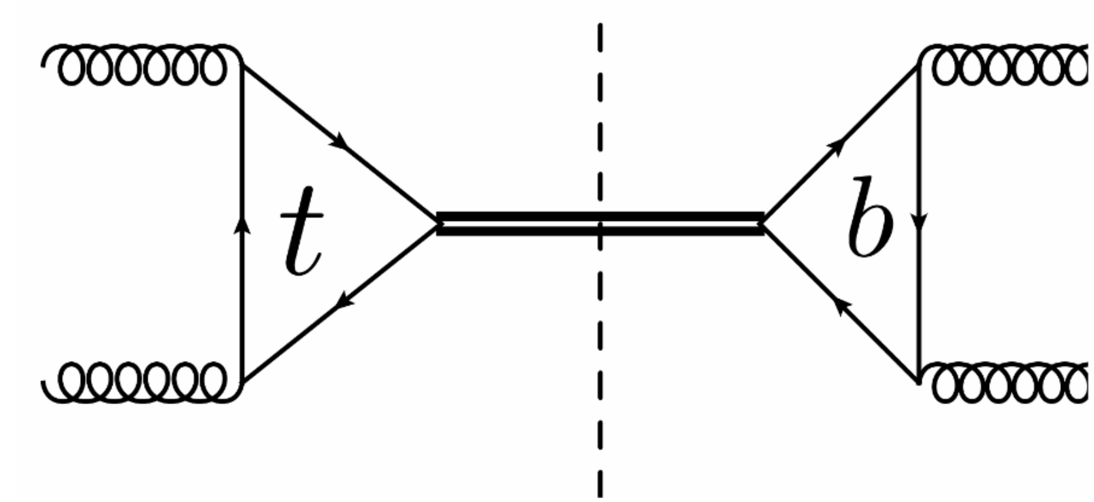
$$\sigma = \sigma_{QCD} \times (1 + \delta_{EWK})$$



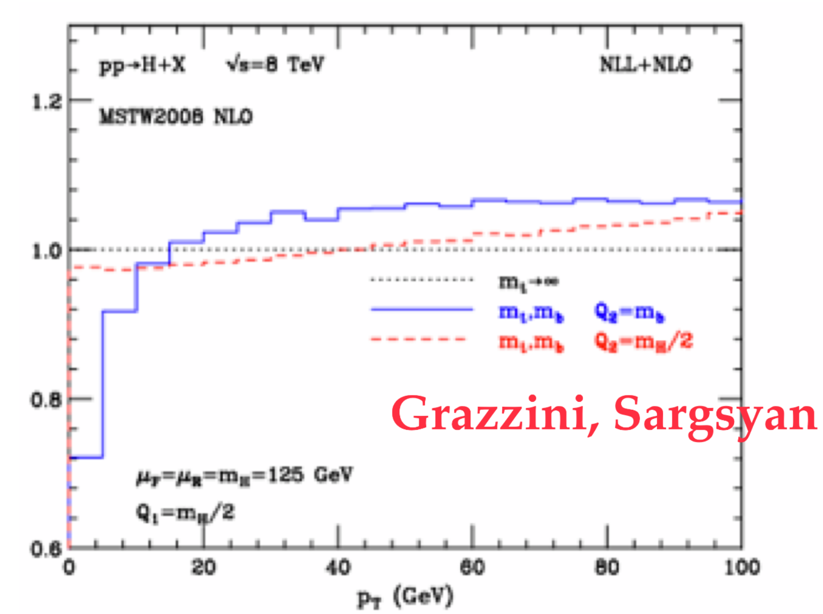
[Actis, Passarino, Sturm, Uccirati; Degrassi, Maltoni; Anastasiou, Boughezal, Petriello; ...]

- Residual uncertainty: ~1%
- Factorized vs non-factorized corrections (recently: LO through $\mathcal{O}(\epsilon^2)$) [Bonetti, Melnikov, Tancredi]
- Corrections to (Higgs+Jet) [Keung, Petriello]
- Small corrections for inclusive Higgs, but need to be taken into account at current level of precision (could be larger for differential)

- Infinite top-mass EFT is just an approximation
- Exact mass dependence known at NLO [Dawson; Djouadi, Spira, Zerwas]
- Corrections to EFT at NNLO [Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven]
- Interference with light quarks is large and negative
- Particularly import in differential distributions (some progress towards NNLO) [Bonciani, del Duca, Frellesvig, Henn, Moriello, Smirnov; Melnikov, Tancredi, Wever]



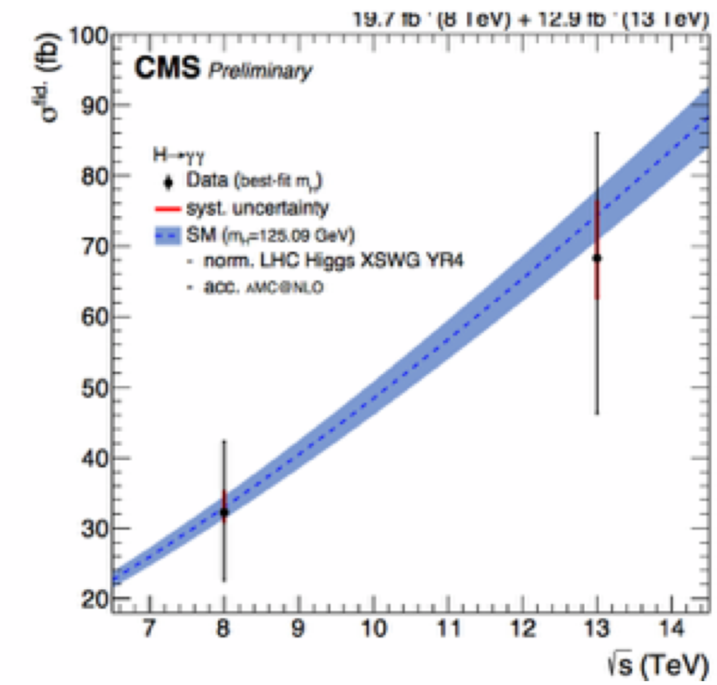
σ^{NLO}_{eft}	34.81[1]	
$\sigma^{NLO}_{eft;R}$	37.00[2]	+6.3%
$\sigma^{NLO}_{ex;t}$	36.76[1]	+5.6%
$\sigma^{NLO}_{ex;t+b}$	35.09[1]	+0.8%
$\sigma^{NLO}_{ex;t+b+c}$	34.91[1]	+0.3%



- Experiments don't measure inclusive cross sections
- Instead: Differential distributions, fiducial cross sections
- We need high precision predictions for observables that are close to the experiment

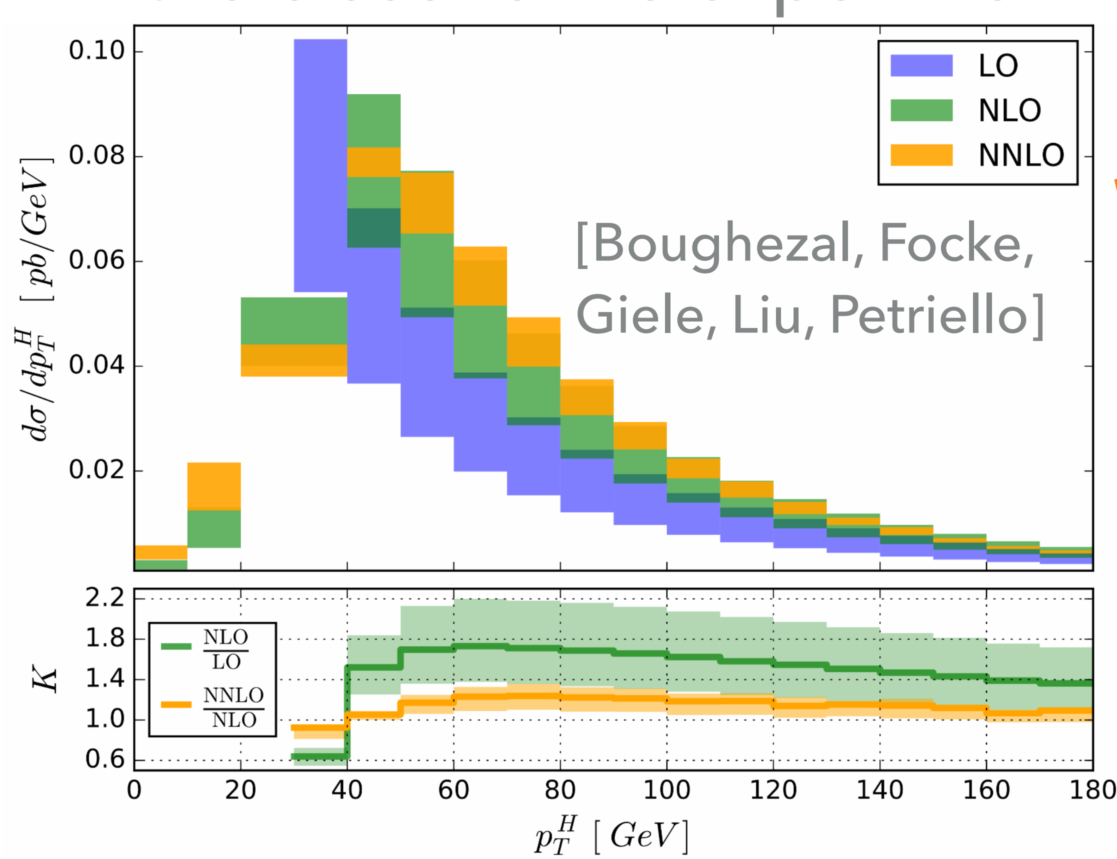
$$|\eta| < 2.37 \qquad p_T^{\gamma_1} > 0.25\ m_{\gamma\gamma}$$
$$|\eta| \notin [1.37,\ 1.52] \qquad p_T^{\gamma_2} > 0.35\ m_{\gamma\gamma}$$

$$H \to \gamma\gamma$$

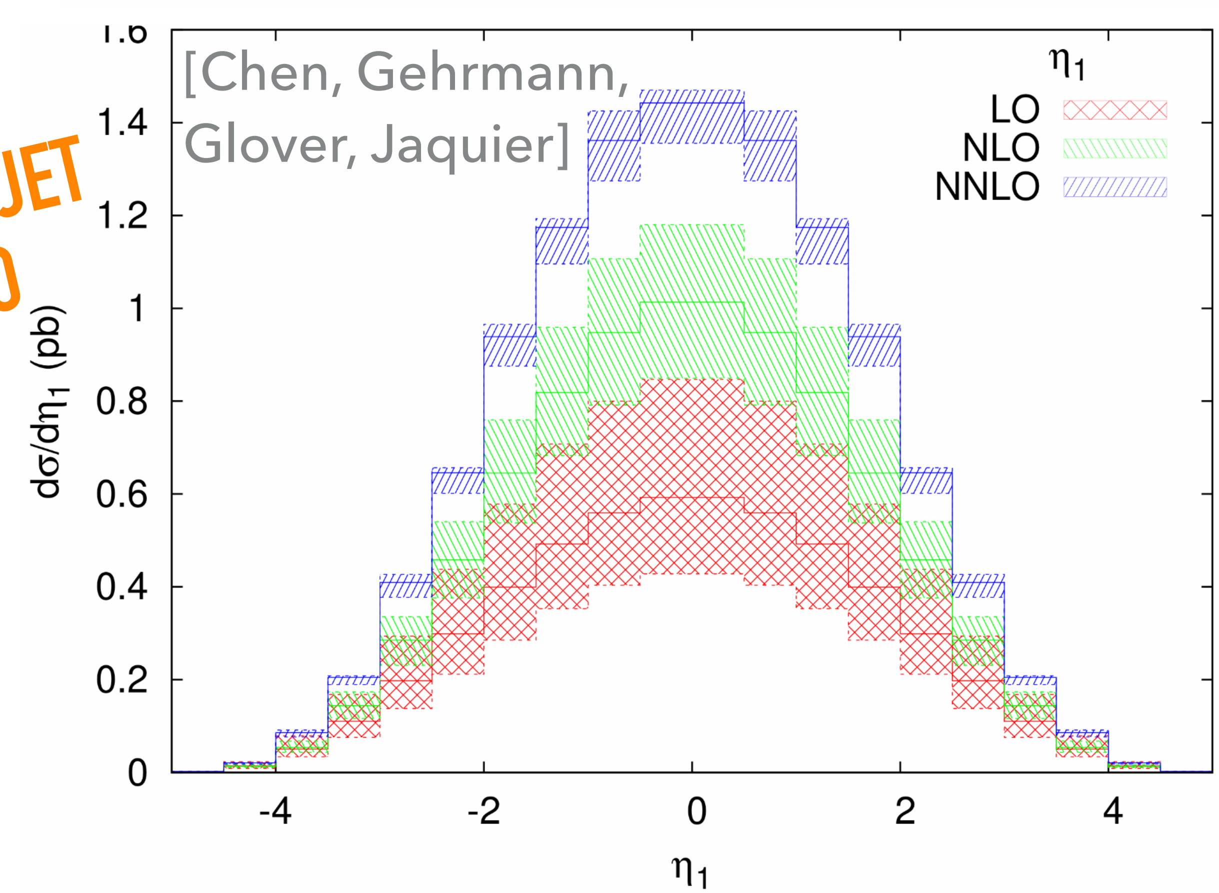


CMS

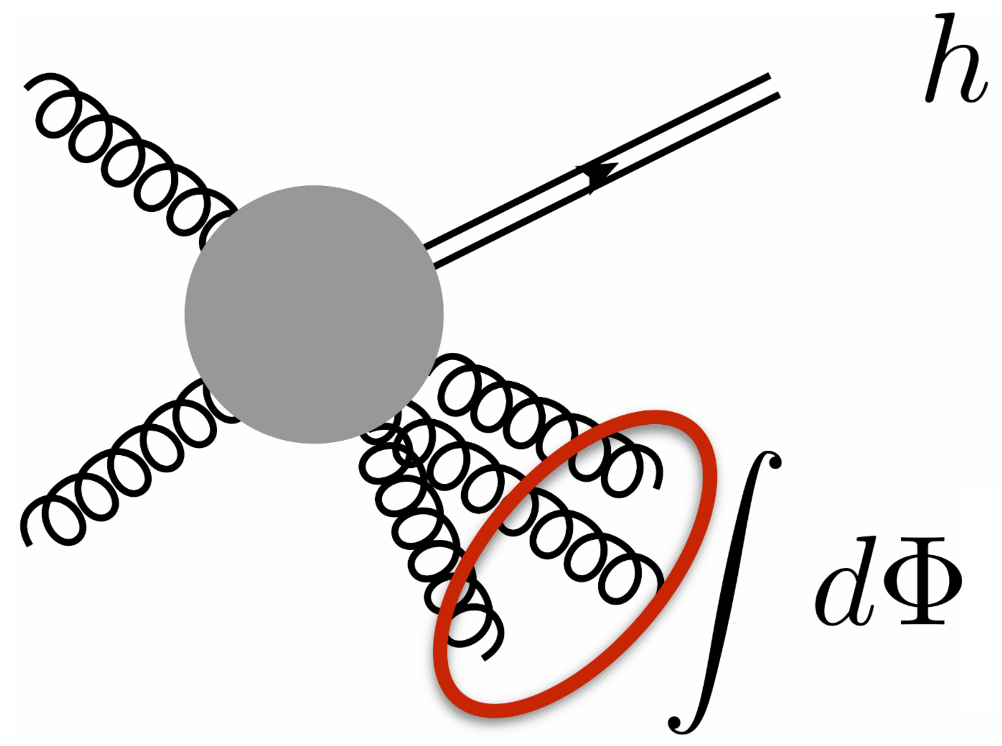
$$\sigma_{\text{tot}}^{\text{fid}} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst})\ \text{fb}$$



HIGGS+JET AT NNLO



- Fully differential N3LO is difficult
- Focus on Higgs-differential observables
- Calculate semi-inclusively by integrating out QCD radiation

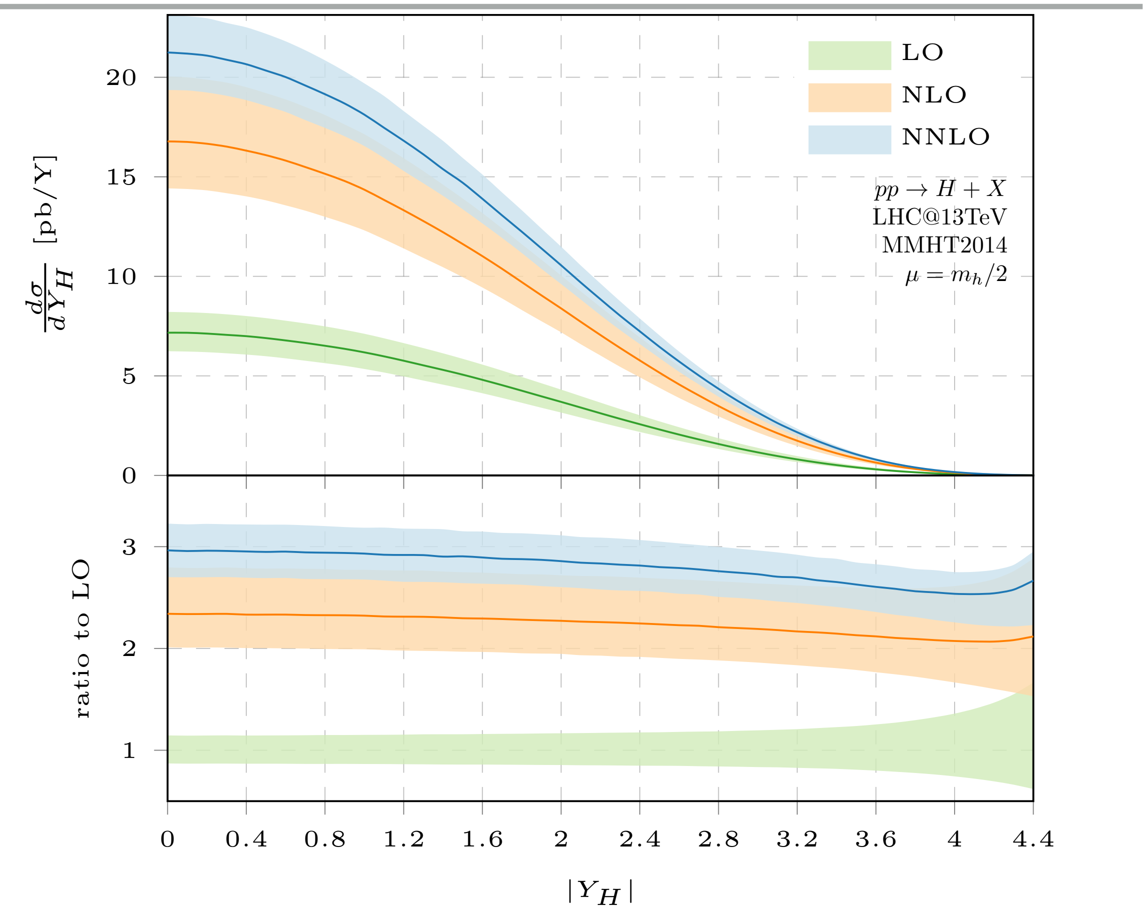


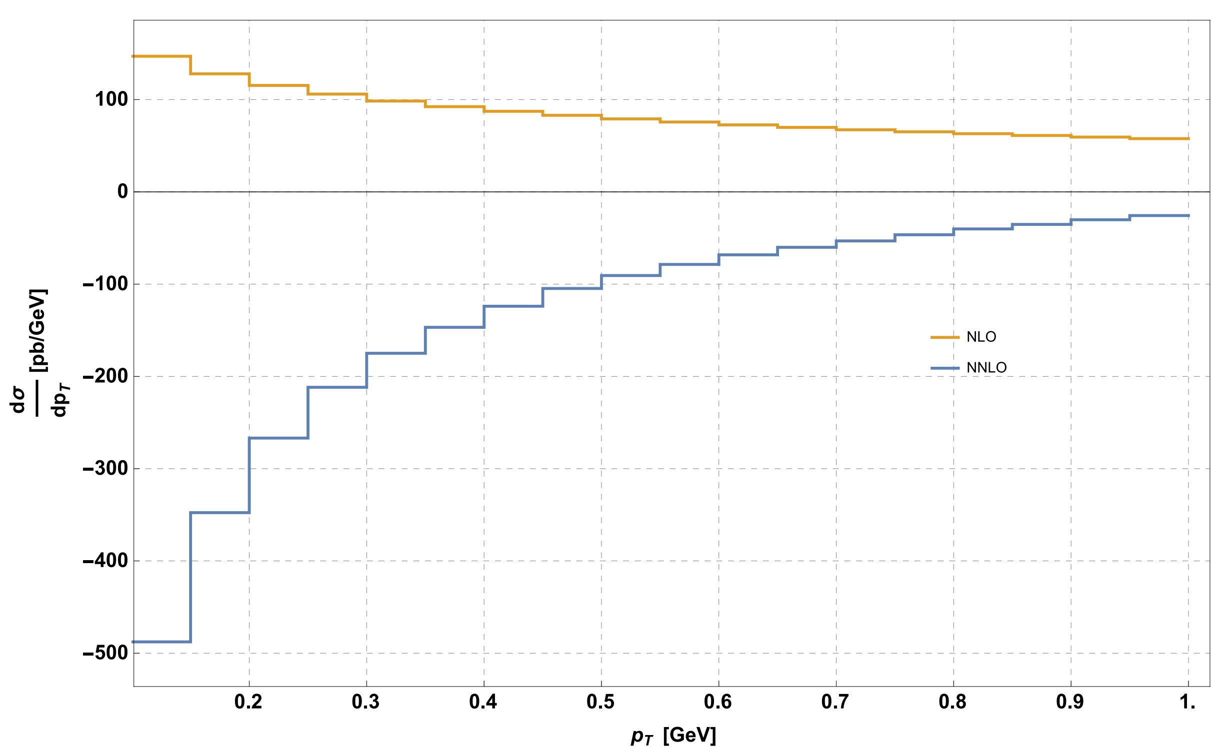
Y	Rapidity
p_T	Transverse momentum
m_h	Mass / Virtuality
ϕ	Azimutal angle

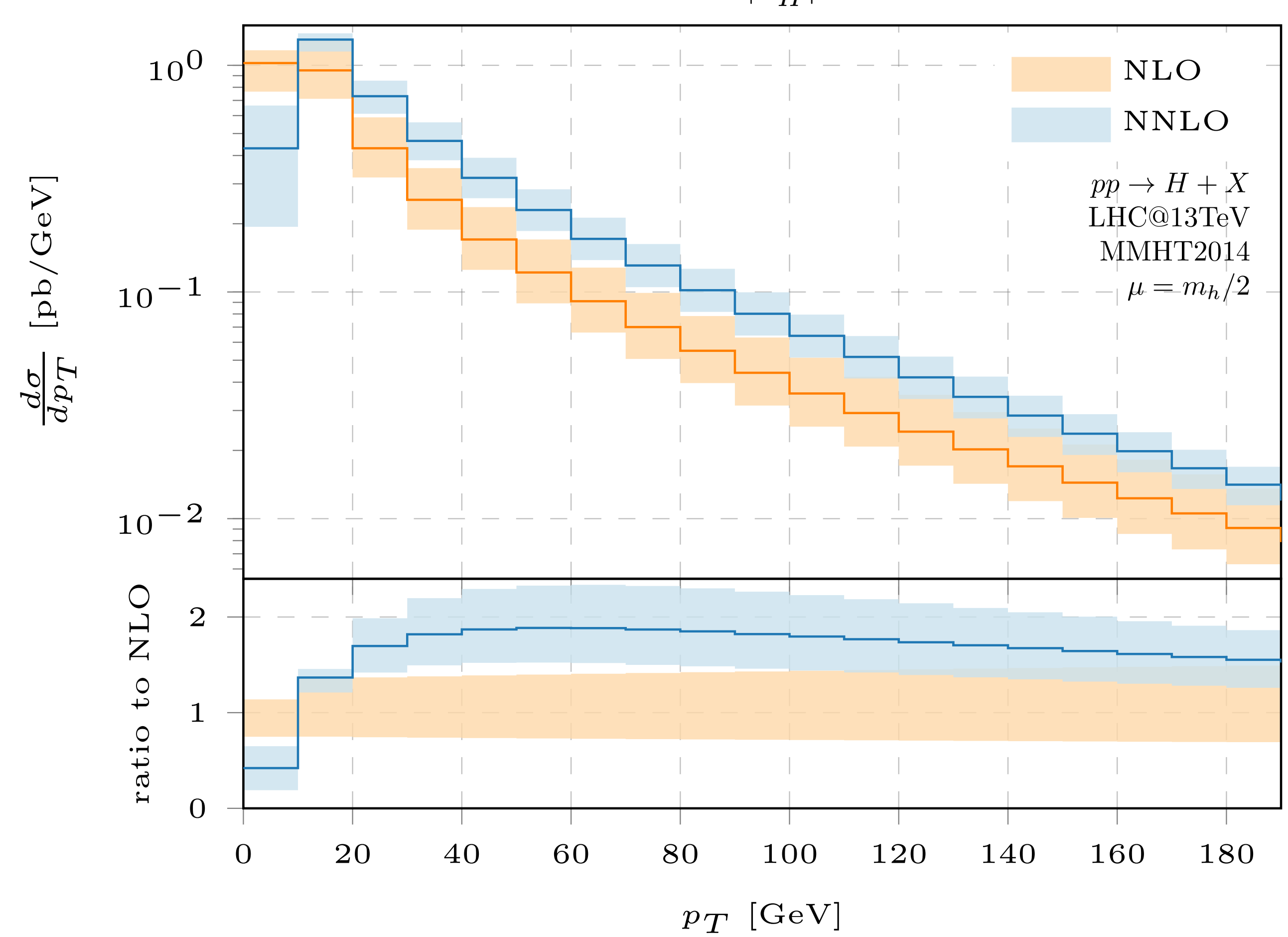
$$P\ P \to H + X \to \gamma\gamma + X$$

$$P\ P \to H + X \to 4l + X$$

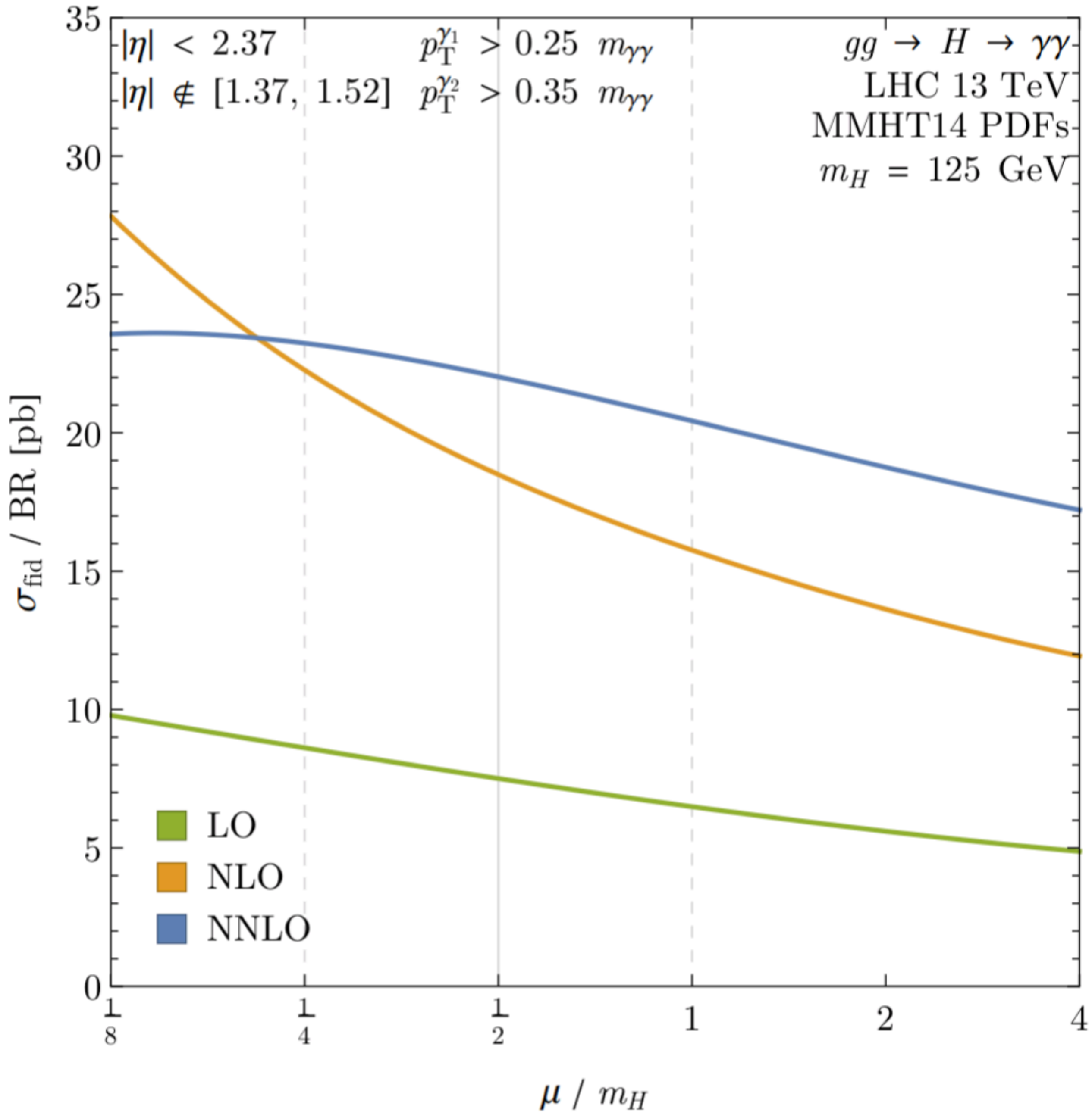
- Proof of principle at NNLO
- Stable distributions
- Theoretically interesting low-pt results
- Realistic observables

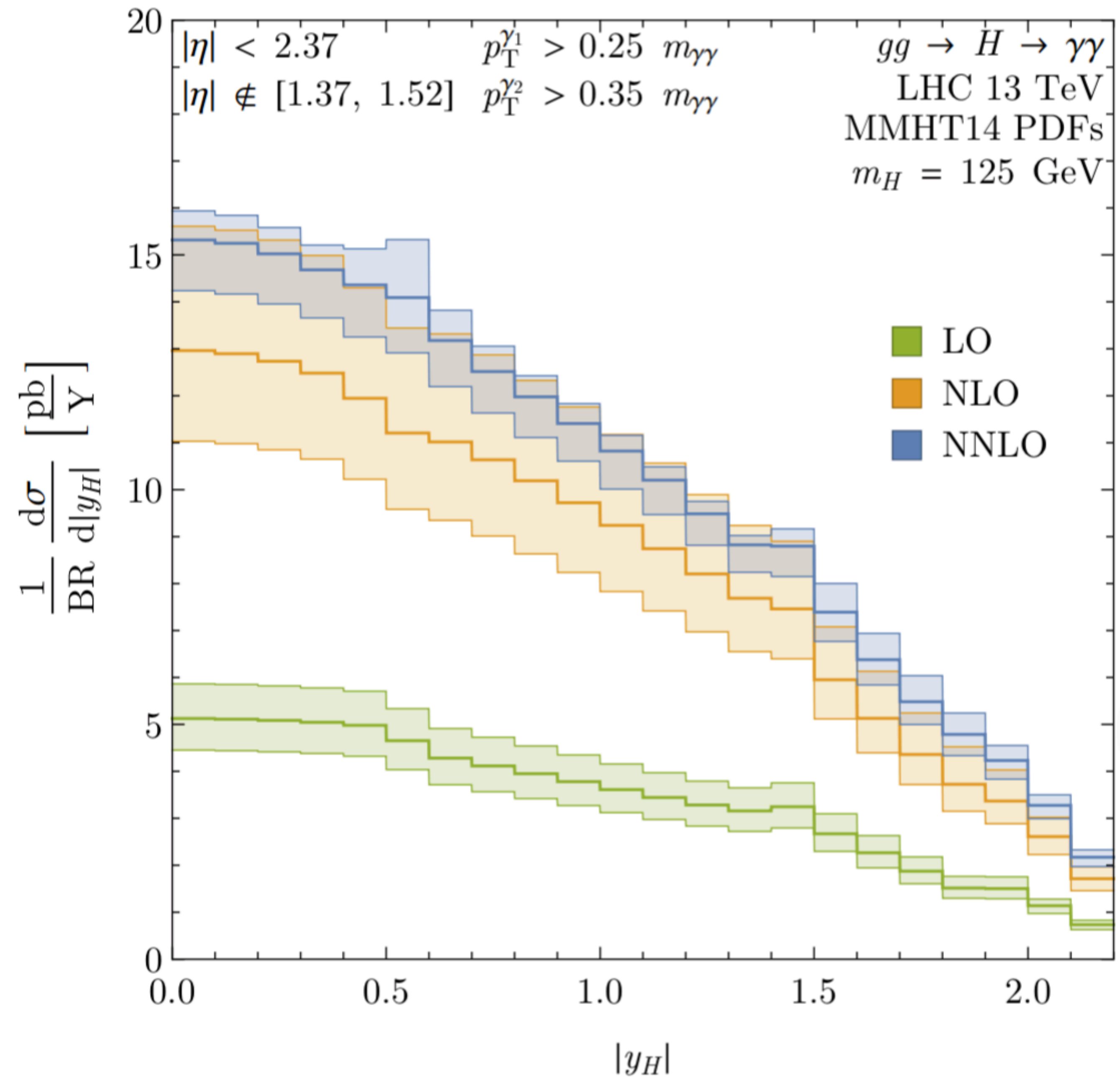






[FD, Lionetti, Mistlberger, Pelloni, Specchia]

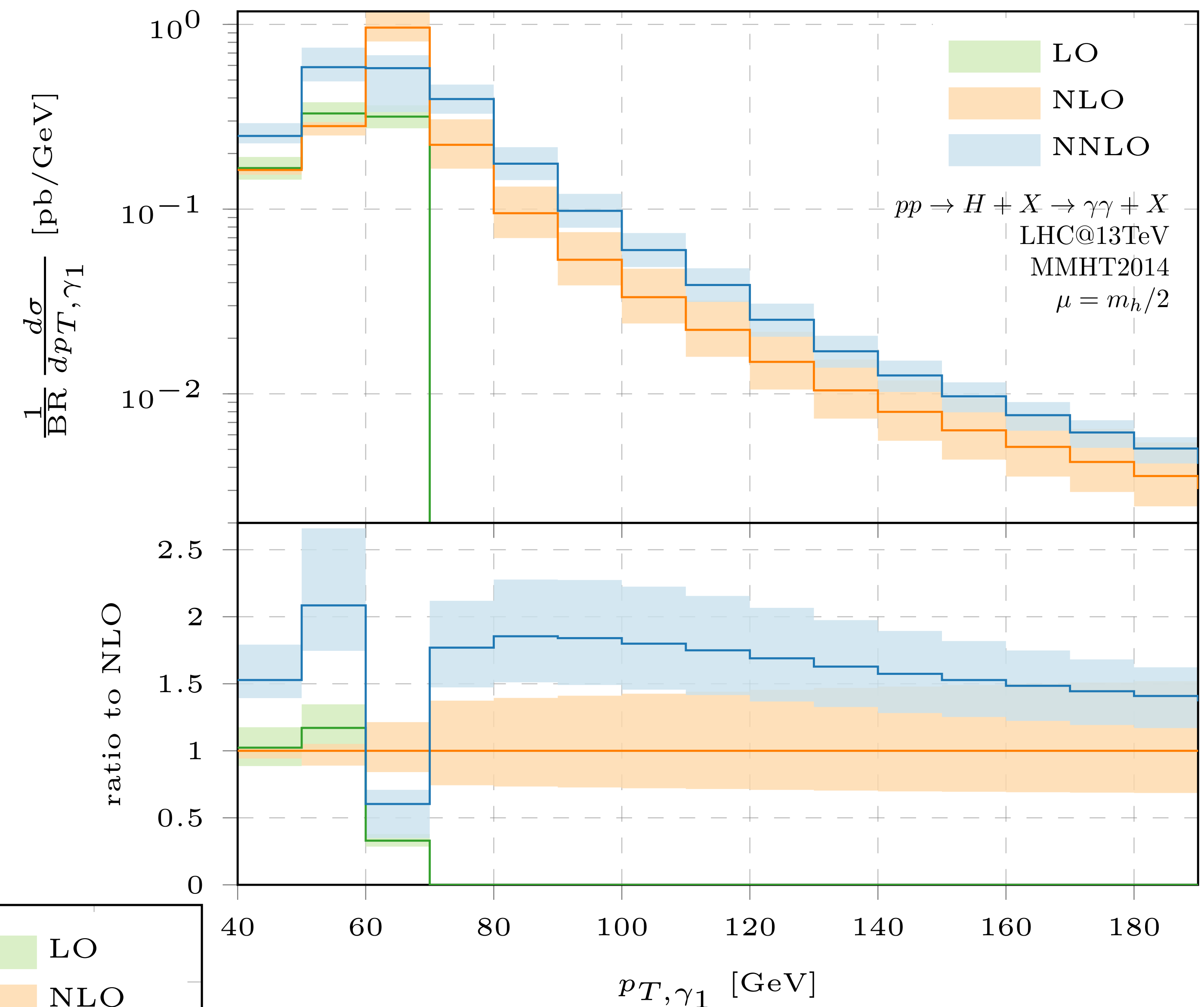


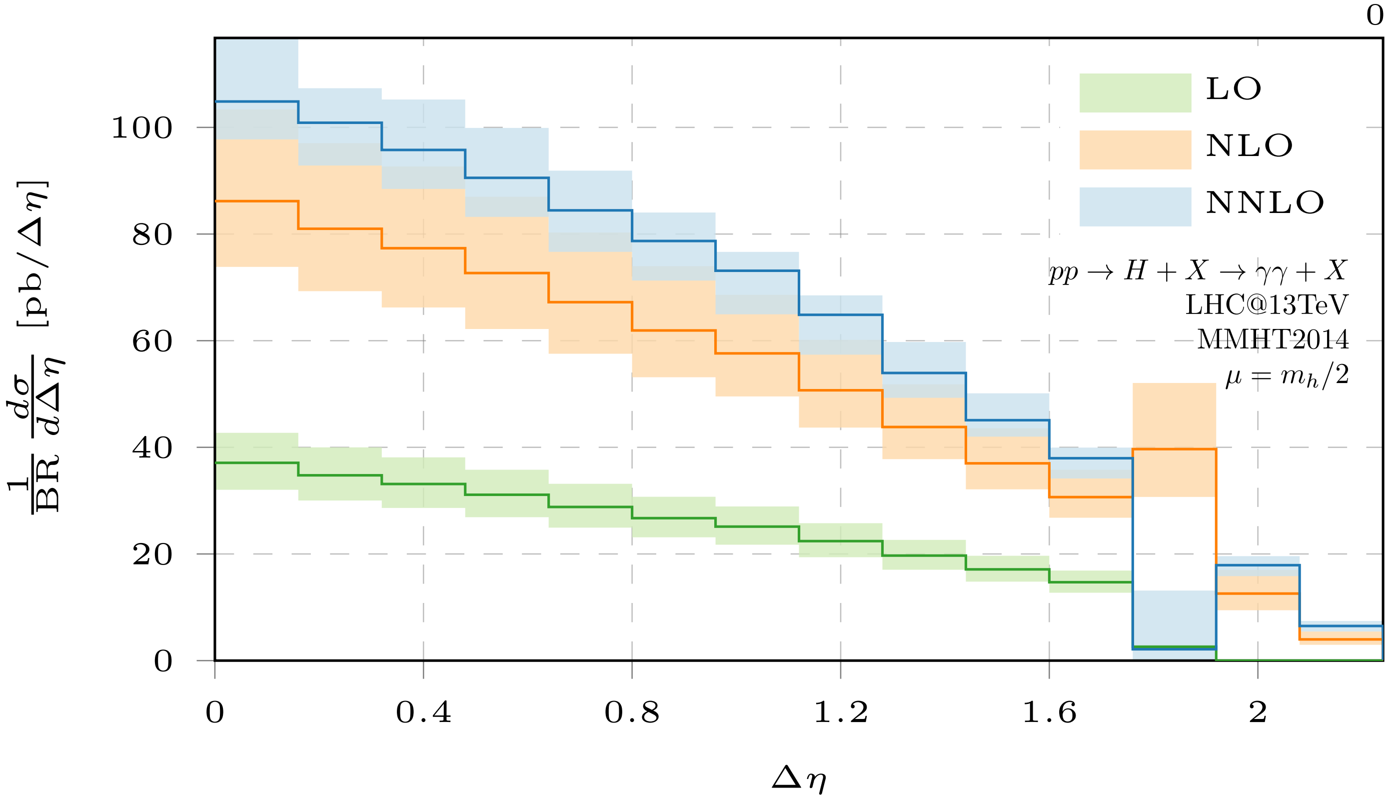


$$\frac{\sigma_{\rm fid}^{\rm NLO}}{\rm BR} = 18.5^{+3.8}_{-2.7}\,{\rm pb} \qquad \frac{\sigma_{\rm fid}^{\rm NNLO}}{\rm BR} = 22.1^{+1.1}_{-1.6}\,{\rm pb}$$

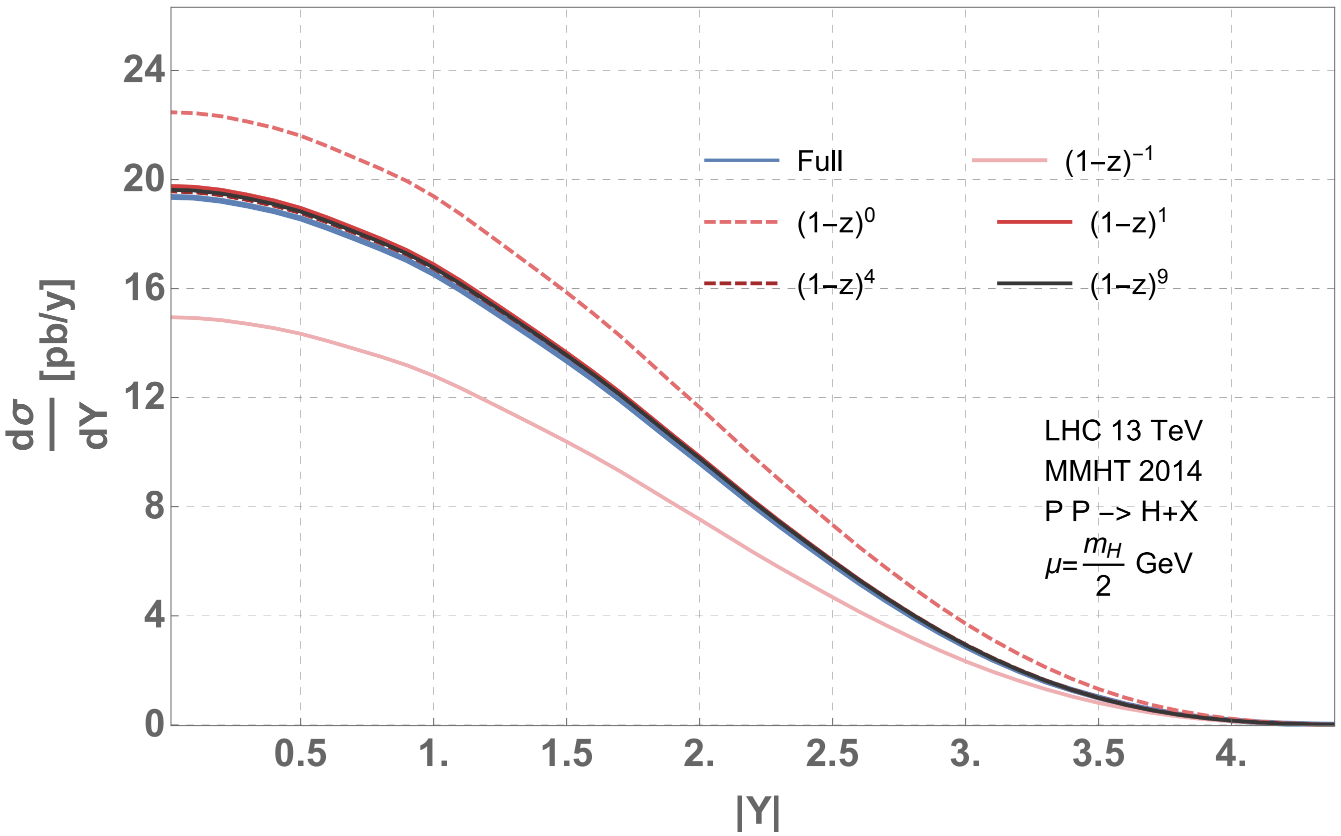
REALISTIC ATLAS CUTS

- Distributions of final state momenta:
- Leading photon pT
- Rapidity difference

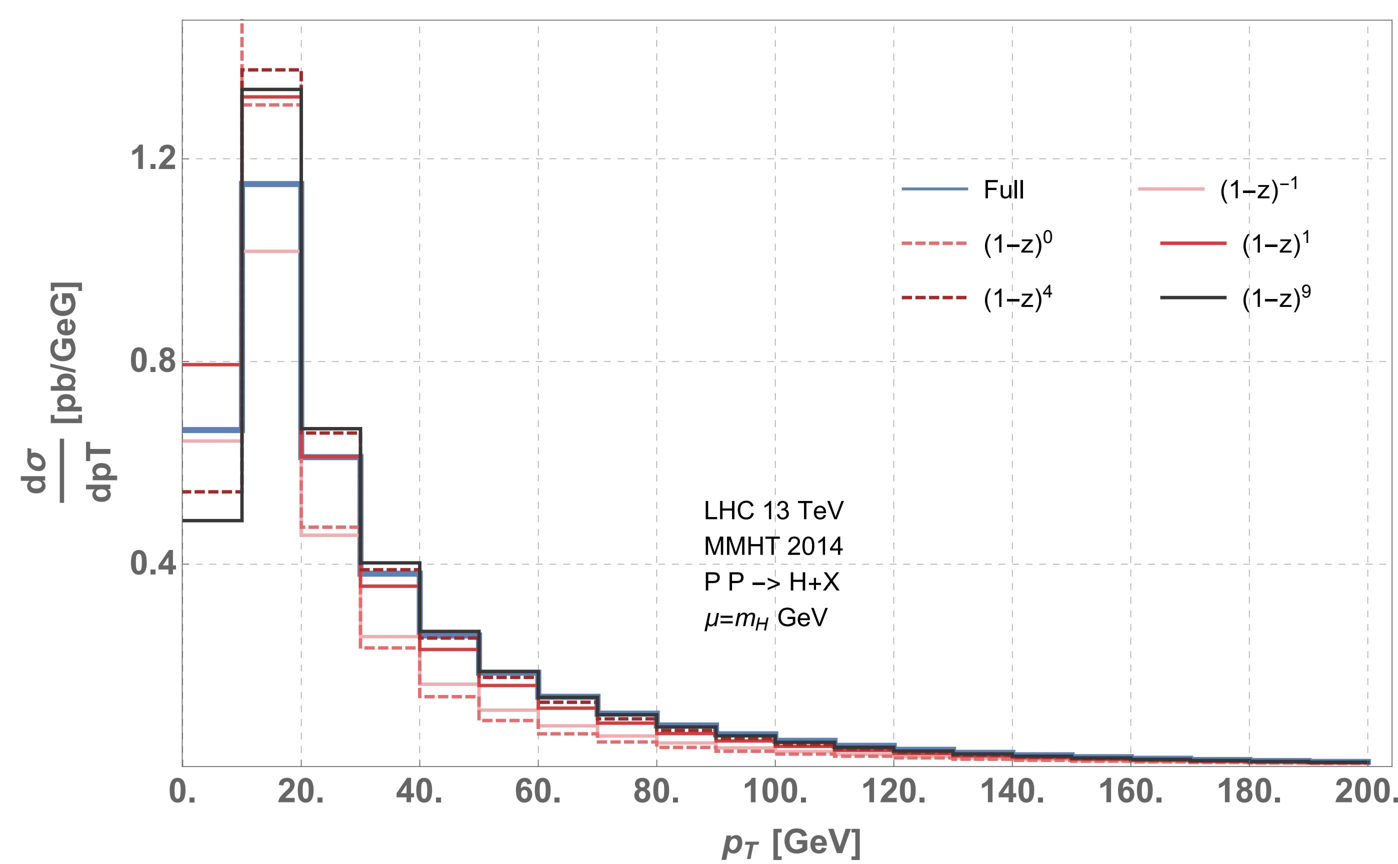


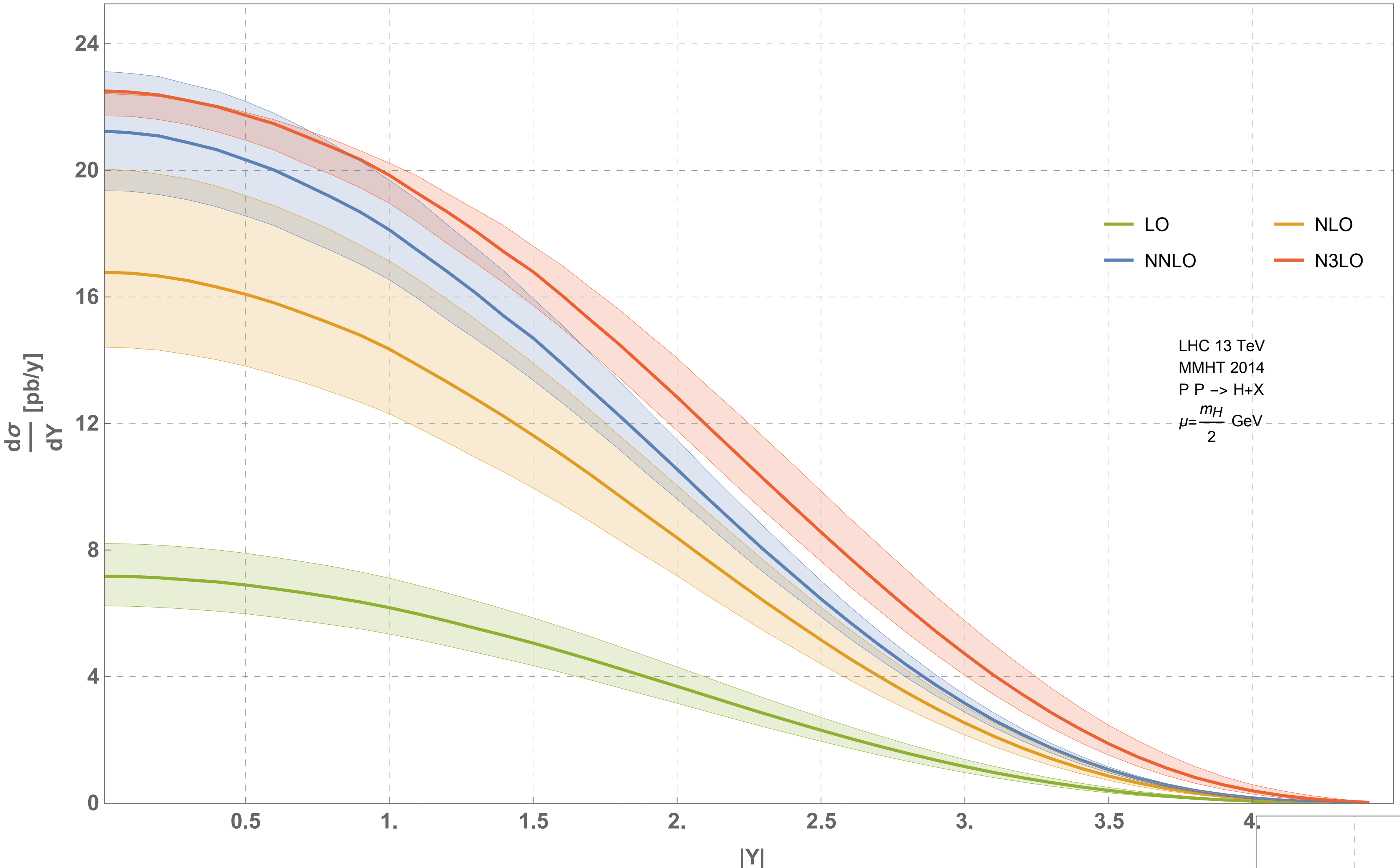


$$\Delta\eta = |\eta_{\gamma_1} - \eta_{\gamma_2}|$$

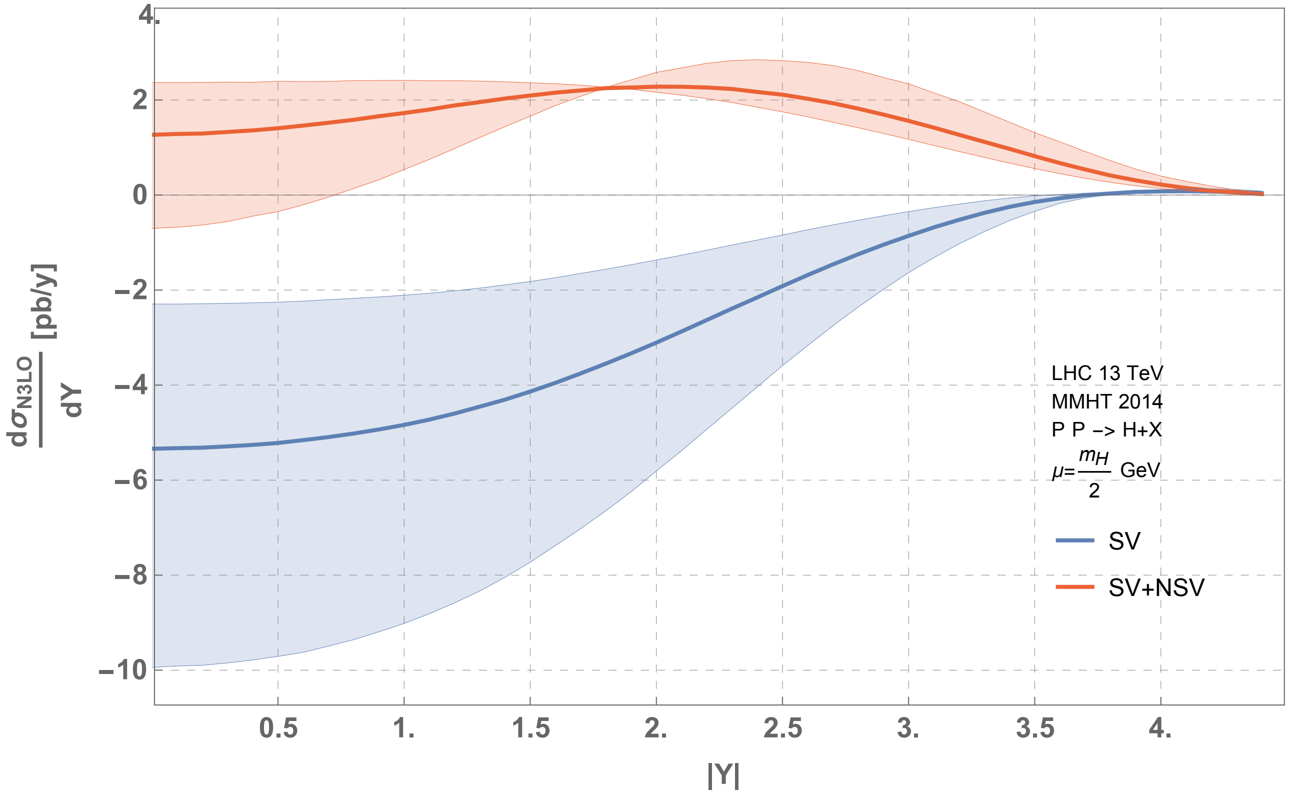


- N3LO is still difficult
- Again: Threshold expansion
- Validate at NNLO





- Threshold expansion for rapidity distribution at N3LO



Two orders in threshold expansion

[FD, Mistlberger, Pelloni]

- LHC experiments demand high-precision predictions
- Precision observables can shed light onto possible BSM physics
- Lot of progress in theoretical observables, many high precision predictions available
- New level of precision requires careful reevaluation of previously neglected effects
- Next goal: push differential distributions to % level accuracy

FULLY DIFFERENTIAL N3LO IS WITHIN REACH!