FALKO DULAT

PRECISION HIGGS CROSS SECTION CALCULATIONS

THE N3LOTEAM

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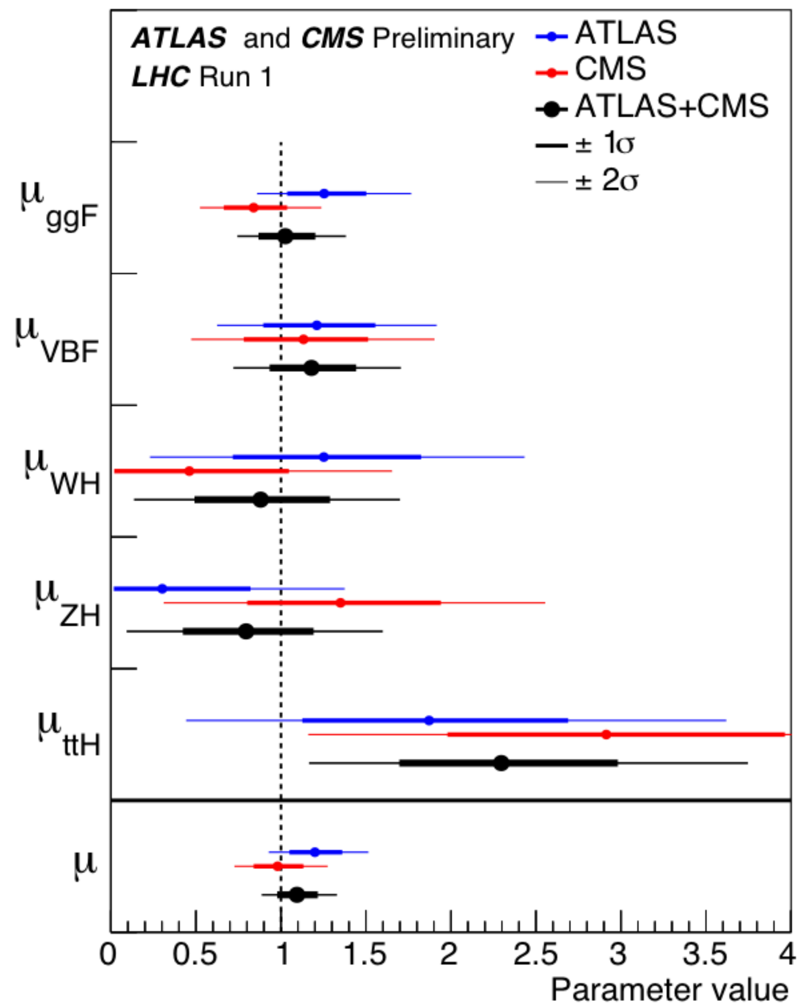
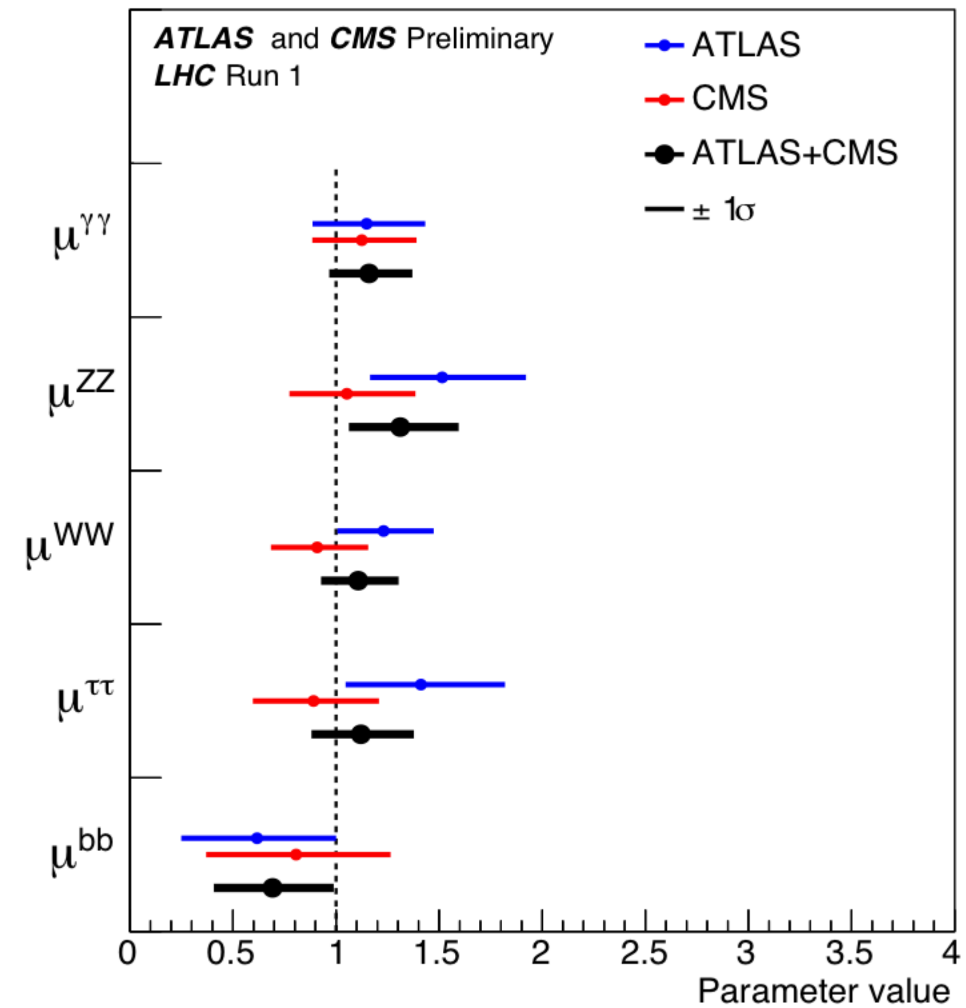
$$\mu_i = \sigma_i/(\sigma_i)_{SM}$$

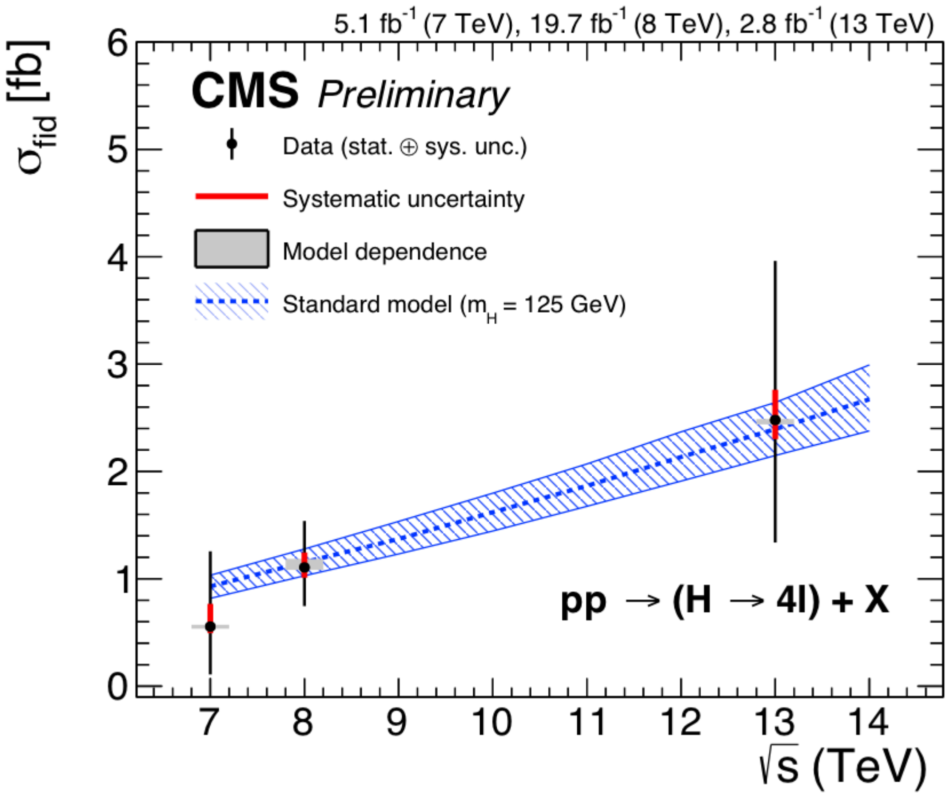


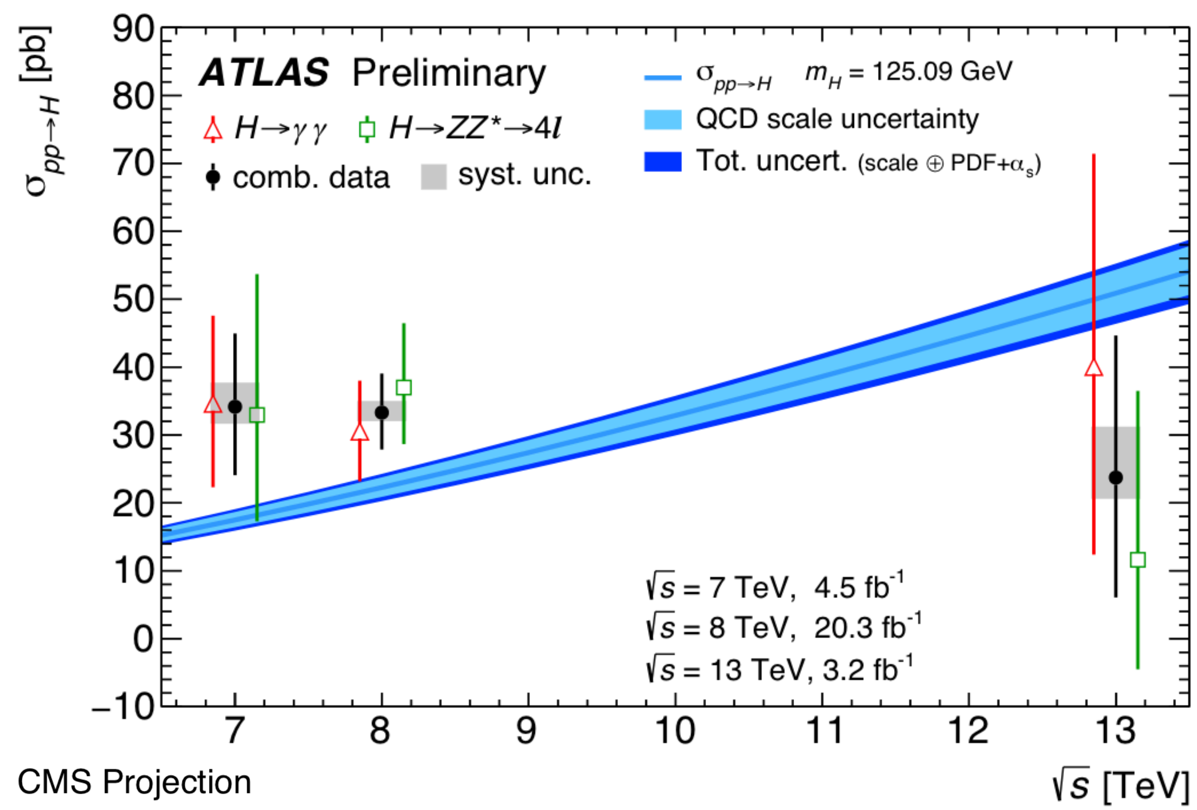
$$\mu_f = \mathrm{BR}_f/(\mathrm{BR}_f)_{SM}$$

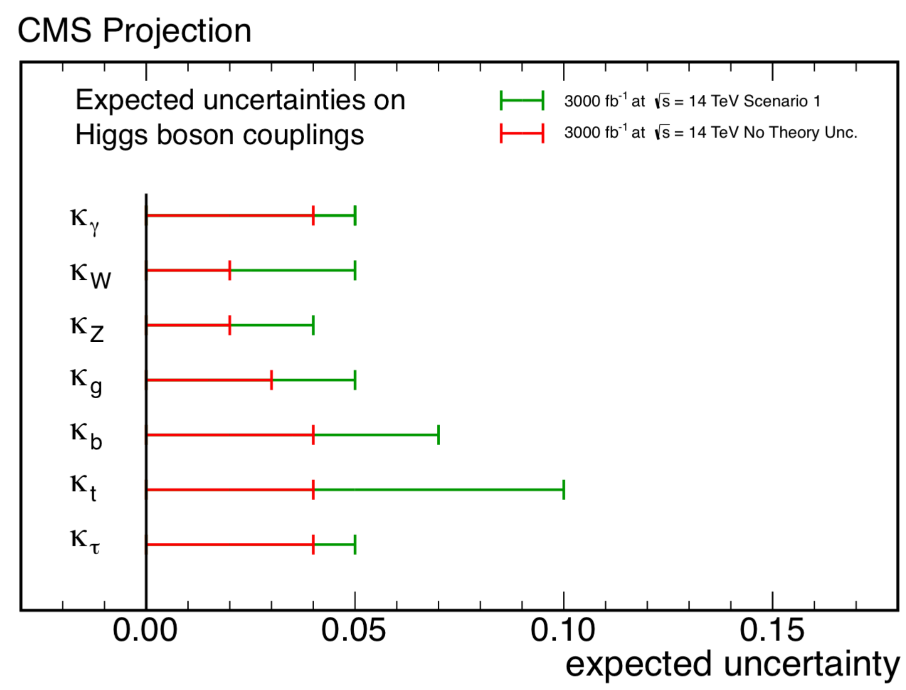


Global signal strength for all prod. and decay modes measured with ~10% accuracy

$$\mu = 1.09 \pm 0.07_{\text{stat}} \pm 0.04_{\text{exp syst.}} \pm 0.03_{\text{th. bkg}} \pm 0.07_{\text{th. signal}}$$







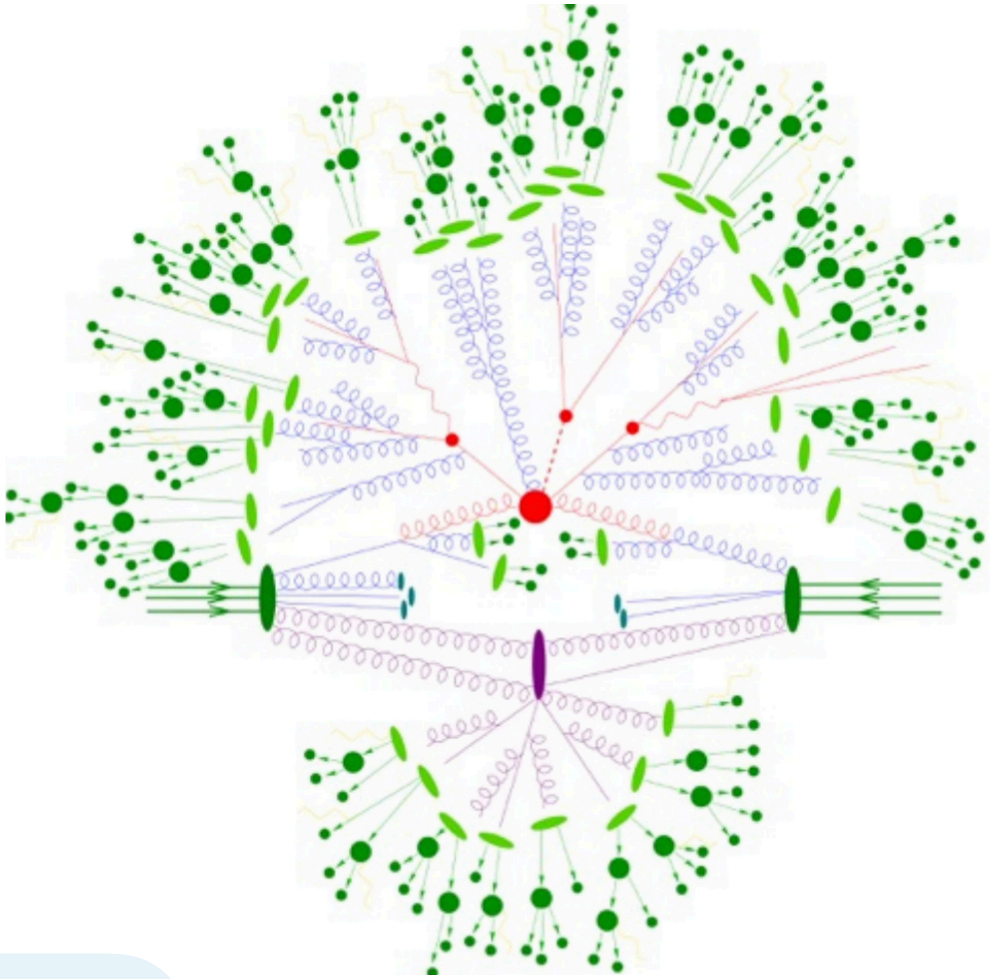
REDUCTION OF THEORETICAL UNCERTAINTIES IS CRUCIAL

Great effort in the theory community to reduce uncertainties

Lots of different sources

Many new calculations that push perturbative QCD to new levels of accuracy

Reduction of perturbative uncertainty



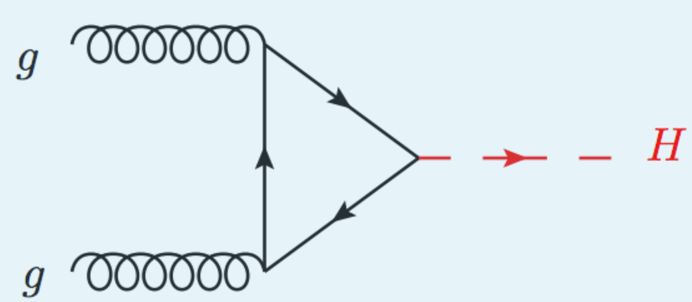
VBF

inclusive ggF @ N3LO

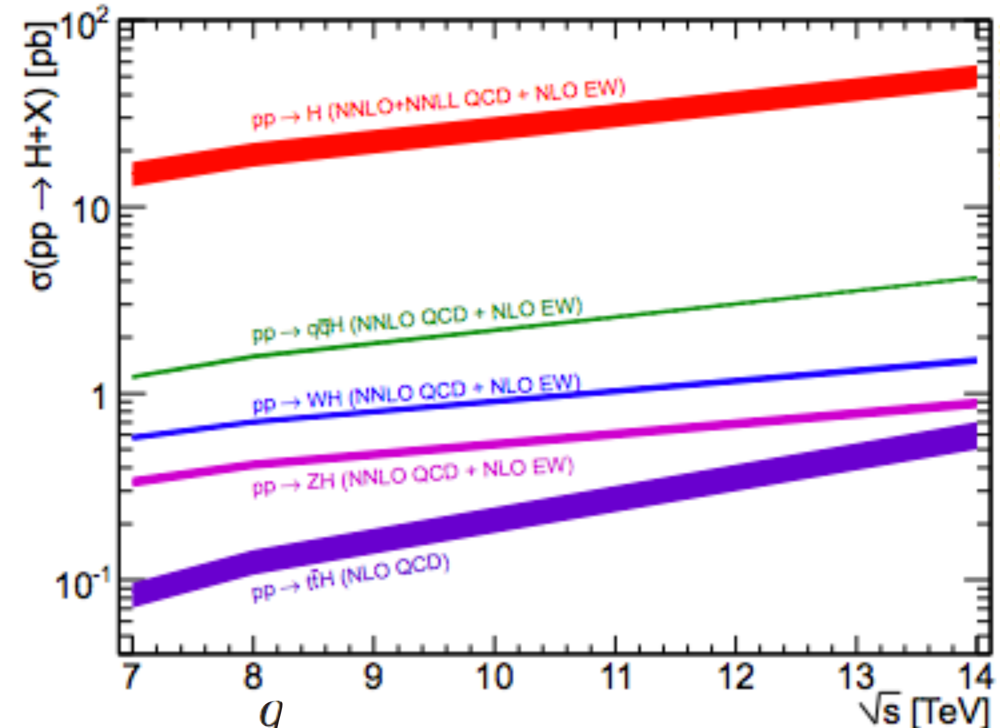
Higgs+Jet

Resummation

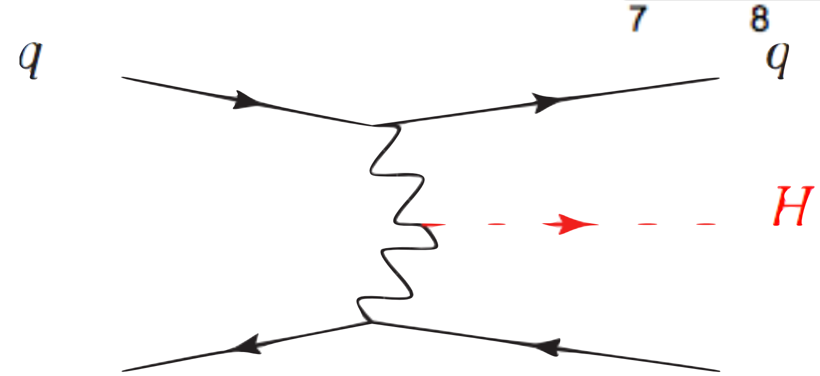
Jet-Veto



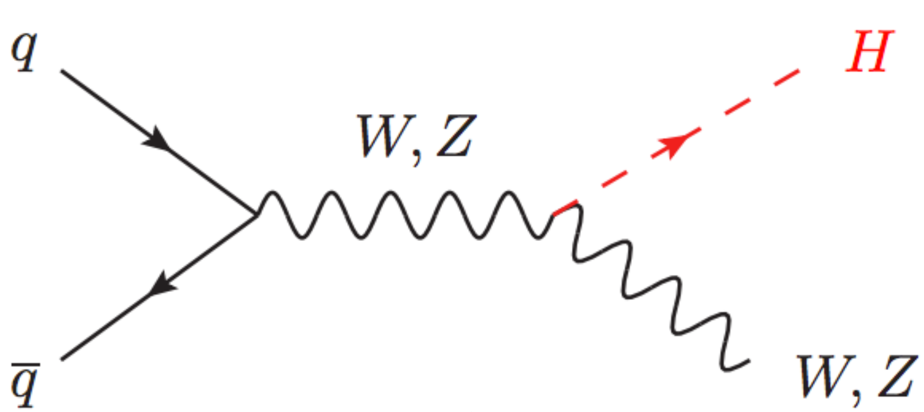
87%



LHC@14TEV



7%



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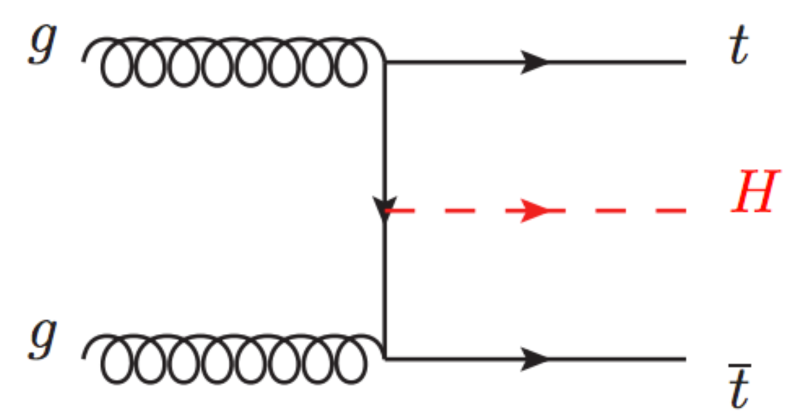

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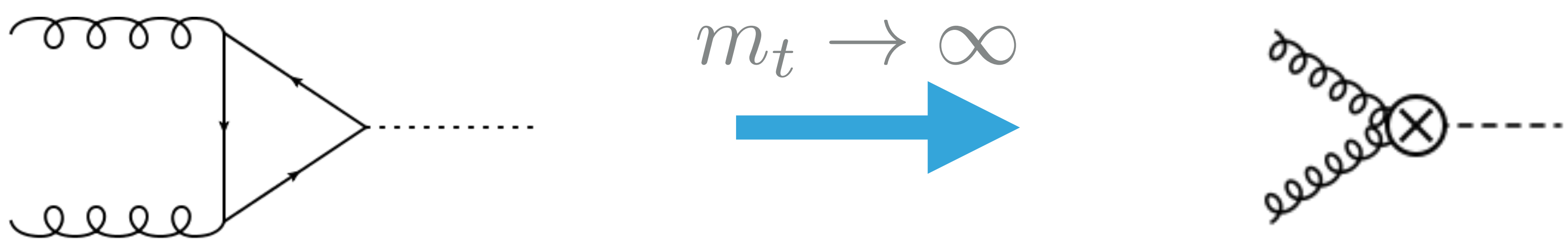
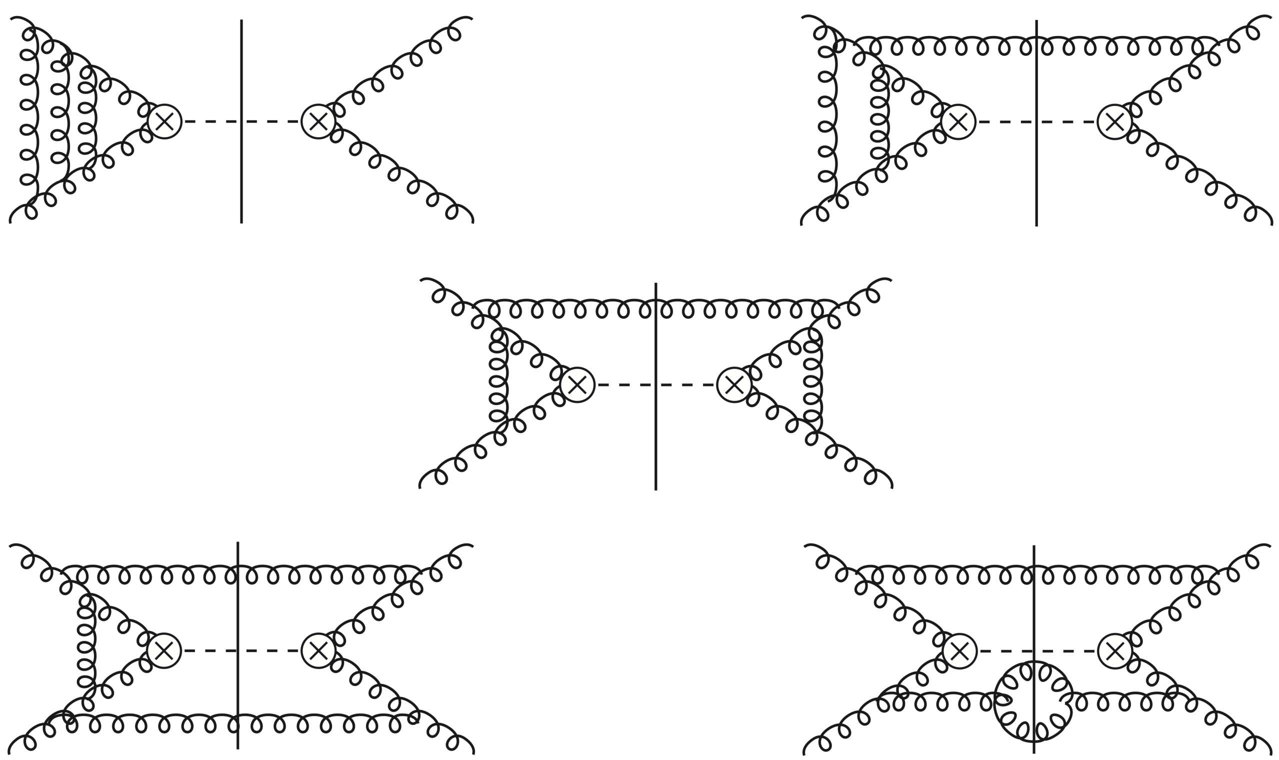


$$\hat{\sigma} = \alpha_s^2 \sigma^{\mathrm{LO}} + \alpha_s^3 \sigma^{\mathrm{NLO}} + \alpha_s^4 \sigma^{\mathrm{NNLO}} + \alpha_s^5 \sigma^{\mathrm{N3LO}}$$

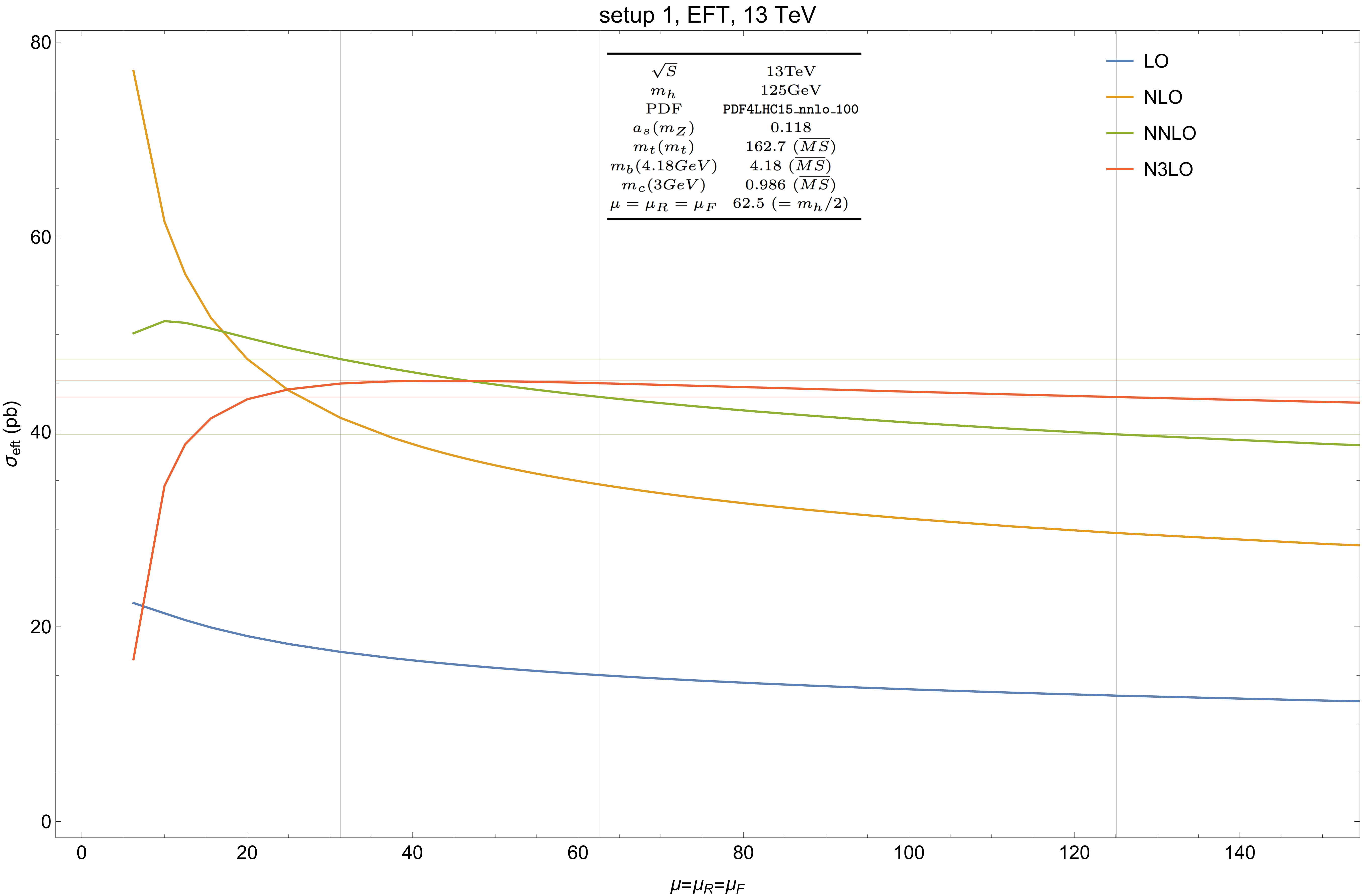


$$K_{\mathrm{LO}} = \frac{\sigma^{\mathrm{LO}}_{\mathrm{exact}}}{\sigma^{\mathrm{LO}}_{\mathrm{EFT}}}$$

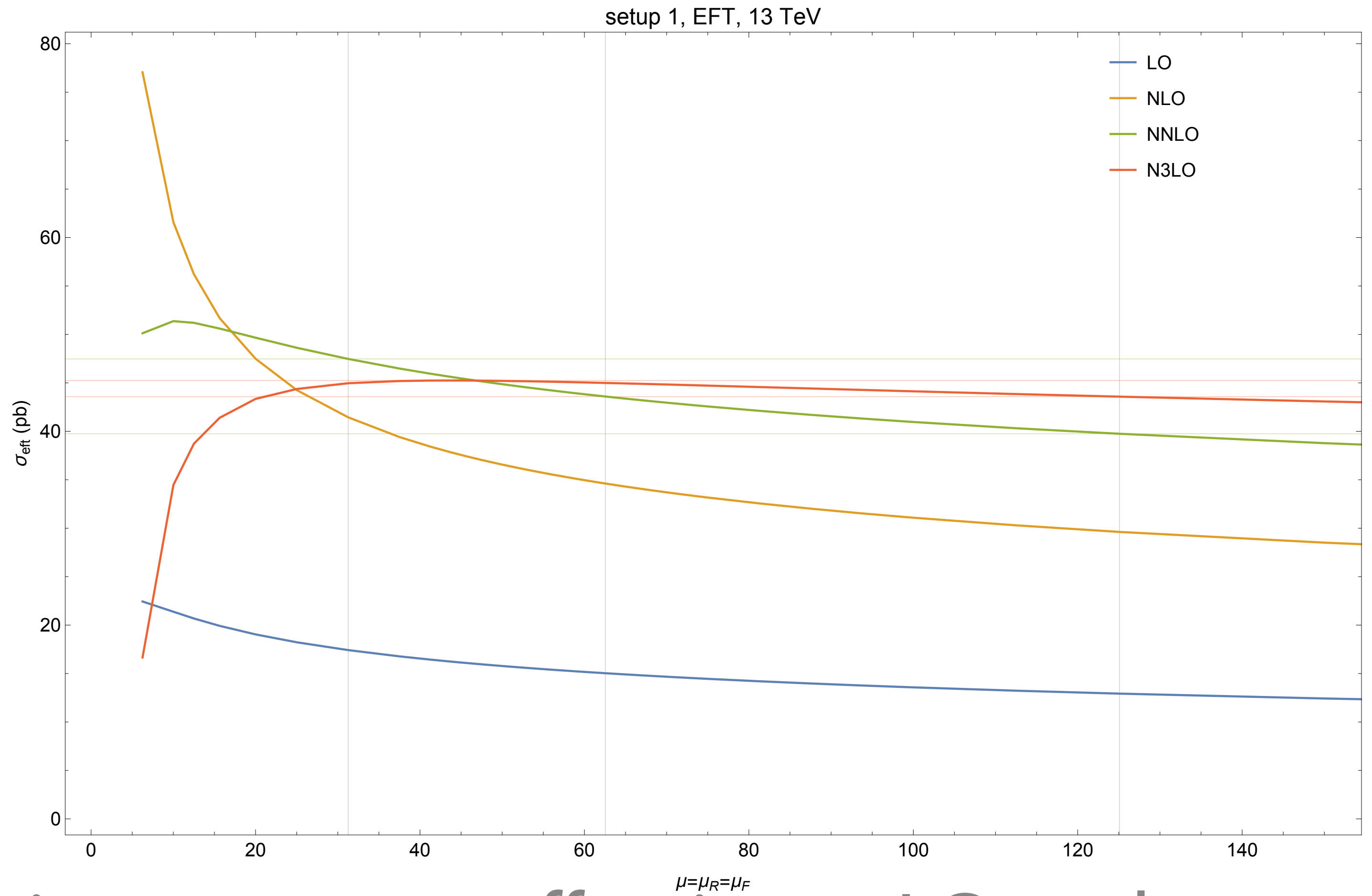
BETTER THAN 0.6%

FIRST N3LO CALCULATION FOR HADRON COLLIDERS

SCALE VARIATION UNCERTAINTY


setup 1, EFT, 13 TeV
$\sqrt{S}$ 13TeV
m_h 125GeV
PDF PDF4LHC15_nnlo_100
$a_s(m_Z)$ 0.118
$m_t(m_t)$ 162.7 ($\overline{MS}$)
$m_b(4.18GeV)$ 4.18 ($\overline{MS}$)
$m_c(3GeV)$ 0.986 ($\overline{MS}$)
$\mu = \mu_R = \mu_F$ 62.5 ($= m_h/2$)
LO
NLO
NNLO
N3LO
σ_{eft} (pb)
μ=μ_R=μ_F
0
20
40
60
80
100
120
140

Estimate missing higher orders (MHO) from scale variation



Vary scale in interval $\left[\frac{m_H}{4}, m_H\right]$

Estimating MHO from scale variations not very effective at LO and NLO because of larger corrections

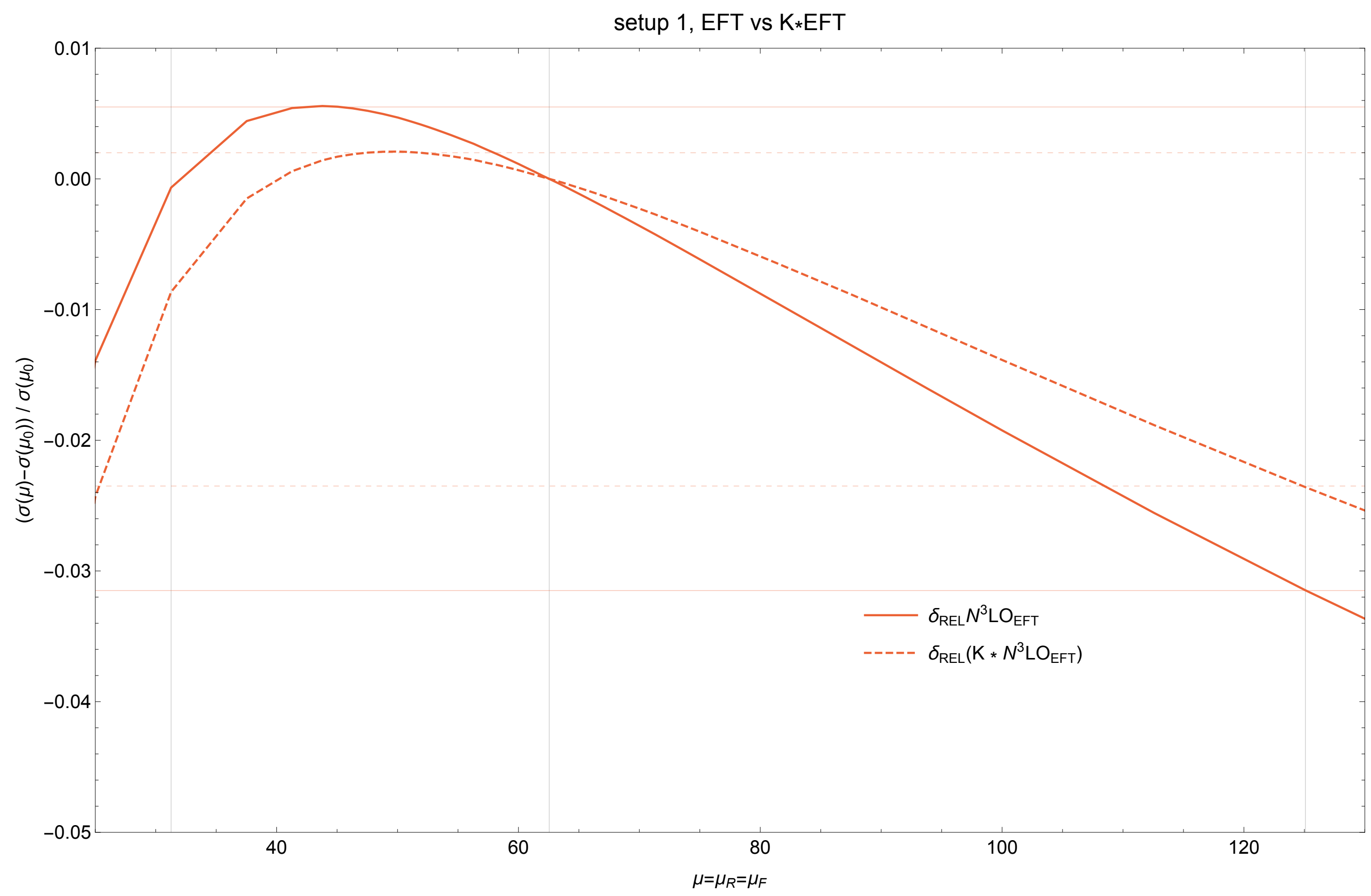
Perturbative series seems to stabilize from NNLO on

$$\pm\frac{\sigma_{\rm max}-\sigma_{\rm min}}{\sigma_{\rm max}+\sigma_{\rm min}} \rightarrow$$

LO	$\pm 14.8\%$
NLO	$\pm 16.6\%$
NNLO	$\pm 8.8\%$
N^3LO	$\pm 1.6\%$

Scale dependence is improved by inclusion of the rescaled LO

Running of the top mass in MSbar compensates partially the running of the cross section



Scale uncertainty from variation with all channels in $\left[\frac{m_H}{4}, m_H\right]$

$$\delta_{\text{scale}} = {}^{+0.13}_{-1.24}\,\text{pb} = {}^{+0.30}_{-2.79}\,\%$$

IS SCALE VARIATION A GOOD ESTIMATOR

Wilson coefficient receives QCD corrections

$\mathcal{O}\left(\alpha_s^n\right)$

$$\hat{\sigma} = \left|C(\alpha_s)\right|^2 \times \eta(\alpha_s)$$

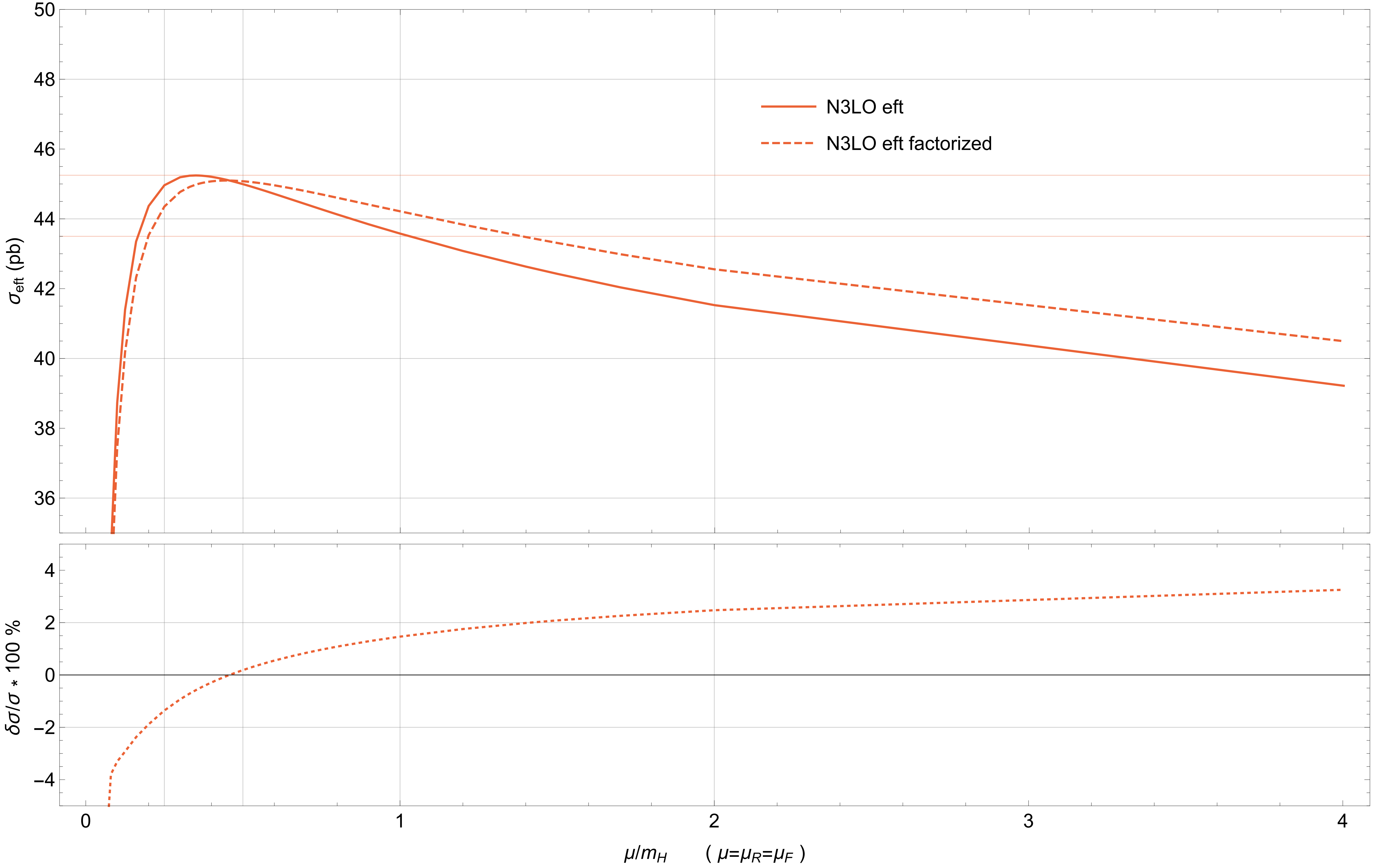
PERTURBATIVE SERIES

Conventional approach: Expand the product to $\mathcal{O}\left(\alpha_s^n\right)$

Alternative approach: Keep terms of up to $\mathcal{O}\left(\alpha_s^{2n}\right)$ in the product

Captures some pieces of higher order cross sections

FACTORIZATION OF THE WILSON COEFFICIENT



Cross section factorizes in the soft limit in Mellin space $z \to 1$

$$\sigma_{res} = \alpha_s^2(\mu_r) e^{\mathcal{G}(\alpha_s, \mu_r, \mu_f)} C_{gg}(\alpha_s(\mu_r), \mu_r, \mu_s)$$

EXPONENTIATE DIVERGENT TERMS

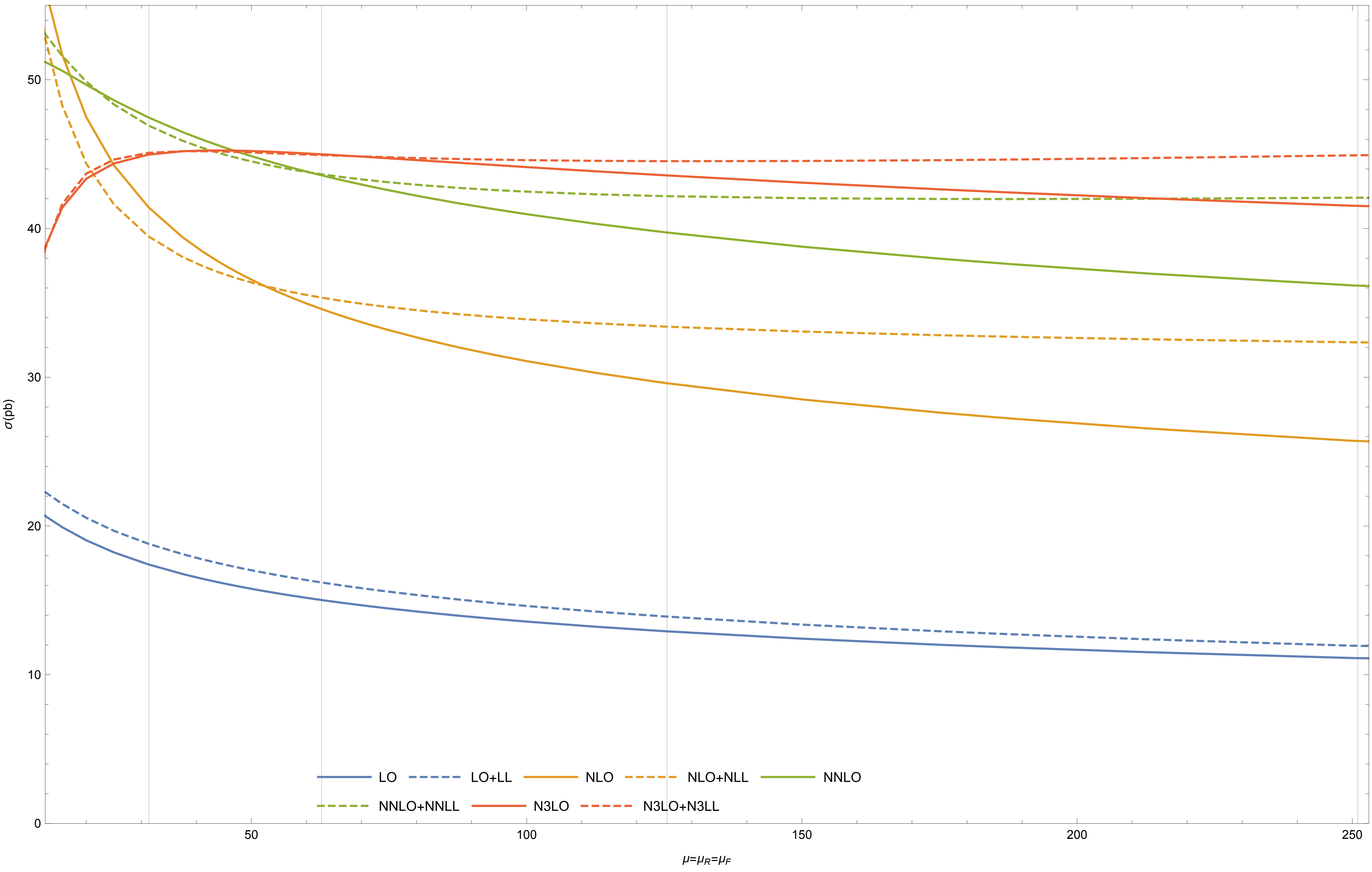
FINITE PIECES

Exponentiate universal emission of soft gluons

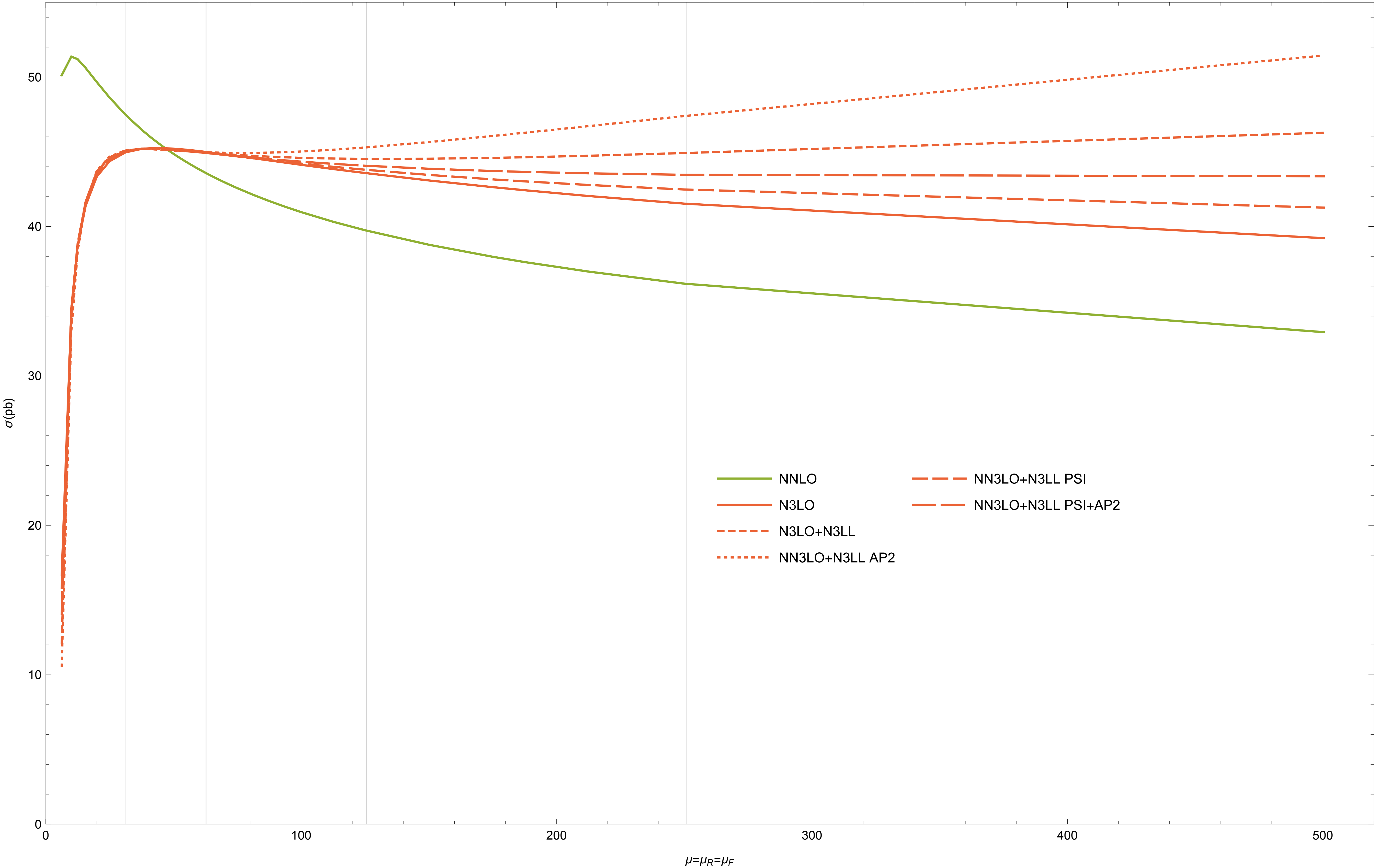
MELLIN SPACE

Captures the n most leading threshold logarithms

Different resummation prescriptions differ by subleading terms



50
40
30
20
10
0
σ(pb)
50
100
150
200
250
μ=μ_R=μ_F
LO
LO+LL
NLO
NLO+NLL
NNLO
NNLO+NNLL
N3LO
N3LO+N3LL

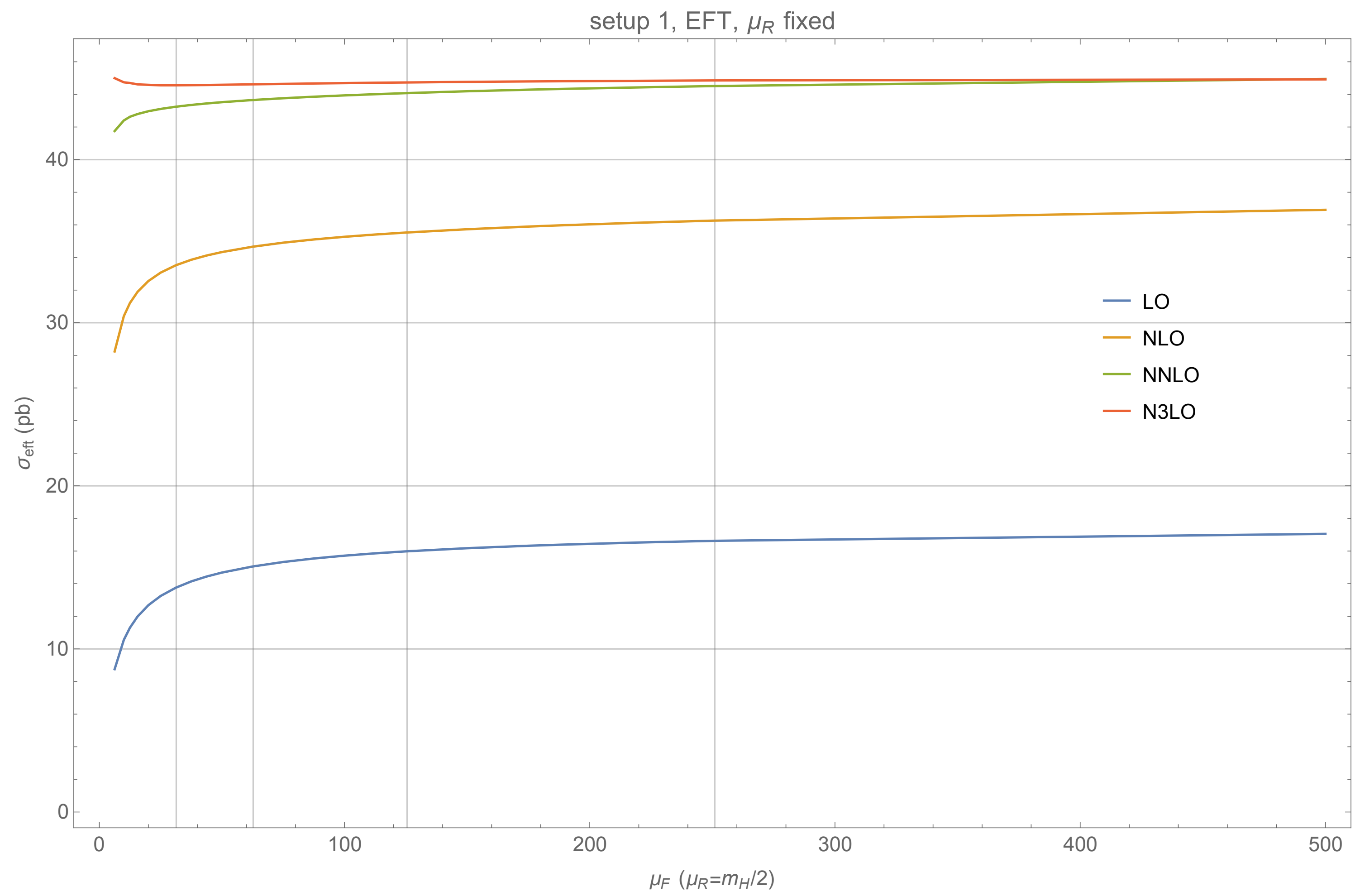

50
40
30
20
10
0
σ(pb)
0
100
200
300
400
500
μ=μR=μF
NNLO
N3LO
N3LO+N3LL
NN3LO+N3LL AP2
NN3LO+N3LL PSI
NN3LO+N3LL PSI+AP2

MISSING N3LO PDFS

We use NNLO PDFs

Contain data extracted using (almost) NNLO calculations

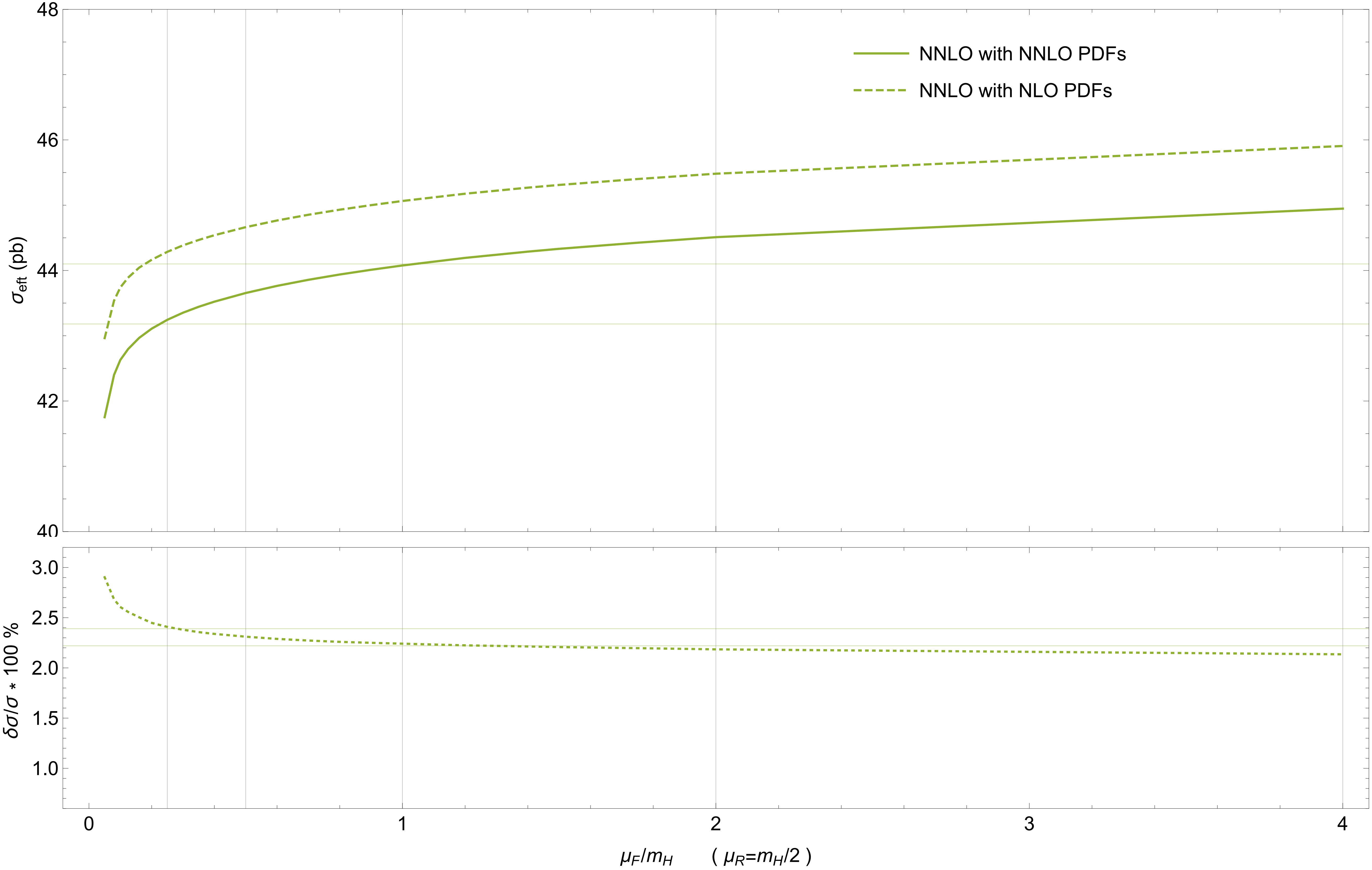
We should be using be using N3LO PDFs



Missing N3LO corrections in the extraction processes

This uncertainty is not accounted for by the PDF uncertainties

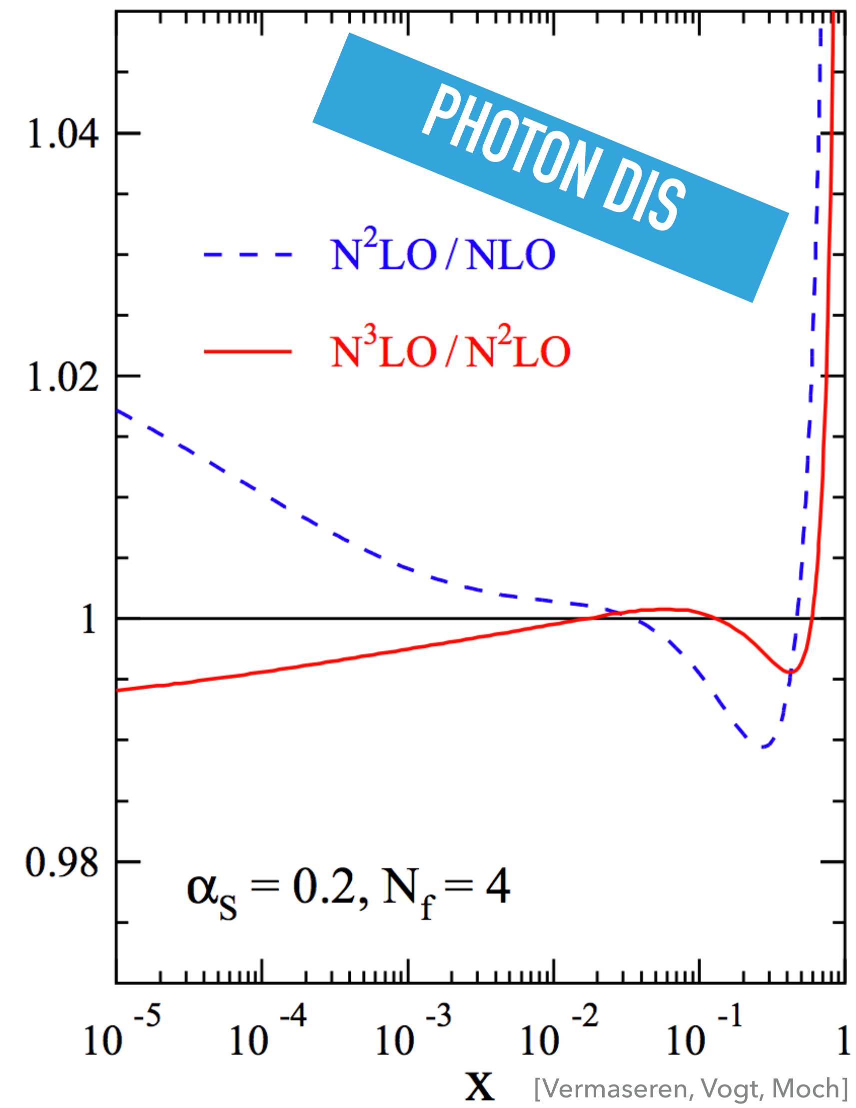
Estimate the effect of higher orders in the extraction processes


NNLO with NNLO PDFs
NNLO with NLO PDFs
σ_{eft} (pb)
$\delta\sigma/\sigma * 100$ %
μ_F/m_H (μ_R=m_H/2)
48
46
44
42
40
3.0
2.5
2.0
1.5
1.0
0
1
2
3
4

Estimation based on the change from NLO PDFs to NNLO PDFs at NNLO

Conservative estimator, N3LO corrections likely smaller

DIS coefficients are smaller at N3LO



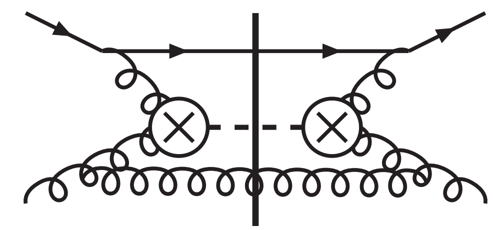
[Vermaseren, Vogt, Moch]

$$\delta_{\mathrm{pdfTh}} = \pm\frac{1}{2} \times \frac{\sigma^{\mathrm{NNLO}}_{\mathrm{NNLO\ PDF}} - \sigma^{\mathrm{NNLO}}_{\mathrm{NLO\ PDF}}}{\sigma^{\mathrm{NNLO}}_{\mathrm{NLO\ PDF}}} \sigma^{\mathrm{N^3LO}}_{\mathrm{NNLO\ PDF}}$$

CONSISTENT WITH PDF FROM HIGGS @ N3LO ESTIMATE

$$\delta_{\mathrm{pdfTh}} = \pm 0.55\mathrm{pb} = \pm 1.15\%$$

FINITE QUARK MASS EFFECTS



No exact mass effects starting from NNLO

We rescale the effective theory with the exact LO k-factor at NNLO and N3LO

$$K_{\mathrm{LO}} = \frac{\sigma^{\mathrm{LO}}_{\mathrm{exact}}}{\sigma^{\mathrm{LO}}_{\mathrm{EFT}}} \approx 1.062$$

$$\sigma^{\mathrm{N^3LO}}_{\mathrm{rEFT}} = K_{\mathrm{LO}} \times \sigma^{\mathrm{N^3LO}}_{\mathrm{EFT}}$$

At NNLO corrections beyond rescaled EFT as 1/mt expansion

[Harlander, Mantler, Marzani, Ozeren]

We add these corrections to the rescaled gg and qg channels

$$gg \;\sim 1.2\%$$

$$qg \;\sim -0.5\%$$

Expansion at NNLO is an expansion in $$\frac{\hat{s}}{4m_t^2} = \frac{m_h^2}{4m_t^2}\frac{1}{z}$$

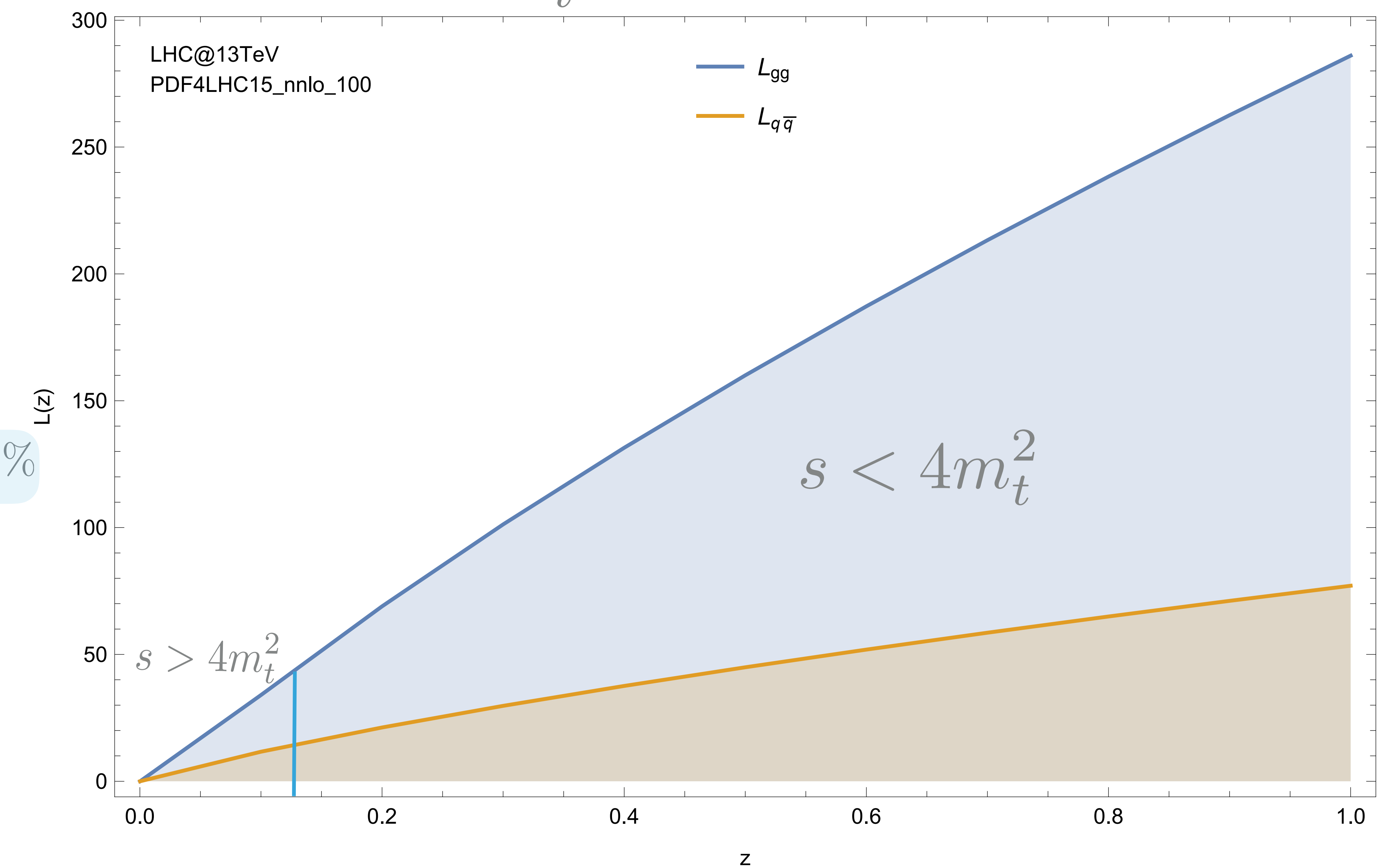
Potentially problematic because z is integrated over

Expansion of order 1 for $$z < \frac{m_h^2}{4m_t^2} \approx 0.13$$

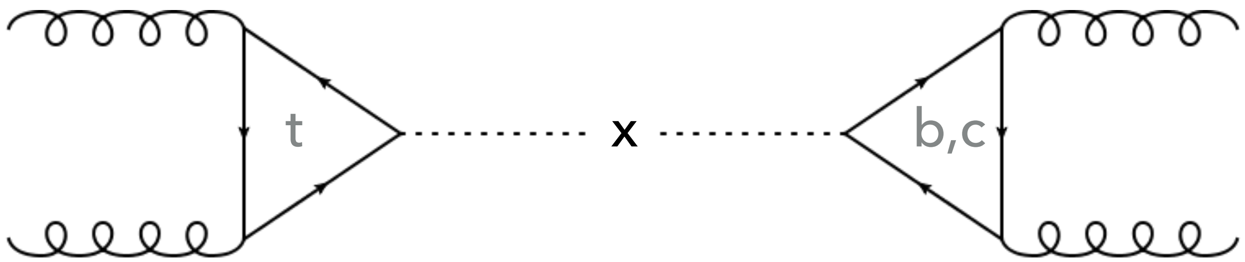
Only luminosity suppressed

$$\delta_{1/mt} = \pm 0.54\text{pb} = \pm 1\%$$

[Harlander, Mantler, Marzani, Ozeren]



Contributions from light quarks at LO and NLO



$$\mathrm{LO}: -7.3\% \ \mathrm{NLO}: -5.6\%$$

t-b interference not known at NNLO

We estimate the uncertainty as

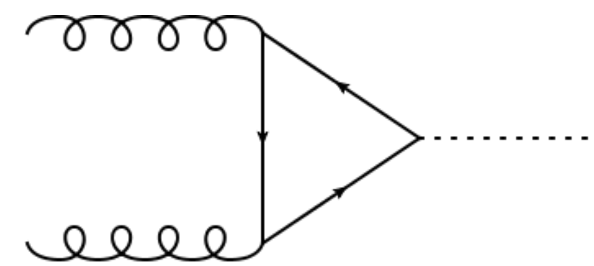
$$\delta_{tb} = \Delta_{\mathrm{rEFT}}^{\mathrm{NNLO}} \frac{\Delta_{t+b}^{\mathrm{NLO}} - \Delta_{t}^{\mathrm{NLO}}}{\Delta_{t}^{\mathrm{NLO}}}$$

$$\boxed{\delta_{\mathrm{tb}} = \pm 0.38\mathrm{pb} = \pm 0.7\%}$$

ELECTROWEAK CORRECTIONS

Electroweak corrections to LO process are known

$\mathcal{O}(\alpha\alpha_s^2)$



5.2% corrections to the LO cross section

[Actis, Passarino, Sturm, Uccirati]

Exact EW corrections to the NLO QCD correction are unknown

Mixed corrections due to light quarks are computed in an EFT

$\mathcal{O}(\alpha\alpha_s^3)$

Light quarks account for 80% of the LO EW correction

Leads to 5.1% correction at NLO and 5% correction at NNLO

[Anastasiou, Boughezal, Petriello]

$$C_{\mathrm{QCD}} \to C_{\mathrm{QCD}} + \lambda_{\mathrm{EW}} \left(1 + C_{1w}\alpha_s + C_{2w}\alpha_s + \ldots\right)$$

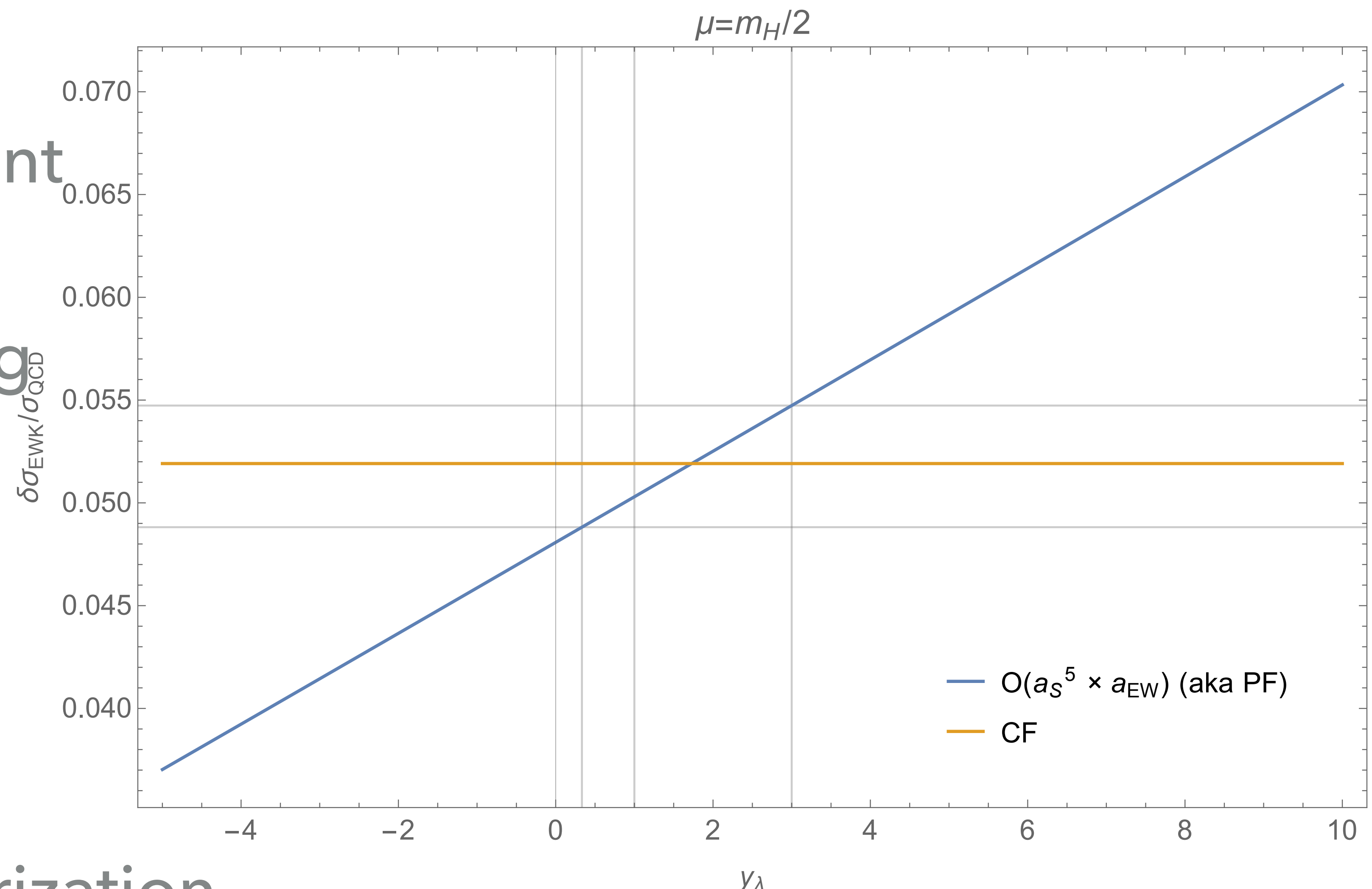
Almost complete factorization

EXACT

LIGHT QUARKS

UNKNOWN

Estimate uncertainty by varying the wilson coefficient



1% uncertainty from varying by a factor in [-3,+6]

Alternative argumentation

Calculation based on factorization

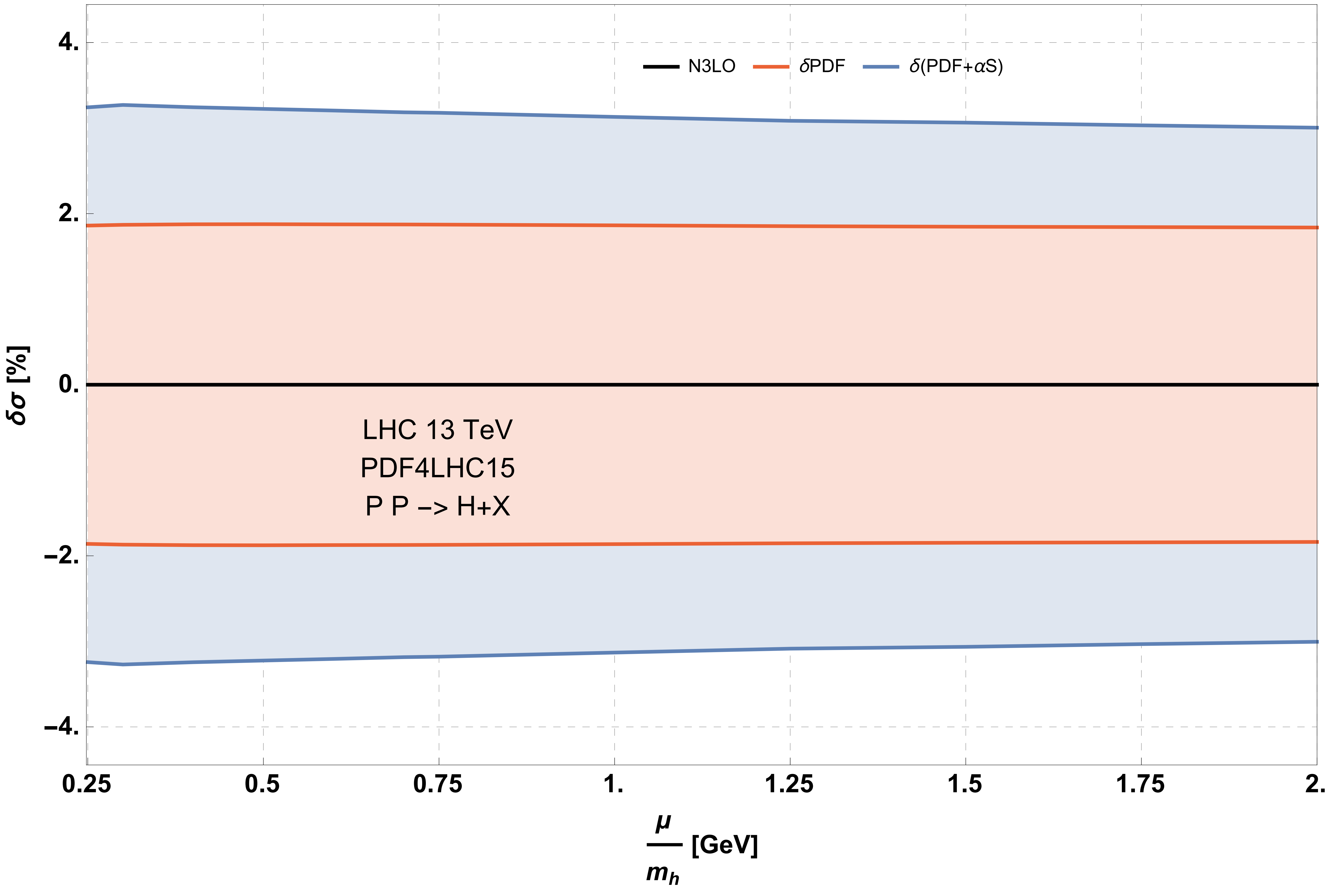
Hard part of the NLO QCD cross section is ~40%

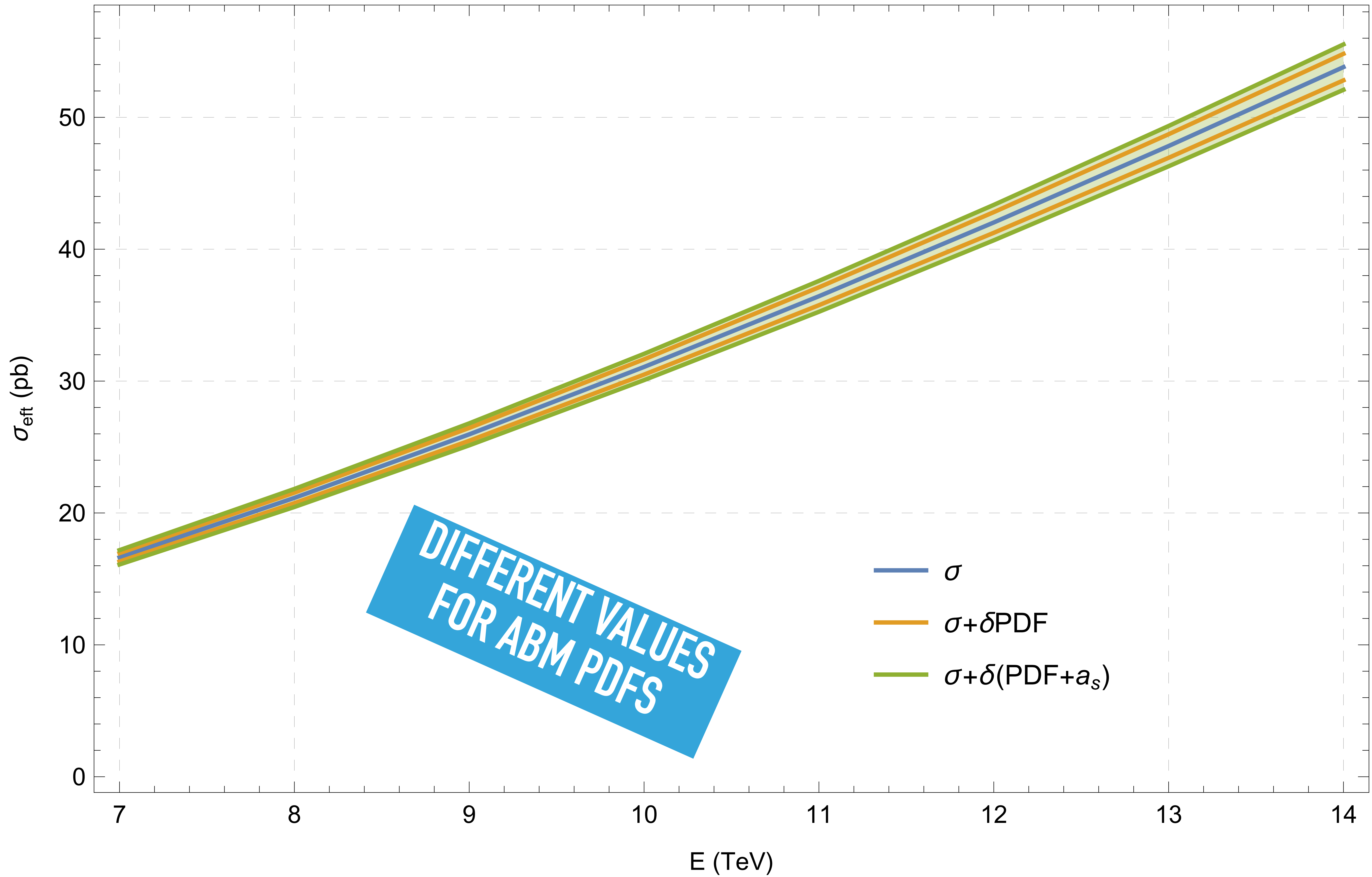
Calculation misses the hard part of the corrections

BETTER CALCULATIONS NEEDED

$$\delta_{\mathrm{EW}} = \pm 0.48\mathrm{pb} = \pm 1$$

PDF+ALPHA_S UNCERTAINTY


N3LO
δPDF
δ(PDF+αS)
LHC 13 TeV
PDF4LHC15
P P –> H+X
4.
2.
0.
–2.
–4.
δσ [%]
0.25
0.5
0.75
1.
1.25
1.5
1.75
2.
μ/m_h [GeV]


σ_{eft} (pb)
0
10
20
30
40
50
7
8
9
10
11
12
13
14
E (TeV)
σ
$\sigma+\delta$PDF
$\sigma+\delta$(PDF+a_s)
DIFFERENT VALUES FOR ABM PDFS

CONCLUSION

13 TEV

σ/pb	$\delta_{\mathrm{PDF}}/\mathrm{pb}$	$\delta_{\alpha_s}/\mathrm{pb}$	$\delta_{\mathrm{scale}}/\mathrm{pb}$	$\delta_{\mathrm{trunc}}/\mathrm{pb}$	$\delta_{\mathrm{pdfTH}}/\mathrm{pb}$	$\delta_{\mathrm{EW}}/\mathrm{pb}$	δ_{tb}/pb	$\delta_{1/m_t}/\mathrm{pb}$
48.48	± 0.90	± 1.26	${}^{+0.09}_{-1.11}$	± 0.12	± 0.56	± 0.48	± 0.34	± 0.48
48.48	$\pm 1.86\%$	$\pm 2.60\%$	${}^{+0.2}_{-2.3}\%$	$\pm 0.25\%$	$\pm 1.15\%$	$\pm 1.00\%$	$\pm 0.70\%$	$\pm 1.00\%$

ADD IN QUADRATURE

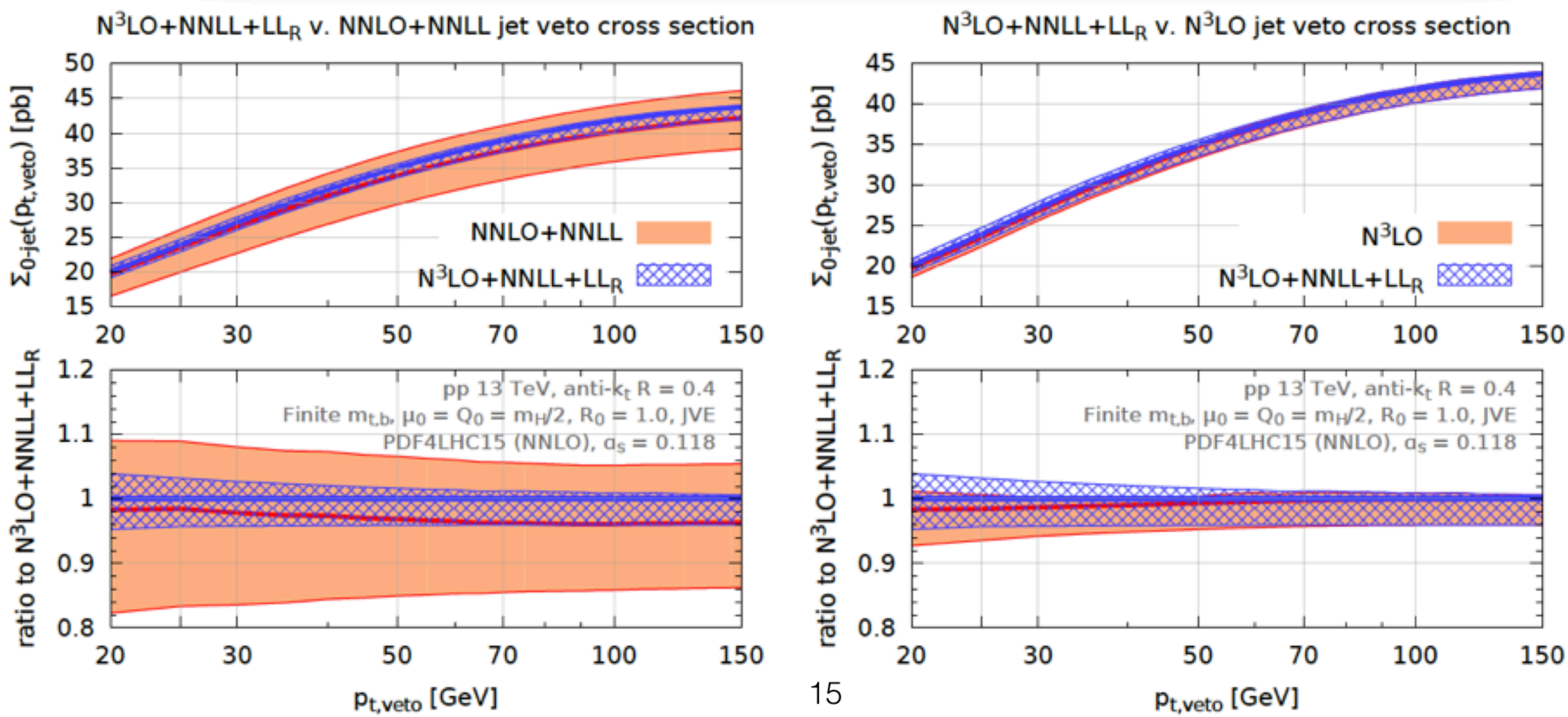
ADD LINEARLY

$$\sigma = \left(48.48 \pm 1.55\ {}^{+2.08}_{-3.10}\right)\ \mathrm{pb}$$

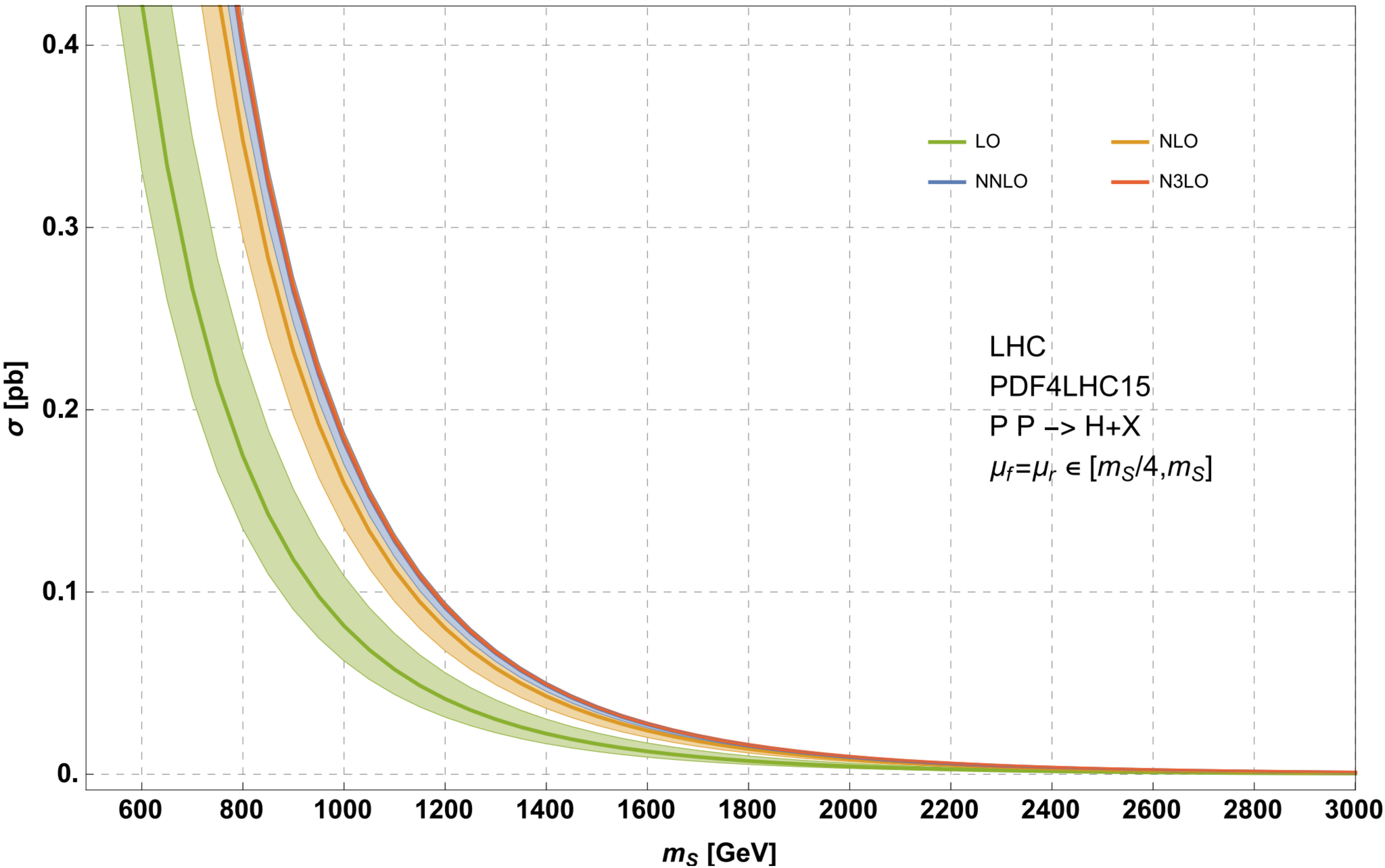
$$\sigma = 48.48\mathrm{pb} \pm 3.19\ {}^{+4.29\%}_{-6.40\%}$$

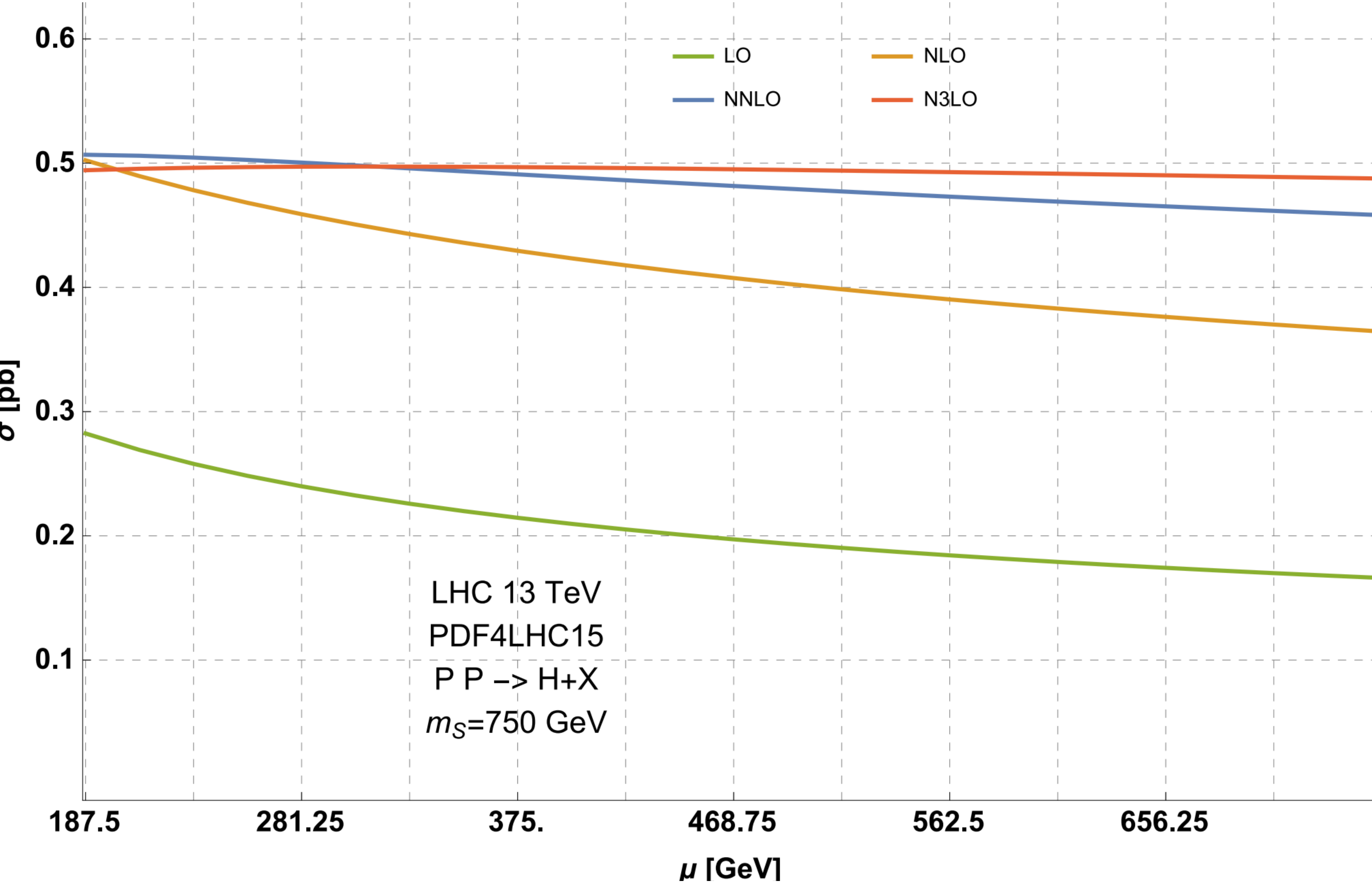
$$\sigma = 48.48\,{}^{+2.60}_{-3.47}\mathrm{pb} = 48.48\mathrm{pb}\,{}^{+5.36\%}_{-7.15\%}$$

Combination of the N3LO inclusive cross section with the NNLO Higgs+Jet cross section



[Banfi, Caola, Dreyer, Monni, Salam, Zanderighi, FD]


0.4
0.3
0.2
0.1
0.
σ [pb]
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
m_S [GeV]
LO
NLO
NNLO
N3LO
LHC
PDF4LHC15
P P –> H+X
$\mu_f=\mu_r \in [m_S/4, m_S]$


0.6
0.5
0.4
0.3
0.2
0.1
σ [pb]
LO
NLO
NNLO
N3LO
LHC 13 TeV
PDF4LHC15
P P –> H+X
m_S=750 GeV
187.5
281.25
375.
468.75
562.5
656.25
μ [GeV]

σ/pb	$\delta_{\mathrm{PDF}}/\mathrm{pb}$	$\delta_{\alpha_s}/\mathrm{pb}$	$\delta_{\mathrm{scale}}/\mathrm{pb}$	$\delta_{\mathrm{trunc}}/\mathrm{pb}$	$\delta_{\mathrm{pdfTH}}/\mathrm{pb}$	$\delta_{\mathrm{EW}}/\mathrm{pb}$	δ_{tb}/pb	$\delta_{1/m_t}/\mathrm{pb}$
48.48	± 0.90	± 1.26	$^{+0.09}_{-1.11}$	± 0.12	± 0.56	± 0.48	± 0.34	± 0.48
48.48	$\pm 1.86\%$	$\pm 2.60\%$	$^{+0.2}_{-2.3}\%$	$\pm 0.25\%$	$\pm 1.15\%$	$\pm 1.00\%$	$\pm 0.70\%$	$\pm 1.00\%$

Great success in reducing the QCD uncertainty, now it is time to work on other sources of uncertainty

Full massive calculation at NNLO will drastically reduce the uncertainty

PDFs at N3LO will also reduce the uncertainty considerably

Best theoretical prediction for a hadron collider observable

Let's use it to find out if the Higgs has some surprises in store for us