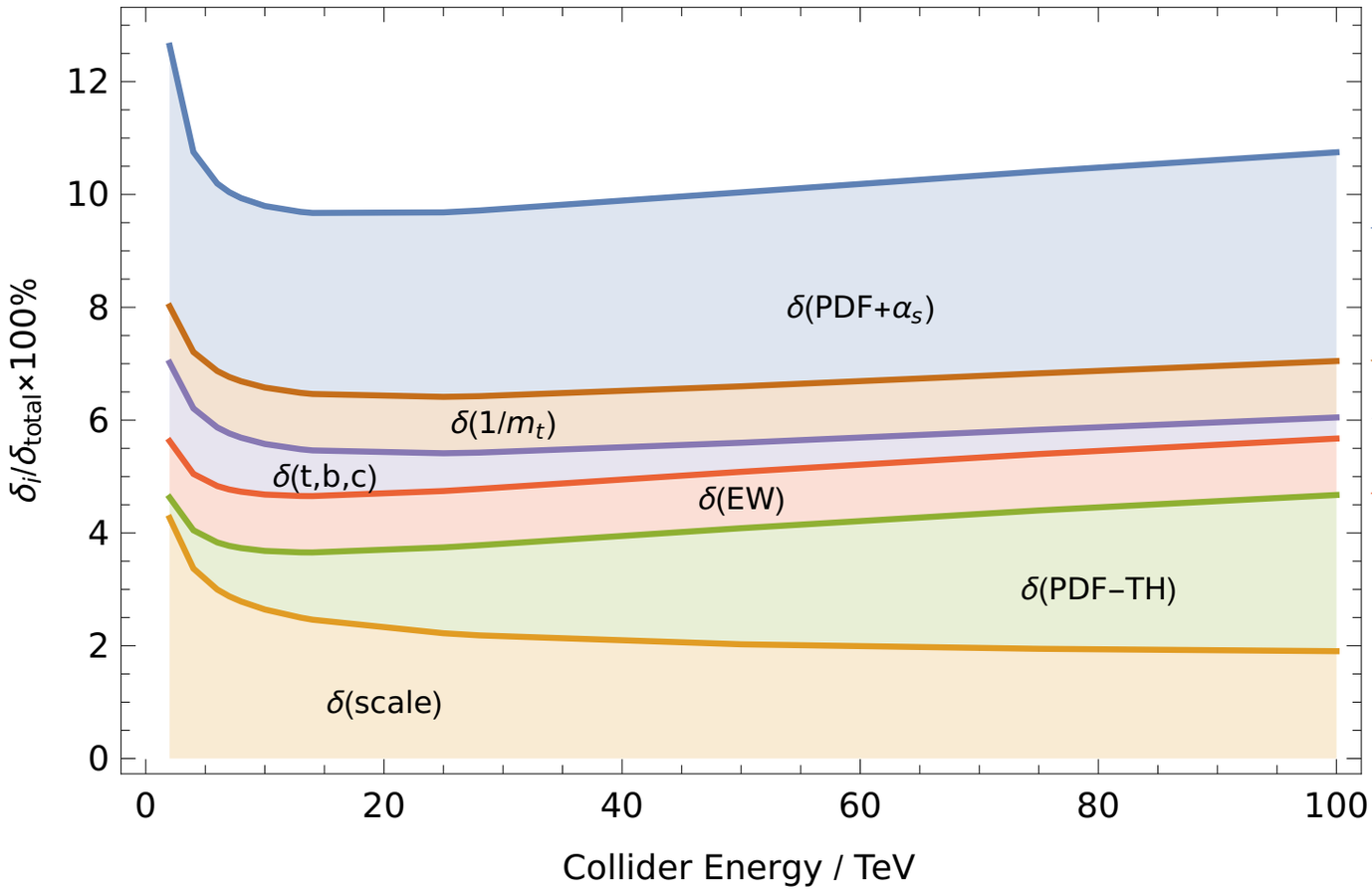
Working Group 1: ggF Cross Section Update

Conveners:
(EXP) Jonathon Langford, Haider Abidi, Robin Hayes
(TH) Stephen Jones, Alexander Huss

Overview

Goal: accurately reflect changes in TH uncertainty since YR4



iHixs2: Dulat, Lazopoulos, Mistlberger 18

PDF4LHC WG 22

Czakon, Harlander, Klappert, Niggetiedt 21

$\mathcal{O}$(half year) (?)

Reduced to 0.6% (gg light-quark)
Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20

Study aN^{3}LO PDFs
McGowan, Cridge, Harland-Lang, Thorne 22

$\text{N}^3\text{LO}_{\text{HTL}}$ - use iHixs2 Dulat, Lazopoulos, Mistlberger 18 (done)

$\delta(1/m_t)$ - NNLO QCD w/ m_T use Czakon et al. 21 (requested & confirmed; awaiting input)

$\delta(t,b,c)$ - Not yet in literature ($m_q \sim 0$, m_b & m_t) (not likely for current update)

$\delta(\text{EW})$ - gg-channel light-quark contributions use Becchetti et al 20. (requested; awaiting input)

$\delta(\text{PDF}-\text{TH})$ - estimate with individual sets, separate comparison to aN^3LO

Timeline

Sep 22 Identify results of interest to WG

Nov 22 Authors summarise work at general assembly

+ Assess $\delta(t, b, c)$ and $\delta(\mathrm{EW})$ outlook
+ Community feedback

Dec 22 Initial exploratory runs of iHixs ($\mathrm{N^3LO_{HTL}}$)

Dec 22 Initial meeting with $\mathrm{aN^3LO}$ authors (Cridge)

Mar 23 Request Czakon et al. 21 results for updating $\delta(1/m_t)$

Request Becchetti et al 20. results for updating $\delta(\mathrm{EW})$

Apr 23 Begin full runs of iHixs ($\mathrm{N^3LO_{HTL}}$)

Ask $\mathrm{aN^3LO}$ and other PDF authors for input/study of $\delta(\mathrm{PDF-TH})$

~~**Jun 23**~~ awaiting input

WG1: ggF meeting

+ Presentation of results from each group
+ Initial combination
+ Community feedback

Aug 11 Update twiki & fully document all input/choices

Sep 23 WG note with studies (e.g. PDFs, EW TH uncert, …)

iHixs2 — Run 3 Update

$$\delta\sigma_{PP\to H+X} = \delta(\mathrm{PDF}{+}\alpha_S) + \delta(\mathrm{theory})$$

$$\delta(\mathrm{theory}) = \delta(\mathrm{scale}) + \delta(\mathrm{PDF\text{-}TH}) + \delta(\mathrm{EWK}) + \delta(\mathrm{t,b,c}) + \delta(1/m_t)$$

updated predictions: (similar tables for $\sqrt{s}$ = 7, 8, 13, 14 TeV)

$\sqrt{s}$ [TeV]	M_{H} [GeV]	σ [pb]	δ(theory)	δ(scale)	δ(EWK)	δ(t, b, c)	$\delta(1/m_{\mathrm{t}})$	$\delta(\mathrm{PDF}+\alpha_s)$	δ(PDF)	$\delta(\alpha_s)$	$\delta(\mathrm{PDF}-\mathrm{TH})$
13.6	120.00	56.03	$^{+3.16}_{-5.42}\%$	$^{+0.31}_{-2.57}\%$	$\pm1.00\%$	$\pm0.85\%$	$\pm1.00\%$	$^{+2.67}_{-2.27}\%$	$^{+1.65}_{+1.65}\%$	$^{+2.11}_{-1.56}\%$	$\pm1.21\%$
13.6	122.00	54.40	$^{+3.14}_{-5.37}\%$	$^{+0.30}_{-2.53}\%$	$\pm1.00\%$	$\pm0.84\%$	$\pm1.00\%$	$^{+2.67}_{-2.26}\%$	$^{+1.65}_{+1.65}\%$	$^{+2.10}_{-1.55}\%$	$\pm1.20\%$
13.6	124.00	52.87	$^{+3.12}_{-5.33}\%$	$^{+0.29}_{-2.50}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.67}_{-2.26}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.55}\%$	$\pm1.18\%$
13.6	124.60	52.43	$^{+3.11}_{-5.32}\%$	$^{+0.28}_{-2.49}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.67}_{-2.26}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	124.80	52.28	$^{+3.11}_{-5.32}\%$	$^{+0.28}_{-2.49}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.67}_{-2.26}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	125.00	52.13	$^{+3.11}_{-5.31}\%$	$^{+0.28}_{-2.48}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.67}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	125.09	52.07	$^{+3.11}_{-5.31}\%$	$^{+0.28}_{-2.48}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.67}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	125.20	51.99	$^{+3.11}_{-5.31}\%$	$^{+0.28}_{-2.48}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.67}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	125.30	51.92	$^{+3.10}_{-5.30}\%$	$^{+0.28}_{-2.48}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.66}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	125.38	51.86	$^{+3.10}_{-5.30}\%$	$^{+0.28}_{-2.48}\%$	$\pm1.00\%$	$\pm0.83\%$	$\pm1.00\%$	$^{+2.66}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.18\%$
13.6	125.60	51.70	$^{+3.10}_{-5.30}\%$	$^{+0.28}_{-2.47}\%$	$\pm1.00\%$	$\pm0.82\%$	$\pm1.00\%$	$^{+2.66}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.17\%$
13.6	126.00	51.41	$^{+3.10}_{-5.29}\%$	$^{+0.27}_{-2.47}\%$	$\pm1.00\%$	$\pm0.82\%$	$\pm1.00\%$	$^{+2.66}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.10}_{-1.54}\%$	$\pm1.17\%$
13.6	128.00	50.00	$^{+3.07}_{-5.24}\%$	$^{+0.26}_{-2.43}\%$	$\pm1.00\%$	$\pm0.81\%$	$\pm1.00\%$	$^{+2.66}_{-2.25}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.09}_{-1.54}\%$	$\pm1.16\%$
13.6	130.00	48.65	$^{+3.05}_{-5.19}\%$	$^{+0.25}_{-2.39}\%$	$\pm1.00\%$	$\pm0.80\%$	$\pm1.00\%$	$^{+2.66}_{-2.24}\%$	$^{+1.64}_{+1.64}\%$	$^{+2.09}_{-1.53}\%$	$\pm1.15\%$

c.f. previous extrapolated numbers: (differences: PDF4LHC 15 → 21)

2	ggF (N3LO QCD + NLO EW)							
3	MH	XS	Uncertainty					
4		Interpolation	Theory			PDF+αs	PDF	αs
5	[GeV]	[pb]	pos [%]	neg [%]	Gauss [%]	[%]	[%]	[%]
6	120.00	5.611E+01	+4.7	−6.9	±4.0	±3.2	±1.9	±2.6
24	125.00	5.223E+01	+4.6	−6.7	±3.9	±3.2	±1.9	±2.6
25	125.09	5.217E+01	+4.6	−6.7	±3.9	±3.2	±1.9	±2.6
26	125.10	5.216E+01	+4.6	−6.7	±3.9	±3.2	±1.9	±2.6
43	130.00	4.875E+01	+4.5	−6.6	±3.8	±3.2	±1.8	±2.6

Estimate for PDF-TH & aN³LO PDFs

numbers for $\sqrt{s} = 13.6\,\text{TeV}$ & $M_\text{H} = 125.09\,\text{GeV}$

baseline: $$\delta(\text{PDF-TH}) = \pm\frac{1}{2}\left|\sigma^{(2),\,\text{EFT},\,\text{NNLO}}_{PP\to H+X} - \sigma^{(2),\,\text{EFT},\,\text{NLO}}_{PP\to H+X}\right|$$

- PDF4LHC21 — no NLO set available

  ⇒ switch to PDF4LHC15 *just* for δ(PDF-TH) estimate (robust w.r.t. PDF var.)

  ↪ PDF4LHC15 $\pm 1.18\,\%$

  ↪ MSHT20 $\pm 1.43\,\%$

  ↪ CT18 $\pm 1.03\,\%$

  ↪ NNPDF3.1 $\pm 0.92\,\%$

  ↪ NNPDF4 $\pm 0.18\,\%$

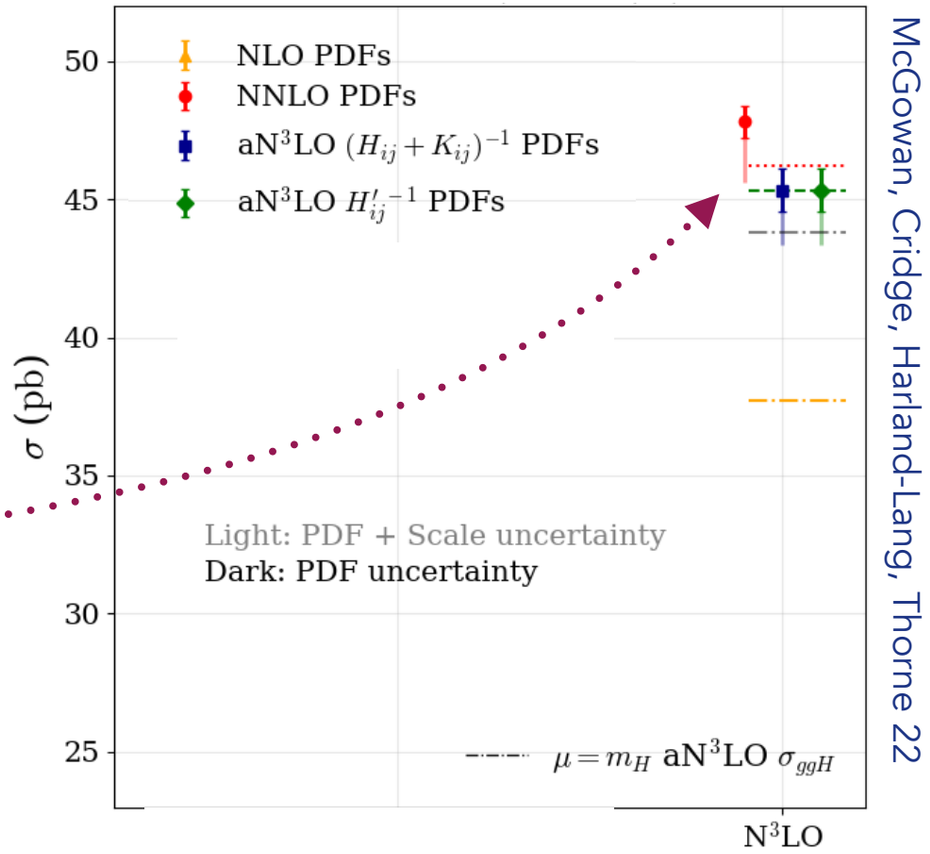
- c.f. actual shift from NNLO → aN³LO PDFs

  ↪ MSHT20 $-5\,\%$

  ↪ NNPDF4 $-0.15\,\%$ **(PRELIMINARY)**

  source of differences still under study.

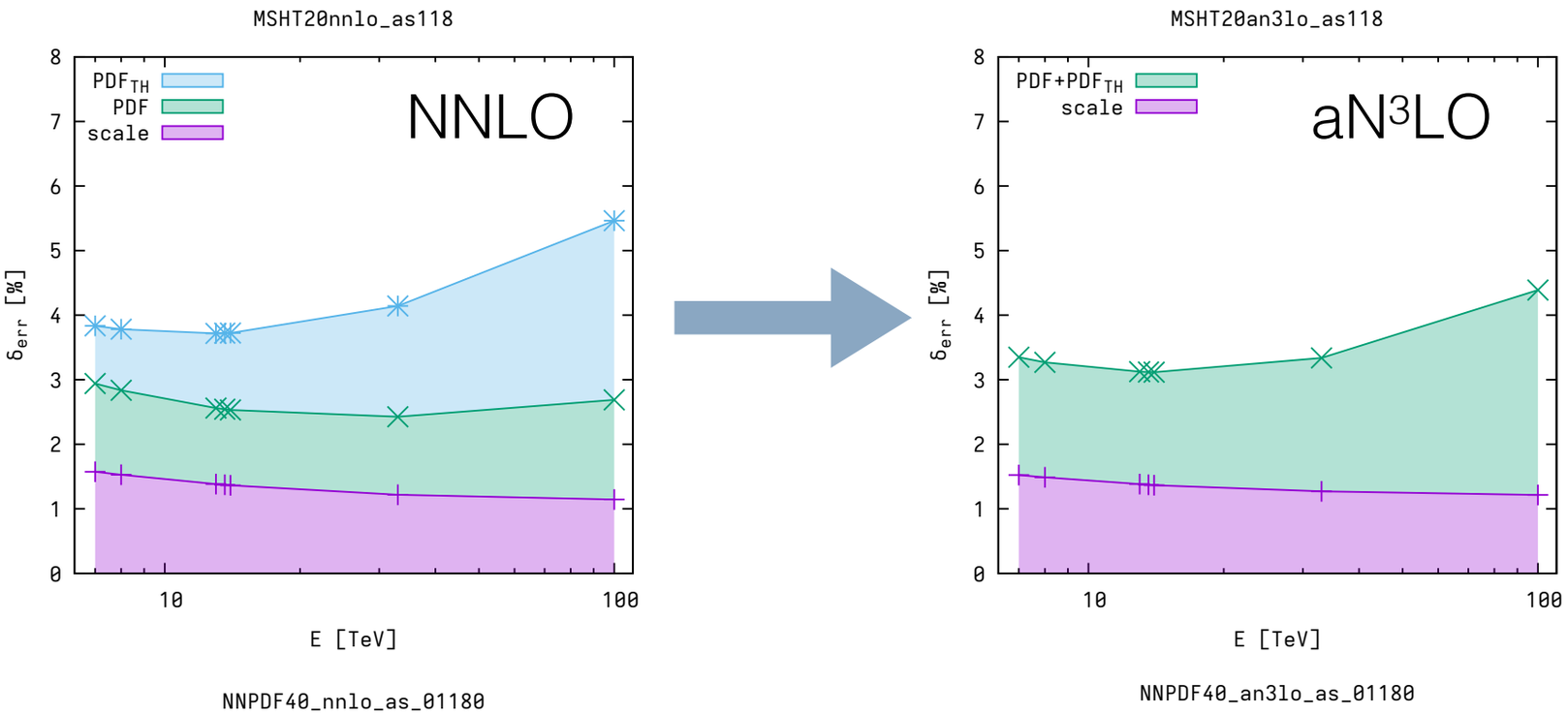
  * difference for $\sigma^{(3)}(\text{aN}^3\text{LO})$: 5 %



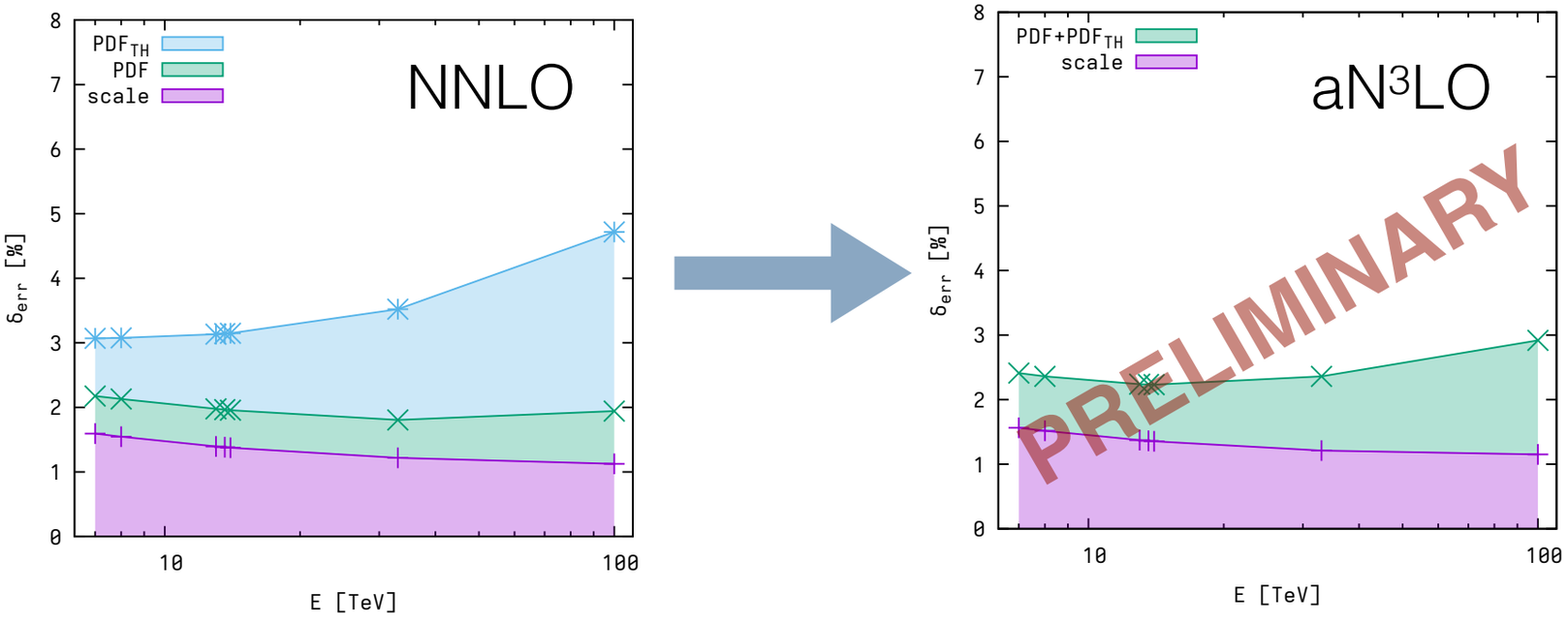
proposal: stick with baseline using PDF4LHC15, report numbers for aN³LO set(s).

Error Estimates from aN3LO sets

MSHT20



NNPDF4



overall error budget reduces with aN3LO PDFs ⇜⇝ "PDF-TH" removed & partially absorbed into PDF uncertainties
(incomplete splitting functions, missing N3LO XS, methodology…)

Inclusion of NNLO m_t

iHixs:

$$\hat{\sigma}_{ij} = \mathrm{R_{LO}} C^2 \left[\sigma_{ij}^{\mathrm{LO,\ EFT}} + \sigma_{ij}^{\mathrm{NLO,\ EFT}} + \sigma_{ij}^{\mathrm{NNLO,\ EFT}} + \sigma_{ij}^{\mathrm{N^3LO,\ EFT}} \right]$$
$$+ \delta\sigma_{ij}^{\mathrm{LO,\ (t,b,c)}} + \delta\sigma_{ij}^{\mathrm{NLO,\ (t,b,c)}} + \delta\sigma_{ij}^{\mathrm{NNLO,\ (t)}} + \mathrm{R_{LO}} C^2\, \delta\sigma_{ij}^{\mathrm{Res}} .$$

- start with iHixs prediction and systematically incorporate new results
- exact top mass at NNLO Czakon, Harlander, Klappert, Niggetiedt 21

$$\delta\sigma_{ij}^{\mathrm{NNLO,\ (t)}} = \boxed{\sigma_{ij}^{\mathrm{NNLO,\ approx.}}} - \left[C_{\mathrm{QCD}}^2 \mathrm{R_{LO}} \sigma_{ij}^{\mathrm{EFT}} \right]_{\alpha_S^4} \quad \text{for} \quad (ij) \in \{(gg), (gq)\}$$

iHixs gives access to each part:

↪ substitution $\sigma_{ij}^{\mathrm{NNLO,\ approx}} \rightarrow \sigma_{ij}^{\mathrm{NNLO,\ exact}}$ straightforward

(computation of "exact" already as a difference to EFT ⇝ compatibility checks)

Inclusion of mixed QCD-EW

iHixs:
$$\hat{\sigma}_{ij} = \mathrm{R_{LO}} C^2 \left[\sigma_{ij}^{\mathrm{LO,\ EFT}} + \sigma_{ij}^{\mathrm{NLO,\ EFT}} + \sigma_{ij}^{\mathrm{NNLO,\ EFT}} + \sigma_{ij}^{\mathrm{N^3LO,\ EFT}}\right]$$
$$+ \delta\sigma_{ij}^{\mathrm{LO,\ (t,b,c)}} + \delta\sigma_{ij}^{\mathrm{NLO,\ (t,b,c)}} + \delta\sigma_{ij}^{\mathrm{NNLO,\ (t)}} + \mathrm{R_{LO}} C^2\, \delta\sigma_{ij}^{\mathrm{Res}}\,.$$

- start with iHixs prediction and systematically incorporate new results
- inclusion of EW corrections by Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20
  iHixs formula based on *factorization hypothesis*:

$$C = C_{\mathrm{QCD}} + \lambda_{\mathrm{EWK}}(1 + \frac{\alpha_S}{\pi} C_{1w} + \dots).$$

↪ iHixs uses $C_{1w} = 7/6$ as estimated from the $M_V \to \infty$ limit

↪ full result gives: $C_{1w} = -1.7$ $(\mu_R = M_{\mathrm{H}}/2)$ $C_{1w} = -2.1$ $(\mu_R = M_{\mathrm{H}})$

but note: $\delta(\mathrm{EW}) \sim \pm 1\,\%$ ⇜⇝ vary C_{1w} by factor in range $[-3, 6]$

proposal: incorporate new result with an additional correction term (1st step)

$$\delta\sigma_{ij}^{\mathrm{EW}} = \sigma_{ij}^{\mathrm{EW}} - \left[C^2 R_{\mathrm{LO}} \sigma_{ij}^{\mathrm{EFT}}\right]_{\alpha_s^3\alpha^2}$$

and define error estimates on correction factor (beyond light quarks, gg channel, …)

Community Input / Requests

1) BSM scan with non-SM Higgs Mass

Assuming step size and range ($m_H = [10{,}3000]$ GeV) of Report 4

Higgs Mass range	step size	# of points	addendum
[10,150] GeV	5 GeV	29 points	
[150,500] GeV	10 GeV	35 points	+ M_H=125.09 GeV
[500,3000] GeV	50 GeV	50 points	

- Total 115 points for M_H=[10,3000] GeV.

Can run iHixs2 with same setup; unlikely to have most recent $\delta(1/m_t)$ or $\delta(\mathrm{EW})$

but: HTL not valid above $2m_t$ how were the cross sections computed/provided in the past?

2) $\sigma(gg \to H) = \sigma_{tt} + \sigma_{tb} + \sigma_{bb}$ **breakdown**

Corrections can have different K-factors

Useful for BSM studies with different t/b weighting

$$\begin{aligned} \sigma(gg \to H) &= \sigma_{tt} + \sigma_{tb} + \sigma_{bb} \\ K_{tt} &\sim 1.68 \\ K_{tb} &\sim 0.97 \\ K_{bb} &\sim 1.20 \end{aligned}$$

$\Rightarrow$ up to $20-30\%$ differences in NLO cxn [m_b: scheme/scale dep.?]

$\Rightarrow$ not possible to use SM-like cxns in many BSM cases for different weighting of top and bottom loops

iHixs2 outputs partially decomposed information; would still rely on on support from the authors of the code

Talk: M. Spira (19th General Assembly)

Conclusions & Next Steps

Status

N³LO QCQ (iHixs)	**DONE**
NNLO QCD w/mt	**AWAITING INPUT (CONFIRMED 5/04/23)**
QCD-EW gg	**AWAITING INPUT (CONFIRMED 17/05/23)**
aN³LO PDFs	**DONE (PROPOSAL + ongoing LH study)**

Initially asked feasibility of computations for all points on twiki
Settled with each group on reduced range of computations (will need to interp.)
Requested any available results on 05/06/23 for initial combination

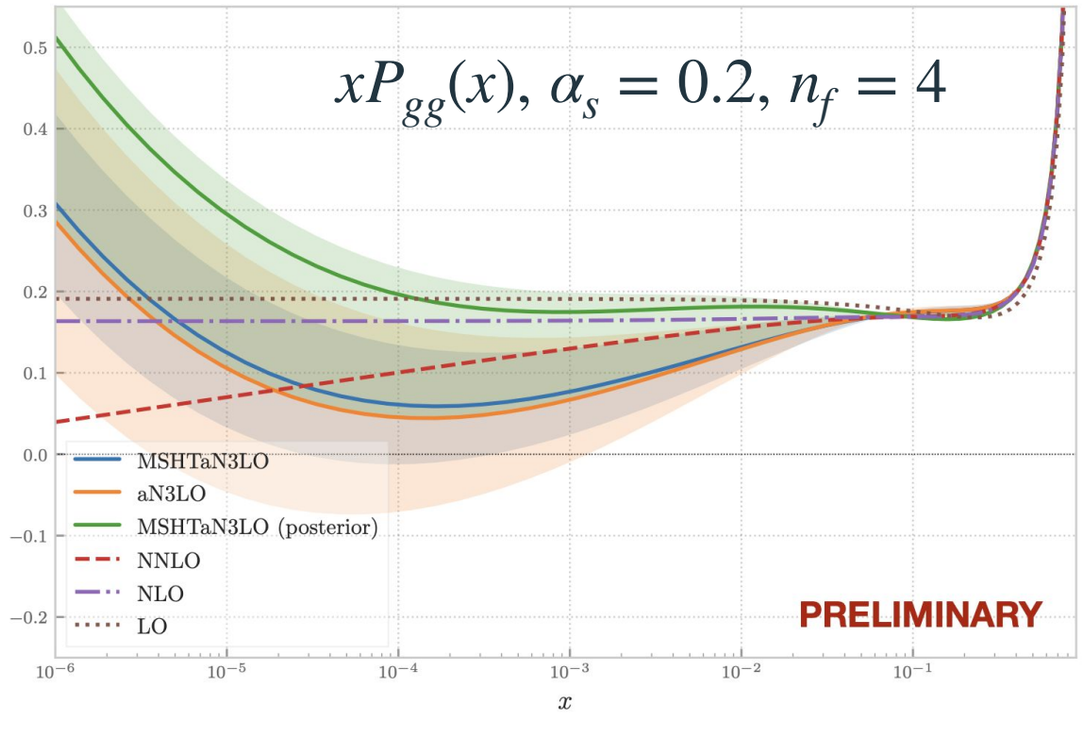
Next Steps

Re-ping groups and share details of how their numbers will be combined
Produce initial combination based on numbers in their publications (for validation)

Comments and Questions?

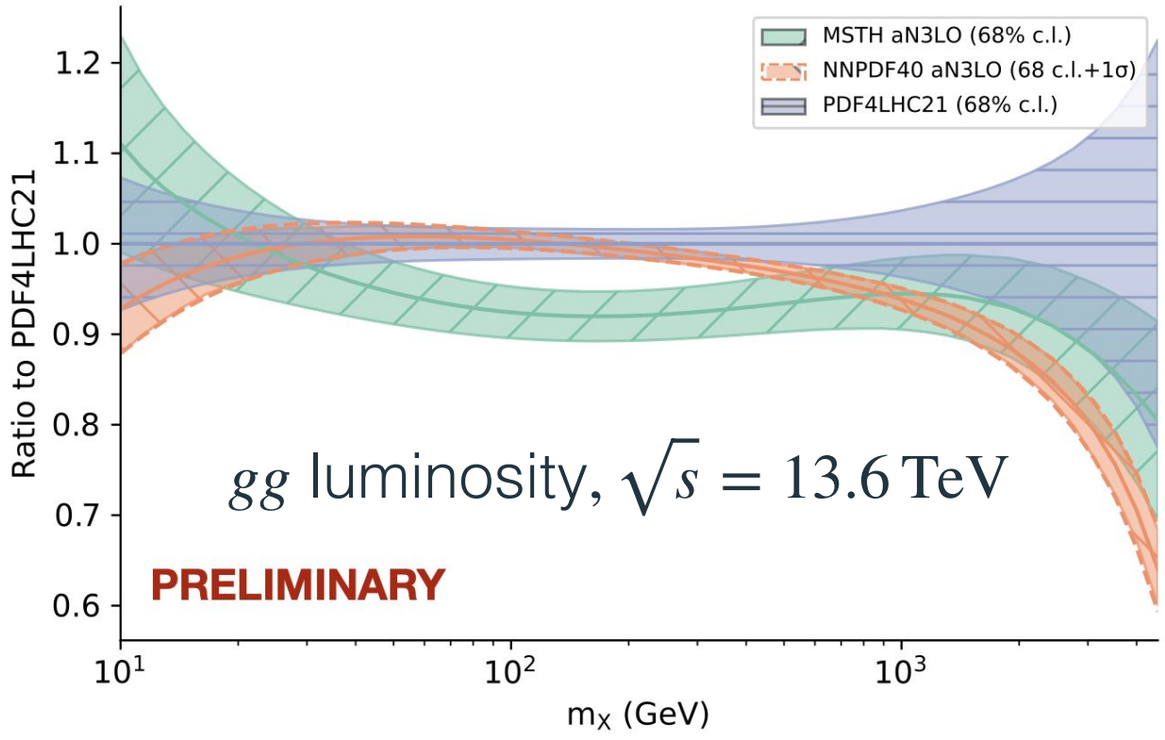
Backup

aN3LO PDFs Comparison



MSHT (prior) ≃ **NNPDF**

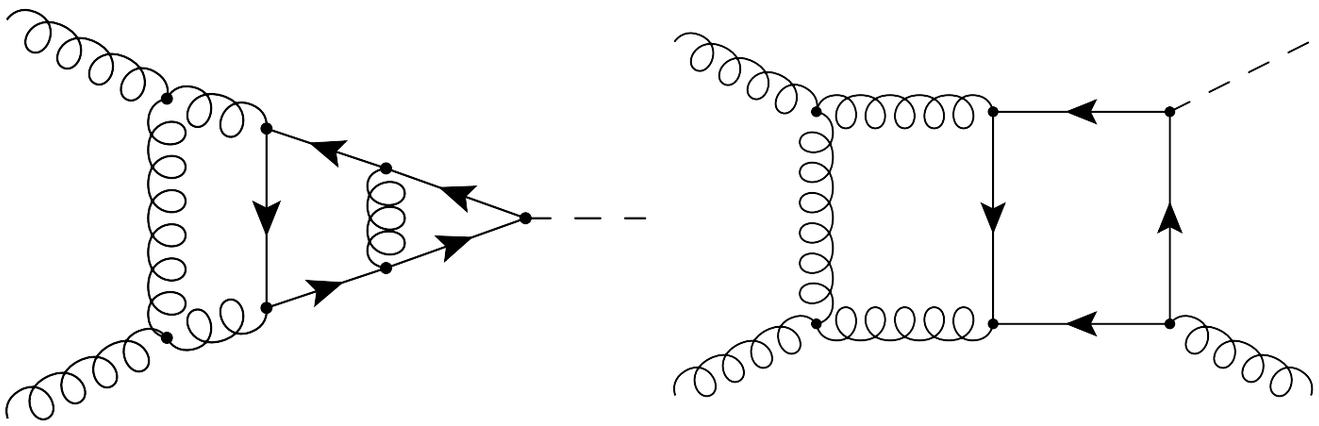
MSHT (posterior) shifts within uncertainty band
(absorbs some low-x logs?)



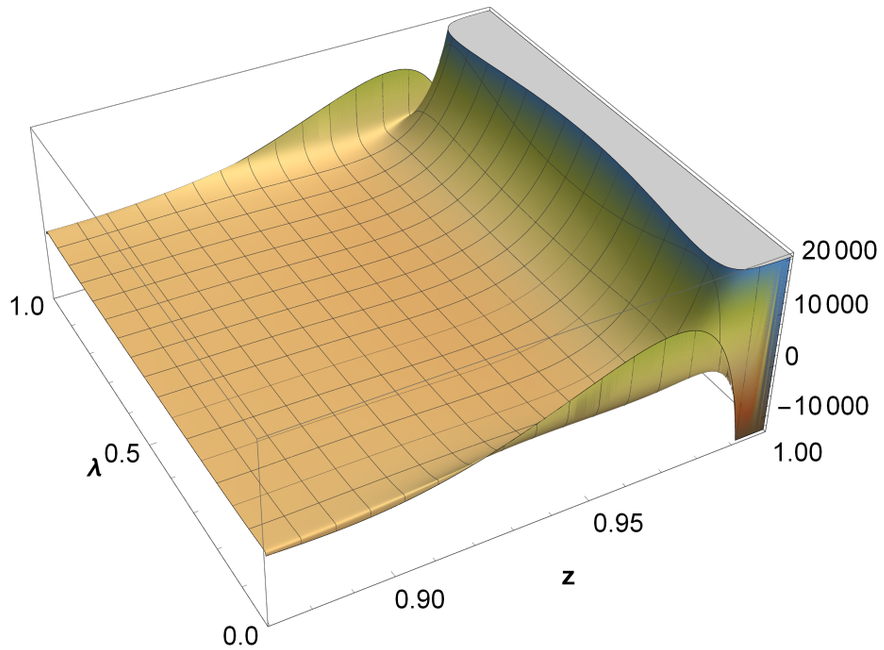
Followup studies:

- Understand origin of differences
  (impact from prior → posterior?
  treatment of MHO uncertainties
  & other N3LO inputs?
  difference in methodology? …)
- Compare evolution of toy PDFs
- Cross-section level comparisons
- …

NNLO with full top-quark mass



$gg \to Hg$



$2\mathrm{Re}\langle M^{(1)}_{\mathrm{exact}} | M^{(2)}_{\mathrm{exact}} \rangle |_{\mathrm{regulated}}$

H+1jet @ 2-loop & H @ 3-loop with m_T using numerical solution of differential equations

Czakon, Niggetiedt 20;
Czakon, Harlander, Klappert, Niggetiedt 21

Decreases σ_{tot} by $-0.26\,\%$ @ 13 TeV compared to heavy top limit (HTL)

Intricate interplay between mass effects $gg\ (+0.62\%), qg\ (-16\%), qq\ (-15\%)$
Complete NNLO results obtained using STRIPPER framework

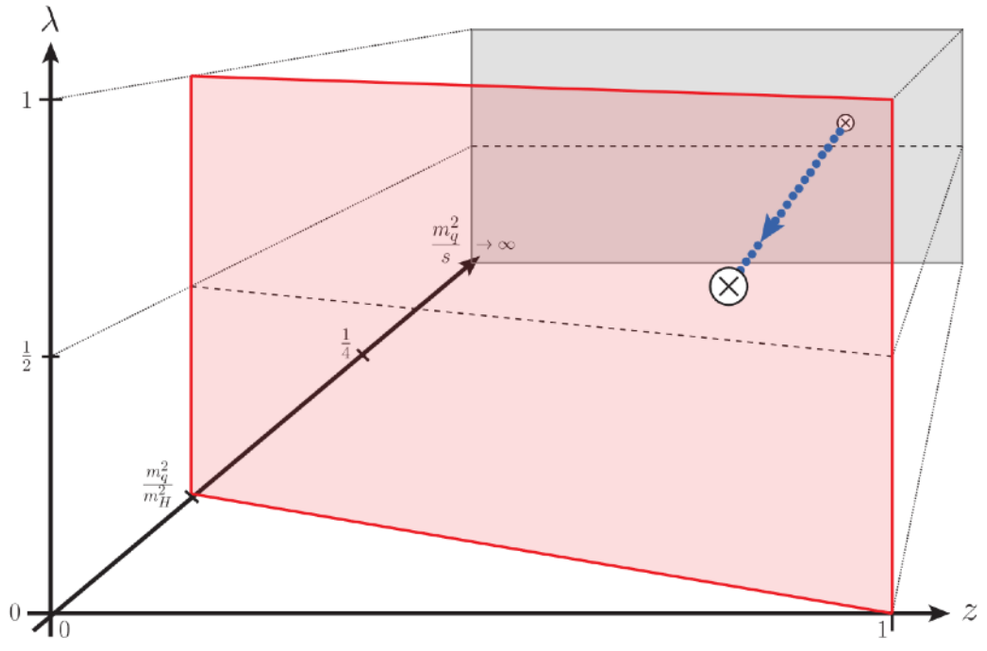
What to do with bottom/charm quarks?

Would be very useful to know bottom/charm effects @ NNLO (reduce $\delta(t, b, c)$)

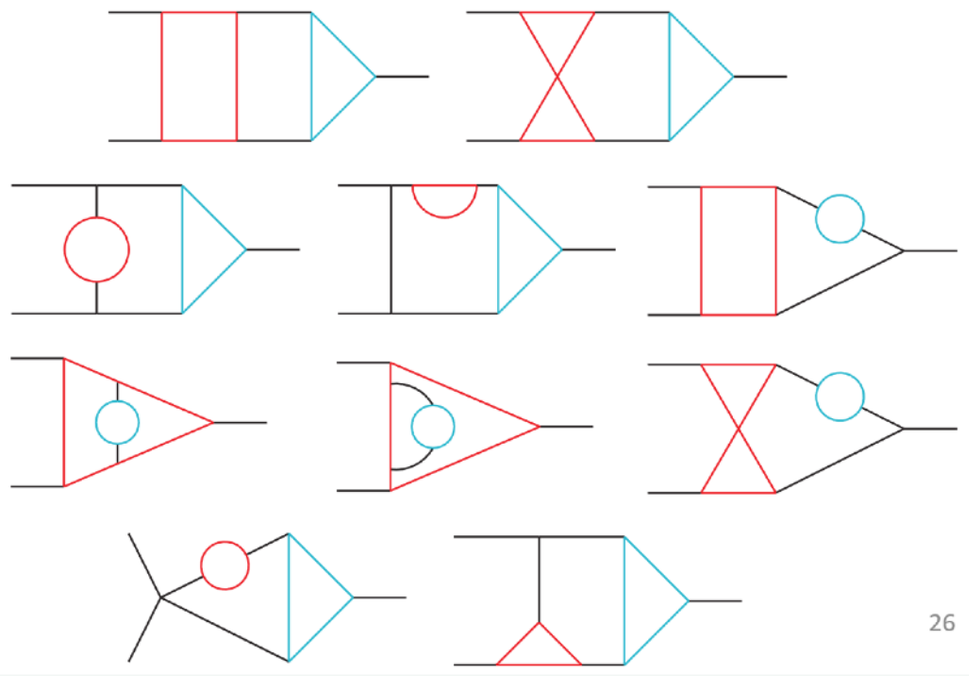
However, technically very challenging to get NNLO results

Summary

- Same techniques can be applied to compute bottom quark mass effects…
- Large hierarchy between m_b^2 and m_H^2 can lead to numerical instabilities when solving the differential equations
- Boundaries at $m_q^2 \to \infty$ not optimal



Corrections to $gg \to H$ at three loops for two different massive quark flavors unknown



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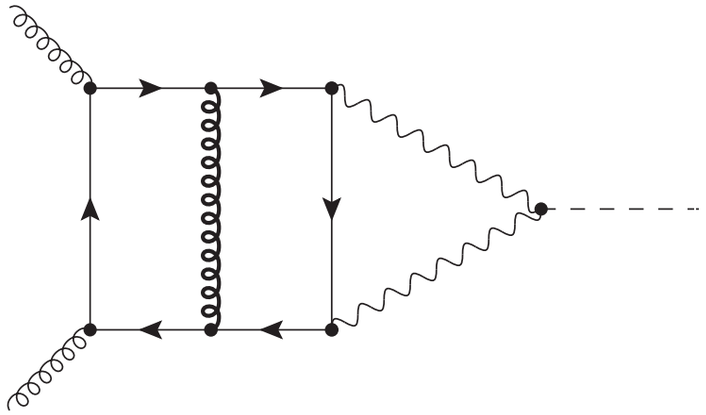
Slide: Marco (Monday)

Mixed QCD-EW Corrections @ $\mathrm{NLO}_{\mathrm{QCD}}$

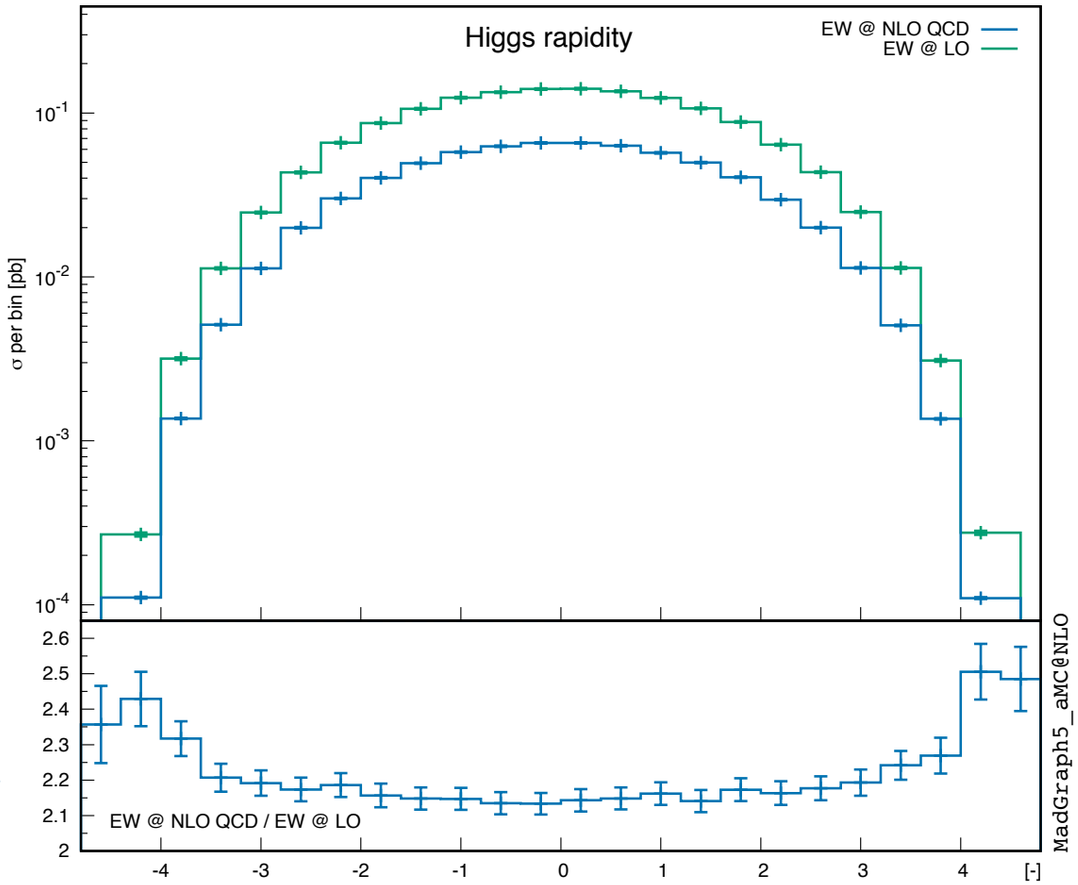


Challenging calculations

Bonetti, Melnikov, Tancredi 17

Bonetti, Panzer, Smirnov, Tancredi 20

Dominant light-quark mediated contributions computed, rather flat K-factor (for rapidity distribution)



Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 20

Increases σ_{tot} by $+5.1\,\%$ @ 13 TeV, reduces residual uncertainty $\delta(\mathrm{EW}) \sim 0.6\,\%$

Favouring factorisation of EW corrections: $\sigma = \sigma_{\mathrm{LO}}\,(1+\delta_{\mathrm{QCD}}) \times (1+\delta_{\mathrm{EWK}})$

Compatible with previous estimates:

Soft approx: $+5.4\,\%$,
Bonetti, Melnikov, Tancredi 18;

$M_H \ll M_V : +5.2\,\%$,
Anastasiou, Boughezal, Petriello 09;

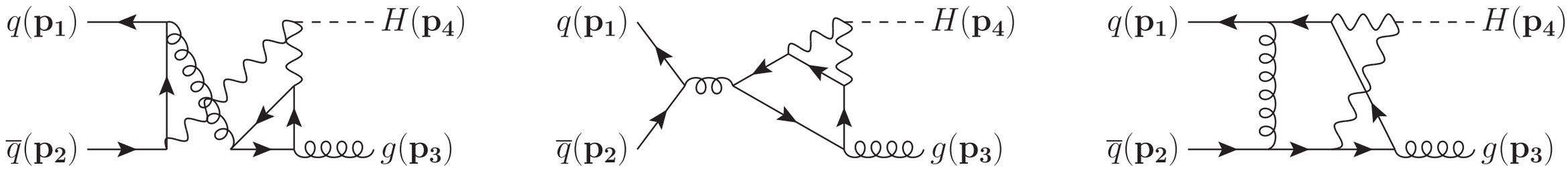
$M_H \gg M_V : +5.4\,\%$
Anastasiou, Del Duca, Furlan, Mistlberger, Moriello, Schweitzer, Specchia 19

What to do with the $qg, \bar{q}g, q\bar{q}$ channels?

Previous calculation of QCD-EW corrections only considers dominant gg channel

Impact of the quark channels expected to be relatively suppressed (due to large gg lumi), primary impact likely to be $\mathcal{O}(-2\%)$ shift at large/moderate p_T

But: 2-loop $q\bar{q}Hg$ amplitudes known



Bonetti, Panzer, Tancredi 22

Presumably, all-channel QCD-EW estimate is within reach

Proposal:
The sub-group should continue assembling the ingredients required for an update (including the existing QCD-EW corrections), iron out any issues, keep in touch with authors who may produce an improved QCD-EW estimate.