Summary of ggf contributions to YR4

Chris Hays, Oxford University

for the ggf conveners:
Stefano Forte, Dag Gillberg, Achilleas Lazopoulos,
Andrea Massironi, Giovanni Petrucciani, Giulia Zanderighi

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LHC Higgs WG1 meeting
7 July 2016

Overview

Inclusive cross section

Jet-binned cross sections

Benchmark distributions

Heavy-quark masses

Andrea's talk

Inclusive cross section

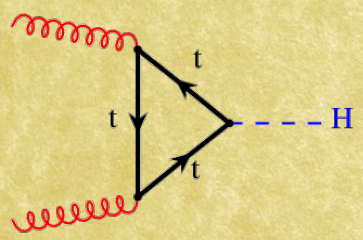
Structure of the cross section:

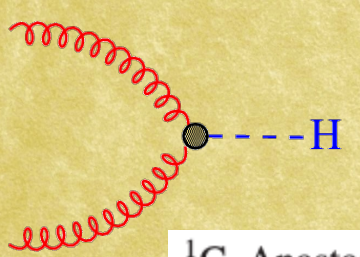
Correction for electroweak contributions to NLO in α

$$\hat{\sigma}_{ij} \simeq R_{LO}\left(\hat{\sigma}_{ij,EFT} + \delta_t \hat{\sigma}^{NNLO}_{ij,EFT} + \delta\hat{\sigma}_{ij,EW}\right) + \delta\hat{\sigma}^{LO}_{ij,ex;t,b,c} + \delta\hat{\sigma}^{NLO}_{ij,ex;t,b,c}$$

$$R_{LO} \equiv \frac{\sigma^{LO}_{ex;t}}{\sigma^{LO}_{EFT}}$$

Correction for massive top quark in loop



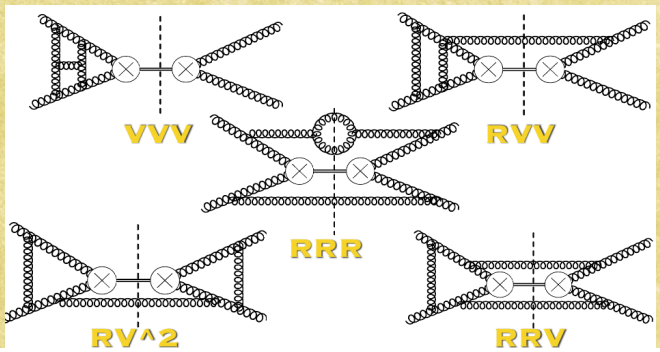


Correction for top mass at NNLO (inverse mass expansion)

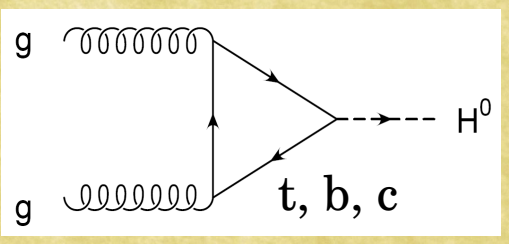
$$\{a, b_k, h_{\alpha\beta}(x)\} = \sum_{i\geq 0}\left(\frac{M_{\rm H}}{M_t}\right)^i \{a_i, b_{k,i}, h_{\alpha\beta,i}(x)\}$$

Cross section in heavy top quark limit

Now calculated to N³LO



Corrections for t, b, and c quark masses to NLO



[1]C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog, A. Lazopoulos, B. Mistlberger

Inclusive cross section: N^{3}LO result

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

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

$\sqrt{S}$	13 TeV
m_h	125 GeV
PDF	PDF4LHC15_nnlo_100
$\alpha_s(m_Z)$	0.118
$m_t(m_t)$	162.7 GeV ($\overline{\text{MS}}$)
$m_b(m_b)$	4.18 GeV ($\overline{\text{MS}}$)
$m_c(3GeV)$	0.986 GeV ($\overline{\text{MS}}$)
$\mu = \mu_R = \mu_F$	62.5 GeV ($= m_H/2$)

Truncation of threshold expansion at 37th order

$$\delta(\text{trunc}) = 10 \times \frac{\sigma^{(3)}_{EFT}(37) - \sigma^{(3)}_{EFT}(27)}{\sigma^{\text{N}^3\text{LO}}_{EFT}}$$

Mixed QCD-EW corrections use m_H/m_V expansion

Three methods to estimate uncertainty give 0.2-1.3%

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\,\text{pb}}_{-1.15\,\text{pb}}$	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	±0.37%	±1.16%	±1%	±0.83%	±1%

Uncertainty from matching to high energy limit (known to LL)

Scales in range $[m_H/4, m_H]$ are within NNLO band

No N^{3}LO PDFs: Estimate using difference between NLO & NNLO PDFs in NNLO cross section

$$\delta(\text{PDF}-\text{TH}) = \frac{1}{2}\left|\frac{\sigma^{(2),NNLO}_{EFT} - \sigma^{(2),NLO}_{EFT}}{\sigma^{(2),NNLO}_{EFT}}\right|$$

Missing NNLO interference between t, b, c

$$\delta(t,b,c)^{\overline{\text{MS}}} = \pm\left|\frac{\delta\sigma^{NLO}_{ex;t} - \delta\sigma^{NLO}_{ex;t+b+c}}{\delta\sigma^{NLO}_{ex;t}}\right|(R_{LO}\delta\sigma^{NNLO}_{EFT} + \delta_t\hat{\sigma}^{NNLO}_{gg+qg,EFT})$$

$$\delta(t,b,c) = 1.3\,\delta(t,b,c)^{\overline{\text{MS}}}$$

Inclusive cross section: N^{3}LO + N^{3}LL

Additional estimates of the perturbative uncertainty can be obtained using resummation: vary the order of the soft expansion & the exponentiation procedure

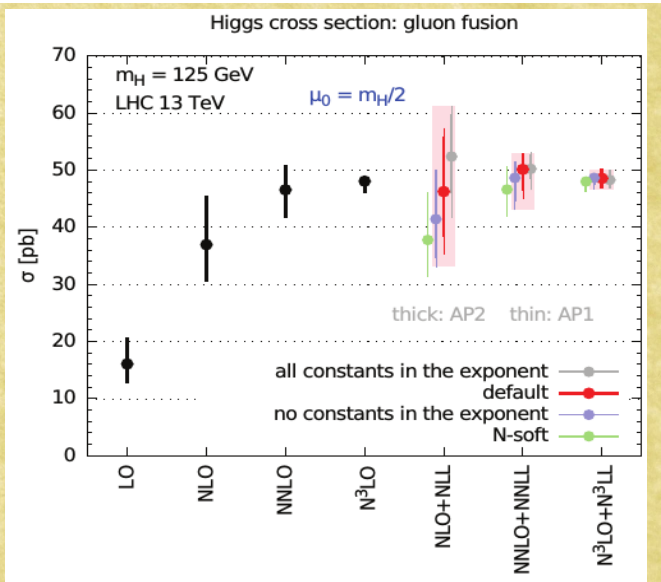
– AP2 (default): P_{gg} is retained to second order in $1-z$;
– AP1: P_{gg} is retained to first order in $1-z$.

[2]M. Bonvini, S. Marzani

– default: those constants coming from the Mellin transform of plus distributions are in the exponent, the others are not;
– all constants in the exponent;
– no constants in the exponent.

$\delta(\text{mho})$: envelope of the canonical 7-point scale variations and the 6 variants of ψ-soft resummation

	$\mu_0 = m_H/4$	$\mu_0 = m_H/2$	$\mu_0 = m_H$	$\mu_0 = 2m_H$
LO	$18.6^{+5.8}_{-3.9}$	$16.0^{+4.3}_{-3.1}$	$13.8^{+3.2}_{-2.4}$	$11.9^{+2.5}_{-1.9}$
NLO	$44.2^{+12.0}_{-8.5}$	$36.9^{+8.4}_{-6.2}$	$31.6^{+6.3}_{-4.8}$	$27.5^{+4.9}_{-3.9}$
NNLO	$50.7^{+3.4}_{-4.6}$	$46.5^{+4.2}_{-4.7}$	$42.4^{+4.6}_{-4.4}$	$38.6^{+4.4}_{-4.0}$
N^{3}LO	$48.1^{+0.0}_{-7.5}$	$48.1^{+0.1}_{-1.8}$	$46.5^{+1.6}_{-2.6}$	$44.3^{+2.5}_{-2.9}$
LO+LL	$24.0^{+8.9}_{-6.8}$	$20.1^{+6.2}_{-5.0}$	$16.9^{+4.5}_{-3.7}$	$14.3^{+3.3}_{-2.8}$
NLO+NLL	$46.9^{+15.1}_{-12.6}$	$46.2^{+15.0}_{-13.2}$	$46.7^{+20.8}_{-13.8}$	$47.3^{+26.1}_{-15.8}$
NNLO+NNLL	$50.2^{+5.5}_{-5.3}$	$50.1^{+3.0}_{-7.1}$	$51.9^{+9.6}_{-8.9}$	$54.9^{+17.6}_{-11.5}$
N^{3}LO+N^{3}LL	$47.7^{+1.0}_{-6.8}$	$48.5^{+1.5}_{-1.9}$	$50.1^{+5.9}_{-3.5}$	$52.9^{+13.1}_{-5.3}$



$\sigma_{\text{N}^3\text{LO+N}^3\text{LL}} - \sigma_{\text{N}^3\text{LO}} = +0.4\,\text{pb}, \qquad \delta(\text{mho}) = \pm 4\%,$

Authors advocate this result with symmetrized uncertainty

Inclusive cross section: recommendations

Resummation has a negligible impact on central value

LHC WG recommendation: Use N^3LO central value of 48.58 pb

Two options considered for uncertainties: "F" (flat) or "G" (Gaussian)

F: 100% confidence interval with a flat distribution, add uncertainties linearly

G: 68% confidence level Gaussian distribution, add uncertainties in quadrature

Uncertainty	**F**	**G**
Scale	Scan over $[m_H/4, m_H]$: +0.2%, -2.4%	Symmetrized 7-point variation: ±3.0%
EW corrections	Intermediate value of three methods: ±1.0%	Average of additive correction and removal of mixed QCD-EW: ±2.5%
t, b, c masses	Fractional correction based on differences between successive orders: ±0.8%	Scheme dependence of NLO interference: ±1.5%

Inclusive cross section: recommendations

Uncertainty	F	G
finite top mass @ NNLO	Uncertainty from matching to high energy limit (known to LL): ±1.0%	
NNNLO PDFs	Estimate using difference between NLO & NNLO PDFs in NNLO cross section: ±1.2%	
Truncation of threshold expansion	Ten times fractional effect from 27th order to 37th order: ±0.4%	
Total	**+4.6%, -6.7%**	**±4.5%**

Experimentalists prefer "G", (majority of) theorists prefer "F"

Theory uncertainties inherently not statistical, most appropriate estimate is 100% flat confidence interval

LHC WG recommendation: Use "F" uncertainty, translate to symmetric Gaussian uncertainty if necessary (±3.9%)

Kinematic binning: general treatment

Binning in jet multiplicity historically important for separating signal from background, and for separating different signal processes

In Run 2 binning will be extended to other kinematic variables in the context of simplified template cross sections

General framework: Covariance based on uncertainties on yields and migrations

Example of three jet bins:

$$\kappa^{\mathrm{y}}: \quad \{\Delta^{\mathrm{y}}_{\geq 0}, \Delta^{\mathrm{y}}_{0}, \Delta^{\mathrm{y}}_{\geq 1}, \Delta^{\mathrm{y}}_{1}, \Delta^{\mathrm{y}}_{\geq 2}\} \quad \text{with} \quad \Delta^{\mathrm{y}}_{\geq 0} = \Delta^{\mathrm{y}}_{0} + \Delta^{\mathrm{y}}_{\geq 1}\,, \qquad \Delta^{\mathrm{y}}_{\geq 1} = \Delta^{\mathrm{y}}_{1} + \Delta^{\mathrm{y}}_{\geq 2}$$

$$\kappa^{0/1}_{\mathrm{cut}}: \quad \Delta^{0/1}_{\mathrm{cut}} \times \{0,\, 1,\, -1,\, -(1-x_1),\, -x_1\}\,,$$

$$\kappa^{1/2}_{\mathrm{cut}}: \quad \Delta^{1/2}_{\mathrm{cut}} \times \{0,\, x_2,\, -x_2,\, 1-x_2,\, -1\}\,,$$

$$C(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) = C^{\mathrm{y}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) + C^{0/1}_{\mathrm{cut}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) + C^{1/2}_{\mathrm{cut}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\})$$

$$C^{\mathrm{y}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) = \begin{pmatrix} (\Delta^{\mathrm{y}}_0)^2 & \Delta^{\mathrm{y}}_0\Delta^{\mathrm{y}}_1 & \Delta^{\mathrm{y}}_0\Delta^{\mathrm{y}}_{\geq 2} \\ \Delta^{\mathrm{y}}_0\Delta^{\mathrm{y}}_1 & (\Delta^{\mathrm{y}}_1)^2 & \Delta^{\mathrm{y}}_1\Delta^{\mathrm{y}}_{\geq 2} \\ \Delta^{\mathrm{y}}_0\Delta^{\mathrm{y}}_{\geq 2} & \Delta^{\mathrm{y}}_1\Delta^{\mathrm{y}}_{\geq 2} & (\Delta^{\mathrm{y}}_{\geq 2})^2 \end{pmatrix}$$

$$C^{0/1}_{\mathrm{cut}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) = (\Delta^{0/1}_{\mathrm{cut}})^2 \begin{pmatrix} 1 & -(1-x_1) & -x_1 \\ -(1-x_1) & (1-x_1)^2 & x_1(1-x_1) \\ -x_1 & x_1(1-x_1) & x_1^2 \end{pmatrix}$$

$$C^{1/2}_{\mathrm{cut}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) = (\Delta^{1/2}_{\mathrm{cut}})^2 \begin{pmatrix} x_2^2 & x_2(1-x_2) & -x_2 \\ x_2(1-x_2) & (1-x_2)^2 & -(1-x_2) \\ -x_2 & -(1-x_2) & 1 \end{pmatrix}$$

[10] F. J. Tackmann, K. Tackmann

Jet binning: ST scheme

$$\Delta_0^y = \Delta_{\geq 0}^{FO}, \Delta_1^y = \Delta_{\geq 2}^y = 0$$

$$\Delta_{cut}^{0/1} = \Delta_{\geq 1}^{FO}, \Delta_{cut}^{1/2} = \Delta_{\geq 2}^{FO}$$

$$x_1 = x_2 = 0$$

Migrations only between neighboring bins

Uncertainties on inclusive cross sections (≥n jets) given by usual perturbative uncertainties

Calculations with HNNLO ($\sigma_{\geq 0}$) and MCFM ($\sigma_{\geq 1}$, $\sigma_{\geq 2}$) at 13 TeV:

	Summary of jet-bin uncertainties related to the S.T. method.	
$\Delta\sigma_{\geq 0}$	$[-4.6, +4.6]$ pb	
	$p_T > 25$ GeV	$p_T > 30$ GeV
$\Delta\sigma_{\geq 1}$	$[-3, +2.9]$ pb	$[-2.7, +2.5$ pb
$\Delta\sigma_{\geq 2}^{LO}$	$[-3.3, +6.0]$ pb	$[-2.5, +4.7]$ pb
σ_0	26.2 pb	28.9 pb
σ_1	10.9 pb	10.3 pb
$\Delta\sigma_0/\sigma_0$ S.T	[-0.21, +0.21]	[-0.18,+0.18]
$\Delta\sigma_1/\sigma_1$ S.T	[-0.62, +0.40]	[-0.53,+0.34]

[11]B. Di Micco

Jet binning: JVE scheme

$$\Delta^{\rm y}_{\geq 0} = \Delta^{\rm FO}_{\geq 0}\,, \quad \Delta^{\rm y}_{0} = \epsilon_0\,\Delta^{\rm FO}_{\geq 0}\,, \quad \Delta^{\rm y}_{\geq 1} = (1-\epsilon_0)\,\Delta^{\rm FO}_{\geq 0}\,, \qquad \Delta_{\rm cut} = \sigma_{\geq 0}\,\Delta(\epsilon_0)$$

Yield uncertainties: inclusive cross section; *migration uncertainties*: efficiencies

Probe higher orders with scale variations and multiple efficiency calculations

$$\epsilon^a_N = 1 - \frac{\sigma^{\rm NLO}_{\geq N+1}}{\sigma^{\rm NNLO}_{\geq N}} \quad \epsilon^b_N = 1 - \frac{\sigma^{\rm NLO}_{\geq N+1}}{\sigma^{\rm NLO}_{\geq N}} \quad \epsilon^c_N = 1 - \frac{\sigma^{\rm NLO}_{\geq N+1}}{\sigma^{\rm NLO}_{\geq N}} + \left(\frac{\sigma^{\rm NLO}_{\geq N}}{\sigma^{\rm LO}_{\geq N}} - 1\right)\frac{\sigma^{\rm LO}_{\geq N+1}}{\sigma^{\rm LO}_{\geq N}}$$

Calculations with NNLO+NNLL ($\sigma_{\geq 0}$), MCFM ($\sigma_{\geq 1}$, $\sigma_{\geq 2}$), and JetVHeto (0-jet resummation) at 13 TeV:

Summary of JVE related uncertainties.

	$p_T > 25$ GeV	$p_T > 30$ GeV
ϵ_0	0.57	0.64
$\Delta\epsilon_0$ RES.	[- 0.06,+0.18]	[-0.06, +0.18]
$\Delta\epsilon_0$ F.O.	[-0.12, +0.36]	[-0.10, +0.31]
$\Delta\epsilon_0/\epsilon_0$ RES.	[-0.11 , +0.32]	[-0.09, +0.28]
ϵ_1	0.81	0.84
$\Delta\epsilon_1$	[-0.18, +0.16]	[-0.16, +0.32]
$\Delta\epsilon_1/\epsilon_1$	[-0.22, +0.20]	[-0.19, +0.38]
$\Delta\sigma_0/\sigma_0$	[-0.13, +0.32]	[-0.12, +0.29]
$\Delta\sigma_1/\sigma_1$	[-0.48, +0.25]	[-0.54, +0.42]

Jet binning: JVE @ N3LO

Calculations with N3LO ($\sigma_{\geq 0}$) and JetVHeto (0-jet resummation) at 13 TeV

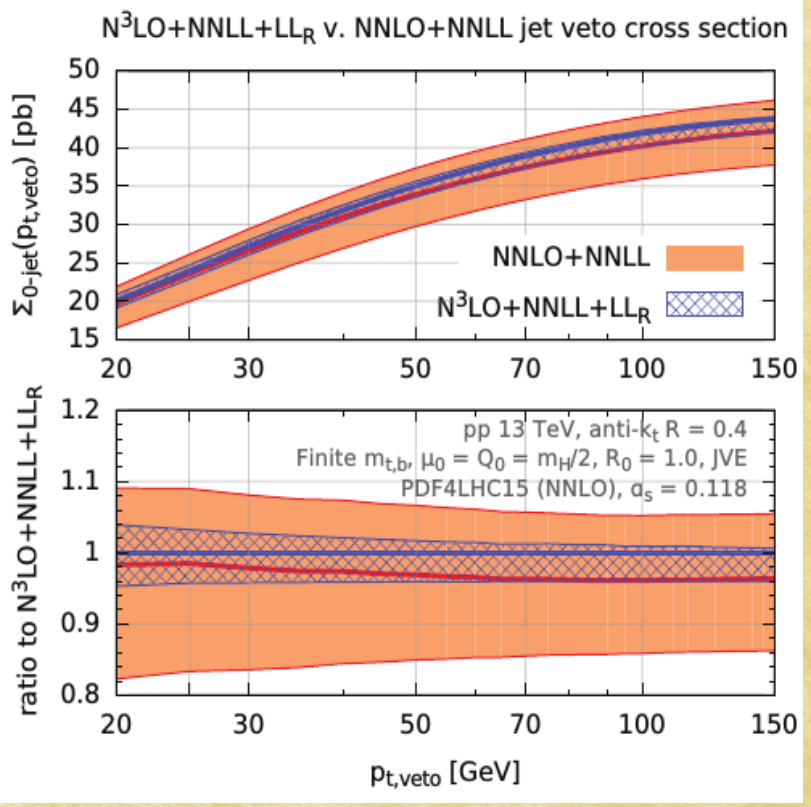
Uncertainties:

Fixed order scale varied by factors of 1/2 & 2

Resummation scale varied by factors of 2/3 & 3/2

Subleading logs estimated by a second resummation scale varied by 1/2 and 2

Use two efficiency calculations (schemes 'a' & 'b')



LHC 13 TeV	$\epsilon^{\mathrm{N^3LO+NNLL+LL_R}}$	$\Sigma_{\text{0-jet}}^{\mathrm{N^3LO+NNLL+LL_R}}$ [pb]	$\Sigma_{\text{0-jet}}^{\mathrm{N^3LO}}$	$\Sigma_{\text{0-jet}}^{\mathrm{NNLO+NNLL}}$
$p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}$	$0.534^{+0.017}_{-0.008}$	$24.0^{+0.8}_{-1.0}$	$23.6^{+0.5}_{-1.2}$	$23.6^{+2.5}_{-3.6}$
$p_{\mathrm{t,veto}} = 30\,\mathrm{GeV}$	$0.607^{+0.016}_{-0.008}$	$27.2^{+0.7}_{-1.1}$	$26.9^{+0.4}_{-1.2}$	$26.6^{+2.8}_{-3.9}$

[13] Andrea Banfi, Fabrizio Caola, Frédéric A. Dreyer, Pier Francesco Monni, Gavin P. Salam, Giulia Zanderighi, Falko Dulat

Jet binning: Resummation @ NNLO

Yield uncertainties: fixed-order scale; *migration uncertainties*: resummation scale

$$\kappa_\mu^{\rm y}: \quad \{\Delta_{\mu\geq 0},\, \Delta_{\mu 0},\, \Delta_{\mu\geq 1}\}\,, \qquad \kappa_\varphi^{\rm y}: \quad \{\Delta_{\varphi\geq 0},\, \Delta_{\varphi 0},\, \Delta_{\varphi\geq 1}\}$$

$$\kappa_{\rm cut}^{0/1}: \quad \Delta_{\rm resum}^{0/1} \times \{0,\, 1,\, -1\}\,.$$

$$\mu_H = \mu_{\rm FO} \exp(-i\varphi)$$

$p_T^{\rm cut} = 25$ GeV	σ/pb	Δ_μ	Δ_φ	$\Delta_{\rm cut}^{0/1}$	$\Delta_{\rm cut}^{1/2}$	total pert. unc.
$\sigma_{\geq 0}$	47.41±2.40	4.6%	2.0%	-	-	5.1%
σ_0	26.25±1.97	4.7%	0.6%	5.8%	-	7.5%
$\sigma_{\geq 1}$	21.16±1.96	4.5%	3.8%	7.1%	-	9.3%
σ_1	13.28±1.76	4.2%	3.3%	9.8%	7.2%	13.3%
$\sigma_{\geq 2}$	7.88±1.12	5.1%	4.6%	2.7%	12.2%	14.3%
$p_T^{\rm cut} = 30$ GeV	σ/pb	Δ_μ	Δ_φ	$\Delta_{\rm cut}^{0/1}$	$\Delta_{\rm cut}^{1/2}$	total pert. unc.
$\sigma_{\geq 0}$	47.41±2.40	4.6%	2.0%	-	-	5.1%
σ_0	29.51±1.65	3.8%	0.1%	4.1%	-	5.6%
$\sigma_{\geq 1}$	17.90±1.88	6.0%	5.2%	6.8%	-	10.5%
σ_1	11.94±1.58	5.5%	4.8%	8.4%	7.2%	13.2%
$\sigma_{\geq 2}$	5.96±1.05	7.1%	6.1%	3.6%	14.5%	17.6%

[15] R. Boughezal, X. Liu, F. Petriello, I. W. Stewart, F. J. Tackmann