MATRIX alle Hawaii – interface to fast-interpolation tools

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(ongoing work with Simone Devoto, Tomas Ježo and Christopher Schwan - built upon the MATRIX framework)







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Outline

Motivation



The MATRIX framework for precision calculations



First applications of PINEAPPL grids in MATRIX

5 Conclusions & Outlook

Precision calculations — the key to fully exploit LHC measurements

Sample case: diboson production

- important SM test

 trilinear couplings
- background for Higgs analyses and BSM searches
- very clean signatures in leptonic decay channels
- good statistics already with available data

All diboson processes available at NNLO QCD accuracy in the public MATRIX framework

inevitable for data-theory agreement

Mandatory steps to match experimental precision also in the future

- Ieading QCD corrections beyond NNLO
- EW corrections and combination with QCD
- MATRIX v2 [Grazzini, SK, Wiesemann (2021)]



[ATLAS collaboration (2022)]

The MATRIX framework for automated NNLO QCD calculations (and beyond)

[Grazzini, SK, Wiesemann (2018) + Rathlev; Buonocore, Devoto, Mazzitelli, Rottoli, Sargsyan, Savoini, Yook, ...]

Amplitudes				
$\begin{array}{c} OPENLOOPS \\ (Collier, CutTOols, \ldots) \end{array}$	$\begin{array}{c} \textbf{Dedicated 2-loop codes} \\ (\textbf{VVAMP}, \textbf{GiNAC}, \textbf{TDHPL}, \dots) \end{array}$			

MUNICH MUlti-chaNnel Integrator at Swiss (CH) precision



available under https://matrix.hepforge.org/

MATRIX v1 (fall 2017)

 Η, V, γγ, Vγ, VV at NNLO QCD for all leptonic decay channels

MATRIX v2 (summer 2021)

- combination with NLO EW for all leptonic V and VV processes
- loop-induced gg channel at NLO QCD for neutral VV processes

MATRIX v2.1 (spring 2023)

- bin-wise $q_{T,cut} \rightarrow 0$ extrapolation also for all distributions
- recoil-driven linear power corrections (relevant for Drell-Yan)
- $\gamma\gamma\gamma$ at NNLO QCD (2 ightarrow 3)
- $t\bar{t}$ at NNLO QCD (heavy-quark FS)

Motivation for having a MATRIX interface to fast-interpolation tools

Choice in MATRIX: Interface to PINEAPPL — can be converted to APPLgrid/fastNLO formats

• PDF and α_s uncertainties

- in principle possible directly in MATRIX, but very expensive in runtime and/or disk space
- PINEAPPL grids allow PDF uncertainties to be calculated a posteriori at basically no cost

• Scale (regularization and factorization) variation uncertainties

- available in MATRIX, simulaneously for different dynamic scale choices (and variation by factors)
- PINEAPPL requires dedicated grids for each dynamic scale, variation by arbitrary factors a posteriori

• Splitting of results into partonic channels

- available in MATRIX, but needs to be specified a priori (precision goals for different channels)
- PINEAPPL grids store information on luminosities to achieve channel splitting a posteriori

• Performing PDF fits based on full NNLO information

- practically impossible directly in MATRIX since repeated expensive NNLO runs would be required
- PINEAPPL grids store all information about results of higher-order calculation
- Interface to fast-interpolation tools highly desirable in particular in context of PDFs
- Goal: make all MATRIX features available in the format of PINEAPPL grids

The MUNICH/MATRIX framework for automated NNLO calculations

MATRIX — MUNICH Automates qT-subtraction and Resummation to Integrate X-sections [Grazzini, SK, Wiesemann (2018)]

- public tool to perform fully differential NNLO QCD calculations for a large class of processes
- ${\scriptstyle \bullet }$ core of the framework: the C_++ parton-level Monte Carlo generator

MUNICH — MUlti-chaNnel Integrator at swiss (CH) precision [SK]

- bookkeeping of partonic subprocesses for all contributions
- fully automated dipole subtraction for NLO calculations (massive, QCD and EW) [Catani, Seymour (1997), Catani, Dittmaier, Seymour, Trocsanyi (2002), Dittmaier (2000), SK, Lindert, Maierhöfer, Pozzorini, Schönherr (2015)]
- general amplitude interface

amplitudes 2

2-loop amplitudes

- highly efficient multi-channel Monte Carlo integration with several optimization features
- simultaneous monitoring of slicing parameter and automated extrapolation
- PYTHON script to simplify the use of MATRIX
 - $\bullet~$ installation of MUNICH and all supplementary software
 - interactive shell steering all run phases without human intervention (grid-, pre-, main-run, summary)
 - organization of parallelized running on multicore machines and commonly used clusters: SLURM, HTCONDOR, LSF, etc.

Idea of the $q_{\rm T}$ subtraction method for (N)NLO cross sections

Consider the production of a colourless final state F via $q\bar{q} \rightarrow F$ or $gg \rightarrow F$: $d\sigma_{F}^{(N)NLO}\Big|_{q_{T}\neq 0} = d\sigma_{F+jet}^{(N)LO}$ where q_{T} refers to the transverse momentum of the colourless system F [catani, Grazzini (2007)]

- $\left. {
 m d} \sigma_{
 m F}^{({
 m N}){
 m NLO}}
 ight|_{q_{
 m T}
 eq 0}$ is singular for $q_{
 m T} o 0$
 - limiting behaviour known from transverse-momentum resummation [Bozzi, Catani, de Florian, Grazzini (2006)]
- Define a universal counterterm Σ with the complementary $q_{\rm T} \rightarrow 0$ behaviour [Bozzi, Catani, de Florian, Grazzini (2006)] $d\sigma^{\rm CT} = \Sigma(q_{\rm T}/q) \otimes d\sigma^{\rm LO}$ where q is the invariant mass of the colourless system F
- Add the $q_{\rm T} = 0$ piece with the hard-virtual coefficient $\mathcal{H}_{\rm F}$, which contains the 1-(2-)loop amplitudes at (N)NLO and compensates for the subtraction of Σ [Catani, Cieri, de Florian, Ferrera, Grazzini (2013)]
- Master formula for (N)NLO cross section in $q_{\rm T}$ subtraction method

$$\mathrm{d}\sigma_{\mathrm{F}}^{(\mathrm{N})\mathrm{NLO}} = \mathcal{H}_{\mathrm{F}}^{(\mathrm{N})\mathrm{NLO}} \otimes \mathrm{d}\sigma^{\mathrm{LO}} + \left[\mathrm{d}\sigma_{\mathrm{F+jet}}^{(\mathrm{N})\mathrm{LO}} - \boldsymbol{\Sigma}^{(\mathrm{N})\mathrm{NLO}} \otimes \mathrm{d}\sigma^{\mathrm{LO}}\right]_{\mathrm{cut}_{\sigma_{\mathrm{T}}} \to \mathrm{O}}$$

all ingredients known for extension to N³LO [Luo, Yang, Zhu, Zhu (2019; 2020), Ebert, Mistlberger, Vita (2020), Cieri, Chen, Gehrmann, Glover, Huss, (2019), Camarda, Cieri, Ferrera (2021), Chen, Gehrmann, Glover, Huss, Yang, Zhu (2021)]

Extension to heavy coloured particles at NNLO QCD and beyond

Extension of $q_{\rm T}$ subtraction method to production of heavy coloured particles ($Q\bar{Q}, Q\bar{Q}X$, etc.)

$$d\sigma_{Q\bar{Q}X}^{\rm NNLO} = \mathcal{H}_{Q\bar{Q}X}^{\rm NNLO} \otimes d\sigma_{\rm LO} + \left[d\sigma_{Q\bar{Q}X+\rm jet}^{\rm NLO} - d\sigma_{Q\bar{Q}X,\rm CT}^{\rm NNLO} \right]_{\rm cut_{q_T} \to 0}$$

 counterterm accounts for IR behaviour of real contribution, including soft singularities related to emissions from final-state quarks [Catani, Grazzini, Torre (2014), Ferroglia, Neubert, Pecjak, Yang (2009), Li, Li, Shao, Yang, Zu (2013)]

- massive NLO subtraction required for real-emission part, e.g. massive dipole subtraction [Catani, Seymour (1997), Catani, Dittmaier, Seymour, Trocsanyi (2002)]
- $\mathcal{H}_{NNLO}^{Q\bar{Q}X}$ contains remainder of integrated final-state soft singularities
 - known for heavy-quark pairs [Catani, Devoto, Grazzini, Mazzitelli (2023), Angeles-Martinez, Czakon, Sapeta (2018)]
 - more involved kinematics for associated heavy-quark pair production [Devoto, Mazzitelli (to appear)]

Extension of $q_{\rm T}$ subtraction method to mixed QCD-EW corrections of $\mathcal{O}(\alpha_s^m \alpha^n)$

$$d\sigma_{\mathrm{F}}^{(m,n)} = \mathcal{H}_{\mathrm{F}}^{(m,n)} \otimes d\sigma_{\mathrm{LO}} + \left[d\sigma_{\mathrm{F,R}}^{(m,n)} - d\sigma_{\mathrm{F,CT}}^{(m,n)}
ight]_{\mathrm{cut}_{\mathrm{GT}} o 0}$$

• limitation: F contains no massless jets (for $m \ge 1$) and no massless charged particles (for $n \ge 1$) [Buonocere, Grazzini, Tramontano (2020), Buonocere (2020), De Florian, Der, Fabre (2018), Cieri, De Florian, Der, Mazzitelli (2020)]

Investigation of $r_{\rm cut} = {\rm cut}_{q_T/a}$ dependence — sample case ${\rm pp} \to \gamma \gamma + X$

Result for $r_{\rm cut} \rightarrow 0$ via extrapolation

- automated and simultaneous scan over reasonable range of $r_{\rm cut}$ values
- quadratic least- χ^2 fit with variable range

 $\sigma_{(N)NLO}(r_{cut}) = Ar_{cut}^2 + Br_{cut} + \sigma_{(N)NLO}$

- error estimate based on combination of statistical error and variation of $r_{\rm cut}$ range
- Significant $r_{\rm cut}$ dependence for processes involving isolated photons (similar between NLO and NNLO QCD)
- good agreement of extrapolated results within errors for different start values
 - $r_{\rm cut} \ge 0.15\%$ • $r_{\rm cut} > 0.05\%$ • $r_{\rm cut} > 0.001\%$
 - $r_{\rm cut} > 0.01\%$



Investigation of $r_{\rm cut} = {\rm cut}_{q_{\rm T}/q}$ dependence — sample case ${\rm pp} \to \ell^- \ell^+ \ell'^- \ell'^+ + X$

Result for $r_{\rm cut} \rightarrow 0$ via extrapolation \circ same procedure for all processes

 $\sigma_{(\mathrm{N})\mathrm{NLO}}(r_{\mathrm{cut}}) = Ar_{\mathrm{cut}}^2 + Br_{\mathrm{cut}} + \sigma_{(\mathrm{N})\mathrm{NLO}}$

- No significant r_{cut} dependence for processes without isolated photons (similar between NLO and NNLO QCD)
- good agreement of extrapolated results within errors for different start values
 - $r_{\rm cut} \ge 0.15\%$ $r_{\rm cut} \ge 0.05\%$ • $r_{\rm cut} \ge 0.01\%$
- larger cancellation between contributions (factor of ≈ 15 at $r_{\rm cut} = 0.01\%$)
- Important exception: linear power corrections induced by particular fiducial cut configurations



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Main features of EW corrections

 Shape corrections in invariant-mass distributions



Pure QED effect: photon bremsstrahlung off decay leptons (migration effect)

Negative corrections in high-energy observables



Genuine EW effect:

enhancement due to large universal Sudakov logarithms

Photon-induced processes

- inclusion via LUXQED PDFs [Manohar, Nason, Salam, Zanderighi (2016; 2017)]
 - as Born processes, e.g. $\gamma\gamma \rightarrow WW$
 - as EW corrections, from IS $\gamma \to q \bar{q}^*$ splittings
- Subdominant production modes (not maximal in α_s)
 - e.g. $q \bar{q}
 ightarrow Z^* / \gamma^*
 ightarrow t ar{t}$
 - interferences between QCD and EW production modes
 - corresponding tower of NLO contributions that cannot be uniquely qualified as QCD or EW corrections (in parts)

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Performance features of the MUNICH phase space integrator

Issue of poorly populated regions

- sample case: high-energy tails
- standard phase space optimization samples points in bulk region

Solution in MUNICH integrator

- additional runs with optimization including a general bias factor
- sophisticated automated combination with results from standard runs

Significantly improved errors

\$\mathcal{O}\$(10) and better with doubled runtime simultaneous enhancement of observables

Good performance also for off-shell regions of intermediate resonances



Available processes in MATRIX v2.1 and beyond

<i>H</i> (HTL)		NNLO QCD				
Z [Phys.Rev.Lett. 128	(<i>ll</i> / <i>vv</i>) (2022) 1, 012002, Phys.	NNLO QCD Lett.B 829 (2022) 137118]	NLO EW	NNLO QCD-EW	ggNLO QCD	(linPCs)
₩ [±] [Phys.Rev.D 103 (20	(ℓν)	NNLO QCD	NLO EW	NNLO QCD-EW	(linPCs)	
HH (HTL, [JHEP 09 (2016) 15	FT _{approx}) (1, JHEP 05 (2018) 059]	NNLO QCD				
ZH	$(\ell\ell H/ u u H)$	NNLO QCD	NLO EW			
$W^{\pm}H$	$(\ell \nu H)$	NNLO QCD	NLO EW			
$\gamma\gamma$		NNLO QCD	NLO EW			
$Z\gamma$ [Phys.Lett.B 731 (2	$(\ell\ell\gamma/ u u\gamma)$	NNLO QCD (2015) 085]	NLO EW			
$W^{\pm}\gamma$ [Jhep 07 (2015) 08	$(\ell u\gamma)$	NNLO QCD	NLO EW			

Available processes in MATRIX v2.1 and beyond

 $W^+W^ (2\ell 2\nu)$ NNLO QCD NLO EW ggNLO QCD [Phys.Rev.Lett. 113 (2014) 21, 212001. JHEP 08 (2015) 154. JHEP 08 (2016) 140. Phys.Lett.B 786 (2018) 382-389. JHEP 02 (2020) 087. Phys.Lett.B 804 (2020) 135399] $(4\ell/2\ell 2\nu/4\nu)$ NNLO QCD NLO EW ggNLO QCD ZΖ [Phys.Lett.B 735 (2014) 311-313, JHEP 08 (2015) 154, Phys.Lett.B 750 (2015) 407-410, Phys.Lett.B 786 (2018) 382-389, JHEP 03 (2019) 070. JHEP 02 (2020) 087] [Phys.Lett.B 819 (2021) 136465] $W^{\pm}Z$ $(3\ell\nu/\ell 3\nu)$ NNLO QCD NLO EW [Phys.Lett.B 761 (2016) 179-183, JHEP 05 (2017) 139, JHEP 02 (2020) 087] NNLO QCD NLO EW ggNLO QCD $\gamma\gamma\gamma$ [Phys.Lett.B 812 (2021) 136013] tŦ NNLO QCD NLO EW [Phys.Rev.D 99 (2019) 5, 051501, JHEP 07 (2019) 100, JHEP 08 (2020) 08, 027] NNLO QCD NLO EW [JHEP 03 (2021) 029] NNLO QCD NLO EW [Eur, Phys. J.C 81 (2021) 6, 491. Phys. Rev. Lett. 130 (2023) 11, 111902] $W^{\pm}b\bar{b}$ NNLO QCD NLO EW [Phys.Rev.D 107 (2023) 7, 074032]

Implemented features regarding **PINEAPPL** grids

- General interface to generate **PINEAPPL** grids at runtime
 - separate grids for each contribution and each subprocess according to run organisation in MATRIX:
 - re-organisation of convolution with PDFs for contributions with collinear splittings
 - extraction of coefficients of $\mu_{R/F}$ logarithms to reconstruct scale variations
 - parallel runs produce individual grids
 - ${\scriptstyle \circ }$ grids stored for several $\mathit{r}_{\mathrm{cut}}$ values in $\mathit{r}_{\mathrm{cut}}\text{-dependent}$ contributions
 - individual grids for each dynamic scale choice required
 - MATRIX summary routine merges all individual grids to result grids for desired orders (e.g. NNLO QCD)

• Extrapolation $r_{\rm cut} \rightarrow 0$ of PINEAPPL grids

- $\, \bullet \,$ bin-wise quadratic least- χ^2 fits to find optimal extrapolation range
 - no integration error information contained in grids, thus extracted from MATRIX
- $\circ\,$ extrapolated result grid through linear combination of fixed- $r_{\rm cut}$ grids

• Single- and double-differential distributions supported

- PINEAPPL grids only deal with single-differential distributions, but contain remapping information
- extension to multi-differential distributions straightforward, but not supported by MATRIX (yet)

Practical issues/to-be-completed features related to PINEAPPL grids

• Memory consumption of **PINEAPPL** grids (and disk space)

- $\,\bullet\,\propto\,$ number of non-trivial distribution bins
- $\, \bullet \, \propto$ number of fixed $r_{\rm cut}$ values (for $r_{\rm cut}\text{-dependent contributions})$
- $\, \bullet \, \propto$ number of luminosities (i.e. groups of luminosities)
- $\, \bullet \, \propto \,$ number of dynamic scales
- $\, \bullet \, \propto$ number of required coefficients of $\mu_{R/F}$ logarithms (up to 6 at NNLO)
- memory becomes a limitation for some contributions (mostly the NNLO counterterm)
 - several directions to avoid this problem under investigation...

• Optimized integration for subdominant phase space regions (e.g. high-energy tails)

- feature requires information about integration errors, event numbers, etc. for each distribution bin
- information available in MATRIX needs to be carefully transferred to PINEAPPL grids
- General interface to provide PDF uncertainties from **PINEAPPL** grids in MATRIX
- Complete metadata in **PINEAPPL** grids
 - store all information to make the grids fully reproducible (MATRIX version, runcards, etc.)
- Automated installation of **PINEAPPL** and all prerequisites through MATRIX script

Inclusive results with uncertainties calculated through PINEAPPL grids

Sample application from LHCHXSWG

Reduced mass and energy scan for $t\bar{t}H$ cross sections:

- NNLO QCD+NLO SM
 - $(\mu_R = \mu_F = m_t + m_H/2)$
- PDF recommendation:

PDF4LHC21_40

for partons,

LUXqed17_plus_PDF4LHC15_nnlo_100 for photons

 can be straightforwardly achieved through PINEAPPL grids, together with scale, PDF and α_s uncertainties

(theory uncertainties calculated directly in MATRIX)

$\sqrt{s}~[{\rm TeV}]$	$m_H ~[{\rm GeV}]$	XS [fb]	\pm QCD Scale Unc.	\pm THU	$\pm \; \alpha_s \; {\rm Unc.}$	\pm PDF Unc.
13	124.6	532.0	$\pm 3.1\%$	$\pm0.6\%$	$\pm1.7\%$	$\pm 2.3\%$
13	125	528.4	$\pm 3.2\%$	$\pm0.7\%$	$\pm1.7\%$	$\pm 2.3\%$
13	125.09	526.6	$\pm 3.1\%$	$\pm0.7\%$	$\pm1.7\%$	$\pm2.3\%$
13	125.38	522.7	$\pm 3.1\%$	$\pm0.7\%$	$\pm1.7\%$	$\pm2.3\%$
13	125.6	519.9	$\pm 3.1\%$	$\pm0.7\%$	$\pm1.7\%$	$\pm2.3\%$
13	126	515.4	$\pm 3.1\%$	$\pm0.7\%$	$\pm1.7\%$	$\pm2.3\%$
13.6	124.6	596.6	$\pm 3.0\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
13.6	125	589.9	$\pm2.9\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
13.6	125.09	589.6	$\pm 3.0\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
13.6	125.38	586.2	$\pm 3.0\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
13.6	125.6	583.5	$\pm 3.0\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
13.6	126	577.9	$\pm 3.1\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
14	124.6	639.7	$\pm 2.9\%$	$\pm0.7\%$	$\pm1.6\%$	$\pm 2.2\%$
14	125	636.1	$\pm 3.0\%$	$\pm0.6\%$	$\pm1.6\%$	$\pm 2.2\%$
14	125.09	633.3	$\pm 2.9\%$	$\pm0.6\%$	$\pm1.6\%$	$\pm 2.2\%$
14	125.38	632.4	$\pm 3.1\%$	$\pm0.6\%$	$\pm1.6\%$	$\pm 2.2\%$
14	125.6	627.9	$\pm 3.0\%$	$\pm0.6\%$	$\pm1.6\%$	$\pm 2.2\%$
14	126	621.2	$\pm 3.0\%$	$\pm 0.7\%$	$\pm 1.6\%$	$\pm 2.2\%$

Accuracy of distributions generated through PINEAPPL grids

Sample case: $t\bar{t}H$ production at NNLO QCD

- *p*_{T,H} distribution with 25 bins in [0 GeV; 500 GeV]
- result of bin-wise
 r_{cut} extrapolation
- agreement better than $\sim 0.03\%$ in each bin
- agreement as good as for fixed r_{cut} values and for other orders
- size of final
 PINEAPPL grid:
 ~ 375 MB

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0		0.90440995	0.00549583				9.0458193e-1	-3.63	1.88		-3.58%	1.76%
20	40	2.4605761	0.0150870			40	2.4610136e0	-3.70	1.78		-3.71%	1.78%
40	60	3.3852751	0.0100831		40	60	3.3859742e0	-3.61	1.50		-3.61%	1.50%
60	80	3.6492825	0.0211383		60	80	3.6500180e0	-3.70	1.57		-3.70%	1.57%
80	100	3.4609797	0.0186034		80	100	3.4617300e0	-4.15	2.19		-4.15%	2.19%
100		2.9717763	0.0102315		100	120	2.9723958e0	-4.02	1.85		-4.02%	1.85%
120	140	2.4616175	0.0113061		120	140	2.4621663e0	-4.38	2.18		-4.38%	2.18%
140	160	1.9688005	0.0128041		140	160	1.9692536e0	-4.84	2.75		-4.84%	2.75%
160	180	1.5219598	0.00660146		160	180	1.5223256e0	-4.58	2.19		-4.58%	2.19%
180	200	1.1913389	0.00603956		180	200	1.1916387e0	-4.94	2.64		-4.94%	2.63%
200	220	0.90771561	0.00768397	10	200		9.0795859e-1	-4.47	1.76		-4.33%	1.76%
220	240	0.70924849	0.00530301	11	220	240	7.0942032e-1	-5.11	2.54		-5.11%	2.54%
240	260	0.54602671	0.00290328	12	240	260	5.4615548e-1	-4.98	2.37		-4.99%	2.37%
260	280	0.42878350	0.00278757		260	280	4.2889888e-1	-5.37	2.81		-5.46%	2.81%
280	300	0.34270377	0.00464514	14	280	300	3.4278488e-1	-6.10	3.89		-6.09%	3.90%
300	320	0.26198858	0.00231887		300		2.6207046e-1	-5.14	2.38		-5.15%	2.38%
320	340	0.20382791	0.00266034		320	340	2.0387881e-1	-5.01	2.11		-5.04%	3.05%
340	360	0.16427982	0.00280818		340	360	1.6432641e-1	-5.17	2.17		-5.19%	2.17%
360	380	0.13332749	0.00165457	18	360	380	1.3336398e-1	-5.83	3.44		-5.82%	3.44%
380	400	0.10627041	0.00108398	19	380	400	1.0631281e-1	-6.08	3.90		-6.09%	3.90%
400	420	0.087583302	0.00146375	20	400	420	8.7610131e-2	-6.57	4.52		-6.59%	4.51%
420	440	0.069157405	0.000999297		420	440	6.9175489e-2	-5.72	2.99		-5.73%	2.84%
440	460	0.056410183	0.000777354		440	460	5.6423229e-2	-6.20	4.37		-6.20%	4.38%
460	480	0.045612428	0.000950293		460	480	4.5623885e-2	-5.81	3.02		-5.80%	3.04%
480	500	0.037404533	0.000685949	24	480	500	3.7415691e-2	-5.92	3.14		-5.92%	3.15%
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Conclusions & Outlook

The MATRIX framework for NNLO QCD calculations

• based on the MUNICH integrator, amplitudes from OPENLOOPS and dedicated 2-loop amplitudes

- v1: available processes: H, V, $\gamma\gamma$, V γ , VV at NNLO QCD for all leptonic decay channels
 - combination of NNLO QCD and NLO EW corrections for Drell-Yan and massive diboson processes
 - leading N³LO contributions in terms of NLO QCD corrections to loop-induced gluon fusion channels
- recoil-driven linear power corrections and bin-wise $r_{\rm cut}$ extrapolation for distributions v2.1:
 - new processes: $\gamma\gamma\gamma\gamma$ (first 2 \rightarrow 3 application), $t\bar{t}$ (heavy-quark final state)

Interface to PINEAPPL interpolation grids in MATRIX under construction • general interface established for NNLO QCD and NLO EW computations • extrapolation $r_{cut} \rightarrow 0$ in q_T -subtraction approach implemented on level of interpolation grids

- single- and double-differential distributions available, reproducing direct results with high accuracy
- New MATRIX v2.2 release with PINEAPPL interface planned as soon as remaining issues are fixed!

v2:

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Stefan Kallweit (UNIMIB)

MATRIX alle Hawaii

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Stefan Kallweit (UNIMI

MATRIX alle Hawai

May 4, 2023, xFitter External meeting

Supplying MUNICH/MATRIX with 1-loop amplitudes

Process-independent interfaces to general automated amplitude generators

- general code and process libraries
- on-the-fly tensor reduction [Buccioni, Pozzorini, Zoller (2018)] with hybrid-precision stability system
- scalar integrals from COLLIER [Denner, Dittmaier, Hofer (2006); Denner, Dittmaier (2011)] or ONELOOP [van Hameren (2011)]

 RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati (2017)] v2 [Denner, Lang, Uccirati (2017)]
 , written in FORTRAN

- on-the-fly generation of amplitudes
- tensor reduction and scalar integrals via COLLIER [Denner, Dittmaier, Hofer (2006); Denner, Dittmaier (2003, 2006, 2011)]
- different model files available, also for SMEFT and BSM applications
- ${\scriptstyle \bullet }$ modular structure of ${\scriptstyle MUNICH}$ allows other generators to be interfaced as well

Several dedicated interfaces developed in context of MATRIX applications

- Ioop×tree and Ioop×Ioop colour (and spin) correlators
- helicity amplitudes, colour-stripped amplitudes to construct 4-colour correlators
- $\bullet\,$ imaginary parts of loop $\times tree$ amplitudes and correlators, helicity-flip amplitudes

Interfacing dedicated 2-loop amplitudes to MUNICH/MATRIX

- Higgs, Drell–Yan, VH, $\gamma\gamma$, V γ production
 - $\circ\,$ direct implementation of public analytic results, e.g. for V γ [Gehrmann, Tandredi (2012)]
- VV production qqVVAMP [Gehrmann, von Manteuffel, Tancredi (2015)] and ggVVAMP [von Manteuffel, Tancredi (2015)] libraries
 - C++ libraries using GINAC [Bauer, Frink, Kreckel (2002); Vollinga, Weinzierl (2005)] and CLN for arbitrary precision arithmetics
 - IBP approach, generated using MATHEMATICA, FORM [Vermaseren et al.], REDUZE2 [von Manteuffel, Studerus ('12)]
 - independent calculation of amplitudes in [Caola, Henn, Melnikov, Smirnov, Smirnov (2015; 2016)]
 - Higgs-mediated helicity amplitudes with full m_t dependence from [Harlander, Prausa, Usovitsch (2019; 2020)]
- $\gamma\gamma\gamma$ production amplitudes from [Abreu, Page, Pascual, Sotnikov ('20)]
 - C++ library, generated by CARAVEL [Abreu et al. (2020)], applying PENTAGONFUNCTIONS++ [Chicherin, Sotnikov (2020)]
 - numerical unitarity and analytic reconstruction techniques [Ita (2015); Abreu et al. (2018; 2018; 2019; 2019)]
- HH production (full mt dependence) HHGRID library [Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)]
 - PYTHON based numerical interpolation of amplitude grid
 - generated by 2-loop extension of GOSAM [Jones (2016)], REDUZE2 [von Manteuffel, Studerus (12)], SECDEC3 [Borowka et al. (2015)]
- $\mathbf{Q}\mathbf{\bar{Q}}$ production amplitude grids from [Bärnreuther, Czakon, Fiedler (2014)]
 - FORTRAN routine for numerical interpolation of 2-dimensional grid, improved by expansions

Recoil-driven linear power corrections in neutral-current Drell-Yan process

Transverse-momentum cuts on undistinguished particles in two-body final states introduce enhanced sensitivity to low momentum scales [Salam, Slade (2021)]

• Linear power corrections (linPCs) in context of q_T subtraction

Recoil prescription can be used to predict linPCs also in fixed-order calculations [Buonocore, SK, Rottoli, Wiesemann (2022), Camarda, Cieri, Ferrera ('21)]:

$$\Delta\sigma^{\mathsf{linPCs}}(r_{\mathrm{cut}}) = \int d\Phi_F \int_{\epsilon}^{r_{\mathrm{cut}}} dr' \left(\frac{d\sigma^{\mathrm{CT}}}{d\Phi_F dr'} \Theta_{\mathrm{cuts}}(\Phi_F^{\mathrm{rec}}) - \frac{d\sigma^{\mathrm{CT}}}{d\Phi_F dr'} \Theta_{\mathrm{cuts}}(\Phi_F) \right)$$

• Φ_F^{rec} describes frame where system F is assigned a recoil q_T (boost from Collins–Soper frame, but precise prescription irrelevant)

- Adding the contribution $\Delta \sigma^{\text{linPCs}}(r_{\text{cut}})$ reduces leading (recoil-driven) r_{cut} dependence from linear (without linPCs) to (at most) quadratic
 - Illustration for symmetric cuts at NLO (upper plot) and NNLO (lower plot; reference result from NNLOjet [Bizon et al. (2021)])



have been resummed to all orders for s-channel (DY, Higgs) production [Ebert, Michel, Stewart, Tackmann (2021); Billis, Dehnadi, Ebert, Michel, Tackmann (2021)]

Distributions with linPCs for neutral-current DY process with symmetric cuts

Sample distribution: ℓ^+ rapidity at NLO (left) and NNLO (right)

- up to $\sim 2\%$ deviations for highest considered value $r_{\rm cut} = 1\%$ without linPCs
- good agreement between considered r_{cut} values with linPCs (within errors)

Note: The extrapolated results with linPCs and without linPCs agree well within errors!

- higher efficiency with linPCs (larger r_{cut} values sufficient)
- accurate results also from binwise extrapolation without including linPCs





Recoil-driven linear power corrections for different fiducial cut configurations



• similarly sizable linPCs (with opposite sign) for symmetric and asymmetric cuts

• linPCs absent for staggered cuts (as long as $q_T < \delta p_T$) \Rightarrow also for other alternative cuts [Salam, Siade (2021)]

Recoil-driven linear power corrections for diboson processes

Investigation of linPCs for diboson processes (two-body kinematics and symmetric cuts)



- For ZZ production, linPCs from recoil prescription reduce *r*_{cut} dependence to (at most) quadratic
 - formally proven only for s-channel production [Ebert, Michel, Stewart, Tackmann (2021)]
- For $\gamma\gamma$ production, $r_{\rm cut}$ dependence from photon isolation dominates over recoil-driven linPCs

Breakdown into partonic channels for $\gamma\gamma$ case



linear r_{cut} dependence
 in qq̄ channel only due
 to kinematic effects



[Buonocore, SK, Rottoli, Wiesemann (2022)]

rightarrow cured by recoil-driven linPCs for $q\bar{q}$ channel

Note: Recoil-driven linPCs absent for staggered cuts (e.g. on |y|-ordered bosons), like in Drell-Yan case

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Summary of ATLAS diboson measurements

[ATLAS collaboration (2022)]



.....

Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,V_2}}$

Both corrections sizable, particularly in high-energy tails of distributions

 approximation of leading O(α_sα) effects desirable

Different combination approaches

additive:

 $d\sigma^{
m LO}(1+\delta^{
m (N)NLO}_{
m QCD}+\delta^{
m NLO}_{
m EW})$

• multiplicative:

 $d\sigma^{
m LO}(1+\delta^{
m (N)NLO}_{
m QCD})(1+\delta^{
m NLO}_{
m EW})$

• multiplicative (only $q\bar{q}$):

 $d\sigma_{
m qar q}^{
m LO}(1+\delta_{
m qar q}^{
m (N)NLO})(1+\delta_{
m qar q,EW}^{
m NLO}) \ +\sigma_{\gammam ind.,EW}^{
m NLO}$



Factorized approaches well motivated for **genuine VV observables** (dominated by hard-VV topologies) • catch leading mixed QCD–EW effects and may thus be considered preferrable

Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,V1}}$

Situation more involved in presence of so-called **giant** *K*-factors

- QCD corrections in tails dominated by hard-Vj topologies
- also large positive EW corrections (photon-induced hard-Vj topologies)
- additive underestimates EW effects
- multiplicative combination multiplies large QCD and EW K-factors
 discarded
- multiplicative (only qq̄) shows expected Sudakov behaviour, but overestimates the EW effects (VV K-factor applied in hard-Vj region)



None of the approaches works perfectly well for observables dominated by hard-Vj topologies merged prediction, full mixed QCD-EW calculation, or phase space restriction to hard-VV topologies

Combination of QCD and EW corrections for diboson production – $p_{\rm T,V_2}/p_{\rm T,V_1}$

Restriction to hard-VV topologies

- direct requirement on the hardness of the two vector bosons
- moderate jet veto to suppress hard-Vj topologies: $H_{\rm T}^{\rm jet} < 0.2 H_{\rm T}^{\rm lep}$

Illustration of effect on distribution in $r_{21} = p_{T,V_2}/p_{T,V_1}$ at NLO QCD ($r_{21} = 1$ for LO kinematics)

- only baseline cuts (upper panels)
- \blacktriangleright cross section peaked at $r_{21}\gtrsim 0.8$; widely unaffected by $H_{\mathrm{T}}^{\mathrm{jet}}$ cut
- $\bullet~$ region $p_{\mathrm{T},\mathrm{V}_1} > 1\,\mathrm{TeV}$ (lower panels)
 - second peak at $r_{21} \lesssim 0.3$ where hard-Vj topologies dominate; completely removed by $H_{\mathrm{T}}^{\mathrm{jet}}$ cut



Remaining cross section after application of $H_{\rm T}^{\rm jet}$ cut completely dominated by the (desired) hard-VV region

Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,V1}}$ – $H_{\mathrm{T,iet}}$ cut

With $H_{\rm T}^{\rm jet} < 0.2 H_{\rm T}^{\rm lep}$, cross section dominated by hard-VV region

- justification to apply NLO EW correction factor on (N)NLO QCD cross sections
- additive underestimates EW effects; difference to multiplicative would overestimate uncertainties
- both multiplicative approaches well motivated to catch leading effects from mixed QCD-EW corrections
 - difference between the two as a rough estimate of O(α_sα) uncertainties



 Restriction to hard-VV topologies reduces uncertainties from mixed QCD–EW higher-order effects, but should also increase the sensitivity of experimental searches for BSM effects (like AGCs)

NLO QCD corrections to loop-induced gluon channel in ZZ/WW production



only LO-accurate at O(α_s²)
 enhanced by large gluon luminosity
 presumably dominant O(α_s³) contribution

Approximate nNNLO QCD prediction

- full $m_{\rm t}$ dependence in 1-loop terms
- massless 2-loop amplitudes from ggVVAMP [von Manteuffel, Tancredi (2015)]
 - reweighted by full-mt Born amplitude

Effect of NLO QCD in gg channel

- highest impact in low-energy regions
- enhancement beyond NNLO QCD scale band



Best available fixed-order predictions for ZZ/WW production

- NNLO QCD for qq̄ channel
- NLO EW combination for $q\bar{q}$ channel
- NLO QCD corrections for gg channel
- available for all VV processes in MATRIX v2 [Grazzini, SK, Wiesemann (2021)]

(refinements on m_t effects in gg amplitudes still to be added [Grazzini, SK, Wiesemann, Yook (2021)])

Diboson production beyond fixed order

- resummation ($p_{T,VV}$, $p_{T,jet}^{veto}$, ...) MATRIX+RADISH [SK, Re, Rottoli, Wiesemann (2020)]
- event generation at NNLO QCD
 NNLOPS [WW: Re, Wiesemann, Zanderighi (2018)]

MINNLO_{PS} [Z₇: Lombardi, Wiesemann, Zanderighi (2021); WW: Lombardi, Wiesemann, Zanderighi (2021); ZZ: Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi (2022)]

GENEVA

 $\begin{array}{l} [\gamma\,\gamma: \mbox{ Alioli, Broggio, Gavardi, SK, Lim, Nagar, Napoletano, Rottoli (2021) \\ ZZ: \mbox{ Alioli, Broggio, Gavardi, SK, Lim, Nagar, Napoletano (2021); \\ W\gamma: \mbox{ Cridge, Lim, Nagar (2022)]} \end{array}$



data from [JHEP 04, 048 (2019)]

data from [Eur. Phys. J. C 79 (2019) 884]

NLO QCD corrections to loop-induced gluon channel in ZZ/WW production

Integrated cross sections for $pp \rightarrow e^- e^+ \mu^- \mu^+$ (setup of ATLAS 8 TeV ZZ analysis [JHEP 01, 099 (2017)])

\sqrt{s}	8 TeV	13 TeV	8 TeV	13 TeV
	σ [f	$\sigma/\sigma_{\rm NI}$	$_{\rm LO} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(1)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
qqNNLO	$12.09(2)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	+7.0%	+8.6%
	σ [f	$\sigma/\sigma_{ m gg}$	LO - 1	
ggLO	$0.79355(6)^{+28.2\%}_{-20.9\%}$	$2.0052(1)^{+23.5\%}_{-17.9\%}$	0%	0%
ggNLOgg	$1.4787(4)^{+15.9\%}_{-13.1\%}$	$3.626(1)^{+15.2\%}_{-12.7\%}$	+86.3%	+80.8%
ggNLO	$1.3892(4)^{+15.4\%}_{-13.6\%}$	$3.425(1)^{+13.9\%}_{-12.0\%}$	+75.1%	+70.8%
	σ [f	$\sigma/\sigma_{\rm NI}$	$_{\rm LO} - 1$	
NNLO	$12.88(2)^{+2.8\%}_{-2.2\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	+14.0%	+18.7%
nNNLO	$13.48(2)^{+2.6\%}_{-2.3\%}$	24.97(2) ^{+2.9%}	+19.3%	+25.8%

[Grazzini, SK, Wiesemann, Yook (2019)]

 relatively large corrections of 5% - 7% for ZZ, exceeding the NNLO QCD uncertainty bands (slightly smaller effect of 2% - 3% for WW) Integrated cross sections for $pp \rightarrow e^- \mu^+ \nu_\mu \bar{\nu}_e$ (setup of ATLAS 13 TeV WW analysis [EPJC 79, 884 (2019)])

		[Grazzini,	SK, Wiesemar	in, Yook (2020)
\sqrt{s}	jet veto	no veto	jet veto	no veto
13 TeV	σ[fb]	$\sigma/\sigma_{\rm NI}$.o - 1
LO	$284.11(1)^{+5.5\%}_{-6.5\%}$	$284.11(1)^{+5.5\%}_{-6.5\%}$	-15.5%	-43.7%
NLO	$336.42(3)^{+1.6\%}_{-2.0\%}$	504.36(3) ^{+4.1%}	+0.%	+0.%
qą̄NNLO	$336.8(2)^{+0.7\%}_{-0.5\%}$	$558.5(2)^{+2.1\%}_{-1.9\%}$	+0.1%	+10.7%
	σ[$\sigma/\sigma_{ m gg}$	$_{\rm LO} - 1$	
ggLO	$21.965(4)^{+25.7\%}_{-18.4\%}$	$21.965(4)^{+25.7\%}_{-18.4\%}$	+0.%	+0.%
ggNLOgg	$31.68(6)^{+10.8\%}_{-10.6\%}$	$38.49(6)^{+15.9\%}_{-13.3\%}$	+44.2%	+75.2%
ggNLO	$28.79(6)^{+7.8\%}_{-9.1\%}$	$37.57(6)^{+15.3\%}_{-13.0\%}$	+31.1%	+71.0%
	σ[fb]	$\sigma/\sigma_{\rm NI}$.o - 1
NNLO	$358.7(2)^{+1.2\%}_{-0.9\%}$	$580.5(2)^{+2.9\%}_{-2.6\%}$	+6.6%	+15.1%
nNNLO	$365.6(2)^{+0.4\%}_{-0.6\%}$	$596.1(2)^{+2.8\%}_{-2.6\%}$	+8.7%	+18.2%
	σ[fb]	$\sigma/\sigma_{\rm nNN}$	$_{\rm NLO} - 1$
$nNNLO_{\mathrm{EW}}$	$354.3(2)^{+0.5\%}_{-0.8\%}$	$580.2(2)^{+2.7\%}_{-2.6\%}$	-3.1%	-2.7%

• similar size as (negative) EW corrections

Summary of ATLAS triboson, VBF and VBS measurements

[ATLAS collaboration (2022)]



VBF, VBS, and Triboson Cross Section Measurements Status: February 2022



Triboson production at NNLO QCD accuracy

Relevance of triboson production

- important SM test important SM test
- background for BSM searches
- very clean signatures in leptonic decay channels
- at least $\gamma\gamma\gamma$ and $V\gamma\gamma$ processes measured already with statistics collected during LHC Run I
 - much smaller cross sections for massive VVV
 - only WWW and WWZ observed recently

Prospects for triboson predictions at NNLO

- two-loop amplitudes as the bottleneck (only available for triphoton production by now)
- NNLO subtraction methods applicable in principle
- complicated calculation (amplitudes, phase spaces)
 - challenge for technical performance, but feasible in the MATRIX framework

[ATLAS collaboration (2021)]



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Triphoton production at NNLO QCD accuracy

First MATRIX calculation for genuine 2 \rightarrow 3 process at NNLO QCD

• $q_{\rm T}$ subtraction method for colourless final states directly applicable:

 $d\sigma_{\rm NNLO}^{\gamma\gamma\gamma} = \mathcal{H}_{\rm NNLO}^{\gamma\gamma\gamma} \otimes d\sigma_{\rm LO} + \left[d\sigma_{\rm NLO}^{\gamma\gamma\gamma+\rm jet} - d\sigma_{\rm NNLO}^{\gamma\gamma\gamma,\rm CT} \right]_{r_{\rm out} \to 0}$

- remarkable numerical control over slicing parameter dependence
- full agreement with independent calculation [Chawdhry, Czakon, Mitov, Poncelet (2020)]

Further important ingredients of the calculation

- highly efficient phase space integration in MUNICH [SK]
- fast and stable 1-loop amplitudes from OPENLOOPS [Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller (2019)]
- fast and stable 2-loop amplitudes [Abreu, Page, Pascual, Sotnikov (2021)] generated with CARAVEL, using PENTAGONFUNCTIONS++ [Abreu et al. (2020)] [Chicherin, Sotnikov (2020)]
 - talks by Vasily Sotnikov and Ben Page







Triphoton production at NNLO QCD accuracy

Comparison with ATLAS data at 8 TeV

- perfect agreement with NNLO QCD predictions, due to both normalization and shape corrections
- significant discrepancies at lower orders



[SK, Sotnikov, Wiesemann (2021)]



- great numerical performance also with refined resolution and in suppressed phase space regions
- MATRIX fully suitable for triboson processes



[SK, Sotnikov, Wiesemann (2021)] data from [Phys. Lett. B 781 (2018) 55]



Stefan Kallweit (UNIMIB

May 4, 2023, xFitter External meeting

Feasibility studies on massive triboson production at NNLO QCD accuracy

 $\sigma_{\text{WATRIX}}^{\text{MATRIX}}(r_{\text{ext}} \rightarrow 0)$ $\sigma_{\rm NNLO}^{\rm MATRIX}(r_{est})$

aMATRIX(real)

Studies on $r_{\rm cut}$ dependence for inclusive massive VVV production processes

very good numerical control
 permille-level precision achievable within reasonable runtime





Obviously, no robust conclusion on the size of NNLO QCD corrections can be drawn without knowledge of the two-loop amplitudes

Finite remainder of two-loop amplitudes set to zero for these technical feasibility studies.

• impact of finite remainder of two-loop amplitudes $H^{(2)}$ typically small, only $\mathcal{O}(2\%)$ for VV processes • NNLO K-factors without $H^{(2)}$: $\mathcal{O}(1-2\%)$ ($\approx +6\%$ from gg channel for WWZ)

no huge NNLO QCD corrections expected for massive VVV production processes

Feasibility studies on V $\gamma\gamma$ production processes at NNLO QCD accuracy

Studies on r_{cut} dependence for $V\gamma\gamma$ processes (standard cuts and photon isolation) • large power corrections due to photon isolation (as for $\gamma\gamma\gamma$), but numerically well under control



• impact of finite remainder of two-loop amplitudes $H^{(2)}$ small, only $\mathcal{O}(2-3\%)$ for V γ processes • NNLO K-factors without $H^{(2)}$: $\mathcal{O}(10-30\%)$ (depending on final state and fiducial cuts)

• comparable size of NNLO QCD corrections as for V γ expected for V $\gamma\gamma$ processes

Production of heavy coloured particles at NNLO QCD accuracy

Extension of $q_{\rm T}$ subtraction method to production of heavy coloured particles (e.g. top-quark pairs)

$$d\sigma_{\rm NNLO}^{t\bar{t}} = \mathcal{H}_{\rm NNLO}^{t\bar{t}} \otimes d\sigma_{\rm LO} + \left[d\sigma_{\rm NLO}^{t\bar{t}+\rm jet} - d\sigma_{\rm NNLO}^{t\bar{t},\rm CT} \right]_{r_{\rm eut} \to 0}$$

- counterterm accounts for IR behaviour of real contribution, including soft singularities related to emissions from final-state quarks [Catani, Grazzini, Torre (2014), Ferroglia, Neubert, Pecjak, Yang (2009), Li, Li, Shao, Yang, Zu (2013)]
- *H*^{tt}_{NNLO} contains remainder of integrated final-state soft singularities
 [Catani, Devoto, Grazzini, Mazzitelli (to appear), Angeles-Martinez, Czakon, Sapeta (2018)]
- massive NLO subtraction required for real-emission part, e.g. massive dipole subtraction [Catani, Seymour (1997), Catani, Dittmaier, Seymour, Trocsanyi (2002)]

Associated heavy-quark pair production ($t\bar{t}H$, $t\bar{t}V$, ...) with identical singularity structure

numerical solutions for required for evaluation of the soft function due to more involved kinematics

- no back-to-back configuration of heavy quarks
- proof-of-principle calculation for non-diagonal channels in $tar{t}H$ [Catani, Fabre, SK, Grazzini (2021)]
- ${\scriptstyle \bullet}\,$ two-loop amplitudes as the bottleneck for any beyond 2 \rightarrow 2 NNLO calculations

Top-quark pair production at NNLO QCD accuracy

First MATRIX calculation for colourful final states at NNLO QCD

- 2-loop amplitudes from numerical result [Bärnreuther, Czakon, Fiedler (2014)]
- slicing parameter dependence under good numerical control; investigation after splitting into partonic channels
 - full agreement with TOP++ [Czakon, Mitov (2014)]
- successful validation also on the level of differential distributions [Catani, Devoto, Grazzini, SK, Mazzitelli (2019)]

(comparison against results from [Czakon, Heymes, Mitov (2017)])



[Catani, Devoto, Grazzini, SK, Mazzitelli, Sargsyan (2019)]



Top-quark pair production at NNLO QCD accuracy

Good agreement with (multi)differential CMS data

- lowest $m_{t\bar{t}}$ bin problematic: sensitivity to m_t value, threshold effects, extrapolation to stable tops, ...
- instabilities related to $p_{T,t\bar{t}} \rightarrow 0$ region
 - would require resummation/shower matching



Indications for perturbative convergence

 widely overlapping bands from NLO to NNLO with reduced scale variation uncertainties



[Catani, Devoto, Grazzini, SK, Mazzitelli (2019)] data from [Phys. Rev. D 97 (2018) 112003]

Bottom-quark pair production at NNLO QCD accuracy

Application to bottom quarks

- conceptionally similar to $t\overline{t}$ production
- applications in all LHC experiments
- larger uncertainties due to lower scales
 - reduction through ratios with partial cancellation of uncertainties
- numerically more challenging $(m_b \ll m_t)$
 - calculation still remarkably stable





[ALICE Collaboration (2021)]





MATRIX alle Hawai

May 4, 2023, xFitter External meeting

Feasibility studies on associated heavy-guark pair production at NNLO QCD accuracy

Studies on $r_{\rm cut}$ dependence for inclusive $Q\bar{Q} + X$ processes

- proof-of-principle for non-diagonal channels in $t\bar{t}H$ [Catani, Fabre, SK, Grazzini (2021)]
- finite remainders of two-loop amplitudes and of the soft function neglected in these studies
 - no reliable estimate of NNLO QCD result, but cancellation of IR divergences well under control
 - permille-level precision achievable within reasonable runtime



Mixed NNLO QCD-EW calculation for production of massive charged particles

Extension of $q_{\rm T}$ subtraction method to mixed QCD-EW corrections of $\mathcal{O}(\alpha_s^m \alpha^n)$

$$d\sigma_{(m,n)}^{\ell\ell/\ell\nu} = \mathcal{H}_{(m,n)}^{\ell\ell/\ell\nu} \otimes d\sigma_{\rm LO} + \left[d\sigma_{(m,n)}^{\ell\ell/\ell\nu,\rm R} - d\sigma_{(m,n)}^{\ell\ell/\ell\nu,\rm CT} \right]_{r_{\rm cut} \to 0}$$

- m = 1(2) and n = 0: (N)NLO QCD corrections
- m = 0 and n = 1: NLO EW corrections
- m = 1 and n = 1: mixed NNLO QCD-EW corrections

(limitation: no massless jets (for $m \ge 1$) and no massless charged particles (for $n \ge 1$) allowed at LO)

Strategy to cancel IR singularities in mixed QCD-EW corrections

abelianisation procedure, starting from heavy-quark pair production at NNLO QCD

← for neutral final states, abelianisation of standard $q_{\rm T}$ subtraction method is sufficient (mixed QCD-QED corrections on $pp \rightarrow Z$ [De Florian, Der, Fabre (2018)], $pp \rightarrow \nu \bar{\nu}$ [Cieri, De Florian, Der, Mazzitelli (2020)])

 \circ colourless final state ($\ell\ell/\ell
u$) results in soft final-state singularities of pure QED origin

much simpler IR structure than in heavy-quark pair production at NNLO QCD

• finite charged-lepton mass required to regularize collinear final-state singularities

Towards mixed NNLO QCD-EW corrections for Drell-Yan processes

Mixed NNLO QCD-QED corrections

- on-shell Z production [De Florian, Der, Fabre (2018)]
- off-shell Z $\rightarrow \nu \bar{\nu}$ production [Cieri, De Florian, Der, Mazzitelli (2020)]
- $\label{eq:stability} \begin{array}{l} \bullet \quad \text{on-shell Z production with decay, including} \\ \begin{array}{l} \text{NLO QCD (production)} \times \text{ NLO QED (decay)} \\ \\ \text{[Delto, Jaquier, Melnikov, Röntsch (2019)]} \end{array} \end{array}$

Mixed NNLO QCD-EW corrections for on-shell DY production

- on-shell Z production [Bonciani, Buccioni, Rana, Vicini (2020)]
- on-shell W production [Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch (2021)]
- estimate of the impact on W mass extraction [Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch (2021)]

Mixed NNLO QCD-EW corrections beyond the on-shell approximation

• pole approximation (PA) [Dittmaier, Huss, Schwinn (2014 & 2015)]

Recent progress towards full mixed NNLO QCD-EW corrections

- two-loop master integrals [Bonciani, Di Vita, Mastrolia, Schubert (2016), Heller, von Manteuffel, Schabinger (2019), Hasan, Schubert (2020)]
- two-loop amplitude for neutral current DY [Heller, von Manteuffel, Schabinger, Spiesberger (2020)]
- complete result for $\mathcal{O}(n_{\mathrm{F}}\alpha_{s}\alpha)$ effects [Dittmaier, Schmidt, Schwarz (2020)]

Mixed NNLO QCD-EW calculation within the MATRIX framework with massive leptons (muons)

- off-shell $pp \rightarrow W \rightarrow \mu^+ \nu_{\mu}$ calculation with two-loop amplitudes in a reweighted PA approach [Buonocore, Grazzini, SK, Savoini, Tramontano (2021)]
- off-shell $pp \rightarrow Z/\gamma \rightarrow \mu^+\mu^-$ calculation with full two-loop amplitudes [Bonciani, Rana, Vicini (to appear)] [Bonciani, Buoncore, Grazzini, SK, Tramontano, Rana, Vicini ('21)]

Triboson production

Justification of (reweighted) pole approximation approaches

PA vs. reweighted PA at NLO EW

$$\begin{split} H_{\mathrm{PA}}^{(0,1)} &= 2\mathrm{Re}\left(\mathcal{M}_{\mathrm{fin}}^{(0,1)}\mathcal{M}^{(0,0)*}\right)_{\mathrm{PA}} \middle/ \left|\mathcal{M}^{(0,0)}\right|^2 \\ H_{\mathrm{PA,rwg}}^{(0,1)} &= 2\mathrm{Re}\left(\mathcal{M}_{\mathrm{fin}}^{(0,1)}\mathcal{M}^{(0,0)*}\right)_{\mathrm{PA}} \middle/ \left|\mathcal{M}_{\mathrm{PA}}^{(0,0)}\right|^2 \end{split}$$

Reweighted PA versions at NNLO QCD-EW

$$\begin{split} H_{\rm PA, rwg_B}^{(1,1)} &= H_{\rm PA}^{(1,1)} \times \left| \mathcal{M}^{(0,0)} \right|^2 / \left| \mathcal{M}_{\rm PA}^{(0,0)} \right|^2 \\ H_{\rm PA, rwg_V}^{(1,1)} &= H_{\rm PA}^{(1,1)} \times H^{(0,1)} / H_{\rm PA}^{(0,1)} \end{split}$$



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Results for mixed NNLO QCD-EW corrections in off-shell W production

Setup and integrated results

• NNPDF31_nnlo_as_0118_luxqed
$$\mu_R = \mu_F = m_W$$

•
$$p_{\mathrm{T},\mu} > 25 \,\mathrm{GeV}\,, \quad |y_{\mu}| < 2.5\,, \quad p_{\mathrm{T},\mathrm{miss}} > 25 \,\mathrm{GeV}$$

		NLO QCD	NLO EW	NNLO QCD	NNLO QCD-EW
σ [pb]	$\sigma_{ m LO}$	$\sigma^{(1,0)}$	$\sigma^{(0,1)}$	$\sigma^{(2,0)}$	$\sigma^{(1,1)}$
qq	5029.2	970.5(3)	-143.61(15)	251(4)	- 7.0(1.2)
qg	—	-1079.86(12)	—	-377(3)	39.0(4)
$q(g)\gamma$	—	_	2.823(1)	_	0.055(5)
$q(\bar{q})q'$	_	_	—	44.2(7)	1.2382(3)
gg	—	-	—	100.8(8)	—
tot	5029.2	-109.4(4)	-140.8(2)	19(5)	33.3(1.3)
		-2.2%	-2.8%	+0.4%	+0.6%

- large cancellations between partonic channels in NLO and NNLO QCD corrections
- similar size of NLO QCD and EW corrections
- no dedicated scale dependence studies performed

Differential distribution in p_{T,μ^+}



[Buonocore, Grazzini, SK, Savoini, Tramontano (2021)]

Results for mixed NNLO QCD-EW corrections in off-shell Z production

Setup and integrated results

• NNPDF31_nnlo_as_0118_luxqed $\mu_R = \mu_F = m_Z$ • $p_{T,\mu} > 25 \text{ GeV}$, $|y_{\mu}| < 2.5$, $m_{\mu\mu} > 50 \text{ GeV}$

		NLO QCD	NLO EW	NNLO QCD	NNLO QCD-EW
σ [pb]	$\sigma_{ m LO}$	$\sigma^{(1,0)}$	$\sigma^{(0,1)}$	$\sigma^{(2,0)}$	$\sigma^{(1,1)}$
qq	809.56(1)	191.85(1)	-33.76(1)	49.9(7)	-4.8(3)
qg	—	-158.08(2)	—	-74.8(5)	8.6(1)
$q(g)\gamma$	_	_	-0.839(2)	_	0.084(3)
$q(\bar{q})q'$	—	_	—	6.3(1)	0.19(0)
gg	_	_	_	18.1(2)	—
$\gamma\gamma$	1.42(0)	_	-0.0117(4)	—	—
tot	810.98(1)	33.77(2)	-34.61(1)	-0.5(9)	4.0(3)
		+4.2%	-4.3%	-0.1%	+0.5%

- large cancellations between partonic channels in NLO and NNLO QCD corrections
- almost complete (accidental) compensation between NLO QCD and EW corrections

Differential distribution in p_{T,μ^+}



[Bonciani, Buonocore, Grazzini, SK, Tramontano, Rana, Vicini ('21)]

Iriboson production

Results for mixed NNLO QCD-EW corrections in off-shell Z production

Differential distribution in $m_{\mu\mu}$



Numerical control over power corrections by binwise $\textit{r}_{\rm cut} \rightarrow 0$ extrapolation



 inclusion of power corrections could significantly improve numerical performance

NNLO QCD subtraction/slicing methods and implementations (status Oct 2021)

Subtraction/slicing methods

- q_T subtraction [Catani, Grazzini (2007)]
- N-jettiness subtraction [Boughezal, Focke, Liu, Petriello (2015); Gaunt, Stahlhofen, Tackmann, Walsh (2015)]
- Antenna subtraction [Gehrmann, Gehrmann-De Ridder, Glover (2005)]
- Sector-improved residue subtraction [Czakon (2010); Boughezal, Melnikov, Petriello (2012)]
- ColorFul subtraction [Somogyi, Trocsanyi, Del Duca (2005)]
- Nested soft-collinear subtraction [Caola, Melnikov, Röntsch (2017)]
- Analytic local sector subtraction [Magnea, Maina, Pelliccioli, Signorile-Signorile, Torrielli, Uccirati (2018)]
- Projection to Born [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)]
- Geometric subtraction [Herzog (2018)]

General (public) frameworks

- MATRIX (q_T slicing) [Grazzini, SK, Wiesemann, ...]
 - Z, W, H, $\gamma\gamma$, Z γ , W γ , WW, ZZ, WZ
 - ZH, WH, HH, $t\bar{t}$, $b\bar{b}$, $\gamma\gamma\gamma$, ...
- MCFM (*N*-jettiness slicing) [Campbell, K. Ellis, Giele, Neumann, Williams, ...]
 - Z, W, H, ZH, WH, $\gamma\gamma$, Z γ • W γ , γ j, Zj, Wj, Hj, ...
- NNLOJET (antennna subtraction) [Gehrmann, Gehrmann-de Ridder, Glover, Huss, Chen, Gauld, ...]
 jj, γj, Zj, Wj, Hj, Zb, ...
- **STRIPPER** (sector-improved residue subtraction) [Czakon, Mitov, Poncelet, Chawdhry...]
 - $t\bar{t}$, jj, WW, Wc, $\gamma\gamma\gamma$, $\gamma\gamma$ j, jjj, ...

- . . .
- \hookrightarrow Extension beyond 2 \rightarrow 2 conceptionally straightforward if amplitudes become available!

• . . .

Recent achievements in (N)NNLO QCD calculations (status Oct 2021)

First $2 \rightarrow 3$ calculations at NNLO QCD

- $\gamma \gamma \mathbf{j}$ [Chawdhry, Czakon, Mitov, Poncelet ('21)]
- III [Czakon, Mitov, Poncelet ('21)]

Recent achievements in 2-loop $2 \rightarrow 3$ amplitudes

- leading-colour jjj [Abreu, Page, Pascual, Sotnikov (2021), Abreu, Febres Cordero, Ita, Page, Sotnikov (2021)] ۲
- $a\bar{a} \rightarrow \gamma \gamma i$ [Agarwal, Buccioni, von Manteuffel, Tancredi ('21)]
- $\bullet ~~gg \rightarrow \gamma \gamma g ~~ {}^{[{\rm Badger, ~Brønnum-Hansen, ~Chicherin, ~Gehrmann, ~Hartanto,} \\ {}^{{\rm Henn, ~Marcoli, ~Moodie, ~Peraro, ~Zoia} ~~ ('21)] }$
- leading-colour $Wb\bar{b}$ [Badger, Hartanto, Zoia (2021)]
- leading-colour $Hb\bar{b}$ [Badger, Hartanto, Kryś, Zoia ('21)]

Heavy-quark loops for $gg \rightarrow$ diboson processes

- HH [Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016), Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, Wellmann (2019)]
- $\gamma\gamma$ [Maltoni, Mandal, Zhao (2019), Chen, Heinrich, Jahn, Jones, Kerner (2020)]
- ZZ [Agarwal, Jones, von Manteuffel (2021), Brønnum-Hansen, Wang (2021)]
- WW [Brønnum-Hansen, Wang (2021)] ۵
- ZH [Chen, Heinrich, Jones, Kerner, Klappert, Schlenk (2021)]

Inclusive $2 \rightarrow 1$ calculations at N³LO QCD

- H [Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015), + Furlan, Gehrmann,Lazopoulos (2016), Mistlberger (2018)]
- $b\bar{b} \rightarrow H$ [Duhr. Dulat. Mistlberger (2020). + Hirschi (2020)]
- W [Duhr, Dulat, Mistlberger (2020 & 2020)]
- γ^* [Duhr, Dulat, Mistlberger (2020)]

Fully differential $2 \rightarrow 1$ calculations at N³LO QCD

- H [Dulat, Mistlberger, Pelloni (2019), Cieri, Chen, Gehrmann, Glover, Huss (2019)]
- H ($\rightarrow \gamma \gamma$) [Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni ('21)]
- ${\sf Z}/\gamma^*$ [Camarda, Cieri, Ferrera ('21), Chen, Gehrmann, Glover, Huss, Yang ('21)]
- combination of local NNLO subtraction with slicing/projection methods promoted to N³LO

First 3-loop amplitudes beyond $2 \rightarrow 1$

- leading-colour $\gamma\gamma$ [Caola, von Manteuffel, Tancredi (2021)]
- four-quark scattering [Caola, Chakraborty, Gambuti, yon Manteuffel, Tancredi ('21)]

Status of NLO EW calculations (status Oct 2021)

Dedicated comparison in Les Houches 2017 proceedings

- BBMC + Recola
- MUNICH/MATRIX + OPENLOOPS
- MoCaNLO + Recola
- Sherpa + GoSam/ OpenLoops/ Recola
- MADGRAPH5_AMC@NLO + MADLOOP
- conceptionally solved, as for NLO QCD calculations

Recent highlights: high-multiplicity processes

- off-shell $t\bar{t}W$ production (2 \rightarrow 8) [Denner, Pelliccioli (2021)]
- off-shell $t\bar{t}H$ production (2
 ightarrow 7) [Denner, Lang, Pellen, Uccirati (2017)]
- off-shell WWW production $(2 \rightarrow 6)$ [Dittmaier, Knippen, Schwan (2020)]
- vector boson scattering (2 ightarrow 6)
 - $W^{\pm}W^{\pm}$ [Biedermann, Denner, Pellen (2017), Denner, Lang, Pellen, Uccirati (2017)]
 - WZ [Denner, Dittmaier, Maierhöfer, Pellen, Schwan (2019)]
 - ZZ [Denner, Franken, Pellen, Schmidt (2020)]

