MATRIX alle Hawaii – PINEAPPL interpolation grids at NNLO accuracy

Stefan Kallweit

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Culinaric introduction to “MATRIX alle Hawaii”

[Foto: https://www.istockphoto.com/de/portfolio/Grafner]

“Toast Hawaii”

[Foto: https://www.pizzaroberto.ch/pizza-hawaii-die-perfekte-kombination-aus-ananas-und-schinken]

“Pizza Hawaii”

```
$ ./matrix --hawaii
```

⇒ MATRIX + PINEAPPL

"MATRIX alle Hawaii" – an AI image generator's interpretation

[taken from Marius Wiesemann's talk at Matrix meeting (Zurich, February 2024)]

Outline

Precision calculations — the key to fully exploit LHC measurements

[ATLAS collaboration (2022)]

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

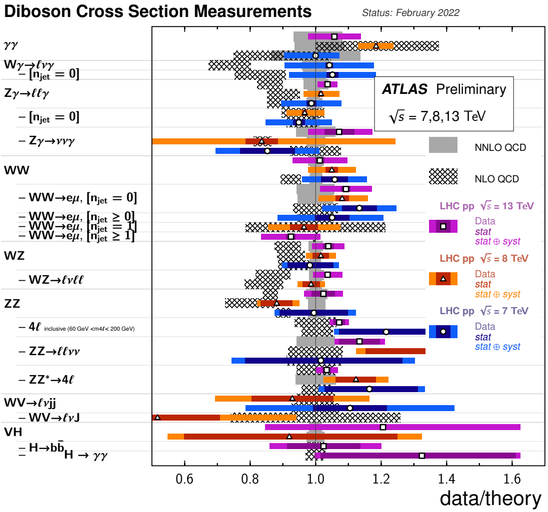
[Grazzini, SK, Wiesemann (2018)]

- inevitable for data–theory agreement

Mandatory steps to match experimental precision also in the future

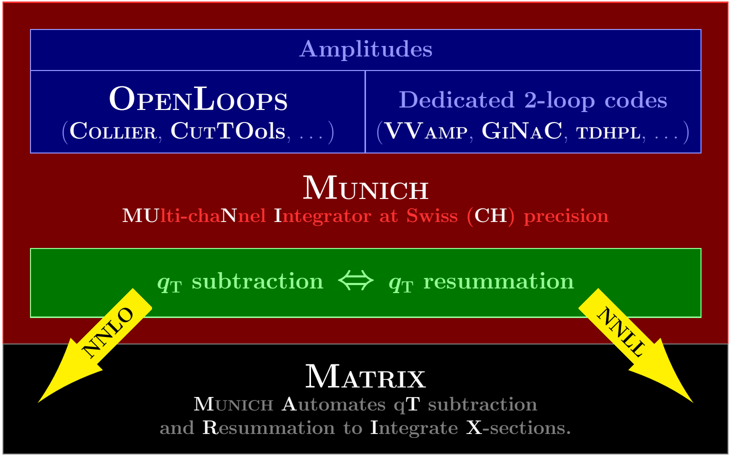
- leading QCD corrections beyond NNLO
- EW corrections and combination with QCD

➥ **MATRIX v2** [Grazzini, SK, Wiesemann (2021)]



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

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



Amplitudes

OpenLoops (Collier, CutTOols, . . .)

Dedicated 2-loop codes (VVamp, GiNaC, tdhpl, . . .)

Munich

MUlti-chaNnel Integrator at Swiss (CH) precision

q_T subtraction ⇔ q_T resummation

NNLO

NNLL

Matrix

Munich Automates qT subtraction and Resummation to Integrate X-sections.

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

Matrix v1 (fall 2017)

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

Fast-interpolation grids with PINEAPPL

PINEAPPL — PINEAPPL is not an extension of APPLgrid

[Carrazza, Nocera, Schwan, Zaro (2020)]

- public tool to store PDF-independent Monte Carlo integration information in terms of interpolation grids
  - ➥ convolution with PDFs a posteriori takes only seconds (or less)!
- other available interpolation grid tools and formats:
  - **APPLgrid** [Carli, Clements, Cooper-Sarkar, Gwenlan, Salam, Siegert, Starovoitov, Sutton (2010)]
  - **fastNLO** [Kluge, Rabbertz, Wobisch ('06), Britzger, Kluge, Rabbertz, Stober, Wobisch ('11), Britzger, Rabbertz, Stober, Wobisch ('12)]
  - ➥ conversion of PINEAPPL grids into both formats (and vice versa) possible in principle
- Features of PINEAPPL
  - written in Rust, but CAPI, CLI and Python bindings available
    - ➥ precompiled libraries available such that Rust installation is no longer required!
  - treatment of contributions with arbitrary orders of α and α_s (including mixed QCD–EW corrections)
  - inclusion of arbitrary initial-state combinations (including photons, leptons, etc.)
  - renormalization and factorization scale variations (coefficients of logarithms stored in subgrids)
  - very efficient (in terms of speed and memory) organization of interpolation grids

available under `https://github.com/nnpdf/pineappl`

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
- 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 1-loop amplitudes 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
  - 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.

Available processes in MATRIX v2.1 and beyond

- **H (HTL)**
  NNLO QCD
- **Z $(\ell\ell/\nu\nu)$**
  NNLO QCD (linPCs)
  NLO EW
  NNLO QCD–EW
  ggNLO QCD
  [Phys.Rev.Lett. 128 (2022) 1, 012002]
  [Phys.Lett.B 829 (2022) 137118]
- **$W^{\pm}$ $(\ell\nu)$**
  NNLO QCD (linPCs)
  NLO EW
  NNLO QCD–EW
  [Phys.Rev.D 103 (2021) 114012]
- **ZH $(\ell\ell H/\nu\nu H)$**
  NNLO QCD
  NLO EW
- **$W^{\pm}H$ $(\ell\nu H)$**
  NNLO QCD
  NLO EW
- **$\gamma\gamma$**
  NNLO QCD
  NLO EW
- **$Z\gamma$ $(\ell\ell\gamma/\nu\nu\gamma)$**
  NNLO QCD
  NLO EW
  [Phys.Lett.B 731 (2014) 204-207]
  [JHEP 07 (2015) 085]
- **$W^{\pm}\gamma$ $(\ell\nu\gamma)$**
  NNLO QCD
  NLO EW
  [JHEP 07 (2015) 085]
- **HH (HTL, $\text{FT}_{\text{approx}}$)**
  NNLO QCD
  [JHEP 09 (2016) 151]
  [JHEP 05 (2018) 059]
- **$W^{\pm}Z$ $(3\ell\nu/\ell3\nu)$**
  NNLO QCD
  NLO EW
  [Phys.Lett.B 761 (2016) 179-183]
  [JHEP 05 (2017) 139]
  [JHEP 02 (2020) 087]
- **W^+W^- $(2\ell2\nu)$**
  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]
- **ZZ $(4\ell/2\ell2\nu/4\nu)$**
  NNLO QCD
  NLO EW
  ggNLO QCD
  [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]
- **$\gamma\gamma\gamma$**
  NNLO QCD
  NLO EW
  ggNLO QCD
  [Phys.Lett.B 812 (2021) 136013]
- **$t\bar{t}$**
  NNLO QCD
  NLO EW
  [Phys.Rev.D 99 (2019) 5, 051501]
  [JHEP 07 (2019) 100]
  [JHEP 08 (2020) 08, 027]
- **$b\bar{b}$**
  NNLO QCD
  NLO EW
  [JHEP 03 (2021) 029]
- **$Ht\bar{t}$**
  NNLO QCD
  NLO EW
  [Eur.Phys.J.C 81 (2021) 6, 491]
  [Phys.Rev.Lett. 130 (2023) 11, 111902]
- **$W^{\pm}b\bar{b}$ $(\ell\nu b\bar{b})$**
  NNLO QCD
  NLO EW
  [Phys.Rev.D 107 (2023) 7, 074032]
- **$W^{\pm}t\bar{t}$**
  NNLO QCD
  NLO EW
  [Phys.Rev.Lett. 131 (2023) 23, 231901]

Idea of the q_T subtraction method for (N)NLO cross sections

Consider the production of a **colourless final state F** via $\mathbf{q\bar{q} \to F}$ or $\mathbf{gg \to F}$: $\mathrm{d}\boldsymbol{\sigma}_\mathrm{F}^\mathrm{(N)NLO}\big|_{q_\mathrm{T}\neq 0} = \mathrm{d}\boldsymbol{\sigma}_\mathrm{F+jet}^\mathrm{(N)LO}$ where q_T refers to the transverse momentum of the colourless system F [Catani, Grazzini (2007)]

- $\mathrm{d}\boldsymbol{\sigma}_\mathrm{F}^\mathrm{(N)NLO}\big|_{q_\mathrm{T}\neq 0}$ is singular for $q_\mathrm{T} \to 0$
  - ➥ limiting behaviour known from transverse-momentum resummation [Bozzi, Catani, de Florian, Grazzini (2006)]
- Define a universal counterterm $\boldsymbol{\Sigma}$ with the complementary $q_\mathrm{T} \to 0$ behaviour [Bozzi, Catani, de Florian, Grazzini (2006)]
  $\mathrm{d}\boldsymbol{\sigma}^\mathrm{CT} = \boldsymbol{\Sigma}(q_\mathrm{T}/q) \otimes \mathrm{d}\boldsymbol{\sigma}^\mathrm{LO}$ where q is the invariant mass of the colourless system F
- Add the $q_\mathrm{T} = 0$ piece with the hard–virtual coefficient $\mathcal{H}_\mathrm{F}$, which contains the 1-(2-)loop amplitudes at (N)NLO and compensates for the subtraction of $\boldsymbol{\Sigma}$ [Catani, Cieri, de Florian, Ferrera, Grazzini (2013)]

➥ **Master formula for (N)NLO cross section in q_T subtraction method**

$$\mathrm{d}\boldsymbol{\sigma}_\mathrm{F}^\mathrm{(N)NLO} = \boldsymbol{\mathcal{H}}_\mathrm{F}^\mathrm{(N)NLO} \otimes \mathrm{d}\boldsymbol{\sigma}^\mathrm{LO} + \left[\mathrm{d}\boldsymbol{\sigma}_\mathrm{F+jet}^\mathrm{(N)LO} - \boldsymbol{\Sigma}^\mathrm{(N)NLO} \otimes \mathrm{d}\boldsymbol{\sigma}^\mathrm{LO}\right]_{\mathrm{cut}_{q_\mathrm{T}} \to 0}$$

- all ingredients known for extension to N^{3}LO [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_{T} subtraction method to production of heavy coloured particles ($Q\bar{Q}$, $Q\bar{Q}X$, etc.)

$$d\sigma^{\mathrm{NNLO}}_{Q\bar{Q}X} = \mathcal{H}^{\mathrm{NNLO}}_{Q\bar{Q}X} \otimes d\sigma_{\mathrm{LO}} + \left[d\sigma^{\mathrm{NLO}}_{Q\bar{Q}X+\mathrm{jet}} - d\sigma^{\mathrm{NNLO}}_{Q\bar{Q}X,\mathrm{CT}} \right]_{\mathrm{cut}_{q_{\mathrm{T}}} \to 0}$$

- 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)]
- $\mathcal{H}^{Q\bar{Q}X}_{\mathrm{NNLO}}$ 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_{T} subtraction method to mixed QCD–EW corrections of $\mathcal{O}(\alpha_s^m \alpha^n)$

$$d\sigma^{(m,n)}_{\mathrm{F}} = \mathcal{H}^{(m,n)}_{\mathrm{F}} \otimes d\sigma_{\mathrm{LO}} + \left[d\sigma^{(m,n)}_{\mathrm{F,R}} - d\sigma^{(m,n)}_{\mathrm{F,CT}} \right]_{\mathrm{cut}_{q_{\mathrm{T}}} \to 0}$$

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

Extrapolation of $r_{\mathrm{cut}} (= \mathrm{cut}_{q_\mathrm{T}/q}) \to 0$ to control power corrections

Automated and simultaneous scan over reasonable range of r_{cut} values

- quadratic least-χ^2 fit with variable range

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

- error estimate from combination of statistical error and variation of r_{cut} range
  - ➥ good agreement of extrapolated results for different start values

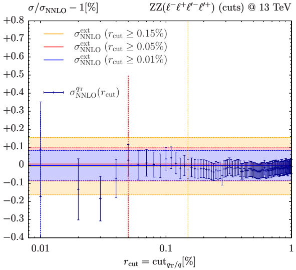
Reasonable performance of $r_{\mathrm{cut}} \to 0$ extrapolation for all MATRIX processes

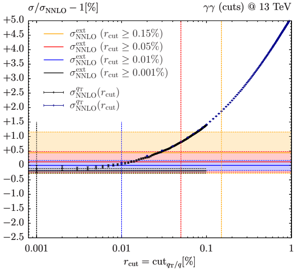
- (at most) quadratic r_{cut} dependence for heavy-boson processes
  - ➥ **exception:** linPCs induced by particular fiducial cut configurations
- significant r_{cut} dependence for processes involving isolated photons
- also (at least) linear power corrections for heavy-quark processes

Solution for r_{cut}-extrapolated PINEAPPL grids

- store several ($\mathcal{O}(10)$) interpolation grids at fixed r_{cut} values
- use least-χ^2 fit information from direct MC output (with integration errors)

➥ final $r_{\mathrm{cut}} \to 0$ extrapolated grid is a linear combination of fixed-r_{cut} grids





Performance improvement features of the Munich phase space integrator

Issue of poorly populated phase space regions

- standard phase space optimization samples points in bulk region
- sample case: high-energy tails of invariant-mass or p_T distributions
- other application: off-shell regions of intermediate resonances

Solution in Munich integrator (and thereby in Matrix)

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

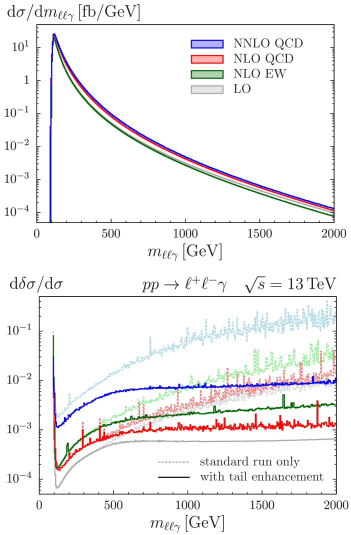
➥ **significantly improved errors in subdominant regions**

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

Solution for subdominant-region improved PineAPPL grids

- store interpolation grids for both standard and extra runs
- use combination information from direct (channel-wise) MC output

➥ final combined grid is a linear combination of individual grids



Implementation of interface to PINEAPPL grids in MATRIX

General interface to write 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
- grids stored for several r_{cut} values in r_{cut}-dependent contributions
- individual grids for each dynamic scale choice required
- 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)

Merging of individual PINEAPPL grids by MATRIX summary routine

- $r_{\mathrm{cut}} \to 0$ extrapolation of PINEAPPL grids using direct MC information
- subdominant-region improved runs taken into account at the level of subprocess grids

➥ **A single resulting PINEAPPL grid (per distribution) contains PDF-independent information to reconstruct the full integration result, separable into available α_s and α orders and luminosities.**

Further remarks on Matrix + PineAPPL interface

Automated installation of PineAPPL with all other prerequisites through Matrix script

- no Rust installation required, precompiled libraries available to be downloaded

Metadata stored in PineAPPL grids

- Matrix runcards with all information to re-generate the PineAPPL grid
- validation output with direct MC result (with MC error) and that from a-posteriori convolution of PineAPPL grid with the generation PDF set
- bibliography file with a list of all publications to be cited if this PineAPPL grid is used

Memory consumption of PineAPPL grids (and disk space)

- $\propto$ number of non-trivial distribution bins
- $\propto$ number of fixed r_{cut} values (separate grids for r_{cut}-dependent contributions)
- $\propto$ number of luminosities (i.e. groups of luminosities)
- $\propto$ number of dynamic scales
- $\propto$ 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 mitigate this problem under investigation. . .

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)

$\sqrt{s}$ [TeV]	m_H [GeV]	XS [fb]	± QCD Scale Unc.	± THU	± α_s Unc.	± PDF Unc.
13	124.6	532.0	± 3.1%	± 0.6%	± 1.7%	± 2.3%
13	125	528.4	± 3.2%	± 0.7%	± 1.7%	± 2.3%
13	125.09	526.6	± 3.1%	± 0.7%	± 1.7%	± 2.3%
13	125.38	522.7	± 3.1%	± 0.7%	± 1.7%	± 2.3%
13	125.6	519.9	± 3.1%	± 0.7%	± 1.7%	± 2.3%
13	126	515.4	± 3.1%	± 0.7%	± 1.7%	± 2.3%
13.6	124.6	596.6	± 3.0%	± 0.7%	± 1.6%	± 2.2%
13.6	125	589.9	± 2.9%	± 0.7%	± 1.6%	± 2.2%
13.6	125.09	589.6	± 3.0%	± 0.7%	± 1.6%	± 2.2%
13.6	125.38	586.2	± 3.0%	± 0.7%	± 1.6%	± 2.2%
13.6	125.6	583.5	± 3.0%	± 0.7%	± 1.6%	± 2.2%
13.6	126	577.9	± 3.1%	± 0.7%	± 1.6%	± 2.2%
14	124.6	639.7	± 2.9%	± 0.7%	± 1.6%	± 2.2%
14	125	636.1	± 3.0%	± 0.6%	± 1.6%	± 2.2%
14	125.09	633.3	± 2.9%	± 0.6%	± 1.6%	± 2.2%
14	125.38	632.4	± 3.1%	± 0.6%	± 1.6%	± 2.2%
14	125.6	627.9	± 3.0%	± 0.6%	± 1.6%	± 2.2%
14	126	621.2	± 3.0%	± 0.7%	± 1.6%	± 2.2%

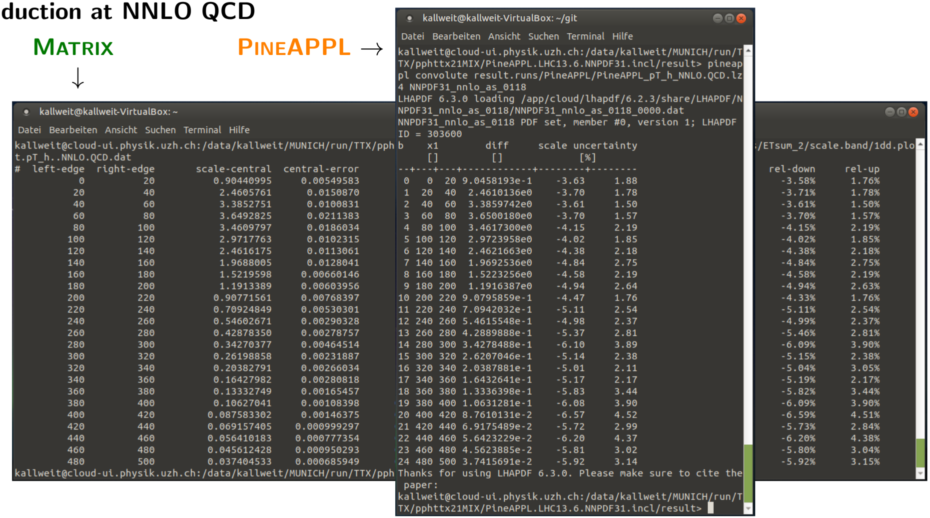
Accuracy of distributions generated through PineAPPL grids

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

- $p_{T,H}$ distribution with 25 bins in $[0\,\mathrm{GeV}; 500\,\mathrm{GeV}]$
- 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: $\sim 375\,\mathrm{MB}$**

Matrix ↓

PineAPPL →



```
kallweit@cloud-ui.physik.uzh.ch:/data/kallweit/MUNICH/run/TTX/pph
t.pT_h..NNLO.QCD.dat
#  left-edge  right-edge       scale-central  central-error
           0          20          0.90440995     0.00549583
          20          40           2.4605761      0.0150870
          40          60           3.3852751      0.0100831
          60          80           3.6492825      0.0211383
          80         100           3.4609797      0.0186034
         100         120           2.9717763      0.0102315
         120         140           2.4616175      0.0113061
         140         160           1.9688005      0.0128041
         160         180           1.5219598     0.00660146
         180         200           1.1913389     0.00603956
         200         220          0.90771561     0.00768397
         220         240          0.70924849     0.00530301
         240         260          0.54602671     0.00290328
         260         280          0.42878350     0.00278757
         280         300          0.34270377     0.00464514
         300         320          0.26198858     0.00231887
         320         340          0.20382791     0.00266034
         340         360          0.16427982     0.00280818
         360         380          0.13332749     0.00165457
         380         400          0.10627041     0.00108398
         400         420         0.087583302     0.00146375
         420         440         0.069157405    0.000999297
         440         460         0.056410183    0.000777354
         460         480         0.045612428    0.000950293
         480         500         0.037404533    0.000685949
kallweit@cloud-ui.physik.uzh.ch:/data/kallweit/MUNICH/run/TTX/pph
```

```
s/ETsum_2/scale.band/1dd.plo

  rel-down     rel-up
    -3.58%      1.76%
    -3.71%      1.78%
    -3.61%      1.50%
    -3.70%      1.57%
    -4.15%      2.19%
    -4.02%      1.85%
    -4.38%      2.18%
    -4.84%      2.75%
    -4.58%      2.19%
    -4.94%      2.63%
    -4.33%      1.76%
    -5.11%      2.54%
    -4.99%      2.37%
    -5.46%      2.81%
    -6.09%      3.90%
    -5.15%      2.38%
    -5.04%      3.05%
    -5.19%      2.17%
    -5.82%      3.44%
    -6.09%      3.90%
    -6.59%      4.51%
    -5.73%      2.84%
    -6.20%      4.38%
    -5.80%      3.04%
    -5.92%      3.15%
```

```
kallweit@cloud-ui.physik.uzh.ch:/data/kallweit/MUNICH/run/T
TX/pphttx21MIX/PineAPPL.LHC13.6.NNPDF31.incl/result> pineap
pl convolute result.runs/PineAPPL/PineAPPL_pT_h_NNLO.QCD.lz
4 NNPDF31_nnlo_as_0118
LHAPDF 6.3.0 loading /app/cloud/lhapdf/6.2.3/share/LHAPDF/N
NPDF31_nnlo_as_0118/NNPDF31_nnlo_as_0118_0000.dat
NNPDF31_nnlo_as_0118 PDF set, member #0, version 1; LHAPDF
ID = 303600
b    x1         diff     scale uncertainty
     []          []             [%]
--+---+---+------------+--------+--------
 0   0  20 9.0458193e-1   -3.63    1.88
 1  20  40  2.4610136e0   -3.70    1.78
 2  40  60  3.3859742e0   -3.61    1.50
 3  60  80  3.6500180e0   -3.70    1.57
 4  80 100  3.4617300e0   -4.15    2.19
 5 100 120  2.9723958e0   -4.02    1.85
 6 120 140  2.4621663e0   -4.38    2.18
 7 140 160  1.9692536e0   -4.84    2.75
 8 160 180  1.5223256e0   -4.58    2.19
 9 180 200  1.1916387e0   -4.94    2.64
10 200 220 9.0795859e-1   -4.47    1.76
11 220 240 7.0942032e-1   -5.11    2.54
12 240 260 5.4615548e-1   -4.98    2.37
13 260 280 4.2889888e-1   -5.37    2.81
14 280 300 3.4278488e-1   -6.10    3.89
15 300 320 2.6207046e-1   -5.14    2.38
16 320 340 2.0387881e-1   -5.01    2.11
17 340 360 1.6432641e-1   -5.17    2.17
18 360 380 1.3336398e-1   -5.83    3.44
19 380 400 1.0631281e-1   -6.08    3.90
20 400 420 8.7610131e-2   -6.57    4.52
21 420 440 6.9175489e-2   -5.72    2.99
22 440 460 5.6423229e-2   -6.20    4.37
23 460 480 4.5623885e-2   -5.81    3.02
24 480 500 3.7415691e-2   -5.92    3.14
Thanks for using LHAPDF 6.3.0. Please make sure to cite the
 paper:
kallweit@cloud-ui.physik.uzh.ch:/data/kallweit/MUNICH/run/T
TX/pphttx21MIX/PineAPPL.LHC13.6.NNPDF31.incl/result> 
```

Conclusions & Outlook

MATRIX framework for NNLO QCD calculations

- based on the MUNICH integrator, q_T subtraction, amplitudes from OPENLOOPS, interfaced to dedicated 2-loop amplitudes, ...
- (publicly) available processes: H, V, $\gamma\gamma$, Vγ, VV, $\gamma\gamma\gamma$, $t\bar{t}$, ...
- NLO EW, linPCs, ggNLO QCD, ...

PINEAPPL interpolation grids for arbitrary orders in α_s and α

- store MC integration information in PDF-independent grids
  - ➥ a-posteriori convolution with PDFs within seconds (or less)

➥ **MATRIX + PINEAPPL** interface ➥ **MATRIX alle Hawaii**

- all MATRIX features preserved in grid approach ($r_{\text{cut}} \to 0$ extrapolation, tail-enhancements, ...)
- applicable for all processes available in MATRIX and for all provided orders in α_s and α
- easy to use: `$ ./matrix --hawaii` in compilation and `switch_PineAPPL = 1` in runcard

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Backup

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Supplying MUNICH/MATRIX with 1-loop amplitudes

Process-independent interfaces to general automated amplitude generators

- OPENLOOPS [Cascioli, Maierhöfer, Pozzorini (2012); SK, Lindert, Maierhöfer, Pozzorini, Schönherr (2015)] v2 [Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller (2019)], written in FORTRAN
  - 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
- modular structure of MUNICH allows other generators to be interfaced as well

Several dedicated interfaces developed in context of MATRIX applications

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

Interfacing dedicated 2-loop amplitudes to MUNICH/MATRIX

- Higgs, Drell–Yan, **VH**, $\gamma\gamma$, **V**γ production
  - direct implementation of public analytic results, e.g. for Vγ [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 m_t 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)]
- $\mathbf{Q\bar{Q}}$ production — amplitude grids from [Bärnreuther, Czakon, Fiedler (2014)]
  - FORTRAN routine for numerical interpolation of 2-dimensional grid, improved by expansions