

# Mixed QCD-EW corrections to NC-DY: numerical challenges

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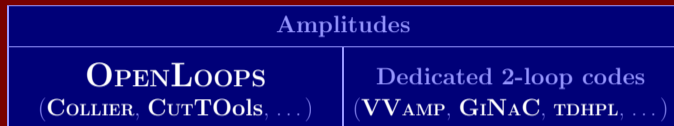


Milano-Pisa PRIN meeting, Milan, Italy, October 5-6, 2021

- 1 The MATRIX framework for precision calculations
  - Basic features of the MUNICH/MATRIX framework
  - Implementation of external amplitudes
  - The  $q_T$  subtraction method for higher-order corrections
- 2 Numerical challenges in the  $q_T$  subtraction method
  - Production of colourless final states at NNLO QCD accuracy
  - Extension to (associated) heavy-quark pair production at NNLO QCD accuracy
  - Extension to mixed NNLO QCD–EW corrections for charged massive colourless final states

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

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



## MUNICH

MULTI-chaNnel Integrator at Swiss (CH) precision

$q_T$  subtraction  $\Leftrightarrow$   $q_T$  resummation

NNLO

NNLL

## MATRIX

MUNICH Automates  $q_T$  subtraction  
and Resummation to Integrate X-sections.

### MATRIX v1

- H, V,  $\gamma\gamma$ ,  $V\gamma$ , VV at NNLO QCD for all leptonic decay channels

### MATRIX v2

- combination with NLO EW for all leptonic V and VV processes
- loop-induced  $gg$  channel at NLO QCD for neutral VV processes
- several technical improvements, e.g. tail enhancement runs

still not included:  $q_T$  resummation

but: **MATRIX+RADISH** available

- ➔ public interface to provide direct-space resummation ( $q_T$ ,  $p_{T,jet}$ , combined) for all **MATRIX** processes

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

# The MUNICH/MATRIX framework for automated NNLO calculations

## **MATRIX** — **MUNICH** Automates qT-subtraction and Resummation to Integrate X-sections

[Grazzini, SK, Wieseemann (2018)]

- first public tool that performs 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)
- general amplitude interface
- 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.

# 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

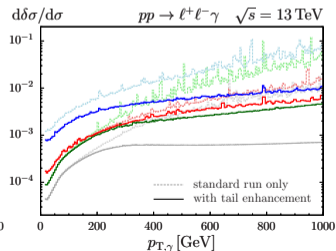
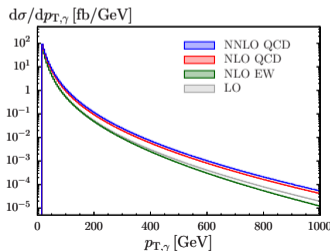
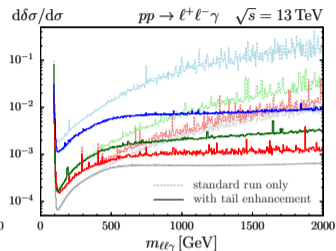
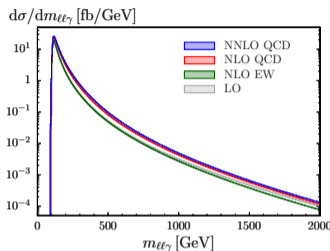
## Solution in MUNICH integrator

- 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



# 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 $\gamma$**  production
  - direct implementation of public analytic results, e.g. for **V $\gamma$**  [Gehrmann, Tandreli (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** [Vermaas 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)]
- **Q $\bar{Q}$**  production — amplitude grids from [Bärnreuther, Czakon, Fiedler (2014)]
  - **FORTTRAN** routine for numerical interpolation of 2-dimensional grid, improved by expansions

## Idea of the $q_T$ 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)]

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

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

$$d\sigma_F^{(N)NLO} = \mathcal{H}_F^{(N)NLO} \otimes d\sigma^{LO} + \left[ d\sigma_{F+jet}^{(N)LO} - \Sigma^{(N)NLO} \otimes d\sigma^{LO} \right]_{\text{cut}_{q_T} \rightarrow 0}$$

- all ingredients known for extension to  $N^3LO$  [Luo, Yang, Zhu, Zhu (2019; 2020), Ebert, Mistlberger, Vita (2020), Cieri, Chen, Gehrmann, Glover, Huss (2019), Camarda, Cieri, Ferrera ('21), Chen, Gehrmann, Glover, Huss, Yang, Zhu (2021)]



Investigation of  $r_{\text{cut}} = \text{cut}_{q_T/q}$  dependence — sample case  $pp \rightarrow \gamma\gamma + X$ Result for  $r_{\text{cut}} \rightarrow 0$  via extrapolation

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

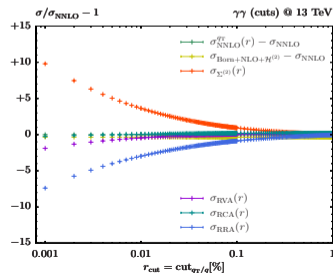
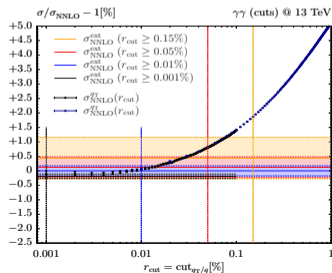
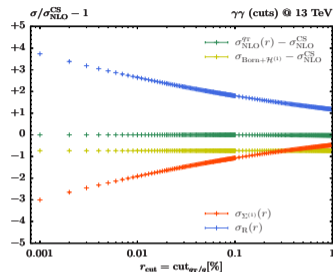
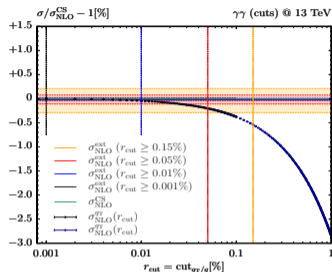
$$\sigma_{(N)NLO}(r_{\text{cut}}) = Ar_{\text{cut}}^2 + Br_{\text{cut}} + \sigma_{(N)NLO}$$

- error estimate based on combination of statistical error and variation of  $r_{\text{cut}}$  range

➔ **Significant  $r_{\text{cut}} \rightarrow 0$  dependence for processes involving isolated photons** (similar between NLO and NNLO QCD)

➔ good agreement of extrapolated results within errors for different start values

- $r_{\text{cut}} \geq 0.15\%$
- $r_{\text{cut}} \geq 0.05\%$
- $r_{\text{cut}} \geq 0.01\%$
- $r_{\text{cut}} \geq 0.001\%$



Investigation of  $r_{\text{cut}} = \text{cut}_{q_T/q}$  dependence — sample case  $pp \rightarrow \ell^- \ell^+ \ell'^- \ell'^+ + X$ Result for  $r_{\text{cut}} \rightarrow 0$  via extrapolation

- same procedure for all processes

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

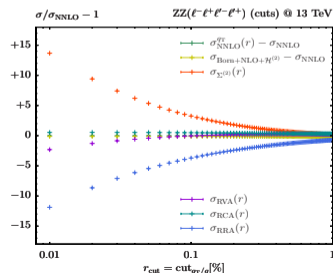
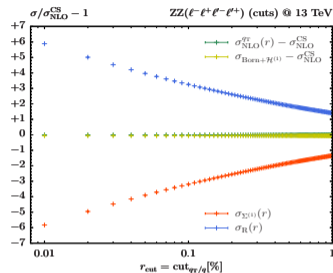
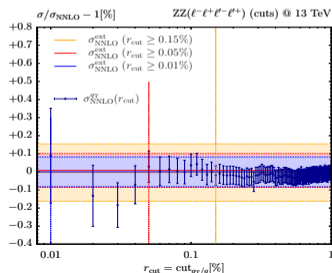
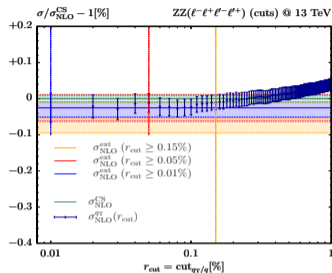
- No significant  $r_{\text{cut}} \rightarrow 0$  dependence for processes without isolated photons** (similar between NLO and NNLO QCD)

- Important exception: symmetric cut configurations (e.g. standard Drell-Yan setup)

- good agreement of extrapolated results within errors for different start values

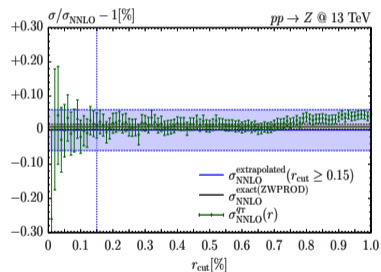
- $r_{\text{cut}} \geq 0.15\%$
- $r_{\text{cut}} \geq 0.05\%$
- $r_{\text{cut}} \geq 0.01\%$

- larger cancellation between contributions (factor of  $\approx 15$  at  $r_{\text{cut}} = 0.01\%$ )



Investigation of  $r_{\text{cut}} = \text{cut}_{q_T/q}$  dependence — Drell–Yan processes $pp \rightarrow Z$ 

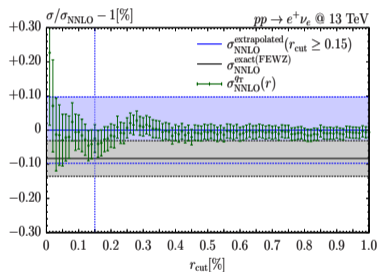
- fully inclusive



- no phase space restrictions
- no significant dependence on  $r_{\text{cut}}$

 $pp \rightarrow \ell^+ \nu_\ell$ 

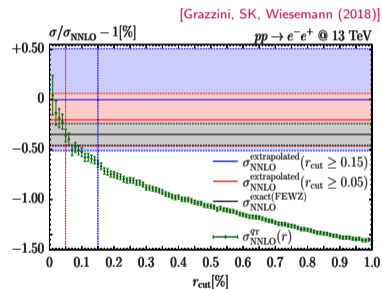
- $p_{T,\ell^+} > 25 \text{ GeV}$   $\eta_{\ell^+} < 2.47$
- $p_{T,\text{miss}} > 20 \text{ GeV}$



- asymmetric cuts on two individual leptons ( $\ell^+$  and  $\nu_\ell$ )
- no significant dependence on  $r_{\text{cut}}$

 $pp \rightarrow \ell^- \ell^+$ 

- $p_{T,\ell^\pm} > 25 \text{ GeV}$   $\eta_{\ell^\pm} < 2.47$
- $66 \text{ GeV} < m_{\ell^+ \ell^-} < 116 \text{ GeV}$



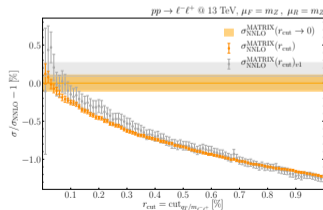
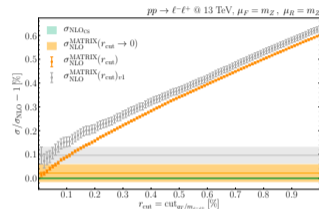
- symmetric cuts on both leptons (either on  $\ell^+/\ell^-$  or on  $\ell_1/\ell_2$ )
- large power corrections in  $r_{\text{cut}}$

[Grazzini, SK, Wiesemann (2018)]

# Dependence on $r_{\text{cut}}$ in different cut scenarios for the NC Drell–Yan process

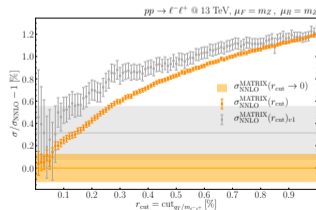
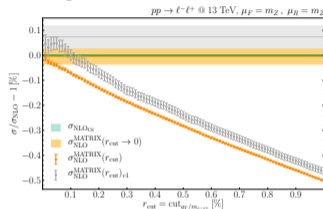
## Symmetric cuts

- $p_{T,\ell^\pm} > 25 \text{ GeV}$



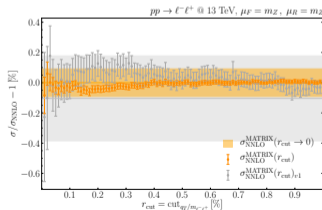
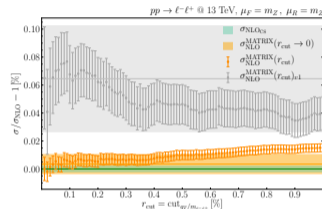
## Asymmetric cuts on $\ell_1$ and $\ell_2$

- $p_{T,\ell_1} > 25 \text{ GeV}$   $p_{T,\ell_2} > 20 \text{ GeV}$



## Asymmetric cuts on $\ell^+$ and $\ell^-$

- $p_{T,\ell^+} > 25 \text{ GeV}$   $p_{T,\ell^-} > 20 \text{ GeV}$



➔ large power corrections in  $r_{\text{cut}}$

➔ large power corrections in  $r_{\text{cut}}$

➔ no significant dependence on  $r_{\text{cut}}$

# Production of heavy coloured particles at NNLO QCD accuracy

## Extension of $q_T$ subtraction method to production of heavy coloured particles (e.g. top-quark pairs)

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

- 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)]
- $\mathcal{H}_{\text{NNLO}}^{t\bar{t}}$  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)]

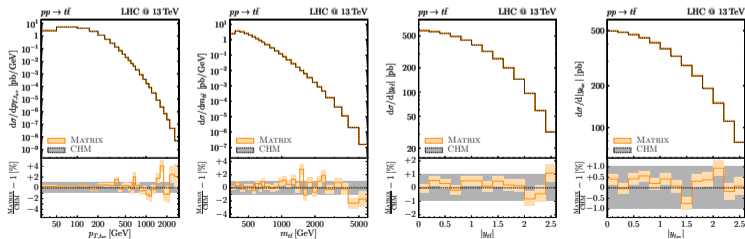
## Associated heavy-quark pair production ( $t\bar{t}H$ , $t\bar{t}V$ , ...) with identical singularity structure

- 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  $t\bar{t}H$  [Catani, Fabre, SK, Grazzini (2021)]
- two-loop amplitudes as the bottleneck for any beyond  $2 \rightarrow 2$  NNLO calculations

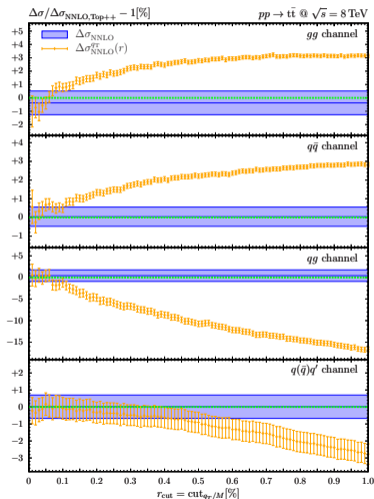
# Top-quark pair production at NNLO QCD accuracy

## 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)]



# Mixed NNLO QCD–EW calculation for production of massive charged particles

## Extension of $q_T$ subtraction method to mixed QCD–EW corrections of $\mathcal{O}(\alpha_s^m \alpha^n)$

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

- $m = 1(2)$  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  $m \geq 1$ ) and no massless charged particles (for  $n \geq 1$ ) allowed at LO)

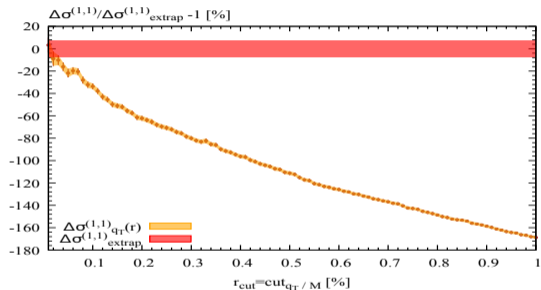
## Strategy to cancel IR singularities in mixed QCD–EW corrections

- abelianisation procedure, starting from heavy-quark pair production at NNLO QCD
  - for neutral final states, abelianisation of standard  $q_T$  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)])
- colourless final state ( $\ell\ell/\ell\nu$ ) 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

# Dependence on $r_{\text{cut}}$ of the mixed NNLO QCD–EW corrections for NC Drell–Yan

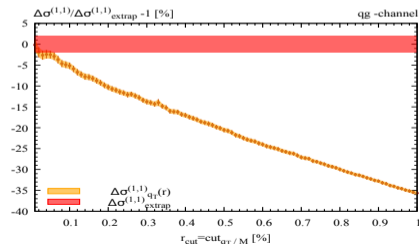
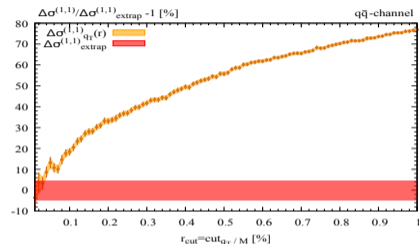
## Symmetric-cut scenario

$$p_{T,\ell^\pm} > 25 \text{ GeV} \quad y_{\ell^\pm} < 2.5 \quad m_{\ell\ell} > 50 \text{ GeV}$$



- **large power corrections in  $r_{\text{cut}}$  for mixed corrections**
  - ➔ explained by overall small size of corrections, and in parts also by cancellation between partonic channels
- **by far less dramatic dependence at level of cross sections**
  - ➔ better than permille precision at inclusive level

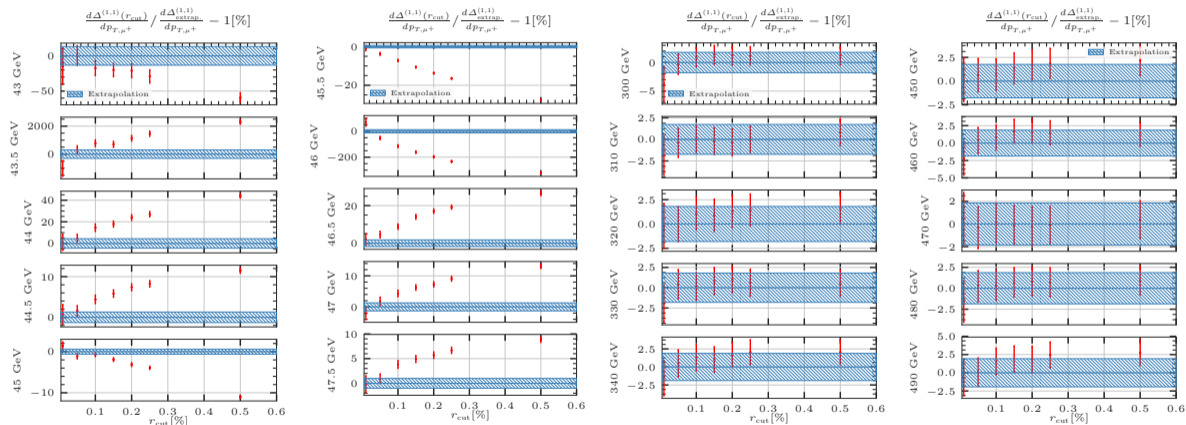
## Splitting into partonic channels



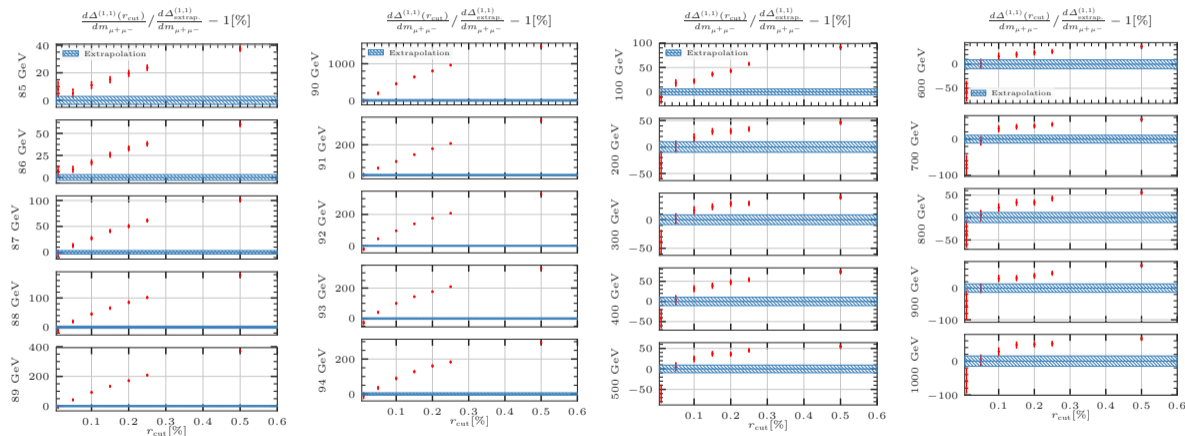


# Binwise $r_{\text{cut}}$ dependence of the mixed NNLO QCD-EW corrections for NC Drell-Yan

Differential distribution in  $p_{T,\mu^+}$ : peak (left panels) and tail (right panels) regions



large  $r_{\text{cut}}$  dependence in particular around the peak of the distribution, and typically precision of  $\lesssim 3\%$  on the relative mixed QCD-EW corrections (artificially large where corrections are basically zero)

Binwise  $r_{\text{cut}}$  dependence of the mixed NNLO QCD-EW corrections for NC Drell-YanDifferential distribution in  $m_{\mu^+\mu^-}$ : peak (left panels) and tail (right panels) regions

➔ quite large  $r_{\text{cut}}$  dependence throughout, and lower numerical precision of  $\lesssim 10\%$  on the relative mixed QCD-EW corrections (but still permille-level precision at the level of cross sections)

## The Matrix framework for automated NNLO QCD calculations (and beyond)

OpenLoops  
NLO, NNLO, 3-Loop  
2-Loop, 3-Loop, 4-Loop  
Matrix

**Matrix v1**

- N, V,  $\eta$ , VV,  $\eta$  at NNLO QCD for all public soft or large class of process

**Matrix v2**

- combination with NLO EW for all helicity V and VV processes
- beyond  $gg$  channel at NLO QCD for several VV processes
- several technical improvements, e.g. tail renormalization

**not included:  $\eta$  remnant**

But: Matrix+BSM available  
public interface to provide direct-q processes ( $p_{T, \eta}(\mu_{\text{IR}})$  combined) for all Matrix processes

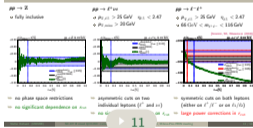
available under <https://matrix.lrz.de>

03

## Interfacing dedicated 2-loop amplitudes to Matrix/Matrix

- Hgg, Drell-Yan, WH,  $\tau\tau$  VV production
- direct implementation of public results, e.g. for VV (see [Arora et al.](#))
- VV production  $\rightarrow$  eVVSPP (see [Arora et al.](#)) and ggVVSPP (see [Arora et al.](#))
- C, J: libraries using GRACE (see [Arora et al.](#)) and COLA for arbitrary precision arithmetic
- BFP approach: generated using MellinSpace, FORM (see [Arora et al.](#)), Binoletti (see [Arora et al.](#))
- independent calculation of amplitudes in  $\mu_{\text{IR}}$  (see [Arora et al.](#))
- Hgg-modulated helicity amplitudes with full  $gg$  dependence (see [Arora et al.](#))
- $\tau\tau$  production  $\rightarrow$  amplitude from  $\tau$  (see [Arora et al.](#)), applying PIRTHOMPRES (see [Arora et al.](#))
- C, J: library generated by COLA (see [Arora et al.](#)), applying PIRTHOMPRES (see [Arora et al.](#))
- numerical unitarity and analytic continuation techniques (see [Arora et al.](#))
- HH production (full on dependence)  $\rightarrow$  Matrix library (see [Arora et al.](#))
- Process level numerical compilation of amplitude grid
- generated by 2-loop extension of GoSAM (see [Arora et al.](#)), NLO3 (see [Arora et al.](#)), SecDec3 (see [Arora et al.](#))
- QQ production  $\rightarrow$  amplitude grids from  $\tau$  (see [Arora et al.](#))
- Fortran routine for numerical integration (see [Arora et al.](#))

07

Investigation of  $\epsilon_{\text{cut}}$  in  $\text{cut}_{\text{IR}}$  dependence — Drell-Yan processes

- no phase space restrictions
- no significant dependence on  $\epsilon_{\text{cut}}$

- asymmetric cuts on two leptons ( $\tau^+\tau^-$  or  $\mu^+\mu^-$ )
- large power corrections to  $\epsilon_{\text{cut}}$

- asymmetric cuts on both leptons (either on  $\tau^+\tau^-$  or  $\mu^+\mu^-$ )
- no significant dependence on  $\epsilon_{\text{cut}}$

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

Extension of  $\eta$  subtraction method to mixed QCD-EW corrections of  $\text{O}(\alpha_s^2\alpha)$ 

$$\delta^{\text{NLO}} = \delta^{\text{QCD}} + \delta^{\text{EW}} + \delta^{\text{EW}^2} - \delta^{\text{EW}^2} \delta^{\text{QCD}} + \dots$$

- $m = 123$  and  $m = 0$  (NNLO QCD corrections)
- $m = 0$  and  $m = 1$  (NLO EW corrections)
- $m = 1$  and  $m = 1$  (mixed NNLO QCD-EW corrections)
- (inclusion: no massive jets (for  $m \geq 1$ ) and no massive charged particles (for  $m \geq 1$ ) allowed at LO)

Strategy to cancel IR singularities in mixed QCD-EW corrections

- subtraction procedure: starting from heavy-quark pair production at NNLO QCD
- for neutral final state, identification of standard  $\eta$  subtraction method is sufficient (mixed QCD-EW corrections for  $gg \rightarrow Z$ ,  $gg \rightarrow \gamma\gamma$ ,  $gg \rightarrow \mu^+\mu^-$ )
- calculate final state IR(1) results to reach  $\epsilon_{\text{cut}}$  dependence of pure QCD, might be much simpler IR structure than in heavy-quark pair production at NNLO QCD
- finite charge/legion mass required to regularize IR singularities

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## The Matrix/Matrix framework for automated NNLO calculations

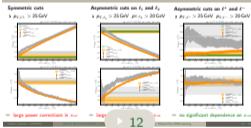
- Matrix  $\rightarrow$  Matrix Automates  $\eta$ -subtraction and Resummation to integrate  $X$ -sections
- first public tool that performs NNLO QCD calculations for a large class of process
- core of the framework: the C++ partition-level Monte Carlo generator **Matrix**  $\rightarrow$  Monte-carlo level integrator at each (CPU) resolution  $\rightarrow$  ... bookkeeping of particles: sub-processes for all contributions
- fully automated dipole subtraction for NLO calculations (resonance, QCD and EW)
- general amplitude interface
  - 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 Matrix and all supplementary software
- interactive chat channel of user planes without forum interaction (github, pre, main repo, summary)
- organization of parallelized running on multicore machines and commonly used clusters: **Sherpa**, **HTCondor**, **LSF**, etc.

04

Idea of the  $\eta$  subtraction method for (N)NLO cross sections

- Consider the production of a **colorless final state F** via  $gg \rightarrow F$  or  $q\bar{q} \rightarrow F$  ( $\epsilon_{\text{cut}} = \epsilon_{\text{cut}}^{\text{IR}}$ )
- where  $\eta$  refers to the transverse momentum of the colorless system F
- $\delta^{\text{NLO}}$  (cut)  $\rightarrow$  Starting behavior from loop transverse-momentum resummation
  - Define a universal counterterm  $\delta^{\text{CT}}$  with the complementary  $\eta$ -to  $\eta$ -behavior ( $\delta^{\text{CT}} \sim \mathcal{O}(\epsilon_{\text{cut}}^2/\eta)$  where  $\eta$  is the invariant mass of the colorless system F)
  - Add the  $\delta^{\text{CT}} \rightarrow 0$  piece with the hard-scaled coefficient  $\delta^{\text{HS}}$ , which contains the (2-loop amplitudes at (N)NLO) and compensates for the subtraction of  $\delta^{\text{CT}}$
  - Matrix formula for (N)NLO cross section in  $q$ -quark extraction method
- $\delta^{\text{NLO}} + \delta^{\text{CT}} \sim \delta^{\text{HS}} + \delta^{\text{CT}} + \delta^{\text{NLO}}$
- $\delta^{\text{NLO}} + \delta^{\text{CT}} \sim \delta^{\text{HS}} + \delta^{\text{CT}} + \delta^{\text{NLO}}$
- all ingredients known for extension to N<sup>2</sup>LO

08

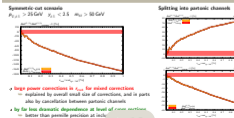
Dependence on  $\epsilon_{\text{cut}}$  in different cut scenarios for the NC Drell-Yan process

- large power corrections to  $\epsilon_{\text{cut}}$

- large power corrections to  $\epsilon_{\text{cut}}$
- large power corrections to  $\epsilon_{\text{cut}}$

- no significant dependence on  $\epsilon_{\text{cut}}$

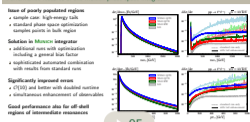
12

Dependence on  $\epsilon_{\text{cut}}$  of the mixed NNLO QCD-EW corrections for NC Drell-Yan

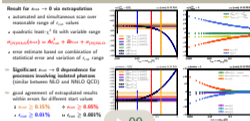
- large power corrections to  $\epsilon_{\text{cut}}$  for related corrections
- explained by overall small size of corrections, and in parts due by cancellation between partonic channels
- by the first characteristic dependence at level of cross-sections, better than possible precision at each  $\epsilon_{\text{cut}}$

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## Performance features of the Matrix phase space integrator

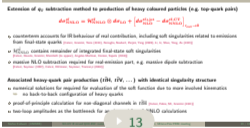


05

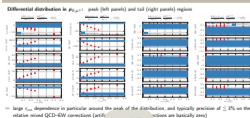
Investigation of  $\epsilon_{\text{cut}}$  in  $\text{cut}_{\text{IR}}$  dependence — sample case  $gg \rightarrow \tau^+\tau^- X$ 

09

## Production of heavy coloured particles at NNLO QCD accuracy



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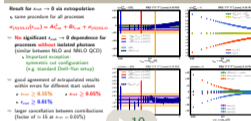
Bimodal  $\epsilon_{\text{cut}}$  dependence of the mixed NNLO QCD-EW corrections for NC Drell-Yan

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## Supplying Matrix/Matrix with 1-loop amplitudes

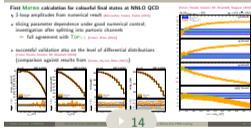
- Process independent interfaces to general automated amplitude generators
- **OneLoop** ([https://github.com/one-loop/one-loop](#)), written in **Fortran**
    - general code and general libraries
    - on-the-fly tensor reduction (see [Arora et al.](#)) with hybrid precision stability system
    - scalar integrals from **COLLA** (see [Arora et al.](#)) or **OneLoop** (see [Arora et al.](#))
  - **onePy** generation of amplitudes, written in **Fortran**
    - tensor reduction and scalar integrals via **COLLA** (see [Arora et al.](#)) or **OneLoop** (see [Arora et al.](#))
    - different model file available, also for SHERPA and BSM applications
  - modular structure of Matrix allows other generators to be interfaced as well
- Several dedicated libraries have been developed to extend Matrix applications
- top-quark and loop-top color (and spin) correlation
  - helicity amplitudes, colour-ordered amplitudes to construct 4-colour correlation
  - magnetic parts of loop-top amplitudes  $\rightarrow$  flip amplitudes

06

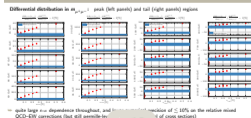
Investigation of  $\epsilon_{\text{cut}}$  in  $\text{cut}_{\text{IR}}$  dependence — sample case  $gg \rightarrow \tau^+\tau^- \ell^+\ell^- X$ 

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## Top-quark pair production at NNLO QCD accuracy



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Bimodal  $\epsilon_{\text{cut}}$  dependence of the mixed NNLO QCD-EW corrections for NC Drell-Yan

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