Precision calculations in the MUNICH/MATRIX framework

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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
[Grazzini, SK, Wiesemann (2018)]

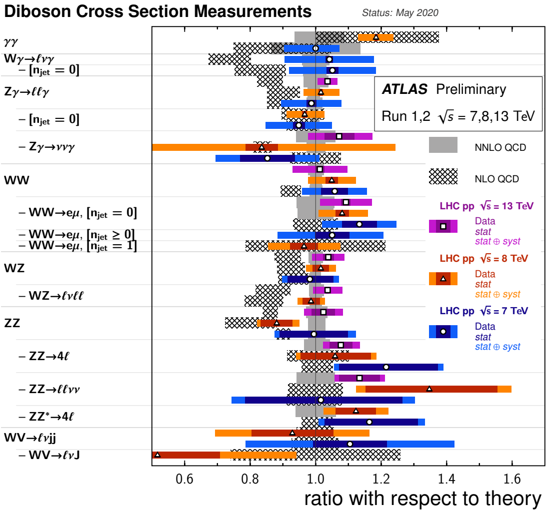
- inevitable for data–theory agreement

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 (beta version available)]

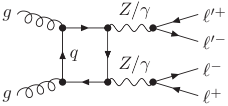
[ATLAS collaboration (2020)]

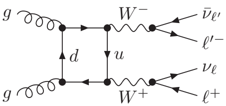


Outline

1. Motivation
2. Precision calculations for LHC processes
   - Diboson production beyond NNLO QCD accuracy
   - Triboson production at NNLO QCD accuracy
   - Heavy-quark pair production at NNLO QCD accuracy
3. The MUNICH/MATRIX framework for precision calculations
   - Structure of the computational framework
   - Implementation of amplitudes
   - Monte Carlo integration
   - Combination with external programs
4. Conclusions

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





- only LO-accurate at $\mathcal{O}(\alpha_s^2)$
- enhanced by large gluon luminosity
- presumably dominant $\mathcal{O}(\alpha_s^3)$ contribution

Approximate nNNLO QCD prediction

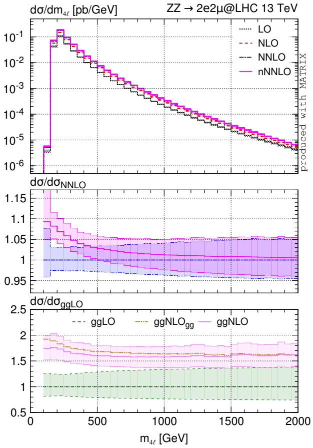
- full m_t dependence in 1-loop terms
- massless 2-loop amplitudes from ggVVAMP [von Manteuffel, Tancredi (2015)]

  ↪ reweighted by full-m_t Born amplitude

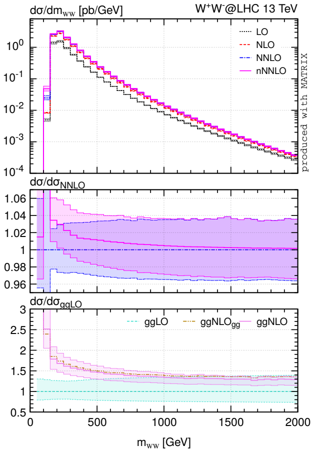
Effect of NLO QCD in *gg* channel

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

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



[Grazzini, SK, Wiesemann, Yook (2020)]



Combination of QCD and EW corrections for diboson production

NLO EW corrections included for all processes in MATRIX v2 [Grazzini, SK, Wiesemann (beta version available)]

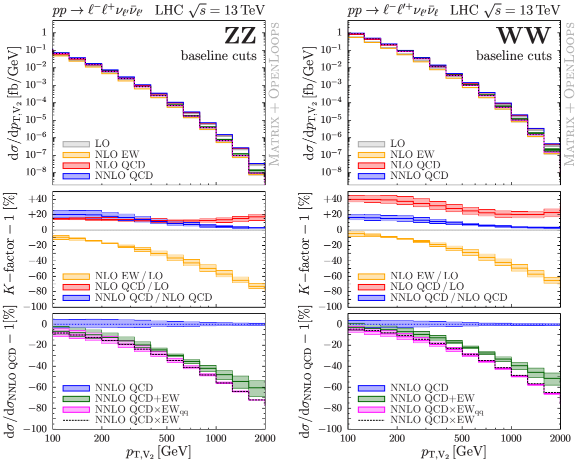
Dominant EW effects

- shape distortion of resonances → QED effect
- photon-induced processes via LUXQED PDFs [Manohar, Nason, Salam, Zanderighi (2016; 2017)]
- negative corrections in high-energy observables
  ↪ genuine EW effect from Sudakov logarithms

Combination with QCD corrections

- factorized approaches well motivated
  ↪ catch leading mixed QCD×EW effects
- valid for genuine VV observables
  ↪ observables driven by V+jet topologies require further investigation

[Grazzini, SK, Lindert, Pozzorini, Wiesemann (2020)]



Best available fixed-order predictions for ZZ/WW production

- NNLO QCD for $q\bar{q}$ channel
- NLO EW combination for $q\bar{q}$ channel
- NLO QCD corrections for gg channel

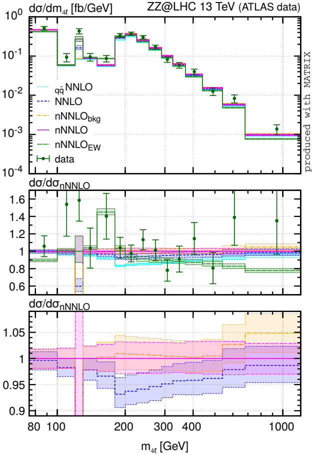
Advancements in 2-loop amplitudes for $m_{4\ell}$ lineshape (off-shell Higgs effects)

- exact m_t dependence in $\mathrm{gg} \to \mathrm{H} \to \mathrm{ZZ}$
- reweighting only for continuum/interference
- missing Higgs terms (EW, beyond NLO QCD)

Diboson production beyond fixed order

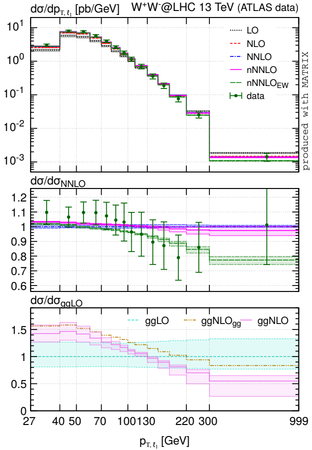
- resummation ($p_{T,VV}$, $p_{T,\mathrm{jet}}^{\mathrm{veto}}$, ...)
  MATRIX+RADISH [SK, Re, Rottoli, Wiesemann (2020)]
- event generation at NNLO QCD
  NNLOPS [Re, Wiesemann, Zanderighi (2018)]
  MiNNLO$_{\mathrm{PS}}$ [Lombardi, Wiesemann, Zanderighi ('20)]
  GENEVA [Alioli, Broggio, Gavardi, SK, Lim, Nagar, Napoletano, Rottoli ('20)]

[Grazzini, SK, Wiesemann, Yook (to be published)]



data from [JHEP 04, 048 (2019)]

[Grazzini, SK, Wiesemann, Yook (2020)]



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

Triphoton production at NNLO QCD accuracy

First MATRIX calculation for a genuine $2 \to 3$ process at NNLO QCD

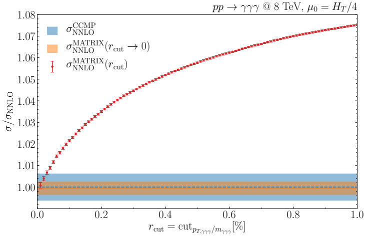
- q_T subtraction method applicable: remarkable numerical control over slicing cut-off parameter dependence
- perfect agreement with independent calculation [Chawdhry, Czakon, Mitov, Poncelet (2020)]

On-the-fly amplitude evaluation
[Abreu, Page, Pascual, Sotnikov ('20)]

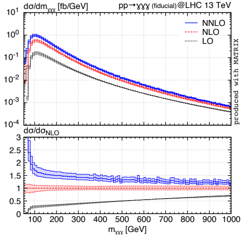
- generated with the novel CARAVEL framework [Abreu et al. (2020)]

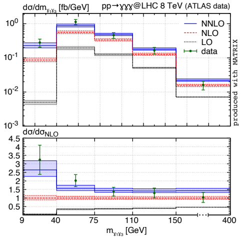
Great agreement of NNLO QCD predictions with data

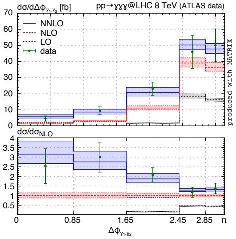
MATRIX and q_T subtraction suitable for triboson processes

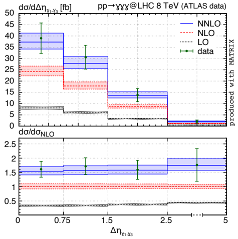


[SK, Sotnikov, Wiesemann (2021)]







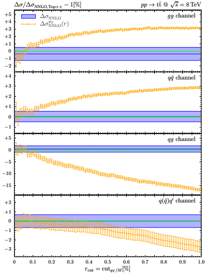


data from [Phys. Lett. B 781 (2018) 55]

Top-quark pair production at NNLO QCD accuracy

First MATRIX calculation for production of colourful final states at NNLO QCD

- extension of q_T subtraction method to production of heavy coloured particles
- good control over slicing-cut dependence: channel-wise validation
- full agreement with TOP++ [Czakon, Mitov (2014)] , also on differential level [Czakon, Heymes, Mitov (2017)]



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

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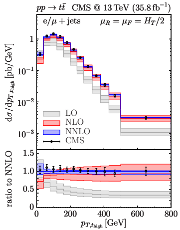
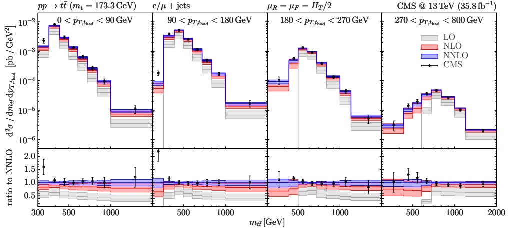


Good agreement with (multi-)differential data

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



data from [Phys. Rev. D 97 (2018) 112003]

Essential ingredient for event generation at NNLO

- MINNLO$_{PS}$ [Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi (2020)]

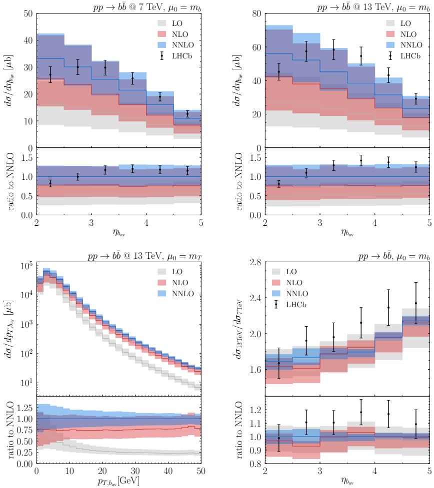
Bottom-quark pair production at NNLO QCD accuracy

- conceptionally similar to $\mathrm{t\bar{t}}$ production
- interesting application for all LHC experiments
- larger uncertainties due to lower involved scales
  $\hookrightarrow$ reduction through consideration of ratios

Great performance paves the way for MATRIX extensions

- associated top-pair production ($\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}W^{\pm}}$, $\mathrm{t\bar{t}\gamma}$)
  - same QCD structure, but more involved kinematics
  - numerical solutions in soft contributions
- off-shell top-pair production ($\mathrm{WWb\bar{b}}$)
  - numerically challenging $2 \to 4$ QCD process
  - approximation for two-loop amplitudes
- mixed NNLO QCD×EW corrections for Drell–Yan production
  - abelianization of subtraction method
  - massive lepton treatment

[Catani, Devoto, Grazzini, SK, Mazzitelli (2021)]



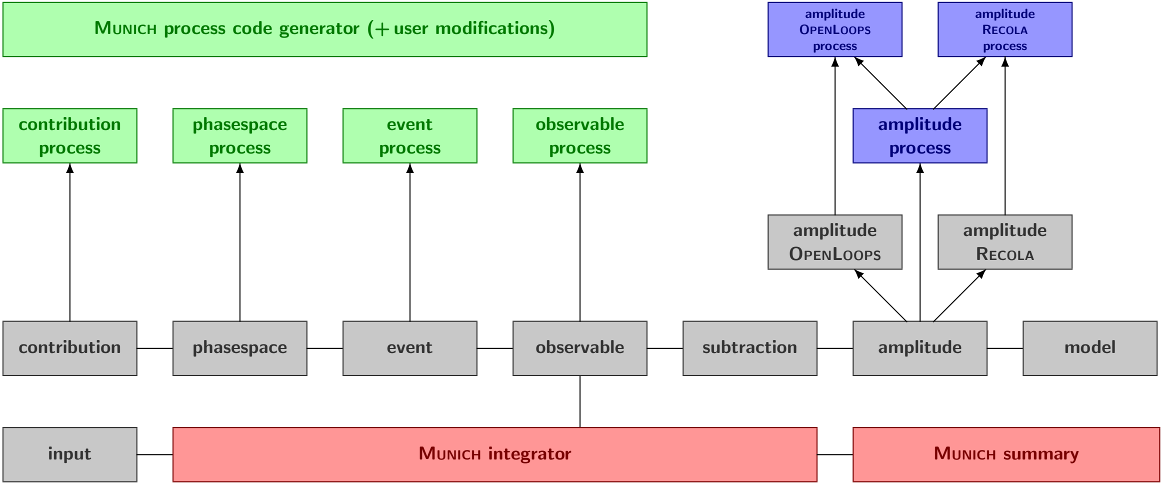
data from [Phys. Rev. Lett. 118 (2017), no. 5 052002]

The MUNICH/MATRIX framework for automated NNLO calculations

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

- first, and so far only, 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.

Schematic overview of the MUNICH/MATRIX framework



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$\times$tree and loop$\times$loop colour (and spin) correlators
- helicity amplitudes, colour-stripped amplitudes to construct 4-colour correlators
- 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
  - 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

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

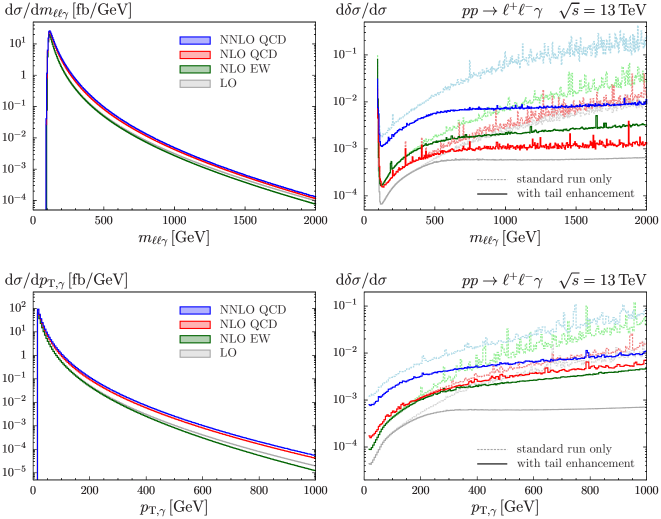
Solution in MUNICH integrator

- 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



Interfacing MUNICH/MATRIX with external codes

Interfacing external code to MATRIX framework

- all-order resummation with MATRIX+RADISH [SK, Re, Rottoli, Wiesemann (2020)]

RADISH [Bizon, Monni, Re, Rottoli, Torielli (2018)]: FORTRAN code to perform various resummations in direct space

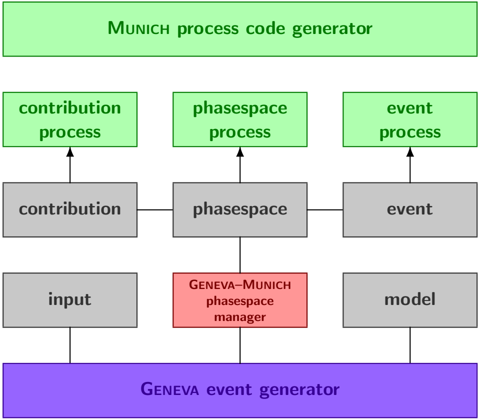
- N^3LL for p_T
- NNLL for $p_{T,\mathrm{jet}}^{\mathrm{veto}}$
- NNLL for combined p_T and $p_{T,\mathrm{jet}}^{\mathrm{veto}}$ [Monni, Rottoli, Torielli (2020)]

Implementation into MATRIX framework

- dependencies like HOPPET [Salam, Rojo (2009)] and CHAPLIN [Bühler, Duhr (2014)] installed by the script
- RADISH called directly from MUNICH, which provides phase space points, amplitudes, etc.
- additive/multiplicative matching with fixed order performed in the MATRIX script

Interfacing of MUNICH methods to external code

- NNLO event generation with GENEVA+MUNICH



Conclusions & Outlook

NNLO QCD accuracy and beyond required to succesfully confront theory with LHC data

- diboson production
- triphoton production
- heavy-quark pair production

The MUNICH/MATRIX framework

- modular C++ code, user-friendly PYTHON interface
- use of state-of-the-art amplitudes
- highly efficient Monte Carlo integration
- combination with other programs

The future of precision calculations

- mass effects, NNLO QCD×EW, N^{3}LO QCD
- $2 \to 3$ era of NNLO QCD calculations
- automation of NNLO event generation