Recent results in the computation of EW and QCD corrections for LHC processes

Stefan Kallweit

Joint workshop "GDR–QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOaccess"
Paris, France, May 31 – June 4, 2021

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)]

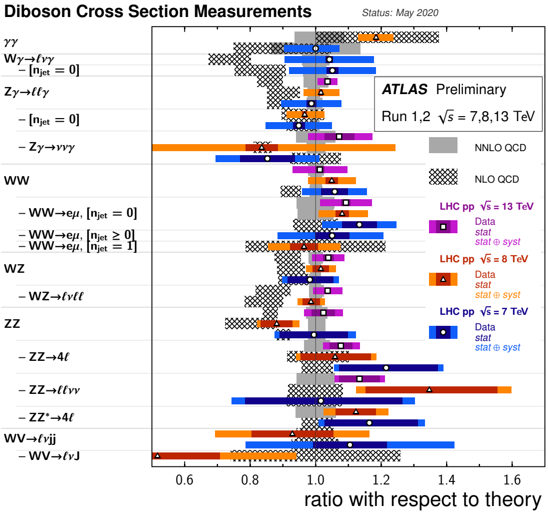
- inevitable for data–theory agreement

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 (to be released, beta version available)]

[ATLAS collaboration (2020)]



Outline

1. Motivation
2. Status and recent results in QCD calculations for LHC processes
   - Triphoton production at NNLO QCD accuracy
   - Heavy-quark pair production at NNLO QCD accuracy
3. Status and recent results in EW calculations for LHC processes
   - Combination of NNLO QCD and NLO EW predictions for diboson production
   - Mixed QCD–EW corrections for Drell–Yan production
4. Conclusions

NNLO QCD subtraction/slicing methods and implementations

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, $\gamma\gamma$, Zγ, Wγ, 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, $\gamma\gamma$, Zγ
  - Wγ, γj, 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

First $2 \to 3$ calculations at NNLO QCD

- $\gamma\gamma\gamma$ [Chawdhry, Czakon, Mitov, Poncelet (2020), SK, Sotnikov, Wiesemann (2021)]
- $\gamma\gamma$j [Chawdhry, Czakon, Mitov, Poncelet ('21)]
- (jjj) [Chawdhry, Czakon, Mitov, Poncelet (preliminary results at RADCOR 2021)]

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

- leading-colour jjj
  [Abreu, Page, Pascual, Sotnikov (2021), Abreu, Febres Cordero, Ita, Page, Sotnikov ('21)]
- full-colour $\gamma\gamma$j [Agarwal, Buccioni, von Manteuffel, Tancredi ('21)]
- leading-colour W$b\bar{b}$ [Badger, Hartanto, Zoia ('21)]

Heavy-quark loops for $gg \to$ 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 ('20), Brønnum-Hansen, Wang ('20)]
- WW [Brønnum-Hansen, Wang ('20)]
- ZH [Chen, Heinrich, Jones, Kerner, Klappert, Schlenk (2021)]

Inclusive $2 \to 1$ calculations at N^{3}LO QCD

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

Fully differential $2 \to 1$ calculations at N^{3}LO QCD

- H [Dulat, Mistlberger, Pelloni (2019), Cieri, Chen, Gehrmann, Glover, Huss (2019)]
- H ($\to \gamma\gamma$) [Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni ('21)]
- Z/γ^* [Camarda, Cieri, Ferrera ('21)]

↪ combination of local NNLO subtraction with slicing/projection methods promoted to N^{3}LO

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

- leading-colour $\gamma\gamma$ [Caola, von Manteuffel, Tancredi (2021)]

Triphoton production at NNLO QCD accuracy

First MATRIX calculation for genuine 2 → 3 process at NNLO QCD

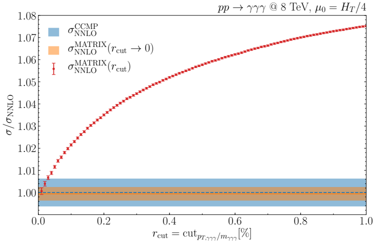
- q_T subtraction method for colourless final states directly applicable:

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

↪ remarkable numerical control over slicing parameter dependence

↪ full agreement with independent calculation [Chawdhry, Czakon, Mitov, Poncelet (2020)]

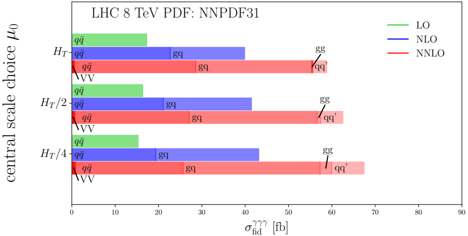
[SK, Sotnikov, Wiesemann (2021)]



Further important ingredients of the calculation

- fast and stable 2-loop amplitudes [Abreu, Page, Pascual, Sotnikov ('20)] generated with CARAVEL, using PENTAGONFUNCTIONS++
  [Abreu et al. (2020)] [Chicherin, Sotnikov (2020)]
- fast and stable 1-loop amplitudes from OPENLOOPS
  [Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller (2019)]
- highly efficient phase space integration in MUNICH [SK]

[Chawdhry, Czakon, Mitov, Poncelet (2020)]



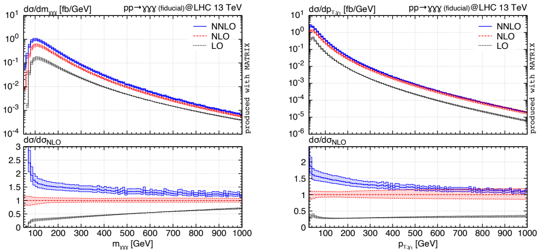
Huge NLO and NNLO QCD corrections, similar to diphoton production ⇒ split cross section into partonic channels

Triphoton production at NNLO QCD accuracy

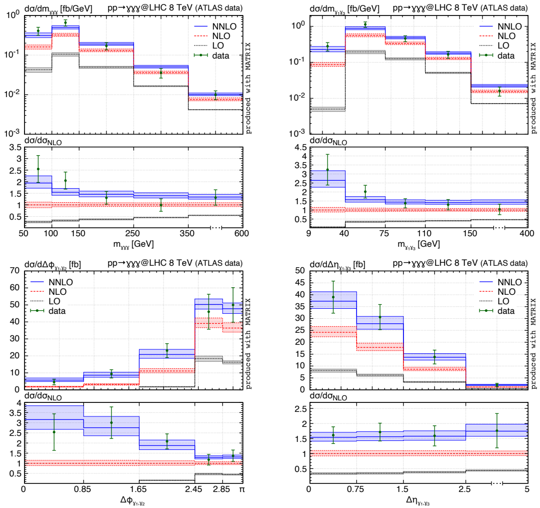
Comparison with ATLAS data at 8 TeV

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

[SK, Sotnikov, Wiesemann (2021)]



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



- great numerical performance also with refined resolution and in suppressed phase space regions

↪ **MATRIX fully suitable for triboson processes**

Top-quark pair production at NNLO QCD accuracy

First MATRIX calculation for colourful final states at NNLO QCD

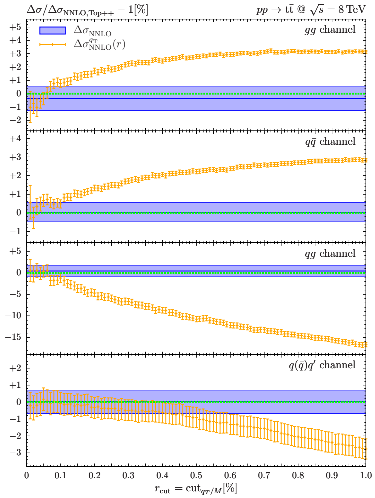
[Catani, Devoto, Grazzini, SK, Mazzitelli, Sargsyan (2019)]

- extension of q_T subtraction method to production of heavy quarks:

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

  - counterterm needs to account for IR behaviour of real contribution, including soft singularities related to final-state quarks [Catani, Grazzini, Torre (2014), Ferroglia, Nuebert, Pecjak, Yang (2009), Li, Li, Shao, Yang, Zu (2013)]
  - $\mathcal{H}^{t\bar{t}}_{\rm NNLO}$ contains remainder of integrated final-state soft singularities [Catani, Devoto, Grazzini, Mazzitelli (to appear), Angeles-Martinez, Czakon, Sapeta (2018)]
  - 2-loop amplitudes from numerical result [Bärnreuther, Czakon, Fiedler (2014)]
  - massive NLO subtraction scheme required, e.g. dipole subtraction [Catani, Seymour (1997), Catani, Dittmaier, Seymour, Trocsanyi (2002)]

- slicing parameter dependence under good numerical control; investigation after splitting into partonic channels
  - ↪ full agreement with TOP++ [Czakon, Mitov (2014)]
  - ↪ validation also on the level of differential distributions [Catani, Devoto, Grazzini, SK, Mazzitelli (2019), Czakon, Heymes, Mitov (2017)]

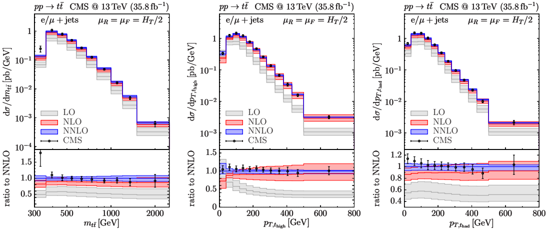


Top-quark pair production at NNLO QCD accuracy

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 $p_{T,t\bar{t}} \to 0$ region

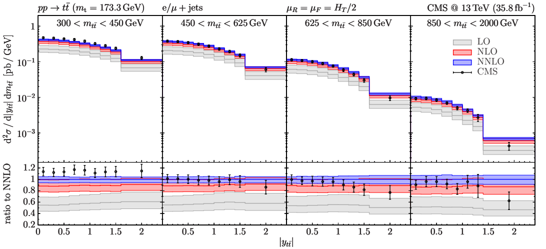
↪ would require resummation/shower matching

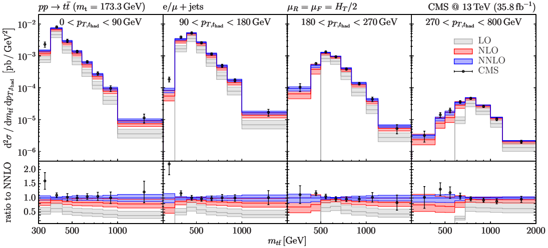


Indications for perturbative convergence

↪ 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]



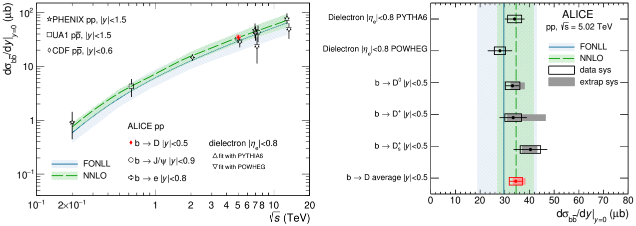


Bottom-quark pair production at NNLO QCD accuracy

Application to bottom quarks

- conceptionally similar to $t\bar{t}$ 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

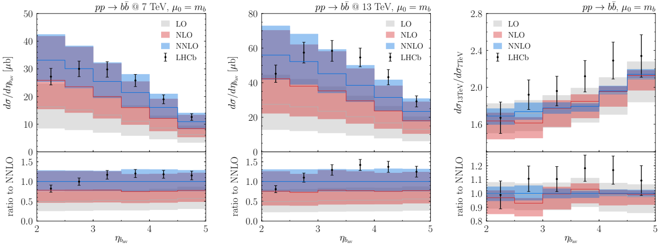
[ALICE Collaboration (2021)]



Matrix applications beyond $Q\bar{Q}$

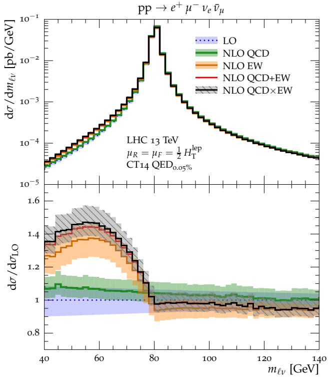
- associated top-pair production
  - same QCD structure as $Q\bar{Q}$
  - more involved kinematics require numerical solutions in soft terms
- ↪ proof of principle for diagonal channels in $t\bar{t}\mathrm{H}$ [Catani, Fabre, SK, Grazzini (2021)]

[Catani, Devoto, Grazzini, SK, Mazzitelli (2021)] data from [Phys. Rev. Lett. 118 (2017), no. 5 052002]



Main features of EW corrections

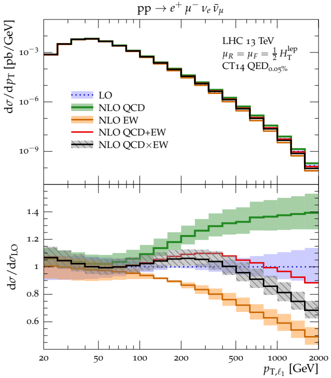
- **Shape corrections in invariant-mass distributions**



[SK, Lindert, Pozzorini, Schönherr (2017)]

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

- **Negative corrections in high-energy observables**



[SK, Lindert, Pozzorini, Schönherr (2017)]

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. $\gamma\gamma \to WW$
  - as EW corrections, from IS $\gamma \to q\bar{q}^*$ splittings
- **Subdominant production modes (not maximal in α_s)**
  - e.g. $q\bar{q} \to Z^*/\gamma^* \to t\bar{t}$
  - interferences between QCD and EW production modes
  - corresponding tower of NLO contributions that cannot be uniquely qualified as QCD or EW corrections (in parts)

Status of NLO EW calculations

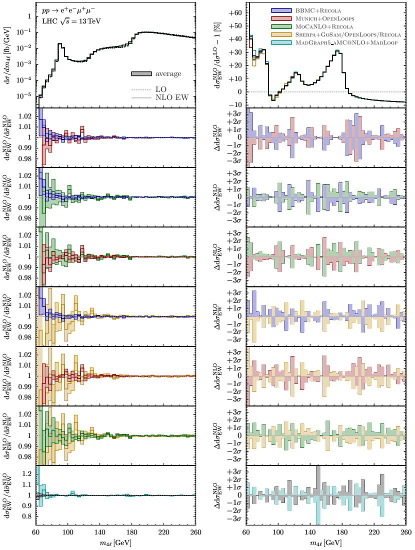
Dedicated comparison in Les Houches 2017 proceedings

- 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 → 8) [Denner, Pelliccioli (2021)]
- off-shell $t\bar{t}$H production (2 → 7) [Denner, Lang, Pellen, Uccirati (2017)]
- off-shell WWW production (2 → 6) [Dittmaier, Knippen, Schwan (2020)]
- vector boson scattering (2 → 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)]
  - (W^+W^-) [Denner, Franken, Pellen, Schmidt (preliminary results at RADCOR 2021)]



[Les Houches 2017: Physics at TeV Colliders SM WG Report (2018)]

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 $\mathcal{O}(\alpha_s\alpha)$ effects desirable**

Different combination approaches

- **additive:**

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

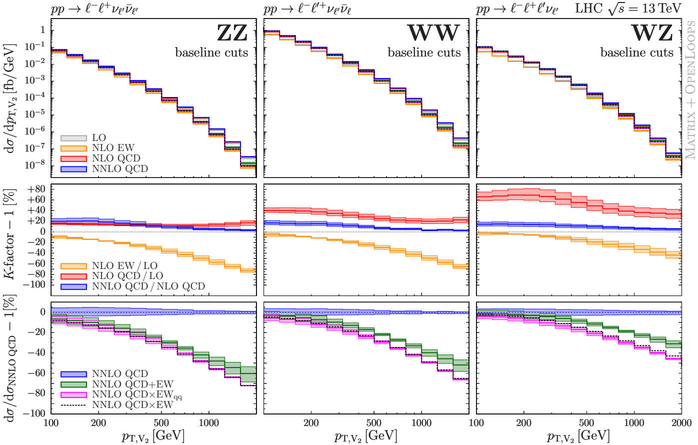
- **multiplicative:**

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

- **multiplicative (only $q\bar{q}$):**

  $d\sigma^{\mathrm{LO}}_{\mathrm{q\bar{q}}}(1+\delta^{\mathrm{(N)NLO}}_{\mathrm{q\bar{q},QCD}})(1+\delta^{\mathrm{NLO}}_{\mathrm{q\bar{q},EW}})$
  $+\sigma^{\mathrm{NLO}}_{\gamma-\mathrm{ind.,EW}}$

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



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 – $p_{\mathrm{T,V_1}}$

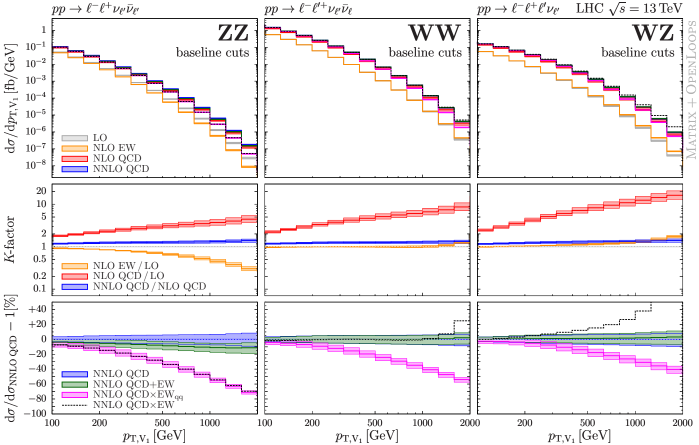
Situation more involved in presence of so-called **giant *K*-factors**

↪ QCD corrections in tails dominated by **hard V+jet topologies**

↪ also large positive EW corrections (photon-induced V+jet topologies)

- **additive** underestimates EW effects
- **multiplicative** combination multiplies large QCD and EW *K*-factors
  ↪ **discarded**
- **multiplicative (only $q\bar{q}$)** shows expected Sudakov behaviour, but overestimates the EW effects (VV *K*-factor applied in V+jet region)

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



None of the approaches works perfectly well for **observables dominated by V+jet topologies**

↪ merged prediction, full mixed QCD–EW calculation, or phase space restriction to hard-VV topologies.

Best available fixed-order predictions for ZZ/WW production

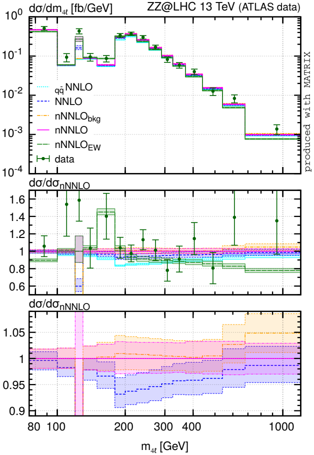
- NNLO QCD for $q\bar{q}$ channel
- NLO EW combination for $q\bar{q}$ channel
- NLO QCD corrections for gg channel (2-loop amplitudes from ggVVamp, [von Manteuffel, Tancredi (2015)] improved by reweighting for m_t effects)

↪ **will be made publicly available for all VV processes in MATRIX v2** [Grazzini, SK, Wiesemann] (beta version already available for a while)

Diboson production beyond fixed order

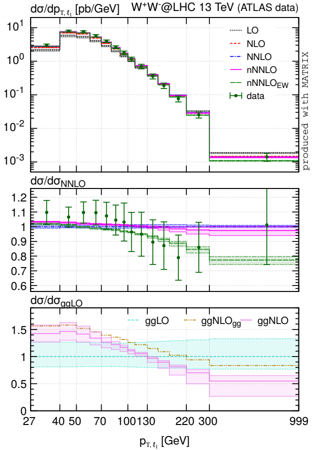
- resummation ($p_{T,VV}$, $p_{T,\mathrm{jet}}^{\mathrm{veto}}$, …)
  MATRIX+RADISH [SK, Re, Rottoli, Wiesemann (2020)]
- event generation at NNLO QCD
  NNLOPS [Re, Wiesemann, Zanderighi (2018)]
  MiNNLO$_{PS}$ [Lombardi, Wiesemann, Zanderighi ('21)]
  GENEVA [Alioli, Broggio, Gavardi, SK, Lim, Nagar, Napoletano, Rottoli (2021)]

[Grazzini, SK, Wiesemann, Yook ('21)]



data from [JHEP 04, 048 (2019)]

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



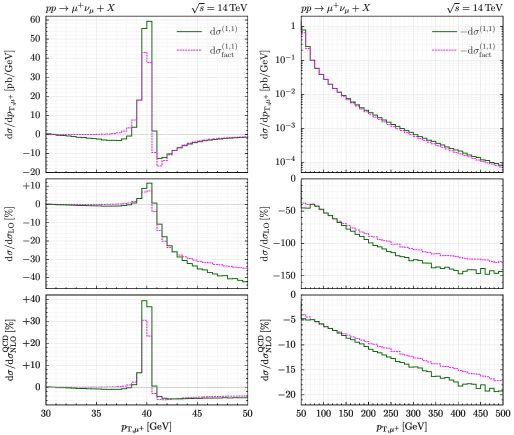
data from [Eur. Phys. J. C 79 (2019) 884]

Mixed NNLO QCD–EW calculation for off-shell W production

Calculation in the MATRIX framework

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

- subtraction of IR singularities by abelianisation of the q_T subtraction formalism for heavy quarks
  - ↪ massive leptons to regularize collinear singularities
- almost all contributions treated exactly
  - ↪ pole approximation for mixed 2-loop amplitude, improved by dedicated reweighting procedure
- qualitative agreement with the approximate result of [Dittmaier, Huss, Schwinn (2015)] around the Jacobian peak
  - ↪ also reliable in the remaining phase space
- Recent achievements in mixed 2-loop amplitudes
  - Z [Bonciani, Buccioni, Rana, Vicini (2020)]
  - W [Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch (2021)]
  - off-shell Z/W at $\mathcal{O}(N_f \alpha_s \alpha)$ [Dittmaier, Schmidt, Schwarz (2020)]
  - off-shell Z [Heller, von Manteuffel, Schabinger, Spiesberger (2021)]



General implementation in the MATRIX framework (for colourless massive charged particles)

Conclusions

Status of higher-order QCD calculations

- $2 \to 2$ calculations at NNLO (almost) completed
- first $2 \to 3$ calculations at NNLO appeared
- $\mathrm{N^3LO}$ calculations for $2 \to 1$ processes available
- great progress in 2-loop (and 3-loop) amplitudes

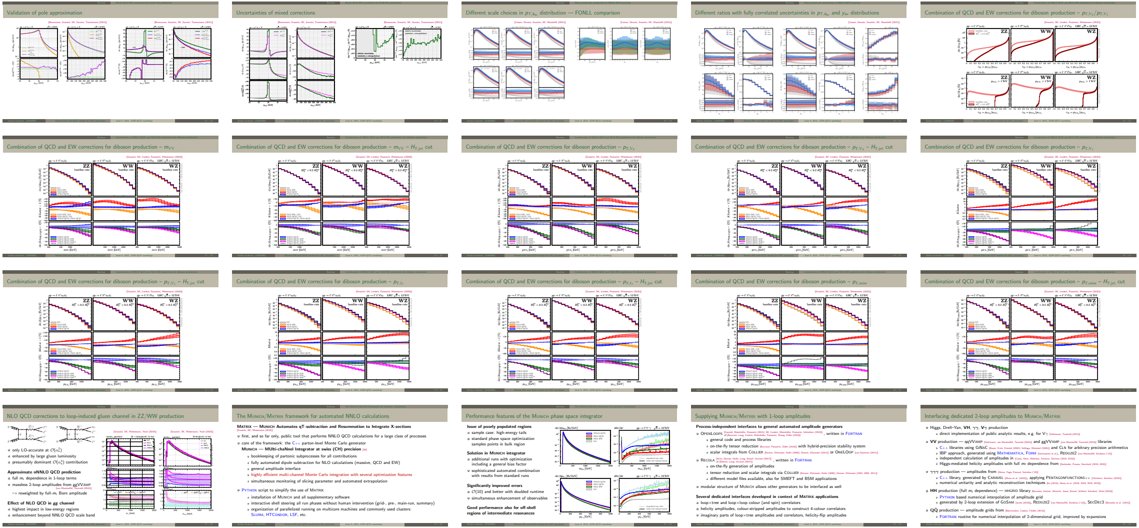
Status of EW calculations

- NLO EW widely automated in several tools
- high-multiplicity processes calculated (up to $2 \to 8$)

Recent achievements in the MATRIX framework

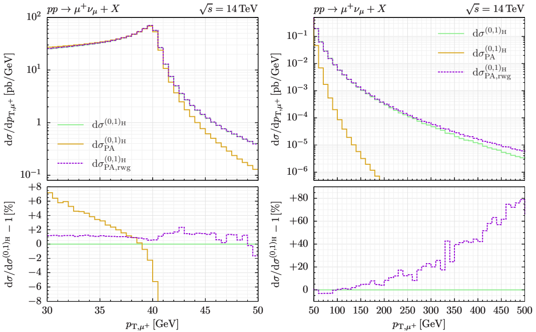
- triphoton production at NNLO QCD
- heavy-quark pair production at NNLO QCD
- combination of NNLO QCD and NLO EW corrections in diboson production
- mixed NNLO QCD–EW corrections for off-shell W production

Backup

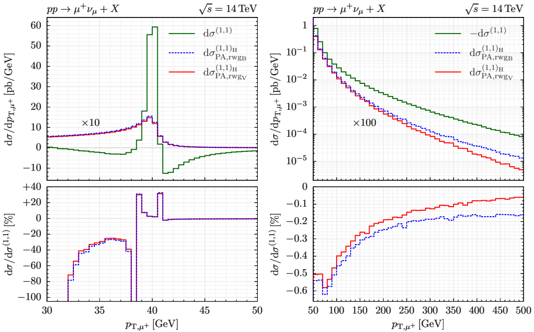

Validation of pole approximation
Uncertainties of mixed corrections
Different scale choices in p_{T,b_μ} distribution — FONLL comparison
Different ratios with fully correlated uncertainties in p_{T,b_μ} and $y_{\mu\nu}$ distributions
Combination of QCD and EW corrections for diboson production – $p_{T,V_2}/p_{T,V_1}$
Combination of QCD and EW corrections for diboson production – m_{VV}
Combination of QCD and EW corrections for diboson production – m_{VV} – $H_{T,\mathrm{jet}}$ cut
Combination of QCD and EW corrections for diboson production – p_{T,V_2}
Combination of QCD and EW corrections for diboson production – p_{T,V_2} – $H_{T,\mathrm{jet}}$ cut
Combination of QCD and EW corrections for diboson production – p_{T,V_1}
Combination of QCD and EW corrections for diboson production – p_{T,V_1} – $H_{T,\mathrm{jet}}$ cut
Combination of QCD and EW corrections for diboson production – p_{T,ℓ_1}
Combination of QCD and EW corrections for diboson production – p_{T,ℓ_1} – $H_{T,\mathrm{jet}}$ cut
Combination of QCD and EW corrections for diboson production – $p_{T,\mathrm{miss}}$
Combination of QCD and EW corrections for diboson production – $p_{T,\mathrm{miss}}$ – $H_{T,\mathrm{jet}}$ cut
NLO QCD corrections to loop-induced gluon channel in ZZ/WW production
The Munich/Matrix framework for automated NNLO calculations
Performance features of the Munich phase space integrator
Supplying Munich/Matrix with 1-loop amplitudes
Interfacing dedicated 2-loop amplitudes to Munich/Matrix

Validation of pole approximation

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

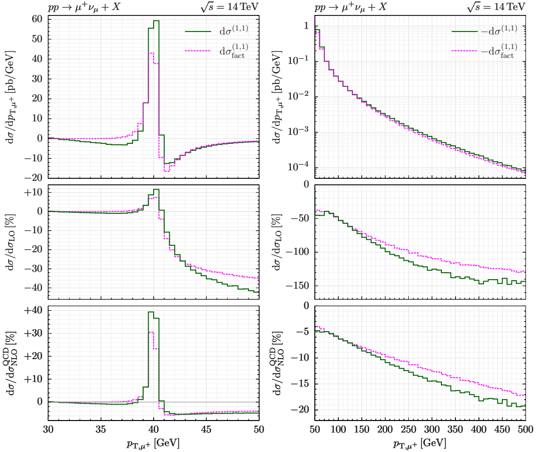


[Buonocore, Grazzini, SK, Savoini, Tramontano (2021)]

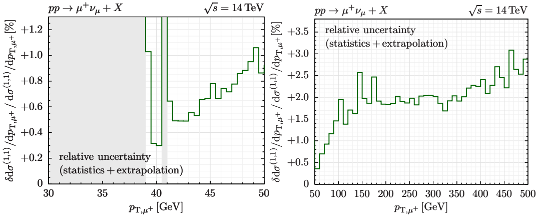


Uncertainties of mixed corrections

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

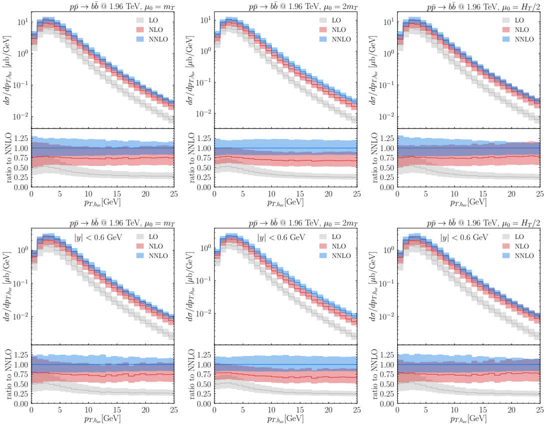


[Buonocore, Grazzini, SK, Savoini, Tramontano (2021)]

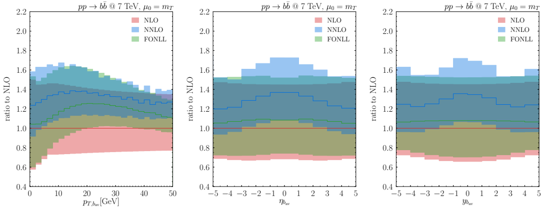


Different scale choices in $p_{T,b_{av}}$ distribution — FONLL comparison

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

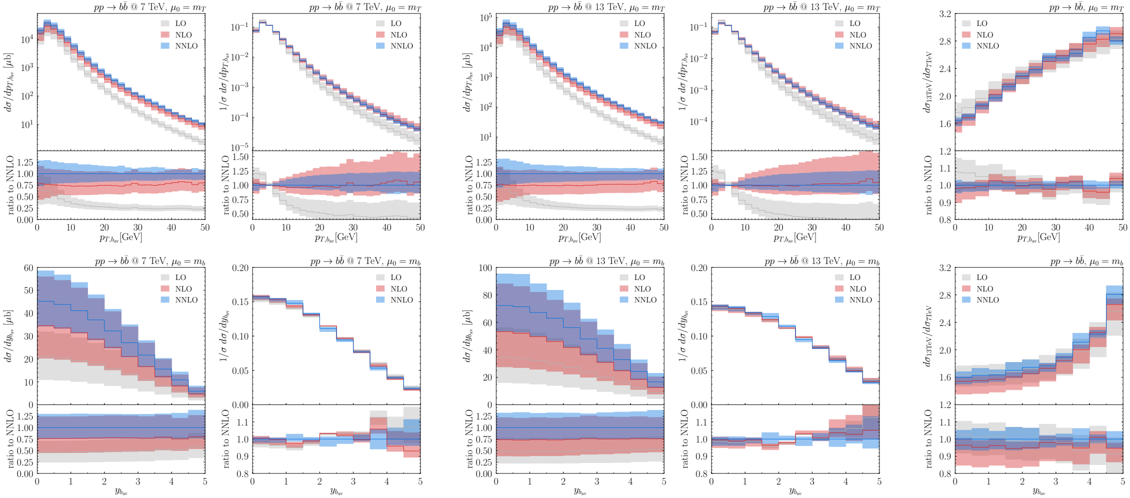


[Catani, Devoto, Grazzini, SK, Mazzitelli (2021)]



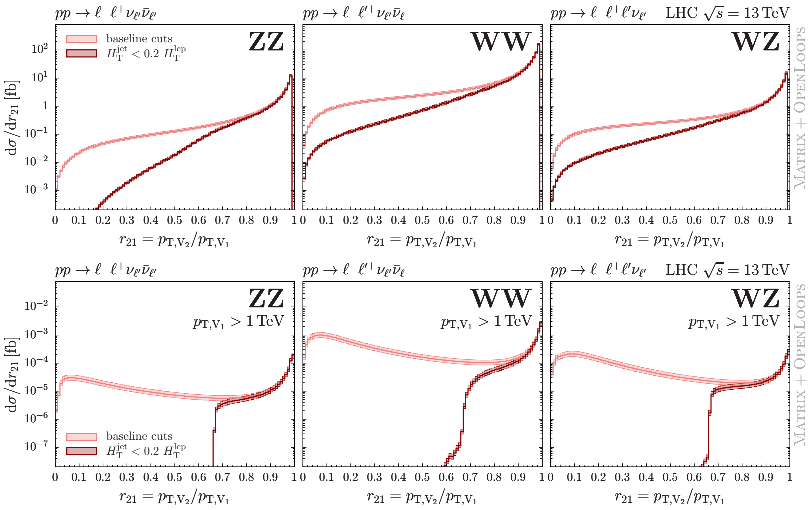
Different ratios with fully correlated uncertainties in $p_{T,b_{av}}$ and y_{av} distributions

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



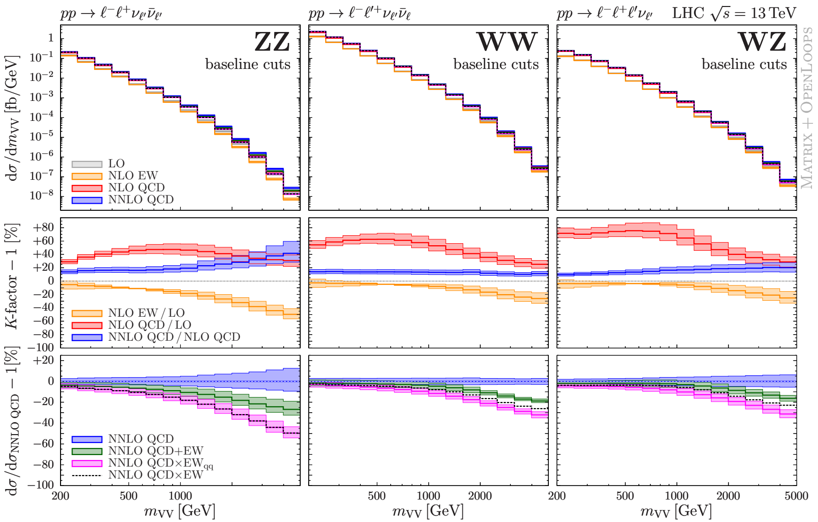
Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,V_2}}/p_{\mathrm{T,V_1}}$

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



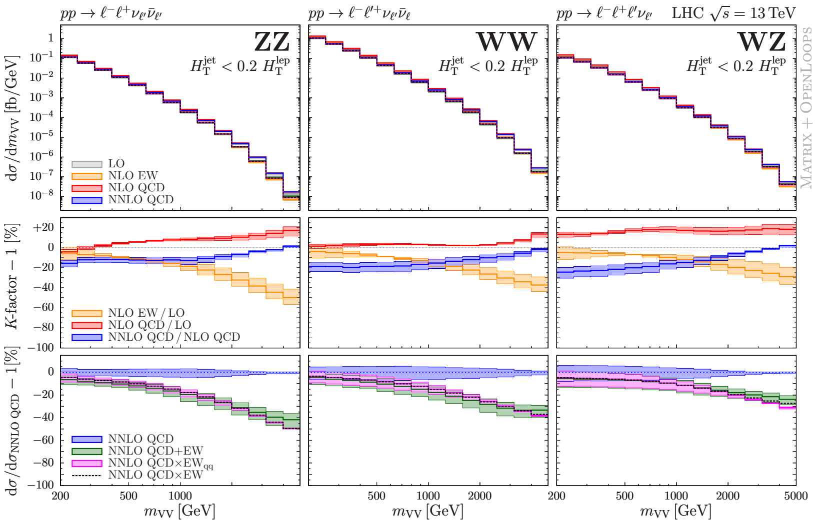
Combination of QCD and EW corrections for diboson production – m_{VV}

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



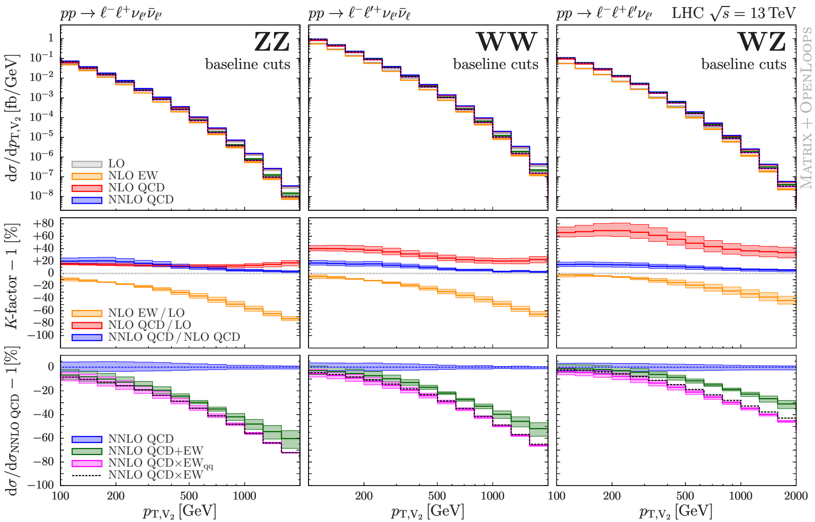
Combination of QCD and EW corrections for diboson production – m_{VV} – $H_{\mathrm{T,jet}}$ cut

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



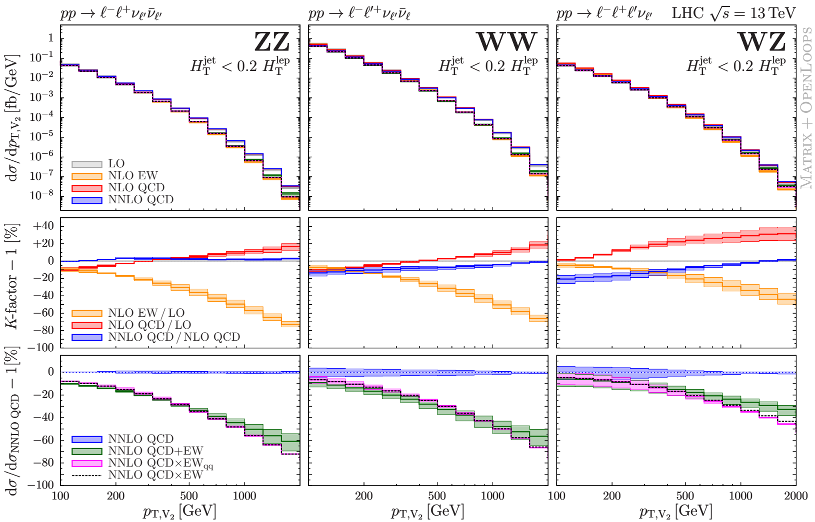
Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,V_2}}$

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



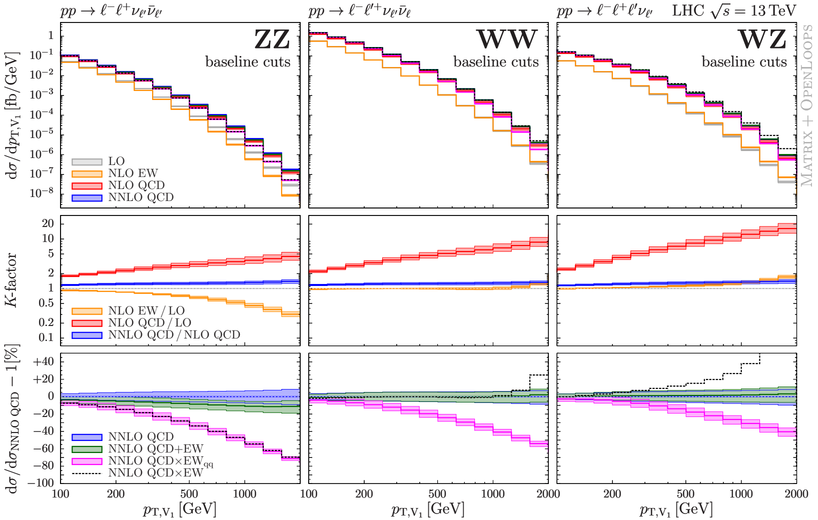
Combination of QCD and EW corrections for diboson production – p_{T,V_2} – $H_{T,jet}$ cut

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



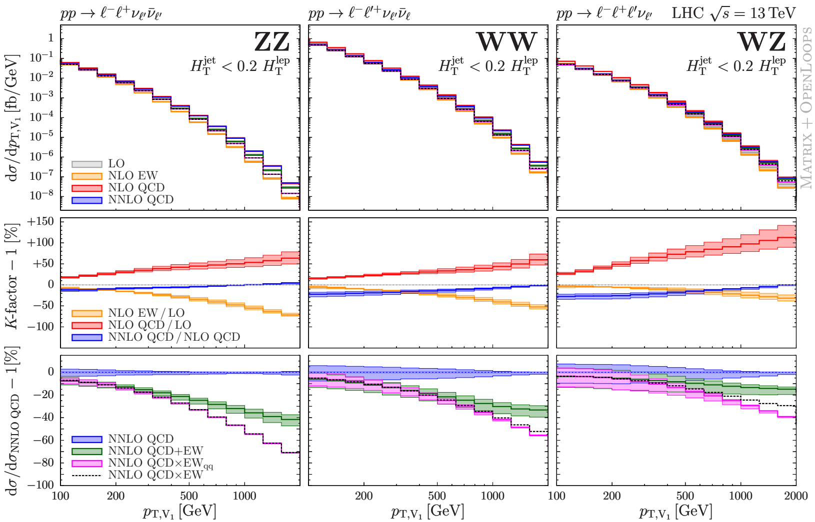
Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T},\mathrm{V}_1}$

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



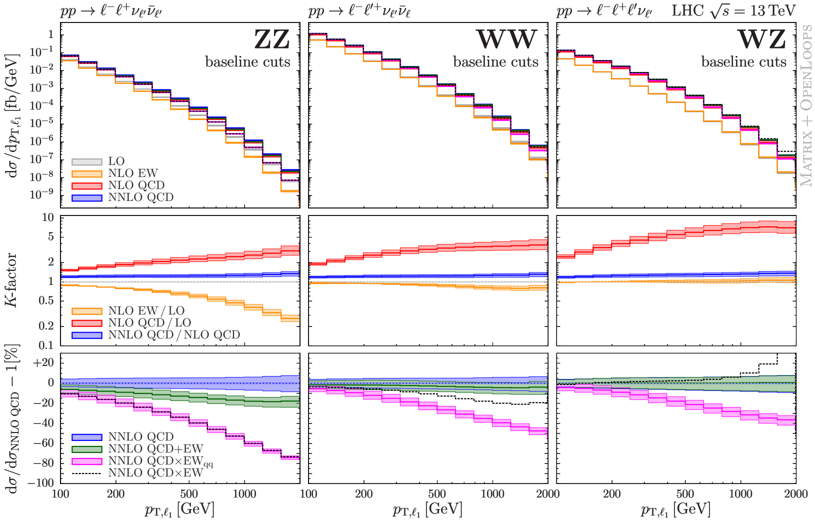
Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,V_1}}$ – $H_{\mathrm{T,jet}}$ cut

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



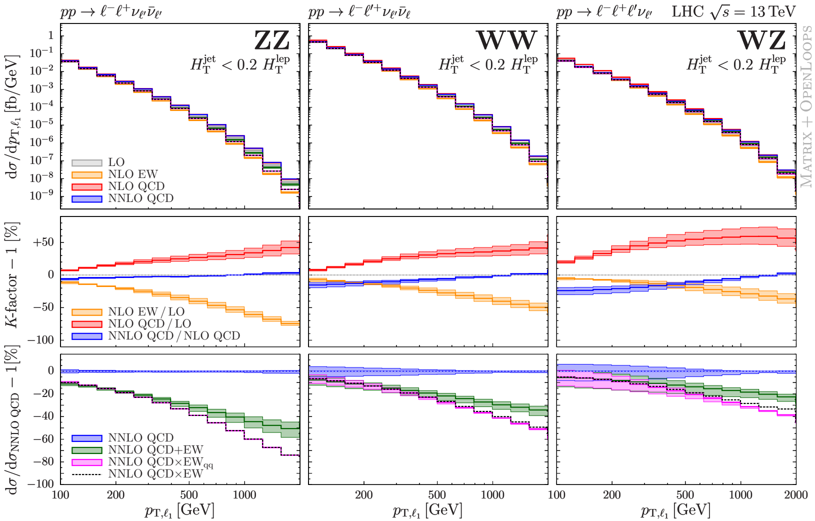
Combination of QCD and EW corrections for diboson production – p_{T,ℓ_1}

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



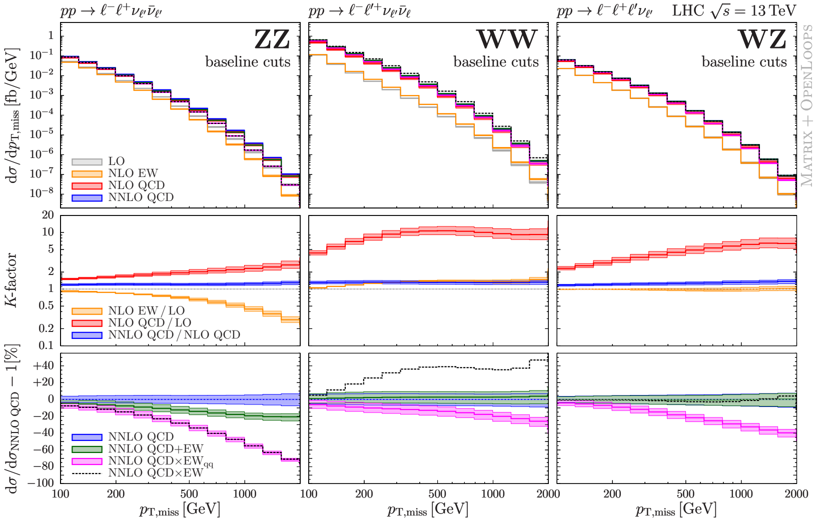
Combination of QCD and EW corrections for diboson production – p_{T,ℓ_1} – $H_{T,jet}$ cut

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



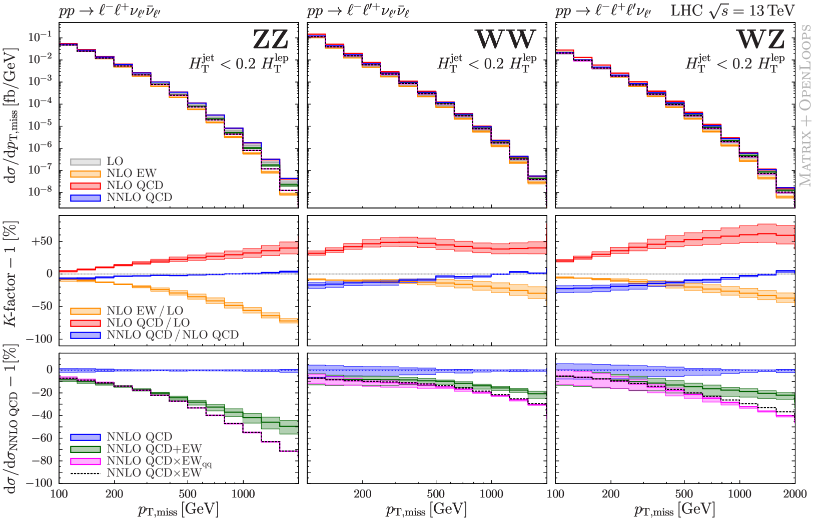
Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,miss}}$

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

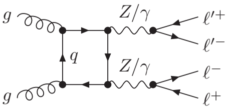


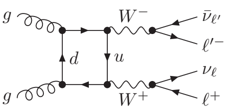
Combination of QCD and EW corrections for diboson production – $p_{\mathrm{T,miss}}$ – $H_{\mathrm{T,jet}}$ cut

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



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

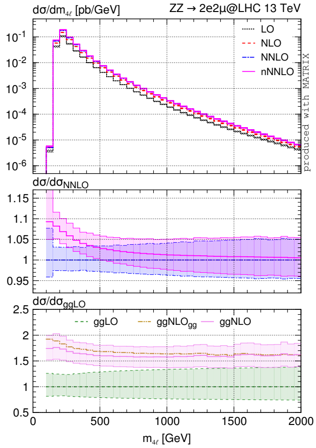
- full m_t dependence in 1-loop terms
- massless 2-loop amplitudes from ggVVAMP [von Manteuffel, Tancredi (2015)]

  ↪ reweighted by full-m_t Born amplitude

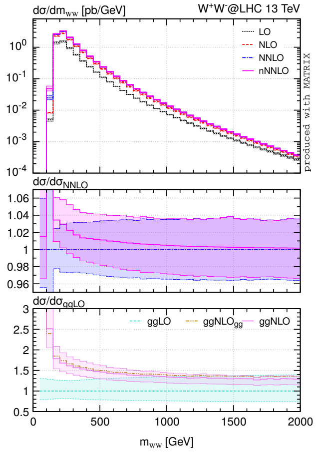
Effect of NLO QCD in *gg* channel

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

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



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



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.

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

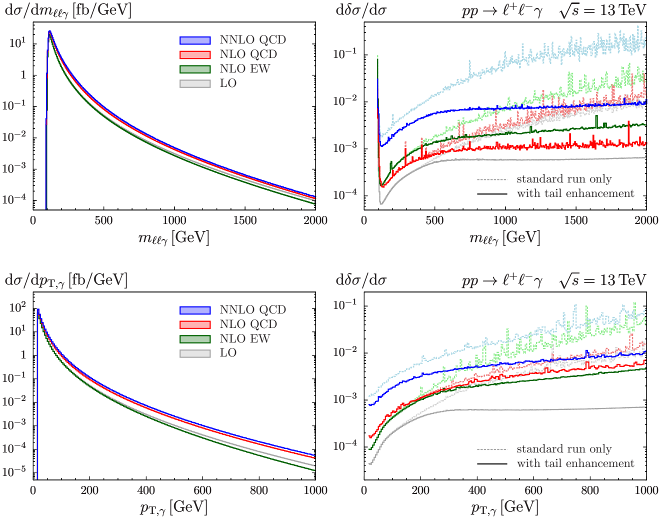
Solution in MUNICH integrator

- 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$\times$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)]
- $\mathrm{Q\bar{Q}}$ production — amplitude grids from [Bärnreuther, Czakon, Fiedler (2014)]
  - FORTRAN routine for numerical interpolation of 2-dimensional grid, improved by expansions