# Monte-Carlo developments and Electroweak/mixed QCD-EW corrections

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Marco Zaro LHC EWWG, July 2024







### Outline

- Recent progress in the computation of EW corrections
	- Introduction on EW and mixed QCD-EW corrections
	- EW corrections in the high-energy limit
	- The problem of PS matching
	- Mixed QCD/EW corrections to Drell-Yan at NNLO
- Recent and future developments in MC tools
	- NNLO+PS predictions
	- Techniques for the reduction of negative weights in MC@NLO-type matching
	- GPU/AI related developments





# EW corrections and mixed-coupling expansion Part 1





$$
\sigma_{pp \to X}(s) = \sum_{ab} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab \to X}(\hat{s} = x_1 x_2 s)
$$





• The way we do precise predictions: perturbation theory

Probability of finding a parton into the proton

$$
\sigma_{pp \to X}(s) = \sum_{ab} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab \to X}(\hat{s} = x_1 x_2 s)
$$
  
Parton distribution functions:

must be fit to data, process independent





### • The way we do precise predictions: perturbation theory

 $\sigma_{pp \to X} (s) = \sum$ *ab* Z  $dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab \to X} (\hat{s} = x_1 x_2 s)$ Parton distribution functions: Partonic cross section: Probability of finding a parton Probability that two partons into the proton scatter into a given final state

must be fit to data, process independent

can be computed in perturbation theory, process dependent





• The way we do precise predictions: perturbation theory

 $\sigma_{pp \to X} (s) = \sum$ *ab* Z  $dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab \to X} (\hat{s} = x_1 x_2 s)$ Parton distribution functions: must be fit to data, process can be computed in perturbation independent Probability of finding a parton Probability that two partons into the proton scatter into a given final state Partonic cross section: theory, process dependent  $\hat{\sigma}_{ab \to X} = \hat{\sigma}_{ab \to X}^{(0)} + \alpha_s \hat{\sigma}_{ab \to X}^{(1)} + \alpha_s^2 \hat{\sigma}_{ab \to X}^{(2)} + \alpha_s^3 \hat{\sigma}_{ab \to X}^{(3)} + \ldots$ strong coupling, ~0.





Probability of finding a parton Probability that two partons into the proton scatter into a given final state Z *pp*!*<sup>X</sup>*(*s*) = <sup>X</sup> *dx*1*dx*2*fa*(*x*1)*fb*(*x*2)ˆ*ab*!*<sup>X</sup>*(ˆ*s* = *x*1*x*2*s*) *ab* Parton distribution functions: Partonic cross section: must be fit to data, process can be computed in perturbation independent theory, process dependent ˆ*ab*!*<sup>X</sup>* = ˆ(0) *ab*!*<sup>X</sup>* <sup>+</sup> ↵*s*ˆ(1) *s*ˆ(2) *s*ˆ(3) *ab*!*<sup>X</sup>* <sup>+</sup> ↵<sup>2</sup> *ab*!*<sup>X</sup>* <sup>+</sup> ↵<sup>3</sup> *ab*!*<sup>X</sup>* <sup>+</sup> *...* LO strong coupling, ~0.1





Probability of finding a parton probability that two partons into the proton scattering is the given final state of 
$$
p_{\text{p}} \rightarrow X(s) = \sum_{ab} \int \frac{dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab \rightarrow X}(\hat{s} = x_1 x_2 s)}{2a_1 x_2 x_3}
$$





*pp*!*<sup>X</sup>*(*s*) = <sup>X</sup> *ab* Z *dx*1*dx*2*fa*(*x*1)*fb*(*x*2)ˆ*ab*!*<sup>X</sup>*(ˆ*s* = *x*1*x*2*s*) Parton distribution functions: must be fit to data, process independent Probability of finding a parton into the proton Partonic cross section: can be computed in perturbation theory, process dependent Probability that two partons scatter into a given final state ˆ*ab*!*<sup>X</sup>* = ˆ(0) *ab*!*<sup>X</sup>* <sup>+</sup> ↵*s*ˆ(1) *ab*!*<sup>X</sup>* <sup>+</sup> ↵<sup>2</sup> *s*ˆ(2) *ab*!*<sup>X</sup>* <sup>+</sup> ↵<sup>3</sup> *s*ˆ(3) *ab*!*<sup>X</sup>* <sup>+</sup> *...* LO NLO NNLO strong coupling, ~0.1











### • The way we do precise predictions: perturbation theory



• Going higher orders, the complexity of the computation explodes

Marco Zaro, 10-7-2024





### Electroweak corrections: a multi-coupling expansion

- If EW corrections come into play, one must carry the expansion both in α and α*<sup>s</sup>*
- The structure of a given process are something like







Some comments







Some comments



• For IR-finiteness, contributions of QCD and EW origin to a given contribution must *both* be included







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- The presence of different powers of α and α*s* hints at a power-counting estimate for the contributions. Such an estimate is often misleading!





Some comments



- For IR-finiteness, contributions of QCD and EW origin to a given contribution must *both* be included
- The presence of different powers of α and α*s* hints at a power-counting estimate for the contributions. Such an estimate is often misleading!
- Predictions including all the contributions at LO/NLO/… are typically called "Complete-LO/NLO/…" NLO EW and Complete-NLO predictions can be obtained with automatic (and mostly public) tools

Collier, GoSam, MG5\_aMC, Recola, Sherpa+Collier/OpenLoops/OpenLoops2/…



### Coupling-hiearchy violation Drell-Yan

Dittmaier et al, 0911.2329



- *• Because of photon radiation from events on the peak, the region M(e+e- )<mZ receives huge EW corrections*
- *• NLO QCD corrections remain fairly stable across the peak*



INFN





#### Coupling-hiearchy violation **VBS** -25  $\overline{z}$  $\overline{1}$ und de la construction de la const  $\overline{a}$ νµ **\_/**

Express and Biedermann et al, 1708.00268  $\overline{a}$ 





- 0  $\mathcal{T}$ maacca production modes **•** *In VBS, EW and QCD induced production modes • In VBS, EW and QCD induced production modes*  $combarable$  at  $IO$ comparable at LO *comparable at LO*
- $\sqrt{2}$  $\mathbf{v}$  $F(M)$  corrections to  $F(M)$  induced mode -1 1 2  $\bullet$  NLO EW corrections to EW-induced mode  $\mathbf{r}$  in Fig. 1, the contraction of the  $\mathbf{r}$ *(NLO<sub>4</sub>) are by far the dominant NLO* α2 sα5" , and O! α3 sα4" *contribution* . The situation
- -6 contributions furnish the QCD corrections to  $\overline{z}$ y ا، -2  $-1$  -0.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $-0.5$  1.5  $\overline{M}$  $\mathbf{Z}$  $\overline{a}$  ,  $\overline{a}$  ,  $\overline{a}$  ,  $\overline{a}$  $\mu$ t gonoral foaturo of VRS the general learnie of LDP. A list of all contributions in Eq. (2.1). A list of all contributions in Eq. (2.1)  $\delta Z$  and  $\delta Z$  and  $\delta Z$  and EW corrections to each LO contributions to each LO contribution. This is a contribution of  $\delta Z$ " contributions are simply the NLO EW **FIGHE-INDUCED PROCESS** • Not only for ssWW, but general feature of VBS **WZ: Denner et al, 1904.00882**



NFN

<u> \On</u>



# Coupling-hiearchy violation







- *• 4top production receives contributions induced by y<sub>t</sub>* which ends up in (N)LO<sub>2→</sub>*…*
- *• Despite being subleading by power-counting, even NLO4 can amount to some 10%s wrt LO1*
- *• Accidental cancelations occur among the various contributions with the complete-NLO being very close to LO1+NLO1 (NLO QCD)*
- *• A non-SM yt will spoil these cancelations* 
	- *• 4top as BSM probe*





## Approximate EW corrections in the high-energy limit



## Approximate EW corrections in the high-energy limit



- EW corrections show universal behaviour when all invariants are large  $\blacksquare$  **CIM** corrections show  $\blacksquare$   $\blacks$ NLO QCD :VV COLLECTIONS SHOW UNIVELLS IHDENSANIONLY QCD×EW a Hobenaviour when all invamants are a QCD×EW **in Mau Ada**
- **Logarithmic enhancement due to would-be IR singularities related to W**  $\Box$  and Z masses, the so-called Sudakov logs  $\Box$  **b** Logariumine chilancell The absolute predictions in *p*T*,j*<sup>1</sup> are rescaled by a factor 10<sup>3</sup>. d*/*d  $\overline{a}$  $\overline{\phantom{0}}$  $\overline{\phantom{a}}$ due to would-be IR sing<br>and the loss of the single
- **1 Fixed-order in this limit, the logarithmic e<mark>t prinbution can be computed using onl</mark>y tree**level amplitudes Denner, Pozzorini, <sub>ep-ph/0010201 & hep-ph/0104127</sub> *p*T*,*j<sup>1</sup> 1.8 1.4 1@ **EDIT LATER UNC.** P<sup>scale unc.</sup>  $\lambda$ .95 1 10<sup>1</sup> **OFADULEGGRISING 4.**9 1 (QCD×EW)/QCD
- This can be very helpful if  $EW$  corrections for a given process are dominated by Sudakov logs, if the large-invariants regime is considered, and if the process is not mass-suppressed  $\blacksquare$  • This can be very helpful if EV.  $\blacksquare$ **p p**  $\frac{1}{2}$  **d**  $\frac{$ */*d NLO QCD  $\mathsf{L}\mathsf{C}$  $\sum_{\text{odd}}$ 0 Figure 1. Our best predictions for the four LHC 13 TeV *tt* 0.998 1.002 1.004 (QCD×EW)/QCD ר∨חו−מסממ⊢ ממ ,<br>y(tt) 1 1.01  $\mathbf{F1} \mathbf{M} \mathbf{P} \mathbf{I} \mathbf{C}^T \mathbf{C} \mathbf{C} \mathbf{D} \mathbf{C} \mathbf{I} \mathbf{C}$

 $\mathfrak{z}$ 

 $\mathcal{N}$ 



 $\begin{array}{ccc} \text{SSSC} & & \text{o}^{\text{L}} \\ \end{array}$ Sherpa: Bothmann et al, 2006.14635; MG5\_aMC: Pagani, MZ, 2110.03714; OpenLoops: Lindert et al, 2312.07927 and compared to approximative EW calculations. The NLO EW is given for the *G<sup>µ</sup>* (black line) and Sherpa: Bothmann et al. 2006. 14635: MG5; aMC+Pagani: MZ, 21 IC  $\frac{1}{\sqrt{1-\frac{1}{2}}}\left(\frac{1}{\sqrt{2}}\right)^{1-\frac{1}{2}}\left(\frac{1}{\sqrt{2}}\right)^{1-\frac{1}{2}}\left(\frac{1}{\sqrt{2}}\right)^{1-\frac{1}{2}}$ <sup>10</sup> <sup>3</sup> <sup>0</sup> **D.5 - 1999**<br>D.5 - 1999 SSC SSSC C PR  $\begin{array}{c} \Pi(\mathsf{Z}_1,\mathsf{Z}_2) \end{array}$ SSC  $\mathsf{F}$ C :655; MG54 al TC: <u>Pagant, MZ, ZTT0.037.1</u>4; OpenLoops: Lir 1 LSC SSC SSSC C  $\mathbb{P}_{\mathbb{R}}$  and  $\mathbb{P}_{\mathbb{F}}$  reason by  $\mathbb{E}[\mathbf{L},\mathbf{L}]$  for LI 3 SSC SSSC C PR

- $\text{NS}$  to difficultial distributions for a nonapplied. Right: cuts as defined in (4.1) applied. **o** They provide easy solutions to difficult problems.  $p: f \cap$  difficult problems  $e^{y}$ For on-hell *pp* ! *<sup>W</sup>*<sup>+</sup>*W* the longitudinal-longitudinal (LL) and opposite transverse-transverse  $\overline{r}$ *m*ZZ [GeV]  $10^{14}$   $\leq$   $^{10}$ 
	- proton collisions at 13 TeV: the transverse momentum of the hardest *Z* boson *p<sup>T</sup>* (*Z*1) in Fig. 6 and of the softest one *p<sup>T</sup>* (*Z*3) in Fig. 7, the invariant mass of the two hardest *Z* bosons *m*(*Z*1*Z*2) • Much more stable and faster than EW corrections TUCH THOTE STADIE AND TASTEL THAT EVV COLLECT  $\mathbf{r}$  than  $\mathsf{E}[\Lambda]$  corrections in Fig. 7 the TT configurations in Fig. 7 the TT configurations in Fig. 7 the TT configuration of  $\mathbf{r}$  $\alpha$  chart EVV corrections distribution where it saturates the unpolarised LO Figure 6: Differential distribution in the invariant mass *m*ZZ in the inclusive phase-space (left) and faster than EW corrections and laster than EVV corrections
	- $\mathcal{L}$ roximate-EVV corrections with NLO-QCD distributions in Sec. 4.1. As already observed in the literature, in the case of multi-boson produckslow in multuet-merged samples. **EXEC** case of *the production* in the production. In Figs. 6–9 we observe a much larger in the EWSL than in production of  $\frac{1}{2}$ Bothmann et al, 2111.13453; Pagani, Vitos, MZ, 2309.00452 proton collisions at 13 TeV: the transverse momentum of the hardest *Z* boson *p<sup>T</sup>* (*Z*1) in Fig. 6 predictions matched to PS (possibly in multijet-merged samples) • Possibility to combine approximate-EW corrections with NLO-QCD difference comes from phase-space regions dominated by real-photon radiation, such as *R*2*e,*2*<sup>µ</sup> <* ⇡. There is the implies of  $\mathbf{F}_{\text{F}}$  is the soft photons through  $\mathbf{F}_{\text{F}}$ if we expand the YFS resummation to *O*(↵), as discussed above, we reproduce the NLO EW result  $\mathcal{L}$ similar over all  $\mathcal{L}$  in the Suday and Sum, victor, in  $\mathcal{L}$ ,  $\sum_{i=1}^n$ **SAMIALE-LYY COLLECTIONS WILL INLO-QUD**  $\mathbf{v}_{\text{max}}$ plot to explicit the treatment of the treatment of longitudinal polarization of the GBET. The GBET S For on-hell *pp* ! *<sup>W</sup>*<sup>+</sup>*W* the longitudinal-longitudinal (LL) and opposite transverse-transverse (TT) polarisations are not mass-suppressed. For the longitudinal-longitudinal (LL) and opposite transverse-transverse-transverse-transverse-transverse-transverse-transverse-transverse-transverse-transverse-transverse-trans od to PS (possibly in multijat-merged samples)  $\epsilon$ u to i 5 (possibiy in multij $\epsilon$ trii $\epsilon$ i  $\epsilon$ u sampi $\epsilon$ s)  $\mathcal{L}$  polarisations are not mass-suppressed. For both observables in  $\mathcal{L}$  the TT configuration  $\mathcal{L}$
	- does not depend on ↵*S*. Therefore scale uncertainties are smaller than in the *ttH*¯ production. n he resummed to all-orders can be very large in the very large in  $\sim$ the difference between NLOQUD+EWSL+PS and NLOQUD+EWSL+PS and NLOQUD+EW +PS is enhanced, the number of  $\mathcal{L}$ Before discussing the specific distributions we focus on the main differences with the *ttH*¯ n be resummed to all-orders in the literature, in the case of multi-• They exponentiate and can be resummed to all-orders energy-dependent observables, such as the invariant mass of the four leptons and the *p*<sup>T</sup> of the electron pair, and energy-independent observables, such as the separation of the separation of the two lepton pairs and We now consider hadronic *ZZ*+jet production and focus on the inclusive *p*T*,*Z<sup>1</sup> (left) and *p*T*,*<sup>j</sup> (right) distributions in Fig. 8. In the case of the transverse momentum of the transverse momentum of the hardest *D*-boson we have the transverse momentum of the hardest *Z-boson we have a verse momentum of the hardest an* e and can be resummed to all-orders
- 24 case of *ttH*¯ production. Indeed, in Figs. 6–9 we observe a much larger impact of EWSL than in /s cneck wnetner the **Sugakov approx** nc • However, one should always check whether the Sudakov approx holds against the exact EW corrections therefore also the difference between  $\mathcal{L}_{\mathcal{L}}$  and  $\mathcal{L}_{\mathcal{L}}$  and  $\mathcal{L}_{\mathcal{L}}$  and  $\mathcal{L}_{\mathcal{L}}$ with a typical and typical de typical substitutions in the independent is dominated by large angular-independen<br>Substitution of the Ludwig and LSCC angular substitutions of LSCC and Lord Lord Lord and Lord Lord Lord Lord L effects. For this observable we observe the one-loop EW relative corrections to the *ZZj* process to  $\epsilon$  and EW effects motivating a multiplicative combination of higher-order  $\epsilon$ ZZ+jet We now consider hadronic *ZZ*+jet production and focus on the inclusive *p*T*,*Z<sup>1</sup> (left) and *p*T*,*<sup>j</sup> cross section for *p*T*,W*<sup>1</sup> *>* 300 GeV. VV c

Marco Zaro, 10-7-2024





## Don't buy everything they sell

*<u>zh zemene</u>* In ZHH production, at *large*  $p_T(Z)$ , EWSLs fail to reproduce EW corrections







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In ZHH production, at *large*  $p_T(Z)$ , EWSLs fail to reproduce EW corrections







#### Resummation of EW Sudakov logs FeynRules  $M$ motion of FWV sudel $N$  $T$

#### **ELERROLESS** Denner, Rode, 2402.10503  $\frac{1}{\sqrt{2}}$  the use of polarised cross sections and the approximation of large kinematical invariants.

- Since EW corrections are non-diagonal wrt flavour, exponentiation of Sudakov-logs is highly non-triviat Rept1l Collier uis are livre-ui Model $\sqrt{\text{Repr1L}}$  collier production production production production production production  $\blacksquare$  $\alpha$ ccureis ale hou-diagonal will havour, expond  $\sum_{n=1}^{\infty} \frac{1}{n} \frac{\log \left| \sum_{n=1}^{\infty} \alpha_n x_n \right|}{\log \left| \sum_{n=1}^{\infty} \alpha_n x_n \right|}$  $\log_{10}$ uon production processes
- Seminal studies for 2-loop amplitudes suggested to exponentiate separately weak and QED terms, and about their order Denner et al, hep-ph/0301241 10<sup>8</sup> pp ! WW ! 4*f* (FCC-hh setup) Born i**v**iis bb/0301241 Born Scene (SCET)  $w$ ank and  $\bigcap$  FD tarn  $\mathbf{e}$  $\left( \frac{\text{RECOLA}}{\text{RECOLA} \ 2 \ \text{(SYSM)}} \right)$ al  $\mathbf{C}$ MoCaNLO Recola 2 (SySM) Recola 1 (SM) LHAPDF **MADE LETTING**  $\left\{\begin{array}{l} \text{Recoa 2 (SvSM)} \\ \text{for } 2\text{-loop} \end{array}\right\}$  amplitudes suggested to expone **SCETE AS IN A** *LACTER ALL MACHER SUSSESTED TO EXPOLIC*  $FD$  tarms, and about their order  $D$  $\mathcal{L}$  by  $\underbrace{\mathbf{C}\mathbf{C}\mathbf{P}}_{\text{DE}}$  in  $\underbrace{\mathbf{C}\mathbf{A}\mathbf{R}}_{\text{MOCANLO}}$  and  $\underbrace{\mathbf{C}\mathbf{A}\mathbf{C}\mathbf{A}}$  in equality  $\underbrace{\mathbf{C}\mathbf{A}\mathbf{R}}_{\text{DE}}$  in  $\underbrace{\mathbf{C}\mathbf{A}\mathbf{R}}_{\text{DE}}$  in  $\underbrace{\mathbf{C}\mathbf{R}}_{\text{DE}}$  in  $\underbrace{\mathbf{C}\mathbf{R}}_{$

 $\mathbb{R}^n$  have considered two di $\mathbb{R}^n$  setups inspired by the CLIC and FCC–CLIC and FC

- Resummation achieved using the EW version of SCET, included in a fullydifferential MC 10<sup>4</sup> *N*ev*/*bin 400 *N*ev*/*bin  $\frac{1}{\sqrt{2\pi}}$ events n achieved using the EVV version of SCET inclu  $\sum_{i=1}^n$  accounts a complete that  $\sum_{i=1}^n$   $\sum_{i=1}^n$   $\sum_{i=1}^n$   $\sum_{i=1}^n$   $\sum_{i=1}^n$  with the major  $\sum_{i=1}^n$   $\sum_{i=1}^n$   $\sum_{i=1}^n$  $\mathbf{10}$
- Results presented for CLIC@3TeV and FCC-hh@100 TeV esults presented for  $CLIC(\omega)$  J leV and Figure 3. Used software and dependencies in the setup.  $H$ ed for  $\bigcap \bigcap (\bigcap \mathcal{X} \cup \{1\} \cup \{0\})$  and  $\bigcap \bigcap \bigcap \bigcap (\bigcap \{1\} \cup \{0\})$

 $_{\rm H0}^{\rm G}$ 



and requires a number of approximations that need to be carefully checked. **z**  $\blacksquare$  **i**  $\blacksquare$ ers, the application of the  $SCET_{EW}$  formalism to realistic diboson processes is nontrivial While the resummation of large EW logarithms is a must at future high-energy collid-

Marco Zaro, 10-7-2024  $\mathbf{a}$ In the previous section we described in detail the implementation of all ingredients of the

<sup>e</sup>+e ! WW ! <sup>4</sup>*<sup>f</sup>* (CLIC setup)

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## Matching with parton shower?

- EW corrections matched with PS still not available for general processes
	- Approximate approaches exist, only including n-body contribution ("EWvirt" or EWSL). Accuracy depends on kinematics region **EWVirt:** VV(J): Brauer et al, 2005.12128; top: Gutschov et al, 1803.00950; V+jets: Kallweit et al, 1511.08692, …

• Exact matching performed only for processes with just  $LO<sub>1</sub>$  (in the Powheg scheme) DY: Barzè et al,1302.4606; HV(J): Granata et al, 1706.03522; VBS: Chiesa et al, 1906.01863, VV: Chiesa et al, 2005.12146; WZ@NNLO+PS: Lindert et al, 2208.12660

• Main issue: how to assign colour-flows to interferences  $(LO<sub>2</sub>)$  is mostly an interference contribution) Some ideas: Frixione et al, 2106.13471







### Attaining the highest precision: Drell-Yan NNLO QCD×EW





## Attaining the highest precision: Drell-Yan NNLO QCD×EW

- Lepton-pair production (Drell-Yan) is a highprecision probe of the EW sector ( $M_W$ , sin $\theta_W$ , ...)
- NNLO QCD+NLO EW not enough for current and upcoming exp. data
- NNLO<sub>2</sub> has been the frontier for long time:
	- Historically, different approaches have been pursued for the pole vs large-m(I+I-) region
	- Complicated topologies (massive double box)
- Recently, full computations of NNLO<sub>2</sub> have become available, both for NC and CC process
- I will briefly review these works, focusing on pheno results







2106.<sup>11953</sup>

### Mixed QCD-EW corrections to NC Drell-Yan

Mixed Strong-Electroweak Corrections to the Drell-Yan Process

Roberto Bonciani<sup>®</sup>,<sup>1,\*</sup> Luca Buonocore<sup>®</sup>,<sup>2,†</sup> Massimiliano Grazzini<sup>®</sup>,<sup>2,‡</sup> Stefan Kallweit<sup>®</sup>,<sup>3,§</sup> Narayan Rana $\mathbf{Q},^{4,\parallel}$  Francesco Tramontano $\mathbf{Q},^{5,\parallel}$  and Alessandro Vicini $\mathbf{Q}^{4,*}$ Dipartimento di Fisica, Universit `a di Roma "La Sapienza" and INFN, Sezione di Roma, I-00185 Roma, Italy

- First computation of NNLO<sub>2</sub> (with massive leptons) putation of  $NNLO_2$  (with massive leptons)  $\overline{\mathsf{A}}$ 
	- Amplitues computed with semi-analytical approach Amplitues computed with semi-analytical approach
	- IR Subtraction with Matrix Grazzini et al, 1711.06631 With Matrix crazini of all  $1711.06631$ neutral-current Dread-Yan process. Superseding previously approximations, our calculations, our calculations, o rith Matrix Grazzini e 1*.*0
- Comparison with pole approx and naive factorisation of K-factors provides the first result at this order that is valid in the entire range of dilepton invariant masses. The  $\bullet$ luitipuit appliux aliu fiante tactulisalic problems in the evaluation of the relevant master integrals. The cancellation of soft and collinear a polo approx and 1 pois app. ox. a.  $\overline{\mathbf{y}}$  and 0*.*5  $\blacktriangledown$ */*GeV]



1

- $\mathbb{E}[\mathbb{I}^{10^{-3}}]$   $\mathbb{I}^{10^{-3}}$   $\mathbb{I}^{10^{-3}}$   $\mathbb{I}^{10^{-3}}$  wery large effects due to radiation. Naive • Peak region: excellent agreement with PA. factorisation fails
	- and poive fact due to genu and naive fact, due to genuinely non $t_{\text{action}}$  for toricable contributions  $\mathbf{f}_\parallel$  factorisable contributions Large inv.mass:  $O(0.5%)$  difference wrt PA
	- $\frac{1}{2}$  news new-physics scenarios. • NNLO<sub>2</sub> corrections at the 1% level in the for which radiative corrections in the strong and  $\mathbf{F}$ large inv.mass region tions of the next-to-leading-order (NLC)  $\frac{1}{2}$  and next-to-leading-order (NLC)  $\frac{1}{2}$





#### Mixed QCD-EW corrections at large invariant mass  $\bullet$   $\bullet$   $\bullet$   $\bullet$ Received: *April 5, 2022* Accepted: *May 4, 2022*

- Two-loop amplitudes computed in 2020, without widths Heller et al, 2012.05918
- IR subtraction with nested softcollinear scheme Caola et al, 1702.01352
- Computation with massless leptons (recombination needed)
- $NNLO<sub>2</sub>$  corrections at the 1% level wrt NLOQCD+EW in the large inv.mass region (up to 1 TeV)
- Growth with invariant mass due to Sudakov effects, up to 3% at 3 TeV
- Surprisingly large size in the TeV region wrt to power counting

**Mixed QCD-electroweak corrections to dilepton production at the LHC in the high invariant mass region**

**Federico Buccioni,***<sup>a</sup>* **Fabrizio Caola,***a,b* **Herschel A. Chawdhry,***<sup>a</sup>* **Federica Devoto,***<sup>a</sup>* **Matthias Heller,***<sup>c</sup>* **Andreas von Manteuffel,***<sup>d</sup>* **Kirill Melnikov,***<sup>e</sup>* **Raoul Röntsch***<sup>f</sup>* **and Chiara Signorile-Signorile***e,g* 2203.11237





#### From NC to CC T2P9 N4  $\blacksquare$

Armadillo, Bonciani, Devoto, Rana, Vicini, 2405.00612

- The CC case requires new topologies wrt the NC one
	- Most complicated: double-box, with 2 different internal masses uble-box, with 2 different
	- Solved by in-house package for differential equations, based on LiteRed and SeaSyde (series expansion wrt invariants)
	- Boundary condition evaluated with AMFlow
	- Checked that the result matches the equal-masses topology
	- Complex-mass scheme and lepton mass≠0
- Results available as a grid, including full dependence on W mass



μ



500

 $\ddot{\phantom{0}}$ 

Marco Zaro, 10-7-2024

**LiteRed**: Lee, 1310.1145; **AMFlow**: Liu et al, 220.11669; **SeaSyde**: Armadillo et al, 2205.03345  $\overline{\phantom{a}}$ 





#### Resummation of QED effects  $\mathbb{R}$  Decimination of  $\cap$   $\Box$  of  $\circ$ (CONDITION CONTRIBUTION  $\bigcup$  critten as

Buonocore, Rottoli, Torrielli, 2404.15112 *<sup>R</sup>*MIX(*kt*1) = *<sup>g</sup>*11(*,* <sup>0</sup>

- Soft QED and mixed effects added on top of QCD ones, within the Radish framework Monni et al, 1604.02191
	- QED soft effects due to correlations with final-state leptons included
- See also earlier work with stable W/Z Autieri et al, 2302.05403 then reads N3LL' QCD NLL' MIX α<sub>S</sub>mαn Lm+n

$$
R(k_{t1}) = [R(k_{t1})]_{\text{eq. (2.4)}} + R^{\text{QED}}(k_{t1}) + R^{\text{MIX}}(k_{t1}) + \frac{\alpha_s}{2\pi} \frac{\alpha}{2\pi} B^{(1,1)} L
$$
  
**NLL' QED FORMALLY NNLL' MIX**







# Recent and planned developments for MC tools Part 2





## NNLO+PS predictions





### MiNNLO+PS

- NLO QCD+PS has been the golden standard for long time MG5\_aMC/Sherpa/Powheg
- Going beyond NLO: NNLO
	- NNLO+PS relies on rather mature technology (MiNNLOPS) Monni et al, 1908.06987
	- All currently-available NNLO QCD computation can (in principle) be included into a NNLO+PS generator
	- Implementation is still process-dependent, and mostly done by hand

bbH: Biello et al, 2402.04025; b prod: Mazzitelli et al, 2302.01645; WZ (+EW) Lindert et al, 2208.12660; ZH (SMEFT): Haisch et al, 2204.00663; top: Mazzitelli et al, 2112.12135, …







### NNLO+PS in Geneva **Implemented processes**

- The Geneva method combines NNLO+PS with N-jettiness resummation at NNLL' Alioli et al, 1211.7049  $\det MNL$  Alioli et al, 1211.7049
- $\gamma$  Implemented and validated for several color-singlet processes  $_{\rm V\,Y}$   $W\gamma$  <code>lmple</code>ppented and validated for several color-singlet processes ac i vi ville Alloli et al, 1211.7047<br>Exp. legale mented and validated for several color singlet prosesses *yγ Wγ* impi<del>y</del>yiented and vandated for several color-singlet pro



- New developments:
	- Resumming second jet resolution at NLL'
	- Extension towards color-singlet+jet processes WIP





## Reduction of negative weights in MC@NLO-type matching





- MC@NLO-matched MCs affected by negative weights
	- Reduce the statistical quality of the event sample
	- More events need to be generated than with positiveonly events
- Recent progress both in Sherpa and MG5 aMC:
	- MG5 aMC: modify the matching by a term which improves the IR behaviour of the MC counterterms Frederix et al, 2002.12716

Alternatively, spread the Born over the radiative PS in **ALLEQ ALGONLO** order to compensate for over-cancelation of local  $CTs$   $p p \rightarrow e^+e^ 3.5\%$  (1.2)  $2.4\%$  (1.1) **or negative virtuals Frederix, Torrielli, 2310.04160**  $pp \to e^+ \nu_e$  3.8% (1.2)  $2.5\%$  (1.1)

- Sherpa: use leading-colour approximation+move K-<br>• Sherpa: use leading-colour approximation+move K-<br>•  $p_p \rightarrow H_b$   $\frac{4.9\% (1.2)}{38.4\% (19)}$   $\frac{2.0\% (1.1)}{32.6\% (8.2)}$ factor to low-mult. processes in merged samples  $p p \rightarrow W^{+} j$   $16.5\% (2.2)$   $7.9\% (1.4)$ Danzinger et al, 2110.15211 *pp* ! *<sup>W</sup>*+*tt*
- Other approaches (MC-agnostic):
	- Positive resampler: resample cross section to eliminate negative weights Andersen et al, 2005.09375 Table 1: Fractions of negative-weight events, *f*, and the corresponding relative costs, *c*(*f*) (*f*) (*f for the processes* in the processes in the contractions of negative-weight events,  $\frac{1}{2}$  $\sim$  09375 and with MC@NLO- (columns  $\sim$ *c*(*f*) (in round brackets), for the processes in eqs. (5.7)–(5.13), computed with MC@NLO









 $d\sigma/dp_{\perp}$  (jet 1) [pb/GeV]  $\sigma/dp_\perp(\text{jet 1})$  [pb/GeV]

Ratio

Deviation

Negative Fraction  $\epsilon$ 

*f*(*#*)

### Results









## Towards the usage of GPUs and AI in the MG5\_aMC framework





### Improving computing performances

- Computing demand requires more efficient and smarter handling of resources
- On one side, move away from multi-threading in favour of multiprocessing (SIMD/OpenMP), suitable for GPUs
	- This requires rewriting and rethinking our (old) codes
- On the other, benefit from AI to improve some specific aspects (integration/event-gen./…)

### • See also:

"Event Generators for High-Energy Physics Experiments", 2203.11110 "Machine learning and LHC event generation", 2203.07460 "Challenges in Monte Carlo event generator software for High-Luminosity LHC", 2004.13687





#### Towards MG5\_aMC on GPU in Fig. 1, which shows the variation of the combined ME throughput achievable from a single fro  $\mathbf{r}$  and  $\mathbf{r}$ CPU threads. The notable e↵ect that we were hoping to see, and which is indeed achieved, is  $t_{\rm eff}$  through curve moves to the number of  $C_{\rm eff}$  $\Gamma$  ...  $\Gamma$  DU applications with smaller CPU and  $\Gamma$  $\blacksquare$ sizes, rather than a single application with a very large grid size. Another positive result,  $\blacksquare$  $\mathbf v$  will  $\mathbf v$  we were in-depth and will desire  $\mathbf v$ implementations using performance portability frameworks. Most recently, this work has focused  $\overline{\phantom{a}}$ those based on Alpaka have stopped. As noted in Ref. [1], the main interest of the main interest of the main in  $M \cap T$  architectures, including GPUs from di $T$ erent vendors such as NVI di $T$  $T$  $\mathbf{u}_1$  is  $\mathbf{v}_2$  on  $\mathbf{v}_3$  plots  $\mathbf{v}_4$

#### MadFlow: Carrazza, Cruz-Martinez, Rossi, MZ, 2106.10279





#### of the infrastructure developed for the HEP-SCORE benchmarking project at Aurora GPU. Valassi et al, 2106.12631, 2303.18244, 2312.02898 kernels from di∟erent CPU threads. It should be stressed that the stressed that this plot, which was obtained<br>It should be stressed that this plot, which was obtained that the stressed that the stressed that the stressed values of all  $\epsilon$  footh  $\epsilon$  and  $\epsilon$  is the function of  $\epsilon$  in  $\epsilon$  and  $\epsilon$  workflows,  $\epsilon$ implementation of the ME calculation is now also fully integrated into  $\frac{1}{2}$  and  $\frac{1}{2}$  means  $\frac{1}{2}$  $f(z)$  is a valued to all  $f(z)$  and  $f(z)$  is produce cross-sections by our data fields by  $f(z)$





Marco Zaro, 10-7-2024 and RTX A6000, such as the RTX A6000, such as the RTX A6000, such as the RTX A6000, such a

# Using NN's for importance sampling (INFN MadNIS



- Use NN to overcome some limitations of VEGAS
- Do not reinvent the wheel:
	- Pre-training with VEGAS (fast) used as starting point of normalizing-flow
	- Use NF on top of known analytical mappings
	- NF adjust the weight of each channel
- Important improvement both on variance and on unweighting efficiency, even for large multiplicities



All figures by R. Winterhalder

Marco Zaro, 10-7-2024



Conclusions

Part 1



- Kinematics, couplings (e.g. Yukawa), radiative return, EWSL
- EW corrections are moving beyond NLO
	- Drell-Yan corrections available for NNLO<sub>2</sub>, both NC and CC
	- Resummation available both for soft γs (jointly with QCD) and for EWSLs
- Still, we miss a general procedure for PS matching at NLO
	- EWSL approximation +PS seems a good compromise
	- But the validity of EWSL approximation (both in principle and in practice) should always be checked
- Lot of progress also beyond LHC physics (e<sup>+</sup>e-/ μ<sup>+</sup>μ-colliders, g-2) not covered in this talk





- Understanding and improving MC tools is crucial for a proper and efficient collaboration between theory and experiments
- Lot of recent activity, only a glimpse of it in these slides
	- Inclusion of higher orders beyond NLO QCD
	- Reduction of negative weights leads to reduction in needed n of events. Some methods already implemented in public tools
	- Faster simulations can profit of modern hardwares (GPUs) and of AI for integration/event generation. At the moment most WIP, but stay tuned!