

# Recent progress on high order calculations and matching to parton showers

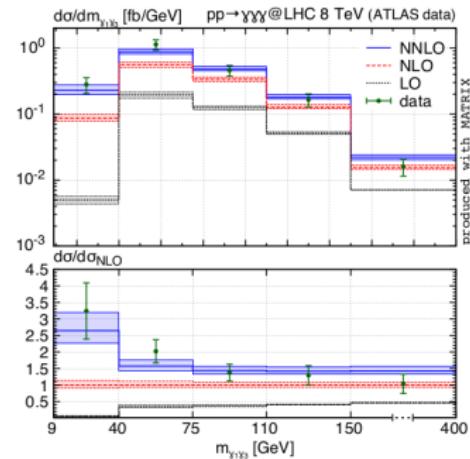
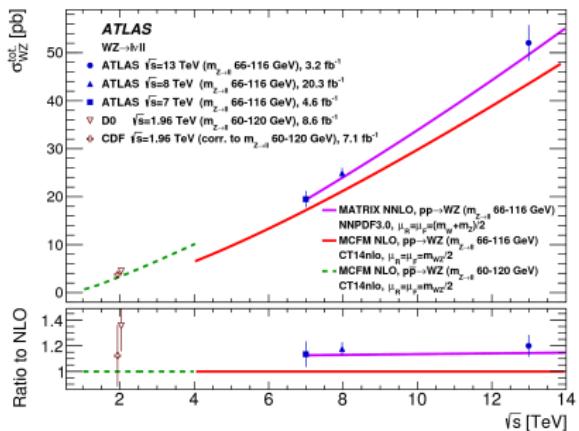
Emanuele Re

LAPTh Annecy



Large Hadron Collider Physics 2021  
10 June 2021

# Introduction



$\gamma\gamma\gamma\gamma$  @ NNLO: plot from [Kallweit,Sotnikov,Wiesemann '21]

- Current EXP precision demands for TH to be accurate at the  $\mathcal{O}(10)\%$  level (often less).
  - residual TH uncertainty  $\lesssim 10\%$
- Fully-exclusive predictions, from Monte Carlo event generators, enter in nearly all experimental analysis.
- This requires to go beyond  $\text{NLO}_{\text{QCD}}(+\text{PS})$  accuracy.

# Introduction and outline

$$d\sigma_{pp \rightarrow X} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\sigma_{ij \rightarrow X}(x_1, x_2) \mathcal{O}(X)$$

- ▶ subleading effects from FO calculations:

$$d\sigma = d\sigma_{\text{LO}} \left[ 1 + \left( \frac{\alpha}{2\pi} \right) \delta_{\text{NLO}} + \left( \frac{\alpha}{2\pi} \right)^2 \delta_{\text{NNLO}} + \dots \right]$$

$$[\alpha_S(Q) \sim 0.1 \quad \alpha_{\text{EW}}(Q) \sim 0.01]$$

- NNLO QCD and/or NLO EW
- EW: photon bremsstrahlung off leptons, Sudakov logs

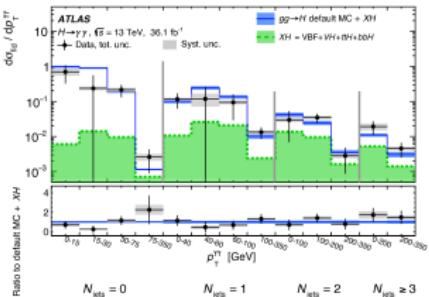
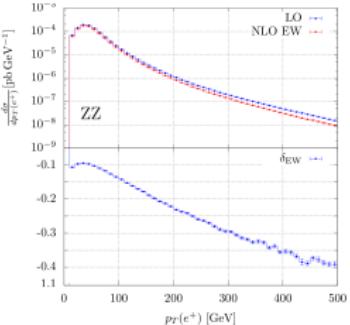
- ▶ all-order effects large when  $\mathcal{O}(X)$  constrains radiation to be soft/collinear ( $\mu < Q$ )

- resummation
- jet-veto, corners of phase space
- formal accuracy of PS relevant

- ▶ Focus of this talk:

NNLO<sub>QCD</sub>+PS , NLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS

- only relatively recent results, by no means fully comprehensive, apologies in advance for leaving out important results



[ATLAS, 1802.04146]

$NNLO_{QCD+PS}$

# NNLO+PS: what do we want to achieve?

- ▶ Consider  $F + X$  production ( $F$ =massive color singlet)
- ▶ NNLO accuracy for observables inclusive on radiation.  $[d\sigma/dy_F]$
- ▶ NLO(LO) accuracy for  $F + 1(2)$  jet observables (in the hard region).  $[d\sigma/dp_{T,j_1}]$ 
  - appropriate scale choice for each kinematics regime
- ▶ Sudakov resummation from the Parton Shower (PS)  $[\sigma(p_{T,j} < p_{T,\text{veto}})]$
- ▶ preserve the PS accuracy (leading log - LL)
  - possibly, no merging scale required.
- ▶ methods: **reweighted MiNLO'** (“**NNLOPS**”) [Hamilton,et al. '12,'13,...], **UNNLOPS** [Höche,Li,Prestel '14,...] / [Plätzer '12] **Geneva** [Alioli,Bauer,et al. '13,'15,'16,...], **MiNNLO<sub>PS</sub>** [Monni,Nason,ER,Wiesemann,Zanderighi '19,...]

- from  $p_T$  resummation, differential cross section for  $F+X$  production can be written as:

$$\frac{d\sigma}{dp_T d\Phi_F} = \frac{d}{dp_T} \left\{ \mathcal{L}(\Phi_F, p_T) \exp(-\tilde{S}(p_T)) \right\} + R_{\text{finite}}(p_T)$$

$$\mathcal{L}(\Phi_F, p_T) \ni \{H^{(1)}, H^{(2)}, C^{(1)}, C^{(2)}, (G^{(1)} \cdot G^{(1)})\} \quad R_{\text{finite}}(p_T) = \frac{d\sigma_{FJ}}{d\Phi_F dp_T} - \frac{d\sigma^{\text{sing}}}{d\Phi_F dp_T}$$

- $\mathcal{L}(\Phi_F, p_T)$ : all the terms needed to obtain NNLO<sup>(F)</sup> accuracy upon integration in  $p_T$

- ▶ from  $p_T$  resummation, differential cross section for  $F+X$  production can be written as:

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- ▶ recast it, to match the POWHEG  $\bar{B}^{(FJ)}(\Phi_{FJ})$

$$\frac{d\sigma}{d\Phi_F dp_T} = \exp[-\tilde{S}(p_T)] \left\{ D(p_T) + \frac{R_{\text{finite}}(p_T)}{\exp[-\tilde{S}(p_T)]} \right\}$$

$$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T} \mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T} \quad \tilde{S}(p_T) = \int_{p_T}^Q \frac{dq^2}{q^2} \left[ A_f(\alpha_S(q)) \log \frac{Q^2}{q^2} + B_f(\alpha_S(q)) \right]$$

- ▶ expand the above integrand in power of  $\alpha_S(p_T)$ , keep the terms that are needed to get  $\text{NLO}^{(F)}$  &  $\text{NNLO}^{(F)}$  accuracy, when integrating over  $p_T$

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- Final master formula

$$\begin{aligned} \frac{d\bar{B}(\Phi_{FJ})}{d\Phi_{FJ}} &= \exp[-\tilde{S}(p_T)] \left\{ \frac{\alpha_S(p_T)}{2\pi} \left[ \frac{d\sigma_{FJ}}{d\Phi_{FJ}} \right]^{(1)} \left( 1 + \frac{\alpha_S(p_T)}{2\pi} [\tilde{S}(p_T)]^{(1)} \right) \right. \\ &\quad \left. + \left( \frac{\alpha_S(p_T)}{2\pi} \right)^2 \left[ \frac{d\sigma_{FJ}}{d\Phi_{FJ}} \right]^{(2)} + \left( \frac{\alpha_S(p_T)}{2\pi} \right)^3 [D(p_T)]^{(\geq 3)} F^{\text{corr}}(\Phi_{FJ}) \right\} \end{aligned}$$

- Second radiation: usual POWHEG mechanism.

- if emissions are strongly ordered, same emission probabilities as in  $k_t$ -ordered shower
- LL shower accuracy preserved

- ▶ from  $p_T$  resummation, differential cross section for  $F+X$  production can be written as:

$$\frac{d\sigma}{dp_T d\Phi_F} = \frac{d}{dp_T} \left\{ \mathcal{L}(\Phi_F, p_T) \exp(-\tilde{S}(p_T)) \right\} + R_{\text{finite}}(p_T)$$

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- ▶ Final master formula

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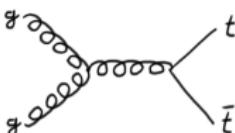
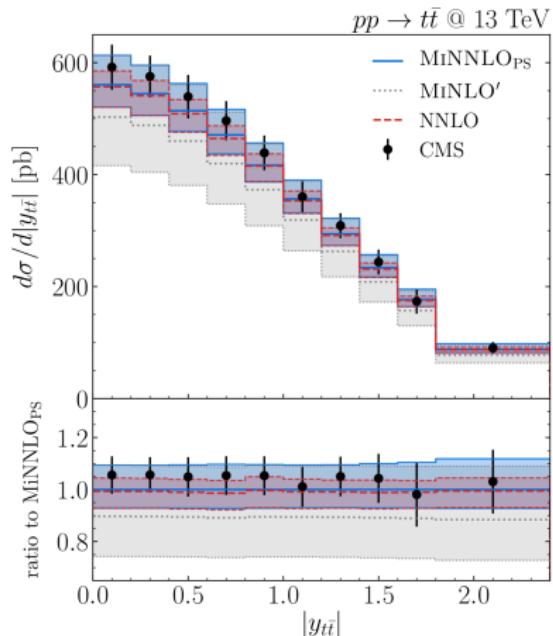
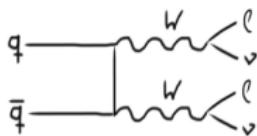
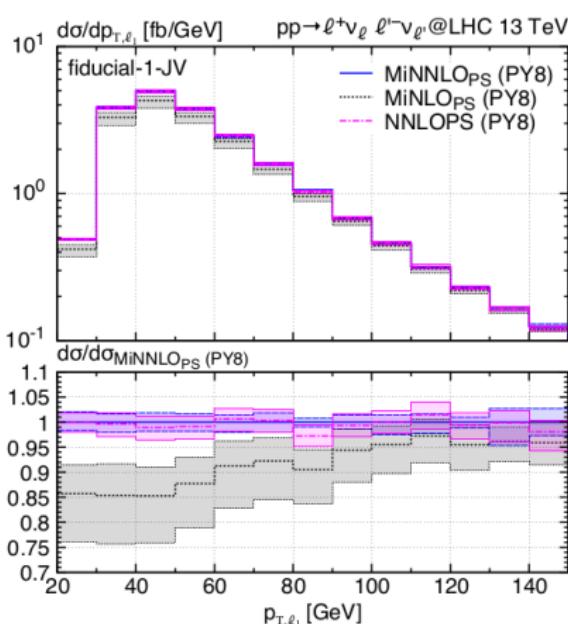
- ▶ Second radiation: usual POWHEG mechanism.
- ▶ Method extended to deal with heavy quarks in the final state:  $t\bar{t}$  at NNLO+PS !

[Mazzitelli, Monni, Nason, ER, Wiesemann, Zanderighi '20]

- starting point: resummation formula for  $t\bar{t}$  transverse momentum. [Catani, Grazzini, Torre '14]
- some inputs derived in [Catani, Devoto, Grazzini, Kallweit, Mazzitelli + Sargsyan '19]

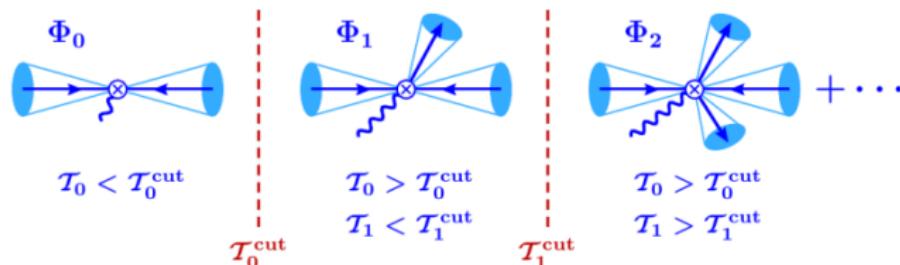
# MiNNLO<sub>PS</sub>: results

- ▶ Processes studied so far:  $ggH$ ,  $W$ ,  $Z$ ,  $Z\gamma$ ,  $WW$ ,  $t\bar{t}$

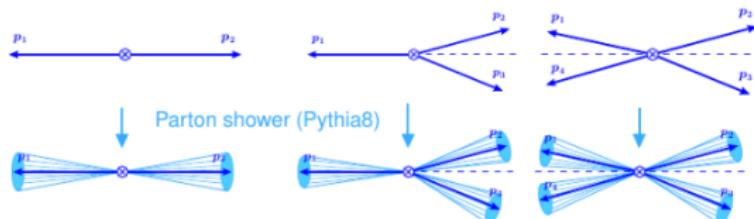


plots from [Lombardi, Wiesemann, Zanderighi '21] and [Mazzitelli, Monni, Nason, ER, Wiesemann, Zanderighi '20]

- ▶ Main idea: construct IR-finite events using a resolution parameter  $\tau_N$ , whose resummation properties are accurately known
  - slice phase space into jet-bins:  $\tau_N^{\text{cut}}$  translate an M-parton event to a N-jet event ( $N \leq M$ ), fully differential in  $\Phi_N$ .



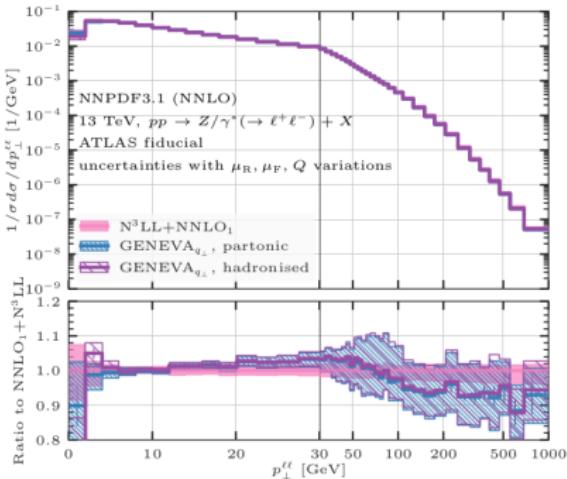
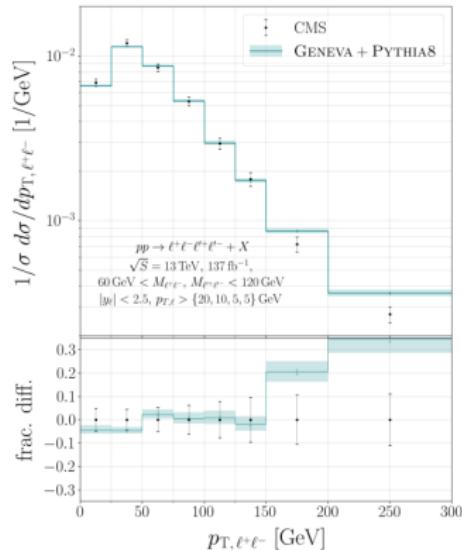
- ▶ Parton Shower: add radiation to higher multiplicities bins, fill 0- and 1-jet bins
  - constraints on  $\tau_N^{\text{cut}}$ : PS not allowed to affect the accuracy of the cross section reached at partonic level



- ▶ Much progress in the last couple of years:  $VH, Z, H \rightarrow \text{hadrons}, \gamma\gamma, ZZ, W\gamma$ .

# Geneva: results

plots from [Alioli et al, 2103.01214] and [2102.08390]

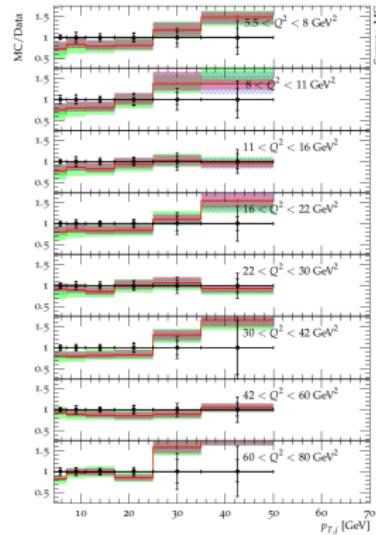


- ▶ Careful checks to have power corrections in  $\tau^{\text{cut}}$  under control.
- ▶ Left: All as expected for  $ZZ$  (large  $p_T \leftrightarrow$  EW Sudakov).
- ▶ Right:  $p_T$  as resolution parameter. Comparison with RadISH+NNLOJET gives good agreement up to large  $p_T$  (where NNLO is important).

- ▶ Main idea: Promote to NLO accuracy an “unitarised” CKKW approach, by carefully adding higher order contributions, and removing the pre-existing approximate  $\alpha_S$  terms.
- ▶ Supplement results with missing NNLO ingredients.

## - DIS @ NNLO+PS

[Höche,Kuttimalai,Li '18]



- plot: DIS 1-jet inclusive
- red/blue: UNNLOPS, green: NLO result

## - towards N3LO+PS

[Prestel '21]

Combining  $d\sigma_{n+1,k}^{(0)+1+2+\text{NNLO}}(\Phi_n)$  with eq. 23 and eq. 21 allows to construct the TOME matching formulae. As before, pairwise canceling term will indicated with identical (hyperlined) boxes. This acts as visual help to allow the reader to confirm that the criteria listed in Table III are indeed fulfilled. The final TOME matching formula reads

$$\begin{aligned}
 & F_n^{(0)}(\text{unref}(\Phi_n, t_{n+1})) \\
 & := O_n \left\{ \begin{array}{l} d\sigma_{n+1,k}^{(0)+1+2+\text{NNLO}}(\Phi_n) \\ + \int\limits_{t_n}^{t_n} d\sigma_{n+1,k}^{(2)\{q_{n+1,k} > q_n\} \times q_n}(t_{n+1}) \left[ \mathbb{1}_{n+2}^{n+2} - \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \right] \\ + \int\limits_{t_n}^{t_n} d\sigma_{n+1,k}^{(1)}(\Phi_{n+1}) \left[ \mathbb{1}_{n+1}^{n+1} - \left[ 1 - w_{n+1}^{(1)}(\Phi_{n+1}) - w_{n+1}^{(2)}(\Phi_{n+1}) - \Delta_n^{(1)}(t_n, t_{n+1}) - \Delta_n^{(2)}(t_n, t_{n+1}) \right] \right. \\ \quad \left. + \left[ w_{n+1}^{(1)}(\Phi_{n+1}) \right]^2 + \left[ w_{n+1}^{(1)}(\Phi_{n+1}) \Delta_n^{(1)}(t_n, t_{n+1}) \right] \right] \\ + \int\limits_{t_n}^{t_n} d\sigma_{n+1,k}^{(1)\{q_{n+1,k} > q_n\}}(\Phi_{n+1}) \left[ \mathbb{1}_{n+1}^{n+1} - \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \left( 1 - w_{n+1}^{(1)}(\Phi_{n+1}) - \Delta_n^{(1)}(t_n, t_{n+1}) \right) \right] \\ + \iint\limits_{t_n}^{t_n} d\sigma_{n+2,k}^{(0)\{q_{n+2,k} > q_n\}}(\Phi_{n+2}) \left[ \mathbb{1}_{n+2}^{n+2} - \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \left( 1 - w_{n+1}^{(1)}(\Phi_{n+1}) - \Delta_n^{(1)}(t_n, t_{n+1}) \right) \mathbb{1}_{n+2}^{n+2} \right] \\ + \iint\limits_{t_n}^{t_n} d\sigma_{n+2,k}^{(1)\{q_{n+2,k} > q_n\}}(\Phi_{n+2}) \left[ \mathbb{1}_{n+2}^{n+2} - \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \right] \\ + \iint\limits_{t_n}^{t_n} d\sigma_{n+2,k}^{(2)\{q_{n+2,k} > q_n\}}(\Phi_{n+2}) \left[ \mathbb{1}_{n+2}^{n+2} - \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \mathbb{1}_{n+2}^{n+2} \right] \Big\} \\ + O_{n+1} \left\{ \begin{array}{l} d\sigma_{n+1,k}^{(2)\{q_{n+1,k} > q_n\} \times q_n}(\Phi_{n+1}) \\ \quad \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \\ + d\sigma_{n+1,k}^{(0)}(\Phi_{n+1}) \otimes \left( 1 - w_{n+1}^{(1)}(\Phi_{n+1}) - w_{n+1}^{(2)}(\Phi_{n+1}) - \Delta_n^{(1)}(t_n, t_{n+1}) - \Delta_n^{(2)}(t_n, t_{n+1}) \right. \\ \quad \left. + \left[ \Delta_n^{(1)}(t_n, t_{n+1}) \right]^2 + \left[ w_{n+1}^{(1)}(\Phi_{n+1}) \right]^2 + w_{n+1}^{(1)}(\Phi_{n+1}) \Delta_n^{(1)}(t_n, t_{n+1}) \right) \\ + d\sigma_{n+1,k}^{(0)\{q_{n+1,k} > q_n\}}(\Phi_{n+1}) \\ \quad \otimes \left[ 1 - w_{n+1}^{(1)}(\Phi_{n+1}) - \Delta_n^{(1)}(t_n, t_{n+1}) \right] \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \\ + \int\limits_{t_n}^{t_n} d\sigma_{n+2,k}^{(0)\{q_{n+1,k} > q_n\}}(\Phi_{n+2}) \\ \quad \otimes \Delta_n(t_n, t_{n+1}) w_{n+1}^{(n)}(\Phi_{n+1}) \\ \otimes \left[ \left( 1 - w_{n+1}^{(1)}(\Phi_{n+1}) - \Delta_n^{(1)}(t_n, t_{n+1}) \right) \mathbb{1}_{n+2}^{n+2} \right. \\ \quad \left. - \Delta_{n+1}(t_{n+1}, t_{n+2}) w_{n+2}^{(n)}(\Phi_{n+2}) \right]
 \end{array} \right\}
 \end{aligned}$$

$NLO_{QCD} + NLO_{EW} + PS$

- ▶ NLO EW calculations for multileg processes conceptually solved and automated.
- ▶ automated 1-loop providers:  
[GoSam, MadLoop/MG5\_aMC, NLOX, OpenLoops, Recola]
- ▶ often (not always) performed using general purpose frameworks:  
[MG5\_aMC, Sherpa, MATRIX, POWHEG BOX]

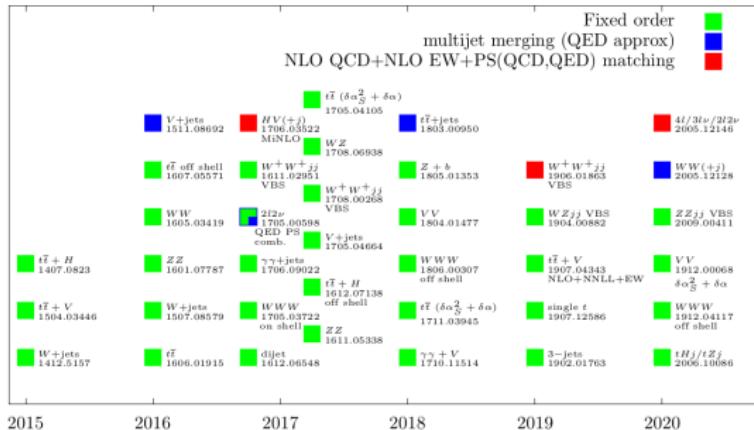


table from M. Chiesa

- ▶ (NLO<sub>QCD+</sub>) NLO<sub>EW+PS</sub>: not conceptually solved.

# NLO<sub>EW+PS</sub>

Currently two main approaches:

## ► Approximate NLO EW corrections

1st paper: [Kallweit et al. '15]

- "EWvirt" scheme: include them through a local K-factor

$$\delta_{\text{EW}}^{\text{approx}}(\Phi_n) = \frac{V_n^{\text{EW}}(\Phi_n) + I_n^{\text{EW}}(\Phi_n)}{B_n(\Phi_n)}$$

- $I_n^{\text{EW}}$ : approximated integrated real contribution
- QED corrections only from PS: **not valid for hard photon radiation**
- typically used for the production of heavy objects + light jets: MEPS@NLO (**add. or mult. scheme**)

$$\bar{B}_{n,\text{QCD+EW approx}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + B_n(\Phi_n) \delta_{\text{EW}}^{\text{approx}} + B_{n,\text{mix}}(\Phi_n)$$

$$\bar{B}_{n,\text{QCDxEW approx}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) \left( 1 + \delta_{\text{EW}}^{\text{approx}} \right) + B_{n,\text{mix}}(\Phi_n)$$

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## ► Exact matching of EW corrections for $n$ - and $n + 1$ -body contributions

1st papers: [Barze et al. '12,'13, Carloni et al. '16]

- Use the POWHEG BOX RES framework

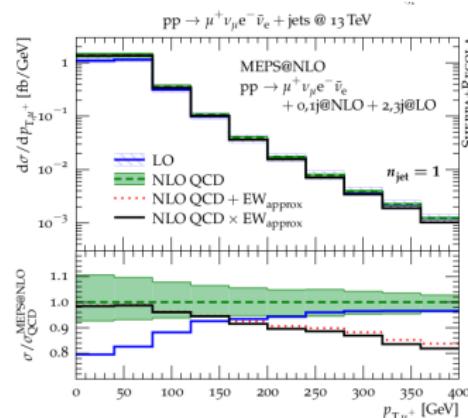
[Jezo, Nason '15]

$$\bar{B}(\Phi_B) = B(\Phi_B) + [V_{\text{QCD}}(\Phi_B) + V_{\text{EW}}(\Phi_B)] + \int d\Phi_{\text{rad}} [R_{\text{QCD}}(\Phi_B, \Phi_{\text{rad}}) + R_{\text{EW}}(\Phi_B, \Phi_{\text{rad}})]$$

$$\Delta_{p_T}(\Phi_B) = \Delta_{p_T}^{\text{QCD}}(\Phi_B) \times \Delta_{p_T}^{\text{EW}}(\Phi_B)$$

- generate one radiation from each resonance
- requires dedicated interface to Parton Shower
- additive scheme + **factorizable & mixed**  $\alpha_S^n \alpha_{\text{EW}}^m$  terms, only in collinear limit

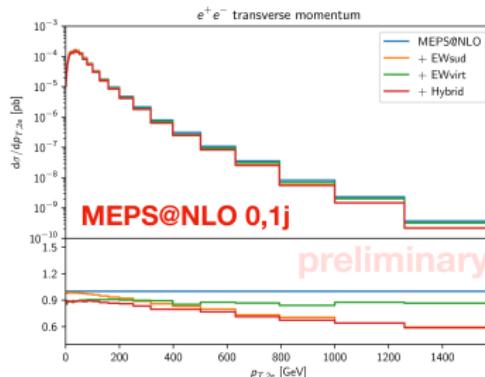
# EWvirt & EWsud schemes



WW & WW + 1 jet

[Bräuer et al, '20]

- ▶ NLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS: EWvirt scheme
- ▶ MEPS@NLO merging: allows to have stable predictions for  $n_j = 0$  and  $n_j = 1$



- ▶ "EWsud" scheme [Bothmann,Napoletano '20]
- ▶ LL and NLL EW corrections in Sudakov limit, following [Denner,Pozzorini '01]

$$\frac{\alpha}{4\pi} \log^2 \frac{s}{M^2}$$

$$\frac{\alpha}{4\pi} \log \frac{s}{M^2} \log \frac{p_k \cdot p_l}{s}$$

- ▶ apply corrections to all multiplicities, not only to  $\bar{B}$
- ▶ "hybrid" scheme: preliminary results for ZZ

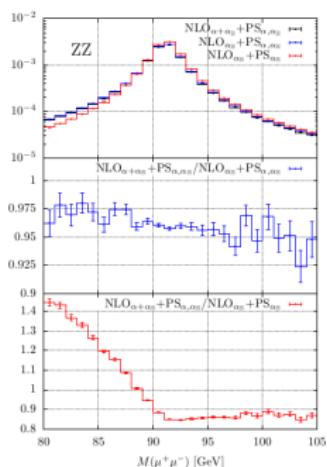
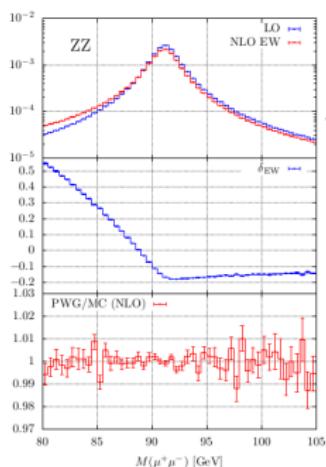
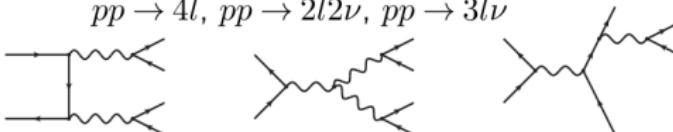
E. Bothmann@PSR21

# VV: exact NLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS<sub>QCD,QED</sub>

[Chiesa,ER '20]

loop amplitudes from Recola2

$pp \rightarrow 4l, pp \rightarrow 2l2\nu, pp \rightarrow 3l\nu$



- possible to have control on few percent effects

- $NLO_{\alpha_S+\alpha} + PS_{\alpha_S,\alpha} / NLO_{\alpha_S} + PS_{\alpha_S,\alpha}$ :

  - NLO weak, non-log QED  $\mathcal{O}(\alpha)$ , mixed
  - $NLO_{\alpha_S+\alpha} + PS_{\alpha_S,\alpha} / NLO_{\alpha_S} + PS_{\alpha_S}$ :

    - NLO weak, QED  $\mathcal{O}(\alpha)$ , leading-log QED  $\mathcal{O}(\alpha^n)$  ( $n > 2$ ), mixed

Future:

- photons in initial state
- merge with QCD corrections for  $WW + 1$  jet

# Conclusions and Future challenges

## Summary:

- ▶ Presented recent NNLO<sub>QCD</sub>+PS results: diboson production with `MinNLOPS` and `Geneva`
- ▶ top-pair production: first NNLO+PS result for a colored final state (at the LHC)
- ▶ Beyond NLO<sub>QCD</sub>+PS accuracy, EW corrections are important too
- ▶ Ongoing activity, several interesting results, still a lot to understand

## Future challenges:

- ▶ NNLO<sub>QCD</sub>+PS: beyond color singlet, decays
- ▶ Establish general method(s) for NLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS  
(conceptually difficult: e.g. processes with “QCD/EW interference” at LO)
- ▶ NNLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS, at least when already EXP important
- ▶ Interplay with NLL-accurate shower algorithms (e.g. local vs. global recoil(s))
  - will probably require re-thinking at the subtle details of current matching approaches

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*Thank you for your attention!*