QCD corrections in DY with POWHEG

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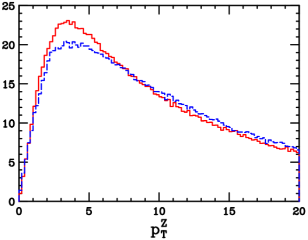
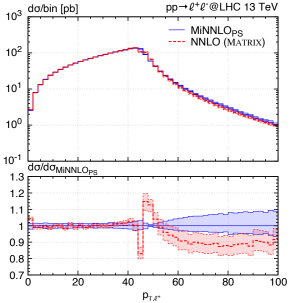
Plan of the talk

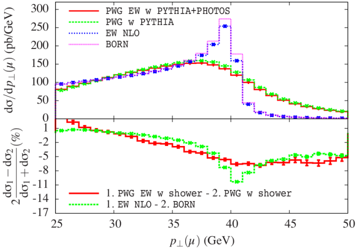
- Recap of (old) NLO_{QCD}+PS results



- $NNLO_{QCD}$+PS

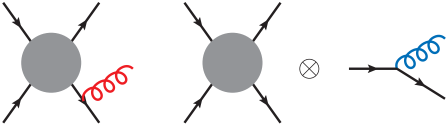


- NLO_{QCD}+NLO_{EW}+PS



NLO+PS

- POWHEG: method to achieve NLO+PS. Match fixed-order computation at NLO in QCD with Parton Showers
- Problem: overlapping regions



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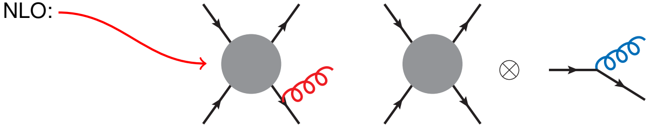

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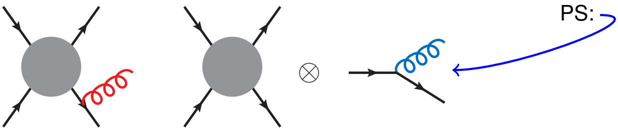

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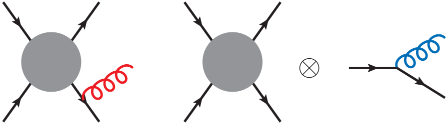


- NLO+PS is well understood, general solutions applicable to virtually any process: MC@NLO and POWHEG [Frixione-Webber '03, Nason '04]
- Other approaches exist, e.g.
  KrkNLO, Vincia [Jadach et al., Skands et al.]
  Geneva, U(N)NLOPS, MAcNLOPS [Alioli et al., Prestel et al./Plätzer, Nason,Salam]

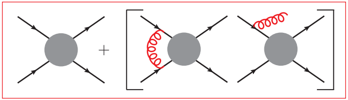
POWHEG in a nutshell

$$d\sigma_{\mathrm{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{ \Delta(\Phi_n; k_{\mathrm{T}}^{\mathrm{min}}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\}$$

[+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting]

POWHEG in a nutshell

$$B(\Phi_n) \Rightarrow \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})\, d\Phi_r\right]$$



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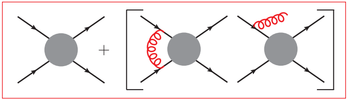
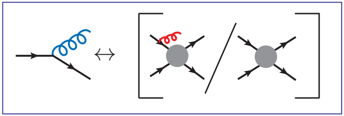


$$d\sigma_{\mathrm{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{\Delta(\Phi_n; k_{\mathrm{T}}^{\mathrm{min}}) + \Delta(\Phi_n; k_{\mathrm{T}})\frac{\alpha_s}{2\pi}\frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r\right\}$$

[+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting]



$$\Delta(t_{\mathrm{m}}, t) \Rightarrow \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\frac{\alpha_s}{2\pi}\int \frac{R(\Phi_n, \Phi_r')}{B(\Phi_n)}\theta(k_{\mathrm{T}}' - k_{\mathrm{T}})\, d\Phi_r'\right\}$$

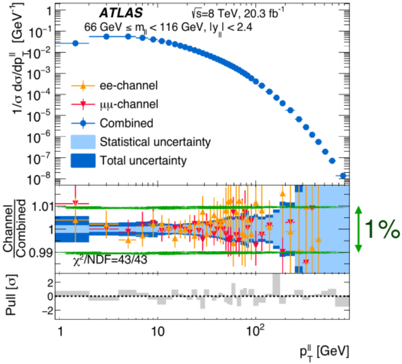
The POWHEG BOX framework

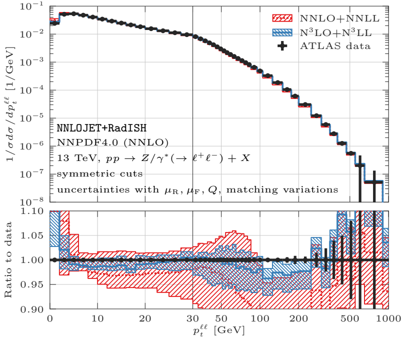
- Main focus: matching of accurate fixed-order predictions with PS for SM processes.
- All publicly available at

  powhegbox.mib.infn.it
- Two main releases:
  - POWHEG BOX V2: main release, almost all processes are here
  - POWHEG BOX RES: most recent one, able to deal with processes with resonances
- Drell-Yan in POWHEG BOX:
  - $\mathrm{NLO_{QCD}}$+PS
  - $\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$+PS
  - $\mathrm{NNLO_{QCD}}$+PS

Drell-Yan: data and theory

- Astonishing EXP precision, implications for pheno: PDF, EW parameters (e.g. m_W), ...



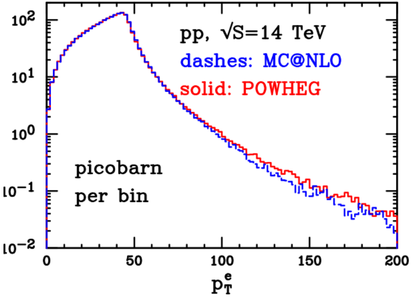


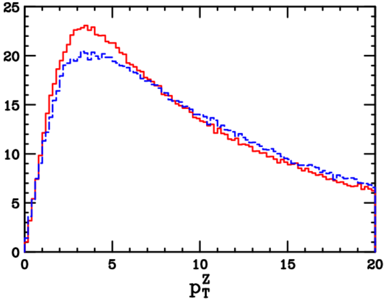
plot from [2203.01565]

- total x-section: known at N3LO [Duhr,Dulat,Mistlberger '20,'21]
- $p_T^{\ell\ell}$ known at NNLO [NNLOJET, MCFM]
- $p_T^{\ell\ell}$ known at N3LL$^{(\prime)}$ [Radish, CuTe, Nanga Parbat, DYTurbo, reSolve, SCETlib, ResBos2]
- total x-section: mixed QCD-EW corrections known [2005.10221, 2009.10386, 2106.11953]
- NLL QED + LL mixed QED-QCD for $p_T^{\ell\ell}$ [2302.05403]

NLO$_{QCD}$+PS

[Alioli,Nason,Oleari,ER '08]





- At that time: validation with `MC@NLO`
- Not concerned with theoretical uncertainties

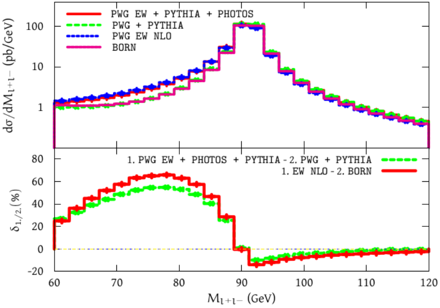
$\mathrm{NLO}_{\mathrm{QCD}}+\mathrm{NLO}_{\mathrm{EW}}+\mathrm{PS}$

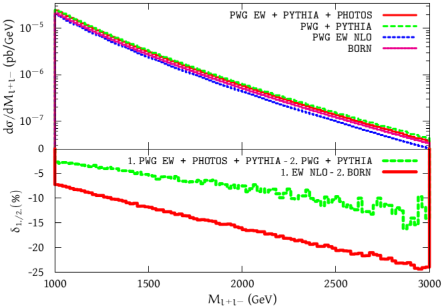
[Barzè et al. ’12,’13, Carloni et al. ’16]

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

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

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

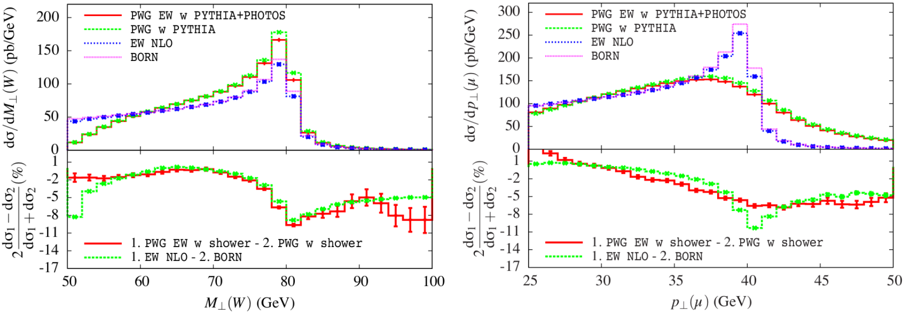




- red vs green: measure of “factorizable & mixed”

NLO$_{QCD}$+NLO$_{EW}$+PS

[Barzè et al. '12,'13, Carloni et al. '16]



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) $[\sigma(p_{T,j} < p_{T,\mathrm{veto}})]$
- 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,...],
  Geneva [Alioli,Bauer,et al. ’13,’15,’16,...],
  MiNNLO$_{\mathrm{PS}}$ [Monni,Nason,ER,Wiesemann,Zanderighi ’19,...],
  Vincia+sector showers [Campbell et al, ’21]

MiNNLO$_{PS}$: why?

- `FJ-MiNLO'` (+`POWHEG`) generator gives F-FJ @ NLOPS:

	F (inclusive)	$F+j$ (inclusive)	$F+2j$ (inclusive)
F-FJ @ NLOPS	NLO	NLO	LO
F @ NNLOPS	NNLO	NLO	LO

- reweighting (differential on $\Phi_{\rm F}$) $\Rightarrow$ by construction NNLO accuracy on inclusive observables

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MiNNLO$_{\text{PS}}$: why?

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- reweighting (differential on Φ_{F}) $\Rightarrow$ by construction NNLO accuracy on inclusive observables

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- Albeit formally correct, reweighting is a bottleneck for complex processes
  - approximations needed
  - discrete binning $\rightarrow$ delicate in less populated regions
  - it remains very CPU intensive
  - for complicated processes, it's not user friendly
- In 1908.06987, we developed a new method: NNLOPS accuracy without reweighting
- Through a precise connection of the MiNLO′ method and p_{T} resummation, possible to isolate the missing ingredients and reach NNLO accuracy
- In the follow-up paper 2006.04133 we refined some implementational aspects

[Notation: From this point, $X = \sum_k \left(\frac{\alpha_{\text{S}}}{2\pi}\right)^k [X]^{(k)}$]

MiNNLO$_{\rm PS}$ in a nutshell I

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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}\Phi_\mathrm{F}} = \frac{\mathrm{d}}{\mathrm{d}p_\mathrm{T}}\Big\{\mathcal{L}(\Phi_\mathrm{F},p_\mathrm{T})\exp(-\tilde{S}(p_\mathrm{T}))\Big\} + R_\mathrm{finite}(p_\mathrm{T})$$

$$\mathcal{L}(\Phi_\mathrm{F},p_\mathrm{T}) \ni \{H^{(1)},H^{(2)},C^{(1)},C^{(2)},(G^{(1)}\cdot G^{(1)})\} \qquad R_\mathrm{finite}(p_\mathrm{T}) = \frac{\mathrm{d}\sigma_\mathrm{FJ}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}} - \frac{\mathrm{d}\sigma^\mathrm{sing}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}}$$

  - $\mathcal{L}(\Phi_\mathrm{F},p_\mathrm{T})$: all the terms needed to obtain NNLO$^{(\mathrm{F})}$ accuracy upon integration in p_T

MiNNLO$_{\text{PS}}$ in a nutshell I

- 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 $\bar{B}^{(\mathrm{FJ})}(\Phi_{\mathrm{FJ}})$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_\mathrm{F}\mathrm{d}p_\mathrm{T}} = \exp[-\tilde{S}(p_\mathrm{T})]\left\{D(p_\mathrm{T}) + \frac{R_{\mathrm{finite}}(p_\mathrm{T})}{\exp[-\tilde{S}(p_\mathrm{T})]}\right\}$$

$$D(p_\mathrm{T}) \equiv -\frac{\mathrm{d}\tilde{S}(p_\mathrm{T})}{\mathrm{d}p_\mathrm{T}}\mathcal{L}(p_\mathrm{T}) + \frac{\mathrm{d}\mathcal{L}(p_\mathrm{T})}{\mathrm{d}p_\mathrm{T}} \qquad \tilde{S}(p_\mathrm{T}) = \int_{p_\mathrm{T}}^{Q}\frac{dq^2}{q^2}\Big[A_\mathrm{f}(\alpha_\mathrm{S}(q))\log\frac{Q^2}{q^2} + B_\mathrm{f}(\alpha_\mathrm{S}(q))\Big]$$

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

MiNNLO$_{\text{PS}}$ in a nutshell I

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Phi_{\mathrm{F}}} = \frac{\mathrm{d}}{\mathrm{d}p_{\mathrm{T}}}\left\{\mathcal{L}(\Phi_{\mathrm{F}}, p_{\mathrm{T}})\exp(-\tilde{S}(p_{\mathrm{T}}))\right\} + R_{\text{finite}}(p_{\mathrm{T}})$$

$$\mathcal{L}(\Phi_{\mathrm{F}}, p_{\mathrm{T}}) \ni \{H^{(1)}, H^{(2)}, C^{(1)}, C^{(2)}, (G^{(1)}\cdot G^{(1)})\} \qquad R_{\text{finite}}(p_{\mathrm{T}}) = \frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} - \frac{\mathrm{d}\sigma^{\text{sing}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}$$

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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]\left\{D(p_{\mathrm{T}}) + \frac{R_{\text{finite}}(p_{\mathrm{T}})}{\exp[-\tilde{S}(p_{\mathrm{T}})]}\right\}$$

$$D(p_{\mathrm{T}}) \equiv -\frac{\mathrm{d}\tilde{S}(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\mathcal{L}(p_{\mathrm{T}}) + \frac{\mathrm{d}\mathcal{L}(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}} \qquad \tilde{S}(p_{\mathrm{T}}) = \int_{p_{\mathrm{T}}}^{Q}\frac{dq^2}{q^2}\left[A_{\mathrm{f}}(\alpha_{\mathrm{S}}(q))\log\frac{Q^2}{q^2} + B_{\mathrm{f}}(\alpha_{\mathrm{S}}(q))\right]$$

- expand the above integrand in power of $\alpha_{\mathrm{S}}(p_{\mathrm{T}})$, keep the terms that are needed to get NLO$^{(\mathrm{F})}$ & NNLO$^{(\mathrm{F})}$ accuracy, when integrating over p_{T}
- after expansion, all the terms with explicit logs will be of the type $\alpha_{\mathrm{S}}^m(p_{\mathrm{T}})L^n$, with $n = 0, 1$.

$$\int^{Q}\frac{dp_{\mathrm{T}}}{p_{\mathrm{T}}}L^n\alpha_{\mathrm{S}}^m(p_{\mathrm{T}})\exp(-\tilde{S}(p_{\mathrm{T}})) \sim (\alpha_{\mathrm{S}}(Q))^{m-(n+1)/2} \qquad L = \log Q/p_{\mathrm{T}}$$

MiNNLO$_{\rm PS}$ in a nutshell II

Final master formula:

$$\frac{d\bar{B}(\Phi_{\rm FJ})}{d\Phi_{\rm FJ}} = \exp[-\tilde{S}(p_{\rm T})]\left\{\frac{\alpha_{\rm S}(p_{\rm T})}{2\pi}\left[\frac{d\sigma_{\rm FJ}}{d\Phi_{\rm FJ}}\right]^{(1)}\left(1+\frac{\alpha_{\rm S}(p_{\rm T})}{2\pi}[\tilde{S}(p_{\rm T})]^{(1)}\right) + \left(\frac{\alpha_{\rm S}(p_{\rm T})}{2\pi}\right)^2\left[\frac{d\sigma_{\rm FJ}}{d\Phi_{\rm FJ}}\right]^{(2)} + [D(p_{\rm T})]^{(\geq 3)} F_\ell^{\rm corr}(\Phi_{\rm FJ})\right\}$$

- MiNLO′ recovered
- $[D(p_{\rm T})]^{(\geq 3)} = \underbrace{-\frac{d\tilde{S}(p_{\rm T})}{dp_{\rm T}}\mathcal{L}(p_{\rm T}) + \frac{d\mathcal{L}(p_{\rm T})}{dp_{\rm T}}}_{D} - \frac{\alpha_{\rm S}(p_{\rm T})}{2\pi}[D(p_{\rm T})]^{(1)} - \left(\frac{\alpha_{\rm S}(p_{\rm T})}{2\pi}\right)^2 [D(p_{\rm T})]^{(2)}$
- $F_\ell^{\rm corr}(\Phi_{\rm FJ})$: projection $\rightarrow$ recover $[D(p_{\rm T})]^{(\geq 3)}$ when integrating over $\Phi_{\rm FJ}$ at fixed $(\Phi_{\rm F}, p_{\rm T})$

. The second radiation is generated by the usual POWHEG mechanism.

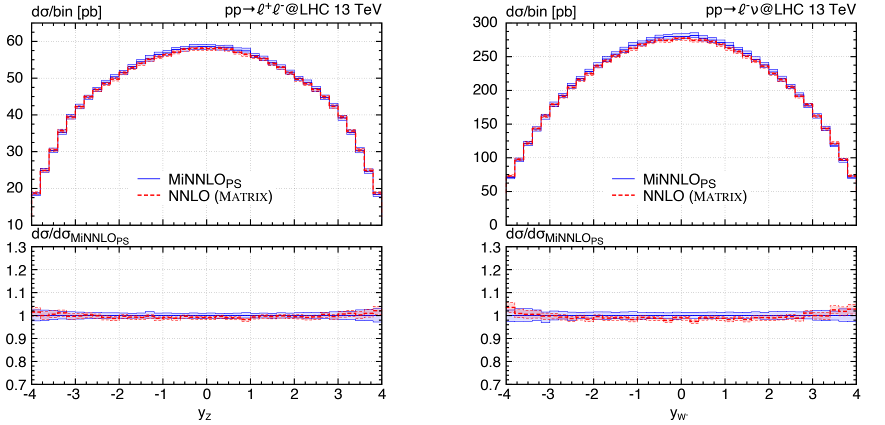
$$d\sigma = \bar{B}(\Phi_{\rm FJ})\, d\Phi_{\rm FJ}\left\{\Delta_{\rm pwg}(\Lambda_{\rm pwg}) + d\Phi_{\rm rad}\Delta_{\rm pwg}(p_{\rm T,rad})\frac{R(\Phi_{\rm FJ},\Phi_{\rm rad})}{B(\Phi_{\rm FJ})}\right\}$$

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

MiNNLO$_{PS}$: Drell-Yan I

results from 2006.04133

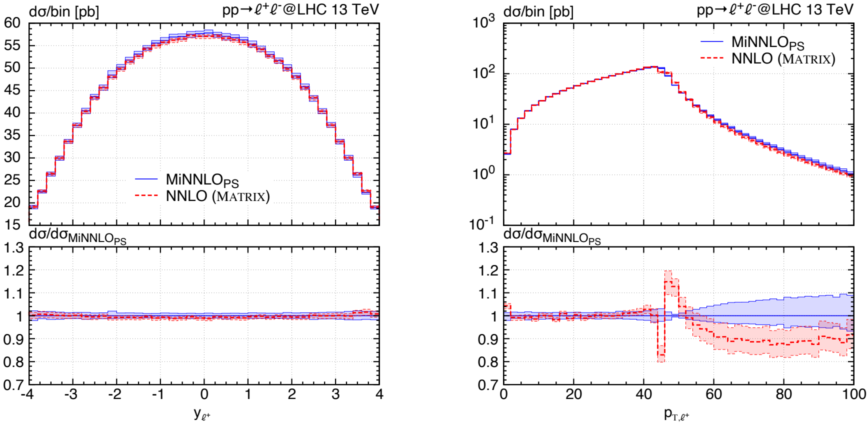
PS, no hadronization, no MPI



MiNNLO$_{\rm PS}$: Drell-Yan II

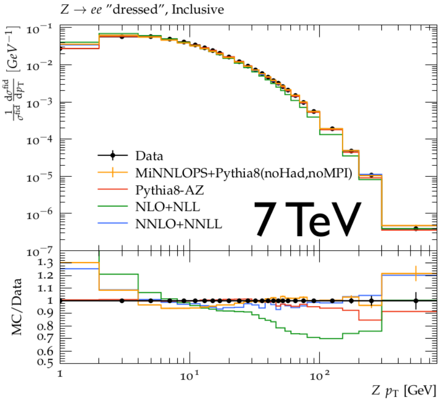
results from 2006.04133

PS, no hadronization, no MPI



- even such accurate MC predictions are not enough to meet EXP needs
- MiNNLO$_{\rm PS}$ $\to$ NLO at large $p_{\rm T}$

MiNNLO$_{PS}$: Drell-Yan



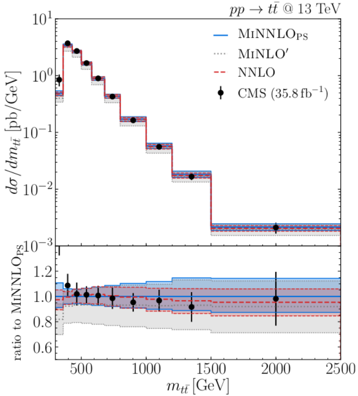
- plot from S. Amoroso

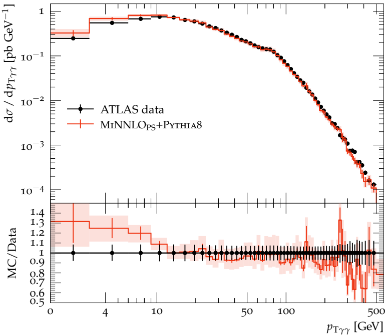
MiNNLO$_{PS}$: more recent results

- $pp \to VV$, $pp \to VH$

  [Buonocore,Chiesa,Haisch,Koole,Lombardi,ER,Rottoli,Scott,Wiesemann,Zanderighi,Zanoli '20-]

- $pp \to Q\bar{Q}$ [Mazzitelli,Monni,Nason,ER,Wiesemann,Zanderighi,Ratti '20,'21,'23]

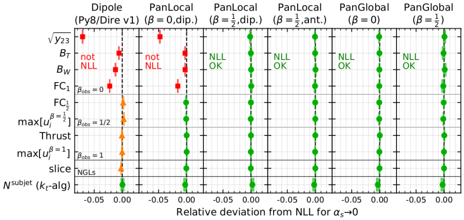


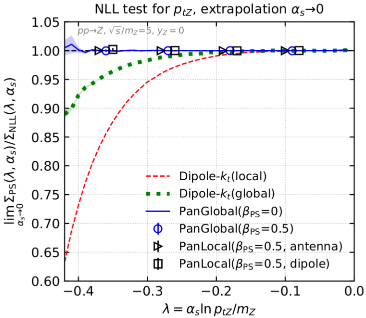


- Left: $pp \to t\bar{t} + t$ decays @ LO (including spin correlations) [Mazzitelli et al. '21]
- Right: diphoton production [Gavardi,Oleari,ER '22]

Recent progress in Parton Showers

- Differences between showers are a limiting factor for LHC phenomenology
- Huge effort towards improving many aspects of parton showers:
  - Going beyond LL
  - Subleading color
  - Spin correlations
  - EW showers





. plots from `PanScales` collaboration [2002.11114,2207.09467]

Summary

- (N)NLO$_{\mathrm{QCD}}$+PS results for the Drell-Yan process, using the MiNNLO$_{\mathrm{PS}}$ method. Available in the POWHEG BOX framework.
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Thank you for your attention!