The POWHEG BOX event generator:

Recent Developments

Emanuele Re

LAPTh Annecy

Joint Workshop: GDR QCD: "QCD@short distances" &
STRONG 2020: "Fixed target experiments at LHC", "3DPartons", "NLOAccess"

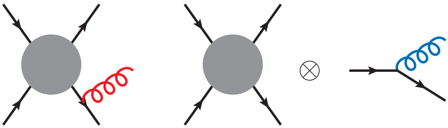
4 June 2021

Plan of the talk

- The POWHEG method in a nutshell
- The POWHEG BOX event generator
- Recent results on NNLO+PS matching
- Conclusion and Outlook

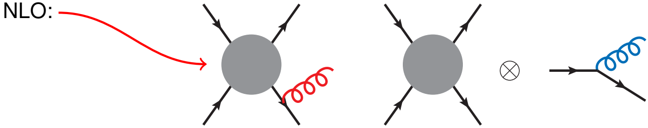
NLO+PS

- NLO+PS: match fixed-order computation at NLO in QCD with Parton Showers
- Problem: overlapping regions



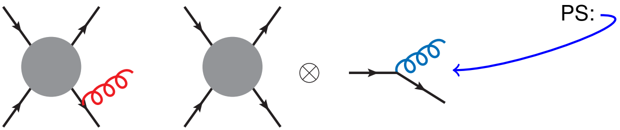
NLO+PS

- NLO+PS: match fixed-order computation at NLO in QCD with Parton Showers
- Problem: overlapping regions



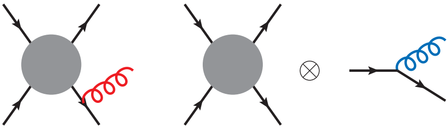
NLO+PS

- NLO+PS: match fixed-order computation at NLO in QCD with Parton Showers
- Problem: overlapping regions



NLO+PS

- NLO+PS: match fixed-order computation at NLO in QCD with Parton Showers
- Problem: overlapping regions



- 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.]

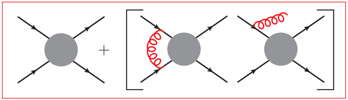
POWHEG in a nutshell

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

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

POWHEG in a nutshell

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

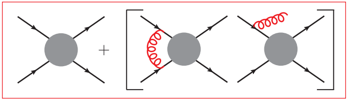


$$d\sigma_{\mathrm{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{\Delta(\Phi_n; k_{\mathrm{T}}^{\min}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)}\, d\Phi_r\right\}$$

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

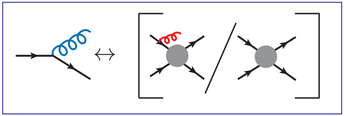
POWHEG in a nutshell

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



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

[+ 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.
- Several BSM applications exist (by far, not as many as in `MG5_aMC@NLO`).
- $\sim$ 100 processes, $\sim$ 100 authors contributed.
- 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

The POWHEG BOX framework

slide from C. Oleari

Processes implemented in the POWHEG BOX (I)

- Vector bosons
  - Z/W (with decay) (Alioli, Nason, Re, C.O., 2008)
  - Z/Wj (with decay) (Alioli, Nason, Re, C.O., 2010)
  - W^+W^+jj (Melia, Nason, Röntsch, Zanderighi, 2011)
  - W^+W^+jj and W^+W^-jj via VBF (Jäger, Zanderighi, 2011 and 2013)
  - diboson production (with decay), (Melia, Nason, Röntsch, Zanderighi, 2011)
  - W production with some EW corrections, (Bernaciak, Wackeroth, 2012)
  - W/Z production with EW corrections and QED shower, (Barzè, Montagna, Nason, Nicrosini, Piccinini, 2012 + Vicini, 2013)
  - Zjj in VBF (Jäger, Schneider, Zanderighi, 2012)
  - Zjj (Re, 2012)
  - Wjj and Zjj (Campbell, Ellis, Nason, Zanderighi, 2013)
  - ZZ, WZ and W^+W^- (Nason, Zanderighi, 2013)
  - W/Z in VBF (Schissler, Zeppenfeld, 2013)
  - $ZZjj$ in VBF (Jäger, Karlberg, Zanderighi, 2013)
  - $W\gamma$ (Barzè, Montagna, Nason, Nicrosini, Piccinini, 2012 + Vicini, 2013)
  - Zjj in VBF (Jäger, Schneider, Zanderighi, 2012)
  - Zjj (Re, 2012)
  - Wjj and Zjj (Campbell, Ellis, Nason, Zanderighi, 2013)
  - ZZ, WZ and W^+W^- (Nason, Zanderighi, 2013)
  - W/Z in VBF (Schissler, Zeppenfeld, 2013)
  - $ZZjj$ in VBF (Jäger, Karlberg, Zanderighi, 2013)
  - $W\gamma$ (Barzè, Chiesa, Montagna, Nason, Nicrosini, Piccinini, Prosperi, 2014)
  - γj (Ježo, Klasen, Klein-Bösing, König, Poppenborg, 2016 and 2017)
  - WW and WWj with MiNLO (Hamilton, Melia, Monni, Re, Zanderighi, 2016)
  - $WZjj$ in VBF (Jäger, Karlberg, Scheller, 2018)
  - $W^\pm W^\pm jj$ in VBF with EW corrections (Chiesa, Denner, Lang, Pellen, 2019)
  - $gg \to VV$ plus decay (Alioli, Ferrario Ravasio, Lindert, Röntsch, 2021)
  - diboson production (with decay) with EW corrections, (Chiesa, Re, C.O., 2020)

- Heavy quarks
  - heavy-quark pair production (Frixione, Nason, Ridolfi, 2007)
  - $t\bar{t}$ production with decay, with exact spin-correlations in decay products. NLO corrections only in the production part of the process (Campbell, Ellis, Nason, 2012)
  - single top (Alioli, Nason, Re, C.O., 2009) and tW (Re, 2010) + t-channel four-flavor scheme (Frederix, Re, Torrielli, 2012)
  - $t\bar{t}j$ (Kardos, Papadopoulos, Trocsanyi, 2011) and (Alioli, Moch, Uwer, 2011)
  - $t\bar{t}Z/W$ (Garzelli, Kardos, Papadopoulos, Trocsanyi, 2011-12)
  - $Wb\bar{b}$ (Reina, C.O., 2011)
  - $Wb\bar{b}$ and $Wb\bar{b}j$ with decay (Luisoni, Tramontano, C.O., 2015)
  - $t\bar{t}$ with approx decay (Campbell, Ellis, Nason, Re, 2014); with exact decay (Ježo, Lindert, Nason, Pozzorini, C.O., 2016)
  - $Wt\bar{t}$ with decay (Febres Cordero, Kraus, Reina, 2021)

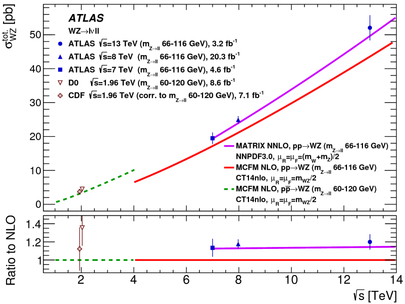
slide from C. Oleari

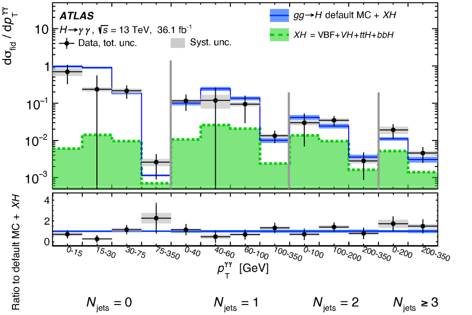
Processes implemented in the POWHEG BOX (II)

- Higgs boson
  - H in gluon fusion (Alioli, Nason, Re, C.O., 2008); with mass and EW effects, (Bagnaschi, Degrassi, Slavich, Vicini, 2011)
  - Hjj in VBF (Nason, C.O., 2010)
  - $t\bar{t}H$ (Garzelli, Kardos, Papadopoulos, Trocsanyi, 2011; Hartanto, Jäger, Reina, Wackeroth, 2015)
  - tH^- (Klasen, Kovarik, Nason, Weydert, 2012)
  - H in gluon fusion with quark mass and EW effects (Bagnaschi, Degrassi, Slavich, Vicini, 2011)
  - Hj and Hjj in gluon fusion (Campbell, Ellis, Frederix, Nason, Williams, C.O., 2012)
  - HV and HVj, $V = W^{\pm}, Z$ (with decay) (Luisoni, Nason, Tramontano, C.O., 2013); with EW effects (Granata, Lindert, Pozzorini, C.O., 2017)
  - $gg \to HZ$ (Luisoni, Tramontano, C.O., 2013)
  - $Hjjj$ in VBF (Jäger, Schissler, Zeppenfeld, 2014)
  - $b\bar{b}H$ (Jäger, Reina, Wackeroth, 2015)
  - HH in gluon fusion (Heinrich, Jones, Kerner, Luisoni, Vryonidou + Scyboz, 2017)
  - HW^+W^- and HZZ (Baglio, 2015 and 2016)
- Jet production
  - jj (Alioli, Hamilton Nason, Re, C.O., 2010)
  - jjj (Kardos, Nason, C.O., 2014)
- Beyond SM
  - H in gluon fusion in the MSSM and 2HDM (Bagnaschi, Degrassi, Slavich, Vicini, 2011)
  - Slepton pair production (Jäger, von Manteuffel, Thier, 2012)
  - Squark pair production (Gavin, Hangst, Krämer, Mühlleitner, Pellen, Popenda, Spira, 2013)
  - Dark matter + monojet (Haisch, Kahlhoefer, Re, 2013 and 2015)
  - Slepton pair production + j (Jäger, von Manteuffel, Thier, 2014)
  - Electroweakino pair production in SUSY-QCD (Baglio, Jäger, Kesenheimer, 2016)
  - Electroweakino pair production + j (Baglio, Jäger, Kesenheimer, 2017)
  - $X_0 jj$ (scalar CP violating production) (Nason, Rocco, Zaro, C.O., 2020)
- EFT
  - HW/Z (Mimasu, Sanz, Williams, 2016)
  - W/Z and HW/Z and H via VBF (Alioli, Dekens, Girard, Mereghetti, 2018) and (Alioli, Cirigliano, Dekens, de Vries, Mereghetti, 2017)
  - W^+W^- (Baglio, Dawson, Lewis, 2018)
- NNLO+PS
  - H and W/Z (Monni, Nason, Re, Wiesemann, Zanderighi, 2018 and 2020)
  - W^+W^- (Re, Wiesemann, Zanderighi, 2018)
  - $t\bar{t}$ (Mazzitelli, Monni, Nason, Re, Wiesemann, 2020)

Beyond NLO+PS

- current EXP precision demands for predictions beyond NLO(+PS) accuracy.





[ATLAS, 1802.04146]

- NNLO QCD corrections + resummation in corners of phase-space.
  [e.g. ggH: jet-vetos, DY: measurements at the Z peak]
- Often NLO EW corrections are important too:
  $\alpha_S^2 \sim \alpha$ + enhanced effects in some phase-space regions
- Focus of the rest of the talk: $\boxed{\text{NNLO+PS}}$

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) $[\sigma(p_{T,j} < p_{T,\mathrm{veto}})]$
- 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,...]

The MiNLO method

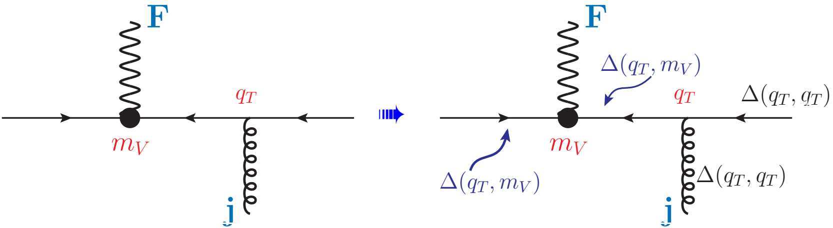
Multiscale Improved NLO

[Hamilton,Nason,Zanderighi, '12]

- original goal: method to a-priori choose scales in multijet NLO computation
- non-trivial task: hierarchy among scales can spoil accuracy (large logs can appear, without being resummed)
- how: correct weights of different NLO terms with CKKW-inspired approach, i.e. using PS concepts (without spoiling formal NLO accuracy)
- from $F + n$ jets at NLO+PS, one gets finite results also for $F + (n-1)$, $F + (n-2)$,... jets
  - $\Rightarrow$ it is a merging, without an external merging scale (just 1 event sample)

"color singlet (F) + 1 j" processes

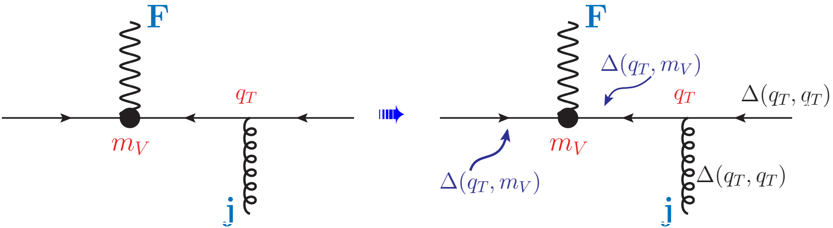
[Hamilton,Nason,Oleari,Zanderighi '12]



MiNLO for F+j

“color singlet (F) + 1 j” processes

[Hamilton,Nason,Oleari,Zanderighi ’12]



$$\bar{B}^{(\mathrm{FJ})}_{\mathrm{NLO}} = \frac{\alpha_{\mathrm{S}}(\mu_R)}{2\pi}\left[B^{(\mathrm{FJ})} + \frac{\alpha_{\mathrm{S}}}{2\pi} V^{(\mathrm{FJ})}(\mu_R) + \frac{\alpha_{\mathrm{S}}}{2\pi}\int d\Phi_{\mathrm{r}} R^{(\mathrm{FJ})}\right]$$

$$\bar{B}^{(\mathrm{FJ})}_{\mathrm{MiNLO}} = \frac{\alpha_{\mathrm{S}}(q_{\mathrm{T}})}{2\pi}\left[\Delta_{\mathrm{f}}^2(q_{\mathrm{T}})\left[B^{(\mathrm{FJ})}\left(1 + \frac{\alpha_{\mathrm{S}}}{2\pi}\tilde{S}_{\mathrm{f}}^{(1)}(q_{\mathrm{T}})\right) + \frac{\alpha_{\mathrm{S}}}{2\pi} V^{(\mathrm{FJ})}(q_{\mathrm{T}})\right] + \frac{\alpha_{\mathrm{S}}}{2\pi}\int d\Phi_{\mathrm{r}} \Delta_{\mathrm{f}}^2(q_{\mathrm{T}}) R^{(\mathrm{FJ})}\right]$$

- MiNLO-improved FJ yields finite results also when 1st jet is unresolved ($q_{\mathrm{T}} \to 0$)
- straightforward to apply to the POWHEG $\bar{B}^{(\mathrm{FJ})}$ function

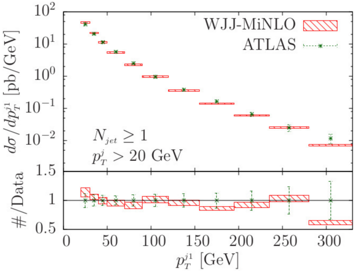
MiNLO′ and NLO+PS merging

- MiNLO: $F + 2$ j: finite and nicely working also for 0- and 1-jet region, but no exact claim on the accuracy in those regions.
- MiNLO′: $F + 1$ j: claim on the accuracy is possible.
- inclusive NLO can be recovered (NLO$^{(0)}$), without spoiling NLO accuracy of F+j (NLO$^{(1)}$):

NLO+PS merging, without merging scale

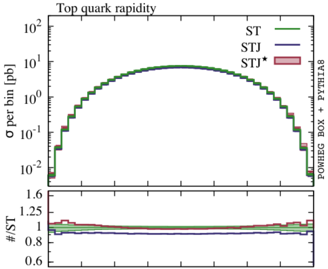
- accurate control of subleading small-p_T logarithms is needed (e.g. B_2 (NNLL))

* V + 0,1,2 jets



plot from [Campbell,Ellis,Nason,Zanderighi, '13]

* single-top + 0,1 jets



plot from [Carrazza et al. '18]

From NLO+PS merging to NNLO+PS

- starting from a `MiNLO'` generator, it's possible to match a PS simulation to NNLO.
- `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

From NLO+PS merging to NNLO+PS

- starting from a `MiNLO′` generator, it's possible to match a PS simulation to NNLO.
- `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 $\Phi_{\rm F}$) of "`MiNLO`-generated" events:

$$W(\Phi_{\rm F}) = \frac{\left(\frac{d\sigma}{d\Phi_{\rm F}}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_{\rm F}}\right)_{\rm FJ-MiNLO'}}$$

  - by construction NNLO accuracy on inclusive observables; [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `FJ−MiNLO′` in 1-jet region; [ ]

From NLO+PS merging to NNLO+PS

- starting from a `MiNLO'` generator, it's possible to match a PS simulation to NNLO.
- `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 $\Phi_{\rm F}$) of "`MiNLO`-generated" events:

$$W(\Phi_{\rm F}) = \frac{\left(\frac{d\sigma}{d\Phi_{\rm F}}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_{\rm F}}\right)_{\rm FJ-MiNLO'}} = \frac{c_0 + c_1\alpha_{\rm S} + c_2\alpha_{\rm S}^2}{c_0 + c_1\alpha_{\rm S} + d_2\alpha_{\rm S}^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_{\rm S}^2 + \mathcal{O}(\alpha_{\rm S}^3)$$

  - by construction NNLO accuracy on inclusive observables; [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `FJ-MiNLO'` in 1-jet region; [✓]

From NLO+PS merging to NNLO+PS

- starting from a MiNLO′ generator, it's possible to match a PS simulation to NNLO.
- 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 $\Phi_{\rm F}$) of "MiNLO-generated" events:

$$W(\Phi_{\rm F}) = \frac{\left(\frac{d\sigma}{d\Phi_{\rm F}}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_{\rm F}}\right)_{\rm FJ-MiNLO'}} = \frac{c_0 + c_1\alpha_{\rm S} + c_2\alpha_{\rm S}^2}{c_0 + c_1\alpha_{\rm S} + d_2\alpha_{\rm S}^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_{\rm S}^2 + \mathcal{O}(\alpha_{\rm S}^3)$$

  - by construction NNLO accuracy on inclusive observables; [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of FJ−MiNLO′ in 1-jet region; [✓]

- succesfully employed for ggH, Drell-Yan, VH, WW production, $H \to b\bar{b}$

[Hamilton,Nason,ER,Zanderighi '13 / Karlberg,ER,Zanderighi '14 / Astill,Bizon,ER,Zanderighi '16-'18 ER,Wiesemann,Zanderighi '18, Bizon,ER,Zanderighi '19]

  - $pp \to W^+W^- \to 4\ell$: doable, but at the edge of feasibility: dim($\Phi_{4\ell}$) = 9

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

- Albeit formally correct, reweighting is a bottleneck for complex processes
  - approximations needed
  - discrete binning $\to$ 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, $X = \sum_k \left(\frac{\alpha_S}{2\pi}\right)^k [X]^{(k)}$]

MiNNLO$_{\mathrm{PS}}$ in a nutshell

- 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

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

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

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

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

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

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

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

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

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

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

- 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

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

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

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

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

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

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

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

- 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$_{\text{PS}}$

Final master formula:

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

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

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

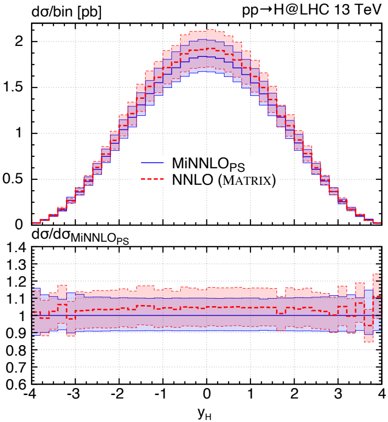
$$\mathrm{d}\sigma = \bar{B}(\Phi_{\mathrm{FJ}})\,\mathrm{d}\Phi_{\mathrm{FJ}}\left\{\Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \mathrm{d}\Phi_{\mathrm{rad}}\Delta_{\mathrm{pwg}}(p_{\mathrm{T,rad}})\frac{R(\Phi_{\mathrm{FJ}},\Phi_{\mathrm{rad}})}{B(\Phi_{\mathrm{FJ}})}\right\}$$

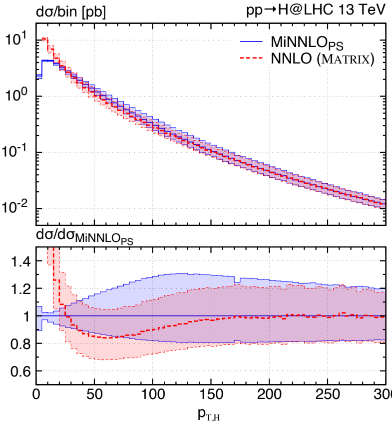
. if emissions are strongly ordered, same emission probabilities as in k_t-ordered shower $\rightarrow$ LL shower accuracy preserved

MiNNLO$_{\mathrm{PS}}$: ggH

results from 2006.04133

PS, no hadronization, no MPI



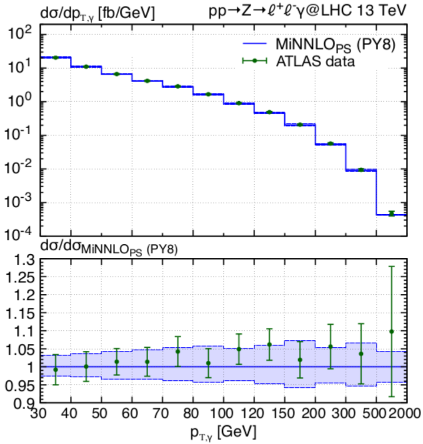


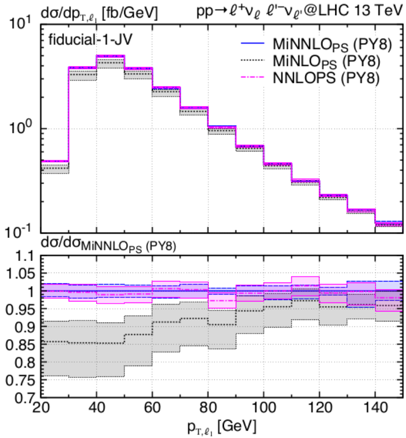
- expected very good agreement with NNLO: 4% difference
- results from 1908.06987: 8% difference
- correct shape

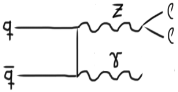
- expected Sudakov shape
- MiNNLO$_{\mathrm{PS}}$ $\rightarrow$ NLO at large p_{T}

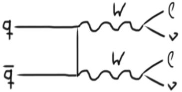
MiNNLO$_{PS}$: diboson production

The method is general: recently, applied to more complex color-singlet production processes.









plots from [Lombardi, Wiesemann, Zanderighi '20,'21]

MiNNLO$_{\text{PS}}$: top-pair production

- Method extended to deal with heavy quarks in the final state: $t\bar{t}$ at NNLO+PS !!

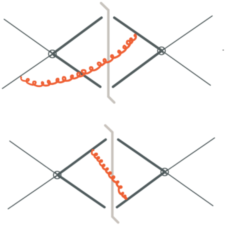
  [Mazzitelli,Monni,Nason,ER,Wiesemann,Zanderighi '20]

- Starting point: resummation formula for $t\bar{t}$ transverse momentum. [Catani,Grazzini,Torre '14]
  Very schematically:

$$d\sigma^F_{\text{res}} \sim \frac{d}{dp_T}\left\{e^{-S}\,\text{Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$S = -\int \frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\left(A^{(1)}\log(M/q)+B^{(1)}\right)+\frac{\alpha_s^2(q)}{(2\pi)^2}\left(A^{(2)}\log(M/q)+B^{(2)}\right)+\ldots\right]$$

$$\text{Tr}(\mathbf{H}\boldsymbol{\Delta}) = \langle M|\boldsymbol{\Delta}|M\rangle, \quad \boldsymbol{\Delta} = \mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V}, \quad \mathbf{V} = \exp\left\{-\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\mathbf{t}}+\frac{\alpha_s^2(q)}{(2\pi)^2}\boldsymbol{\Gamma}^{(2)}_{\mathbf{t}}\right]\right\}$$



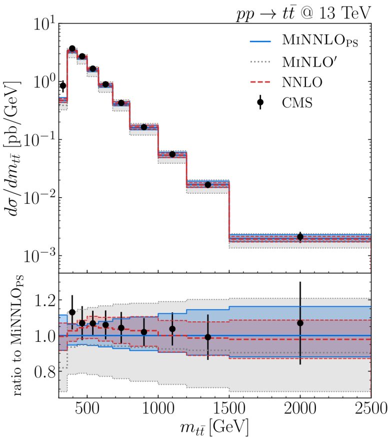
- With some approximations (respecting our goal), terms due to soft interference can be rearranged so that the "resummation" can be eventually recasted as:

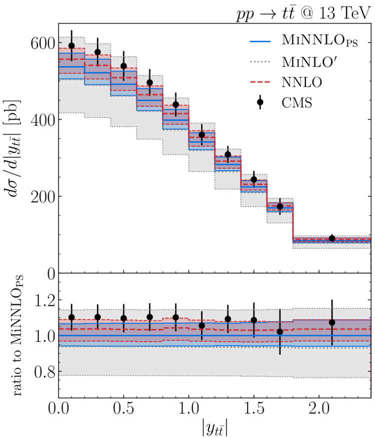
$$d\sigma^F_{\text{res}} \sim \frac{d}{dp_T}\left\{\sum_{i\in\text{colours}} e^{-\bar{S}_i}\,\underbrace{c_i\,\overline{H}\,\overline{(C\otimes f)}\,\overline{(C\otimes f)}}_{\equiv\,\overline{\mathscr{L}}_i}\right\} + \mathcal{O}(\alpha_S^5)$$

some inputs derived in [Catani, Devoto, Grazzini, Kallweit, Mazzitelli + Sargsyan '19]

- Each term has the same structure as in the color-singlet case!

MiNNLO$_{PS}$: $t\bar{t}$ results





- Good agreement with data.
- $m_{t\bar{t}}$: finite width & non-relativistic effects in very first bin.
- So far, on-shell top quarks.
- NWA + decay at tree-level, retaining sping correlations, should be doable.

Summary

- NLO+PS, status of the POWHEG BOX framework, `MiNLO` idea
- Shown NNLO+PS accurate results
  - **MiNNLO$_{PS}$**: NNLO+PS, without reweighting and with no merging scales
  - NNLO+PS results for top-pair production
  - several applications are now possible, certainly all $2 \to 2$ color-singlet production (i.e. dibosons)

What next?

- Consider other subleading effects, e.g.:
  - formal accuracy of the PS $\leftrightarrow$ logarithmic accuracy of a matched computation
  - EW corrections: (N)NLO$_{QCD}$+NLO$_{EW}$+PS
- Applications in EXP analysis

Summary

- NLO+PS, status of the POWHEG BOX framework, MiNLO idea
- Shown NNLO+PS accurate results
  - **MiNNLO$_{PS}$**: NNLO+PS, without reweighting and with no merging scales
  - NNLO+PS results for top-pair production
  - several applications are now possible, certainly all $2 \to 2$ color-singlet production (i.e. dibosons)

What next?

- Consider other subleading effects, e.g.:
  - formal accuracy of the PS $\leftrightarrow$ logarithmic accuracy of a matched computation
  - EW corrections: (N)NLO$_{\text{QCD}}$+NLO$_{\text{EW}}$+PS
- Applications in EXP analysis

Thank you for your attention!