MiNNLO$_{PS}$: a new method to match NNLO QCD and parton showers

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LAPTh Annecy

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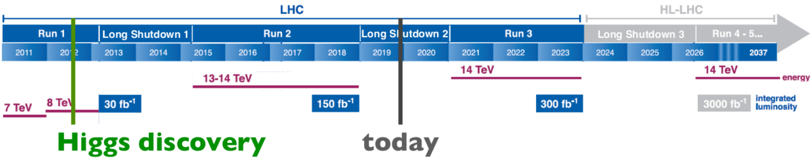
Precision as a path to New Physics

- especially after the Higgs discovery, no clear sign of tension between the SM and experimental results (except possibly, and hopefully, in the flavour sector)...
- ...but we know that the SM is not the full story!
- plenty of data still to come from the LHC (as well as other experiments).

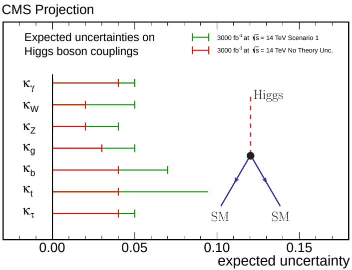


$\Rightarrow$ uttermost importance to look everywhere, and be able to find hints of New Physics looking at small deviations from SM predictions:

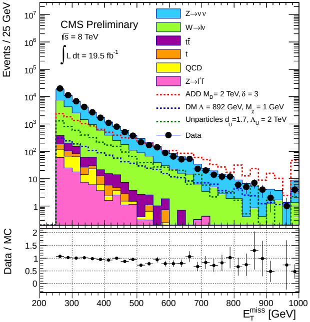
- precise and accurate predictions, with solid estimate of theory uncertainties
- strategies to measure/bound relevant quantities

Importance of SM predictions

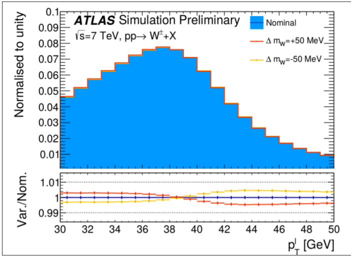
Higgs couplings

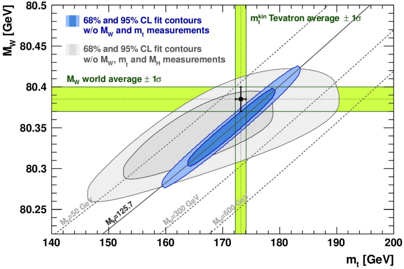


backgrounds to New Physics



indirect searches





Where do we stand?

- use perturbation theory to compute subleading effects, especially when they are expected to be large:

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

  - for all (relevant) SM processes NLO QCD corrections are known
  - focus has now shifted towards NNLO QCD / NLO EW computations

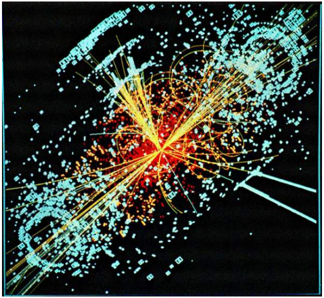
    $\sim \mathcal{O}(\text{few})\%$ residual uncertainty $[\leq 10\%]$

  - interplay between (N)NLO computations and extraction of parameters (PDFs, α_S) crucial
  - in some kinematics region, all-order results are needed ("resummation")

- MC event generators enter in almost all experimental analyses: important to make them as accurate as possible.
- this talk: matching QCD NNLO corrections with PS

Plan of the talk

1. quickly review how MC event generators work
2. discuss how to match them to NLO and NNLO computations
   - NNLOPS for $pp \to WW$ (with reweighting)
3. MiNNLO$_{\text{PS}}$: NNLOPS without reweighting



- in collaboration with G. Zanderighi, K. Hamilton, P. Nason, A. Karlberg, W. Bizon, W. Astill, P. Monni, M. Wiesemann

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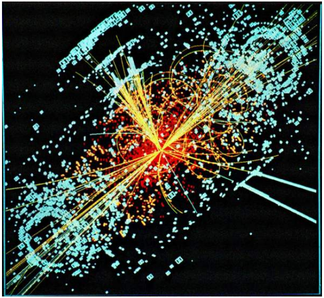
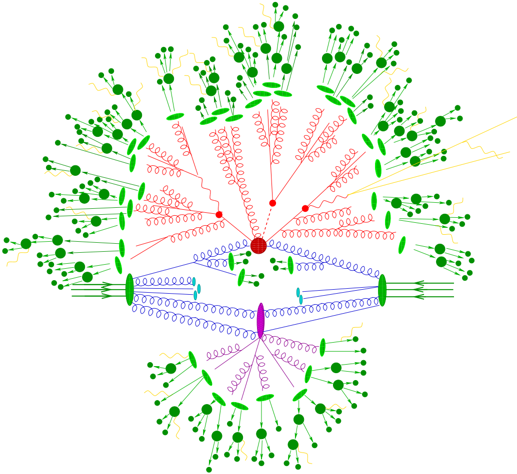


Event generators: what they are?



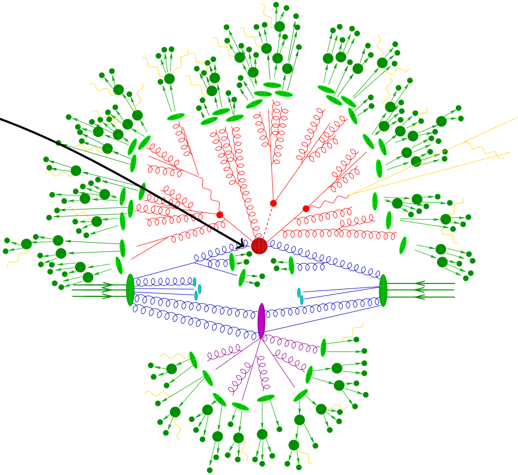
[sherpa's artistic view]

Event generators: what they are?

hard scattering

$\Lambda_{\text{QCD}} \ll \mu \approx Q$

. perturbation theory



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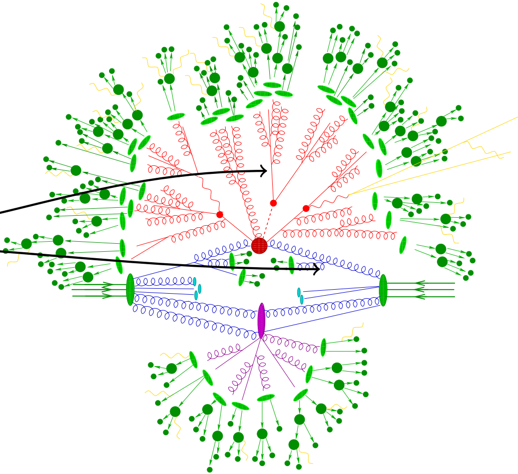
parton shower

$\Lambda_{\text{QCD}} < \mu < Q$

- hierarchy of scales
- resummation of large logarithms



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parton shower

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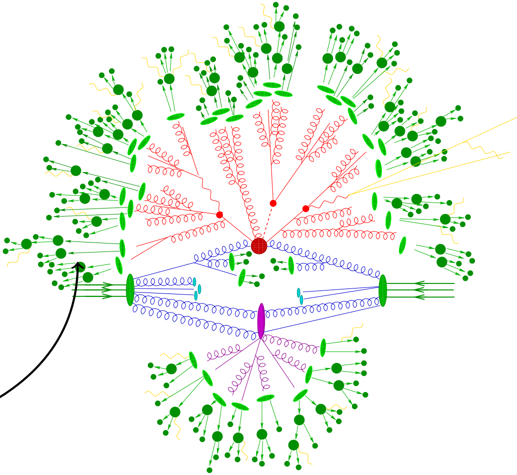
hadronisation

$\mu \approx \Lambda_{\text{QCD}}$

- non-perturbative model, tuned on e^+e^- data



[sherpa's artistic view]

The hard scattering

$$d\sigma = d\sigma_{\text{LO}} + \left(\frac{\alpha_S}{2\pi}\right) d\sigma_{\text{NLO}} + \left(\frac{\alpha_S}{2\pi}\right)^2 d\sigma_{\text{NNLO}} + \ldots$$

$\mu \gg \Lambda_{\text{QCD}},\ \alpha_S \sim 0.1$
$\Leftarrow$ perturbation theory

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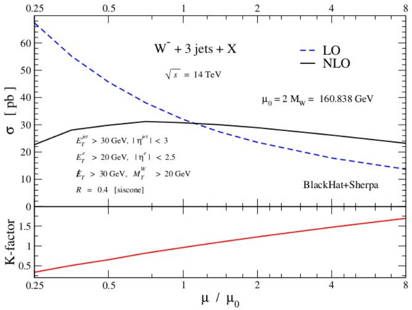
☞ Why NLO?

- first order where rates are reliable
- shapes are, in general, better described
- sensible theoretical uncertainties [done typically by changing ren. and fac. scales]



plot from BlackHat+Sherpa [Berger et al. '09]

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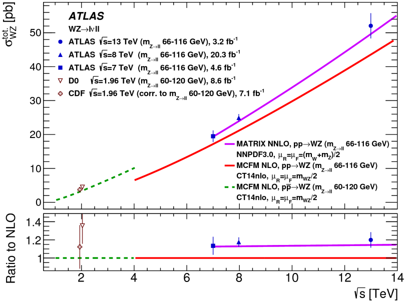
☞ Why NNLO?

- when NLO corrections large
- very high-precision needed
  [$\leftrightarrow$ match EXP accuracy]

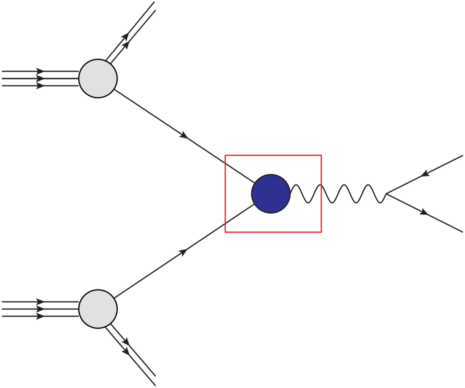
NNLO result from MATRIX [Grazzini et al. '16]



- NNLO is the frontier! Nearly all $2 \to 2$ processes at the LHC are now known

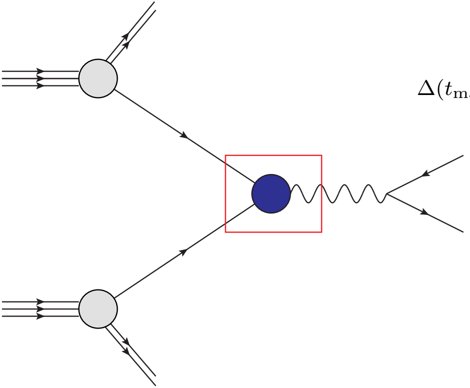
Parton showers

$$d\sigma_{\rm SMC} = \underbrace{B(\Phi_{\rm F})\, d\Phi_{\rm F}}_{d\sigma_{\rm LO}} \Big\{ \qquad \Big\}$$



Parton showers

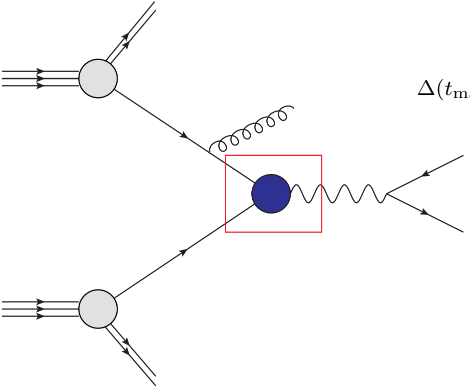
$$d\sigma_{\text{SMC}} = \underbrace{B(\Phi_{\text{F}})\, d\Phi_{\text{F}}}_{d\sigma_{\text{LO}}} \left\{ \Delta(t_{\max}, t_0) \right\}$$



$$\Delta(t_{\max}, t) = \exp\left\{ - \int_{t}^{t_{\max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers

$$d\sigma_{\rm SMC} = \underbrace{B(\Phi_{\rm F})\, d\Phi_{\rm F}}_{d\sigma_{\rm LO}} \left\{ \Delta(t_{\max}, t_0) + \Delta(t_{\max}, t) \quad \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\ \frac{1}{t} P(z)\ d\Phi_r} \right\}$$



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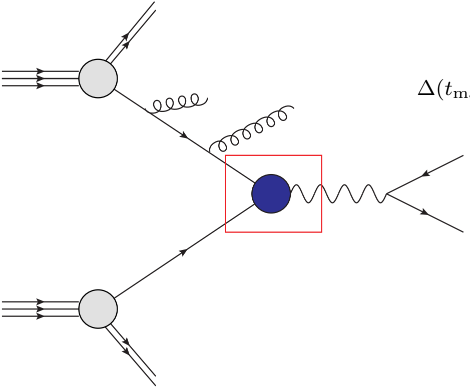

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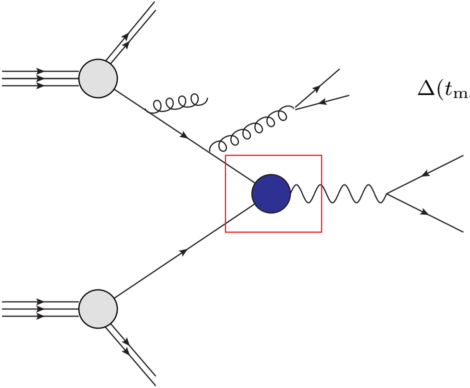

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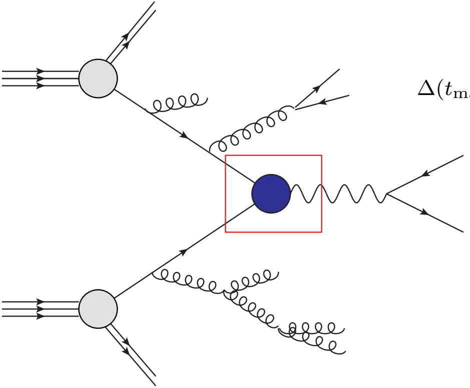

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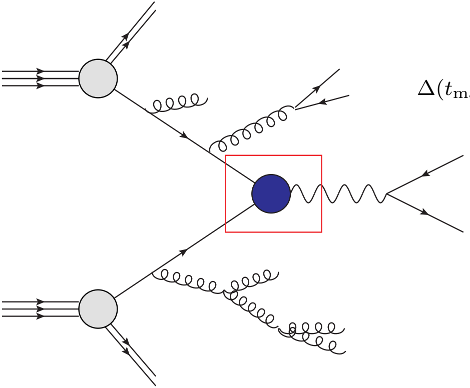

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$d\sigma_{\mathrm{LO}} \leftrightarrow$ "LO+PS"

- PS formulated probabilistically:
  - shapes change, but overall normalization fixed: it stays LO (*unitarity*)
  - they are only LO+LL accurate (whereas we want more precise tools)

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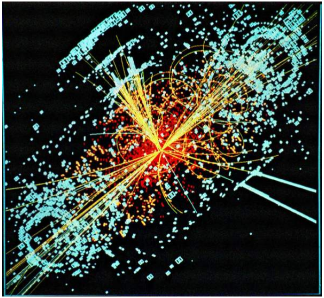


NLO+PS I

Q: can we combine a NLO result with a PS ?

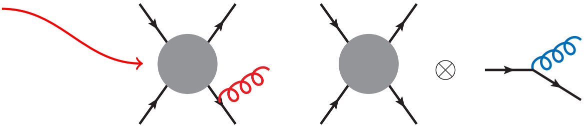
Problem:

NLO+PS I

Q: can we combine a NLO result with a PS ?

<u>Problem:</u> overlapping regions!

NLO:



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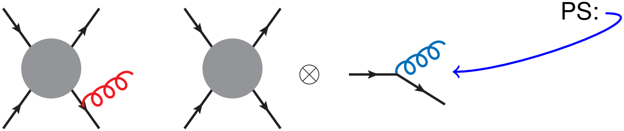

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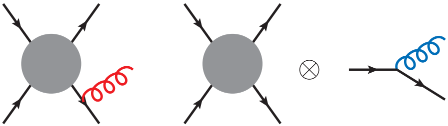


There's a double-counting to take care of.

✓ several proposals, 2 well-established methods available to solve this problem: MC@NLO and POWHEG [Frixione-Webber '03, Nason '04]

- other more recent approaches: KrKNLO, Vincia, Geneva

NLO+PS II: POWHEG

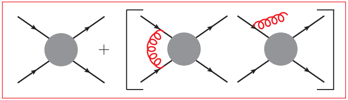
$$d\sigma_{\text{LOPS}} = d\Phi_n \quad B(\Phi_n) \quad \left\{ \Delta(t_{\max}, t_0) + \Delta(t_{\max}, t) \frac{\alpha_s}{2\pi} \frac{1}{t} P(z)\, d\Phi_r \right\}$$

NLO+PS II: POWHEG

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

NLO+PS II: POWHEG

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



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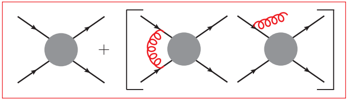

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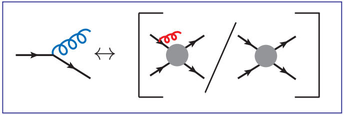

$$\Delta(t_{\mathrm{m}}, t) \Rightarrow \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\int \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r')}{B(\Phi_n)} \theta(k_{\mathrm{T}}' - k_{\mathrm{T}})\, d\Phi_r'\right\}$$

NNLO+PS

NLO(+PS) often not enough.

Moreover, many NNLO results for color-singlet production at the LHC are known.

- Higgs (ggH, VH), Drell-Yan, diboson

[Catani,Grazzini,de Florian,Cieri,Ferrera,Tramontano - Campbell,Ellis,Williams - Grazzini,Kallweit,Wiesemann - Caola,Melnikov,Rontsch - ...]

Q: can we match NNLO and PS (for color-singlet production)?

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- methods presented in this talk:
  - `POWHEG+MiNLO`, used so far for ggH, Drell-Yan, VH, WW production

    [Hamilton,Nason,ER,Zanderighi '13 / Karlberg,ER,Zanderighi '14 / Astill,Bizon,ER,Zanderighi '16-'18 ER,Wiesemann,Zanderighi '18]
  - `MiNNLOPS`: proof of concept for ggH and Drell-Yan

    [Monni,Nason,ER,Wiesemann,Zanderighi '19]

- other available methods: `UNNLOPS` [Höche,Li,Prestel '14], `Geneva` [Alioli,Bauer,et al. '13,'15,'16,'19]

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  - MiNNLOPS: proof of concept for ggH and Drell-Yan

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- other available methods: UNNLOPS [Höche,Li,Prestel '14], Geneva [Alioli,Bauer,et al. '13,'15,'16,'19]
- at the core of all methods: "merging" of 2 NLO(+PS) results

$\Longrightarrow$

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

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 (without spoiling formal NLO accuracy)

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- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)
  - for each phase space point, build the “more-likely” shower history that would have produced that kinematics

    ☞ cluster kinematics with k_{T}-algo $\rightarrow$ undo the clustering $\rightarrow$ assign scales
  - “correct” original NLO à la CKKW

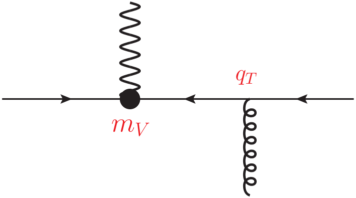
    $\rightarrow$ α_{S} evaluated at nodal scales

    $\rightarrow$ Sudakov FFs

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

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

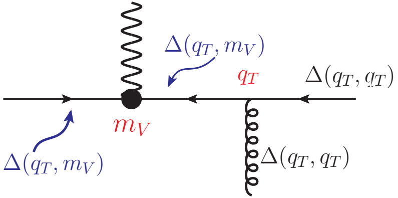


Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

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

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



Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

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

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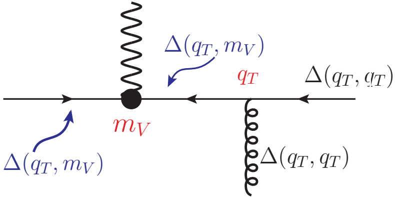

- $\bar{\mu}_R = q_{\mathrm{T}}$
- $\Delta^2_{\mathrm{f}}(q_{\mathrm{T}}) = \exp(-\tilde{S}_{\mathrm{f}}(q_{\mathrm{T}}))$
- $\tilde{S}_{\mathrm{f}}(q_{\mathrm{T}}) = \int_{q^2_{\mathrm{T}}}^{m^2_{\mathrm{F}}} \frac{dq^2}{q^2}\left[A_{\mathrm{f}}(\alpha_{\mathrm{S}}(q^2))\log\frac{m^2_{\mathrm{F}}}{q^2} + B_{\mathrm{f}}(\alpha_{\mathrm{S}}(q^2))\right]$
- $\frac{\alpha_{\mathrm{S}}}{2\pi}\tilde{S}^{(1)}_{\mathrm{f}}(q_{\mathrm{T}}) = \frac{\alpha_{\mathrm{S}}}{2\pi}\left[\frac{1}{2}A_{1,\mathrm{f}}\log^2\frac{m^2_{\mathrm{F}}}{q^2_{\mathrm{T}}} + B_{1,\mathrm{f}}\log\frac{m^2_{\mathrm{F}}}{q^2_{\mathrm{T}}}\right]$
- $\mu_F = q_{\mathrm{T}}$

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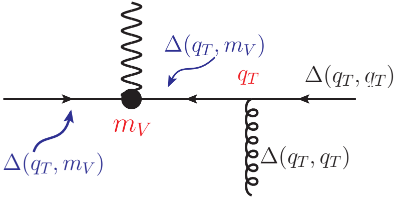

☞ Sudakov FF included on F+j Born kinematics

- MiNLO-improved FJ yields finite results also when 1st jet is unresolved ($q_{\mathrm{T}} \to 0$)
- $\bar{B}^{(\mathrm{FJ})}_{\mathrm{MiNLO}}$ allows to extend the validity of FJ−POWHEG [called "FJ−MiNLO" hereafter]

MiNLO′

- formal accuracy of FJ-MiNLO for inclusive observables carefully investigated.

[Hamilton et al. 1212.4504]

- possible to improve FJ-MiNLO such that inclusive NLO is recovered (NLO$^{(\mathrm{F})}$), without spoiling NLO accuracy of F+j (NLO$^{(\mathrm{FJ})}$):

MiNLO′ : NLO+PS merging, without merging scale

- accurate control of subleading small-p_{T} logarithms is needed:
  - include B_2 (NNLL) coefficient in MiNLO-Sudakov.
  - set scales in R, V and subtraction terms equal to q_{T}.
  - without the above requirements, spurious $\alpha_{\mathrm{S}}^{3/2}$ terms show up in $\sigma_{\mathrm{NLO}}^{(\mathrm{F})}$ upon integration over q_{T}.

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- for color-singlet production F, the above procedure is general, and (almost) process independent.

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

. a generalization of the MiNLO′ approach for processes with jets at LO has also been proposed (but here we are not using it). [Frederix,Hamilton '15, see also Carrazza et al. '18]

`MiNLO'` : details

- the differential cross section for $F{+}X$ production can be written as

$$\frac{d\sigma}{dq_{\mathrm{T}}^2 d\Phi_{\mathrm{F}}} = \frac{d}{dq_{\mathrm{T}}^2}\left\{\mathcal{L}(\Phi_{\mathrm{F}}, q_{\mathrm{T}}) \exp(-\tilde{S}(q_{\mathrm{T}}))\right\} + R_f(q_{\mathrm{T}})$$

$$\mathcal{L}(\Phi_{\mathrm{F}}, q_{\mathrm{T}}) = B^{(\mathrm{F})}_{cc'}(\Phi_{\mathrm{F}})\left\{\left[C_{ci} \otimes f_i\right](q_{\mathrm{T}})\ H(q_{\mathrm{T}})\ \left[C_{c'j} \otimes f_j\right](q_{\mathrm{T}})\right\}$$

  - can be obtained from p_{T} resummation formalism(s)
  - $$R_f(p_{\mathrm{T}}) = \frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}} - \frac{\mathrm{d}\sigma^{\mathrm{sing}}}{\mathrm{d}\Phi_{\mathrm{F}}\mathrm{d}p_{\mathrm{T}}}$$
  - hard virtual corrections are evaluated at $\mu_R = q_{\mathrm{T}}$, while their scale should be $\mu_R \simeq m_{\mathrm{F}} \Rightarrow$ in $\tilde{S}(q_{\mathrm{T}})$, B_2 contains $H^{(1)} \equiv [V^{(\mathrm{F})}/B^{(\mathrm{F})}]$

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$$\mathcal{L}(\Phi_F, q_T) = B^{(F)}_{cc'}(\Phi_F)\Big\{\Big[C_{ci}\otimes f_i\Big](q_T)\; H(q_T)\; \Big[C_{c'j}\otimes f_j\Big](q_T)\Big\}$$

- with $C^{(1)}_{ij}$, $H^{(1)}$, and R_f at $\mathcal{O}(\alpha_S) \Rightarrow$ NLO$^{(F)}$ upon integration
- differentiate, then compare with MiNLO

$$\sim B^{(F)}\frac{1}{q_T^2}[\alpha_S, \boxed{\alpha_S^2}, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L]\exp(-\tilde{S}(q_T)) + R_f \qquad L = \log(Q^2/q_T^2)$$

- highlighted terms are needed to reach NLO$^{(F)}$:

$$\int^{Q^2}\frac{dq_T^2}{q_T^2}L^n\alpha_S^m(q_T)\exp(-\tilde{S}) \sim \left(\alpha_S(Q^2)\right)^{m-(n+1)/2}$$

(scaling in low-p_T region is $\alpha_S L^2 \sim 1$!)

- if B_2 not included in MiNLO Sudakov, a term $(1/q_T^2)\ \boxed{\alpha_S^2}\ B_2\exp(-\tilde{S})$ is missed
- upon integration, violate NLO$^{(F)}$ by a term of relative $\mathcal{O}(\alpha_S^{3/2})$

NNLO+PS for color-singlet production

- starting from a `MiNLO'` generator, it's possible to match a PS simulation to NNLO.
- `FJ-MiNLO'` (+`POWHEG`) generator gives F-FJ @ NLOPS:

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- 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; [✓]
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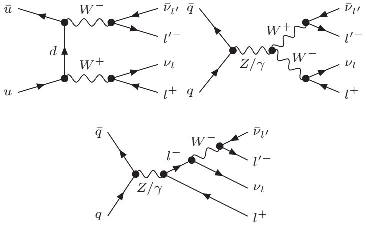
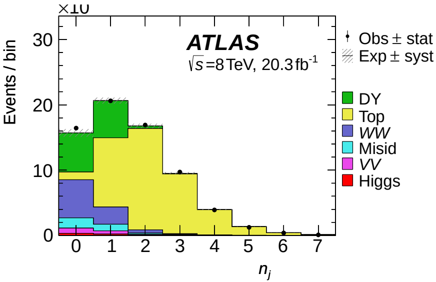
- possible to obtain $pp \to WW$ @ NNLOPS

vector boson pair production





- access to anomalous gauge couplings + background for several searches, for instance $H \to WW$.
- current experimental precision already demands for predictions that go beyond NLO(+PS) accuracy.
- NNLO corrections are certainly needed, and resummation too, in corners of phase-space.
- [WW here stands for the “different sign” channel ($\ell \neq \ell'$)]

MiNLO′ : from Drell-Yan to WW

A MiNLO′ generator that merges WW and WW + 1 jet at NLO+PS was obtained a while ago

[Hamilton,Melia,Monni,ER,Zanderighi '16]

- POWHEG WWJ generator obtained ex-novo using interfaces to Madgraph and Gosam 2.0

  [Campbell et al. 1202.547; Luisoni et al. 1306.2542; Cullen et al. 1404.7096]

- starting from the Drell-Yan case, we extracted the $B_2^{\text{(WW)}}$ term from the virtual ($V^{\text{(WW)}}$) and Born ($B^{\text{(WW)}}$) contributions of $pp \to WW$.

  - for Drell-Yan, $V^{\text{(V)}}$ and $B^{\text{(V)}}$ are proportional, hence $B_2^{\text{(V)}}$ is just a number.
  - in $pp \to WW$, this is no longer true: $B_2^{\text{(WW)}} = B_2^{\text{(WW)}}(\Phi_{WW})$:
    - for $q\bar{q}$-initiated color singlet production, B_2 has the form

$$B_2 = -2\gamma^{(2)} + \beta_0 C_F \zeta_2 + 2(2C_F)^2\zeta_3 + \boxed{2\pi\beta_0 H^{(1)}(\Phi)}$$

- $H_1(\Phi)$ (process-dependent part of B_2) extracted on an event-by-event basis:
  - projection of Φ_{WWJ} onto Φ_{WW} $\Rightarrow$ used FKS ISR mapping (smooth collinear limit).

WW at NNLO from MATRIX

- q_T*-subtraction* formalism, in a nutshell [Catani,Grazzini '07]

$$d\sigma^{\rm F}_{\rm (N)NLO} = \mathcal{H}^{\rm F}_{\rm (N)NLO} \otimes d\sigma^{\rm F}_{\rm LO} + \left[d\sigma^{\rm F+jet}_{\rm (N)LO} - d\sigma^{\rm CT}_{\rm (N)NLO} \right]$$

  - subtraction term known from resummation, and process independent (apart from LO dependence).
  - hard-collinear function: can be extracted from 2-loops amplitudes.
  - extensively used for color-singlet production at NNLO, and recently also for $t\bar{t}$

- as shown above, for NNLOPS, one needs

$$\left(\frac{d\sigma}{d\Phi_{\rm F}} \right)_{\rm NNLO} \leftarrow \text{fully differential in the Born phase space}$$

- we used MATRIX: [Grazzini,Kallweit,Wiesemann'17]

  2-loops amplitudes from VVAMP [Gehrmann et al. '15]
  tree-level and 1-loop from OPENLOOPS [Cascioli et al. '11]
  see also: [Grazzini,Kallweit,Pozzorini,Rathlev,Wiesemann '16]

- worked in 4F scheme; gg loop-induced channel NOT included
  - it's about 30% of the NNLO correction.

WW at NNLO+PS, in practice

- $pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu$: Φ_B is 9-dimensional [impossible]
- choose variables, drop dependence upon (ℓ, ν_ℓ) invariant masses (fairly flat)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B} = \frac{\mathrm{d}^9\sigma}{\mathrm{d}p_{T,W^-}\,\mathrm{d}y_{WW}\,\mathrm{d}\Delta y_{W^+W^-}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^+}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^+}\,\mathrm{d}\cos\theta^{\mathrm{CS}}_{W^-}\,\mathrm{d}\phi^{\mathrm{CS}}_{W^-}\,\cancel{\mathrm{d}m_{W^+}}\,\cancel{\mathrm{d}m_{W^-}}}$$

- use "Collins-Soper" angles for both W decays

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_B} = \frac{9}{256\pi^2}\sum_{i=0}^{8}\sum_{j=0}^{8} AB_{ij}\, f_i(\theta^{\mathrm{CS}}_{W^-}, \phi^{\mathrm{CS}}_{W^-})\, f_j(\theta^{\mathrm{CS}}_{W^+}, \phi^{\mathrm{CS}}_{W^+})$$

$$AB_{ij} = AB_{ij}(p_{T,W^-}, y_{WW}, \Delta y_{W^+W^-})$$

- final complexity: 81 triple-differential distributions at NNLO [doable]

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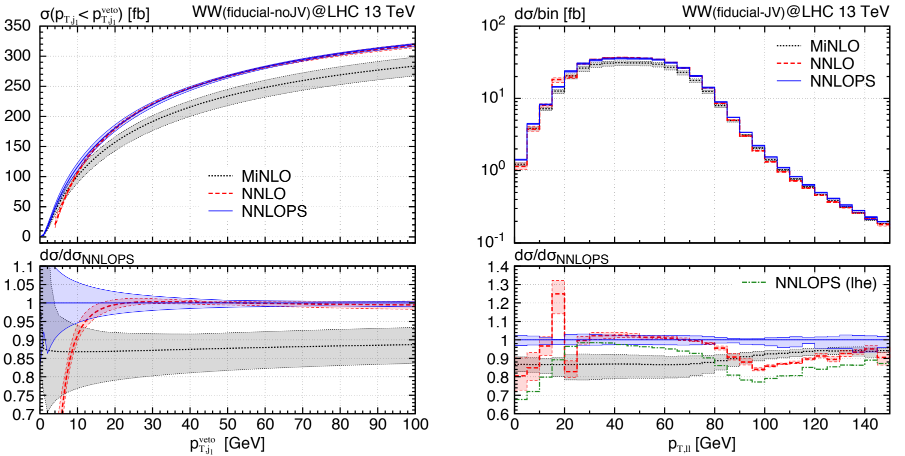
- final complexity: 81 triple-differential distributions at NNLO [doable]
- [yes...doable, but very intensive and CPU demanding]

WW at NNLO+PS: results

[ER,Wiesemann,Zanderighi, ’18]

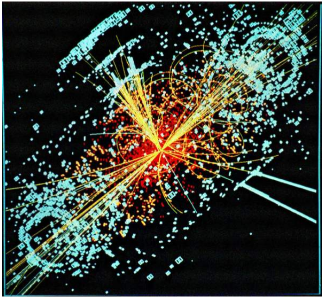
PS, no hadronization, no MPI



- left: fiducial cuts almost identical to ATLAS analysis [1702.04519], where jet-veto at 25/30 GeV.
- right: perturbative instability, due to $p_{\mathrm{T,miss}} > 20$ GeV. Dip at 100 GeV, due to recoil effects from multiple emissions, resulting in migration of events. Larger impact close to point of inflection.

Plan of the talk

1. quickly review how MC event generators work
2. discuss how to match them to NLO and NNLO computations
   - NNLOPS for $pp \to WW$ (with reweighting)
3. MiNNLO$_{\mathrm{PS}}$: NNLOPS without reweighting



MiNNLO$_{PS}$

- Albeit formally correct, the reweighting described above is a bottleneck
  - 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 that allows to achieve 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

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

MiNNLO$_{\rm PS}$

- manipulate the differential cross section for F+X production to recover the `MiNLO′` formula

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

  - keep the full $\mathcal{L}(\Phi_{\mathrm{F}}, p_{\mathrm{T}})$, with all the terms needed to obtain NNLO$^{(\mathrm{F})}$ accuracy, i.e. $H^{(1)}$, $H^{(2)}$, $C^{(1)}$, $C^{(2)}$ (and $[G^{(1)}\otimes f][G^{(1)}\otimes f]$ for $gg \to H$)

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

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

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

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

- expand the above integrand in power of $\alpha_{\mathrm{S}}(p_{\mathrm{T}})$, keep only the terms that are needed to get NLO$^{(\mathrm{F})}$ and, then, NNLO$^{(\mathrm{F})}$ accuracy, upon integration over p_{T}

MiNNLO$_{\mathrm{PS}}$

- manipulate the differential cross section for $F{+}X$ production to recover the `MiNLO′` formula

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

  - keep the full $\mathcal{L}(\Phi_\mathrm{F}, p_\mathrm{T})$, with all the terms needed to obtain NNLO$^{(\mathrm{F})}$ accuracy, i.e. $H^{(1)}$, $H^{(2)}$, $C^{(1)}$, $C^{(2)}$ (and $[G^{(1)}\otimes f][G^{(1)}\otimes f]$ for $gg \to H$)

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

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

- expand the above integrand in power of $\alpha_\mathrm{S}(p_\mathrm{T})$, keep only the terms that are needed to get NLO$^{(\mathrm{F})}$ and, then, NNLO$^{(\mathrm{F})}$ accuracy, upon integration 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 $n = 0, 1$.

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

MiNNLO$_{\rm PS}$

$$\frac{d\sigma}{d\Phi_F dp_T} = \exp[-\tilde{S}(p_T)]\left\{ \frac{\alpha_S(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)}\left(1+\frac{\alpha_S(p_T)}{2\pi}[\tilde{S}(p_T)]^{(1)}\right) + \left(\frac{\alpha_S(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)} + \left(\frac{\alpha_S(p_T)}{2\pi}\right)^3 [D(p_T)]^{(3)} + \text{regular terms}\right\}$$

- as expected, for NLO$^{(F)}$ accuracy, we recovered `MiNLO'`, exactly
- $[D(p_T)]^{(3)}$ is the $\alpha_S^3(p_T)$ expansion of $D(p_T) = -\frac{d\tilde{S}(p_T)}{dp_T}\mathcal{L}(p_T) + \frac{d\mathcal{L}(p_T)}{dp_T}$
- "regular terms": $[R_f(p_T)/\exp[-\tilde{S}(p_T)]]^{(3)}$.
  - no $1/p_T$ factor, hence upon integration they are of order $\mathcal{O}(\alpha_S^3)$.

MiNNLO$_{\rm PS}$

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- as expected, for NLO$^{(F)}$ accuracy, we recovered `MiNLO'`, exactly
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- "regular terms": $[R_f(p_T)/\exp[-\tilde{S}(p_T)]^{(3)}$.
  - no $1/p_T$ factor, hence upon integration they are of order $\mathcal{O}(\alpha_S^3)$.
- $[D(p_T)]^{(3)}$ contains many terms, but symbolically is rather compact:

$$[D(p_T)]^{(3)} = -\left[\frac{d\tilde{S}(p_T)}{dp_T}\right]^{(1)}[\mathcal{L}(p_T)]^{(2)} - \left[\frac{d\tilde{S}(p_T)}{dp_T}\right]^{(2)}[\mathcal{L}(p_T)]^{(1)} - \left[\frac{d\tilde{S}(p_T)}{dp_T}\right]^{(3)}[\mathcal{L}(p_T)]^{(0)} + \left[\frac{d\mathcal{L}(p_T)}{dp_T}\right]^{(3)}$$

$$= \frac{2}{p_T}\left(A^{(1)}\ln\frac{Q^2}{p_T^2}+B^{(1)}\right)[\mathcal{L}(p_T)]^{(2)} + \frac{2}{p_T}\left(A^{(2)}\ln\frac{Q^2}{p_T^2}+\tilde{B}^{(2)}\right)[\mathcal{L}(p_T)]^{(1)} + \frac{2}{p_T}\left(A^{(3)}\ln\frac{Q^2}{p_T^2}\right)[\mathcal{L}(p_T)]^{(0)} + \left[\frac{d\mathcal{L}(p_T)}{dp_T}\right]^{(3)}$$

$$\mathcal{L}(\Phi_F, p_T) = B^{(F)}_{cc'}(\Phi_F)\left\{\left[C_{ci}\otimes f_i\right](p_T)\, H(p_T)\, \left[C_{c'j}\otimes f_j\right](p_T) + \left[G_{ci}\otimes f_i\right](p_T)\, H(p_T)\, \left[G_{c'j}\otimes f_j\right](p_T)\right\}$$

[used `HOPPET` and `hplog`]

MiNNLO$_{\mathrm{PS}}$: implementation I

$$\frac{d\sigma}{d\Phi_F dp_T} = \exp[-\tilde{S}(p_T)]\left\{ \frac{\alpha_S(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(1)}\left(1+\frac{\alpha_S(p_T)}{2\pi}[\tilde{S}(p_T)]^{(1)}\right) + \left(\frac{\alpha_S(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_F dp_T}\right]^{(2)} + \left(\frac{\alpha_S(p_T)}{2\pi}\right)^3[D(p_T)]^{(3)} \right\}$$

- $[D(p_T)]^{(3)}$: extracted from $p_T \to 0$ limit, depends on (Φ_F, p_T), not on Φ_{FJ}
  - to reach NNLO accuracy, singular region must be treated exactly
- in practice, we need to integrate over $\Phi_{FJ} \Rightarrow$ mapping to evaluate $[D(p_T)]^{(3)}$:
  a) $\Phi_{FJ} \to \Phi_F$ smoothly when $p_T \to 0$ [FKS ISR mapping (preserves rapidity of F)]
  b) recover the above equation, when integrating over Φ_{FJ} at fixed (Φ_F, p_T)

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$$F^{\rm corr}(\Phi_{FJ}) = \frac{J(\Phi_{FJ})}{\int d\Phi'_{FJ} J(\Phi'_{FJ})\delta(p_T - p'_T)\delta(\Phi_F - \Phi'_F)}$$

$$\int d\Phi'_{FJ} G(\Phi'_F, p'_T) F^{\rm corr}(\Phi'_{FJ}) = \int d\Phi_F\, dp_T G(\Phi_F, p_T)$$

- to avoid spurious effects at large y_j: use rapidity of radiation
  . full matrix element: $J(\Phi_{FJ}) = |M^{FJ}(\Phi_{FJ})|^2 (f^{[a]} f^{[b]})$
  . compromise: $J(\Phi_{FJ}) = P(\Phi_{\rm rad})(f^{[a]} f^{[b]})$

MiNNLO$_{\rm PS}$: implementation II

Final master formula:

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

MiNNLO$_{\text{PS}}$: implementation II

Final master formula:

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

- large p_{T} region: freedom to switch off logarithms in Sudakov, $[\tilde{S}(p_{\text{T}})]^{(1)}$ and $[D(p_{\text{T}})]^{(3)}$
  - original `MiNLO'`: Θ function
  - this work: . modified logs in Sudakov, $[\tilde{S}(p_{\text{T}})]^{(1)}$ and $[D(p_{\text{T}})]^{(3)}$

$$\ln\frac{Q}{p_{\text{T}}} \to \frac{1}{p}\ln\left(1+\left(\frac{Q}{p_{\text{T}}}\right)^p\right)$$

. Jacobian in front of $[D(p_{\text{T}})]^{(3)}$

MiNNLO$_{\text{PS}}$: implementation II

Final master formula:

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

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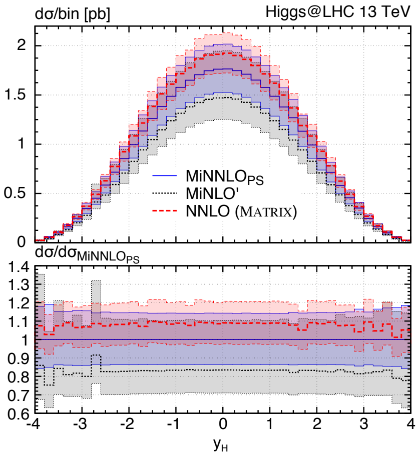
    . Jacobian in front of $[D(p_{\text{T}})]^{(3)}$

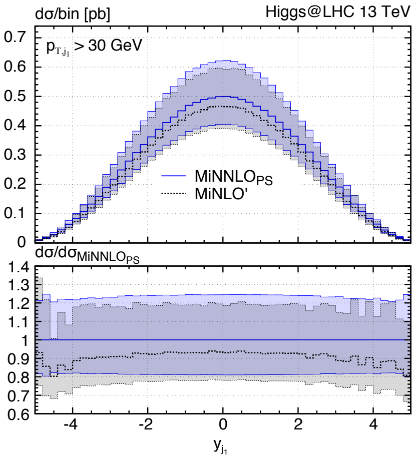
- lot of effort to obtain scale variation
  - particularly delicate: $\mu_{R/F} = K_{R/F}\,p_{\text{T}}$, and we must integrate down to $p_{\text{T}} \to 0$.
  - included also in Sudakov FF

MiNNLO$_{PS}$: ggH

[Monni,Nason,ER,Wiesemann,Zanderighi '19]

PS, no hadronization, no MPI





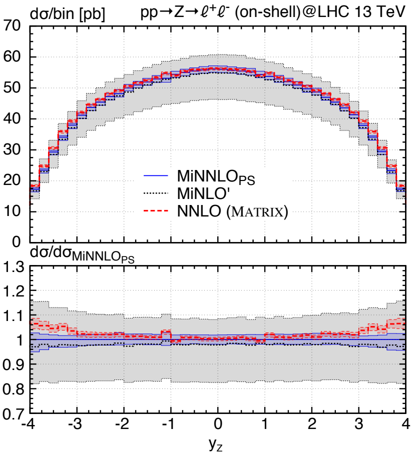
- $\sigma_{\text{MiNNLOPS}}/\sigma_{\text{NNLO}} = 0.92$
- larger scale uncertainty:
  . scale dependence in Sudakov FF
- flat ratios for y_H

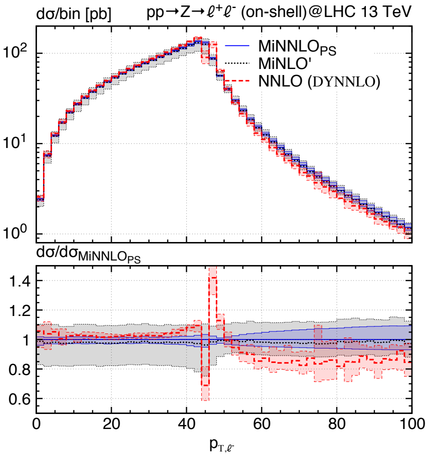
- $p_{\text{T,j}} > 30$ GeV, $R = 0.4$, anti-k_{T}
- $[D(p_{\text{T}})]^{(3)} \leftrightarrow \Phi_{\text{FJ}}$

MiNNLO$_{PS}$: Drell-Yan

[Monni,Nason,ER,Wiesemann,Zanderighi ’19]

PS, no hadronization, no MPI





- $\sigma_{\text{MiNNLOPS}}/\sigma_{\text{NNLO}} = 0.98$
- visible pattern for $|y_Z| > 3$

- expected pattern for $p_{T,\ell}$

MiNNLO$_{PS}$: Drell-Yan

[Monni,Nason,ER,Wiesemann,Zanderighi '19]

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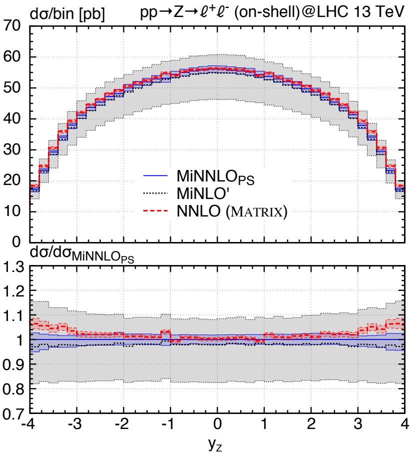

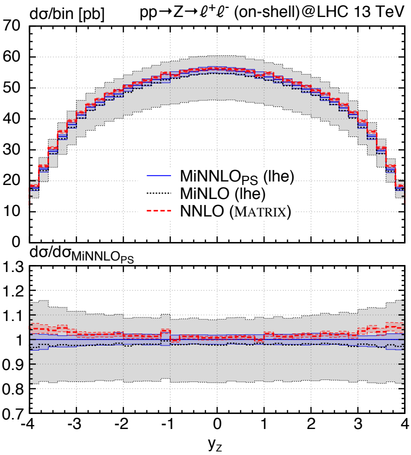

- $\sigma_{\text{MiNNLOPS}}/\sigma_{\text{NNLO}} = 0.98$
- visible pattern for $|y_Z| > 3$

- better agreement with NNLO before parton shower
- shower recoil scheme has an impact
- suppression of radiation collinear to the beam

MiNNLO$_{\text{PS}}$: summary

[Monni,Nason,ER,Wiesemann,Zanderighi '19]

- no reweighting
- better analytical understanding
- efficient event generation (factor 2 slower than `MiNLO'`)
- no unphysical merging scale
- leading-log accuracy of (p_{T}-ordered) PS preserved

- features observed at large y_Z currently under study
- PDFs have a cutoff, whereas we would like to go below it with μ_F

conclusions

- Monte Carlo tools play a major role for LHC searches
- especially if no “smoking gun” new-Physics around the corner, precision will be the key to maximise the impact of LHC results
- many improvements over the last few years

- NLO+PS tools are now well established.
- NNLO+PS is doable, at least for color-singlet production.
- presented new method [MiNNLO$_{PS}$], obtained through a connection with p_{T}-resummation:
  - NNLO+PS much more efficiently for color singlet final states

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Thank you for your attention!

Extra slides

POWHEG

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

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

- inclusive observables: @NLO
- first hard emission: full tree level ME
- (N)LL resummation of collinear/soft logs
- extra jets in the shower approximation

} "NLOPS"

POWHEG

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

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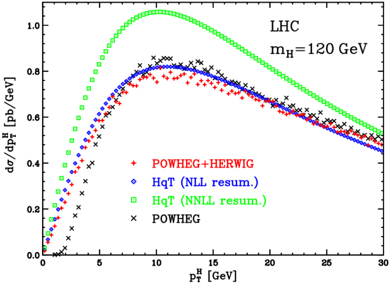
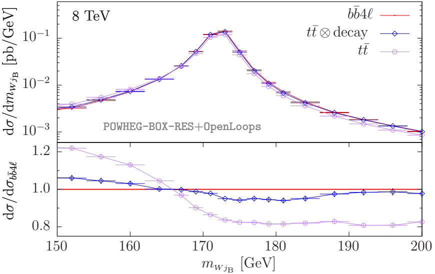
} "NLOPS"

[Alioli,Nason,Oleari,ER '08]



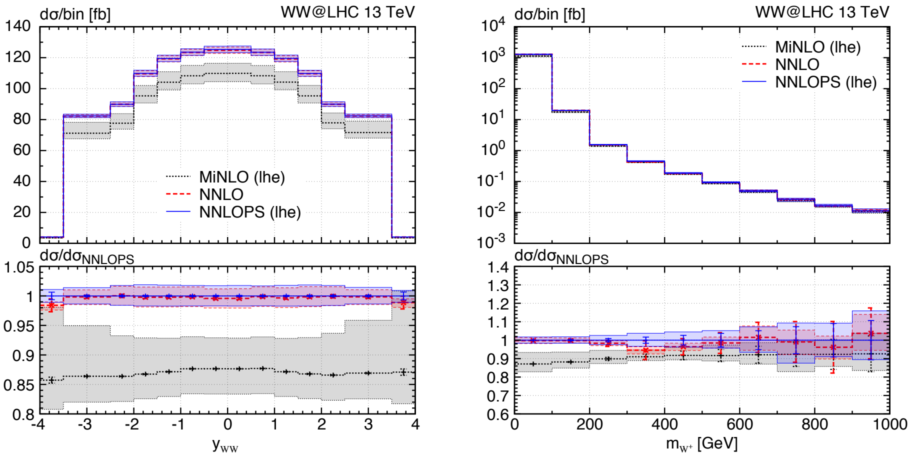
[Jezo,Lindert,Nason,Oleari,Pozzorini '16]



WW at NNLO+PS: validation

[ER,Wiesemann,Zanderighi, '18]

PS, no hadronization, no MPI



- ► y_{WW} distribution as expected. Validated also other "Born" observables, as well as angular dependence (Collins-Soper angles) [not shown].
- ► m_W distribution well reproduced also off from peak.