Event generators for the LHC: status and perspectives

Emanuele Re

CERN & LAPTh Annecy

LAL Orsay, 22 November 2016
LHC Run I & II, so far

Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1,2 \( \sqrt{s} = 7, 8, 13 \text{ TeV} \)

Status: August 2016

Theory

LHC pp \( \sqrt{s} = 7 \text{ TeV} \)
- Data 4.5 – 4.9 fb\(^{-1}\)

LHC pp \( \sqrt{s} = 8 \text{ TeV} \)
- Data 20.3 fb\(^{-1}\)

LHC pp \( \sqrt{s} = 13 \text{ TeV} \)
- Data 0.08 – 14.8 fb\(^{-1}\)
but LHC is a discovery machine
LHC Run I & II

- so far no sign of new Physics at the TeV scale from direct searches
- Higgs couplings have started to be measured: SM-like values, within 20-30 %
- BSM hints might eventually be found in:
LHC Run I & II

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  - detection of small deviations from SM backgrounds
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  - accurate measurement of Higgs couplings
  - extraction of SM parameters
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\[ \begin{align*}
\text{Higgs} & \quad \text{SM} \\
\text{SM} & \quad \text{SM}
\end{align*} \]

important also in presence of new discovery
LHC Run I & II

- so far no sign of new Physics at the TeV scale from direct searches
- Higgs couplings have started to be measured: SM-like values, within 20-30%
- BSM hints might eventually be found in:

  . require accurate understanding of signals and backgrounds:
    “precision Physics”
  . accurate measurement of Higgs couplings
  . extraction of SM parameters
precise predictions and MC: an example

measuring the $HWW$ coupling

- higher-order corrections:
  - relevant when they are large or if experimental precision is extremely high.
  - relevant also to have reliable theoretical uncertainties.
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- S/B optimized using cuts/BDT
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⇒ NLO+PS event generators include both effects and allow for flexible and fully differential simulations.
Event generators: what they are?

ideal world: high-energy collision and detection of elementary particles
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real world:

- collide non-elementary particles
- we detect $e, \mu, \gamma$, hadrons, “missing energy”

- we want to predict final state
  - realistically
  - precisely
  - from first principles

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⇒ full event simulation needed to:
  - compare theory and data
  - estimate how backgrounds affect signal region
  - test/build analysis techniques

soner or later, at some point a MC is used...
ideal world: high-energy collision and detection of elementary particles
real world:

- hard scattering
  \[ \Lambda_{QCD} \ll \mu \approx Q \]
  - perturbation theory

- parton shower
  \[ \Lambda_{QCD} < \mu < Q \]
  - hierarchy of scales
  - resummation of large logarithms

- hadronisation
  \[ \mu \approx \Lambda_{QCD} \]
  - non-perturbative model, tuned on \( e^+e^- \) data

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<td></td>
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<th>$\Lambda_{QCD} &lt; \mu &lt; Q$</th>
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</table>
Event generators: what’s the output?

- In practice: momenta of all outgoing leptons and hadrons:

<table>
<thead>
<tr>
<th>IHEP</th>
<th>ID</th>
<th>IDPDG</th>
<th>IST</th>
<th>MO1</th>
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<td>109</td>
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<td>1</td>
<td>111</td>
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</table>
Plan of the talk

1. quickly review how these tools work
2. discuss how their accuracy can be improved
3. show “NNLO matched to parton showers” results (NNLOPS)
parton showers and fixed order
- connect the hard scattering ($\mu \approx Q$) with the final state hadrons ($\mu \approx \Lambda_{QCD}$)
- need to simulate production of many quarks and gluons
Parton showers I

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\[ |M_{n+1}|^2 d\Phi_{n+1} \rightarrow |M_n|^2 d\Phi_n \alpha_S \frac{\pi}{2} dt P_{q,qg}(z) dz d\phi \]

\[ z = \frac{k_0}{k_0 + l_0} \]

\[ t = \{ \left( k_0 + l_0 \right)^2, l_0 T, E_2, \theta_2 \} \]

\[ P_{q,qg}(z) = C_F \left( \frac{1 + z^2}{1 - z^2} \right) A_P \text{ splitting function} \]

\[ \alpha_S \frac{\pi}{2} \]
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(p_1 + p_2)^2 = \frac{1}{2} E_1 E_2 (1 - \cos \theta)
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|M_{n+1}|^2 d\Phi_{n+1} \rightarrow |M_n|^2 d\Phi_n \alpha_s^2 \pi dt P_{q,qg}(z) dz d\phi
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\[
t = \begin{cases} 
(k + l)^2, l^2 T, E^2 \theta^2 
\end{cases}
\]

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[notice: \(\alpha_s L^2 \frac{8}{32}\)]
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3. soft-collinear emissions are enhanced:
   \[
   \frac{1}{(p_1 + p_2)^2} = \frac{1}{2E_1E_2(1 - \cos \theta)}
   \]
4. in soft-collinear limit, factorization properties of QCD amplitudes

\[
|M_{n+1}|^2 d\Phi_{n+1} \rightarrow |M_n|^2 d\Phi_n \quad \frac{\alpha_s}{2\pi} \frac{dt}{t} P_{q,qg}(z) dz \frac{d\varphi}{2\pi}
\]

\[
z = k^0 / (k^0 + l^0)
\]

\[
t = \{ (k + l)^2, l_T^2, E^2 \theta^2 \}
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\[
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quark energy fraction
splitting hardness

AP splitting function
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probabilistic interpretation!

[notice: \(\alpha_S L^2\)]
5. dominant contributions for multiparticle production due to strongly ordered emissions

\[ t_1 > t_2 > t_3 \ldots \]

6. at any given order, we also have virtual corrections: include them with the same approximation

- LL virtual contributions: Sudakov form factor for each internal line:

\[
\Delta_a(t_i, t_{i+1}) = \exp \left[ - \sum_{(bc)} \int_{t_{i+1}}^{t_i} \frac{dt'}{t'} \int \frac{\alpha_s(t')}{2\pi} P_{a,bc}(z) \, dz \right]
\]

- \( \Delta_a \) corresponds to the probability of having no resolved emission between \( t_i \) and \( t_{i+1} \) off a line of flavour \( a \)

\[ \text{resummation of collinear logarithms} \]

[very soft/collinear emissions are suppressed - all order effect!]
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[very soft/collinear emissions are suppressed - all order effect!]

- PS formulated probabilistically:
  - shapes change, but overall normalization fixed: it stays LO (unitarity)
  - they are only LO+LL accurate (whereas we want (N)NLO QCD corrections)
$\alpha_S \sim 0.1 \Rightarrow$ to improve the accuracy, use exact perturbative expansion

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

LO: Leading Order
NLO: Next-to-Leading Order

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**LO:** Leading Order

**NLO:** Next-to-Leading Order

\[
d\sigma = d\Phi_n \left\{ B(\Phi_n) \right\}_{\text{LO}} + \frac{\alpha_s}{2\pi} \left[ V(\Phi_n) + R(\Phi_{n+1}) d\Phi_r \right]_{\text{NLO}} \right\}
\]
Next-to-Leading Order

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Why NLO is important?

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

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NLO: Next-to-Leading Order

When NNLO is needed?

- NLO corrections large
- very high-precision needed

⇒ Drell-Yan, Higgs, \( t \bar{t} \) production

---

DESIGN

\( W^- + 3 \text{ jets} + X \)
\( \sqrt{s} = 14 \text{ TeV} \)
\( \mu_R = 2 \, M_W = 160.838 \text{ GeV} \)

\( k^- > 30 \text{ GeV}, \, |\eta| < 3 \)
\( k^- > 20 \text{ GeV}, \, |\eta| < 2.5 \)
\( k^- > 30 \text{ GeV}, \, M_W > 20 \text{ GeV} \)
\( k^- > 100 \text{ GeV}, \, \mu_R = 0.4 \) [tically]

BlackHat+Sherpa

K-factor

\[
\begin{align*}
\text{K-factor} &= \mu / \mu_0 \\
\end{align*}
\]
Next-to-Leading Order

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<td>✗ limited multiplicity</td>
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<tr>
<td>✗ (fail when resummation needed)</td>
<td>✗ (fail when multiple hard jets)</td>
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Can we merge them and build an NLOPS generator?

**Problem:**
## PS vs. NLO

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Can we merge them and build an NLOPS generator?

**Problem:** overlapping regions!

![Diagram showing overlapping regions for NLO and parton showers]
PS vs. NLO

**NLO**
- ✔ precision
- ✔ nowadays this is the standard
- ✗ limited multiplicity
- ✗ (fail when resummation needed)

**Parton showers**
- ✔ realistic + flexible tools
- ✔ widely used by experimental coll’s
- ✗ limited precision (LO)
- ✗ (fail when multiple hard jets)

-can we merge them and build an NLOPS generator?

**Problem:** overlapping regions!
PS vs. NLO

NLO

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- nowadays this is the standard
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parton showers

- realistic + flexible tools
- widely used by experimental coll’s
- limited precision (LO)
- (fail when multiple hard jets)

Can we merge them and build an NLOPS generator?

Problem: overlapping regions!

- many proposals, 2 well-established methods available to solve this problem:
  - MC@NLO
  - POWHEG

[Frixione-Webber ’03, Nason ’04]
matching NLO and PS

- POWHEG (POsitive Weight Hardest Emission Generator)
\[ d\sigma_{\text{LOPS}} = d\Phi_n \cdot B(\Phi_n) \begin{cases} \Delta(t_{\text{max}}, t_0) + \Delta(t_{\text{max}}, t) \frac{\alpha_s}{2\pi} \left( \frac{1}{t} P(z) \right) d\Phi_r \end{cases} \]
\[ d\sigma_{\text{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{ \Delta(\Phi_n; \kappa_T^{\text{min}}) + \Delta(\Phi_n; \kappa_T) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\} \]
\[
B(\Phi_n) \Rightarrow \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi} \left[ V(\Phi_n) + \int R(\Phi_{n+1}) \, d\Phi_r \right] \\
\]

\[
d\sigma_{\text{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \left\{ \Delta(\Phi_n; k_T^{\text{min}}) + \Delta(\Phi_n; k_T) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\} 
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\[ \Delta(t_m, t) \Rightarrow \Delta(\Phi_n; k_T) = \exp \left\{ -\frac{\alpha_s}{2\pi} \int \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \theta(k'_T - k_T) \, d\Phi'_r \right\} \]
NLOPS: POWHEG II

\[ d\sigma_{\text{POW}} = d\Phi_n \, \bar{B}(\Phi_n) \left\{ \Delta(\Phi_n; k_T^{\text{min}}) + \Delta(\Phi_n; k_T) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\} \]

[+ \text{ } p_T \text{-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

This is “NLOPS”
NLOPS: POWHEG II

\[ d\sigma_{\text{POW}} = d\Phi_n \bar{B}(\Phi_n) \left\{ \Delta(\Phi_n; k_T^{\text{min}}) + \Delta(\Phi_n; k_T) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \ d\Phi_r \right\} \]

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This is “NLOPS”

POWHEG BOX

- large library of SM processes, (largely) automated
- used by LHC collaborations and other theorists
  [ together with similar tools as \text{MG5.aMC@NLO, Herwig7 and Sherpa} ]
- lot achieved, but important developments still happening
  . for instance \text{full } W^+W^-b\bar{b} \text{ @ NLOPS available only since few months}
$d\sigma_{\text{POW}} = d\Phi_n \bar{B}(\Phi_n) \left\{ \Delta(\Phi_n; k_T^{\text{min}}) + \Delta(\Phi_n; k_T) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} d\Phi_r \right\}$

- inclusive observables: @NLO
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- (N)LL resummation of collinear/soft logs
- extra jets in the shower approximation
- large library of SM processes (largely) automated
- used by LHC collaborations and other theorists

[ Jezo et al '16 ]
NLO+PS merging and NNLO+PS
ME+PS merging is particularly important to model “S+jets” processes, where:

- $S$ = hard system = $\{\ell, \nu, V, t\}$
- jets are from QCD emissions (as opposed to jets from SUSY cascades)

it becomes crucial to model kinematics regions characterized by variable number of jets:

- cuts on $H_T = \ldots + \sum_{\text{all jets}} |\vec{p}_T,j|$ and/or tails of $p_T$ distributions

plot from [Gianotti,Mangano 0504221]

$t\bar{t}$+jets:Sherpa+OpenLoops [Hoeche,Krauss et al. 1402.6293]
ME+PS merging is particularly important to model “S+jets” processes, where:

- it becomes crucial to model kinematics regions characterized by variable number of jets:

rest of the talk: NLO+PS merging is at the core of all approaches aiming for NNLO+PS accuracy
NNLO+PS: why and where?

NLO(+PS) not always enough: NNLO needed when

1. large NLO/LO “K-factor”  
   [as in Higgs Physics]

2. very high precision needed  
   [e.g. Drell-Yan, top pairs]

- last couple of years:  
  huge progress in NNLO
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[Anastasiou et al., '03]
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Q: can we merge NNLO and PS?

[Anastasiou et al., '03]
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   ▶ last couple of years:
   huge progress in NNLO

Q: can we merge NNLO and PS?

- realistic event generation with state-of-the-art perturbative accuracy!
- important for precision studies for several processes

▶ method presented here: based on POWHEG+MiNLO, used so far for
  - Higgs production
  - neutral & charged Drell-Yan
  - associated WH production

[Anastasiou et al., ’03]

[Hamilton,Nason,ER,Zanderighi, 1309.0017]
[Karlberg,ER,Zanderighi, 1407.2940]
[Astill,Bizon,ER,Zanderighi, 1603.01620]
what do we need and what do we already have?

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towards NNLO+PS

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a merged H-HJ@NLOPS generator is “almost” OK
towards NNLO+PS

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A merged H-HJ@NLOPS generator is “almost” OK

- many of the multijet NLO+PS merging approaches work by combining 2 (or more) NLO+PS generators, introducing a merging scale (except Geneva)*

- **POWHEG + MiNLO** [Multiscale Improved NLO].
  
  **No need of merging scale**: it extends the validity of a NLO+PS computation with jets in the final state to phase-space regions where jets become unresolved

---

* [Hoeche,Krauss, et al.,1207.5030] [Frederix,Frixione,1209.6215] [Lonnblad,Prestel,1211.7278] [Platzer,1211.5467] [Alioli,Bauer, et al.,1211.7049] ...
**POWHEG → MiNLO → NNLO+PS**

Higgs at NNLO:

- **(a)** 1 and 2 jets: POWHEG H+1j
- **(b)** integrate down to $q_T = 0$ with MiNLO
- **(c)** 2 loops missing: from exact fixed-order NNLO

\[
\frac{d\sigma(y)}{dy}_{\text{NNLO}} = \frac{d\sigma(y)}{dy}_{\text{MINLO}} - \text{improved MiNLO}
\]
Higgs at NNLO:

(a) 1 and 2 jets: POWHEG H+1j
Higgs at NNLO:

(b) - integrate down to $q_T = 0$ with MiNLO
   - “Improved MiNLO” allows to build a H-HJ @ NLOPS generator

(a) 1 and 2 jets: POWHEG H+1j
Higgs at NNLO:

(c) 2 loops missing: from exact fixed-order NNLO

\[ W(y) = \frac{d\sigma(y)_{\text{NNLO}}}{d\sigma(y)_{\text{MiNLO}}} \]

(b) - integrate down to \( q_T = 0 \) with MiNLO
- “Improved MiNLO” allows to build a H-HJ @ NLOPS generator

(a) 1 and 2 jets: POWHEG H+1j
original goal: method to a-priori choose scales in multijet NLO computation

how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

\[
\bar{B}_{\text{MiNLO}} = \alpha_S^2 \left( m_h q_T \right) \alpha_S^2 \left( \frac{q_T}{m_h} \right) \Delta g(q_T, m_h) \left[ B(1 - 2\Delta_f(q_T, m_h)) + \alpha_S V(\bar{\mu}_R) + \alpha_S \int d\Phi r \right] .
\]

\[
\bar{\mu}_F = \left( \frac{m_h^2 q_T^2}{3} \log \Delta_f(q_T, m_h) \right) = \int m_h^2 q_T^2 dq_2 q_2 \alpha_S \left( q_2^2 \right)^2 \pi \left[ A_f \log m_h^2 q_T^2 + B_f \right] .
\]

\[
\Delta_f(q_T, m_h) = -\alpha_S^2 \pi \left[ \frac{1}{2} A_{1, f} \log 2 m_h^2 q_T^2 + B_{1, f} \right] .
\]
MiNLO (Multiscale Improved NLO)

- original goal: method to a-priori choose scales in multijet NLO computation
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

- for each point sampled, build the “more-likely” shower history that would have produced that kinematics (can be done by clustering kinematics with $k_T$-algo, then, by undoing the clustering, build “skeleton”)

- “correct” original NLO à la CKKW:
  \[ \alpha_S \text{ evaluated at nodal scales} \]
  \[ \text{Sudakov FFs} \]

\[
\bar{B}_{\text{MiNLO}} = \alpha^2 S(m_h) \alpha S(q^2) \Delta^2 g(q^2, m_h) \left[ B(1 - 2\Delta^2 g(q^2, m_h)) + \alpha S V(\bar{\mu}_R) + \alpha S \int d\Phi r R \right]
\]

\[
\bar{\mu}_R = \left( \frac{m^2}{m_h q^2} \right)^{1/3} \log \Delta f(q^2, m_h) = -\int m^2 q^2 dq^2 \alpha S \left[ A_f \log m^2 + B_f \right]
\]

\[
\Delta^2 f(q^2, m_h) = -\alpha S \pi \left[ \frac{1}{2} A_{1, f} \log m^2 + B_{1, f} \right]
\]

\[
\mu_F = q^2 S \text{Sudakov FF included on } H + j \text{ Born kinematics}
\]

- MiNLO-improved HJ yields finite results also when 1st jet is unresolved ($q^2 \rightarrow 0$)
- \( \bar{B}_{\text{MiNLO}} \) ideal to extend validity of HJ-POWHEG [called "HJ-MiNLO" hereafter]
MiNLO (Multiscale Improved NLO)

- original goal: method to \textit{a-priori} choose scales in multijet NLO computation
- how: correct weights of different NLO terms with CKKW-inspired approach \((\text{without spoiling formal NLO accuracy})\)

\[
\bar{B}_{\text{NLO}} = \alpha_S^3(\mu_R)\left[ B + \alpha_S V(\mu_R) + \alpha_S \int d\Phi R \right]
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\[
\bar{B}_{\text{MiNLO}} = \alpha_S^2(m_h) \alpha_S(q_T) \Delta^2_g(q_T, m_h) \left[ B \left( 1 - 2\Delta_{g}(1)(q_T, m_h) \right) + \alpha_S V(\bar{\mu}_R) + \alpha_S \int d\Phi R \right]
\]

- \( \bar{\mu}_R = (m_h^2 q_T)^{1/3} \)
- \( \log \Delta_f(q_T, m_h) = -\int_{q_T^2}^{m_h^2} \frac{dq^2}{q^2} \frac{\alpha_S(q^2)}{2\pi} \left[ A_f \log \frac{m_h^2}{q^2} + B_f \right] \)
- \( \Delta_f(1)(q_T, m_h) = -\frac{\alpha_S}{2\pi} \left[ \frac{1}{2} A_{1,f} \log^2 \frac{m_h^2}{q_T^2} + B_{1,f} \log \frac{m_h^2}{q_T^2} \right] \)
- \( \mu_F = q_T \)
MiNLO (Multiscale Improved NLO)

- original goal: method to a-priori choose scales in multijet NLO computation
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

\[
\tilde{B}_{\text{NLO}} = \alpha_s^3(\mu_R) \left[ B + \alpha_s V(\mu_R) + \alpha_s \int d\Phi_R R \right]
\]

\[
\tilde{B}_{\text{MiNLO}} = \alpha_s^2(m_h) \alpha_s(q_T) \Delta_g^2(q_T, m_h) \left[ B \left( 1 - 2\Delta_g^{(1)}(q_T, m_h) \right) + \alpha_s V(\bar{\mu}_R) + \alpha_s \int d\Phi_R R \right]
\]

- Sudakov FF included on \( H + j \) Born kinematics

- MiNLO-improved HJ yields finite results also when 1st jet is unresolved \( (q_T \to 0) \)
- \( \tilde{B}_{\text{MiNLO}} \) ideal to extend validity of HJ–POWHEG [called “HJ–MiNLO” hereafter]
“Improved” MiNLO & NLOPS merging

- untill this point: no claim about accuracy!

- formal accuracy of HJ-MiNLO for inclusive observables carefully investigated [Hamilton et al., 1212.4504]

- HJ-MiNLO describes inclusive observables at order $\alpha_S$ to reach genuine NLO when fully inclusive (NLO(0)), "spurious" terms must be of relative order $\alpha_S^2$, i.e. $O_{HJ-MiNLO} = O_{H@NLO} + O(\alpha_S^2 + 2)$ if $O$ is inclusive

- "Original MiNLO" contains ambiguous $O(\alpha_S^{2+1.5})$ terms

- Possible to improve HJ-MiNLO such that inclusive NLO is recovered (NLO(0)), without spoiling NLO accuracy of $H_j(NLO(1))$

- accurate control of subleading small-$p_T$ logarithms is needed (scaling in low-$p_T$ region is $\alpha_S L^2 \sim 1$, i.e. $L \sim 1/\sqrt{\alpha_S}$)

- Effectively as if we merged NLO(0) and NLO(1) samples, without merging different samples (no merging scale used: there is just one sample).
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- formal accuracy of HJ-MiNLO for inclusive observables carefully investigated
  - HJ-MiNLO describes inclusive observables at order $\alpha_S$
  - to reach genuine NLO when fully inclusive ($\text{NLO}^{(0)}$), “spurious” terms must be of relative order $\alpha_S^2$, i.e.
    \[
    O_{\text{HJ-MiNLO}} = O_{\text{H@NLO}} + O(\alpha_S^{2+2}) \quad \text{if } O \text{ is inclusive}
    \]
  - “Original MiNLO” contains ambiguous “$O(\alpha_S^{2+1.5})$” terms

[Hamilton et al., 1212.4504]
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$$O_{\text{HJ-MiNLO}} = O_{\text{H@NLO}} + O(\alpha_S^{2+2}) \quad \text{if } O \text{ is inclusive}$$

▶ “Original MiNLO” contains ambiguous “$O(\alpha_S^{2+1.5})$” terms

▶ Possible to improve HJ-MiNLO such that inclusive NLO is recovered ($\text{NLO}^{(0)}$), without spoiling NLO accuracy of $H+j$ ($\text{NLO}^{(1)}$).
▶ accurate control of subleading small-$p_T$ logarithms is needed (scaling in low-$p_T$ region is $\alpha_S L^2 \sim 1$, i.e. $L \sim 1/\sqrt{\alpha_S}$!)

Effectively as if we merged $\text{NLO}^{(0)}$ and $\text{NLO}^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).
“Improved” MiNLO & NLOPS merging: details

- Resummation formula can be written as

\[
\frac{d\sigma}{dq_T^2 dy} = \sigma_0 \frac{d}{dq_T^2} \left\{ [C_g a \otimes f_a](x_A, q_T) \times [C_g b \otimes f_b](x_B, q_T) \times \exp S(q_T, Q) \right\} + R_f
\]

\[
S(q_T, Q) = -2 \int_{q_T^2}^{Q^2} \frac{dq^2}{q^2} \frac{\alpha_S(q^2)}{2\pi} \left[ A_f \log \frac{Q^2}{q^2} + B_f \right]
\]

- If \( C_{ij}^{(1)} \) included and \( R_f \) is LO\(^{(1)} \), then upon integration we get NLO\(^{(0)} \)

- **MiNLO** formula is not written as a total derivative: “expand” the above expression, then compare with **MiNLO**:

\[
\sim \sigma_0 \frac{1}{q_T^2} \left[ \alpha_S, \alpha_S^2, \alpha_S^3, \alpha_S^4, \alpha_SL, \alpha_S^2L, \alpha_S^3L, \alpha_S^4L \right] \exp S(q_T, Q) + R_f \quad L = \log(Q^2/q_T^2)
\]

- **Highlighted terms** are needed to reach NLO\(^{(0)} \):

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

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

- if I don’t include \( B_2 \) in **MiNLO** \( \Delta g \), I miss a term \( (1/q_T^2) \left[ \alpha_S^2 \right] B_2 \exp S \)

- upon integration, violate NLO\(^{(0)} \) by a term of relative \( \mathcal{O}(\alpha_S^{3/2}) \)
**MiNLO merging: results**

- "H+Pythia": standalone **POWHEG** ($gg \to H$) + **PYTHIA** (PS level) [7pts band, $\mu = m_H$]
- "HJ+Pythia": **HJ-MiNLO*** + **PYTHIA** (PS level) [7pts band, $\mu$ from **MiNLO**]

- very good agreement (both value and band)

⚠️ Notice: band is $\sim 20 - 30\%$
**Higgs at NNLO+PS: details**

- **HJ-MiNLO+POWHEG generator gives H-HJ @ NLOPS**

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- reweighting (differential on $\Phi_B$) of “MiNLO-generated” events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\text{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\text{HJ-MiNLO}^*}}$$

- **by construction** NNLO accuracy on fully inclusive observables ($\sigma_{\text{tot}}, y_{H}; m_{\ell\ell},...$) [✓]
- to reach NNLOPS accuracy, need to be sure that the reweighting doesn’t spoil the NLO accuracy of HJ-MiNLO in 1-jet region [ ]
Higgs at NNLO+PS: details

- **HJ–MiNLO+POWHEG** generator gives H-HJ @ NLOPS

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- reweighting (differential on $\Phi_B$) of “MiNLO-generated” events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\text{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\text{HJ–MiNLO}^*}} = \frac{\alpha_S^2 c_0 + c_1 \alpha_S^3 + c_2 \alpha_S^4}{\alpha_S^2 c_0 + c_1 \alpha_S^3 + d_2 \alpha_S^4} \approx 1 + \frac{c_2 - d_2}{c_0} \alpha_S^2 + \mathcal{O}(\alpha_S^3)$$

- **by construction** NNLO accuracy on fully inclusive observables ($\sigma_{\text{tot}}, y_H; m_{\ell\ell}, \ldots$) [✓]
- to reach NNLOPS accuracy, need to be sure that the reweighting doesn’t spoil the NLO accuracy of HJ–MiNLO in 1-jet region [✓]
Higgs at NNLO+PS: details

- **HJ-MiNLO+POWHEG** generator gives H-HJ @ NLOPS

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- to reach NNLOPS accuracy, need to be sure that the reweighting doesn’t spoil the NLO accuracy of HJ-MiNLO in 1-jet region [✓]

- notice: formally works because no spurious $\mathcal{O}(\alpha_s^{2+1.5})$ terms in H-HJ @ NLOPS
Variants for reweighting \(W(y_H), W(\Phi_B)\) are also possible:

\[
W(y, p_T) = h(p_T) \frac{\int d\sigma_A^{\text{NNLO}} \delta(y - y(\Phi))}{\int d\sigma_A^{\text{MiNLO}} \delta(y - y(\Phi))} + (1 - h(p_T)) \\
\int d\sigma_A^{\text{MiNLO}} \delta(y - y(\Phi)) + (1 - h(p_T)) \\
d\sigma_A = d\sigma h(p_T), \quad d\sigma_B = d\sigma (1 - h(p_T)), \quad h = \frac{(\beta m_H)^2}{(\beta m_H)^2 + p_T^2}
\]

- freedom to distribute “NNLO/NLO K-factor” only over medium-small \(p_T\) region
  - \(h(p_T)\) controls where the NNLO/NLO K-factor is distributed
    (in the high-\(p_T\) region, there is no improvement in including it)
  - \(\beta\) cannot be too small, otherwise resummation spoiled:
    for Higgs, chosen \(\beta = 1/2\); for DY, \(\beta = 1\)

in practice, we used

\[
W(y, p_T) = h(p_T) \frac{\int d\sigma^{\text{NNLO}} \delta(y - y(\Phi)) - \int d\sigma_B^{\text{MiNLO}} \delta(y - y(\Phi))}{\int d\sigma_A^{\text{MiNLO}} \delta(y - y(\Phi))} + (1 - h(p_T)) \\
\]

- one gets exactly \((d\sigma/dy)_{\text{NNLOPS}} = (d\sigma/dy)_{\text{NNLO}}\) (no \(\alpha_S^5\) terms)
- chosen \(h(p_T^j)\)
To reweight, use $y_H$

- NNLO with $\mu = m_H/2$, HJ-MiNLO “core scale” $m_H$
- $(7_{Mi} \times 3_{NN})$ pts scale var. in NNLOPS, 7 pts in NNLO

![Graphs showing the ratio of $d\sigma/dy$ between NNLOPS and HNNLO with error bands.]

Notice: band is 10% (at NLO would be $\sim 20-30\%$)

[Until and including $O(\alpha_S^4)$, PS effects don’t affect $y_H$ (first 2 emissions controlled properly at $O(\alpha_S^4)$ by MiNLO+POWHEG)]
To reweight, use \((y_{\ell \ell}, m_{\ell \ell}, \cos \theta_{\ell})\).

- **not** the observables we are using to do the NNLO reweighting
  - **observe** exactly what we expect:
    - \(p_{T,\ell}\) has NNLO uncertainty if \(p_T < M_W/2\), NLO if \(p_T > M_W/2\)
    - smooth behaviour when close to Jacobian peak (also with small bins)
      (due to resummation of logs at small \(p_{T,V}\))
  - **just above peak**, \textsc{Dynnlo} uses \(\mu = M_W\), \textsc{Wj-Minlo} uses \(\mu = p_{T,W}\)
    - here \(0 \lesssim p_{T,W} \lesssim M_W\) (so resummation region does contribute)
**H@NNLOPS** (\(p_T^H\))

- **HqT**: NNLL+NNLO, \(\mu_R = \mu_F = m_H/2\) [7pts], \(Q_{\text{res}} \equiv m_H/2\) [HqT, Bozzi et al.]

  - uncertainty bands of HqT contain NNLOPS at low-/moderate \(p_T\)
  - very good agreement with HqT resummation at low \(p_T\) ["∼ expected", since \(Q_{\text{res}} \equiv m_H/2\), and \(\beta = 1/2\)]
  - HqT tail harder than NNLOPS tail
    - understood: \(\mu_{\text{HqT}} < "\mu_{\text{MiNLO}}"\)
Separation of $H \rightarrow WW$ from $t\bar{t}$ bkg: x-sec binned in $N_{jet}$

$0$-jet bin $\Leftrightarrow$ jet-veto accurate predictions needed!

\[ \varepsilon(p_{T,\text{veto}}) = \frac{\Sigma(p_{T,\text{veto}})}{\sigma^{\text{tot}}} = \frac{1}{\sigma^{\text{tot}}} \int d\sigma \theta(p_{T,\text{veto}} - p_{j1}^{T}) \]

- **JetVHeto**: NNLL resum, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\text{res}} \equiv m_H/2$, (a)-scheme only

  [JetVHeto, Banfi et al.]

- nice agreement, differences never more than 5-6 %
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- nice agreement, differences never more than 5-6 %
To reweight, use \((y_{HW}, \Delta y_{HW}, p_{t,H})\) + Collins-Soper angles

\[
\frac{d\sigma}{d\Phi_B} = \frac{d\sigma}{dy_{HW} d\Delta y_{HW} dp_{t,H} d\cos \theta^* d\phi^*}
\]

\[
= \frac{3}{16\pi} \left( \frac{d\sigma}{d\Phi_{HW^*}} (1 + \cos^2 \theta^*) + \sum_{i=0}^{7} A_i(\Phi_{HW^*}) f_i(\theta^*, \phi^*) \right)
\]

- left plot: angular dependence in slice of \(y_{HW}\)
- right plot: hardest-jet spectrum
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 impact of LHC results
- huge amount of improvements over the last few years

- **NLO+PS** tools are now well established and very mature
  - by now they are basically automated also for BSM processes

- major developments in last 3-4 years: **NLOPS multijet merging**
  - it might play a very important role in absence of smoking-gun BSM signal

- **NNLO+PS** is doable, at least for color-singlet production.
Outlook

What next?

- "proof of principle" results for NLOPS merging for higher multiplicity, using MiNLO
  - H+jj @ NLO, H+j @ NLO and H @ NNLO

[Frederix, Hamilton '15]

 NNLOPS for more complicated processes

understand and improve resummation property of (N)NLOPS tools.

electroweak corrections

phenomenology in experimental analyses

Thank you for your attention!
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