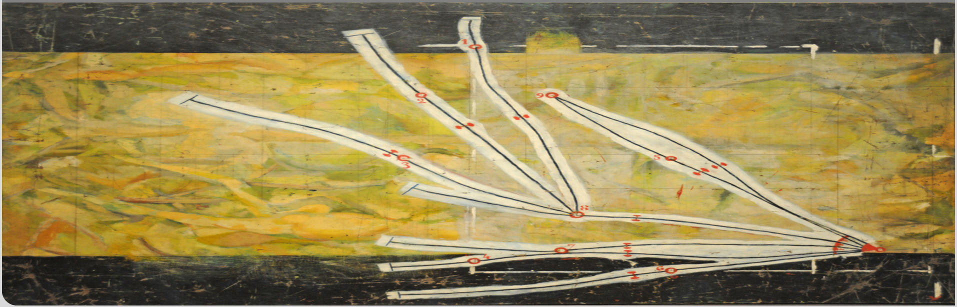
Herwig++@NLO

together with the Herwig++ collaboration

Johannes Bellm (ITP/KIT) | 27.5.2015

PARTON SHOWERS, EVENT GENERATORS AND RESUMMATION 2015, KRAKÓW



Outline

- Herwig++/Matchbox
  - Overview
  - Validation
  - Systematics
- LO-Merging
  - LO+PS
  - Unitarization
- NLO-Merging
  - α_s expansion
  - Comparison to MINLO
  - NLO+PS

Parton Shower
(Unitarity and Ordering)

$$PS[\sigma] = PS_0[B_0] = B_0 \Delta^{\mu}_{PS_0} + PS_1[B_0 P_1 \Delta^{q_1}_{PS_0}]$$

Matching

(Subtract and Add)

$$PS[\sigma_{Matched}] = PS[B_0] + PS[V_0 + B_1 - \alpha_s \frac{\partial}{\partial \alpha_s^{add}} PS[B_0]|_{\alpha_s^{add}=0}]$$

$$
\begin{aligned}
\sigma_{\text{NLO}} = \int_n d\sigma_{\text{LO}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}_{n,0}|^2 \end{pmatrix} \quad &+ \quad \int_n \left[d\sigma_{\text{V}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle, |\mathcal{M}_{n,1}\rangle \\ 2\text{Re}(\langle \mathcal{M}_{n,0} | \mathcal{M}_{n,1} \rangle) \end{pmatrix} + \int_1 d\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right] \\
&+ \quad \int_{n+1} \left[d\sigma_{\text{PS}} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\text{ME}}(p_\perp) \end{pmatrix} - d\sigma_{\text{A}} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right] \\
&+ \quad \int_{n+1} \left[d\sigma_{\text{R}} \begin{pmatrix} |\mathcal{M}_{n+1,0}\rangle \\ |\mathcal{M}_{n+1,0}|^2 \end{pmatrix} - d\sigma_{\text{PS}} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\text{ME}}(p_\perp) \end{pmatrix} \right]
\end{aligned}
$$

Matchbox infrastructure

based on [S. Plätzer & S. Gieseke – Eur.Phys.J. C72 (2012) 2187]

- Process generation and bookkeeping, integration.
- Automated Catani-Seymour dipole subtraction.
- Diagram-based mutli-channel phase space.
- CellGrid and Monaco (Vegas-like) Sampler.

Shower plugins

matching details & uncertainties [in preparation]

- Dipole shower $D(p_\perp)$.
- Angular ordered shower $P(\tilde{q})$.
- ME correction $R_{\text{ME}}(p_\perp)$.

$$\sigma_{\rm NLO} = \int_n \mathrm{d}\sigma_{\rm LO} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}_{n,0}|^2 \end{pmatrix} + \int_n \left[\mathrm{d}\sigma_{\rm V} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle, |\mathcal{M}_{n,1}\rangle \\ 2\mathrm{Re}(\langle \mathcal{M}_{n,0}|\mathcal{M}_{n,1}\rangle) \end{pmatrix} + \int_1 \mathrm{d}\sigma_{\rm A} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$

$$+ \int_{n+1} \left[\mathrm{d}\sigma_{\rm PS} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\rm ME}(p_\perp) \end{pmatrix} - \mathrm{d}\sigma_{\rm A} \begin{pmatrix} |\mathcal{M}_{n,0}\rangle \\ |\mathcal{M}^{ij}_{n,0}|^2 \end{pmatrix} \right]$$

$$+ \int_{n+1} \left[\mathrm{d}\sigma_{\rm R} \begin{pmatrix} |\mathcal{M}_{n+1,0}\rangle \\ |\mathcal{M}_{n+1,0}|^2 \end{pmatrix} - \mathrm{d}\sigma_{\rm PS} \begin{pmatrix} P(\tilde{q}), D(p_\perp) \\ R_{\rm ME}(p_\perp) \end{pmatrix} \right]$$

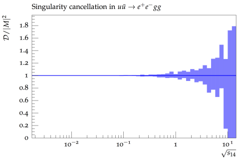
Interfaces at amplitude level

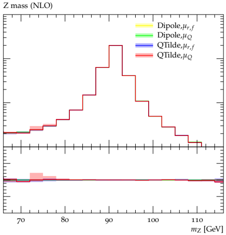
- Color bases provided, including interface to `ColorFull`. [M. Sjödahl, S. Plätzer]
- Spinor helicity library and caching facilities.
- MadGraph5 from 2.3.0 on.
  [MadGraph & JB, S. Gieseke, S. Plätzer, A. Wilcock]
- Some in-house calculations and parts of `HJets++`.
  [F. Campanario, T. Figy, S. Plätzer, M. Sjödahl]

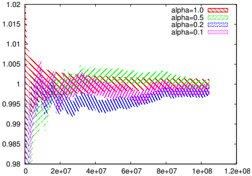
Interfaces at squared amplitude level

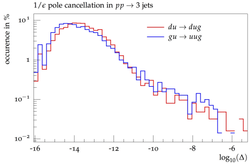
- Dedicated interfaces.
  [HEJ & S. Plätzer]
  [nlojet++ & J. Kotanski, J. Katzy, S. Plätzer]
- BLHA2. [arXiv:1308.3462]
  [GoSam & JB, S. Gieseke, S. Plätzer, C. Reuschle]
  [NJet & S. Plätzer]
  [OpenLoops & JB, S. Gieseke]
  [VBFNLO & K. Arnold, S. Gieseke, S. Plätzer]

Matching-Validation







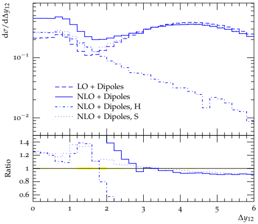


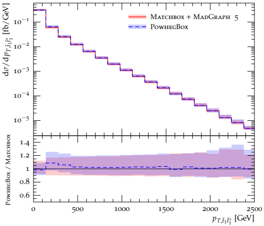
- Subtraction
- Pole-checks
- α-Parameter

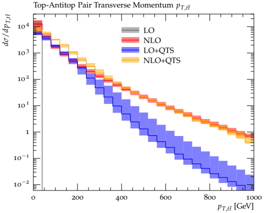
  Nagy [Phys Rev D.68.094002]

  (here: Dijet only virt & real)
- Shower Unitarity

Matching







Examples:

- EW Higgs+2jets Hjet++
- Powheg Box comparisons for stop-pair production.
  Plätzer, Richardson, Wilcock
- Top Pair production Plätzer, D. Rauch, Reuschle

LO-Merging

(Replace and Reweight)

$$PS[\sigma^{2LO}_{Merged}] = PS^V[B_0 \Delta^{\rho}_{PS_0}] + PS[B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta(q_1 > \rho)]$$

Merging fixed order ME with PS

$$PS[\sigma^{2LO}_{Merged}] = PS^V[B_0\Delta^{\rho}_{PS_0}] + PS[B_1\tilde{\Delta}^{q_1}_{PS_0}\theta(q_1 > \rho)]$$

B_1	replaced $P \cdot B_0$ to produce ME corrections.
$PS^V[\bullet]$	Vetoed Shower, rejecting all emissions above ρ.
ρ	Merging Scale, separates ME region from PS region.
$\Delta^{\rho}_{PS_0}$	Sudacov Factor, no emission probability.
$\tilde{\Delta}^{q}_{PS_0}$	Sudacov Factor, with weight for splitting: $\Delta^{q}_{PS} w_{\alpha_s} w_{pdf}$.
w_{α_s}&w_{pdf}	α_s & pdf ratio to produce shower scales.

Merging fixed order ME with PS

$$
\begin{aligned}
PS[\sigma^{3LO}_{Merged}] &= PS^V[B_0 \Delta^{\rho}_{PS_0}] \\
&+ PS^V[B_1 \tilde{\Delta}^{q_1}_{PS_0} \Delta^{\rho}_{PS_1} \theta(q_1 > \rho)] \\
&+ PS[B_2 \tilde{\Delta}^{q_2}_{PS_1} \tilde{\Delta}^{q_1}_{PS_0} \theta(q_1 > q_2 > \rho)]
\end{aligned}
$$

Parton shower ordering should be encoded in the choice of q_i.

CKKW(-L) [Catani et. al. ,JHEP 0111:063,2001][Lönnblad, JHEP 0205 (2002) 046]
MLM [Mangano et. al., JHEP 0701:013,2007]

Corrections vs. Unitarity

But:

$$B_1 \neq P \cdot B_0$$

So the cross section can change at $\mathcal{O}(\alpha_s)$.

Goal: Add NLO corrections!
$\rightarrow$ Need to repair the cross section at $\mathcal{O}(\alpha_s)$.

Solution: Subtract the same contributions we added by,

$$\Delta^{\rho}_{PS_n} \rightarrow 1 - \int dq_{n+1} \frac{B_{n+1}}{B_n} \tilde{\Delta}^{q_{n+1}}_{PS_n}$$

Prestel, Lönnblad [JHEP 1302 (2013) 094] and
Plätzer [JHEP 1308 (2013) 114]
close to Rubin, Salam, Sapeta [JHEP 09 (2010) 084] with Parton Shower.

NLO-Merging

(Replace, Reweight, Subtract and Add)

$$PS[\sigma^{2LO+1NLO}_{Merged}] \quad = \quad PS[\sigma^{2LO}_{Merged}] + PS_0[V_0 + \int dq_1 B_1]$$

NLO-Merging
(Replace, Reweight, Subtract and Add)

$$
\begin{aligned}
PS[\sigma^{3LO+2NLO}_{Merged}] \;&=\; PS[\sigma^{3LO}_{Merged}] + PS^{V}_{0}[V_0 + \int dq_1 B_1] \\
&-\; PS^{V}_{0}[-\int dq_1 B_1 \alpha_s \frac{\partial}{\partial \alpha_s^{add}} \tilde{\Delta}^{q_1}_{PS_0}|_{\alpha_s^{add}=0} \theta(q_1 > \rho)] \\
&-\; PS^{V}_{0}[\int dq_1 \tilde{\Delta}^{q_1}_{PS_0}(V_1 + \int dq_2 B_2)\theta(q_1 > \rho)] \\
&+\; PS_1[-B_1 \alpha_s \frac{\partial}{\partial \alpha_s^{add}} \tilde{\Delta}^{q_1}_{PS_0}|_{\alpha_s^{add}=0} \theta(q_1 > \rho)] \\
&+\; PS_1[\tilde{\Delta}^{q_1}_{PS_0}(V_1 + \int dq_2 B_2)\theta(q_1 > \rho)]
\end{aligned}
$$

Inclusive one jet

$$B_1 \ \tilde{\Delta}^{q_1}_{PS_0} \ \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \ \Delta^{q_1}_{PS_0} \ \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \ \frac{f_0(Q_f)}{f_0(q_1)} \ \frac{f_1(q_1)}{f_1(Q_f)} \ \theta_\rho$$

is the contribution we get from LO-merging for $q_1 > \rho$.

Details: Prestel, Lönnblad [JHEP 1302 (2013) 094]

Inclusive one jet

$$B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta^{q_1}_{PS_0} \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_\rho$$

- $\tilde{\Delta}^{q_1}_{PS_0} = 1 + \alpha_s f(PS_0, Q_h, Q_r, Q_f, q_1) + \mathcal{O}(\alpha_s^2)$
- $\Delta^{q_1}_{PS_0} = 1 - \sum_i \frac{\alpha_s}{2\pi} \int_{q_1}^{Q_h} d\Phi^i_{PS} P_i + \mathcal{O}(\alpha_s^2)$
- $\frac{\alpha_s(q_1)}{\alpha_s(Q_r)} = 1 - \frac{\alpha_s}{2\pi} \cdot \beta_0 \ln\left(\frac{q_1^2}{Q_r^2}\right) + \mathcal{O}(\alpha_s^2)$
- $\frac{f_0(Q_f)}{f_0(q_1)} = 1 - \frac{\alpha_s}{2\pi} \cdot \ln\left(\frac{q_1^2}{Q_r^2}\right) \int_x^1 dz P_+^{0j}(z) \frac{f_j(x/z)}{f_0(x)} + \mathcal{O}(\alpha_s^2)$
- $\frac{f_1(q_1)}{f_1(Q_f)} = 1 - \frac{\alpha_s}{2\pi} \cdot \ln\left(\frac{Q_r^2}{q_1^2}\right) \int_x^1 dz P_+^{1j}(z) \frac{f_j(x/z)}{f_1(x)} + \mathcal{O}(\alpha_s^2)$

Inclusive one jet

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$$B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta^{q_1}_{PS_0} \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_\rho$$

- $\tilde{\Delta}^{q_1}_{PS_0} = 1 + \alpha_s f(PS_0, Q_h, Q_r, Q_f, q_1) + \mathcal{O}(\alpha_s^2)$
- $\Delta^{q_1}_{PS_0} = 1 - \sum_i \frac{\alpha_s}{2\pi} \int_{q_1}^{Q_h} d\Phi^i_{PS} P_i + \mathcal{O}(\alpha_s^2)$
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Inclusive one jet

$$B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta^{q_1}_{PS_0} \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_\rho$$

- $\tilde{\Delta}^{q_1}_{PS_0} = 1 + \alpha_s f(PS_0, Q_h, Q_r, Q_f, q_1) + \mathcal{O}(\alpha_s^2)$
- $\Delta^{q_1}_{PS_0} = 1 - \sum_i \frac{\alpha_s}{2\pi} \int_{q_1}^{Q_h} d\Phi^i_{PS} P_i + \mathcal{O}(\alpha_s^2)$
- $\frac{\alpha_s(q_1)}{\alpha_s(Q_r)} = 1 - \frac{\alpha_s}{2\pi} \cdot \beta_0 \ln\left(\frac{q_1^2}{Q_r^2}\right) + \mathcal{O}(\alpha_s^2)$
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- $\frac{f_1(q_1)}{f_1(Q_f)} = 1 - \frac{\alpha_s}{2\pi} \cdot \ln\left(\frac{Q_r^2}{q_1^2}\right) \int_x^1 dz P_+^{1j}(z) \frac{f_j(x/z)}{f_1(x)} + \mathcal{O}(\alpha_s^2)$

Inclusive one jet

$$B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta^{q_1}_{PS_0} \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_\rho$$

- $\tilde{\Delta}^{q_1}_{PS_0} = 1 + \alpha_s f(PS_0, Q_h, Q_r, Q_f, q_1) + \mathcal{O}(\alpha_s^2)$
- $\Delta^{q_1}_{PS_0} = 1 - \sum_i \frac{\alpha_s}{2\pi} \int_{q_1}^{Q_h} d\Phi^i_{PS} P_i + \mathcal{O}(\alpha_s^2)$
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Inclusive one jet

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$$B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta^{q_1}_{PS_0} \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_\rho$$

- $\tilde{\Delta}^{q_1}_{PS_0} = 1 + \alpha_s f(PS_0, Q_h, Q_r, Q_f, q_1) + \mathcal{O}(\alpha_s^2)$
- $\Delta^{q_1}_{PS_0} = 1 - \sum_i \frac{\alpha_s}{2\pi} \int_{q_1}^{Q_h} d\Phi^i_{PS} P_i + \mathcal{O}(\alpha_s^2)$
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Inclusive one jet

$$B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta_\rho = f_1(Q_f)\alpha_s^n(Q_r)\tilde{B}_1 \cdot \Delta^{q_1}_{PS_0} \frac{\alpha_s(q_1)}{\alpha_s(Q_r)} \frac{f_0(Q_f)}{f_0(q_1)} \frac{f_1(q_1)}{f_1(Q_f)} \theta_\rho$$

- $\tilde{\Delta}^{q_1}_{PS_0} = 1 + \alpha_s f(PS_0, Q_h, Q_r, Q_f, q_1) + \mathcal{O}(\alpha_s^2)$
- $\Delta^{q_1}_{PS_0} = 1 - \sum_i \frac{\alpha_s}{2\pi} \int_{q_1}^{Q_h} d\Phi^i_{PS} P_i + \mathcal{O}(\alpha_s^2)$
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Comparison to MINLO-inspired Merging

$$PS_1[\tilde{\Delta}^{q_1}_{PS_0}(-B_1\alpha_s \frac{\partial}{\partial \alpha_s^{add}} \tilde{\Delta}^{q_1}_{PS_0}|_{\alpha_s^{add}=0} + V_1 + \int dq_2 B_2)]\theta(q_1 > \rho)$$

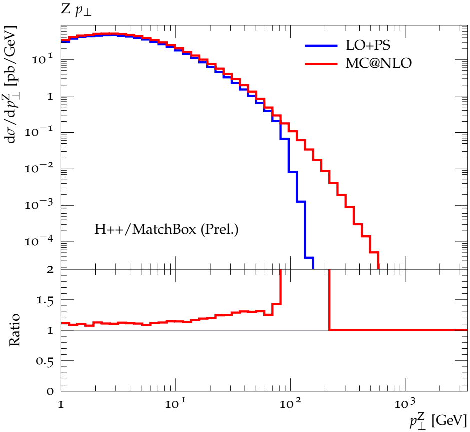
- MINLO Hamilton, Nason , Zanderighi [JHEP 10 (2012) 155] and later with Oleari in [JHEP 05 (2013) 082] they produce similar parts up to $\mathcal{O}(\alpha_s^2)$.

$$\begin{aligned}\bar{B}_{\texttt{HJ-MiNLO}} &= \alpha_S^2(M_H)\alpha_S(q_T)\Delta_g^2(q_T, M_H) \\ &\times \left[B(1 - 2\Delta_g^{(1)}(q_T, M_H)) + \alpha_S V(\bar{\mu}_R) + \alpha_S \int d\Phi_{\text{rad}} R\right],\end{aligned}$$

$\Delta^{q_1}_{PS_0}$	$\frac{f_0(Q_f)}{f_0(q_1)}$	$\frac{\alpha_s(q_1)}{\alpha_s(Q_r)}$	$\frac{f_1(q_1)}{f_1(Q_f)}$

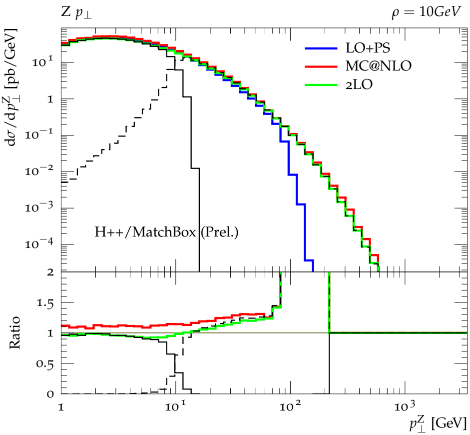
There are also other Algorithms like FxFx arXiv:1209.6215, Geneva arXiv:1211.7049 and MEPS@NLO arXiv:1207.5030, which are not discussed here. And even aims to go to NNLO+PS (see next talk by E. Re and e.g. UNNLOPS)

Story of $p_\perp^Z$



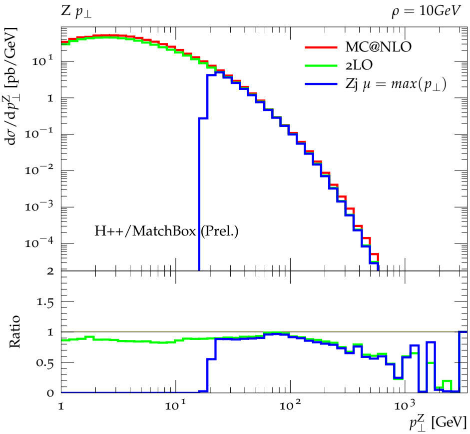
- LO+PS:
  $p_\perp^Z < M_Z$.
  Dies at the hard scale!
- MC@NLO:
  Z+jet@LO $\rightarrow p_\perp^Z > M_Z$

Story of $p_\perp^Z$



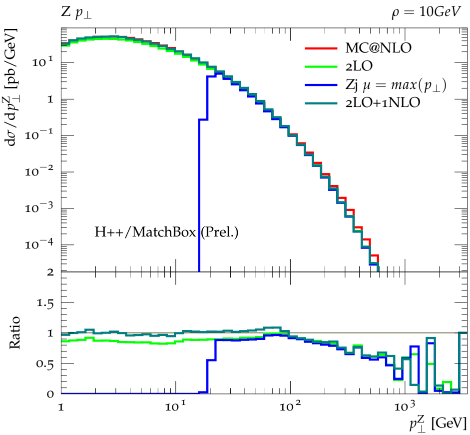
- 2LO:
  Z+jet@LO $\rightarrow p_\perp^Z > M_Z$
- μ_0=max(M_Z, min(m_{ij}))

Story of $p_\perp^Z$



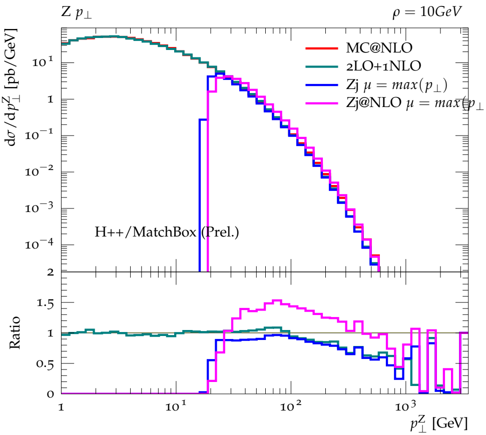
- No NLO corrections yet.
- Dynamical scale above the hard scale.

Story of $p_\perp^Z$



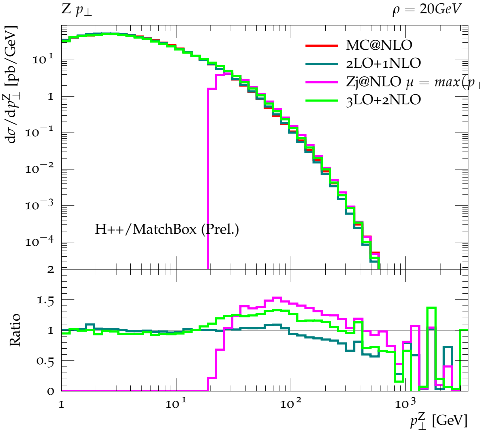
- 2LO+1NLO: Comparable to MC@NLO.

Story of $p_\perp^Z$



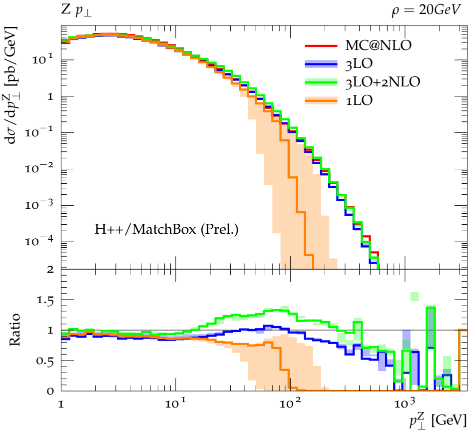
- Expect large NLO corrections to Z+jet.
- max($p_\perp$) a good scale?

Story of $p_\perp^Z$



- 3LO+2NLO: Corrected 1jet observables with improved scale choice.

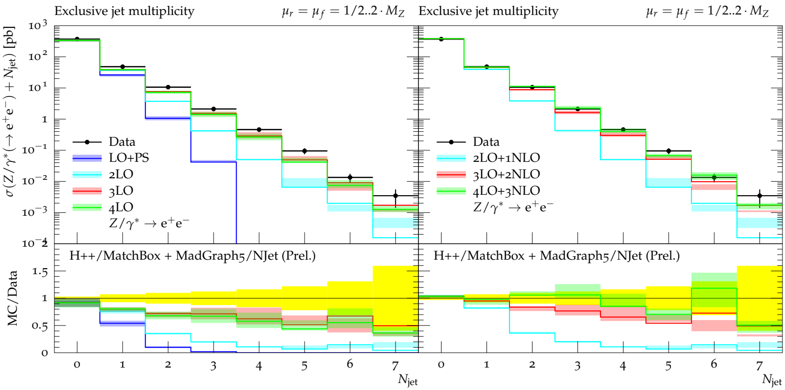
Story of $p_\perp^Z$



- Shower scale variation.

Lets see what data tells us...

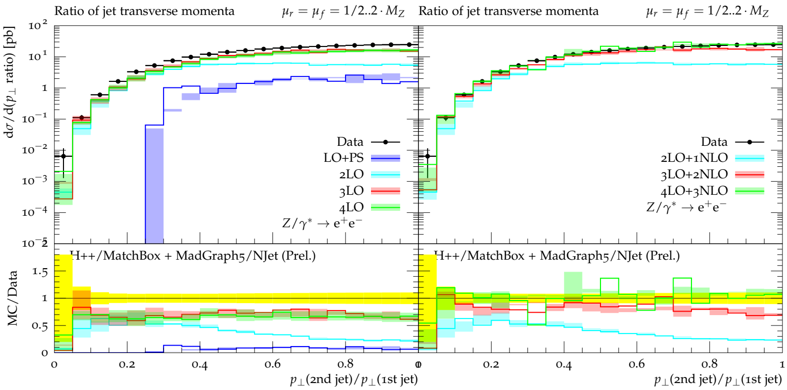
Z production



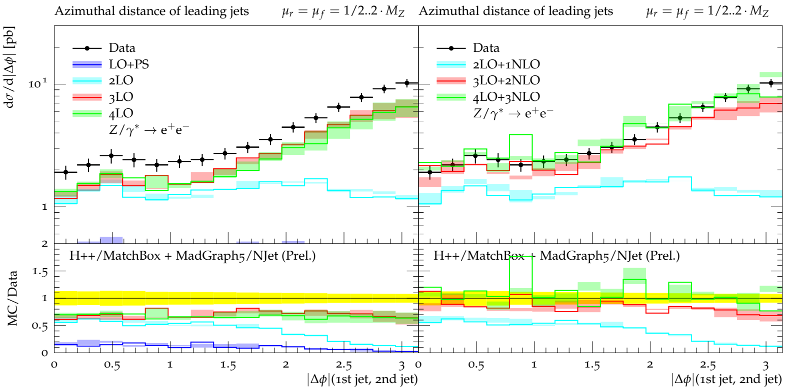
Need the 3NLO merging.

MadGraph5 interfaced with Colorfull

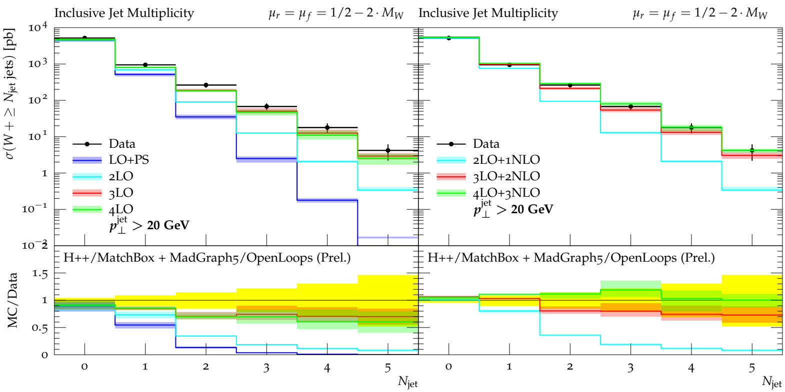
Z production



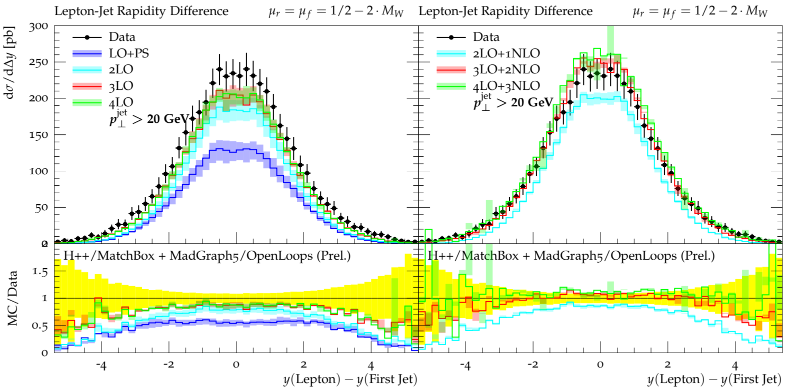
Z production



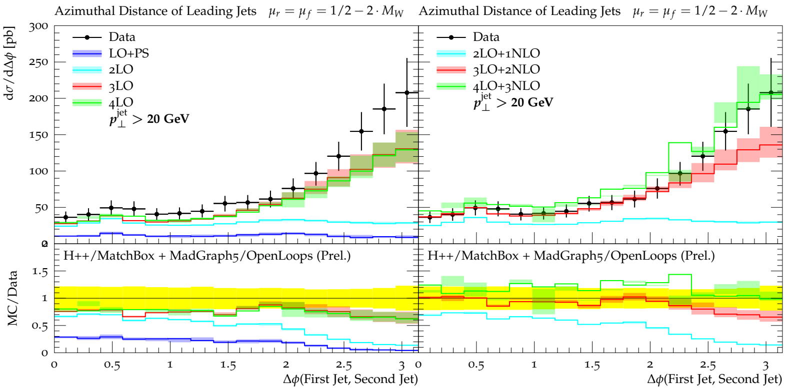
W production



W production



W production



Conclusion

- Gave an overview on the NLO development in Herwig++.
- For Matching we have two showers with various parameters to vary.
- Implemented Interfaces to many external NLO providers.
- Implemented (N)LO-merging in Herwig++/Matchbox with Dipole Shower.
- Take care of $\mathcal{O}(\alpha_s)$ accuracy and full phase space.

Stay tuned on herwig.hepforge.org.

The end

Thank you for your attention!

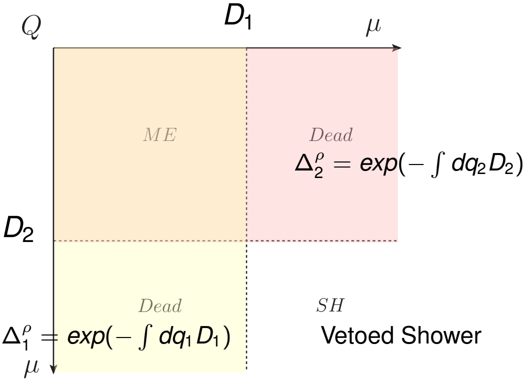
The end

Backup

Overlapping Phase Space

Not unitarized merging with overlapping phase spaces of the kernels:

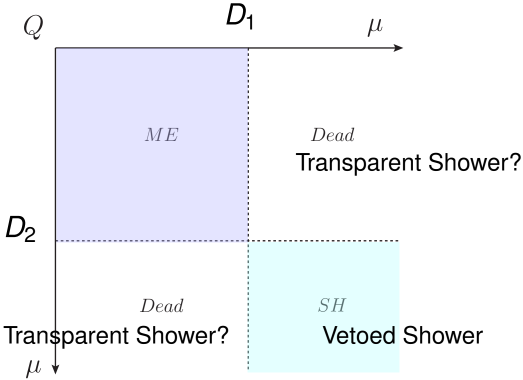
$$PS[\sigma^{2LO}_{Merged}] = PS^V[B_0\Delta^{\rho}_{PS_0}] + PS[B_1\tilde{\Delta}^{q_1}_{PS_0}\theta(q_1 > \rho)]$$



Overlapping Phase Space

With unitarized merging with overlapping phase spaces:

$$PS[\sigma^{2LO}_{Merged}] = PS^V[B_0 - \int_{ME} B_1 \Delta^{q_1}_{PS_0}] + PS[B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta(q_1 > \rho)]$$



Transparent Shower

Transparent Shower means:

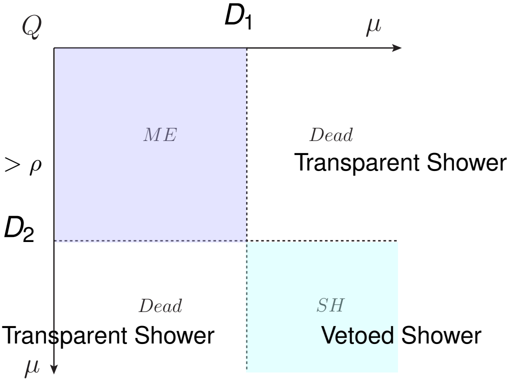
$$PS[\sigma^{2LO}_{Merged}] = PS^{T}[B_0] + PS^{V}[-\int_{ME} B_1 \Delta^{q_1}_{PS_0}] + PS[B_1 \tilde{\Delta}^{q_1}_{PS_0} \theta(q_1 > \rho)]$$

$PS^{T}[B_0]$:

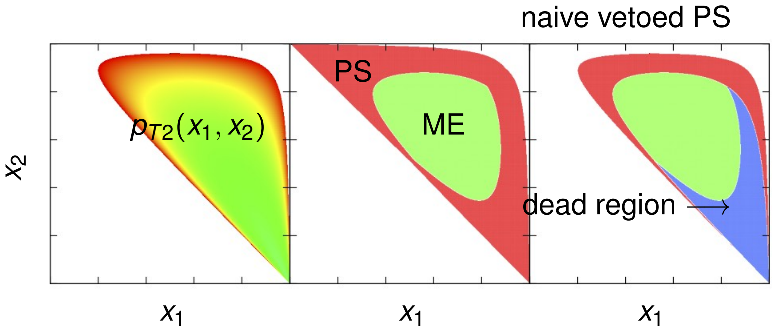
if trial emission has $q_1 > \rho$

but $q_2 < \rho$

accept emission!



Transparent Shower



$$x_1 + x_2 + x_3 = 1 \;,\; x_i = \frac{p_i * Q}{Q^2}$$

It must be possible to emit above the merging scale if any other clustering returns a lower scale.