NLO Parton Shower Matching and Electroweak Corrections in the POWHEG BOX

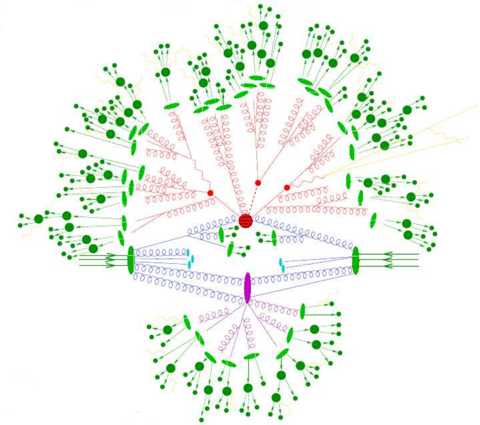
Christian Weiss
In collaboration with A. Mück, M. Krämer and M. Kraus

Institut für Theoretische Teilchenphysik und Kosmologie
RWTH Aachen

DESY Theory Workshop, September 26, 2013

Simulating a QCD Event

Hadron collisions are messy!



- $2 \to n$ parton interaction. Method: Calculating Feynman diagrams (MADGRAPH,HELAC,etc.)
- Off-shell partons radiate. Method: Parton showers (Pythia,Herwig)
- Finally, hadrons form. Diverse phen. models.
- Photons might be emitted from every charged particle. Method: QED shower

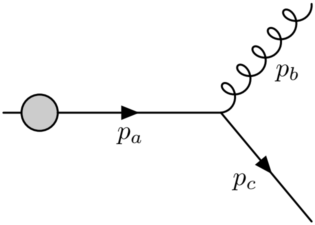
Table of Contents

1. Parton Showers and the POWHEG Method

2. Elecotroweak Corrections to the Drell-Yan Process in the POWHEG BOX

3. Phenomenological Checks

Parton Branching



- Emission from an off-shell quark: $p_b^2, p_c^2 \ll p_a^2 = t$
- $z = E_c/E_a$
- $\sim \frac{1}{(p_b+p_c)^2} = \frac{1}{p_b^0 p_c^0 (1-\cos\theta_{bc})}$
  $\rightarrow$ Enhancement for small emission angles or transverse momenta

Collinear factorization of matrix elements:

$$|\mathcal{M}_{n+1}|^2 \sim \frac{\alpha_s}{t} \hat{P}_{qq}(z) |\mathcal{M}_n|^2,$$

Spin-averaged Altarelli-Parisi splitting function

$$\hat{P}_{qq}(z) = C_F \frac{1+z^2}{1-z}$$

The Shower Approach

- Probability for one parton splitting

$$d\mathcal{P} = \frac{\alpha_s}{2\pi}\hat{P}_{ij}(z)\frac{dt}{t}dz = F(z,t)dtdz$$

- Non-splitting probability $\Delta(t_1, t_2)$: **Sudakov form factor**

$$\Delta(t_1, t_2) = \exp\left[-\int_{t_2}^{t_1} dzdtF(z,t)\right]$$

- Cross section after first splitting:

$$d\sigma_{\mathrm{PS}} = B(\Phi_n)d\Phi_n \left[\underbrace{\Delta(t_1, t_2)}_{\text{No emission - Born like}} + \underbrace{\Delta_R(t_1, t_{\mathrm{em}})F(z_{\mathrm{em}}, t_{\mathrm{em}})d\Phi_{\mathrm{rad}}}_{\text{Emission at } (z_{\mathrm{em}}, t_{\mathrm{em}})}\right]$$

$B(\Phi_n)$: Born matrix element (including PDFs, flux, etc.),
Φ_n: n-particle phase space, Φ_{rad}: Radiation phase space

Parton Shower beyond Leading Order

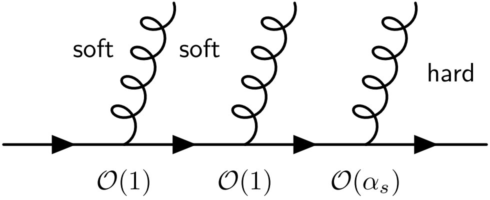
NLO matrix element

- Reliable in the non-collinear region (production of jets)
- Complicated calculation
- Effective for inclusive quantities

Parton shower

- Reliable in the collinear region (internal structure of jets)
- Easy calculation
- Resums leading logarithms

Problem: Soft emissions only count as $\mathcal{O}(1)$!



- Because: $|\mathcal{M}_{\text{soft}}|^2 \sim \frac{1}{k_T^2} \to \log \frac{p_T^{\max}}{p_T^{\min}}$ after phase-space integration
- Smallness of α_s is compensated by this logarithm: $\alpha_s \log \frac{p_T^{\max}}{p_T^{\min}} \sim 1$

POWHEG: Hardest Emission First!

- Generate events according to

$$d\sigma = \bar{B}(\Phi_n)\left[\Delta_R^{\mathrm{NLO}}(p_T^{\mathrm{min}}) + \Delta_R^{\mathrm{NLO}}(k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)}d\Phi_{\mathrm{rad}}\right],$$

with

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\mathrm{rad}} R(\Phi_{n+1})$$

Paolo Nason, hep-ph/0409146

and

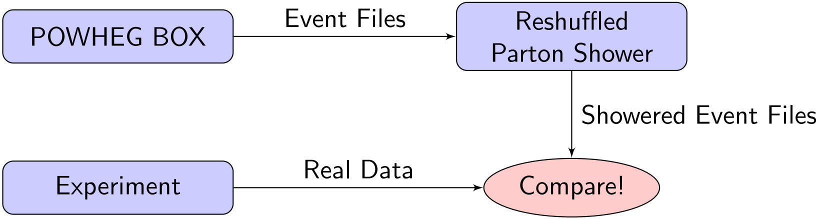
$$\Delta_R^{\mathrm{NLO}}(p_T) = \exp\left[-\int d\Phi_{\mathrm{rad}} \frac{R(\Phi_{n+1})}{B(\Phi_n)}\theta(k_T(\Phi_{n+1}) - p_T)\right]$$

- Perform re-arranged parton shower, where the hardest emission is generated first!

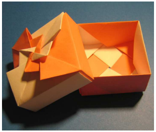
Table of Contents

1. Parton Showers and the POWHEG Method
2. Elecotroweak Corrections to the Drell-Yan Process in the POWHEG BOX
3. Phenomenological Checks

The POWHEG BOX



- Up to recently, only QCD calculations
- Various different processes implemented so far: Z,H + 0,1,2 jet; single top and $t\bar{t}$, dijet, vector-boson fusion, ...
- Several electroweak additions on the way!
- Uses the FKS subtraction scheme

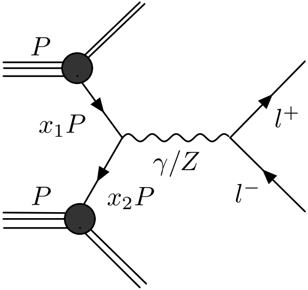


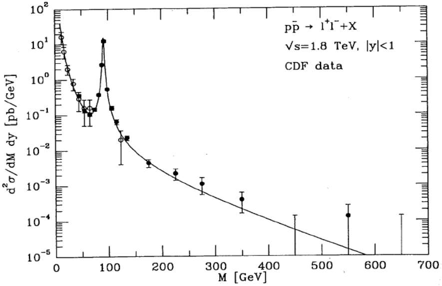
Frixione,Nason, Oleari, arXiv: 0709.2092

Alioli,Nason, Oleari,Re,arXiv: 1002.2581

Frixione,Kunszt, Signer,1995

The Drell-Yan Process



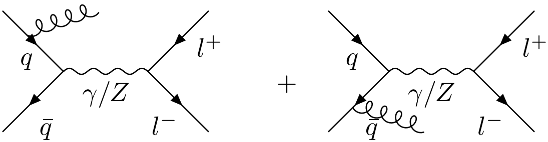


- Easy to detect lepton pair
- Sensitive to electroweak parameters, $M_{Z,W}$, $\Gamma_{Z,W}$, $\cos\theta_W$.
- PDF measurement
- Background process for many searches
- Possibly new physics in high energy tail
- Final state not affected by QCD corrections, but photon radiation

Idea: Use POWHEG to create photon. QED-Shower will be NLO-accurate.

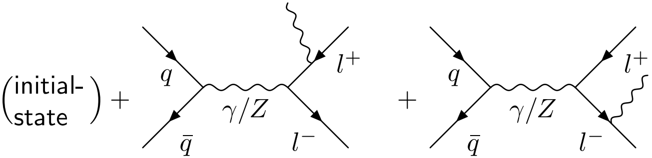
Two particles which can come from the same splitting make up a singular region.

QCD:



One singular region, (0,g)

QED:



Three singular regions, $(0,\gamma)$, $(+,\gamma)$, $(-,\gamma)$

Teach the POWHEG BOX how to take into account leptons as emitters both in real and virtual amplitudes.

Electroweak Corrections - QCD vs. EW

QCD	Electroweak
Strong scale variance of α_S, $\rightarrow$ Use running coupling	Almost no scale variance of α_e, $\rightarrow$ Use $\alpha(0) = 1/137$
Color Correlation between different legs, $\rightarrow C_F, C_A, T_F$	Color Correlation replaced by charge correlation, $C_F \rightarrow Q_f^2$, $C_A \rightarrow 0$
Only one virtual graph	A multitude of virtual graphs, including exchange of γ, Z, $W^{\pm}$, Higgs,...
One singular region	Three singular regions: one initial-state and two final-state ones

The POWHEG BOX is now able to deal with user-defined electroweak processes.

Table of Contents

1 Parton Showers and the POWHEG Method

2 Elecotroweak Corrections to the Drell-Yan Process in the POWHEG BOX

3 Phenomenological Checks

Phenomenological Checks

To test the implementation, several checks ware made. Two of them:

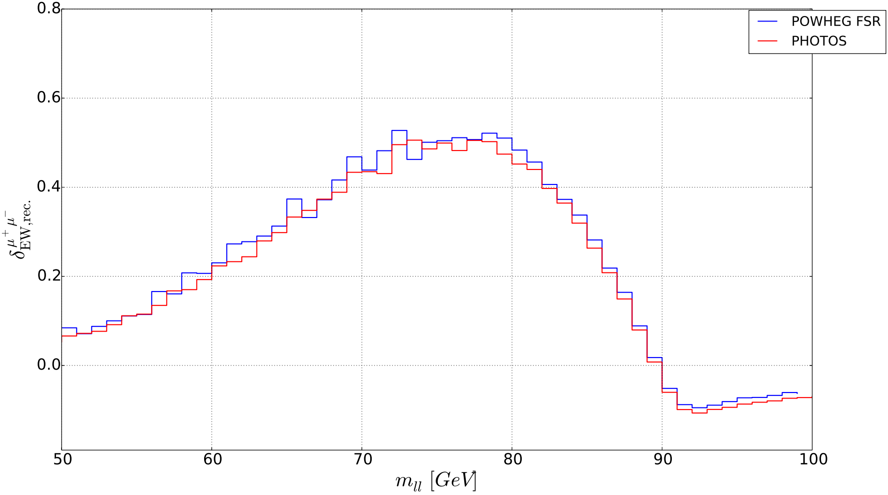
- **Comparison to the QED shower PHOTOS**[1]
  - Only final-state radiation $\rightarrow$ Check of emission generation.
  - Different regularization of IR-divergences requires recombination.
- **Comparison to a fixed-order calculation**[2]
  - Difference to the POWHEG BOX calculation is small.
  - Most comprehensive test of a single process implementation.

---

[1] P. Golonka, Z. Was, hep-ph/0506026

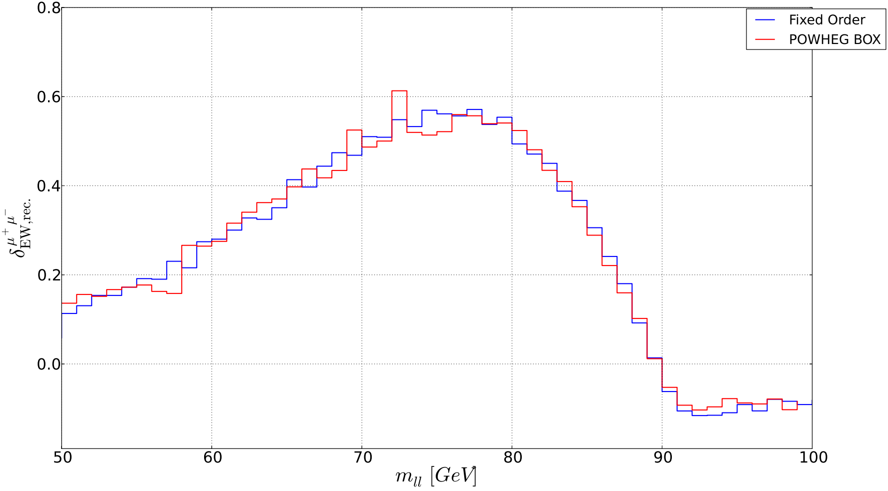
[2] Provided by A. Mück and checked against the results of S. Dittmaier and M. Huber, arXiv:0911.2329

Comparison with PHOTOS



$$\delta^{\mu^+\mu^-}_{\mathrm{phot,rec.}} = \frac{\sigma_{\mathrm{NLO}} - \sigma_{\mathrm{LO}}}{\sigma_{\mathrm{LO}}}$$

Comparision to a fixed-order calculation



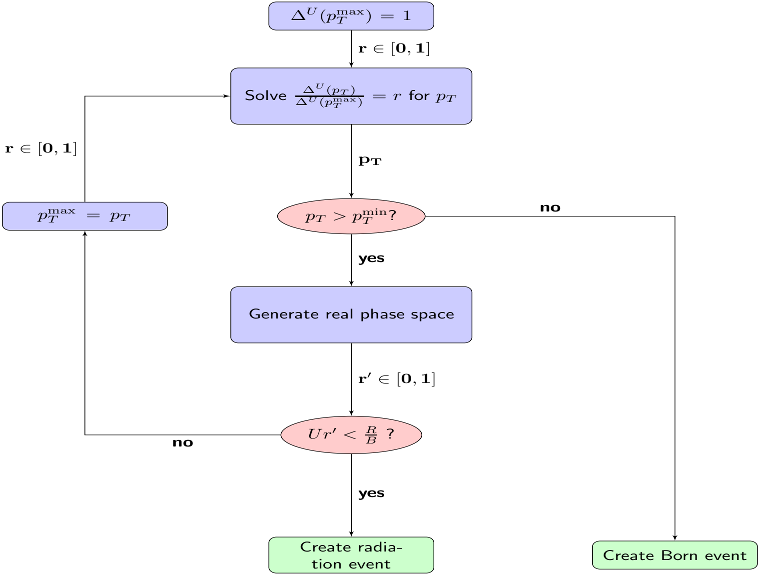
$$\delta^{\mu^+\mu^-}_{\mathrm{EW,rec.}} = \frac{\sigma_{\mathrm{NLO}} - \sigma_{\mathrm{LO}}}{\sigma_{\mathrm{LO}}}$$

Summary and Conclusion

- POWHEG solves the problem of parton shower - matrix element - matching by rearranging the emissions of the parton shower.
- We have introduced the possibility to implement arbitrary electroweak processes in the POWHEG BOX.

Possible Future Work:

- For the Drell-Yan process:
  - Completely massive treatment.
  - Inclusion of real massive gauge boson emissions.
  - Inclusion of photon-induced processes.
- In general:
  - Combined QCD/QED.
  - Check that application of a p_T-ordered shower keeps NLO accuracy.
  - Implementation of more processes.


$\Delta^U(p_T^{max}) = 1$
$\mathbf{r} \in [\mathbf{0}, \mathbf{1}]$
Solve $\frac{\Delta^U(p_T)}{\Delta^U(p_T^{max})} = r$ for p_T
$\mathbf{r} \in [\mathbf{0}, \mathbf{1}]$
$\mathbf{p_T}$
$p_T^{max} = p_T$
$p_T > p_T^{min}$?
no
yes
Generate real phase space
$\mathbf{r}' \in [\mathbf{0}, \mathbf{1}]$
$Ur' < \frac{R}{B}$?
no
yes
Create radiation event
Create Born event

Mapping into singular regions using the FKS scheme

- Project real matrix elements onto singular regions via $\mathcal{R}_\alpha = \mathcal{R} S_\alpha$, $\alpha \in \{(0,\gamma),(+,\gamma),(-,\gamma)\}$
- S_α is purely phase-space dependent. In the α-singular region $S_\alpha \approx 1$, in all others $S_\alpha \approx 0$
- **Example:** Mappings for electroweak Drell Yan, $\underbrace{S_{(0,\gamma)}}_{\text{ISR}}, \underbrace{S_{(+,\gamma)}, S_{(-,\gamma)}}_{\text{FSR}}$

$$S_{(i,j)} = \frac{1}{d_{(i,j)}/d_{(0,\gamma)} + d_{(i,j)}/d_{(+,\gamma)} + d_{(i,j)}/d_{(-,\gamma)}}$$

$d_{(i,j)} \to 0$ if i,j are soft or i is collinear w.r.t. j

- Suppose e.g. γ is collinear w.r.t. l^+, $\to d_{(+,\gamma)} = 0$

$$\Rightarrow S_{(0,\gamma)} = S_{(-,\gamma)} = \tfrac{1}{\infty} = 0, \text{ but } S_{(+,\gamma)} = \tfrac{1}{0+1+0} = 1$$

Only $R_{(+,\gamma)}$ contributes to real matrix element!

Subtraction in the FKS scheme

Define:

$$\xi_i = \frac{2k_i^0}{\sqrt{s}}\, y_i = \cos\theta_i\, y_{ij} = \cos\theta_{ij}$$

Define also $f(\xi, y) = \frac{J(\xi,y,\phi)}{\xi}\left[(1-y)\xi^2 R_\alpha\right]$.
Subtraction terms are generated automatically using plus-distrubitons:

$$\bar{B}_{\text{real}} = \int d\Phi_n \int_0^{2\pi} d\phi \int_{-1}^{1} dy \int_0^1 d\xi \left(\frac{1}{1-y}\right)_+ \left(\frac{1}{\xi}\right)_+ f(\xi, y)$$

$$= \int d\Phi_n \int_0^{2\pi} d\phi \int_{-1}^{1} \frac{dy}{1-y} \int_0^1 d\xi \left[\frac{f(\xi,y)}{\xi} - \underbrace{\frac{f(0,y)}{\xi}}_{\text{soft}} - \underbrace{\frac{f(\xi,1)}{\xi}}_{\text{coll.}} - \underbrace{\frac{f(0,1)}{\xi}}_{\text{soft}-\text{coll.}}\right]$$