NLO Event Generation with SHERPA

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Contents

Part I

NLO Event Generation

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in collaboration with J. Archibald, T. Gleisberg, S. Höche, F. Krauss, S. Schumann, F. Siegert, J. Winter

NLO Cross Section

- LO cross section

$$\sigma_{LO} = \int_N \mathrm{d}\sigma_B$$

- NLO cross section

$$\sigma_{NLO} = \int_N \mathrm{d}\sigma_B + \int_N \mathrm{d}\sigma_V + \int_{N+1} \mathrm{d}\sigma_R$$

- $\mathrm{d}\sigma_V$ may be IR-divergent due to massless loop propagators
- $\int_1 \mathrm{d}\sigma_R$ may be IR-divergent due to emission of massless line
  $\rightarrow$ sum is finite (KLN-theorem)

NLO Cross Section

Problem: $\mathrm{d}\sigma_V$ and $\mathrm{d}\sigma_R$ live in different phase spaces

- in $\mathrm{d}\sigma_V$ the loop integral is IR divergent
  $\rightarrow$ every point in the N-dim. phase space carries the divergence structure as poles in $\frac{1}{\epsilon}$ and $\frac{1}{\epsilon^2}$ (in dim. renormalisation)
- for $\mathrm{d}\sigma_R$ the phase space integral over the extra emission is IR divergent
  $\rightarrow$ a similar pole structure cannot be achieved by Monte Carlo integration (integration in integer number of dimensions only)

$\rightarrow$ NLO cross section cannot be directly integrated using Monte Carlo methods
$\rightarrow$ no obvious cancellation of divergences

Subtraction Schemes

$$\sigma_{NLO} = \int\limits_{N} \mathrm{d}\sigma_B + \int\limits_{N} \mathrm{d}\sigma_V + \int\limits_{N+1} \mathrm{d}\sigma_R$$

individual terms rendered integrable by subtraction scheme
→ needs to provide local counter terms $\mathrm{d}\sigma_A$ which are integrable over extra emission phase space

$$\sigma_{NLO} = \int\limits_{N} \mathrm{d}\sigma_B + \int\limits_{N} \overbrace{\left[\mathrm{d}\sigma_V + \int\limits_{1} \mathrm{d}\sigma_A\right]}^{\text{IR-finite loop integration}} + \int\limits_{N+1} \underbrace{\left[\mathrm{d}\sigma_R - \mathrm{d}\sigma_A\right]}$$

The Generalised POWHEG Method

- generate N-jet event with

$$\mathrm{d}\sigma_B + \mathrm{d}\sigma_V + \mathrm{d}\sigma_I + \int_1 \left[\mathrm{d}\sigma_R - \mathrm{d}\sigma_S\right]$$

- use Catani-Seymour variables as real radiation variables
- shower radiates real emission with Sudakov form factor

$$\Delta_t = \exp\left[-\int \theta(t_r - t)\,\frac{R}{B}\,\mathrm{d}\Phi_r\right]$$

  $\rightarrow$ shower needs to cover the whole phase space JHEP11(2007)070

- also correct if real emission constrained to $Q^2 < J$
  $\rightarrow$ positive weights only for large enough J

Multijet Matching

$$\mathrm{d}\sigma_B + \mathrm{d}\sigma_V + \mathrm{d}\sigma_I + \int_1 \left[\mathrm{d}\sigma_R \Theta(J - Q^2) - \mathrm{d}\sigma_S\right] + \int_1 \mathrm{d}\sigma_R \Theta(Q^2 - J)$$

- $\mathrm{d}\sigma_R \Theta(Q^2 - J)$ of a $2 \to N$ process identified with $\mathrm{d}\sigma_B$ of a $2 \to N+1$ process
- generate $2 \to N$ event according to above formula
  $\to$ first emission with $Q^2 < J$ via POWHEG to NLO accuracy
- possibility to replace $\mathrm{d}\sigma_B$ of $2 \to N+1$ with

$$\mathrm{d}\sigma_B + \mathrm{d}\sigma_V + \mathrm{d}\sigma_I + \int_1 \left[\mathrm{d}\sigma_R - \mathrm{d}\sigma_S\right]$$

- successively merge
  NLO $2 \to N$, NLO $2 \to N+1$, ...,
  LO $2 \to N+M$, LO $2 \to N+M+1$, ...

Available in SHERPA-1.2.0 (released 28/09/09)

- automated Catani-Seymour subtraction term generation (in AMEGIC++) Eur.Phys.J.C53(2008)501-523
- LO ME generators (AMEGIC++, COMIX)
  JHEP02(2002)044, JHEP12(2008)039
- few built-in virtual MEs + extensive tensor integral library
- interfaces to NLO codes (BLACKHAT, GOLEM, etc.)
  arXiv:0902.2760, arXiv:0810.0992
- parton shower (CSSHOWER++) JHEP03(2008)038

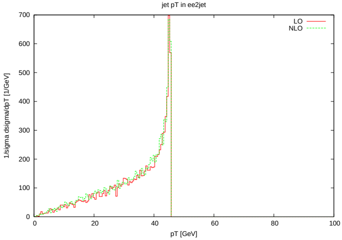
→ rearrange terms to give N-jet event with NLO weight
→ get correct real emission via POWHEG method

First Results on $ee \to 2jets$ at 91.25 GeV

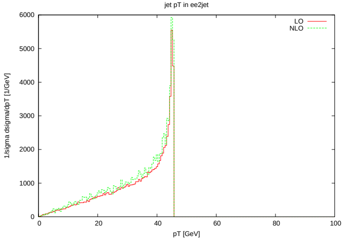
fixed order result:

$$d\sigma_{NLO} = \left(1 + \frac{\alpha_S}{\pi}\right) d\sigma_{LO} \quad \text{with } (J = 1)$$

unweighted event generation



weighted event generation




```
LO:     2_2__e-__e+__j__j :                40189.9 pb +- ( 18.29 pb = 0.045509 % )
NLO:    2_2__e-__e+__j__j__QCD(BVIRS) :    41712.5 pb +- ( 20.79 pb = 0.049842 % )
```

Further Ideas

Resummation Effects:

- determine $k_\perp^2$ of most probable splitting for real emission
  $\longrightarrow$ shower language
- consistently replace one power of α_S with $\alpha_S(k_T^2)$
  $\longrightarrow$ capture resummed large logarithms from higher orders
  $\longrightarrow$ enlarged possibility of softer emission

```
LO:        2_2__e-__e+__j__j :               40189.9 pb +- ( 18.29 pb = 0.045509 % )
NLO:       2_2__e-__e+__j__j__QCD(BVIRS) :   41712.5 pb +- ( 20.79 pb = 0.049842 % )
NLO+NLL:   2_2__e-__e+__j__j__QCD(BVIRS) :   42757.4 pb +- ( 20.41 pb = 0.047748 % )
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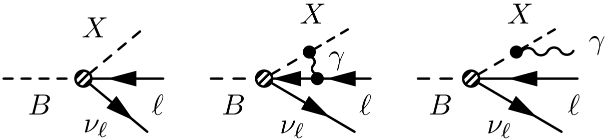
Part II

Radiative Corrections to Semileptonic Meson Decays

–

in collaboration with F. Bernlochner

Motivation



- Determination of V_{xb}

$$\Gamma_{\text{measured}} = \eta^2_{\text{QCD}}\eta^2_{\text{QED}}|V_{xb}|^2\Gamma'_{\text{Born}}$$

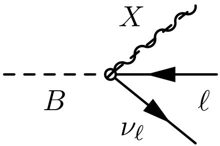
$\longrightarrow$ experiments extract rates which include radiative effects

- Corrections to measured kinematics

$\longrightarrow$ real and virtual photons alter momenta of involved particles

$\longrightarrow$ fits to kinematic variables can be very sensitive to slight changes Phys. Rev. D 79, 012002(2009)

Model



$$\begin{aligned}\mathcal{M} &= \sqrt{2} G_F V_{xb} H_\mu L^\mu \\ L^\mu &= \bar{u}_\nu P_R \gamma^\mu v_\ell \\ H^\mu &= \langle X|V^\mu|B\rangle - \langle X|A^\mu|B\rangle\end{aligned}$$

- supplement phenomenological model with QED
  - scalar, fermion, vector QED
  - emission off phen. vertex through minimal coupling
  - fully gauge invariant effective theory, Ward identities are fulfilled
- renormalise analoguous to QED
  - on-shell
  - vanishing $\mathcal{O}(eG_F)$ corrections at maximum momentum transfer
  - additional counter terms needed

Asumptions

1. QED corrections can be adequately described at $\mathcal{O}(\alpha)$
2. hadronic model fully characterises weak interaction
3. presence of QED radiation does not modify structure of form factors
4. momentum dependence of form factors negligible in loop integrations
5. scalar/vector QED is sufficient to describe meson-photon interaction

$\Gamma_{\text{measured}} = \eta_{tot}^2 |V_{xb}|^2 \Gamma'_{\text{Born}}$

$$\eta^2 \;=\; (\eta_{\text{QCD}}^{SD}\, \eta_{\text{QED}}^{SD}\, \eta_{\text{QED}}^{LD})^2 \;=\; 1 + \delta^{SD} + \delta_{\text{QED}}^{LD}$$

- η_{QCD}^{SD} from HQET, χPT, etc. Nucl.Phys.Proc.Suppl.140,461(2005)
- η_{QED}^{SD} known in LL Nucl.Phys.B196,83(1982)

$$\eta_{\text{QED}}^{SD\;2} \;=\; 1 + \frac{\alpha}{\pi} \ln \frac{m_Z^2}{\Lambda^2}$$

- η_{QED}^{LD} to be determined through

$$1 + \delta_{\text{QED}}^{LD} \;=\; \frac{\Gamma^{\mathcal{O}(\alpha G_F^2)}}{\Gamma^{\mathcal{O}(G_F^2)}}$$

Resummation Effects – YFS-scheme

- resummation of soft limit $(k \to 0)$
- separation of soft limit of real and virtual amplitudes
  $\to$ YFS form factor $\exp[Y(\Omega)]$
- reorganisation of perturbative series
  $\to$ series in e with infrared divergent amplitudes into series in α with infrared subtracted squared amplitudes

$$\left|\mathcal{M}_0^0 + \mathcal{M}_1^{\frac{1}{2}} + \mathcal{M}_0^1 + \ldots\right|^2 = e^{Y(\Omega)} \prod_0^i \tilde{S}(k_i, \Omega) \left(\tilde{\beta}_0^0 + \tilde{\beta}_0^1 + \sum_i \frac{\tilde{\beta}_1^1(k_i)}{\tilde{S}(k_i)} + \ldots \right)$$

- improved predictions

η_{QED} – BLOR (no resummation)

- first preliminary results

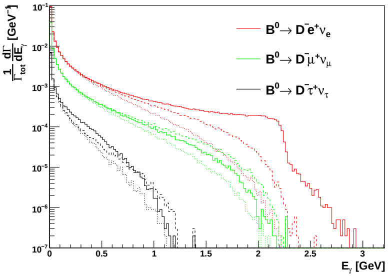
$$\eta_{\text{QED}} = \sqrt{1+\delta^{SD}+\delta^{LD}}$$

- η_{QED} includes statistical + lattice model error of δ^{SD}

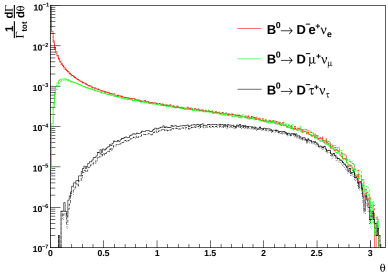
	$1+\delta^{LD}_{\text{QED}}$	stat. error	η_{QED}	error
$B^{\pm}\to D^0 e^{\pm}\nu_e$	1.00452	0.00012	1.078	0.034
$B^0\to D^{\mp} e^{\pm}\nu_e$	1.01946	0.00014	1.085	0.034
$B^{\pm}\to D^0 \mu^{\pm}\nu_e$	1.00456	0.00007	1.078	0.034
$B^0\to D^{\mp} \mu^{\pm}\nu_e$	1.01983	0.00010	1.085	0.034

$\to$ QED breaks isospin symmetry

Differential distributions – SHERPA/PHOTONS++



spectrum of radiative energy loss



photon angular distribution

sold line – full $\mathcal{O}(\alpha G_F^2)$ result
dashed line – approximated $\mathcal{O}(\alpha G_F^2)$ result using dipole splitting kernels
dotted line – exponentiated YFS-kernels only

Conclusion

Done:

- consistent use of already built-in components in new approach
- integration of $R + S$ converges
- numbers seem to be right
- inclusion of resummed corrections real extra emission via α_S rescaling

Todo:

- determine $\left(\frac{R}{B}\right)_{max}$ for POWHEG matching
- imposing upper cut-off J on real emission to make cross sections exclusive for multijet merging

Conclusion

Done:

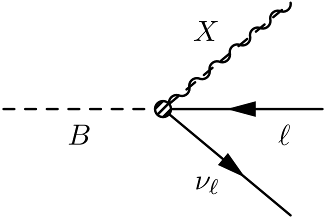
- calculation of $\mathcal{O}(eG_F)$ amplitudes and counter terms (exept for $S \to V\ell\nu$)
- almost everything is implemented in BLOR and PHOTONS++

Todo:

- finalise implementations
- cross check of Monte Carlo output for the two different methods
- cross check for different renormalisation schemes
- write-up

Appendix

Phenomenological LO decay – $\mathcal{O}(G_F)$



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FS scalar
$$\begin{aligned} \langle X|V^\mu|B\rangle &= f_+(t)(p_B+p_X)^\mu + f_-(t)(p_B-p_X)^\mu \\ \langle X|A^\mu|B\rangle &= 0 \end{aligned}$$

FS vector
$$\begin{aligned} \langle X|V^\mu|B\rangle &= 2ig(t)\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu p_{B\rho} p_{X\sigma} \\ \langle X|A^\mu|B\rangle &= f(t)\varepsilon^{\mu *} + a_+(t)(p_B+p_X)^\mu(p_B-p_X)^\nu\varepsilon^*_\nu \\ &\quad + a_-(t)(p_B-p_X)^\mu(p_B+p_X)^\nu\varepsilon^*_\nu \end{aligned}$$

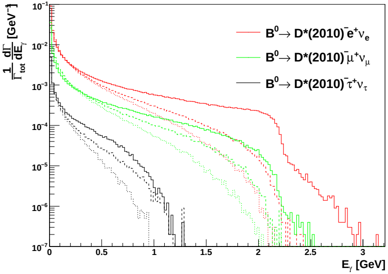
Renormalisation Schemes

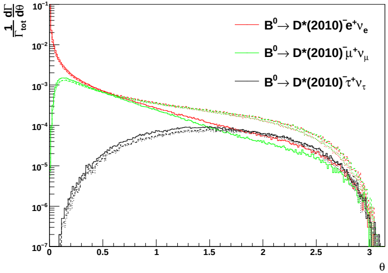
- dimensional regularisation
- on-shell scheme, best suited to be interfaced with otherwise LO Monte Carlo
- need to renormalise only wave functions and phen. vertex:
  1. residues vanish at pole
  2. first order corrections vanish at maximum physical momentum transfer to leptonic system

Advantages over LL Factorization

		phen. model	PHOTOS
V	t dependency in FF	approximate	none
V	corrections on kinematics	yes	none
V	vertex emission	yes	none
V	contribution to decay rate	yes	none
R	t dependency in FF	yes	none
R	full photon emission coupling	yes	resummed soft limit
R	vertex emission	yes	none
R	parton level emission	none	none
R	emission ration at first order	yes	approximate
RV	total rate change	yes/no	none

Differential distributions – SHERPA/PHOTONS++





spectrum of radiative energy loss photon angular distribution

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