Anomalous gauge couplings in SHERPA

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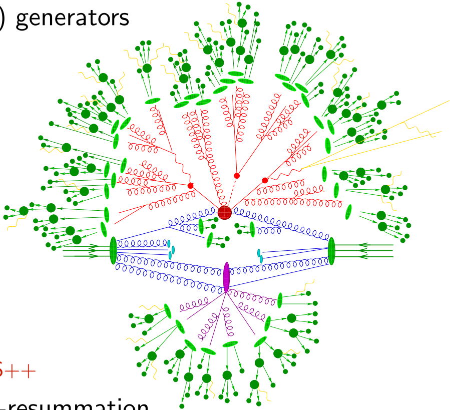
Contents

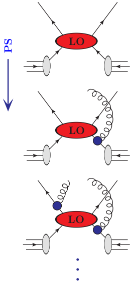
The SHERPA event generator framework



- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044
  COMIX JHEP12(2008)039
  CS subtraction EPJC53(2008)501
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using YFS-resummation
  PHOTONS++ JHEP12(2008)018

Sherpa's traditional strength is the perturbative part of the event
MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO
$\rightarrow$ full analytic control mandatory for consistency/accuracy

Recent developments – MEPS@NLO



Parton showers

resummation of (soft-)collinear limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- MEPS@NLO combines multiple NLOPS – keeping either accuracy

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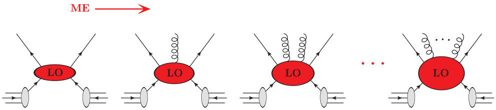

Matrix elements

fixed-order in α_s
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

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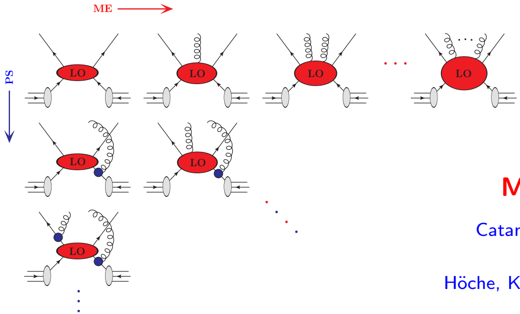

MEPS (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053

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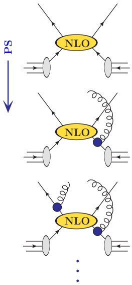

NLOPS (MC@NLO,POWHEG)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

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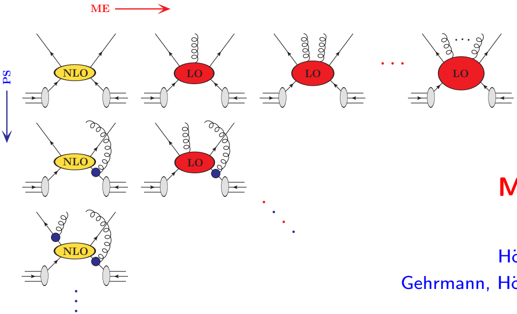

MENLOPS

Hamilton, Nason JHEP06(2010)039

Höche, Krauss, MS, Siegert JHEP08(2011)123

Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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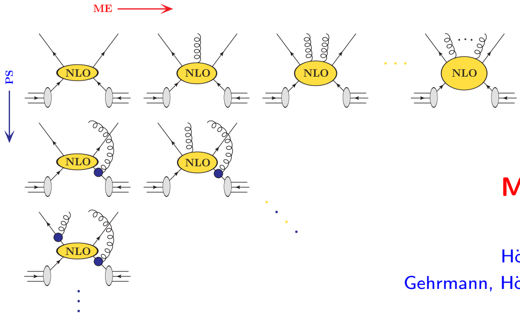

MEPS@NLO

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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Recent results

Fixed-mulitplicity NLOPS (MC@NLO)

- $pp \to W + 0, 1, 2, 3$jets – SHERPA+BLACKHAT
  Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001
- $pp \to$ jets – SHERPA+BLACKHAT Höche, MS Phys.Rev.D86(2012)094042
- $pp \to t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS
  Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

Multijet merging at NLO accuracy (MEPS@NLO)

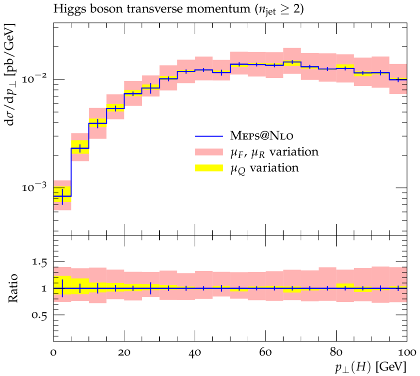
- $pp \to W +$ jets – SHERPA+BLACKHAT Höche, Krauss, MS, Siegert JHEP04(2013)027
- $e^+e^- \to$ jets – SHERPA+BLACKHAT
  Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
- $pp \to h +$ jets – SHERPA+GOSAM Höche, Krauss, MS, Siegert, in YR3 arXiv:1307.1347
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM
  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS
  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

Recent results

$pp \to h$+jets (0,1,2 @ NLO; 3 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{def}}$
  $\mu_{\text{core}} = m_h$
- NLO dependence
  for $pp \to h$+0,1,2 jets
  LO dependence
  for $pp \to h$+3 jets
- $Q_{\text{cut}} = 20$ GeV

Höche, Krauss, MS, Siegert in preparation



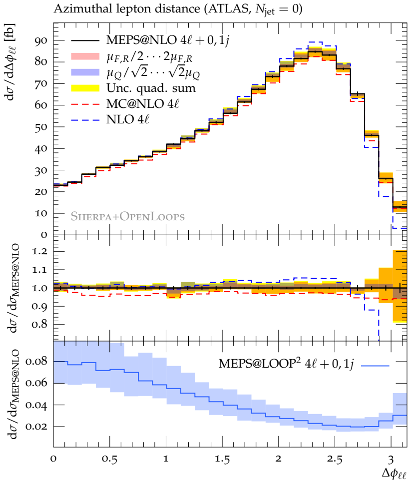
Recent results

Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

$pp \to 4\ell + 0, 1$ jets

- virtuals from OPENLOOPS
- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{core}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
  $\mu_{\text{core}} = \frac{1}{2}\left(E_\perp^{W^+} + E_\perp^{W^-}\right)$
- NLO dependence
  for $pp \to 4\ell$+0,1 jets
  LO dependence
  for $pp \to 4\ell$+2 jets
- $Q_{\text{cut}} = 20$ GeV

includes loop-induced processes
$gg \to 4\ell$ and
$gg \to 4\ell+g$, $gq \to 4\ell+q$, $q\bar{q} \to 4\ell+g$



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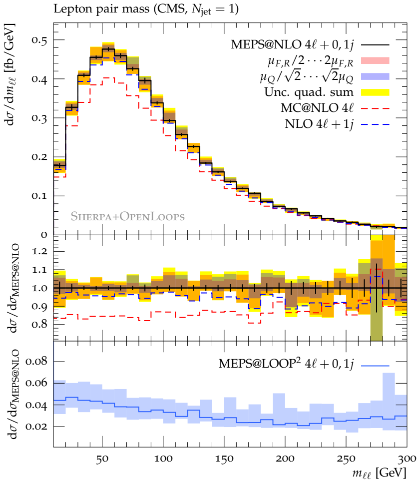
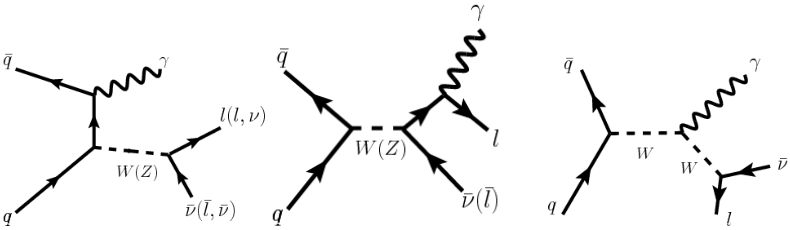


Anomalous gauge coupling model in SHERPA

Gleisberg et.al. JHEP02(2009)007

- available since ∼2005
- details of Lagrangian or Feynman rules implemented
- unitarisation based on form factors
- e.g. $pp \to W\gamma/Z\gamma + X$



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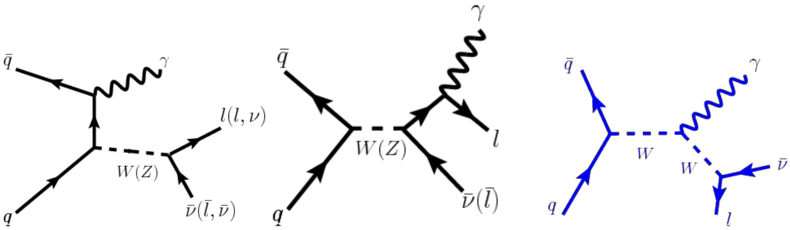


Anomalous triple gauge couplings

Hagiwara et.al. Nucl.Phys.B282(1987)253

Operators for interaction of two charged and one neutral gauge boson

$$\begin{aligned}\mathcal{L}_{WWV}/g_{WWV} =& ig_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V^\nu W^{\mu\nu}\right)\\ &+ i\kappa_V W^\dagger_\mu V_\nu W^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu}W^\mu_\nu V^{\nu\lambda}\\ &- g_4^V W^\dagger_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V \epsilon^{\mu\nu\rho\sigma}(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu)V_\sigma\\ &+ \frac{i\tilde{\kappa}_V}{2}\,\epsilon^{\mu\nu\rho\sigma}W^\dagger_\mu W_\nu V_{\rho\sigma} + \frac{i\tilde{\lambda}_V}{2m_W^2}\,\epsilon^{\mu\nu\rho\sigma}W^\dagger_{\mu\lambda}W^\lambda_\nu V_{\rho\sigma}\ ,\end{aligned}$$

- $V = \gamma/Z$, $g_{WW\gamma} = -e$ and $g_{WWZ} = -e\cot\theta_W$
- $g_1^V = 1 + \Delta g_1^V$ and $\kappa_V = 1 + \Delta\kappa_V$
- in Standard Model:
  $\Delta g_1^V = \Delta\kappa_V = \lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$

Anomalous triple gauge couplings – $\gamma - Z$ ints.

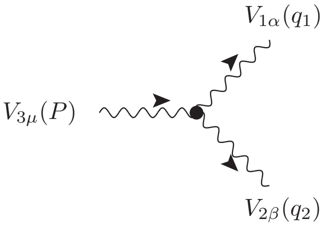
Hagiwara et.al. Nucl.Phys.B282(1987)253

$$\Gamma^{\alpha\beta\mu}_{ZZV^*}(q_1,q_2,P) = \frac{i\left(P^2-m_V^2\right)}{m_Z^2}\left[f_4^V\left(P^\alpha g^{\mu\beta}+P^\beta g^{\mu\alpha}\right)+f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right]$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V^*}(q_1,q_2,P) = \frac{i\left(P^2-m_V^2\right)}{m_Z^2}\left[h_1^V\left(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}\right)\right.$$

$$+\frac{h_2^V}{m_Z^2}P^\alpha\left[(Pq_2)g^{\mu\beta}-q_2^\mu P^\beta\right]$$

$$\left.+h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho}+\frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\right]$$



- in limit on two on-shell coupling to one off-shell gauge boson
  $\rightarrow$ in general more coupling terms   Gounaris et.al. Phys.Rev.D62(2000)073012
- $\Gamma_{Z^*Z^*Z^*} = \Gamma_{Z_1Z_2Z_3^*}+\Gamma_{Z_2Z_3Z_1^*}+\Gamma_{Z_3Z_1Z_2^*}$
- in Standard Model: $f_4^V = f_5^V = h_1^V = h_2^V = h_3^V = 0$

Anomalous quartic gauge couplings

Gangemi et.al. hep-ph/0001065

Quartic interactions respecting $SU(2)$ custodial symmetry

$$\mathcal{L}_4 = \alpha_4 e^4 \bigg(\tfrac{1}{2} W^\dagger_\mu W^{\dagger\mu} W_\nu W^\nu + \tfrac{1}{2} \left(W^\dagger_\mu W^\mu\right)^2 + \frac{1}{c_W^2} W^\dagger_\mu Z^\mu W_\nu Z^\nu + \frac{1}{4c_W^4} \left(Z^\mu Z^\mu\right)^2 \bigg)$$

$$\mathcal{L}_5 = \alpha_5 \left(\left(W^\dagger_\mu W^\mu\right)^2 + \frac{1}{c_W^2} W^\dagger_\mu Z^\mu W_\nu Z^\nu + \frac{1}{4c_W^4} \left(Z^\mu Z^\mu\right)^2 \right)$$

- in Standard Model: $\alpha_4 = \alpha_5 = 0$

Unitarisation

Introduce $\hat{s}$ dependent form factor

$$a(\hat{s}) = \frac{a_0}{(1 + \hat{s}/\Lambda^2)^n}$$

- a coupling parameter
- Λ new physics scale, typically $\mathcal{O}(1) - \mathcal{O}(10)$ TeV
- n exponent, typically 2 or 3
- m exponent, typically 1

$\Rightarrow$ regularises cross sections for suitable Λ, n and m

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SHERPA's AGC model used in

Usage in ATLAS

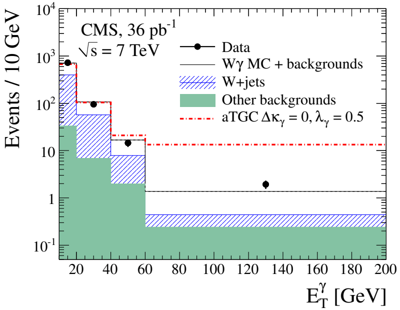
- arXiv:1110.5016 neutral triple gauge couplings in ZZ
- arXiv:1211.6096 neutral triple gauge couplings in ZZ

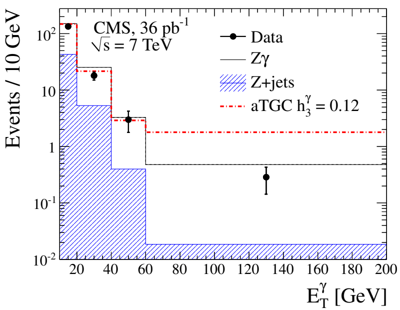
Usage in CMS

- arXiv:1105.2758 neutral and charged triple gauge couplings in $W\gamma$ and $Z\gamma$
- arXiv:1211.4890 neutral triple gauge couplings in ZZ
- arXiv:1308.6832 neutral and charged triple gauge couplings in $W\gamma$ and $Z\gamma$
- arXiv:1309.1117 neutral triple gauge couplings in $Z\gamma$
- CMS-PAS-SMP-13-005 neutral triple gauge couplings in ZZ

Example results

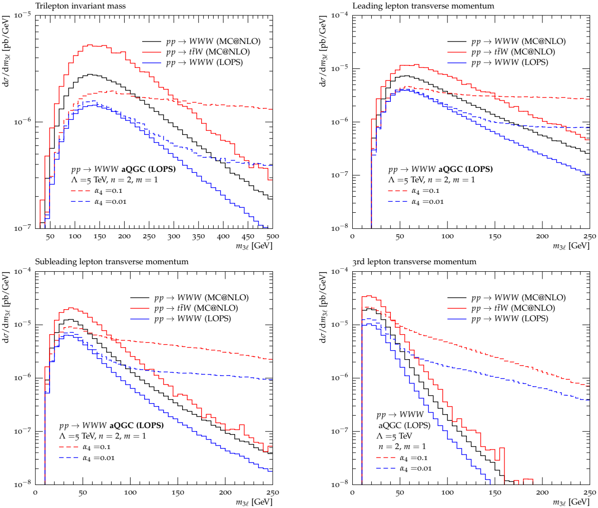
CMS collaboration Phys.Lett.B701(2011)535-555





Example for scan used to derive limits on $\Delta\kappa_\gamma$, λ_γ, h_3^γ, h_4^γ with $a \to a/\Lambda^n$.

Example results



$pp \to 3\ell + \text{MET} + X$

- SM signal and backgrounds can be simulated at NLOPS/MEPS@NLO accuracy
- AGC signal can be simulated at NLOPS accuracy if virtual correction is known
- MEPS (CKKW) does give the correct shapes

Photon induced processes

Archibald, et.al. Nucl.Phys.179(2008)218-225; Hall, Krauss, Schönherr in preparation

Photon initial state $\gamma\gamma \to X$

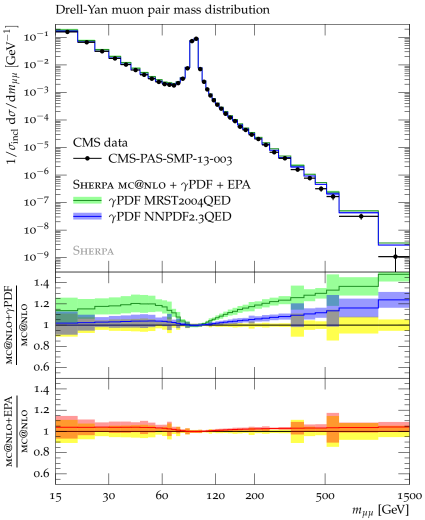
a) γPDF
inelastic process
probes photon content of proton

b) EPA
elastic process
photon bremsstrahlung
(Weizsäcker-Williams approx.)

Examples:

- $pp \to \ell\ell + X$
- $pp \to W^+W^- + X$

MC@NLO (QCD), γPDF, EPA contribs can also be used to probe AGCs



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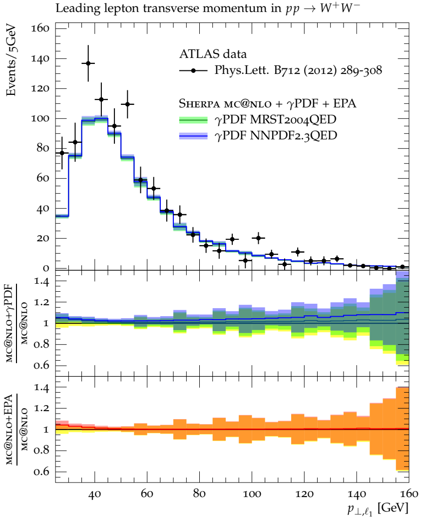

Matrix element weights and reweighting

SHERPA-2.0.0 will contain an Python interface
(available since SHERPA-2.0.β_2)

- gives access to SHERPA's matrix elements (AMEGIC++ & COMIX)
- takes external four momenta and flavours
- returns colour and helicity summed/averaged matrix elements including symmetry and flux factors

$\Rightarrow$ can be used to reweight a given sample to different AGCs

- care must be taken for very different values of the AGCs or in the case of the emerging of new Lorentz structures (cannot reweight what is missing in the original sample)

Conclusions

- MC@NLO including exact soft-gluon colour coherence
- multijet merging at NLO accuracy (MEPS@NLO)
  $\rightarrow$ preserves NLO accuracy at every jet multiplicity and and all resummation properties of the parton shower
- extensive implementation of anomalous gauge couplings (aTGCs, aQGCs)
- restrictions in neutral triple AGC sector
  $\rightarrow$ practically irrelevant when $m_{\ell\ell} \sim m_Z$ is used in analysis
- can be embedded in MEPS (multijet merging)
- can be embedded in MC@NLO, MENLOPS, MEPS@NLO where one-loop is known
- tools for ME-reweighting provided

imminent release SHERPA-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!