HERWIG 7
&
Anomalous coupling, top-mass and parton-shower effects in W^+W^-

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1) Introduction to HERWIG 7

2) Anomalous coupling, top-mass and parton-shower effects in W^+W^-
With HERWIG 7 & GOSAM

Introduction to HERWIG 7

[https://herwig.hepforge.org/]

[herwig@projects.hepforge.org]

On behalf of the HERWIG team

J. Bellm, S. Gieseke, D. Grellscheid, S Plätzer, M. Rauch,
CR, P. Richardson, P. Schichtel, M.H. Seymour, A. Siódmok, A. Wilcock;
N. Fischer, M.A. Harrendorf, G. Nail, A. Papaefstathiou, D. Rauch

- Exclusive event generation in particle collisions at HEP colliders, up to the particle level
- Successor of the HERWIG++ 2 and HERWIG 6 series, superseding the physics capabilities of both
- Written in C++ and based on THEPEG

  Supports LHAPDF and HepMC event output and/or Rivet

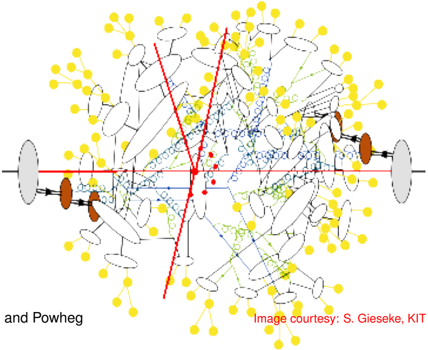
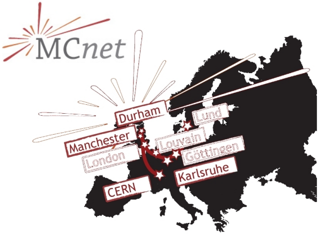


Image courtesy: S. Gieseke, KIT

- Perturbative physics
  - ⇝ Hard process at NLO QCD
    - -.- LHE file input
    - -.- Built-in LO and NLO matrix elements (MEs)
    - -.- Automated assembly of NLO QCD calculations
    - -.- Interfacing various external ME providers
  - ⇝ Parton shower Monte Carlo
    - -.- Angular-ordered parton shower
    - -.- Dipole shower
    - -.- Decays of heavy resonances (incl. spin correlations)
    - -.- Dedicated Powheg matched / matrix element corrected
    - -.- Automated matching machinery, algorithms based on MC@NLO and Powheg
- Non-perturbative physics
  - ⇝ Hadronization
    - -.- Cluster hadronization model
    - -.- Color reconnection
    - -.- Decays
  - ⇝ Underlying event
    - -.- MPI (eikonal multiple interaction model)
  - ⇝ Diffractive processes
- BSM machinery: Built-in processes as well as UFO model file input

[https://thepeg.hepforge.org/]
[https://lhapdf.hepforge.org/]
[https://rivet.hepforge.org/]

- HERWIG 7 $\in$ MCnet
  [http://www.montecarlonet.org/]
  [http://www.montecarlonet.org/index.php?p=Projects/herwig]



- Distributed over several institutes
  - IPPP, Durham
  - KIT, Karlsruhe
  - CERN Theory Group
  - Particle Physics Group, Manchester
  - CR at FSU, Tallahassee (no official MCnet node)

- HERWIG++ has been developed over $\sim$10 years [hep-ph/0311208, ..., 0803.0883, ..., 1310.6877]
  Intention: Fully replace and supersede the capabilities of FORTRAN HERWIG [hep-ph/0011363, hep-ph/0210213]

- Paradigm shift towards NLO $\rightarrow$ Release of HERWIG 7 [arXiv:1512.01178]
  The current version is Herwig 7.0.3

- As the successor of the HERWIG++ 2 and HERWIG 6 series
  HERWIG 7 supersedes the physics capabilities of both its predecessors
  Focusing greatly on precission and NLO automatization

- The MATCHBOX module forms the basis for the automated NLO capabilities of HERWIG 7
  Fully integrated framework for automated NLO matching, with full control over the fixed order input
  Effort led by S. Plätzer with substantial contributions by J. Bellm, M. Rauch, CR, A. Wilcock

  - ⇝ Automated setup for a full NLO QCD calculation in the subtraction formalism
  - ⇝ Implementation of the CS dipole subtraction method (massless [Catani, Seymour, '96] and massive [Catani, Dittmaier, Seymour, Trocsanyi, '02])
  - ⇝ Fixed-order input: In-house calculations and Interfaces to various external matrix-element providers
  - ⇝ Automated diagram based multi-channel phase-space sampling and adaptive phase-space integration
  - ⇝ Fully automated matching algorithms: Subtractive (based on MC@NLO [Frixione, Webber, '02, '06]) and multiplicative (based on Powheg [Nason '04; Aliolo, Nason, Oleari, Re '08])
  - ⇝ Plug-ins to the two shower variants in HERWIG 7

  All in one framework: External matrix-element codes fully interfaced, no event files to move around anymore
  Beta version of MATCHBOX already introduced previously. Technical report about the recently extended MATCHBOX version in HERWIG 7 in preparation

- Two showers: Angular ordered and dipole based
  Spin correlations and QED radiation
  Improved kinematic reconstructions

- Validation facilities
  Internal cross-checks on matrix-element level and phase-space generation
  Determining shower uncertainties

- EW corrections and several other CONTRIB extensions
  E.g. third matching scheme (KRKNLO [Jadach, Nail, Placzek, Sapeta, Siodmok, Skrzypek]) available in H7 for Drell-Yan and Higgs boson production

- Greatly improved installation, steering and documentation

$A_n^{(0)}, A_n^{(1)}$
$|A_n^{(0)}|^2, \langle A_n^{(0)}|A_n^{(1)}\rangle, |A_n^{(0)}|_{ij}^2$

$P(\tilde{q}), D(p_\perp)$
$R_{MEC}(p_\perp)$

$A_n^{(0)}$
$|A_n^{(0)}|_{ij}^2$

$$O_{\rm NLO}^{\rm matched} = \left[\int \mathrm{d}\Phi_n\left(\mathcal{B}+\bar{\mathcal{V}}\right)+\int \mathrm{d}\Phi_n\,\mathcal{B}\int_{\mu_{IR}^2}^{Q^2} \mathrm{d}\mathcal{P}(q^2) - \int \mathrm{d}\Phi_{n+1}\,\mathcal{A}\,\Theta(q^2-\mu_{IR}^2)\right]O_n$$

$$+\left[\int \mathrm{d}\Phi_{n+1}\,\mathcal{R} - \int \mathrm{d}\Phi_n\,\mathcal{B}\int_{\mu_{IR}^2}^{Q^2} \mathrm{d}\mathcal{P}\left(q^2\right) - \int \mathrm{d}\Phi_{n+1}\,\mathcal{A}\,\Theta\left(\mu_{IR}^2-q^2\right)\right]O_{n+1}$$

$A_{n+1}^{(0)}$
$|A_{n+1}^{(0)}|^2$

$P(\tilde{q}), D(p_\perp)$
$R_{MEC}(p_\perp)$

$A_n^{(0)}$
$|A_n^{(0)}|_{ij}^2$

- Interfaces at amplitude level
  - Built-in (one-loop) helicity sub-amplitudes, spinor helicity library and caching facilities
  - MG5_aMC@NLO [https://launchpad.net/mg5amcnlo] (color-ordered sub-amplitudes) Color bases: ColorFull [M. Sjödahl, S. Plätzer], CVolver [S. Plätzer]
  - In-house calculations, e.g. parts of HJets++ [F. Campanario, T. Figy, S. Plätzer, M. Sjödahl]

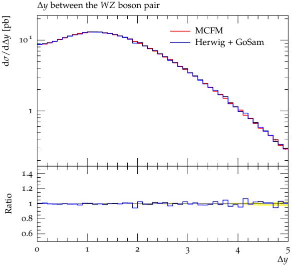
- Interfaces at squared amplitude level
  - Dedicated interfaces [HEJ [https://hej.hepforge.org/]; NLOJET++ [www.desy.de/ znagy/Site/NLOJet++.html]]
  - BLHA(2) [GoSam [https://gosam.hepforge.org/]; NJet [https://bitbucket.org/njet/njet/]; OpenLoops [https://openloops.hepforge.org/]; VBFNLO [https://www.itp.kit.edu/vbfnlo/]]

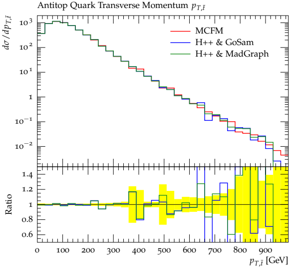
- Shower plugins:
  - Angular ordered $P(\tilde{q})$ or Dipole shower $D(p_\perp)$
  - MEC $R_{MEC}(p_\perp)$

MATCHBOX VALIDATION FIXED ORDER

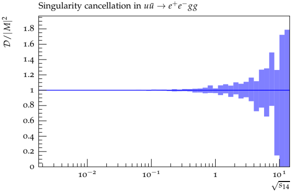
Plots by N. Fischer, D. Rauch, J. Bellm, S. Plätzer (pre-release: HERWIG++ and MATCHBOX beta)

- Extensive validation against e.g. MCFM

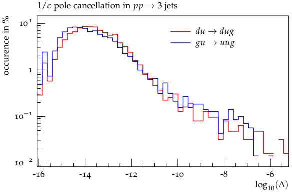




- Various internal cross checks: Subtraction checks, pole cancellation.



$pp \to Z +$ jet (GoSam)



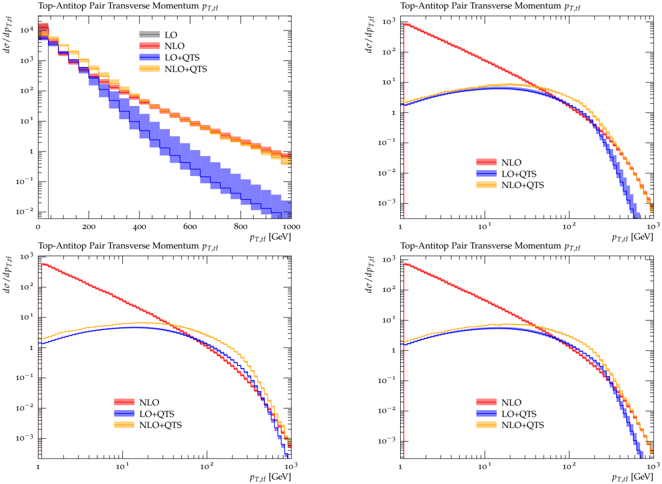
$pp \to 3$ jets (NJet)

MATCHING VALIDATION: TTBAR@NLO

NLO matched, 14TeV

[J. Bellm, S. Gieseke, D. Rauch, CR, S. Plätzer, P. Richardson, A. Wilcock; in prep.]

Plots by D. Rauch (pre-release: HERWIG++ and MATCHBOX beta)



- Subtractive matching with angular-ordered shower. Shower start scale $Q^2 = \mu_Q^2 = \mu^2$
- Hard scale variation: $\mu^2 = \mu_F^2 = \mu_R^2$ by factors of 0.5 and 2
- Top: TopMinMTScale $\mu^2 = \mu^2_{\min_{t\bar{t}}\{m_T\}} = \min_{i=t,\bar{t}}\left(m_i^2 + p_{T,i}^2\right)$
- Bottom: TopMassScale $\mu^2 = \mu^2_{m_{t\bar{t}}} = (p_t + p_{\bar{t}})^2$ and TopMTScale $\mu^2 = \mu^2_{m_{T,t\bar{t}}} = \sum_{i=t,\bar{t}}\left(m_i^2 + p_{T,i}^2\right)$ respectively

- Necessary dependencies
  - ⇝ THEPEG (LHAPDF, HEPMC, RIVET), FASTJET, BOOST
- OLP dependencies (if desired)
  - ⇝ GOSAM, MG5_AMC@NLO, OPENLOOPS, NJET, VBFNLO, ...
- Installing HERWIG 7 is as easy as it gets:
  - ⇝ Go to https://herwig.hepforge.org/downloads.html
  - ⇝ Either download and install manually (just follow the instructions)

    `./configure --prefix=/Your-Desired-Installation-Path/`
    `--with-thepeg=/Path-To-ThePEG-Installation/ --with-fastjet=/.../`
    `--with-gosam=/.../ --with-madgraph=/.../ --with-openloops=/.../` etc.
    `make && make install`
  - ⇝ Or get the automated bootstrap script, which will install everything for you, including all dependencies
- Using HERWIG 7
  - ⇝ Define your "infile", e.g. `LHC-Matchbox.in` (a set of default infiles also comes with the installation)
  - ⇝ Read: `Herwig read LHC-Matchbox.in` → Returns the generator run card `LHC-Matchbox.run`
    Builds the MEs and performs the grid adaption for the phase-space sampling
    The grid adaption can also be done in parallel: `Herwig build` and `Herwig integrate`
  - ⇝ Run: `Herwig run LHC-Matchbox.run -N 1000000` → Produces 1M events as HEPMC, RIVET histograms, ...
  - ⇝ A detailed tutorial can be found on https://herwig.hepforge.org/tutorials/index.html
- The "infile"
  - ⇝ HERWIG++ is/was known to have complicated input cards
  - ⇝ With the new release of HERWIG 7 also the infile structure received a face lifting:
    - -.- Based on MATCHBOX infiles
    - -.- New: Snippet structure, i.e. dedicated infile snippets to contain a specific set of commands for a specific task

Choose collider type and energy

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 14000*GeV

## Process
cd /Herwig/MatrixElements/Matchbox
set Factory:OrderInAlphaS 2
set Factory:OrderInAlphaEW 0
do Factory:Process p p -> t tbar

## ME provider
# read Matchbox/MadGraph-GoSam.in
# read Matchbox/MadGraph-NJet.in
read Matchbox/MadGraph-OpenLoops.in

## Cut selection and scale choice
# read Matchbox/DefaultPPJets.in
# insert JetCuts:JetRegions 0 FirstJet
cd /Herwig/MatrixElements/Matchbox
set Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/TopMinMTScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
# read Matchbox/FourFlavourScheme.in
read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014.in

## Analyses
# insert /Herwig/Analysis/Rivet:Analyses 0 XXX_2015_ABC123
# insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to t\bar{t}$

Which hard process do you want?

Choose order in α_S and α_{EW}, choose process

Have your favourite choice of ME provider!

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Choose cuts and scale

More examples can be found in the documentation

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```

Match on two choices of shower algorithms
MC@NLO or Powheg / angular ordered or dipole shower
Simple MEC also possible

Fixed order runs at LO or NLO are also an option!
Just pick your favourite process, or give us your favourite ME

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```

E.g. `MuDown.in`

```
cd /Herwig/MatrixElements/Matchbox
set Factory:RenormalizationScaleFactor 0.5
set Factory:FactorizationScaleFactor 0.5
set MEMatching:RenormalizationScaleFactor 0.5
set MEMatching:FactorizationScaleFactor 0.5
cd /Herwig/Shower
set ShowerHandler:RenormalizationScaleFactor 0.5
set ShowerHandler:FactorizationScaleFactor 0.5
cd /Herwig/DipoleShower
set DipoleShowerHandler:RenormalizationScaleFactor 0.5
set DipoleShowerHandler:FactorizationScaleFactor 0.5
```

Scale variations on hard scales
and
shower scales!

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Which flavour(s)?
Which PDF set?
Other choices are also possible

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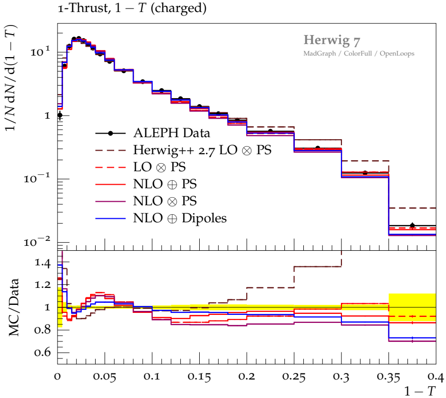
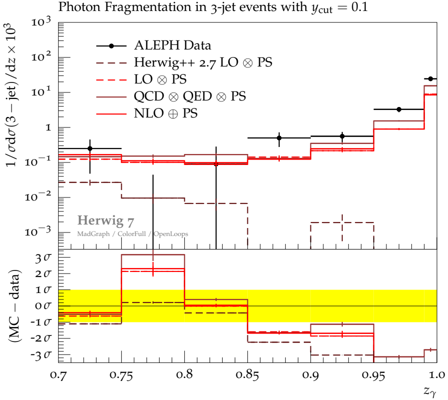
Which RIVET analyses?

HEPMC output also possible

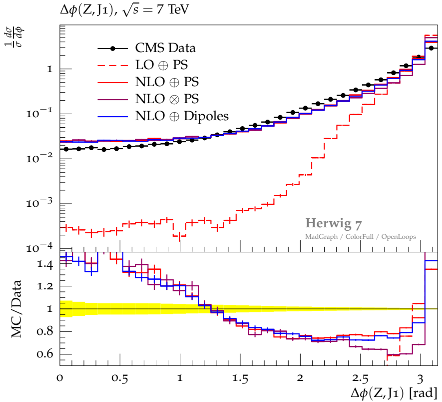
built–in analyses also possible

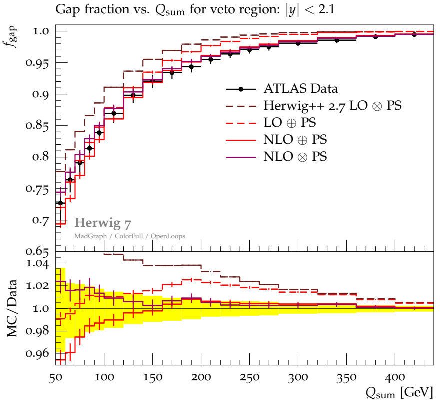




- Thrust distribution at LEP.
  ALEPH_1996_S3486095 [Phys. Rept. 294 (1998) 1-165].
- HERWIG++: Too many hard events (regardless of NLO matching).
- Improvements to the angular-ordered parton shower in HERWIG 7: All matching variants give a similarly good description of the data.

- Photon fragmentation in three-jet events at LEP.
  ALEPH_1996_S3196992 [Z. Phys. C69 (1996) 365-378].
- Events at $z_\gamma = 1$ are isolated photons, events at lower z_γ are from hard collinear photon emission off final state quark jets.
- HERWIG++: No component at large z_γ at all.
- Including photon emission in the angular-ordered parton shower in HERWIG 7: All variants are much closer to the data.





- Separation in azimuthal angle between Z boson and hardest jet, in $Z + \text{jets}$ at 7 TeV LHC. CMS_2013_I1209721 [Phys. Lett. B722 (2013) 238-261].
- $\Delta\phi \sim \pi$: The Z gains transv. momentum from recoiling against a single hard parton (LO conf.).
- $0 < \Delta\phi < \pi$: Z recoils against two or more jets.
- Need NLO corrections: Cross-checking the two NLO matching schemes and the two shower variants in HERWIG 7 (both w/ subtr. matching).

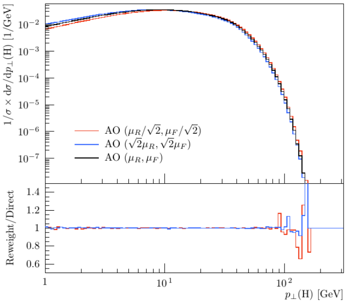
- Fraction of events with less than Q_{sum} transverse energy in $|y| < 2.1$, in $t\bar{t}$ events at 7 TeV LHC. ATLAS_2012_I1094568 [Eur. Phys. J. C72 (2012) 2043].
- HERWIG++: Far too little jet activity (too many gap events).
- HERWIG 7: LO plus angular-ordered shower is closer to the data at small Q_{sum}, but not at high Q_{sum}. However, both NLO matching schemes describe the data well.

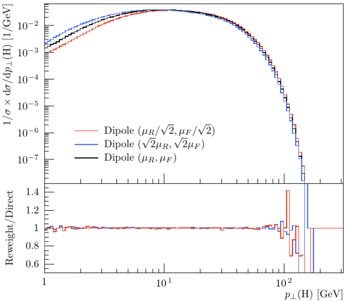
Parton-Shower Reweighting

[Bellm, Plätzer, Richardson, Siodmok, Webster, arXiv:1605.08256]

Run-time improvement via parton-shower reweighting

Transverse momentum of Higgs boson in $pp \to gg \to H$, $\sqrt{S} = 13$ TeV





- Very good agreement between individual runs for different scales and reweighting
- **Significant speed improvements**: Time in seconds for 10 000 events ...

Shower	Hadron-ization & Decays	No MPI			MPI					
					Primary			All		
		Direct	Reweight	Frac. Diff.	Direct	Reweight	Frac. Diff.	Direct	Reweight	Frac. Diff.
AO	Off	79.8	94.2	-0.18	384.4	249.1	0.35	416.7	375.1	0.09
	On	183.2	128.3	0.30	738.7	364.3	0.51	751.4	482.3	0.35
Dipole	Off	99.6	52.8	0.47	435.4	161.9	0.63	462.7	213.6	0.54
	On	271.8	108.2	0.60	831.7	286.6	0.65	859.2	340.1	0.60

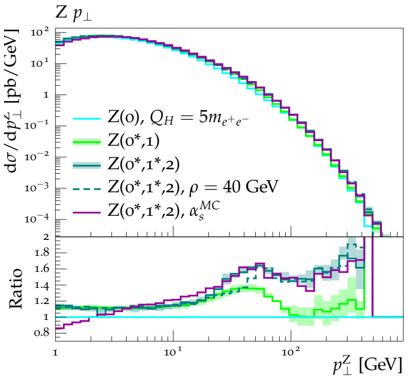
[Bellm, Gieseke, Plätzer]

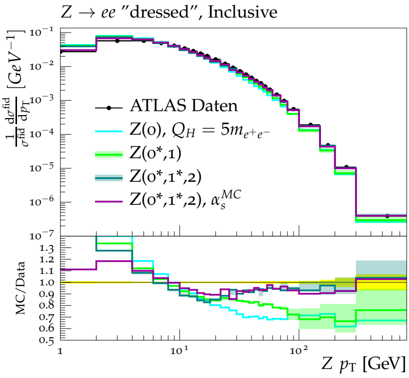
See also [arXiv:1607.02002] for an outlook

Outlook: **Combination** of different **jet multiplicities**

Part of next release → HERWIG 7.1

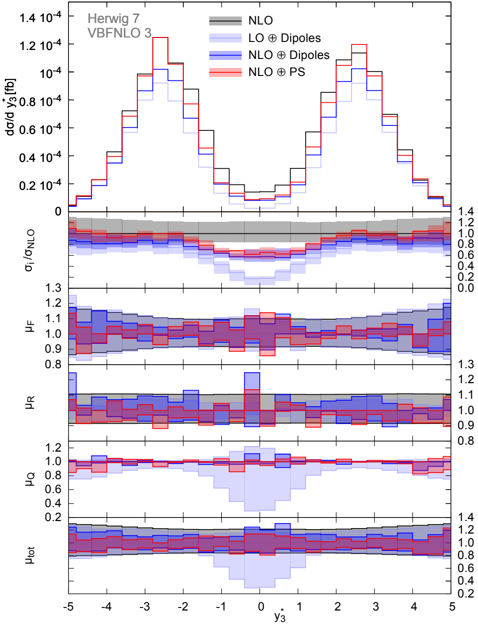
Example: $pp \to e^+e^- + X$





[ATLAS Collaboration, JHEP 1409 (2014) 145]

- $Z(0*,1*,2) \to Zj$@NLO in hard region
- soft region stable



Parton-shower effects and matching systematics in

$$pp \to W^+W^-jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$$

via vector-boson fusion

Rapidity of third jet relative to two tagging jets

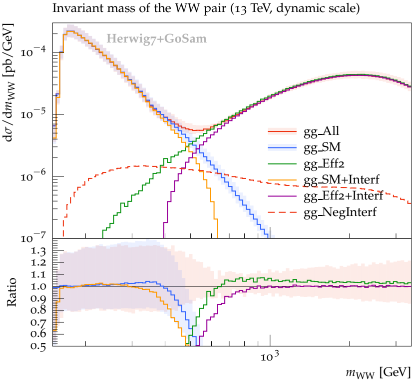
$$y_3^* = y_3 - \frac{y_1+y_2}{2}$$

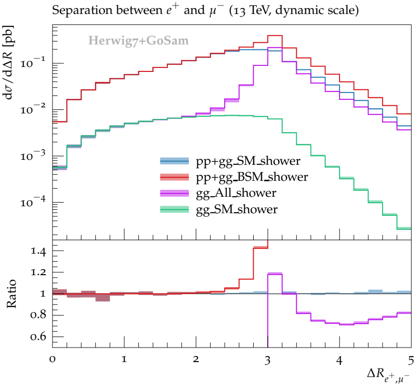
central rapidity gap is an important feature of the process

$\to$ stabilized at NLO

$\to$ good agreement between both parton showers

- Special focus on gluon SM initiated (loop-induced) as well as BSM initiated (EFT dimension-8 operators).
- Further: Add SM quark initiated as well as a parton shower (angular-ordered shower with subtractive matching).





- Gluon initiated, fixed order, varying μ_R and μ_F.
- Various contributions:
  - SM (gg_SM), pure BSM (gg_Eff2) and SM+BSM (gg_All).
  - Negative SM/BSM interference (gg_NegInterf).
  - SM plus interf. (gg_SM+Interf), pure BSM plus interf. (gg_Eff2+Interf).

See part 2)

- All partonic channels (either w/ or w/o BSM), plus shower, varying μ_Q.
- 0-jet limit: ΔR from difference in rapidity; $\Delta\phi = 0$.
- Additional radiation: $\Delta R < \pi$ from NLO real and shower emissions off gg.
- $\Delta R > \pi$: With full partonic contribution still sensitive to BSM (stable against QCD activity).

- HERWIG 7 has expanded its range of applicability to a multitude of underlying hard processes at NLO QCD, where the NLO automatization is centered on the MATCHBOX module:
  - ⇝ Fully automated NLO QCD setup in the subtraction paradigm.
  - ⇝ Two NLO matching algorithms, with plug-ins to the two shower algorithms of HERWIG 7.
  - ⇝ Multi-channel phase-space sampling and adaptive Monte Carlo integration.
  - ⇝ Interfaces to various external matrix-element providers (through BLHA(2) or on the amplitude level).
- The shower algorithms in HERWIG 7 have been improved greatly.
- The whole framework has been extensively tested.
  - ⇝ Various internal cross checks
  - ⇝ Previous feasability study: NJet+Herwig++/Matchbox [arXiv:1405.1067]
  - ⇝ Previously: GoSam+Herwig++/Matchbox: $pp \to$Z+jet, NLO matched [arXiv:1405.1067]
  - ⇝ Relevant physics processes and data comparison: https://herwig.hepforge.org/plots/herwig7.0/
  - ⇝ Dedicated studies: $pp \to WW$ (SM gluon induced and EFT) [arXiv:1602.05141],
    WW production in VBF [arXiv:1605.07851],
    Shower uncertainties and reweighting [arXiv:1605.01338, arXiv:1605.08256]
- More studies are on their way
  - ⇝ $pp \to t\bar{t}$@NLO, $t\bar{t}j$@NLO, $t\bar{t}H$@NLO
  - ⇝ Heavy flavour production in $Zb\bar{b}$ (4FS vs. 5FS) first applications in [arXiv:1605.04692]
- Always looking to interface new matrix-element providers
- Extending the new framework
  - ⇝ LO and NLO multi-jet merging first applications in [arXiv:1605.04692] (H+jets)
  - ⇝ Improving the shower accuracy by including sub-leading contributions
  - ⇝ EW corrections
  - ⇝ Further studies on mass effects

Stay tuned on https://herwig.hepforge.org/

Anomalous coupling, top-mass and parton-shower effects in W^+W^-

With HERWIG 7 & GOSAM

[JHEP 1605 (2016) 106, arXiv:1602.05141]

J. Bellm (IPPP Durham), S. Gieseke (University Karlsruhe), N. Greiner (University Zurich), G. Heinrich (MPI Munich), S.Plätzer (IPPP Durham & University Manchester), CR (FSU), J.F. v. Soden-Fraunhofen (formerly MPI Munich)

- $pp \to W^+W^- \to e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO QCD, matched to one of HERWIG 7's parton showers
  (GOSAM matrix elements with HERWIG 7 angular ordered parton shower in the HERWIG 7/MATCHBOX framework)
  - ⇝ ... quark induced production channels at NLO
  - ⇝ ... loop induced $gg \to W^+W^- \to e^+\nu_e\mu^-\bar{\nu}_\mu$
  - ⇝ ... effects of anomalous ggW^+W^- couplings
  - ⇝ ... mass effects through top-quark loops
  - ⇝ ... parton-shower effects (HERWIG 7 angular ordered parton shower, subtractive matching)

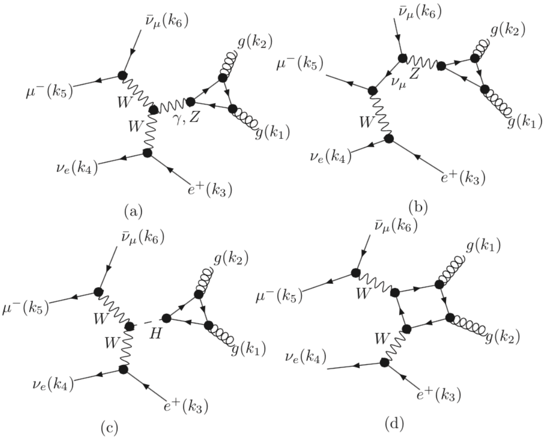
- LHC run II: Precisions tests of EWSB and search for new physics
  (The W^+W^- final state plays thereby a prominent role)
  - ⇝ Continuum $pp \to W^+W^- \to e^+\nu_e\mu^-\bar{\nu}_\mu$ as background to $H \to W^+W^- \to e^+\nu_e\mu^-\bar{\nu}_\mu$
  - ⇝ $pp \to W^+W^-$ +jets as background to new physics

- As we started out
  - ⇝ Slight 2 TeV excess for di-boson resonances (mostly in hadronic decays) reported by ATLAS [arXiv:1506.00962,1503.04677] and CMS [arXiv:1405.1994,1405.3447].
    - -.- Not persisting
  - ⇝ Measured W^+W^- total inclusive Xsec (using leptonic decays) at 7 TeV [arXiv:1210.2979(ATLAS),1306.1126(CMS)] and 8 TeV [ATLAS-CONF-2014-033,arXiv:1301.4698(CMS)] 20% higher compared to (MCFM) NLO calculations [hep-ph/9905386,arXiv:1105.0020], including SM gg [1107.5569]
    - -.- Partially resolved by NNLO prediction [arXiv:1408.5243,1507.02565,1511.08617]
    - -.- Resummation of large logs from jet veto need to be taken into account carefully [1405.5534,1407.4537,1410.4745,1509.07118]
    - -.- Discrepancy for the fiducial Xsec is only at the 1σ level; extrapolation procedure should be revisited [arXiv:1410.4745]

Need for precise studies, at the level of distributions, in view of possible BSM effects!

- $gg \to W^+W^-$ in continuously improving approximations
  - On-shell W bosons [Phys.Rev. D36 (1987) 1570; Phys.Lett. B219 (1989) 488]
  - Leptonic decays (massless fermion loops) [hep-ph/0503094]
  - Leptonic decays (massive bottom and top loops) [hep-ph/0611170]
  - Analytic results, including top-mass and interference effects with $H \to W^+W^-$ [arXiv:1105.0020,1107.5569]
  - ... updated for a Higgs mass of 125 GeV [arXiv:1206.4803,1310.7011]
  - ... NNLO contributions in soft/collinear approximation [1304.3053]
- NNLO corrections to $pp \to W^+W^-$ [arXiv:1408.5243]
  - Removing the discrepancy to data at 7 TeV and reducing the excess at 8 TeV
- Electroweak corrections to $pp \to W^+W^-$
  - EW corrections to the full 4-lepton final state (DPA) [arXiv:1310.1564]
  - Phenomenological study of EW and QCD effects [arXiv:1307.4331]
  - Phenomenological study of EW and QCD corrections[arXiv:1305.5402,1208.3147], plus matching to the angular-ordered PS of Herwig (available in HERWIG 7) [arXiv:1401.3964]
  - EW corrections to the full 4-lepton final state (full) [arXiv:1605.03419]
- $q\bar{q} \to W^+W^-$
  - NLO QCD corrections with on-shell Ws [Phys. Rev. D44 (1991) 1403-1414; Nucl. Phys. B410 (1993) 280-324]
  - Helicity amplitudes, including decays [hep-ph/9803250]
  - Phenomenological studies [hep-ph/9905386,hep-ph/9907305]
  - Matching to PS included in MC@NLO [hep-ph/0204244]]
  - Matching to PS with the POWHEG method implemented in Herwig++ [arXiv:1009.5391]
- Higgs width determination from off-shell production and decay
  - $H \to W^+W^-$ [arXiv:1206.4803,1312.1628,1405.0285,1410.5806]
  - Similarly done recently for $H \to ZZ$ [arXiv:1307.4935]; CMS measurement [arXiv:1405.3455]
- W^+W^-+jet(s)
  - $pp \to W^+W^-$+jet, w/o gg initial state [arXiv:0710.1577,0710.1832,0908.4124], incl. EW corrections [arXiv:1507.07332]
  - Loop induced $gg \to W^+W^-$+jet [arXiv:1205.6987]
  - 4-lepton, $0,1$-jet final states, incl. NLO matching, $H \to WW^*$ interef. and squared quark-loops [arXiv:1309.0500]

- Doubly resonant (two W bosons) and singly resonant (one W)
  - Both necessary in order to maintain gauge invariance
- Include massive top- and bottom-quark loops (the other quarks are assumed massless)
  - Photon-exchange diagrams vanish due to Furry's theorem
  - Z-exchange diagrams: summed over up- and down-type $\propto (m_u^2 - m_d^2) = 0$
  - For arbitrary $p_3^2 \neq p_4^2$ and $m_t \neq m_b \neq 0$, we find: doubly and singly resonant contributions with internal Z cancel
  - Left with Higgs-exchange triangles and gauge-invariant subset of boxes



More details: 2.2 in arXiv:1602.05141

- Include most general EFT operators mediating ggW^+W^-, which first occur at dimension 8

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{dim-8}}, \quad \mathcal{L}_{\text{dim-8}} = \frac{1}{\Lambda^4}\sum_{i=1}^{3} c_i \mathcal{O}_i$$

$$\mathcal{O}_1 = G^a_{\mu\nu} G^{a,\mu\nu} W^I_{\rho\sigma} W^{I,\rho\sigma} \quad , \quad \mathcal{O}_2 = \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} W^I_{\rho\sigma} W^{I,\rho\sigma} \quad , \quad \mathcal{O}_3 = G^a_{\mu\nu} G^{a,\mu\nu} \tilde{W}^I_{\rho\sigma} W^{I,\rho\sigma}$$

G and W: gluon and W field-strength tensors

$\tilde{G}^{a,\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma} \quad , \quad \tilde{W}^{I,\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} W^I_{\rho\sigma} \quad \rightarrow$ Yield CP-odd operators

- Combining QCD corrections from $\mathcal{L}_{\text{SM}}$ and EFT operator contributions from $\mathcal{L}_{\text{dim-8}}$

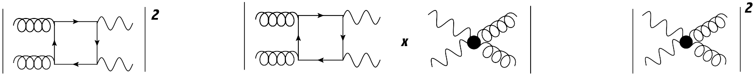
  Simultaneously expand in $\frac{\alpha_s}{2\pi}$ and $\frac{c_i}{\Lambda^4}$

  Requires careful assessment of the various terms

- ggW^+W^- Xsec contribution (loop induced in the SM)

$$\sigma_{ggWW} \sim |\mathcal{M}^{\text{1-loop}}_{\text{SM}}|^2 + 2\,\text{Re}\left(\mathcal{M}^{\text{1-loop}}_{\text{SM}}\,\mathcal{M}^*_{\text{dim-8}}\right) + |\mathcal{M}_{\text{dim-8}}|^2$$

(last term suppressed by $1/\Lambda^8$)



More details and references: 3.1.1 in arXiv:1602.05141

- Effects of EFT operators grow with energy: Eventually violate unitarity
- For stable W bosons ($2 \to 2$): Upper limit on the Xsec (from unitarity requirements)

$$\sigma_{ggWW} \leq \pi/(2\hat{s})$$

- For the process including decays, one could rescale the above by branching ratios
  - ⇝ Does not take into account final-state cuts
  - ⇝ Restrains us from showing a bound in the plots
- One can also calculate upper bounds on the absoulte value of the anom. couplings
  - ⇝ Require unitarity of amplitude for certain set of helicities & project onto partial waves
  - ⇝ Strongest constraints usually from lowest order partial waves
- Strongest constraints come usually from longitud. polarized W bosons
  - ⇝ Due to their pol. vectors' large-momentum behaviour

$$\lim_{k\to\infty} \epsilon^{\mu}_{L}(k) = \frac{k^{\mu}}{M_W} + O(\frac{M_W}{E})$$

Projecting onto the 0th wave shows

The contribution of $\mathcal{O}_3$ vanishes for longitud. polarized W bosons

For $\mathcal{O}_{1/2}$ we get

$$|\frac{c_1}{\Lambda^4}|, |\frac{c_2}{\Lambda^4}| \leq 2\pi/(M_W^2 \hat{s}) \quad , \quad \text{increasing more mildly with energy than expected}$$

So, also look at transverse polarizations as well

$$|\frac{c_1}{\Lambda^4}|, |\frac{c_2}{\Lambda^4}| \leq 30\pi/\left(\hat{s}(26\hat{s} - 11M_W^2)\right) \quad , \quad |\frac{c_3}{\Lambda^4}| \leq \pi/\left(\hat{s}^{3/2}\sqrt{\hat{s} - M_W^2}\right)$$

- **Overall:** $|c_i/\Lambda^4| \lesssim \pi/\hat{s}^{4/2}$

- Hard sub-process generation
  - ⇝ Virtual as well as spin- and colour-correlated tree amplitudes
  - ⇝ One-loop QCD: Fully UV renormalized
  - ⇝ Feynman diagrammatic approach
  - ⇝ QGRAF, FORM and SPINNEY for diagram generation and producing optimized FORTRAN90 code
  - ⇝ 3 libraries for the reduction of one-loop amplitudes: NINJA, GOLEM95, SAMURAI
  - ⇝ Scalar integrals: GOLEM95, ONELOOP
  - ⇝ Complex mass scheme
  - ⇝ Extended rescue system for loop-induced processes

- Extended BSM support
  - ⇝ Import of BSM model files in UFO format
  - ⇝ In accordance with the prescription in the BLHA2 standard for the definition of new couplings
  - ⇝ GoSam input card:
    BSM-SM interferences by specifying the corresponding coupling orders and other sub-process specific settings
    Values of the EFT operator coefficients

- For the processes considered here
  - ⇝ Model file in UFO format, created by extending the SM Lagrangian of FEYNRULES with our EFT operators
  - ⇝ The UFO SM parameters are overwritten in accordance to the BLHA2 standard
  - ⇝ GoSam's diagram filter facilities:
    Compute the additional interference between SM one-loop and EFT coupling with one model file
    Restrict the one-loop contributions to allow for only SM couplings
    Tree-level contributions are allowed to have the EFT couplings

Also specifiy UFO EFT model & diagram filters through GOSAM infile in CWD

Choose collider type and energy

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 13000*GeV

## Process
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaS 2
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaEW 4
# do /Herwig/MatrixElements/Matchbox/Factory:LoopInducedProcess g g -> e+ nu_e mu- nu_mubar
do /Herwig/MatrixElements/Matchbox/Factory:Process p p -> e+ nu_e mu- nu_mubar

## ME provider
# read Matchbox/MadGraph-GoSam.in
read Matchbox/GoSam-GoSam.in

## Cut selection and scale choice
set /Herwig/Cuts/ChargedLeptonCut:PtMin 15.0*GeV
do  /Herwig/Cuts/ChargedLeptonCut:YRange -3.5 3.5
set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
set /Herwig/MatrixElements/Matchbox/Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/FixedScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
read Matchbox/FourFlavourScheme.in
# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to W^+W^-$

Also specifiy UFO EFT model & diagram filters through GOSAM infile in CWD

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 13000*GeV

## Process
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaS 2
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaEW 4
# do /Herwig/MatrixElements/Matchbox/Factory:LoopInducedProcess g g -> e+ nu_e mu- nu_mubar
do /Herwig/MatrixElements/Matchbox/Factory:Process p p -> e+ nu_e mu- nu_mubar
```

Which hard process do you want?

Choose order in α_S and α_{EW}, choose process

```
## ME provider
# read Matchbox/MadGraph-GoSam.in
read Matchbox/GoSam-GoSam.in
```

Have your favourite choice of ME provider!

```
## Cut selection and scale choice
set /Herwig/Cuts/ChargedLeptonCut:PtMin 15.0*GeV
do  /Herwig/Cuts/ChargedLeptonCut:YRange -3.5 3.5
set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
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read Matchbox/FourFlavourScheme.in
# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to W^+W^-$

Also specifiy UFO EFT model & diagram filters through GOSAM infile in CWD

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## Process
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set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaEW 4
# do /Herwig/MatrixElements/Matchbox/Factory:LoopInducedProcess g g -> e+ nu_e mu- nu_mubar
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set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
set /Herwig/MatrixElements/Matchbox/Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/FixedScale
```

Choose cuts and scale

More examples can be found in the documentation

```
## Matching and shower selection
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# read Matchbox/Powheg-DefaultShower.in
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# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
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HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to W^+W^-$

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do /Herwig/MatrixElements/Matchbox/Factory:Process p p -> e+ nu_e mu- nu_mubar

## ME provider
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read Matchbox/GoSam-GoSam.in

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set /Herwig/Cuts/ChargedLeptonCut:PtMin 15.0*GeV
do  /Herwig/Cuts/ChargedLeptonCut:YRange -3.5 3.5
set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
set /Herwig/MatrixElements/Matchbox/Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/FixedScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in
```

Match on two choices of shower algorithms
MC@NLO or Powheg / angular ordered or dipole shower
Simple MEC also possible

Fixed order runs at LO or NLO are also an option!
Just pick your favourite process, or give us your favourite ME

```
## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
read Matchbox/FourFlavourScheme.in
# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to W^+W^-$

Also specifiy UFO EFT model & diagram filters through GoSAM infile in CWD

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 13000*GeV

## Process
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaS 2
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaEW 4
# do /Herwig/MatrixElements/Matchbox/Factory:LoopInducedProcess g g -> e+ nu_e mu- nu_mubar
do /Herwig/MatrixElements/Matchbox/Factory:Process p p -> e+ nu_e mu- nu_mubar

## ME provider
# read Matchbox/MadGraph-GoSam.in
read Matchbox/GoSam-GoSam.in

## Cut selection and scale choice
set /Herwig/Cuts/ChargedLeptonCut:PtMin 15.0*GeV
do  /Herwig/Cuts/ChargedLeptonCut:YRange -3.5 3.5
set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
set /Herwig/MatrixElements/Matchbox/Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/FixedScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
read Matchbox/FourFlavourScheme.in
# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

E.g. MuDown.in

```
cd /Herwig/MatrixElements/Matchbox
set Factory:RenormalizationScaleFactor 0.5
set Factory:FactorizationScaleFactor 0.5
set MEMatching:RenormalizationScaleFactor 0.5
set MEMatching:FactorizationScaleFactor 0.5
cd /Herwig/Shower
set ShowerHandler:RenormalizationScaleFactor 0.5
set ShowerHandler:FactorizationScaleFactor 0.5
cd /Herwig/DipoleShower
set DipoleShowerHandler:RenormalizationScaleFactor 0.5
set DipoleShowerHandler:FactorizationScaleFactor 0.5
```

Scale variations on hard scales
and
shower scales!

HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to W^+W^-$

Also specifiy UFO EFT model & diagram filters through GOSAM infile in `CWD`

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 13000*GeV

## Process
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaS 2
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaEW 4
# do /Herwig/MatrixElements/Matchbox/Factory:LoopInducedProcess g g -> e+ nu_e mu- nu_mubar
do /Herwig/MatrixElements/Matchbox/Factory:Process p p -> e+ nu_e mu- nu_mubar

## ME provider
# read Matchbox/MadGraph-GoSam.in
read Matchbox/GoSam-GoSam.in

## Cut selection and scale choice
set /Herwig/Cuts/ChargedLeptonCut:PtMin 15.0*GeV
do  /Herwig/Cuts/ChargedLeptonCut:YRange -3.5 3.5
set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
set /Herwig/MatrixElements/Matchbox/Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/FixedScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
read Matchbox/FourFlavourScheme.in
# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

Which flavour(s)?
Which PDF set?
Other choices are also possible

HERWIG 7 (MATCHBOX) EXAMPLE INPUT FILE $pp \to W^+W^-$

Also specifiy UFO EFT model & diagram filters through GOSAM infile in CWD

```
## Collider type and energy
read Matchbox/PPCollider.in
set /Herwig/EventHandlers/EventHandler:LuminosityFunction:Energy 13000*GeV

## Process
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaS 2
set /Herwig/MatrixElements/Matchbox/Factory:OrderInAlphaEW 4
# do /Herwig/MatrixElements/Matchbox/Factory:LoopInducedProcess g g -> e+ nu_e mu- nu_mubar
do /Herwig/MatrixElements/Matchbox/Factory:Process p p -> e+ nu_e mu- nu_mubar

## ME provider
# read Matchbox/MadGraph-GoSam.in
read Matchbox/GoSam-GoSam.in

## Cut selection and scale choice
set /Herwig/Cuts/ChargedLeptonCut:PtMin 15.0*GeV
do  /Herwig/Cuts/ChargedLeptonCut:YRange -3.5 3.5
set /Herwig/Cuts/MissingPtCut:PtMissMin 15.0*GeV
set /Herwig/MatrixElements/Matchbox/Scales/FixedScale:FixedScale 80.403*GeV
set /Herwig/MatrixElements/Matchbox/Factory:ScaleChoice /Herwig/MatrixElements/Matchbox/Scales/FixedScale

## Matching and shower selection
read Matchbox/MCatNLO-DefaultShower.in
# read Matchbox/Powheg-DefaultShower.in
# read Matchbox/MCatNLO-DipoleShower.in
# read Matchbox/Powheg-DipoleShower.in
# read Matchbox/NLO-NoShower.in
# read Matchbox/LO-NoShower.in

## Scale variations in hard process and shower
# read Matchbox/MuDown.in
# read Matchbox/MuUp.in
# read Matchbox/MuQDown.in
# read Matchbox/MuQUp.in

## 4FS vs. 5FS and PDF choice
read Matchbox/FourFlavourScheme.in
# read Matchbox/FiveFlavourScheme.in
read Matchbox/MMHT2014_nf4.in

## Analyses
insert /Herwig/Analysis/Rivet:Analyses 0 MC_WWINC
insert /Herwig/Generators/EventGenerator:AnalysisHandlers 0 Rivet
```

Which RIVET analyses?

HEPMC output also possible

built–in analyses also possible

MMHT2014nlo68cl_nf4 PDF set
$\alpha_s(M_Z) = 0.12$
$M_t = 174.2$ GeV, $\Gamma_t = 1.4$ GeV
$M_b = 4.2$ GeV
$M_H = 125.7$ GeV, $\Gamma_H = 4.11$ MeV
$\Gamma_Z = 2.4952$ GeV, $\Gamma_W = 2.085$ GeV

Default: $\frac{c_i}{\Lambda^4} = 0.1\,\text{TeV}^{-4}$ $(i = 1, 2, 3)$

Scale variations: Factors of 2 up and down

SLHA EW scheme

Default in many FEYNRULES/UFO models
Input: $M_Z = 91.1876$ GeV, $\alpha(M_Z) = 1/128.91$
$G_F = 1.16637 \cdot 10^{-5}\text{GeV}^{-2}$
Derive: M_W, $\sin^2(\Theta_w)$

Various energies and central scales

$\sqrt{s}$ =13 TeV, dynamic scale $\mu_R = \mu_F = m_{WW}$
$\sqrt{s}$ =13 TeV, fixed scale $\mu_R = \mu_F = M_W$
$\sqrt{s}$ =8 TeV, fixed scale $\mu_R = \mu_F = M_W$

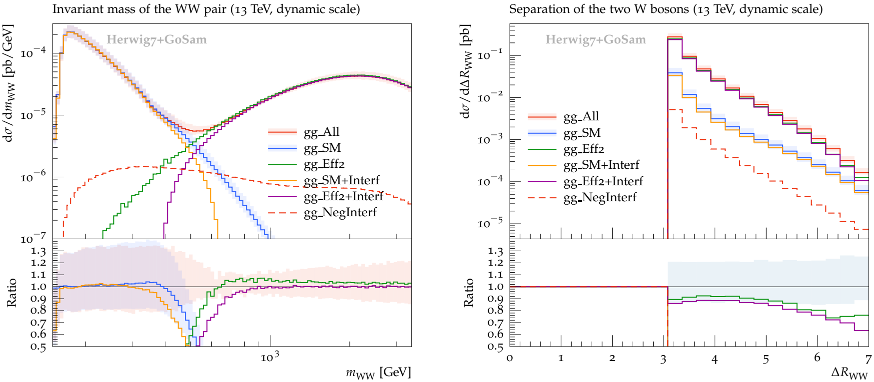
$$m_{WW} = \sqrt{(p_e + p_\mu + p_{\nu_e} + p_{\nu_\mu})^2}$$

RIVET-2.4.0 MC study

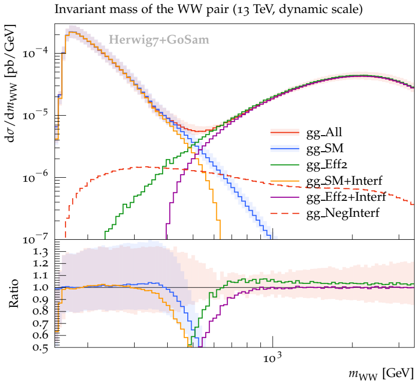
In-house analysis, modifying the existing MC_WWINC and MC_WWJETS RIVET routines
Custom W-boson reconstruction from leptonic decay products, instead of built-in `WFinder`

MC analysis cuts ... use also cuts on the generator level, but less restrictive

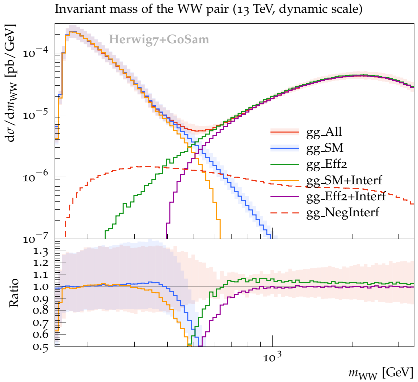
Same-flavour $l\nu_l$ pairs: 60 GeV $\leq m_{l\nu_l} \leq$ 100 GeV, $p^{\perp}_{l\nu_l} \geq$ 10 GeV
Identified leptons: $p^{\perp}_l \geq$ 25GeV, -3 $\leq y_l \leq$ 3
Missing energy: $p^{\perp}_{\text{miss}} \geq$ 25GeV



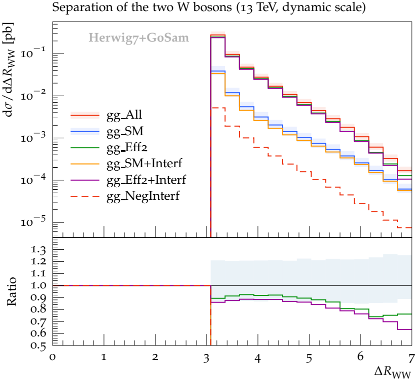
- W-boson pair invariant-mass and ΔR_{WW} distribution for SM/BSM gg-initiated contributions, at $\sqrt{s} = 13\,\text{TeV}$
- Various contributions
  - SM (`gg_SM`), pure BSM (`gg_Eff2`) and SM+BSM (`gg_All`)
  - SM/BSM interference (`gg_Interf`), linear in EFT op.
  - Negative interference term of SM loop-induced $gg \to W^+W^-$ with EFT operators
    - Display it with the sign switched (`gg_NegInterf`)
  - SM plus interf. (`gg_SM+Interf`), pure BSM plus interf. (`gg_Eff2+Interf`)
- The shaded bands show the scale-variation uncertainties
- Ratio plots wrt `gg_All`



- Term linear in EFT operators dominates over pure (quadratic) EFT contribution (`gg_Eff2`)
  - ⇝ Quadratic terms receive additional suppression of c_i/Λ^4
  - ⇝ Increase with the center-of-mass energy (here $\sqrt{\hat{s}} = m_{WW}$); eventually dominate over the linear term
  - ⇝ In our setup this happens at about 500 GeV (yellow and purple curves cross)
  - ⇝ Related to point where the sum of the two EFT contributions (`gg_Eff2+Interf`) becomes positive, at about 400 GeV (green and the dashed red curves cross)
- SM contribution drops rapidly as m_{WW} is increasing
- EFT contributions increase and start to dominate at around $m_{WW} \sim 500$ GeV.
- Relatively large scale-variation uncertainties: The results for the gg-initiated subprocess are LO predictions

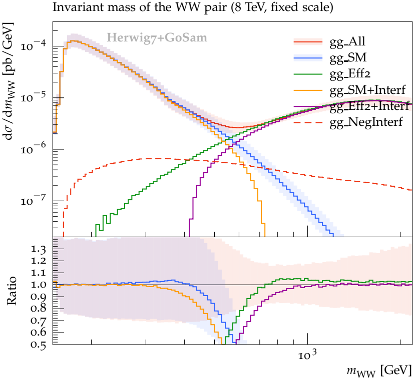


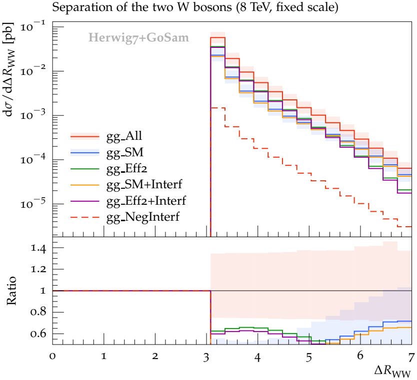
- Negative term (linear in the EFT operators): Interesting constellation
- Region where the linear term is dominant: Decrease in the cross section compared to the SM prediction
- Along invariant-mass spectrum
  - ⇝ In the low energy region the effects of the EFT operators are suppressed by a factor of $1/\Lambda^4$
  - ⇝ Larger energies: (partial) cancellation between the linear and the quadratic term
- Linear and quadratic term are of the same magnitude: Recover the SM contribution
  - ⇝ Experimental constraints on these types of couplings will be more difficult; signs of new physics would be masked
- The sign of the EFT operators is not necessarily positive
  - ⇝ A negative value would lead to a constructive interference between linear and the quadratic term
  - ⇝ The bounds on negative values will therefore be much more restrictive than on positive values



$\Delta R_{WW} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$, the separation in rapidity and azimuthal angle between the two W bosons

- The effects of EFT operators lead to an enhancement of the distribution over the whole range
- Only fixed-order: Region below $\Delta R_{WW} = \pi$ not populated because



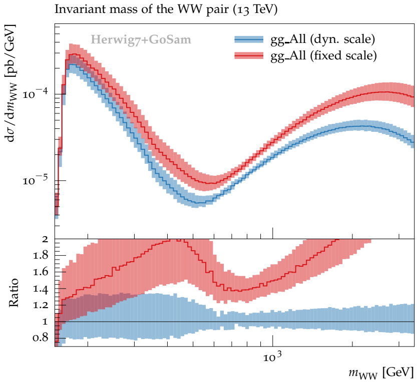


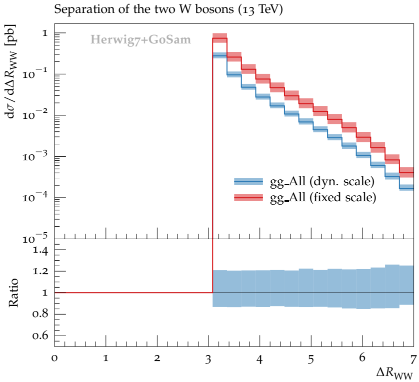
- W-boson pair invariant-mass and ΔR_{WW} distribution for the gg-initiated contributions, at $\sqrt{s} = 8$ TeV
- The shaded bands show the scale-variation uncertainties
- Ratio plots wrt `gg_All`

On-set of the BSM effects in the m_{WW} distribution is around 550 GeV

The relative size of the BSM contributions with respect to the SM contribution is much larger at $\sqrt{s} = 13$ TeV

The qualitative behaviour in comparing 13 to 8 TeV is also the same if we use a fixed scale (M_W) for $\sqrt{s} = 13$ TeV

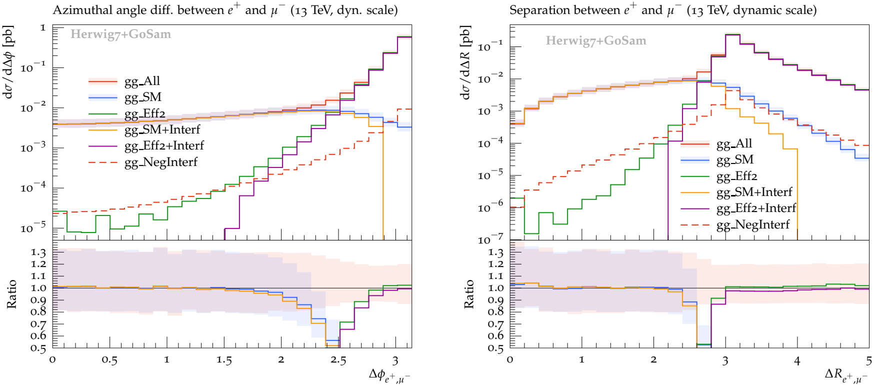




- Compare the two scale choices $\mu_r = \mu_F = M_W$ and $\mu_r = \mu_F = m_{WW}$
- Invariant-mass of the W-boson pair and ΔR_{WW} for the gg-initiated contributions
- Scale uncertainty bands from varying $\mu_F = \mu_R$ by factors of 2 up and down
- Ratio plots wrt `gg_All (dyn. scale)`

The fixed scale M_W, being relatively low, leads to a larger value of α_s and therefore an increase in the cross section.

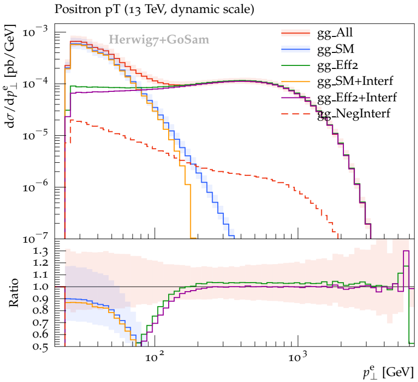
The scale variations by factors of 2 up and down are not sufficient to capture the uncertainties correctly.

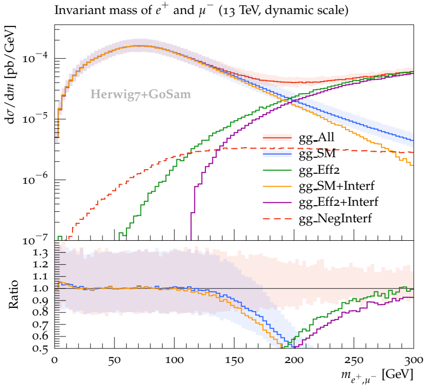


- Relative azimuthal angle $\Delta\phi_{e^+\mu^-}$ and $\Delta R_{e^+\mu^-}$ of the charged leptons for the gg-initiated contributions
- Scale uncertainty bands from varying $\mu_F = \mu_R$ by factors of 2 up and down
- Ratio plots wrt `gg_All`

The EFT contributions yield more highly boosted W bosons.

The associated leptons are more likely to be "back-to-back".





- Transverse momentum of the positron and invariant mass of the charged leptons, for the gg-initiated contributions
- Scale uncertainty bands from varying $\mu_F = \mu_R$ by factors of 2 up and down
- Ratio plots wrt `gg_All`

$p_\perp^e$ spectrum

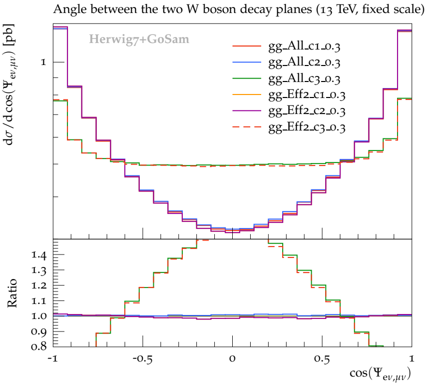
EFT effects lead to clear enhancement already for $p_\perp^e$ values as low as ~ 60 - 100 GeV

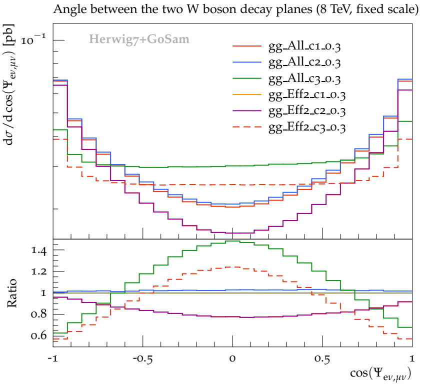
$m_{e^+\mu^-}$ distribution

The effect of the EFT operators is clearly visible for energies $>$ 150 - 190 GeV (considering scale-variation uncert.)

Effect will be washed out once all pp sub-processes, plus higher-order corrections, are taken into account

- Study each $\mathcal{O}_i$ separately, consider for $i = 1, 2, 3$, $\mathcal{O}_i = 0.3$, while $\mathcal{O}_{j \neq i} = 0$

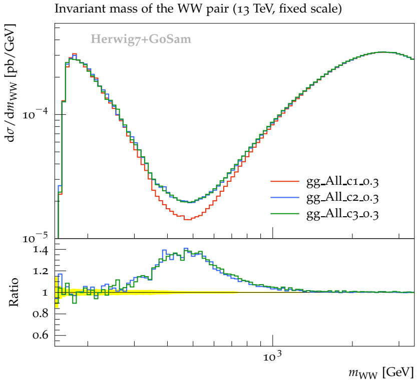


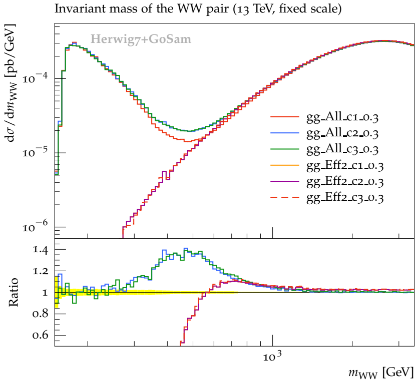


- Angle between the W-boson decay planes for 13 TeV (left) and 8 TeV (right)
  - ⇝ Fixed scale $\mu_r = \mu_F = M_W$
  - ⇝ Ratio plots wrt `gg_All_c1_0.3` ($c_1 = 0.3$, $c_2 = c_3 = 0$)
- Comparing 13 TeV to 8 TeV
  - ⇝ Differences to the contributions from the third operator $\mathcal{O}_3$ are more prominent at 13 TeV
  - ⇝ Linear term in $\mathcal{O}_3$ has a bigger effect at 13 TeV.
- $\mathcal{O}_1$ and $\mathcal{O}_2$ show the same angular dependence; the angular dependence of $\mathcal{O}_3$, containing the dual field-strength tensor $\tilde{W}^{I,\mu\nu}$, is different, and more prominent for $\sqrt{s} = 13$ TeV.

PHENO: GLUON-INDUCED PROCESS AND ANOMALOUS COUPLINGS VI

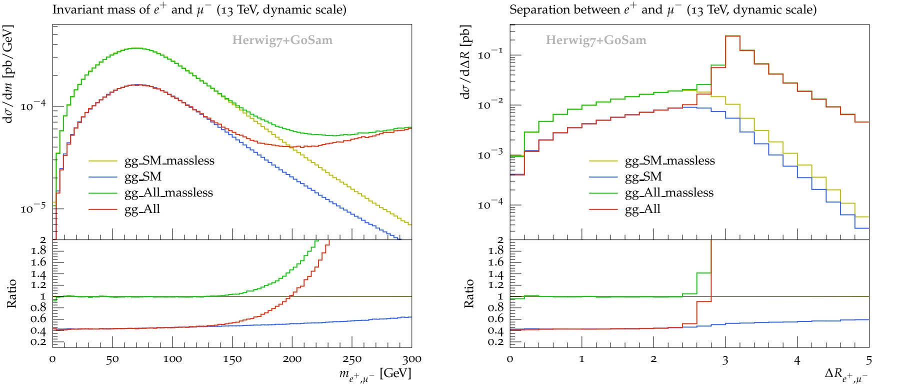
- Distinguish between the first and the second operator





- Invariant mass of the W-boson pair, for gg at 13 TeV, for various values of the an. couplings.
- Sum of SM and anomalous contributions (left); in addition the pure squared EFT contributions (right).
  - ⇝ The contributions from $\mathcal{O}_1$ and $\mathcal{O}_2$ are identical in the pure squared EFT contribution (orange and purple).
  - ⇝ The interference terms involving $\mathcal{O}_1$ and $\mathcal{O}_2$ differ (red and blue curves).
  - ⇝ Ratio plots wrt `gg_All_c1_0.3` ($c_1 = 0.3$, $c_2 = c_3 = 0$)
  - ⇝ $\mathcal{O}_1$ leads to a stronger decrease in the region around $m_{WW} \sim 500\,\text{GeV}$.
- Combining $\cos(\Psi_{e\nu,\mu\nu})$ and m_{WW} in principle allows to distinguish between the three operators.
- This can only be a qualitative discussion, as this strongly depends on the size (and sign) of the c_i.

- Massive b- and t-quark loops in $gg \to W^+W^-$
- Negligible b-quark mass effect (order of the Monte Carlo integration error)
- Considerable impact from t-quark mass effects

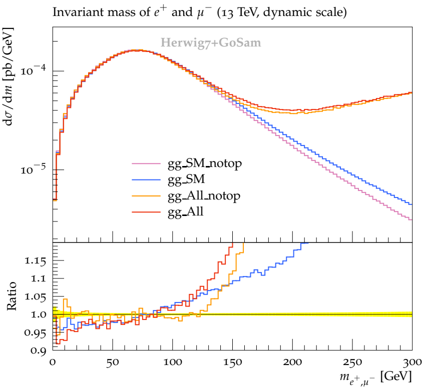


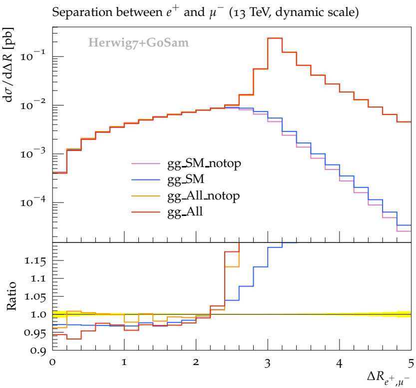
- t-quark mass effects on invariant mass and R-separation of the charged leptons
- `*_massless`: Masses of t- and b- quarks in the loops are set to zero
- Ratio plots wrt to `gg_SM_massless`
- Limit $m_{e^+\mu^-}$ range to 300 GeV for visibility. Verified that for large values, yellow and blue merge again

Below $m_{e^+\mu^-} \sim 250$ - 300 GeV: t-quark mass effects decrease $m_{e^+\mu^-}$ distro by more than 30%

SM with $M_t = 0$ (`gg_SM_massless`) is of same size as SM+EFT with masses (`gg_All`) at $m_{e^+\mu^-} \sim 200$ GeV
Neglecting the t-quark mass in the SM calculation could "fake" BSM effects

PHENO: HEAVY-QUARK LOOPS II



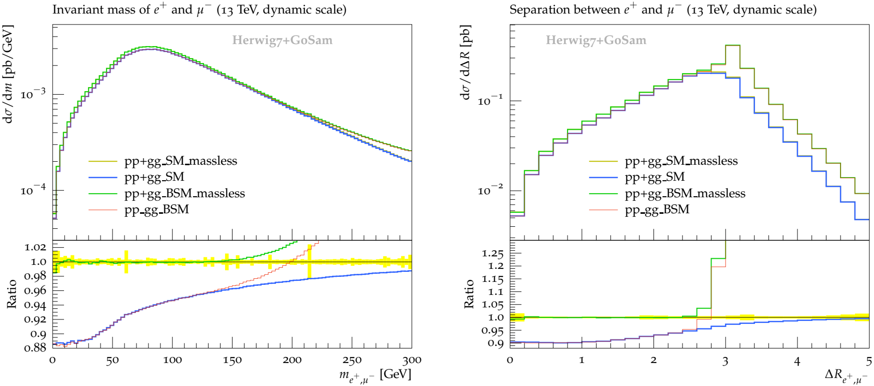


- Impact of t-quark loops on invariant mass and the R-separation of the charged leptons
- `*_notop`: Diagrams with t-quarks in the loops are omitted altogether
- Ratio plots wrt `gg_SM_notop`.

Conrast this result where the t-quark loops are dropped altogether to the previous one, where we include massless t-quarks

Considerable impact on $m_{e^+\mu^-}$ distro beyond about 150 GeV

Effect much less pronounced than for including massless t-quark loops (previous slide)

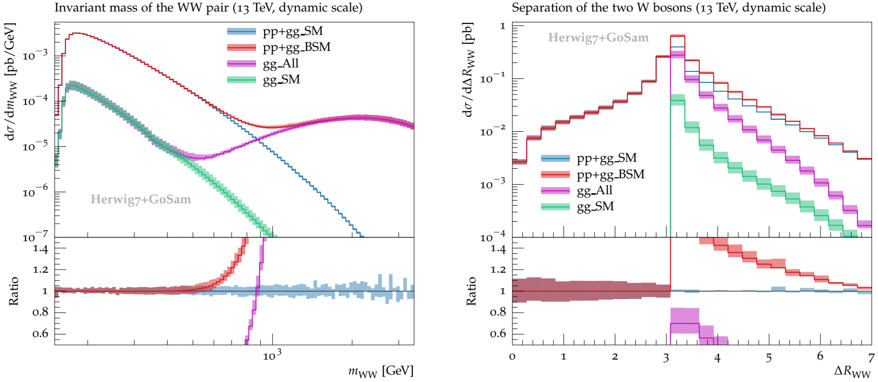


- Impact of t-quark loops on the invariant mass of the charged leptons and $\Delta R_{e^+\mu^-}$
- Considering full pp initial state
- Ratio plots wrt `pp+gg_SM_massless`

With full pp initial state including the NLO corrections

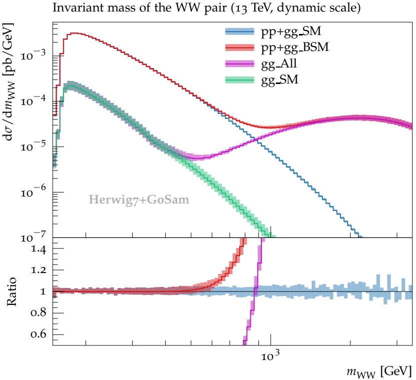
Mass effects are below 10%: Still - massive t-quark loops should be taken into account for highly boosted Ws

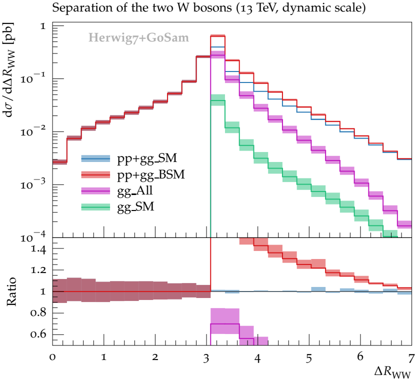
- Compare gg contribution to full process $pp\ (\to W^+W^-) \to e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO QCD



- Invariant mass m_{WW} and ΔR_{WW}-separation of reconstructed W-boson pair
- `pp+gg_SM`: All partonic channels (quark-initiated up to NLO QCD, loop-induced SM gg-initiated `gg_SM`)
- `pp+gg_BSM`: Similar, but includes loop-induced SM+EFT gg-initiated `gg_All` instead of just `gg_SM`
- Additionally: Show SM and SM+EFT gg-initiated separately
- Shaded bands: Scale-variation of $\mu_R = \mu_F = m_{WW}$ by factors of 2 up and down
- Ratio plots wrt `pp+gg_SM`

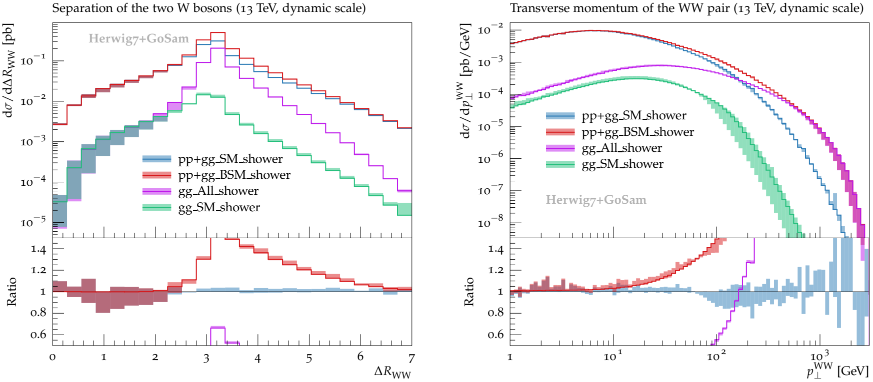
- Compare gg contribution to full process $pp\ (\rightarrow W^+W^-) \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO QCD





- Loop-induced, gg-initiated SM yields $\mathcal{O}(10\%)$ increase over quark-initiated NLO
- Combining all channels, deviations from the SM prediction start at larger m_{WW} values of about 700 GeV
  - ⇝ In the gg-initiated alone, deviations already start at about 500 GeV - 600 GeV (considering scale-variations)
- m_{WW} ∼600 - 700 GeV: Size of the BSM effects comparable to size of scale uncertainties
- $m_{WW} >$ 700 GeV: Deviations start to become clearly visible
  - ⇝ Beyond 1 TeV: EFT approach starts to become invalid

- Combine NLO results (incl. loop-induced and EFT) with HERWIG 7 angular-ordered parton shower
- Needed for realistic desciption of observable in hadron collisions
- Subtractive, MC@NLO-like matching (loop-induced and EFT treated as LO QCD)



- ΔR_{WW} and $p_\perp^{WW}$ distributions for the sum of all partonic channels, including SM+EFT gg
- Uncertainty bands: Varying hard shower scale μ_Q
  - ⇝ Reliably estimate missing logarithms and impact of unreliably modelled large-angle, hard emissions
  - ⇝ Check to verify improvements expected from NLO plus parton-shower matching
- Large contributions, through NLO real radiation and parton-shower emissions, for IR sensitive observables
- Typical IR sensitive observables: R-separation of the W bosons and $p_\perp$ of reconstructed W^+W^- system
  - ⇝ Zero-jet limit: ΔR solely composed of difference in rapidity, while $\Delta\phi = \pi$

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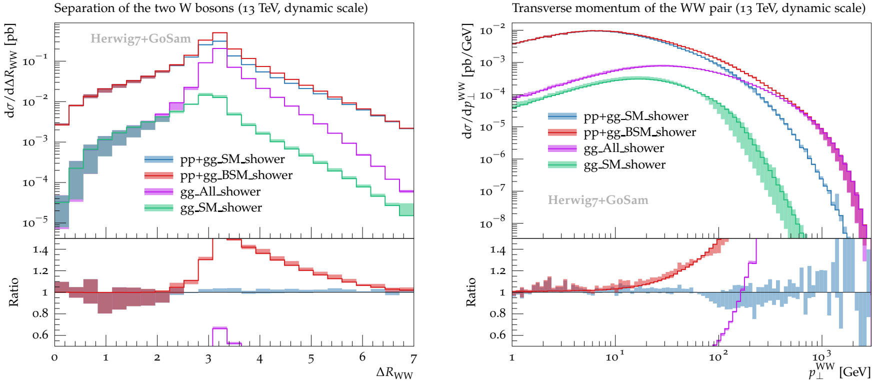
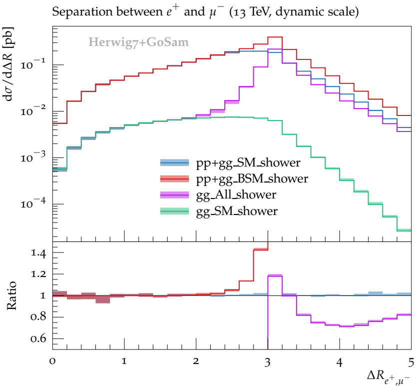
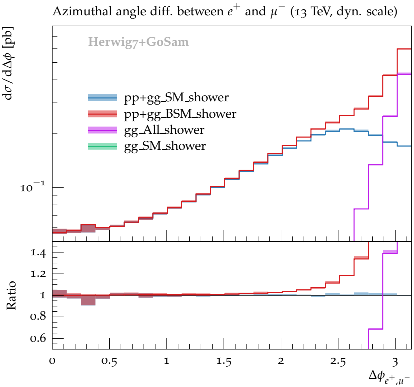


Expected behaviour with respect to additional radiation

- $\Delta R < \pi$: NLO real emission and shower emissions off the gg-induced channel contribute.
  - ⇝ The first contribution includes a small shower uncertainty, as this kinematic range has been improved by the NLO matching
  - ⇝ Once the EFT contribution to the gg-channel becomes dominant, pure shower emissions off this sub-process become more important and yield a larger uncertainty
  - ⇝ Ultimately, NLO QCD corrections, or at least a leading-order multi-jet merging are desirable in this case
- Similar features present in the $p_\perp$ of the reconstructed W^+W^- pair

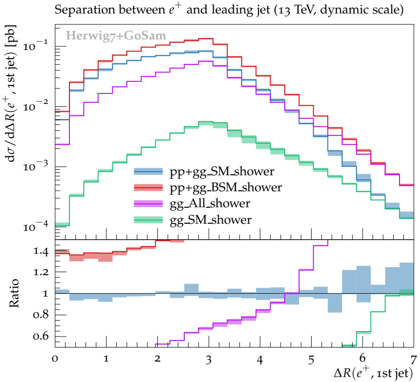


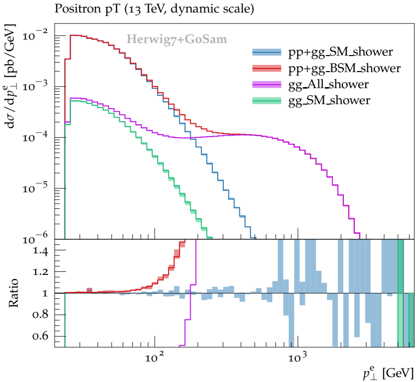


- Azimuthal separation and R-separation of the charged leptons

⇝ Sensitive to the BSM contribution and very stable against QCD activity

- Lepton-jet separations and missing $p_\perp$
- Observables relevant to the experimental reconstruction of the W^+W^- final state





- While shower uncertainties at the level of 10% are observed, the lepton-jet separation is rather stable against QCD activity, and BSM contributions only affect the normalization in the small-ΔR region
- Experimentally required lepton-jet isolation is thus not introducing any bias
- Larger impact observed on the $p_\perp$s of the charged leptons (shown for the positron)

⇝ However: Turn out to be rather stable with respect to parton-shower scale variations

- VV production is one of the most important signatures at the LHC, to study EWSB and NP

- We studied the off-shell production of a W^+W^- pair at NLO QCD, incl. anomalous couplings
  - ⇝ Included the gg-initiated (loop-induced) process $gg\ (\to W^+W^-) \to e^+\nu_e\mu^-\bar{\nu}_\mu$
  - ⇝ Formally a NNLO contribution, but enhanced due to the large gluon PDF
  - ⇝ gg-initiated contributions from dim-8 operators, which induce a tree-level coupling between gluons and W bosons
    - -.- Not discussed in the literature so far (to the best of our knowledge)
    - -.- Interference between the SM gg-induced one-loop amplitude and a tree-level amplitude mediated by dim-8 operators

- Discussed the EFT effects on a variety of important observables
  - ⇝ The presence of dim-8 operators can lead to substantial effects in the high-energy tails of distributions
  - ⇝ Could be used by the LHC experiments to constrain the parameter space for the associated effective couplings

- Investigated the importance of heavy (SM) quarks in the loop-induced process
  - ⇝ Corrections of up to 10%, depending on cuts and center-of-mass energy

- Combined fixed-order results with the HERWIG 7 angular-ordered parton shower
  - ⇝ Studied parton-shower effects on leptonic observables and on observables related to the reconstructed W^+W^-
  - ⇝ Included variations of the hard shower scale

- Used a fully automated and consistent interface between Monte Carlo event generator (HERWIG 7) and OLP (GOSAM), in accordance with BLHA2
  - ⇝ No intermediate file writing
  - ⇝ Hard matrix element can be used directly in the NLO matching with the shower
  - ⇝ Phase-space sampling and NLO setup (NLO fixed-order subtraction and matching) fully managed by HERWIG 7
  - ⇝ All necessary MEs from GOSAM

THANK YOU!