Electroweak Interactions at the LHC and Beyond: Studies and Simulations

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Particle phenomenology

All* observed effects in nature can be traced back to a quantum theory based on a Lagrangian density.

1. a finite number of degrees of freedom (particles),
2. a finite set of weak local interaction terms at a given energy scale
3. a closed system of symmetries and long-distance constraints.

* except: “dark matter” gravitation and some big-bang issues

Open landscape of potential BSM physics

- Incomplete SM spectrum, portals, low flavor scale, axions, ...
- Low gravitation scale, new strong interactions, emergent SM symmetries, ...

⇒ either represented by Lagrangian or approximated by low-energy EFT

Hence, all known and (most?) unknown particle-pheno observables are calculable, *to some extent*, in principle.

Theory, calculation and simulation tasks:

- get SM interactions under control for multi-TeV phenomenology
- support Lagrangian BSM models at leading order and higher orders
- support (truncated) EFT models = SMEFT and/or HEFT

$\Rightarrow$ can be captured by Lagrangian field theory, ie, Feynman rules

Not covered:

long-range superweak interactions (strongly self-coupled), ...?

Calculational framework for Particle Phenomenology

If fundamental interactions are described by a local Lagrangian
(or can be approximated in this way, cf. SMEFT):

1. Implement algorithms which turn Lagrangians into amplitudes
2. Integrate squared amplitudes to compute inclusive observables and/or invert density to generate simulated events
3. Account for long-distance effects (QED, QCD)
4. Account for collider and detector environment

Some challenges:

- Mass effects and resonances (low energy)
- High multiplicity (high energy)
- Calculational efficiency

The Whizard MC generator

1999 WHIZARD 1 + 2007 Whizard 2

[WK, T. Ohl, J. Reuter, EPJC 71 (2011), 1742]

- Multi-particle processes, complete partonic amplitudes
  account for all signal and background
- Model library
- Phase-space integration, interfaced shower/hadronization, events

$\Rightarrow$ Event-sample data base for future lepton collider studies

2021 Whizard 3 (this talk): NLO

- Model library supplemented by UFO support
- NLO virtuals with help of OpenLoops/Recola/GoSaM matrix elements
- Resonance-aware subtraction, NLO matching, shower, event samples

$\Rightarrow$ Precision studies for LHC and future colliders

Calculation and simulation I

Matrix elements

1. Tree level: **O'Mega** = full off-shell final state, direct recursive amplitude evaluation instead of Feynman-graph expansion

   [M. Moretti, T. Ohl, J. Reuter, hep-ph/0102195]

   Parallel evaluation of helicity states (OpenMP)
2. NLO via **BLHA**: e.g. OpenLoops = QCD 1-loop + real radiation, off-shell processes, spin correlations
3. Reassign IR radiation / divergences: identify and add/subtract IR/singular regions = **FKS**
4. Resonances: steer parton shower via resonance weights evaluate radiation in moving resonance frame (e.g., $t\bar{t}$ off-shell)

Calculation and simulation II

Cross section and distributions for multi-parton processes

1. Phase-space parameterization along singularity patterns of matrix element = **multi-channel**
2. ML integration algorithm: iterative simultaneous training of binned invertible mappings ("network", "flow") with multi-channel weight functions ("attention"): **VAMP**

   [T. Ohl, CPC120 (1999), 13-19]
3. Parallel evaluation on multi-CPU system: **MPI**

   [S. Brass, WK, J. Reuter, EPJC 79 (2019), 344]
4. Trained parameter set suitable for integration and event generation

Calculation and simulation III

Realistic event samples

1. First radiation (NLO) compatible with shower: **PowHeg**
2. Resonant subamplitudes, e.g. single-top: assign shower history statistically according to auxiliary factorized matrix elements
3. Shower and hadronization: **Pythia**
4. Hadronic event samples ready for detector simulation

Case Study for LHC: top-pair production and simulation

Workflow and toolset: validate by comparison with LHC data

Process:

$$pp \to b\bar{b} + \ell^+\ell^- + 2\nu \ (+\text{jets}) \quad \text{LHC 13 TeV}$$

[P. Bredt, WK, J. Reuter, in preparation]

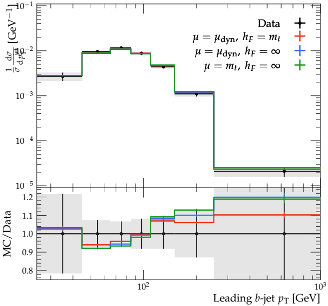
Analyses considered for validation:

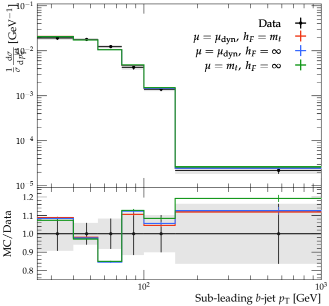
- Eur. Phys. J. C77 (2017) 220:
  $t\bar{t}$ + jets
- Phys. Rev. Lett. 121, 152002 (2018):
  top-pair and single-top interference
- JHEP 01 (2025) 068:
  top-pair + b jets

and comparison with bb4l dedicated MC

Top pairs at the LHC (ATLAS data) vs. Whizard

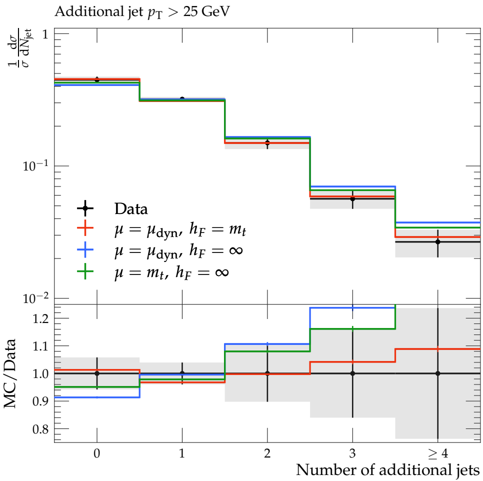
Top-quark remnants: look for hardest b jets





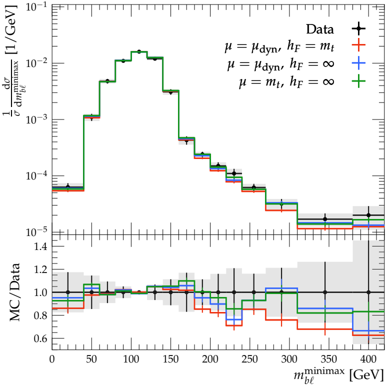
Top pairs at the LHC (ATLAS data) vs. Whizard

Matching and shower: look at additional jets



Top pairs at the LHC (ATLAS data) vs. Whizard

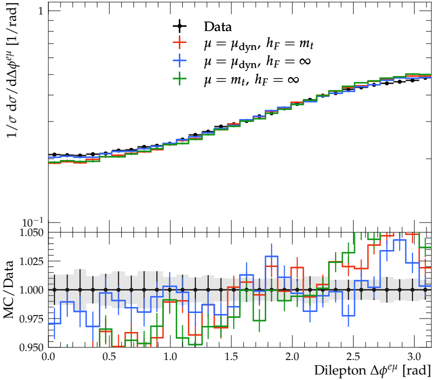
Combinatorics and off-shell: identify the most likely top-quark system



$$m_{b\ell}^{\rm minimax} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

Top pairs at the LHC (ATLAS data) vs. Whizard

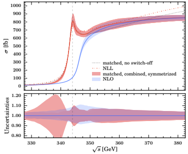
Spin correlations: lepton angles



Prospects for HL-LHC simulation

Automated framework for exclusive events, fully showered and hadronized

⇒ Threshold enhancement (analogous to $e^+e^- \to t\bar{t}$)



[B. Chokoufé Nejad, W. Kilian, J. M. Lindert, S. Pozzorini, J. Reuter and C. Weiss, JHEP 12 (2016), 075;
F. Bach, B. C. Nejad, A. Hoang, W. Kilian, J. Reuter, M. Stahlhofen, T. Teubner and C. Weiss, JHEP 03 (2018), 184]

⇒ Further resonant processes

⇒ Studies of spin correlations

⇒ Shower effects (eg PYTHIA vs HERWIG)

⇒ NLO EW, NNLO

Case Study for FCC/ILC: Higgs production and BSM

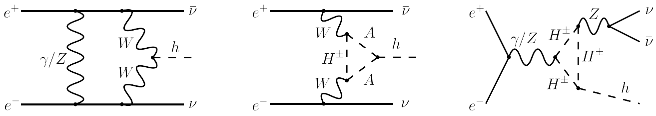
Traces of an extended Higgs sector in loop corrections?

Process:

$$e^+e^- \to \bar{\nu}\nu h$$

[P. Bredt, T. Banno, M. Höfer, S. Iguro, W. Kilian, Y. Ma, J. Reuter and H. Zhang, PRL 136 (2026), 081801]

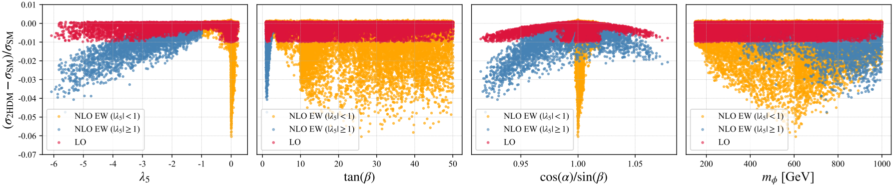
SM + 2HDM (alignment limit ⇒ undetected so far but not heavy)



Calculational framework: Whizard with OpenLoops and Recola

SM-NLO correction vs BSM-NLO

	$\sqrt{s} = 365$ GeV		$\sqrt{s} = 550$ GeV	
	LO [fb]	NLO EW [fb]	LO [fb]	NLO EW [fb]
SM	55.79	52.44(1)	97.82(1)	88.45(2)
2HDM	55.71	51.45(1)	97.67(1)	86.59(2)
Rel.Diff.	-0.1%	-1.9%	-0.2%	-2.1%
2HDM (aligned)	55.79	51.58(1)	97.81(1)	86.83(2)
Rel.Diff.	0.0%	-1.7%	0.0%	-1.8%



Case Study: Multi-Boson production at NLO-SM

Cross-validation of WHIZARD and MUNICH/MATRIX orig. ref. [Kallweit *et. al.*: 1412.5157]

process $pp \to$	MUNICH$_{(CS)}$ +OpenLoops σ^{tot}_{NLO} [fb]	WHIZARD +OpenLoops σ^{tot}_{NLO} [fb]	δ [%]	dev [%]	σ^{sig}_{NLO}
ZZ	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	-4.20	0.0001	0.01
W^+Z	$1.71505(2) \cdot 10^4$	$1.71507(2) \cdot 10^4$	-0.15	0.001	0.88
W^-Z	$1.08576(1) \cdot 10^4$	$1.08574(1) \cdot 10^4$	$+0.07$	0.001	0.90
W^+W^-	$7.93106(7) \cdot 10^4$	$7.93087(21) \cdot 10^4$	$+4.55$	0.002	0.89
ZH	$6.18523(6) \cdot 10^2$	$6.18533(6) \cdot 10^2$	-5.29	0.002	1.17
W^+H	$7.18070(7) \cdot 10^2$	$7.18072(9) \cdot 10^2$	-2.31	0.0003	0.18
W^-H	$4.59289(4) \cdot 10^2$	$4.59299(5) \cdot 10^2$	-2.15	0.002	1.62
ZZZ	$9.7429(2) \cdot 10^0$	$9.7417(11) \cdot 10^0$	-9.47	0.012	1.01
W^+W^-Z	$1.08288(2) \cdot 10^2$	$1.08293(10) \cdot 10^2$	$+7.67$	0.004	0.45
W^+ZZ	$2.0188(4) \cdot 10^1$	$2.0188(23) \cdot 10^1$	$+1.58$	0.0001	0.01
W^-ZZ	$1.09844(2) \cdot 10^1$	$1.09838(12) \cdot 10^1$	$+3.09$	0.006	0.51
$W^+W^-W^+$	$8.7979(2) \cdot 10^1$	$8.7991(15) \cdot 10^1$	$+6.18$	0.014	0.79
$W^+W^-W^-$	$4.9447(1) \cdot 10^1$	$4.9441(2) \cdot 10^1$	$+7.13$	0.013	2.52
ZZH	$1.91607(2) \cdot 10^0$	$1.91614(18) \cdot 10^0$	-8.78	0.004	0.39
W^+ZH	$2.48068(2) \cdot 10^0$	$2.48095(28) \cdot 10^0$	$+1.64$	0.011	0.96
W^-ZH	$1.34001(1) \cdot 10^0$	$1.34016(15) \cdot 10^0$	$+2.51$	0.011	1.02
W^+W^-H	$9.7012(2) \cdot 10^0$	$9.700(2) \cdot 10^0$	$+9.83$	0.014	0.75
ZHH	$2.39350(2) \cdot 10^{-1}$	$2.39337(32) \cdot 10^{-1}$	-11.06	0.005	0.41
W^+HH	$2.44794(2) \cdot 10^{-1}$	$2.44776(24) \cdot 10^{-1}$	-12.04	0.007	0.74
W^-HH	$1.33525(1) \cdot 10^{-1}$	$1.33471(19) \cdot 10^{-1}$	-11.53	0.041	2.80

LHC setup (Run II) $\delta \equiv \frac{\sigma^{tot}_{NLO} - \sigma^{tot}_{LO}}{\sigma^{tot}_{LO}}$ $\quad$ $\text{dev} \equiv \frac{|\sigma^{tot}_{\texttt{WHIZARD}} - \sigma^{tot}_{\texttt{MUNICH}}|}{\sigma^{tot}_{\texttt{WHIZARD}}}$ $\quad$ $\sigma^{sig} \equiv \frac{|\sigma^{tot}_{\texttt{WHIZARD}} - \sigma^{tot}_{\texttt{MUNICH}}|}{\sqrt{\Delta^2_{err,\texttt{WHIZARD}} + \Delta^2_{err,\texttt{MUNICH}}}}$

Off-shell NLO-SM at LHC

IR-safety conditions:

- photon recombination with charged leptons – ‘dressed’ leptons
- jet clustering including photon – ‘democratic’ jets

Pure electroweak pp processes with off-shell vector bosons

LHC setup (Run II): $\sqrt{s} = 13$ TeV $\quad \mu_R = \mu_F = \frac{1}{2}\sum_i \sqrt{p_{T,i}^2 + m_i^2}$ EW scheme: G_μ CMS

PDF set: `LUXqed_plus_PDF4LHC15_nnlo_100` cuts from ref. [1804.10017]

process $pp \to$	α^m	`MG5_aMC@NLO`[1804.10017] $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	`WHIZARD+OpenLoops` $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
$e^+\nu_e$	α^2	$5.2005(8) \cdot 10^3$	$5.1994(4) \cdot 10^3$	-0.73	1.24
e^+e^-	α^2	$7.498(1) \cdot 10^2$	$7.498(1) \cdot 10^2$	-0.50	0.004
$e^+\nu_e\mu^-\bar{\nu}_\mu$	α^4	$5.2794(9) \cdot 10^{-1}$	$5.2816(9) \cdot 10^{-1}$	$+3.69$	1.69
$e^+e^-\mu^+\mu^-$	α^4	$1.2083(3) \cdot 10^{-2}$	$1.2078(3) \cdot 10^{-2}$	-5.25	1.26
$He^+\nu_e$	α^3	$6.4740(17) \cdot 10^{-2}$	$6.4763(6) \cdot 10^{-2}$	-4.04	1.24
He^+e^-	α^3	$1.3699(2) \cdot 10^{-2}$	$1.3699(1) \cdot 10^{-2}$	-5.86	0.32
Hjj	α^3	$2.7058(4) \cdot 10^0$	$2.7056(6) \cdot 10^0$	-4.23	0.27
tj	α^2	$1.0540(1) \cdot 10^2$	$1.0538(1) \cdot 10^2$	-0.72	0.74

Multi-boson processes at a muon collider

[P. M. Bredt, W. Kilian, J. Reuter and P. Stienemeier, JHEP **12** (2022), 138]

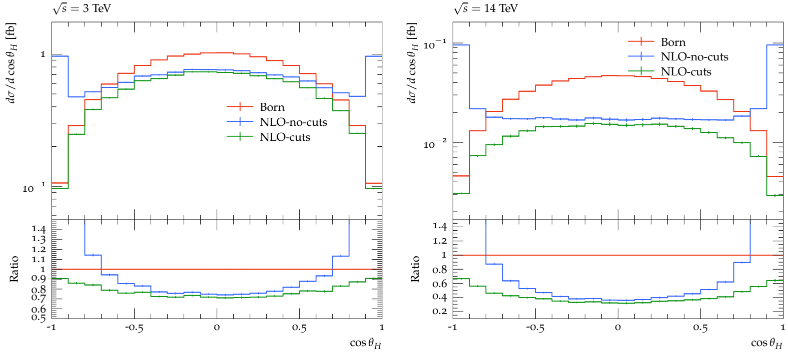
$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma_{\text{LO}}^{\text{incl}}$ [fb]	δ_{EW} [%]	δ_{ISR} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$+4.0(2)$	$+13.82(4)$
ZZ	$2.5988(1) \cdot 10^1$	$+2.19(6)$	$+15.71(4)$
HZ	$1.3719(1) \cdot 10^0$	$-1.51(4)$	$+30.24(3)$
W^+W^-Z	$3.330(2) \cdot 10^1$	$-22.9(2)$	$+2.90(9)$
W^+W^-H	$1.1253(5) \cdot 10^0$	$-20.5(2)$	$+7.10(8)$
ZZZ	$3.598(2) \cdot 10^{-1}$	$-25.5(3)$	$+5.24(8)$
HZZ	$8.199(4) \cdot 10^{-2}$	$-19.6(3)$	$+8.39(8)$
HHZ	$3.277(1) \cdot 10^{-2}$	$-25.2(1)$	$+7.58(7)$
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$-33.1(4)$	$-1.3(1)$
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$-42.2(6)$	$-1.8(1)$
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$-30.9(5)$	$-0.1(1)$
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$-38.1(4)$	$+1.7(1)$
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$-42.2(2)$	$+0.8(1)$
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$-34.4(2)$	$+1.4(1)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$-36.5(2)$	$+2.2(1)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$-25.7(2)$	$+5.7(1)$

with $\delta_{\text{EW}} = \sigma_{\text{NLO}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$ and $\delta_{\text{ISR}} = \sigma_{\text{LO,LL-ISR}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$

Multi-boson processes at a muon collider at NLO EW

[P. M. Bredt, WK, J. Reuter and P. Stienemeier, JHEP **12** (2022), 138]

Fixed order differential distributions: $d\sigma(\mu^+\mu^- \to HZ)/d\cos\theta_H$



SM (and BSM) processes at multi-TeV

Ideal properties

- Neglect all SM particle masses
  $\Rightarrow$ parton-distribution functions of whole SM with symmetry restored.
- Initial-state splitting and radiative return with log-enhancement
- Hard processes with large mass scales
- Final-state radiation and decays: EW parton shower
- Fixed-multiplicity final states: suppressed by Sudakov factors

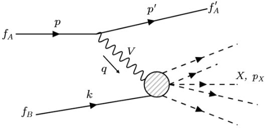
Realistic phenomenology: collider energy is still in the transition region.

- Mass effects remain relevant at all stages.
- Fixed-order calculations involve huge gauge cancellations
- Higher-order resummation desirable but challenging

Implementing electroweak PDFs: photon, W and Z

EWA: PDF for W/Z in transversal and longitudinal modes

[S. Dawson, NPB 249 (1985), 42], ..., [B. Dahlén, M. Löschner, K. Mękała, J. Reuter, P. Stylianou, JHEP 11 (2025), 002]

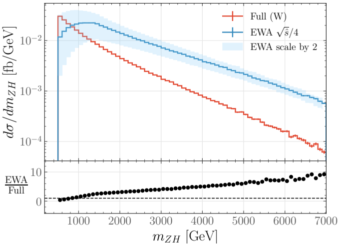


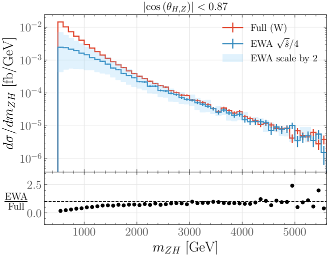
Caveat (kinematics!)

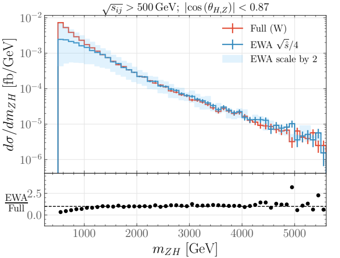
- Intrinsic $p_T(f'_A)$ peaks around $p_T \sim m_W/2$
- Photon: $Q_{\text{min}} = x^2 m_f$ vs W boson: $Q_{\text{min}} = m_W$
  $\Rightarrow$ huge difference in $\log(Q_{\text{max}}/Q_{\text{min}})$
- Double EWA: momentum balance between beam remnant and X
  $\Rightarrow$ effective Q_{max} cutoff / factorization scale $\sim M_X \ll \sqrt{s}$
  $\Rightarrow$ factorization fails for leading $p_T(X)$, better for subleading
- Limit: $x > m_W/E$ implies $M_X > \sqrt{2m_W\sqrt{s}}$.
  $\Rightarrow$ Muon collider 10 TeV, double EWA: $M_X > 1.2$ TeV.

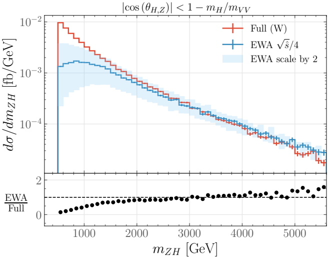
Also (dynamics): Missing gauge cancellations and on-shell W decays

EWA vs fixed-order: ZH production

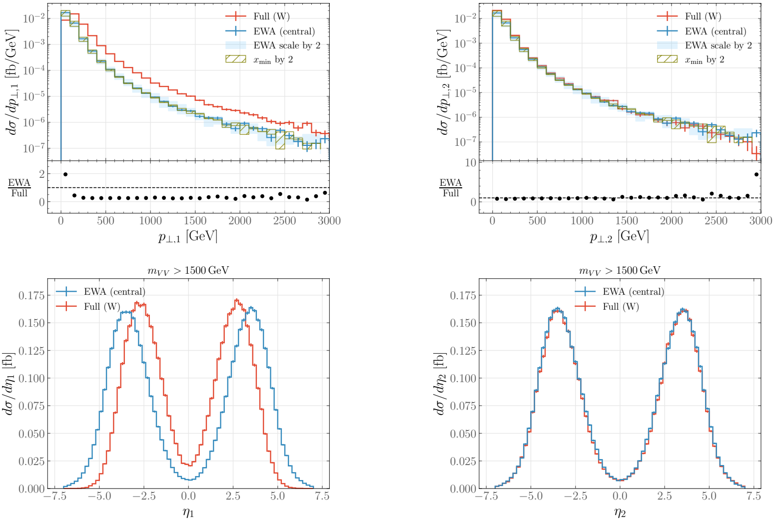




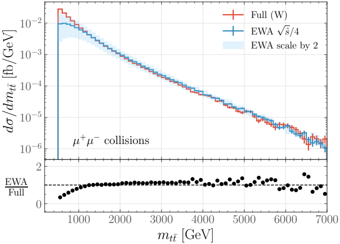


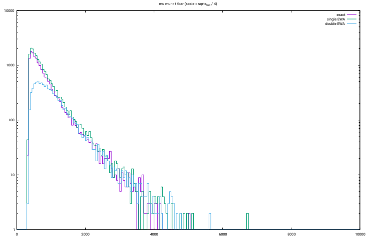


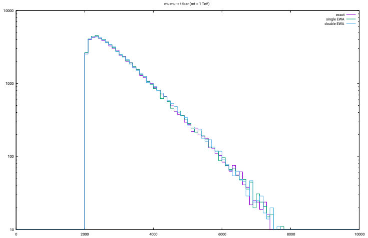
EWA vs fixed-order: *HH* production



EWA vs fixed-order: (heavy) top-quark pair production







Electroweak PDFs

[T. Han, Y. Ma and K. Xie, PRD 103 (2021), L031301], [T. Han, WK, K. Mękała, Y. Ma, J. Reuter, K. Xie, in preparation]

- System of PDFs which include all SM particles
- Splitting sequence and leading-log resummation
- Polarized components separate (massless, unbroken-symmetry SM)
- Implementation as PDF library for Monte-Carlo simulation at highest energies

Accounting for mass effects:

Interconnected splitting of massless and massive partons

$\Rightarrow$ iterate and match single- and double-PDF regions

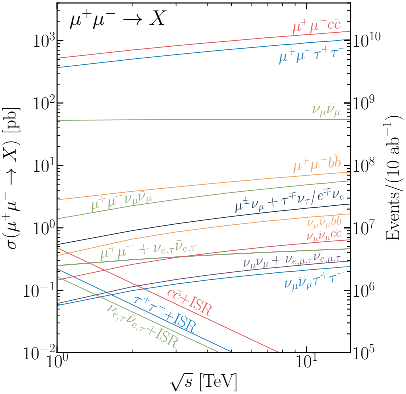
$\Rightarrow$ merge hard-process multiplicities

$\Rightarrow$ properly combine with final-state radiation

Application: neutrino flux at a muon collider

Forward neutrino detector, analogous to FASER

- Huge number of neutrinos coming from beam-muon decay (primary and secondary)
- Straight sections
- Oscillations between interaction and detector
- Additional source: collisions (tau neutrinos)



[F. M. Burk, T. Han, WK, F. Kling, J. Kopp and Z. Tabrizi, 2608.02714]

Outlook

- Whizard continues to provide a universal framework for high-energy phenomenology
  also: MadGraph, Sherpa, and dedicated codes
- Efficiency and accuracy (phase space, NLO matrix elements)
- LHC: off-shell resonance production; shower and hadronization models
- FCC-ee: higher-order loop corrections, photon resummation
- High energy (MuCol, FCC-hh): Electroweak processes in the symmetry-restoration range

The WHIZARD 3 Team

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(S. Brass, B. Chokoufe, V. Rothe, P. Stienemeier, C. Weiss)

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Links

- Reference: WK/Ohl/Reuter, EPJ C71 (2011) 1742
- Whizard Launchpad Portal: `https://launchpad.net/whizard`
- gitlab repo: `https://gitlab.tp.nt.uni-siegen.de/whizard/public`

BACKUP

Technical Remarks

Language: `Fortran` (2018, object-oriented/modular) with `O'Caml`

Development: `gitlab` with automated test suite and CI

Installation: `configure && make && make install`

Numerics: Support for extended and quadruple precision (if needed)

Running: Options

1. Stand-alone with input script: `whizard` ⟨*input*⟩`.sin` (optional workspace transfer for cluster operation)
2. As a library, callable from: `Fortran`, `C`, `C++`, `Python`

BSM: Predefined (many models) and UFO (everything else)

Script: SINDARIN (input, parameters, cuts, workflow, result aggregation, output control, ...)

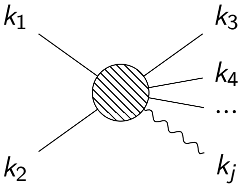
Parallel: OpenMP (multi-core), MPI (HPC cluster)

FKS subtraction for soft/collinear cancellation

$$\sigma_{\text{NLO}} = \underbrace{\int d\Phi_n \mathcal{B}}_{\text{Born}} + \underbrace{\int d\Phi_{n+1} \mathcal{R}}_{\text{div. real}} + \underbrace{\int d\Phi_n \mathcal{V}}_{\text{div. virtual}} = \text{finite}$$

For observables **exclusive** in kinematic properties:

$$\sigma_{\text{NLO}} = \int d\Phi_n \mathcal{B} + \int \underbrace{d\Phi_{n+1}\left[\mathcal{R} - d\sigma_S\right]}_{\text{finite by construction}} + \underbrace{\int d\Phi_n \mathcal{V} + \int d\Phi_n d\sigma_{S,\text{int}}}_{\text{IR poles cancelled analyt.}}$$

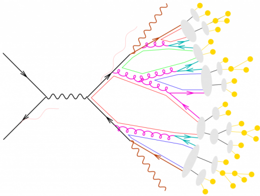


'j' radiated with several different emitters $\Rightarrow$ Subtract singularities related to QED splittings systematically

Divide phase space into disjoint regions with **at most one** soft and/or collinear singularity.

$\Rightarrow$ kinematical weight factors related to pairs (i, j)

Final-state effects



- Jets: integrated `FastJet` interface
- Polarized decays (e.g., W, Z, H, t) as alternative to full matrix elements
- Tau decays via TAOLA
- Resonance selection for shower initialization
- Parton shower + hadronization: PYTHIA6 (integrated)
- Parton shower + hadronization: Pythia 8 (interface or via event file)
- Event file formats: ILC-like (legacy, LCIO/Key4HEP) and LHC-like (legacy, LHE, HepMC)