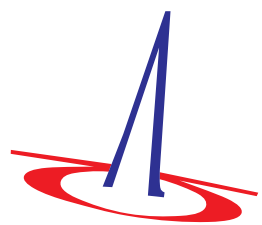
The Whizard Monte Carlo Generator

(and a few physics results)

Wolfgang Kilian

CPPS, University of Siegen

LCWS 26, Tsukuba, Nov 12, 2026



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

⇒ 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

⇒ 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. Phase-space sampling: **VAMP** [Thorsten Ohl, CPC120 (1999), 13-19]

   phs mapping: invertible linear interpolation = *NN and NF*

   channel weights: pointwise importance ratio = *cross-attention*

   optimization: iterative, variance sampling = *training, loss f.*

   $\Rightarrow$ *transformer mechanism*

   $\Rightarrow$ (Details to be improved)

   Caveat: Training counts for CPU time $\Rightarrow$ ML efficiency limited

3. Parallel evaluation on multicore/HPC system: **OpenMP** + **MPI**

   [S. Brass, WK, J. Reuter, EPJC 79 (2019), 344]

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

Precision analysis of Higgs production and BSM sentivity

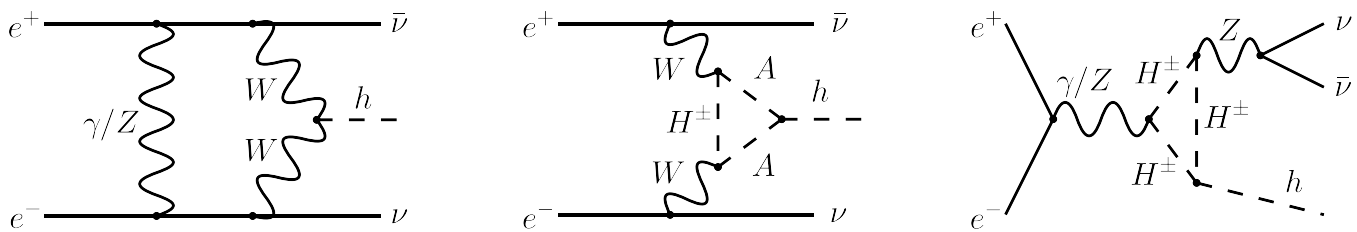
Traces of an extended Higgs sector in loop corrections?

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]

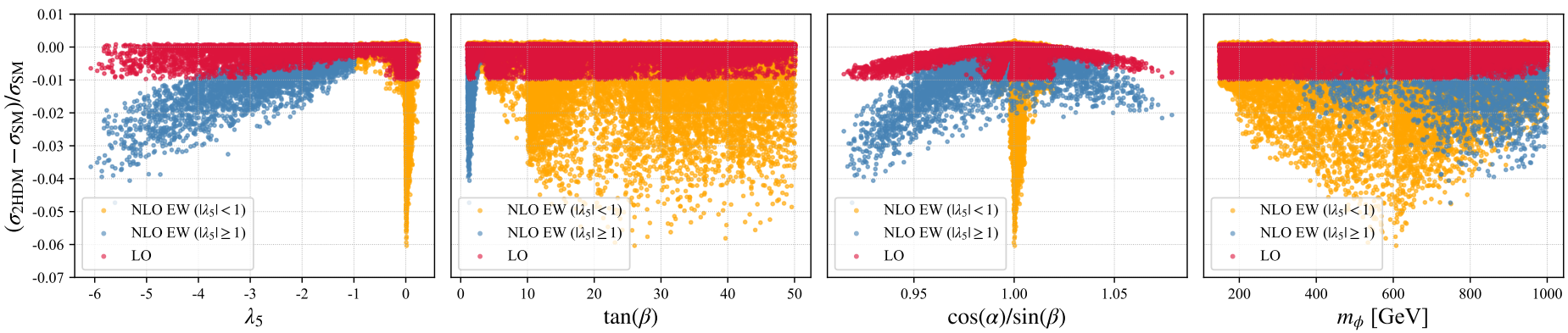
SM + 2HDM (alignment limit ⇒ undetected so far but not heavy)



Calculational framework: Whizard with OpenLoops and Recola

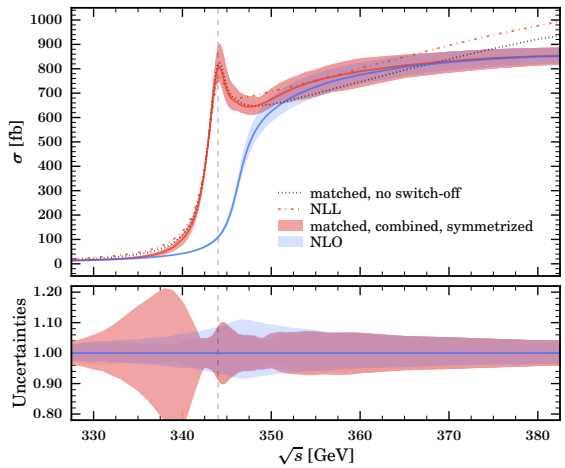
SM-NLO correction vs BSM-NLO

	$\sqrt{s} = 365\,\text{GeV}$		$\sqrt{s} = 550\,\text{GeV}$	
	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%



The top-quark threshold

Threshold enhancement (NRQCD Green function = toponium resonance) matched to NLO QCD off-shell



[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]

- 2026: Revived interest from LHC measurement (note: different spin)
- Threshold scan indispensable if (FCC-ee) precision is to be useful

Scattering processes for ILC/CLIC/PWA, MuCol, FCC-hh

Electroweak restoration at 10 TeV pcm: prepare for it – make use of it

Ideal properties (multi-TeV)

- 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

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

- Mass effects remain relevant at all stages.
- Fixed-order calculations involve gauge cancellations and Sudakov suppression

$\Rightarrow$ framework which complements bottom-up (conventional) results with top-down (symmetric phase) approach

Electroweak PDFs for High-Energy Collider

[T. Han, Y. Ma and K. Xie, PRD 103 (2021), L031301]

[T. Han, WK, K. Mękała, Y. Ma, J. Reuter, K. Xie, arXiv:2611.12793]

- 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

Accounting for mass effects:

Interconnected splitting of massless and massive partons

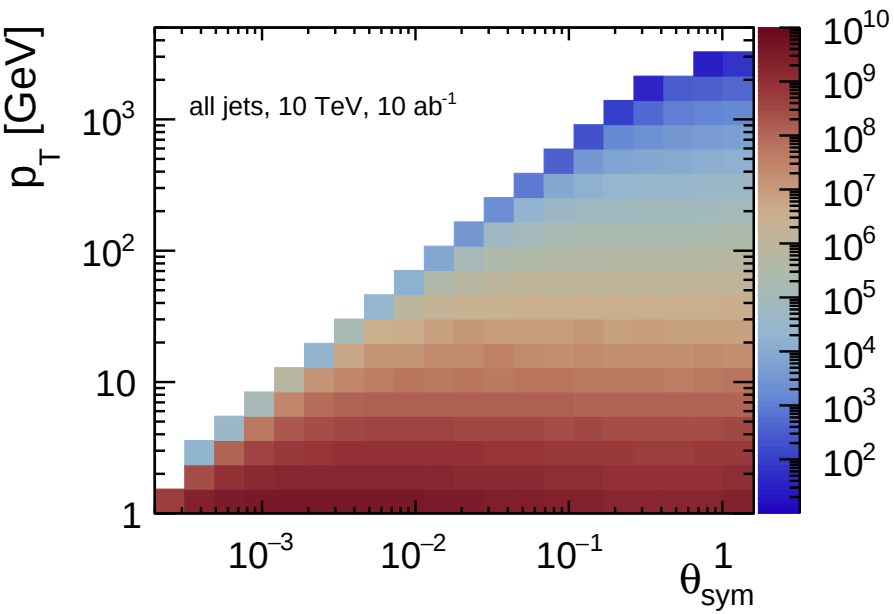
$\Rightarrow$ low energy: only QED/QCD (dijet!)

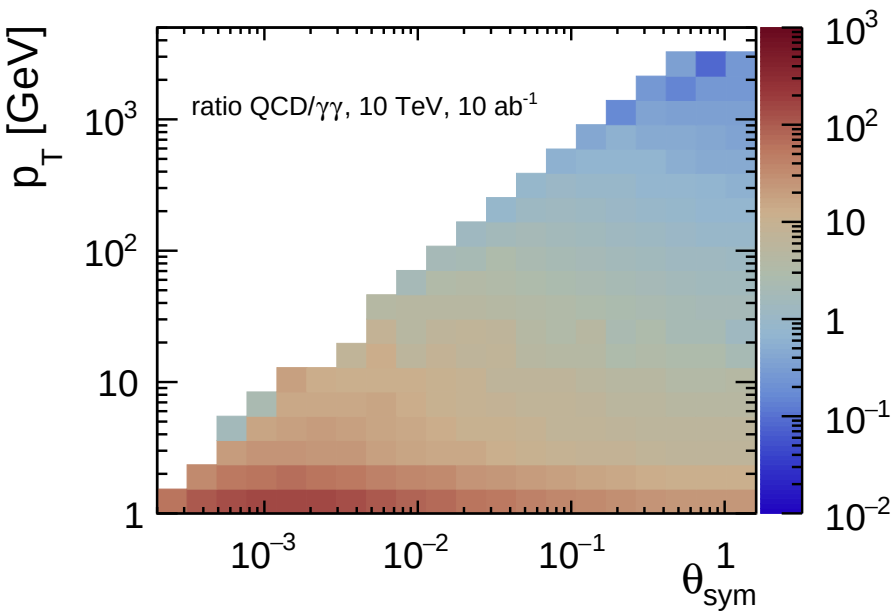
$\Rightarrow$ iterate and match single- and double-PDF regions

$\Rightarrow$ properly combine with EW shower

Implementing electroweak PDFs below m_Z: QCD/QED

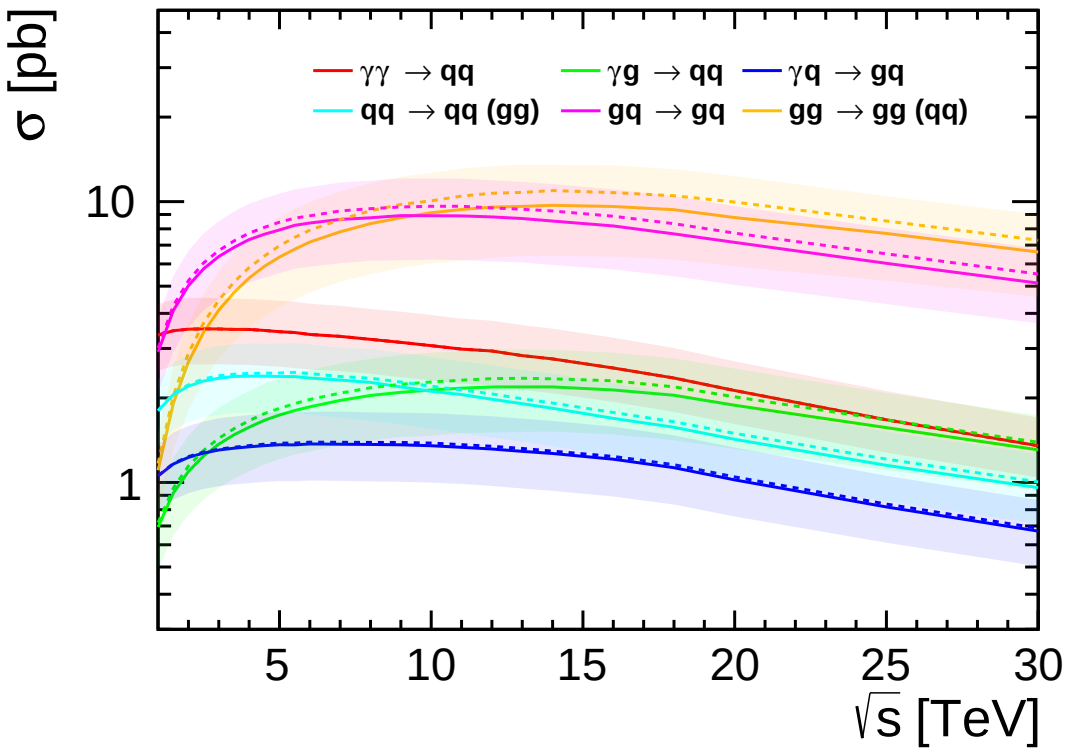
Splitting: $\mu/e \to \gamma \to q \to g$





Implementing electroweak PDFs below m_Z: QCD/QED

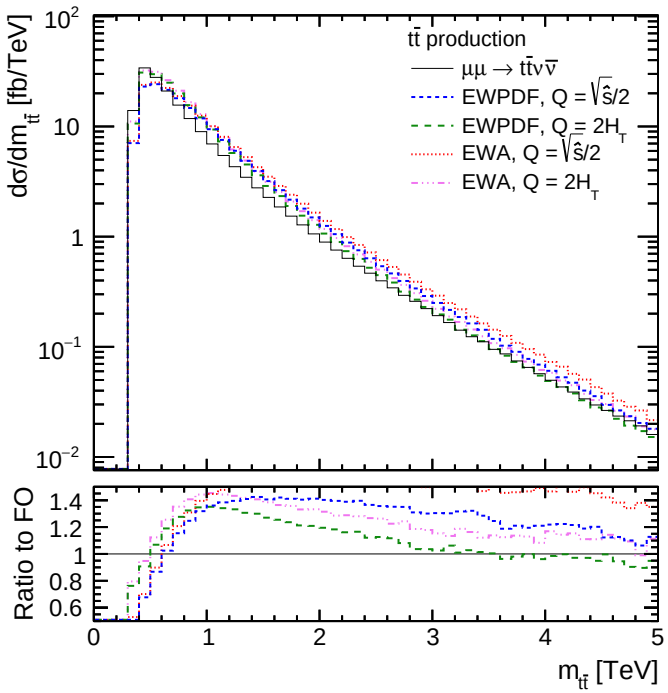
Splitting: $\mu/e \to \gamma \to q \to g$

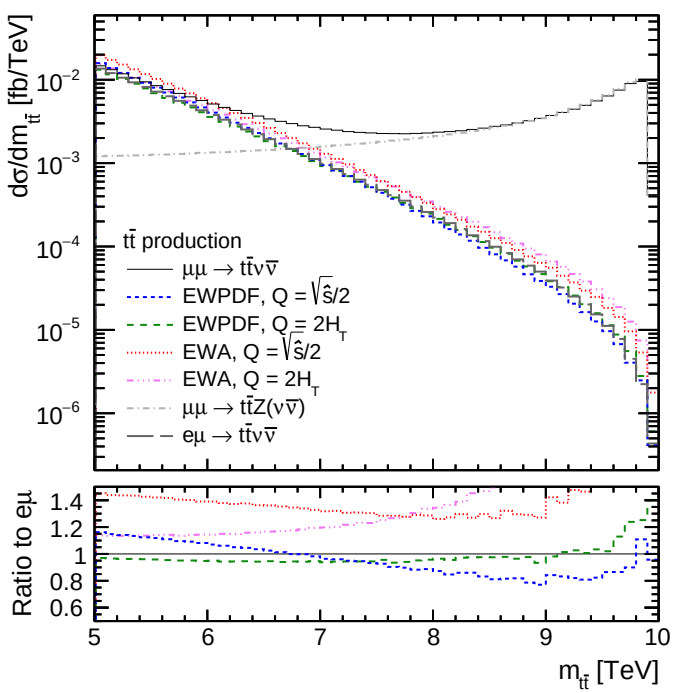


EW-PDF complete: $t\bar{t} + \bar{\nu}\nu$ production

EWA: Factorization for intermediate W/Z bosons

New: Polarized PDF set for all SM particles, DGLAP resummation



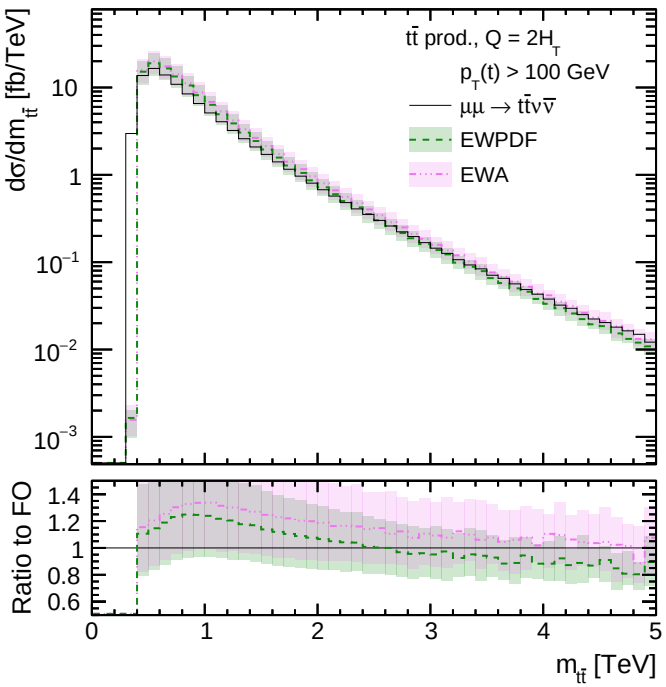


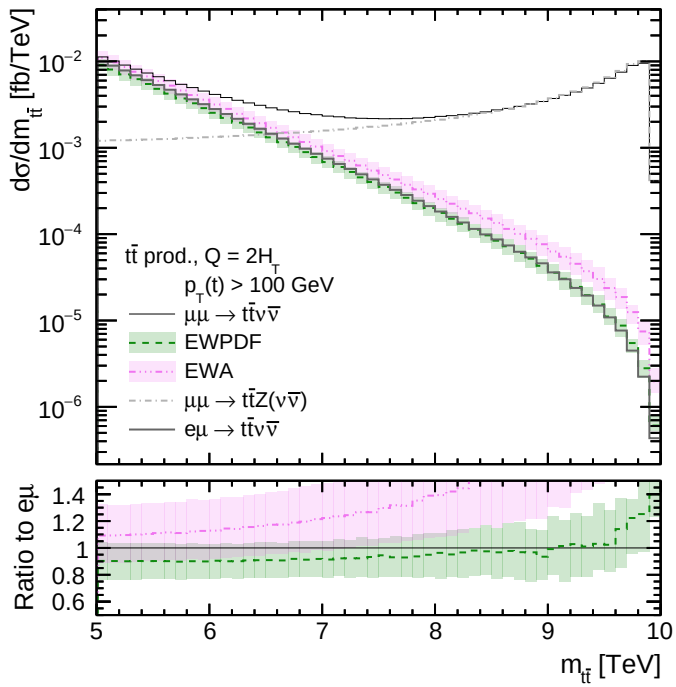
no phase-space cut

EW-PDF complete: $t\bar{t} + \bar{\nu}\nu$ production

EWA: Factorization for intermediate W/Z bosons

New: Polarized PDF set for all SM particles, DGLAP resummation



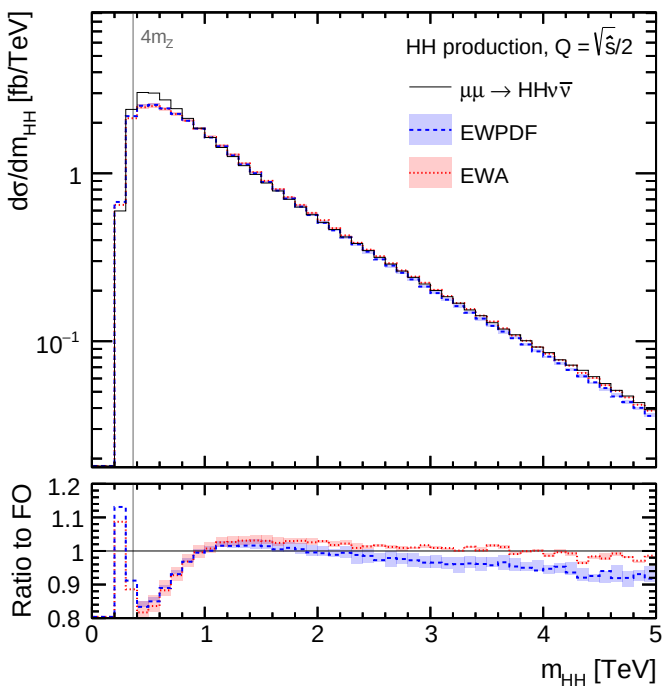


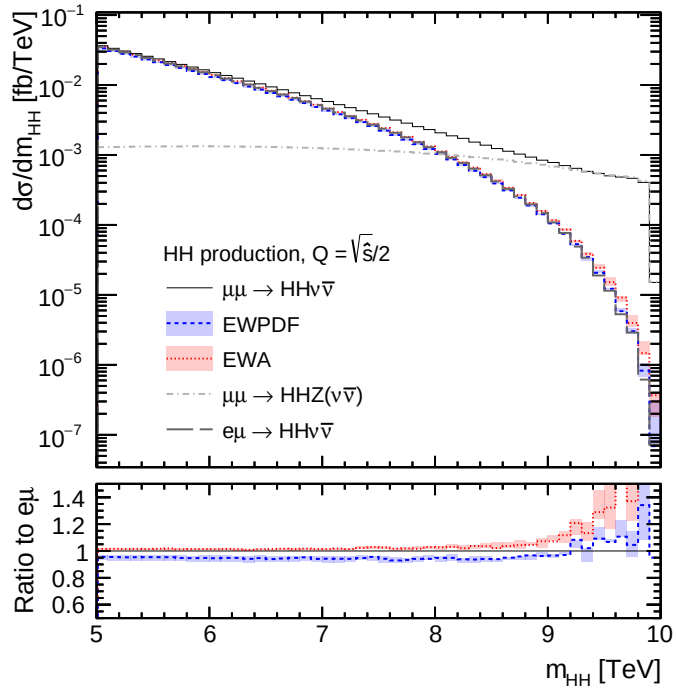
with cut $p_T > 100$ GeV

EW-PDF complete: $HH + \bar{\nu}\nu$ production

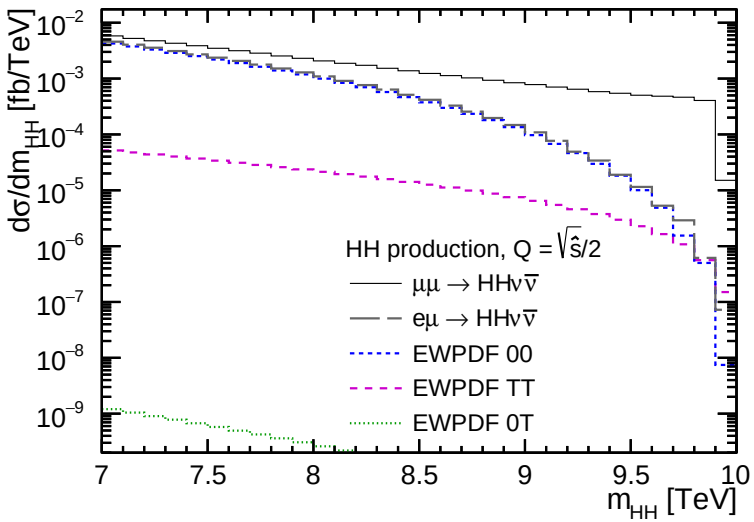
Hard process: $W^+W^- \to HH$

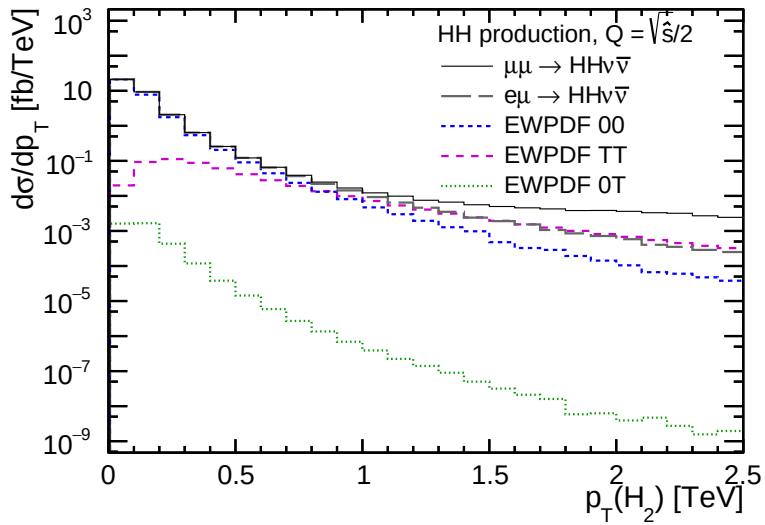
- Low-energy POV: measurement of triple Higgs coupling (HHH)
- High-energy POV: measurement of quartic Higgs coupling ($W_L W_L HH$)





EW-PDF complete: $HH + \bar{\nu}\nu$ W-helicity breakdown

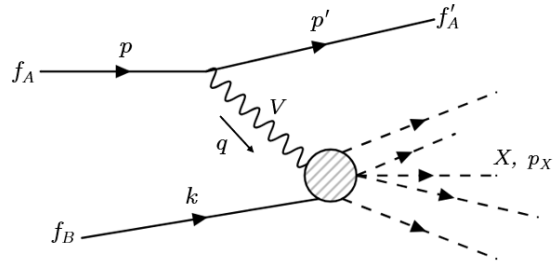




$\Rightarrow$ Longitudinal dominance for most of phase space

$\Rightarrow$ Transversal dominance at high p_T

EW PDFs: Fine Print



Caveat:

- Intrinsic $p_T(f'_A)$ peaks around $p_T \sim m_W/2$
- Photon: $Q_{\min} = x^2 m_f$ vs W boson: $Q_{\min} = m_W$
  $\Rightarrow$ huge difference in $\log(Q_{\max}/Q_{\min})$
- 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 $M_X > \sqrt{2 m_W \sqrt{s}}$.
  $\Rightarrow$ Muon collider 10 TeV, double EWA: $M_X > 1.2$ TeV.

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

Summary and Outlook

- Whizard provides a universal framework for high-energy phenomenology, in particular: lepton colliders
- Low energy: higher orders EW/QED + BSM
  Physics result: Precision Higgs data indirectly sensitive to extended Higgs sector ($E = 365,\ 550$ GeV)
- Medium energy: Thresholds ($t\bar{t}$, $t\bar{t}H$, ...)
- High energy: electroweak processes and BSM in the symmetry-restoration range
- New collaboration with Herwig (S. Plätzer @ Siegen)
- Efficiency and accuracy (phase space, NLO matrix elements)



The WHIZARD 3 Team

U Siegen: WK, Pia Bredt, ElMahdi Houmani, Nils Kreher, Francesco Ucci

DESY: Jürgen Reuter

INFN Frascati: Krzysztof Mękała

U Warsaw: A. Filip Żarnecki

U Würzburg: Thorsten Ohl

Links

- Reference: WK/Ohl/Reuter, EPJ C71 (2011) 1742
- Whizard Launchpad Portal: `https://launchpad.net/whizard`
- public gitlab repo: (migrated to DESY!)
  `https://gitlab.desy.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, . . .)

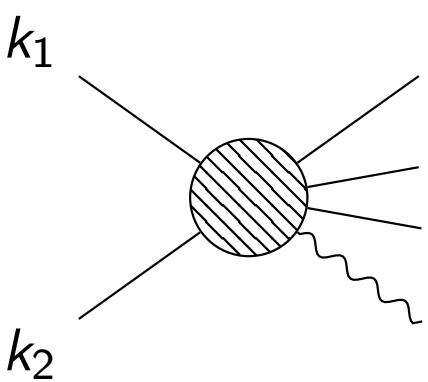
Parallel: OpenMP (multi-core), MPI (HPC cluster)

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:

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

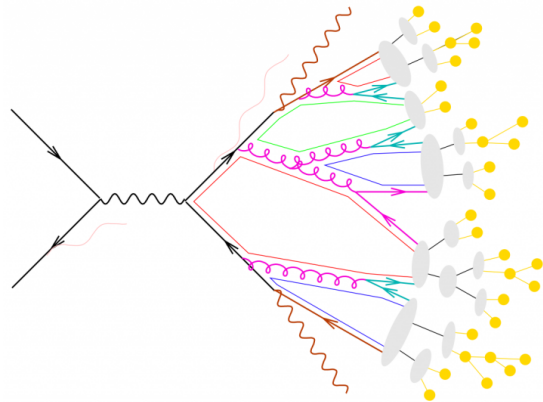


'j' radiated with several different emitters $\Rightarrow$ Subtract singularities related to QED splittings systematically

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)