WHIZARD

A new package for multi-particle Monte-Carlo integration and event generation

(to deal with
W, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays)

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Automatic systems

At the Linear Collider, multi-particle processes become increasingly important:

$$e^+e^- \to \text{4 fermions}, \quad \text{4 fermions} + \gamma, \quad \text{6 fermions}, \ldots$$

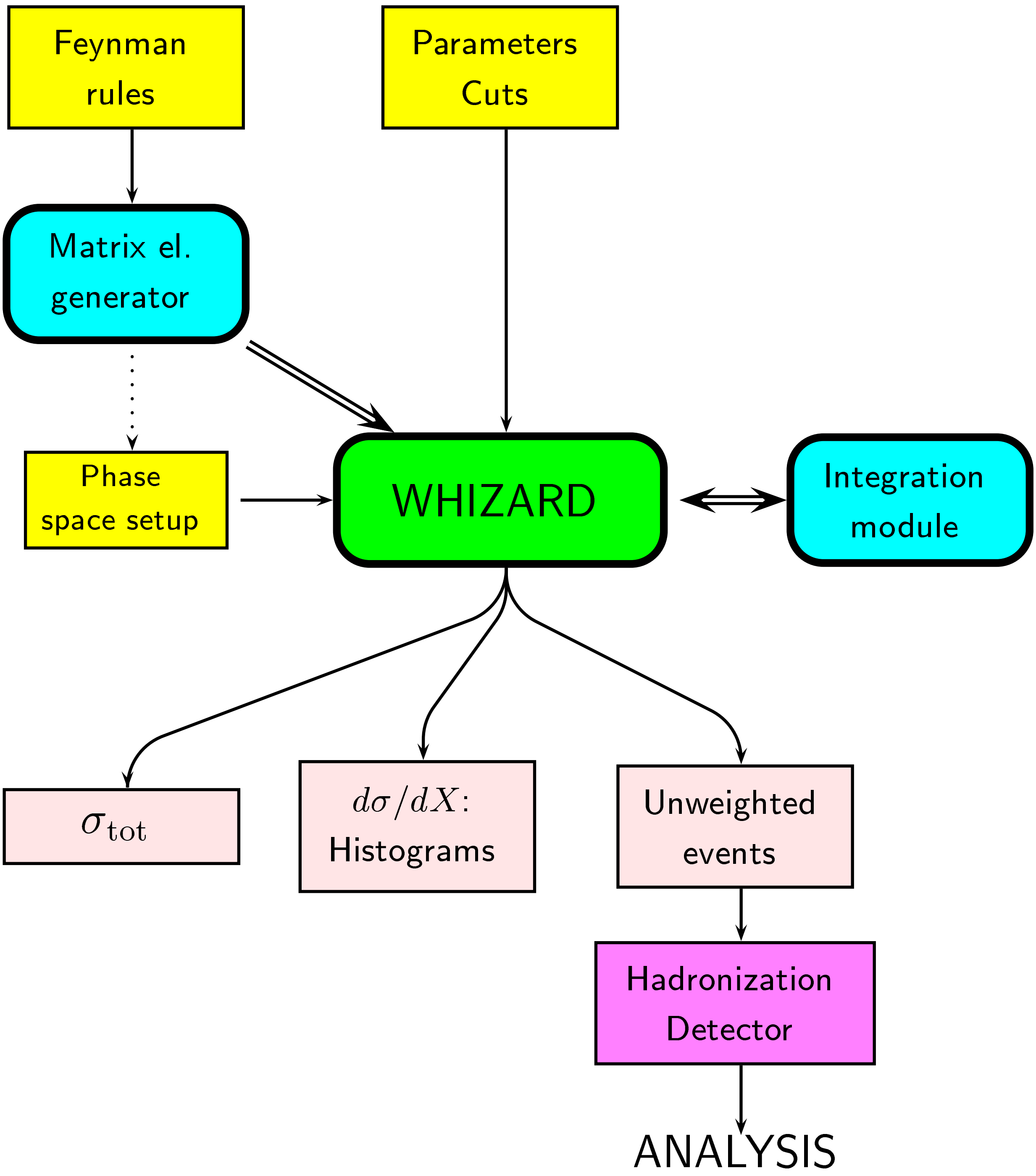
There is need for a high level of automatization:

- Matrix elements become very complicated
- Phase space has a complex singularity structure
- Number of processes to be considered becomes large

Goal: Fully automatic system:

- put in
  - Physical model [Feynman rules/Lagrangian]
  - Process to be studied
    (at least: up to 6 final-state particles)
  - Set of parameters and canonical cuts
- get out
  - Total cross section to a high level of accuracy
  - Efficient generator for unweighted events

WHIZARD structure



Auxiliary packages

Matrix element generator:

use any of

- CompHEP (any model, up to $2 \to 4$)
- MadGraph (restricted SM, up to $2 \to 6$)
- O'Mega (under construction)
- your own matrix element

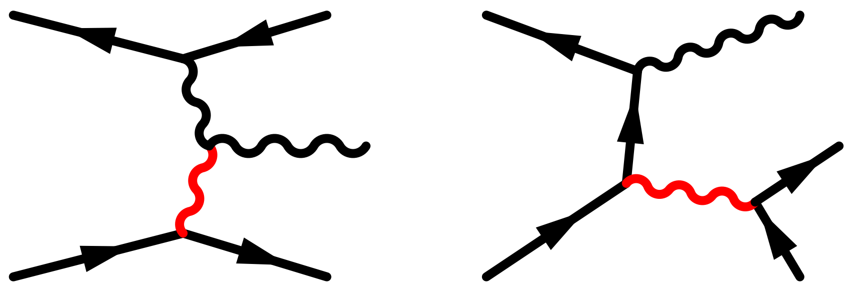
[Switch between ME for the same process generated by different programs $\Rightarrow$ cross-checks]

Integration module:

- VAMP: (by Th.Ohl)
  self-adaptive multi-channel integration
  and event generation
  (based on the VEGAS algorithm)

The singularity (peak) structure of a matrix element is determined by the corresponding Feynman diagrams

Example: $e^- e^+ \to e^- \bar{\nu} W^+$



Any internal line is either s-channel-like or t-channel-like.

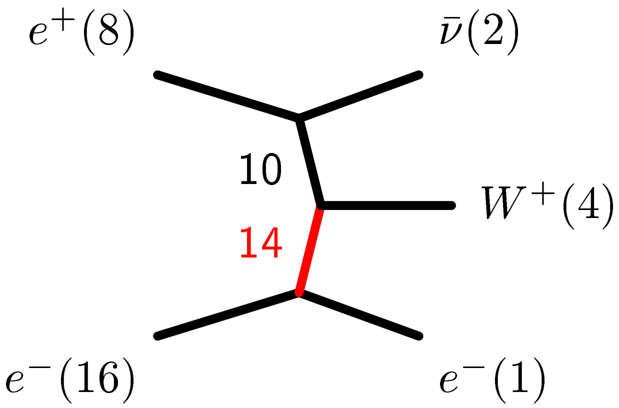
$\Rightarrow$ WHIZARD provides one parameterization appropriate for s-channel and one for t-channel
$+$ a recursive procedure to link them when generating momenta
(option: Breit-Wigner mapping for resonances)

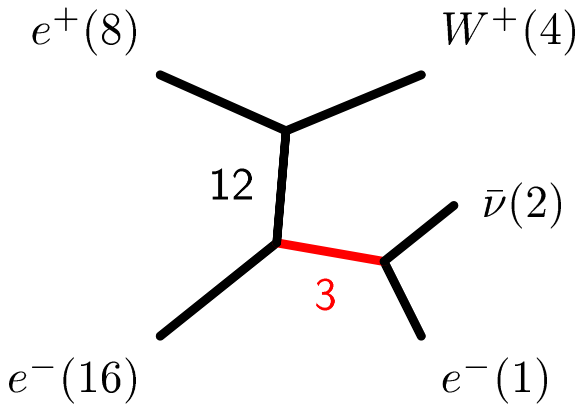
$\Rightarrow$ correspondence between diagrams and phase-space parameterizations

$\Rightarrow$ For each process:
specify the dominant Feynman diagrams

$\rightsquigarrow$ Multi-channel integration can handle all singularities (in principle)

Example:





Phase space configuration file:

```
process ee_enw
    map 3 s-channel W-boson
    tree 3 12
    tree 10 14
```

Analogously: Cut configuration file:

```
process ee_enw
    cut E of 1 within 10 1000
```

$\Rightarrow$ cut on the electron energy: $E_e > 10\ \mathrm{GeV}$

1. Specify processes to be considered: `processes.conf`

ID	In	Out	Method
ee_enw	e1,E1	e1,N1,W+	chep
ee_enwa	e1,E1	e1,N1,W+,A	omega

2. Make the executable

```
make prg
```

3. If necessary: Edit phase space configuration file: `whizard.phs`

4. Edit the main input file: `whizard.in`
   (ID, $\sqrt{s}$, $n_{\rm it}$, $N_{\rm evt}$, …)

5. Start the integration

```
make run
```

6. Inspect the results:
   - Screen output (grid adaptation and integration)
   - Output file
   - Optional: Histogram data
   - Optional: ASCII file with unweighted events (SIMDET input format)

Results

Higgs-strahlung and WW fusion, including complete 4-fermion background (MadGraph):

$$e^-e^+ \to \nu_e\bar{\nu}_e b\bar{b}$$

$\sqrt{s} = 350$ GeV and $m_H = 120$ GeV

```
! WHIZARD run for process n1n1bb_m:
!-----------------------------------------------------------------------------
! It      Calls    Integral[fb]  Error[fb]  Err[%] Err/Exp Eff[%]   Chi2
!-----------------------------------------------------------------------------
   2      20000   6.0917020E+01  2.18E+00    3.58    5.07*  1.30    0.31
!-----------------------------------------------------------------------------
   3      10000   5.8750342E+01  1.14E+00    1.94    1.94*  6.09
   4      10000   5.8275477E+01  7.18E-01    1.23    1.23*  8.90
   5      10000   5.8506865E+01  6.07E-01    1.04    1.04*  9.83
   6      10000   5.9165366E+01  6.20E-01    1.05    1.05  10.33
   7      10000   5.7405511E+01  4.81E-01    0.84    0.84* 14.16
   8      10000   5.9118249E+01  4.83E-01    0.82    0.82* 15.16
   9      10000   5.8384828E+01  5.26E-01    0.90    0.90  14.95
  10      10000   5.9404372E+01  9.16E-01    1.54    1.54   8.09
!-----------------------------------------------------------------------------
  12      20000   5.8799458E+01  3.45E-01    0.59    0.83   9.97    0.29
!=============================================================================
```

Result: $\sigma = 58.80 \pm 0.35$ fb and eff $= 15\%$

Performance

Accuracy of Monte Carlo integration:

$$\Delta\sigma/\sigma = \alpha/\sqrt{N}$$

Goal: α as small as possible

Efficiency of event generation:

$$\epsilon = f_{\rm avg}/f_{\rm max}$$

Goal: ϵ as large as possible

Typical `WHIZARD` results (after complete adaptation)

Process	α	ϵ
$2 \to 3$	$0.1 - 0.5$	$30 - 50\ \%$
$2 \to 4$	$0.5 - 1.5$	$5 - 20\ \%$
$2 \to 5$	$1.0 - 2.0$	$2 - 10\ \%$
$2 \to 6$	$1.5 - 3.0$	$1 - 5\ \%$

Empirically:

$$\epsilon \approx 7\ \% \times \alpha^{-1.7}$$

Example: $\alpha = 2$ and $\epsilon = 3\ \%$, use 1M calls
$\Rightarrow$ 0.2 % integration error / 30k unweighted events

Results

Application to electroweak processes:
Interference of $WW + \gamma$ and single $W + \gamma$:

$$e^- e^+ \to e^- \bar{\nu}_e u\bar{d} + \gamma$$

complete matrix element (`O'Mega`) with canonical cuts:

$$E(\gamma) > 0.1 \text{ GeV}$$
$$\theta(\gamma/\text{jet},\ \gamma/\text{beam},\ \text{jet}/\text{beam}) > 5^\circ$$
$$E(\text{jet}) > 3 \text{ GeV} \qquad M(jj) > 10 \text{ GeV}$$
$$\text{no cut on } e^- \ (m_e \neq 0)$$

Difficulty: Width prescription for off-shell W bosons must be consistent with gauge invariance. Here: use $\Gamma = 0$ and multiply result by

$$\frac{(s - M^2)^2}{(s - M^2)^2 + M^2\Gamma^2} \tag{1}$$

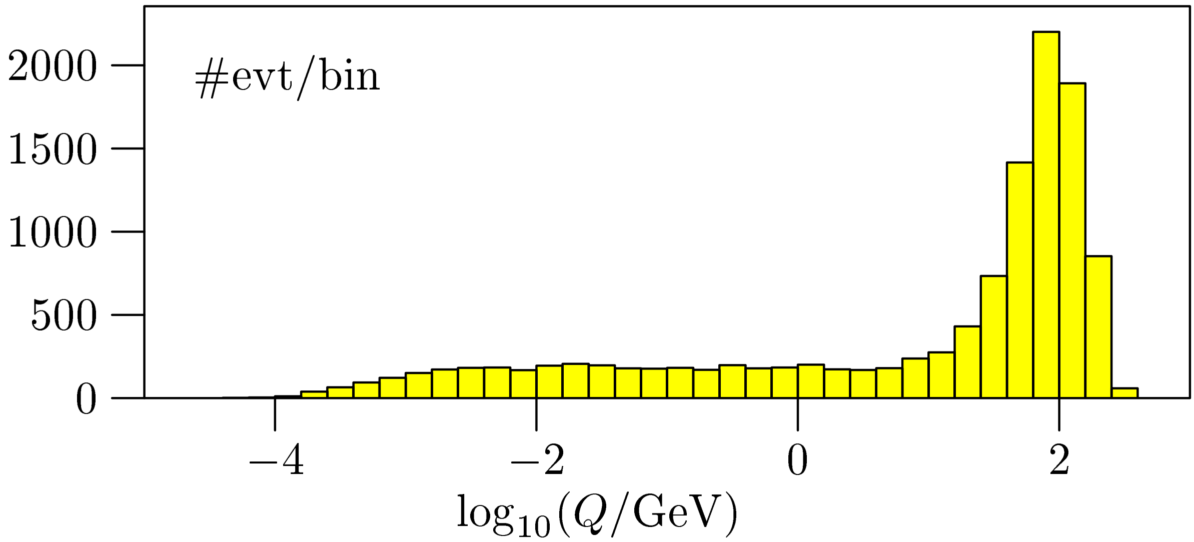
for resonant propagators

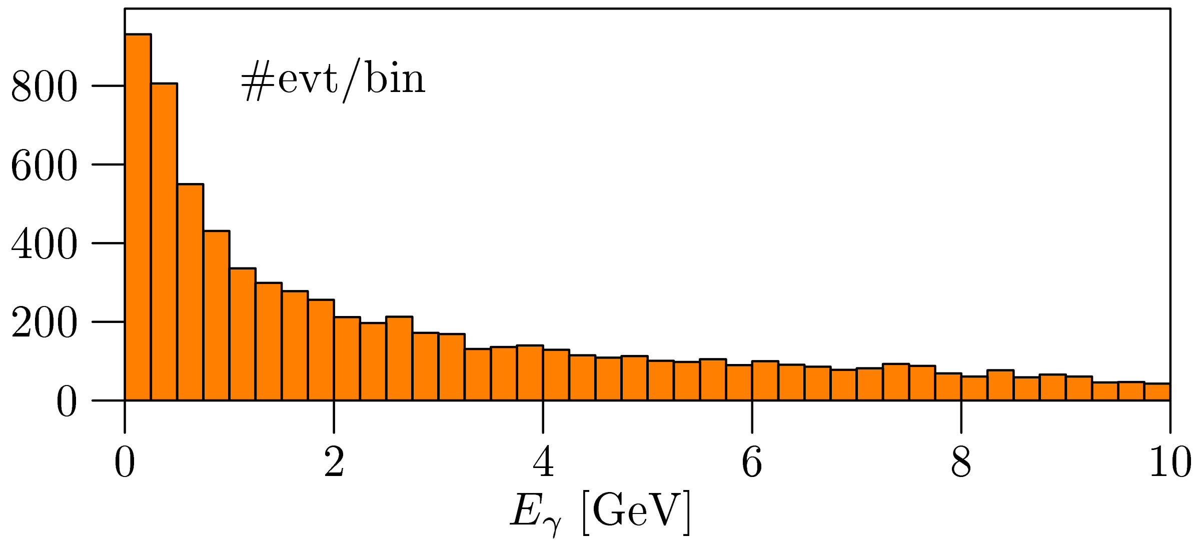
Result (after $20 - 30$ iterations with 100000 calls each):

$$\sqrt{s} = 350 \text{ GeV} : \qquad \sigma = 118.3 \pm 0.5 \text{ fb} \quad (\epsilon = 2.8\ \%)$$

Process: $e^- e^+ \to e^- \bar{\nu}_e u \bar{d} \gamma$

$$\sqrt{s} = 350.0 \text{ GeV} \qquad \int \mathcal{L} = 100.0 \text{ fb}^{-1}$$





SM Higgs physics:

Higgs production with decay $H \to WW^*, ZZ^*$

Complete matrix elements (`MadGraph`)

1. $H \to WW^*$:

$$e^- e^+ \to \nu_e \bar{\nu}_e \, u\bar{d}s\bar{c}$$

$$\sqrt{s} = 500 \text{ GeV and } M_H = 140 \text{ GeV} \qquad [V_{\rm CKM} = 1]$$

$$\sigma = 2.534 \pm 0.010 \text{ fb} \qquad (\epsilon = 3.2\ \%)$$

2. $H \to ZZ^*$ and $H \to WW$:

$$e^- e^+ \to \nu_e \bar{\nu}_e \, u\bar{u}d\bar{d}$$

$$\sqrt{s} = 500 \text{ GeV and } M_H = 180 \text{ GeV}:$$

$$\sigma = 3.769 \pm 0.015 \text{ fb} \qquad (\epsilon = 5.4\ \%)$$

3. QCD contribution to 2.:

$$\sigma = 7.56 \pm 0.02 \text{ ab [sic]} \qquad (\epsilon = 2.0\ \%)$$

Outlook

Problems:

- Adaptation may take as long as event generation
  $\Rightarrow$ keep pre-generated grids
- Phase space configuration file still written by hand
  $\Rightarrow$ may be prepared by `O'Mega`
- Events with weight > 1 can't be excluded (stochastic adaptation procedure)
  $\Rightarrow$ Record resulting error in event generation
  [$<$ integration error]

To be done:

- Beamstrahlung, structure functions (interface present)
- Parallelization (prepared, not yet tested)
- More tests