WHiZard & O'Mega

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Institute for Theoretical Physics and Astrophysics
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LoopFest V
SLAC, June 20th, 2006

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- ingredients:
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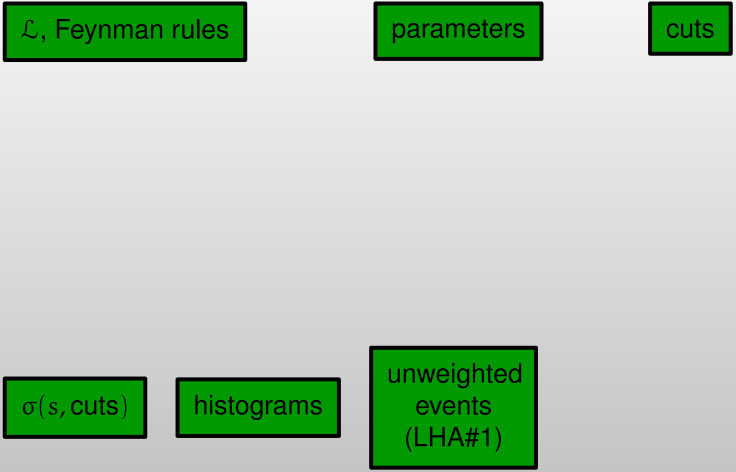
  - integration and sampling
  - cuts and (simple) analysis
  - interfacing to the rest of the world

$\mathcal{L}$, Feynman rules

parameters

cuts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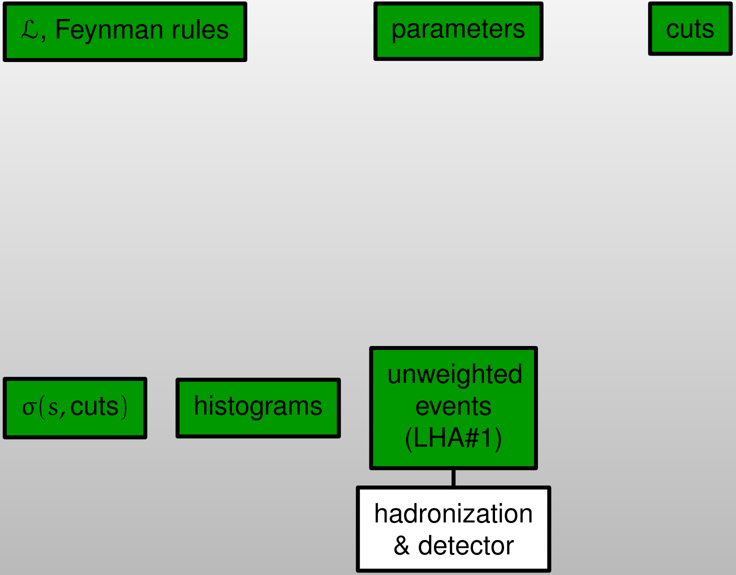
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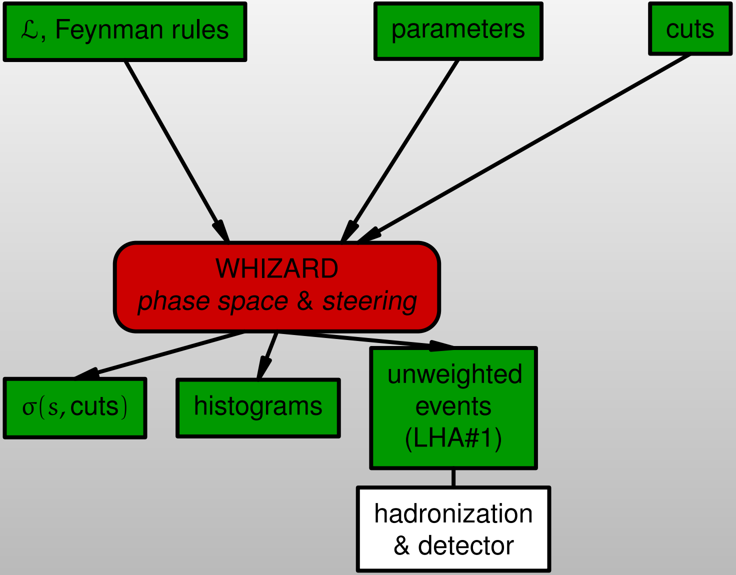
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WHIZARD
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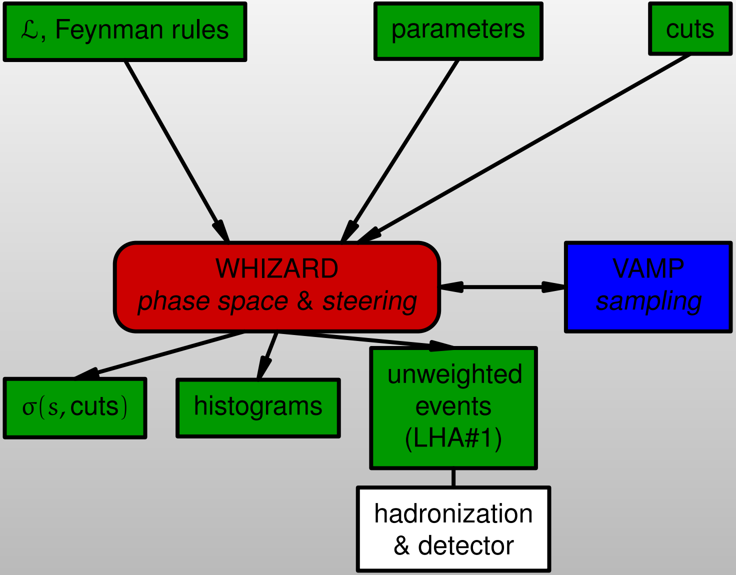
Kilian



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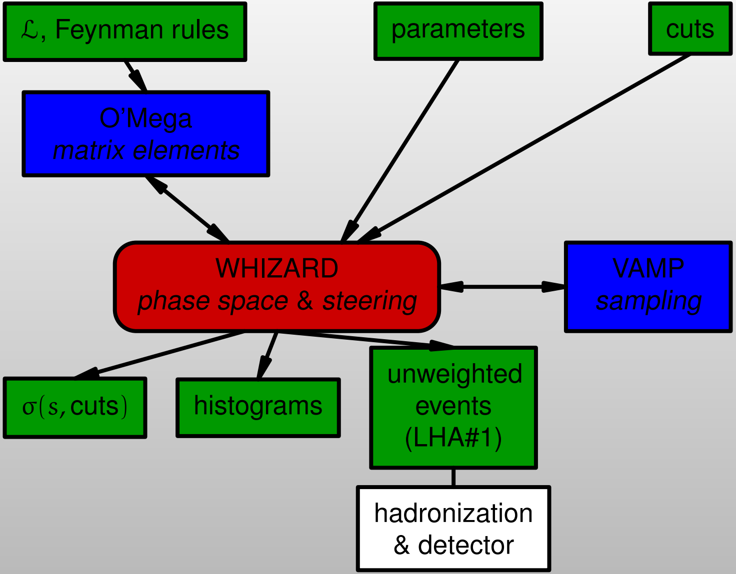
T. O., *et al.*



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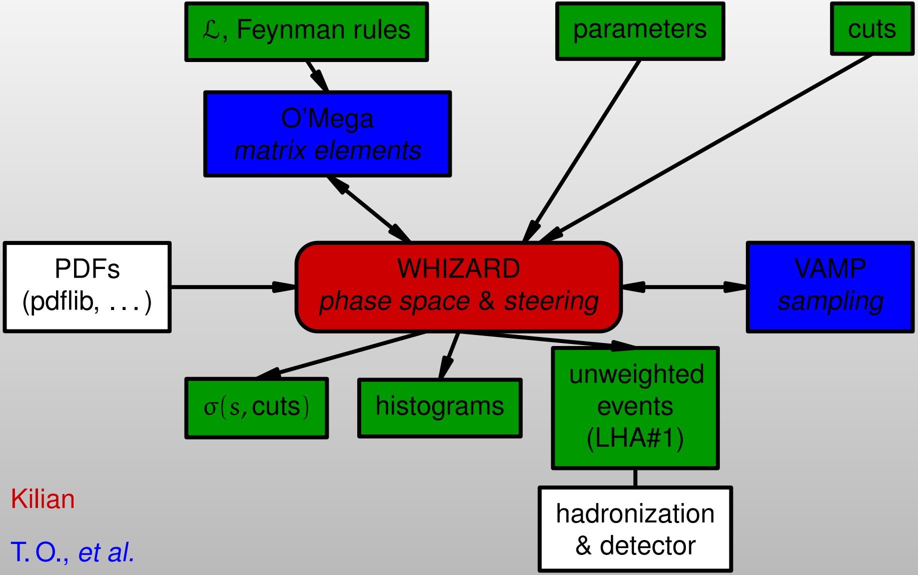

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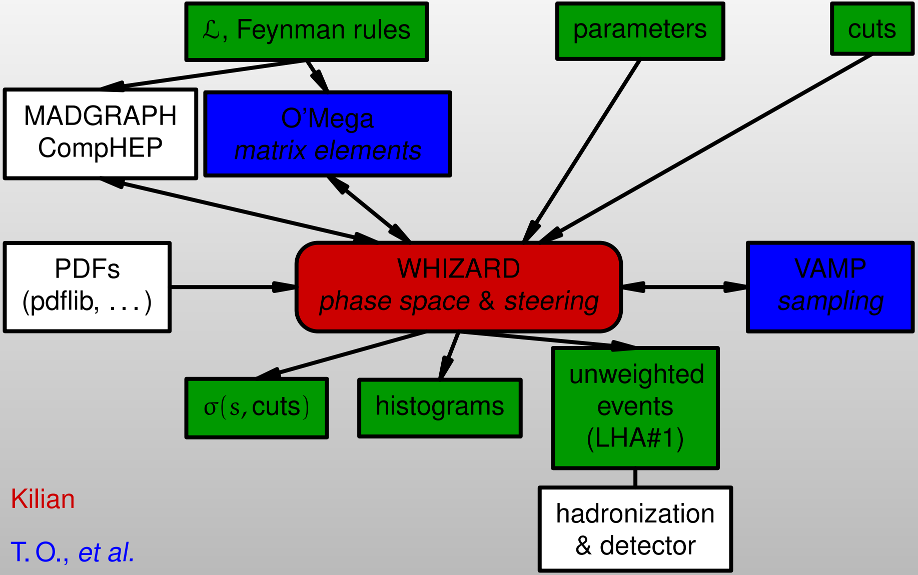

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The number of tree Feynman diagrams w/ n legs in vanilla ϕ^3-theory grows like a factorial

$$F(n) = (2n-5)!! = (2n-5)\cdot(2n-7)\cdot\ldots\cdot3\cdot1$$

n		
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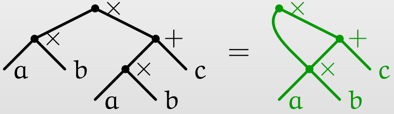
∴ Feynman diagrams redundant for many external particles!

∴ Replace the forest of tree diagrams by the Directed Acyclical Graph (DAG) of the algebraic expression.

$$ab(ab+c) =$$



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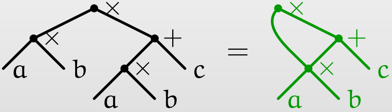

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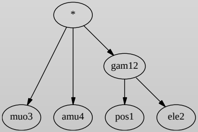

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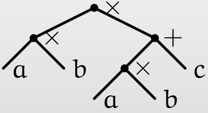
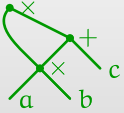
$ab(ab+c) =$ 

$=$ 

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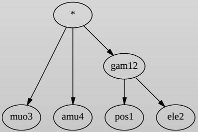

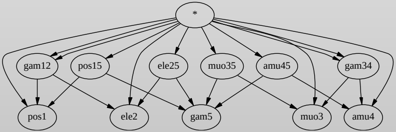

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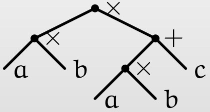
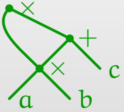
$ab(ab+c) =$ 

$=$ 

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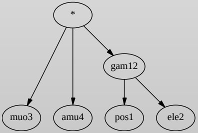

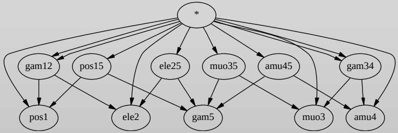

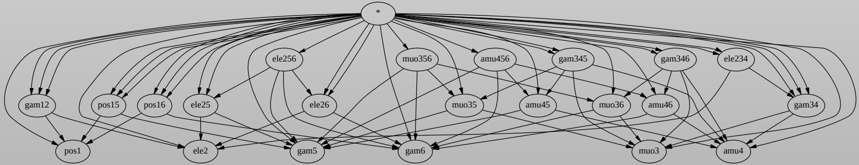

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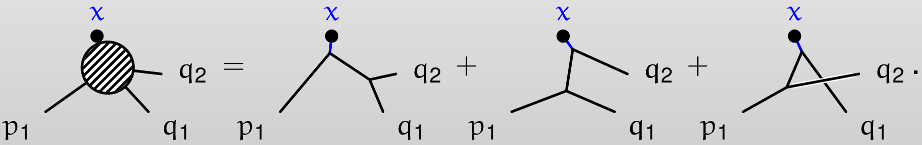

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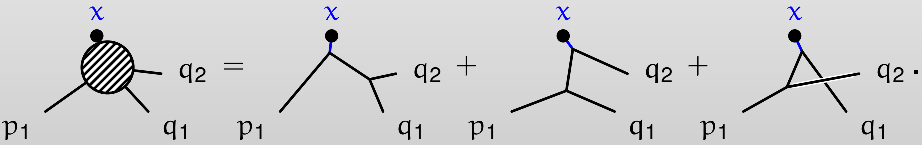

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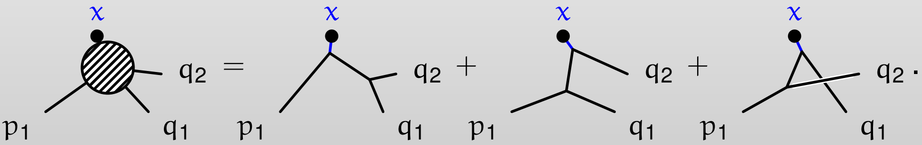

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There exists a well defined set of keystones K that allow to express the sum of Feynman diagrams through 1POWs:

$$T = \sum_{i=1}^{F(n)} D_i = \sum_{k,l,m=1}^{P(n)} K^3_{f_k f_l f_m}(p_k,p_l,p_m) W_{f_k}(p_k) W_{f_l}(p_l) W_{f_m}(p_m)$$

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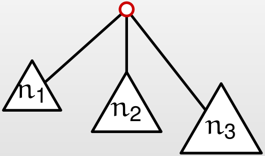

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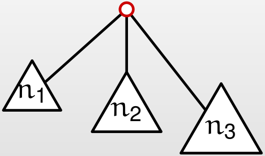

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4	4	$1 \cdot (1,1,1,1) + 3 \cdot (1,1,2)$
5	26	$1 \cdot (1,1,1,1,1) + 10 \cdot (1,1,1,2) + 15 \cdot (1,2,2)$
6	236	$1 \cdot (1,1,1,1,1,1) + 15 \cdot (1,1,1,1,2) + 40 \cdot (1,1,1,3)$ $+ 45 \cdot (1,1,2,2) + 120 \cdot (1,2,3) + 15 \cdot (2,2,2)$

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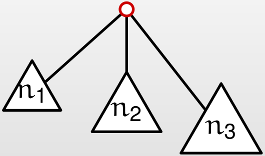

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Subtlety: some partitions for an even number of external lines are degenerate

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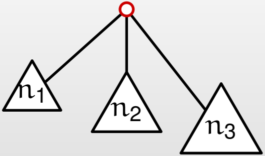

n	$\sum$	$\sum$
4	4	$1 \cdot (1,1,1,1) + 3 \cdot (1,1,2)$
5	26	$1 \cdot (1,1,1,1,1) + 10 \cdot (1,1,1,2) + 15 \cdot (1,2,2)$
6	236	$1 \cdot (1,1,1,1,1,1) + 15 \cdot (1,1,1,1,2) + 40 \cdot (1,1,1,3)$
		$+ 45 \cdot (1,1,2,2) + 120 \cdot (1,2,3) + 15 \cdot (2,2,2)$

Subtlety: some partitions for an even number of external lines are degenerate, e. g. $(1,1,1,3)$ and $(1,2,3)$ contain the same diagram

and representatives must be chosen consistently.

Non trivial cross check from self-consistency of counting
$F(d_{\text{max}}, n) = \#$ of Feynman diagrams with n external legs in unflavored

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m^2}{2}\phi^2 - \sum_{d=3}^{d_{\text{max}}} \frac{\lambda_d}{d!}\phi^d$$

theory. In a partition $N_{d,n} = \{n_1, n_2, \ldots, n_d\}$ with $n = n_1 + n_2 + \cdots + n_d$, there are

$$\tilde{F}(d_{\text{max}}, N_{d,n}) = \frac{1}{(1 + \delta_{n_d, n_1+n_2+\cdots+n_{d-1}})} \frac{n!}{|\mathcal{S}(N_{d,n})|} \prod_{i=1}^{d} \frac{F(d_{\text{max}}, n_i + 1)}{n_i!}$$

Feynman diagrams ($|\mathcal{S}(N)|$ the size of the symmetric group of N).

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Feynman diagrams ($|\mathcal{S}(N)|$ the size of the symmetric group of N).

$$F(d_{\max}, n) = \sum_{d=3}^{d_{\max}} \sum_{\substack{N=\{n_1,n_2,\ldots,n_d\} \\ n_1+n_2+\cdots+n_d=n \\ 1\leqslant n_1\leqslant n_2\leqslant\cdots\leqslant n_d\leqslant\lfloor n/2\rfloor}} \tilde{F}(d_{\max}, N)$$

can be be checked numerically up to $n = \mathcal{O}(100)$.

Even for vector particles, the 1POWs are 'almost' physical objects and satisfy simple Ward Identities in unbroken gauge theories

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Amplitudes can be continued off-shell:

- Slavnov-Taylor Identities can be checked numerically by adding operator insertions implementing BRS transformations.

Slightly simplified `Model.T` signature that all models must implement:

```
module type Model.T =
  sig
    type flavor (* all quantum numbers *)
    val flavor_symbol : flavor -> string
    val conjugate : flavor -> flavor (* antiparticles *)
    val lorentz : flavor -> Coupling.lorentz (* spin *)
    val fermion : flavor -> int (* fermion, boson, antifermion *)
    val width : flavor -> Coupling.width (* scheme, not value! *)
    type gauge (* parametrized gauges *)
    val gauge_symbol : gauge -> string
    val propagator : flavor -> gauge Coupling.propagator
    type constant (* coupling constants *)
    val constant_symbol : constant -> string
    val fuse2 : flavor -> flavor ->
     (flavor * constant Coupling.t) list (* A_μ(p_12) ← gψ̄(p_1)γ_μψ(p_2) *)
    val fuse3 : flavor -> flavor -> flavor ->
     (flavor * constant Coupling.t) list (* φ(p_123) ← gφ(p_1)φ(p_2)φ(p_3) *)
    val fuse : flavor list -> (flavor * constant Coupling.t) list
  end
```

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  - some NMSSM
- BSM models remain constantly evolving (as is the nature of BSM physics ...)
  - "anomalous couplings": robust since TESLA TDR
  - various little higgs models available
  - extra dimension models available
  - feel free to DIY ...

credit for many recent implementations and applications: [J. Reuter]

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  - AMEGIC++ / SHERPA
  - MADGRAPH / HELAS
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- read all about it in [Hagiwara, Kilian, Krauss, T. O., Plehn, Rainwater, Reuter, Schumann, PRD73 (2006) 055005]
  - ☺ contains comprehensive list of $2 \to 2$ cross sections for testing your own Feynman rules

$W^- Z \to X^-$						
Final state	MADGRAPH / HELAS		WHiZard / O'Mega		AMEGIC++ / SHERPA	
	0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV
$\tilde{e}_L \tilde{\nu}_e^*$						
$\tilde{\mu}_L \tilde{\nu}_\mu^*$						
$\tilde{\tau}_1 \tilde{\nu}_\tau^*$						
$\tilde{\tau}_2 \tilde{\nu}_\tau^*$						
$\tilde{d}_L \tilde{u}_L^*$	—		—		—	
$\tilde{s}_L \tilde{c}_L^*$	—		—		—	
$\tilde{b}_1 \tilde{t}_1^*$	—		—		—	
$\tilde{b}_2 \tilde{t}_2^*$	—		—		—	
$\tilde{b}_1 \tilde{t}_2^*$	—		—		—	
$\tilde{b}_2 \tilde{t}_1^*$	—		—		—	
$\tilde{\chi}_1^0 \tilde{\chi}_1^-$						
$\tilde{\chi}_2^0 \tilde{\chi}_1^-$						
$\tilde{\chi}_3^0 \tilde{\chi}_1^-$	—		—		—	
$\tilde{\chi}_4^0 \tilde{\chi}_1^-$	—		—		—	
$\tilde{\chi}_1^0 \tilde{\chi}_2^-$						
$\tilde{\chi}_2^0 \tilde{\chi}_2^-$	—		—		—	
$\tilde{\chi}_3^0 \tilde{\chi}_2^-$	—		—		—	
$\tilde{\chi}_4^0 \tilde{\chi}_2^-$	—		—		—	
$h^0 H^-$	—		—		—	
$H^0 H^-$	—		—		—	
$A^0 H^-$	—		—		—	
$W^- h^0$						
$W^- H^0$						
$W^- A^0$						
$Z H^-$						

$W^- Z \to X^-$						
Final state	MADGRAPH / HELAS		WHiZard / O'Mega		AMEGIC++ / SHERPA	
	0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV
$\tilde{e}_L \tilde{\nu}_e^*$			96.639(2)			
$\tilde{\mu}_L \tilde{\nu}_\mu^*$			96.638(2)			
$\tilde{\tau}_1 \tilde{\nu}_\tau^*$			14.952(1)			
$\tilde{\tau}_2 \tilde{\nu}_\tau^*$			85.875(2)			
$\tilde{d}_L \tilde{u}_L^*$	—		—		—	
$\tilde{s}_L \tilde{c}_L^*$	—		—		—	
$\tilde{b}_1 \tilde{t}_1^*$	—		—		—	
$\tilde{b}_2 \tilde{t}_2^*$	—		—		—	
$\tilde{b}_1 \tilde{t}_2^*$	—		—		—	
$\tilde{b}_2 \tilde{t}_1^*$	—		—		—	
$\tilde{\chi}_1^0 \tilde{\chi}_1^-$			61.626(3)			
$\tilde{\chi}_2^0 \tilde{\chi}_1^-$			2.8350(3)e3			
$\tilde{\chi}_3^0 \tilde{\chi}_1^-$	—		—		—	
$\tilde{\chi}_4^0 \tilde{\chi}_1^-$	—		—		—	
$\tilde{\chi}_1^0 \tilde{\chi}_2^-$			11.7619(7)			
$\tilde{\chi}_2^0 \tilde{\chi}_2^-$	—		—		—	
$\tilde{\chi}_3^0 \tilde{\chi}_2^-$	—		—		—	
$\tilde{\chi}_4^0 \tilde{\chi}_2^-$	—		—		—	
$h^0 H^-$	—		—		—	
$H^0 H^-$	—		—		—	
$A^0 H^-$	—		—		—	
$W^- h^0$			7.6213(6)e4			
$W^- H^0$			4.2446(2)			
$W^- A^0$			1.07037(1)			
$Z H^-$			0.17723(2)			

$W^- Z \to X^-$						
Final state	MADGRAPH / HELAS		WHiZard / O'Mega		AMEGIC++ / SHERPA	
	0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV
$\tilde{e}_L \tilde{\nu}_e^*$	96.635(6)		96.639(2)		96.632(5)	
$\tilde{\mu}_L \tilde{\nu}_\mu^*$	96.635(6)		96.638(2)		96.631(5)	
$\tilde{\tau}_1 \tilde{\nu}_\tau^*$	14.9542(8)		14.952(1)		14.953(1)	
$\tilde{\tau}_2 \tilde{\nu}_\tau^*$	85.875(5)		85.875(2)		85.870(4)	
$\tilde{d}_L \tilde{u}_L^*$	—		—		—	
$\tilde{s}_L \tilde{c}_L^*$	—		—		—	
$\tilde{b}_1 \tilde{t}_1^*$	—		—		—	
$\tilde{b}_2 \tilde{t}_2^*$	—		—		—	
$\tilde{b}_1 \tilde{t}_2^*$	—		—		—	
$\tilde{b}_2 \tilde{t}_1^*$	—		—		—	
$\tilde{\chi}_1^0 \tilde{\chi}_1^-$	61.634(6)		61.626(3)		61.633(3)	
$\tilde{\chi}_2^0 \tilde{\chi}_1^-$	2.8355(7)e3		2.8350(3)e3		2.8356(2)e3	
$\tilde{\chi}_3^0 \tilde{\chi}_1^-$	—		—		—	
$\tilde{\chi}_4^0 \tilde{\chi}_1^-$	—		—		—	
$\tilde{\chi}_1^0 \tilde{\chi}_2^-$	11.7607(3)		11.7619(7)		11.7602(6)	
$\tilde{\chi}_2^0 \tilde{\chi}_2^-$	—		—		—	
$\tilde{\chi}_3^0 \tilde{\chi}_2^-$	—		—		—	
$\tilde{\chi}_4^0 \tilde{\chi}_2^-$	—		—		—	
$h^0 H^-$	—		—		—	
$H^0 H^-$	—		—		—	
$A^0 H^-$	—		—		—	
$W^- h^0$	7.620(3)e4		7.6213(6)e4		7.6209(4)e4	
$W^- H^0$	4.2446(2)		4.2446(2)		4.2445(2)	
$W^- A^0$	1.07034(3)		1.07037(1)		1.07017(6)	
$Z H^-$	0.177241(1)		0.17723(2)		0.17714(4)	

$W^- Z \to X^-$						
Final state	MADGRAPH / HELAS		WHiZard / O'Mega		AMEGIC++ / SHERPA	
	0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV
$\tilde{e}_L \tilde{\nu}_e^*$	96.635(6)		96.639(2)	15.728(2)	96.632(5)	
$\tilde{\mu}_L \tilde{\nu}_\mu^*$	96.635(6)		96.638(2)	15.727(2)	96.631(5)	
$\tilde{\tau}_1 \tilde{\nu}_\tau^*$	14.9542(8)		14.952(1)	1.4268(2)	14.953(1)	
$\tilde{\tau}_2 \tilde{\nu}_\tau^*$	85.875(5)		85.875(2)	14.478(2)	85.870(4)	
$\tilde{d}_L \tilde{u}_L^*$	—		—	24.220(1)	—	
$\tilde{s}_L \tilde{c}_L^*$	—		—	24.221(1)	—	
$\tilde{b}_1 \tilde{t}_1^*$	—		—	40.676(4)	—	
$\tilde{b}_2 \tilde{t}_2^*$	—		—	8.3706(7)	—	
$\tilde{b}_1 \tilde{t}_2^*$	—		—	63.592(6)	—	
$\tilde{b}_2 \tilde{t}_1^*$	—		—	3.9236(5)	—	
$\tilde{\chi}_1^0 \tilde{\chi}_1^-$	61.634(6)		61.626(3)	16.389(1)	61.633(3)	
$\tilde{\chi}_2^0 \tilde{\chi}_1^-$	2.8355(7)e3		2.8350(3)e3	668.1(1)	2.8356(2)e3	
$\tilde{\chi}_3^0 \tilde{\chi}_1^-$	—		—	278.53(1)	—	
$\tilde{\chi}_4^0 \tilde{\chi}_1^-$	—		—	270.97(2)	—	
$\tilde{\chi}_1^0 \tilde{\chi}_2^-$	11.7607(3)		11.7619(7)	12.380(1)	11.7602(6)	
$\tilde{\chi}_2^0 \tilde{\chi}_2^-$	—		—	218.38(2)	—	
$\tilde{\chi}_3^0 \tilde{\chi}_2^-$	—		—	76.494(5)	—	
$\tilde{\chi}_4^0 \tilde{\chi}_2^-$	—		—	97.693(7)	—	
$h^0 H^-$	—		—	4.4399(5)e-3	—	
$H^0 H^-$	—		—	6.1592(2)	—	
$A^0 H^-$	—		—	5.9726(5)	—	
$W^- h^0$	7.620(3)e4		7.6213(6)e4	8.289(2)e4	7.6209(4)e4	
$W^- H^0$	4.2446(2)		4.2446(2)	15.783(3)	4.2445(2)	
$W^- A^0$	1.07034(3)		1.07037(1)	0.24815(7)	1.07017(6)	
$Z H^-$	0.177241(1)		0.17723(2)	0.25403(7)	0.17714(4)	

$W^- Z \to X^-$						
Final state	MADGRAPH / HELAS		WHiZard / O'Mega		AMEGIC++ / SHERPA	
	0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV
$\tilde{e}_L \tilde{\nu}_e^*$	96.635(6)	15.726(1)	96.639(2)	15.728(2)	96.632(5)	15.7249(8)
$\tilde{\mu}_L \tilde{\nu}_\mu^*$	96.635(6)	15.726(1)	96.638(2)	15.727(2)	96.631(5)	15.7264(8)
$\tilde{\tau}_1 \tilde{\nu}_\tau^*$	14.9542(8)	1.427(1)	14.952(1)	1.4268(2)	14.953(1)	1.42747(7)
$\tilde{\tau}_2 \tilde{\nu}_\tau^*$	85.875(5)	14.479(1)	85.875(2)	14.478(2)	85.870(4)	14.4780(7)
$\tilde{d}_L \tilde{u}_L^*$	—	24.220(3)	—	24.220(1)	—	24.219(1)
$\tilde{s}_L \tilde{c}_L^*$	—	24.220(3)	—	24.221(1)	—	24.220(1)
$\tilde{b}_1 \tilde{t}_1^*$	—	40.676(2)	—	40.676(4)	—	40.677(2)
$\tilde{b}_2 \tilde{t}_2^*$	—	8.3717(5)	—	8.3706(7)	—	8.3722(4)
$\tilde{b}_1 \tilde{t}_2^*$	—	63.596(3)	—	63.592(6)	—	63.591(3)
$\tilde{b}_2 \tilde{t}_1^*$	—	3.9242(2)	—	3.9236(5)	—	3.9244(2)
$\tilde{\chi}_1^0 \tilde{\chi}_1^-$	61.634(6)	16.389(5)	61.626(3)	16.389(1)	61.633(3)	16.391(1)
$\tilde{\chi}_2^0 \tilde{\chi}_1^-$	2.8355(7)e3	668.2(4)	2.8350(3)e3	668.1(1)	2.8356(2)e3	668.34(3)
$\tilde{\chi}_3^0 \tilde{\chi}_1^-$	—	278.5(1)	—	278.53(1)	—	278.58(2)
$\tilde{\chi}_4^0 \tilde{\chi}_1^-$	—	270.9(1)	—	270.97(2)	—	271.02(2)
$\tilde{\chi}_1^0 \tilde{\chi}_2^-$	11.7607(3)	12.379(4)	11.7619(7)	12.380(1)	11.7602(6)	12.380(1)
$\tilde{\chi}_2^0 \tilde{\chi}_2^-$	—	218.3(1)	—	218.38(2)	—	218.40(1)
$\tilde{\chi}_3^0 \tilde{\chi}_2^-$	—	76.50(3)	—	76.494(5)	—	76.497(4)
$\tilde{\chi}_4^0 \tilde{\chi}_2^-$	—	97.70(4)	—	97.693(7)	—	97.693(4)
$h^0 H^-$	—	4.439(6)e-3	—	4.4399(5)e-3	—	4.4395(2)e-3
$H^0 H^-$	—	6.1592(6)	—	6.1592(2)	—	6.1589(3)
$A^0 H^-$	—	5.9728(6)	—	5.9726(5)	—	5.9723(3)
$W^- h^0$	7.620(3)e4	8.29(1)e4	7.6213(6)e4	8.289(2)e4	7.6209(4)e4	8.2909(4)e4
$W^- H^0$	4.2446(2)	15.78(2)	4.2446(2)	15.783(3)	4.2445(2)	15.7848(8)
$W^- A^0$	1.07034(3)	0.24799(1)	1.07037(1)	0.24815(7)	1.07017(6)	0.24801(1)
$Z H^-$	0.177241(1)	0.25405(1)	0.17723(2)	0.25403(7)	0.17714(4)	0.25404(1)

- ILC example: sbottom pair production

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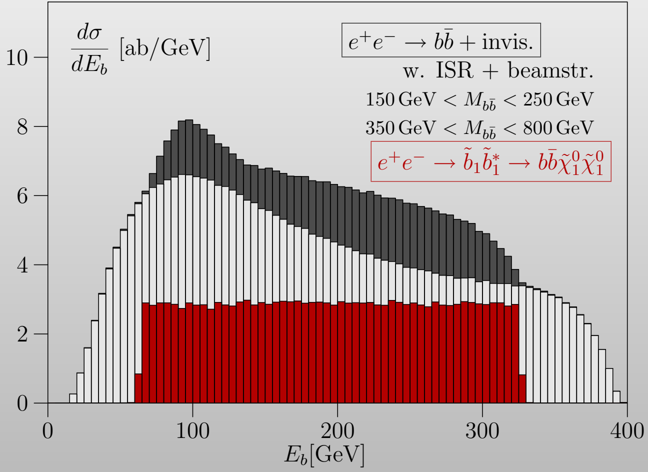
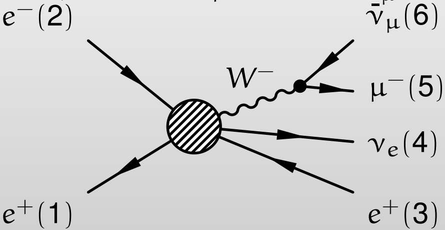
- complete irreducible background, ISR and beamstrahlung



Cascade decays are supported

- ```
  $ f90_SM -scatter "e+ e- -> e+ nue mu- numubar" \
           -cascade "3 + 4 ~ W-"
  ```

  select only diagrams, where the μ^- and the $\bar{\nu}_\mu$ derive from a $W^\pm$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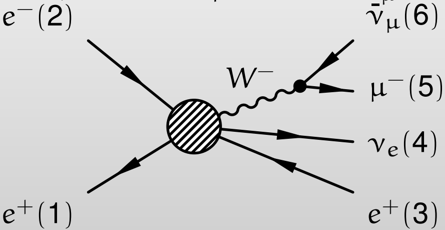
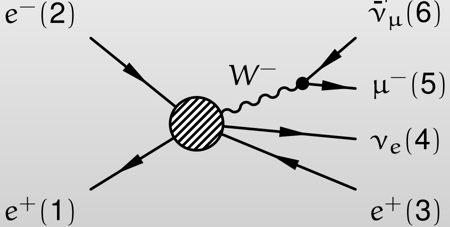


☹ not necessarily fully gauge invariant, but correct spin correlations from compact expressions
  ```

Cascade decays are supported

```
$ f90_SM -scatter "e+ e- -> e+ nue mu- numubar" \
              -cascade "3 + 4 ~ W-"
```

select only diagrams, where the μ^- and the $\bar{\nu}_\mu$ derive from a $W^\pm$



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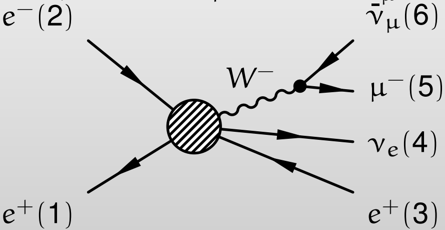

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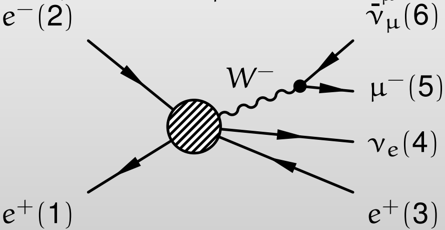

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☺ gauge invariant

- both can be combined arbitrarily with boolean operators && and ||

- O’Mega / WHiZard does general colored amplitudes

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- finally . . .

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  - color flow representation

$$\psi \rightarrow \psi^i$$

$$\psi \rightarrow \psi^{ij}, \psi^0$$

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- finally ...
  - color flow representation

$$\psi \to \psi^i$$
$$\phi \to \phi^{ij}, \phi^0$$

- can be implemented by enlarging the flavor quantum number and using special Feynman rules [à la Stelzer/Willenbrock]

$$|\text{flavor}\rangle \to |\text{flavor}\rangle \otimes |\text{color}\rangle$$

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$$|\text{flavor}\rangle \to |\text{flavor}\rangle \otimes |\text{color}\rangle$$

  - currently complete "proof of concept" implementation in Whizard
- generation of matrix elements can be time-consuming
  - fast implementation in O'Mega on the way: general "`Colorize`" functor mapping of any uncolored model to a $SU(N)$ colorized model

Forthcoming native model file format:

- particle declarations

```
particle e- e+ : spin=1/2, fermion, pdg=11, tex="e^-", tex.anti="e^+"
particle nue nuebar : spin=1/2, fermion, pdg=12, tex="\nu_e", tex.anti="\bar\nu_e"
particle A : spin=1, boson, pdg=22, tex="\gamma"
particle Z : spin=1, boson, pdg=23, tex="Z"
particle W+ W- : spin=1, boson, pdg=24, tex="W^+", tex.anti="W^-"

coupling e
coupling g
coupling gv
coupling ga
```

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- gauge currents $e\bar{e}\not{A}e$, $\bar{e}\not{Z}(g_V - g_A\gamma_5)e$ and $g\bar{e}\not{W}(1-\gamma_5)\nu_e$

```
vertex e+, A, e- :   { e * <1|V.e2|3> }
vertex e+, Z, e- :   { gv * <1|V.e2|3> - ga * <1|A.e2|3> }
vertex e+, W-, nue : { g * <1|(V-A).e2|3> }
```

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- particle declarations

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vertex e+, W-, nue : { g * <1|(V-A).e2|3> }
```
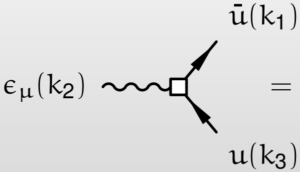

- triple gauge couplings

```
vertex W+, A, W- :   { e * ((k1 - k2).e3*e1.e2
                          + (k2 - k3).e1*e2.e3 + (k3 - k1).e2*e3.e1) }
vertex W+, Z, W- :   { g * ((k1 - k2).e3*e1.e2
                          + (k2 - k3).e1*e2.e3 + (k3 - k1).e2*e3.e1) }
```

- noncommutative QED [à la Seiberg/Witten, Witten]



$$= ig \cdot \frac{i}{2} \left[(k\theta)_\mu \not{p} + (\theta p)_\mu \not{k} - (k\theta p)\gamma_\mu \right]$$

```
vertex e+, A, e- :   {   e * k2.[mu1]*[mu2].k3*<1|V.e2|3>
                       - e * k2.[mu1]*[mu2].e2*<1|V.k3|3>
                       - e * e2.[mu1]*[mu2].k3*<1|V.k2|3> }
```

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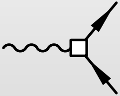

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                       - e * k2.[mu1]*[mu2].e2*<1|V.k3|3>
                       - e * e2.[mu1]*[mu2].k3*<1|V.k2|3> }
```

- Tradeoff: convenience vs. complexity
  - ☹ full programming language harder to learn, but more appropriate than model file format for defining complicated models with many couplings, e. g. the MSSM, from scratch
  - ☺ physics motivated model file format simplifies small extensions
    - additional particles
    - new vertices

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$:

```
$ f90_MSSM -scatter "e+ e- -> ch1+ ch1-"
```

$e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-$:

```
$ f90_MSSM -scatter "e+ e- -> ch1+ ch1-"
```

```
pure function l1bl1cp1cm1 (k, s) result (amp)
  real(kind=omega_prec), dimension(0:,:), intent(in) :: k
  integer, dimension(:), intent(in) :: s
  complex(kind=omega_prec) :: amp
  type(momentum) :: p1, p2, p3, p4
  type(bispinor) :: cp1_4, l1_2
  type(bispinor) :: cm1_3, l1b_1
  complex(kind=omega_prec) :: snc1_13
  type(vector) :: a_12, z_12
  type(momentum) :: p12, p13
  p1 = - k(:,1) ! incoming e+
  p2 = - k(:,2) ! incoming e-
  p3 =   k(:,3) ! outgoing ch1+
  p4 =   k(:,4) ! outgoing ch1-
  l1b_1 = u (mass(11), - p1, s(1))
  l1_2 = u (mass(11), - p2, s(2))
  cm1_3 = v (mass(69), p3, s(3))
  cp1_4 = v (mass(69), p4, s(4))
```

```
  p12 = p1 + p2
  a_12 = pr_feynman(p12, + v_ff(qlep,l1b_1,l1_2))
  z_12 = pr_unitarity(p12,mass(23),wd_tl(p12,width(23)), &
     + va_ff(gnclep(1),gnclep(2),l1b_1,l1_2))
  p13 = p1 + p3
  snc1_13 = pr_phi(p13,mass(54),wd_tl(p13,width(54)), &
     + sr_ff(g_yuk_ch1_sn1_1_c,l1b_1,cm1_3))
  amp = 0
  amp = amp + snc1_13*( - sl_ff(g_yuk_ch1_sn1_1,l1_2,cp1_4))
  amp = amp + z_12*( + va_ff(-gczc_1_1(1),-gczc_1_1(2),cm1_3,cp1_4))
  amp = amp + a_12*( + v_ff(qchar,cm1_3,cp1_4))
  amp = - amp ! 2 vertices, 1 propagators
end function l1bl1cp1cm1
```

9 fusions, 3 propagators, 3 diagrams

```
    p12 = p1 + p2
    a_12 = pr_feynman(p12, + v_ff(qlep,l1b_1,l1_2))
    z_12 = pr_unitarity(p12,mass(23),wd_tl(p12,width(23)), &
       + va_ff(gnclep(1),gnclep(2),l1b_1,l1_2))
    p13 = p1 + p3
    snc1_13 = pr_phi(p13,mass(54),wd_tl(p13,width(54)), &
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    amp = 0
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  end function l1bl1cp1cm1
```

9 fusions, 3 propagators, 3 diagrams

- ☺ readable code, can edited for exotic models (see below) or NLO vertex functions (see below)

Adding a photon $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$:

```
$ f90_MSSM -scatter "e+ e- -> ch1+ ch1- A"
```

Adding a photon $e^+e^- \to \tilde\chi_1^+\tilde\chi_1^-\gamma$:

```
$ f90_MSSM -scatter "e+ e- -> ch1+ ch1- A"
```

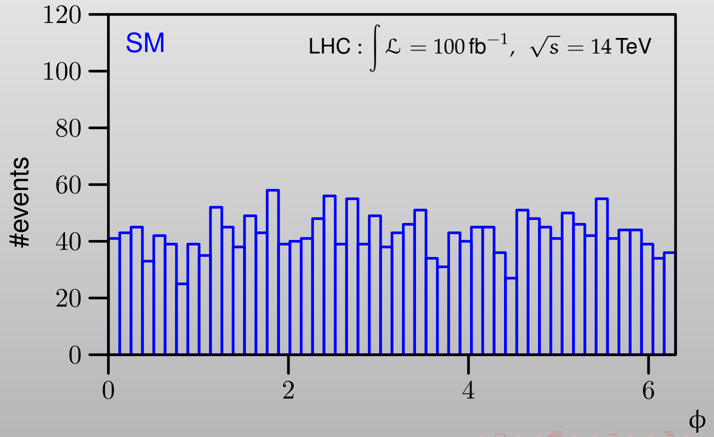
```
pure function l1bl1cp1cm1a (k, s) result (amp)
  real(kind=omega_prec), dimension(0:,:), intent(in) :: k
  integer, dimension(:), intent(in) :: s
  complex(kind=omega_prec) :: amp
  type(momentum) :: p1, p2, p3, p4, p5
  type(bispinor) :: cp1_4, l1_2
  type(bispinor) :: cm1_3, l1b_1
  type(vector) :: a_5
  complex(kind=omega_prec) :: sn1_24, snc1_13
  type(bispinor) :: cp1_45, l1_25
  type(bispinor) :: cm1_35, l1b_15
  type(vector) :: a_34, a_12, z_34, z_12
  type(momentum) :: p12, p13, p15, p24, p25, p34, p35, p45
  p1 = - k(:,1) ! incoming e+
  p2 = - k(:,2) ! incoming e-
  p3 =   k(:,3) ! outgoing ch1+
  p4 =   k(:,4) ! outgoing ch1-
  p5 =   k(:,5) ! outgoing A
  l1b_1 = u (mass(11), - p1, s(1))
  l1_2 = u (mass(11), - p2, s(2))
  cm1_3 = v (mass(69), p3, s(3))
  cp1_4 = v (mass(69), p4, s(4))
  a_5 = conjg (eps (mass(22), p5, s(5)))
  p12 = p1 + p2
  a_12 = pr_feynman(p12, + v_ff(qlep,l1b_1,l1_2))
  z_12 = pr_unitarity(p12,mass(23),wd_tl(p12,width(23)), &
     + va_ff(gnclep(1),gnclep(2),l1b_1,l1_2))
```

```
  p13 = p1 + p3
  snc1_13 = pr_phi(p13,mass(54),wd_tl(p13,width(54)), &
     + sr_ff(g_yuk_ch1_sn1_1_c,l1b_1,cm1_3))
  p24 = p2 + p4
  sn1_24 = pr_phi(p24,mass(54),wd_tl(p24,width(54)), &
     + sl_ff(g_yuk_ch1_sn1_1,l1_2,cp1_4))
  p34 = p3 + p4
  a_34 = pr_feynman(p34, + v_ff(qchar,cm1_3,cp1_4))
  z_34 = pr_unitarity(p34,mass(23),wd_tl(p34,width(23)), &
     + va_ff(-gczc_1_1(1),-gczc_1_1(2),cm1_3,cp1_4))
  p15 = p1 + p5
  l1b_15 = pr_psi(p15,mass(11),wd_tl(p15,width(11)), + f_vf(-qlep,a_5,l1b_1))
  p25 = p2 + p5
  l1_25 = pr_psi(p25,mass(11),wd_tl(p25,width(11)), + f_vf(qlep,a_5,l1_2))
  p35 = p3 + p5
  cm1_35 = pr_psi(p35,mass(69),wd_tl(p35,width(69)), &
     + f_vf(-qchar,a_5,cm1_3))
  p45 = p4 + p5
  cp1_45 = pr_psi(p45,mass(69),wd_tl(p45,width(69)), + f_vf(qchar,a_5,cp1_4))
  amp = 0
  amp = amp + sn1_24*( + sr_ff(g_yuk_ch1_sn1_1_c,cm1_35,l1b_1))
  amp = amp + snc1_13*( - sl_ff(g_yuk_ch1_sn1_1,l1_25,cp1_4) &
     + sl_ff(g_yuk_ch1_sn1_1,cp1_45,l1_2))
  amp = amp + l1_25*( - f_vf(-qlep,a_34,l1b_1) &
     - f_vaf(-(gnclep(1)),gnclep(2),z_34,l1b_1))
  amp = amp + l1b_15*( - f_srf(g_yuk_ch1_sn1_1_c,sn1_24,cm1_3) &
     + f_vf(qlep,a_34,l1_2) + f_vaf(gnclep(1),gnclep(2),z_34,l1_2))
  amp = amp + z_12*( - va_ff(-(-gczc_1_1(1)),-gczc_1_1(2),cp1_45,cm1_3) &
     + va_ff(-gczc_1_1(1),-gczc_1_1(2),cm1_35,cp1_4))
  amp = amp + a_12*( - v_ff(-qchar,cp1_45,cm1_3) + v_ff(qchar,cm1_35,cp1_4))
end function l1bl1cp1cm1a
```

28 fusions, 10 propagators, 12 diagrams

- using omegalib and WHiZard [Alboteanu/T. O.,Rückl, 2005]

- using omegalib and WHiZard [Alboteanu/T. O.,Rückl, 2005]
- standard acceptance cuts and 85 GeV $< m_{\ell^+\ell^-} <$ 97 GeV, 200 GeV $< m_{\ell^+\ell^-\gamma} <$ 1 TeV, $0 < \cos\theta^*_\gamma < 0.9$, $\cos\theta_Z > 0$ and $\cos\theta_\gamma > 0$ (favoring $\bar{q}q$ over $q\bar{q}$!)



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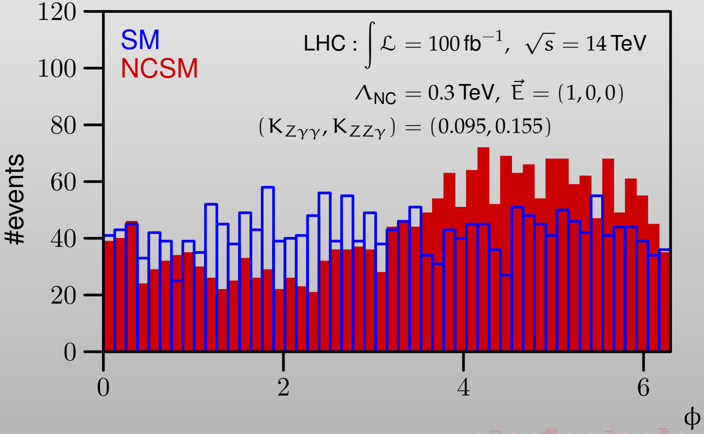
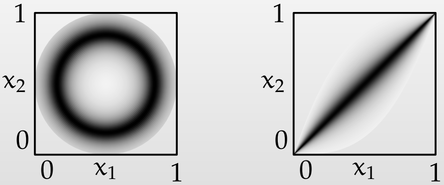
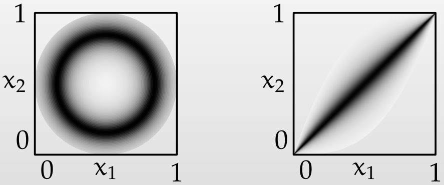


VEGAS' factorized ansatz handles



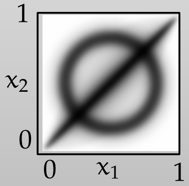
separately after mappings

VEGAS' factorized ansatz handles



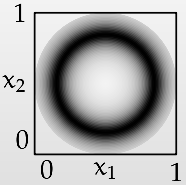
separately after mappings

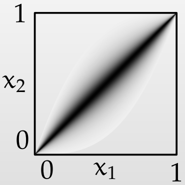
- ☹ fails for overlapping sing'ies



which is the common case (for more than one Feynman diagram)

VEGAS' factorized ansatz handles





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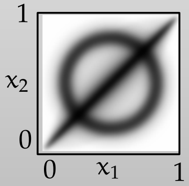


which is the common case (for more than one Feynman diagram)

∴ adaptive multichannel approach

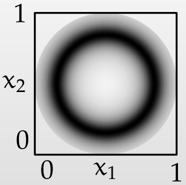
$$I(f) = \int_M d\mu(p)\, f(p)$$

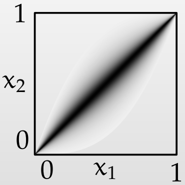
$$I(f) = \sum_{i=1}^{N_c} \alpha_i \int_0^1 g_i(x) d^n x \, \frac{f(\phi_i(x))}{g(\phi_i(x))}$$

with

$$g = \sum_{i=1}^{N_c} \alpha_i \cdot (g_i \circ \phi_i^{-1}) \left| \frac{\partial \phi_i^{-1}}{\partial p} \right|$$

VEGAS' factorized ansatz handles





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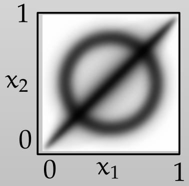

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with

$$g = \sum_{i=1}^{N_c} \alpha_i \cdot (g_i \circ \phi_i^{-1}) \left| \frac{\partial \phi_i^{-1}}{\partial p} \right|$$

- ☺ works with factorized g_i adapted by VEGAS and α_i adapted by variance reduction.

- WHiZard calls O'Mega to generate matrix elements according to `conf/whizard.prc`

```
model   SM
uuza    u,U                        Z,A            omega
ppza    u:d:s:U:D:S,u:d:s:U:D:S   Z,A            omega
uulla   u,U                        e1:e2,E1:E2,A  omega
pplla   u:d:s:U:D:S,u:d:s:U:D:S   e1:e2,E1:E2,A  omega
```

(CompHEP notation for historical reasons . . .)

- WHiZard calls O'Mega to generate matrix elements according to `conf/whizard.prc`

```
model   SM
uuza    u,U                          Z,A              omega
ppza    u:d:s:U:D:S,u:d:s:U:D:S      Z,A              omega
uulla   u,U                          e1:e2,E1:E2,A    omega
pplla   u:d:s:U:D:S,u:d:s:U:D:S      e1:e2,E1:E2,A    omega
```

  (CompHEP notation for historical reasons ...)

- generated Fortran90 code for matrix elements is compiled and linked with support libraries (PDFs, vamp, etc.)

- WHiZard calls O'Mega to generate matrix elements according to `conf/whizard.prc`

```
model   SM
uuza    u,U                       Z,A              omega
ppza    u:d:s:U:D:S,u:d:s:U:D:S   Z,A              omega
uulla   u,U                       e1:e2,E1:E2,A    omega
pplla   u:d:s:U:D:S,u:d:s:U:D:S   e1:e2,E1:E2,A    omega
```

  (CompHEP notation for historical reasons . . .)
- generated Fortran90 code for matrix elements is compiled and linked with support libraries (PDFs, vamp, etc.)
- generates unweighted events according to `results/whizard.in`

```
&process_input
process_id = "pplla"
sqrts = 14000
luminosity = 0
polarized_beams = F
structured_beams = T
/
```

  etc.

- event samples are generated according to phase space cuts

```
process pplla
  cut E of 1 within 10 9999
  cut E of 2 within 10 9999
  cut E of 4 within 10 9999
  cut THETA(DEG) of 8 1 within 5 175
  cut THETA(DEG) of 8 2 within 5 175
  cut THETA(DEG) of 8 4 within 5 175
```

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  cut E of 1 within 10 9999
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  cut THETA(DEG) of 8 1 within 5 175
  cut THETA(DEG) of 8 2 within 5 175
  cut THETA(DEG) of 8 4 within 5 175
```

- simple analysis can be performed by filling histograms

```
process pplla
  histogram M of 3  within 0 600 nbin 60
  histogram PT of 1 within 0 200 nbin 50
  histogram PT of 2 within 0 200 nbin 50
  histogram PT of 4 within 0 200 nbin 50
```

(will be generalized in the next version)

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- parallelization build into vamp, not enabled yet ...