Tools and Monte-Carlos
for the
New Physics

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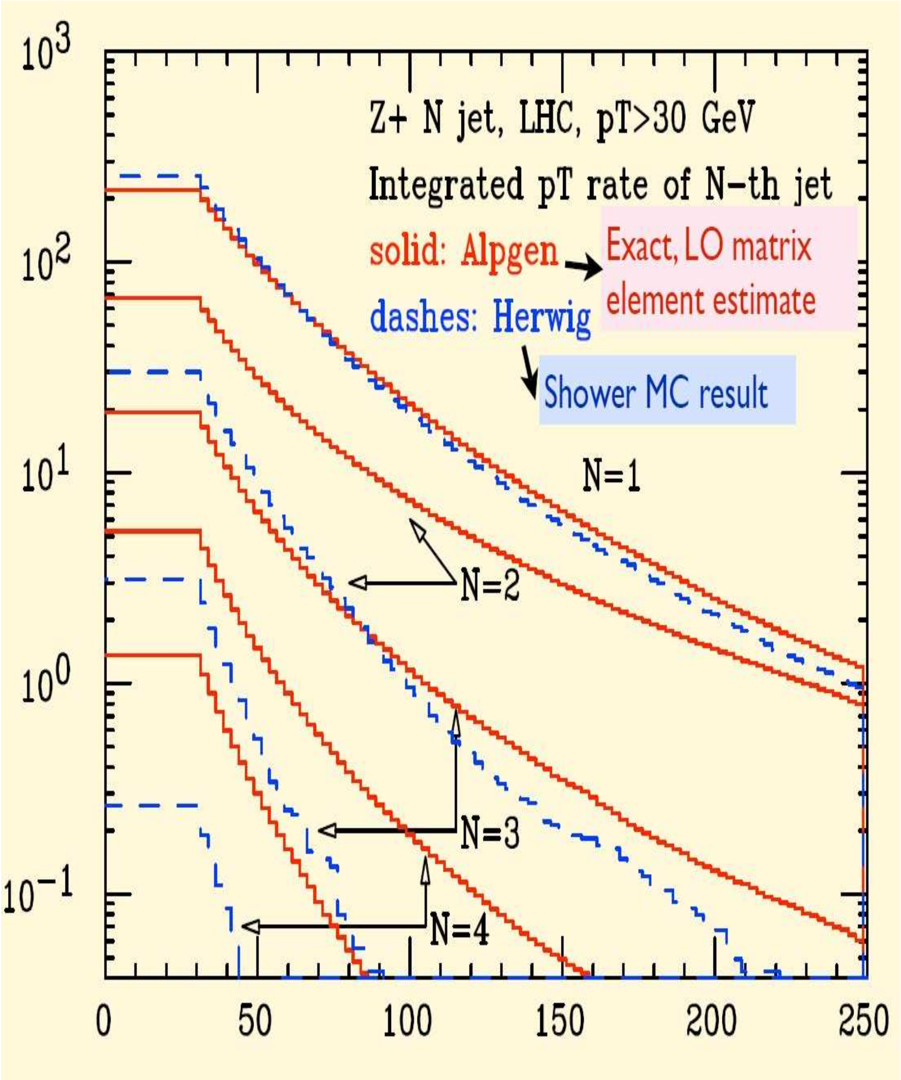
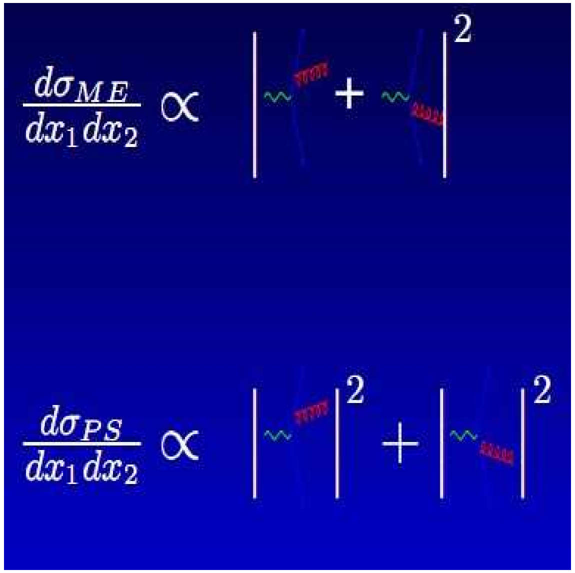
Part B

MEG, Codes, Accords

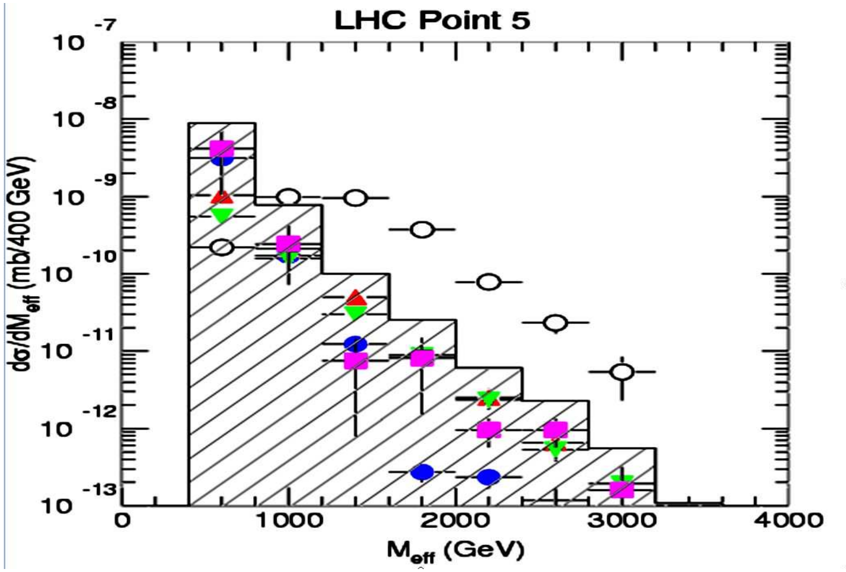
ME vs PS: Limitations of PS



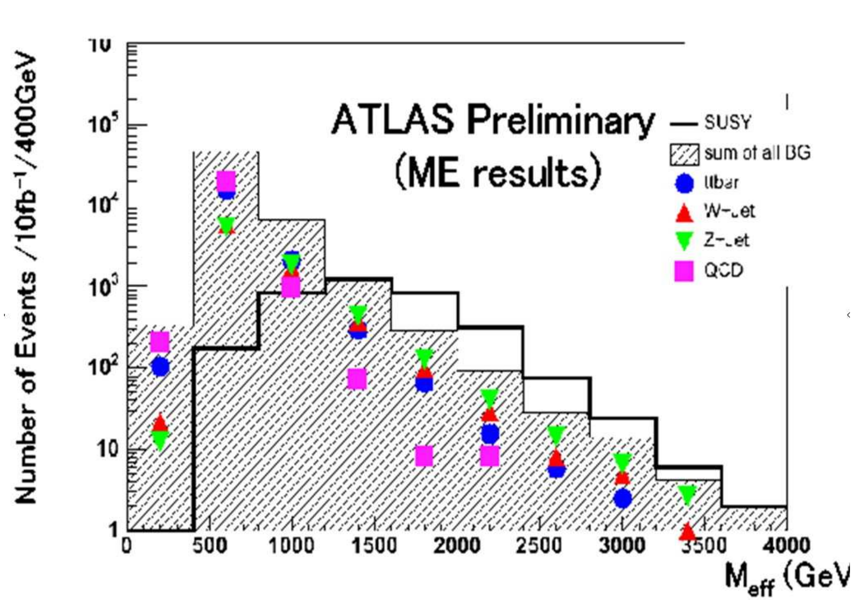
- PS do not describe hard jets
- ME do but in practice can not produce as many jets as PS
- ME evaluates the complete set of all diagrams/configurations: costly
- some real progress has been made in interfacing ME with PS



ATLAS TDR (same with CMS)



ATLAS TDR 98
(mSUGRA point, PreWMAP)



ATLAS 2006

QCD and SM processes can also produce hard jets! and these are/were lacking in PS/MC

ME vs PS: Limitations of PS

- The majority of the processes in the general purpose event generators were implemented one by one, most of them are $2 \to 2$ processes.
- However for the LHC we are often interested in higher multiplicity final states.
- These require specialized matrix element generators
- These are usually dedicated specialised stand-alone codes or recently some of the EG have built in MEG or at least part of the components of these MEG

ME vs PS: Limitations of PS, Pythia classes of processes

ffff 1

Currently implemented processes, complete with respect to groups, but with some individual processes missing for lack of space (represented by "..."). In the names, a "2" separates initial and final state, an "(s:X)", "(t:X)" or "(l:X)" occasionally appends info on an s- or t-channel- or loop-exchanged particle X.

ProcessGroup	ProcessName
SoftQCD	minBias,elastic, singleDiffractive, doubleDiffractive
HardQCD	gg2gg, gg2qqbar, qg2qg, qq2qq, qqbar2gg, qqbar2qqbarNew, gg2ccbar, qqbar2ccbar, gg2bbbar, qqbar2bbbar
PromptPhoton	qg2qgamma, qqbar2ggamma, gg2ggamma, ffbar2gammagamma, gg2gammagamma
WeakBosonExchange	ff2ff(t:gmZ), ff2ff(t:W)
WeakSingleBoson	ffbar2gmZ, ffbar2W, ffbar2ffbar(s:gm)
WeakDoubleBoson	ffbar2gmZgmZ, ffbar2ZW, ffbar2WW
WeakBosonAndParton	qqbar2gmZg, qg2gmZq, ffbar2gmZgm, fgm2gmZf qqbar2Wg, qg2Wq, ffbar2Wgm, fgm2Wf
Charmonium	gg2QQbar[3S1(1)]g, qg2QQbar[3PJ(8)]q, ...
Bottomonium	gg2QQbar[3S1(1)]g, gg2QQbar[3P2(1)]g, ...
Top	gg2ttbar, qqbar2ttbar, qq2tq(t:W), ffbar2ttbar(s:gmZ), ffbar2tqbar(s:W)
FourthBottom, FourthTop, FourthPair (fourth generation)	
HiggsSM	ffbar2H, gg2H, ffbar2HZ, ff2Hff(t:WW), ...
HiggsBSM	h, H and A as above, charged Higgs, pairs
SUSY	qqbar2chi0chi0 (not yet completed)
NewGaugeBoson	ffbar2gmZZprime, ffbar2Wprime, ffbar2R0
LeftRightSymmmetry	ffbar2ZR, ffbar2WR, ffbar2HLHL, ...
LeptoQuark	ql2LQ, qg2LQl, gg2LQLQbar, qqbar2LQLQbar
ExcitedFermion	dg2dStar, qq2uStarq, qqbar2muStarmu, ...
ExtraDimensionsG*	gg2G*, qqbar2G*, ...

ffff 1

ME vs PS: Limitations of PS, Pythia classes of processes

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WeakDoubleBoson	ffbar2gmZgmZ, ffbar2ZW, ffbar2WW
WeakBosonAndParton	qqb ffbar2gmZgm, fgm2gmZf qqb r2Wgm, fgm2Wf
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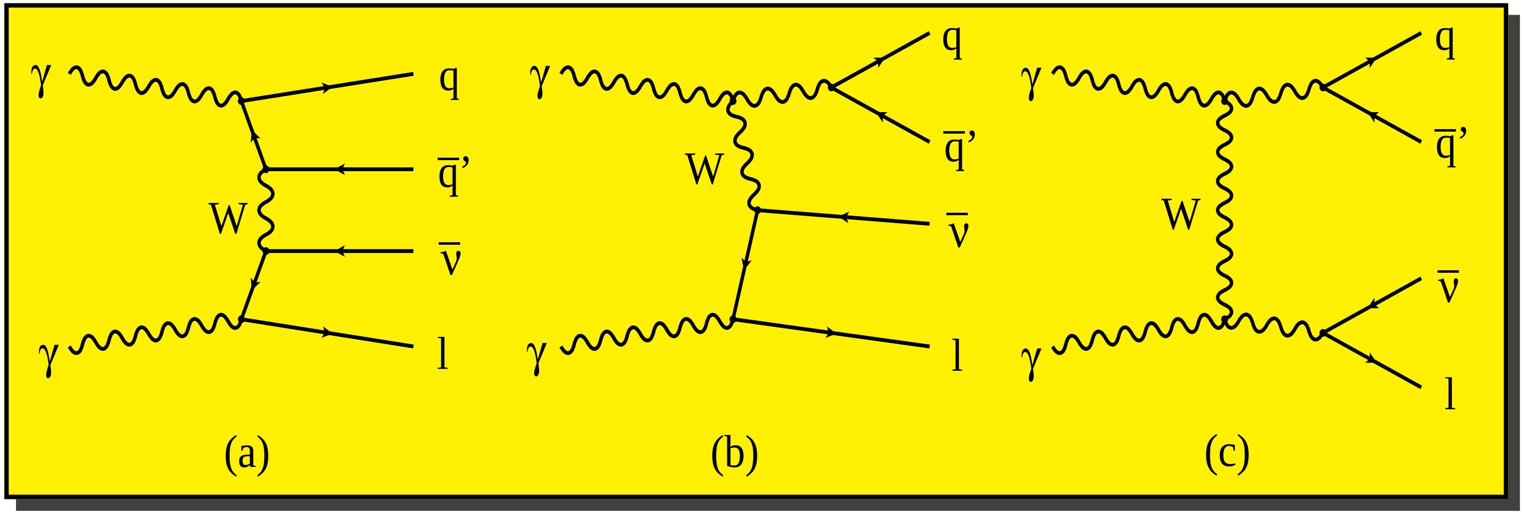
mostly $2 \to 2$

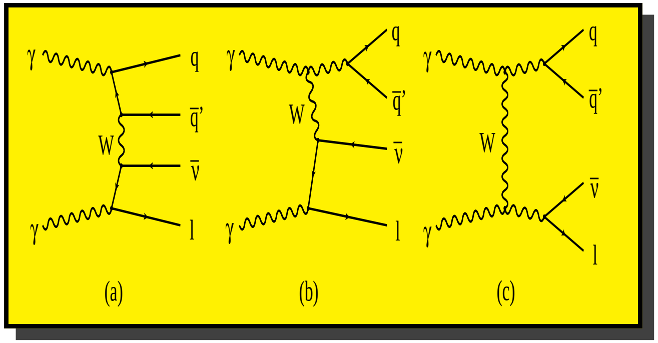
ME vs PS: Resonant vs non resonant



(a) Peripheral (b) single W production (c) Resonant diagram

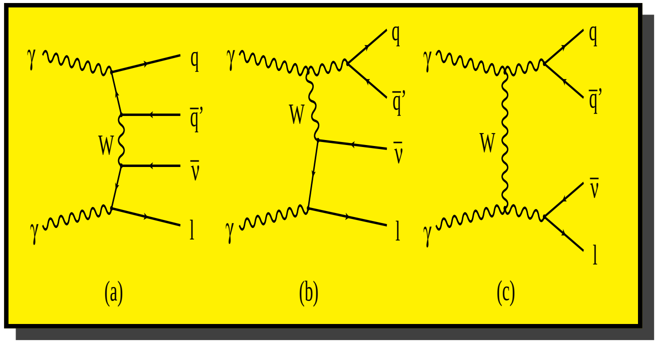
$\gamma\gamma \to W^- W^+ \, W^{\pm} \to l\nu_l, W^{\mp} \to jj'$ with $l = e, \mu$.

ME vs PS: Resonant vs non resonant



- Full calculation needs to evaluate $|\mathcal{M}|^2$
- draw all Feynman diagrams,
- associate Feynman rules to each vertex,
- sum over all diagrams $\mathcal{M} = \sum_i \mathcal{M}_i$

ME vs PS: Resonant vs non resonant



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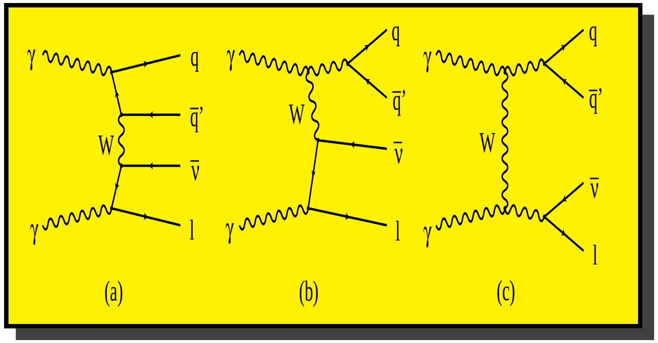
Squaring technique

- Most textbook will tell you to **square** summing over all polarisations, with tricks like spinors leading to traces, pola. vectors to completeness relations $\sum_\lambda (\epsilon_\mu \epsilon_\nu) \rightarrow -g_{\mu\nu}$,....
- with more than $2 \rightarrow 2$ this is intractable wit huge number of terms (due to *interference*) $\mathcal{M}_i \mathcal{M}_j^*$ with long expressions from squaring
- Any info on polarisation (initial or final, that can be crucial) is lost
- This technique can be automatised and is used in `CompHEP, CalcHEP`

ME vs PS: Resonant vs non resonant



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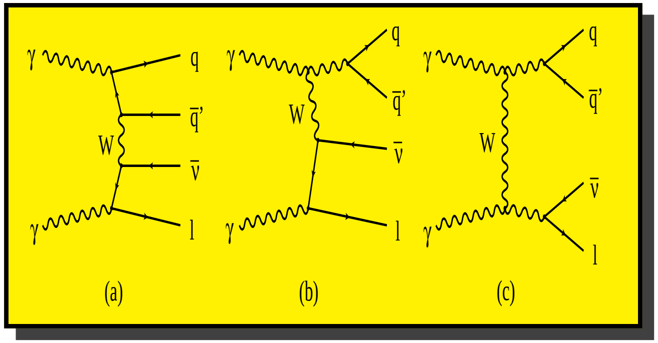
Helicity amplitude

- Calculate each $\mathcal{M}_i$ for a helicity configuration h_α, $\mathcal{M}_i(h_\alpha)$
- each $\mathcal{M}_i(h_\alpha)$ is a c-number
- Sum over i to get the full amplitude (sum before squaring) $\sum_i \mathcal{M}_i(h_\alpha) = \mathcal{M}(h_\alpha)$
- Store $\mathcal{M}(h_\alpha)$ to get polarised/unpolarised/spin-correlation
- Used in GRACE, MadGraph,...

ME vs PS: Resonant vs non resonant

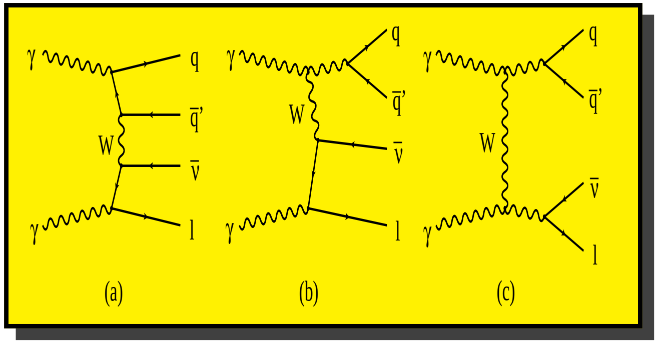


- Full calculation needs to evaluate $|\mathcal{M}|^2$
- draw all Feynman diagrams,
- associate Feynman rules to each vertex,
- sum over all diagrams $\mathcal{M} = \sum_i \mathcal{M}_i$

Recursion relations (mostly for massless states within QCD)

- not based on Feynman diagrams
- idea is to build amplitude for $N+1$ leg from N leg recursively
- Methods based on off-shell currents (Berends-Giele)
- New techniques MHV (Maximum Helicity Violating) based on *formal, twistor inspired* work by Cachazo-Svreck-Witten(CVS)
- Many developments (BCFW, Britto-Cachazo-Feng-Witten) including some applications to massive states

ME vs PS: Resonant vs non resonant



- Full calculation needs to evaluate $|\mathcal{M}|^2$
- draw all Feynman diagrams,
- associate Feynman rules to each vertex,
- sum over all diagrams $\mathcal{M} = \sum_i \mathcal{M}_i$

Approximation: Resonant diagrams only?

- Production $\times$ decay
- $\sigma = \sigma_{WW} \times Br_{W+} Br_{W-}$ is OK only for total cross section without cuts
- distribution sensitive to the spin of decaying particles
- improve with full spin correlation

ME vs PS: Resonant vs non resonant, Density Matrix, Full Spin Correlation

$$\frac{\mathrm{d}\sigma(\gamma(\lambda_1)\gamma(\lambda_2) \to W^+W^- \to f_1\bar{f}_2 f_3\bar{f}_4)}{\mathrm{d}\cos\theta\ \ \mathrm{d}\cos\theta^*_-\ \ \mathrm{d}\phi^*_-\ \ \mathrm{d}\cos\theta^*_+\ \ \mathrm{d}\phi^*_+} = Br_W^{f_1\bar{f}_2} Br_W^{f_3\bar{f}_4} \frac{\beta}{32\pi s}\left(\frac{3}{8\pi}\right)^2 \quad \times$$

$$\sum_{\lambda_-\lambda_+\lambda'_-\lambda'_+} \mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)\ \mathcal{M}^*_{\lambda_1,\lambda_2;\lambda'_-\lambda'_+}(s,\cos\theta)\times$$

$$D_{\lambda_-\lambda'_-}(\theta^*_-,\phi^*_-) D_{\lambda_+\lambda'_+}(\pi-\theta^*_+,\phi^*_++\pi)$$

$$\equiv \frac{\mathrm{d}\sigma(\gamma(\lambda_1)\gamma(\lambda_2)\to W^+W^-)}{\mathrm{d}\cos\theta}\left(\frac{3}{8\pi}\right)^2 Br_W^{f_1\bar{f}_2} Br_W^{f_3\bar{f}_4}$$

$$\sum_{\lambda_-\lambda_+\lambda'_-\lambda'_+} \rho^{\lambda_1,\lambda_2}_{\lambda_-\lambda_+\lambda'_-\lambda'_+}\ D_{\lambda_-\lambda'_-}(\theta^*_-,\phi^*_-)\ D_{\lambda_+\lambda'_+}(\pi-\theta^*_+,\phi^*_++\pi)$$

with $$\rho^{\lambda_1,\lambda_2}_{\lambda_-\lambda_+\lambda'_-\lambda'_+}(s,\cos\theta) = \frac{\mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)\ \mathcal{M}^*_{\lambda_1,\lambda_2;\lambda'_-\lambda'_+}(s,\cos\theta)}{\sum_{\lambda_-\lambda_+}|\mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)|^2},$$

ME vs PS: Resonant vs non resonant, Density Matrix, Full Spin Correlation

$$\frac{\mathrm{d}\sigma(\gamma(\lambda_1)\gamma(\lambda_2) \to W^+W^- \to f_1\bar{f}_2 f_3\bar{f}_4)}{\mathrm{d}\cos\theta \;\; \mathrm{d}\cos\theta^*_- \;\; \mathrm{d}\phi^*_- \;\; \mathrm{d}\cos\theta^*_+ \;\; \mathrm{d}\phi^*_+} = Br_W^{f_1\bar{f}_2} Br_W^{f_3\bar{f}_4} \frac{\beta}{32\pi s}\left(\frac{3}{8\pi}\right)^2 \quad \times$$

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$$\equiv \frac{\mathrm{d}\sigma(\gamma(\lambda_1)\gamma(\lambda_2)\to W^+W^-)}{\mathrm{d}\cos\theta}\left(\frac{3}{8\pi}\right)^2 Br_W^{f_1\bar{f}_2} Br_W^{f_3\bar{f}_4}$$

$$\sum_{\lambda_-\lambda_+\lambda'_-\lambda'_+} \rho^{\lambda_1,\lambda_2}_{\lambda_-\lambda_+\lambda'_-\lambda'_+}\; D_{\lambda_-\lambda'_-}(\theta^*_-,\phi^*_-)\; D_{\lambda_+\lambda'_+}(\pi-\theta^*_+,\phi^*_+ + \pi)$$

with $$\rho^{\lambda_1,\lambda_2}_{\lambda_-\lambda_+\lambda'_-\lambda'_+}(s,\cos\theta) = \frac{\mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)\,\mathcal{M}^*_{\lambda_1,\lambda_2;\lambda'_-\lambda'_+}(s,\cos\theta)}{\sum_{\lambda_-\lambda_+}|\mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)|^2},$$

ME vs PS: Resonant vs non resonant, Density Matrix, Full Spin Correlation

$$\frac{d\sigma(\gamma(\lambda_1)\gamma(\lambda_2) \to W^+W^- \to f_1\bar{f}_2 f_3\bar{f}_4)}{d\cos\theta \;\; d\cos\theta_-^* \;\; d\phi_-^* \;\; d\cos\theta_+^* \;\; d\phi_+^*} = Br_W^{f_1\bar{f}_2} Br_W^{f_3\bar{f}_4} \frac{\beta}{32\pi s}\left(\frac{3}{8\pi}\right)^2 \quad \times$$

$$\sum_{\lambda_-\lambda_+\lambda'_-\lambda'_+} \mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)\, \mathcal{M}^*_{\lambda_1,\lambda_2;\lambda'_-\lambda'_+}(s,\cos\theta)\times$$

$$D_{\lambda_-\lambda'_-}(\theta_-^*,\phi_-^*) D_{\lambda_+\lambda'_+}(\pi-\theta_+^*,\phi_+^*+\pi)$$

$$\equiv \frac{d\sigma(\gamma(\lambda_1)\gamma(\lambda_2) \to W^+W^-)}{d\cos\theta}\left(\frac{3}{8\pi}\right)^2 Br_W^{f_1\bar{f}_2} Br_W^{f_3\bar{f}_4}$$

$$\sum_{\lambda_-\lambda_+\lambda'_-\lambda'_+} \rho^{\lambda_1,\lambda_2}_{\lambda_-\lambda_+\lambda'_-\lambda'_+}\, D_{\lambda_-\lambda'_-}(\theta_-^*,\phi_-^*)\, D_{\lambda_+\lambda'_+}(\pi-\theta_+^*,\phi_+^*+\pi)$$

$$\text{with} \qquad \rho^{\lambda_1,\lambda_2}_{\lambda_-\lambda_+\lambda'_-\lambda'_+}(s,\cos\theta) = \frac{\mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)\, \mathcal{M}^*_{\lambda_1,\lambda_2;\lambda'_-\lambda'_+}(s,\cos\theta)}{\sum_{\lambda_-\lambda_+}|\mathcal{M}_{\lambda_1,\lambda_2;\lambda_-\lambda_+}(s,\cos\theta)|^2},$$

W decay functions

$$D^{W^-}_{\lambda,\lambda'}(\theta^*,\phi^*) \equiv D_{\lambda,\lambda'}, \qquad D_{\lambda,\lambda'} = D^*_{\lambda',\lambda}$$

$$D_{+,-} = \frac{1}{2}(1-\cos^2\theta^*)e^{2i\phi^*}, \qquad D_{\pm,0} = -\frac{1}{\sqrt{2}}(1\mp\cos\theta^*)\sin\theta^* e^{\pm i\phi^*},$$

$$D_{\pm,\pm} = \frac{1}{2}(1\mp\cos\theta^*)^2, \qquad D_{0,0} = \sin^2\theta^*.$$

ME vs PS: Resonant vs non resonant

$\lambda_1\ \lambda_2$	Inv. Mass. Cuts	Narrow Width Improved	All diag. $\Gamma_W(M_W^2)$	All diag. $\Gamma_W(s)$	All diag. Fudge	"Resonant" Subset
$\sqrt{s} = 400$ GeV						
$+\,+$	None	2288	2310	2312	2309	2354
$+\,-$	None	1893	1926	1927	1923	1975
$-\,+$	None	1890	1927	1927	1926	1975
$-\,-$	None	2186	2184	2183	2183	2252
$+\,+$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	1759	1762	1764	1761	1761
$+\,-$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	1455	1458	1458	1456	1456
$-\,+$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	1454	1457	1458	1457	1456
$-\,-$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	1681	1683	1681	1682	1682
$\sqrt{s} = 1600$ GeV						
$+\,+$	None	377	389	389	389	456
$+\,-$	None	320	335	335	335	388
$-\,+$	None	320	336	336	336	391
$-\,-$	None	427	447	447	447	490
$+\,+$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	290	291	291	291	291
$+\,-$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	246	246	246	246	246
$-\,+$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	246	246	247	246	247
$-\,-$	$\Delta_{jj}, \Delta_{l\nu} < 5$ GeV	328	329	329	330	329

Spin Correlation and Radiation

Usual techniques require production and decay to be generated at the same time

In a generator the difficulty is that

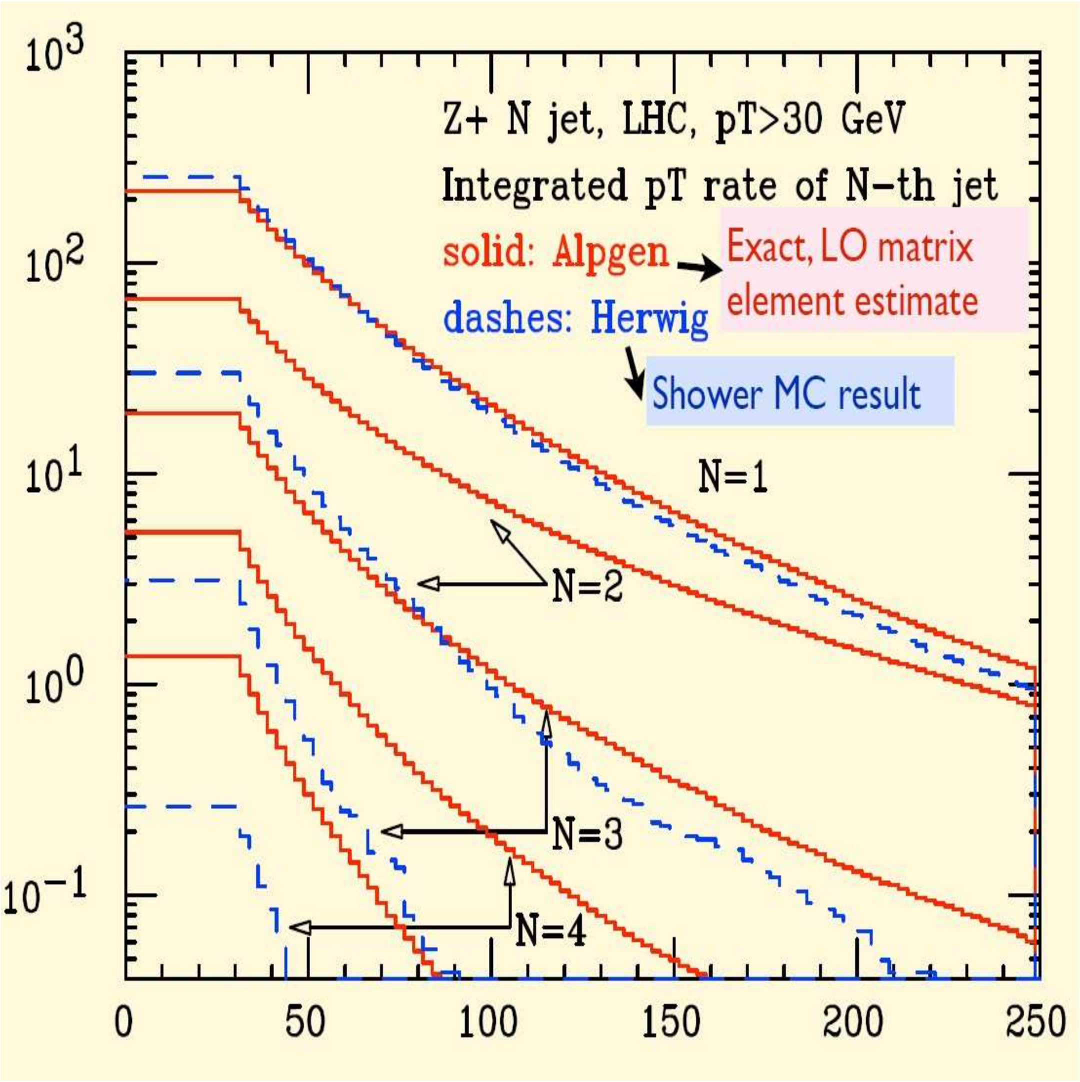
- We need to generate QCD radiation before particle decays
- There may be a long chain of sequential decays
- The particle may have different decay channels
- There may be a few final state particles

Need an algorithm for the production and decay to be done separately

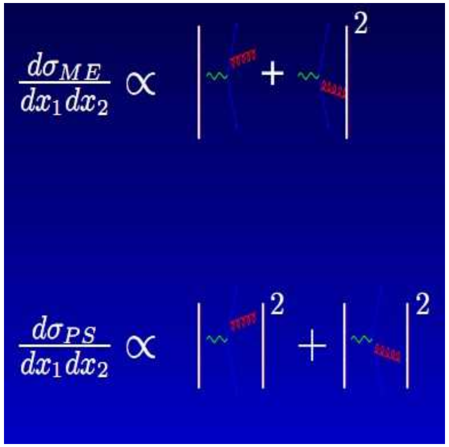
Complexity should not grow more than the number of external particles

in HERWIG spin correlation is implemented not always the case for Pythia (even without radiation)

ME vs PS: Limitations of PS



- PS do not describe hard jets
- some real progress has been made in interfacing ME with PS
- CKKW, MLM (say more if time permits)



Automation of LO calculations of (partonic) processes $2 \longrightarrow N$ are now automatised including integration, for (say) $N < 8$ based on different methods

- ALPGEN
- CompHEP/CalcHEP
- Grace
- HELAS/PHEGAS
- MADGRAPH/MADEVENT
- O'Mega/WHIZARD
- SHERPA/Amegic

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the more particles one deals with a (Feynman) diagrammatic calculations is costly as the number of diagrams grows N!

#gluons	2	3	4	5	6	7	8
#diagrams	4	25	220	2485	34300	0.5M	80M

Take as an example GRACE and $e^+e^- \rightarrow W^+W^-\gamma$

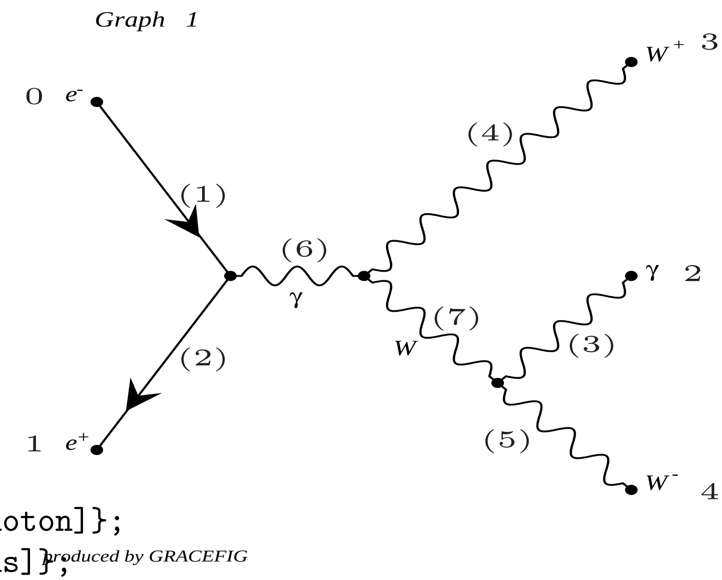
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Model="sm.mdl";
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Process;
  ELWK=3;
  Initial={electron, positron};
  Final  ={photon, W-plus, W-minus};
  Kinem="2302";
Pend;
```

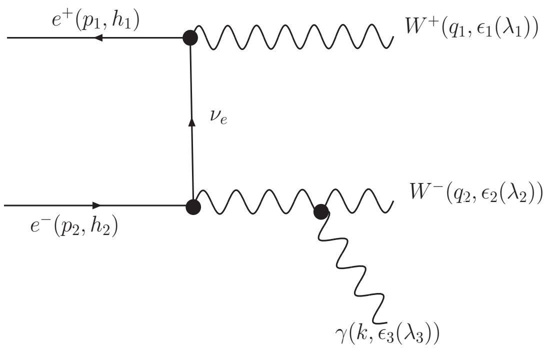
Take as an example GRACE and $e^+e^- \to W^+W^-\gamma$

1. Generate the number of vertices.
   The number of vertices is restricted by the order of the coupling constants for the physical process. Each vertex has a fixed number of propagators and external particles to be connected.
2. Connect vertices with propagators or external particles.
   There are multiple ways to connect vertices. All possible configuration are to be generated.
3. Particle assignment.
   Particles are assigned to propagators confirming that the connected vertex is defined in the model. As there will be many ways to assign particles to propagators, all possible configurations are to be generated.
4. Conservation laws such as electric charge and fermion numbers conservation will be employed in order to avoid fruitless trials.
5. Avoid duplication, use graph theory (edges and nodes)
6. QGRAPH: Powerful generator of graphs

Take as an example GRACE and $e^+e^- \rightarrow W^+W^-\gamma$

```
Process=1; External=5;
      0= initial electron;
      1= initial positron;
      2= final photon;
      3= final w-plus;
      4= final w-minus;
   Eend; elwk=3;Loop=0;

   Graph=1; Gtype=1; Sfactor=-1; Vertex=3;
      0={    1[positron]};
      1={    2[electron]};
      2={    3[photon]};
      3={    4[w-plus]};
      4={    5[w-minus]};
      5[order={1,0}]={    1[electron],    2[positron],    6[photon]};
      6[order={1,0}]={    4[w-minus],    6[photon],    7[w-plus]};
      7[order={1,0}]={    3[photon],    5[w-plus],    7[w-minus]};
   Vend; Gend;

   Graph=2;
       ...
```





$$T_{fi}\big((p_1,h_1),(p_2,h_2),(q_1,\lambda_1),(q_2,l_2),(k,\lambda_3)\big) =$$

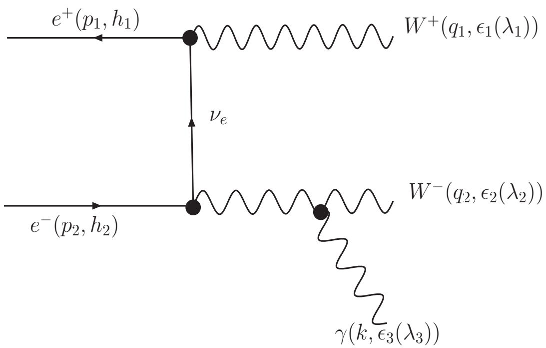
$$\overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, S_F(-p_1+q_1,0)\, c^{\mu}_{eW}\, u(p_2,h_2)$$

$$\times D_{V\,\mu\nu}(q_2+k,M_W)\, c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k)$$

$$c^{\mu}_{eW} = \frac{eM_Z}{\sqrt{2(M_Z^2-M_W^2)}}\,\gamma^{\mu}\,\frac{1-\gamma_5}{2}$$

$$c^{\nu\rho\sigma}_{WW\gamma}(p,q,r) = e[(p-q)^{\sigma}g^{\nu\rho}+(q-r)^{\nu}g^{\rho\sigma}+(r-p)^{\rho}g^{\sigma\nu}]$$

Matrix Elements Generation and Automation: Helicity amplitude, How it works



$$T_{fi}\big((p_1,h_1),(p_2,h_2),(q_1,\lambda_1),(q_2,l_2),(k,\lambda_3)\big) =$$

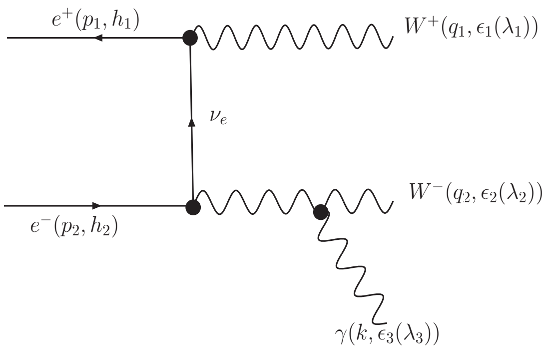
$$\overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, S_F(-p_1+q_1,0)\, c^{\mu}_{eW}\, u(p_2,h_2)$$

$$\times D_{V\;\mu\nu}(q_2+k,M_W)\, c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k)$$

$$c^{\mu}_{eW} = \frac{eM_Z}{\sqrt{2(M_Z^2-M_W^2)}}\gamma^{\mu}\frac{1-\gamma_5}{2}$$

$$c^{\nu\rho\sigma}_{WW\gamma}(p,q,r) = e[(p-q)^{\sigma}g^{\nu\rho}+(q-r)^{\nu}g^{\rho\sigma}+(r-p)^{\rho}g^{\sigma\nu}]$$

$$S_F(p,m) = (\not{p}+m)D(p,m) \qquad D_{V\;\mu\nu}(p) = \Big(-g_{\mu\nu}+\frac{p_\mu p_\nu}{M^2}\Big)D(p,m) \qquad D(p,m) = \frac{1}{p^2-m^2}$$



$$T_{fi}\Big((p_1,h_1),(p_2,h_2),(q_1,\lambda_1),(q_2,l_2),(k,\lambda_3)\Big) =$$

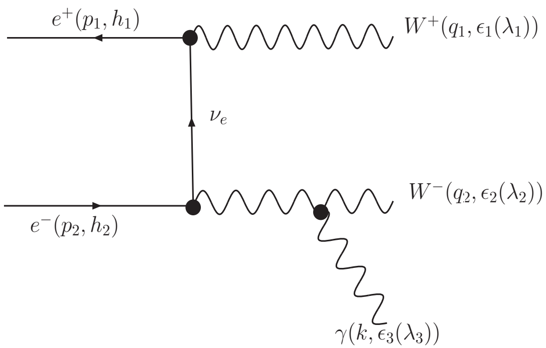
$$\overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, S_F(-p_1+q_1,0)\, c^{\mu}_{eW}\, u(p_2,h_2)$$

$$\times D_{V\ \mu\nu}(q_2+k,M_W)\, c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k)$$

$$c^{\mu}_{eW} = \frac{eM_Z}{\sqrt{2(M_Z^2-M_W^2)}}\gamma^{\mu}\,\frac{1-\gamma_5}{2}$$

$$c^{\nu\rho\sigma}_{WW\gamma}(p,q,r) = e[(p-q)^{\sigma}g^{\nu\rho}+(q-r)^{\nu}g^{\rho\sigma}+(r-p)^{\rho}g^{\sigma\nu}]$$

$$S_F(p) = \frac{\sum_{\alpha i} w_{\alpha,i}\, U^{\alpha}(h^{(i)},p^{(i)})\,\overline{U}^{\alpha}(h^{(i)},p^{(i)})}{p^2-m^2}, \qquad D_{V\ \mu\nu}(p) = \frac{\sum_i w_i\, \epsilon^{(i)}_{\mu}(p)\, \epsilon^{(i)}_{\nu}(p)}{p^2-m^2}$$



$$T_{fi}\big((p_1,h_1),(p_2,h_2),(q_1,\lambda_1),(q_2,l_2),(k,\lambda_3)\big) =$$

$$\overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, S_F(-p_1+q_1,0)\, c^{\mu}_{eW}\, u(p_2,h_2)$$

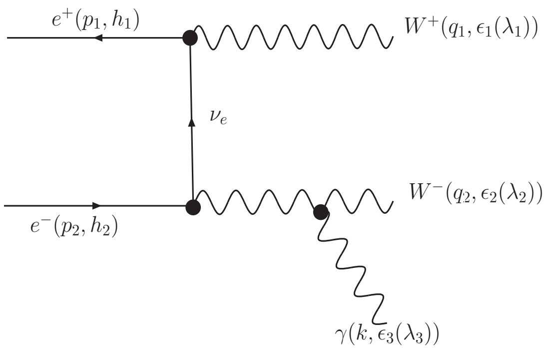
$$\times D_{V\,\mu\nu}(q_2+k,M_W)\, c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k)$$

$$c^{\mu}_{eW} = \frac{eM_Z}{\sqrt{2(M_Z^2-M_W^2)}}\,\gamma^{\mu}\,\frac{1-\gamma_5}{2}$$

$$c^{\nu\rho\sigma}_{WW\gamma}(p,q,r) = e[(p-q)^{\sigma}g^{\nu\rho}+(q-r)^{\nu}g^{\rho\sigma}+(r-p)^{\rho}g^{\sigma\nu}]$$

$$S_F(p) = \frac{\sum_{\alpha i} w_{\alpha,i}\, U^{\alpha}(h^{(i)},p^{(i)})\,\overline{U}^{\alpha}(h^{(i)},p^{(i)})}{p^2-m^2}, \qquad D_{V\,\mu\nu}(p) = \frac{\sum_i w_i\, \epsilon^{(i)}_{\mu}(p)\,\epsilon^{(i)}_{\nu}(p)}{p^2-m^2}$$

$$T_{fi} = D(-p_1+q_1,0)\; D(q_2+k,m_W)\,\sum_{\alpha,i} w_{\alpha,i}\sum_{l} w_l \times V^{(\alpha,i)}_{eW+}\,V^{(\alpha,i,l)}_{eW-}\,V^{(l)}_{WW\gamma},$$



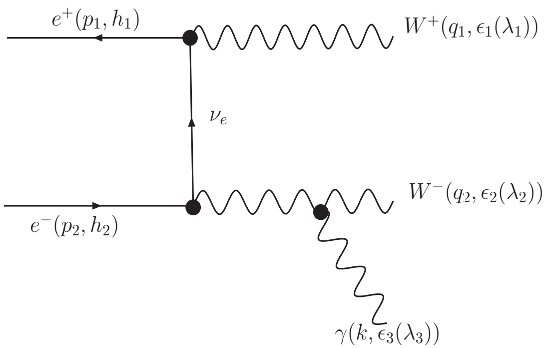
$$T_{fi}((p_1,h_1),(p_2,h_2),(q_1,\lambda_1),(q_2,l_2),(k,\lambda_3)) =$$
$$\overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, S_F(-p_1+q_1,0)\, c^{\mu}_{eW}\, u(p_2,h_2)$$
$$\times D_{V\,\mu\nu}(q_2+k,M_W)\, c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k)$$
$$c^{\mu}_{eW} = \frac{eM_Z}{\sqrt{2(M_Z^2-M_W^2)}}\gamma^{\mu}\,\frac{1-\gamma_5}{2}$$
$$c^{\nu\rho\sigma}_{WW\gamma}(p,q,r) = e[(p-q)^{\sigma}g^{\nu\rho} + (q-r)^{\nu}g^{\rho\sigma} + (r-p)^{\rho}g^{\sigma\nu}]$$

$$S_F(p) = \frac{\sum_{\alpha i} w_{\alpha,i}\, U^{\alpha}(h^{(i)},p^{(i)})\, \overline{U}^{\alpha}(h^{(i)},p^{(i)})}{p^2-m^2}, \qquad D_{V\,\mu\nu}(p) = \frac{\sum_i w_i\, \epsilon^{(i)}_{\mu}(p)\, \epsilon^{(i)}_{\nu}(p)}{p^2-m^2}$$

$$T_{fi} = D(-p_1+q_1,0)\, D(q_2+k,m_W)\, \sum_{\alpha,i} w_{\alpha,i} \sum_{l} w_l \times V^{(\alpha,i)}_{eW+}\, V^{(\alpha,i,l)}_{eW-}\, V^{(l)}_{WW\gamma},$$

The building blocks: c-numbers Library subroutines

$$\begin{aligned}
V^{(\alpha,i)}_{eW+} &= \overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, U^{\alpha}((-p_1+q_1)^{(i)},h^{(i)}), \quad \text{FFV}\\
V^{(\alpha,i,l)}_{eW-} &= \overline{U}^{\alpha}(p^{(i)},h^{(i)})\, c^{\mu}_{eW}\, \epsilon^{(l)}_{\mu}(q_2+k)\, u(p_2,h_2),\\
V^{(l)}_{WW\gamma} &= c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon^{(l)}_{\nu}(q_2+k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k) \quad \text{VVV}.
\end{aligned}$$



$$T_{fi}\big((p_1,h_1),(p_2,h_2),(q_1,\lambda_1),(q_2,l_2),(k,\lambda_3)\big) =$$
$$\overline{v}(p_1,h_1)\, c^{\eta}_{eW}\, \epsilon_{1\eta}(q_1)\, S_F(-p_1+q_1,0)\, c^{\mu}_{eW}\, u(p_2,h_2)$$
$$\times D_{V\,\mu\nu}(q_2+k,M_W)\, c^{\nu\rho\sigma}_{WW\gamma}(q_2+k,-q_2,-k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k)$$
$$c^{\mu}_{eW} = \frac{eM_Z}{\sqrt{2(M_Z^2-M_W^2)}}\gamma^{\mu}\,\frac{1-\gamma_5}{2}$$
$$c^{\nu\rho\sigma}_{WW\gamma}(p,q,r) = e[(p-q)^{\sigma}g^{\nu\rho}+(q-r)^{\nu}g^{\rho\sigma}+(r-p)^{\rho}g^{\sigma\nu}]$$

$$S_F(p) = \frac{\sum_{\alpha i} w_{\alpha,i}\, U^{\alpha}(h^{(i)},p^{(i)})\, \overline{U}^{\alpha}(h^{(i)},p^{(i)})}{p^2-m^2}, \qquad D_{V\,\mu\nu}(p) = \frac{\sum_i w_i\, \epsilon^{(i)}_{\mu}(p)\, \epsilon^{(i)}_{\nu}(p)}{p^2-m^2}$$

$$T_{fi} = D(-p_1+q_1,0)\; D(q_2+k,m_W)\; \sum_{\alpha,i} w_{\alpha,i} \sum_{l} w_l \times V^{(\alpha,i)}_{eW+}\, V^{(\alpha,i,l)}_{eW-}\, V^{(l)}_{WW\gamma},$$

The building blocks: c-numbers Library. If New Physics? extend library?

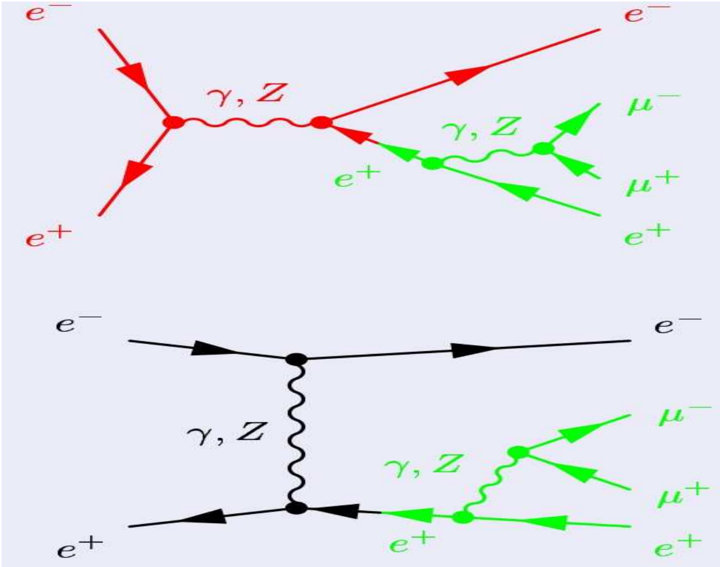
read in new Feynman rules, calculate new entries for subroutines

$$\begin{aligned}
V^{(\alpha,i)}_{eW+} &= \overline{v}(p_1,h_1)\, c^{\eta}_{eW,NP}\, \epsilon_{1\eta}(q_1)\, U^{\alpha}((-p_1+q_1)^{(i)},h^{(i)}),\\
V^{(\alpha,i,l)}_{eW-} &= \overline{U}^{\alpha}(p^{(i)},h^{(i)})\, c^{\mu}_{eW,NP}\, \epsilon^{(l)}_{\mu}(q_2+k)\, u(p_2,h_2),\\
V^{(l)}_{WW\gamma} &= c^{\nu\rho\sigma}_{WW\gamma,NP}(q_2+k,-q_2,-k)\, \epsilon^{(l)}_{\nu}(q_2+k)\, \epsilon_{2\rho}(q_2)\, \epsilon_{3\sigma}(k).
\end{aligned}$$

- This is now used in SHERPA and HERWIG
- The method is purely numerical.
- The amplitude for each Feynman graph is first decomposed into vertex sub-amplitudes
- Each of these sub-amplitudes is read from a pre-defined model file library
- **drawback:** Library exists for Standard Couplings, higher order operators, spin > 2, need to be generated from scratch

Speed up

can speed up by reusing common pieces `GRACE, AMEGIC`



but we need to feed in the Feynman rules

what if the new physics is like the MSSM? huge number of vertices?

need to input new models quickly and efficiently

ME based MC Codes

Int/Amp.	Squaring	Helicity	Off-Shell	On-Shell
Adaptive	CompHEP/CalcHEP	GRACE	ALPGEN	?
Multi-Channel	-	MadGraph/Sherpa		?
	-	HELAC/Whizard		

- LanHEP Developed since 1994 as a part of CompHEP to help from the Lagrangian the complete set of Feynman rules, the first goal was MSSM.
- can now output to FeynArts/FeynCalc
- extremely powerful, extended to one-loop
- recently (2008) FeynRules is on the market, more limited though for the moment

A physical model in CompHEP is defined by the (3) tables of

- parameters
- particles
- interaction vertices with implicit Lorentz structure (any Lorentz structure is allowed)

A physical model in CompHEP is defined by the tables of parameters, particles and interaction vertices

Parameters

```
EE     |0.31345     |Electromagnetic coupling constant (<->1/127.9)
MW     |MZ*CW
```

Particles

```
photon       |A  |A  |2      |0      |0      |1     |G  |A
Z boson      |Z  |Z  |2      |MZ     |wZ     |1     |G  |Z
W boson      |W+ |W- |2      |MW     |wW     |1     |G  |W^+
electron     |e  |E  |1      |Me     |0      |1     |   |e
```

Vertices

```
E    |e     |A    |     |EE                       |G(m3)
E    |e     |H    |     |-EE*Me*ca/(2*MW*SW*cb)   |1
E    |e     |H3   |     |i*EE*Me*tb/(2*MW*SW)     |G5
E    |e     |Z    |     |EE/(2*S2W)               |C2W*G(m3)*(1-G5)-2*SW^2*
E    |e     |Z.f  |     |-i*EE*Me/(2*MW*SW)       |G5
E    |e     |h    |     |EE*Me*sa/(2*MW*SW*cb)    |1
E    |ne    |H-   |     |EE*Me*Sqrt2*tb/(4*MW*SW)|(1-G5)
E    |ne    |W-   |     |-EE*Sqrt2/(4*SW)         |G(m3)*(1-G5)
E    |ne    |W-.f |     |-EE*Me*Sqrt2/(4*MW*SW)   |(1-G5)
```

Description of the physical model for LanHEP

- The user declares the physical parameters to be included in the Lagrangian. The value of a parameter can be a number or an expression:

```
parameter ee=0.31333:'elementary electric charge'.
parameter sw=0.478:'sinus of weak angle'.
parameter cw=Sqrt(1-sw**2):'cosine of weak angle'.
```

- The user declares scalar, spinor, vector, (also spin 3/2 and 2) particles . It is possible to prescribe the colour structure for a particle:

```
spinor e1/E1:(electron, mass Me=0.000511).
spinor q/Q:(quark, color c3, mass Mq=10).
vector A/A:(photon, gauge).
```

- New symmetry groups are also possible. They can be defined in a way like color $SU(3)$ symmetry is defined, as well as corresponding matrices and structure constants:

```
group color:SU(3).
repres color:(c3/c3b,c8).
special lambda:(color c3, color c3b, color c8).
```

- The user can define the substitution rules, for example for covariant derivative $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$:

```
let F^mu^nu = deriv^mu*A^nu - deriv^nu*A^mu.
```

- It is possible to define multiplets, and their components:

```
let l1 = {n1,e1}, L1 = {N1,E1}.
```

- The user can write Lagrangian terms with Lorenz and multiplet indices explicitly or omit indices (all or part of them):*(QED vertex $\bar{e}(x)\gamma^\mu A_\mu(x)e(x)$)*

```
lterm E1^a*gamma^a^b^mu*A^mu*e1^b.
lterm E1*gamma^mu*A^mu*e1.
lterm E1*gamma*A*e1.
```

- LanHEP performs explicit summation over the indices of Lagrangian terms, if the corresponding components for multiplets and matrices are introduced.

LanHEP features

- 2-component fermion notation makes possible the introduction of supersymmetric Lagrangian in a more natural way, closer to the form used in most textbooks on the supersymmetry.
- Superpotential can be used for supersymmetric theories; this option allows to introduce easily various extensions of MSSM (R-parity violation, NMSSM, etc). Yukawa and F^*F terms are now automatically derived by the program.
- Generating Hermitian conjugate terms allow to simplify model description.
- Constructing the ghost Lagrangian from BRST transformation.
- Conterterms can be generated if the necassy shifts for parameters and fields are prescribed.

LanHEP features

- Checking the correctness of the model
  - Electric charge conservation
  - Hermiticity
  - Probing kinetic and mass terms, the mass matrix is extracted
  - BRST invariance
  - Extracting classes of vertices
- Simplifying the expression for vertices
  - Orthogonal (and hermitian) matrices
  - Trigonometric expressions ($\sin\alpha \pm \beta$)
  - Lengthly expressions in the vertices can be transferred to the table of parameters.

Some new Lagrangians implemented by LanHEP

- Complete MSSM in unitary and t'Hooft-Feynman gauges with the Higgs sector by linking with the FeynHiggs, effective potential is used to take into account radiative corrections to Higgs masses and interaction; mSUGRA and GMSB by means of SLHA interface
- MSSM extensions include:
  - MSSM with R-parity violation
  - Model with gravitino and sgoldstinos
  - NMSSM (an extension of the MSSM by a gauge singlet N with hypercharge 0)
  - MSSM with CP violation
- Complete Leptoquark model which includes Yukawa couplings for all types of LQ, gauge couplings and anomalous gauge couplings for vector LQ
- Complete two-Higgs-doublet model with conserved or broken CP invariance
- Anomalous quartic vector bosons self-couplings

More new Lagrangians implemented by LanHEP

- A new signature for color octet pseudoscalars at the LHC, in theories of extra-dim. Alfonso R. Zerwekh, Claudio O. Dib, Rogerio Rosenfeld;
- Minimal Higgsless model, Chivukula et al;
- Inert Doublet Model, Pierce and Thaler;
- Excited fermions, Boos et al;
- Technihadrons, technicolour, Zerwekh;
- Little Higgs Models, Phenomenology of littlest Higgs model with T-parity: including effects of T-odd fermions. Alexander Belyaev, Chuan-Ren Chen, Kazuhiro Tobe, C.-P. Yuan (Michigan State U.);
- Universal extra-dim, Matchev et al.

New option allows to modify the format of the output particle table and to add new proprties (new columns in the table). One can add, say, PDG particle number to the table:

```
prtcformat fullname:' Full   Name ',
           name:' p ',
           aname:' ap',
           spin2,color,mass,width, aux,
           pdg:'PDG ID',
           texname:'  latex P name ',
           atexname:' latex aP name ' .
```

Then the new property value can be written in the particle declaration statement:

```
scalar h:(higgs, mass Mh, pdg 123, width wh).
```

- Electric charge can be extracted automatically from the photon interaction and then added to the table.

Vertices table format: explicit colour structure

Color matrices and dot products can be optionally written in the Lorentz Part, e.g. QCD plus quark-photon interactions produces the following vertices file:

```
P1    |P2    |P3    |P4    |>    Factor    <|> dLagrangian/ dA(p1) dA(p2) dA(p3
G     |G     |G     |      |gg             |m2.p3*m1.m3*F(c1,c2,c3)
      |      |      |      |                -m1.p3*m2.m3*F(c1,c2,c3)
      |      |      |      |                +m3.p1*m1.m2*F(c1,c2,c3)
      |      |      |      |                -m2.p1*m1.m3*F(c1,c2,c3)
      |      |      |      |                -m3.p2*m1.m2*F(c1,c2,c3)
      |      |      |      |                +m1.p2*m2.m3*F(c1,c2,c3)
G.C   |G.c   |G     |      |-gg            |m3.p2*F(c1,c2,c3)
Q     |q     |G     |      |gg             |L(c1,c2,c3)*G(m3)
Q     |q     |A     |      |ee/3           |c1.c2*G(m3)
G     |G     |G     |G     |gg^2           |m1.m3*m2.m4*F(c1,c2,c0)*F(c3,c4,c0
      |      |      |      |                -m1.m4*m2.m3*F(c1,c2,c0)*F(c3,c4,c
      |      |      |      |                +m1.m2*m3.m4*F(c1,c3,c0)*F(c2,c4,c
      |      |      |      |                -m1.m4*m2.m3*F(c1,c3,c0)*F(c2,c4,c
      |      |      |      |                +m1.m2*m3.m4*F(c1,c4,c0)*F(c2,c3,c
      |      |      |      |                -m1.m3*m2.m4*F(c1,c4,c0)*F(c2,c3,c
```

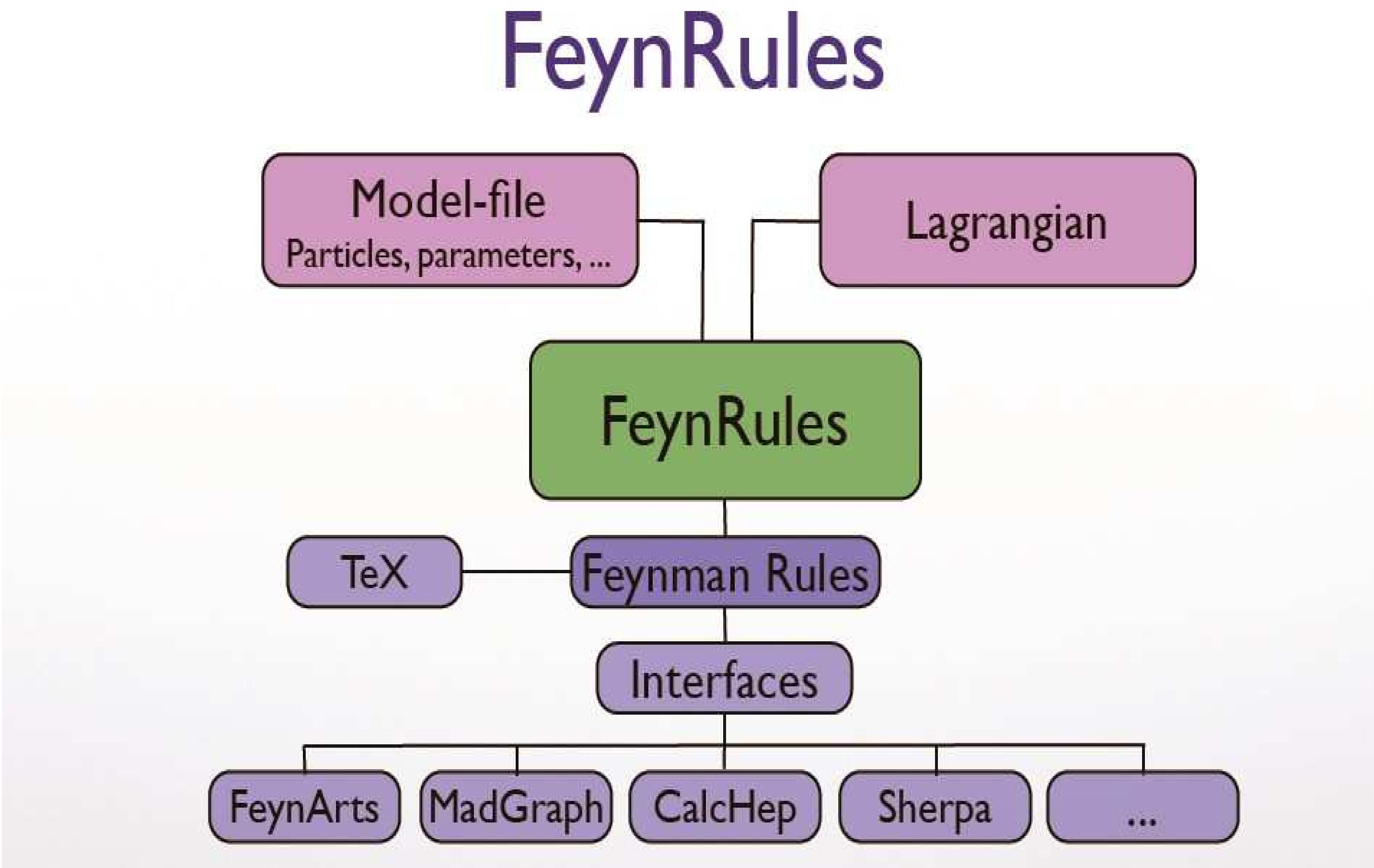
FeynRule, Madgraph component but outputs to other MEG

FeynRules

- The FR model file contains all the information about the model:
  - Particles & fields
  - Parameters (masses, coupling constants,...)
  - mixing matrices
  - etc.
- The syntax of the FR model-files is an extension of syntax used in FeynArts.
- Feynman rules are calculated by Mathematica using the information from the model-file and the Lagrangian.
- The vertices can be exported into a TeX-file.

(Needs Mathematica as does FeynArts)

FeynRule, Madgraph component but outputs to other MEG



Validation

- 3-site model: 222 key-processes tested in CalcHep/CompHep

	Lanhep CalcHEP Feynman	Lanhep CalcHEP Unitary	FeynRules CalcHEP Feynman	FeynRules CalcHEP Unitary	FeynRules CompHEP Feynman
$u\bar{u} \to gg$	170.5	170.5	170.5	170.5	170.49
$u'\overline{u'} \to gg$	0.098763	0.098763	0.098763	0.098763	0.098761
$t\bar{t} \to \gamma Z$	1.1233	1.1233	1.1233	1.1233	1.1233
$t'\bar{t} \to \gamma Z$	0.033204	0.033204	0.033204	0.033204	0.033204
$t'\overline{t'} \to Z'Z'$	1.887	1.887	1.887	1.887	1.887
$t\bar{b} \to ZW^{+\prime}$	1.5603	1.5603	1.5603	1.5603	1.5604
$e\bar{e} \to e'\bar{e}$	0.093127	0.093127	0.093127	0.093127	0.093127
$e'\bar{e} \to u'\bar{u}$	2.3603	2.3603	2.3603	2.3603	2.3603
$e\overline{\nu_e} \to \mu'\overline{\nu_\mu{}'}$	0.0005618	0.0005618	0.0005618	0.0005618	0.00056181
$e'\overline{\nu_e{}'} \to d'\overline{u'}$	2.5761	2.5761	2.5761	2.5761	2.5762
$gg \to gg$	114310.	114310.	114310.	114310.	114310.
$ZZ \to Z'Z'$	0	0	0	0	0
$W^+W^{-\prime} \to \gamma Z$	8.329	8.329	8.329	8.329	8.3288

Existing Models: SM+scalars, 3-site model, Higgs effective

Large ExtraDim soon,

comment: these models are (from MEG/Feynman rules) simple extensions of the SM

- Goal — loop calculation in susy (MSSM and extensions), for Colliders and Dark Matter, On-Shell scheme
- *FeynArts* and *FormCalc* are used for matrix element calculation: *FeynArts* model format output implemented in LanHEP.
- Shifts in fields and parameters to produce counterterms by LanHEP:

```
infinitesimal dMHsq, dMZsq, dMWsq,dZAA, dZAZ, dZZA, dZZZ, dZW, dZ
infinitesimal   dEE= -(dZAA - SW/CW*dZZA)/2.
transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
        'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2), H->H*(1+dZH/2).
```

  Different normalization schemes can be used, easy to switch
- Non-linear gauge fixing
  - quite a handful of gauge parameters, but with $\xi_i = 1$, no "unphysical threshold"
  - more important: no need for higher (than the minimal set)for higher rank tensors and tedious algebraic manipulations

From the Lagrangian to the Feynman Rules

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

```
RenConst[ dMHsq ] := ReTilde[SelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZH ] := -ReTilde[DSelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZZf ] := -ReTilde[DSelfEnergy[prt["Z.f"] -> prt["Z.f"],
MZ]] RenConst[ dZWf ] := -ReTilde[DSelfEnergy[prt["W+.f"] ->
prt["W+.f"], MW]]
```

Output of Feynman Rules with Counterterms !!

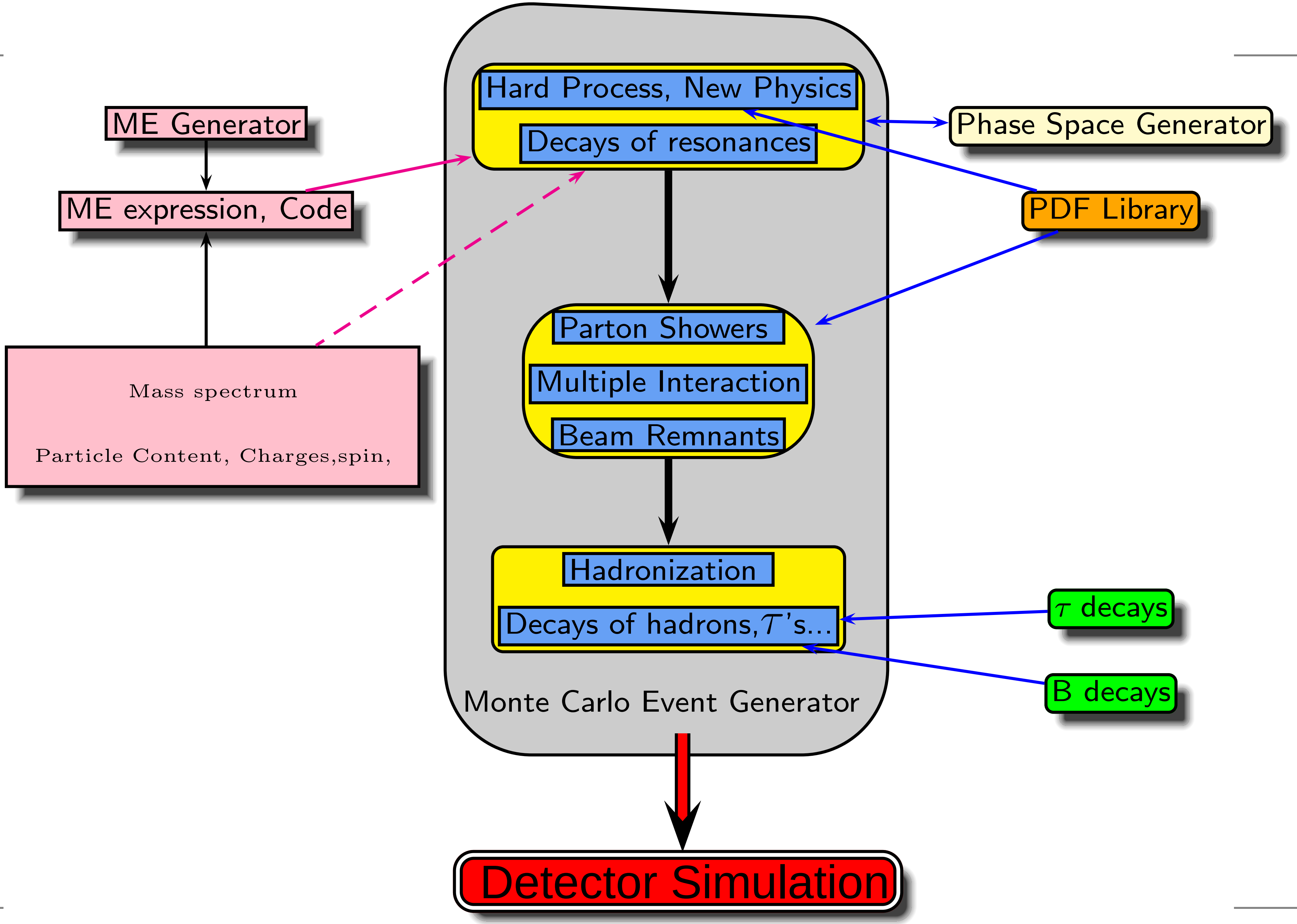
```
M$CouplingMatrices = {
(*------    H  H  ------*)
   C[ S[3], S[3] ] == - I *
{
 { 0 , dZH },
 { 0 , MH^2 dZH + dMHsq }
},
(*------    W+.f  W-.f  ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
}, (*------    A  Z  ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},


(*------    H  H  H  ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
{ 2 MH^2,3 MH^2 dZH -2 MH^2/SW dSW - MH^2/MW^2 dMWsq +
2 MH^2 dEE } },
  (*------    H  W+.f  W-.f  ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
{ 2 MH^2,MH^2 dZH +2 MH^2 dZWf -2 MH^2/SW dSW - MH^2/
+ 2 dMHsq + 2 MH^2 dEE } },


(*------    W-.C  A.c  W+  ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

LanHEP: Summary

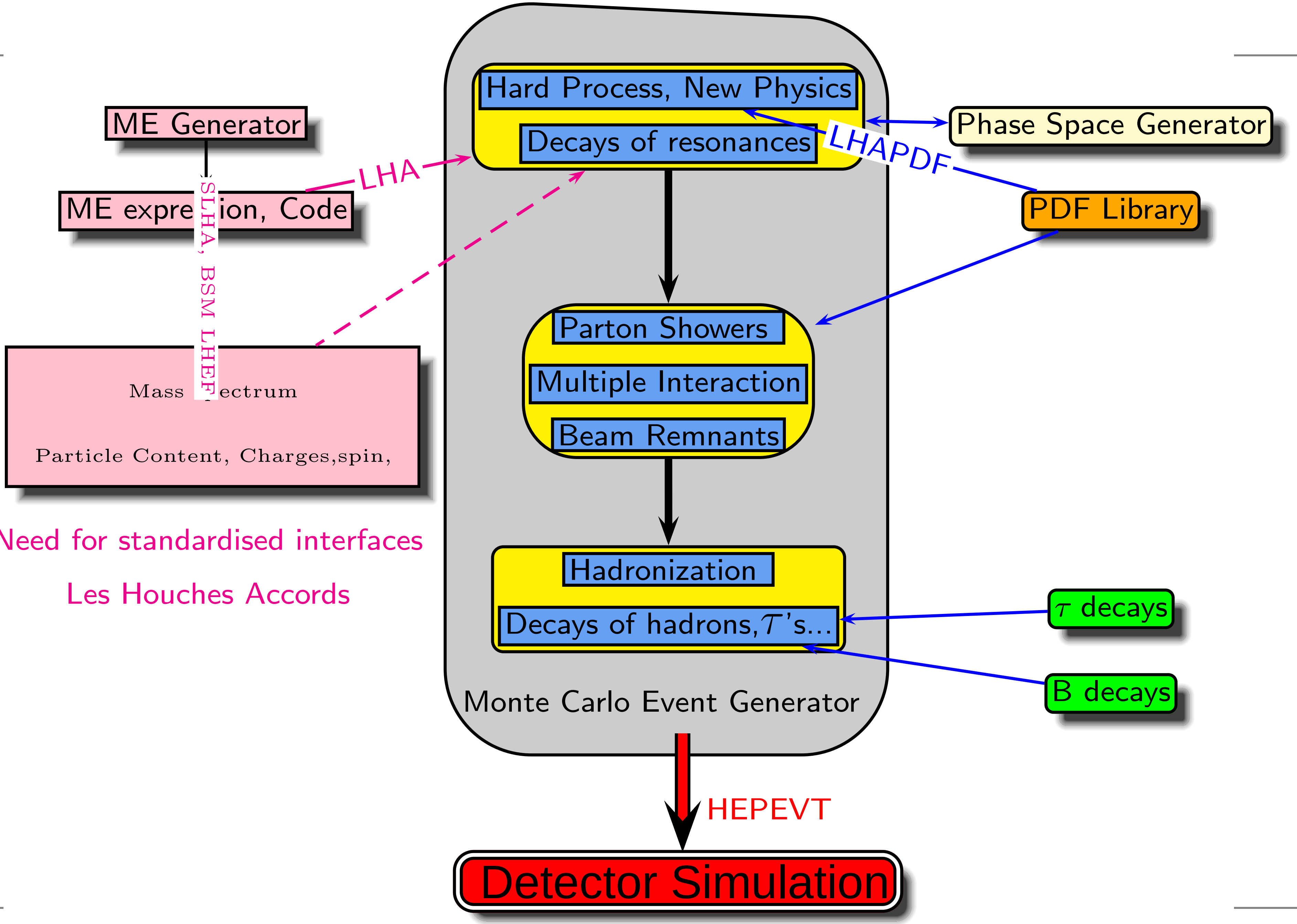
- Efficient and well-tried tool for the implementation of a model file for the New Physics
  - Lagrangian can be written in form close to textbooks, in terms of initial fields before symmetry breaking
  - SUSY-friendly: 2-component fermions and superpotential notation
  - Checking the correctness of the model, simplifying the expressions for vertices
- Extentions of CompHEP tables format
- LaTeX output
- FeynArts output
- Counterterms generation for 1-loop computation
- Use it!
- The program is available at

  `http://theory.sinp.msu.ru/~semenov/lanhep.html`

Putting all together



Putting all together, Les Houches Accords



Need for standardised interfaces

Les Houches Accords

Pass on the names in a standard manner: PDG code.

Code	Name	Code	Name	Code	Name	Code	Name
1	d	11	e^-	21	g		
2	u	12	ν_e	22	γ	35	H^0
3	s	13	μ^-	23	Z^0	36	A^0
4	c	14	ν_μ	24	W^+	37	H^+
5	b	15	τ^-	25	h^0		
6	t	16	ν_τ			39	G (graviton)

SM fundamental particle codes (+ extended Higgs sector)

Les Houches Accord: Examples

Pass on the names in a standard manner: PDG code.

Code	Name	Code	Name	Code	Name	Code	Name
1	d	11	e^-	21	g		
2	u	12	ν_e	22	γ	35	H^0
3	s	13	μ^-	23	Z^0	36	A^0
4	c	14	ν_μ	24	W^+	37	H^+
5	b	15	τ^-	25	h^0		
6	t	16	ν_τ			39	G (graviton)

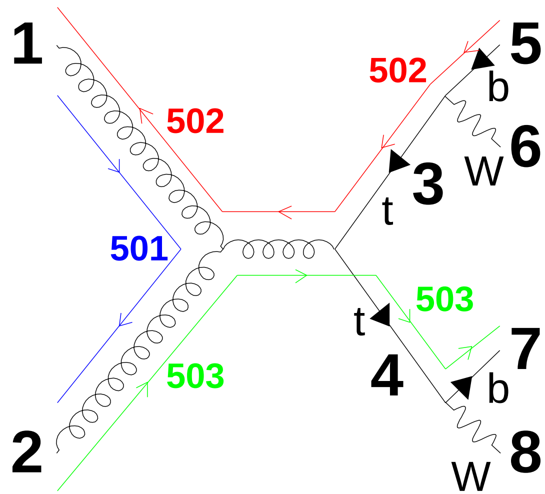
SM fundamental particle codes (+ extended Higgs sector)

For New Physics particles, create new code names (1000000+), SLHA2

Scalar Quarks

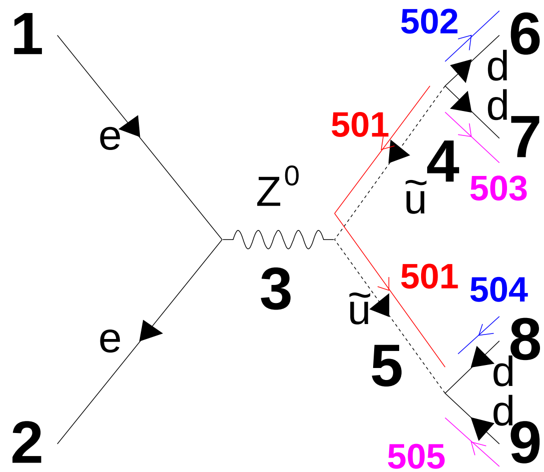
FLV / RPV / CPV	No / No / No	Yes / No / No	No / Yes / No	No / No / Yes	Yes / Yes / No	Yes / No / Yes	NMSSM
1000001	$\tilde{d}_L$	$\tilde{d}_1$	$\tilde{d}_1$	$\tilde{d}_L$	$\tilde{d}_1$	$\tilde{d}_1$	$\tilde{d}_L$
1000002	$\tilde{u}_L$	$\tilde{u}_1$	$\tilde{u}_1$	$\tilde{u}_L$	$\tilde{u}_1$	$\tilde{u}_1$	$\tilde{u}_L$
1000003	$\tilde{s}_L$	$\tilde{d}_2$	$\tilde{d}_2$	$\tilde{s}_L$	$\tilde{d}_2$	$\tilde{d}_2$	$\tilde{s}_L$
1000004	$\tilde{c}_L$	$\tilde{u}_2$	$\tilde{u}_2$	$\tilde{c}_L$	$\tilde{u}_2$	$\tilde{u}_2$	$\tilde{c}_L$
1000005	$\tilde{b}_1$	$\tilde{d}_3$	$\tilde{d}_3$	$\tilde{b}_1$	$\tilde{d}_3$	$\tilde{d}_3$	$\tilde{b}_1$
1000006	$\tilde{t}_1$	$\tilde{u}_3$	$\tilde{u}_3$	$\tilde{t}_1$	$\tilde{u}_3$	$\tilde{u}_3$	$\tilde{t}_1$
2000001	$\tilde{d}_R$	$\tilde{d}_4$	$\tilde{d}_4$	$\tilde{d}_R$	$\tilde{d}_4$	$\tilde{d}_4$	$\tilde{d}_R$
2000002	$\tilde{u}_R$	$\tilde{u}_4$	$\tilde{u}_4$	$\tilde{u}_R$	$\tilde{u}_4$	$\tilde{u}_4$	$\tilde{u}_R$
2000003	$\tilde{s}_R$	$\tilde{d}_5$	$\tilde{d}_5$	$\tilde{s}_R$	$\tilde{d}_5$	$\tilde{d}_5$	$\tilde{s}_R$
2000004	$\tilde{c}_R$	$\tilde{u}_5$	$\tilde{u}_5$	$\tilde{c}_R$	$\tilde{u}_5$	$\tilde{u}_5$	$\tilde{c}_R$
2000005	$\tilde{b}_2$	$\tilde{d}_6$	$\tilde{d}_6$	$\tilde{b}_2$	$\tilde{d}_6$	$\tilde{d}_6$	$\tilde{b}_2$
2000006	$\tilde{t}_2$	$\tilde{u}_6$	$\tilde{u}_6$	$\tilde{t}_2$	$\tilde{u}_6$	$\tilde{u}_6$	$\tilde{t}_2$

Particle codes and corresponding labels for squarks.
The labels in the first column correspond to the current PDG nomenclature.



I	ISTUP(I)	IDUP(I)	MOTHUP(1,I)	MOTHUP(2,I)	ICOLUP(1,I)	ICOLUP(2,I)
1	–1	21 (g)	0	0	501	502
2	–1	21 (g)	0	0	503	501
3	+2	–6 ($\bar{t}$)	1	2	0	502
4	+2	6 (t)	1	2	503	0
5	+1	–5 ($\bar{b}$)	3	3	0	502
6	+1	–24 (W^-)	3	3	0	0
7	+1	5 (b)	4	4	503	0
8	+1	24 (W^+)	4	4	0	0

Pass the colour information, essential for parton shower and hadronisation, apart of course from the kinematics



I	ISTUP(I)	IDUP(I)	MOTHUP(1,I)	MOTHUP(2,I)	ICOLUP(1,I)	ICOLUP(2
1	–1	11 (e^-)	0	0	0	0
2	–1	–11 (e^+)	0	0	0	0
3	+2	23 (Z^0)	1	2	0	0
4	+2	–1000002 ($\tilde{\bar{u}}$)	3	3	0	501
5	+2	1000002 ($\tilde{u}$)	3	3	501	0
6	+1	1 (d)	4	4	502	0
7	+1	1 (d)	4	4	503	0
8	+1	–1 ($\bar{d}$)	5	5	0	504
9	+1	–1 ($\bar{d}$)	5	5	0	505

Baryon number violation, SUSY RPV

Great Idea: A New Physics Model

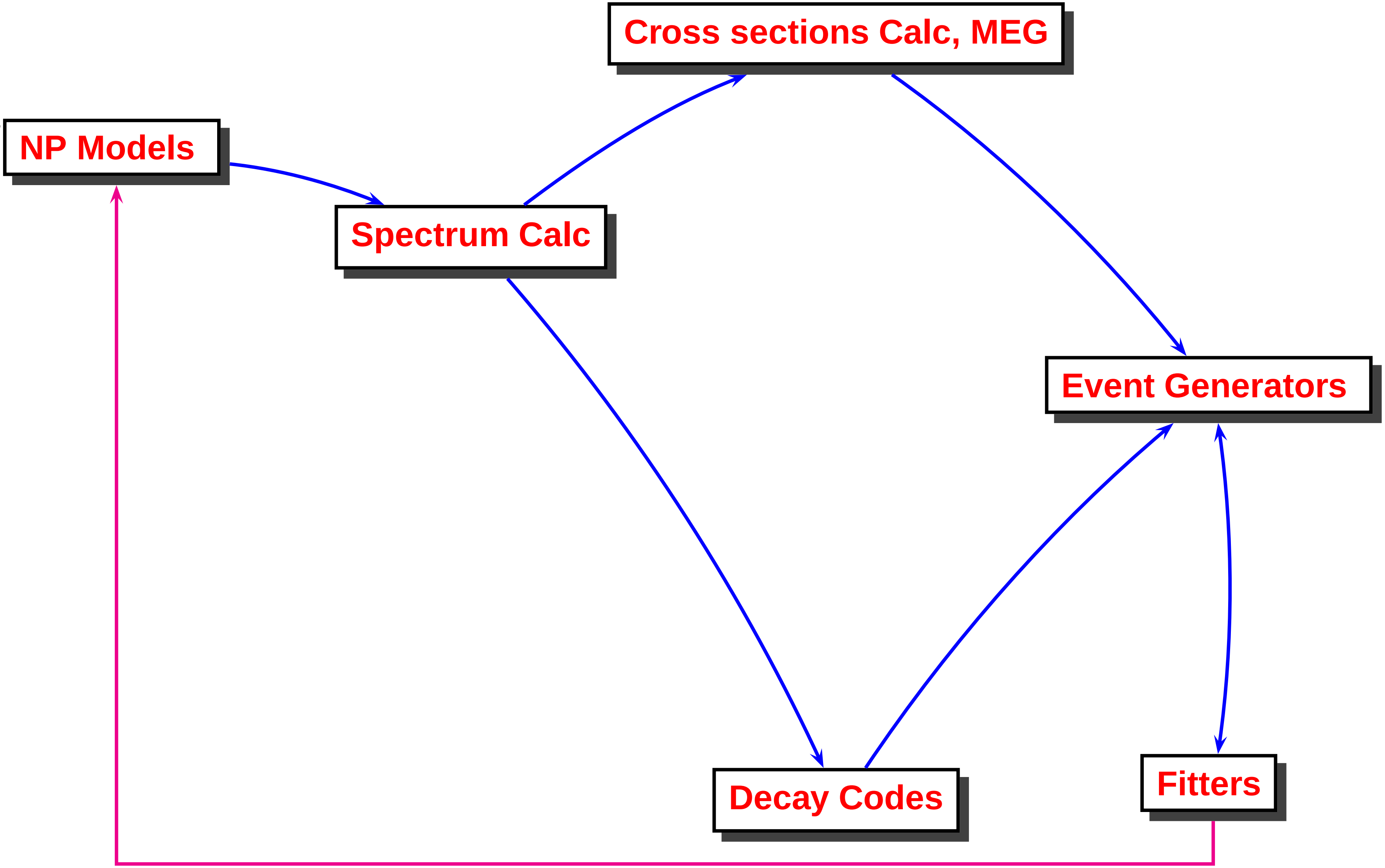
FINAL AIM

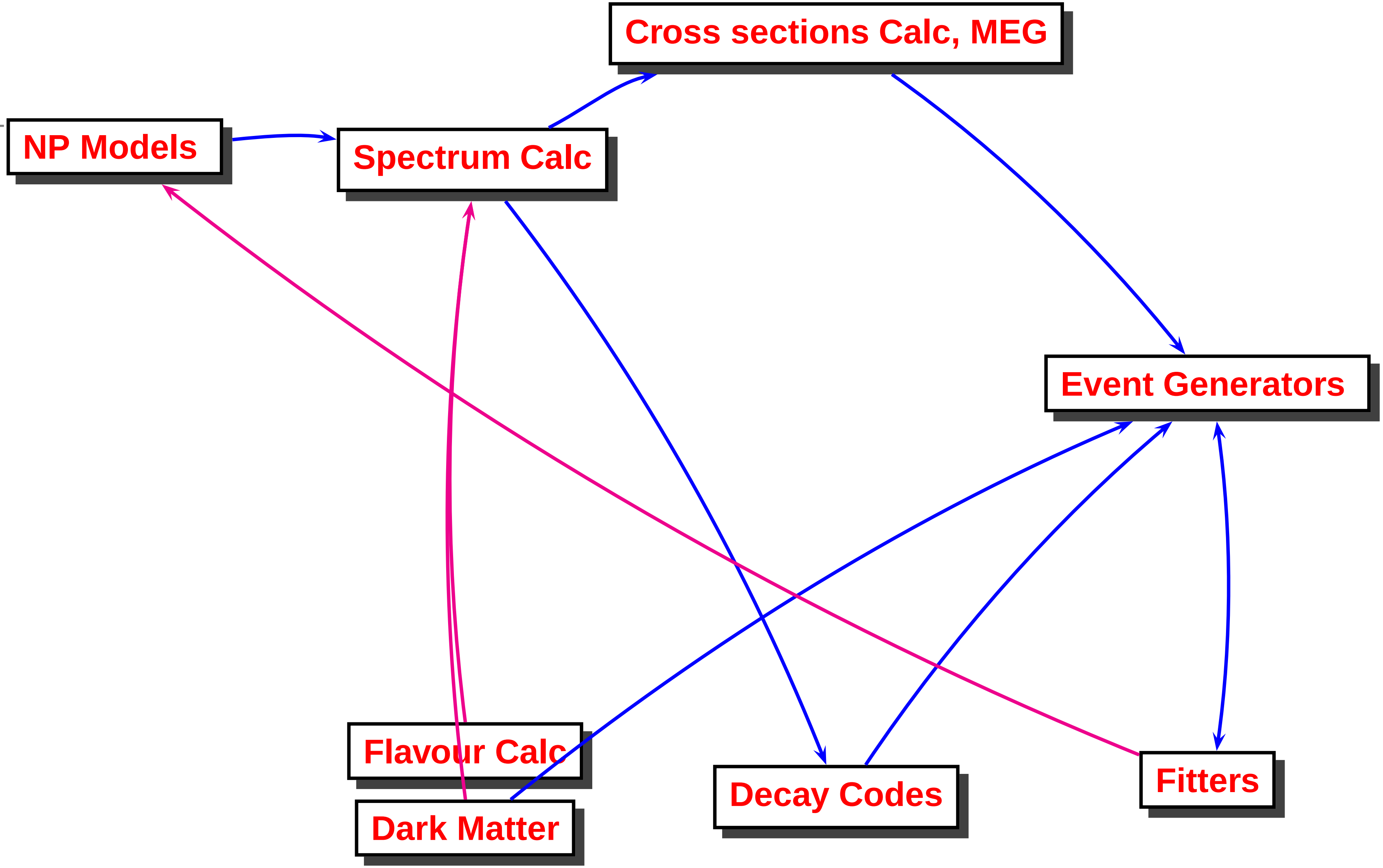
Nobel Prize if LHC validates!

NP Models

FINAL AIM

Event Generators


Cross sections Calc, MEG
NP Models
Spectrum Calc
Event Generators
Decay Codes
Fitters


Cross sections Calc, MEG
NP Models
Spectrum Calc
Event Generators
Flavour Calc
Dark Matter
Decay Codes
Fitters

Cross sections Calc, MEG

NP Models

Spectrum Calc

- SUSY
  - MSSM
  - mSUGRA
  - GMSB, AMSB
  - NMSSM
  - RPV, CPV,...
- TeXColour
- Extra-dim
- Little Higgs
- $f^\star, V'$
- Black Holes (!)

Event Generators

Flavour Calc

Dark Matter

Decay Codes

Fitters

Cross sections Calc, MEG

NP Models

- SUSY

  MSSM

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  GMSB, AMSB

  NMSSM

  RPV, CPV,...
- TeXColour
- Extra-dim
- Little Higgs
- $f^\star, V'$
- Black Holes (!)

Spectrum Calc

- FeynHiggs
- NMHDECAY⋆
- CPSuperH
- RGE Codes

  Isasusy

  SoftSusy

  Spheno

  Suspect

Event Generators

Flavour Calc

Dark Matter

Decay Codes

Fitters

NP Models

- SUSY
  - MSSM
  - mSUGRA
  - GMSB, AMSB
  - NMSSM
  - RPV, CPV,...
- TeXColour
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Spectrum Calc

- FeynHiggs
- NMHDECAY$\star$
- CPSuperH
- RGE Codes
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  - Spheno
  - Suspect

Cross sections Calc, MEG

Flavour Calc

- $(g-2)_\mu$
- $b \to s\gamma$
- $B_s \to \mu^+\mu^-$
- Asym, $\Delta M, \cdots$

Dark Matter

Event Generators

Decay Codes

Fitters

NP Models

- SUSY
  - MSSM
  - mSUGRA
  - GMSB, AMSB
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  - RPV, CPV,...
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Spectrum Calc

- FeynHiggs
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- RGE Codes
  - Isasusy
  - SoftSusy
  - Spheno
  - Suspect

Flavour Calc

Dedicated Codes

- SusyBSG
- SuperIso

Dark Matter

Cross sections Calc, MEG

- Tree-level,any
  - CalcHEP, CompHEP
  - GRACE, FORMCalc
  - Madgraph
  - SHERPA/Amegic++
  - Whizard/O'Mega
- 1-loop dedicated
  - AF's SLEPTONS
  - Prospino, hprod
- 1-loop/General
  - GRACE-SUSY
  - FormCalc,SloopS

Event Generators

Decay Codes

Fitters

NP Models

- SUSY

  MSSM

  mSUGRA

  GMSB, AMSB

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Spectrum Calc

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Flavour Calc

Dark Matter

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  FormCalc,SloopS

Event Generators

Fitters

Decay Codes

- BRIDGE
- HDECAY
- NMHDECAY$\star$
- SDECAY

NP Models

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Spectrum Calc

- FeynHiggs
- NMHDECAY⋆
- CPSuperH
- RGE Codes
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  - SoftSusy
  - Spheno
  - Suspect

Flavour Calc

Dark Matter

- IsaRED/RES
- micrOMEGAs
  - SloopS⋆
- DARKSUSY

Cross sections Calc, MEG

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Event Generators

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Decay Codes

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Event Generators

- Isajet
- Herwig++
- Pythia
- Sherpa

Fitters

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- Fittino
- SFitter
- SuperBayes

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Black Holes

CatFish, Charybdis, TrueNoir

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$\mathcal{L}$

Feynman rules

(Eff. Pot.)

Spectrum Calc

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$\mathcal{L}$

manual

Feynman rules

(Eff. Pot.)

Spectrum Calc

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manual

Cross sections Calc, MEG

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$\mathcal{L}$

LanHEP/FeynRules

Feynman rules

(Eff. Pot.)

Spectrum Calc

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automated

Flavour Calc

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Feynman rules

(Eff. Pot.)

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$\mathcal{L}$

Feynman rules

(Eff. Pot.)

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Flavour Calc

Dark Matter

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Cross sections Calc, MEG

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$\mathcal{L}$

Feynman rules

(Eff. Pot.)

Spectrum Calc

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Flavour Calc

Dark Matter

- IsaRED/RES
- micrOMEGAs
  - SloopS$\star$
- DARKSUSY

Cross sections Calc, MEG

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  - CalcHEP, CompHEP
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  - Prospino, hprod
- 1-loop/General
  - GRACE-SUSY
  - FormCalc,SloopS

Decay Codes

- BRIDGE
- HDECAY
- NMHDECAY$\star$
- SDECAY

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Black Holes

CatFish, Charybdis, TrueNoir

Cross talks

NP Models

- SUSY
  - MSSM
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- Extra-dim
- Little Higgs
- $f^\star, V'$
- Black Holes (!)

$\mathcal{L}$

Feynman rules

SLHA,BSM-LHEF

Spectrum Calc

- `FeynHiggs`
- `NMHDECAY⋆`
- `CPSuperH`
- RGE Codes
  `Isasusy`
  `SoftSusy`
  `Spheno`
  `Suspect`

Flavour Calc

Dark Matter

- `IsaRED/RES`
- `micrOMEGAs`
  `SloopS⋆`

Cross sections Calc, MEG

- Tree-level,any
  `CalcHEP, CompHEP`
  `GRACE, FORMCalc`
  `Madgraph`
  `SHERPA/Amegic++`
  `Whizard/O'Mega`
- 1-loop dedicated
  `AF's SLEPTONS`
  `Prospino, hprod`
- 1-loop/General
  `GRACE-SUSY`
  `FormCalc,SloopS`

Decay Codes

- `BRIDGE`
- `HDECAY`
- `NMHDECAY⋆`
- `SDECAY`

Event Generators

- `Isajet`
- `Herwig++`
- `Pythia`
- `Sherpa`

Fitters

- `Fittino`
- `SFitter`
- `SuperBayes`

Black Holes

CatFish, Charybdis, TrueNoir

SLHA 1 and 2

SLHA (1): MSSM, SLHA2 (CPV,RPV,NMSSM) Most of the authors have adopted it

- Signs (μ,..), factors of $\sqrt{2}$
- Mixing angles conventions
- Eigenstates decomposition
- Renormalisation schemes/scales !!!
- Effective field content (sparticles integrated out or not)
- SLHA2 more of a headache, but we got there eventually

BSM LHEF

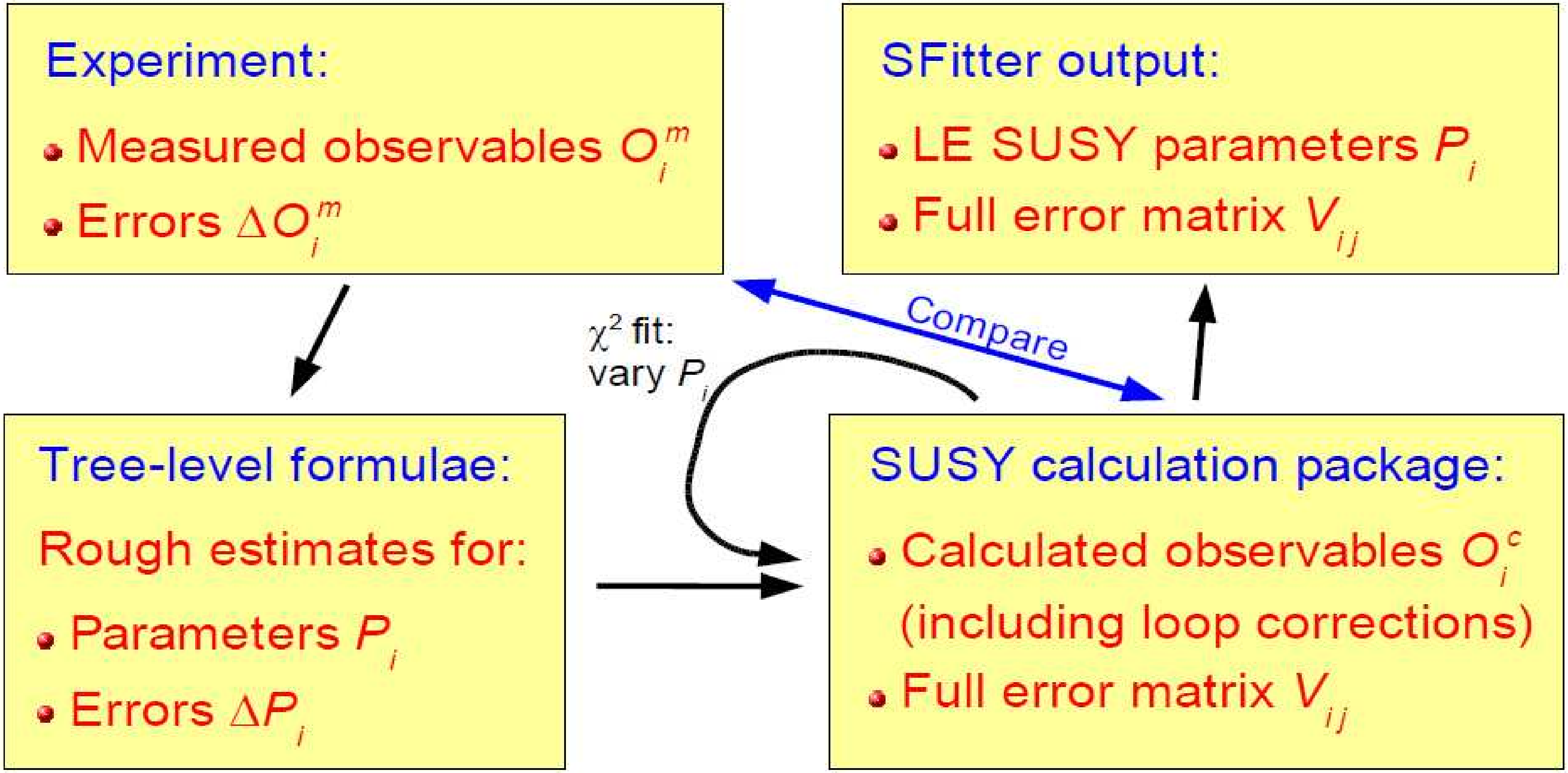
This is a mix of

- SLHA2 and (model parameters)

  introduce new SLHA like blocks QNUMBERS for each BSM particle containing PDG code, spin, elec. charge, colour rep., particle/antiparticle

- and LHEF2 (xml format) for event files

Codes for Fit"s: Fittino, SFITTER



tree-level vs "1-loop level"

- I have not said much about MC at NLO
- Essential for normalisation
- Intense activity these last few years in NLO multi-leg
- many new techniques
- plans for $2 \to 3, 4$ and benchmark cross sections

Yuri Dokhsitzer: "virtual SUSY is helping QCD (*twistor techniques!)*, QCD will pay back discovering *"real"* SUSY

BSM Tools Repository

- http://www.ippp.dur.ac.uk/montecarlo/BSM

  Please submit your code or get a code from there

  otherwise google the codes I have described

  for SUSY, see recent review by Ben Allanach (arxiV:0805.2088[hep-ph]

  If you contribute a code make it SLHA/LHEF compliant, if SLHA exists for the model please give a description of the code: what physics there is inside not just how to run it!!

  at the moment 37 BSM tools listed so far...

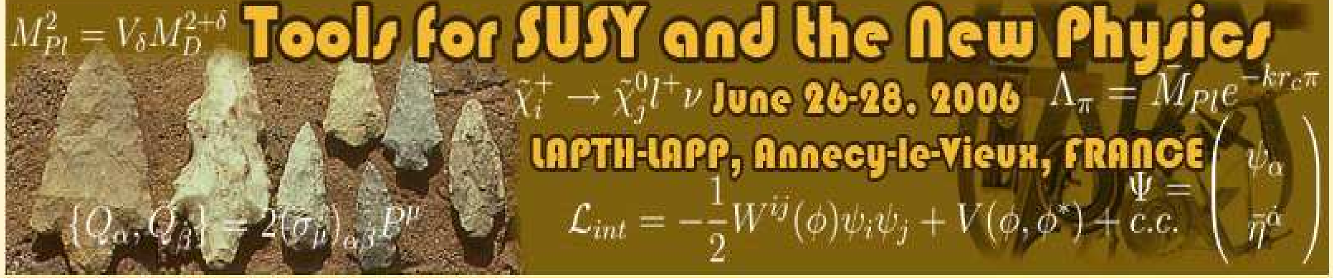
- other repositories, e.g. http://mcelrath.org/Notes/Software (see also open directory project)
- old tools for susy, GDR Outils

  http://wwwlapp.in2p3.fr/gdr-outils/GDRoutils/outilsp1.html

- For codes that do the same things (or supposed to do the same thing)
  Comparison page like what is done with RGE (see Sabine Kraml's page)

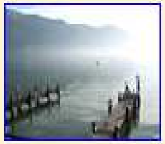
Organise round-tables involving model builders, calculation theorists, experimentalists

- More work on New Physics which is not SUSY
- for some SUSY models, probably need "background tools": contact with SM/QCD tools
- experimentalists need to speak up and ask what is needed most urgently : priority list (similar to what has been done for SM in Les Houches)
- how should codes be interfaced and written: modules, C++, SLHA,LHEF
- go to the Monte Carlo Schools and or the SUSY tools



Welcome | Registration | Program | Participants | Accomodation | Committee

TOOLS 2006



Tools for Susy and the New Physics
June 26-28, 2006 LAPTH-LAPP, Annecy-le-Vieux, France

The aim of the Workshop is to review the main calculational tools, including generators and Monte-Carlos, for the beyond standard model particle searches at present and future colliders as well as in non collider physics experiments such as dark matter searches. Apart from the talks, discussion sessions are planned. In these round tables we expect to discuss how the existing programs could be improved, how to incorporate different existing constraints, how to best present future data and how modules from different codes could sewn together and interchanged.

Tools for SUSY : 1998 - 1999 - 2000

Secretariat

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Secretary : Turc-Poencier Dominique Tel : +33 4 50 09 16 84

Progress/Conclusions

- A lot of progress and a lot of tools
- more and more on modularity and exchange of modules
- much easier now to contribute a new model
- Flexibility is the key
  [-] Need to be ready to implement a model quickly
  [-] Check output with different ME Calc./MC/MG
- This is now possible, while earlier even parameters of simple models hard wired, model implementation needed experts
- Now many tools automatize the different steps and as long as
  [-] particles has spin ≤ 2
  [-] Standard couplings through known Lorentz structures, this preclude higher order operators
  [-] decay chain does not end up in higher order or unusual colour representation

End

That's all folks do go through the notes

and send typos to

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