MONTE CARLO SIMULATION TECHNIQUES

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A Brief Outline

* What is simulation? Monte Carlo?
* Short story of a CERN experiment
* Brief introduction to event generators
* Full simulation of detectors : What can Geant4 do, what does it cover?
* Fast simulation : PGS4 and more
* A few concluding remarks and homework...

Simulation in General

* To simulate: To model, replicate, duplicate the behavior, appearance or properties of. (from wiktionary.org)
  * Simplest/most common simulators in engineering/physics:
    * Put together mathematical models of components => obtain a set of equations => solve equations exactly or through numerical recipes.
  * Consider SPICE (Simulation Program with Integrated Circuit Emphasis) : the indispensable tool of circuit designers since 1973.
    * I-V characteristics of circuit components => differential algebraic equations => solved using Newton's method & sparse matrix techniques, etc.

Horse Simulator - teaches you how not to fall

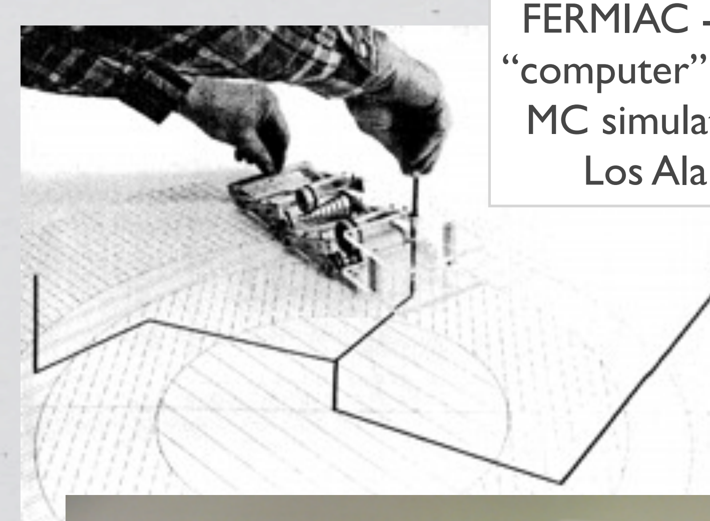
```
Sec.Order High-Pass Filter
Vin 1 0 AC 12V
CF 1 2 3.0uF
Rf 2 3 4.0
Lf 3 0 150uH
.AC DEC 20 10Hz 10MEG
.PROBE
.END
```

SPICE - teaches you how not to burn your components

Monte Carlo Simulation

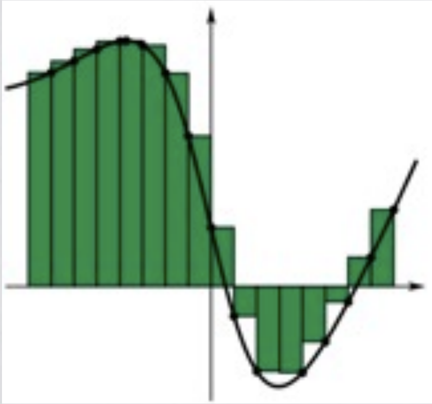
* Monte Carlo simulation:
  * Instead of deterministic solutions, use repeated random samplings to compute results.
  * Name suggested by Nick Metropolis, who was inspired by Stan Ulam's uncle, who would borrow money from relatives to go to Monte Carlo.
  * "Invented" to solve nuclear fission problems in the late 1940s (Fermi, Metropolis, Ulam, von Neumann,...)
    * Start with randomly located neutrons moving in random directions, than move them on the model of the proposed reactor, randomly scattering.
* In particle physics, "simulation" is synonymous with Monte Carlo.

FERMIAC - Analog "computer" used for MC simulations at Los Alamos



http://jackman.stanford.edu/mcmc/metropolis1.pdf

Numerical Integration



(CC)http://en.wikipedia.org/wiki/File:Riemann_sum_convergence.png

- Compute: $I = \int_0^1 f(x)dx$
- Simplest numerical method: $I \approx \sum_{i=1}^{n} \frac{1}{n} f(\frac{i}{n})$
- d-dimensional: $I = \int_{[0,1]^d} f(x_1, x_2, ..., x_d) dx_1 dx_2 ... dx_d$
- We need to evaluate the function $N = n^d$ times. Furthermore, one can show that the "error" will be: $\mathcal{O}(N^{-2/d})$
- Solution: Randomly (uniform pdf) choose N points, $\mathbf{x_i}$, in the d-dimensional space.
  - Then: $I \approx \sum_{i=1}^{N} \frac{1}{N} f(\mathbf{x_i})$
- "Statistical" error scales like, $\frac{1}{\sqrt{N}}$, independent of d.

http://arxiv.org/abs/hep-ph/0006269/

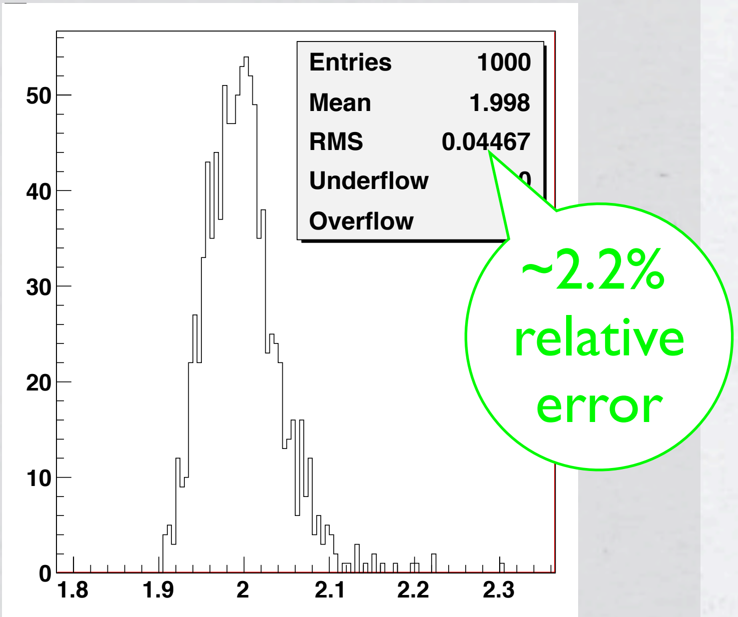
A Simple Example

* Compute : $I = \int_0^1 \frac{dx}{\sqrt{x}}$
* A single "experiment" implemented as a single line in ROOT:

```
root [0] float s=0; int n=10000; for (int i=0; i<n; ++i)
s+=1/sqrt(gRandom->Rndm()); cout << s/n << endl;
2.02832
```

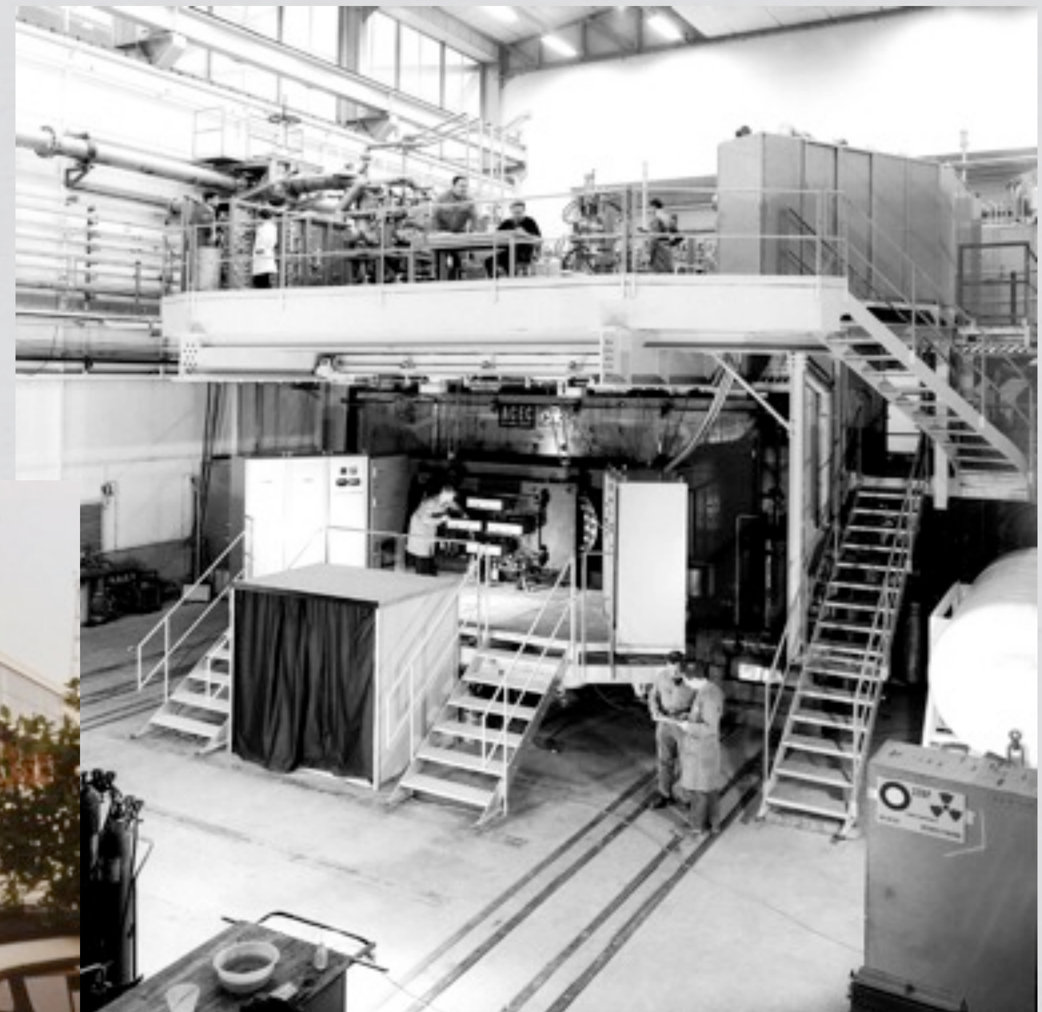
* What is the "error" on our computation?
  * Find using Monte Carlo technique! Perform experiments and see distribution of results.

```
TH1F h("h","h",1000,0,5.);
int nexp = 1000;  // number of experiments
int n=5000;  // number of iterations per experiment

for (unsigned int j=0; j<nexp; j++) {
  float s=0;
  for (int i=0; i<n; ++i) s+=1/sqrt(gRandom->Rndm());
  h.Fill(s/n); }
h.Draw();
```



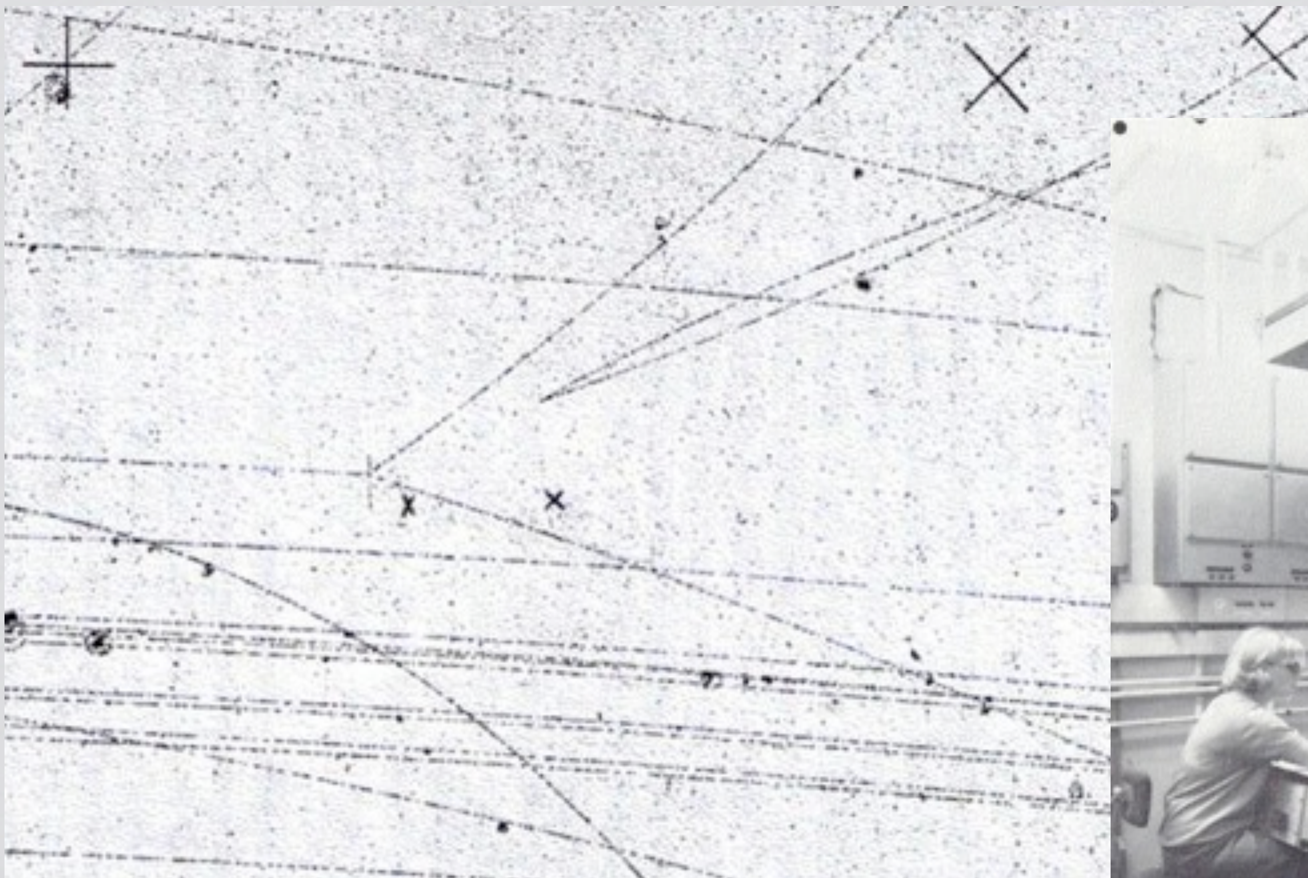
Story of an Experiment @ CERN

- CERN 2m Bubble Chamber
- Source: 4.2 GeV K^- beam
- Ran between 1965-1977

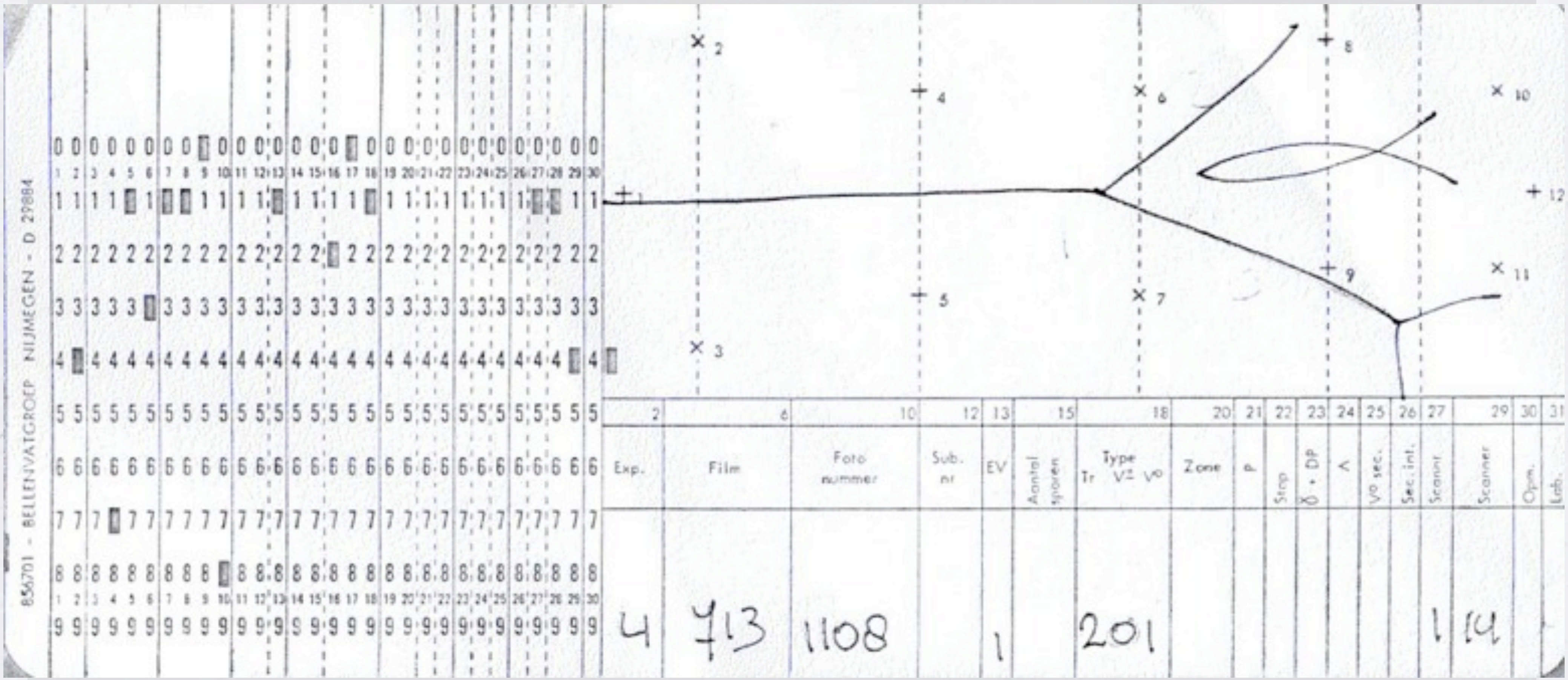


Photos from Henk Tiecke

Press the shutter button, make shots, select interesting ones



Record and digitise the data

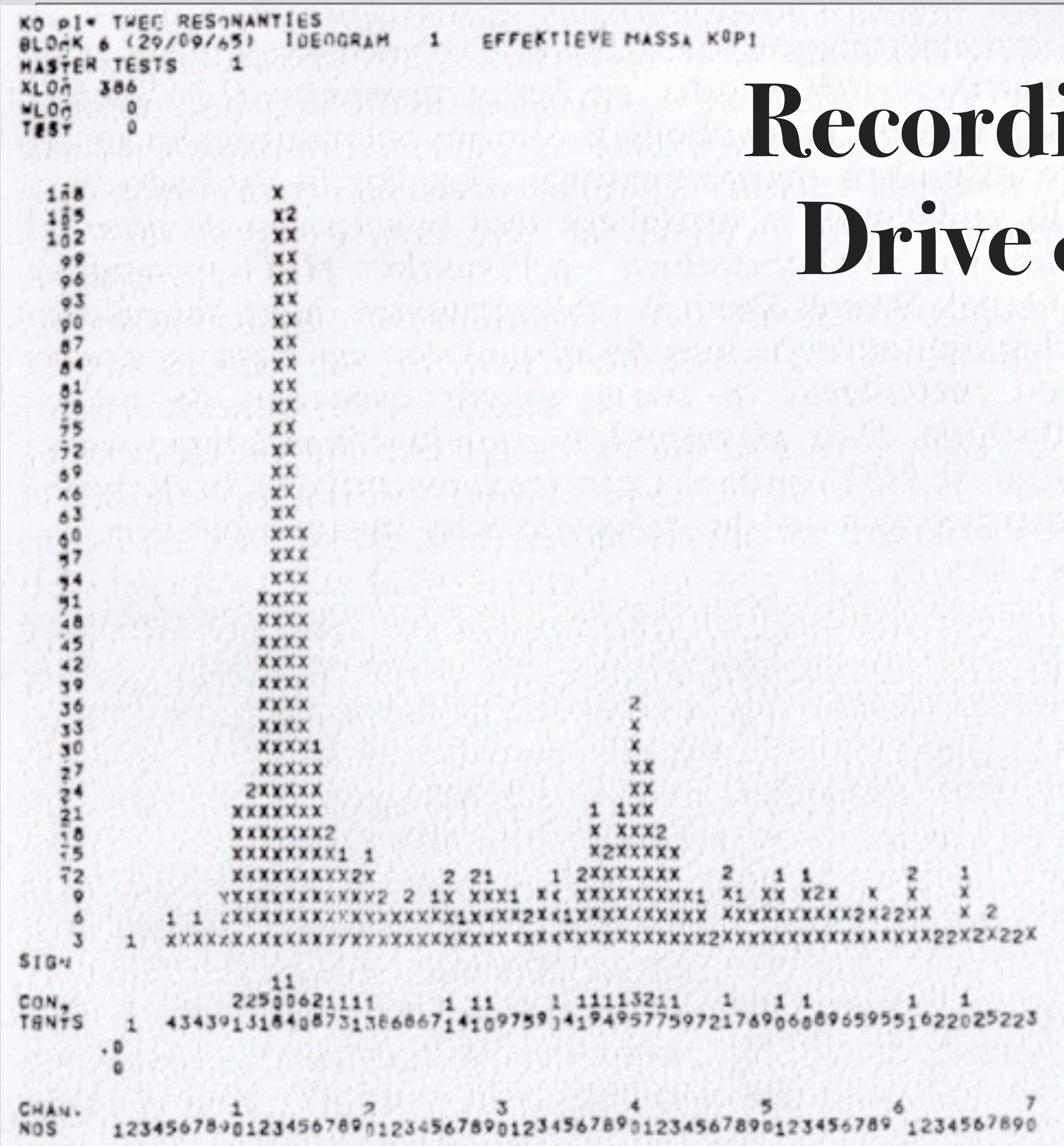


...

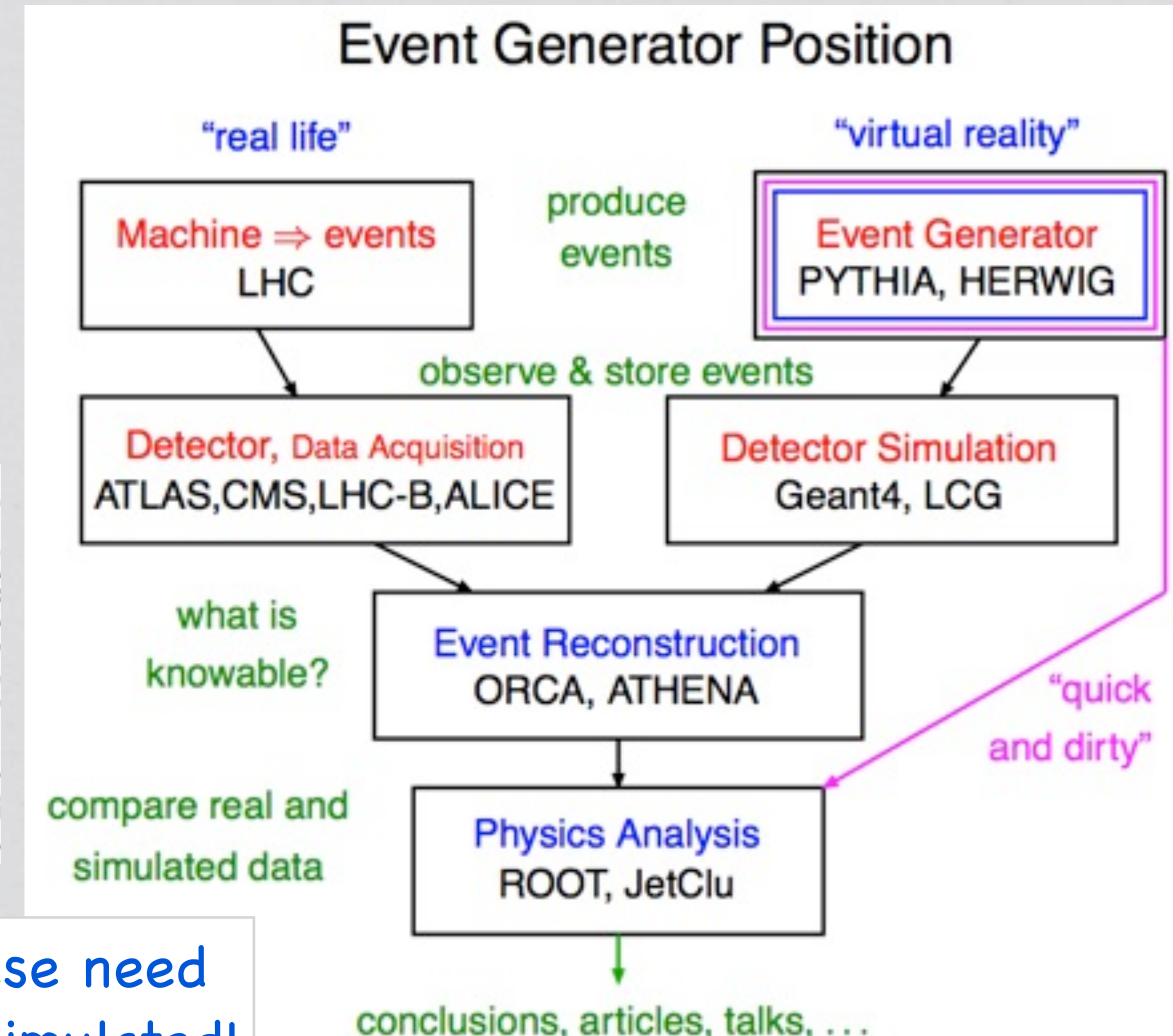
Event Reconstruction

```
EVENT  4- 722-1759-1 BOX  401 (21/11/72  100331)(TAPE       -   1) SERIAL    1 (TITLES   444/   44) (VE

POINTS  NTR NAT GEN    X        Y        Z      DX    DY    DZ          OP 48 TRA 3 AUTL 1 MEAS. 2
   1 A   5   1              2.73   -33.44 0.010 0.011 0.070
   2 M   2   8              1.23   -31.78 0.020 0.012 0.103

TRACK  NATURE  CODE     P    DIP   PHI  THETA     ERRORS    LENGTH  +-  SAGITTA PCOSL  MAG.F   IONIZAT ME
                                                                            RESIDL HIST    MEAS.ION.

  1 A1              WWW  4224    8   3153         67  3  1   -27.57 0.05   1201  4224 -17.25  10 10 10  5
           0.4938   4225    8   3153          67  3  1
  2 A2  -       WWW   274  -217   357   402     1  3  1    40.88 0.05
  3 A3  -       WWW   901   447   290   529     5  1  0    77.36 0.05
           0.1396    911   448   289           13  3  2
           0.4938    912   448   289           15  3  2
  4 A4  +       WWW   313     8    71    62     2  2  1    37.30 0.05
           0.1396    319     9    72            6  6  4
           0.4938    334     9    77           12 10  7
  5 A5  +       WWW   863  -423    93   423     6  2  1    41.91 0.05
           0.1396    868  -422    94           17  3  2
           0.4938    869  -422    94           19  3  2
           0.9383    875  -422    94           25  4  2
  6 M2  +       WWW  1013   301  6153   338     5  1  0    80.82 0.05
           0.1396   1017   300  6153           13  3  2
           0.9383   1028   300  6154           17  4  3
  7 M3  -       WWW   326    30  6074   223     2  2  0    42.62 0.05
           0.1396    333    31  6071            5  7  5
                 MEV/C      MILLI-RAD                     CM

*** R6 CANDIDATE - ERR 100 ETC.A1
*** R6 CANDIDATE - ERR 40  ETC.A2  A4  A5

FIT NOPT 1   NOTR  3     TYPE 5101C     HYP     2   TARG 0.0      ERRORS    NONE  NONE      CHISQ  0.55

TRACK   MASS     CODE    BUB     P U   DIP U  PHI U   DP U  DDP U DPH U     P F   DIP F  PHI F   DP F DDP F
 M0 0  1.1154 U U U F   1.7    1.354 -0.235  2.991  0.0    0.0   0.0     1.354 -0.236  2.992  0.017 0.003
 M2 +  0.9383 W W W F   1.9    1.028  0.300  6.154  0.017 0.004 0.003   1.034  0.300  6.154  0.015 0.004
 M3 -  0.1396 W W W F   1.2    0.333  0.031  6.071  0.005 0.007 0.005   0.330  0.033  6.072  0.003 0.007

FIT NOPT 1   NOTR  6     TYPE  2020     HYP   104   TARG 0.9383  ERRORS    MI 3   NONE      CHISQ -0.00
```

Recording on Hard Drive & Analysis



Summary of the Story

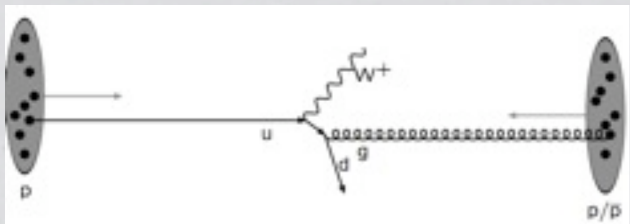


* All these need to be simulated!

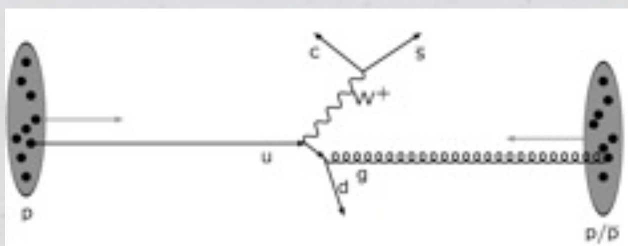
T. Sjostrand, http://indico.cern.ch/getFile.py/access?resId=0&materialId=3&confId=a042790

Step 1 - Event Generation

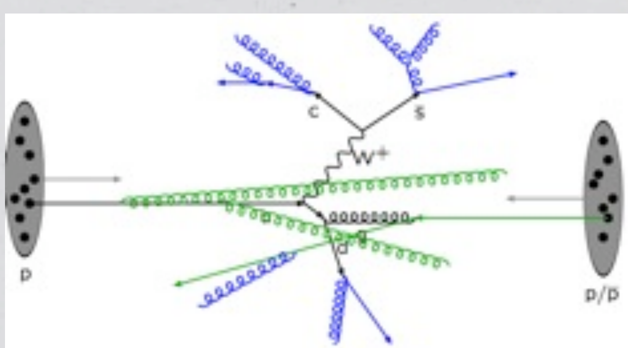
1-partons in incoming beams (PDFs)



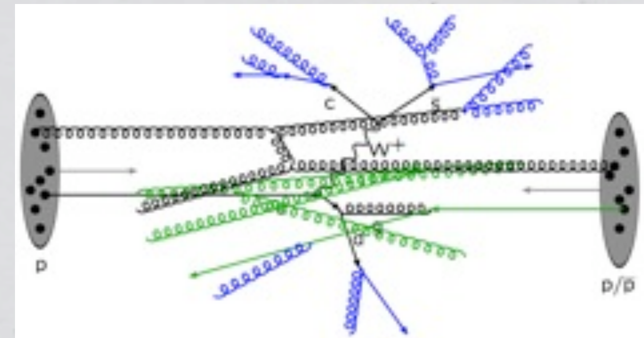
2-hard scatter (matrix elements)



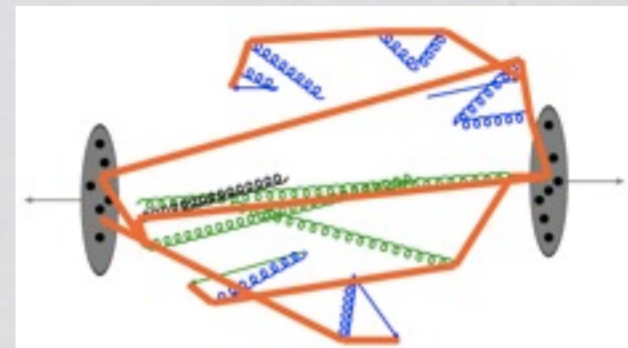
3-resonance decays



4-Initial & Final-state radiation



5-Multiple interactions + ISR/FSR



6-All outgoing partons & beam remnants, color connected

7-Hadronisation, fragmentation & decays of hadrons

Available Event Generation Tools

- Luckily you don't need to do all the steps manually.
  - Most often one does a matrix-element level simulation of the physics process first.
    - Generic ME calculators that can compute any 2->n process (n upto 6-7) at the tree level.
      Examples: CompHEP/CalcHEP, MadGraph, etc.
    - Specialized (only a set of predetermined physics processes) ME simulators - fast tree-level or beyond tree level.
      Examples: MC@NLO, PowHEG, Alpgen, etc., but also Pythia & Herwig.
  - Thanks to the Les Houches Event (LHE) format, the output of the above can be fed into programs that simulate all/most of the "rest".
    - Some common examples are Pythia and Herwig.
    - Occasionally you might need special treatment though.
      Examples: for QED radiative effects PHOTOS, EvtGen for the decays of B-mesons, etc.
  - The names and the variety of functions can sometimes be quite confusing.

Pythia

Pythia6 running on an OLPC XO!

- Pythia does ME, ISR/FSR, multiple interactions, hadronization, fragmentation, ie. everything you want from an event generator.
- But if you need to enter new processes, do higher-order corrections, depend on spin statistics, etc., then better consider interfacing it with outer programs.
  - Important: Parton shower matching. Pythia adds new partons, you need to make sure no duplication happens.

Disclaimer: The main alternative to Pythia is Herwig, for which most of what is in this presentation also apply. The choice of Pythia as the "representative" has been done purely due to historical reasons.

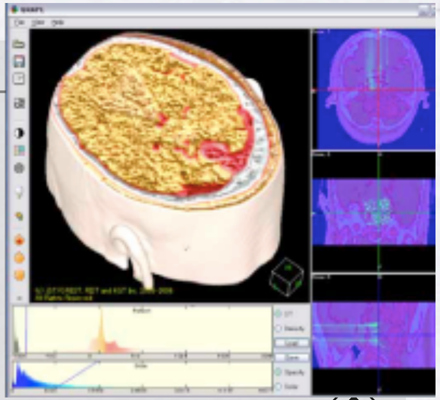
No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi\gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi\gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g\gamma^*_T \to f_i \bar{f}_i$
136	$g\gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}^*_\ell$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

Available processes in Pythia6.

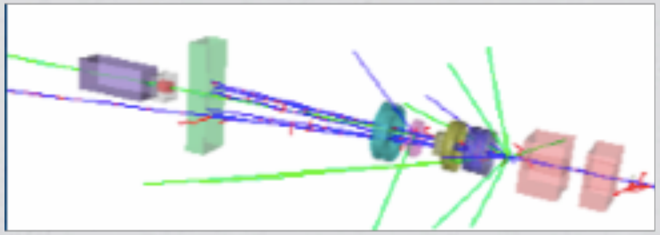
Step 2 - Detector Simulation

- Geometry of the system
- Materials used
- Particles of interest
- Generation of test events or particles
- Interactions of particles with matter and EM fields
- Response to detectors
- Records of events and tracks
- Visualisation of the system and the tracks
- Analysis of the full simulation at whatever detail you like

Geant4



* Stands for "Geometry and Tracking"
  * Don't let the name confuse you: Event reconstruction (including the tracking of charged particles) has nothing to do with Geant.
* Earlier versions developed at CERN with Fortran, now it is being written in C++ by an international collaboration, aptly called Geant4.
* It is the standard in modern HEP experiments, but its penetration to other fields is also on the rise.
  * Some experiments using Geant4: ATLAS, CMS, LHCb, BaBar, Borexino, MINOS, ...
  * Space science, biomedical search, etc.



How does G4 work?

- Define the initial particles and place them (use the interface to an event generator, or place a radioactive source or a particle gun)
- Within the defined volume, move all the particles in small steps.
  - Define the step size according to the cross-sections of the relevant processes and the dimensions of the used materials.
  - At each step engage the processes: Generate new particles, absorb or create new particles, etc.
  - Loop until no particles are left within a predefined volume.

Processes in GEANT

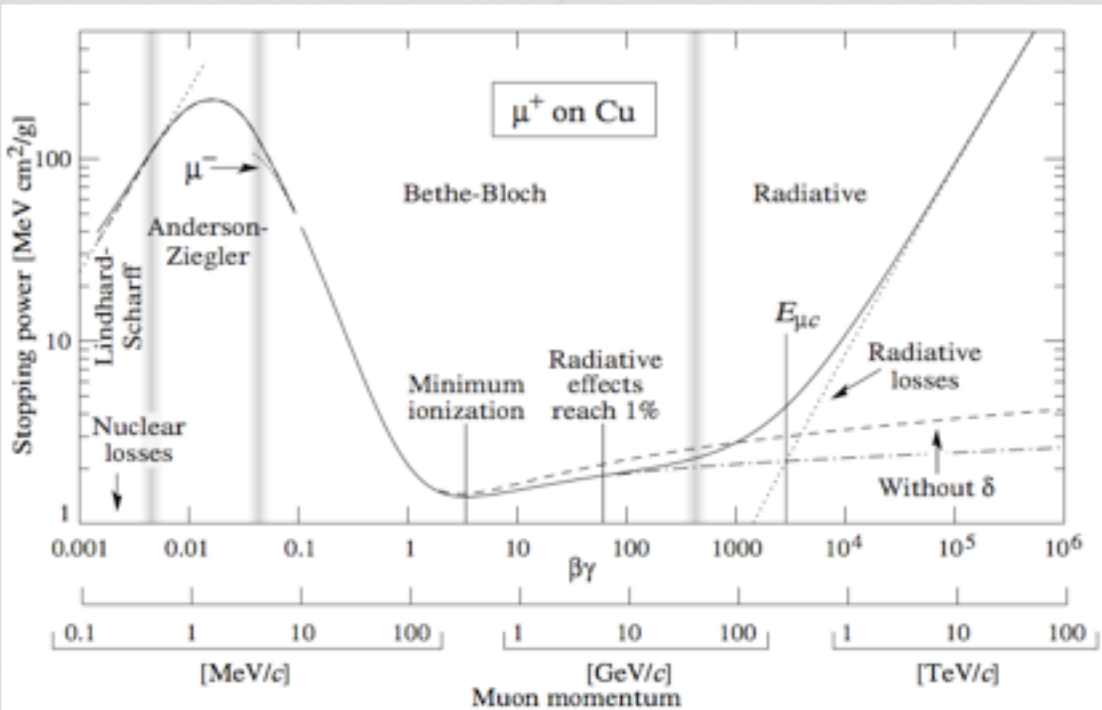
* Photons: Photoelectric effect, Compton & Rayleigh scattering, electron/muon pair production.
* Electrons: e-ionisation/energy loss (Moller, Bhabha scatterings, Berger-Stelzer dE/dx etc.), bremsstrahlung, e+e- annihilation, syncrotron radiation.
* Muons: μ ionisation/energy loss, bremsstrahlung, e+e- pair production.
* Hadrons/ions: ionisation/energy loss
* Multiple scattering, transition radiation, scintillation, Čerenkov radiation, delta rays...

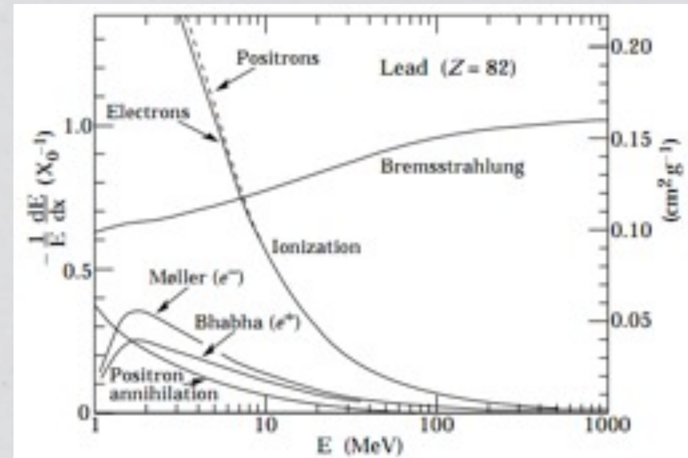
* This is just the list for EM interactions!
  * Hadronic interactions
  * Particle decays
  * Optical processes ($\lambda_{photon} \gg d_{atom\text{-}atom}$)
* Know what is relevant to your energy-scale!

http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/ForApplicationDeveloper/html/TrackingAndPhysics/physicsProcess.html

http://geant4.web.cern.ch/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html

Interaction of Particles with Matter





K. Nakamura et al.,
JPG 37, 075021 (2010)

http://pdg.lbl.gov/2010/reviews/rpp2010-rev-passage-particles-matter.pdf

- What do we mean by the "**relevant energy scale**"?
- Answer: Read the "Passage of Particles Through Matter" in the Particle Physics Booklet!
  - Actually, while at it, read the rest of the PDG too – excellent bedtime book!

After Geant

- After we get the response of the active detector elements to our particles, we are still not done:
  - Consider a scintillator. After the "creation" of the photons due to our muon, we need to:
    - carry the photons through a light guide
    - convert them into electrical charges with a PMT
    - convert the charges (analog data) into digital data
  - All these steps need to be simulated as well. They will need the characteristics of your devices, ie. the dark currents and the quantum efficiency of the PMTs, response times of the components, etc.
- And of course, we need to reconstruct the event and do the analysis!

Quick and Dirty Way

* Geant is extremely detailed, but also extremely slow.
  * For an LHC detector, simulation of a single hadronic tt event takes up to 20 minutes!, and depending on the analysis we need millions/billions of events.
  * Theorists come up with many models and do not have the detailed detector descriptions and reconstruction algorithms of the experimentalists.
* Solution: Fast simulation (as opposed to Geant "full" simulation)
  * Can parameterize the slowest parts of Geant simulation (like the calorimeter response) and use Geant on the rest of the simulation.
  * Parameterize the whole response of the detector/reconstruction etc.
    * Examples: AcerDet, ATLFast, FAMOS, PGS, Delphes...

PGS4

- Started life in 1998 (under the name SHW) during the Tevatron Run2 SUSY/Higgs Workshop. Being maintained by: John Conway (UC Davis).
  - Not only for Tevatron dedectors - it can be parameterized for any generic cylindrical HEP detector.
  - Latest version PGS4 - 090401.
  - Simple, fast, quite standard for feasibility studies. Fits the meaning of its name: "pretty good simulator".

http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.htm

PGS Source Code

* Written with Fortran, compileable with g77 or gfortran, only dependence is the STDHEP library.
* Kernel library : Essentially all the functionality of PGS is in a library, as individual fortran functions.
* Driver code : Calls the library functions one by one. Once the process is complete, it can also call some analysis code written by the enduser.
    * The driver that comes with Madgraph (pythia-pgs_V2.1.5.tar.gz) has been prepared for the LHC Olympics, and can nowadays be considered "the standard". It applies the minimum cuts of the detector trigger and provides output in the LHCO format.

What do we expect from PGS?

Generated event (Pythia, Herwig, etc.)

↓

Particles in STDHEP format

→

PGS

- Detector acceptance
- Detector efficiency
- Mom./energy resolution
- Reconstruction of jets/objects

→

"Measured" event in LHCO format

↓

Data analysis (ROOT etc.)

So how does PGS work?

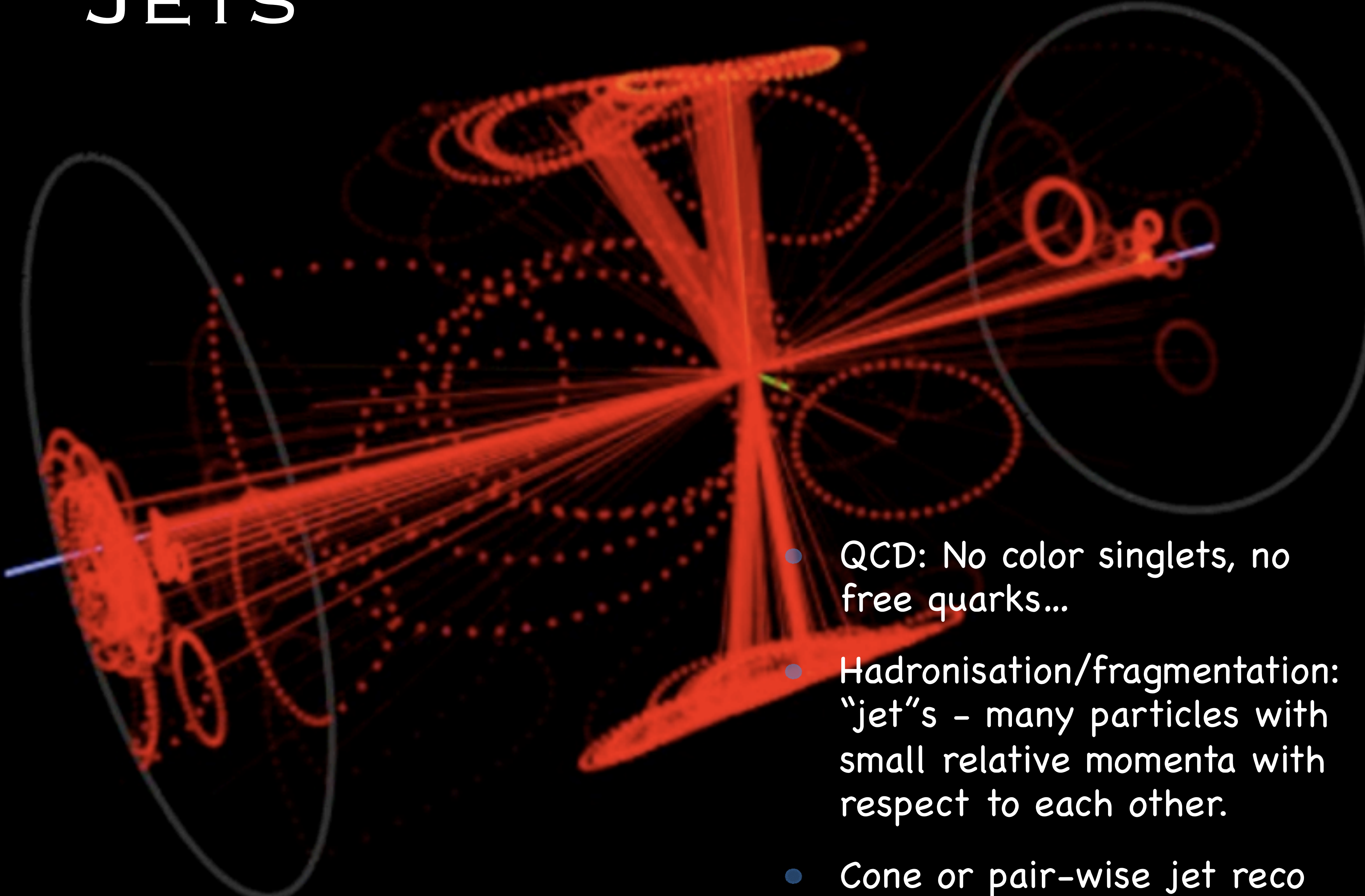
- Process all final state particles if they are within the acceptance of the detector components:
  - If charged particle, put a straight track (no bending in the B-field), but take the track sagitta resolution into account.
  - Calorimeters segmented in η & Φ. Find which segment each particle is pointing to and deposit its energy into that segment.
    - electrons/photons: almost all energy to EM calorimeter.
    - hadrons: most energy to hadronic calorimeter.
    - muons: minimum ionisation.
    - Energy resolutions:

Warning! This is not such a good model for the LHC detectors!

$$\Delta E^{em}/E^{em} = a \oplus b/\sqrt{E^{em}} \qquad \Delta E^{had}/E^{had} = b/\sqrt{E^{had}}$$

What do these formulas mean? Read your PDG!

Jets



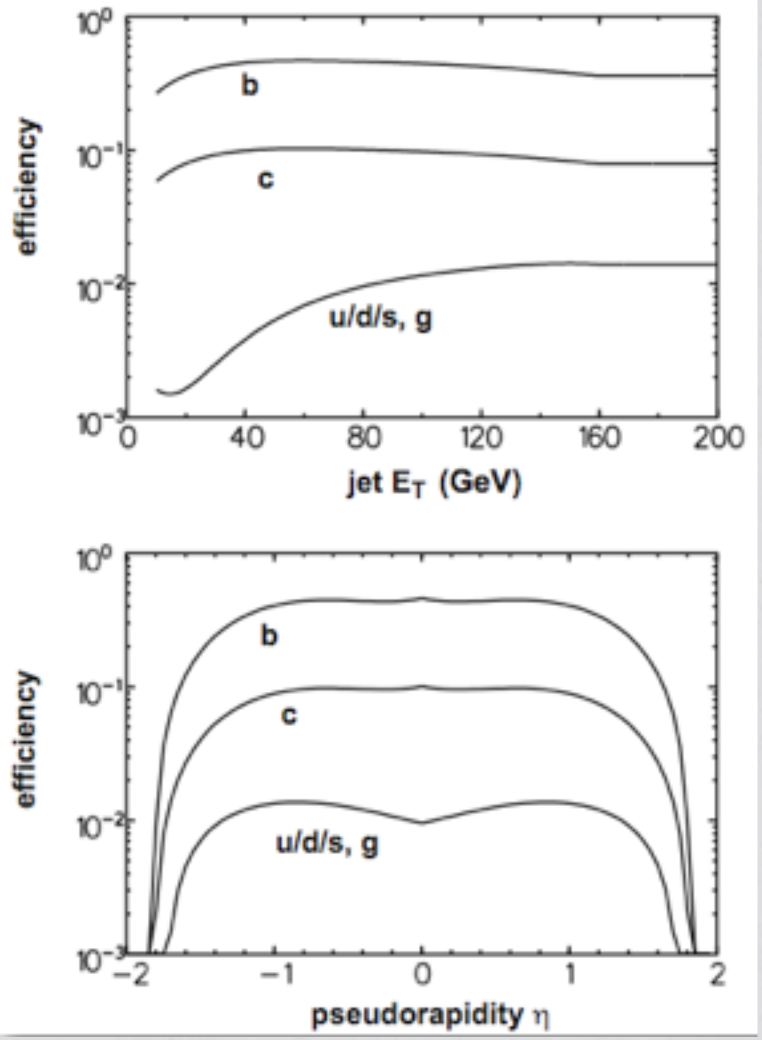
- QCD: No color singlets, no free quarks…
- Hadronisation/fragmentation: "jet"s - many particles with small relative momenta with respect to each other.
- Cone or pair-wise jet reco algorithms.

About Jet Reconstruction

- Cone-based algorithms: Start with the highest-energy calorimeter cell above a minimum energy and draw a cone around it. Add in the energies of the other cells within that cone. Call the sum a jet. Then start over and repeat the procedure with the remaining cells.
- Pairwise combination algorithms (ktjet): Take pairs of cells/subjets. If their transverse momenta with respect to each other is smaller than their transverse momenta with respect to the beam axis by a predetermined factor, merge the pair into a subjet. Repeat this procedure until there are no remaining cells/subjets that can be merged.

Heavy-flavor jets in PGS

- If the partons that initiate jets are c or b quarks, it is possible to "tag" them as such.
- PGS checks where the jet originates, and then does a random tagging whose PDFs are taken from CDF performance, as a function of jet E_T & η.



Warning! This parameterization is pessimistic for the LHC detectors. Moreover, LHC detectors have tracking beyond $|\eta|<2$.

This ATLAS card file comes with Madgraph.

```
ATLAS          ! name of the parameter set
81             ! number of eta cells in the calorimeter
63             ! number of phi cells in the calorimeter
0.1            ! eta width of calorimeter cells  |eta| < 5
0.099733101    ! phi width of calorimeter cells
0.01           ! resolution of EM calorimeter (constant term)
0.1            ! resolution of EM calorimeter (*sqrt(E) term)
0.8            ! resolution of hadronic calorimeter (*sqrt(E) term)
0.2            ! missing ET resolution in the trigger
0.00           ! calorimeter cell edge crack fraction
cone           ! jet finding algorithm (cone veya ktjet)
3.0            ! calorimeter trigger cluster finding seed threshold (GeV)
0.5            ! calorimeter trigger cluster finding shoulder threshold (GeV)
0.70           ! calorimeter kt cluster finder cone size (delta R)
1.0            ! outer radius of the tracking detector (m)
2.0            ! magnetic field strength (Tesla)
0.000005       ! sagitta resolution (m)
0.98           ! track finding efficiency
0.30           ! lowest track PT (GeV)
2.5            ! tracking eta acceptance
3.0            ! electron/photon eta acceptance
2.4            ! muon eta acceptance
2.0            ! tau eta acceptance
```

PGS Input Card

Warning! Hidden Parameters

- Beyond those listed on the input card file, there are many more parameters hardcoded into PGS:
  - A few are in the PGS library file (`pgslib.f`). For example the efficiency of the muon trigger: `muon_trig_eff = 0.98`
  - Others are in the PGS driver file (`pgs.f`). For instance, the minimum trigger momenta in the LHCO driver: `single_lepton_rectrig_threshold=30.0`
  - Occasionally same/similar parameter can appear in both places. For example, in the definition of the muon trigger inside the PGS library file, there is an intrinsic cut on the minimum PT of the muon: ... `et_gen(ihep).ge.3.0` ...

LHCO Format

- PGS's pure-ASCII-type output file format. Prepared initially for the LHC Olympics, but has recently become quite standard.

#	type	eta	phi	pt	jmass	#trk	btag	had/em	dum1	dum2
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00	0.0	0.0
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02	0.0	0.0
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	0.0	0.0
4	4	-0.629	4.998	308.94	85.25	12.0	2.0	0.33	0.0	0.0
5	4	-2.061	1.571	455.01	156.56	32.0	0.0	1.19	0.0	0.0
6	4	-1.954	2.699	24.07	2.38	32.0	0.0	11.60	0.0	0.0
7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	0.0	0.0
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

http://v1.jthaler.net/olympicswiki/doku.php?id=lhc_olympics:data_file_format

LHCO Format

* PGS's pure-ASCII-type output file format. Prepar
for the LHC Olympics, but has recently become q

event number 39; trigger word 1043

#	type	eta	phi	pt	jmass	#trk	btag	had/em		
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00	0.0	0.0
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02	0.0	0.0
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	0.0	0.0
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8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

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LHCO Format

- PGS's pure-ASCII-type output file format. Prepare
  for the LHC Olympics, but has recently become q

0 = photon
26.11 GeV
$\eta = -1.350$
$\varphi = 3.341$

#	type	eta	phi	pt	jmass	#trk	btag	had/em	d	
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00	0.0	0.0
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02	0.0	0.0
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	0.0	0.0
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5	4	-2.061	1.571	455.01	156.56	32.0	0.0	1.19	0.0	0.0
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7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	0.0	0.0
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

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LHCO Format

* PGS's pure-ASCII-type output file format. Prepared i
for the LHC Olympics, but has recently become qu

type = 1
#track = 1
positron
164.4 GeV

#	type	eta	phi	pt	jmass	#trk	btag	had/em	[illegible]	[illegible]
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00	[illegible]	[illegible]
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02	0.0	0.0
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	0.0	0.0
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7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	0.0	0.0
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

http://v1.jthaler.net/olympicswiki/doku.php?id=lhc_olympics:data_file_format

LHCO Format

* PGS's pure-ASCII-type output file format. Prepared initially for the LHC Olympics, but has recently become quit

μ⁻
close to jet #4;
95GeV energy
deposited
around it

#	type	eta	phi	pt	jmass	#trk	btag	had/em		
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00	[illegible]	[illegible]
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02	[illegible]	[illegible]
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	0.0	0.0
4	4	-0.629	4.998	308.94	85.25	12.0	2.0	0.33	0.0	0.0
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7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	0.0	0.0
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

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8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

> b-tagged jet
> of mass
> 85.25 GeV
> "has" 12 tracks

http://v1.jthaler.net/olympicswiki/doku.php?id=lhc_olympics:data_file_format

LHCO Format

- PGS's pure-ASCII-type output file format. Prepared initially for the LHC Olympics, but has recently become quite standard.

#	type	eta	phi	pt	jmass	#trk	btag	had/em	du	
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00		
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02		
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99		
4	4	-0.629	4.998	308.94	85.25	12.0	2.0	0.33		
5	4	-2.061	1.571	455.01	156.56	32.0	0.0	1.19	0.0	0.0
6	4	-1.954	2.699	24.07	2.38	32.0	0.0	11.60	0.0	0.0
7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	0.0	0.0
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

3 jets. Note that $e^{Hadronic} > e^{EM}$

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LHCO Format

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#	type	eta	phi	pt	jmass	#trk	btag	had/em	dum1	dum2
0		39	1043							
1	0	-1.350	3.341	26.11	0.00	0.0	0.0	0.00	0.0	[illegible]
2	1	-0.663	5.233	164.40	0.00	1.0	0.0	0.02	0	[illegible]
3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	[illegible]	[illegible]
4	4	-0.629	4.998	308.94	85.25	12.0	2.0	0.33	[illegible]	[illegible]
5	4	-2.061	1.571	455.01	156.56	32.0	0.0	1.19	[illegible]	[illegible]
6	4	-1.954	2.699	24.07	2.38	32.0	0.0	11.60	[illegible]	[illegible]
7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	.0	[illegible]
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

missing transverse energy
p_x=−27 GeV
p_y=−11 GeV

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LHCO Format

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3	2	-0.589	4.675	147.62	0.11	-1.0	4.0	95.99	0.0	0.0
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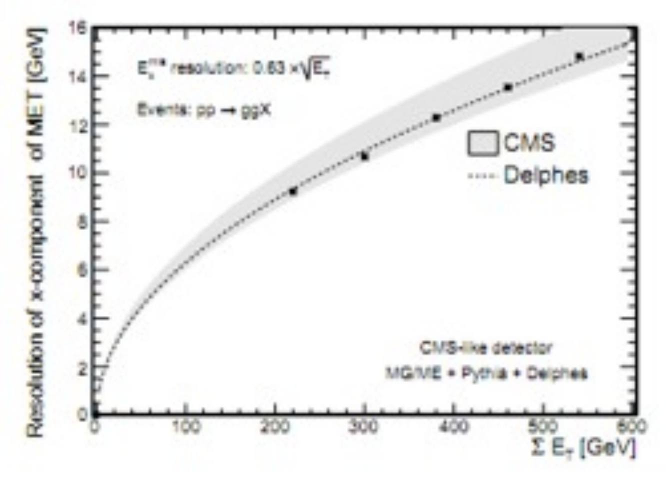
5	4	-2.061	1.571	455.01	156.56	32.0	0.0	1.19	0.0	0.0
6	4	-1.954	2.699	24.07	2.38	32.0	0.0	11.60	0.0	0.0
7	4	1.149	5.756	6.23	1.93	2.0	0.0	3.73	0.0	0.0
8	6	0.000	3.521	28.86	0.00	0.0	0.0	0.00	0.0	0.0

http://v1.jthaler.net/olympicswiki/doku.php?id=lhc_olympics:data_file_format

New Kid on the Block - Delphes

- **Delphes** is a new generic fast simulation package developed by S. Ovyn, X. Rouby, V. Lemaitre (UC Louvain), written in C++.
- Some extra features beyond PGS:
  - Separate treatment of barrel, endcap and forward calorimeters.
  - Calorimeter energy resolution has noise term (1/E).
  - Bending of charged particles in the B-field.
  - SISCone, Cambridge/Aachen, anti-kT jet algorithms.
  - Optional energy-flow algorithm to improve resolutions.
  - Zero-degree calorimeters, roman pots.
  - Smart tau reconstruction model.



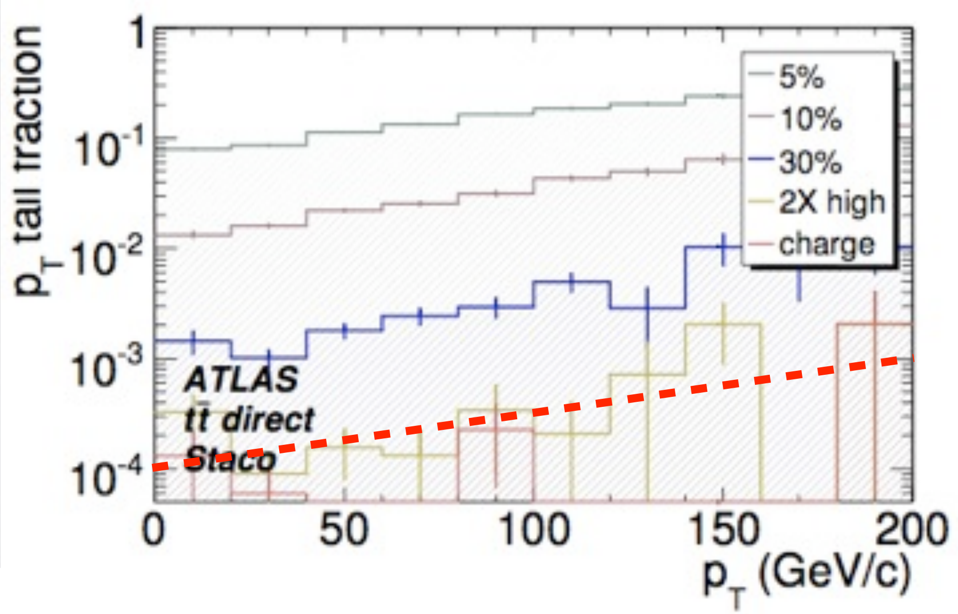
- Default parameterizations well tested against expected response of ATLAS & CMS.
- What is the catch? Very recent, prepare to fight with possible bugs!

http://arxiv.org/abs/0903.2225v3

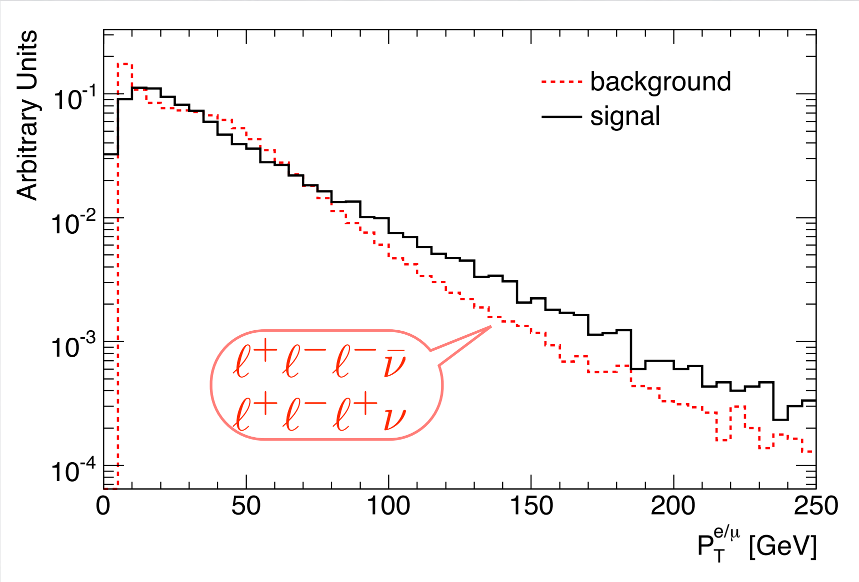
Doing your own…

- Neither PGS nor Delphes simulates charge mis-identification for leptons.
- If you have a special signal, like some supersymmetric particle or heavy Majorana leptons, etc., the distinguishing feature of your signal can be 2 or 3 same-sign e/μ. How do you estimate the background from SM lll+ν process with one of leptons being mis-measured?
  - Go to published performance of the detector you are interested in.
  - Find the part relevant to you, ie. some sort of plot or number that shows what is the charge mis-measurement rate. Parameterize the plot by extracting bin-by-bin numbers or doing a conservative fit.
  - As you loop through your generated MC events, roll a die for each lepton and flip its charge based on the expected rate of mismeasurement as extracted from your parameterization.

3 Leptons in SM



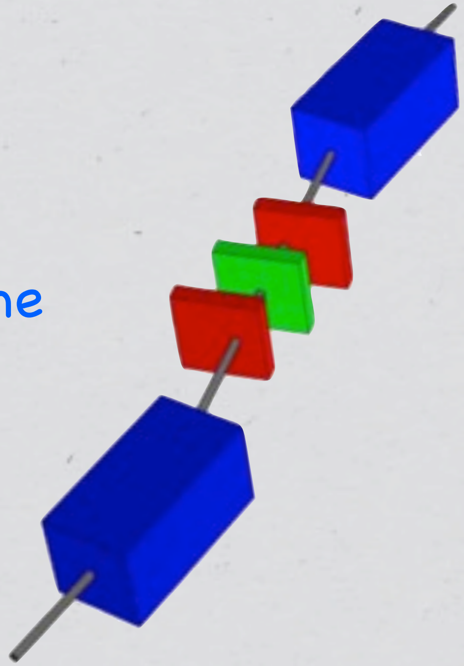
$\Delta P_T/P_T$ outside indicated ranges from **CERN-OPEN-2008-020 (ATLAS)**, for the combined muon algorithm with worse performance. The last tail curve ("charge"), shows charge mis-measurement fraction. In red dashed line, our conservative parameterization.

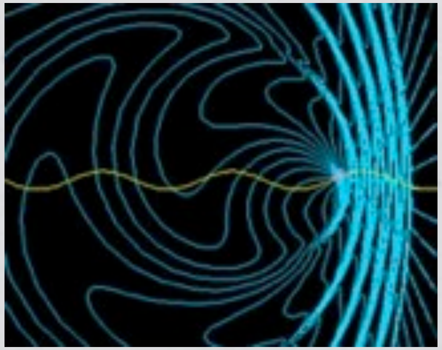


- charge mis-measurement conservatively parameterized: $\varepsilon_{mischarge}\ (P_T) = 10^{-4+PT/200GeV}$
- For each muon, get a random number distributed uniformly in [0,1]. If that number is smaller than $\varepsilon_{mischarge}(P_T{}^{muon})$, flip sign of muon.

Want more?

- We did not talk about simulators that are relevant for studies of future accelerators/detectors.
  - Accelerator Design: madx (from CERN, used in the design of the LHC, for magnet structure, beam transport, etc.) ; parmela (from LANL, for FEL and photoinjector design, beam transport, etc.)
  - Computing beam-beam interactions, brightness, inpurs to event generators: Guinea-PIG, Cain, Calypso, ...
  - For fun and education: Radiation2D (2D EM wave simulation)





Summary

- Monte Carlo Simulation is an indispensable tool in PP.
    - Allows calculation of acceptances, cut efficiencies, background estimations, cross-sections... (Also enables PhD students to graduate when LHC is not running. :-))
- Simulation happens mainly in two steps: Event generators and detector simulation.
    - Detector simulation with Geant4 is amazingly accurate, but very slow.
    - Fast simulation uses parameterization of the detector to smear generator-level quantities.
- Know the limits of your simulation tools.
    - If your simulation package fails to address an important component of the detector response, write your own small MC.

Homework

- Write short programs (possibly as a ROOT macro) to compute the following definite integrals using Monte Carlo methods.

$$\int_0^1 \int_0^1 cos(x+y)\, dxdy \quad \int_{-1}^0 \int_0^1 cos(x+y)\, dxdy \quad \int_{-1}^1 \int_{-1}^1 cos(x+y)\, dxdy$$

- Repeat the computation of the first integral 1000 times and fill a histogram of the values you get. What is the rms value of the distribution?

- Bonus puzzle: Can you identify what physics signal is the event listed on the slide that discussed the LHCO format.

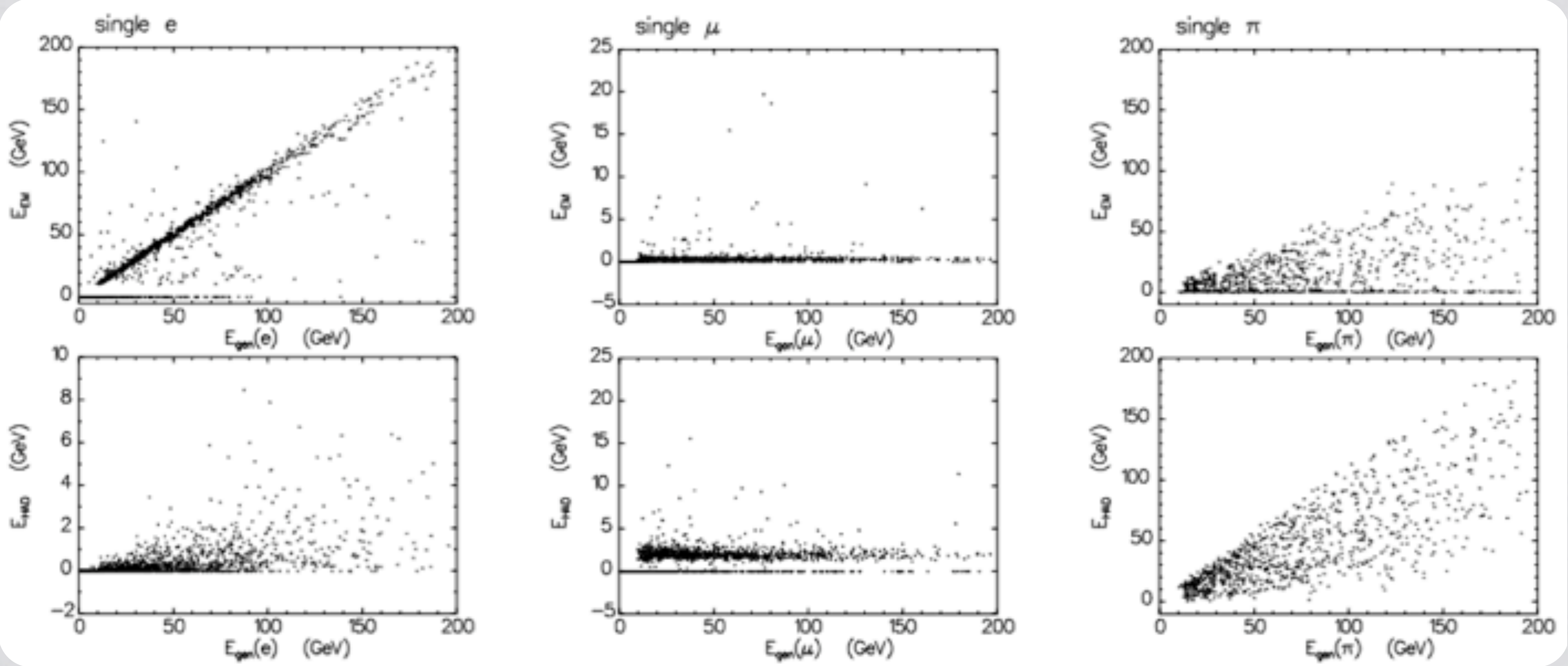
BONUS STUFF

How to use events in StdHep format with PGS or Delphes

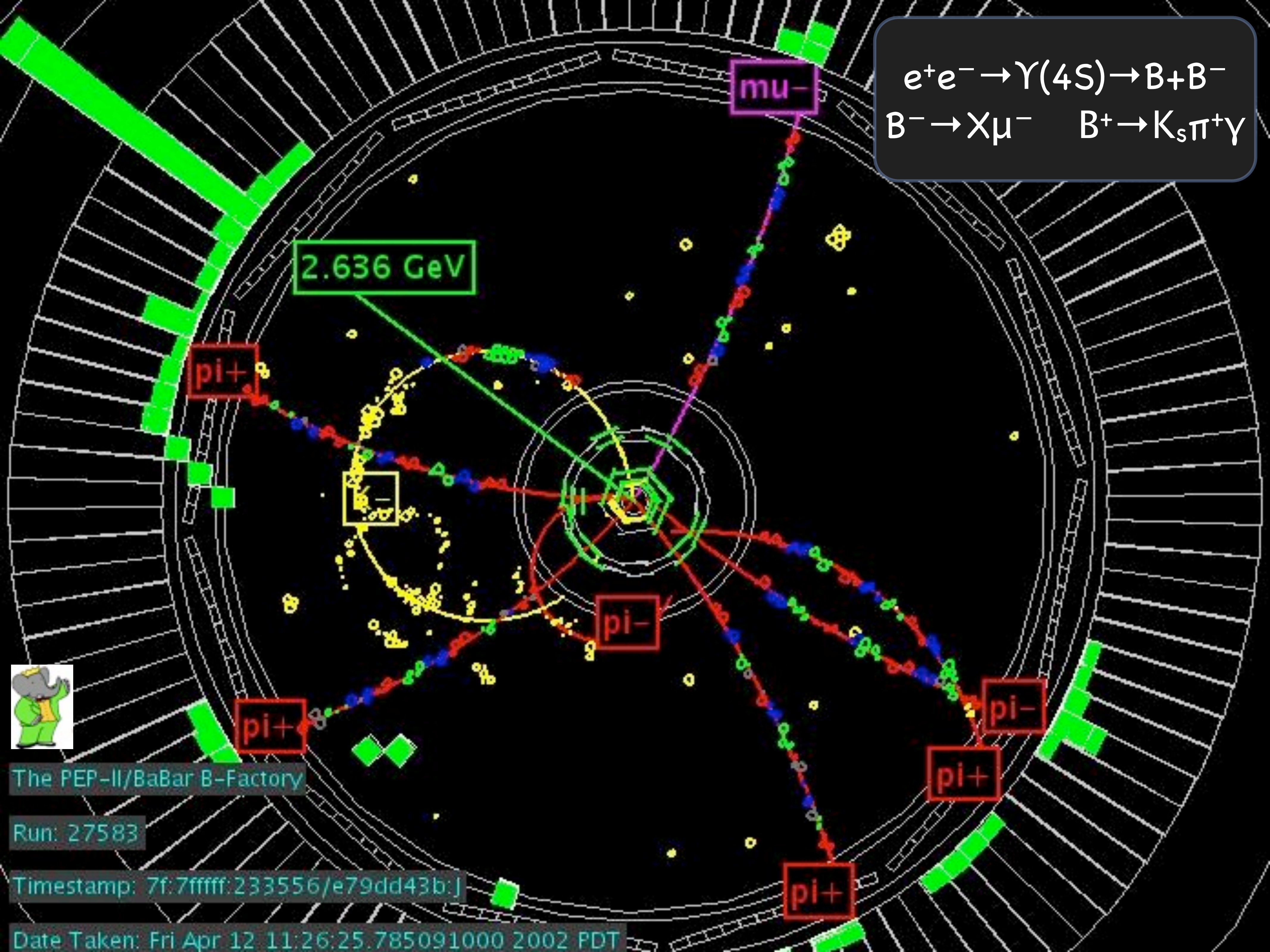
- The easiest way of doing this is using the pythia-pgs and the Delphes packages that are provided as supporting components to Madgraph.
  - Change to the Madgraph install directory.
  - Make a clean copy of the Template directory and change into that copy: `cp -r Template test ; cd test`
  - Prepare your PGS input card, ie. edit the Cards/pgs_card.dat file with your favorite text editor.
  - Move into the Events directory: `cd Events`
  - Copy your Stdhep event file into the current directory and name it as pythia_events.hep: `cp whereeverYourFileIs/eventFileName pythia_events.hep`
  - Run PGS or Delphes: `../bin/run_pgs` or `../bin/run_delphes`
  - To make ROOT files out of them (assuming you have ExRootAnalysis too):

```
../../ExRootAnalysis/ExRootLHCOlympicsConverter
pgs_events.lhco pgs_events.root
```

Models of Electron, Pion and Muon Energy in PGS



http://online.itp.ucsb.edu/online/lhco_c06/conway/


$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-$
$B^- \rightarrow X\mu^-$ $B^+ \rightarrow K_s\pi^+\gamma$
mu-
2.636 GeV
pi+
pi-
pi+
pi-
pi+
pi+
The PEP-II/BaBar B-Factory
Run: 27583
Timestamp: 7f:7fffff:233556/e79dd43b:J
Date Taken: Fri Apr 12 11:26:25.785091000 2002 PDT