Introduction to Monte Carlo for Particle Physics Study

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Credit where credit is due

I collected (stole) most of my slide from

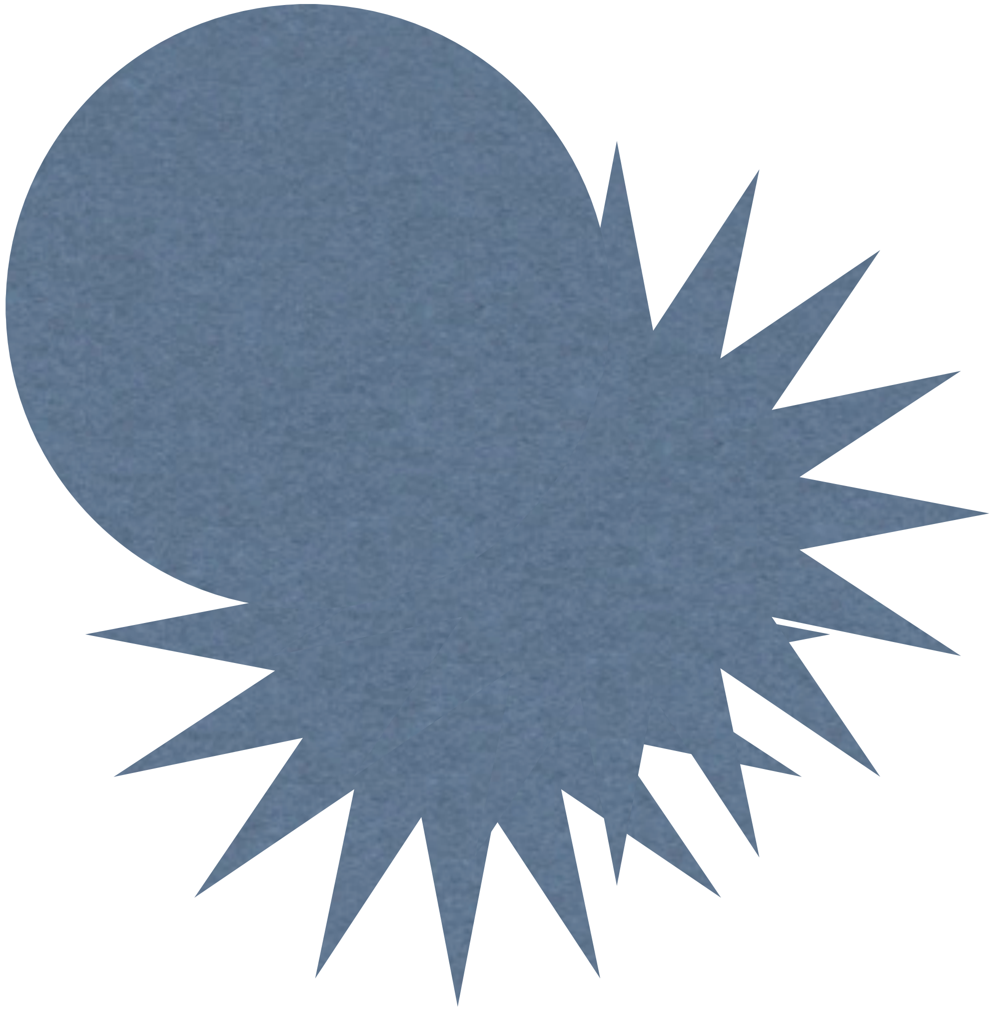
- Tomasz Wlodek (Monte Carlo methods in HEP)
- Concezio Bozzi (Monte Carlo simulation in Particle Physics)
- P. Richardson
- CERN-Fermilab school 2009
- Geant4 school 2009


[redacted]

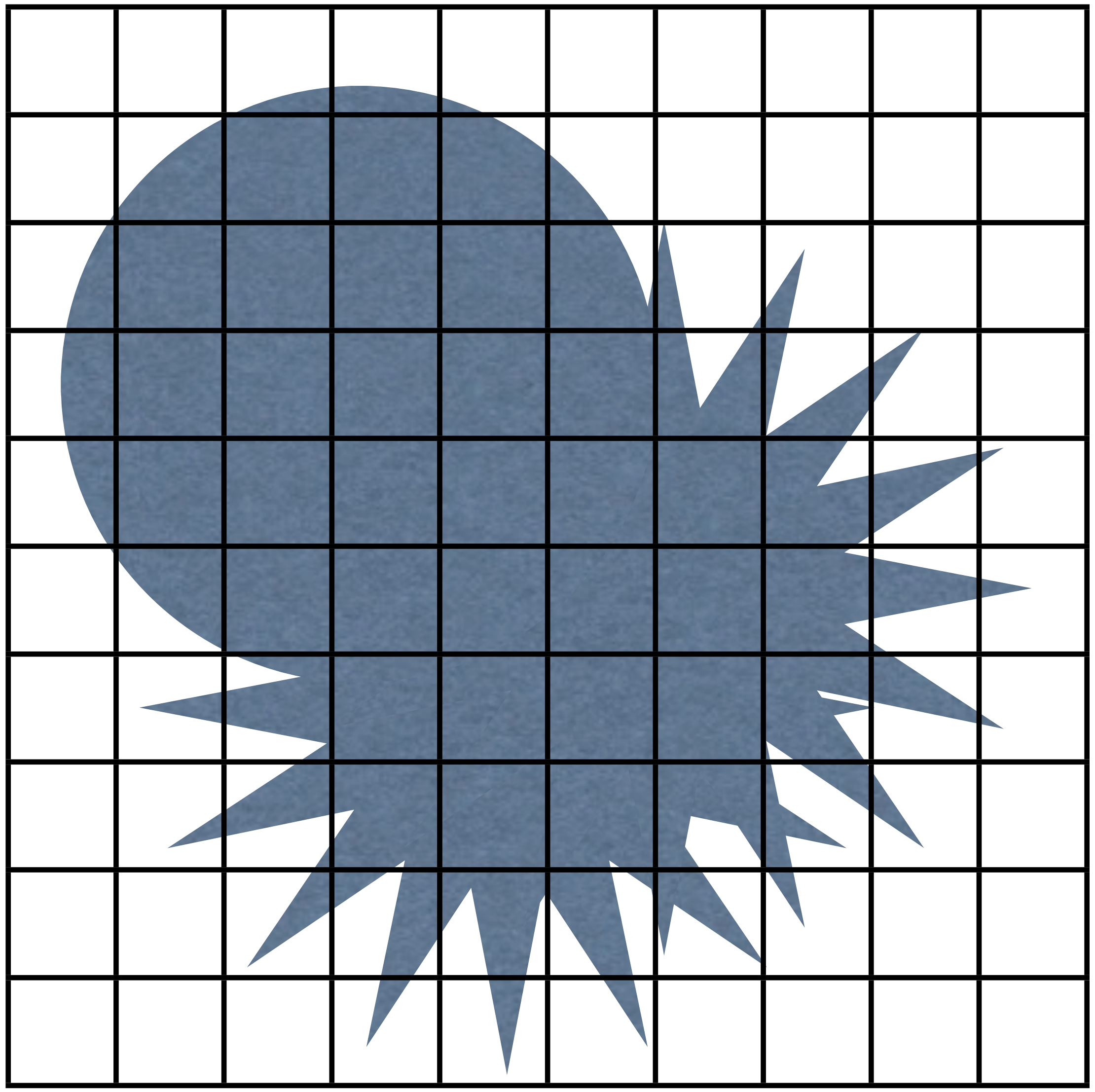
Monte Carlo (MC) [From Tomasz Wlodek slides]

General idea is "Instread of performing long complex calculations, perform large number of experiments using random number generation and see what happens"

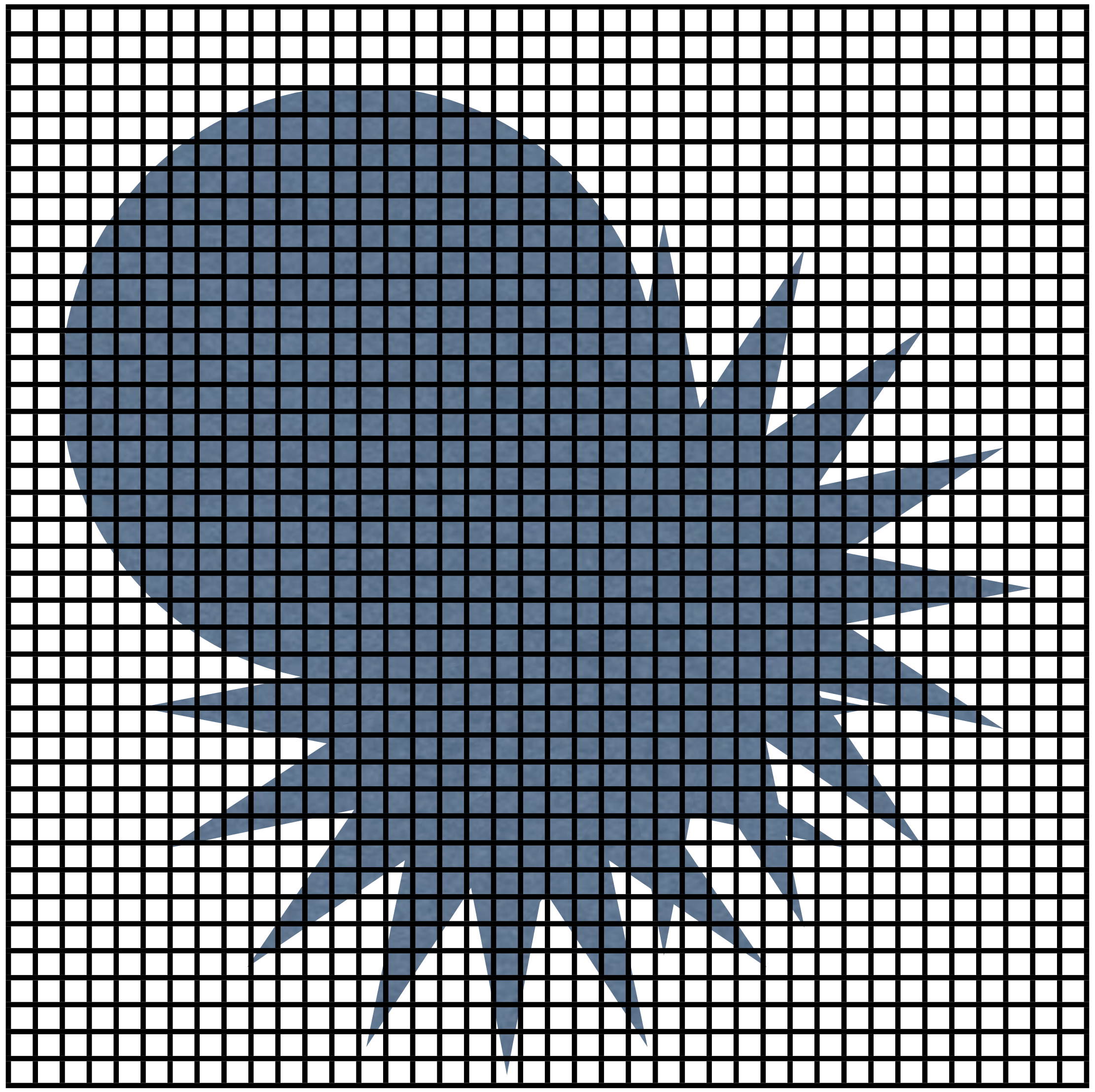
Problem: Calculate the area of this shape



Any idea?



10x10



40x40

Area = (# Hits)/(# Total) x total area

History

Method formally developed by John Neumann during the World War II, but already known before. It was used to study radiation shielding and distance that neutrons would likely travel through material.

Von Neumann chose the codename "Monte Carlo". The name is a reference to the Monte Carlo Casino in Monaco where Ulam's uncle would borrow money to gamble.

Why Monte Carlo?

Monte Carlo assumes the system is described by probability density functions (PDF) which can be modeled. It does not need to write down and solve equation analytically/numerically.

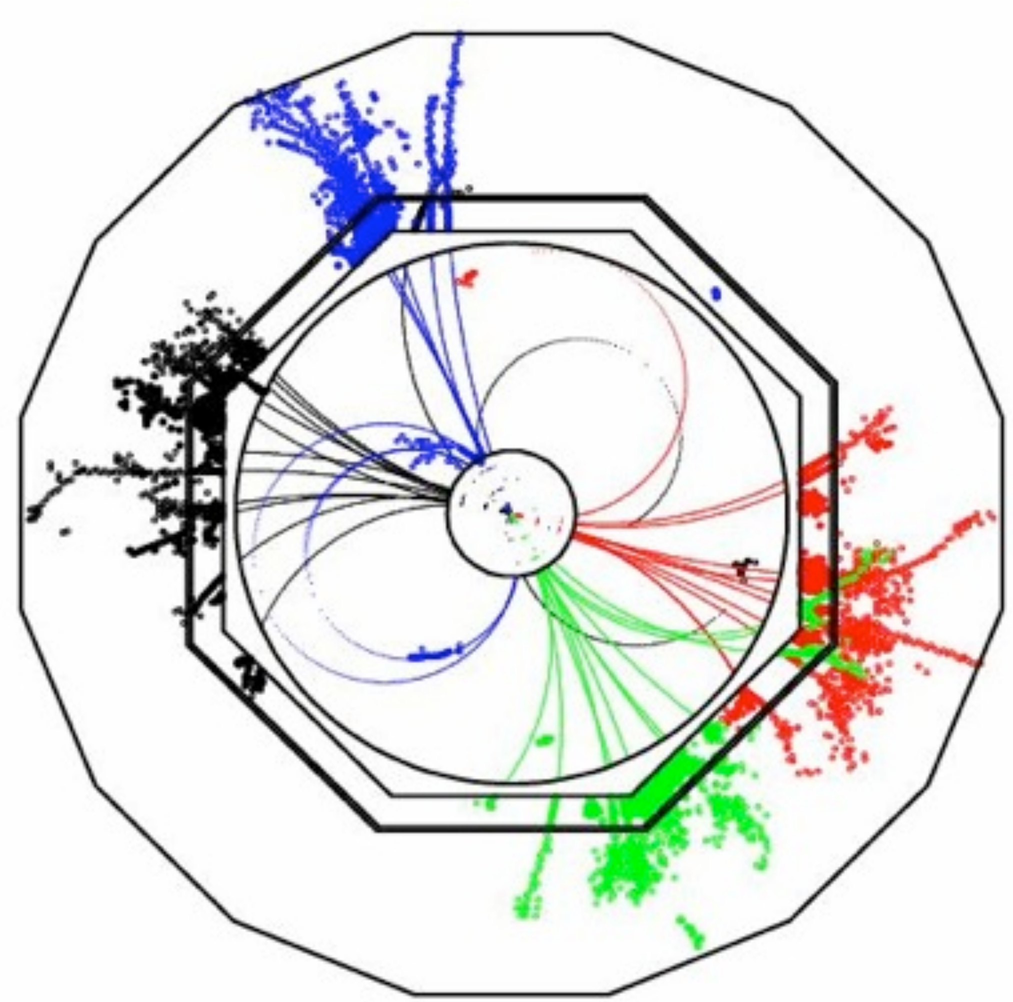
PDF comes from
- Data driven
- Theory driven
- Data + Theory fitting

Particle physics uses MC for

(1) Detector design and optimization
  - Complicate and huge detector
  - Very expensive

(2) Simulation of particle interactions with detector's material

(3) Physics analysis
  - New predicted physics: SUSY, UED, ...
  - Event selection
  - Background estimation
  - Efficiencies of detector/algorithm/...



Monte Carlo Simulation in HEP

Choose model, constraints, parameters, decay chain of interest

Proposed Theory

Kinematics, information from a known (detectable) particles

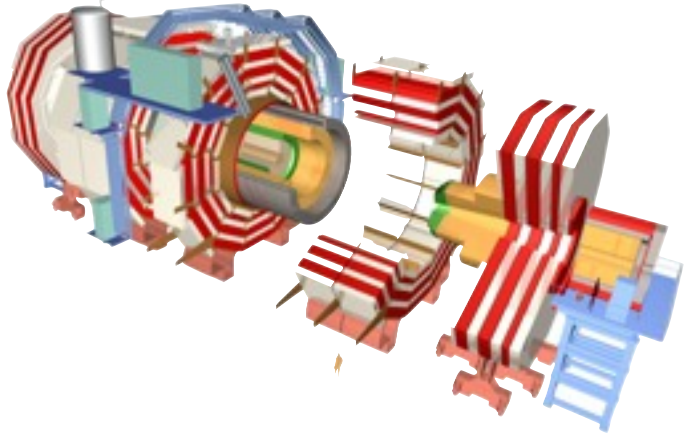
Generator

Detector Simulation
- Hardware
- Software

Simulation Digitization Triggering

Offline software
- Event selection

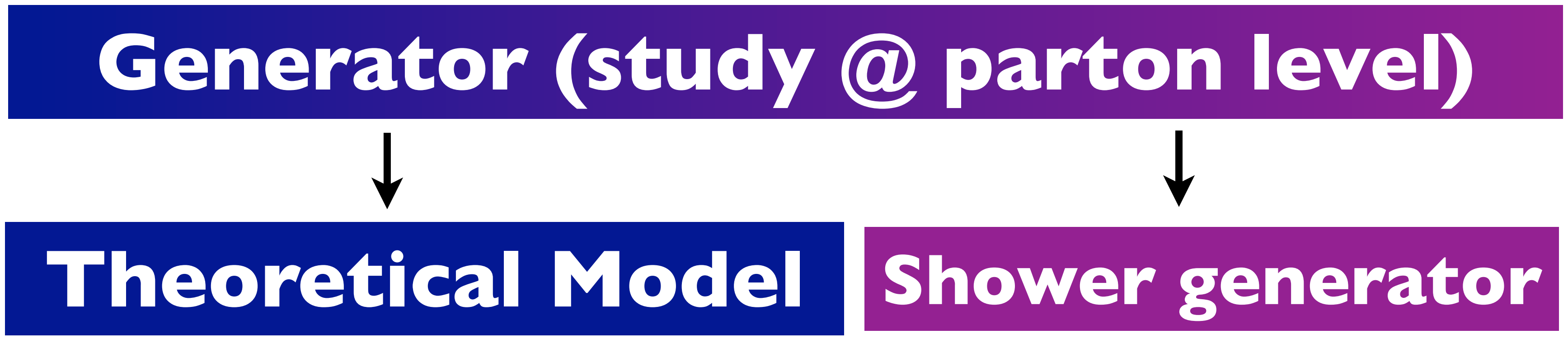
Reconstruction Analysis



Experiment Triggering

Results
Improvement

Monte Carlo generators



Generator (study @ parton level)

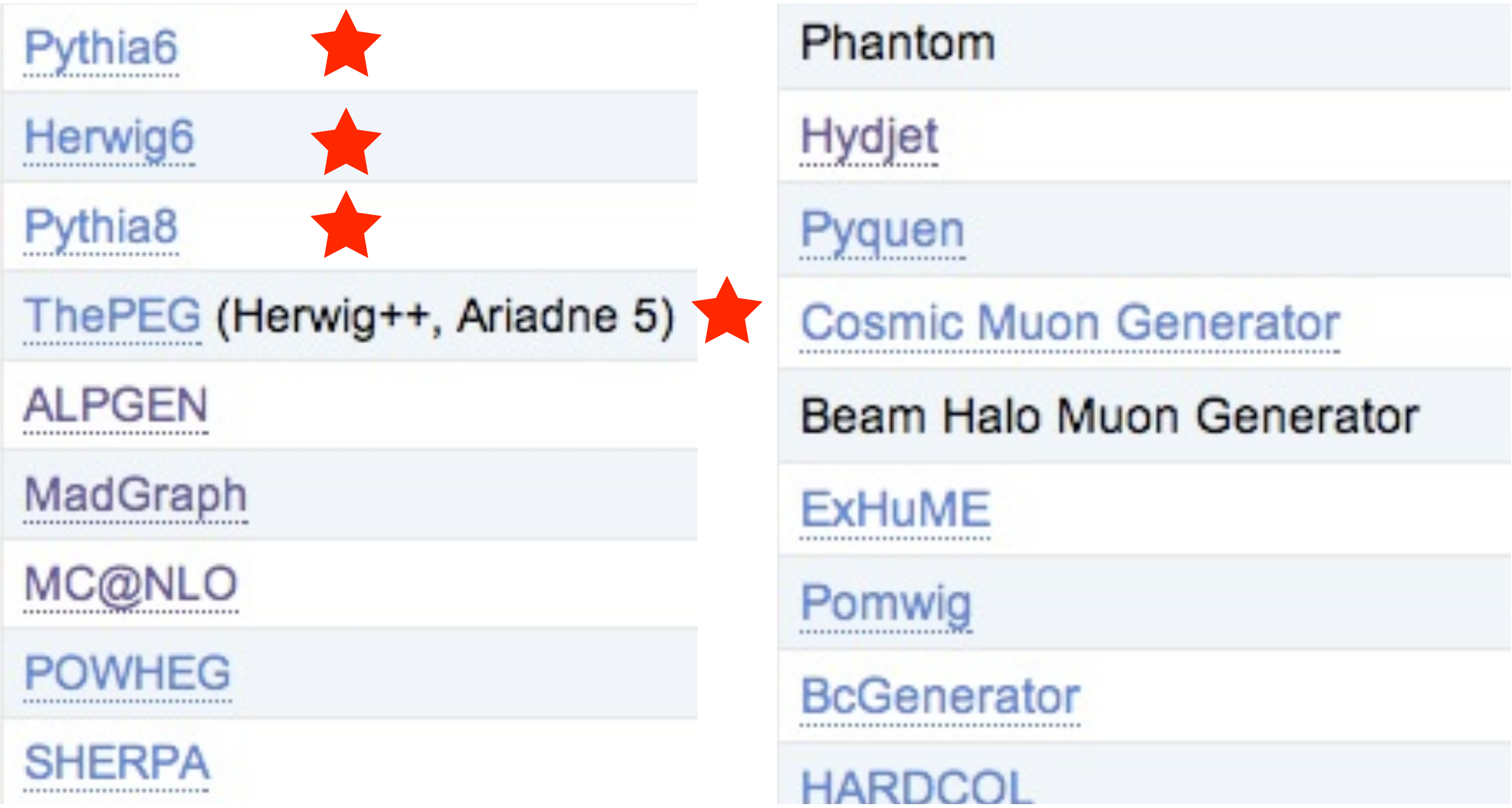
Theoretical Model

Shower generator

Input: Model parameters.

Output: Four-vector of momenta of stable/quasi-stable particles produced in interactions

Example MC generator Inteface with CMSSW



Pythia6 ★

Herwig6 ★

Pythia8 ★

ThePEG (Herwig++, Ariadne 5) ★

ALPGEN

MadGraph

MC@NLO

POWHEG

SHERPA

Phantom

Hydjet

Pyquen

Cosmic Muon Generator

Beam Halo Muon Generator

ExHuME

Pomwig

BcGenerator

HARDCOL

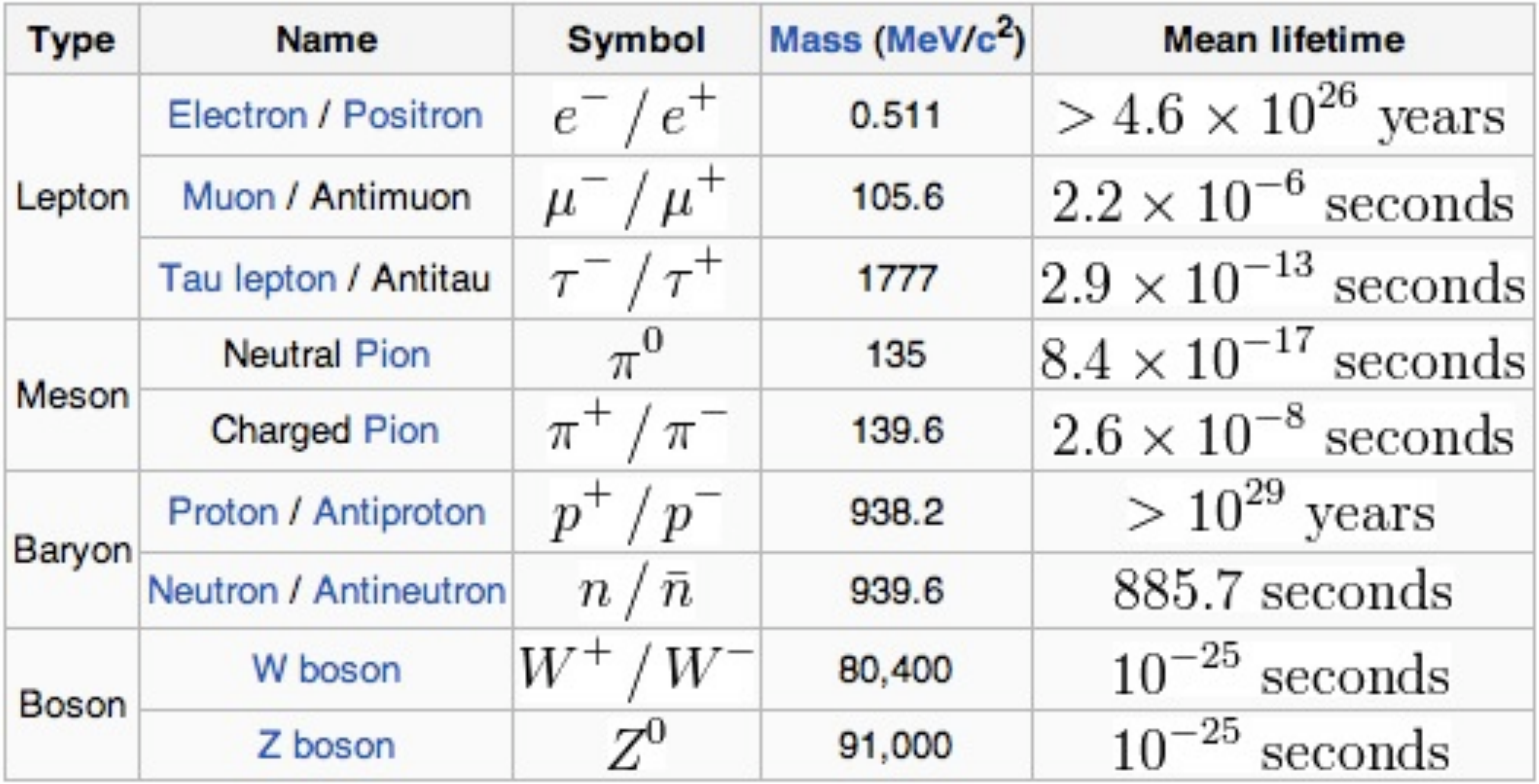
A list of MC generator can be found in [http://www.hepforge.org/]

Questions

Why do we need quasi-stable particles for output?

Questions

Why do we need quasi-stable particles for output?

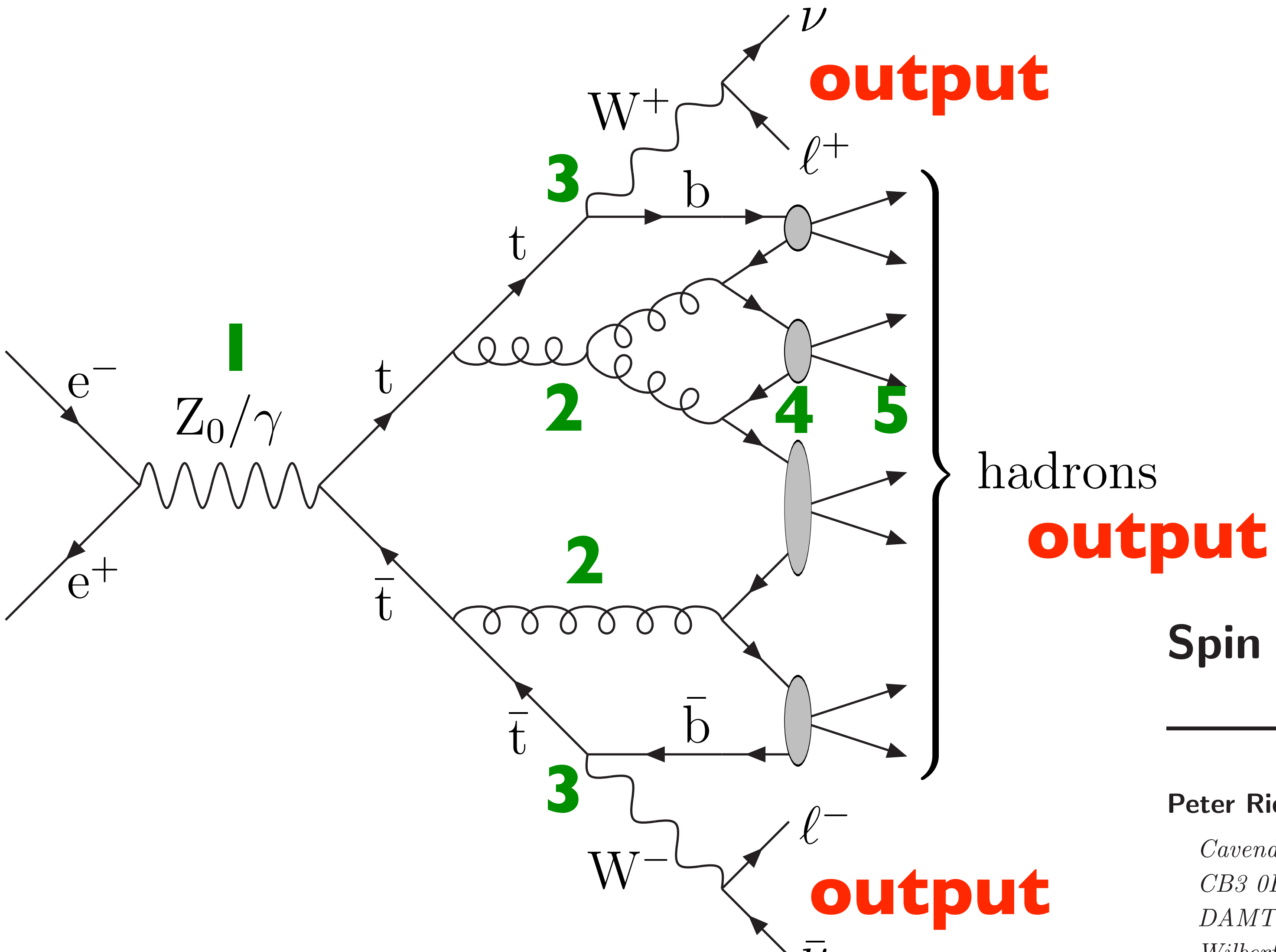


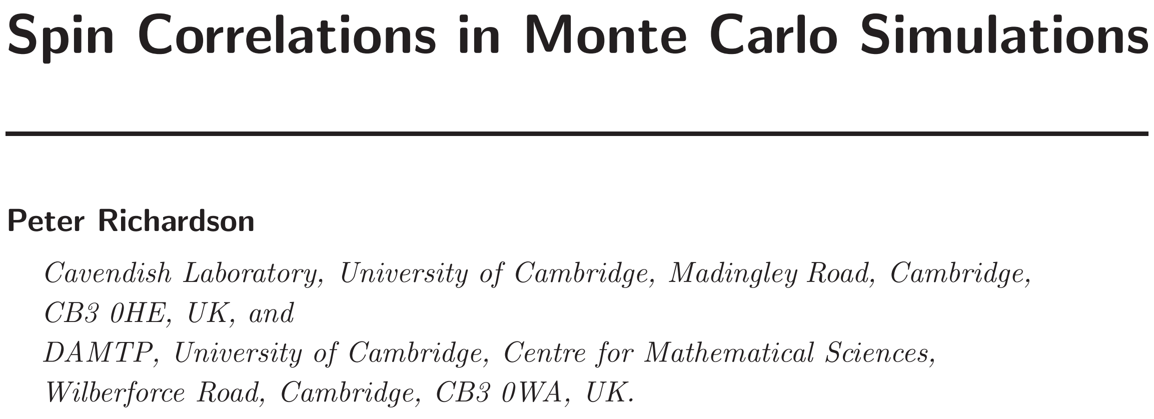
Type	Name	Symbol	Mass (MeV/c^2)	Mean lifetime
Lepton	Electron / Positron	e^- / e^+	0.511	$> 4.6 \times 10^{26}$ years
	Muon / Antimuon	μ^- / μ^+	105.6	2.2×10^{-6} seconds
	Tau lepton / Antitau	τ^- / τ^+	1777	2.9×10^{-13} seconds
Meson	Neutral Pion	π^0	135	8.4×10^{-17} seconds
	Charged Pion	π^+ / π^-	139.6	2.6×10^{-8} seconds
Baryon	Proton / Antiproton	p^+ / p^-	938.2	$> 10^{29}$ years
	Neutron / Antineutron	$n / \bar{n}$	939.6	885.7 seconds
Boson	W boson	W^+ / W^-	80,400	10^{-25} seconds
	Z boson	Z^0	91,000	10^{-25} seconds

http://en.wikipedia.org/wiki/Particle_decay

Monte Carlo event generator process

(1) Hard process: What do you want to study?
(2) Parton-shower phase:
(3) Hard particles decay before hadronizing: e.g. top, SUSY
(4) Hadronization: form observed hadron
(5) Unstable hadrons decay: Experimentally measured BR, phase-space distribution of the decay product




Spin Correlations in Monte Carlo Simulations

Peter Richardson

Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, UK, and
DAMTP, University of Cambridge, Centre for Mathematical Sciences, Wilberforce Road, Cambridge, CB3 0WA, UK.

Verbosity: Tell in detail what program is doing
Example: Herwig log file

```
Since SUSY processes are called,
please also reference: S.Moretti, K.Odagiri,
P.Richardson, M.H.Seymour & B.R.Webber,
JHEP 0204 (2002) 028

Reading in SUSY data from unit 66

INPUT CONDITIONS FOR THIS RUN

BEAM 1 (P       ) MOM. =   7000.00
BEAM 2 (P       ) MOM. =   7000.00
PROCESS CODE (IPROC)   =    3000
NUMBER OF FLAVOURS     =    6
STRUCTURE FUNCTION SET =    8
AZIM SPIN CORRELATIONS =    T
AZIM SOFT CORRELATIONS =    T
QCD LAMBDA (GEV)       =    0.1800
DOWN     QUARK  MASS   =    0.3200
UP       QUARK  MASS   =    0.3200
STRANGE  QUARK  MASS   =    0.5000
CHARMED  QUARK  MASS   =    1.5500
BOTTOM   QUARK  MASS   =    4.9500
TOP      QUARK  MASS   =  175.0000
GLUON EFFECTIVE MASS   =    0.7500
EXTRA SHOWER CUTOFF (Q)=    0.4800
EXTRA SHOWER CUTOFF (G)=    0.1000
PHOTON SHOWER CUTOFF   =    0.4000
CLUSTER MASS PARAMETER =    3.3500
SPACELIKE EVOLN CUTOFF =    2.5000
```

```
      INTRINSIC P-TRAN (RMS) =    0.0000
      DECAY SPIN CORRELATIONS=    T

      SUSY THREE BODY ME     =    T
      SUSY FOUR  BODY ME     =    F

      NO EVENTS WILL BE WRITTEN TO DISK

      B_d: Delt-M/Gam =0.7000 Delt-Gam/2*Gam =0.0000
      B_s: Delt-M/Gam = 10.00 Delt-Gam/2*Gam =0.2000

      PDFLIB USED FOR BEAM 1: SET*** OF HWLHAPDF
      PDFLIB USED FOR BEAM 2: SET*** OF HWLHAPDF
==== HERWIG WILL USE LHAPDF ====
*************************************
*      LHAPDF Version 5.2.2         *
*************************************


>>>>>> PDF description: <<<<<<
CTEQ5L
Reference:
H.L. Lai et al.
hep-ph/9903282
This set has 1 member PDFs.
 Leading Order
>>>>>>                <<<<<<


===============================================
 PDFset name /hepsw/cms/slc4_ia32_gcc345/external/lhapdf/5.2.3-
cms2/PDFsets/cteq5l.LHgrid
```

```
                 EVENT       1: 7000.00 GEV/C P       ON  7000.00 GEV/C P       PROCESS:  3000
                 SEEDS:       41410 &       50928   STATUS:  100 ERROR:   0  WEIGHT:  3.2279E-02


                                                   ---INITIAL STATE---

 IHEP    ID      IDPDG IST MO1 MO2 DA1 DA2   P-X     P-Y     P-Z  ENERGY    MASS    V-X       V-Y       V-Z       V-C*T
    1 P           2212 101   0   0   0   0    0.00    0.00 7000.0 7000.0    0.94 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    2 P           2212 102   0   0   0   0    0.00    0.00-7000.0 7000.0    0.94 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    3 CMF            0 103   1   2   0   0    0.00    0.00    0.014000.014000.00 0.000E+00 0.000E+00 0.000E+00 0.000E+00

                                                   ---HARD SUBPROCESS---

 IHEP    ID      IDPDG IST MO1 MO2 DA1 DA2   P-X     P-Y     P-Z  ENERGY    MASS    V-X       V-Y       V-Z       V-C*T
    4 GLUON         21 121   6   7   9   8    0.00    0.00  370.3  370.3    0.75 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    5 UQRK           2 122   6   8  23   7    0.00    0.00-1825.6 1825.6    0.32 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    6 HARD           0 120   4   5   7   8   -0.93  -37.21-1455.3 2196.1 1644.30 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    7 GLUINO   1000021 123   6   5  33   4  109.61   -6.30-1522.1 1641.6  604.81 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    8 SSUR     2000002 124   6   4  35   5 -109.61    6.30   66.8  554.3  539.15 0.000E+00 0.000E+00 0.000E+00 0.000E+00

                                                   ---PARTON SHOWERS---

 IHEP    ID      IDPDG IST MO1 MO2 DA1 DA2   P-X     P-Y     P-Z  ENERGY    MASS    V-X       V-Y       V-Z       V-C*T
    9 GLUON         94 141   4   6  11  22   -4.81  -25.73  387.2  354.0 -158.95 0.000E+00 0.000E+00 0.000E+00 0.000E+00
   10 CONE           0 100   4   7   0   0    1.00   -0.06   -1.3    1.6    0.00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
   11 GLUON         21   2   9  12 348 349   -1.71   -0.67   -1.5    2.5    0.75-1.884E-13 1.924E-14-3.534E-13 1.456E-13
   12 GLUON         21   2   9  13 350 351   -0.88    0.78   -0.9    1.7    0.75-1.884E-13 1.924E-14-3.534E-13 1.456E-13
   13 GLUON         21   2   9  14 352 353   -2.10    1.29   -0.6    2.6    0.75 7.628E-16 1.278E-14-1.909E-13-1.791E-13
   14 GLUON         21   2   9  15 354 355   -1.94    1.53    3.4    4.3    0.75 4.095E-15 2.568E-14-7.810E-13-7.659E-13
   15 GLUON         21   2   9  47 356 357   -2.13   -0.76   95.8   95.8    0.75-5.939E-15 3.248E-14-4.639E-12-4.624E-12
   16 UD          2101   3   9   0  46   0    0.00    0.00 4705.8 4705.8    0.64 3.135E-13 9.477E-13-5.015E-10-5.014E-10
   17 UQRK           2   2   9  18 358 301    0.37    1.05 1723.7 1723.7    0.32 3.135E-13 9.477E-13-5.015E-10-5.014E-10
   18 GLUON         21   2   9  19 359 360    2.18    2.40   27.5   27.7    0.75 2.027E-13 2.212E-13 1.855E-12 1.884E-12
   19 GLUON         21   2   9  20 361 362    3.43    3.08   57.2   57.4    0.75 2.027E-13 2.212E-13 1.855E-12 1.884E-12
```

Test @ parton result --- You know what you generate ---

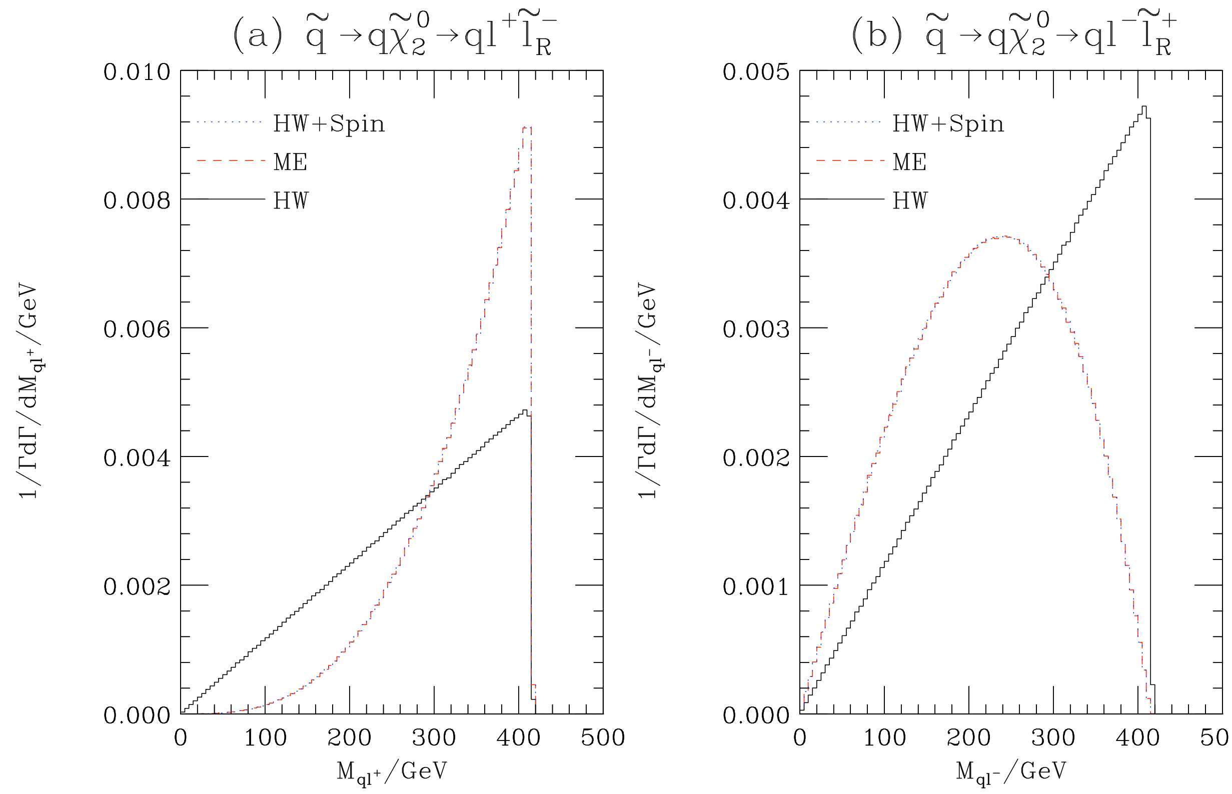


Figure 3: Distribution of the mass of quark and lepton produced in the decay $\tilde{q}_L \to q\tilde{\chi}^0_2 \to q\ell^\pm\tilde{\ell}^\mp_R$. The solid line gives the result of phase space, the dashed line gives the full result and the dotted line the result of the spin correlation algorithm.

Proposed by generator

Spin Correlations in Monte Carlo Simulations

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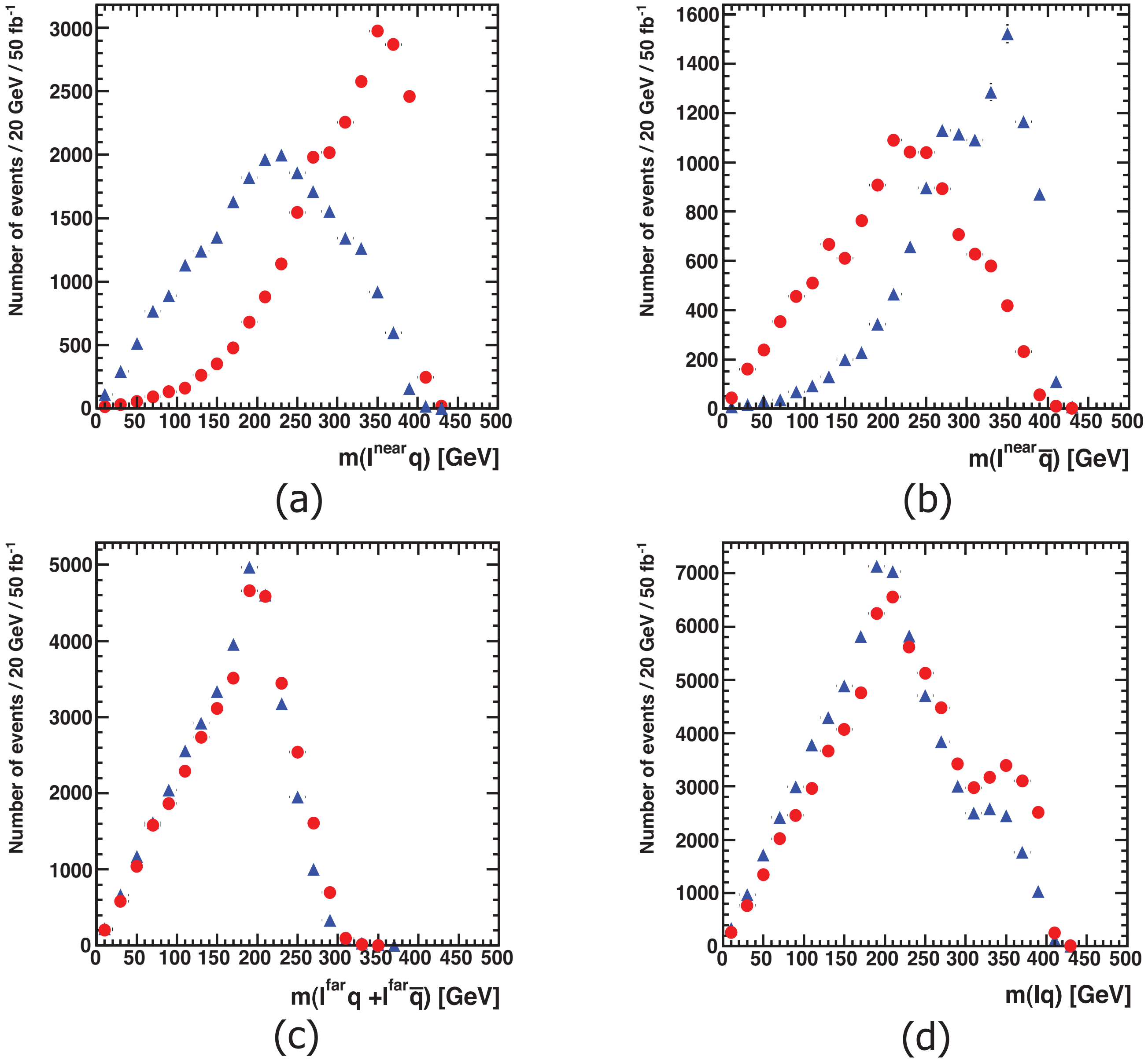
What you got from generator



Monte Carlo generators (theoretician)

Remember: You need PDF to build MC program
- Learn to describe particle production/decay by matrix element (amplitude) of that process (Explain in QFT)
- Calculate PDF by squaring matrix element, integrate, approximate
- Learn QCD (to deal with jet fragmentation, parton)
- Computaional + Mathematical skills are needed

<u>Real life</u>

There are few theoretical groups who provide us the MC event generator:
- Lund University, Sweden (PYTHIA)
- INP, Krakow, Poland (TAUOLA, PHOTOS)
- Other groups
  - HERWIG
  - ISAJET
  - ...

Monte Carlo generators (experimentalist)

HEP experimentalists do not write MC generator ourselves (^_^)!!

We use/modify MC generators proposed by theoretical groups.

Your best MC generator is a generator which serve you results that you believe/study.

Read manual (VERY IMPORTANT)

You may need more than a MC generator to generate particles for the new physics.

For SUSY, you need mass spectrum + BR + hadronization

Link with standard txt files, i.e. LHE

The `Les Houches Events` (LHE) file format is an agreement between Monte Carlo event generators and theorists to define **Matrix Element** level event listings in a common language.

HEP event generation can typically be split into the following steps: Matrix Element calculation, Parton Shower, and Hadronisation. Usually the physics event of interest, as well as the cross-section information is done with the computation of the Matrix Element (PDF evaluation, phase space, amplitudes, spin correlations, etc...) and the remaining steps are used to evolve the parton-level event to its final state. All these secondary steps rely heavily on models and are generally independent from the Matrix Element calculation. Therefore only few, typically multi-purpose event generators, implement those additional steps. Examples are Pythia (6 and 8), Herwig (Fortran and C++ versions) and Sherpa.

https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideLHEInterface

Monte Carlo for detector simulation

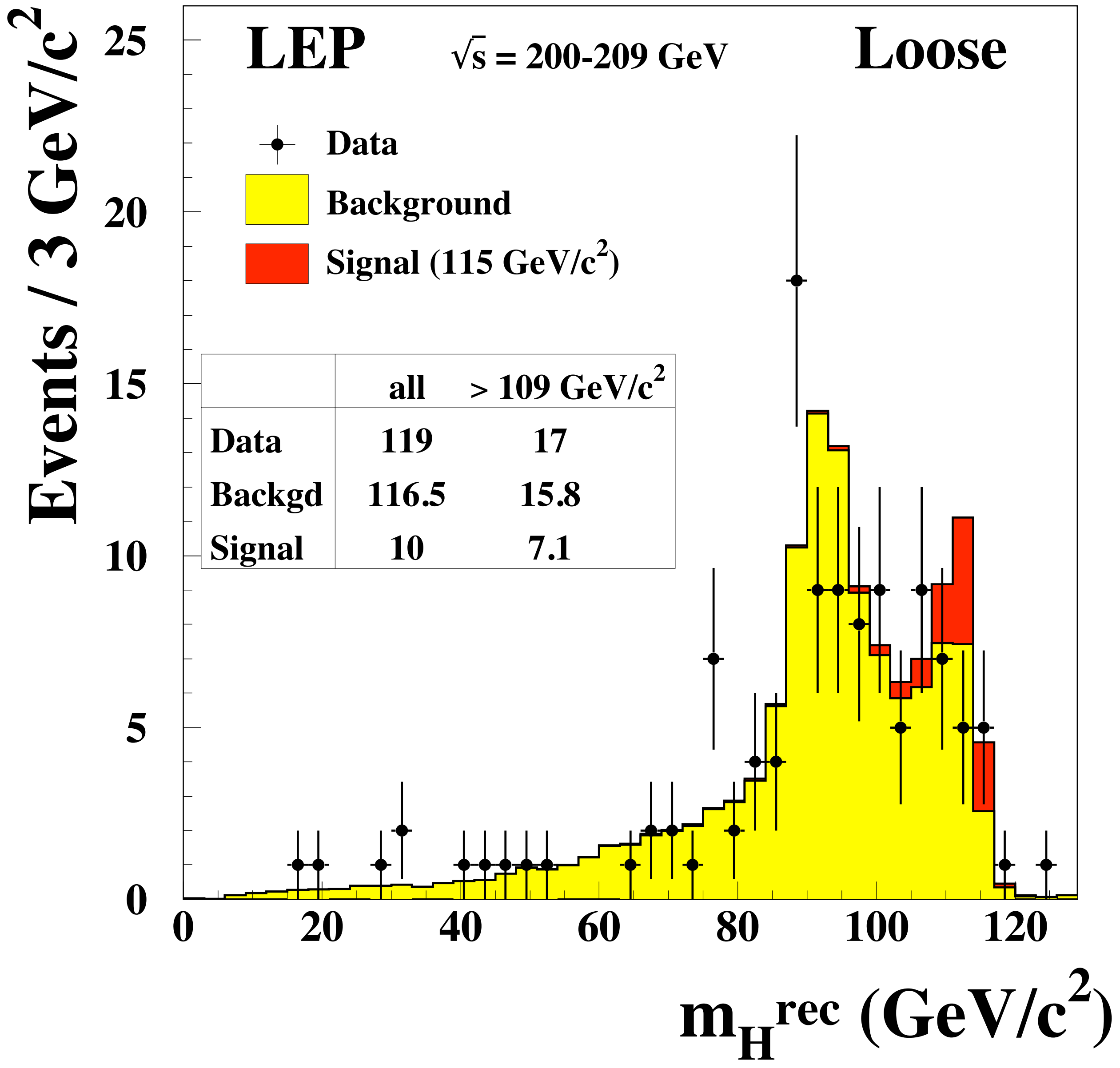
We need to know how our detector will see the productions from collisions.

Detector simulation tracks the particles through detector material (simulating their interactions with material)

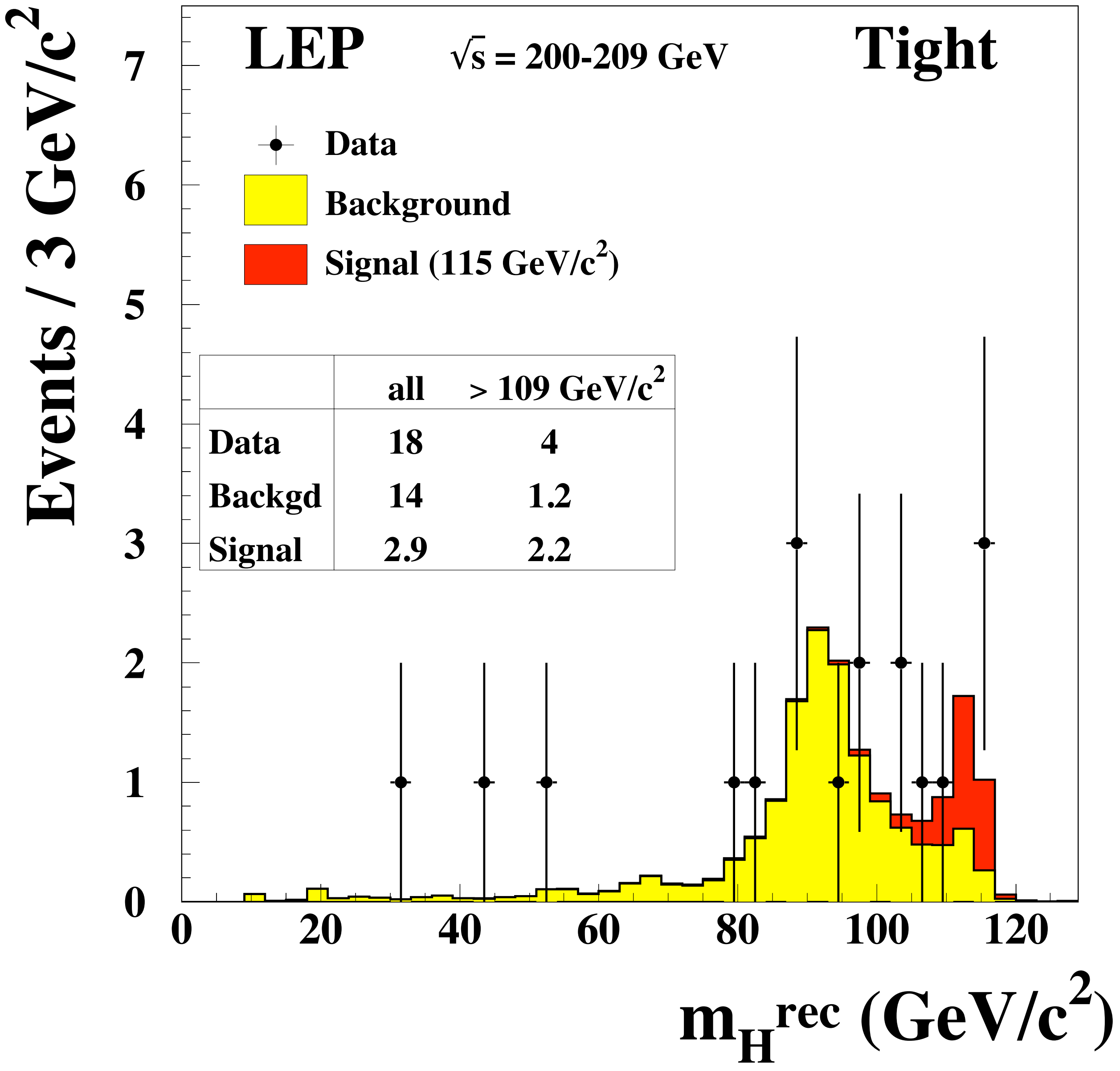
Input: group of (quasi)-stable of particles from MC generator
group of particles from particle-gun
Output: Depend on your analysis

Popular detector simulation
- GEANT4 (http://geant4.web.cern.ch)
- FLUKA (http://www.fluka.org/fluka.php)

Example: Higgs searches at LEP



	all	> 109 GeV/c²
Data	119	17
Backgd	116.5	15.8
Signal	10	7.1

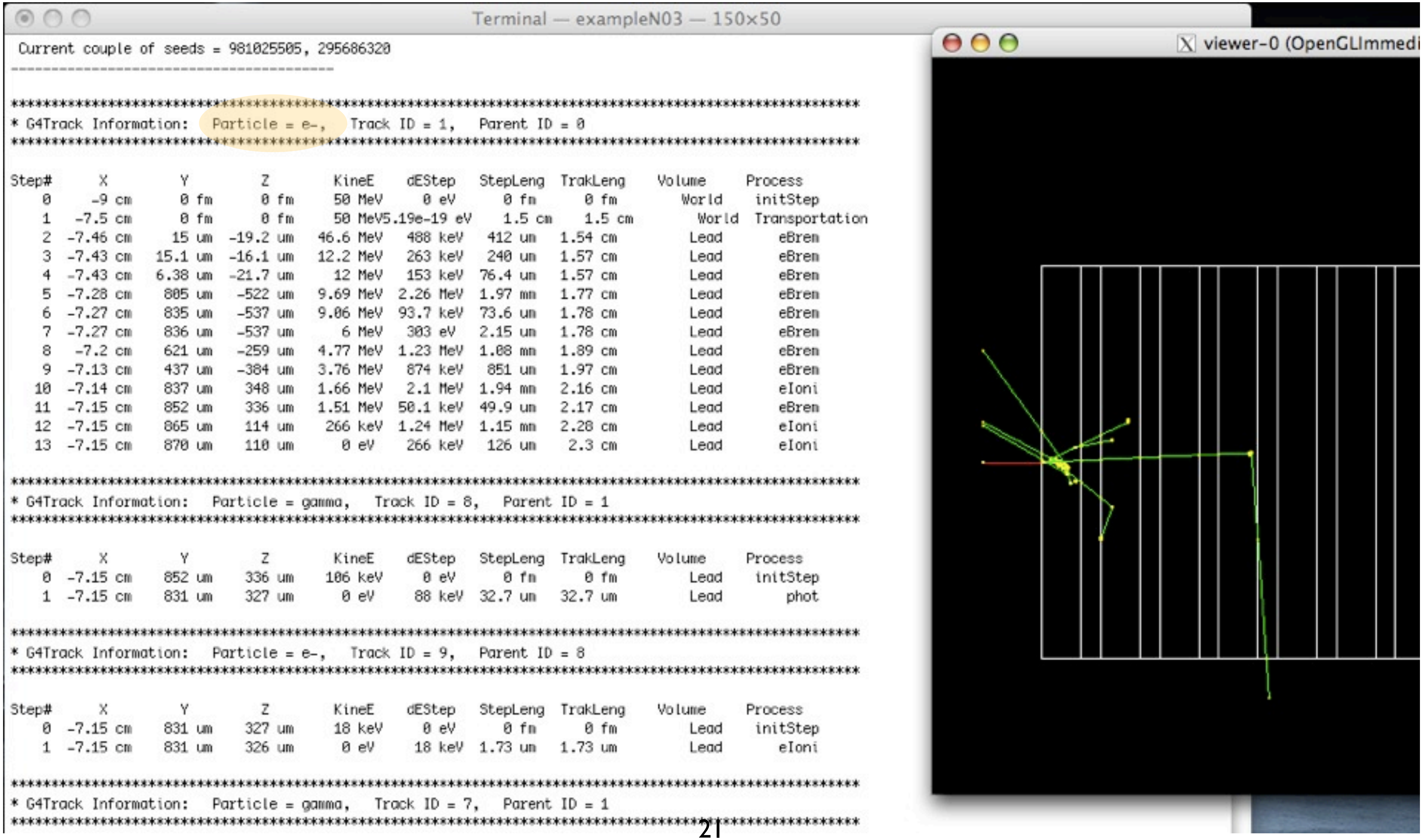


	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html

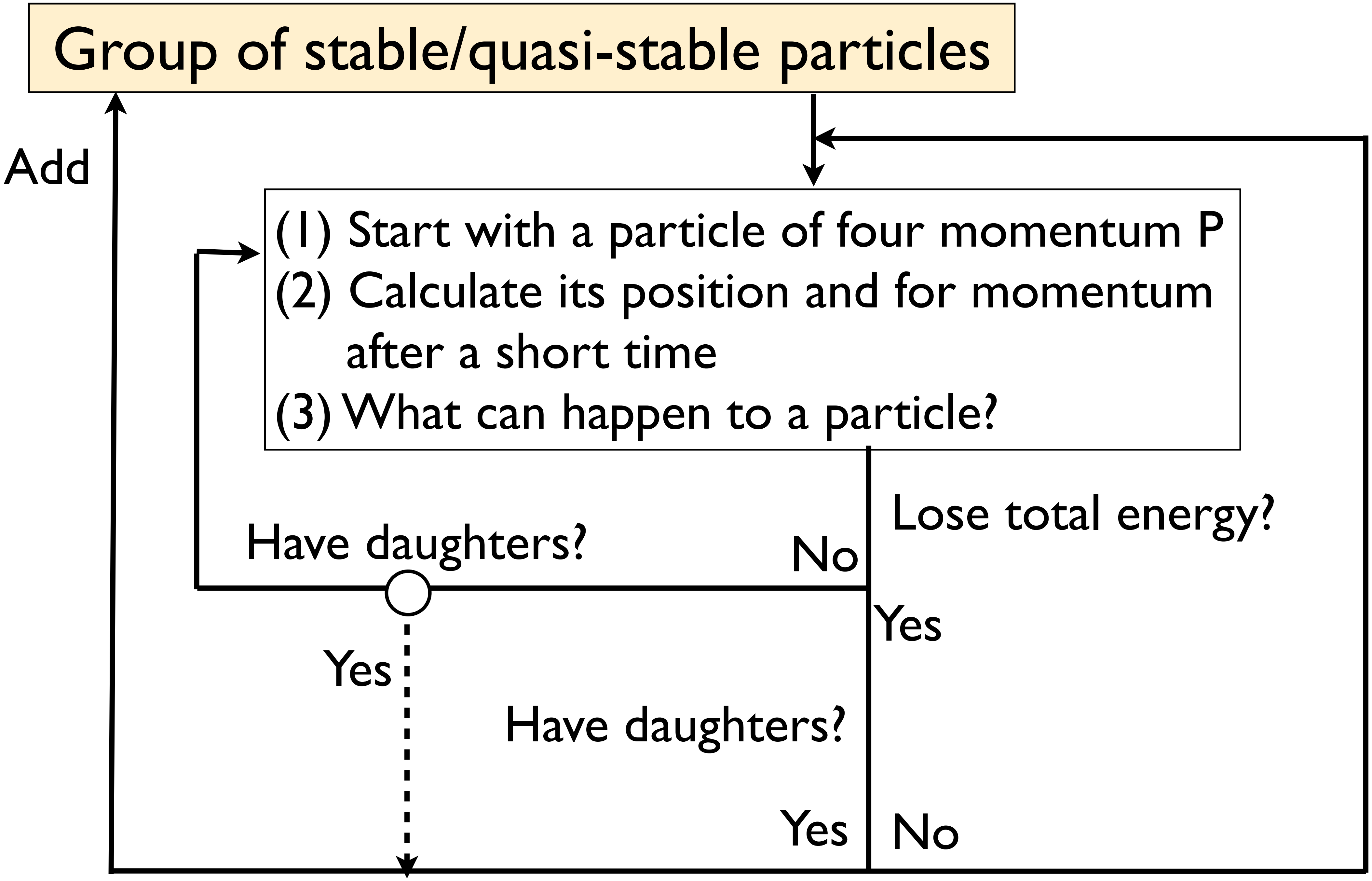
Example from GEANT4 novice

Simulation of the calorimeter with Pb layers and liquid Ar detection gaps



```
 Current couple of seeds = 981025505, 295686320
 ---------------------------------------

*********************************************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 1,   Parent ID = 0
*********************************************************************************************************

Step#      X         Y         Z        KineE    dEStep   StepLeng  TrakLeng    Volume     Process
    0     -9 cm      0 fm      0 fm     50 MeV     0 eV      0 fm      0 fm      World    initStep
    1   -7.5 cm      0 fm      0 fm     50 MeV5.19e-19 eV   1.5 cm    1.5 cm      World  Transportation
    2  -7.46 cm     15 um  -19.2 um   46.6 MeV   488 keV    412 um   1.54 cm       Lead       eBrem
    3  -7.43 cm   15.1 um  -16.1 um   12.2 MeV   263 keV    240 um   1.57 cm       Lead       eBrem
    4  -7.43 cm   6.38 um  -21.7 um     12 MeV   153 keV   76.4 um   1.57 cm       Lead       eBrem
    5  -7.28 cm    805 um   -522 um   9.69 MeV  2.26 MeV   1.97 mm   1.77 cm       Lead       eBrem
    6  -7.27 cm    835 um   -537 um   9.06 MeV  93.7 keV   73.6 um   1.78 cm       Lead       eBrem
    7  -7.27 cm    836 um   -537 um      6 MeV   303 eV    2.15 um   1.78 cm       Lead       eBrem
    8   -7.2 cm    621 um   -259 um   4.77 MeV  1.23 MeV   1.08 mm   1.89 cm       Lead       eBrem
    9  -7.13 cm    437 um   -384 um   3.76 MeV   874 keV    851 um   1.97 cm       Lead       eBrem
   10  -7.14 cm    837 um    348 um   1.66 MeV   2.1 MeV   1.94 mm   2.16 cm       Lead       eIoni
   11  -7.15 cm    852 um    336 um   1.51 MeV  50.1 keV   49.9 um   2.17 cm       Lead       eBrem
   12  -7.15 cm    865 um    114 um    266 keV  1.24 MeV   1.15 mm   2.28 cm       Lead       eIoni
   13  -7.15 cm    870 um    110 um      0 eV    266 keV    126 um    2.3 cm       Lead       eIoni

*********************************************************************************************************
* G4Track Information:   Particle = gamma,   Track ID = 8,   Parent ID = 1
*********************************************************************************************************

Step#      X         Y         Z        KineE    dEStep   StepLeng  TrakLeng    Volume     Process
    0  -7.15 cm    852 um    336 um    106 keV     0 eV      0 fm      0 fm       Lead    initStep
    1  -7.15 cm    831 um    327 um      0 eV     88 keV   32.7 um   32.7 um       Lead        phot

*********************************************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 9,   Parent ID = 8
*********************************************************************************************************

Step#      X         Y         Z        KineE    dEStep   StepLeng  TrakLeng    Volume     Process
    0  -7.15 cm    831 um    327 um     18 keV     0 eV      0 fm      0 fm       Lead    initStep
    1  -7.15 cm    831 um    326 um      0 eV     18 keV   1.73 um   1.73 um       Lead       eIoni

*********************************************************************************************************
* G4Track Information:   Particle = gamma,   Track ID = 7,   Parent ID = 1
*********************************************************************************************************
```

How does MC work in detector simulation?



Group of stable/quasi-stable particles

Add

(1) Start with a particle of four momentum P

(2) Calculate its position and for momentum after a short time

(3) What can happen to a particle?

Lose total energy?

Have daughters?

No

Yes

Yes

Have daughters?

Yes

No

How does MC work in detector simulation?

In electron case:

☑ With probability **p1**: ionize the gas, loose some momentum, produce N secondary electrons with momentum p_{e1N1},...

☑ Do nothing with probability **1-p1**

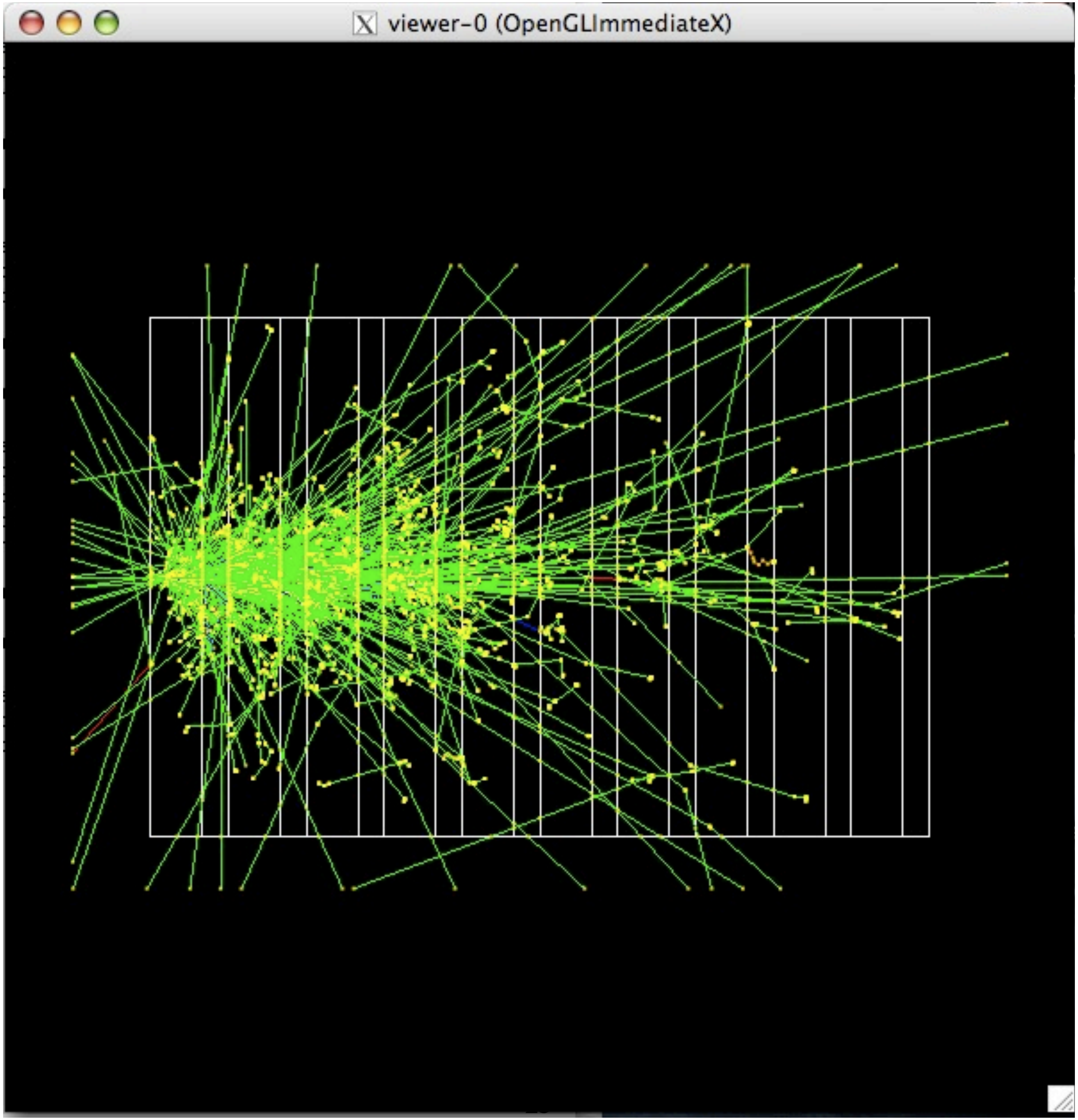
☑ Generate random number **r** in the range [0,1]

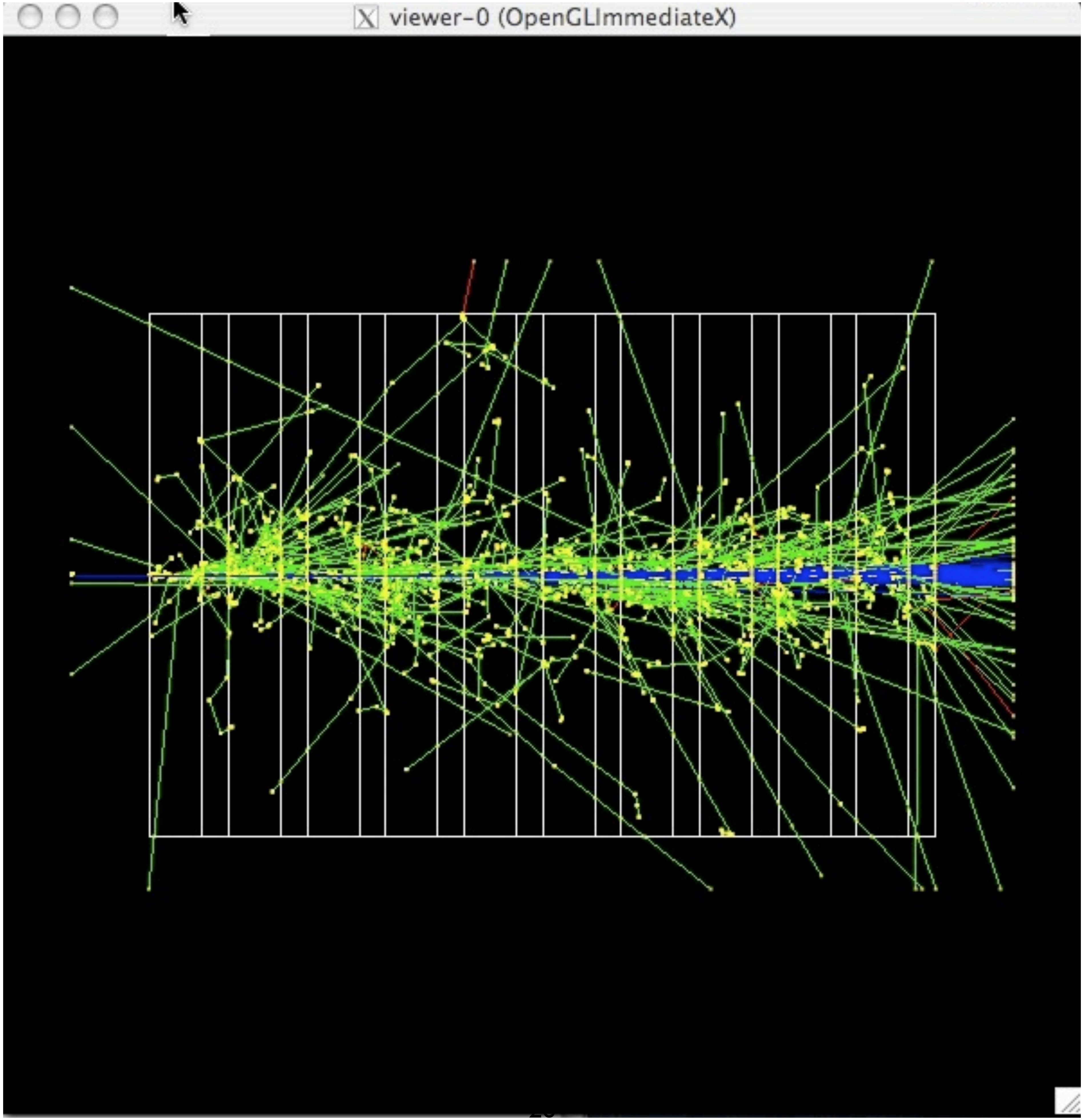
☑ If **r**<**p1**, generate momenta of secondary electrons, add them to particles list, reduce the momentum of initial electron.

How does MC work in detector simulation?

In photon case:

- ☑ With probability **p1**: convert and produce electron-positron pair
- ☑ With probability **p2**: Compton scattering
- ☑ With the probability **p3**: ionizing the matter
- ☑ Generate random number **r** in the range [0,1]
- ☑ Three cases:
  - ☑ **r < p1**
  - ☑ **p1 < r <p1+p2**
  - ☑ **p1+p2 < r < p1+p2+p3**


viewer-0 (OpenGLImmediateX)


viewer-0 (OpenGLImmediateX)

Geant4 EM packages

- ***Standard***
  - γ, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- ***Muons***
  - up to 1 PeV
  - Energy loss propagator
- ***Xrays***
  - X-ray and optical photon production processes
- ***High-energy***
  - Processes at high energy (E>10GeV)
  - Physics for exotic particles
- ***Polarisation***
  - Simulation of polarized beams
- ***Optical***
  - Optical photon interactions
- Low-energy
  - **Livermore *library*** γ, e- from 10 eV up to 1 GeV
  - **Livermore library based polarized processes**
  - **PENELOPE code rewrite , γ, e- , e+ from 250 eV up to 1 GeV**
  - **hadrons and ions up to 1 GeV**
  - **Microdosimetry models (Geant4-DNA project) from 7 eV to 10 MeV**
  - **Atomic deexcitation**
- Adjoint
  - **New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation**
- **Utils – general EM interfaces**

How does MC work in detector simulation?

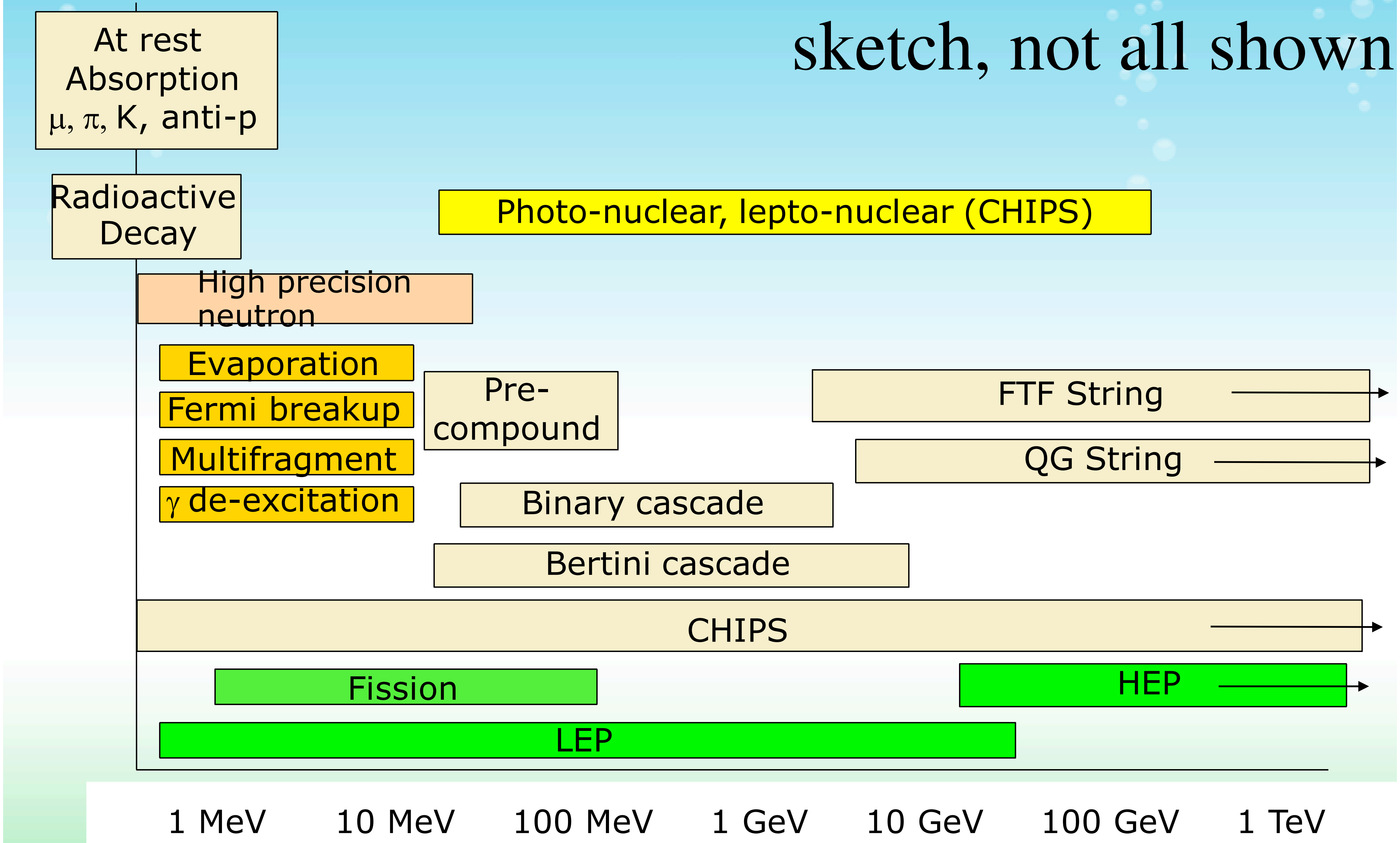
In hadron case:

Simulate its interaction with matter, produce hadronic showers, add them to you list of particles.

Same as EM physics, we have physics packages, called physics list, to work on hadron physics.
- Data driven model
- Parametrized model
- Theory driven model

Hadronic Process/Model Inventory

sketch, not all shown



At rest Absorption
μ, π, K, anti-p

Radioactive Decay

Photo-nuclear, lepto-nuclear (CHIPS)

High precision neutron

Evaporation

Fermi breakup

Multifragment

γ de-excitation

Pre-compound

FTF String

QG String

Binary cascade

Bertini cascade

CHIPS

Fission

HEP

LEP

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV

Be careful with MC detector

- VERY CPU intensive: Complicated detector, ton of primary particle

- Random number & Random seed!

- No perfect physics list! You need to choose it by yourself.

- Fast simulation can be shown, but it always needs to validate with full simulation.

Link among MC software

You need a powerful/flexible framework to link MC software
- Will be discussed on Tue 12 and Wed 13 by Lucia Silvestris

You need powerful computer (s) + Huge storage
Supercomputer / Grid
- Will be discussed on Tue 12 and Wed 13 by Dirk Duellmann

Here, I provide an easy framework based on Virtual Monte Carlo
NEED: Someone to use ^_^

Let’s see more complicated examples

We will generate TTbar events and then pass it to CMS detector simulation.

งานวิจัยทางด้านฟิสิกส์อนุภาคพลังงานสูง		
ด้านการจำลองเครื่องตรวจวัดอนุภาค และเครื่องเร่งอนุภาค	ด้านทฤษฎีแบบจำลองมาตรฐาน (Standard Model)	ด้านทฤษฎีนอกเหนือจากทฤษฎีแบบจำลองมาตรฐาน (Beyond Standard Model)
1.1 Study of the Zero Degree Calorimeter data on forward neutrons in CMS 1.2 Study of missing transverse momentum in the CMS detector 1.3 Studies for the preparation of detectors for the upgrade of CMS 1.4 การประยุกต์ใช้เทคโนโลยีกริดเพื่อลดเวลาการประมวลผล การจำลองหลักการของระบบตรวจกับระเบิดที่ใช้เทคนิคทางนิวเคลียร์ ด้วยโปรแกรมมอนติคาร์โล 1.5 A Simulation of Neutron Scattering in the Collimator 1.6 A Simulation of Radiation Shielding in the Collimator	2.1 Excess of events with top quarks in order to search for supersymmetry in CMS 2.2 Excess of events with multiple leptons in order to search for supersymmetry in CMS 2.3 Excess of events with jets and missing transverse energy in order to search for supersymmetry in CMS 2.4 SU(2) Lattice QCD in Coulomb Gauge at Finite Temperature 2.5 การศึกษาไฮเปอร์นิวเคลียสในการชนของแอนติโปรตอน-นิวเคลียส 2.6 Lattice QCD approach to Yang-Mills theory in Coulomb gauge at finite temperature 2.7 การไหลรวมของการชนในไอออนหนักโดยใช้แบบจำลอง QMD และ UrQMD 2.8 การศึกษาเคออนิคอะตอมและพายออนิคอะตอมโดยใช้วิธีทางฟังก์ชันสเตอร์เมียน	3.1 Search for an excess of events with photons as a signature of GMSB SUSY models 3.2 Search for exotica signatures using events with high charged particle multiplicities 3.3 Search for events with one jet and Missing ET for extra dimensions and unparticles 3.4 Search for events with a photon and Missing ET for extra dimensions and unparticles **Open now!!!**