Geant4

Lecture 3: Physics Processes

Overview

- The Different Physics Processes
- Their implementation in Physics Lists

Type of interaction

Basic split into

- **Electromagnetic (EM). Involving charges and (virtual) photons. Well modelled by Quantum Electrodynamics (QED)**

- **Hadronic. Not always well modelled (gluons/pions) so sometimes `libraries' of measured cross sections are used.**

Hadronic force is strong but short range. So sometimes important and sometimes not.

Conceptual split into

- **Gentle. Particle energy/momentum/velocity is modified**
- **Drastic. Particle is replaced by something different.**

Hadronic interactions are generlly drastic. EM interactions can be gentle or drastic

Neutrons only interact hadronically. Electrons and photons only interact electromagnetically. Protons do both

Charged particles

Consider electrons in atoms in the material

Charged particle goes past

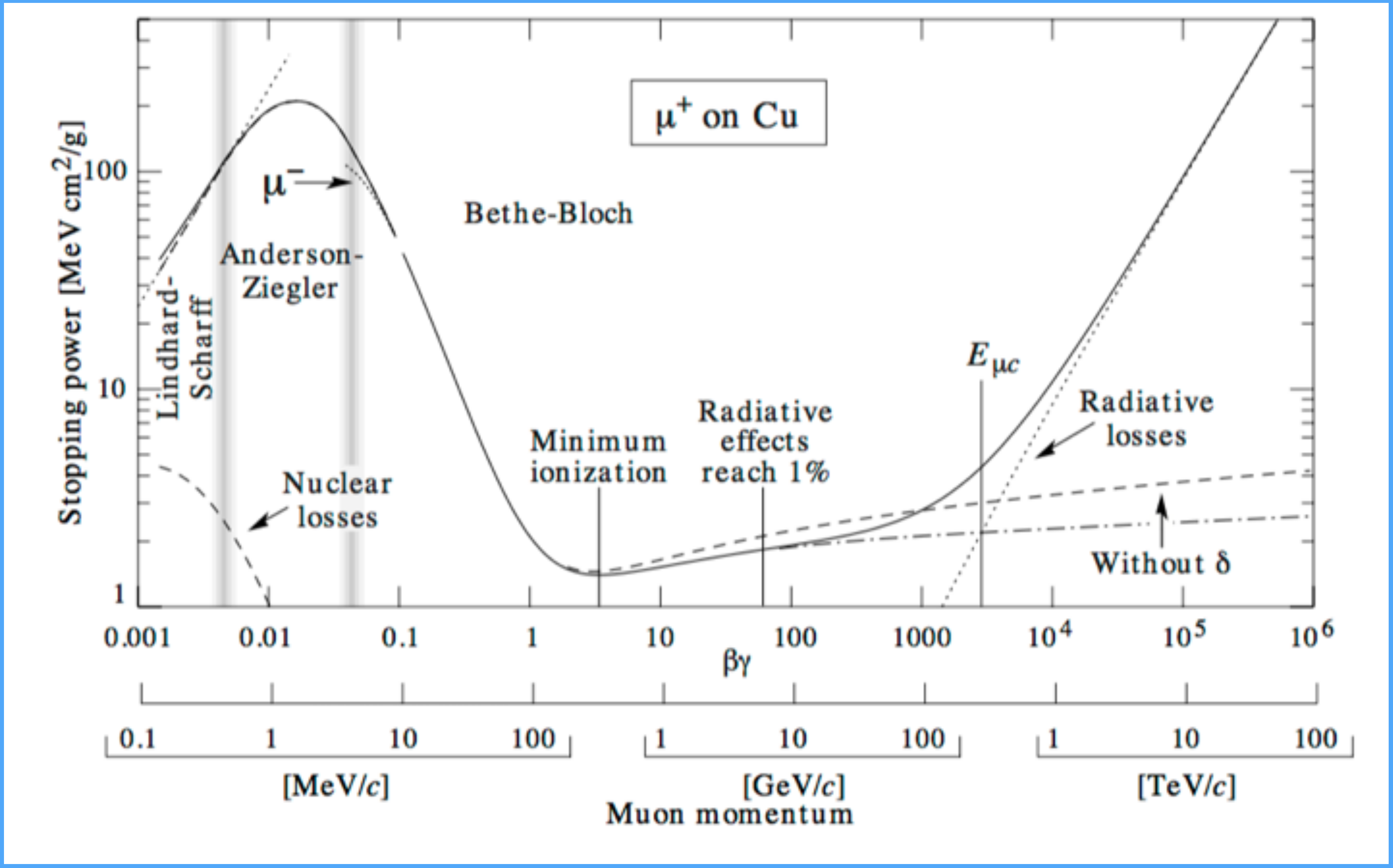
Atomic electron sees sudden electric/magnetic field

Electron gets excited: moves to higher level- or even ionizes

Energy gained by electron is lost by beam particle

Known as dE/dx (physicists) or LET (biologists)

dE/dx and energy

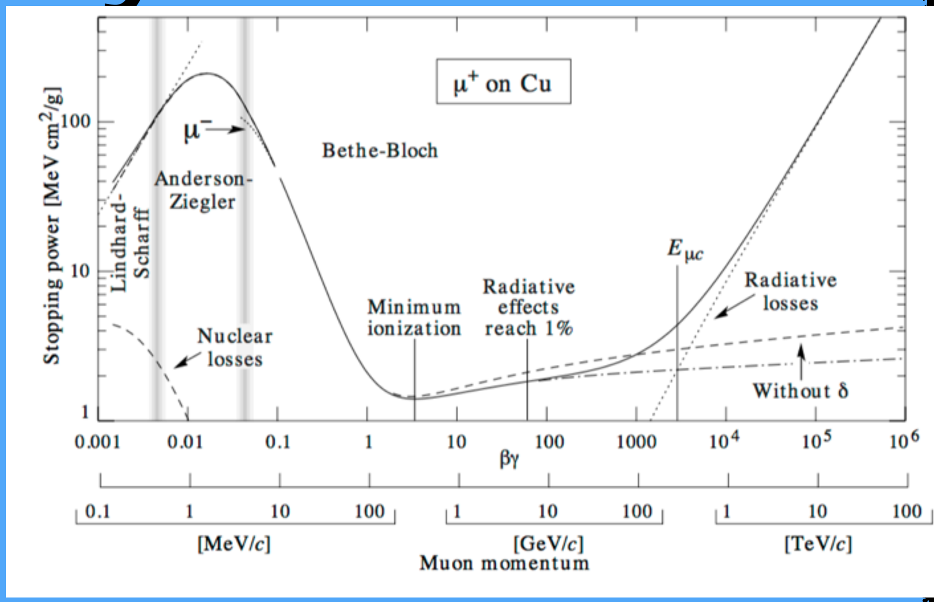


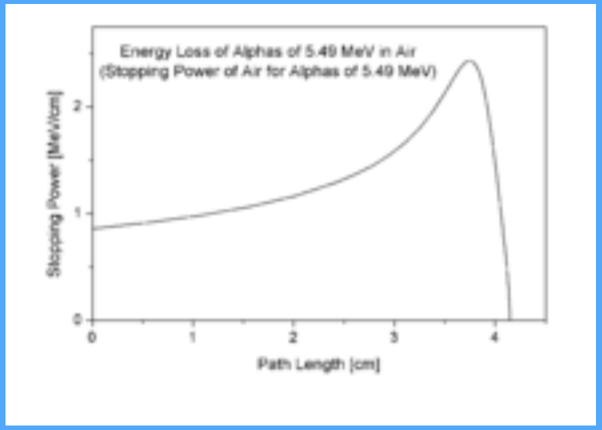
Bethe-Bloch formula (or just Bethe)

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

So much to say…

- dE/dx basically depends on velocity.
- Bethe-Bloch falls as energy (beta) increases. Counterintuitive. But atomic electrons see faster particles for shorter times, so less effect
- Hence the 'Bragg peak'
- At VERY low energies it falls off. Not in B-B formula
- Large 'minimum ionising' plateau
- 'Relativistic rise' due to increase in T_{max} and increased E/M field due to flattening. Latter is moderated by polarisation (delta term)
- `Radiative effects' are important for electrons

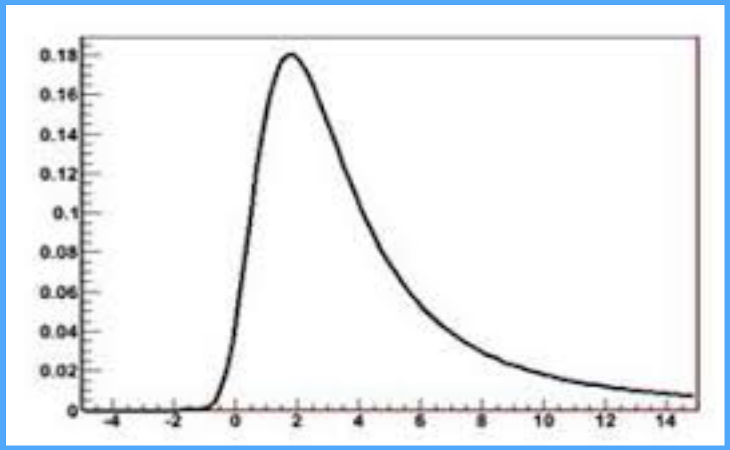




It gets more complicated…

Bethe-Bloch tells you the average dE/dx

Actual dE/dx has wide variations
Described by Landau distribution



Very non-Gaussian. Positive skew.

$$p(x) = \frac{1}{\pi}\int_0^\infty e^{-t\log t - xt}\sin(\pi t)\,dt.$$

Horrible function - does not have a standard deviation or even a mean

Most probable value and scale

$$\Delta_p = \xi\left[\ln\frac{2mc^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma)\right]$$

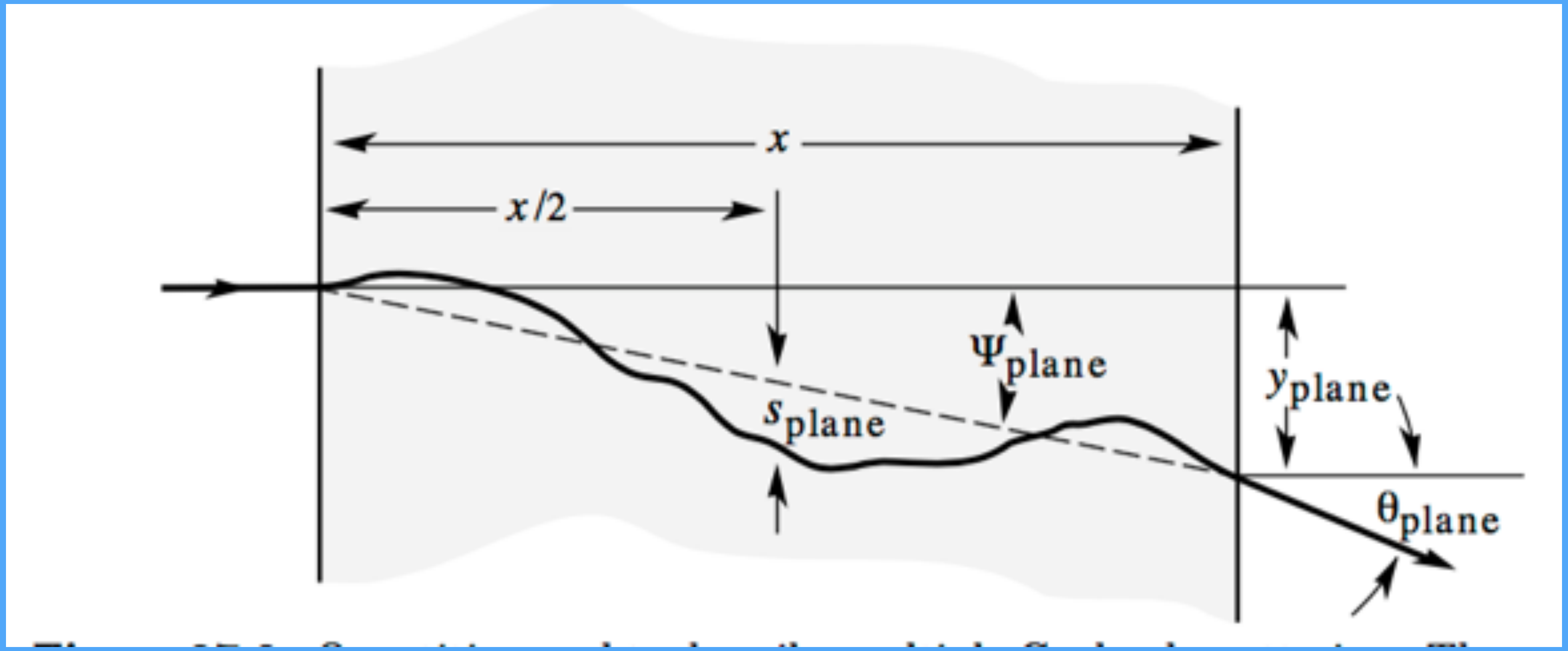
$$\xi = (K/2)\,\langle Z/A\rangle\,(x/\beta^2)$$

$$p(x) = \frac{1}{\sqrt{2\pi}}\exp\left\{-\frac{1}{2}(x+e^{-x})\right\}.$$

is sometimes used as an approximation but it is BAD!!!

Multiple scattering

These collisions also transfer momentum



Spread in position and angle

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

$$\theta_0 = \theta^{\,\mathrm{rms}}_{\mathrm{plane}} = \frac{1}{\sqrt{2}}\,\theta^{\mathrm{rms}}_{\mathrm{space}}$$

Randomly generated y and theta are correlated…

More about X_0 coming up

Radiation Length X_0

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}\ \mathrm{g \cdot cm^{-2}}$$

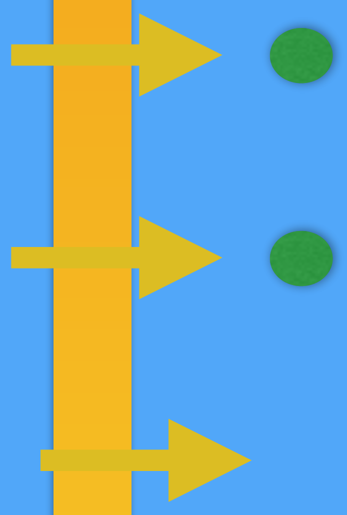
Basically counts electrons
Divide by density before use

Table 2.6 Values of radiation lengths X_{g0} in units of g/cm² from Eq. (2.80) (see [Tsai (1974)]), and atomic number Z for elements with Z up to 46.

Element	Z	X_{g0} g/cm²	Element	Z	X_{g0} g/cm²
H	1	63.05	Cr	24	14.94
He	2	94.32	Mn	25	14.64
Li	3	82.76	Fe	26	13.84
Be	4	65.19	Co	27	13.62
B	5	52.69	Ni	28	12.68
C	6	42.70	Cu	29	12.86
N	7	37.99	Zn	30	12.43
O	8	34.24	Ga	31	12.47
F	9	32.93	Ge	32	12.25
Ne	10	28.94	As	33	11.94
Na	11	27.74	Se	34	11.91
Mg	12	25.04	Br	35	11.42
Al	13	24.01	Kr	36	11.37
Si	14	21.82	Rb	37	11.03
P	15	21.02	Sr	38	10.76
S	16	19.50	Y	39	10.41
Cl	17	19.28	Zr	40	10.19
Ar	18	19.55	Nb	41	9.92
K	19	17.32	Mo	42	9.80
Ca	20	16.14	Tc	43	9.69
Sc	21	16.55	Ru	44	9.48
Ti	22	16.18	Rh	45	9.27
Va	23	15.84	Pd	46	9.20

Interactions of photons

Considering x-rays / gamma rays with energies much bigger than ~eV chemical energies.



Three Important Processes, all drastic in nature:

1. Photoelectric effect. Photon interacts with an atomic electron and gives it all its energy. Result one electron with all the photon energy. Dominant below ~1 MeV photon energy
2. Compton Effect. Photon scatters off atomic electron. Result one electron with some of the photon energy and a photon of reduced energy
3. Pair production. Photon converts to electron-positron pair. Result one electron and one positron which share the photon energy (not even split). Photon energy must be at least 1.022 MeV, and this really only becomes imporant above ~4 MeV. Mean free path 9/7 X_0

Notice (1) and (3) as described violate energy/momentum conservation. Actually only occur in electric field near nucleus. Hence cross sections rise with Z, and also lowest level electrons are hit.

Interactions of electrons (and positrons)

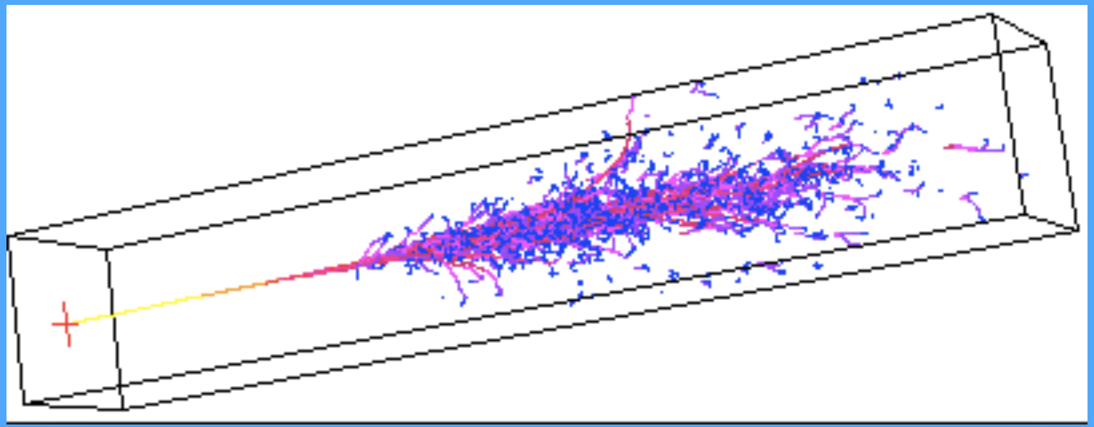
All Electromagnetic

Gentle: Energy loss to electrons in atoms. They see a changing electric/magnetic field, get excited (maybe even ionised) by it. Called dE/dx or LET. Also get randomly deflected in direction.

Drastic: Bremsstrahlung (note spelling!) Accelerated charges radiate. If an electron suffers a big energy/momentum deflection it can radiate a photon. Energy loss like e^{-x/X_0}

Positrons can also annihilate - but they usually slow down and stop first

Combination of electron and photon processes leads to the 'Electromagnetic Shower'. developing with typical length X_0,



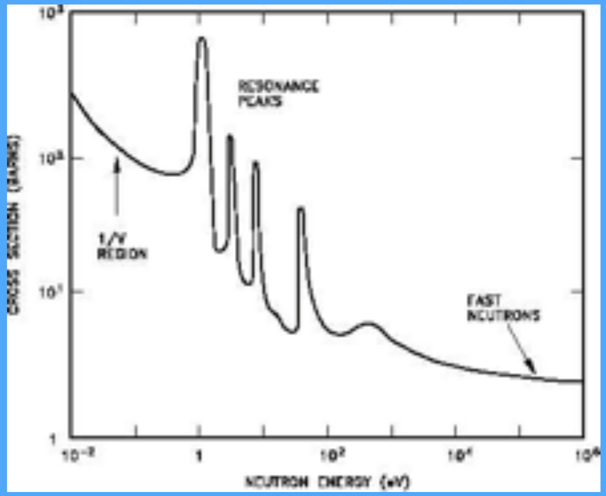
Interactions of neutrons

Entirely hadronic

Elastic collisions - bounce off target nuclei. Energy loss greater for light nuclei - hence ‘moderation’ in reactors and neuton sources using H, D, C…

Inelastic - absorption, fission, etc

Low energy behaviour dominated by resonances and hard to model



Protons also do all this. Relatively less important
 - but not negligible

How does Geant do it?

Program covers many orders of magnitude in particle energy

Can’t have universal package - 1 MeV is trivial at the LHC, enormous in medical simulations

Solution: the ‘Physics List’

In detail, particles separately, or as ‘reference physics list’

Some standard reference physics lists

- LHEP fastest but not always accurate. Good for showers
- QGSP_BERT Bertini cascade switching to QGS (quark gluon string) model above 20 GeV. Used by ATLAS
- QGSP_BERT_EMV similar but faster/cruder EM processes. Used by CMS
- QGSP_BERT_HP similar high precision neutrons (<20 eV) hence slower. Used for shielding etc
- QGSP_BIC Binary cascade. Recommended below 200 MeV (Medical)
- QGSP_BIC_HP similar but does low energy neutrons better (and slower)

The easy way: put something like this in your main program

```
G4PhysListFactory *physListFactory = new G4PhysListFactory();
G4VUserPhysicsList *physicsList
=physListFactory->GetReferencePhysList("QGSP_BERT");
runManager->SetUserInitialization(physicsList);
```

The hard way

For each particle species:

Register the relevant processes

Register one or more models for each processes

particles like

“proton”, “neuton", “alpha”,”mu+”…

process names like

G4MuIonisation, G4hMultiplescattering…

Model names like

G4CascadeInterface, G4hBinaryCascade…

Assessment

- Simulate 1 GeV electrons bombarding a 1m cube of Alumiunium. Generate an event and find instances of the important physical processes.
- Repeat for 1 GeV photons, muons, protons and neutrons.
- Choose a different physics list and repeat. Each student should use a different list. (Explain why you chose this particular list)