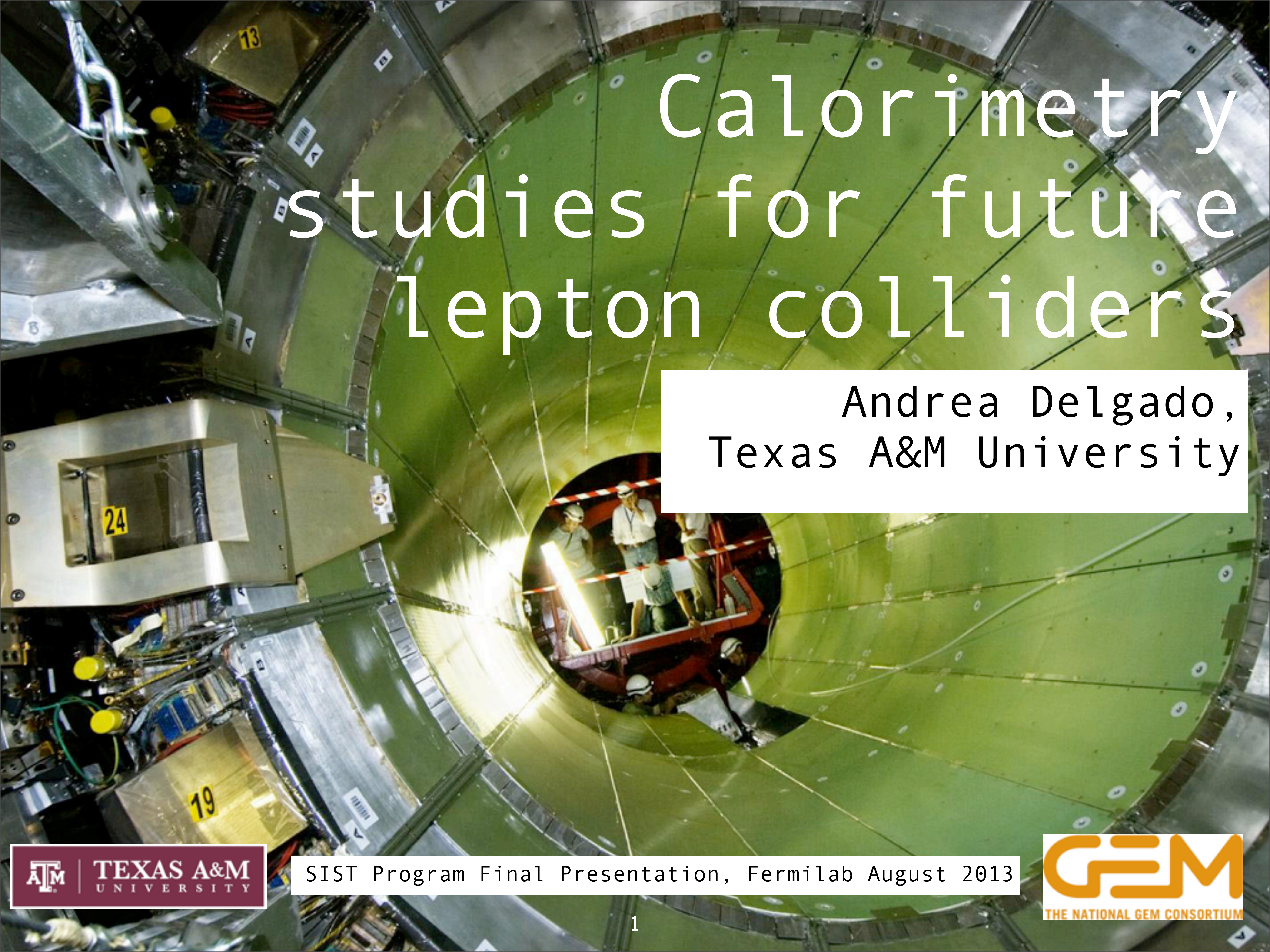
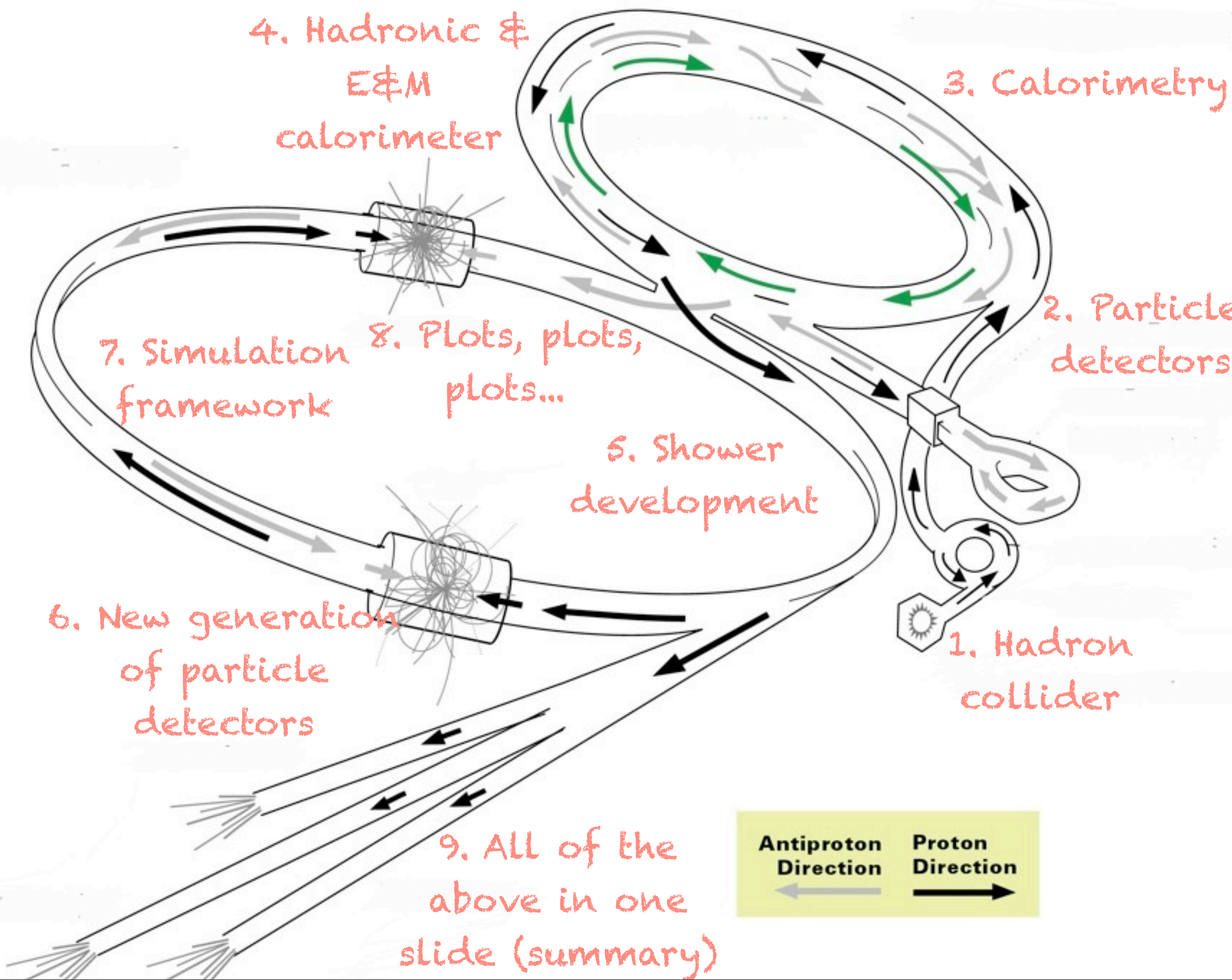


Calorimetry studies for future lepton colliders

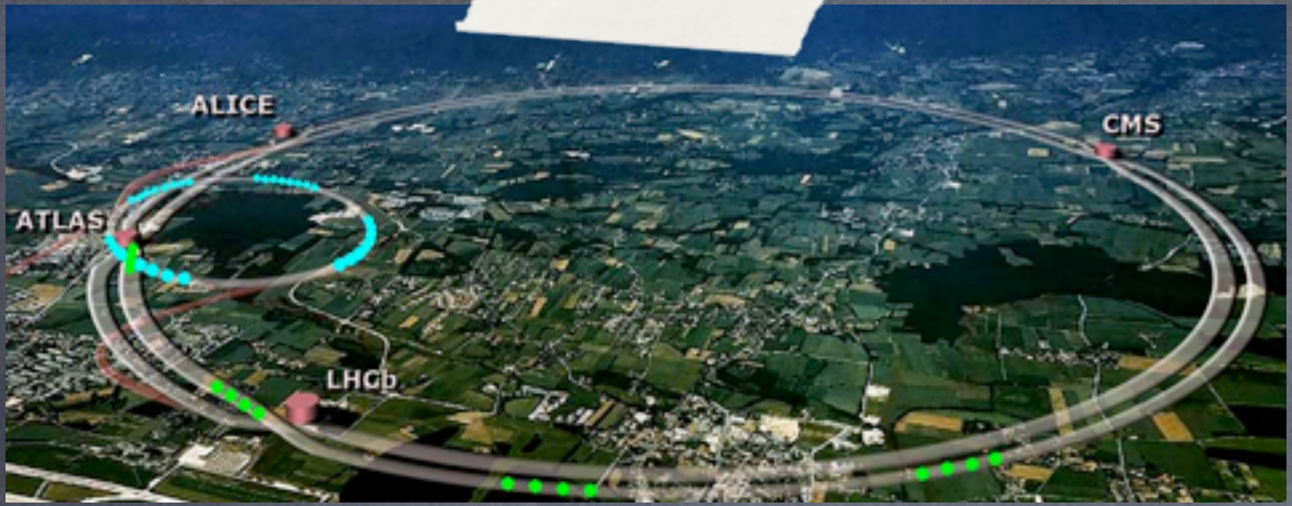
Andrea Delgado,
Texas A&M University

SIST Program Final Presentation, Fermilab August 2013

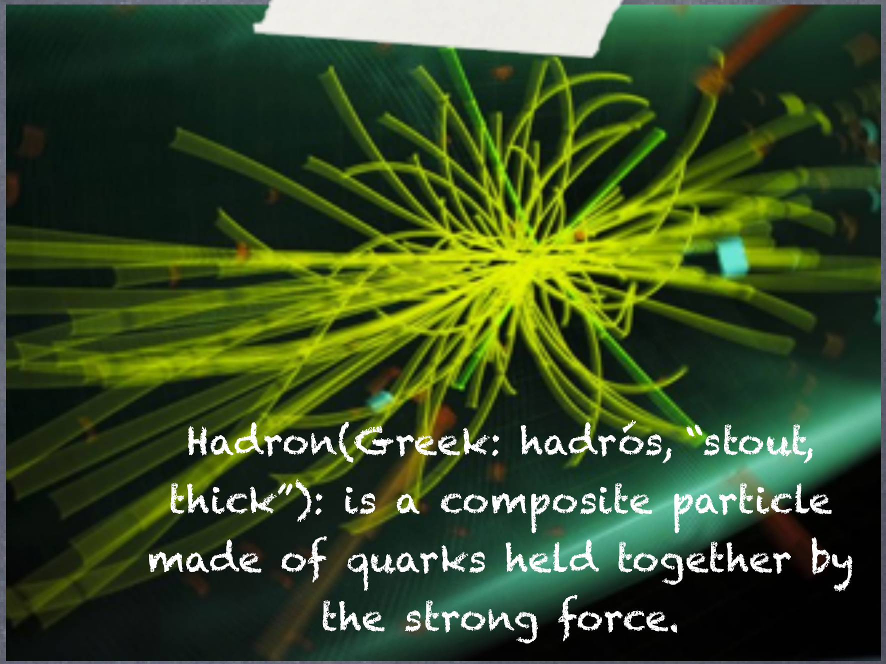
Talk's accelerator chain (outline)



#hadroncollider, #Higgsboson



- Spend $4.4-billion building a 27-kilometer underground tunnel that provides work for about 10,000 scientists and engineers.



Hadron(Greek: hadrós, "stout, thick"): is a composite particle made of quarks held together by the strong force.

- Then send protons whizzing around the tunnel at about the speed of light until they crash into each other.

- It is at this point -where man has created conditions similar to those at the birth of the universe- that a glimpse of the Higgs boson may be seen. But you have to be quick because the Higgs boson decays almost instantly after it interacts with other particles

#particledetector, #calorimeter

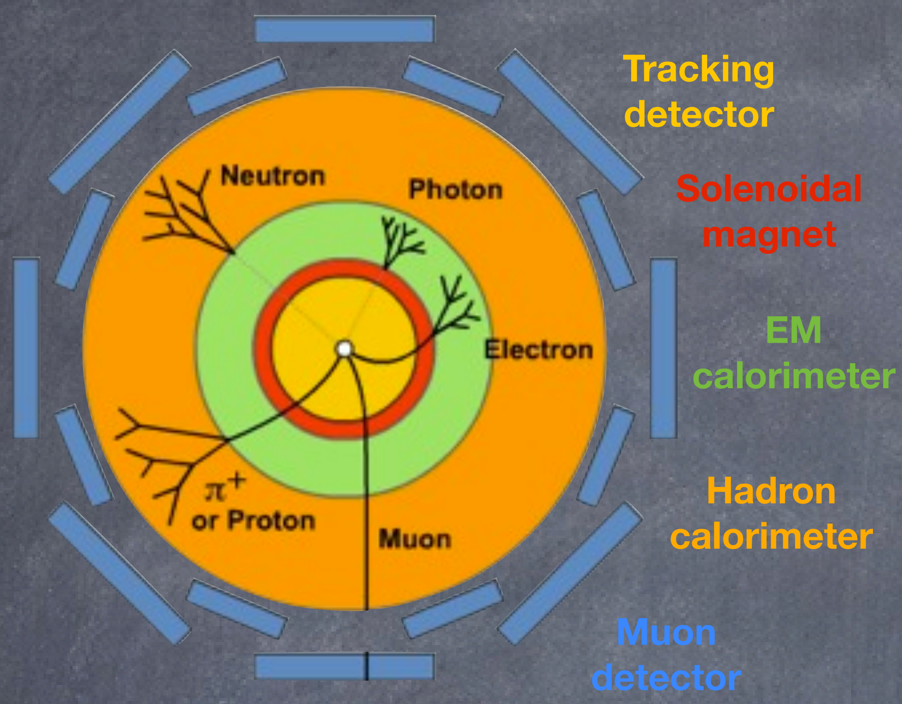
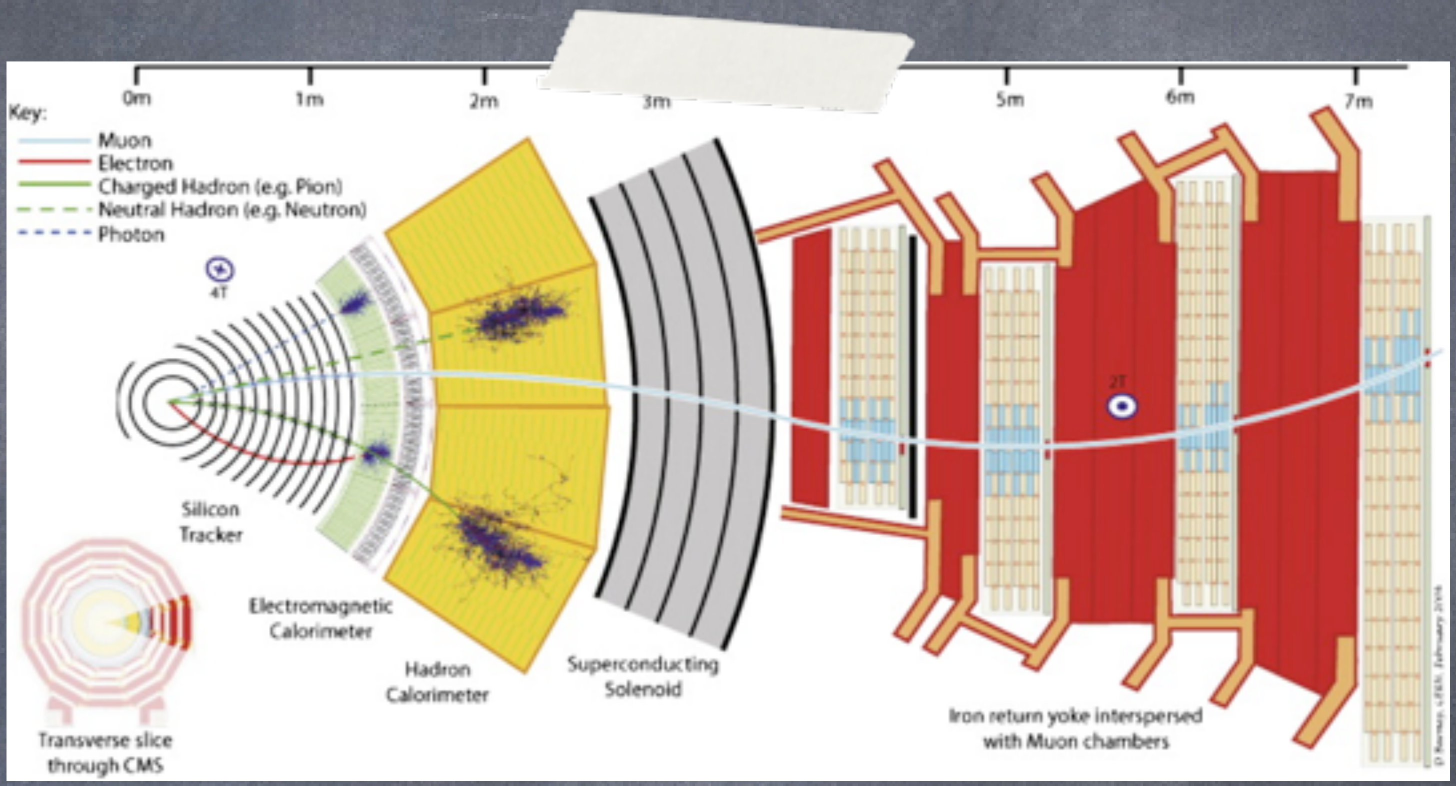
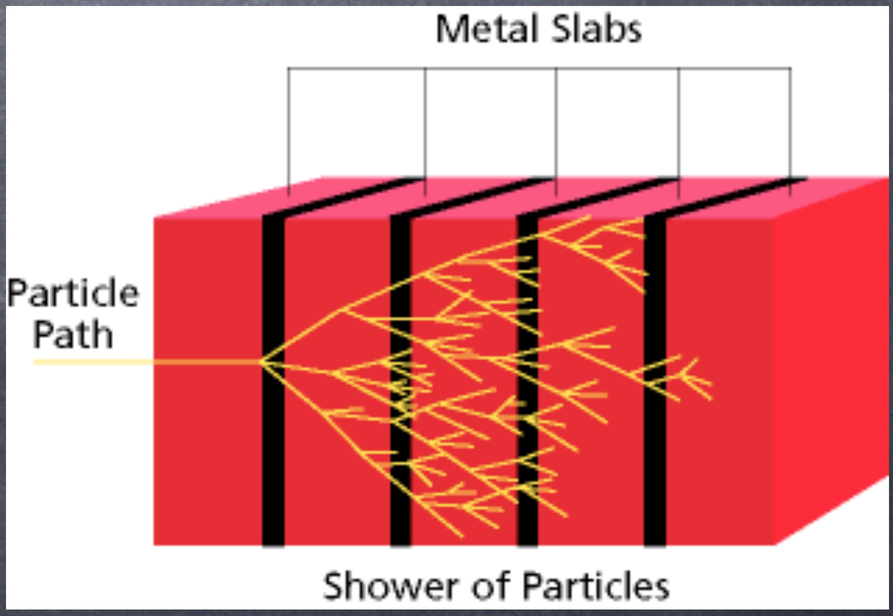


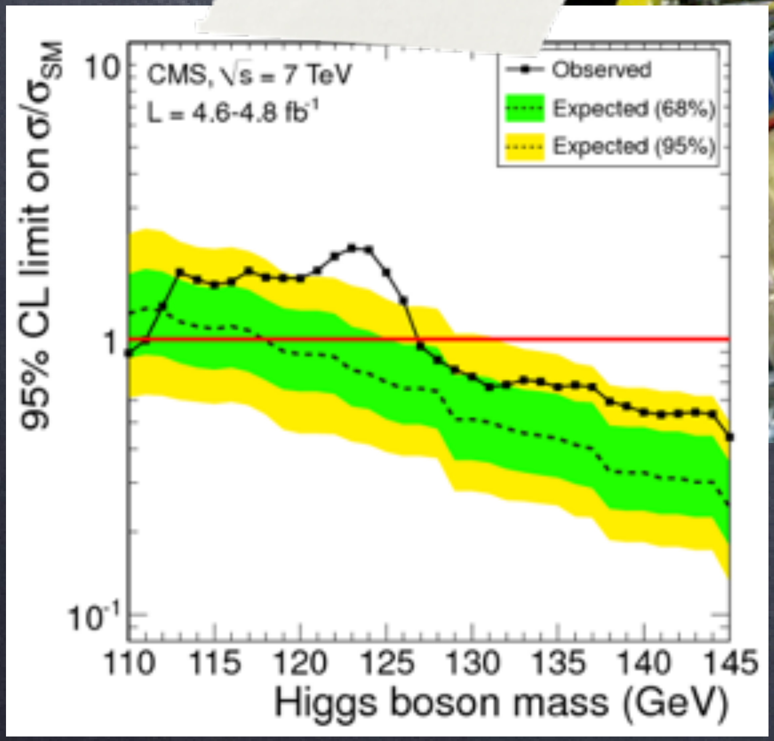
Fig. 1.1. End-view cross-section of the ATLAS detector



- A calorimeter is a block of matter in which the particle that is to be measured interacts and deposits its energy in the form of a shower of increasingly lower-energy particles.
- This block is made in such a way that a certain fraction of the initial particle energy is transformed into a measurable signal (light, electrical charge).

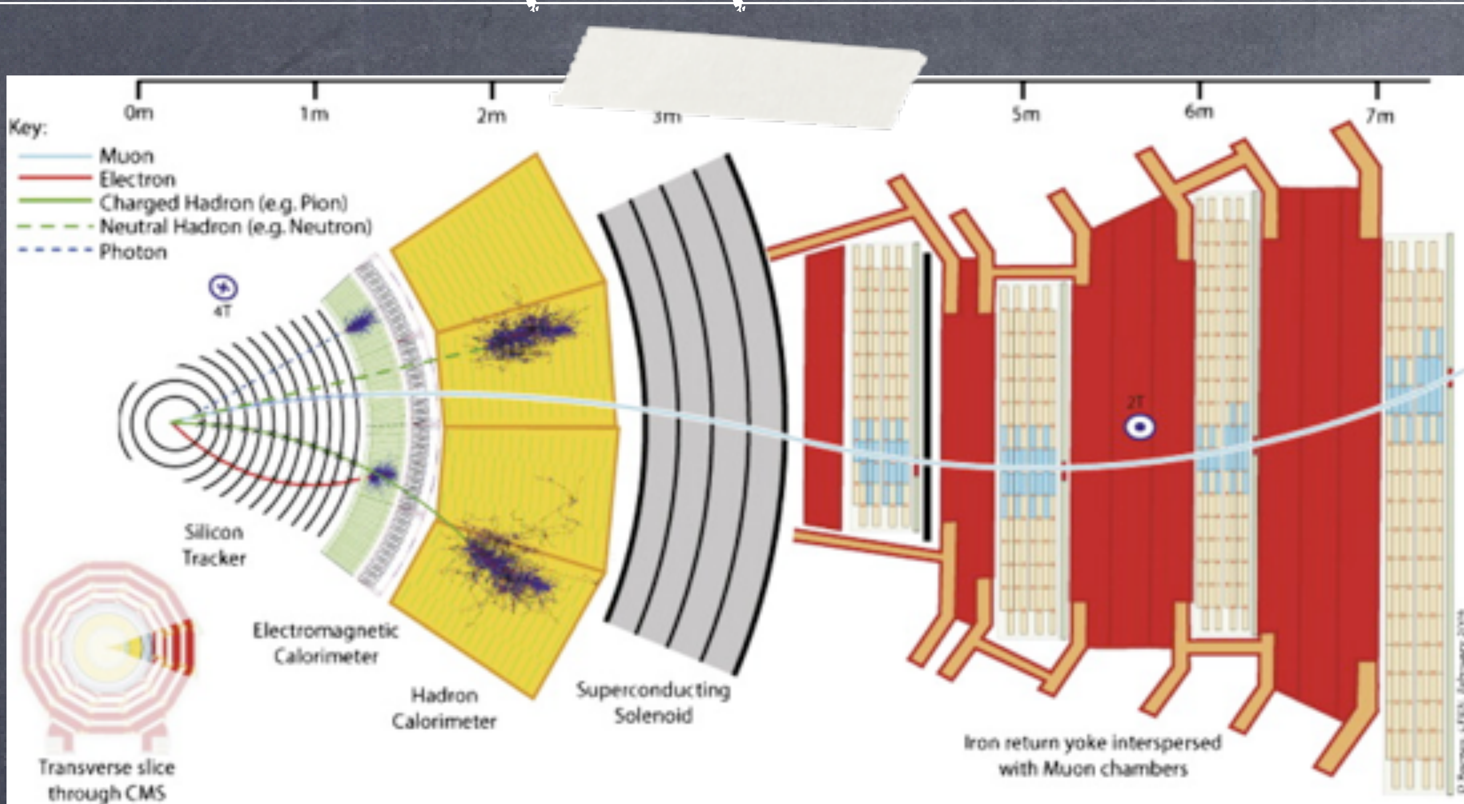


Sampling calorimeter



CMS ECal -> Lead Tungsten Crystals

Hadronic & E&M calorimeter



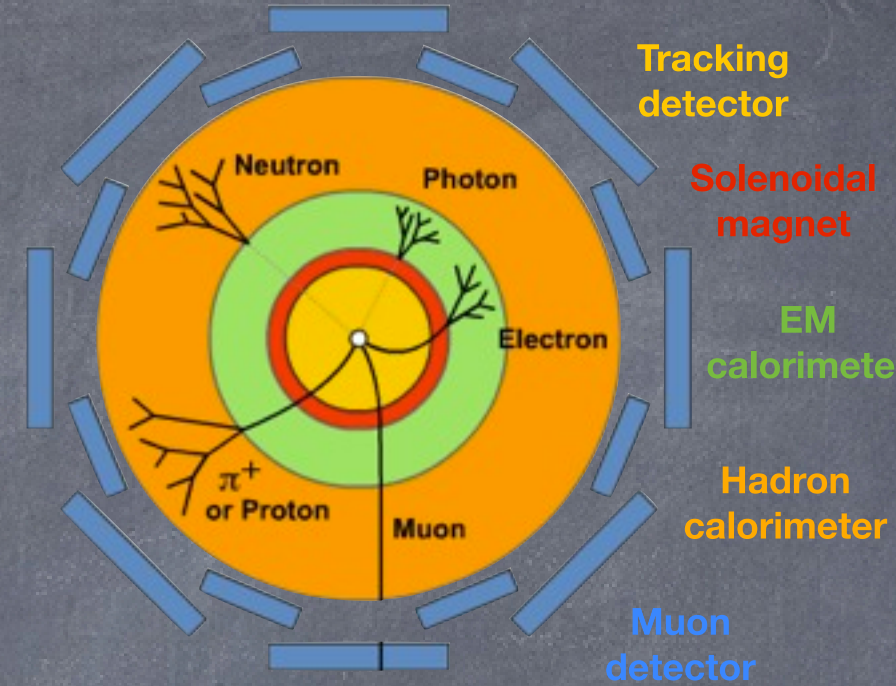


Fig. 1.1. End-view cross-section of the ATLAS detector

Hadronic processes

- Elastic
- Capture
- Fission
- Pi+ inelastic
- K+ inelastic
- K- inelastic
- K0L inelastic
- K0S inelastic
- Proton inelastic
- Neutron inelastic
- Sigma+ inelastic
- Sigma - inelastic
- Xi- inelastic
- Deuteron inelastic
- Triton inelastic
- Alpha inelastic
- Ion inelastic
- Pi- absorption
- K- absorption
- Anti-proton annihilation
- Anti-neutron annihilation
- Neutron capture at rest
- Negative hadron capture
- Radioactive decay
- Electron nuclear
- positron nuclear
- Omega- inelastic
- Anti-proton inelastic
- Anti-neutron inelastic
- Anti-lambda inelastic
- Anti-sigma+ inelastic
- Anti-sigma- inelastic
- Anti-Xi- inelastic
- Anti-xi0 inelastic
- Anti-omega- inelastic
- Gamma nuclear
- Muon capture
- and many more!

E&M processes

- Coulomb scattering
- Bhabha scattering
- Möller scattering
- Compton scattering
- Bremsstrahlung
- Annihilation
- Pair creation
- Cerenkov radiation

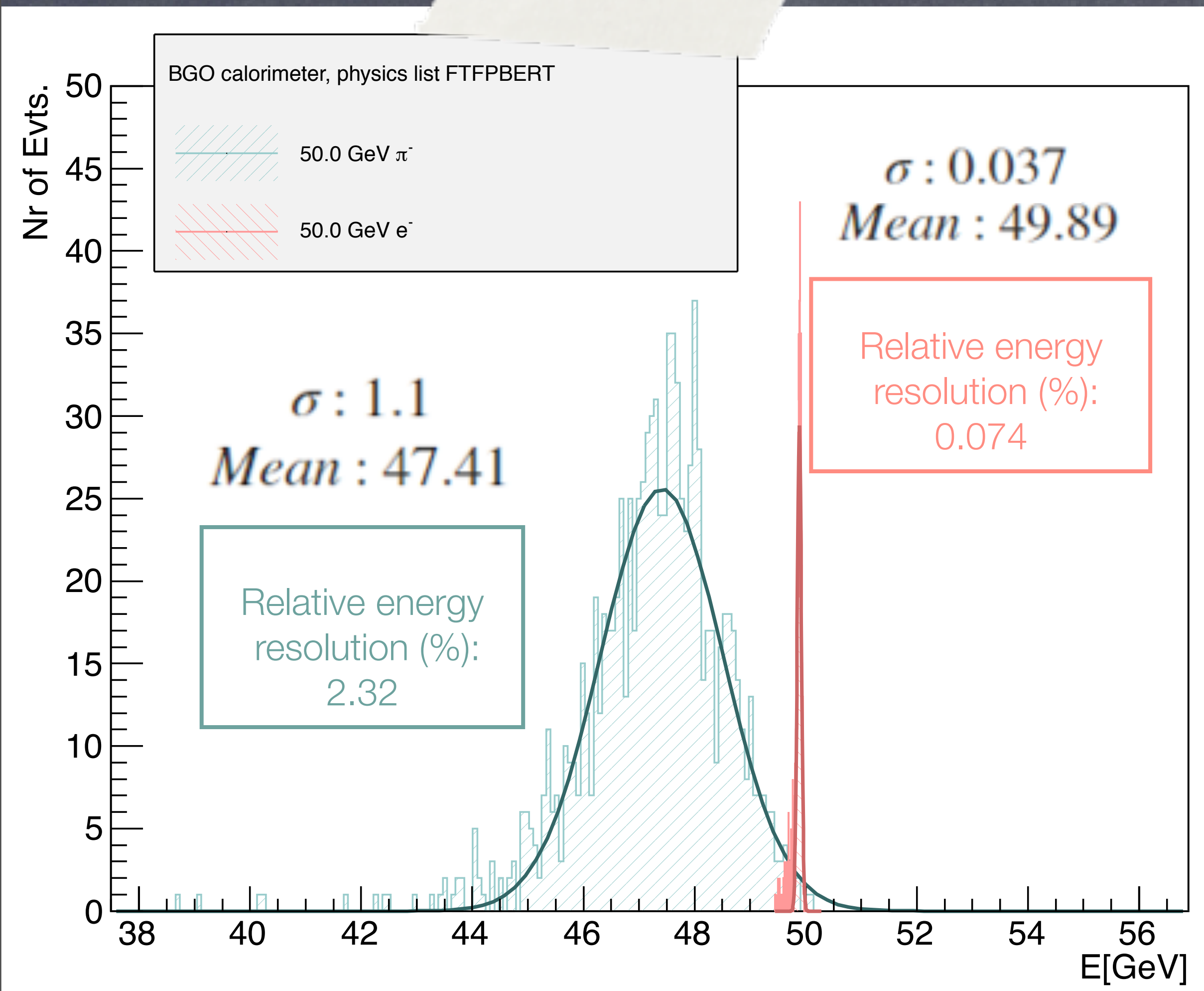
E&M cascade

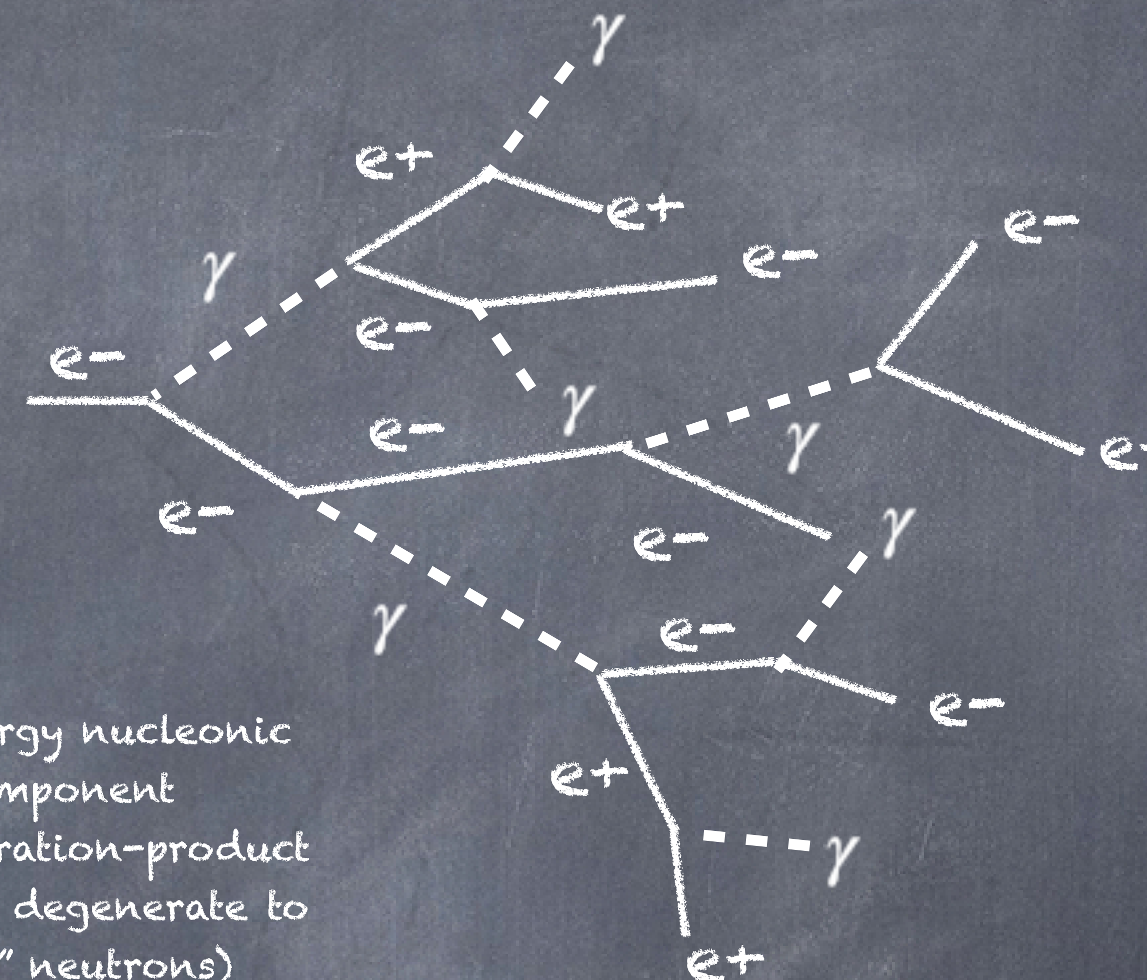
- e-
- e+
- photons

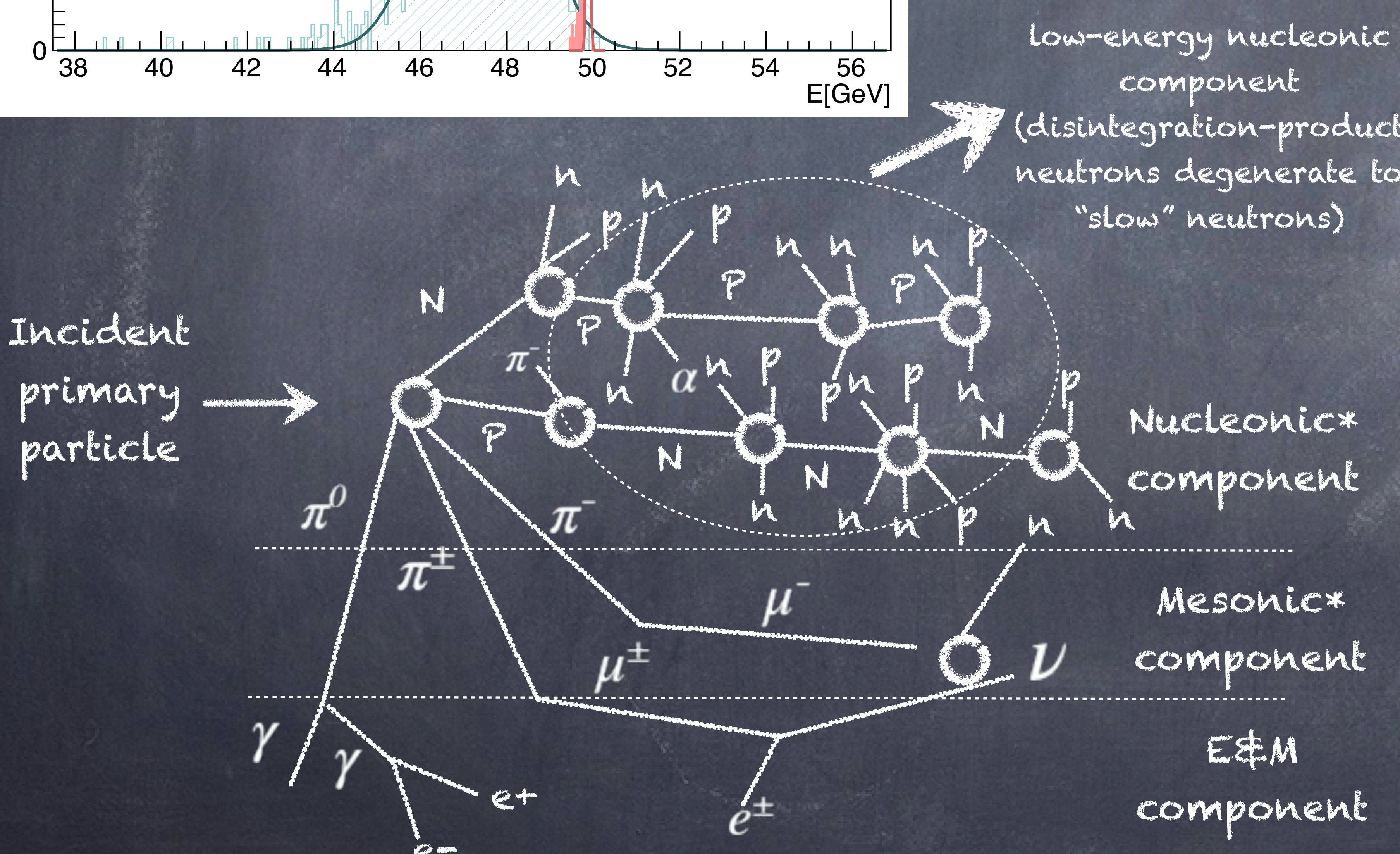
Hadronic cascade

- protons
- neutrons
- anti-protons
- pions
- kaons
- muons
- ...everything else decays very quickly into these particles

Particle cascades







Key:

N & P = high energy nucleons

n & p = disintegration-product nucleons

○ = nuclear disintegration

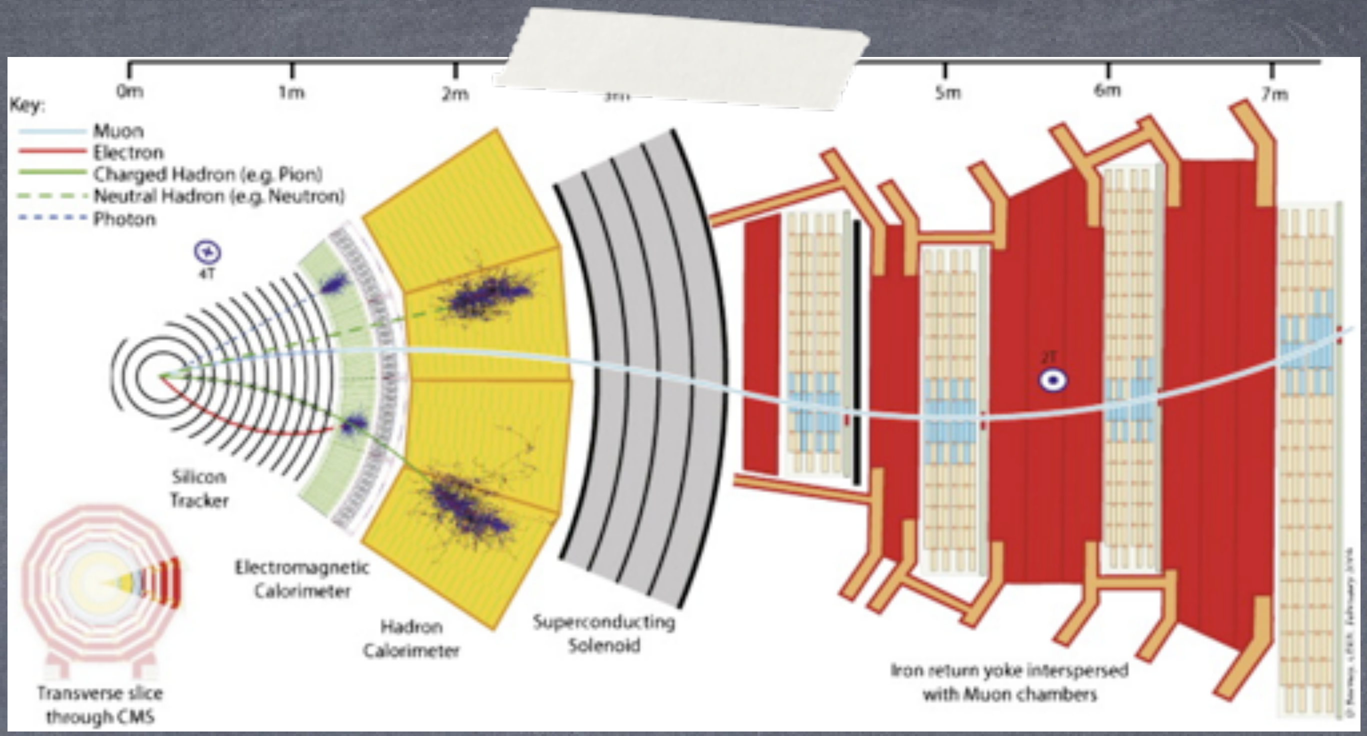
*Nucleon: proton or neutron

**Meson: hadron composed of one quark and one antiquark (pions, kaons).

Scaling variables

Radiation length = Related to the distance over which a high energy (> 1GeV) electron or position loses, on average, 63.2% of its energy to bremsstrahlung (~10 cm).

Nuclear interaction length = Related to the average distance a high energy hadron has to travel inside a medium before a nuclear interaction occurs.



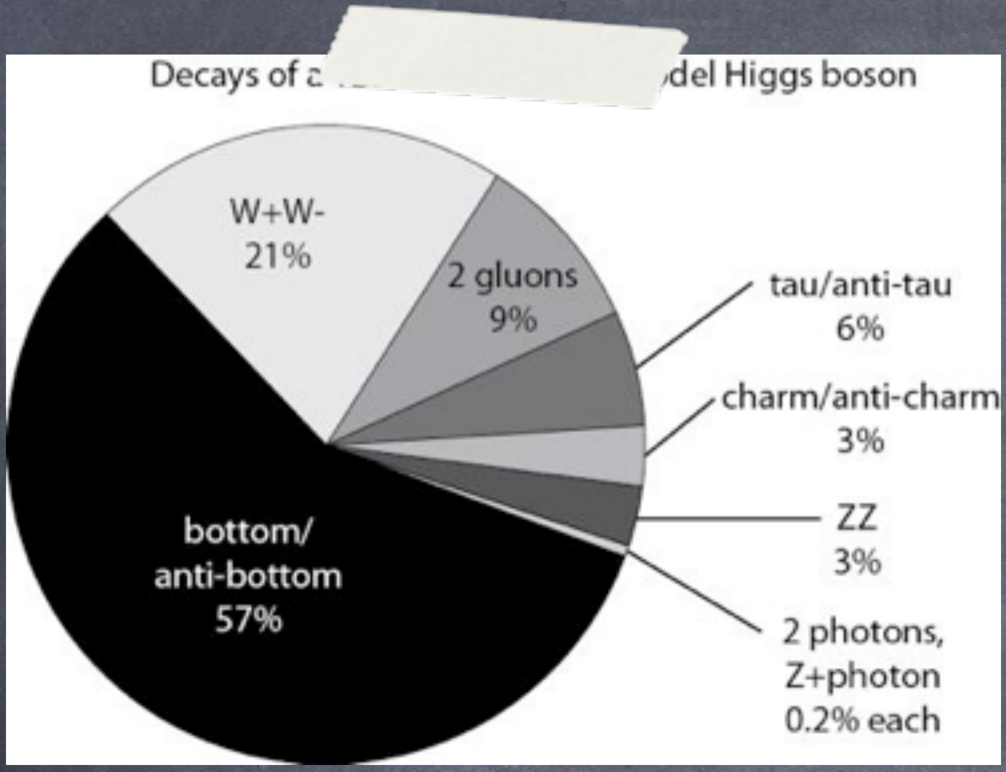
These processes determine not only the energetic resolution, but also the size of the shower and therefore calorimeter volume needed to contain such showers.

Since the E&M shower development is primarily determined by the electron density in the medium, it is to some extent possible to describe the shower characteristics in a material -independent way.

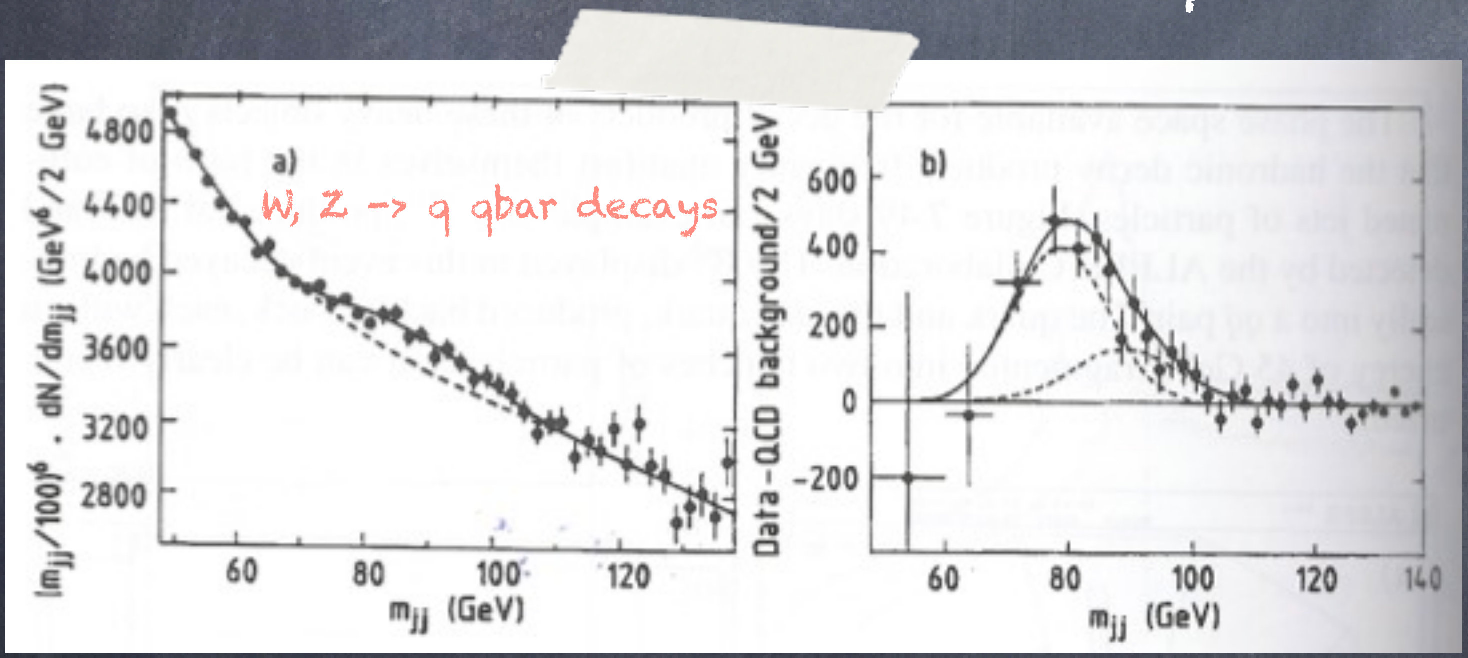
Material	Density [g/cm3]	Radiation length [cm]	Nuclear interaction length [cm]	Z	A [g/mole]
Scintillator (C9H10)	1.032	43	46.89	3.94	118.18
Fe	7.874	1.757	16.77	26	55.85
W	19.25	0.354	9.946	74	183.84
Pb	11.34	0.5612	17.59	82	207.2

More volume is needed to contain a hadronic shower !

Motivation for a next generation of calorimeters



- so....it's a complicated story!
- A better understanding of the physics involved in shower development (more specifically, hadronic cascades) is required.
- Future lepton collider will require improved precision of all detector systems.



Two-jet invariant mass distribution from UA2 experiment.

- A benchmark of this new type of calorimeter is the requirement to be able to distinguish W and Z vector bosons in their hadronic decay mode.

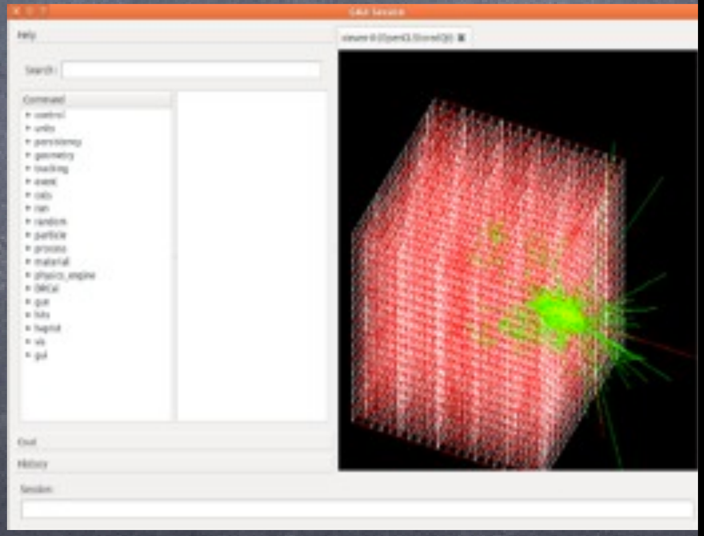
This requires a di-jet mass resolution better than the natural width of these bosons and hence a jet energy resolution better than 3%... for hadron calorimetry this implies an energy resolution of a factor of 2 better than previously achieved by any large-scale experiment!

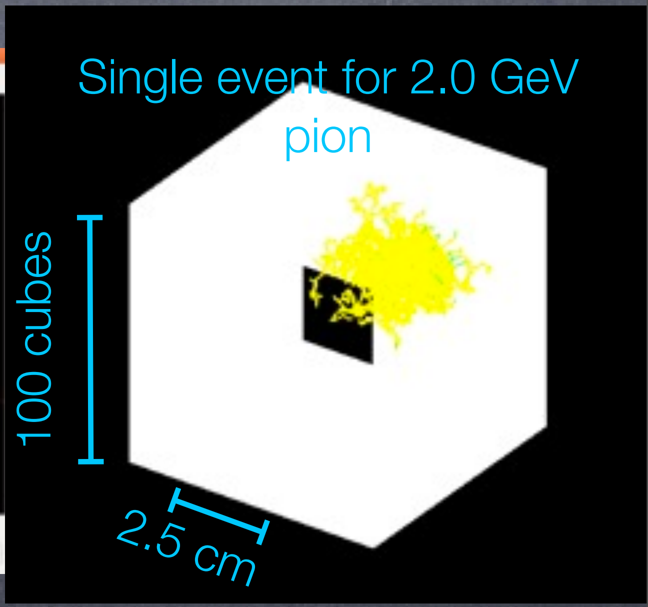
The actual work
=
Calorimeter simulation studies

Simulation framework: CaTS (Calorimeter and Tracker Simulation) (Hans Wenzel, Peter Hansen)

CaTS → **Simulation:** Geant4, A powerful tool to describe how particles interact with matter. → **Analysis:** ROOT

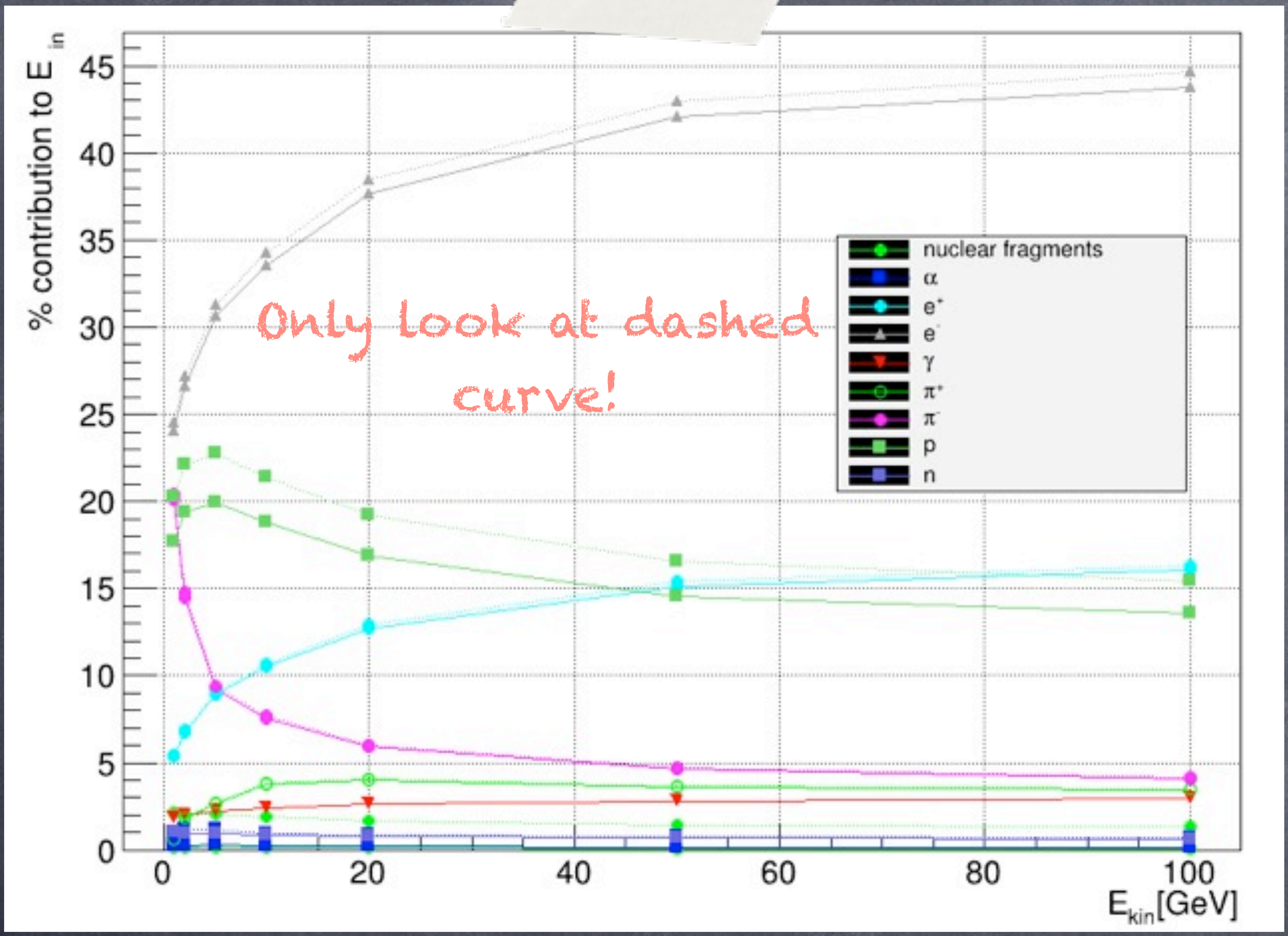
- Facilitates the description of the detector geometry by using an input file in xml format which contains relevant optical properties (refraction index, absorption length, etc..).
- Provides the possibility of writing the simulated events, an analysis framework and the capability of filling histograms in various user actions.
- Allows for total volume (general) studies as well as for a detailed study of single calorimeter cells, and for the modification of the detector settings without having to recompile.





Simplifies working with Geant4!

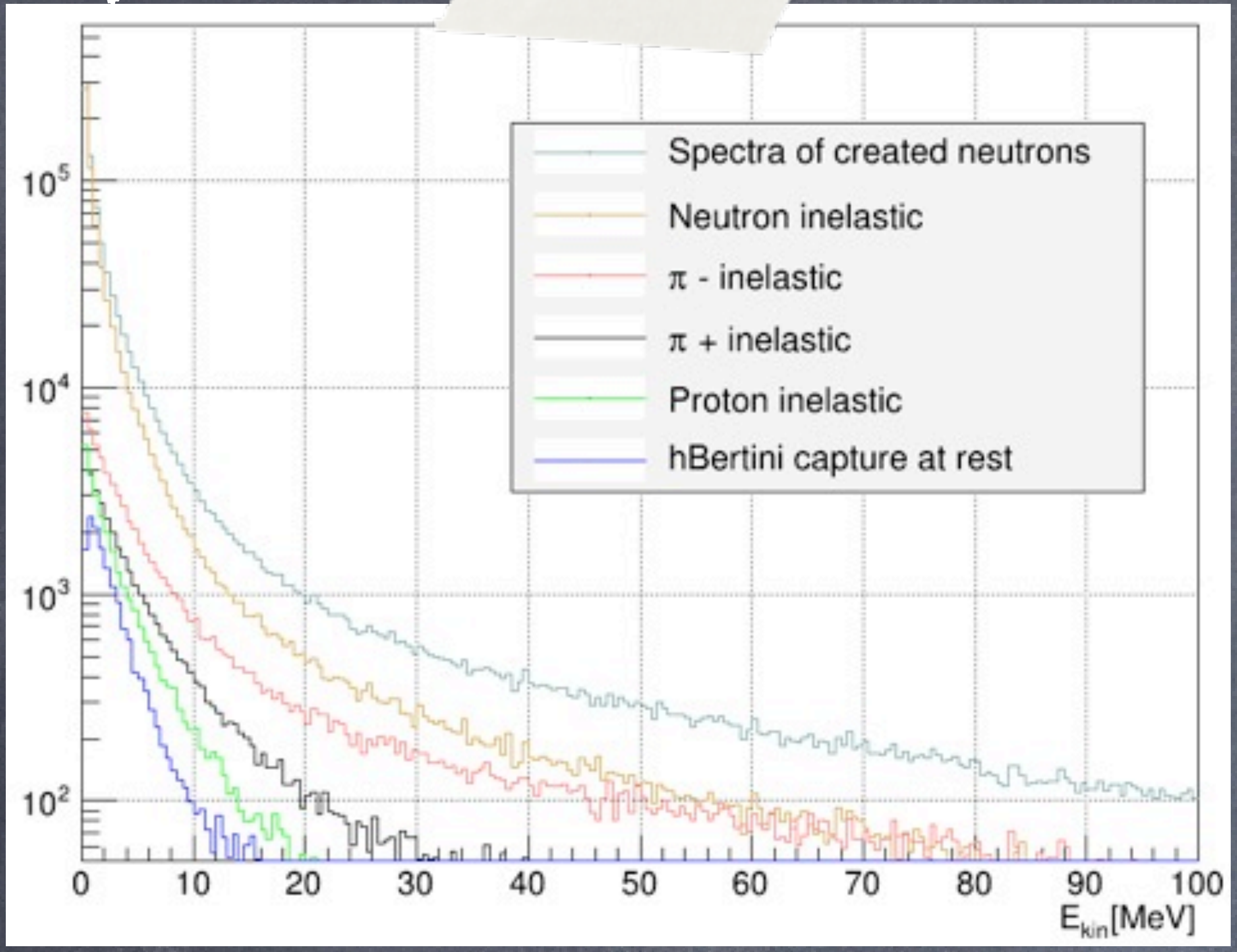
Contribution to signal by particle

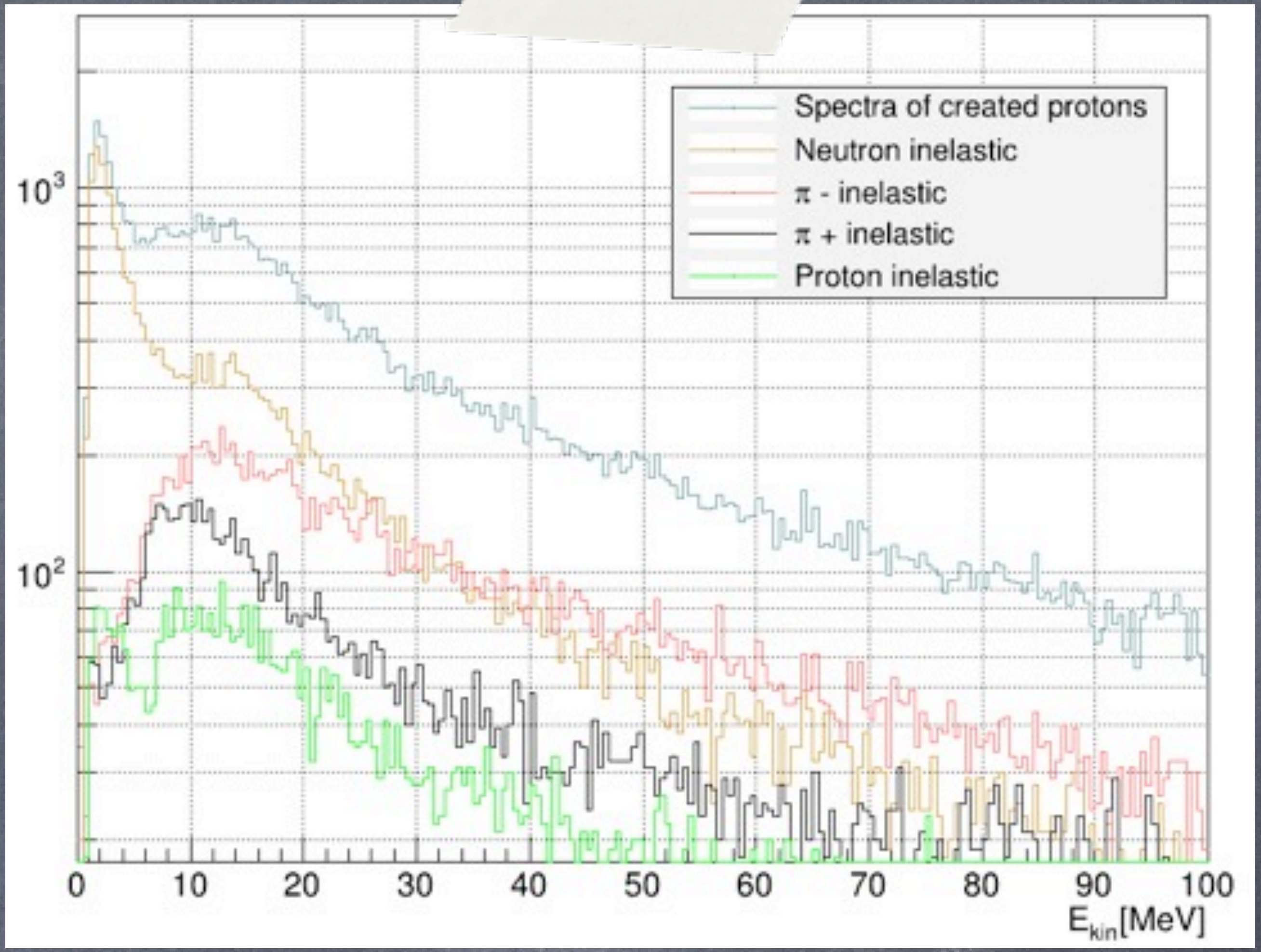


Showers produced with single charged pions

- Electrons and positrons are important for signal but their interactions are well-understood.
- Protons are important for signal!
- Neutrons will also contribute to signal if we wait long enough for them to be captured!

Spectra of created neutrons & protons





- Soft (low kinetic energy) protons & neutrons are created by neutrons (mostly). -> Important for signal generation!
- Leading particle effect -> More neutrons & protons are created in pi- inelastic processes than they are in pi+ inelastic processes.
- Two components in spectra of created protons -> Nuclear spallation process.
- In general neutrons are easier than protons to produce -> Coulomb barrier.

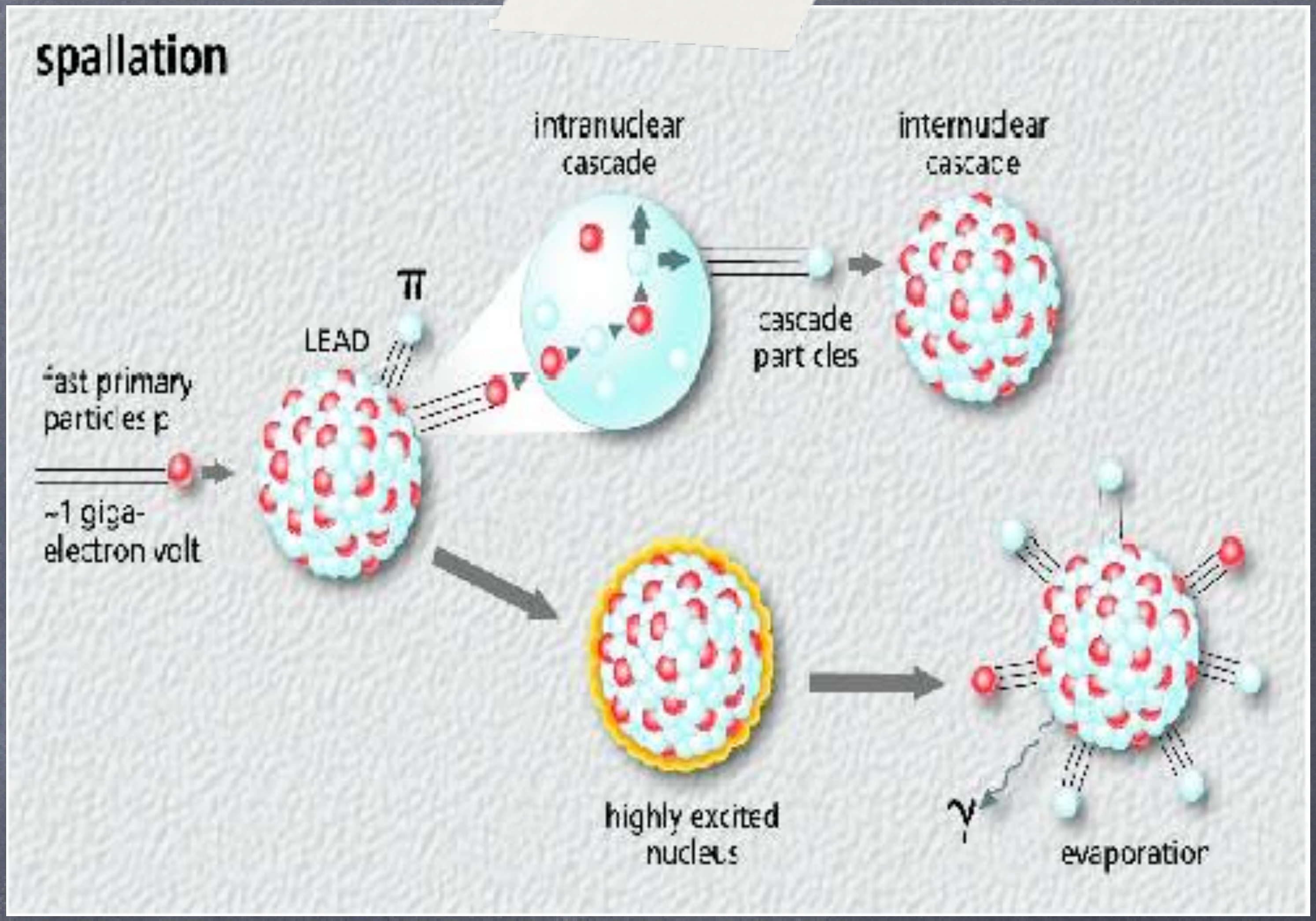
What do we learn from these plots?

- 20 GeV incident pi-
- PbF2 crystal calorimeter
- 1000 evts.
- FTFP_BERT physics list
- Geant4 version 9.6p2

Nuclear spallation reactions

Two step process:

- Intra-nuclear cascade: incoming hadrons makes quasi-free collisions with nucleons inside the struck nucleus.
- Evaporation or de-excitation: most of the particles involved are free nucleons and it goes on until excitation energy is less than binding energy.



Most likely process to occur when an incoming high-energy hadron strikes an atomic nucleus!

Nuclear spallation reactions

- In the fast cascade stage, protons and neutrons are emitted in the ratio in which they are present in the target nucleus.

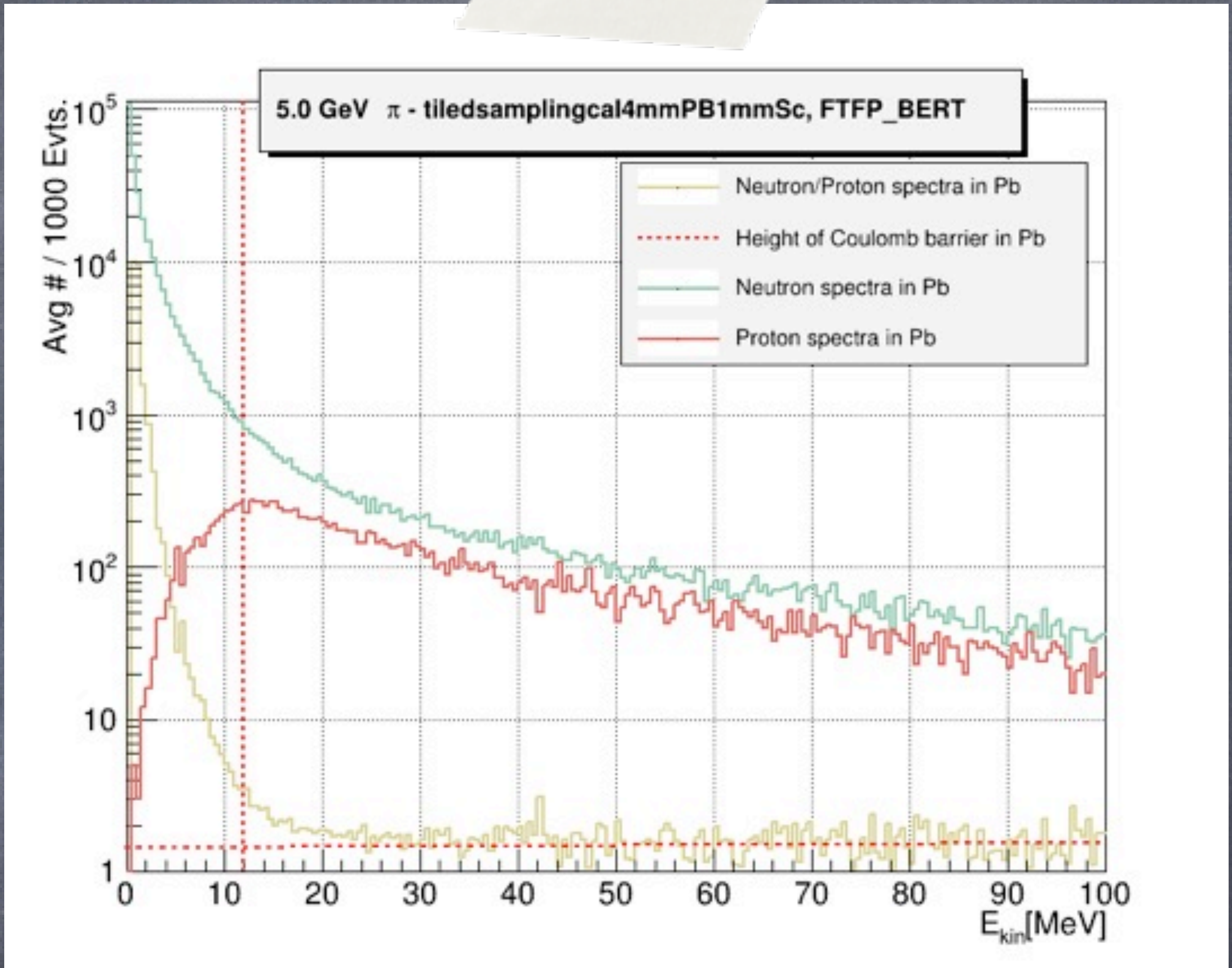
Pb^{208}_{82} for every cascade proton, ~1.5 cascade neutrons

- Height of Coulomb barrier (~12 MeV in Pb) is given by:

$$\frac{z_1 z_2 e^2}{4\pi\varepsilon_0 r}$$

where

r = Pb atomic radius (~ 0.175 nm)
e = proton charge
Z1 = Pb atomic number (82)
Z2 = atomic number of incident particle



Where do protons and neutrons go?

Protons

- Ionize medium, contributing to signal.

→ Suppression?

Neutrons

- Escape calorimeter volume.
- nKiller(in Geant4) above 10 micro-seconds or below threshold.
- Inelastic scattering -> low momentum hadrons, protons.
- Thermalization -> neutron capture -> gamma -> e&m shower

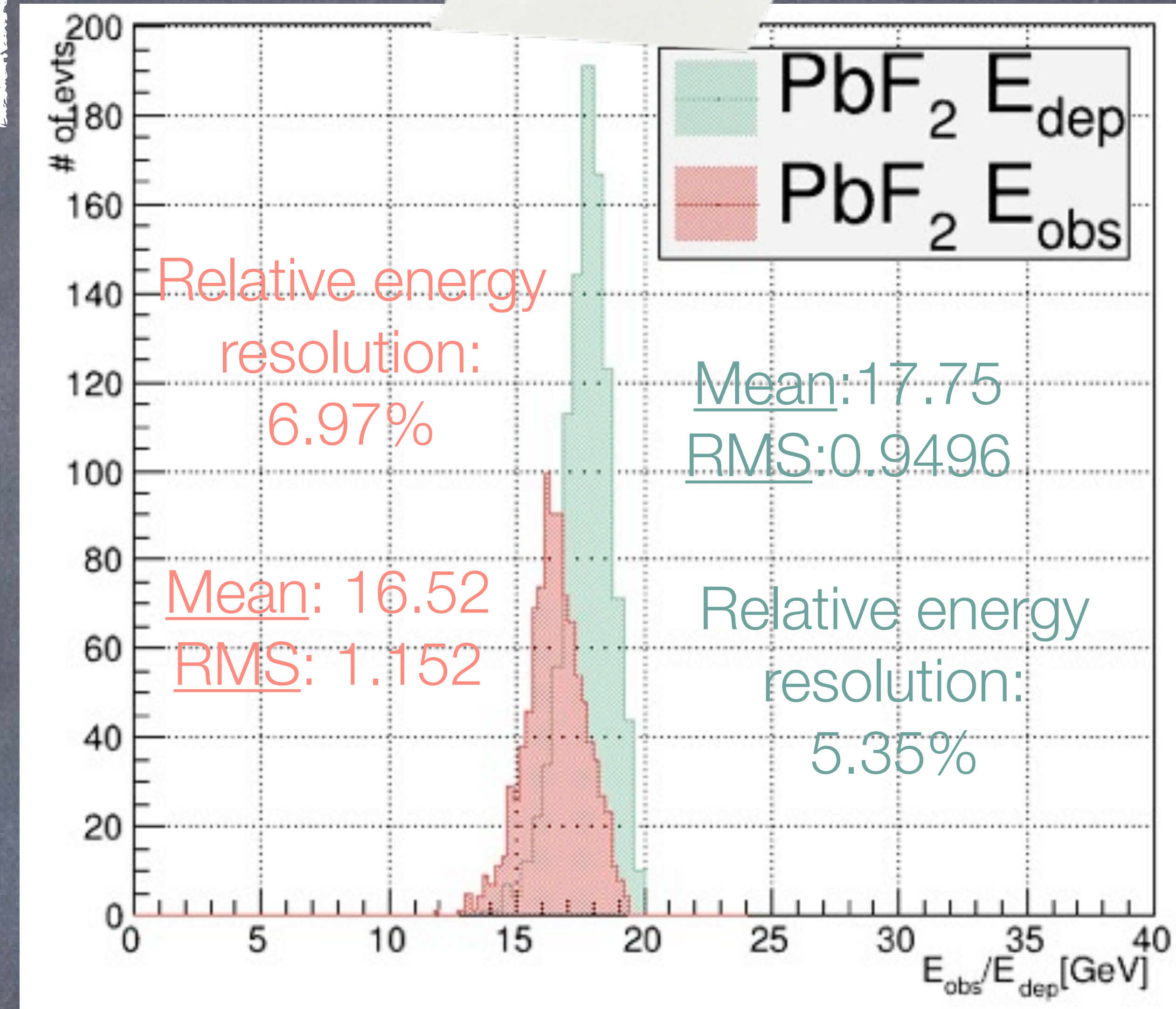
Birks' attenuation

- Empirical formula for the light yield per path length as a function of the energy loss per path length for a particle traversing a scintillator.
- Heavily ionizing particles produce less light.

$$\frac{dL}{dr} = \frac{S\cdot {dE}/{dr}}{1 + c_1\cdot {dE}/{dr} + c_2\cdot({dE}/{dr})^2}$$

$$c_1 = 1.29\times10^{-2} g\cdot cm^{-2}\cdot MeV^{-1}$$
$$c_2 = 9.59\times10^{-6} g^2\cdot cm^{-4}\cdot MeV^{-2}$$
$$S = 1$$

Values used by ATLAS TileCal and CMS HCAL (also default in Geant3)



where:

Edep -> energy deposited in the entire calorimeter volume.

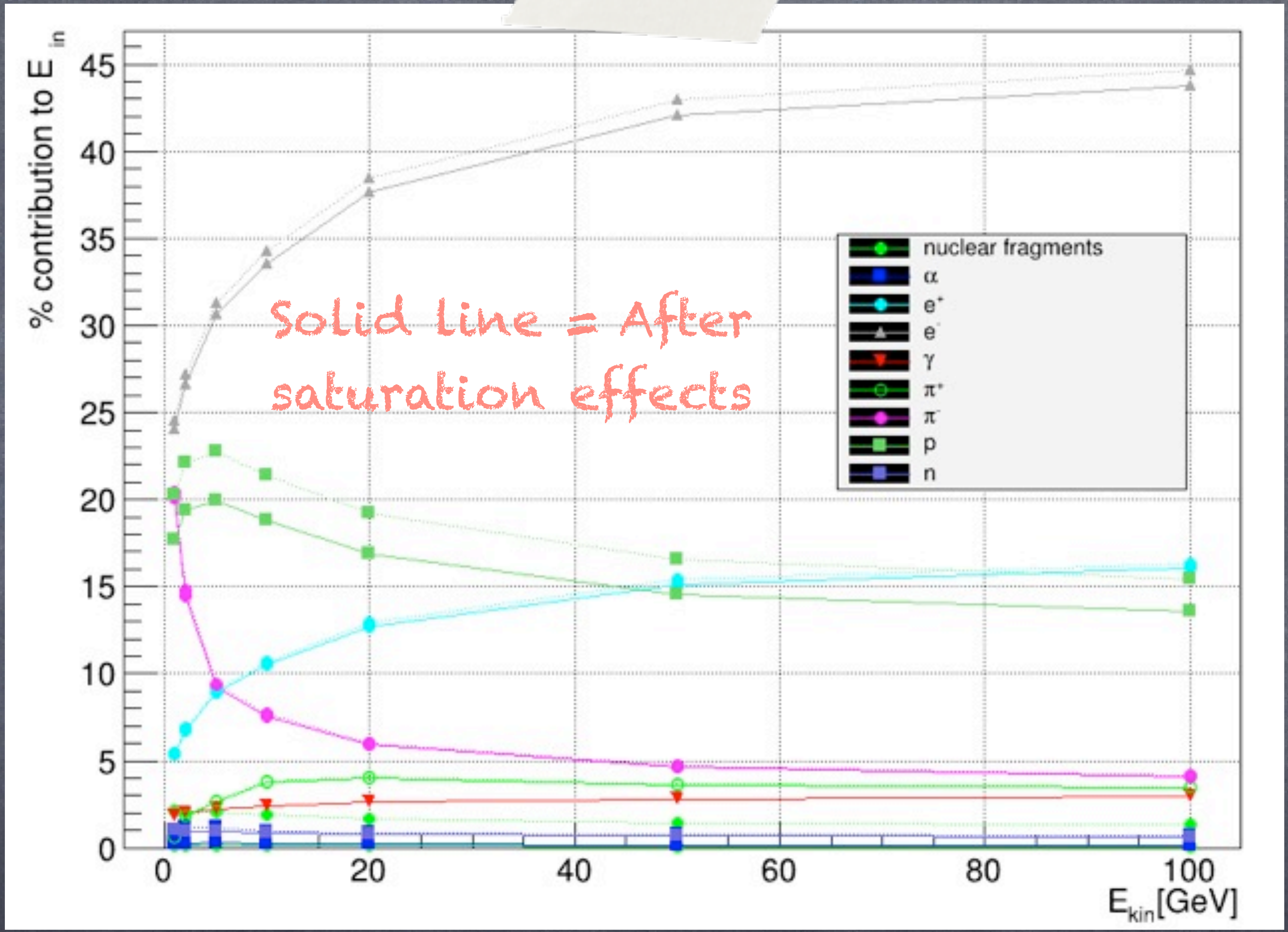
Eobs-> observed energy after applying Birks suppression

S -> scintillation efficiency (1)

c1, c2 -> Birks constants

dL/dx -> light output

Contribution to signal by particle: before and after saturation effects.



- Protons are the most affected by saturation effects leading to a suppression of about 3% throughout the energy range.

Summary

- Physics behind hadronic shower development is not yet understood completely, further study on the processes and particles involved is required.
- New and more precise instruments like in this case high precision hadronic calorimetry open the path to new discoveries.
- Simulation is a great tool to understand all processes and particles that contribute to the signal in a hadronic calorimeter.
- Overall, knowledge about particles and processes that play an important role in signal generation will allow us to optimize detector resolution.