4-й семестр
Statistical methods in experiments.

- \- Компьютерное слово, типы переменных
- \- языки программирования, С++
- \- операционная система LINUX, основные команды, редактор VI
- \- статистические распределения
- \- система ROOT
- \- 1-мерные гистограммы (booking, filling, edition, Read/Write, доступ к деталям
- \- 2-мерные гистограммы
- \- NTuples, Trees
- \- использование Trees с Make Class
- \- простейшие задачи на оптимизацию
- \- фит 1-мерных распределений
- \- MINUIT
- \- likelihood
- \- введение в ROOIT и фит 2-мерных распределений
- \- по ходу занятий используются данные VES и ATLAS
- \- в основном должны быть семинары на компьютерах + несколько лекций

Introduction

- Work on experimental data is performed on computers under LUNUX, mainly with programs written at C++
- Analysis of data after geometrical reconstruction is usually produced with CERN ROOT tools https://root.cern.ch/guides/users-guide
- Presentations of results are usually prepared with Windows tools (PowerPoint)
- Detailed information concerning Particle Properties, interactions with matter, Standard Model can be found in http://pdg.lbl.gov/
- A simplified review of particle interactions with matter and particle detection follows.

Accelerators and Cosmic Rays

- The highest detected energy of cosmic ray particle is of order of 10^{21} eV, however the flow is low (less than one event per km^2 per year). The energy in the center of mass system in collision of this particle with proton $\sqrt{s} \approx 10^{15}$ eV.
- The highest energy reached in proton-proton colliders is $1.3 \cdot 10^{13}$ eV and $2.1 \cdot 10^{11}$ eV in e^+e^- collisions.
- Time interval between collisions of proton bunched at LHC experiments is 50 ns of 25 ns, and mean number of interactions per bunch crossing in ATLAS and CMS experiments is of order of 20 and rising from year to year with LHC modifications.
- Trigger system restricts the number of recorded events to 1000 events per second. Typical event volume is or order of 1 Mbyte.

Detection of charged particles

- Charged particles detected due to ionization in the matter, i.e. many electrons (mainly slow(kicked an the charged particle trajectory. Momentum of Charged particle is measured by a curvature of trajectory in magnetic field. Other processes with charged particles: bremsstrahlung (photon emission in electric field from nuclei or electrons), Cherenkov light emission (if velocity of charged particle is greater than the speed of light in medium), transition radiation (due to a light emission by a dipol which arises when charged particle fly through surface which separate vacuum from medium), and the synchrotron radiation due to curvature of trajectory in magnetic field.

Mean Energy losses for muon

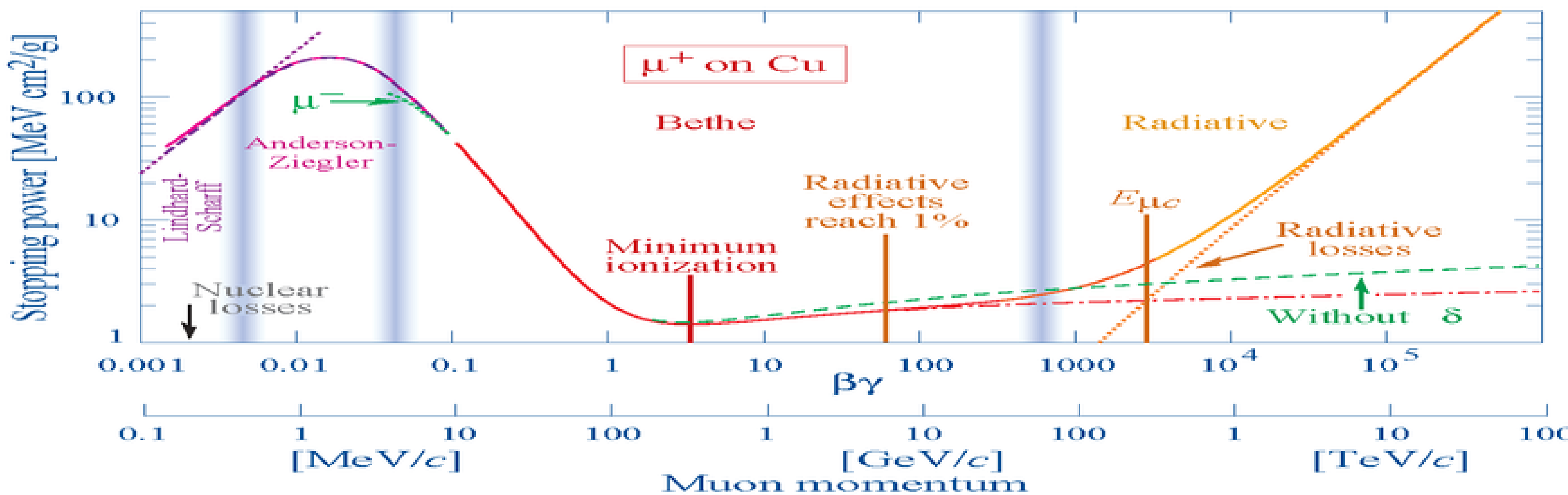
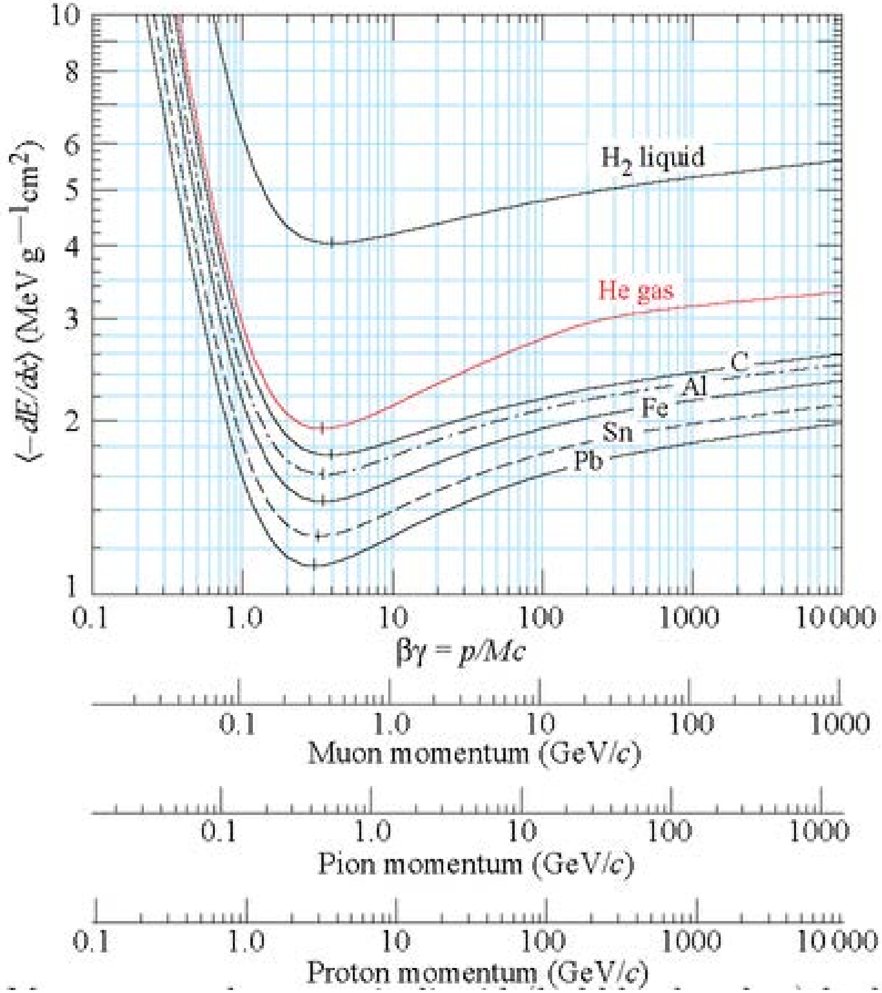
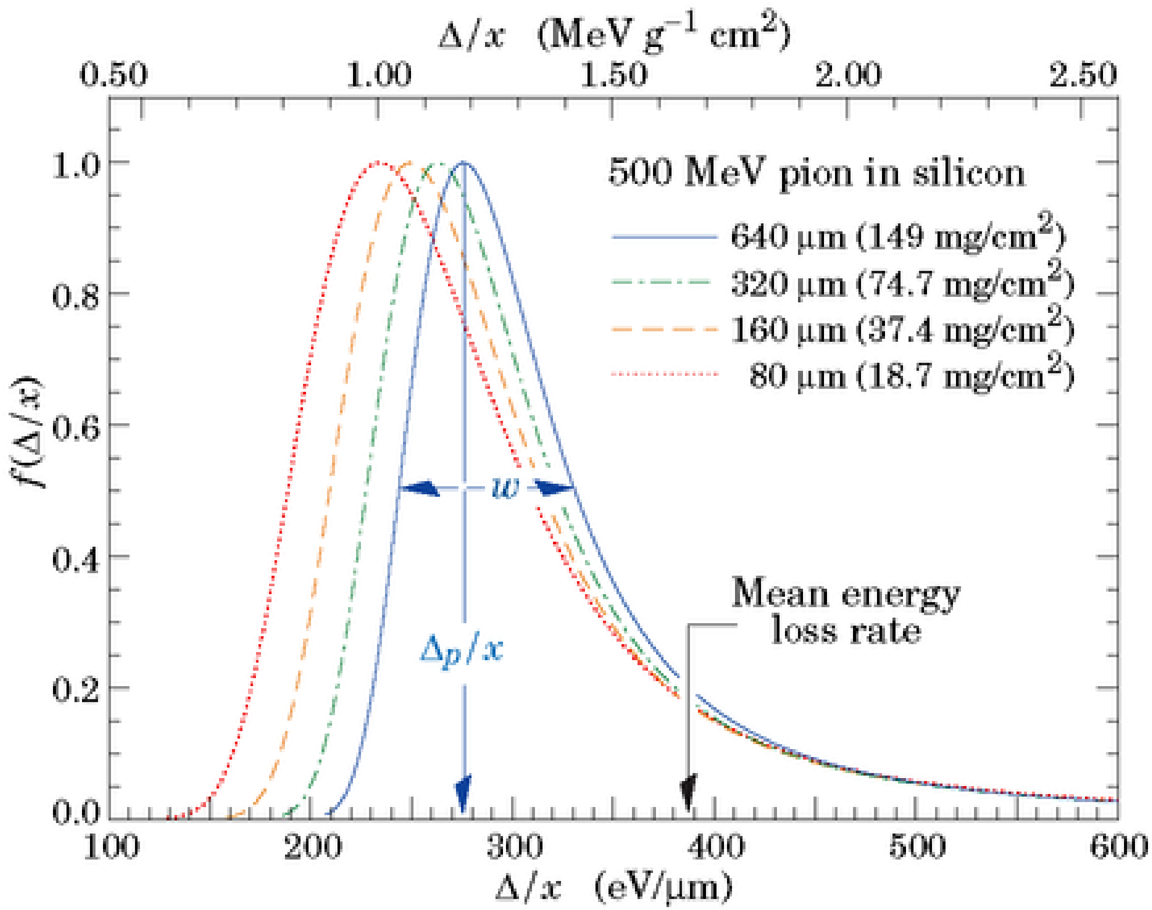


Fig. 32.1: Stopping power (= $\langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [4], and data at higher energies are from Ref. 5. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [6]. dE/dx in the radiative region is not simply a function of β.

Mean ionization losses of single-charged particles in liquid hydrogen, gaseous He and solid C, Al, Fe, Sn, Pb



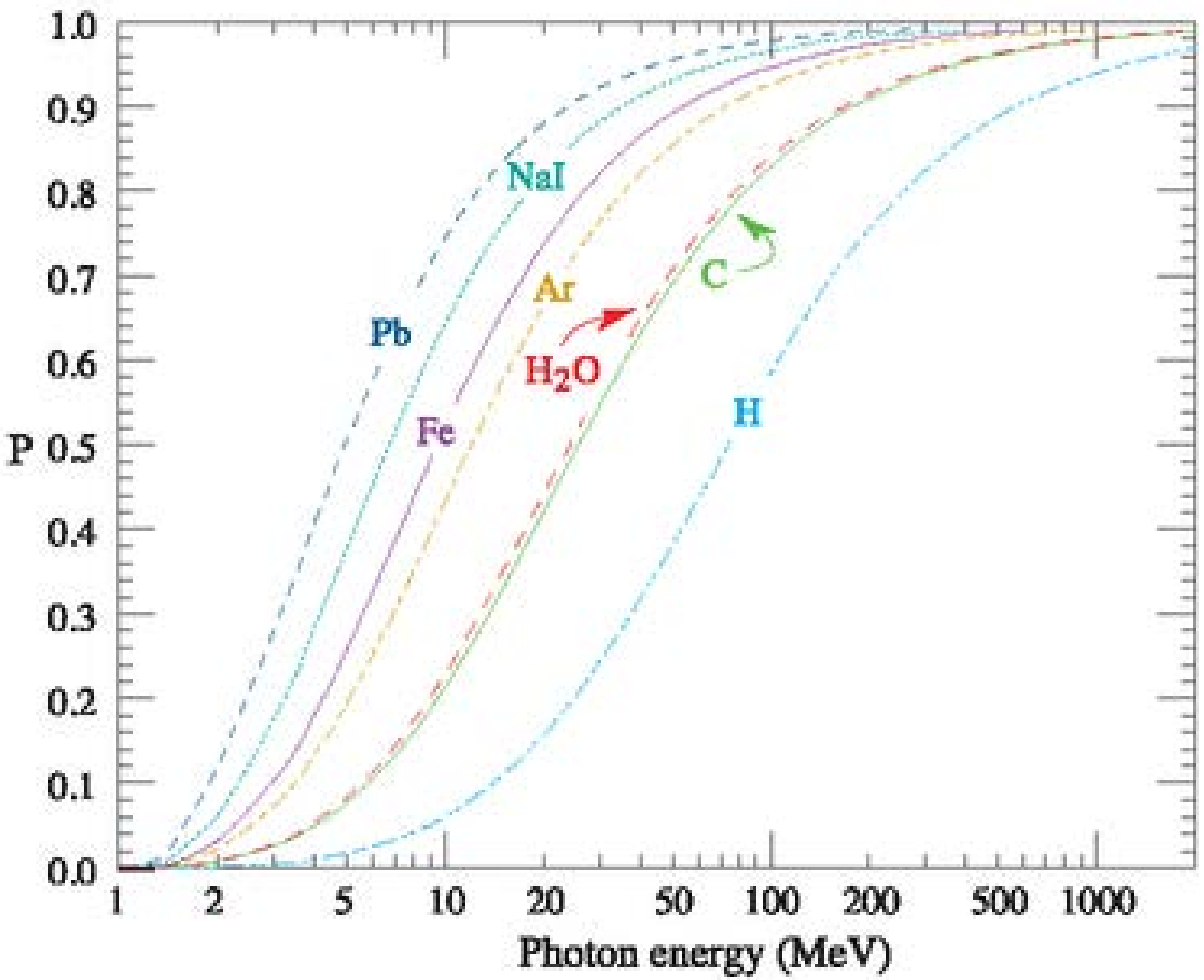
Shape of ionization loss distribution functions in matter layers of different width



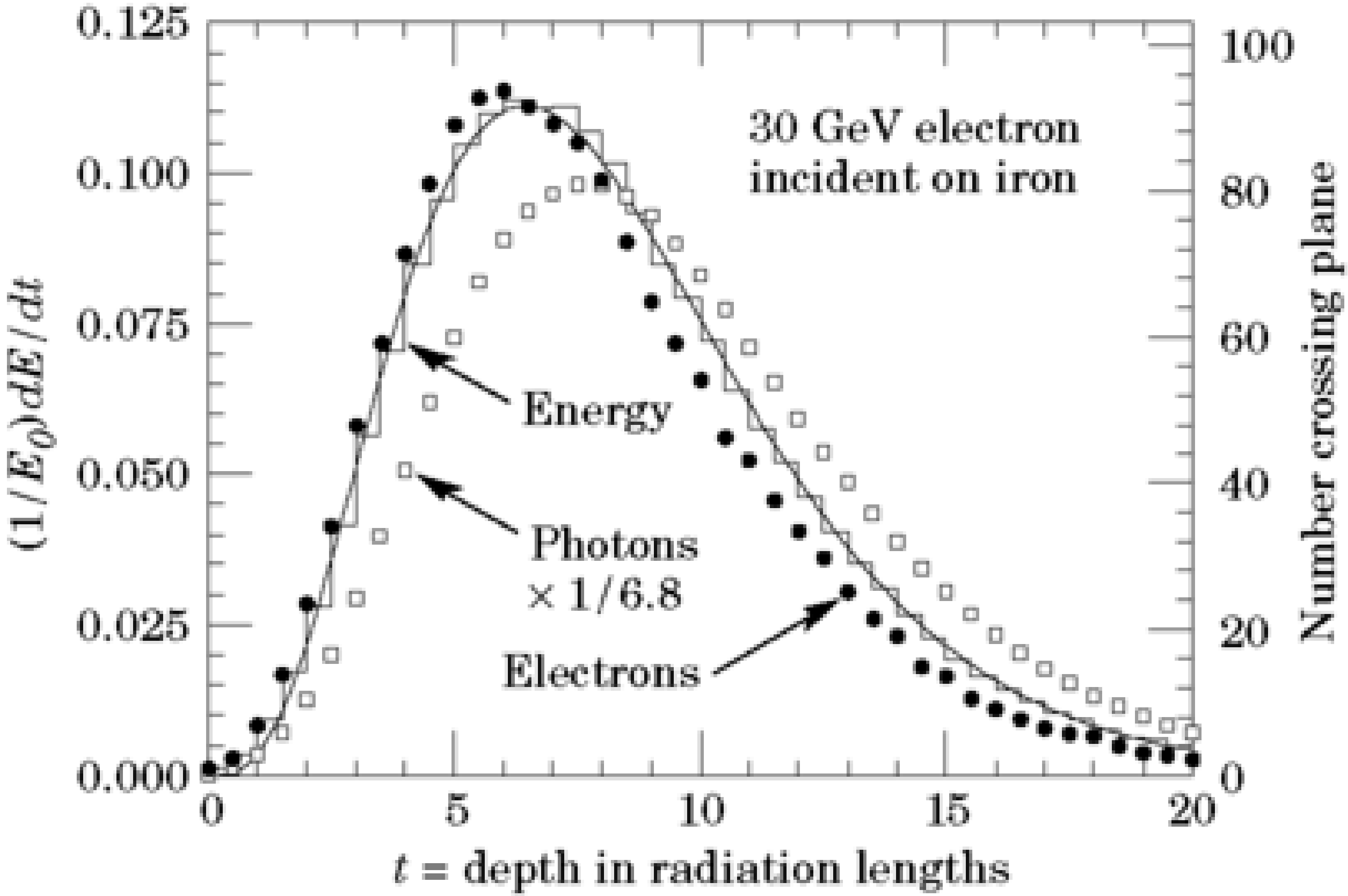
Detection of neutral particles

- High-energy gamma particles can be detected due to electrons kicked from atoms (photo-effect, Compton-effect) and due to production of e^+e^- pairs at higher energies. If energy of initial gamma quanta is high enough, then produced e^{+-} can generate secondary gammas, and so called electromagnetic cascade emerges. This cascade is detected usually in electromagnetic calorimeter due to light generated by e^{+-} in scintillator or via Cherenkov light. Important characteristic is so called radiation length. It means the amount matter at which the number of initial high-energy photons decreases by a factor of e=2.71828… due to production of e^+e^- pairs, usually measured in g/cm ^{2} .
- Radiation length X_0=13.8 g/cm^2 in Fe and 6.0 g/cm^2 in U .

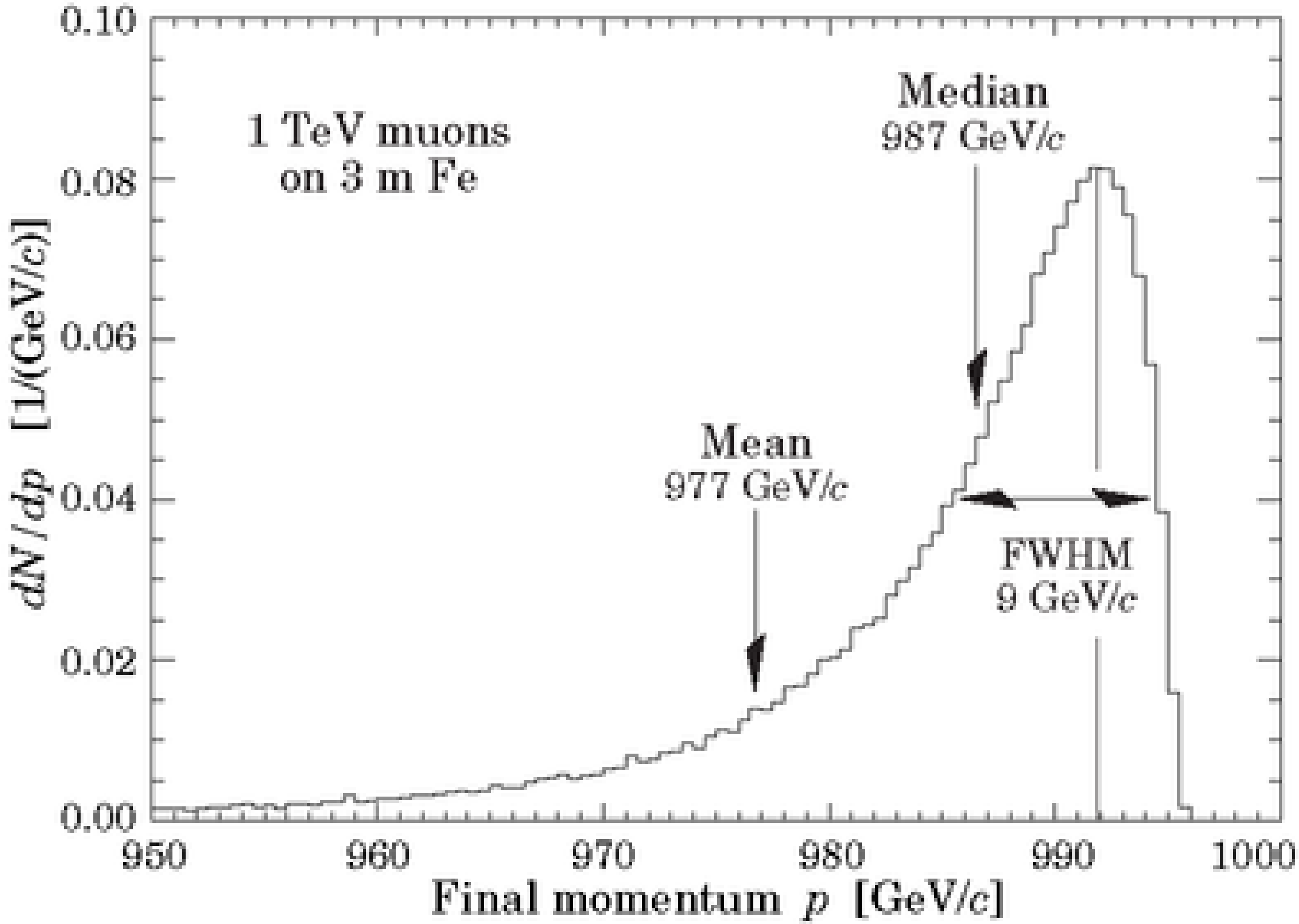
Probability P that a photon interaction will result in conversion to an $e^+ e^-$ pair



Fractional energy deposition per radiation length for a 30 GeV electron-induced shower in iron



The momentum distribution of 1 TeV/c muons after traversing 3 m of iron



Bremsstrahlung becomes important at high energies, even for muons.

Hadronic calorimeters

- π^0 and η mesons decay to pairs of γ and can be detected in Electromagnetic calorimeters.
- Other long-living neutral hadrons (neutron, K^0_{long}) can be detected via hadron interaction in the matter, which generate mainly charged hadrons and π^0. Then the energetic π^0 generate Electromagnetic showers which are measured in sensitive elements of the calorimeter, as well as ionization from charged hadrons. Notice strong fluctuations in the fraction of electromagnetic energy. A value of so called "nuclear interaction length" λ_I varies from 132.1 g/cm^2 in Fe to 209 g/cm^2 in U .

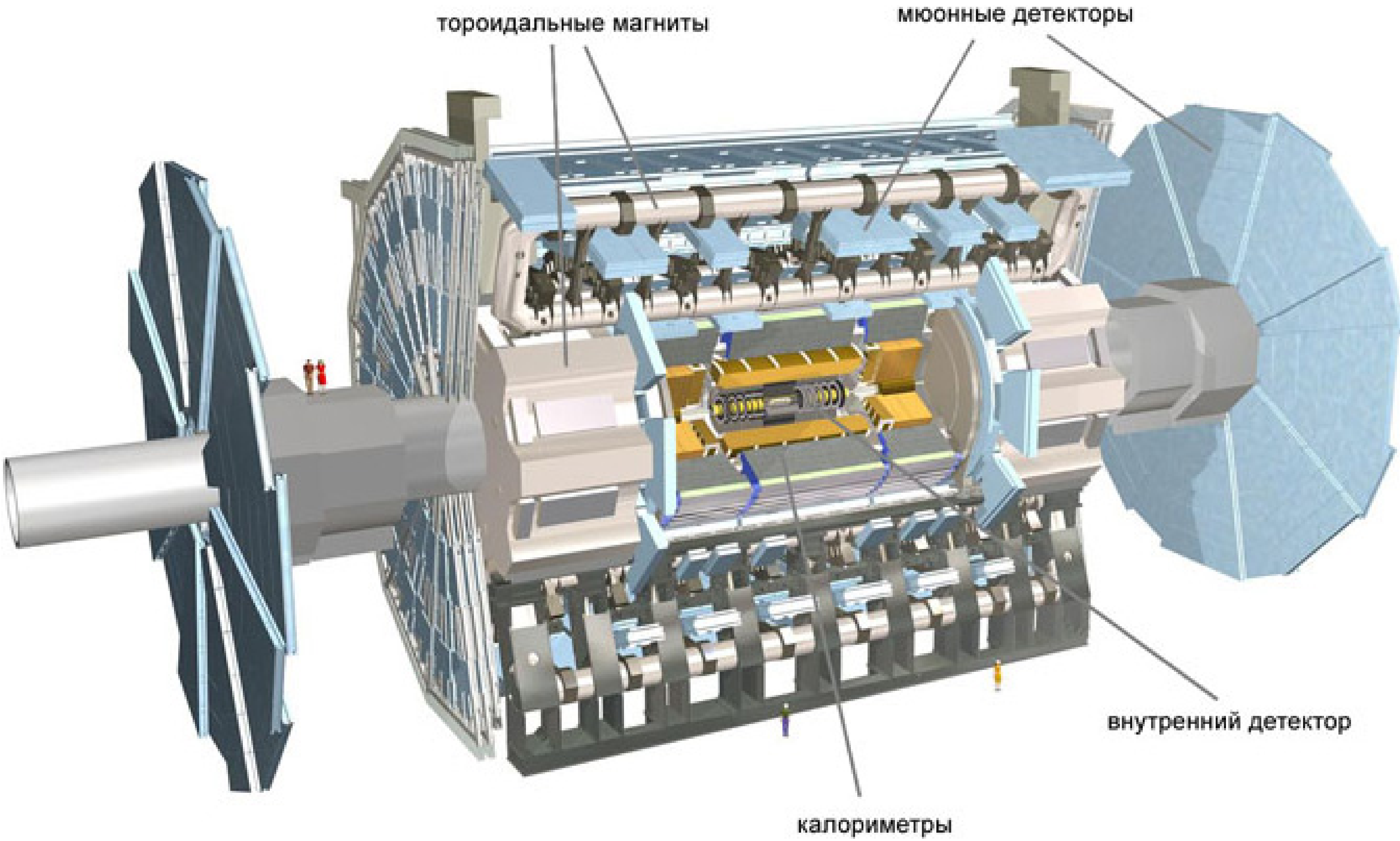
Precision of measurements

- Precision of charged particle momentum measurement in magnetic spectrometer depends on construction (transverse momentum kick in magnetic field, precision of sensitive elements and orientation of particle momentum). For charged hadrons with a few GeV momentum, $\Delta p/p < 1\%$. A limit for slow particles arises from multiple scattering, for high energies from precision of curvature measurement.
- Precision of energy energy measurement in calorimeters $\Delta E/E = A / \sqrt{E} + \text{const} + B/E$.
- Hadronic calorimetry is considerably more difficult than EM calorimetry. It is clearly desirable to compensate the e/hadron response. However, with geometrical and cost constraints, the calorimeters in modern collider experiments are not compensated.

Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	**Depth**	**Energy resolution**	**Date**
CsI(Tl) (BELLE)	16 X_0	1.7% for E_γ > 3.5 GeV	1998
$PbWO_4$ (PWO) (CMS)	25 X_0	3% / √ E + 0.5% + 0.2 / E	1997
Liquid Kr (NA48)	27 X_0	3.2% / √E + 0.42% + 0.09/E	1998
Liquid Ar/Pb accordion (ATLAS)	25 X_0	10% / √E + 0.4% + 0.3/E	1996

ATLAS detector at LHC



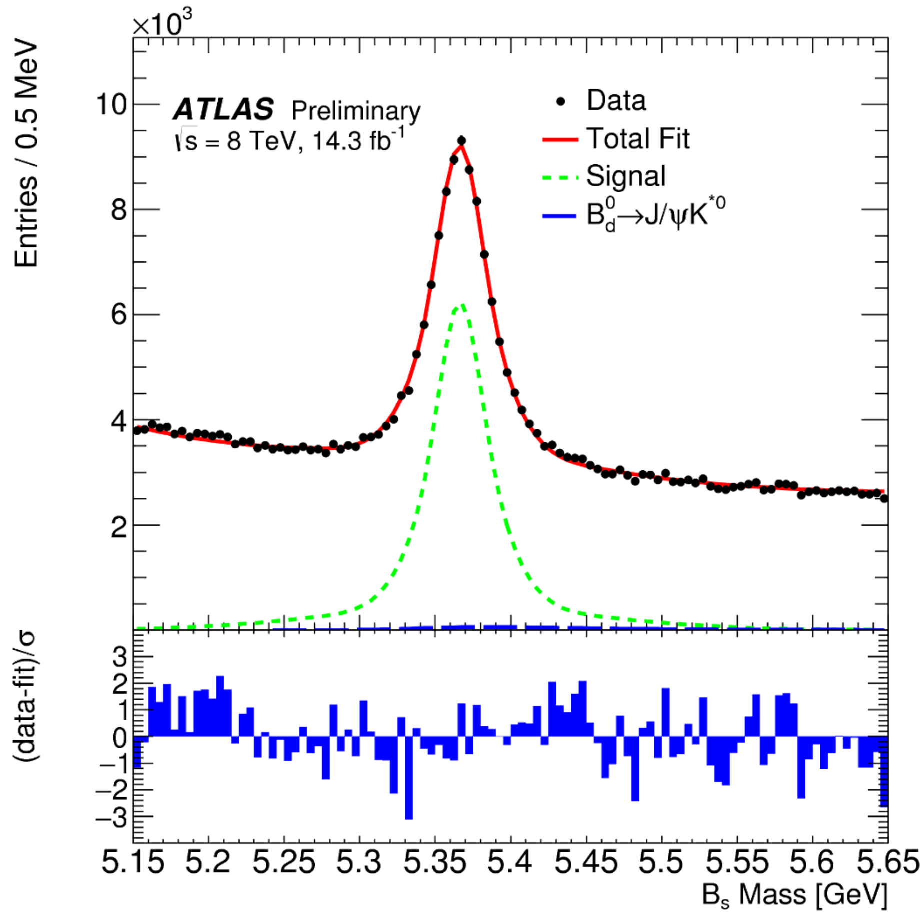
Some details of ATLAS detector

- Beams squeezed in a small transverse spot near the center of detector, beam pipe radius is 3 cm
- The Inner detector is close to beam pipe, consists from several layers of Pixel and Strip sensors, with magnetic field provided by a superconducting solenoid. The magnetic field direction is along the beam pipe.
- Then the Transition radiator tracker (TRT)
- Then in the Barrel : EM calorimeter (liquid Ar), then Hadronic calorimeter (iron and scintillator layers, with granularity)
- In Endcaps: EM and Hadronic calorimeters (liquid Ar)
- Then the muon chambers in Toroidal magnetic field.

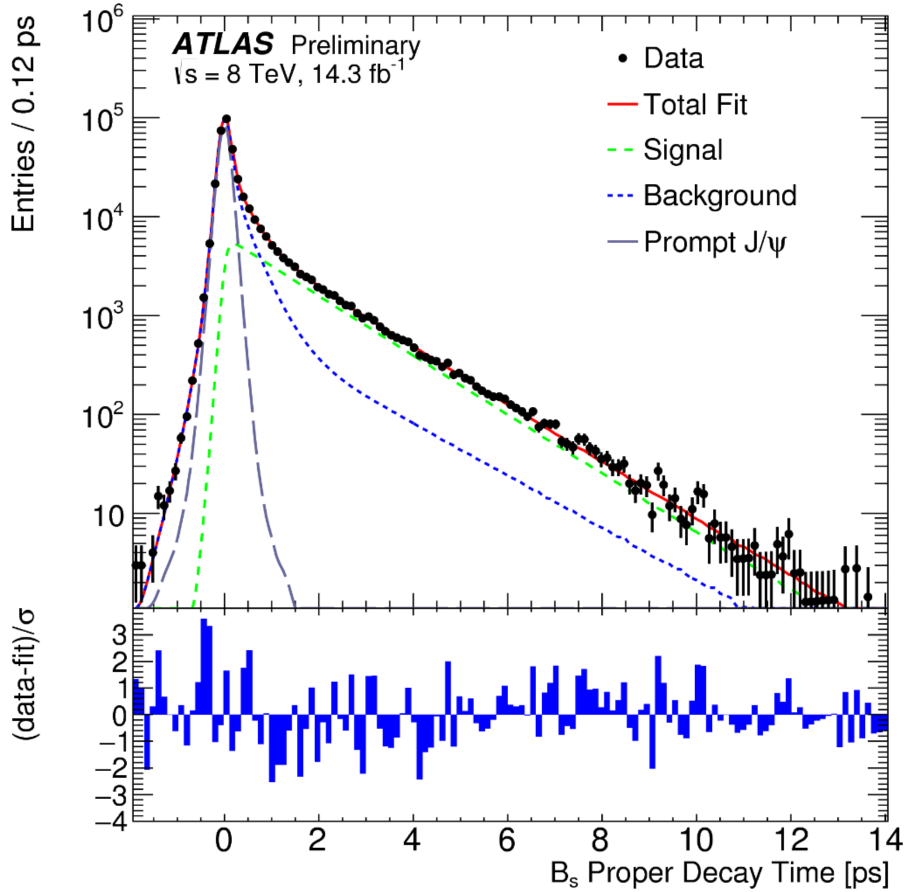
Analysis of ATLAS data

- Preliminary reconstruction of small samples and calibration is performed at CERN.
- Reconstruction of full statistics is performed in GRID system – a network with > 100 computer centers incl. Australia and Taiwan. At least 2 copies of reconstructed data are kept in different computer centers.
- Analysis jobs are submitted in GRID, the system detects where the data are available and submit jobs to corresponding nodes. Results can be analyses via GRID or copied to local disks.

An example of 1-dimensional histogram $B_s \rightarrow J/\psi\phi(1020) \rightarrow \mu^+\mu^-K^+K^-$ decay



Time projection of $B_s \rightarrow J/\psi\phi$ decay



Computer word

- Information in computers is presented in bits,
- computer word contains 64 (or 32) bits
- Apart from the bit pattern, a context should be defined, p.ex. Integer, float, double precision, character
- An example of double precision in Wikipedia: https://en.wikipedia.org/wiki/Double-precision_floating-point_format
- An example of double precision, from left to right: 1 sign bit, then exponent E (11 bits), then fraction or mantissa M (52 bits).
- The double-precision binary floating-point exponent is encoded using an offset-binary representation, with the zero offset being 1023. Examples:
- $3ff0\ 0000\ 0000\ 0000_{16}$ = 1
- $3ff0\ 0000\ 0000\ 0001_{16}$ ≈ 1.0000000000000002, the smallest number > 1
- $3ff0\ 0000\ 0000\ 0002_{16}$ ≈ 1.0000000000000004
- $4000\ 0000\ 0000\ 0000_{16}$ = 2
- $c000\ 0000\ 0000\ 0000_{16}$ = –2