Instrumentation for High Energy Physics

Ludwik Dobrzynski

Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

Split 14-18 September 2015

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- *Introduction*
- *Particle ID*
- *Particle momenta measurement*
- *Particle Energy measurement*

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Instrumentation

- "New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson

- "Instrumentation for the 21st century. No one does it better than physicists when it come to innovation for instrumentation, and thus the future of all scientific fields rests on our hands."

Michael S. Turner

Basic particle interactions in detector processes

Every effect of particles or radiation can be used as a working principle for a particle detector. Claus Grupen

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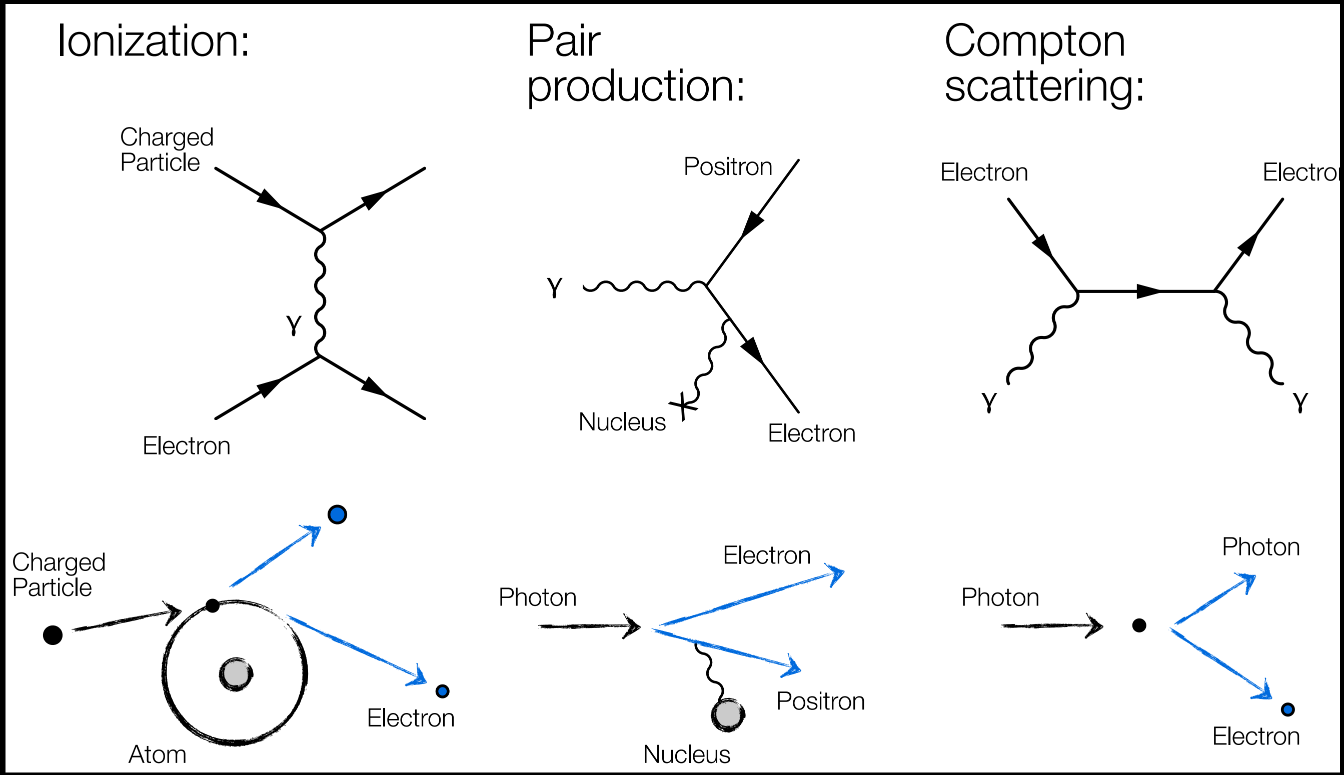

Particle discoveries

By 1959: 20 particles

e^- : fluorescent screen
n : ionization chamber

7 Cloud Chamber:

- e^+
- μ^+, μ^-
- K^0
- Λ^0
- Ξ^-
- Σ^-

6 Nuclear Emulsion:

- π^+, π^-
- anti-Λ^0
- Σ^+
- K^+, K^-

2 Bubble Chamber:

- Ξ^0
- Σ^0

3 with Electronic techniques:

- anti-n
- anti-p
- π^0

NOBEL PRIZES FOR INSTRUMENTATION

http://www.lhc-closer.es/php/index.php?i=1&s=9&p=2&e=0

1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron

1948: P.M.S. Blacket, Cloud Chamber

1950: C. Powell Photographic Method

1954: W. Bothe Coincidence method

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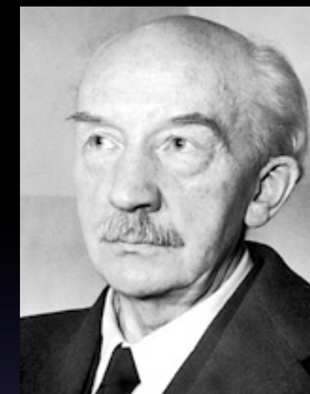
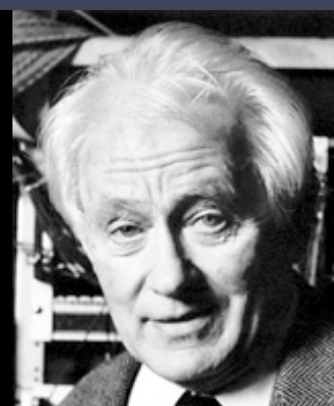


1954: W. Bothe Coincidence method

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez Hydrogen Bubble Chamber



1992: G. Charpak Multi Wire Prop. Chamber

2009: W. S. Boyle & G. E. Smith
CCD sensors

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- ***Particle momentum measurement***

Lecture 1 (Introduction, Particle ID)

Lecture 2 (Particle momentum measurement)

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Lecture 1

- *Particle momentum measurement* — *Lecture 2*

- *Particle energy measurement* — *Lecture 3*

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Lecture 1 (Introduction, Particle ID)

Lecture 2 (Particle momentum measurement)

- ***Particle energy measurement***

Lecture 3

Caution *: These topics are very wide so it would be a non sense to believe that they can be fully covered in 3 lectures. So a choice has been made.*
OF COURSE, I (might) have some personal bias, so I apologize in advance if your expectations are not full field.

Instrumentation in HEP

Over three lectures, I propose to review the techniques used in High Energy Physics experiments for Particle Identification and their kinematic parameter measurement.

- ***Introduction***
- ***Particle ID*** *Lecture 1*
- ***Particle momentum measurement*** *Lecture 2*

- ***Particle energy measurement*** *Lecture 3*

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For a more complete set of lectures go for instance to:

http://www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors/

http://www.kip.uni-heidelberg.de/~coulon/Lectures/JCDet/

http://cds.cern.ch/collection/Summer%20Student%20Lectures (D. Bortoletto Oxford Univ.)

Start of a HEP experiment, one needs

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A theory:

O. Ullaland/2006

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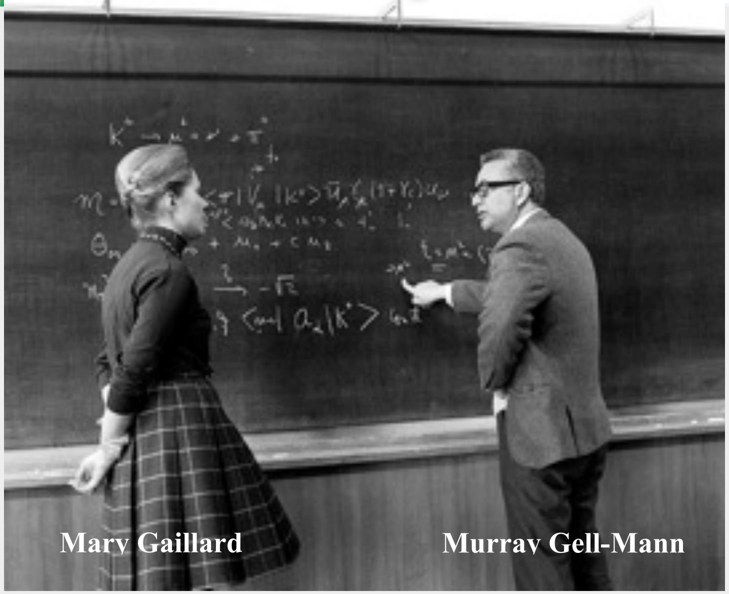

Mary Gaillard Murray Gell-Mann

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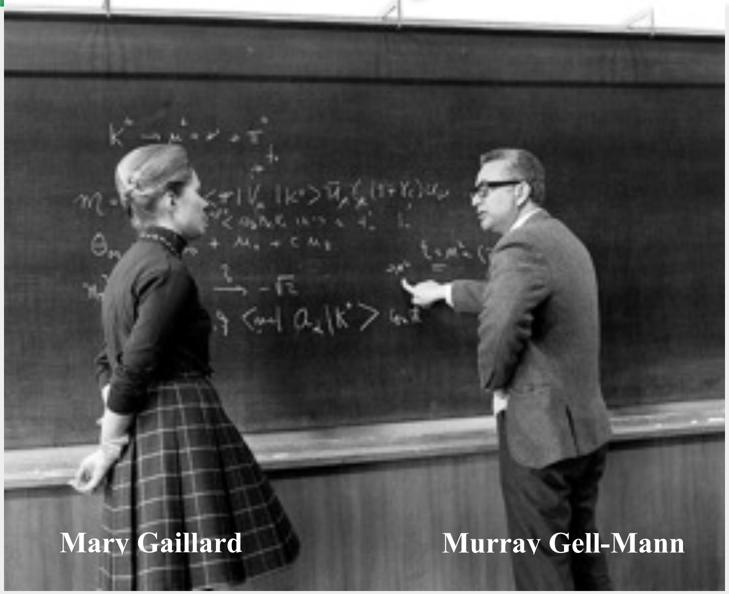

A theory:

and a cafeteria

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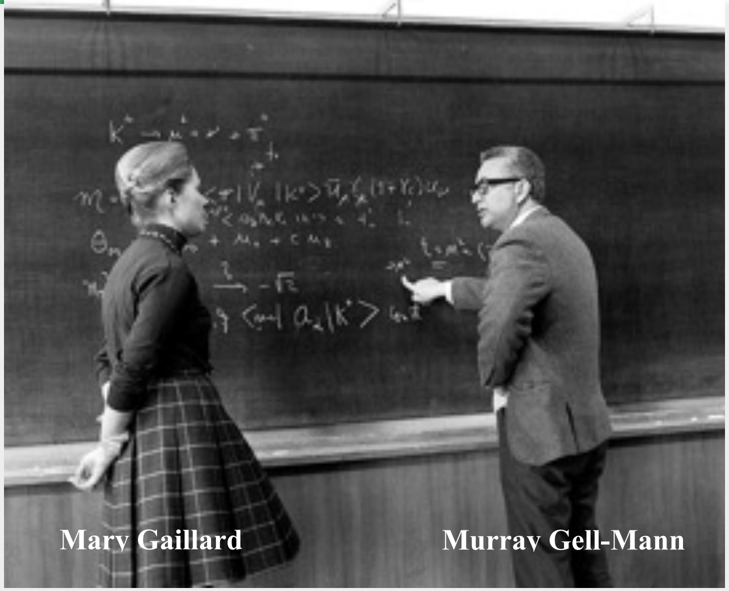

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Clear and easy understandable drawings

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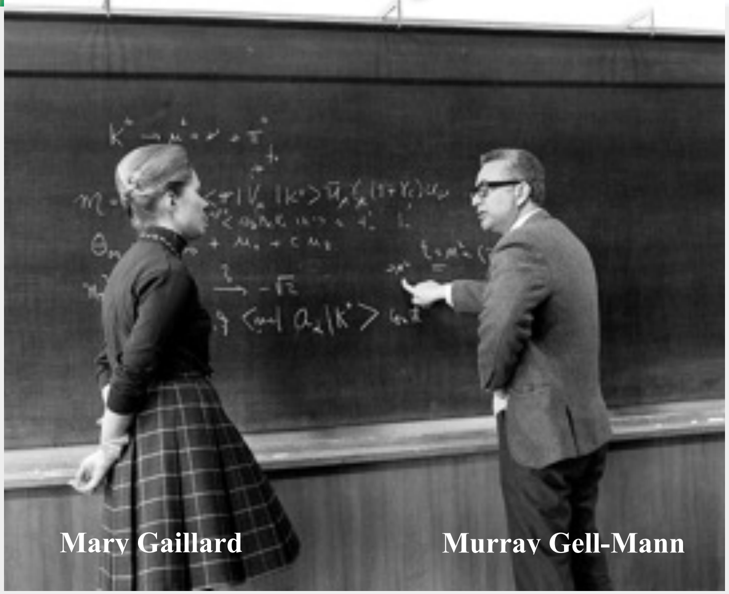

A theory:

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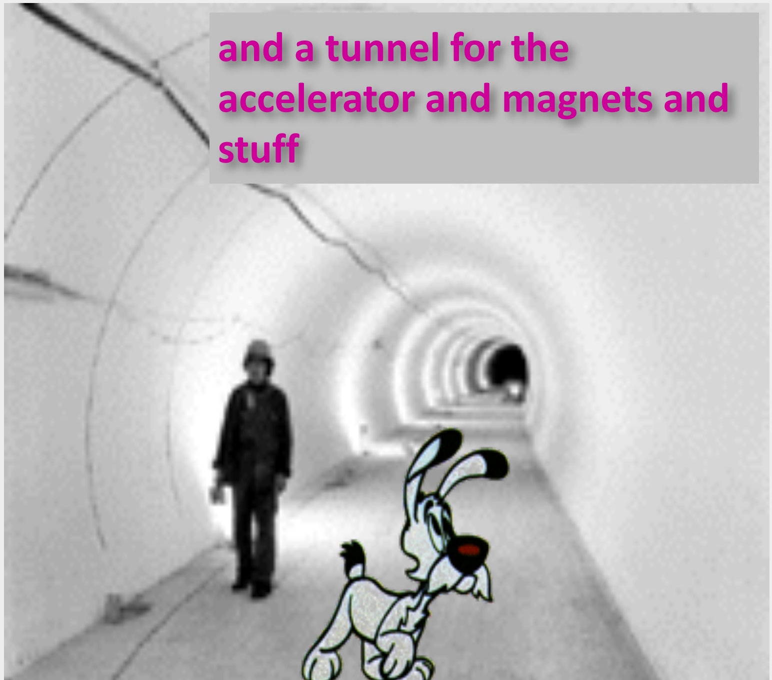
Clear and easy understandable drawings

and a tunnel for the accelerator and magnets and stuff



O. Ullaland/2006

Easy access to
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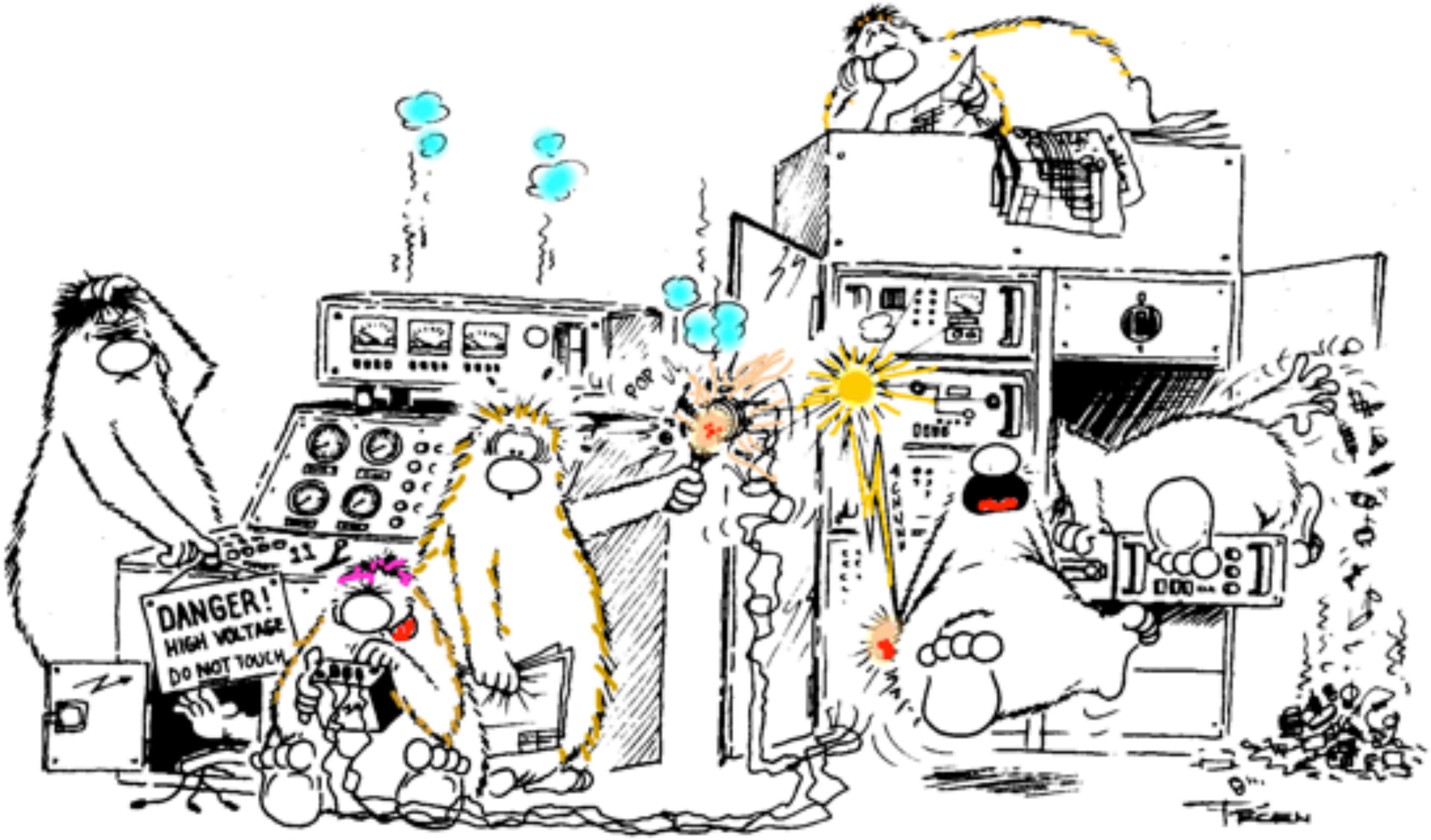
Physicists to operate detector/analyze data

Easy access to the experiment

Physicists to operate detector/analyze data

and a Nobel prize

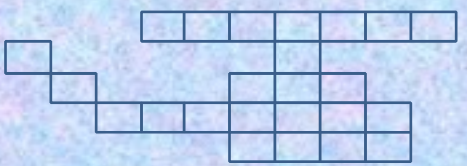
O. Ullaland/2006



My lectures will just concentrate on the detectors

HEP Experiment: Simplified View

Proton
(quarks & gluons)



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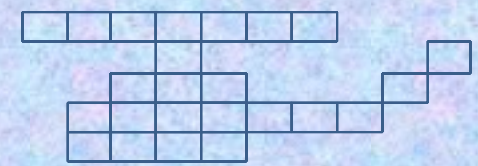

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We "see" the resulting particles – so we have to be like detectives – precisely reconstruct particle tracks in the detector to understand what happened !

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E … c2

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Which Concepts for the detector

- ***For which Physics?***
  - *Higgs : photon and lepton reconstruction*
  - *Top : lepton and jets reconstruction*
  - *SUSY : soft leptons, jets and Missing transverse energy*
  - *B mesons ….*
- ***In which environment?***
  - *Radiation level*
  - *Accessibility limited sitting on the Collider*
- ***A difficult compromise : look for the best performance within a given budget and feasibility***

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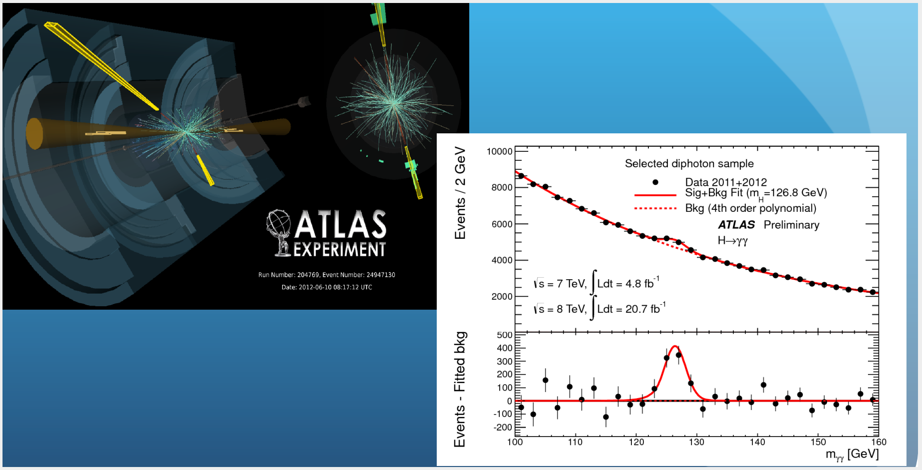
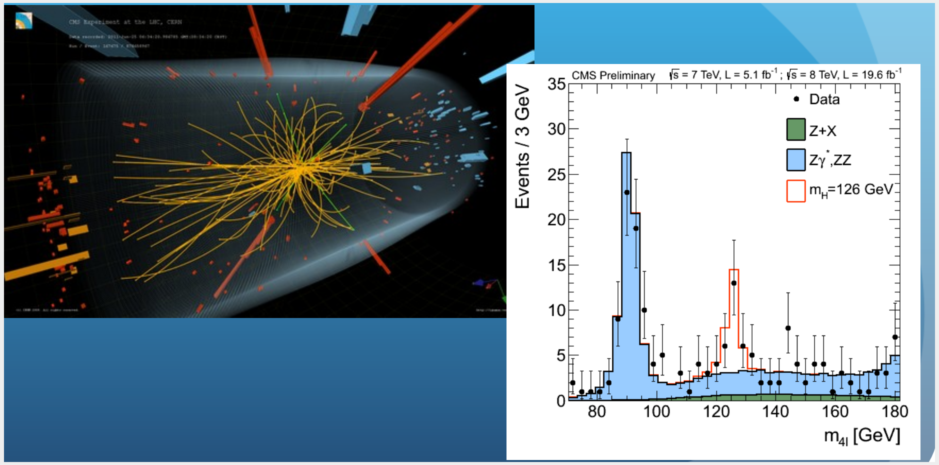
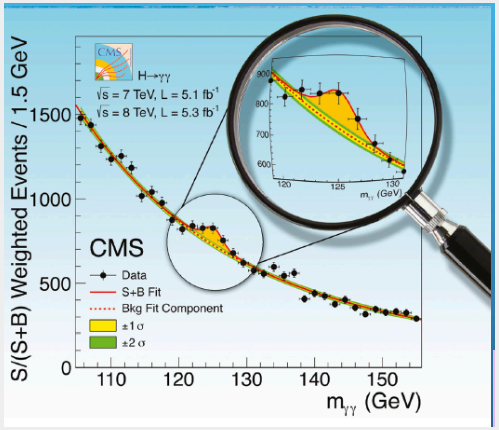
- *=> Real detector*

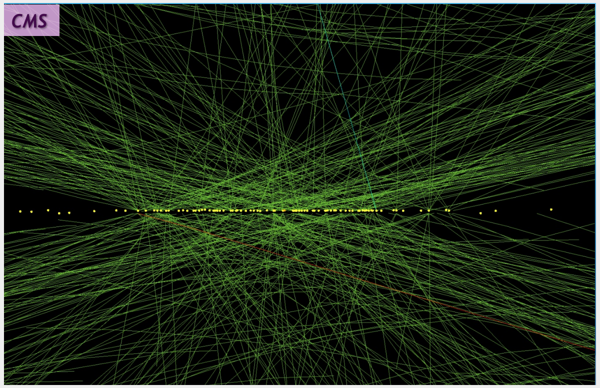
Physics case 1: Higgs => 2 photons + 4 leptons

- ***Reconstruct and identify isolated photons and leptons in a huge hadronic background (large pileup).***









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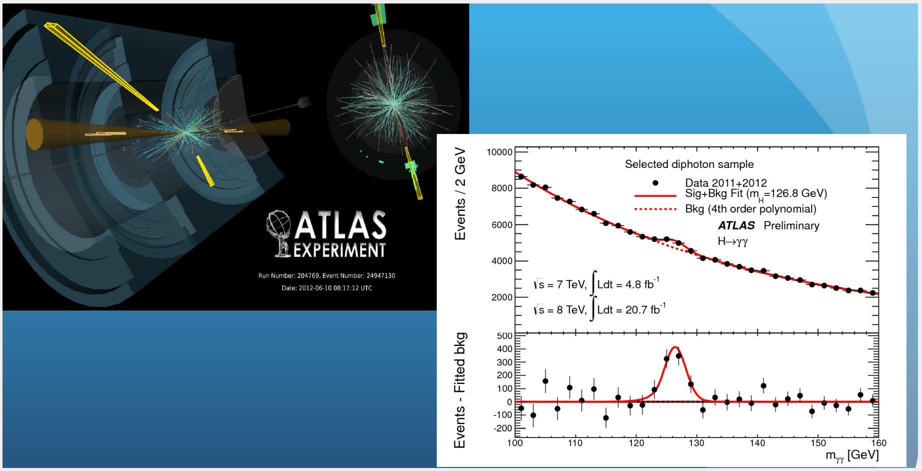

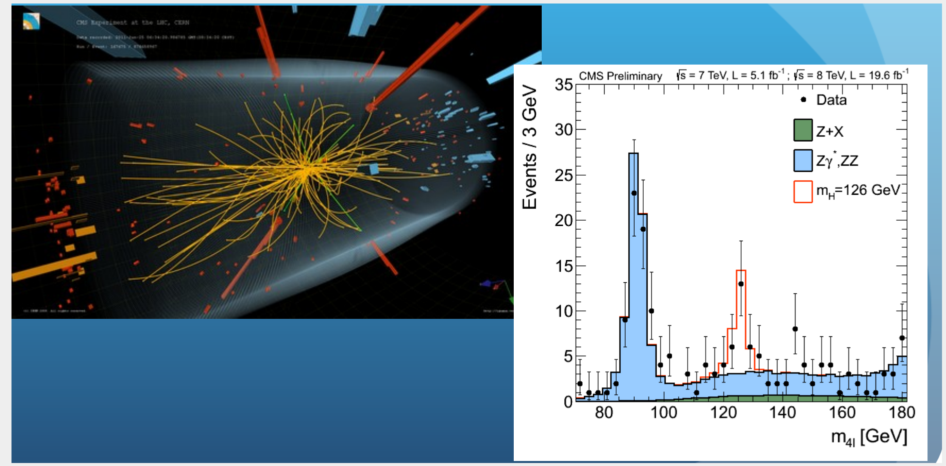

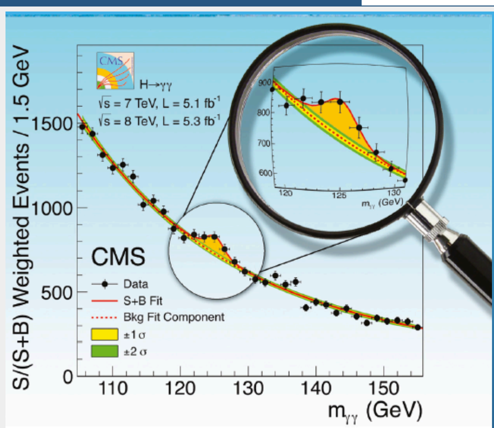

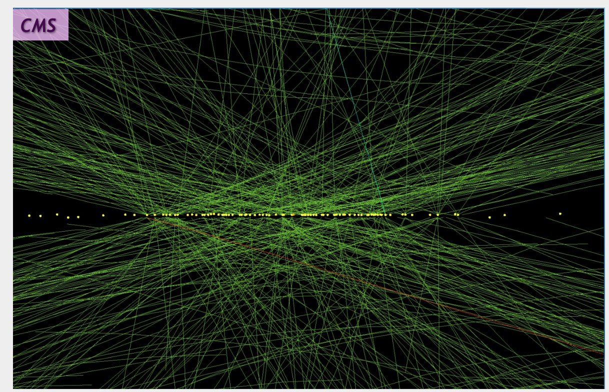

Questions :

- How to measure the photon energy with precision. Is a tracker necessary?
- Which is the dominant background and how do I get rid of it?
- What kind of calorimeter do I need

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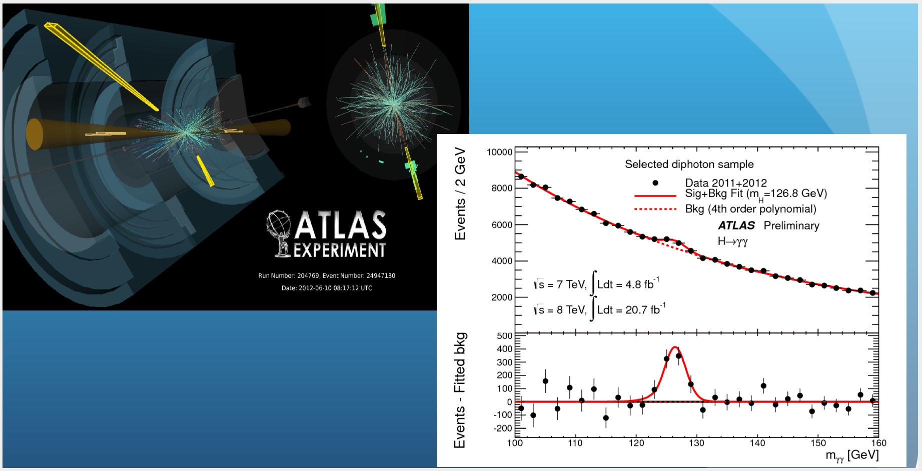

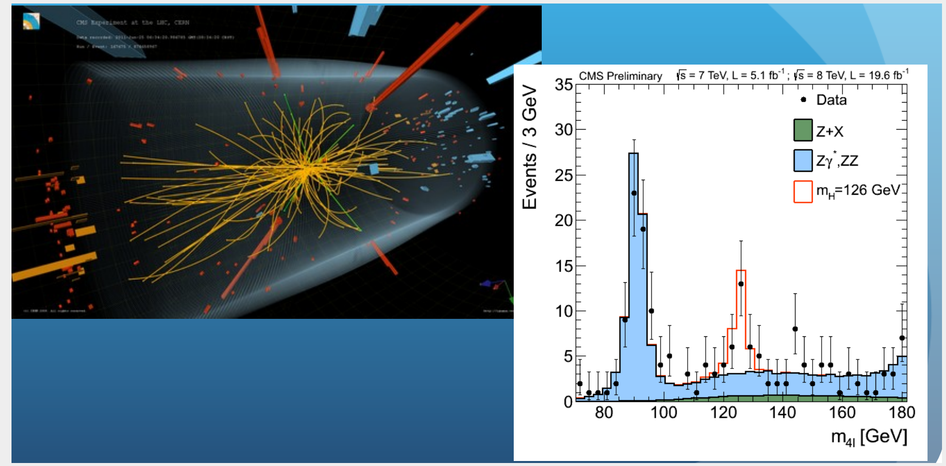

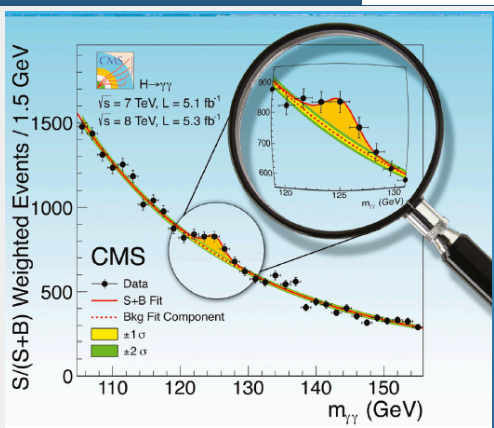

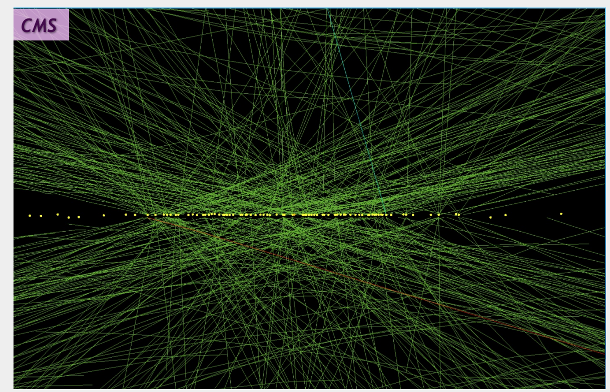

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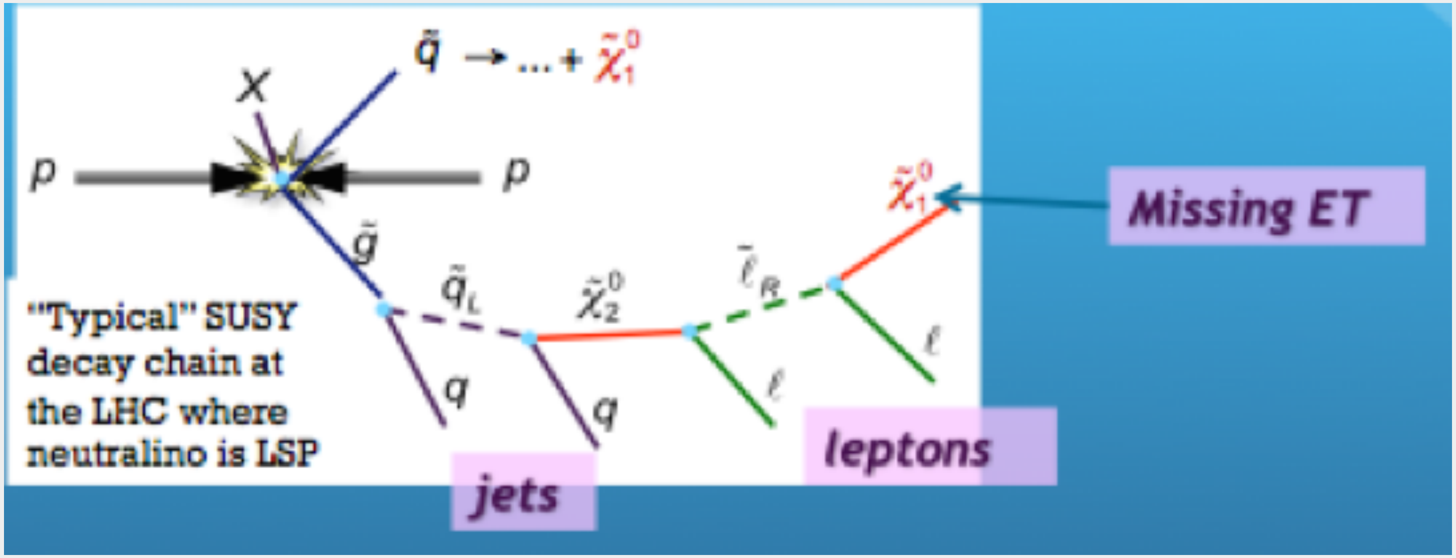
The response is straight forward : Best tracking system and Best Electromagnetic calorimeter

Physics case 2: Susy

- *In a cascade disintegration : look for soft leptons and large number of jets as well as “Missing ET”*



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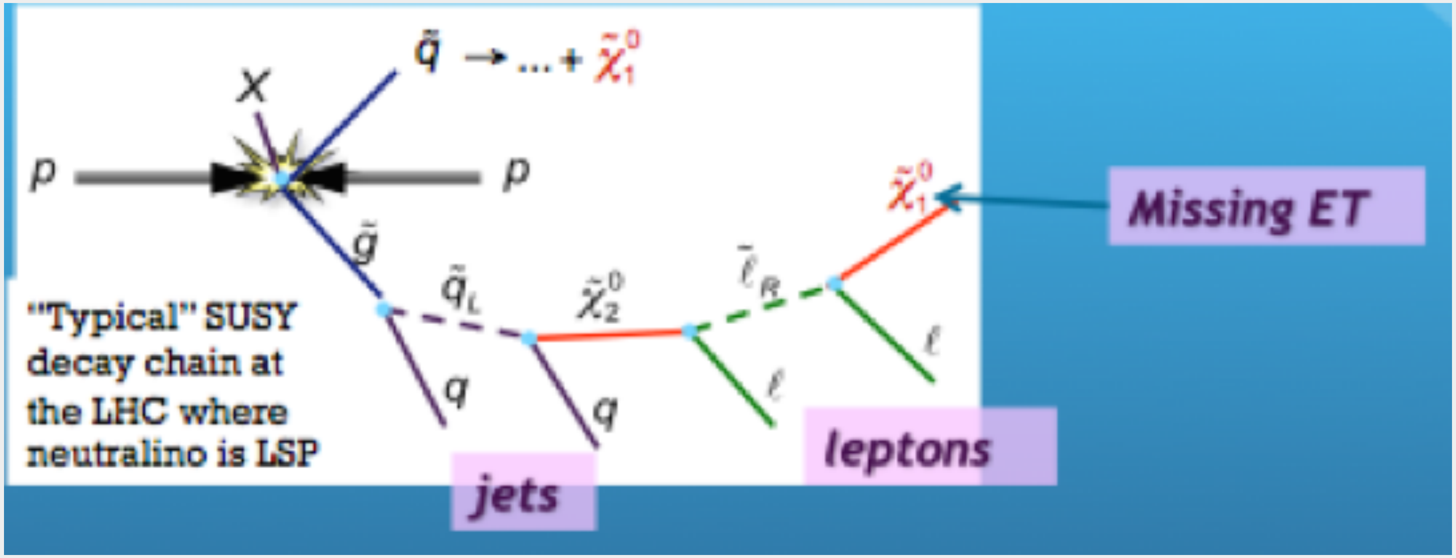
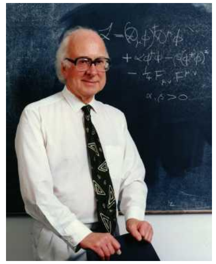


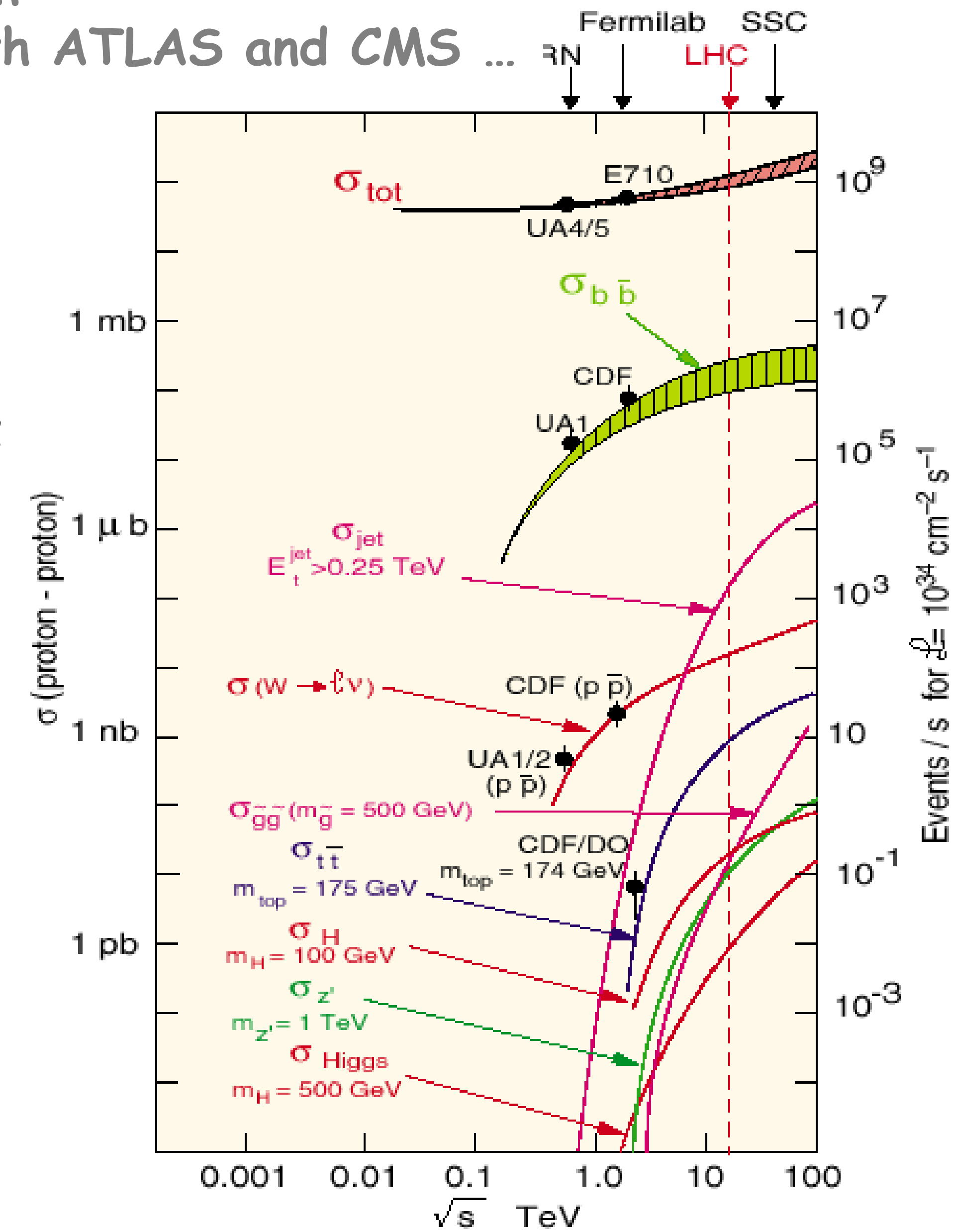
- *Other Physics and technical goals :*
  - *Blast of Higgs sector*
  - *Extra dimensions*
  - *Vector Boson fusion*
  - *Forward Physics ….*
  - *tau lepton reconstruction algorithms*
  - *live at very high luminosity*

Challenges

... or to discover  boson with ATLAS and CMS ...

- Inelastic: 10^9 Hz
- Higgs (100 GeV/c^2): 0.1 Hz
- Higgs (600 GeV/c^2): 10^{-2} Hz
- Selection : 1:10^{10-11}
- Operate in high radiation environment
- Resolve 20-25 superimposed events per BX
- High granularity detectors
- Fast electronics/detectors (25 ns)

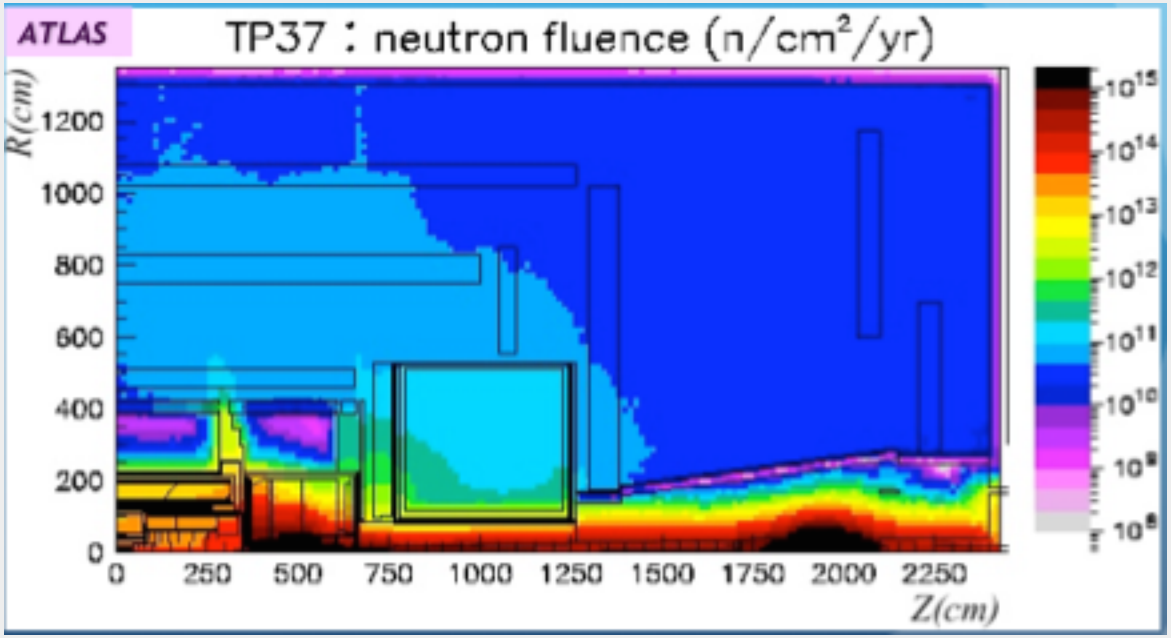
Energy scale crucial !



Challenges

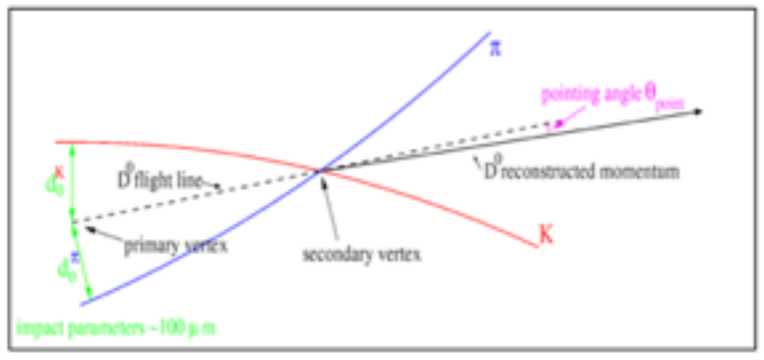
Particle detector concept (1)

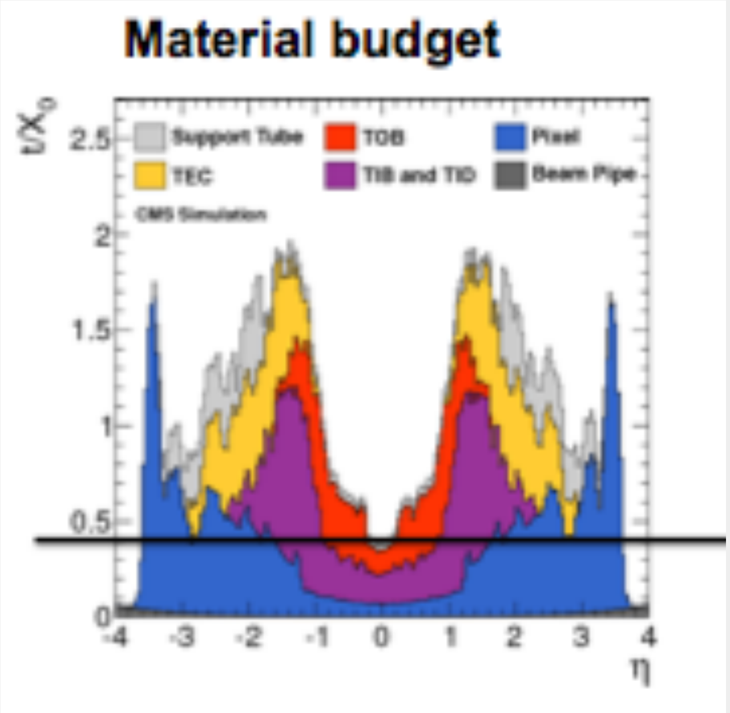
- All detector concept are based on basic knowledge of particle interactions with matter. Most involved processes are implying : electromagnetic interaction, ionisation, excitation, photo-electric effects, pair creation, bremsstrahlung, Cerenkov effect, transition radiation….
- The detector construction
  - result from a detailed study of all types of particles propagation through the detector
  - and the confirmation of the prediction by the results obtained in a test beam
- The detector should be as radiation hard as possible :
  - it’s a strong constraint on the detector material and on the electronics



Particle Detector concept (2)

- What determines the Size, Material and Geometry of the Detector?
  - Impact Parameter Measurement
  - Momentum Measurement
  - Energy Measurement
  - Muon Measurement



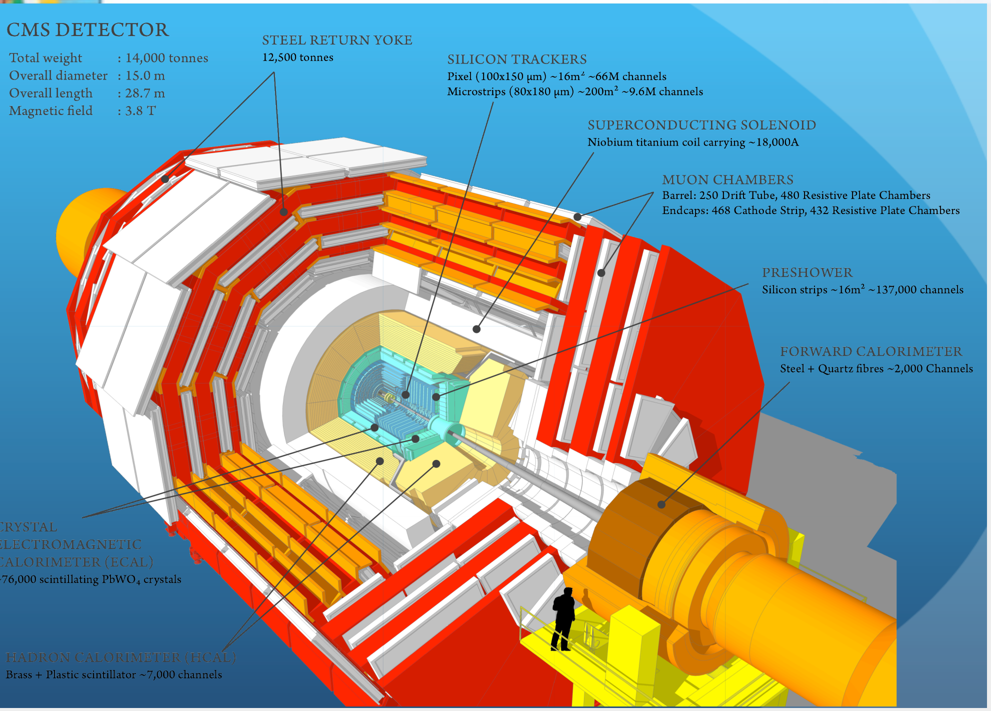


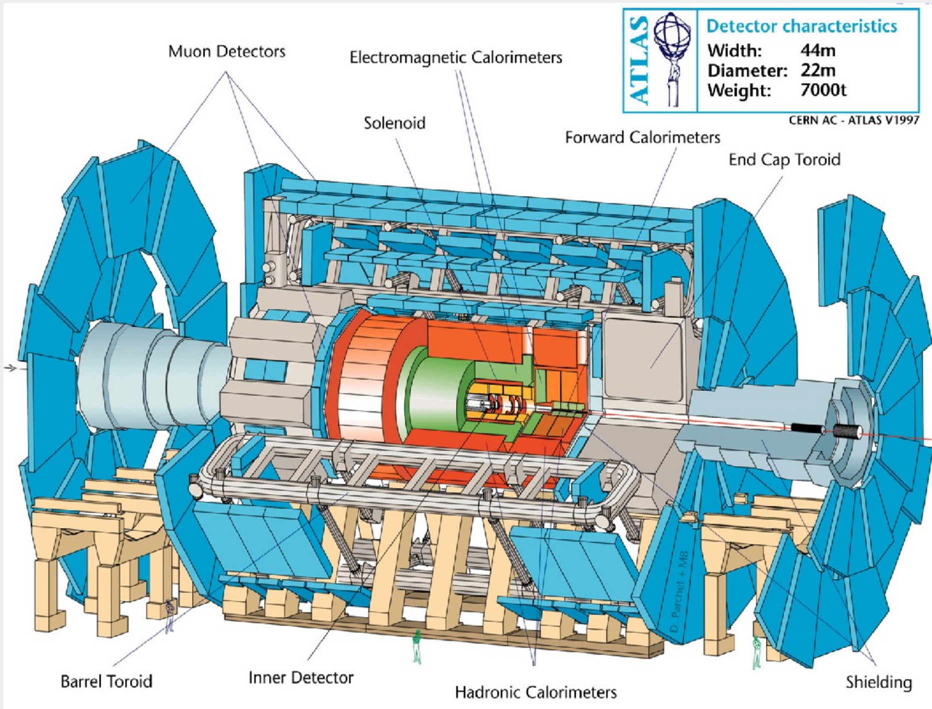
- Constraints
  - Multiple scattering which has to be reduced as much as possible
  - Impact Parameter resolution (Secondary Vertex)
  - Lever arm and Magnetic Field for Momentum Measurement
  - Material budget

LHC experimental challenge

- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns
    - → integrate over 1-2 bunch crossings → pile-up of 25-50 min-bias
    - → very challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from $H \to \gamma\gamma$ decays)
    - → large number of electronic channels
    - → high cost
- **LHC detectors must be radiation resistant:**
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

Exemple : Atlas and CMS Detector





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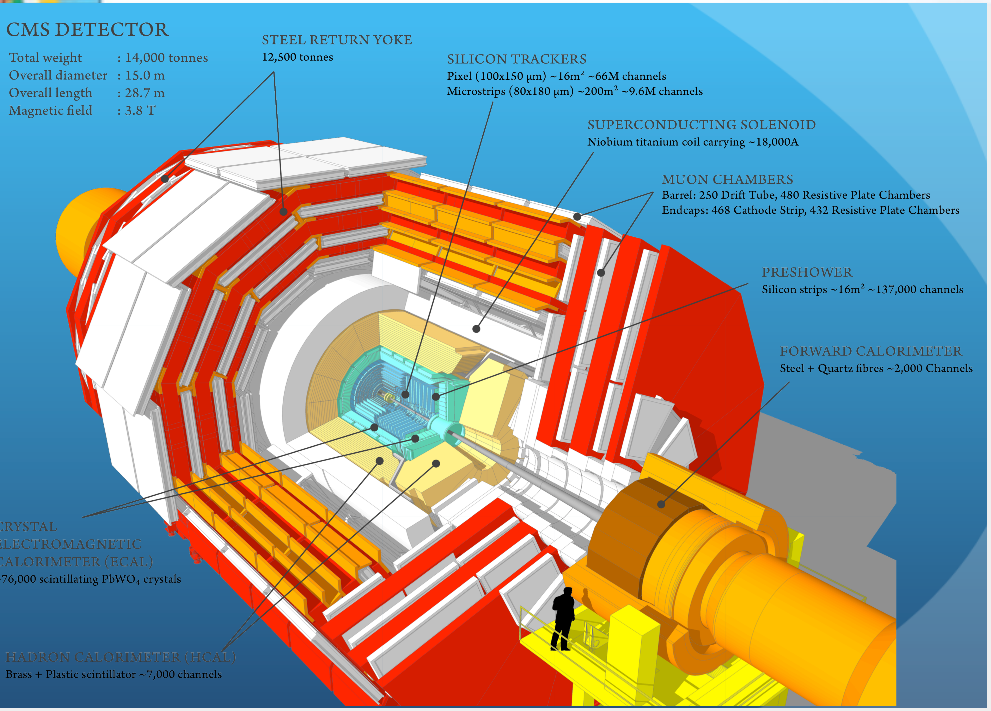

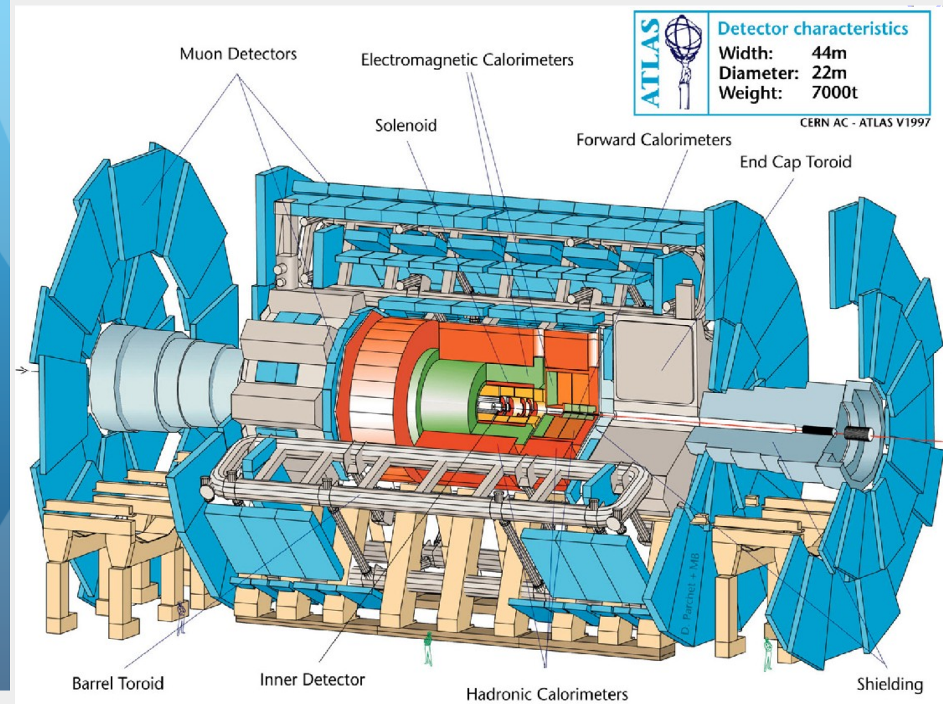

- *Large volume for precise charged tracks measurement*
- *Strong magnetic field*
- *Hermetic*
- *Best stand alone muon chambers system*
- *Highly segmented*
- *Radiation hard*

The LHC Spectrometers: Triumph of Instrumentation

the largest and most complex "microscopes" we've ever built

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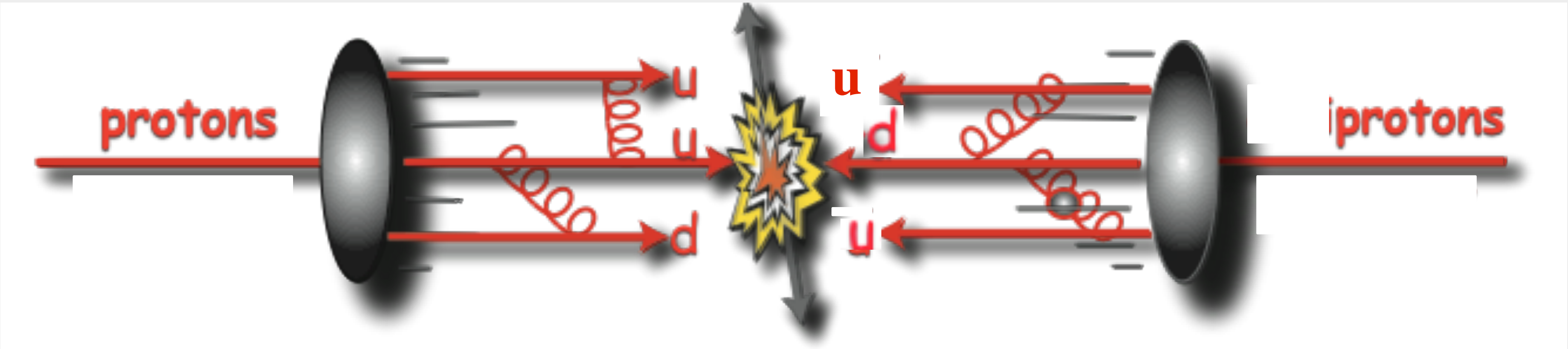
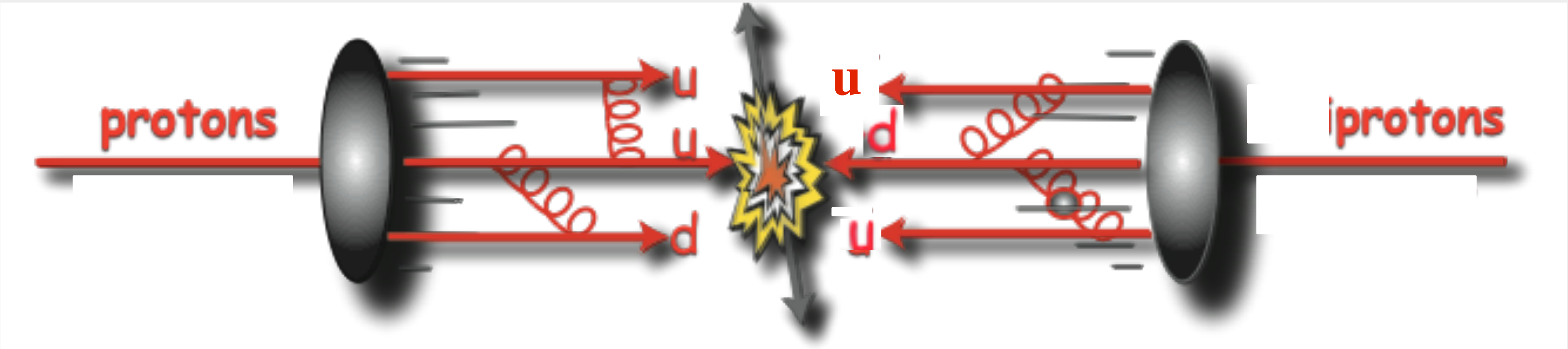
The detectors together have 140 million data channels observing at 40 million times a second.

Hadron Colliders



- ***Protons are composite***
  Partons (valence+sea quarks, gluons) carry longitudinal momentum fraction of the proton (x)
  Longitudinal parton momenta are unknown
- Parton distribution functions (PDFs): estimate the momentum fraction carried by a parton inside the proton

Hadron Colliders



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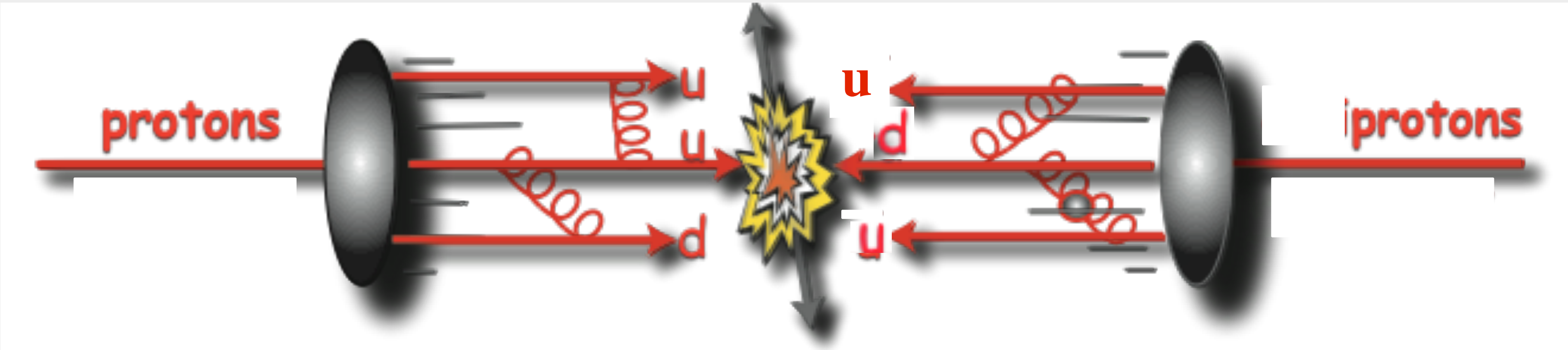
Hadron Colliders



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What do we want to measure

- ***Number of particles***
- ***Event topologie***
- ***momentum / Energie***
- ***Particle identity***
- ***Transverse Missing energy/momentun***

→ Can't be achieved with a single detector → Integrate detectors to a detector system

Particle detection

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Particles characteristics are measured through different type of detectors and identified thanks to specific behaviours due to their interaction with matter

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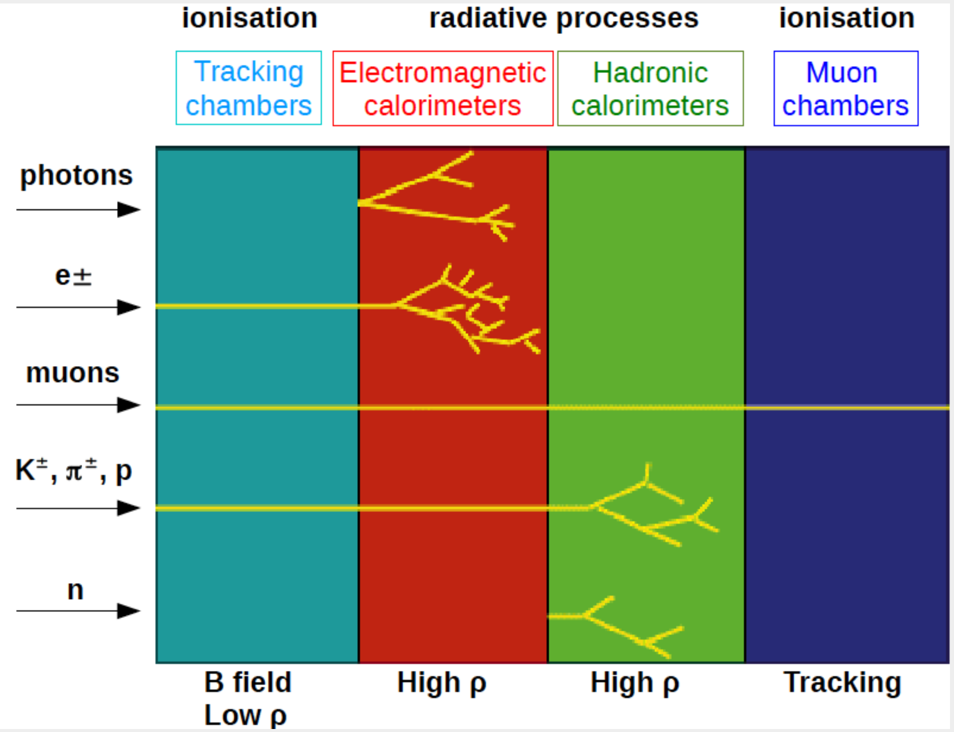

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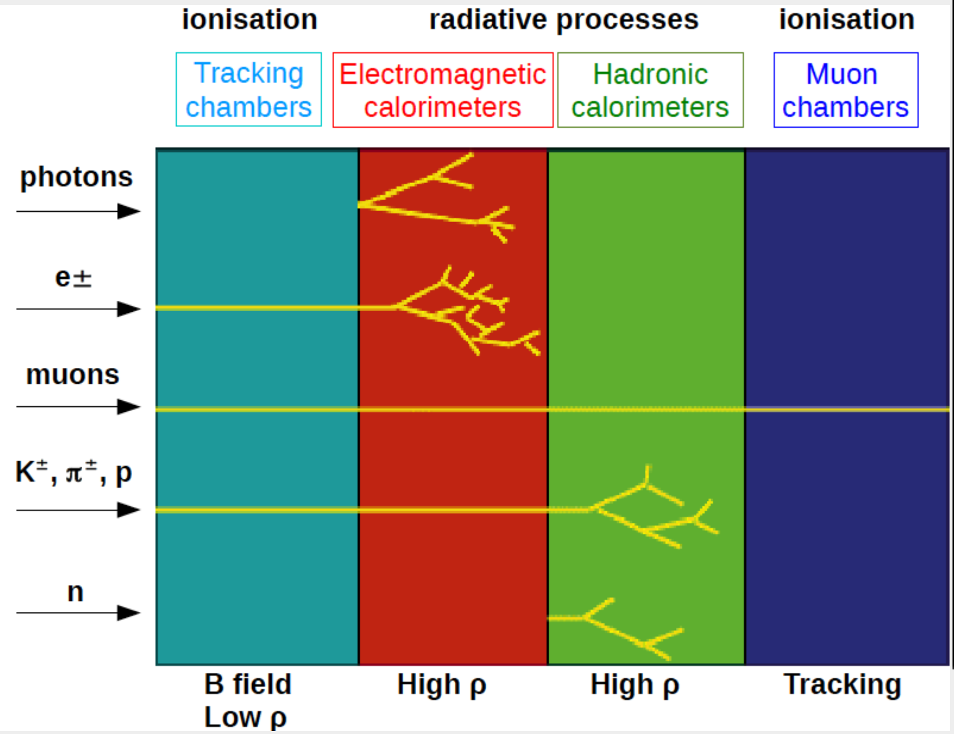

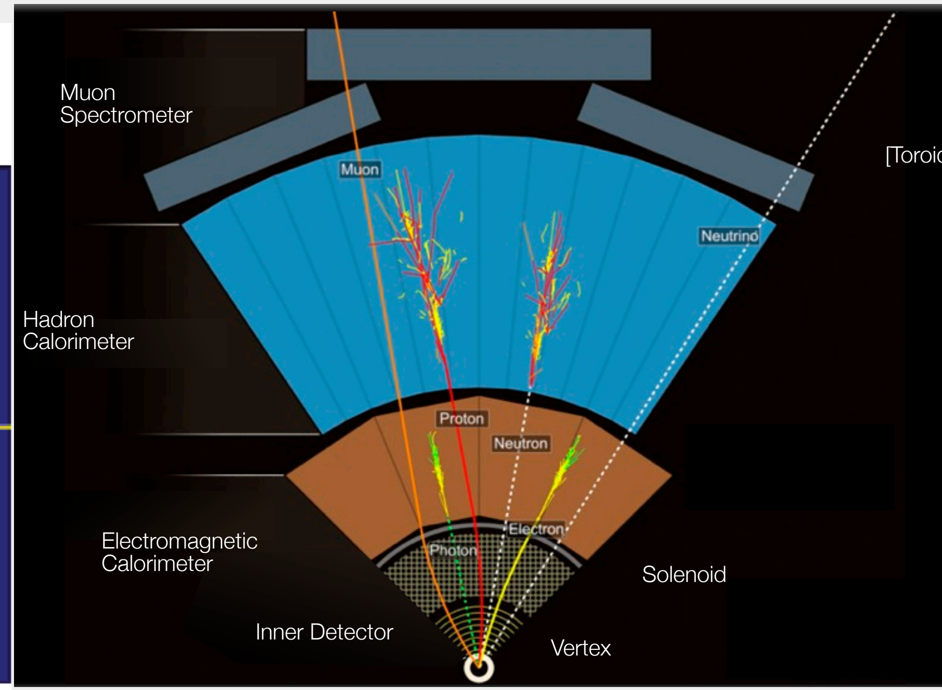

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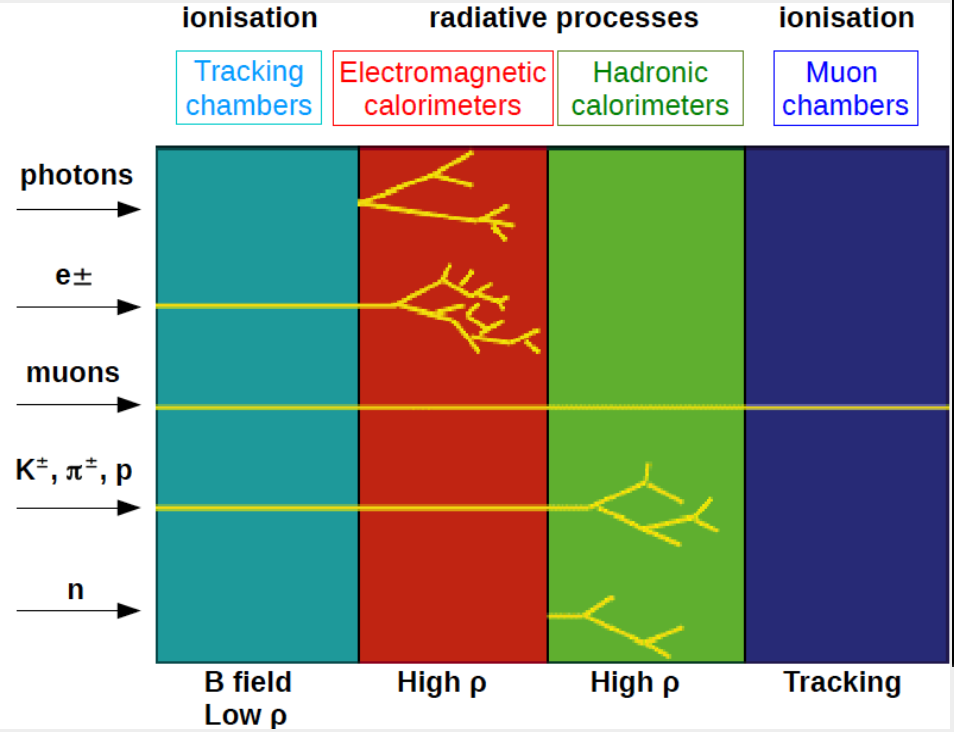

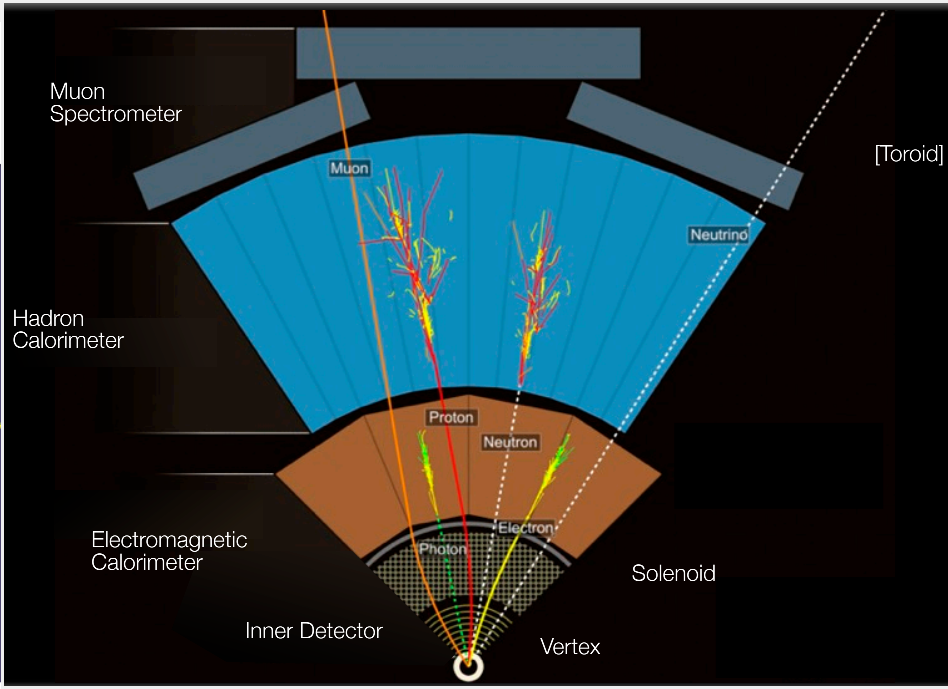

γ , e , jets (q,g), missing energy (e.g. ν), are detected with calorimeters

What can we access?

Measure stable and quasi-stable particles (e, γ, μ, π, K, p, n, ν) :

Kinematics (momentum and/or energy)

The way particle interacts with / passes through detectors

All other particles reconstructed via their decays to (quasi-) stable particles :

Invariant mass of the system of daughter particles

+ Decay vertex separated from production vertex for some particles decaying via weak interaction

Main goal of instrumentation for HEP :

Precisely/fast **measure kinematics** of (quasi-) stable particles

Unambiguously/fast **identify** them

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How perform the measurements (p,E)

- ***Use of a magnetic field***
  Obvious now but UA2 (SPS) and D0 (run I) had no magnetic field !!!

- ***Use of position detectors :***
  - ***gazeous :*** multi wires chambers, Time Projection chambers, drift tube ....
  - ***Solid :*** Silicium detectors
  - ***Try to do if possible a non destructive measurement***

    ==> minimize the amount of material in the detector itself

- ***Use calorimetry for the Energy measurement***

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- There are four main processes that depend on the velocity of a particle :
  1. Most direct is to measure the ***Time Of Flight (TOF)*** of the particles over a fixed distance
  2. Alternatively one can look at the detail of their interaction with matter
     The main source of energy loss is via Ionization ***(dE/dx)***
  3. If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as ***Transition radiation***
  4. If a particle travels at greater than the local speed of light, it will radiate ***Cherenkov radiation***

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Basics: Particle Detection/Identification

- ***For low-momentum***– typically up to a few GeV
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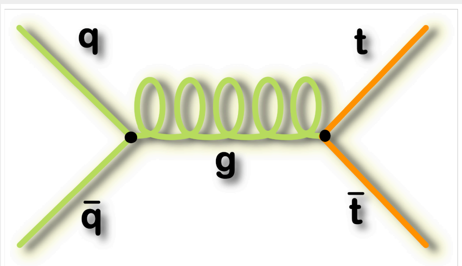
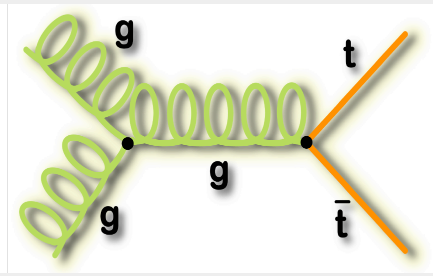
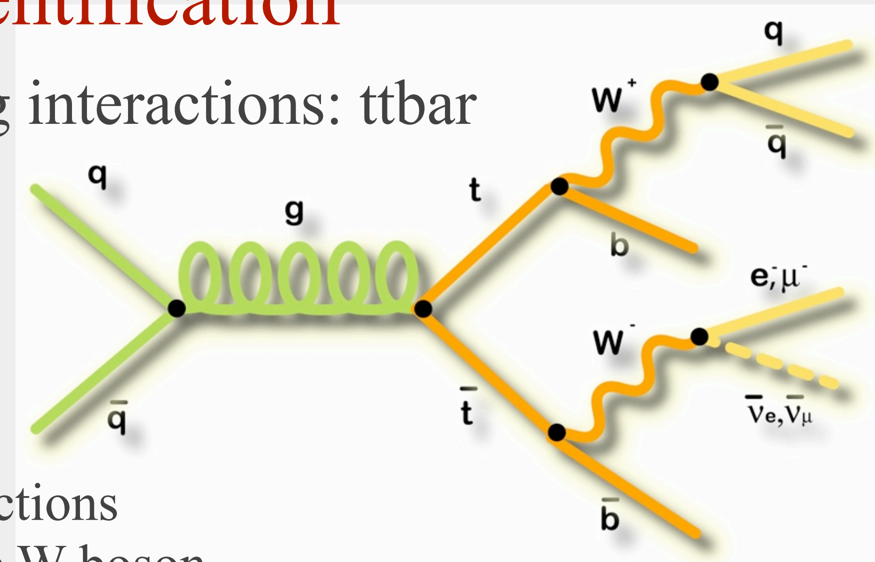
Objects for Top Quark identification

- Mainly produced in pairs via strong interactions: ttbar







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- Final state characterized by the decay of the W boson
- **Dilepton** (lepton = e or μ) (7%): 2 leptons, 2 b quarks, 2 neutrinos
- **Lepton+Jets** (lepton = e or μ) (34%): 2 b quarks, 2 light quarks, 1 lepton, 1 neutrino
- **All-Jets** (44%): 2 b quarks, 4 light quarks

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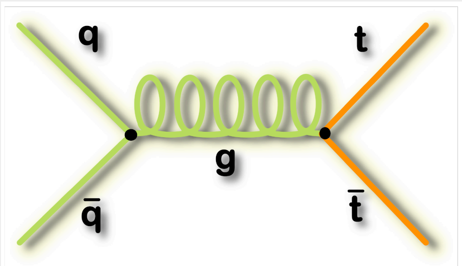

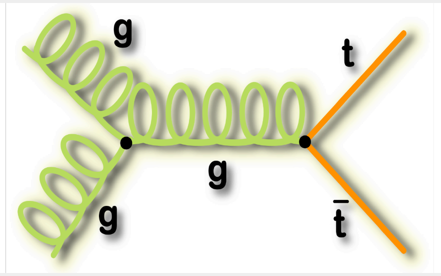

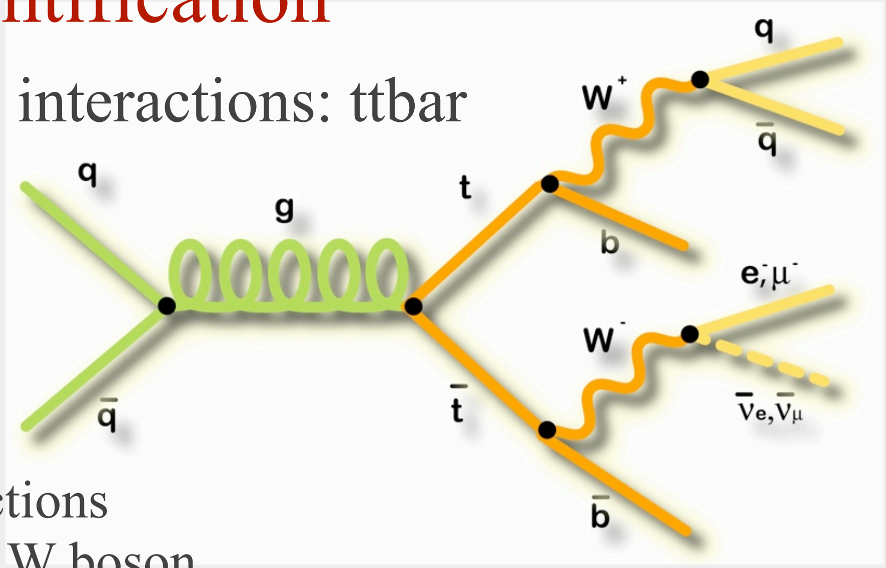

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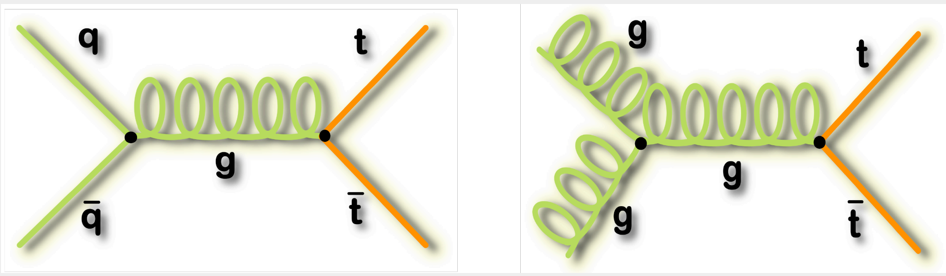

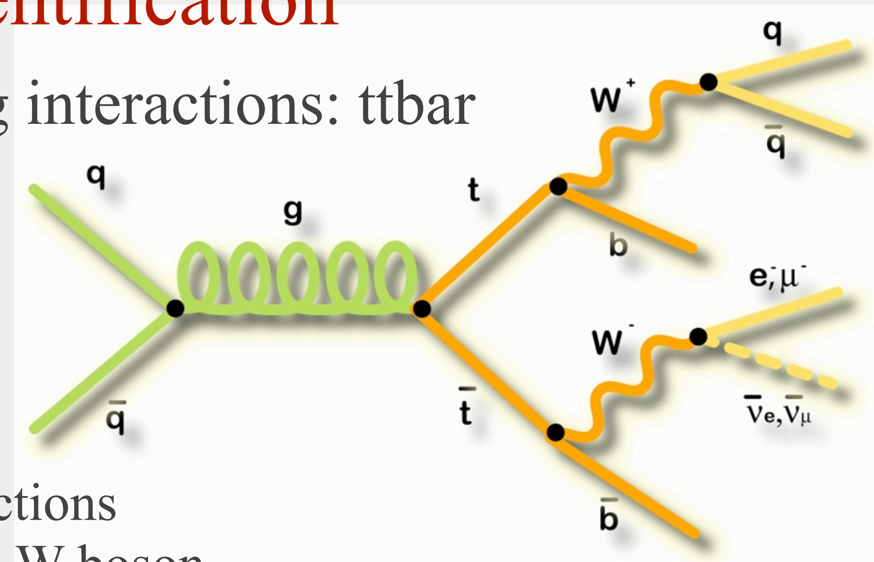

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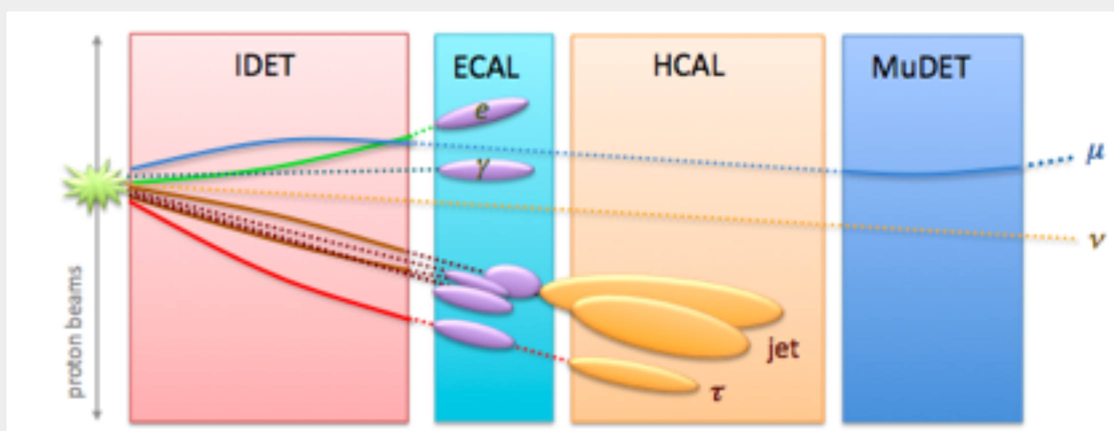

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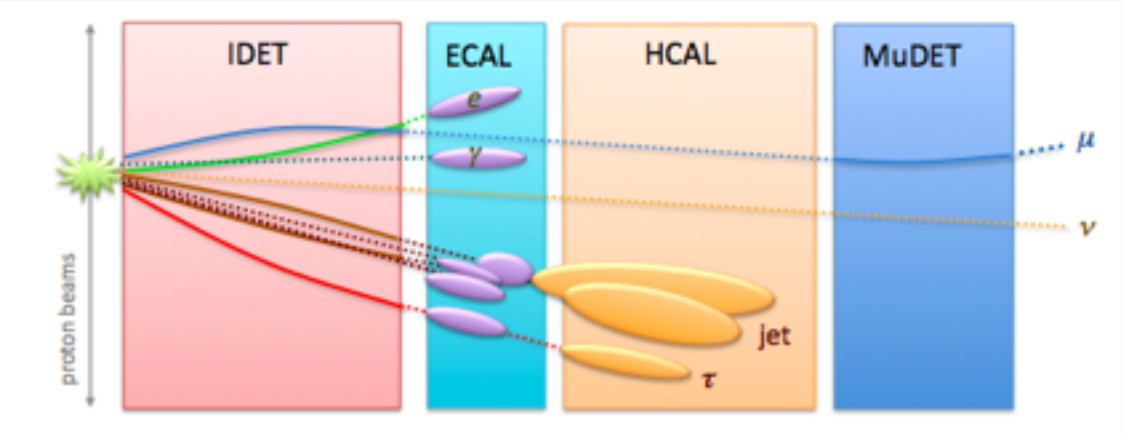

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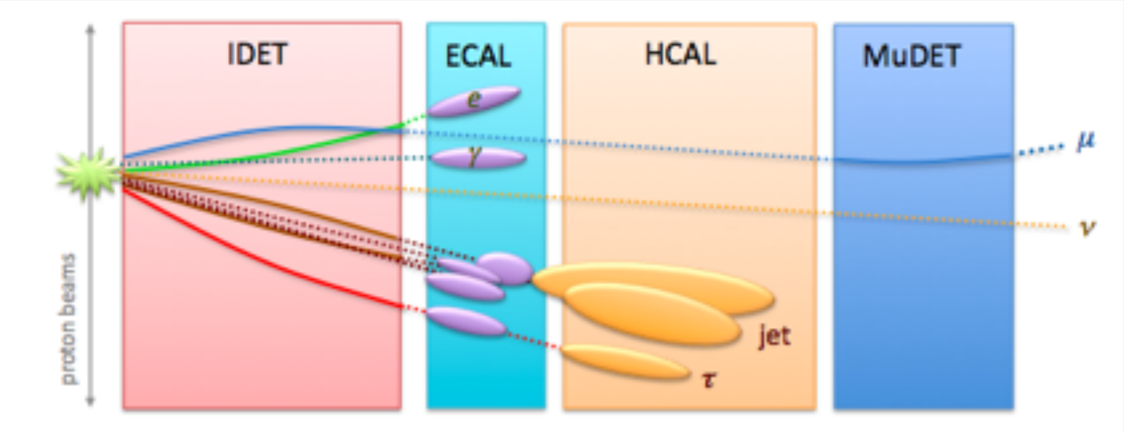

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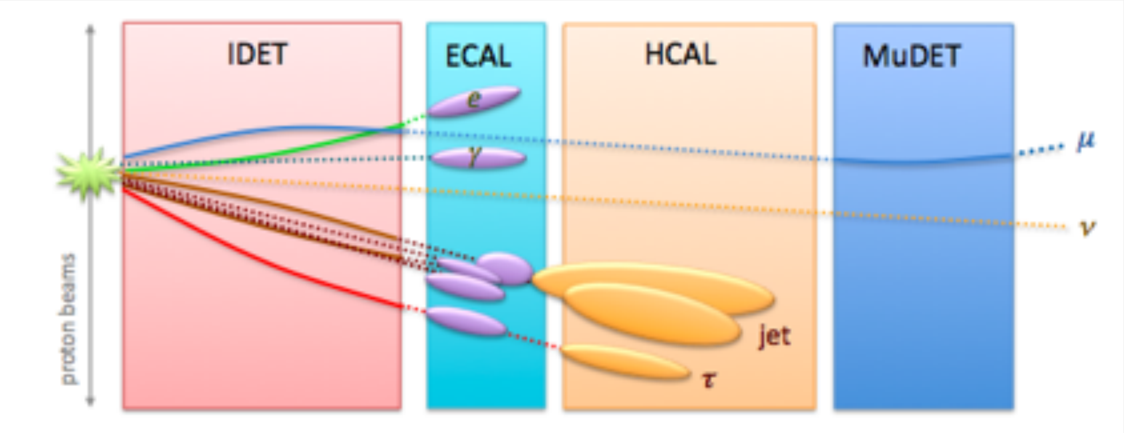

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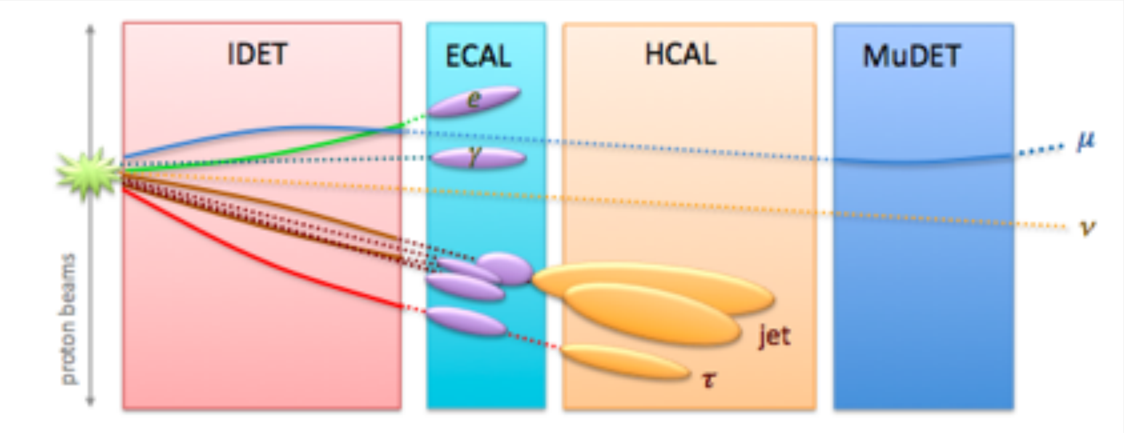

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- Calibrations and alignments applied at nearly every step (see lectures 2 and 3)

Vertex detectors : b quarks ID

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Requirements based on b-jets parameters

- -B hadrons lifetime : average of ~1.6 ps
- -semi-leptonic fraction ~10%e, and 10%μ
- -cτ =470 microns →impact parameter d ~100 microns
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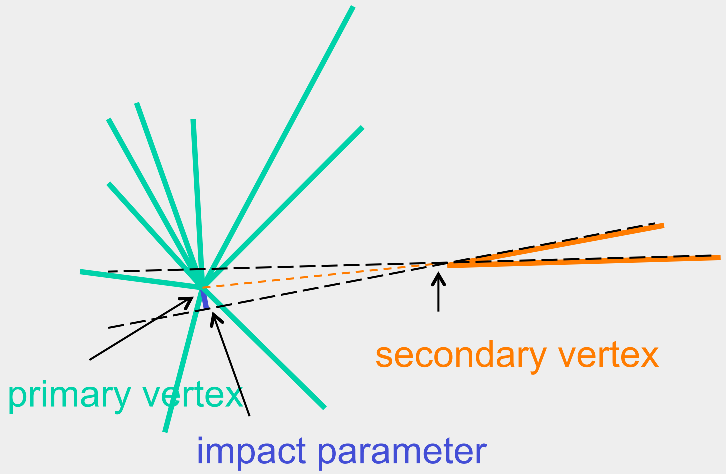

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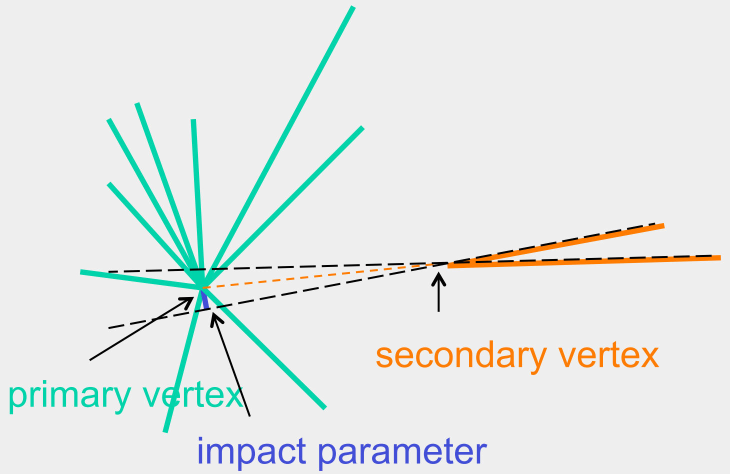


Accuracy limited by

- -lever arm,
- -granularity,
- - number of layers

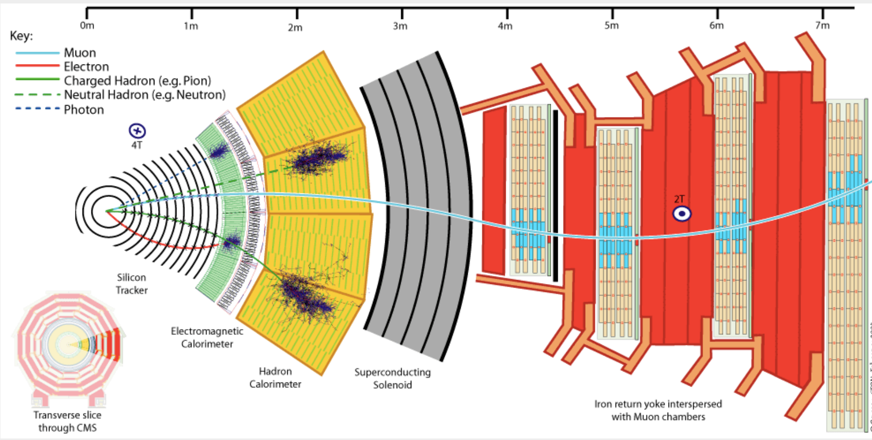
Solution:

- -3 layer pixel detector
- -first layer as close as possible to beam pipe
- -single hit accuracy < 15 microns in rφ
- -equipped with fast electronics

Beware -of radiation damage

- -multiple scattering in material
- -power dissipation

Objects: Electrons ID



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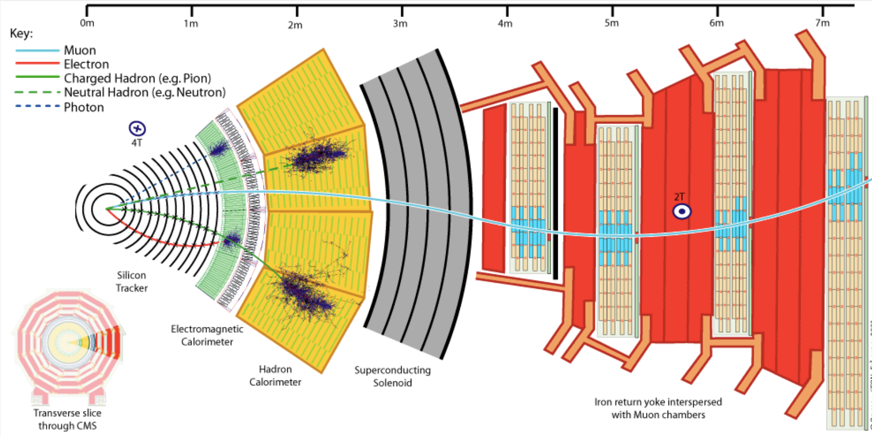

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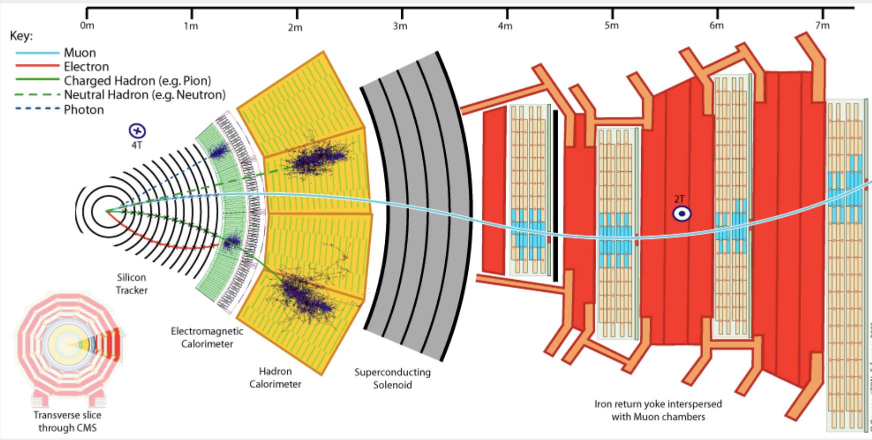
- **Backgrounds**
  - Jets
  - Early showering charged pions
  - Conversions: $\pi^0 \rightarrow \gamma\gamma \rightarrow ee+X$
  - Semileptonic b-decays
  - Photon conversions
  - Photons similar to electrons



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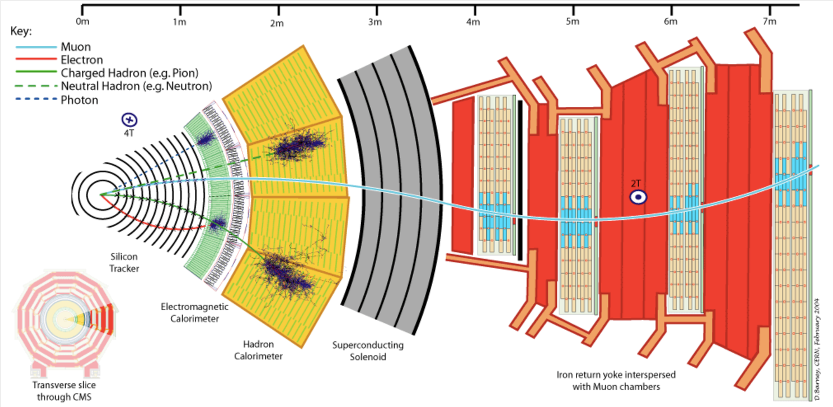

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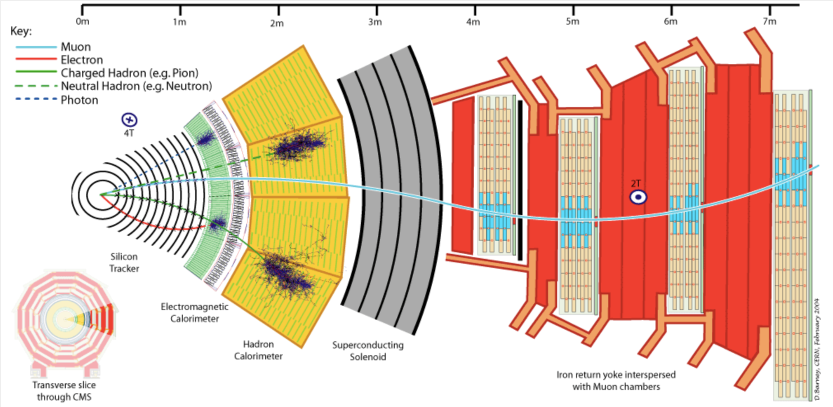

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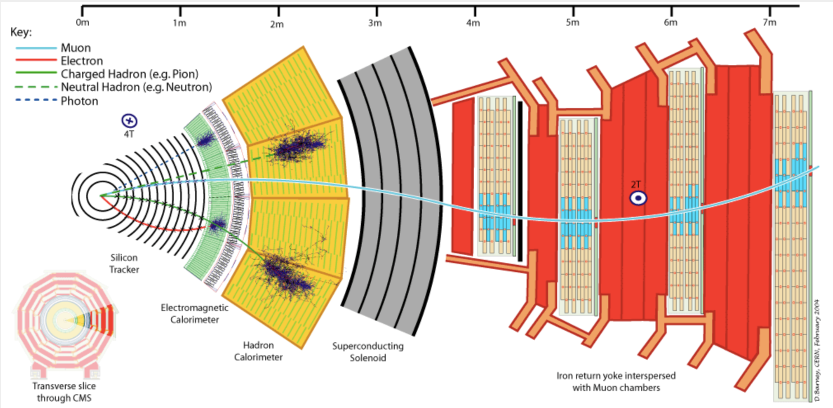

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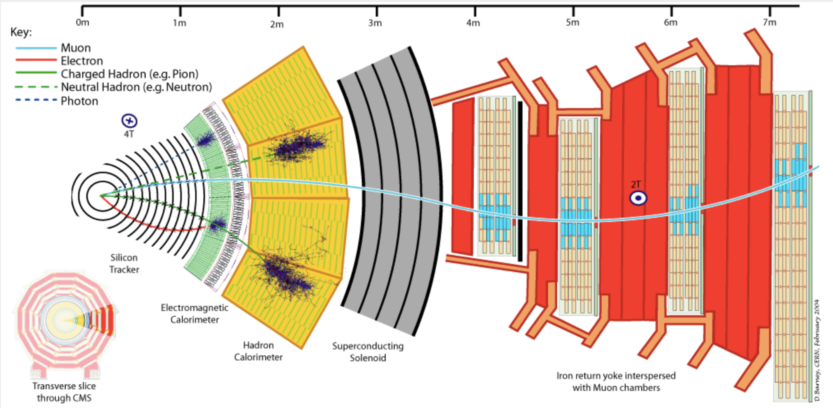

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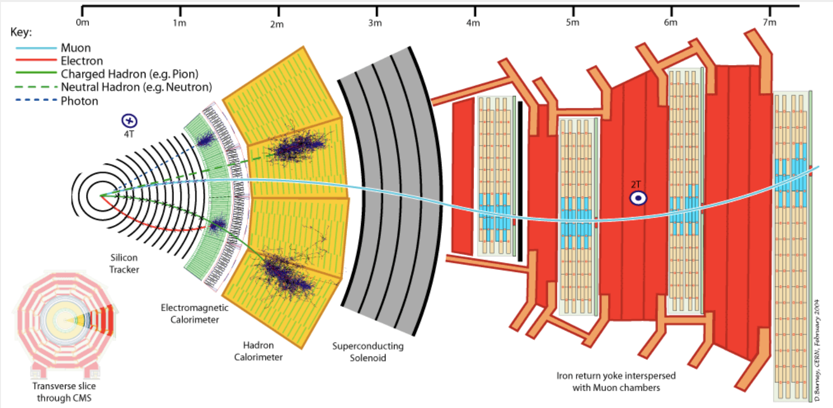

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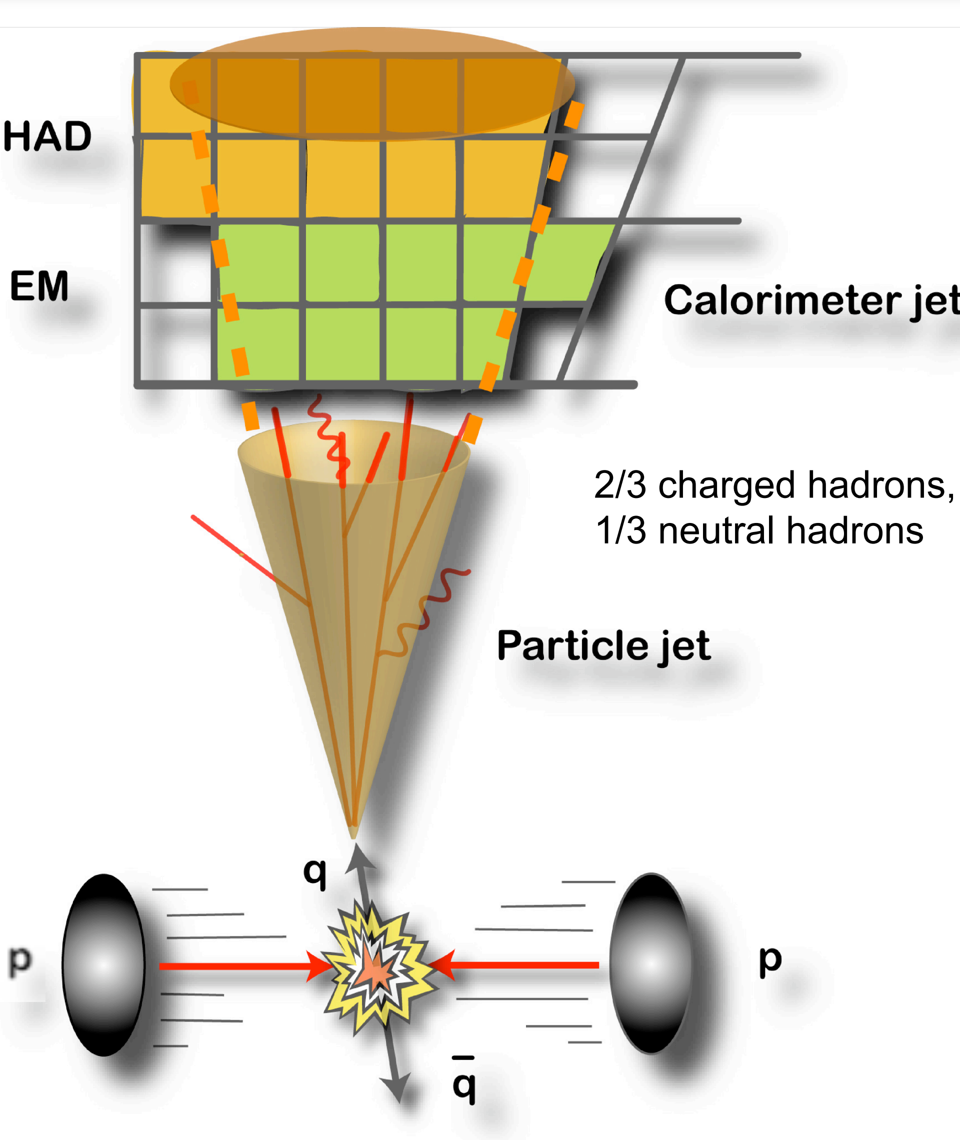
- **Performance**
  - Measured using Z's
  - 60-100% depending on |η|

Objects: Jets ID

- Measurement of the kinematics of a hard parton emission requires



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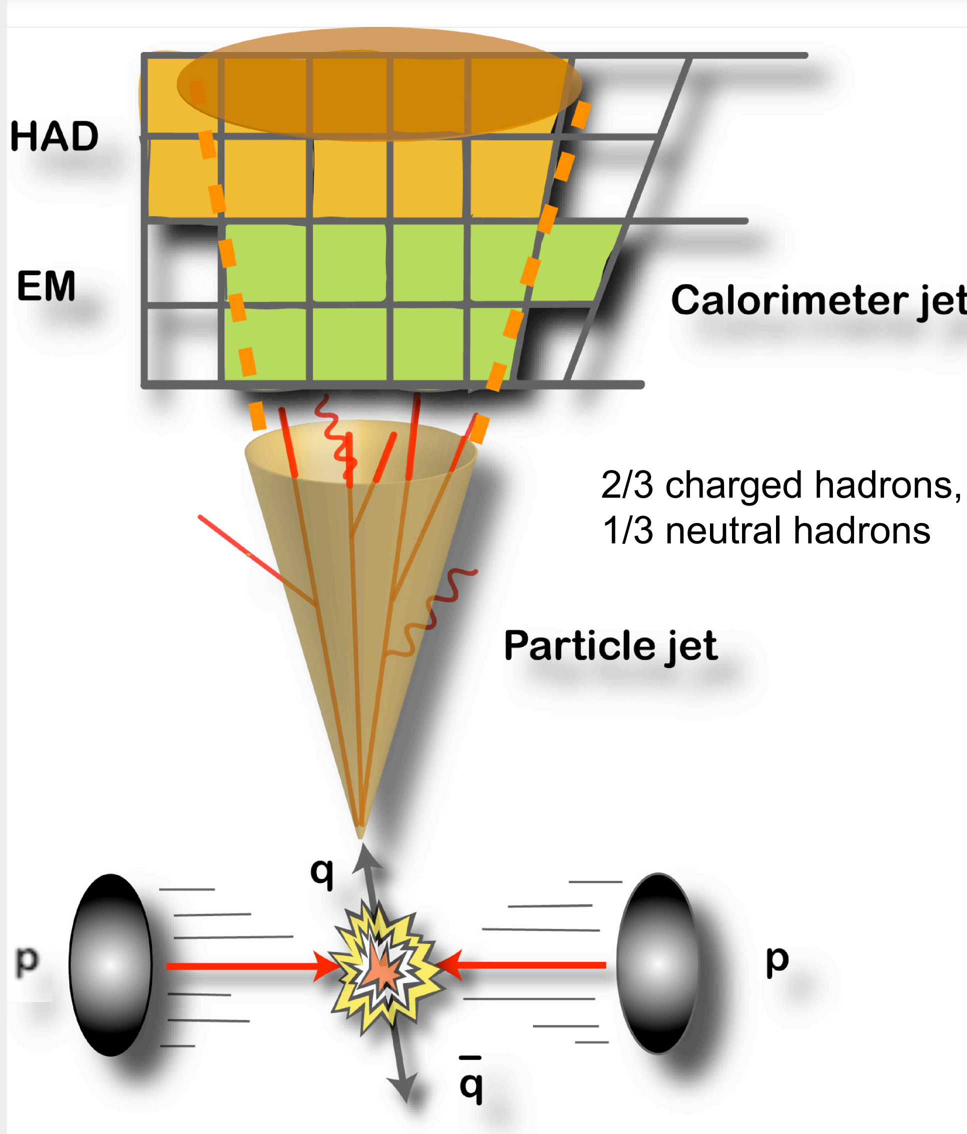

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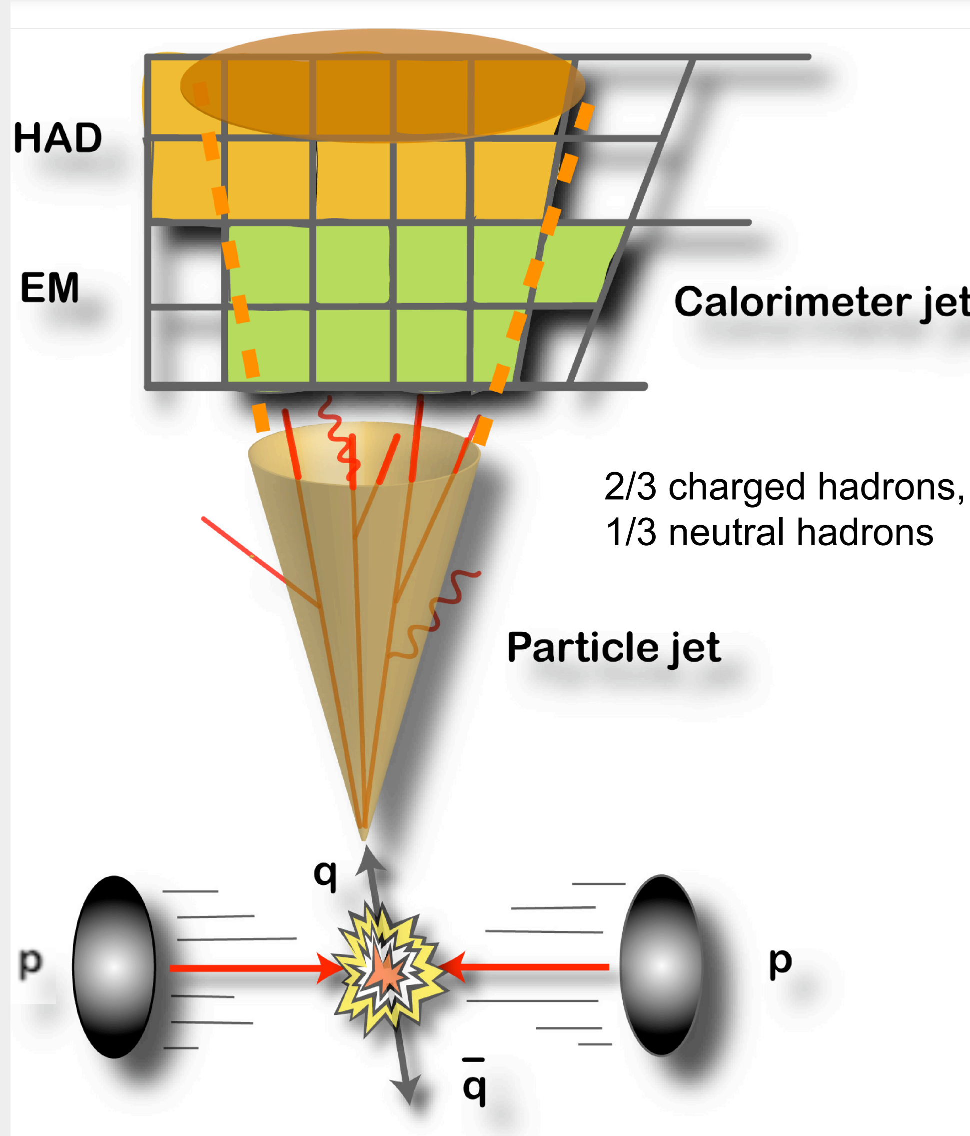
- Reconstruction:

One needs : best matching to hard parton and jet identification. Many algorithms available: Cone, midpoint, KT



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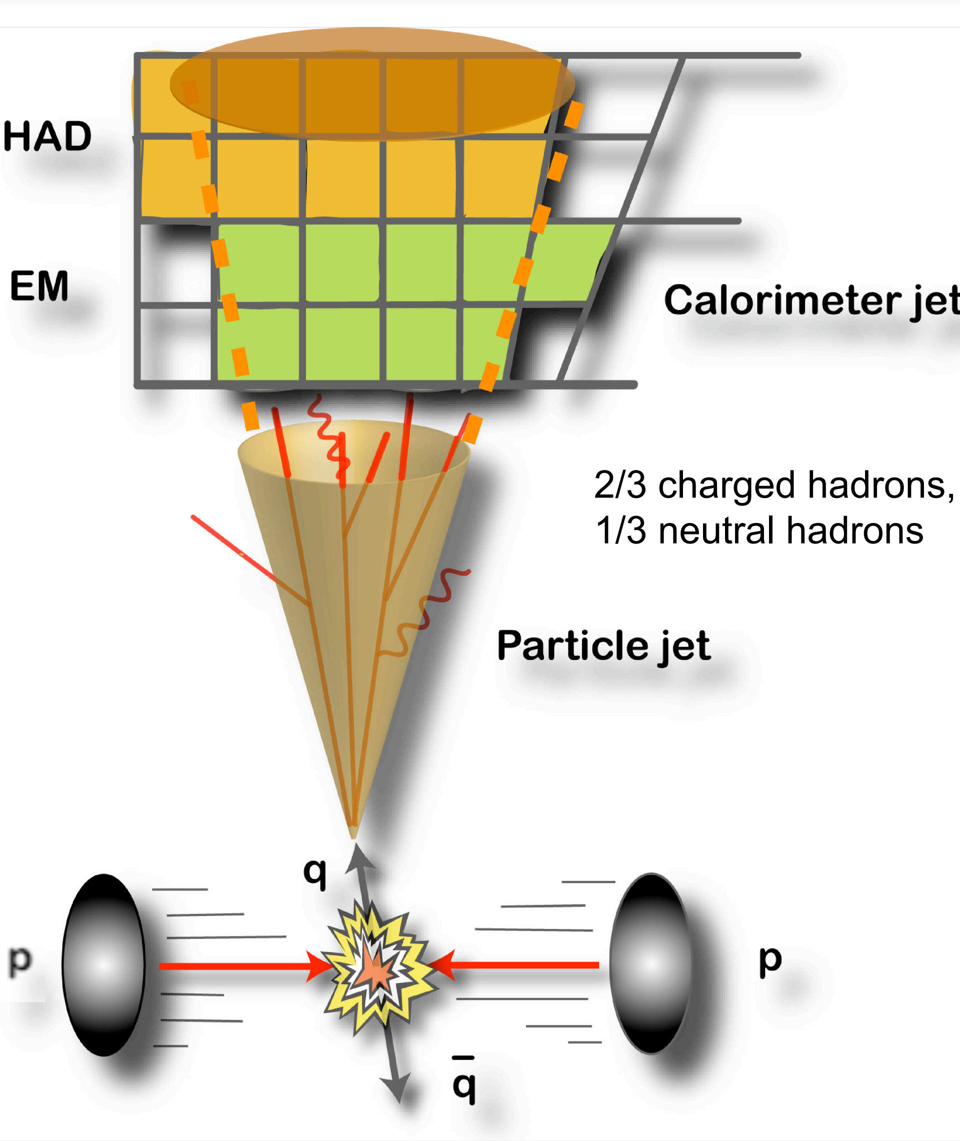

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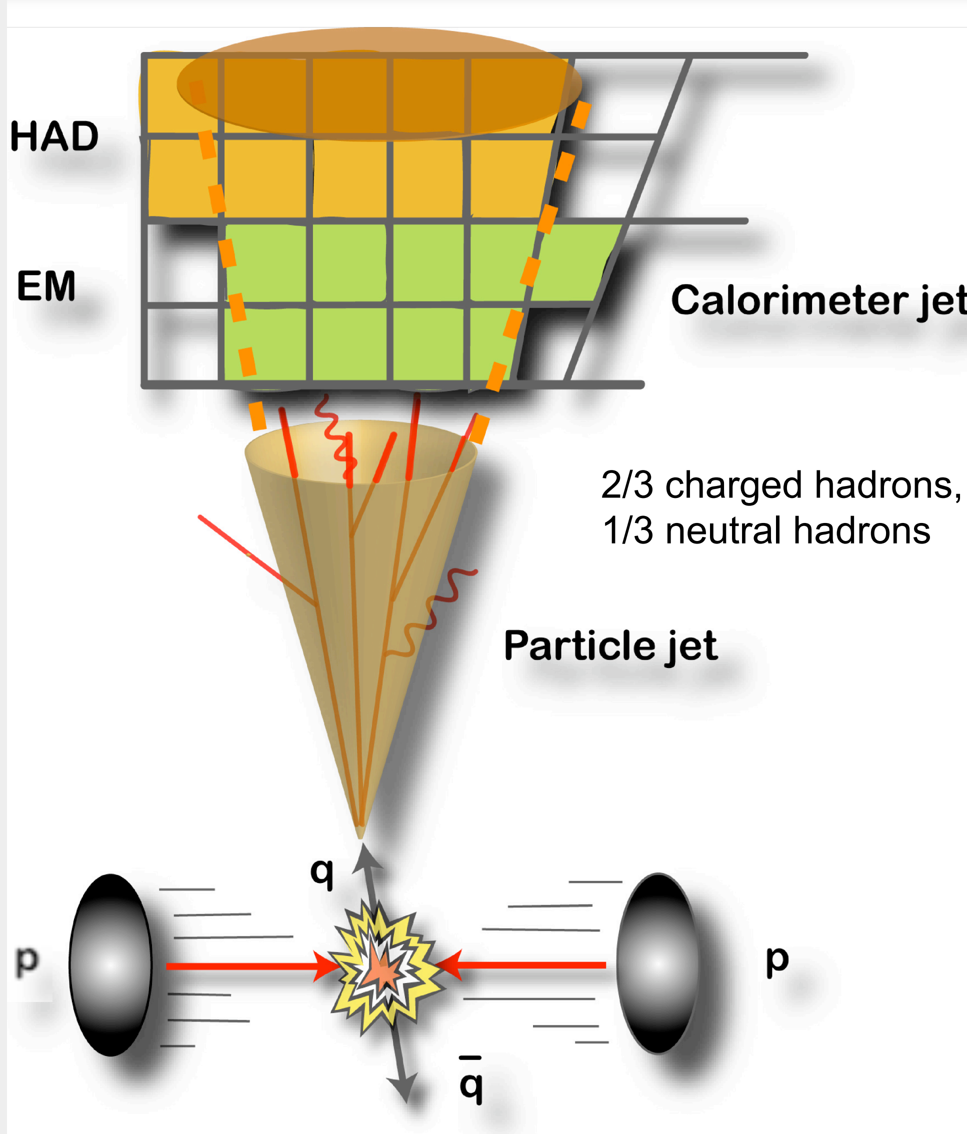

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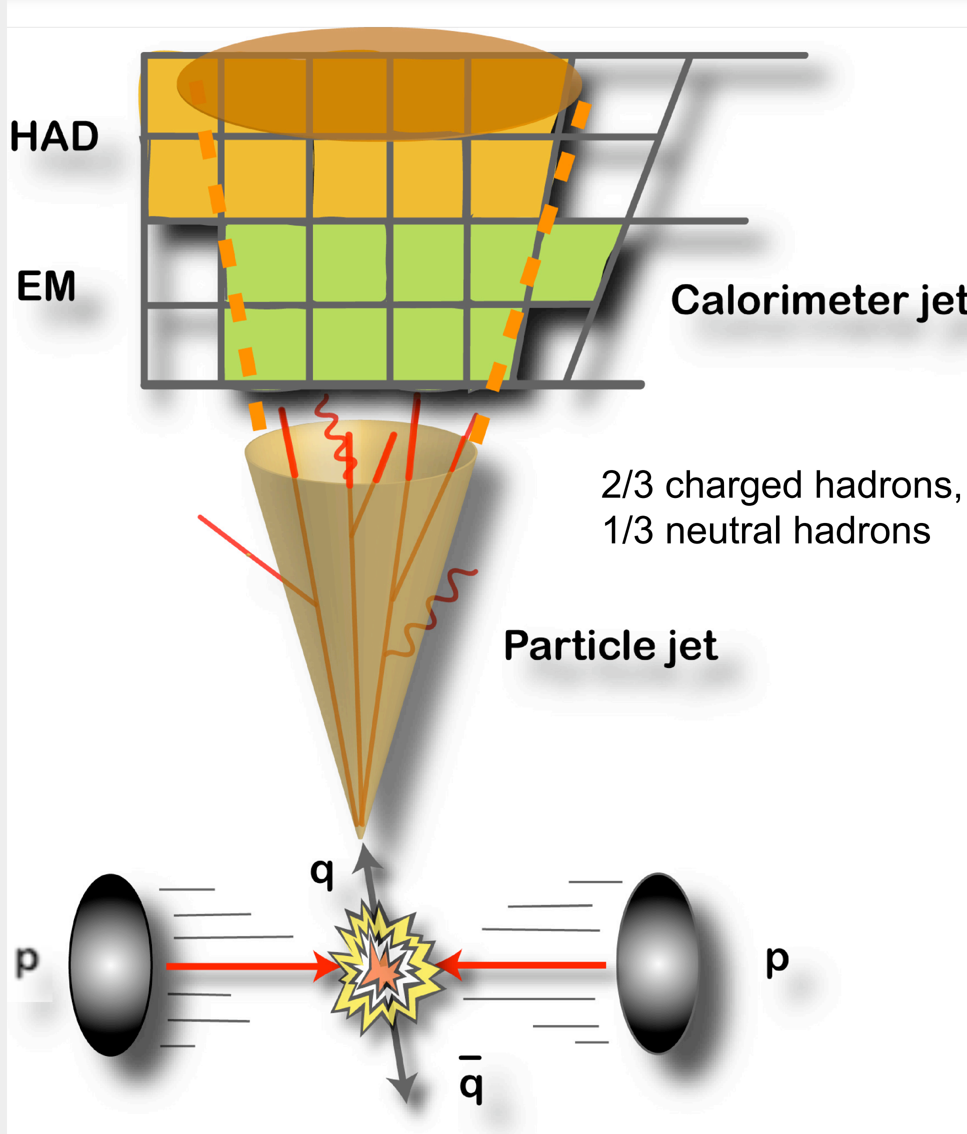

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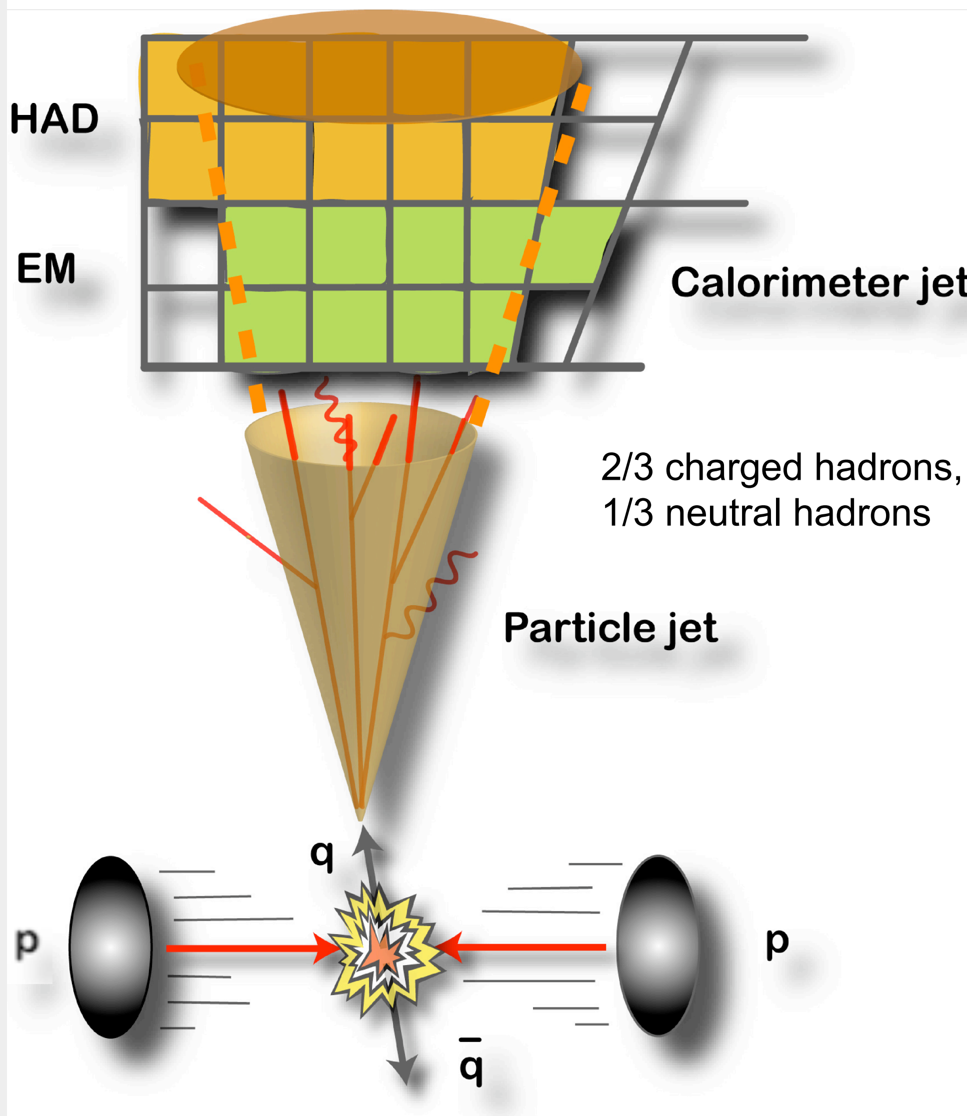

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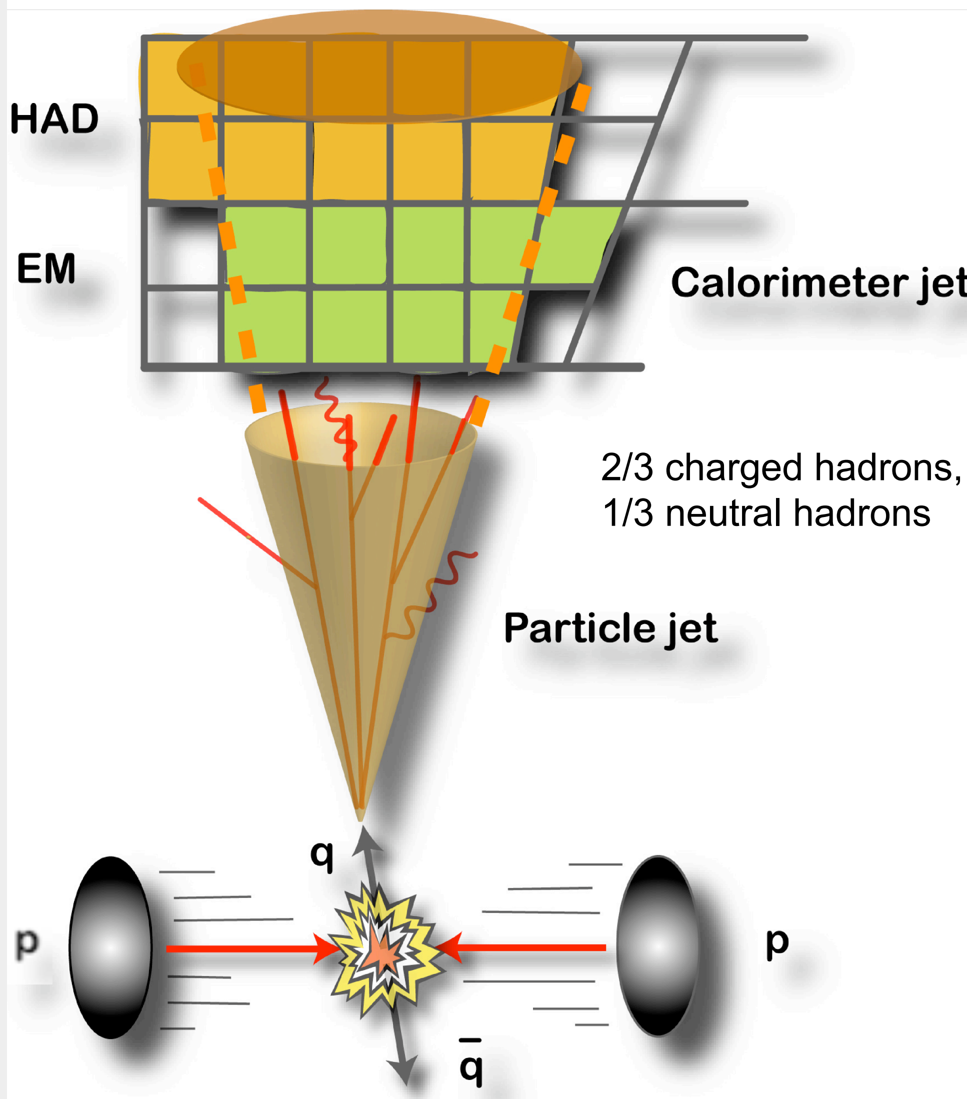

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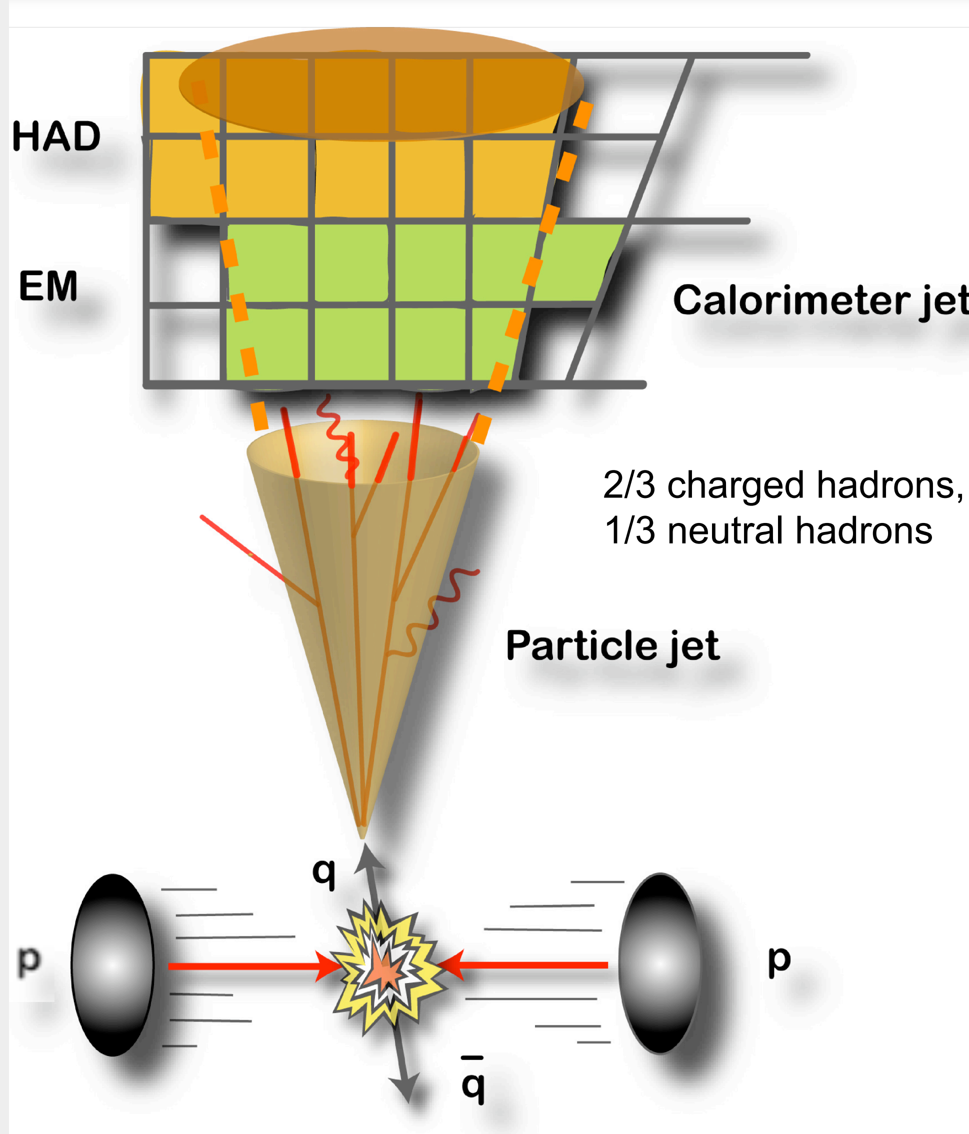
- Reconstruction and Scale are fundamental for precision measurements. Resolution is critical for the successful identification of low S/B signal



Objects: Neutrino ID

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- **Signature**
  - No interaction in the detector

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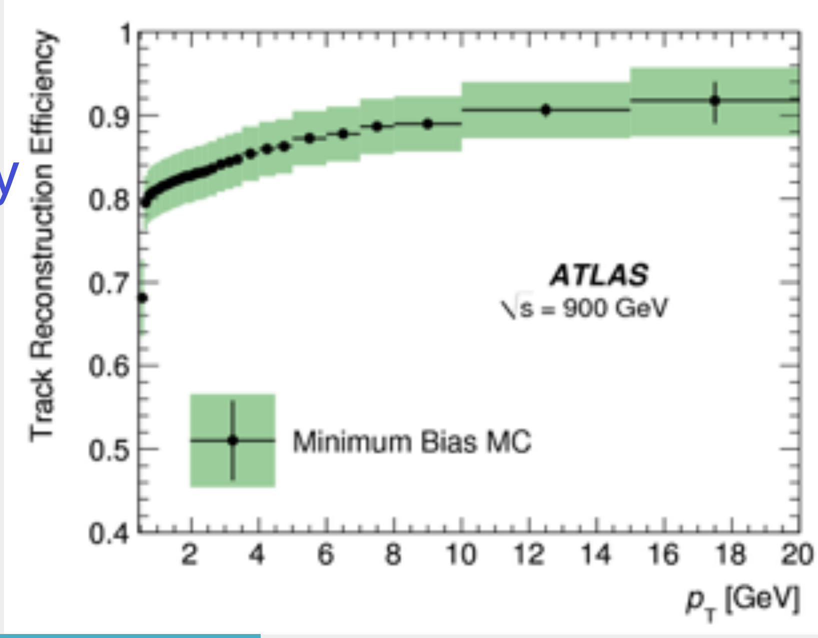
- **Signature**
  - No interaction in the detector
- **Reconstruction**
  - Look for momentum imbalance and assign the missing momentum to the ν
  - But in hadron colliders, limited to using only the 2 transverse components of the momentum -> p_T
  - ETmiss Resolution depends on calorimeter resolution
  - Degrades with detector imperfection (cracks) and pile up

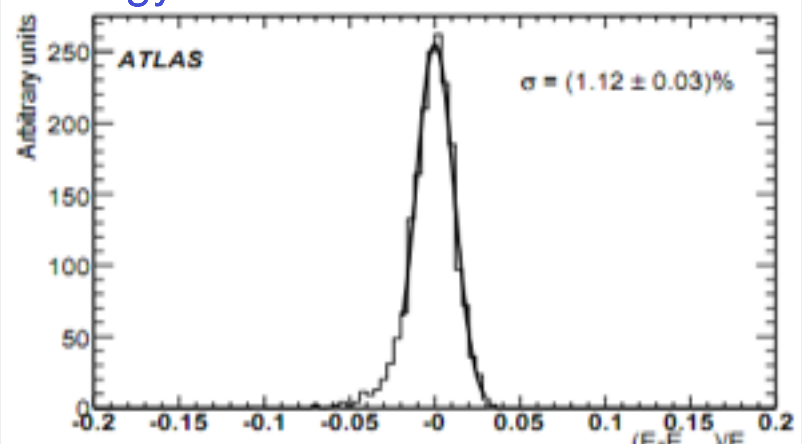
Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency



Efficiency = (Number of Reconstructed Tracks) / (Number of True Tracks)

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency
- **Resolution**
  - how accurately do we reconstruct it – e.g. energy resolution

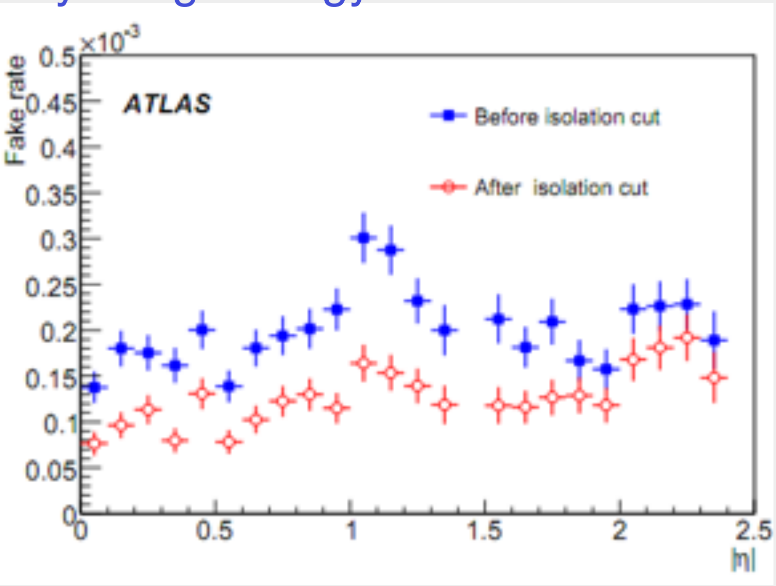


Electron energy resolution from simulation

Energy resolution = (Measured_Energy – True_Energy)/ True_Energy

Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency
- **Resolution**
  - how accurately do we reconstruct a quantity – e.g. energy resolution
- **Fake rate**
  - how often we reconstruct a different object as the object we are interested in – e.g. a jet faking a electron



Fake rate = (Number of jets reconstructed as an electron) / (Number of jets)

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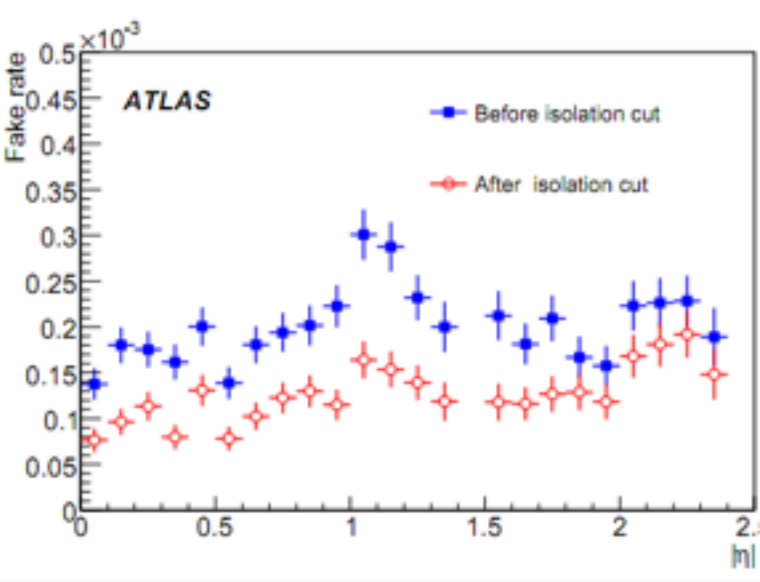

- ***For physics analysis it is important to have high efficiency, good resolution, and low fake rates***
- ***to be able to measure the efficiencies, resolutions and fake rates and their uncertainties <u>is not easy</u>***
- ***Robust against detector problems***
  - •Noise
  - •Dead regions of the detector
- ***Be able to run within the computing resources limitations***
  - •CPU time per event
  - •Memory use

ID summary

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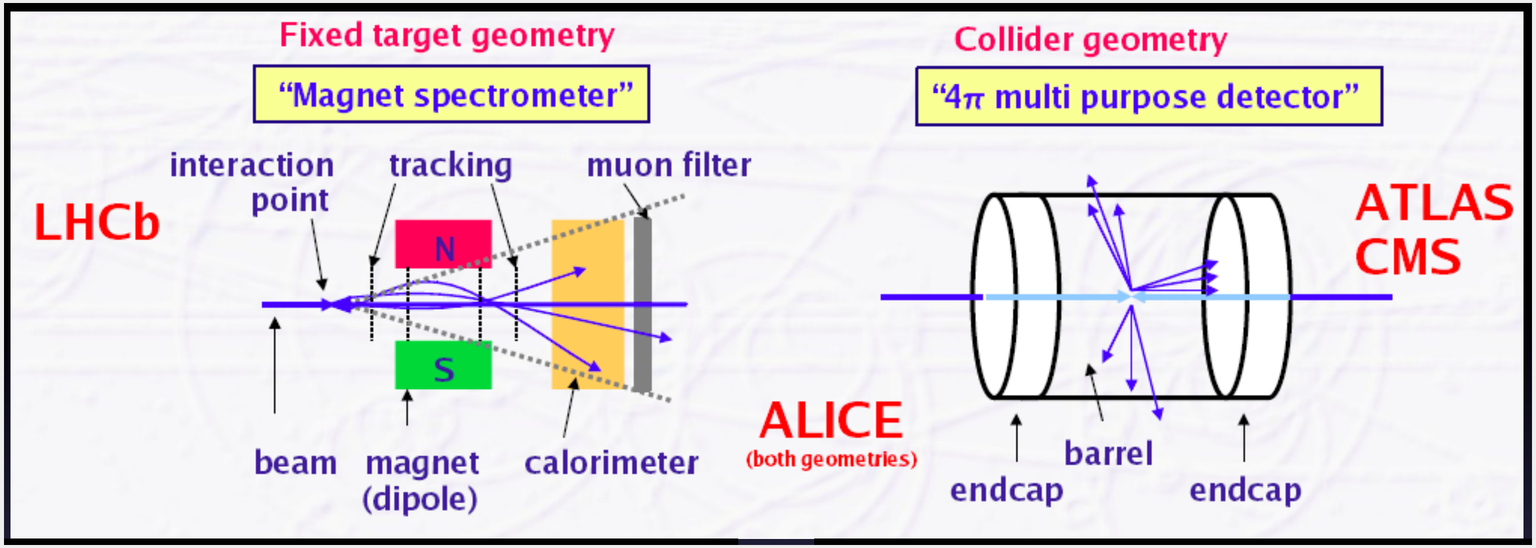
- Distinguishing the different long-lived charged hadrons (π, K, p) is more challenging, and usually requires dedicated detectors
- Their identification is based on four main processes:
  TOF, dE/dx, Transition radiation and the Cherenkov effect

Towards detector definition

Lets look how were build the LHC detectors

Configuration of HEP Detectors



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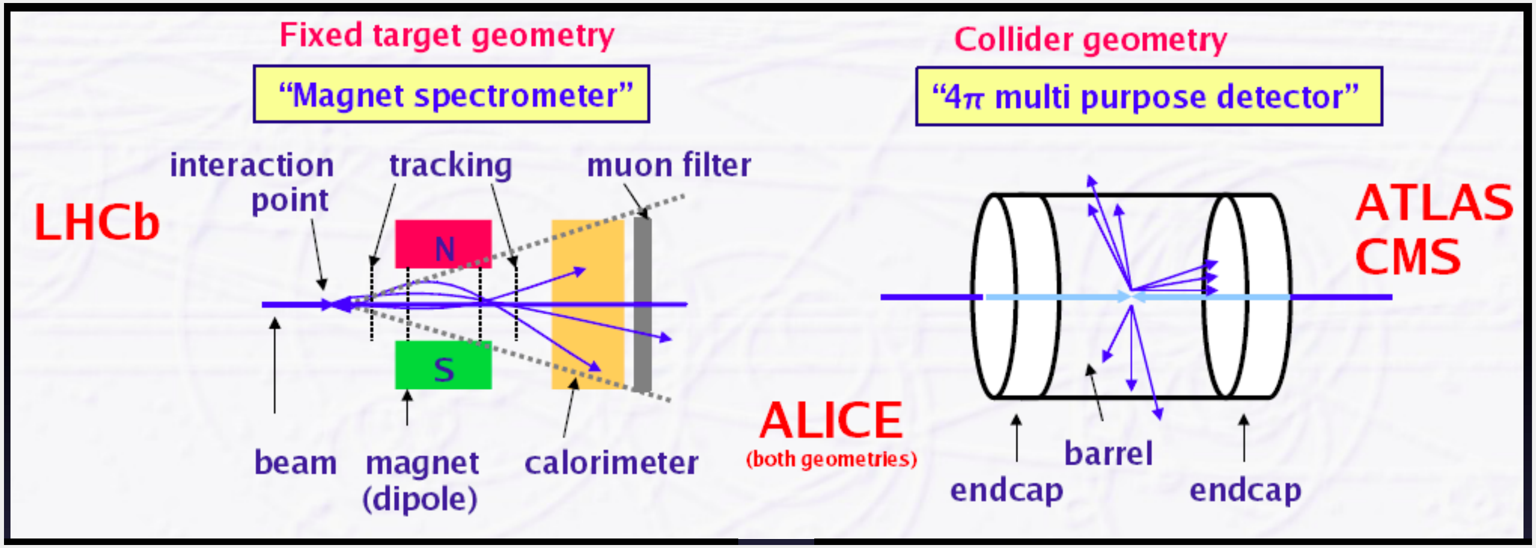

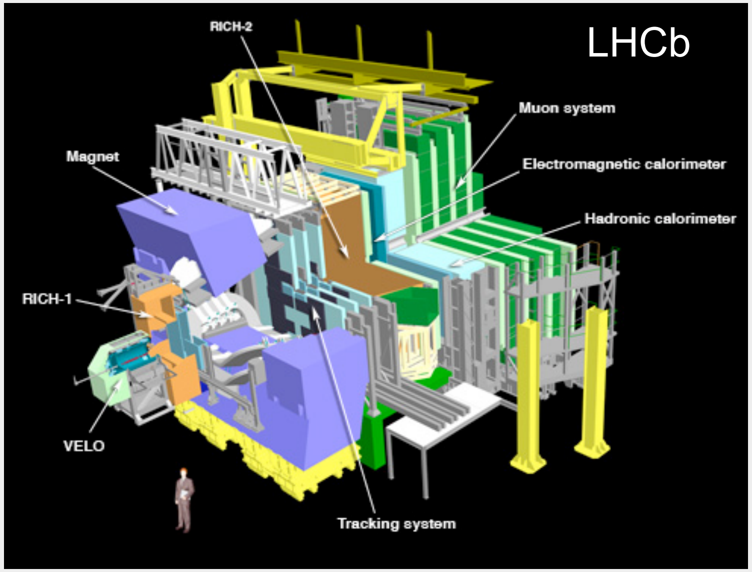

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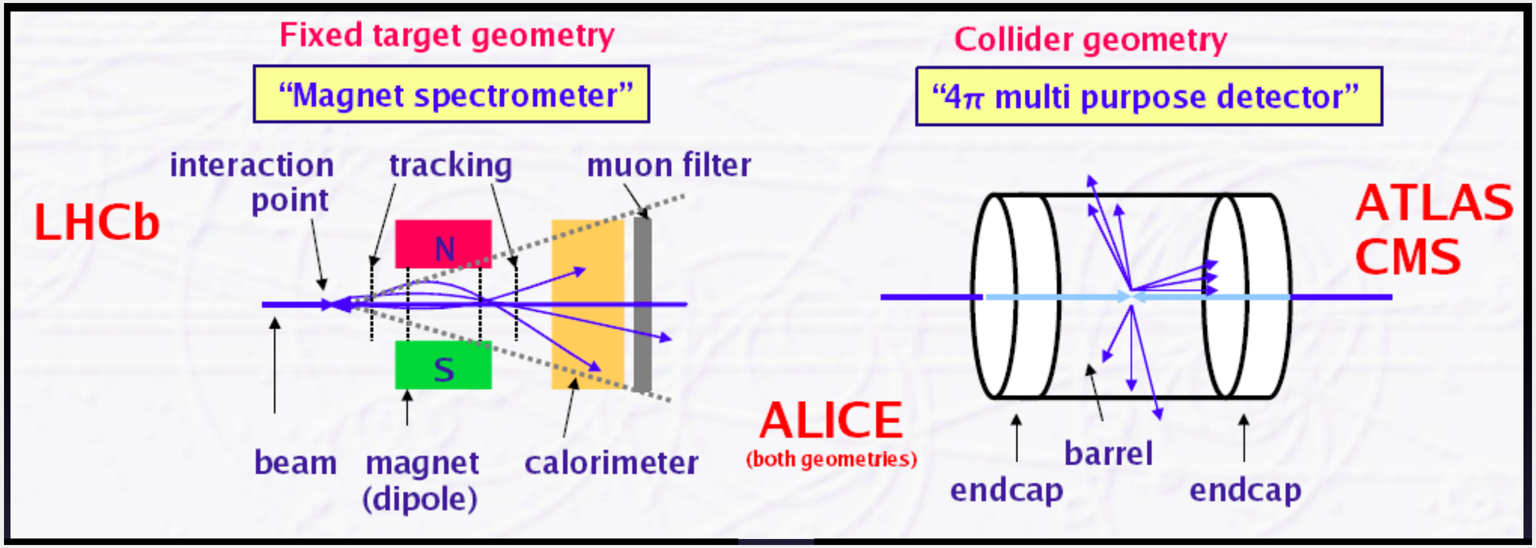
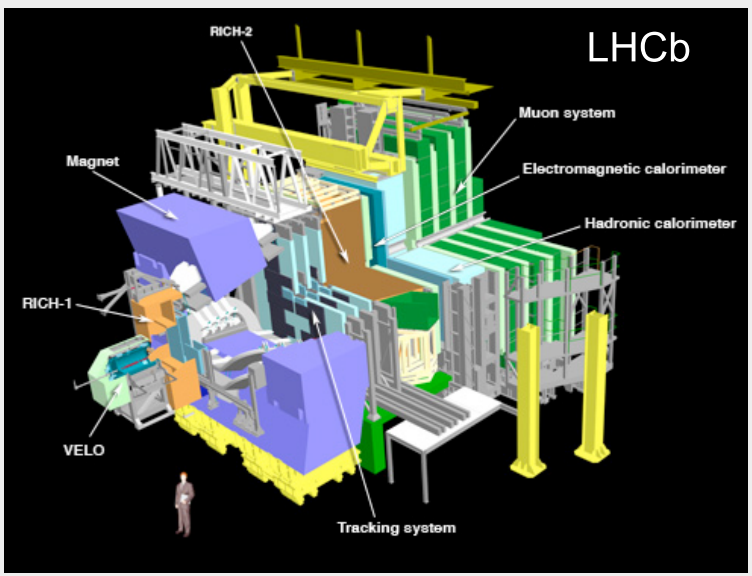
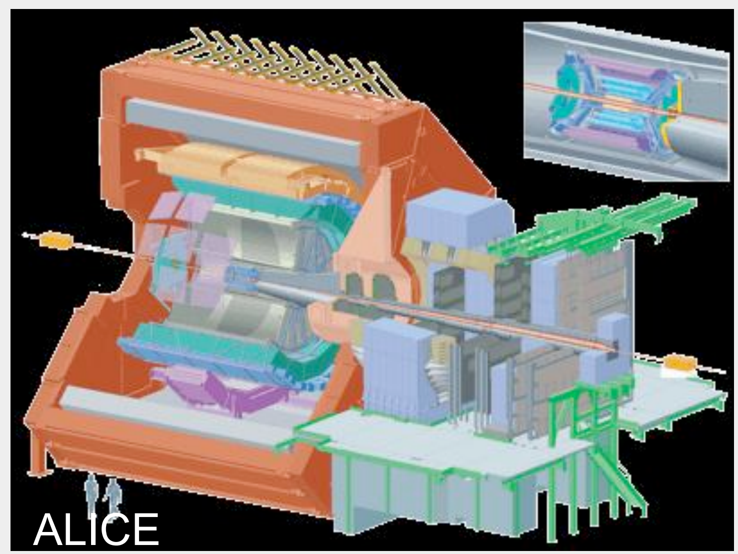
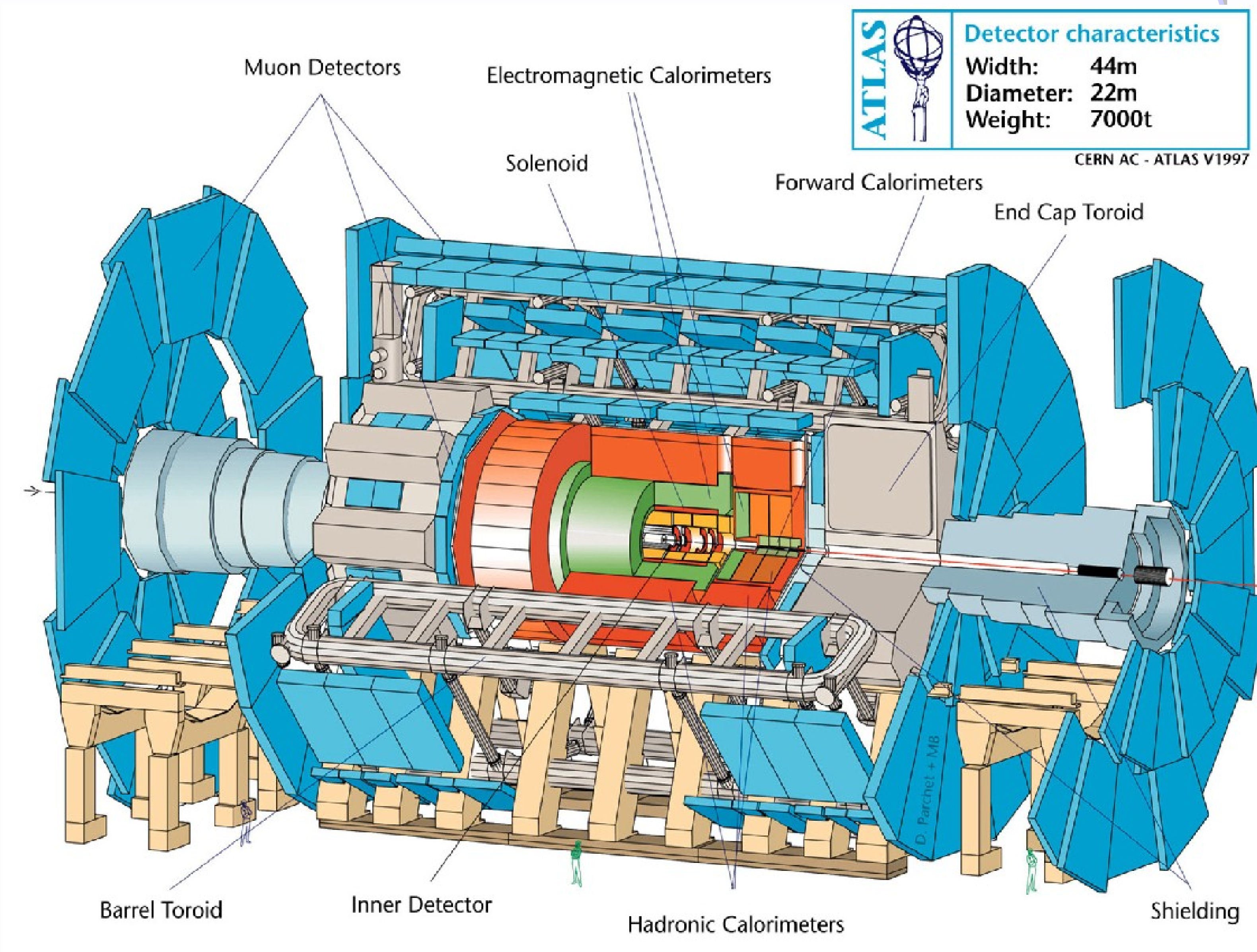




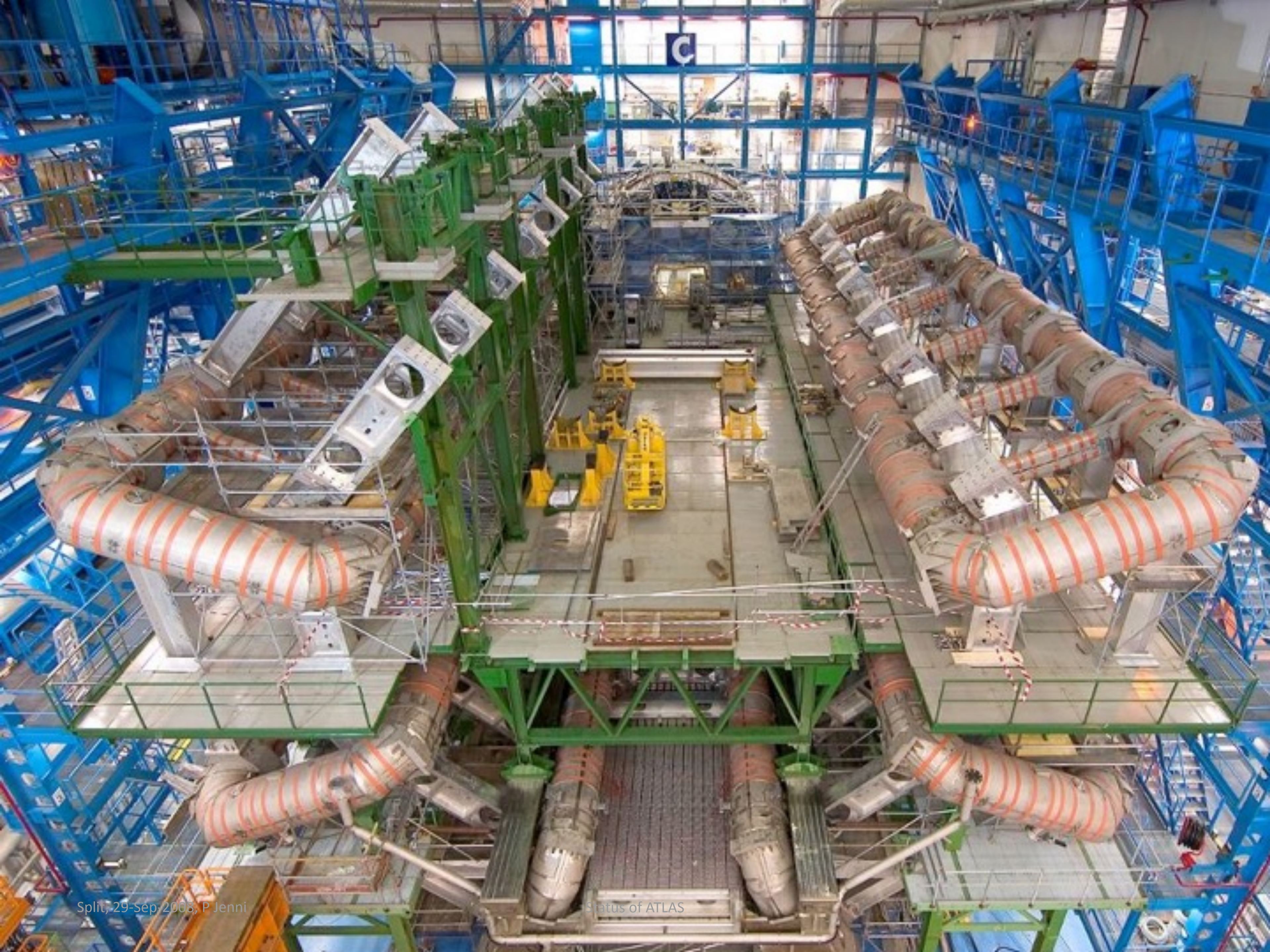


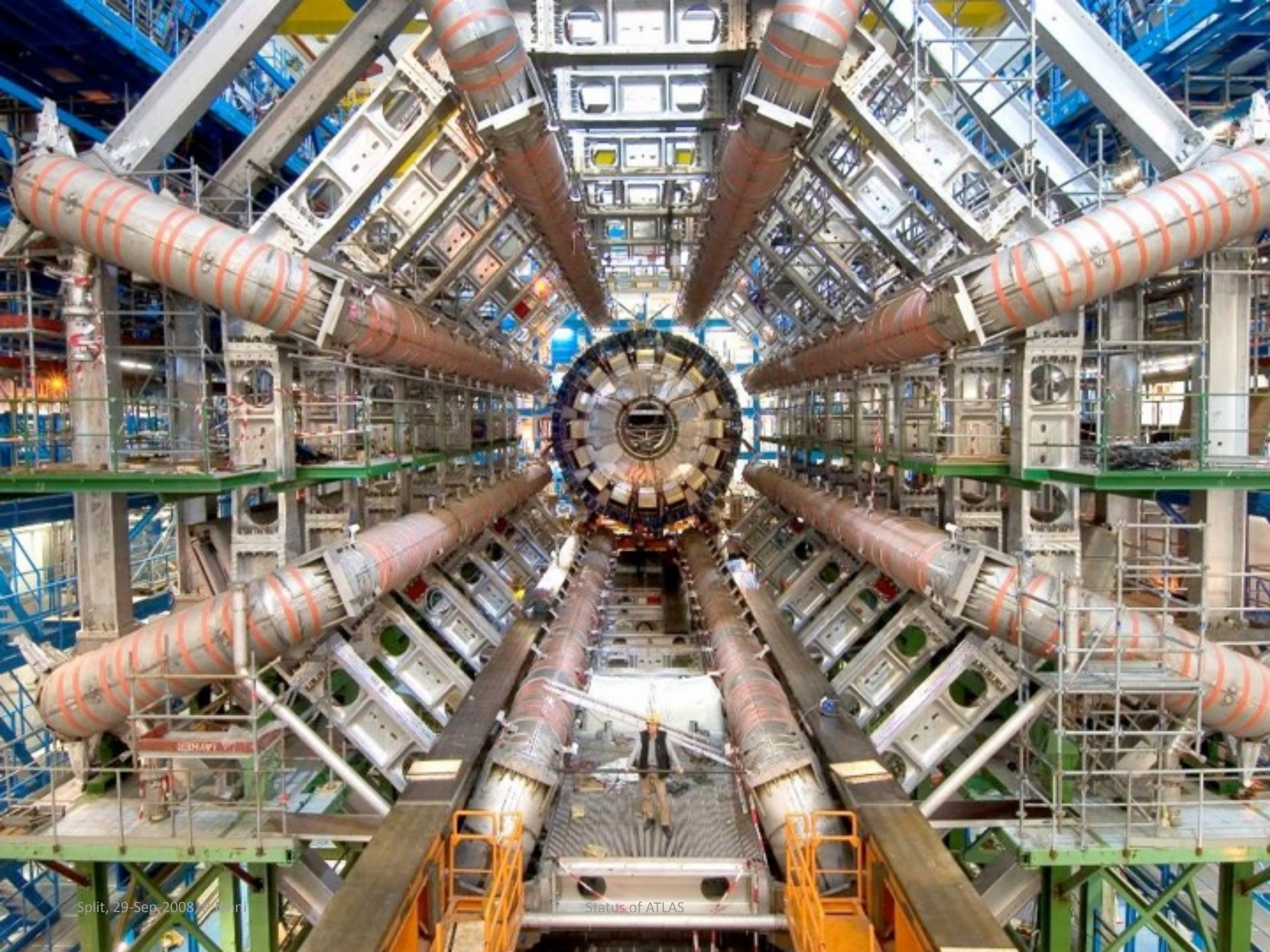

Muon Detectors
Electromagnetic Calorimeters
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V1997
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB


A

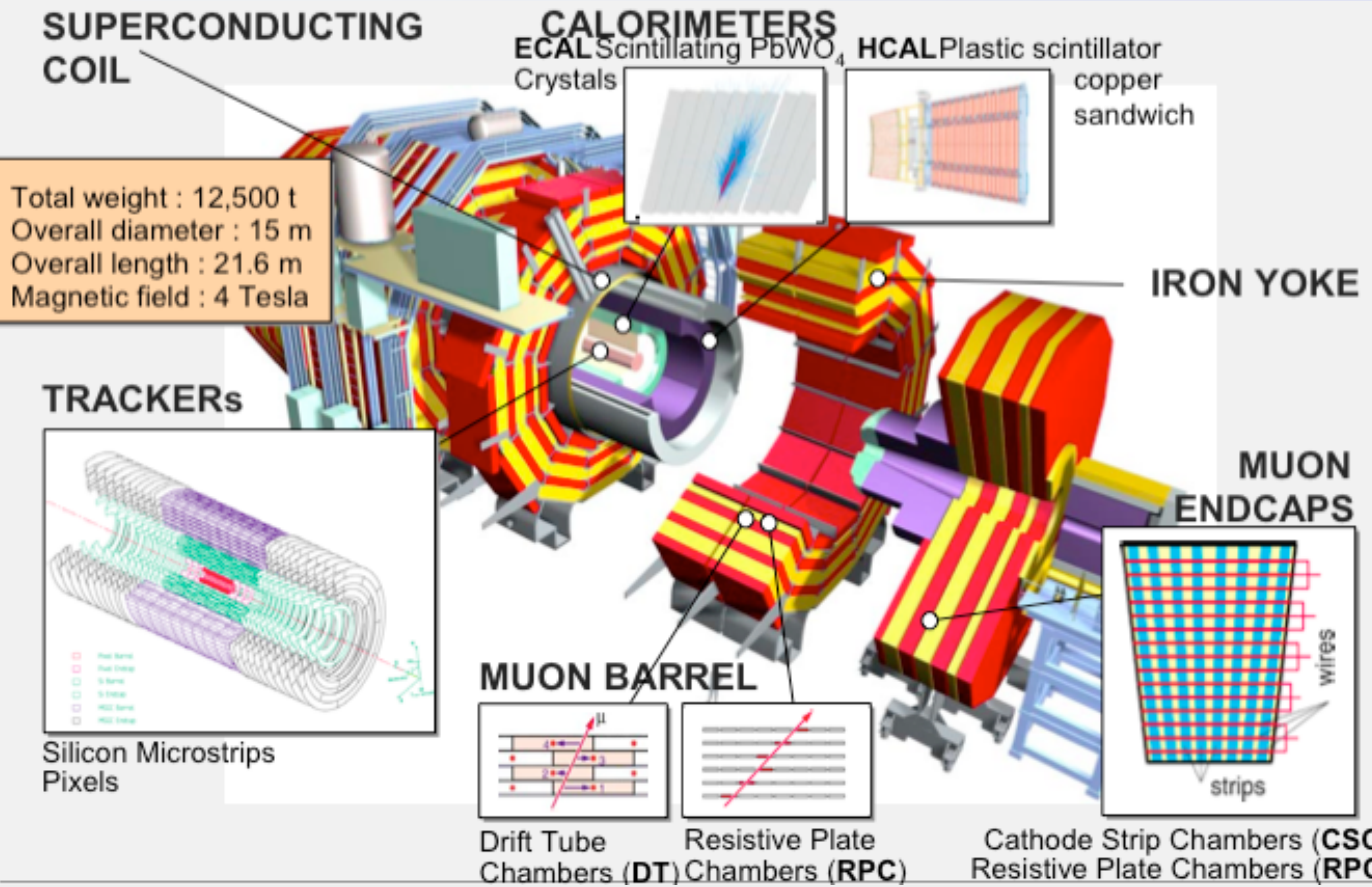

C

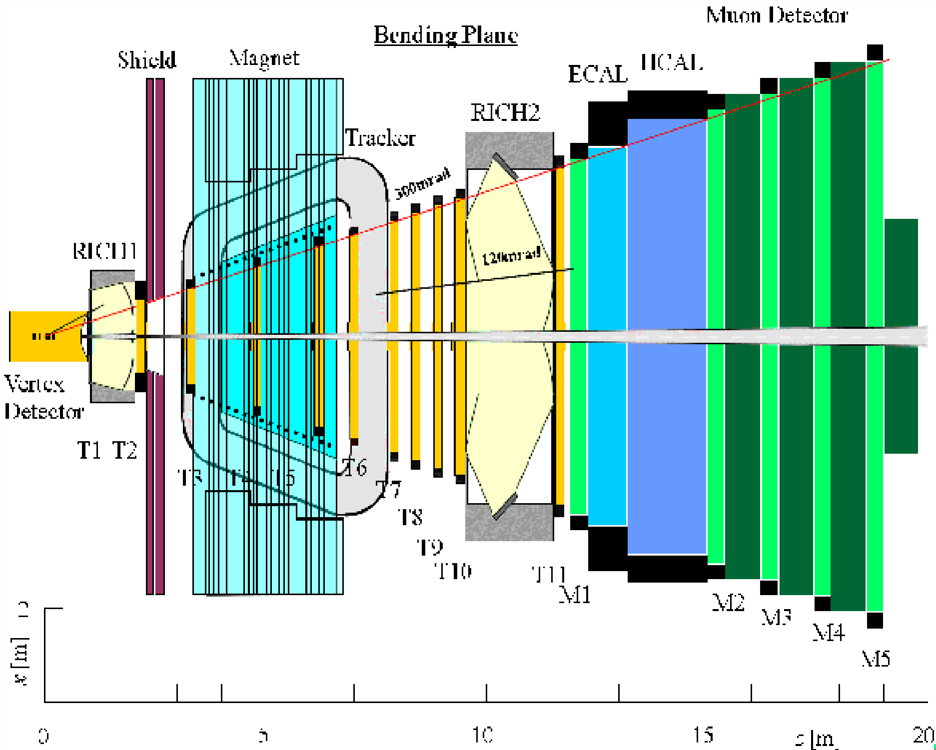

C

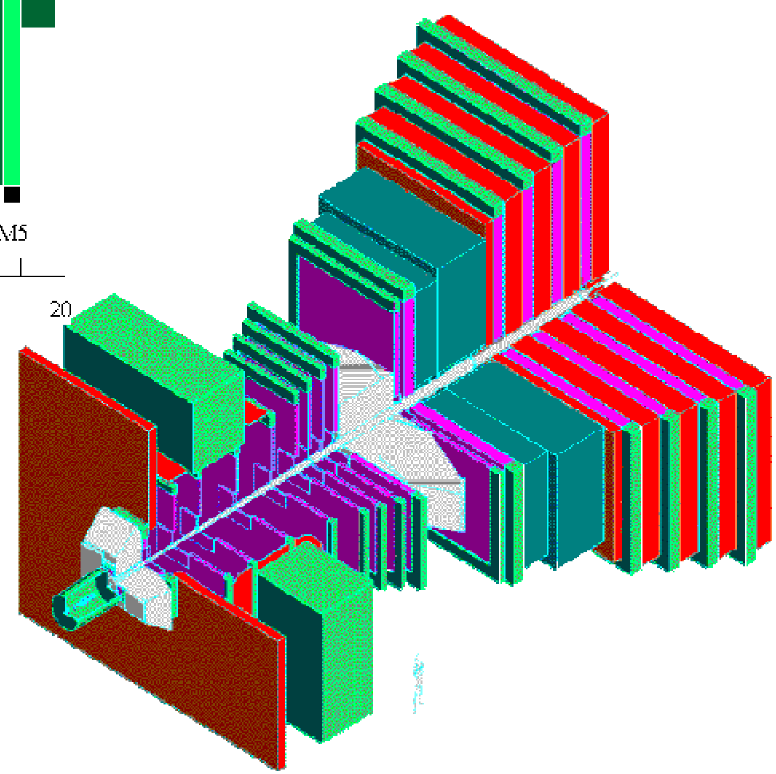

C



The Compact Muon Solenoid (CMS)







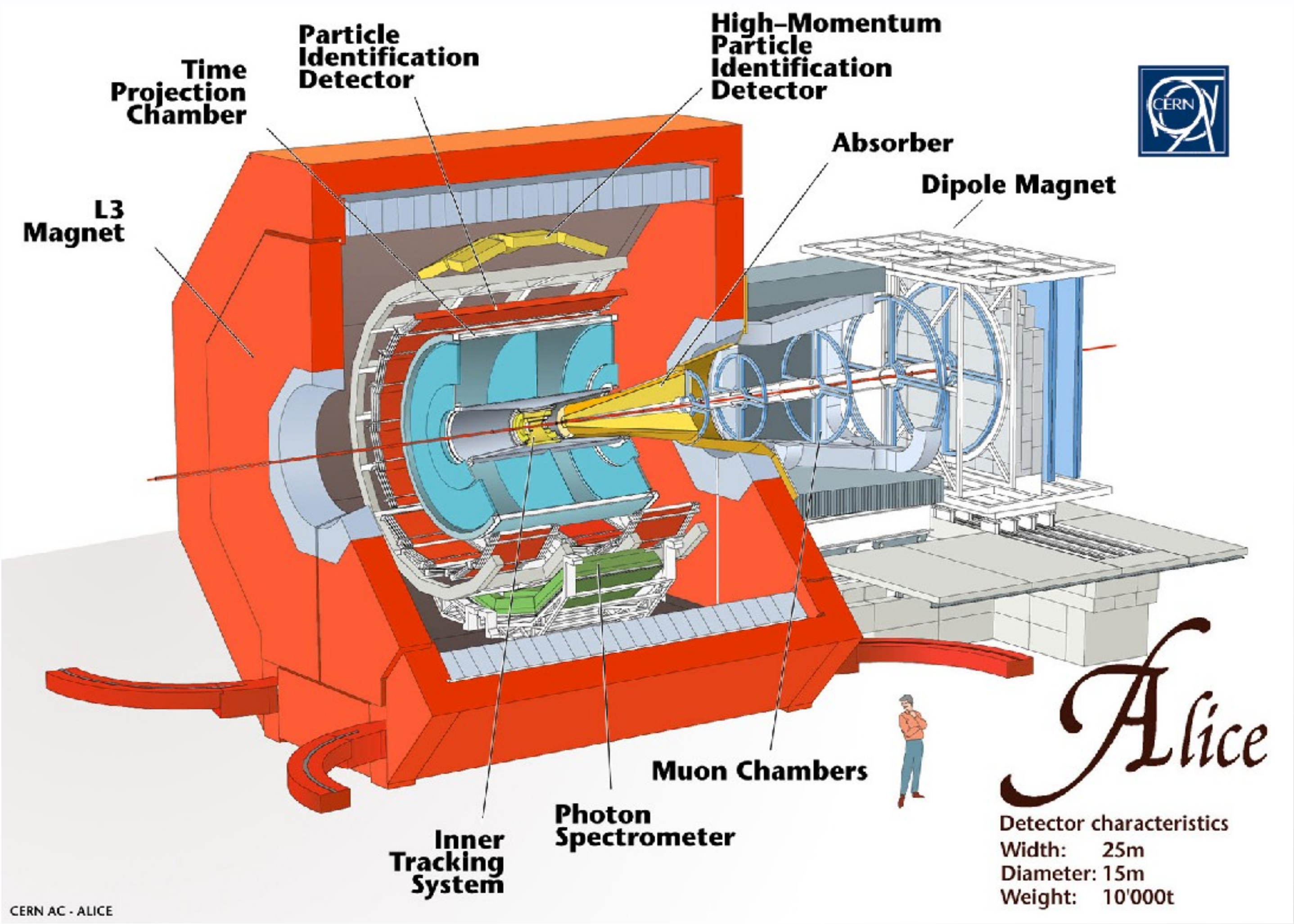
Detector Characteristics

Length: 20 m

Width: 12 m

Height: 12 m

Weight: 2'000 tons



Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice
Detector characteristics
Width: 25m
Diameter: 15m
Weight: 10'000t
CERN AC - ALICE

Summary

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- ***Through the electronic revolution and the development of new detectors, both traditions merged into the 'electronics image' in the 1970ies.***
- ***Particle detectors with over 100 million readout channels are operating now at LHC.***

Questions (1)

- ***which particles are the most penetrating? depending on energy?***
- ***what particle qualities (mass, charge,..) are the most important for the interaction with matter***
- ***how to distinguish photons and electrons at 100 GeV in matter?***

Questions (2) for home

- ***compare decay and interaction probability for GeV pion***
- ***compare λ_{hadr} and x_0 sizes of e.m. and hadronic showers***
- ***multiple scattering angle vs. momentum of particle, vs. thickness of absorber***
- ***compare ratio of particle energies to masses in hadronic and e.m. showers***
- ***draw dE/dx from Bethe-Bloch for muons in iron in the range of 0.1 to 100 GeV***

To extend your knowledge

Text books (a selection)

– C. Grupen, B. Shwartz, Particle Detectors, 2nd ed., Cambridge University Press, 2008
– G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
– W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
– R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
– K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
– W. Blum, W. Reigler, L. Rolandi, Particle Detection with Drift Chambers, Springer, 2008
– R. Wigmans, Calorimetry, Oxford Science Publications, 2000
– G. Lutz, Semiconductor Radiation Detectors, Springer, 1999

Review Articles

– Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
– Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.
– Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

Other sources

– Particle Data Book Phys. Lett. B592, 1 (2008) http://pdg.lbl.gov/pdg.html
– R. Bock, A. Vasilescu, Particle Data Briefbook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
- ICFA schools lectures : http://www.ifm.umich.mx/school/ICFA-2002/
- O. Ullaland http://lhcb-doc.web.cern.ch/lhcbdoc/presentations/lectures/Default.htm
– Proceedings of detector conferences (Vienna VCI, Elba, IEEE, Como)
– Journals: Nucl. Instr. Meth. A, Journal of Instrumentation

Trigger and DAQ

- R. Fernow : Introduction to experimental particle physics (C.U.P. 1986)
- R. Frühwirth, M. Regler, R.K. Bock, H. Grote and D. Notz ; Data Analysis Techniques for High-Energy Physics (2nd ed.) (C.U.P. 2000)
- CERN-Latin American Schools of Physics : Usually an article on trigger and DAQ

Useful material & acknowledgments

- I have taken part of the content of these lecture from Werner Riegler's summer student lectures in 2011 and Erika Garutti's DESY lecture notes
- Useful books
  - Detector for particle radiation, Konrad Kleinknecht
  - Techniques for Nuclear and Particle Physics Experiments, W. R. Leo
  - Particle Detectors, Claus Grupen
  - Introduction to Experimental Particle Physics, R. Fernow
  - The Physics of Particle Detectors, D. Green
  - Review in data particle book on Passage of particles through matter
  - Review in data particle book on Particle Detectors at accelerators

To extend your knowledge (2)

- D.H. Wilkinson: *Ionization Chambers and Counters* (Cambridge Univ. Press, 1950)
- S.A. Korff: *Electron and Nuclear Counters* (Van Nostrand, 1955)
- P. Rice-Evans: *Spark, Streamer, Proportional and Drift Chambers* (Richelieu, 1974)
- F. Sauli: *Principles of Operation of Multiwire Proportional and Drift Chambers* (CERN 77-
- Th. Ferbel, Editor: *Techniques and Concepts of High-energy Physics* (Plenum, 1983)
- R.C. Fernow: *Introduction to Experimental Particle Physics* (Cambridge Univ. Press, 198
- W.R. Leo: *Techniques for Nuclear and Particle Physics Experiments* (Springer, 1987)
- C. Fabjan and J. Pilcher, ed.: *Instrumentation in Elementary Particle Physics* (World Scie 1988)
- C.F.G. Delaney and E.C. Finch: *Radiation Detectors* (Clarendon Press, 1992)
- R. Gilmore: *Single Particle Detection and Measurement* (Taylor and Francis, 1992)
- F. Sauli, ed.: *Instrumentation in High Energy Physics* (World Scientific, 1992)
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- K. Kleinknecht: *Detectors for Particle Radiation* (Cambridge Univ. Press 1998)
- G.F. Knoll: *Radiation Detection and Measurements, 3d Ed.* (Wiley, 2000)
- W. Blum, W. Riegler and L. Rolandi: *Particle Detection with Drift Chambers, 2d Ed.* (Sprin

BACKUP - More

- Definitions and Units — for details clic
- Time Of Flight — for details clic
- Ionization — for details clic
- Transition radiation — for details clic
- Particle Detection principle — for details clic
- About Cross Section — for details clic
- Electromagnetic Shower Development
- Diffusion in gases — for details clic
- Particle ID - Distinguishing particles nature
- Historical examples — for details clic
- Applications — for details clic
- Neutrino detectors — for details clic
- Effective mass calculation — for details clic
- Detector Systems — for details clic

Some important definitions and units

Back

$$E^2 = \vec{p}^{\,2}c^2 + m_0^2 c^4$$

- energy E: measure in eV
- momentum p: measure in eV/c
- mass m_o: measure in eV/c^2

$$\beta = \frac{v}{c} \quad (0 \le \beta < 1) \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \quad (1 \le \gamma < \infty)$$

$$E = m_0 \gamma c^2 \qquad p = m_0 \gamma \beta c \qquad \beta = \frac{pc}{E}$$

1 eV is a tiny portion of energy. 1 eV = $1.6 \cdot 10^{-19}$ J

m_{bee} = 1g = $5.8 \cdot 10^{32}$ eV/c^2

v_{bee} = 1m/s → E_{bee} = 10^{-3} J = $6.25 \cdot 10^{15}$ eV

E_{LHC} = $14 \cdot 10^{12}$ eV

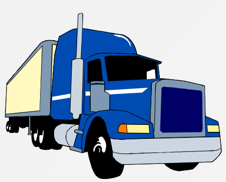
For times practical units are

- 1 μs (10^{-6} s), an electron drifts in a gas 5 cm
- 1 ns (10^{-9} s), a relativistic e^- travels 30 cm
- 1 ps (10^{-12} s), mean life time of a B meson

To rehabilitate LHC…

Total stored beam energy: E_{total} = 10^{14} protons · $7 \cdot 10^{12}$ eV ≈ $7 \cdot 10^{26}$ eV ≈ $1 \cdot 10^{8}$ J

this corresponds to a



m_{truck} = 100 T

v_{truck} = 120 km/h

Stored energy in LHC magnets ~ 1 GJ

m_{747} = 400 T

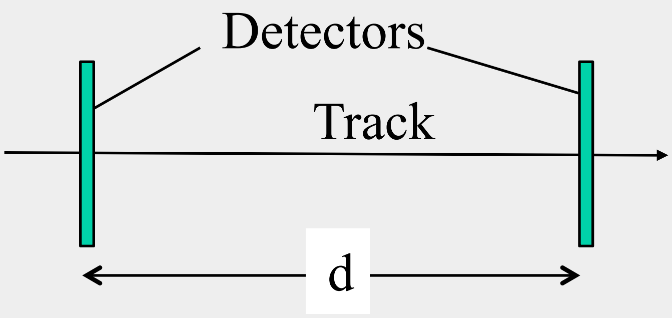
v_{747} = 255 km/h

To Backup

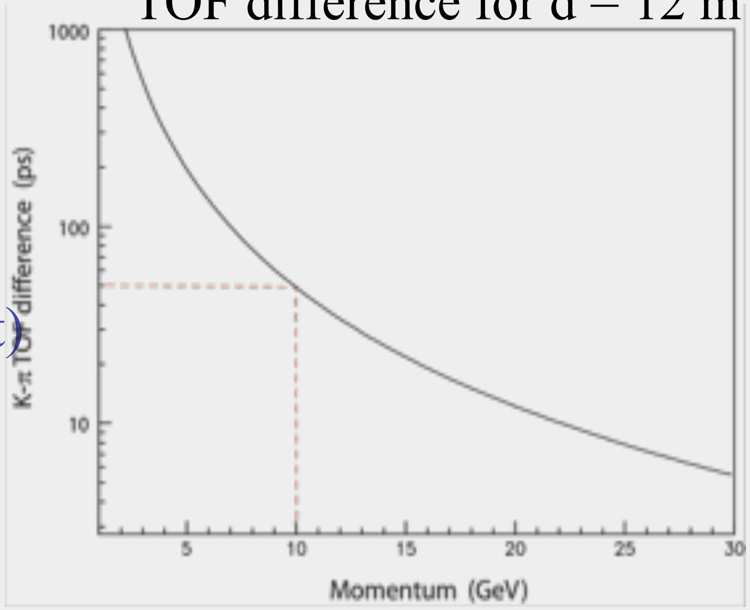
Time Of Flight

Back

- Simple concept: measure the time difference between two detector planes
  $\beta = d / c \Delta t$
- At high energy, particle speeds are relativistic, closely approaching to c
- ***For a 10 GeV K***, the time to travel 12 m is 40.05 ns, whereas for a π it would be 40.00 ns, so the difference is only 50 ps
- Modern detectors + readout electronics have resolution $\sigma_t \sim 10$ ns, fast enough for the LHC (bunch crossings 25 ns apart) but need $\sigma_t < 1$ ns to do useful TOF
- TOF gives good ID at low momentum
  Very precise timing required for p > 5 GeV



TOF difference for d = 12 m

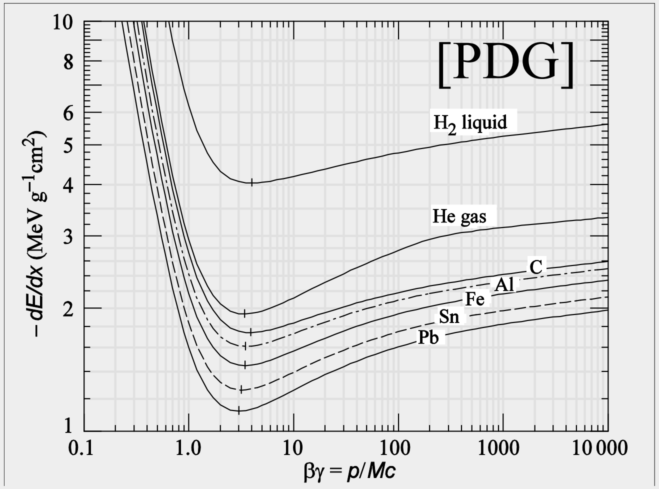


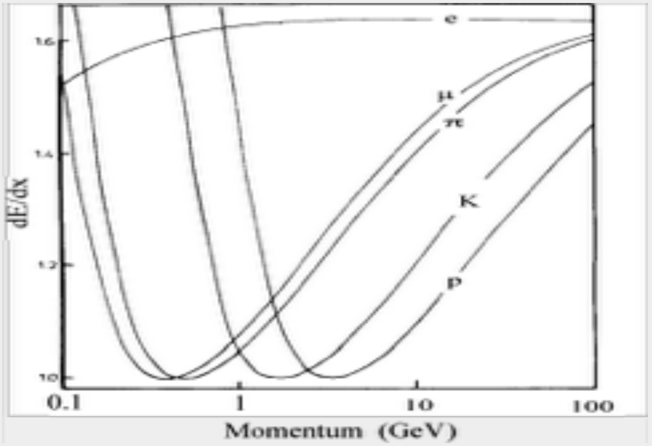
To Backup

Ionization

- Charged particles passing through matter can knock out electrons from atoms of the medium: ionization
- Energy loss described by the Bethe-Bloch formula, which gives the universal velocity dependence: $dE/dx \propto \log(\beta^2 \gamma^2) / \beta^2$
- This can be used to identify particles, particularly at low momentum where dE/dx varies rapidly

- ***Advantage:***
  uses existing detectors needed for tracking
- Note: these techniques all provide signals for charged leptons e, μ as well as π, K, p
  But $m_\mu \approx m_\pi$, so they are not well separated

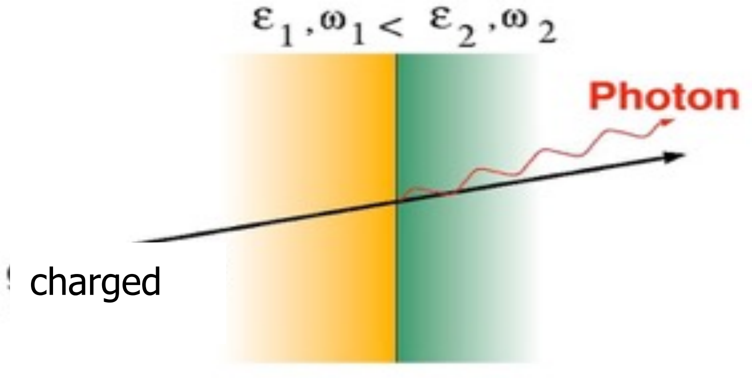




To Backup

Transition radiation

- Local speed of light in a medium with refractive index n is $c_p = c/n$
- If its relative velocity v/c_p changes, a particle will radiate photons:
  1. Change of direction v (in magnetic field) → Synchrotron radiation
  2. Change of |v| (passing through matter) → Bremsstrahlung radiation
  3. Change of refractive index n of medium → Transition radiation
- ***Transition radiation*** is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)



- The energy emitted is proportional to the boost γ of the particle

  → Particularly useful for electron ID
  Can also be used for hadrons at high energy

- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (Nobel Prize 1958)

To Backup Cherenkov light Back

Particle Detection Principle

Back

In order to detect a particle

- it must interact with the material of the detector
- transfer energy in some recognizable fashion

i.e. The detection of particles happens via their energy loss in the material it traverses ...

Possibilities:

Charged particles	Ionization, Bremsstrahlung, Cherenkov ...
Hadrons	Nuclear interactions
Photons	Photo/Compton effect, pair production
Neutrinos	Weak interactions

Energy loss by multiple reactions

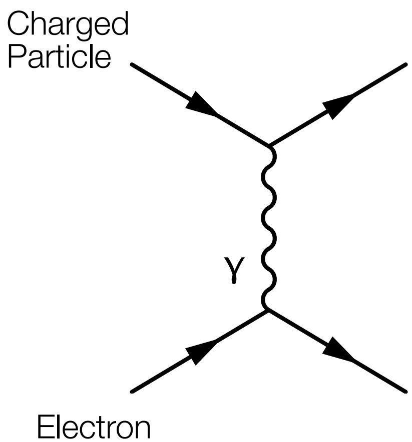
Total energy loss via single interaction

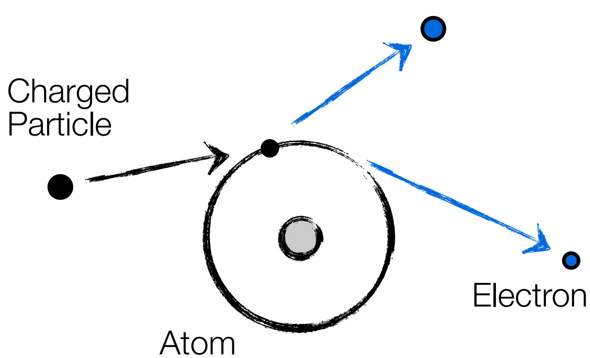
➛ charged particles

To Backup

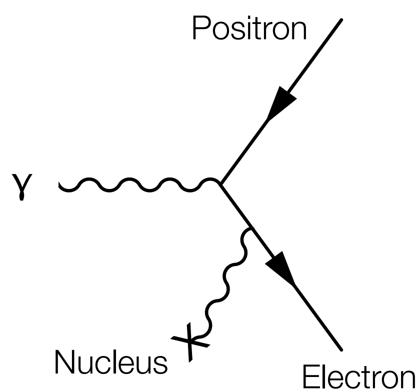
Particle Interactions – Examples

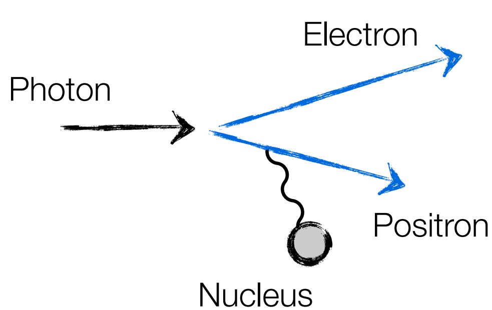
Ionization:



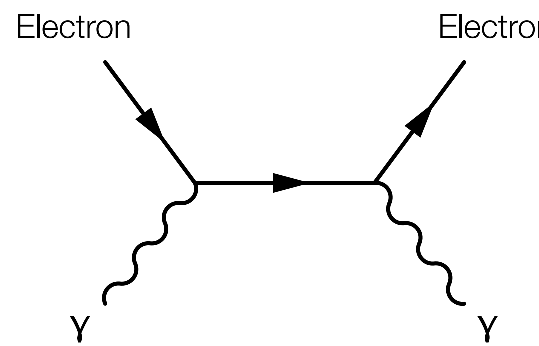


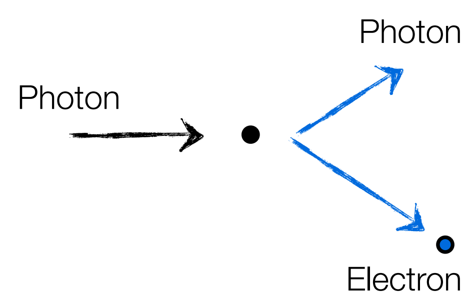
Pair production:





Compton scattering:



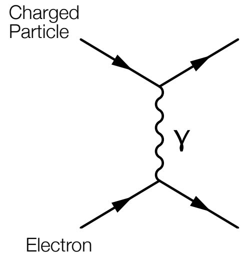


Energy Loss by Ionization – dE/dx

For now assume: $Mc^2 \gg m_e c^2$

i.e. energy loss for heavy charged particles
[dE/dx for electrons more difficult ...]

Interaction dominated
by elastic collisions with electrons ...



Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$\propto 1/\beta^2 \cdot \ln(\text{const} \cdot \beta^2\gamma^2)$

Energy Loss of Electrons

Bethe-Bloch formula needs modification

Incident and target electron have same mass m_e
Scattering of identical, undistinguishable particles

$$-\left\langle \frac{dE}{dx} \right\rangle_{\text{el.}} = K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e \beta^2 c^2 \gamma^2 T}{2 I^2} + F(\gamma) \right]$$

[T: kinetic energy of electron]

$W_{max} = ½T$

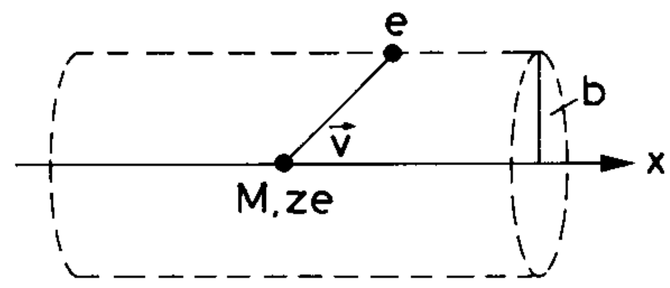
Remark: different energy loss for electrons and positrons at low energy as positrons are not identical with electrons; different treatment ...

Bethe-Bloch – Classical Derivation

Bohr 1913

Particle with charge ze and velocity v moves through a medium with electron density n.

Electrons considered free and initially at rest.



Interaction of a heavy charged particle with an electron of an atom inside medium.

Momentum transfer:

Symmetry!

$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dt}{dx} dx = \int F_\perp \frac{dx}{v} \qquad \Delta p_{||} \;:\; \text{averages to zero}$$

$$= \int_{-\infty}^{\infty} \frac{ze^2}{(x^2+b^2)} \cdot \frac{b}{\sqrt{x^2+b^2}} \cdot \frac{1}{v}\, dx = \frac{ze^2 b}{v} \left[\frac{x}{b^2\sqrt{x^2+b^2}} \right]_{-\infty}^{\infty} = \frac{2ze^2}{bv}$$

More elegant with Gauss law:
[infinite cylinder; electron in center]

$$\int E_\perp\, (2\pi b)\, dx = 4\pi (ze) \rightarrow \int E_\perp dx = \frac{2ze}{b}$$

and then ...

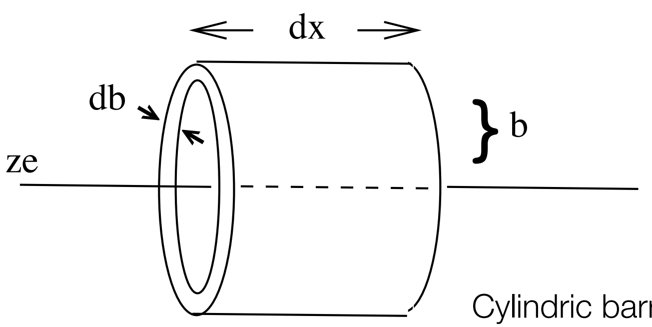
$$\begin{cases} F_\perp = eE_\perp \\ \Delta p_\perp = e \int E_\perp \frac{dx}{v} = \frac{2ze^2}{bv} \end{cases}$$

Bethe-Bloch – Classical Derivation

Bohr 1913

Energy transfer onto single electron
for impact parameter b:

$$\Delta E(b) = \frac{\Delta p^2}{2m_\mathrm{e}}$$



Cylindric barrel
with N_e electrons

Consider cylindric barrel ➛ $N_e = n \cdot (2\pi b) \cdot db\,dx$

Energy loss per path length dx for
distance between b and b+db in medium with electron density n:

Energy loss!

$$-dE(b) = \frac{\Delta p^2}{2m_\mathrm{e}} \cdot 2\pi n b\, db\, dx = \frac{4z^2e^4}{2b^2v^2m_\mathrm{e}} \cdot 2\pi n b\, db\, dx = \frac{4\pi\, n\, z^2 e^4}{m_\mathrm{e} v^2} \frac{db}{b} dx$$

Diverges for b ➛ 0; integration only
for relevant range [b_{min}, b_{max}]:

Bohr 1913

$$-\frac{dE}{dx} = \frac{4\pi\, n\, z^2 e^4}{m_\mathrm{e} v^2} \cdot \int_{b_\mathrm{min}}^{b_\mathrm{max}} \frac{db}{b} = \frac{4\pi\, n\, z^2 e^4}{m_\mathrm{e} v^2} \ln \frac{b_\mathrm{max}}{b_\mathrm{min}}$$

Bethe-Bloch – Classical Derivation

Bohr 1913

Determination of relevant range [b_{min}, b_{max}]:
[Arguments: $b_{min} > \lambda_e$, i.e. de Broglie wavelength; $b_{max} < \infty$ due to screening ...]

$$b_{\text{min}} = \lambda_e = \frac{h}{p} = \frac{2\pi\hbar}{\gamma m_e v}$$

Use Heisenberg uncertainty principle or that electron is located within de Broglie wavelength ...

$$b_{\text{max}} = \frac{\gamma v}{\langle \nu_e \rangle} ; \quad \left[\gamma = \frac{1}{\sqrt{1-\beta^2}} \right]$$

Interaction time (b/v) must be much shorter than period of the electron (γ/ν_e) to guarantee relevant energy transfer ...

[adiabatic invariance]

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} n \cdot \ln \frac{m_e c^2 \beta^2 \gamma^2}{2\pi\hbar \langle \nu_e \rangle}$$

Deviates by factor 2 from QM derivation

Electron density: $n = N_A \cdot \rho \cdot Z/A$!!

Effective Ionization potential: $I \sim h\langle \nu_e \rangle$

Bethe-Bloch Formula

[see e.g. PDG 2010]

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad [\cdot\, \rho]$$

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307\ \text{MeV g}^{-1}\ \text{cm}^2$

$T_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

$m_e = 511$ keV
[Electron mass]

$\beta = v/c$
[Velocity]

$\gamma = (1-\beta^2)^{-2}$
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$
$M > m_\mu$

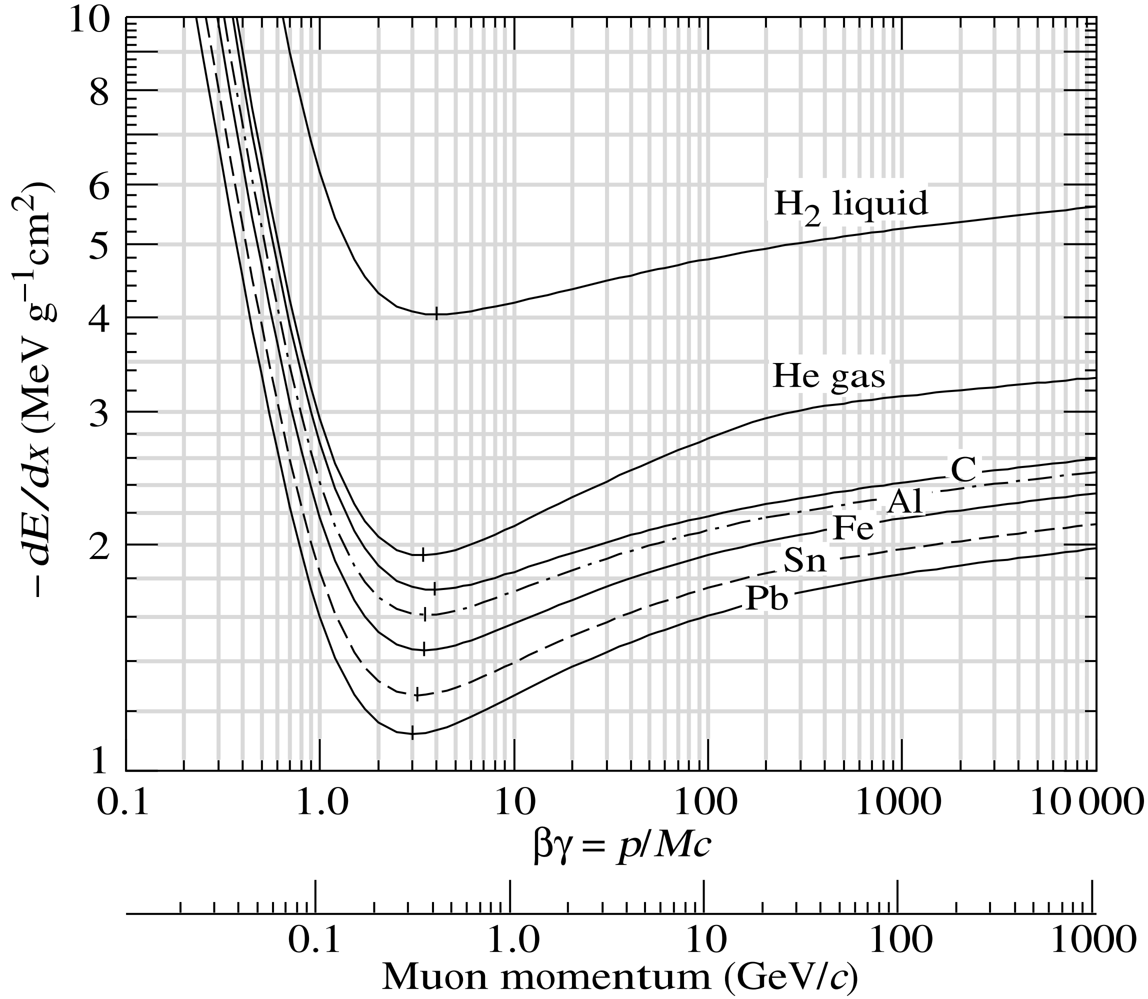
Energy Loss of Charged Particles

Dependence on

Mass A
Charge Z
of target nucleus

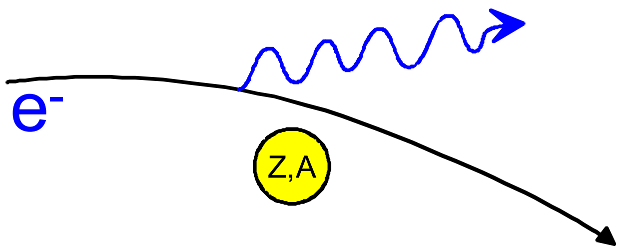
Minimum ionization:

ca. 1 - 2 MeV/g cm^{-2}
[H_2: 4 MeV/g cm^{-2}]



Bremsstrahlung

Bremsstrahlung arises if particles
are accelerated in Coulomb field of nucleus



$$\frac{dE}{dx} = 4\alpha N_A \, \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \, \ln \frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

i.e. energy loss proportional to $1/m^2$ ➙ main relevance for electrons ...

... or ultra-relativistic muons

Consider electrons:

$$\frac{dE}{dx} = 4\alpha N_A \, \frac{Z^2}{A} r_e^2 \cdot E \, \ln \frac{183}{Z^{\frac{1}{3}}}$$

$$\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{with} \quad X_0 = \frac{A}{4\alpha N_A \, Z^2 r_e^2 \, \ln \frac{183}{Z^{\frac{1}{3}}}}$$

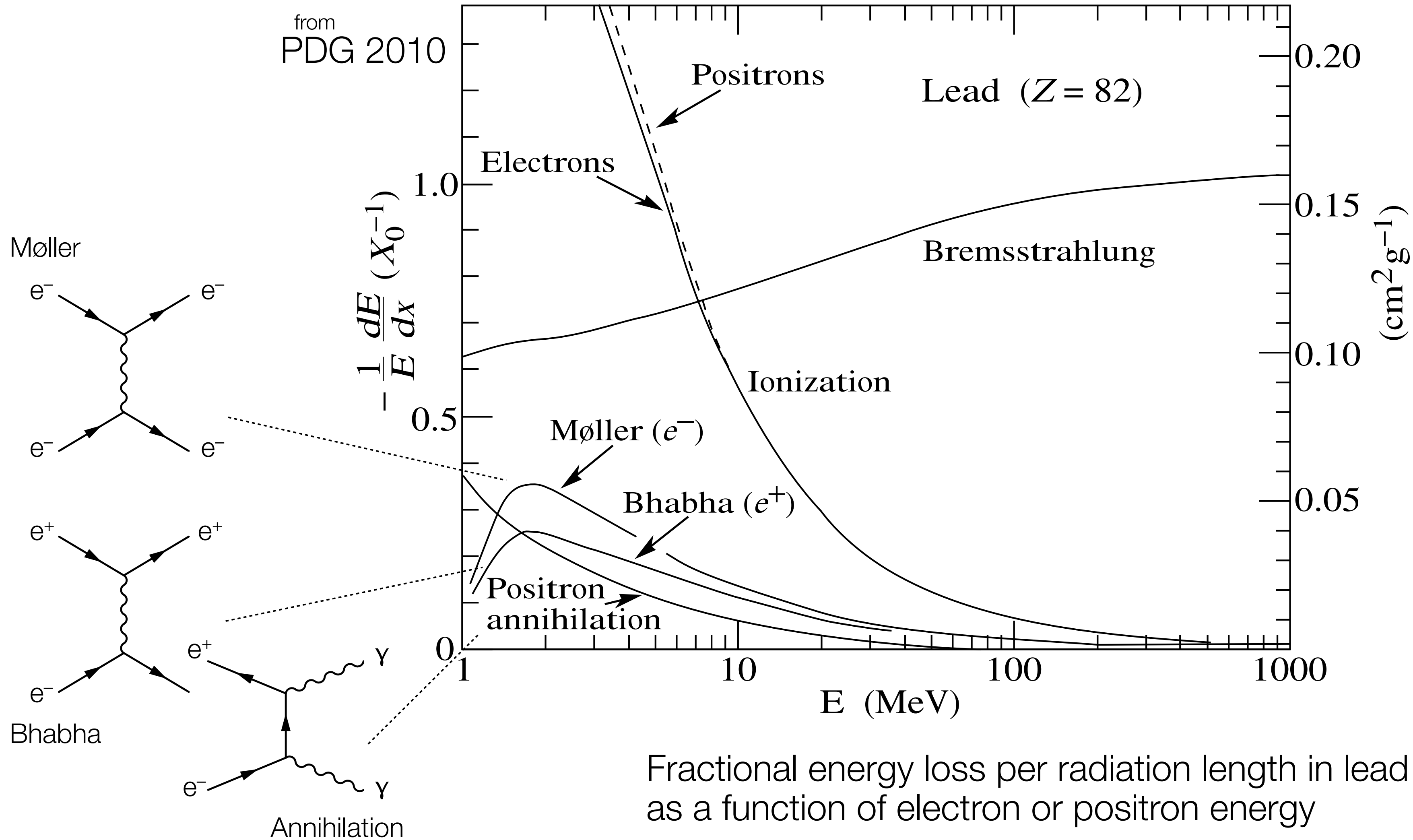
[Radiation length in g/cm²]

➨ $E = E_0 e^{-x/X_0}$

After passage of one X_0 electron has lost all but $(1/e)^{th}$ of its energy

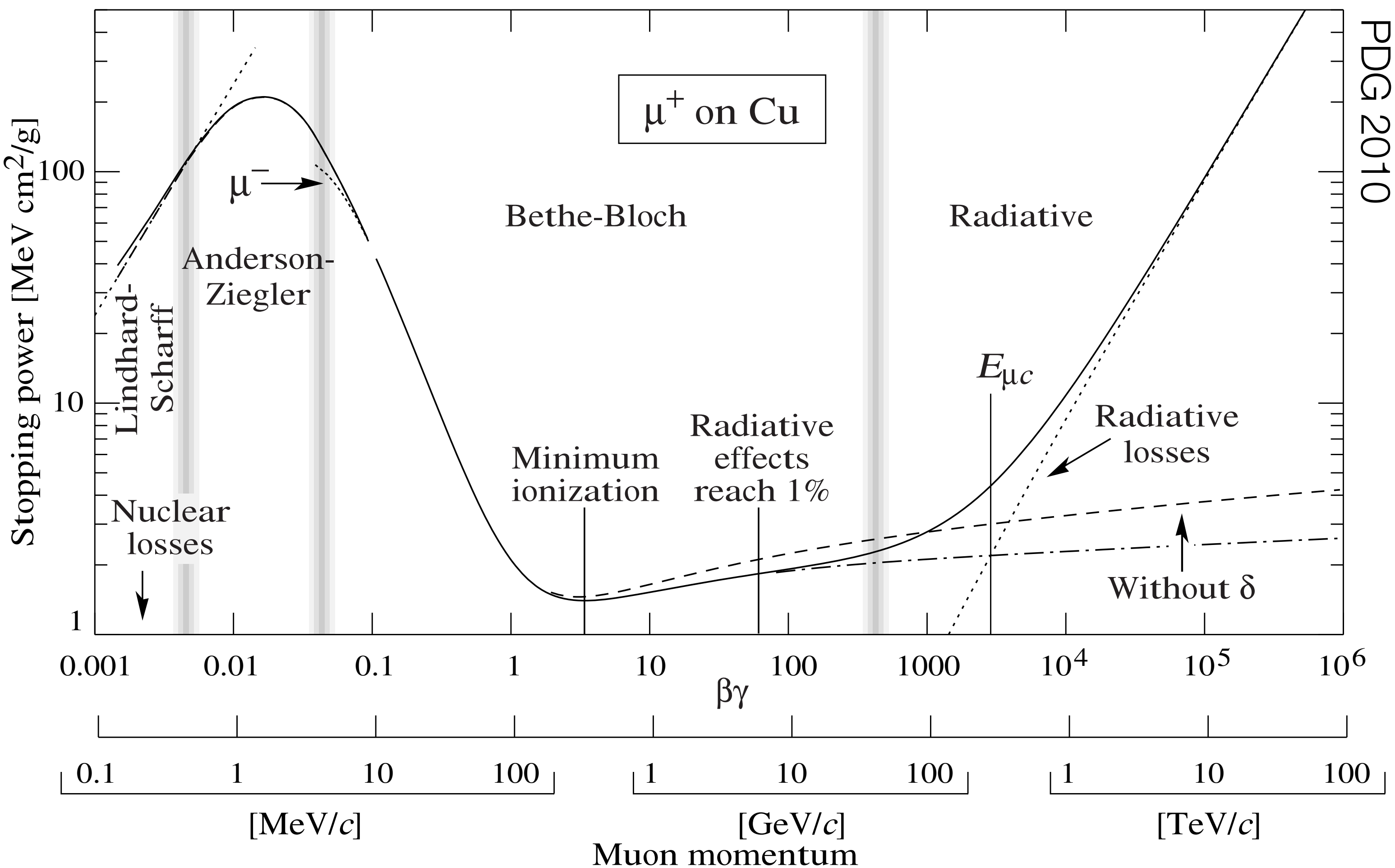
[i.e. 63%]

Total Energy Loss of Electrons



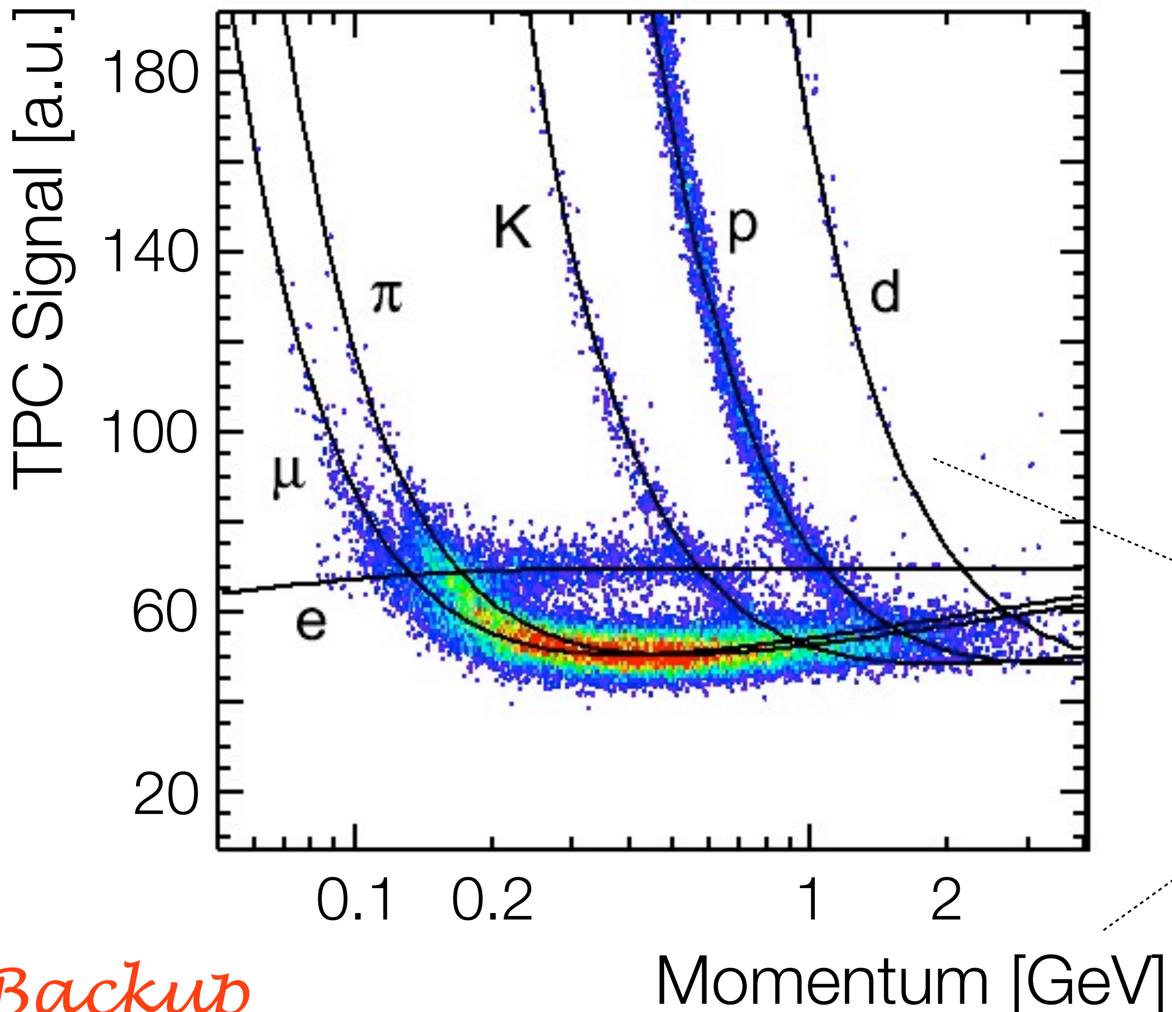
Fractional energy loss per radiation length in lead as a function of electron or positron energy

Energy Loss – Summary Plot for Muons



Back

dE/dx and Particle Identification



Measured
energy loss

[ALICE TPC, 2009]

Bethe-Bloch

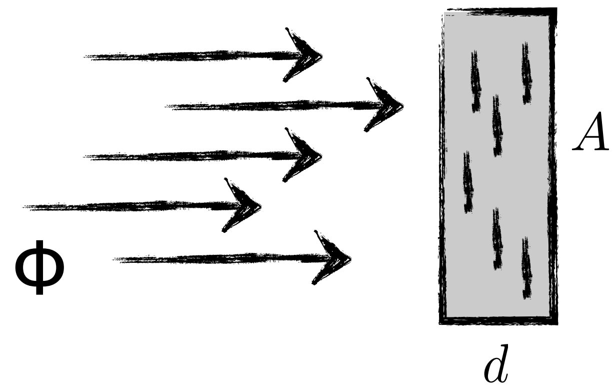
Remember:
dE/dx depends on β!

To Backup
To Backup

Cross Section - Definition

Incoming flux:

$$\Phi = \frac{1}{A} \cdot \frac{\Delta N}{\Delta t} = \frac{\dot{N}_{\mathrm{in}}}{A}$$



Absorbing target area

Effective cross section

$$A_{\mathrm{tar}} = \sigma \cdot N_{\mathrm{tar}}$$

$$= \sigma \cdot \frac{\rho \cdot Ad}{m_{\mathrm{mol}}} \cdot N_{\mathrm{A}}$$

with

ρ :	target density
m_{mol} :	molar mass
N_{A} :	$6.022 \cdot 10^{23}\ \mathrm{mol}^{-1}$

Reaction rate:

$$\dot{N}_{\mathrm{reac}} = \dot{N}_{\mathrm{in}} \frac{A_{\mathrm{tar}}}{A} = \Phi \cdot A_{\mathrm{tar}}$$

$$= \Phi \cdot N_{\mathrm{tar}} \cdot \sigma$$

Cross section:

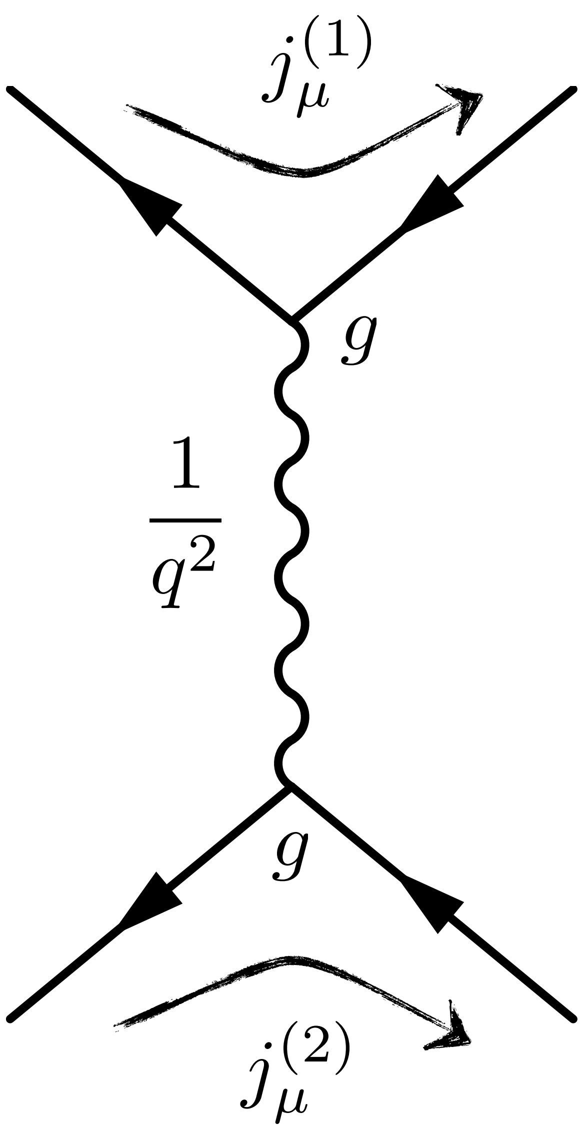
$$\sigma = \frac{\text{Number of reactions (of given type) per unit time}}{\text{Incoming flux} \cdot \text{Number of target particles}}$$

$$= \frac{\dot{N}_{\mathrm{reac}}}{\Phi \cdot N_{\mathrm{tar}}} = \frac{\dot{N}_{\mathrm{reac}}}{\dot{N}_{\mathrm{in}} \cdot N_{\mathrm{A}} \cdot \rho \cdot d / m_{\mathrm{mol}}}$$

Transition rate W_{fi}

Unit: $[\sigma] = \mathrm{cm}^2$

To Backup



Fermi's Golden Rule

$$W_{\mathrm{fi}} = 2\pi \, |M_{\mathrm{fi}}|^2 \cdot \frac{dN}{dE_{\mathrm{f}}}$$

Transition probability

Matrix element

Phase space

4-vector current

$$M_{\mathrm{fi}} = -i \int j_\mu^{(1)} \cdot \left(\frac{1}{q^2} \right) \cdot j_\mu^{(2)} d^4x$$

Propagator

$$\sigma \sim |M_{\mathrm{fi}}|^2$$

$$\sim g^4 \cdot \left(\frac{1}{q^4} \right)$$

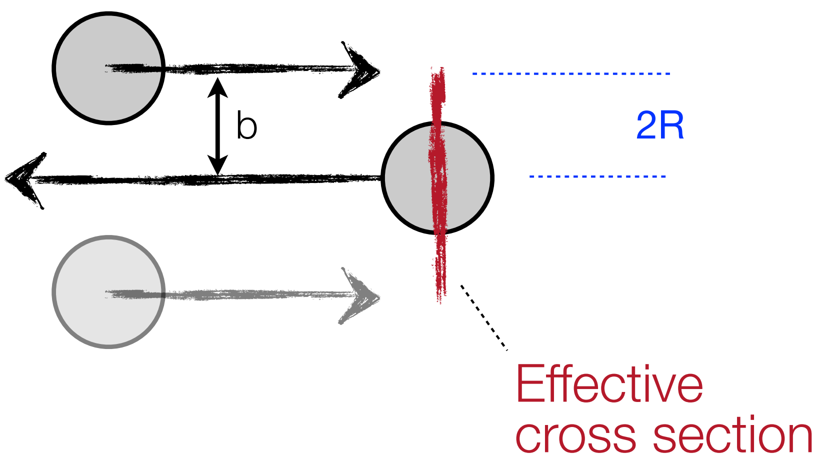
Cross Section - Magnitude and Units

Standard
cross section unit: $[\sigma] = \text{mb}$ with $1\ \text{mb} = 10^{-27}\ \text{cm}^2$

or in
natural units: $[\sigma] = \text{GeV}^{-2}$ with $1\ \text{GeV}^{-2} = 0.389\ \text{mb}$
$1\ \text{mb} = 2.57\ \text{GeV}^{-2}$

using: $\hbar c = 0.1973\ \text{GeV fm}$
$(\hbar c)^2 = 0.389\ \text{GeV}^2\ \text{mb}$

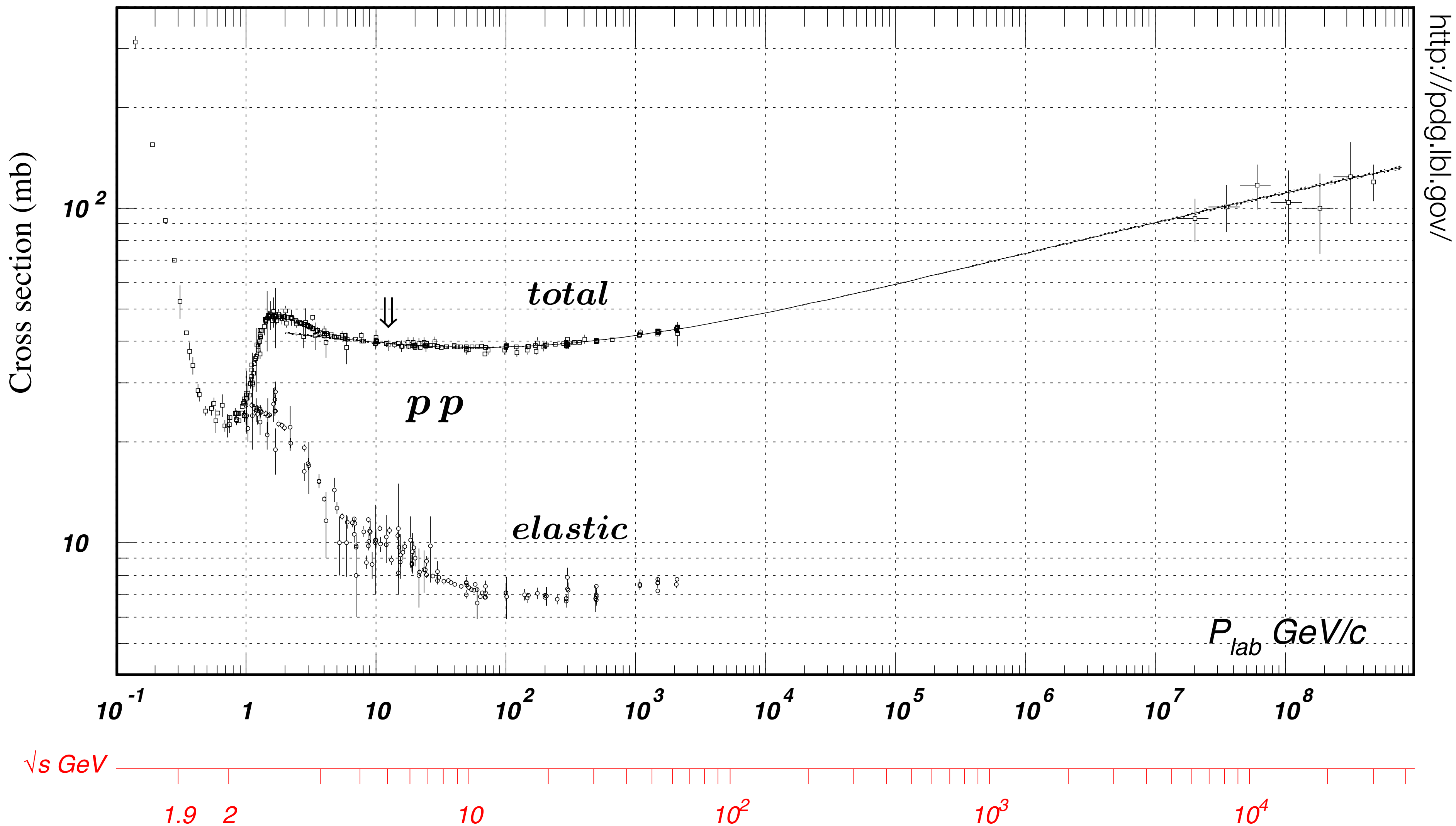
Estimating the
proton-proton cross section:

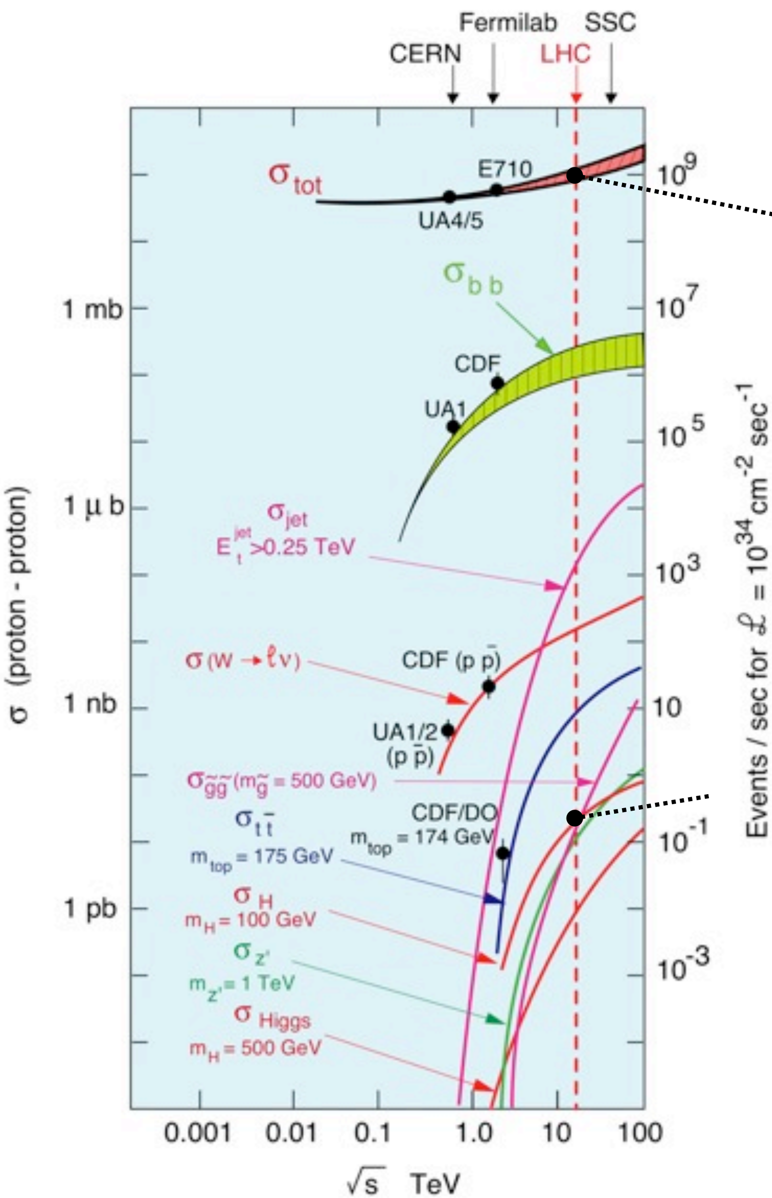


Proton radius: $R = 0.8\ \text{fm}$
Strong interactions happens up to $b = 2R$

$$\sigma = \pi (2R)^2 = \pi \cdot 1.6^2\ \text{fm}^2$$
$$= \pi \cdot 1.6^2\ 10^{-26}\ \text{cm}^2$$
$$= \pi \cdot 1.6^2\ 10\ \text{mb}$$
$$= 80\ \text{mb}$$

Proton-Proton Scattering Cross Section





10^9 Events/sec
[1 Mbyte/Event]

$\sim 10^{10}$

Efficient
rate reduction needed

[Storage rate: 100 Hz]

10 Events/min
[$m_H \approx 100$ GeV]

with 0.2% H → γγ
1.5% H → ZZ

Trigger !

To Backup

Electromagnetic Shower Development

Detecting a signal:

To Backup

→ The contribution of an electromagnetic interaction to energy loss usually depends on the energy of the incident particle and on the properties of the absorber

→ At "high energies" (> ~*10 MeV*):

→ electrons lose energy mostly via Bremsstrahlung

→ photons via pair production

→ Photons from Bremsstrahlung can create an electron-positron pair which can radiate new photons via Bremsstrahlung in a process that last as long as the electron (positron) has energy $E > E_c$

→ At energies $E < E_c$, energy loss mostly by ionization and excitation

→ Signals in the form of light or ions are collected by some readout system

Building a detector

→ X_0 and E_c depends on the properties of the absorber material

→ Full EM shower containment depends on the geometry of the detector

Electromagnetic Shower Development

A simple shower model (Rossi-Heitler)

Considerations:

B. Rossi, High Energy Particles, New York, Prentice-Hall (1952)
W. Heitler, The Quantum Theory of Radiation, Oxford, Claredon Press (1953)

→ Photons from bremsstrahlung and electron-positron from pair production produced at angles $\theta = mc^2/E$ (E is the energy of the incident particle) → **jet character**

Assumptions:

→ $\lambda_{pair} \approx X_0$

→ Electrons and positrons behave identically

→ Neglect energy loss by ionization or excitation for $E > E_c$

→ Each electron with $E > E_c$ gives up half of its energy to bremsstrahlung photon after $1X_0$

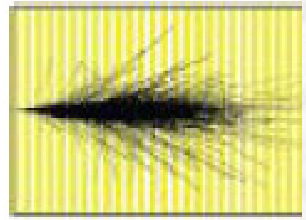
→ Each photon with $E > E_c$ undergoes pair creation after $1X_0$ with each created particle receiving half of the photon energy

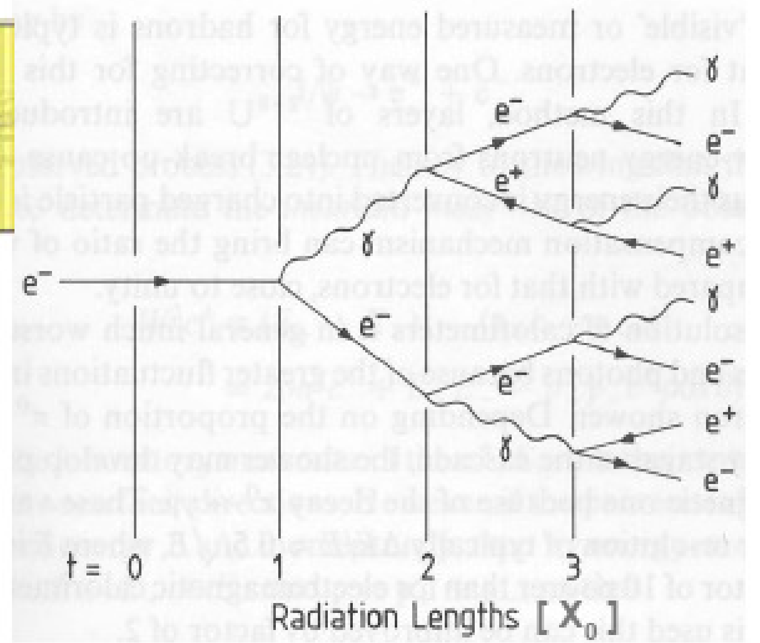
→ Shower development stops at $E = E_c$

→ Electrons with $E < E_c$ do not radiate → remaining energy lost by collisions 14

Electromagnetic Shower Development

A simple shower model





Shower development:

Start with an electron with $E_0 >> E_c$

→ After $1X_0$: $1\ e^-$ and $1\ \gamma$, each with $E_0/2$

→ After $2X_0$: $2\ e^-$, $1\ e^+$ and $1\ \gamma$, each with $E_0/4$

→ After tX_0 :

$$N(t) = 2^t = e^{t \ln 2}$$

$$E(t) = E_0 / 2^t$$

→ Number of particles increases exponentially with t

→ equal number of e^+, e^-, γ

$$t(E') = \frac{\ln(E_0/E')}{\ln 2}$$

→ Depth at which the energy of a shower particle equals some value E'

$$N(E > E') = \frac{1}{\ln 2}\frac{E_0}{E'}$$

→ Number of particles in the shower with energy > E'

Maximum number of particles reached at $E = E_c$ →

$$t_{max} = \frac{\ln(E_0/E_c)}{\ln 2}$$

$$N_{max} = e^{t_{max} \ln 2} = E_0/E_c$$

Electromagnetic Shower Development

A simple shower model

Concepts introduce with this simple mode:

→ Maximum development of the shower (multiplicity) at t_{max}

→ Logarithm growth of t_{max} with E_0 :

→ implication in the calorimeter longitudinal dimensions

→ Linearity between E_0 and the number of particles in the shower

Electromagnetic Shower Development

A simple shower model

What about the energy measurement?

Assuming, say, energy loss by ionization

→ **Counting charges:**

→ Total number of particles in the shower:

$$N_{all} = \sum_{t=0}^{t_{max}} 2^t = 2 \times 2^{t_{max}} - 1 \approx 2 \times 2^{t_{max}} = 2\frac{E_0}{E_c}$$

→ Total number of charge particles (e^+ and e^- contribute with 2/3 and γ with 1/3)

$$N_{e^+e^-} = \frac{2}{3} \times 2\frac{E_0}{E_c} = \frac{4}{3}\frac{E_0}{E_c}$$

→ Measured energy proportional to E_0

Electromagnetic Shower Development

A simple shower model

What about the energy resolution?

Assuming Poisson distribution for the shower statistical process:

$$\frac{\sigma(E)}{E} = \frac{1}{\sqrt{N_{e^+e^-}}} = \frac{\sqrt{3E_c/2}}{\sqrt{E}}$$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

→ Resolution improves with E

Example: For lead (Pb), $E_c \approx 6.9$ MeV:

$$\frac{\sigma(E)}{E} = \frac{7.2\%}{\sqrt{E\,[GeV]}}$$

More general term:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- a: Statistic fluctuations
- b: Constant term (calibration, non-linearity, etc
- c: Noise, etc

Electromagnetic Shower Development

A simple shower model

Simulation of the energy deposit in copper as a function of the shower depth for incident electrons at 4 different energies showing the logarithmic dependence of t_{max} with E.

EGS4* (electron-gamma shower simulation)

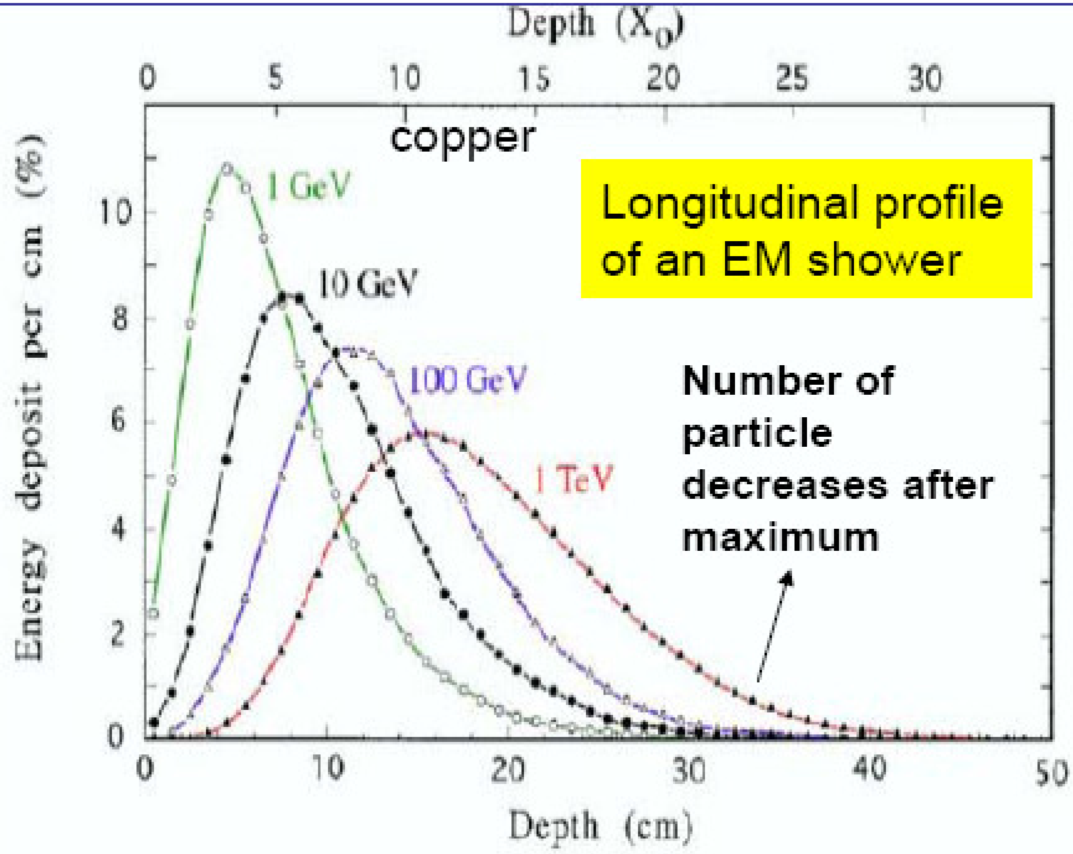


FIG. 2.9. The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalized to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 calculations.

*EGS4 is a Monte Carlo code for doing simulations of the transport of electrons and photons in arbitrary geometries.

Electromagnetic Shower Development

Shower Profile

→ Longitudinal development governed by the radiation length X_0

→ Lateral spread due to electron undergoing multiple Coulomb scattering:

→ About **90%** of the shower up to the shower maximum is contained in a cylinder of radius < $1X_0$

→ Beyond this point, electrons are increasingly affected by multiple scattering

→ Lateral width scales with the **Molière radius ρ_M**

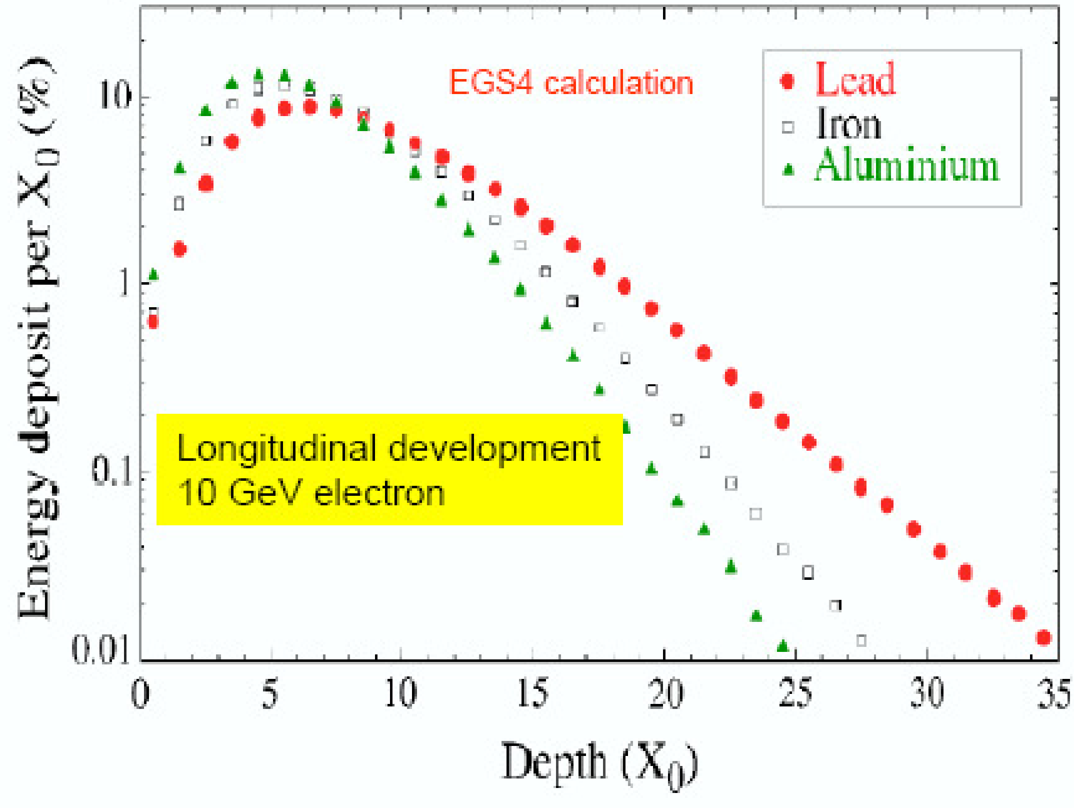
$$\rho_M = X_0 \frac{E_s}{E_c} \quad [g/cm^2] \qquad , \quad E_s \approx 21\,\mathrm{MeV}$$

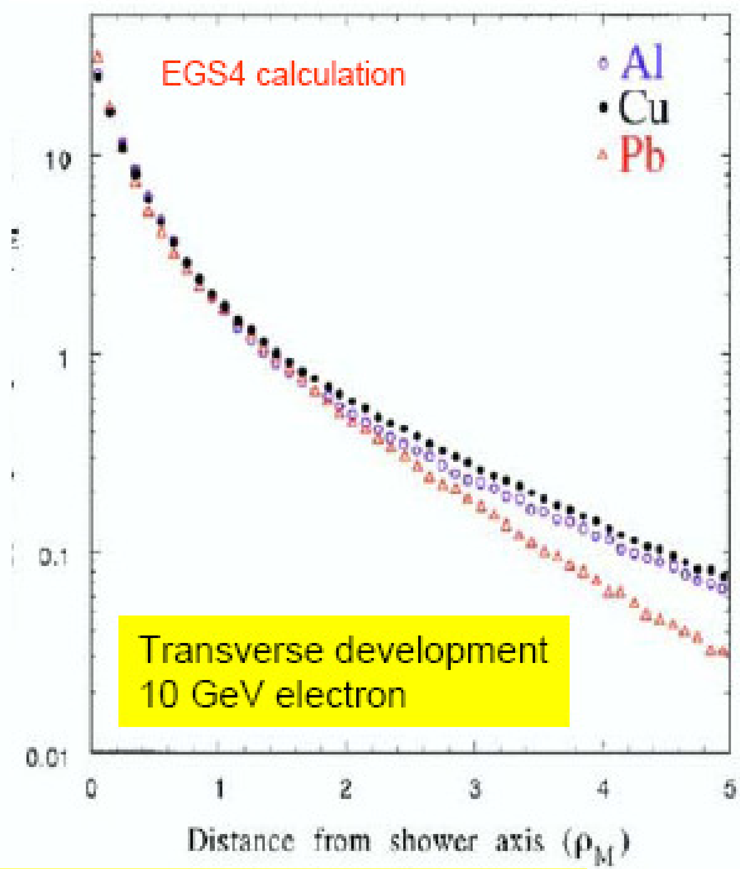
95% of the shower is contained laterally in a cylinder with radius $2\rho_M$

Electromagnetic Shower Development

Shower profile

From previous slide, one expects the longitudinal and transverse developments to scale with X_0





→ ρ_M less dependent on Z than X_0: $X_0 \propto A/Z^2$, $E_c \propto 1/Z \Rightarrow \rho_M \propto A/Z$

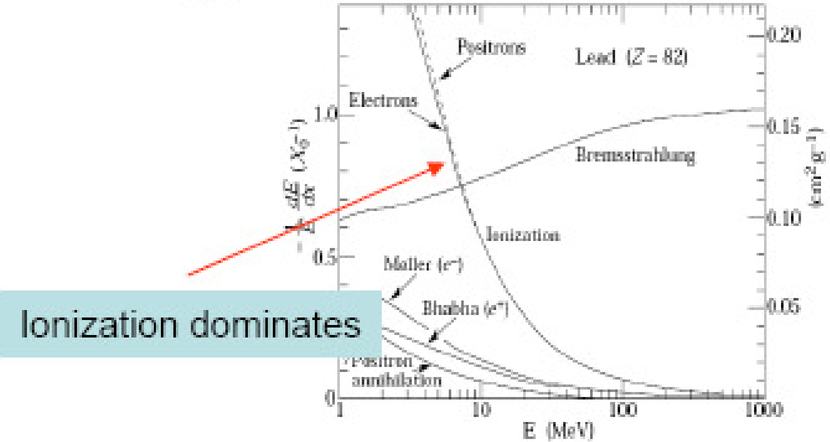
Electromagnetic Shower Development

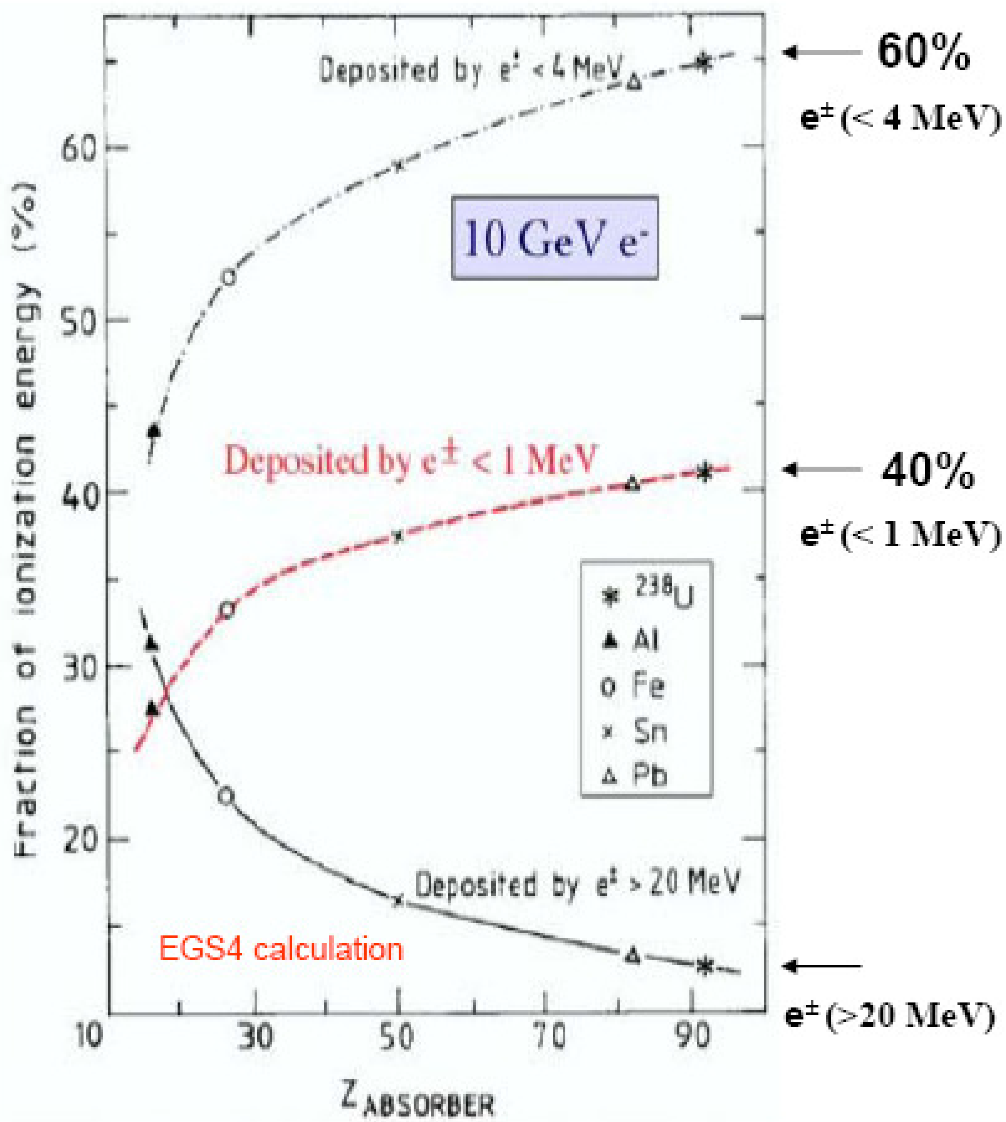
Energy deposition

The fate of a shower is to develop, reach a maximum, and then decrease in number of particles once $E_0 < E_c$

Given that several processes compete for energy deposition at low energies, it is important to understand how the fate of the particles in a shower.

→ Most of energy deposition by low energy e±'s.





To Backup

Diffusion in gases (no E-field)

To Backup

* In absence of other effects, at thermal energies, the mean speed of the charges (given by the Maxwell distribution of the energies) is:

$$v = \sqrt{\frac{8kT}{\pi m}}$$

where k is Boltzmann's constant, T the temperature and m the mass of the particle

* The charges diffuse by multiple collisions, and a local distribution follows a Gaussian law:

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right)$$

where N_0 is the total number of charges, x the distance from the point of creation and D the diffusion coefficient

* Then the linear and volume r.m.s. of the spread are:

$$\sigma_x = \sqrt{2Dt}$$

$$\sigma_V = \sqrt{6Dt}$$

For instance, the radial spread of ions in air in normal conditions is about 1 mm after 1 second

Drift and mobility in gas

- In the presence of an electric field, electrons and ions will drift in the gas. The drift velocity for electrons can be much higher w.r.t. ions since they are much lighter.
- $\mu = v/E$ is the mobility of a charge where v is the drift velocity and E the electric field.
- Ions :
  - Mean velocity v^{+} is proportional to E/P
  - Mobility μ^{+} is constant (average energy of ions almost unmodified up to very high electric fields)
- Electrons:
  - Drift velocity $v^{-} = (e/2m).E.\tau$ where τ is the mean time between collision
  - Typical value around 5 cm/μs are obtained (ions thousand times slower)

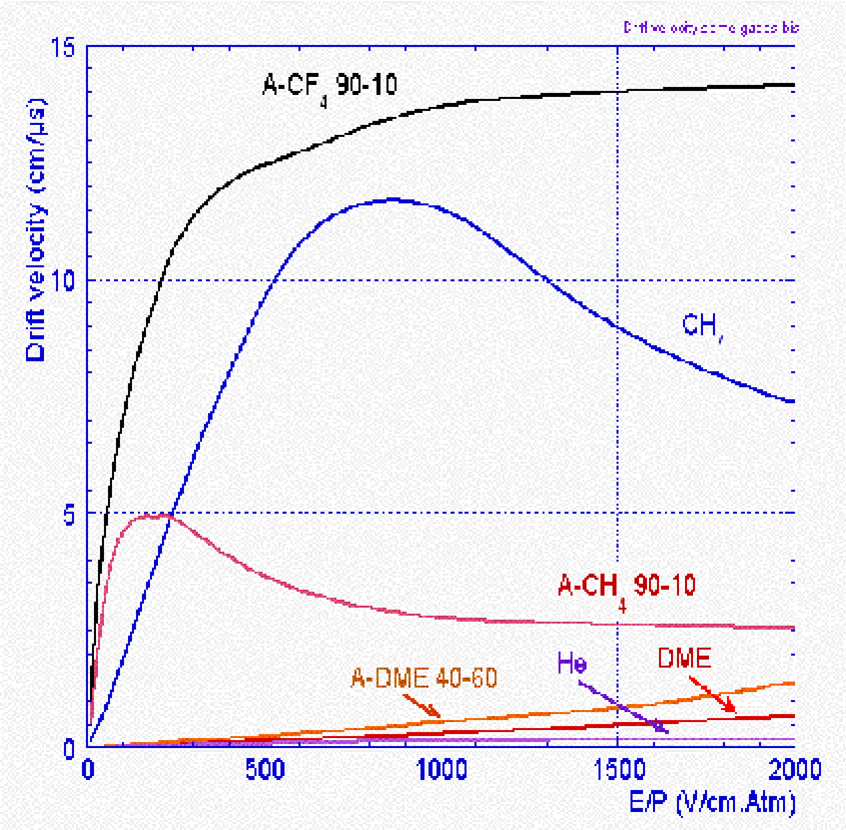
Electrons drift and diffusion

Drift velocity and diffusion of electrons vary in a wide range, depending the gas mixture.

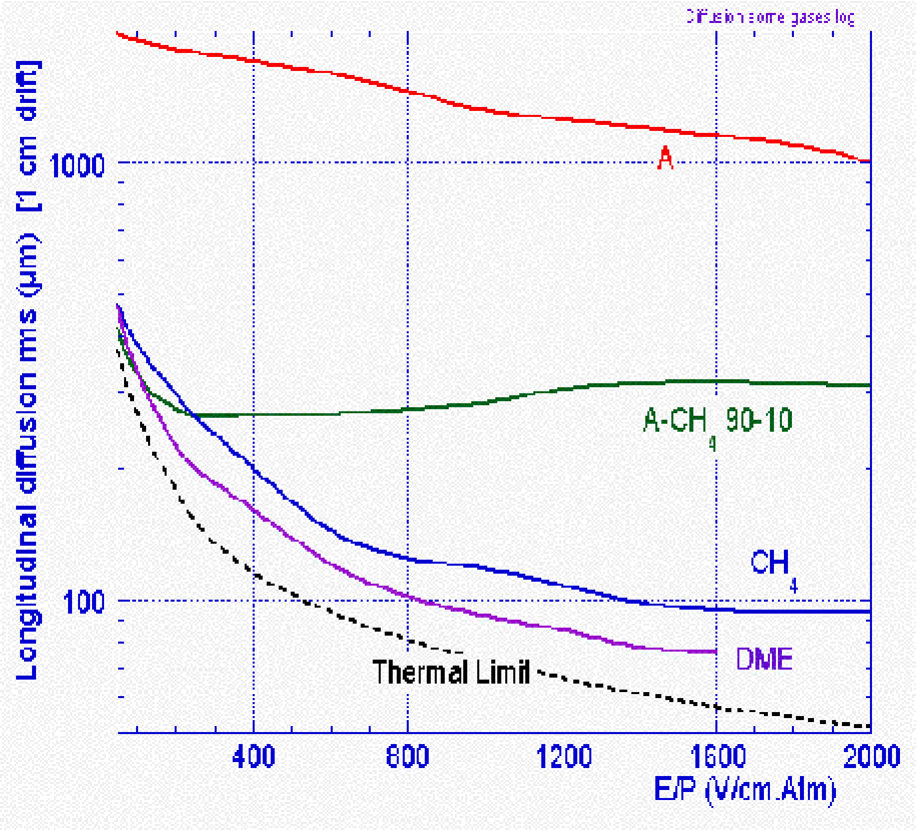
Relation between mobility and diffusion: $\frac{D}{\mu} = \frac{kT}{e} \approx 0.026\ \mathrm{eV}$

The minimum diffusion at a given field is given by the thermal value: $\sigma_x = \sqrt{\frac{2kT}{e}\frac{x}{E}}$

Drift velocity:



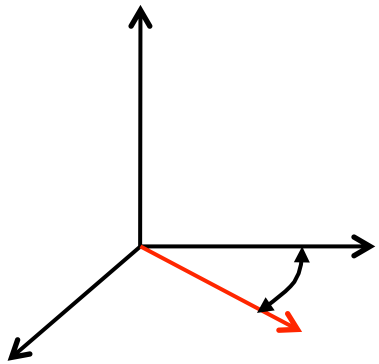
Diffusion:



Magnetic field

The drifting electrons cloud is rotated by an angle θ_B in the plane perpendicular to E and B.

$\vec{E} \perp \vec{B}$



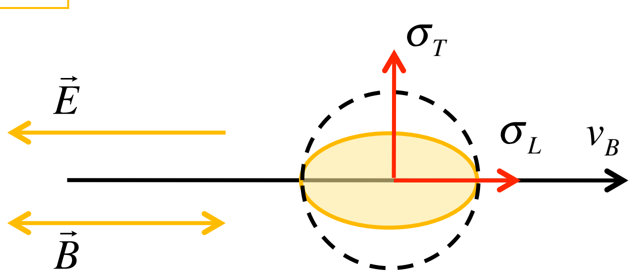
$$\tan\theta_B = \omega\tau$$

τ : mean collision time

$$v_B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

$\omega = eB/m \rightarrow$ Larmor frequency

$\vec{E} \parallel \vec{B}$



$$v_B = v_0$$

$$\sigma_L = \sigma_0$$

Drift velocity unchanged

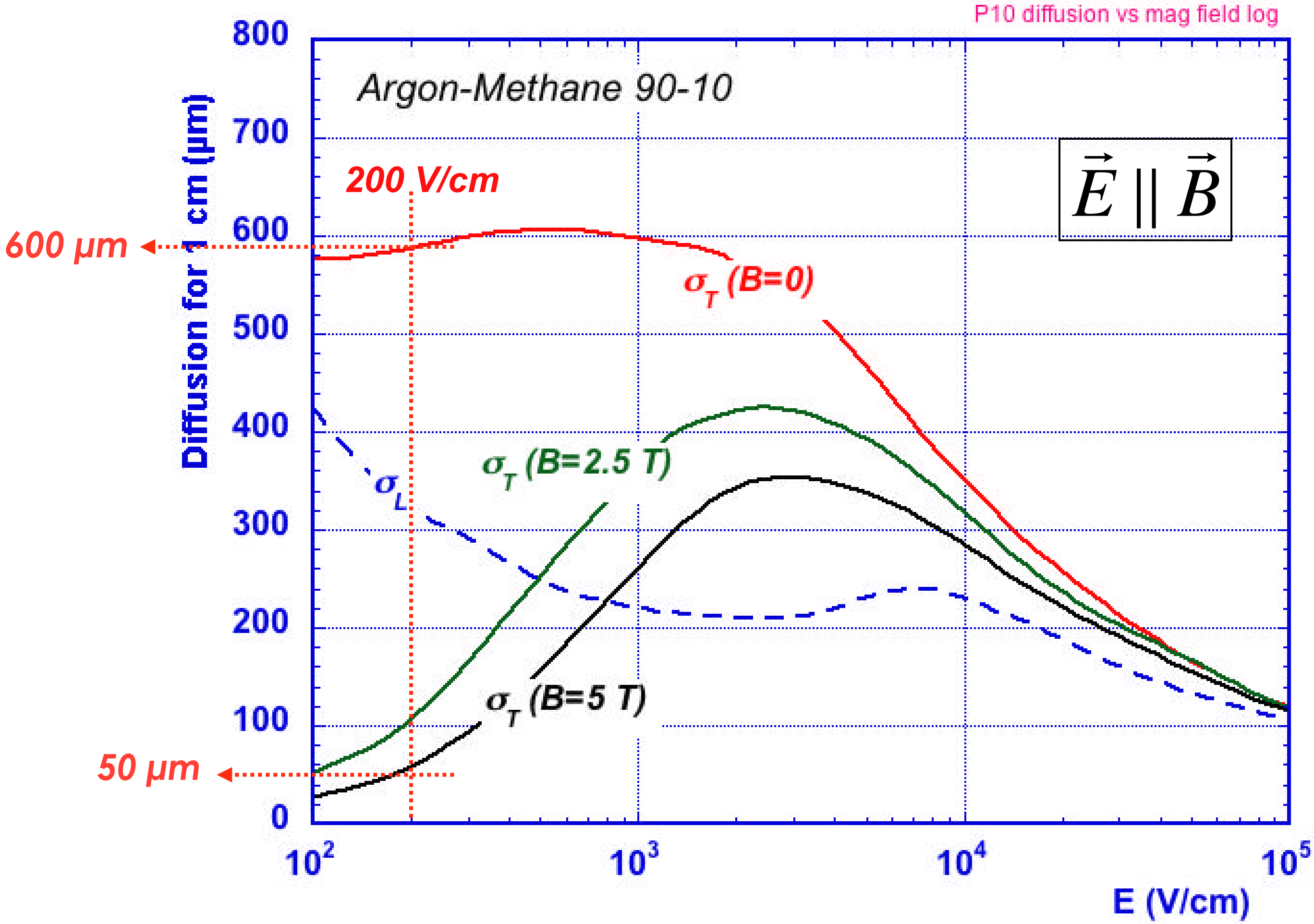
$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

Transverse diffusion is reduced

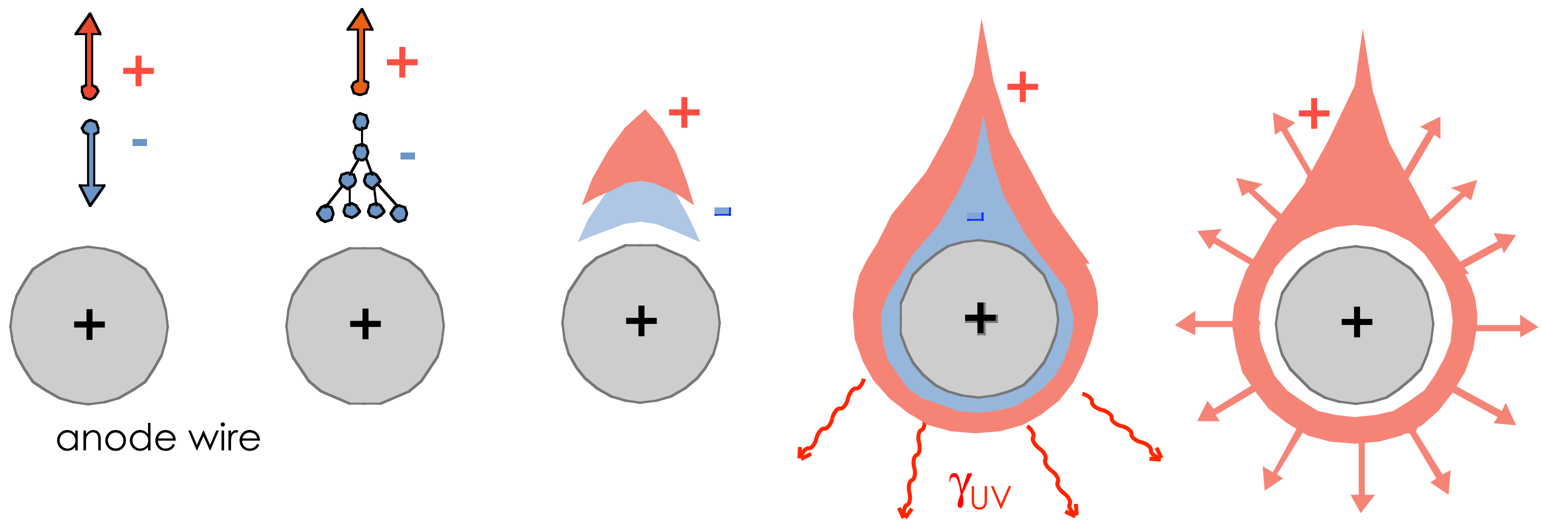
Transverse diffusion in magnetic field

In some gases the transverse diffusion is strongly reduced

→ improves the precision of the projected coordinate measurement in Time Projection Chambers



Avalanche phenomenon



- One electron drifts towards the anode wire:
  - Electric field is increasing
  - Ionizing collisions → pair multiplication

- Due to lateral diffusion and difference of velocity of electrons-ions, a drop-like avalanche develops near the wire

- UV photons are emitted → risk of uncontrolled amplification (spark)

- Electrons are collected in a very short time (few ns) and ions drift slowly towards the cathode

Charge multiplication

* $\alpha = 1/\lambda$ is the probability of ionization per unit length with λ the mean free path of the electron for a secondary ionizing collision
* For n electrons, there will be $dn = n\alpha dx$ new electrons created in a path dx
* Then $n = n_0 e^{\alpha x}$ with α: first Townsend coefficient
* And we can define a multiplication factor M:

$$M = \frac{n}{n_0} = \exp\left[\int_{r_1}^{r_2} \alpha(x)\,dx\right]$$

α is a function of x (non uniform electric fields)

* Limitation of M: above 10^8, sparks occur (Raether limit)
* Calculating α (or gas gain) for different gases (model by Rose and Korff):

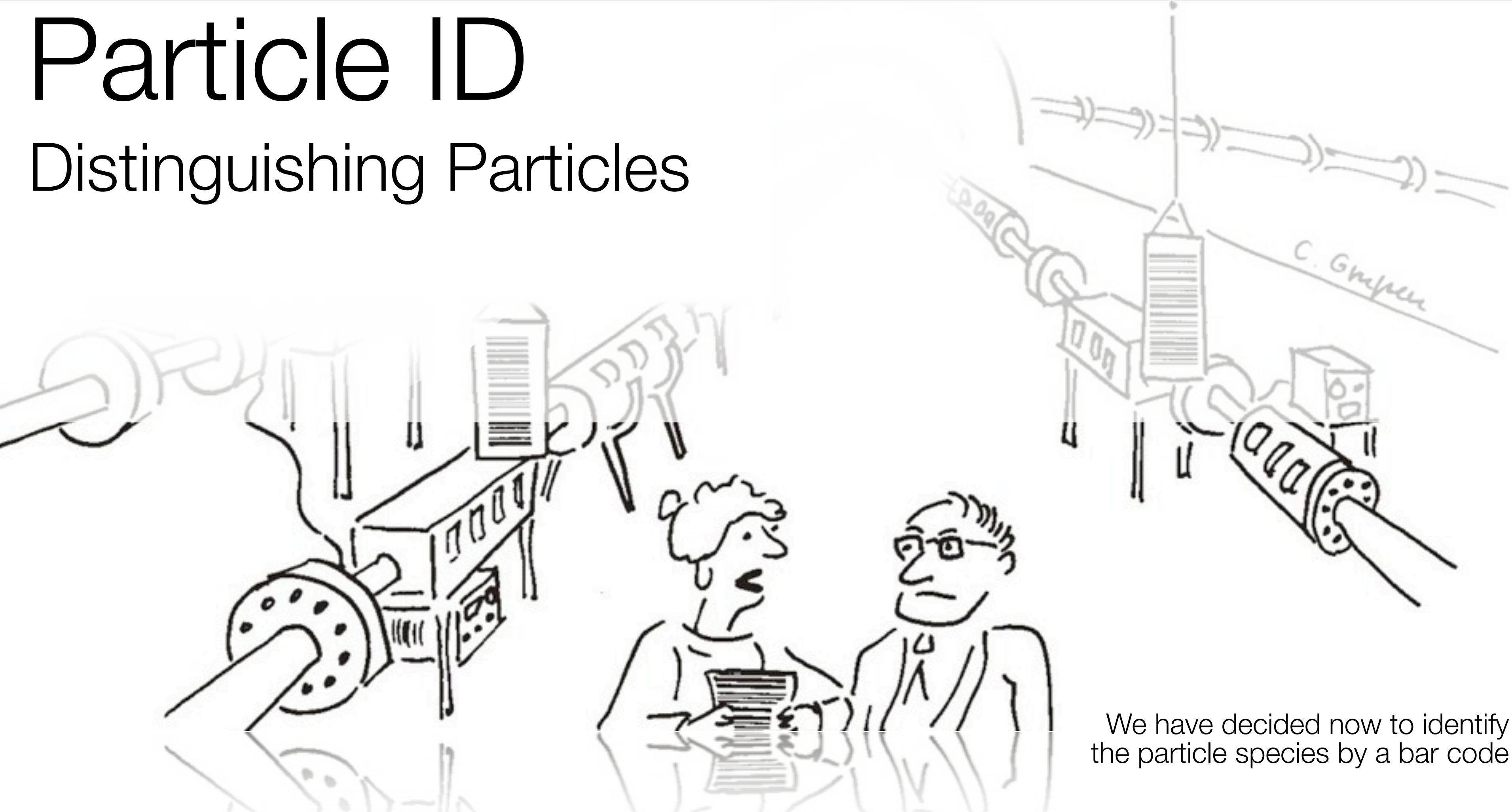
$$\frac{\alpha}{p} = A\exp\left(\frac{-Bp}{E}\right)$$

where A and B depend on the gas

To Backup

Particle ID

Distinguishing Particles



We have decided now to identify
the particle species by a bar code

To Backup

HEP detector: Measures particle momenta ...

by means of a spectrometer (tracker and magnetic field)

With p, γ, β calculate particle mass m_0 ...

$$p = \gamma m_0 \beta c$$

Need second observable

to identify particle type:

Velocity:	Time-of flight	$\tau \propto 1/\beta$	
	Cherenkov angle	$\cos\theta = 1/\beta n$	γ,β
	Transition radiation	$\gamma \geq 1000$	
Energy loss:	Bethe-Bloch	$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$	
Total energy:	Calorimeter	$E = \gamma m_0 c^2$	

Special signatures for neutrals:

Photons : Total energy deposited in electromagnetic shower; use energy measurement, shower shape and information on neutrality (e.g. no track) ...

Neutrons : Energy in calorimeter or scintillator (Li, B, ^{3}He) and information on neutrality (e.g. no track) ...

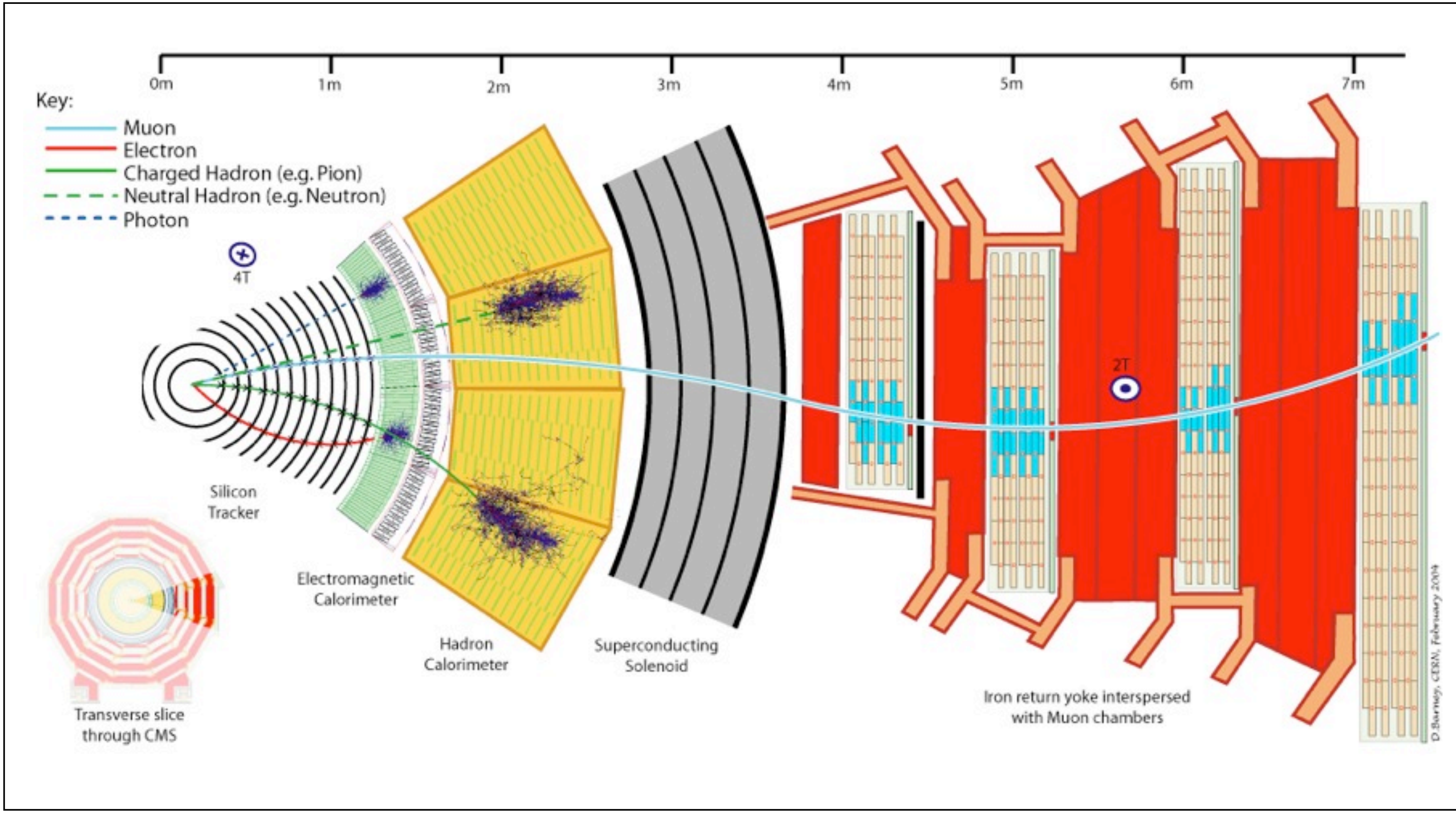
K_0, Λ, ... : Reconstruction of invariant masses ...

Neutrinos : Identify products of charged and neutral current interactions ...

Muons:

Minimum ionizing particles; penetrates thick absorbers; measure signal behind complete detector ...

Particle ID



Particle ID [CMS Detector Slice]

Particle ID - Time-of-Flight Method

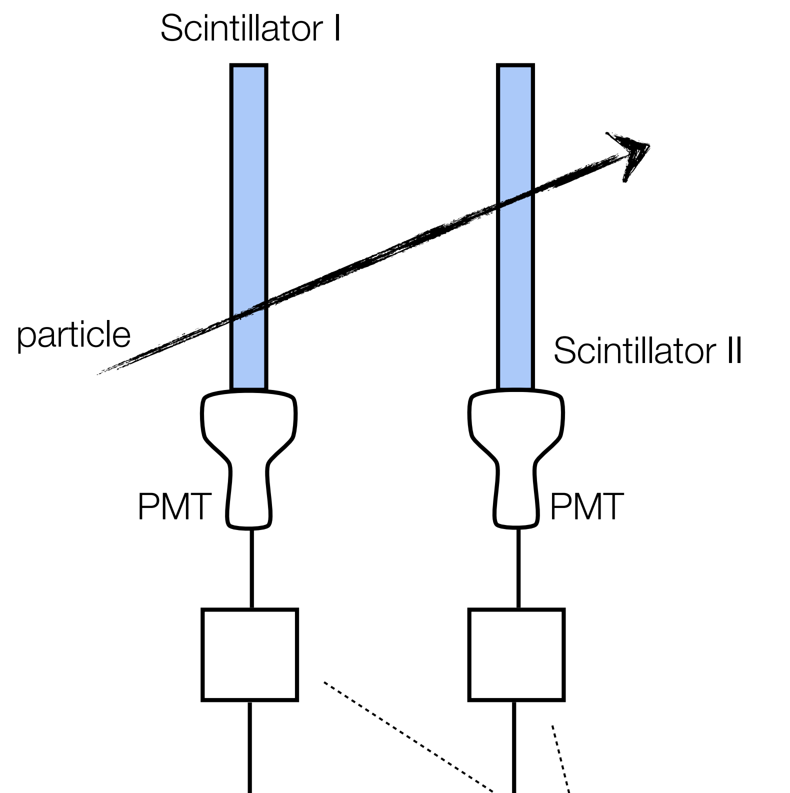
Basic idea:

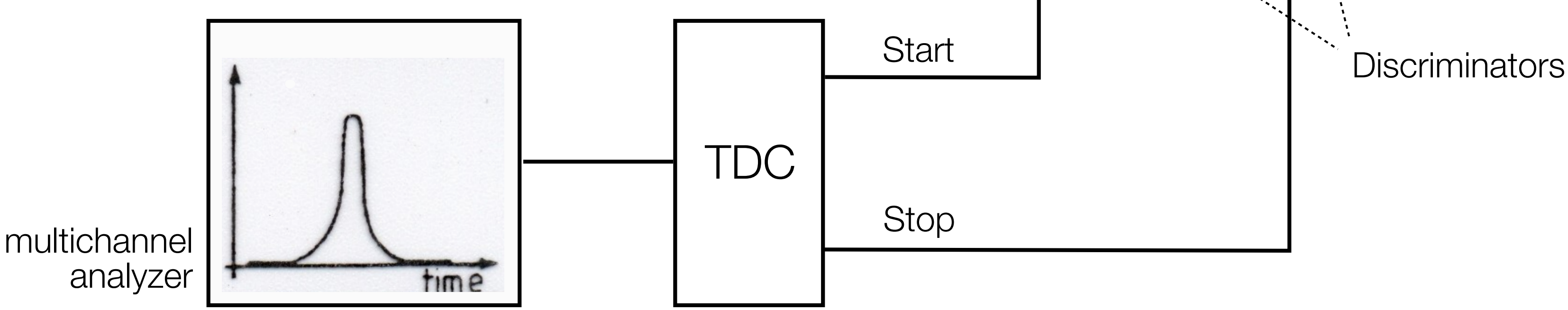
Measure signal time difference between two detectors with good time resolution
[start and stop counter; also: beam-timing & stop counter]

Typical detectors:

- Scintillation counter
- Resistive Plate Chamber (RPC)

Coincidence setup or TDC measurement with common start/stop from interaction time





Time-of-Flight Method

Distinguishing particles with ToF:

[particles have same momentum p]

Particle 1 : velocity v_1, β_1; mass m_1, energy E_1
Particle 2 : velocity v_2, β_2; mass m_2, energy E_2

Distance L : distance between ToF counters

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

Relativistic particles, $E \simeq pc \gg m_i c^2$:

$$\Delta t \approx \frac{L}{pc^2}\left[(pc + \frac{m_1^2c^4}{2pc}) - (pc + \frac{m_2^2c^4}{2pc})\right]$$

$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

For L = 2 m:

Requiring $\Delta t \gtrsim 4\sigma_t$ K/π separation possible up to p = 1 GeV if $\sigma_t \approx$ 200 ps ...

Cherenkov counter, RPC : $\sigma_t \approx$ 40 ps ...
Scintillator counter : $\sigma_t \approx$ 80 ps ...

Example:

Pion/Kaon separation ...
[$m_K \approx$ 500 MeV, $m_\pi \approx$ 140 MeV]

Assume:
p = 1 GeV, L = 2 m ...

$$\rightarrow \quad \Delta t \approx \frac{2\ \mathrm{m}\cdot c}{2\ (1000)^2\ \mathrm{MeV}^2/c^2}\left(500^2 - 140^2\right)\ \mathrm{MeV}^2/c^4$$

$$\approx 800\ \mathrm{ps}$$

Particle ID - Specific Energy Loss

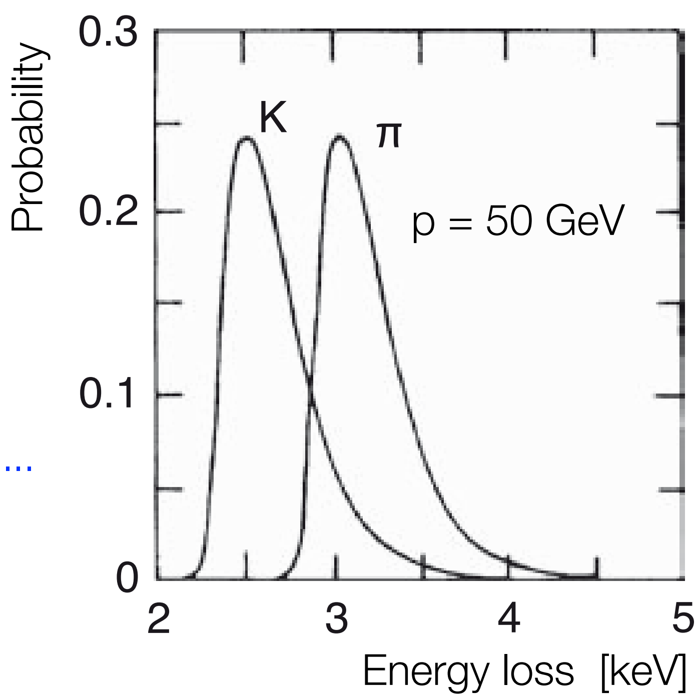
Use relativistic rise of dE/dx
for particle identification ...

Key problem: Landau fluctuations

Need to make many dE/dx measurements
and truncate large energy-loss values ...
[determination of 'truncated mean']

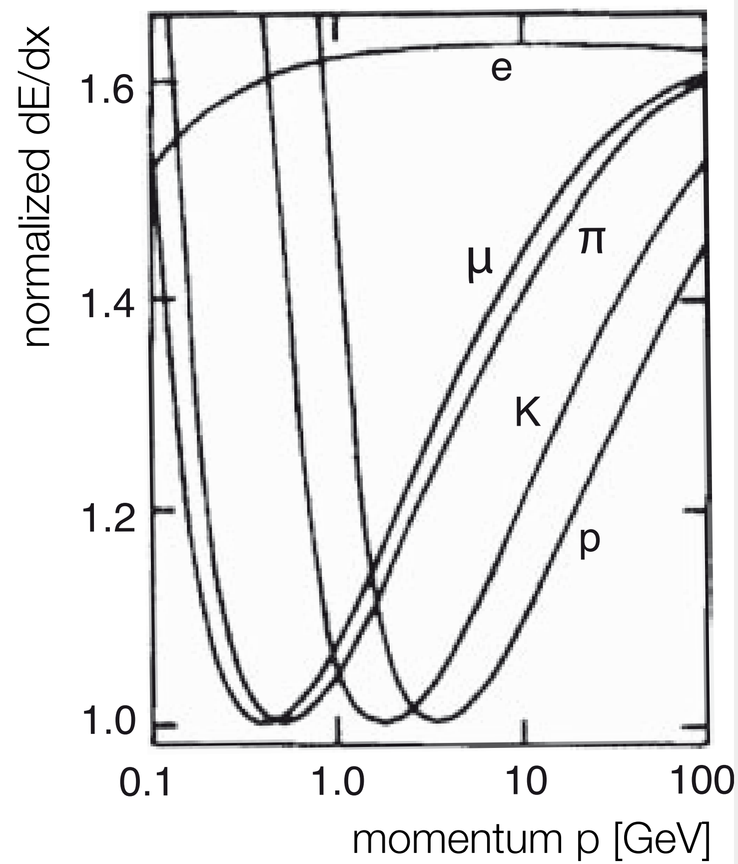
Average energy loss in
a 1 cm layer of argon-methane

μ/π separation impossible, but
π/K/p generally be achievable

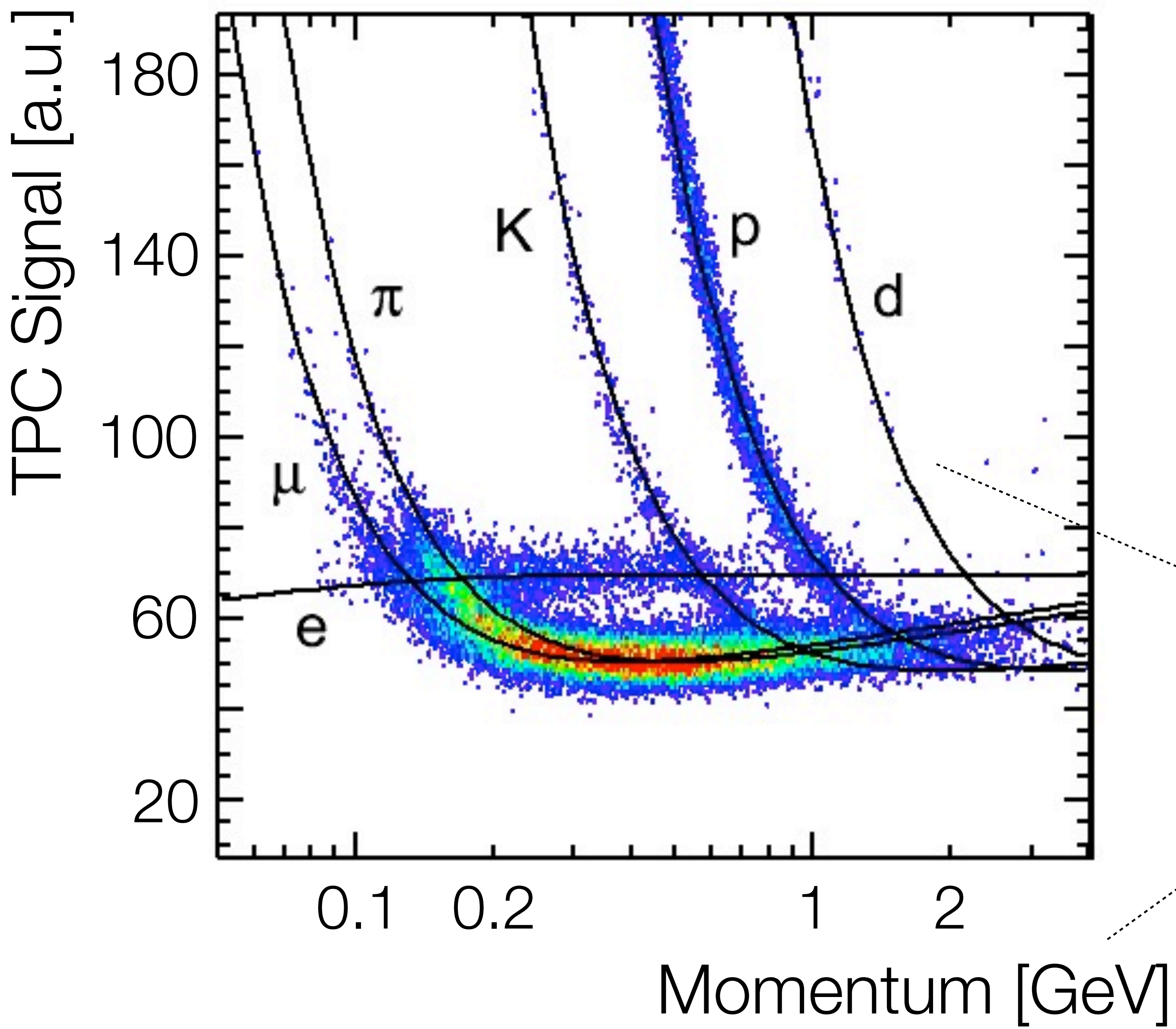


Energy loss distribution;
50 GeV pions and kaons ...

[1 cm layer Ar/Methane]



Particle ID - Specific Energy Loss



Measured
energy loss

[ALICE TPC, 2009]

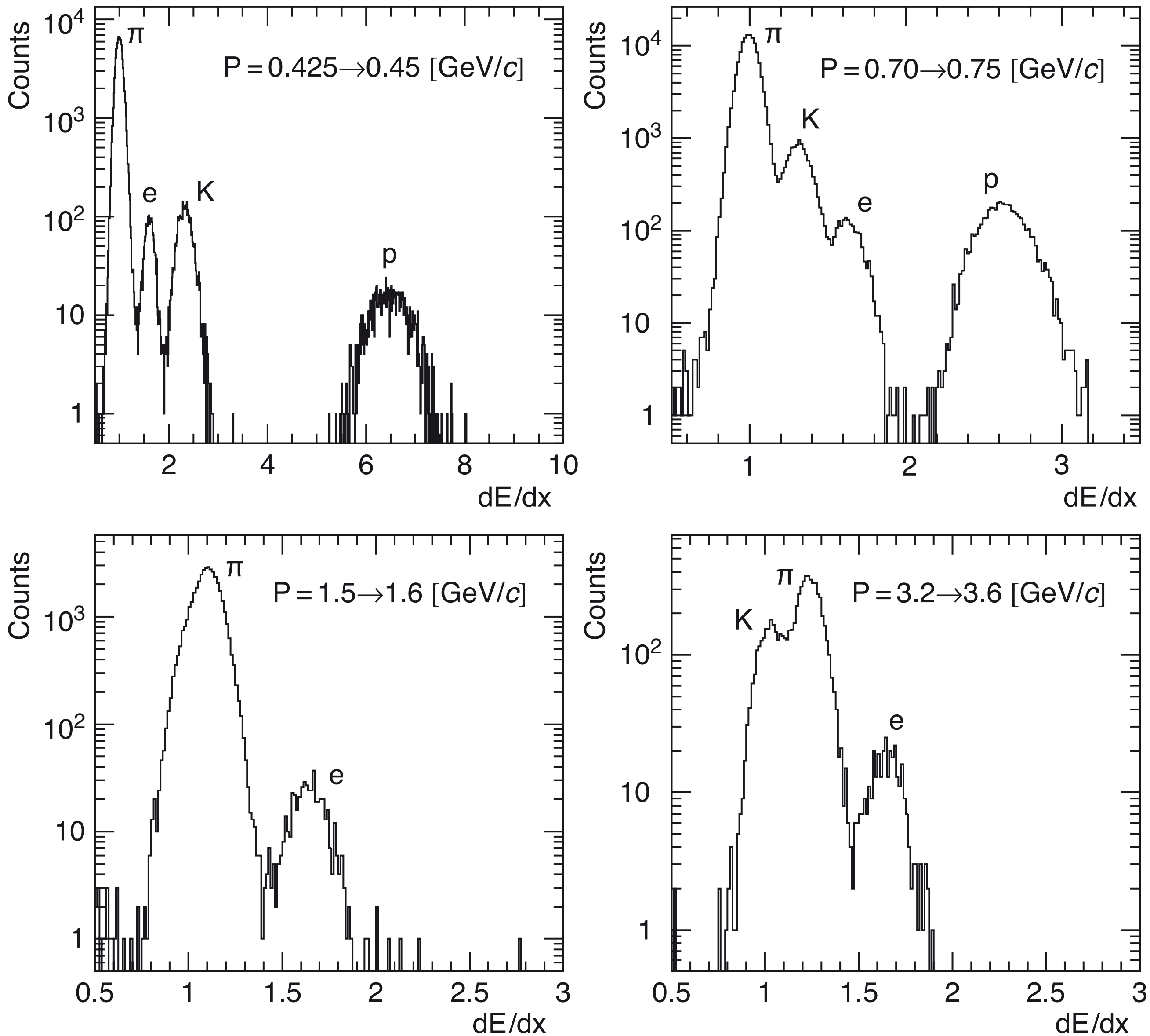
Bethe-Bloch

Remember:
dE/dx depends on β!

Particle ID - Specific Energy Loss

Truncated
energy loss distributions
for various momenta ...

[ALPEH TPC]



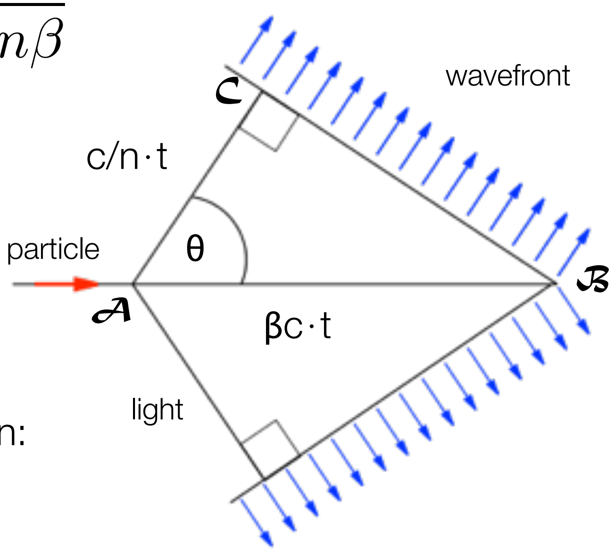
Particle ID - Cherenkov Radiation

Reminder:

Polarization effect ...
Cherenkov photons emitted if v > c/n ...

Cherenkov angle:

$$\cos\theta_c = \frac{1}{n\beta}$$



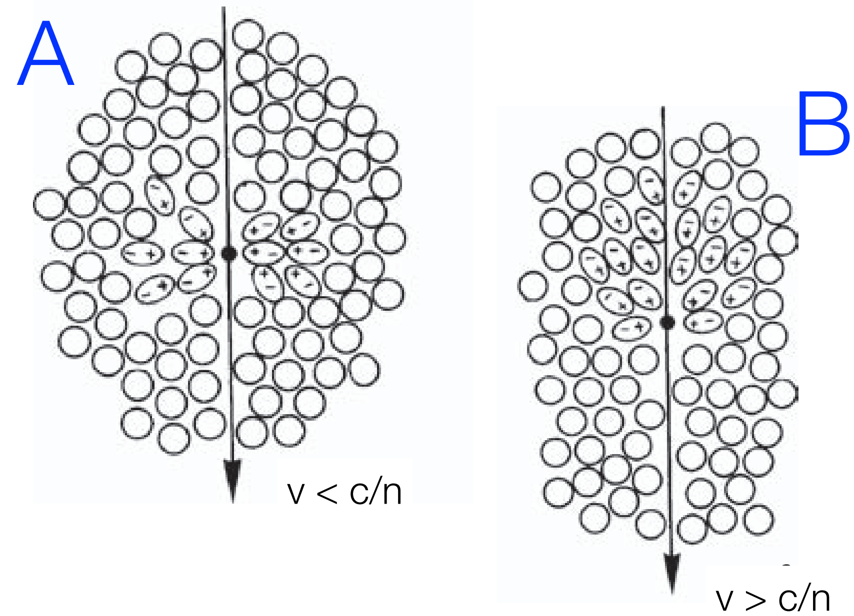
Simple
Geometric derivation:

$\mathcal{AB} = \beta c \cdot t$

$\mathcal{AC} = c/n \cdot t$

$\cos\theta = \mathcal{AC}/\mathcal{AB} = c/n \cdot t/(\beta c \cdot t)$

$= 1/n\beta$



A: v < c/n

Induced dipoles symmetrically arranged around particle path; no net dipole moment; no Cherenkov radiation

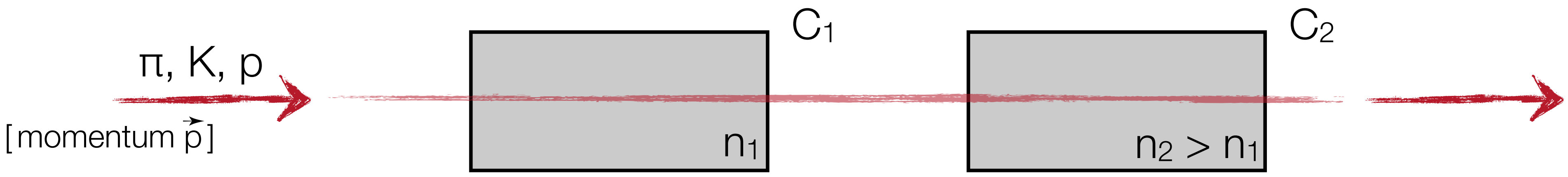
B: v > c/n

Symmetry is broken as particle faster the electromagnetic waves; non-vanishing dipole moment; radiation of Cherenkov photons

To Backup

Threshold detection:

Observation of Cherenkov radiation ➝ $\beta > \beta_{thr}$



Choose n_1, n_2 in such a way that for:

n_2 : $\beta_\pi, \beta_K > 1/n_2$ and $\beta_p < 1/n_2$

n_1 : $\beta_\pi > 1/n_1$ and $\beta_K, \beta_p < 1/n_1$

Light in C_1 and C_2 ➝ identified pion

Light in C_2 and not in C_1 ➝ identified kaon

Light neither in C_1 and C_2 ➝ identified proton

Differential Cherenkov detectors:

Selection of narrow velocity interval
for actual measurement ...

Threshold velocity:
[cos θ = 1]

$$\beta_{\text{min}} = \frac{1}{n}$$

Maximum velocity:
[$\theta = \theta_{max} = \theta_t$]

Cherenkov angle limited
by total reflection

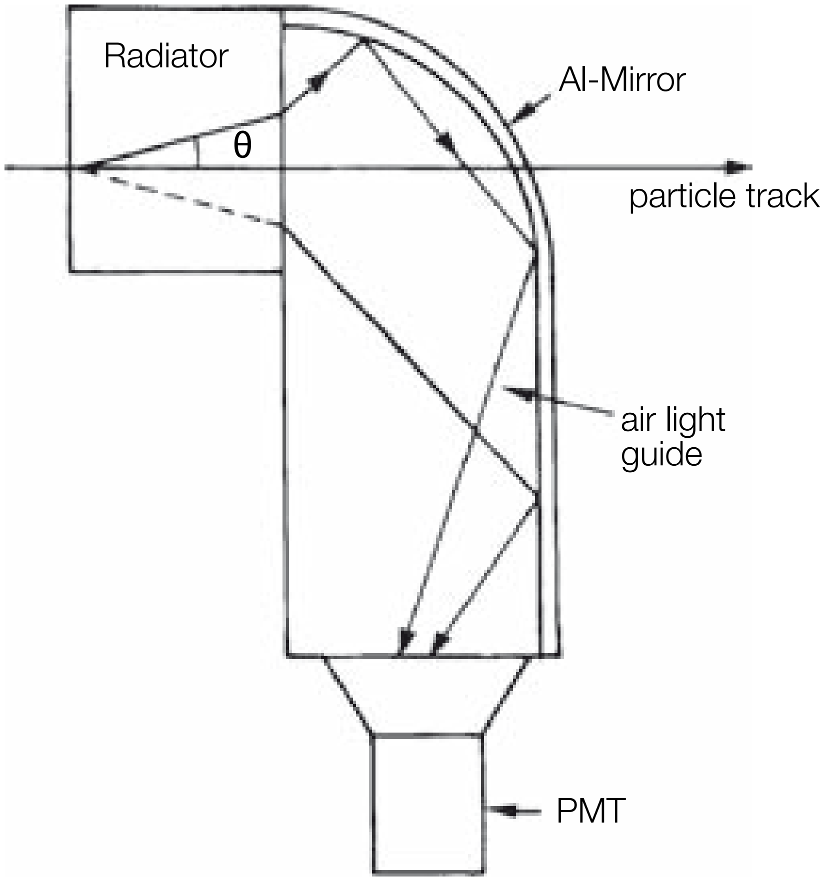
$$\sin\theta_t = 1/n$$
$$\cos\theta_{\text{max}} = \sqrt{1 - \sin^2\theta_t} = 1/n\beta_{\text{max}}$$

$$\beta_{\text{max}} = \frac{1}{\sqrt{n^2 - 1}}$$

Example:

Diamond, n = 2.42 ➛ β_{min} = 0.413, β_{max} = 0.454,
i.e. velocity window of Δβ = 0.04 ...

Suitable optic allows Δβ/β ≈ 10^{-7}



Working principle of a
differential Cherenkov counter

Ring Imaging Cherenkov Counter

Optics such that photons emitted under certain angle form ring ...

Focal length of spherical mirror: $f = R_S/2$ ...
Cherenkov light emitted under angle: θ_C ...

Radius of Cherenkov ring: $r = f \cdot \theta_C = R_S/2 \cdot \theta_C$ ...

$$\rightarrow \beta = \frac{1}{n \cos(2r/R_s)}$$

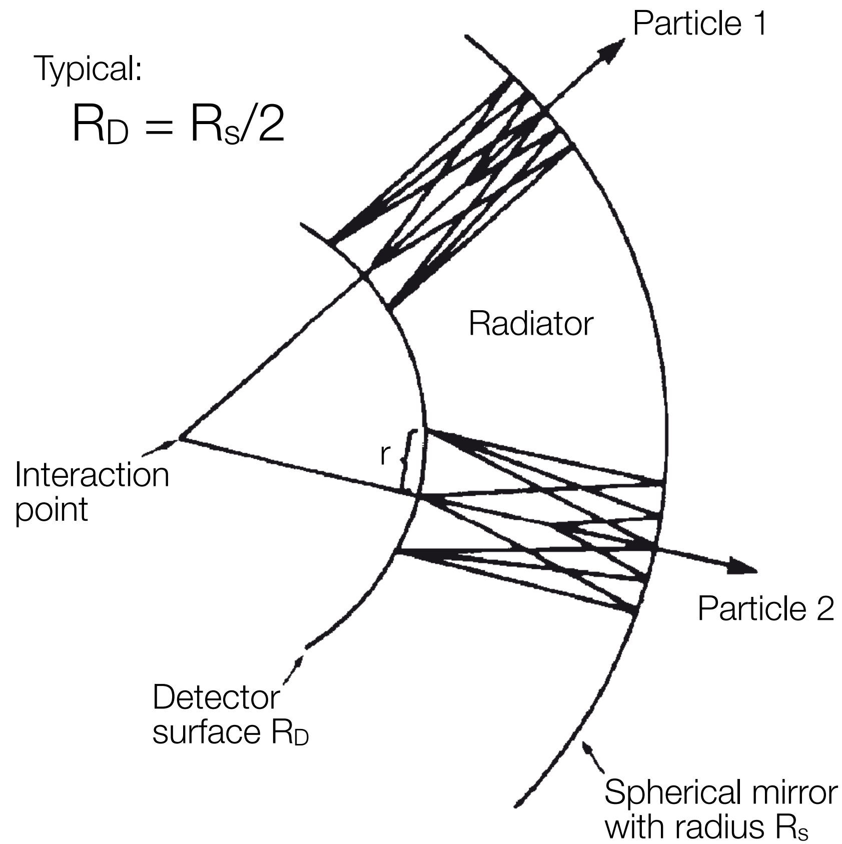
Determination of β from r ....

Photon detection:
Photomultiplier, MWPC
Parallel plate avalanche counter ...

Gas detectors filled with photosensitive gas ...
[e.g. vapor addition or TMAE ($C_5H_{12}N_2$)]

Typical:

$R_D = R_S/2$



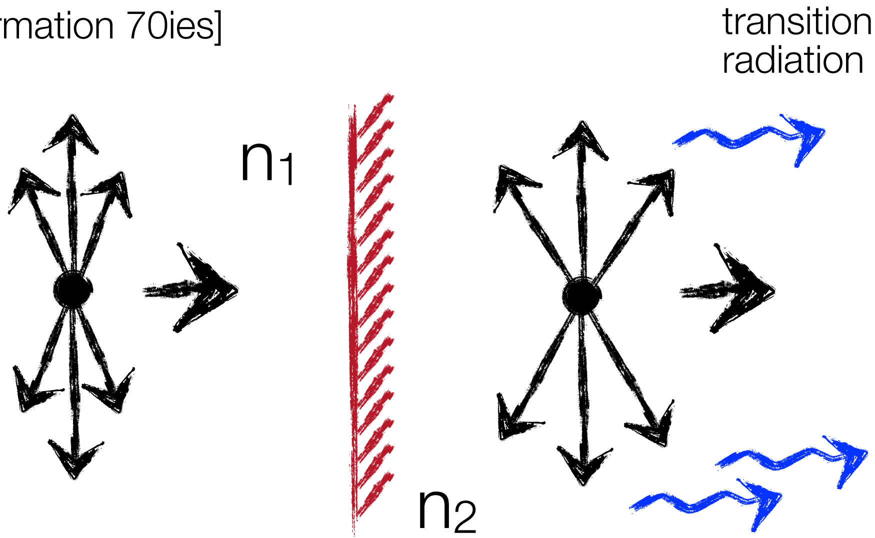
Working principle of a
Ring Imaging Cherenkov Counter (RICH)

Particle ID - Cherenkov Radiation

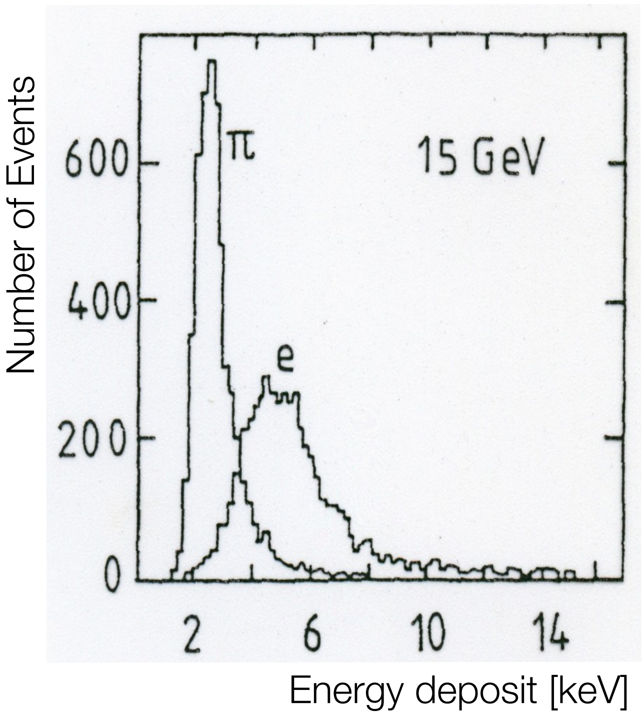
Transition radiation occurs if a relativist particle (large γ) passes the boundary between two media with different refraction indices ...

[predicted by Ginzburg and Frank 1946; experimental confirmation 70ies]

Effect can be explained by rearrangement of electric field ...



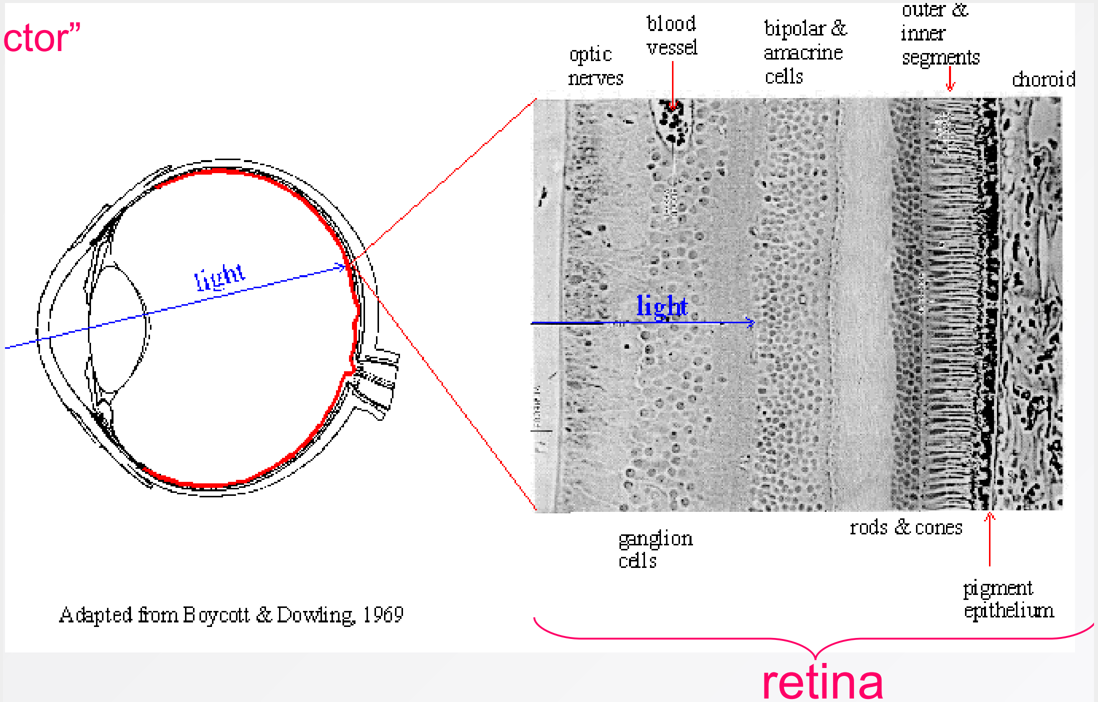
Rearrangement of electric field yields transition radiation



Energy loss distribution for 15 GeV pions and electrons in a TRD ...

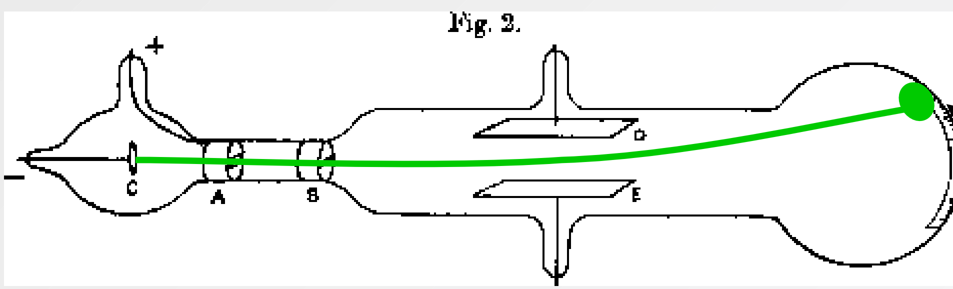
Historical examples

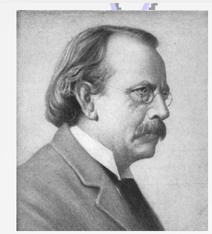
ctor”



cathode ray tube

J. Plücker 1858 ➠J.J. Thomson 1897





Scintillation of glass

accelerator

manipulation
By E or B field

detector

From: J.J. Thomson: Cathode Rays. Philosophical Magazine, **44**, 293 (1897).

To Backup

Historical Development

First

Detection of
α-, β- and γ-rays

1896

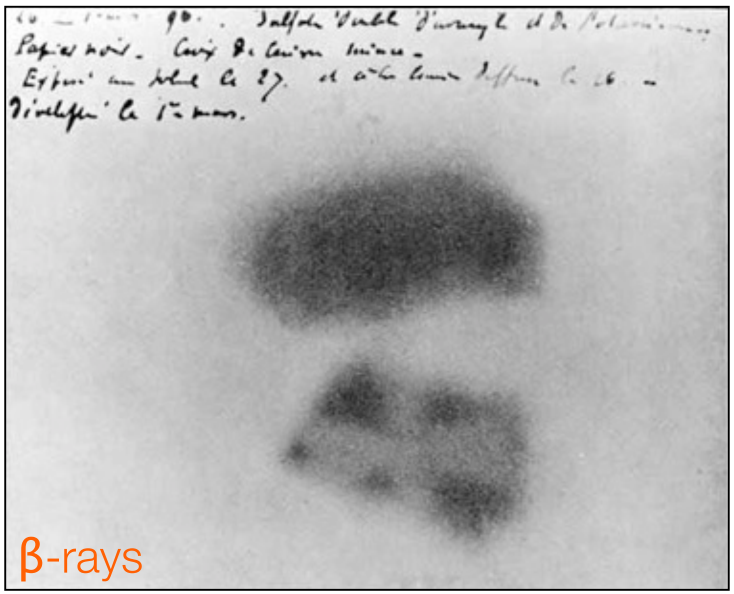
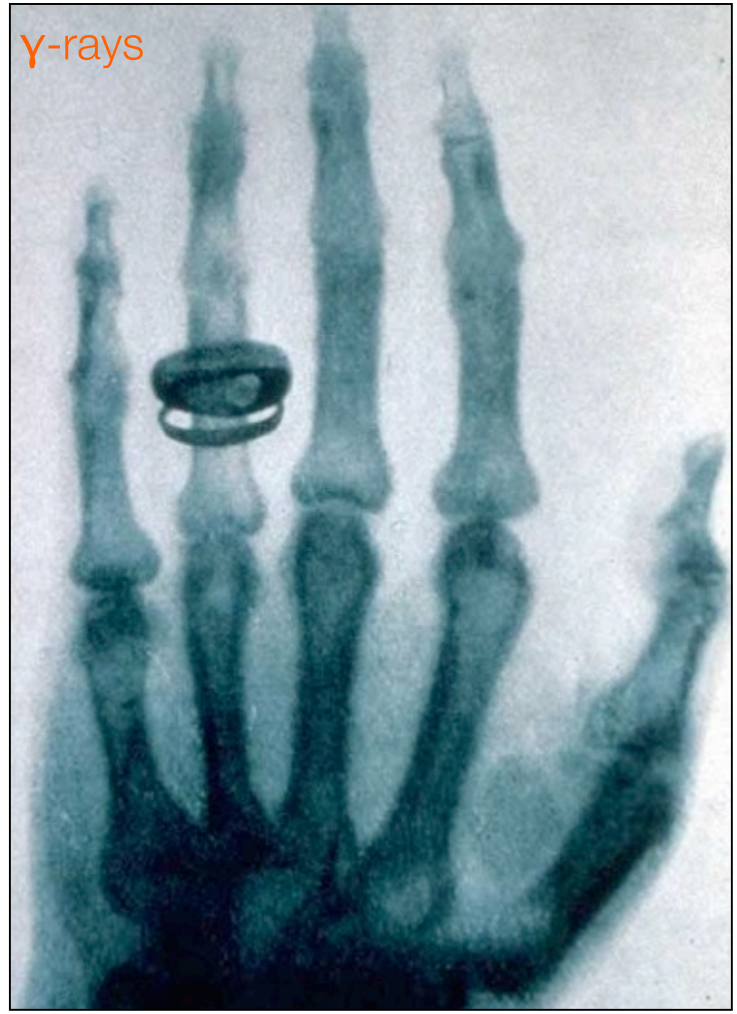


Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt.

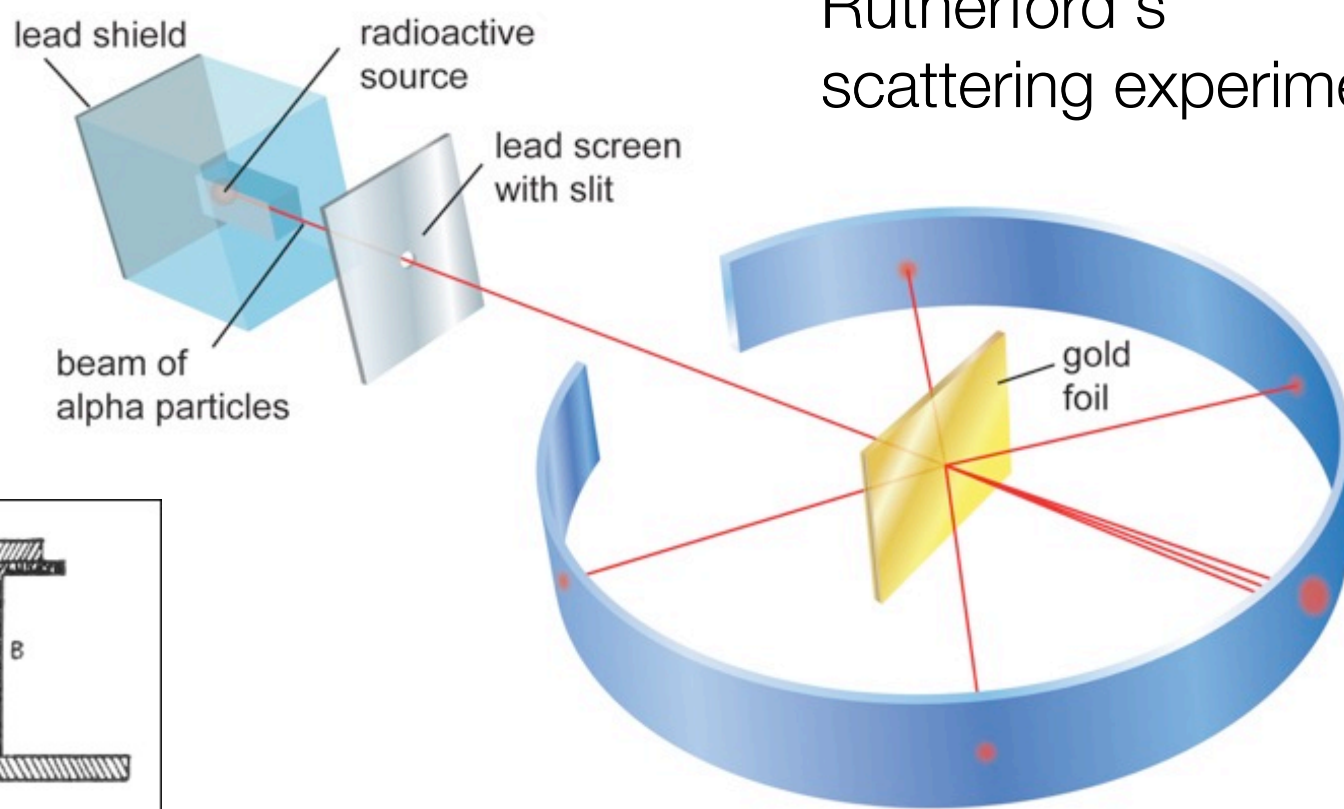
1896



An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January 1896.

Historical Development

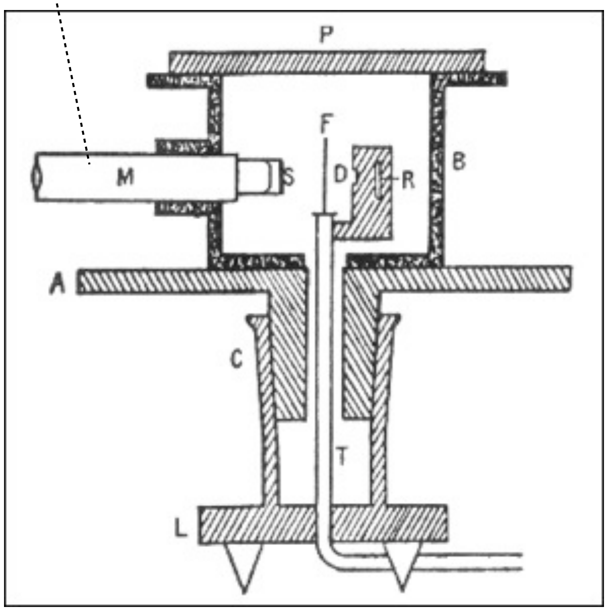
Rutherford's scattering experiment



Schematic view of Rutherford experiment

1911

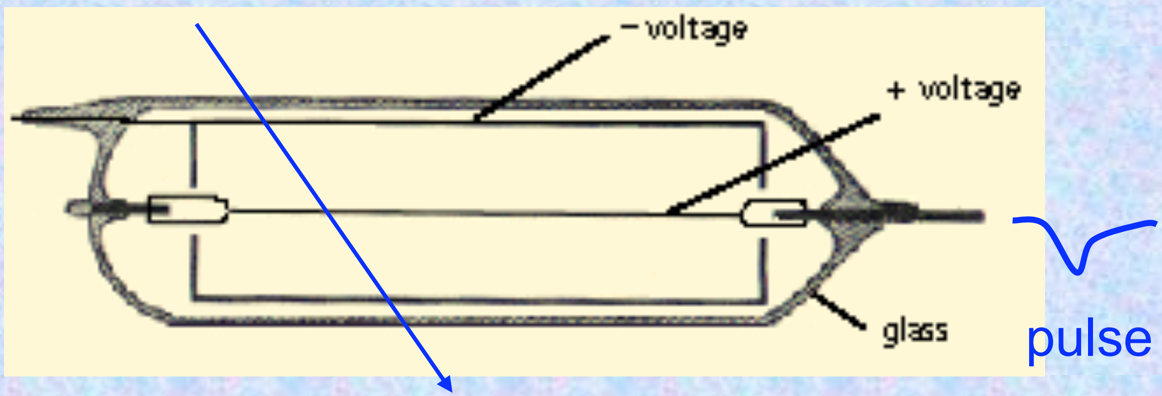
Microscope + Scintillating ZnS screen



Rutherford's original experimental setup

Geiger Counter

E. Rutherford 1909 ***H. Geiger 1927***



The Geiger counter, later further developed and then called Geiger-Müller counter

First electrical signal from a particle

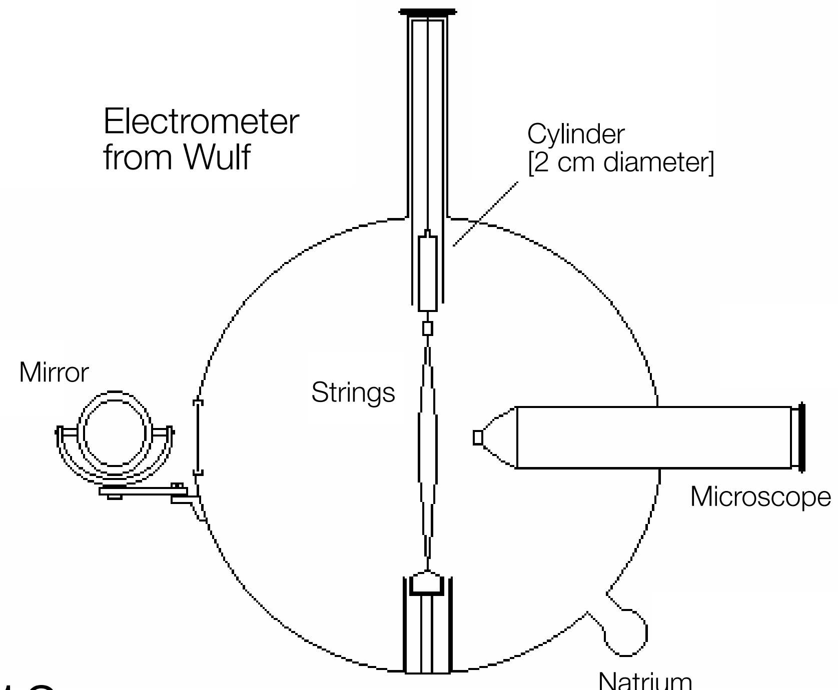
E. Rutherford and H. Geiiger, Proc. Royall Soc. A81 (1908) 141

H. Geiiger and W. Mülllller, Phys. Zeiits. 29 (1928) 839

Historical Development

Detection of cosmic rays

[Hess 1912; Nobel prize 1936]

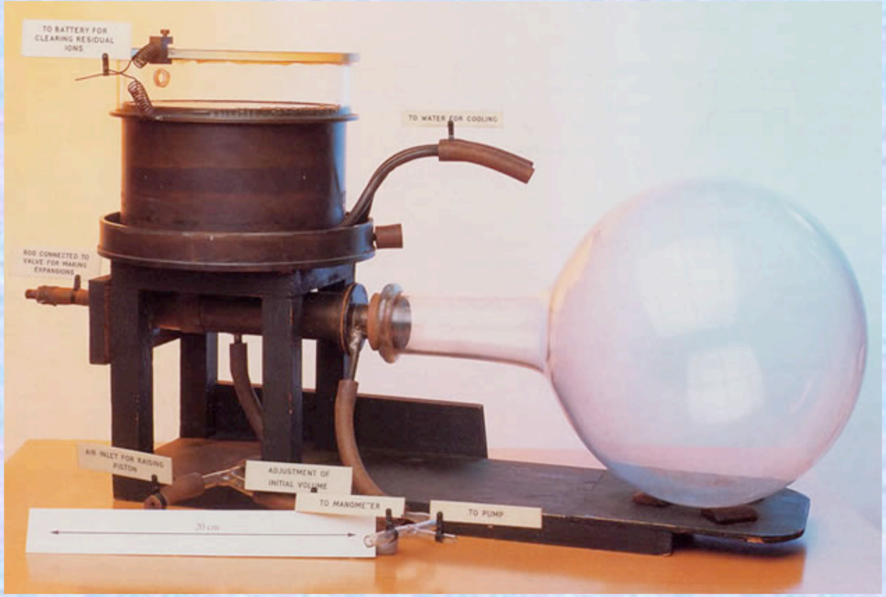


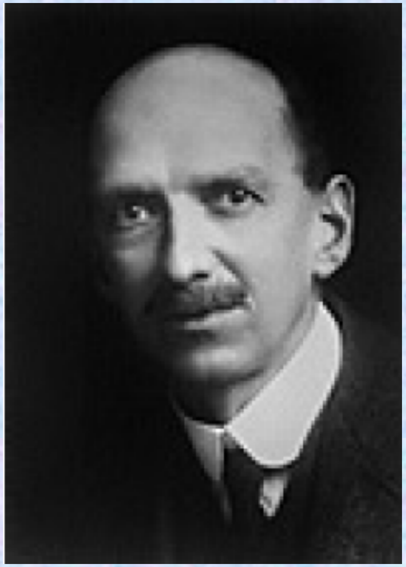
1912

Victor F. Hess before his 1912 balloon flight
in Austria during which he discovered cosmic rays.

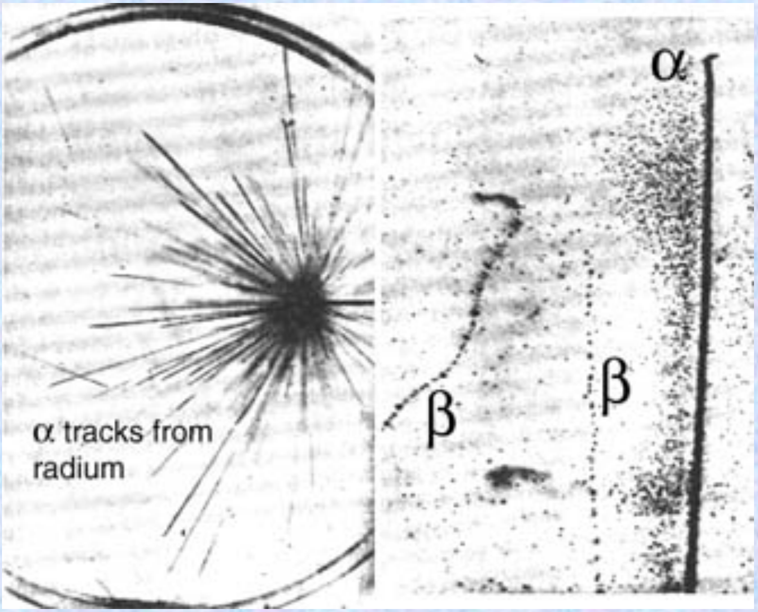
First Tracking Detector: Wilson Chamber

Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)





The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a over-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle's path, their number per unit of length being proportional to the density of ionization (dE/dx).

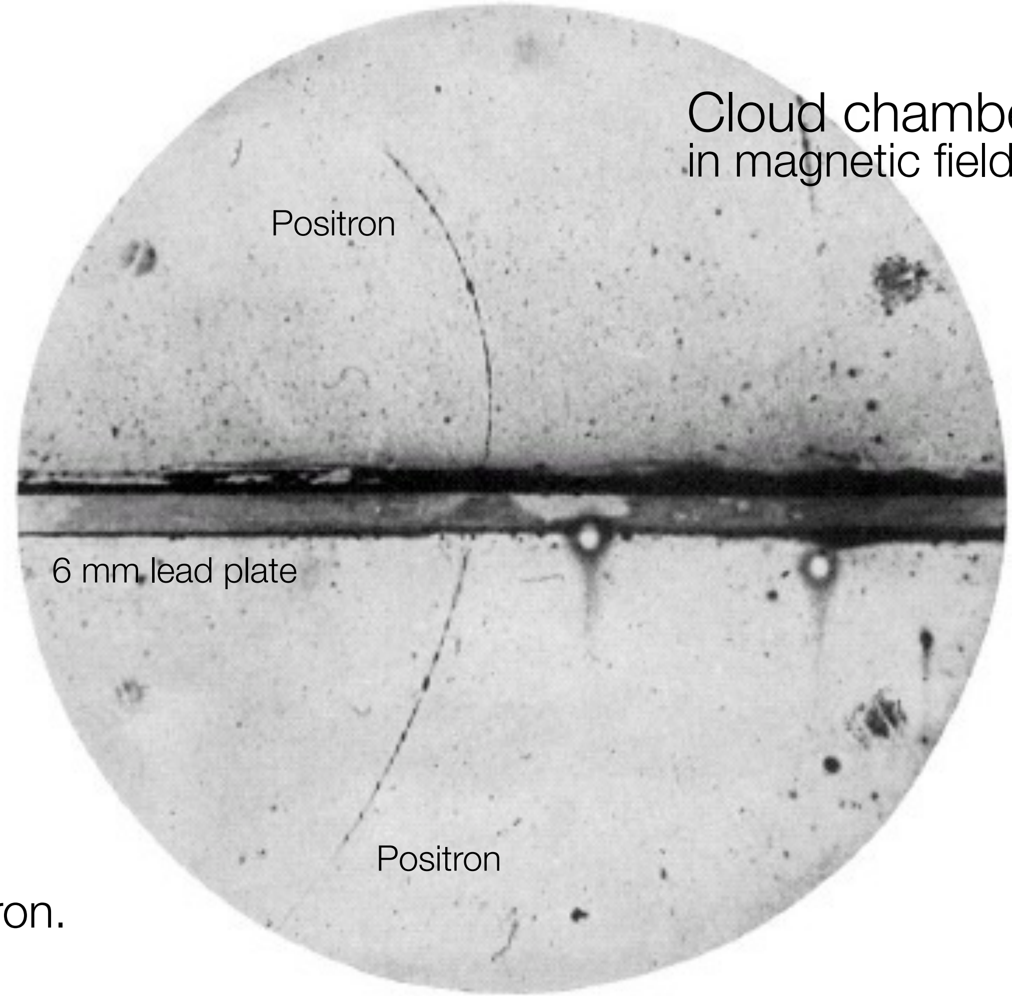


was used at discovery of the positron (1932 by Carl Anderson, Noble Prize 1936)

Historical Development

Discovery of antimatter

[Anderson 1932; Nobel prize 1936]



63 MeV positron passing through
lead plate emerging as 23 MeV positron.

The length of this latter pass is at least ten times
greater than the possible length of a proton path of this curvature.

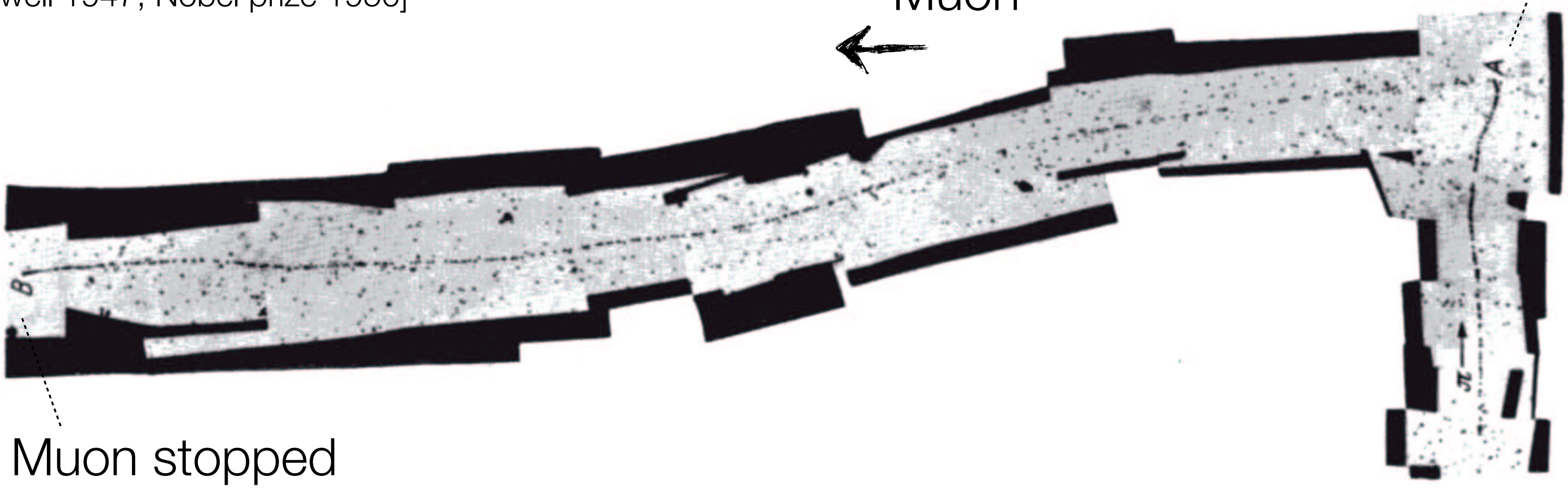
Historical Development

Discovery of the pion
Nuclear emulsion technique

[Powell 1947; Nobel prize 1950]

Muon

Pion
at rest



Muon stopped

Pion

$$\pi \rightarrow \mu\nu$$

$$\mu \rightarrow e\nu\nu$$ [not seen]

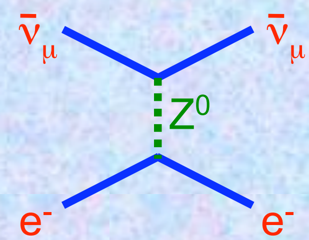
Bubble Chamber

Donald Glaser

LBNL Image Library

Similar principle as cloud chamber:

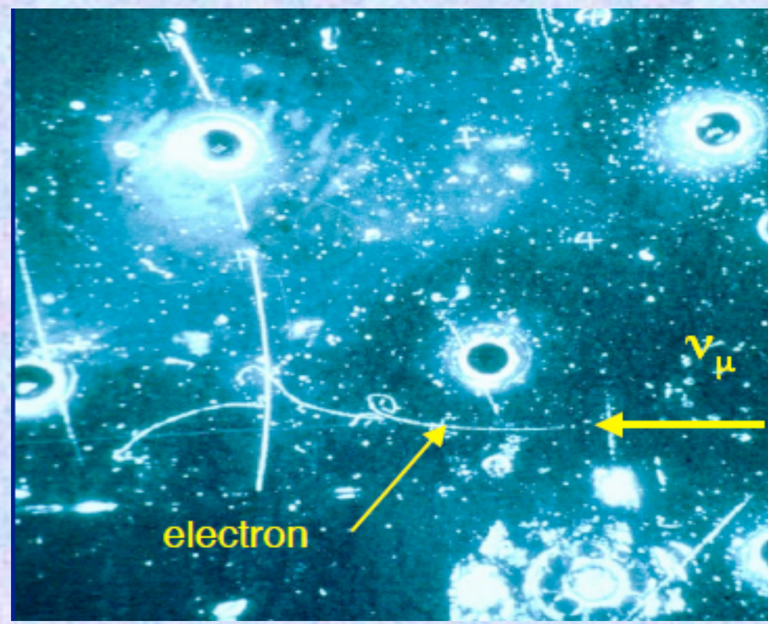
- **Bubble chamber (1952 by Donald Glaser, Noble Prize 1960)**
  - (4.8 x 1.85 m^2) chamber with liquid (e.g. H_2) at boiling point ("superheated")
  - charged particles leave trails of ions
    - formation of small gas bubbles around ions



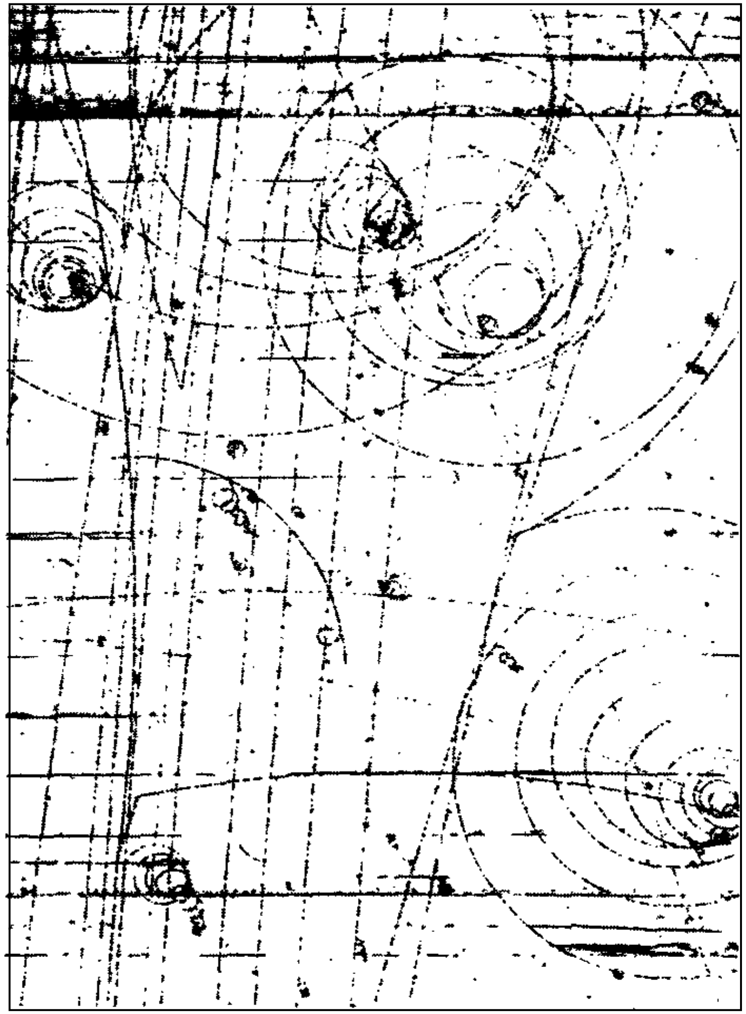
was used at discovery of the "neutral current" (1973 by Gargamelle Collaboration, no Noble Prize yet)

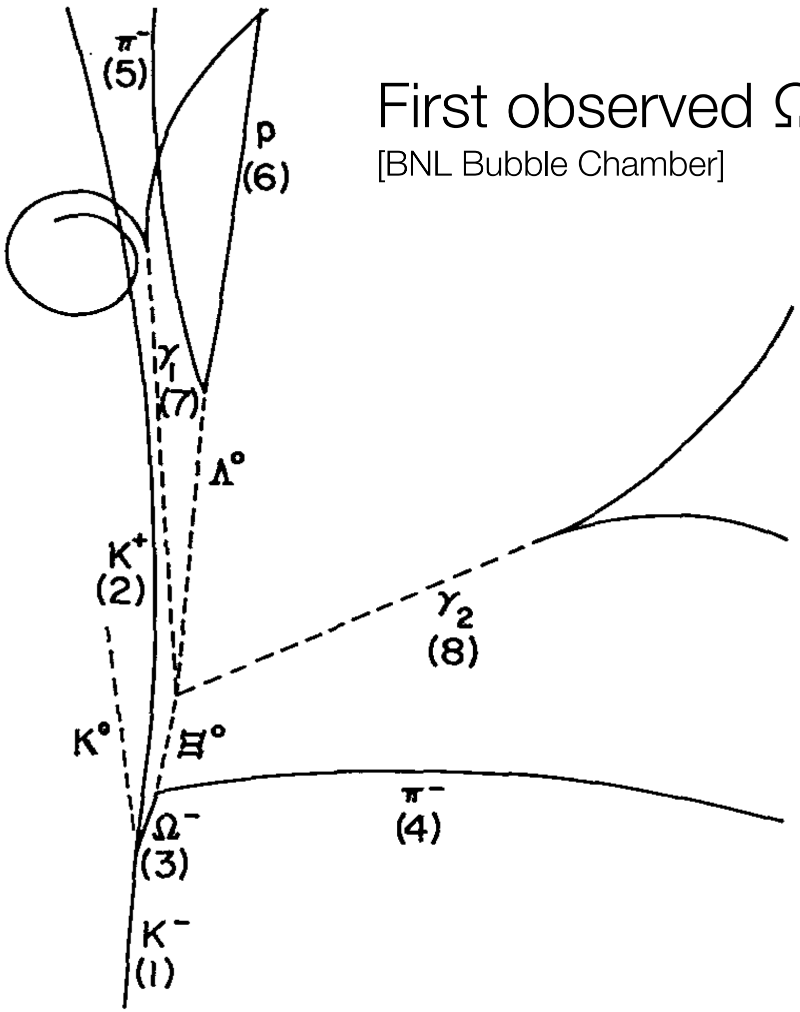
Gargamelle bubble chamber

CERN



Historical Development

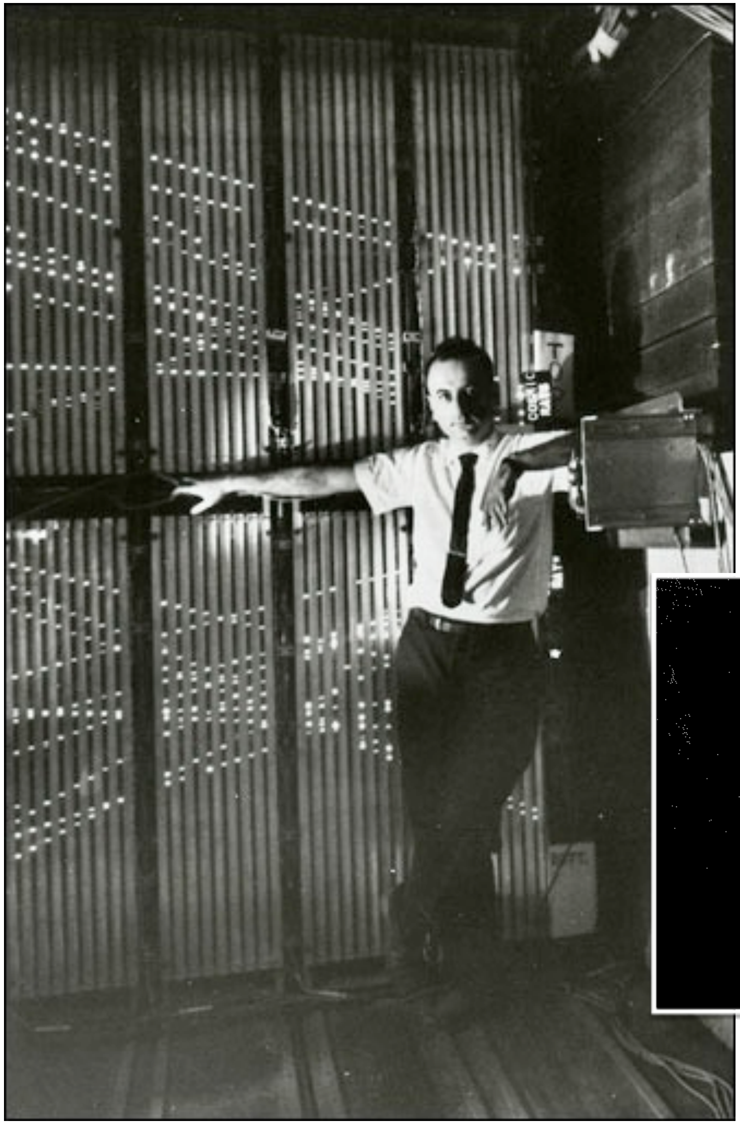




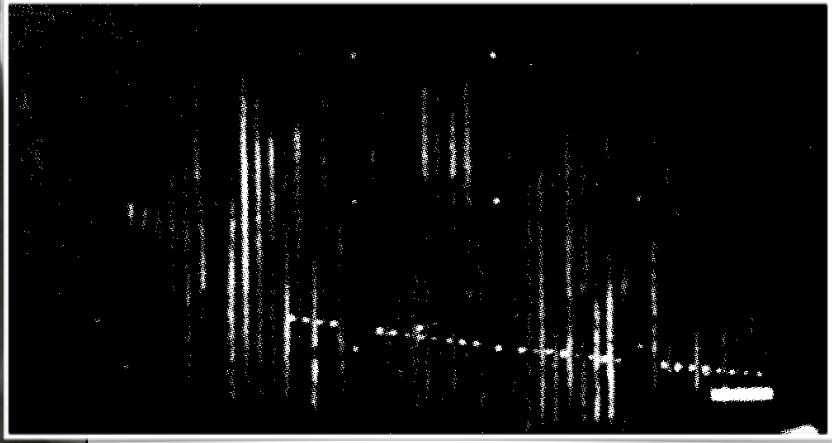
First observed Ω^- event

[BNL Bubble Chamber]

Historical Development



Melvin Schwartz in front of the spark chamber
used to discover the muon neutrino



Single muon event from
original publication

Discovery of the muon neutrino (1962)

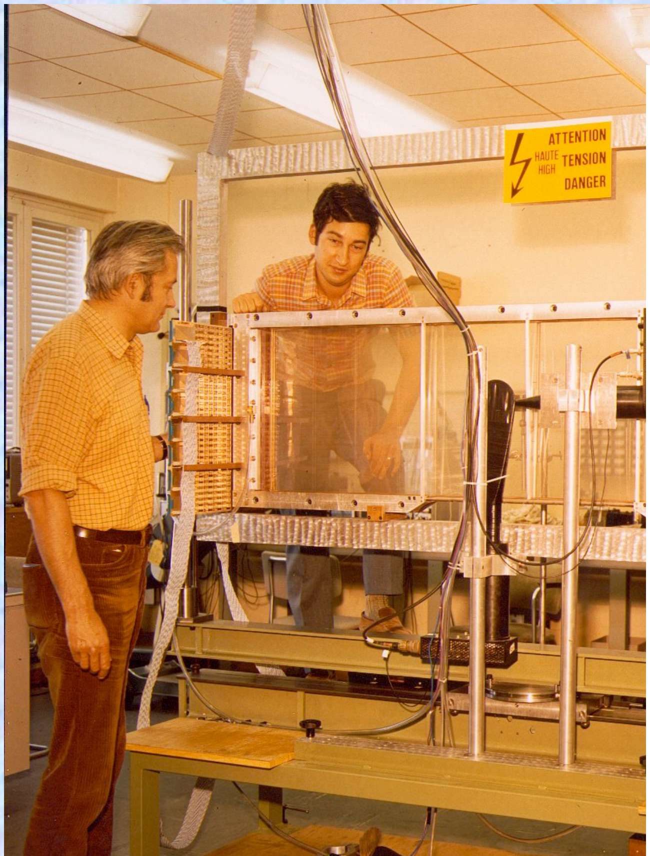
Leon M. Lederman
Melvin Schwartz
Jack Steinberger

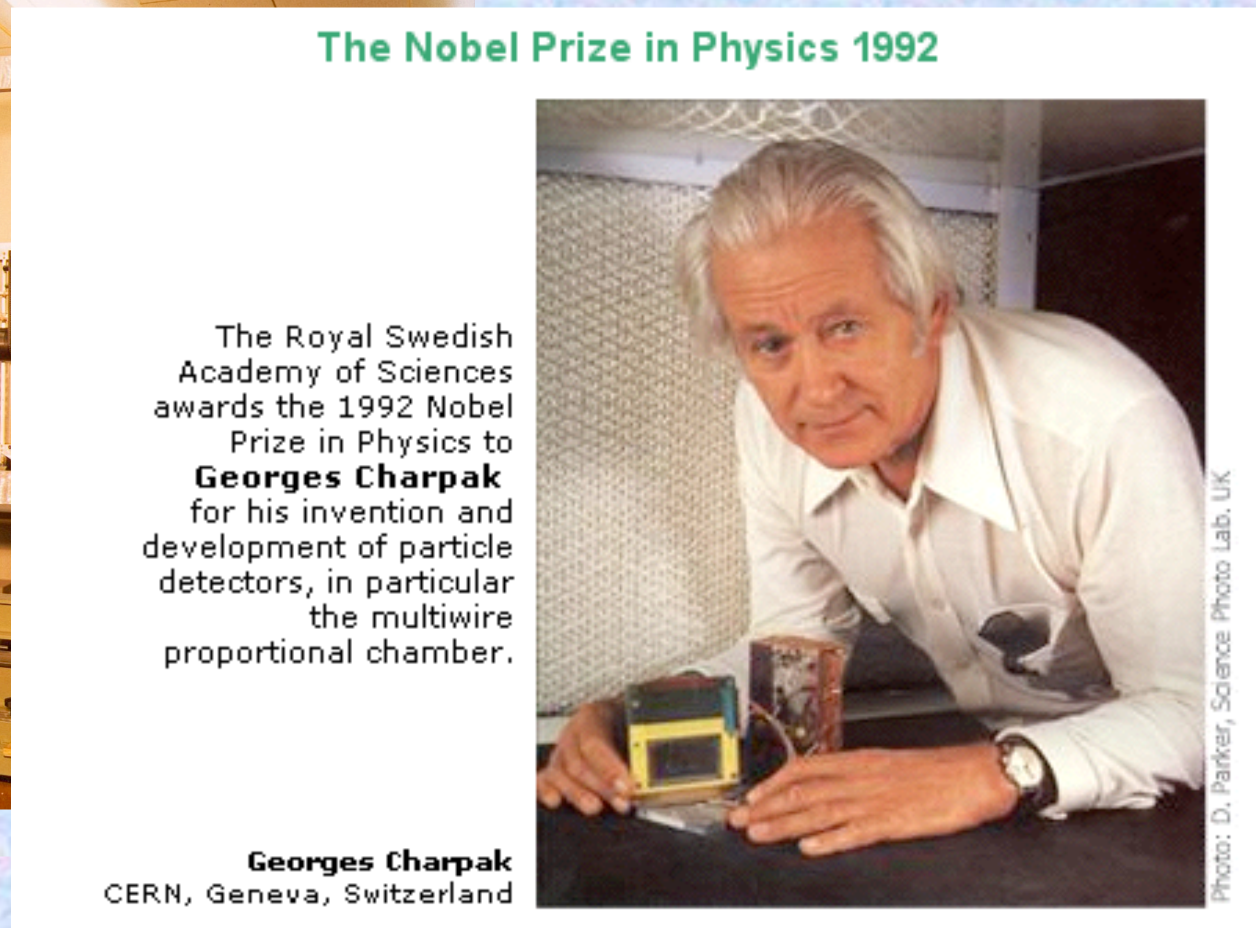
[Nobel prize 1988]

Large Size Multi-Wire Proportional Chamber (1972)

Geiger - Müller tube just good for single tracks with limited precision (no position information) → in case of more tracks more tubes are needed or...

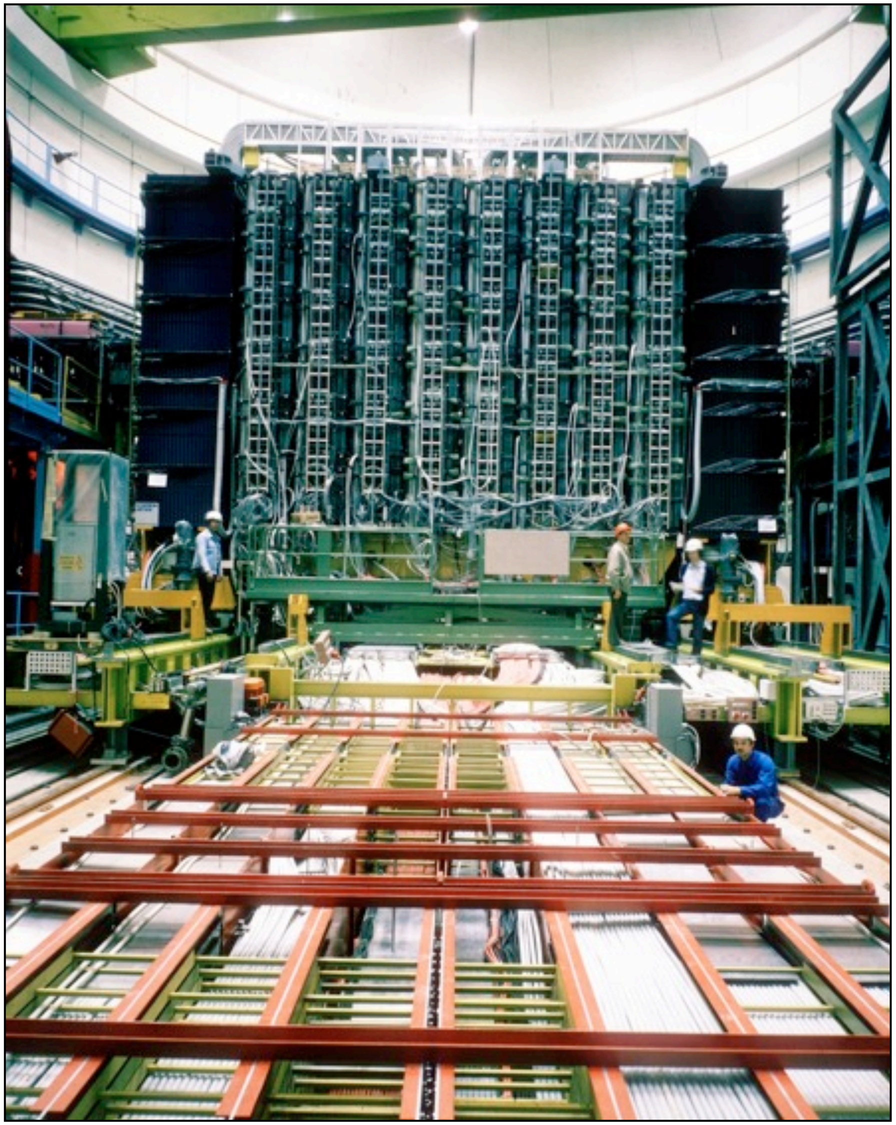
Multi Wire Proportional Chamber → 1968 by Georges Charpak, Nobel Prize 1992)





F. Sauli, http://www.cern.ch/GDD

Historical Development



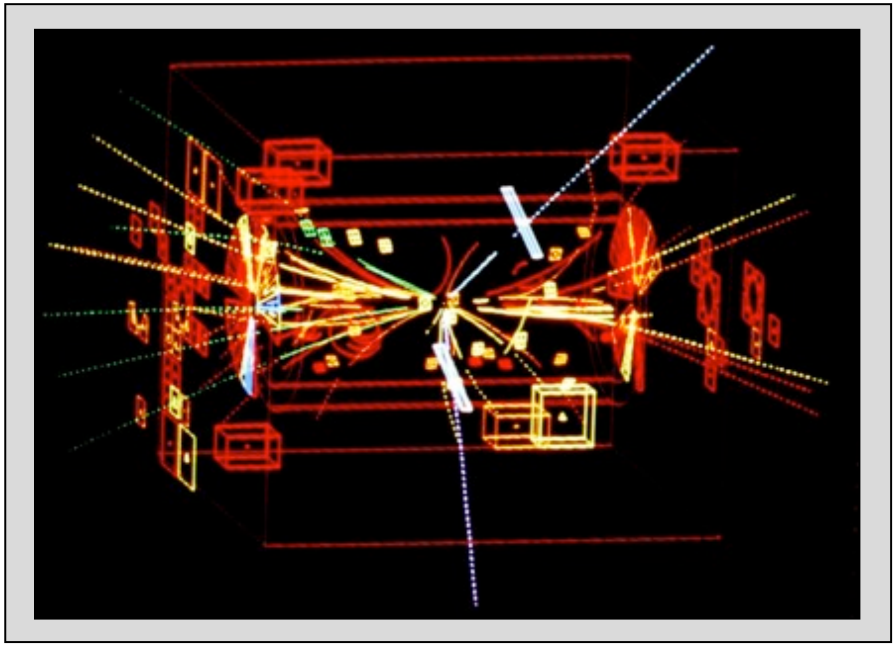
UA1 Detector

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

First Z^0 particle seen by UA1



Historical Development

Some relevant Nobel Prizes

1901	Physics	Wilhelm C. Röntgen	X-rays (1896) [Photographic plate]
1903	Physics	Antoine H. Becquerel Marie Curie Pierre Curie	Radioactivity (1896/99) [Photographic plate & electrometer]
1905	Physics	Philipp Lenard	Lenard window (1904) [Phosphorescent material]
1908	Chemistry	Ernest Rutherford	Atomic nucleus (1911) [Scintillating crystals]
1927	Physics	Charles T. R. Wilson	Cloud chamber (1912)
1935	Physics	James Chadwick	Neutron discovery (1932) [Ionization chamber]
1936	Physics	Victor F. Hess Carl D. Anderson	Cosmic rays (1912) Positron discovery (1932) [Electrometer & cloud chamber]

Historical Development

Some relevant Nobel Prizes

1948	Physics	Patrick M. S. Blackett	e^+e^- Production ... (1933) [Advanced cloud chambers]
1950	Physics	Cecil F. Powell	Pion discovery (1947) [Photographic emulsion]
1953	Physics	Walter Bothe	Coincidence method (1924)
1958	Physics	Pavel A. Cherenkov	Cherenkov effect (1934)
1959	Physics	Emilio G. Segrè Owen Chamberlain	Antiproton discovery (1955) [Spectrometer; Cherenkov counter ...]
1960	Physics	Donald A. Glaser	Bubble chamber (1953)
1976	Physics	Burton Richter Samuel C.C. Ting	J/ψ discovery (1974) [AGS Synchrotron; pBe collisions] [SLAC e^+e^- collider; MARK I]
1980	Physics	James Cronin Val Fitch	CP violation (1963) [Spark chamber; spectrometer]

Historical Development

Some relevant Nobel Prizes

1984	Physics	Carlo Rubbia, Simon Van der Meer	W/Z discovery (1983) [SPS; 4π multi-purpose detector]
1988	Physics	Leon M. Lederman Melvin Schwartz Jack Steinberger	Muon neutrino (1962) [Neutrino beam; spark chambers]
1990	Physics	Jerome I. Friedman Henry W. Kendall Richard E. Taylor	Proton structure (1972+) [ep scattering; spectrometer]
1989	Physics	Hans G. Dehmelt Wolfgang Paul	Electron g-2 (1986) [Ion trap technique]
1992	Physics	Georges Charpak	Multi-Wire Chamber (1968)
2002	Physics	Raymond Davis Jr. Masatoshi Koshiba	Cosmic neutrino (1986) [Large area neutrino detector]

To Backup

Applications

To Backup

Application 1

1/ Explain the difference between electrons and heavy ions when they interact with matter. Why the trajectory is different from the range in the case of electrons?

2/ Which effect arises when an electron beam is passing through an absorber?

3/ What is the critical energy for electrons in Pb (Z=82)? Are such electrons relativists?

4/ Below which energy the Bremsstrahlung is <5%? In order to have a good protection against relativist electrons, is it worth to use light or heavy materials?

5/ Calculate E_C for Carbon (Z=6). Calculate Bremsstrahlung ratio for 10 MeV electrons in carbone and compare with Pb. Then for 300 MeV.

Application 1

1/ Heavy ions: collisions with electrons (no deviation, distance depending on the energy and material) then atomic collisions at low energy. The trajectory is almost equal to the path in the matter.

Electrons: collisions with electrons (deviation, numerous collisions when energy decreasing). Atomic collisions (radiative losses) arise at high E. Due to the high number of deviations, the trajectory of electrons is larger than their range.

2/ Bremsstrahlung is the major effect to take into account (for radioprotection purposes for instance). It is proportional to E and Z^2.

3/ $$E_c^e = 800 \text{ MeV} / (82 + 1.2) = 9.62 \text{ MeV}$$

$$\text{E} = (\gamma - 1)\text{m}_0\text{c}^2 \;\Rightarrow\; \gamma = 19.8$$

$$\beta = v/c = \sqrt{1 - 1/\gamma^2} = 0.9987$$

4/ If r is the Bremsstrahlung ratio then r = [brem] / [brem+coll] and 1/r = 1+ [coll] / [brem] = 1+700/ZE

→ E = 449 keV

In any cases, it is better to minimize the Bremsstrahlung and so to use a low Z material.

5/ Z=6 so E_c = 111,1 MeV.

For 10 MeV electrons the Brem. ratio is 7.9% in carbone and 54% in lead.

For 300 MeV electrons the Brem. ratio is 72% in carbone and 97% in lead.

Application 2

1/ In water, what is the minimum kinetic energy for an electron to undergo a Cherenkov effect?

2/ Calculate this energy for a proton and an alpha.

Water index of refraction: n=4/3

$$m_0^e c^2 = 0,511 \text{ MeV}$$

$$m_0^p c^2 = 938,3 \text{ MeV}$$

$$m_0^n c^2 = 939,6 \text{ MeV}$$

Application 2

The velocity of the charged particle must be v > ¾ . c

Electron kinetic energy is:

$$T = mc^2 - m_0c^2 \quad \text{with} \quad m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

So E_e > 0,26 MeV ; E_p > 480 MeV ; E_α > 1,922 GeV

Application 3

Photons detection:

A gamma source is located behind an aluminium plate of 0.5 cm thickness and detected by a counter at a distance of 4 cm with an effective detection area of 5 cm^2.

The source is emitting 3700 photons/sec with an energy of 0,95 MeV.

For such photons, the mass attenuation coefficient of aluminium is 0,1 cm^2/g.

If the detection efficiency of the counter is 90%, calculate the number of counts per second in the detector.

Aluminium mass density: 2,7 g/cm3

Application 3

Number of photons detected is related to the solid angle fraction, the photons attenuation in the aluminium and the detection efficiency.

$$N = N_0 \times \frac{S_{eff}}{4\pi r^2} \times \exp(-\mu_m \rho x) \times efficiency$$

$$N = 3700 \times \frac{5}{4\pi 4^2} \times \exp(-0,1 \times 2,7 \times 0,5) \times 0,9 = 72,4 \quad \gamma \cdot s^{-1}$$

To Backup

Back

Energy loss for photons → three major physics mechanisms :

- Photo electric effect : absorption of a photon by an atom ejecting an electron

$$\sigma = Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma}\right)^n \quad n = 7/2 \text{ for } E \ll m_e c^2 \text{ and } \rightarrow 1 \text{ for } E \gg m_e c^2$$

Strong dependence with Z, dominant at low photon energy

- Compton scattering

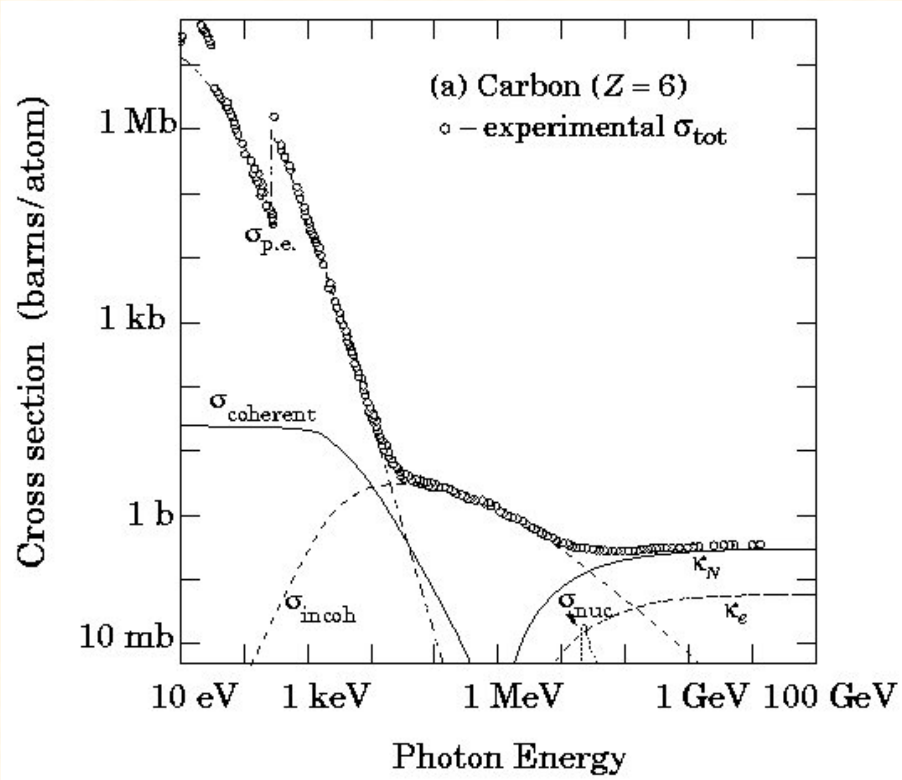
$$\sigma_C^e \propto \frac{\ln E_\gamma}{E_\gamma} \text{ and atomic compton} = Z\,\sigma_C^e$$

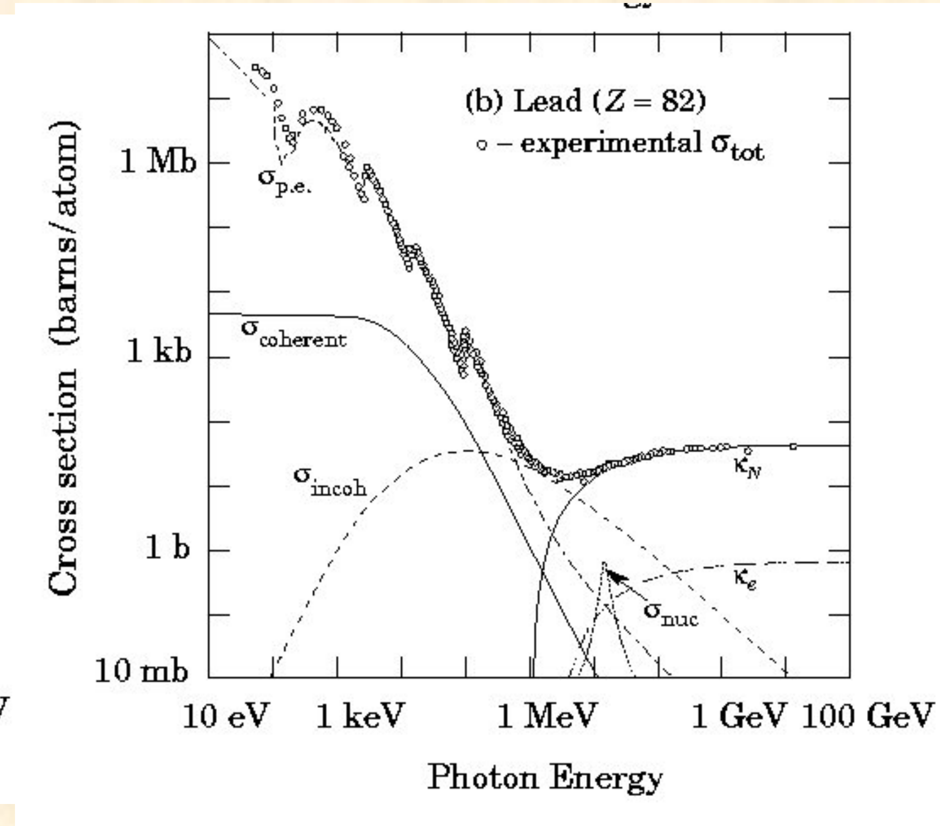
- Pair creation (similar to bremsstrahlung) : dominant for $E \gg m_e c^2$

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}}\right) = \frac{A}{N_A} \frac{7}{9} \frac{1}{X_0}$$

Independent of energy !

Probability of pair creation in 1 X_0 is $e^{-7/9}$, mean free path of a photon before creating a e^+e^- pair is $\Lambda_{pair} = 9/7\ X_0$





$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)

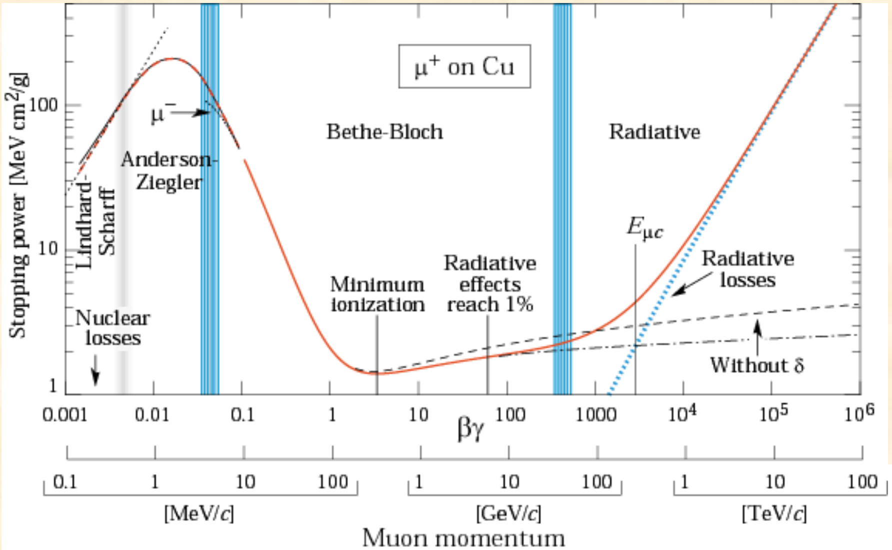
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited

σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

κ_{nuc} = Pair production, nuclear field

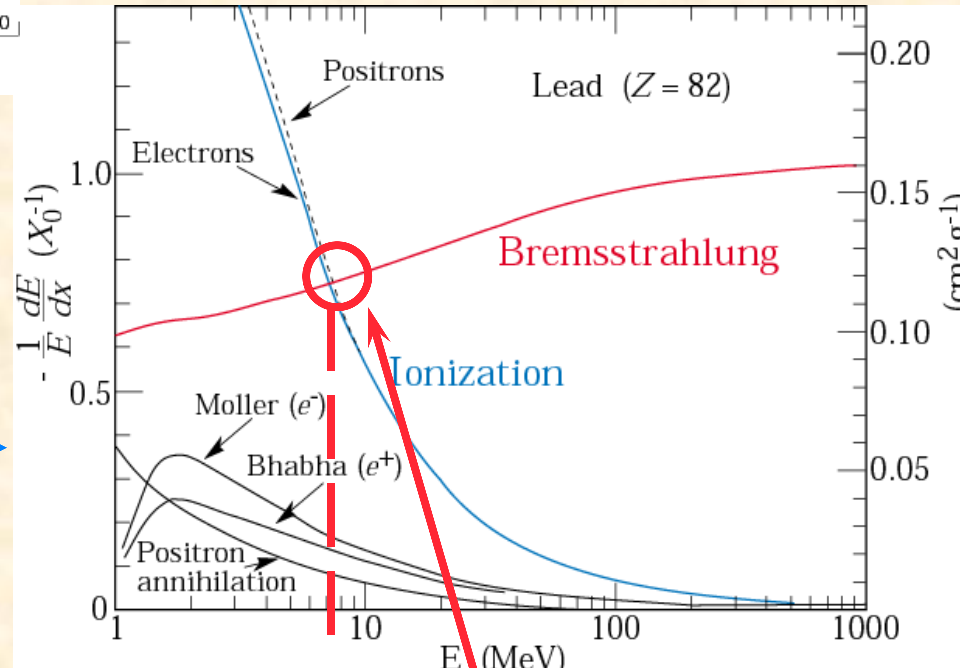
κ_e = Pair production, electron field

$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions



Bethe-Bloch for heavy particles

$$Stopping\ Power \equiv \frac{dE}{dx} \equiv E \cdot \rho \frac{1}{X_0}$$



E_c

Electron (positron) interaction with matter

Critical energy E_c
Ionization = Bremsstrahlung

Define Radiation Length X_0
as the Radiative Mean Path :
i.e. the distance over which the energy of electron/positron is reduced by a factor *e* by Bremsstrahlung.
Measured in units of [g/cm2]

Back

 Back

Energy (kinetic) loss by Coulomb interaction of charged particles with the atoms/electrons :

- Excitation : the atom (or molecule) is excited to a higher level

  atom* → atom + γ

  low energy photons of de-excitation

  → light detection

- Ionization : the electron is ejected from the atom

  electron / ion pair

  → charge detection

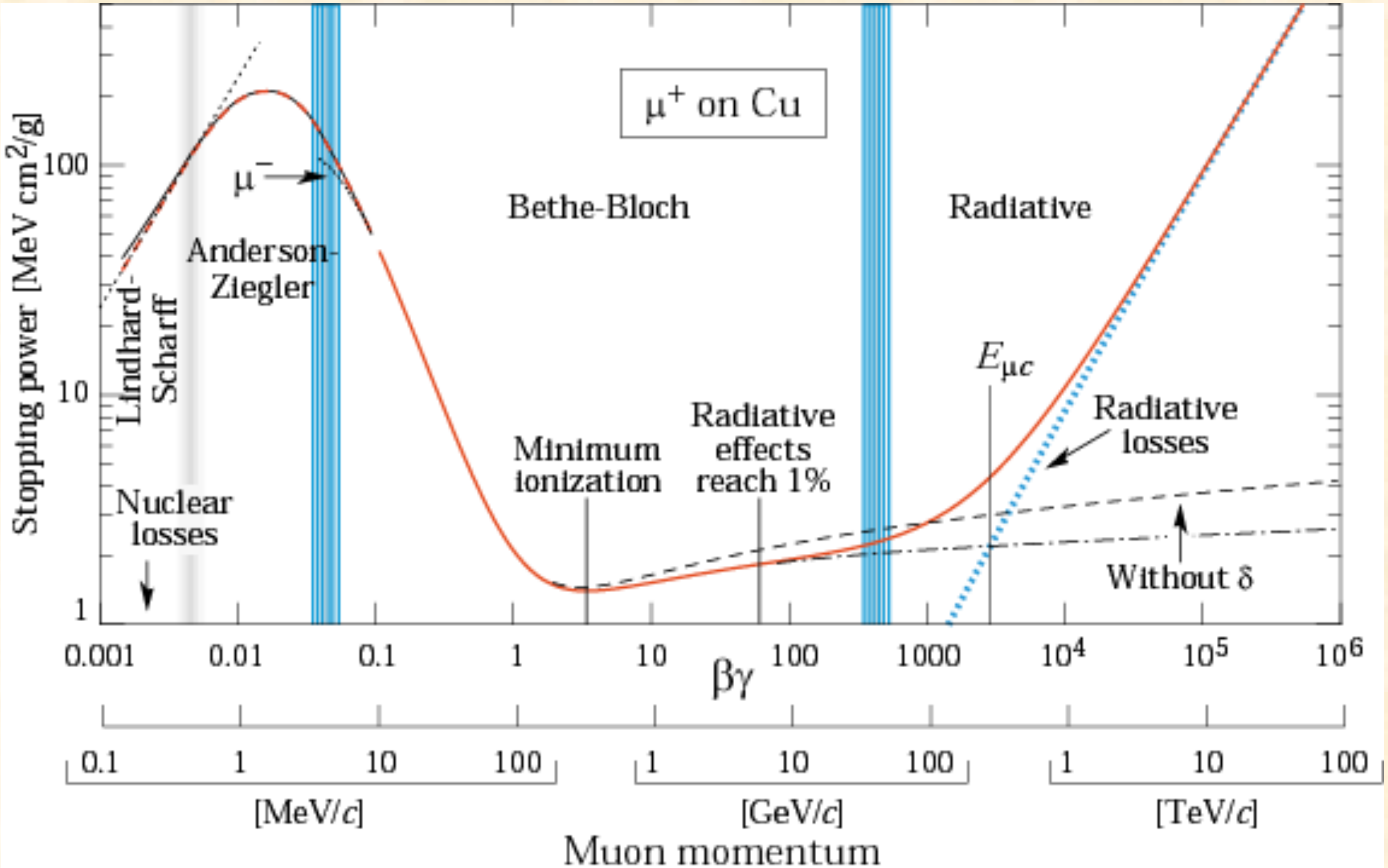
- Instead of ionization/excitation real photon can be produced under certain conditions

  → Cerenkov or Transition radiation

  Contribute very little to the energy loss (< 5%), can be neglected but they are used for particle ID

Bethe-Bloch:

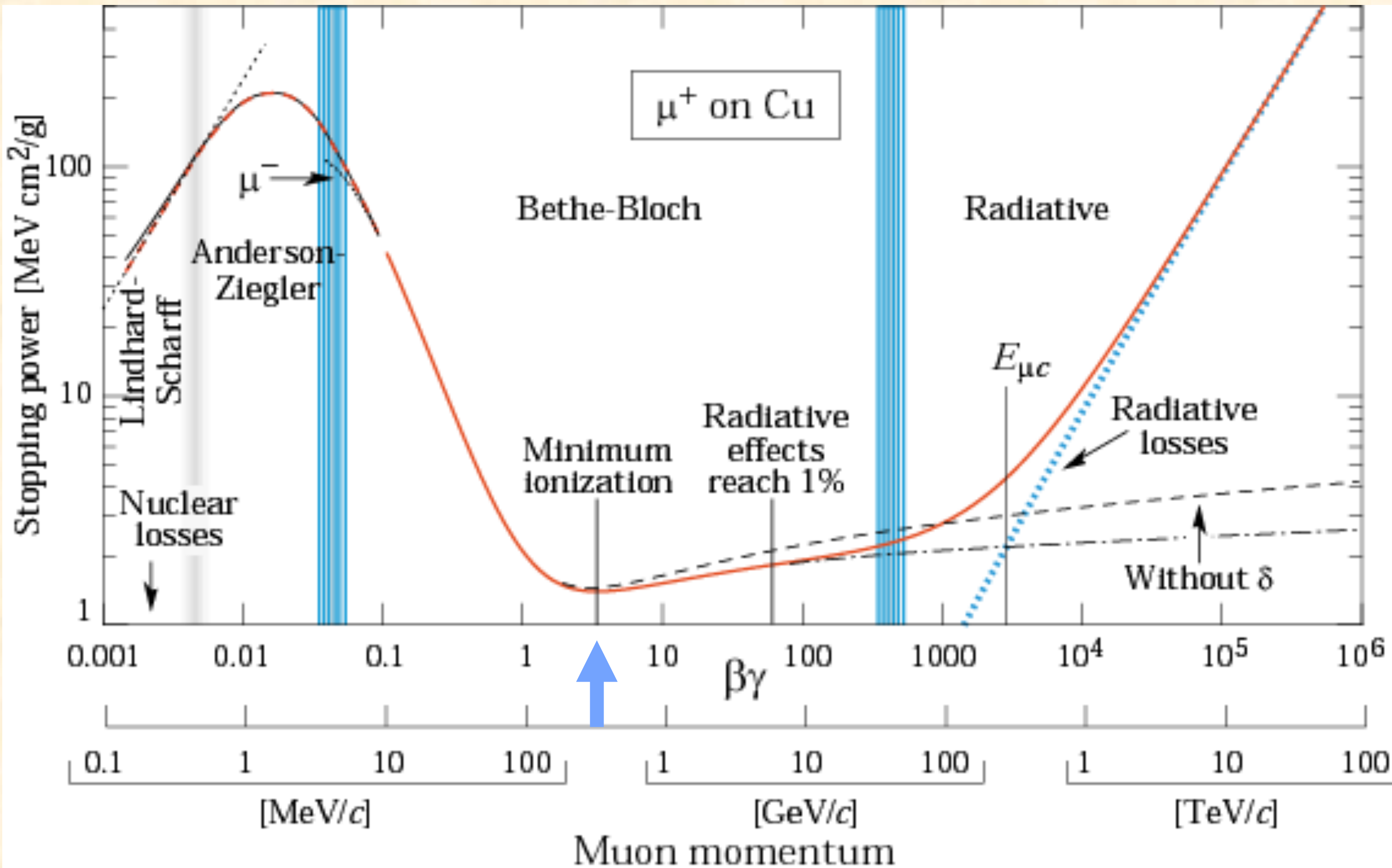
$$\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$



Stopping power (-<dE/dx>) for positive muons in copper as a function of **βγ** = *p/Mc* over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power.

Minimum Ionizing Particle :

- Minimum at βγ ~ 3 … 4
- Similar for all elements ~2 MeV/(g/cm2)



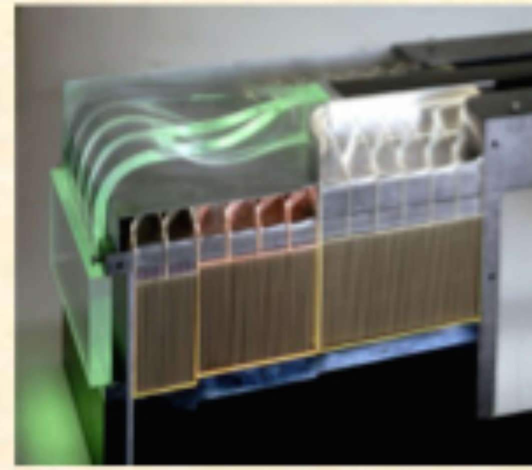
Back

Cherenkov radiation detectors

Unique tool to identify charged particles with a high separation power over a range of momentum from few hundred MeV/c up to several hundred GeV/c

A charged particle with velocity $\beta = v/c$ in a medium with refractive index $n = n(\lambda)$ may emit light along a conical wave front.

Radiator
+
Photon detector



The angle of emission is given by:

$$\cos\Theta_C = \frac{1}{\beta \cdot n}$$

$\cos\theta_{max} = 1/n$
$\beta_{min} = 1/n$

➔ Particle ID : Threshold (detect Cherenkov light) and Imaging (measure Cherenkov angle) techniques

➔ Fast particle counters, tracking detectors, performing complete event reconstruction,

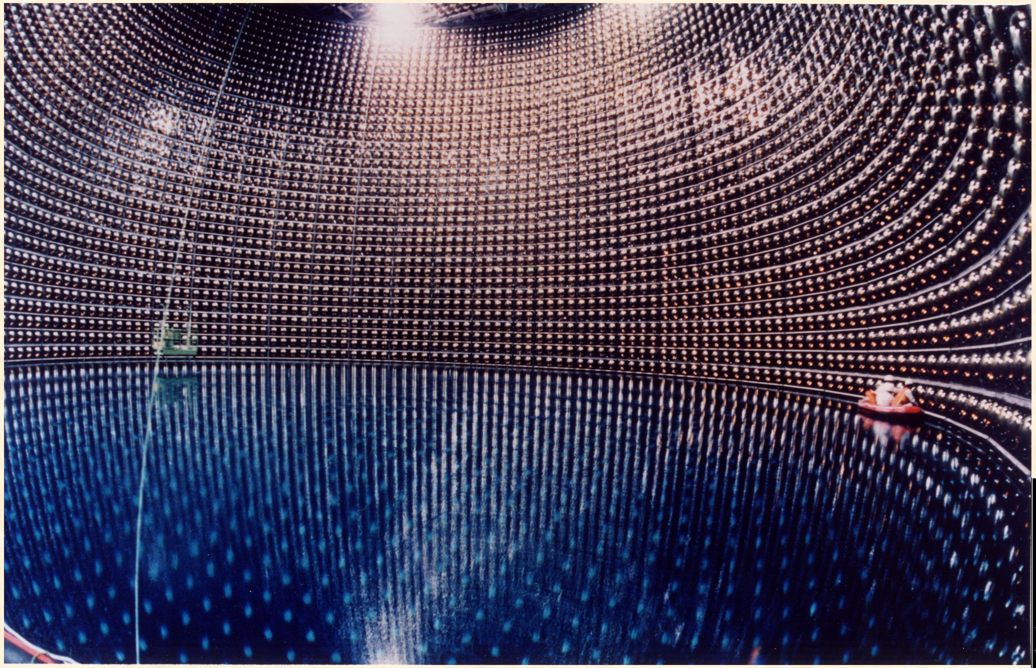
Neutrino detectors

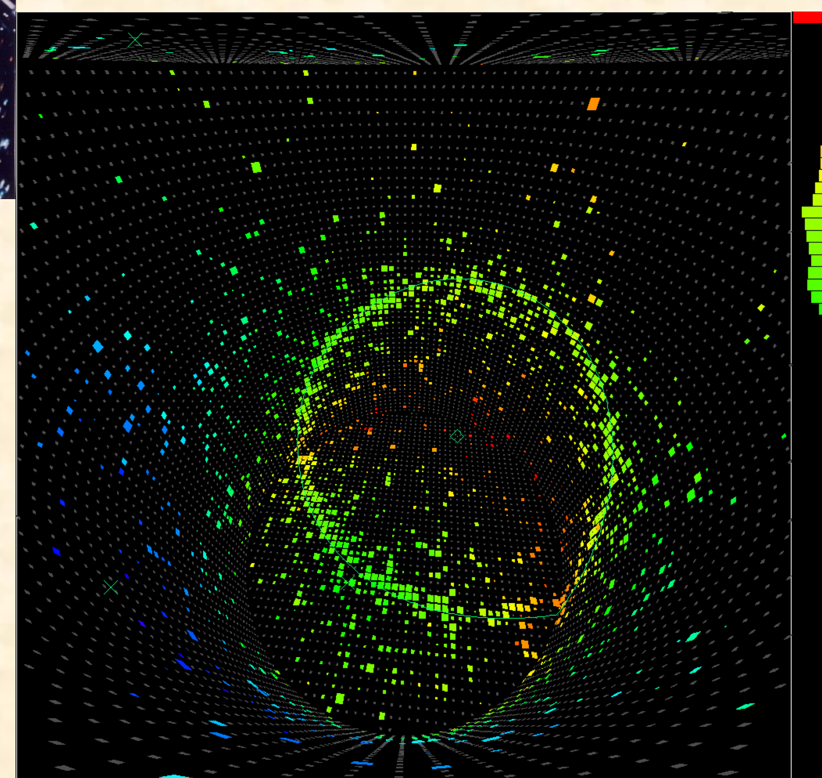
To Backup

Stopping power

- We have seen that to stop a 450 GeV muon beam one needs 900m of concrete.
- Muons interact mostly by electromagnetic interaction.
- Neutrino are neutral and interact only through the weak interaction
  => most of them will go through a 900m block of concrete without interacting (and even through the earth)!
- There is no detector capable of detecting all neutrinos from a beam.
  => we can only sample a fraction of the neutrinos passing through a detector

Super Kamiokande



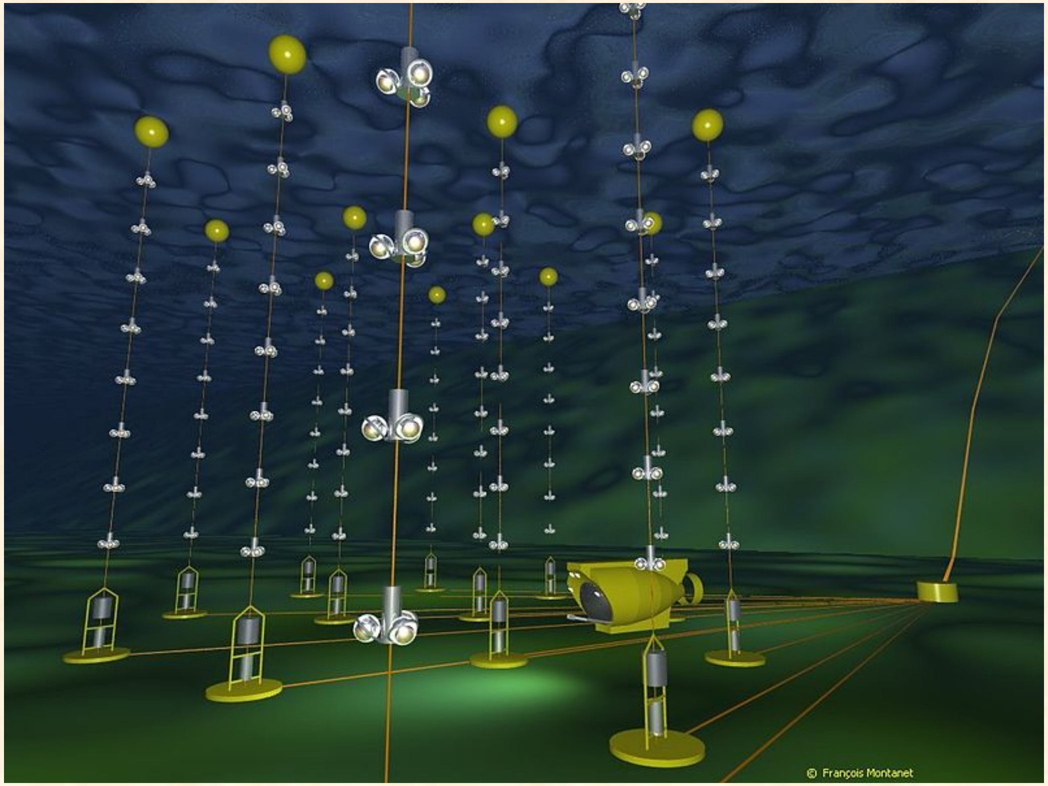


- One of the most successful neutrino observatory (Nobel prize 2002)
- 50 000 tonne of pure water
- Located under Mount Kamioka in Japan.

Sudbury Neutrino Observatory

- 1000 tonnes of heavy water.
- Located in Ontario, Canada
- Because heavy water contains a lot of neutrons, SNO is sensitive to both Neutral currents and charged currents
  => unique in the world.
  => Confirmed solar neutrinos oscillations

Antares / IceCube



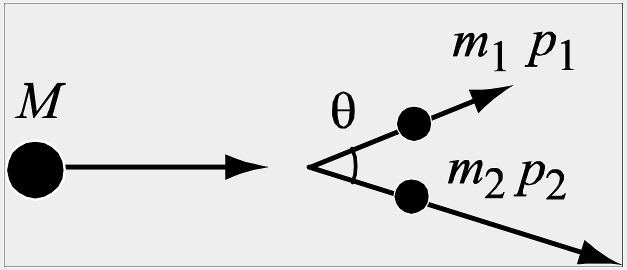
- Because neutrino are (almost) unaffected by matter, they may give a different picture of the Universe than photons or cosmic rays
  => Neutrino telescopes in sea, lake (Baikal) or ice!

To Backup

Invariant mass

- From relativistic kinematics, the relation between energy E, momentum p, and (rest) mass m is: $\mathbf{E^2 = p^2 + m^2}$

- Consider a particle that decays and gives two daughter particles:



- The invariant mass of the two particles from the decay:

$$M^2 = m_1^2 + m_2^2 + 2\,(E_1E_2 - p_1\,p_2\cos\theta\,)$$

→ to reconstruct the parent mass a precise knowledge of the momentum and the angle θ of decay products is needed, there are obtained :

- from the tracking system,
- and their particle type, which determines their masses m_1 and m_2

To Backup

Example: find Higgs boson via its decay :

$p + p \rightarrow H\ X \rightarrow\ Z^0\ Z^{0*}\ X \rightarrow\ e^+ e^-\ \mu^+ \mu^- X$

Compute (from the measured kinematics) :

$$m_H^2 = (E_{Z^0} + E_{Z^{0*}})^2 - (\vec{p}_{Z^0} + \vec{p}_{Z^{0*}})^2$$

Also for each Z^0 compute (e.g. for $Z^0 \rightarrow \mu^+ \mu^-$) :

$$m_{Z^0}^2 = (E_{\mu+} + E_{\mu-})^2 - (\vec{p}_{\mu+} + \vec{p}_{\mu-})^2$$

The same for the other Higgs decay mode : $H \rightarrow \gamma\gamma$

In all cases we have to reconstruct tracks (EM clusters for photons) and measure momenta, energies and idetify particles (charge and mass hypothesis).

Hadron Colliders: Kinematics

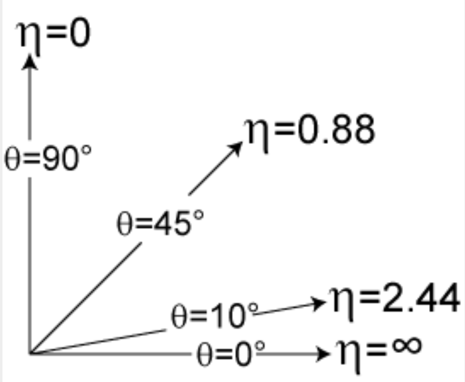
- Given the characteristics of the collisions lets define some useful variables
- **Transverse momentum, p_T (very useful)**
  - Particles that escape detection (θ<3°) have $p_T \approx 0$
  - Transverse momentum conserved imply $\sum p_{Ti} \approx 0$
  - **Longitudinal momentum and energy, p_z (not useful)**
- If particles that escape detection have large p_T
  - It imply that the visible $\sum p_{Ti}$ is not conserved
- **Polar angle, θ (very useful)**
  - Not Lorentz invariant
  - Rapidity: y

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

For m=0

$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

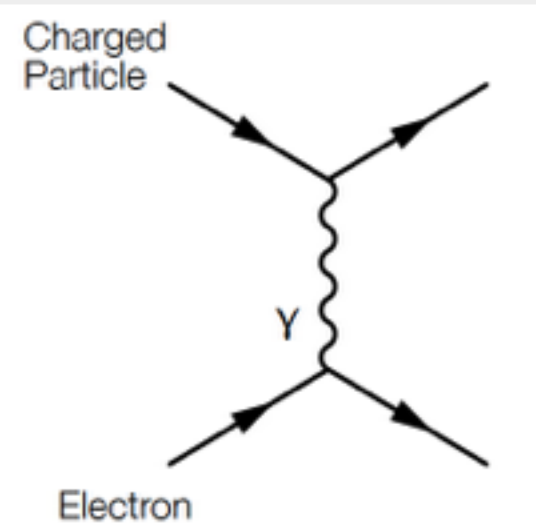
- Pseudorapidity: η

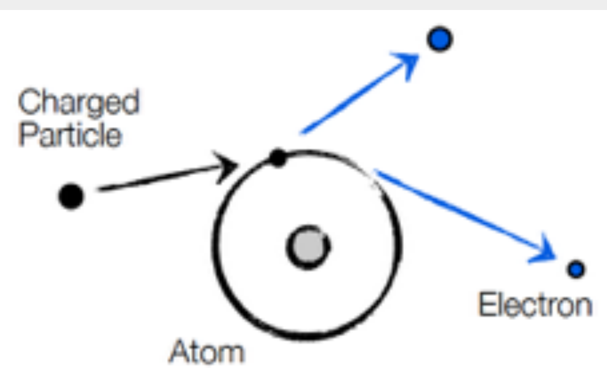


- **Azimuthal angle, φ (very useful)**
  - Well measured since detectors have complete coverage and are azimuthally symmetric at a given η

Example of particle interactions

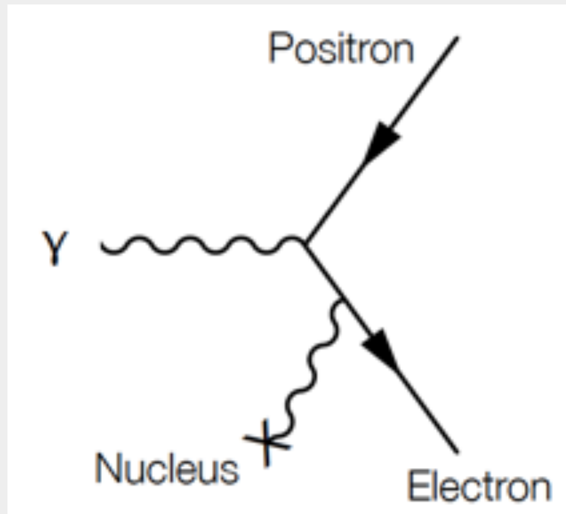
Ionization

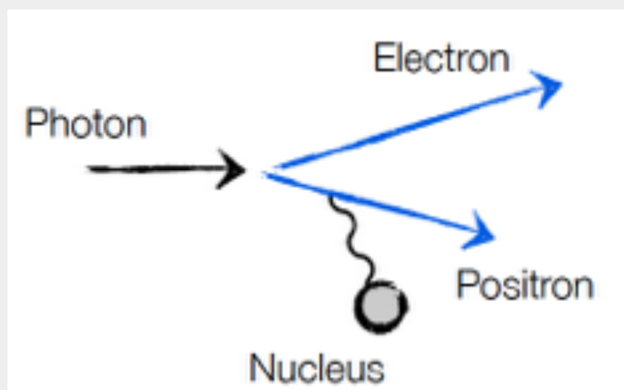




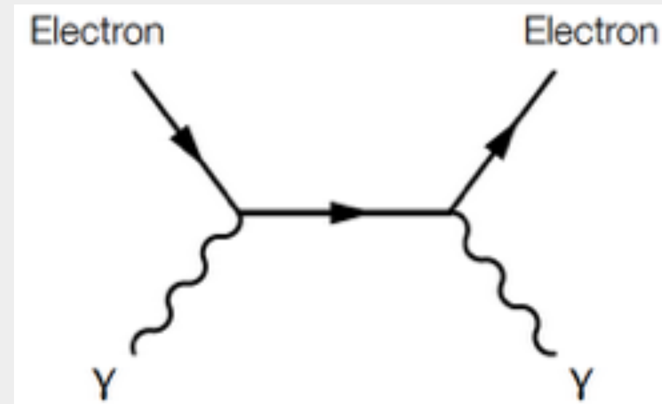
Delta-electrons

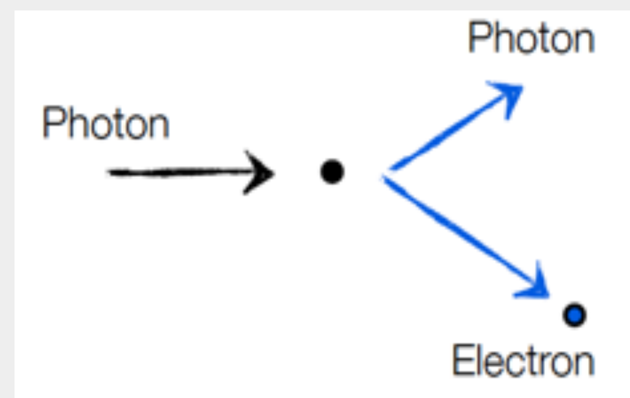
Pair production





Compton scattering





Detector Systems (I)

Non-destructive methods: charged particles

Gaseous detectors

Measure: hit and/or drift time
➔ Position resolution: ~ 50 μm
➔ Tracks reconstruction
+ Magnetic field
➔ Momentum

Measure: energy losses dE/dx
➔ Particle ID

Silicon detectors

Measure: hits and/or amplitude
➔ Position resolution: ~ 5 μm
➔ Tracks & **Vertices** reconstruction

Cherenkov detectors

Measure: Cherenkov photons
➔ Particle ID

Transition radiation detectors, …

To Backup

Detector Systems (II)

Destructive methods

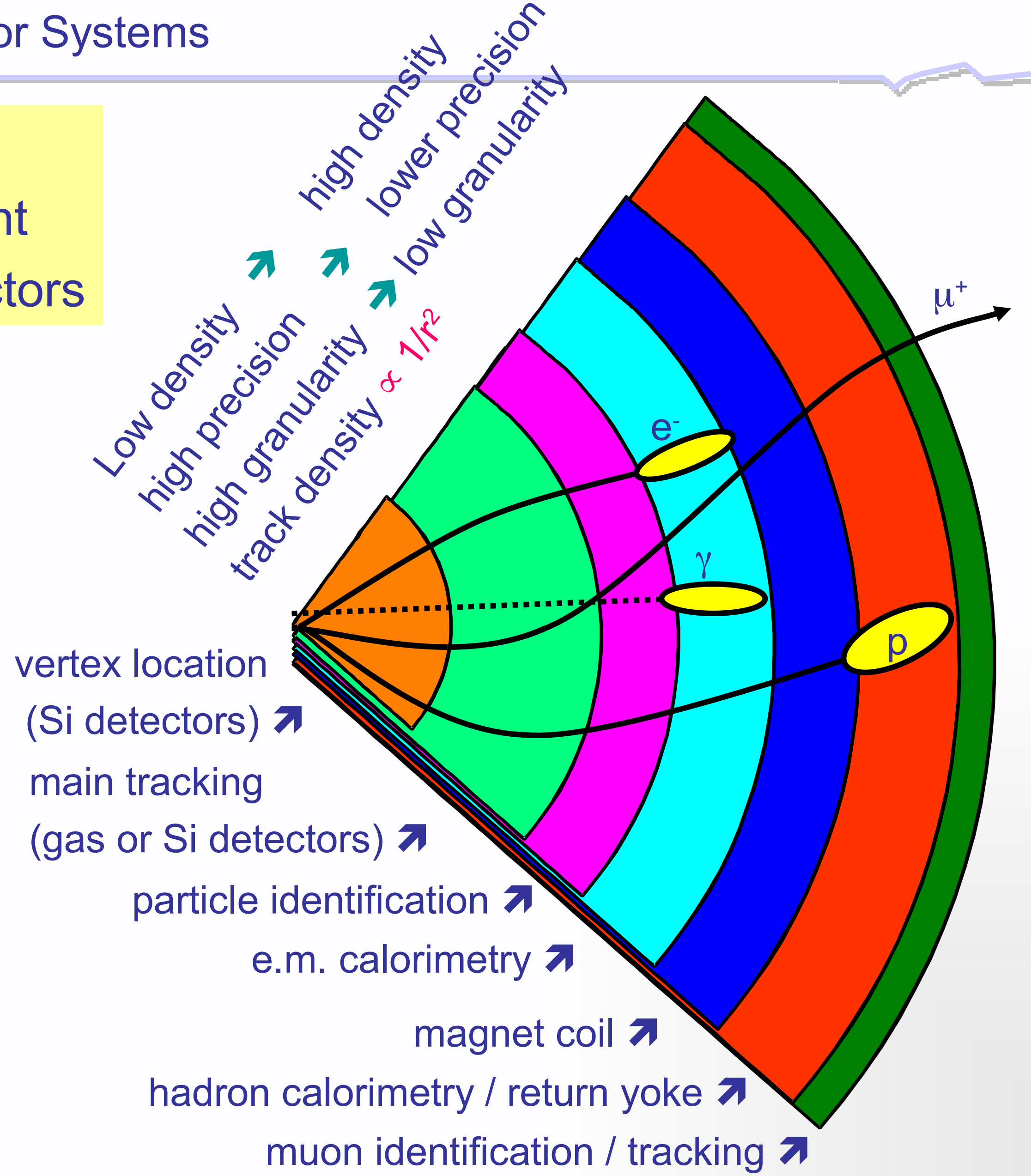
Calorimeters: electromagnetic and hadronic

Measure: shower energy and/or shower shape
➔ Energy resolution
➔ Position resolution: ~few mm
➔ Particle ID

Muon detectors

Measure: hits
➔ Muon track reconstruction after absorber
➔ Particle ID

Typical arrangement of subdetectors



ATLAS and CMS require high precision tracking also for high energetic muons → large muon systems with high spatial resolution behind calorimeters.

IN A P-P COLLISION