Accelerators and particle detectors

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Experimental lecture 28./29.9. 2015

Lectures of 28/29.9.

Click on YouTube CERN to see videos and extra documentaion

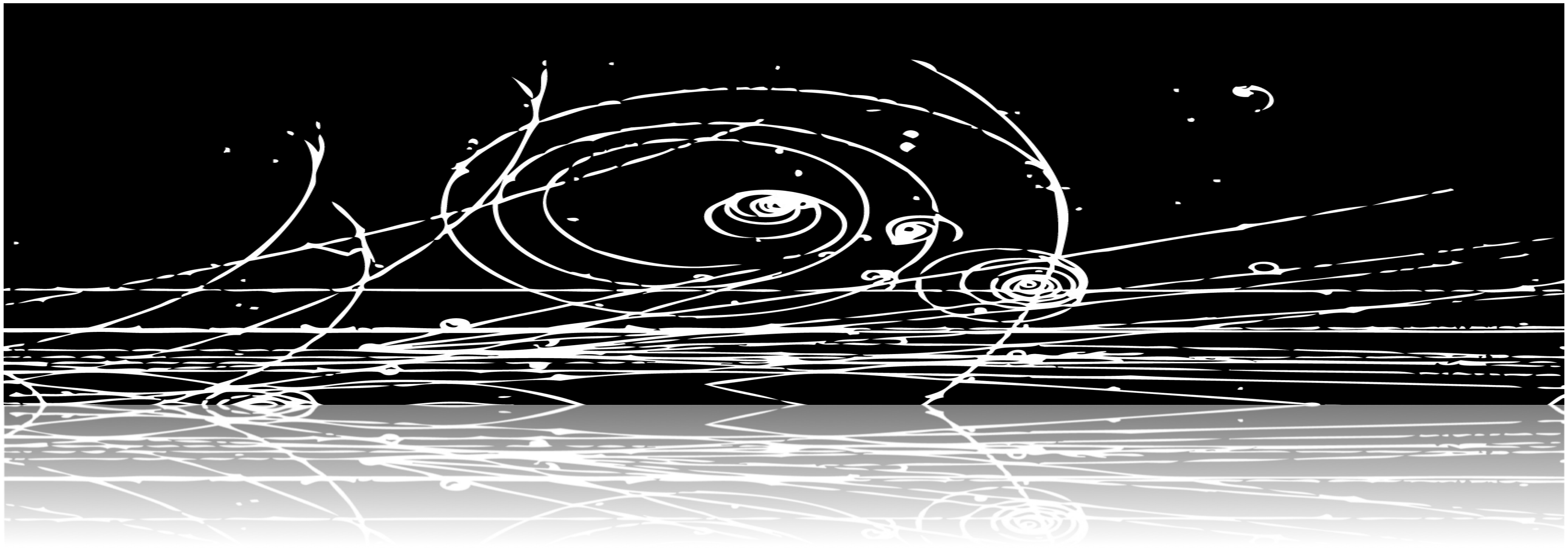
- Kinematics and concepts

- Introduction to particle accelerators
  - Overview on particle accelerators
  - Examples of fixed target and collider experiments
  - Basics on beam dynamics in accelerators
  - Some comments on the LHC machine
  - Important concepts: luminosity, cross sections …

- Introduction to particle detectors
  - Interaction of particles with matter
  - Basic building blocks of a particle physics experiment
  - Examples of detectors

- From detector to data to physics extraction

Particle Interactions with matter for Detection



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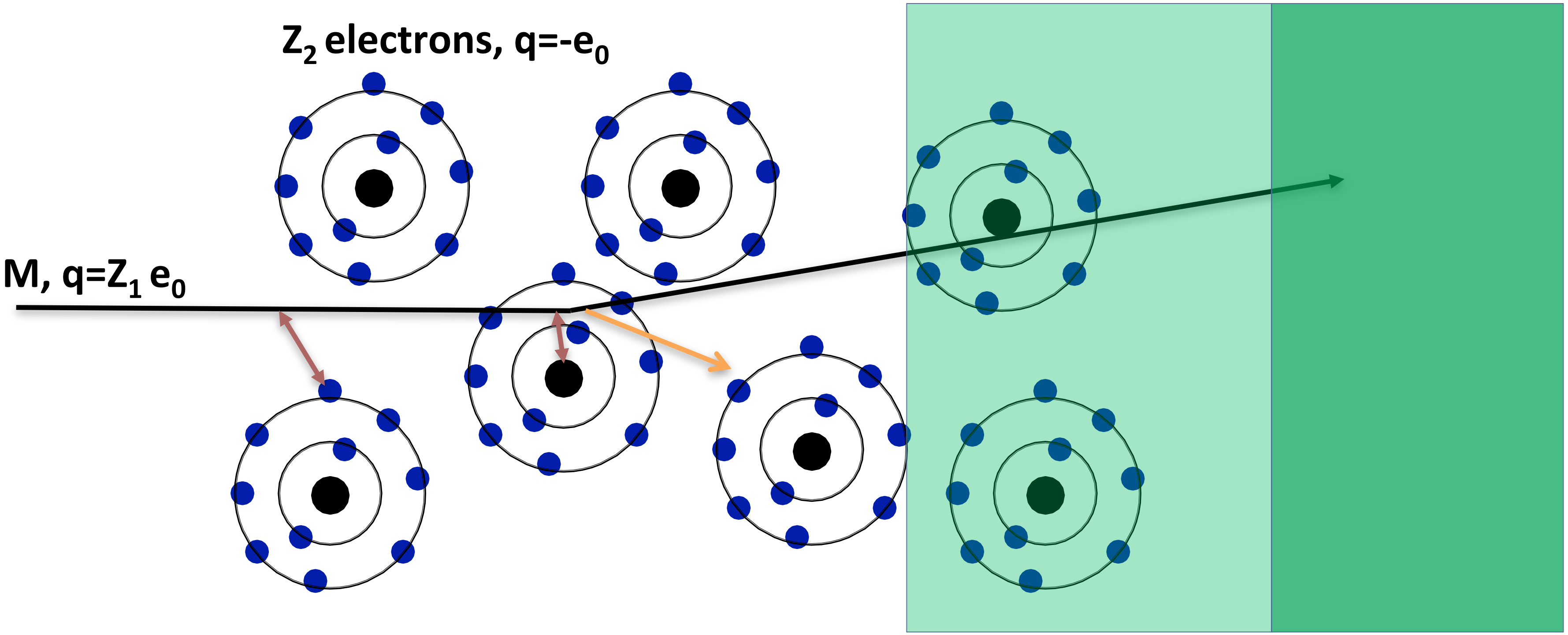
Detector physics

- Precise knowledge of the processes leading to signals in particle detectors is necessary.
- The detectors are nowadays working close to the limits of theoretically achievable measurement accuracy – even in large systems.
- Due to available computing power, detectors can be simulated to within 5-10% of reality, based on the fundamental microphysics processes (atomic and nuclear crossections).

Electromagnetic Interaction of Particles with Matter



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or **ionized**.

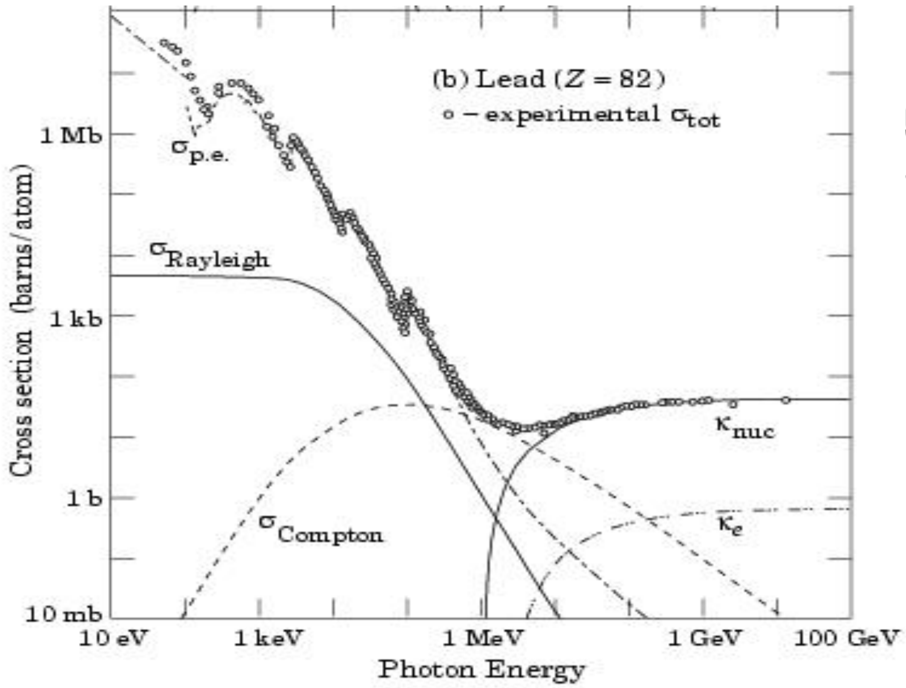
Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a **Bremsstrahlung** photon can be emitted.

Other: In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce an X ray photon, called Transition radiation.

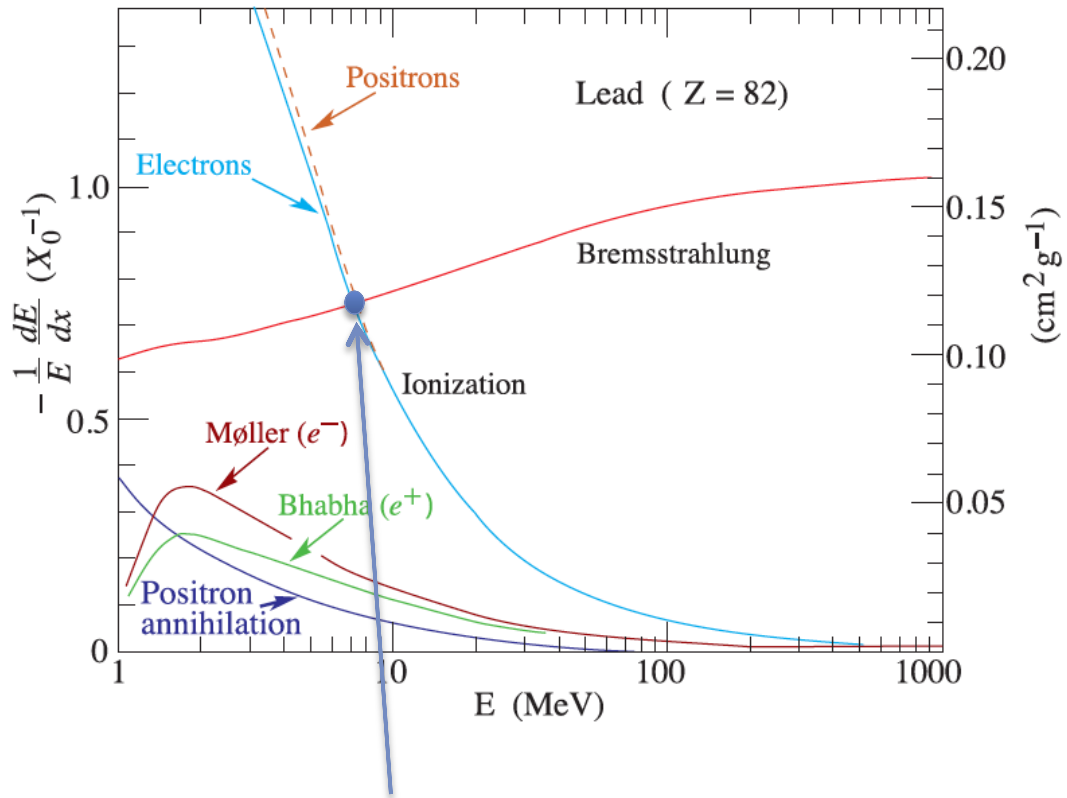
Interactions of Photons with matter

Photons

- Photo Effect
- Compton Scattering
- Pair production



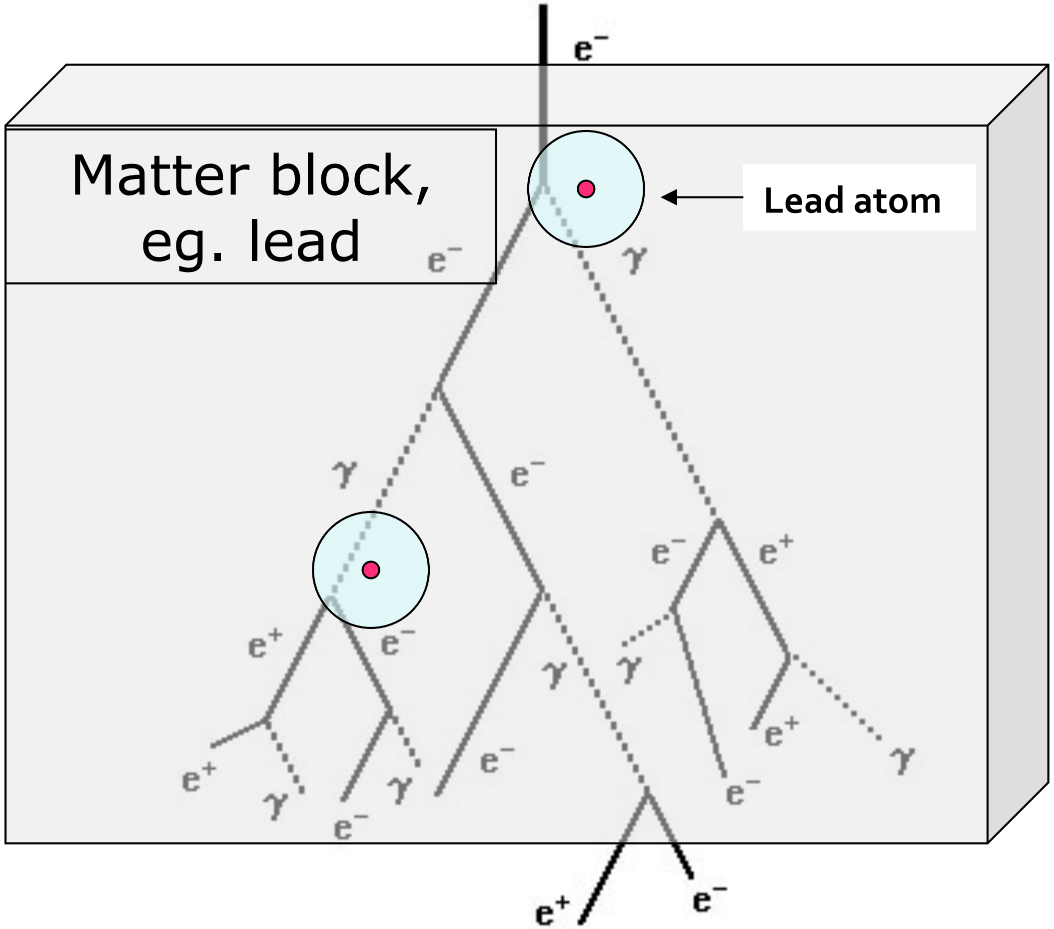
Fractional energy loss for e per X_o in lead



- At critical Energy E_c: $(dE/dx)_{ion}=(dE/dx)_{rad}$
  - Ec(electrons) ~ few MeV
  - Ec(muons) ~ 1 TeV!

Electromagnetic showers

- Interactions of electrons and photons with matter:



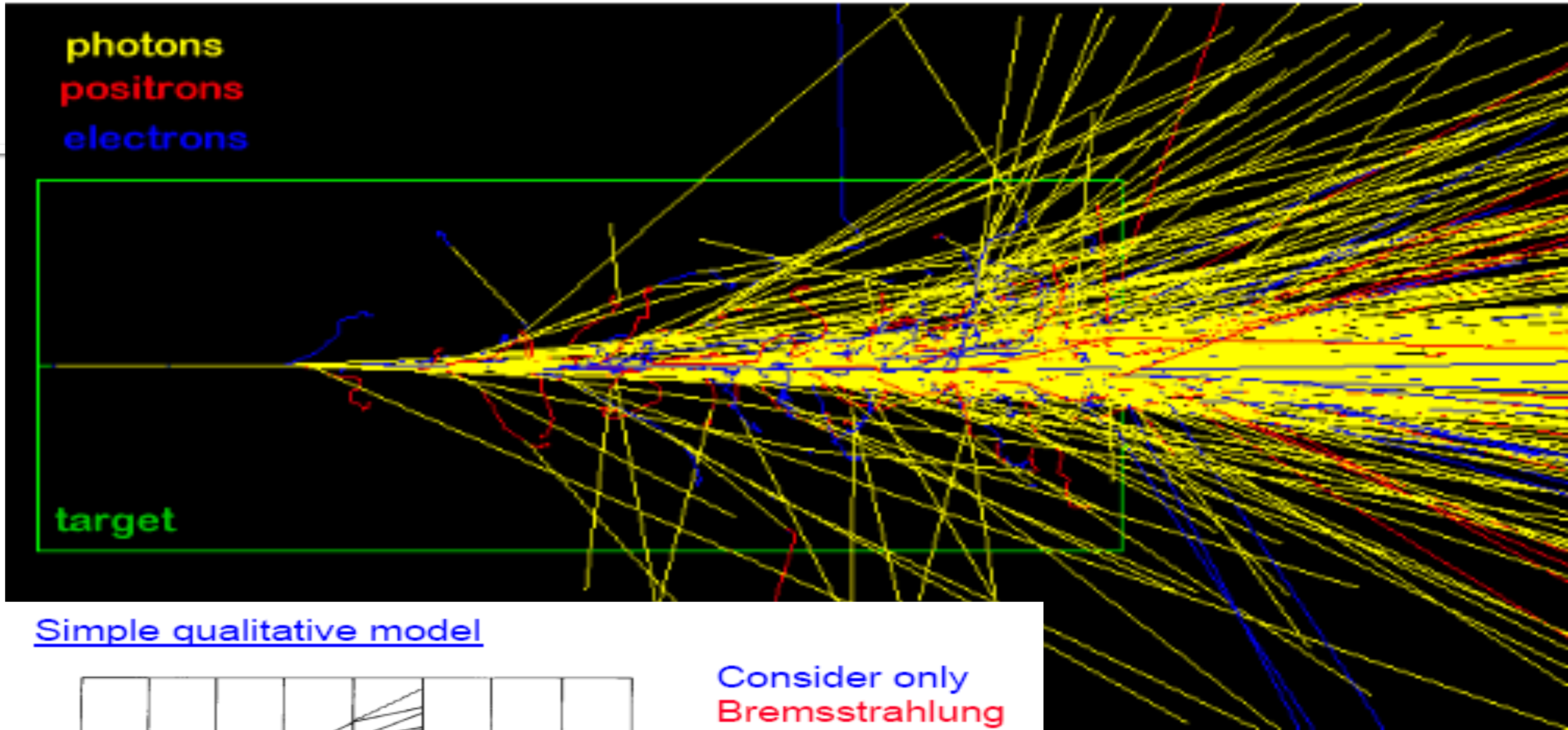
Shower partially or completely absorbed

Relevant quantities are
a) Radiation length X_0
b) Moliere Radius R_M

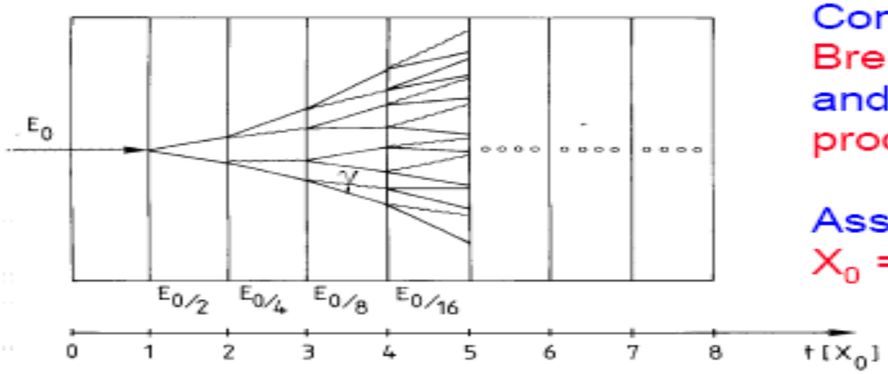
Xo = radiation length = material thickness, within which an electron has (1/e) E energy left (loses (1-1/e) of energy)

Molière Radius R_M
= radius which contains about 90% of the initial energy E_o

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.



Simple qualitative model



$N(t) = 2^t \qquad E(t)\,/\,particle = E_0 \cdot 2^{-t}$

Process continues until $E(t) < E_c$

Consider only Bremsstrahlung and pair production.

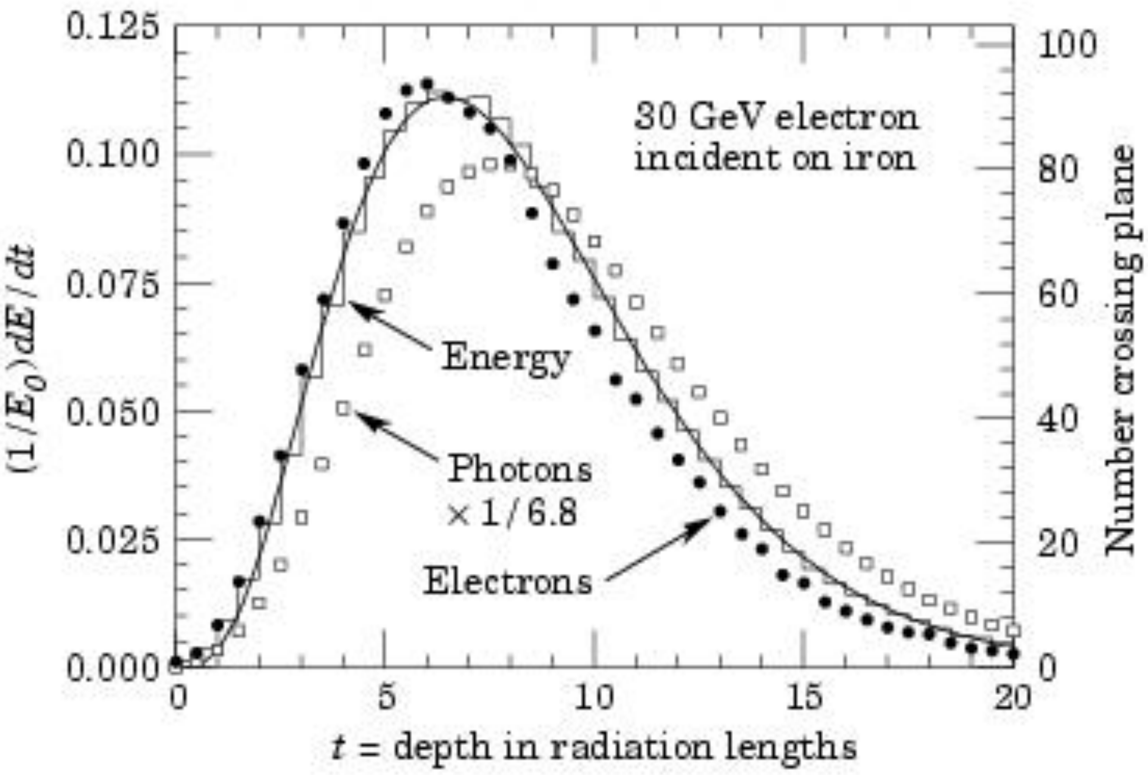
Assume: $X_0 = \lambda_{pair}$

t=depth in X_o

Bremsstrahlung and pair production

→ **electromagnetic shower**

Electromagnetic shower quantities



Shower long. depth $t = x / X_0$

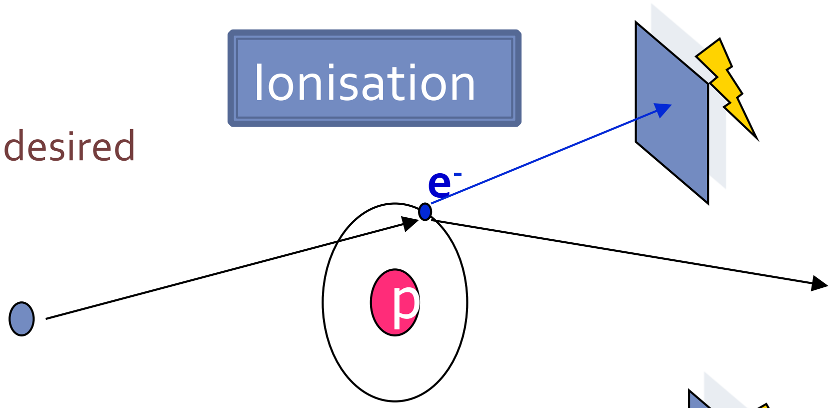
Xo = radiation length = material thickness, within which an electron loses (1-1/e) of energy, ie. has (1/e) E energy left.

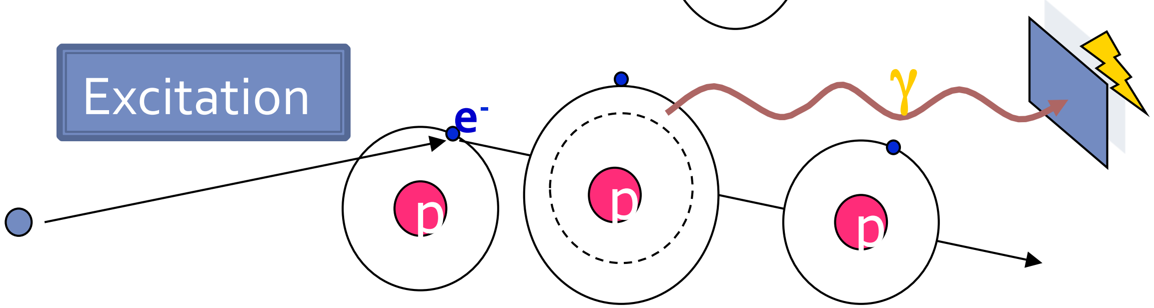
Molière Radius R_M = radius which contains about 90% of the initial energy E_o

- Longitudinal depth in terms of radiation length
- Transverse thickness: characterised by the Molière Radius R_M

Interactions of charged particles with matter

- **Charged Particles**
  - **Scattering** (at atoms, electrons, etc.) -- highly undesired
  - **Ionization** (Kick-off an electron from an atom)
  - **Excitation**: excite electron to higher orbit
    ➔ fall back ➔ light emission
    - (e.g. scintillation)
  - ➔ Ionisation and excitation in intermediate range are described by Bethe-Bloch formula

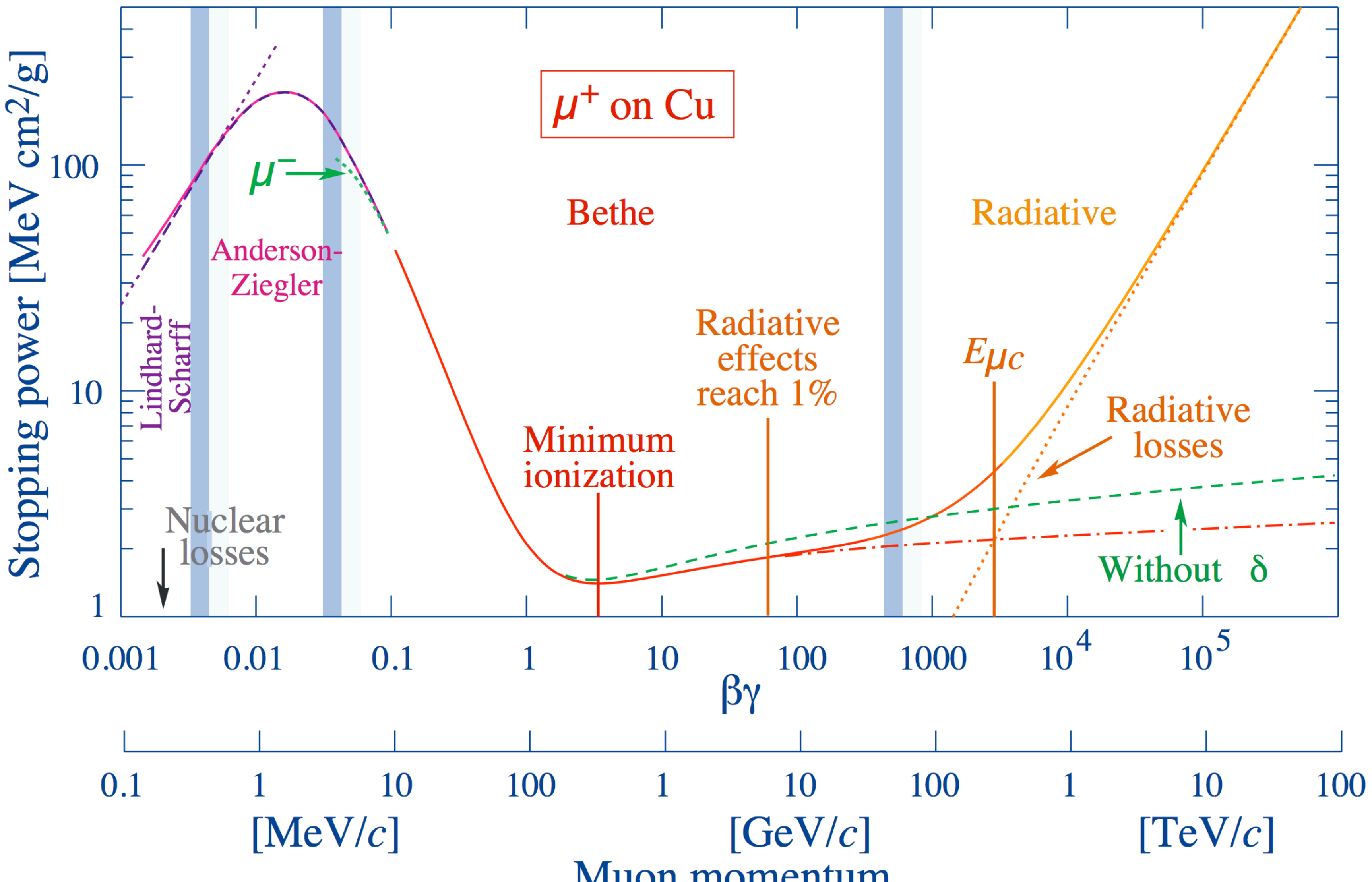




- Charged particles also produce **photon radiation**
  - Bremsstrahlung (accelerated charge emits photons)
  - Transition radiation Δn
  - Cherenkov light (faster than light in a medium)

Stopping power in matter

See: http://pdg.lbl.gov/2014/reviews/rpp2014-rev-passage-particles-matter.pdf

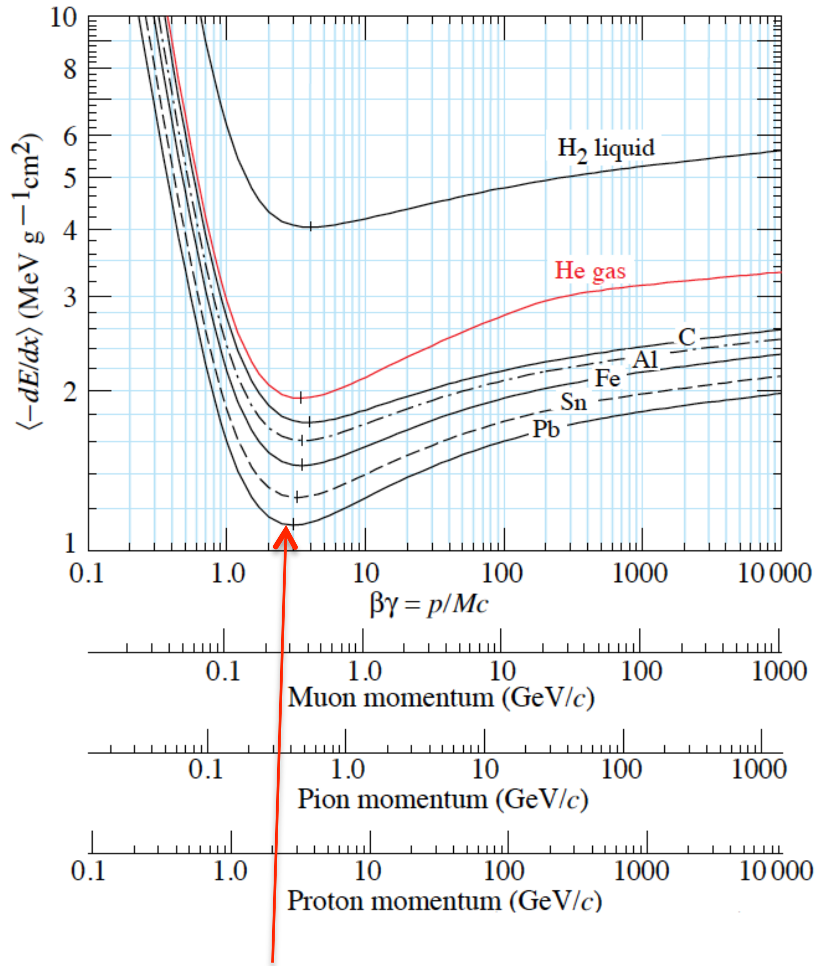


(dx=ρdl density weighted length)

Fig. 32.1: Stopping power $(= \langle -dE/dx \rangle)$ for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic

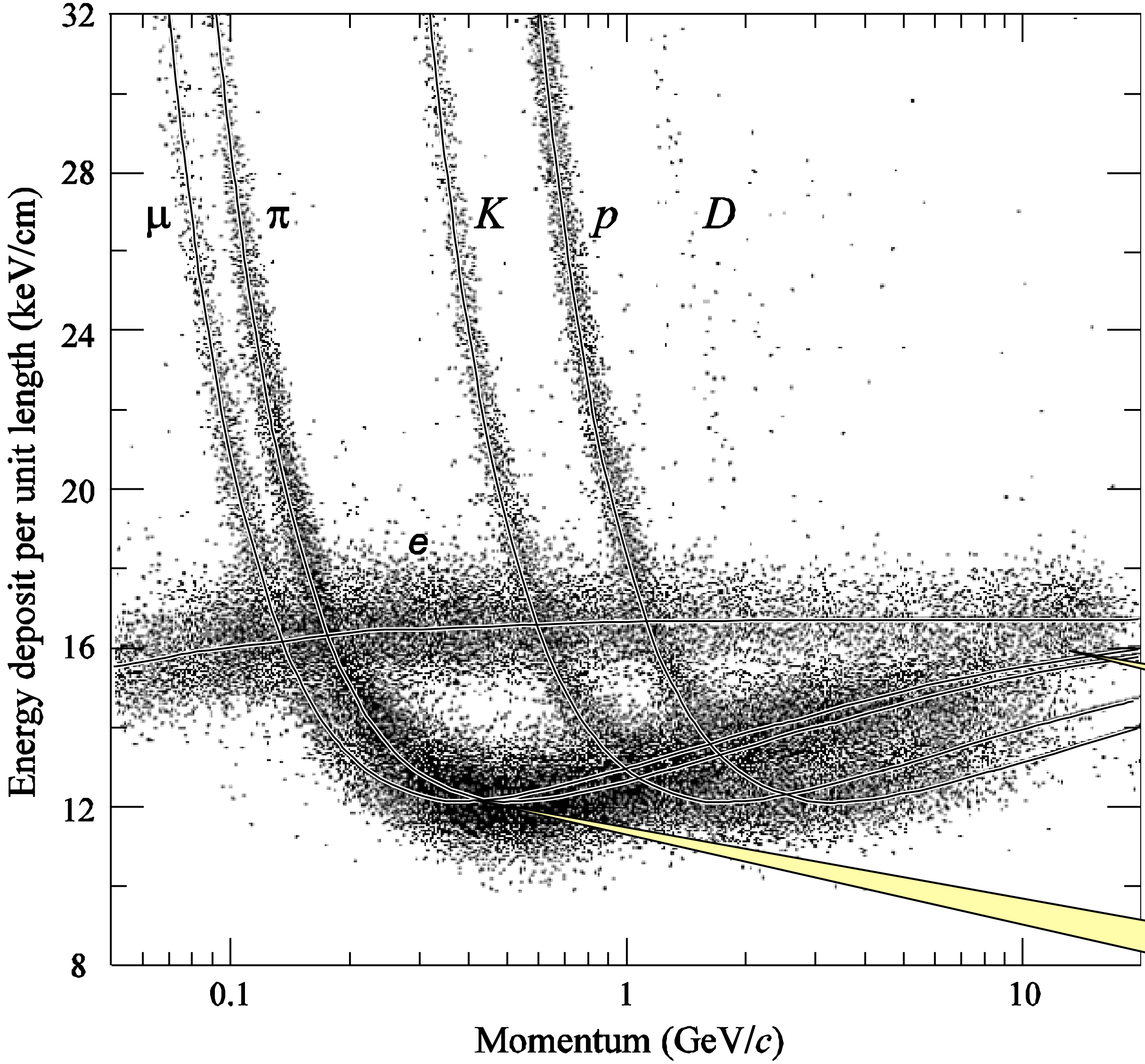
Ionization: Bethe-Bloch formula

- dE/dx: energy loss of heavy charged particles due to ionization and excitation (dx=ρdl density weighted length)
- Independent of M
- Depends on βγ
  - β<<1 dE/dx ~ $1/\beta^2$
  - β>~1 dE/dx ~ ln(βγ)
- Minimum dE/dx at βγ = 3.4 ; minimum Ionizing Particle (MIP)
  - Loses about 1.2 MeV/ (g/cm²)



$$-\left(\frac{dE}{dx}\right)_{coll} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z z^2}{A \beta^2} \cdot \left[\ln\left(\frac{2m_e c^2 \gamma^2 \beta^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

Mean energy loss: Bethe-Bloch



$\langle E_{lost} \rangle$ / path length = function of (velocity)

Use it for particle ID.

$$\left(\frac{dE}{dx}\right) : \frac{1}{\beta^2}\ln(\beta^2\gamma^2)$$

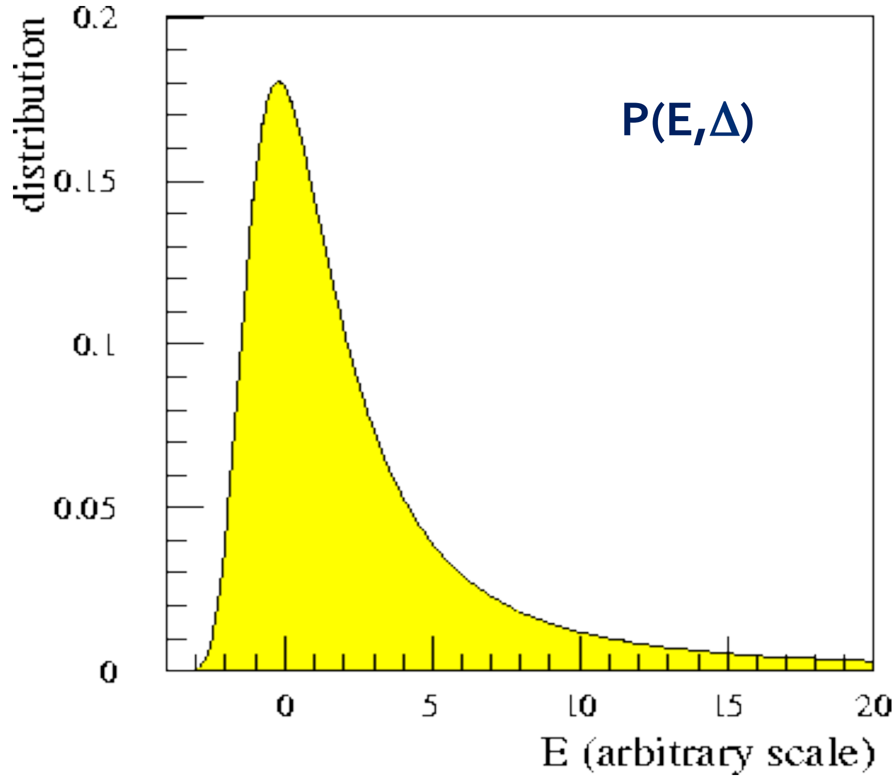
relativistic rise

MIP= minimum ionizing particle

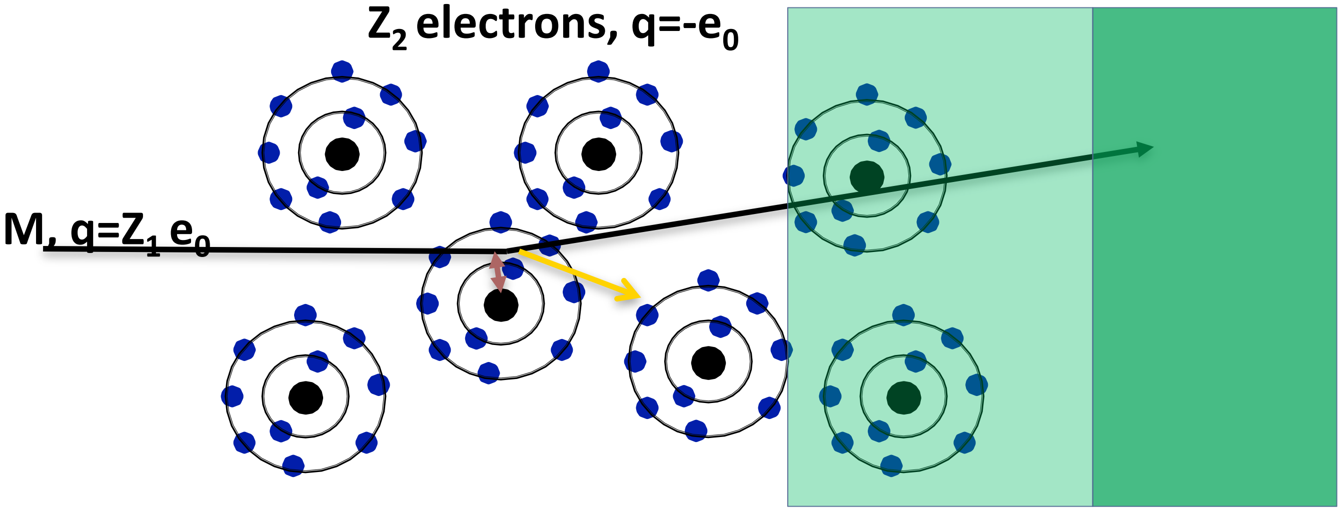
Note : if plotted vs **v** and **not p,** all bands would lie on top of each other!

Fluctuations of the Energy Loss

- P(Δ): Probability for energy loss Δ in matter of thickness D, is given by a Landau distribution.
- Landau distribution is very asymmetric.
- Average and most probable energy loss must be distinguished !
- Measured Energy Loss is usually smaller that the real energy loss:



Particles radiate: Bremsstrahlung

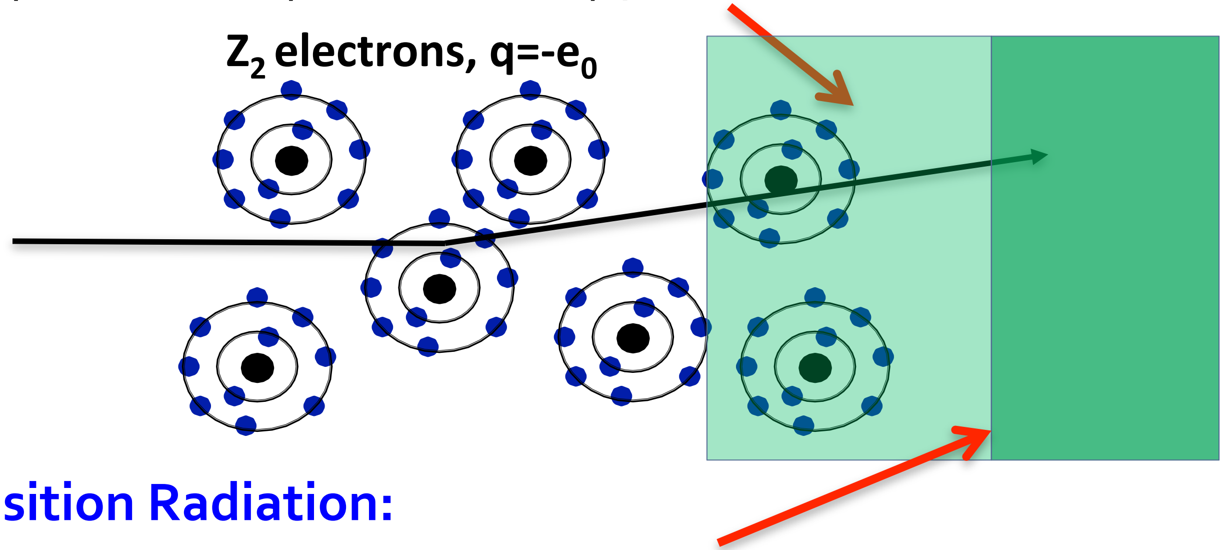


- A charged particle of mass M and charge q=Z1e is deflected by a nucleus of charge Ze which is partially 'shielded' by the electrons. During this deflection the charge is 'accelerated' and it therefore radiated → Bremsstrahlung.

$$\boxed{-\left(\frac{dE}{dx}\right)_{Brems,Q} = 4\pi \cdot N_A z^2 \frac{Z^2}{A} \ln \frac{183}{Z^{1/3}} r_m^2 \cdot E}$$

Interactions of particles

- **Cherenkov Radiation:**
  - If a particle propagates in a material with a velocity larger than the speed of light in this material, Cherenkov radiation is emitted at a characteristic angle θ_c that depends on the particle velocity β and the refractive index n of the material.



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

- **Transition Radiation:**
  - If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is about 1% probability for emission of an X-ray photon; energy for photon from vacuum to medium with plasma frequency ω_p is:

$$\boxed{I = \alpha z^2 \gamma \hbar \omega_p / 3}$$

Interactions with matter

- **Hadronic Interaction:** Strong force
  - Charged and neutral hadrons scatter inelastic (nuclear Interaction) + 20% elastic scattering
  - Nuclei fragment and the charged fragments are recorded → hadronic shower

$$\lambda_{abs} \approx 35 \frac{g}{cm^2} A^{1/3}$$

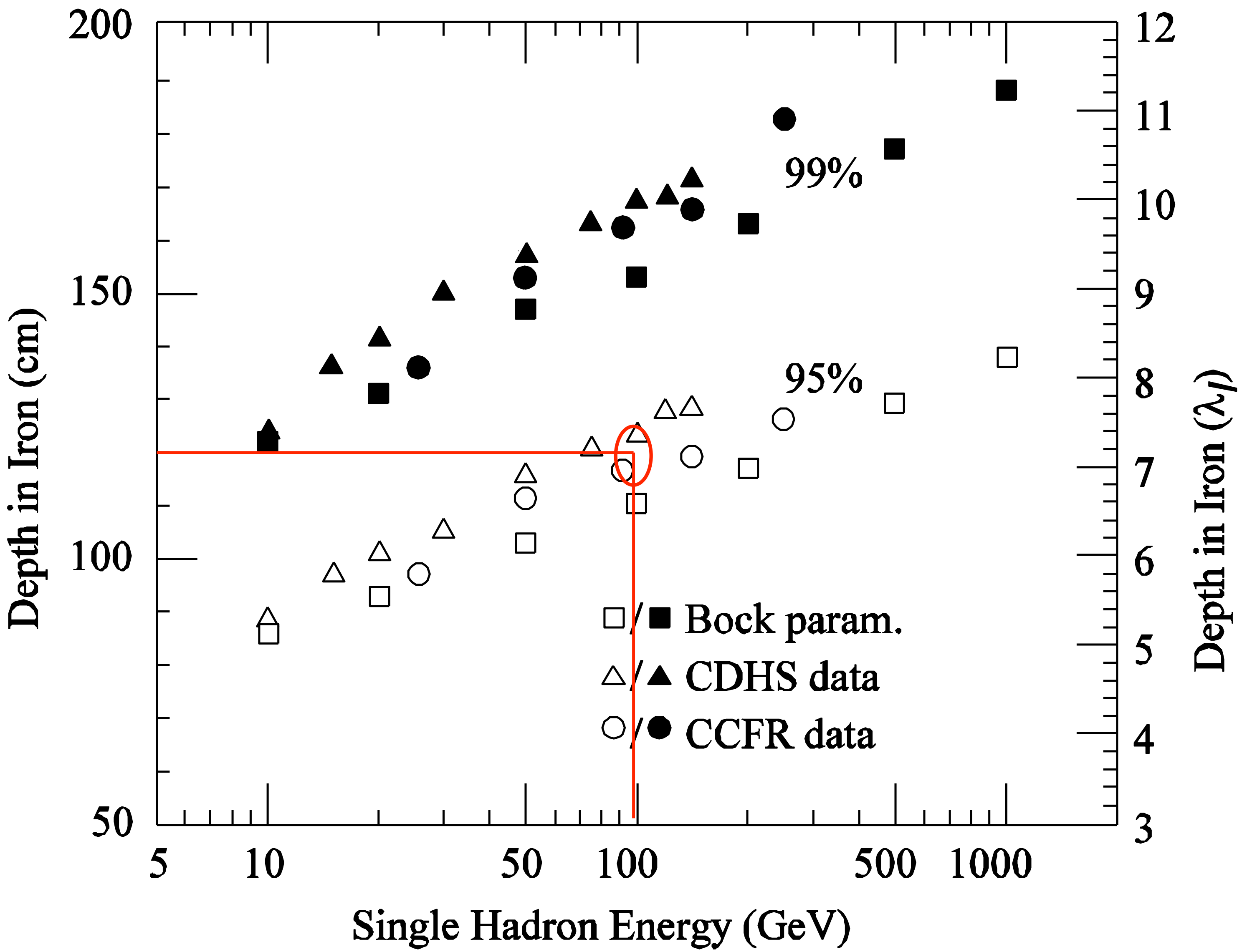
- Characteristics of hadronic showers:
- longitudinal development is governed by absorption cross sections, characterised by the (E-dependent) nuclear absorption length λ_{abs}
- some energy is LOST and needs to be compensated for (by SW or HW)
- ~half of E is transferred to further, fast hadrons (often large pT)
- some of E produces π_o, which produce electromagnetic showers

- Hadronic showers deposit less E/length than ECAL
- HCAL usually is a larger detector (or "denser" materials…)

- longitudinal shower profile : 95% of energy is absorbed after ~ 7.6 λ_{abs}
- transverse shower profile:
  centre contains the fast particles and some 95% of the energy (R_{95}) is contained within one λ_{abs}.

HCAL: thickness for E-containment

How much material needed to absorb % of incident energy?



To absorb a
100 GeV proton
(95% E)

→ need 1.2 m
thick iron block

Interactions with matter

- **Neutrinos**
  - Nearly „NO“ interaction in in HEP detectors at colliders
  - Signature: Missing Energy

νN - cross section (from RPP14)

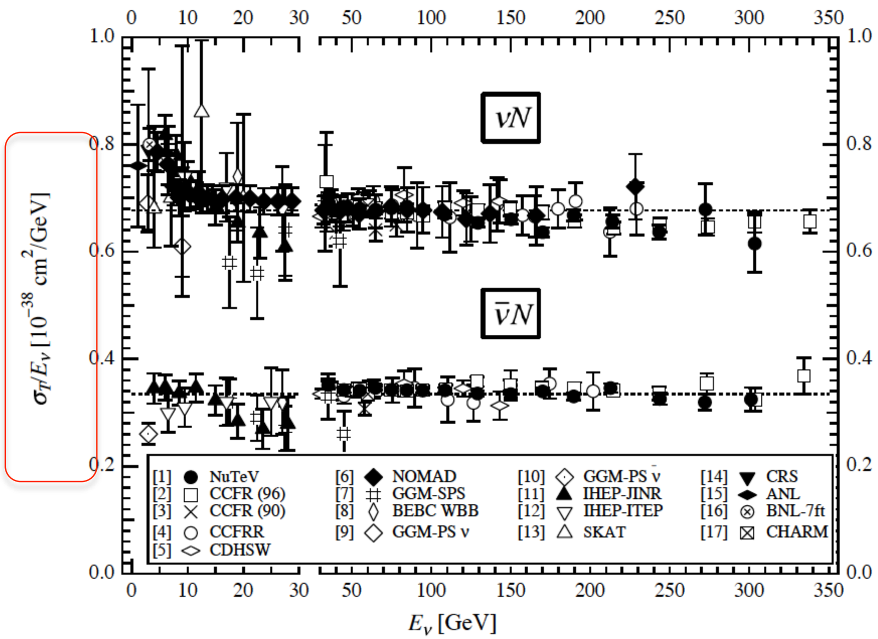
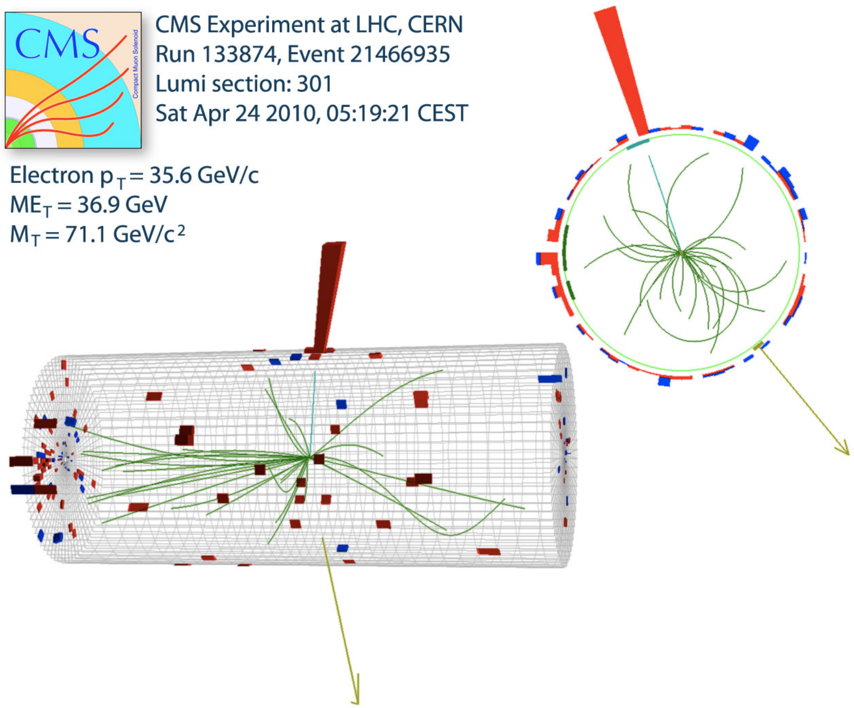


Figure 41.9: σ_T/E_ν for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the isoscalar-corrected total cross-section values averaged over 30-200 *GeV* as measured by the experiments in Refs. [3–5]: $\sigma^{\nu\,Iso}/E_\nu = (0.677 \pm 0.014) \times 10^{-38}\mathrm{cm}^2/\mathrm{GeV}$; $\sigma^{\bar{\nu}\,Iso}/E_{\bar{\nu}} = (0.334 \pm 0.008) \times 10^{-38}\mathrm{cm}^2/\mathrm{GeV}$. The average ratio of the anti-neutrino to neutrino cross section in the energy range 30-200 GeV is $\sigma^{\bar{\nu}\,Iso}/\sigma^{\nu\,Iso} = 0.504 \pm 0.003$ as measured by Refs. [1–5]. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2010)

W→ e ν + missing E



Energy loss by multiple scattering

Charged particles traversing matter are repeatedly scattered (mostly) by

- the Coulomb field of nuclei and electrons (imp. for **low-E)**.
- strong interaction scattering contributes also for heavy hadrons.
  - mean scattering angle is 0 (it's a random statistical process)
  - Distribution of scattering angles is described by Moliere's theory.

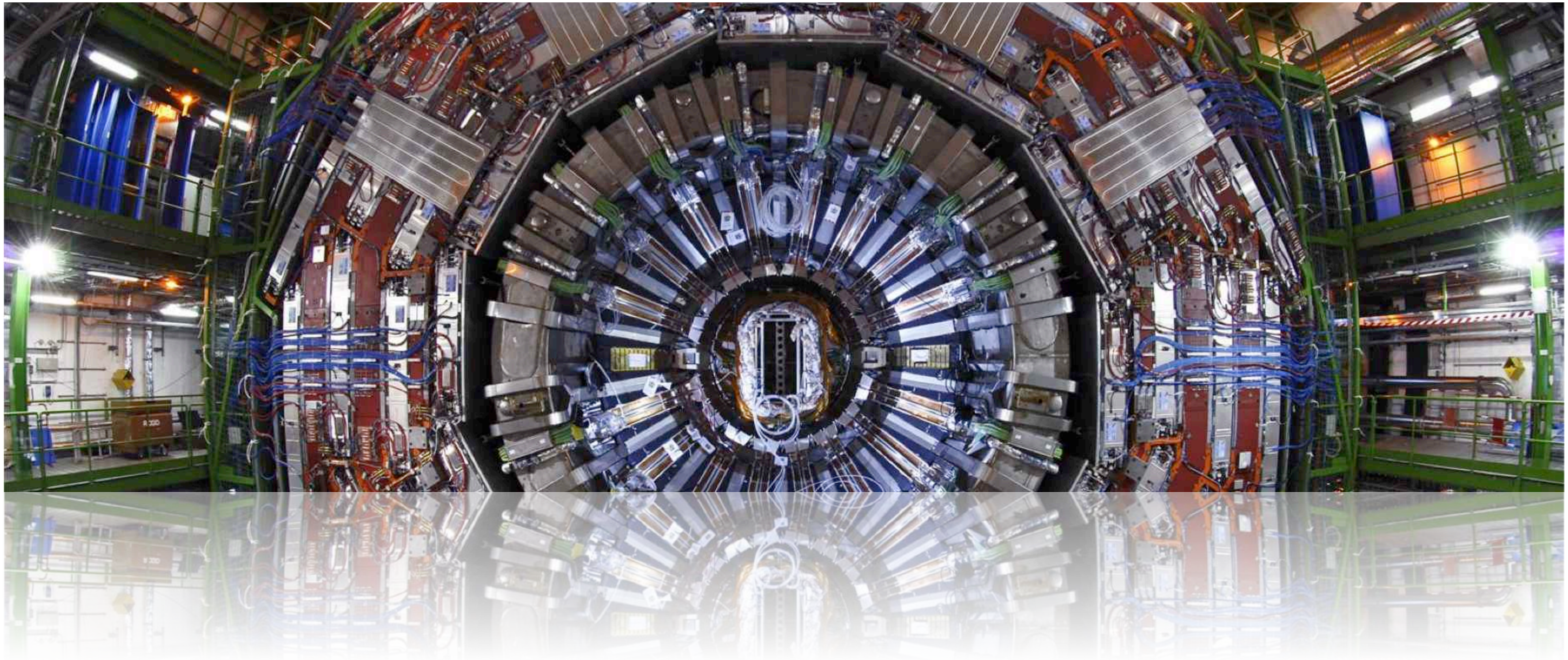
  - For small angles, it is ~Gaussian distributed (a bit wider) of width:

$$\boxed{\Theta_{rms}^{proj} \approx \frac{13.6\ MeV}{\beta c p} \cdot z_p \cdot \sqrt{\frac{x}{X_0}}}$$

X .. thickness
Xo ... Radiation length of the material
z_p ... Charge of the particle
p ... Momentum of the particle

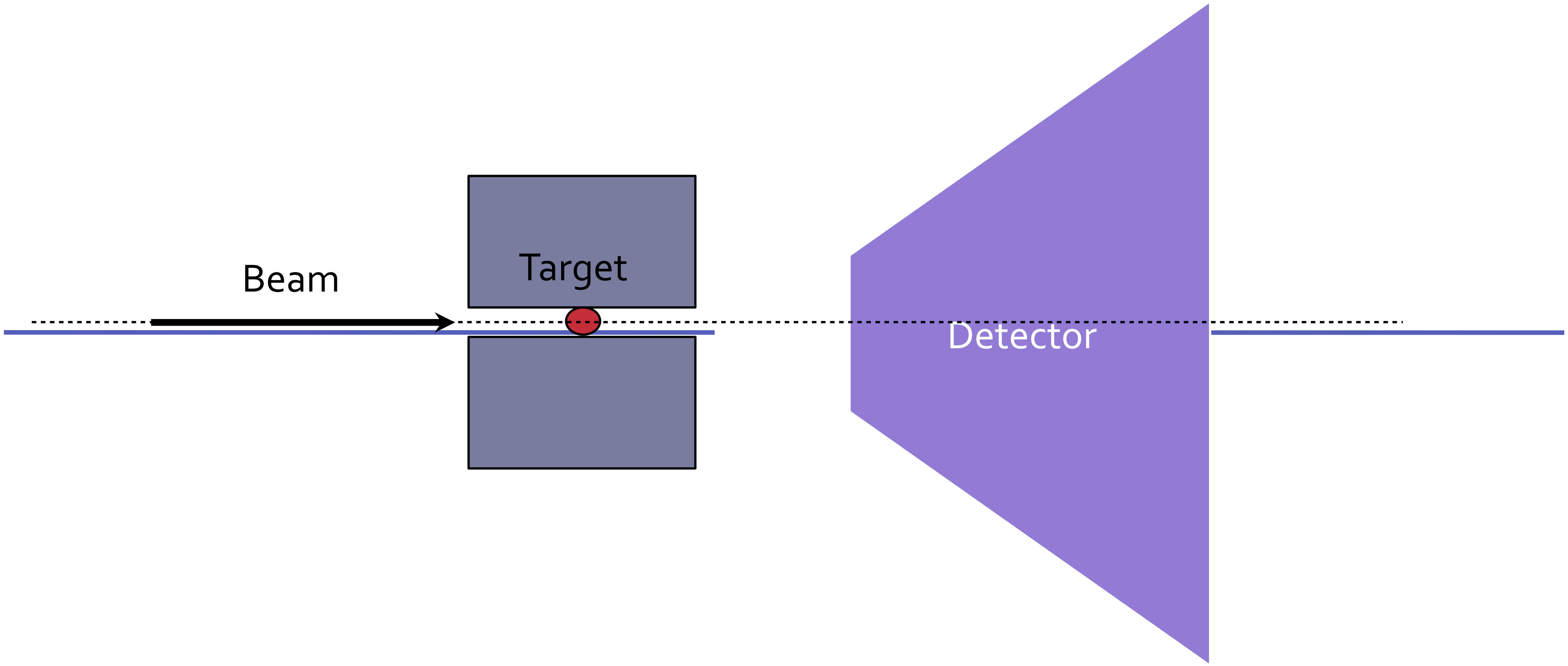
See: http://pdg.lbl.gov/2014/reviews/rpp2014-rev-passage-particles-matter.pdf

Detectors

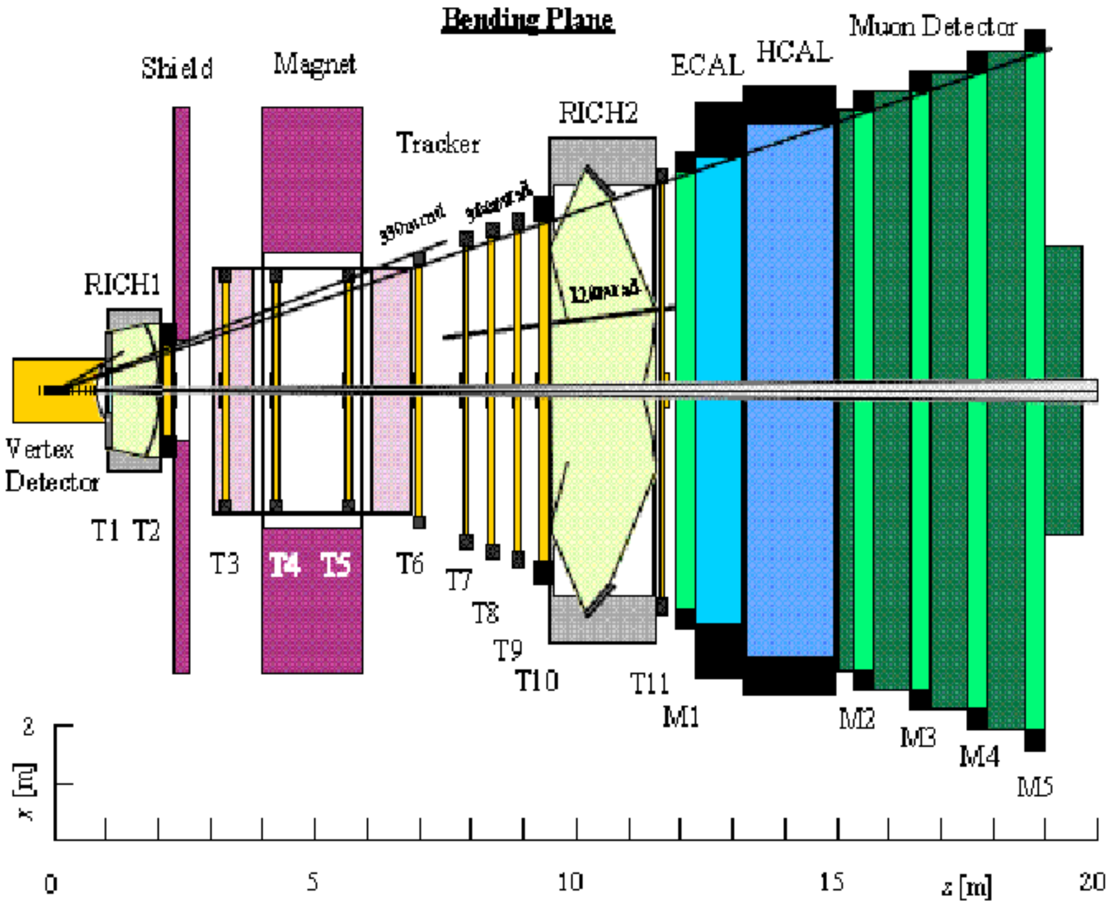


Fixed target experiments

- For fixed target experiments the production is essentially in the forward direction



Example: LHCb experiment

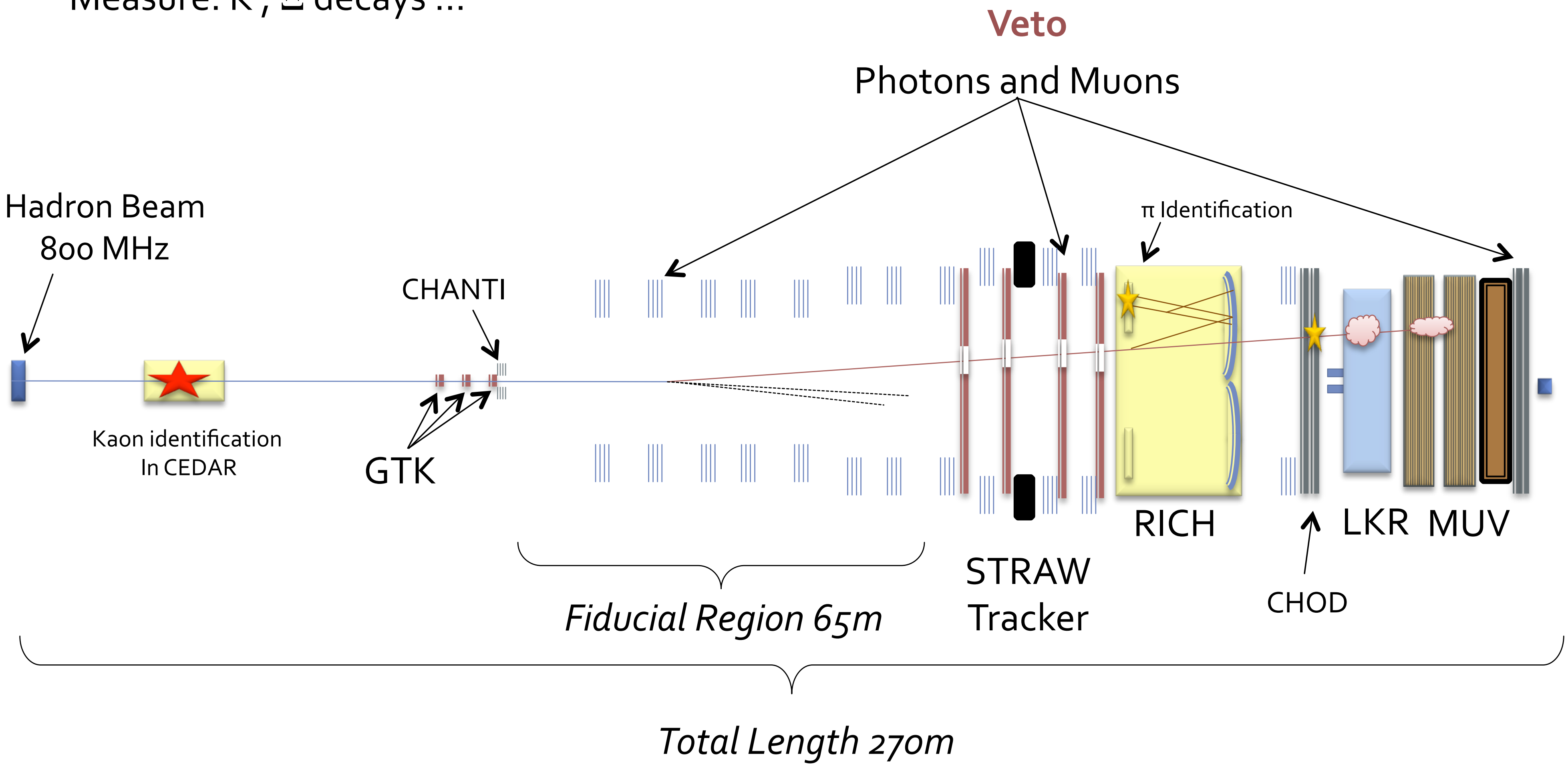


Detectors:

Vertex:	220K
Inner tracker:	220K
Outer tracker:	110K
RICH:	340K
Preshower:	6K
ECAL:	6K
HCAL:	3K
Muon:	45K
Total:	**~ 1 million**

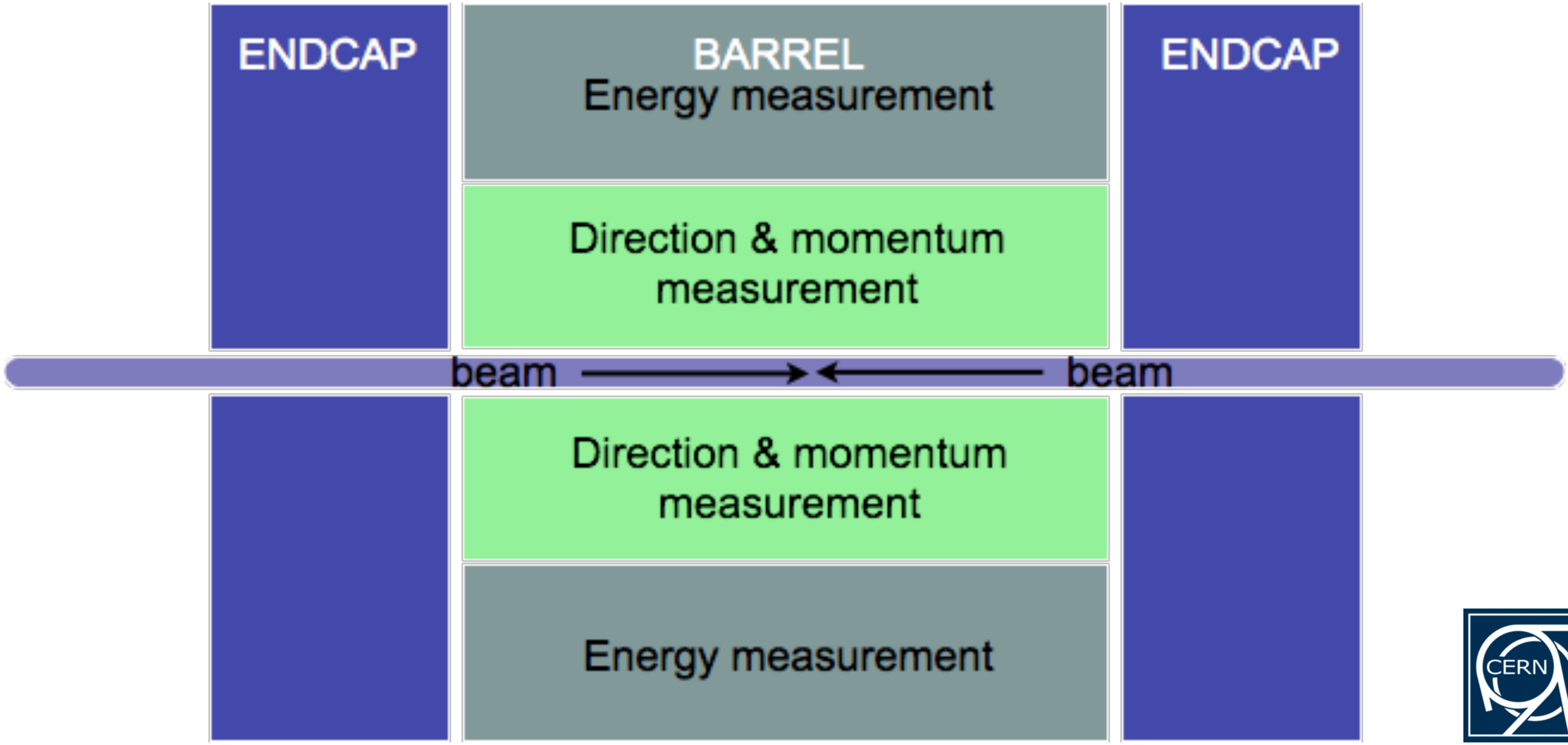
Example: Na62 experiment (at CERN hadron beam facility)

Measure: K , Ξ decays …



Collider experiment

- Particle detectors are disposed around the interaction region and detect (directly or indirectly) the reaction products



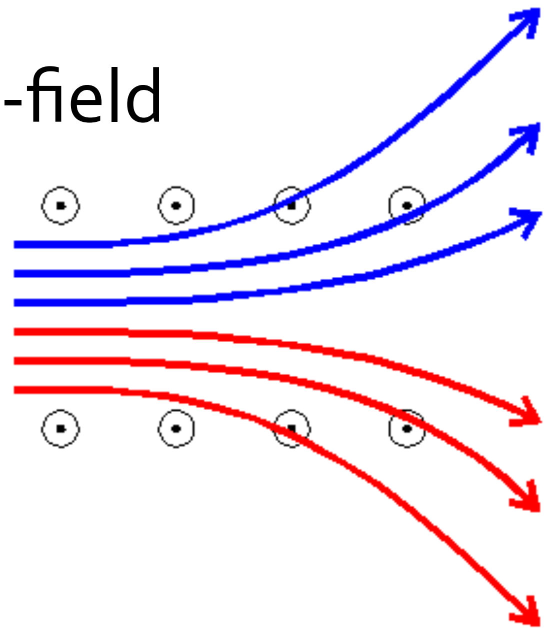
Particle physics experiments

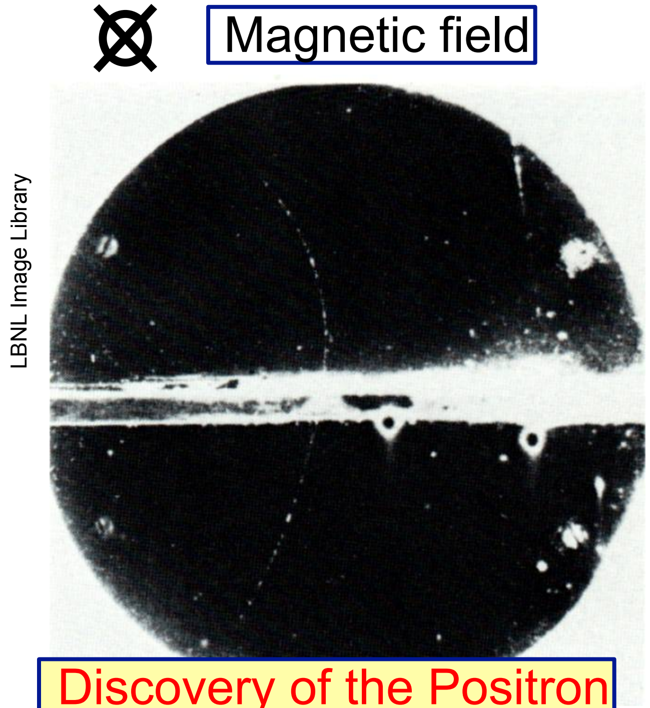
- Typical measurements performed:
  - Spatial coordinates and timing of final state particle
  - Momentum p
  - Energy E
  - Charge Q
  - Type of particle (particle ID) =m

$$\left.\begin{array}{c} E \\ \vec{p} = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} \end{array}\right\} \begin{pmatrix} E \\ \vec{p} \end{pmatrix}$$

Measurements

- Charge
  - Direction in B-field



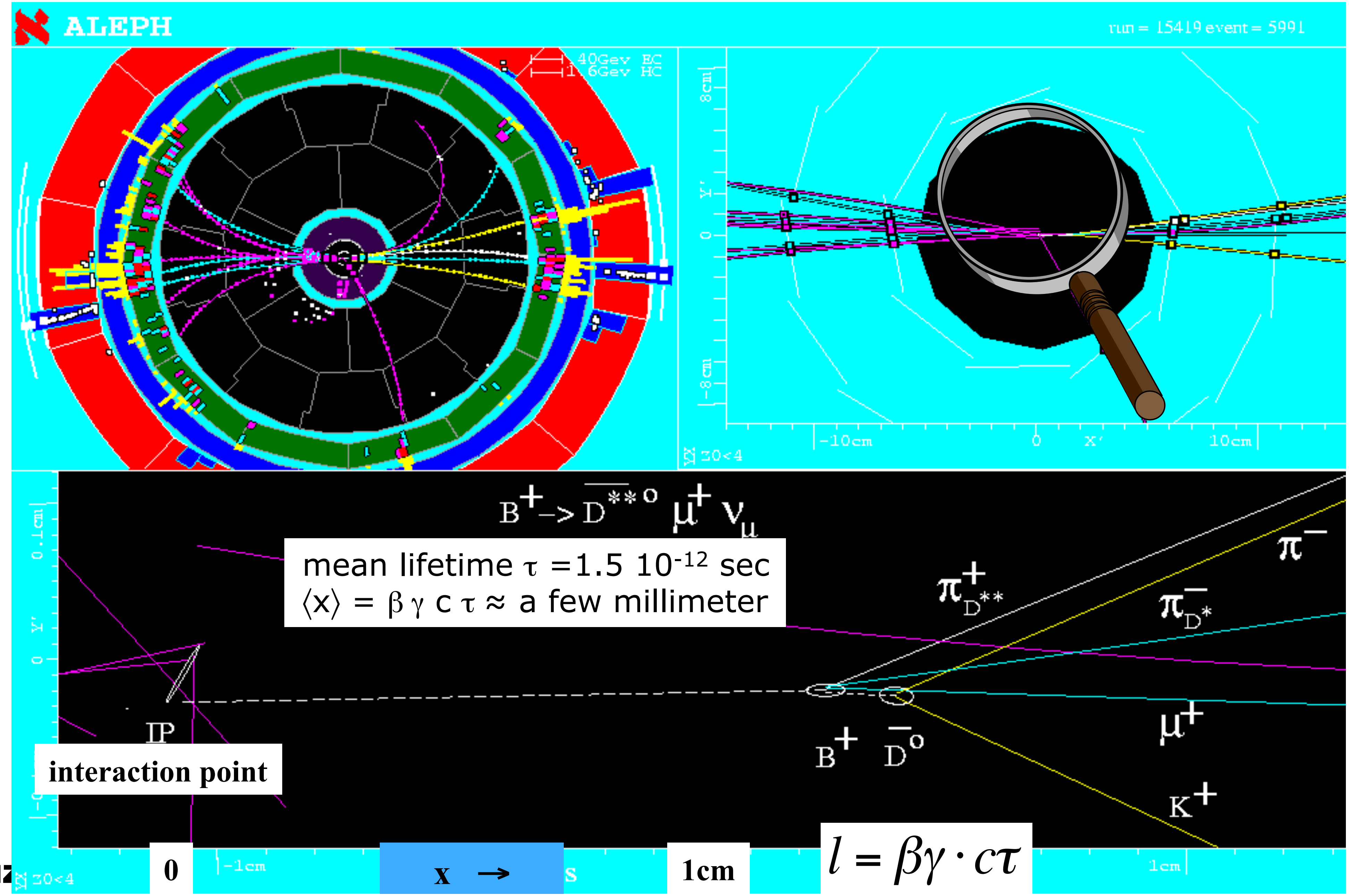


Discovery of the Positron
1932 Carl Anderson,
Noble Prize 1936

- Lifetime
  - Measurement of path length

$$l = \beta\gamma \cdot c\tau$$

Measurements of decay length → lifetime : Aleph at LEP



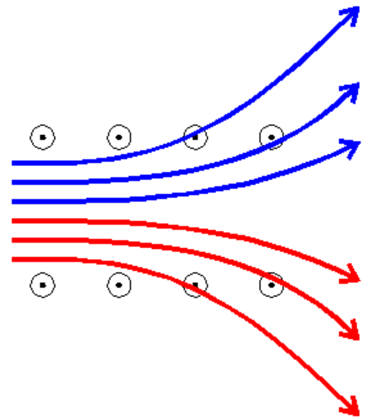
Measurements

- Momentum

  \- momentum measurement is based on the deflection of charged particles in a magnetic field

$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

$$\Rightarrow q \cdot B \cdot R = m \cdot v = |\vec{p}|$$



- Velocity

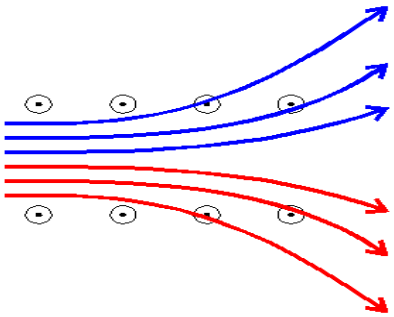
  \- time of flight TOF

- Energy

  \- Calorimeters

Momentum Measurements

- Momentum



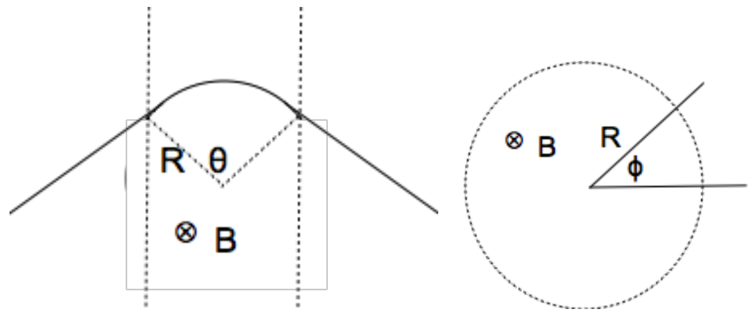
$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$
$$\Rightarrow q \cdot B \cdot R = m \cdot v = |\vec{p}|$$

In collider experiment:
B field parallel to beams
Curvature only in the transverse plane
Momentum resolution:

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B\, l_R^2}\, [720/(n+4)]^{-1/2}$$

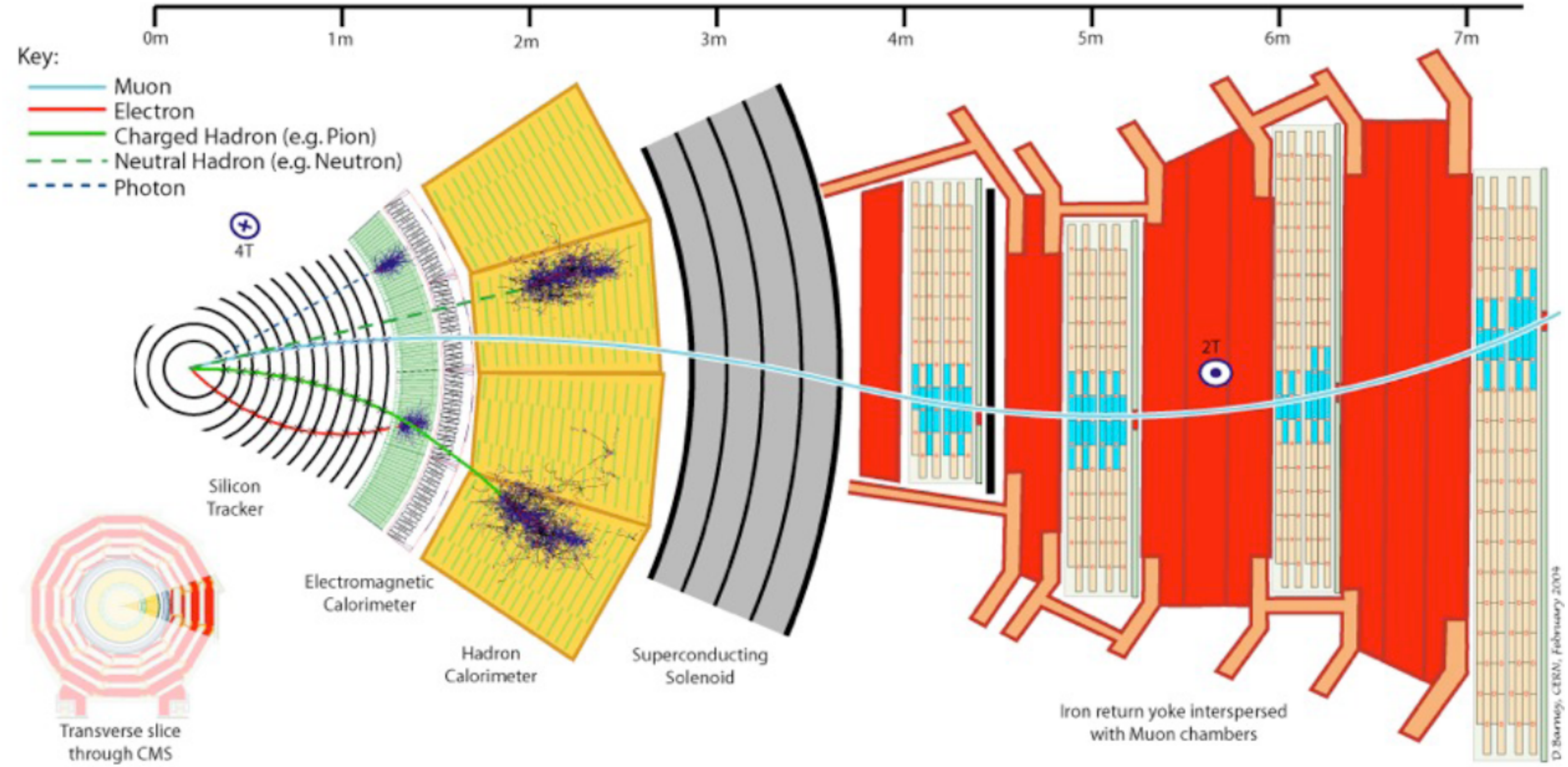
$\sigma_{r\phi}$ = error on each measurement point
l_R = radial length of the track
n = number of equidistant points

R.Glueckstern, NIM, 24(1963)381



p = 0.3 B R
length = l = 2 R sin (θ/2) ~ R θ
θ = length/R = 0.3 B l / p
p = 0.3 B l / θ

CMS detection of hadrons, e, μ , γ

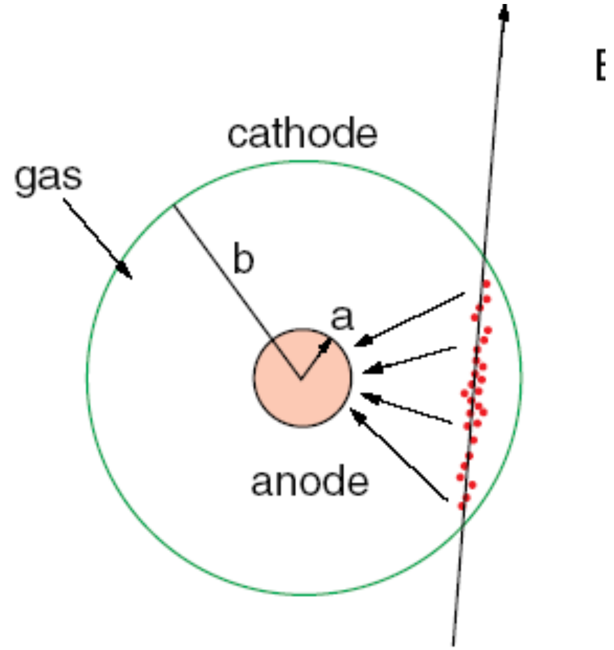


https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

file://localhost/Users/grab/txt/figs/lhc-figs/lhc-figs-media/CMS_Slice_elab.swf

Measure with Gas-detectors

- Charged particles traverse gas-filled detector and ionise gas atoms → produce ion-electron pairs
- These charges are collected in electric field, and thus produce → Signal (eg. typical muon system)

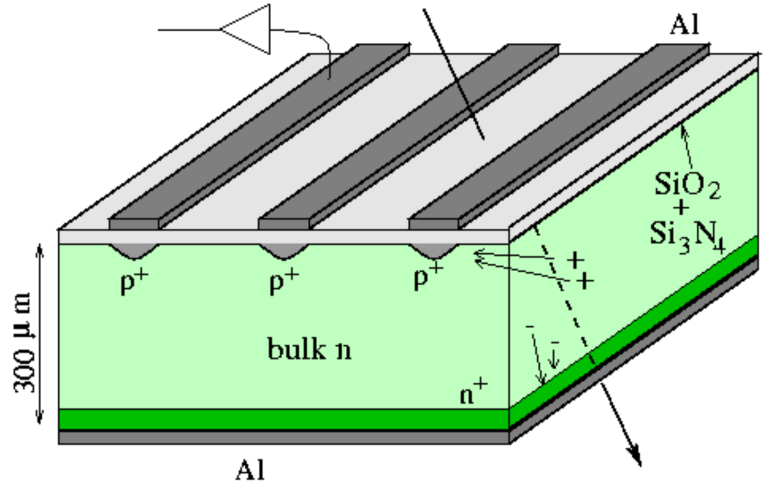


- Ex: "Single Wire Proportional Chamber"
  - Detector tube filled with gas
  - HV between cathode (-) and anode (+)
  - Strong E-field close to anode-wire causes further ionisation by electrons
    → produces charge avalanche → larger signal
    → readout charge eg. via RC to preamp
    → "Signal"

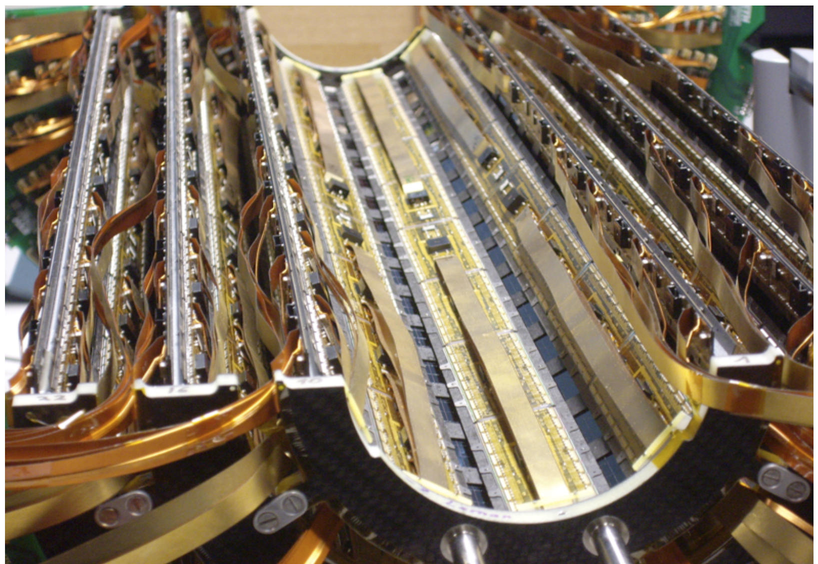
Measure with Si-detectors

- Particle produce e-hole pairs in Si-substrate
- In 0.300 mm Si ca 24000 pairs are being produced
- Charges move in E-field to electrodes
- Read charge as current pulse

- Pulses serve the localisation of particles
- Get high spatial resolution
  ~ 10-20 microns



CMS barrel Pixel



Measure energy = "Calorimeter"

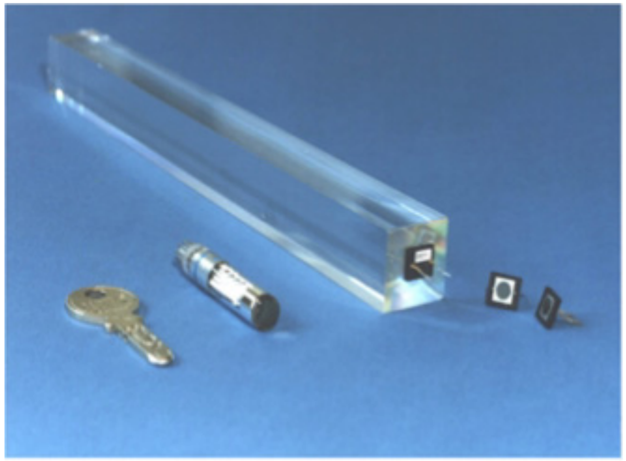
→ Stop particles and measure released energy

Crystal calorimeter

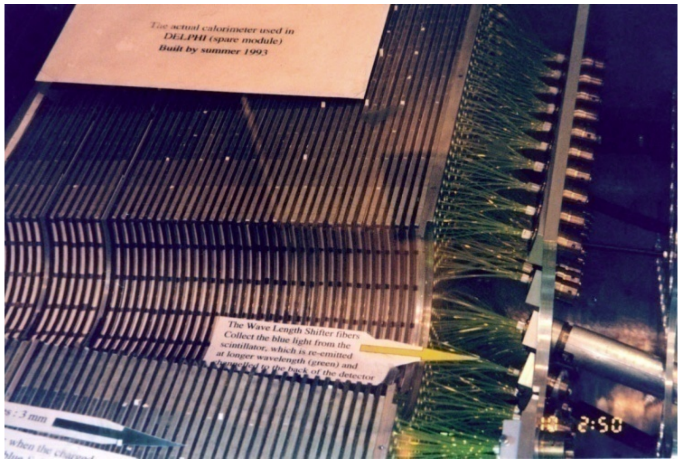
Stop particle in heavy crystal and measure how much light is produced

Sampling Calorimeter

Measure how many layers of material are traversed by particles



CMS: PbWO4



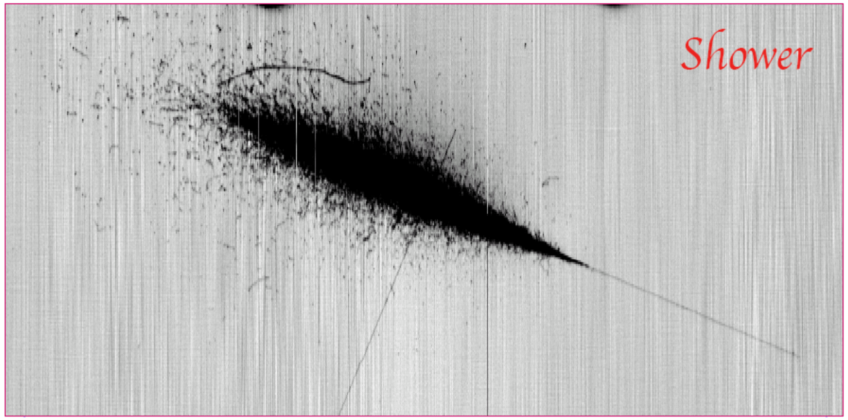
CMS: brass+Scintillator (barrel)

Two kinds of particles = Calorimeter-Types

Electromagnetic

(Elektrons and Photons)

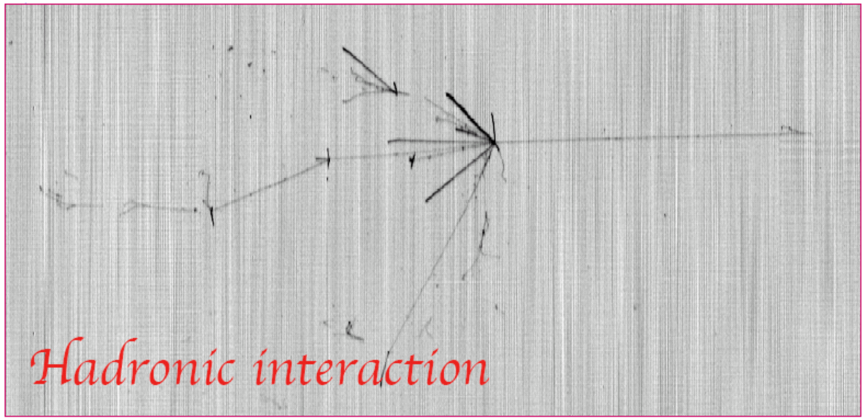
- Electrons emit photons
- Electromagn. interaction
- Photons convert to electron-positron pairs
- Short, intense showers



Hadronic

(p,π,.. Composed of quarks)

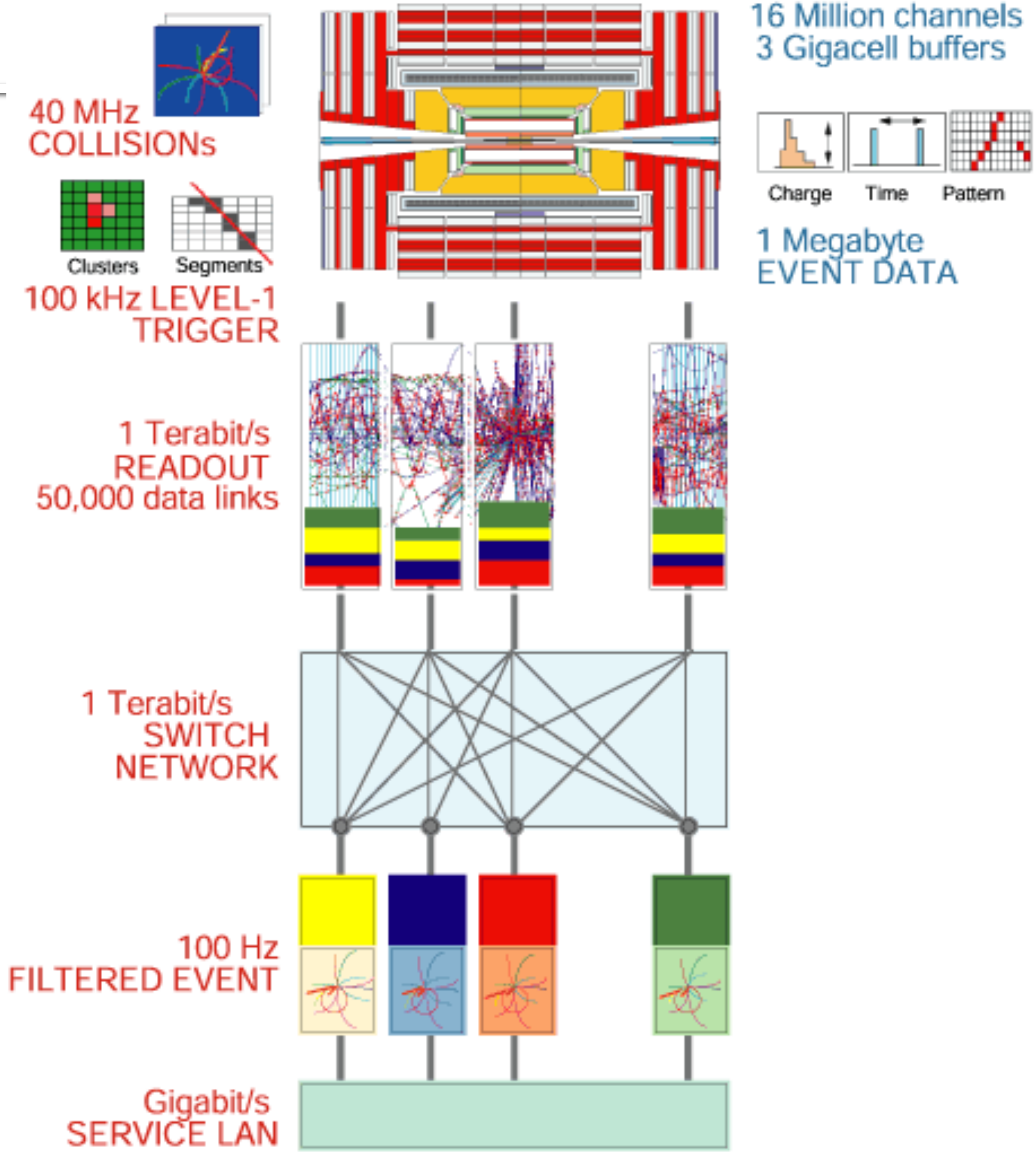
- Interactions with nuclei produce more hadrons
- Strong interaction
- Deep, thin showers



Because hadrons interact deeper in the calorimeter, the inner part is called electromagnetic, the outer hadronic calorimeter

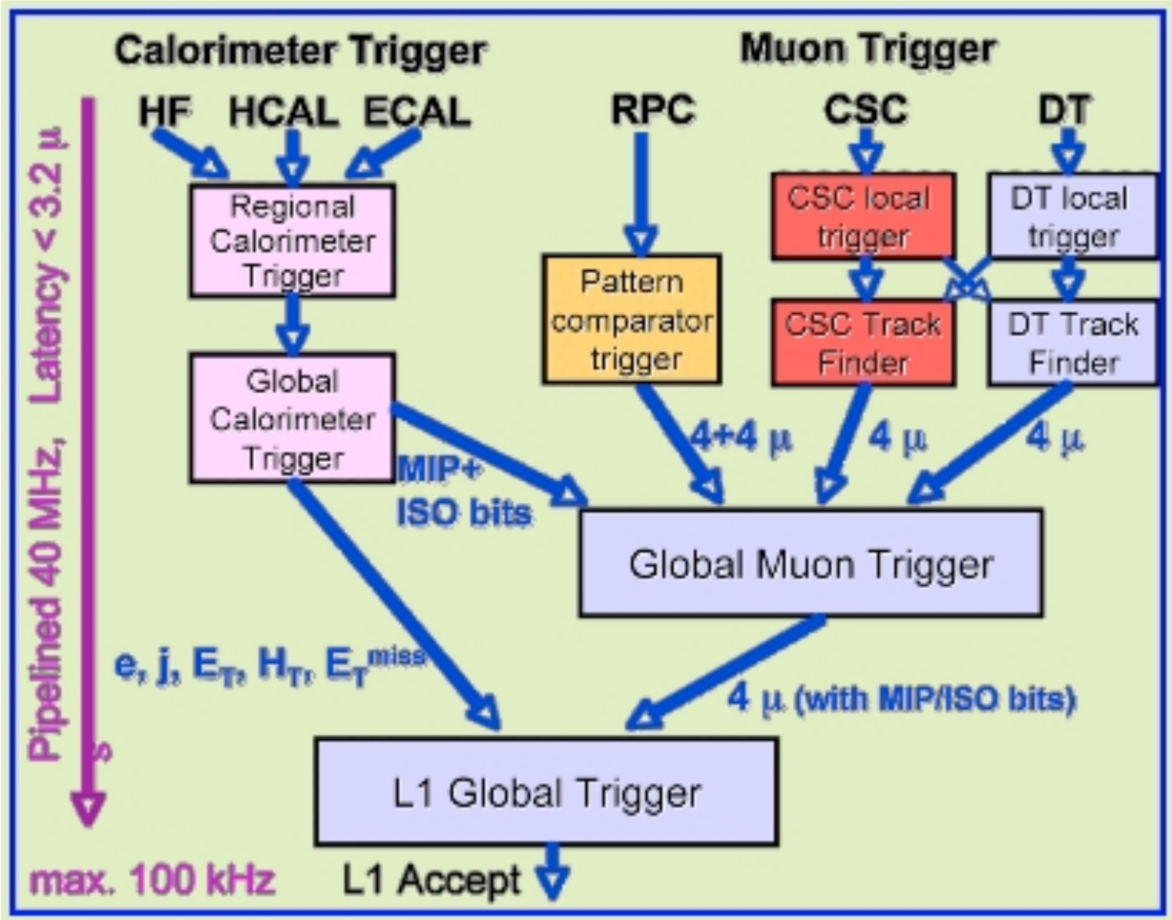
Selection events : trigger

- CMS has ~ 10 million channels
- Cannot write all channels for all beam crossings (is some 4 PB/sec)
- Pre-select interesting events BEFORE fully reading out the detector, and write only those to disk/tape
- Fast online-electronics uses only part of the detector signals
- This is the „**Trigger**“

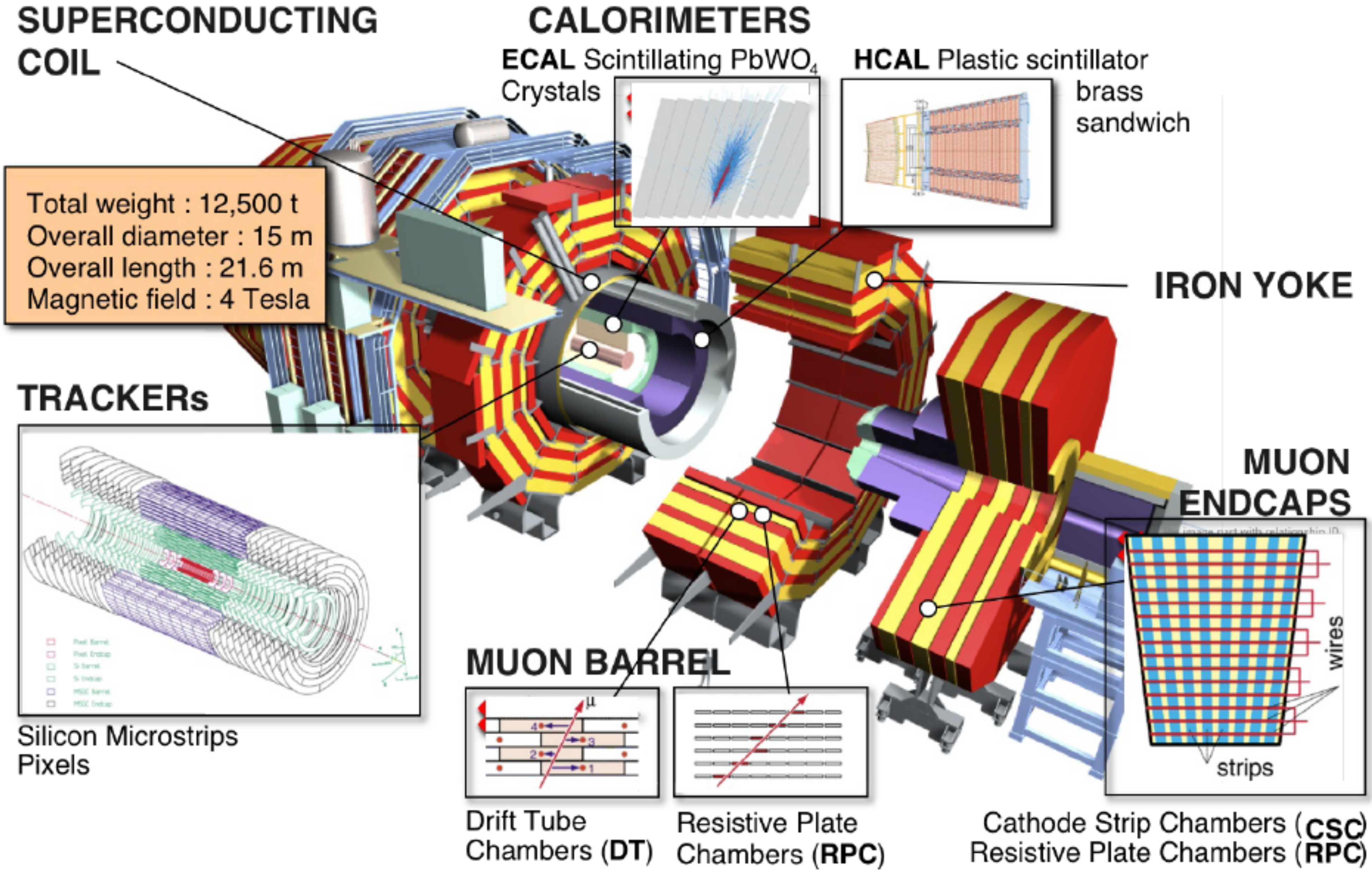


Selection events : trigger logical

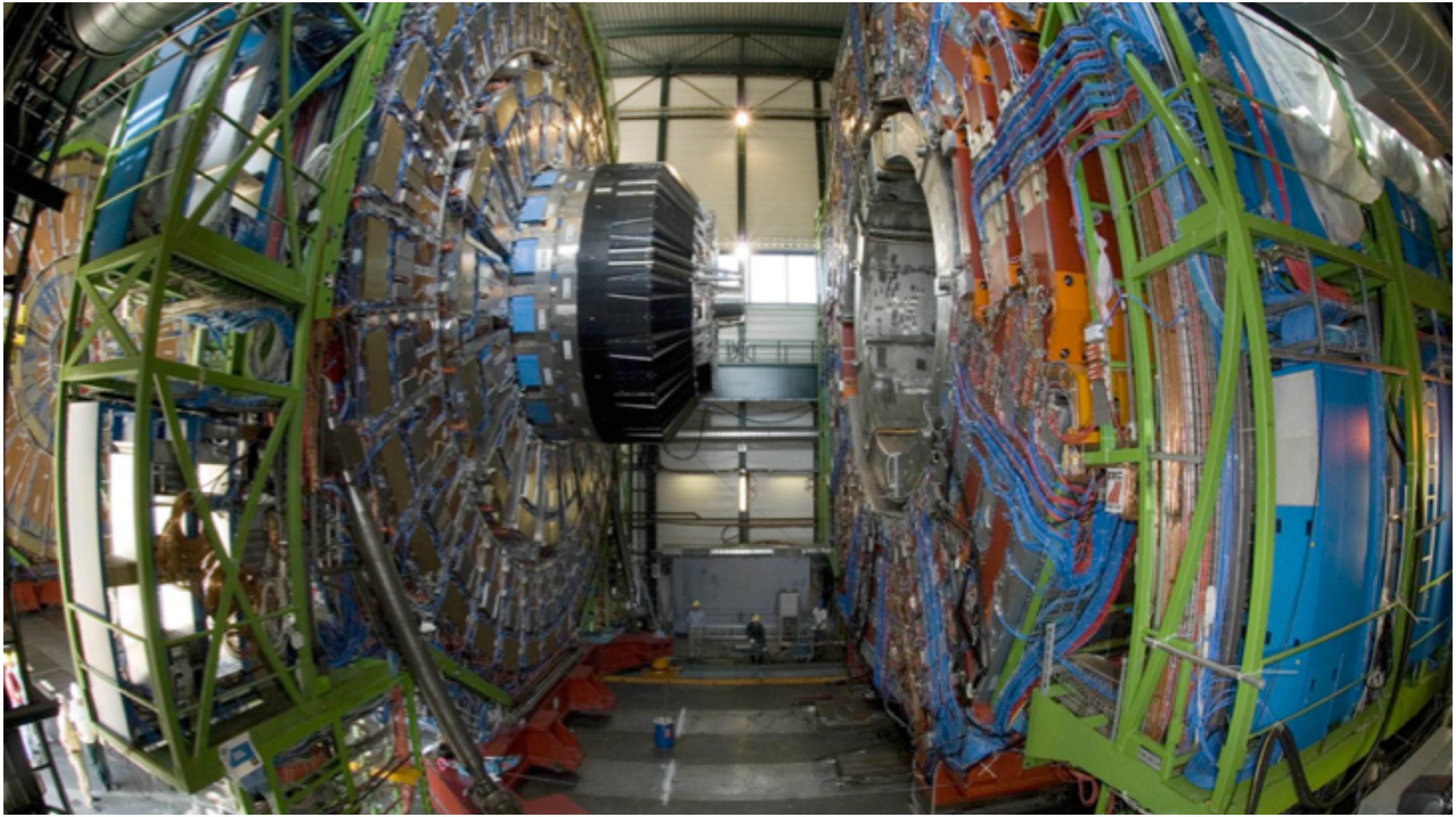
- CMS exploits information first of individual subdetectors
- Then combine information of different subdetectors into „larger logic units“
- Calculate „Observables“ to base decisions on
- „Trigger“

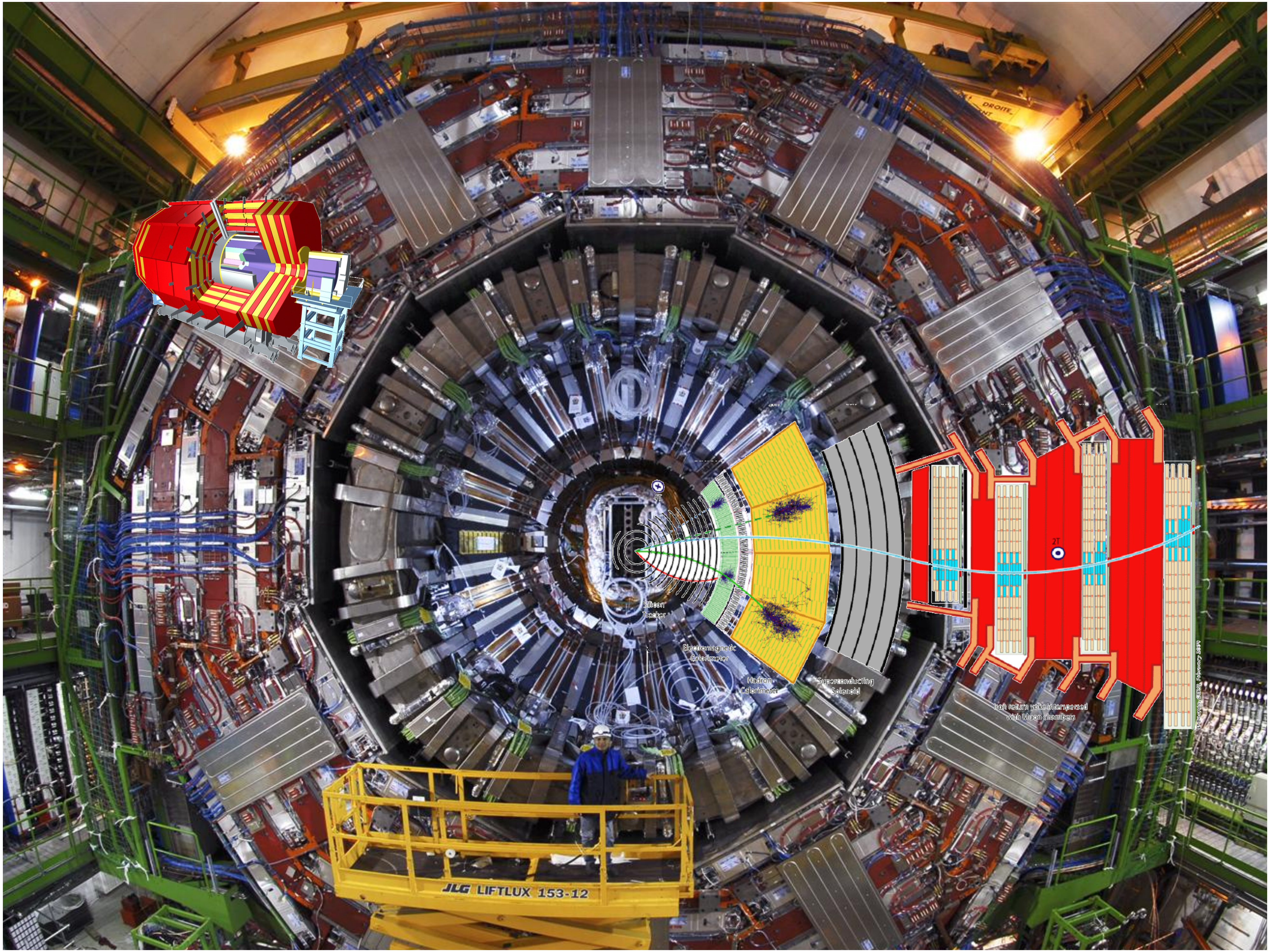


CMS detector

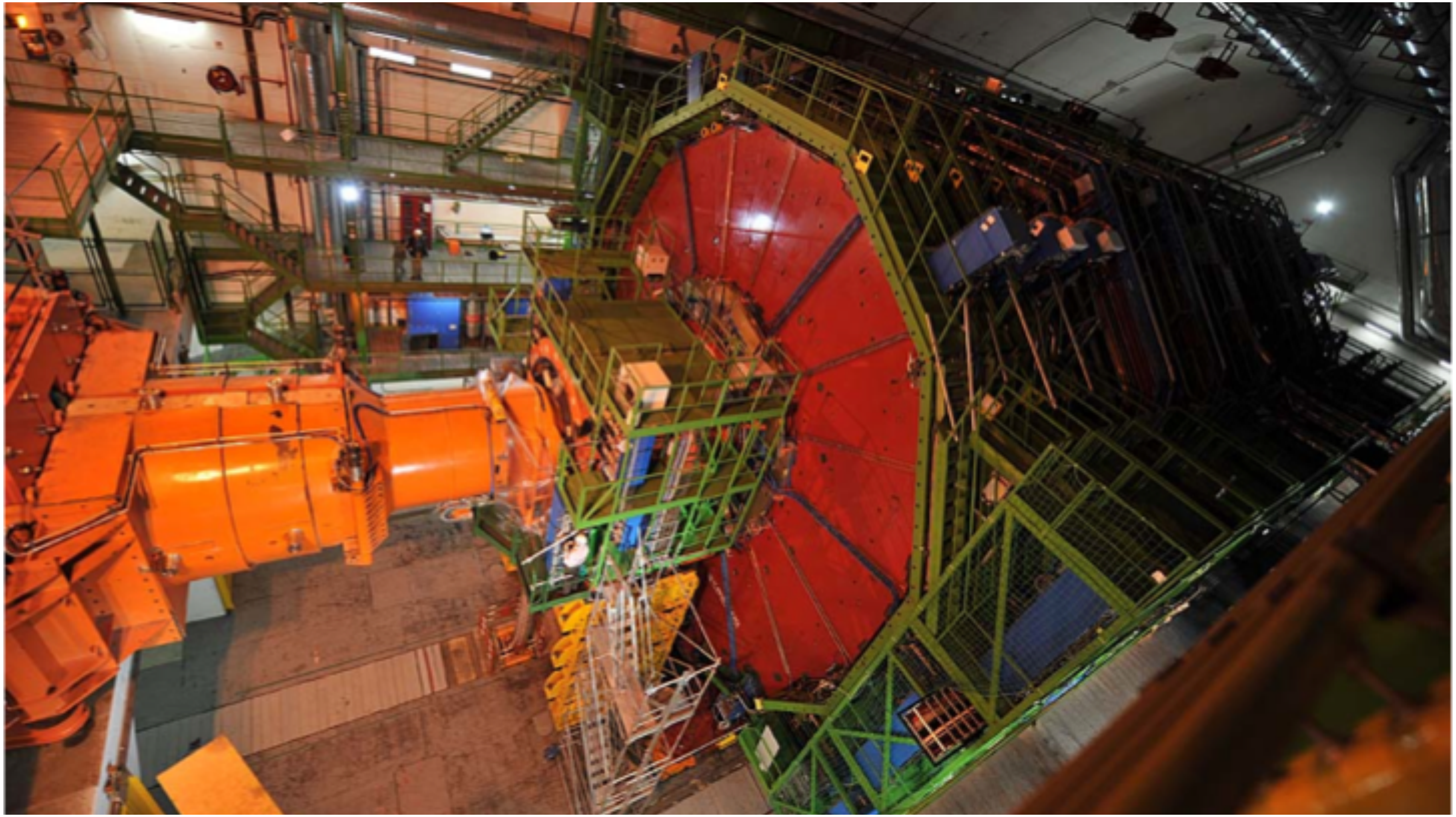


CMS – open configuration

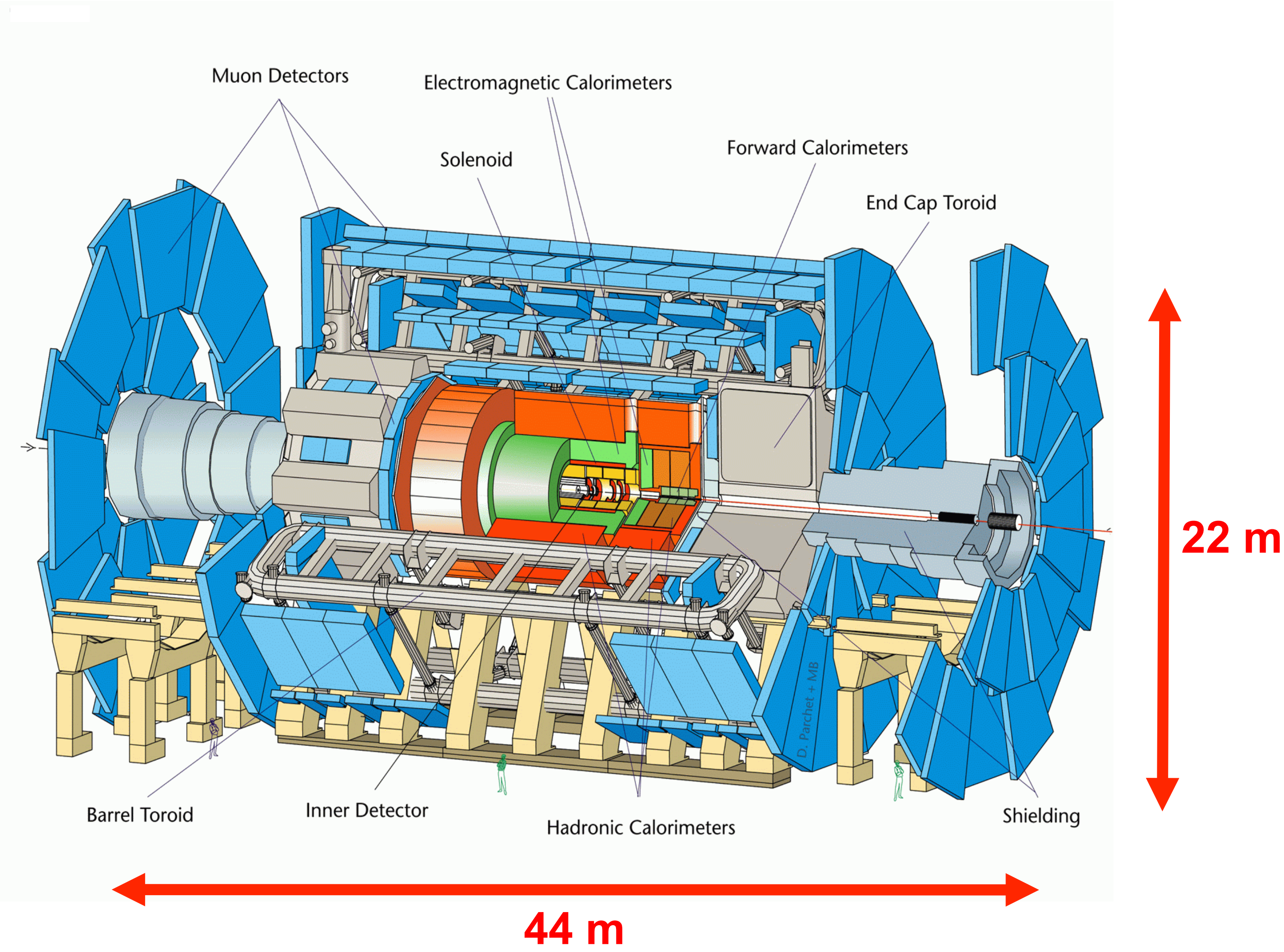



Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
2T
JLG LIFTLUX 153-12

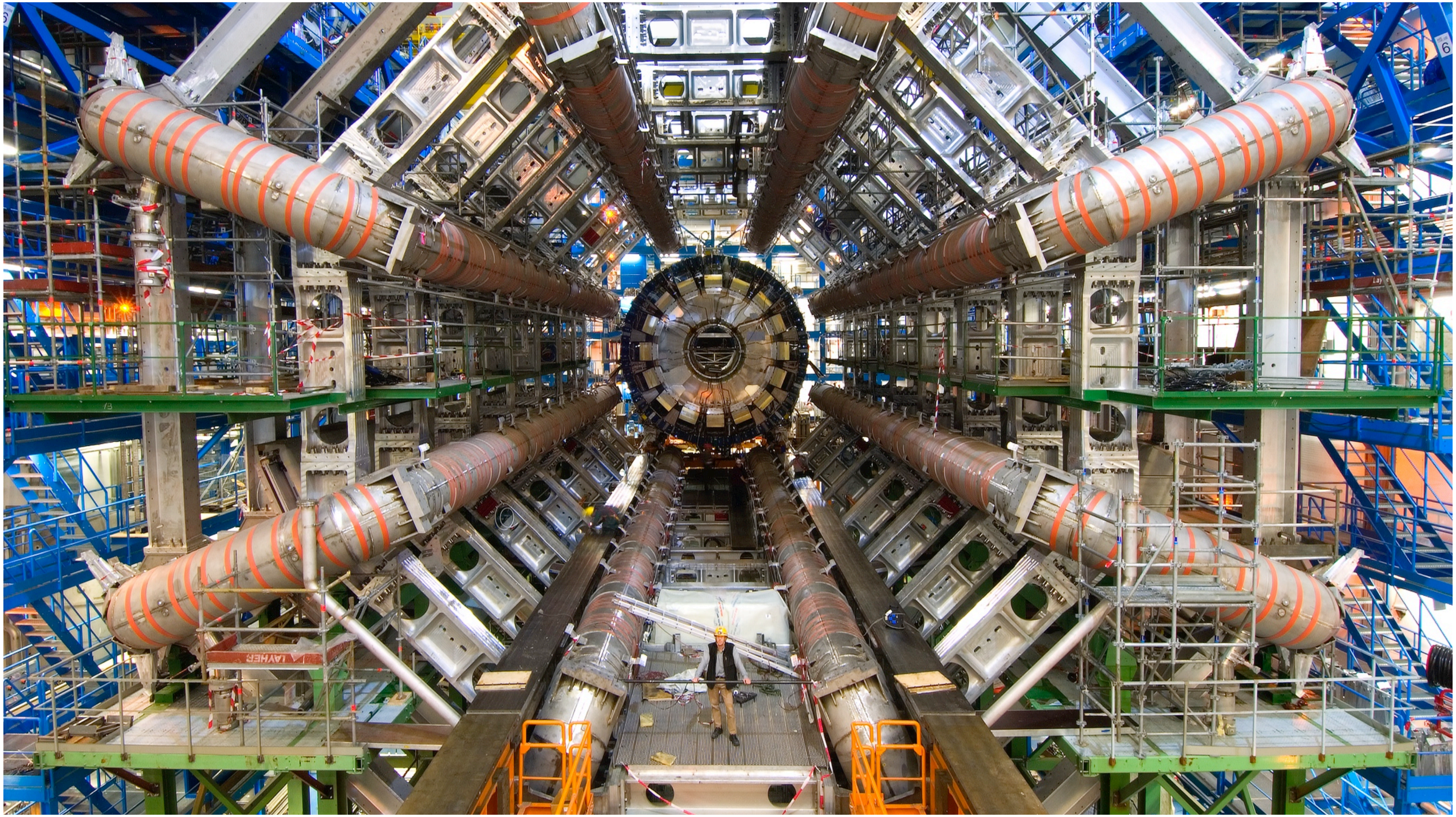
CMS – closed configuration



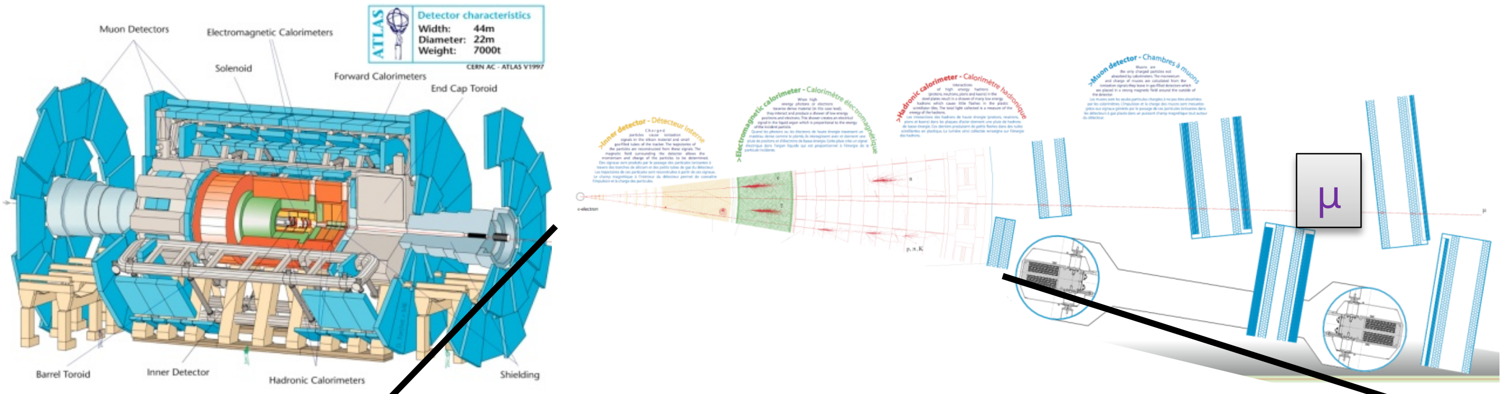
ATLAS detector



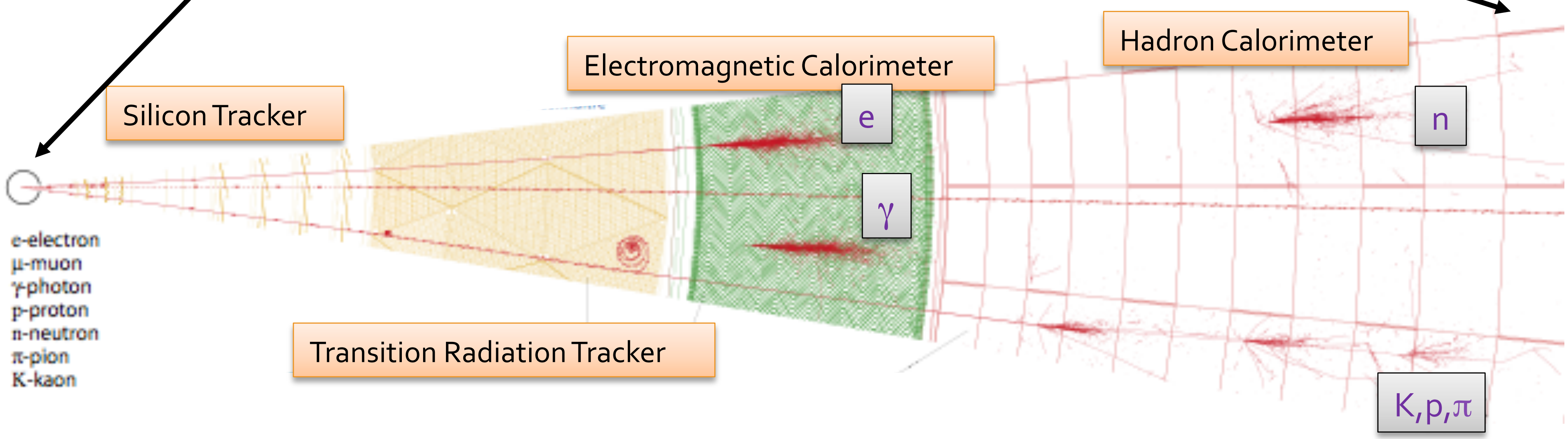
ATLAS detector



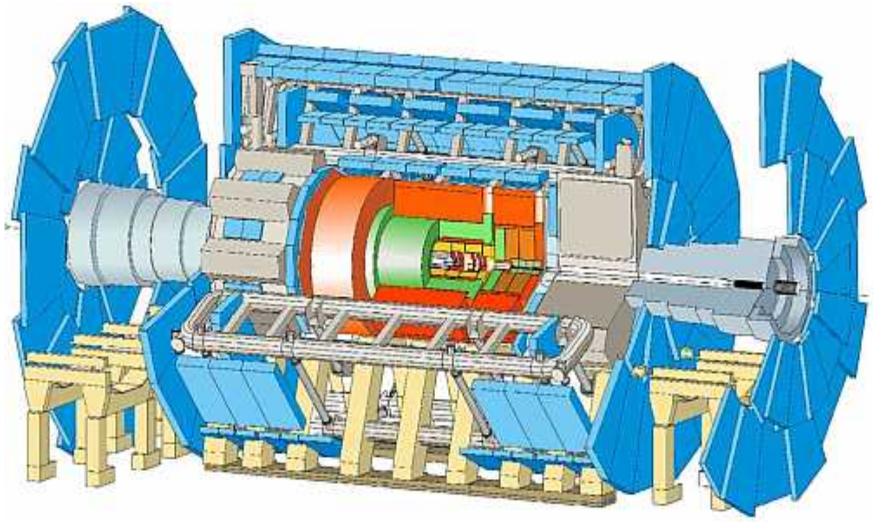
ATLAS

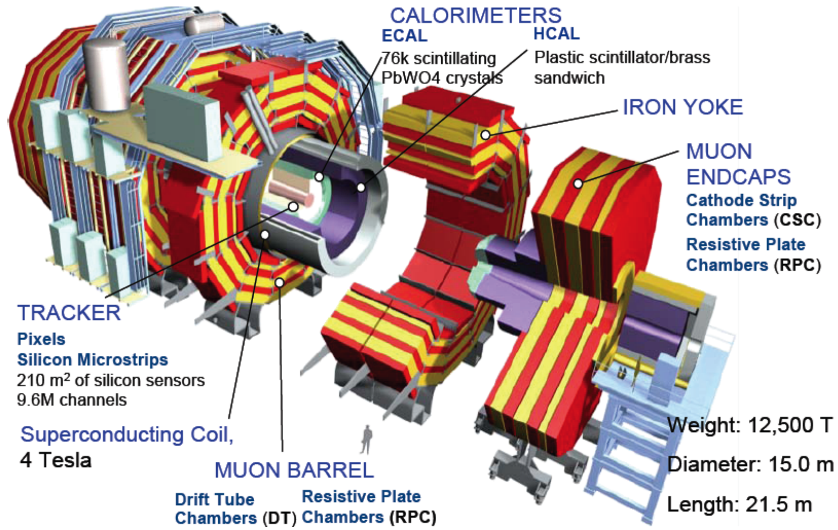


Magnified how real (single) particles
look like in ATLAS



Detector size comparison

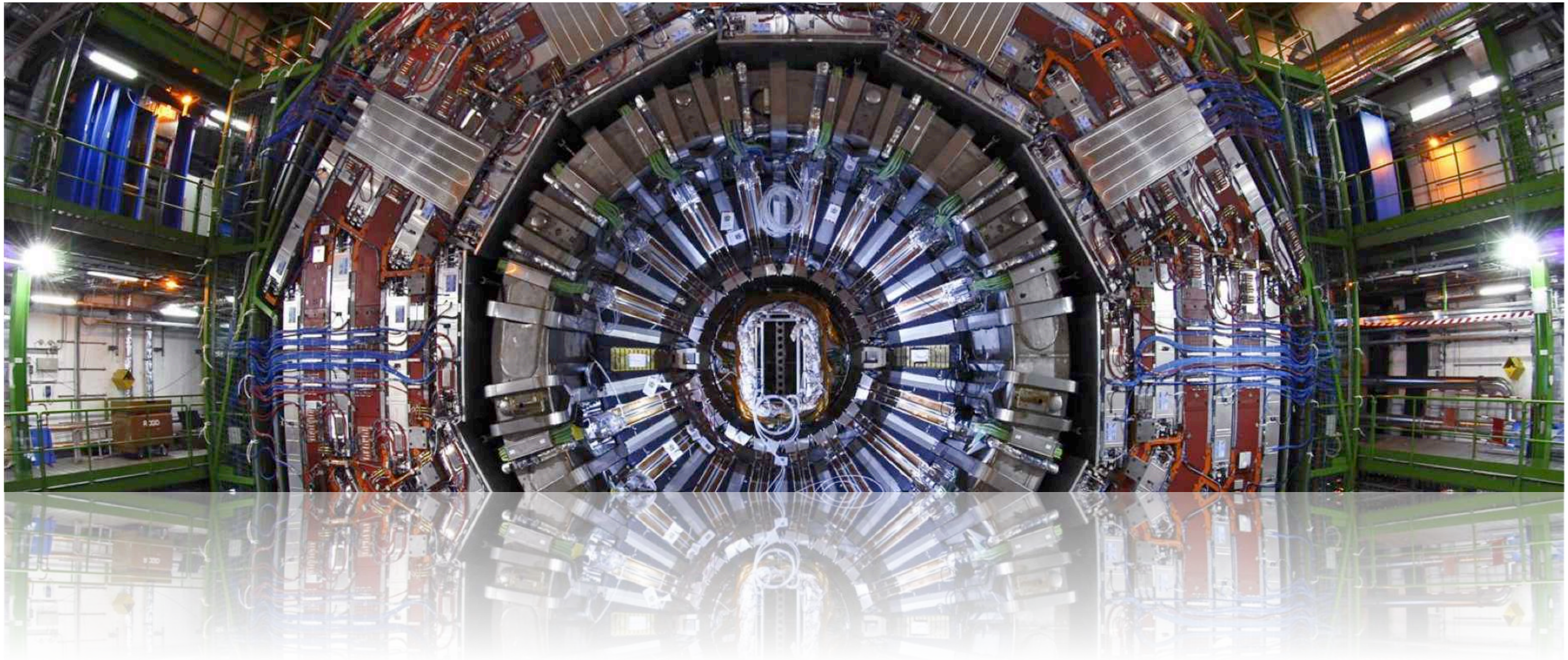




	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

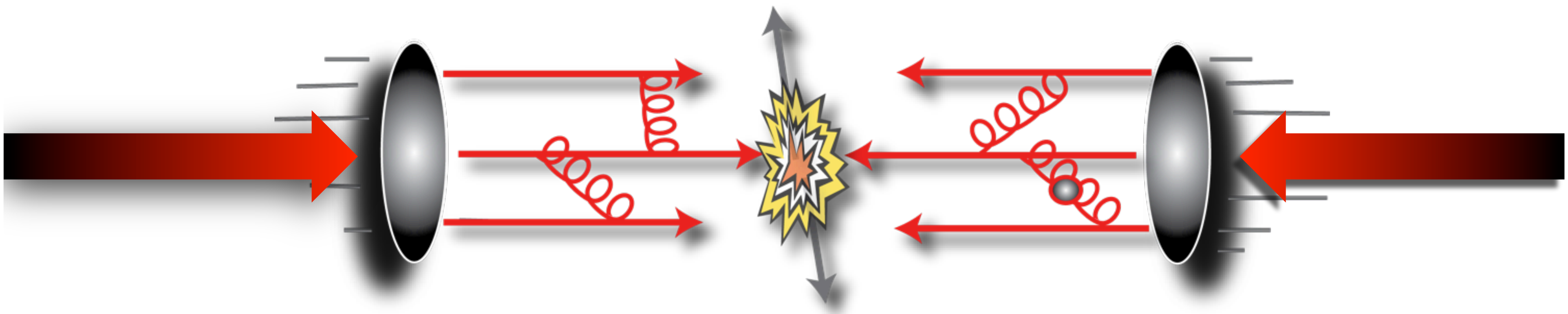
~3000 Scientists per experiment + many engineers and technicians

From detectors to physics



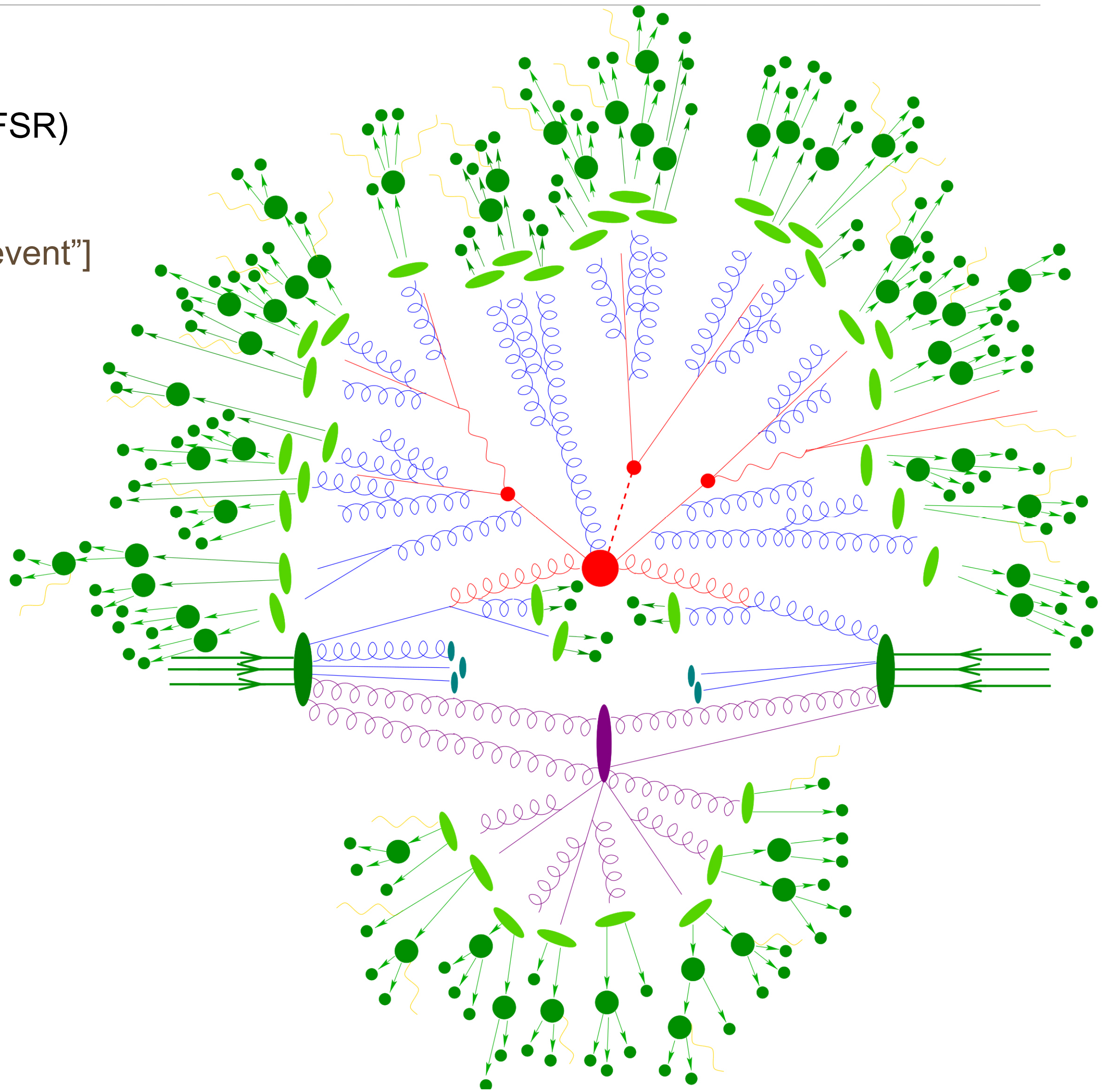
Proton collisions

- Protons are composite particles
- p-p collisions are complicated "objects"

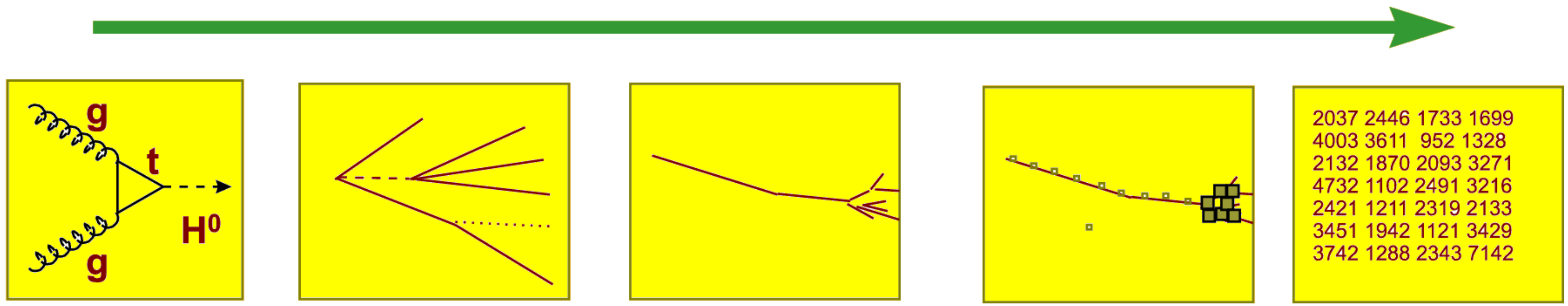


Proton collisions

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Hadronisation (non-perturbative)
- Secondary interaction ["underlying event"]



From physics to raw data : MC



Basic physics

Fragmentation, Decay

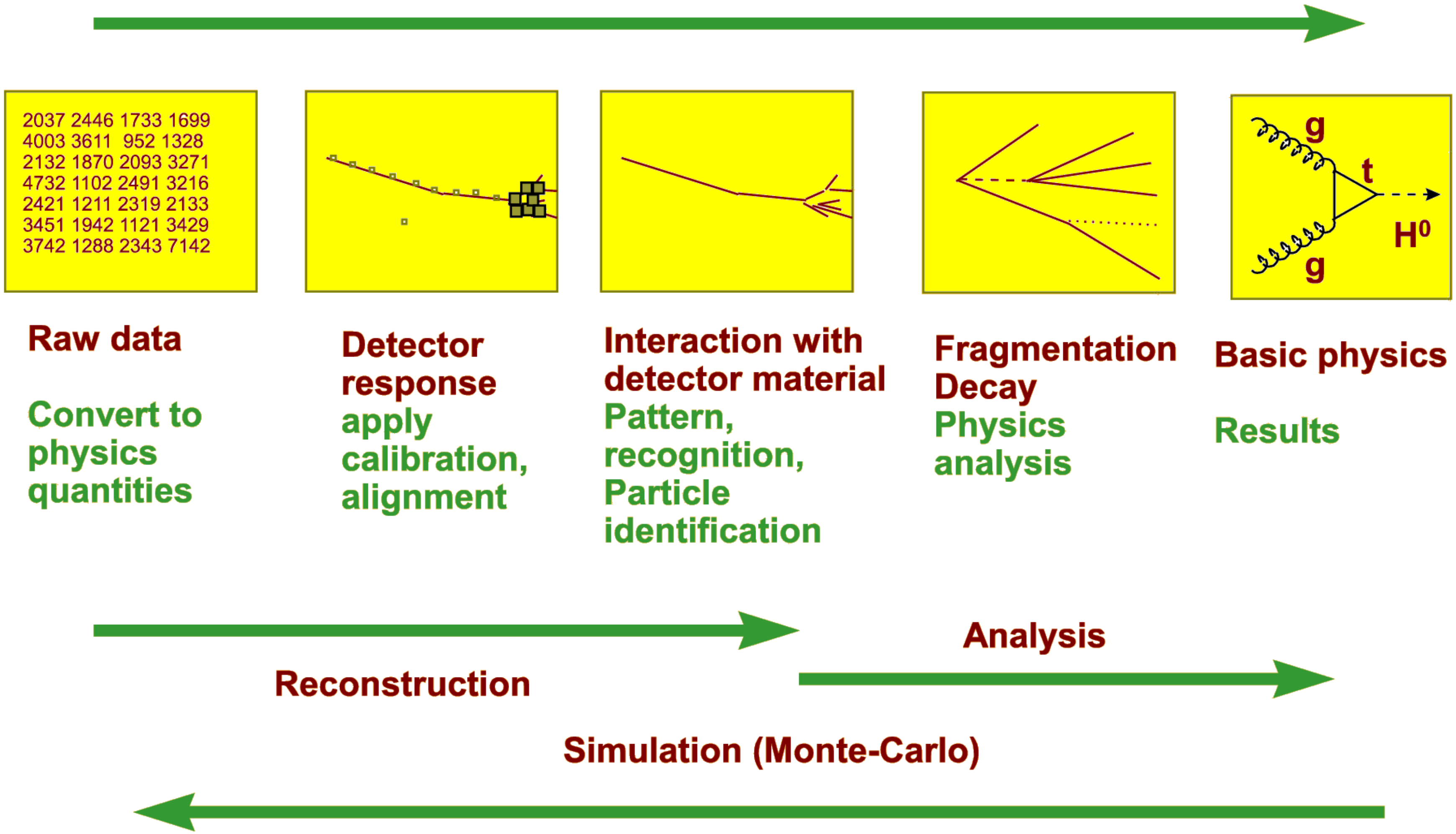
Interaction with detector material
Multiple scattering, interactions

Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data

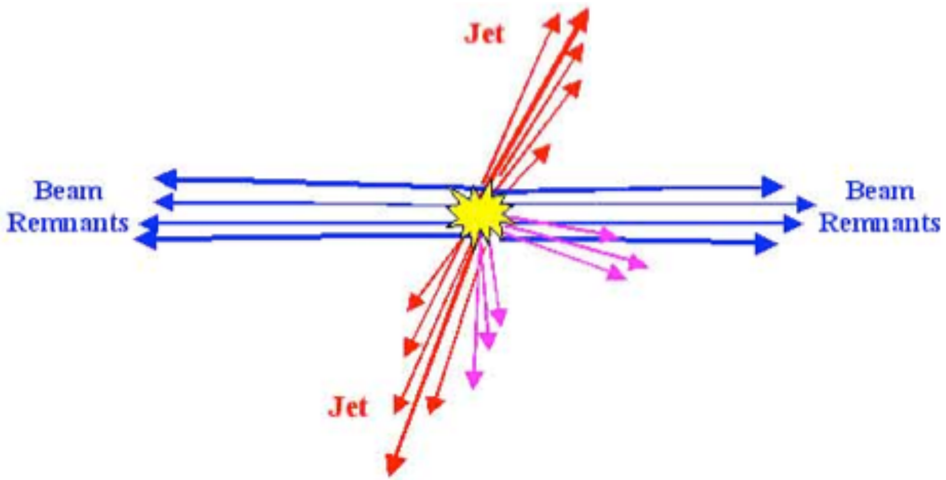
Read-out addresses, ADC, TDC values, Bit patterns

From raw data to physics …



Collider physics

- Experiments in hadron colliders usually deal with particles at high **transverse momentum**
- Reasons:
  - Incoming particles collide head-on (no transverse momentum)
  - Final state particles must have zero total transverse momentum
  - Hard processes (large momentum transfer) produce particles that go to the center of the detector
- *Example: proton + proton → jet + jet*

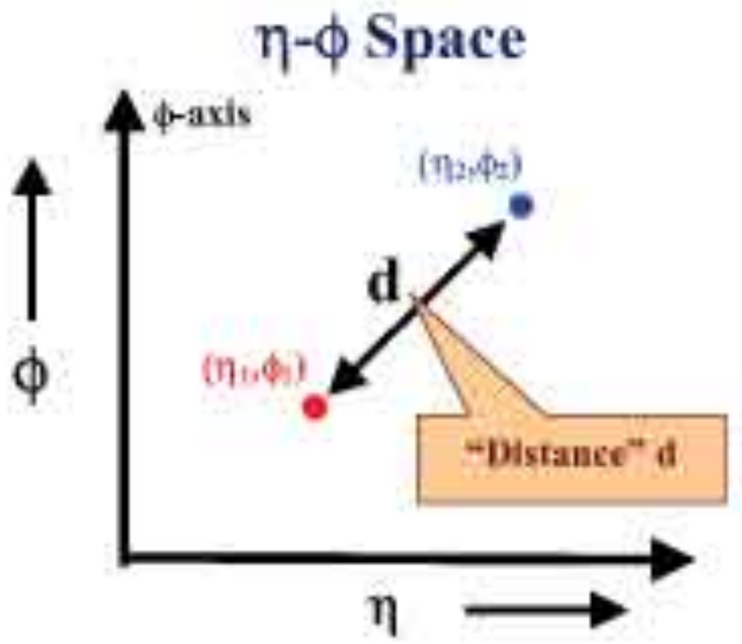


Recap: Inclusive reactions

- Use of invariant observables for inclusive reactions
- Given a preferred direction (usually the z-direction or beam direction), energy and momentum are expressed in terms of transverse variables:
- Transverse mass $m_T{}^2 = m^2 + p_x^2 + p_y^2$
- Rapidity y: $\boxed{y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})}$ $\quad y = \ln(\frac{E+p_z}{m_T}) = \tanh^{-1}(\frac{p_z}{E})$
- Shape of the rapidity distribution is an invariant under boost in z-direction, also difference of y-distributions are invariant
- Energy and momenta are given by: $\left\{ \begin{array}{l} E = m_T \cosh y \\ p_x, p_y, \quad p_z = m_T \sinh y \end{array} \right.$
- For p>> m, expand rapidity → obtain "Pseudorapidity η"
  for θ>>1/γ $\quad \boxed{y \approx -\ln\tan(\theta/2) = \eta} \quad \cos(\theta) = p_z / p$

Identities are: $\sinh\eta = \cot\theta \qquad \tanh\eta = \cos\theta$

Pseudorapidity



- To measure the longitudinal angle of emerging particle jet , use **pseudo-rapidity**

- Distance between particles or jets is usually measured in the **(η,φ) plane**

$$d = \sqrt{(\eta_2 - \eta_1)^2 - (\phi_2 - \phi_1)^2}$$

- **The distance "d" between two objects measured with pseudorapidity (η) is Lorentz invariant under longitudinal boosts,**

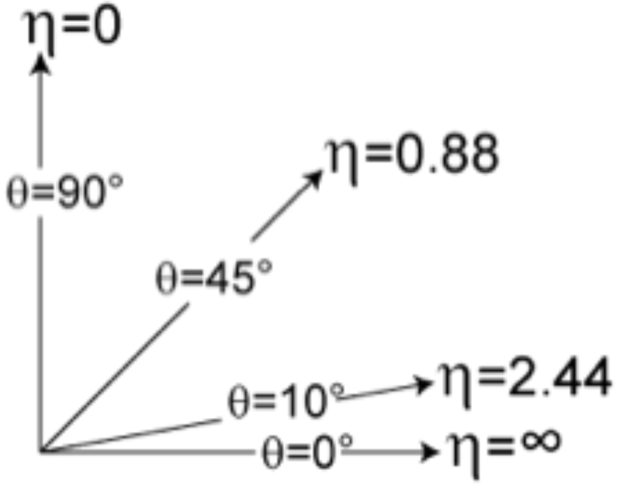
- **particle production is (loosely speaking) constant as a function of η**

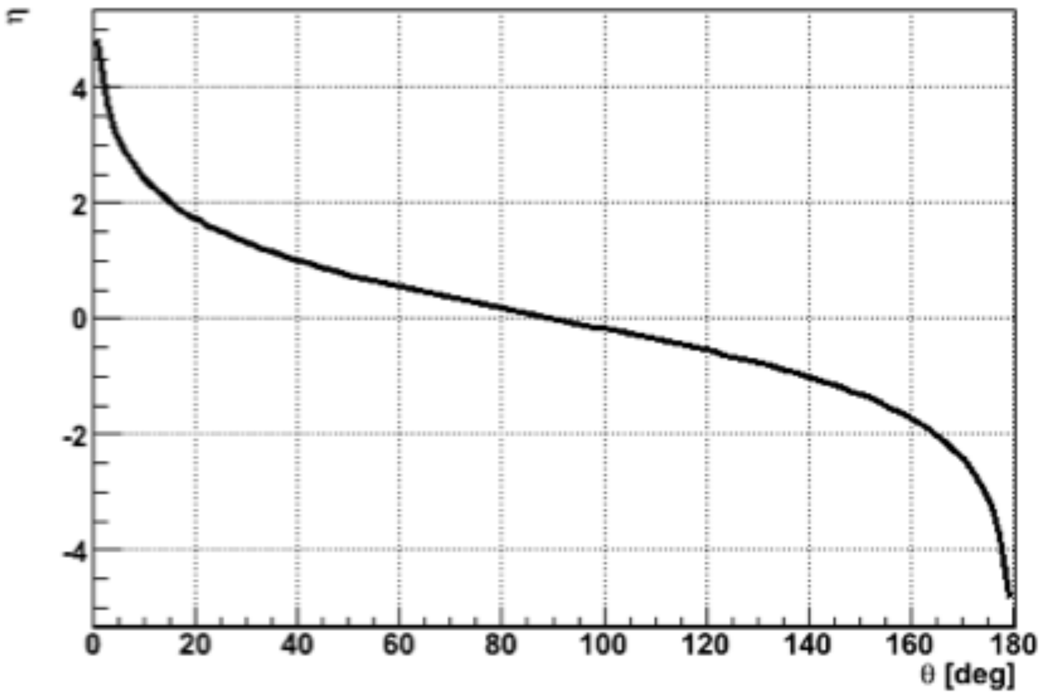
- Momenta in the transverse plane are also invariant under longitudinal relativistic transformations

Pseudorapidity

- Particles produced at θ=90° have zero pseudorapidity
- High |η| values are equivalent to very shallow scattering angles
- Typical coverage of central detectors extends to |η|~3.
- Coverage of high rapidities (θ<5°) achieved with separate detectors at large z positions (far from interaction along beam line)

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$





Next

- Cross section measurement
- Search for a resonance
- Measurements of properties

Cross section measurements

- In principle: $R = L\,\sigma \rightarrow \sigma = \dfrac{N}{\int L dt}$
- In practice: $$\boxed{\sigma = \frac{N}{\varepsilon A \int L dt}}$$
  - N = Number of signal events but there could be background which needs to be subtracted out
  - N = N(measured) – N(background estimated)

Cross section measurements

- In principle: $R = L\,\sigma \rightarrow \sigma = \dfrac{N}{\int L dt}$
- In practice:

$$\boxed{\sigma = \frac{N}{\varepsilon A \int L dt}}$$

  - A = the detector has a finite geometrical acceptance
    - Not full 4π coverage (holes, beam)
    - Particle needs P_T large enough to pass through magnetic field to detectors

Cross section measurements

- In principle: $R = L\,\sigma \rightarrow \sigma = \dfrac{N}{\int L dt}$
- In practice:

$$\boxed{\sigma = \frac{N}{\varepsilon A \int L dt}}$$

  - E = efficiency
    - The detector may not be 100% efficient (≠ acceptance)
    - Events are selected to retain signal and minimize background
      - Ie, muons with $P_T > 20$ GeV, $|\eta| < 2.0$ (highly efficient for signal)
    - Events with poorly measured objects are rejected

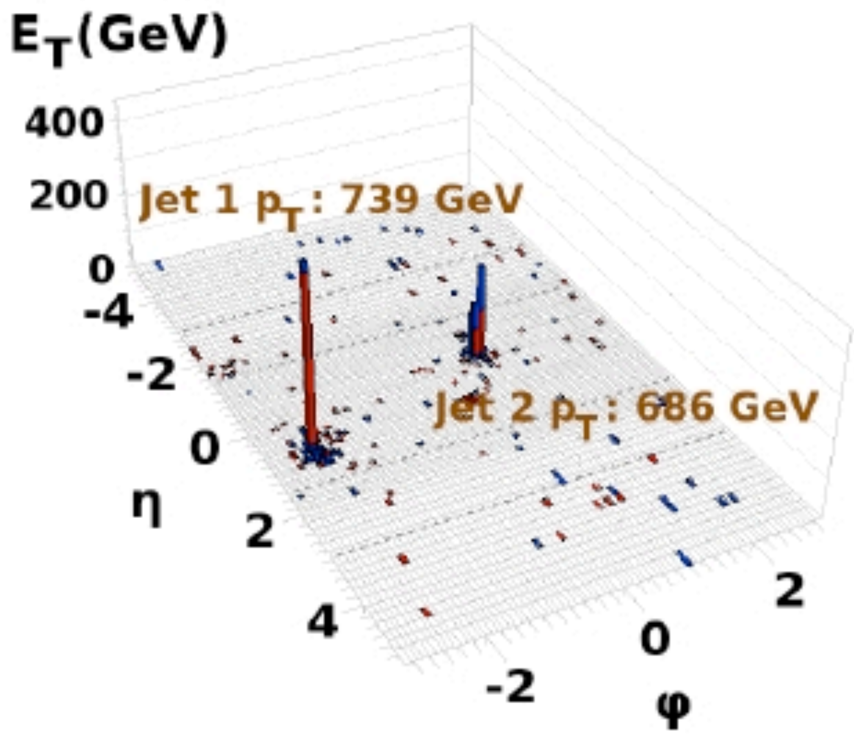
Cross section measurements

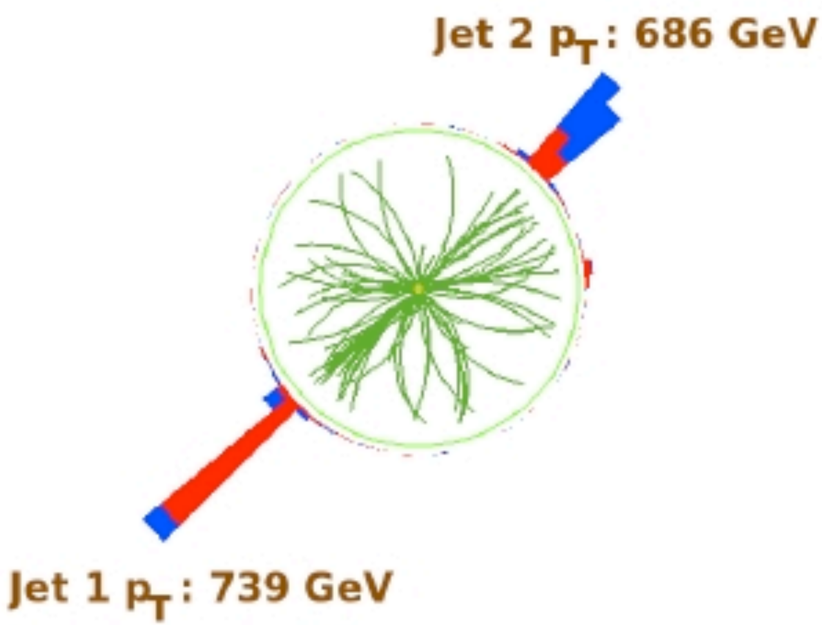
- In principle: $R = L\sigma \rightarrow \sigma = \dfrac{N}{\int L dt}$
- In practice:

$$\boxed{\sigma = \frac{N}{\varepsilon A \int L dt}}$$

  - Systematic uncertainties need to be evaluated
    - What sources could have produced changes in our measurement of N

Example: dijet cross section



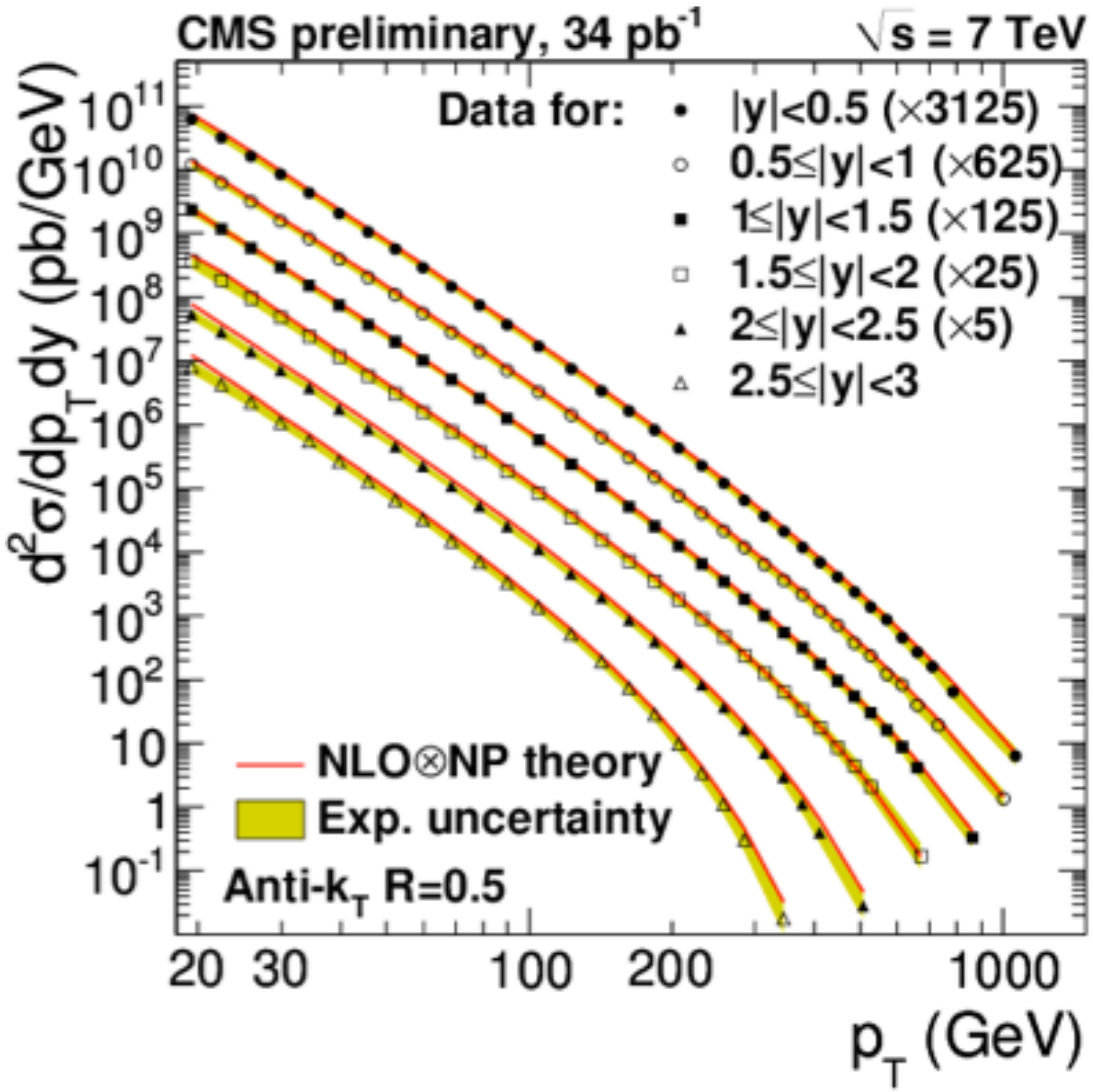


Histogram shows the energy in each cell (after calibration)

The **calorimeter** measures the deposited energy in cells of the (η,φ) plane (including *neutral* particles): need to go from charge signals to energy → calibrate

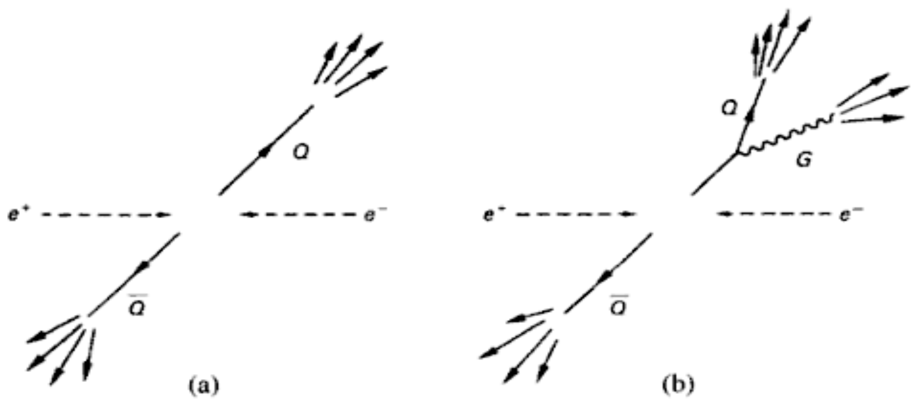
Example: dijet cross section

- Measurement of the "differential" cross section as a function of p_T for different bins of y (rapidity)
- The events migrate between analysis bins due to finite resolution ("smearing acceptance")
  - Effect needs to be corrected

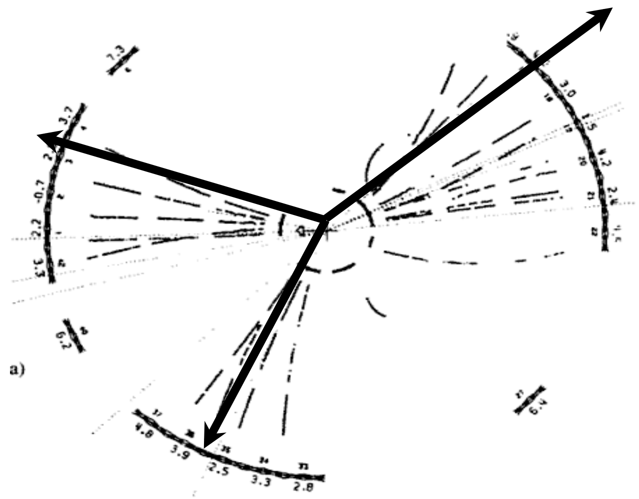


Three jets in e+e- annihilation

- Electron-proton pairs can annihilate producing quark pairs (e.g. at LEP)
- In some cases, a gluon can be radiated from the out-coming quark



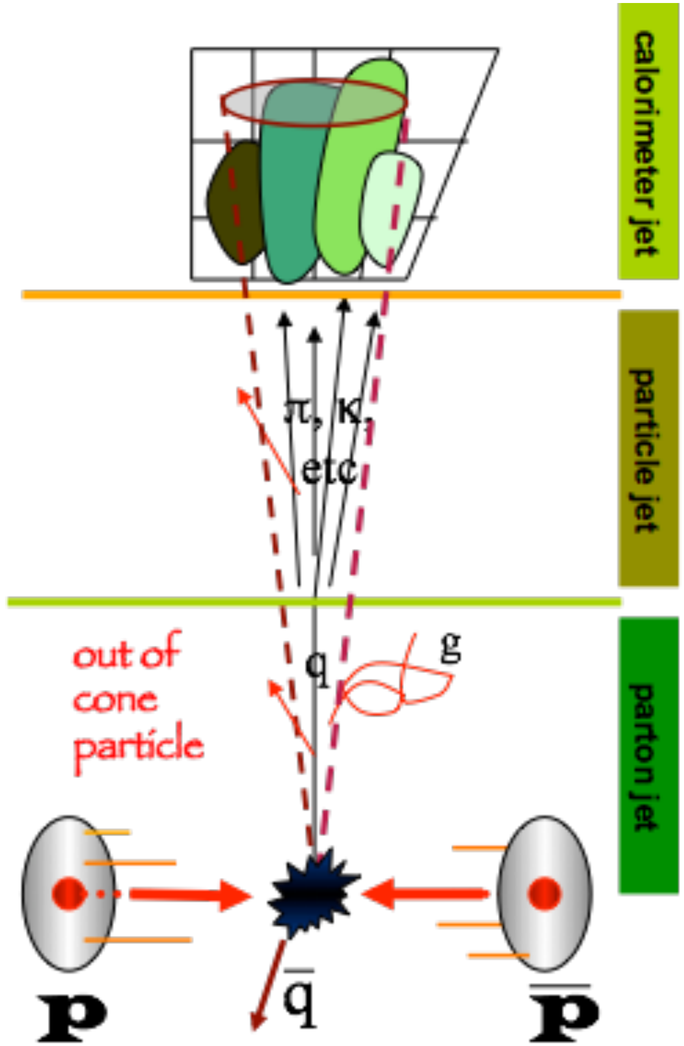
Two quark jets and one gluon jet



- In the latter case one observes three particle jets in the final state:
- Two quark jets and one gluon jet
- If no particle escapes the detector the three jets must have total transverse energy equal to zero

About jet measurements: scale

- Quarks "dress" themselves in hadrons (Pions, Kaons…)
  - Fragmentation
- Quarks give rise to "jets" which carry the momentum of the parent quark
  - Reconstruct quark 4-vector from the jet
- Need a "jet algorithm"
  - Calorimeter does not have a perfect response to measure the energy of all particles
  - The algorithm does not catch all energies belonging to the jet
- Jet energy correction (scale) to get back to the quark energy (+ its systematic uncertainty)

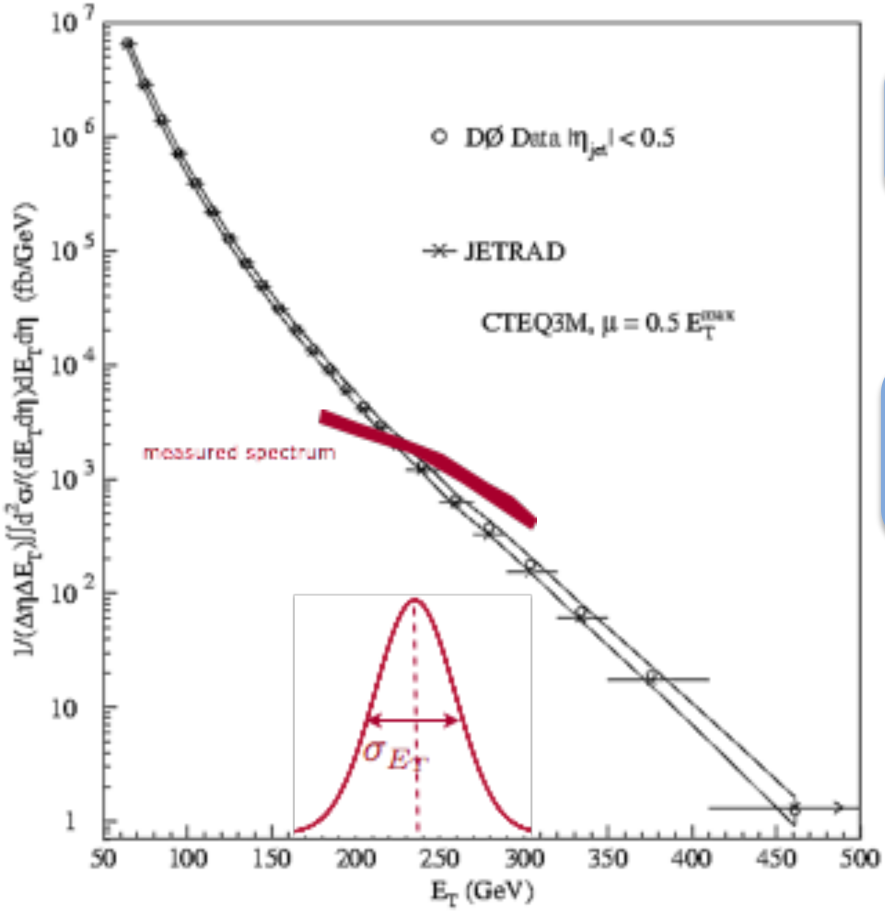


About jet measurements: scale

- Example:
  - True p_T = 10 GeV particle
  - Measurement in calorimeter p_T = 8 GeV
  - Jet energy scale correction (done on average) 1.25 with an uncertainty of 5%
  - Final measurement 10±0.4 GeV

About jet measurements: resolution

- The finite resolution can distort the spectrum
- Critical because of very steeply falling spectrum!



$$N\left(E_T^{\mathrm{meas}}\right) = \int_0^\infty N\left(E_T^{\mathrm{true}}\right) \cdot \mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \mathrm{d}E_T^{\mathrm{true}}$$

eg. Gaussian resolution function

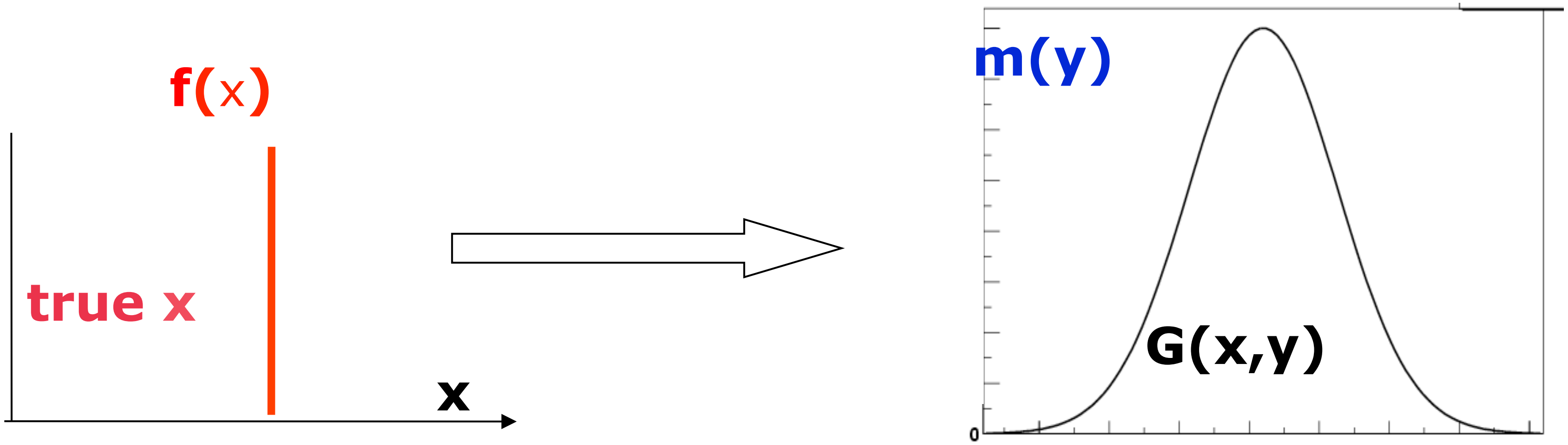
$$\mathrm{Resol}\left(E_T^{\mathrm{meas}}, E_T^{\mathrm{true}}\right) \propto \exp\left[-\frac{\left(E_T^{\mathrm{meas}} - E_T^{\mathrm{true}}\right)^2}{\sigma_{E_T}^2}\right]$$

➔ have to determine the energy resolution
➔ have to “unfold” the measured spectrum
➔ problem is minimized if bin width ~ σ_{E_T}

Unfolding of distributions

- "true" pdf = f(x); true value of x is measured as
- detector resolution = G(x,y); very often a Gaussian, with mean value μ and error σ
  -> actually measured distribution = **m(y)**

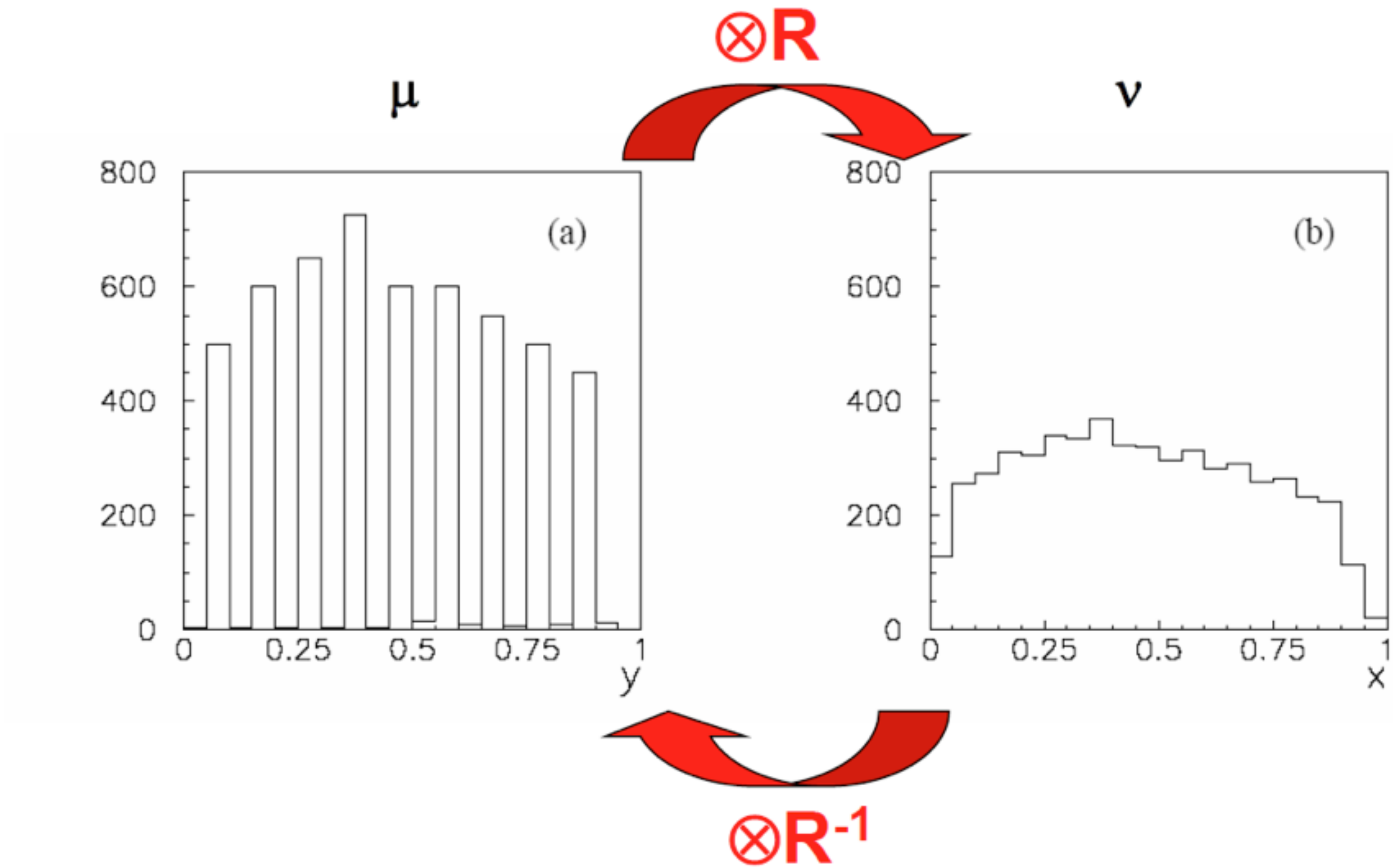
$$m(y) = \int_{x\,min}^{x\,max} G(x,y)\, f(x) \cdot dx$$



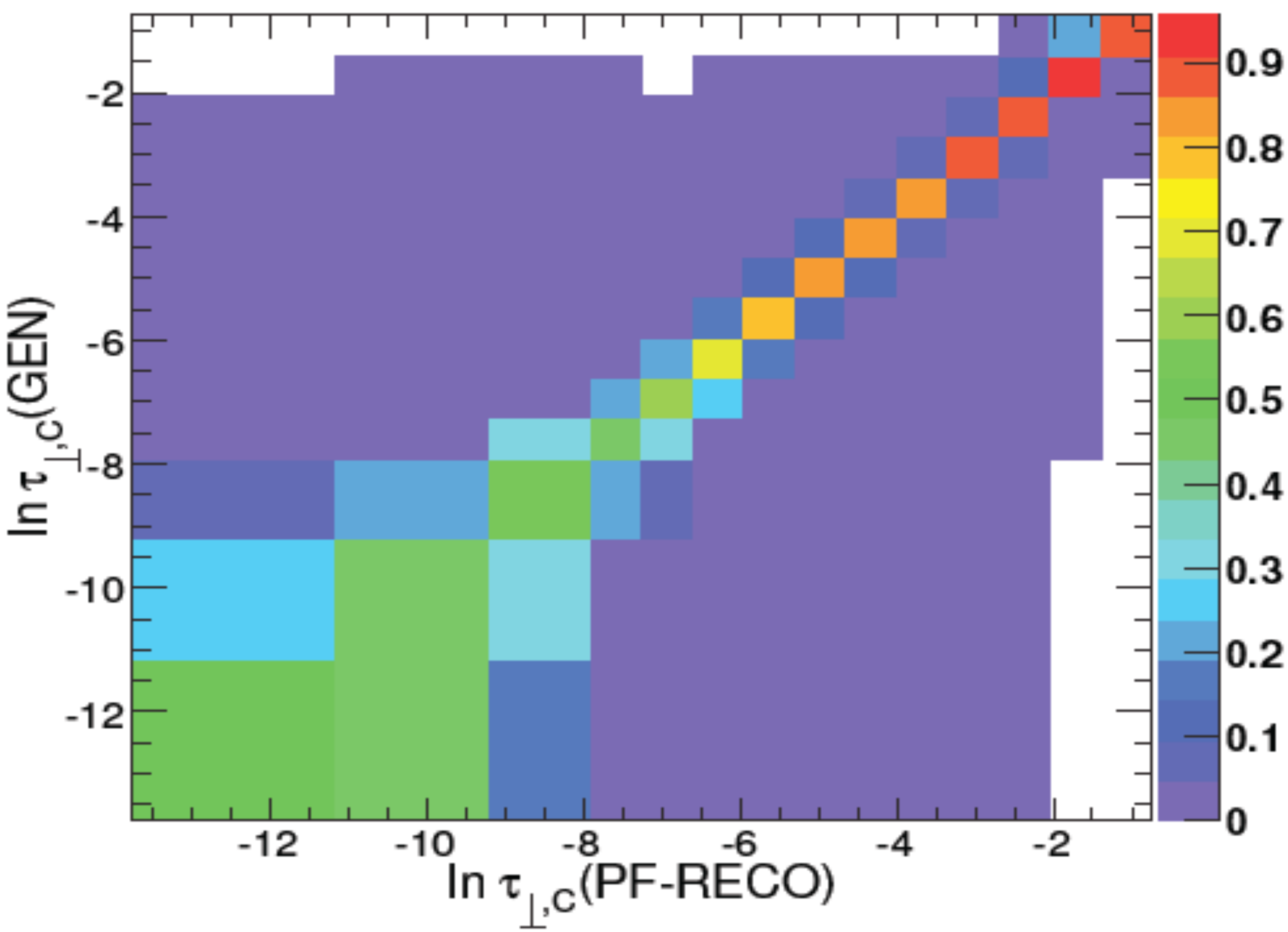
Experimentalists job: extract f(x) from the measured m(y):

- easiest case: pure inversion
- more complicated cases: topic of ***"unfolding"***

Response matrix



Example of a Response matrix



Example for unfolding

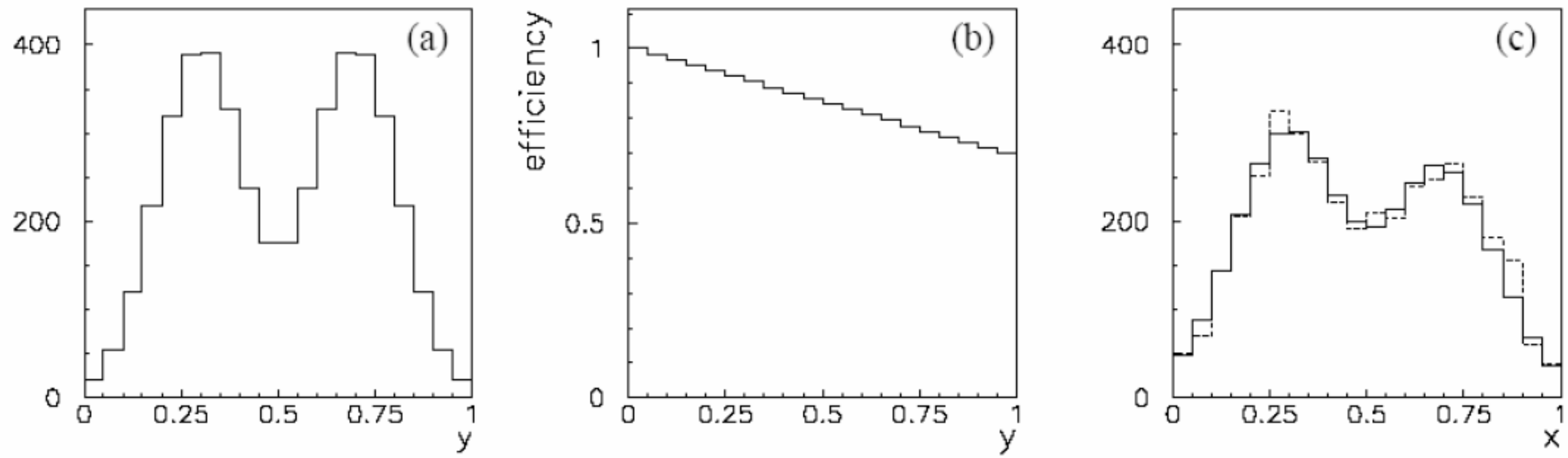


Fig. 1: Illustration of ingredients for unfolding: (a) a 'true histogram' $\boldsymbol{\mu}$, (b) a possible set of efficiencies $\boldsymbol{\varepsilon}$, and (c) the observed histogram $\mathbf{n}$ (dashed) and the corresponding expectation values $\boldsymbol{\nu}$ (solid).

Figures from: A survey of unfolding methods for particle physics. G. Cowan (London, City U.) . Mar 2002.

Example for unfolding

- Simple inversion of the response matrix often unstable:

μ — $\nu \neq \mathbf{n}$ ---- $\hat{\mu} = R^{-1}(\mathbf{n} - \beta)$

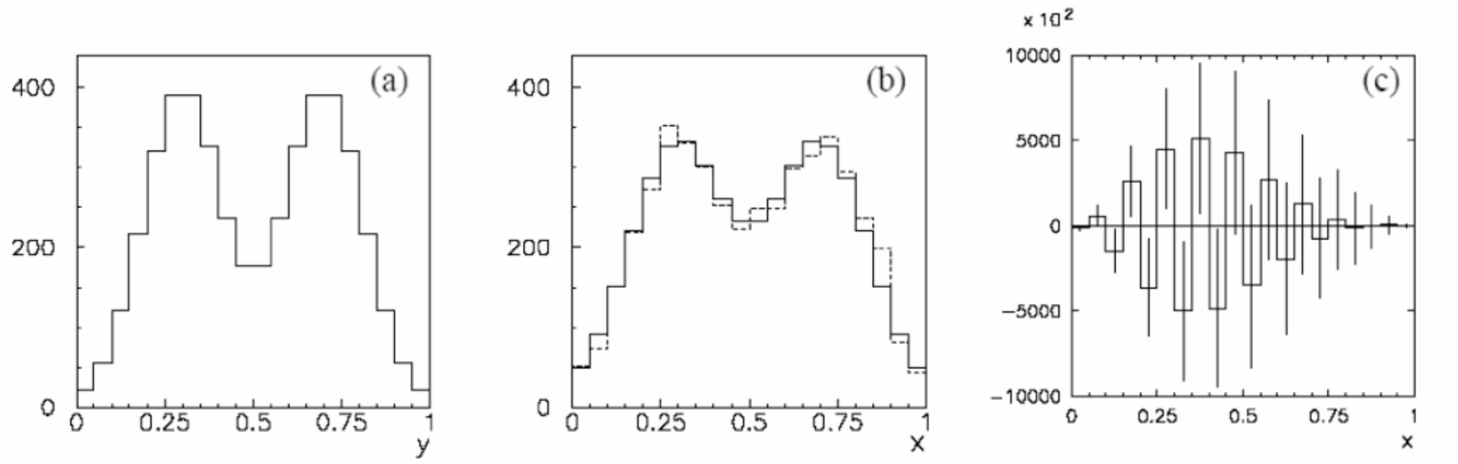


Fig. 2: Attempt to unfold using matrix inversion: (a) the 'true histogram', (b) the observed histogram $\mathbf{n}$ (dashed) and corresponding expectation values $\boldsymbol{\nu}$ (solid), (c) the estimators $\hat{\boldsymbol{\mu}}$ based on equation (8).

- Check course 402-0738-00L" Statistical Methods and Analysis Techniques in Experimental Physics" in Spring (C. Grab, M. Donega)

Search for a resonance

- Many of the searches for new particles are done by scanning the invariant mass spectrum for a given set of final state particles

- This is one of the cleanest ways to discover new particles
  - But less effective if the new particle decays to unobserved particles

Invariant mass – recall

- Characteristic of the total energy and momentum of an object or a system of objects that is the same in all frames of reference

- When the system as a whole is at rest, the invariant mass is equal to the total energy of the system divided by c². If the system consists of one particle, the invariant mass may also be called the **rest mass**

$$\boxed{(mc^2)^2 = E^2 - \|\mathbf{p}c\|^2}$$

natural units (c=1): $\boxed{m^2 = E^2 - \|\mathbf{p}\|^2.}$

- For a system of N particles:

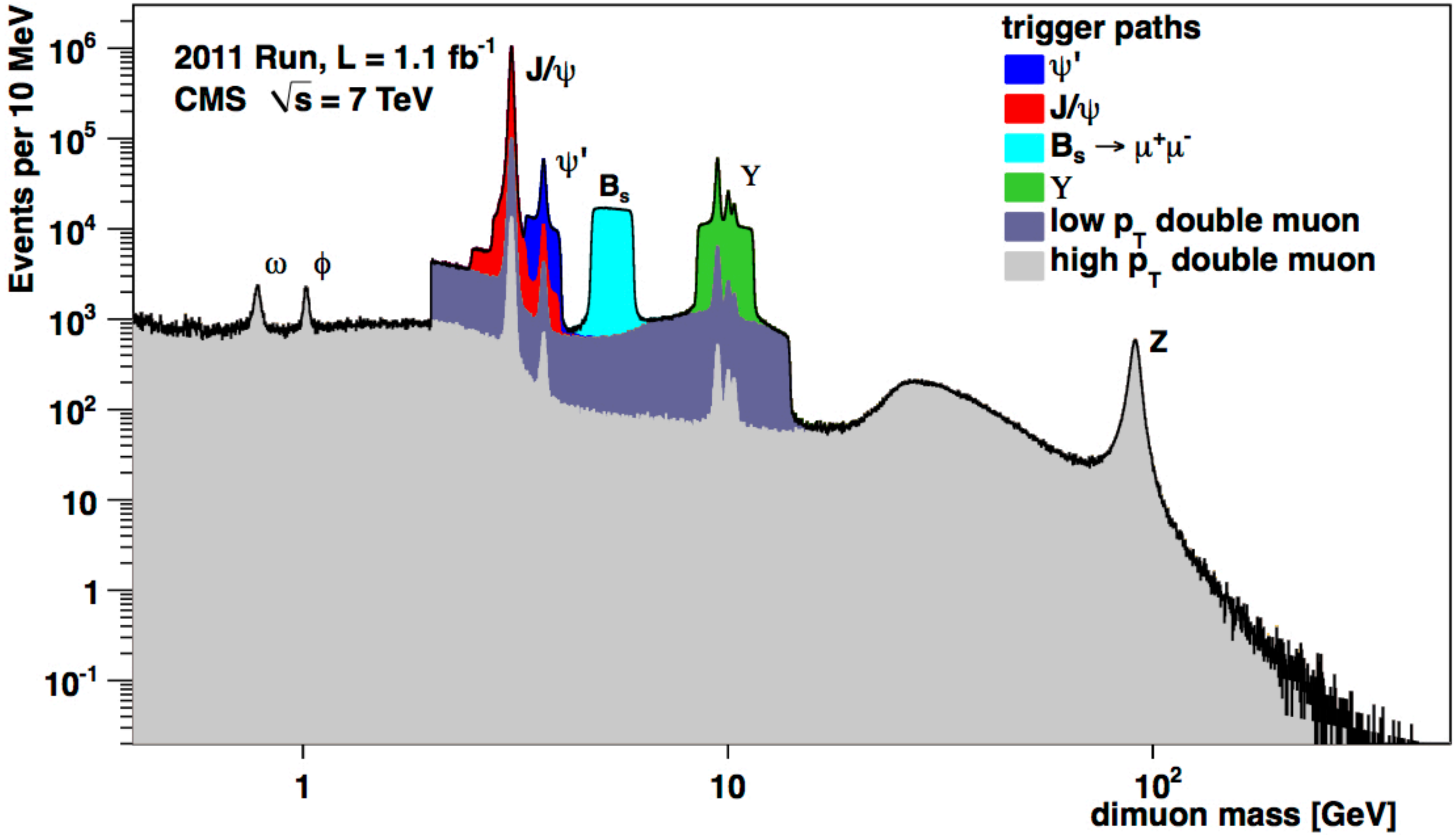
$$(Wc^2)^2 = \left(\sum E\right)^2 - \left\|\sum \mathbf{p}c\right\|^2$$

where W is the invariant mass of the decaying particle

- In a two body decay $M \to 1+2$:

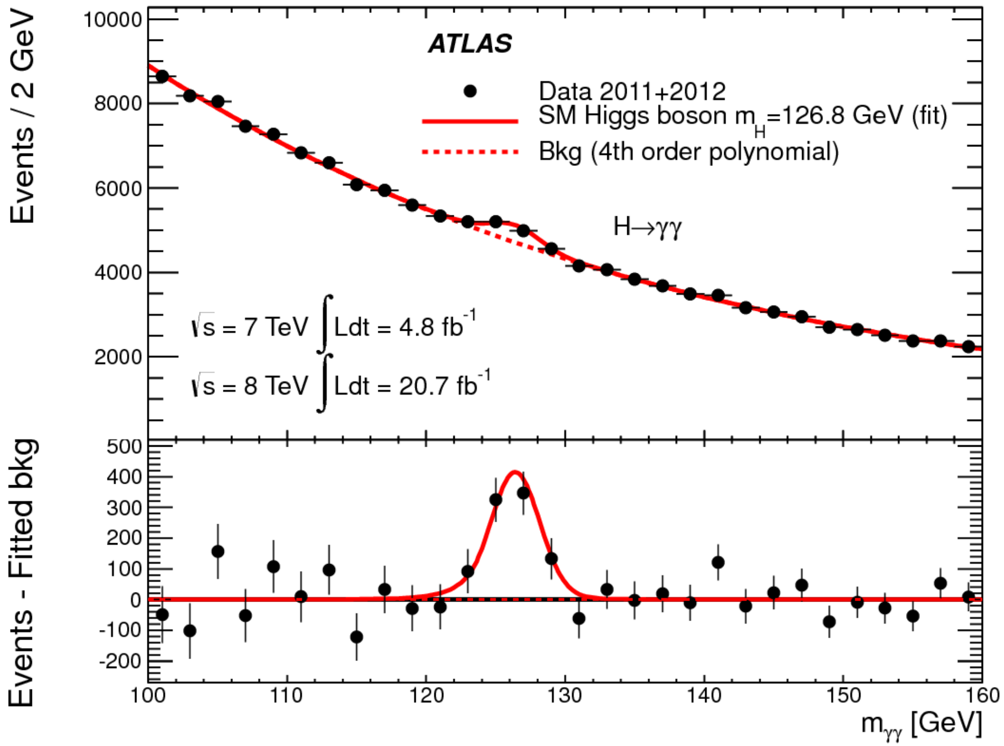
$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 = m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right).$$

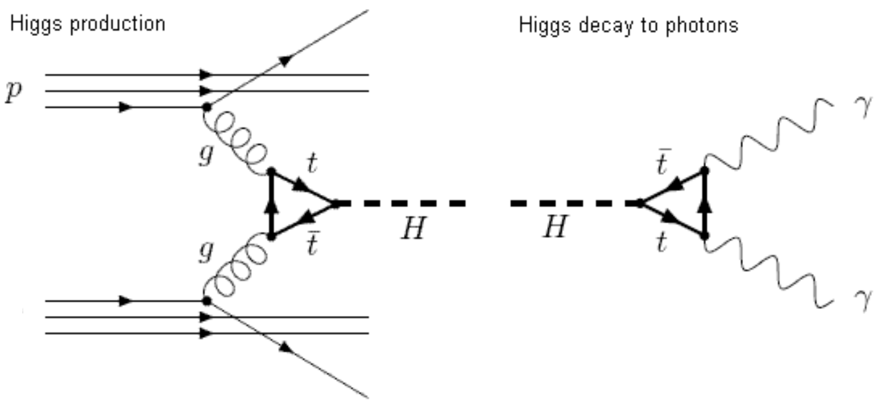
Example: di-muon reconstruction



Example: Higgs → γγ

- Select events with 2 photons
- Calculate invariant mass





Need to understand the backgrounds, amount (normalization) and their shape

Use for the Higgs discovery

Example: 3 body mass decay

- In case of a 3-body decay: $\boxed{R \Rightarrow 1+2+3.}$

- We can construct three invariant masses:

$$\begin{aligned} m_{12}^2 &\equiv (\mathcal{P}_1+\mathcal{P}_2)^2, \\ m_{13}^2 &\equiv (\mathcal{P}_1+\mathcal{P}_3)^2, \\ m_{23}^2 &\equiv (\mathcal{P}_2+\mathcal{P}_3)^2 \end{aligned}$$

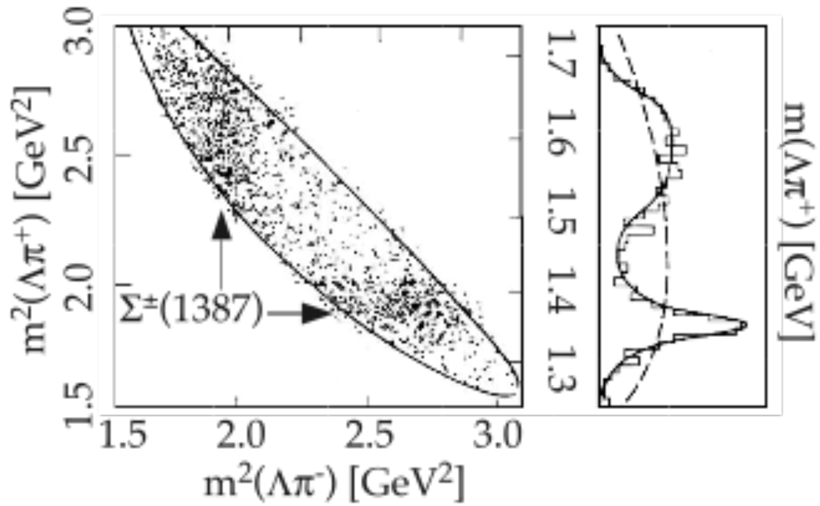
- For the three body case one finds:

$$\begin{aligned} m_{12}^2+m_{13}^2+m_{23}^2 &= m_1^2+m_2^2+m_3^2+(\mathcal{P}_1+\mathcal{P}_2+\mathcal{P}_3)^2 \\ &= m_1^2+m_2^2+m_3^2+M^2. \end{aligned}$$

- Only two independent invariant masses

Example: 3 body decay

- As an example, let's study the reaction: $K^- p \to \Lambda\, \pi^+ \pi^-\ (\Lambda \to \pi^- p),$
- We can measure two invariant masses $m_{12} \equiv m(\Lambda\pi^-)$
  $m_{13} \equiv m(\Lambda\pi^+)$
- The so-called "Dalitz plot" shows the relation between $(m_{13})^2$ and $(m_{12})^2$



- The $\Sigma^\pm$ resonance appears as two bands in the Dalitz plot around 1.4 GeV

$$\Sigma^\pm(1387) \to \Lambda\pi^\pm.$$

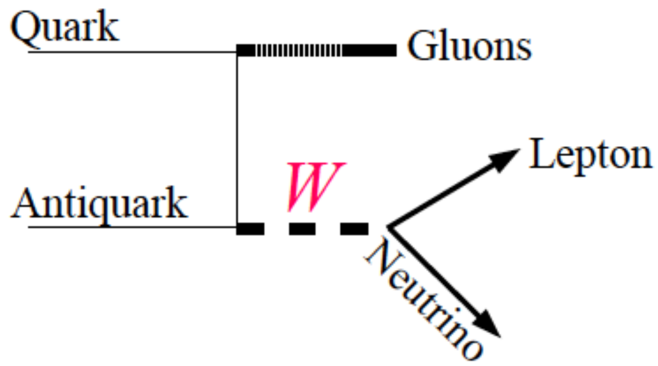
Measurements

- Properties of particles
  - Is it the particle that we think it is ?
  - Mass, couplings to other particles, lifetimes, etc.

- Use variables that can be extrapolated to the original property
  - Use simulation of different properties to fit data shapes

Example: W mass measurement

- The W boson is produced in proton collisions mainly via the following process:



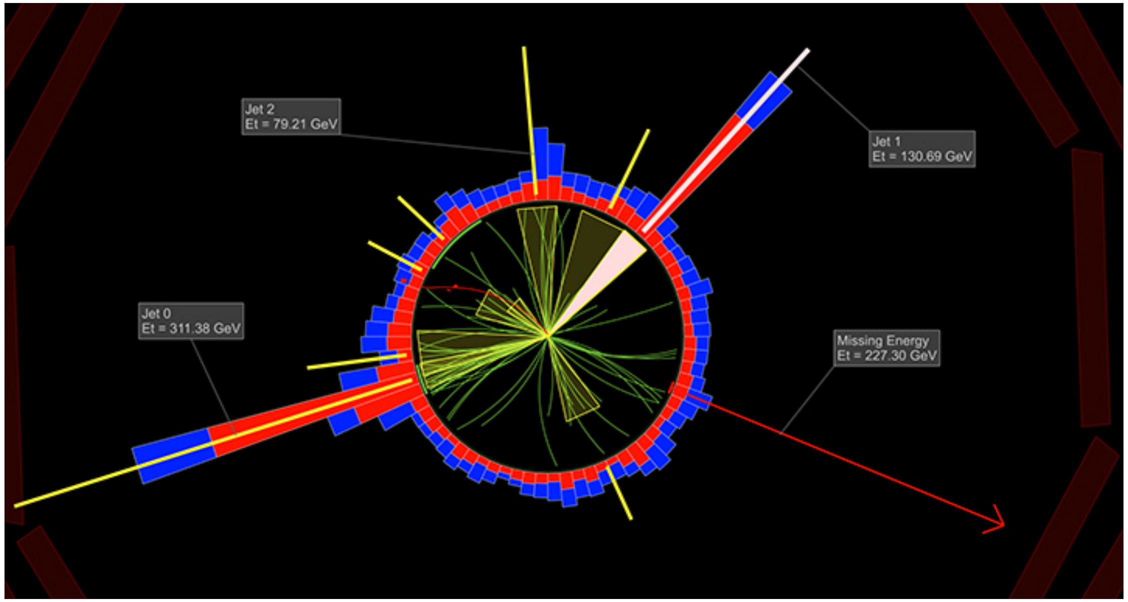
- A u-quark collides with an anti-d quark producing a W^+ boson
- The W^+ decays into lepton (muon) and neutrino pairs
- The lepton is detected and its momentum can be measured
- The neutrino escapes the detector undetected:
  - The total sum of the transverse momenta is not zero!

- In other words, the experimental signature of the neutrino in the experiment is the **missing transverse momentum**

Missing transverse momentum

- An imbalance in the momentum may signal the presence of undetectable particles, such as neutrinos or new stable, weakly-interacting particles

- The vector momentum imbalance in the transverse plane is obtained from the negative vector sum of the momenta of all particles detected in a proton-proton (pp) collision and is denoted as missing transverse momentum, E_T^{miss}, or MET



$$\bar{p}_T^{miss} = -\sum_{i=objects} \bar{p}_{T,i}$$

Example: W-boson discovery

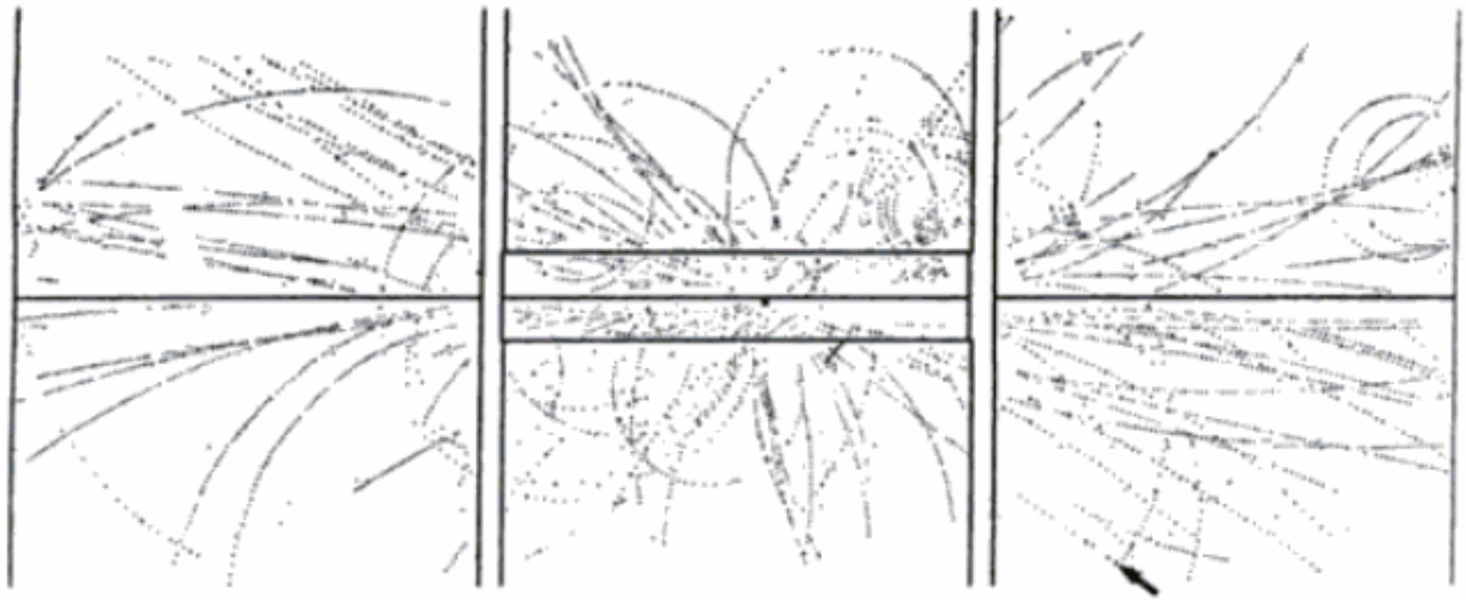


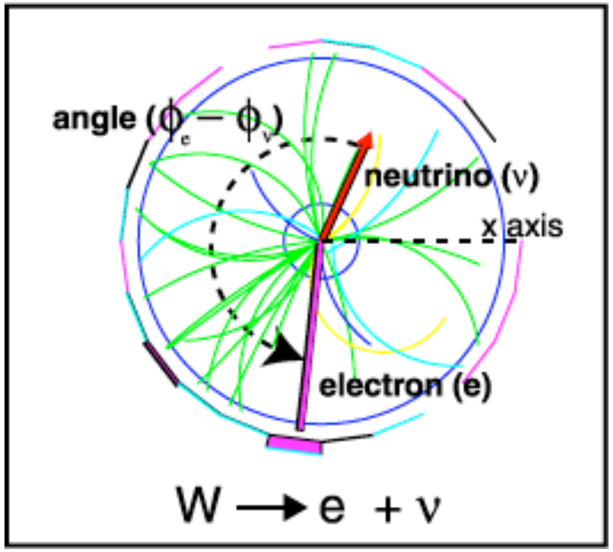
Fig. 2.8. One of the first events attributed to production and decay of a W boson, $W^+ \to e^+ + \nu_e$. The picture shows a reconstruction of the drift chamber signals in a large detector, UA1, surrounding the beam pipe of the CERN proton–antiproton collider. These signals originated in the collision of a 270 GeV proton (from the right) with a 270 GeV antiproton (from the left). Among the 66 tracks observed, one, shown by the arrow, is a very energetic (42 GeV) positron identified in a surrounding electromagnetic calorimeter. The transverse momentum of the positron is 26 GeV/c, while the missing transverse momentum in the whole event is 24 GeV/c, consistent with that of the neutrino (from Arnison *et al.* 1983).

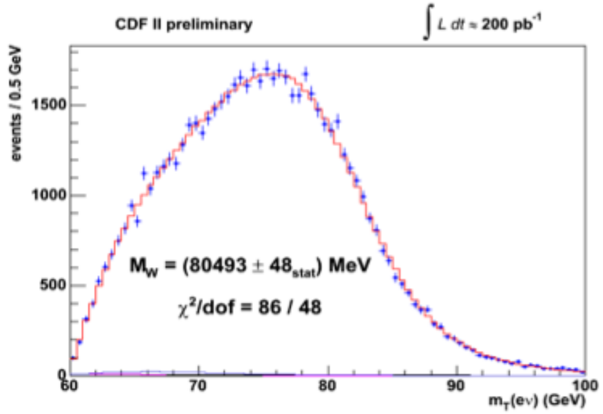
W - “transverse mass”

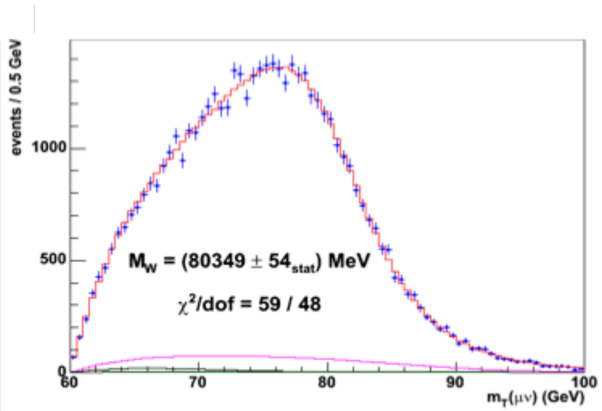
- Partial W-boson mass reconstruction from lepton and neutrino:

$$m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$

$$\leq M = (E^2 - \mathbf{p}^2)^{1/2}$$







CDF II preliminary $\qquad$ L = 200 pb^{-1}

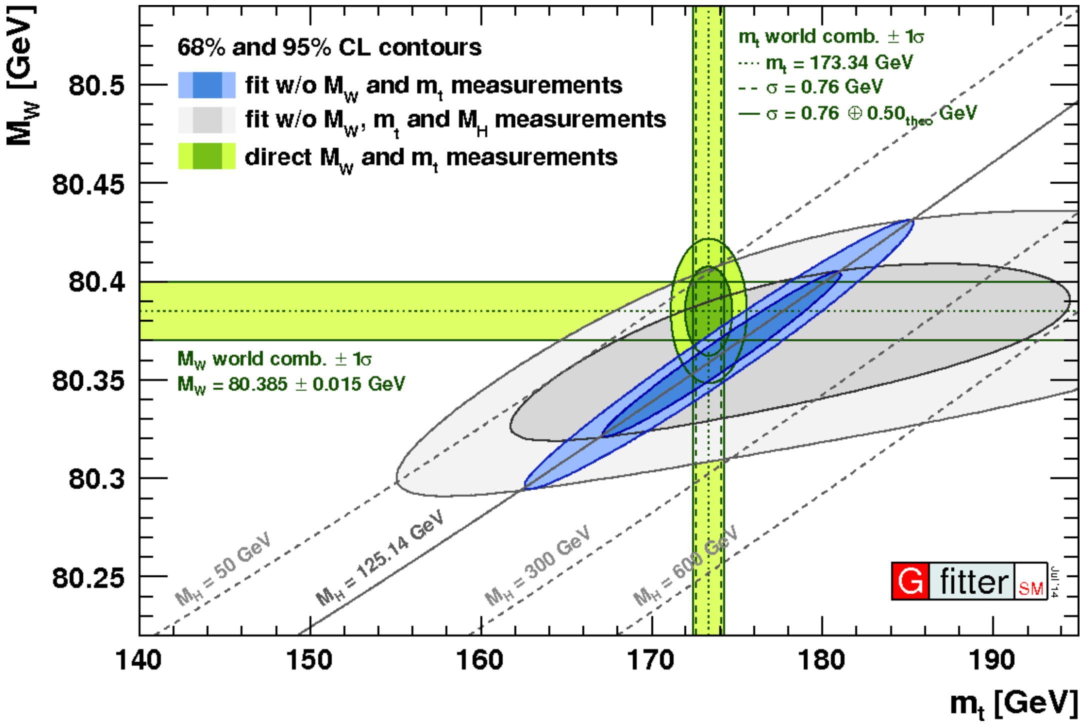
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

0413 ± 34 MeV (stat) ± 34 MeV (sys)

= 80413 ± 48 MeV (stat + sys)

W mass important in el.weak fits

- A precise measurement of MW provides a crucial test of the SM



M_W at tree level

- $-M_{W_2} = (\pi\ \alpha EM) / (\sqrt{2}\ GF\ \sin 2\vartheta W)$
- Where ϑ_W is the weak mixing angle, $\cos\vartheta W = M_W/M_Z$

Missing mass

- A collision is characterized by an initial total energy and momentum

- In the final state we have n particles:
  - $E=\Sigma_i E_i$, $p=\Sigma_i p_i$
  - Sometime we measure $E<E_{in}$ and $p \neq p_{in}$
- In this case one of more particles have not been detected
  - Typically: neutral particles
  - Most often neutrinos, but also neutrons, π^0, K_{0L} (the latter for long decay time)
- We define the concept of missing mass:

$$\boxed{\text{Missing mass} = [(E_{in}-E)^2-(\mathbf{p}_{in}-\mathbf{p})^2]^{1/2}}$$

- If the spectrum of the missing mass has a well-defined peak, then one particular particle has escaped our detector.