Collider-Based Experiments
Lecture 2

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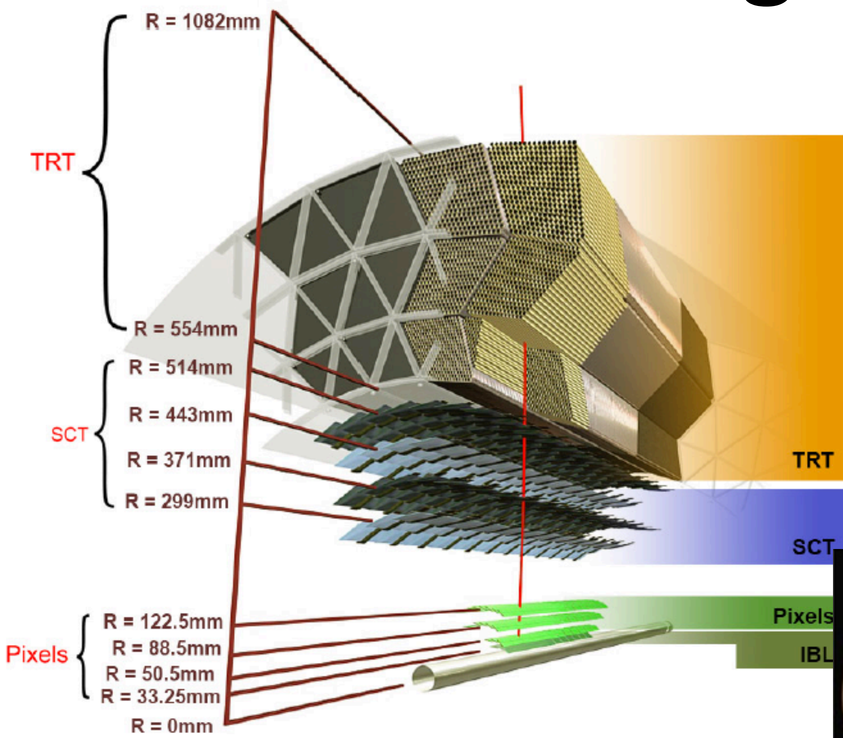
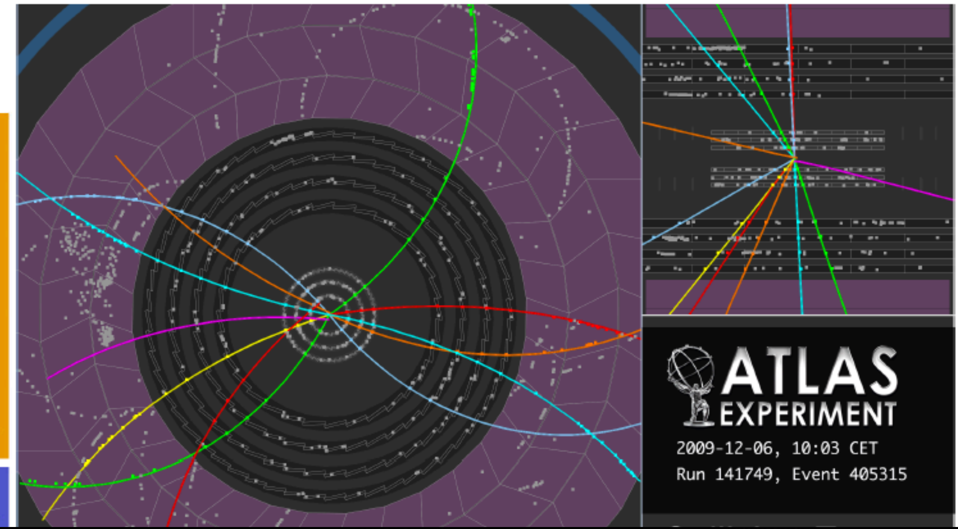
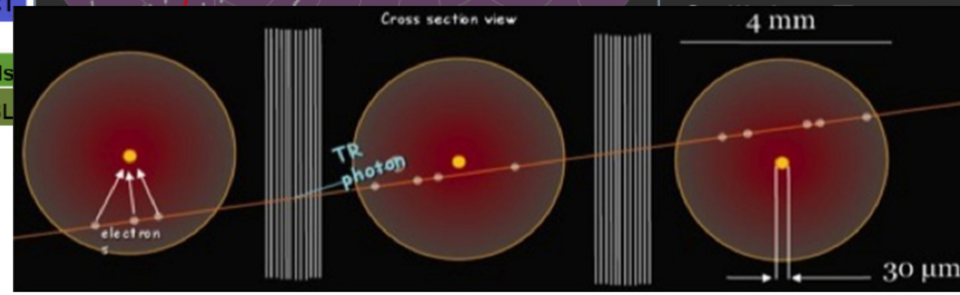
Tracking

Tracking detectors







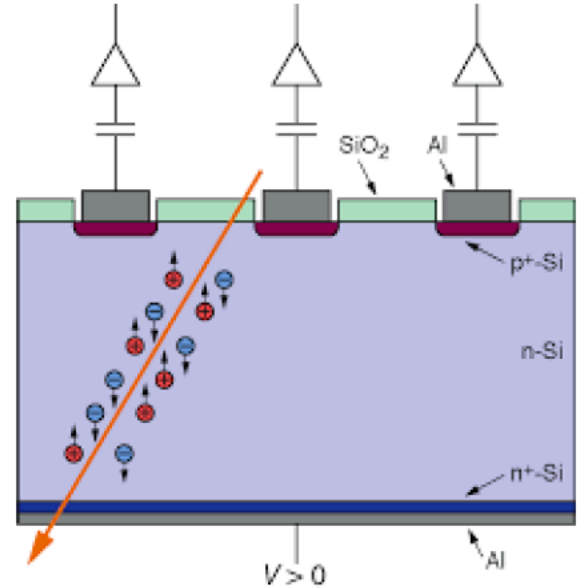
Typical resolutions:

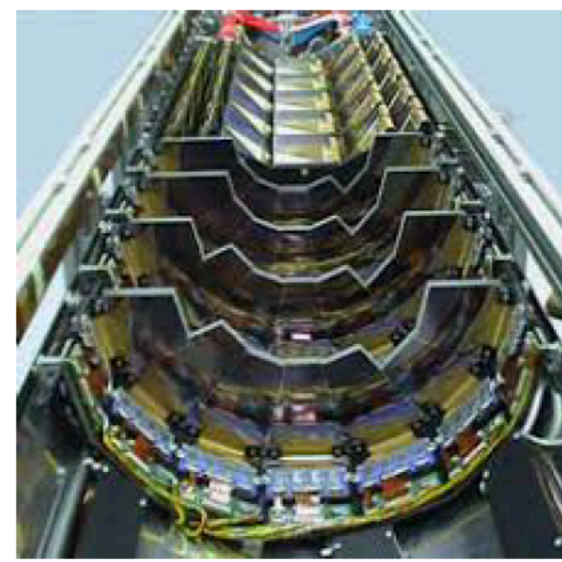
- Transition Radiation Tracker (TRT) straws: 100 – 150 μm/straw
- SemiConductor Tracker (SCT): 20 – 30 μm/silicon strip
- Pixel Detector: 5 – 15 μm/pixel
- Also Inner B-Layer: pixel layer at only 3 cm from beampipe

Example: silicon microstrip detectors

Typical parameters:

- Thickness: 300 – 500 $\mu\mathrm{m}$
- Pitch: 20 – 150 $\mu\mathrm{m}$
- Resolution: pitch$/\sqrt{12} \sim 5 - 40\ \mu\mathrm{m}$
  - In practice can get better than this (e.g. ZEUS MVD):
  - Expected: $120/\sqrt{12}8.3\ \mu\mathrm{m}$
  - Measured: 7.5 $\mu\mathrm{m}$
  - Improvement from adding 5 adjacent strips by capacitive charge division
- Charge collection: 20 ns
- Charge integration: 120 ns
- Operation voltage: 160 V
- Total charge: $\sim 4\ \mathrm{fC}$
- MIP energy loss (Si): $\sim 300\ \mathrm{eV}/\mu\mathrm{m}$



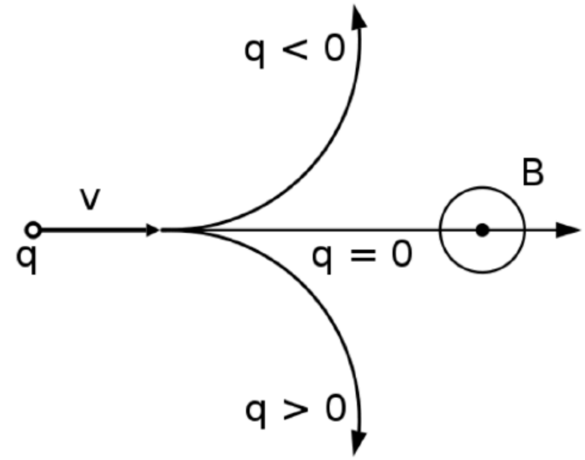


Exercise: What charge is produced by a MIP in a 300 $\mu\mathrm{m}$ thick Si detector? (PDG tab. 6.1)

Momentum measurement

- Charged particle trajectories are bent by magnetic field
- Lorentz force:

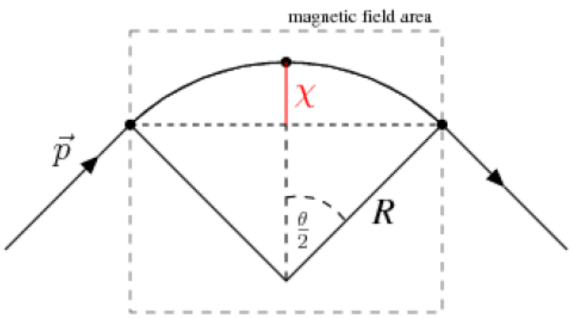
$$\vec{F}_M = q\vec{v} \times \vec{B}$$



- If particle $\perp$ to $\vec{B}$ field:

$$|\vec{F}_M| = |\vec{F}_{centr.}| = \gamma m \omega^2 \Leftrightarrow \gamma m \frac{v^2}{R} = qvB$$

$$\Leftrightarrow p = qRB$$



In a fixed target experiment we usually have a dipole magnet with $\vec{B}$ field perpendicular to the beam

Exercise: What is the radius of a 1 TeV muon in a 4 T magnetic field?

Solution: $R = \frac{1\times10^{12}[\mathrm{eV/c}]\times1.6\times10^{-19}[\mathrm{J/eV}]}{4[\mathrm{T}]\times1.6\times10^{-19}[\mathrm{C}]\times3\times10^{8}[\mathrm{ms^{-1}/c}]}$ or $R = 833$ m

Exercise: Express the momentum measurement in GeV/c as a function of the magnetic field in Tesla and the track radius in metres.

Solution: $p[\mathrm{GeV/c}] = 0.3\mathrm{B[T]} \times \mathrm{R[m]}$

- Writing 1 $[\mathrm{GeV/c}]$ in SI units we have:

$$1\,[\mathrm{GeV/c}] = \frac{10^9[\mathrm{eV/c}] \times 1.602 \times 10^{-19}[\mathrm{J/eV}]}{3 \times 10^8[\mathrm{ms^{-1}/c}]} = 5.34{\times}10^{-19}[\mathrm{Jm^{-1}s}]$$

- I.e., to convert from SI momentum units to $\mathrm{GeV/c}$, divide by $5.34 \times 10^{-16}[\mathrm{Jm^{-1}s}] = 5.34 \times 10^{-16}[\mathrm{Ns}]$
- Assuming a single-charged particle we have $q = 1.602 \times 10^{-19}$ C:

$$p\ [\mathrm{kgm^2}] = \mathrm{eRB} = 1.602 \times 10^{-19}[\mathrm{C}] \times \mathrm{B[T]} \times \mathrm{R[m]}$$

- Converting to SI units we get:

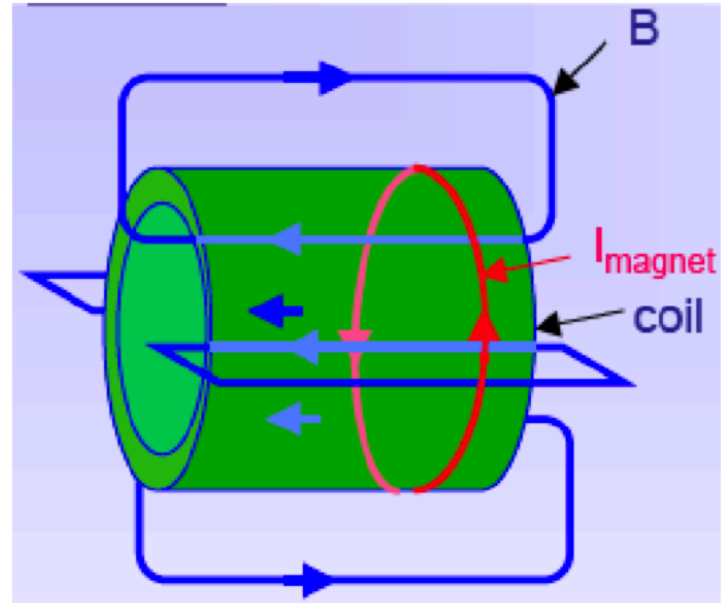
$$p\ [\mathrm{GeV/c}] = \frac{1.602 \times 10^{-19}[\mathrm{C}]}{5.34 \times 10^{-16}[\mathrm{Jm^{-1}s}]} \times \mathrm{B[T]} \times \mathrm{R[m]}$$

- So we finally get:

$$p\ [\mathrm{GeV/c}] = 0.3 \times \mathrm{R}\ [\mathrm{m}] \times \mathrm{B}\ [\mathrm{T}]$$

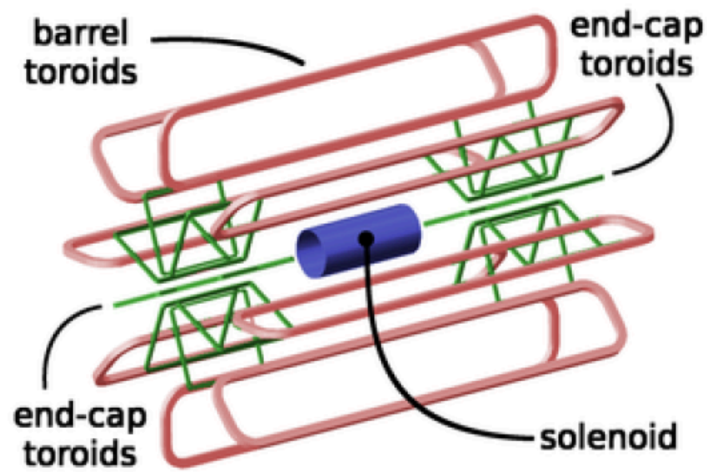
Solenoid:

- + Large homogeneous field inside magnet volume
- - Weak opposite field in return yoke volume
- - Size limited by cost
- - Relatively large material budget

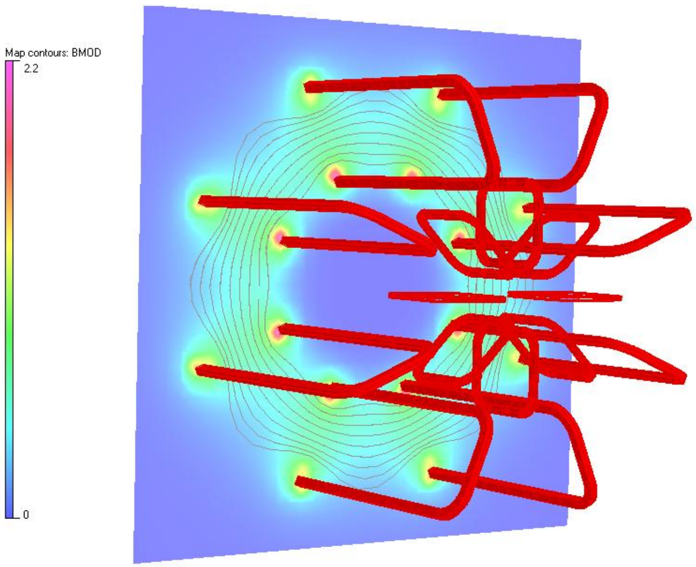


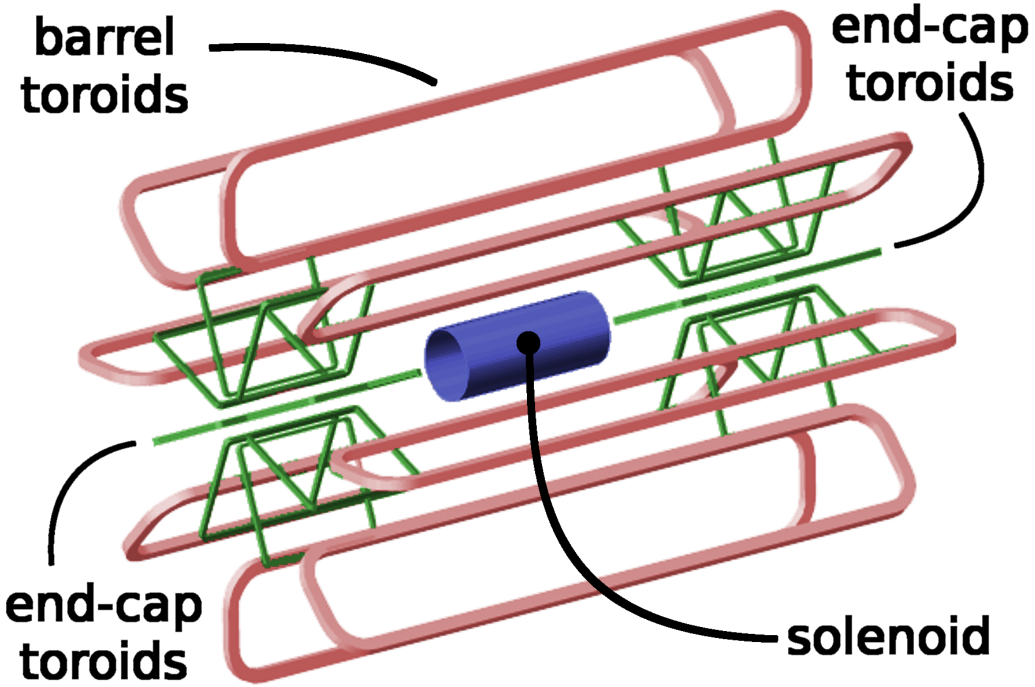
Toroid:

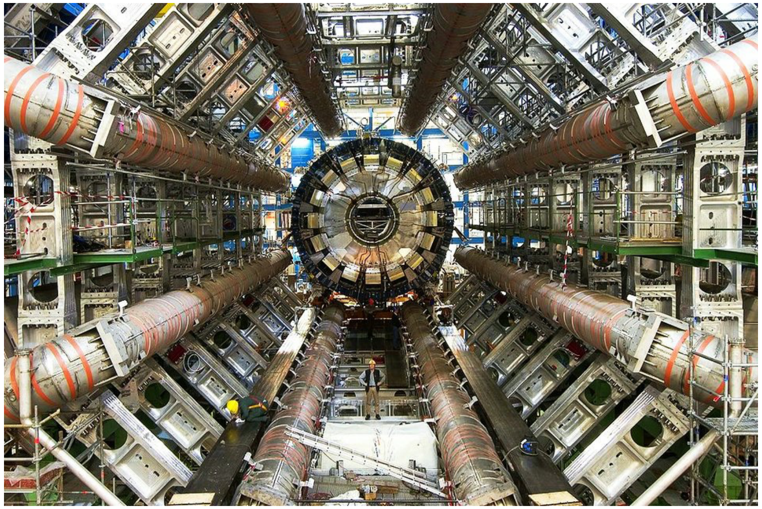
- + Field always perpendicular to transverse momentum
- + Relatively large fields over large volume
- + Rel. low material budget
- - Non-uniform field
- - Complex structural design



ATLAS Magnetic Field







- Strong magnetic fields (2 – 4 T) in a large tracking volume
- Complicated field map needs to be well modelled in reconstruction software

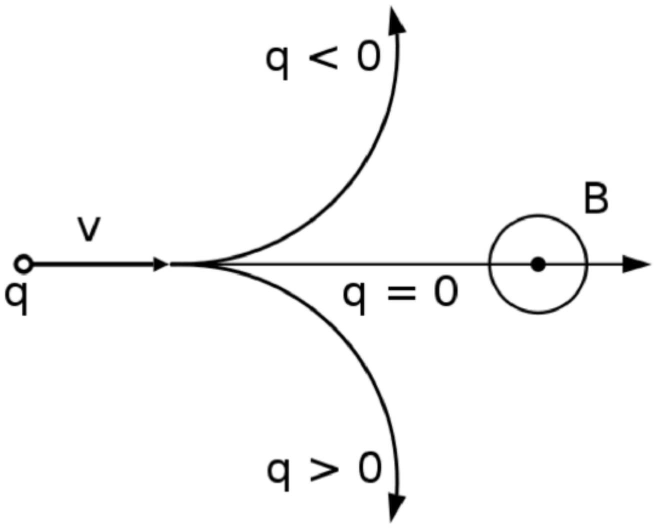
Momentum measurement uncertainty

Using sagitta measurement:

- From the expressions for the transverse momentum and the track radius:

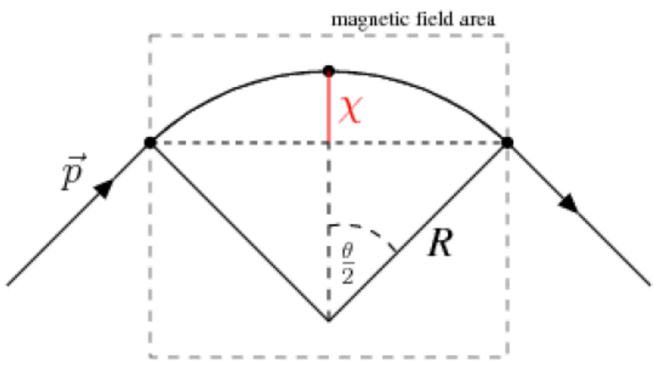
$$p_T = qRB \; ; \; R = \frac{L^2}{8\chi}$$

- Assuming L is fixed (size of tracking volume) we get:



$$\frac{\Delta p_T}{p_T} = \frac{\left|\frac{\partial p_T}{\partial R}\Delta R\right|}{p_T} = \frac{qB\Delta R}{qRB} = \frac{\Delta R}{R}$$

$$= \frac{\left|\frac{\partial R}{\partial \chi}\Delta \chi\right|}{R} = \frac{\frac{L^2}{8\chi^2}\Delta\chi}{R} = \frac{L^2}{8R\chi}\frac{\Delta R}{\chi}$$



Example:

- Assume $L = 4\ \mathrm{m}$ and $B = 4\ \mathrm{T}$ for a particle with $p_T = 1\ \mathrm{TeV}$:
- In that case we have:

$$R = \frac{p}{0.3B} = \frac{1000}{0.3 \times 4} = 833\ \mathrm{m}$$

and

$$\chi = \frac{L^2}{8R} = \frac{16}{8 \times 833} = 2.4\ \mathrm{mm}$$

- If the B field was $1\ \mathrm{T}$ instead of $4\ \mathrm{T}$ we would have:

$$\chi = \frac{L^2}{8R} = \frac{L^2}{8}\frac{0.3B}{p} = \frac{16}{8 \times 3333} = 0.6\ \mathrm{mm}$$

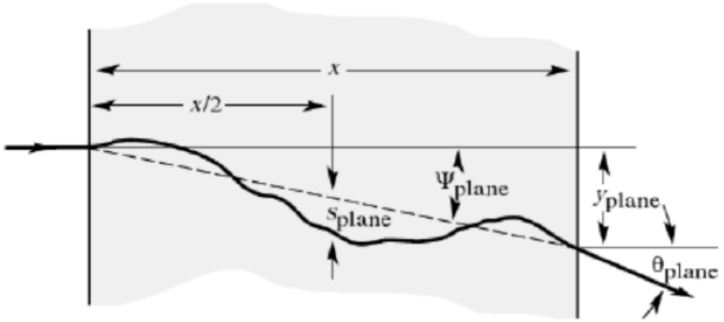
- To measure the momentum with a precision of 10%, i.e. $\frac{\Delta p_T}{p_T} = \frac{\Delta R}{R} = 0.1$ we need $\Delta\chi = 0.1 \times 0.6\ \mathrm{mm} = 60\ \mu\mathrm{m}$ for $B = 1\ \mathrm{TeV}$ or $240\ \mu\mathrm{m}$ for $B = 4\ \mathrm{TeV}$ or

Multiple scattering

Particles moving through the detectors suffer many collisions, causing both energy loss ($\frac{dE}{dx}$) and deviation from the original trajectory

- Multiple scattering adds a second term to the tracking resolution
- The lateral displacement y_p is proportional to the thickness of detectors
  - Can usually be neglected for thin semiconductor detectors
- Effect of multiple scattering depends on $1/p$ – 10 times more for a 1 GeV pion

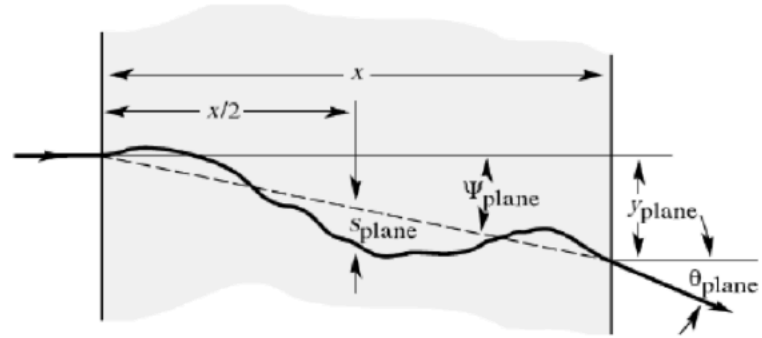
$$\left(\frac{\sigma p_T}{p_T}\right)^2 = \left(\frac{p_T}{BL^2}\right)^2 + \left(\frac{\sigma_\phi}{\phi}\right)^2$$



10 GeV pions:

material	thickness	X_0	θ_p [rad]	y_p [μm]
Ar	1 m	110 m	0.10×10^{-3}	80
Si	300 μm	9.4 cm	0.08×10^{-3}	0.01

Note that θ_p is the projected angle distribution on the scattering plane – otherwise need to consider the 3D broadening of the particle beam

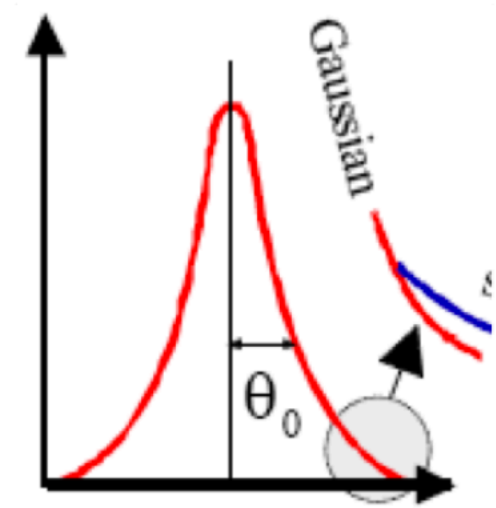


- The scattering angle has a distribution that is almost Gaussian

$$P(\theta_p) = \frac{1}{\sqrt{2\pi\langle\theta_p^2\rangle}} e^{-\frac{\theta_p^2}{2\langle\theta_p^2\rangle}}$$

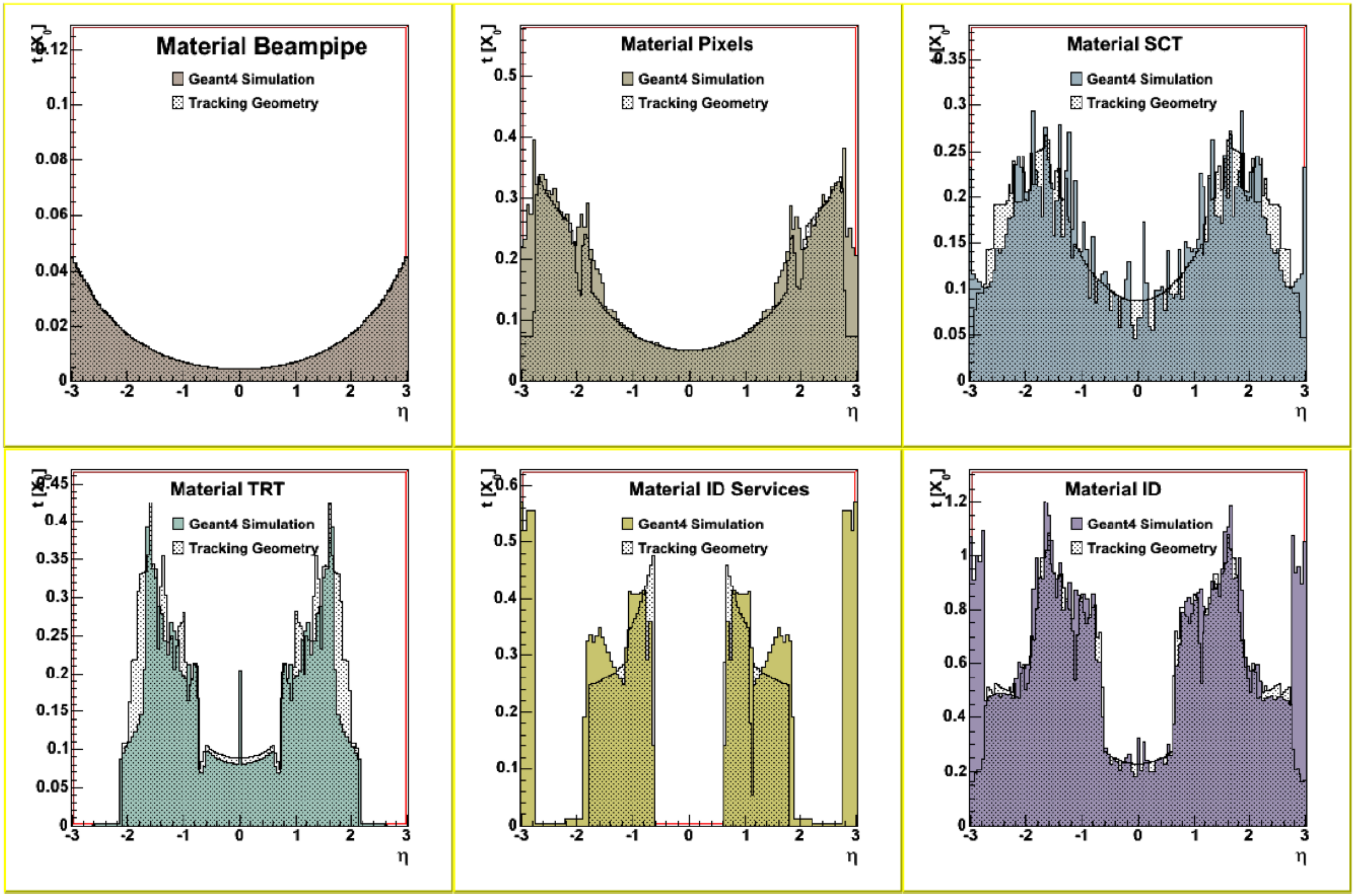
with $\langle\theta_p\rangle$ given by:

$$\langle\theta_p\rangle = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{X}{X_0}}$$

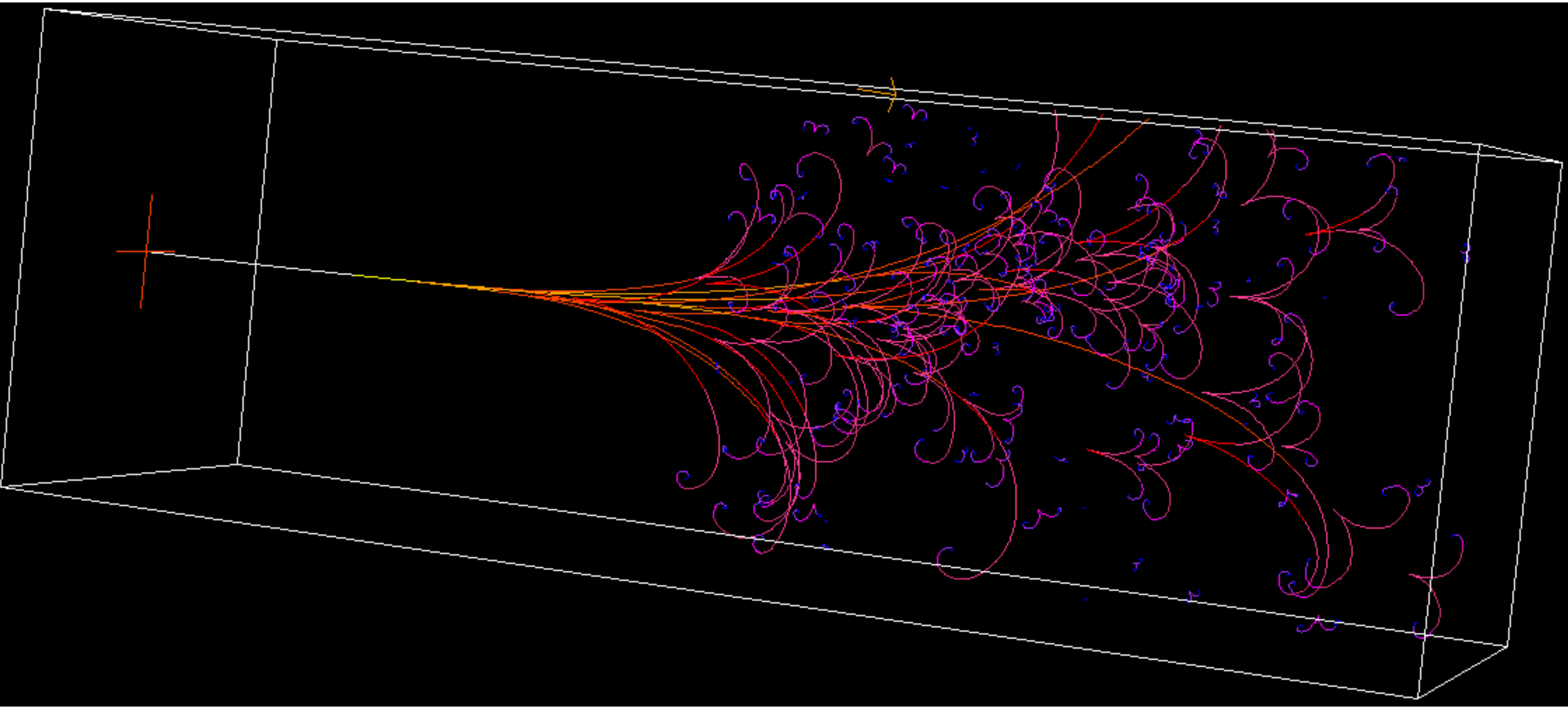


- At large anges, deviations from Gaussian appear as a long tail depending on $\left(\sin^4 \frac{\theta_p}{2}\right)^{-1}$
- The effect of multiple scattering depends on $1/p$

Dead material in ATLAS

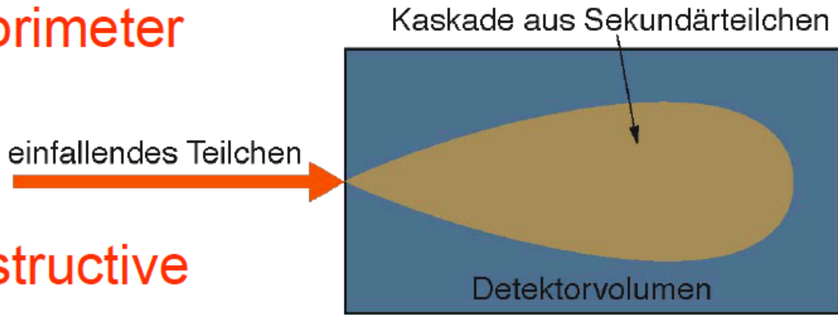


Calorimetry



Calorimeters

- In nuclear and particle physics calorimetry refers to the detection of particles, and measurements of their properties, through total absorption in a block of matter, the calorimeter



- Common feature of all calorimeters

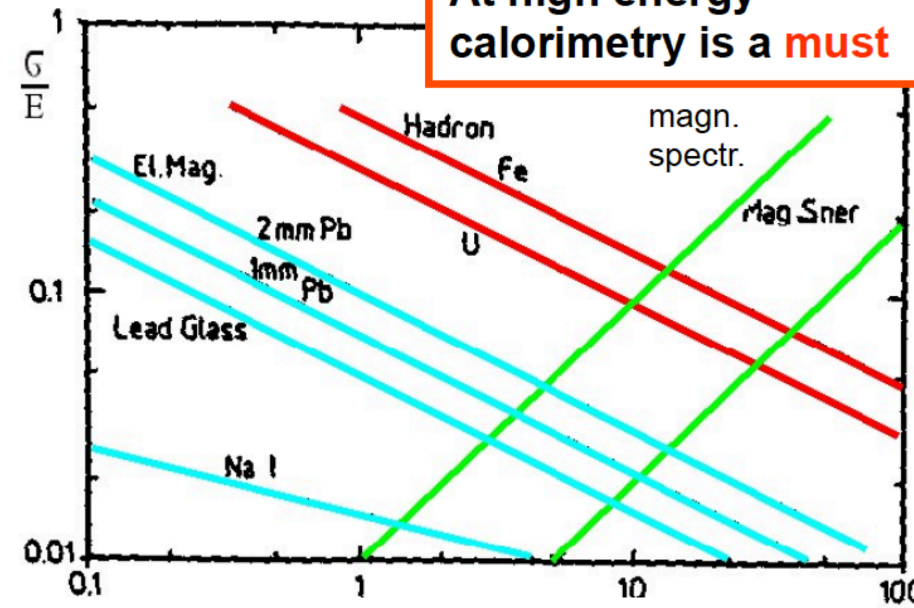
  is that the measurement process is destructive
  - Unlike, for example, wire chambers that measure particles by tracking in a magnetic field, the particles are no longer available for inspection once the calorimeter is done with them.
  - The only exception concerns muons. The fact that muons can penetrate a substantial amount of matter is an important mean for muon identification.

- In the absorption, almost all particle's energy is eventually converted to heat, hence the term calorimeter

> **At high energy calorimetry is a must**

- Measure *charged* + *neutral* particles

- Performance of calorimeters
  improves with energy
  and is ~constant over 4π
  (Magn. Spectr. anisotropy due to B field)



Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$
[see below]

Gas detector: $\frac{\sigma_p}{p} \sim p$
[see above]

e.g. ATLAS:

$$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$$

i.e. $\sigma_E/E = 1\%$ @ 100 GeV

e.g. ATLAS:

$$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$$

i.e. $\sigma_p/p = 5\%$ @ 100 GeV

- Obtain information *fast* (<100ns feasible)
  → recognize and select interesting events in real time (*trigger*)

Electromagnetic calorimeters

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

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

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm²]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

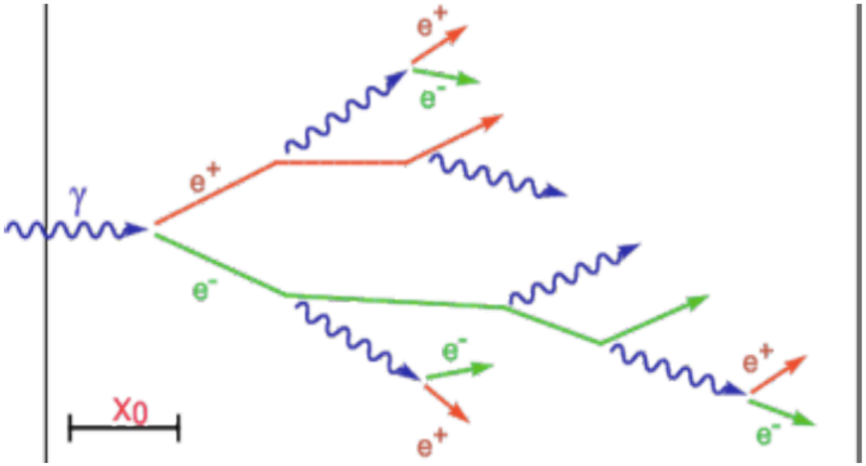
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons : Bremsstrahlung

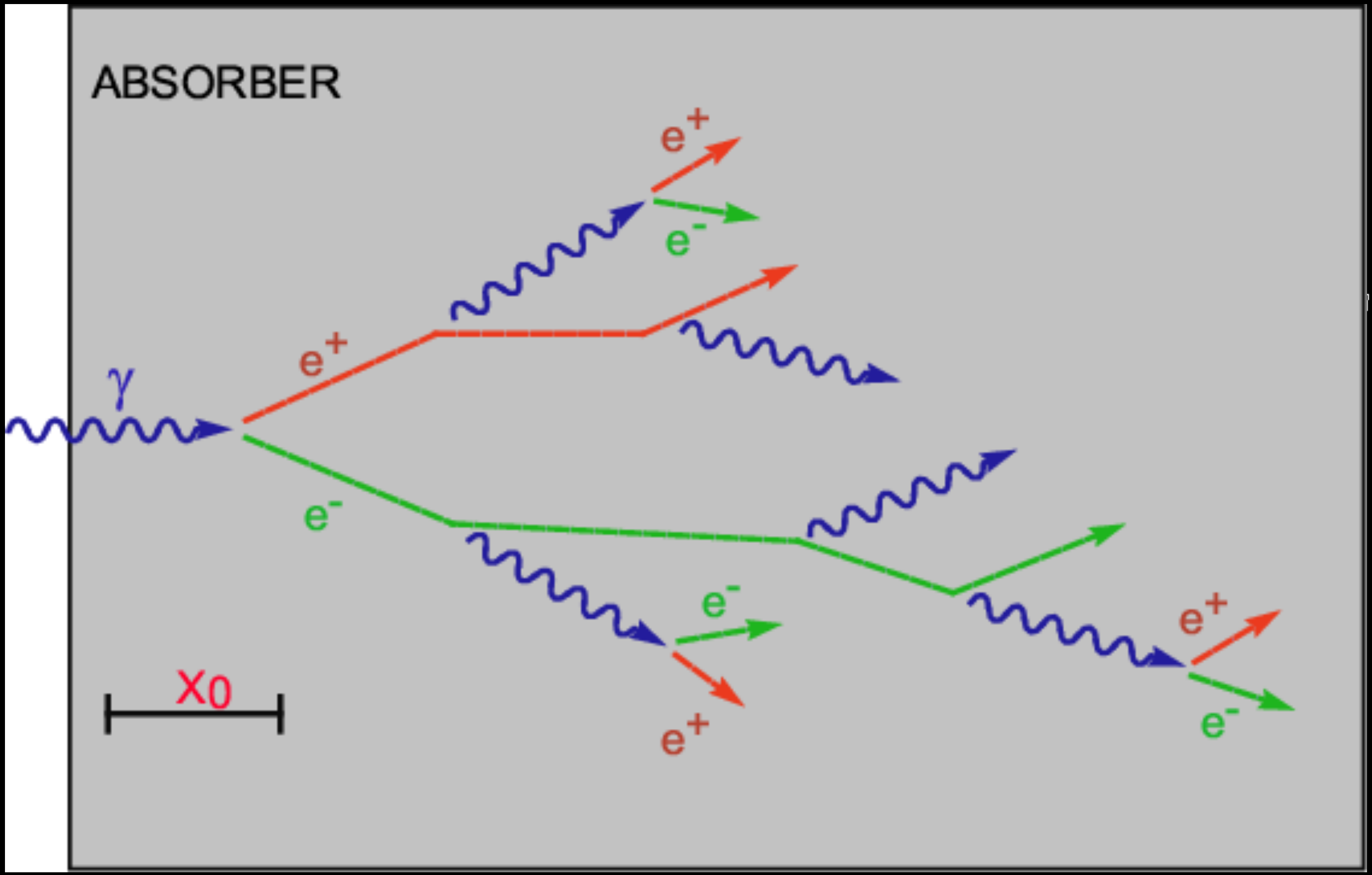
$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A} r_e^2 \cdot E\;\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only $(1/e)^{\text{th}}$ of its primary energy ...
[i.e. 37%]



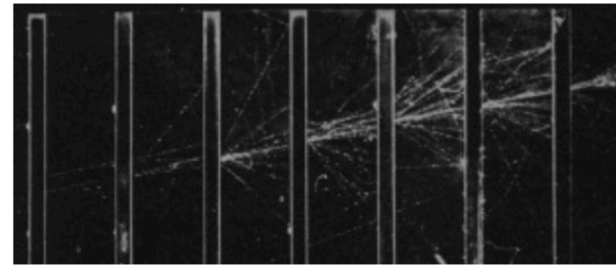
Calorimetry



Simplified model [Heitler]: shower development governed by X_0

e^- loses [1 - 1/e] = 63% of energy in 1 Xo (Brems.)

the *mean free path* of a γ is 9/7 Xo (pair prod.)



Lead absorbers in cloud chamber

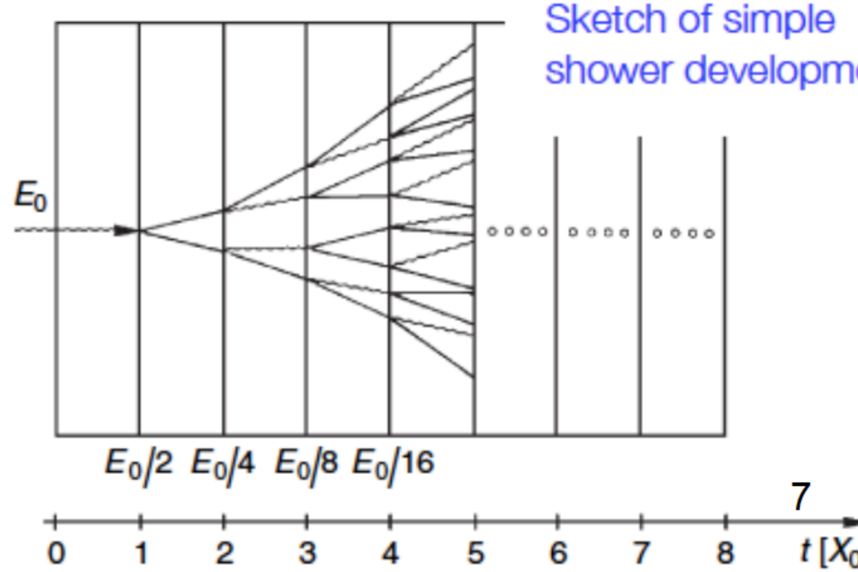
Assume:

$E > E_c$: no energy loss by ionization/excitation

$E < E_c$: energy loss only via ionization/excitation

Simple shower model:

- 2^t particles after t $[X_0]$
- each with energy $E/2^t$
- Stops if E < critical energy ε_C
- Number of particles $N = E/\varepsilon_C$
- Maximum at $t_{\max} \propto \ln(E_0/E_c)$



Sketch of simple shower development

Simple shower model quite powerful ➔ characterized shower by:

- Number of particles in shower
- Location of shower maximum
- Transverse shower distribution
- Longitudinal shower distribution

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$

$$t_{\max} \propto \ln(E_0/E_c)$$

$$L \sim \ln \frac{E}{E_c}$$

Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle, i.e. calorimeters can be compact

Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV ➔ $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$
$E_0 = 100$ GeV ➔ $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$

	Szint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

➔ 100 GeV electron contained in 16 cm Fe or 5 cm Pb

8

Longitudinal profile

Parametrization:
[Longo 1975]

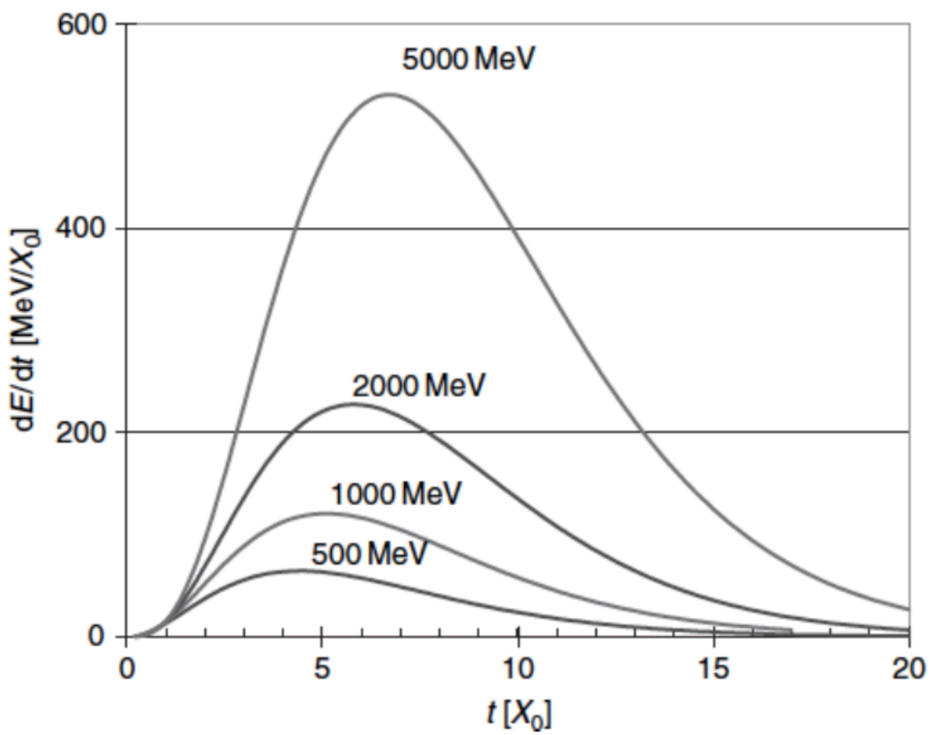
$$\frac{dE}{dt} = E_0 \, t^{\alpha} e^{-\beta t}$$

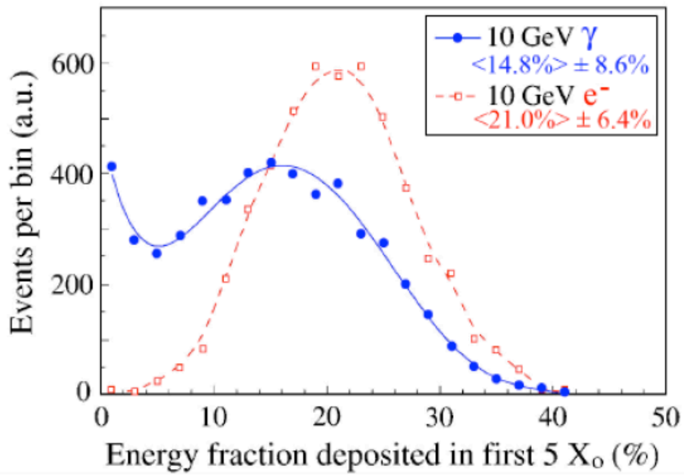
α,β : free parameters

t^{α} : at small depth number of secondaries increases ...

$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
$\alpha = 2$, $\beta = 0.5$, $t_{max} = \alpha/\beta$





important *differences between* showers induced by *e*, *γ*

$$t_{max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

with:

$C_{e\gamma} = -0.5$ [γ-induced]

$C_{e\gamma} = -1.0$ [e-induced]

9

Transverse profile

Parametrization:

$$\frac{dE}{dr} = \alpha e^{-r/R_M} + \beta e^{-r/\lambda_{\min}}$$

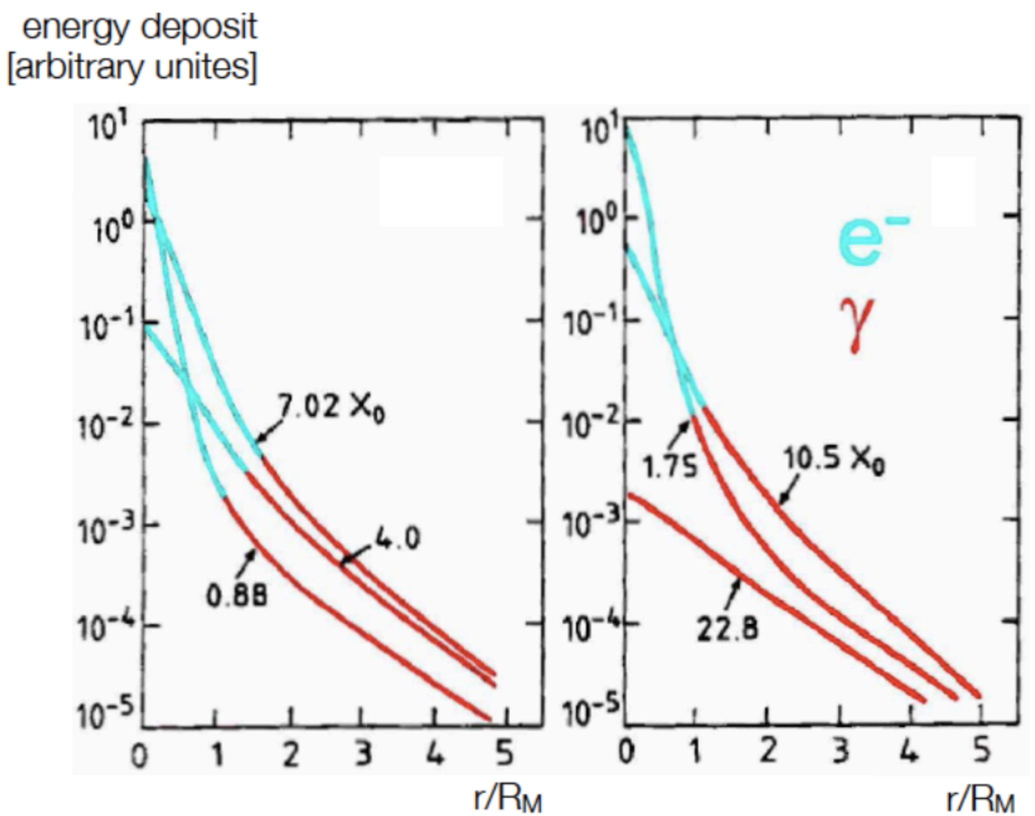
α,β : free parameters

R_M : Molière radius

λ_{min}: range of low energetic photons ...

Inner part: coulomb scattering ...

Electrons and positrons move away from shower axis due to multiple scattering ...



Outer part: low energy photons ...

Photons (and electrons) produced in isotropic processes (Compton scattering, photo-electric effect) move away from shower axis; predominant beyond shower maximum, particularly in high-Z absorber media...

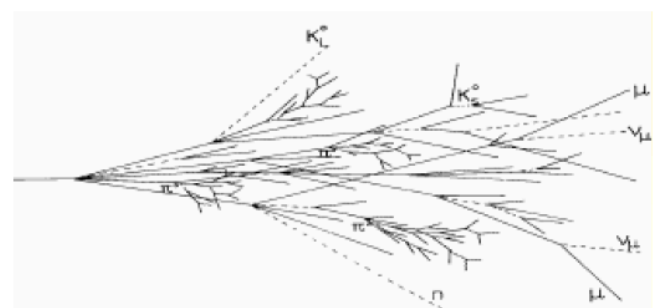
The shower gets wider at larger depth

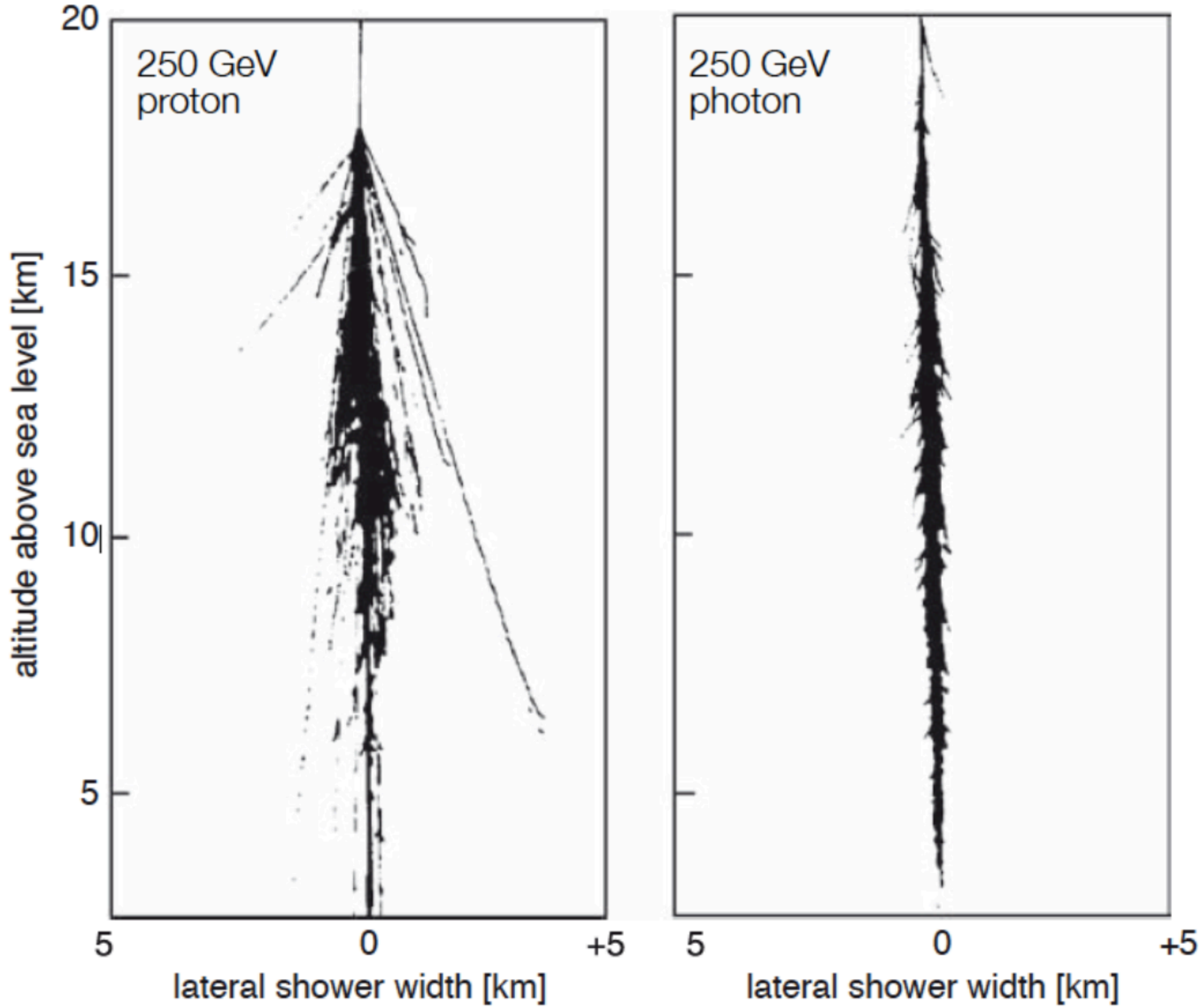
Hadronic calorimeters

- Extra complication: ***The strong interaction*** with detector material
- Importance of calorimetric measurement
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy

- In nuclear collisions numbers of secondary particles are produced
  - Partially undergo secondary, tertiary *nuclear reactions* ➔ formation of hadronic cascade
  - Electromagnetically decaying particles (π, η) initiate EM showers
  - Part of the energy is absorbed as nuclear binding energy or target recoil (*Invisible energy)*
- Similar to EM showers, but much more complex

  ➔ need simulation tools (MC)
- Different scale: hadronic interaction length





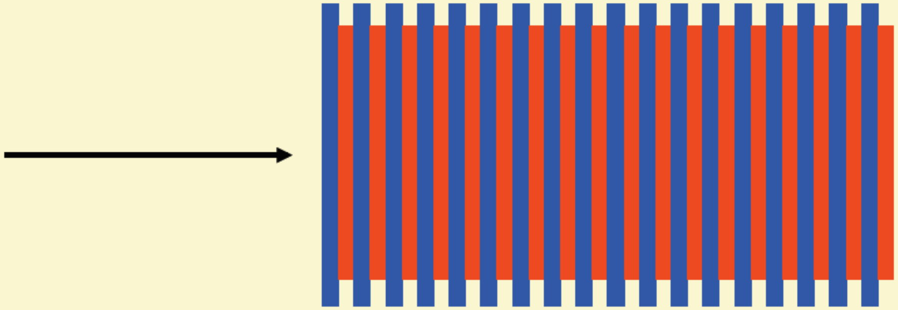
20
250 GeV
proton
15
10
5
altitude above sea level [km]
5
0
+5
lateral shower width [km]
250 GeV
photon
5
0
+5
lateral shower width [km]

Types of calorimeter

There are two general classes of calorimeter:

Sampling calorimeters:

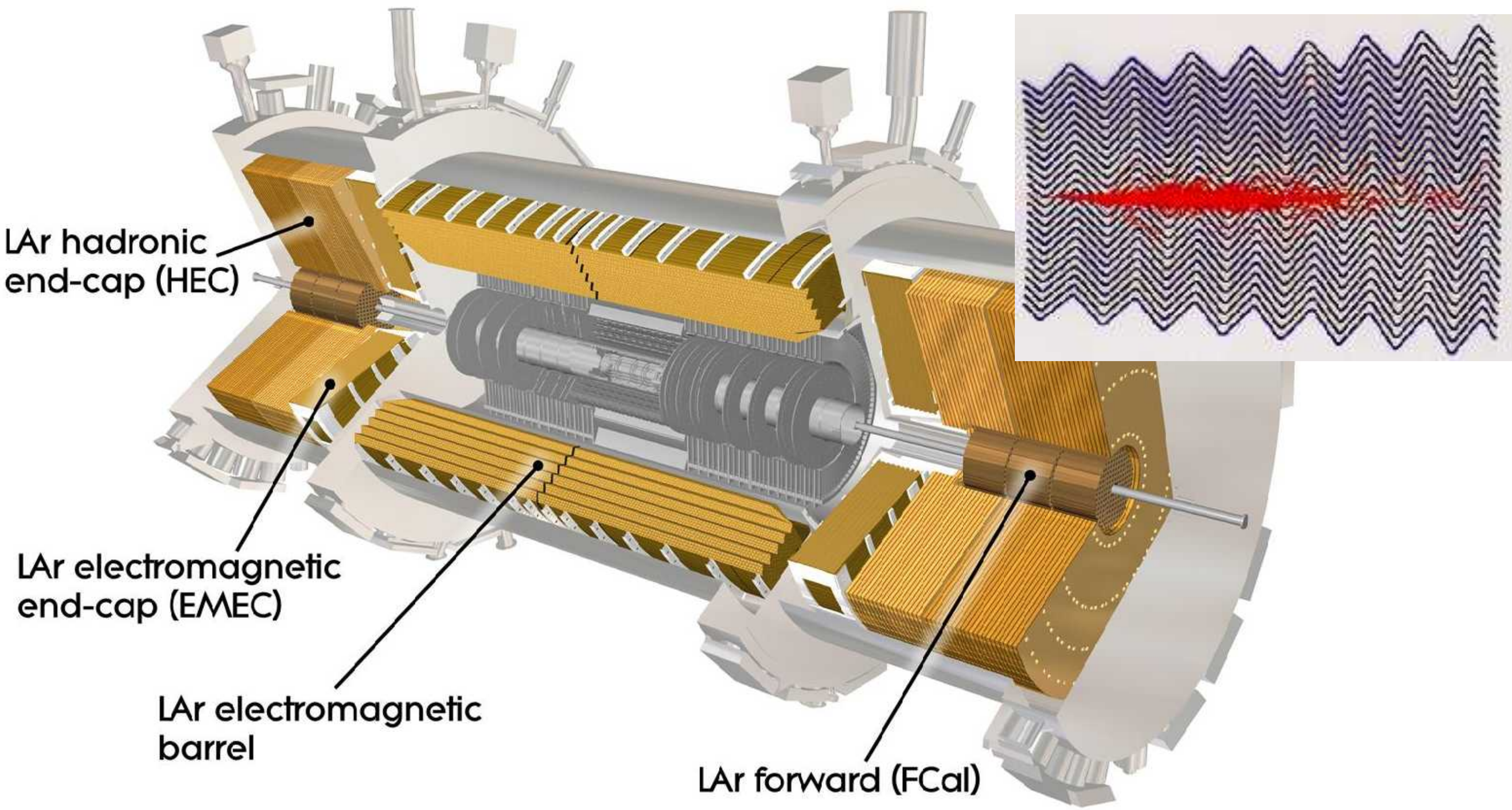
Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon



Homogeneous calorimeters:

A single medium serves as both absorber and detector, eg: liquified Xe or Kr, dense crystal scintillators (BGO, $PbWO_4$ …….), lead loaded glass.

Sampling calorimeters



Homogeneous calorimeters

One block of material serves as absorber and active medium at the same time

Scintillating crystals with high density and high Z

Advantages:

see <u>all</u> charged particles in the shower ➔ best statistical precision

same response from everywhere ➔ good linearity

Disadvantages:

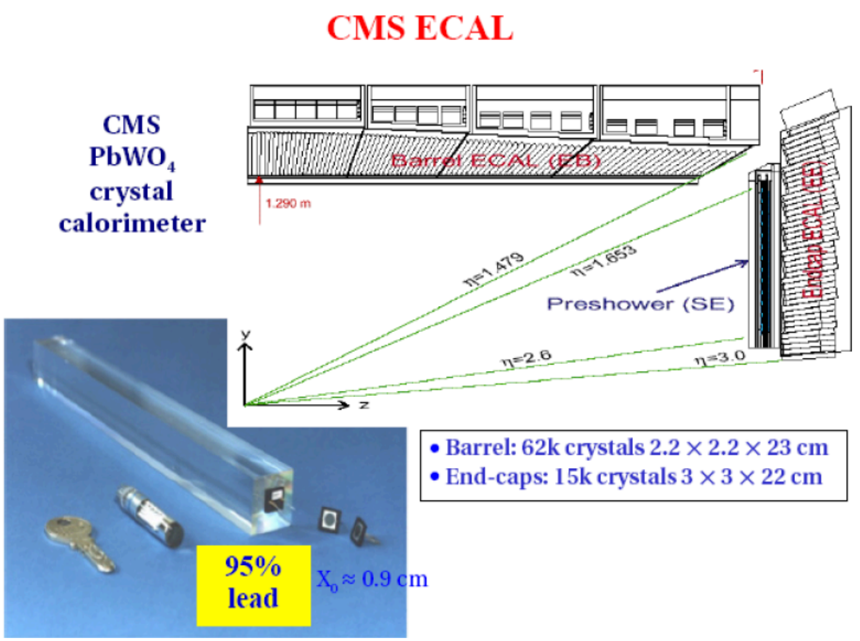
cost and limited segmentation

Examples:

B factories: small photon energies

CMS ECAL:

optimized for H→γγ



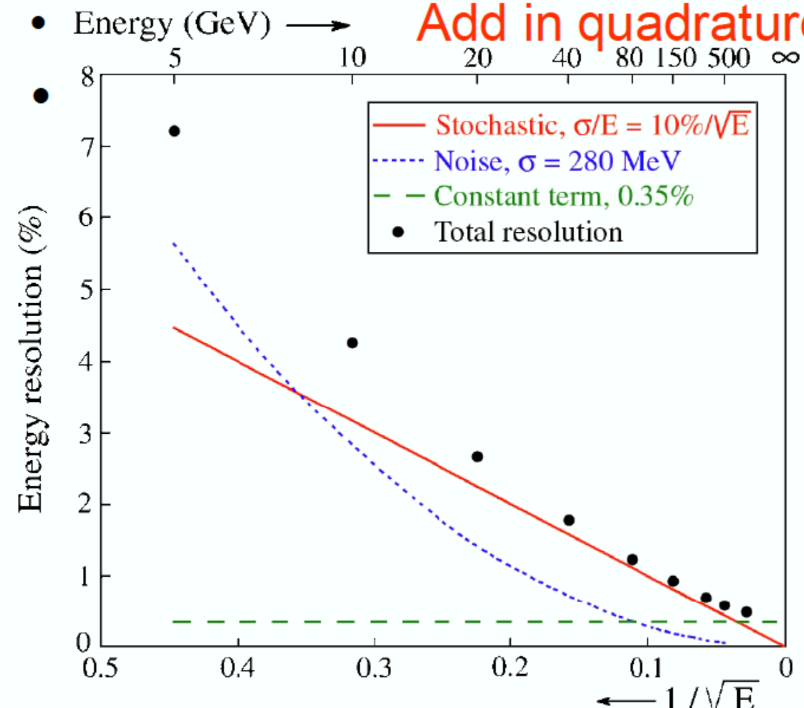
Fluctuations and resolution

Different effects have different energy dependence

- quantum, sampling fluctuations $\sigma/E \sim E^{-1/2}$
- shower leakage $\sigma/E \sim E^{-1/4}$
- electronic noise $\sigma/E \sim E^{-1}$
- structural non-uniformities $\sigma/E = \text{constant}$

Add in quadrature:

$$\sigma^2_{tot} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 + \sigma^2_4 + \ldots$$



← example: ATLAS EM calorimeter

33

Energy resolution

Stochastic term:
Fluctuations related to the physics development of the shower.

Noise term:
From electronics noise of the readout chain.
For constant electronics noise → double signal = double S/N

Constant term:
Instrumental effects that cause variations of the calorimeter response with the particle impact point.

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

Add in squares

For homogeneous calorimeters the noise term and constant term become dominant.

For sampling calorimeters the stochastic term, then called 'sampling' term becomes dominant.

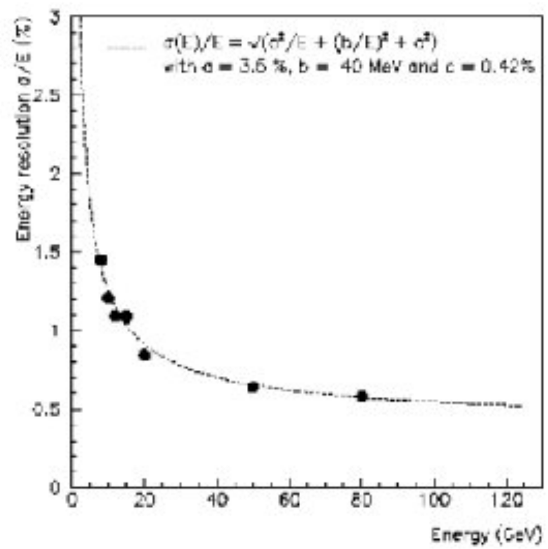
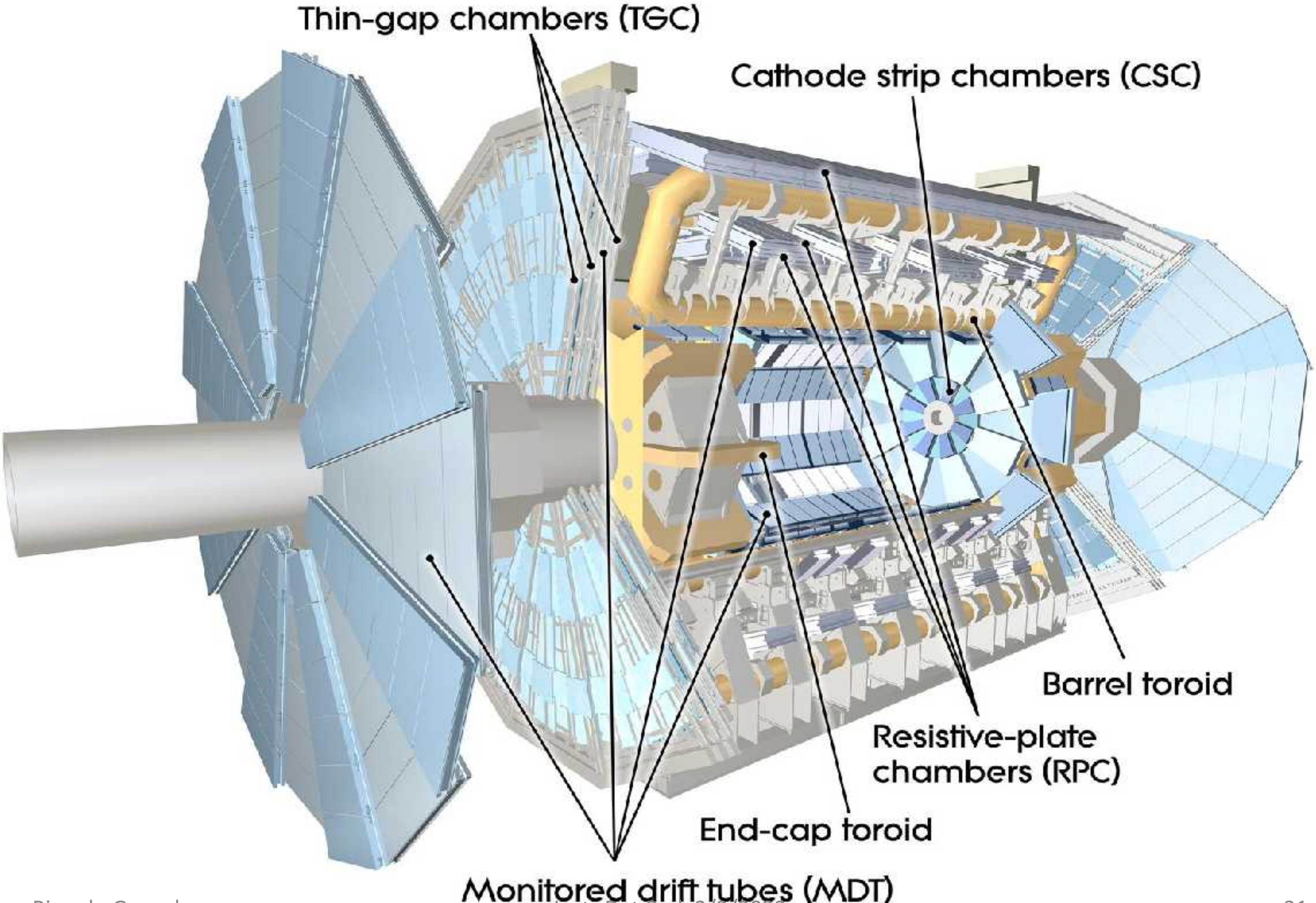
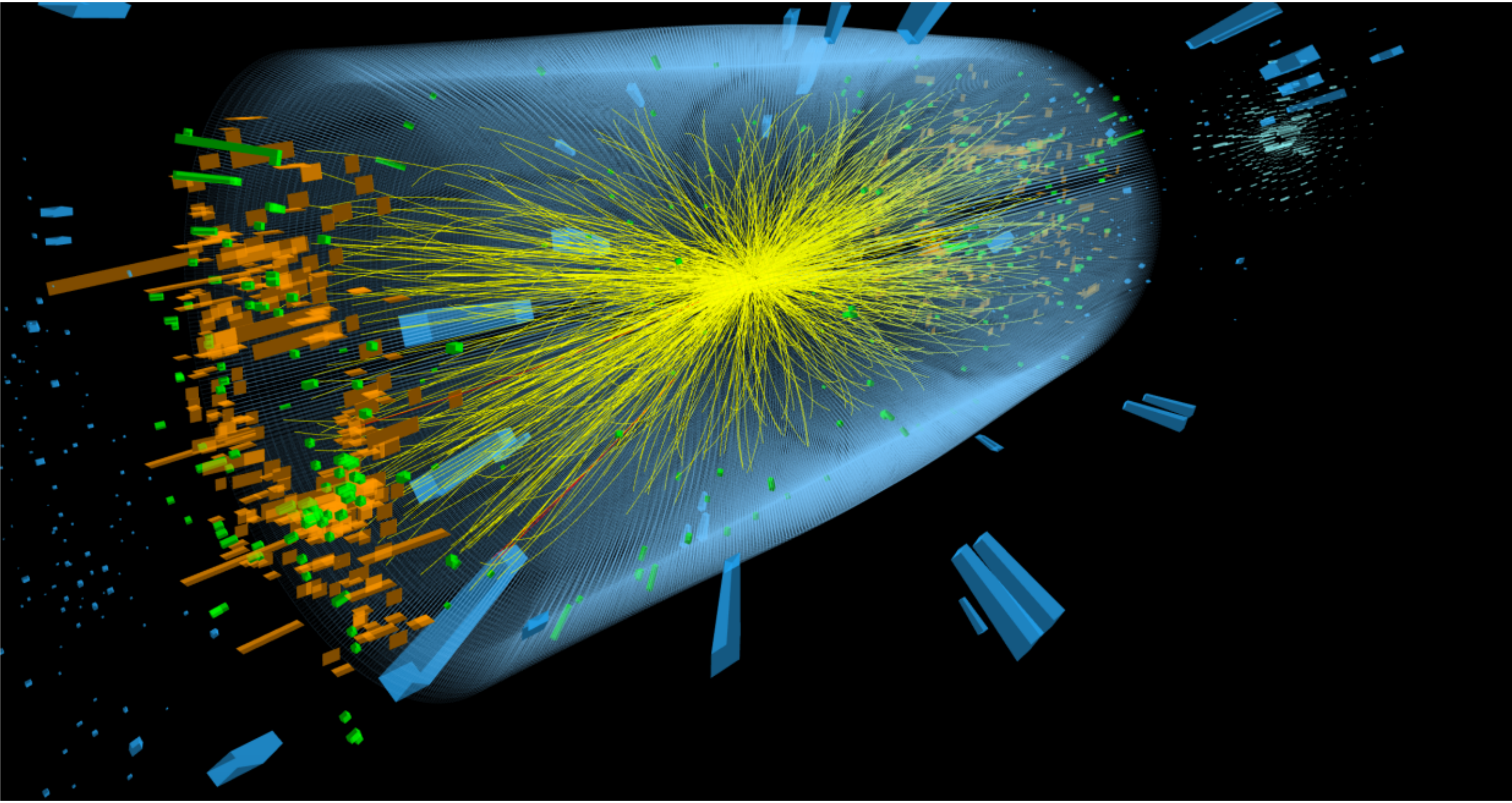


FIG. 3. Fractional electron energy resolution as a function of energy measured with a prototype of the NA48 liquid krypton electromagnetic calorimeter (NA48 Collaboration, 1995). The line is a fit to the experimental points with the form and the parameters indicated in the figure.

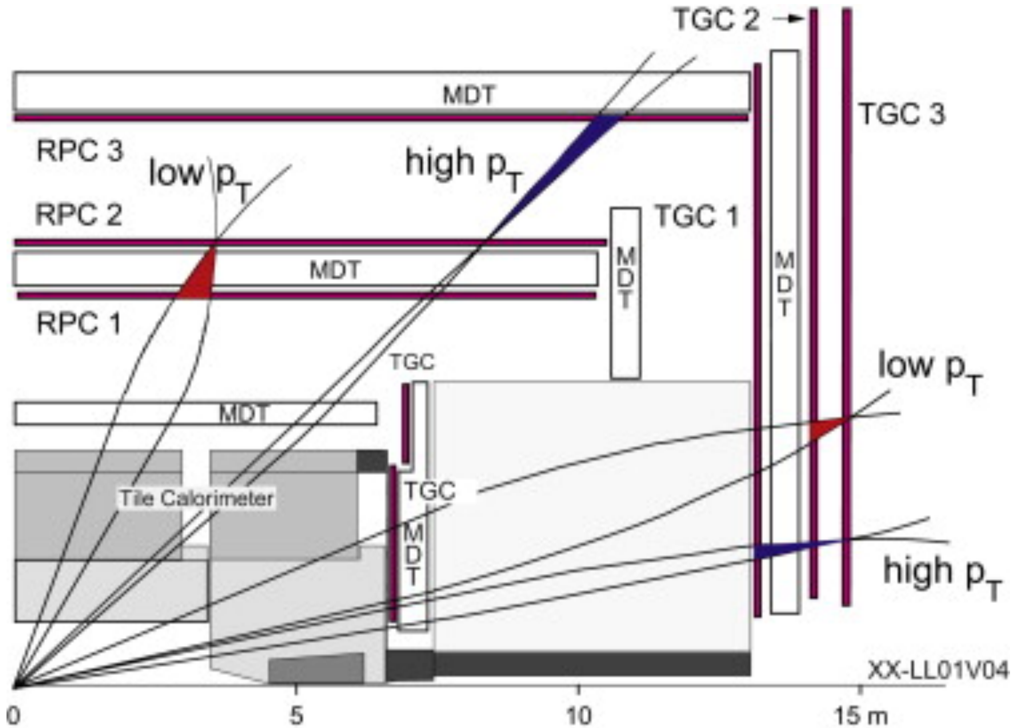
Muon detectors

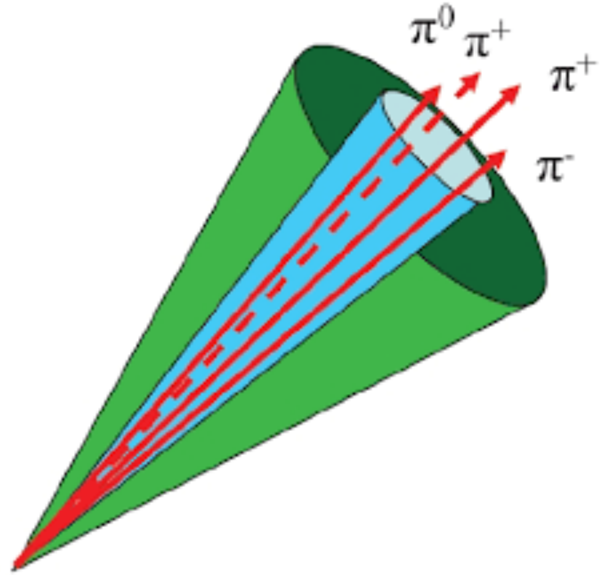


Event reconstruction



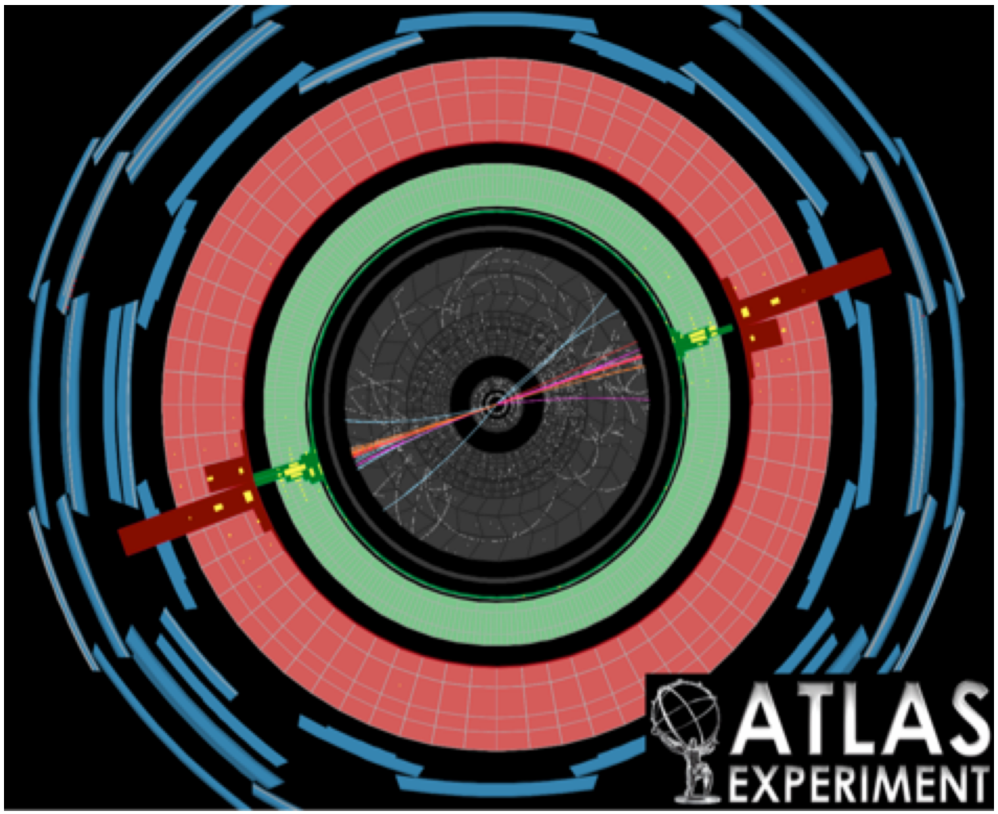
Muões, leptões τ, etc

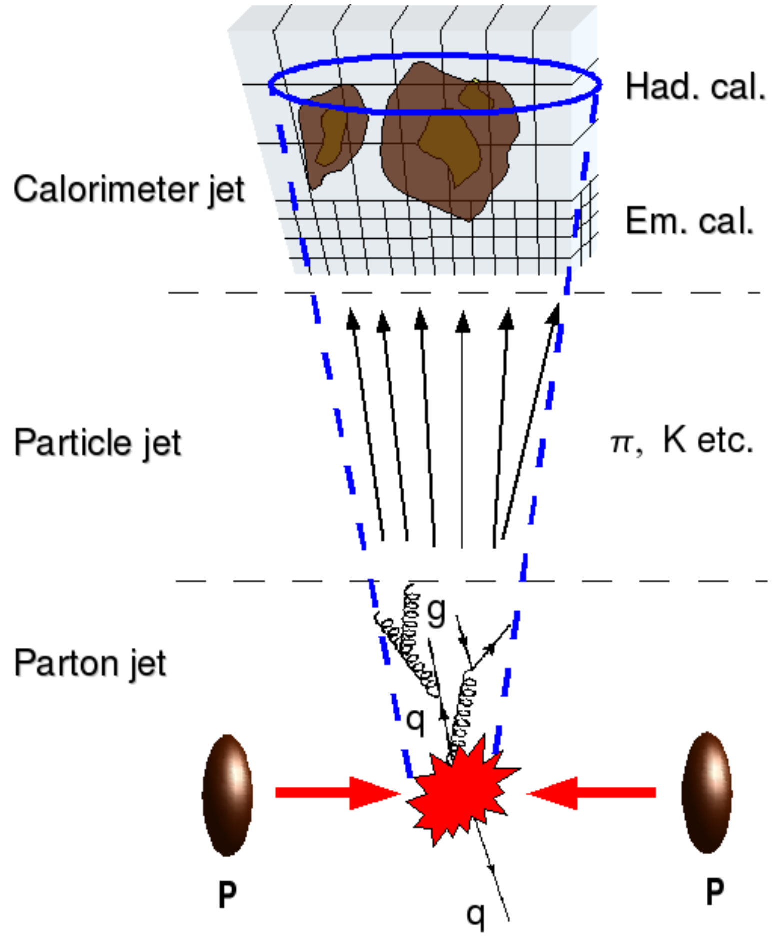




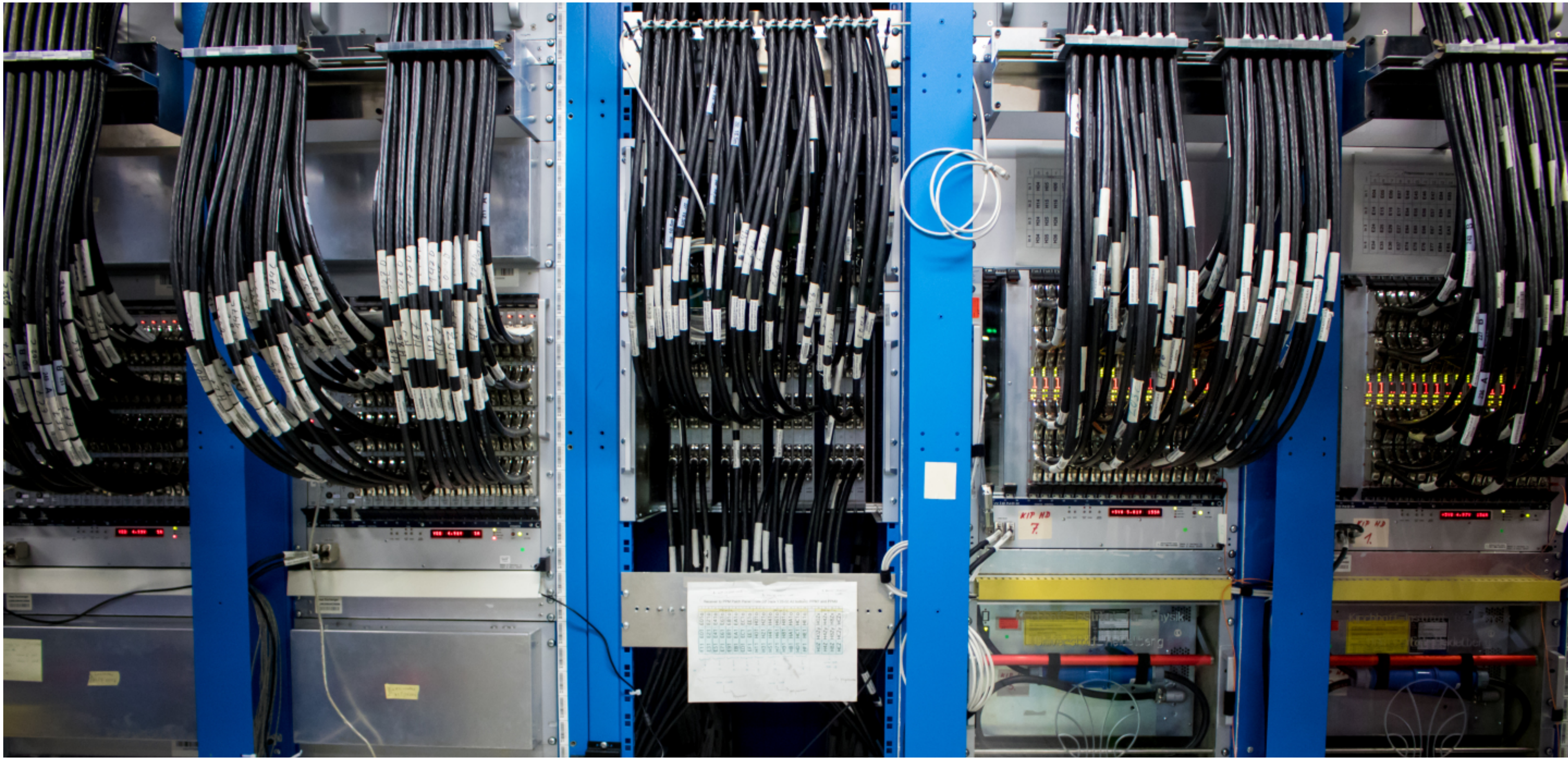
- Em constante evolução para calibrar e alinhar detetores, melhorar técnicas de reconstrução, calibrar algoritmos
- Emprega técnicas sofisticadas de análise incluindo de aprendizagem automática (machine learning)

Jatos hadrónicos

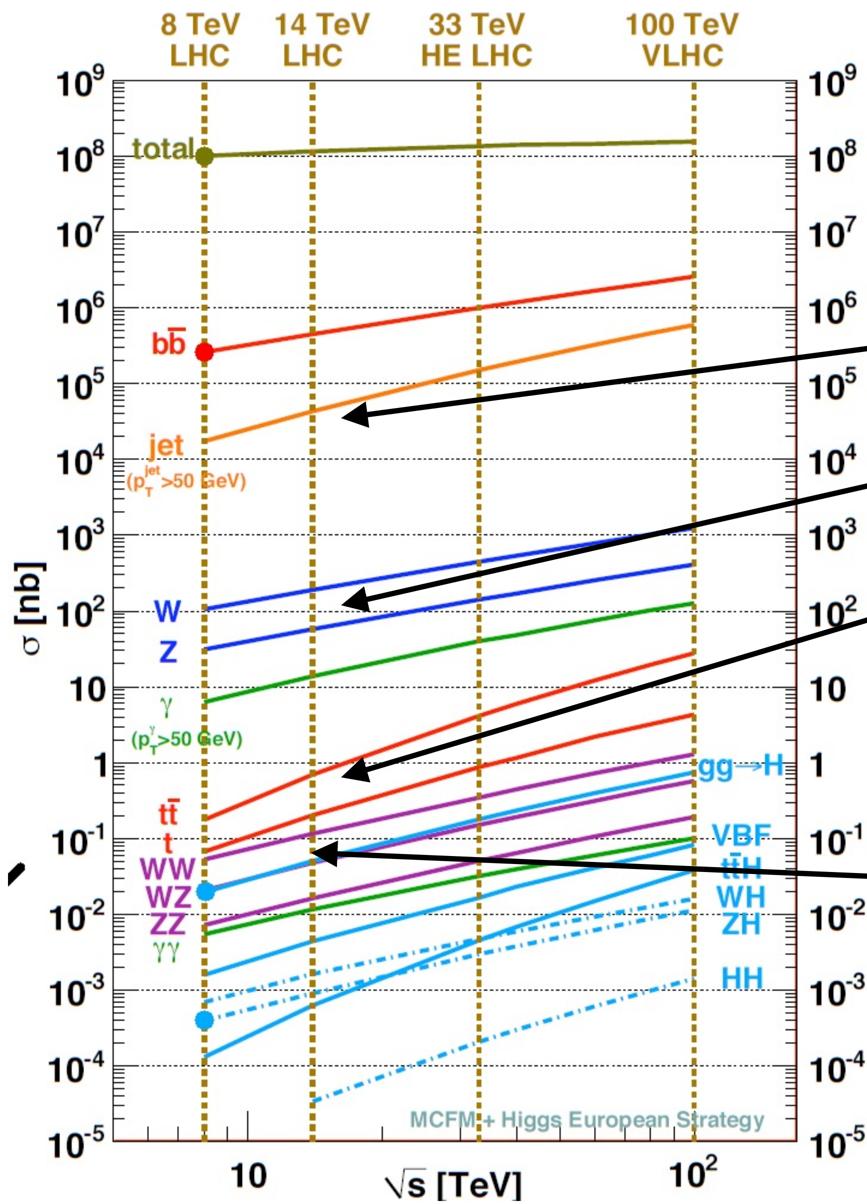




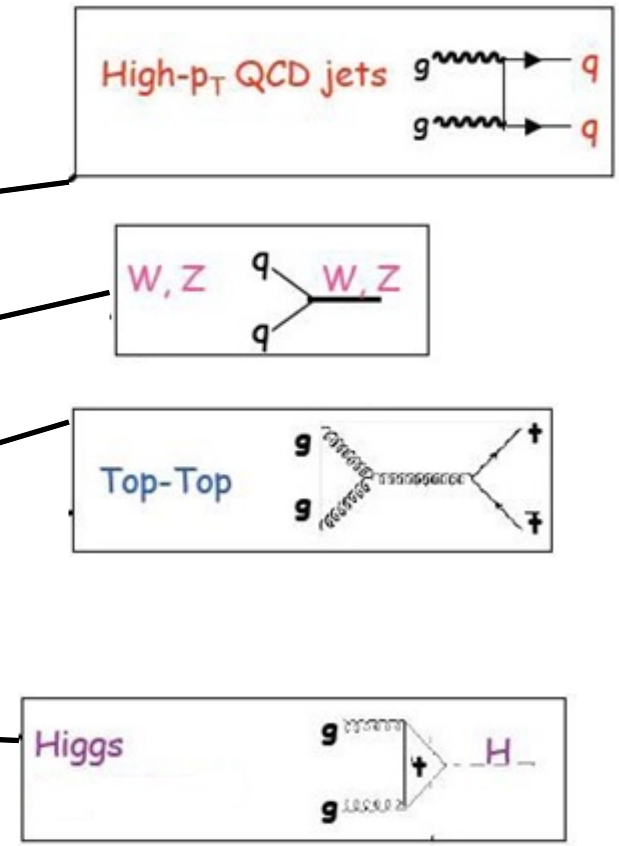
Trigger Systems



Signal and background in the LHC package



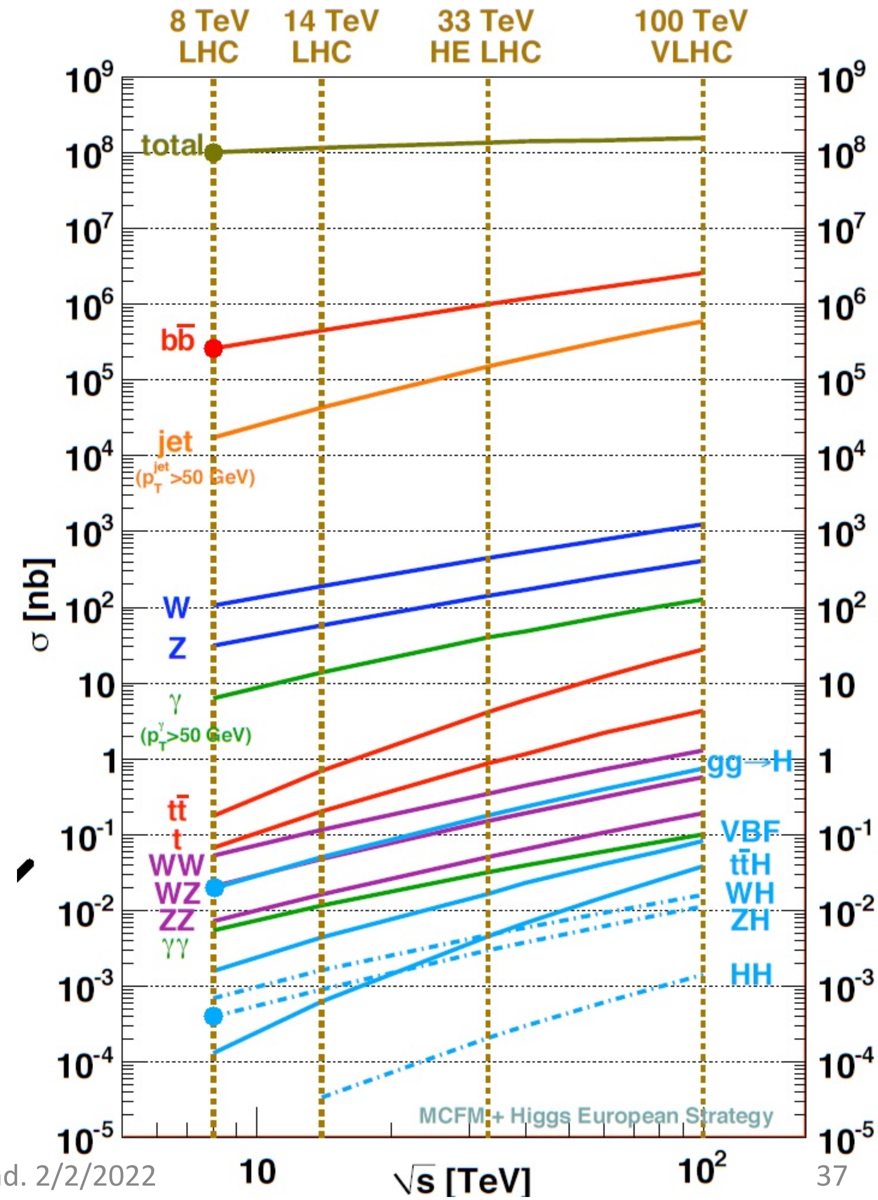
LHC generates trash at huge rates



And the interesting particles we are looking for are rare

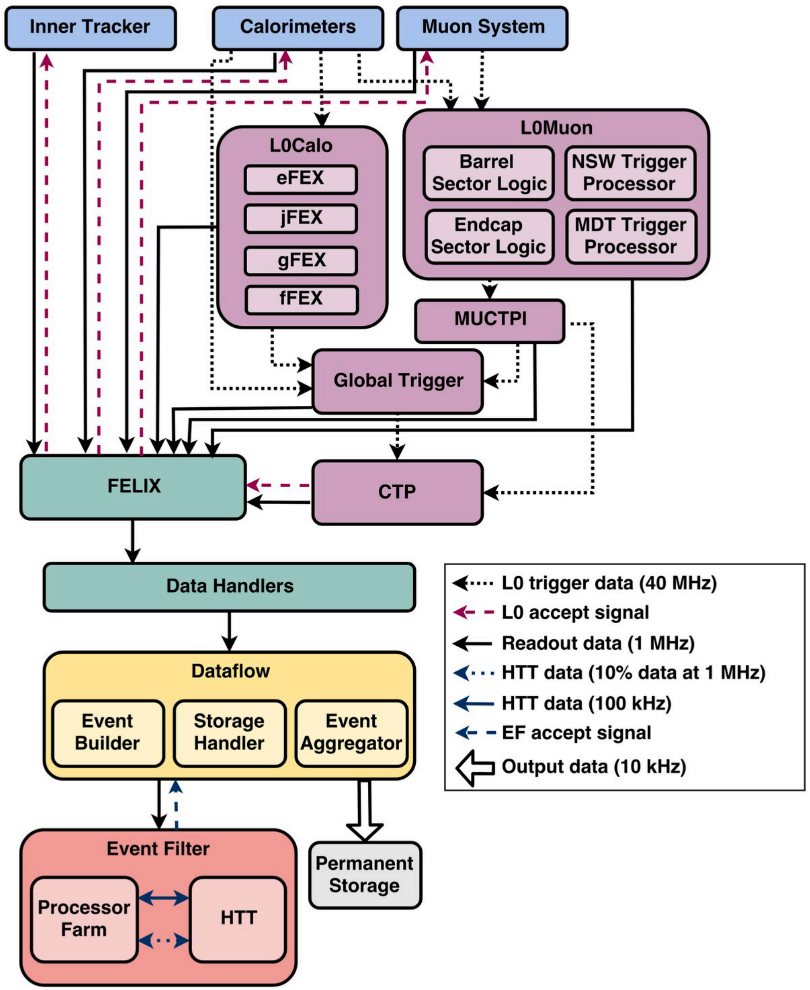
Trigger systems

- Much of LHC physics means cross sections at least ~10^6 times smaller than total cross section
- 25ns bunch crossing interval (40 MHz)
- Offline storing/processing: ~1000 Hz
- In one second at design luminosity:
  - 40 000 000 bunch crossings
  - ~2000 W events
  - ~500 Z events
  - ~10 top events
  - ~0.1 Higgs events
  - **1000 events written out**
- The right 1000 events should be written out!



Trigger systems

- Critical system!
- Use all the tricks in the book
- For LHC: multi-level trigger system
- Fast electronics for 1st level
- Fast algorithms running on large CPU farm



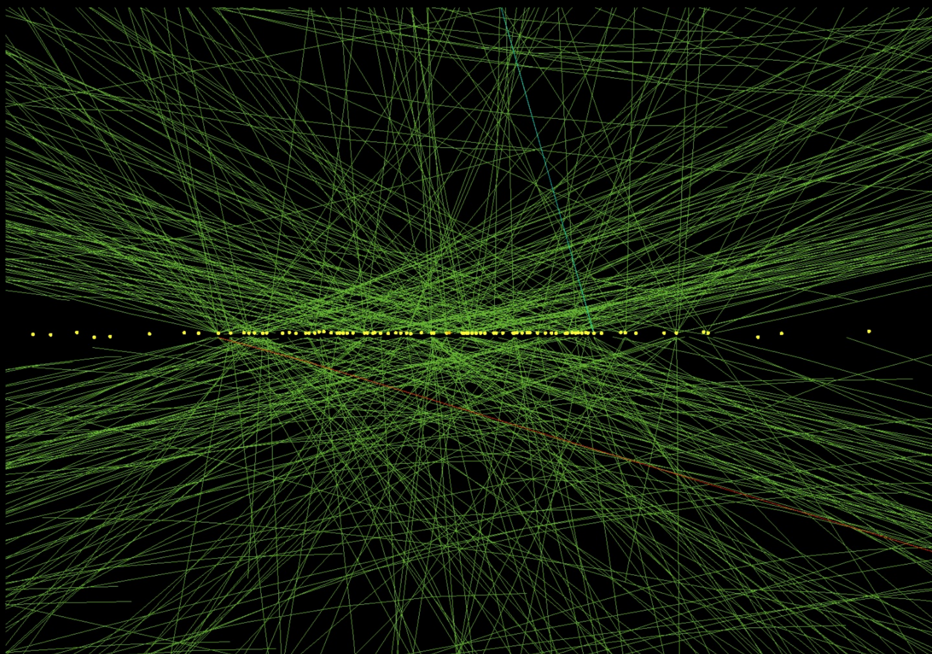
Análise de dados

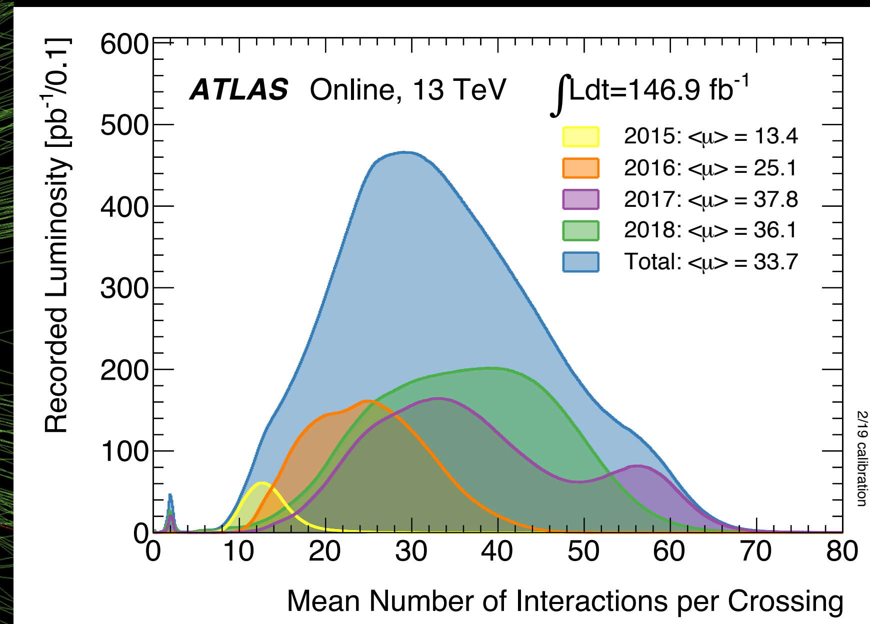
Desafios: Biiiig Data!!!

- Dados gerados por cada experiência antes do trigger semelhantes ao tráfego mundial na internet
- Centro de computadores do CERN não chega para tratar os dados guardados
- LHC Computing Grid!

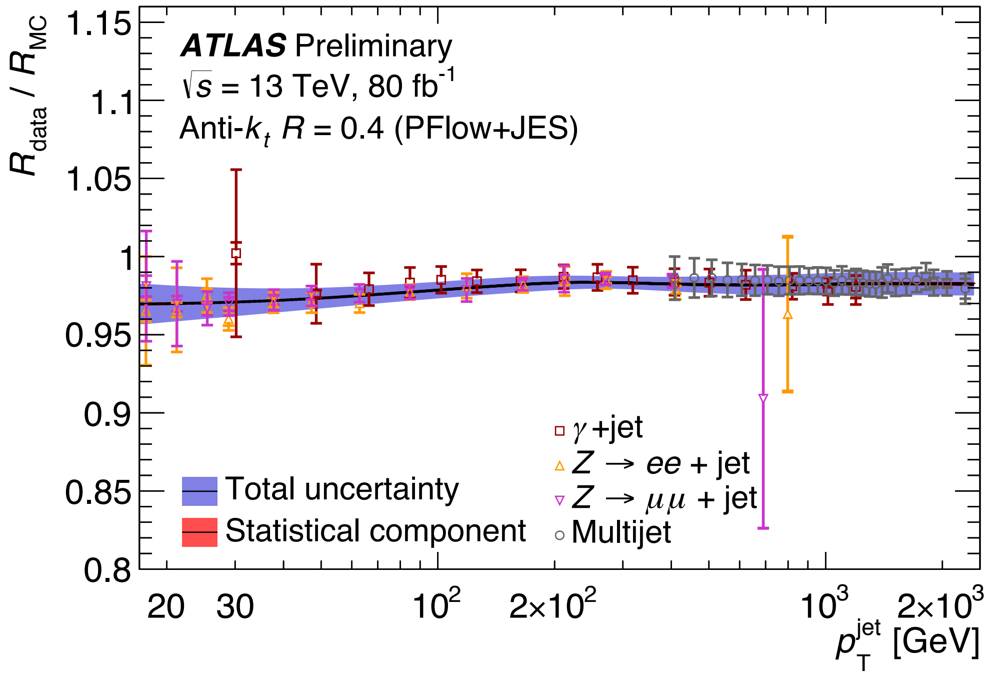
Desafios: Pileup

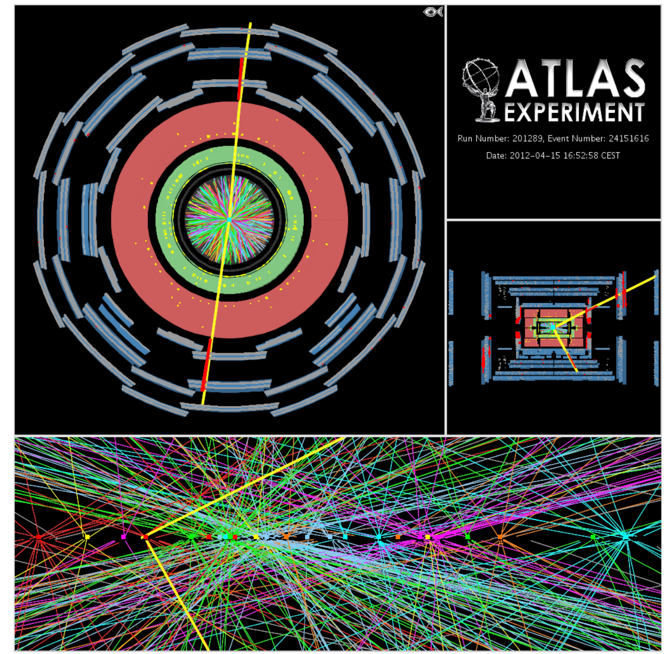
- O preço a pagar pela luminosidade: múltiplas colisões simultâneas de protões

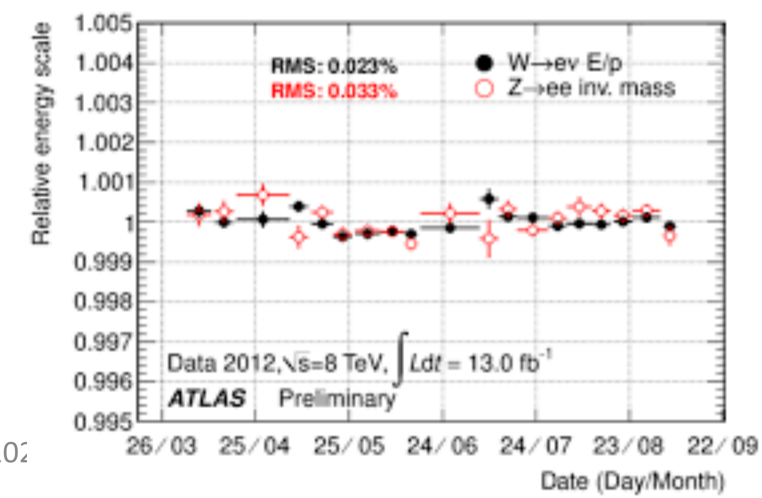




Desafios: Calibração

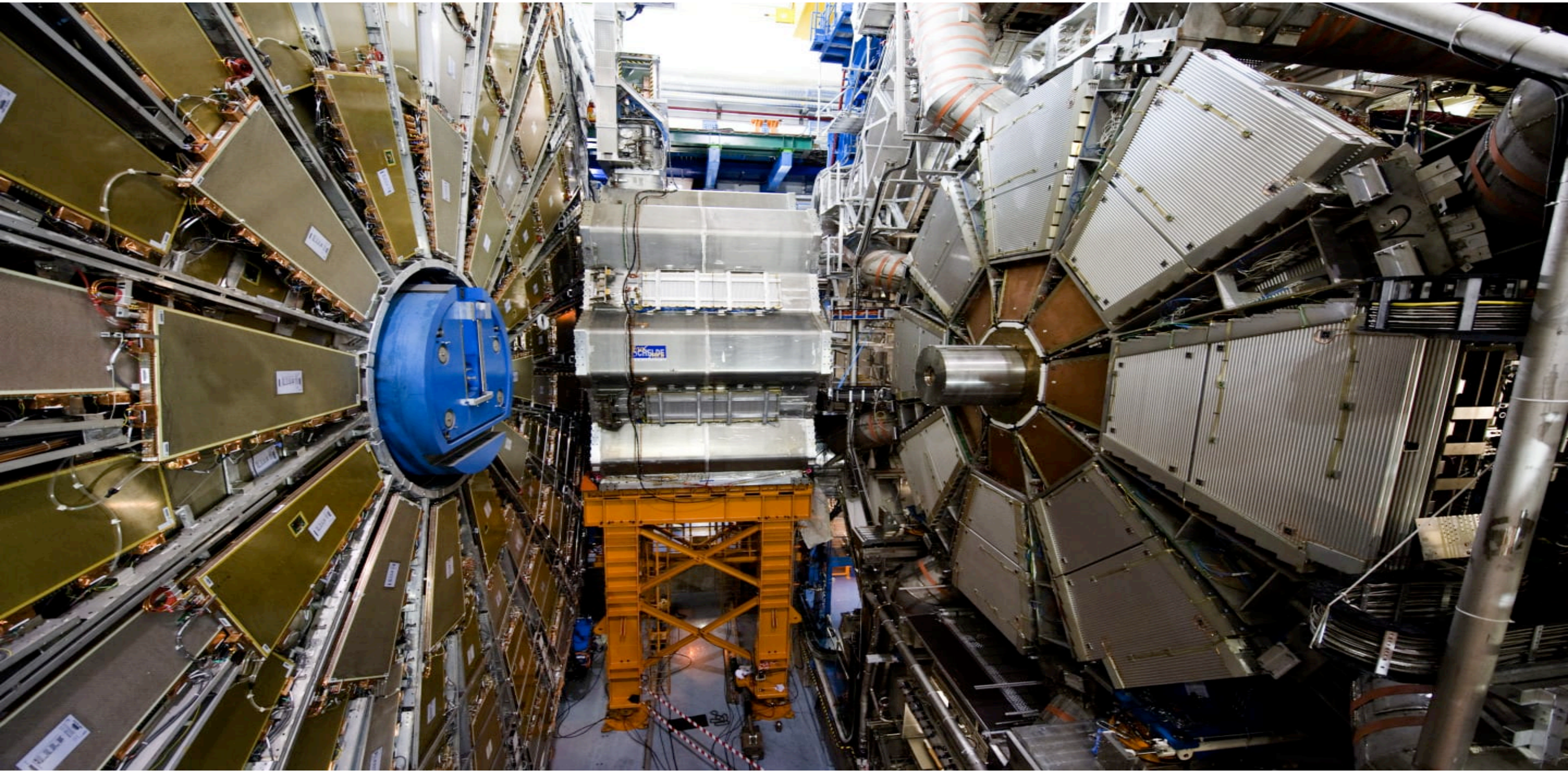


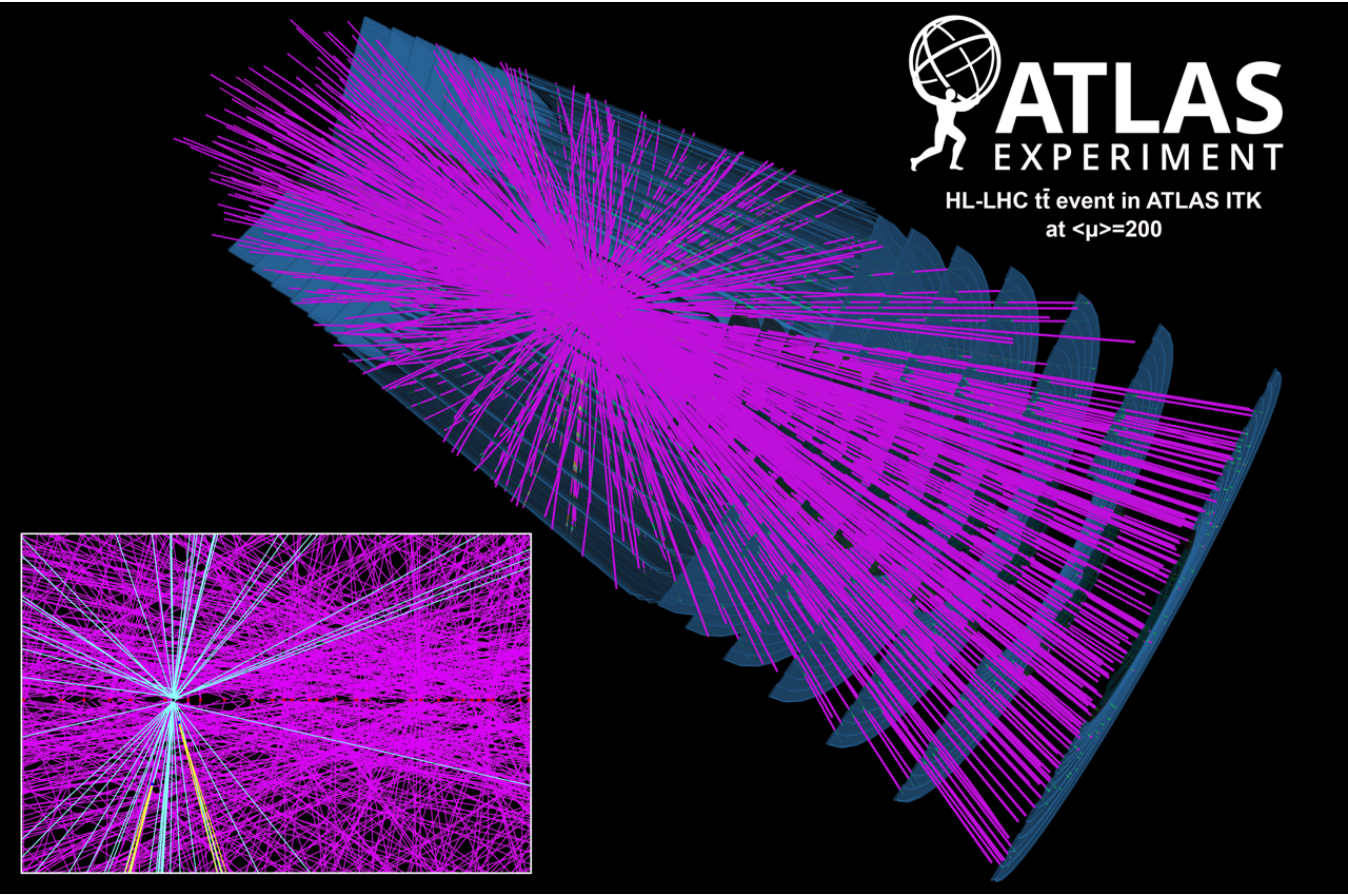


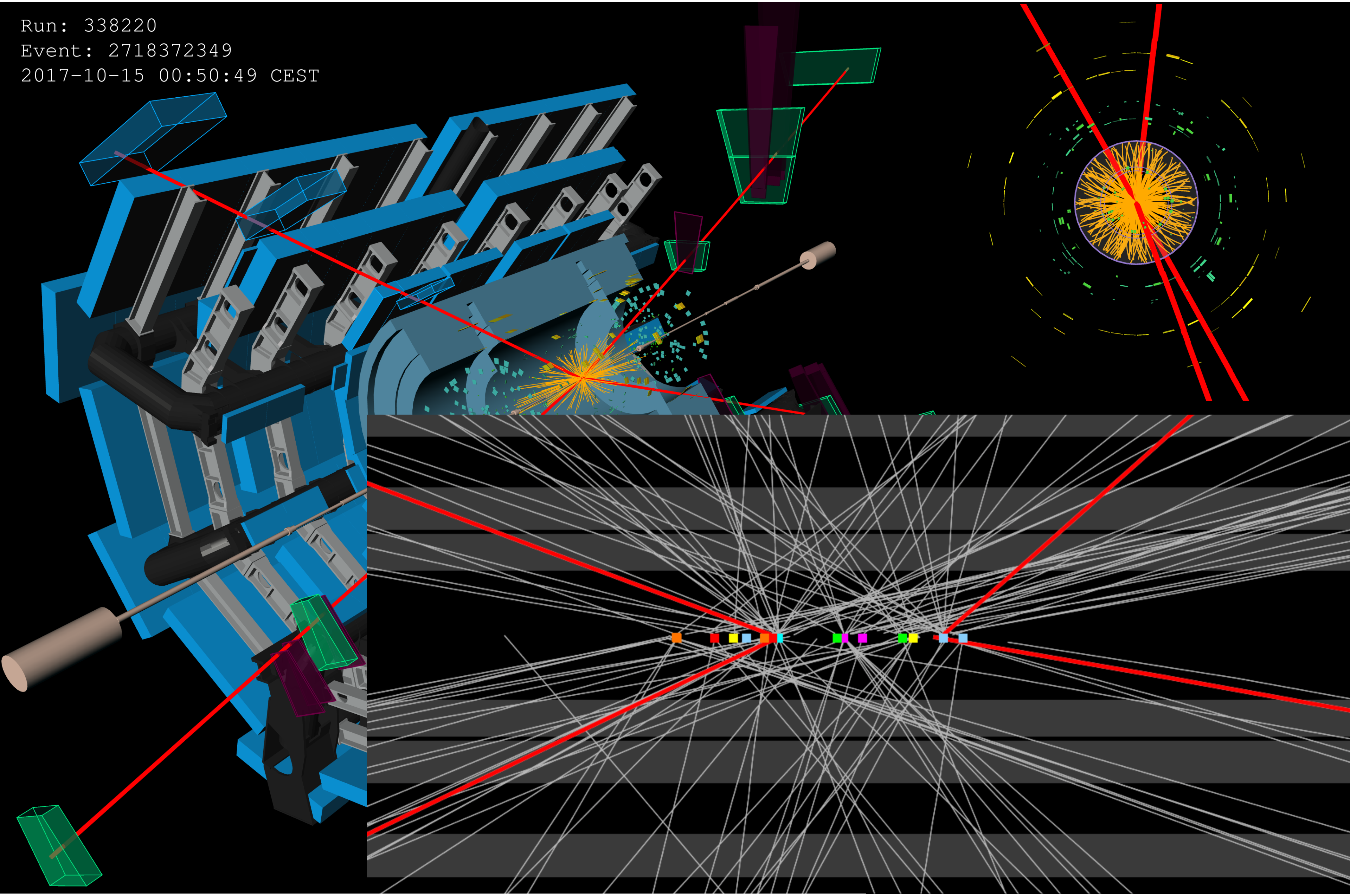


- Extremamente importante!
- Cada sub-detetor tem múltiplos métodos de alinhamento e calibração
- A melhor precisão é normalmente obtida usando os próprios dados de muitas colisões
- Precisamos da melhor calibração possível para os objetos de física: e, μ, τ, jatos, etc

LHC Upgrade

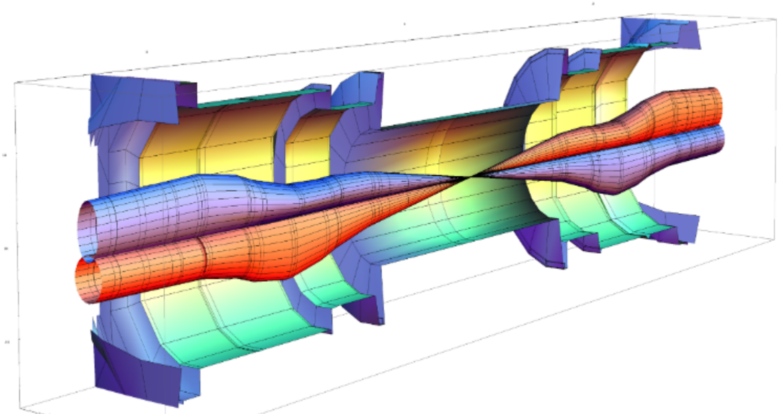


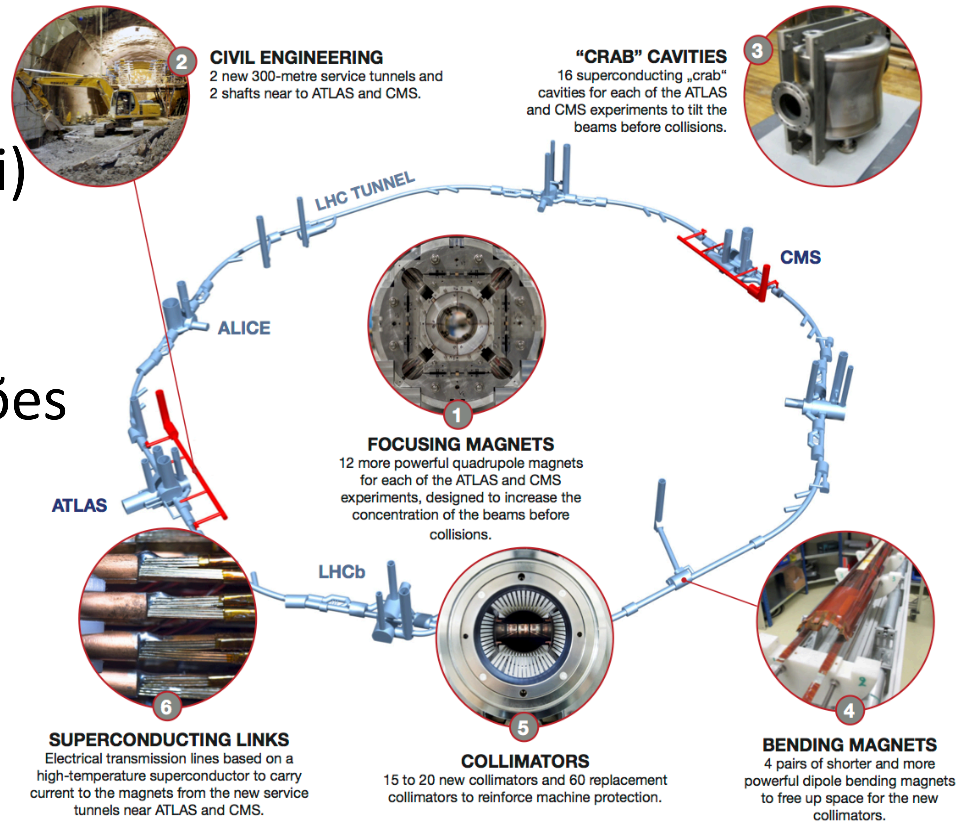

ATLAS
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200


Run: 338220
Event: 2718372349
2017-10-15 00:50:49 CEST

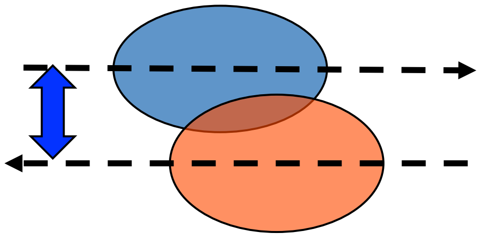
LHC Upgrades

- Desenvolvimento de nova geração de ímanes supercondutores (Nb_3Sn):
- 13.5 T em vez de 8 T (LHC, NbTi)
- Desenvolvimento de "crab cavities"
- Aumentam eficiência das colisões
- Colimadores, conectores, eng. civil, etc

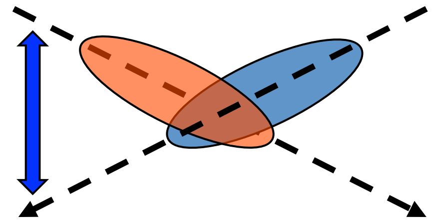




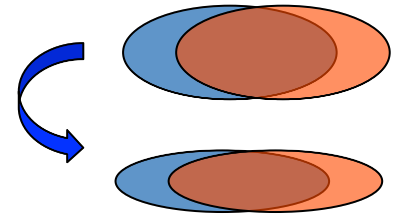
Leveling by beam offset

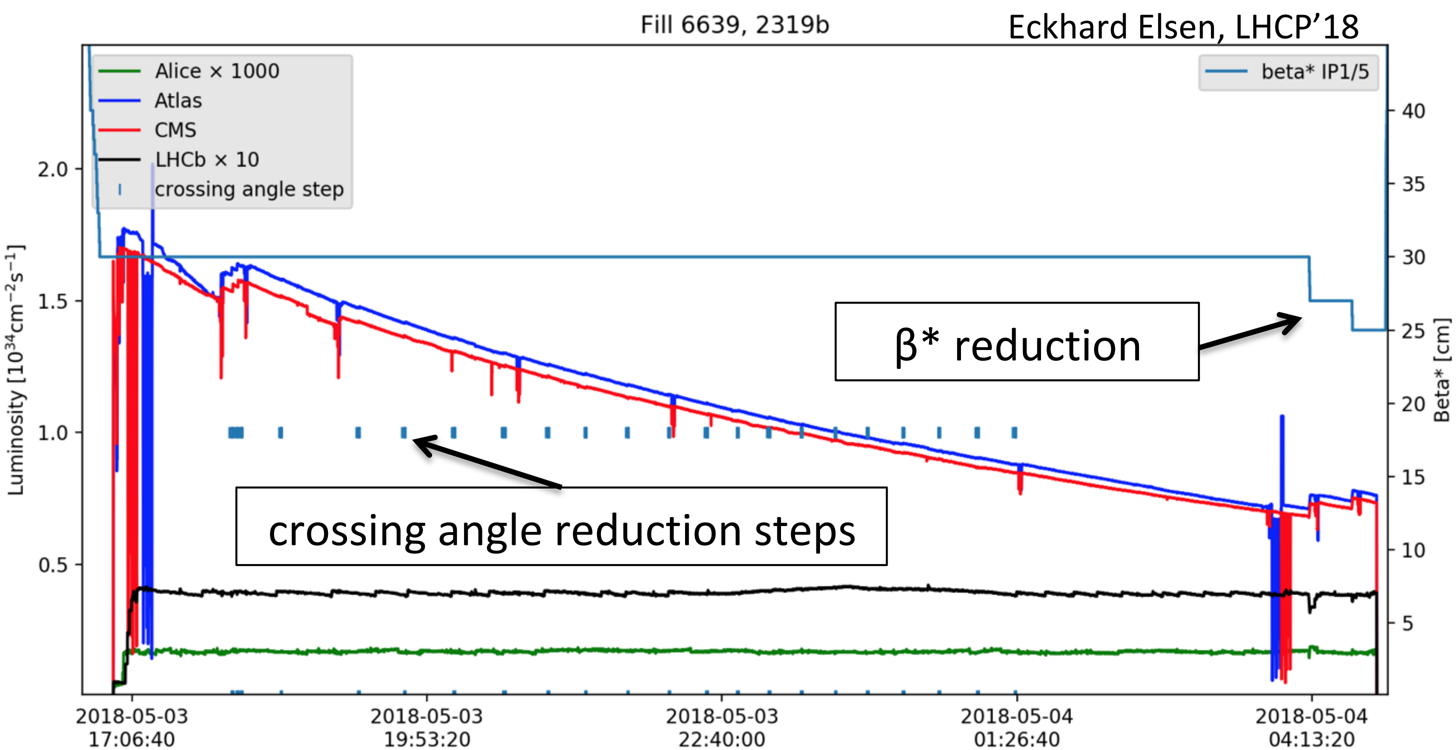


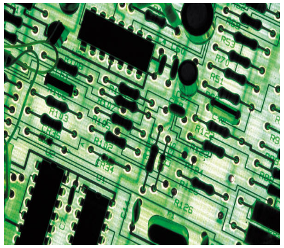
Anti-leveling: crossing angle



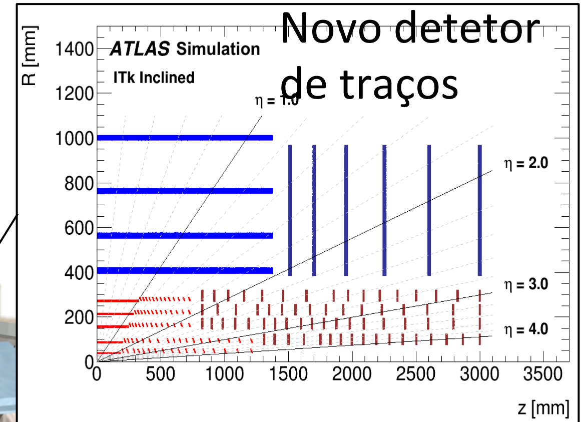
Anti-leveling: β* reduction



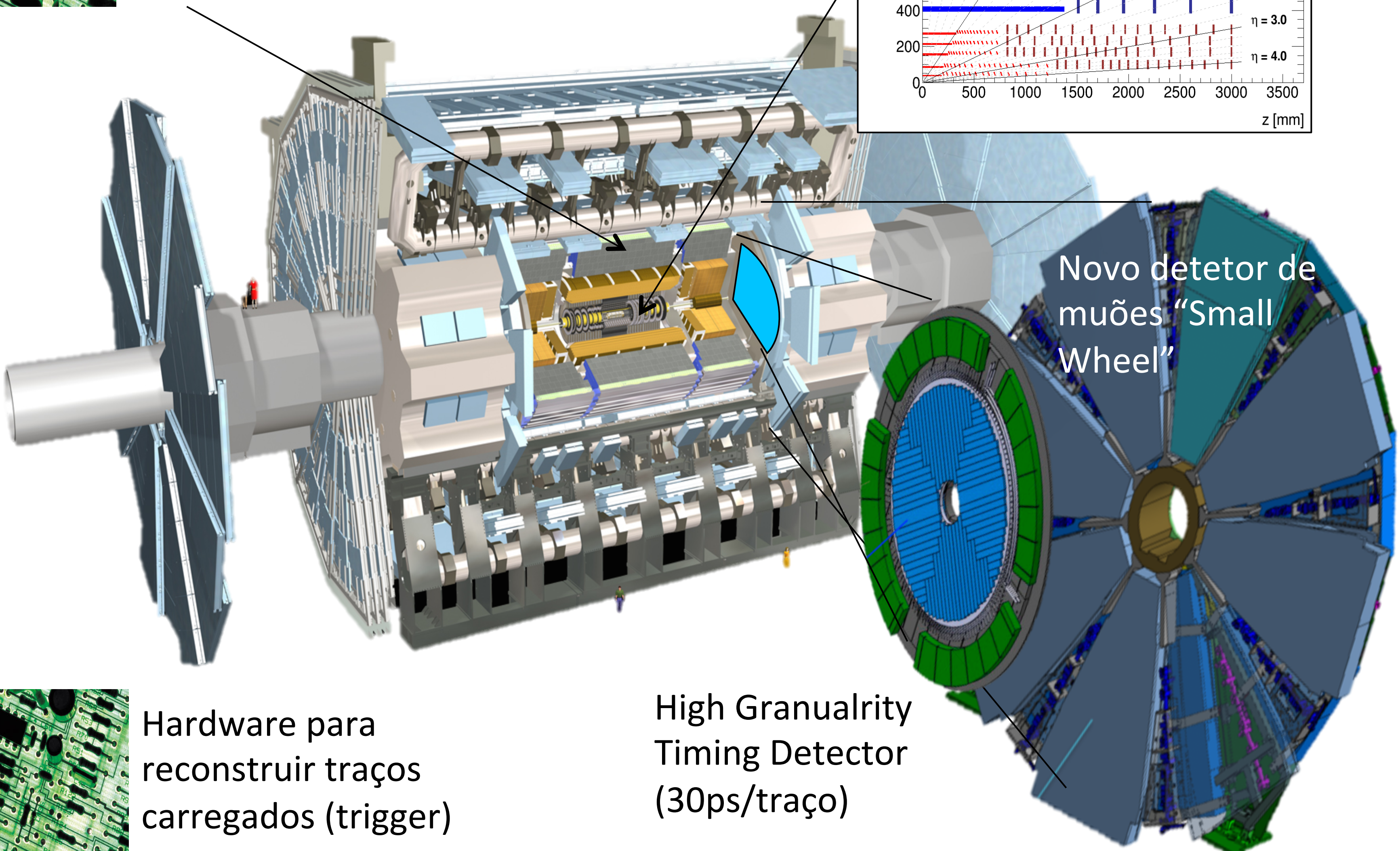




Nova eletrónica, fontes de alta tensão e cintiladores do calorímetro

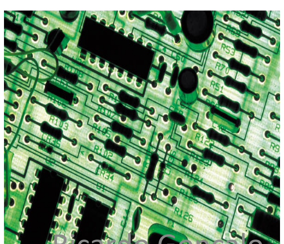


Novo detetor de traços



Novo detetor de muões "Small Wheel"

High Granualrity Timing Detector (30ps/traço)



Hardware para reconstruir traços carregados (trigger)

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Novo MIP Timing Detector (Barrel & Endcap)

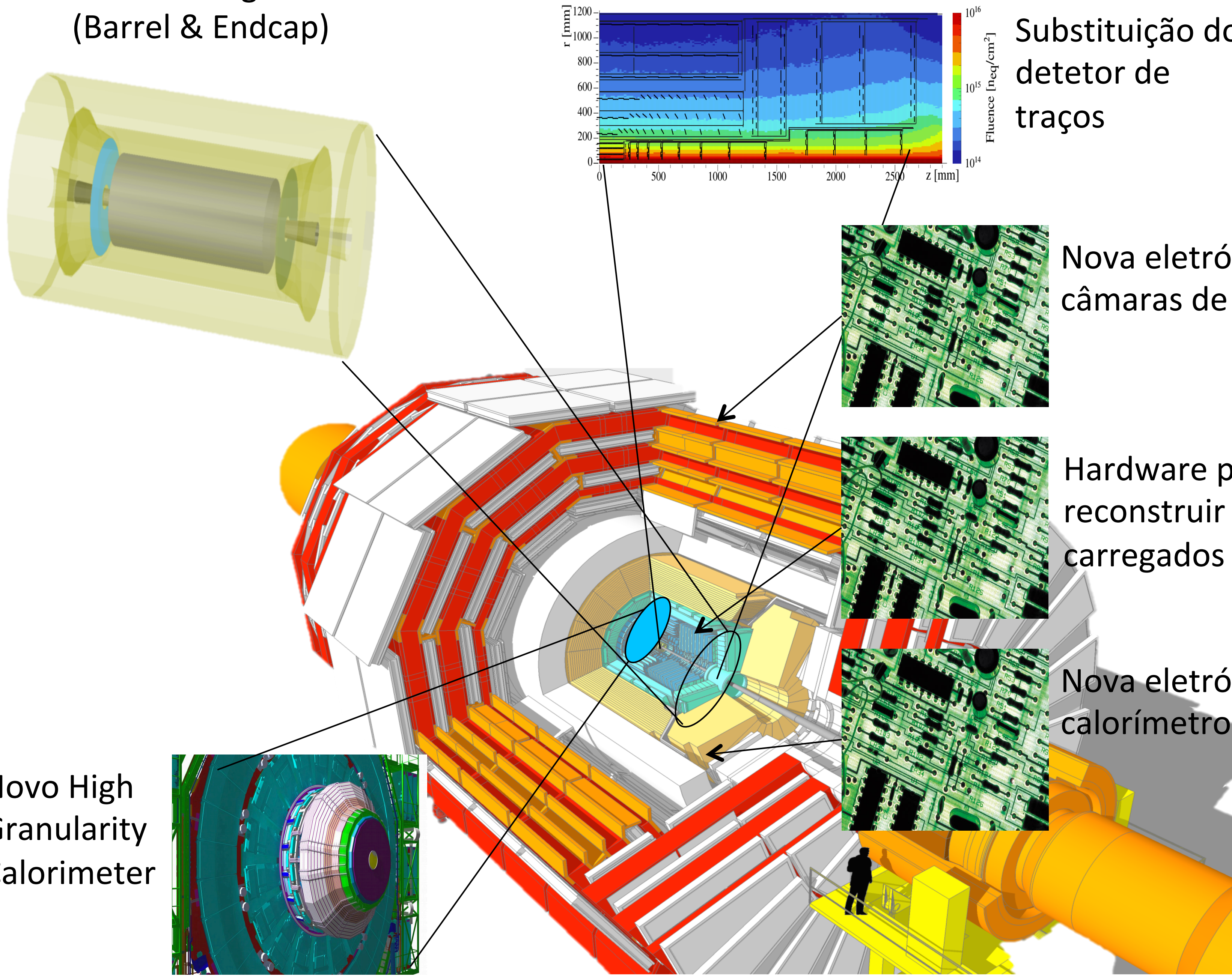
Substituição do detetor de traços

Nova eletrónica e câmaras de muões

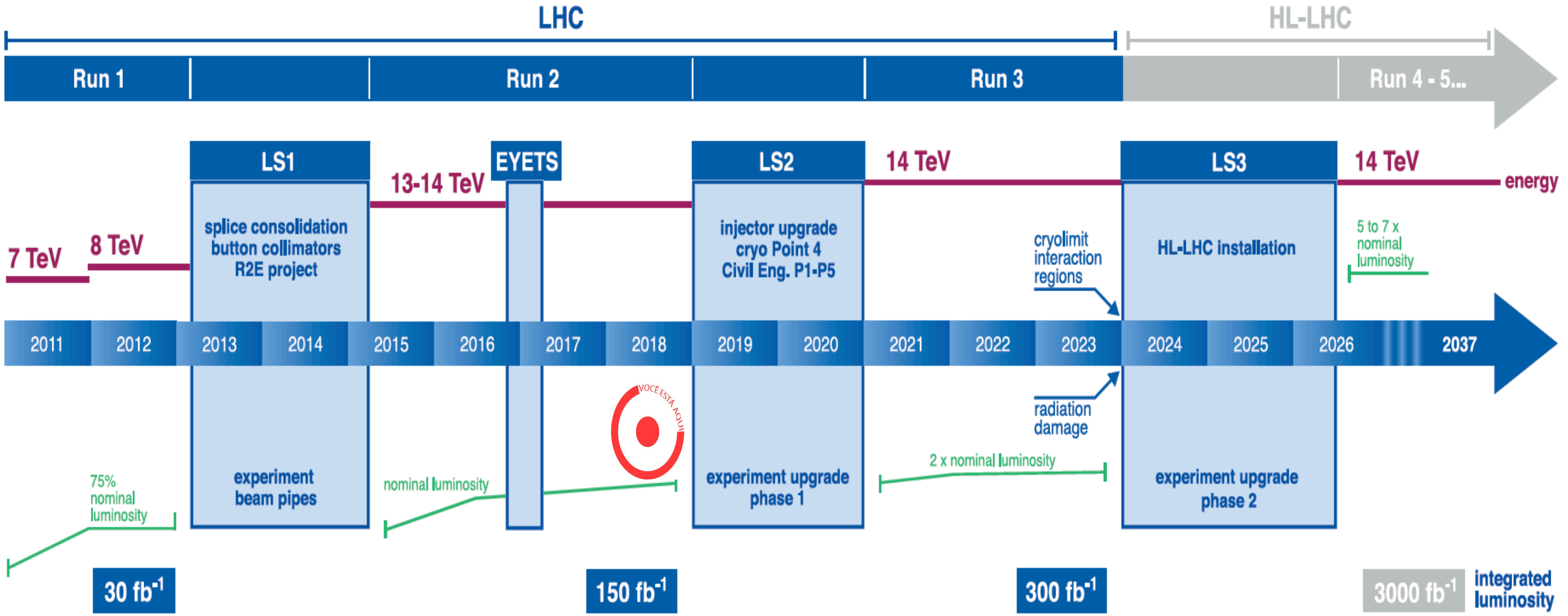
Hardware para reconstruir traços carregados (trigger)

Nova eletrónica do calorímetro

Novo High Granularity Calorimeter



LHC / HL-LHC Plan



Melhoramentos das experiências cruciais para funcionar no ambiente do HL-LHC

Alguns em construção, muitos em fase de R&D

Vão permitir acumular dados únicos na fronteira da alta energia durante 10 anos

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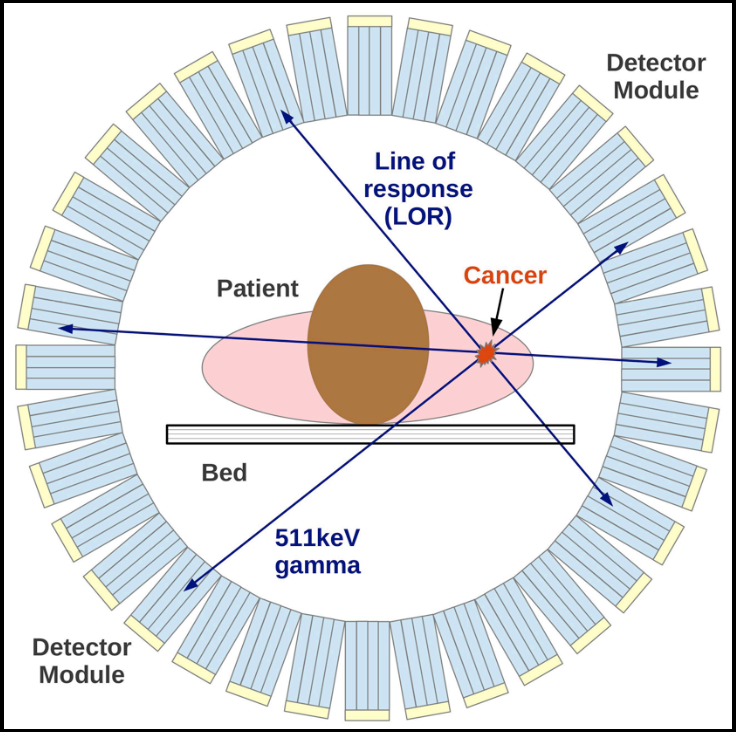
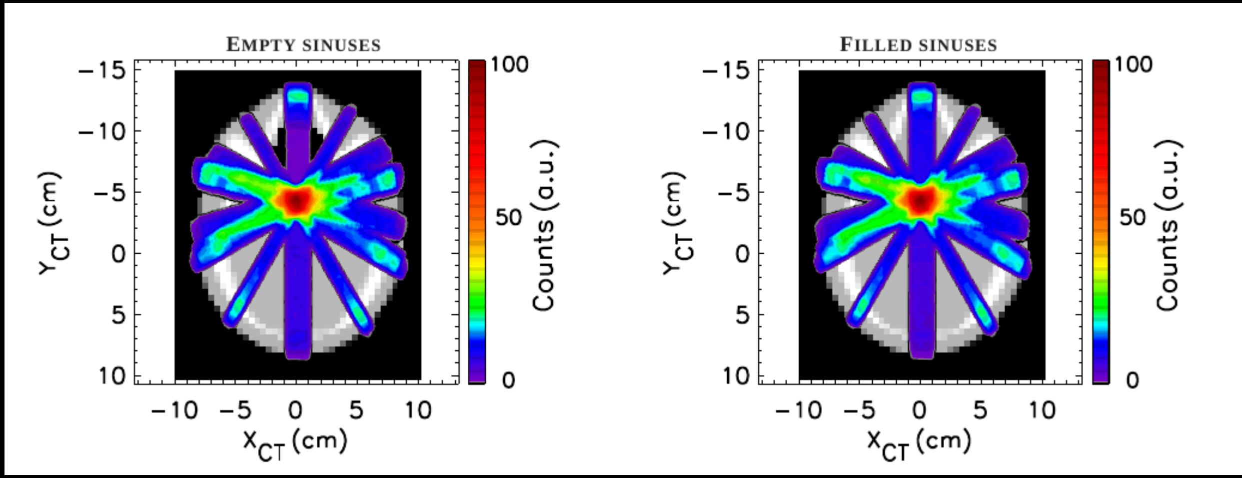
Impacto na sociedade


Prototerapia
Computação na grid
Imagiologia médica
Radioterapia
Tomografia de muões
(Pirâmide de Gizé)
Ciclo Solar
Exploração do espaço
World Wide Web

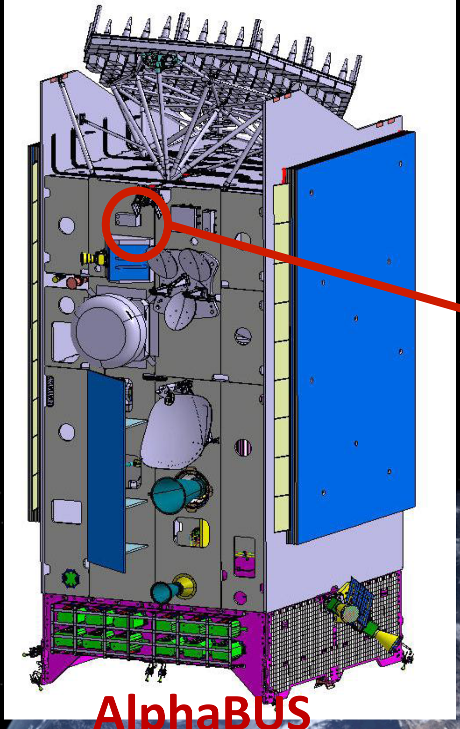


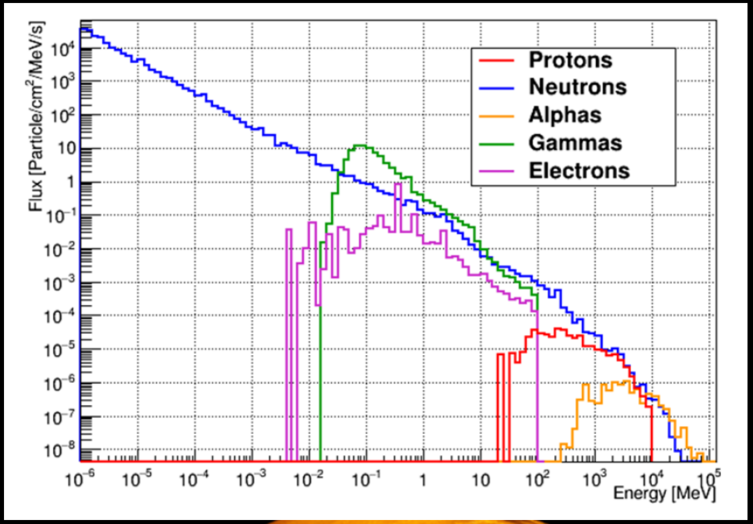
Tomografia de emissão de positrões (PET)

Terapia com feixes de protões



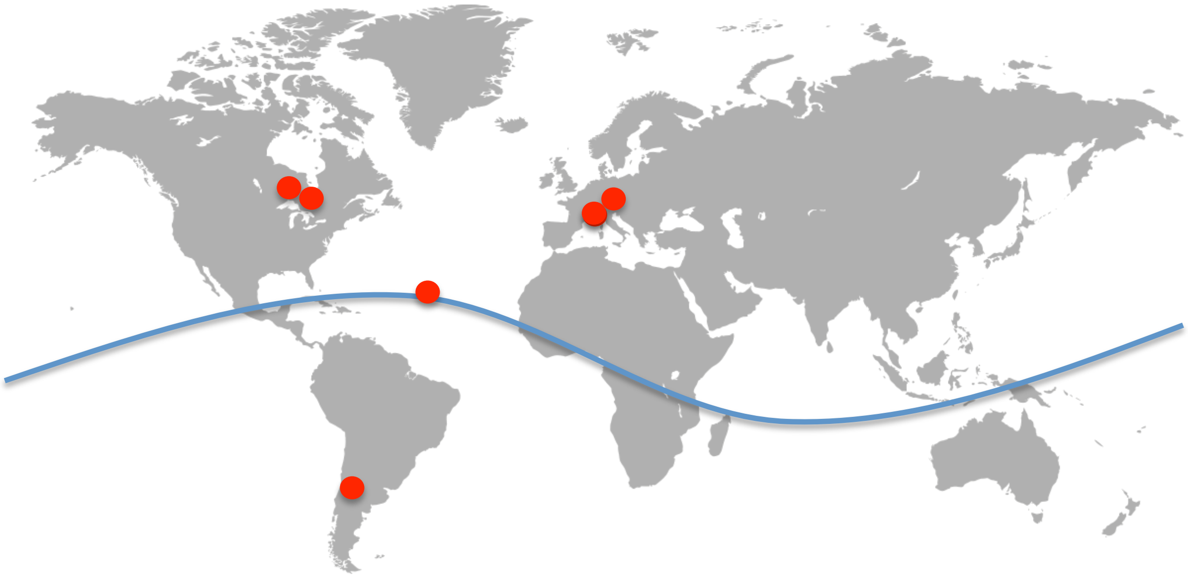
Exploração Espacial





Física (Experimental) de Partículas em Portugal

- Lisboa, Coimbra, Minho
- 200 membros
- 90 doutorados
- 75 estudantes
- 25 engenheiros e administrativos



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Ricardo Gonçalo (UC/LIP) Qualquer duvida: jgoncalo@lip.pt

Bonus slides

- a