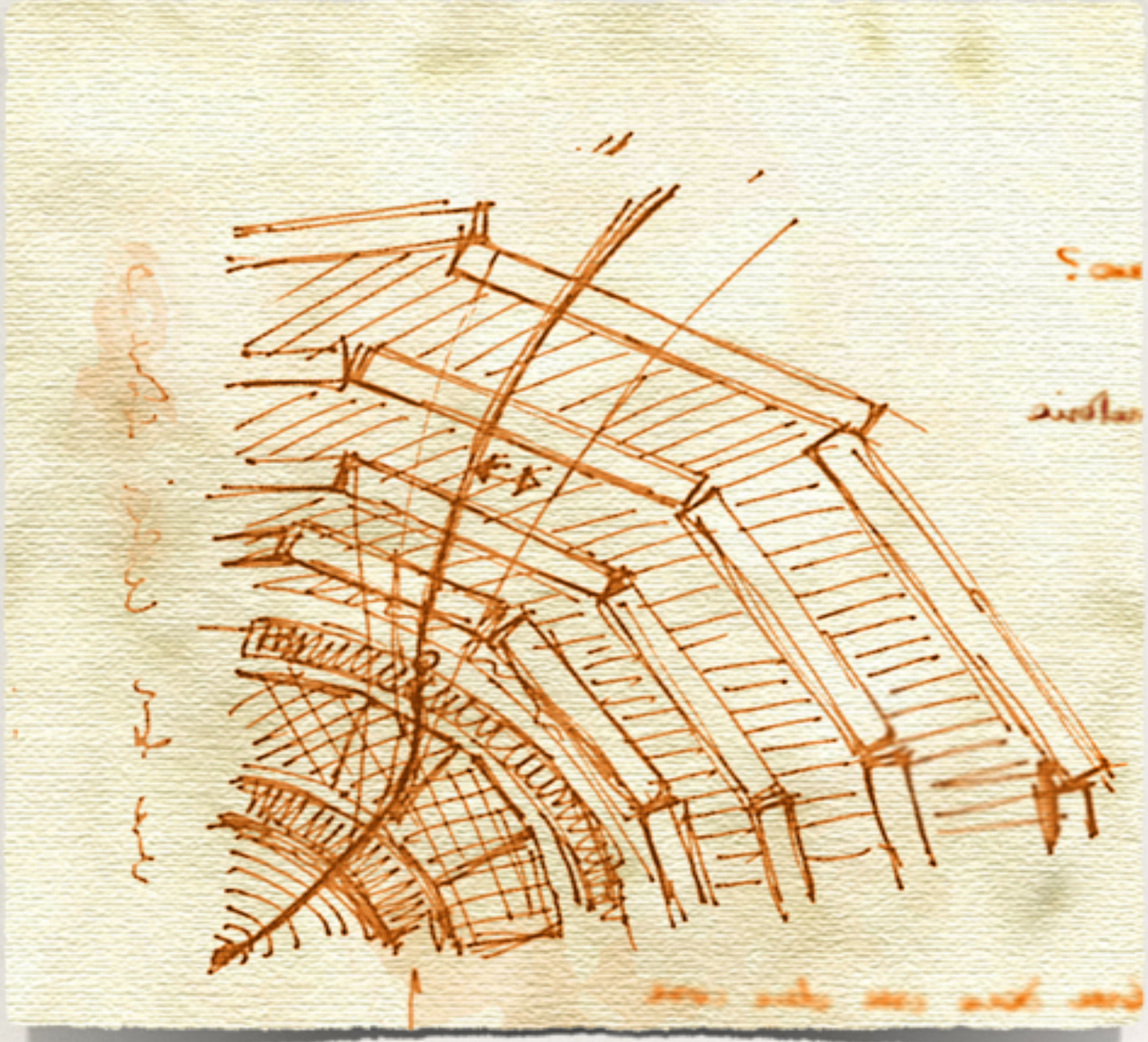

XI Escola do CBPF

Curso de Pós-Graduação

Notas de Aula

A Física dos Detectores de Partículas

Dr Arthur M. Moraes - CBPF

(web-page: http://cern.ch/amoraes)

27 de Julho de 2017

CBPF
Centro Brasileiro de Pesquisas Físicas

Introdução

Programa do Curso:

Aula 1: De Rutherford ao LHC: Desenvolvimento dos detectores ao longo da história da física das partículas elementares. (2ªf. 17/07)

Aula 2: Interações das partículas com a matéria. (3ªf. 18/07)

Aula 3: Detectando partículas carregadas & neutras. (5ªf. 20/07)

Aula 4: Cintiladores: detectando partículas via luminescência. (6ªf. 21/07)

Aula 5: Detectores de semicondutores: medidas de alta precisão. (2ªf. 24/07)

Aula 6: Detectores de gás: medindo partículas em grandes volumes. (3ªf. 25/07)

Aula 7: Calorímetros: eletromagnéticos & hadrônicos. (5ªf. 27/07)

Aula 8: Exemplos de aplicações dos detectores em várias áreas. (6ªf. 28/07)

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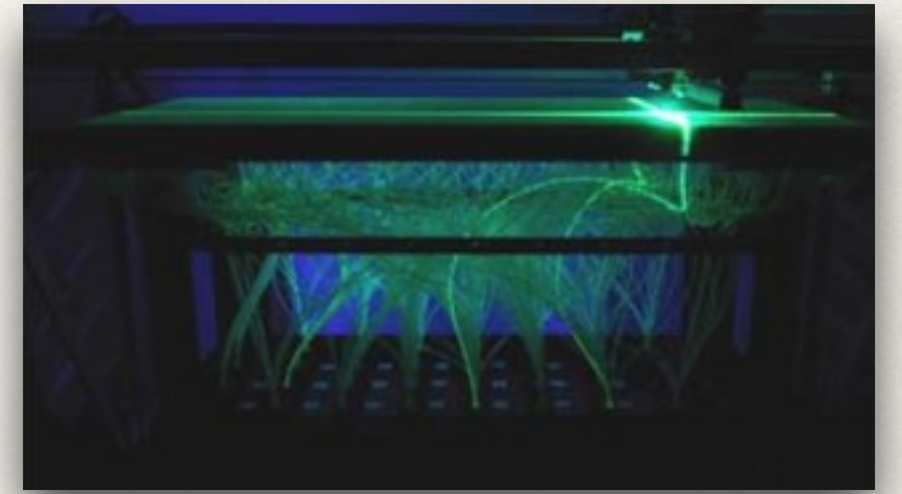
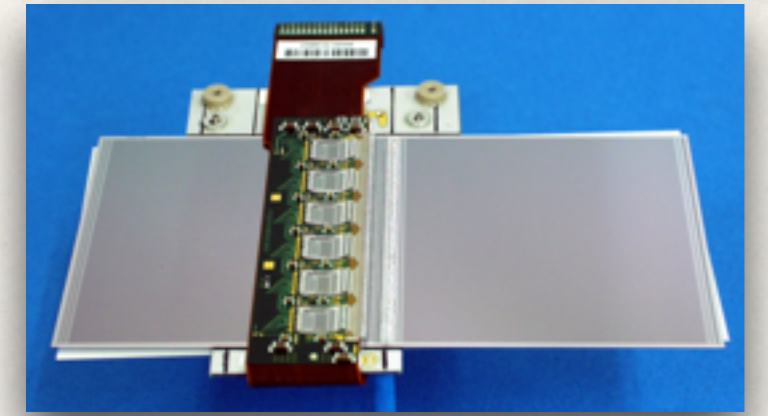
Detectores de partículas

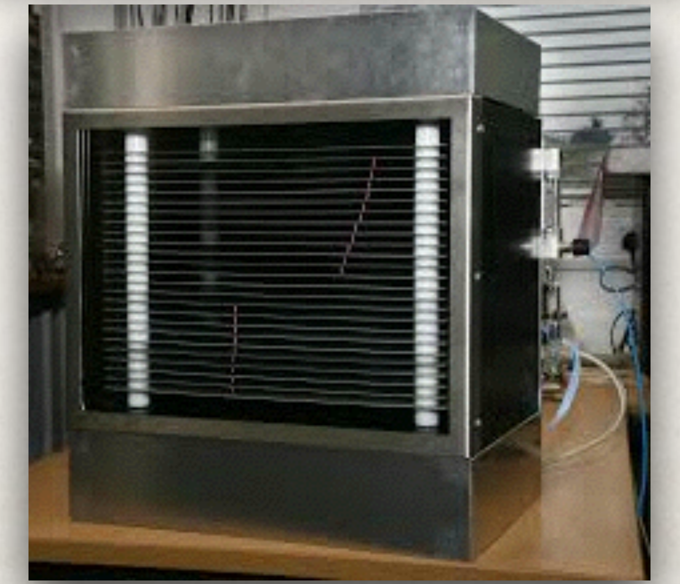
Cintiladores: medem sinais luminosos
cristais, líquidos e gases



Semicondutores: medidas de alta precisão espacial
rápida resposta
boa resistência à irradiação



Gás: medidas em grandes volumes
identificação de partículas
deterioração com uso devido ao efeito avalanche



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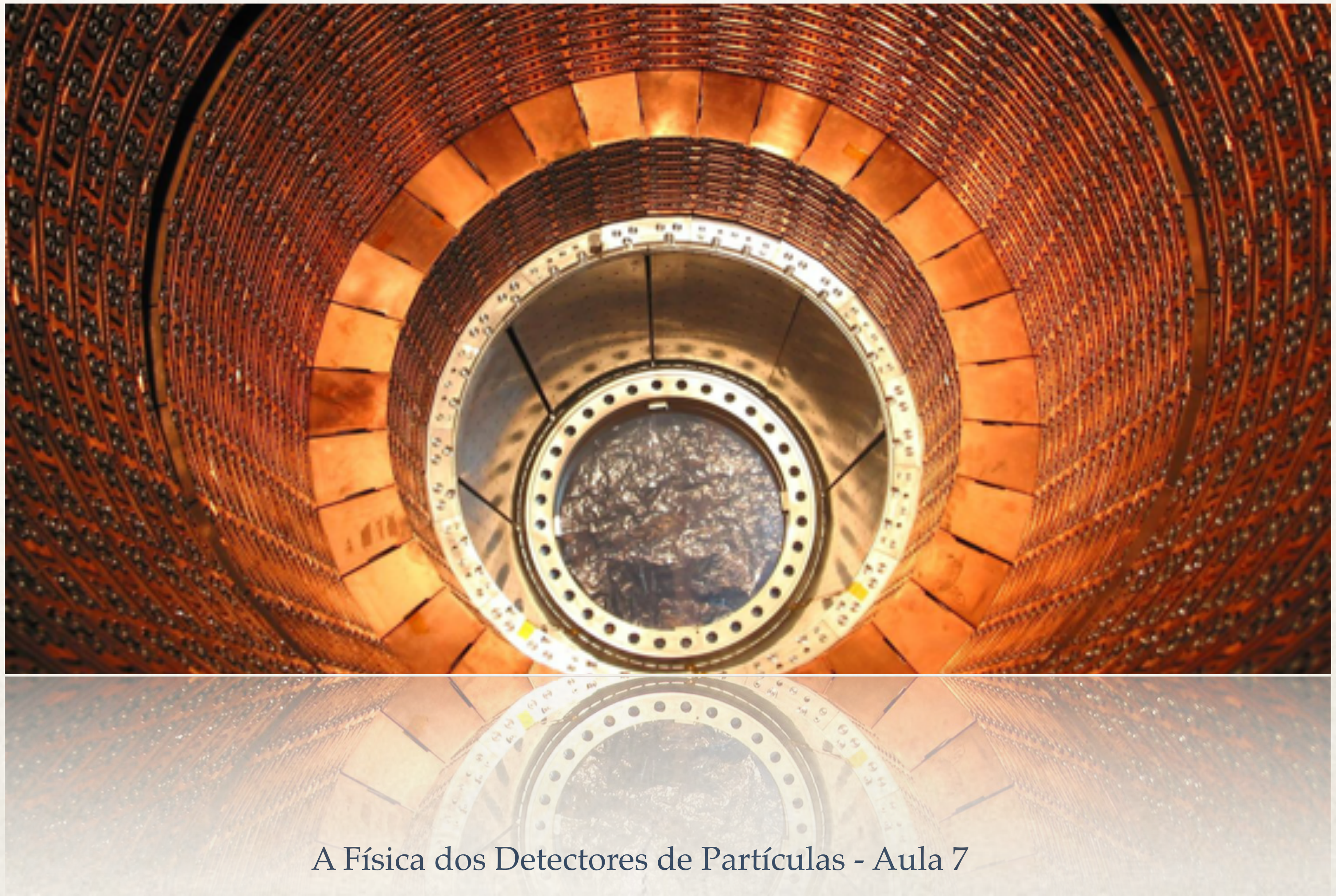
Aula 7

Calorímetros eletromagnético & hadrônico



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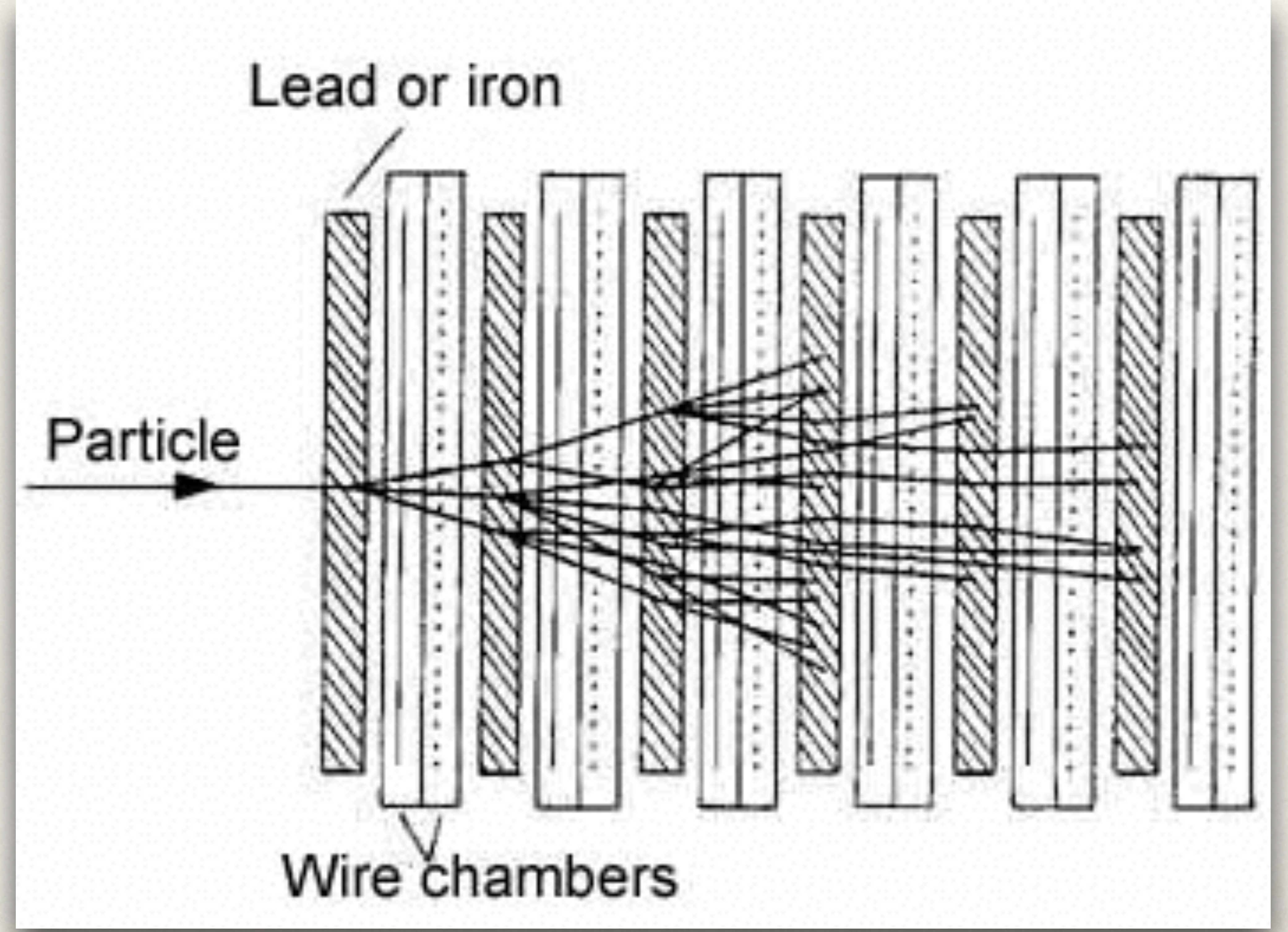
Calorímetros

- Detector para ***medida de energia*** através da absorção das partículas

- Tipicamente, calorímetros também são sensíveis à ***posição*** da absorção de partículas

- Princípio de operação:
  - partículas incidentes iniciam um chuveiro de partículas (composição do chuveiro depende to tipo de partícula incidente e material do detector)
  - energia depositada na forma de calor, ionização, excitação de átomos, luz Cherenkov (diferentes tipos de calorímetros usam diferentes tipos de sinais)
  - sinal proporcional à energia total depositada

Calorímetros



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Calorímetros

Medida da energia vs. momento:

Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$

e.g. ATLAS:

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

i.e. σ_E/E = 1% @ 100 GeV

Gas detector: $\frac{\sigma_p}{p} \sim p$

e.g. ATLAS:

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

i.e. σ_p/p = 5% @ 100 GeV

At very high energies one has to switch to calorimeters because their resolution improves while those of a magnetic spectrometer decreases with E ...

Profundidade do chuveiro de partículas

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

[E_c: critical energy]

Shower depth nearly energy independent i.e. calorimeters can be compact ...

Compare with magnetic spectrometer: $\sigma_p/p \sim p/L^2$
Detector size has to grow quadratically to maintain resolution

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Calorímetros

Outras propriedades dos calorímetros:

- Calorímetros podem ser construídos com cobertura 4π, ou seja podem detectar partículas em quase todo o ângulo sólido.
- Calorímetros fornecem resposta rápida (1 a 10ns), ou seja, podem ser utilizados para "triggering" (seleção online de colisões).
- Calorímetros medem energia de partículas com carga elétrica e/ou neutras dependendo das interações eletromagnéticas ou forte destas com o material do detector.
- Segmentação radial permite separação de hádrons das partículas que interagem apenas eletromagneticamente.

Calorímetro Eletromagnético

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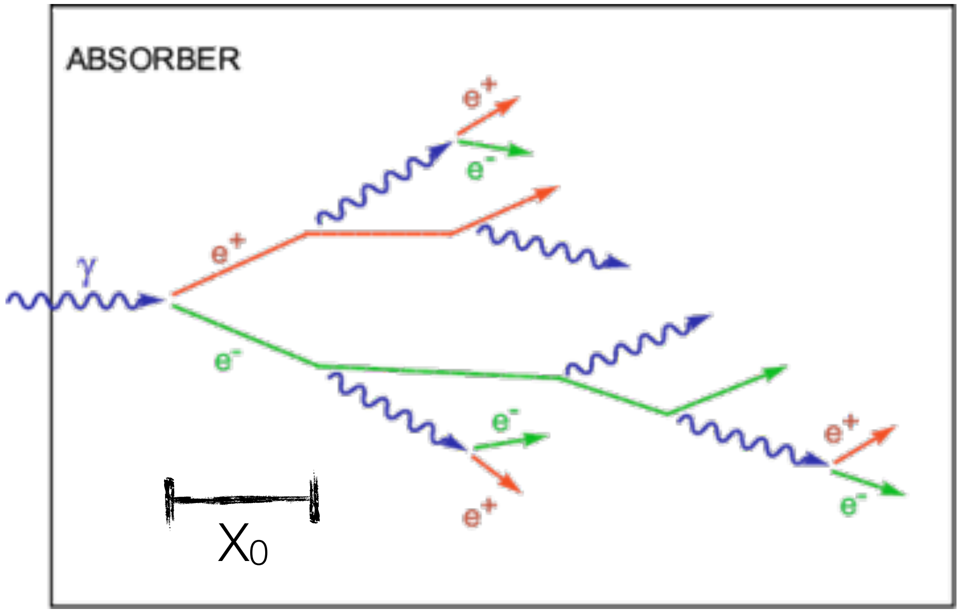
Chuveiro eletromagnético

Reminder:

Dominant processes
at high energies ...

Photons : Pair production
Electrons : Bremsstrahlung



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/cm^2]

Absorption coefficient:

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

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 $(1/e)^{th}$ of its primary energy ...
[i.e. 37%]

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Chuveiro eletromagnético

Further basics:

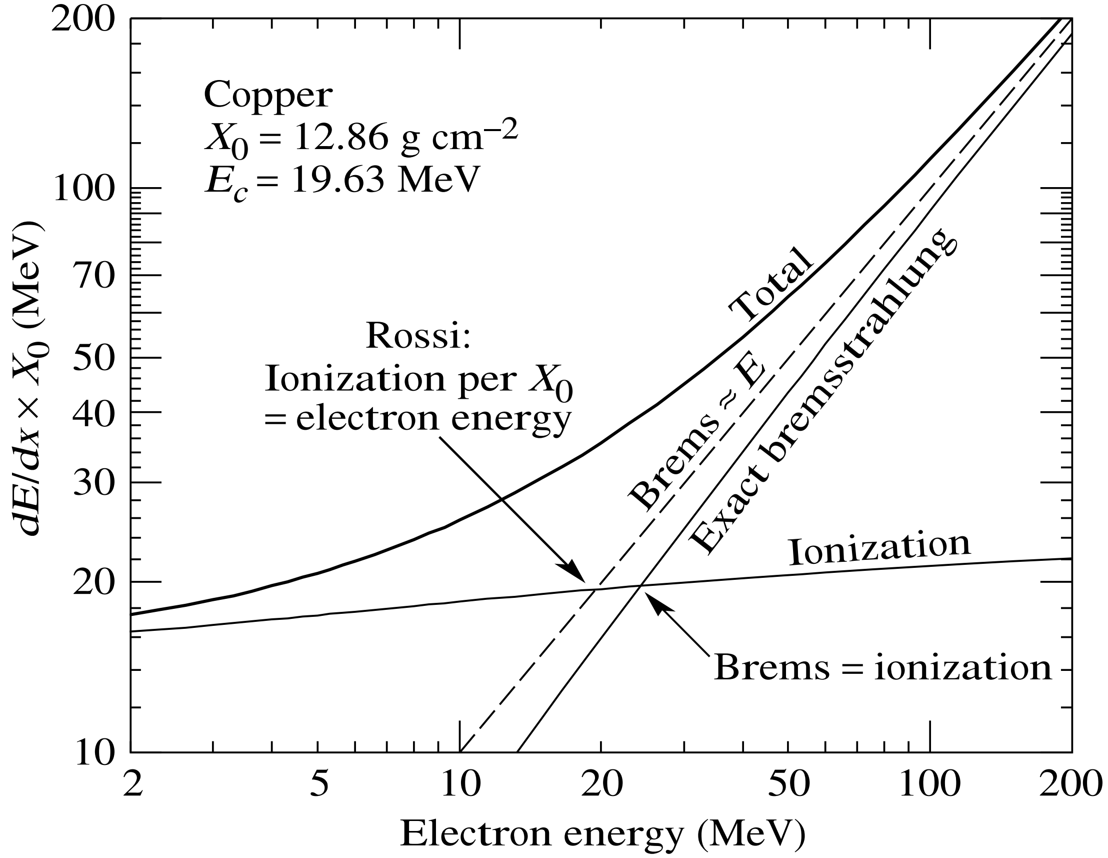
Critical Energy [see above]:

$$\frac{dE}{dx}(E_c)\bigg|_{\text{Brems}} = \frac{dE}{dx}(E_c)\bigg|_{\text{Ion}}$$

Approximations:

$$E_c^{\text{Gas}} = \frac{710\text{ MeV}}{Z+0.92} \qquad \left[E_c^{\text{Sol/Liq}} = \frac{610\text{ MeV}}{Z+1.24} \right]$$

$$\left(\frac{dE}{dx}\right)_{\text{Brems}} \Big/ \left(\frac{dE}{dx}\right)_{\text{Ion}} \approx \frac{Z \cdot E}{800\text{ MeV}}$$



with:

$$\frac{dE}{dx}\bigg|_{\text{Brems}} = \frac{E}{X_0} \quad \& \quad \frac{dE}{dx}\bigg|_{\text{Ion}} \approx \frac{E_c}{X_0} = \text{const.}$$

Transverse size of EM shower given by radiation length via Molière radius

[see also later]

$$R_M = \frac{21\text{ MeV}}{E_c} X_0$$

R_M : Moliere radius
E_c : Critical Energy [Rossi]
X_0 : Radiation length

Chuveiro eletromagnético

Typical values for X_0, E_c and R_M of materials used in calorimeter

	X_0 [cm]	E_c [MeV]	R_M [cm]
Pb	0.56	7.2	1.6
Scintillator (Sz)	34.7	80	9.1
Fe	1.76	21	1.8
Ar (liquid)	14	31	9.5
BGO	1.12	10.1	2.3
Sz/Pb	3.1	12.6	5.2
PB glass (SF5)	2.4	11.8	4.3

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Analisando o modelo dos chuveiros

Simple shower model:

Only two dominant interactions:
Pair production and Bremsstrahlung ...

γ + Nucleus ➛ Nucleus + e^+ + e^-
[Photons absorbed via pair production]

e + Nucleus ➛ Nucleus + e + γ
[Energy loss of electrons via Bremsstrahlung]

Shower development governed by X_0 ...

After a distance X_0 electrons remain with only $(1/e)^{th}$ of their primary energy ...

Photon produces e^+e^--pair after $9/7X_0 \approx X_0$ ...

Assume:

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

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

Electromagnetic Shower
[Monte Carlo Simulation]

Use
Simplification:

$E_\gamma = E_e \approx E_0/2$
[E_e looses half the energy]

$E_e \approx E_0/2$
[Energy shared by e^+/e^-]

... with initial particle energy E_0

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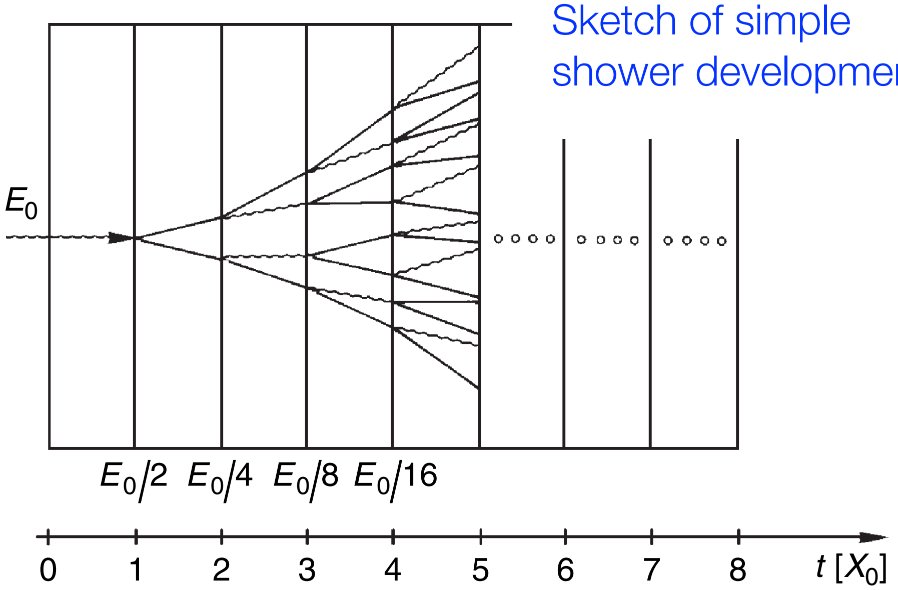
Analisando o modelo dos chuveiros



Simple shower model:
[continued]

Shower characterized by:

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

Longitudinal components; measured in radiation length ...

... use: $t = \frac{x}{X_0}$

Number of shower particles after depth t:

$$N(t) = 2^t$$

Energy per particle after depth t:

$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

$$\rightarrow \quad t = \log_2(E_0/E)$$

Total number of shower particles with energy E_1:

$$N(E_0, E_1) = 2^{t_1} = 2^{\log_2(E_0/E_1)} = \frac{E_0}{E_1}$$

Number of shower particles at shower maximum:

$$N(E_0, E_c) = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c} \propto E_0$$

Shower maximum at:

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

Analisando o modelo dos chuveiros

Transverse shower development ...

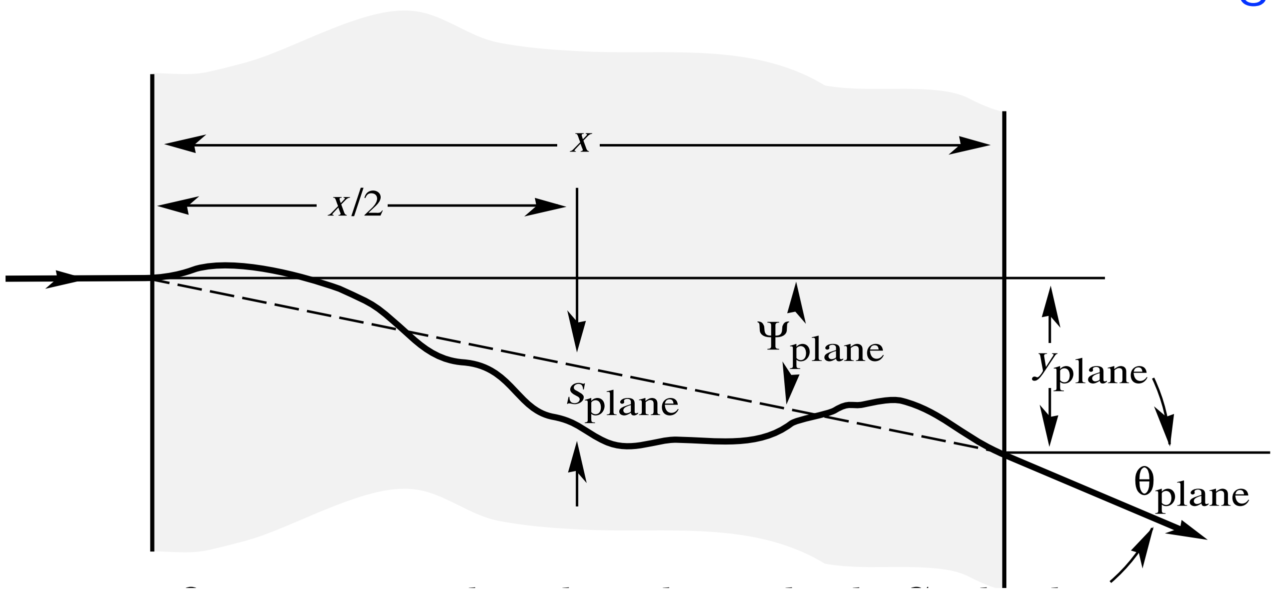
Opening angle

for bremsstrahlung and pair production

$$\langle\theta^2\rangle \approx (m/E)^2 = 1/\gamma^2$$

Small contribution as $m_e/E_c = 0.05$

Multiple coulomb scattering



Multiple scattering

deflection angle in 2-dimensional plane ...

$$\langle\theta_k^2\rangle = \sum_{m=1}^{k} \theta_m^2 = k\langle\theta^2\rangle$$

$$\sqrt{\langle\theta^2\rangle} \approx \frac{13.6\ \mathrm{MeV}/c}{p}\sqrt{\frac{x}{X_0}}$$ [β = 1]

In 3-dimensions extra factor √2:

$$\sqrt{\langle\theta^2\rangle_{3d}} \approx \frac{19.2\ \mathrm{MeV}/c}{p}\sqrt{\frac{x}{X_0}}$$ [β = 1]

Assuming the approximate range of electrons to be X_0 yields lateral extension: $R = \langle\theta\rangle \cdot X_0$ ...

$$R_M = \langle\theta\rangle_{x=X_0} \cdot X_0 \approx \frac{21\mathrm{MeV}}{E_C} X_0$$

Molière Radius;
characterizes lateral shower spread ...

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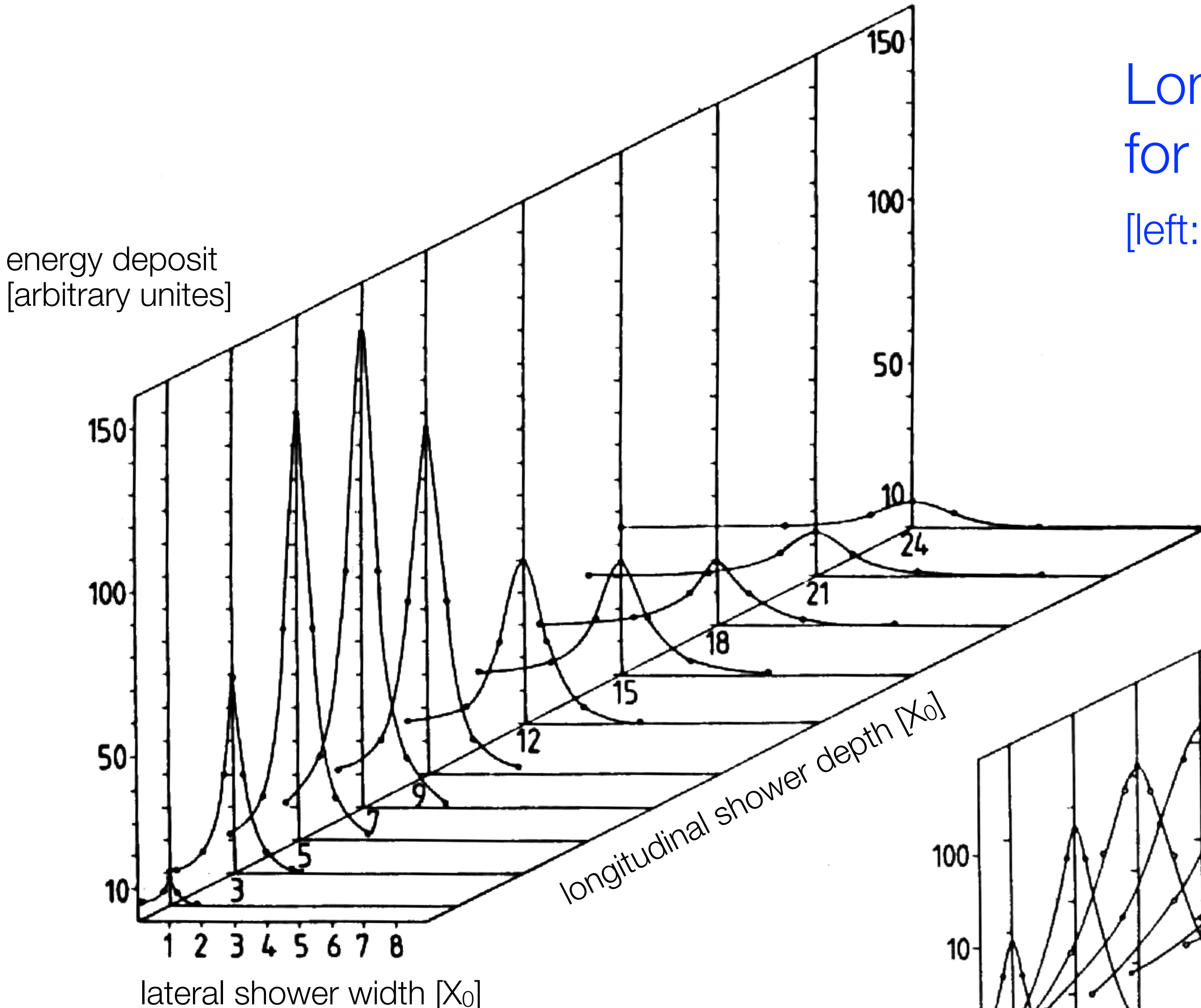
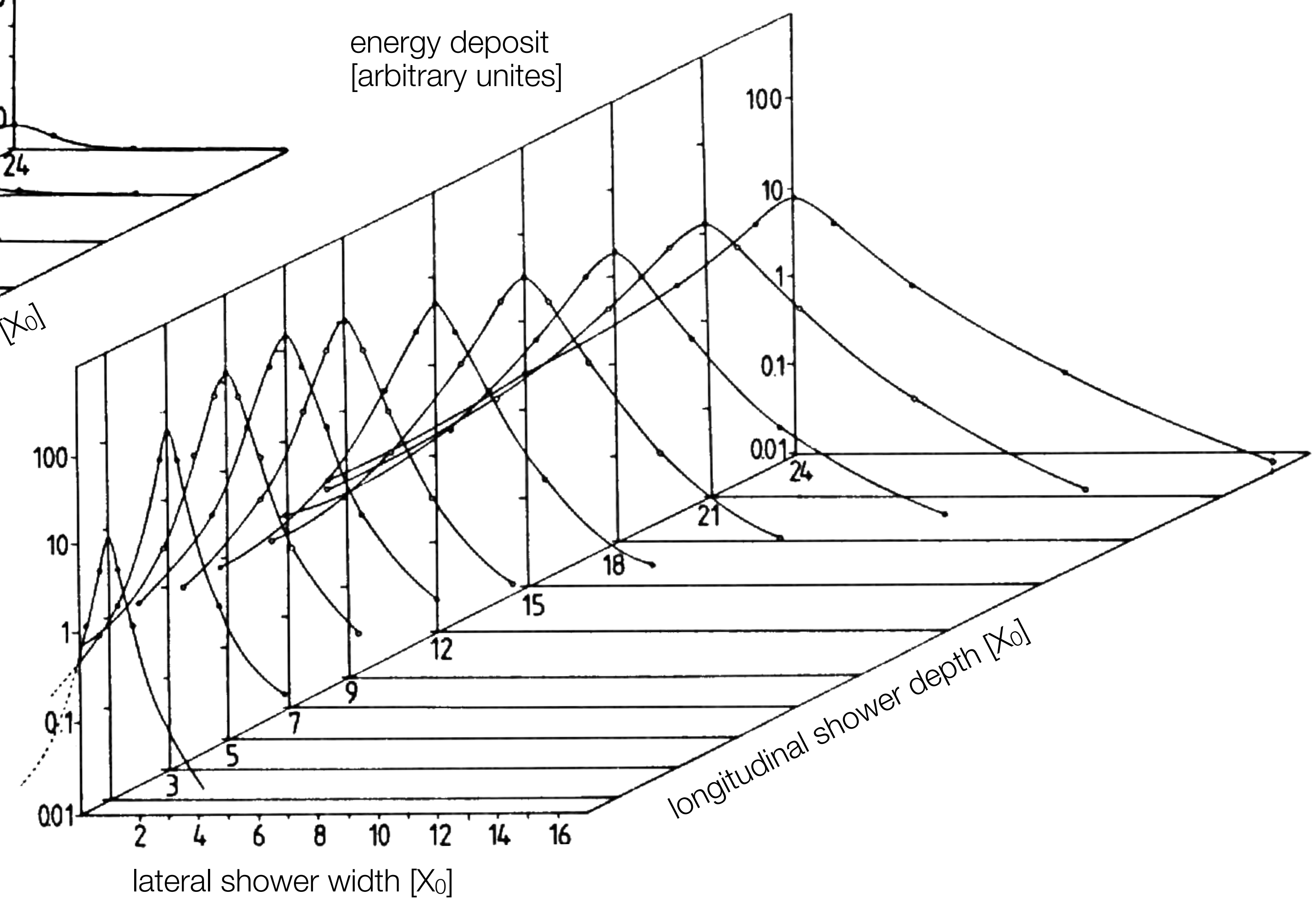
Perfil do chuveiro eletromagnético

Longitudinal and transversal shower profile for a 6 GeV electron in lead absorber ...

[left: linear scale; right: logarithmic scale]





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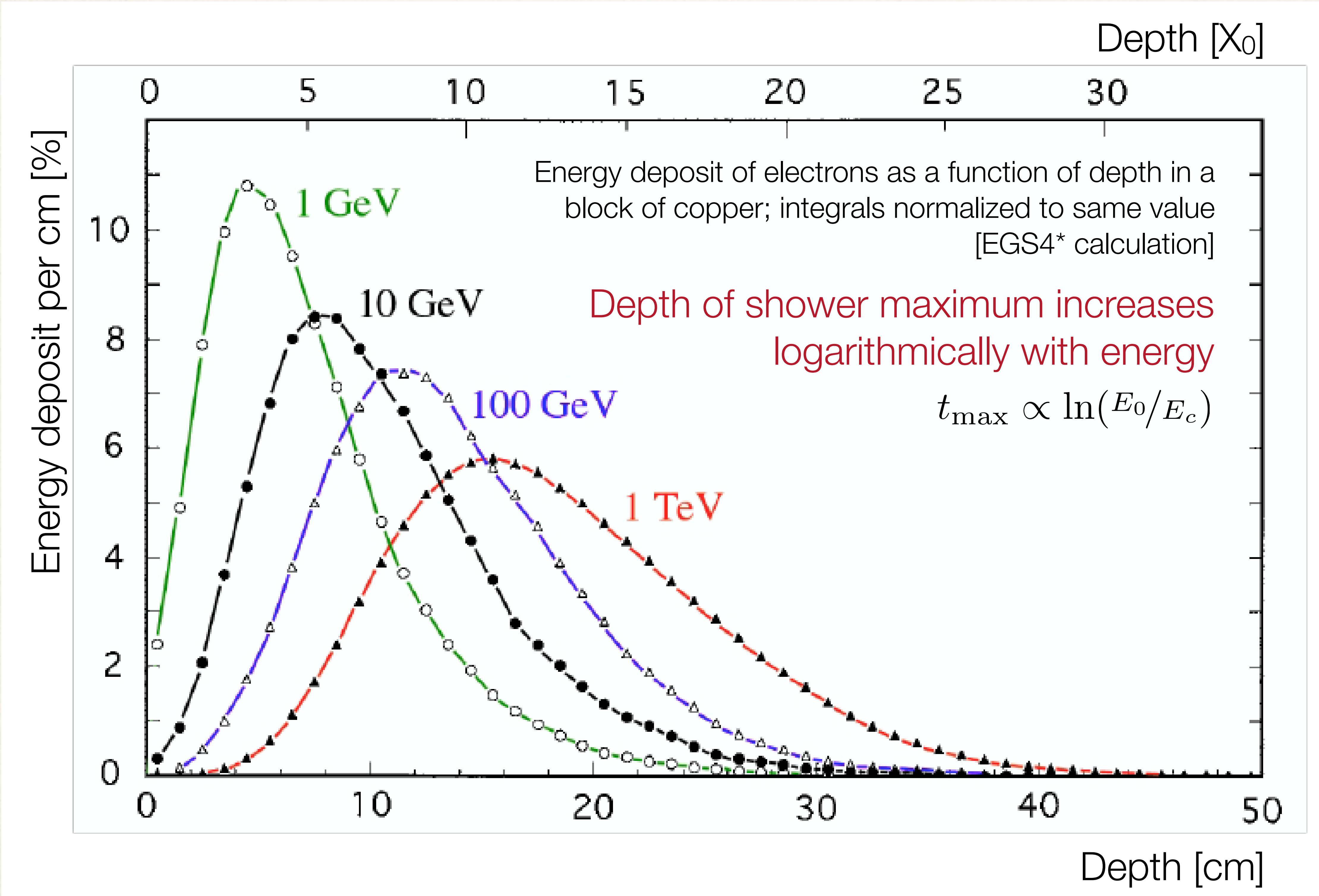
Perfil do chuveiro eletromagnético



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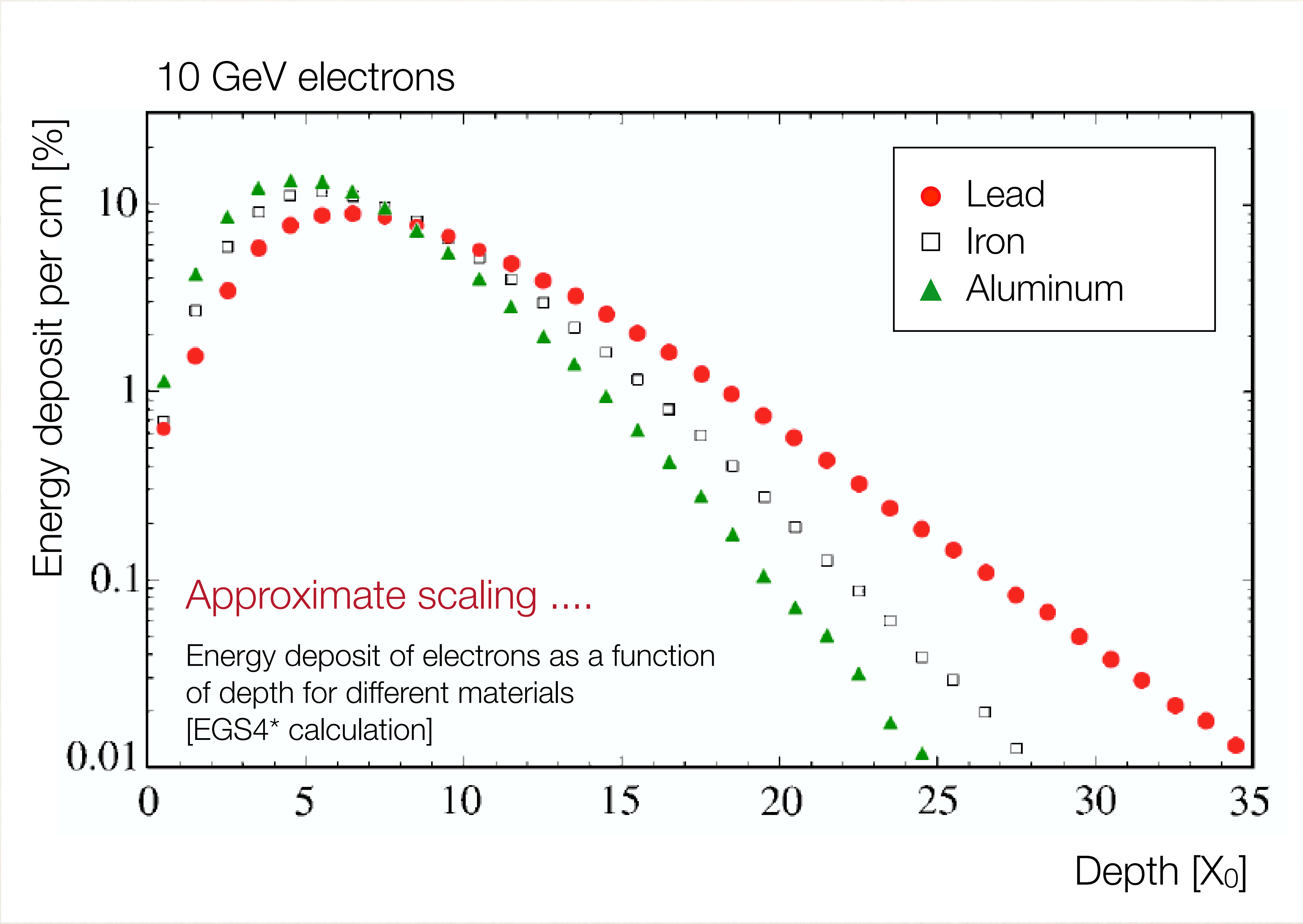
Perfil do chuveiro eletromagnético



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Perfil do chuveiro eletromagnético

Photons:

Photo-electric effect ...

$\sigma \propto Z^5, E^{-3}$

Compton scattering ...

$\sigma \propto Z, E^{-1}$

Pair production ...

σ increases with E, Z
asymptotic at ~ 1 GeV

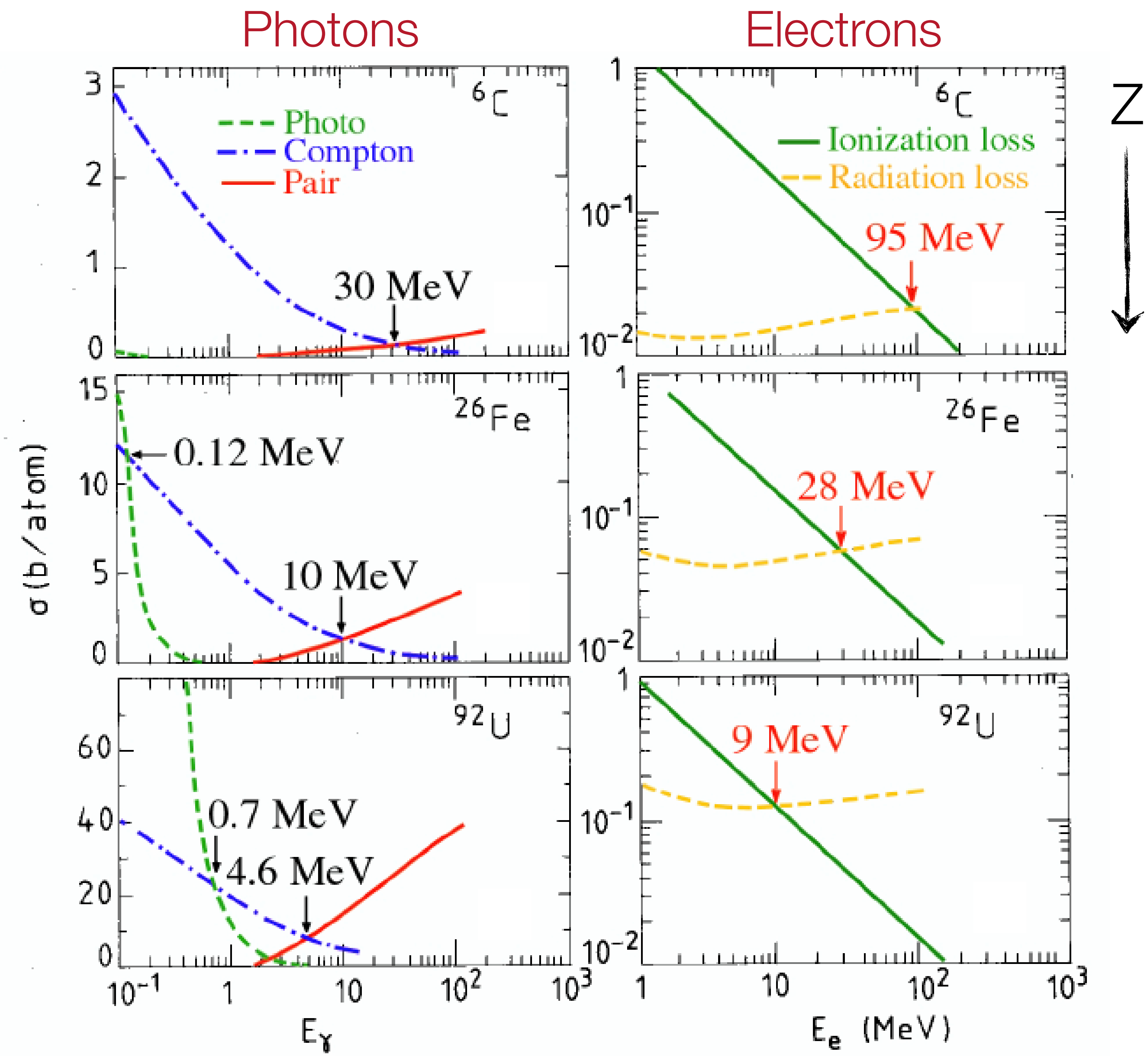
Electrons:

Critical energy ...

$E_c \propto \frac{1}{Z}$

In high Z materials
particle multiplication ...
... down to lower energies

➛ longer showers
[with respect to X_0]



Calorímetros homogêneos

★ In a homogeneous calorimeter the whole detector volume is filled by a high-density material which simultaneously serves as absorber as well as as active medium ...

Signal	Material
Scintillation light	BGO, BaF_2, CeF_3, ...
Cherenkov light	Lead Glass
Ionization signal	Liquid nobel gases (Ar, Kr, Xe)

★ Advantage: homogenous calorimeters provide optimal energy resolution

★ Disadvantage: very expensive

★ Homogenous calorimeters are exclusively used for electromagnetic calorimeter, i.e. energy measurement of electrons and photons

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Calorímetros homogêneos

Calorímetro de cristal do CMS

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Sampling calorimeters

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

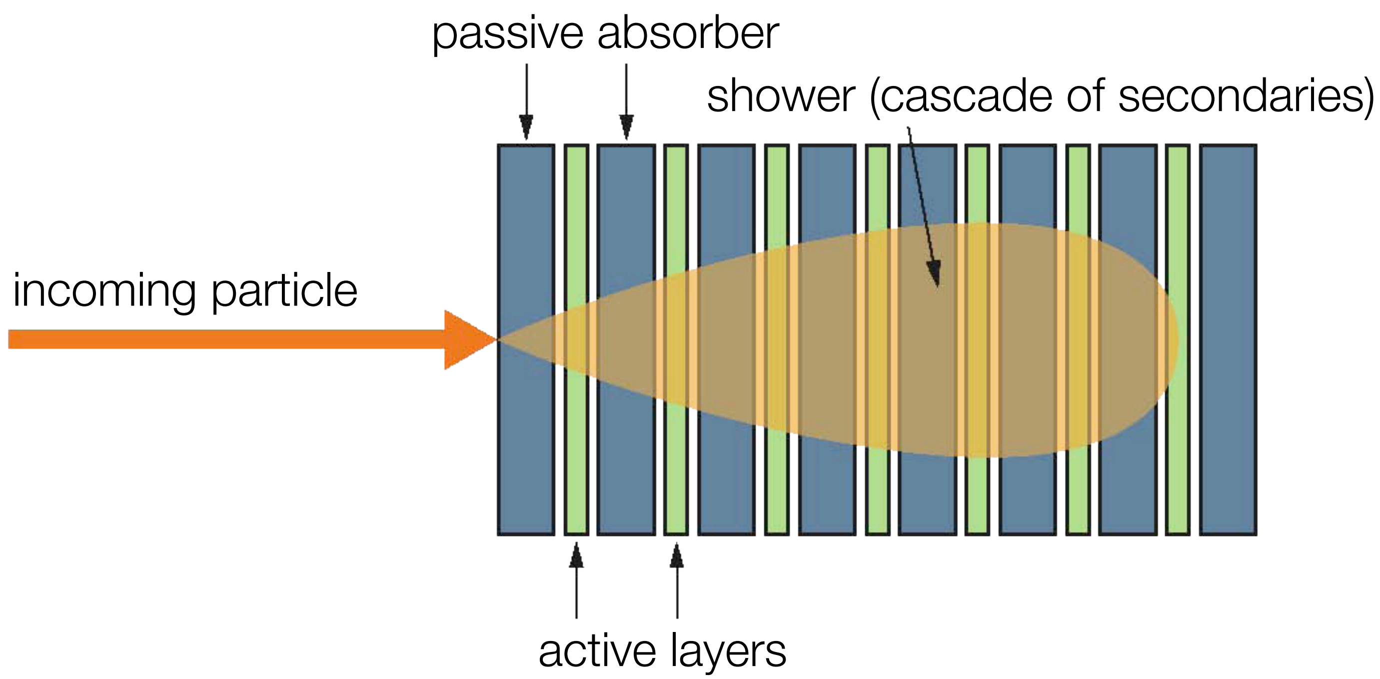
Absorber materials:
[high density]

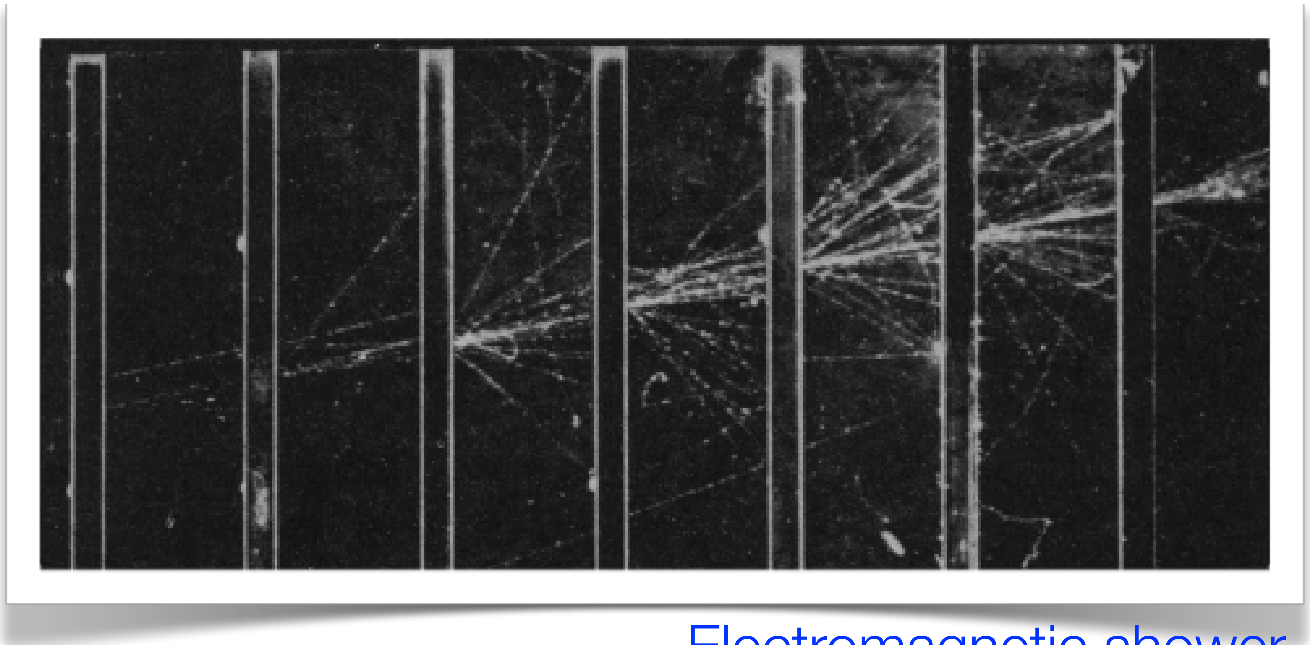
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
[For compensation ...]

Active materials:

- Plastic scintillator
- Silicon detectors
- Liquid ionization chamber
- Gas detectors

Scheme of a sandwich calorimeter





Electromagnetic shower

Sampling calorimeters

★ Advantages:

By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements ...

By freely choosing high-density material for the absorbers one can built very compact calorimeters ...

Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters ...

★ Disadvantages:

Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only ~10^{-5}] ...

Due to this sampling-fluctuations typically result in a reduced energy resolution for sampling calorimeters ...

Calorímetro homogêneo vs Sampling calorimeter

Technology (Experiment)	Depth	Energy resolution	Date	
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983	Homogeneous
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993	
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996	
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999	
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998	
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997	
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990	
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998	
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988	Sampling
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988	
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995	
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988	
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993	
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998	
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993	
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996	

Resolution of typical electromagnetic calorimeter
[E is in GeV]

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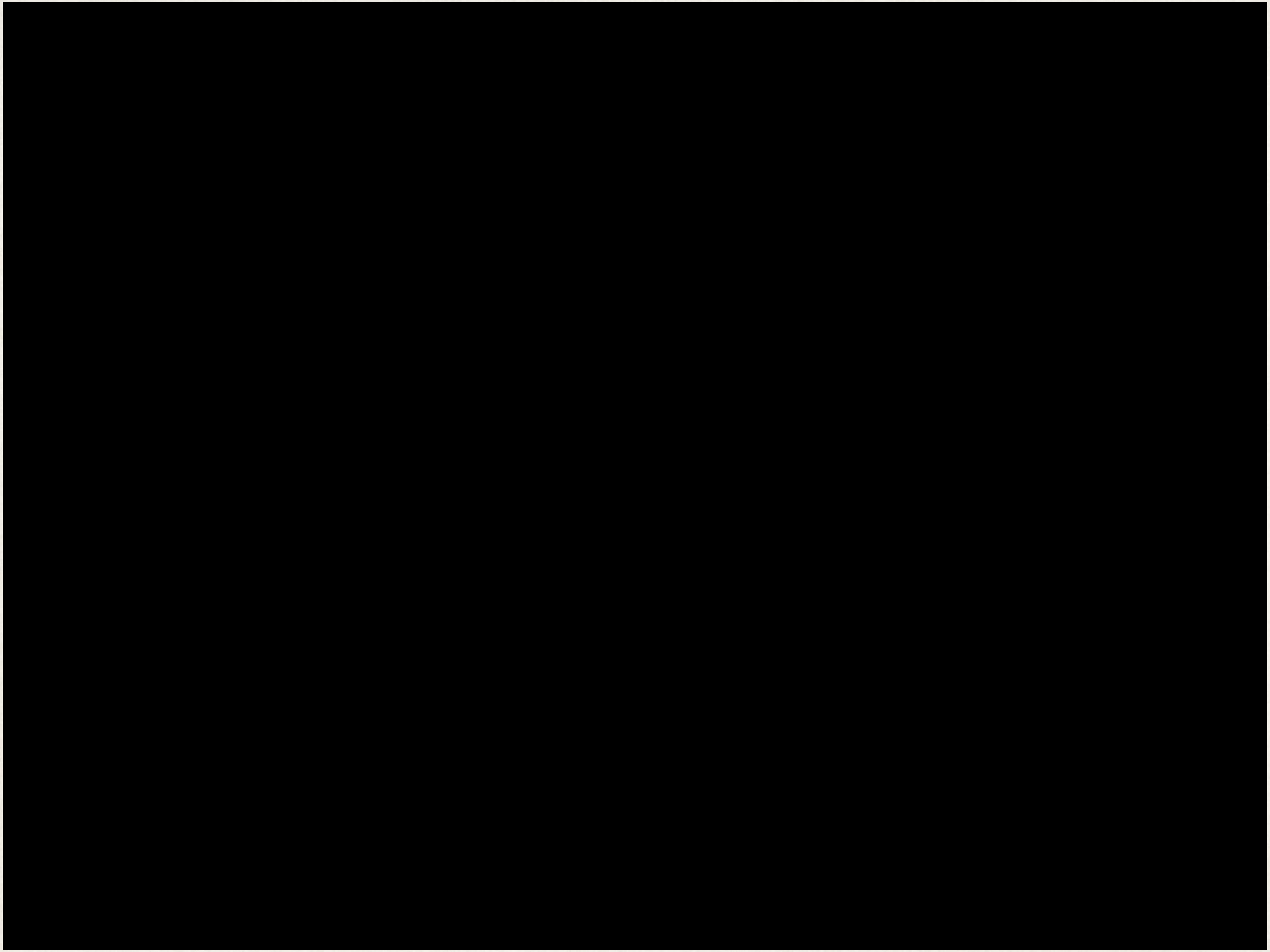

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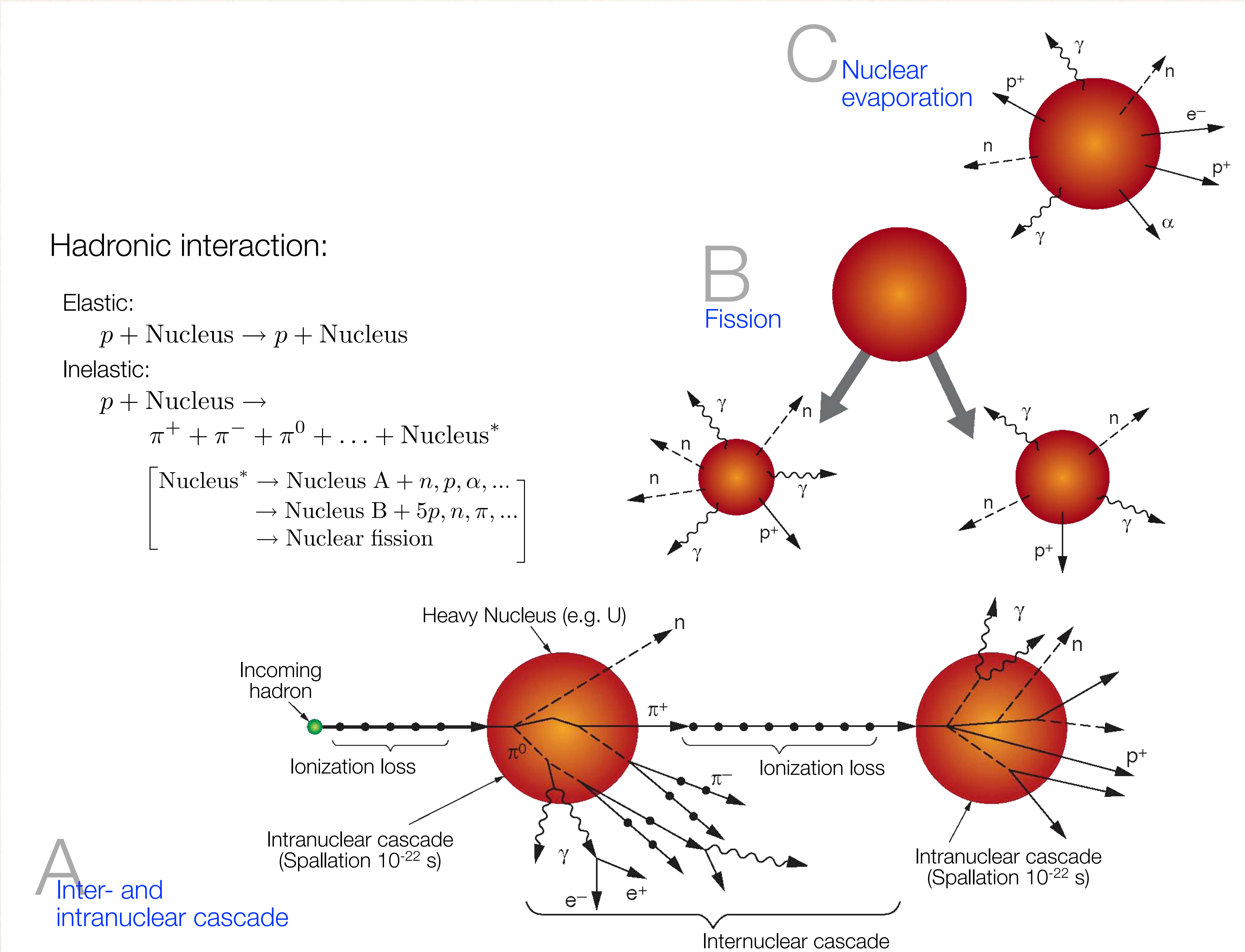
Calorímetro hadrônico

Chuveiro hadrônico



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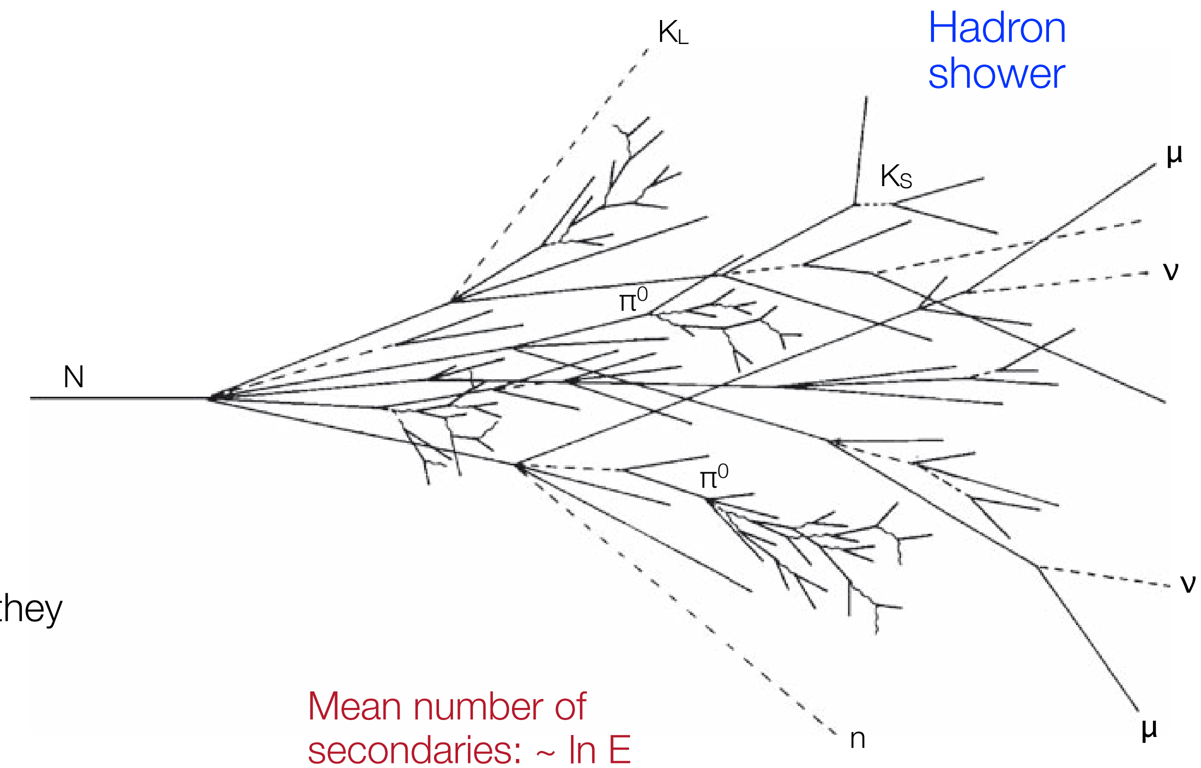
Chuveiro hadrônico

Shower development:

1. p + Nucleus ➛ Pions + N* + ...
2. Secondary particles ...

   undergo further inelastic collisions until they fall below pion production threshold
3. Sequential decays ...

   π_0 ➛ $\gamma\gamma$: yields electromagnetic shower
   Fission fragments ➛ β-decay, γ-decay
   Neutron capture ➛ fission
   Spallation ...



Mean number of secondaries: ~ ln E

Typical transverse momentum: p_t ~ 350 MeV/c

Substantial electromagnetic fraction

f_{em} ~ ln E

[variations significant]

Cascade energy distribution:
[Example: 5 GeV proton in lead-scintillator calorimeter]

Ionization energy of charged particles (p,π,μ)	1980 MeV [40%]
Electromagnetic shower (π^0,η^0,e)	760 MeV [15%]
Neutrons	520 MeV [10%]
Photons from nuclear de-excitation	310 MeV [6%]
Non-detectable energy (nuclear binding, neutrinos)	1430 MeV [29%]
	5000 MeV [29%]

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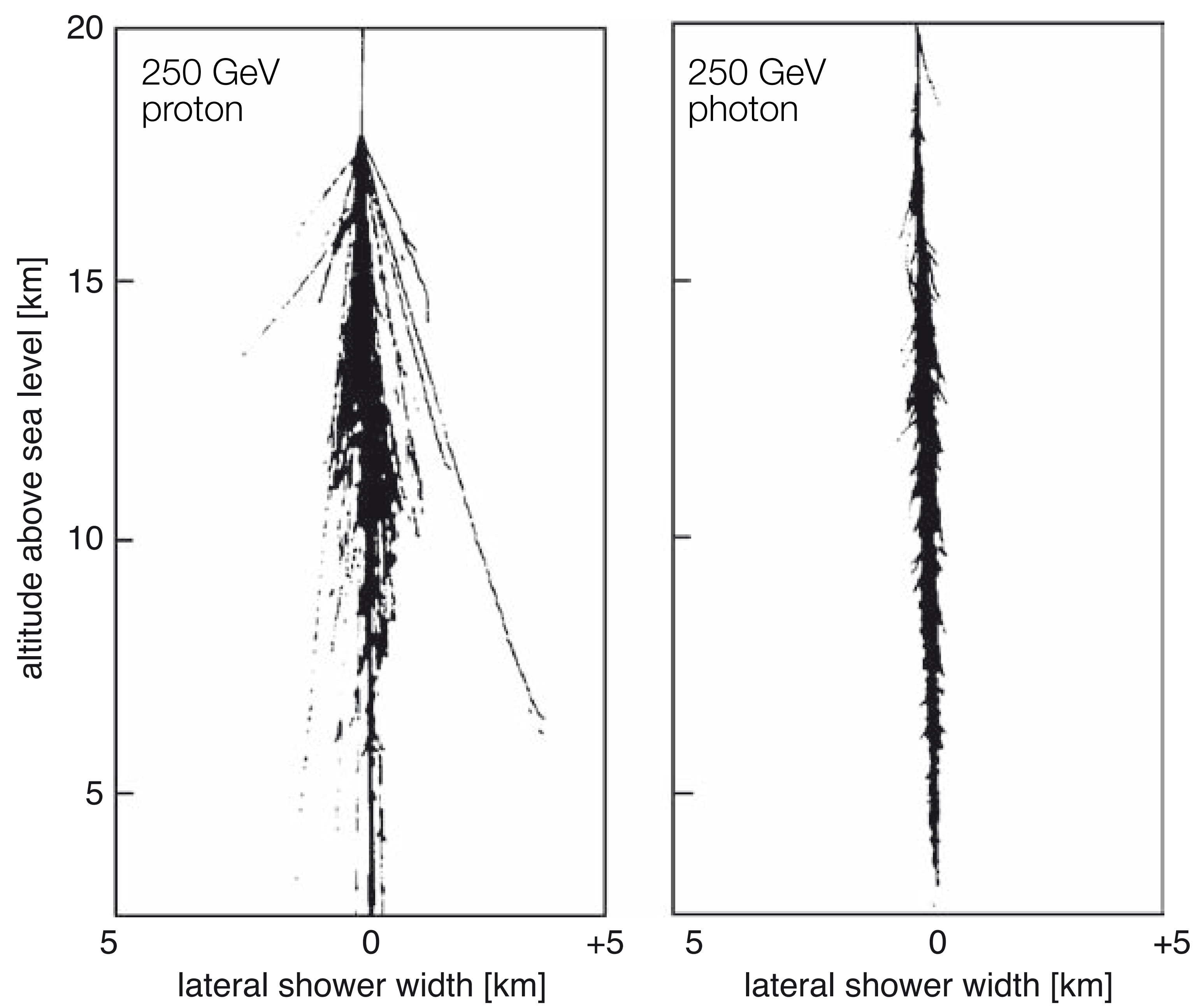
Chuveiro hadrônico

Comparison
hadronic vs. electromagnetic shower ...

[Simulated air showers]



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Chuveiro hadrônico

Hadronic interaction:

Cross Section:

at high energies
also diffractive contribution

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$

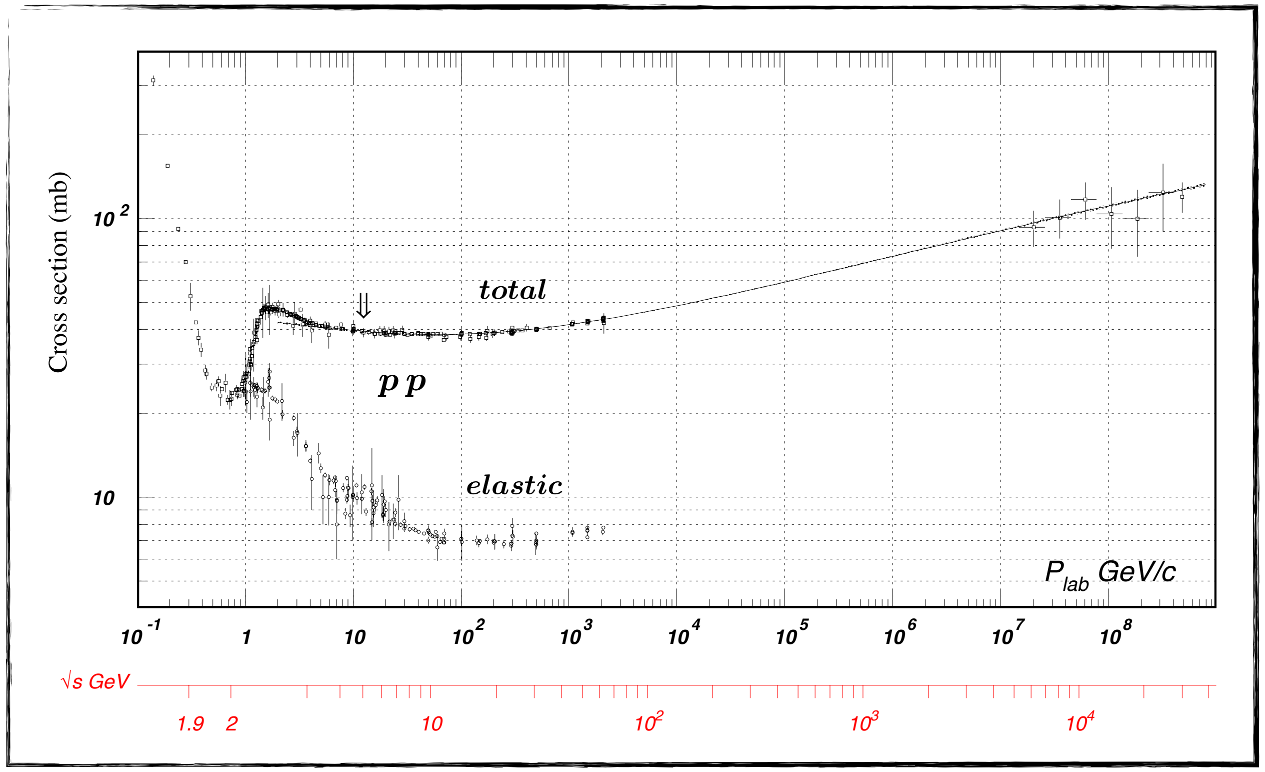
For substantial energies
σ_{inel} dominates:

$$\sigma_{\text{el}} \approx 10 \text{ mb}$$

$$\sigma_{\text{inel}} \propto A^{2/3}$$ [geometrical cross section]

$$\therefore \; \sigma_{\text{tot}} = \sigma_{\text{tot}}(pA) \approx \sigma_{\text{tot}}(pp) \cdot A^{2/3}$$

[σ_{tot} slightly grows with $\sqrt{s}$]



Total proton-proton cross section
[similar for p+n in 1-100 GeV range]

Hadronic interaction length:

$$\lambda_{\text{int}} = \frac{1}{\sigma_{\text{tot}} \cdot n} = \frac{A}{\sigma_{pp}\, A^{2/3} \cdot N_A \rho} \sim A^{1/3}$$ [for $\sqrt{s} \approx 1 - 100$ GeV]

$$\approx 35 \; \mathrm{g/cm^2} \cdot A^{1/3}$$

Interaction length characterizes both, longitudinal and transverse profile of hadronic showers ...

which yields:

$$N(x) = N_0 \exp(-x/\lambda_{\text{int}})$$

Remark: In principle one should distinguish between collision length $\lambda_W \sim 1/\sigma_{\text{tot}}$ and interaction length $\lambda_{\text{int}} \sim 1/\sigma_{\text{inel}}$ where the latter considers inelastic processes only (absorption) ...

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Chuveiro hadrônico

Hadronic vs. electromagnetic interaction length:

$$X_0 \sim \frac{A}{Z^2}$$

$$\lambda_{\rm int} \sim A^{1/3}$$

$$\rightarrow \quad \frac{\lambda_{\rm int}}{X_0} \sim A^{4/3}$$

$$\lambda_{\rm int} \gg X_0$$

[λ_{int}/X_0 > 30 possible; see below]

Typical
Longitudinal size: 6 ... 9 λ_{int} [95% containment] [EM: 15-20 X_0]

Typical
Transverse size: one λ_{int} [95% containment] [EM: 2 R_M; compact]

Hadronic calorimeter need more depth than electromagnetic calorimeter ...

Some numerical values for materials typical used in hadron calorimeters

	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

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Chuveiro hadrônico

Hadronic shower development:

[estimate similar to e.m. case]

Depth (in units of λ_{int}):

$$t = \frac{x}{\lambda_{\text{int}}}$$

Energy in depth t:

$$E(t) = \frac{E}{\langle n \rangle^t} \quad \& \quad E(t_{\text{max}}) = E_{\text{thr}}$$

[with $E_{thr} \approx$ 290 MeV]

$$E_{\text{thr}} = \frac{E}{\langle n \rangle^{t_{\text{max}}}}$$

Shower maximum:

$$\langle n \rangle^{t_{\text{max}}} = \frac{E}{E_{\text{thr}}}$$

Number of particles lower by factor E_{thr}/E_c compared to e.m. shower ...

Intrinsic resolution: worse by factor $\sqrt{E_{thr}/E_c}$

$$t_{\text{max}} = \frac{\ln\left(E/E_{\text{thr}}\right)}{\ln\langle n \rangle}$$

But:

Only rough estimate as ...

energy sharing between shower particles fluctuates strongly ...

part of the energy is not detectable (neutrinos, binding energy); partial compensation possible (n-capture & fission)

spatial distribution varies strongly; different range of e.g. $\pi^\pm$ and π^0 ...

electromagnetic fraction, i.e. fraction of energy deposited by $\pi^0 \rightarrow \gamma\gamma$ increases with energy ...

$$f_{\text{em}} \approx f_{\pi^0} \sim \ln E/(1\ \text{GeV})$$

Explanation: charged hadron contribute to electromagnetic fraction via $\pi^- p \rightarrow \pi^0 n$; the opposite happens only rarely as π^0 travel only 0.2 μm before its decay ('one-way street') ...

At energies below 1 GeV hadrons loose their energy via ionization only ...

Thus: need Monte Carlo (GEISHA, CALOR, ...) to describe shower development correctly ...

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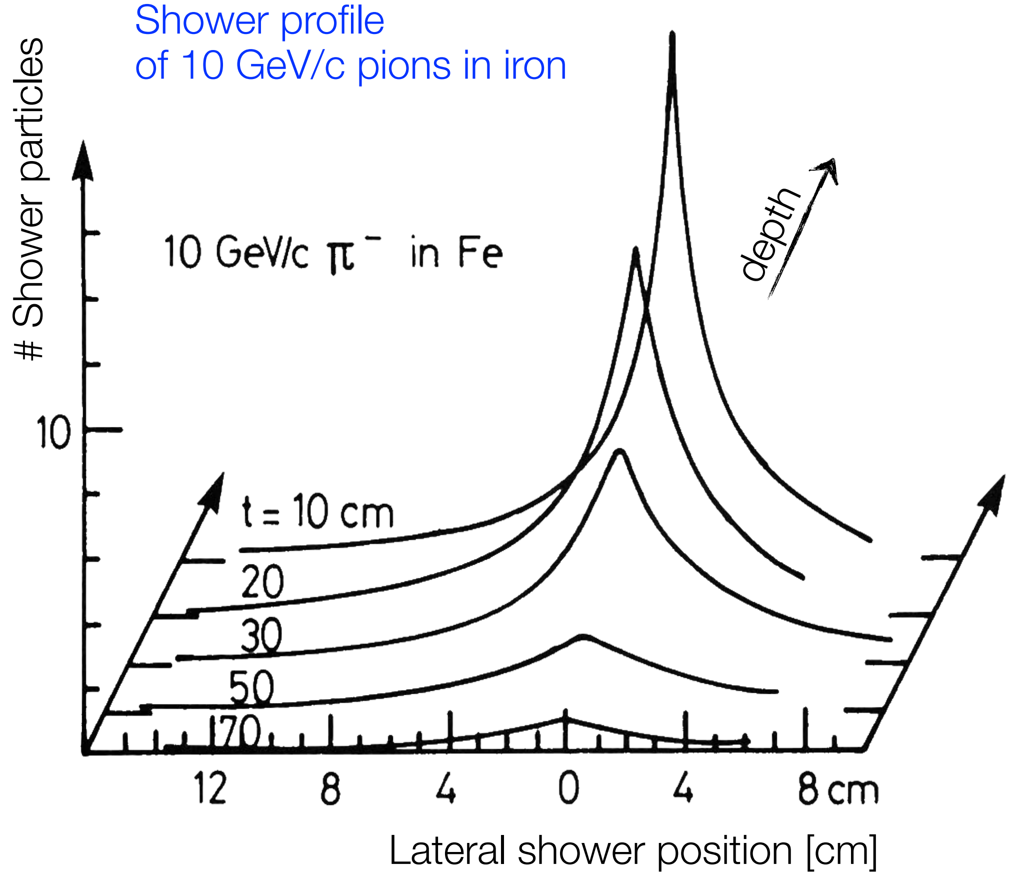
Chuveiro hadrônico



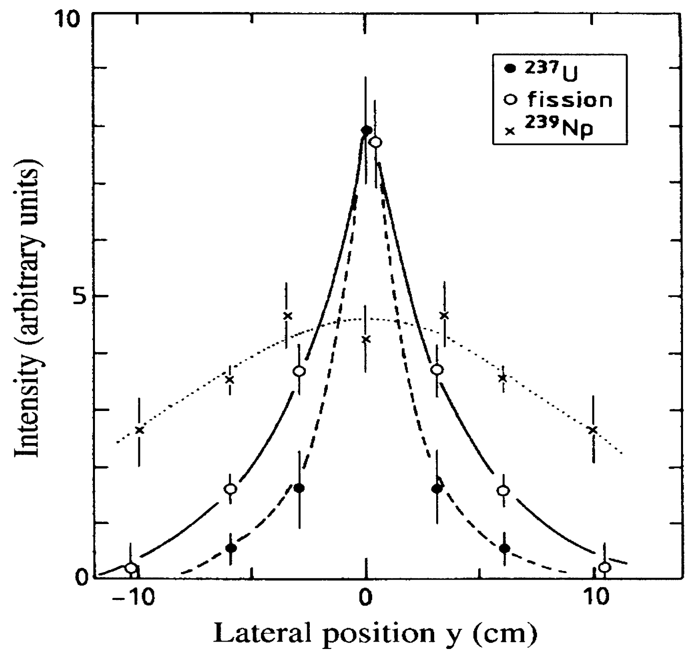
Transverse shower profile

Typical transverse momenta of secondaries: $\langle p_t \rangle \simeq 350\mathrm{MeV}/c$ ...

Lateral extend at shower maximum: $R_{95\%} \approx \lambda_{int}$ ...

Electromagnetic component leads to relatively well-defined core: $R \approx R_M$ ...

Exponential decay after shower maximum ...



Lateral profile for 300 GeV π^-

[target material ^{238}U]
[measured at depth 4 λ_{int}]

More π^0's and γ in core

Energetic neutrons and charged pions form a wider core

Thermal neutrons generate broad tail

Measurement from induced radioactivity:

^{99}Mo (fission): neutron induced ...
[energetic neutron component]

^{237}U: mainly produced via $^{238}U(\gamma,n)^{237}U$ ...
[electromagnetic component]

^{239}Np: from ^{239}U decay ...
[thermal neutrons]

Ordinate indicates decay rate of different radioactive nuclides ...

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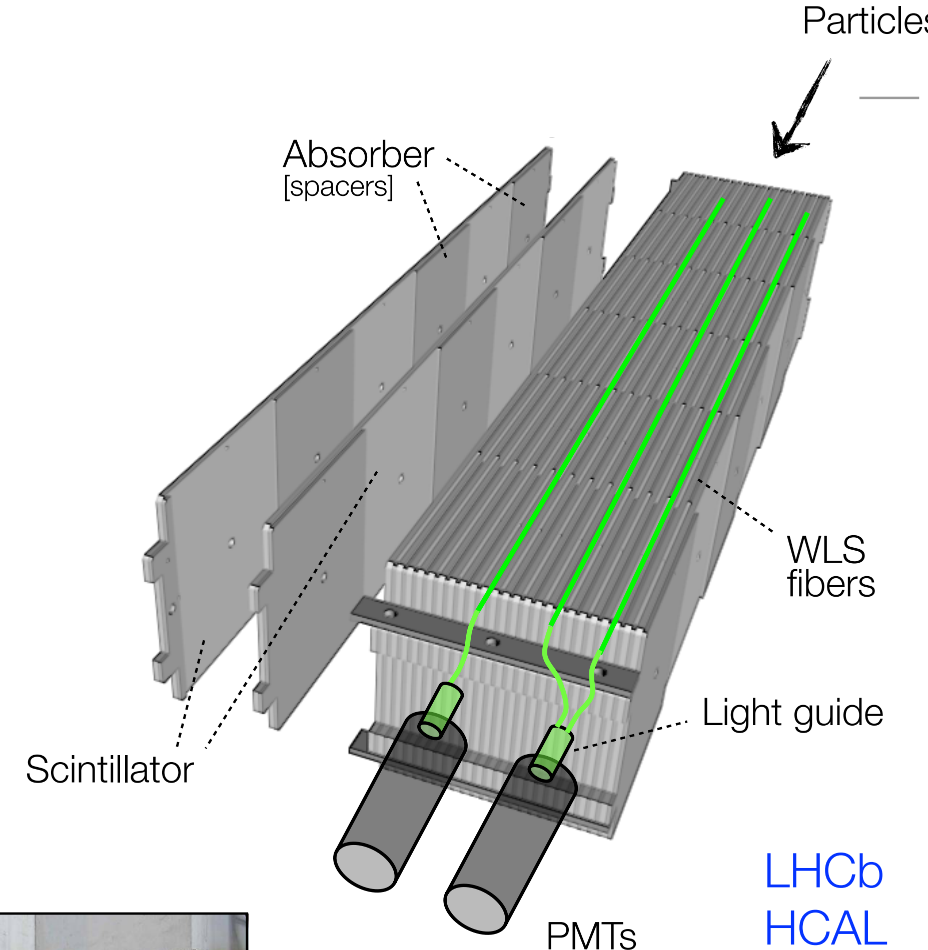
Chuveiro hadrônico

Most common realization: Sampling Calorimeter

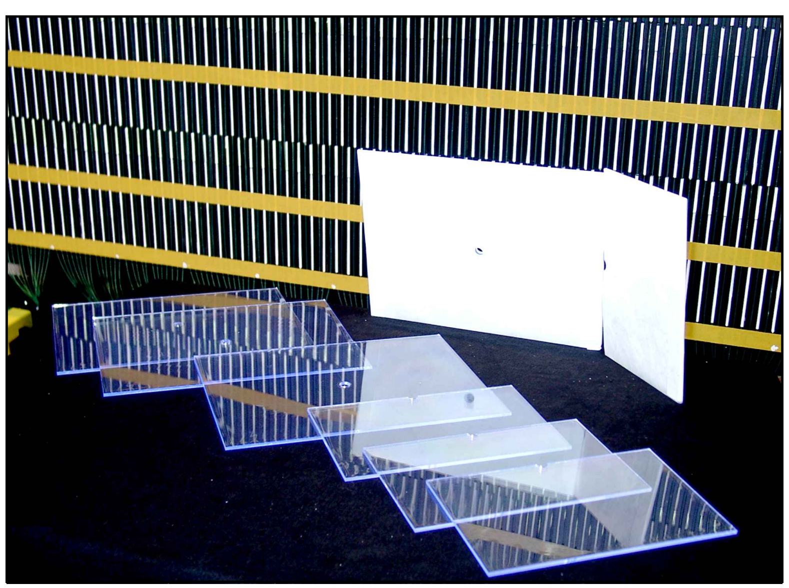
Utilization of homogenous calorimeters unnecessary (and thus too expensive) due to fluctuations of invisible shower components ...

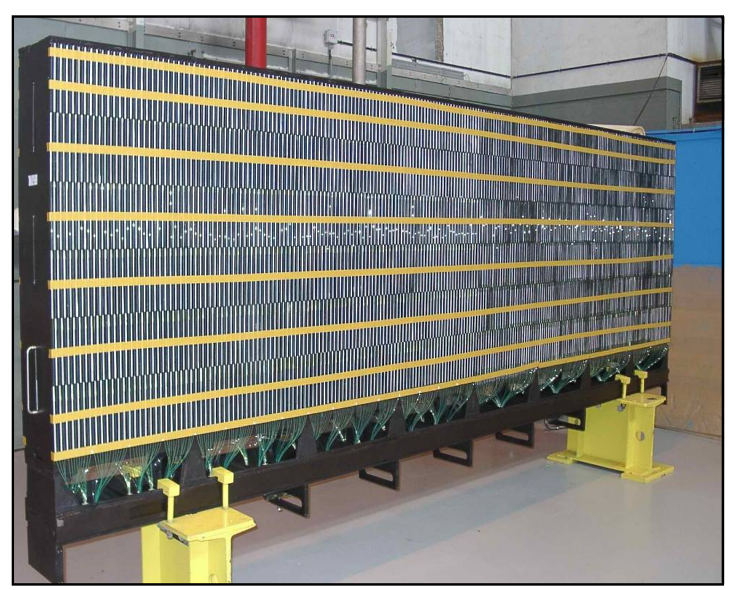
Typical absorbers : Fe, Pb, U ...
Sampling elements : Scintillators, LAr, MWPCs ...

Typical setup:
Alternating layers of active and passive material
[also: 'spaghetti' or 'shashlik' calorimeter]



LHCb
HCAL





Example:
LHCb Hadron Calorimeter

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Medidas com calorímetros

Energy resolution:

e.g. inhomogeneities
shower leakage

e.g. electronic noise
sampling fraction variations

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

Fluctuations:

- Sampling fluctuations
- Leakage fluctuations
- Fluctuations of electromagnetic fraction
- Nuclear excitations, fission, binding energy fluctuations ...
- Heavily ionizing particles

Typical:

A: 0.5 – 1.0 [Record:0.35]
B: 0.03 – 0.05
C: few %

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Medidas com calorímetros

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

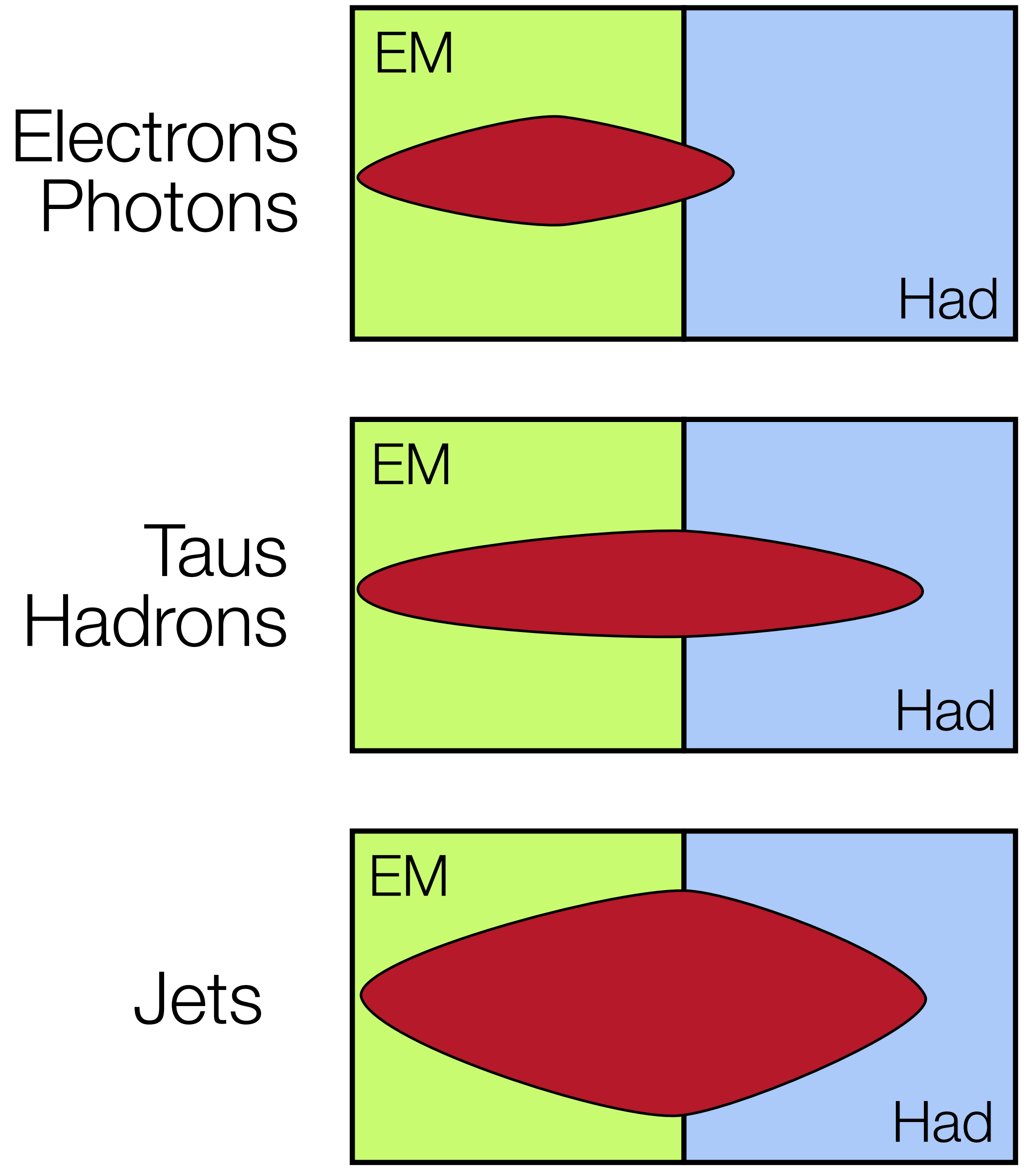
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



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Medidas com calorímetros

Calorimeter requirements:

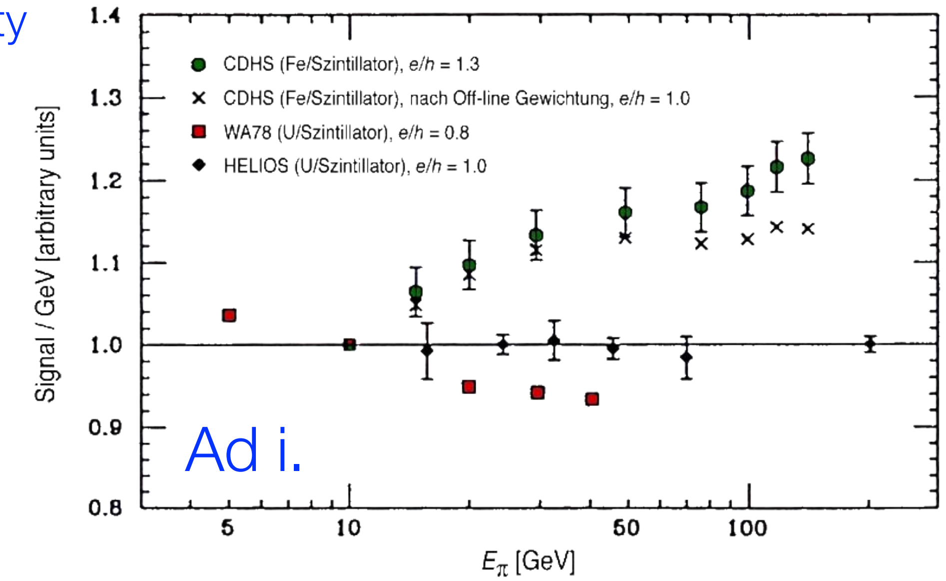
Signal : S ~ Energy (linearity)
Independent of particle type
Gaussian distributed

Resolution : σ/E ~ 1/√E

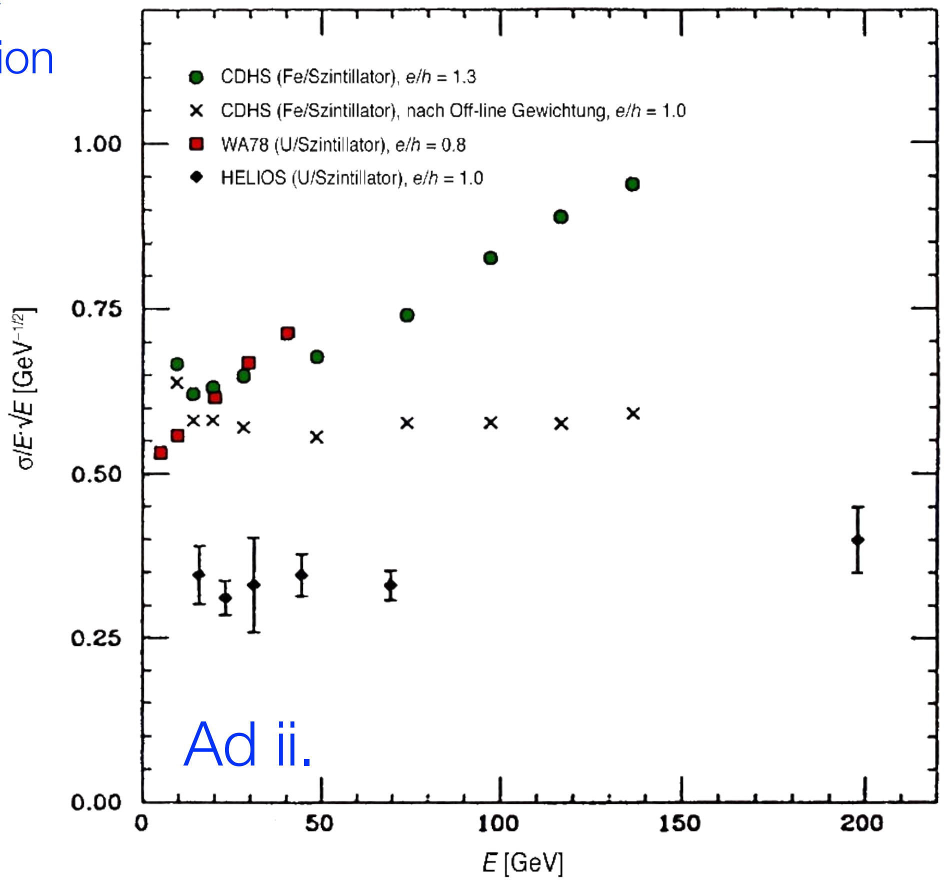
Reality:

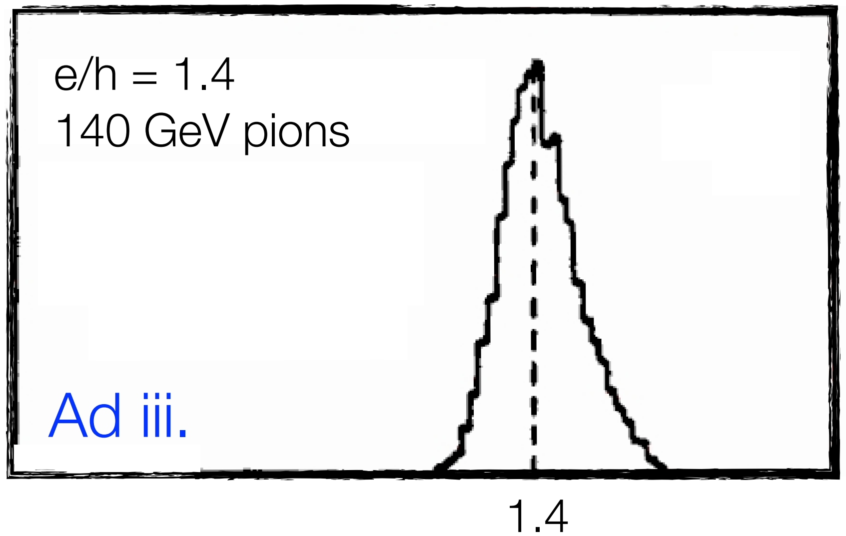
i. Response not completely linear
ii. Resolution deviates from 1/√E dependence
iii. Signal not completely gaussian
iv. e/h-ratio greater 1

Linearity



Energy resolution





Pulse hight distribution

Medidas com calorímetros

e/h ratio:
[This is what it is all about ...]

Generally ...

Response of calorimeters very different to electromagnetic and hadronic energy deposits ...

Usually higher weight for electromagnetic component i.e. e/h > 1 ...

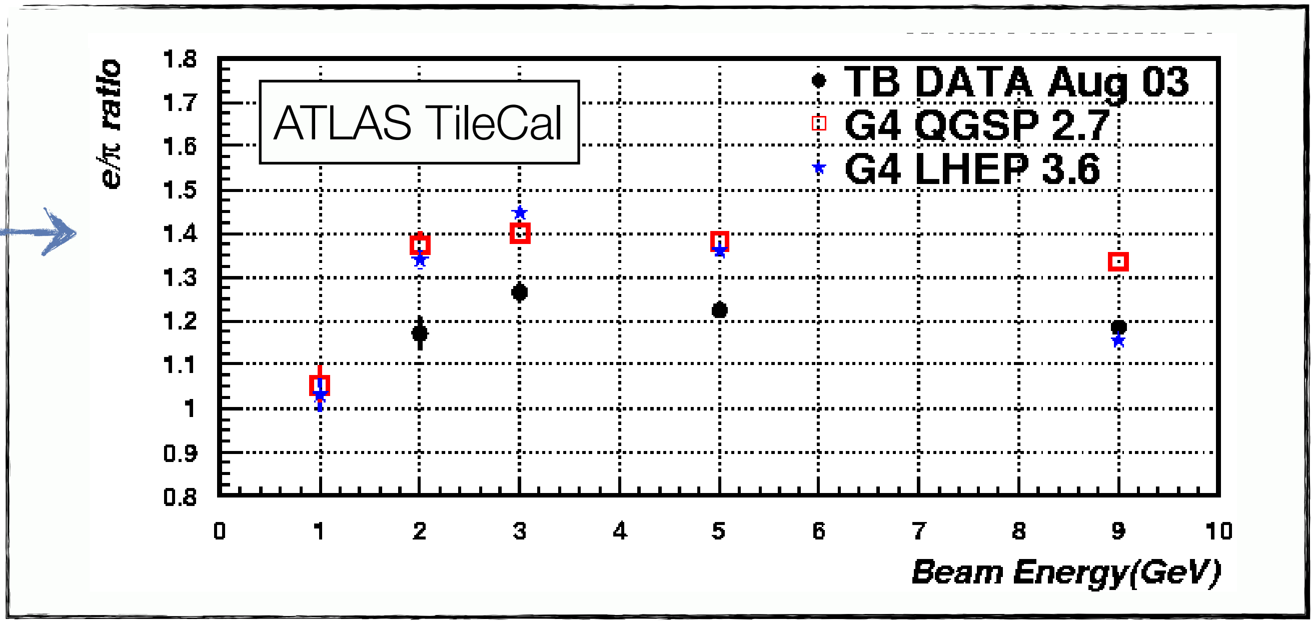
e/h ≠ 1 leads to ...

Non-uniform energy response due to fluctuations in f_{em} ...

Compensation important!

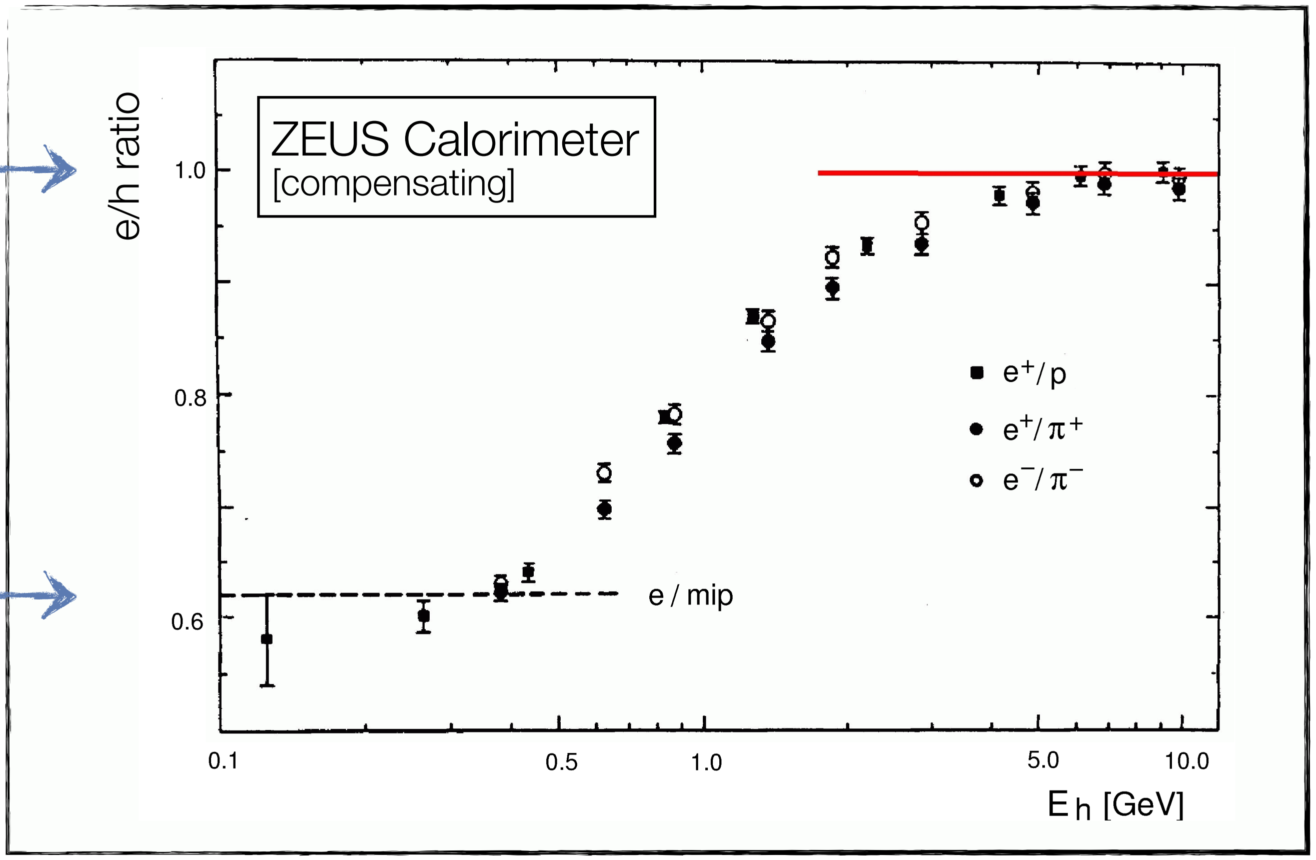
as one generally cannot resolve individual shower components when measuring the total energy flow ...

e/h = 1.4



e/h = 1.0

e/h = 0.8



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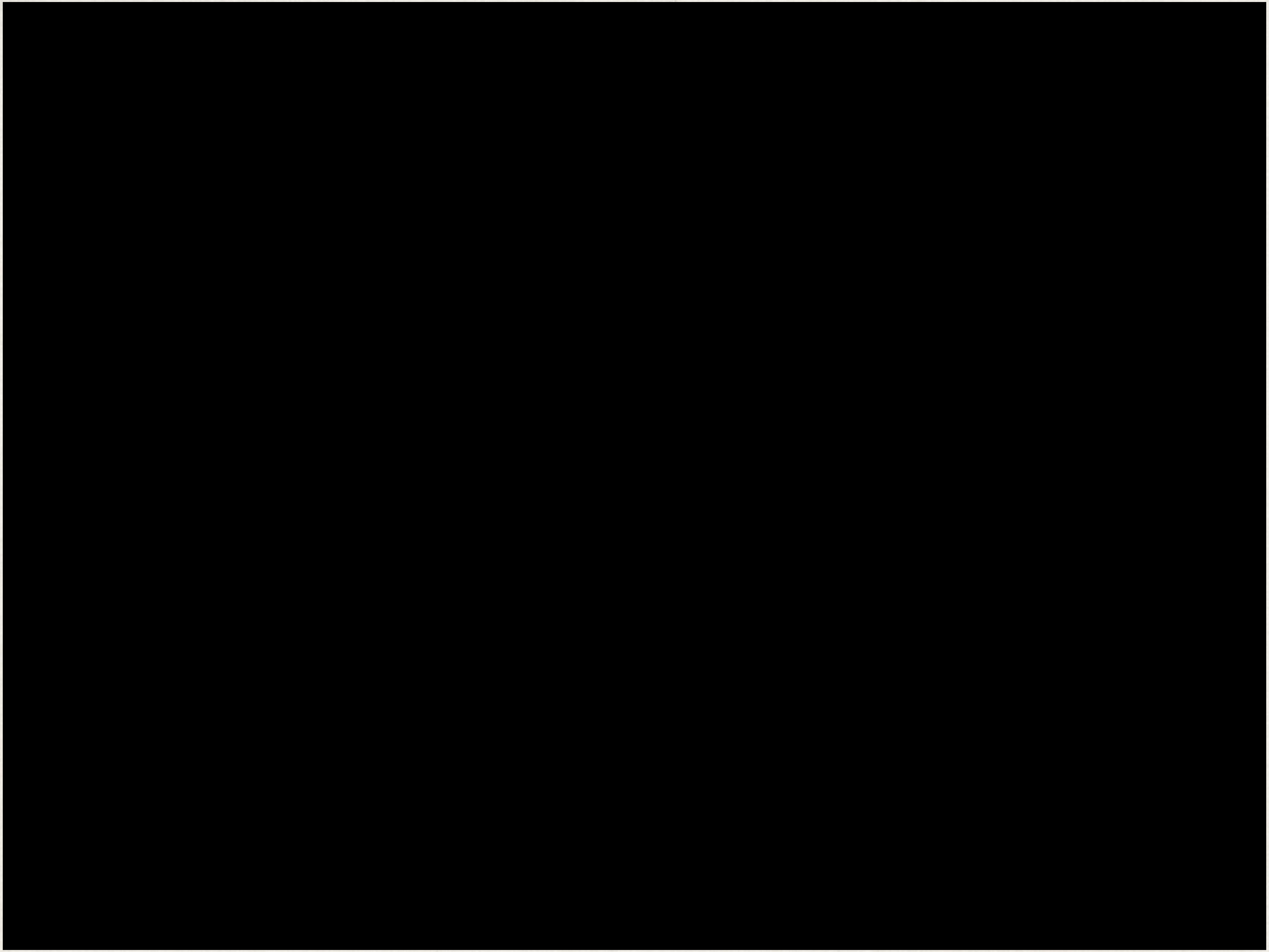

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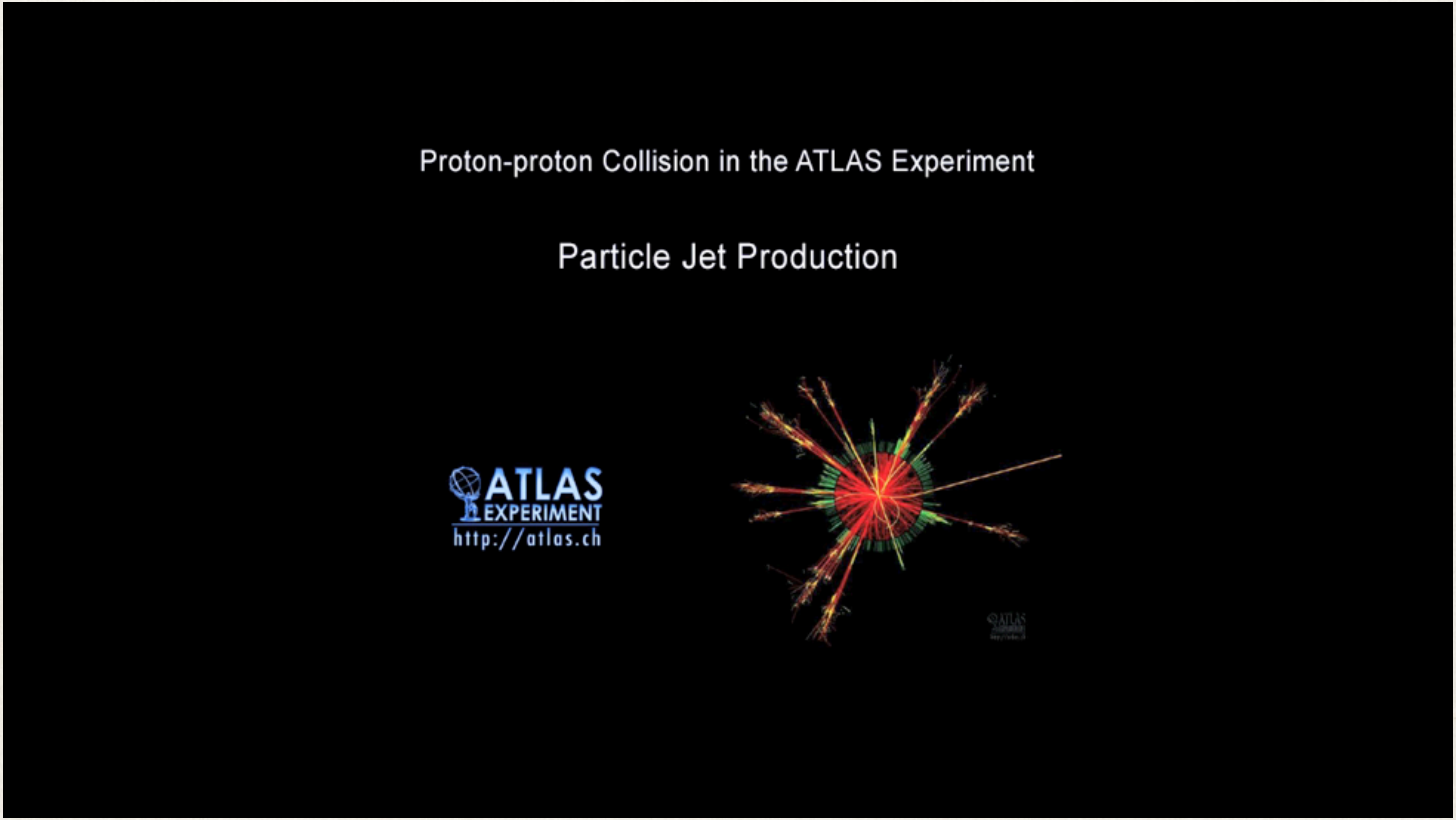
Medindo-se jatos



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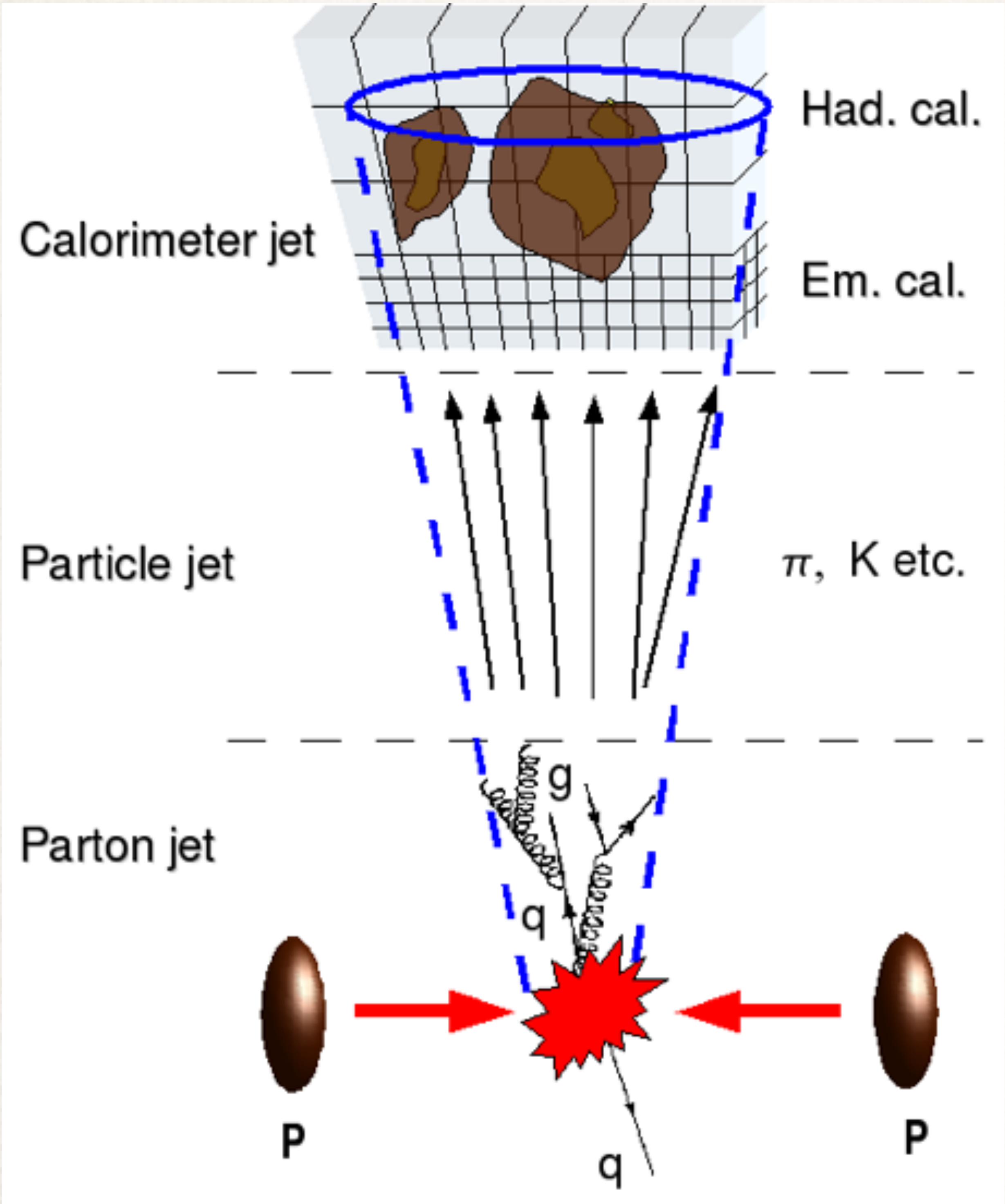

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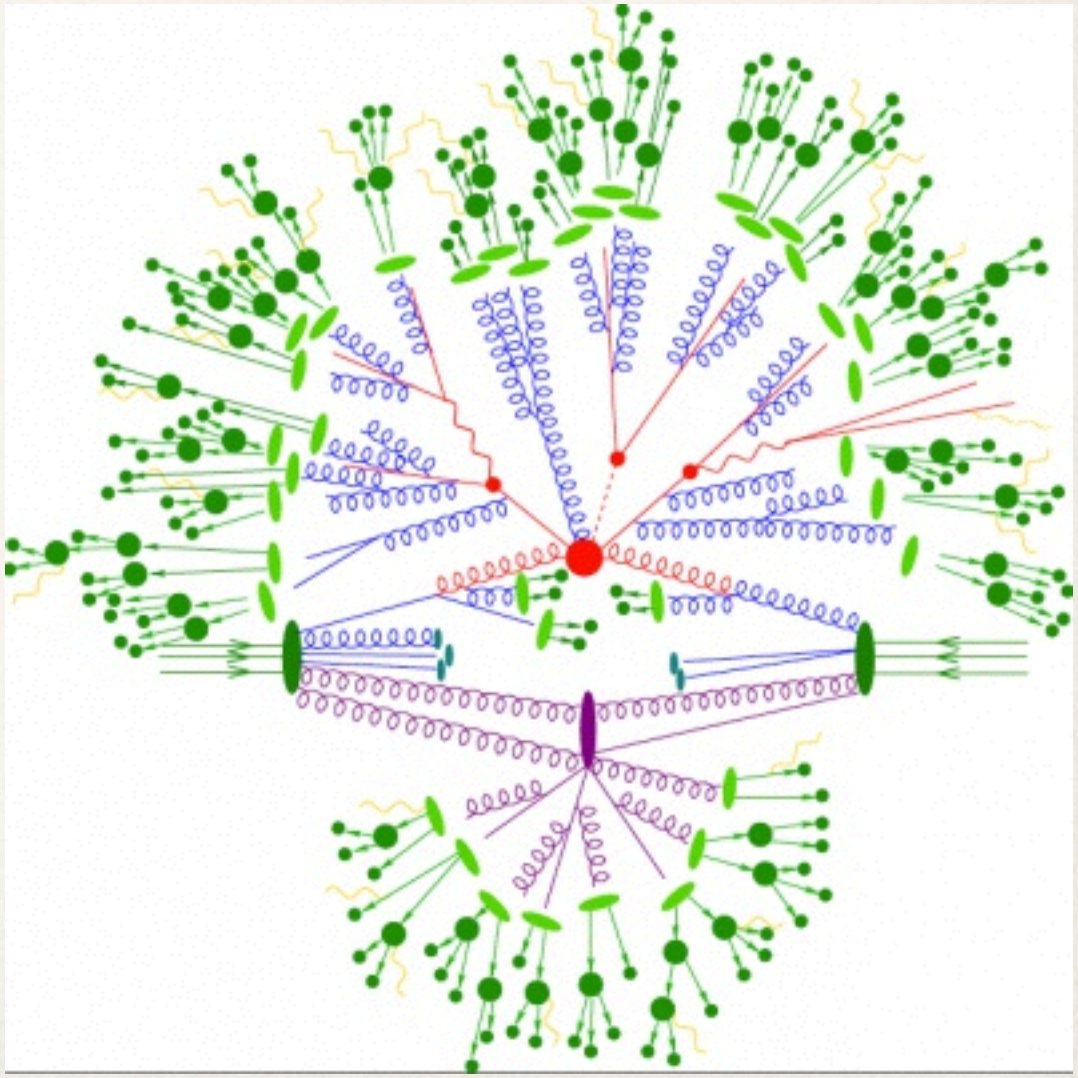

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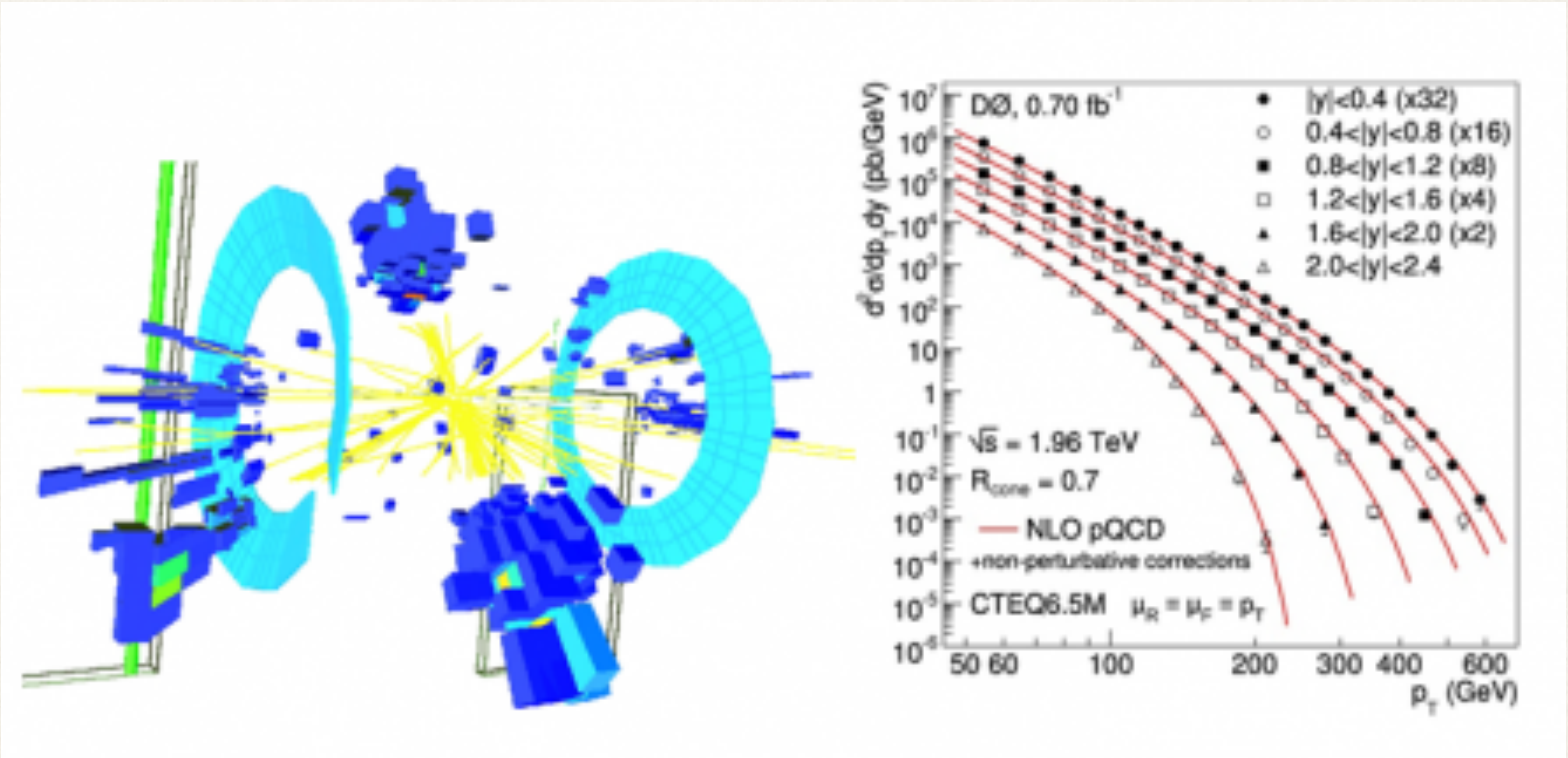

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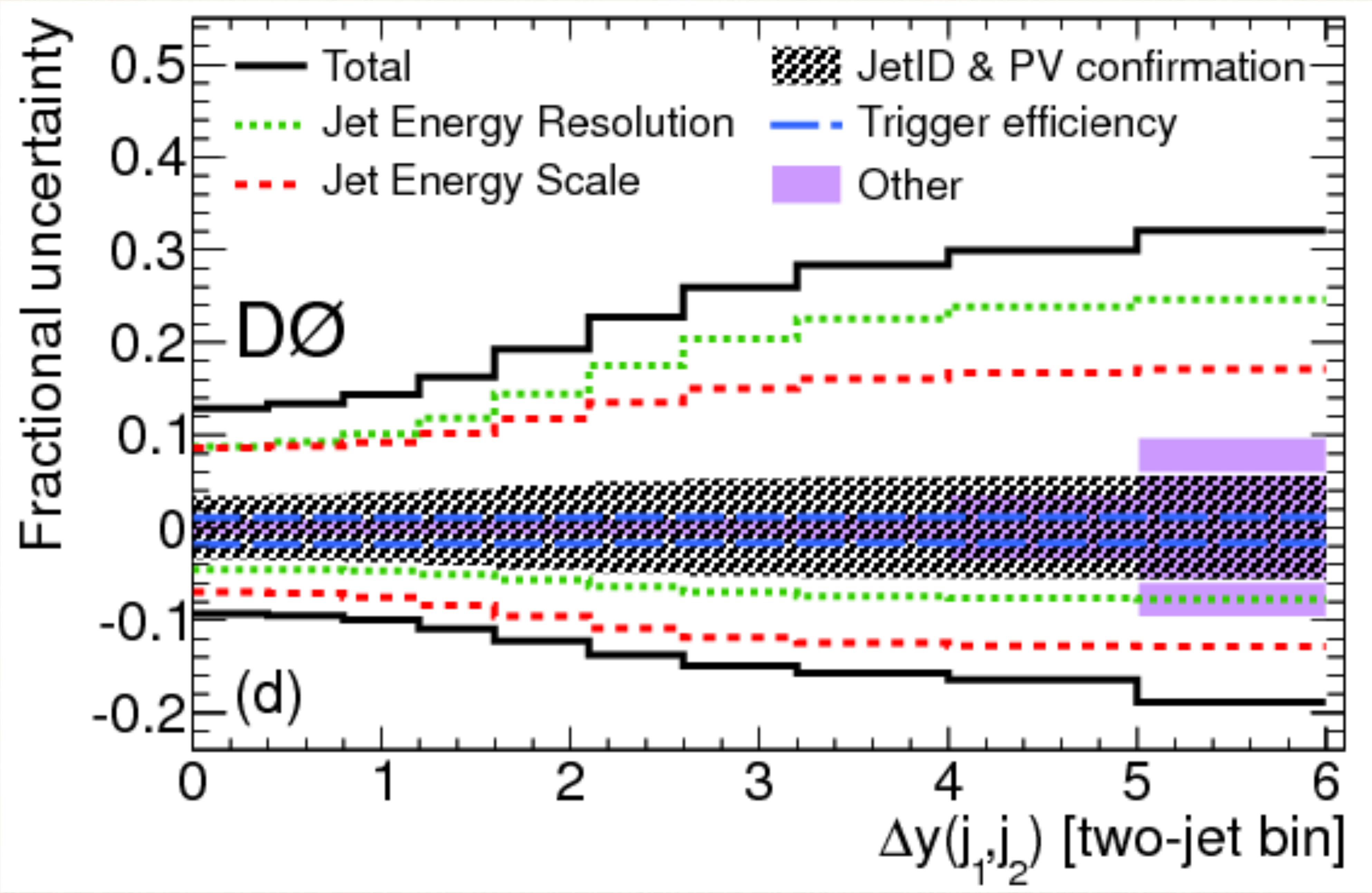
Medindo-se jatos



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