Collider-Based Experiments
Lecture 1

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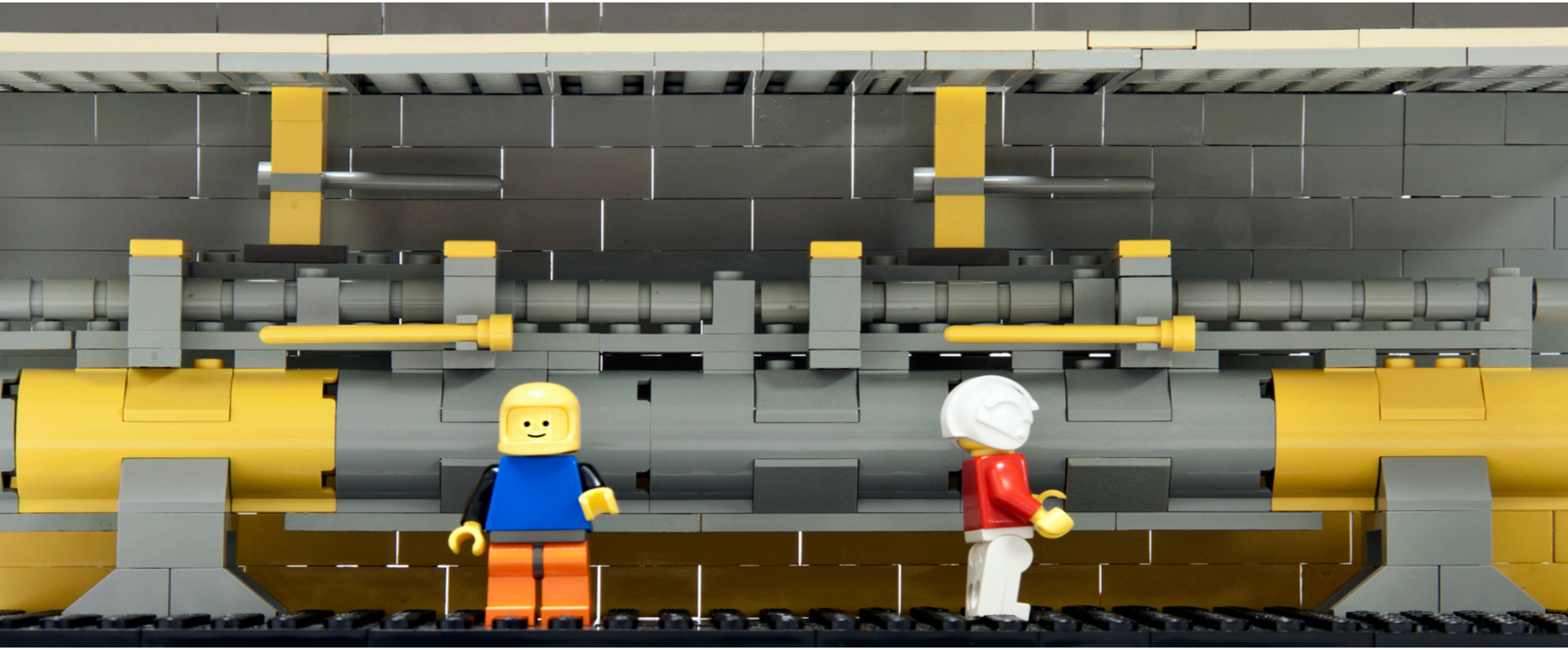
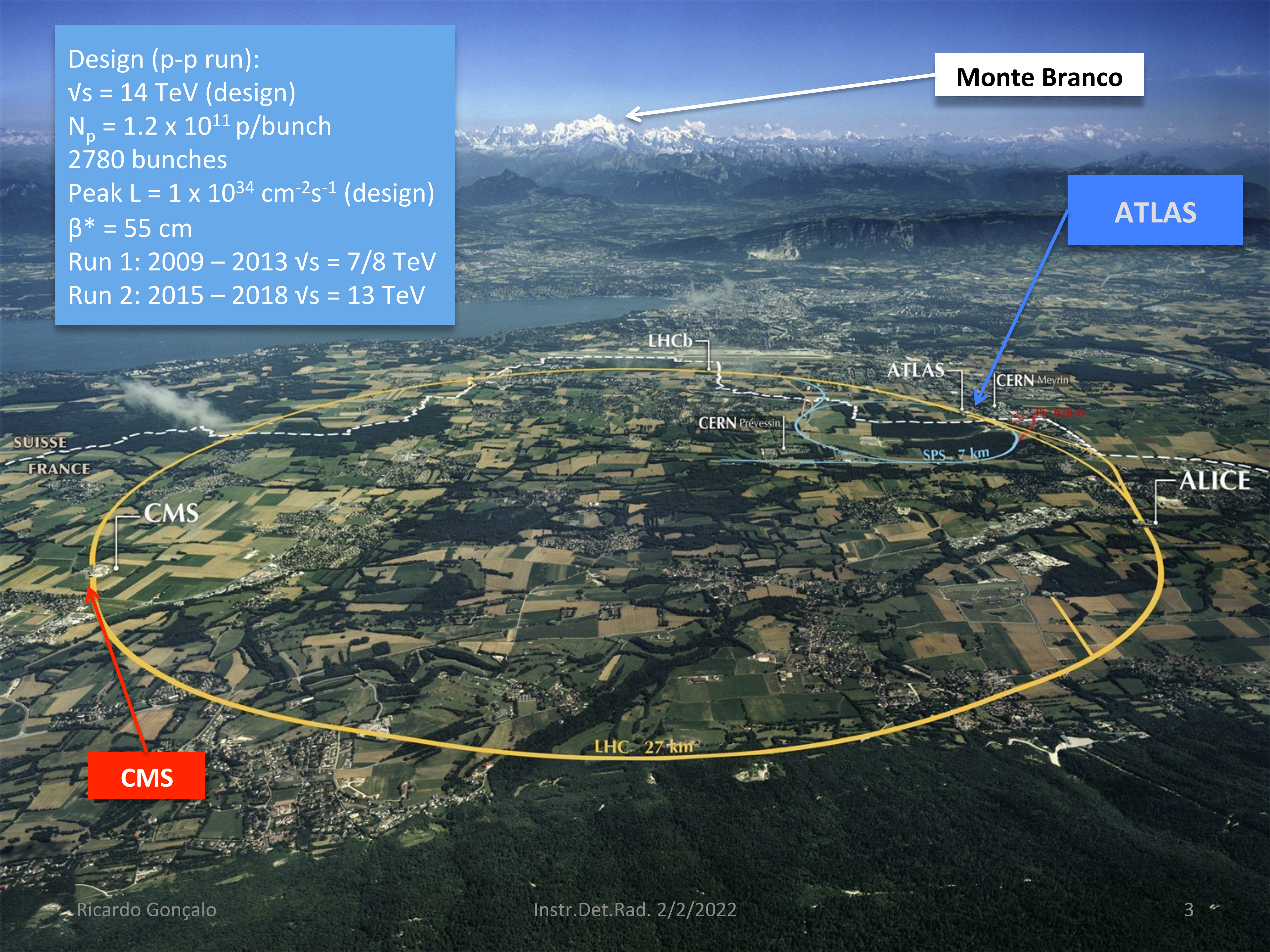
Particle colliders



Design (p-p run):
$\sqrt{s}$ = 14 TeV (design)
$N_p = 1.2 \times 10^{11}$ p/bunch
2780 bunches
Peak $L = 1 \times 10^{34}\ cm^{-2}s^{-1}$ (design)
β^* = 55 cm
Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV



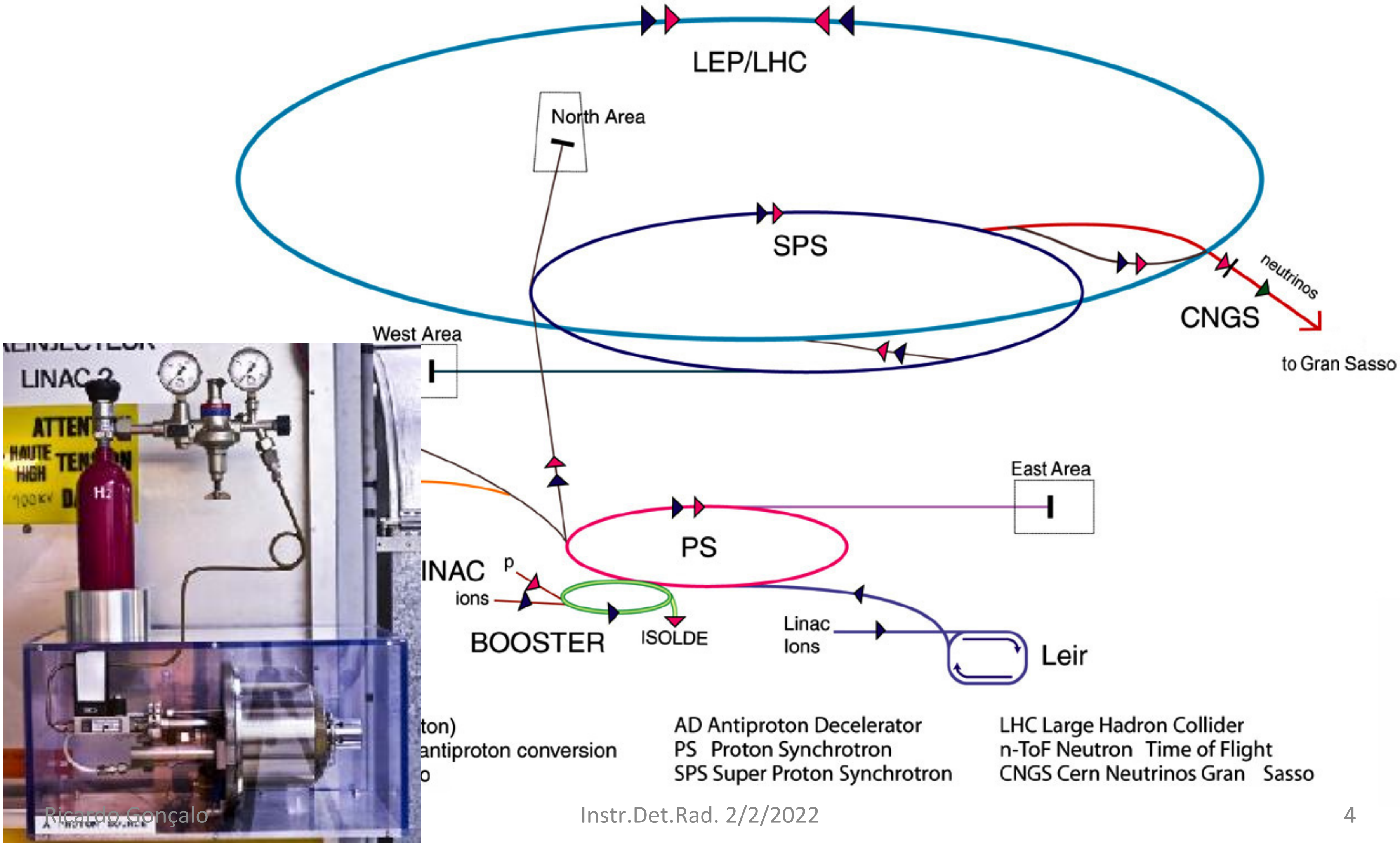
LINAC2 → **50 MeV**

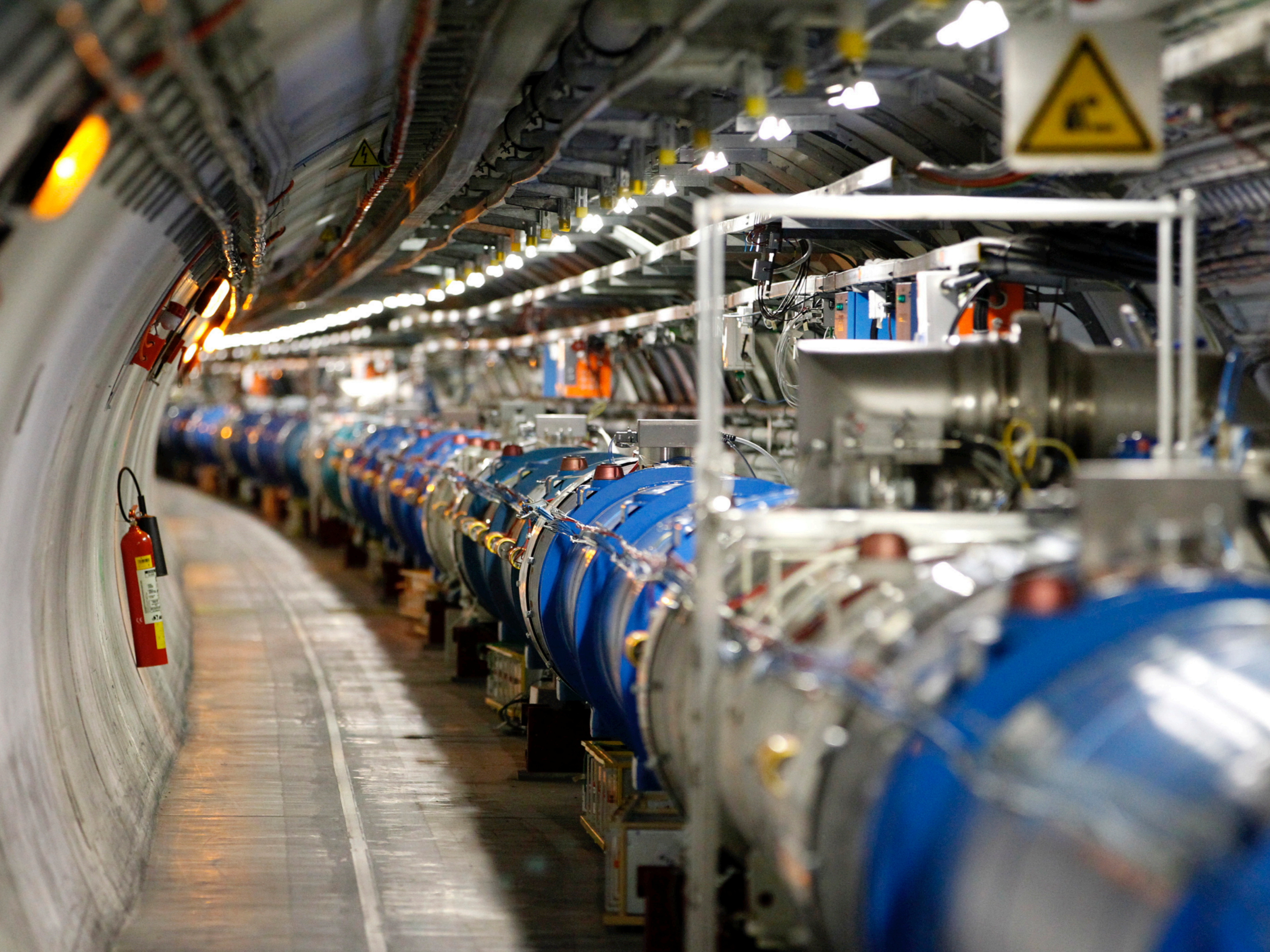
Booster → **1.4 GeV**

Proton Synchroton (PS) → **25 GeV**

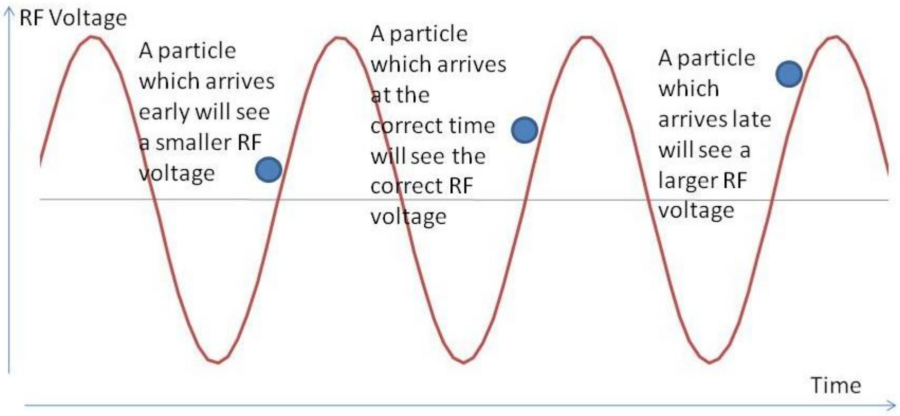
Super Proton Synchrotron (SPS) → **450 GeV**

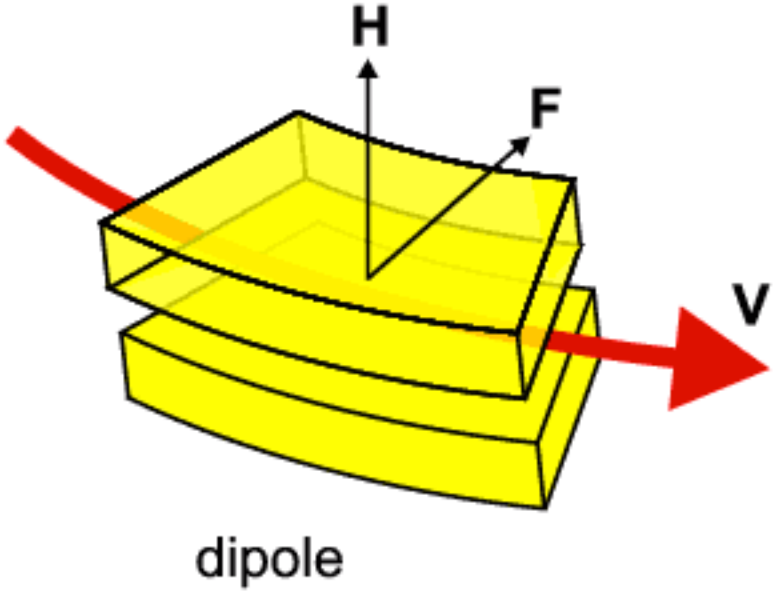
Large Hadron Collider (LHC)→ **7 TeV**

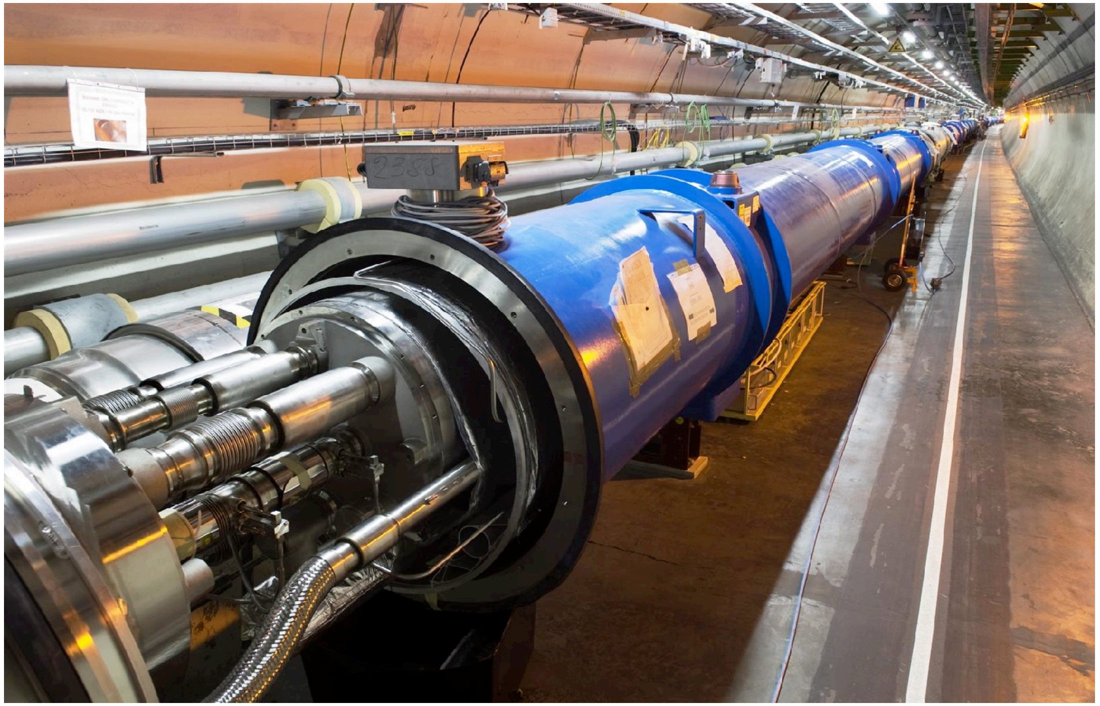




Beam accelleration





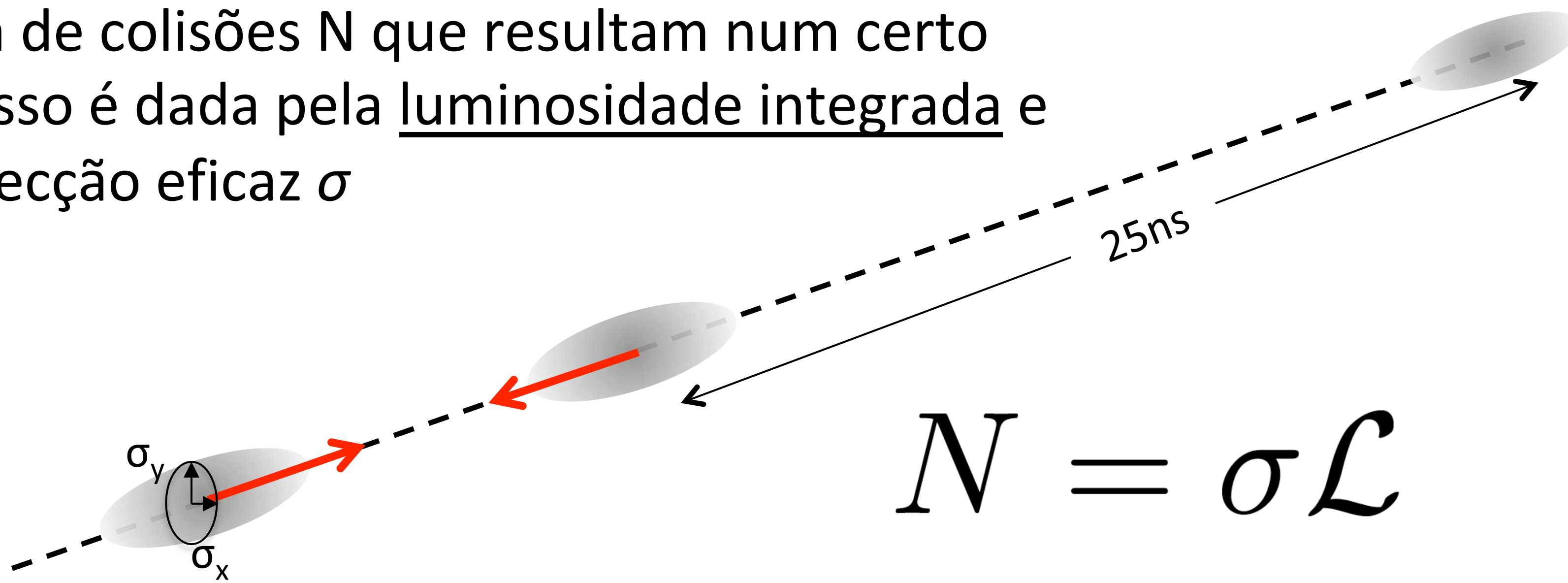


Luminosidade

- A luminosidade instantânea mede a taxa de colisões
- Se colidirmos dois "pacotes" de protões com dimensões σ_x e σ_y (rms) contendo n_1 e n_2 protões, temos a luminosidade:

$$\mathscr{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

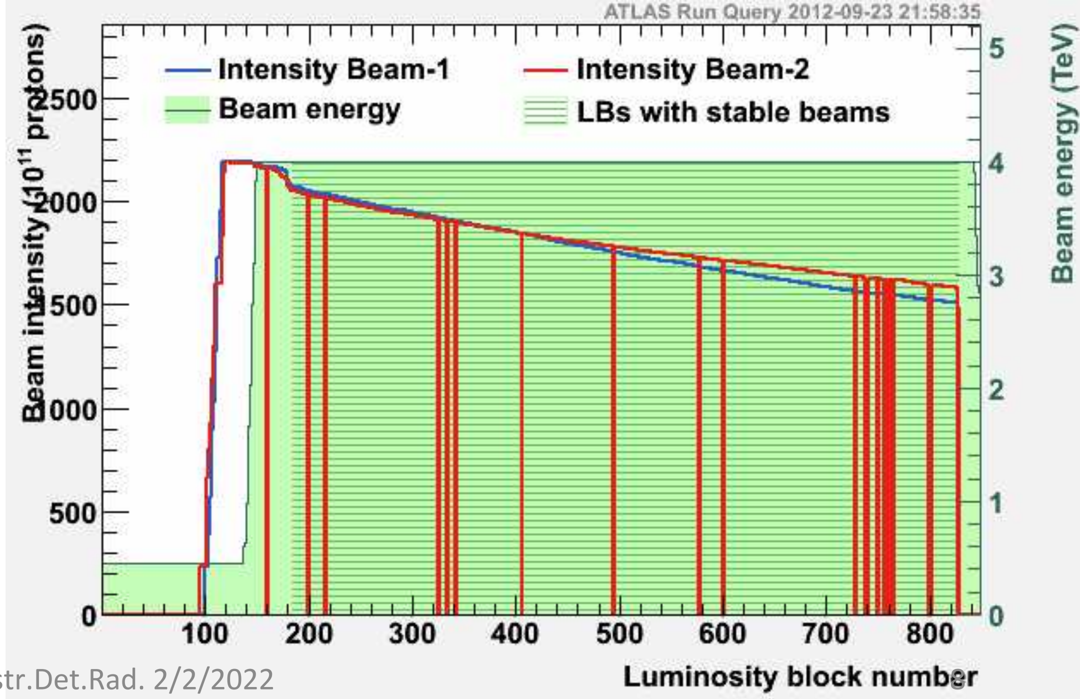
- A taxa de colisões N que resultam num certo processo é dada pela luminosidade integrada e pela secção eficaz σ



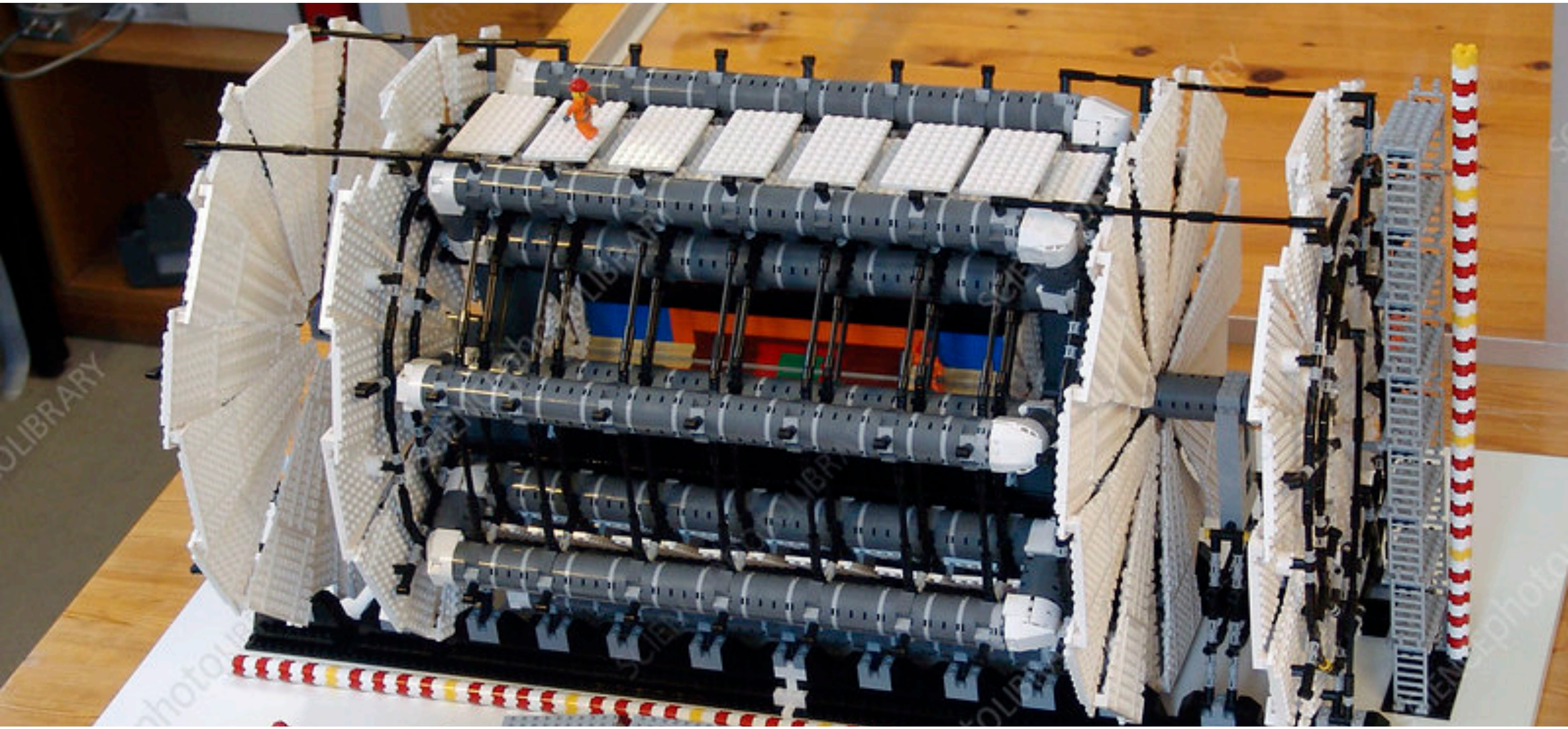
$$N = \sigma\mathcal{L}$$

- Energia do feixe:
- 2802 bunches de 1.15×10^{11} protões
- 7TeV / protão (2015) = $7 \times 10^{12} \times 1.602 \times 10^{-19}$ J
- Dá 362 MJ por feixe…
- Igual à energia cinética de um porta-aviões de 20,000t a viajar a 11,7 nós (21.7 km/h)

- Tudo contido num feixe de ≈16μm
- Runs típicos duram cerca de 8 horas
- Intensidade diminui devido a perdas
- Depois voltamos a injectar novos feixes

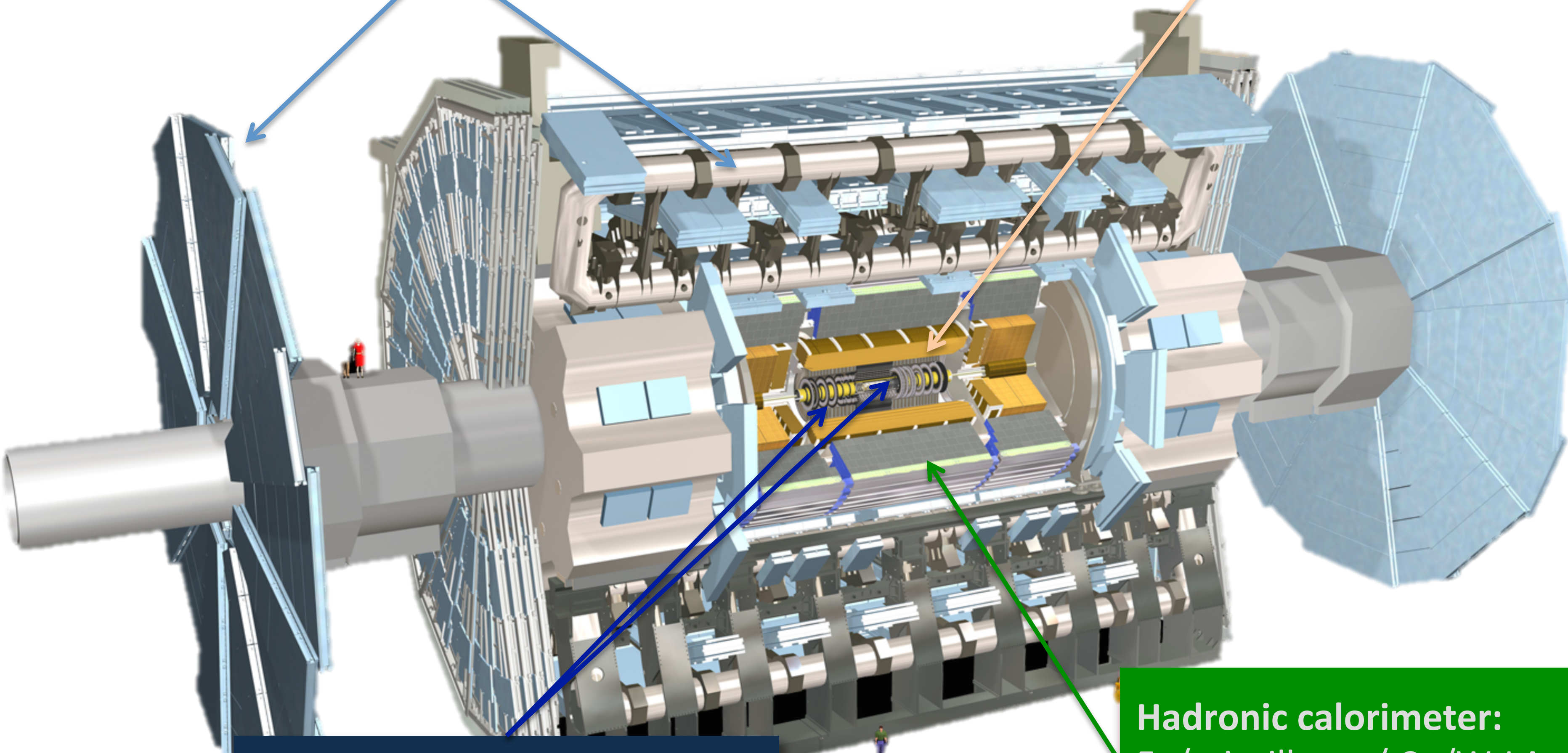


Collider experiments



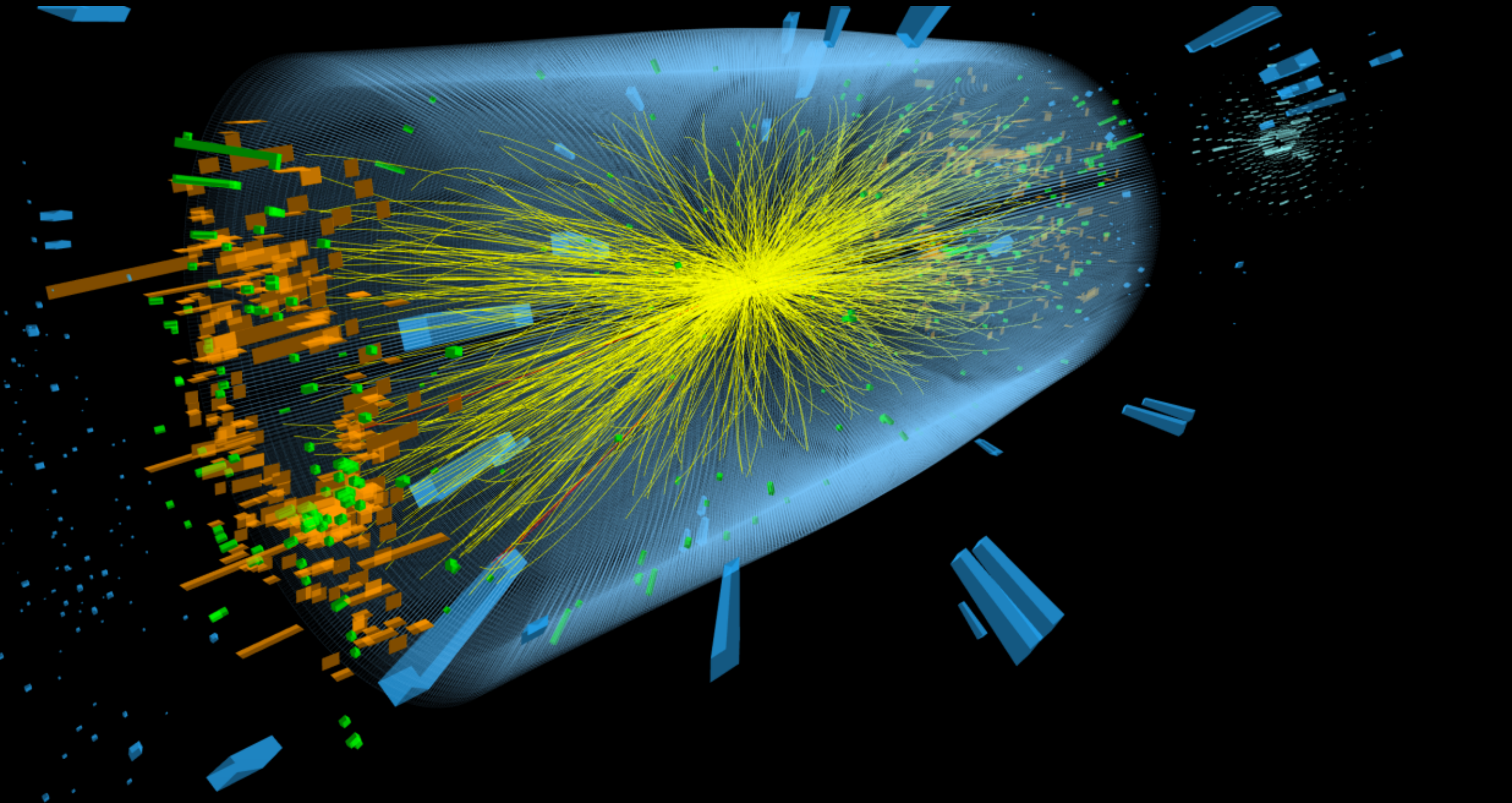
Muon Spectrometer: $|\eta| < 2.7$
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta| < 2.5$ (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$



Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

Solenoid: B = 2 T
Inner Tracker: $|\eta| < 2.5$
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\mathrm{GeV}) \oplus 1\%$



Detector Integration

Most particle physics experiments rely on multiple detectors (and detector types) to **reconstruct** events

Event information is obtained from **correlating** information from different detectors

Examples from the LHC experiments:

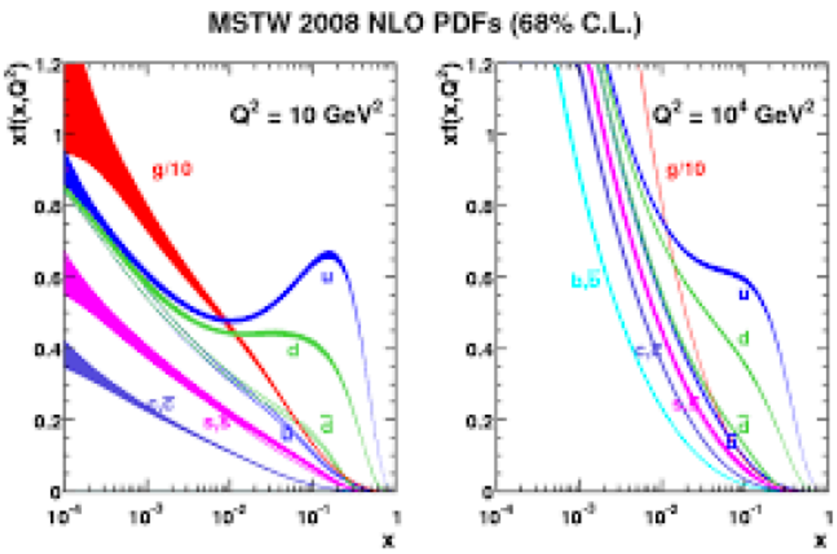
- Muons are reconstructed from a combined track in the inner detector and the muon spectrometer
- Electrons reconstructed from a track in the inner detector and an electromagnetic energy deposit in the calorimeter

How to design the experiment? How to choose what technologies to use? What resolutions etc should we aim for?

- Requirements come from the **physics**!
- Redundancy is important! (e.g. ATLAS and CMS)

Design choices: ATLAS and CMS

- Maximum LHC beam energy: 7 TeV
- $\Longrightarrow$ Maximum possible particle energy would be 7 TeV
- But highly suppressed by PDFs!
- $\Longrightarrow$ Magic energy is 1 TeV



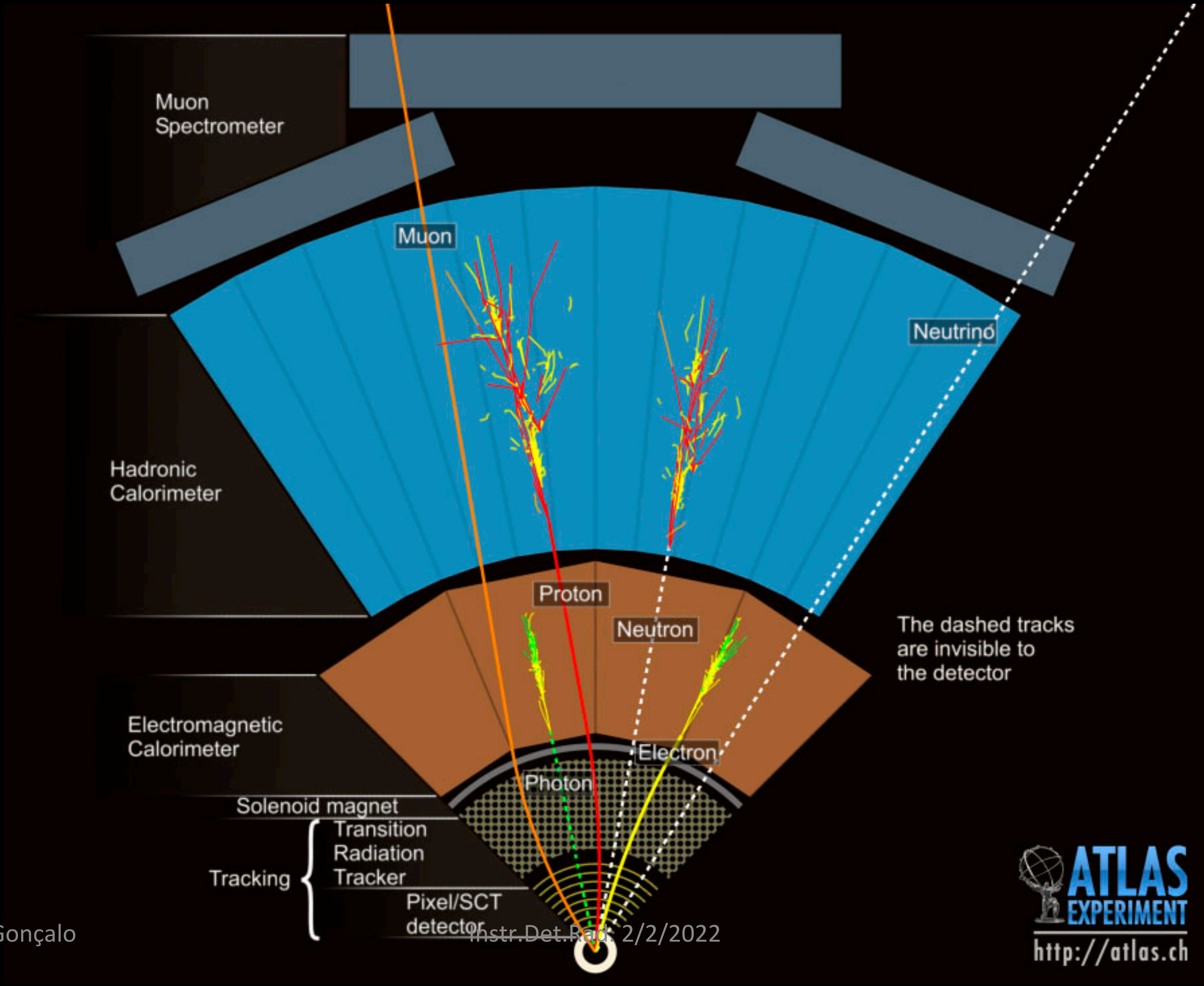
In practice:

- To absorb 1 TeV e or $\gamma \implies$ use $\sim 30X_0$ (i.e. $\sim 18\ \mathrm{cm}$ of lead)
- To absorb 1 TeV hadrons $\implies$ use $\sim 11\lambda_n$ (i.e. $\sim 2m\ \mathrm{cm}$ of iron)
- To measure 1 TeV muons $\implies$ use $|\vec{B}| = 1-4\ \mathrm{T}$ and long lever arm L since $\frac{\Delta p}{p} \simeq \frac{1}{BL^2}$

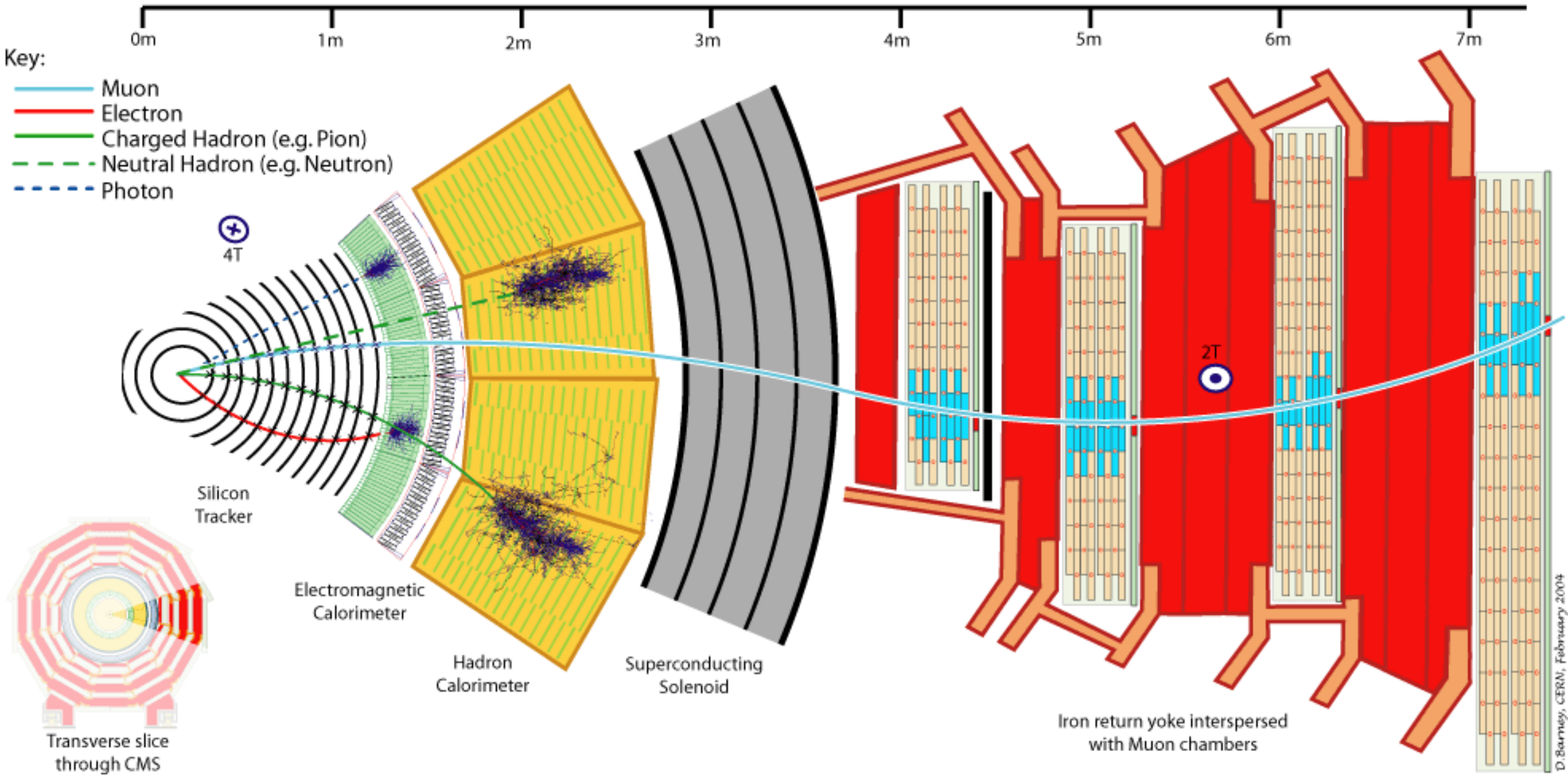
Physics analyses require excellent identification of:

- Electrons: easy to measure; hard to separate from huge background
- Photons: similar to electrons, but harder (no charged track)
- Muons: easy to identify but hard to measure at high momenta
- Taus: quite hard to identify – both leptonic and hadronic decays (1- or 3-prong, like thin jets)
- Hadrons: ~all particles in LHC collisions – hard to identify types
- Quarks and gluons: lead to jets of hadrons – complex objects
- Vertex: which is the relevant collision??

Particle identification

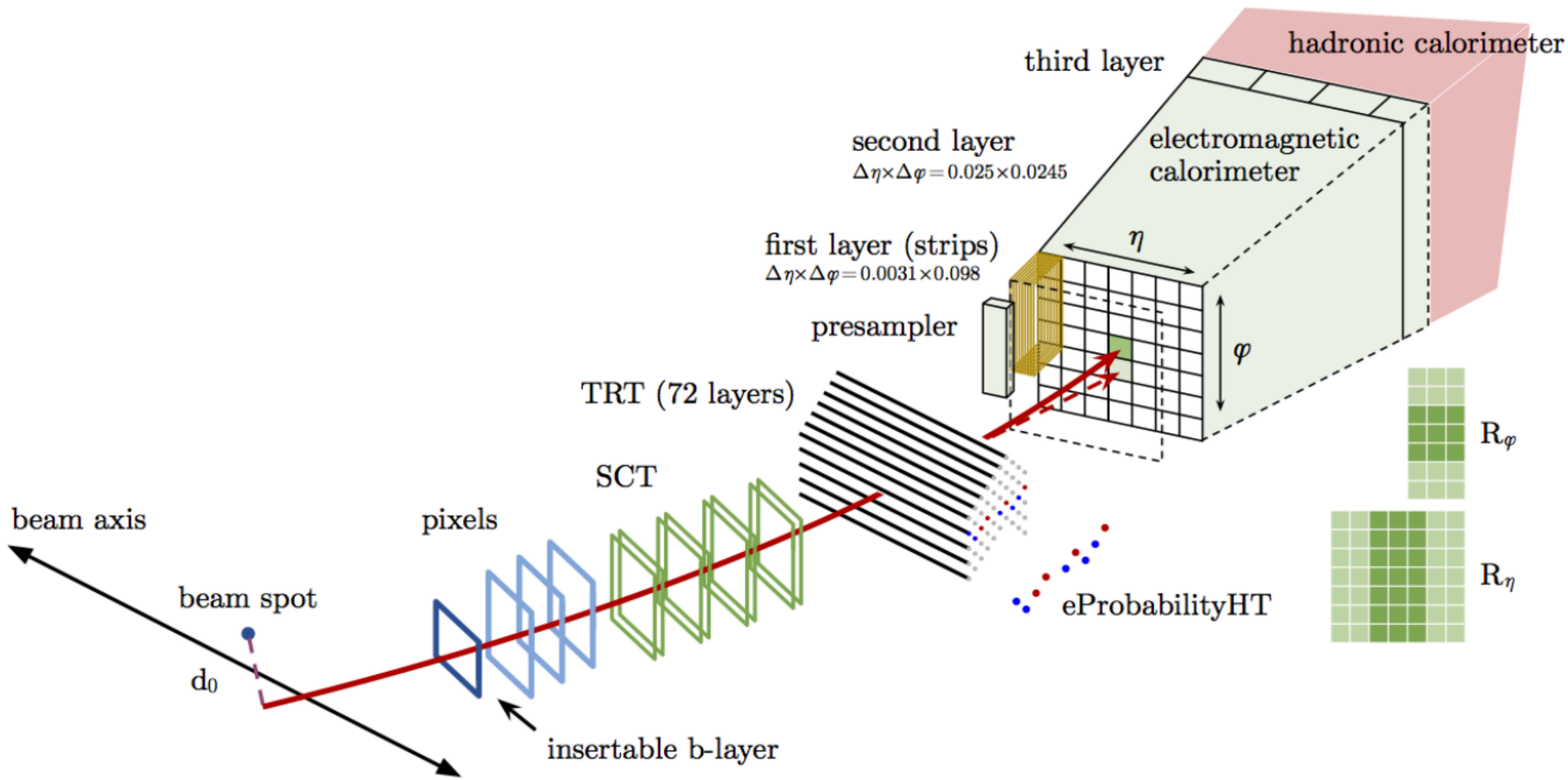


CMS experiment

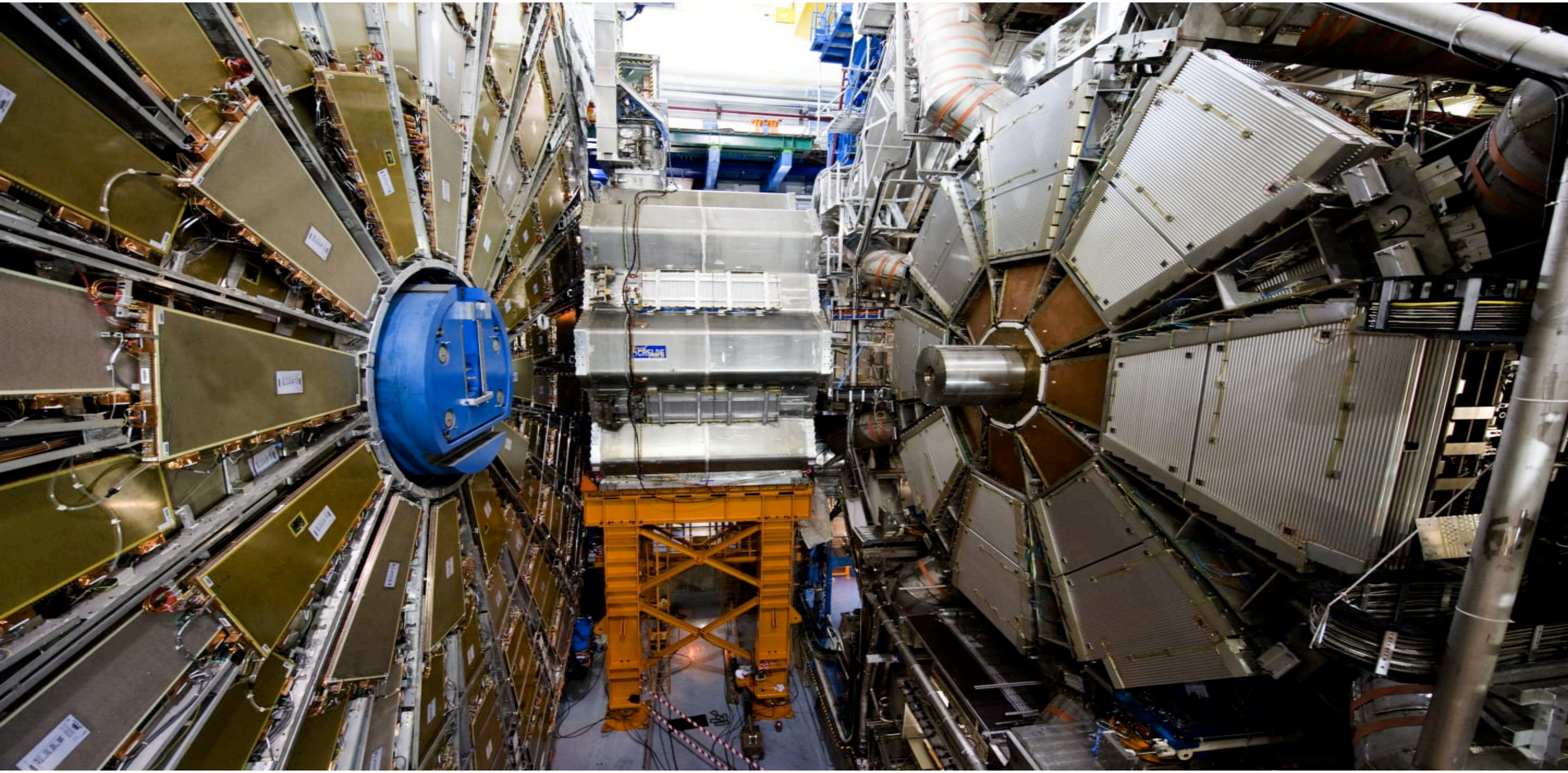


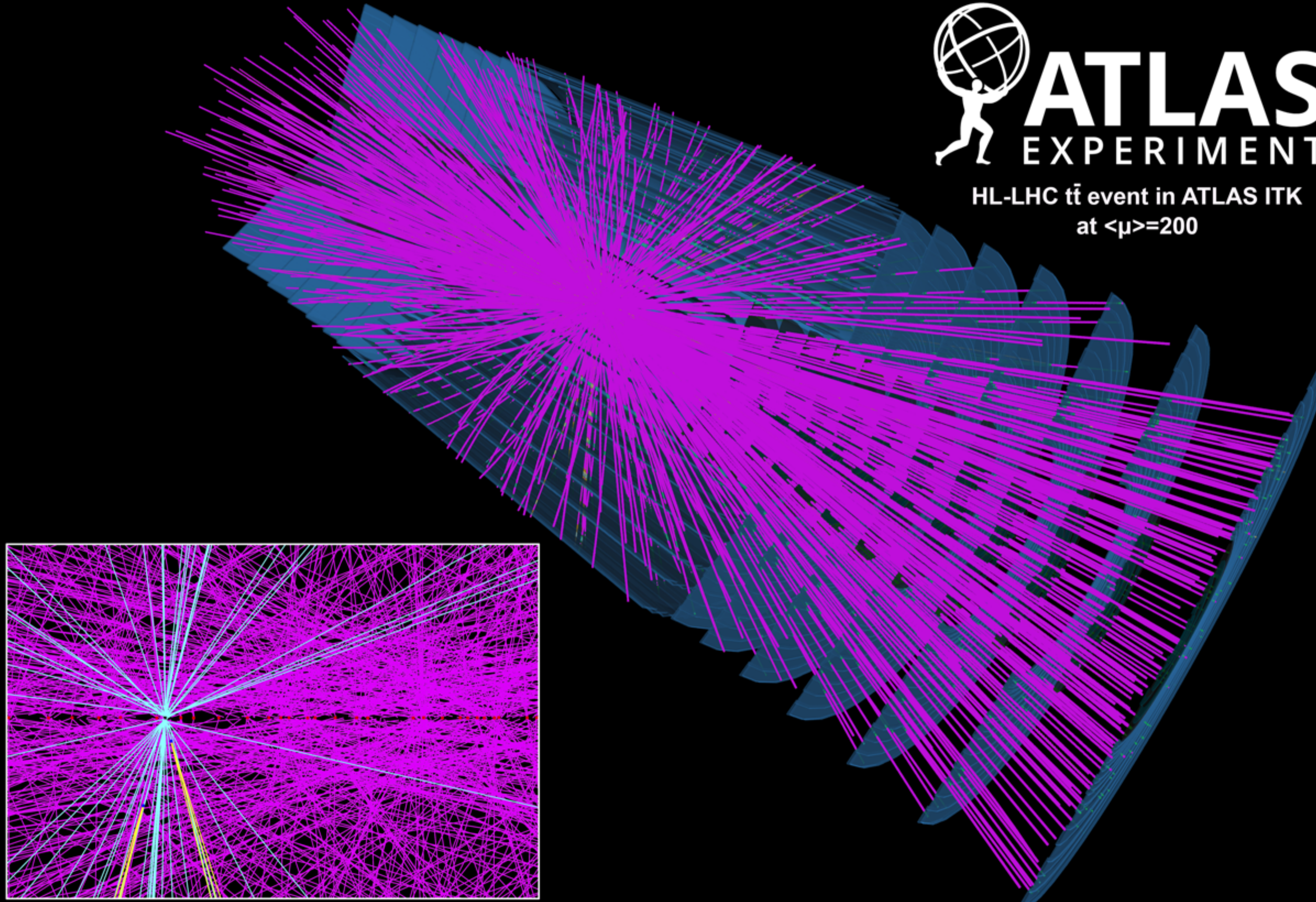
Electrons/positrons:

- Reconstruct a track matching an EM-like energy deposit in the calorimeter
- PID information using Transition Radiation Detector
- Bremsstrahlung photons detected near the track entry point in calorimeter – correct using ϕ strip of cells

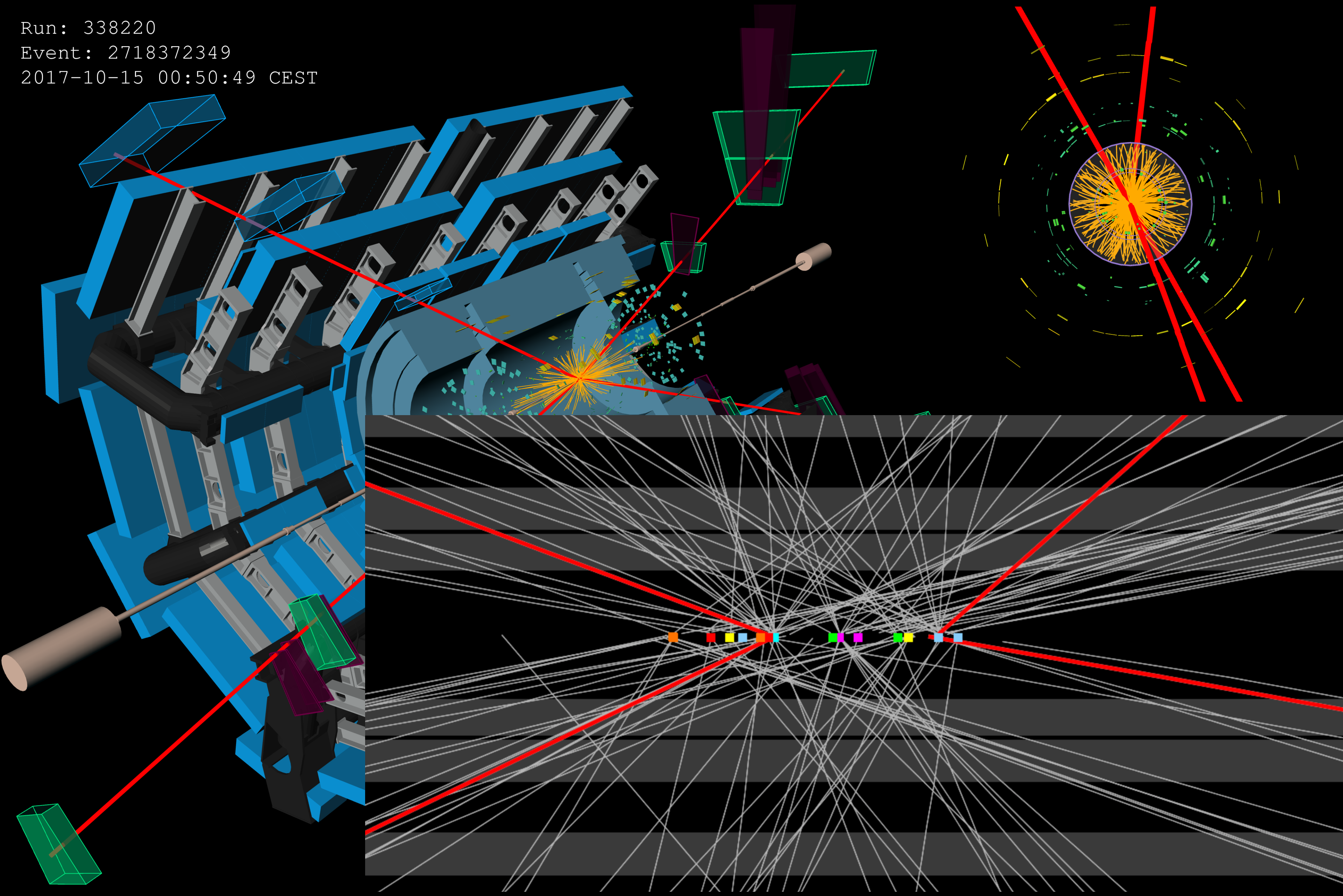


LHC Upgrade



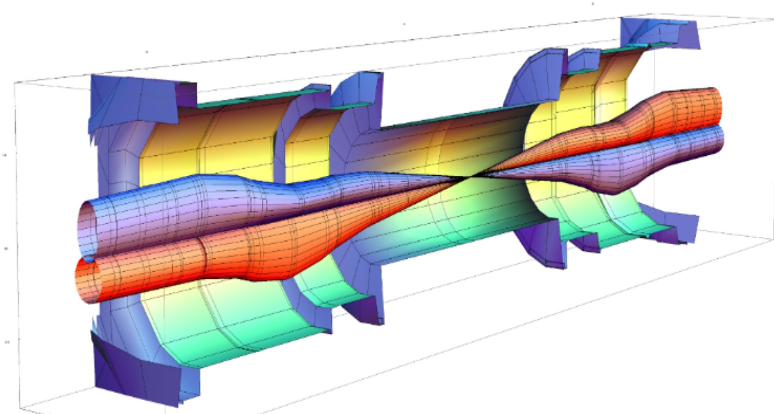


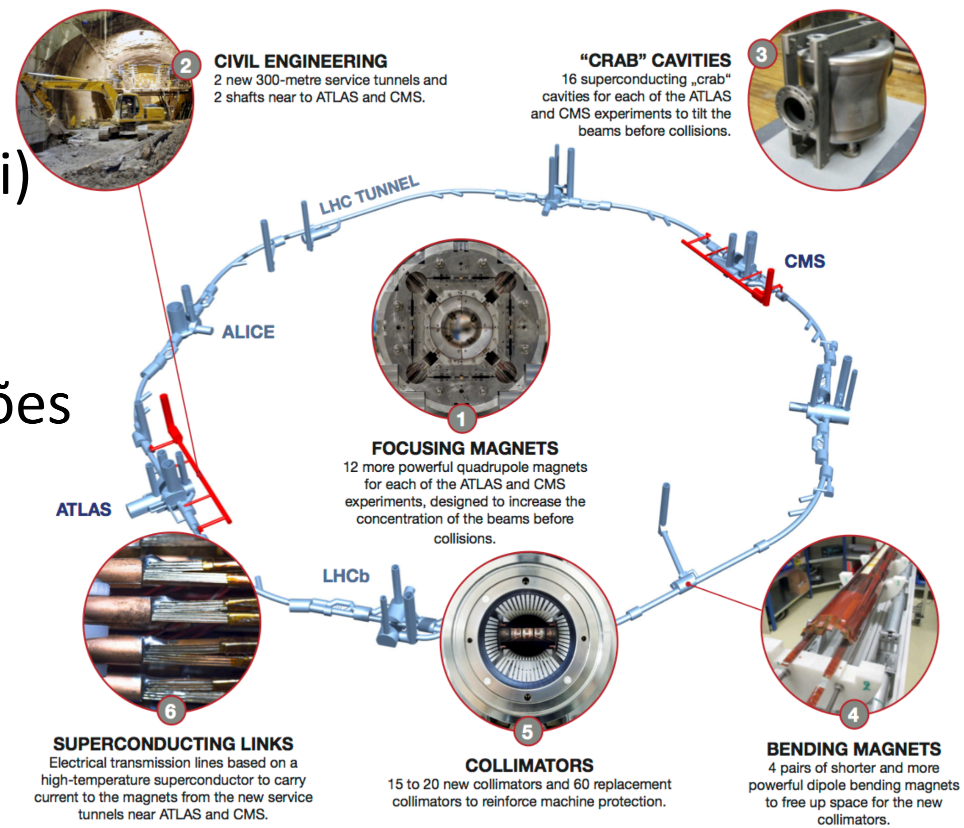
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200


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

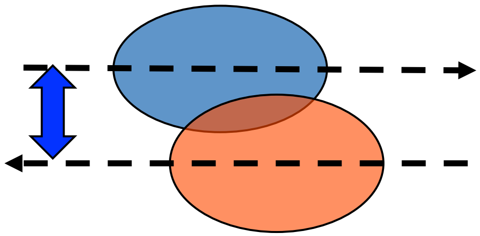
LHC Upgrades

- 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

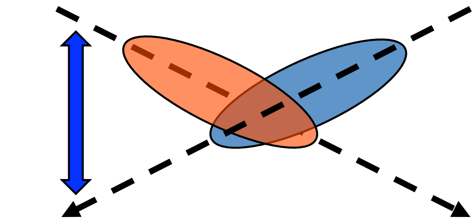




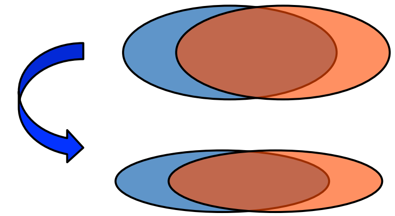
Leveling by beam offset

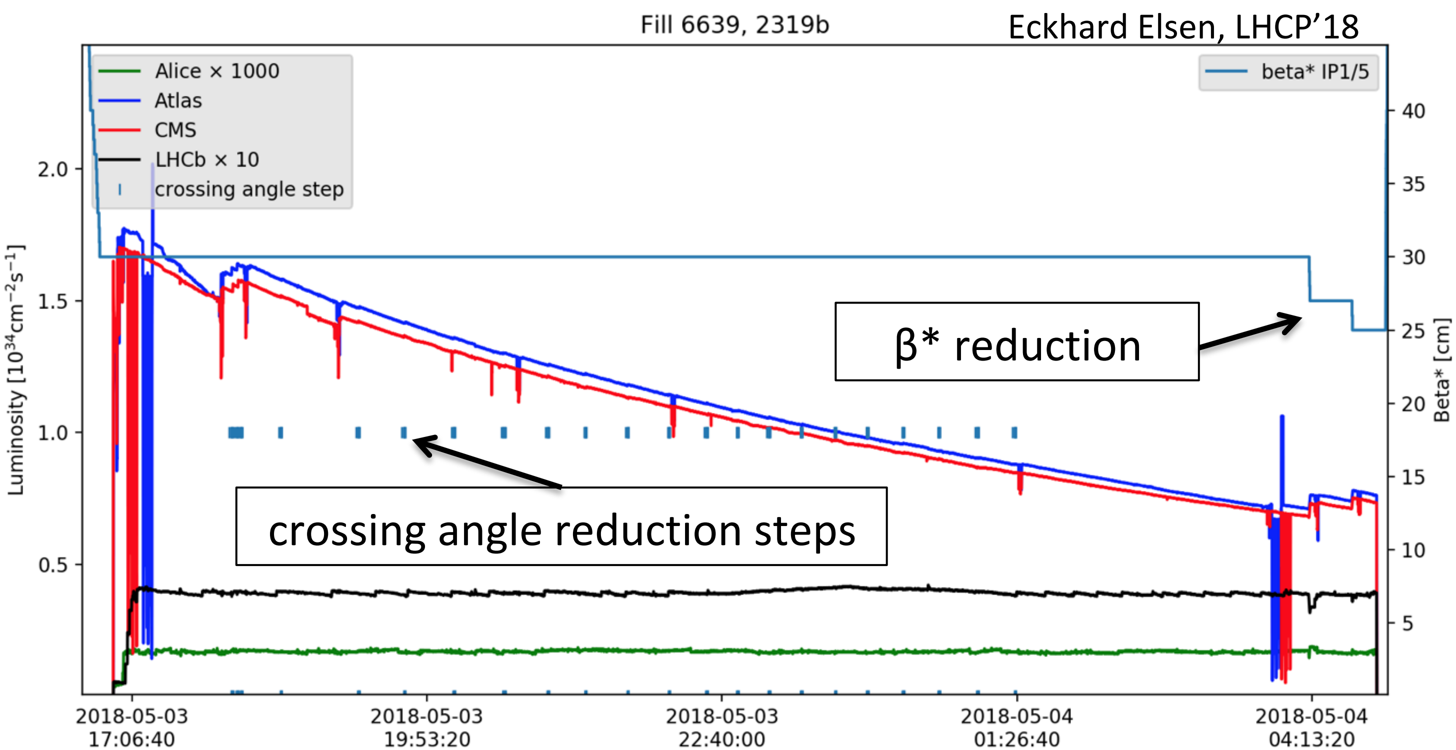


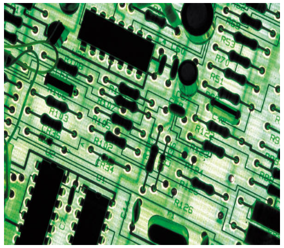
Anti-leveling: crossing angle



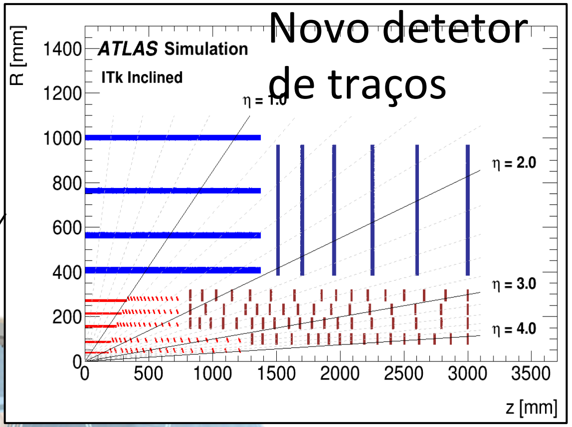
Anti-leveling: β* reduction



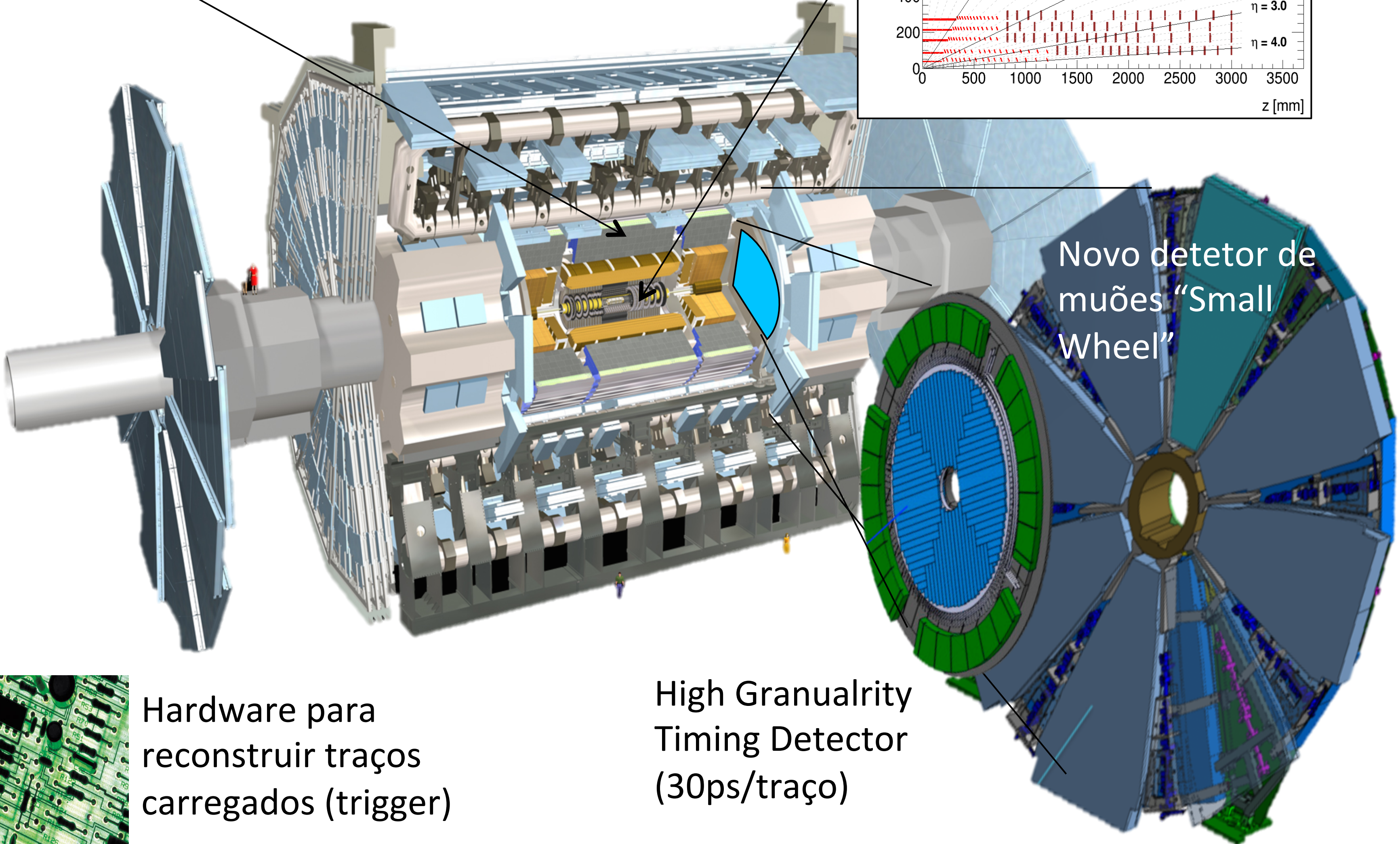




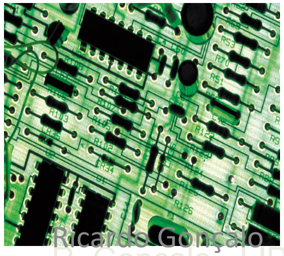
Nova eletrónica, fontes de alta tensão e cintiladores do calorímetro



Novo detetor de traços



Novo detetor de muões "Small Wheel"



Hardware para reconstruir traços carregados (trigger)

High Granualrity Timing Detector (30ps/traço)

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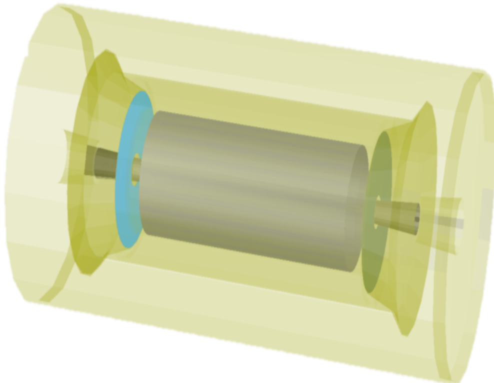
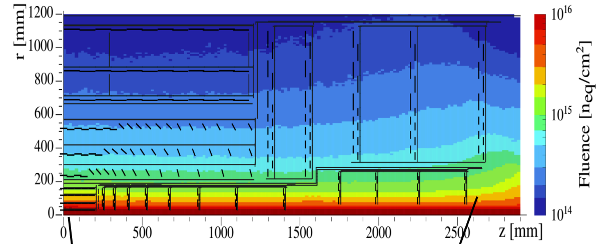
Novo MIP Timing Detector
(Barrel & Endcap)



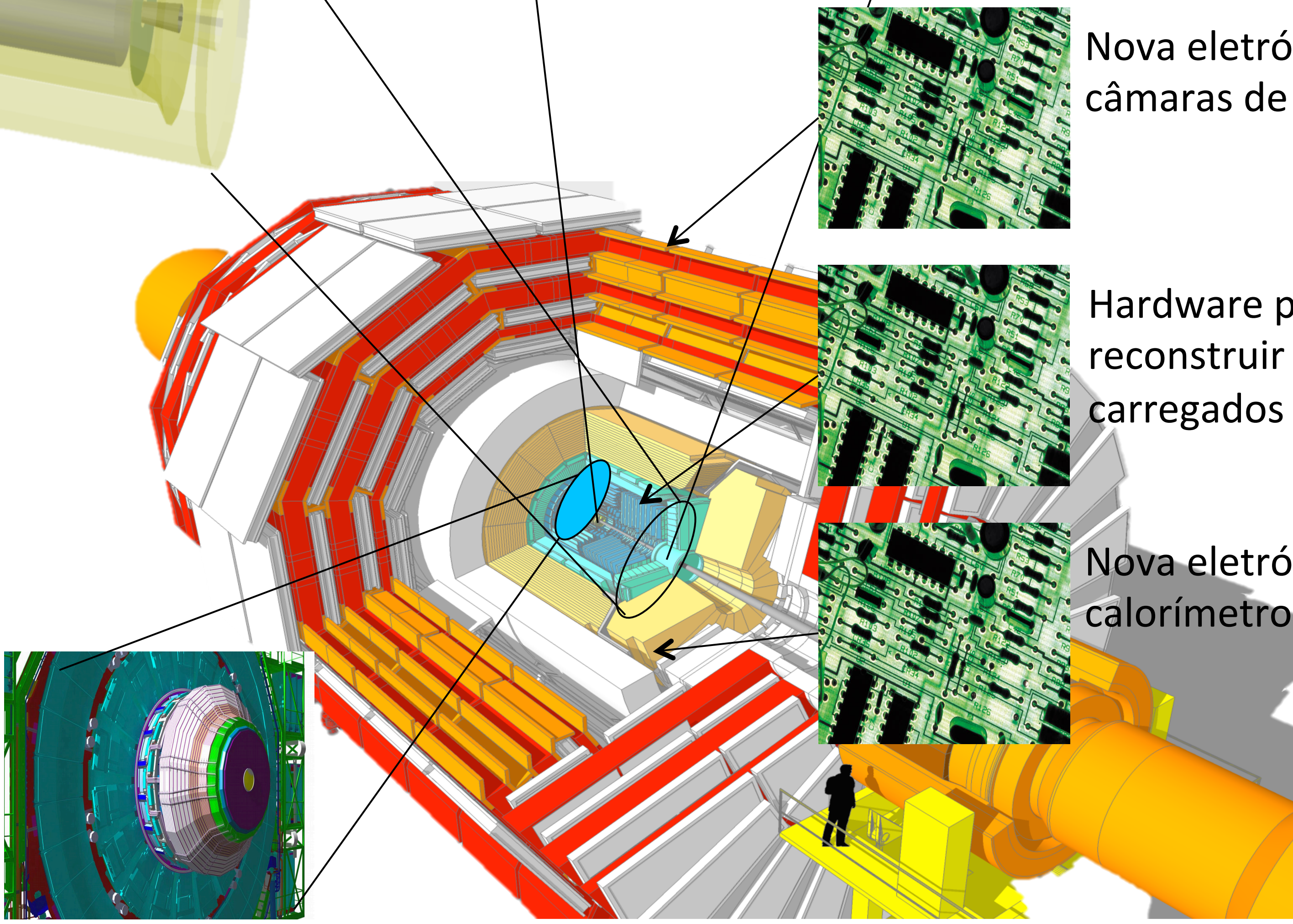


Substituição do detetor de traços

Nova eletrónica e câmaras de muões

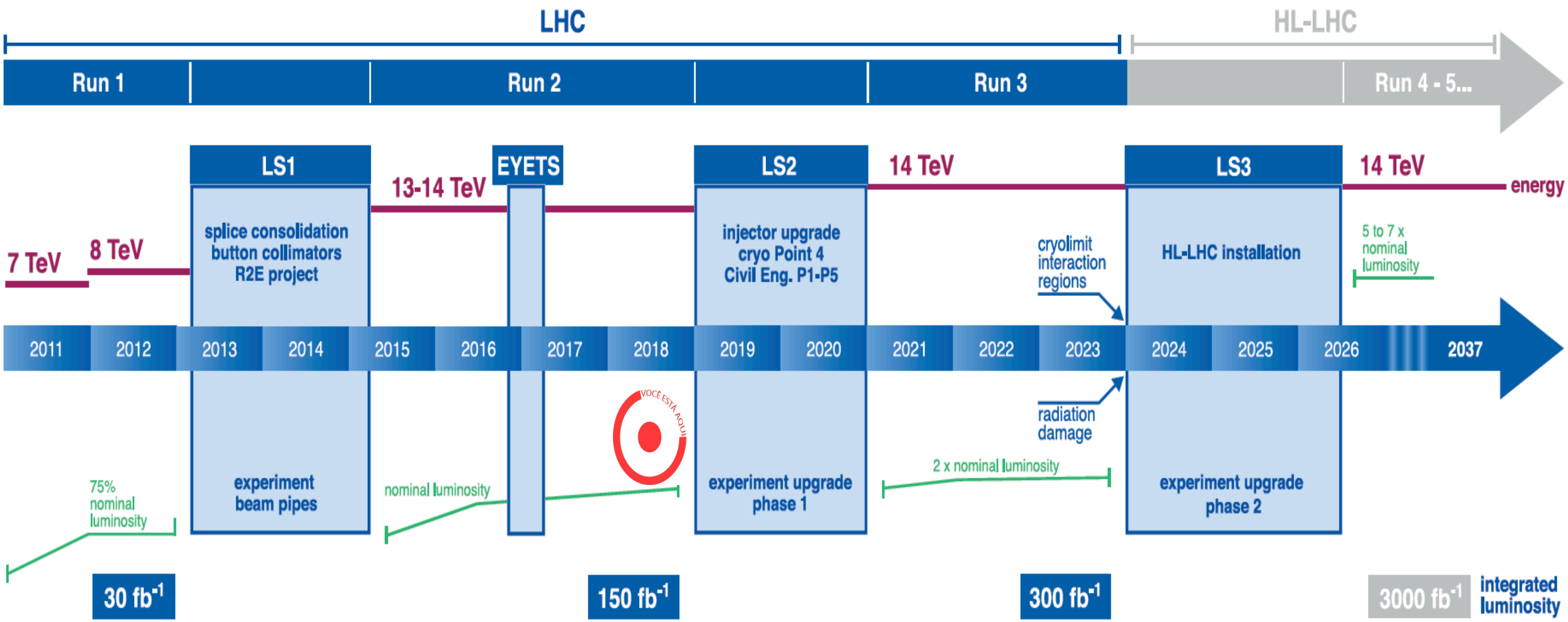
Hardware para reconstruir traços carregados (trigger)

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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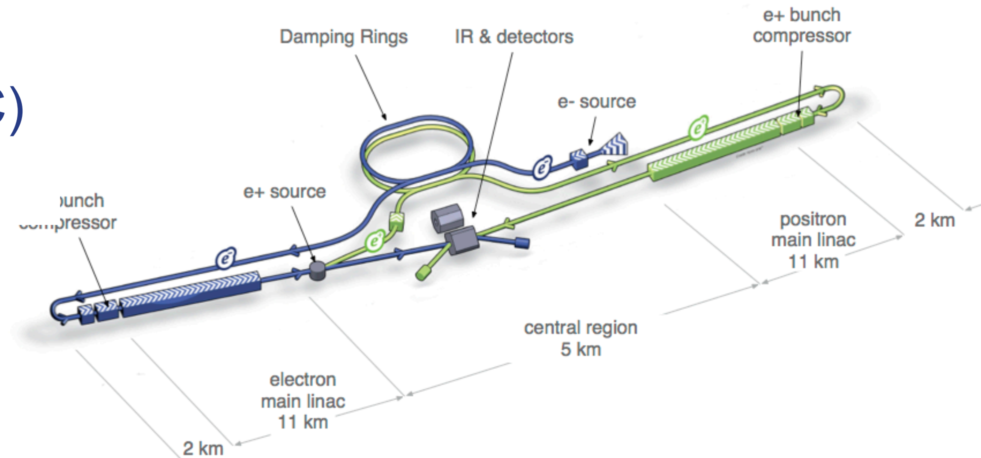
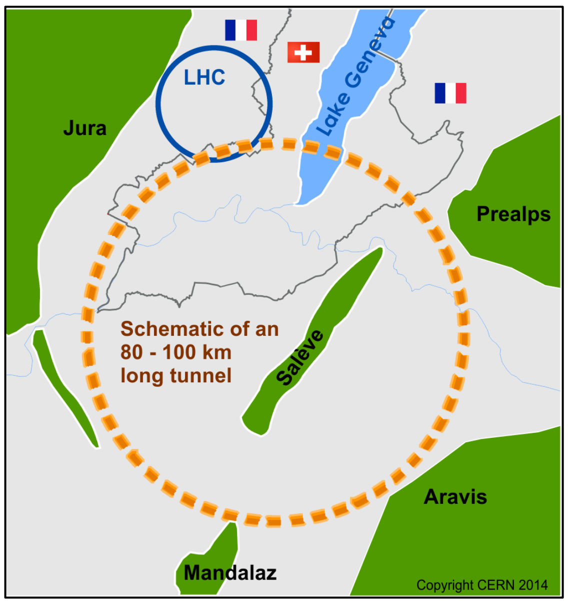
Beyond LHC

Future acellerators?

International Linear Collider (ILC)

- 0.5 TeV machine; 31 km



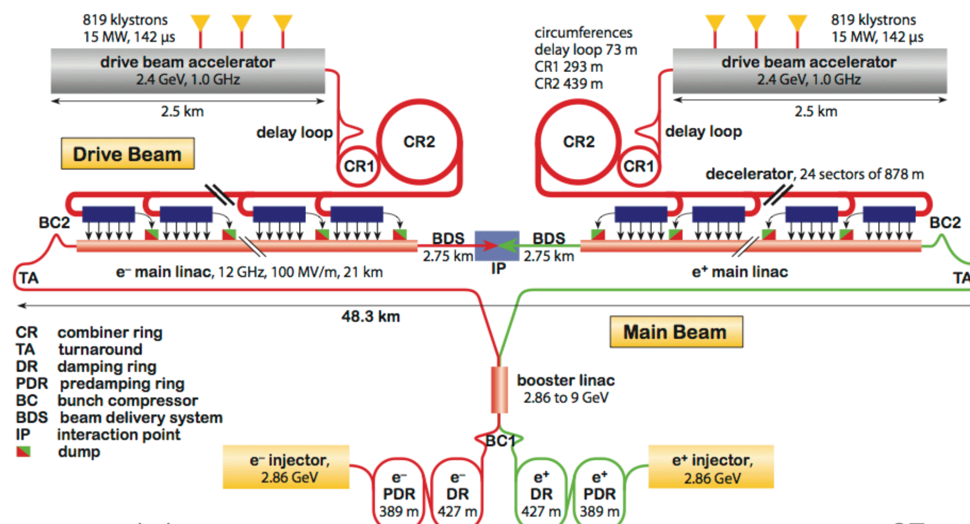


Future Circular Collider: 100 km

e+e- (350 GeV) e mais tarde p-p (100 TeV)

Compact Linear Collider (CLIC)

- 3 TeV collider - 50 km



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Bonus slides

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