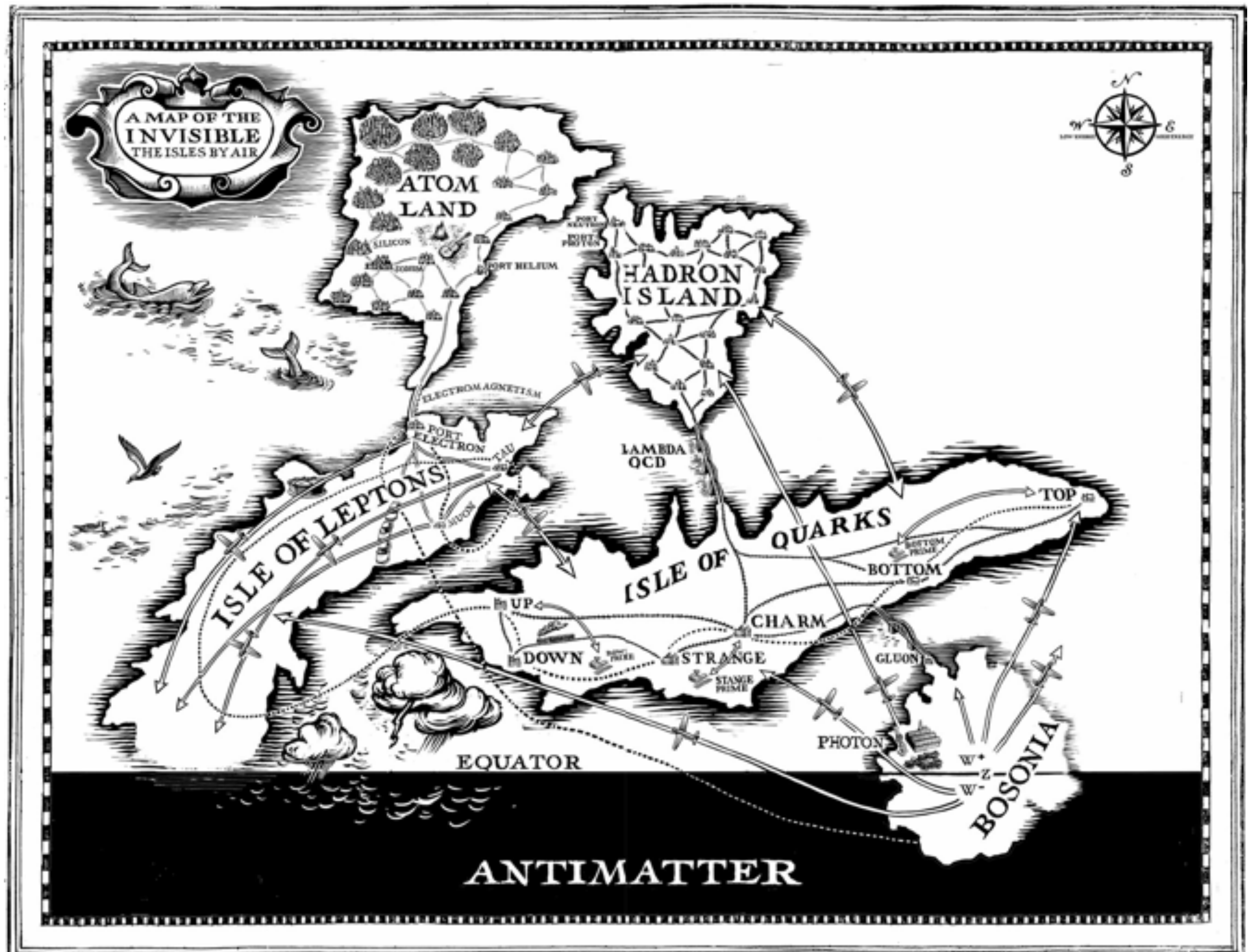
Topics in Experimental Particle Physics

S. Xella



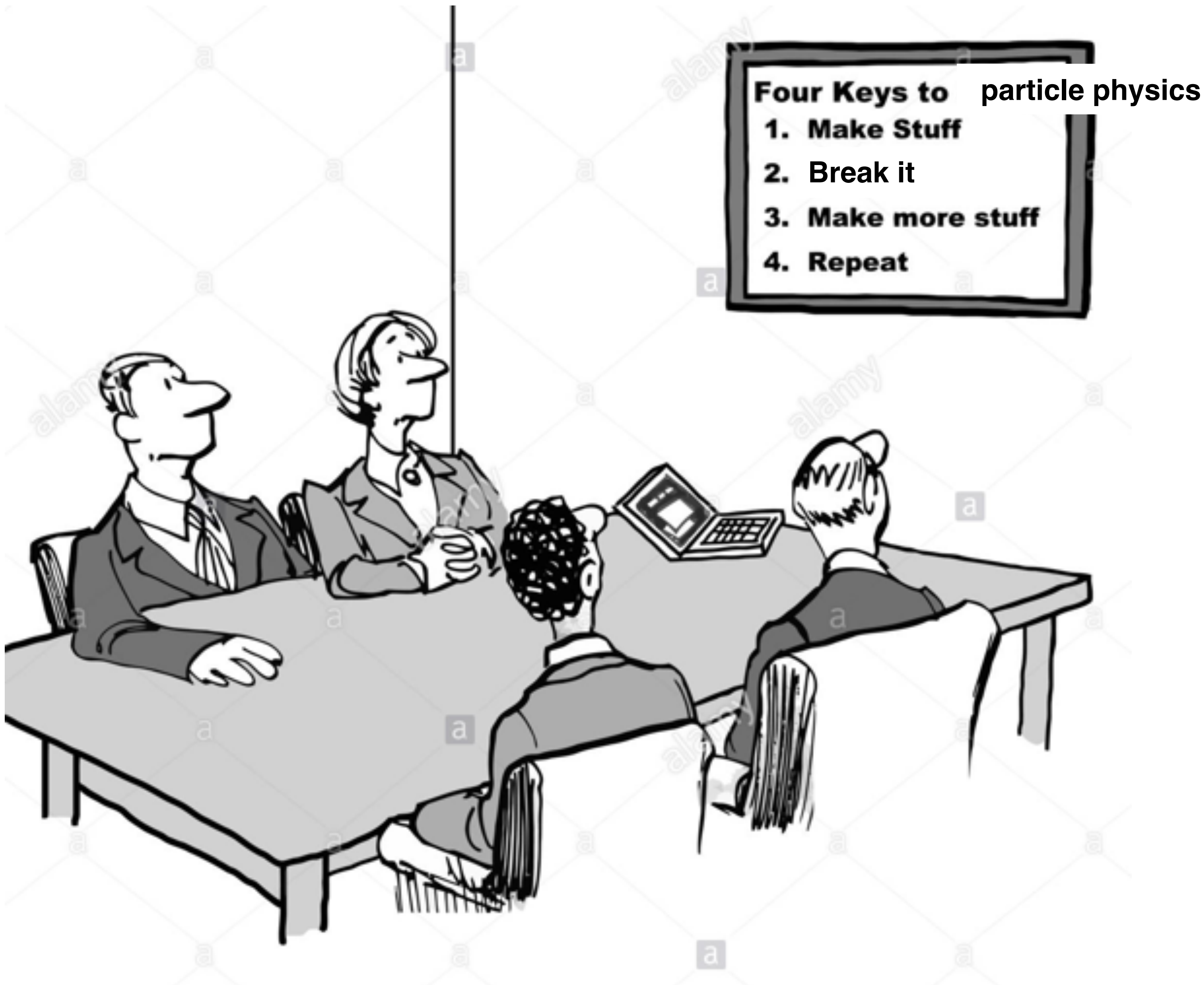
credit
J.Butterworth
"Atomland"

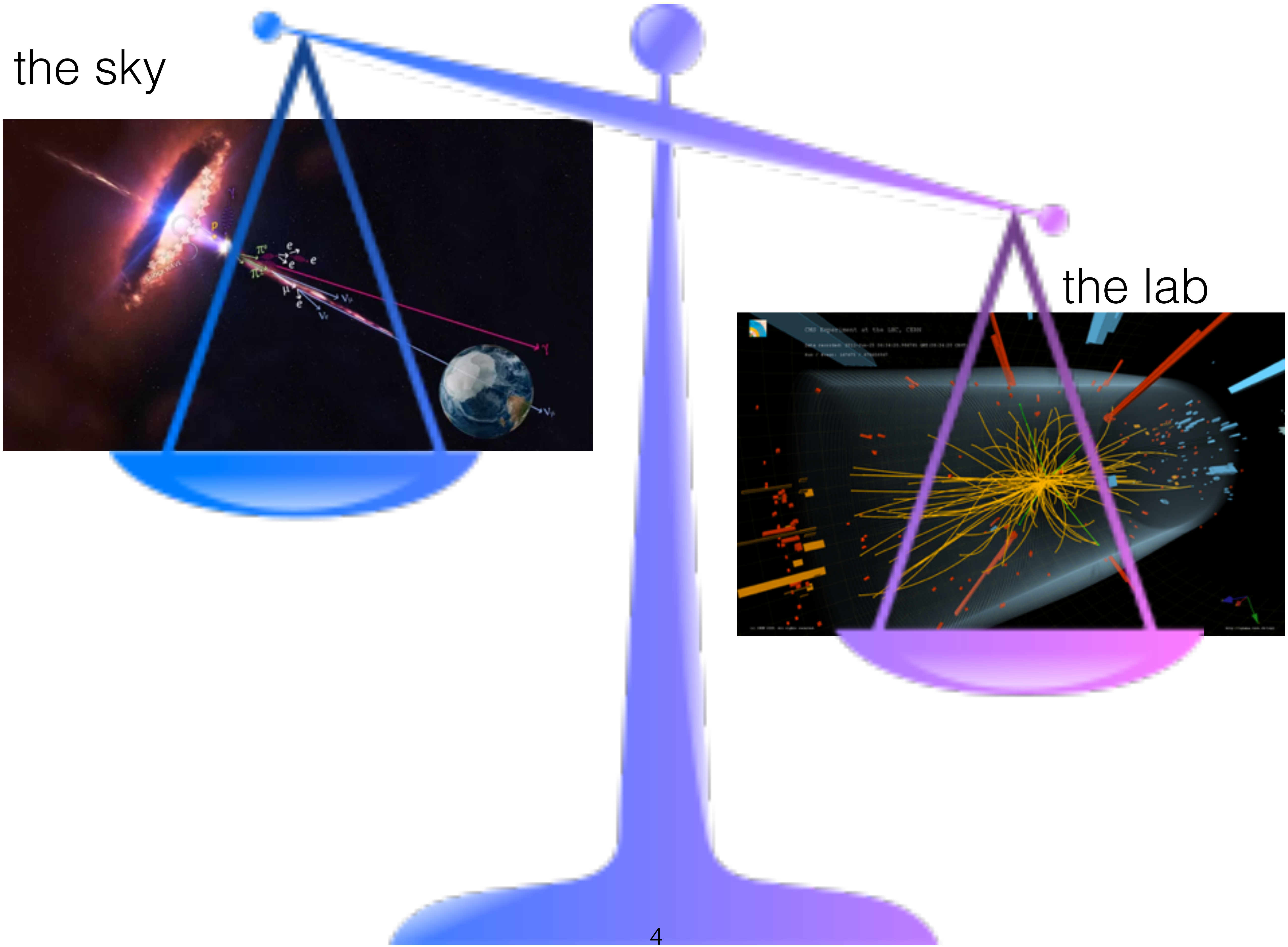
Content

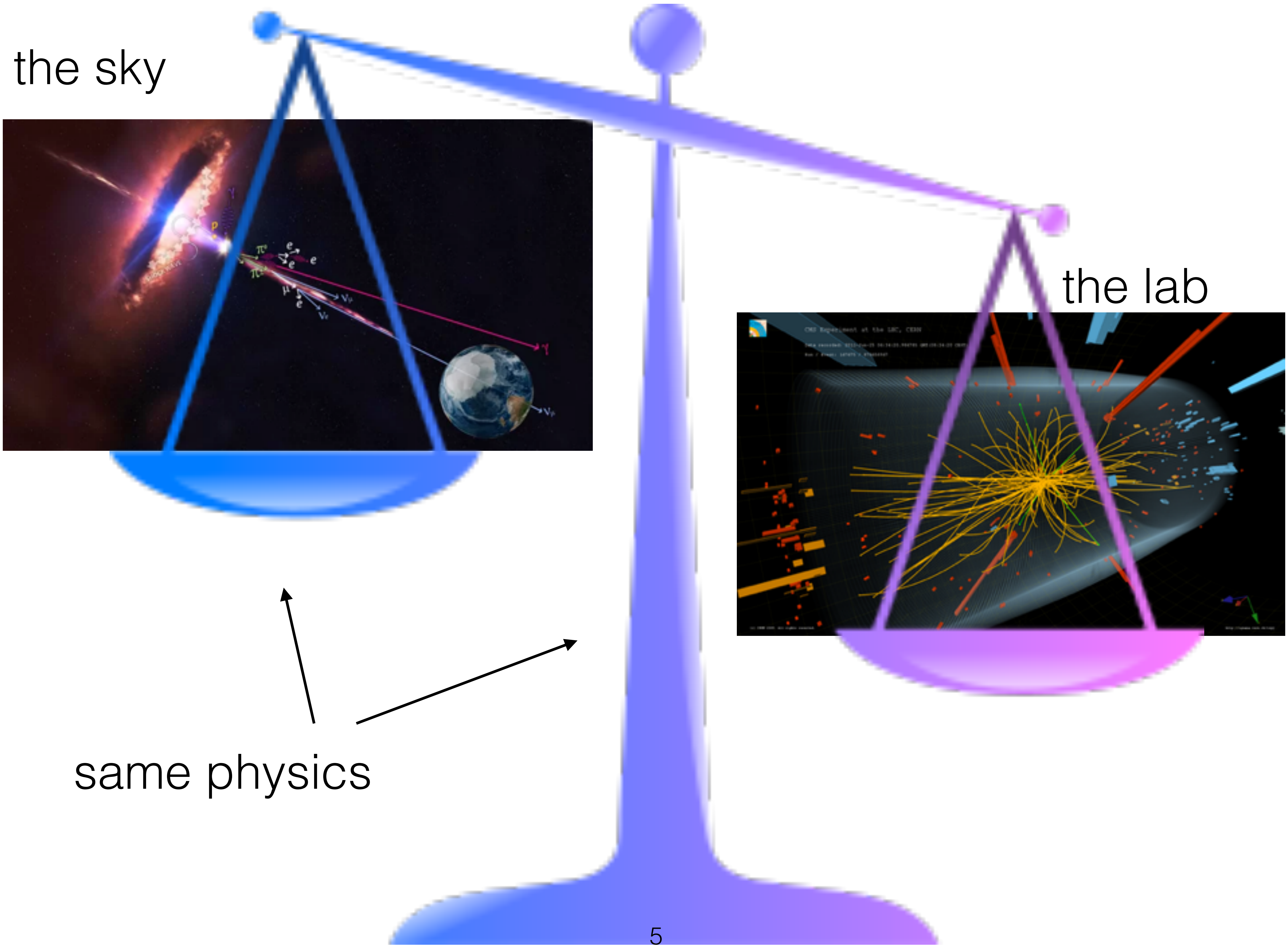
Focus of these lectures is accelerator-based particle physics.

- Lecture 1: Colliders. Focus: LHC. One experiment in details : ATLAS : detector+trigger+reconstruction of collisions.
- Lecture 2: What have we learnt about the Higgs boson so far.
- Lecture 3: New physics beyond the Standard Model: what can the LHC collider tell us (DM, neutrinos, matter-antimatter asymmetry).
- Lecture 4: Possible future accelerator-based research at CERN: FCC, SHiP, Mathusla, FASER. What can they tell us?

Why do we need accelerators?




the sky
the lab


the sky
the lab
same physics

Why do we need accelerators

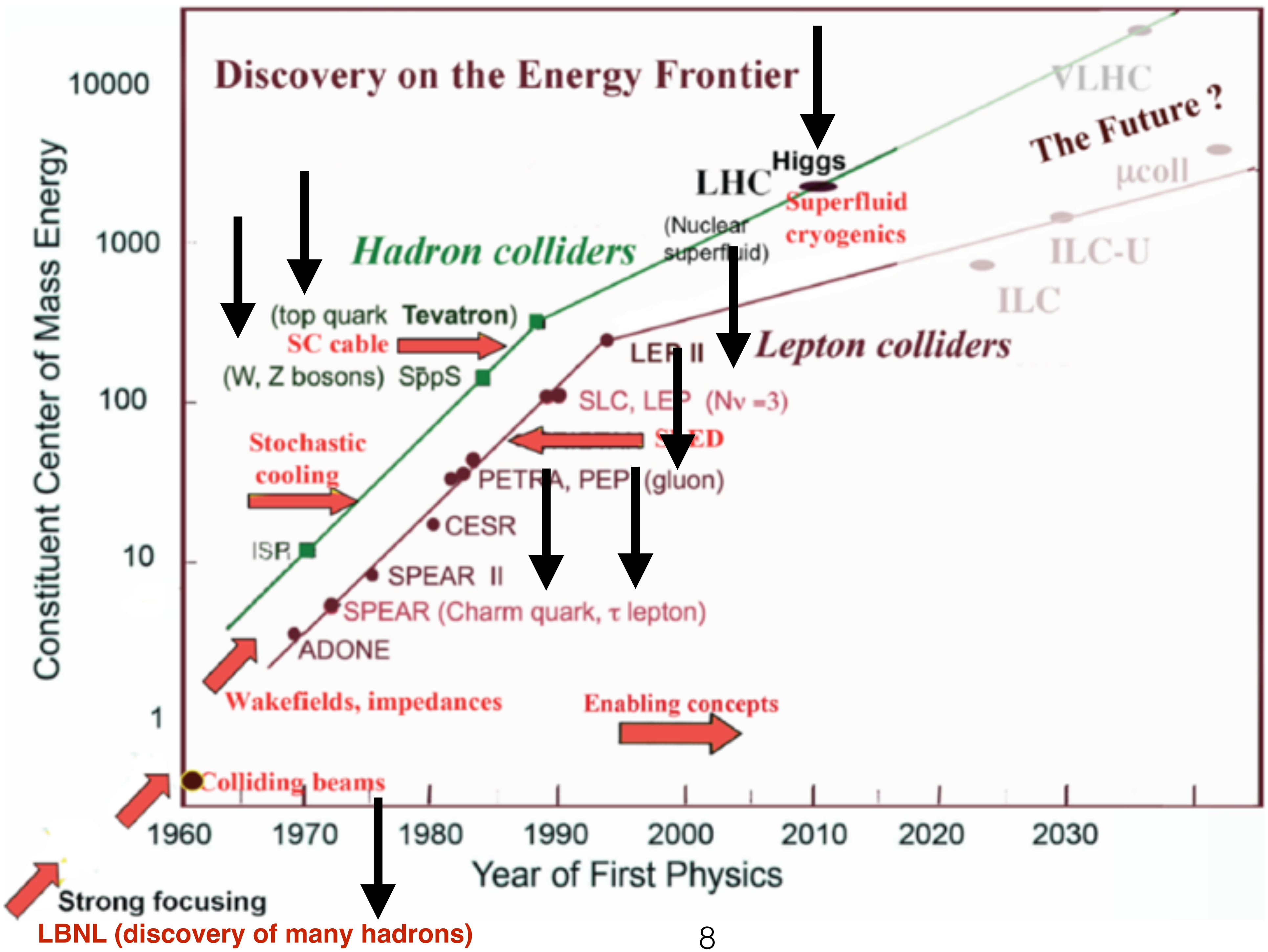
- **Precision tests of** particle physics **theory** are best carried out at accelerator facilities.
    - one can reproduce the outcome of an experiment over and over in the lab and verify definitely that only one interpretation (= theory) is correct.
- **Discoveries of new particle phenomena** are very trustworthy outputs of accelerator experiments : hadrons, J/psi, top quark, Higgs boson, CP violation in quarks processes, ….
- hints from theory or from previous observations are usefull in the first use-case (test of theory) : choice of energy and type and luminosity best suited for testing. For the second case (discovery), simply try to reach a new frontier in energy or intensity (& be lucky?) is a worthwhile approach.

Accelerators are not enough

- Neutrino or dark matter particle properties: questions not addressable with accelerators only. Need to exploit cosmic/atmospheric, nuclear reactors sources, etc… too.

- In general, the current big questions in particle physics are really big ! They need different simultaneous experimental approaches, to find answers. Theory is also of little guidance at the moment.

Discoveries by colliders



The Standard Model has been mostly verified at collider experiments

key parameters

accelerator types

key parameters of an accelerator: setup and energy

- setup: beam on target or collider? collider best :
    - E_{CM} (b-on-target)= $\sqrt{(mE)}$
    - E_{CM} (collider) = 2 E
- energy : circular collider vs linear collider.
    - **circular**: limited by the bending power of the magnets (dipoles). For a given fixed radius (eg LHC, re-using LEP tunnel), energy is limited by the maximum magnetic field achievable. Super-conducting coils, large currents (10 kAmps -> ~ 8 Tesla at LHC) is best method achievable so far.
    - **linear** : limited by the size mainly. much longer instrumented beampipe needed to achieve same energy as in circular collider. eg @ LHC accelerating units 5MV/m x 0.5 m x 8 units, 16 MeV per turn in LHC to bring 450 GeV-> 7 TeV in 10.000 turns per sec and 20 min

key parameters of an accelerator: luminosity

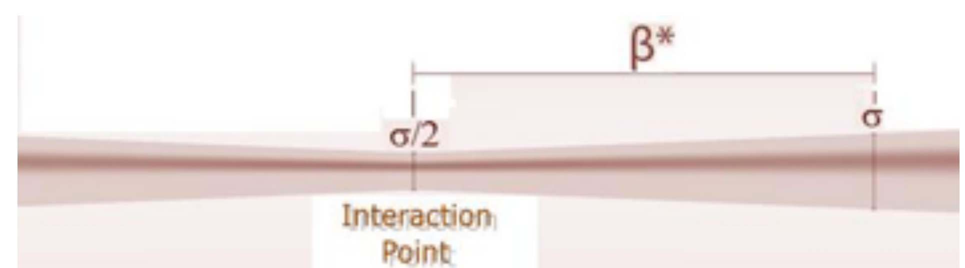
- luminosity [$cm^{-2}\,s^{-1}$] : $$L = \frac{f_{rev} n_b N_b^2}{4\pi\sigma_x{}^*\sigma_y{}^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

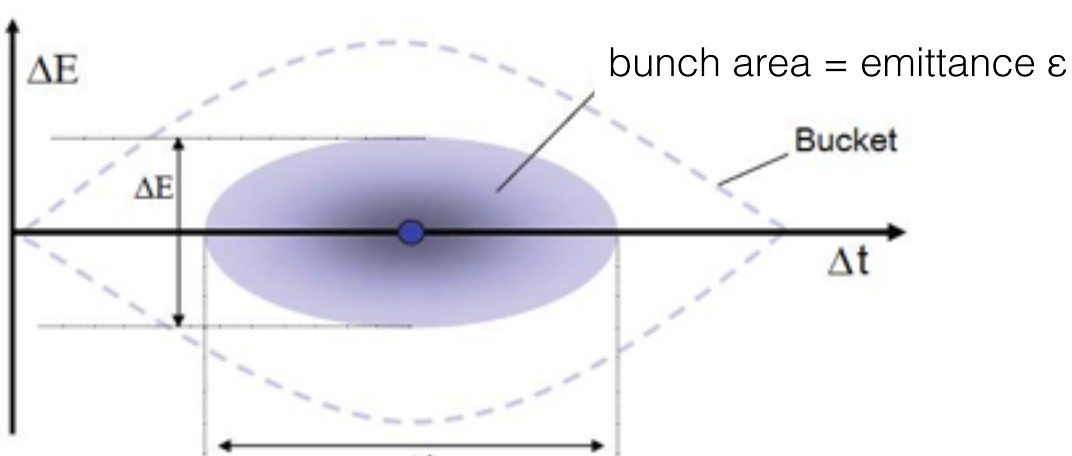
rate of collision events = cross section (E_{CM}) x L

$$L = \frac{1}{4\pi}\left(f_{rev} n_b N_b\right)\frac{N_b}{\varepsilon_N}\frac{\gamma}{\beta^*} R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

compensate reduction factor *R*
crossing angle
hourglass effect

maximize total beam current | **maximize brightness (injectors & beam-beam limit)** | **maximize energy & minimize β***





eg at LHC **β^* = 0.55 m** and **ε_n = 3,75 mm μm**

ε (normalized transverse beam emittance) and β (amplitude function)

$\sigma = \varepsilon\beta^*$

Which type of colliders is usefull to build

- high energy means probing early times of Universe life, means studying something new and likely discovering something interesting, so hadron colliders are best

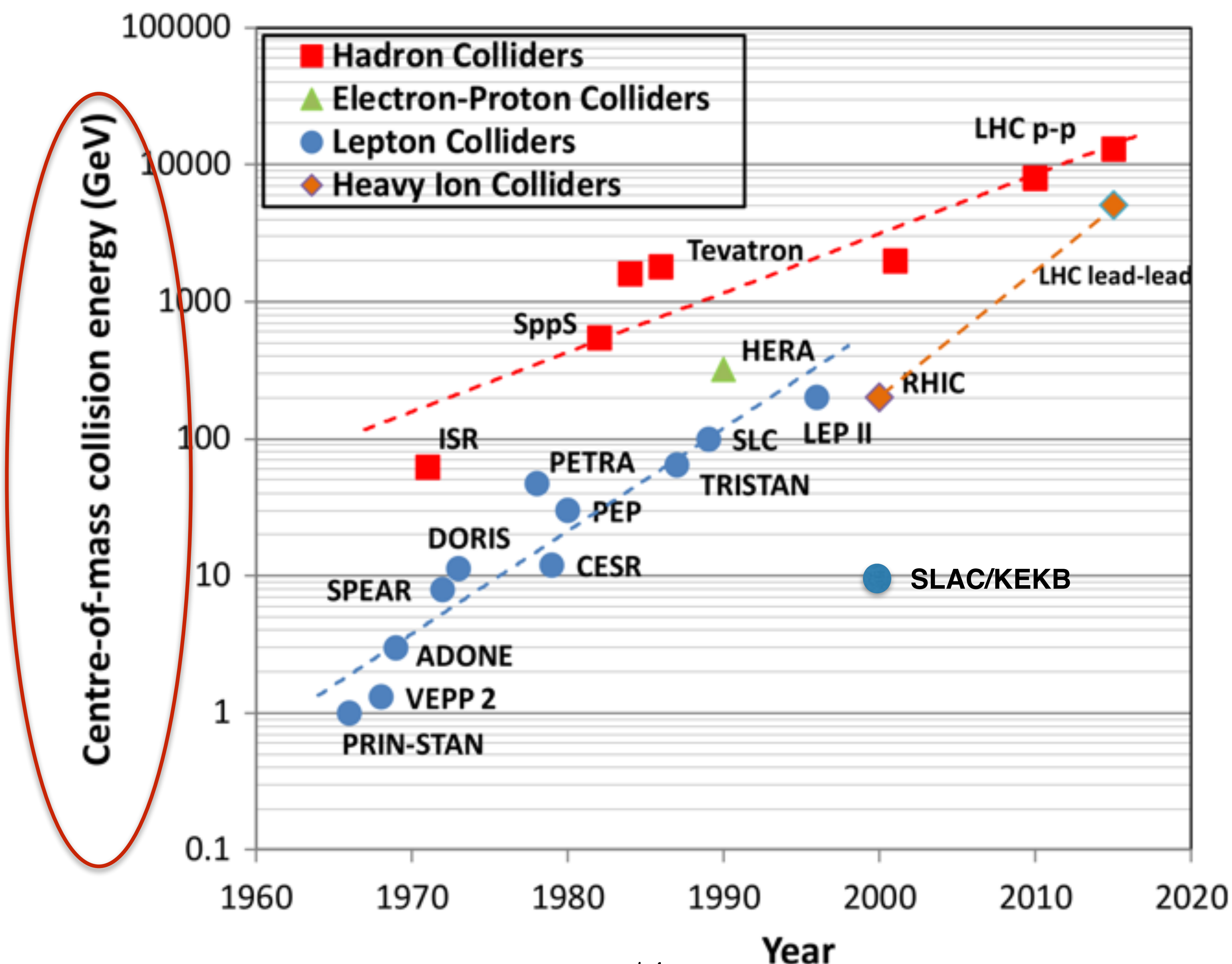
  - harder to achieve high E with light particles, eg electron beams, in circular collider due to synchrotron radiation energy loss : P~ E^4/m^4 . Easier with heavier particles, eg protons. electron beam fill needs to be topped up continously, while proton beam fill can be stable for hours.

  - p-antip Tevatron first (~1 TeV), then p-p LHC (~10 TeV), then maybe p-p FCC later (~100 TeV)

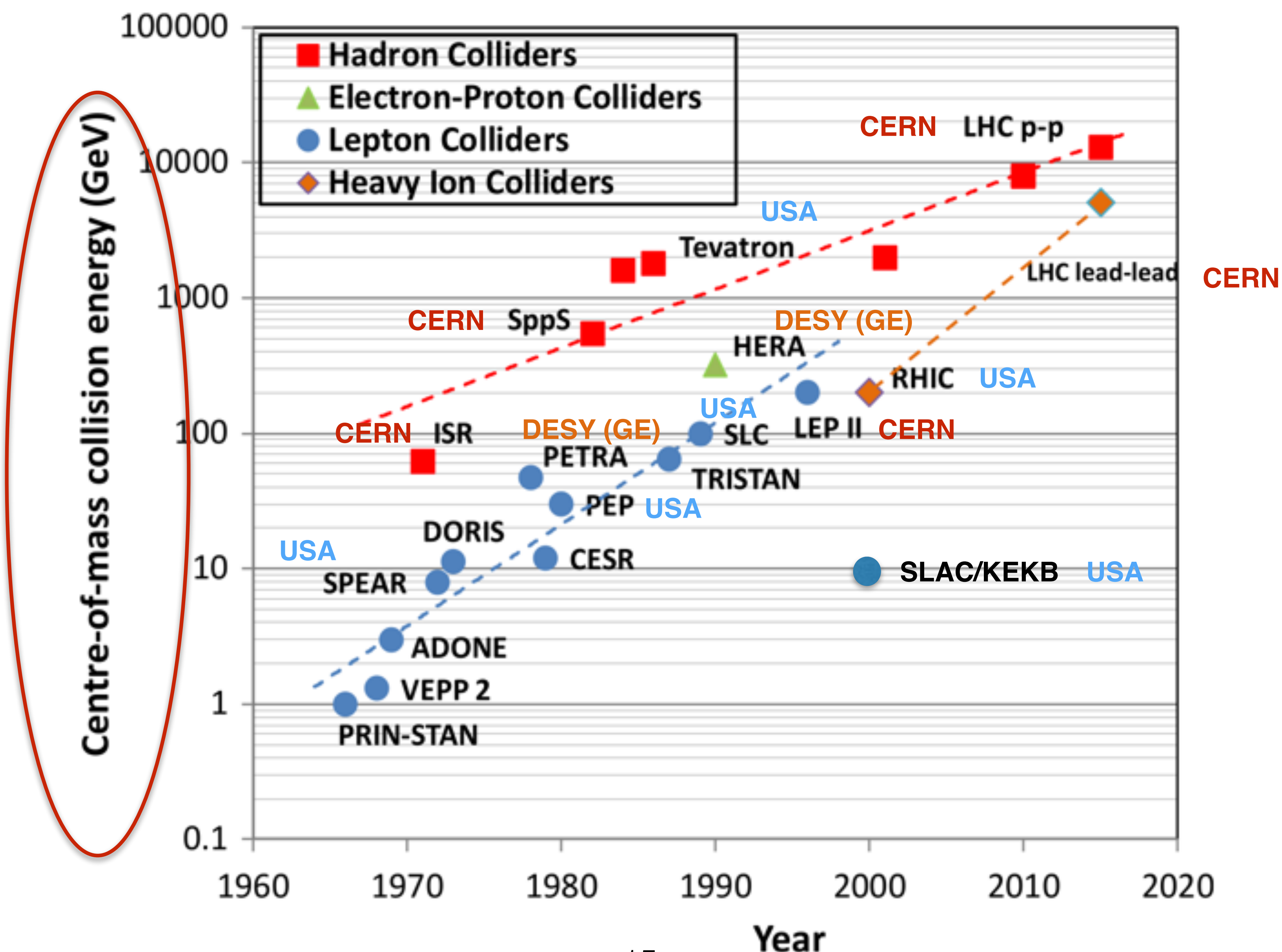
Which type of colliders is usefull to build

- hadron collisions' debris are more difficult to reconstruct precisely than lepton collisions' ones.
  - in hadron colliders, collisions happen between partons in the proton, whose energy and direction is unknown. in lepton colliders one has very good control of these two parameters and can use them to further constraint the output products (energy, momentum conservation rules can be applied)
- typically you would alternate these two types, to achieve the most precise understanding of particle physics processes at a given energy regime
  - e+e- LEP and then p-p LHC, p-p LHC and then maybe e+e- ILC, etc….

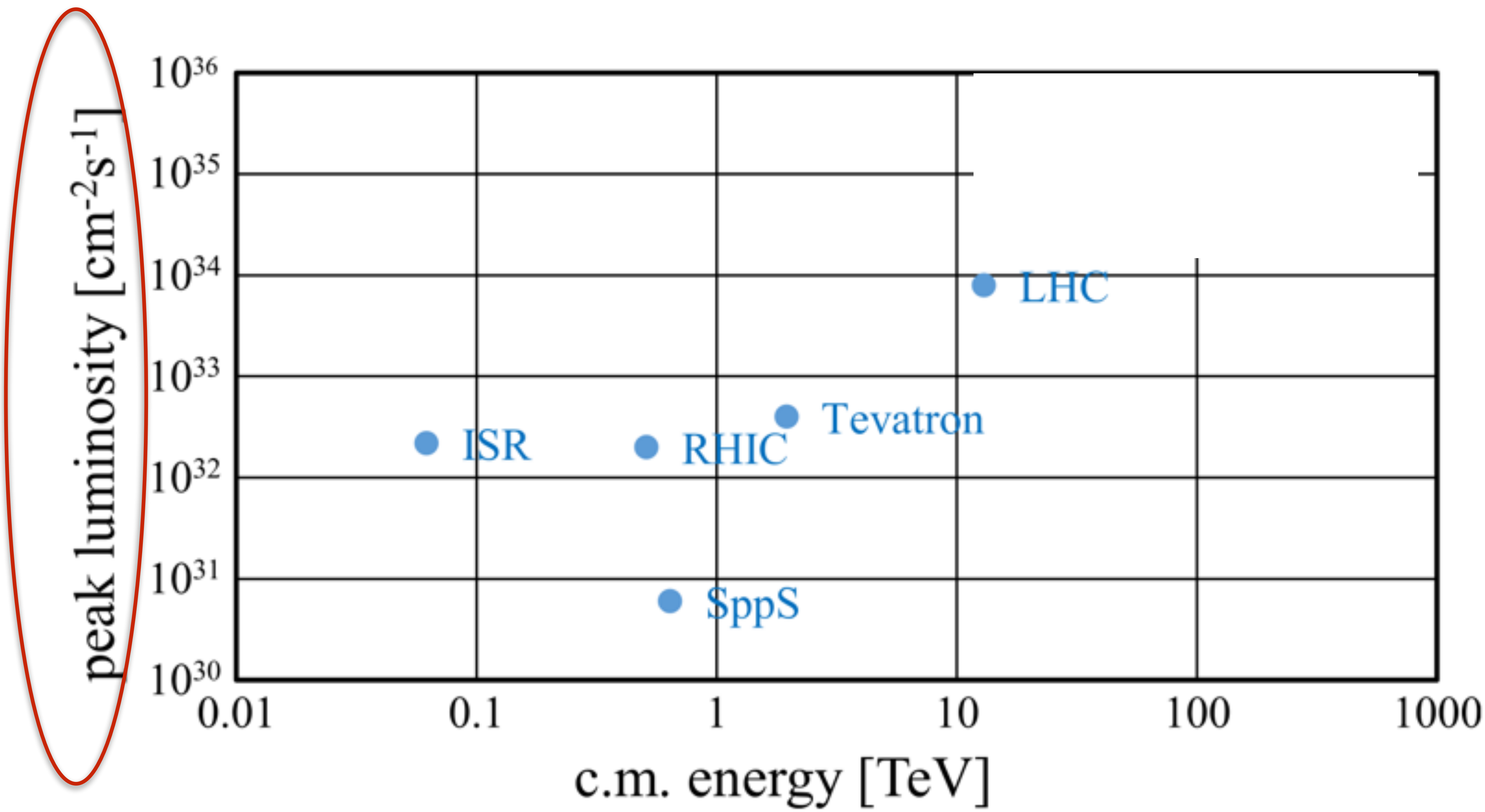
Which type of colliders have been built so far



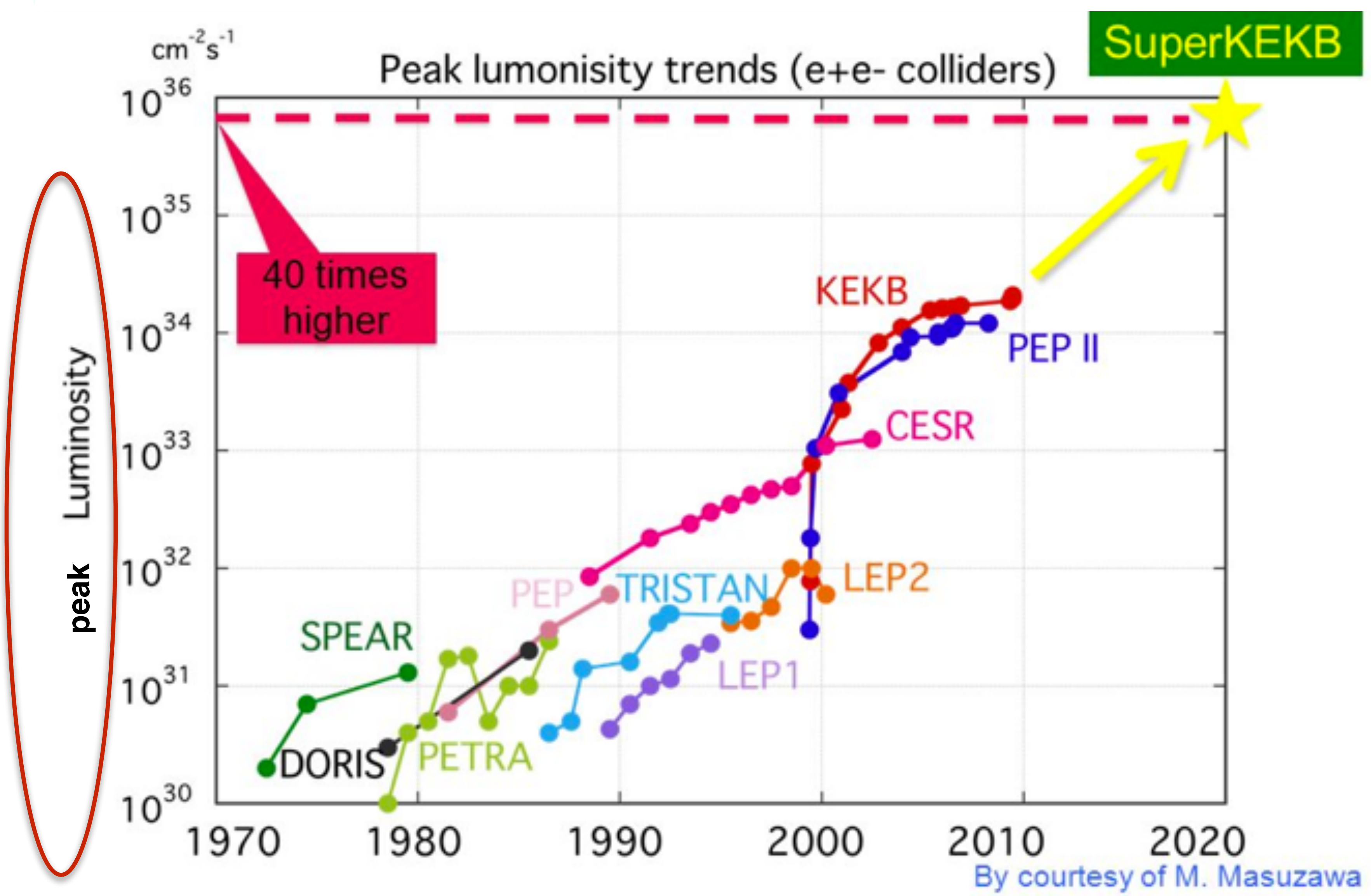
Which type of colliders have been built so far

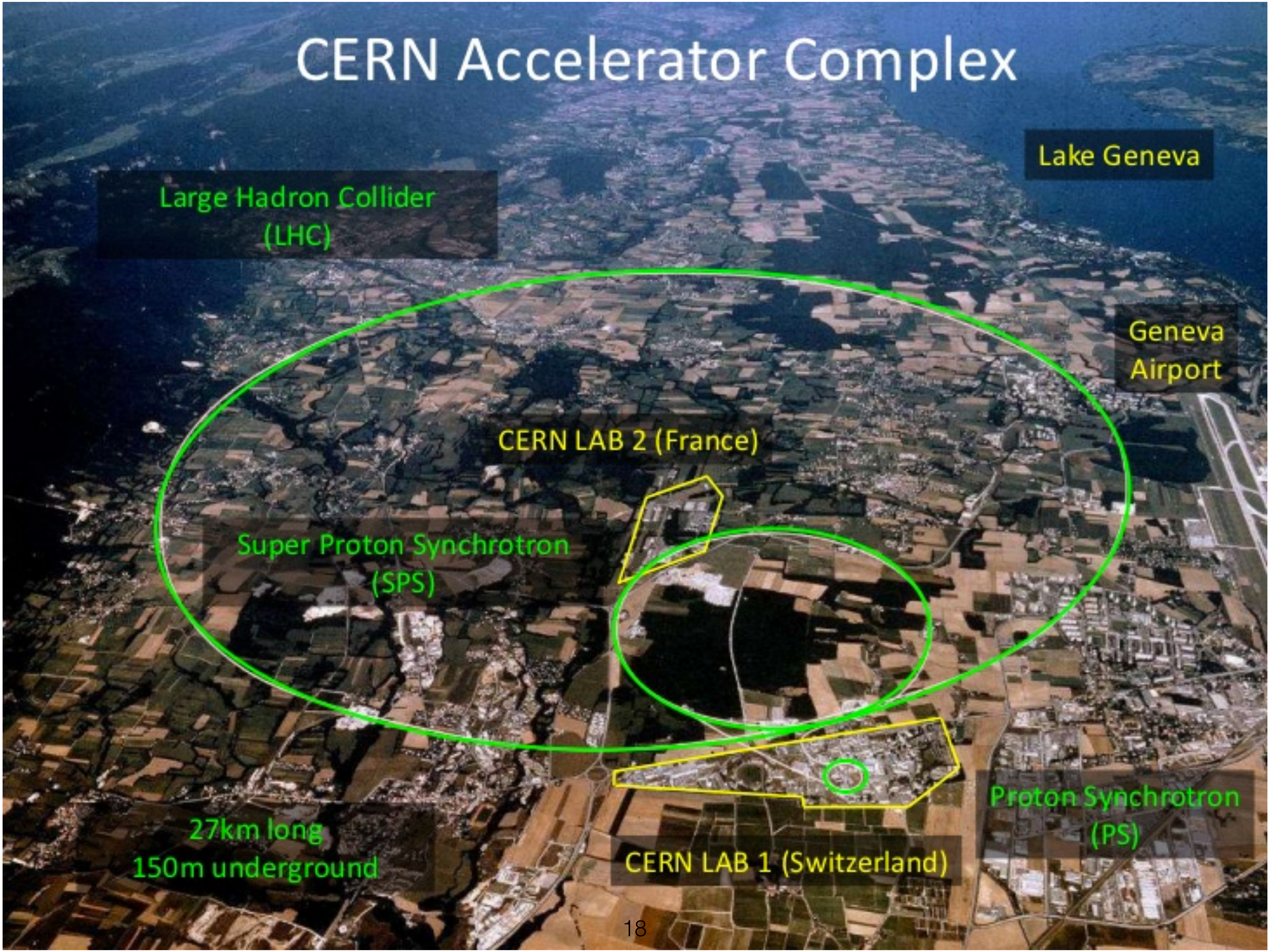


Which type of colliders have been built so far : hadron colliders

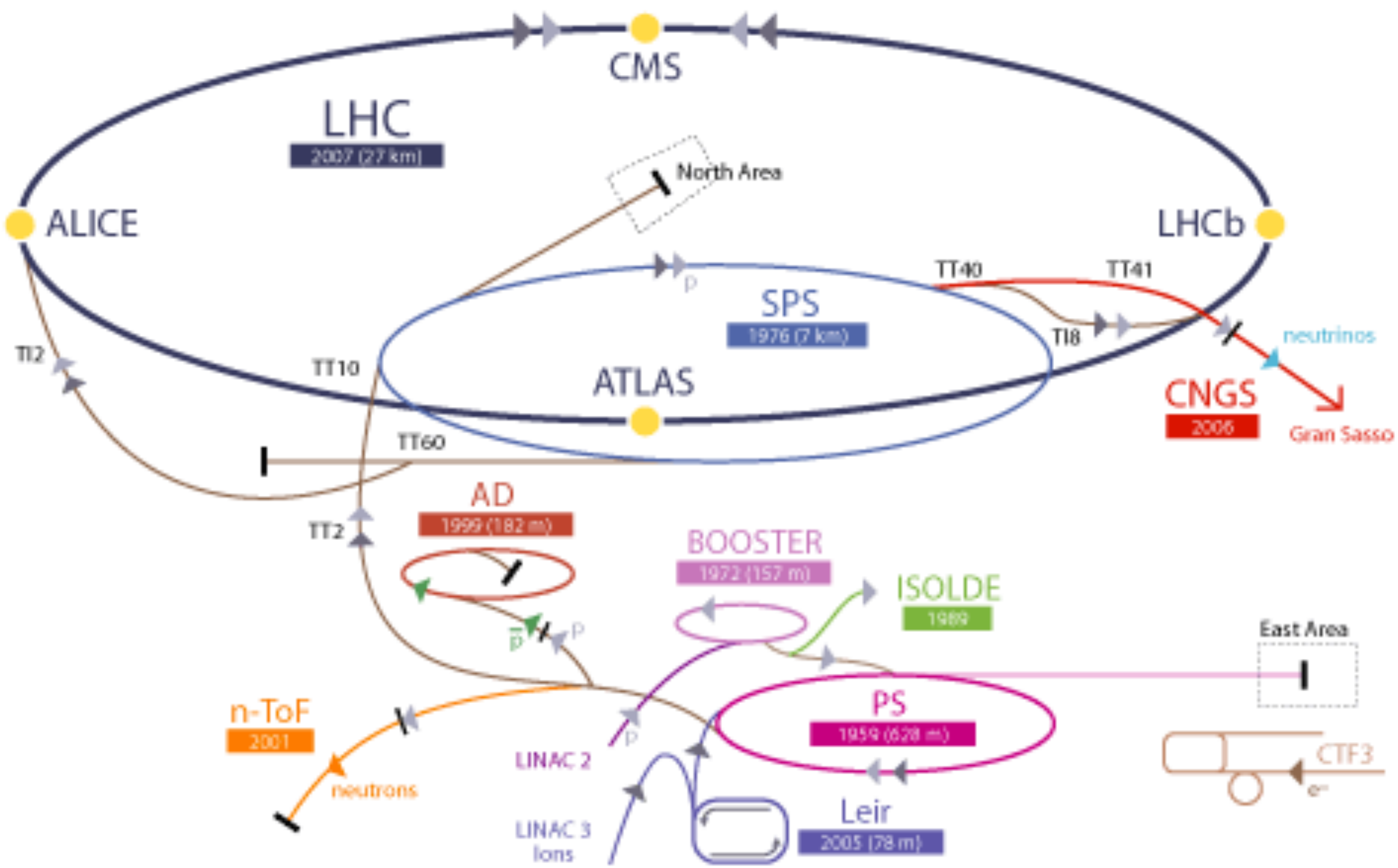


Which type of colliders have been built so far : e+e- colliders




CERN Accelerator Complex
Lake Geneva
Large Hadron Collider
(LHC)
Geneva
Airport
CERN LAB 2 (France)
Super Proton Synchrotron
(SPS)
Proton Synchrotron
(PS)
27km long
150m underground
CERN LAB 1 (Switzerland)

CERN Accelerator Complex



p (proton) ion neutrons p̄ (antiproton) neutrinos electron

proton/antiproton conversion

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility

CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

LHC: fun facts

- The space within the LHC beam pipe is one of the emptiest spaces in the Solar System. In fact, it is an ultra-high vacuum and is as empty as outer space. This is to ensure that the protons do not collide with molecules of gas. The internal pressure is 10^{-13} atmosphere, which is 10 times less than the pressure on the Moon during the day! As the beam pipes are cooled to extremely low temperatures, the gases condense and adhere to the walls of the beam pipe by adsorption. Two weeks are needed to reach 10^{-13} atmosphere.

- In the cryomagnets, insulation vacuum is maintained by cryogenic pumping of 9000 cubic metres of gas. Like pumping down a cathedral.

- Only two nanograms of hydrogen are accelarated each day, which means it would take almost a year for the LHC to accelerate 1 gram of hydrogen.

- The beams throw off billions of stray particles that will heat up anything they hit, and they pass within about a centimeter of thousands of superconducting magnets that have to be kept colder than the vacuum of outer space. If stray particles damage the magnets, the collider could be forced to shut down for weeks, months, or more

- When two beams of protons collide, they will generate temperatures more than 100,000 times hotter than the heart of the sun, concentrated within a miniscule space.

LHC: fun facts

- The LHC can be called the world's largest fridge, because the thousands of magnets within the accelerator are pre-cooled to -193.2°C (80 K) using 10,080 tons of liquid nitrogen, after which they are filled with more than 60 tons of liquid helium to further cool them down to -271.3°C (1.9 K).

- When this amazing machine operates in full power, trillions of protons race around the circumference of the tunnel 11,245 times a second, at a speed that is 99.9999991% of the speed of light, which is equivalent to 671,000,000 mph!

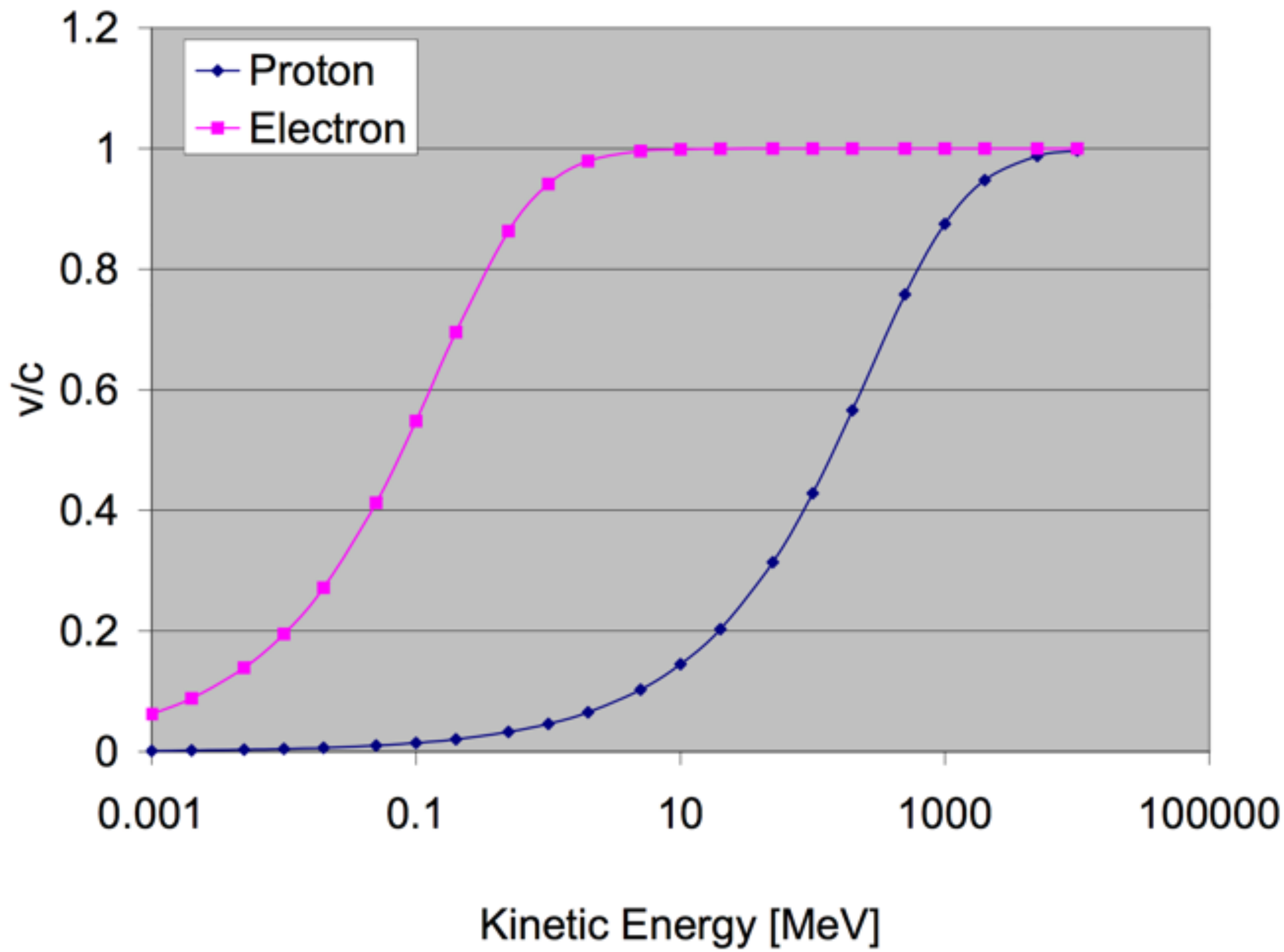
- The cost of building the LHC was estimated around USD 4.1 billion. Not only this, it has a running budget of approximately USD 1 billion per year, which makes it one of the most expensive scientific instruments ever built. Still, it costs less than what US spends in a few weeks of military operations in Middle East.

CERN accelerator complex

- to achieve stable beams at 13 TeV in the LHC, it is necessary to have a set of accelerators bringing the particles slowly up from 0 to the nominal energy.

- the pre-existing accelerators needed only minor modifications to achieve nominal LHC beams energy.

- no single machine to achieve the same. CERN is a unique place in the world for this.



This has important implications for the type of acceleration scheme that is appropriate for protons, wrt electrons. Electrons at the source already are relativistic. Protons are not.

PS, SPS and LHC require different components functionality for accelerating and keeping in orbit

The Synchrotron (circular collider)

- The bending field changes with particle beam energy to maintain a constant radius:

$$\frac{1}{\rho[m]} = 0.3\frac{B[T]}{\beta E[GeV]} = 0.3\frac{B[T]}{cp[GeV]}$$

- So B ramps in proportion to the momentum. The revolution frequency also changes with momentum.
- The synchronicity condition, including the relativistic mass, is:

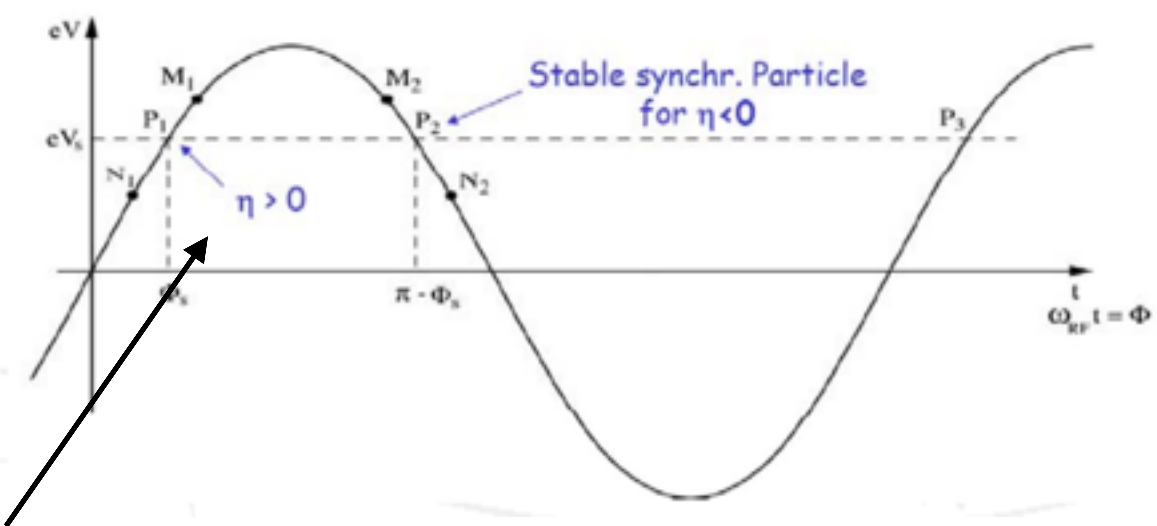
$$\omega = \frac{qB}{m\gamma}$$

- For an electron synchrotron, the injected beam is already relativistic **at source,** so only the magnetic field changes with beam energy.
- For a proton synchrotron, the injected beam is not yet relativistic **at source, so** the RF accelerating frequency and the magnetic field both ramp with energy.

acceleration

- Summary: to ramp up the energy in a synchrotron
  - Simply ramp up the magnetic field (bending units) while RF increases (E increases)
  - With the (automatic) RF frequency modulation the synchronous particle will stay on the reference orbit (keep right E)
  - Due to the phase-stability, the particles in the phase-space vicinity of the synchronous particle will be captured by the RF and will also be accelerated at the same rate, undergoing synchrotron oscillations (stay close to the desired energy)

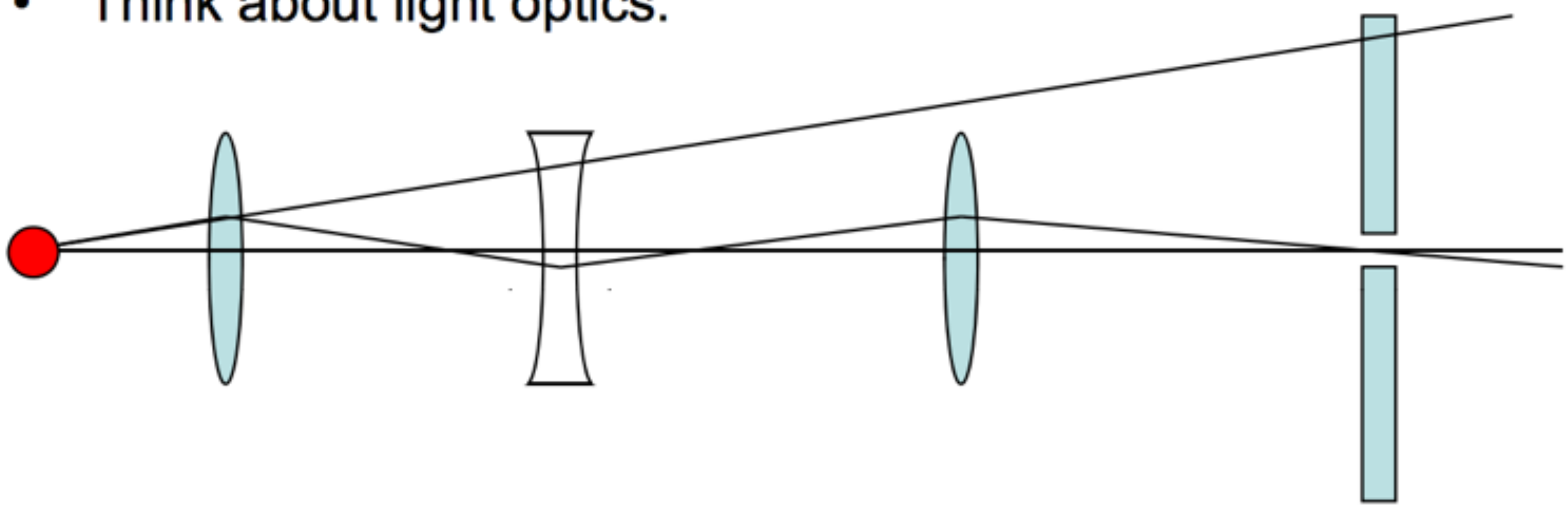
- For a momentum increase dp/p:
  - $\eta>0$: velocity increase dominates (f_r increases)
  - $\eta<0$: circumference increase dominates (f_r decreases)



P1 Synchronous particle stable for $0° < \phi_s < 90°$ **(ϕs = phase of the RF field)**
- A particle N_1 arriving early with $\phi = \phi_s - \delta$ will get a lower energy kick, and arrive relatively later next pass
- A particle M_1 arriving late with $\phi = \phi_s + \delta$ will get a higher energy kick, and arrive relatively earlier next pass

Particle Beam Focusing

- Suppose two particles start the acceleration process. One has exactly the correct energy, position and angle, so that it is properly accelerated. The accompanying particle has slightly different starting parameters. We need some way of ensuring that non-perfect particles are also accelerated.
- Think about light optics:



- This concept was first applied to particle accelerators by Courant, Livingston, and Snyder.
- It is known as "Strong Focusing" or "Alternating Gradient Focusing".
- "Optical" magnetic elements provide focusing

LHC filling scheme

Nominal LHC filling scheme:

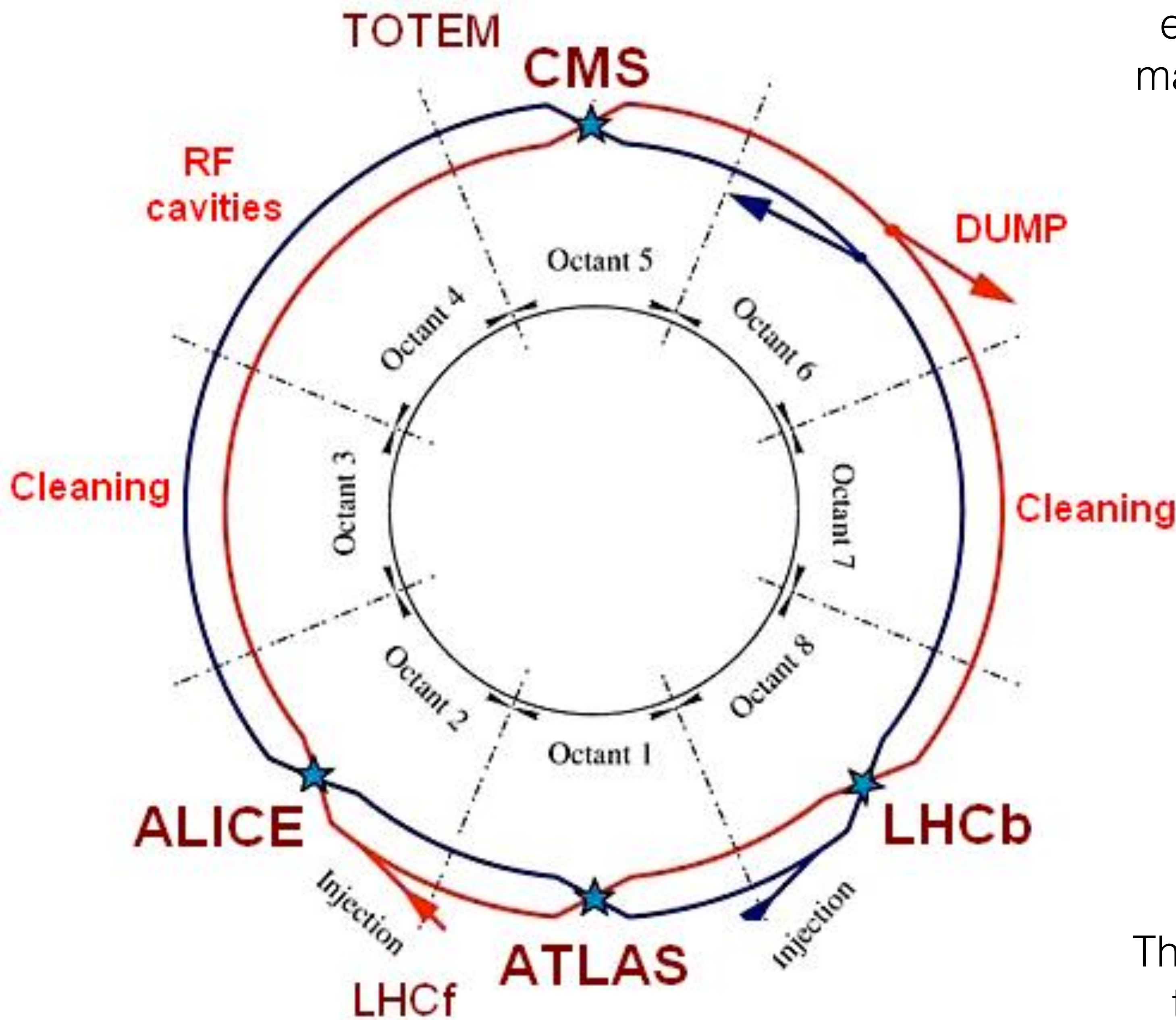
- $N=1.15\times10^{11}$ p/bunch,
- 4x72 bunches/ per train
- $\varepsilon_N=3.75\mu m$
- $\beta^*=55cm$

$L_{peak}=10^{34}cm^{-2}s^{-1}$

27 km, 2760 bunches

LHC

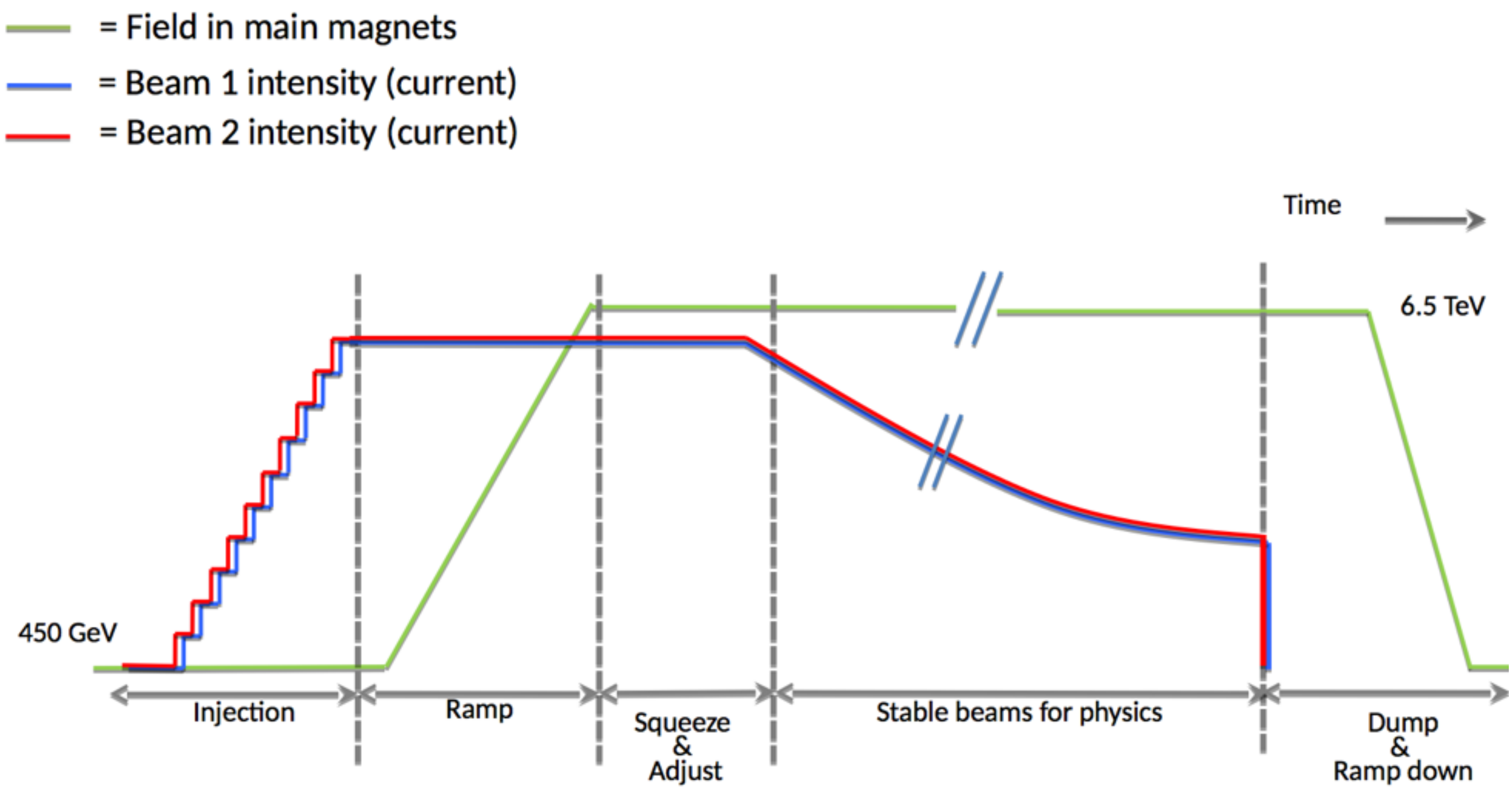
eight arcs (~3 km long) and eight straight 'insertions' (~ 0.5 m long).



The arcs contain the dipole 'bending' magnets, with 154 in each arc. Each arc contains 23 arc cells, and each arc cell has a FODO structure (main dipole magnets + quadrupole magnets + other multipoles magnets), 106.9 m long.

The exact layout of the straight section depends on the specific use of the insertion: physics (beam collisions within an experiment), injection, beam dumping or beam cleaning.

LHC Operational Cycle



Typical times for a good cycle in 2018:

~1 hour 20min 1/2 hour ~12 hours ~1 hour

LHC limitations

- lifetime limitation :
  - beam loss from collisions is main loss

initial beam intensity
1.15 10^11 p

$$\tau_{\text{nuclear}} = \frac{N_{\text{tot},0}}{L\sigma_{\text{tot}}k}$$

=44.85 h

K=2 for
two high lumi
IP

10^34 cm-2 s-1

10^25 cm2 @ 14 TeV

$$N_{\text{tot}}(t) = \frac{N_{\text{tot},0}}{1+t/\tau_{\text{nuclear}}}$$

$$L(t) = \frac{L_0}{(1+t/\tau_{\text{nuclear}})^2}$$

10^34 cm-2 s-1

$L=L_0/e$ at t=29 h

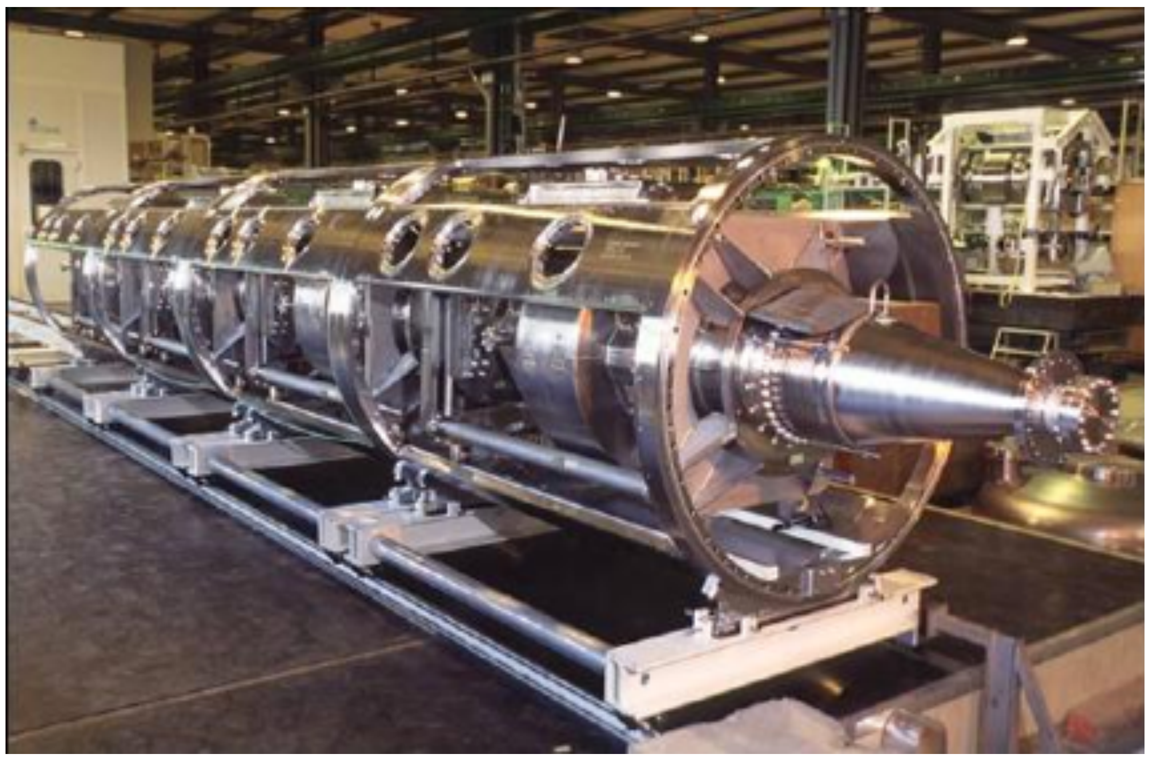
LHC limitations

- lifetime limitation :
  - the scattering of particles on residual gas
  - IBS scattering

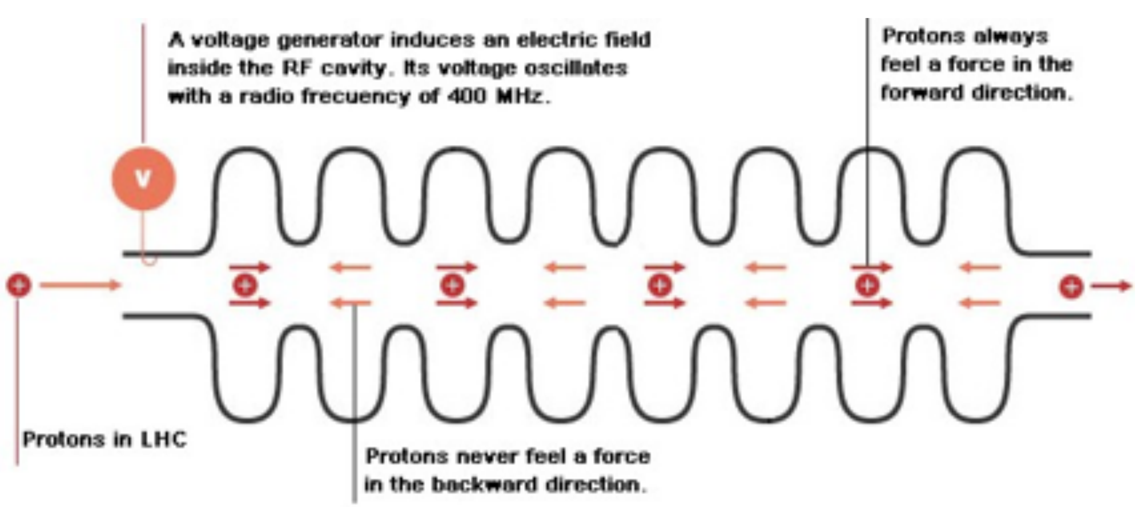
$$\frac{1}{\tau_L} = \frac{1}{\tau_{\rm IBS}} + \frac{1}{\tau_{\rm rest\,gas}} + \frac{1}{\tau_{{\rm nuclear},1/e}}$$

$$\tau_L = 14.9\ h.$$

RF cavities : acceleration



A particle exactly synchronised with the RF frequency is called synchronous particle. All the other particles in the accelerator will oscillate longitudinally around the synchronous particles under the influence of the RF system. This means that instead of being spread uniformly around the circumference of the accelerator the particles get "clumped" around the synchronous particle in a BUNCH. This bunch is contained in an RF bucket.



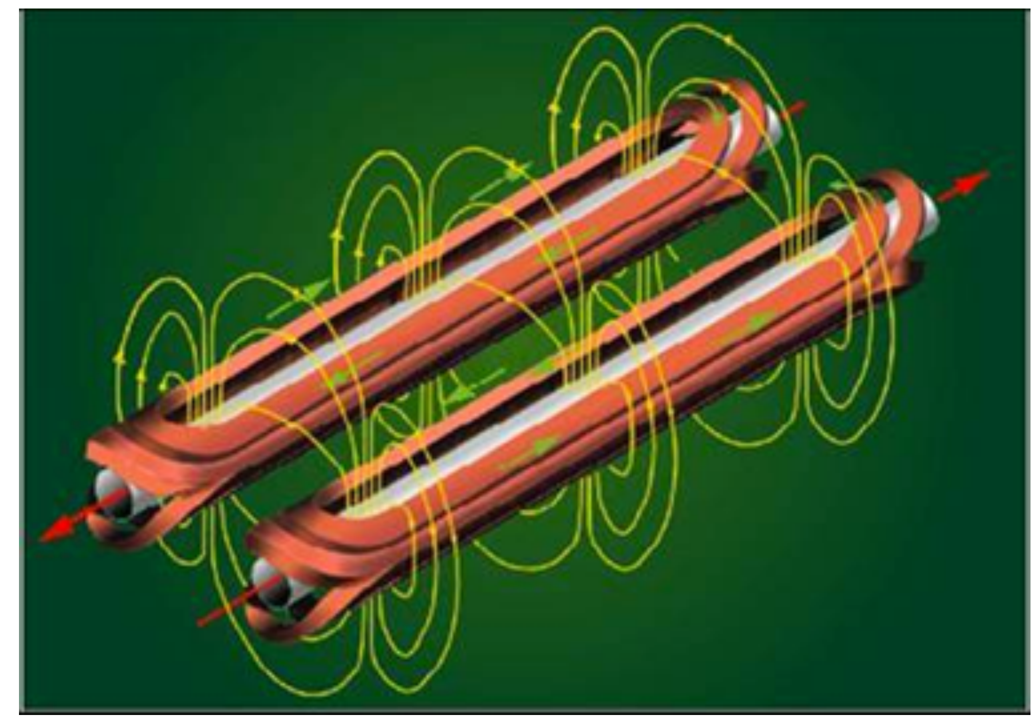
$h = f_{RF}/f_{rev} = (400 \cdot 10^6\ \mathrm{Hz})/(c/26659\ \mathrm{m}) = 35640$ RF buckets (points where synchronous particle sees a accelerating voltage)

Superconducting cavities with small energy losses (synchrotron radiation) and large stored energy : they keep particles bunched and they give power during acceleration

temperature 4.5 Kelvin

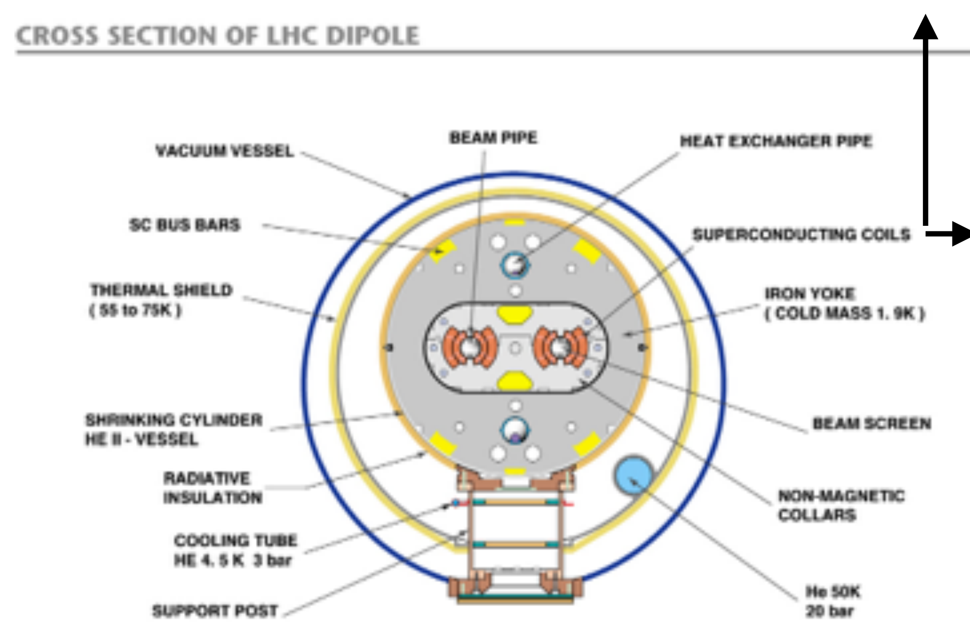
Dipole magnets: bending

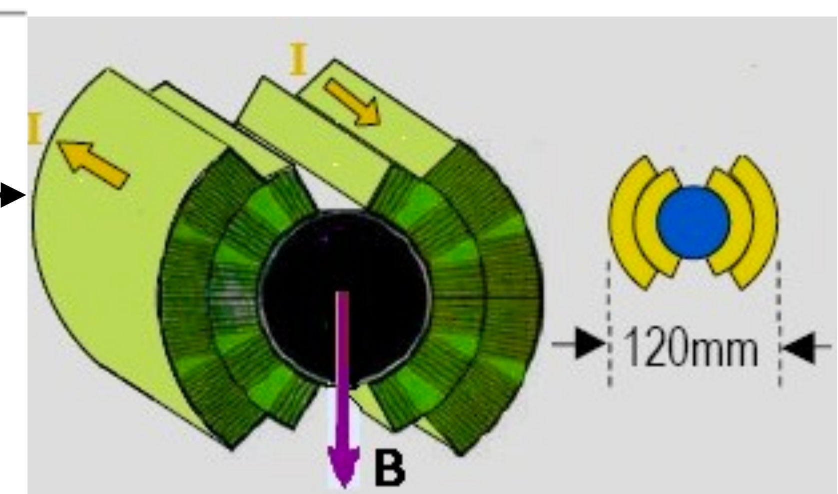
The dipolar magnetic field is created for superconductive currents which circulate on each side of the pipe by where the protons travel. The wiring is arranged in individual double layers around each tube



160 superconducting cables,
6500 superconducting filaments of Niobium-titanium

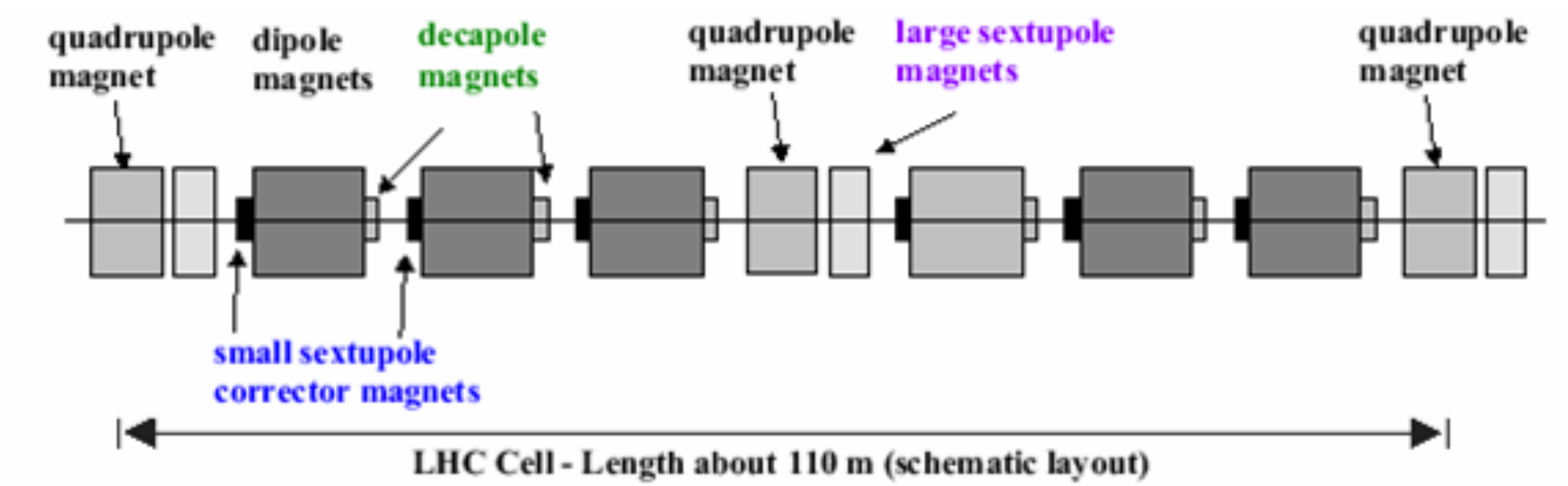
the total superconducting length in the 1232 dipoles (2 tubes per dipole): $1{,}38\cdot10^{12}$ m = 10 times the distance Earth-Sun

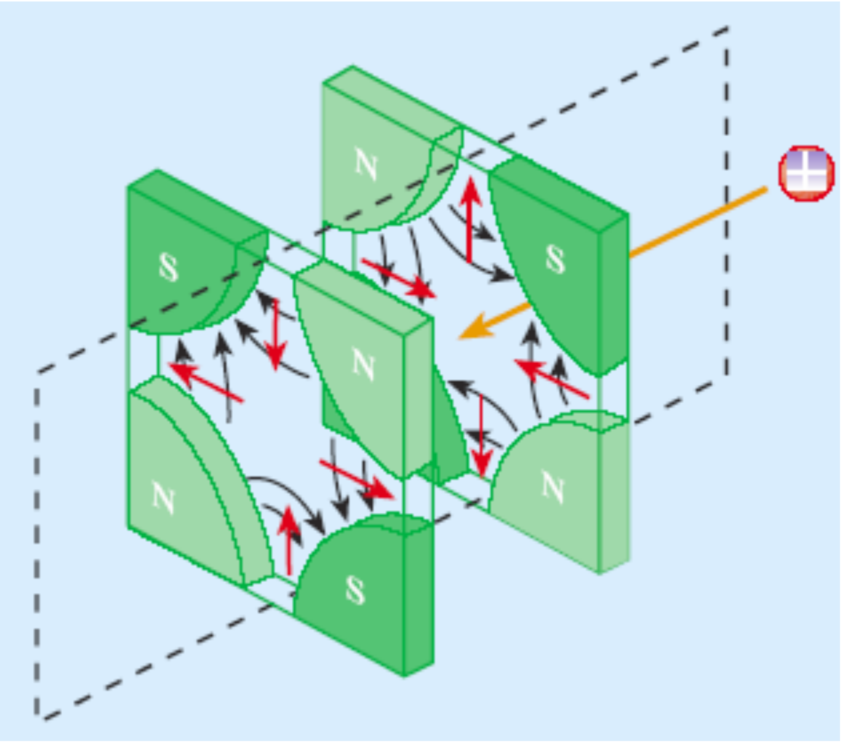




temperature 1.9 Kelvin

Quadrupole magnets: focusing





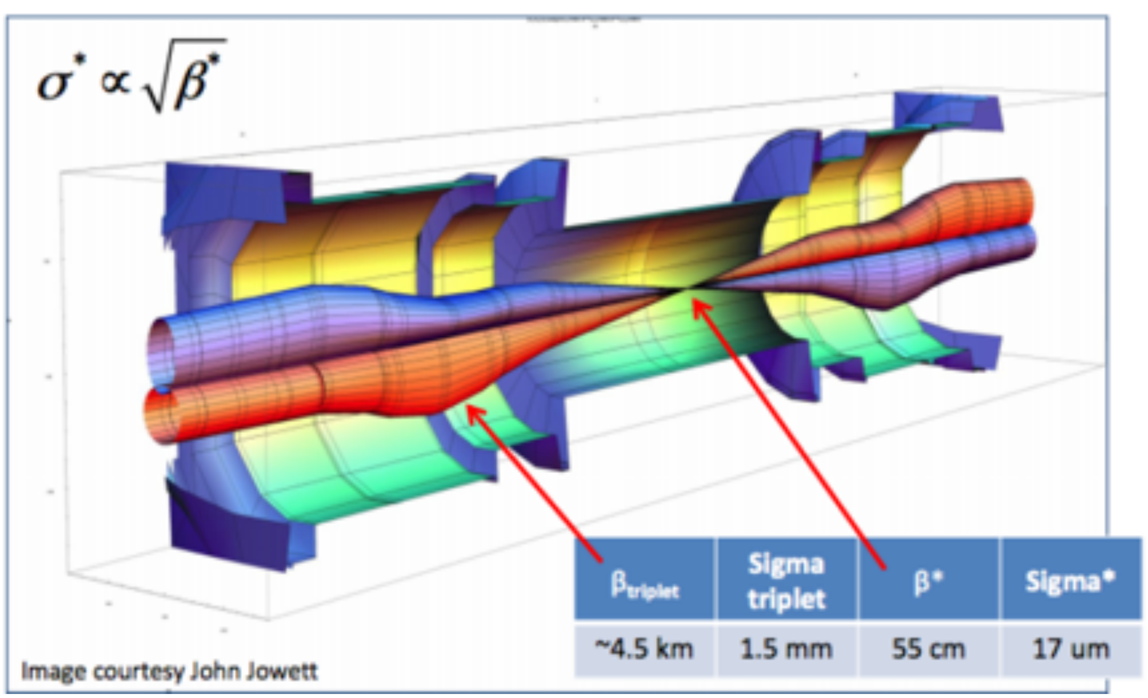
858 quadrupole magnets in the LHC

2808 bunches per beam and a very high intensity (1.15×10^{11} protons per bunch); this requires 9300 superconducting magnets of different types http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/components/magnets/types_of_magnets.htm

Triplet magnets near IP: collisions

"inner triplet" , final focusing, superconducting magnets in the LHC. Their job is to focus the particle beams into the four areas where particles will collide. The size of bunches passes from 0,2 mm to 16 micrometers at the Interaction Points (IP):

- at IP (ATLAS, CMS) 16 μm
- in the triplets ~1.6 mm
- in the arcs ~0.2 mm

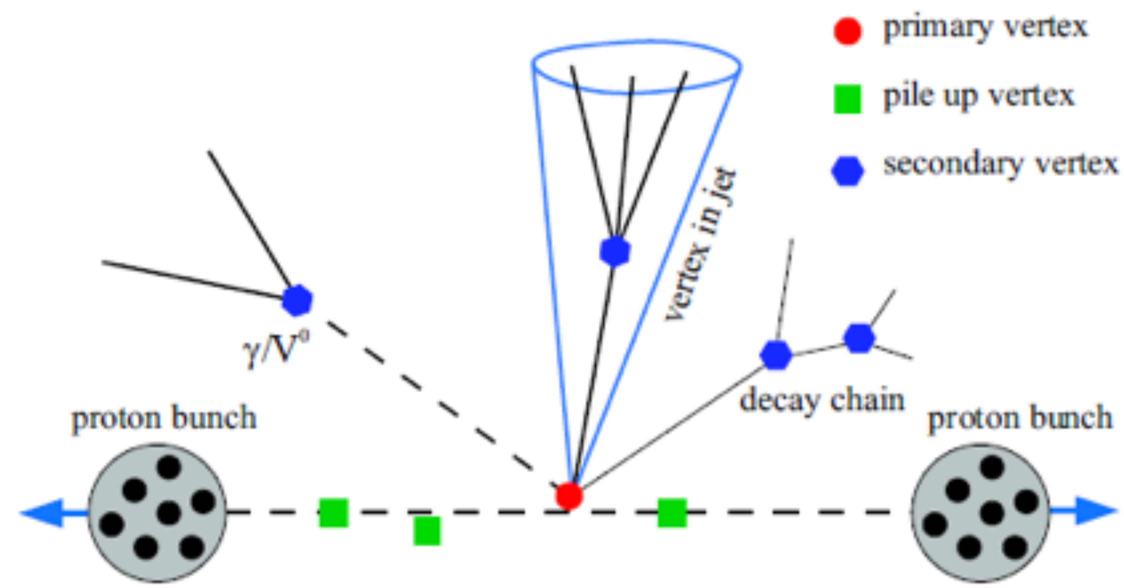


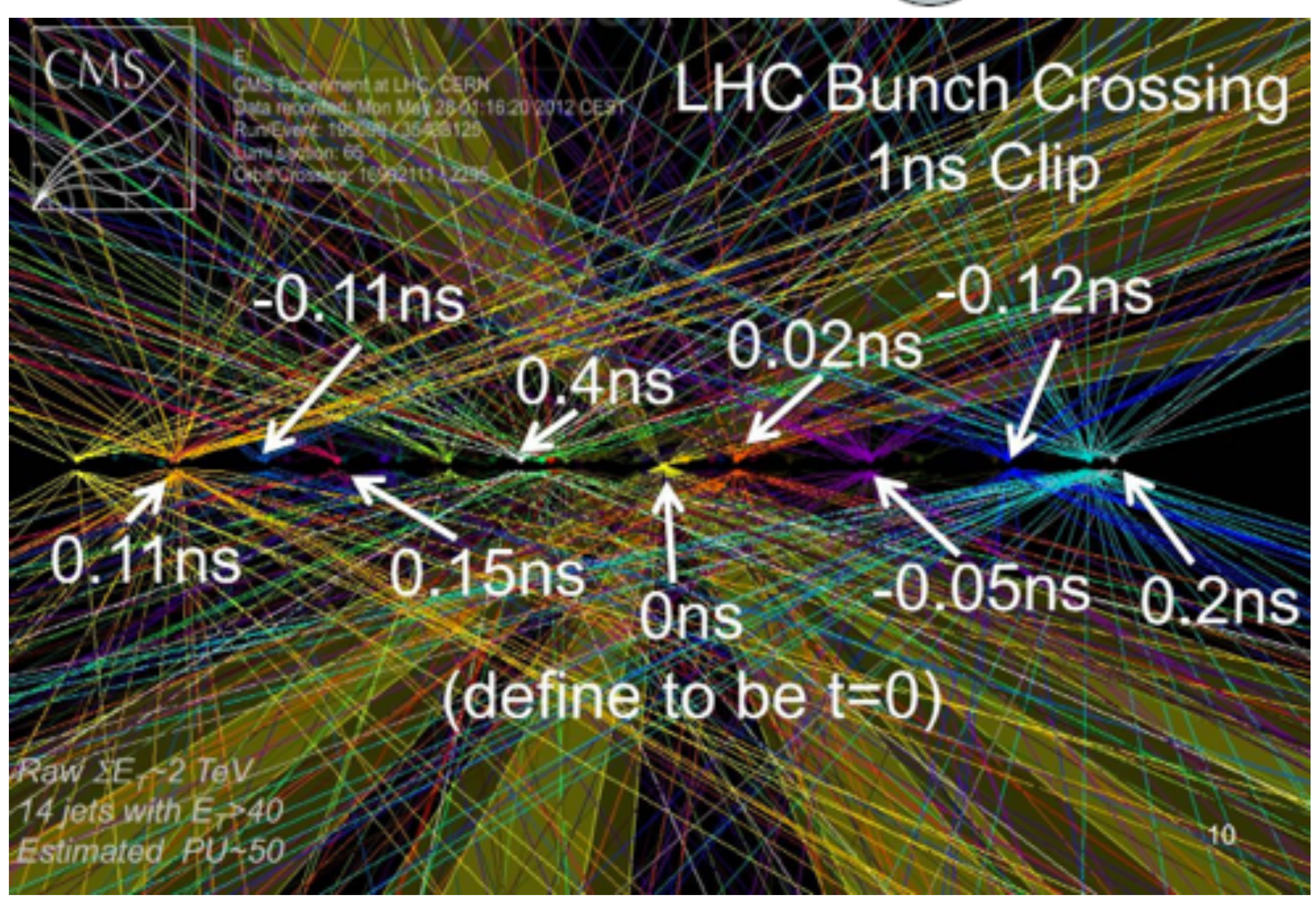
Pile-up

bunch collision rate
= #bunches/beam x revolution frequency

#events per bunch crossing
= cross section x luminosity / bunch collision rate

nominal #events per bunch crossing in the detector
= 8.5×10^{-26} cm^{2} 10^{34} cm^{-2}s^{-1} / (32×10^{6} s^{-1})
= 27

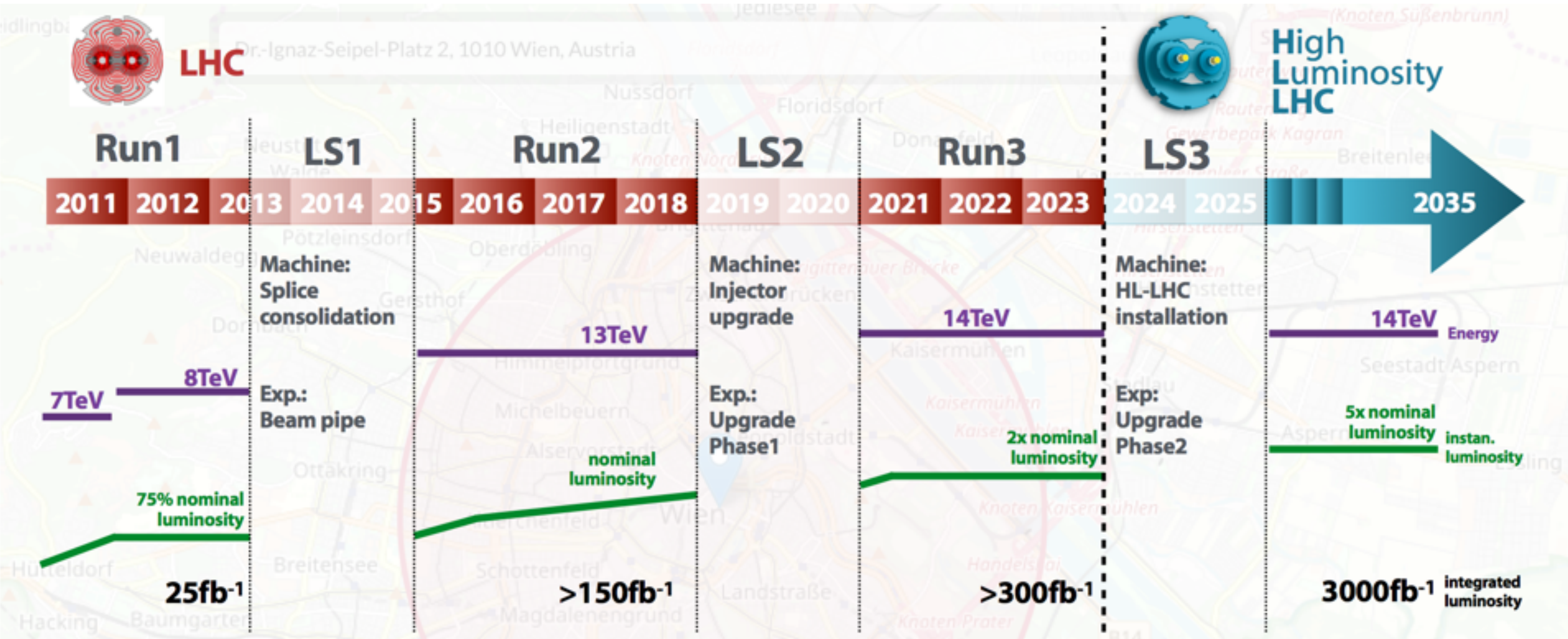




LHC Parameters Achieved in 2018

Parameter	2018	Design
Energy [TeV]	**6.5**	7.0
No. of bunches	**2556**	2808
Max. stored energy per beam (MJ)	**312**	362
β* [cm]	**30→25**	55
p/bunch (typical value) [10^{11}]	**1.1**	1.15
Typical normalized **emittance** [μm]	**~1.8**	3.75
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	**2.1**	1.0

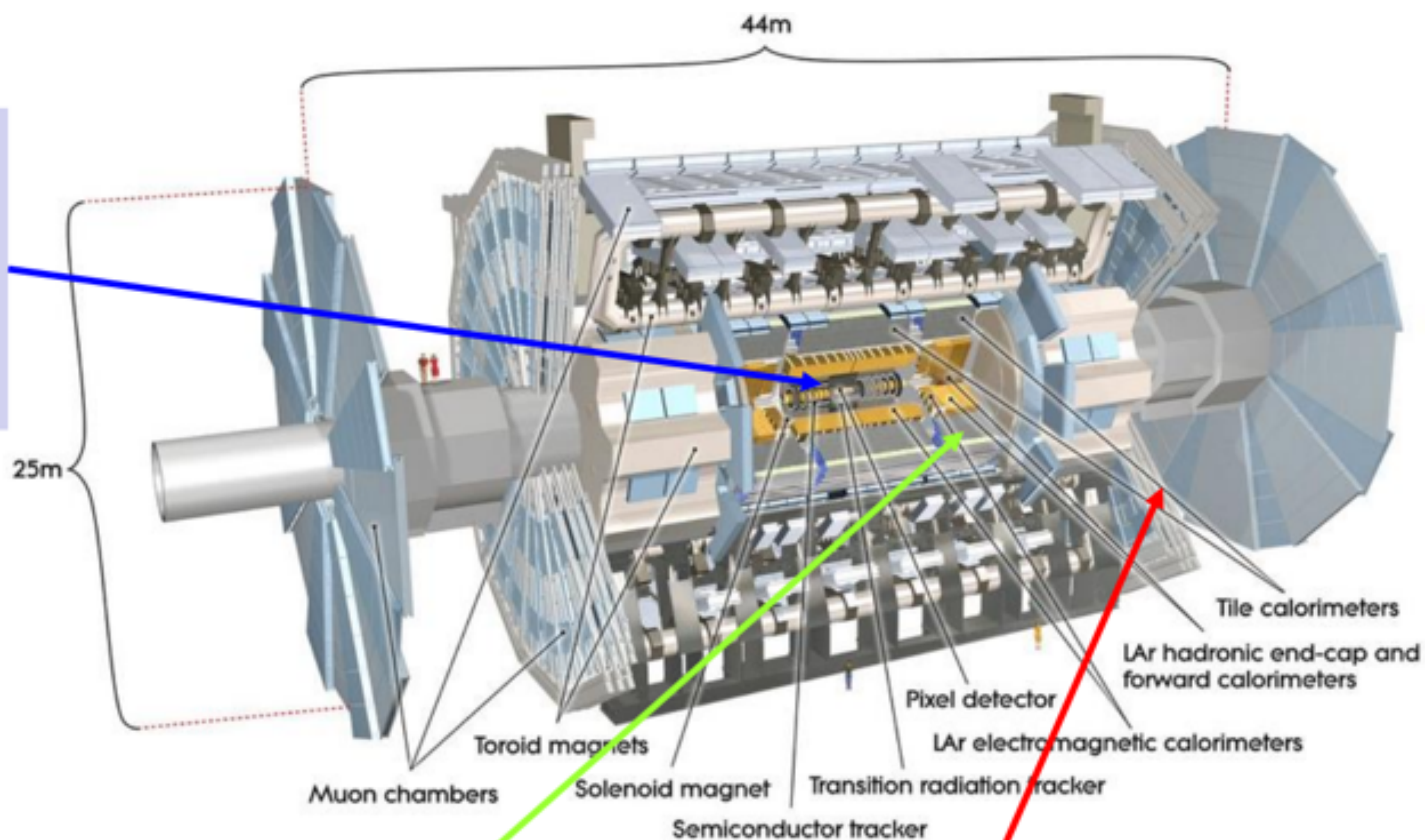
LHC timeline



ATLAS

Inner Detector

- Silicon Pixel Detector (PIX)
- Silicon Strip Detector (SCT)
- Transition Radiation Tracker (TRT)

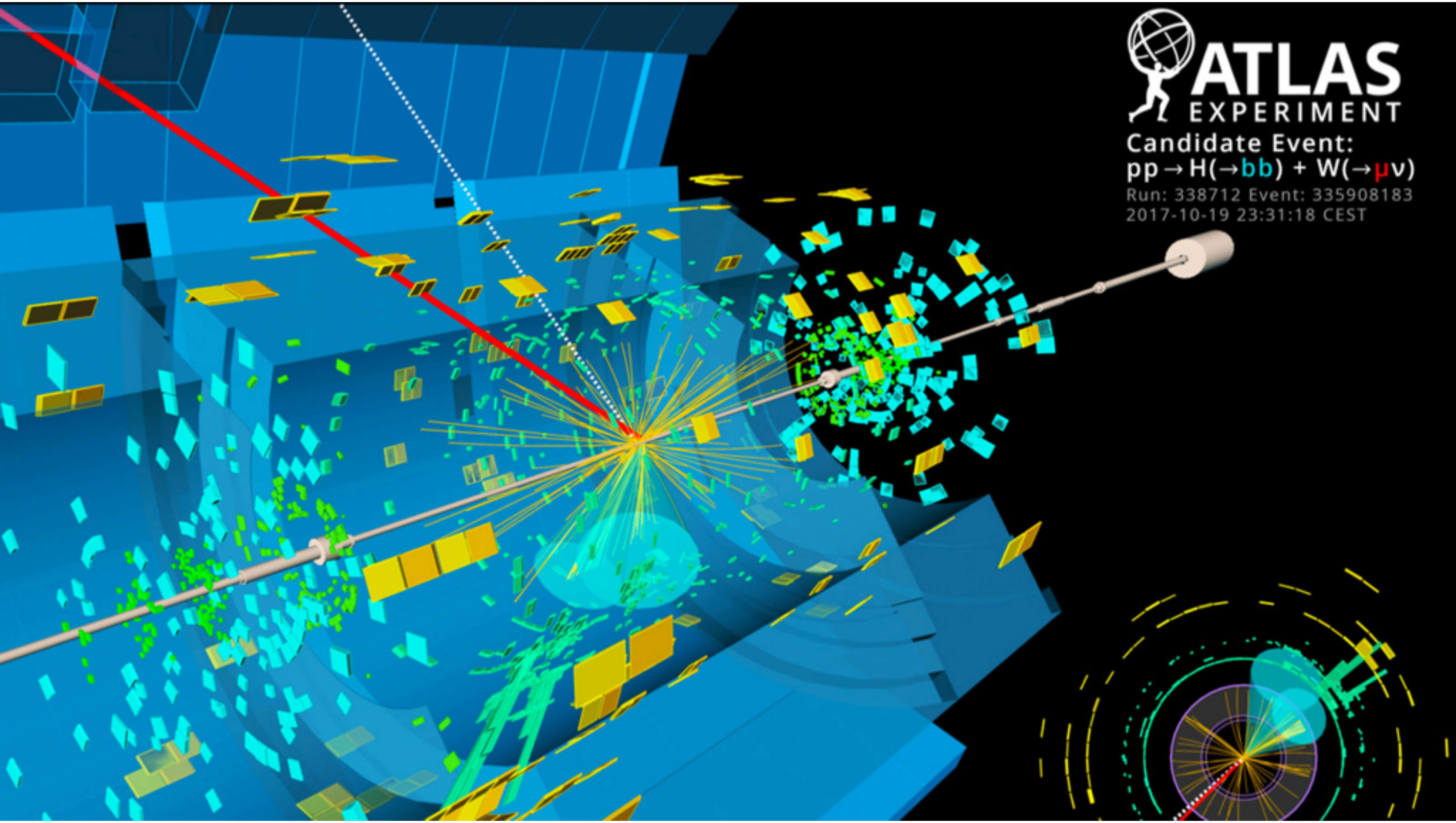


Calorimeter

- Liquid Argon: EM + had EC calorimeter (LAr)
- Fe/Scintillator hadronic Tile calorimeter (TILE)

Muon Spectrometer

- Monitored Drift Tubes (MDT)
- Resistive Plate Chambers (RPC)
- Thin Gap Chambers (TGC)
- Cathode Strip Chambers (CSC)


ATLAS
EXPERIMENT
Candidate Event:
pp → H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

LHC event rate

The probability of one particular proton in a bunch coming from the left hitting a particular proton in a bunch coming from the right depends roughly on the rate of proton size **(d^2 with d~1 fm)** and the cross-sectional size of the bunch (σ^2, with σ =16 microns) in the interaction point.

Then:

$$\textbf{Probability} \approx (d_{proton})^2/(\sigma^2) \Rightarrow \textbf{Probability} \approx (10^{-15})^2/(16\cdot10^{-6})^2 \approx 4\cdot10^{-21}$$

But with **$1{,}15\cdot10^{11}$ protons/bunch** a good number of interactions will be possible every crossing.

Now, the number of interactions will be:

Probability x N^2 (with N = number of protons per bunch)

So, **$(4\cdot10^{-21})$ x $(1{,}15\cdot10^{11})^2$ $\Rightarrow$ ~ 50 interactions every crossing**

But just a fraction of these interactions (~50 %) are inelastic scatterings that give rise to particles at sufficient high angles with respect to the beam axis.

Therefore, there are about 20 "effective" collisions **every crossing**.

With 11245 crosses per second we get:

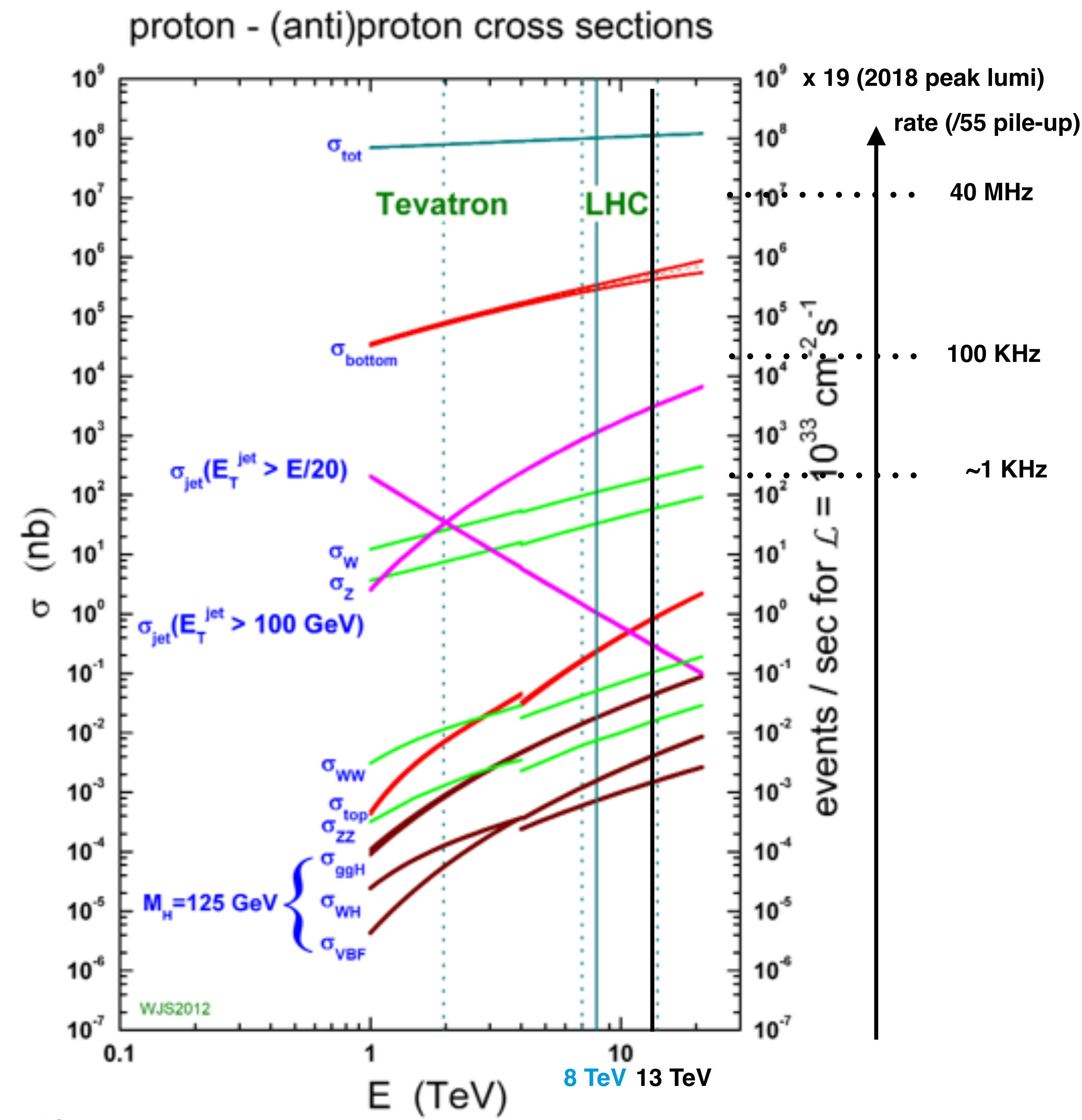
11245 x 2808 = 31,6 millions crosses , the *"average crossing rate"*.

($31{,}6\cdot10^6$crosses/s) x (20 collisions/cross) $\Rightarrow$ 600 millions collision/s

If we consider 3550 bunches: 11245 **x** 3550 = 40 millions crosses $\Rightarrow$ **40 MHz**

Why do we need a trigger?

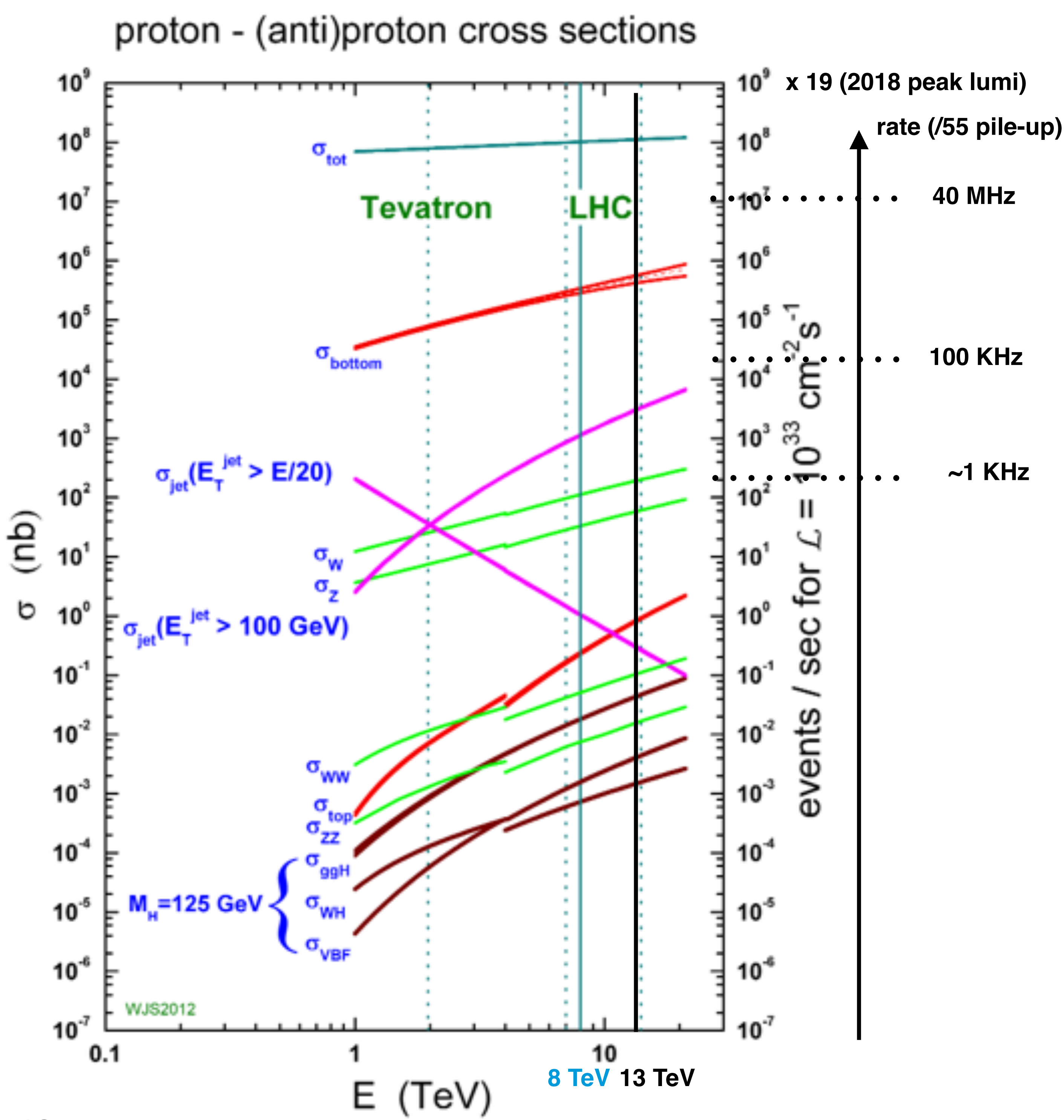
- 40 MHz bunch crossing rate (1 BC every 25 ns when LHC is full). ATLAS sees “bunches of collisions” (eg in 2018 ~ 55 proton-proton scatterings at start of a run)
- 1.3 MBytes ~ size of one event at start of a run in 2018
- 52 TBytes/sec
- Even if one could build a very costly and complex system to assemble, reconstruct and store to disk basic data objects for every event, why would we do that?



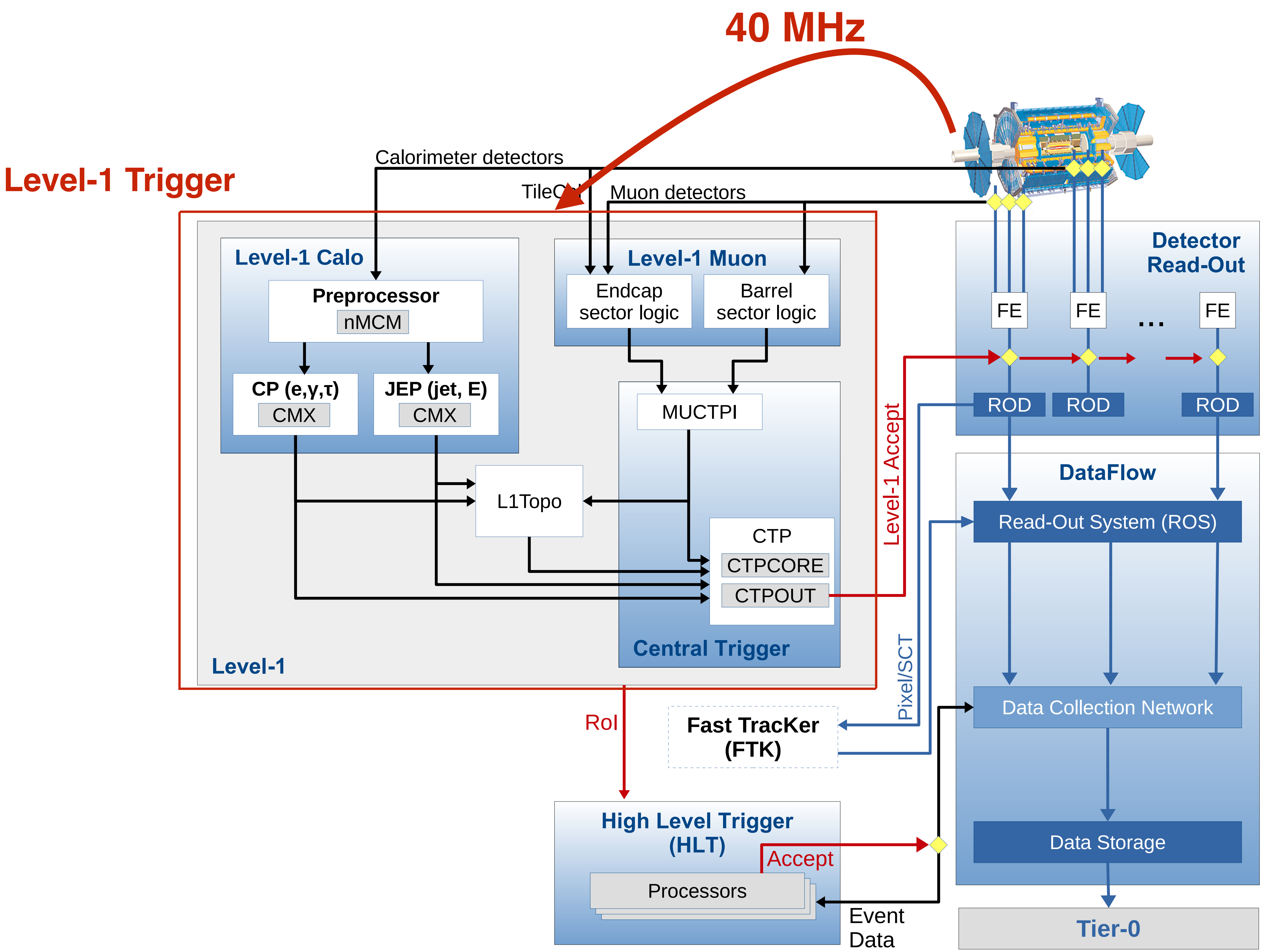
Why do we need a trigger?

pre-LHC
unobserved new physics phenomena
(Higgs, SUSY, exotica,….)
or processes poorly measured
(Z,W top cross sections)
lie in the lower part of this plot.
No need to save all data!

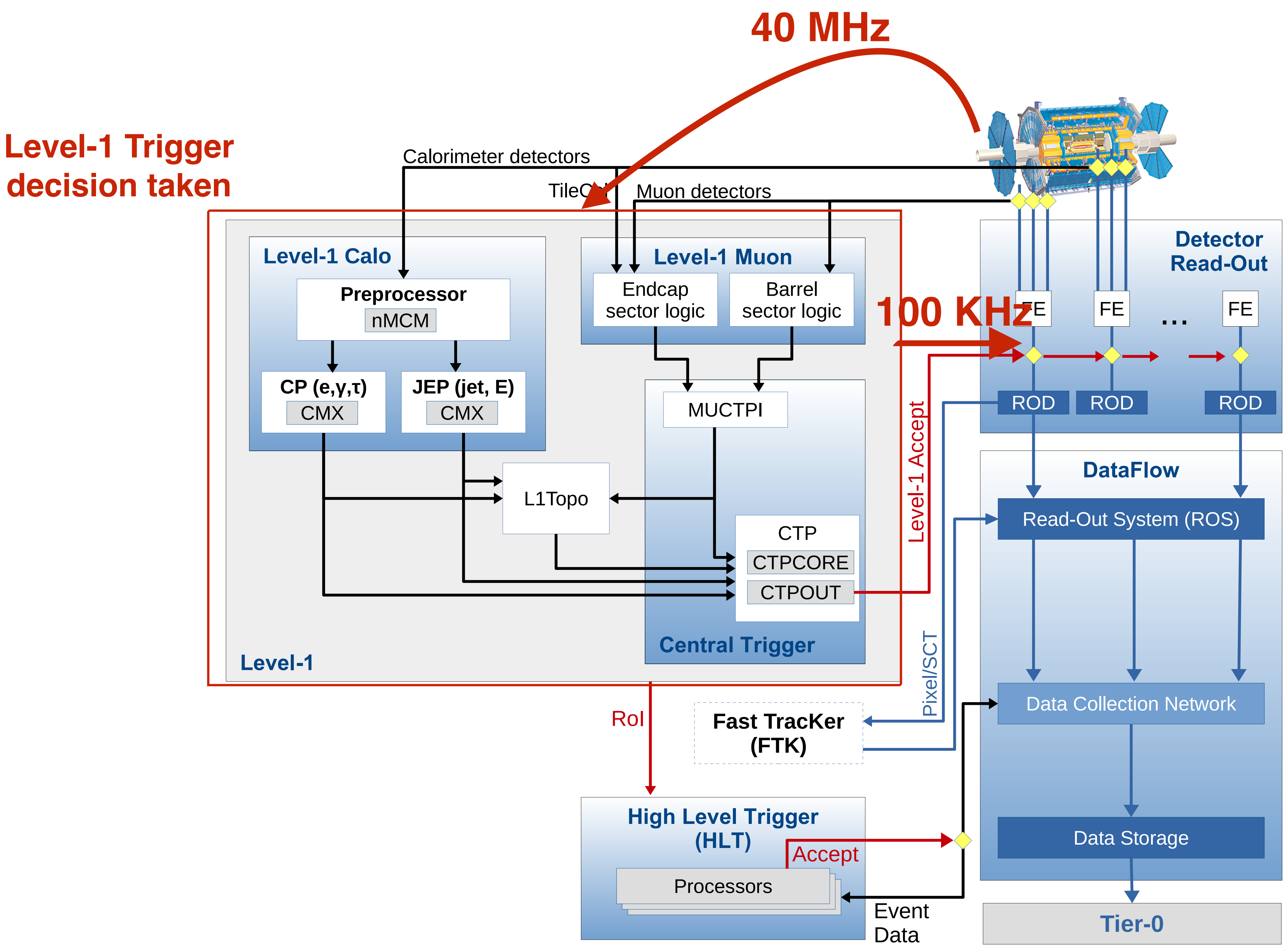
The goal of the trigger system
is to run real-time analysis
of the data and decide
what to keep and
what to throw away.



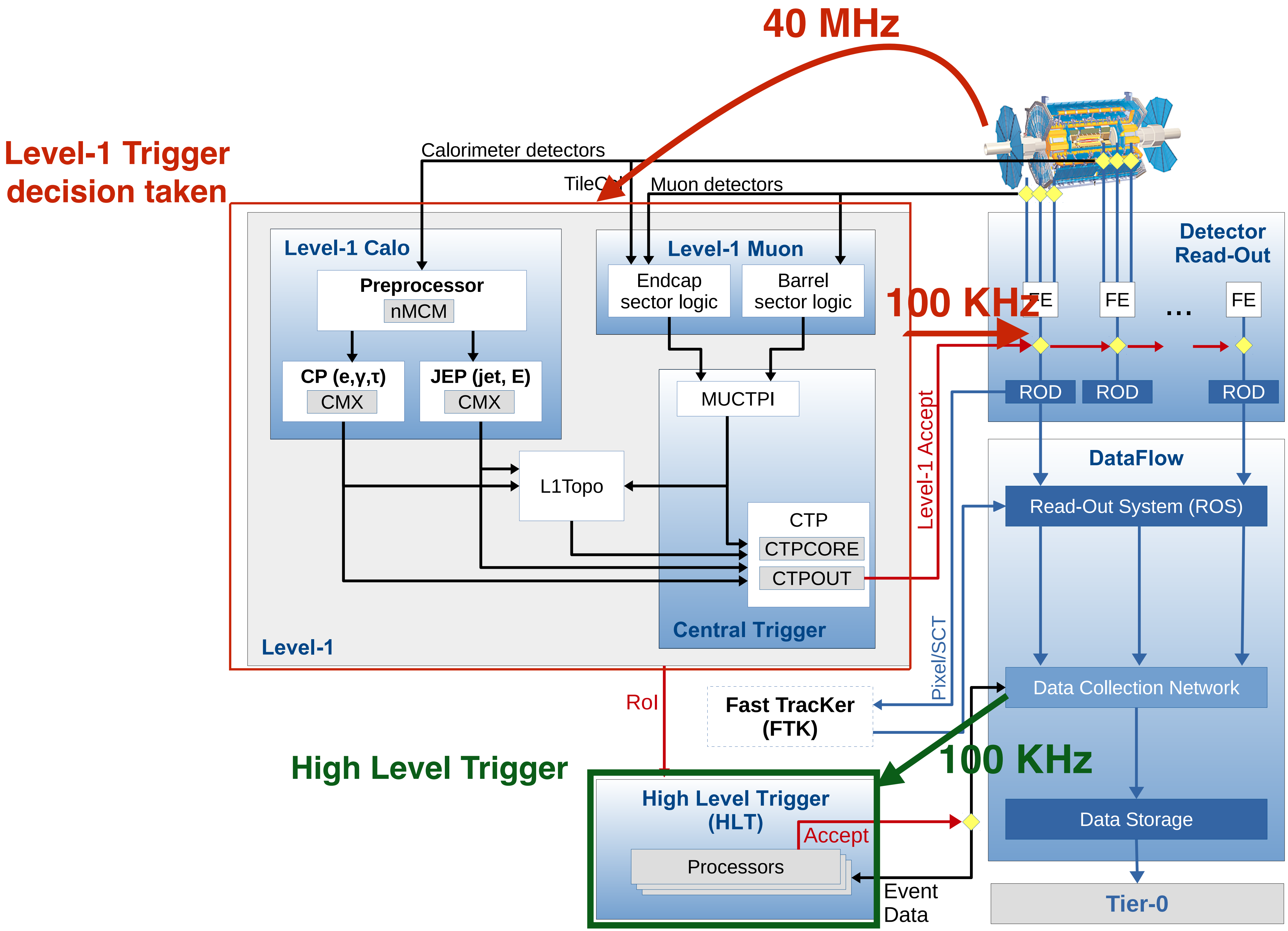
The data path



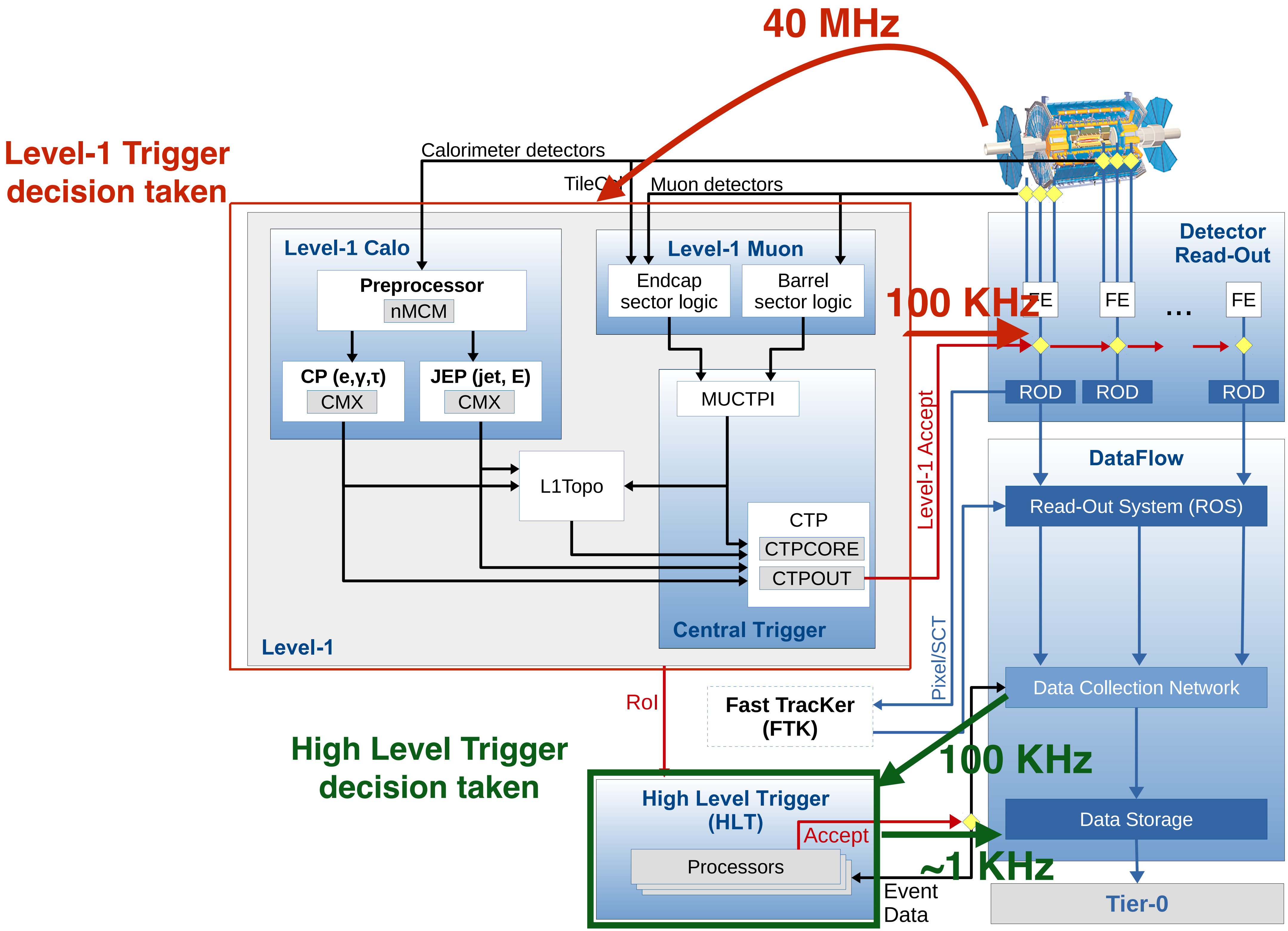
The data path



The data path



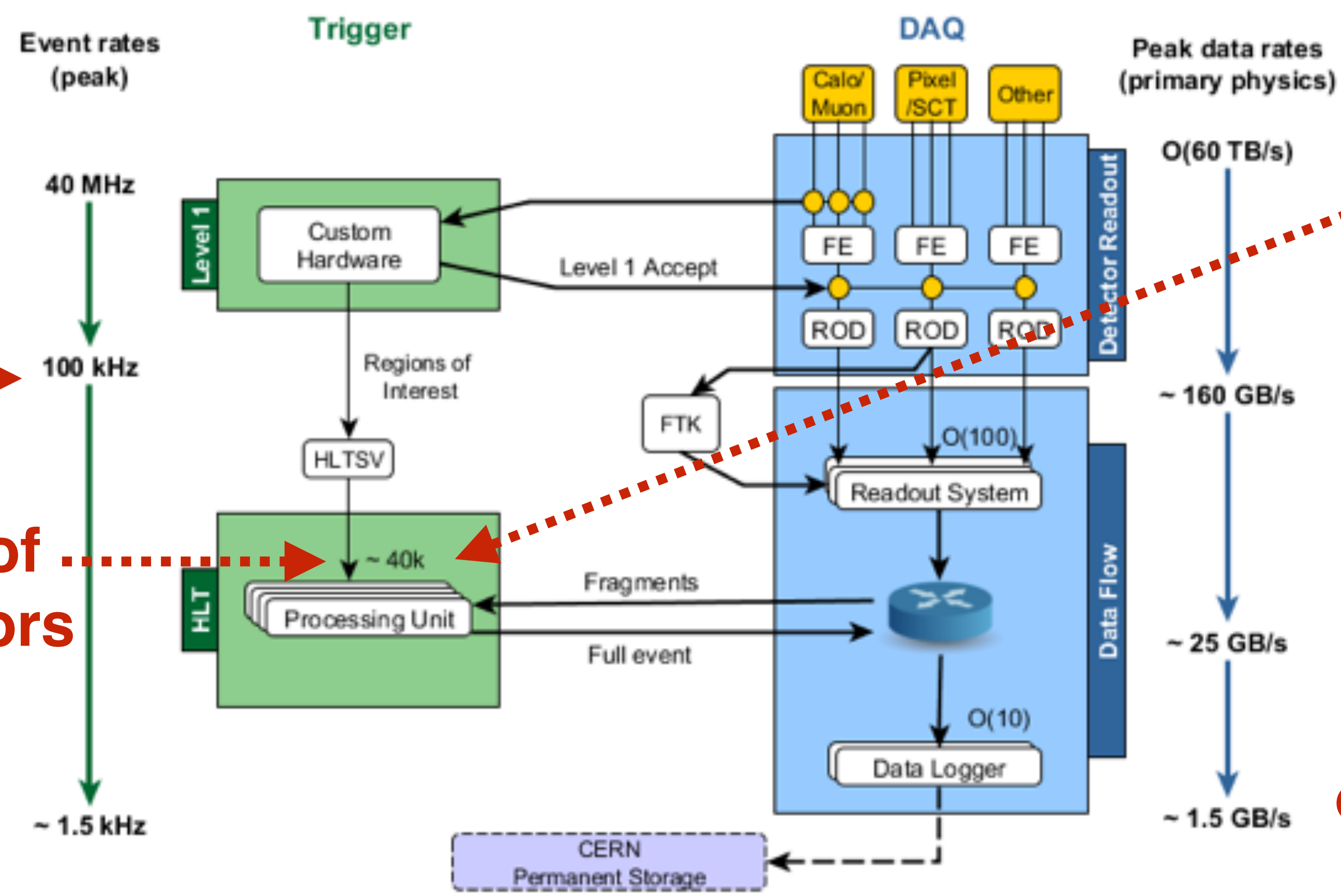
The data path



Constraints on the trigger

detector read-out speed

amount of processors



speed/memory of processors (~400 msec to process one event @ HLT at pile-up 55)

output data speed

storage space available (10 PetaBytes/year)

our imagination

$$$ money

Which triggers do we run ?
Main physics stream

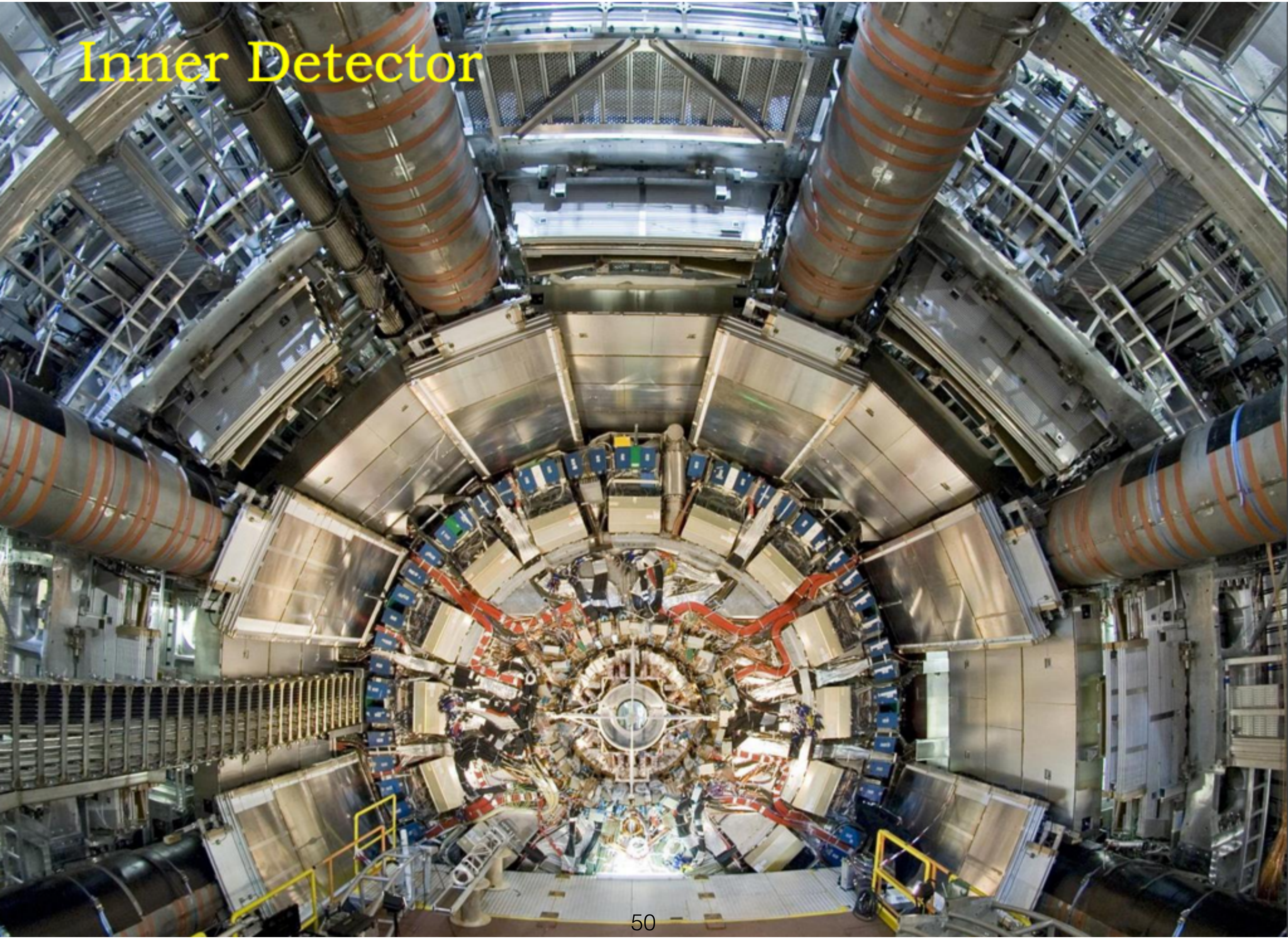
Trigger	Typical offline selection	Trigger Selection		Level-1 Peak Rate (kHz)	HLT Peak Rate (Hz)
		Level-1 (GeV)	HLT (GeV)	$L = 1.7 \times 10^{34}$ cm^{-2}s^{-1}	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	16	187
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	26	178
	Single μ, $p_T > 52$ GeV	20	50	16	65
	Single e, $p_T > 61$ GeV	22 (i)	60	26	17
	Single τ, $p_T > 170$ GeV	100	160	1.2	49
Two leptons	Two μ's, each $p_T > 15$ GeV	2×10	2×14	2.0	30
	Two μ's, $p_T > 23, 9$ GeV	20	22, 8	16	42
	Two very loose e's, each $p_T > 18$ GeV	2×15 (i)	2×17	1.6	11
	One e & one μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	16	5
	One e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	2.0	4
	One e & one μ, $p_T > 27, 9$ GeV	22 (e, i)	26, 8	26	2
	Two τ's, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets, topo)	35, 25	5.1	59
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	2.1	9
	One τ & one isolated e, $p_T > 30, 18$ GeV	12 (i), 15 (i) (+jets)	25, 17 (i)	3.9	16
Three leptons	Three loose e's, $p_T > 25, 13, 13$ GeV	$20, 2 \times 10$	$24, 2 \times 12$	1.2	< 0.1
	Three μ's, each $p_T > 7$ GeV	3×6	3×6	0.2	8
	Three μ's, $p_T > 21, 2 \times 5$ GeV	20	$20, 2 \times 4$	16	8
	Two μ's & one loose e, $p_T > 2 \times 11, 13$ GeV	2×10 (μ's)	$2 \times 10, 12$	2.0	0.3
	Two loose e's & one μ, $p_T > 2 \times 13, 11$ GeV	$2 \times 8, 10$	$2 \times 12, 10$	1.6	0.2
One photon	One loose γ, $p_T > 145$ GeV	22 (i)	140	26	46
Two photons	Two loose γ's, $p_T > 55, 55$ GeV	2×20	50, 50	2.4	6
	Two medium γ's, $p_T > 40, 30$ GeV	2×20	35, 25	2.4	18
	Two tight γ's, $p_T > 25, 25$ GeV	2×15 (i)	2×20 (i)	2.4	15
Single jet	Jet ($R = 0.4$), $p_T > 435$ GeV	100	420	3.4	33
	Jet ($R = 1.0$), $p_T > 480$ GeV	100	460	3.4	24
E_T^{miss}	$E_T^{miss} > 200$ GeV	50	110	4.4	100
Multi-jets	Four jets, each $p_T > 125$ GeV	3×50	4×115	0.5	16
	Five jets, each $p_T > 95$ GeV	4×15	5×85	4.9	10
	Six jets, each $p_T > 80$ GeV	4×15	6×70	4.9	4
	Six jets, each $p_T > 60$ GeV, $\|\eta\| < 2.0$	4×15	6×55, $\|\eta\| < 2.4$	4.9	15
b−jets	One b ($\epsilon = 40\%$), $p_T > 235$ GeV	100	225	3.4	15
	Two b's ($\epsilon = 60\%$), $p_T > 185, 70$ GeV	100	175, 60	3.4	12
	One b ($\epsilon = 40\%$) & three jets, each $p_T > 85$ GeV	4×15	4×75	4.9	15
	Two b's ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160$ GeV	$2 \times 30, 85$	$2 \times 55, 150$	2.7	15
	Two b's ($\epsilon = 60\%$) & two jets, each $p_T > 45$ GeV	4×15	4×35	4.9	13

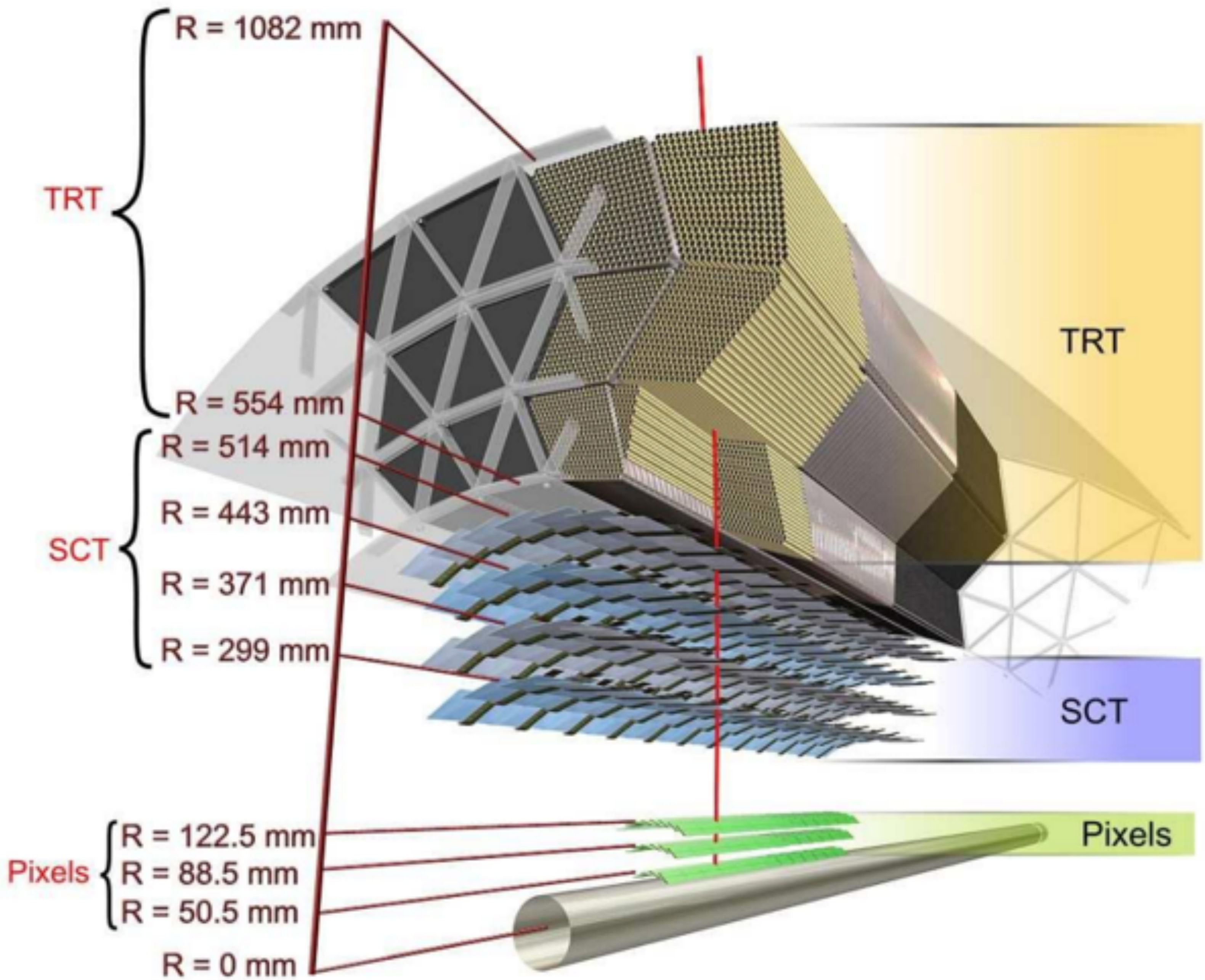
not easy to come up with the "perfect" list

every year we review this carefully

this is the first place where physics reach of ATLAS gets limited

Inner Detector

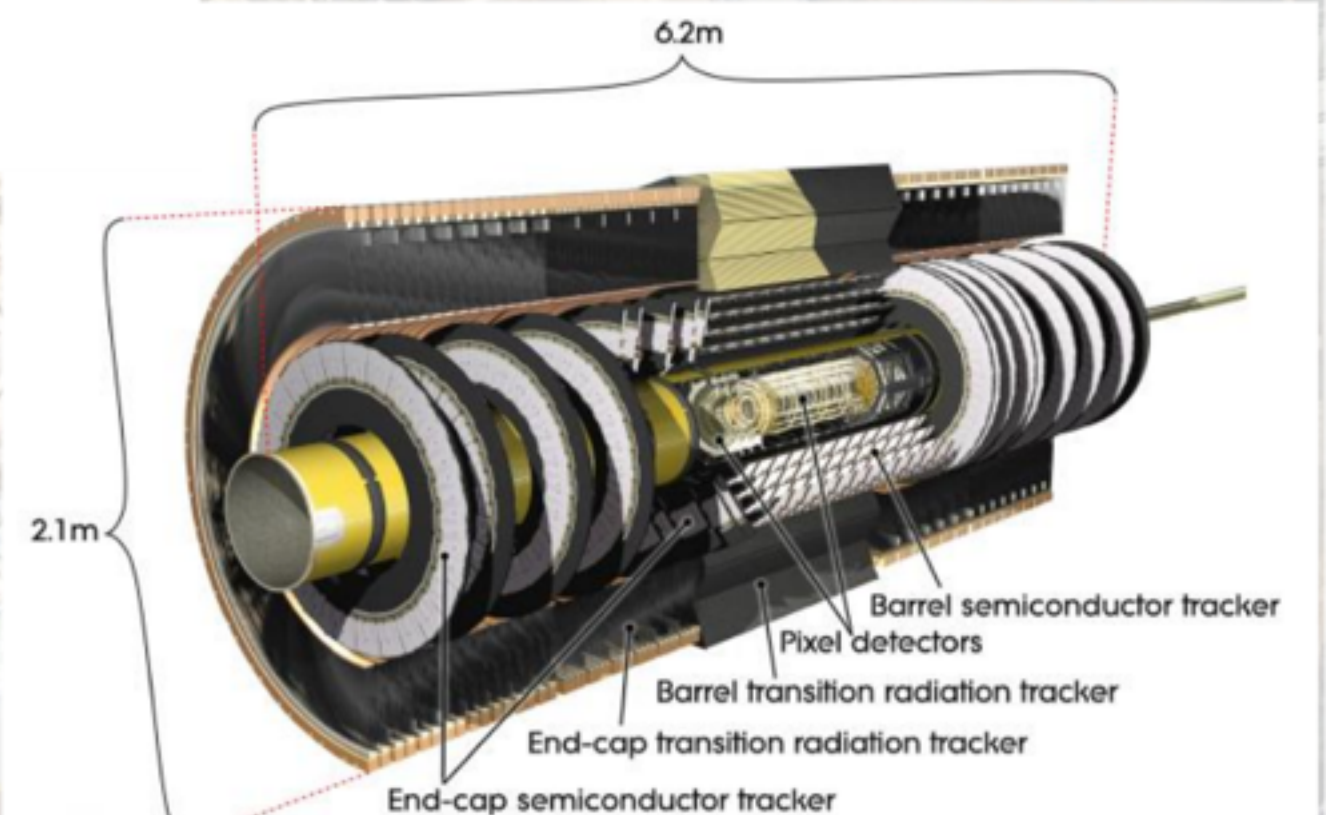




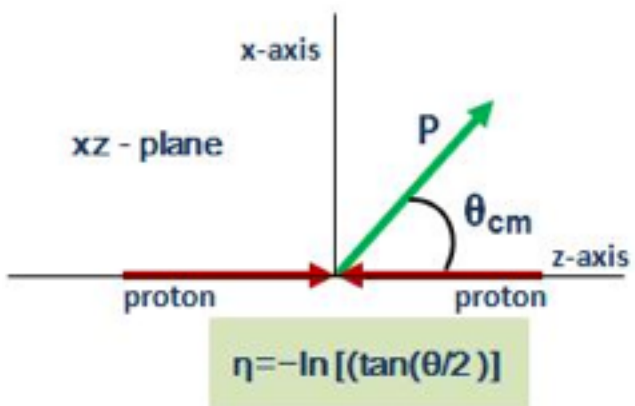
Inner Detector

- Silicon Pixel Detector (PIX)
- Silicon Strip Detector (SCT)
- Transition Radiation Tracker (TRT)

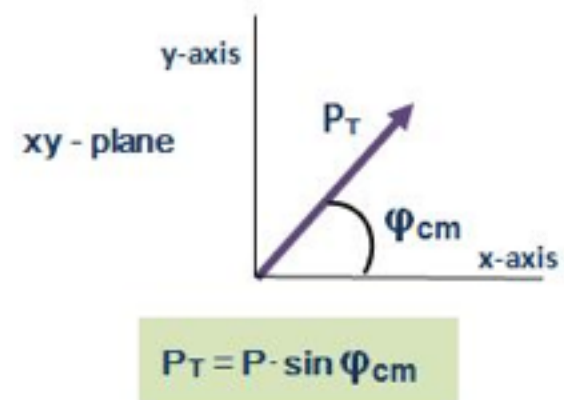
Tracking:
Momentum and Position
Measurement of charged particles



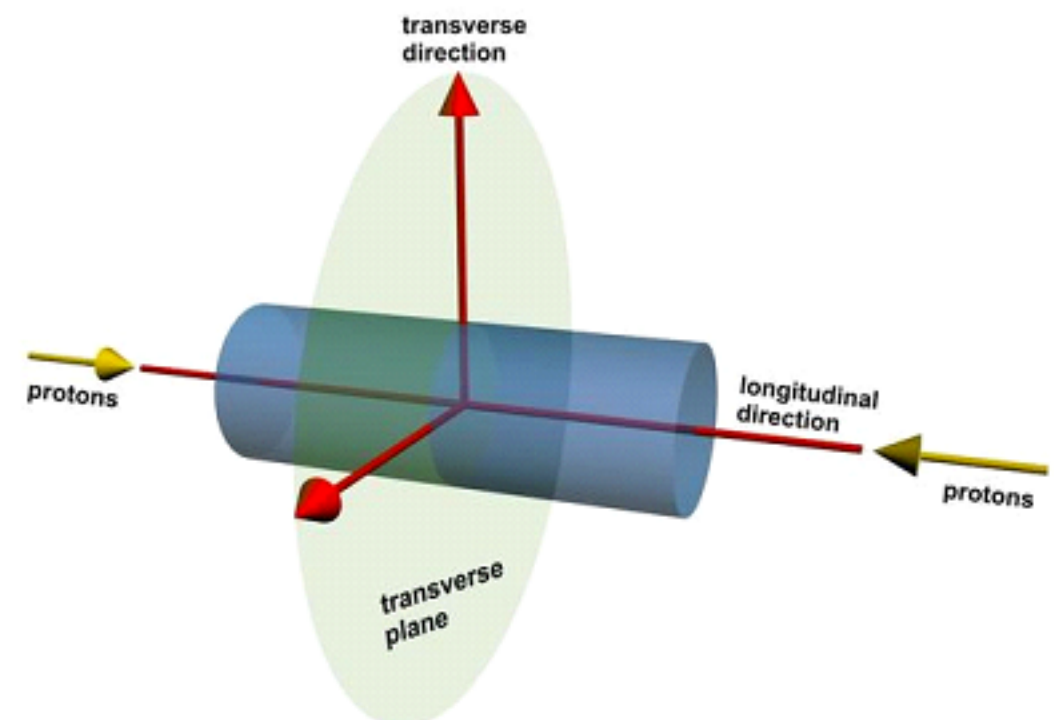
ATLAS: particle kinematic

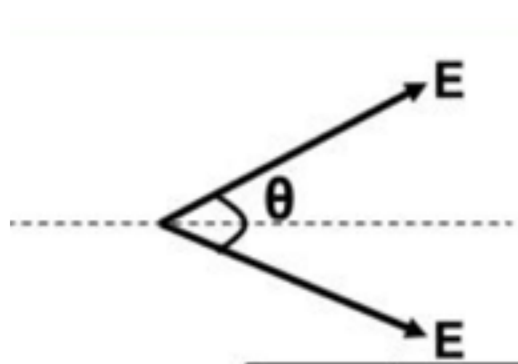


longitudinal



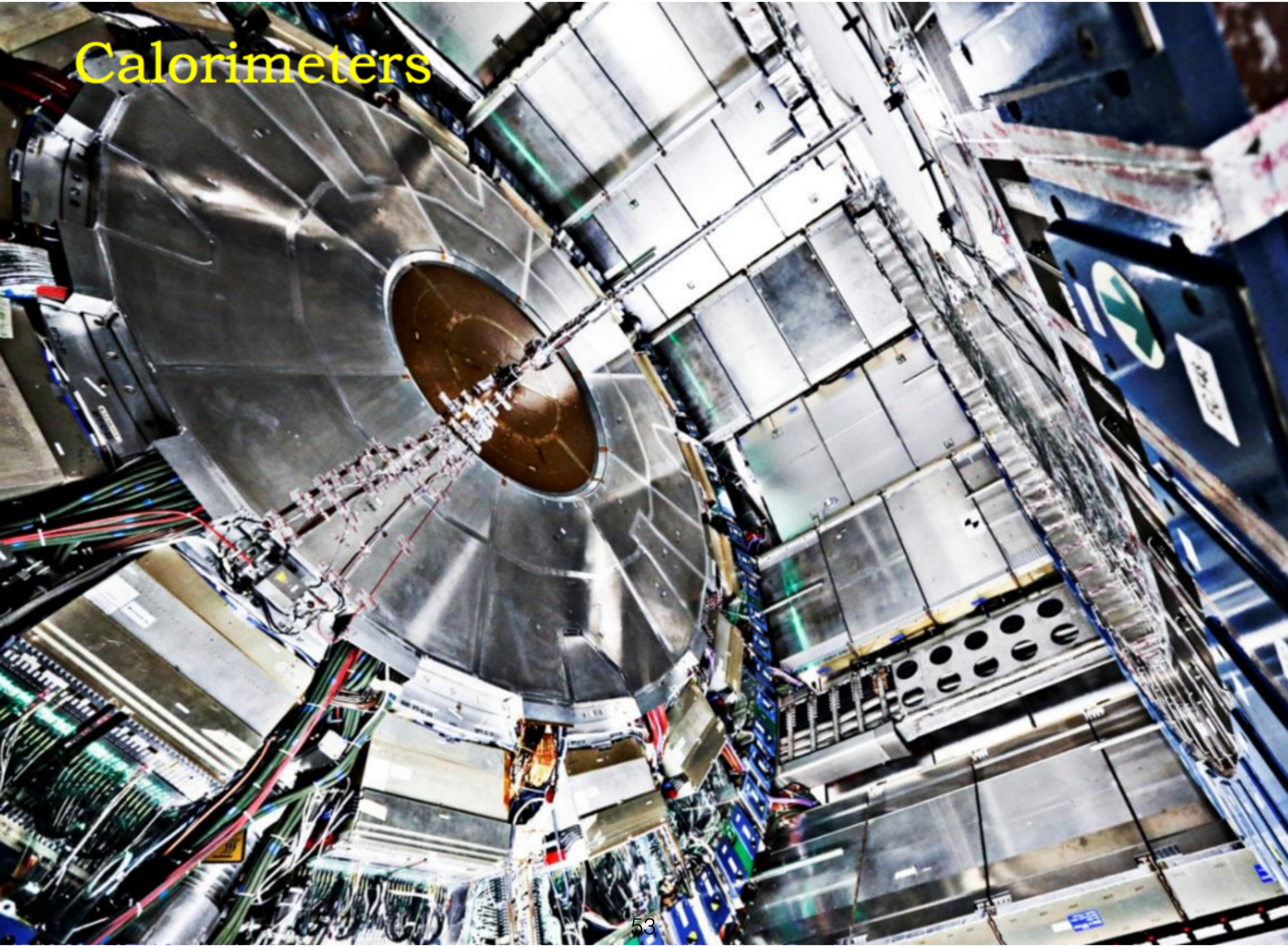
transverse





$$M_{eff} = \sqrt{2EE(1-\cos\theta)}$$

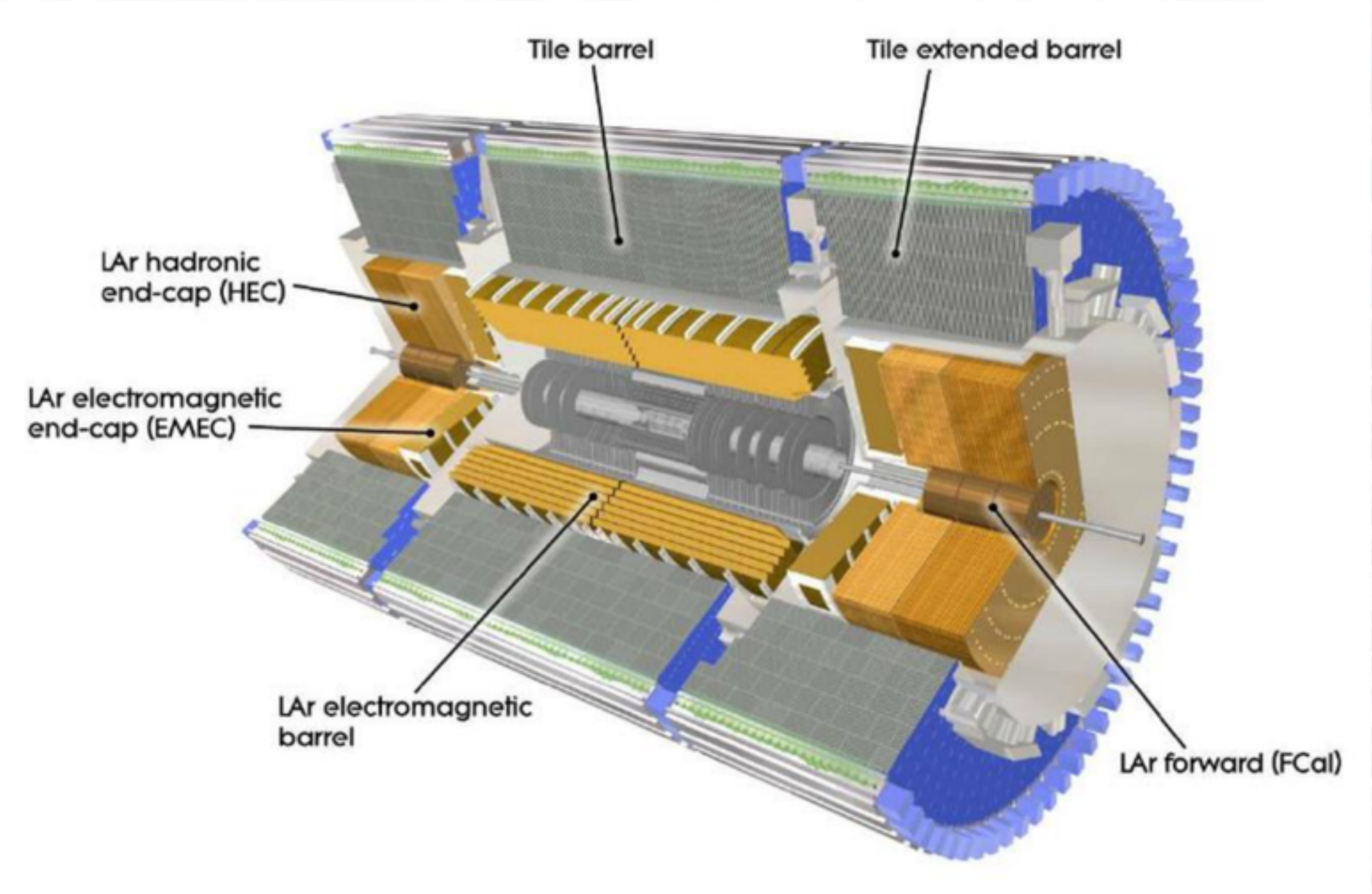
Calorimeters



Calorimeters

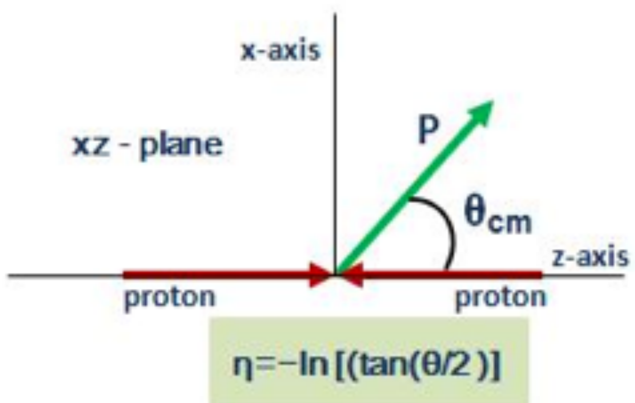
Calorimeter

- Liquid Argon: EM + had EC calorimeter (LAr)
- Fe/Scintillator hadronic Tile calorimeter (TILE)

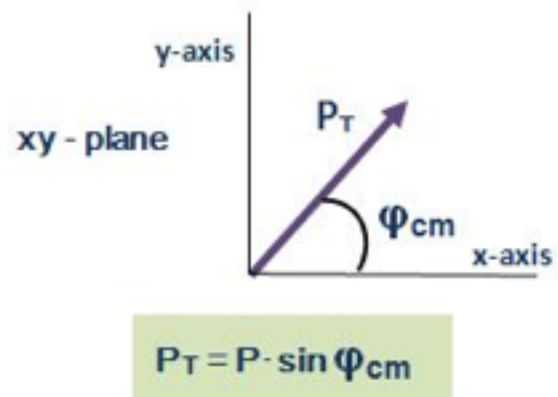


Energy Measurement, Trigger Input

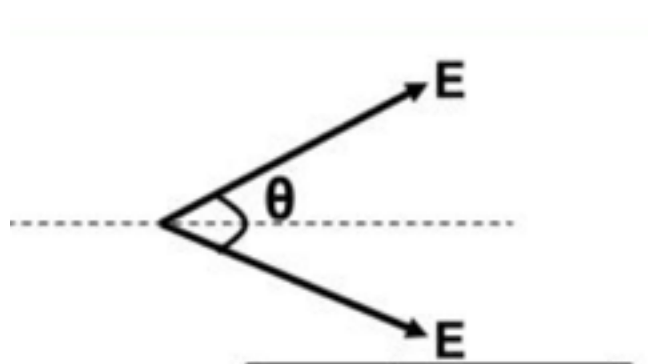
ATLAS: particle kinematic



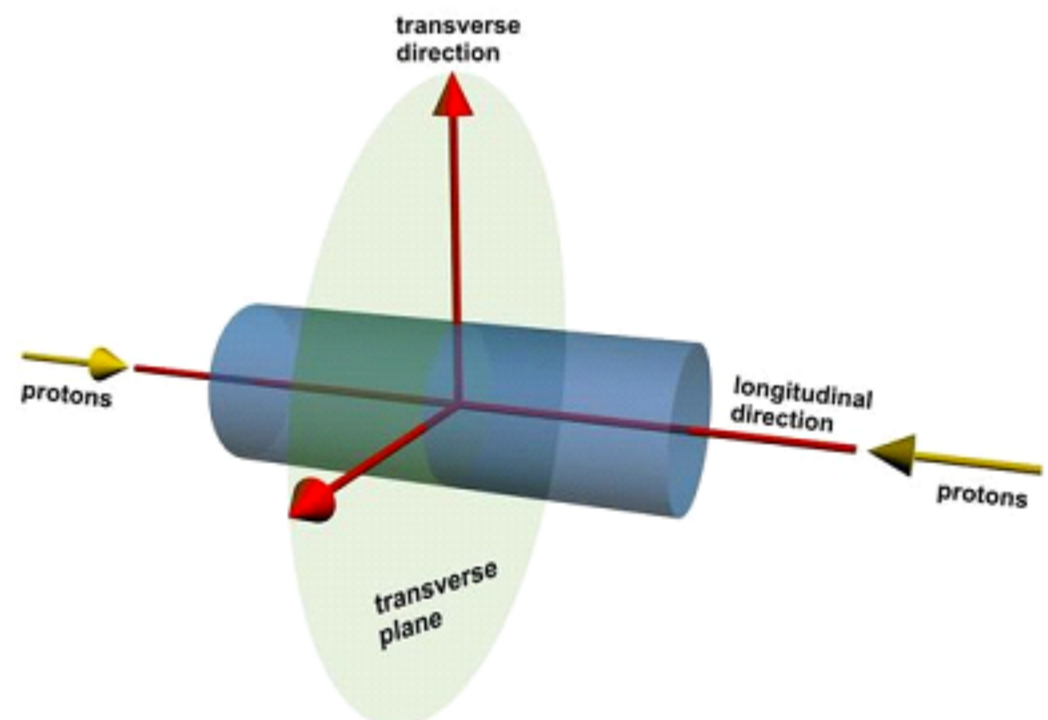
longitudinal

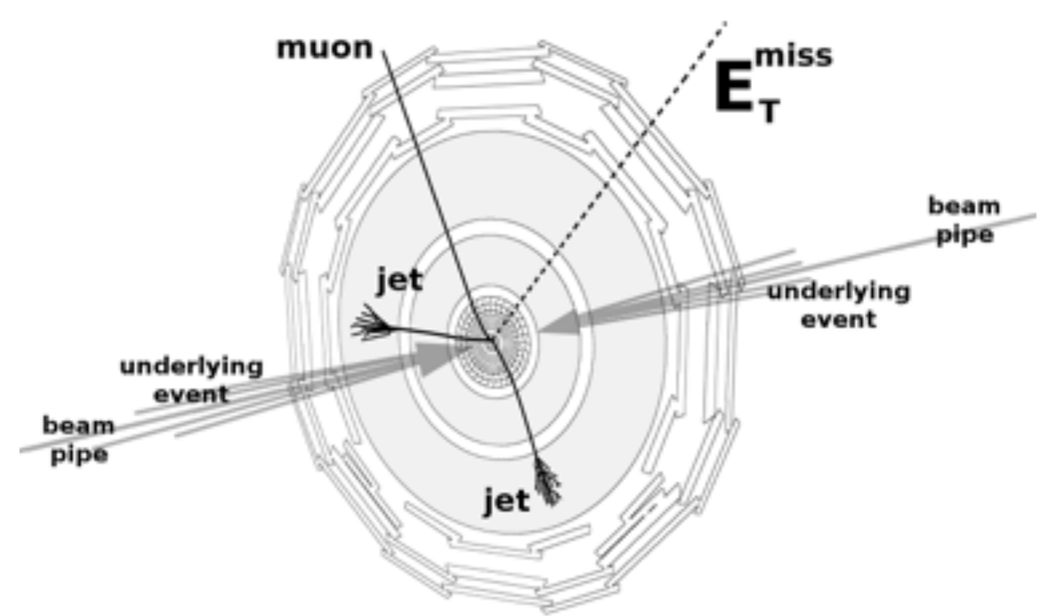


transverse



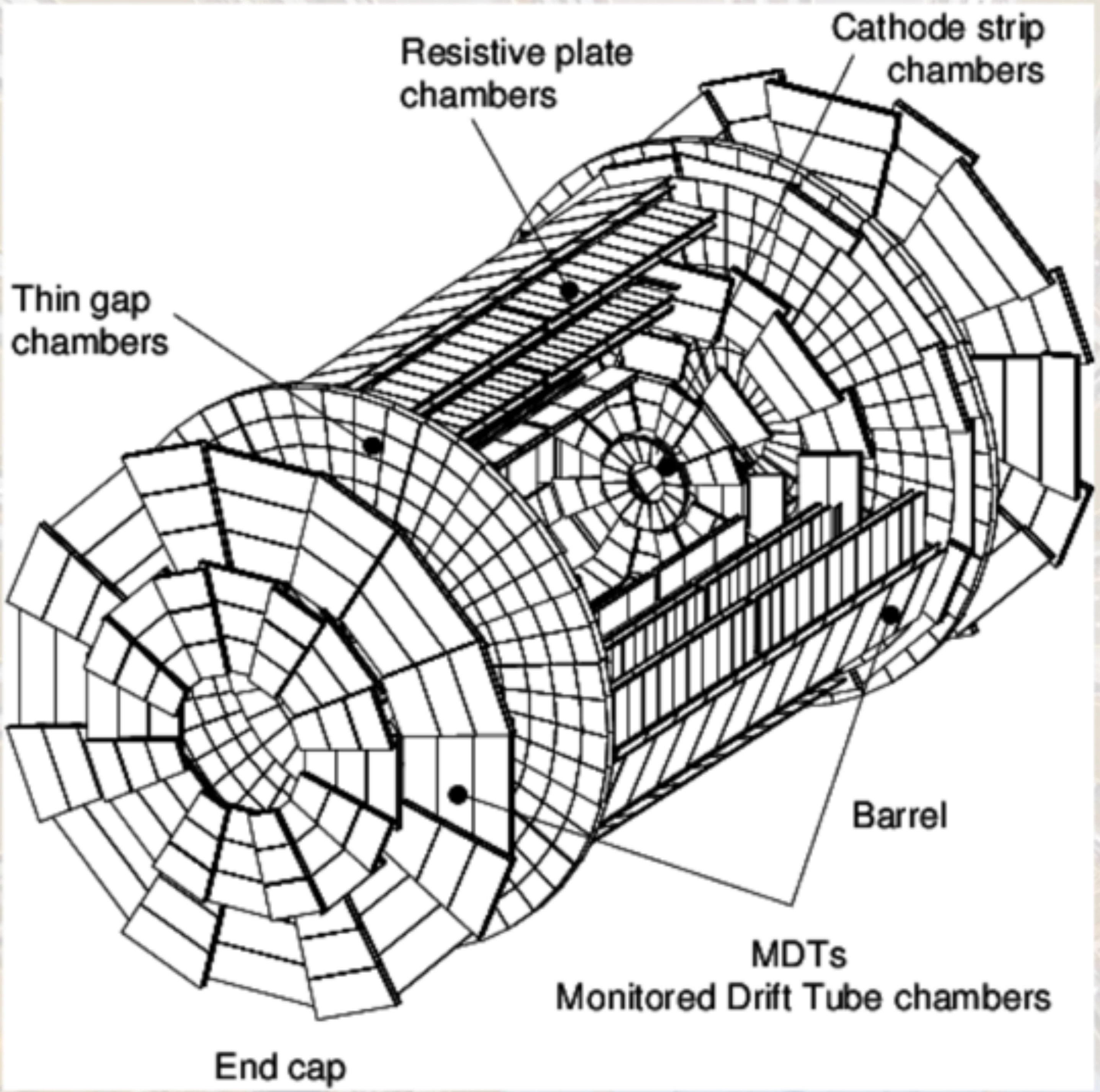
$$M_{eff} = \sqrt{2EE(1-\cos\theta)}$$





Muon Spectrometer

Muon Spectrometer

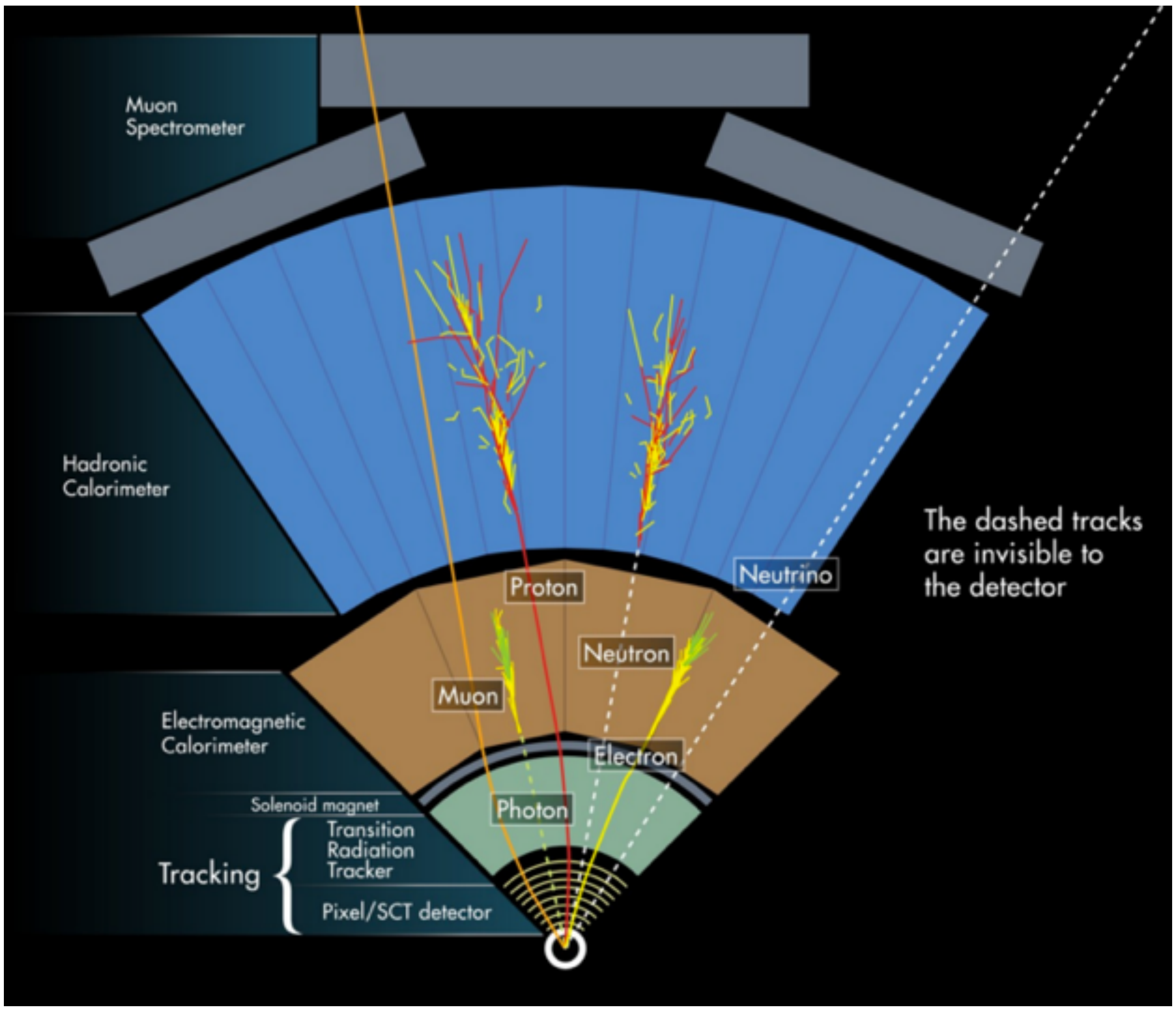


Muon Spectrometer

- Monitored Drift Tubes (MDT)
- Resistive Plate Chambers (RPC)
- Thin Gap Chambers (TGC)
- Cathode Strip Chambers (CSC)

Momentum and Position Measurement of Muons, Trigger

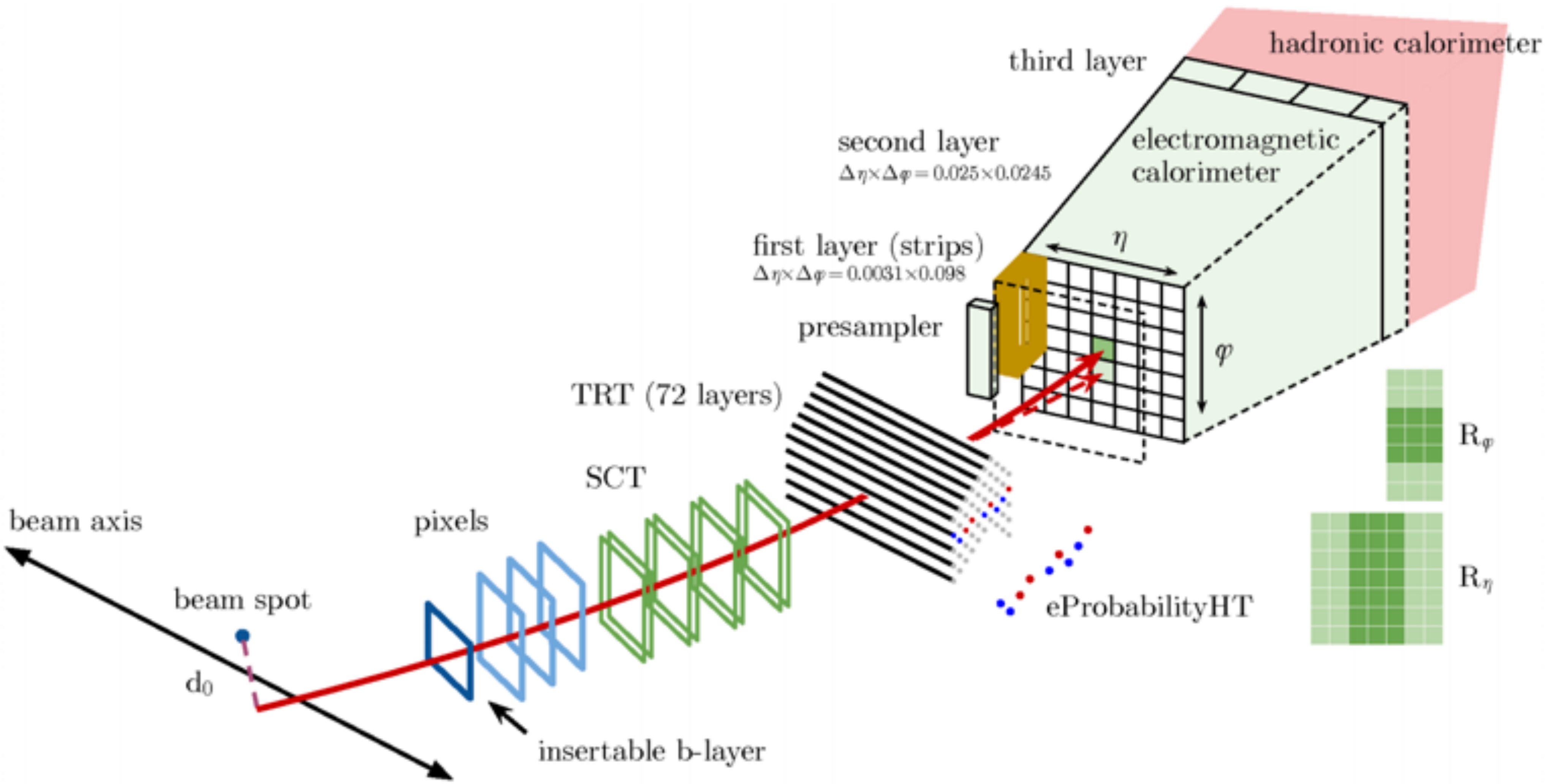
ATLAS: particle identification



electron, photon
and muon (and a.p.)
are the "easiest" to see

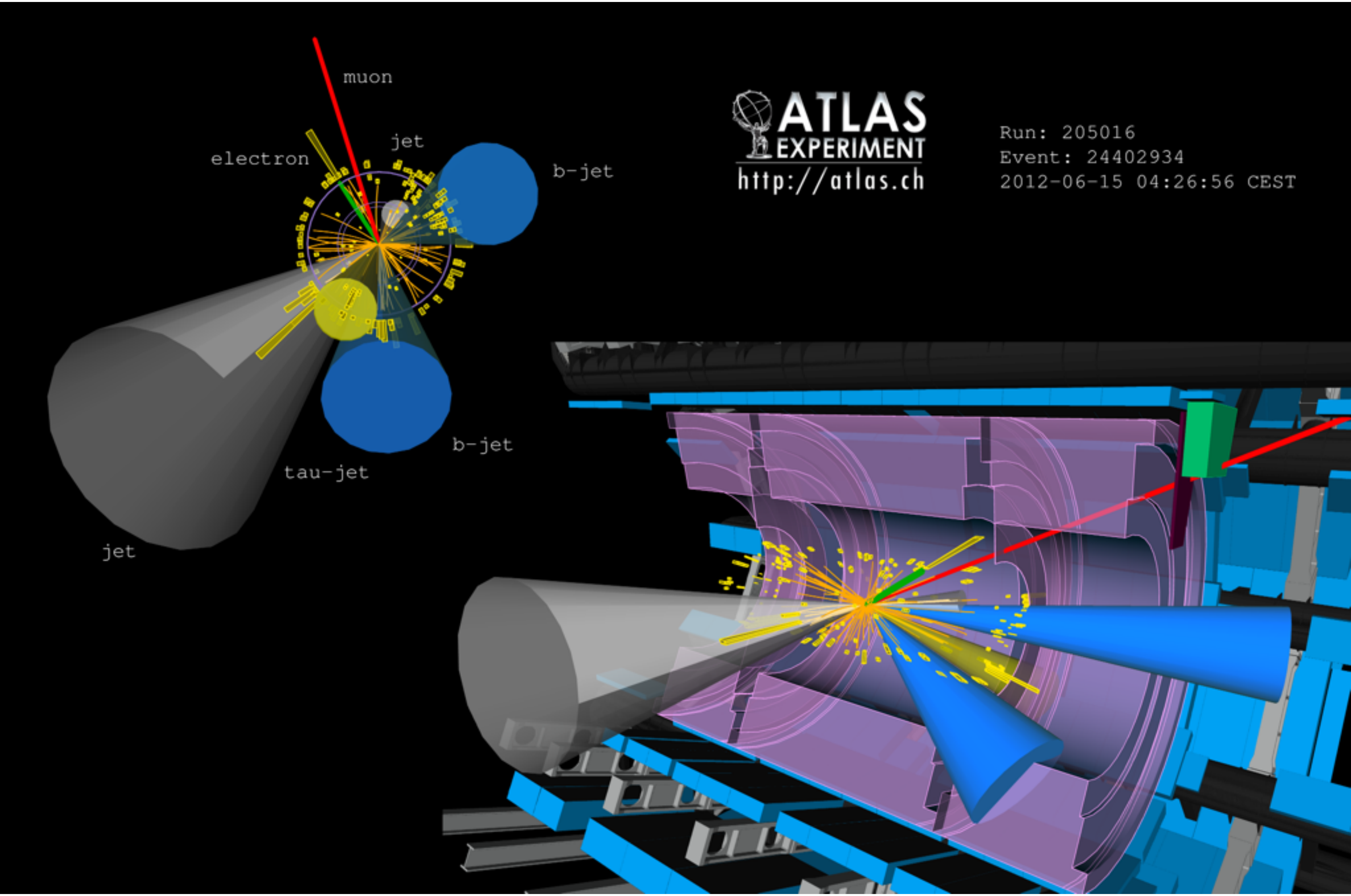
in p-p collisions the
majority of the output products
are jets with hadrons

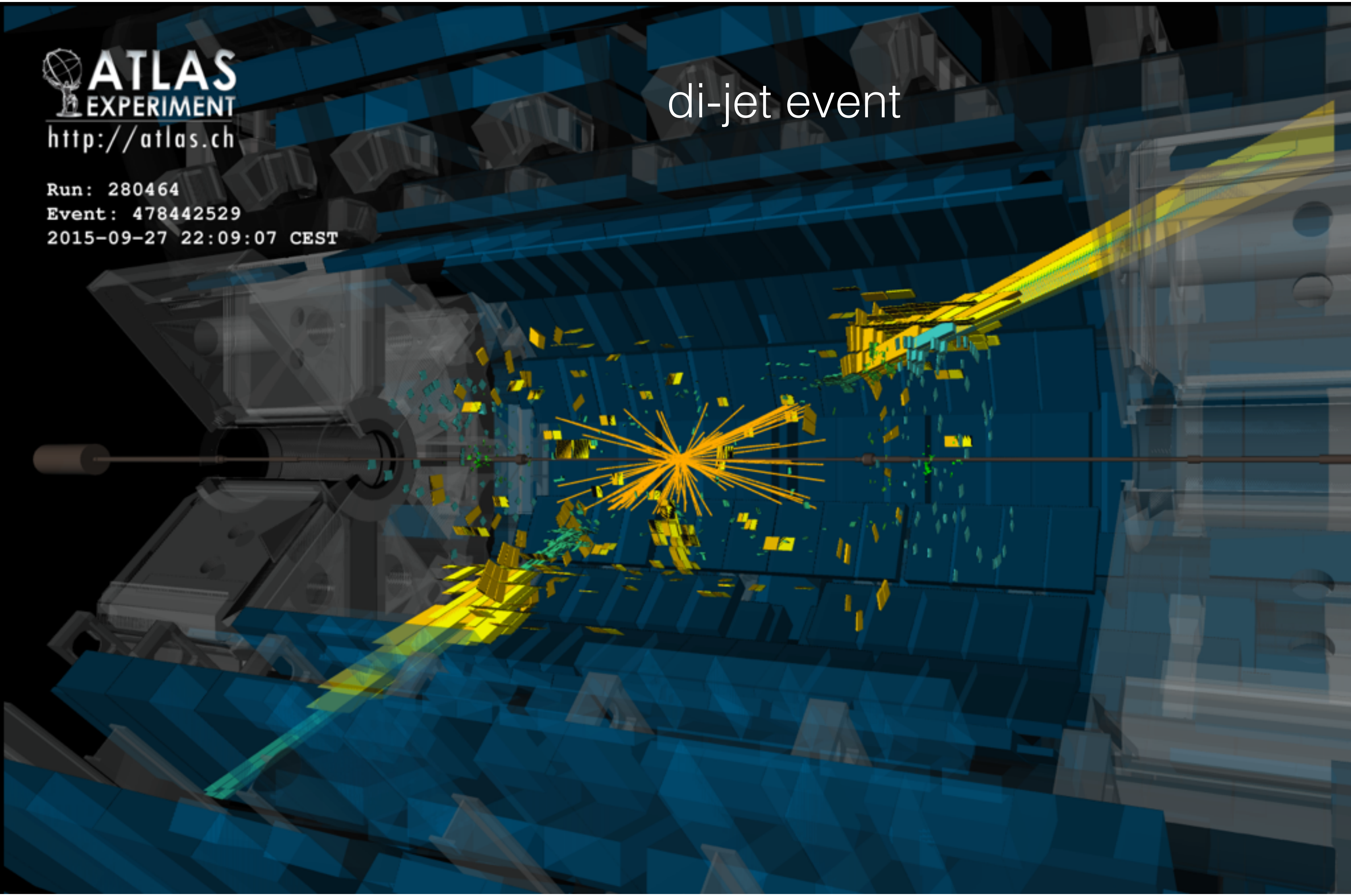
to find a b-quark, a c-quark,
a hadronic decay of a tau
lepton, is a much harder job.
Typically, multi-variate methods
(Boosted Decision trees,
Neural Network, etc) are used.

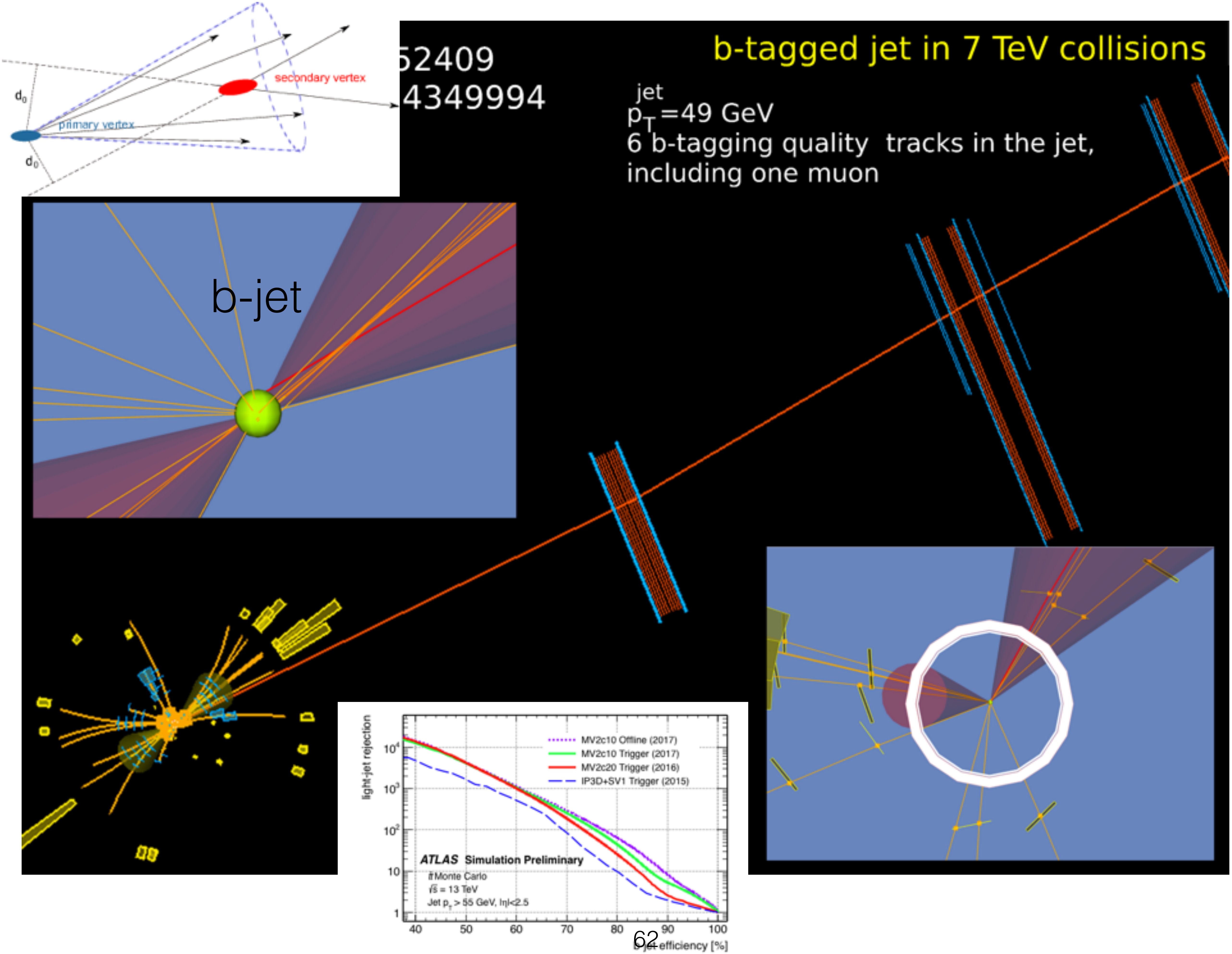


electron reconstruction and identification

Cuts optimized	$E_T > 20$ TeV	
	Efficiency (%)	Jet rejection
	$Z \rightarrow ee$	
Loose	94.30 ± 0.03	1066 ± 4
Medium	89.97 ± 0.03	6821 ± 69
Tight	71.52 ± 0.03	$(1.38 \pm 0.06)10^5$


muon
electron
jet
b-jet
b-jet
tau-jet
jet
ATLAS EXPERIMENT
http://atlas.ch
Run: 205016
Event: 24402934
2012-06-15 04:26:56 CEST


ATLAS
EXPERIMENT
http://atlas.ch
Run: 280464
Event: 478442529
2015-09-27 22:09:07 CEST
di-jet event


d0
d0
primary vertex
secondary vertex
52409
4349994
b-tagged jet in 7 TeV collisions
p_T^{jet}=49 GeV
6 b-tagging quality tracks in the jet,
including one muon
b-jet
light-jet rejection
10^4
10^3
10^2
10
1
40
50
60
70
80
90
100
b-jet efficiency [%]
MV2c10 Offline (2017)
MV2c10 Trigger (2017)
MV2c20 Trigger (2016)
IP3D+SV1 Trigger (2015)
ATLAS Simulation Preliminary
$t\bar{t}$ Monte Carlo
$\sqrt{s}$ = 13 TeV
Jet p_T > 55 GeV, $|\eta|$<2.5

ATLAS: event identification

very often, the characteristics of the whole event are used to discriminate against background

- because backgrounds are very high and everything helps

because one needs data-driven methods (eg ABCD method) for background estimates, since MC simulations are unreliable or with too poor statistics. Additional requests on the event, as well as on single objects, can be inverted to create control regions or regions rich in background to be estimated.

-> very hard to do a general search at the LHC and be sensitive.
for Higgs or for new physics, analyses are typically exclusive if one wants to minimize errors.

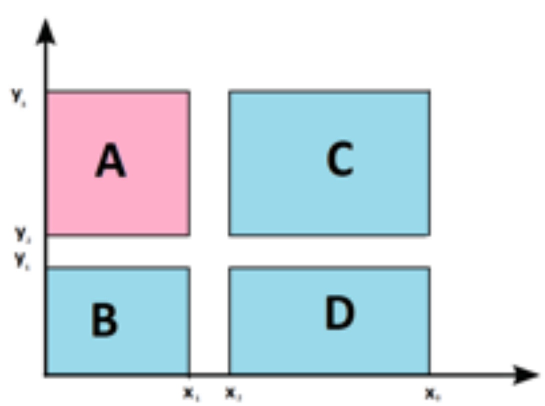


Fig. 1. – The ABCD method. The x and y axis are two uncorrelated variables. The region A is dominated by the signal (for instance, large E_T^{miss} and low isolation or small impact parameter (d_0) significance), while all other regions are dominated by backgrounds, which are characterized e.g. by non-isolated leptons or leptons with large d_0 significance, or events with small E_T^{miss}).

Variable	VBF			Boosted		
	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$m_{\tau\tau}^{MMC}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
p_T^{Total}		•	•			
Sum p_T					•	•
$p_T^{\tau_1}/p_T^{\tau_2}$					•	•
$E_T^{miss}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_T^{\ell_1}$				•		
$p_T^{j_1}$				•		
$E_T^{miss}/p_T^{\ell_2}$				•		
m_T		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,jets})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_\ell)$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			

Table 5. Discriminating variables used in the training of the BDT for each channel and category at $\sqrt{s} = 8$ TeV. The more complex variables are described in the text. The filled circles indicate which variables are used in each case.

H→ττ evidence paper
https://arxiv.org/pdf/1501.04943.pdf

L.Evans "The Large Hadron Collider: A Marvel of Technology" - Google Books

http://cdsweb.cern.ch/record/1017689/files/ab-note-2007-014.pdf

https://www.lhc-closer.es/taking_a_closer_look_at_lhc

http://uspas.fnal.gov/materials/09VU/Lecture1a.pdf

L. Evans, LHC machine, http://iopscience.iop.org/article/10.1088/1748-0221/3/08/S08001/pdf

https://indico.cern.ch/event/22574/contributions/475143/attachments/371243/516589/IntroductionToAccelerators.pdf