Collider experiments

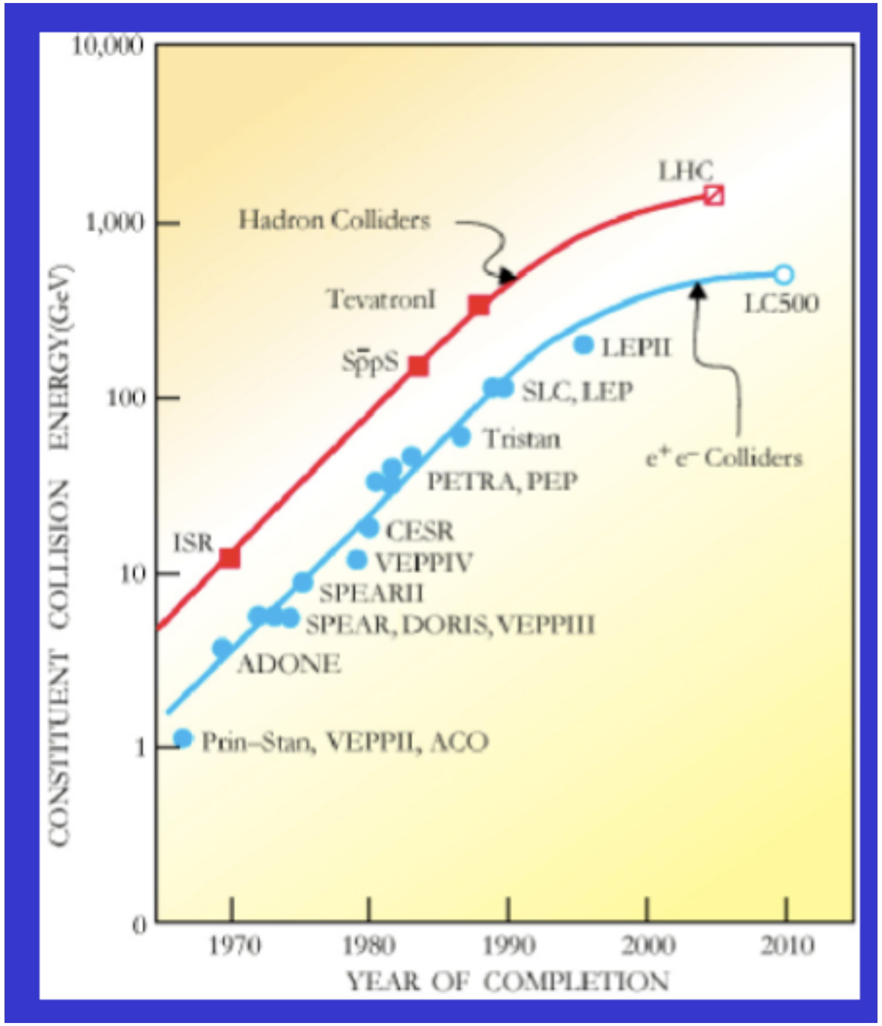
The main parameters of the colliders

LHC: ATLAS+CMS parameters

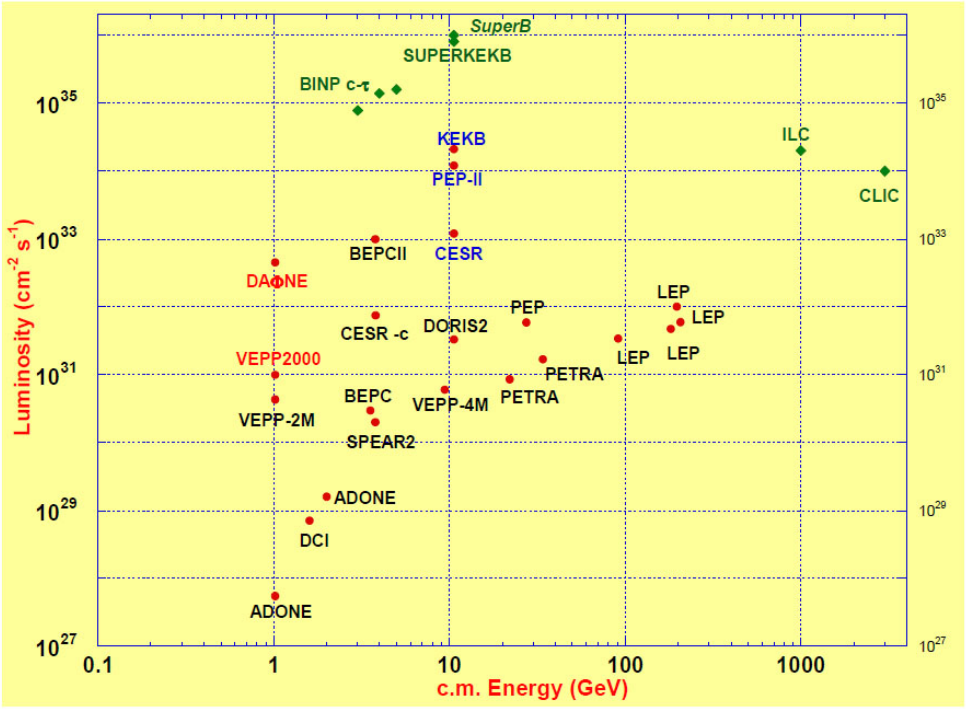
Particle Accelerator Physics

- A new discipline, separation of the communities;
- Many byproducts:
  - Beams for medicine
  - Beams for archeology and determination of age
- Two main quantities define an accelerator: the **center of mass energy** and the **beam intensity** (normally called luminosity)
- Few general aspects to be considered (we consider colliders here):
  - The **center of mass energy** is a "design" quantity: it depends on the machine dimensions, magnets and optics.
  - The **luminosity** is a quantity that has to be reached: it depends on several parameters. In many cases it doesn't reach the "design" value. It is the key quantity for the INTENSITY frontier projects.

Colliders: “Livingston” plots



Here it can be seen the separation
Between *Energy* and *Intensity* frontiers !



Colliders: general aspects - I

- **Storage rings**:

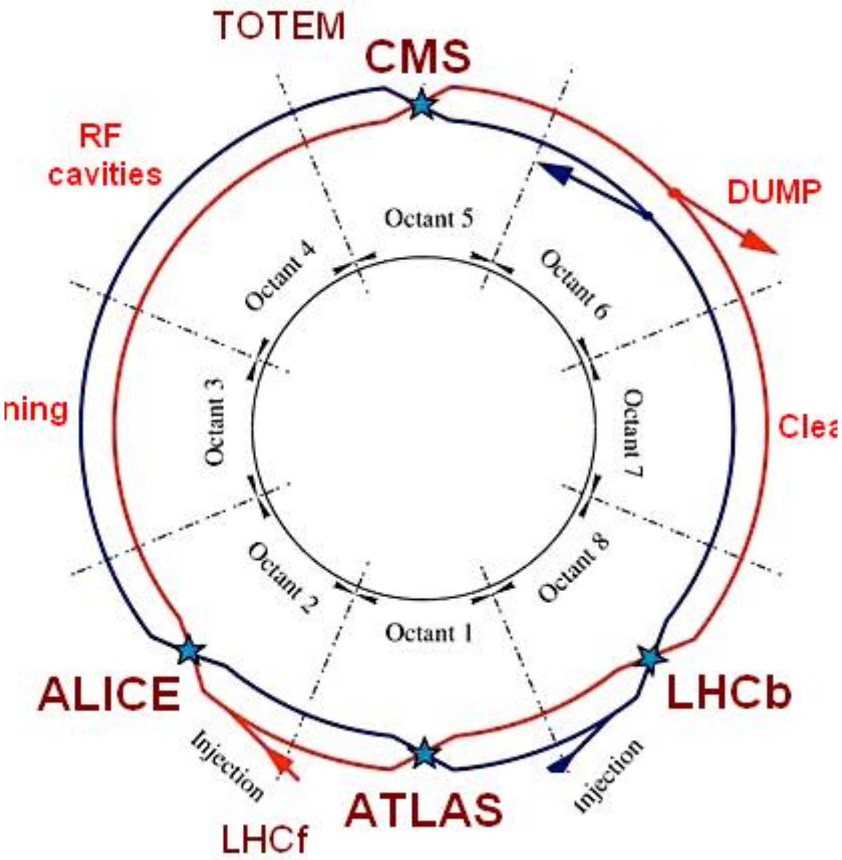
  beams are accumulated in circular orbits and are put in collisions.

  - "bunches" of particles (typically $N \approx 10^{10}$-10^{12} / bunch) in small transverse dimensions (σ_X, σ_Y down to < mm level) and higher longitudinal dimensions (σ_Z at cm level) like *needles* or *ribbons.*
  - the bunches travel along a ≈ circular trajectory (curvilinear coordinate s)
    - magnetic fields to bend them (dipoles) and to focalize them (quadrupoles or higher order)
    - electric fields to increase their energies (RadioFrequency cavities)
  - Multi-bunch operation n_b (increase of luminosity BUT reduction of inter-bunch time)
  - One or more interaction regions (with experiments or not..)
  - History:
    - *e^+e^-: Ada, Adone, Spear,… Lep, flavour-factories*
    - *pp: ISR, LHC*
    - *ppbar: SpS, Tevatron*
    - *ep: HERA*
    - ***muon colliders are considered today (never built)***
- **Linear colliders**:

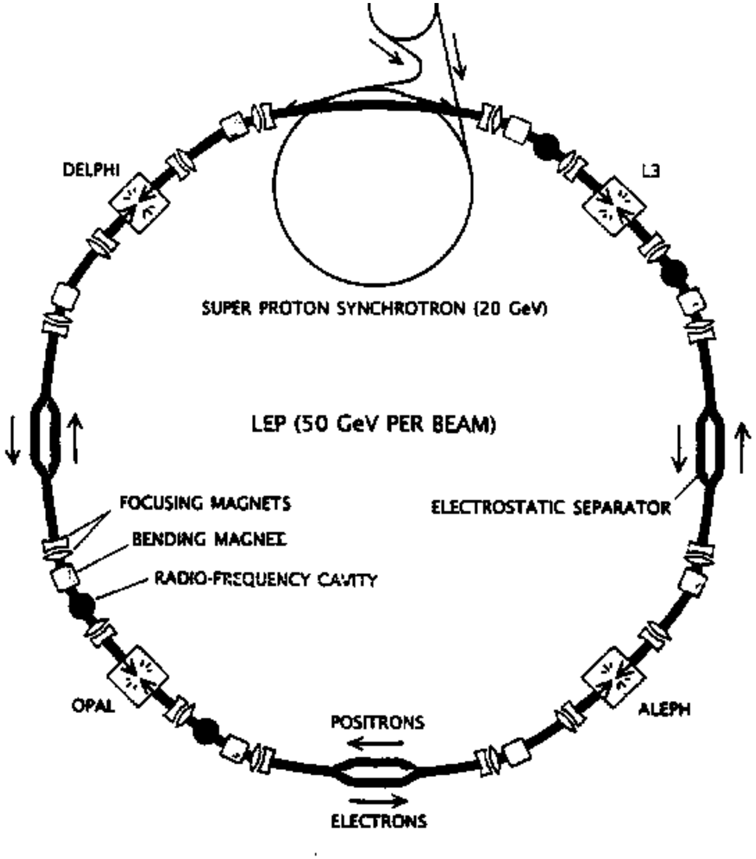
  ambituous projects aiming to reach higher electron energies without the large energy loss due to synchrotron radiation.

Colliders: general aspects - II

LHC scheme: up to 7 TeV per beam

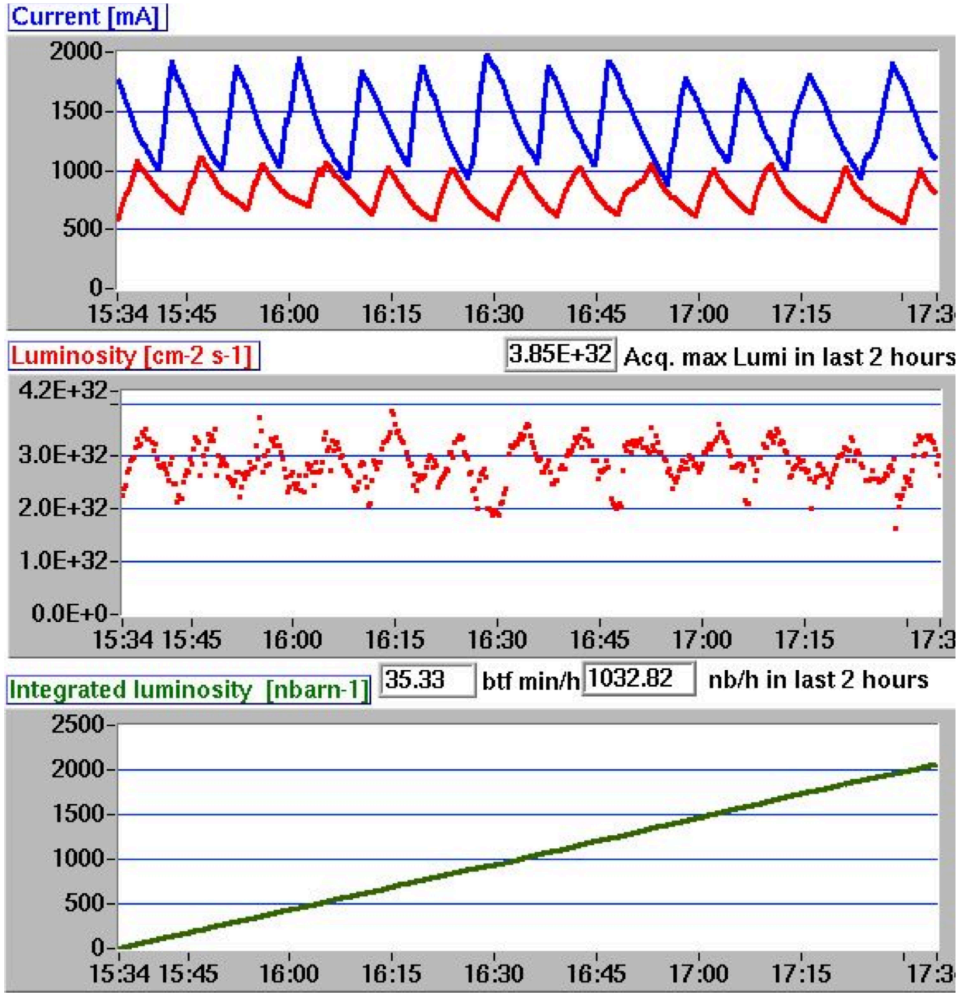


LEP scheme: up to 100 GeV per beam



Colliders: general aspects - III

- Two different operation modes:
  - Single injection (LHC)
  - “top-up” injection, continuos mode.
- Important quantities for the experiment operation are:
  - Integrated luminosity
  - Machine background



3.85E+32 Acq. max Lumi in last 2 hours

35.33 btf min/h 1032.82 nb/h in last 2 hours

LifeTime: 50% reduction in 10 minutes

Colliders: general aspects - IV

“Typical” LHC operation mode: single- injection

15-Nov-2012 11:50:45 Fill #: 3288 Energy: 4000 GeV I(B1): 1.87e+14 I(B2): 1.88e+14

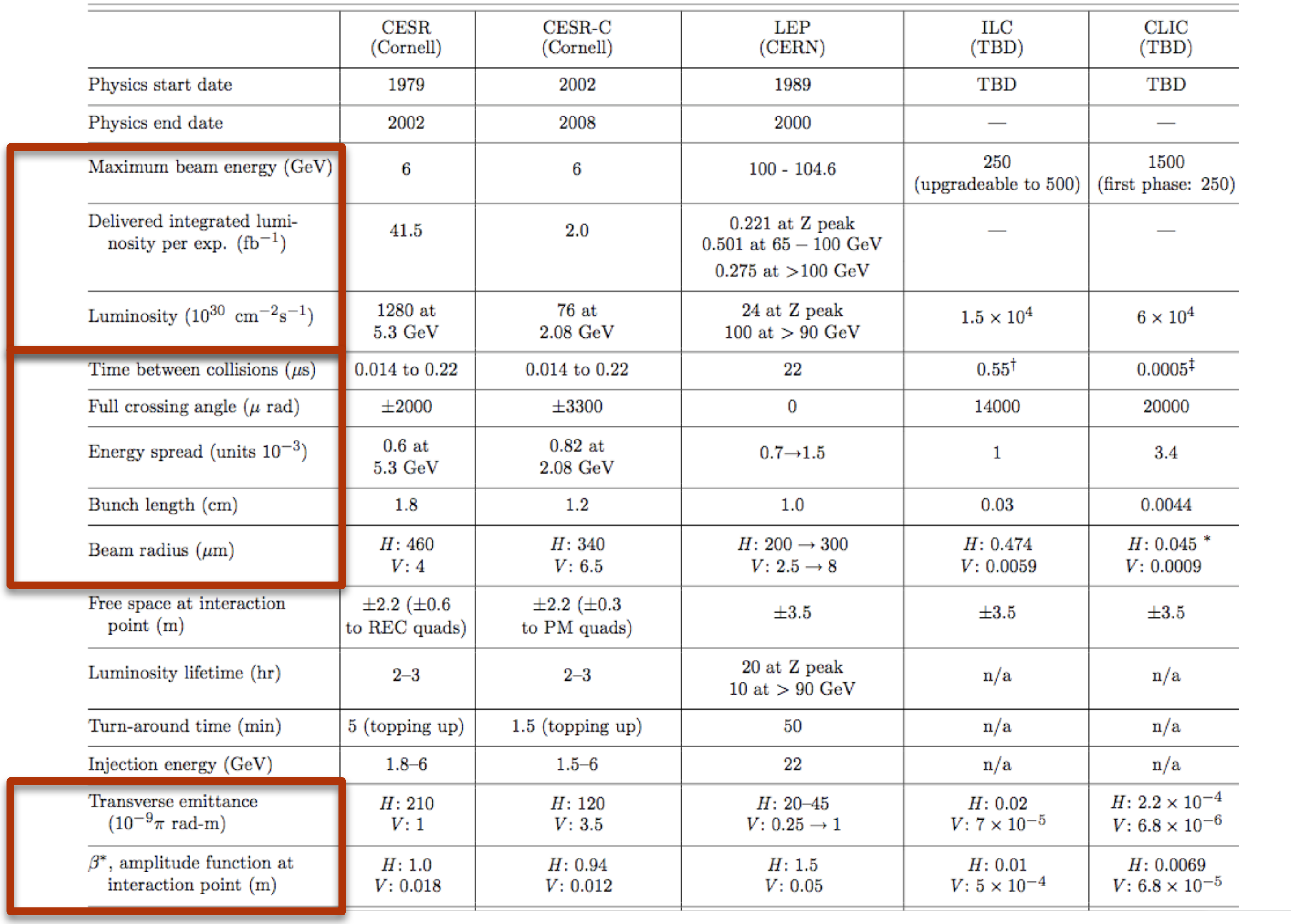
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	THANKS!!
Instantaneous Lumi [(ub.s)^-1]	3993.7	2.511	4080.1	395.9
BRAN Luminosity [(ub.s)^-1]	4083.7	1.632	4078.3	210.5
Fill Luminosity (nb)^-1	87568.7	61.0	89584.7	6829.4
BKGD 1	0.422	0.589	2.586	0.892
BKGD 2	83.489	177.284	3.361	4.286
BKGD 3	1.517	5.974	15.079	1.312

LHCb VELO Position IN Gap: -0.0 mm STABLE BEAMS TOTEM: STANDBY

Performance over the last 24 Hrs Updated: 11:50:41

LifeTime: 25% reduction in 9 h

Collider parameters - I



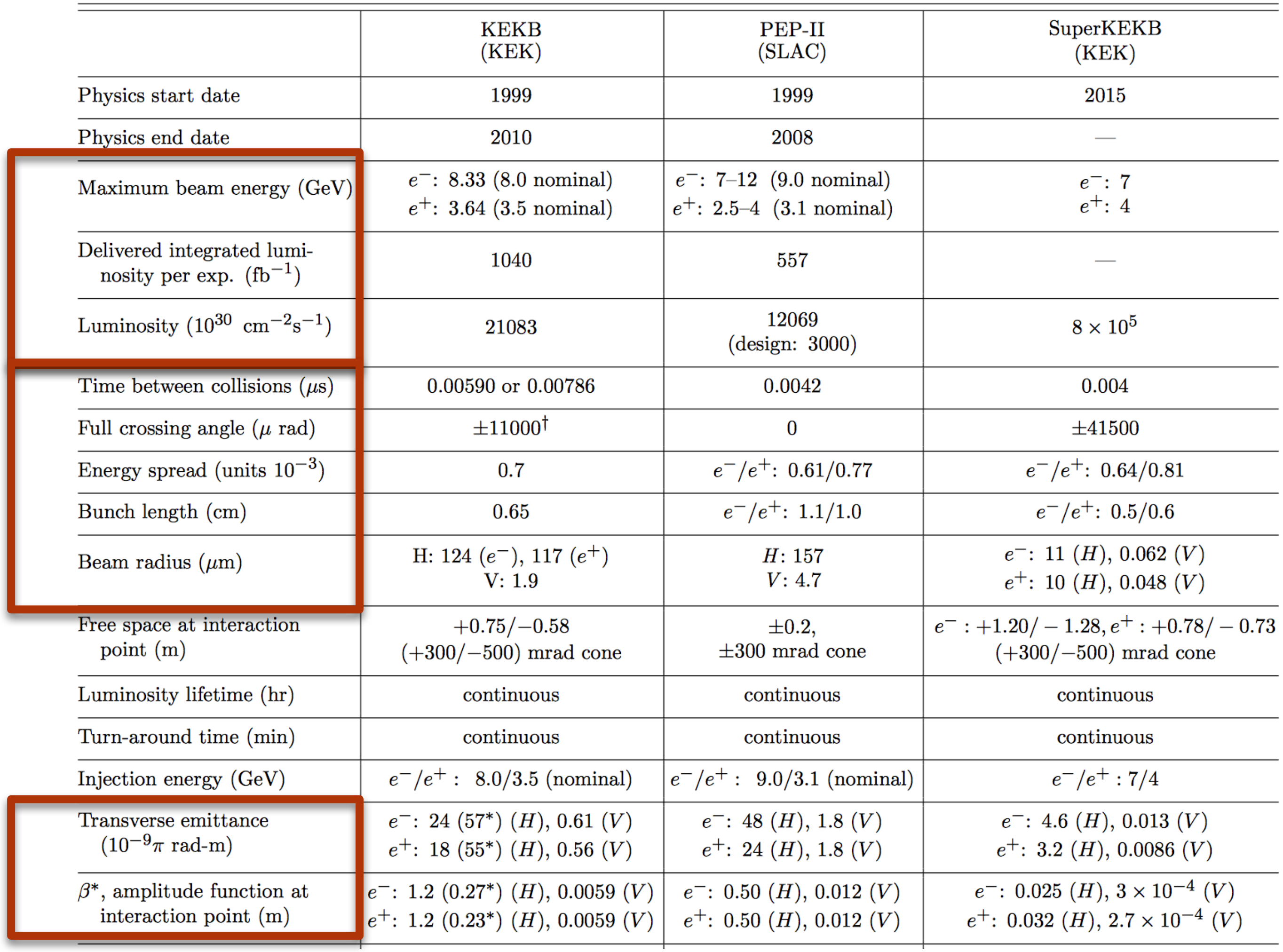
Main parameters

Impact on detector operation

Techical parameters

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	ILC (TBD)	CLIC (TBD)
Physics start date	1979	2002	1989	TBD	TBD
Physics end date	2002	2008	2000	—	—
Maximum beam energy (GeV)	6	6	100 - 104.6	250 (upgradeable to 500)	1500 (first phase: 250)
Delivered integrated luminosity per exp. (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	—	—
Luminosity (10^{30} $cm^{-2}s^{-1}$)	1280 at 5.3 GeV	76 at 2.08 GeV	24 at Z peak 100 at > 90 GeV	1.5×10^4	6×10^4
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	$0.55^\dagger$	$0.0005^\ddagger$
Full crossing angle (μ rad)	±2000	±3300	0	14000	20000
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.82 at 2.08 GeV	0.7→1.5	1	3.4
Bunch length (cm)	1.8	1.2	1.0	0.03	0.0044
Beam radius (μm)	H: 460 V: 4	H: 340 V: 6.5	H: 200 → 300 V: 2.5 → 8	H: 0.474 V: 0.0059	H: 0.045 * V: 0.0009
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	±2.2 (±0.3 to PM quads)	±3.5	±3.5	±3.5
Luminosity lifetime (hr)	2–3	2–3	20 at Z peak 10 at > 90 GeV	n/a	n/a
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	n/a	n/a
Injection energy (GeV)	1.8–6	1.5–6	22	n/a	n/a
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 210 V: 1	H: 120 V: 3.5	H: 20–45 V: 0.25 → 1	H: 0.02 V: 7×10^{-5}	H: 2.2×10^{-4} V: 6.8×10^{-6}
β^*, amplitude function at interaction point (m)	H: 1.0 V: 0.018	H: 0.94 V: 0.012	H: 1.5 V: 0.05	H: 0.01 V: 5×10^{-4}	H: 0.0069 V: 6.8×10^{-5}

Collider parameters - II



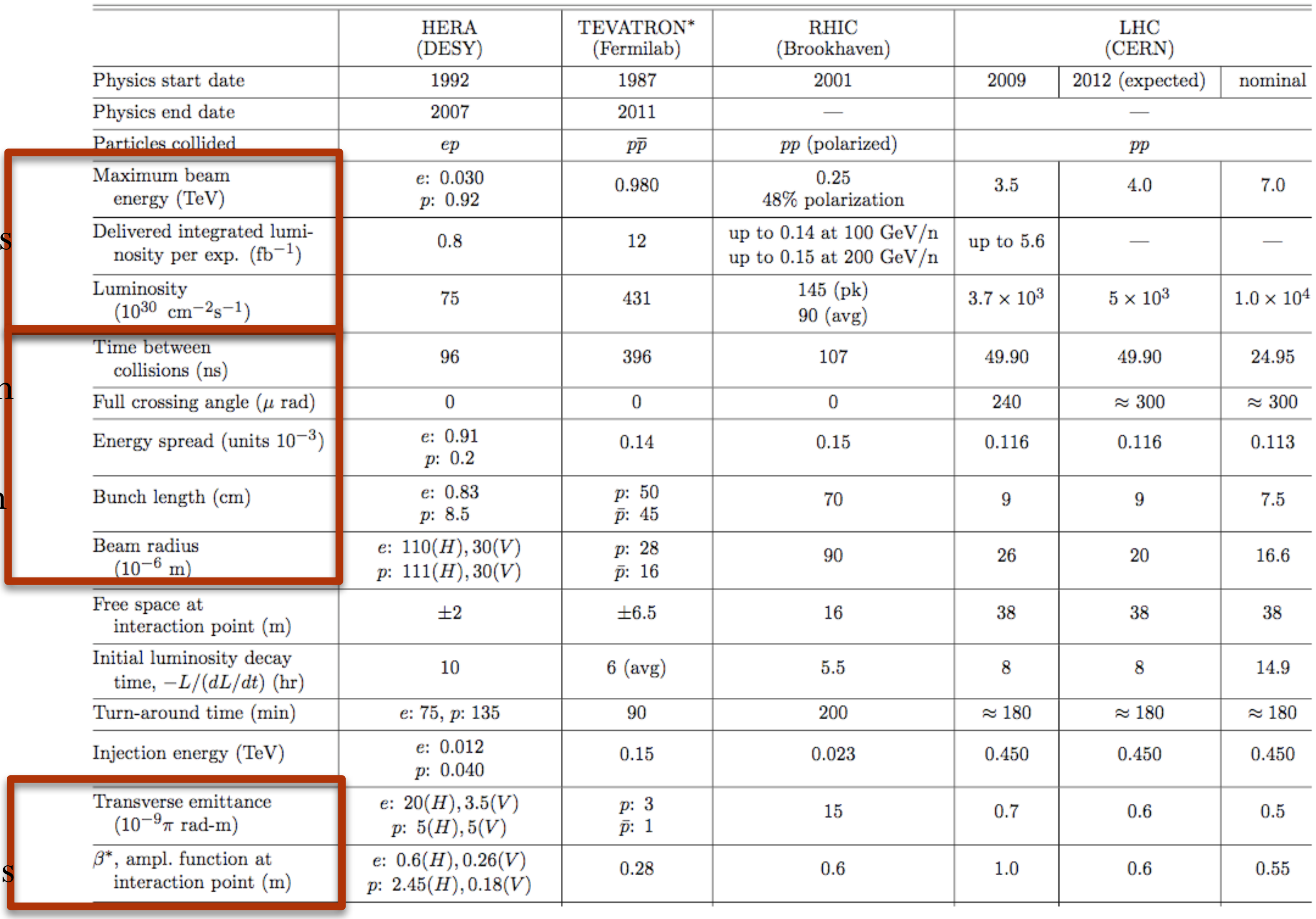
	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1999	1999	2015
Physics end date	2010	2008	—
Maximum beam energy (GeV)	e^-: 8.33 (8.0 nominal) e^+: 3.64 (3.5 nominal)	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 nominal)	e^-: 7 e^+: 4
Delivered integrated luminosity per exp. (fb^{-1})	1040	557	—
Luminosity (10^{30} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	21083	12069 (design: 3000)	8×10^5
Time between collisions (μs)	0.00590 or 0.00786	0.0042	0.004
Full crossing angle (μ rad)	$\pm 11000^\dagger$	0	±41500
Energy spread (units 10^{-3})	0.7	e^-/e^+: 0.61/0.77	e^-/e^+: 0.64/0.81
Bunch length (cm)	0.65	e^-/e^+: 1.1/1.0	e^-/e^+: 0.5/0.6
Beam radius (μm)	H: 124 (e^-), 117 (e^+) V: 1.9	H: 157 V: 4.7	e^-: 11 (H), 0.062 (V) e^+: 10 (H), 0.048 (V)
Free space at interaction point (m)	$+0.75/-0.58$ ($+300/-500$) mrad cone	±0.2, ±300 mrad cone	$e^-: +1.20/-1.28, e^+: +0.78/-0.73$ ($+300/-500$) mrad cone
Luminosity lifetime (hr)	continuous	continuous	continuous
Turn-around time (min)	continuous	continuous	continuous
Injection energy (GeV)	e^-/e^+: 8.0/3.5 (nominal)	e^-/e^+: 9.0/3.1 (nominal)	e^-/e^+: 7/4
Transverse emittance ($10^{-9}\pi$ rad-m)	e^-: 24 (57*) (H), 0.61 (V) e^+: 18 (55*) (H), 0.56 (V)	e^-: 48 (H), 1.8 (V) e^+: 24 (H), 1.8 (V)	e^-: 4.6 (H), 0.013 (V) e^+: 3.2 (H), 0.0086 (V)
β^*, amplitude function at interaction point (m)	e^-: 1.2 (0.27*) (H), 0.0059 (V) e^+: 1.2 (0.23*) (H), 0.0059 (V)	e^-: 0.50 (H), 0.012 (V) e^+: 0.50 (H), 0.012 (V)	e^-: 0.025 (H), 3×10^{-4} (V) e^+: 0.032 (H), 2.7×10^{-4} (V)

Main parameters

Impact on detector operation

Techical parameters

Collider parameters - III



Main parameters

Impact on detector operation

Techical parameters

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2012 (expected)	nominal
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\bar{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.25 48% polarization	3.5	4.0	7.0
Delivered integrated luminosity per exp. (fb^{-1})	0.8	12	up to 0.14 at 100 GeV/n up to 0.15 at 200 GeV/n	up to 5.6	—	—
Luminosity (10^{30} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	75	431	145 (pk) 90 (avg)	3.7×10^3	5×10^3	1.0×10^4
Time between collisions (ns)	96	396	107	49.90	49.90	24.95
Full crossing angle (μ rad)	0	0	0	240	≈ 300	≈ 300
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.15	0.116	0.116	0.113
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{p}$: 45	70	9	9	7.5
Beam radius (10^{-6} m)	e: $110(H), 30(V)$ p: $111(H), 30(V)$	p: 28 $\bar{p}$: 16	90	26	20	16.6
Free space at interaction point (m)	± 2	± 6.5	16	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	6 (avg)	5.5	8	8	14.9
Turn-around time (min)	e: 75, p: 135	90	200	≈ 180	≈ 180	≈ 180
Injection energy (TeV)	e: 0.012 p: 0.040	0.15	0.023	0.450	0.450	0.450
Transverse emittance ($10^{-9}\pi$ rad-m)	e: $20(H), 3.5(V)$ p: $5(H), 5(V)$	p: 3 $\bar{p}$: 1	15	0.7	0.6	0.5
β^*, ampl. function at interaction point (m)	e: $0.6(H), 0.26(V)$ p: $2.45(H), 0.18(V)$	0.28	0.6	1.0	0.6	0.55

The quest for high Luminosity

- Luminosity formula:
  - f is fixed by the collider radius
  - High N_1 and N_2 and n_b
  - Low σ_x, σ_y
- Integrated Luminosity L_{int}: $[L_{int}] = l^{-2}$ ➔ $\text{nbarn}^{-1} = 10^{33}\ \text{cm}^{-2}$
- Problems:
  - Increase number of particles / bunch ? ➔ beam-beam effects generate instabilities;
  - Increase number of bunches reduces the inter-bunch time T_{BC};
  - Decrease σ_x and σ_y ? (see next slides on beam dynamics).

$$L = n_b f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} = \frac{I_1 I_2}{4\pi n_b f e^2 \sigma_x \sigma_y}$$

$$L_{\text{int}} = \int_{Trun} L(t)\,dt$$

$$T_{BC} = \frac{1}{n_b f}$$

The pile-up

- How many interactions take place per bunch crossing ? It depends on:
  - Interaction rate that in turns depends on:
    - Luminosity
    - Total Cross-section
  - Bunch crossing rate that depends on
    - Bunch frequency
    - Number of bunches circulating
- Pile-up $\boldsymbol{\mu}$ = average number of interactions per bunch-crossing

$$\mu = \frac{L\sigma_{tot}}{fn_b}$$

Comparison: e^+e^- vs pp

- DAFNE: e^+e^- @ 1 GeV c.o.m. energy, σ_{tot}=5 μb, L=10^{33}cm^{-2}s^{-1}, n_b=120, f=c/100 m = 3 MHz

    ➔ T_{BC}= , μ=

- LHC: pp @ 13 TeV c.o.m. energy, σ_{tot}=70 mb, L=10^{34}cm^{-2}s^{-1}, n_b=3000, f=c/27 km = 10 kHz

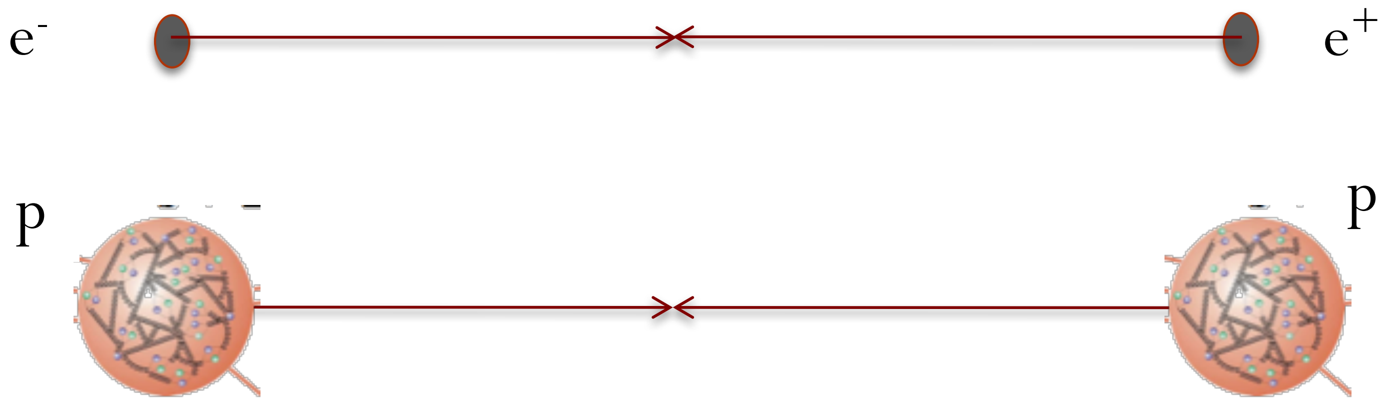
    ➔ T_{BC}= , μ=

Heavy Ion collisions.

- Lead nuclei @ LHC:
  - $Z=82, A=208, M \approx 195$ GeV
  - $\Delta E_K = ZeV$ (proton × Z)
  - $p= ZeRB$ (proton × Z)
  - ➔ $E_{Pb} = 574$ TeV$=82 \times 7$ TeV
  - ➔ E_{Pb}/Nucleon = 574/A = 2.77 TeV
  - $\sqrt{s_{NN}}=5.54$ TeV
- Luminosity: $\approx 10^{27}$ cm^{-2}s^{-1}
- $n_b = 600$
- $N_1=N_2=7\times10^7$ ions/bunch
- Heavy ions program @ RHIC
  - Au, Cu, U ions up to 100 GeV/nucleon
  - Luminosity $\approx 10^{28} \div 10^{29}$ cm^{-2}s^{-1}
- Cross-sections:
  - $\sigma_{pp} \approx 70$ mb
  - $\sigma_{pPb} \approx \sigma_{pp} \times A^{2/3}$
  - $\sigma_{PbPb} \approx \sigma_{pp} \times N_{coll} \approx 10$ barn!
- How much is the pile-up ?

ATLAS and CMS: the LHC giants!

- Proton-proton collisions at the energy frontier $\sqrt{s} = 14$ TeV with huge luminosity ($L = 10^{34}$ cm^{-2}s^{-1} ➔ $\mu = 25$ evts / bunch crossing): $\boldsymbol{\mu} = L\, \sigma_{tot} / f n_b = 10^{34} \times 100$ mb $\times\, 25\ 10^{-9}$ s
- General purpose detector not devoted to a single measurement: detect all what you imagine can come out (with momenta from hundreds of MeV up to few TeV):
  - Leptons (electrons, muons)
  - Tau leptons (through their decays, either leptonic or hadronic)
  - Photons
  - Neutrinos (not directly but using the method of the "Missing Energy")
  - Quark/Gluons (not directly but through the so called "Jets")
- Need of data reduction at trigger level: most events are not interesting and you have to choose in a very short time: DAQ rate limited to O(1 kHz)
- Need to discriminate between simultaneous events (pile-up)



The proton is a complex object done by “partons”:

valence quarks / *sea quarks* / *gluons*

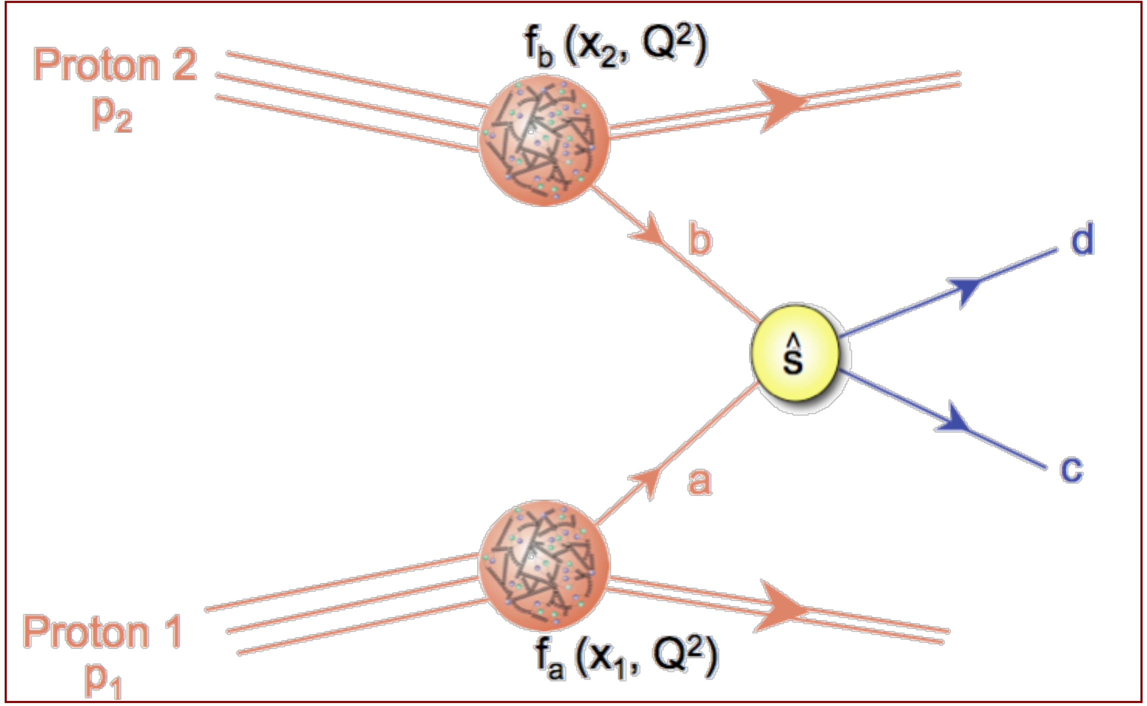
s = (center of mass energy of interaction)^2

$\hat{s}$ = (center of mass energy of *elementary* interaction)^2

e^+e^-: interactions btw point-like particles with $\sqrt{\hat{s}} \approx \sqrt{s}$

pp: interactions btw point-like partons with $\sqrt{\hat{s}} << \sqrt{s}$

Parton-parton collision: a+b → d+c.



a,b = quarks or gluons;
d,c = quarks, gluons, or leptons, vector bosons,…;
x = fraction of proton momentum carried by each parton;
ŝ = parton-parton c.o.m. energy = x_1x_2s (see later);

Theoretical method: the ***factorization theorem***

$$d\sigma(pp \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_a(x_1,Q^2) f_b(x_2,Q^2) d\hat{\sigma}(ab \to cd)$$

Two ingredients to predict pp cross-sections:

→ proton pdfs (f_a and f_b)
→ $\hat{\sigma}$ "fundamental process" cross-section

parton-parton collisions – let's define the relevant variables

- Parton momentum fractions: x_1 and x_2
  - Assume no transverse momentum
  - Assume proton mass negligible

$$p_1 = x_1 P_1 = x_1 \frac{\sqrt{s}}{2}(1,0,0,1)$$

$$p_2 = x_2 P_2 = x_2 \frac{\sqrt{s}}{2}(1,0,0,-1)$$

$$\hat{s} = (p_1 + p_2)^2 = x_1 x_2 s$$

- Rapidity: I evaluate the "velocity" of the parton system in the Lab frame:
  - It measures how fast the parton c.o.m. frame moves along z

$$\beta = \frac{p_z}{E} = \frac{(p_1 + p_2)_z}{(p_1 + p_2)_E} = \frac{x_1 - x_2}{x_1 + x_2}$$

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z} = \frac{1}{2}\ln\frac{1+\beta}{1-\beta} = \frac{1}{2}\ln\frac{x_1}{x_2}$$

- Relation between parton rapidity and each single x:

$$x_1 = \sqrt{\frac{\hat{s}}{s}}e^{y}$$

$$x_2 = \sqrt{\frac{\hat{s}}{s}}e^{-y}$$

Rapidity limit for a resonance of mass M

- Suppose that we want to produce in a partonic interaction a resonance of mass M then decaying to a given final state (e.g. pp→Z+X with Z→μμ. Limits in x and y of the collision ?
  - Completely symmetric case: $x_1=x_2=x$

$$x^2 = \frac{M^2}{s}; x = \sqrt{\frac{M^2}{s}}; e^y = 1; y = 0$$

  - Maximally asymmetric case: $x_1=1$, $x_2=x_{min}$

$$x_1 = 1; x_2 = x_{\min} = \frac{M^2}{s}; y_{\max} = \frac{1}{2}\ln\frac{s}{M^2}$$

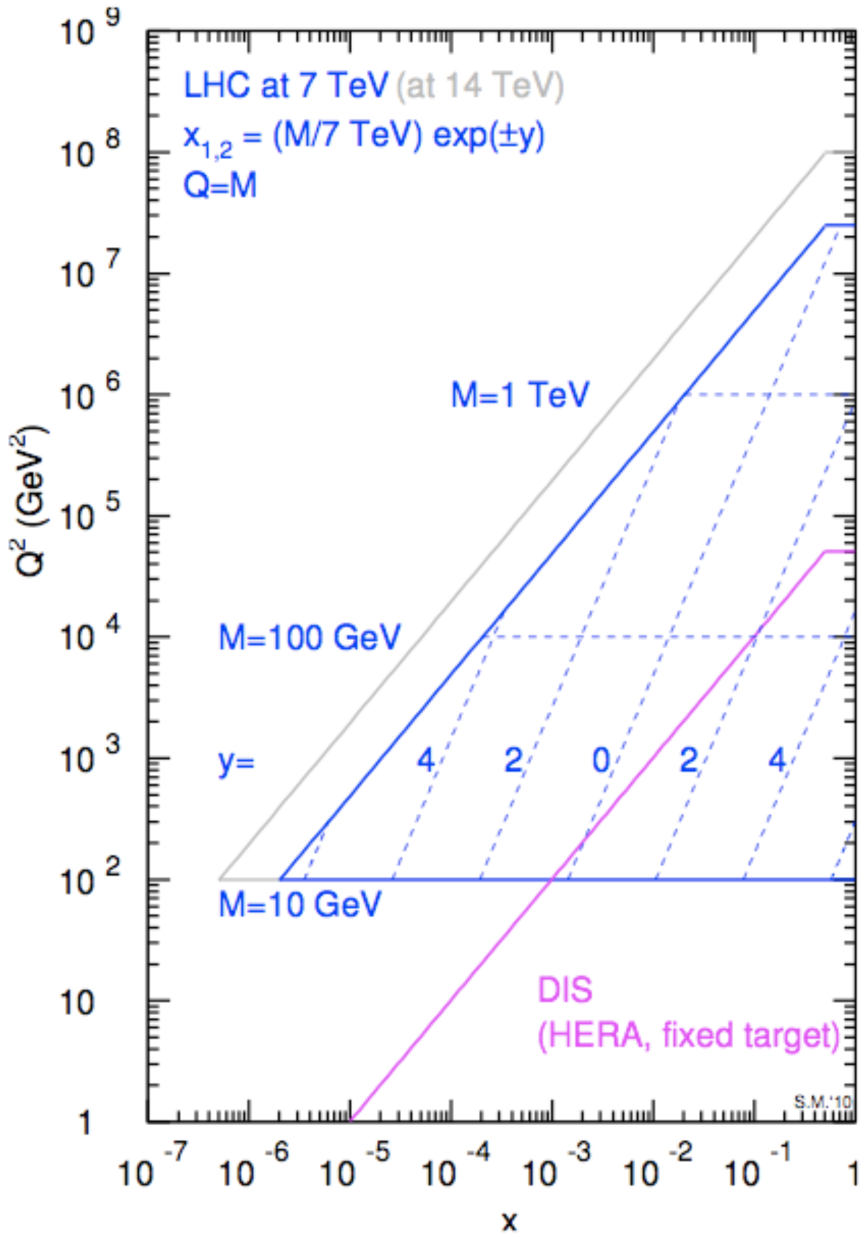
- Z production at LHC, Tevatron and SpS

	LHC (14 TeV)	**Tevatron (1.96 TeV)**	**SpS (560 GeV)**
x_{min}	4.2×10^{-5}	2.1×10^{-3}	0.026
y_{max}	5.03	3.07	1.82

The x-Q^2 plane

→ x – Q^2 plane (Q^2=M=$\hat{s}$) c.o.m. energy of parton interaction. LHC vs. previous experiments showing where PDF are needed to interpret LHC results.

→ NB pp vs. ppbar
ppbar ≈ qqbar collider
pp ≈ gluon collider



Variables for particles emerging from the collision

- Rapidity y can be defined for any particle emerging from the collision. Let's consider a particle of mass m, energy-momentum E, p and define the rapidity
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$
- Pseudorapidity η: it is the rapidity of a particle of 0 mass:
$$\eta = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta} \rightarrow \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$
- Transverse energy and momentum:
$$E_T^2 = p_x^2 + p_y^2 + m^2 = E^2 - p_z^2 = \frac{E^2}{\cosh^2 y}; p_T^2 = p_x^2 + p_y^2 = p^2\sin^2\theta$$
- General consideration: Energy and momentum conservation are expected to hold "roughly" in the transverse plane. This gives rise to the concept of missing E_T
- We do not expect momentum conservation on the longitudinal direction.

Properties of the rapidity

- Rapidity y can be defined for any particle emerging from the collision. Let's consider a particle of mass m, energy-momentum E, p and define the rapidity

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

- Properties
  - If we operate a Lorentz boost along z, y is changed additively (so that Δy the "rapidity gap" is a relativistically invariant quantity):

$$y' = y + y_b$$

$$y_b = \ln\left[\gamma_b\left(1+\beta_b\right)\right]$$

  - If expressed in terms of (p_T, y, ϕ, m) rather than (p_x,p_y,p_z,E) the invariant phase-space volume gets a simpler form:

$$d\tau = \frac{1}{2}dp_T^2\,dy\,d\phi$$

  - so that in case of matrix element uniform over the phase-space, you expect a uniform particle distribution in y and p_T^{2}.

Invariant mass and missing energy

- The invariant mass of 2 particles emerging from the IP can be written in terms of the above defined variables

$$M_W^2 = 2E_{T1}E_{T2}(\cosh\delta\eta - \cos\delta\phi).$$

- Non-interacting particles such as neutrinos can be detected via a momentum imbalance in the event. But since most of the longitudinal momentum is “lost”, the balance is reliable only in the transverse direction. ➔ Missing Transverse Energy $\vec{\not{E}}_T$

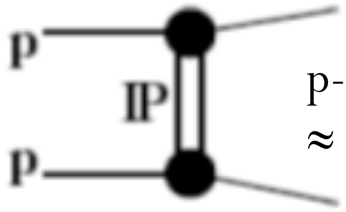
$$\vec{\not{E}}_T = -\sum_{k=1}^{Ncl} \vec{E}_{Tk} - \sum_{i=1}^{Nm} \vec{p}_{Ti}$$

$$\vec{E}_{Tk} = \frac{E_k \cos\varphi_k}{\sinh\eta_k}\hat{x} + \frac{E_k \sin\varphi_k}{\sinh\eta_k}\hat{y}$$

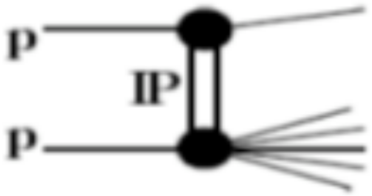
A detailed look at a p-p collision. What really happens ?

(A) "Real" proton-proton collision

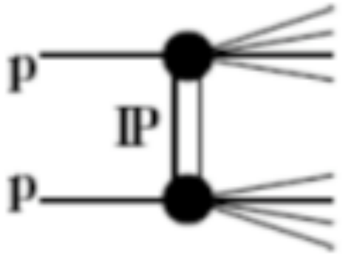
(*pomeron exchange*): 40% of the times



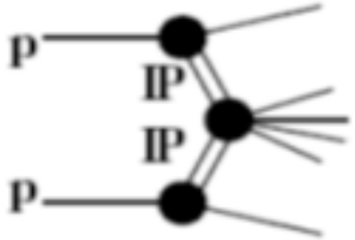
p-p elastic scattering
≈ 25%



Single diffraction
≈ 10%



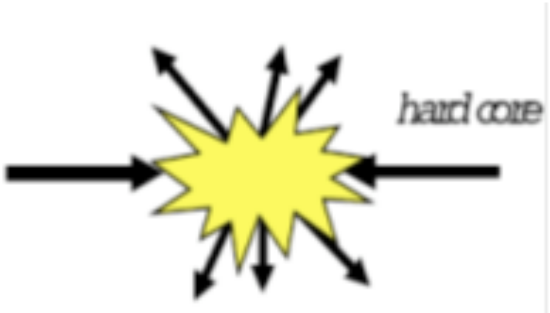
Double diffraction
≈ 1%



Central diffraction
≈ 1%

(B) Inelastic non-diffractive:

60% of the times



Where is the *fundamental physics*
in this picture ?
Among non-diffractive collisions
parton-parton collisions.
Signatures:

proton-proton collision
➔ "forward"

parton-parton collision
➔ "transverse"

Jets - I

Starting from the '70s observation of jet production in e^+e^-, pp and ep collisions. QCD explanation (for e^+e^-):

$e^+e^- \rightarrow$ qqbar $\rightarrow$ hadronisation results in

two jets of hadrons if q (qbar) momenta >> O(100MeV)

NB: in low energy e^+e^- you see multi-hadrons not jets…

2-jet events: qqbar or gg final state that hadronise in 2 jets in back-to-back configuration;

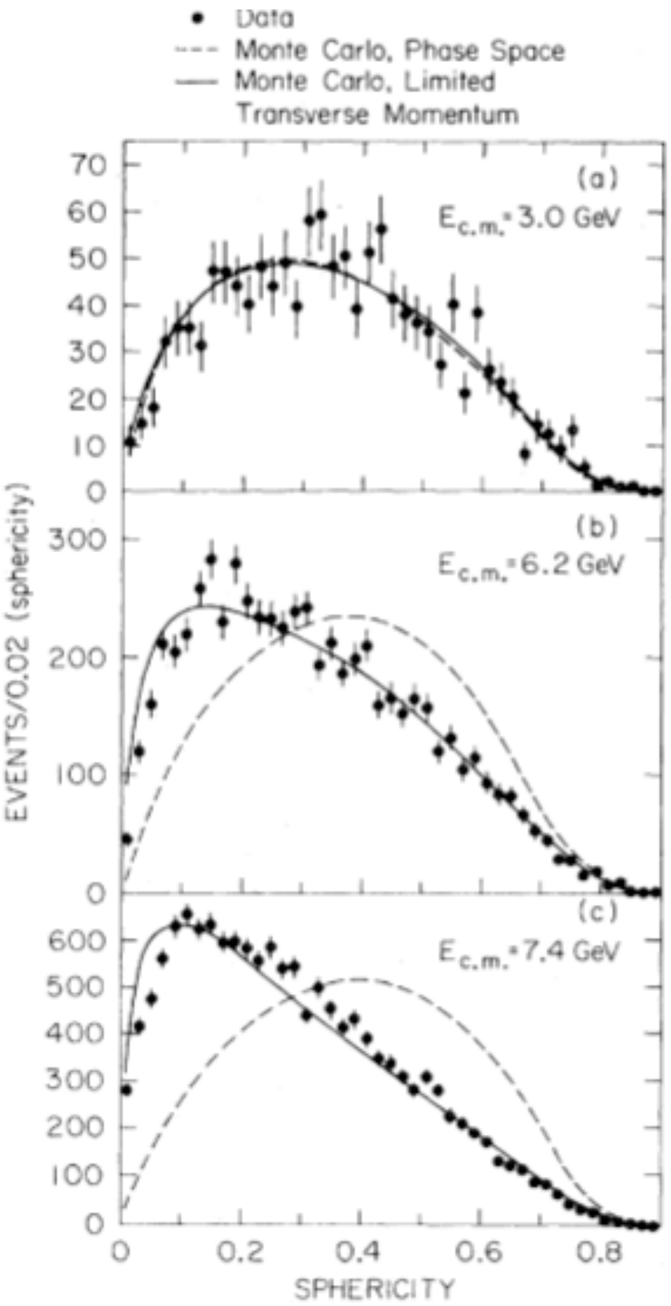
3-jet events: one hard gluon irradiation gives rise to an additional jet (3jet/2jet is a prediction of pQCD)

Several variables can be defined to discriminate "2-jet-like" behaviour wrt isotropic behaviour:

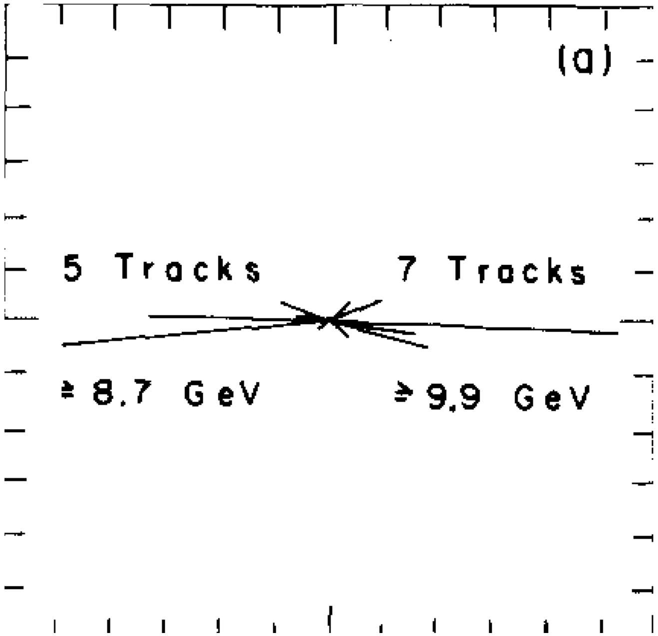
sphericity S $0<S<1$

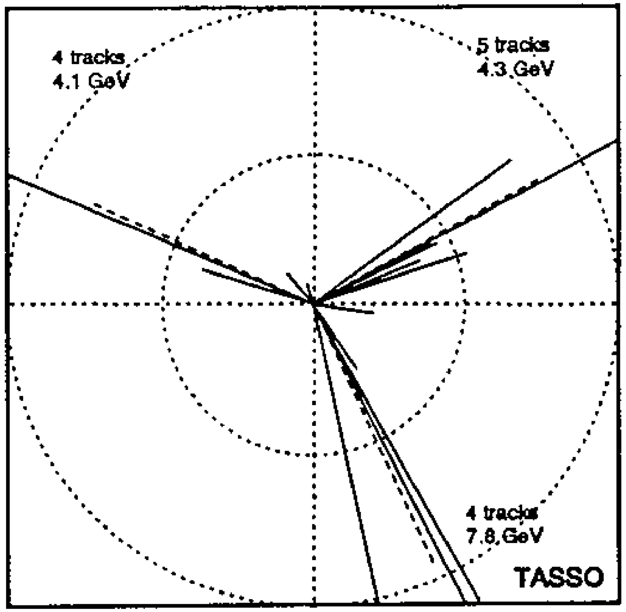
$$S = \frac{3\sum_{k=1}^{N} p_{ti}^2}{2\sum_{k=1}^{N} p_i^2}$$

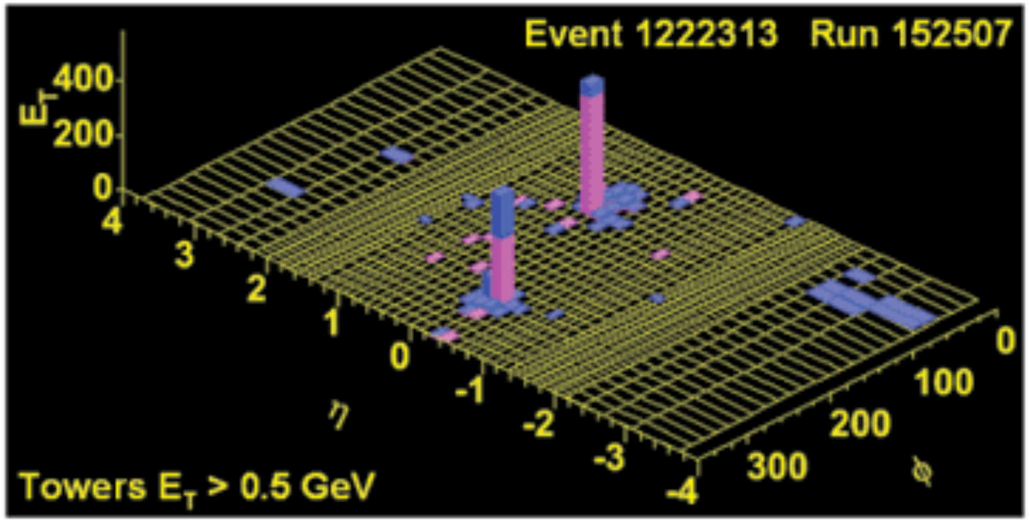
Here, $\boldsymbol{p_{ti}}$ are the transverse momenta of all hadrons in the final state relative to an axis chosen such that the numerator is minimised. (S=0 back-to-back, S=1 isotropic)

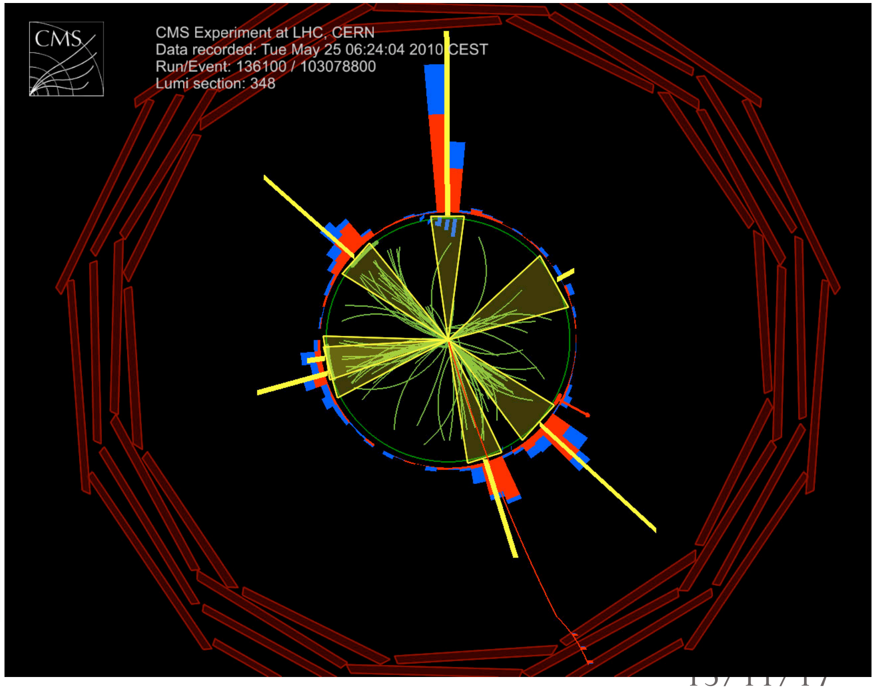


Jets - II


(a)
5 Tracks
7 Tracks
≥ 8.7 GeV
≥ 9.9 GeV


4 tracks
4.1 GeV
5 tracks
4.3 GeV
4 tracks
7.8 GeV
TASSO


Event 1222313 Run 152507
E_T
400
200
0
4
3
2
1
0
-1
-2
-3
-4
η
0
100
200
300
ϕ
Towers E_T > 0.5 GeV

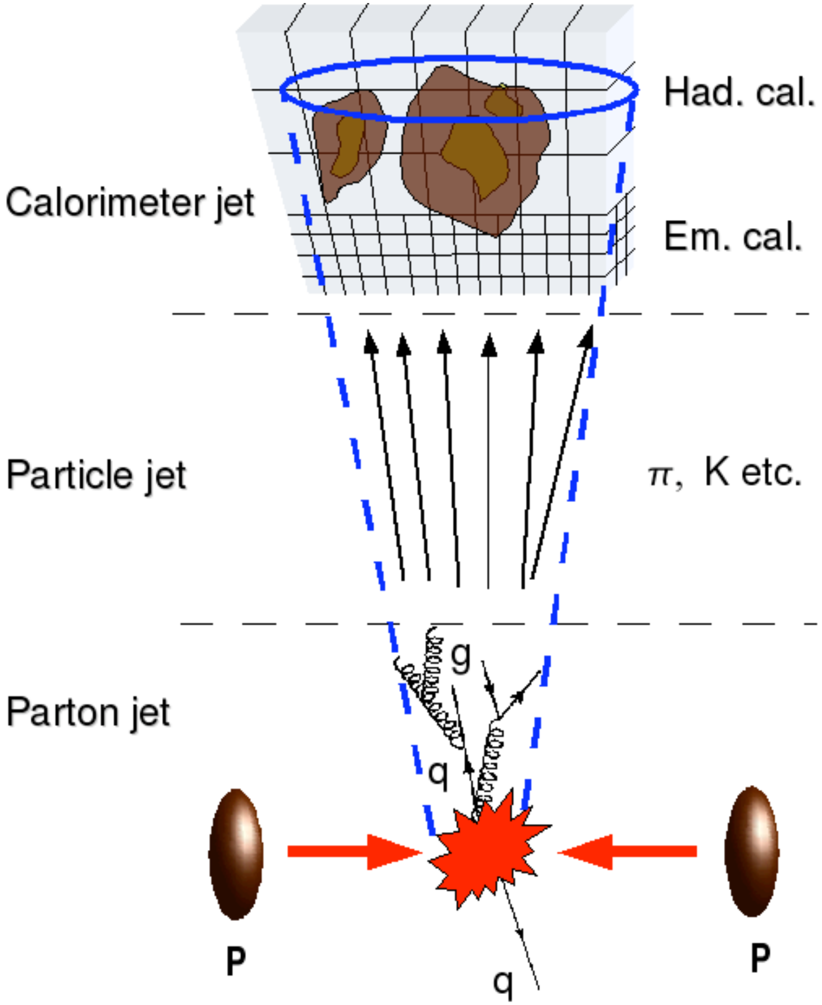

CMS
CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

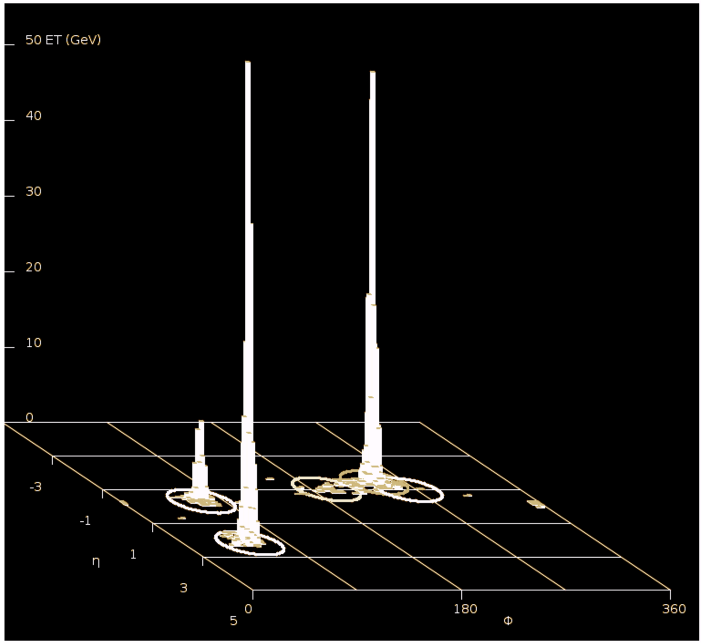
Jets - III

Jet experimental definition:
- based on calorimeter cells
- based on tracks
- → quadri-momentum evaluated (E,p)

Jet algorithms:
- sequential recombination
- cone algorithms
- kT algorithms (against infrared divergences)

$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

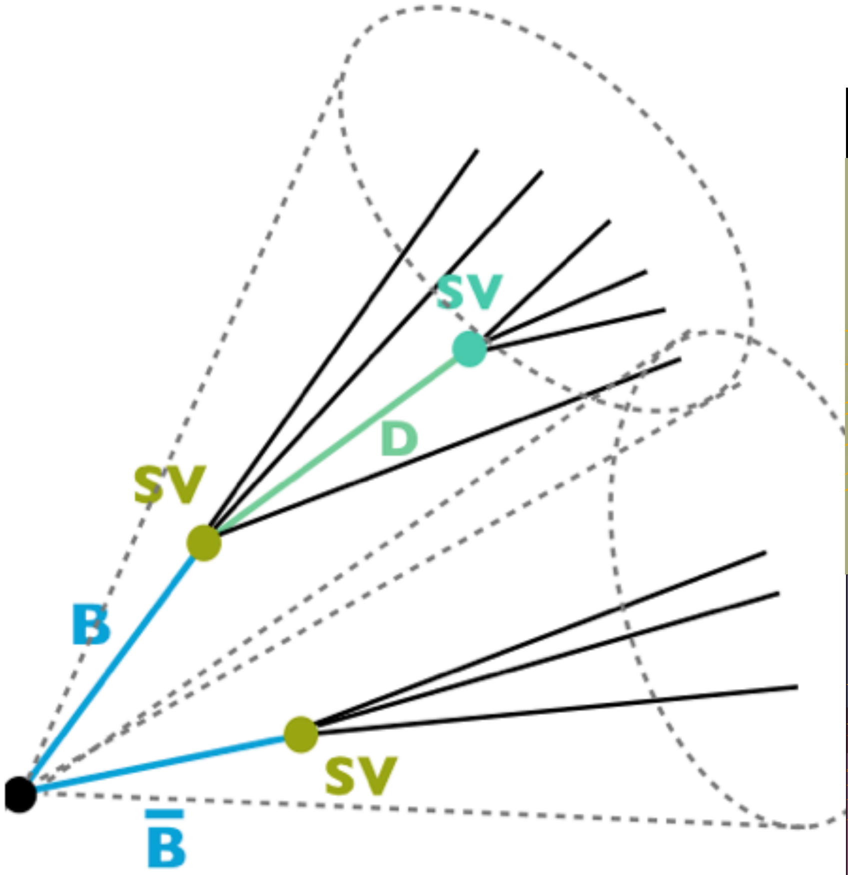


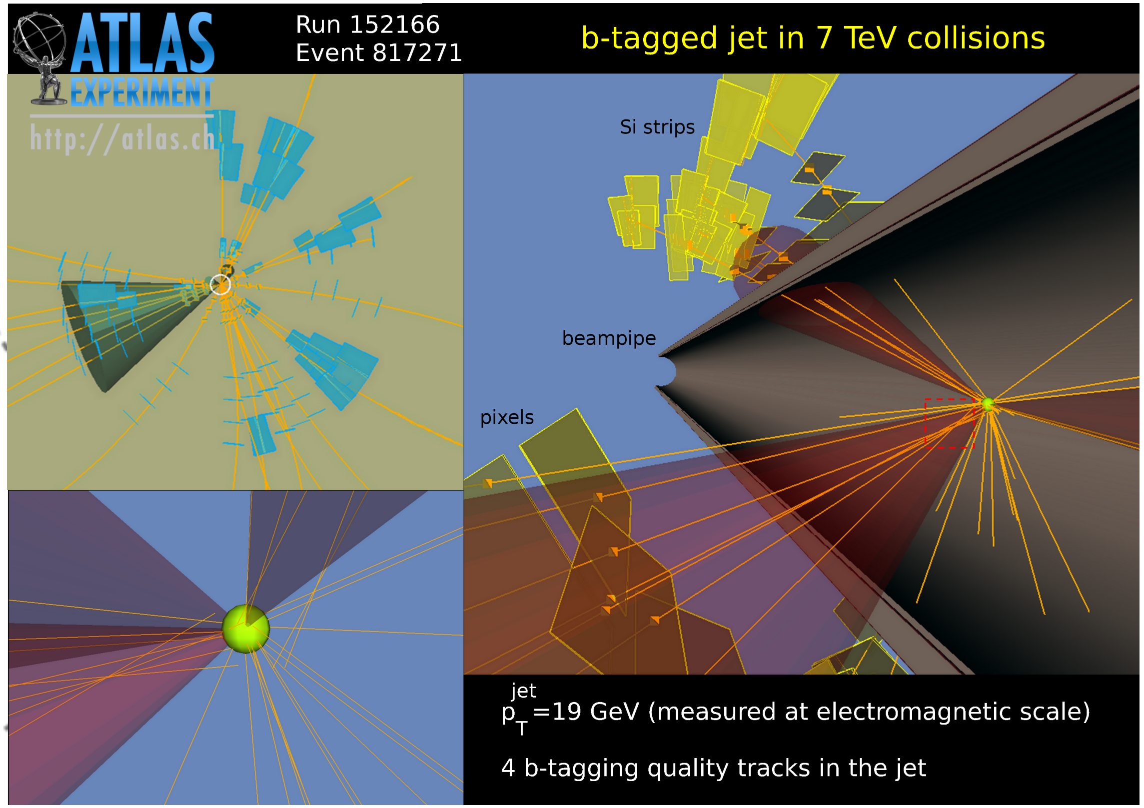


b-Jets

Two main methods to "tag" B-jets:

1) Displaced vertices
2) One or more leptons from semi-leptonic decays. Leptons are not isolated.





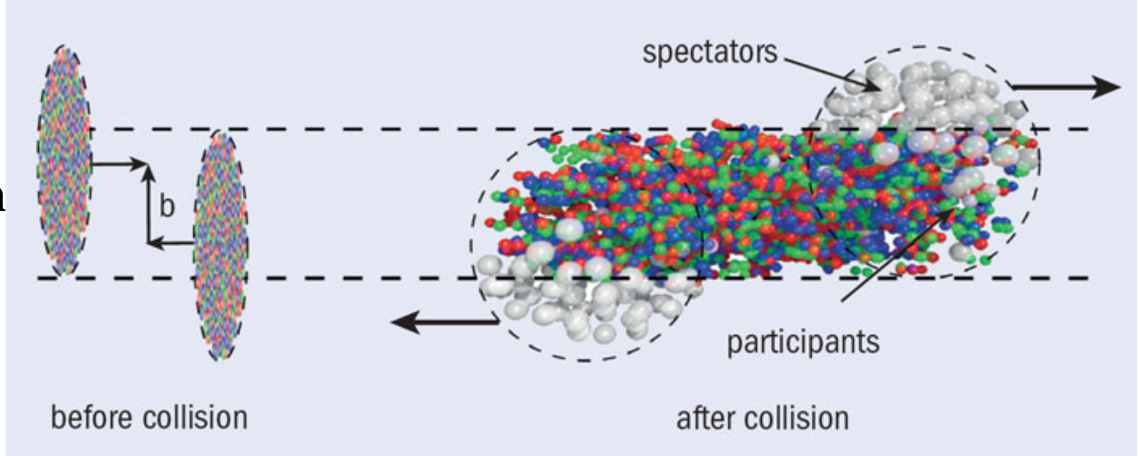
Heavy Ion collisions: the centrality

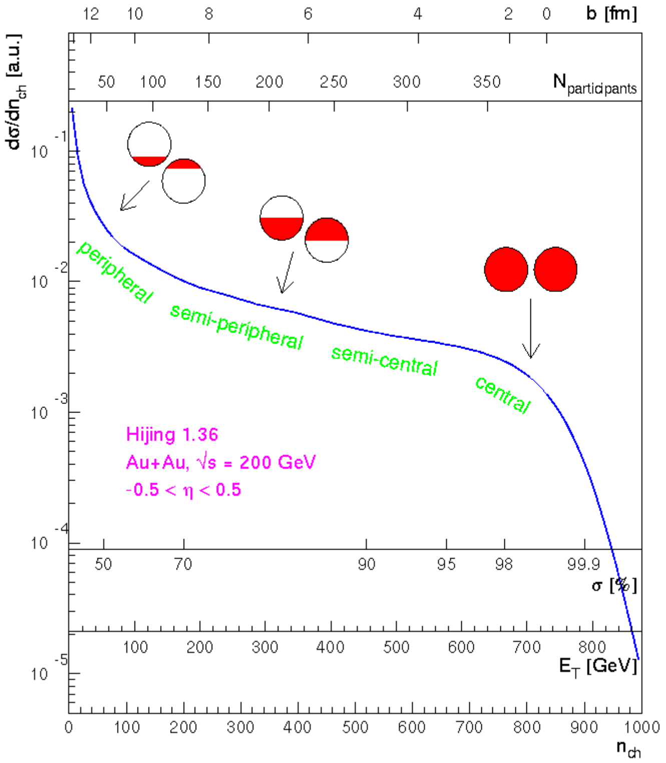
In heavy ion collisions we define the impact parameter ***b***.

b=0 or small ➔ “central” collision

b large ➔ “peripheral” collision

The “***centrality***” is a measure of ***b***





How can we experimentally measure the centrality of each event ?

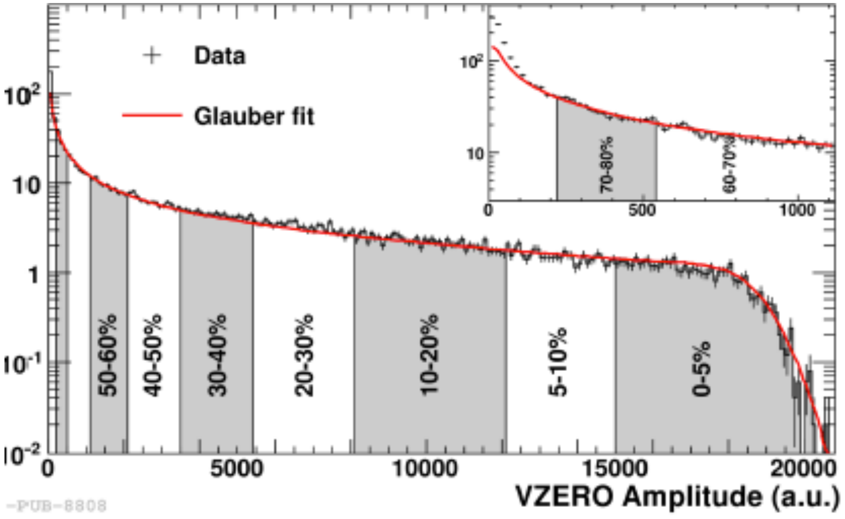
In a heavy ion collision many particles are produced, mostly in the forward region.

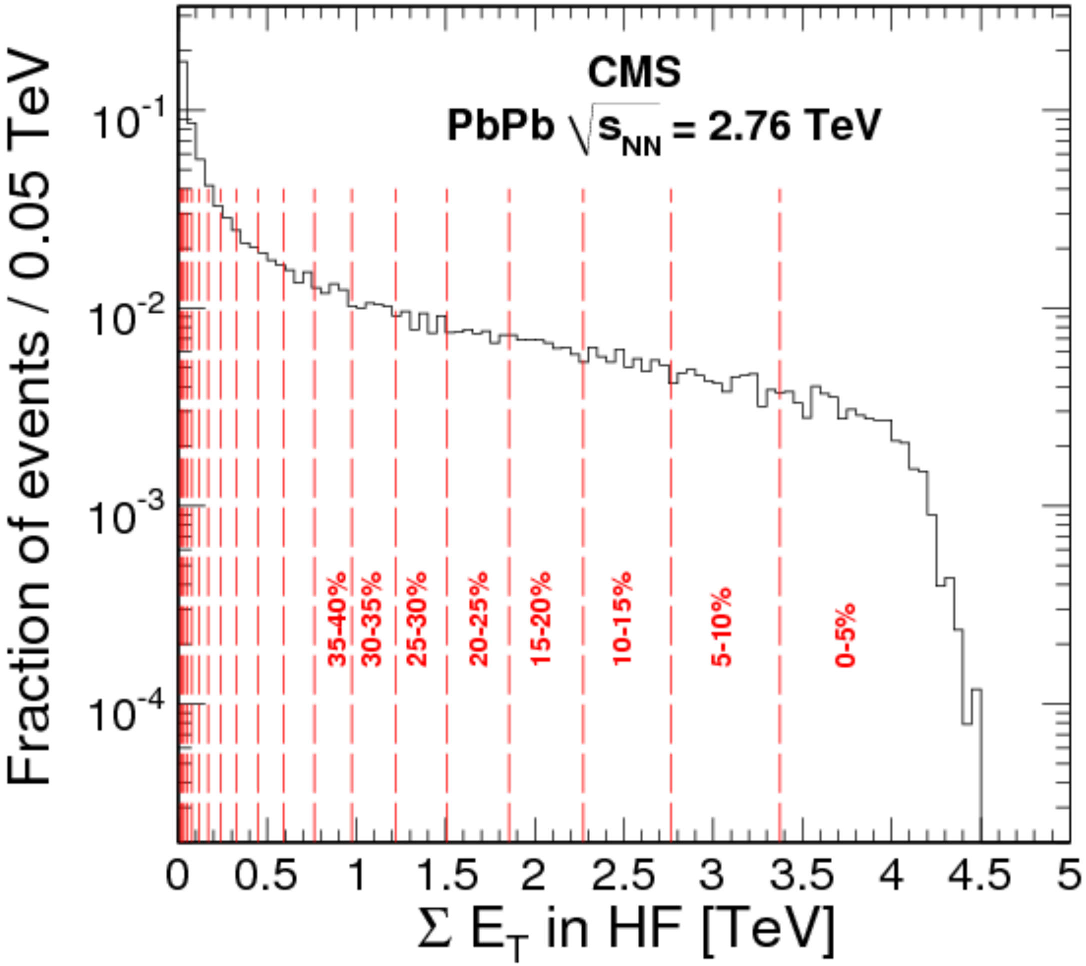
➔ Total energy measured in the Forward detectors

➔ Divide in “percentile” of centralities

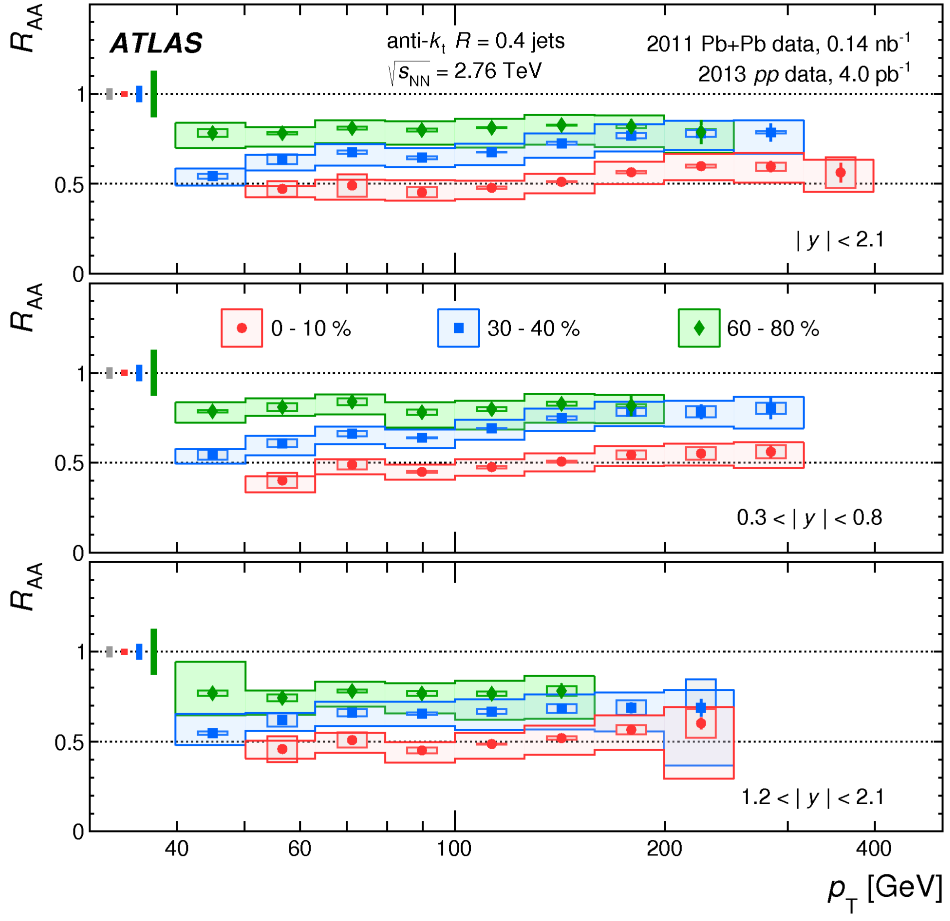
Centrality definition

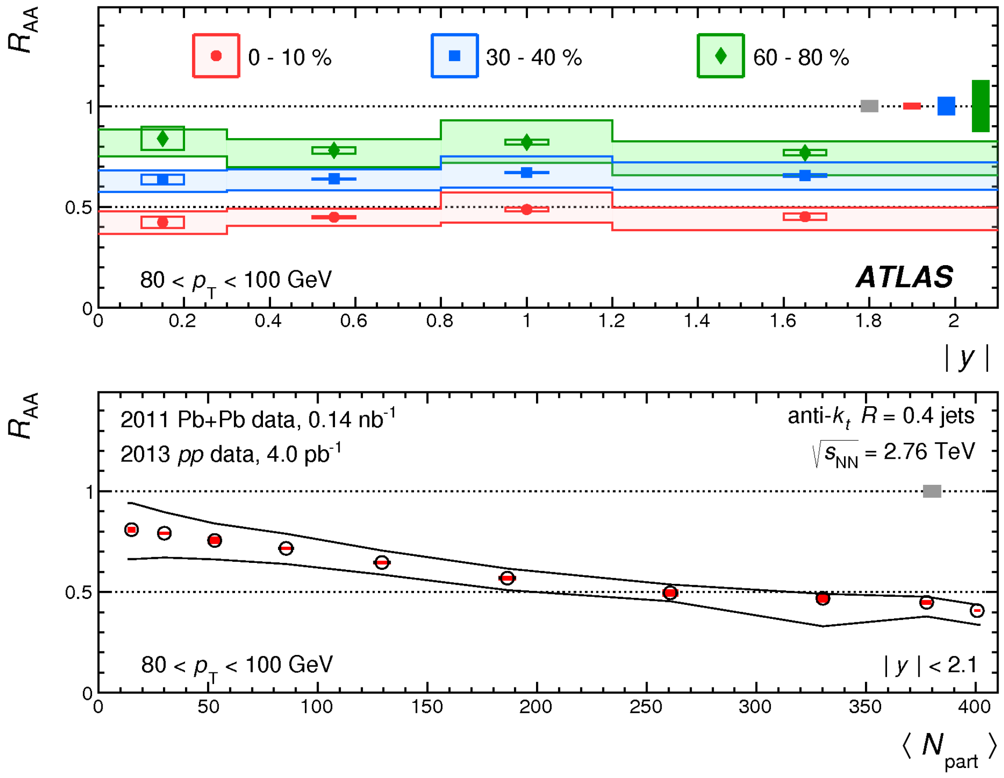
Method: assign to each event a centrality given by the percentile region where the event goes.



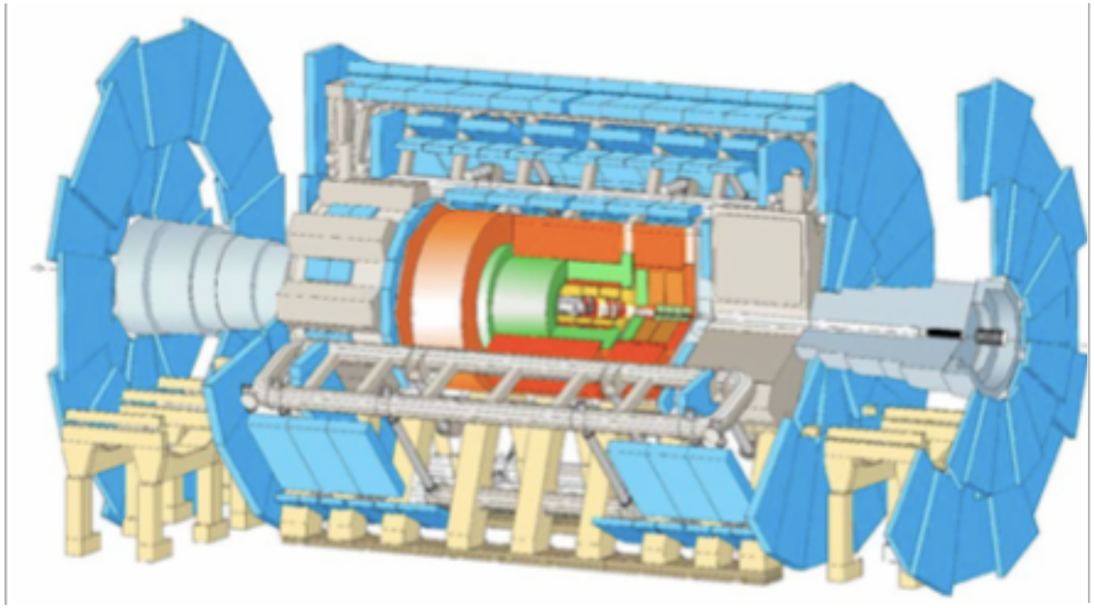


QGP: example of centrality suppression of jets

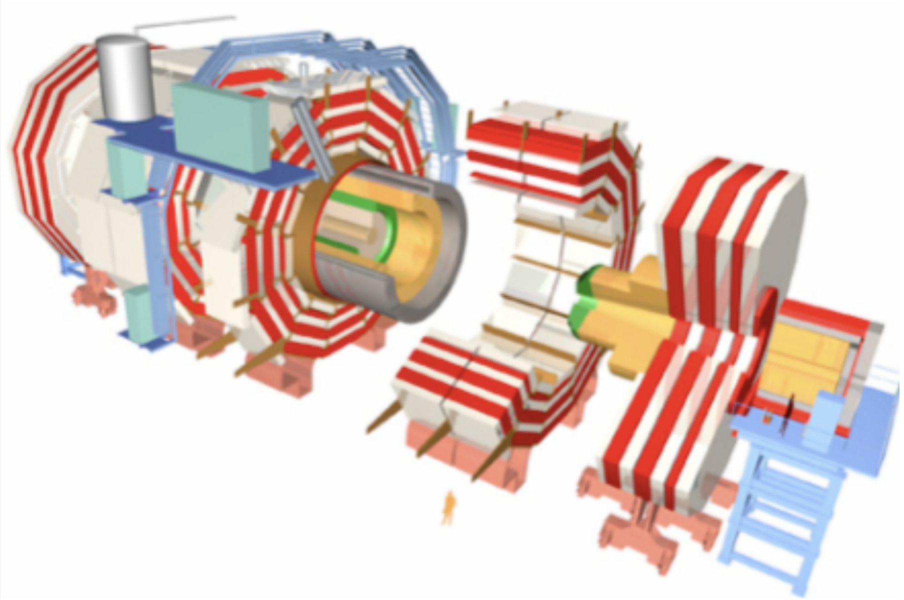




The Giants: ATLAS & CMS



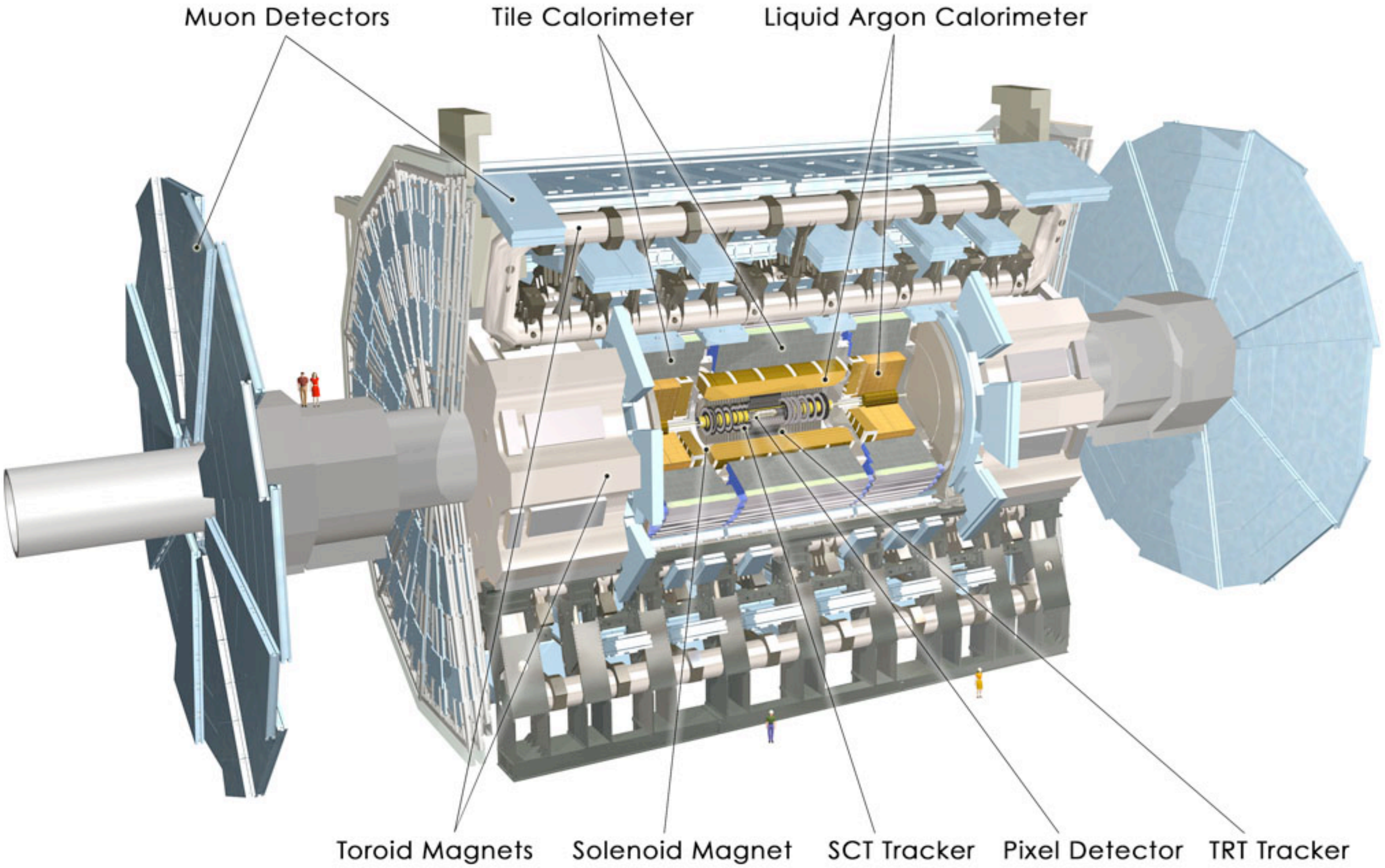
ATLAS (the largest): 46 x 25 m



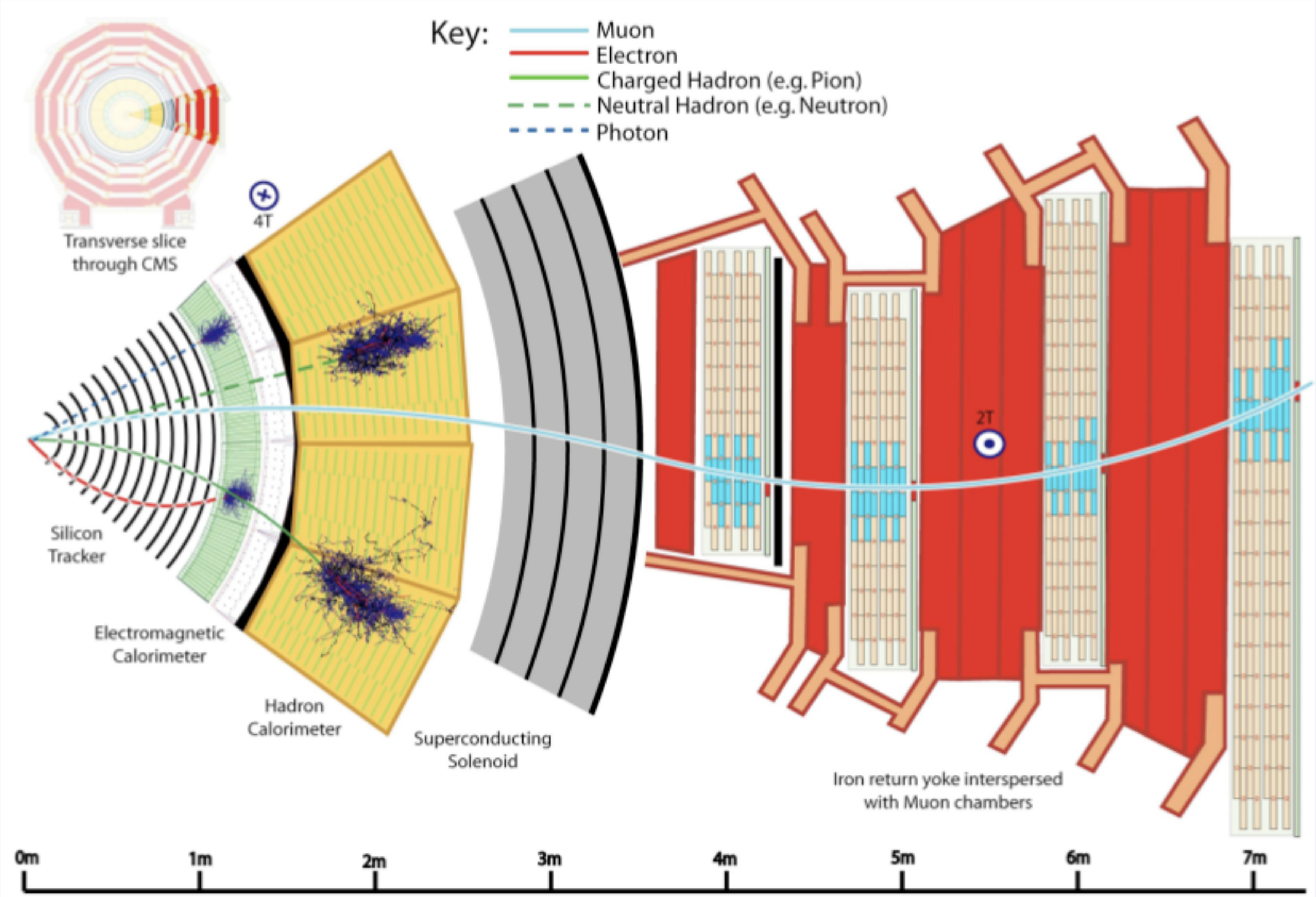
CMS (the heaviest): 12500 tonn

Common structure:	e	μ	Jet	γ	$\not{E}_T$
→ Magnetic Field system	✗	✗			
→ Inner Detector	✗	✗			
→ Electromagnetic Calorimeter	✗		✗	✗	✗
→ Hadronic Calorimeter			✗		✗
→ Muon Spectrometer		✗			

ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

Example: overall structure of the CMS detector



Subdetectors

- Inner Tracker: high space resolution, high resistance to radiation, very high granularity
  - semi-conductor detectors (pixels, silicon strips);
  - gas detectors (ATLAS only) provide electron-hadron separation
- EM calorimetry: good energy resolution, photon identification, high granularity for isolation
- Hadron calorimeter: high eta coverage (for missing mass measurement), moderate granularity to recognize jets
- Muon spectrometer: tagging of muons and standalone trigger. Good momentum resolution (ATLAS only)

ATLAS-CMS: general

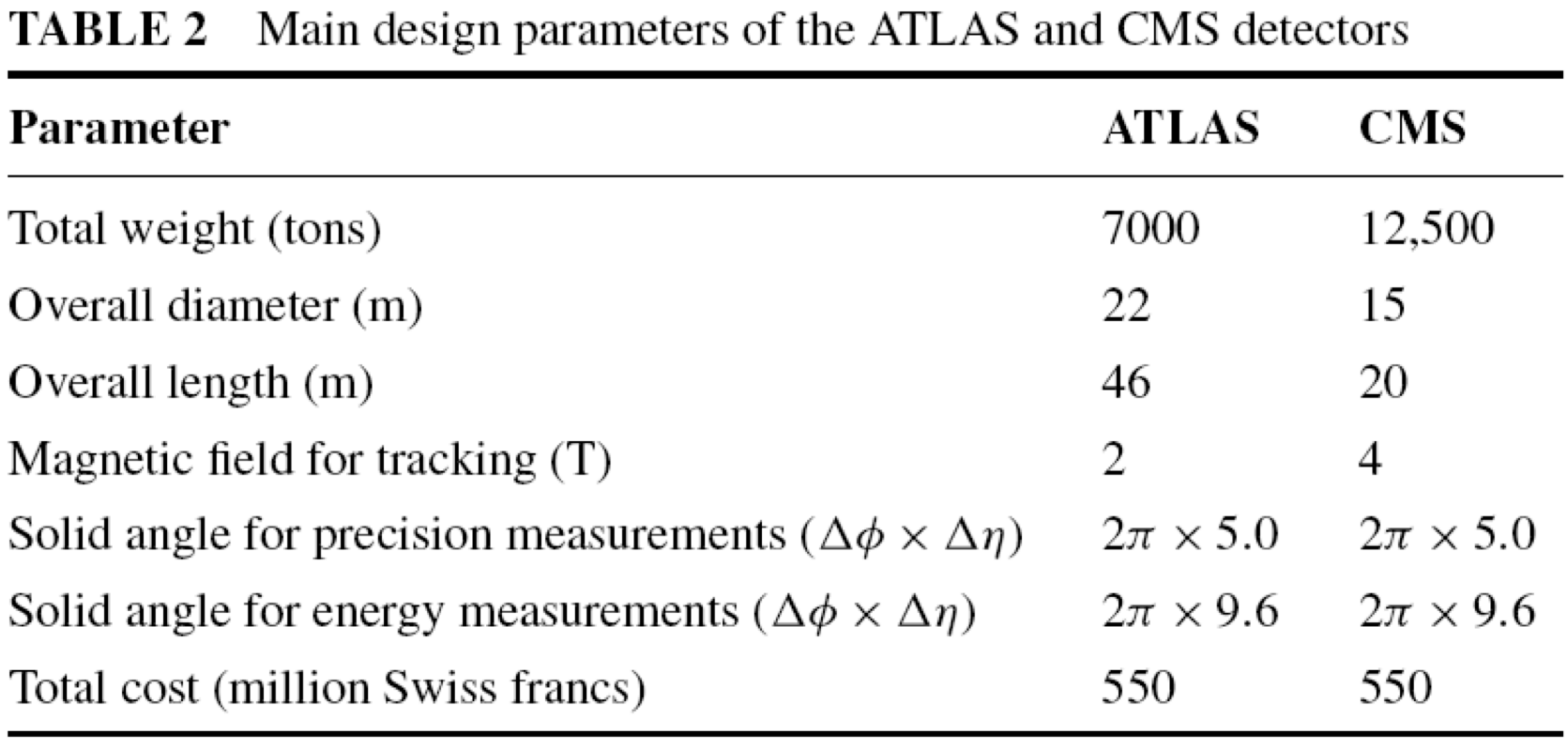


TABLE 2 Main design parameters of the ATLAS and CMS detectors

Parameter	**ATLAS**	**CMS**
Total weight (tons)	7000	12,500
Overall diameter (m)	22	15
Overall length (m)	46	20
Magnetic field for tracking (T)	2	4
Solid angle for precision measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 5.0$	$2\pi \times 5.0$
Solid angle for energy measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 9.6$	$2\pi \times 9.6$
Total cost (million Swiss francs)	550	550

ATLAS-CMS: magnets

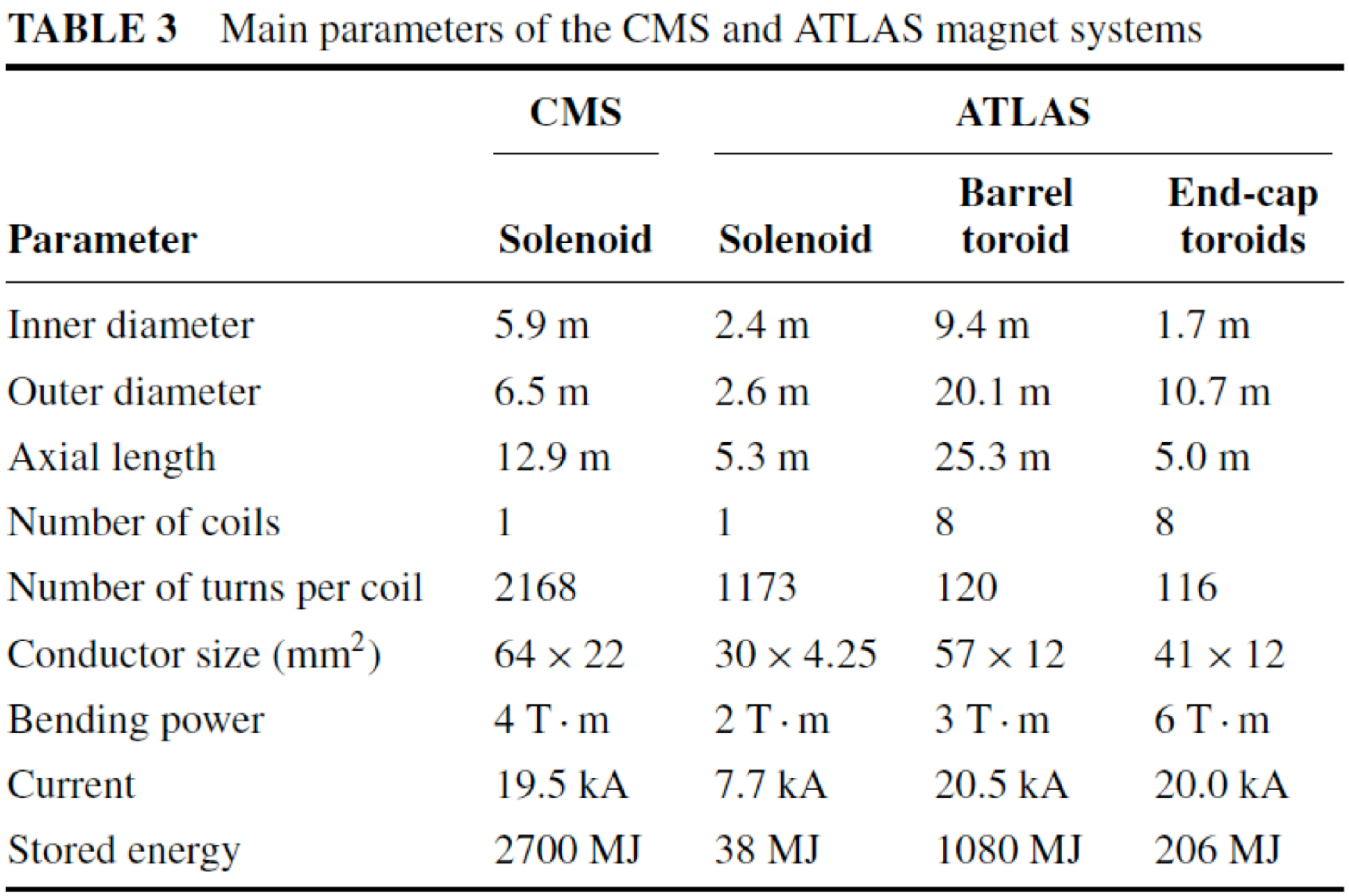


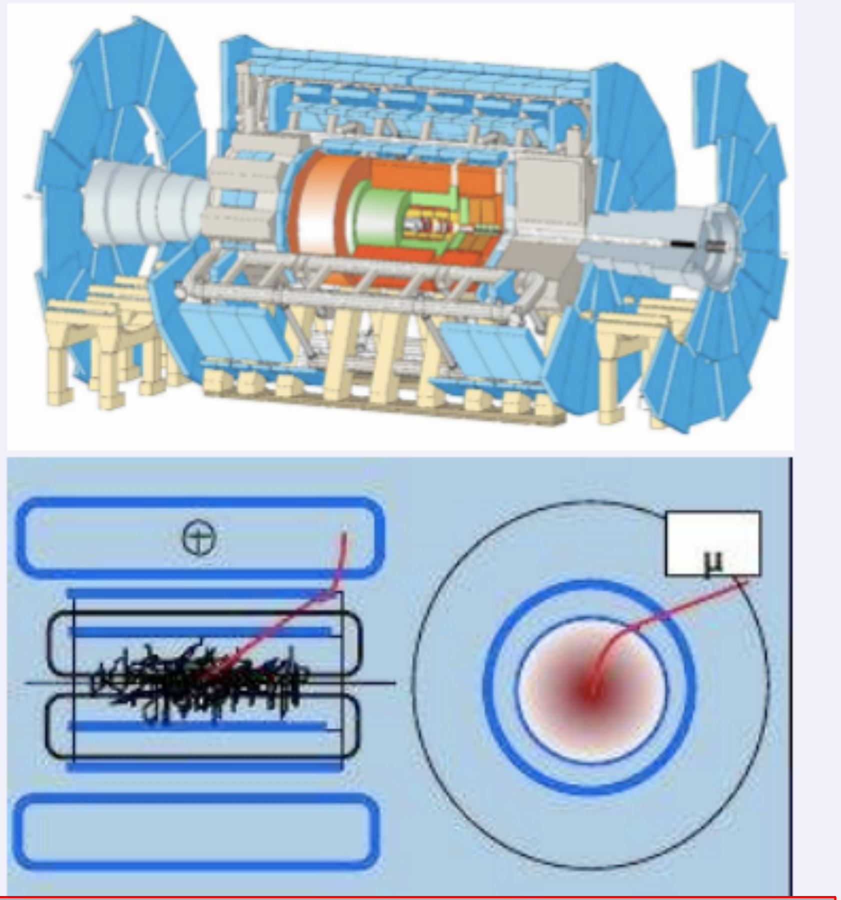
TABLE 3 Main parameters of the CMS and ATLAS magnet systems

	CMS	**ATLAS**		
Parameter	**Solenoid**	**Solenoid**	**Barrel toroid**	**End-cap toroids**
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64×22	30×4.25	57×12	41×12
Bending power	$4\ T \cdot m$	$2\ T \cdot m$	$3\ T \cdot m$	$6\ T \cdot m$
Current	19.5 kA	7.7 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

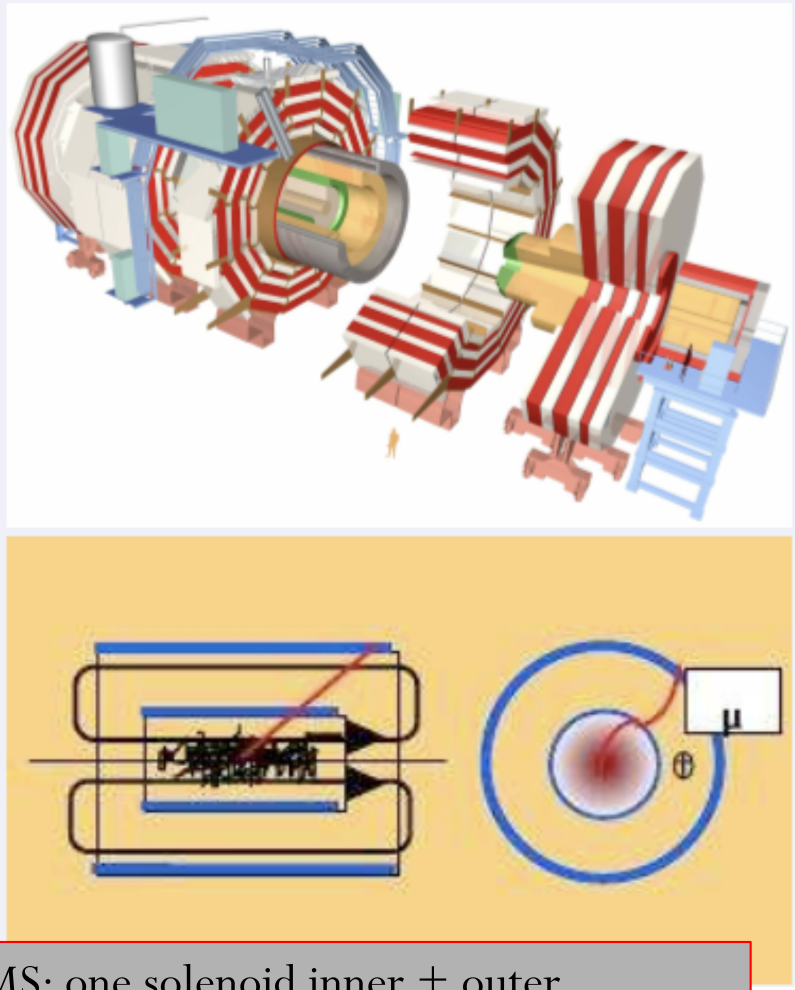
How muons are detected at LHC

→ The calorimeters provide a “natural” muon filter;

→ The magnetic field system. ATLAS and CMS have different approaches



ATLAS: inner solenoid + outer toroids



CMS: one solenoid inner + outer
(reversed direction)

ATLAS-CMS: inner tracker

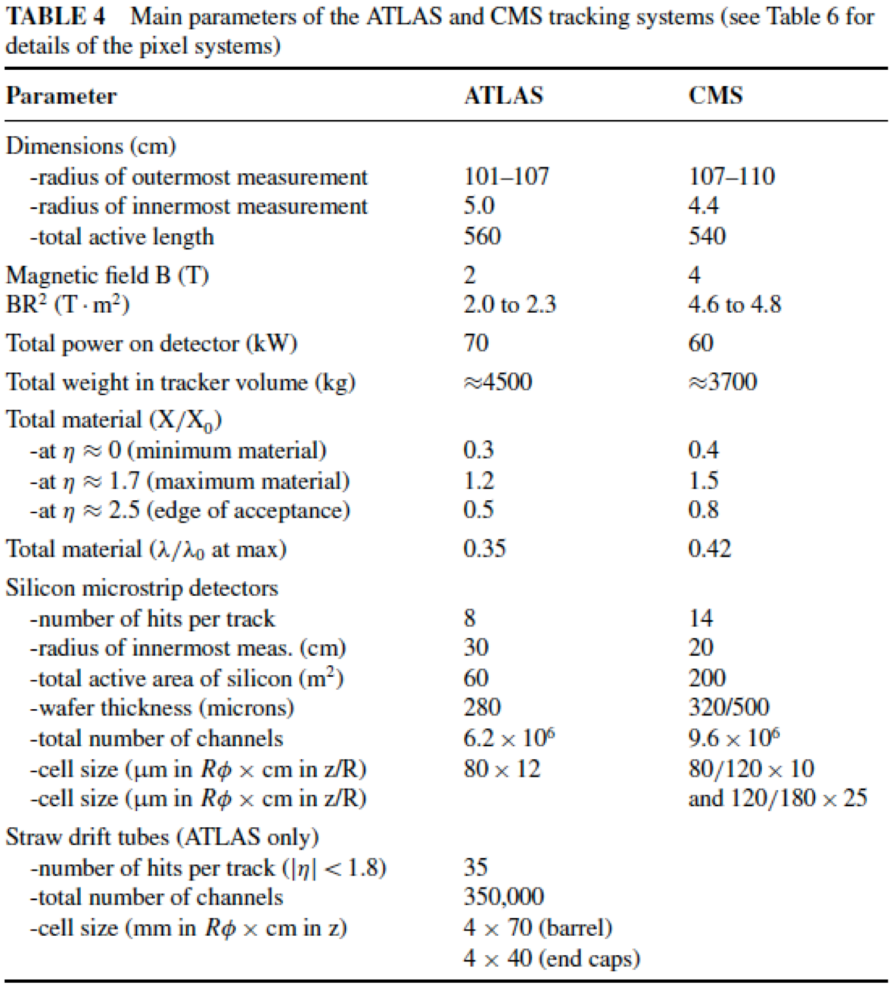


TABLE 4 Main parameters of the ATLAS and CMS tracking systems (see Table 6 for details of the pixel systems)

Parameter	**ATLAS**	**CMS**
Dimensions (cm)		
-radius of outermost measurement	101–107	107–110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Magnetic field B (T)	2	4
BR^2 ($T \cdot m^2$)	2.0 to 2.3	4.6 to 4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈4500	≈3700
Total material (X/X_0)		
-at $\eta \approx 0$ (minimum material)	0.3	0.4
-at $\eta \approx 1.7$ (maximum material)	1.2	1.5
-at $\eta \approx 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon microstrip detectors		
-number of hits per track	8	14
-radius of innermost meas. (cm)	30	20
-total active area of silicon (m^2)	60	200
-wafer thickness (microns)	280	320/500
-total number of channels	6.2×10^6	9.6×10^6
-cell size (μm in $R\phi$ × cm in z/R)	80 × 12	80/120 × 10
-cell size (μm in $R\phi$ × cm in z/R)		and 120/180 × 25
Straw drift tubes (ATLAS only)		
-number of hits per track ($\lvert\eta\rvert < 1.8$)	35	
-total number of channels	350,000	
-cell size (mm in $R\phi$ × cm in z)	4 × 70 (barrel)	
	4 × 40 (end caps)	

ATLAS-CMS: pixel

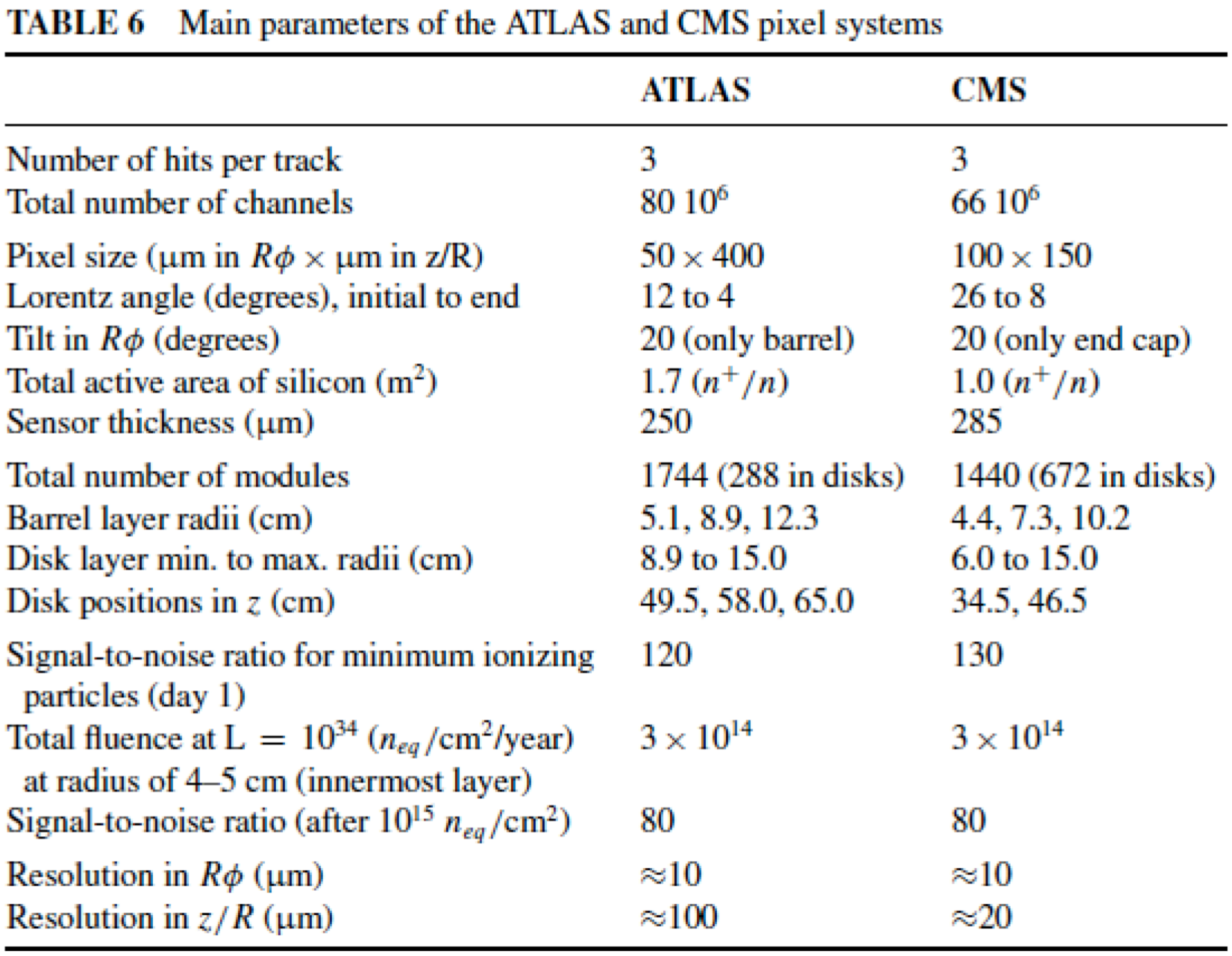


TABLE 6 Main parameters of the ATLAS and CMS pixel systems

	ATLAS	**CMS**
Number of hits per track	3	3
Total number of channels	80 10^6	66 10^6
Pixel size (μm in $R\phi$ × μm in z/R)	50×400	100×150
Lorentz angle (degrees), initial to end	12 to 4	26 to 8
Tilt in $R\phi$ (degrees)	20 (only barrel)	20 (only end cap)
Total active area of silicon (m^2)	1.7 (n^+/n)	1.0 (n^+/n)
Sensor thickness (μm)	250	285
Total number of modules	1744 (288 in disks)	1440 (672 in disks)
Barrel layer radii (cm)	5.1, 8.9, 12.3	4.4, 7.3, 10.2
Disk layer min. to max. radii (cm)	8.9 to 15.0	6.0 to 15.0
Disk positions in z (cm)	49.5, 58.0, 65.0	34.5, 46.5
Signal-to-noise ratio for minimum ionizing particles (day 1)	120	130
Total fluence at $L = 10^{34}$ (n_{eq}/cm^2/year) at radius of 4–5 cm (innermost layer)	3×10^{14}	3×10^{14}
Signal-to-noise ratio (after 10^{15} n_{eq}/cm^2)	80	80
Resolution in $R\phi$ (μm)	≈10	≈10
Resolution in z/R (μm)	≈100	≈20

ATLAS-CMS: ECAL

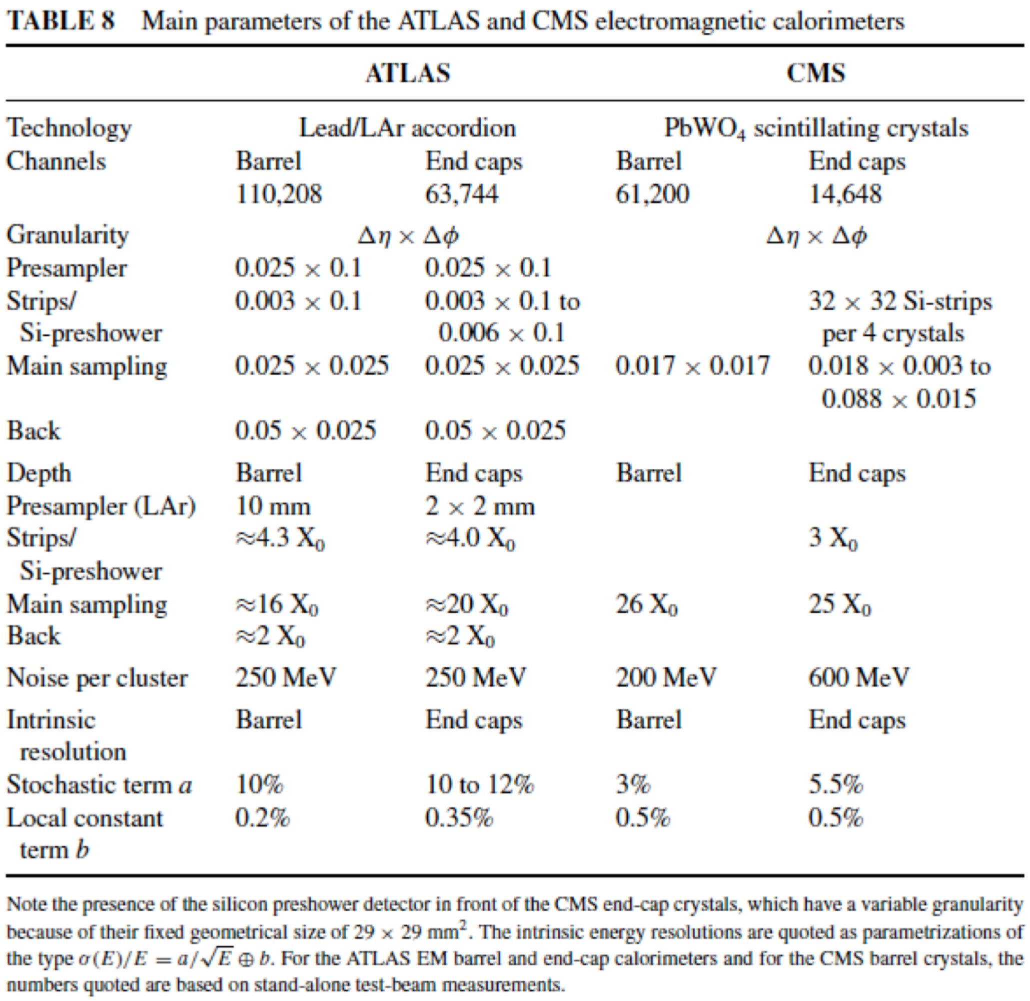


TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		**CMS**	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025 × 0.1	0.025 × 0.1		
Strips/ Si-preshower	0.003 × 0.1	0.003 × 0.1 to 0.006 × 0.1		32 × 32 Si-strips per 4 crystals
Main sampling	0.025 × 0.025	0.025 × 0.025	0.017 × 0.017	0.018 × 0.003 to 0.088 × 0.015
Back	0.05 × 0.025	0.05 × 0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2 × 2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term *a*	10%	10 to 12%	3%	5.5%
Local constant term *b*	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of 29 × 29 mm^2. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

ATLAS-CMS: HCAL

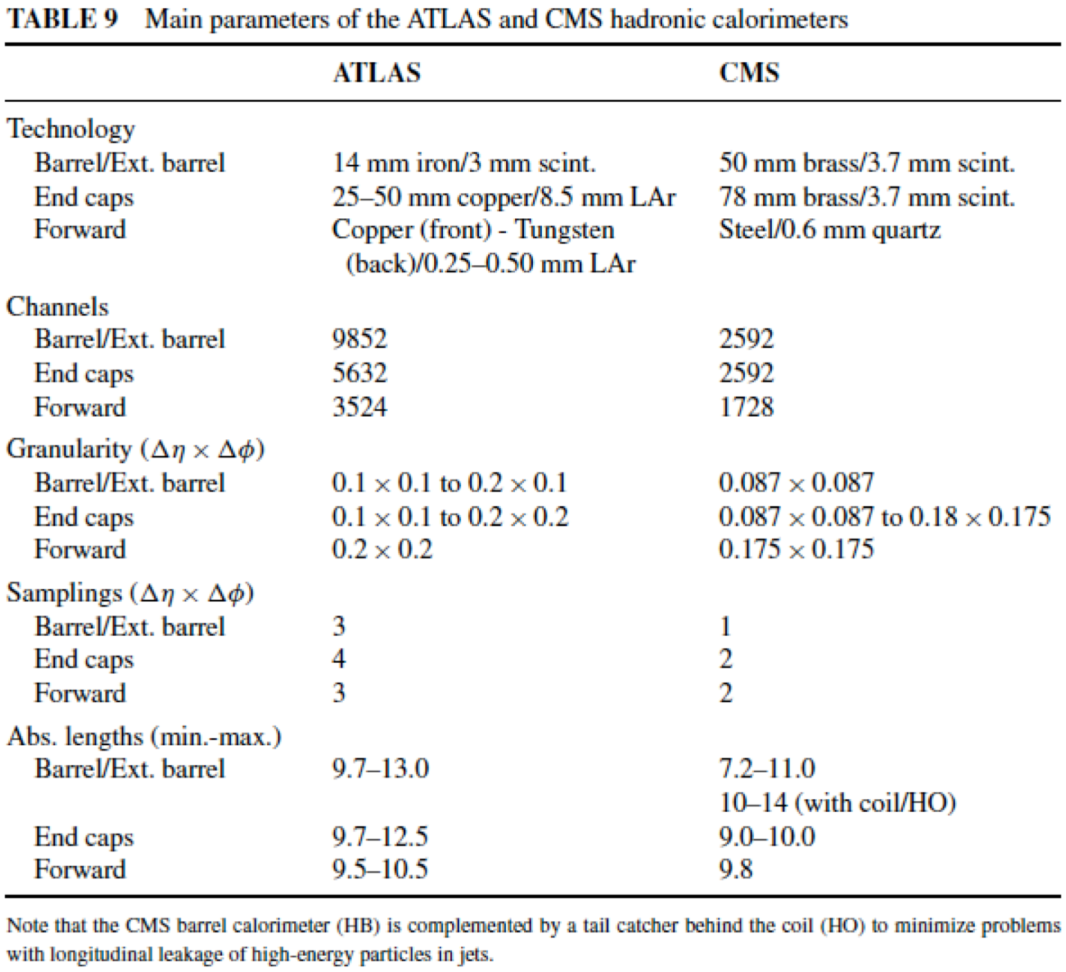
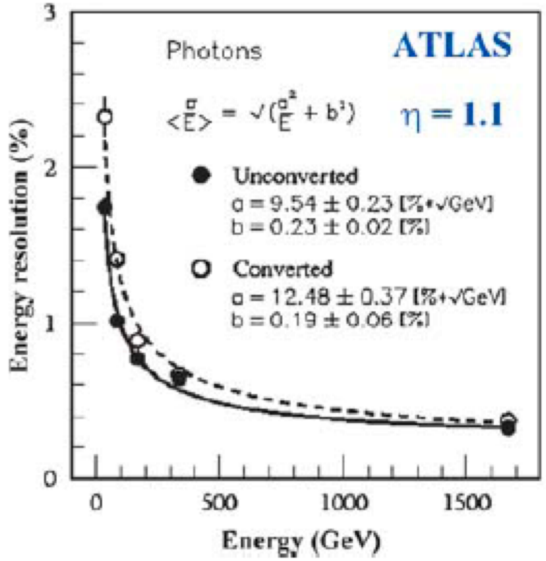


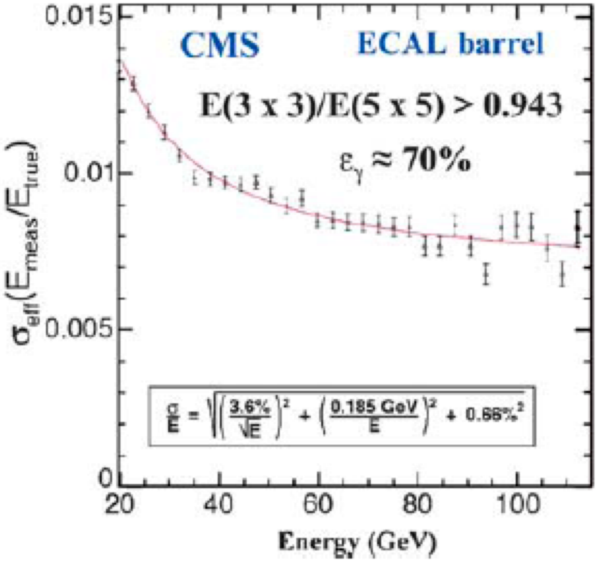
TABLE 9 Main parameters of the ATLAS and CMS hadronic calorimeters

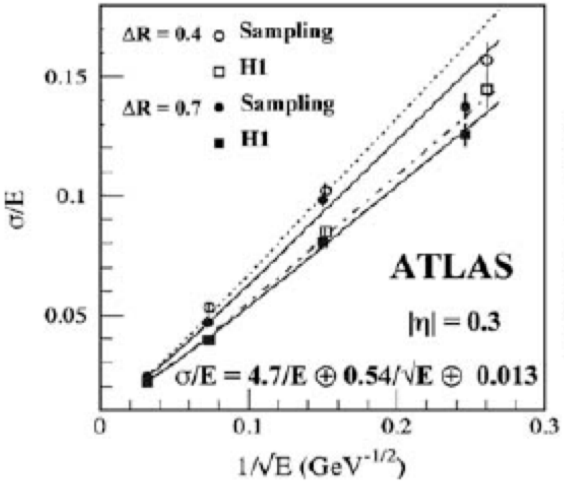
	ATLAS	CMS
Technology		
Barrel/Ext. barrel	14 mm iron/3 mm scint.	50 mm brass/3.7 mm scint.
End caps	25–50 mm copper/8.5 mm LAr	78 mm brass/3.7 mm scint.
Forward	Copper (front) - Tungsten (back)/0.25–0.50 mm LAr	Steel/0.6 mm quartz
Channels		
Barrel/Ext. barrel	9852	2592
End caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	0.1×0.1 to 0.2×0.1	0.087×0.087
End caps	0.1×0.1 to 0.2×0.2	0.087×0.087 to 0.18×0.175
Forward	0.2×0.2	0.175×0.175
Samplings ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	3	1
End caps	4	2
Forward	3	2
Abs. lengths (min.-max.)		
Barrel/Ext. barrel	9.7–13.0	7.2–11.0 10–14 (with coil/HO)
End caps	9.7–12.5	9.0–10.0
Forward	9.5–10.5	9.8

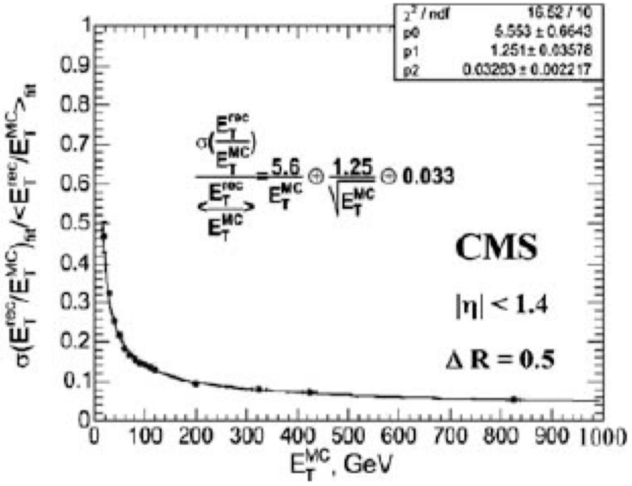
Note that the CMS barrel calorimeter (HB) is complemented by a tail catcher behind the coil (HO) to minimize problems with longitudinal leakage of high-energy particles in jets.

ATLAS-CMS: calorimeters









ATLAS-CMS: muons

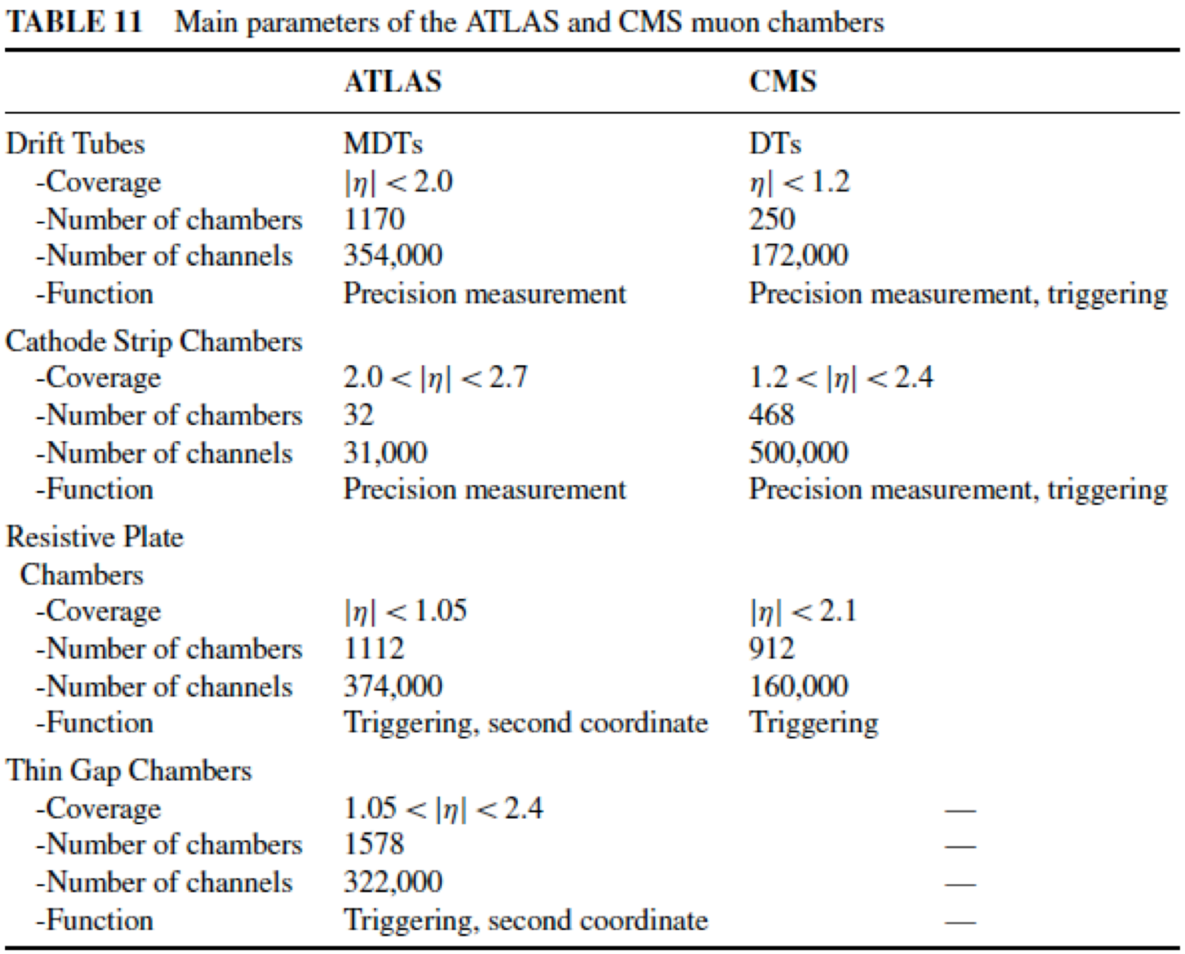


TABLE 11 Main parameters of the ATLAS and CMS muon chambers

	ATLAS	**CMS**
Drift Tubes	MDTs	DTs
-Coverage	$\|\eta\| < 2.0$	$\eta\| < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement, triggering
Cathode Strip Chambers		
-Coverage	$2.0 < \|\eta\| < 2.7$	$1.2 < \|\eta\| < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive Plate Chambers		
-Coverage	$\|\eta\| < 1.05$	$\|\eta\| < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin Gap Chambers		
-Coverage	$1.05 < \|\eta\| < 2.4$	—
-Number of chambers	1578	—
-Number of channels	322,000	—
-Function	Triggering, second coordinate	—

ATLAS-CMS: muon momentum resolutions

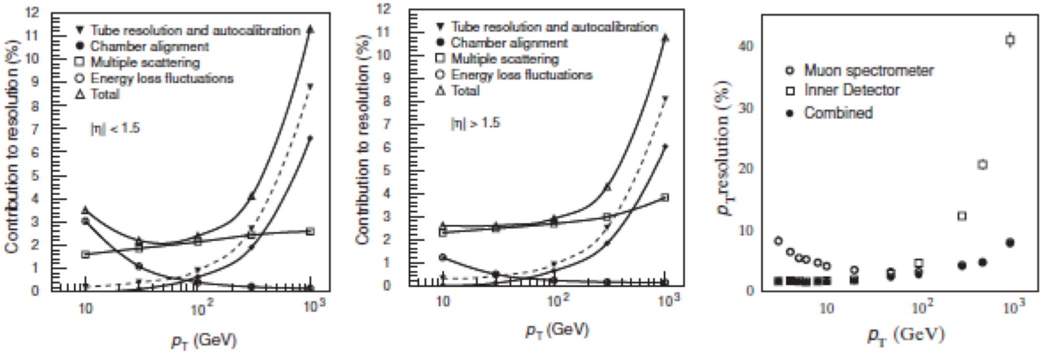


Figure 24 Expected performance of the ATLAS muon measurement. Contributions to the momentum resolution in the muon spectrometer averaged over $|\eta| < 1.5$ (*left*) and $1.5 < |\eta| < 2.7$ (*center*). (*Right*) Muon momentum resolution expected from muon spectrometer, Inner Detector, and their combination together as a function of muon transverse mor

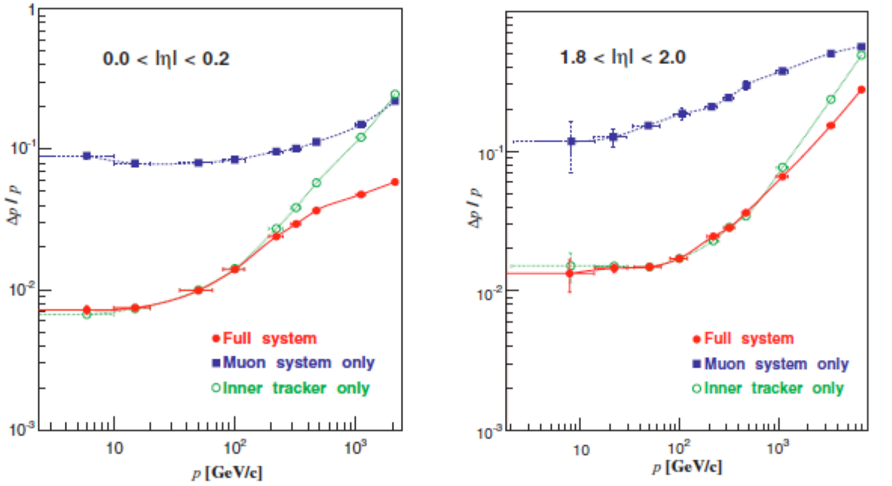


Figure 25 Expected performance of the CMS muon measurement. The muon momentum resolution is plotted versus momentum using the muon system only, the inner tracker only, or their combination (full system). (*Left*) Barrel, with $|\eta| < 0.2$. (*Right*) End cap, with $1.8 < |\eta| < 2.0$.

ATLAS vs. CMS

- Driven by the goal to achieve a high-precision stand-alone momentum measurement of muons "achieved using an arrangement of a small-radius thin-walled solenoid integrated into the cryostat of the barrel ECAL, surrounded by a system of three large air-core toroids, situated outside the ATLAS calorimeter systems, and generating the magnetic field for the muon spectrometer."
- Electrons
  - ECAL, and matching between the E,p measured by ECAL and tracker
  - Also enhenced by ATLAS TRT's ability to separate electrons from charged pions
- ATLAS solenoid is located just in front of the barrel ECAL, resulting in significant energy loss by electrons and photons in the material in front of the active ECAL
- HCAL is thick enough: good jet and missing E_T measurement

- A single magnet with "a high magnetic field in the tracker volume for all precision momentum measurements, and a high enough return flux in the iron outside the magnet to provide a muon trigger and a second muon momentum measurement."
- Invested in highest possible magnetic filed: 4T → better tracking resolution than ATLAS
  - Inner tracker consisting of all silicon detectors
- γ/Electrons → High resolution crystals, better than ATLAS
- The full EM calorimetry and most of its hadronic alorimetry are situated inside the solenoid coil and therefore bathed in the strong 4 T magnetic field
- HCAL. The strong constraints imposed by the CMS solenoid have resulted in a barrel hadronic calorimeter with insufficient absorption (~ 7 absorption lengths). So a tail catcher (HO) has been added around the coil to complement the HB. But still, over-all, CMS jet resolution is worse than ATLAS.

An important quest for pp experiments: the *Trigger*

$$\dot{N} = \sigma_{tot} L \approx 10^{-25} cm^2 \times 10^{32 \div 34} cm^{-2} s^{-1} = 10\,MHz \div 1GHz$$

bunch crossing rate = 40 MHz
➔ every b.c. contains at least
an interaction (25/b.c. at max L)

- Technically impossible and physically not interesting to register all b.c.s
- Retain only "interesting" b.c.
  ➔ TRIGGER = online decision: take or reject the b.c.
- *Decision has to be fast;*
- *Criteria have to be flexible and scalable;*
- *Thresholds have to be defined.*