The projectiles and the targets: cosmic rays, particle accelerators

Cosmic Rays - I

Distinction between "primary" and "secondary" cosmic rays. Primaries are: protons, light Nuclei and γ. (+ others like electrons/positrons…)

Table 28.1: Relative abundances F of cosmic-ray nuclei at 10.6 GeV/nucleon normalized to oxygen ($\equiv 1$) [7]. The oxygen flux at kinetic energy of 10.6 GeV/nucleon is 3.29×10^{-2} $(\mathrm{m}^2\ \mathrm{s}\ \mathrm{sr}\ \mathrm{GeV/nucleon})^{-1}$. Abundances of hydrogen and helium are from Refs. [3,4]. Note that one can not use these values to extend the cosmic-ray flux to high energy because the power law indicies for each element may differ slightly.

Z	Element	F
1	H	540
2	He	26
3–5	Li-B	0.40
6–8	C-O	2.20
9–10	F-Ne	0.30
11–12	Na-Mg	0.22
13–14	Al-Si	0.19
15–16	P-S	0.03
17–18	Cl-Ar	0.01
19–20	K-Ca	0.02
21–25	Sc-Mn	0.05
26–28	Fe-Ni	0.12

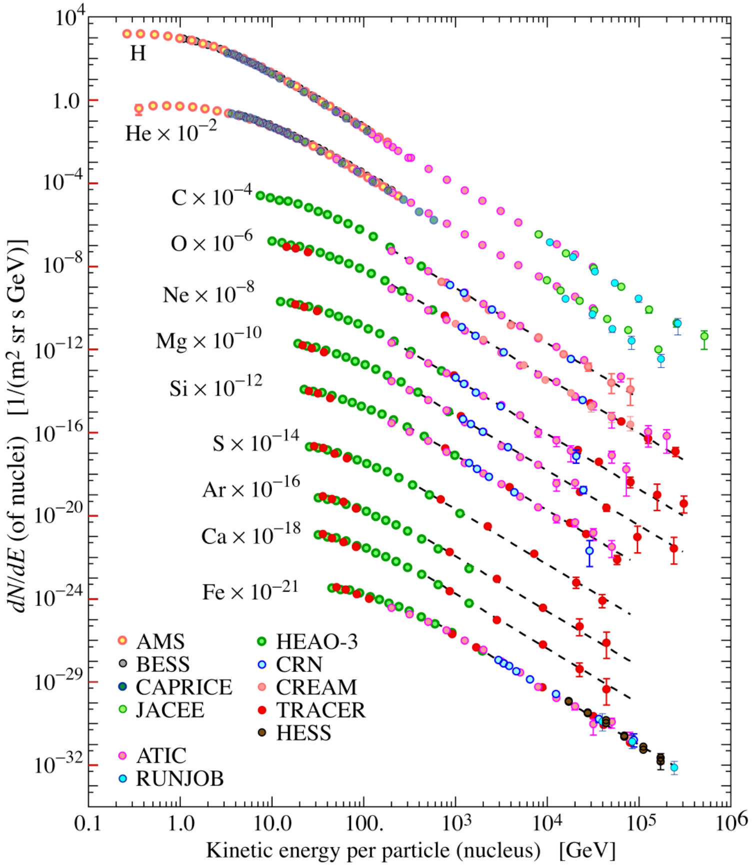
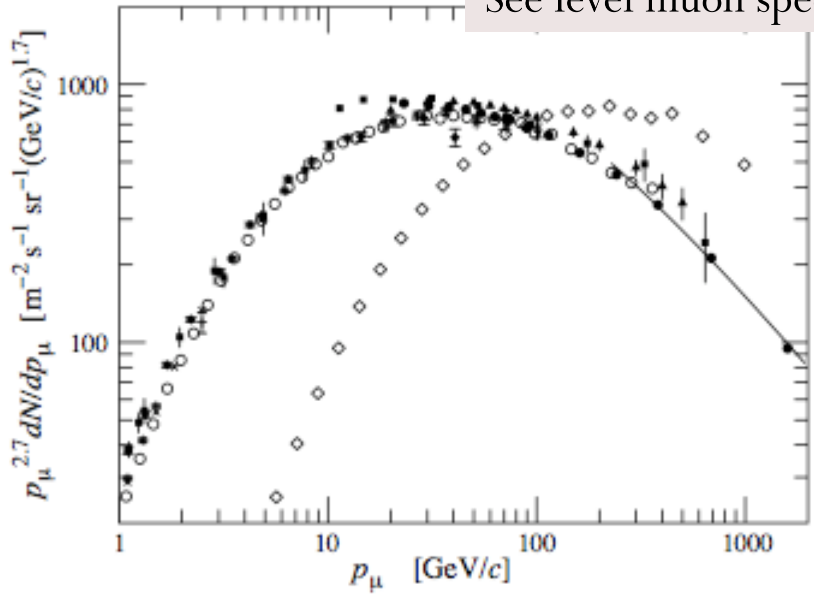


Figure 28.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–13].

Cosmic rays - II

- At sea level cosmic rays are essentially muons. Rate ≈ 70 m^{-2} s^{-1} sr^{-1} ➔ 1 $cm^{-2} min^{-1}$ (≈ 2 Hz/dm^2) horiz. detector.
- Angular distribution: ≈ $\cos^2\theta$



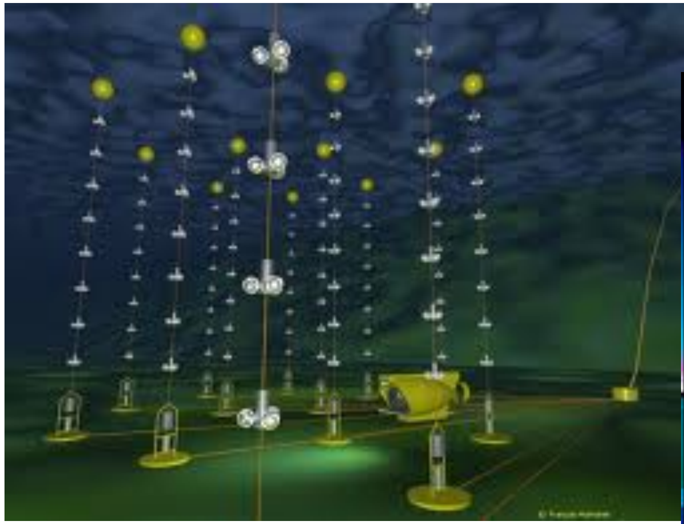
See level muon spectrum

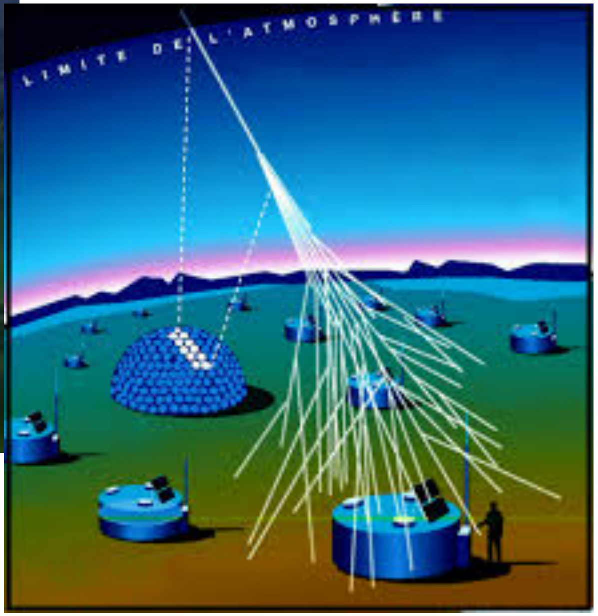
Cosmic rays - III

- Many discoveries of particles have been done in the past in experiments using cosmic rays as projectiles:
  - Positron
  - Muon
  - Pion
  - Kaon
- Today, large experiments use cosmic rays for specific studies:
  - Astrophysical objects (AGN, pulsars, anisotropies,…)
  - Fundamental phsyics phenomena (ZKP effect) profiting of the ultra high energy of the primary
  - Matter/Antimatter and Dark Matter
- Experiments located in the ground, underground (or deep in the oceans) and in the space

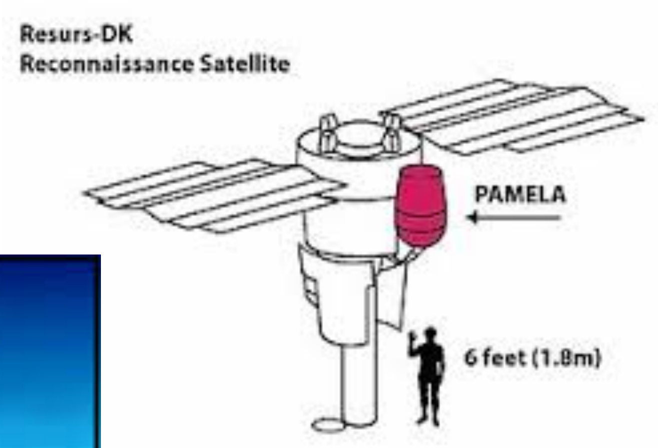
Present cosmic ray experiments

Underwater experiment: ANTARES





Ground based experiment: AUGER



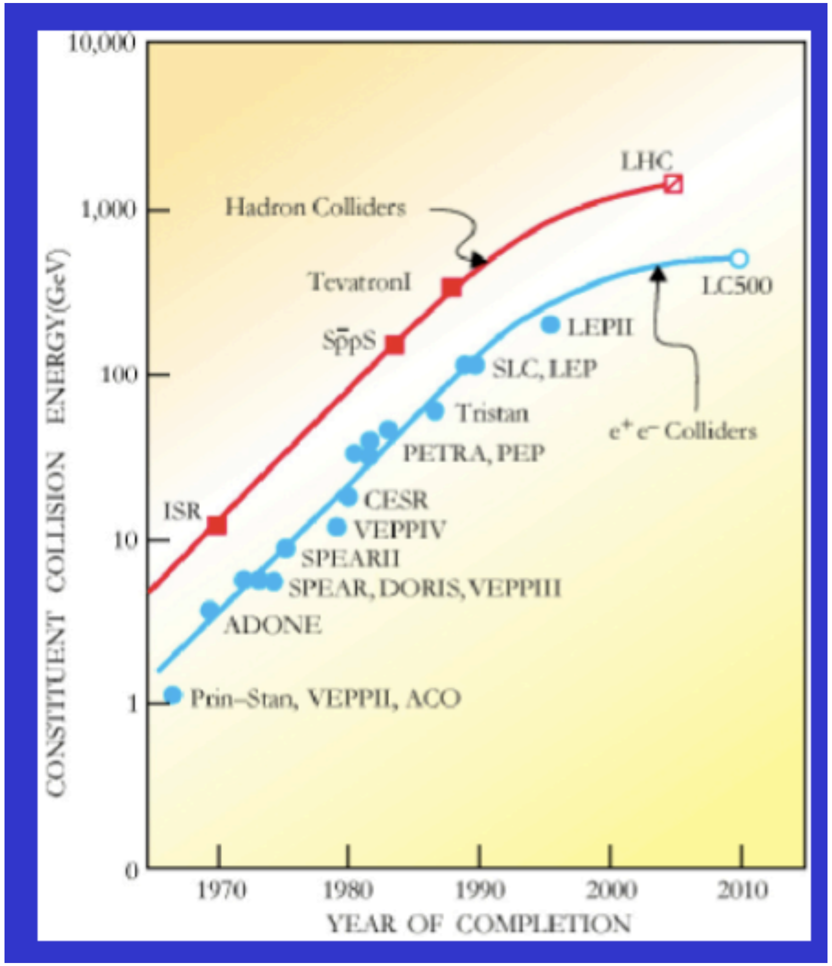
Satellite based experiment: PAMELA

We will discuss AMS in a specific lecture.

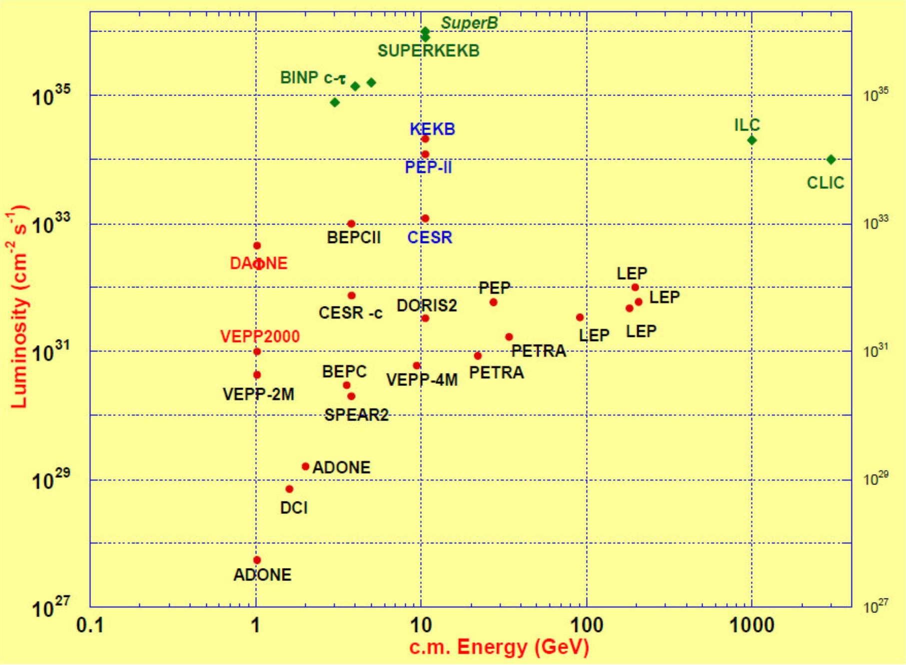
Particle Accelerator Physics

- 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.

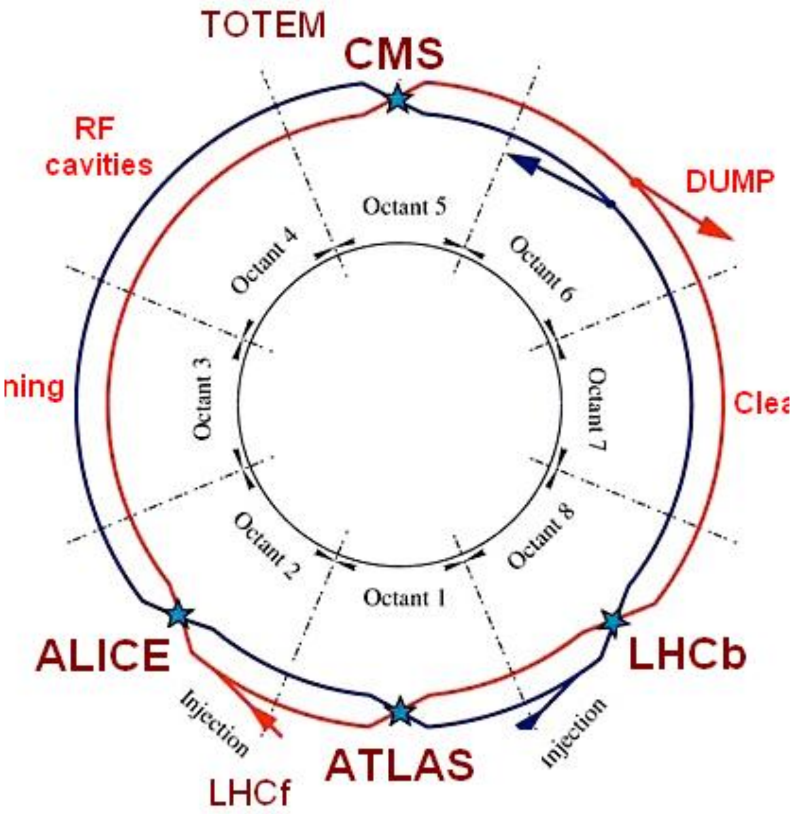
  - "bunches" of particles (typically $N \approx 10^{10}$-10^{12} / bunch) in small transverse dimensions (σ_X, σ_Y down to < mm level) and higher longitudinal dimensions (σ_Z at cm level) like *needles* or *ribbons.*
  - the bunches travel along a ≈ circular trajectory (curvilinear coordinate s)
    - 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**:

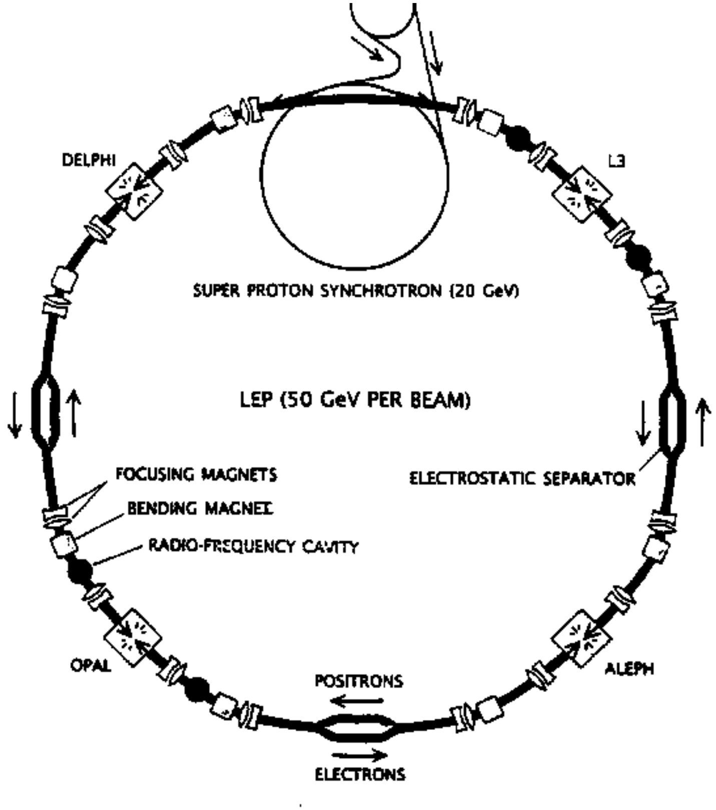
  ambituous projects aiming to reach higher electron energies without the large energy loss due to synchrotron radiation.

Colliders: general aspects - II

LHC scheme: up to 7 TeV per beam

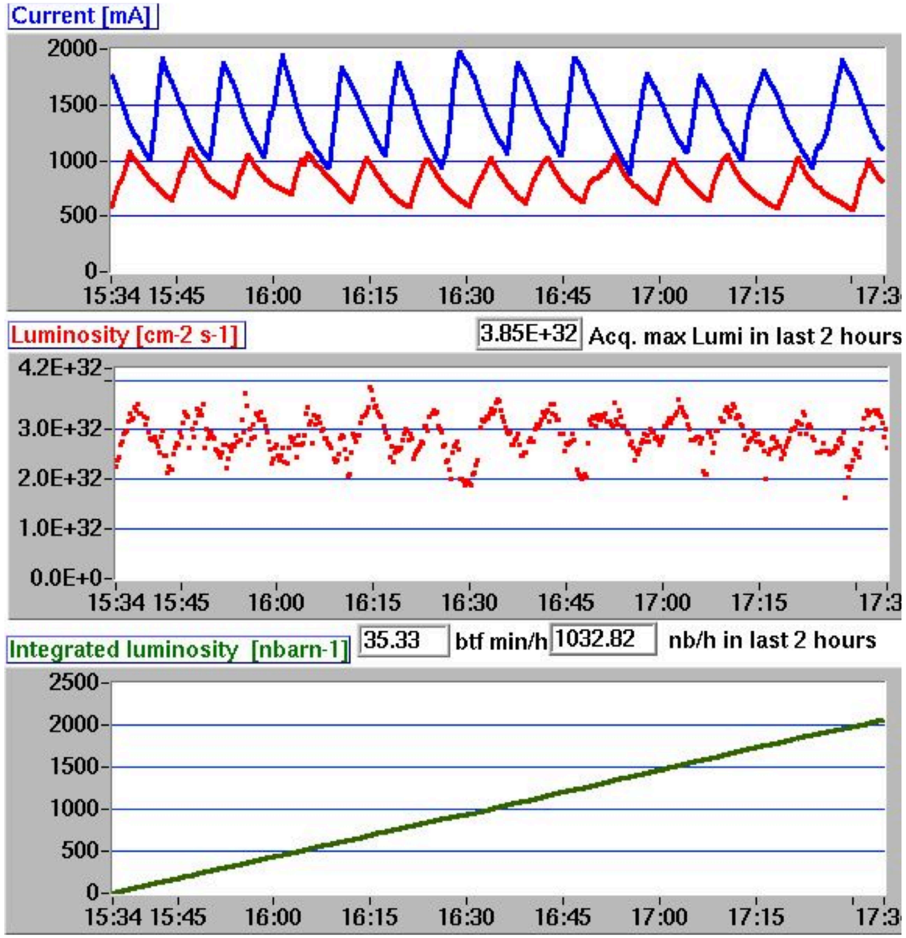


LEP scheme: up to 100 GeV per beam



Colliders: general aspects - III

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



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

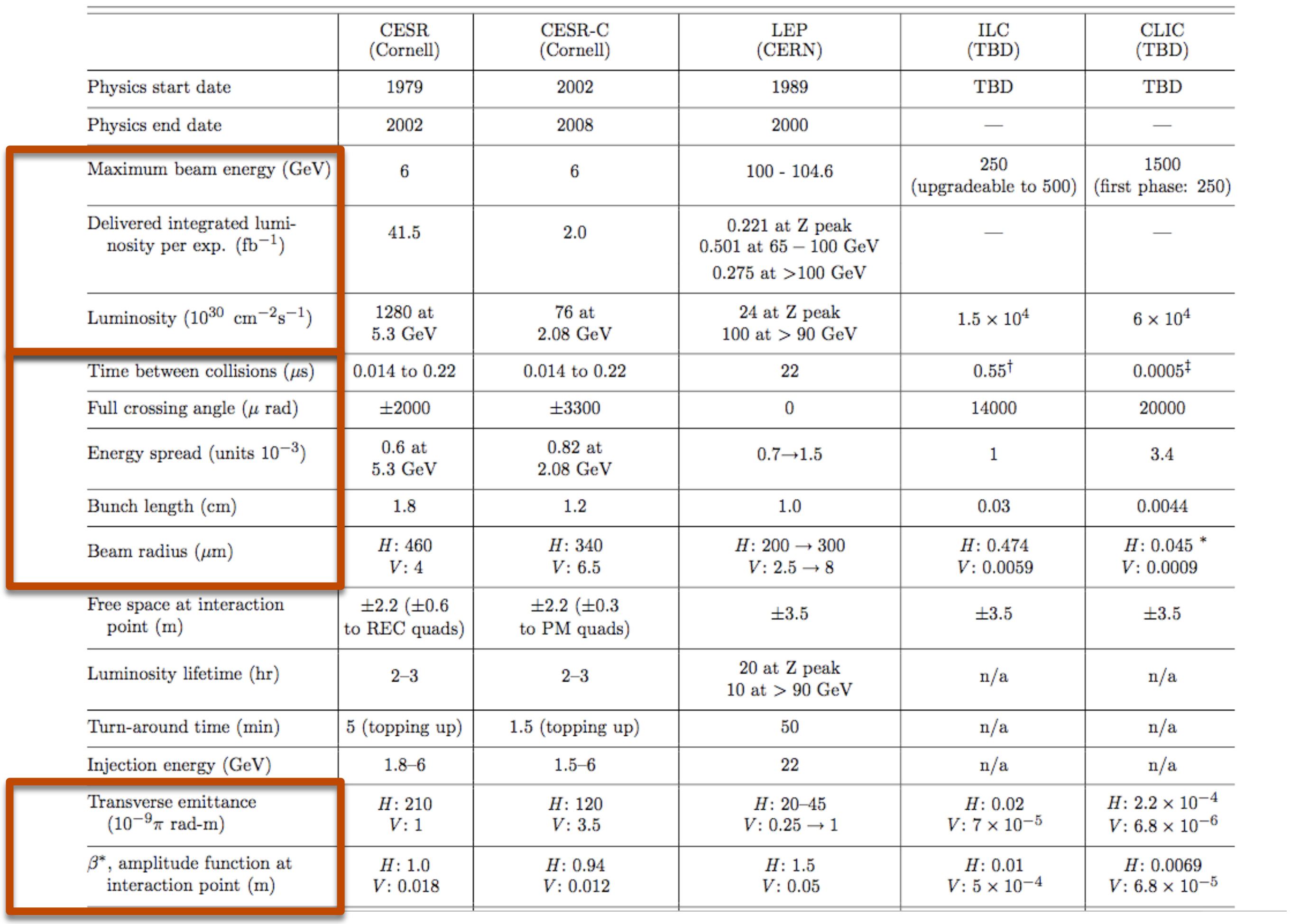
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	THANKS!!
Instantaneous Lumi [(ub.s)^-1]	3993.7	2.511	4080.1	395.9
BRAN Luminosity [(ub.s)^-1]	4083.7	1.632	4078.3	210.5
Fill Luminosity (nb)^-1	87568.7	61.0	89584.7	6829.4
BKGD 1	0.422	0.589	2.586	0.892
BKGD 2	83.489	177.284	3.361	4.286
BKGD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

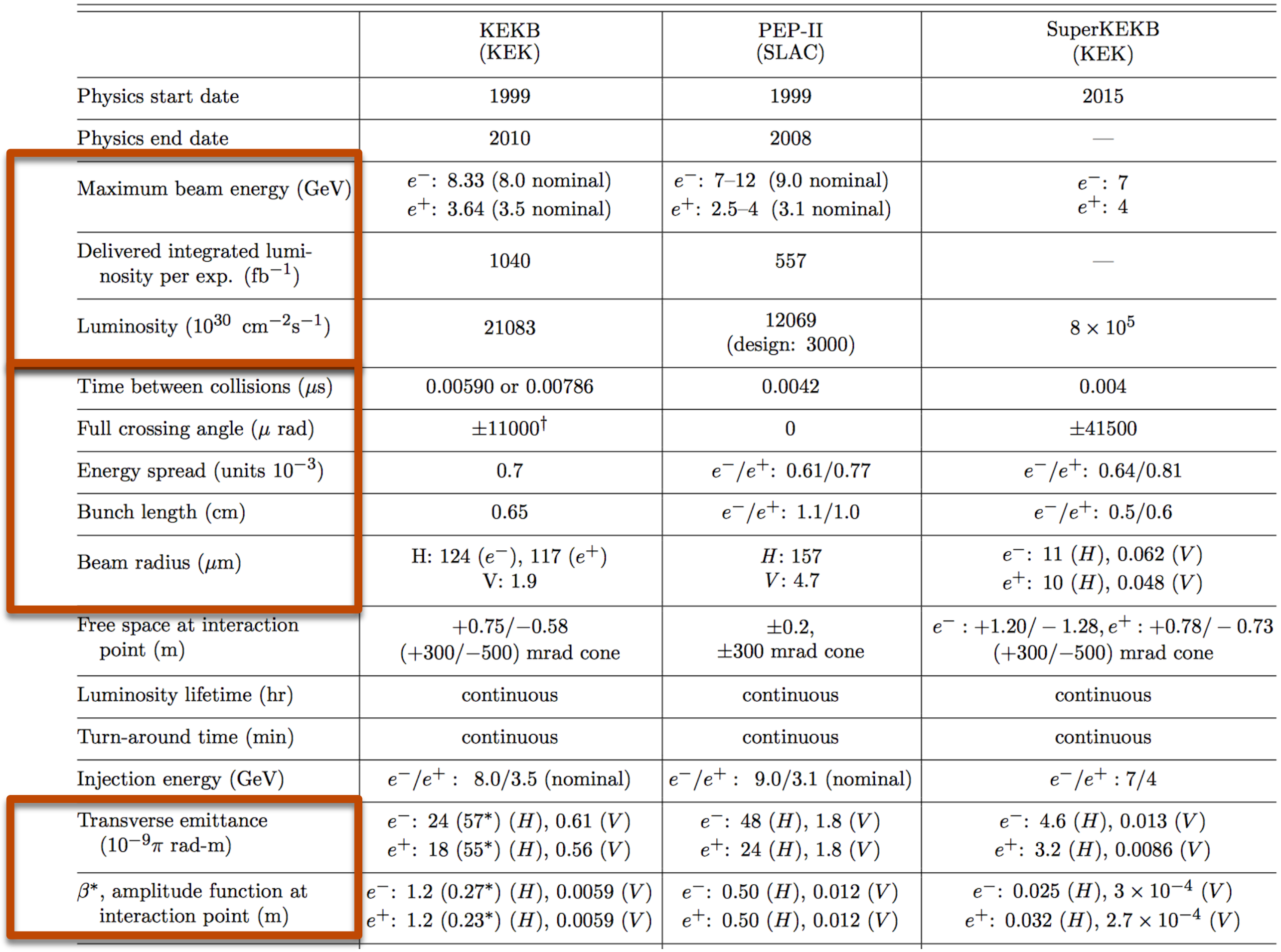
LifeTime: 25% reduction in 9 h

Collider parameters - I



		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	—	—
Main parameters	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} $\text{cm}^{-2}\text{s}^{-1}$)	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
Impact on detector operation	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
Techincal parameters	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)	±11000†	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

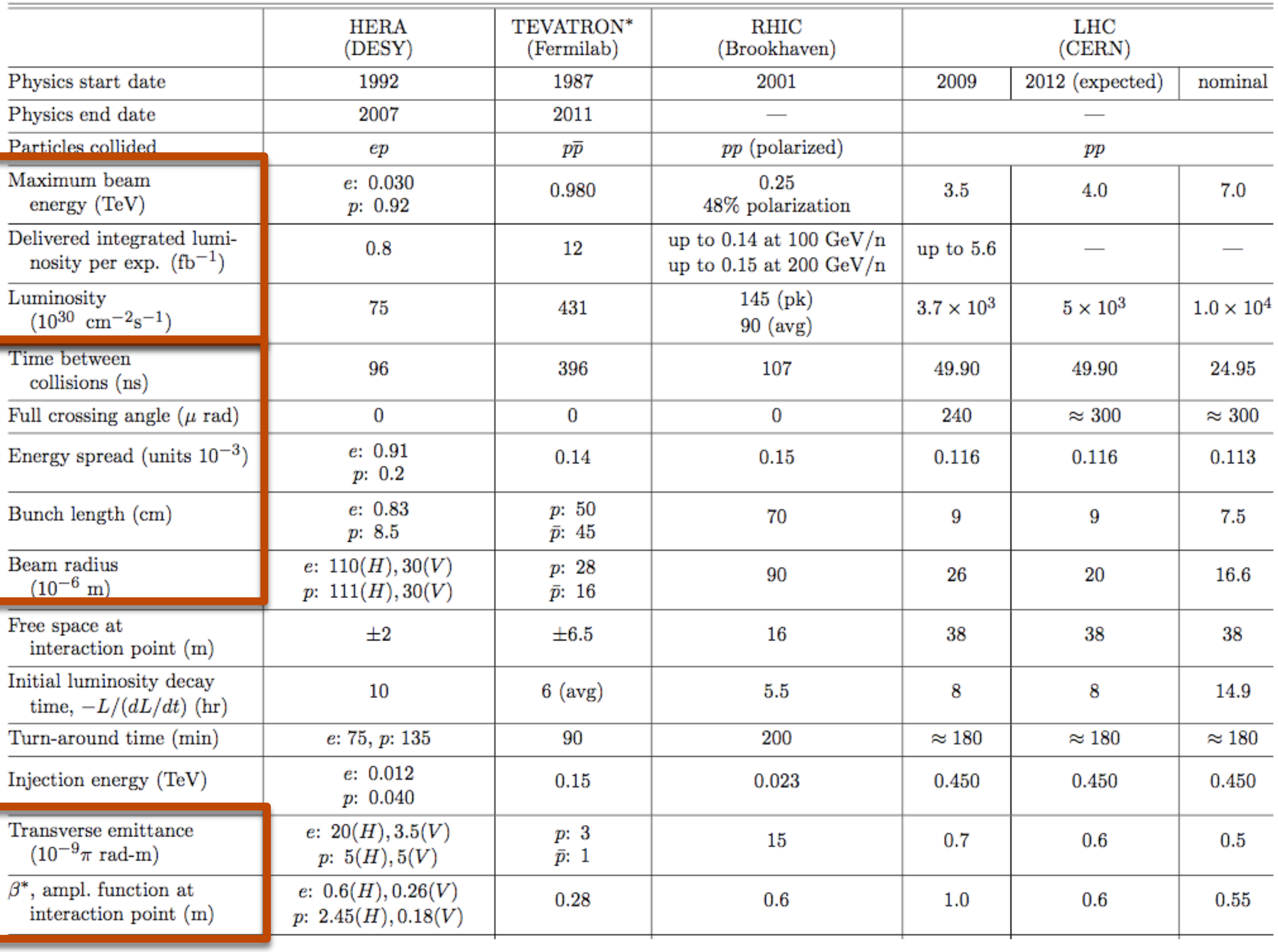
Techical parameters

Collider parameters - III

Main parameters

Impact on detector operation

Techincal 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} cm^{-2}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}: $[L_{int}] = l^{-2}$ ➔ nbarn^{-1} = 10^{33} 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).

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

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

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

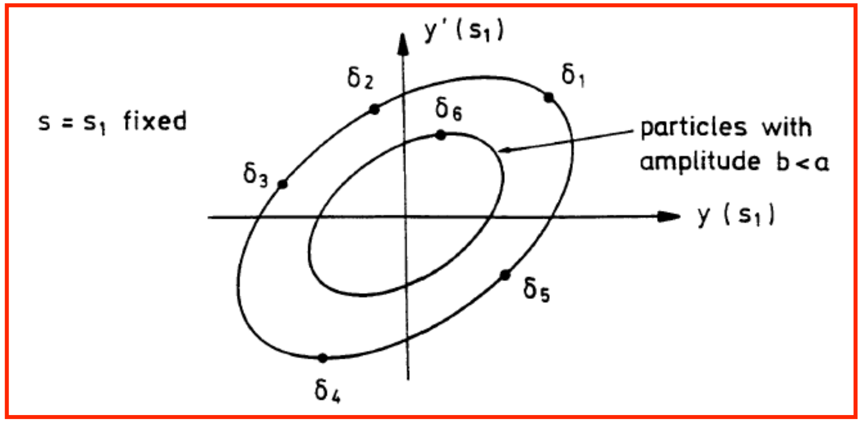
Beam dynamics - I

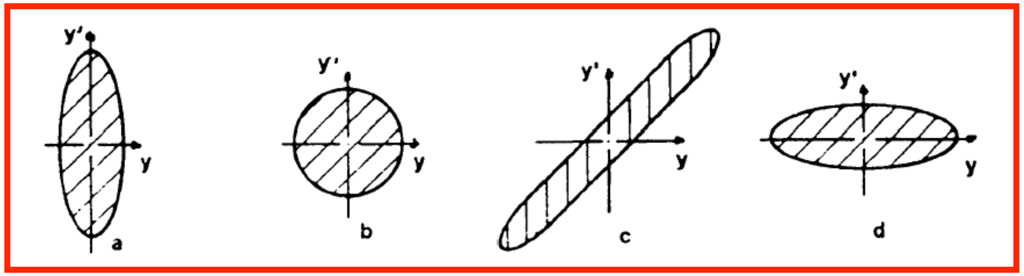
- Along ***s***, the positions ***x***(***s***), ***y***(***s***) (***u***(***s***)) of the particles are characterized by oscillations wrt reference trajectory: "betatron" oscillations and "chromaticity" oscillations
- If we neglect momentum dispersion ($\boldsymbol{\delta p} \approx 0$) only betatron oscillations are relevant:
  - $\boldsymbol{\beta(s)}$ betatron function
  - $\boldsymbol{\phi(s)}$ phase advancement function
  - ***A*** and $\boldsymbol{\phi_0}$ are constants of the motion
- ***u'(s)*** is the "inclination" angle of the trajectory ($\boldsymbol{\alpha(s)}$ is a function of $\boldsymbol{\beta(s)}$)
- At any given ***s*** the ***u***(***s***) % ***u'***(***s***) plane is the phasespace plot. The "area" of the plot is called **emittance** $\boldsymbol{\varepsilon}$. $A=\sqrt{\boldsymbol{\varepsilon}}$
- Emittances are conserved quantities due to the Liouville theorem ➔ small-size beam == large angular spread and viceversa

$$u(s) = u_\beta(s) + \eta(s)\frac{\delta p}{p}$$

$$u_\beta(s) = A\sqrt{\beta(s)}\cos\left(\phi(s)+\phi_0\right)$$

$$u'_\beta(s) = -\frac{A}{\sqrt{\beta(s)}}\left[\sin\left(\phi(s)+\phi_0\right)+\alpha(s)\cos\left(\phi(s)+\phi_0\right)\right]$$





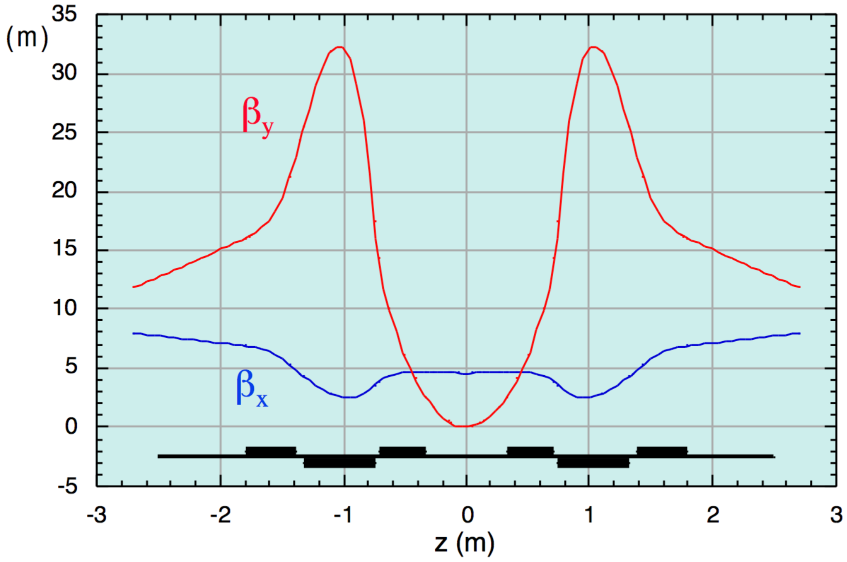
Beam dynamics - II

- **Emittance** is a length × angle (measured in mm × mrad)
- Beam dimensions and angular spread change along *s*. They depend on the emittance and on the betatron functions at the interaction point (IP): $\boldsymbol{\beta^* = \beta(s_{IP})}$.
- Emittance has to be as low as possible
  - In e^+e^- the actual value is an equilibrium between radiation dumping and diffusion
  - In pp it depends on the way the beam is prepared (for anti-p specific cooling systems were invented)
- $\boldsymbol{\beta^*}$ has also to be as low as possible

$$\sigma_x = \sqrt{\varepsilon_x \beta_x^*}$$

$$\sigma_{\vartheta_x} = \sqrt{\varepsilon_x / \beta_x^*}$$

Low Beta Scheme



Beam dynamics - III

$$Q = \frac{1}{2\pi}\oint_L \phi(s)\,ds$$

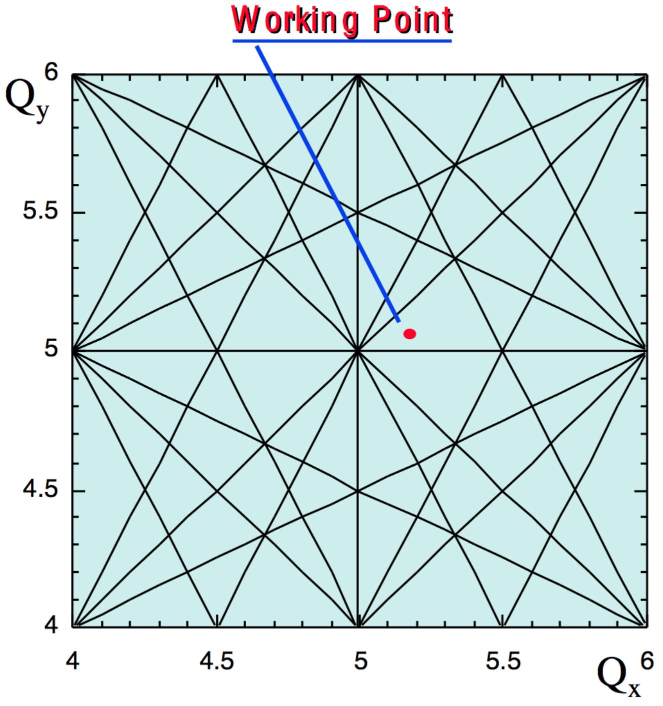
- Q is phase advancement, the number of oscillations per turn: it is the "**tune**". If integer, at any passage in the same point the bias is the same and there are instabilities.
- Q has to be far from an "integer number"
- The beam-beam effect gives rise to a ***"tune shift"*** If, for small tune shifts, we have instabilities we have to reduce N_1 and N_2
- So the luminosity can be expressed in terms of β^*_y and of the maximum "acceptable" tune shift ξ

$$L = \pi\left(\frac{\gamma}{r_e}\right)^2 f_R\, \varepsilon\,(1+\kappa)\,\frac{\xi^2}{\beta_y^*}$$

Tune Resonances

$$mQ_x + nQ_y = p \qquad m,n,p \in \mathbf{N}$$

$$|m| + |n| = resonance\ order$$



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

  ➔ TBC= , 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

  ➔ TBC= , μ=

Colliders: power needed

- Circulating beams loose energy
  - Synchrotron radiation;
  - Beam-gas and beam-beam interactions
  - ➔ finite beam lifetime ➔ need of RF to "push" beams.
- Comparison btw LEP and LHC (consider only synchrotron radiation loss)

$$Power = n_b \times N \times \frac{\delta E}{turn} \times \frac{c}{2\pi R}$$

$$\frac{\delta E}{turn} = \frac{4\pi}{3} \frac{e^2}{4\pi\varepsilon_0} \frac{1}{R} \beta^3 \gamma^4 \propto \frac{E^4}{Rm^4}$$

$$Power(W) = n_b \times N \times 0.5 \cdot 10^{-19} \frac{\gamma^4}{R(m)^2}$$

$$\gamma(LHC) = 7 \cdot 10^3$$

$$\gamma(LEP) = 2 \cdot 10^5$$

$$R = 4300m$$

$$\Rightarrow Power(LHC) \approx 10kW$$

$$\Rightarrow Power(LEP) \approx 10MW$$

Heavy Ion collisions.

- Lead nuclei @ LHC:
  - $Z=82$, $A=208$, $M \approx 195$ GeV
  - $\Delta E_K = ZeV$ (proton $\times$ Z)
  - $p= ZeRB$ (proton $\times$ 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 ?