# Recap

- Let's remind at this point that our aim is to learn how to design an experiment.
- We have seen:
  - Definition of the process we want to study
  - Selection of the events correponding to this process
  - Measurement of the quantities related to the process
  - Other measurements related to the physics objects we are studying.
- Now, in order to really design an experiment we need:
  - To see how projectiles and targets can be set-up
  - To see how to put together different detectors to mesure what we need to measure

# How to design an EPP experiment

# How to design an EPP experiment

- Define which process I want to study:
  - ➔ initial state (particles, energy, required intensities,…)
  - ➔ final state(s) (which particles to detect, which energies, which are the main possible backgrounds etc.): exclusive vs. inclusive.
  - ➔➔ Overall Montecarlo simulation of the process, to understand the main parameters in the game (kinematics, rates, number of particles, backgrounds)
- Overall design parameters:
  - Center of mass energy $\sqrt{s}$
  - Luminosity L / flux $\phi$ to obtain the requires statistical accuracy. For this I need to know (or at least to estimate) the cross-section of the process.
  - Detector general structure: depends on what we want to measure:
    - charged particles momenta ➔ magnetic field
    - neutral particles detection and particles energy ➔ calorimetry
    - special particles: neutrinos, muons, neutrons,…

# Collider experiments

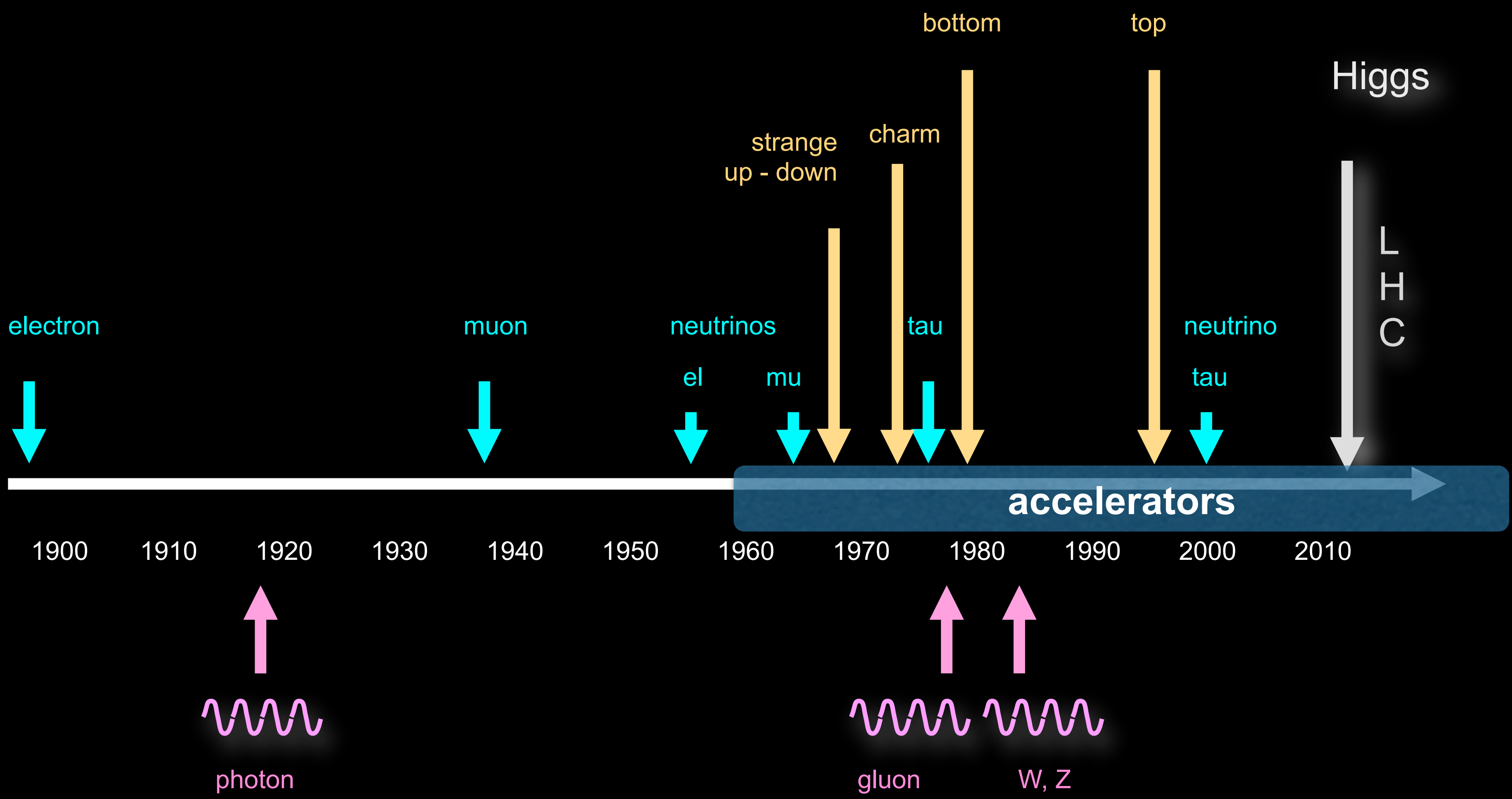
The main parameters of the colliders

LHC: ATLAS+CMS parameters

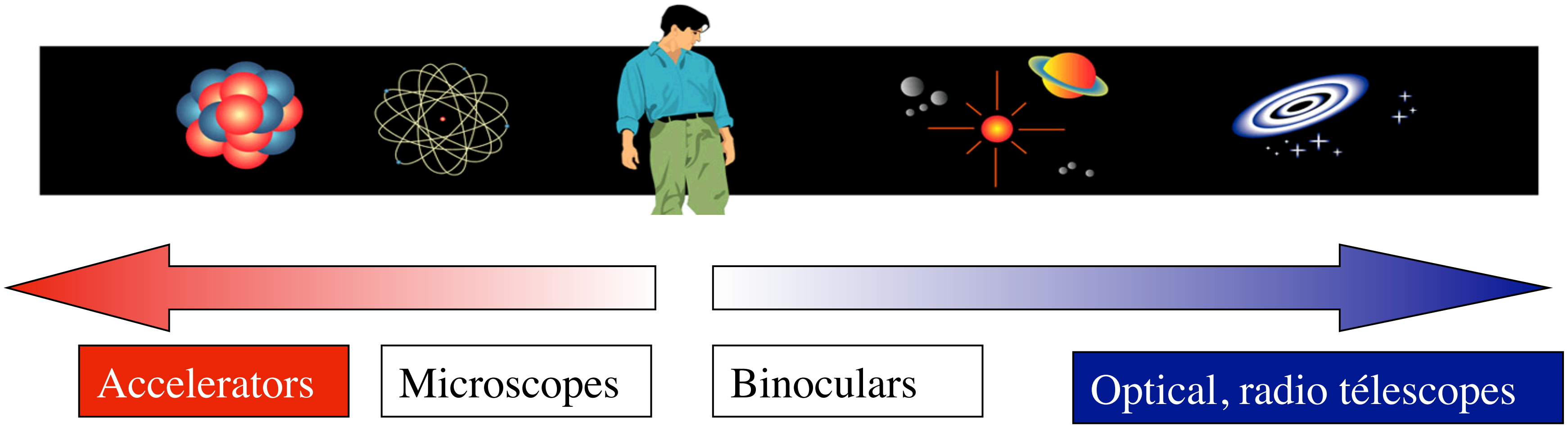
# Particle Accelerator Physics

- 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.

# 60 years of experiments at accelerators have discovered the set of fundamental particles



# Accelerators gain us one frontier of the physics spectrum

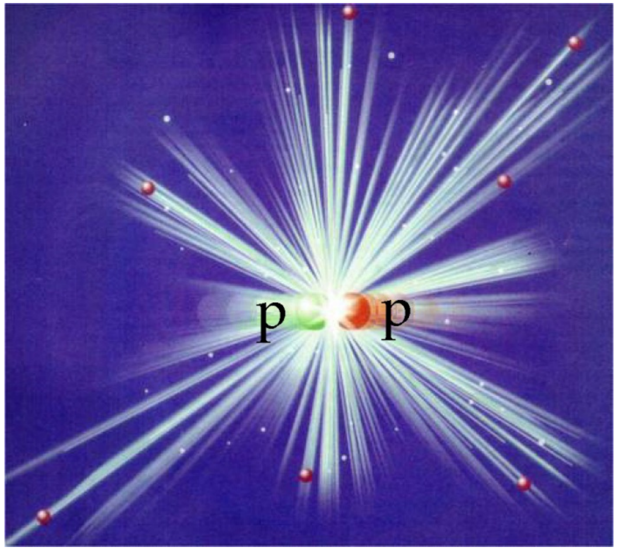


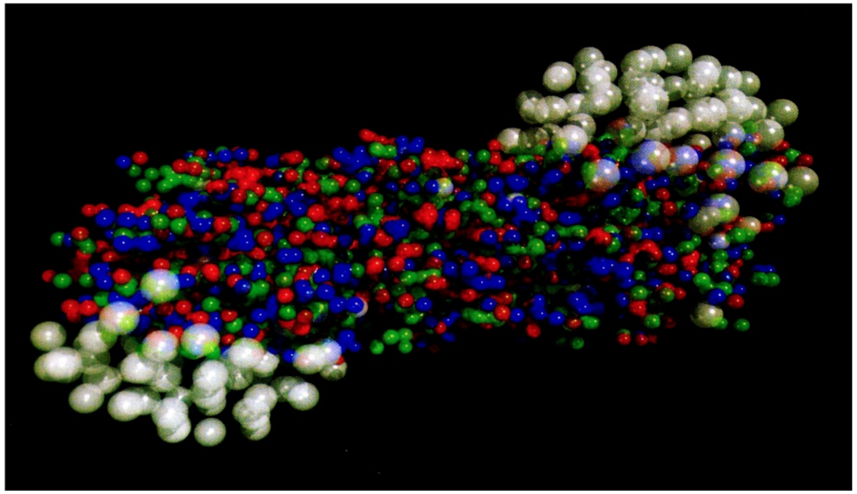

Particle physics looks at matter in its smallest dimensions and accelerators are very fine microscope or, better, *atto-scope!*

$\lambda = h/p$ ; @LHC: $T = 1$ TeV $\Rightarrow \lambda \cong 10^{-18}$ m = 1 *am* (actually 30 *zm*)

# …back to Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{Gev}$
- T ≅ 100 fs after Big Bang for single particle creation (3 TeV)
- T ≅ 1 μs for collective phenomena QGS (Quark-Gluon Soup)



But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about…

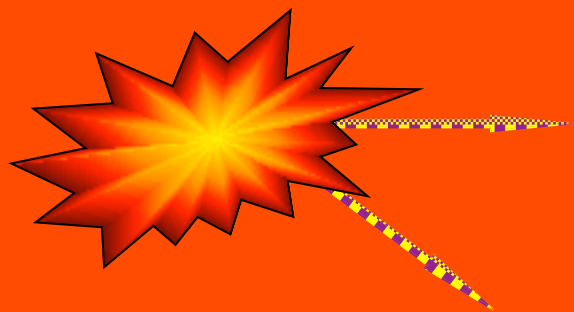
Which is a much more complex task!

# Accelerators: the two frontiers

**2 routes to new knowledge about the fundamental structure of the matter**

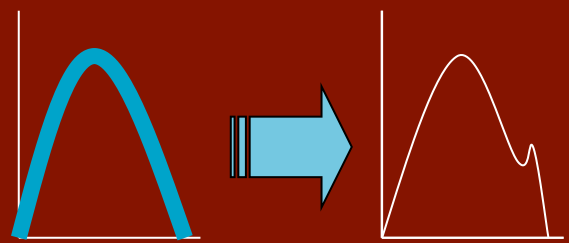
**High Energy Frontier**

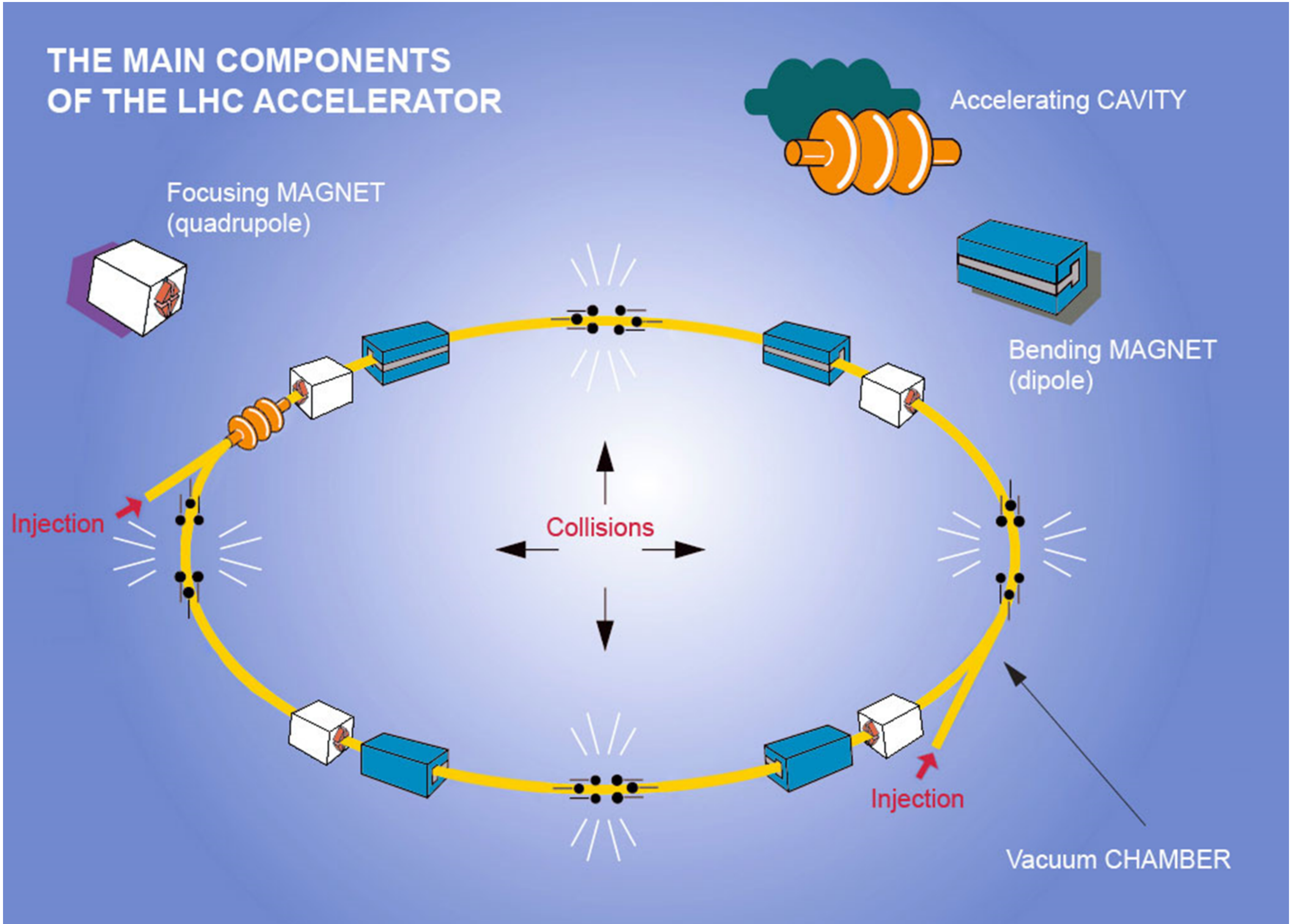
**New phenomena**
**(new particles)**
**created when the**
**"usable" energy > $mc^2$ [×2]**



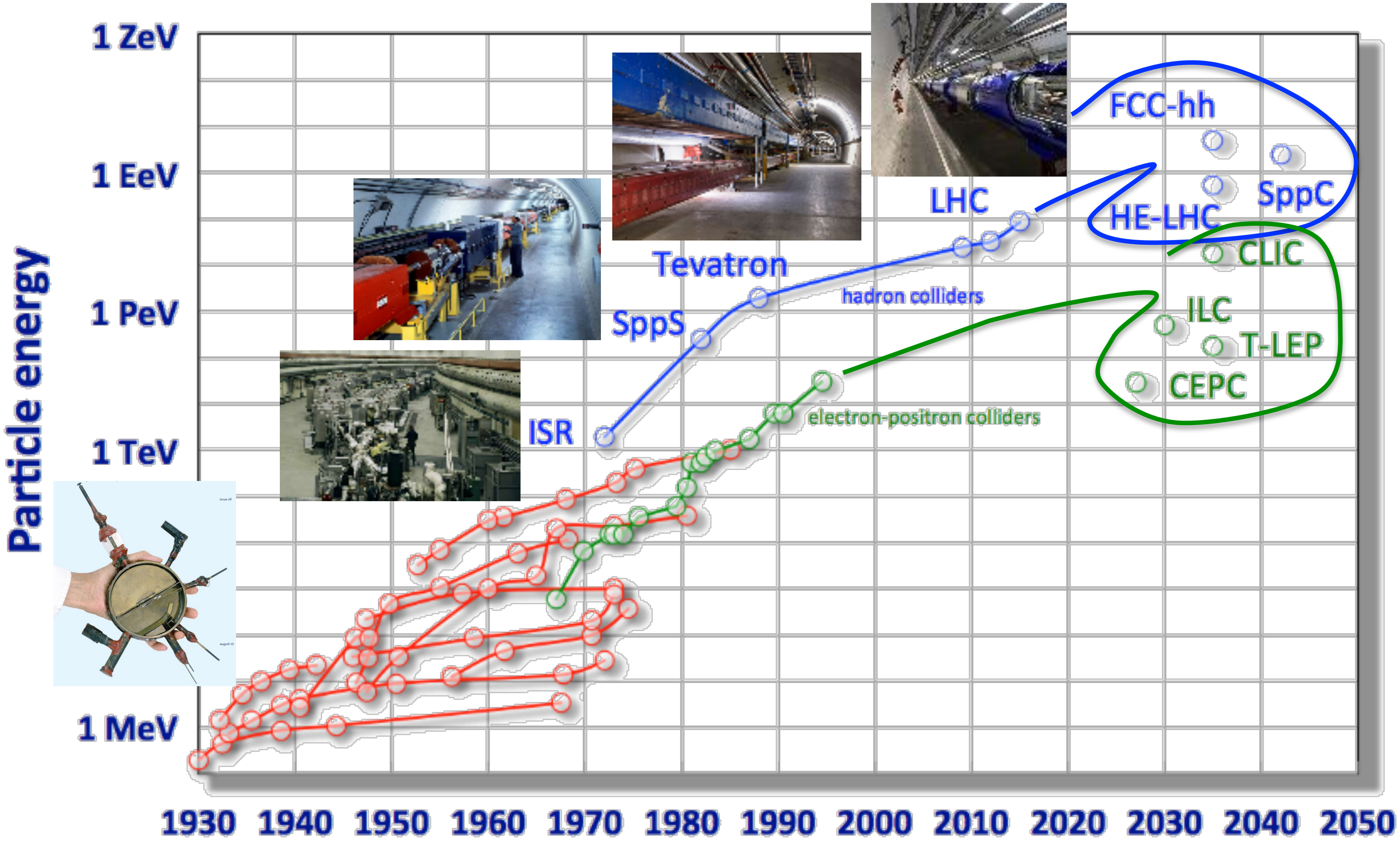
**High Precision Frontier**

**Known phenomena studied with high precision *may* show inconsistencies with theory**



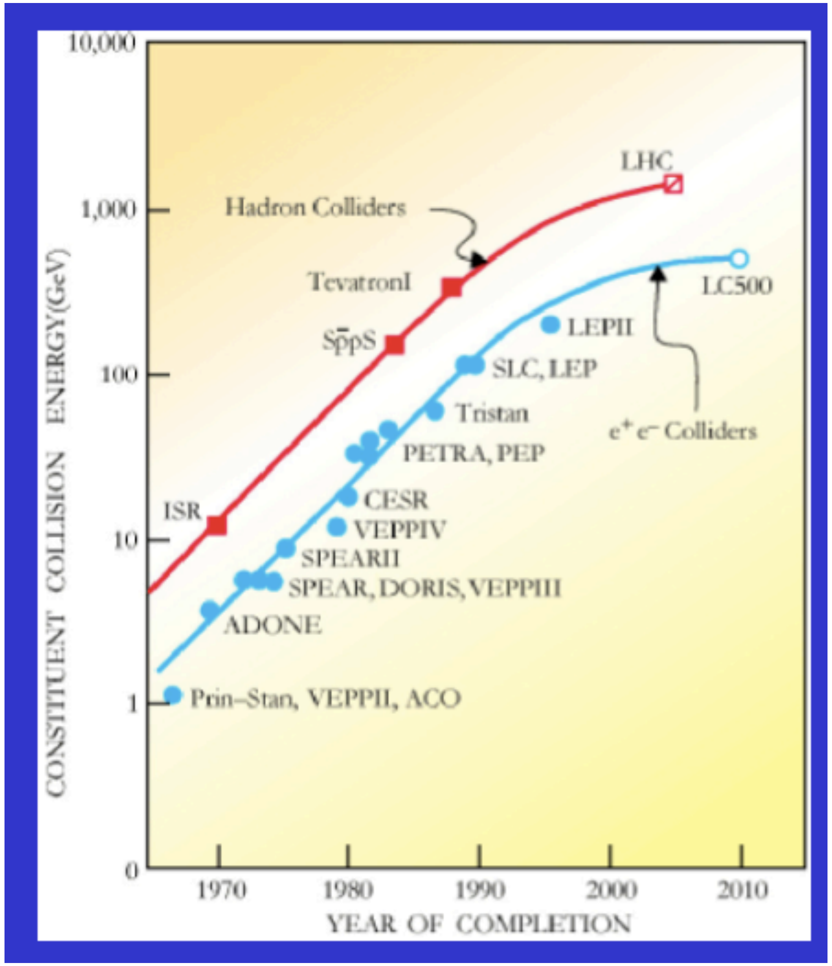

THE MAIN COMPONENTS
OF THE LHC ACCELERATOR
Accelerating CAVITY
Focusing MAGNET
(quadrupole)
Bending MAGNET
(dipole)
Injection
Collisions
Injection
Vacuum CHAMBER

# Livingston plot

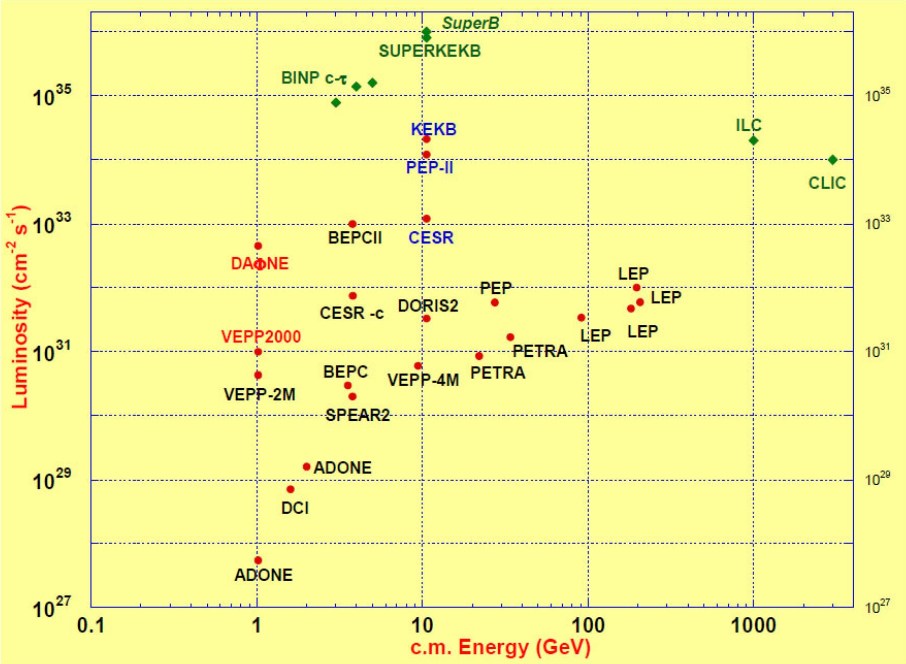



From Luca.Bottura-CERN

# 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.

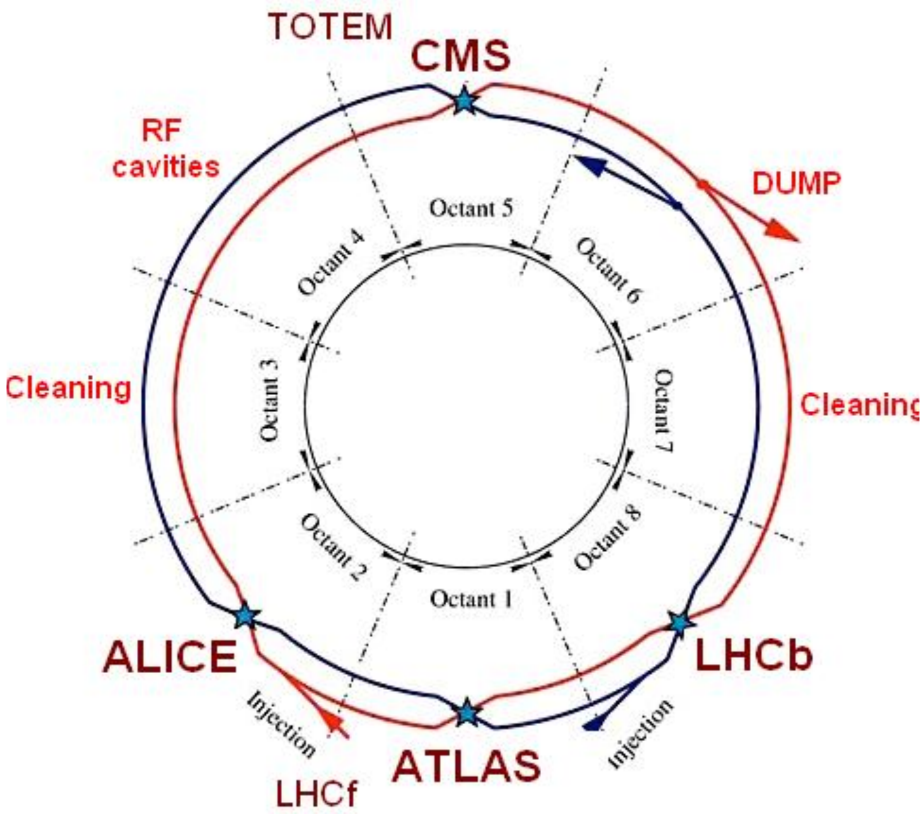
  - "bunches" of particles (typically $N \approx 10^{10}$-$10^{12}$ / bunch) in small transverse dimensions ($\sigma_X$, $\sigma_Y$ down to < mm level) and higher longitudinal dimensions ($\sigma_Z$ at cm level) like *needles* or *ribbons.*
  - the bunches travel along a ≈ circular trajectory (curvilinear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

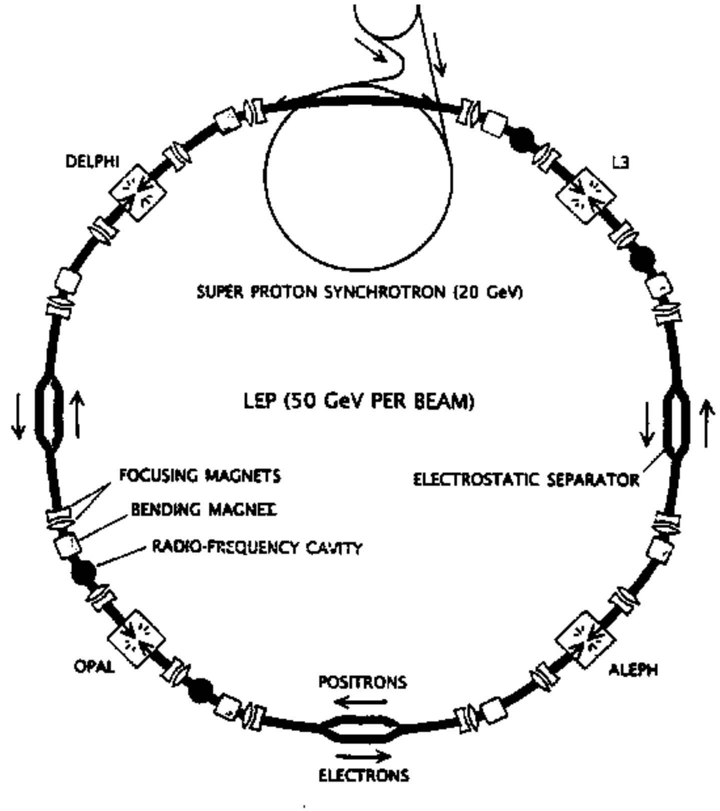
  ambituous projects aiming to reach higher electron energies without the large energy loss due to synchrotron radiation.

# Colliders: general aspects - II

## LHC scheme: up to 7 TeV per beam

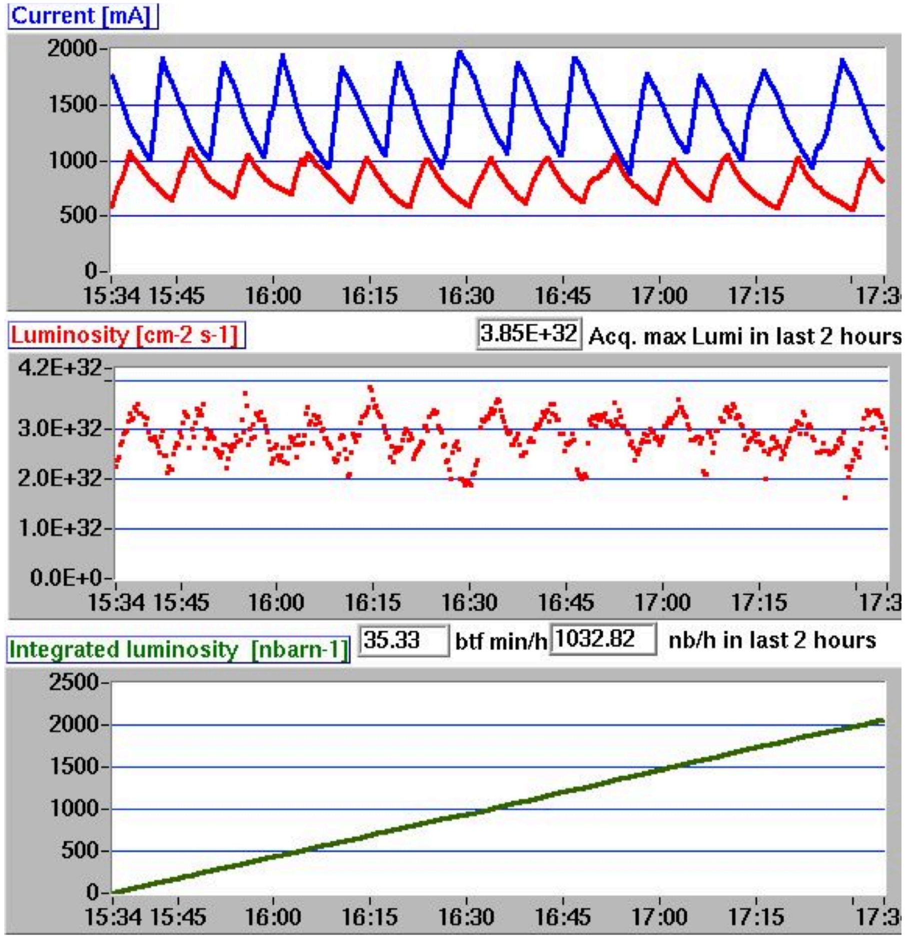



## LEP scheme: up to 100 GeV per beam



# 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




LifeTime: 50% reduction in 10 minutes

# Colliders: general aspects - IV

"Typical" LHC operation mode: single- injection

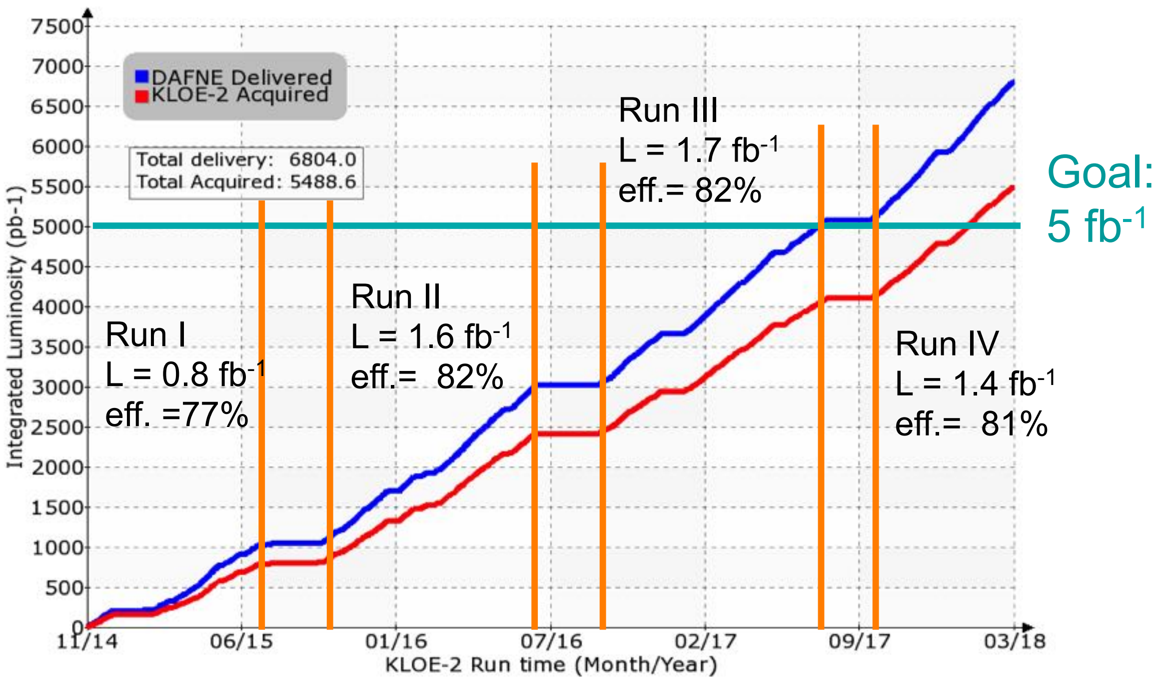

LifeTime: 25% reduction in 9 h

## Proposed exercise

In DAFNE operations for KLOE-2 experiment:

Top-up injection
2 mA injections at a rate of 2 Hz with 60% duty cycle
Veto of KLOE-2 DAQ for 50ms at each single injection
Dead time DAQ 4 μs
Trigger rate ~ 8 kHz

Determine the DAQ inefficiency



# Collider parameters - I

Main parameters

Impact on detector operation

Techincal parameters

| | VEPP-2000 (Novosibirsk) | VEPP-4M (Novosibirsk) | BEPC (China) | BEPC-II (China) | DAΦNE (Frascati) |
|---|---|---|---|---|---|
| Physics start date | 2010 | 1994 | 1989 | 2008 | 1999 |
| Physics end date | — | — | 2005 | — | — |
| Maximum beam energy (GeV) | 1.0 | 6 | 2.5 | 1.89 (2.3 max) | 0.510 |
| Delivered integrated luminosity per exp. ($fb^{-1}$) | 0.125 | 0.027 | 0.11 | 17.5 | $\approx$ 4.7 in 2001-2007<br>$\approx$ 2.7 w/crab-waist<br>$\approx$ 1.8 since Nov 2014 |
| Luminosity ($10^{30}$ $cm^{-2}s^{-1}$) | 40 | 20 | 12.6 at 1.843 GeV<br>5 at 1.55 GeV | 1000 | 453 |
| Time between collisions ($\mu$s) | 0.04 | 0.6 | 0.8 | 0.008 | 0.0027 |
| Full crossing angle ($\mu$ rad) | 0 | 0 | 0 | $2.2 \times 10^4$ | $5 \times 10^4$ |
| Energy spread (units $10^{-3}$) | 0.71 | 1 | 0.58 at 2.2 GeV | 0.52 | 0.40 |
| Bunch length (cm) | 4 | 5 | $\approx 5$ | $\approx 1.2$ | low current: 1<br>at 15mA: 2 |
| Beam radius ($10^{-6}$ m) | 125 (round) | $H$: 1000<br>$V$: 30 | $H$: 890<br>$V$: 37 | $H$: 347<br>$V$: 4.5 | $H$: 260<br>$V$: 4.8 |
| Free space at interaction point (m) | $\pm 0.5$ | $\pm 2$ | $\pm 2.15$ | $\pm 0.63$ | $\pm 0.295$ |
| Luminosity lifetime (hr) | continuous | 2 | 7–12 | 1.5 | 0.2 |
| Turn-around time (min) | continuous | 18 | 32 | 15 | 2 (topping up) |
| Injection energy (GeV) | 0.2–1.0 | 1.8 | 1.55 | 1.89 | on energy |
| Transverse emittance ($10^{-9}$ m) | $H$: 150<br>$V$: 150 | $H$: 200<br>$V$: 20 | $H$: 660<br>$V$: 28 | $H$: 121<br>$V$: 1.56 | $H$: 260<br>$V$: 2.6 |
| $\beta^*$, amplitude function at interaction point (m) | $H$: 0.05 – 0.11<br>$V$: 0.05 – 0.11 | $H$: 0.75<br>$V$: 0.05 | $H$: 1.2<br>$V$: 0.05 | $H$: 1.0<br>$V$: 0.0129 | $H$: 0.26<br>$V$: 0.009 |

# Collider parameters - II

Main parameters / Impact on detector operation / Techincal 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<br>0.501 at 65 – 100 GeV<br>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<br>100 at > 90 GeV | $1.5 \times 10^4$ | $6 \times 10^4$ |
| Time between collisions ($\mu s$) | 0.014 to 0.22 | 0.014 to 0.22 | 22 | $0.55^{\dagger}$ | $0.0005^{\ddagger}$ |
| Full crossing angle ($\mu$ 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 ($\mu m$) | $H$: 460<br>$V$: 4 | $H$: 340<br>$V$: 6.5 | $H$: 200 → 300<br>$V$: 2.5 → 8 | $H$: 0.474<br>$V$: 0.0059 | $H$: 0.045 *<br>$V$: 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<br>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<br>$V$: 1 | $H$: 120<br>$V$: 3.5 | $H$: 20–45<br>$V$: 0.25 → 1 | $H$: 0.02<br>$V$: $7 \times 10^{-5}$ | $H$: $2.2 \times 10^{-4}$<br>$V$: $6.8 \times 10^{-6}$ |
| $\beta^*$, amplitude function at interaction point (m) | $H$: 1.0<br>$V$: 0.018 | $H$: 0.94<br>$V$: 0.012 | $H$: 1.5<br>$V$: 0.05 | $H$: 0.01<br>$V$: $5 \times 10^{-4}$ | $H$: 0.0069<br>$V$: $6.8 \times 10^{-5}$ |

# Collider parameters - III

Main parameters: Maximum beam energy, Delivered integrated luminosity per exp., Luminosity

Impact on detector operation: Time between collisions, Full crossing angle, Energy spread, Bunch length, Beam radius

Techincal parameters: Transverse emittance, $\beta^*$, amplitude function at interaction point

| | 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)<br>$e^+$: 3.64 (3.5 nominal) | $e^-$: 7–12 (9.0 nominal)<br>$e^+$: 2.5–4 (3.1 nominal) | $e^-$: 7<br>$e^+$: 4 |
| Delivered integrated luminosity per exp. ($fb^{-1}$) | 1040 | 557 | — |
| Luminosity ($10^{30}$ $cm^{-2}s^{-1}$) | 21083 | 12069<br>(design: 3000) | $8 \times 10^5$ |
| Time between collisions ($\mu s$) | 0.00590 or 0.00786 | 0.0042 | 0.004 |
| Full crossing angle ($\mu$ rad) | $\pm 11000^\dagger$ | 0 | $\pm 41500$ |
| 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 ($\mu m$) | H: 124 ($e^-$), 117 ($e^+$)<br>V: 1.9 | $H$: 157<br>$V$: 4.7 | $e^-$: 11 ($H$), 0.062 ($V$)<br>$e^+$: 10 ($H$), 0.048 ($V$) |
| Free space at interaction point (m) | +0.75/−0.58<br>(+300/−500) mrad cone | ±0.2,<br>±300 mrad cone | $e^-: +1.20/-1.28, e^+: +0.78/-0.73$<br>(+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 ($V$)<br>$e^+$: 18 (55*) ($H$), 0.56 ($V$) | $e^-$: 48 ($H$), 1.8 ($V$)<br>$e^+$: 24 ($H$), 1.8 ($V$) | $e^-$: 4.6 ($H$), 0.013 ($V$)<br>$e^+$: 3.2 ($H$), 0.0086 ($V$) |
| $\beta^*$, amplitude function at interaction point (m) | $e^-$: 1.2 (0.27*) ($H$), 0.0059 ($V$)<br>$e^+$: 1.2 (0.23*) ($H$), 0.0059 ($V$) | $e^-$: 0.50 ($H$), 0.012 ($V$)<br>$e^+$: 0.50 ($H$), 0.012 ($V$) | $e^-$: 0.025 ($H$), $3 \times 10^{-4}$ ($V$)<br>$e^+$: 0.032 ($H$), $2.7 \times 10^{-4}$ ($V$) |

# Collider parameters - IV

| | | 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) | $pp$ | | |
| Main parameters | Maximum beam energy (TeV) | $e$: 0.030<br>$p$: 0.92 | 0.980 | 0.25<br>48% polarization | 3.5 | 4.0 | 7.0 |
| Main parameters | Delivered integrated luminosity per exp. ($\mathrm{fb}^{-1}$) | 0.8 | 12 | up to 0.14 at 100 GeV/n<br>up to 0.15 at 200 GeV/n | up to 5.6 | — | — |
| Main parameters | Luminosity ($10^{30}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) | 75 | 431 | 145 (pk)<br>90 (avg) | $3.7 \times 10^3$ | $5 \times 10^3$ | $1.0 \times 10^4$ |
| Impact on detector operation | Time between collisions (ns) | 96 | 396 | 107 | 49.90 | 49.90 | 24.95 |
| Impact on detector operation | Full crossing angle ($\mu$ rad) | 0 | 0 | 0 | 240 | $\approx 300$ | $\approx 300$ |
| Impact on detector operation | Energy spread (units $10^{-3}$) | $e$: 0.91<br>$p$: 0.2 | 0.14 | 0.15 | 0.116 | 0.116 | 0.113 |
| Impact on detector operation | Bunch length (cm) | $e$: 0.83<br>$p$: 8.5 | $p$: 50<br>$\bar{p}$: 45 | 70 | 9 | 9 | 7.5 |
| Impact on detector operation | Beam radius ($10^{-6}$ m) | $e$: $110(H), 30(V)$<br>$p$: $111(H), 30(V)$ | $p$: 28<br>$\bar{p}$: 16 | 90 | 26 | 20 | 16.6 |
| | Free space at interaction point (m) | $\pm 2$ | $\pm 6.5$ | 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 | $\approx 180$ | $\approx 180$ | $\approx 180$ |
| | Injection energy (TeV) | $e$: 0.012<br>$p$: 0.040 | 0.15 | 0.023 | 0.450 | 0.450 | 0.450 |
| Techical parameters | Transverse emittance ($10^{-9}\pi$ rad-m) | $e$: $20(H), 3.5(V)$<br>$p$: $5(H), 5(V)$ | $p$: 3<br>$\bar{p}$: 1 | 15 | 0.7 | 0.6 | 0.5 |
| Techical parameters | $\beta^*$, ampl. function at interaction point (m) | $e$: $0.6(H), 0.26(V)$<br>$p$: $2.45(H), 0.18(V)$ | 0.28 | 0.6 | 1.0 | 0.6 | 0.55 |

# Luminosity measurement - I

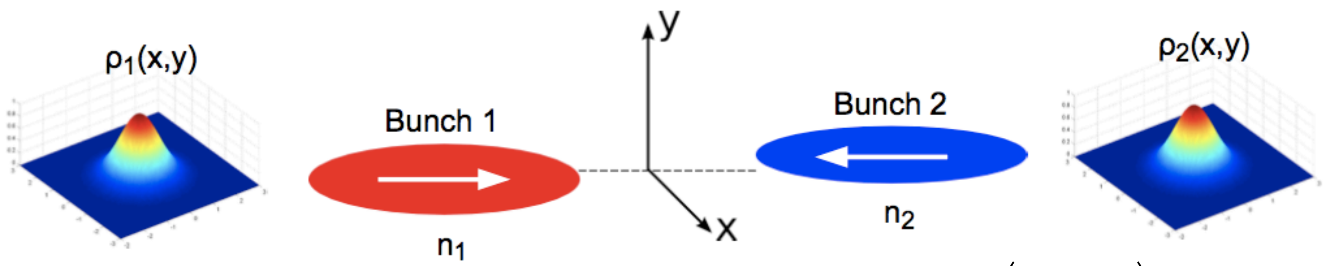
- In order to get the luminosity we need to know the "cross-section" of a candle process:

$$L = \frac{\dot{N}}{\sigma}$$

- In $e^+e^-$ experiments QED helps, since Bhabha scattering can be theoretically evaluated with high precision (< 1%).
- In pp experiment the situation is more difficult.
  - Two-step procedure: continuous "relative luminosity" measurement through several monitors. Count the number of "inelastic interactions";
  - time-to-time using the "Van der Meer" scan the absolute calibration is obtained by measuring the effective $\sigma_{inel}$.

# Luminosity measurement - II

**Van der Meer scan**: Measurement of the rate of inelastic interactions as a function of the bunch horizontal and vertical separations:



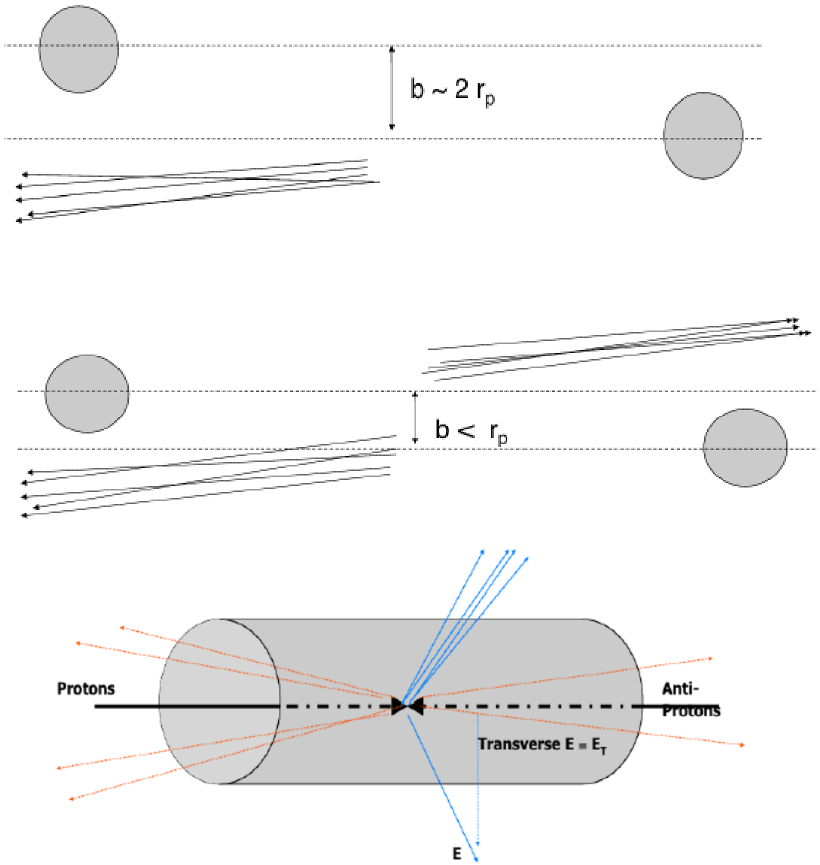

$$R(\delta x) = \int \rho_1(x,y)\rho_2(x+\delta x,y)\,dx\,dy \propto \exp\left(-\frac{\delta x^2}{2\Sigma_x^2}\right)$$

➔Determine the transverse bunch dimensions $\Sigma_x$, $\Sigma_y$ and the inelastic rate at 0 separation.
➔Using the known values of the number of protons per bunch from LHC monitors, one get the ***inelastic cross-section*** that provides the absolute normalization.

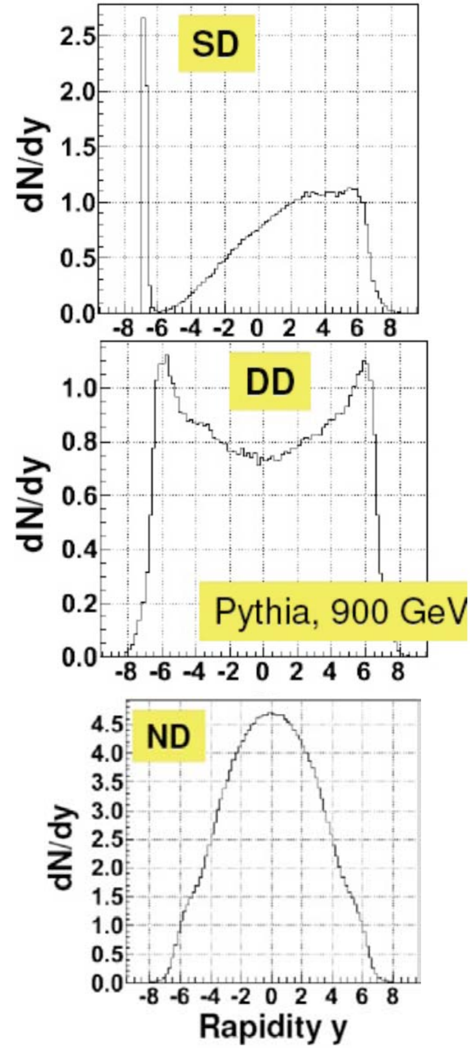
$$L = n_b f \frac{N_1 N_2}{4\pi\Sigma_x\Sigma_y} = \frac{\dot{N}_{inel}}{\sigma_{inel}}$$

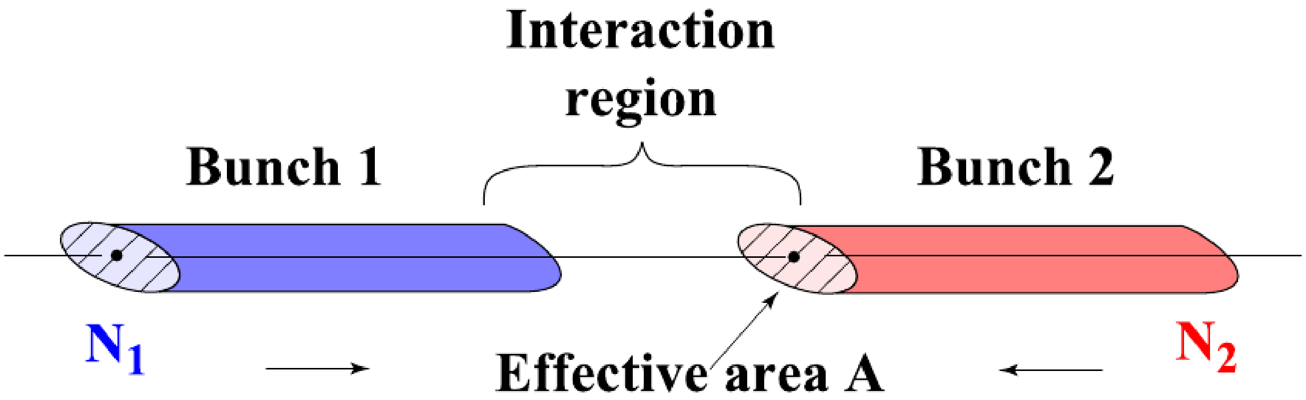
$$\sigma_{inel} = \left(\frac{\dot{N}^0_{inel}}{n_b f}\right)\frac{4\pi\Sigma_x\Sigma_y}{N_1 N_2}$$

high cross section process to monitor relative luminosity ($R=L\sigma$):
pp inelastic scattering ($\sigma \sim 100$ mb)




- Single Diffractive
- Double Diffractive
- Non diffractive




Interaction region
Bunch 1
Bunch 2
$N_1$
Effective area A
$N_2$

# The quest for high Luminosity

- Luminosity formula:
  - $f$ is fixed by the collider radius
  - High $N_1$ and $N_2$ and $n_b$
  - Low $\sigma_x$, $\sigma_y$
- 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 $\sigma_x$ and $\sigma_y$ ? (limits from 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

$$\mu = \dot{n} T_{BC} = \frac{L \sigma_{tot}}{f n_b}$$

# Comparison: $e^+e^-$ vs pp

- DAFNE: $e^+e^-$ @ 1 GeV c.o.m. energy, $\sigma_{tot}$=3 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, $\sigma_{tot}$=70 mb, L=$10^{34}$cm$^{-2}$s$^{-1}$, $n_b$=3000, f=c/27 km = 11 kHz

  ➔ $T_{BC}$= , μ=

# Comparison: $e^+e^-$ vs pp

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

  ➔ $T_{BC}$= 2.7 ns , μ= ~$10^{-5}$
- LHC: pp @ 13 TeV c.o.m. energy, $\sigma_{tot}$=70 mb, $L=10^{34}cm^{-2}s^{-1}$, $n_b$=3000, f=c/27 km = 11 kHz

  ➔ $T_{BC}$= 25 ns , μ= ~18

# Heavy Ion collisions.

- Lead nuclei @ LHC:
  - Z=82, A=208, M ≈ 195 GeV
  - $\Delta E_K$ = ZeV (proton × Z)
  - p= ZeRB (proton × Z)
  - ➔ $E_{Pb}$ = 574 TeV=82 × 7 TeV
  - ➔ $E_{Pb}$/Nucleon = 574/A = 2.77 TeV
  - $\sqrt{s_{NN}}$=5.54 TeV
- Luminosity: ≈ $10^{27}$ $cm^{-2}s^{-1}$
- $n_b$ = 600
- $N_1=N_2=7\times10^7$ ions/bunch

- Heavy ions program @ RHIC
  - Au, Cu, U ions up to 100 GeV/nucleon
  - Luminosity ≈$10^{28}\div10^{29}$ $cm^{-2}s^{-1}$
- Cross-sections:
  - $\sigma_{pp} \approx 70$ mb
  - $\sigma_{pPb} \approx \sigma_{pp} \times A^{2/3}$ $(\approx \sigma_{pp}\times R_{Nuc}{}^2)$
  - $\sigma_{PbPb} \approx \sigma_{pp} \times N_{coll} \approx 10$ barn!
- How much is the pile-up ?

# Proposed exercises

Consider the parameters of the three accelerators:

- LHC: protons, R = 4.3 km, $E_{max}$ = 7 TeV, $T_{BC}$ = 25 ns;
- LEP: electrons, R = 4.3 km, $E_{max}$ = 100 GeV, $T_{BC}$ = 22 $\mu$s;
- DAFNE: electrons, R = 15 m, $E_{max}$ = 500 MeV, $T_{BC}$ = 2.7 ns;

Evaluate for each accelerator the following quantities: the revolution frequency $f$; the number of bunches $n_b$; the minimum value of the magnetic field $B_{min}$ required to hold the particles in orbit. From the luminosity and current profile plots shown as examples in the course slides, determine for DAFNE and LHC, the products $\sigma_x \times \sigma_y$

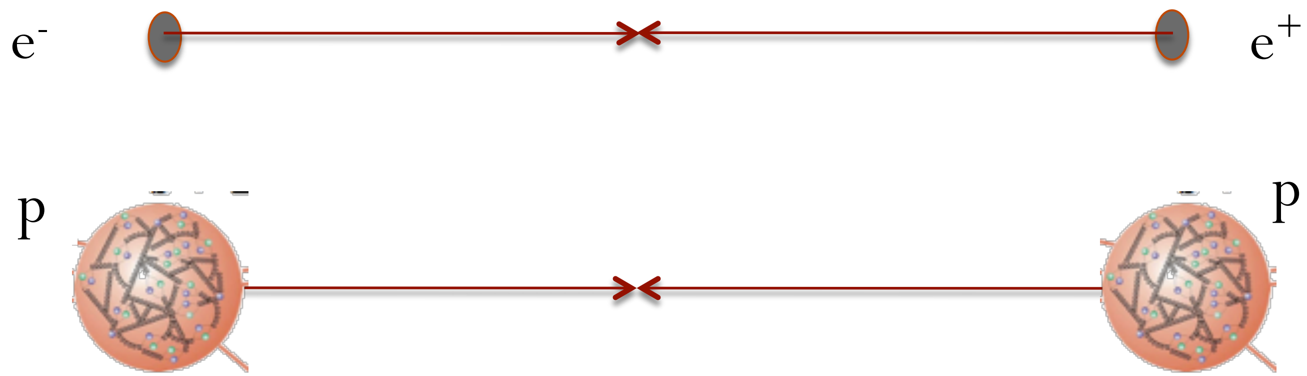
Design a pp machine at $\sqrt{s}$ = 40 TeV and $L = 10^{36}$ cm$^{-2}$s$^{-1}$. Which values of $\sigma_x$ and $\sigma_y$ are needed ? The following limits have to be respected:

- B < 5T
- $N_1$, $N_2 < 10^{11}$/bunch
- $T_{BC} > 10$ ns

Evaluate the maximum $\sqrt{s_{NN}}$ that can be obtained at LHC for Cu-Cu and Pb-Pb collisions respectively.

Evaluate the value of $\sqrt{s_{NN}}$ for Au-Au collisions if the energy of the Au ions is 10.5 TeV. In case these collisions are done at RHIC for which value of the luminosity the pile-up becomes of order 1 ? (RHIC circumference = 3.834 km, $n_b$=111)

# Hadron colliders




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

*valence quarks* / *sea quarks* / *gluons*

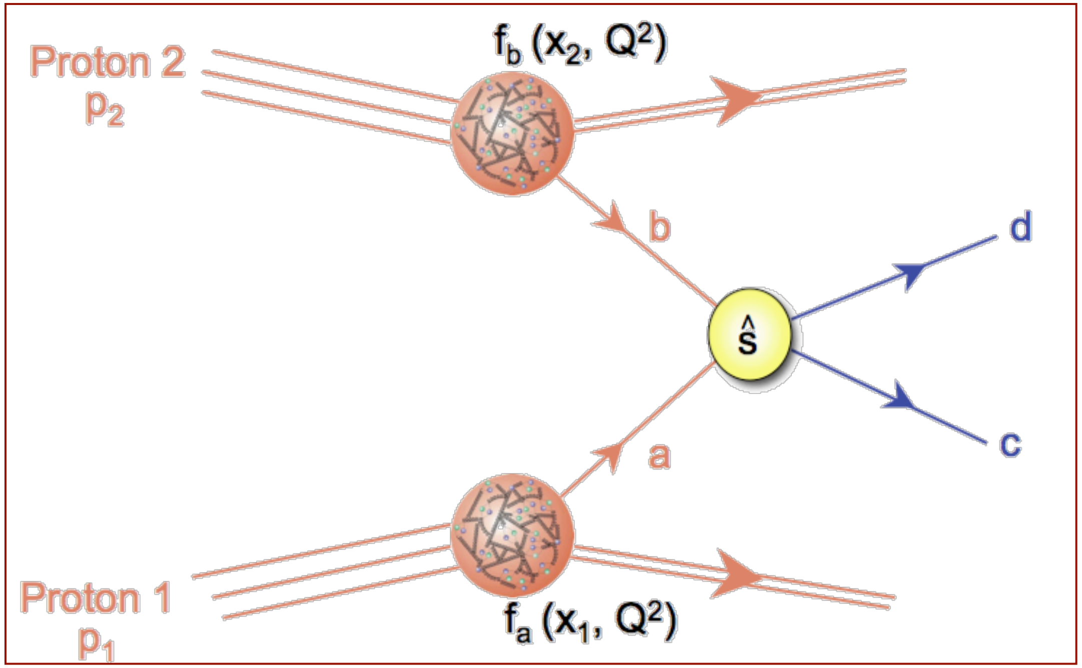
s = (center of mass energy of interaction)$^2$

ŝ = (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;
$\hat{s}$ = parton-parton c.o.m. energy = $x_1 x_2 s$ (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

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

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

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

- Parton momentum fractions: $x_1$ and $x_2$
  - Assume no transverse momentum
  - Assume proton mass negligible
- 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: $x_1=1$, $x_2=x_{min}$

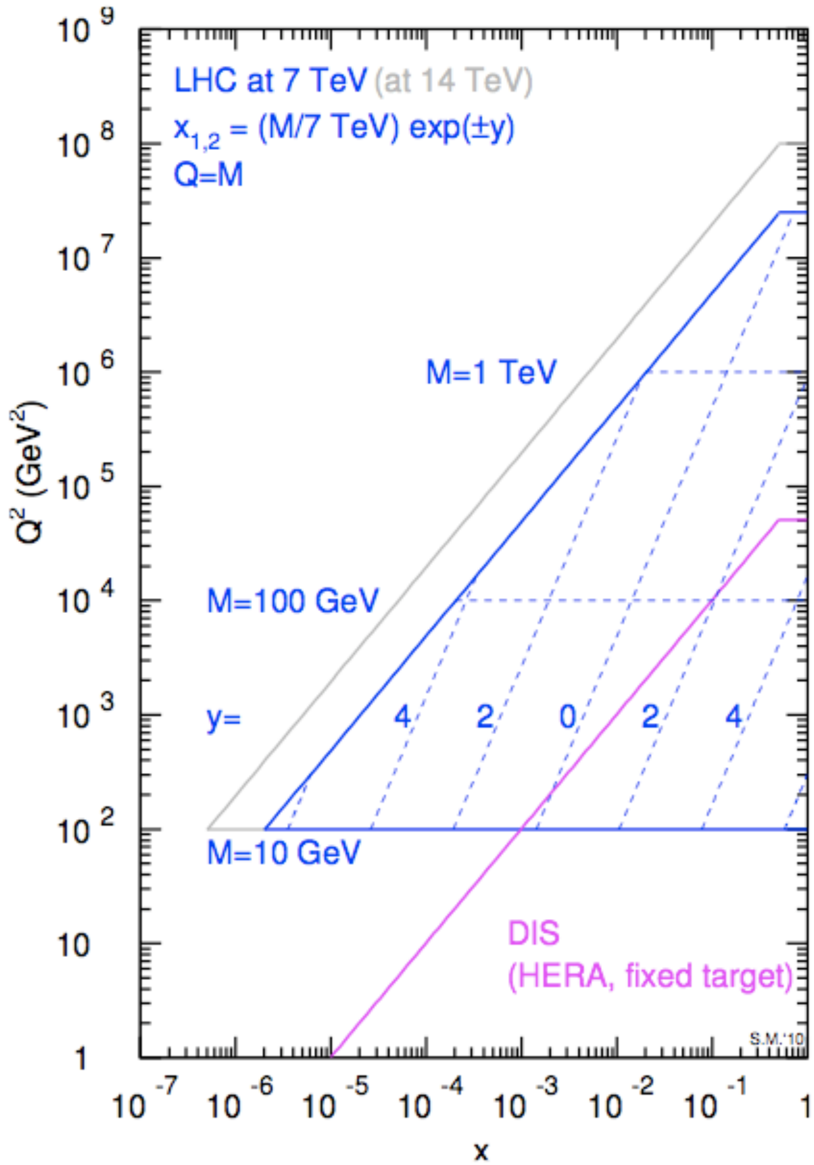
$$x_1 = 1; x_2 = x_{min} = \frac{M^2}{s}; y_{max} = \frac{1}{2}\ln\frac{s}{M^2}$$

- Z production at LHC, Tevatron and SpS

| | LHC (14 TeV) | Tevatron (1.96 TeV) | SpS (560 GeV) |
|---|---|---|---|
| $x_{min}$ | $4.2\times10^{-5}$ | $2.1\times10^{-3}$ | 0.026 |
| $y_{max}$ | 5.03 | 3.07 | 1.82 |

# The x-$Q^2$ plane

- → x – $Q^2$ plane ($Q^2=M^2=\hat{s}$) 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



## Proposed exercise

Consider the Higgs production ($M_H$ =125 GeV) at a pp collider at $\sqrt{s} = 14$ TeV. Evaluate the interval in rapidity $y$ and the minimum value of $x$ for direct Higgs production.

# 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 $\eta$: 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 $\Delta$y the "rapidity gap" is a relativistically invariant quantity):

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

(only for the restricted class of Lorentz transformations corresponding to a boost along the longitudinal z axis)

  - If expressed in terms of ($p_T$, $y$, $\phi$, $m$) 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

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2)\cosh\Delta y - \boldsymbol{p}_T(1)\cdot\boldsymbol{p}_T(2)] \qquad E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2}$$

# Invariant mass and missing energy

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At hadron colliders, a significant and unknown proportion of the energy of the incoming hadrons in each event escapes down the beam-pipe. Consequently if invisible particles are created in the final state, their net momentum can only be constrained in the plane transverse to the beam direction. Defining the $z$-axis as the beam direction, this net momentum is equal to the missing transverse energy vector

$$\boldsymbol{E}_T^{\text{miss}} = -\sum_i \boldsymbol{p}_T(i) \ , \tag{47.49}$$

where the sum runs over the transverse momenta of all visible final state particles.

# 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 $\vec{\not{E}}_T$

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

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

# Example: W mass constraint: evaluation of neutrino direction

Lastly, since the mass of the $W$ particle is well known [5], we can constrain the invariant mass of the $e, \nu$ pair, and solve for the longitudinal momentum of the neutrino. To do this, we can use Eq. (17):

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

Rewriting this expression, we get

$$\cosh\delta\eta = \frac{M_W^2}{2E_{T1}E_{T2}} + \cos\delta\phi. \qquad (21)$$

Solving for $\delta\eta$ gives

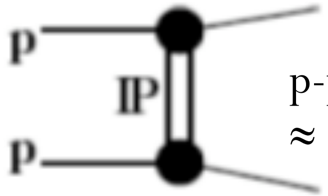
$$\delta\eta = ln\frac{r + \sqrt{r^2 - 1}}{2}, \qquad (22)$$

where $r$ is the right-hand side of Eq. (21). Because $\delta\eta$ is the difference in pseudorapidity between the electron and the neutrino, there are two solutions to the problem. That is, there is no way of resolving the ambiguity of whether the neutrino is at a lower or higher rapidity relative to the electron as seen from the fact that the hyperbolic cosine $\cosh\delta\eta$ is even in $\delta\eta$. Both solutions are possible, at least in principle.

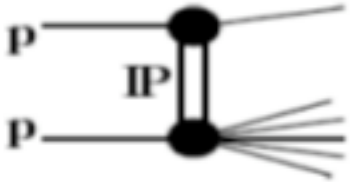
http://vsharma.ucsd.edu/lhc/Baden-Jets-Kinematics-Writeup.pdf

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

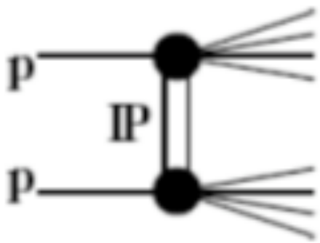
(A) "Real" proton-proton collision (*pomeron exchange*): 40% of the times



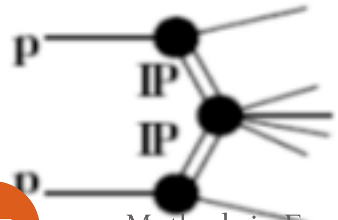

p-p elastic scattering
≈ 25%




Single diffraction
≈ 10%

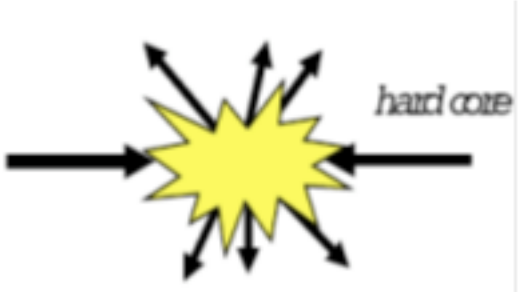



Double diffraction
≈ 1%




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;

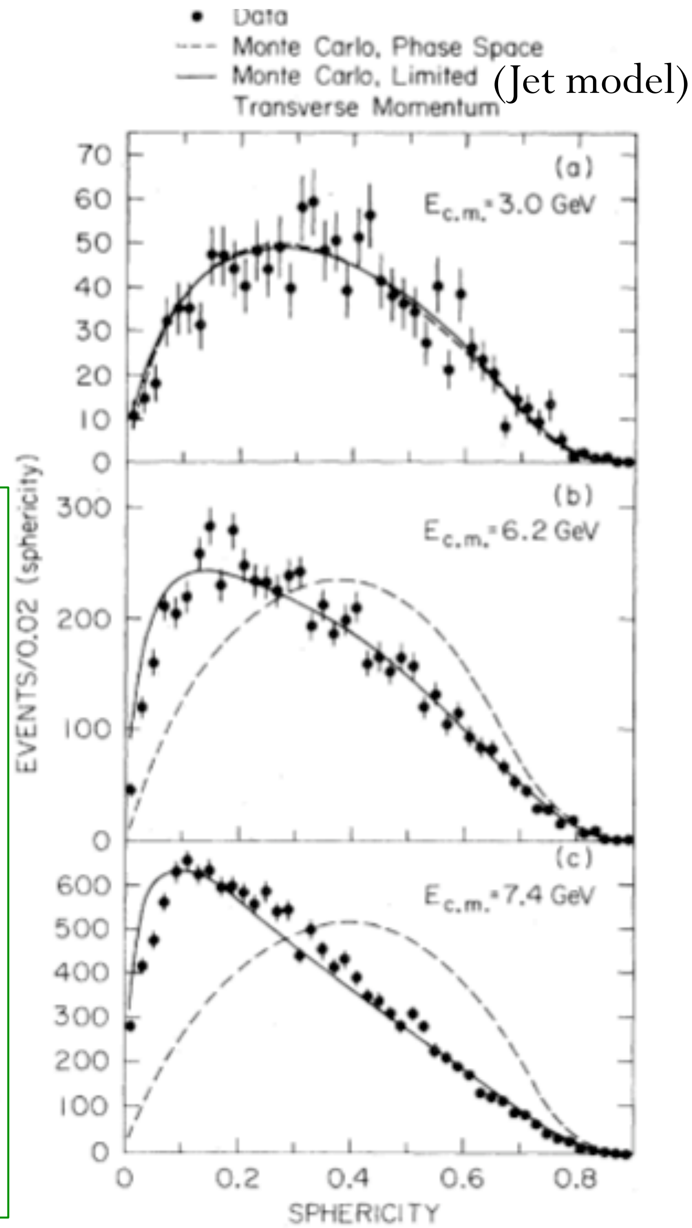
3-jet events: one hard gluon irradiation gives rise to an additional jet (3jet/2jet is a prediction of pQCD)

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

***sphericity*** S $0<S<1$

Here, $p_{ti}$ 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)

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



Several variables have been introduced to specify the jet-like nature of an event. For example:

$$\text{Sphericity} \equiv S' = \frac{3}{2}\min_{\boldsymbol{n}} \left( \frac{\sum_i \boldsymbol{p}_{Ti}^2}{\sum_i \boldsymbol{p}_i^2} \right), \tag{25.2.1}$$

where $\boldsymbol{n}$ is an arbitrary unit vector relative to which $\boldsymbol{p}_{Ti}$ is measured;

$$\text{Thrust} \equiv T = \max_{\boldsymbol{n}} \left( \frac{\sum_i |\boldsymbol{p}_i \cdot \boldsymbol{n}|}{\sum_i |\boldsymbol{p}_i|} \right) \tag{25.2.2}$$

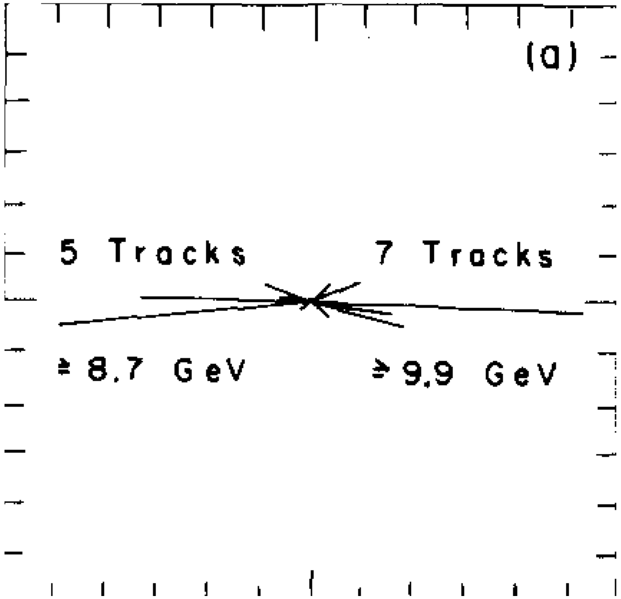
$$\text{Spherocity} \equiv S = \left( \frac{4}{\pi} \right) \min_{\boldsymbol{n}} \left( \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i}|}{\sum_i |\boldsymbol{p}_i|} \right)^2 \tag{25.2.3}$$

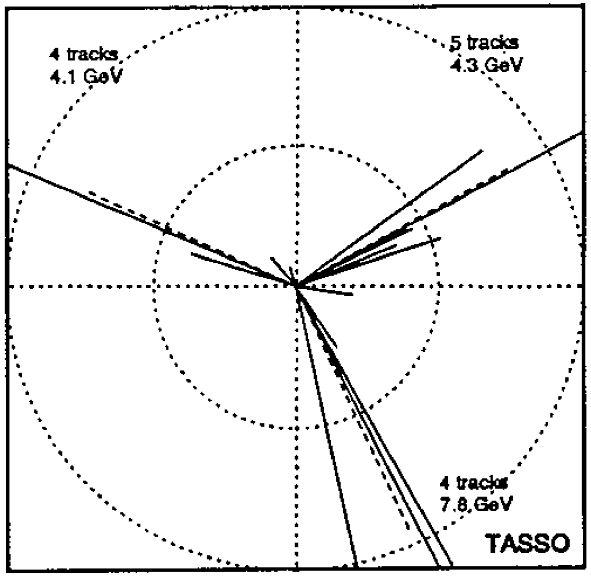
$$\text{Acoplanarity} \equiv A = 4 \min_{\boldsymbol{n}} \left( \frac{\sum_i |\boldsymbol{p}_{\mathrm{out}i}|}{\sum_i |\boldsymbol{p}_i|} \right)^2, \tag{25.2.4}$$

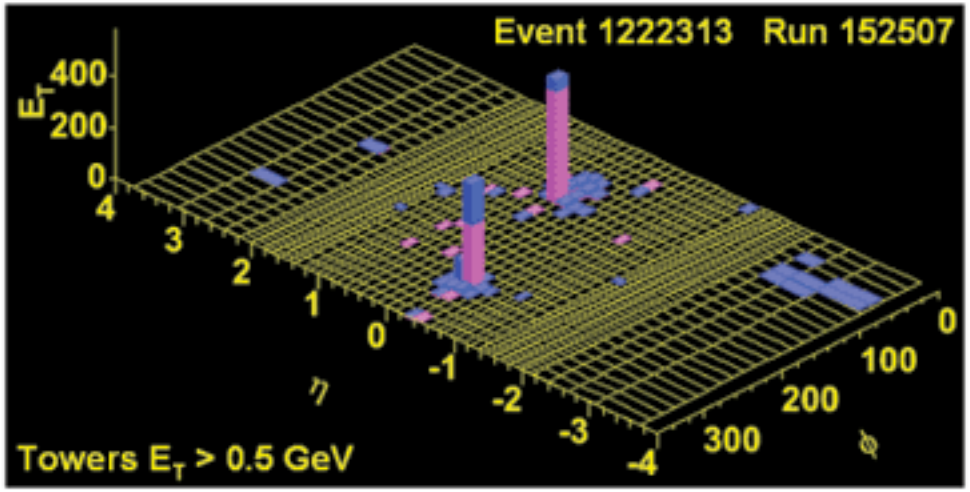
where $\boldsymbol{p}_{\mathrm{out}i}$ is measured transverse to a plane with normal $\boldsymbol{n}$. In these the sum is over all detected particles, and $\boldsymbol{n}$ is varied until the desired maximum or minimum is found.

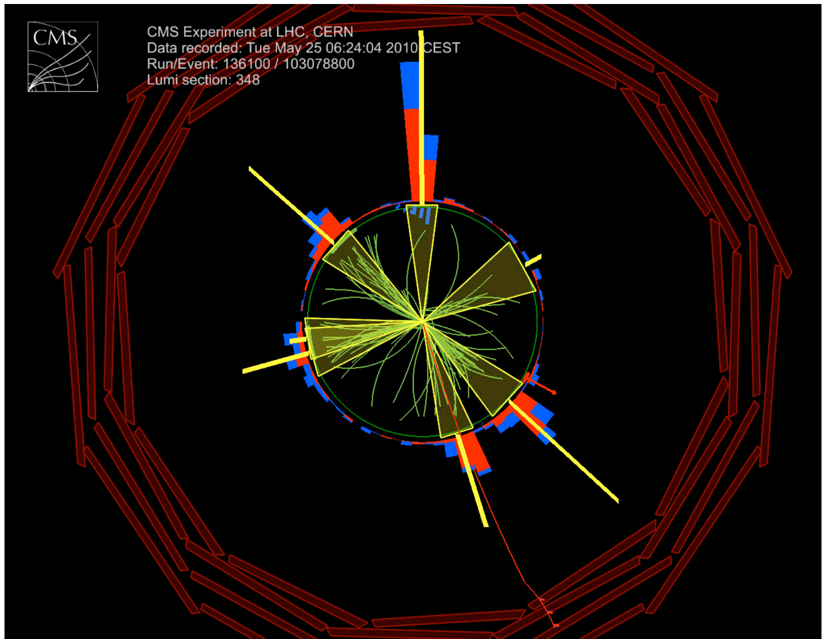
For an ideal two-jet event one would have $S' = 0$, $T = 1$, $S = 0$ and $A = 0$, whereas an isotropic distribution has $S' = 1$, $T = \frac{1}{2}$, $S = 1$ and $A = 1$.

# Jets - II

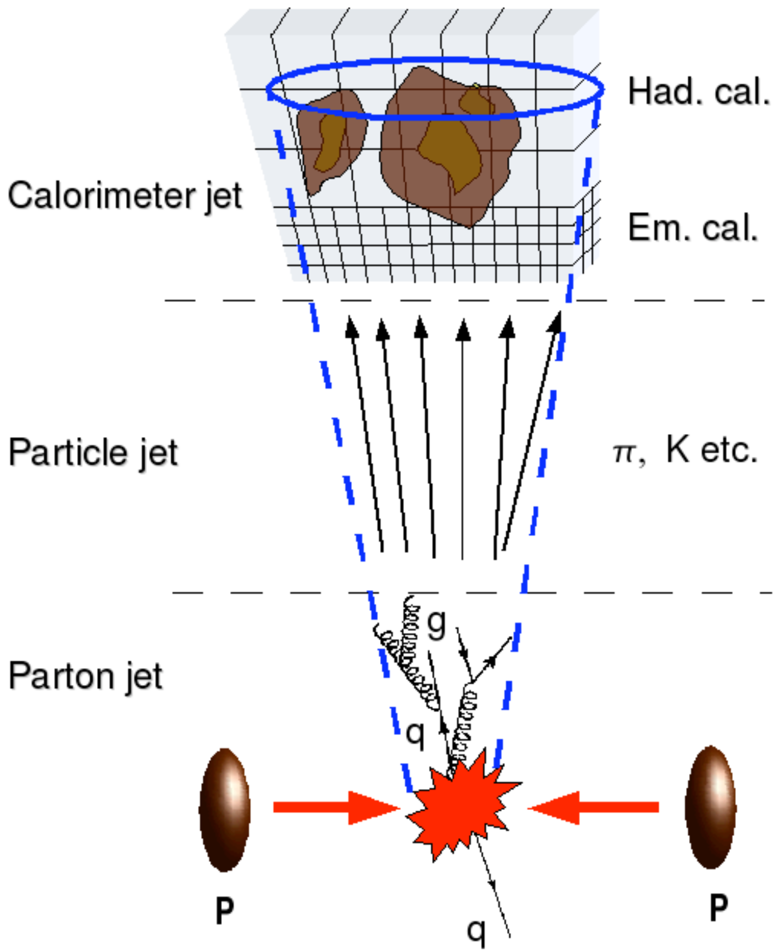

(a)
5 Tracks
7 Tracks
≥ 8.7 GeV
≥ 9.9 GeV


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



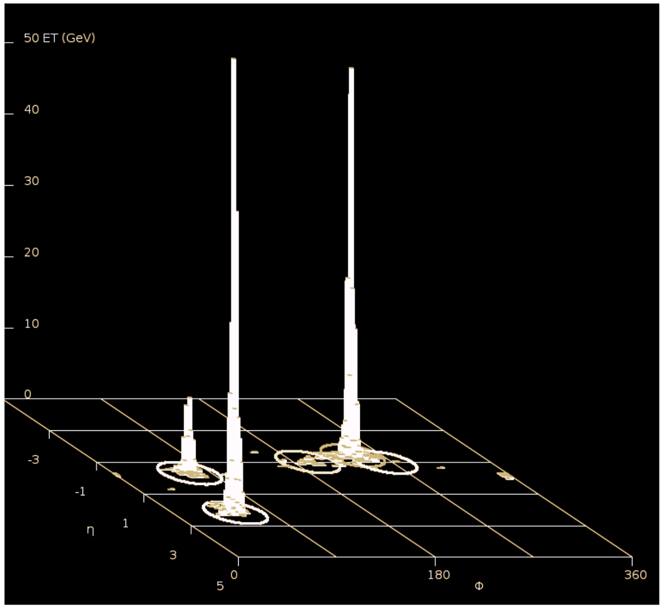

Jet experimental definition:

- based on calorimeter cells
- based on tracks
- → quadri-momentum evaluated (E,p)

Jet algorithms:

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

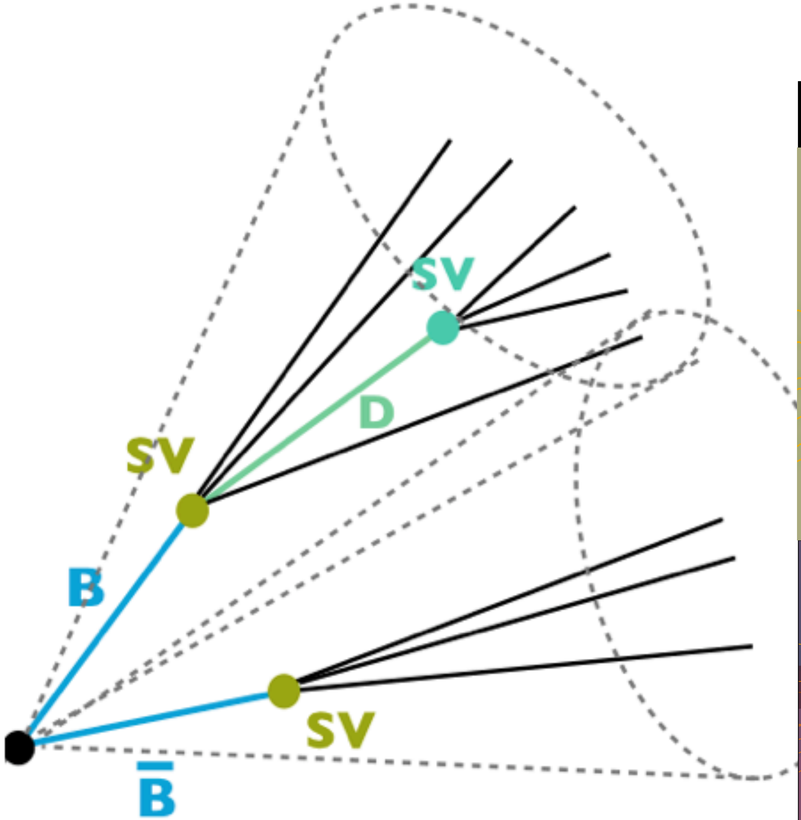
$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

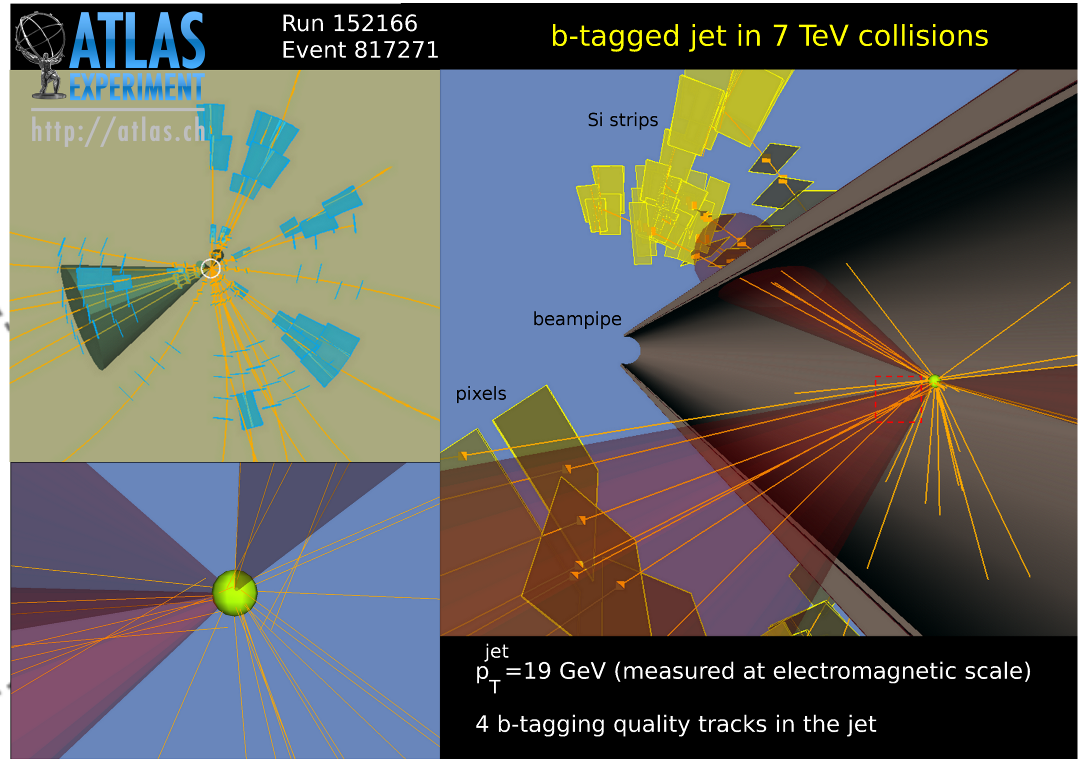


# b-Jets

Two main methods to "tag" B-jets:

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



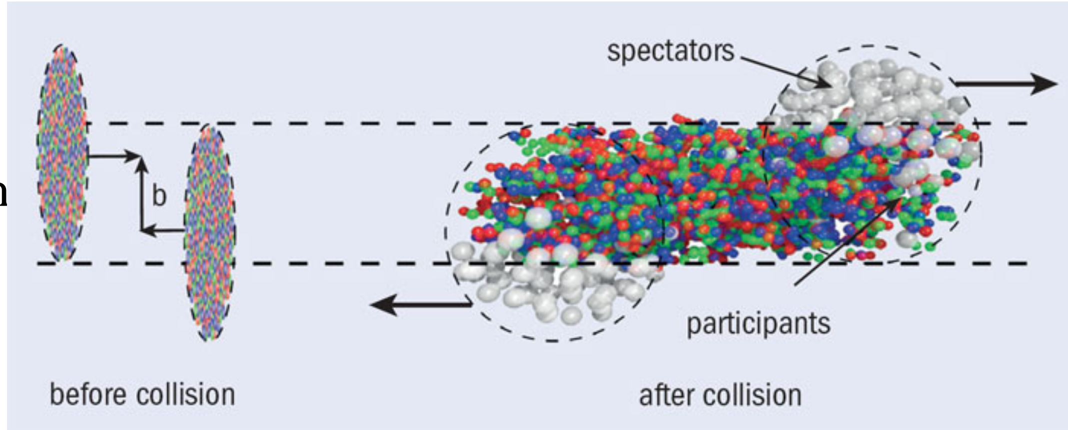
# Heavy Ion collisions: the centrality

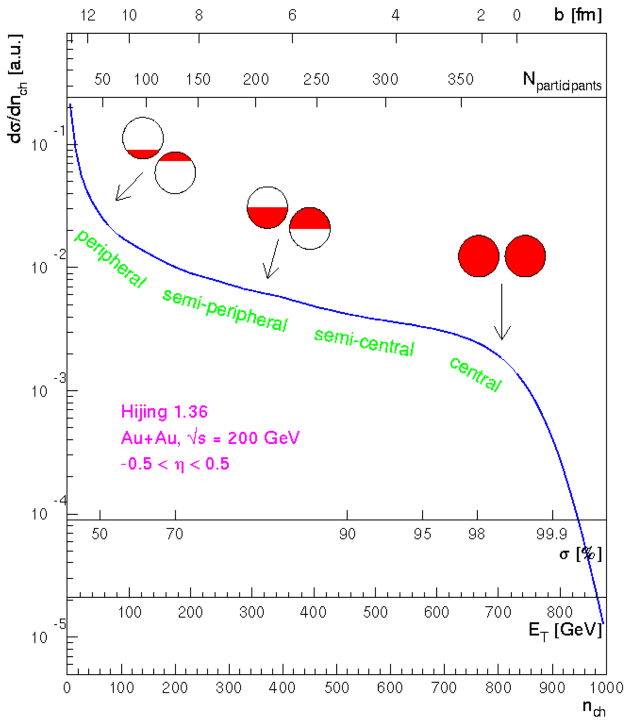
In heavy ion collisions we define the impact parameter ***b***.

***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

The centrality is usually expressed as a percentage of the total nuclear interaction cross section $\sigma$ [2]. The centrality percentile $c$ of an A–A collision with an impact parameter $b$ is defined by integrating the impact parameter distribution $\mathrm{d}\sigma/\mathrm{d}b^{'}$ as

$$c = \frac{\int_0^b \mathrm{d}\sigma/\mathrm{d}b'\,\mathrm{d}b'}{\int_0^\infty \mathrm{d}\sigma/\mathrm{d}b'\,\mathrm{d}b'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{\mathrm{d}\sigma}{\mathrm{d}b'}\,\mathrm{d}b'. \quad (1)$$

# Centrality definition

Events were sorted into different centrality classes. The centrality of heavy-ion interactions is related to the number of participating nucleons and hence to the energy released in the collisions. In CMS, the centrality is defined as percentiles of the energy deposited in the HF. The most central/peripheral event class, i.e. (0–2.5)%/(70–80)% in this analysis, has a large/small number of participants and a large/small energy deposit in HF. In order to estimate the mean number of participating nucleons ($\langle N_{\text{part}} \rangle$) and its systematic uncertainty for each centrality class, a Glauber model of the nuclear collision was used [16–18].

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the central field volume are the silicon pixel and strip trackers, lead-tungstate crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadron calorimeter (HCAL). These calorimeters are physically divided into the barrel and endcap regions covering together the region of $|\eta| < 3.0$. The Hadronic Forward (HF) calorimeters cover $|\eta|$ from 2.9 to 5.2. The HF calorimeters use quartz fibers embedded within a steel absorber. The CMS tracking system, located inside the calorimeter, consists of pixel and silicon-strip layers covering $|\eta| < 2.5$. A set of scintillator tiles, the Beam Scintillator Counters (BSC), are mounted on the inner side of the HF calorimeters to trigger on heavy-ion collisions and reject beam-halo interactions. In addition, two Zero Degree Calorimeters (ZDC) are used for systematic checks. For more details on CMS see [14].

# Centrality definition

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