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 ϕ 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.
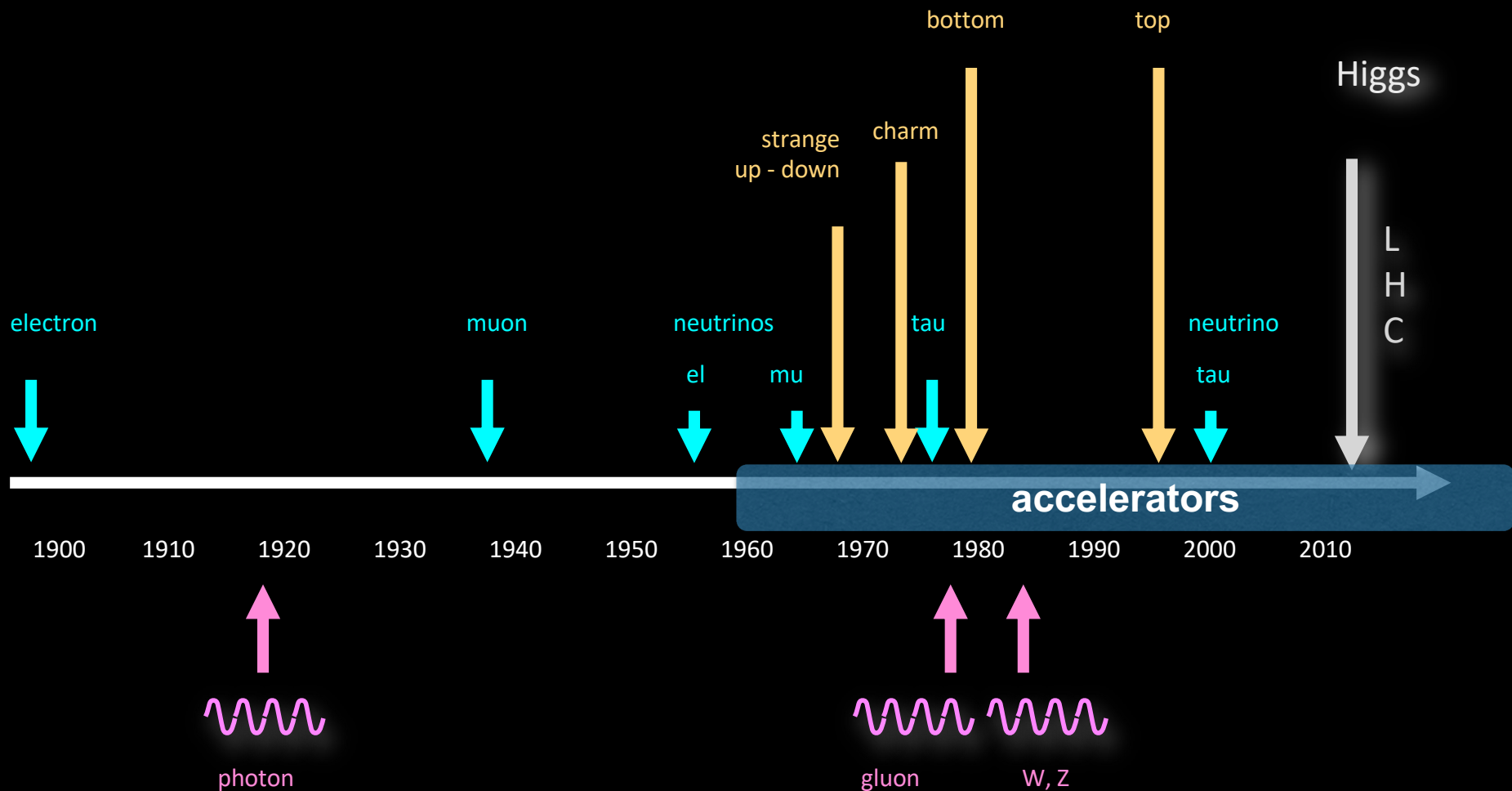
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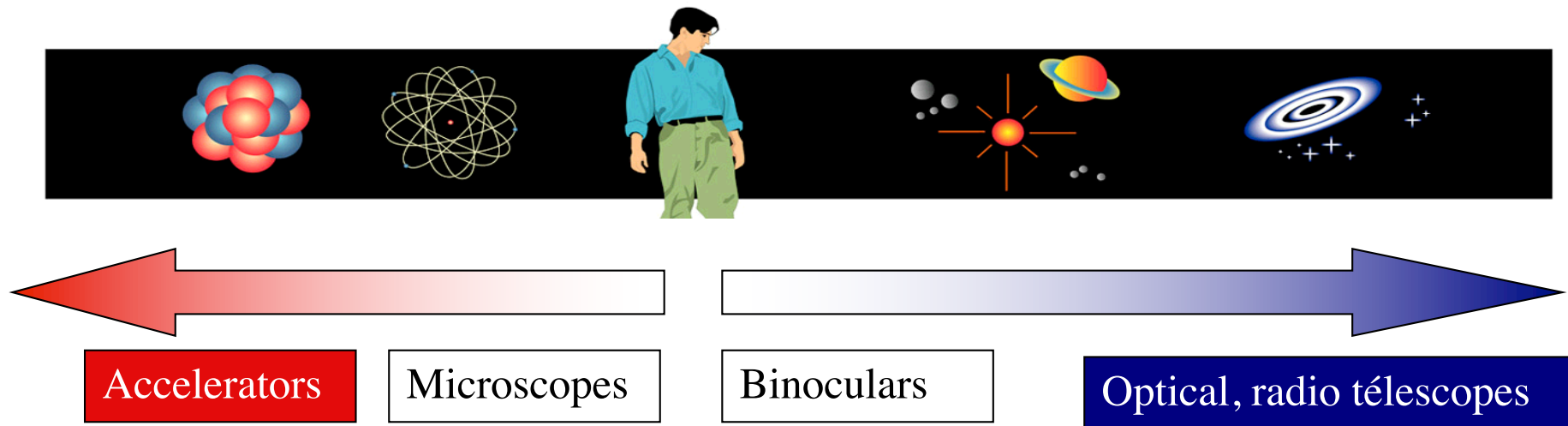
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60 years of experiments at accelerators have discovered the set of fundamental particles
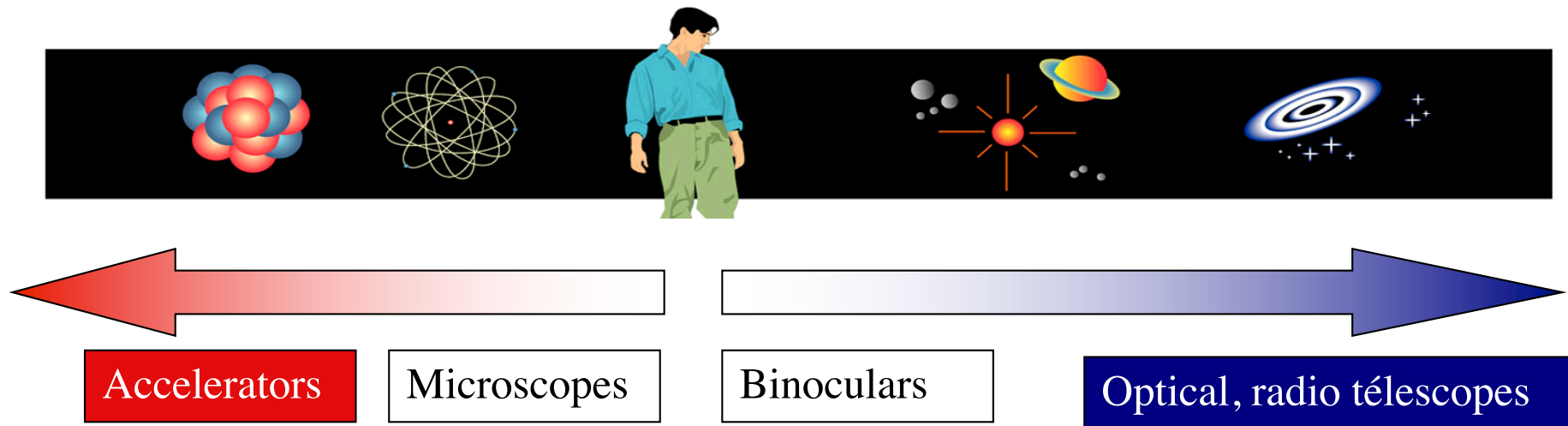
Accelerators gain us one frontier of the physics spectrum

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 a*m* (actually 30 z*m*)

Accelerators gain us one frontier of the physics spectrum

| Accelerators | Microscopes | Binoculars | Optical, radio télescopes |

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: $t_{\mu s} \cong 1/E^2_{Gev}$
- $T \cong 100$ fs after Big Bang for single particle creation (3 TeV)
- $T \cong 1$ μs for collective phenomena QGS (Quark-Gluon Soup)
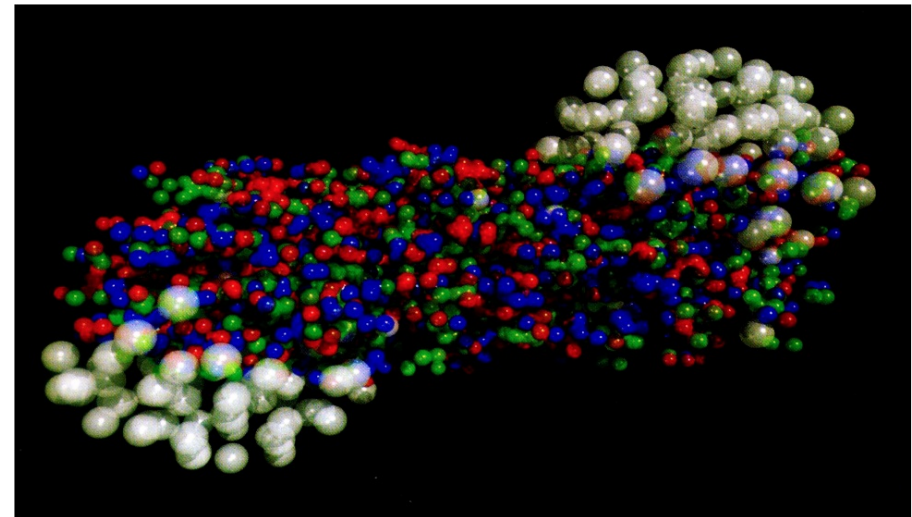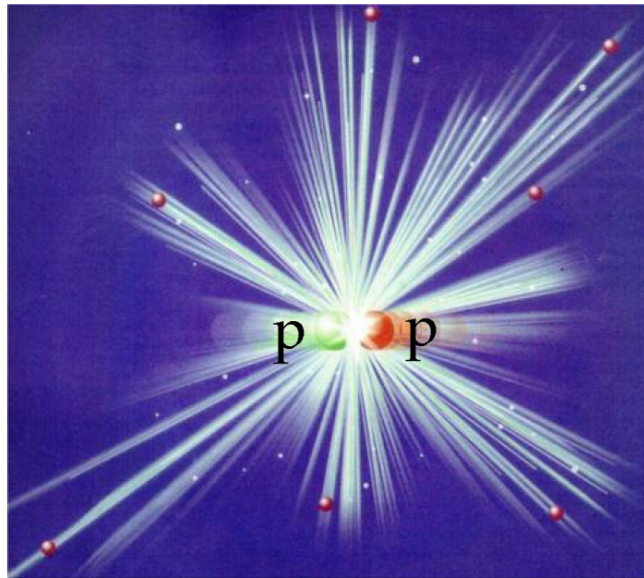
But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about…
Which is a much more complex task!

Accelerators: the two frontiers

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

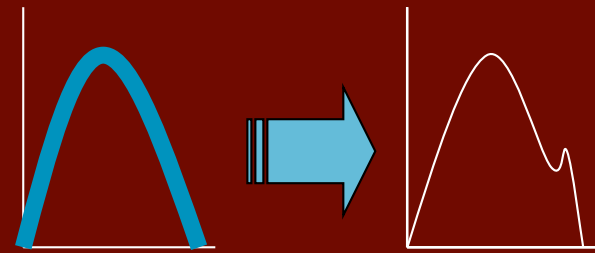## High Energy Frontier

New phenomena
(new particles)
created when the
"usable" energy > mc^2 [×2]
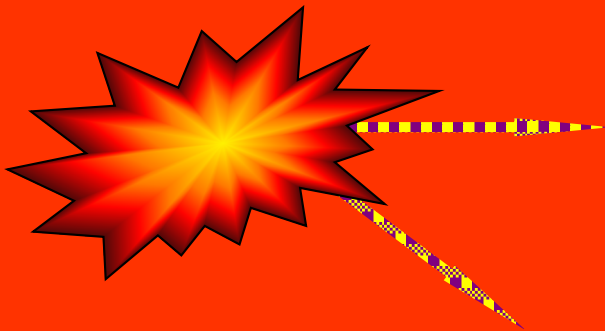
High Precision Frontier
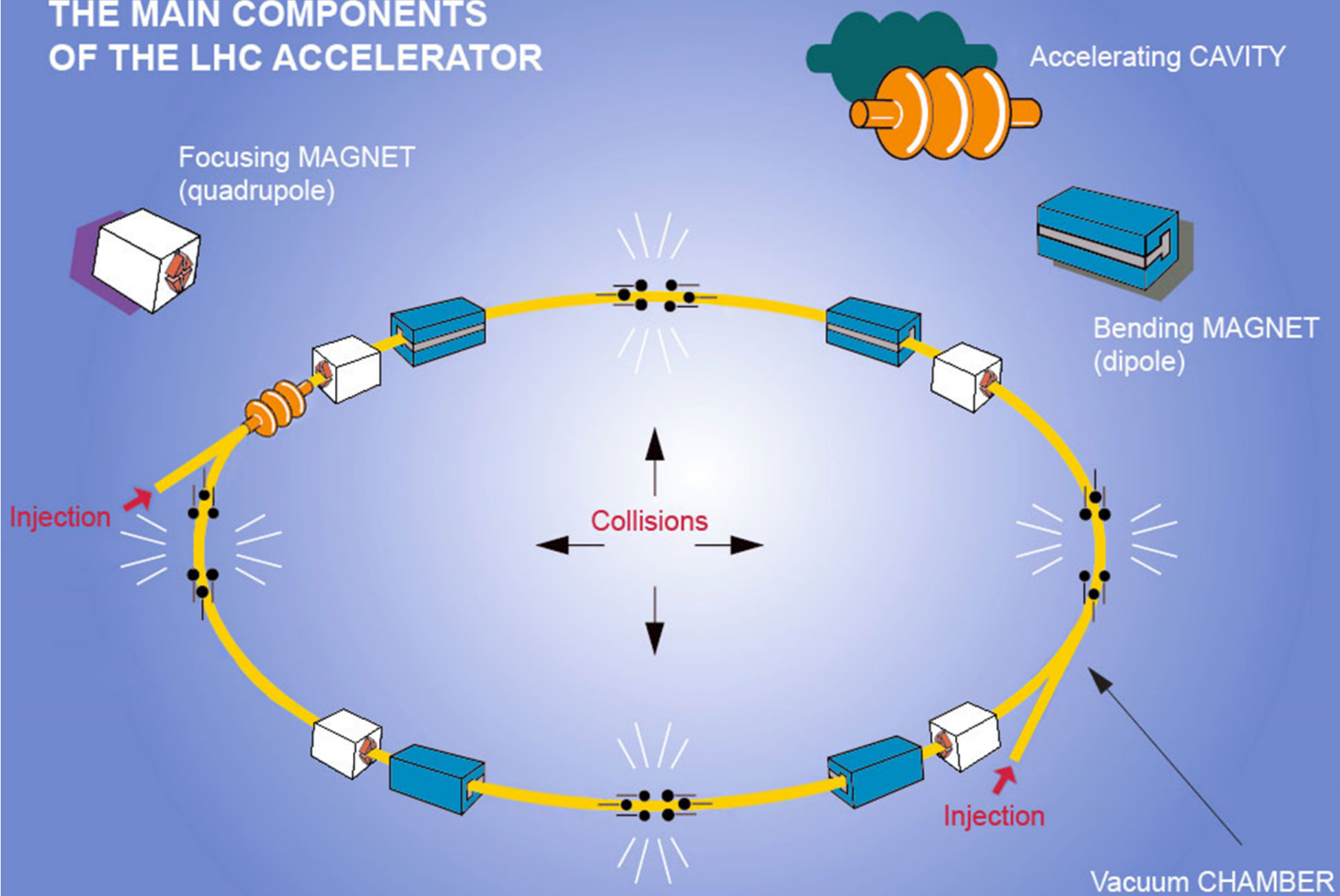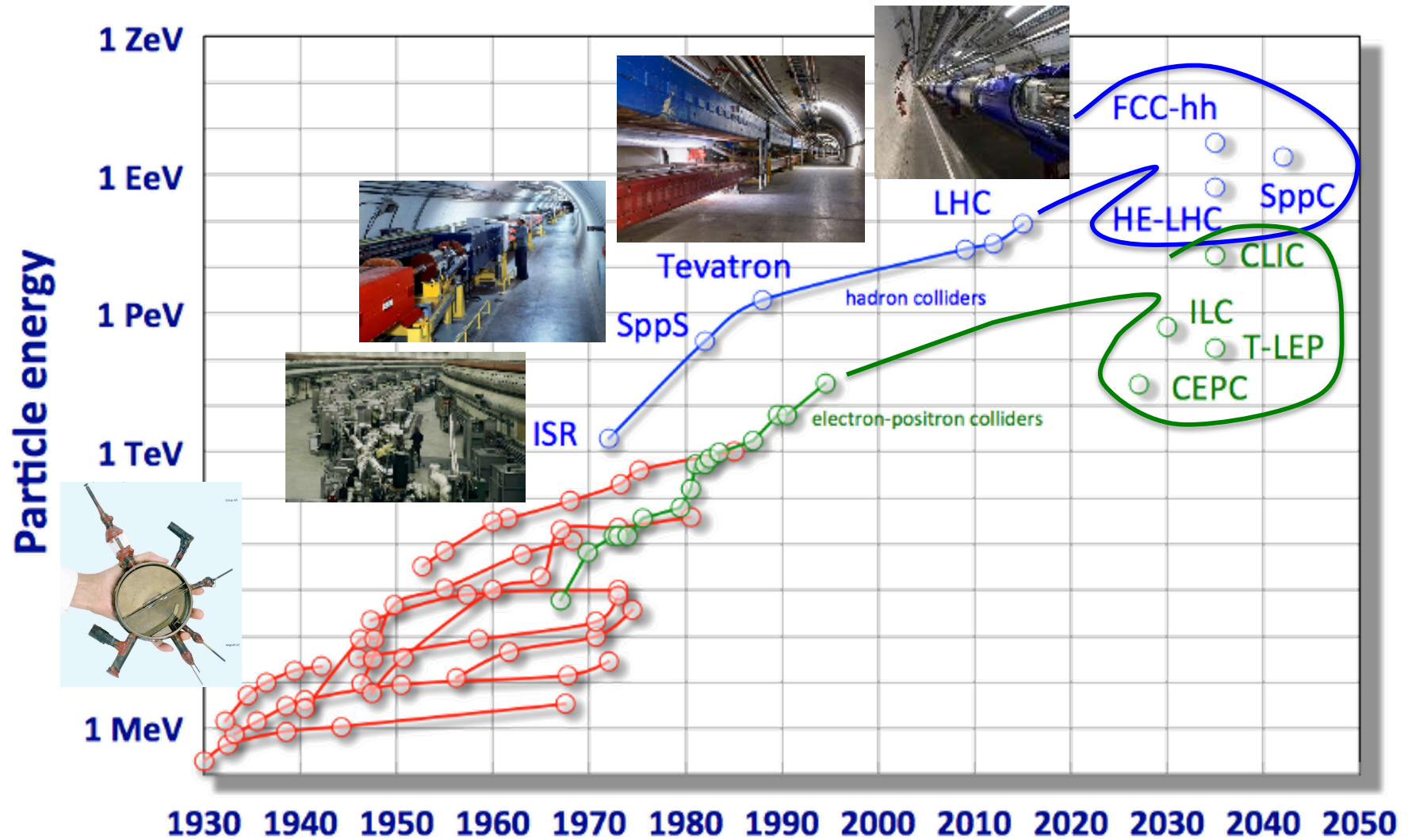
Known phenomena studied
with high precision *may* show
inconsistencies with theory

THE MAIN COMPONENTS
OF THE LHC ACCELERATOR

Accelerating CAVITY

Focusing MAGNET
(quadrupole)

Bending MAGNET
(dipole)

Injection

Collisions

Injection

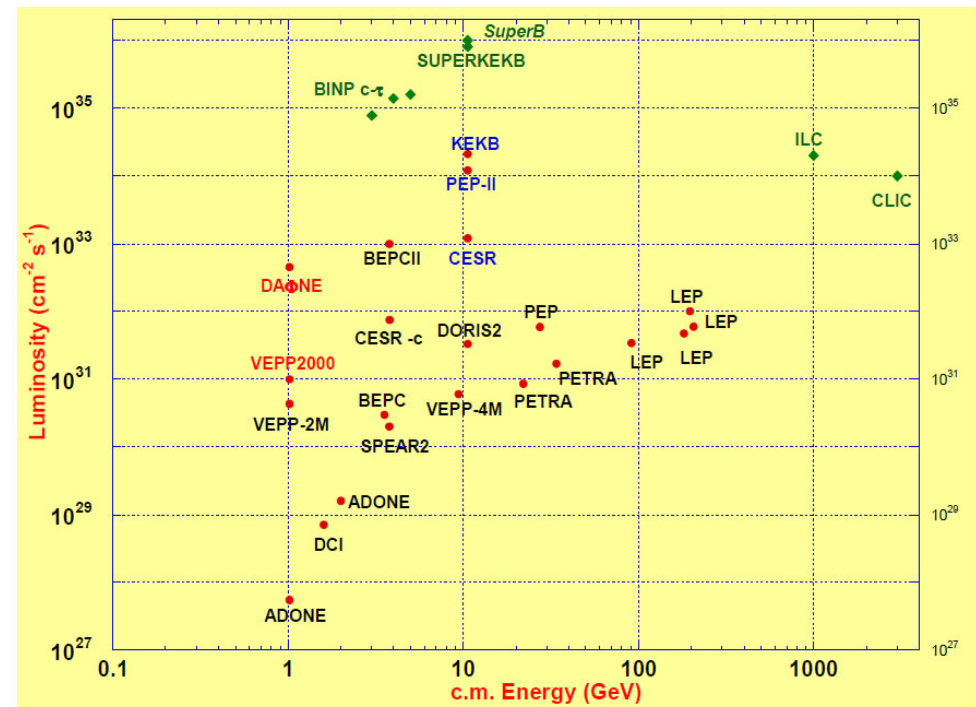Vacuum CHAMBER

Livingston plot

Colliders: "Livingston" plots
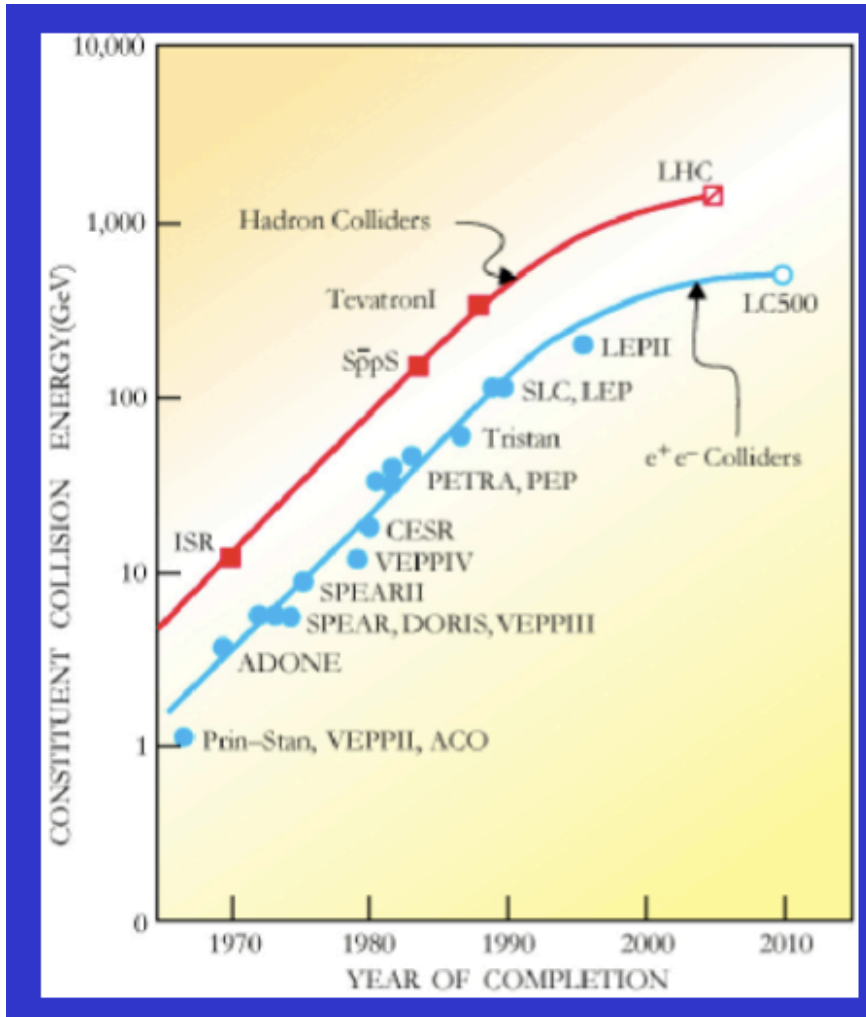
Here it can be seen the separation
Between *Energy* and *Intensity* frontiers !

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 $\approx$ 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: DAΦNE, PEP-II, KEKB, BEPC-II*
    - *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

Methods in Experimental Particle Physics
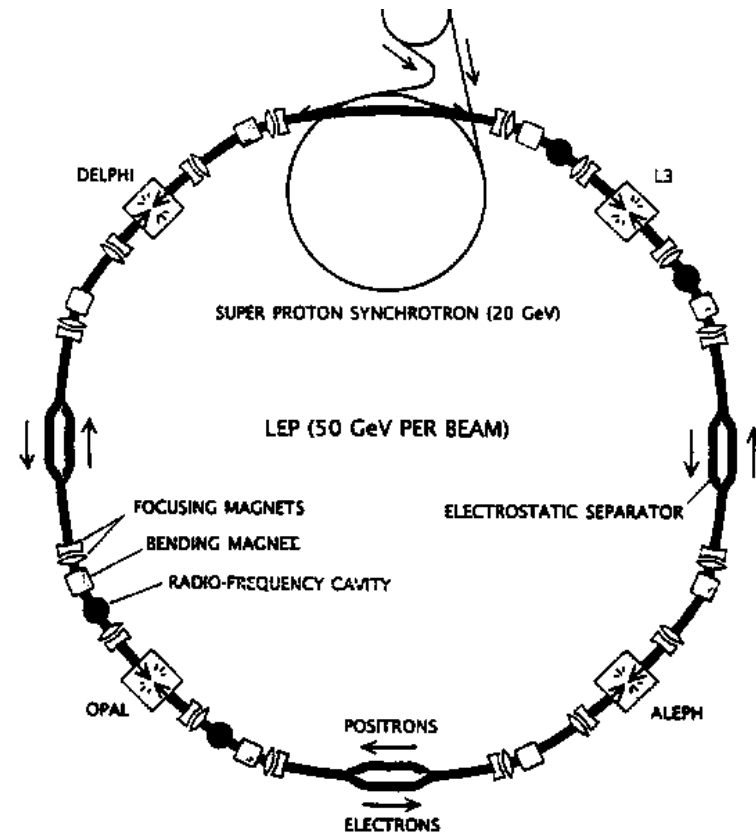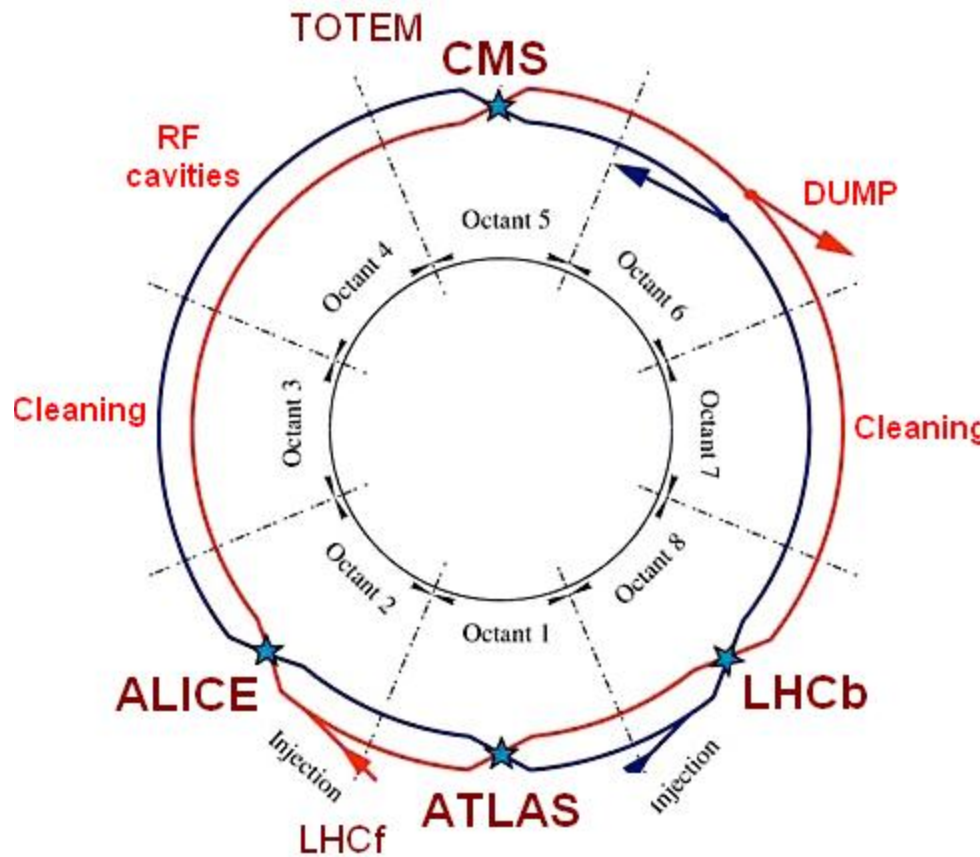
Colliders: general aspects - III

- Two different operation modes:
  - Single injection (LHC)
  - "top-up" injection, continuos mode.
- Important quantities for the experiment operation are:
  - Integrated luminosity
  - Machine background
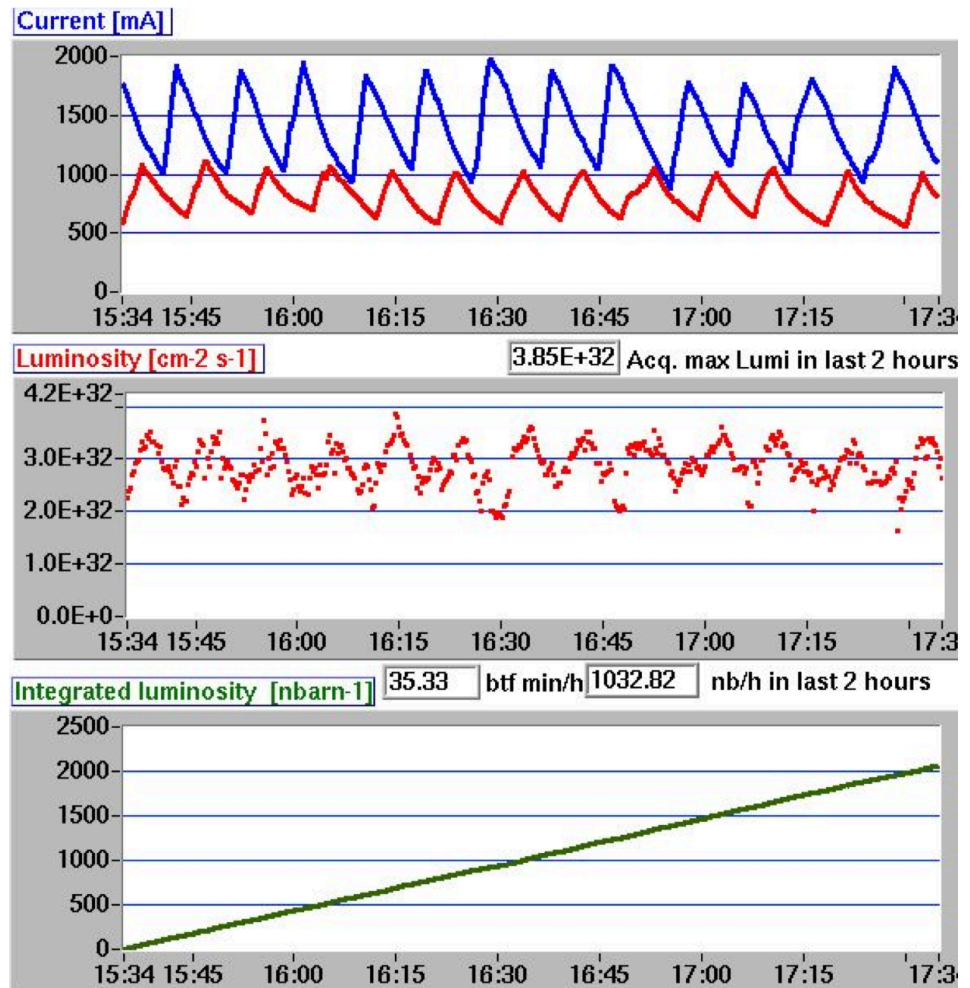
LifeTime: 50% reduction in 10 minutes

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

Methods in Experimental Particle Physics

6/4/20

Collider parameters - I

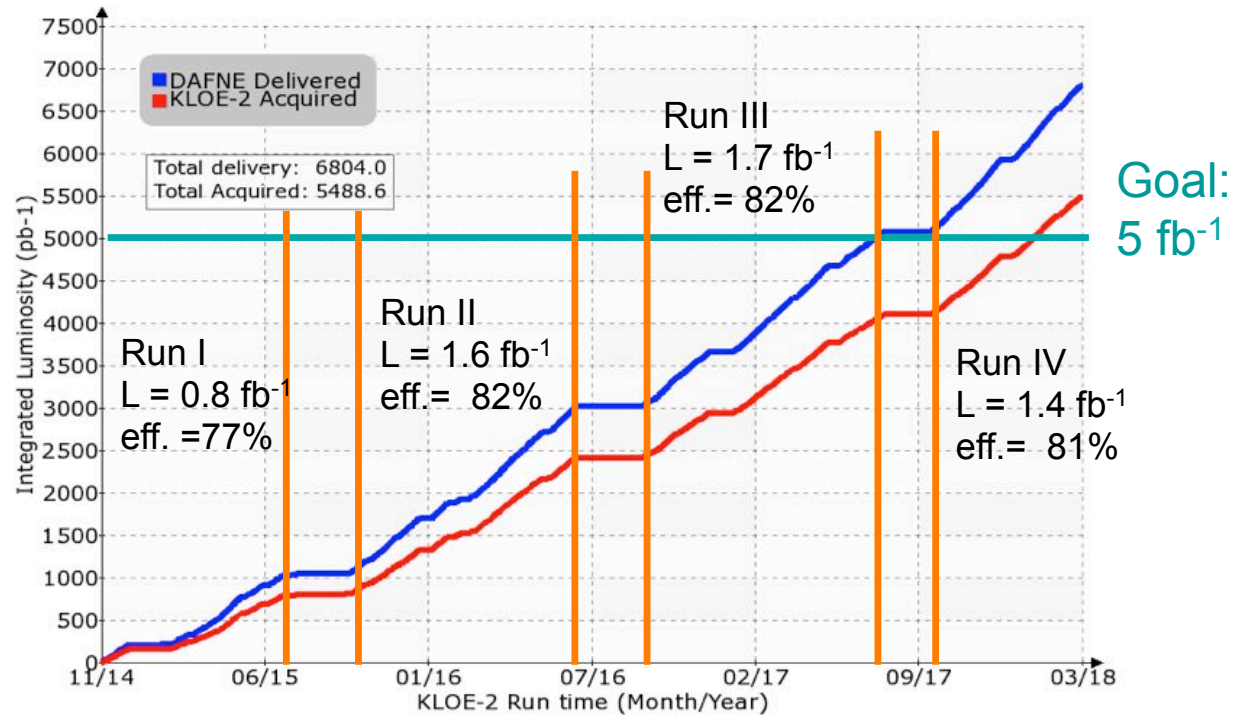|	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Physics start date	2010	1994	1989	2008	1999
Physics end date	—	—	2005	—	—
Maximum beam energy (GeV)	1.0	6	2.5	1.89 (2.3 max)	0.510
Delivered integrated luminosity per exp. (fb^{-1})	0.125	0.027	0.11	17.5	≈ 4.7 in 2001-2007 ≈ 2.7 w/crab-waist ≈ 1.8 since Nov 2014
Luminosity (10^{30} cm^{-2}s^{-1})	40	20	12.6 at 1.843 GeV 5 at 1.55 GeV	1000	453
Time between collisions (μs)	0.04	0.6	0.8	0.008	0.0027
Full crossing angle (μ rad)	0	0	0	2.2×10^4	5×10^4
Energy spread (units 10^{-3})	0.71	1	0.58 at 2.2 GeV	0.52	0.40
Bunch length (cm)	4	5	≈ 5	≈ 1.2	low current: 1 at 15mA: 2
Beam radius (10^{-6} m)	125 (round)	H: 1000 V: 30	H: 890 V: 37	H: 347 V: 4.5	H: 260 V: 4.8
Free space at interaction point (m)	±0.5	±2	±2.15	±0.63	±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 V: 150	H: 200 V: 20	H: 660 V: 28	H: 121 V: 1.56	H: 260 V: 2.6
β^*, amplitude function at interaction point (m)	H: 0.05 − 0.11 V: 0.05 − 0.11	H: 0.75 V: 0.05	H: 1.2 V: 0.05	H: 1.0 V: 0.0129	H: 0.26 V: 0.009

Main parameters

Impact on detector operation

Techincal parameters

Collider parameters - II

	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†	0.0005‡
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	$0.7 \rightarrow 1.5$	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: $200 \rightarrow 300$ V: $2.5 \rightarrow 8$	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: $0.25 \rightarrow 1$	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}

Main parameters

Impact on detector operation

Techincal parameters

Collider parameters - III

Main parameters

Impact on detector operation

Techincal parameters

	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} cm^{-2}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)	$\pm11000^\dagger$	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)

Methods in Experimental Particle Physics

Collider parameters - IV

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
				2009	2012 (expected)	nominal
Physics start date	1992	1987	2001			
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

Main parameters

Impact on detector operation

Techincal parameters

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 σ_{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:
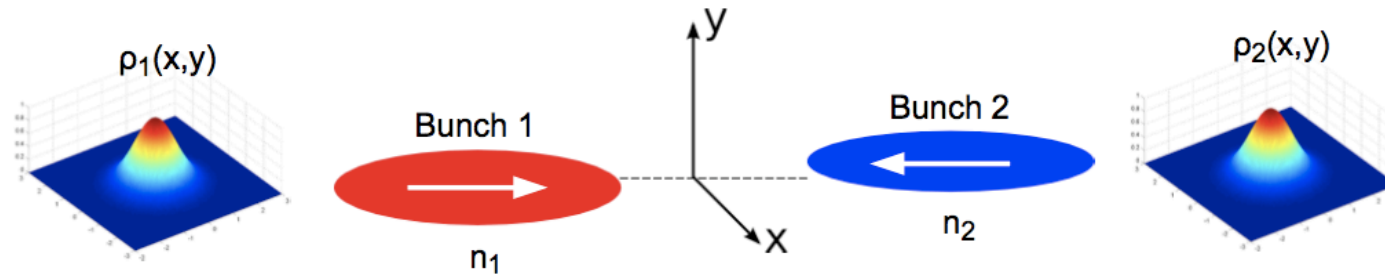
$$R(\delta x) = \int \rho_1(x,y)\rho_2(x+\delta x,y)\,dx\,dy \propto \exp\left(-\frac{\delta x^2}{2\Sigma_x^2}\right)$$
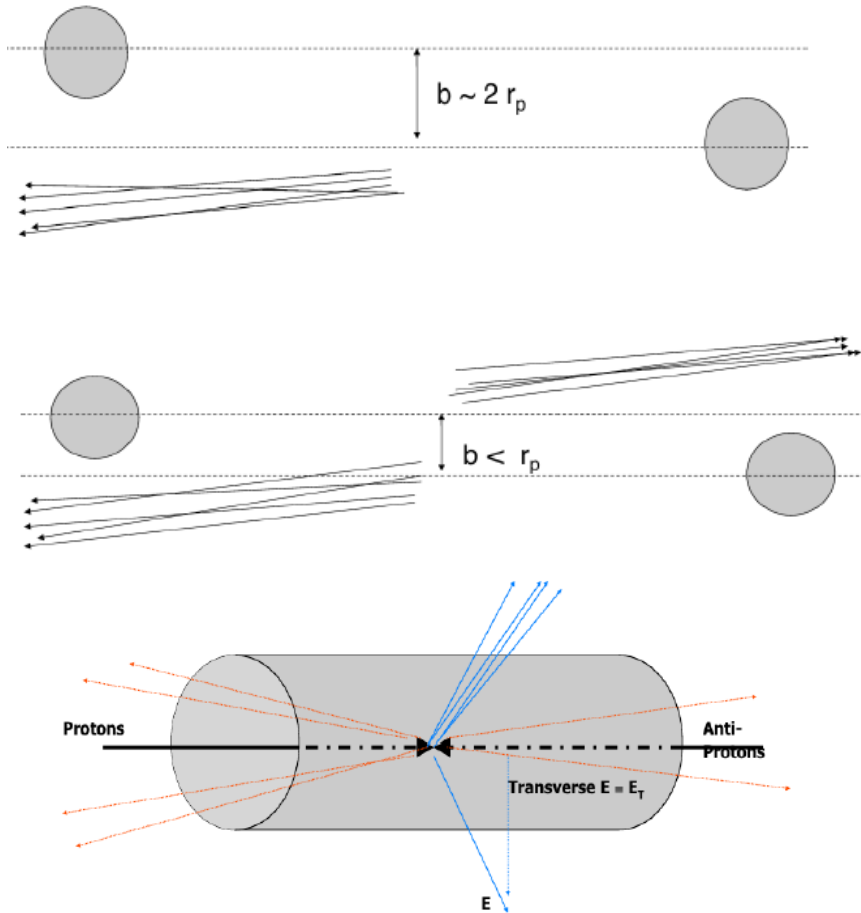
➔ Determine the transverse bunch dimensions Σ_x, Σ_y and the inelastic rate at 0 separation.
➔ Using the known values of the number of protons per bunch from LHC monitors, one get the *inelastic cross-section* that provides the absolute normalization.

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

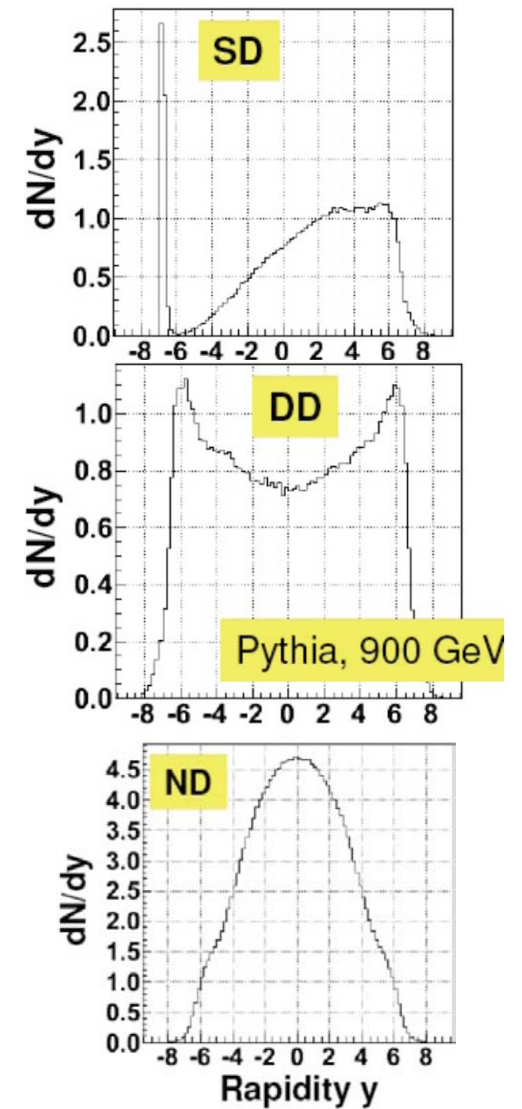$$\sigma_{inel} = \left(\frac{\dot{N}_{inel}^0}{n_b f}\right)\frac{4\pi\Sigma_x\Sigma_y}{N_1 N_2}$$

high cross section process to monitor relative luminosity (R=Lσ):
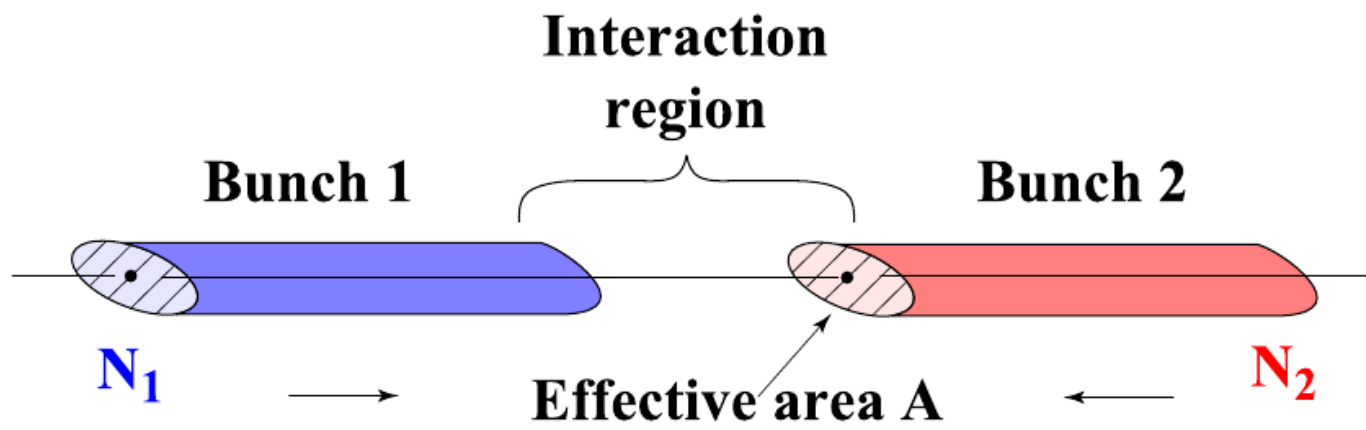pp inelastic scattering   (σ~ 100 mb)

- <u>Single Diffractive</u>

- <u>Double Diffractive</u>

- <u>Non diffractive</u>

Methods in Experimental Particle Physics   6/4/20

Interaction region

Bunch 1

Bunch 2

N_1 →

Effective area A

← N_2

Methods in Experimental Particle Physics

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 ?
    (increase beam divergence
    $$\sigma_x' = \sqrt{\frac{\epsilon_x}{\beta_x^*}} \quad ; \quad \sigma_x = \beta_x \sigma_x'. \;)$$

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

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

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

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 μ = average number of interactions per bunch-crossing

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

Comparison: e⁺e⁻ vs pp

- DAFNE: e^+e^- @ 1 GeV c.o.m. energy, σ_{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, σ_{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:
  - $Z=82, A=208, M \approx 195$ 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}
- $n_b = 600$
- $N_1 = N_2 = 7 \times 10^7$ 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
  - $\sigma_{pPb} \approx \sigma_{pp} \times A^{2/3}$ ($\approx \sigma_{pp} \times R_{Nuc}^2$)
  - $\sigma_{PbPb} \approx \sigma_{pp} \times N_{coll} \approx 10$ 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 μs;
- 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 σ_x and σ_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)
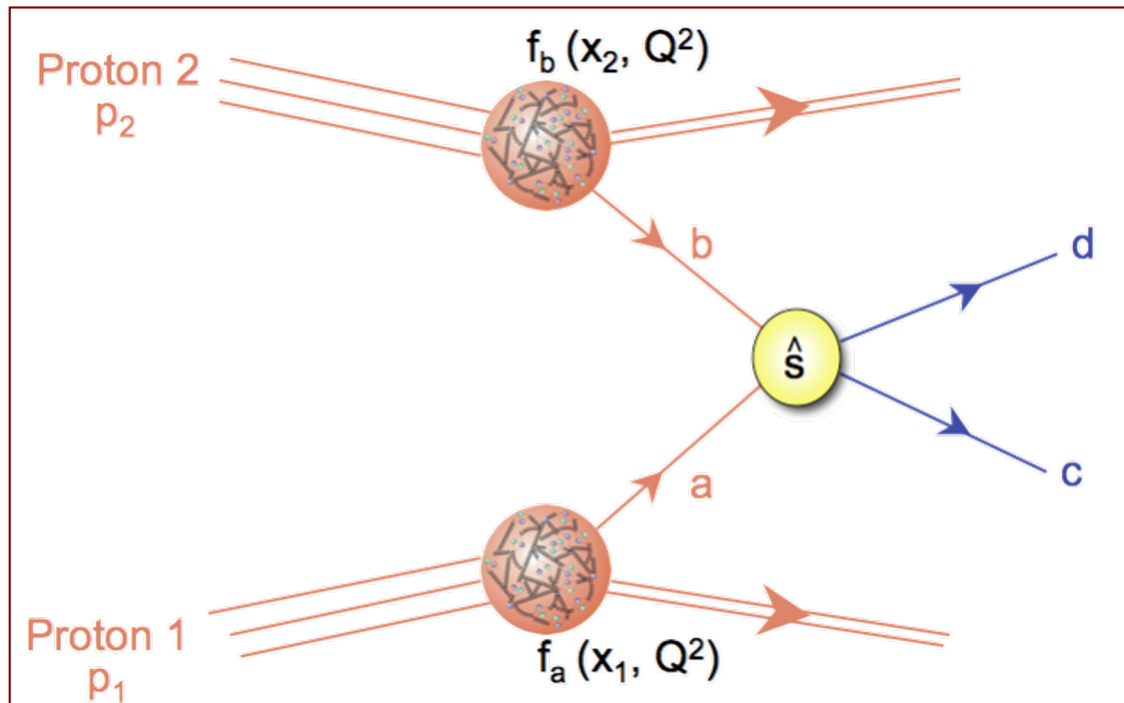
Hadron colliders
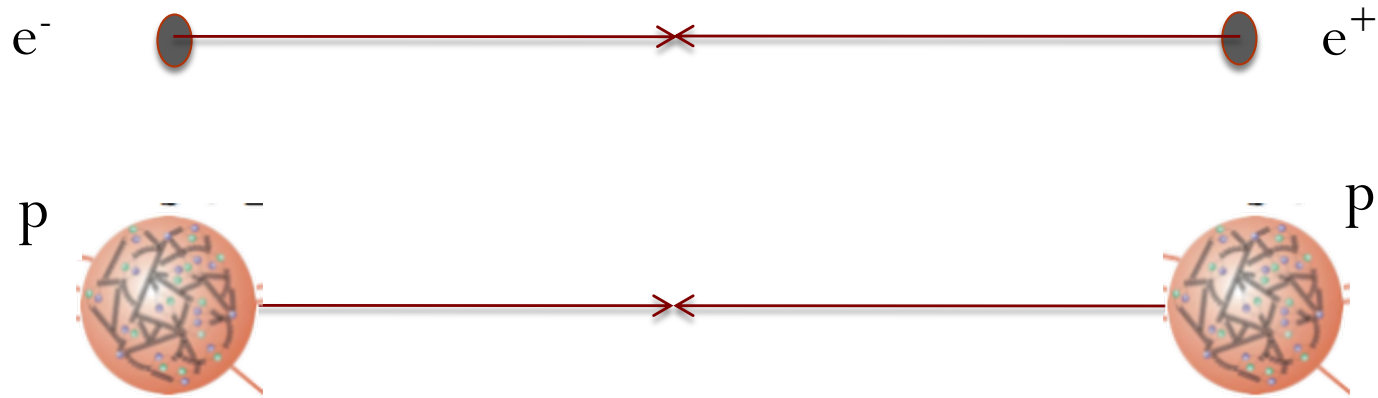
The proton is a complex object done by "partons":

valence quarks / *sea quarks* / *gluons*

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

$\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.

$f_b(x_2, Q^2)$

$\hat{s}$

Proton 2
p_2

b

d

a

c

Proton 1
p_1

$f_a(x_1, Q^2)$

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

Methods in Experimental Particle Physics

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 ($Q^2 = M^2 = \hat{s}$) 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
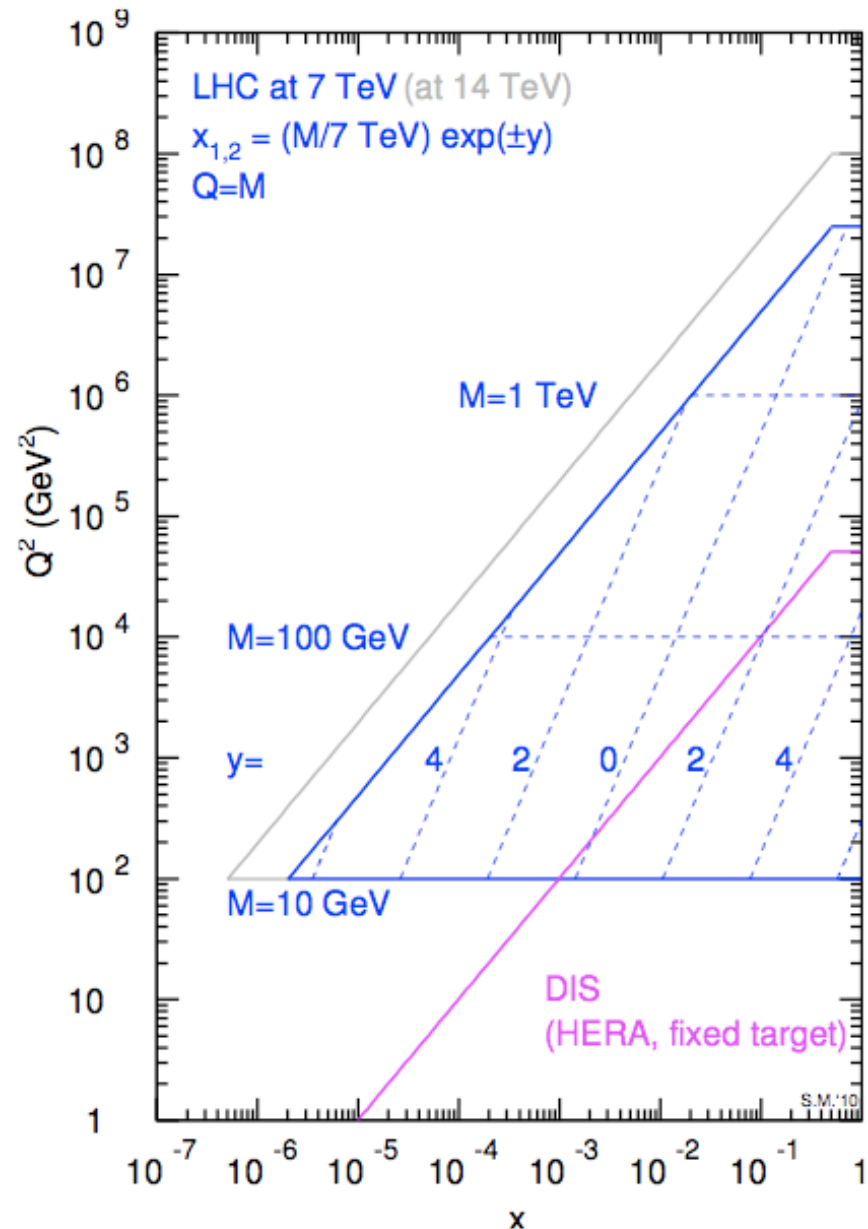
Consider the Higgs production (M_H =125 GeV) at a pp collider at $\sqrt{s} = 14$ TeV. Evaluate the interval in rapidity y and the minimum value of x for direct Higgs production.

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 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

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

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

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

$$y' = y + y_b$$

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

  - 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

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

$$E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2}$$

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

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

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 $\vec{\mathbb{E}}_T$

$$\vec{\mathbb{E}}_T = -\sum_{k=1}^{Ncl} \vec{E}_{Tk} - \sum_{i=1}^{Nm} \vec{p}_{Ti}$$

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

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, ν 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

$$\cosh \delta\eta = \frac{M_W^2}{2E_{T1}E_{T2}} + \cos \delta\phi. \tag{21}$$
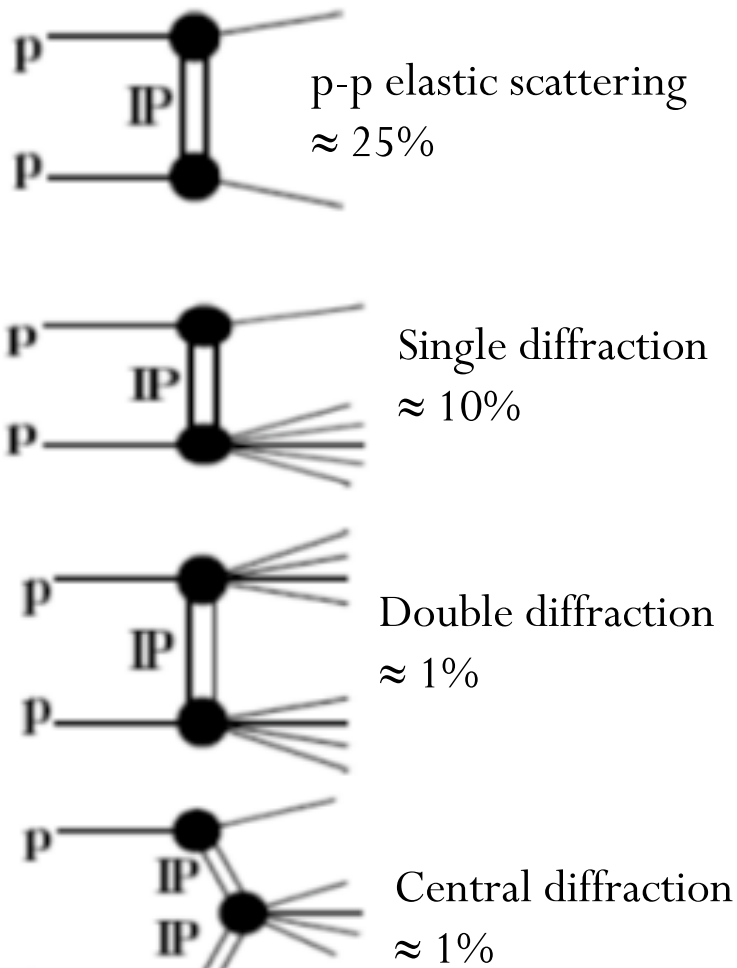
Solving for $\delta\eta$ gives

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

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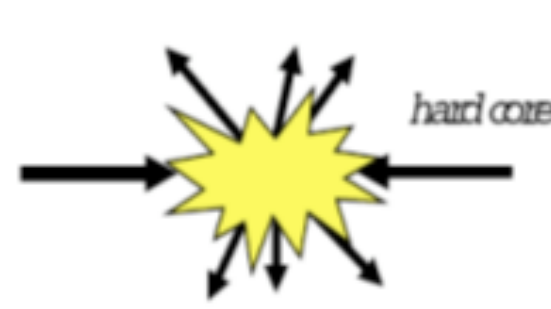
http://vsharma.ucsd.edu/lhc/Baden-Jets-Kinematics-Writeup.pdf

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
$\approx 25\%$

Single diffraction
$\approx 10\%$

Double diffraction
$\approx 1\%$

Central diffraction
$\approx 1\%$

(B) Inelastic non-diffractive:
60% of the times

hard core

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

Data
--- Monte Carlo, Phase Space
— Monte Carlo, Limited (Jet model)
Transverse Momentum

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…

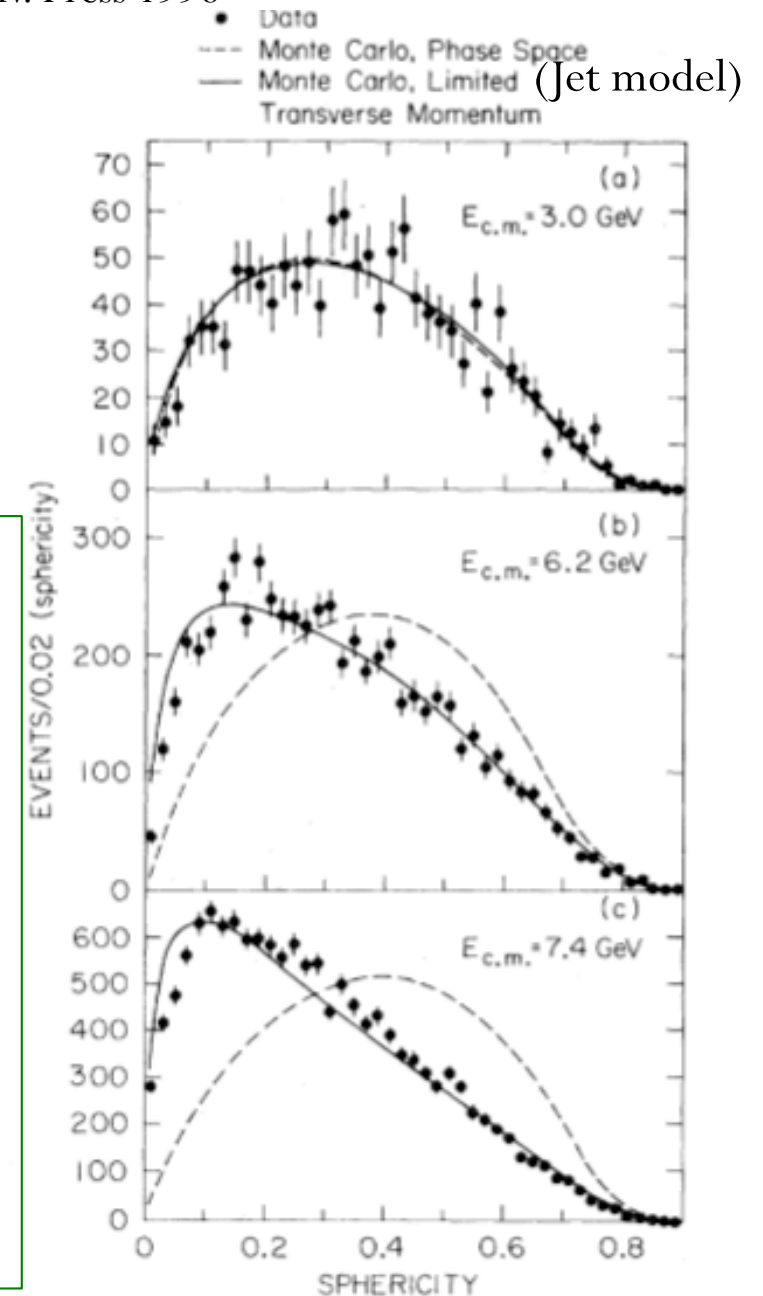2-jet events: qqbar or gg final state that hadronise in 2 jets in back-to-back configuration;

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)

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

(a) $E_{c.m.} = 3.0$ GeV

(b) $E_{c.m.} = 6.2$ GeV

(c) $E_{c.m.} = 7.4$ GeV

EVENTS/0.02 (sphericity)

SPHERICITY

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

$$\text{Sphericity} \equiv S' = \frac{3}{2} \min_n \left(\frac{\sum_i p_{Ti}^2}{\sum_i p_i^2} \right), \qquad (25.2.1)$$

where n is an arbitrary unit vector relative to which p_{Ti} is measured;

$$\text{Thrust} \equiv T = \max_n \left(\frac{\sum_i |p_i \cdot n|}{\sum_i |p_i|} \right) \qquad (25.2.2)$$
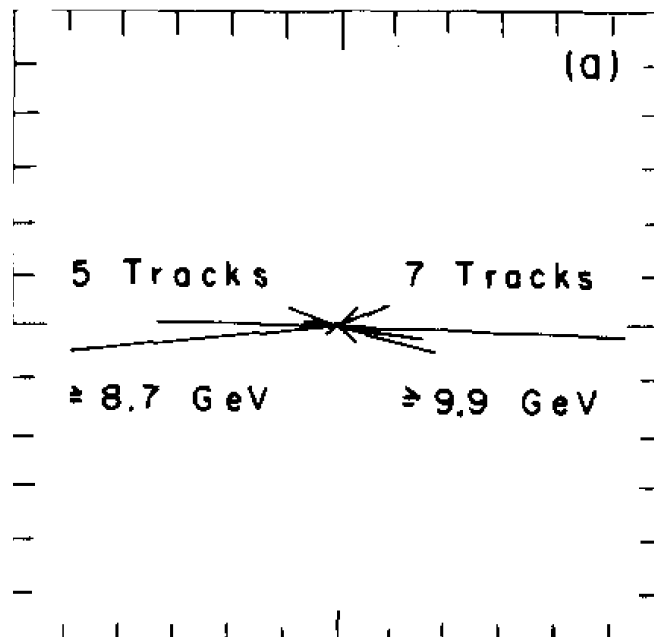
$$\text{Spherocity} \equiv S = \left(\frac{4}{\pi} \right) \min_n \left(\frac{\sum_i |p_{Ti}|}{\sum_i |p_i|} \right)^2 \qquad (25.2.3)$$

$$\text{Acoplanarity} \equiv A = 4 \min_n \left(\frac{\sum_i |p_{outi}|}{\sum_i |p_i|} \right)^2, \qquad (25.2.4)$$

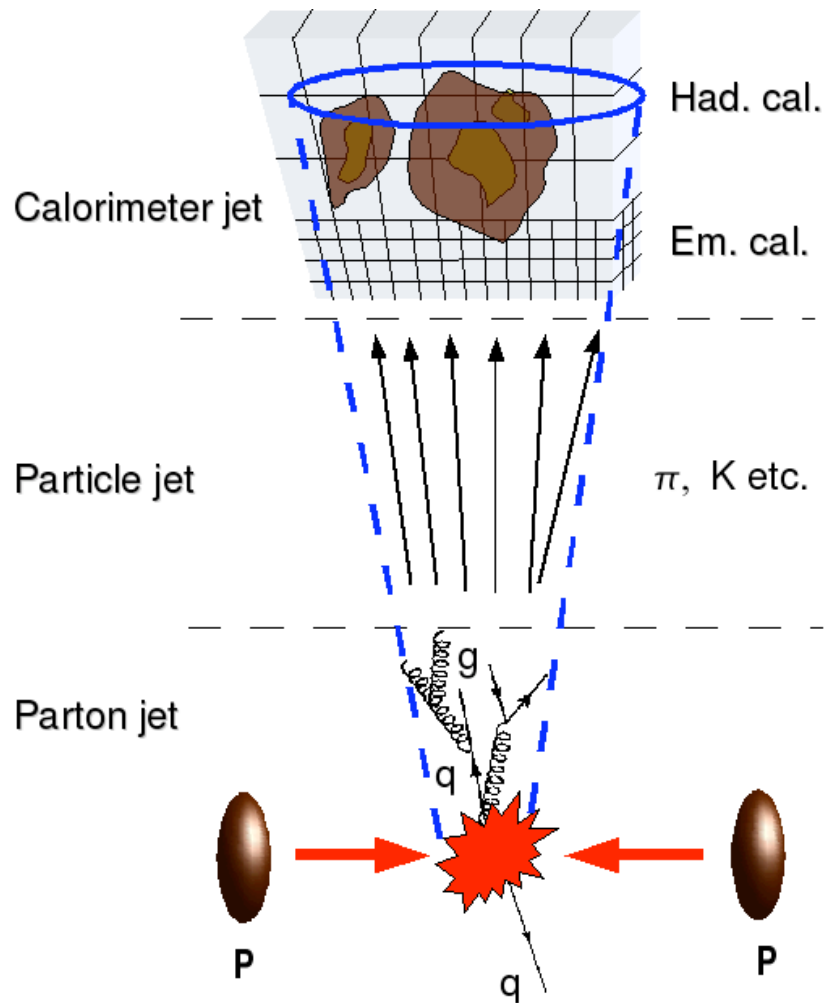where p_{outi} is measured transverse to a plane with normal n. In these the sum is over all detected particles, and n is varied until the desired maximum or minimum is found.

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

E_T 400
200
0

Event 1222313   Run 152507

η

φ

Towers E_T > 0.5 GeV

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

Methods in Experimental Particle Physics
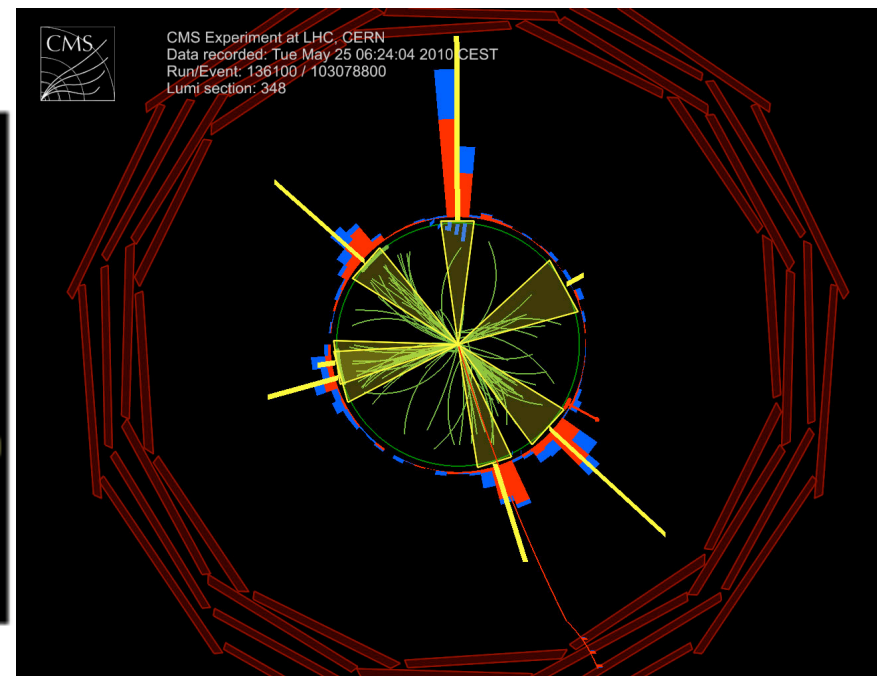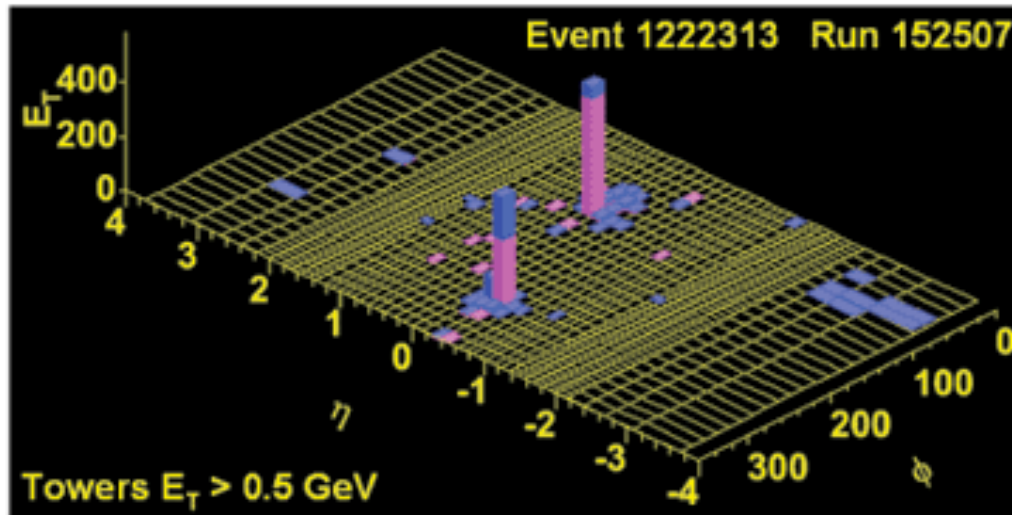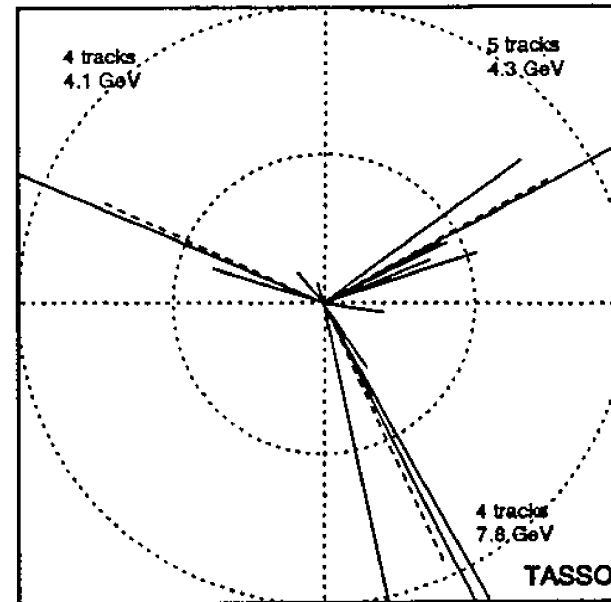
Jets - III

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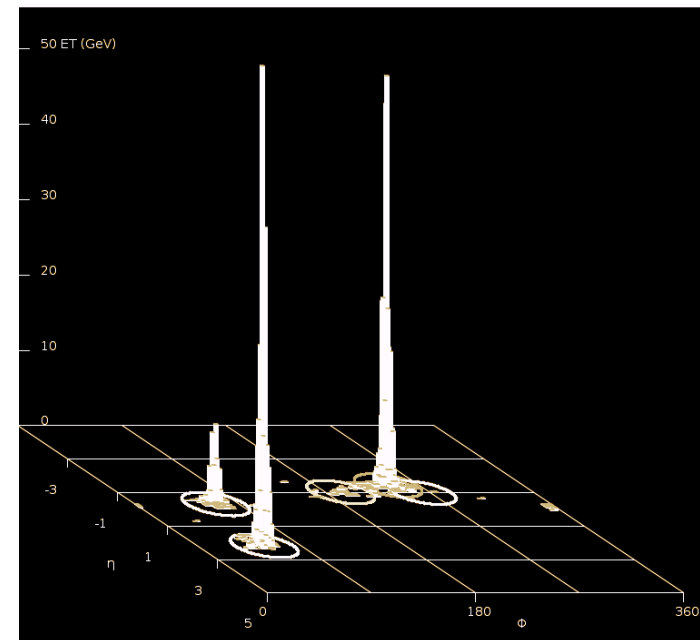- → quadri-momentum evaluated (E,p)

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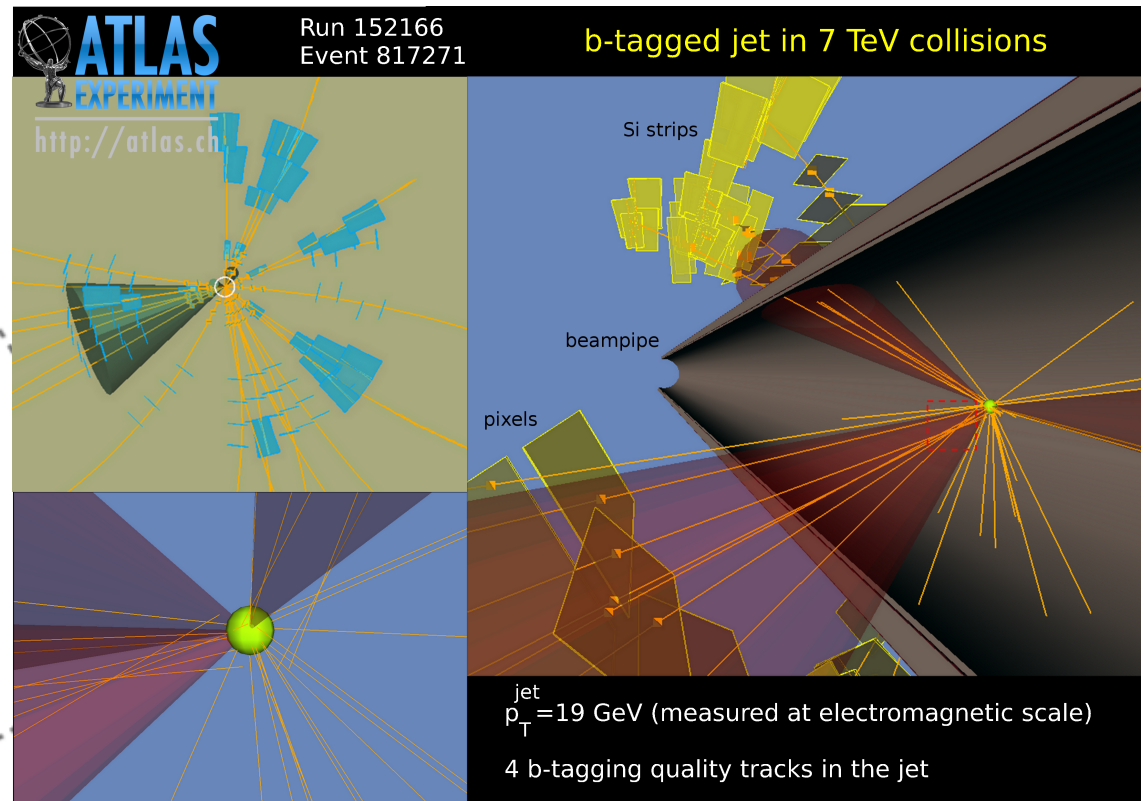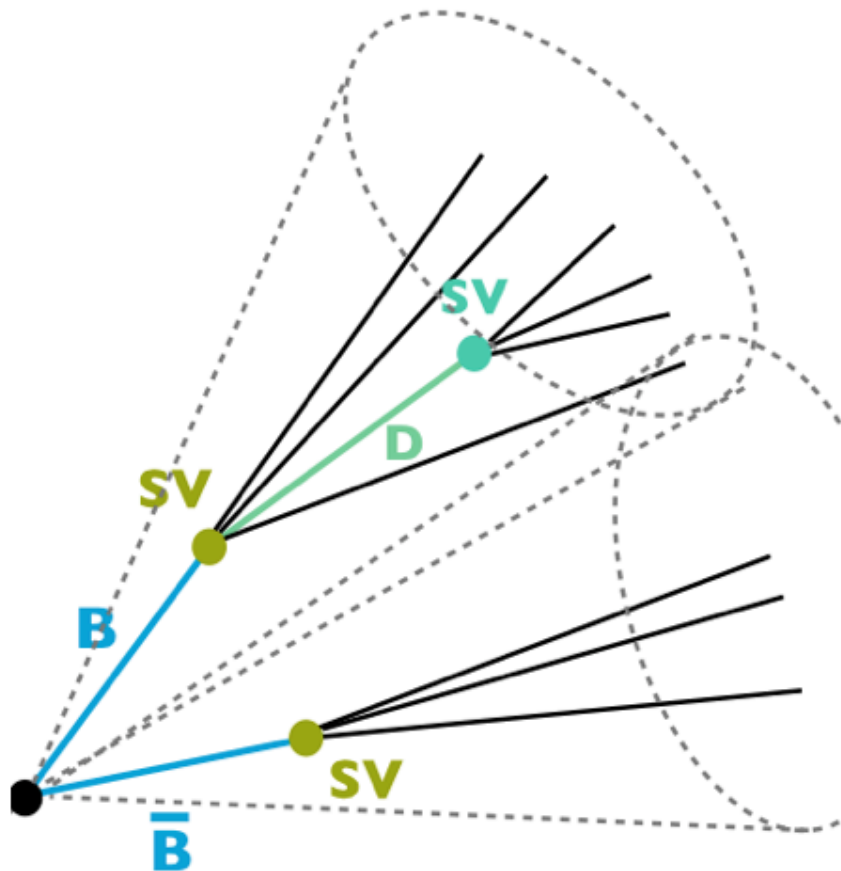- kT algorithms (against infrared divergences)

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

b-Jets

Two main methods to "tag" B-jets:
1) Displaced vertices
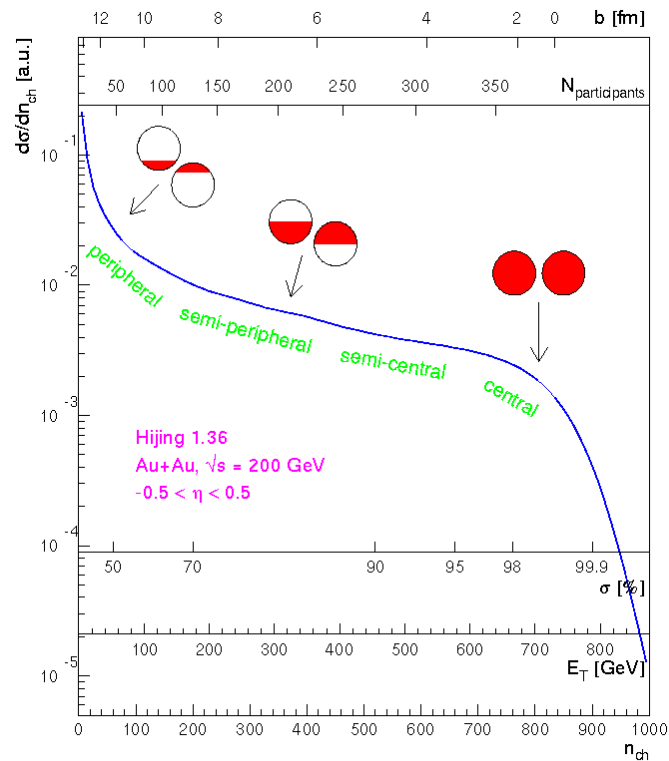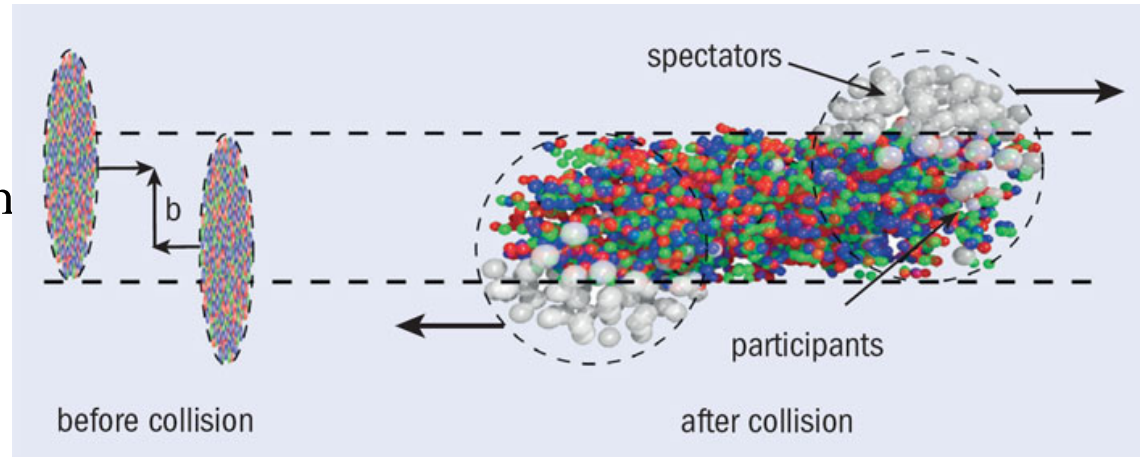2) One or more leptons from semi-leptonic decays. Leptons are not isolated.

Methods in Experimental Particle Physics

Heavy Ion collisions: the centrality

In heavy ion collisions we define the impact parameter b.

$b=0$ or small $\rightarrow$ "central" collision

b large $\rightarrow$ "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.

$\rightarrow$ Total energy measured in the Forward detectors

$\rightarrow$ Divide in "percentile" of centralities

Centrality definition

The centrality is usually expressed as a percentage of the total nuclear interaction cross section σ [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

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

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 ($\langle N_{\mathrm{part}} \rangle$) 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.