SERC School 2011
ON
EXPERIMENTAL HIGH ENERGY PHYSICS @ VECC, KOLKATA

GENERAL DETECTOR SYSTEMS
Part – 1
21 June 2011

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Experimental High Energy Physics

The Time is RIGHT - to be a student of Experimental High Energy Physics:

- Startup of **the LARGE HADRON COLLIDER (LHC)** at CERN became Operational very recently with proton-proton and heavy-ion beams
- **RELATIVISTIC HEAVY ION COLLIDER (BNL)** at BNL is delivering beams at new energies, new species for interesting QGP physics
- **FAIR** Facility at GSI, Germany: work going on at Full swing
- **INO** is now approved and construction work will start soon.

Each start of a new accelerator has been characterized by:

- Dramatic excitement
- Major Discovery Potential

CHALLENGES

ILC detector being designed.

On the heavy-ion front: RHIC is on a discovery path.

LHC is termed as a DISCOVERY Machine.

FAIR coming up strong. NICA at Dubna, Russia coming up as well.

Intimate Connection between THEORY and EXPERIMENT

- **Theoretical predictions**

- **Perform experiments**
  - Start with a particle source at high speed - **Accelerators**
  - Detector modeling - simulations
  - Design Particle detectors
  - Detectors allow one to detect particles
  - New particles are found by direct observation or by observing the decay products
  - New observations are made

- **Comparison with theoretical predictions**

=> Possibility of new discoveries

High Energy Physics Experiments
- A Recipe

Item	What is Needed?
Get particles (e.g. electrons, protons, antiprotons,…heavy-ions)	Particle Source
Accelerate them to high energies	Particle Accelerator
Throw them against each other	Particle Accelerator
Observations in the Detectors	Particle Detector
Data recording and storage	Recording device
Data Analysis	Analysis Tools like root, …. Computing and Data Storage
Interpretation of data	Compare with known theories
For all these	**Lots of dedicated person-power, Lots of money and expertise**

Sources of Elementary Particles

- **Radioactive Sources**
  - High intensity available
  - Can be collimated to point source
  - Energies up to 10 MeV
  - Alpha, beta-, beta+, gamma, neutron sources possible
  - Still used to test detectors

- **Cosmic Rays**
  - Small intensity, direction not properly defined
  - High energy
  - Mainly muons
  - Still used to test detectors

- **Accelerators**
  - High intensities, energies up to several TeV
  - Well defined geometry
  - Well defined timing
  - Different particle species
  - Well controlled

Radioactive Sources

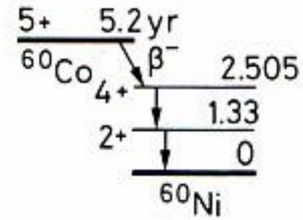
α emitters

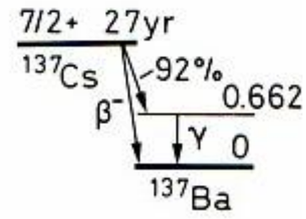
Isotope	Half-life	Energies [MeV]	Branching
^{241}Am	433 yrs.	5.486	85%
		5.443	12.8%
^{210}Po	138 days	5.305	100%
^{242}Cm	163 days	6.113	74%
		6.070	26%

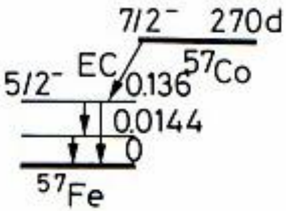
β emitters

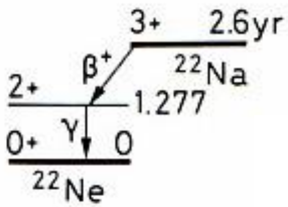
Source	Half-life	E_{max} [MeV]
^{3}H	12.26 yr	0.0186
^{14}C	5730 yr	0.156
^{32}P	14.28 d	1.710
^{33}P	24.4 d	0.248
^{35}S	87.9 d	0.167
^{36}Cl	3.08×10^{5} yr	0.714
^{45}Ca	165 d	0.252
^{63}Ni	92 yr	0.067
^{90}Sr/^{90}Y	27.7 yr/64 h	0.546/2.27
^{99}Tc	2.12×10^{5} yr	0.292
^{147}Pm	2.62 yr	0.224
^{204}Tl	3.81 yr	0.766

γ emitters



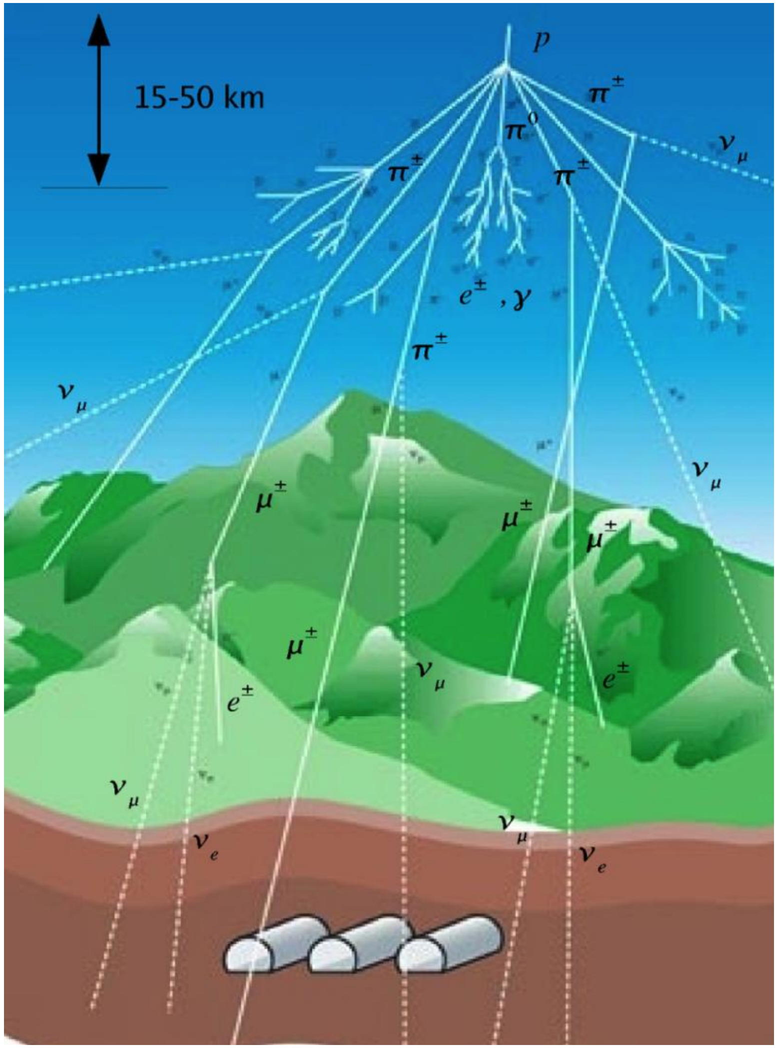






COSMIC RAYS

Cosmic rays are energetic charged subatomic particles, originating from outer space. They may produce secondary particles that penetrate the Earth's atmosphere and surface.



Hess’s work during 1911-1913.

Cosmic rays are source of many important particle discoveries in 1930-1950.

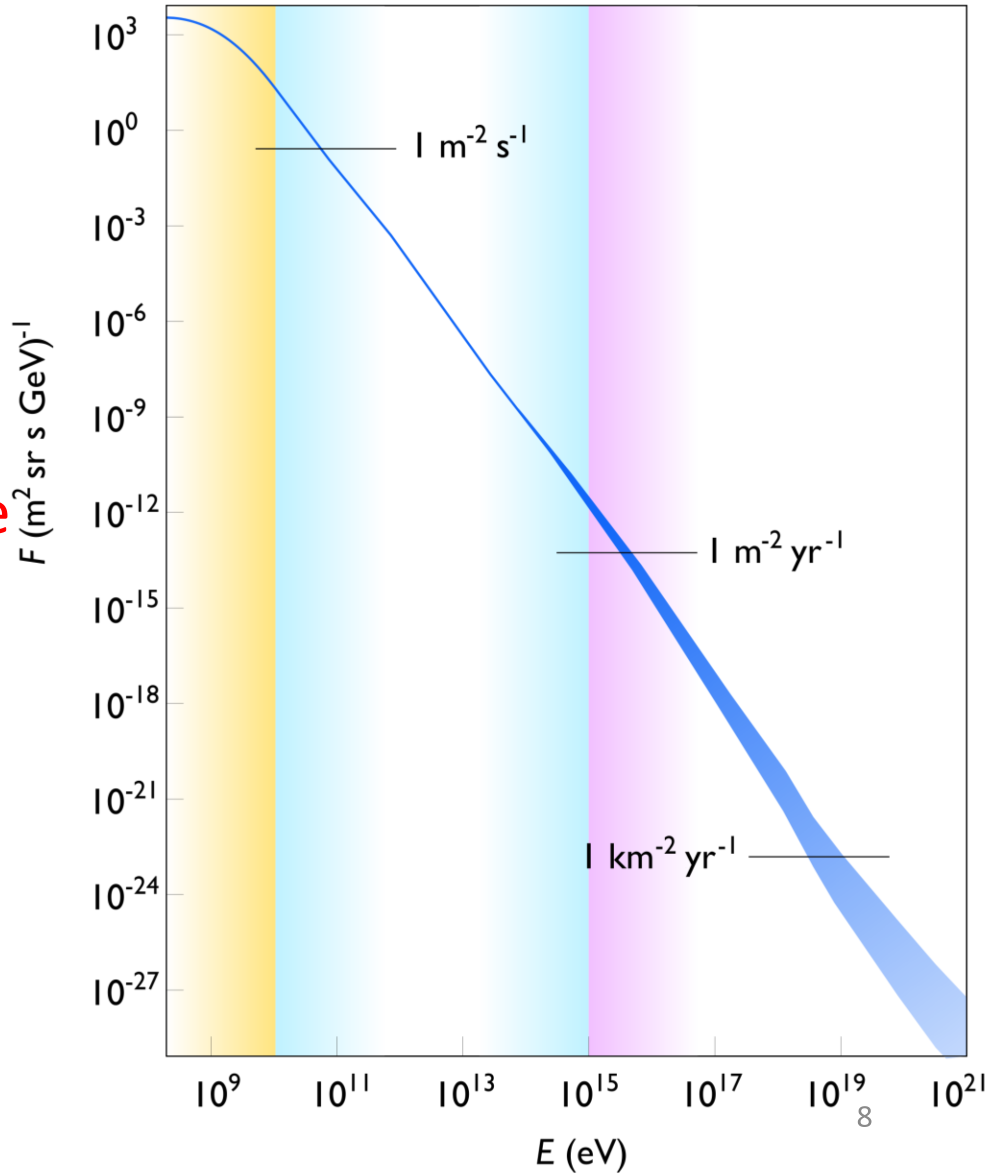
Drawbacks of cosmic ray Experiments:

No control, no knowledge of energy, very low rate

COSMIC RAYS

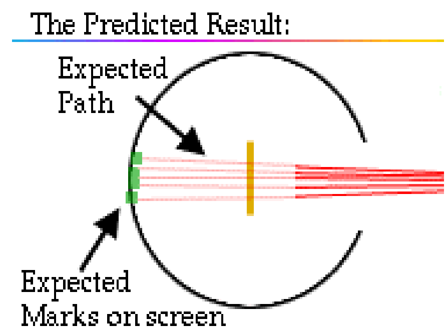
The Nobel Prize in Physics 1936

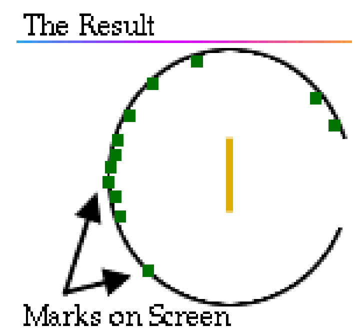
- Hess: “for discovery of cosmic radiation”
- Anderson: “for discovery of the positron”

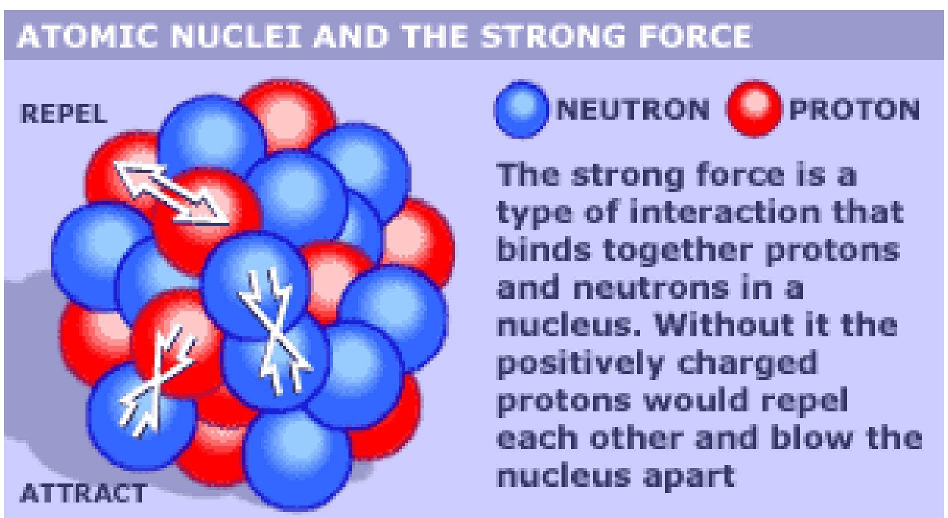


1911: Discovery of the Nucleus

In 1911: Earnest Rutherford postulated that atoms have their positive charge concentrated in a very small nucleus, and thereby pioneered the Rutherford model, or planetary model of the atom, through his discovery and interpretation of the Rutherford scattering in his gold foil experiment.



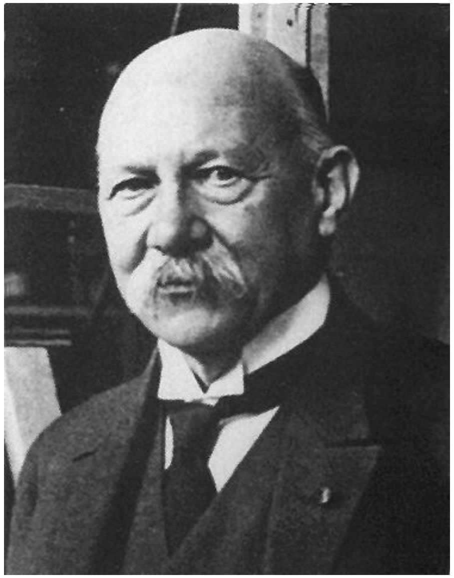


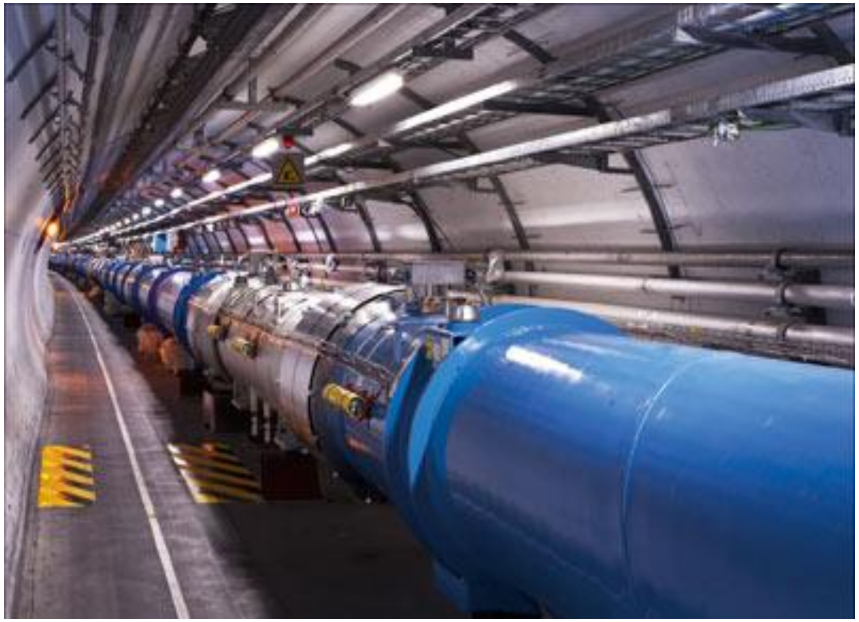


2011: World Year of the Nucleus

1911: The Discovery of Superconductivity

Heike Kamerlingh Onnes's
1911 Discovery



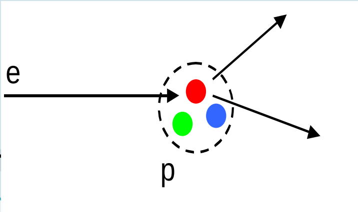


The Large Hadron Collider (LHC) at CERN relies on superconductivity, which plays a fundamental role because it allows magnetic fields in excess of 8 Tesla to be reached.

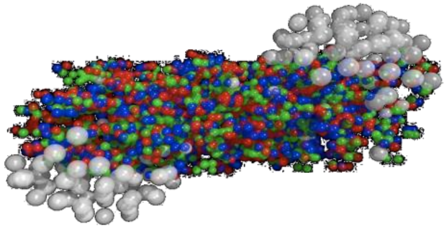
Important Discoveries

1899	Alpha particle discovered by Ernest Rutherford in uranium radiation
1900	Gamma ray discovered by Paul Villard in uranium decay.[
1911	Rutherford's discovery of atomic nucleus (atomi contains a positive nucleus)
1919	Proton discovered by Rutherford
1932	Neutron discovered by James Chadwick
1932	Positron – the first anti-particle by Carl D. Anderson (proposed by Paul Dirac in 1927)
1937	Muon discovered by Seth Neddermeyer, Carl Anderson, J.C. Street and E.C. Stevenson using cloud chamber measurements of cosmic rays (Bhabha suggested the name meson instead of mesotron in a short note to Nature)
1947	Pion discovered by Cecil Powell (predicted by Yakawa in 1935)
1947	Kaon discovered by Gerorge Dixon Rochester and Clifford Butler - cosmic ray particles with masses between pions and protons
1955	Antiproton discovered by Chamberlin, Segre, Wiegand and Ypsilantis at Bevelac (Segrè and Chamberlain: Nobel Prize in Physics 1959)
1956	Electron-neutrino by Reines and Clown (proposed by Pauli in 1931) to explain the apparent violation of energy conservation in beta decay)
1962	Muon-neutrino by group headed by Leon Lederman (Columbia Univ – AGS-BNL) Nobel Prize in 1988 to Lederman, Melvin Schwarz and Jack Steinberger
1964	Discovery of CP violation in neutral K decays. 1980 Nobel Prize for kronin and Fitch.

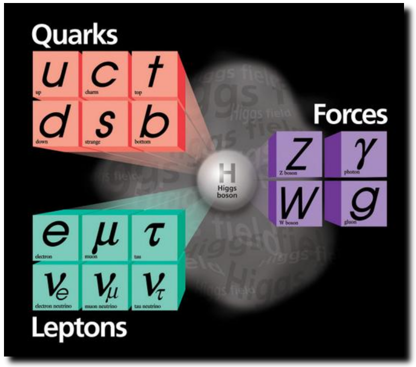
Important Discoveries, contd.

1969	Partons (quarks or gluons) observed in Deep Inelastic Scattering experiments between proton and electron at SLAC. (up, down and strange). 1990 Nobel Prize to Friedman, Kendall, Taylor (*deep inelastic Scattering, which have been of importance for the development of The quark model in particle physics):* A Rutherford type experiment 
1974	J/Ψ particle discovered. Nobel Prize: 1976 Samual Ting and Burton Richter. This demonstrated the existence of charm quark (proposed by Bjorken and Glashow in 1964). Charm quark mass: 1.5 geV. November Revolution.
1975	Discovery of tau lepton, tau lepton mass: 1.8 GeV by Martin Perl at SLAC Nobel Prize: 1995
1977	Discovery of bottom quark (mass: 4.7 GeV) , Leon Lederman – Fermilab E288 expt. Theorized in 1973 by physicists Kobayashi and Maskawa to explain CP violation (Nobel prize 2008 to Kobayashi and Maskawa - for prediction of top quark)
1983	Discovery of mediators of weak interactions, W and Z bosons. UA1 experiment at CERN-SPS by Carlo Rubbia and Simon van der Meer. Their discovery was a major success for standard model. Nobel Prize: 1984
1995	Discovery of top quark (172 GeV) by CDF and D0 at Fermilab.
2002	Nobel Prize to Ray Davis for Detection of Cosmic Neutrinos
2011	Discovery of anti-matter ^{4}He nuclei by STAR experiment
2011	Indications of a New Type of Neutrino Oscillation at the T2K Experiment (ν_μ -> ν_e) CP violation in neutrinos

Contemporary Physics Topics



Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed? Quark Gluon Plasma (QGP)

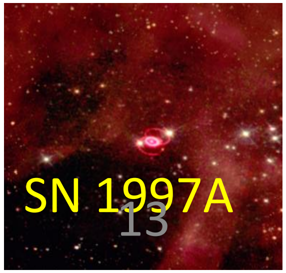


Will we find the **Higgs particle** that is responsible for giving mass to all particles?

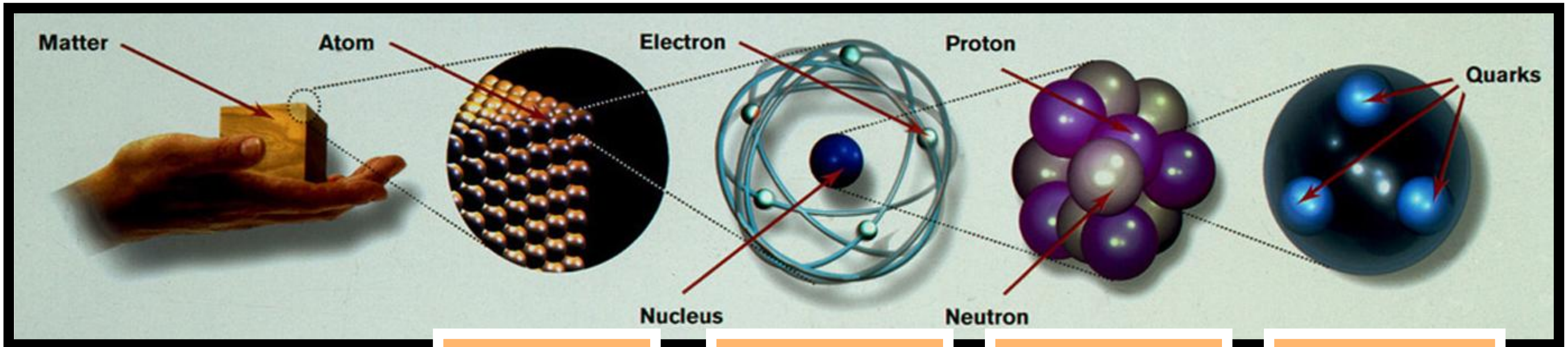
Will we find the reason why antimatter and matter did not completely destroy each other?

Will we find the particle(s) that make up the mysterious '**dark matter**' in our Universe?

Understanding **Neutrinos**: Neutrino Oscillations
Precision measurements of mass and mixing parameters.



Instruments to Probe Small Dimensions



10^{-8}cm 10^{-12}cm 10^{-13}cm 10^{-16}cm

Microscope Electron Microscope Accelerators

$\lambda = h / p$ **(de Broglie, 1924)**

where h is Plank constant ad p is momentum

Energy units: eV, keV, MeV, GeV .... where 1eV = 1.602 . 10^{-19} Joule
Mass units: MeV/c^2, GeV/c^2 ... where 1 MeV/c2 = 1.783 . 10^{-30} kg

http://pdg.lbl.gov/index.html

Particle Acceleration

Lorentz Force:

$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{E} + q(\vec{v} \times \vec{B})$$

Magnetic force perpendicular to velocity

==> no acceleration, changes direction

Only electric force accelerates particles

Synchrotron: particle beams kept in circular orbit by magnetic field; at every turn, particles "kicked" by electric field in accelerating station

Linear Accelerator: Cavity design and length critical

Cyclotron (1929 E. Lawrence):

$$\frac{mv^2}{r} = qvB \quad \rightarrow \quad \omega = \frac{v}{r} = \frac{qB}{m}$$

No dependence on r
Alternating electric field = constant acceleration

Synchrotron: particle beams kept in circular orbit by magnetic field; at every turn, particles "kicked" by electric field in accelerating station.

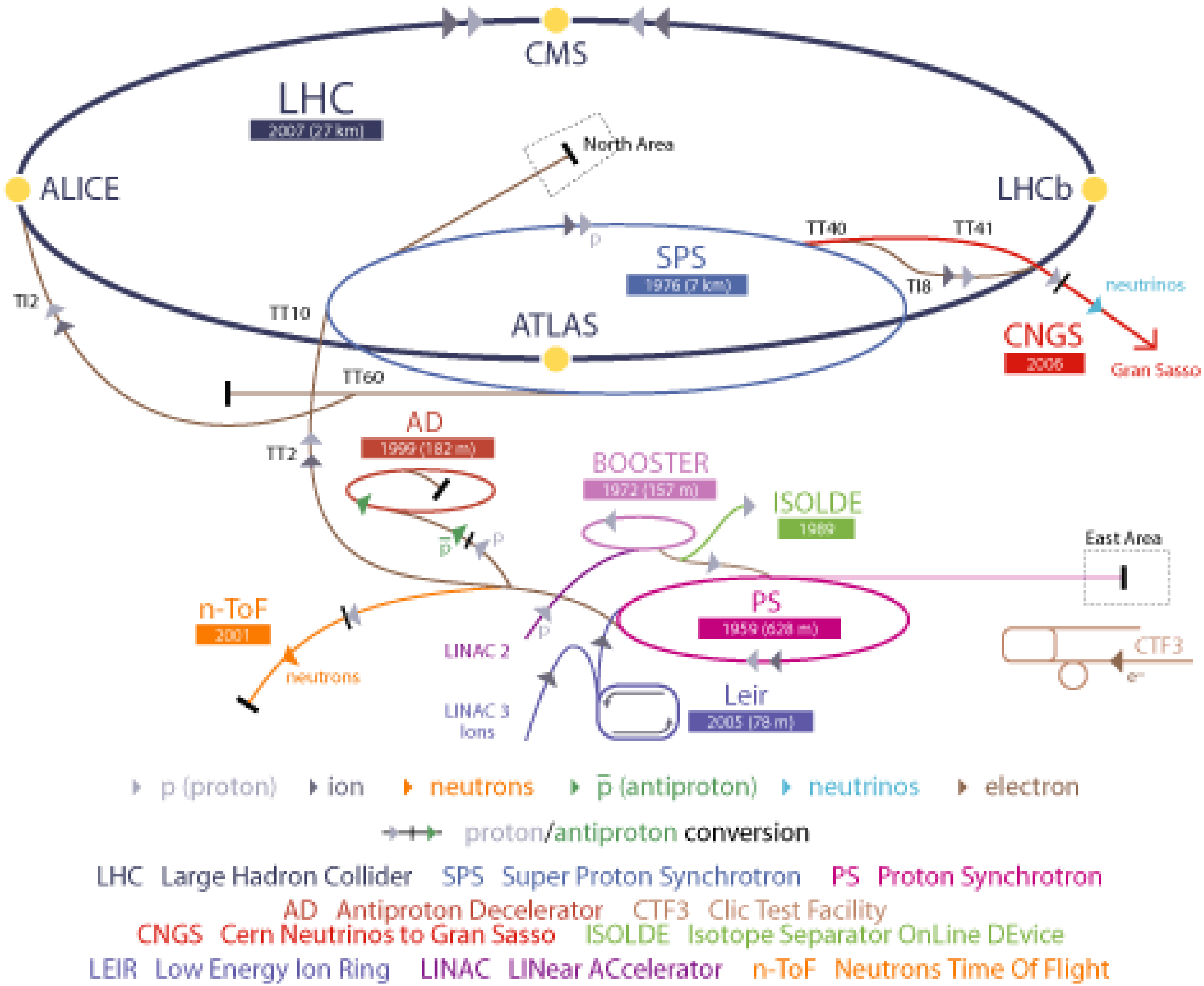
- Constant radius, r
- Changing E and B

CERN Accelerator Complex

1. Protons obtained by stripping electrons from hydrogen
2. Injected into PS BOOSTER from LINAC2 at 50MeV
3. BOOSTER accelerates to 1.4GeV and feeds to PS
4. PS accelerates to 25GeV and sends to SPS
5. SPS accelerates to 450GeV and transfers to LHC

- IONS are passed into LOW ENERGY ION RING (LIER), then to PS to SPS to LHC

CERN Accelerator Complex



Luminosity and Cross Section

=> Luminosity is a measure of the beam intensity (particles per area per second). Luminosity relates the event rate to the interaction cross section:

$$R = L\sigma_{\text{int}}.$$

Luminosity is expressed in $cm^{-2}sec^{-1}$

=> Cross Section is a measure of effective interaction area, proportional to the probability that a given process will occur. Expressed in barn, where 1 barn = 10^{-24} cm^2 , so 1 pb= 10^{-36} cm^2

Give example here.

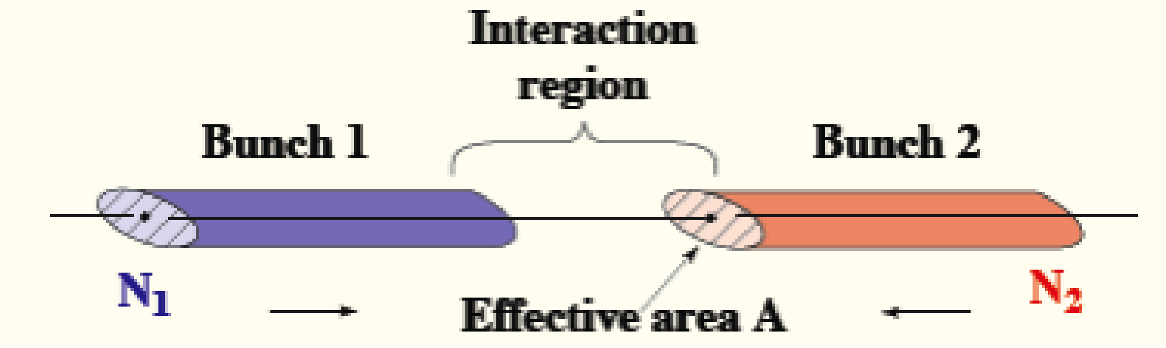
=> Integrated Luminosity is a measure of the amount of data collected. For example, $100pb^{-1}$

Luminosity Measurement

Luminosity is expressed in terms of the characteristics of the colliding beam at the interaction point:

$$L = f n_b \frac{N_{b,1} N_{b,2}}{A_{eff}} F,$$

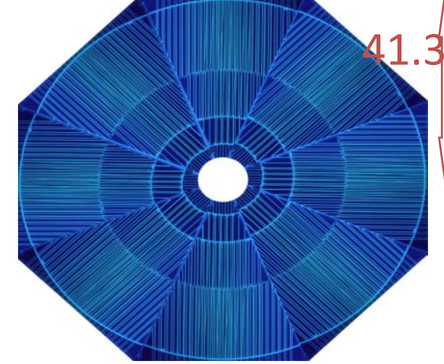
where f is the revolution frequency,
n_b is the number of bunches,
N_b is the number of particles per bunch
A_{eff} is the cross sectional area of the beam
F is the reduction factor due to finite crossing angle of the beam.

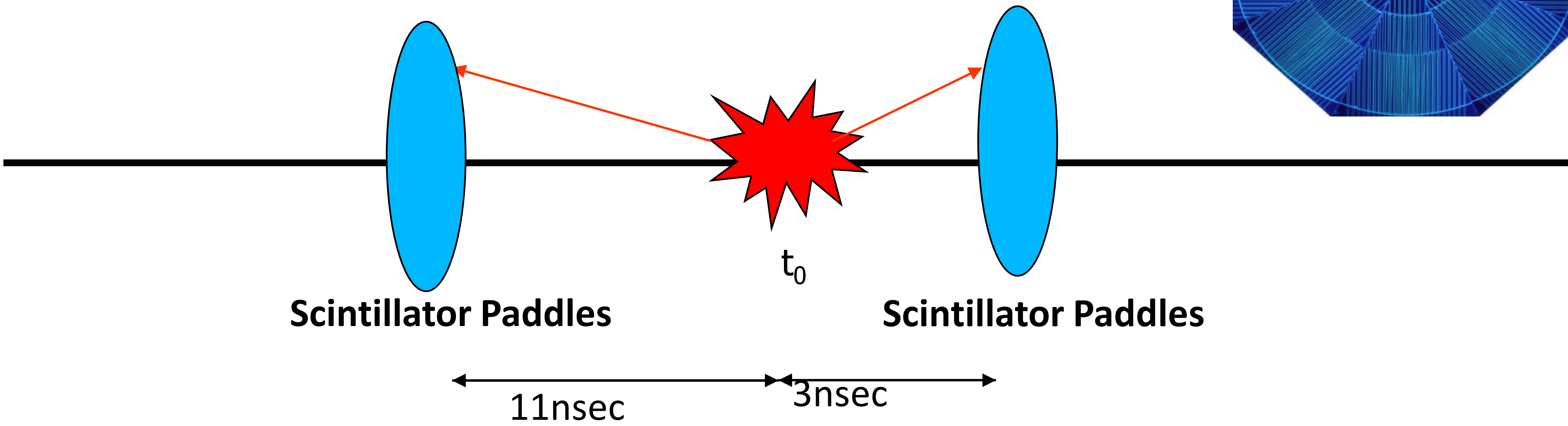


Beam sizes are measured by **van der Meer scan** in the transverse direction.

Talk about Uncertainty in estimated luminosity.

Luminosity Monitoring



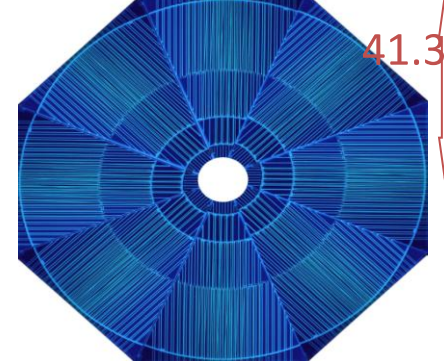


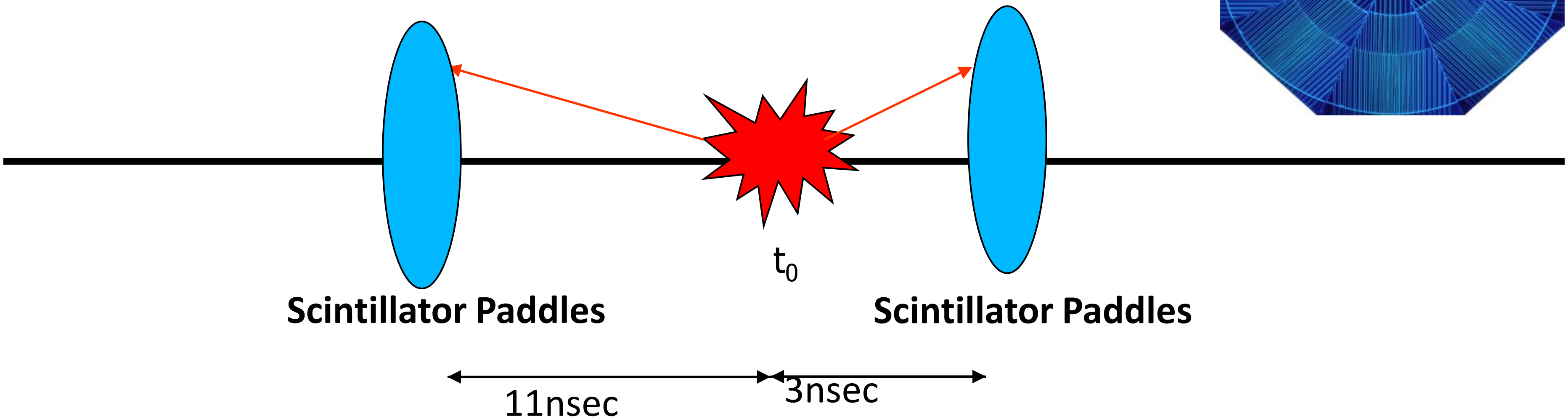
Coincidence signal gives the interaction trigger.

$$dN/dt = L \,.\, \sigma \,.\, (Accetance * Efficiency)$$

Coincidence rate and converted luminosity (by known cross sections) is monitored as a function of time.

Luminosity Monitoring



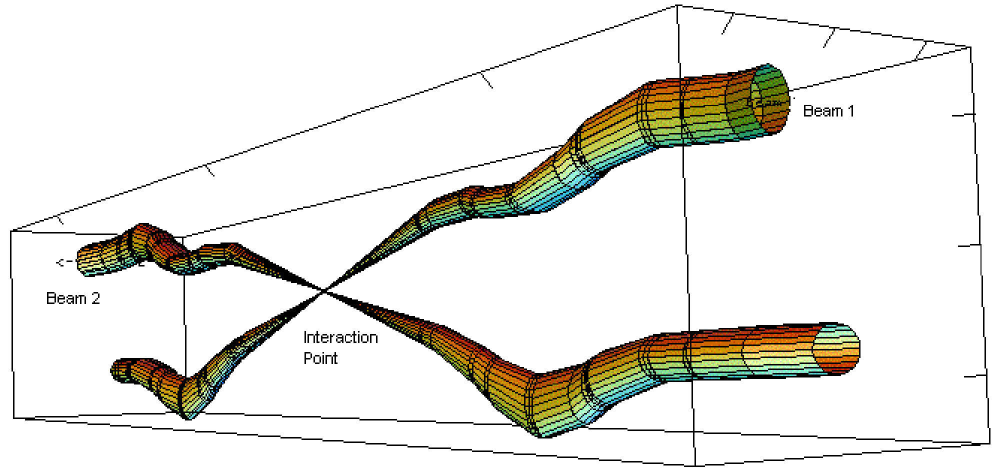


Coincidence signal gives the interaction trigger.

Discuss: timing, coincidence, beam-gas events.

Event Rate:

$$R = L\sigma_{\text{int}}.$$



Relative beam sizes around IP1 (Atlas) in collision

The total proton-proton cross section at 7 TeV is ~100 mbarns.
This total can be broken down in contributions from:

- inelastic 60 mbarn
- elastic 40 mbarn

The cross section from elastic scattering of the protons and diffractive events will not be seen by the detectors as it is only the inelastic scatterings that give rise to particles at sufficient high angles with respect to the beam axis.

Inelastic event rate at nominal luminosity therefore $10^{34} * 60 * 10^{-3} * 10^{-24}$ = 600 million/second per high luminosity experiment.

$$L = f n_b \frac{N_{b,1} N_{b,2}}{A_{eff}} F,$$

$N_1 = N_2 = 10^{11}$ particles/bunch

n_b = 2808 bunches

f = 11.2455 KHz

$\sigma_x = \sigma_y$ = 16 μm, transverse sizes of the beam

Aeff = 4*pi* σ_x * σ_y

Crossing angle = 300 μrad

L = 11.2455 * 2808 * 10^25 / (256*10^-6)

~ 1 * 10^34 cm^-2 s^(-1) for head on collision

Effect of crossing angle will make it 0.97 x 10^34 cm^-2 s^(-1)

Luminosity Calibration using a known process:

Integrated Luminosity

$$L_{int} = \int_0^T L(t)\,dt$$

What we are interested is in the number of events: $L_{int} \cdot \sigma$

$$1\ \text{fbarn}^{-1} \text{ is } 10^{39}\text{cm}^{-2}$$

How much time is required to get 1 fbarn^{-1} ?

At L = 10^(32), we need: 10^7 seconds.

Trigger

Trigger is very crucial in every experiment:

- Interaction trigger to specify that collision happens

- Only the events of interest are written to the tape/disk: sometimes the event rate can be 10 0MHz, but written to tape only 1000 Hz.

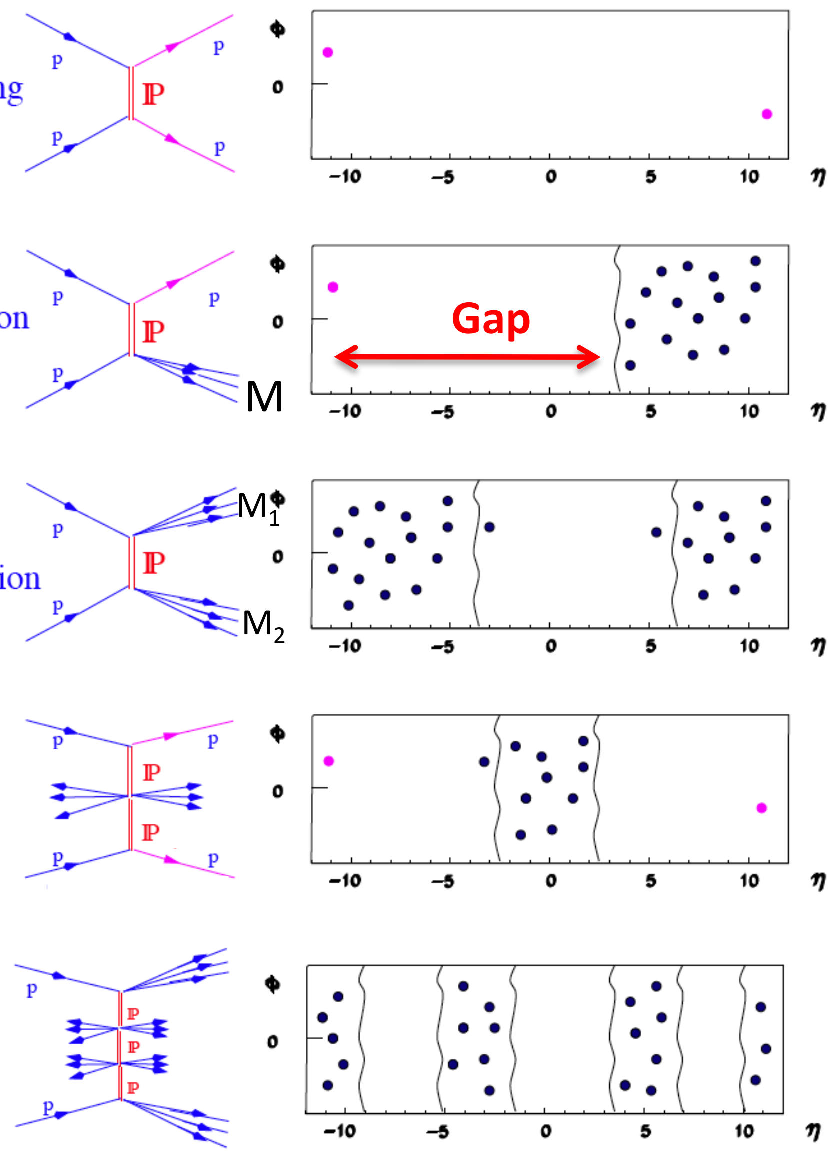
Discuss:

- Minimum Bias Trigger
- Multiplicity and
- Multiplicity Trigger
- Centrality and
- Centrality Trigger
- High p_T Trigger
- Muon Trigger

- Diffraction

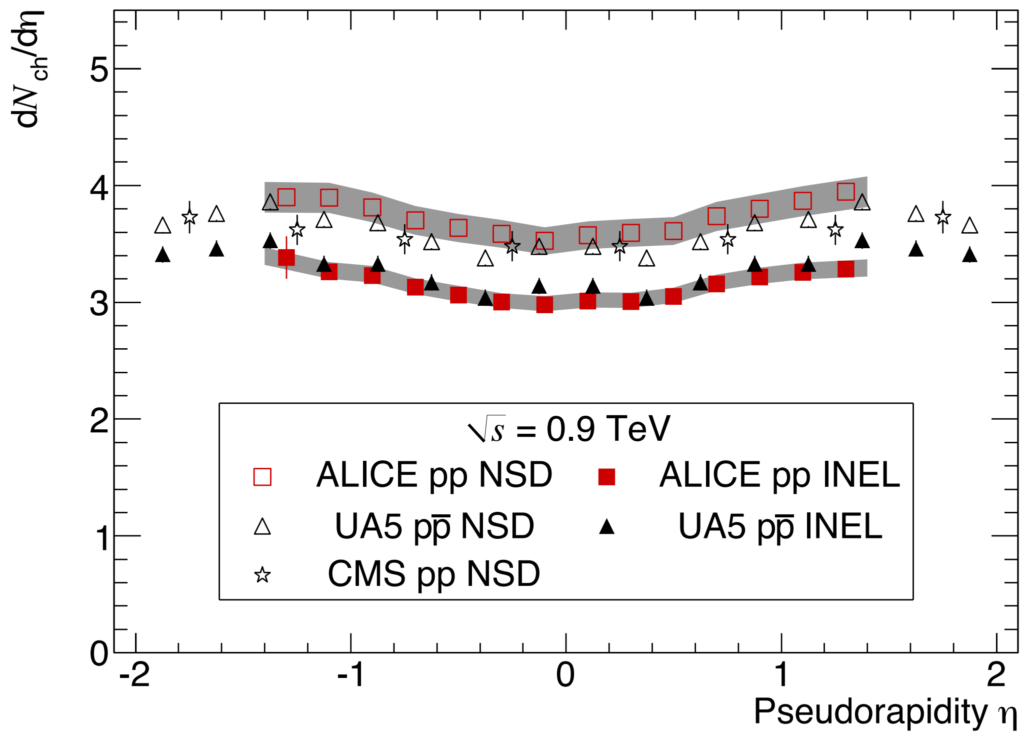
Diffractive processes

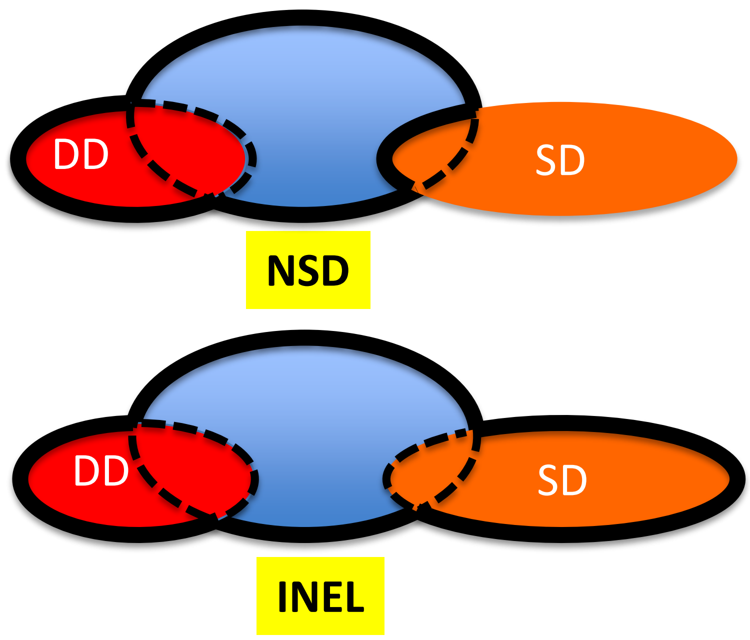
Σ for pp@7 TeV relative to σ_{tot} (QGSM)



- elastic scattering — **26%**
- single diffraction — **12.5%**
- double diffraction — **6.5%**
- Double Pomeron Exchange — **≤1%**
- Multi Pomeron Exchange — **≤0.1%**

- NSD and INEL event classes defined to compare data between experiments. Corrections are largest contribution to systematic uncertainty in multiplicity measurements.





Some Jargons ….

Fill or store

- when Accelerator operators fill machine with a fresh set of p and p at LHC or Au and Au at RHIC ….
- stores can take from several hours to several days: luminosity drops exponentially in beginning, at some point one has to stop.

Run

- Shift person in the experiment gets the good beam signal, sets the proper detector and trigger conditions and starts a run.
- A set of collision data with constant detector conditions
- A run starts after the store. Ideally just one run per store, often many per store.