Karlsruhe Institute of Technology

Particle Acceleration – Detection – Analysis

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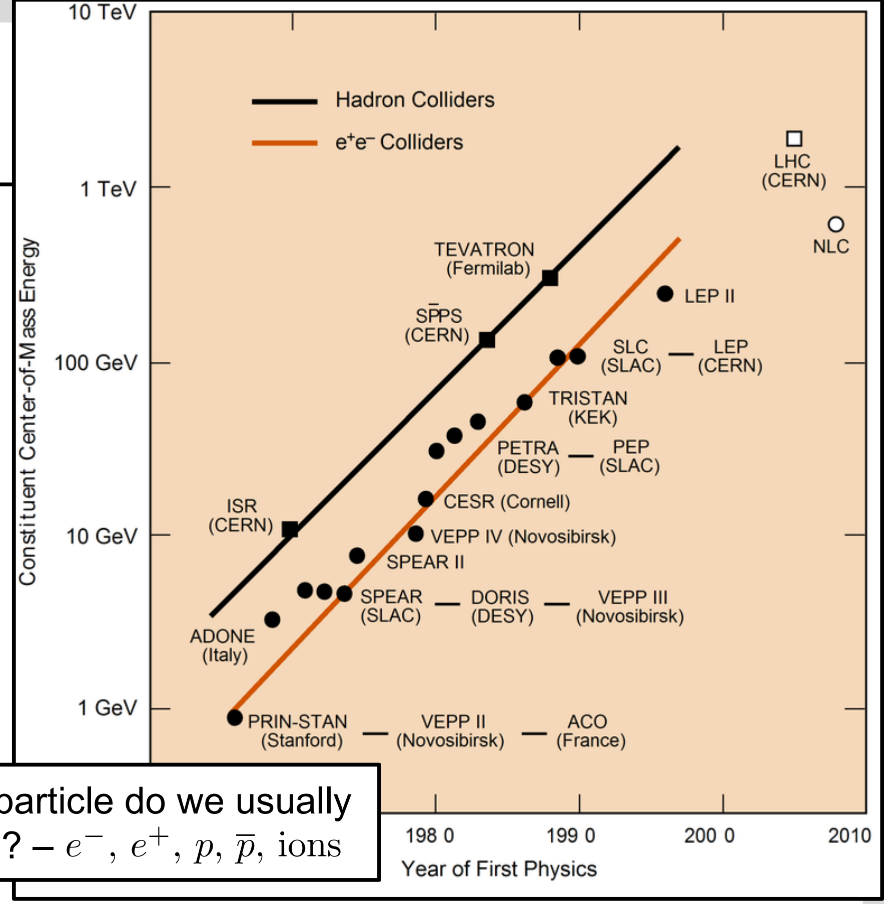
What is a particle accelerator?

M. S. Livingston (1905 – 1986):

A particle accelerator is a machine that uses electromagnetic fields to propel charged particles to nearly light speed and to contain them in well-defined beams.

- Colliding beams are our laboratory.
- Reach out to highest energies (→ resolve smallest structures, Heisenberg uncertainty principle).
- Provide as many collisions per second as possible (→ observe rarest events).



What particle do we usually collide? – e^-, e^+, p, $\bar{p}$, ions

Livingston plot

Cross section:

$$\sigma = \frac{N_{obs} - N_{BG}}{\phi \cdot \epsilon \cdot A} \frac{1}{T}$$

N_{obs} : N observed reactions.

N_{BG} : N expected BG reactions.

ϵ : detection efficiency.

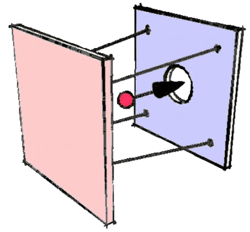
A : detector acceptance.

T : observation time.

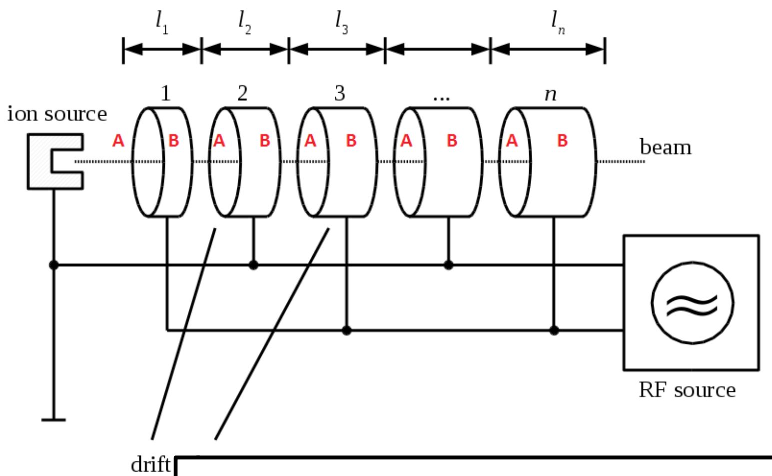
Lecture-1: *Introduction to Particle Physics* (slide 10)

Different ways to build a collider

Electrostatic acceleration:

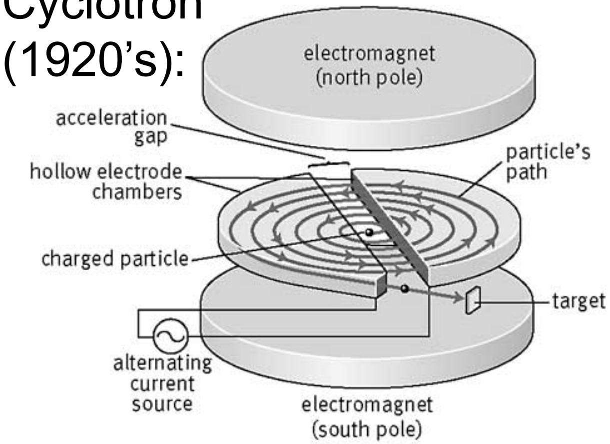


Linear accelerator:



Cyclotron (1920's):

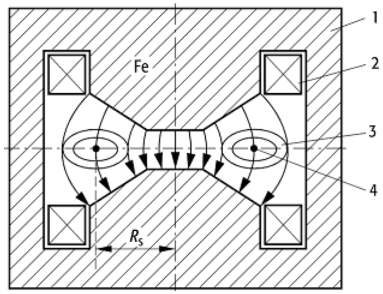
Radius increases with beam energy.



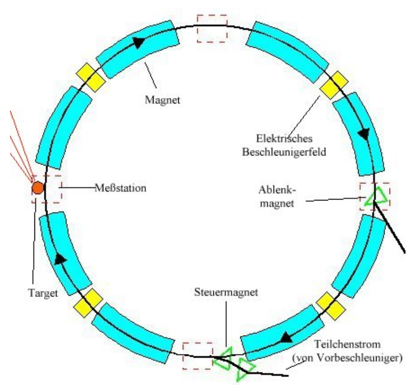
Betatron (1920's):

Radius const. – accelerating field induced by increasing B-field.

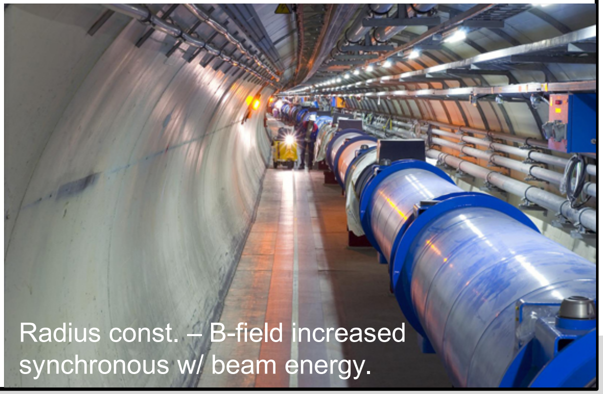
6MeV Betatron 1942 – 44 Siemens-Museum München



Synchrotron:



LHC, CERN 2010



Radius const. – B-field increased synchronous w/ beam energy.

Accelerating power

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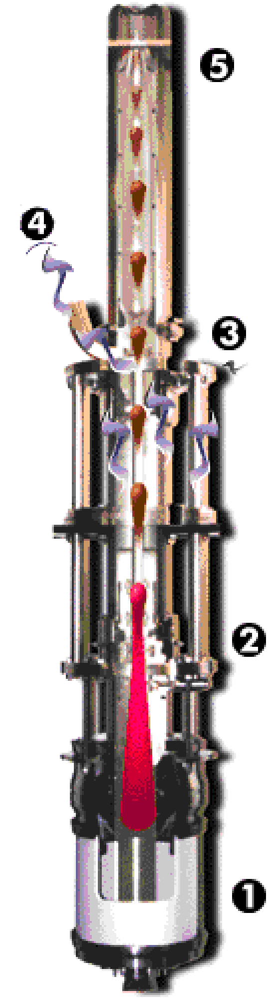
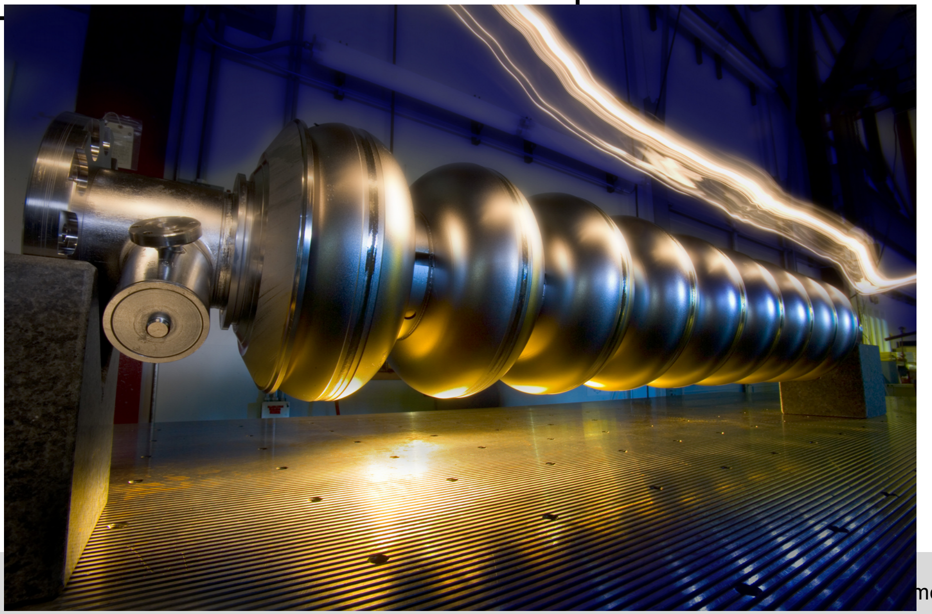
- Acceleration happens via UHF in Klystrons:

  - Acceleration of electrons (1).
  - Density modulations in electron beam implied by external field (2).
  - Due to these modulations electromagnetic wave travels through first cavity (3).
  - Exit hole at end of cavity. The passing wave induces resonant wave in the surface of hole which damps electron beam and couples energy out to second cavity (4).

(1) source
(2) first cavity
(3) UHF created by electron bunches
(4) exit to second cavity
(5) electron beam dump

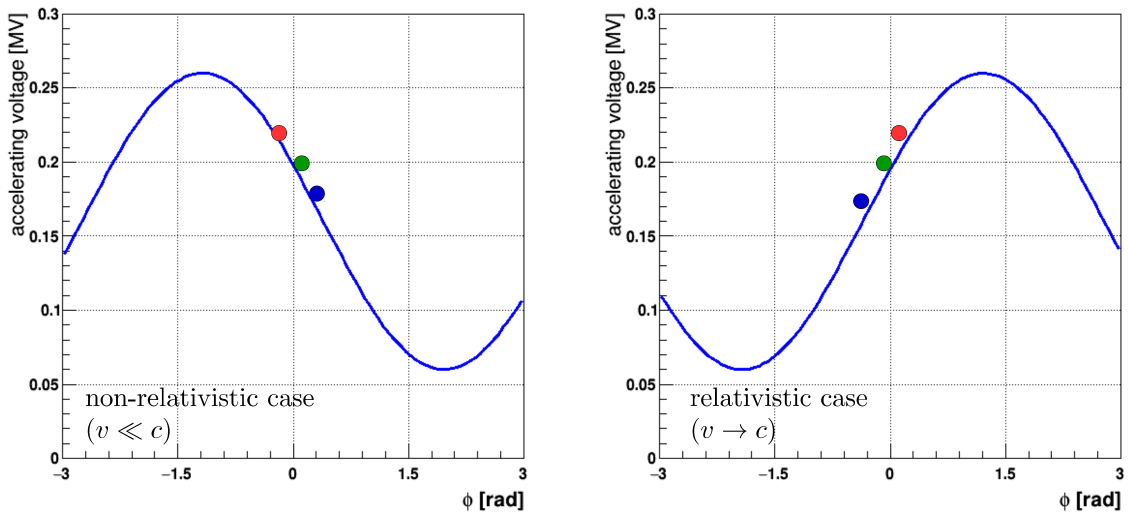


Such cavities have to stand $50 - 80$ MeV/m without discharges.


TESLA 9-cell 1.5 GHz SRF cavities from ACCEL Corp. Germany for the ILC

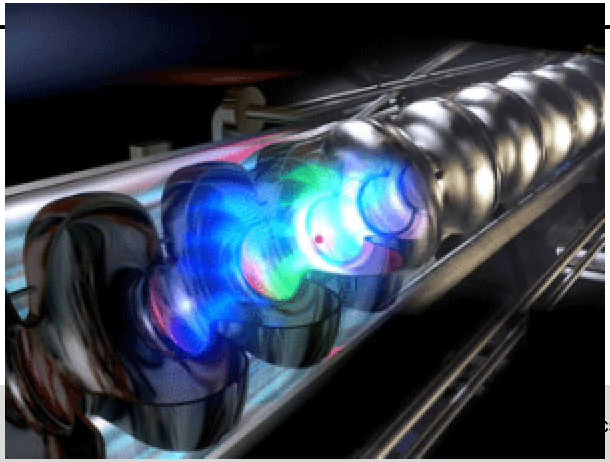
Phase focusing

- Energy focusing achieved by proper choice of phase of accelerating wave:



- energy lower → more acceleration
- energy exact → nominal acceleration
- energy higher → less acceleration

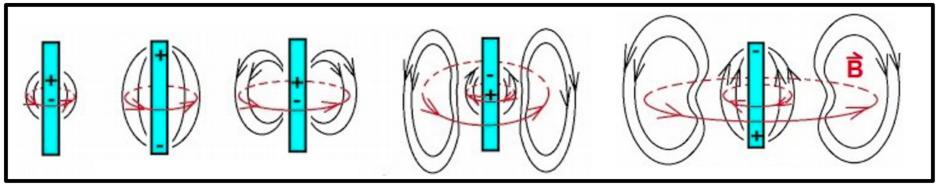
- This kind of acceleration leads to bunching of projectiles.



Synchrotron radiation

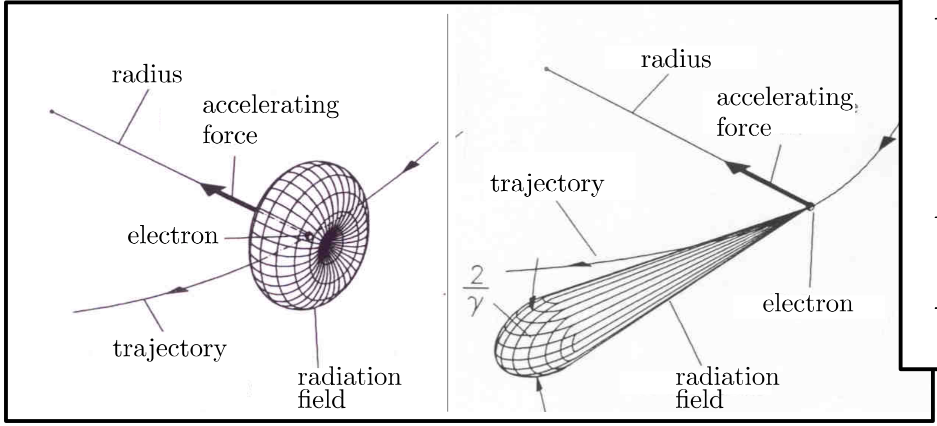
Advantage of circular structures: acceleration infrastructure can be recycled.

Disadvantage: need acceleration energy only to keep particles on track.



Radiation pattern of a dipole antenna.

electron center of mass frame: laboratory frame:



Radiation pattern of a circular accelerated electron.

Energy radiated off per rotation cycle:

$$P = \frac{e^2}{6\pi\epsilon_0 c}|\vec{\beta}|^2\gamma^4 = \frac{e^2 c}{6\pi\epsilon_0\rho^2}\gamma^4$$

$$= \frac{e^4}{6\pi\epsilon_0\rho^2}\frac{E^2B^2}{m^4}$$

$$P(p|_{m_p=1\ \mathrm{GeV}}) \overset{(*)}{=} 280\ \mu\mathrm{W}$$

$$P(e|_{m_e=0.511\ \mathrm{MeV}}) \overset{(*)}{=} 450\ \mathrm{kW}$$

(*) using LHC parameters.

Beam quality parameters

- Energy should be high, accurate and stable (→ chromaticity).
- Particle flux should be high (→ "bright source"):

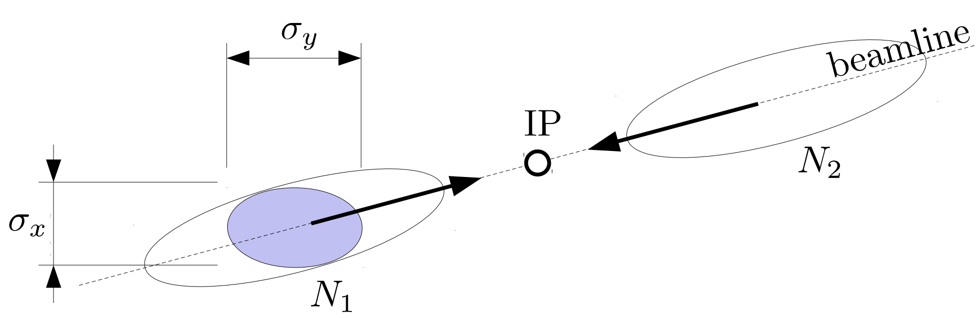
Luminosity:

$$L = \frac{1}{4\pi} \frac{\nu N_1 N_2}{\sigma_x \sigma_y}$$

ν : repetition frequency.

$N_{1,2}$: number of projectiles in beam i.

$\sigma_{x,y}$: beam dimension in x, y.



- In experiment L correlated against quantities that can be easily monitored (→ hits in pixel, energy in low angle calorimeter)
- Most accurate value obtained from reference processes.

- Particles must be kept on track to achieve and sustain highest luminosity.

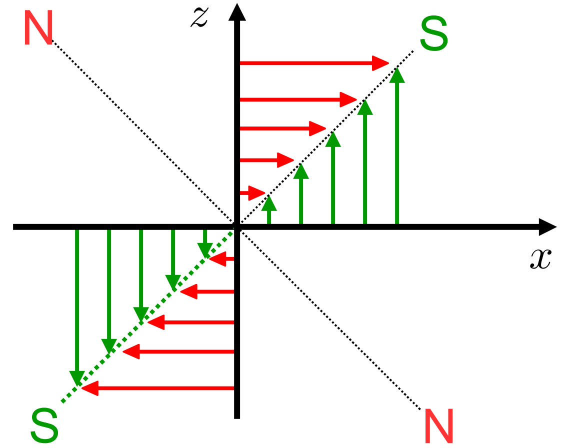
Weak & strong focusing

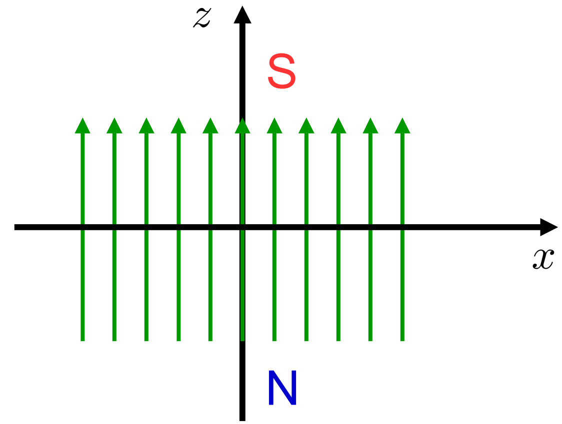
- Projectiles enter acceleration chain with different opening angles.
- Restrict opening angle from beginning (→ collimators).

Strong focusing:

Quadrupole field:

increasing linearly with x, z. Used for focussing.



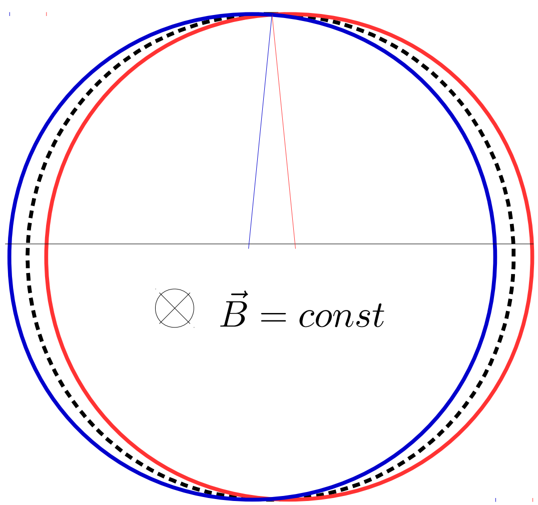


Dipole field:

constant field. Used for bending.

Weak focusing:

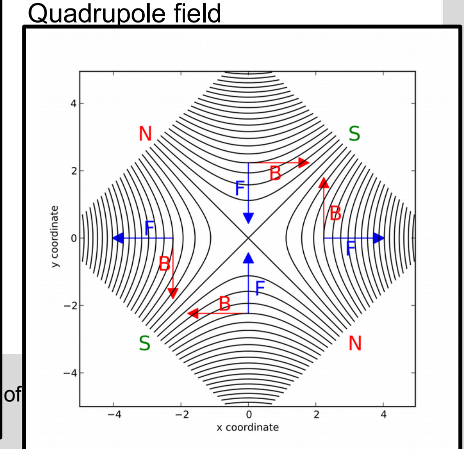
Two particles with small opening angle meet any half cycle.



Imagine opening angle of 1 mrad accelerator radius of $R = 1000$ m:

What maximal distance between the two particles do you expect?

Quadrupole field



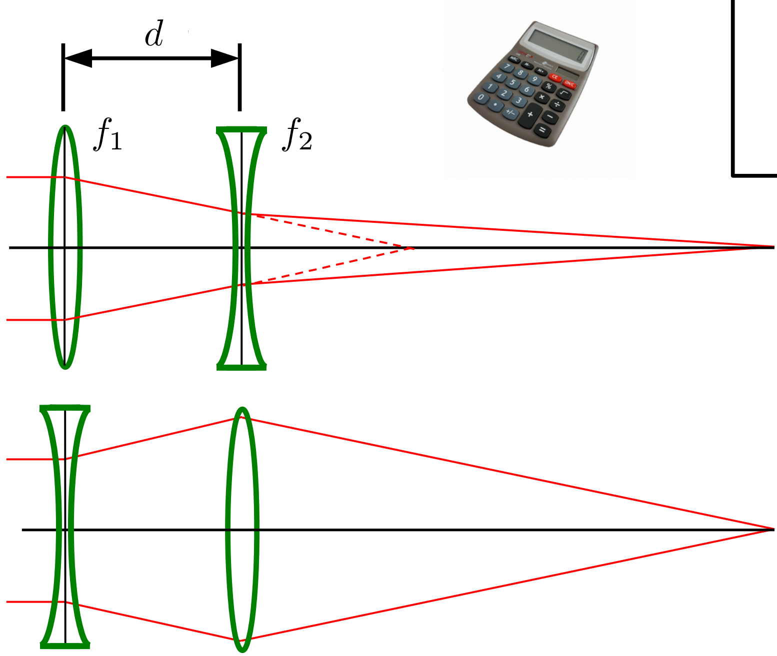
Quadrupole focusing

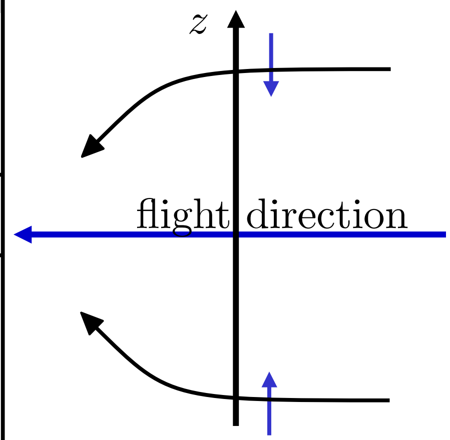
Arrange system of "lenses" to achieve focusing in both planes:

$$f_{12} = \frac{1}{\frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}}$$

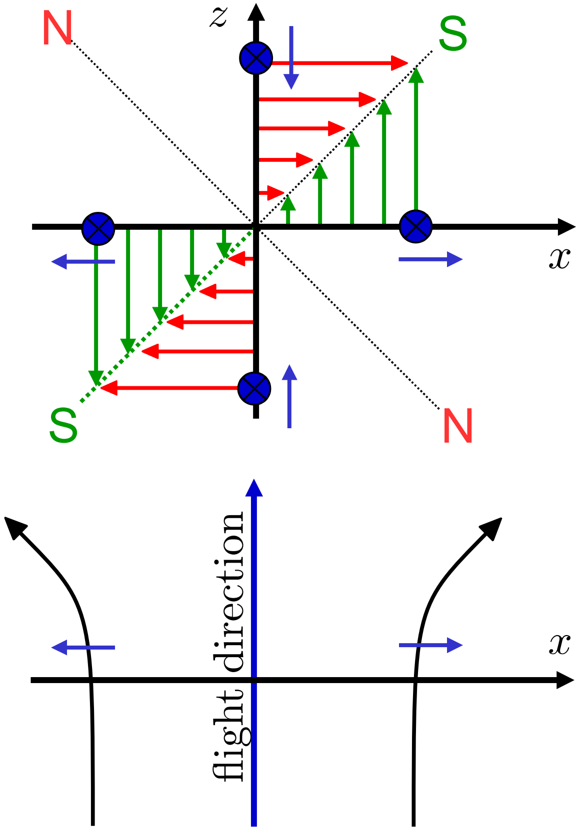
Calculate f_{12} for the simple example:

$f_1 = -f_2 = 100$ m $\quad d = 50$ m





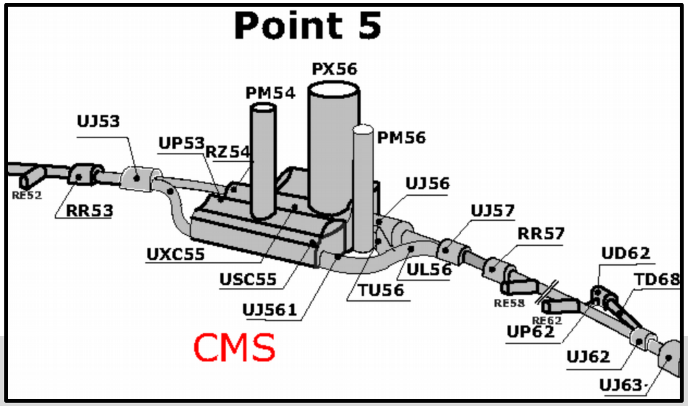
Side-view: focussing



Quadrupole acts like an optical lens focusing in one plane, defocussing in the other.

Up-view: defocussing

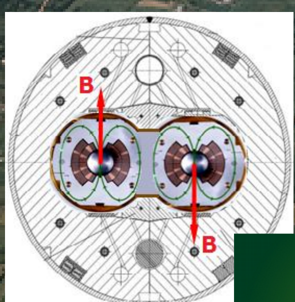
Trajectory of traversing proton



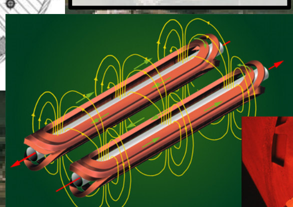
LHC beamline close to CMS

The Large Hadron Collider

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec



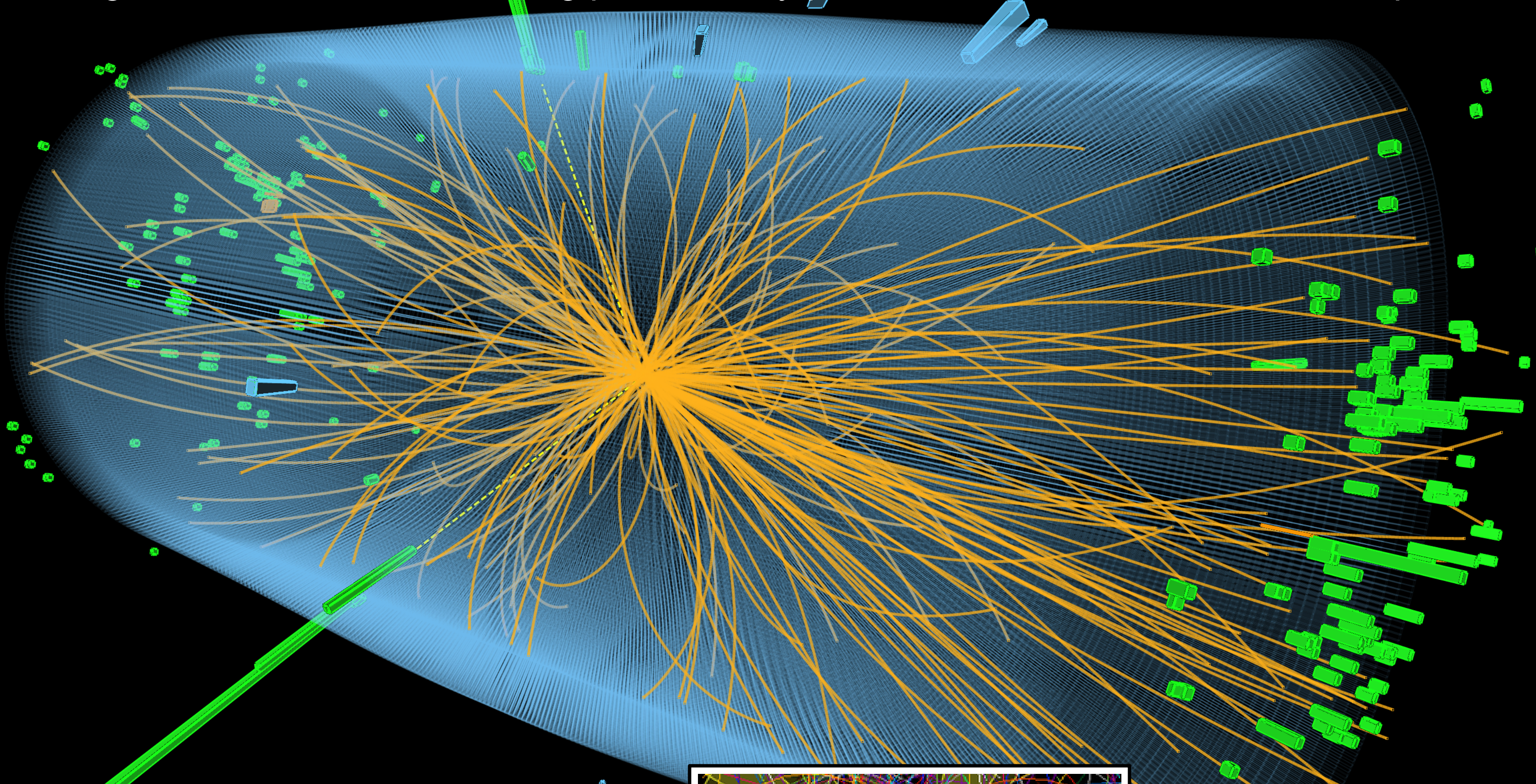
- 8.3 T
- 11.8 kA
- 160 cyc



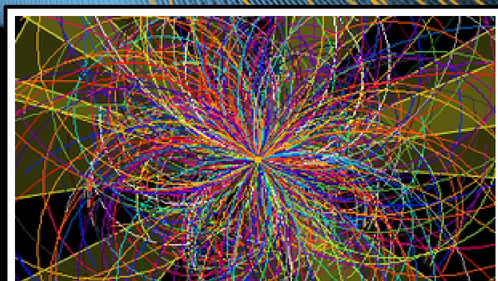
- Energy density 500 kJ/m
- Tension 200'000 t/m

Proton-Proton collision @ CMS

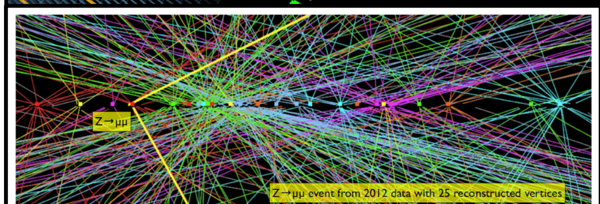
A single collision of two smashing protons may produce several thousand collision products.



- We call this an (exciting) event.
- We try to record it with a “100 Mpx” detector @ 40 MHz rate w/o deadtime.



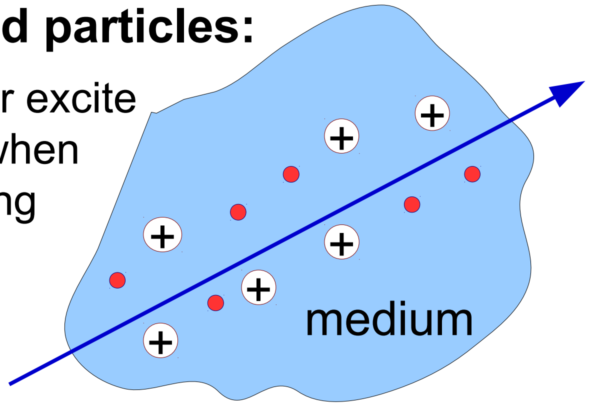
Overlay of 20 pp-collisions.



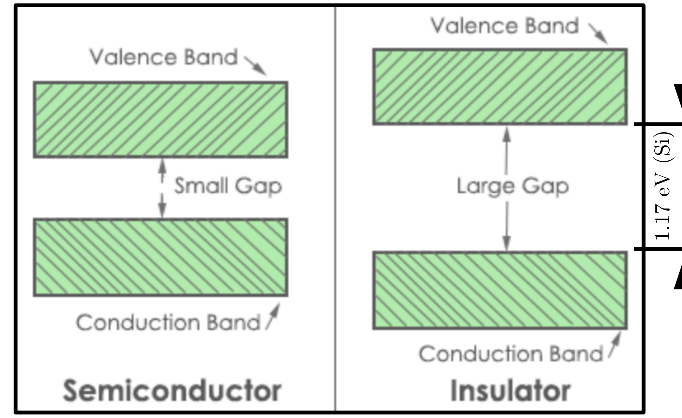
Particle energy loss in matter

Charged particles:

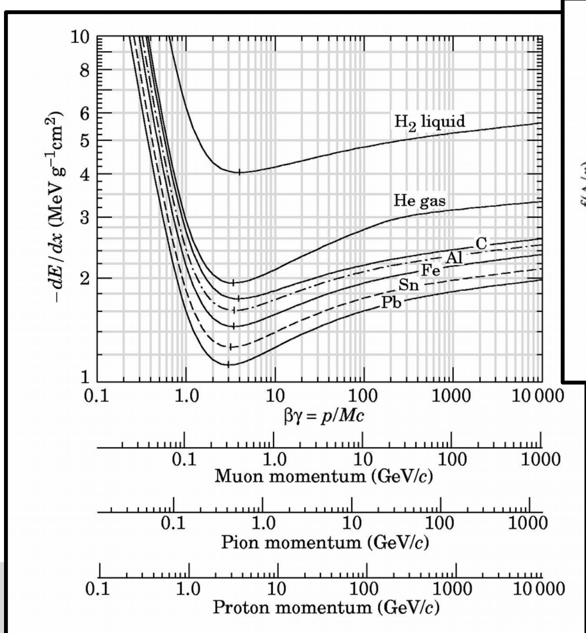
Ionize or excite atoms when traversing media

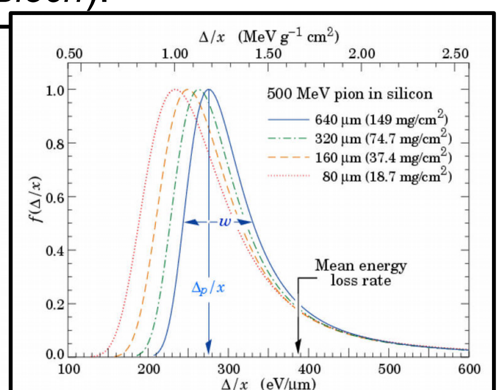


Excitation (band theory):



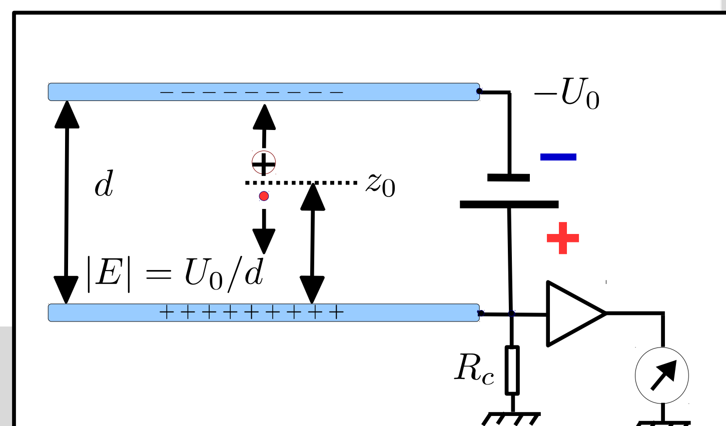
Ionization (energy loss → *Bethe-Bloch*):



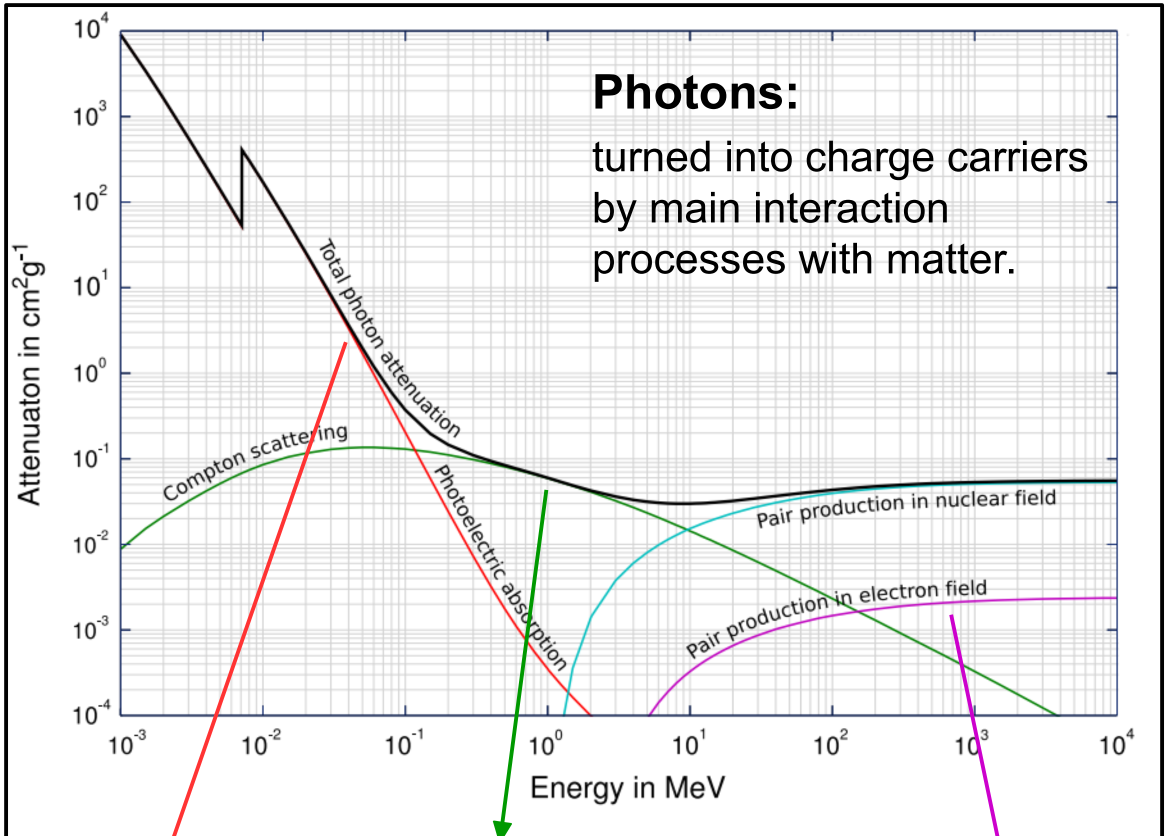


Each point on the left corresponds to the mean of a *Landau* distribution for the actual energy loss (above shown for a π^- in Si).

By the application of an external electric field charge carriers can be separated and electric signal obtained.

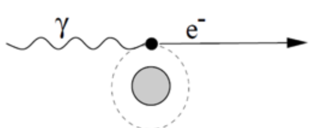


Neutral particles

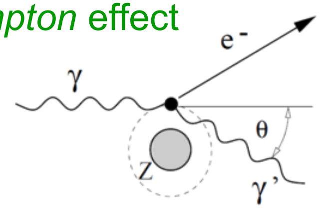


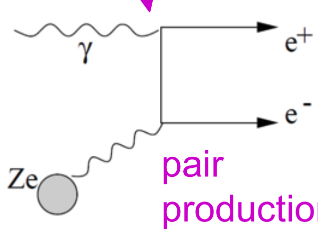
Photons:
turned into charge carriers by main interaction processes with matter.

photoeffect



Compton effect





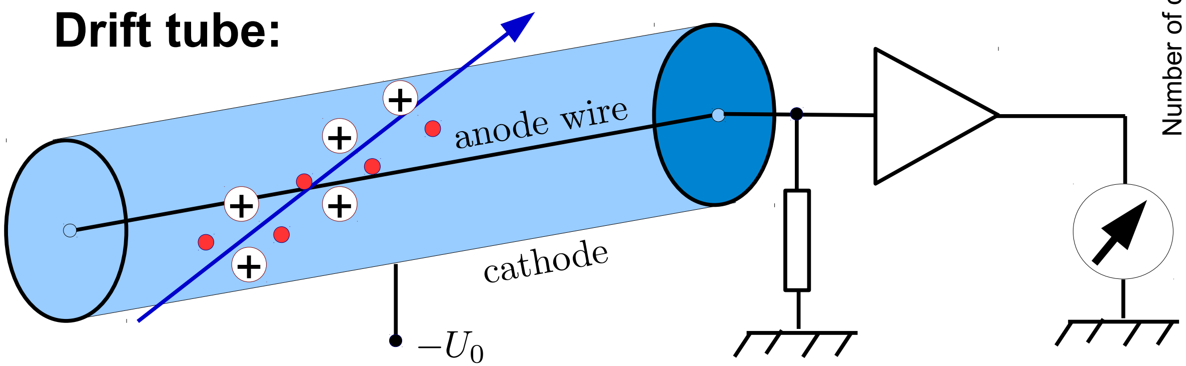
pair production

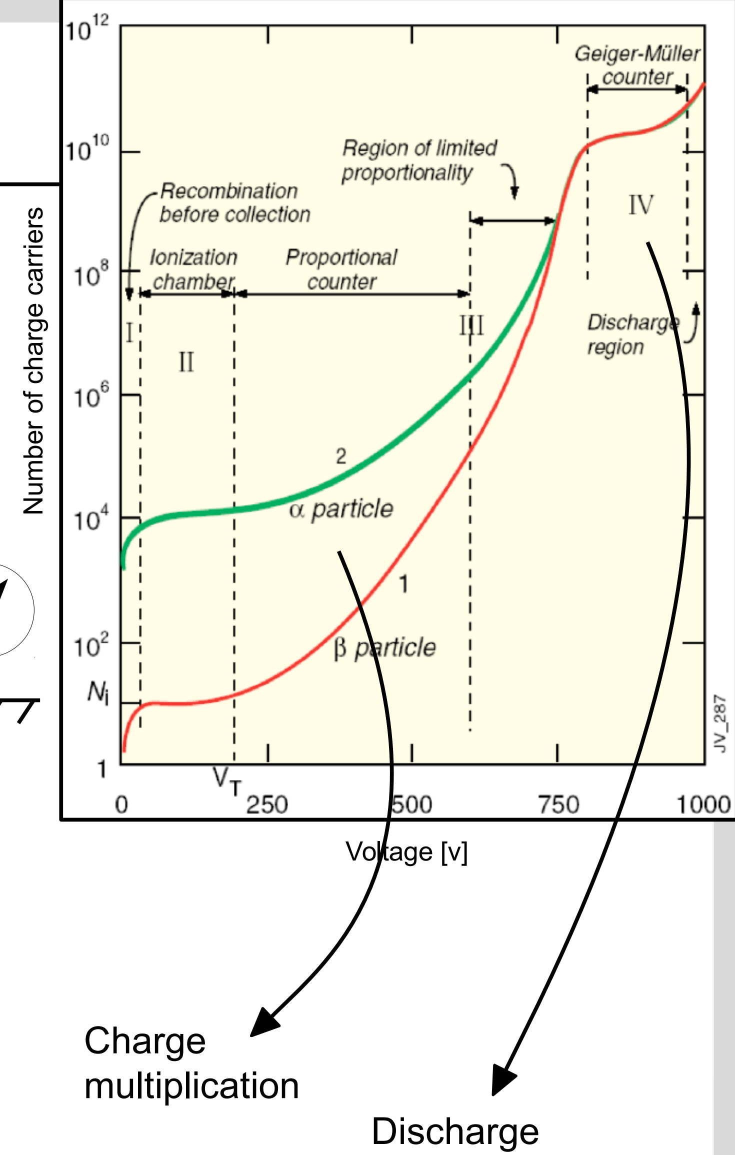
Neutral hadrons:
turned into charge carriers by nuclear interactions (depends on energy of hadron).

Tracking devices

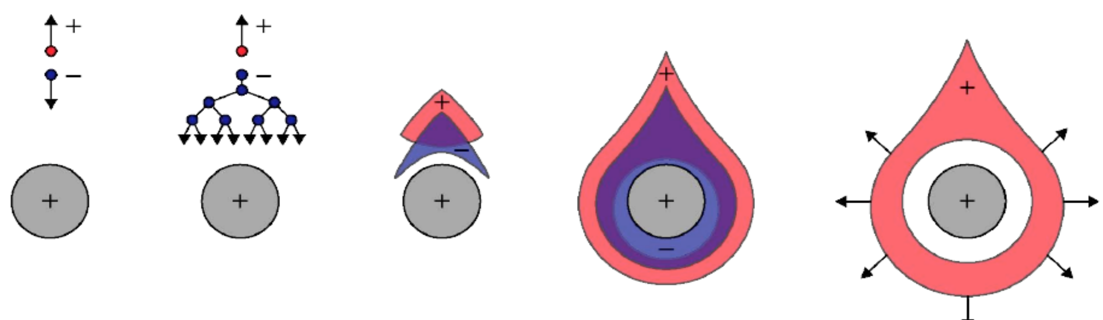
- Make detection devices small/granular enough to identify just where the particle passed the detector.

Drift tube:





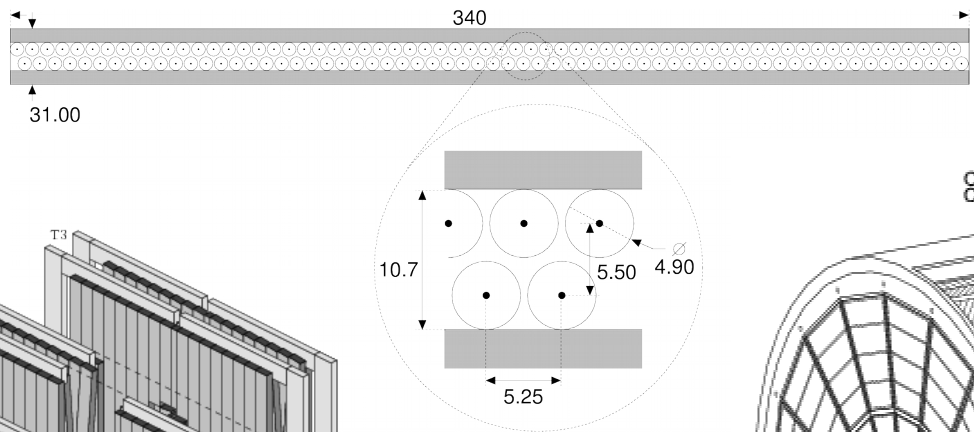
$$\left|\vec{E}(r)\right| = \frac{1}{r}\frac{U_0}{\ln(r_{\mathrm{outer}}/r_{\mathrm{inner}})} \qquad \Delta U = -\frac{Ne}{C}\frac{\ln(r_0/r_{\mathrm{inner}})}{\ln(r_{\mathrm{outer}}/r_{\mathrm{inner}})}$$



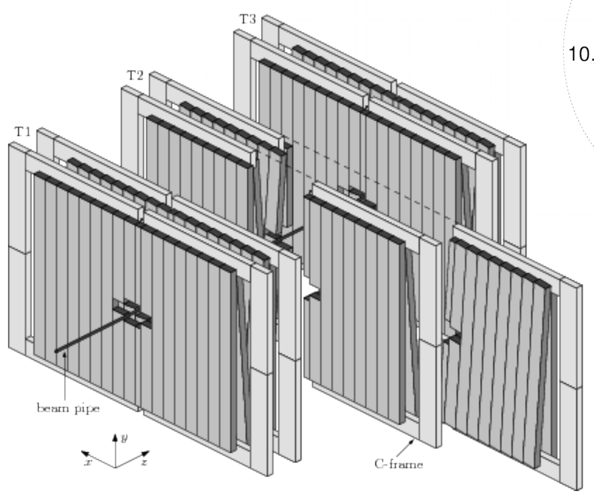
Time evolution of signal build-up in a proportional chamber.

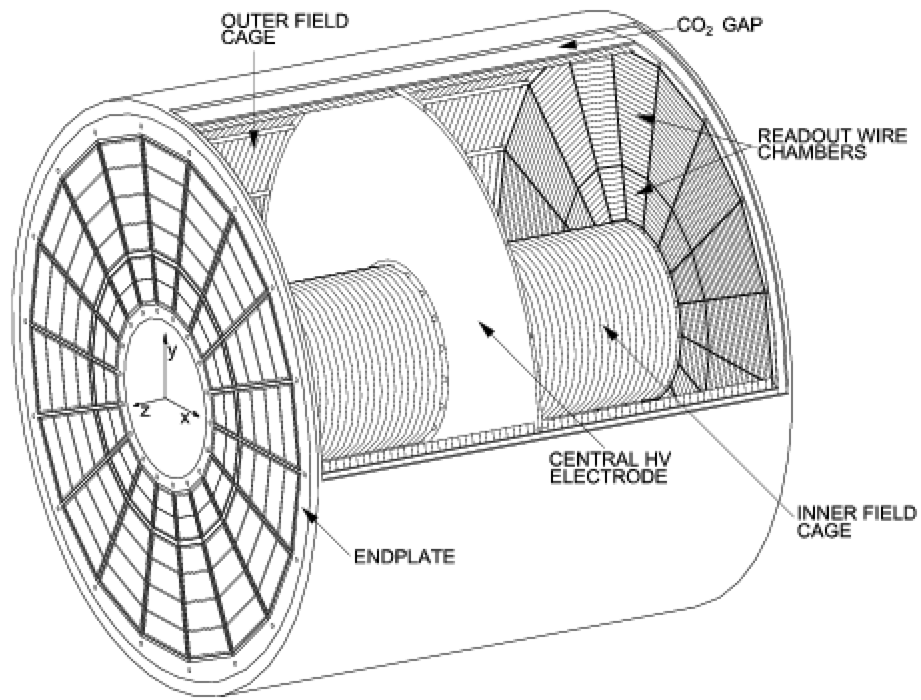
Collection of drift chamber types

Straw tube detectors for OTR of LHCb.

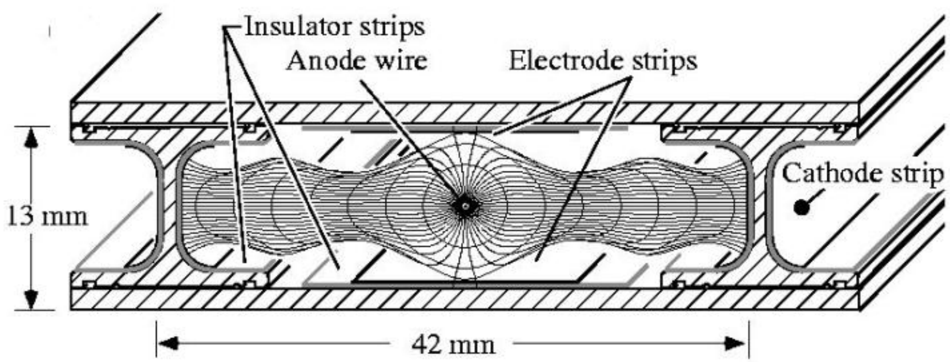


Distances in mm.





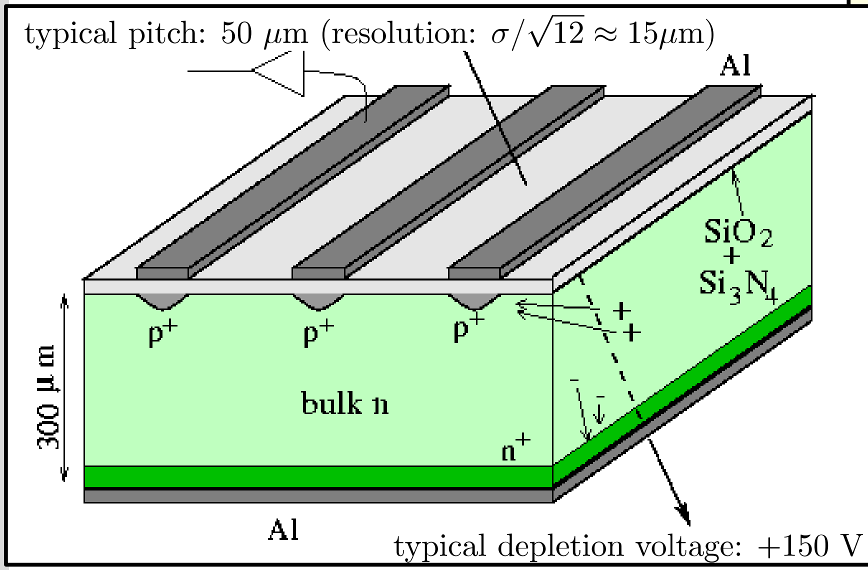
Drift chamber for muon system of CMS.



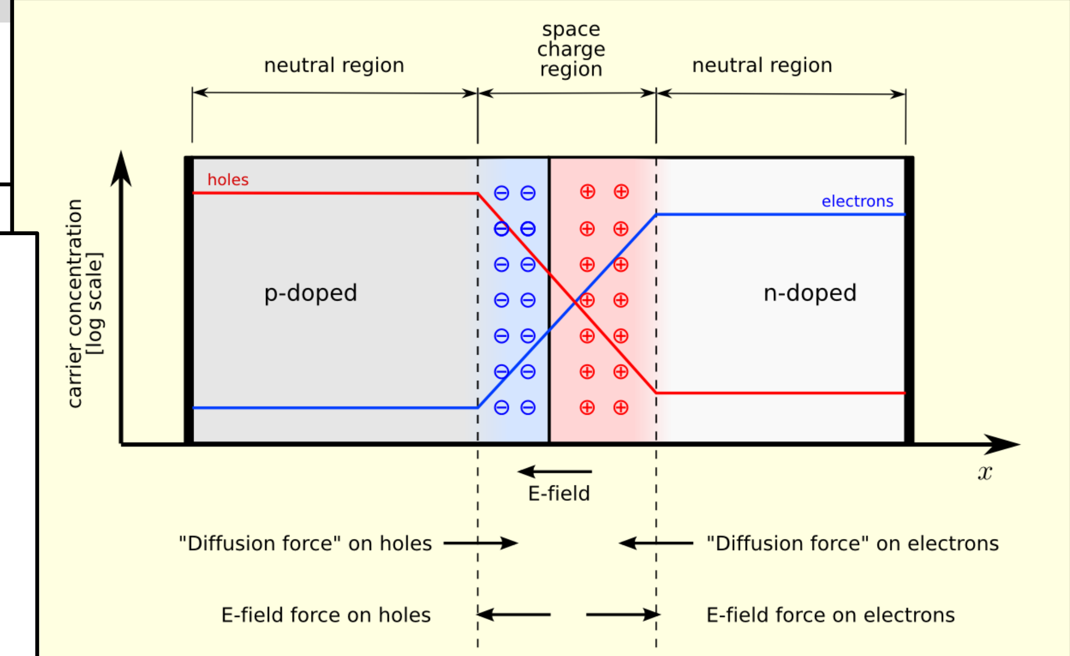
Time projection chamber as in use at ALICE:

- Strong electric field along beam axis.
- Charge carriers drift to segmented endcaps for readout.
- Drift time ~ position in z.

Silicon detectors

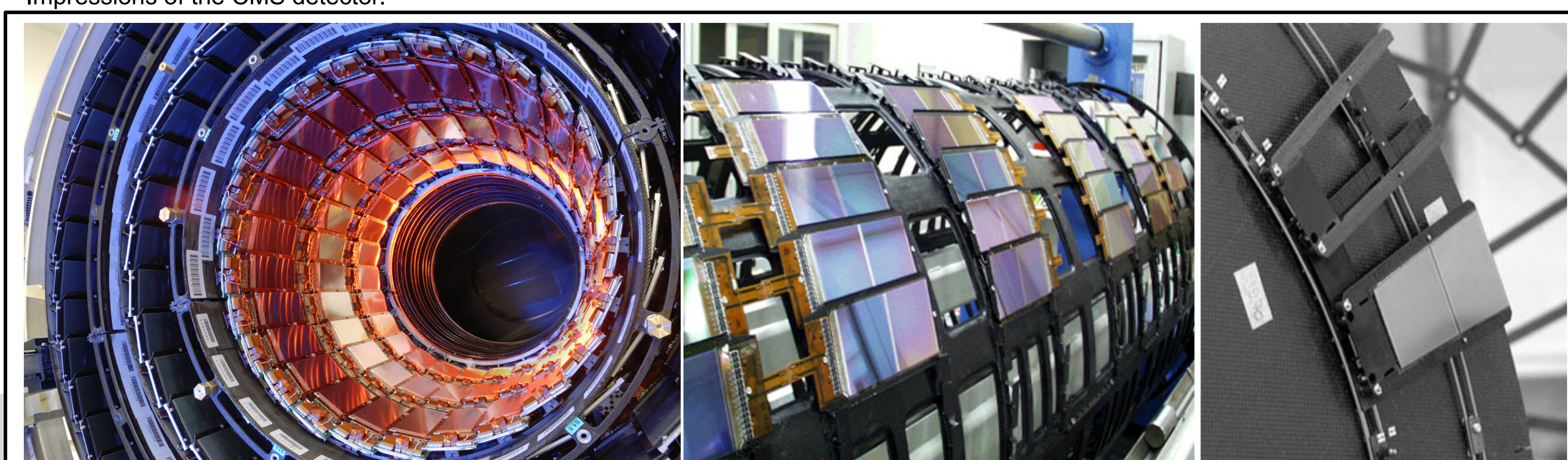


Layout of a typical Si-strip detector.



Reminder: pn-junction.

Impressions of the CMS detector.



Calorimeters

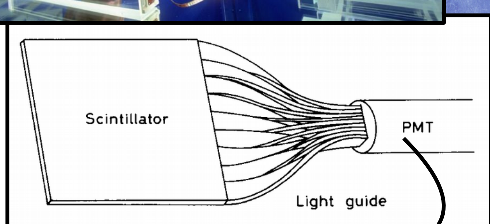
- Stop particle in active device with good energy resolution.

Scintillator:

Use excitation of atoms → turned into scintillation light:

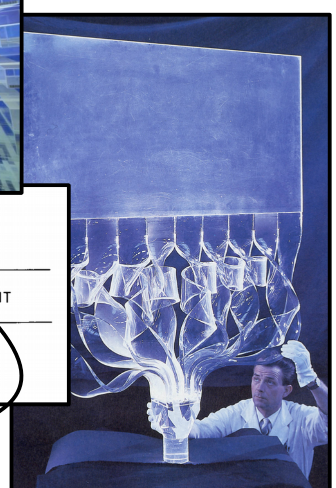
	ρ [g/cm^3]	$\lambda_{max}[nm]$	decay time [μs]	N_γ/MeV
NaI	3.7	303	0.06	$8 \cdot 10^4$
CsI	4.5	565	1	$1.1 \cdot 10^4$
$PbWO_4$	8.3	420	0.006	$2 \cdot 10^2$

Usually connected via light guides to PMTs for readout.



quantum efficiency $\approx 20\%$

signal amplification $\mathcal{O}(10^8)$



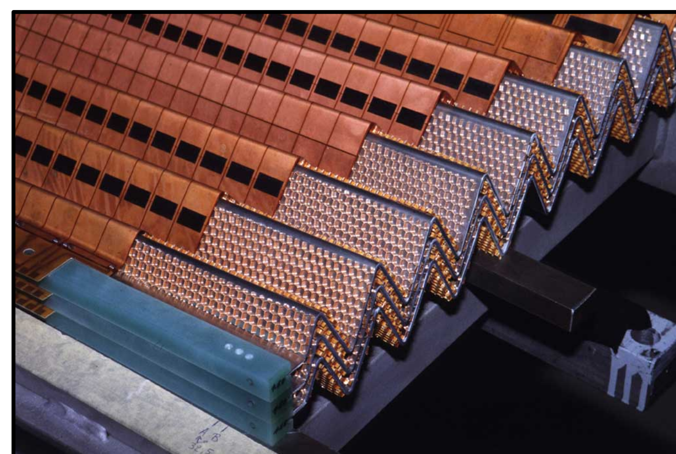
Important material parameters:

- Energy resolution.
- Linearity.
- Same response for all particle types (h/e, → compensation).
- Stopping power (in X_0 or λ_i)
- Radiation hardness.
- Granularity in readout.

For better energy resolution choose homogeneous, for better stopping power use sampling calorimeters.

Ionization:

E.g. by ATLAS Pb-LAr sampling calorimeter: ≈ 100 e's per cm



Key demands on the experiment

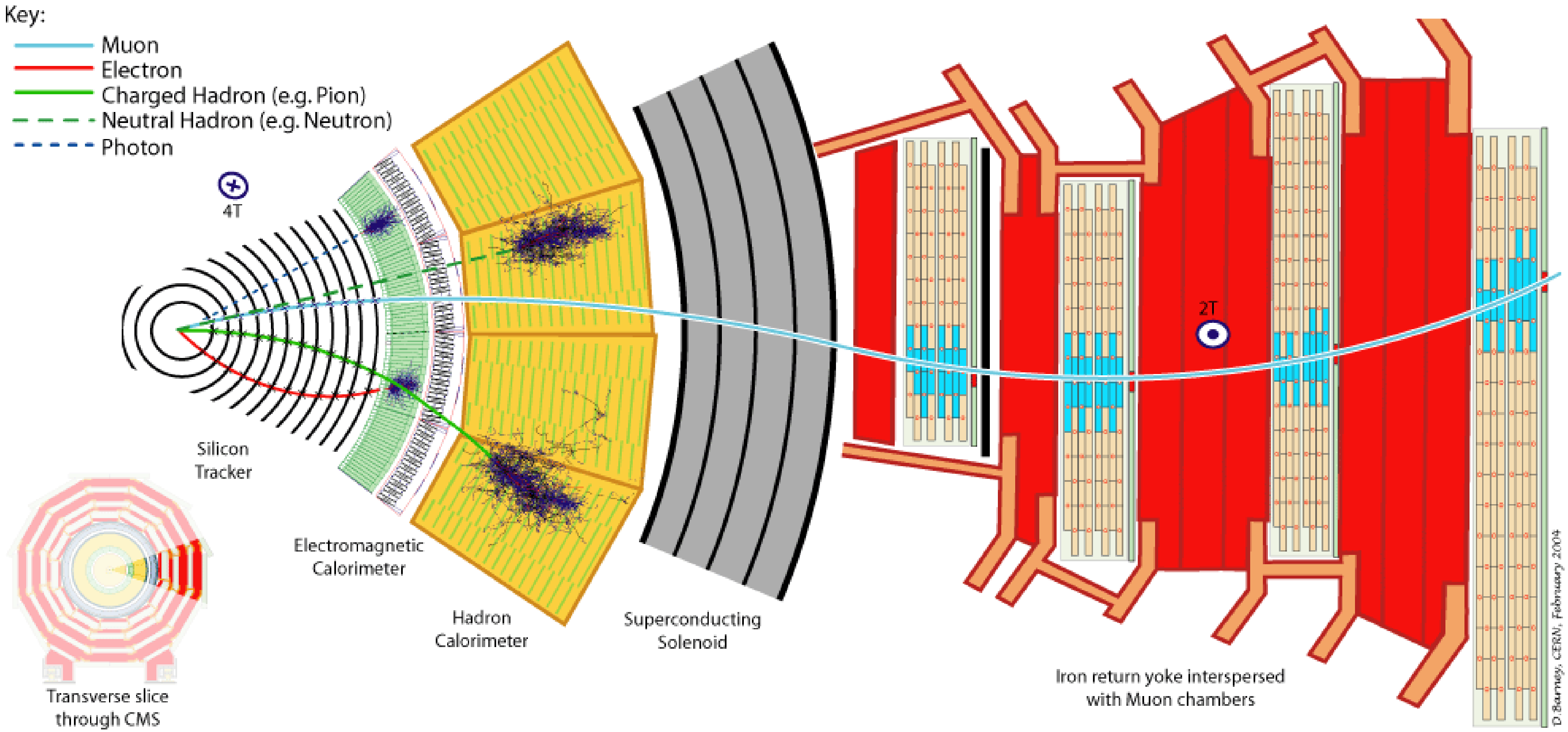
Vertex identification:

Momentum determination:

$$\vec{p} = e \cdot \vec{r} \times \vec{B} \qquad \frac{\delta p}{p} = \frac{\delta B}{erB} \oplus \frac{\delta r}{erB}$$

Energy determination:

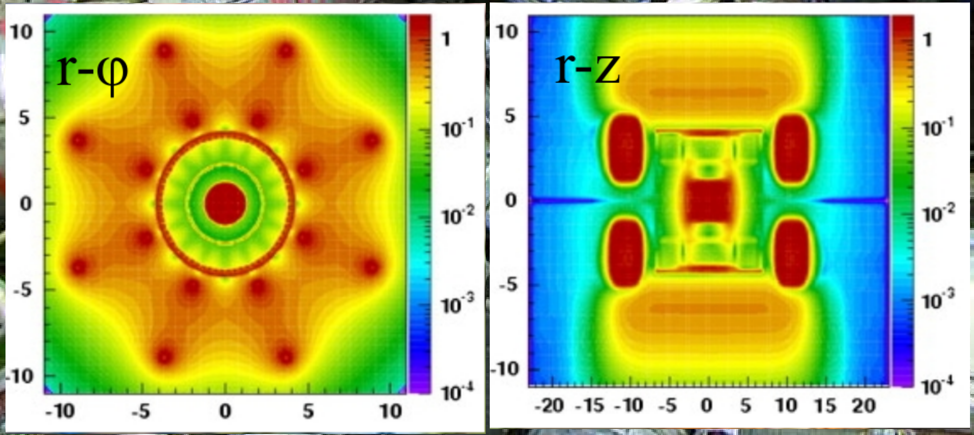
- Energy resolution
- Stopping power



The Large Scale Solution (ATLAS)

- Magnet field (solenoid): 2.6 T (inside calorimeter)
- Magnet field (toroid): ~4 T (outside calorimeter)
- Tracker: Si/multi-wire chambers
- ECAL/HCAL: LAr (varying granularity)

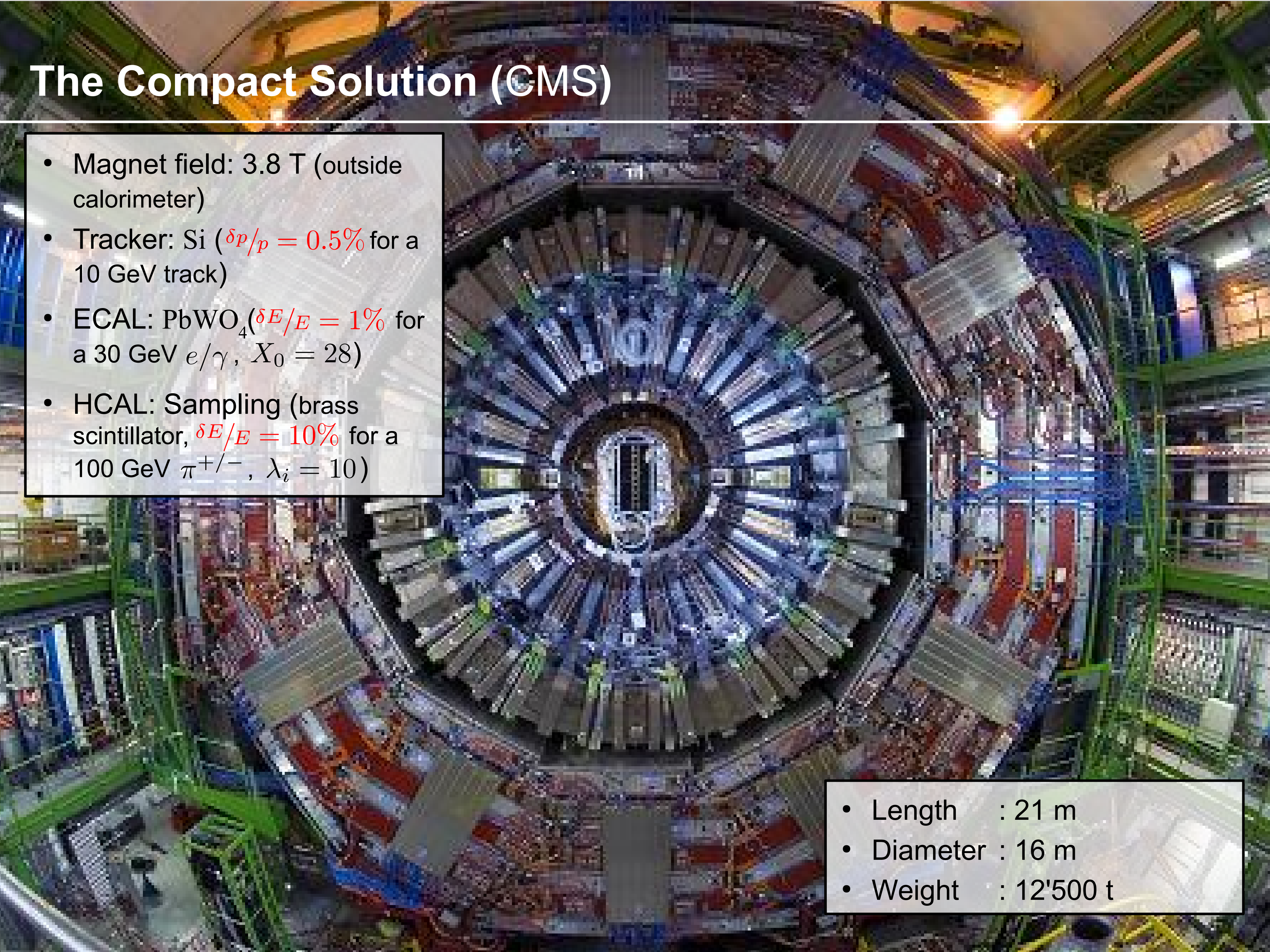
Magnet Field:



- Length : 45 m
- Diameter : 22 m
- Weight : 7'000 t

Courtesy of CERN/Maximili

The Compact Solution (CMS)



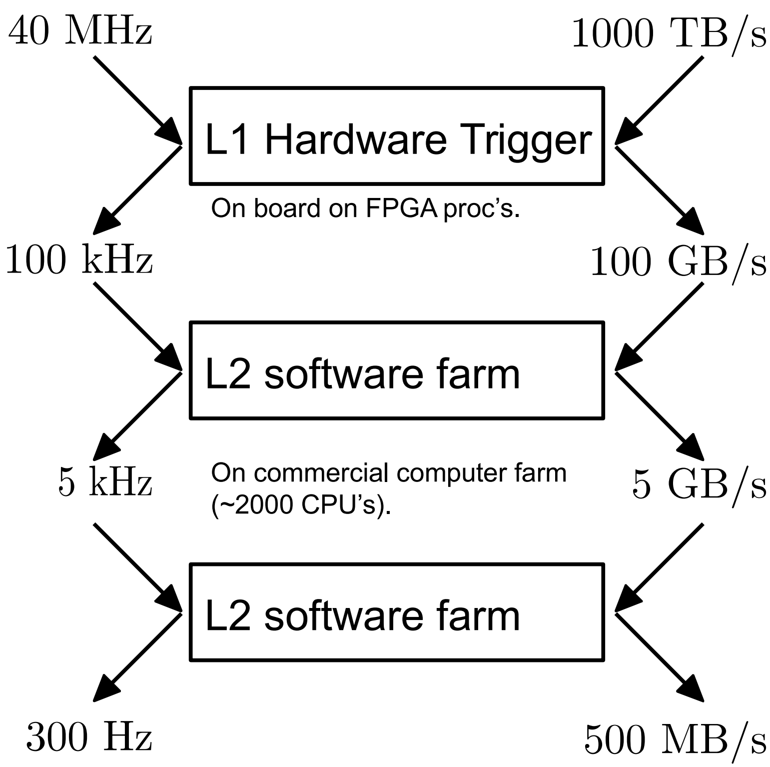
- Magnet field: 3.8 T (outside calorimeter)
- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track)
- ECAL: $PbWO_4$($\delta E/E = 1\%$ for a 30 GeV e/γ, $X_0 = 28$)
- HCAL: Sampling (brass scintillator, $\delta E/E = 10\%$ for a 100 GeV $\pi^{+/-}$, $\lambda_i = 10$)

- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

Deadtime free readout

- Achieve deadtime free readout by sophisticated data acquisition.

Layered trigger system:



Requirements (e.g. CMS):

- ~100 million detector cells.
- 40 MHz event rate.
- 10 – 12 bits/cell.

→ ~1000 TByte/s raw data (most of this data is not of interest).

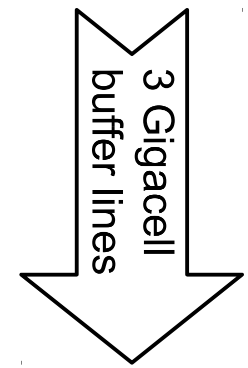
- App. high p_T electron.
- App. high p_T muon
- Decisions within $\mathcal{O}(ns)$.

- Regional readout of tracker and CALO e.g. to check isolation.
- Decisions within $\mathcal{O}(\mu s)$.

- Nearly full event reconstruction.
- Decisions within $\mathcal{O}(ms)$.

Detector granularity available for trigger readout.

Each decision buys the system more time to take a closer look.



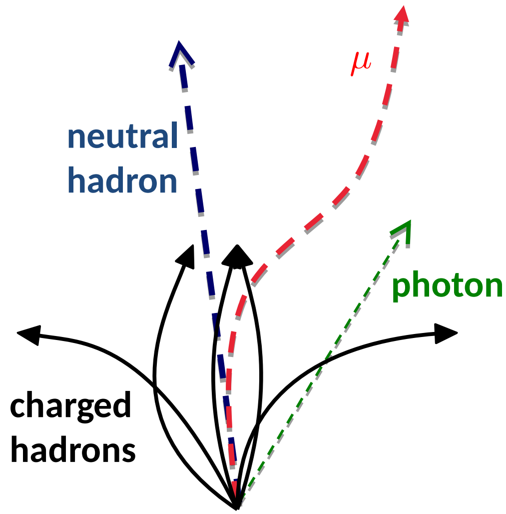
Keep all detector information till trigger decision is reached.

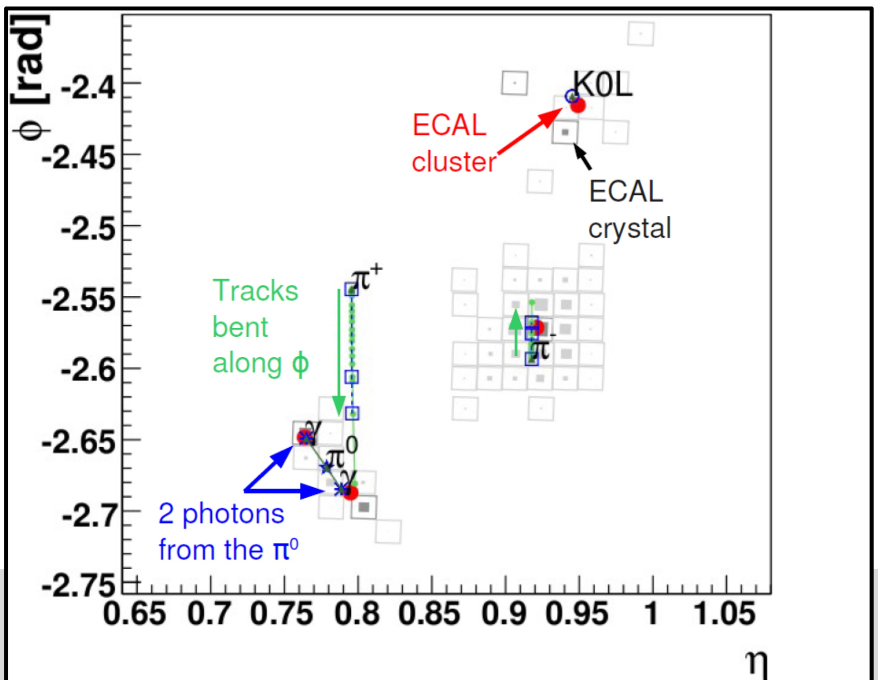
HLT paths with too high rate can be *prescaled* (*prescale*=2 → only any second event recorded).

- $\mathcal{O}(10)$ L1-keep decisions.
- $\mathcal{O}(100)$ HLT trigger bits.

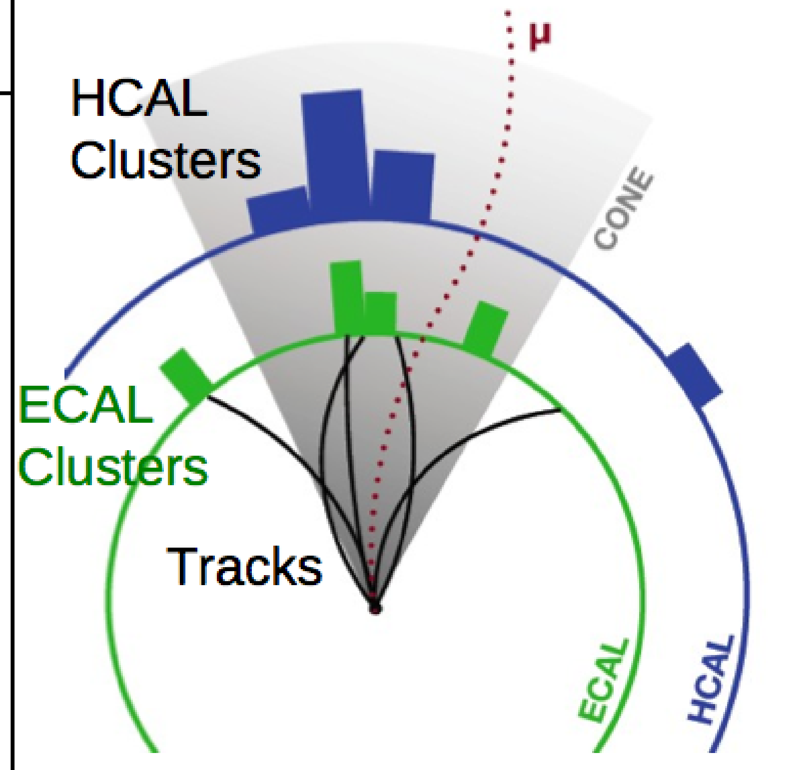
High level object reconstruction

- Combine all energy deposits in detector to a unique event description (→ stable particle level).





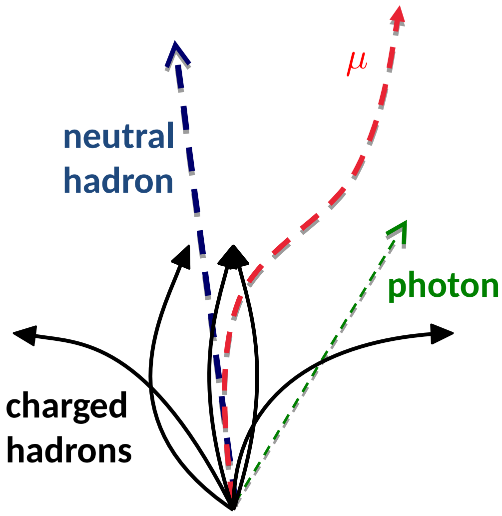
Particle Flow:

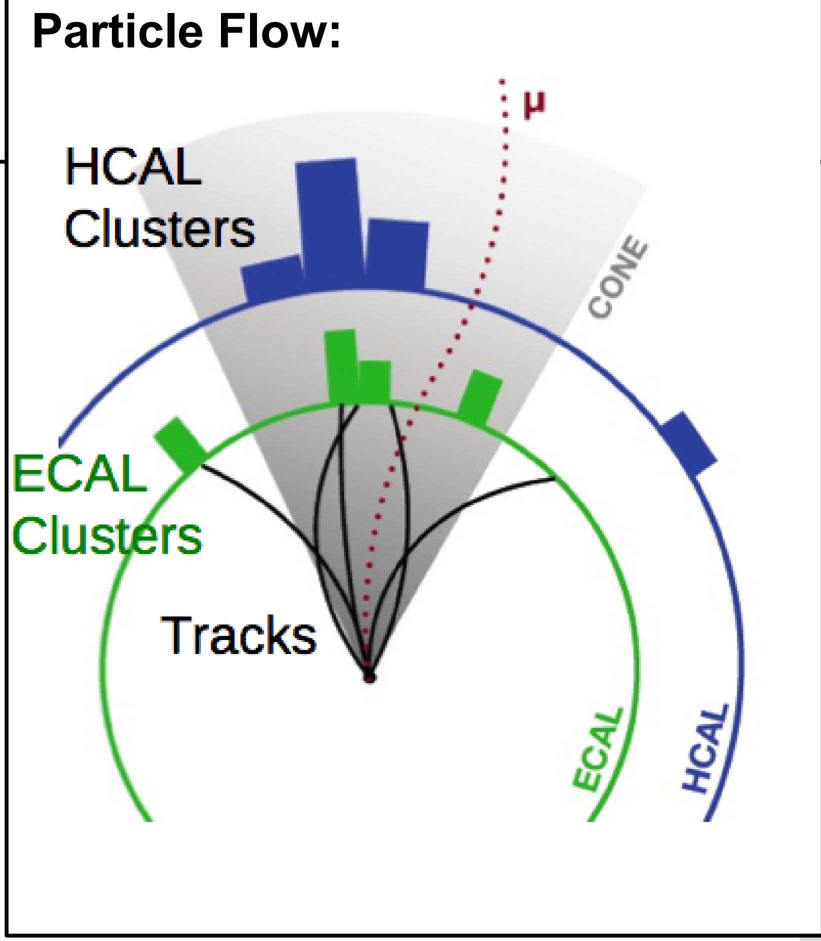


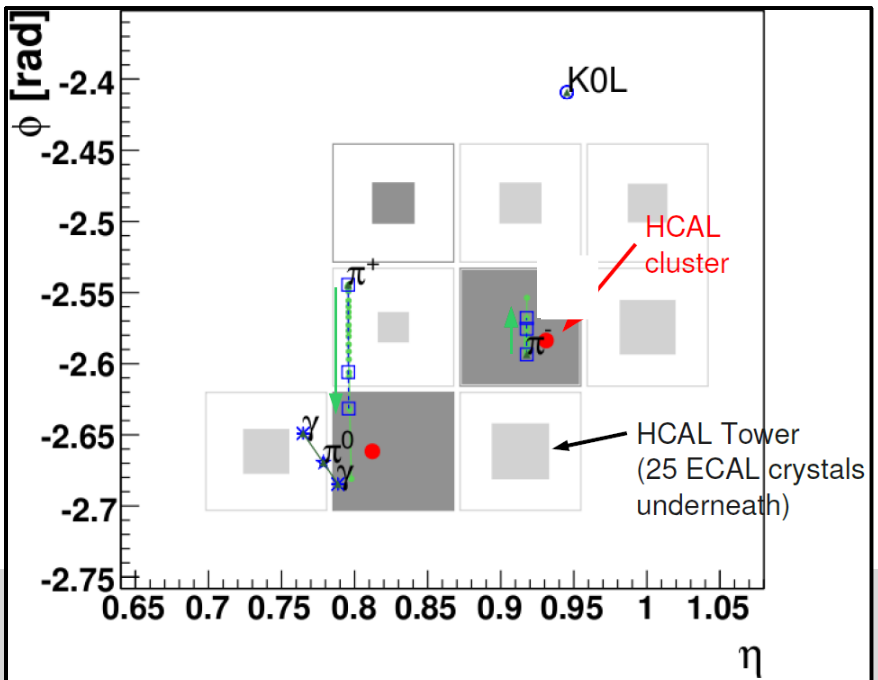
- Unambiguous list of stable particles: muons, electrons, photons, charged & neutral hadrons.

High level object reconstruction

- Combine all energy deposits in detector to a unique event description (→ stable particle level).

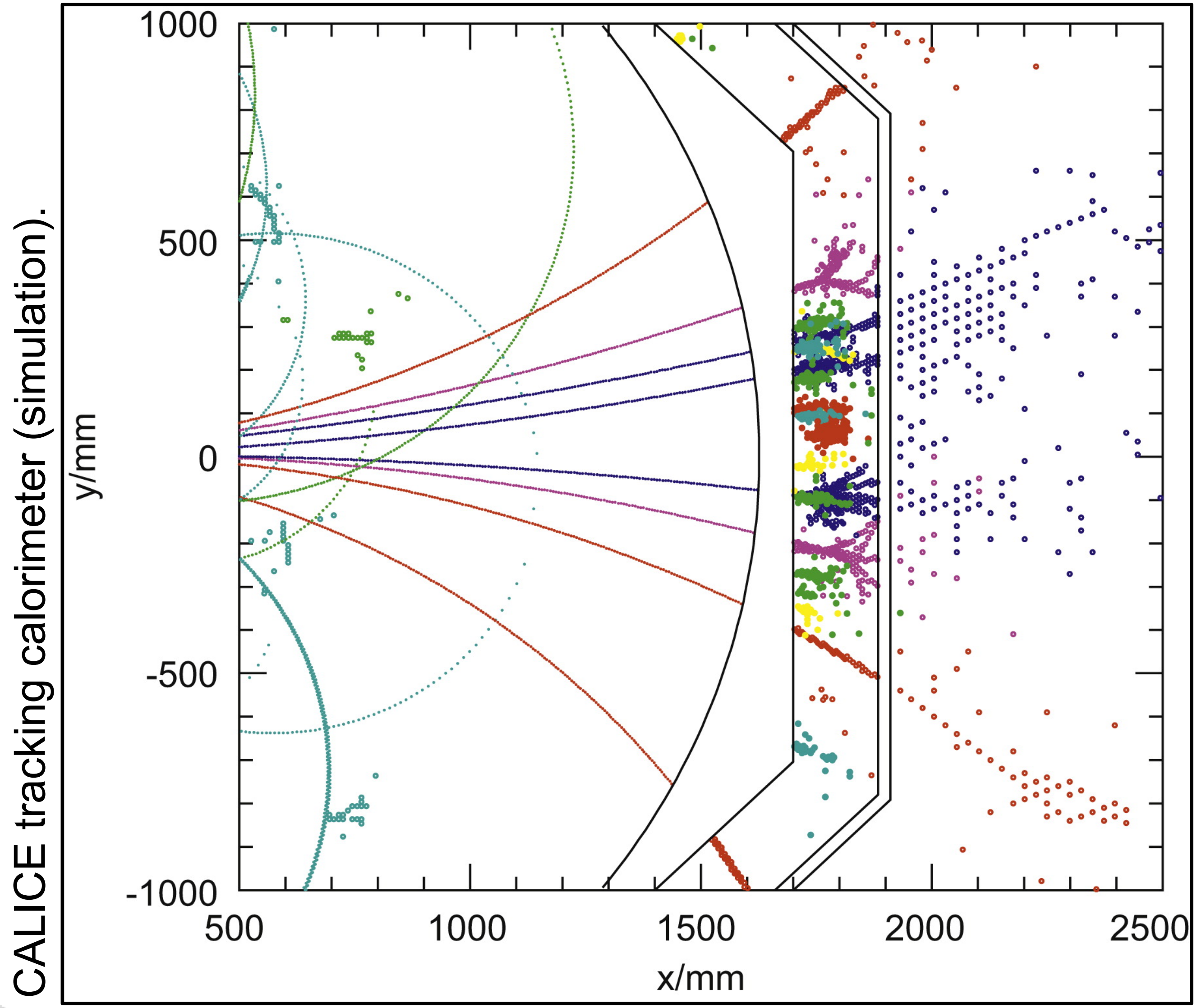






- Unambiguous list of stable particles: muons, electrons, photons, charged & neutral hadrons.

Particle flow of the future

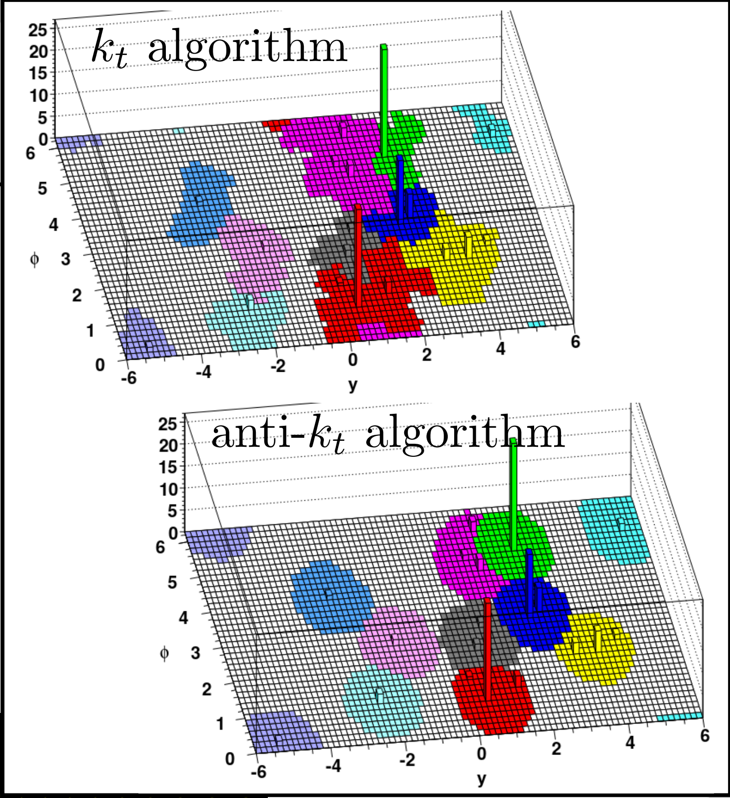


Prerequisites:

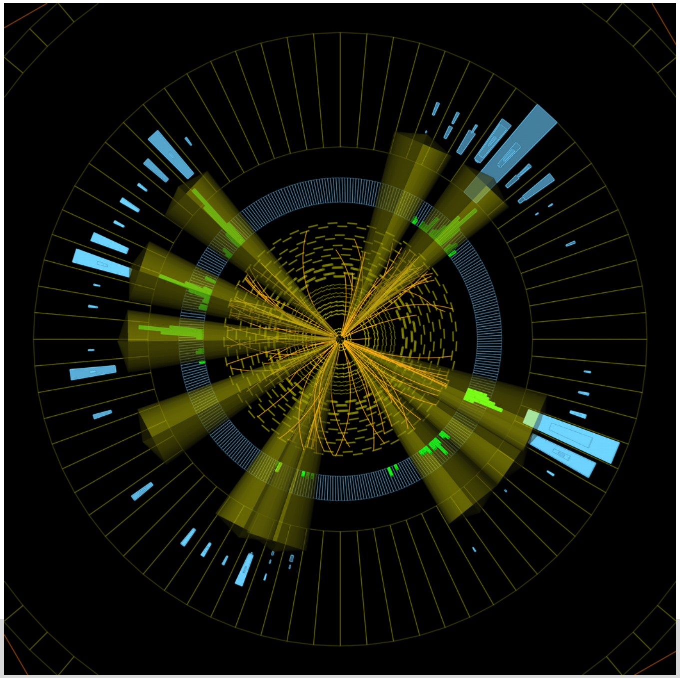
- Excellent separation of neutral & charged hadrons ($\rightarrow \vec{B} \cdot R_{calo}$).
- Minimal material in front of CALO.
- High granularity CALO.

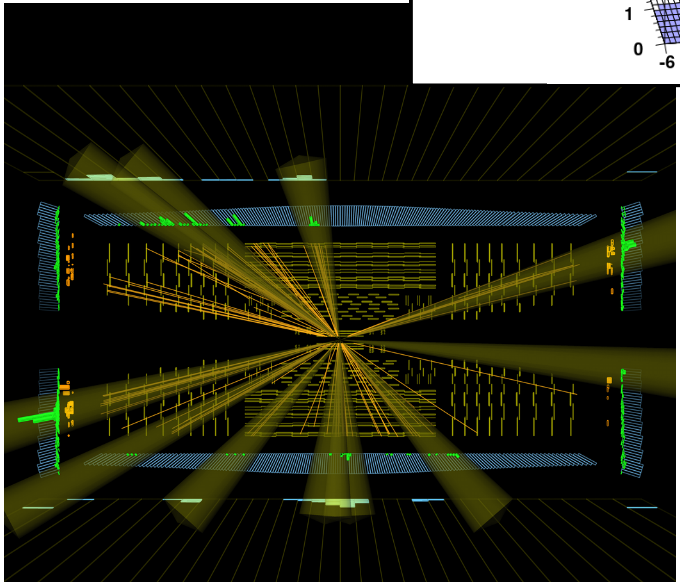
Jet clustering

- At analysis level we are most of the time more interested in partonic structures than all hadrons in the event.
- Today *sequential recombination jet cluster algorithms* are state of the art, which recombine hadrons into jets according to their energy and distance in $\Delta R(y,\phi)$:



G. Salam Towards Jetography



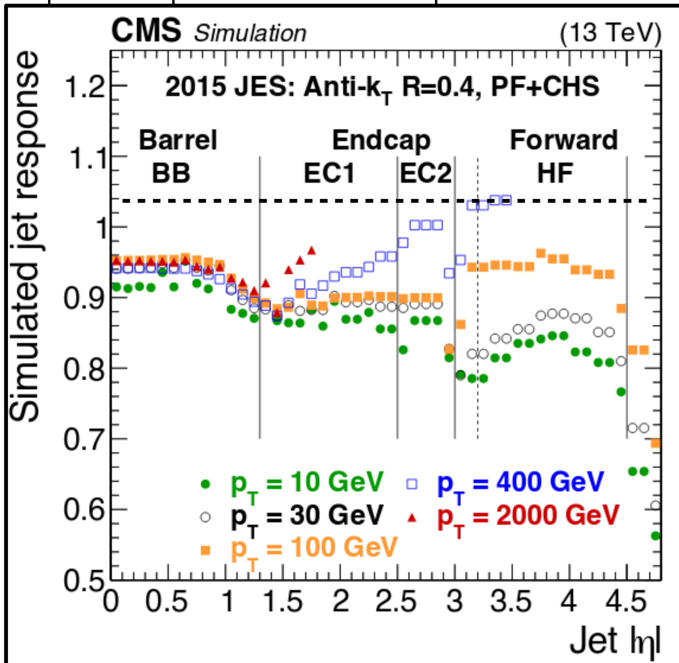


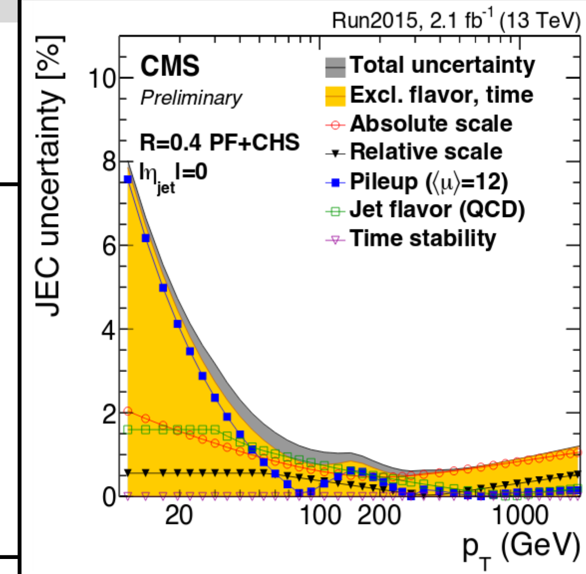
Jets can be associated to partons in hard scattering

CMS 11-jet event

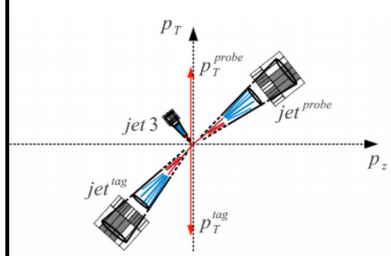
Jet calibration

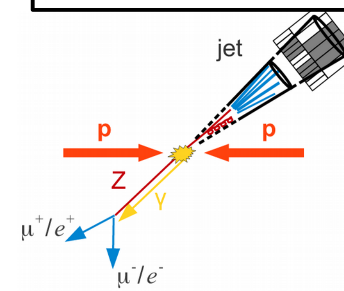
Expected response reconstructed / parton level



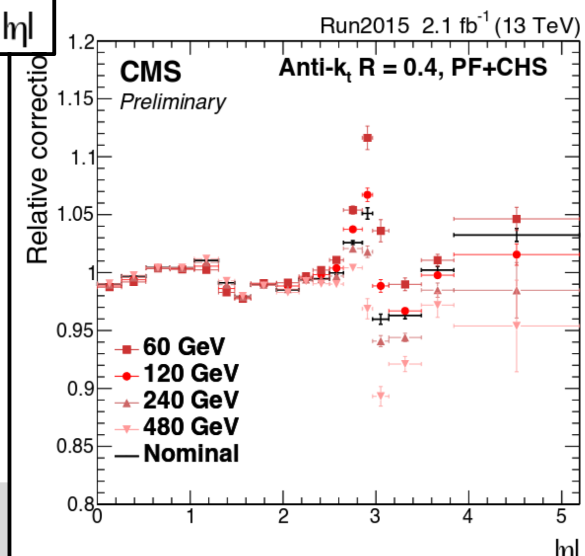


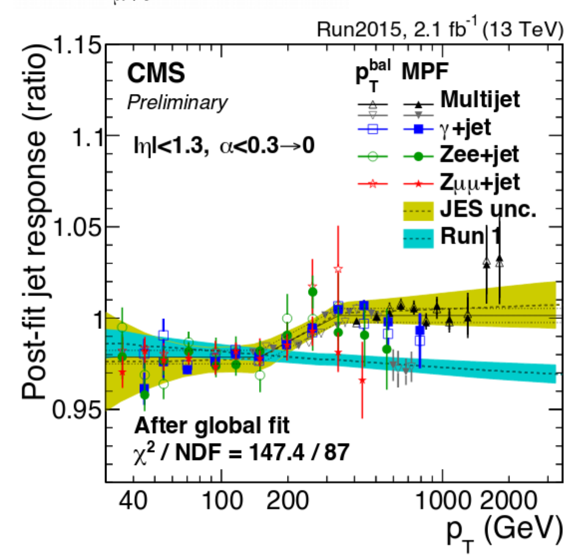
Corrections to simulation





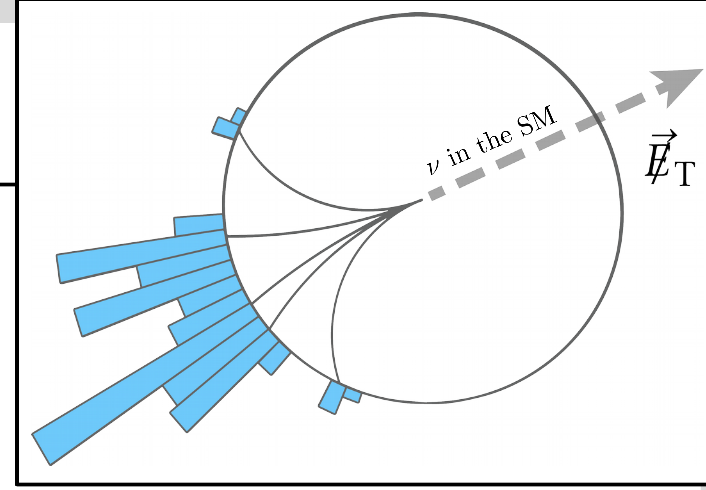
- Response matches expected energy at parton level already within 10%.
- Correction and uncertainty at %-level.





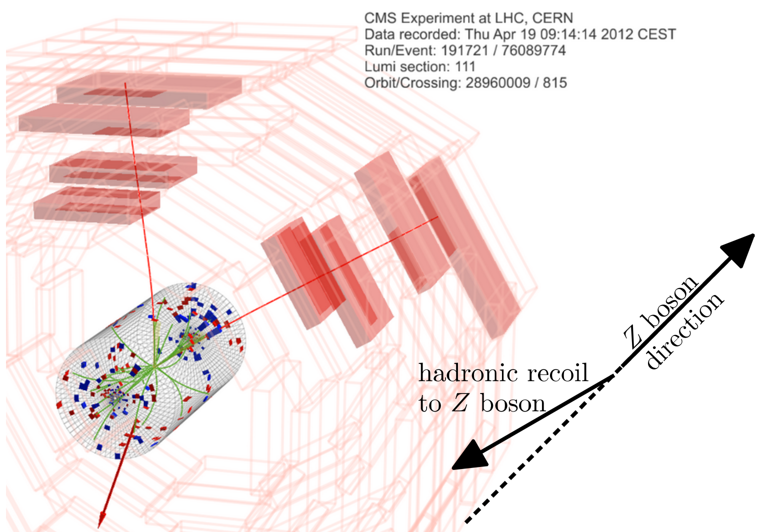
Missing energy

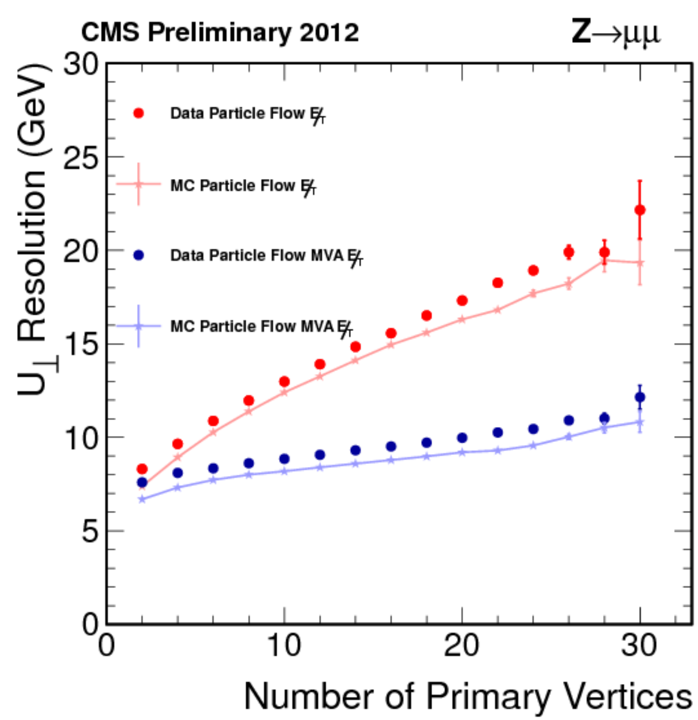
- In the initial state have $p_x = p_y = 0$. Must be true also for final state due to momentum conservation.
- Mis-balance of $\sum_{\text{part}} \vec{p}_T$ indicates presence of undetected energy ($\rightarrow$ MET).



$$\text{MET} = \left| -\sum_{\text{part}} \vec{p}_T \right|$$

MET resolution can be measured in $Z \rightarrow \mu\mu$ events w/o genuine MET.

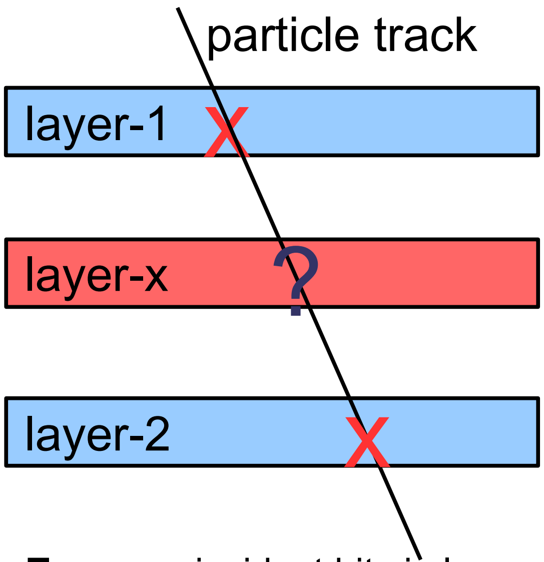




Lepton identification

- Lepton identification can be measured using "Tag & Probe" techniques.

Example: Hit efficiency

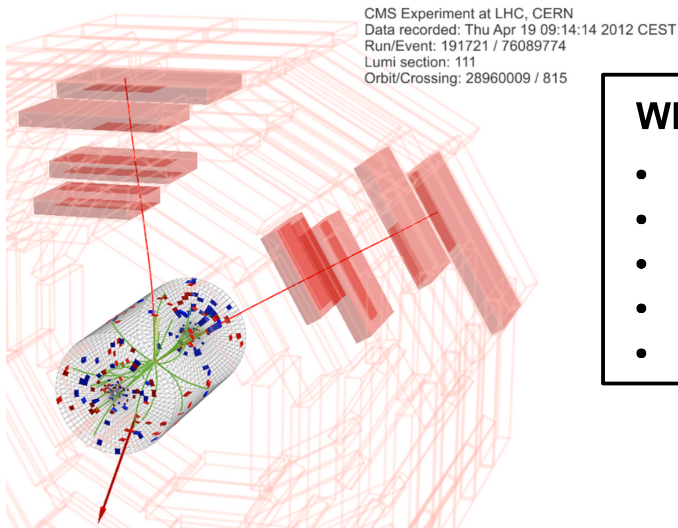


Tag : coincident hits in layer-1 & 2.
Probe: how often do we see a hit in layer-x?

Example: Lepton ID efficiency

$Z \to \ell\ell,\ \ell = e,\ \mu$

Tag : well identified and ID'ed lepton & Z-mass requirement.
Probe: inner/outer track, calo deposit.



What can be tested:

- inner/Outer track reconstruction efficiency,
- efficiency of ID or isolation requirements,
- track-cluster linking efficiency,
- cluster efficiency in calo,
- …

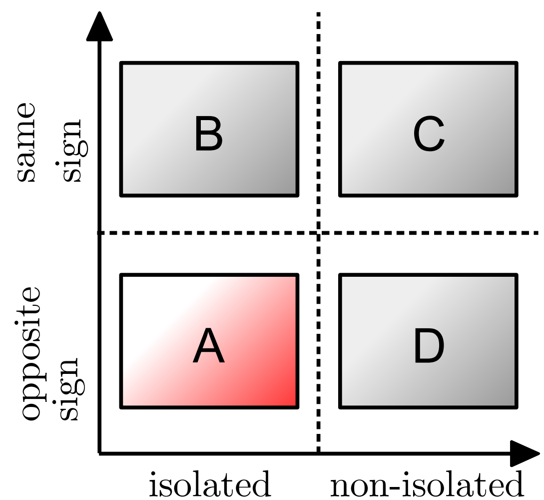
Tag: everything that let's you think that you know the truth of the probe.

Control of background processes

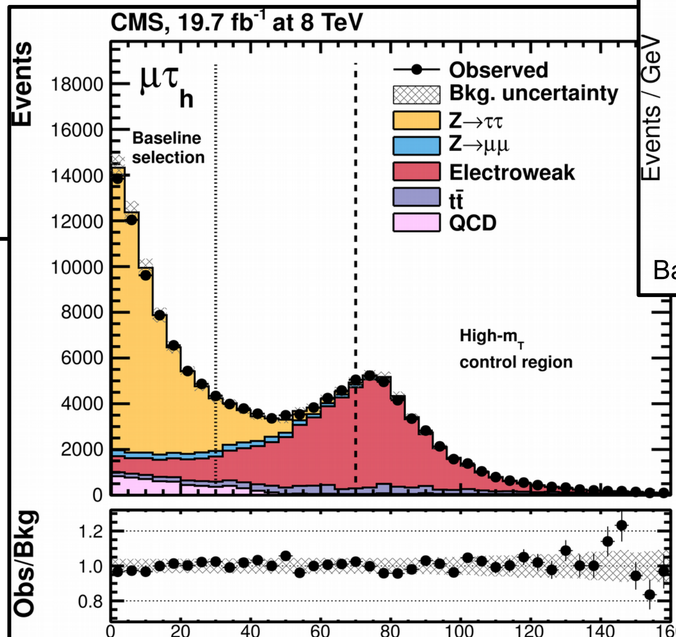
- Several flavors of estimation methods of contributions of background processes in signal regions.

$$N_A = N_B \cdot \frac{N_D}{N_C}$$

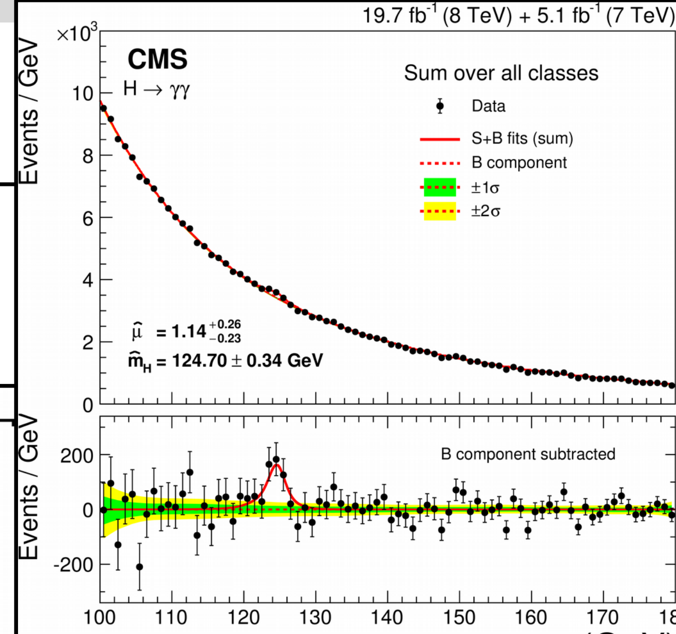
Even shape can be taken from region B.



QCD multijets background for $H \to \tau\tau$



W+jets background for $H \to \tau\tau$



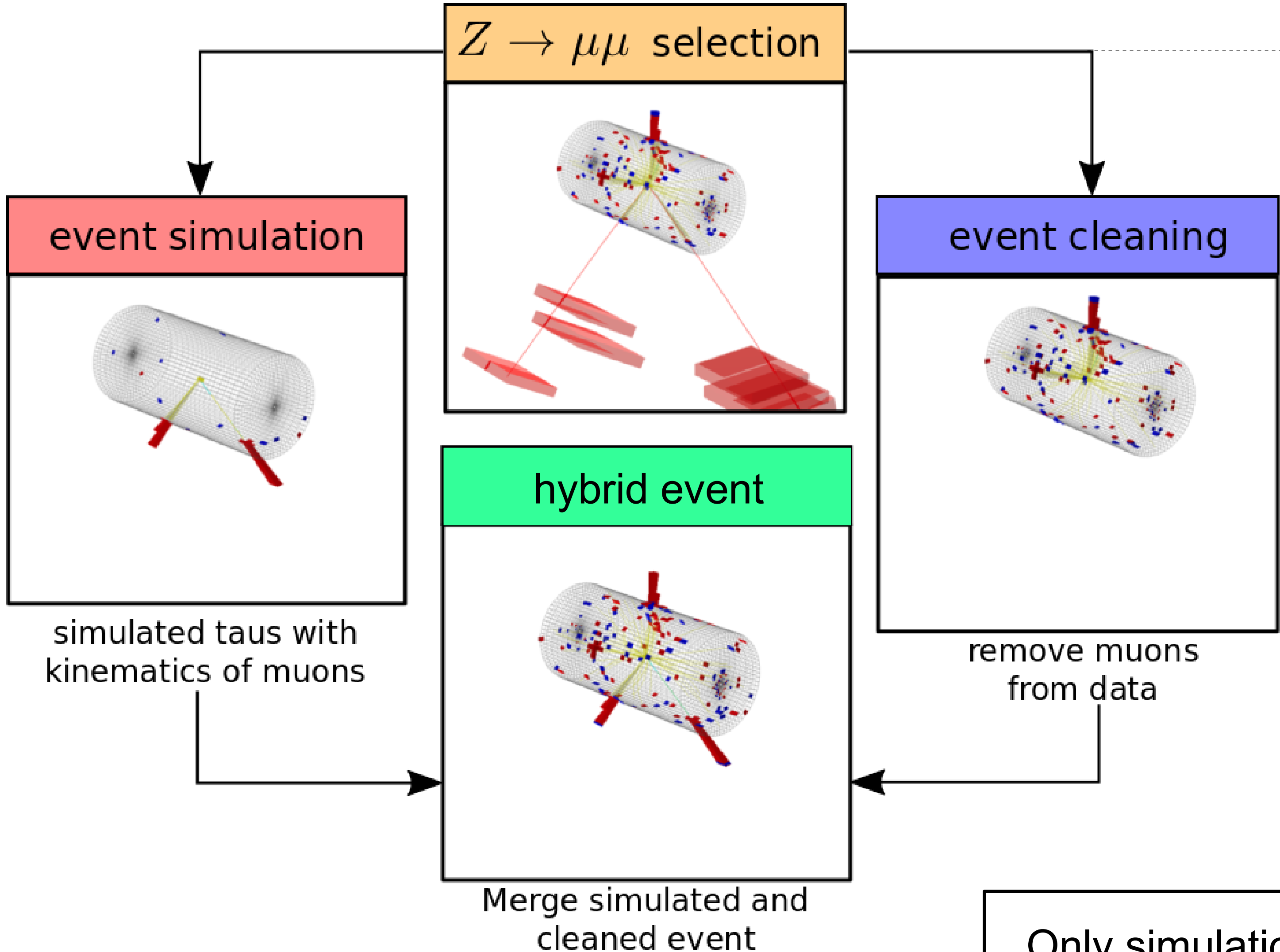
Background for $H \to \gamma\gamma$

Normalize background events in sideband region.

Each of these estimates requires a (more or less sophisticated/robust/physics motivated) model.

More sophisticated methods

Estimate of $Z \to \tau\tau$ background for $H \to \tau\tau$.



Literally background free sideband region for $H \to \tau\tau$.

Only simulation part: decay of τ-lepton.

Remaining lecture program

	Monday (19.09):	Tuesday (20.09.):	Wednesday (21.09.):
13:30 15:00	Introdu[illegible] particle physics[illegible]	Proton structure, QCD and physics with jets (MM).	Flavor physics - including top-quarks (MM).
15:15 16:45	Particle [illegible]ration & detecti[illegible] analysis (RW).	Physics with gauge bosons (MM).	Higgs physics (RW).

- In case of questions – contact us matthias.mozer@cern.ch (Bld. 30.23 Room 9-8)
  roger.wolf@cern.ch (Bld. 30.23 Room 9-20).

Backup