University of Ljubljana, Faculty of Mathematics and Physics

Selected topics in contemporary physics

March 19, 2025

How do we measure what we can't see

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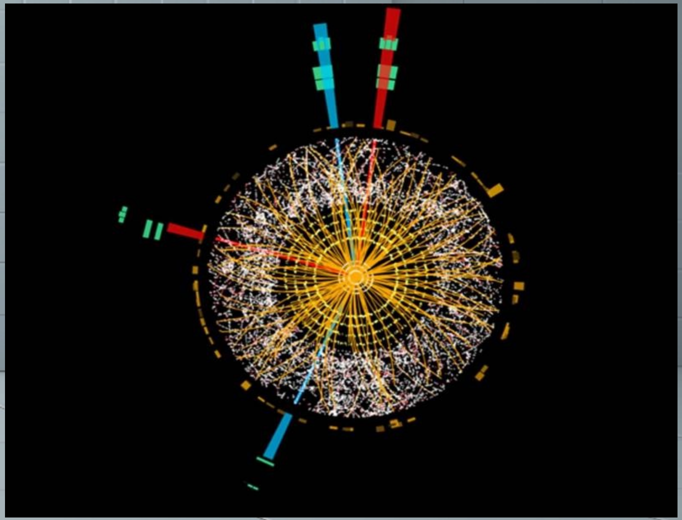
Outline

High energy physics experiments

Particle identification

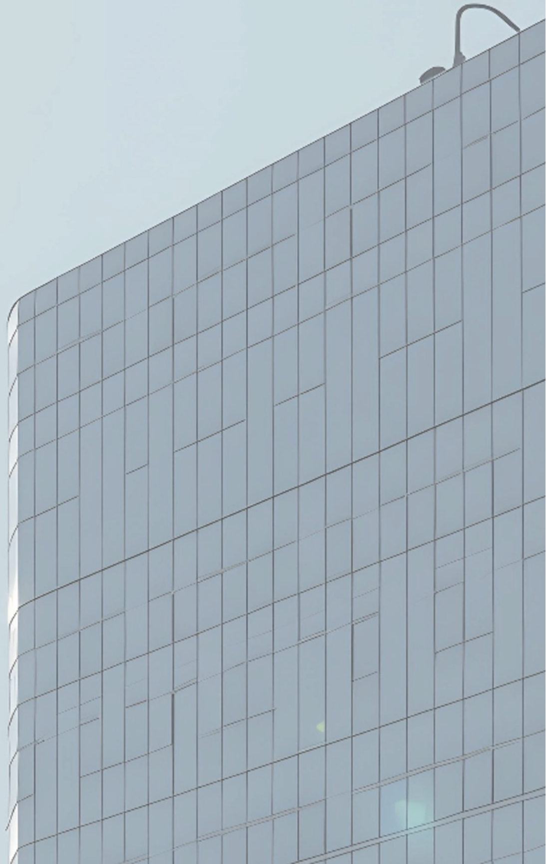
Detection of photons



What should be the description of the basic building blocks of nature?

Two requirements:

- **Simple** (low number of basic building blocks of matter)
- **Correct**

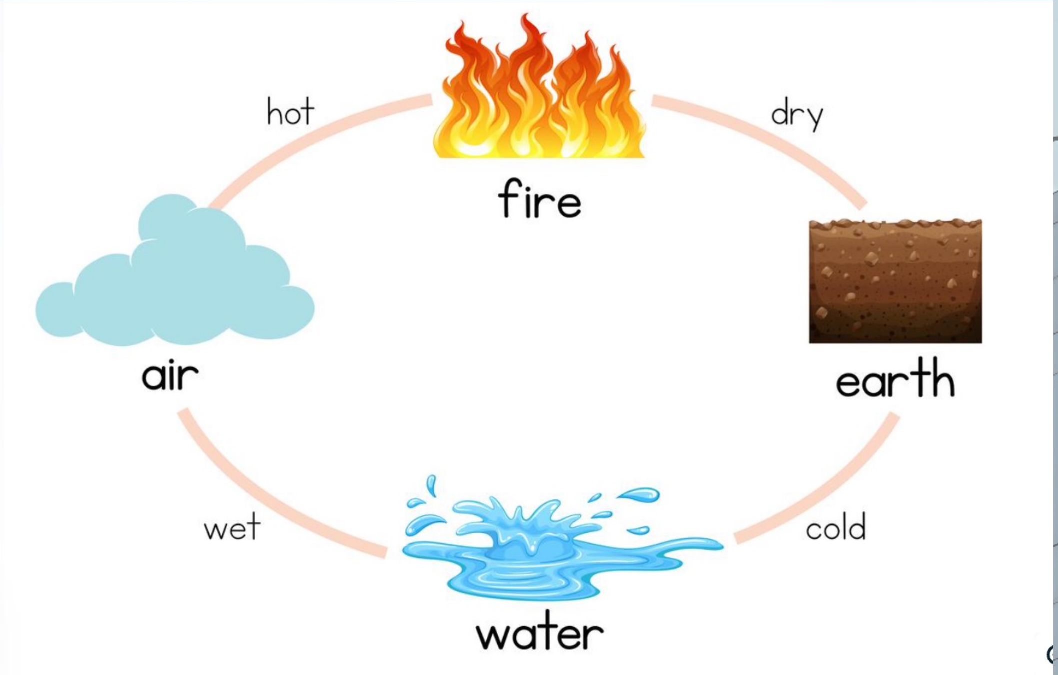


Elementary Particles

- We investigate the properties of interactions by studying the processes between the basic particles

- The concept of fundamental particles has changed throughout the history of human research, but especially through experimental capabilities.

- **Empedocles (c. 492—432 B.C.E.)** one of the most important of the philosophers working before Socrates
- Simple, but wrong



Description of nature by D.I. Mendeliev

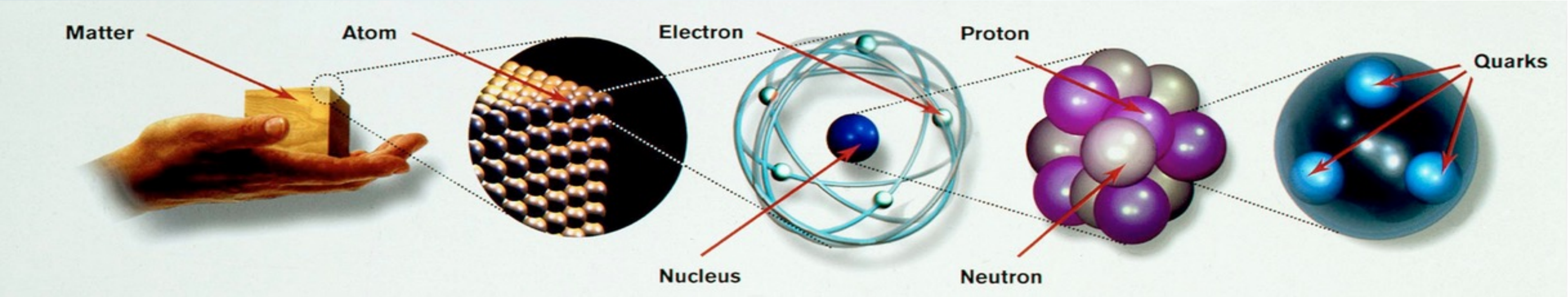
Periodic system of elements :

↓Period \ Group→	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

~more than 100 of elements

Correct, but complex...

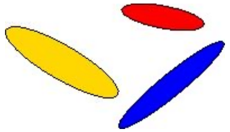
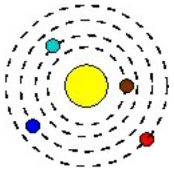
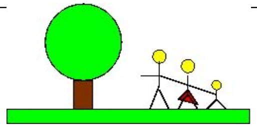
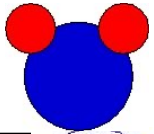
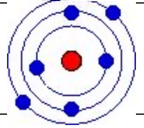
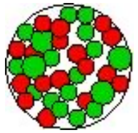
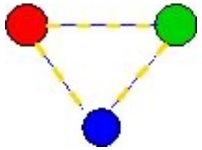
How do we see the world today?



Basic particles

The forces (interactions) between them:

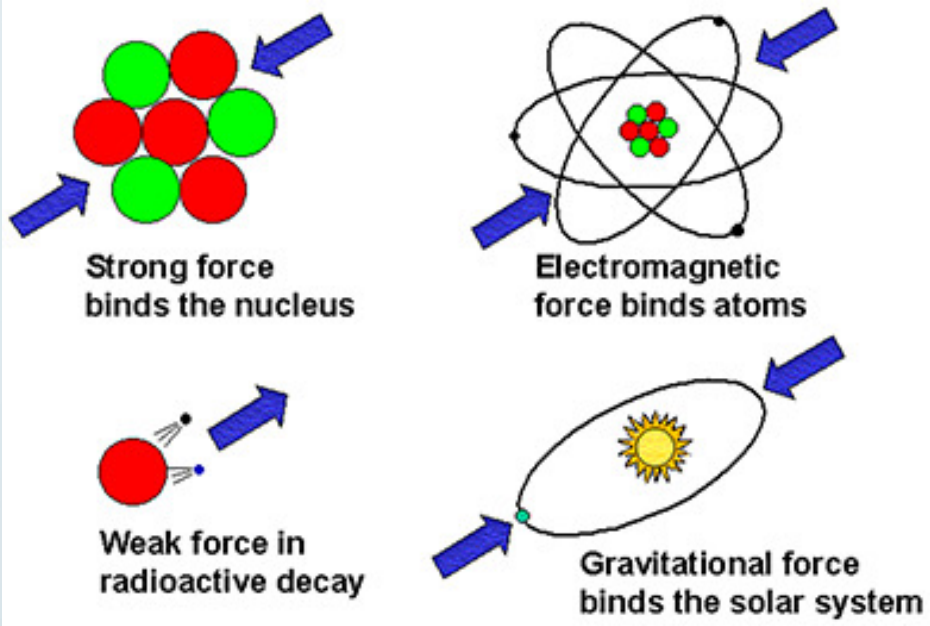
- Gravity
- Electromagnetic interaction
- Weak interaction (beta decay)
- Strong interaction (binds quarks in the nucleus)

Particles	and	Forces			
Dimension(m)	Object		Forces	Meaning	Experts
10^{21}	Galaxy clusters		Gravitation		Philosopher
10^{14}	Galaxies, Stars, Planets				Cosmologist, astophysicist, astronomer
1	Living beings		instincts	Conservation of spicies	biologist Sociologist
10^{-8}	Molecules		electromagnetic	Diversity of life	Chemist, physicist
10^{-10}	atoms			energy	Atomic physicist
10^{-14}	nucleus		nuclear	Chemical elelments, sun, reactor	Nuclear physicist
10^{-15}	nukleons		Strong, weak	My salary	particle physicist
10^{-18}	quarks		?	?	Philosopher

Particle physics

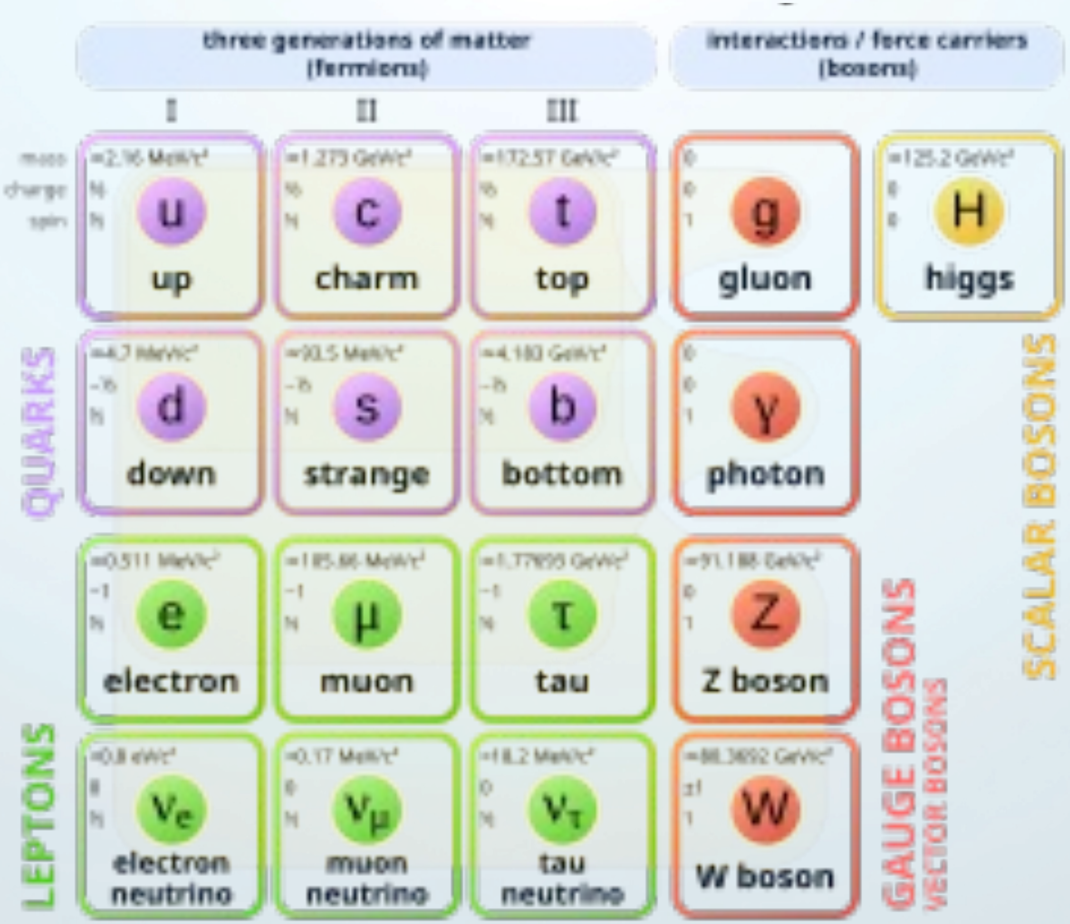
Standard Model (SM) of interactions between basic particles:

- strong,
- electromagnetic,
- weak,
- gravitational



Theory describing three of the four known fundamental forces electromagnetic, weak and strong interactions – excluding gravity) in the universe and
classifying all known elementary particle

Standard model of elementary particles



Each particle has its antiparticle, e.g. e- and e+

Quarks make up heavier particles - hadrons, e.g.

p = uud,

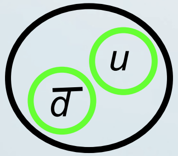
n = udd

Particle physics is concerned with the detection and measurement of properties of basic forces (=interactions) in nature

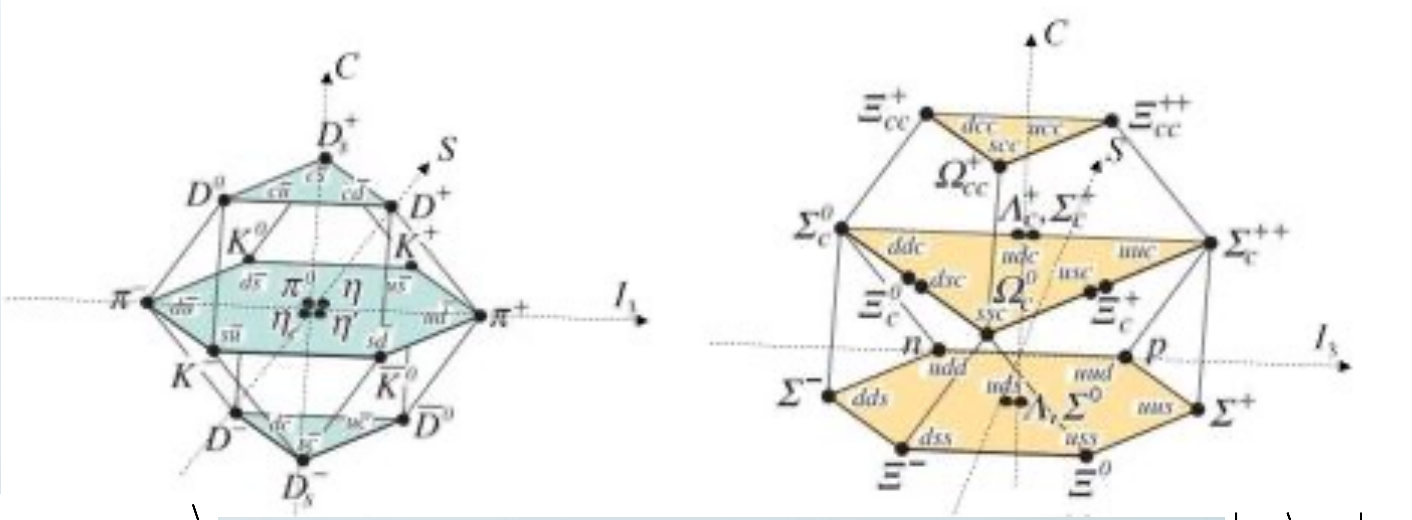
Baryons and mesons: bound states of quarks and antiquarks

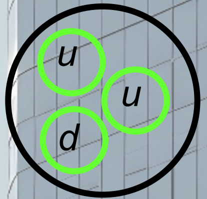
Barions	mass
proton: uud	1 m_p
neutron: udd	~1 m_p
Λ: uds	1.2 m_p

Mesons	mass
π^+: quark u + antiquark d	1/7 m_p
K_S: quark d + antiquark s	1/2 m_p
J/ψ: quark c + antiquark c	3 m_p
B^0: quark d + antiquark b	5.5 m_p



= PION





= PROTON

$$\left|\pi^+\right\rangle = \left|u(+2/3e_0)\bar{d}(+1/3e_0)\right\rangle$$

$$\left|p\right\rangle = \left|u(+2/3e_0)u(+2/3e_0)d(-1/3e_0)\right\rangle$$

http://pdg.lbl.gov ~ **180 Selected Particles**

γ, $W^{\pm}$, Z^0, g, e, μ, τ, ν_e, ν_μ, ν_τ, $\pi^{\pm}$, π^0, η, $f_0(600)$, $\rho(770)$,
$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,
$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,
$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,
$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,
$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,
$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^{\pm}$, K^0, K^0_S, K^0_L, $K^*(892)$,
$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,
$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^{\pm}$, D^0, $D^*(2007)^0$,
$D^*(2010)^{\pm}$, $D_1(2420)^0$, $D_2^*(2460)^0$, $D_2^*(2460)^{\pm}$, $D_s^{\pm}$, $D_s^{*\pm}$,
$D_{s1}(2536)^{\pm}$, $D_{sJ}(2573)^{\pm}$, $B^{\pm}$, B^0, B^*, B_s^0, $B_c^{\pm}$, $\eta_c(1S)$, $J/\psi(1S)$,
$\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$,
$\psi(4415)$, $\Upsilon(1S)$, $\chi_{b0}(1P)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\Upsilon(2S)$, $\chi_{b0}(2P)$,
$\chi_{b2}(2P)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$, p, n, $N(1440)$,
$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,
$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,
$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,
$\Delta(2420)$, Λ, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$,
$\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$,
$\Lambda(2110)$, $\Lambda(2350)$, Σ^+, Σ^0, Σ^-, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$,
$\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, Ξ^0, Ξ^-,
$\Xi(1530)$, $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$, $\Xi(2030)$, Ω^-, $\Omega(2250)^-$,
Λ_c^+, Λ_c^+, $\Sigma_c(2455)$, $\Sigma_c(2520)$, Ξ_c^+, Ξ_c^0, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2780)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are many more

Experimental elementary particle physics

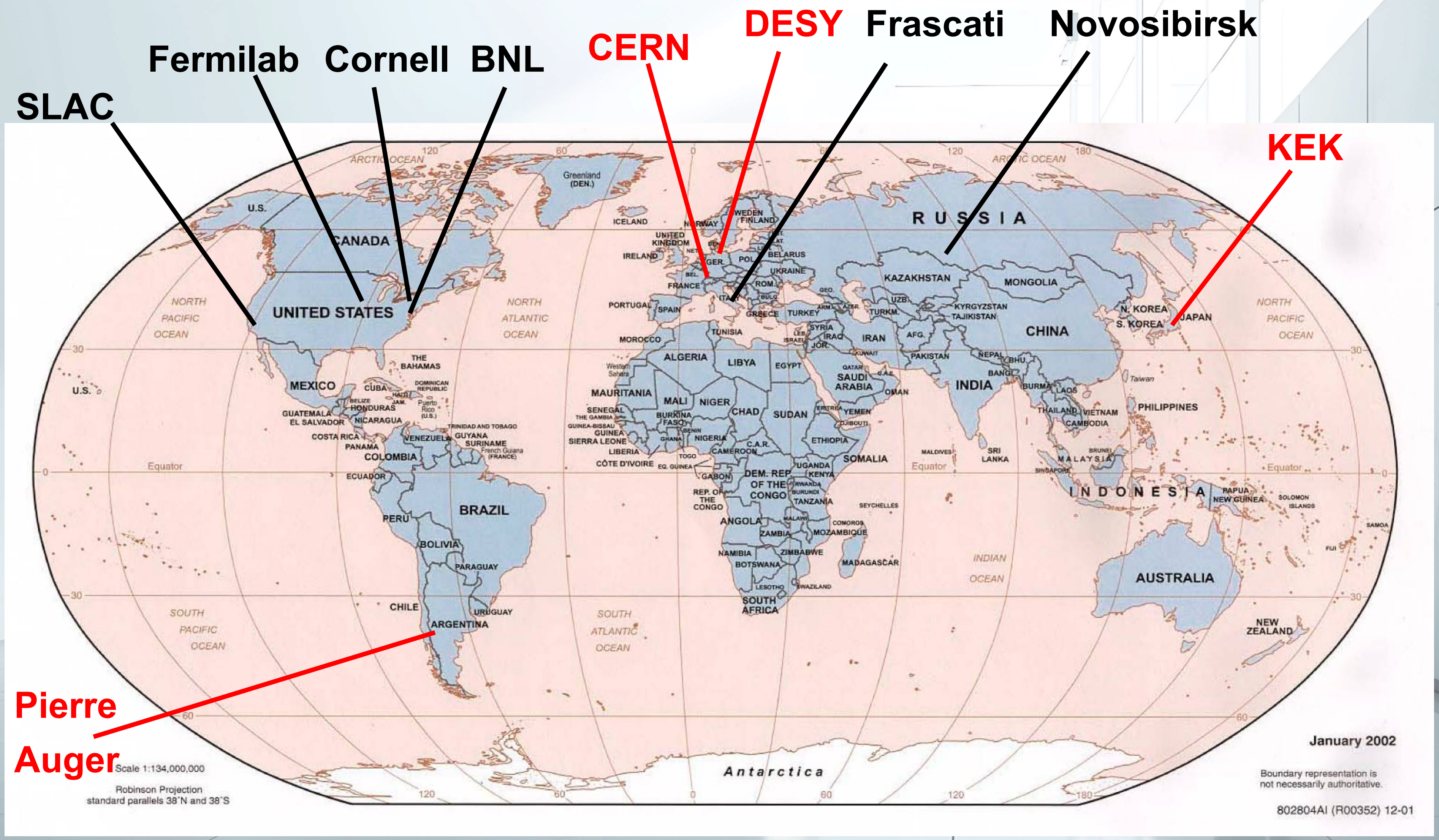
Experimental verification of the basic laws of nature,
testing **theoretical predictions** measurements of processes
at the highest achievable energies in the world of elementary particles

Features:

- ❑ Experiments in only a few research centres around the world.
- ❑ Data analysis is carried out using vast computing resources,
- ❑ Development of particle detectors and applications
- ❑ Work is carried out in international collaborations:

Atlas (CERN), Belle II(KEK), Pierre Auger, etc.

Research centers



Open questions in fundamental particle physics (and cosmology)

Why does the Universe consists of mostly matter and only a sample of anti-matter?

- Where did all the antiparticles from the Big Bang go?
- CP symmetry breaking measurements between particles and anti-particles

Where do particles get their mass?

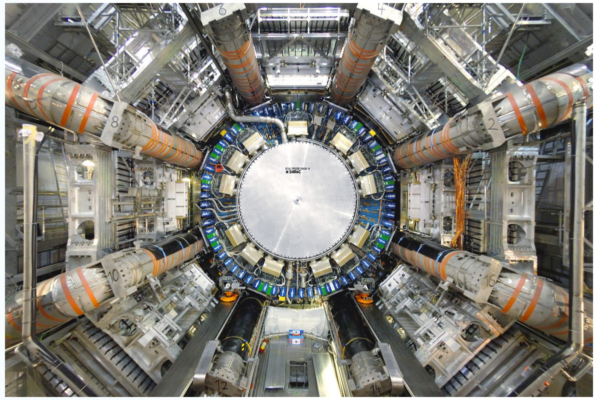
- The search for the Higgs boson

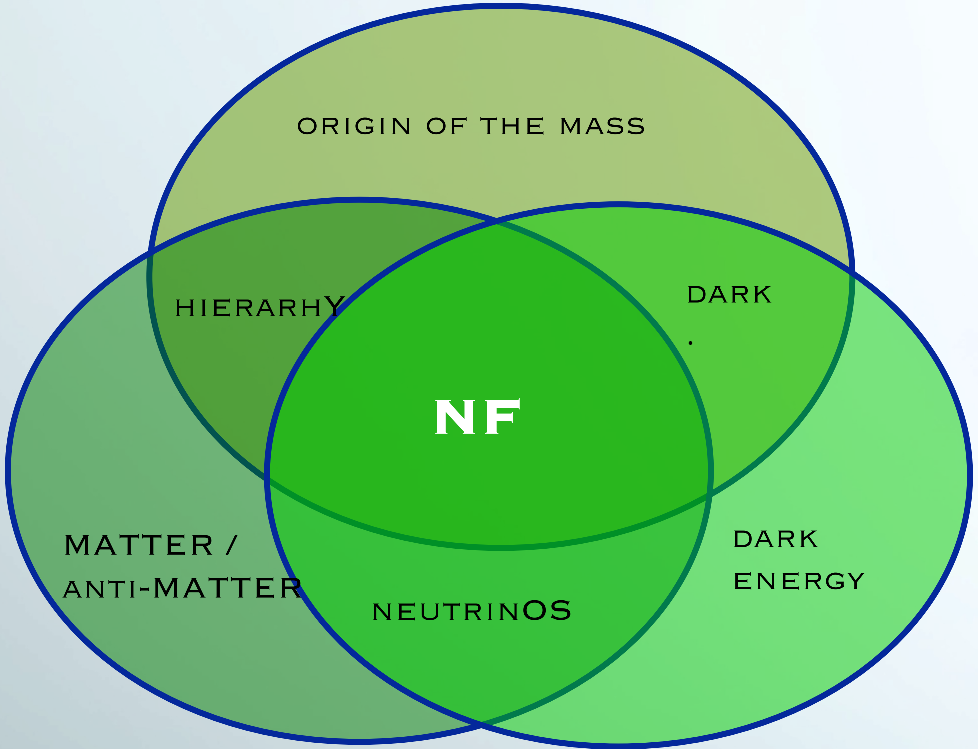
Why do particles have different masses, why are there multiple generations?

- search for supersymmetric partners and their interactions

An experimental approach to NF detection
The triple approach

Energy FRONTIER





Precision FRONTIER

Cosmological FRONTIER

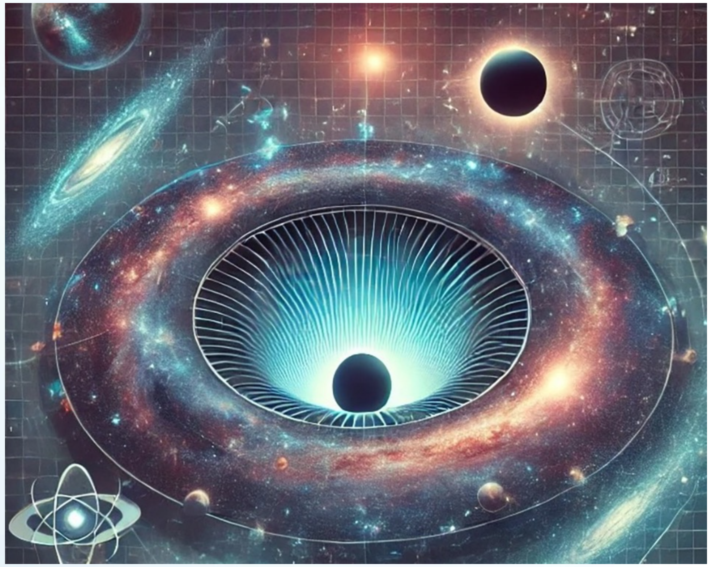
The discovery, and the interpretation of the NF would represent a major scientific breakthrough

Cosmological frontier

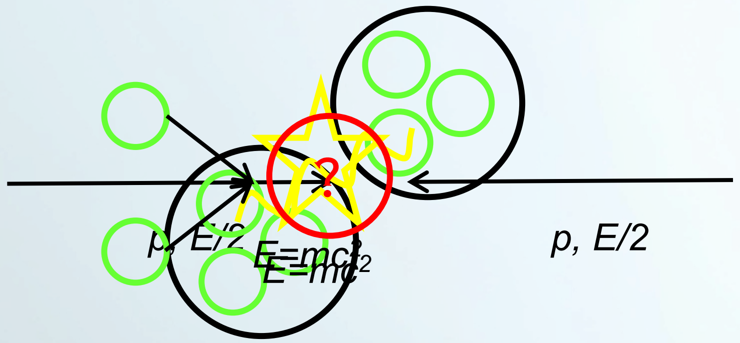
Observation and analysis of the cosmic microwave background (CMB).

The CMB provides insights into the early universe.

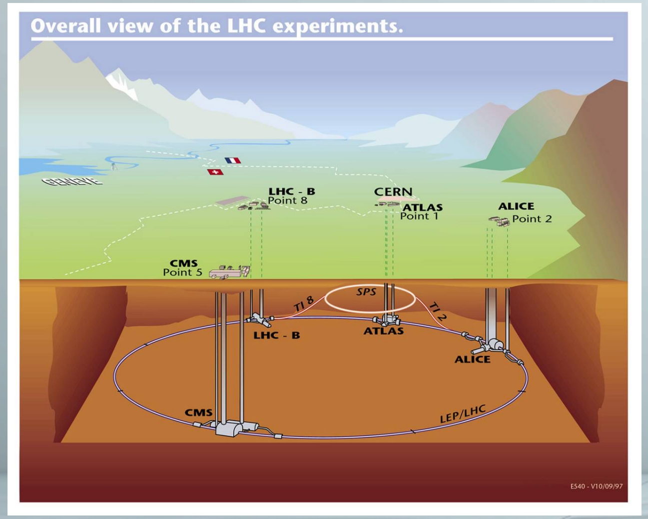
- Temperature Fluctuations
- Baryon Acoustic Oscilltions
- Polarization of the CMB
- Spectral Analysis



Energy frontier



Production of unknown particles and processes at the highest achievable energies



Large Hadron Collder

mc^2 =13 TeV
T=tera=10^{12}

the *p* bunch in the LHC has energy of more than 1500 kg car at 45 km/h

Precision frontier

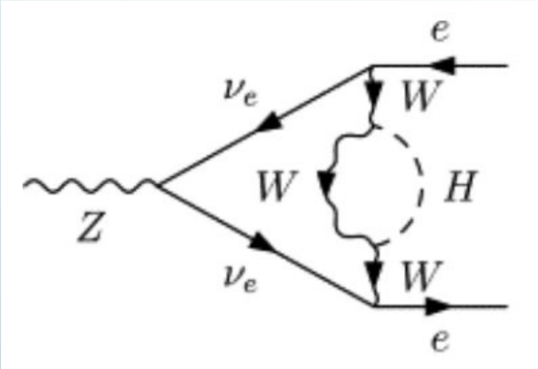
measure (rare) processes with high precision and compare the results with very accurate predictions in the context of the SM

undiscovered particles may contribute to known processes

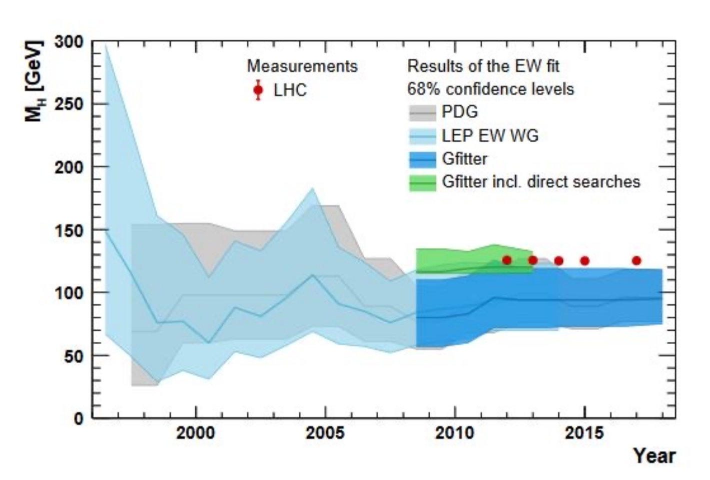
example: $Z^0 \rightarrow e\ e^{+-} = f(m_H)$:

BASIC ORDER

HIGHER ORDER



+ OTHER VARIABLES



J. Haller et al., Eur. Phys. J. C78, 675 (2018)

What is "very" precise ?

CP symetry

- CP Symmetry operation: converts a particle to an anti-particle

- If a particle and an antiparticle do not always behave in the same way
  - e.g. if they decay differently - this is a violation of CP symmetry.

- At the time of the universe creation : equal number of particles and anti-particles,
- Today : composed almost exclusively of matter (=particles), not anti-matter,
  - This symmetry is clearly broken!

Very important: to understand how and why this symmetry is broken.

How to measure CP violation in B mesons?

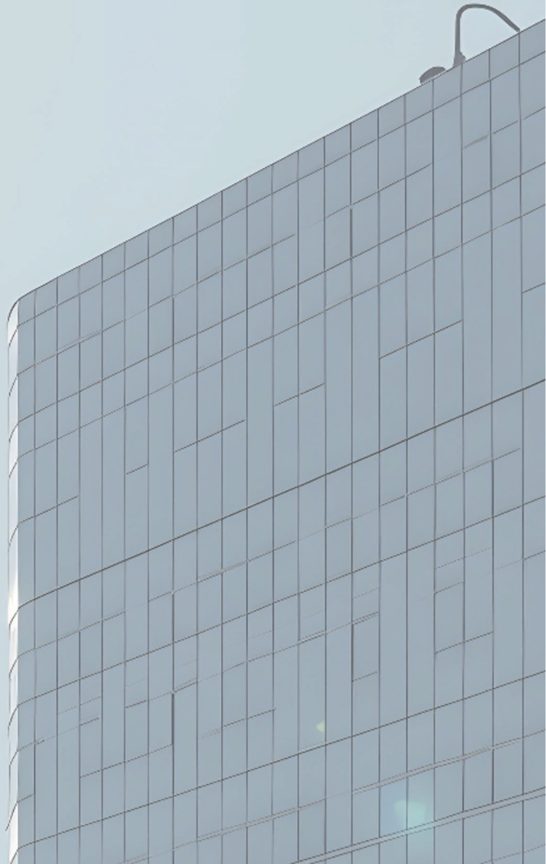
- B^0: quark d + anti quark b
- First, we need to create them: we use a collision reaction between an electron and a positron with a sufficiently high energy:

$$e^+e^- \rightarrow B^0\overline{B^0}$$

- Then we choose a suitable decay type: $B^0 \rightarrow J/\Psi\, K_S$,
- The decay products further decay to

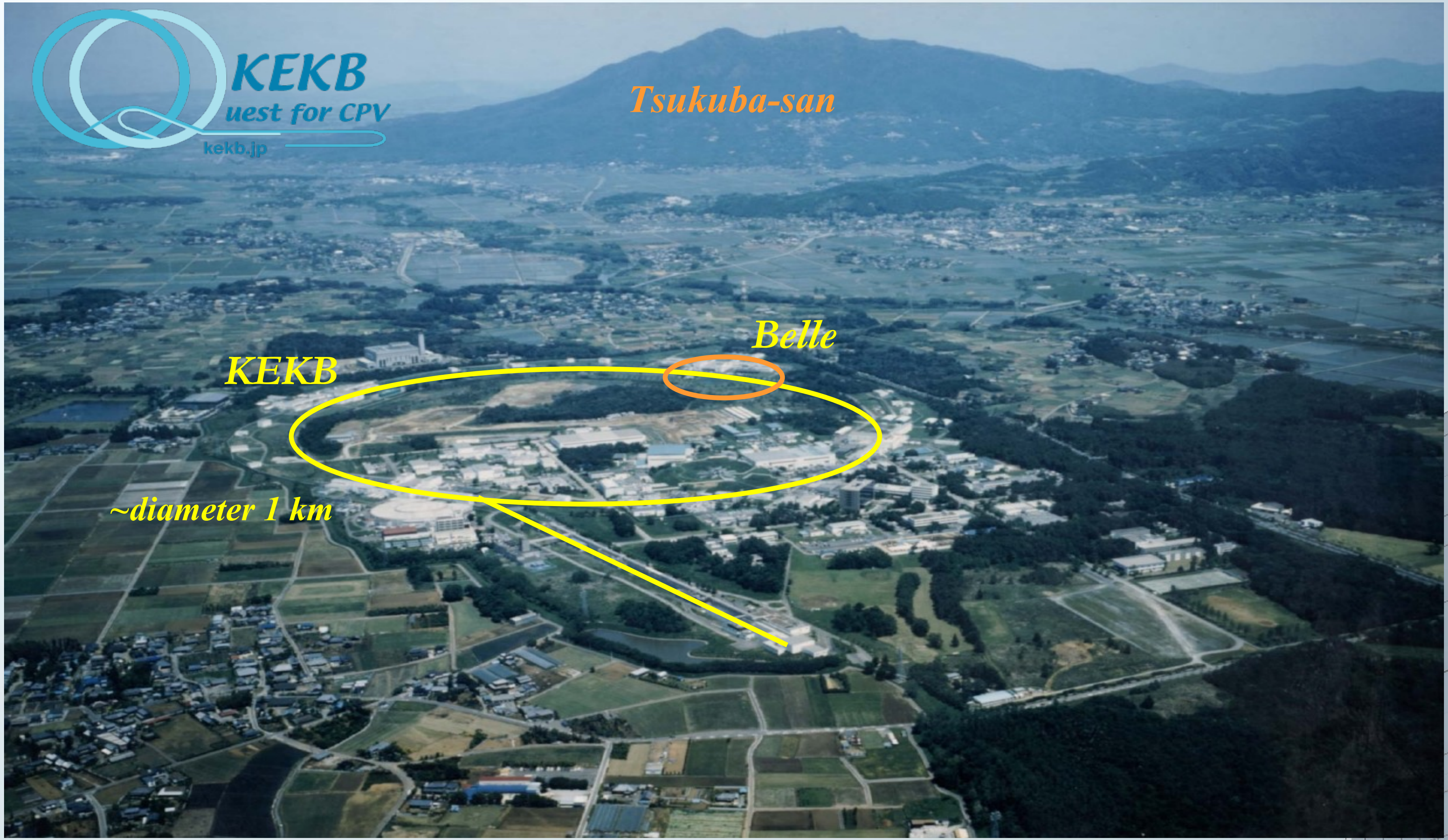
$$J/\Psi \rightarrow \mu^-\mu^+$$
$$K_S \rightarrow \pi^-\pi^+$$

- We need to measure where this happened and determine whether B^0 or its anti-particle $\overline{B^0}$ decayed to the final state $J/\Psi\, K_S$.

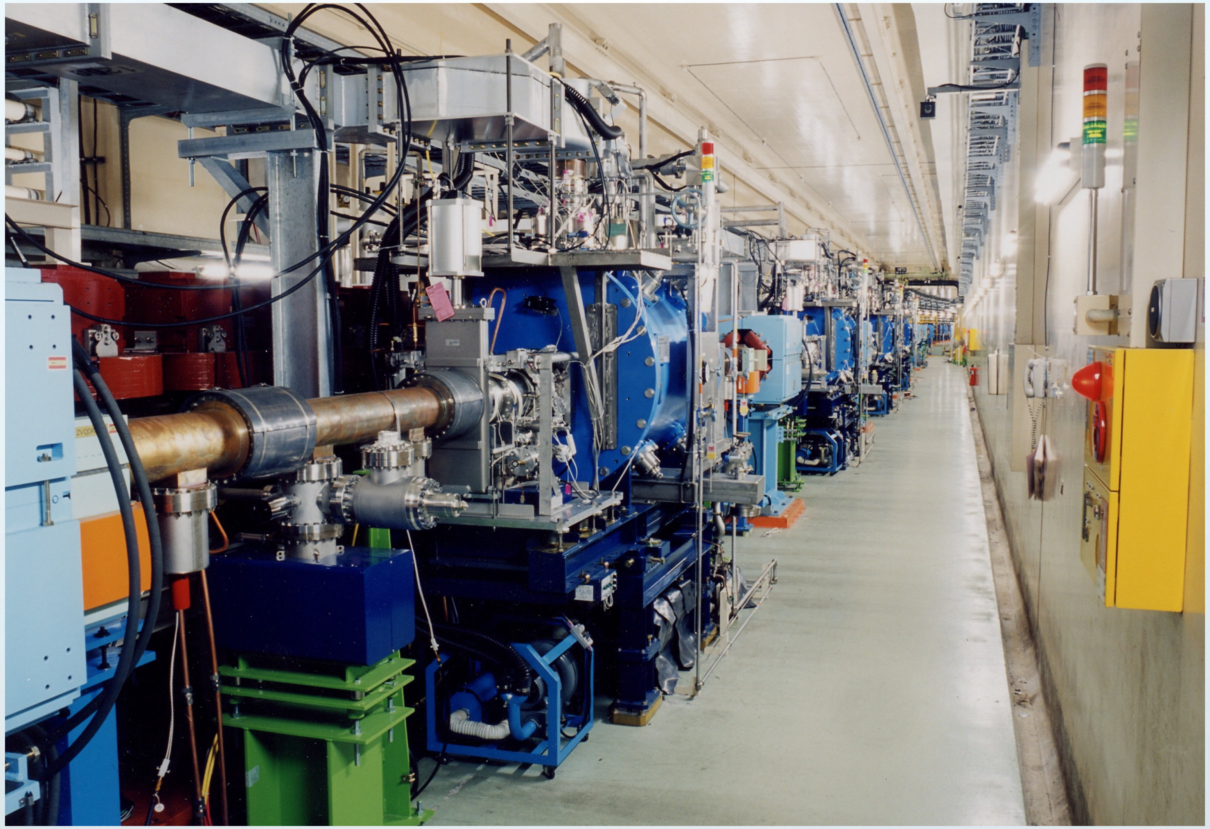


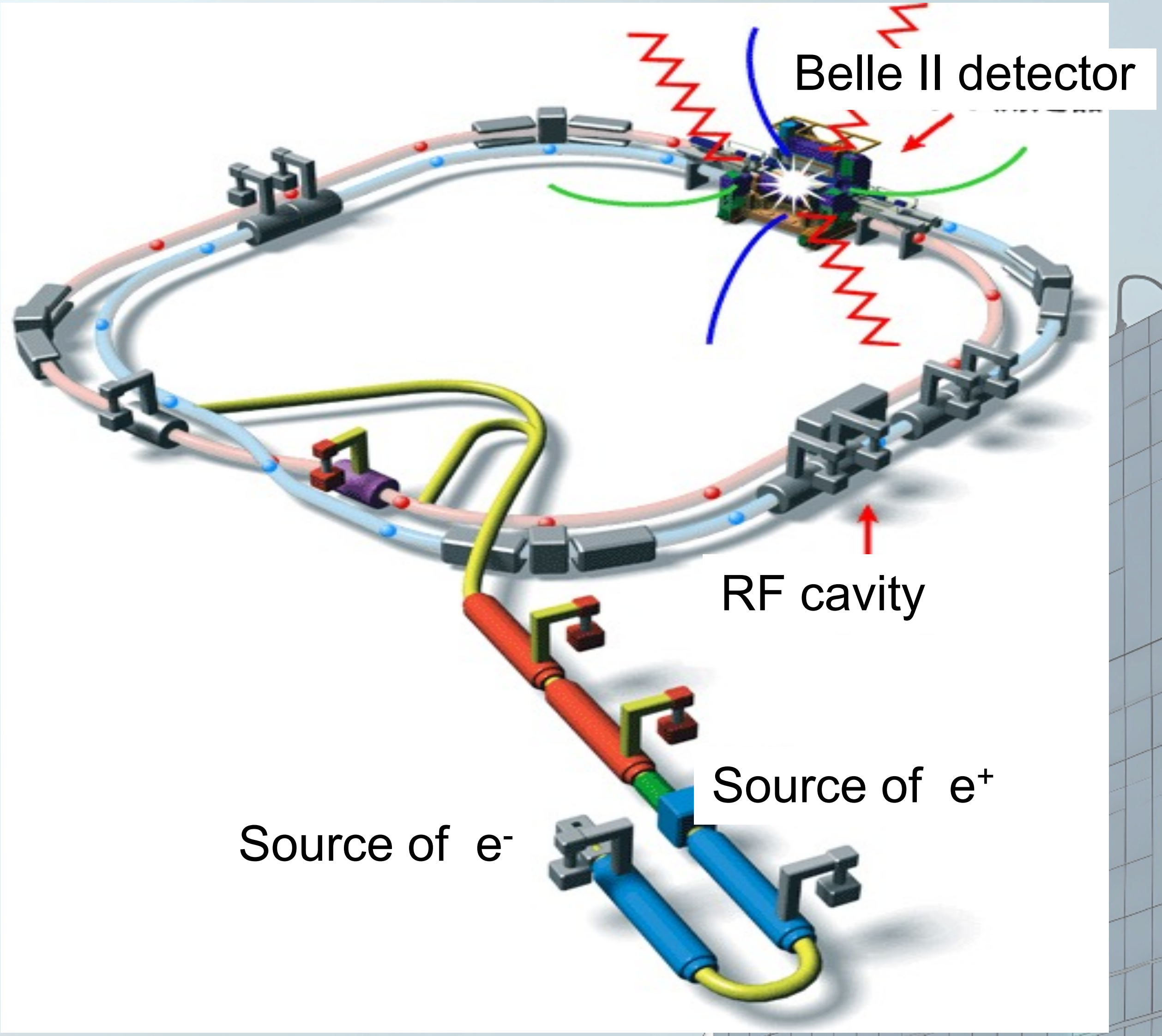
KEK–B accelerator and Belle II in Tsukuba

- 400 researchers from 14 states; 12 from Slovenia



Accelerator KEK-B accelerates electrons and positron until its collision

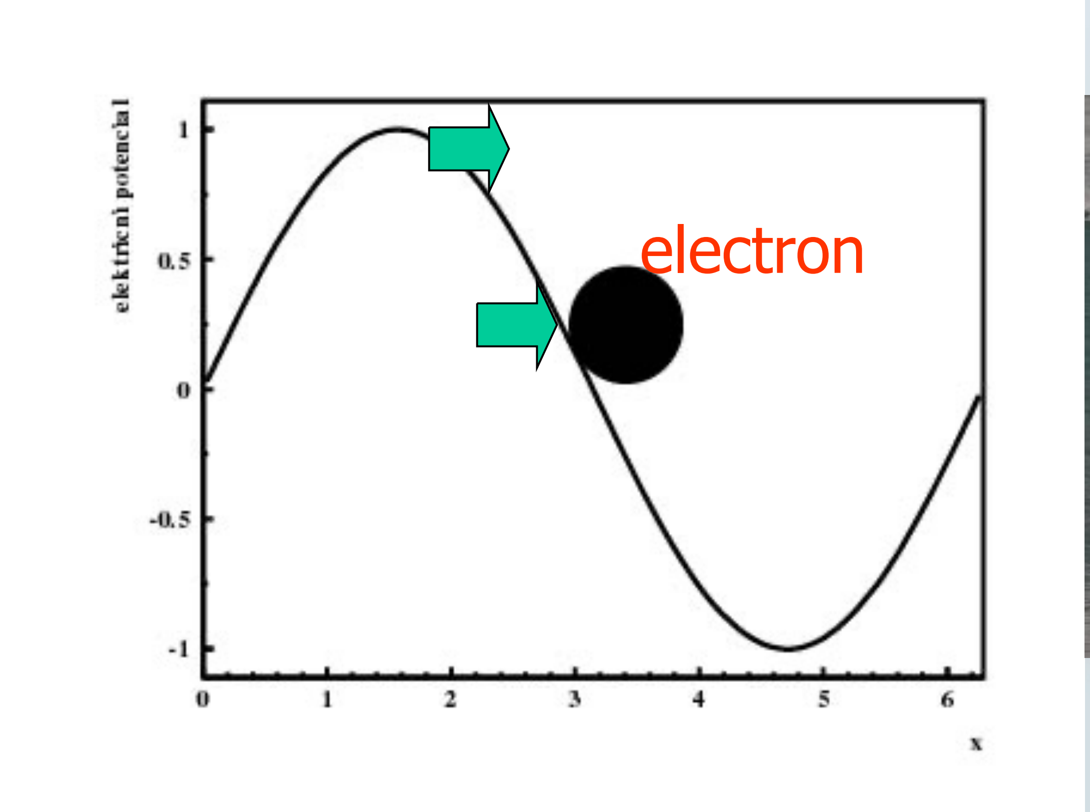




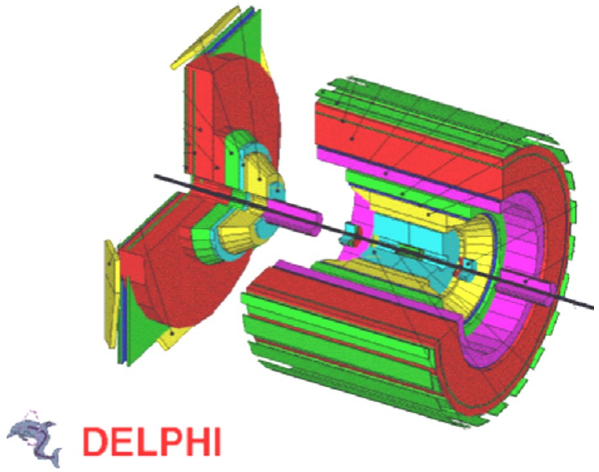
How do we accelerate charged particles?

By electromagnetic waves

- typical frequency 500 MHz
- for comparison: mobile phones 900 and 1800 MHz respectively



... Similar to wavesurfing



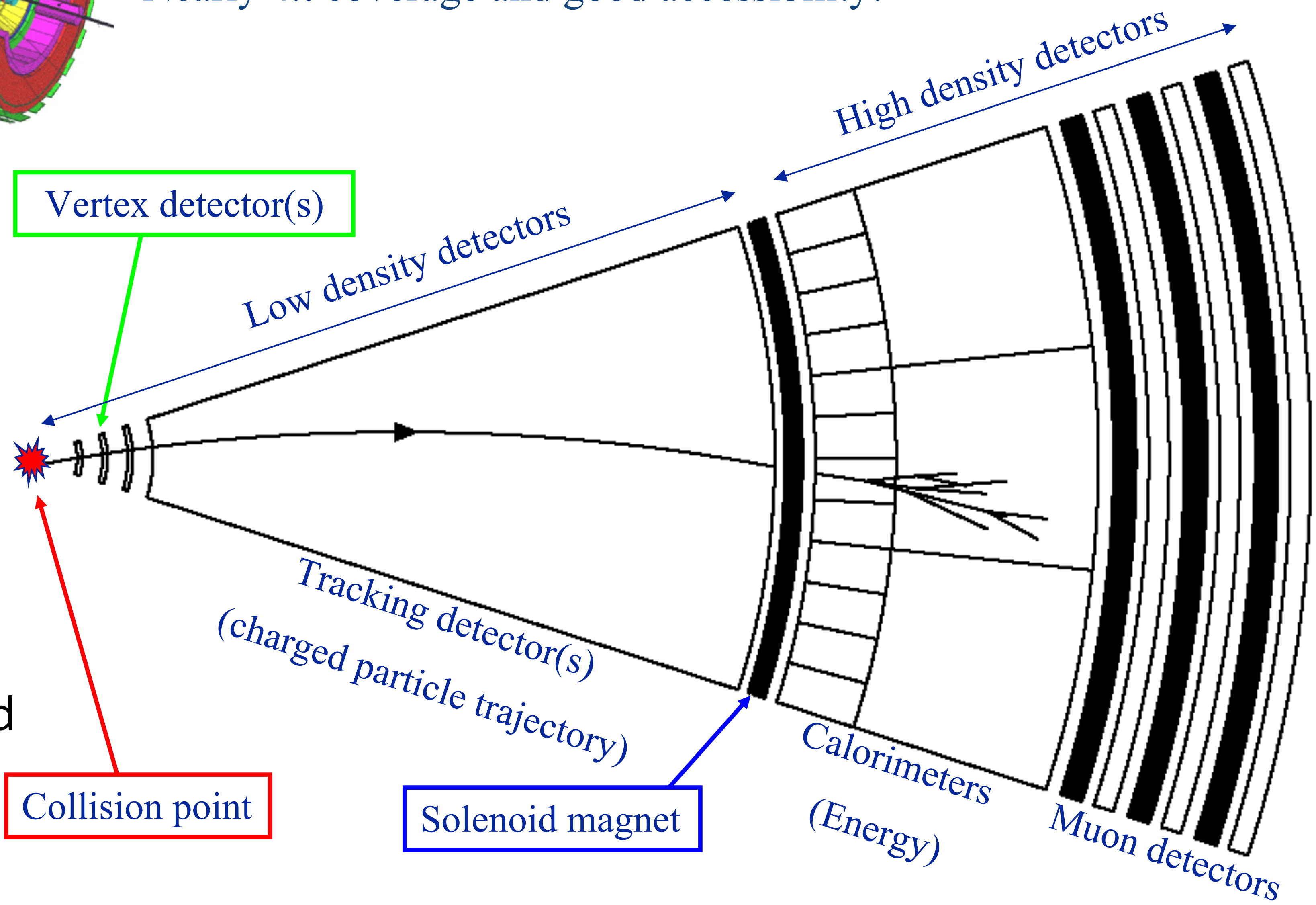
Global detector layout:

• barrel-shape surrounding beam-pipe
• 2 cone- or wheel-shaped end-caps
Nearly 4π coverage and good accessibility!

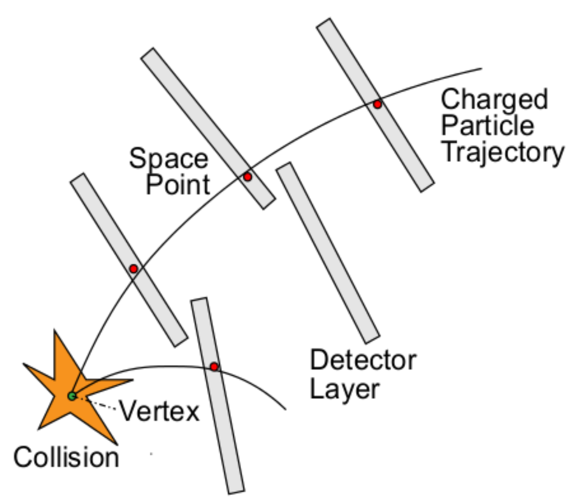
Measure

- Direction
- Energy
- Charge
- Particle identity
- Lifetime

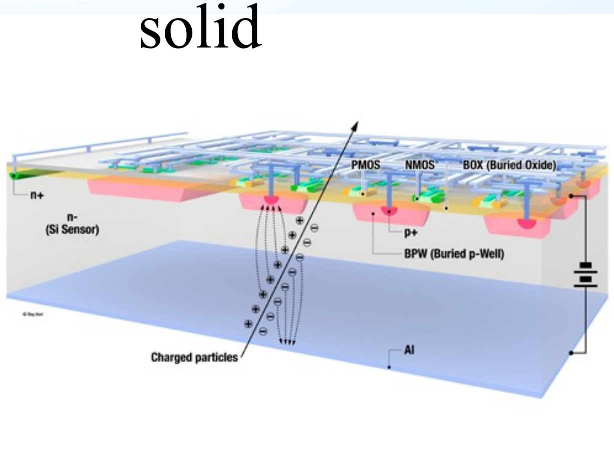
Of all particles produced in an interaction



How do we measure what we can't see?



solid

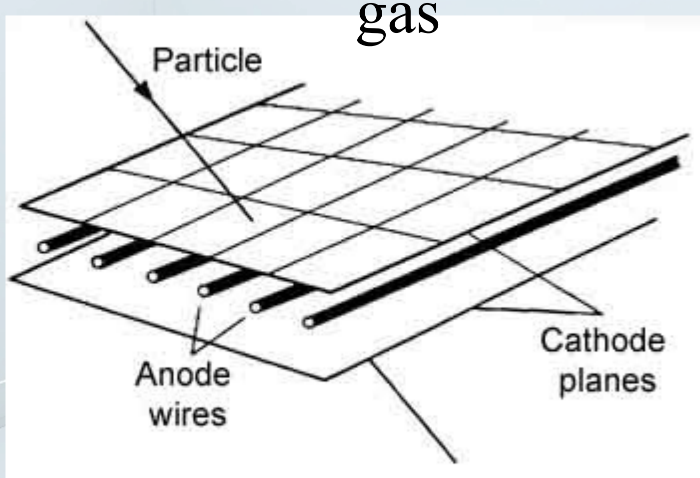


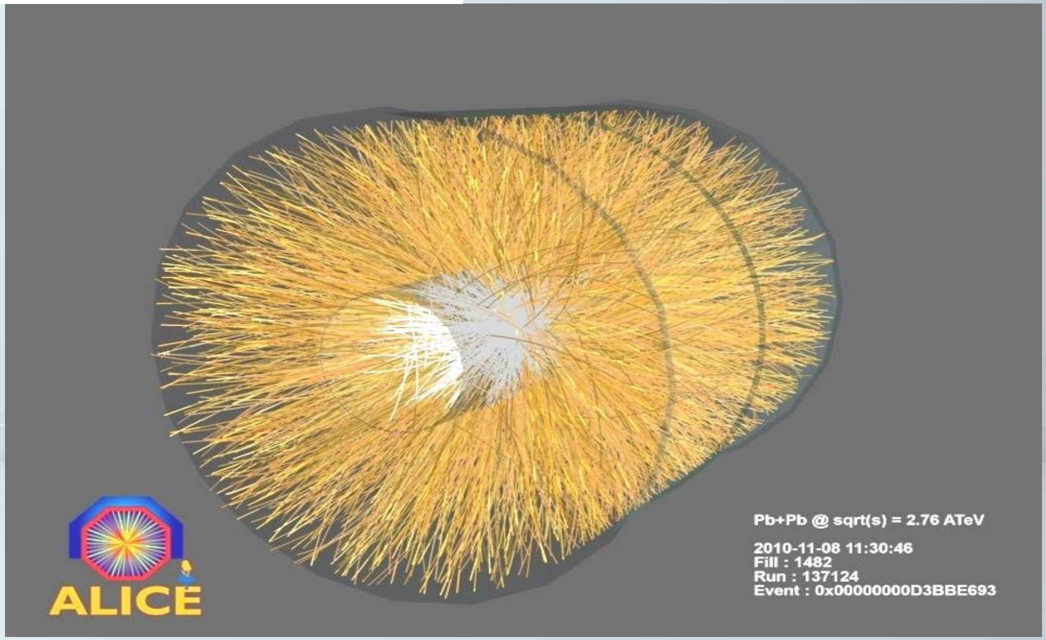
From the track curvature in the magnetic field, we determine the momentum p

$p = m\,v\,\gamma$

$p = e\,B\,R$

gas

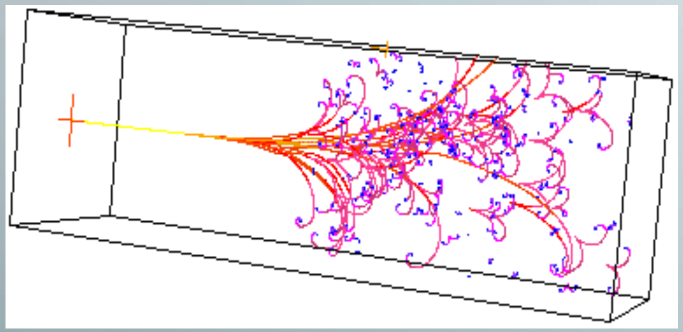


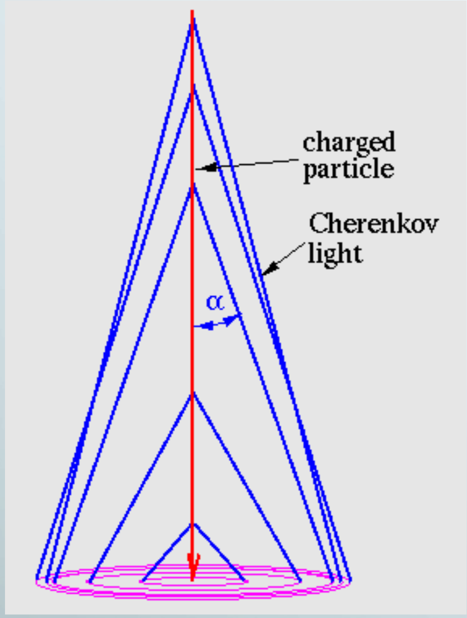


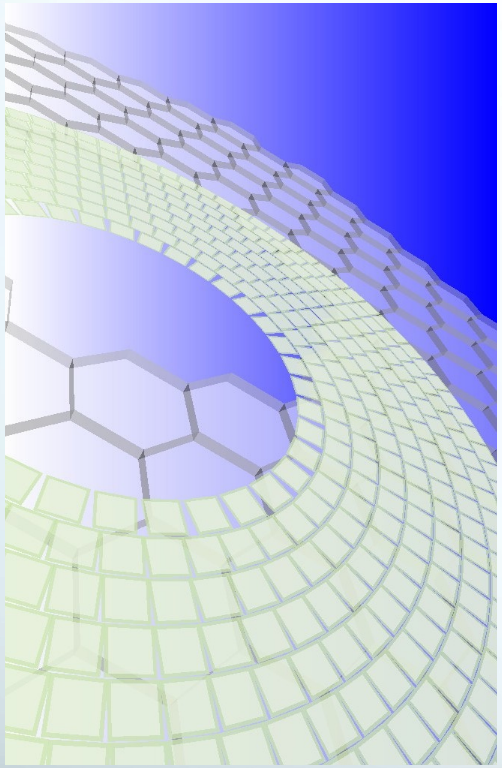
Particle identification

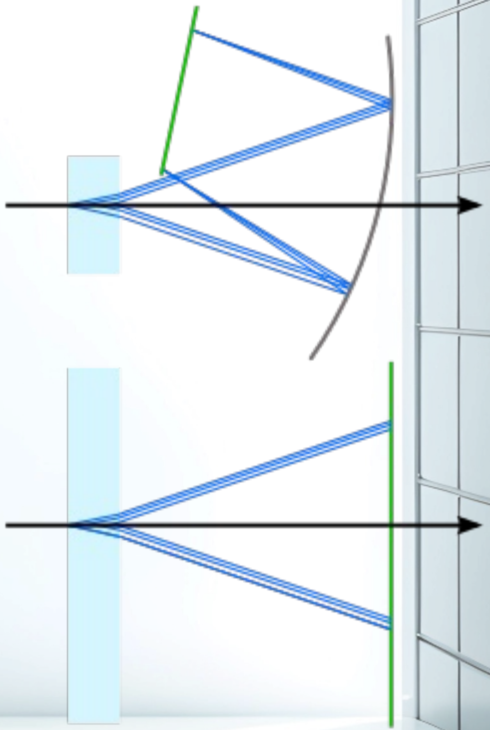
Given a known particle's momentum, we need to measure its mass = identity

- Cherenkov detectors
- Calorimeters
- Muon detectors
- ...

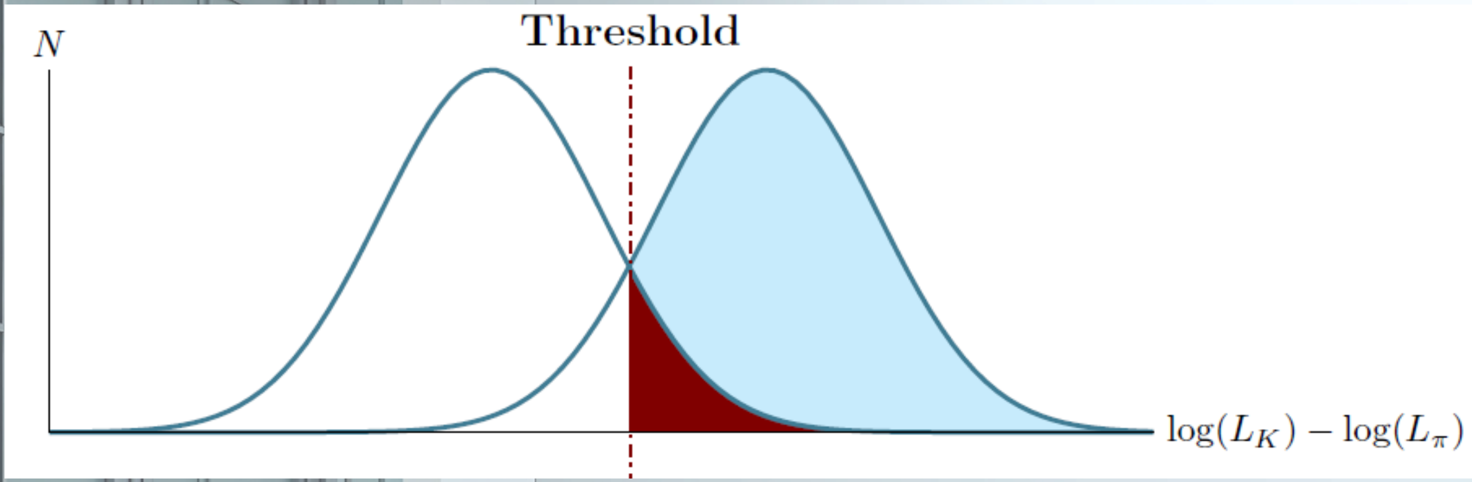


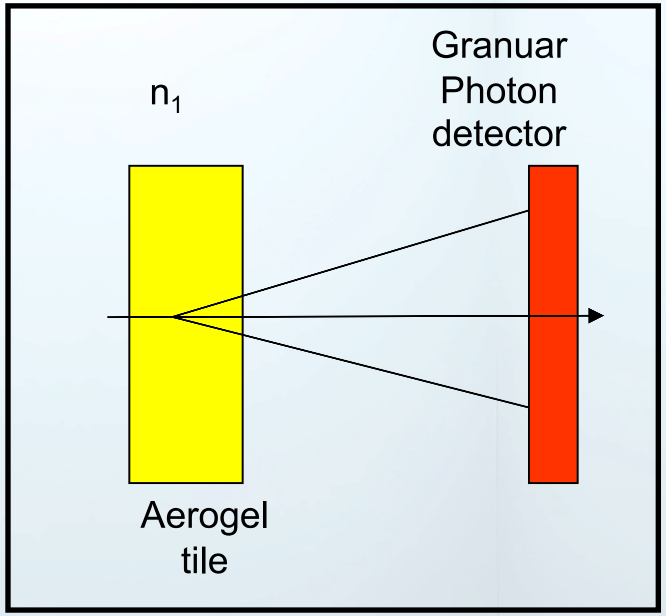


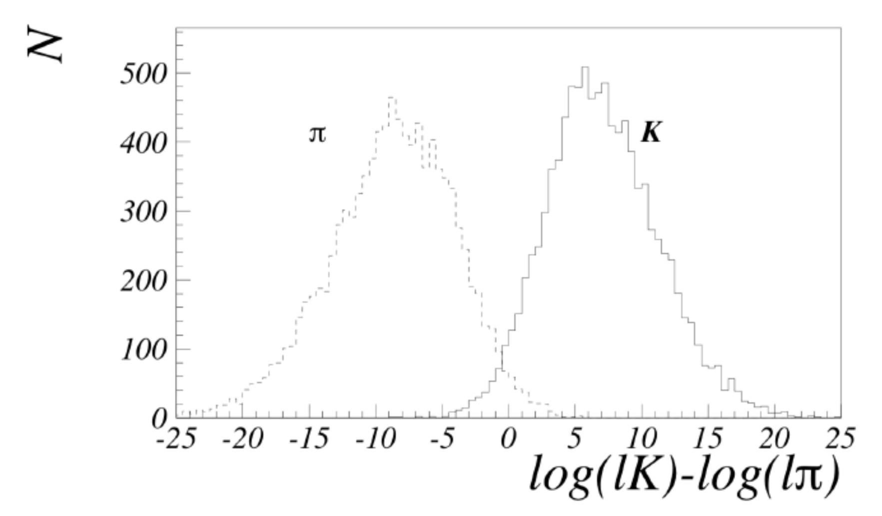




Particle identification







- For each particle hypothesis (e,mu,pi,K,p) evaluate a likelihood function
- Determine threshold based on the sample of independently identified particles
- Determine the identity
- How do we construct the likelihood function?

Likelihood construction (example of Belle II ARICH)

Small number of tracks, overlap of rings from different particles not very likely

p_i – probability that a a pixel i was hit distributed binomially
n_i - expected i.e. calculated average number of hits on the particular pixel
m_i – measured number of photons in the particular pixel

$$p_i = \frac{e^{-n_i} {n_i}^{m_i}}{m_i!} \qquad p_i = \begin{cases} e^{-n_i} & \text{for } m_i = 0 \text{ non hit pixels,} \\ 1 - e^{-n_i} & \text{for } m_i > 0 \text{ hit pixels.} \end{cases}$$

$$L = \prod_{\text{all pixels}} p_i = \prod_{\text{not hit i}} p_i \prod_{\text{hit i}} p_i = \prod_{\text{not hit i}} e^{-n_i} \prod_{\text{hit } i} (e^{n_i} - 1)$$

$$lnL = -\sum_{\text{not hit i}} n_i - \sum_{\text{hit i}} n_i + \sum_{\text{hit i}} n_i + \sum_{\text{hit } i} ln\,(e^{n_i} - 1)$$

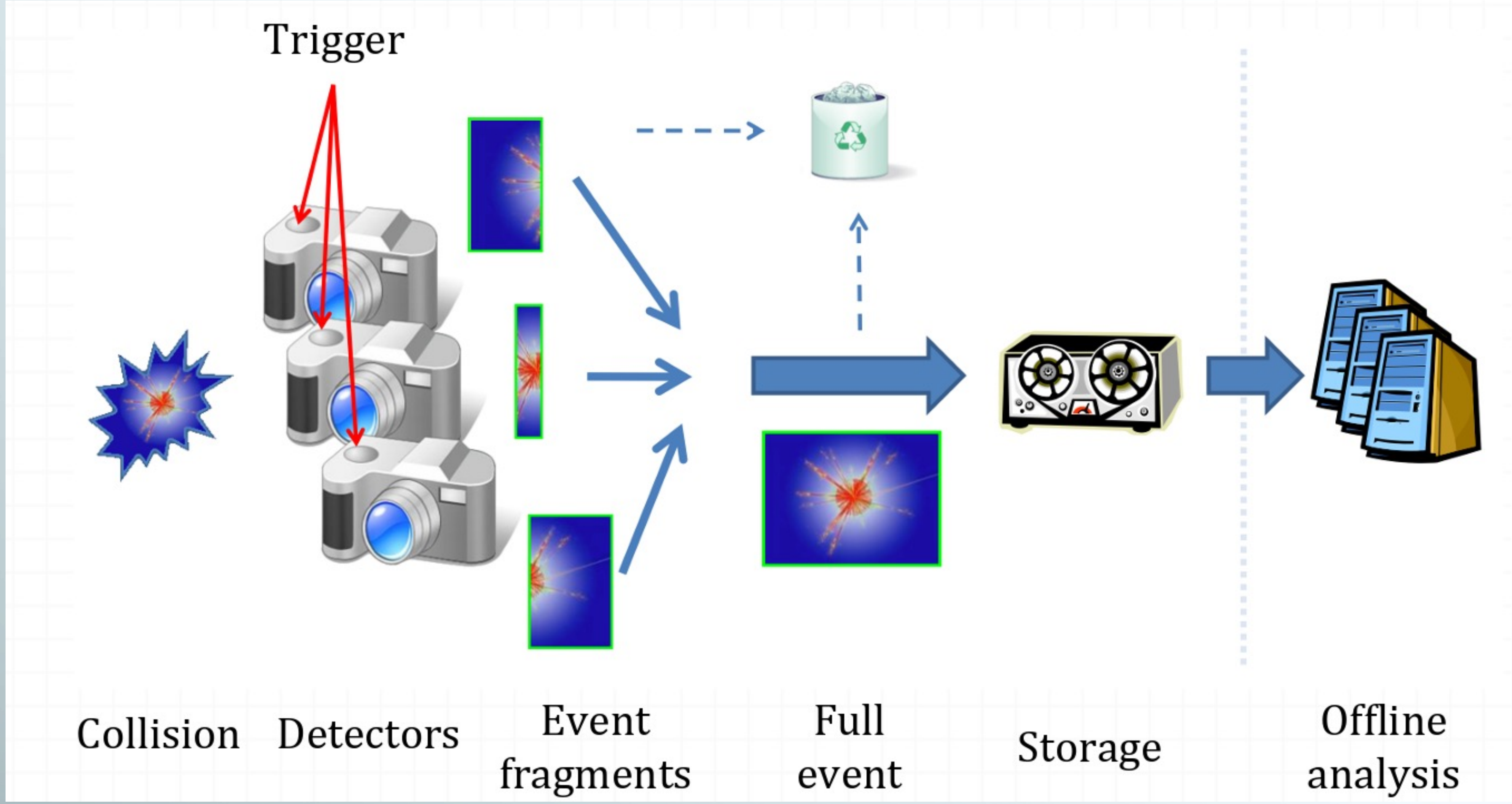
For a given hypothesis:
N number of expected hits = sum of expected average number of hits on the detector

$$lnL = -N + \sum_{\text{hit } i} n_i + ln\,(e^{n_i} - 1)$$

Data path

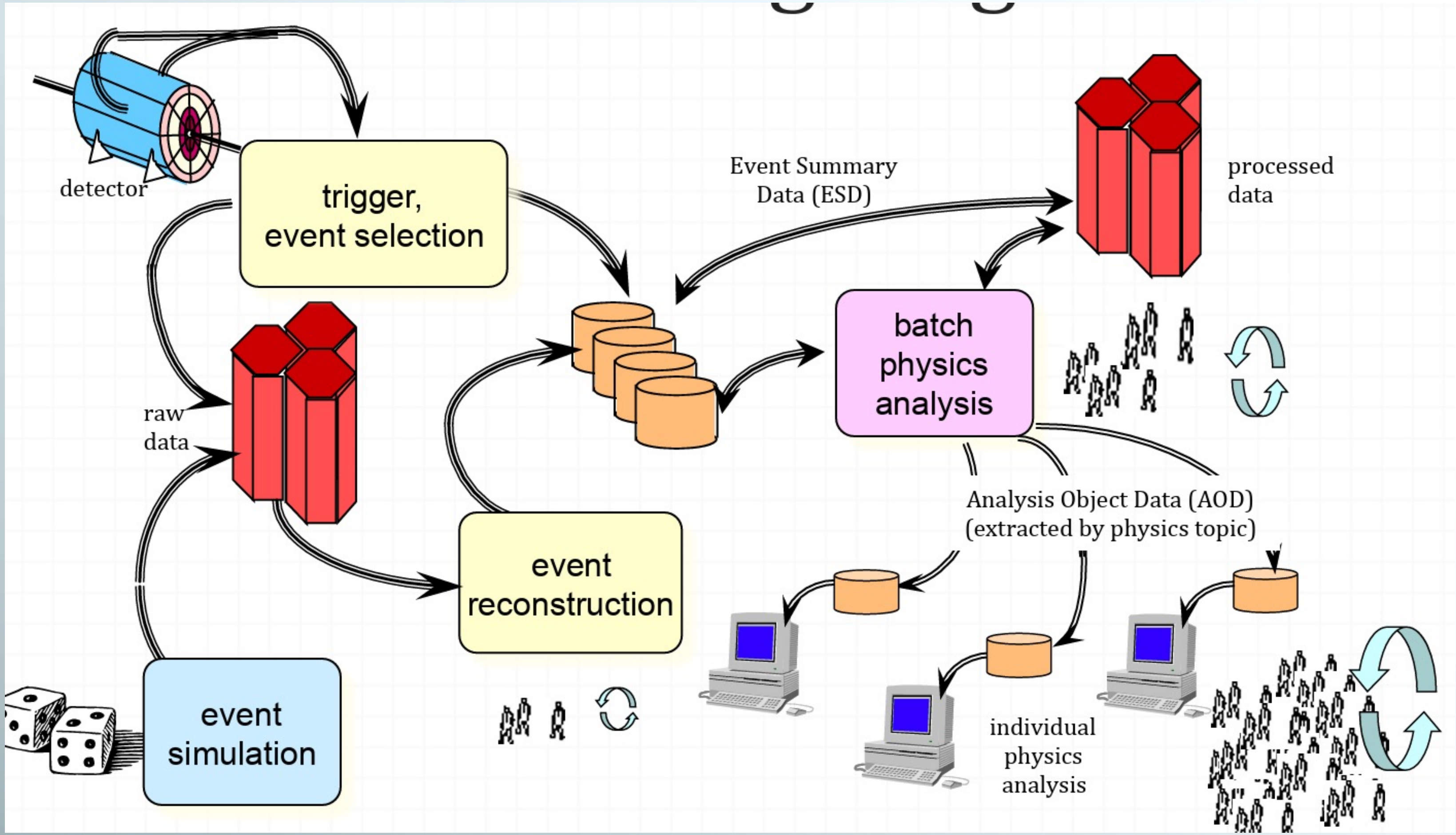
From the hits in the detector particle properties have to be reconstructed

- Direction
- Energy
- Charge
- Particle identity
- Lifetime



For each of the events for all particles produced in an interaction

Data processing

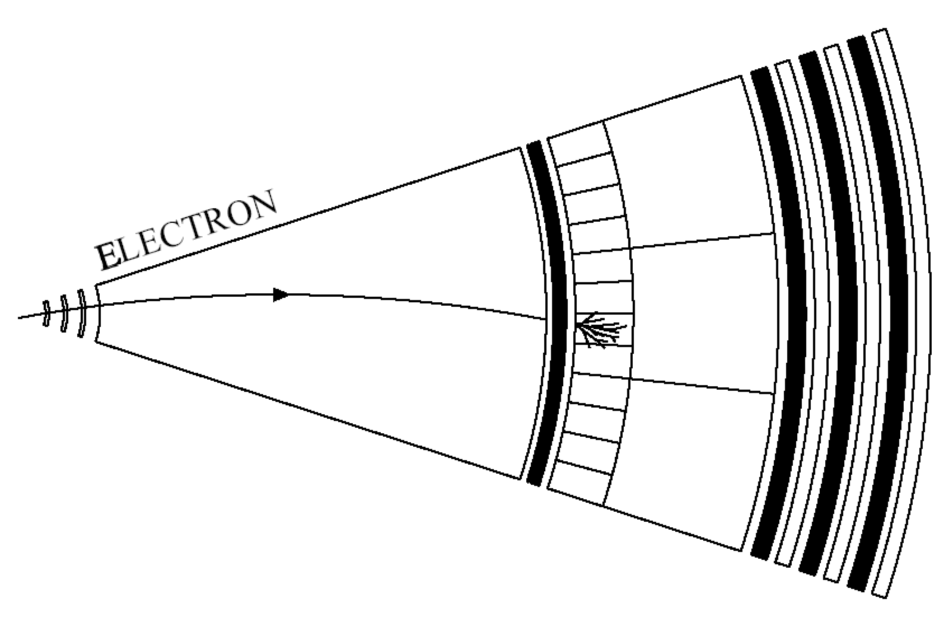


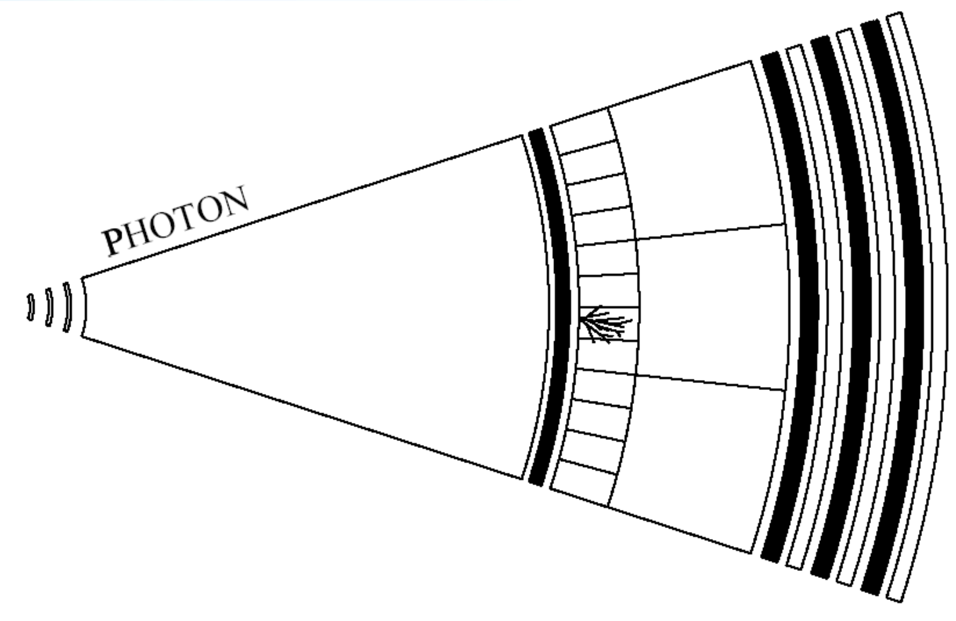
Analysis and role of simulation

- Comparison of measured and expected response
- Expected response: Simulation

- Simulation = doing ‘virtual’ experiment
- take all the known physics
- start from your ‘initial condition’ (two protons colliding)
- calculate the ‘final state’ of your detector to get the ‘experimental’ results
    - solve equations of motion, etc
    - IMPOSSIBLE to be done analytically

Particle signatures





Electrons:

- leave a bent track
- stopped in first layer of calorimeter

(Calorimeter and tracking information)

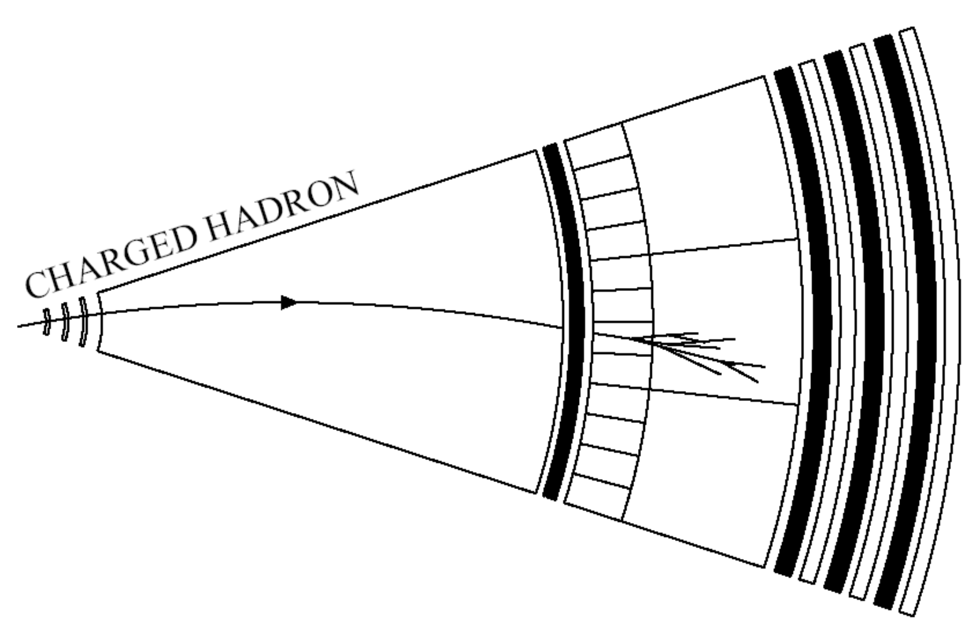
Photons:

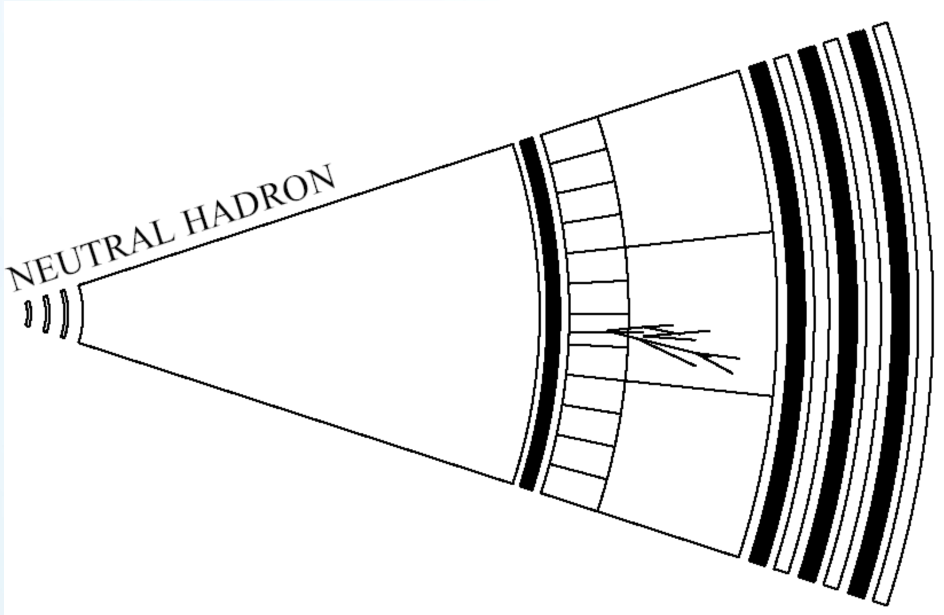
- no track
- stopped in first layer calorimeter

(Only calorimeter information!)

First layer of calorimeter: "*Electro-magnetic calorimeter*"

Particle signatures





Charged hadrons:

- leave a bent track
- stopped deep in calorimeter

(Calorimeter and tracking information)

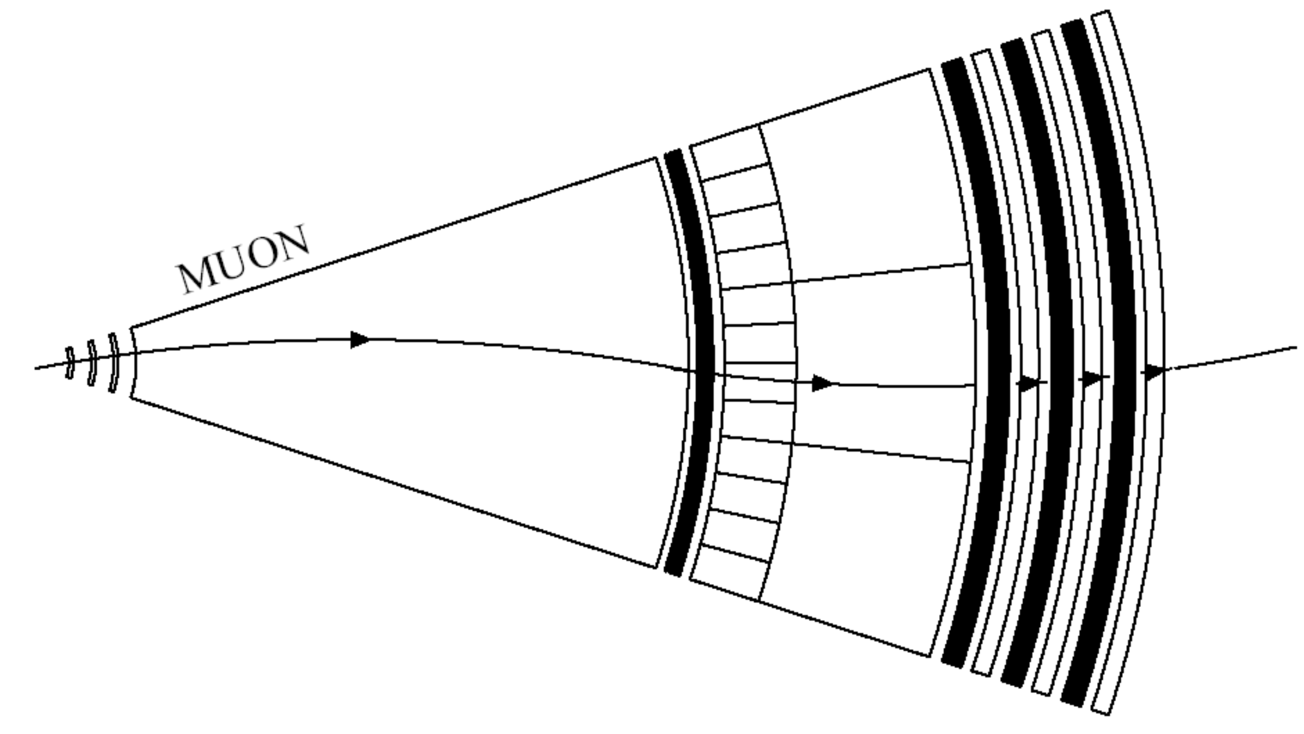
Neutral hadrons:

- no track
- stopped deep in calorimeter

(Only calorimeter information!)

Second (+) layers of calorimeter: "*Hadron calorimeter*"

Particle signatures



Muons:

- leave a bent track
- not stopped in calorimeter
- track in muon detectors

(Calorimeter, tracking and muon-detector information)

The ideal detector

An apparatus that provides (for all types of particles):

- good particle identification
- precise measurement of energy/momentum
- precise measurement of trajectory (direction/origin)
- coverage of the full (4π) angular region

In addition (in some cases) it should be able to:

- take data at a high rate
- cope with a high particle densities
- survive high radiation doses
- survive 10+ years of operation (with little/no intervention)

A real detector will always be a compromise between the various requirements, existing technology and the availability of money, space, time etc…

Particle detection techniques: the physics

Detect/measure properties particles through their interaction with matter:

- Ionisation of atomic electrons
- Bremsstrahlung and photon conversions
- Inelastic nuclear interactions
- Cherenkov or transition radiation
- Emission of scintillation or fluorescence light

How can we “visualise” these processes?

- Photographic techniques
- By collection of induced charge (from ionisation)
- By detection of photons

Basic detection techniques: Electrical

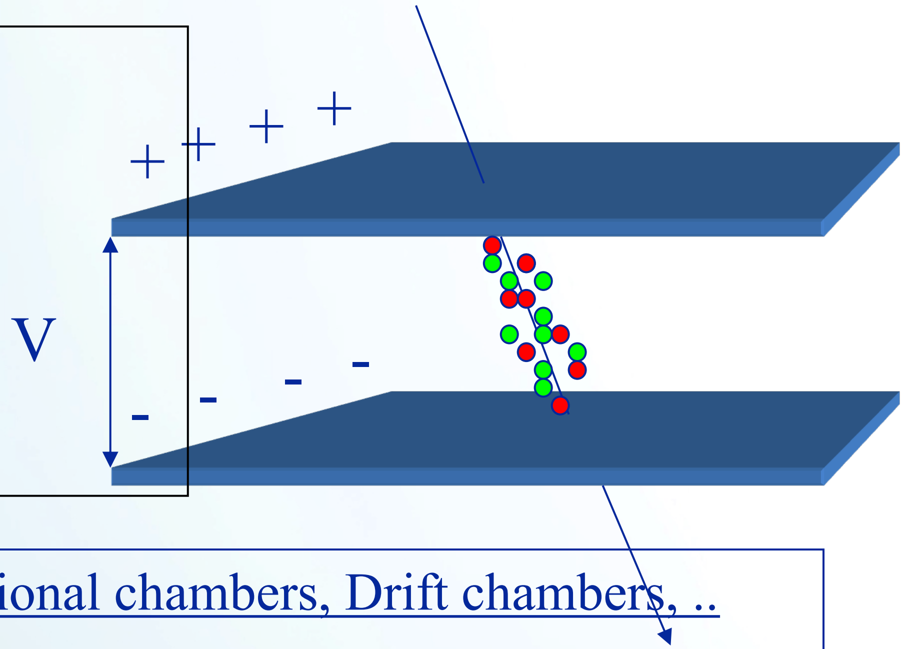
We can also electrically collect the charge produced by the ionisation

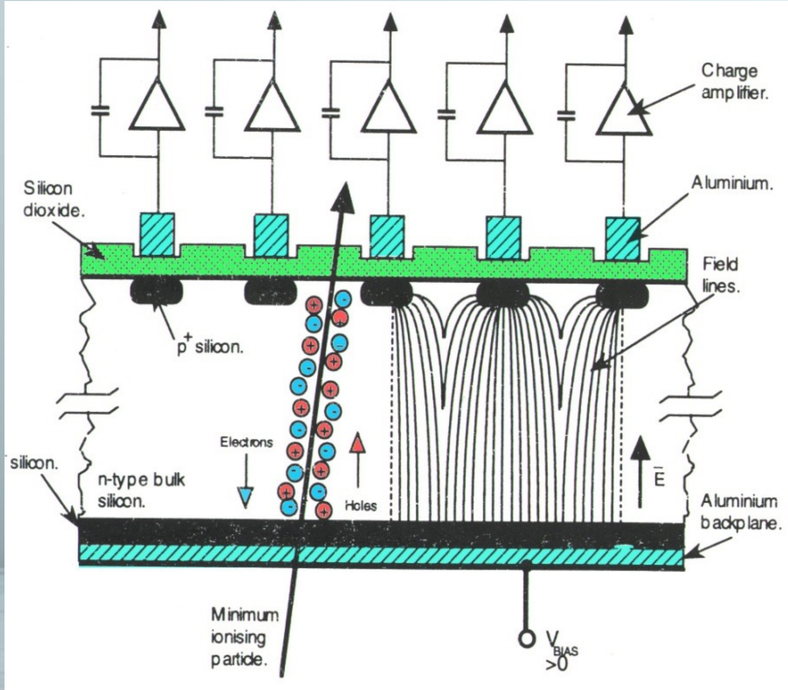
Particle causes ionisation in a material.

Charge is separated/collected by an electric field.

Requirement on material:

- no/few free charge carriers (non-conducting)
- mechanism for transport of charge





Proportional chambers, Drift chambers, ..

Insulating gas/liquid between anode and cathode (transport through drift). Sometimes combined with very low conductivity solids.

Silicon strip detectors, CCDs, ..

Using a semi-conducting material: Mostly in the form of a reverse-biased pn-junction diode.

Basic detection techniques: Photo-detection

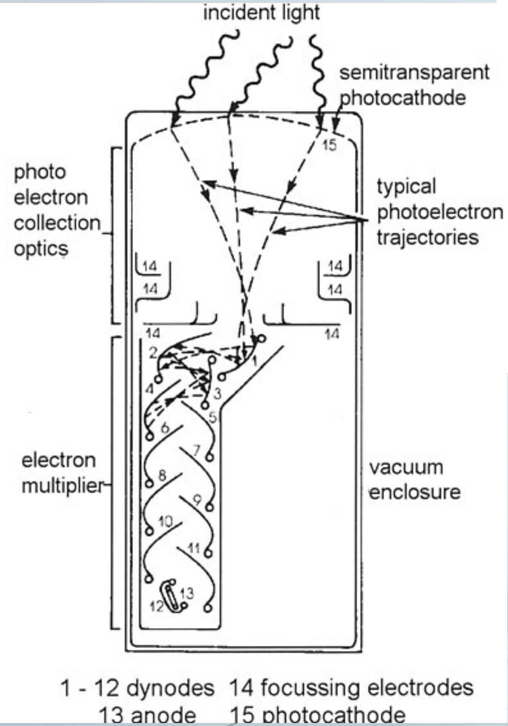
Charged particles can produce photons via scintillation, Cherenkov or transition-radiation etc. To detect these:

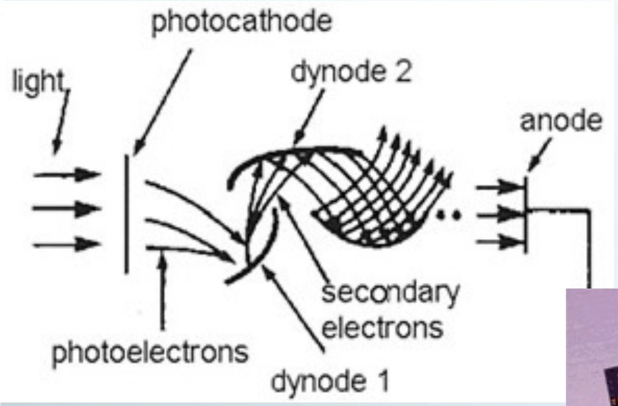
Photo-Multiplier Tube (PMT):

Electrons from photo-electric effect

"Electron multiplier" provides charge cascade

Very sensitive, but also bulky and expensive.



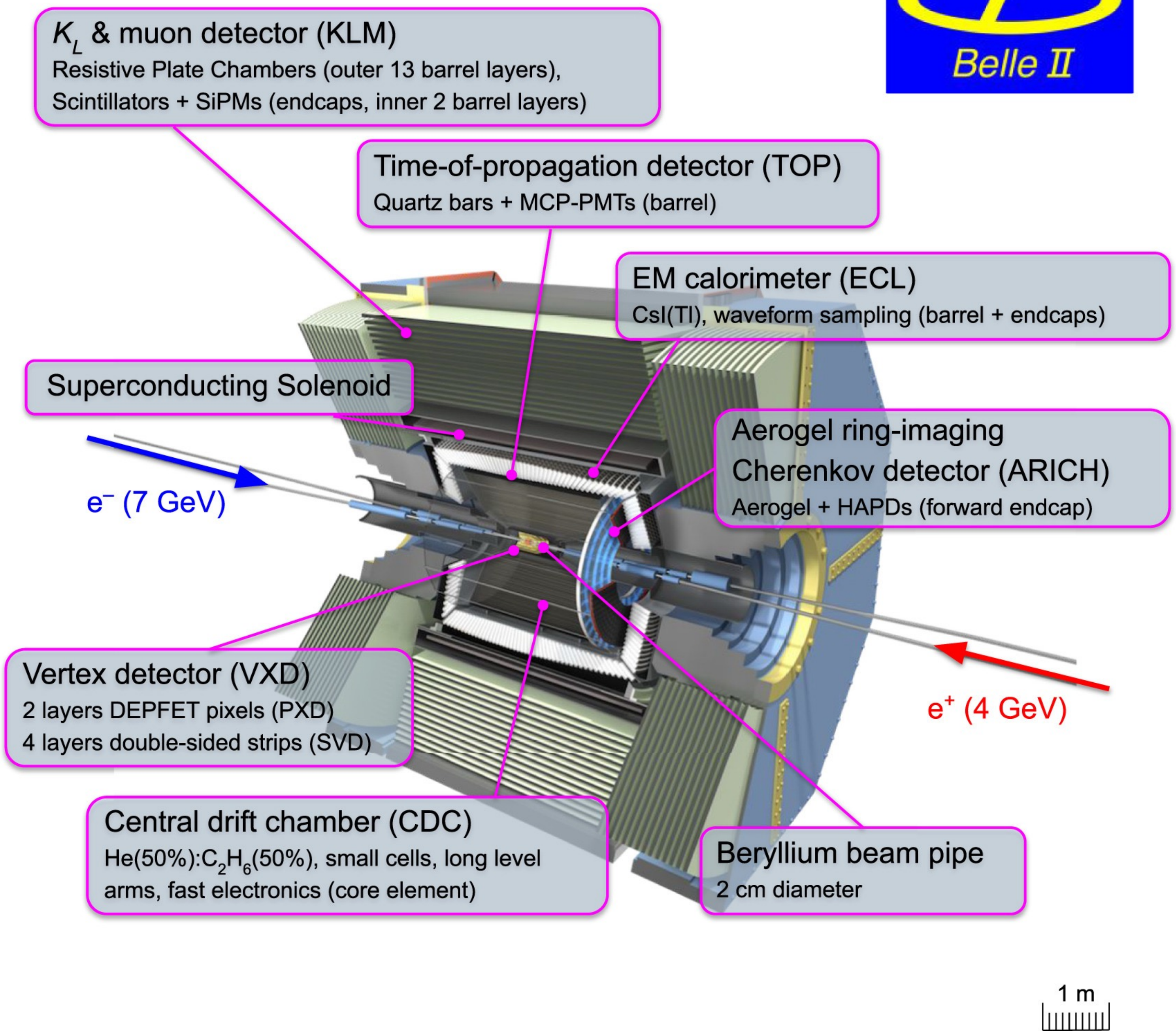


Hamamatsu

Semi-conductor devices:

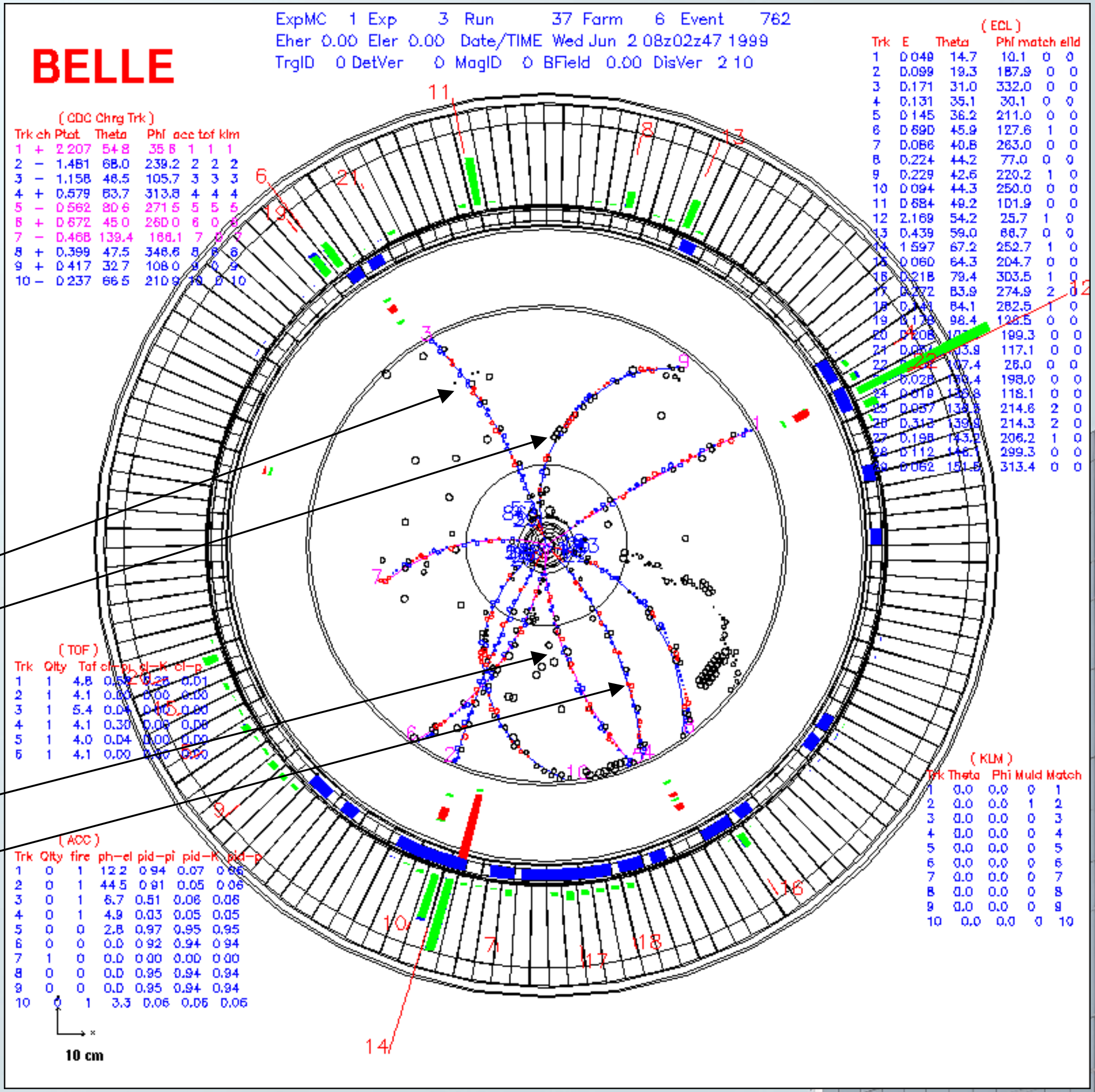
Photo-diodes or CCD's

Spectrometer Belle II



What do we measure with the detector?

- tracks of charged particles in a magnetic field
- the coordinates of the point from which the traces originate
- the type of particle



- $B^0 \to J/\Psi\ K_S$,

  $J/\Psi \to \mu^- \mu^+$

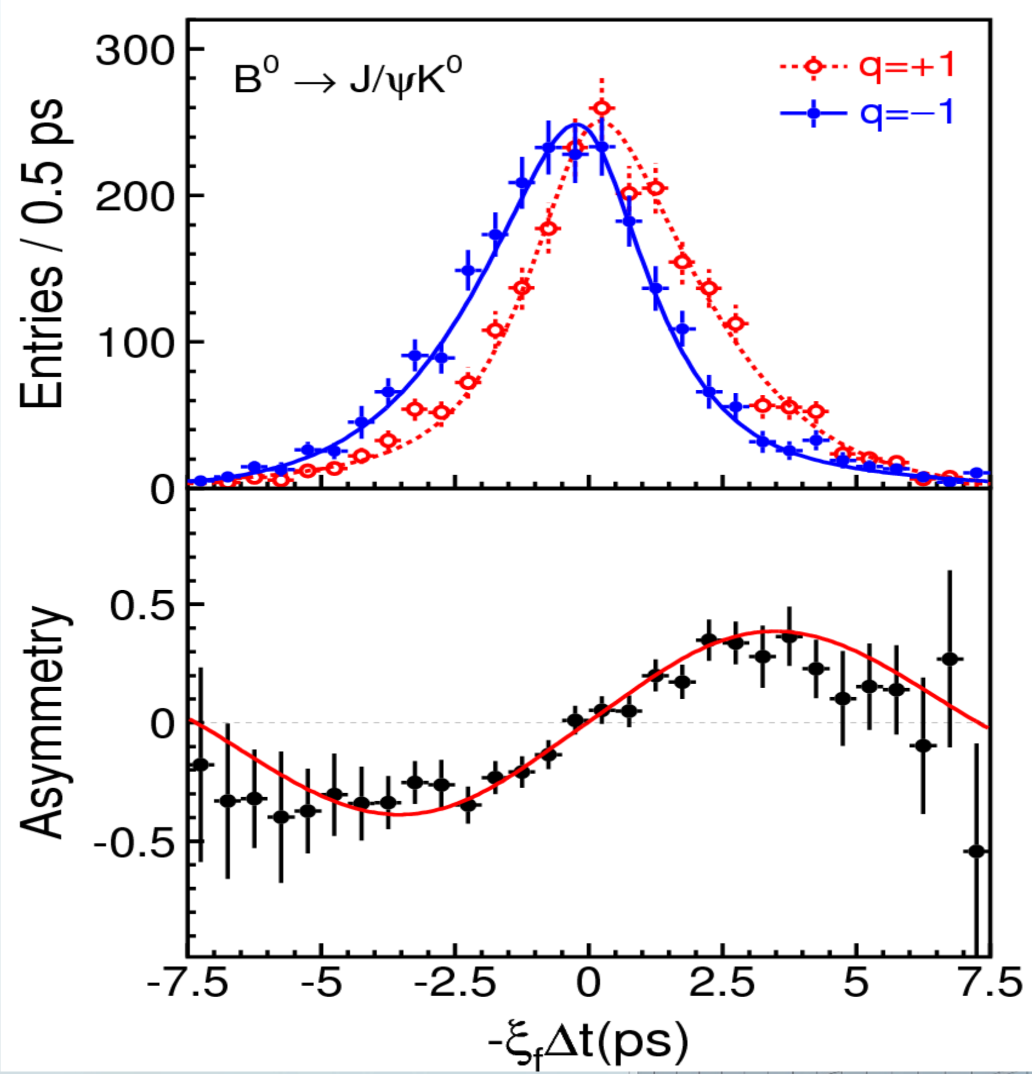
  $K_S \to \pi^- \pi^+$

Measurement result: CP symmetry broken!

The Difference between particles and antiparticles:

- Blue: time course of anti-B decay
- Red: same for B

The relative difference between between the two distributions

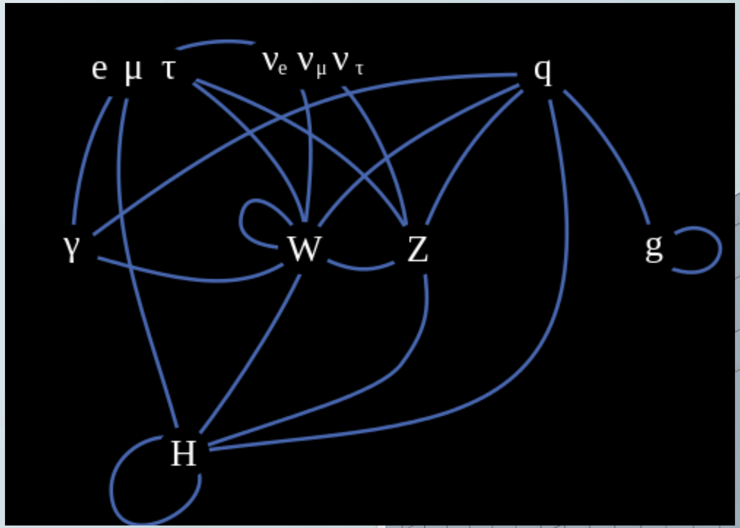


Origin of mass in the Standard Model

The Standard Model is a very rigorously tested theory.

The long missing particle predicted by the Standard Model:

- The Higgs boson



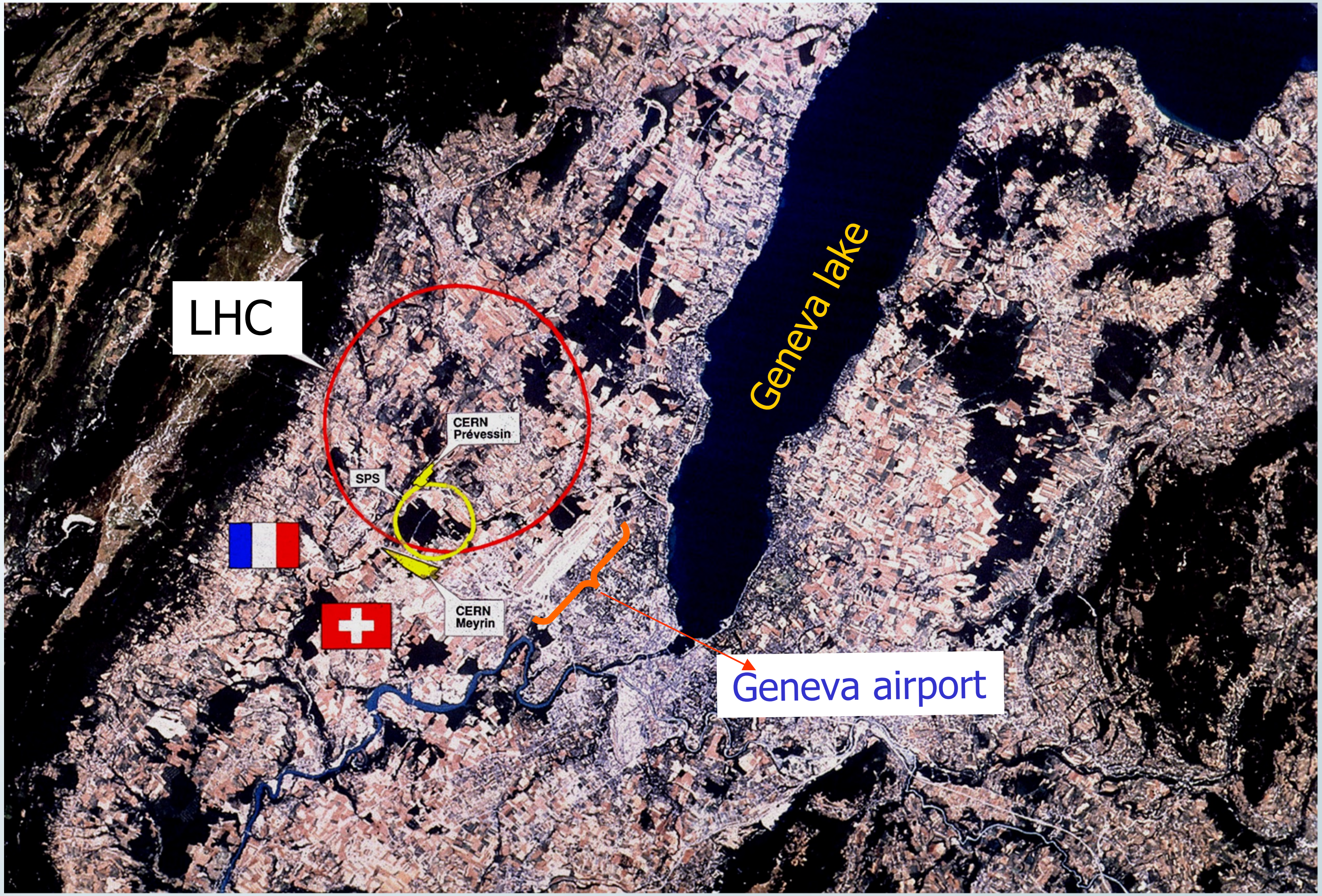
The Higgs boson is responsible for the mass of particles:

- The mass of a particle depends on how strongly it is coupled to the Higgs.

- Very massive: $m_{Higgs} > 120\ m_p$

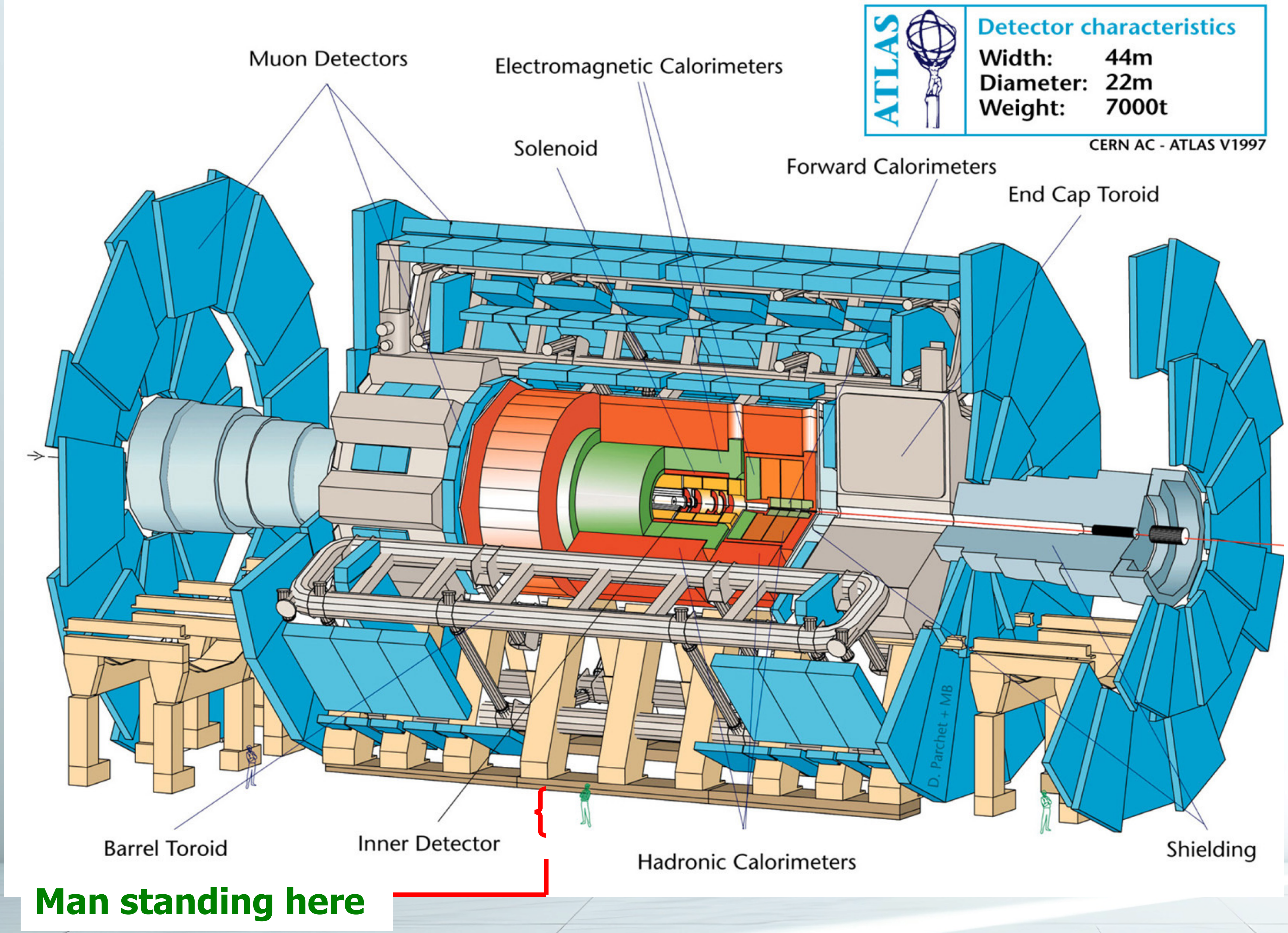
CERN and Large Hadron Collider / LHC

- the largest experimental facility on Earth



ATLAS at LHC

~3000 researchers
15 from Slovenia



Discovery of the Higgs boson

LHC started operating in 2009

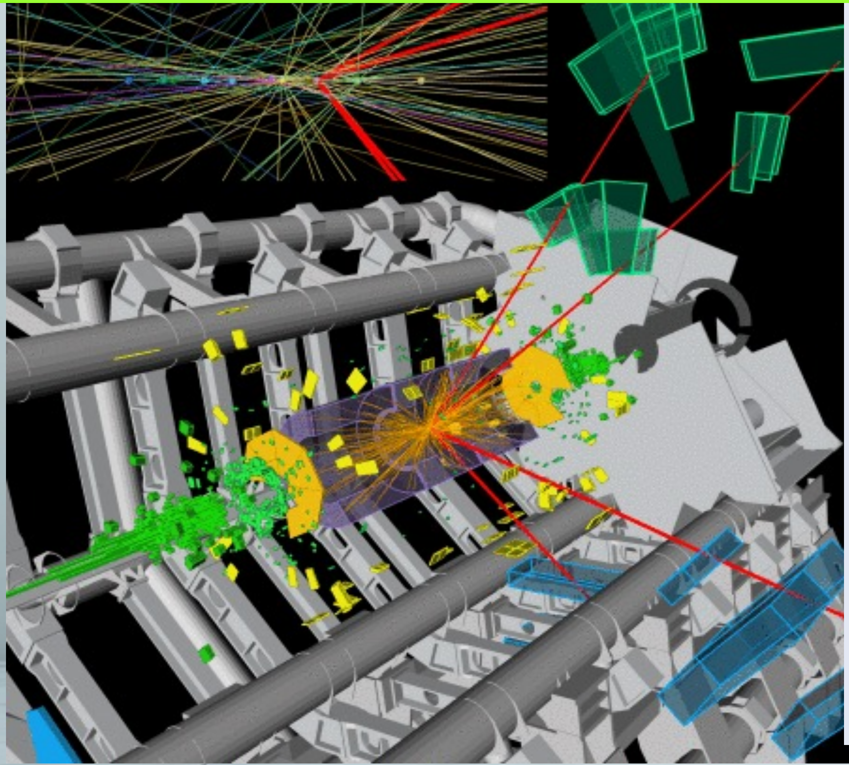
2012 Both major scientific groups (ATLAS, CMS) :

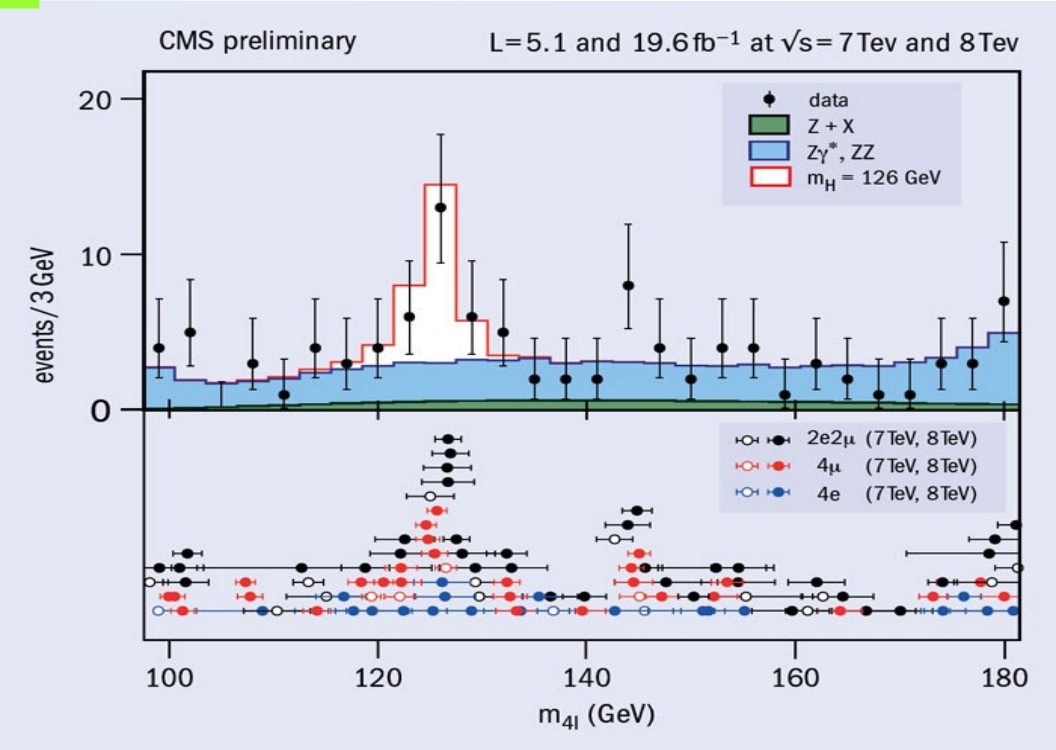
a particle with a mass of 126 GeV/c2 was observed with a probability of 5σ

2013 Nobel Prize: François Englert and Peter W. Higgs

2018 H decay into a pair of b and anti-b quarks observed

Decay of Higgs boson to 4 muons





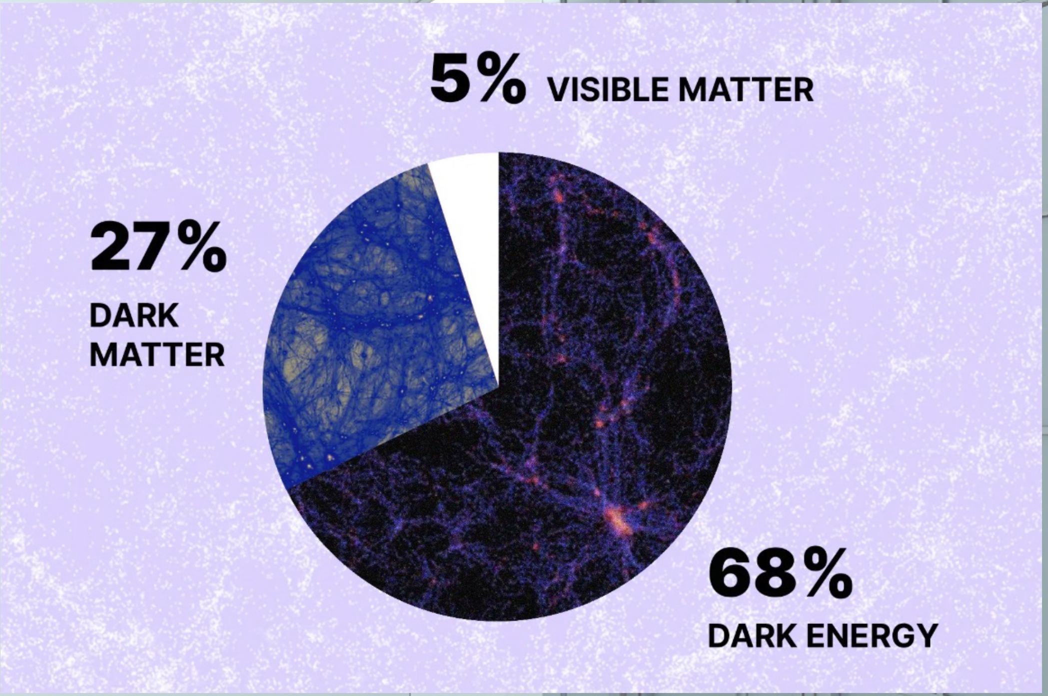
The Standard Model: the definitive theory?

- 12 fundamental particles
- 3 types of interactions, 1+3+8 force carriers
- particle that provides the mass for all the others (Higgs)

- Correct, but with too many particles

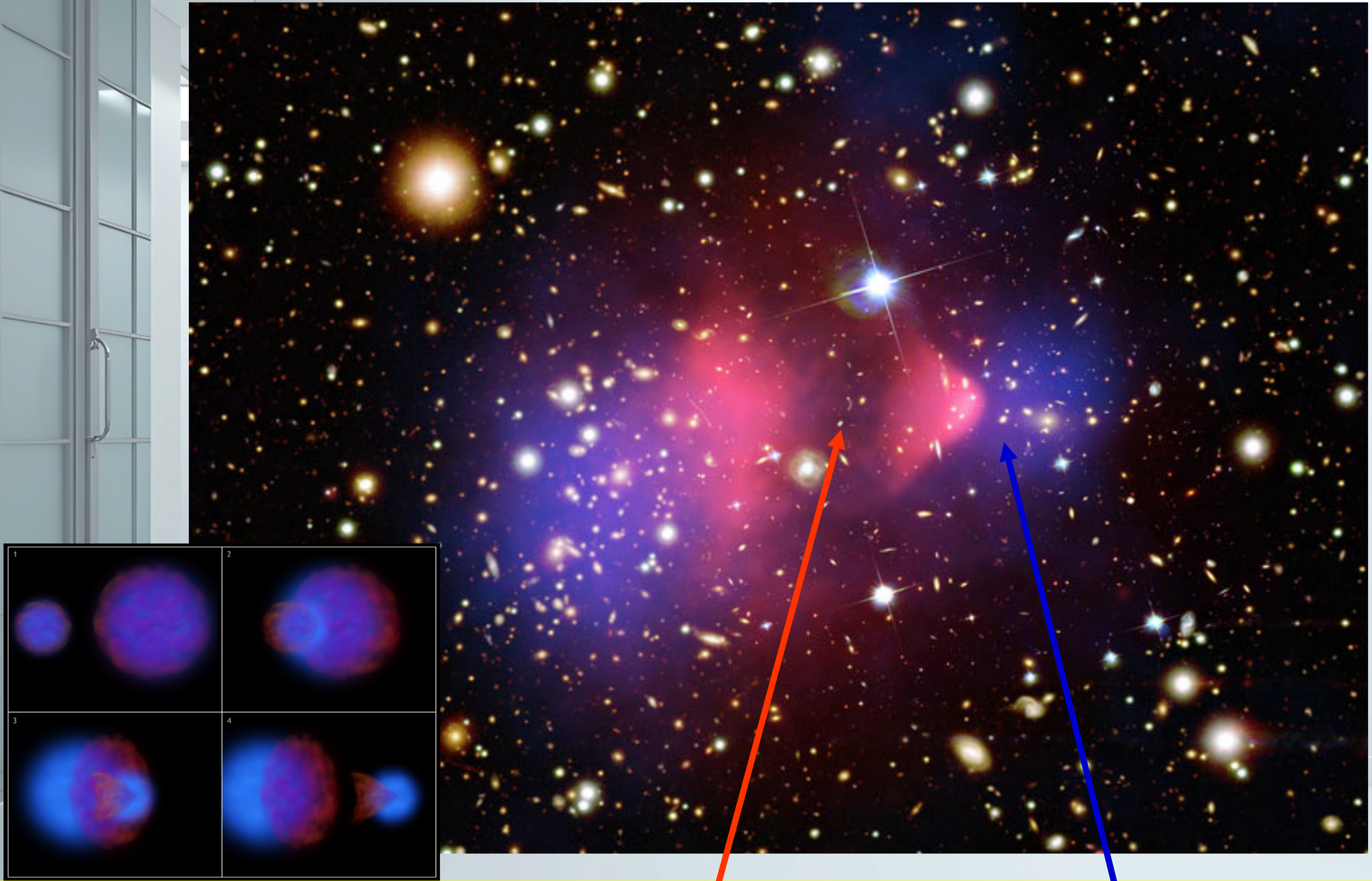
The Standard Model is not a definitive theory

- Neutrinos have a (small) mass
- The observable Universe – complete dominance of substance over anti-substance;
  - one conditions for such an evolution of the Universe - violation of CP symmetry;
  - measured CP symmetry breaking ~10^{10} too small to explain the asymmetries
- Gravity is not yet included
- Most of the Universe is made of matter unknown to us....



SEVERAL PROPOSED (AND YET UNCONFIRMED) SOLUTIONS:
SUPER SYMMETRIC THEORIES, EXTRA DIMENSIONS...
→ "NEW PHYSICS" (NP)

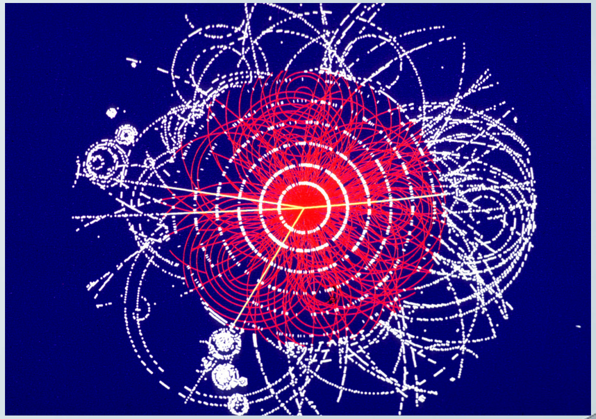
Direct evidence for the existence of dark matter



When two galaxy clusters collide, ordinary matter slows down, but dark matter does not.

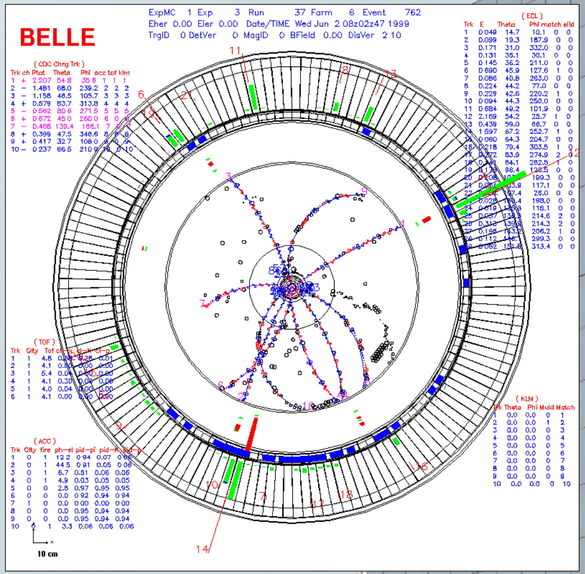
Physics beyond the Standard Model

Search for deviations from the extremely well-tested Standard Model.



Two possibilities:

- Direct search for new particles, supersymmetric partners: particles must be massive
    - search at high energies (LHC)
- Search for deviations from the probability of processes (e.g. in rare B meson decays)
    - Precise Belle II measurements at lower energies



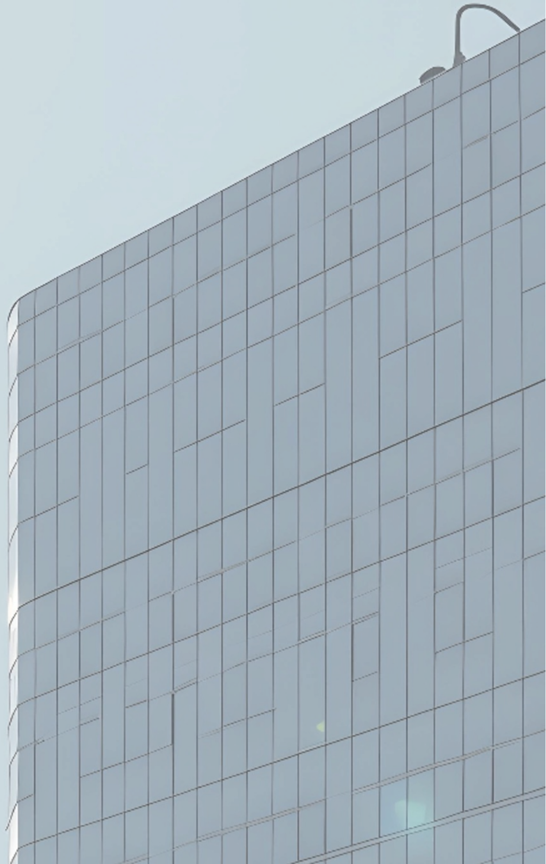
Both approaches are complementary.

NO DISCOVERIES OF NEW PARTICLES WITH MASS ~500 GeV/c^2 - 1 TeV/c^2

What will the future bring us?

We don't really know -
If we did, research would not be necessary ...

We expect very interesting results in the next
few years in fundamental particle physics!



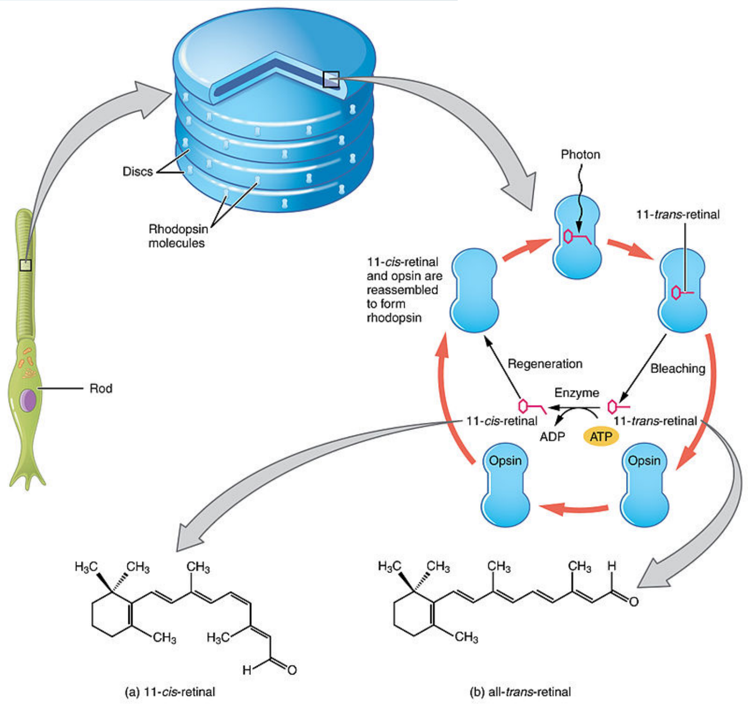
Detection of low light levels

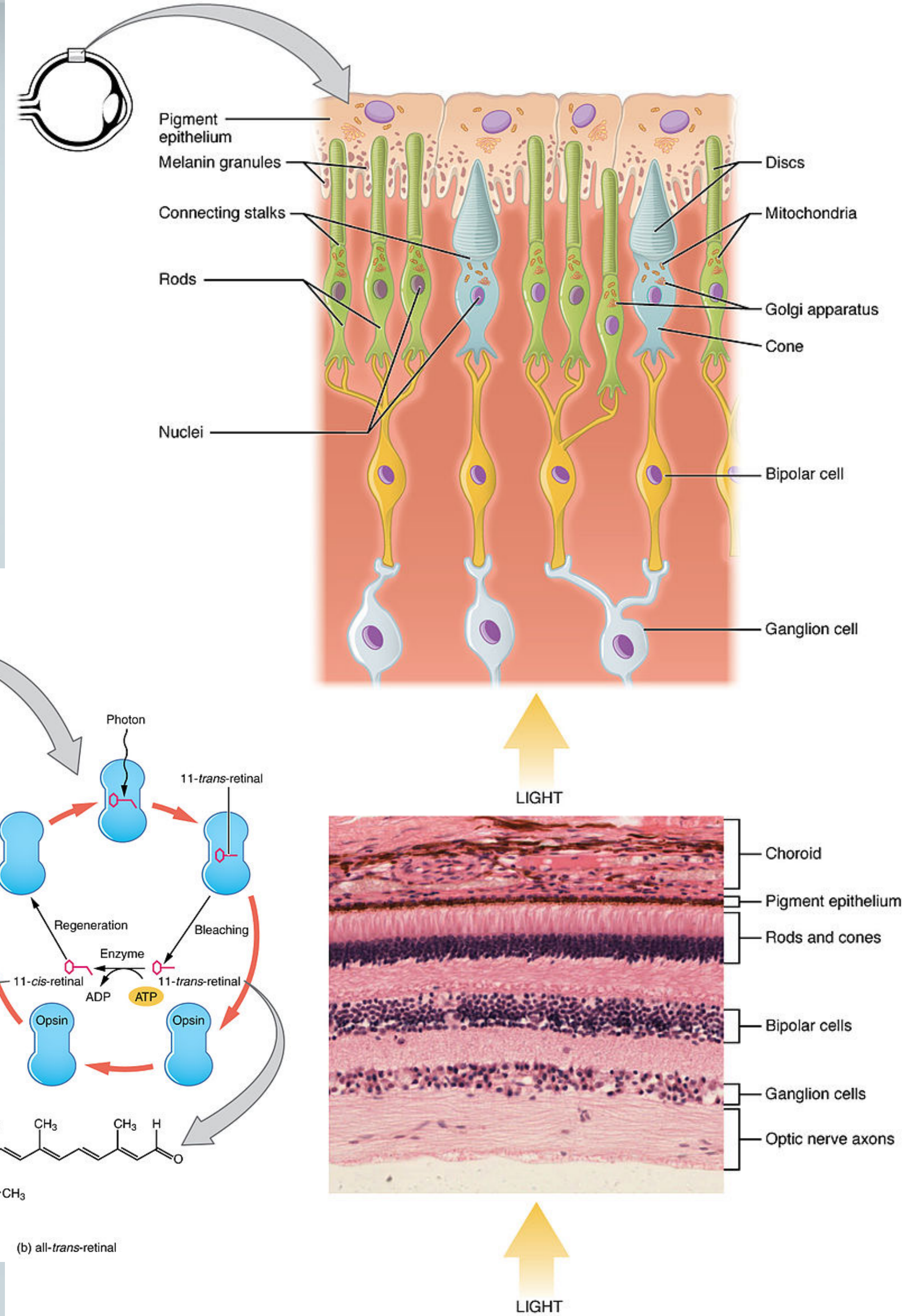
Detection of photons crucial in

- Cherenkov detectors,
- calorimeters,
- fiber trackers,
- etc.

Photon detection in human

- **Photoreceptor cell** : specialized type of neuroepithelial cell found in the retina that is capable of visual phototransduction
- **Photoreceptor proteins** in the cell absorb photons, triggering a change in the cell's membrane potential.





Photodetector

A device that can detect photons

Requirements:

- single photon sensitivity,
- high efficiency,
- good spatial granularity

Detection mechanism:

- Photo-chemical
- Thermal
- Photo-voltaic
- Photo effect

Photo-effect

First we need to convert light into detectable electronic signal

Principle:

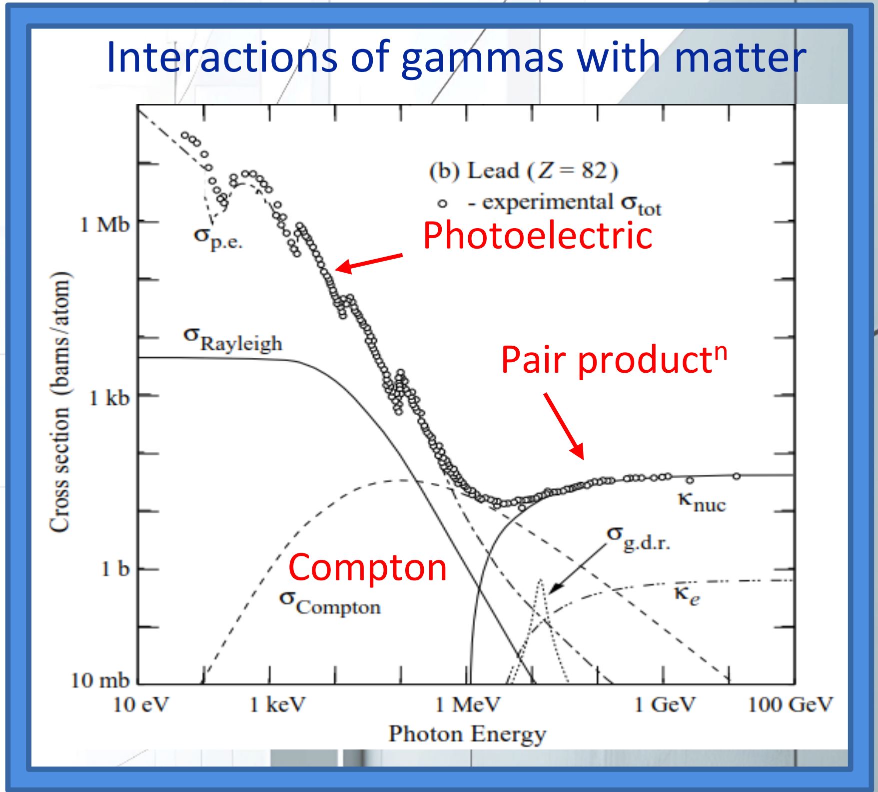
Use photoelectric effect to ‘convert’ photons to photoelectrons

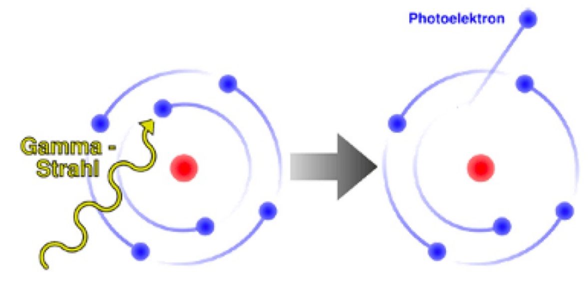
External photelectric effect – emission of free electrons from metal surface due to energy absorption

Photon detection involves often materials like K, Na, Rb, Cs (alkali metals). They have the smallest electronegativity →highest tendency to release electrons.

Most photo-detectors make use of solid or gaseous photosensitive materials.

Internal photoelectric effect – free charge carriers are generated by absorption of incident photons in semiconductor junction detector





Detection of light by sensors

Types:

Vacuum

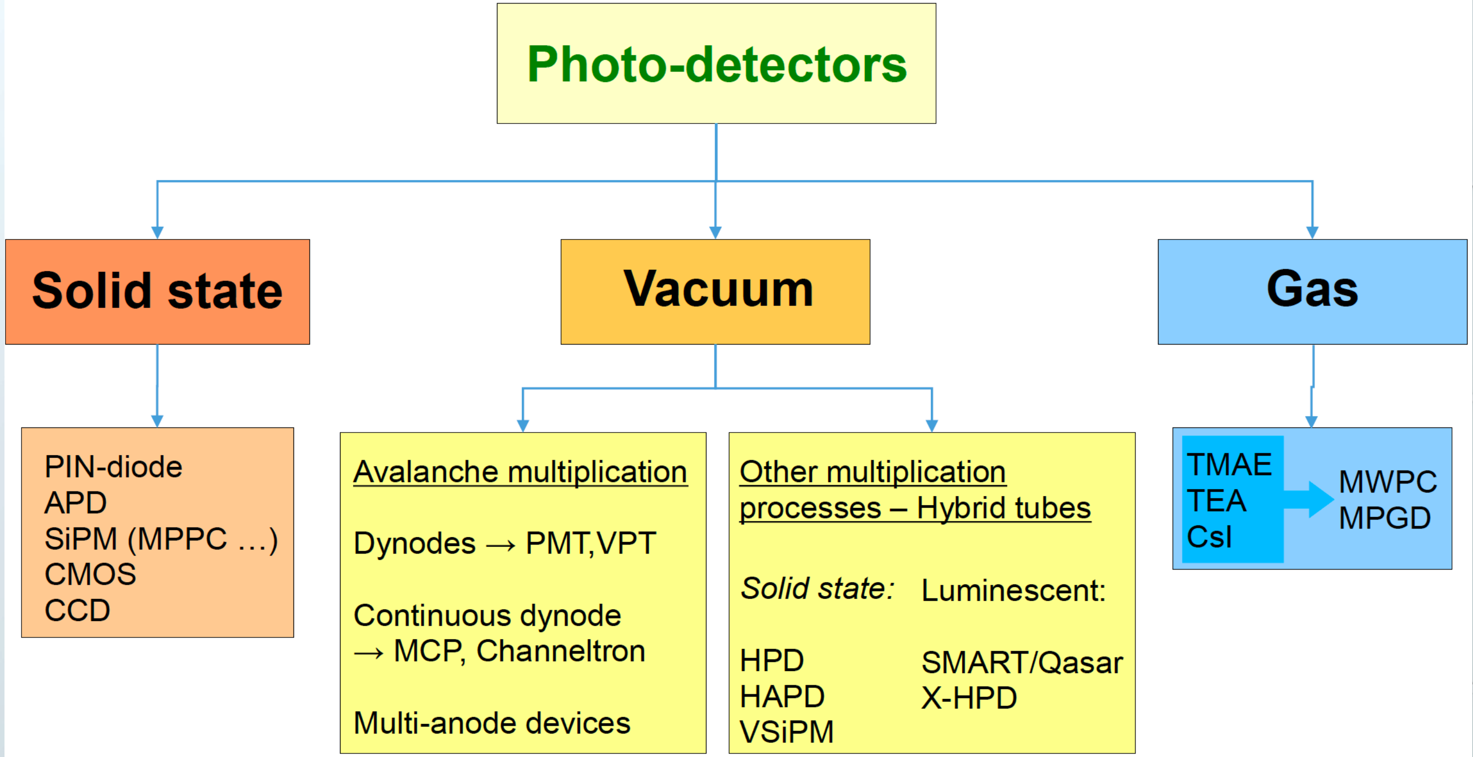
- Photomultiplier tubes (PMT)
- Microchannel plate photomultiplier tubes (MCP-PMT)

Solid-state photon detectors

Hybrid detectors

- HPDs and HAPDs
- Other hybrid photosensors

Gaseous photon detectors

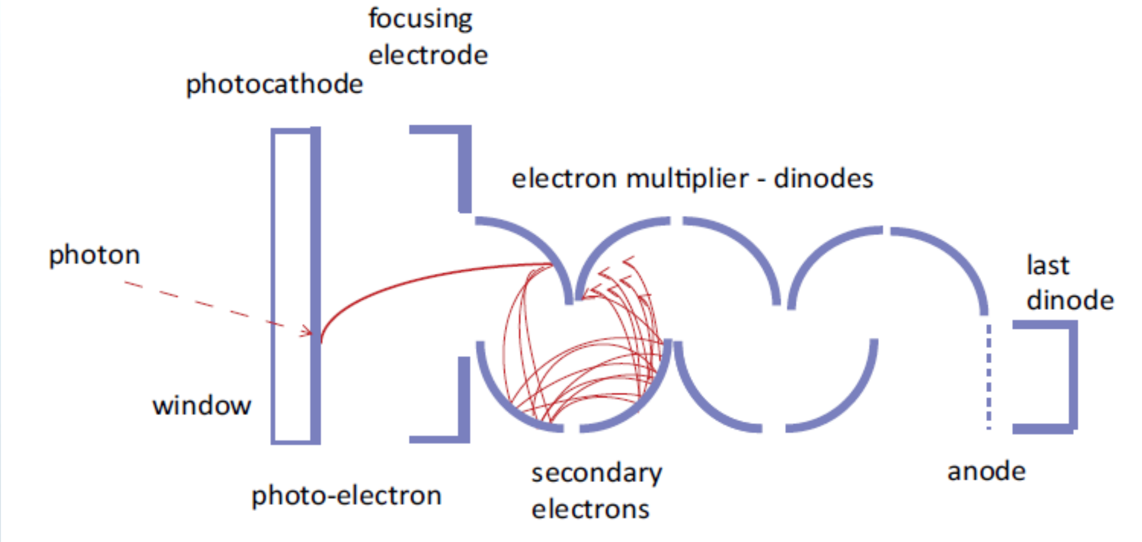


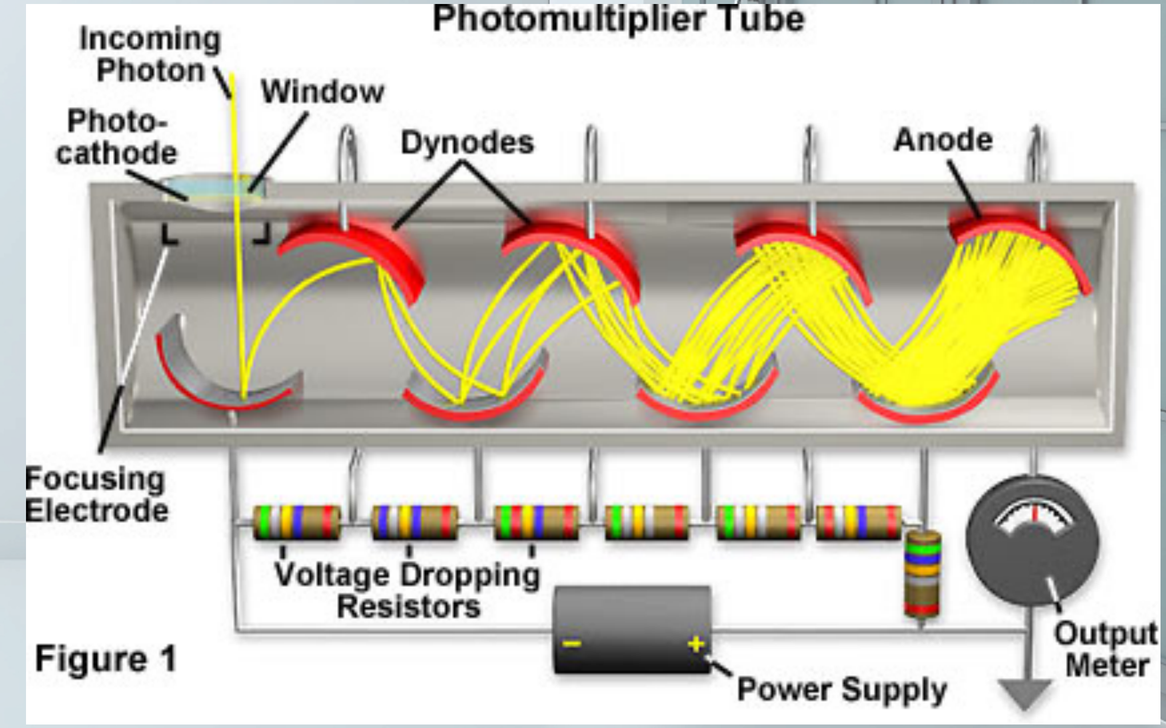
Photon multiplier tube PMT

- After the photo conversion, the photoelectron signal needs to be amplified to give a measurable electronic pulse
- Achieved in traditional photomultiplier by dynode chain
  - exponential multiplication of the charge at each dynode: e.g. if number of electrons is tripled on each stage of a 12 dynode chain

$$G = \delta^n = (kV_d)^n$$

  - Gain = $3^{12} \sim 10^6$





Multiplication system（dynodes)

- *secondary emmision: number of secondary electrons per incoming electron* $\delta \approx$ 3-5
- *dynode material: usually semiconductors or isolators (same reason as for the photocathode)*
- *semiconductor on a metal substrate (electric contact needed for E field for acceleration)*

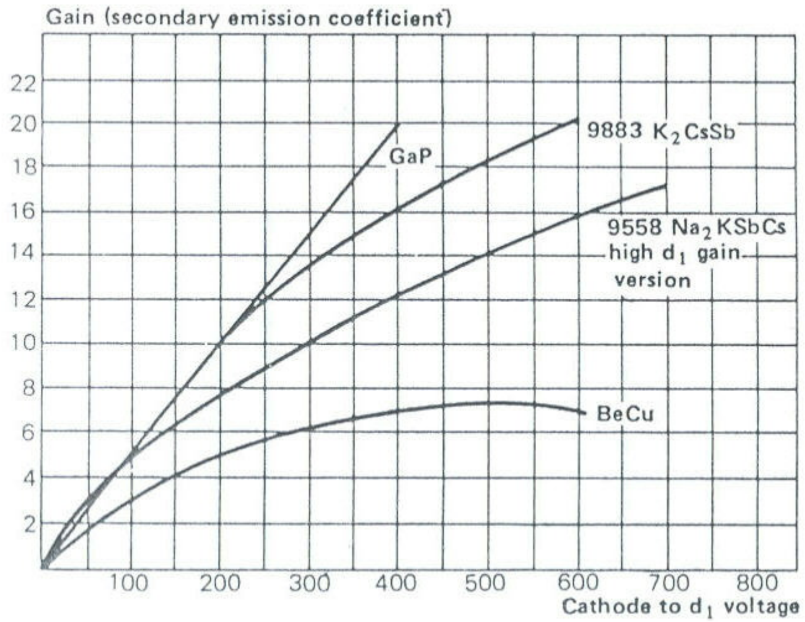
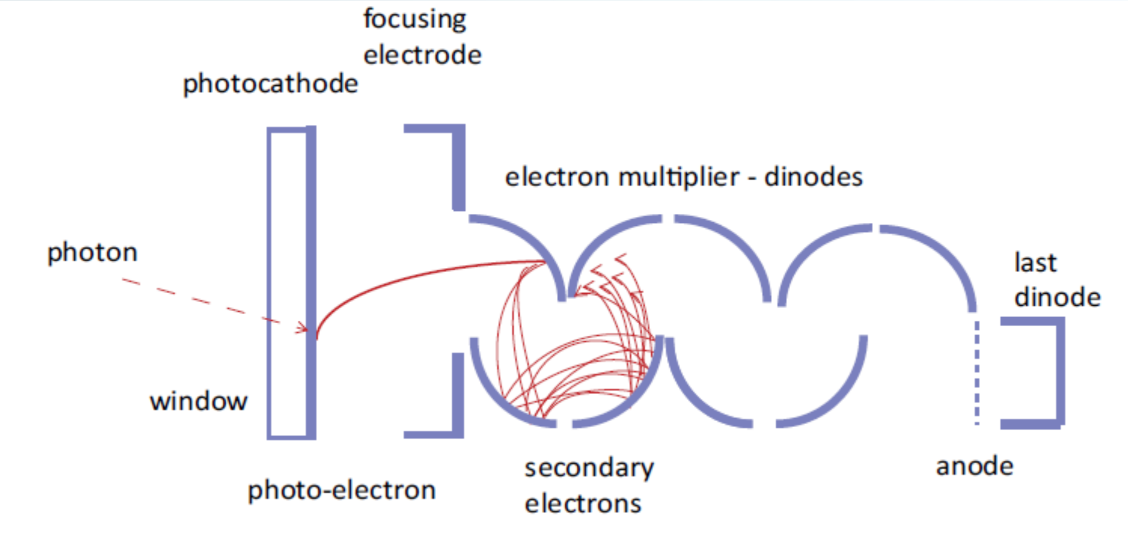
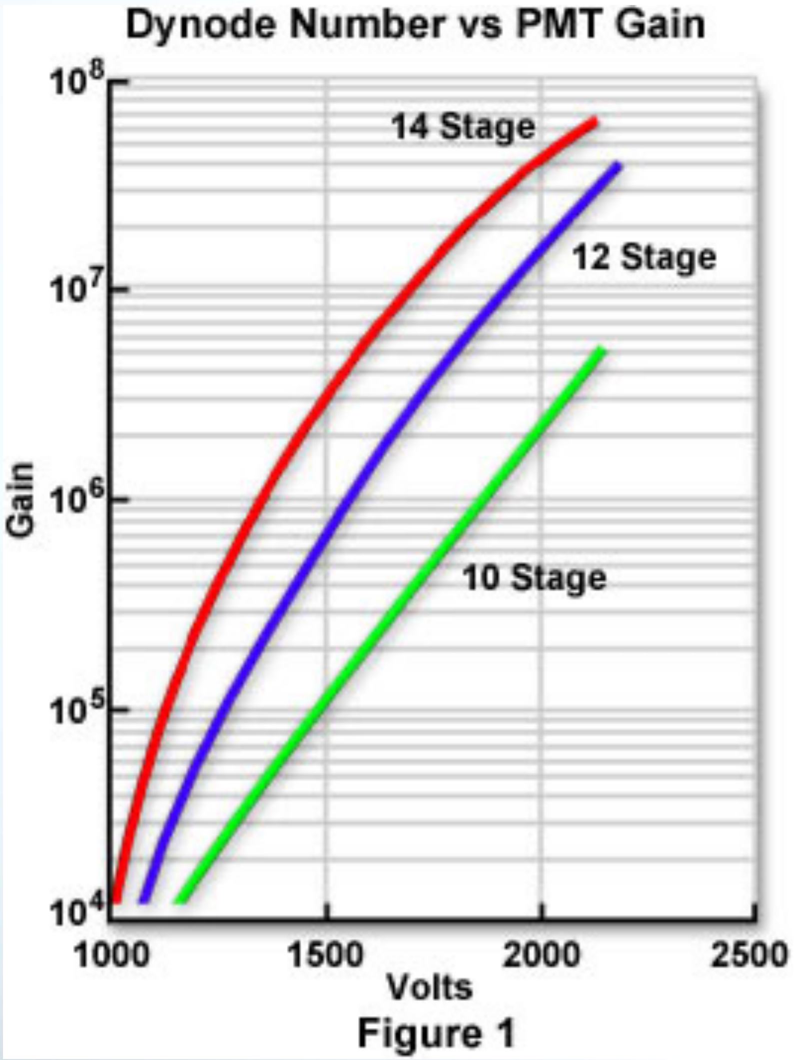


Fig. 8.9. Secondary emission factor for several dynode materials (from *EMI Catalog* [8.2])

- 10-14 dynodes → G $=10^7$-10^8
- GaP dinode → 5 dynodes → same G

Photomultipler gain



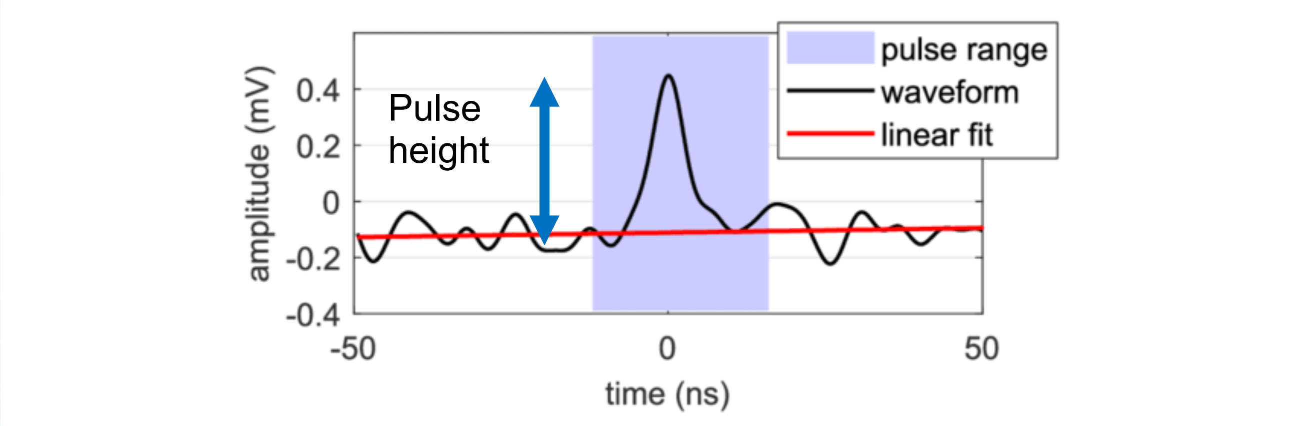


Gain depends on:

- the number of dynodes
- secondary-emission ratio characterised by
  - properties of the material
  - the energy and angle of incidence of the primary electrons

Pulse height distributions for single photoelectrons

(multiple photons: convolution)



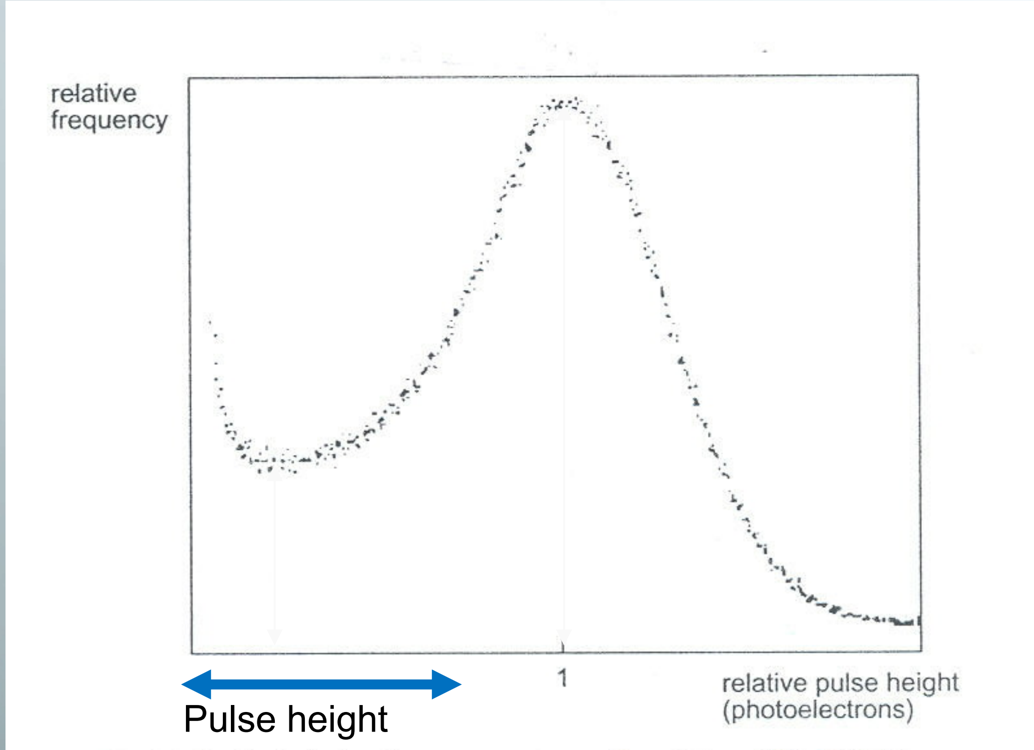
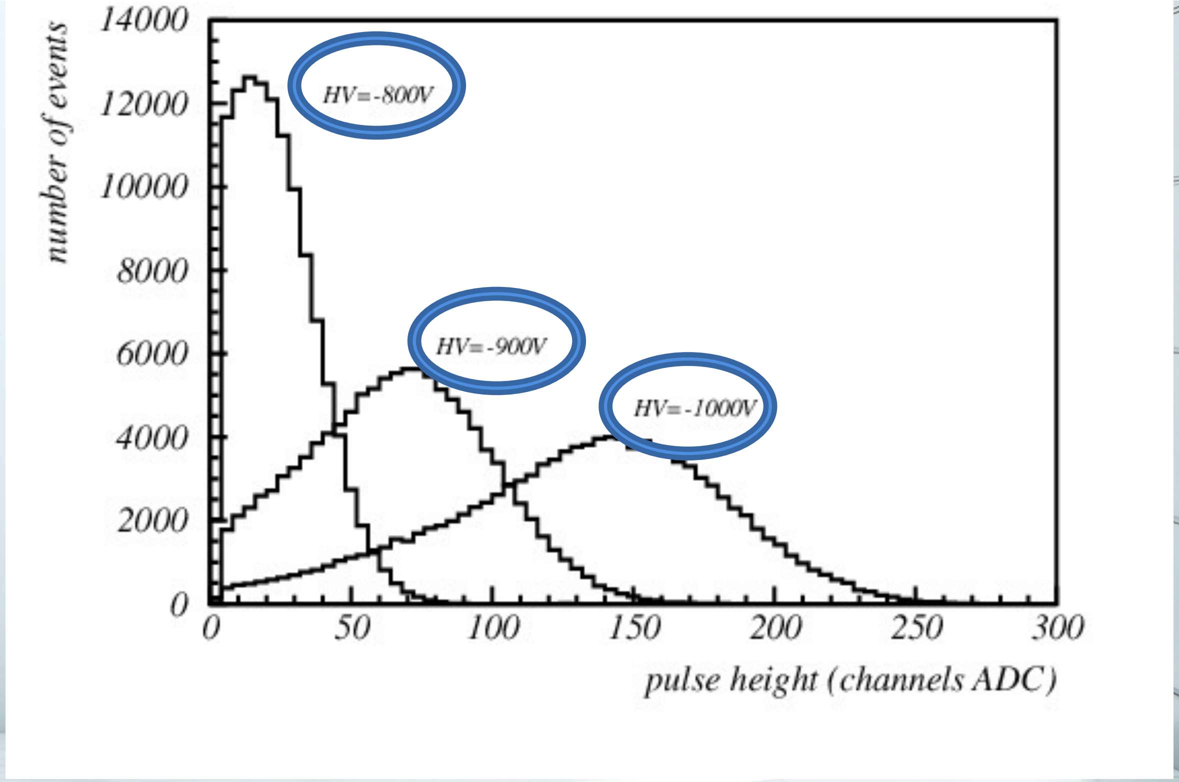


Fig.2.4 Typical single-electron spectrum. Resolution 67% FWHM. Peak-to-valley ratio 2.8:1



Photomultipler tube

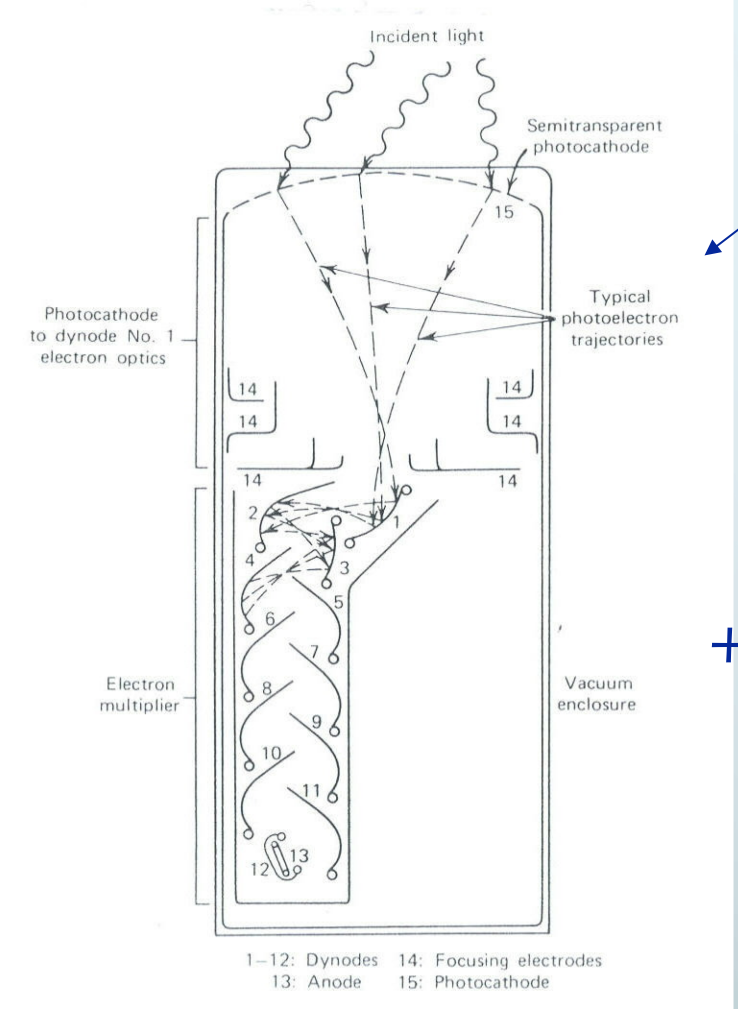
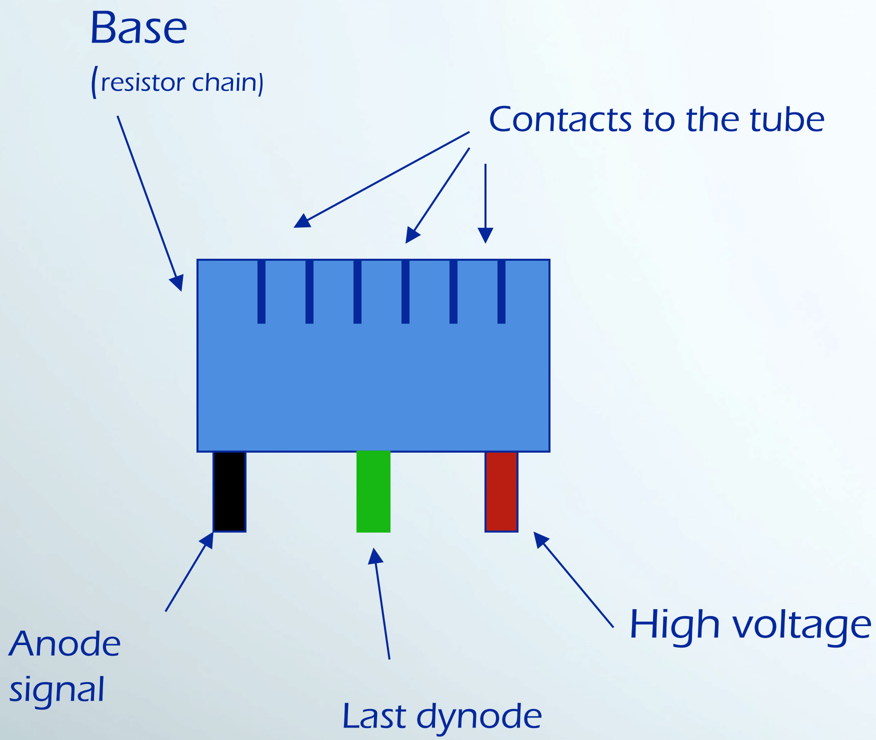


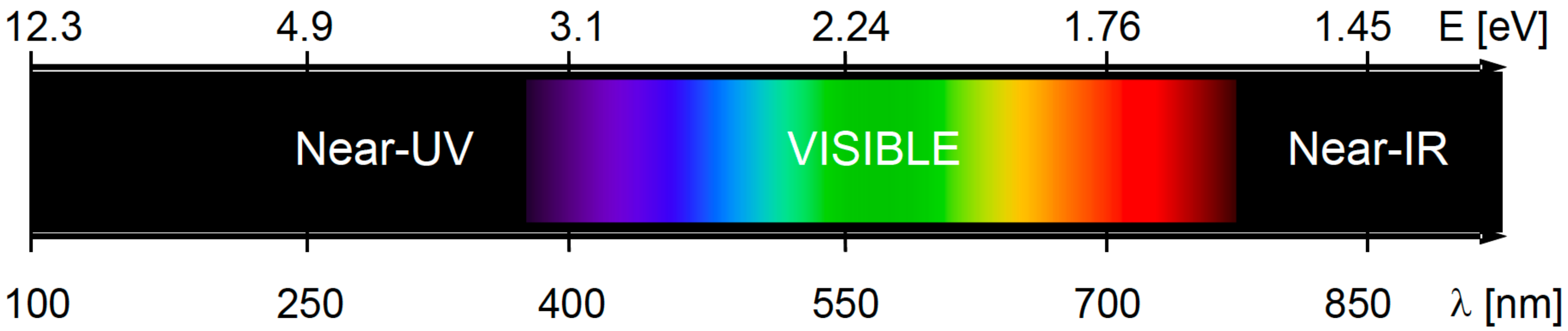
Figure 9-1 Basic elements of a PM tube. (From Ref. 1.)

+



1) Measure pulses
2) Measure current

How to detect visible, near UV and near IR light



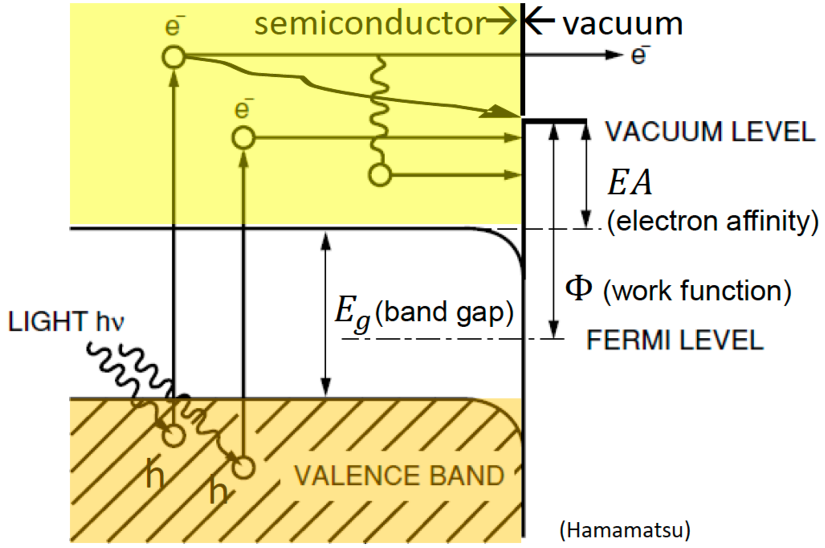
Photon energy:

$$E_\gamma = h\nu = \frac{hc}{\lambda} \approx \frac{1239\ \text{eV} \cdot \text{nm}}{\lambda}$$

visible range 400 nm –780 nm → 3.1 -1.6 eV, $\Delta E\gamma \approx 1.5 eV$

Solid photocathode

Photon can’t transfer its total energy to a free electron due to momentum and energy conservation



Available energy few eV
→ good materials are semiconductors.

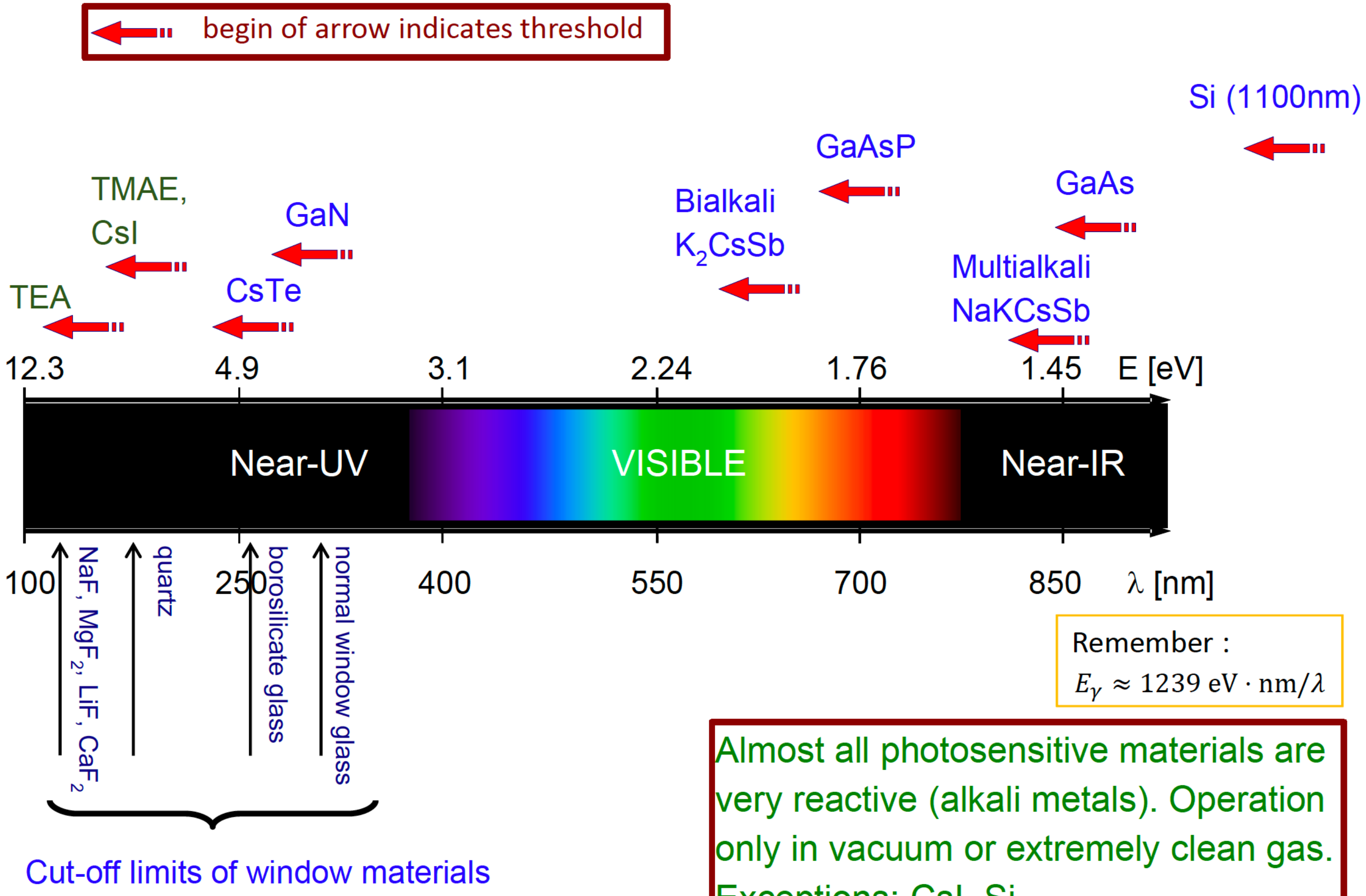
Light has to enter a photosensitive material
→ low reflectivity R

Absorbed photons transfer energy to electrons (e-) in the material;
If $\mathrm{E}_\gamma > E_g$, electrons are raised to conductance band.
→ In a Si-photodiode, these electrons(holes) can create a photo-current.
→ Photoconductive effect.
However, if the detection method requires
extraction of the electron into vacuum, 2 more steps must be accomplished:

- Energized electrons diffuse through the material, losing part of their energy (~random walk) due to electron-phonon scattering. ΔE ~ 0.05 eV per collision.
- Only electrons reaching the surface with sufficient excess energy escape from it

→ minimum required energy $E\gamma > Eg + EA$
→ Photoelectric effect

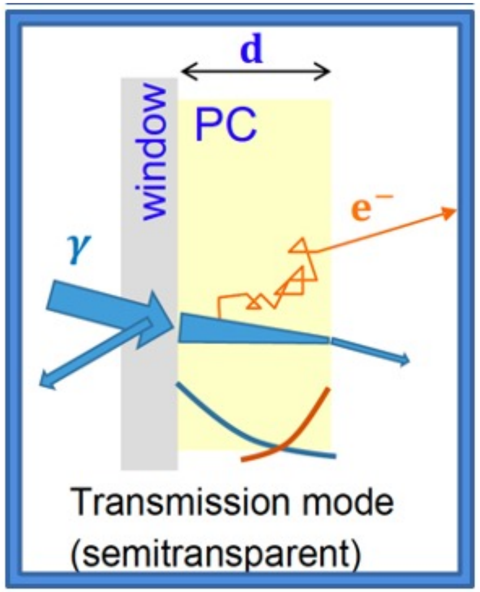
Photosensitive materials – photocathodes

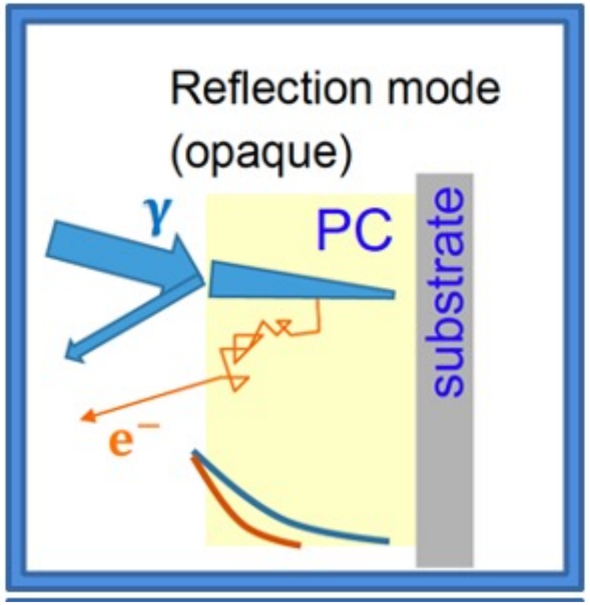


Remember :
$E_\gamma \approx 1239 \text{ eV} \cdot \text{nm}/\lambda$

Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas. Exceptions: CsI, Si.

Transmission vs. reflection mode photocathode





Thickness of transmission mode photo-cathode needs to be optimized!

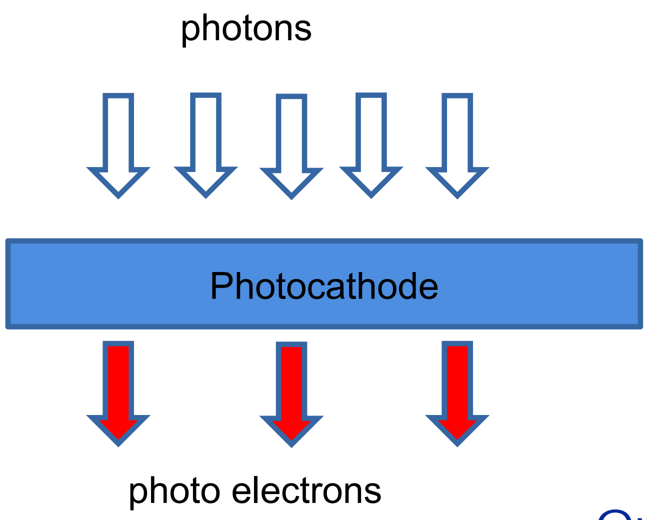
Photocathode sensitivity

Photoeffect : $E_e = h\nu - \Phi$

Max kinetic energy of the photo-electron (E_e)

Energy of the photon ($h\nu$)

Work function (Φ)



$$QE(\lambda) = \frac{\text{Number of photoelectrons exiting the cathode}}{\text{Number of incoming photons}}$$

$$E(\lambda) = \frac{I_k}{P(\lambda)}$$

I_k – Photoelectron current (A)

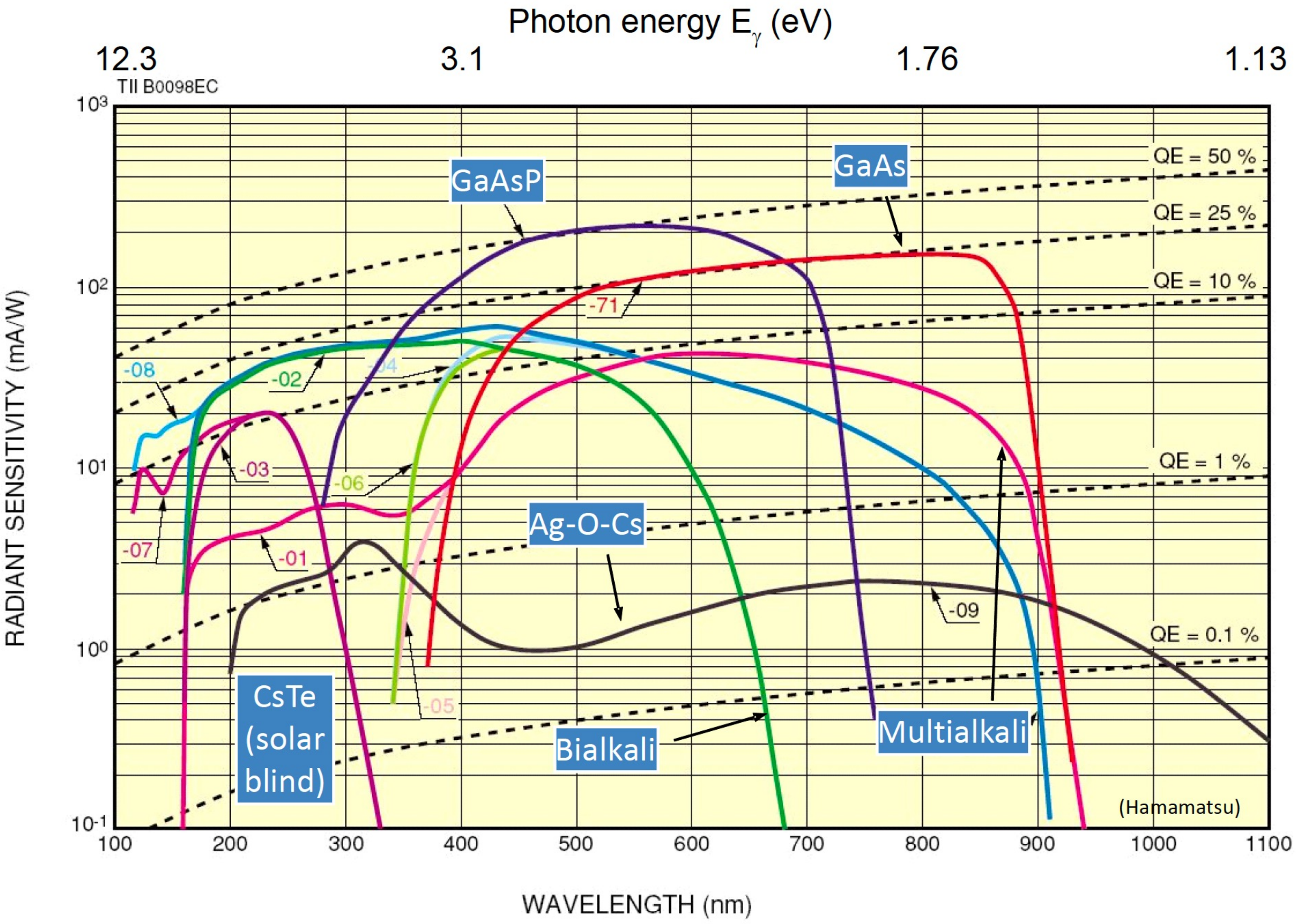
$P(\lambda)$ – Incoming light power (W)

$$QE(\lambda) = \frac{I_k/e_0}{P(\lambda)/h\nu} = \frac{hc}{\lambda e_0} E(\lambda)$$

Quantum efficiency is a product of:

- Transmission probability (window)
- Probability for absorption and photoeffect
- Probability for the electron to exit the photocathode

Transmission mode photo-cathodes

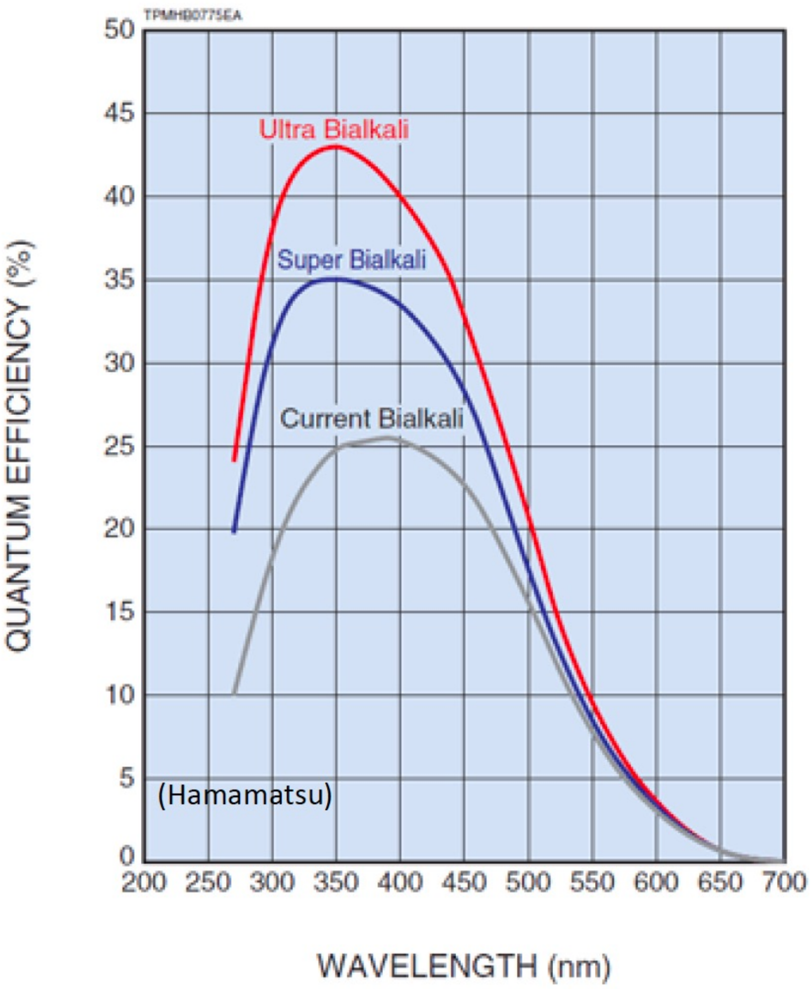


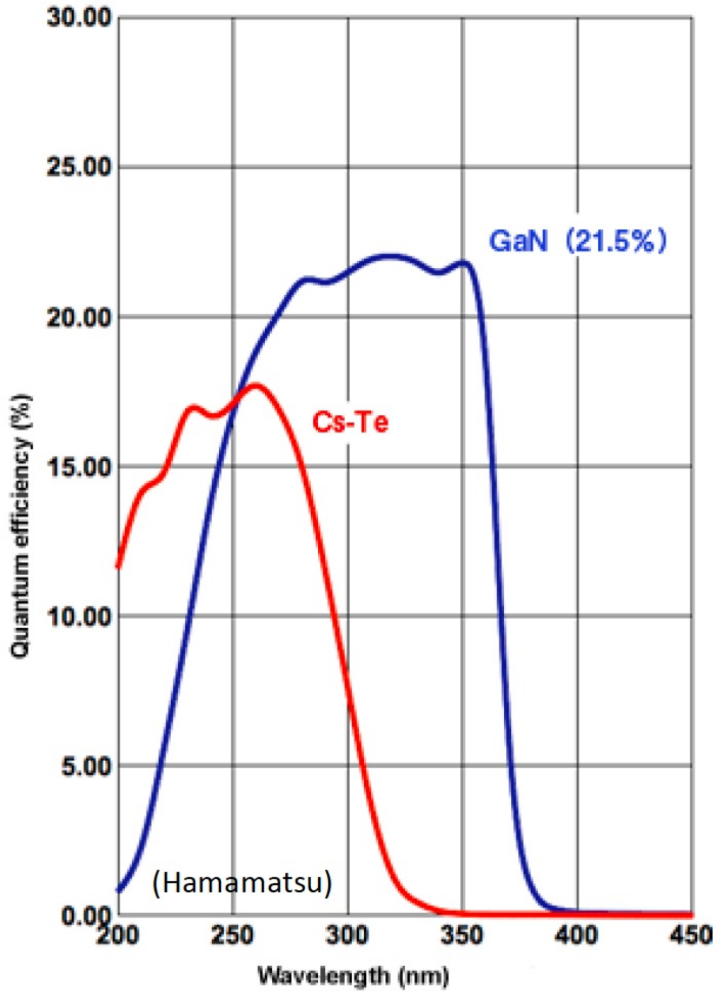
Bi-alkali: Sb-K-Cs, Sb-Rb-Cs, Na-K-Sb

Recent photocathode improvements

Recent improvements of bi-alkali photocathodes:

- Peak QE > 40%
- $\lambda_{peak} \rightarrow$350nm





Collection of photoelectrons

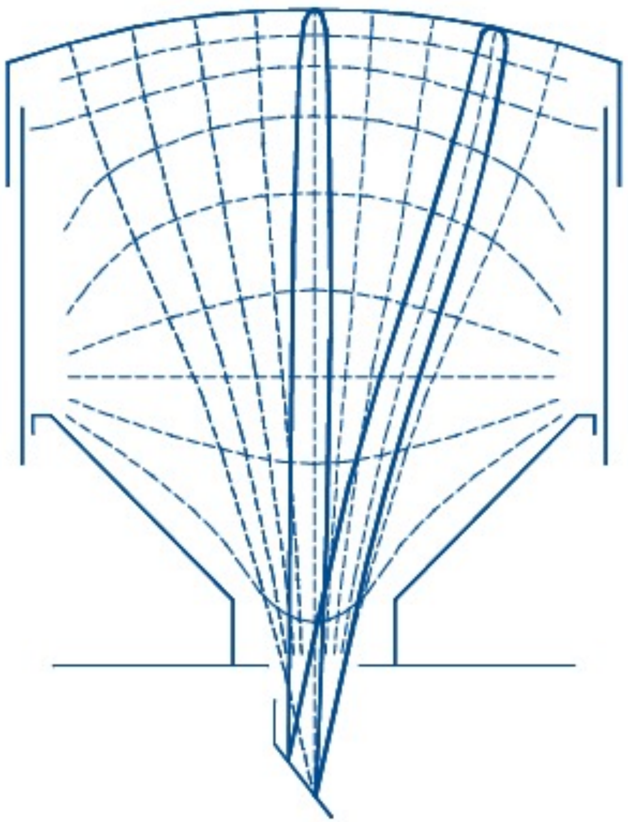
Use a suitably formed electric filed between the photocathode and the first dynode

Requirements:

- *high efficiency for the photo-electron collection (for different paths, exit energies, directions).*

- *the collection efficiency should not depend on the photoelectron exit point*

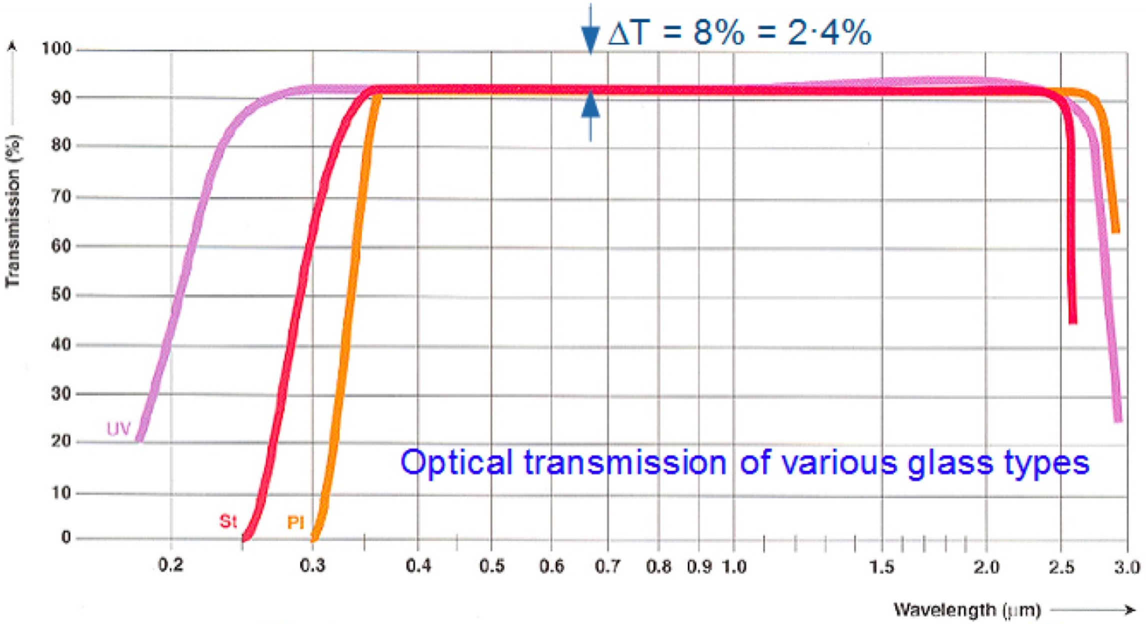
- *the time of flight to the first dynode should also not depend on the photoelectron exit point (impact on time resolution)*



Window transmission

- 2 types of losses:
- **Fresnel reflection** at interface air/window and window/photocathode

- $R_{Fresnel} = \frac{(n-1)^2}{(n+1)^2}$(normal incidence)
- n = refractive index (wavelength dependent!)
- n_{glass}≈1.5 → $R_{Fresnel}$= 0.04 (per interface)
- **Bulk absorption** due to impurities or intrinsic cut-off limit. Absorption is proportional to window thickness (for low absorption)



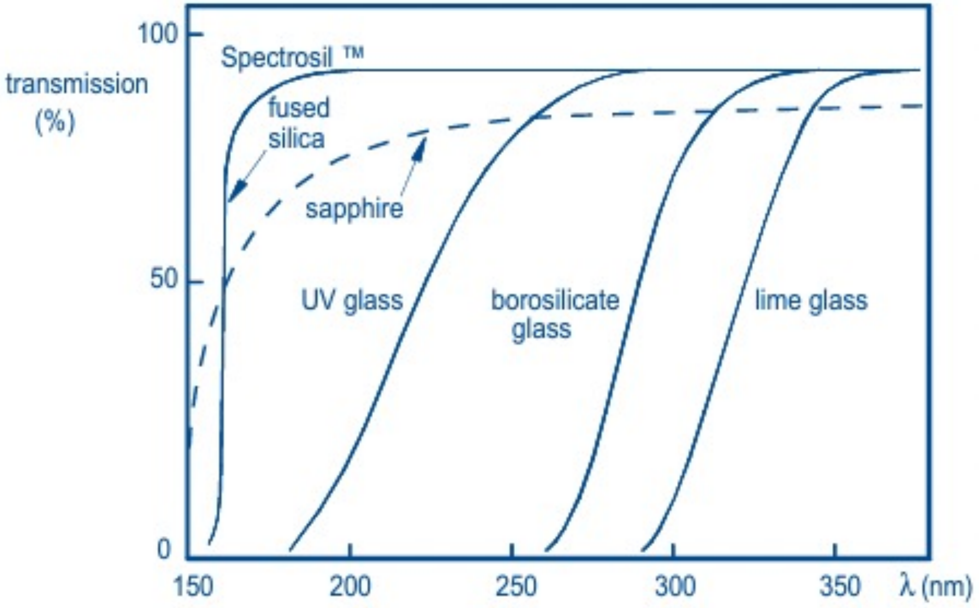


Fig.3 Transmission as a function of wavelength λ for various glasses used in photomultiplier input windows.

Overview of photodetectors

Photo-detectors

Solid state

- PIN-diode
- APD
- SiPM (MPPC …)
- CMOS
- CCD

Vacuum

Avalanche multiplication

Dynodes → PMT,VPT

Continuous dynode
→ MCP, Channeltron

Multi-anode devices

Other multiplication processes – Hybrid tubes

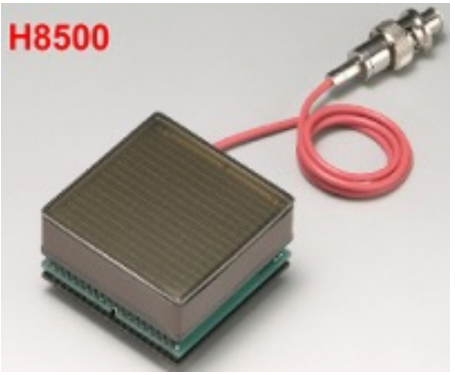
Solid state:	Luminescent:
HPD	SMART/Qasar
HAPD	X-HPD
VSiPM	

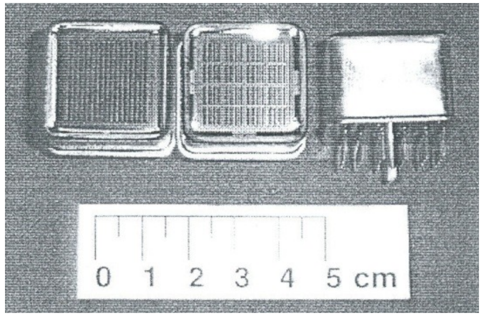
Gas

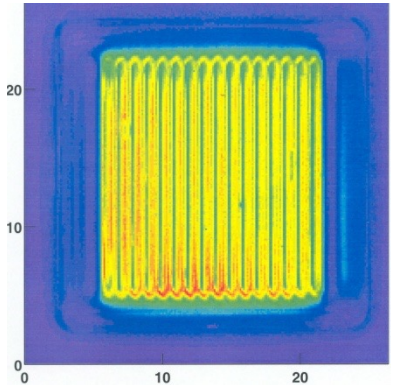
TMAE
TEA
CsI
→
MWPC
MPGD

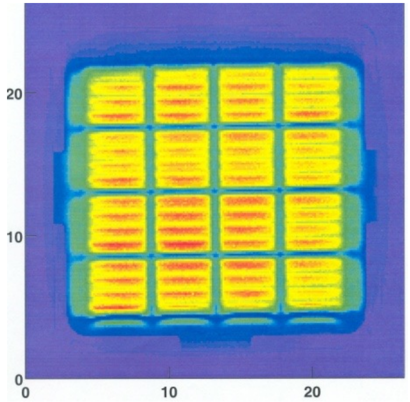
Multianode PMT

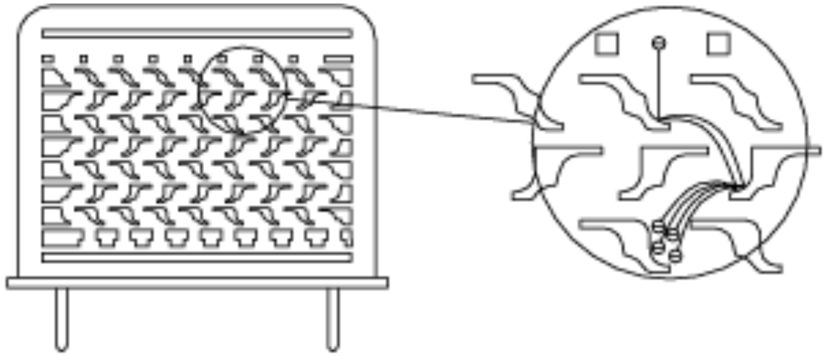
- The **multi-anode** photomultiplier is a marvel of miniaturization → up to 64 pixels in a single tube, each with size ~ 2×2 mm^2
- Dynode structure formed from a stack of perforated metal foils
- Signal width dominated by fluctuations in the charge multiplication of the first dynodes



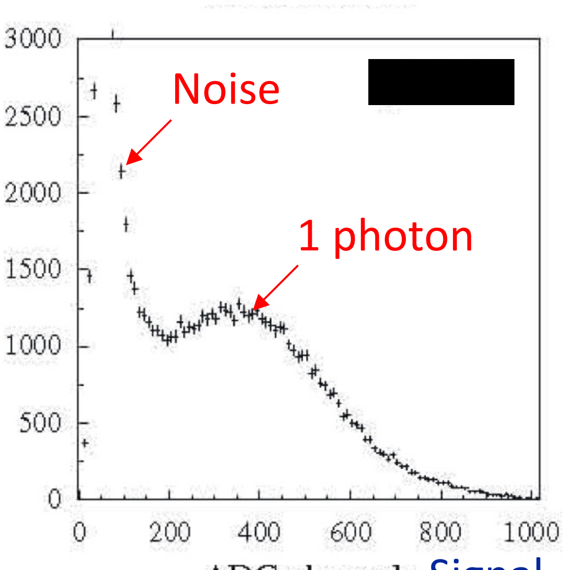




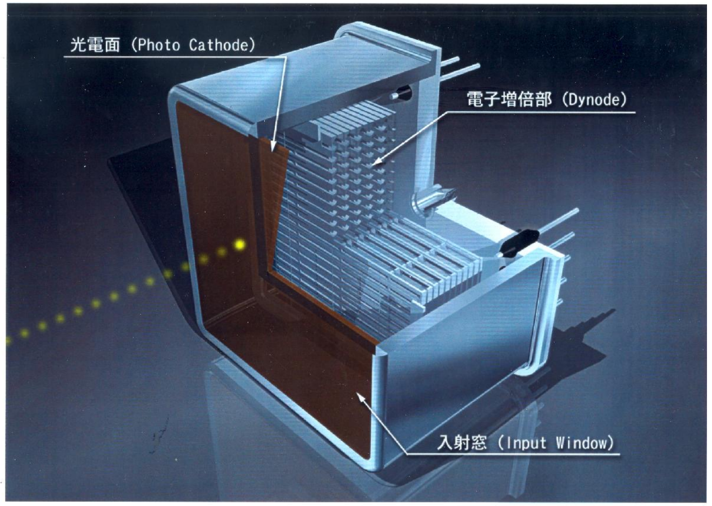


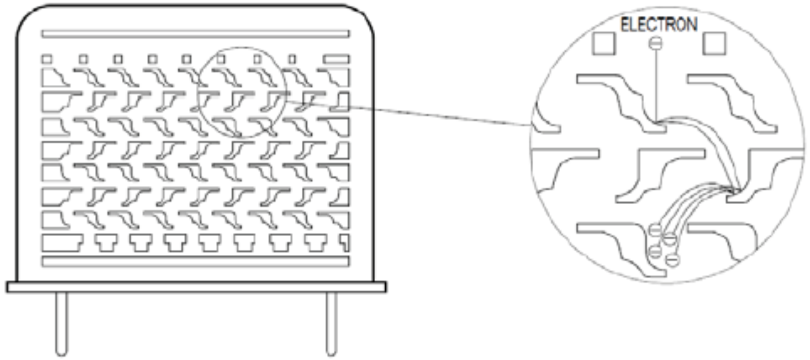


Multi-anode PM (Hamamatsu R5900)
metal foil dynodes

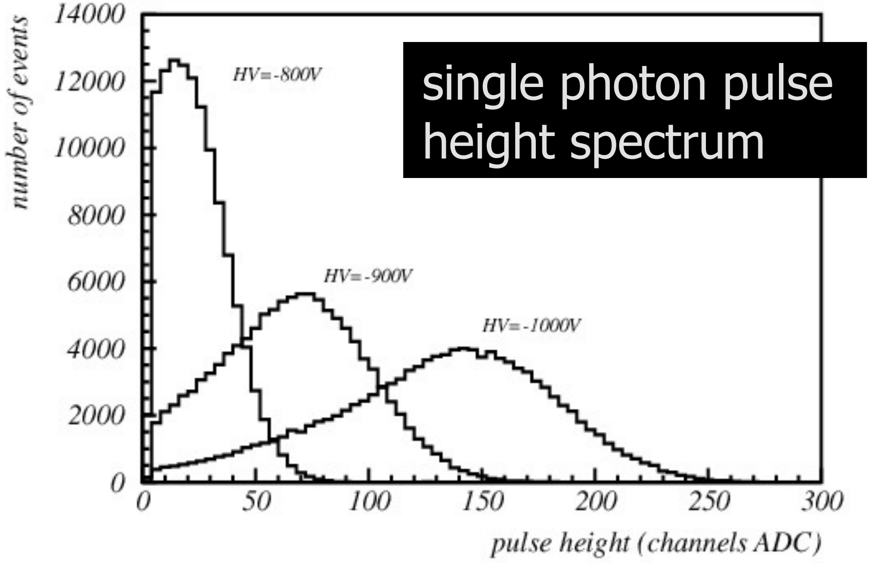


Example - Multianode PMT Hamamatsu R5900





- Excellent single photon pulse height spectrum
- Low noise (few Hz/ch)
- Low cross-talk (<1%)

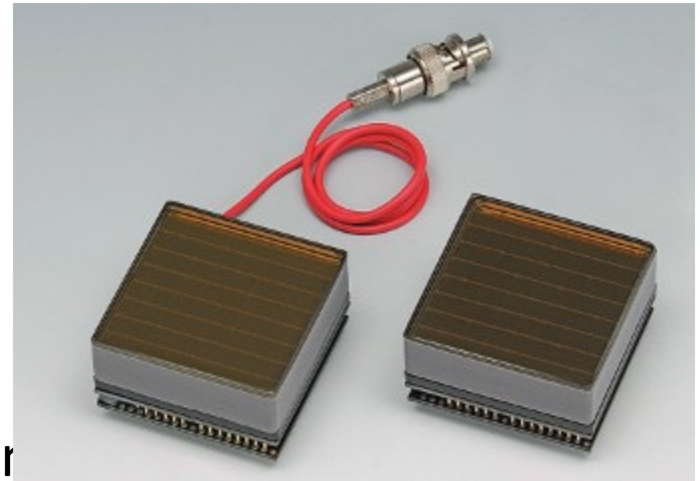


single photon pulse height spectrum

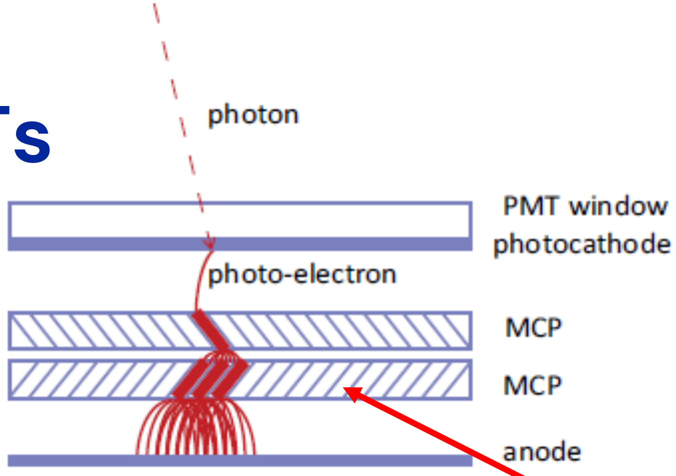
Flat panel multianode PMTs

Problem of vacuum based sensors: active area fraction
One possible solution: make a larger sensor
Hamamatsu: flat panel PMT H8500

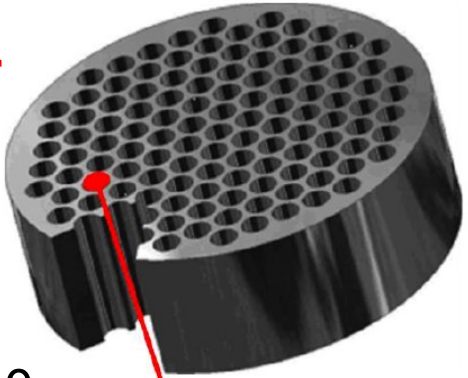
- 52 x 52mm², 89% effective coverage
- 64 channels, pixel size 5.8 x 5.8 mm2
- 12 dynodes, metal foil type
- Bialkali cathode, max 25% quantum efficiency
- single photon pulse height distribution not as good as in the smaller R5900 (and related tubes like 7600)



Micro-Channel Plate PMTs



- Time-of-flight detectors - timing precision at the *picosecond* (10^{-12} s) level
- 1 ps ≈ 0.3 mm for a relativistic particle
  → requires small feature sizes
- **Micro-channel plate** (MCP) photon detectors employ electron multiplication in small (~ 10 μm) pores, used in image intensifiers
- Timing precision of ~ 10 ps achieved



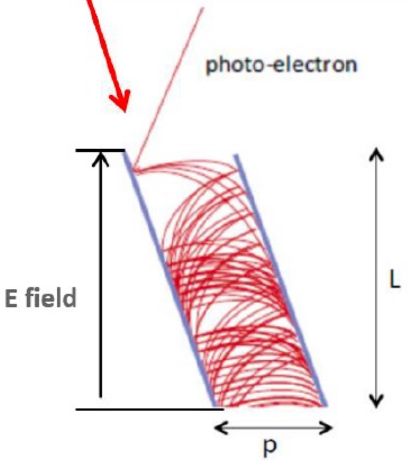
MCP detector
(Photonis)
6 cm width
Up to 1024 anode pads

Immune to an axial magnetic field

MCP is an array of millions of capillaries (~10 um diameter) in a glass plate (d=1mm).

Both faces of the plate are coated by thin metal, and act as electrodes.

The inner side of each tube is coated with electron-emissive material.



Micro channels

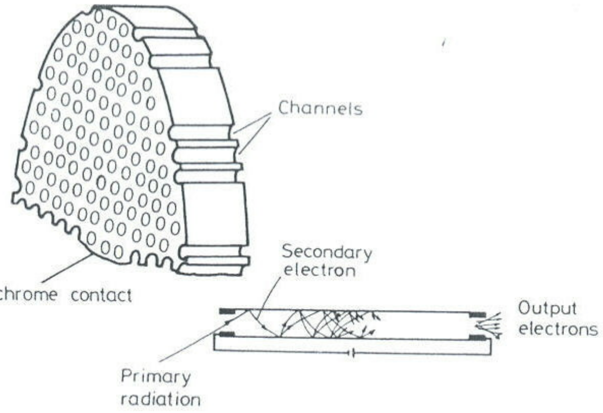


Fig. 8.6. Schematic diagram of a microchannel plate. The many channels act as continuous dynodes (from *Dhawan* [8.4]; picture © 1975 IEEE)

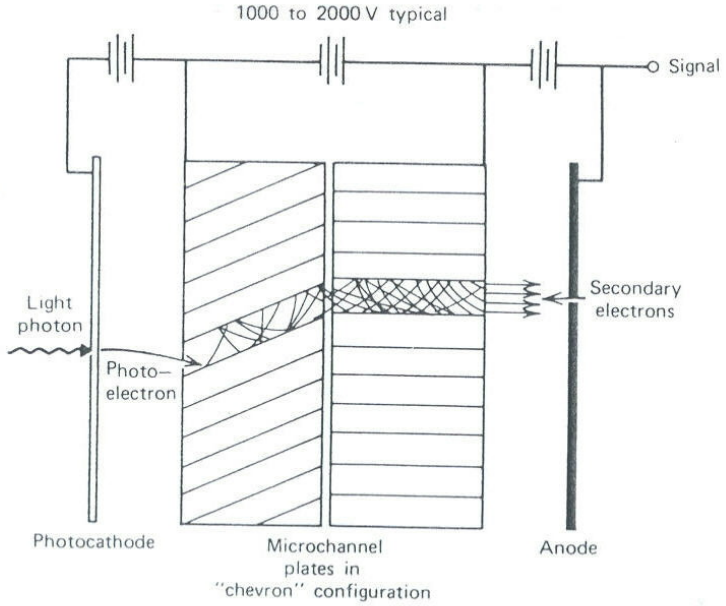
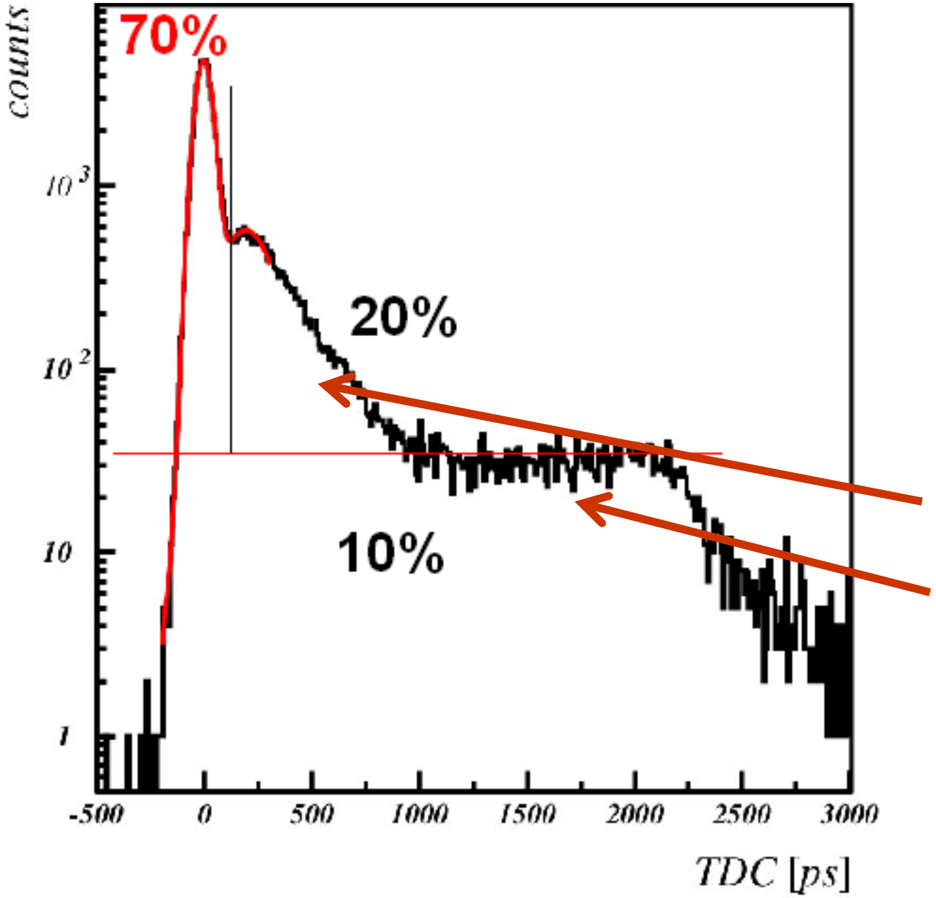


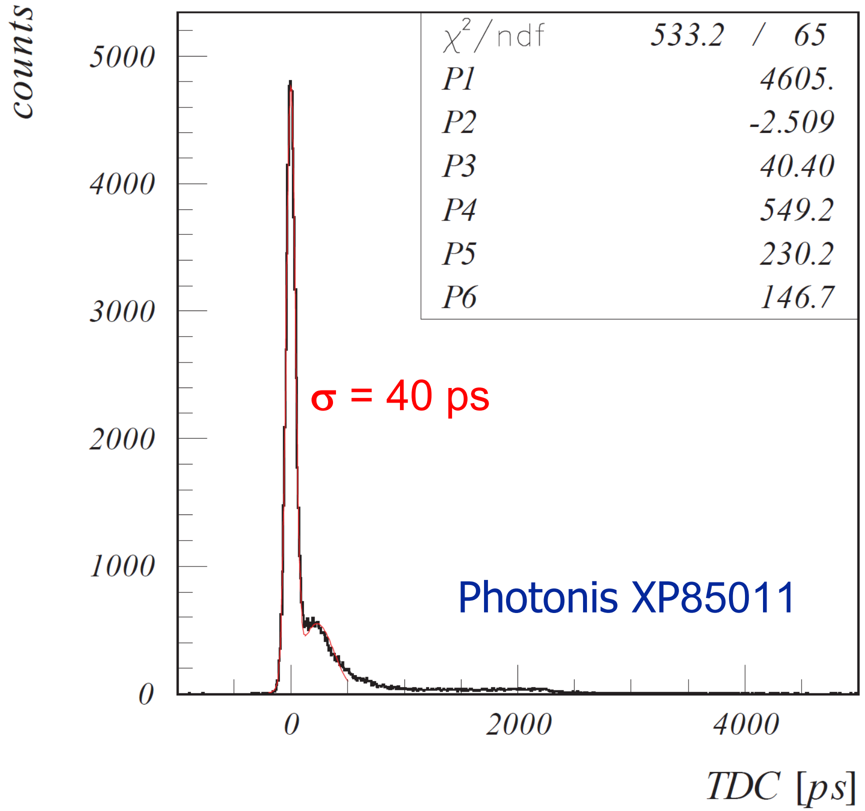
Figure 9-9 Elements of a PM tube based on microchannel plate electron multiplication.

- pore diameter 10-100 μm
- channel length ≈ 1mm
- multiplication G ≈ 10^5-10^7 ("chevron")
- time resolution <100 ps
- spatial sensitivity
- 25 μm pores: up to B ≈ 0.8T
- 10 μm: up to B≈1.5T

MCP PMT timing

MCP PMTs: main peak with excellent timing accompanied with a tail





- Inelastic back-scattering
- Elastic back-scattering

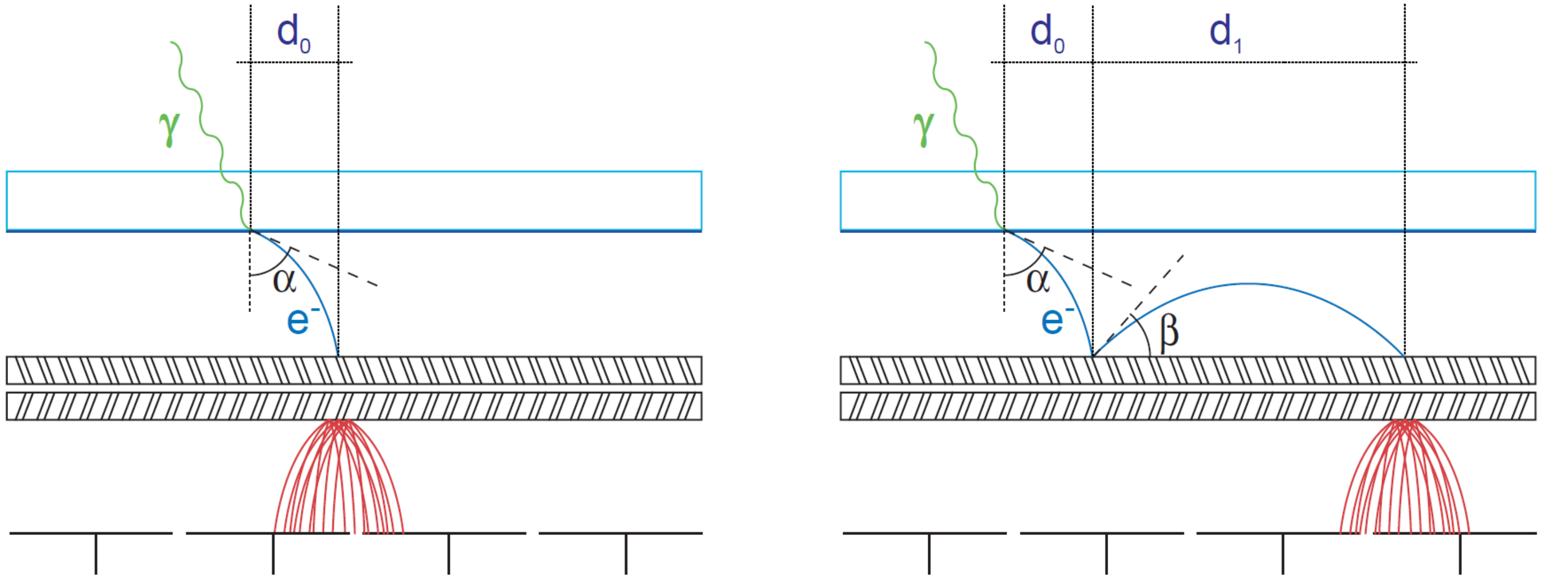
→good agreement with a simple model →

→ NIMA 595 (2008) 169

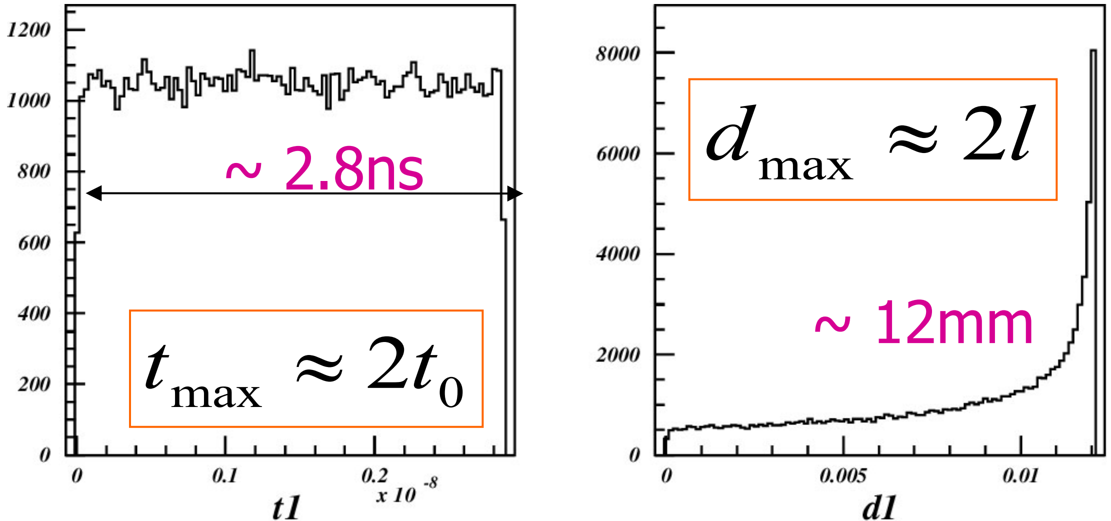
→ JINST 4 (2009) P11017

Elastically backscattered photoelectrons

simple model: assume that the photoelectron back-scattering by the angle β is uniform over the solid angle.



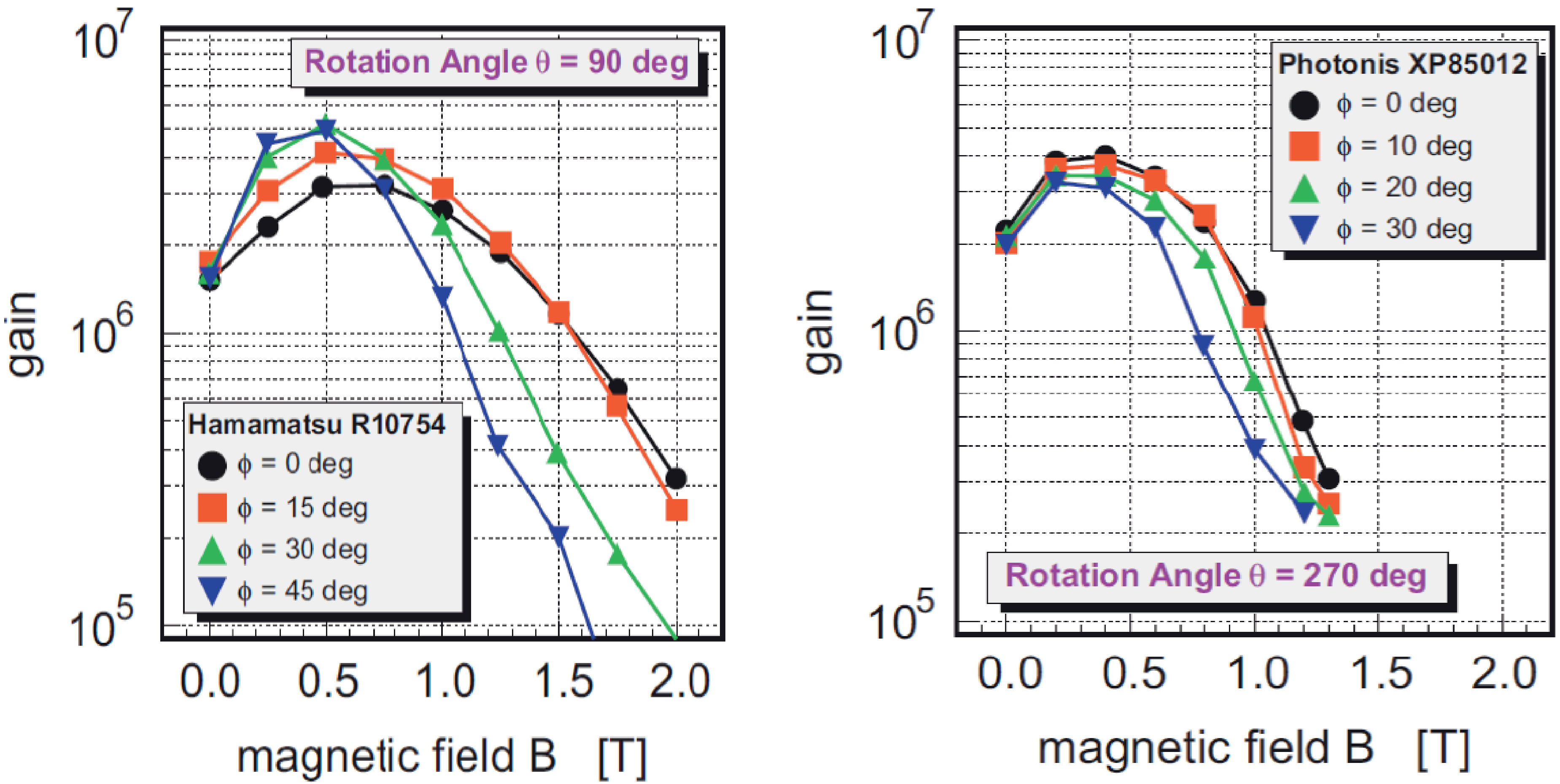
time required for the photoelectron to return to the MCP



lateral distance travelled between point of backscattering and point where charge multiplication in the MCP begins

MCP PMTs in magnetic field

Gain vs B field for different tilt angles



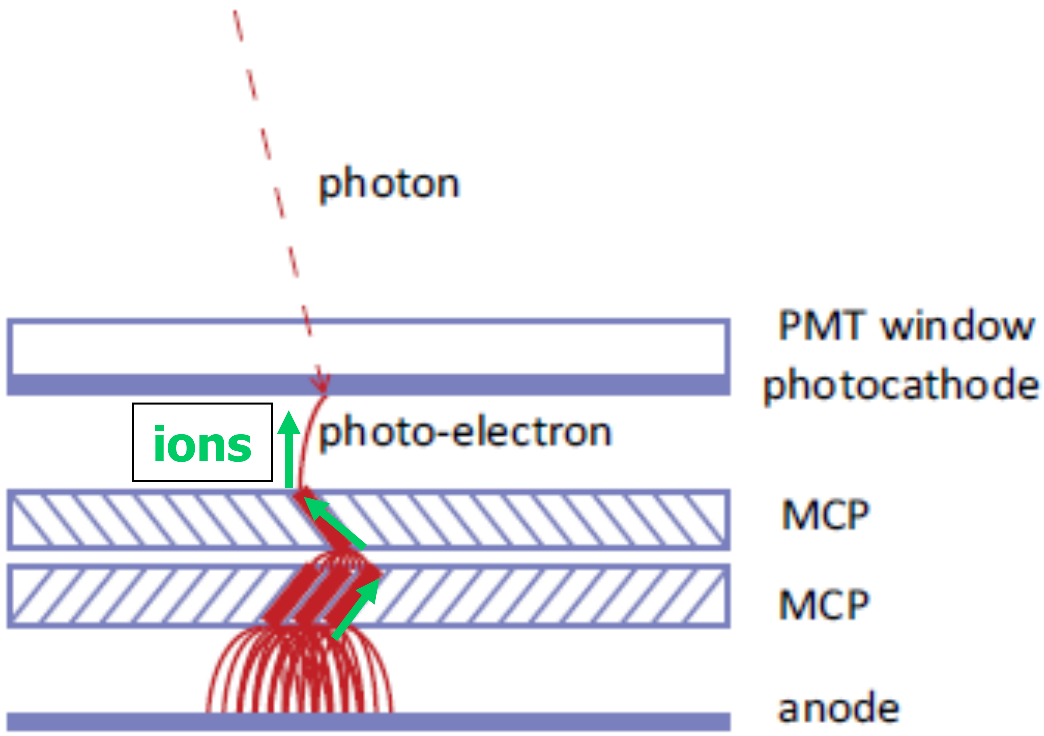
→ NIMA 639 (2011) 144

MCP PMTs ageing

a serious problem in some aplications

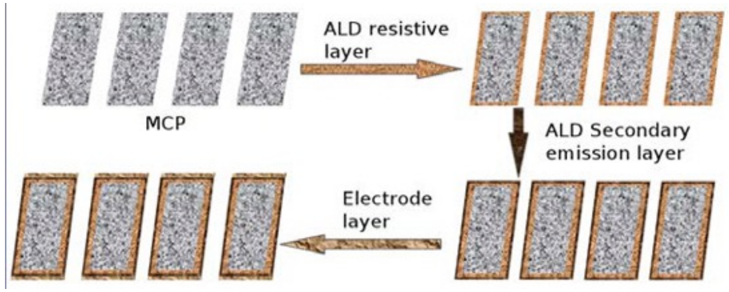
Cures:

- Better cleaning of the MCPs, better vacuum
- Al foil between PC and first MCP
- Al foil between two MPC stages
- Atomic layer deposition (ALD)

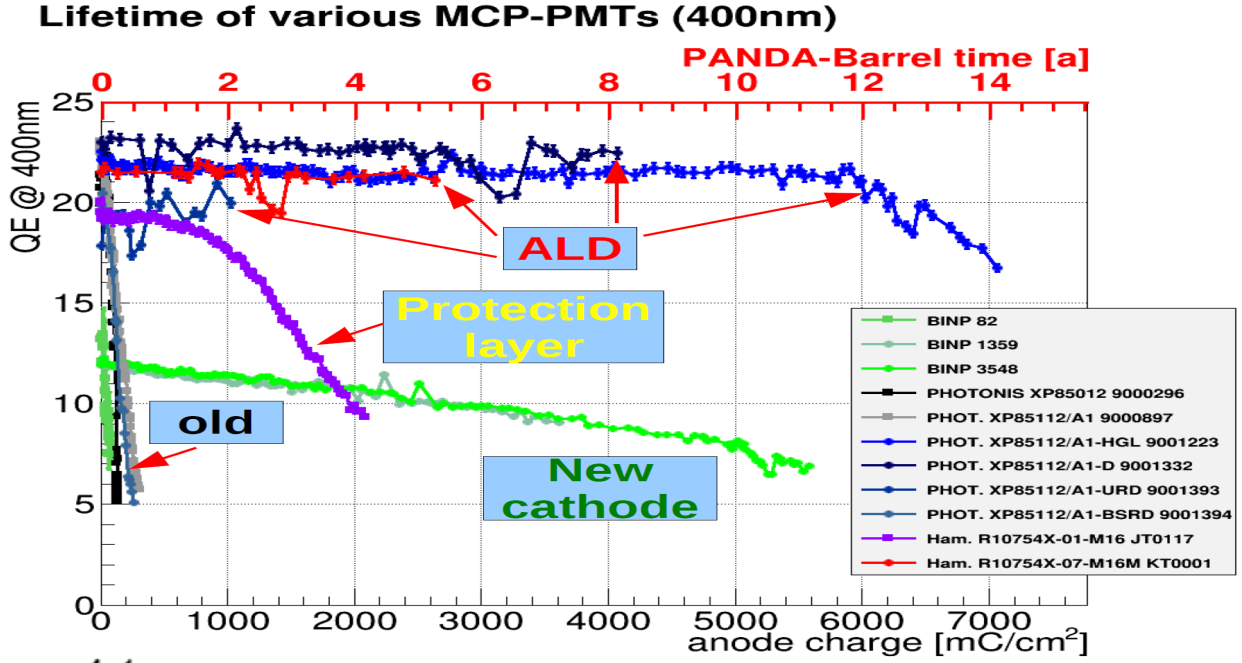


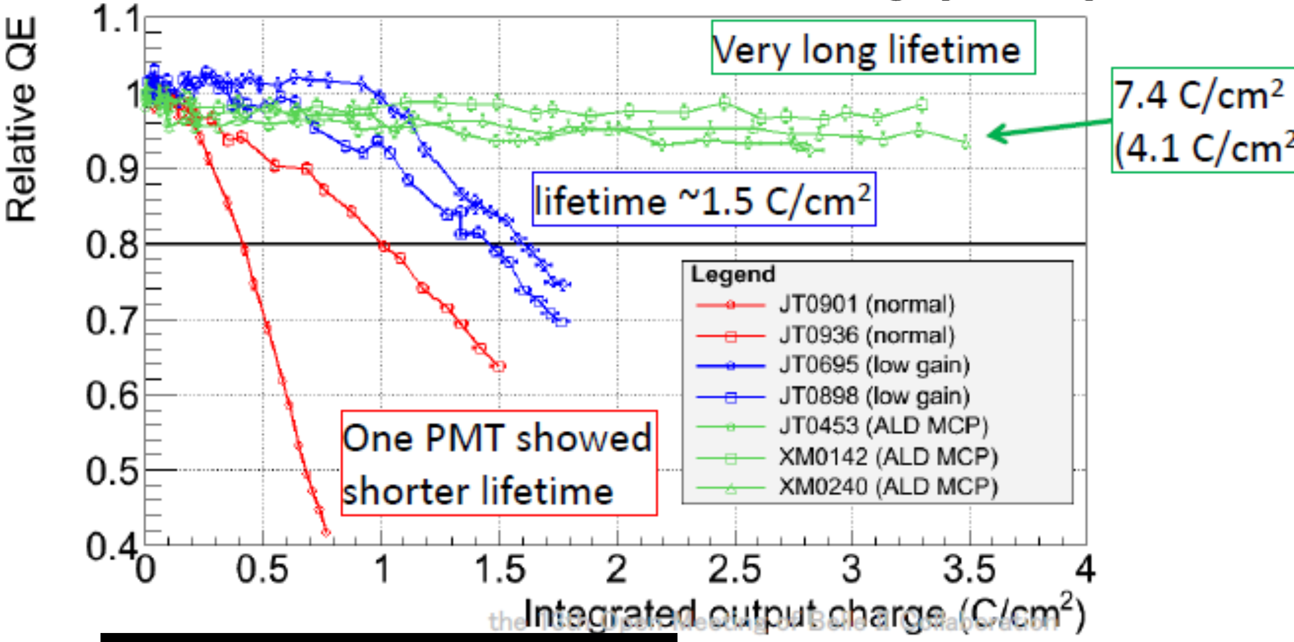
MCP PMTs ageing, cure

Atomic Layer deposition



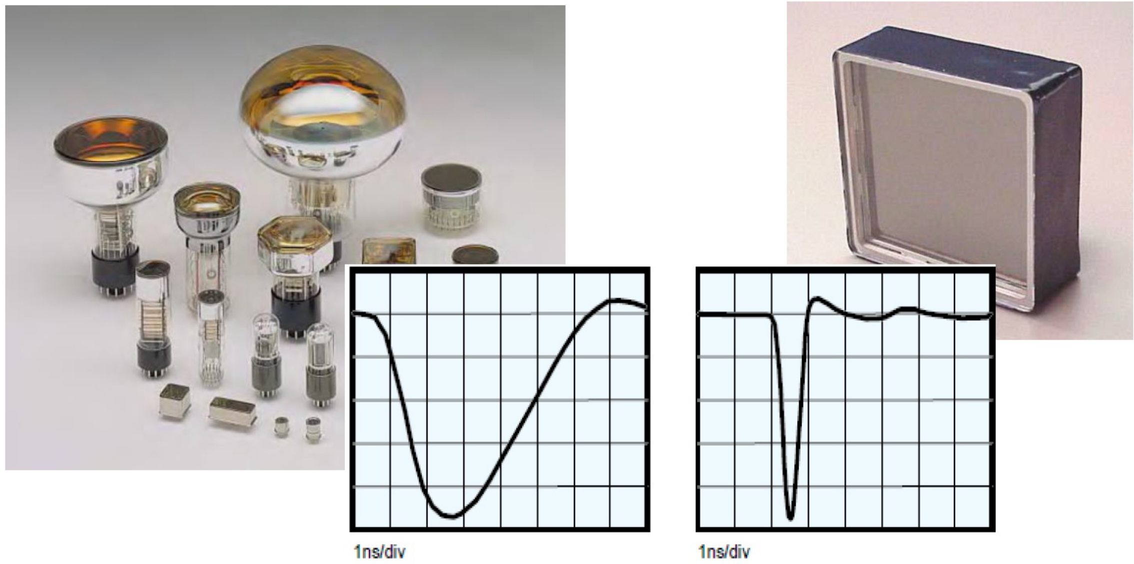
Three-step deposition process
- Resistive layer
- Secondary emission layer
- Electrode layer





Hamamatsu, ALD deposition

PMT vs MCP–PMT



- Successful technology over decades
- Large area available at low cost
- Rather fast: ns timing
- But……
  - Bulky
  - Limited position resolution
  - Low magnetic field tolerance

MCP-based photomultipliers
- Compact design
- Picosecond-level time resolution
- Micron-level spatial resolution
- Good magnetic field tolerance
- But……
  - Few vendors, high cost
  - Limited sizes

Light detection in silicon

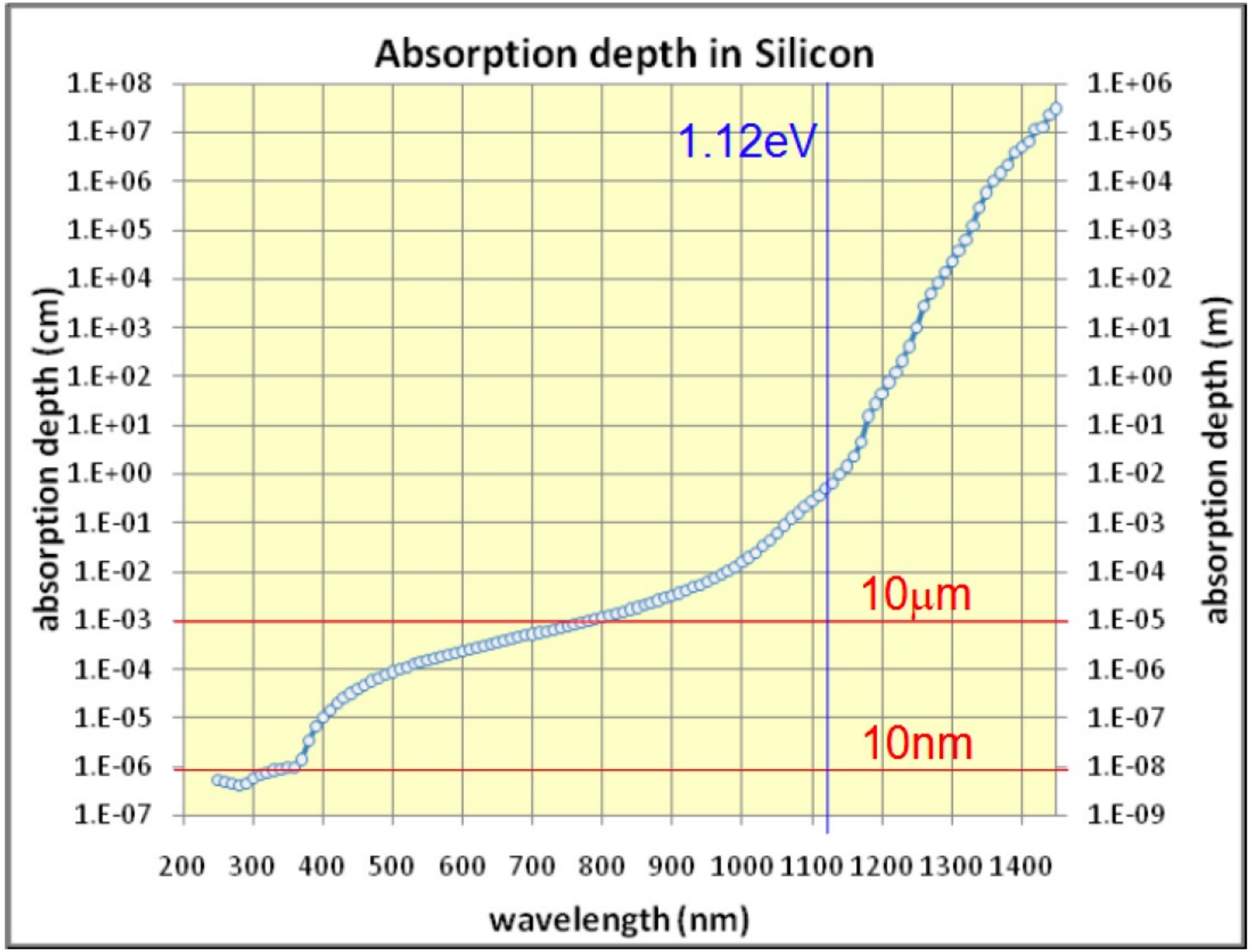
Two main contributions:

- Reflection at the entry surface due to high refractive index n≈5 :

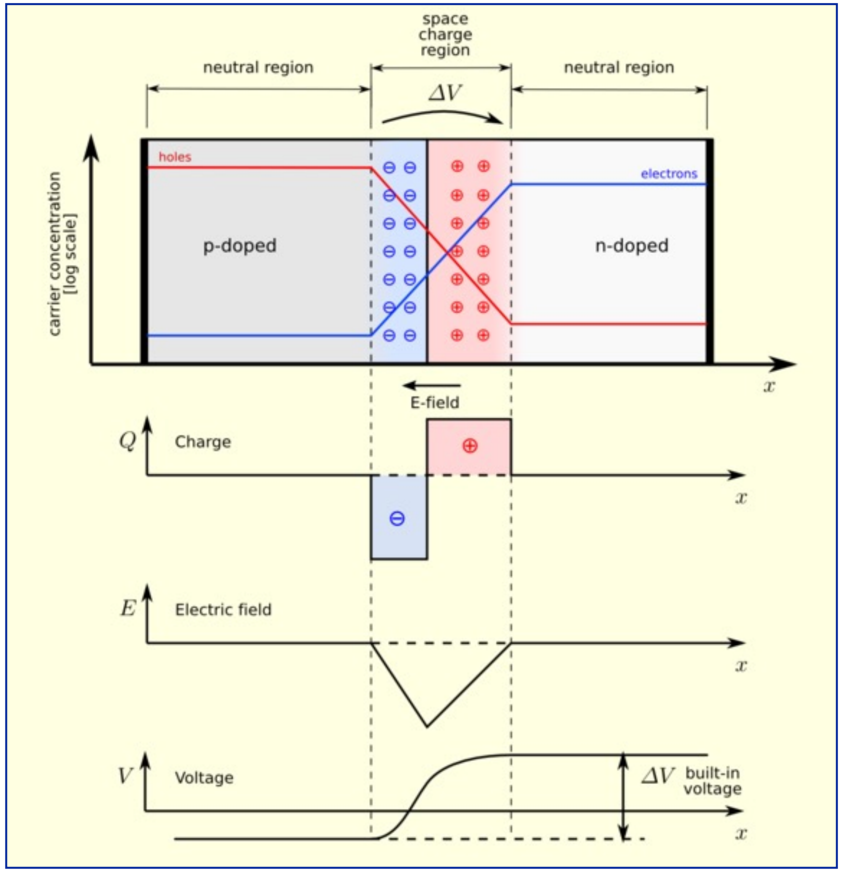
$$\rightarrow R \approx \frac{4^2}{6} = 44\%$$

- Large variation in absorption length

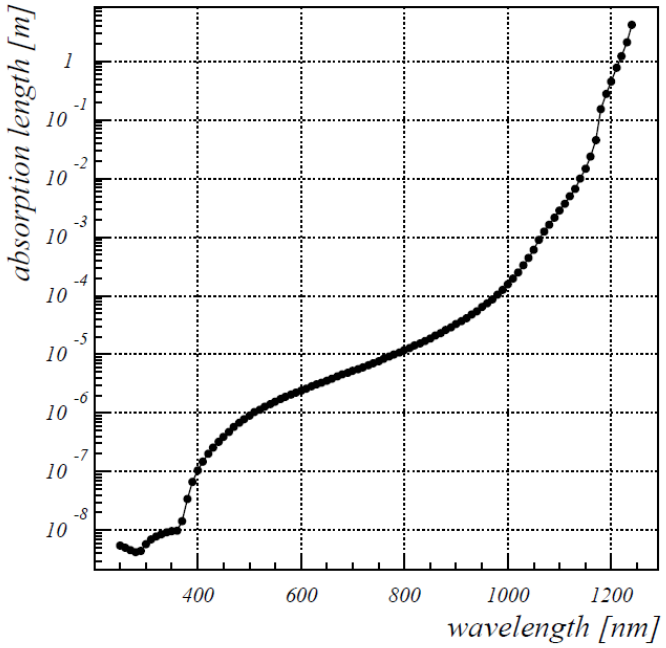
- absorption at the surface for short λ
- transparent for long λ



The P-N Junction

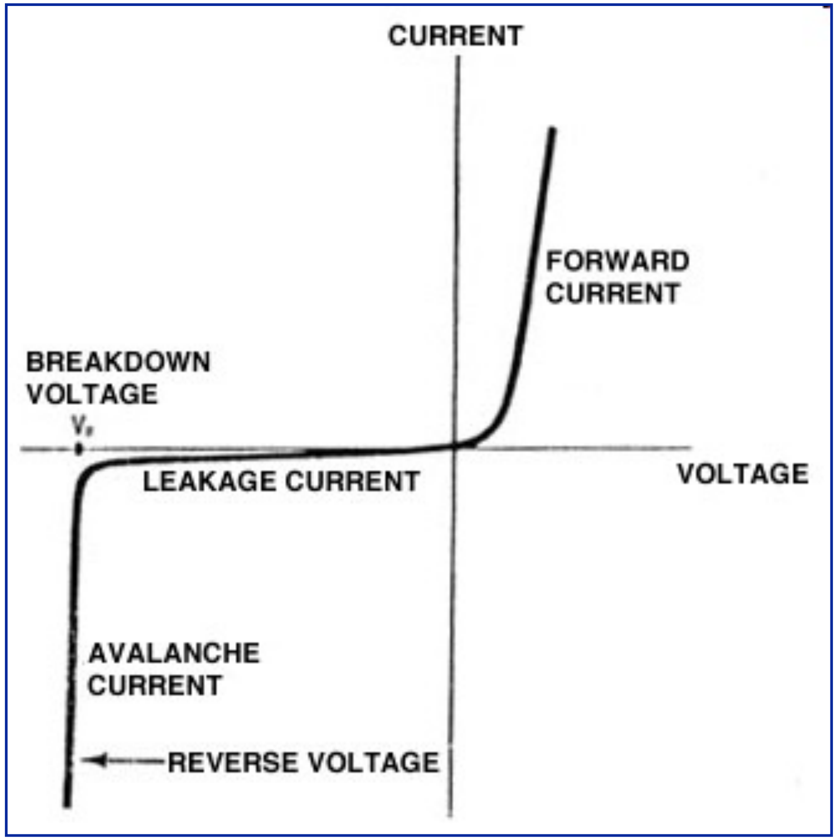


- Electrons and holes diffuse to area of lower concentration
- Electric field is built up in the depletion layer
- Drift of minority carriers
- Capacitance



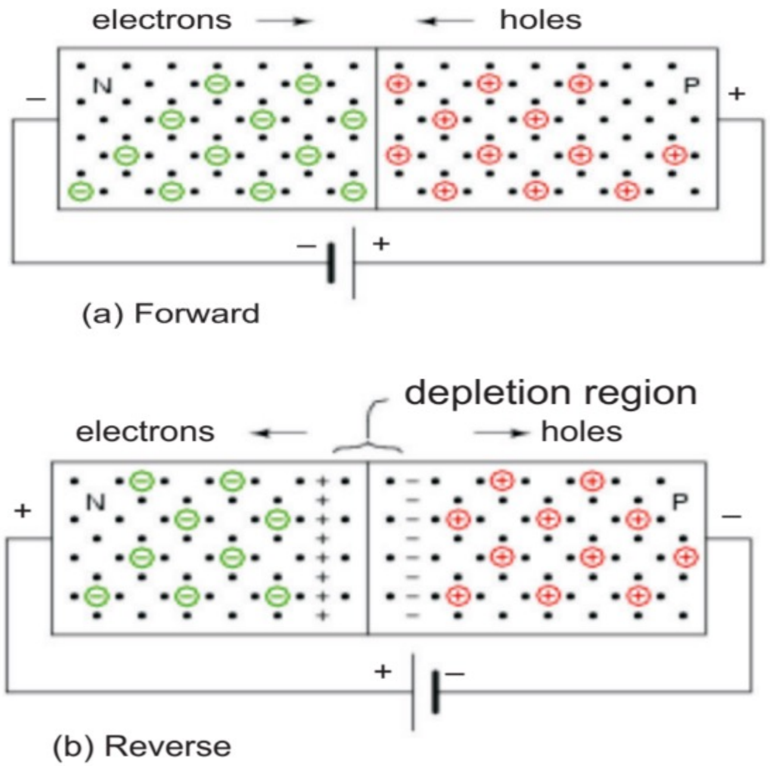
Biased P-N junction

- When connected to a voltage source, the I-V curve of a P-N junction is given by:



We'll focus on reverse biasing:

1. larger electric field in the junction
2. extended space charge region



The P-N photodiode during illumination

- Electrons and holes generated in the depletion area due to photon absorption are drifted outwards by the electric field

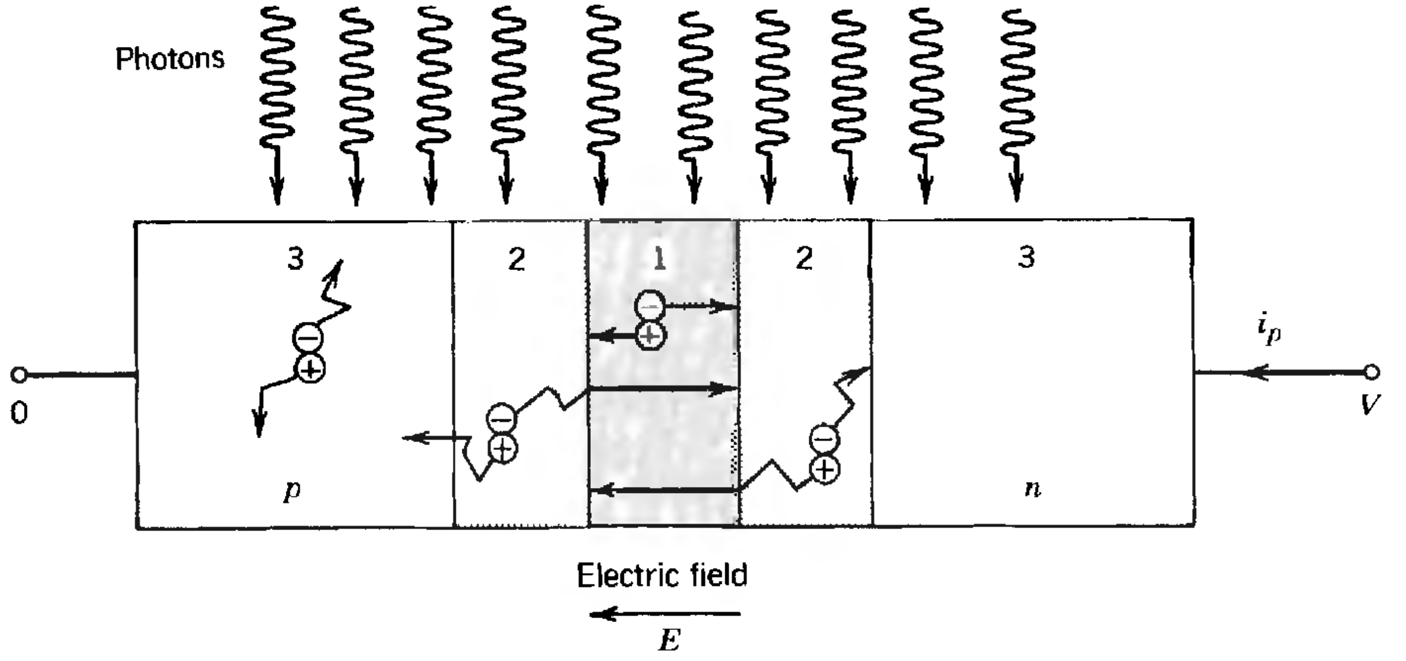


Figure 17.3-1 Photons illuminating an idealized reverse-biased *p-n* photodiode detector. The drift and diffusion regions are indicated by 1 and 2, respectively.

Reverse biasing:

•Electric field in the junction increases quantum efficiency

•Larger depletion layer

•Better signal

Summary: P-N photodiode

- Simple and cheap solid state device
- *High QE (also in the IR region),*
- *No multiplication* -No internal gain, linear response
- Noise (“dark” current) is at the level of several hundred electrons, and consequently the smallest detectable light needs to consist of even more photons
- *Can be used in cases with large light yields (calorimeters)*

Avalanche photodiode

- High reverse-bias voltage enhances the field in the depletion layer
- Electrons and holes excited by the photons are accelerated in the strong field generated by the reverse bias.
- Collisions causing impact-ionization of more electron-hole pairs, thus contributing to the gain of the junction.

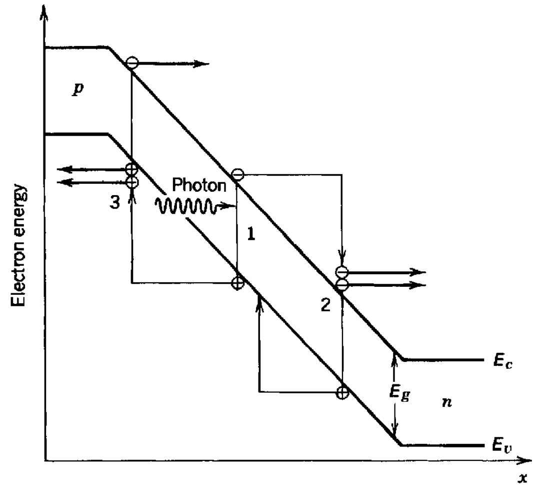
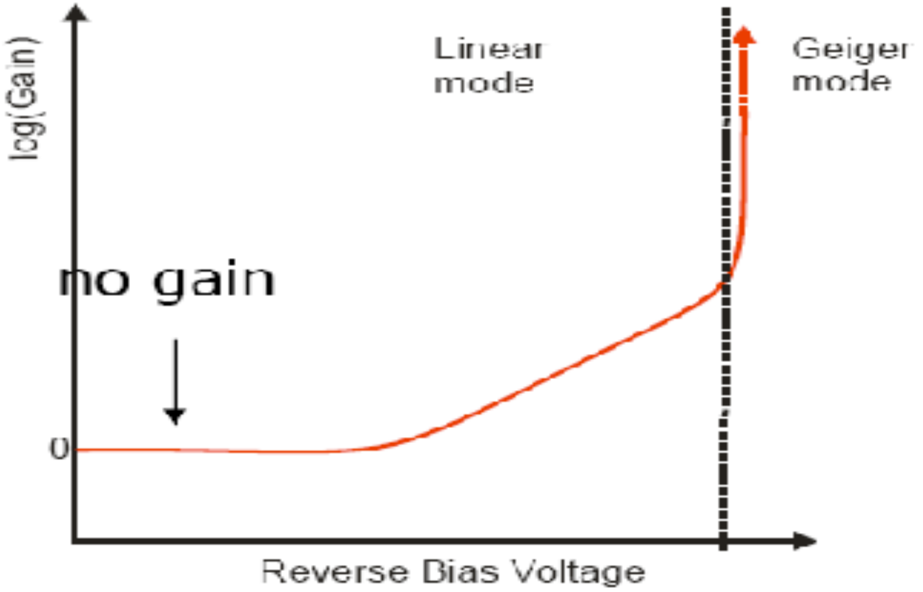


Figure 17.4-1 Schematic representation of the multiplication process in an APD.



Avalanche photodiode

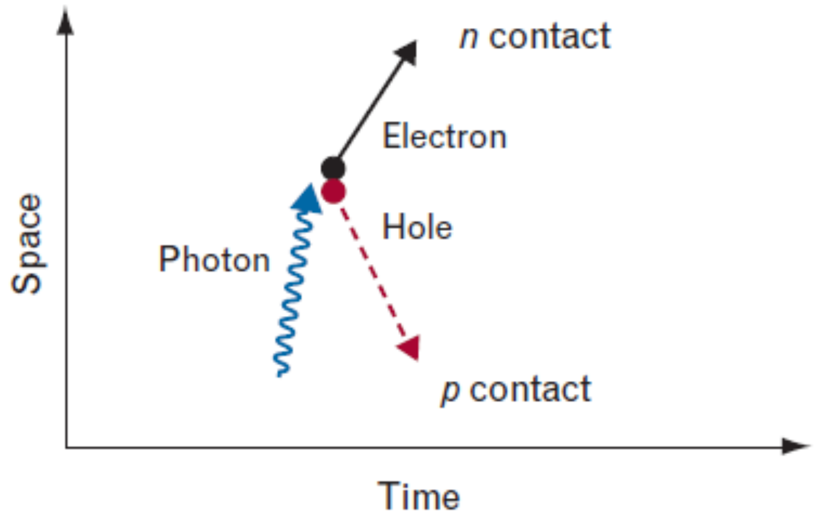


FIGURE 1. Photon detection in a photodiode represented in a simple space-time diagram. The absorption of the photon creates an electron-hole pair, and the two oppositely charged particles drift in opposite directions under the influence of the electric field in the vicinity of the reverse-biased *p-n* junction.

P-N photodiode

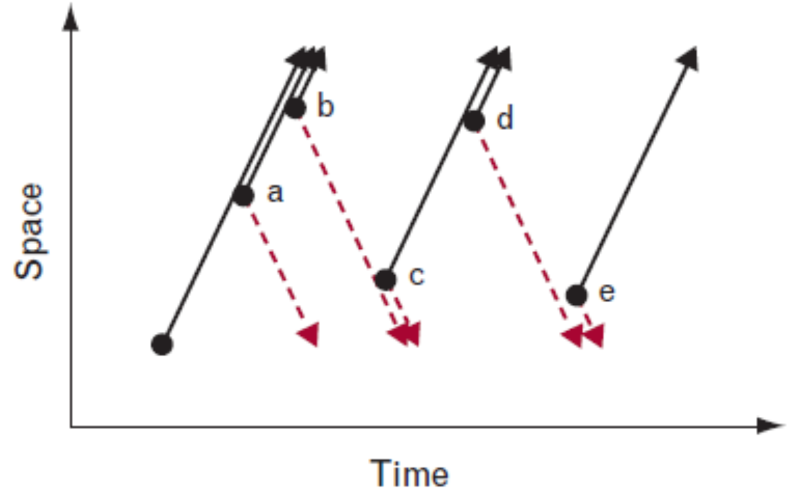


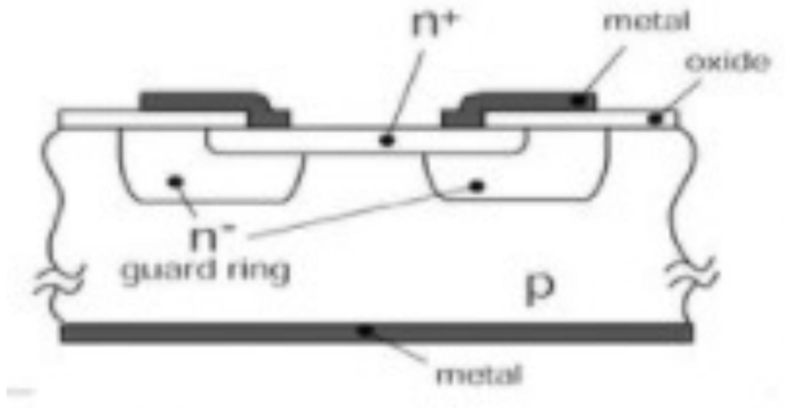
FIGURE 2. Avalanche multiplication illustrated in a space-time diagram. The primary electron (the companion hole is not shown), on the left, starts a chain of impact-ionization events. The solid arrows depict electron trajectories, and the dashed arrows depict hole trajectories. Points a, b, and d represent electron-initiated impact ionizations; points c and e represent hole-initiated impact ionizations.

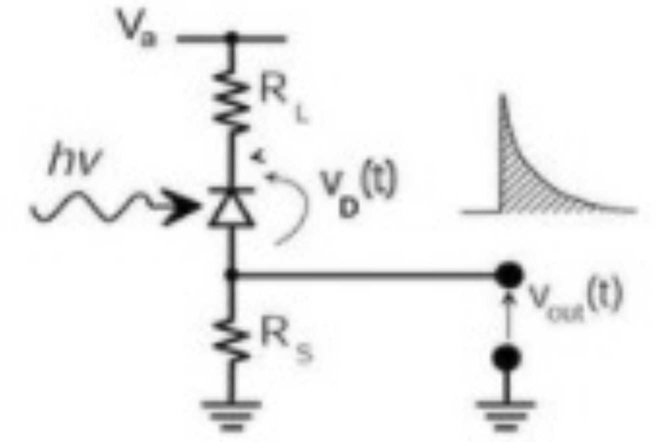
Avalanche photodiode

Summary: APD

- High reverse-bias voltage, but *below* the breakdown voltage.
- region with high E field -> multiplication in an avalanche,
  - $G \approx 10^2$-10^3.
- Detection of weak signals (~20 photons)
- Average photocurrent is proportional to the incident photon flux *(linear mode)*

- signal/noise still poor compared to a PMT
- used for calorimeters





Typical Application Circuit

Geiger mode APD

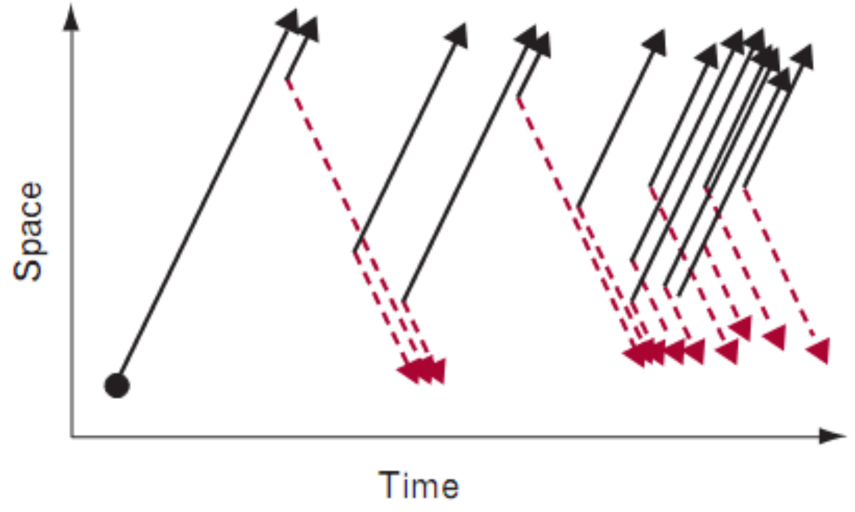


FIGURE 4. Concept of avalanche breakdown voltage. In Geiger mode, in which the avalanche photodiode (APD) is biased above the avalanche breakdown voltage, the growth in the population of electrons and holes due to impact ionization outpaces the rate at which they can be extracted, leading to exponential growth of current.

- In the Geiger mode, the APD is biased above its breakdown voltage for operation in very high gain.
- Electrons and holes multiply by impact ionization faster than they can be collected, resulting in an exponential growth in the current
- Individual photon counting

Geiger mode – quenching

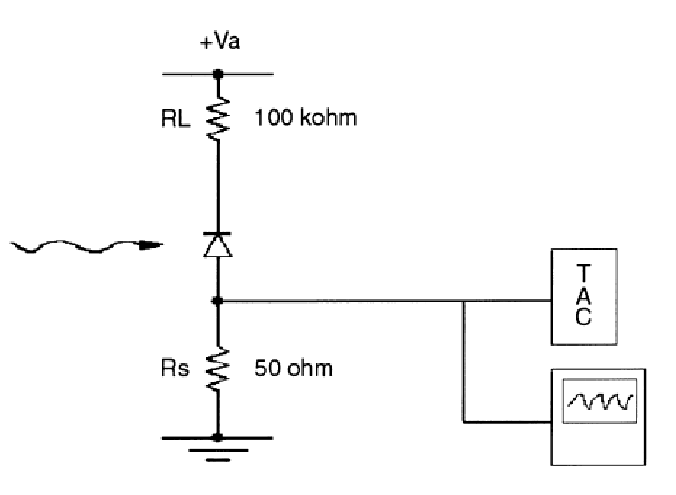
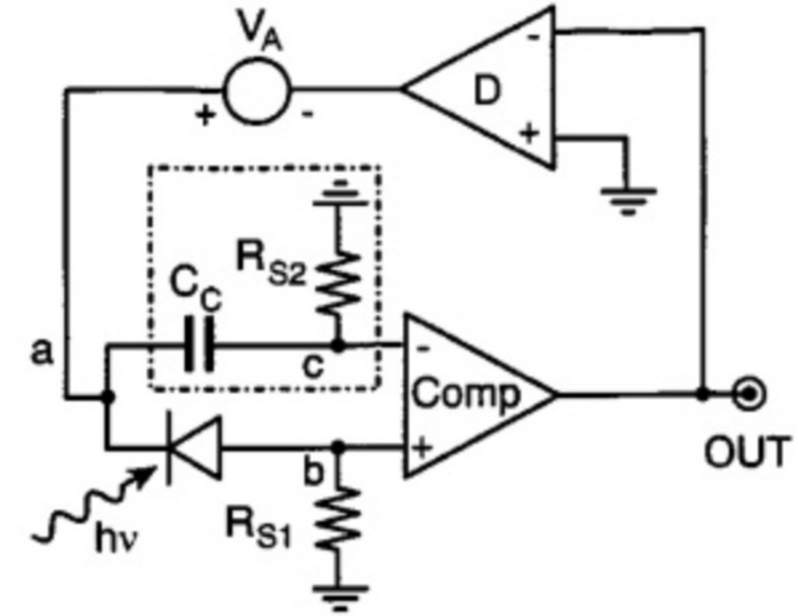
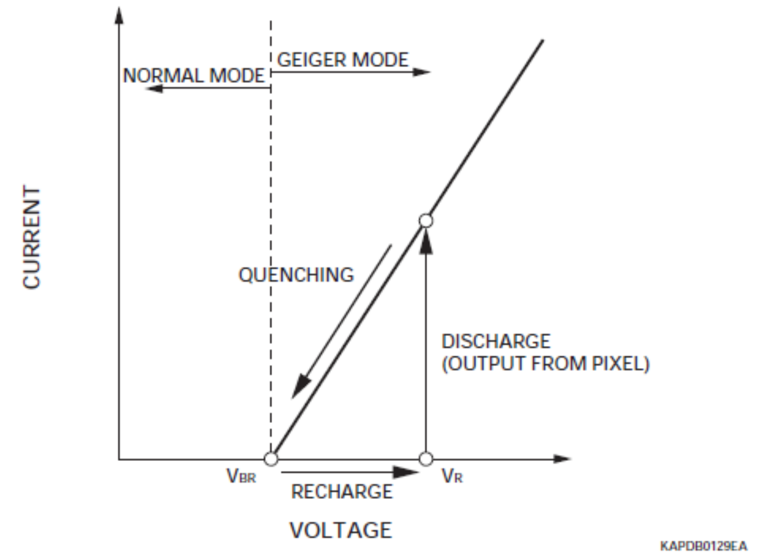
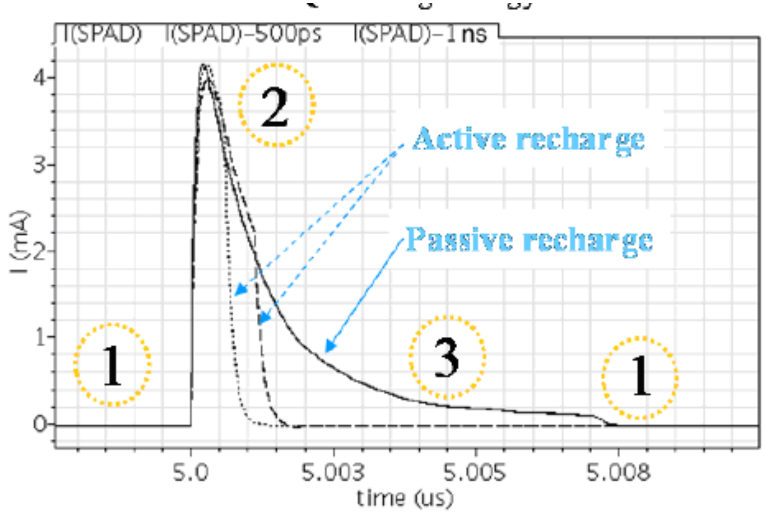


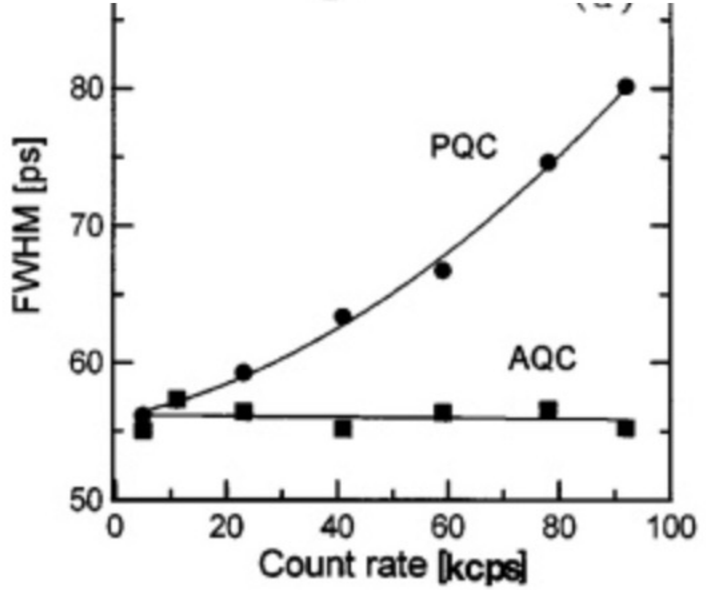
Fig. 3. Diagram of a passive quenching circuit.

- Shutting off an avalanche current is called quenching
- Passive quenching
    - slower, ~10ns dead time
- Active quenching
    - faster







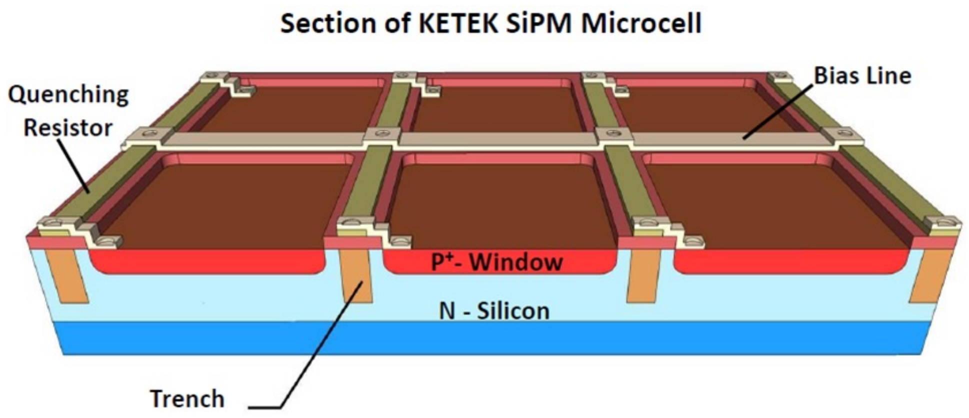


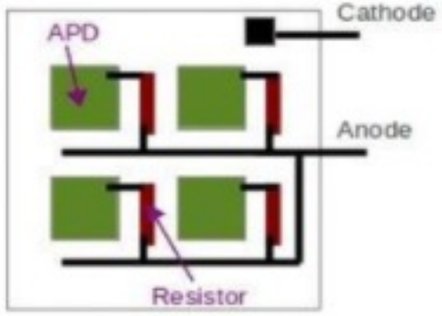
Summary: Geiger mode

- High detection efficiency (80%).
- Dark counts rate (at room temperature) below 1 kHz. Cooling reduces it exponentially.
- After-pulsing caused by carrier trapping and delayed release.
- Correction factor for intensity (due to dead time).

Silicon Photomultipliers

- Array of Geiger mode APDs (above the breakdown voltage) → large gain, binary signal, long recovery
- Microcell = GAPD (~20um)
- made on a silicon substrate, with 100-5000 pixels/mm². Total area 1-40mm².
- The independently operating pixels are connected to the same readout line





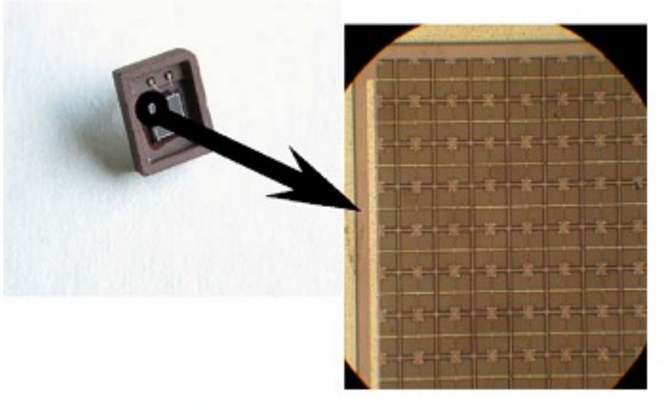
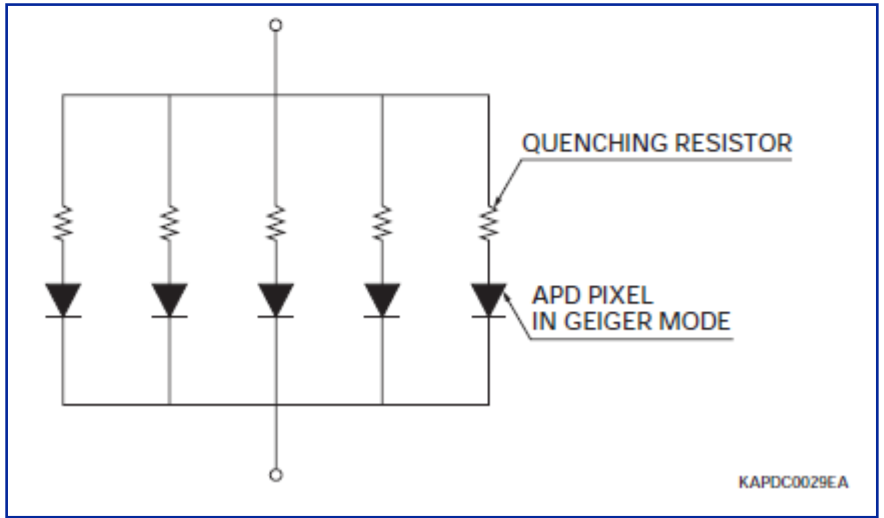
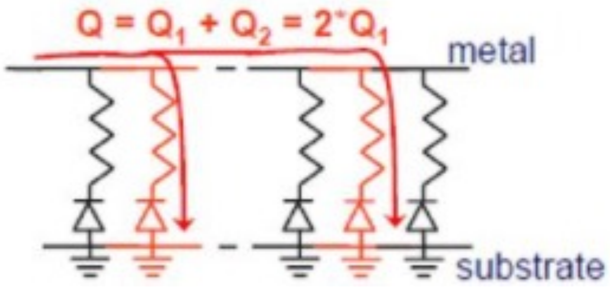


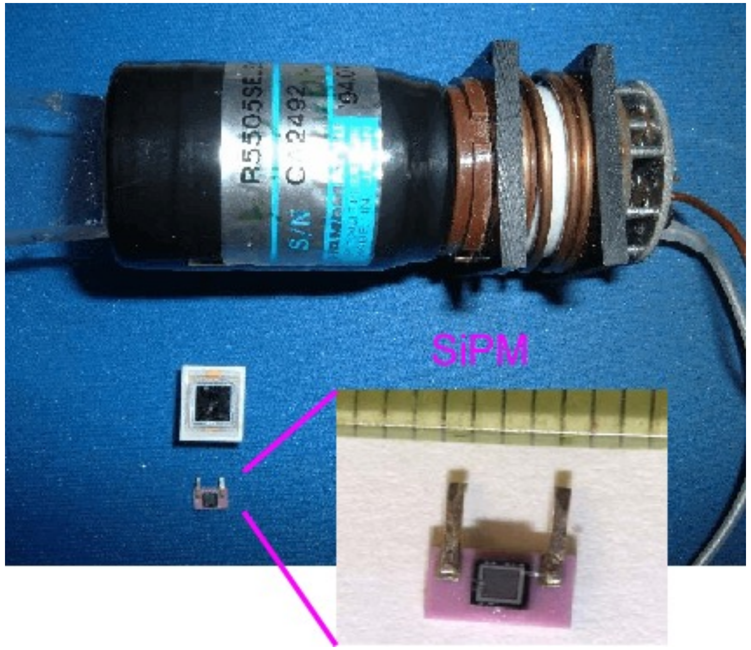
Fig. 9. SiPM 3 × 3 mm², 5625 pixels.





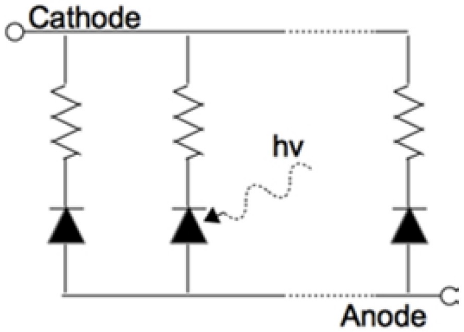
Traditional PM

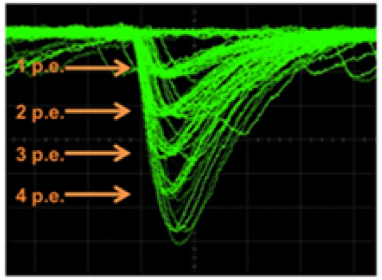
Characteristics of SiPM

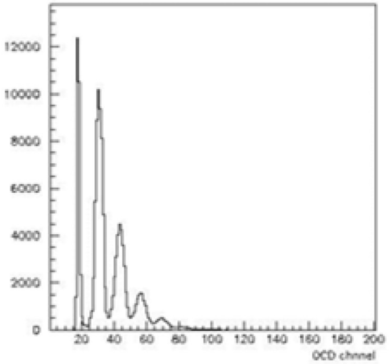


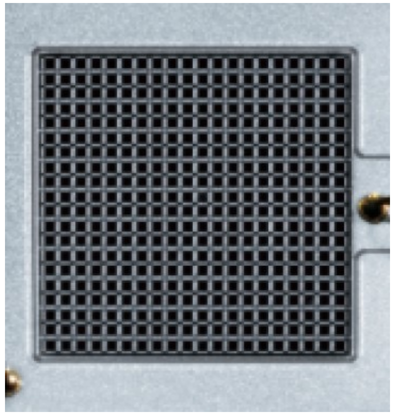
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)

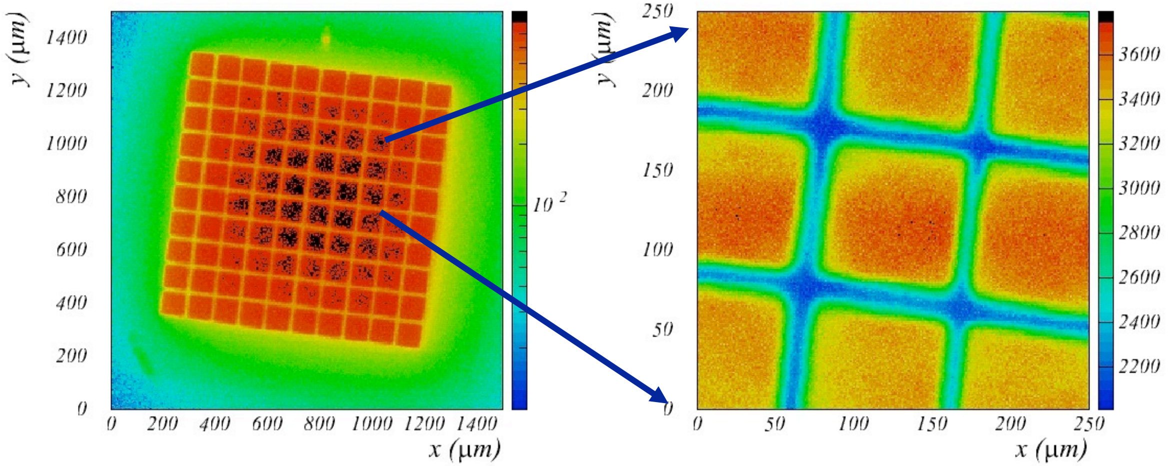


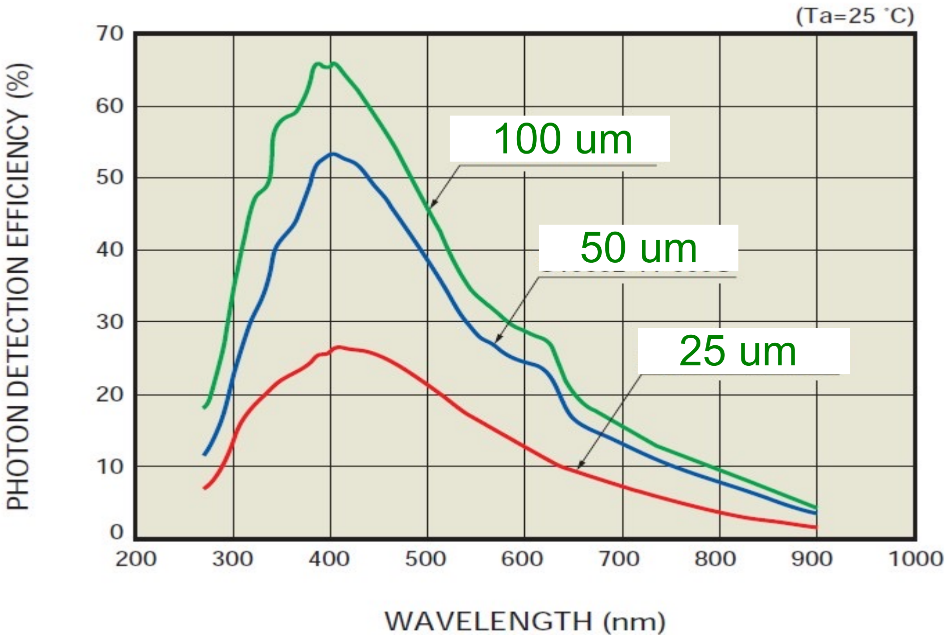




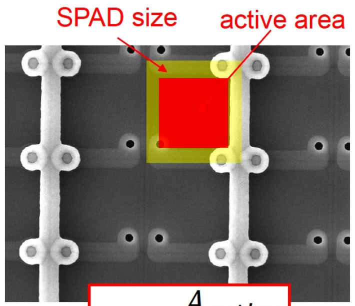


SiPMs as photon detectors

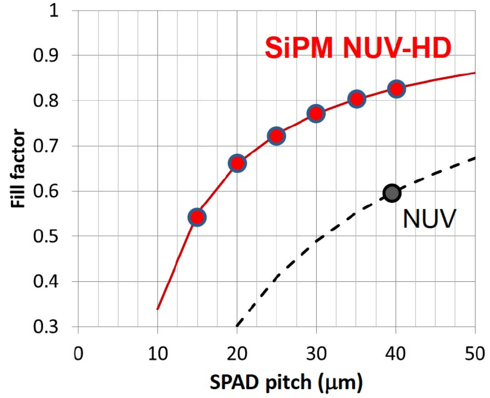




NUV-HD: Fill Factor



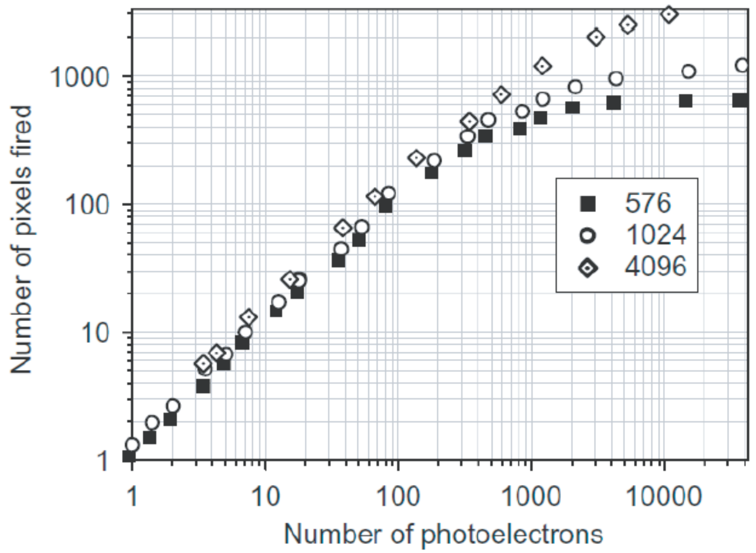
$$FF = \frac{A_{active}}{A_{total}}$$



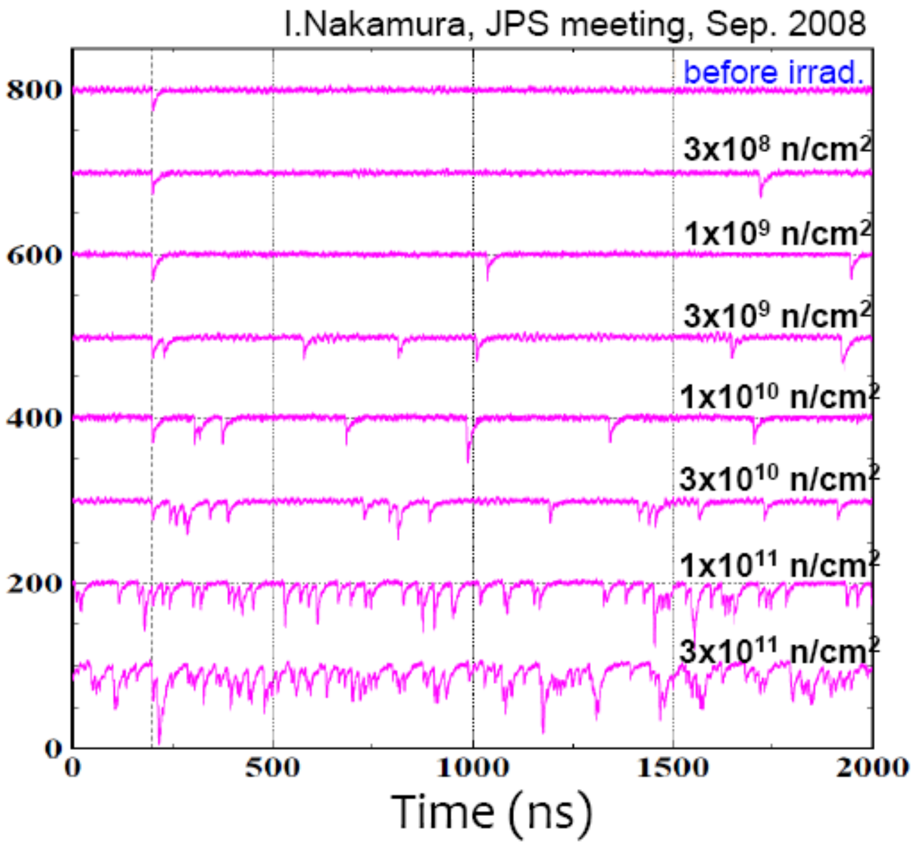
SPAD Pitch	15 μm	20 μm	25 μm	30 μm	35 μm	40 μm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

High Dynamic Range, Low correlated noise ⟷ (20–25 μm)

High PDE ⟷ (35–40 μm)



Radiation damage



Expected fluence at 50/ab at Belle II:
2-20 10^{11} n cm^{-2}

→ Worst than the lowest line

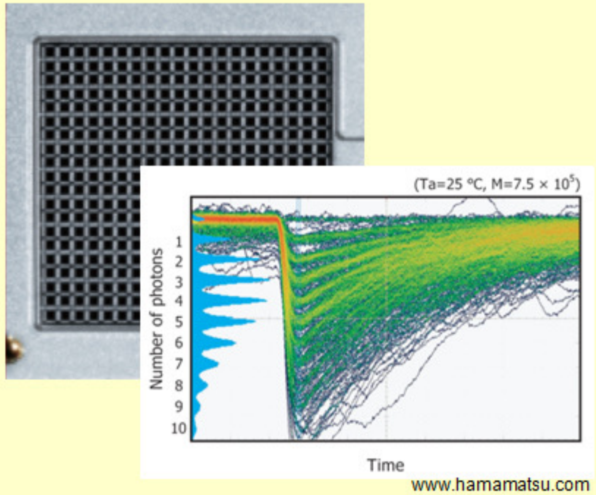
→Very hard to use present SiPMs as single photon detectors in many because of radiation damage by neutrons

→ Also: could only be used with a sofisticated electronics – wave-form sampling

Digital SiPM

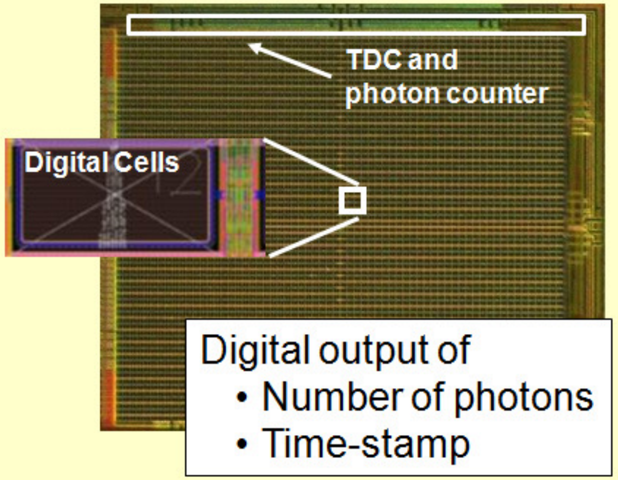
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

analog SiPM

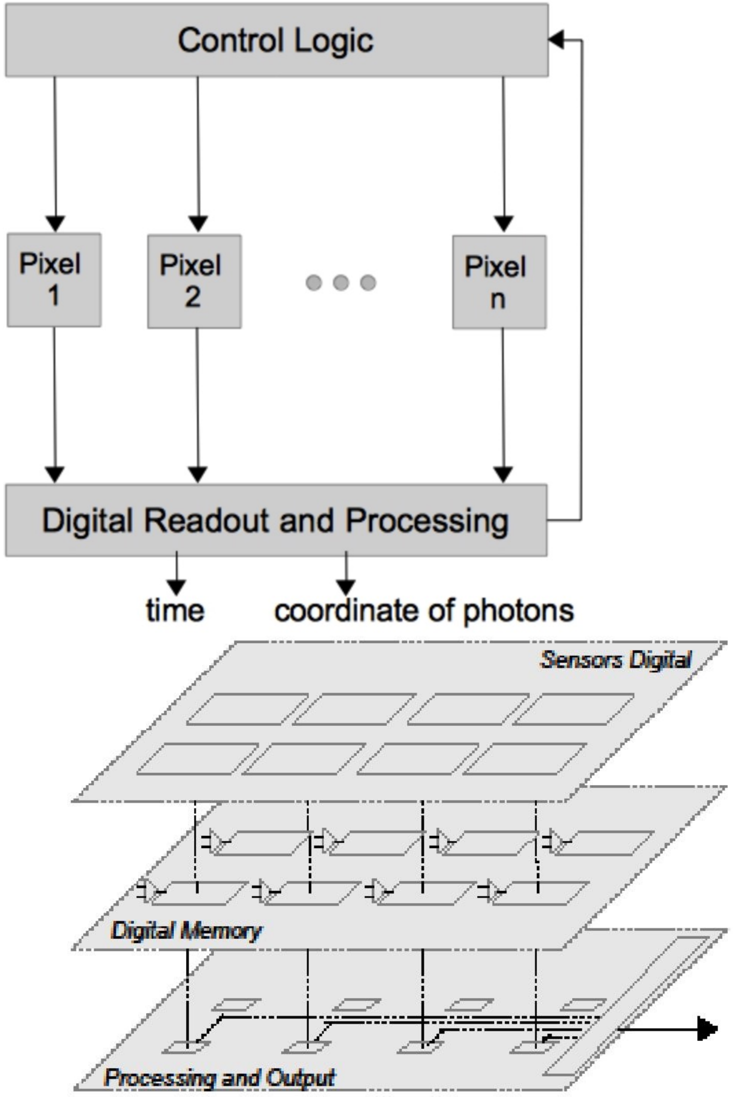


Summing all cell outputs leads to an analog output signal and limited performance

digital SiPM (dSiPM)



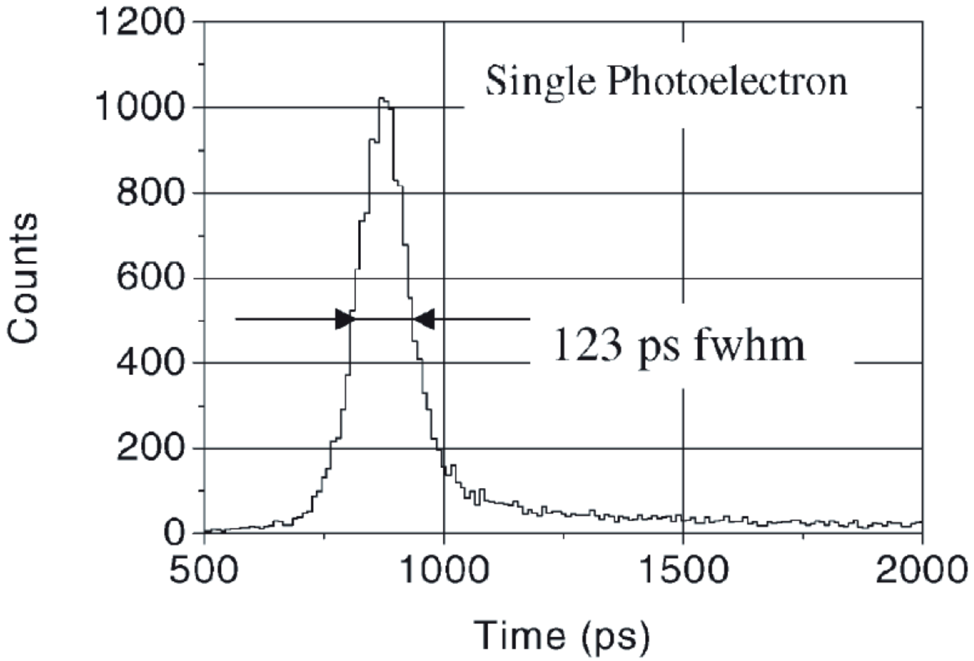
Integrated readout electronics is the key element to superior detector performance



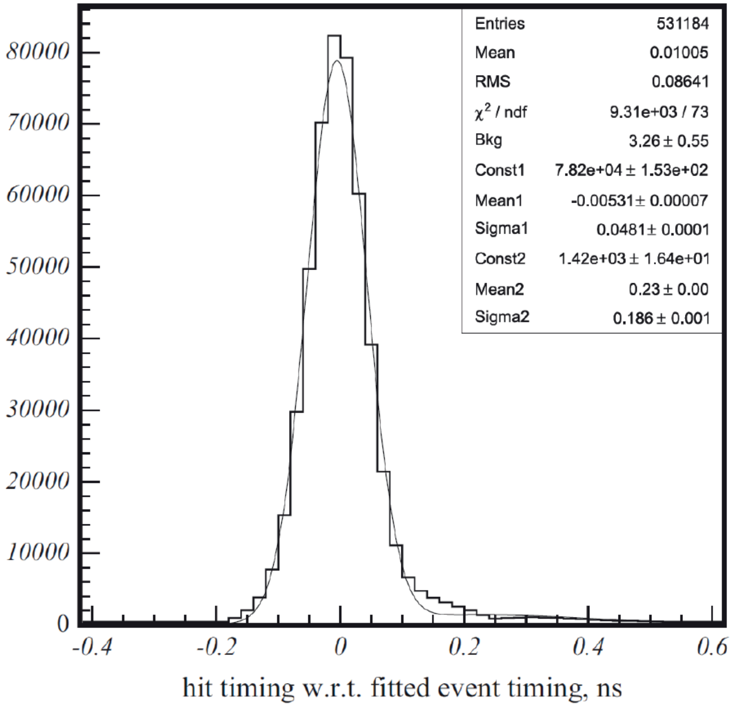
- New perspectives: 3D integration
- advanced photon-detection structures,
    - improved detection efficiency

SiPM: time resolution for single photons

Very fast analog SiPM



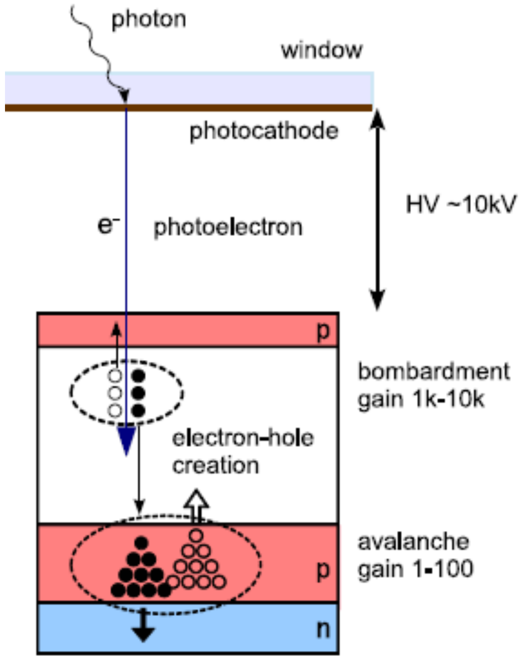
Digital SiPM

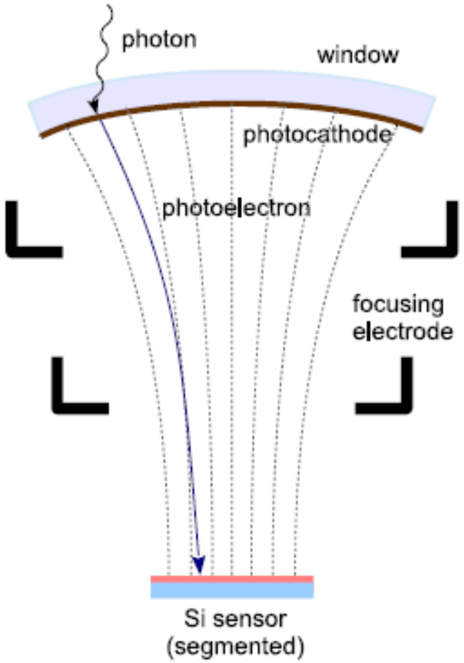


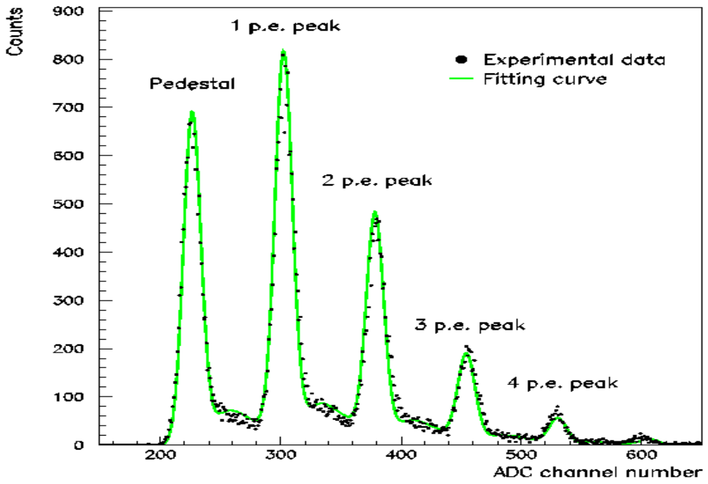
Analog SiPMs: typically 80 ps (sigma), 200 ps FWHM
Digital SiPMs: main peak 48 ps (sigma)!

Hybrid Photon Detectors

- Developed from PMT: Instead of using a dynode chain to provide the amplification, accelerate the photoelectrons with electric field
  and use a silicon sensor as anode
- It takes 3.6 eV to create an electron-hole pair in silicon: for accelerating voltage 20 kV
  → ~ 5000 e^- signal, enough to be detected using low-noise electronics
- *Advantages:* very good energy resolution (sensitivity to number of individual photons), silicon sensor can be segmented as required
  Disadvantages: requires high voltage,
  ion feedback → requires very good vacuum



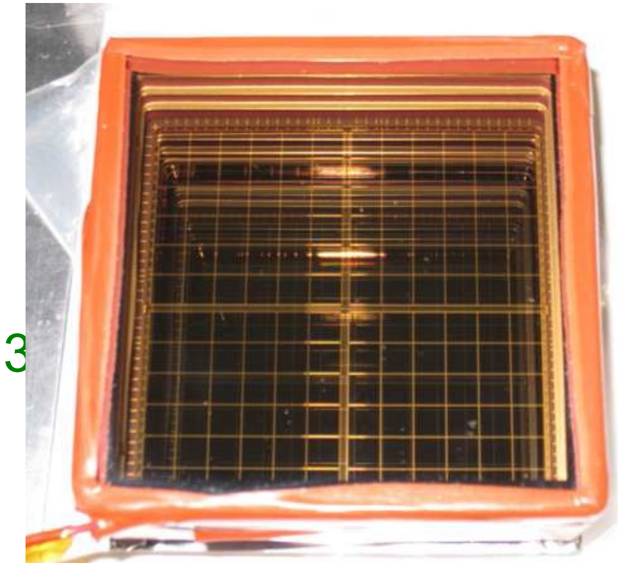


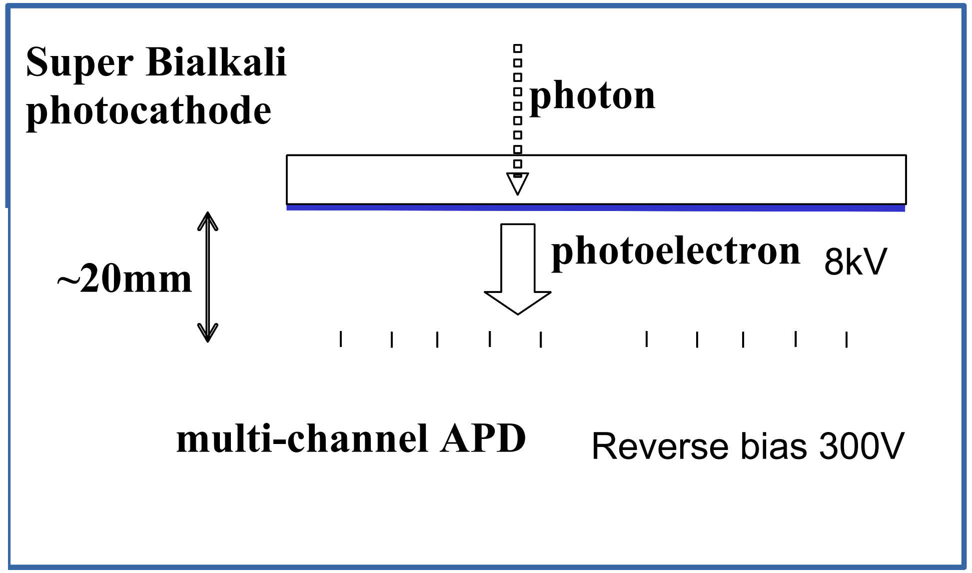


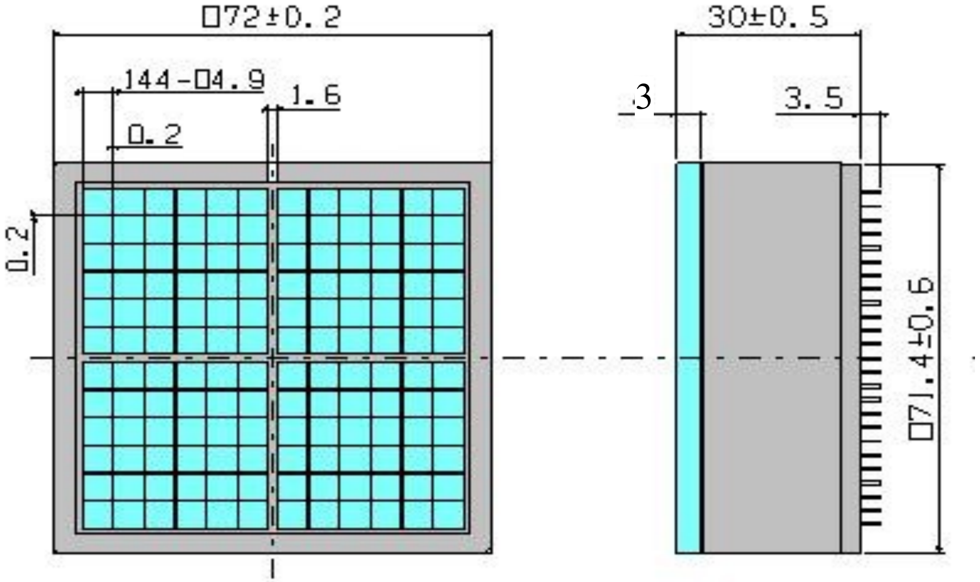
Hybrid Avalanche Photon Detector – Belle II RICH

Hybrid avalanche photo-detector developed in cooperation with Hamamatsu Photonics K.K. (proximity focusing configuration):

- 12 x12 channels (~ 5 x 5 mm^2)
- size ~ 72 mm x 72 mm
- ~ 65% effective area
- total gain > 4.5x10^4 (two steps: bombardment > 1500, avalanche > 3
- detector capacitance ~ 80pF/ch.
- super bi-alkali photocathode, typical peak QE ~ 28% (> 24%)
- works in mag. field (~ perpendicular to the entrance window)

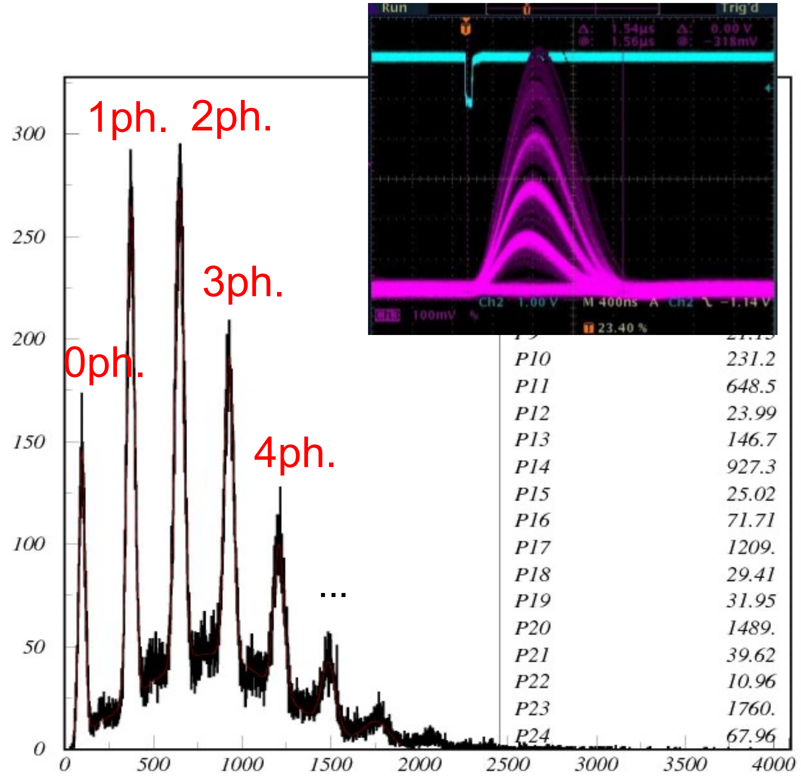


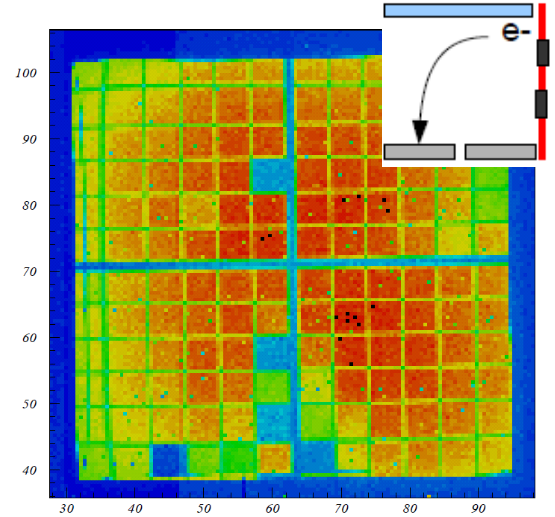


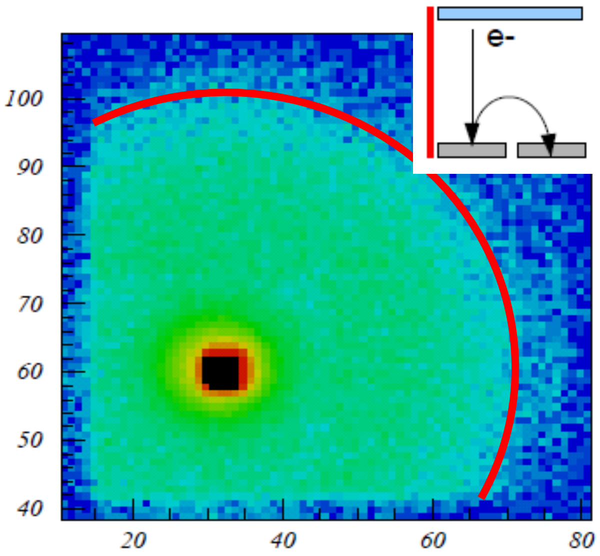


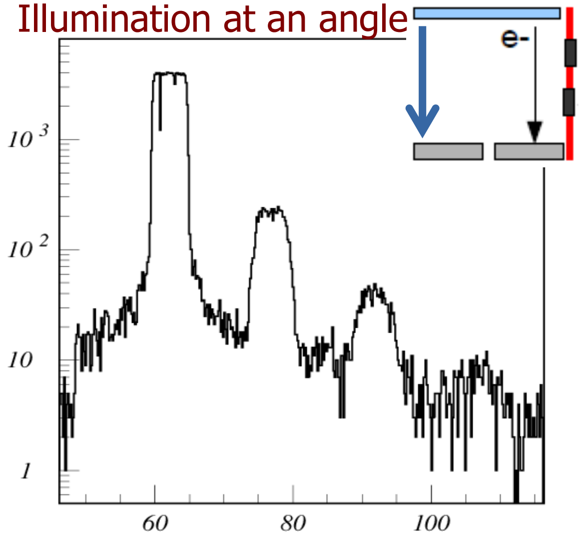
HAPD performance @ B=0T

- excellent photon counting affected only by photo-electron back-scattering → high single photon counting efficiency
- sharp transition between channels
- image distortion due to a non-uniform electric field at the edges
- back-scattering induced cross-talk
- optical cross-talk by reflection from APD surface → weak echo ring





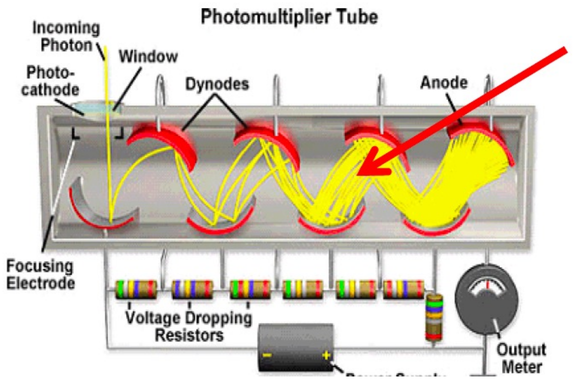




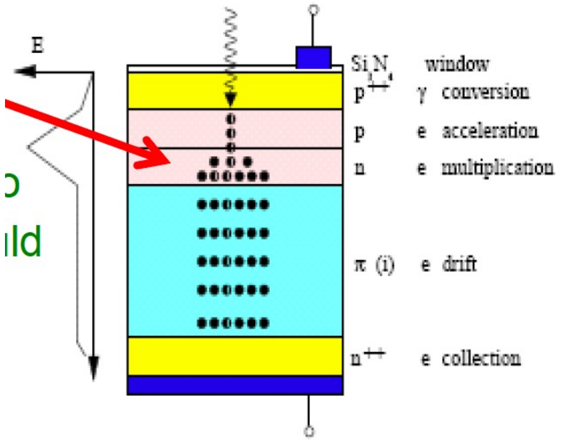
Characteristics

- Sensitivity
- Linearity
- Signal fluctuations
- Time response
- Rate capability / aging
- Dark count rate
- Operation in magnetic field
- Radiation tolerance

Statistical fluctuations –excess noise factor (ENF)



Statistical fluctuation of the avalanche multiplication influence the energy resolution of a photo-detector to a given photon signal beyond what would be expected from simple photoelectron statistics (Poisson distribution).



If photons are Poisson distributed so are photoelectrons with average $n_{pe}=PDE\cdot n_\gamma$
After multiplication with average gain and variance $M,\sigma_M{}^2$ we get average output signal $n=M\cdot n_{pe}$ and

Excess noise factor is $$\frac{\sigma_n^2}{\bar{n}^2}=\left(1+\frac{\sigma_M^2}{M^2}\right)\cdot\frac{\sigma_{pe}^2}{\bar{n}_{pe}^2}=ENF\cdot\frac{1}{\bar{n}_{pe}}=\mathrm{ENF}\cdot\frac{1}{PDE}\cdot\frac{1}{\bar{n}_\gamma}$$

Impact on photon counting capability anc

$$ENF=\frac{\sigma_{out}^2/N_{out}^2}{\sigma_{pe}^2/N_{pe}^2}=1+\frac{\sigma_M^2}{M^2}=\frac{\langle M^2\rangle}{\langle M\rangle^2}$$

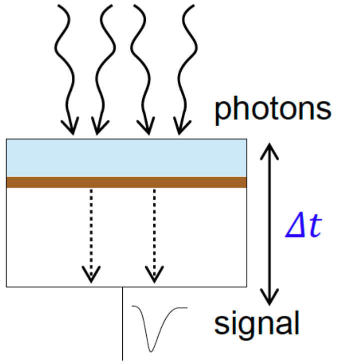
multiplication fluctuations are characterized by Excess Noise Factor-I

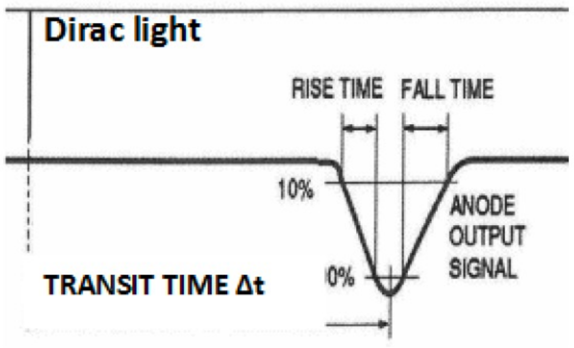
$$\frac{\sigma_E}{E}=\sqrt{\frac{ENF}{PDE}}\sqrt{\frac{1}{N_\gamma}}$$

sensor	ENF
PMT	1-1.5
APD(Si)	~3 @ gain=50
HPD, HAPD	~1
SiPM	1-1.5
MCP-PMT	1-1.5

Time response

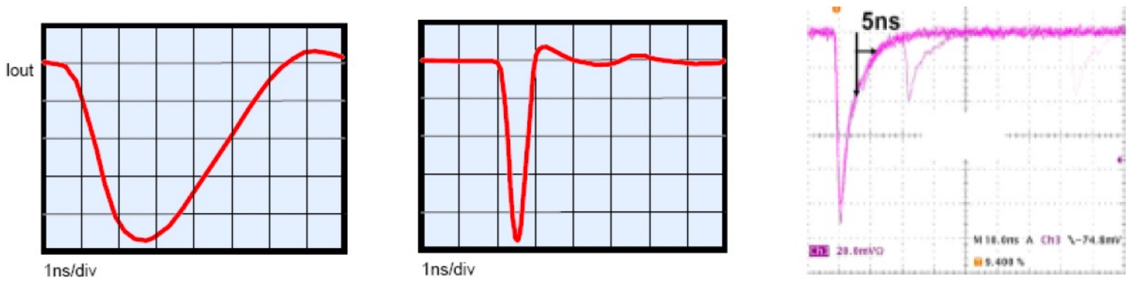
Light travels 3 mm in 10ps (vacuum)



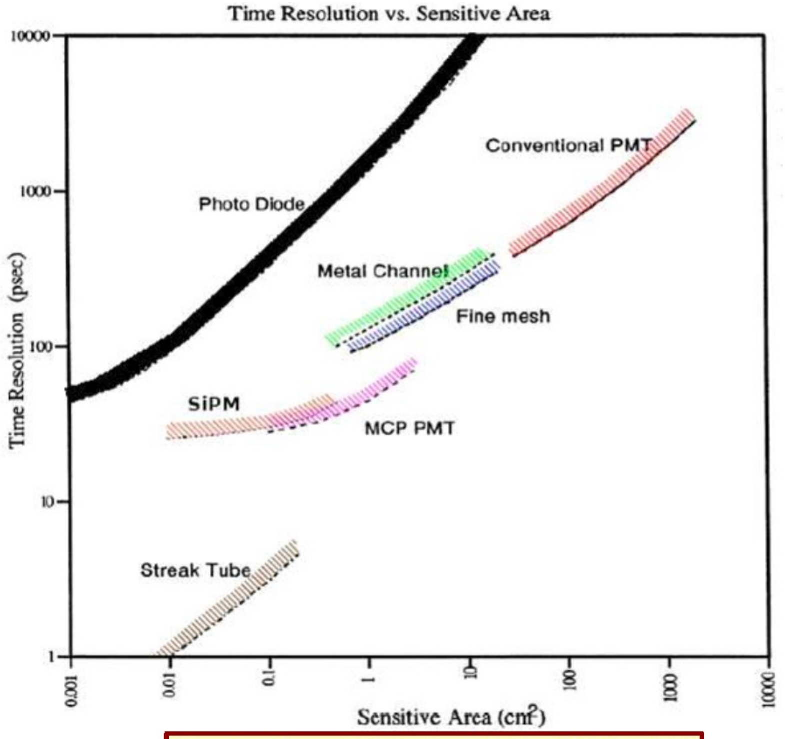


- ●Rise time, fall time (or decay time)
- ●Duration
- ●Transit time (Δt): time between the arrival of the photon and the electrical signal
→ trigger decision time
- ●Transit time spread (TTS): transit time variation between different events
→timing resolution

Some typical signals:



PMT MCP-PMT SiPM



Adapted from K.Arisaka NIMA 442(2000)80

Applications requiring good timing:
- ●Cherenkov light based TOF systems
- ●Time-Of-Propagation counter (Belle II)
- ●Focusing DIRC with chromatic correction (SuperB)
- ●TOF PET

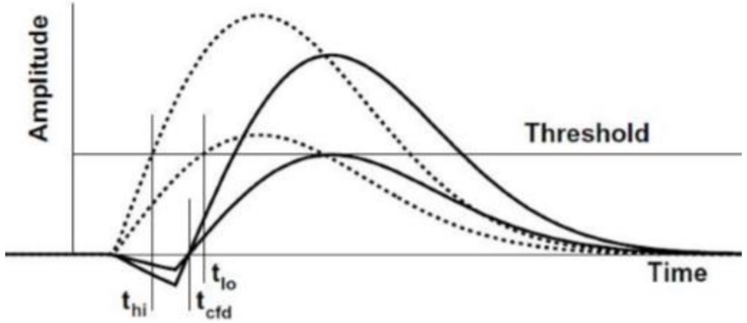
How to measure timing properties

Use laser light source with very short light pulse (~10 ps or less)

- attenuate light to low intensity → single photon level
- Measure the delay between the laser trigger pulse and signal from the photosensor

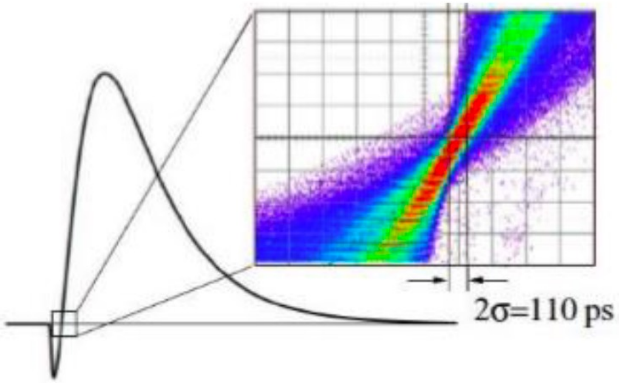
Leading edge discriminator:

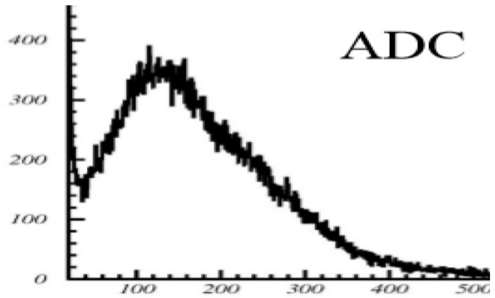
- measure also pulse charge
- make the time-walk correction
    - $TDC = P1 + \frac{P2}{ADC - P3}$

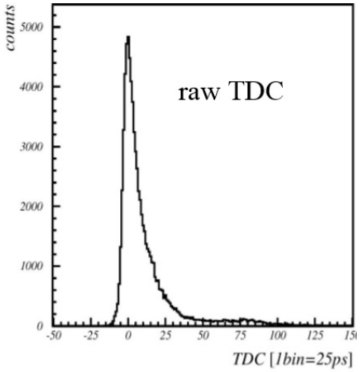


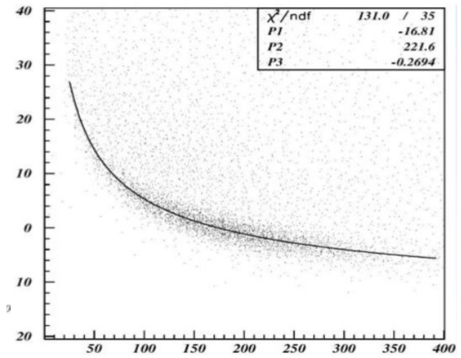
Constant fraction discriminator:

- triggers at constant fraction of the signal
- adjust fraction and delay







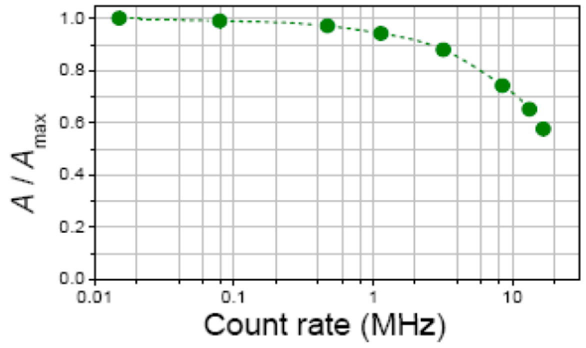


High rate operation, aging

- Rate capability: inversely proportional to the time needed, after the arrival of one photon, to get ready to receive the next
- Requirements in calorimeters: 100 kHz →few MHz

SiPM

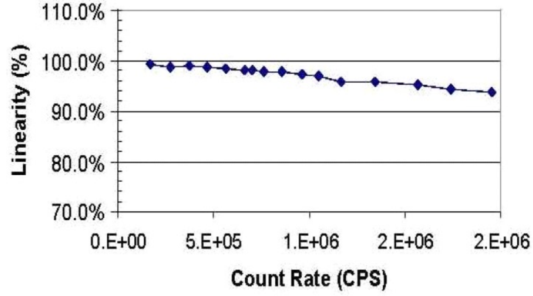
MPPC S10362-33-050C



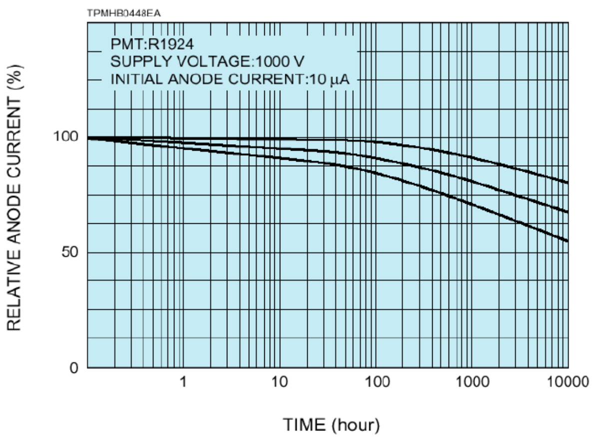
A. Stoykov, μSR at PSI

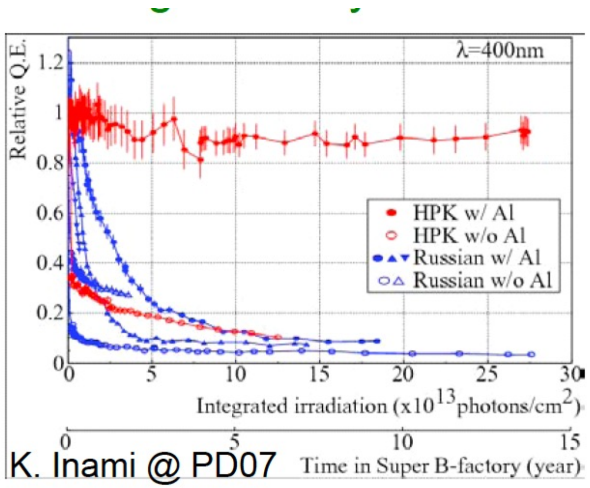
MCP-PMT

Single photo e⁻ events Gain = $5x10^5$



Aging(long-term operation at high counting rates): how is the photo-detector behavior changed when operated at high counting rate during several years ?



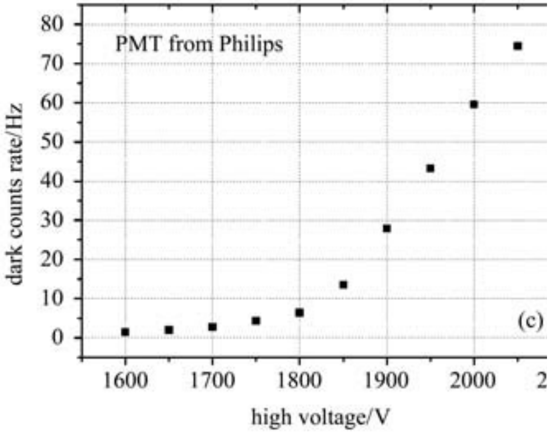


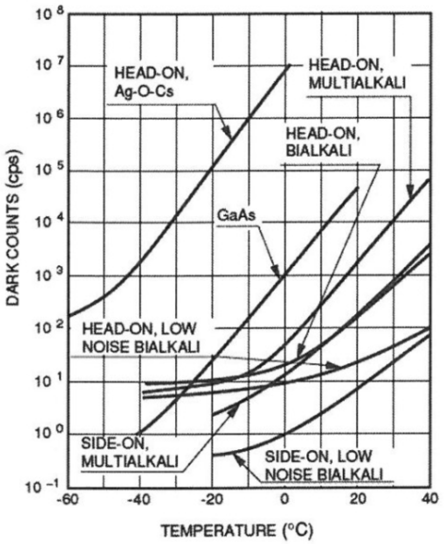
Parameter affected (generally in a negative way):
- gain
- quantum efficiency
- dark current

Dark count rate (DCR)

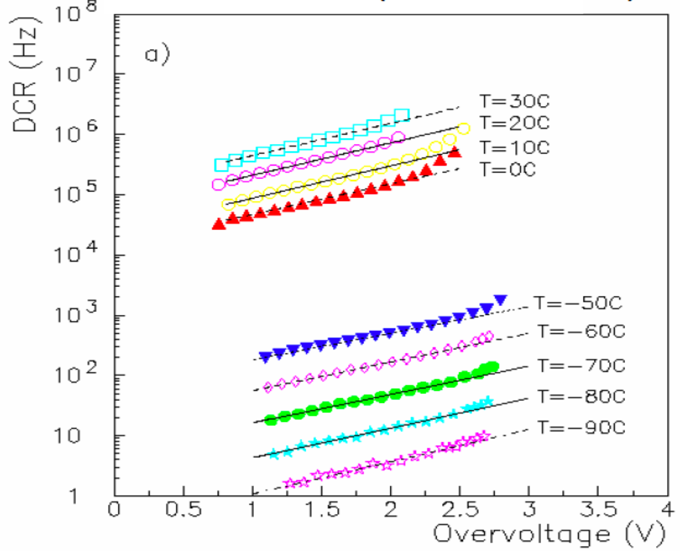
- Sensors produce signals even in total darkness!
- DCR of PMTs:
  - depends on the cathode type, the cathode area, and the temperature.
  - few kHz (threshold = 0.5 p.e.)
  - is highest for cathodes with high sensitivity at long wavelengths.
  - Temporarily increases considerably after exposure to daylight

DCR of different photocathodes





DCR of a SiPM (S1036211-050)



N. Dinu, IEEE NSS 2010

DCR of SiPMs:

- depends on the pixel size, the bias voltage, the temperature
- quite high (~0.1–2MHz/mm² at room temp, threshold = 0.5 p.e.)

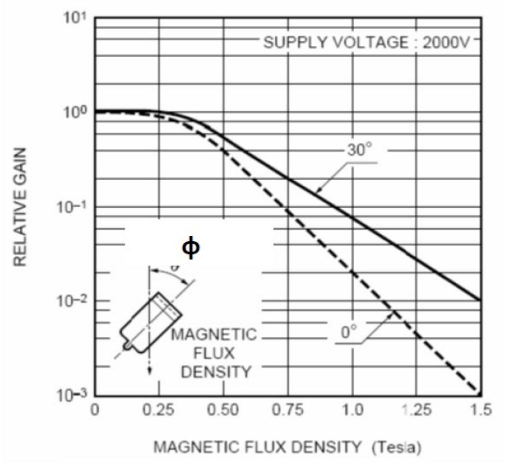
DCR depends strongly on the threshold level → not a problem for detection of many photon signals (threshold >10).
Can be efficiently reduced by lowering the temperature.

Operation in a magnetic field

Earth's magnetic field = 25-65 μT

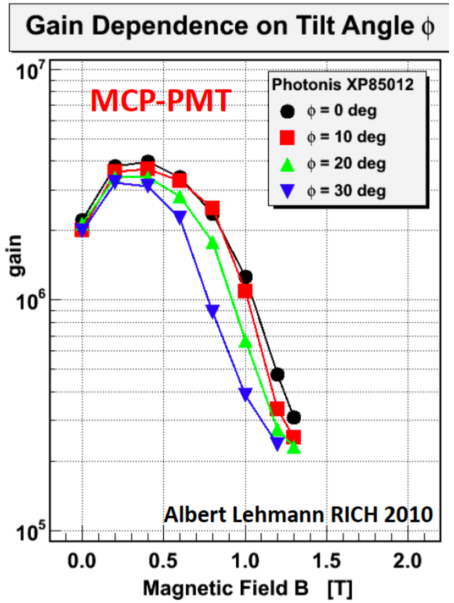
- B curves the trajectory of charged particles
- in combination with tracking provides particle momentum
- separates particle tracks → easier reconstruction
- combination PET + MRI

Typical requirements 1.5T @ Belle II,
2T @ PANDA,
4T @ CMS, ILC,
1.5 T @ MRI

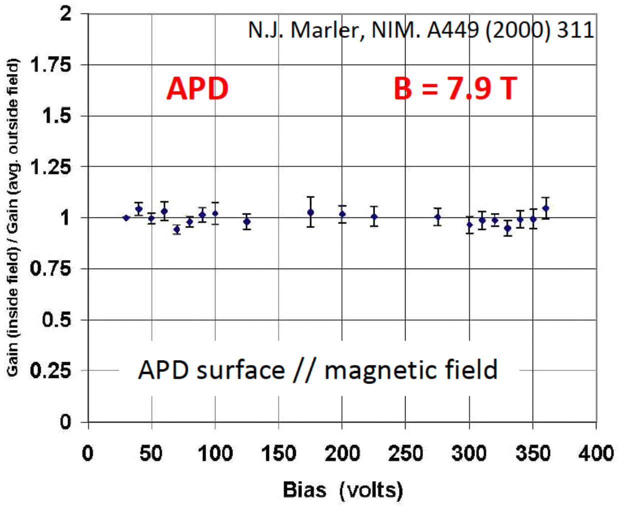


Fine mesh PMT

PMT very sensitive to magnetic Field → shielding required (μ metal)



MCP-PMT tolerant to magnetic field up to ~ 2T (6 μm pores).



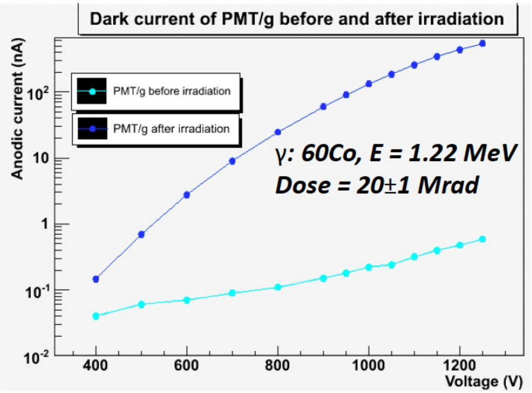
PD, APD, SiPM insensitive to magnetic field

Radiation tolerance

- Damages caused by:
- ionizing radiation: energy deposited in the detector material by particles and by photons from electromagnetic showers(the unit of absorbed dose is Gray [Gy] →1 Gy= 1 J/kg = 100 rad).
- neutrons created in hadronic shower, also in the forward shielding of the detectors and in beam collimators (fluence[1 MeV eq. n/cm2])

  → Result is degradation of DCR, gain, QE ...

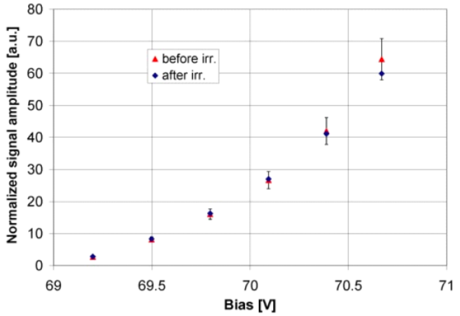
Dark current of PMT



A. Sbrizzi LUCID in ATLAS

SiPM amplitude proton irradiation

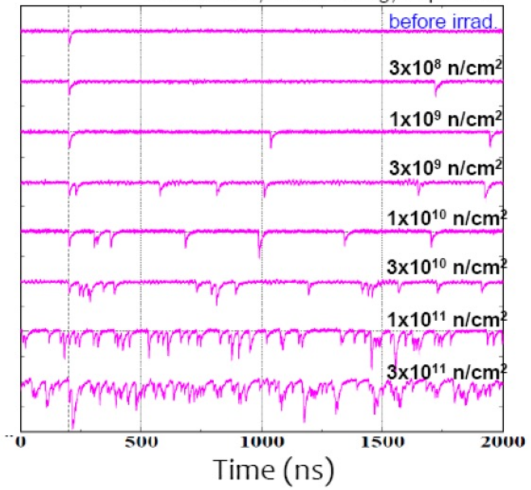
Equivalent to $2*10^{10}$ 1 MeV neutrons/cm^2



Y. Musienko, AMPDs for Frontier Detector Systems

DCR of SiPM after neutron irradiation

I.Nakamura, JPS meeting, Sep. 2008



Belle II ARICH photon detector 10^{11}n/cm^2+ 10 Gy/ year

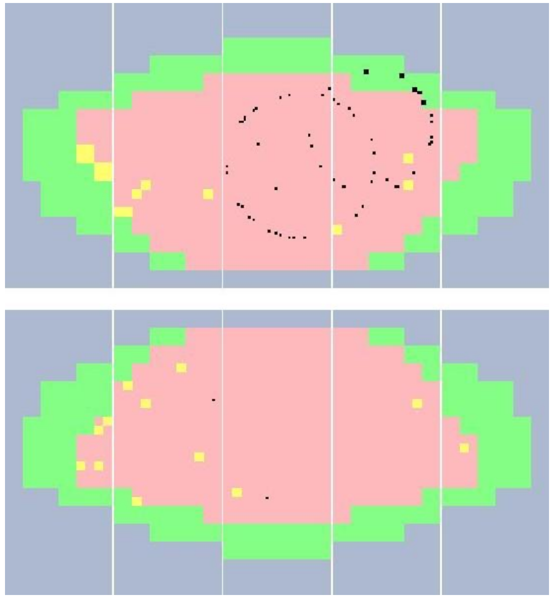
●At LHC, the ionizing dose is ~ $2x10^6$Gy/ r_T**2/ year (r_T= transverse distance to the beam)

→ CMS ECAL (10 years) $2x10^{13}$n/cm^2 + 250 krad

Single photon detectors application examples

- fiber-optic communication
- quantum information science
- quantum encryption
- medical imaging
- light detection and ranging
- DNA sequencing
- astrophysics
- materials science

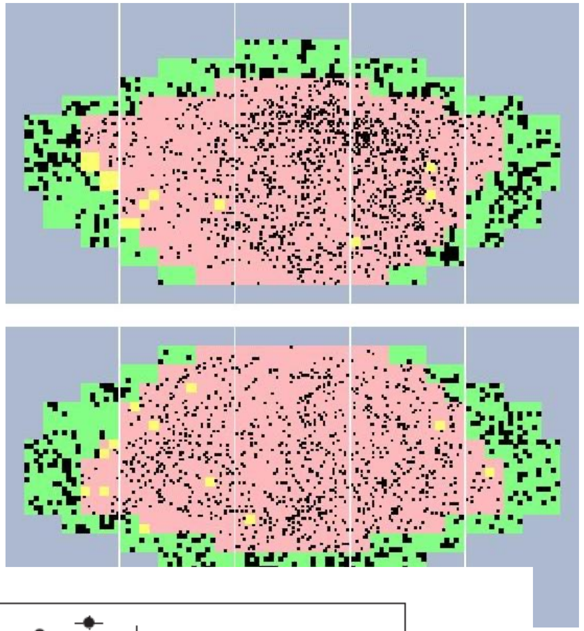
HERA–B RICH



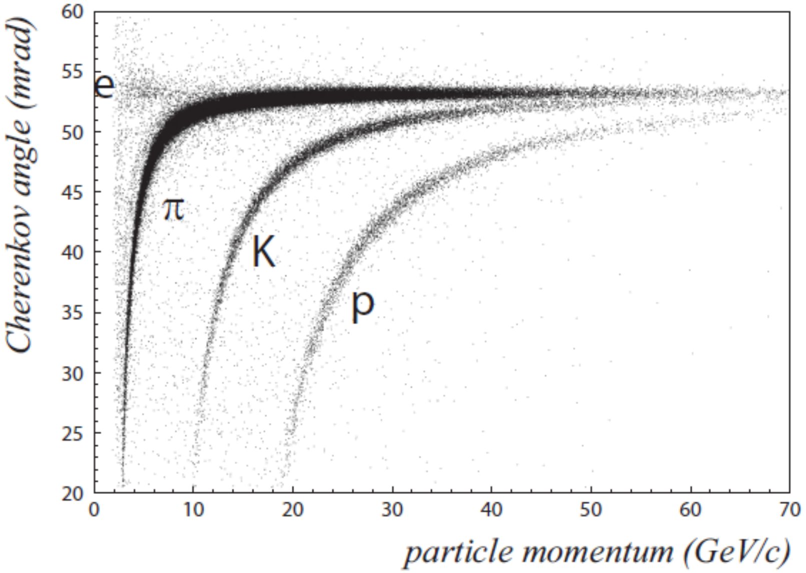
← Little noise,

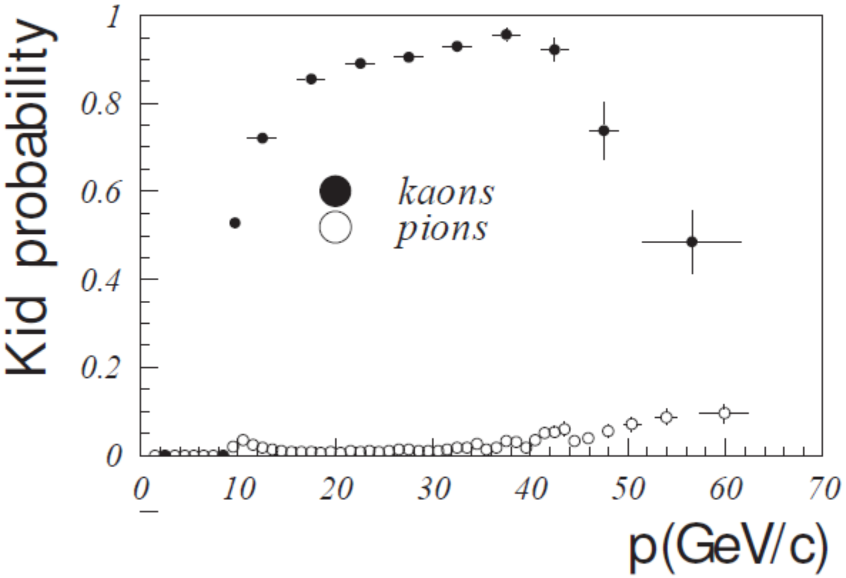
~30 photons per ring

Typical event →



Very good performance:

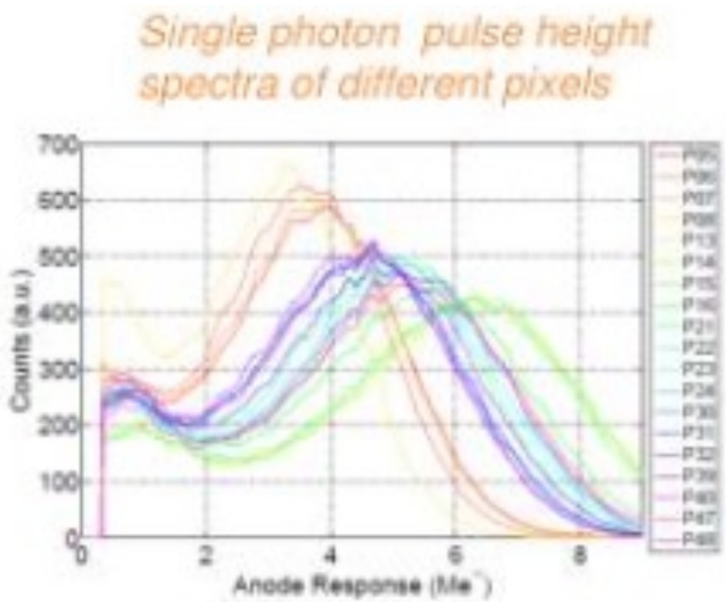


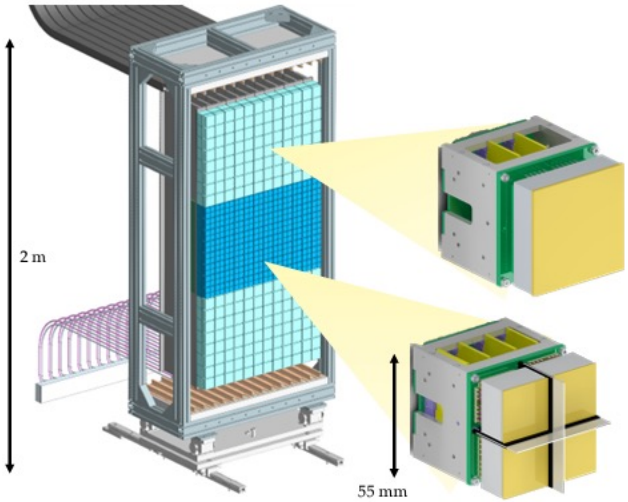


Kaon efficiency and pion fake probability

LHCb RICH

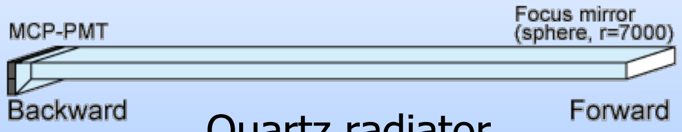
MA-PMTs – 64 ch 2”x2” + 64 ch 1”x1”





Belle II Cherenkov detectors

[redacted]



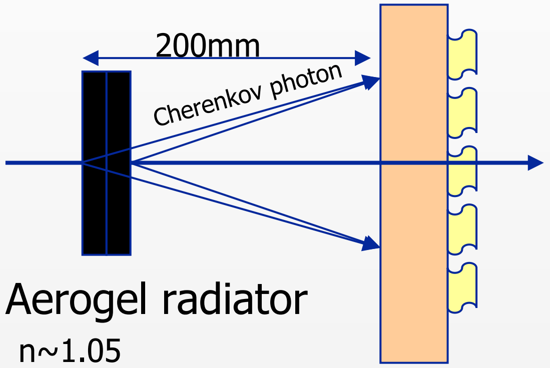
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

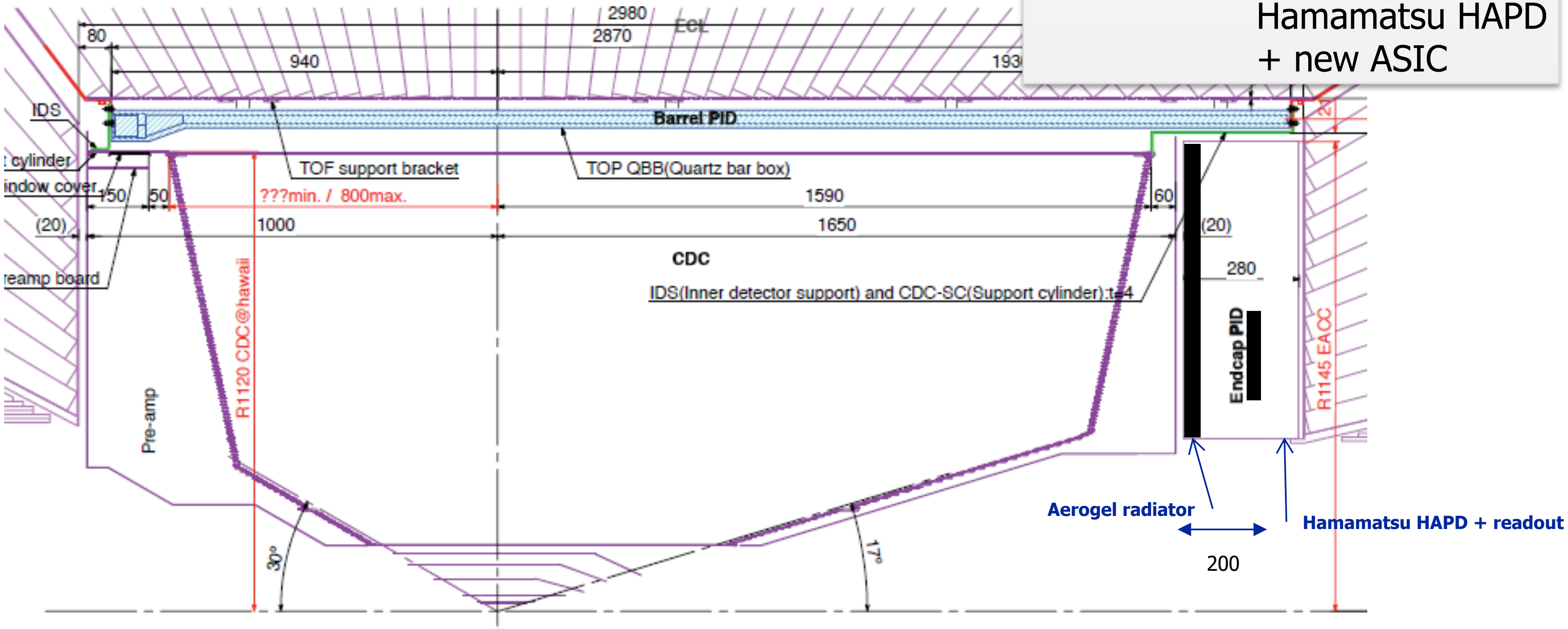
[redacted]



Aerogel radiator

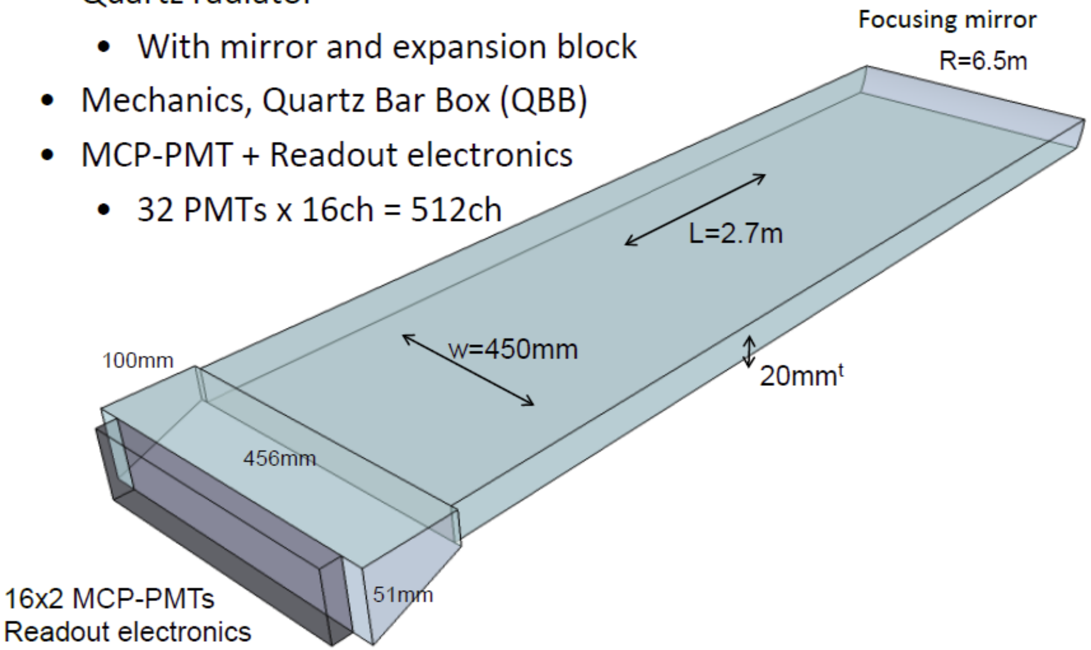
n~1.05

Hamamatsu HAPD
+ new ASIC

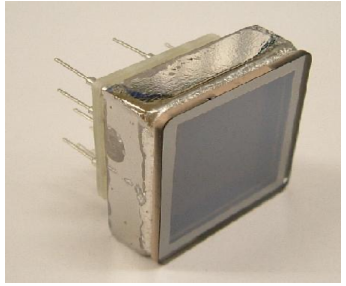


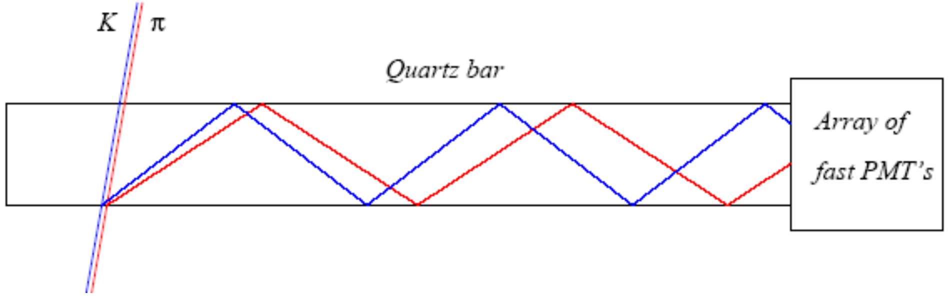
Time-Of-Propagation (TOP) counter

- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch



Hamamatsu
SL10 MCP-PMT





Instead of a 2D image in two coordinates ('ring') measure:

– One (or two coordinates) with a few mm precision

– Time-of-arrival

→ Excellent time resolution < 100ps (incl. read-out)
required for single photons in 1.5T B field

Summary

- Low light level detection is in the heart of many detectors
- New methods require very fast timing
- A number of new detectors has been developed recently to cope with these requirements
- A very active field!