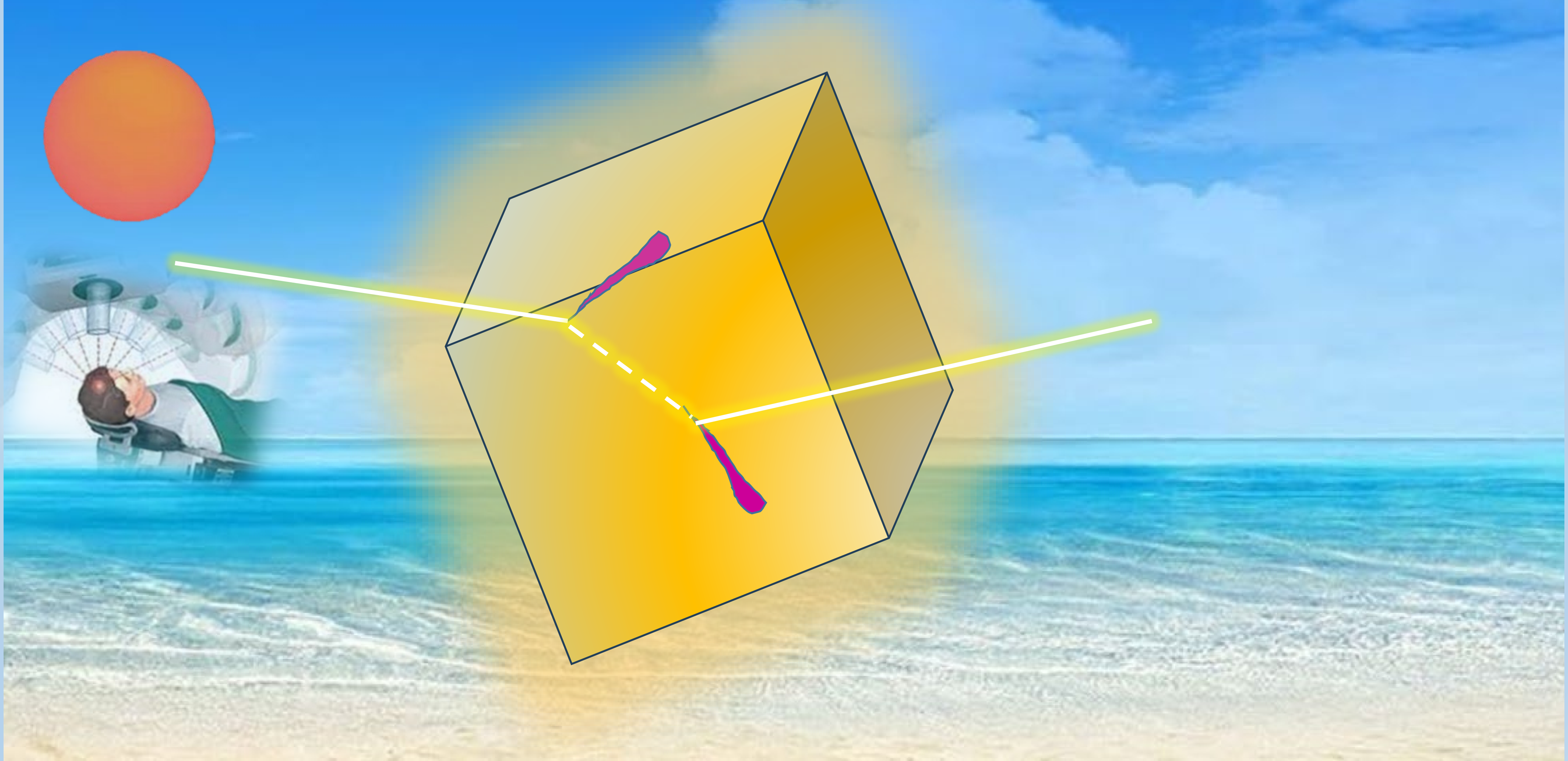
RIPTIDE



Outline

- Group members
- Research fields
  - Nuclear physics
  - Solar neutrons
  - hadrontherapy
- Strategy
  - Recoil proton technique
- Detector concept
  - Daq & trigger
  - Sensor
- Monte Carlo Simulation
  - Optics
  - Track reconstruction
    - Methods
    - Results
- Milestones & Requests
- Bibliography
- Conclusions

Group Members

RIPTIDE: RecoIl ProTon Imaging DEtector

Nome	Ruolo	FTE 2024
Console Camprini Patrizio	Ricercatore ENEA Bologna	0.5
Giacomini Francesco	Primo Tecnologo CNAF Bologna	0.1
Massimi Cristian	Professore associato UNIBO	0.5
Mengarelli Alberto	Tecnologo INFN Bologna	0.2
Ridolfi Riccardo	Assegnista di Ricerca Bologna	0.5
Spighi Roberto	Dirigente di Ricerca INFN Bologna	0.5
Terranova Nicholas	Ricercatore ENEA Frascati	0.5
Pisanti Claudia	Dottoranda	1.0
Musumarra Agatino	Professore Associato UNICT	0
Pellegriti Maria Grazia	Ricercatore INFN	0
Villa Mauro	Professore Ordinario	0
TOTALE FTE		2.8 (3.8)

Research fields: nuclear Physics

Neutron production in NUCLEAR PHYSICS:

Heavy Ions E_n ~ MeV

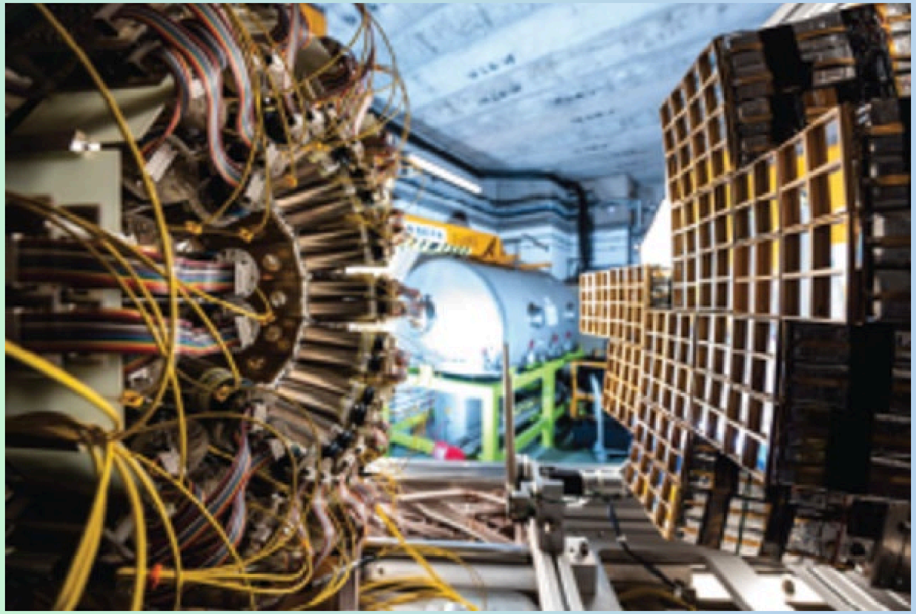
- heavy ions interactions at Fermi energies

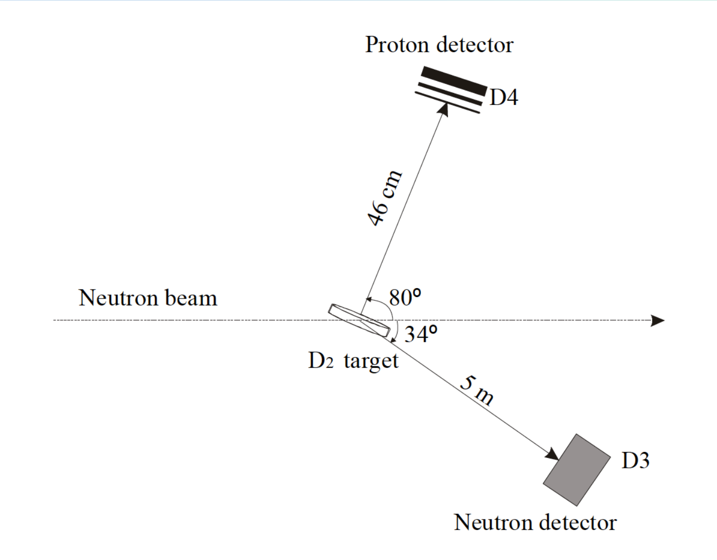
Radioactive beams E_n < 100 MeV

- study of nuclear matter far from stability
- reactions induced by neutron-rich projectiles

Neutron facilities E_n < 1 GeV

- study of neutron-induced reactions
- Neutron-neutron scattering length





Study of the neutron-neutron scattering length by the nuclear reaction:

$n + {}^{2}H \rightarrow n + n + p$

requires information on neutron momentum

Research fields: solar neutrons

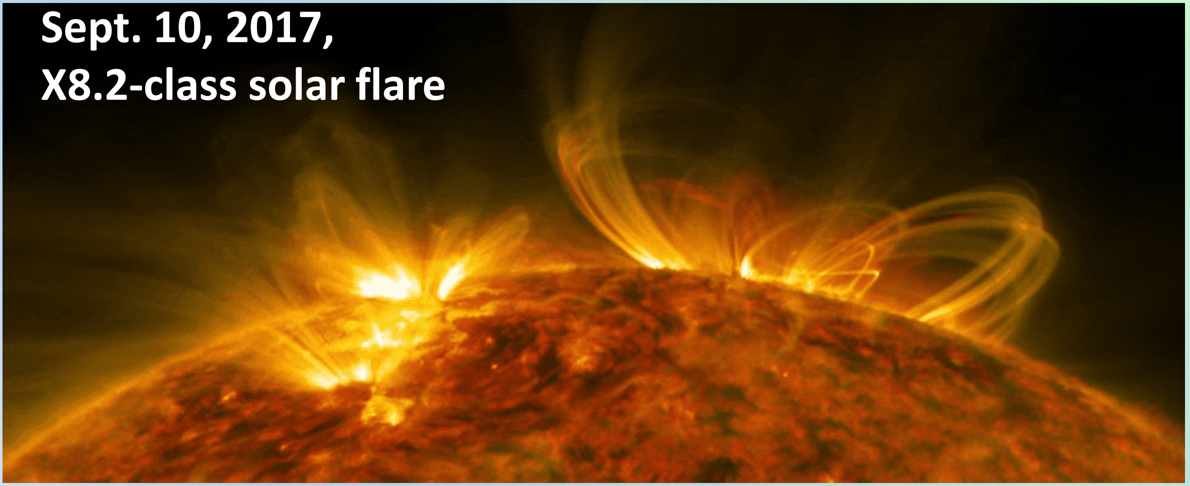
Neutron production processes:

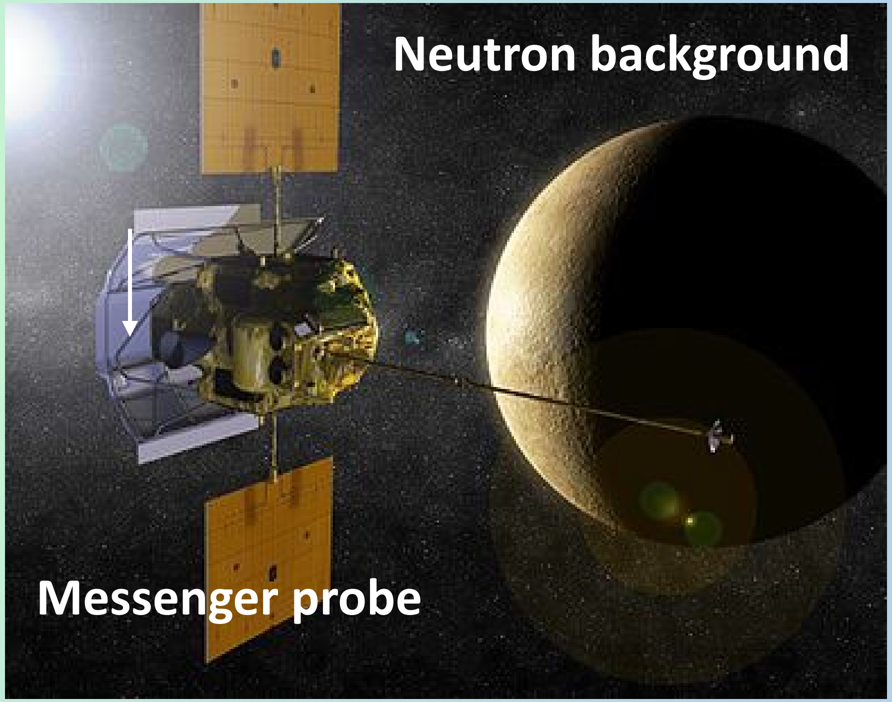
neutron @E<30MeV produced by

- heavy ions interaction on ambient H and ^{4}He (decay before arriving on the earth)

neutron @ E>30MeV produced by

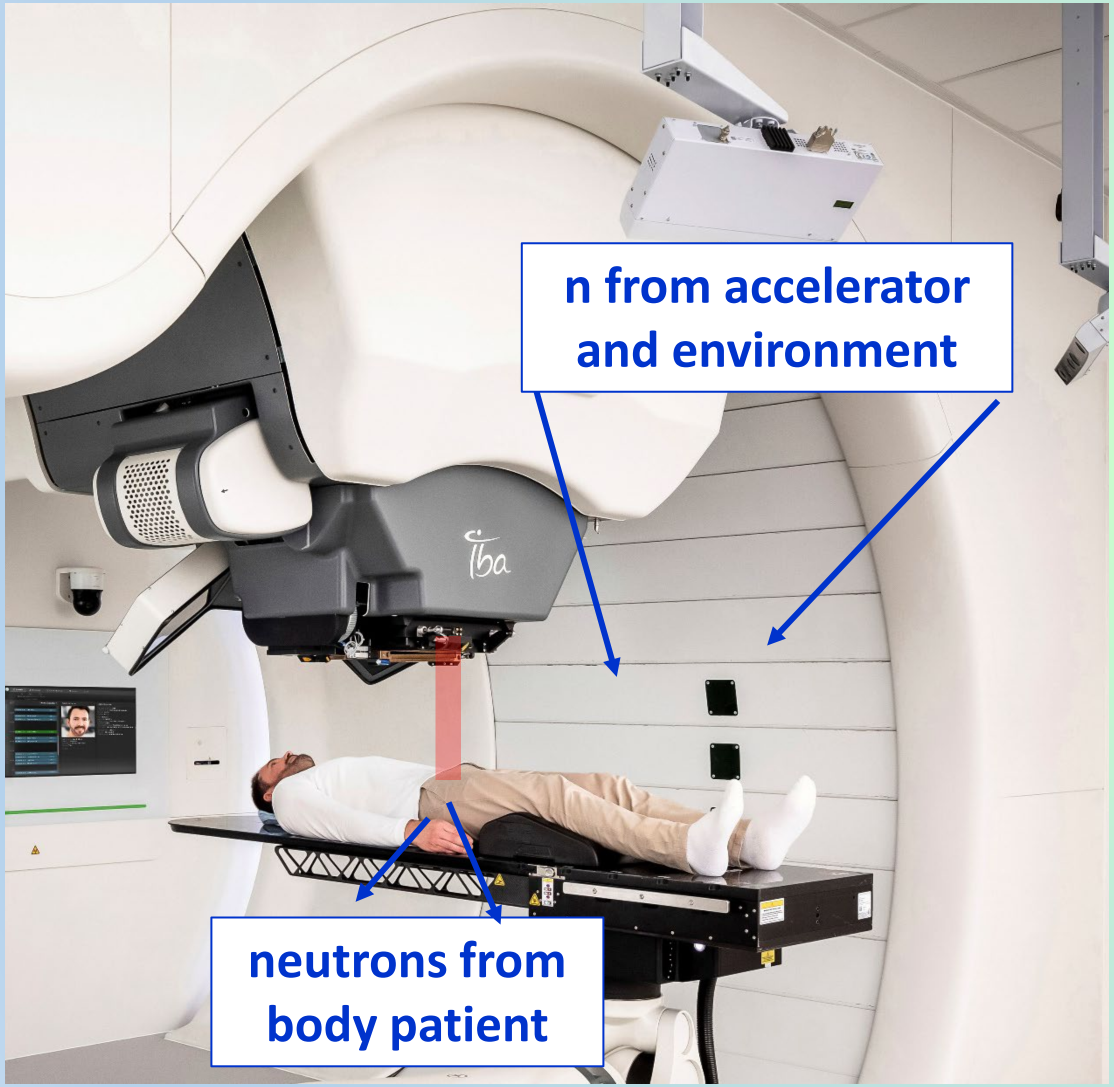
- **α** interaction with ambient H and ^{4}He,
- **proton** interactions with ambient ^{4}He
- Only these can be detected near Earth





Crucial the direction determination to distinguish signal from background:

Research fields: hadrontherapy



Neutrons produced:

- in the accelerator head
- in the body patient
  - $p + {}^{16}O \rightarrow n + p + {}^{15}O$

⬇

Neutron direction distinguishes the two sources

⬇

- improve the TPS
- estimate the secondary production

⬇

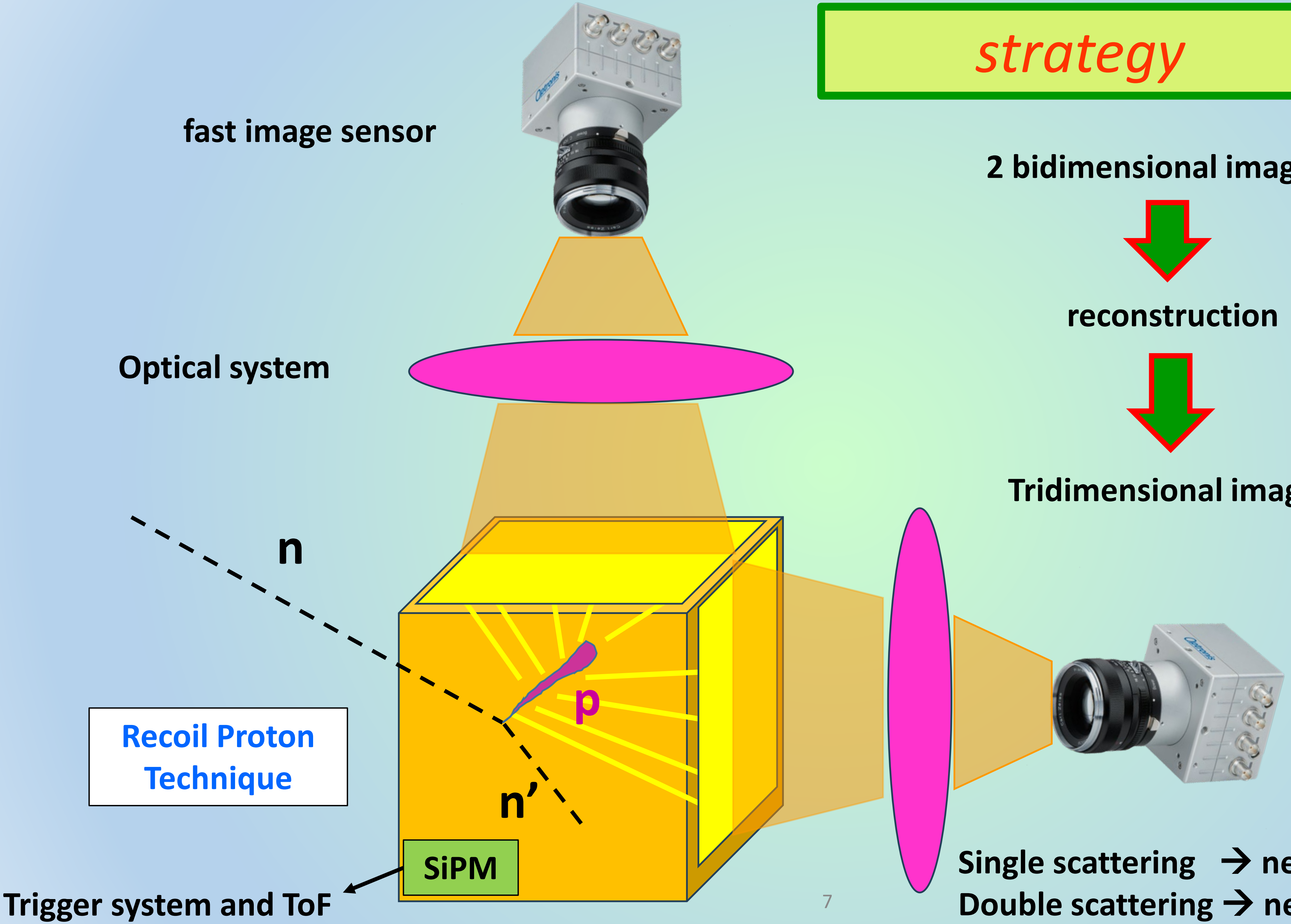
Can be used to monitor the beam in the patient

strategy

2 bidimensional images

reconstruction

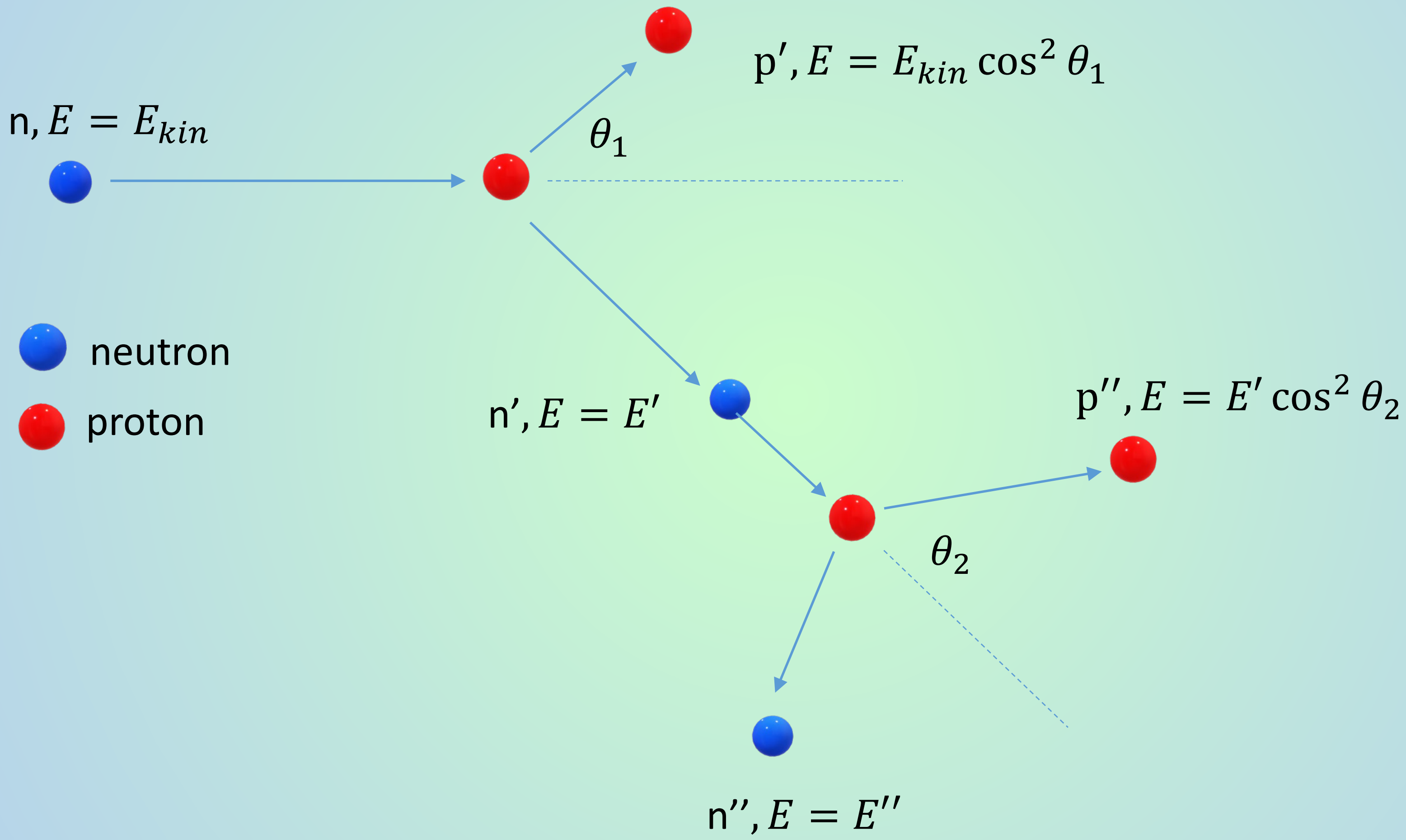
Tridimensional image



Single scattering → neutron source known

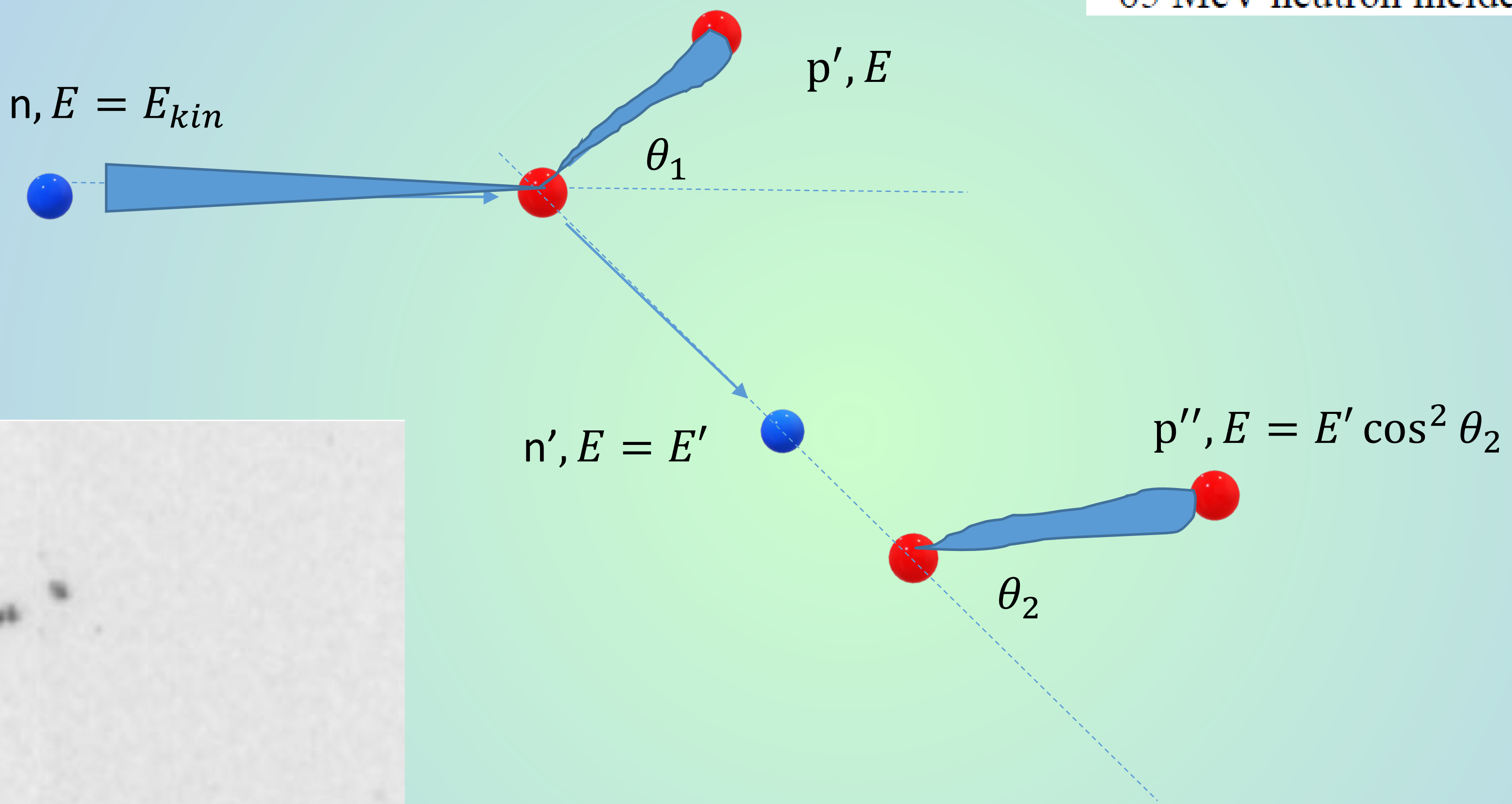
Double scattering → neutron source not known

Metodology: Recoil proton Tecnique



Metodology: Recoil proton Tecnique

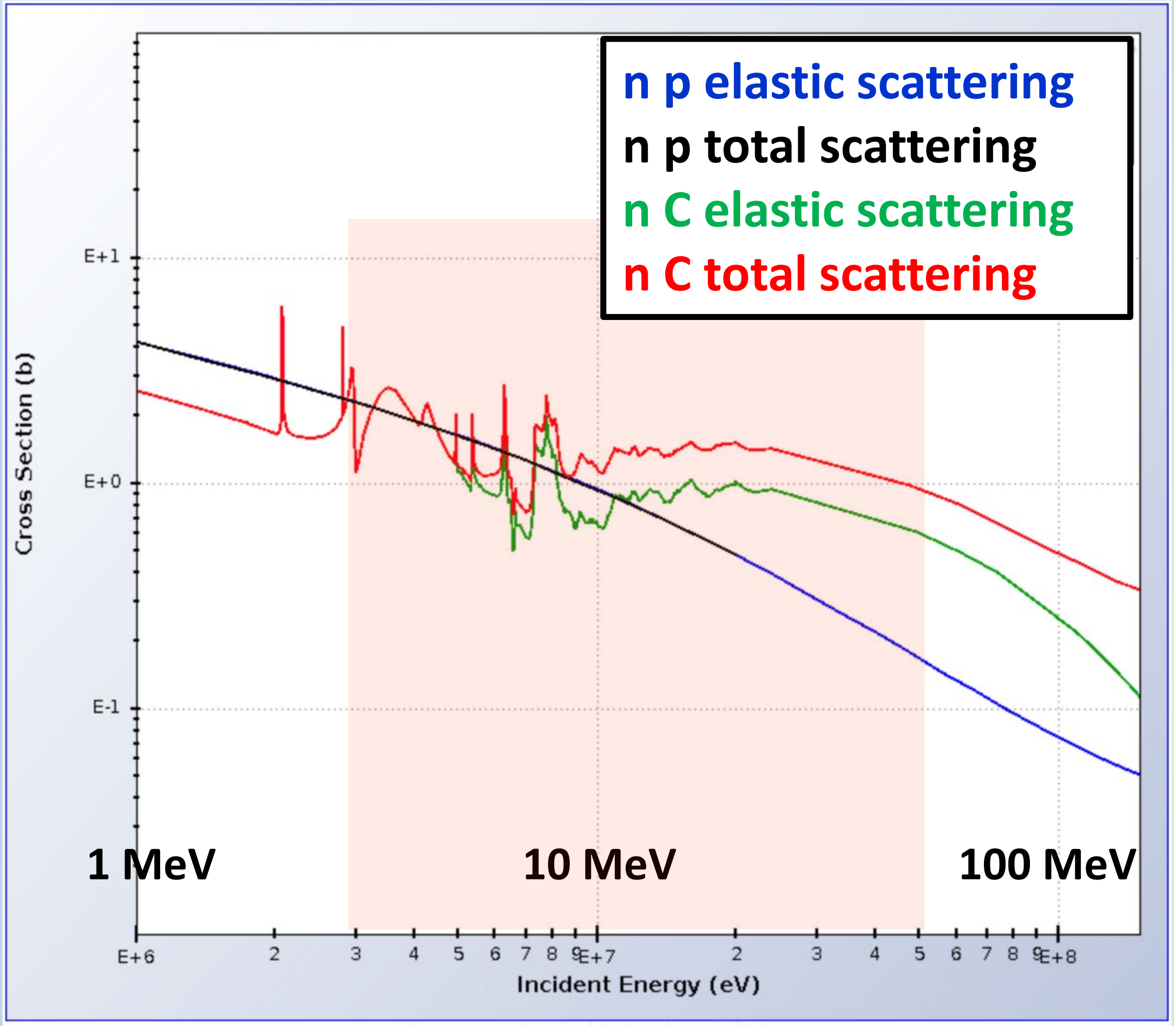
Figure 3. Raw CCD image of a double scatter from a ~65 MeV neutron incident from the top.

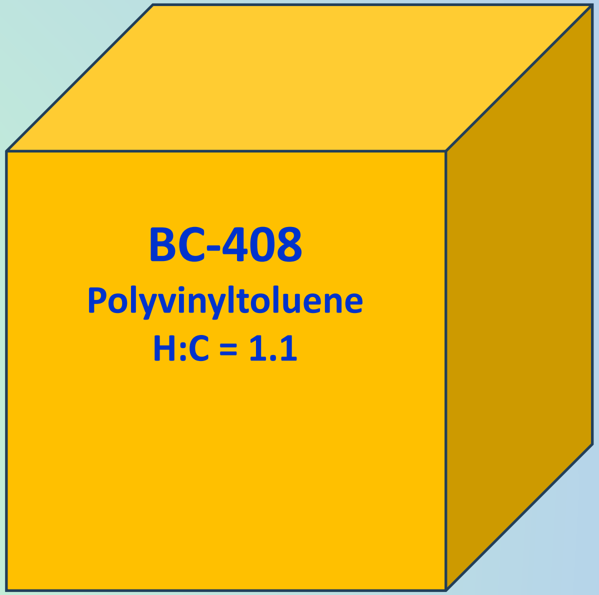


CCD image of a double scatter from a 65 MeV neutron incident from top

James M. Ryan, et al. «A Scintillating Plastic Fiber Tracking Detector for Neutron and Proton Imaging and Spectroscopy», the conference is available at University of new Empshire Scholar's Repository, https://scholars.unh.edu/ssc/208

n in a plastic scintillator





Detection volume: (6 cm)^3

neutron energies: 3-50 MeV

proton ranges: 0.2 – 30 mm

H:C = 1.1

- **n p is only elastic (at this energy)**
- **σ(n C) > σ(n p) → large bkg events?**

but …

transferred energy

proton (A = Z = 1)

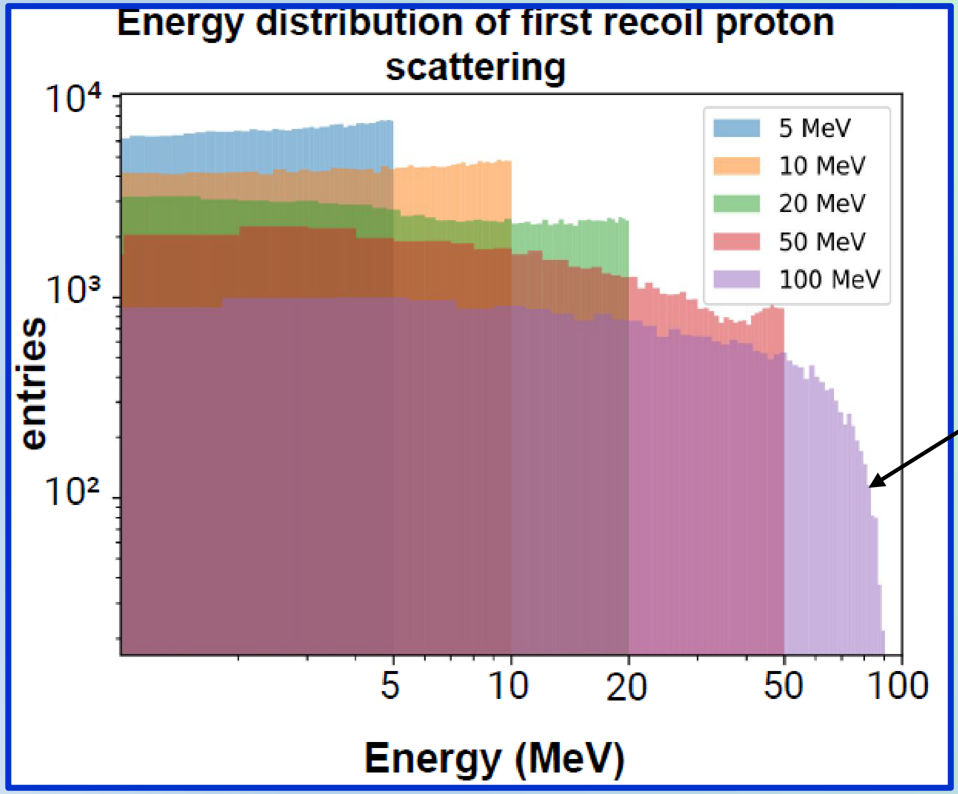
$0 < E_p < E_0$

$$0 < E < \left(1 - \frac{(A-1)^2}{(A+1)^2}\right) E_0$$

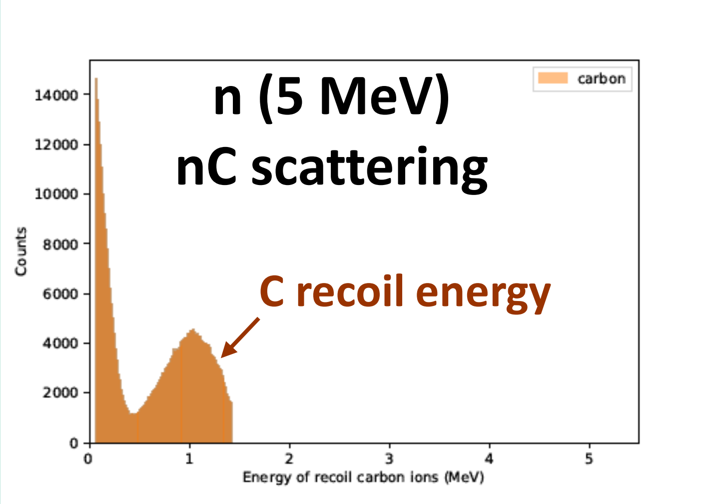
carbon (A = 12, Z = 6)

$0 < E_c < 0.28\ E_0$

n p Single scattering

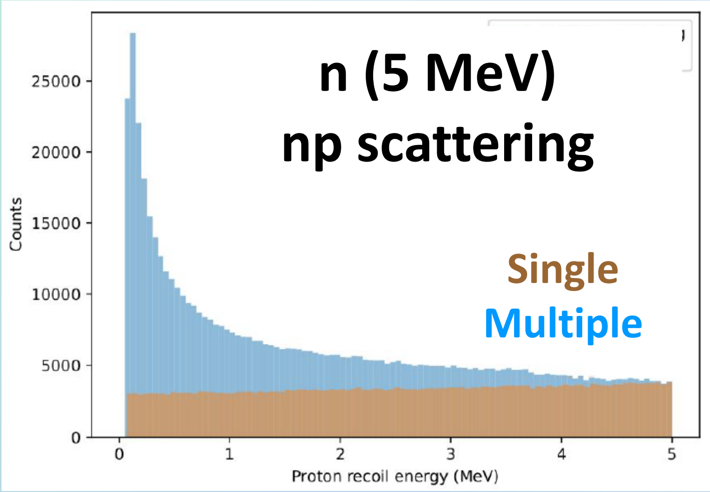


n C
Single scatt



p escape from the scintillator

n p
Single – Multiple scatt



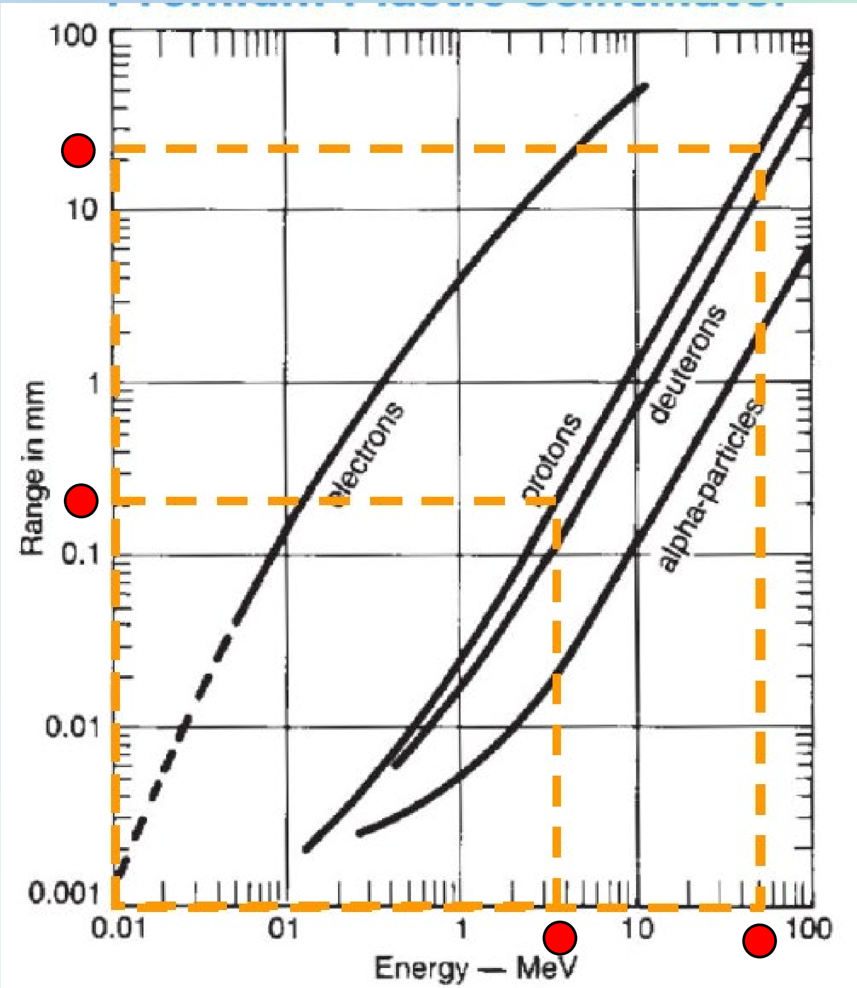
consequence

p & C Range

$$R(E) = \alpha E^{p}$$

α depends on material
p on Energy (~ 1.75)

Range in plastic scintillator

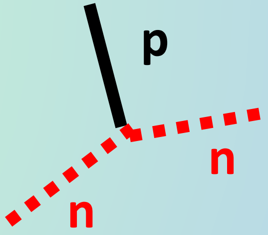


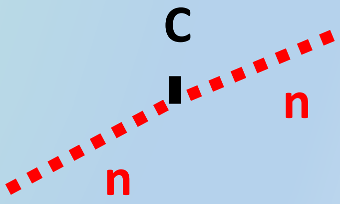
$$R_a(v) = \frac{m_a z_b^2}{m_b z_a^2} R_b(v)$$

a → carbon
b → proton
v→ energy

n at 60 MeV

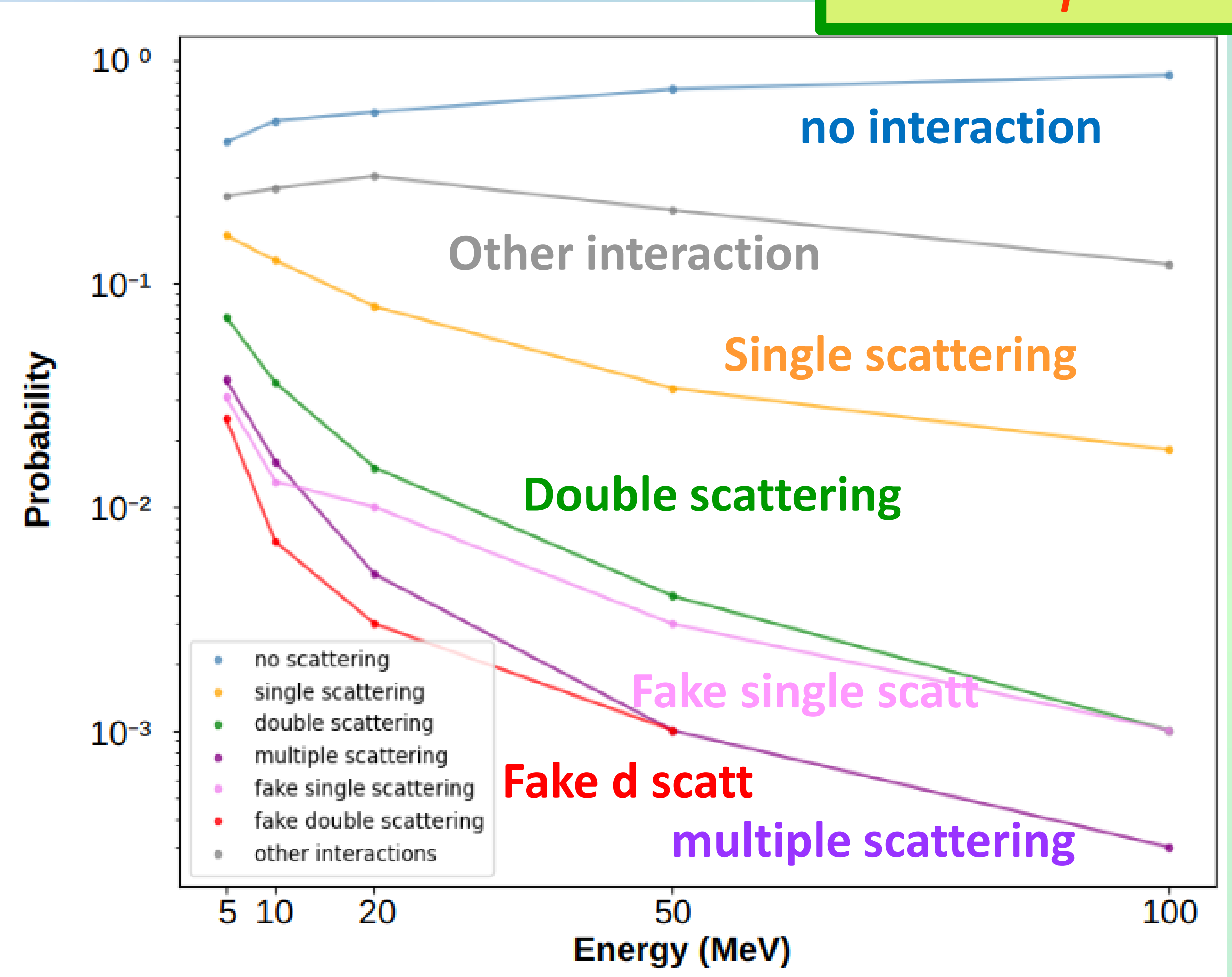
- **R_p = 35 mm**
- **R_c = 1.5 mm**



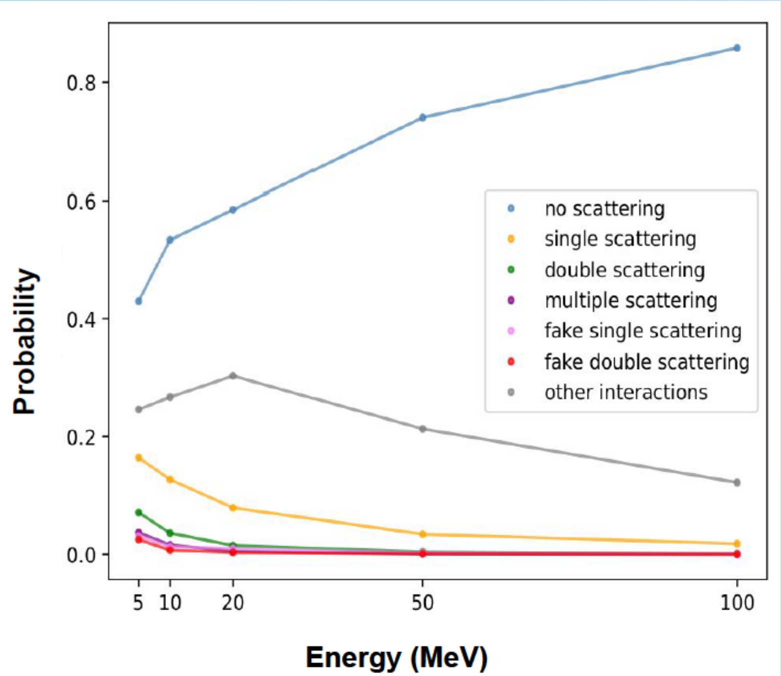


Carbon range → 0 (lighted points)
signal lower than thereshold

n in a plastic scintillator



Linear scale



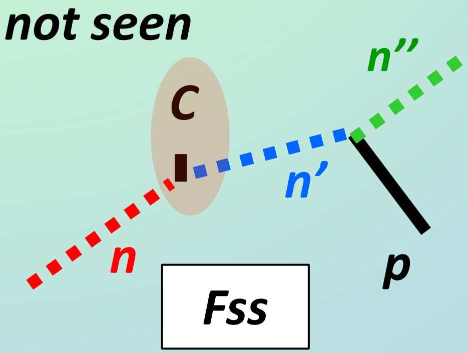
	5 MeV	10 MeV	20 MeV	50 MeV	100 MeV
no scattering	**0.430**	**0.534**	**0.585**	**0.740**	**0.858**
single scattering	0.164	0.127	0.079	0.034	0.018
double scattering	0.071	0.036	0.015	0.004	0.001
fake-single scattering	0.060	0.031	0.020	0.007	0.002
fake-double scattering	0.025	0.011	0.004	0.001	0.0003

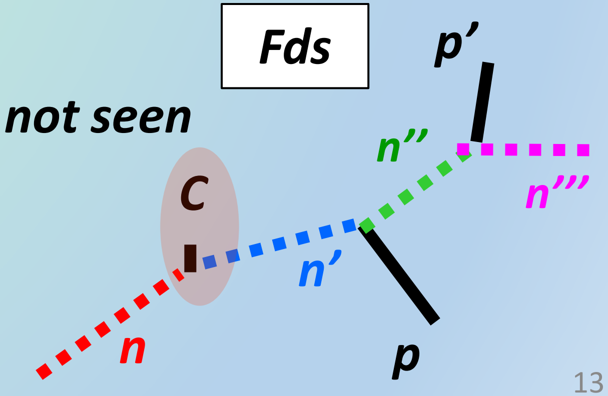
Fss:

- scatt on C (not seen) and then on p

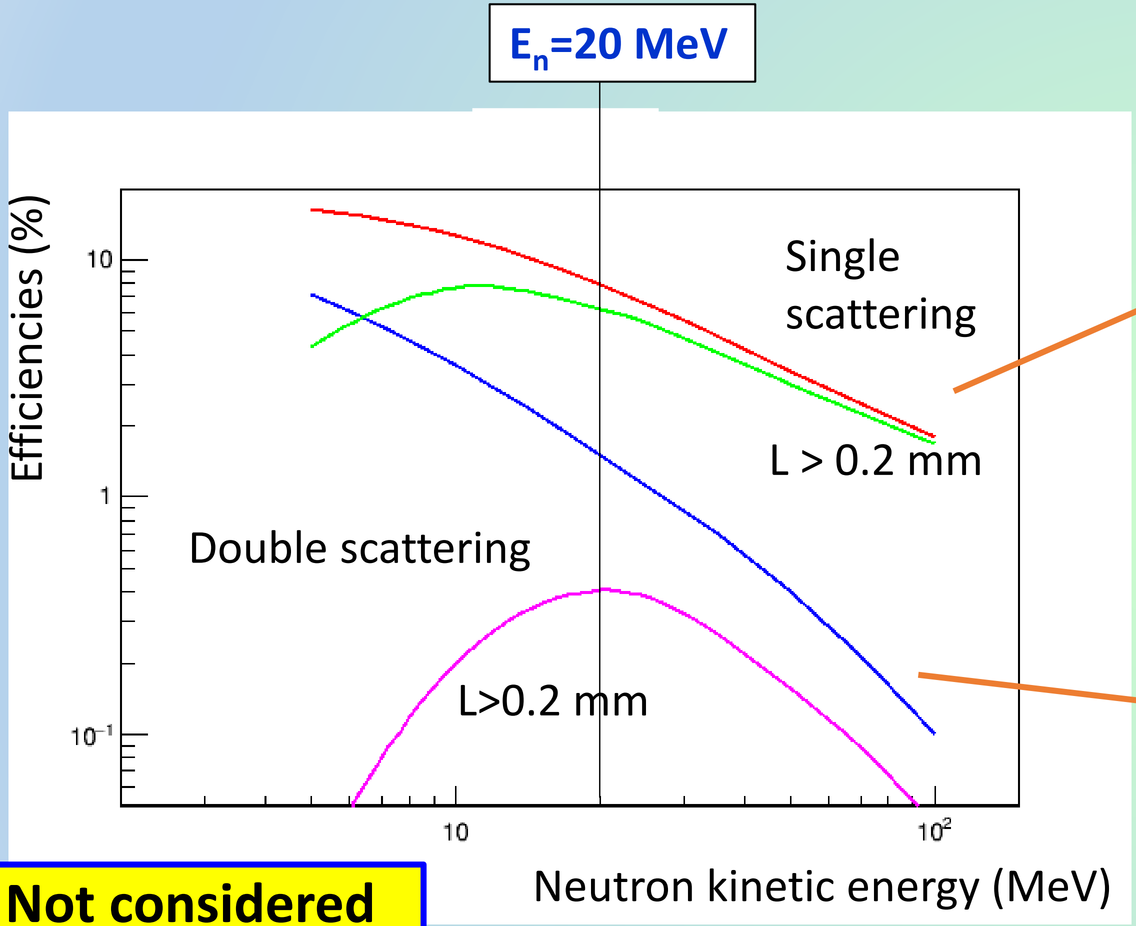
Fds:

- scatt on C (not seen) and then on p and p
- Scatt on p, on C (not seen) and on p

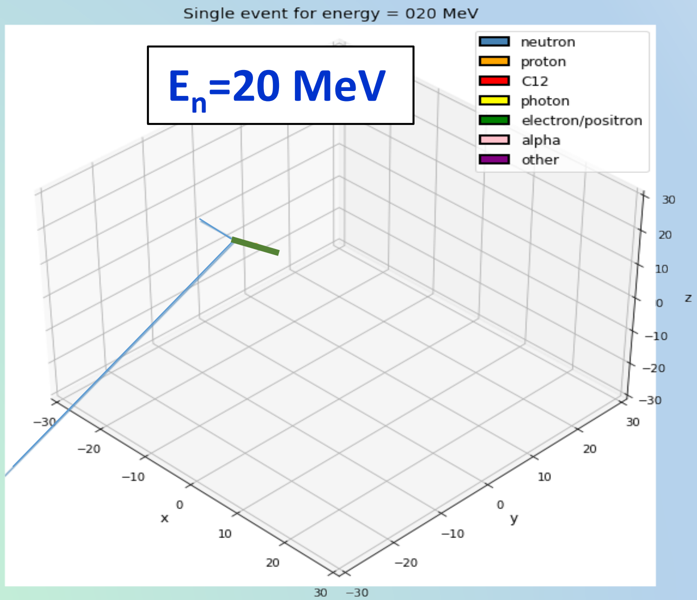




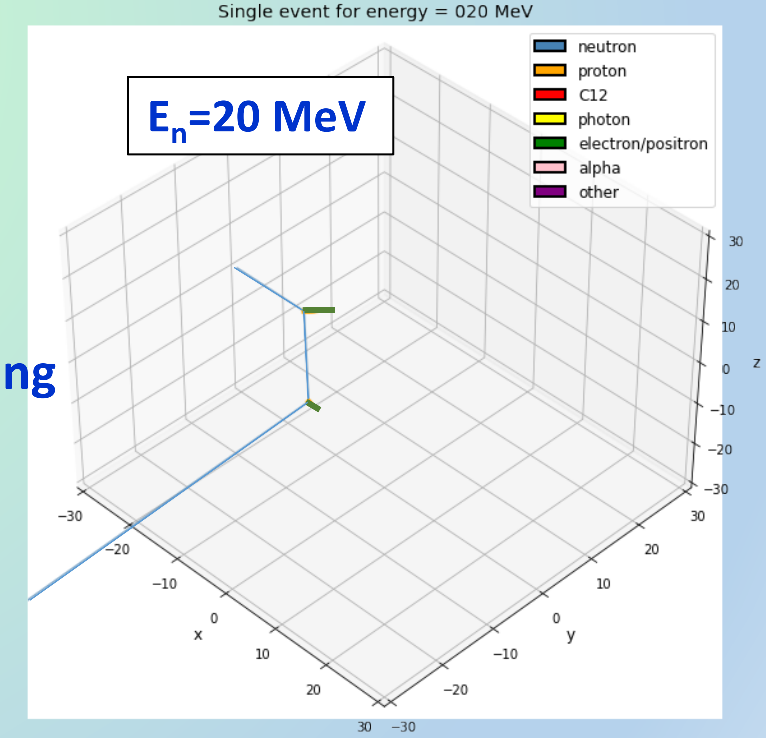
Interaction and detection efficiency



Single scattering



Double scattering



Not considered
Optic efficiency

E_n = 20 MeV

- **Single scattering efficiency ~ 10%**
- **Double scattering efficiency ~ 1%**

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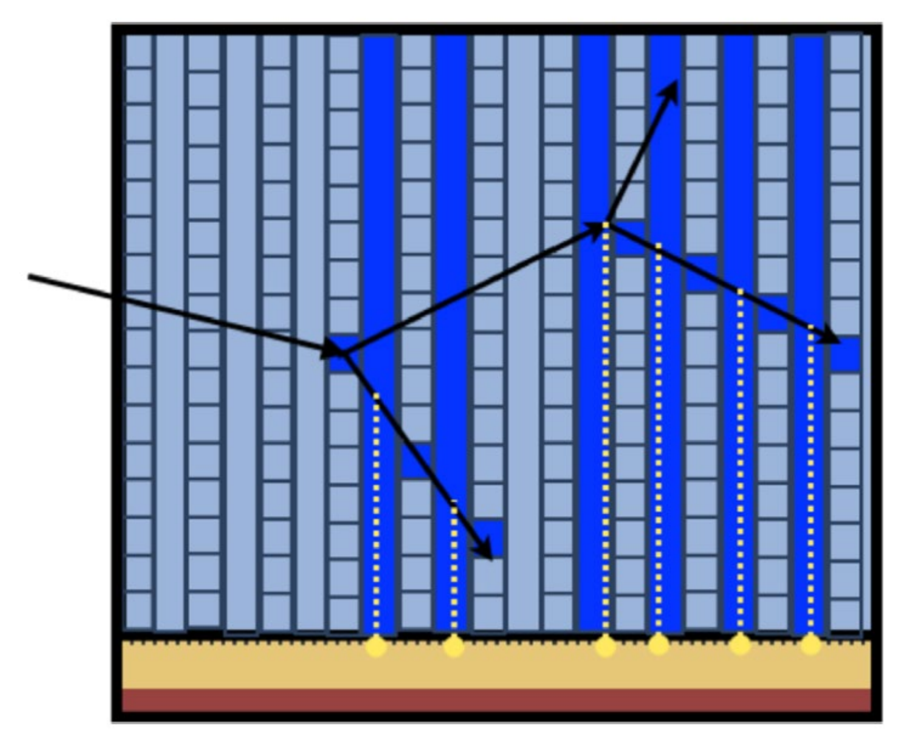
Literature,1

S.M. Valle et al, NIM A 845 (2017) 556; 10.1016/j.nima.2016.05.001
E. Gioscio et al, NIM A 958 (2020) 162862; 10.1016/j.nima.2019.162862
M. Marafini et al, Phys. Med. Biol. 62 (2017) 3299; 10.1088/1361-6560/aa623a

MOnitor for Neutron Dose in HadrOntherapy

Layers of perpendicular scintillating fibers (250 µm)



Light produced in fibers are

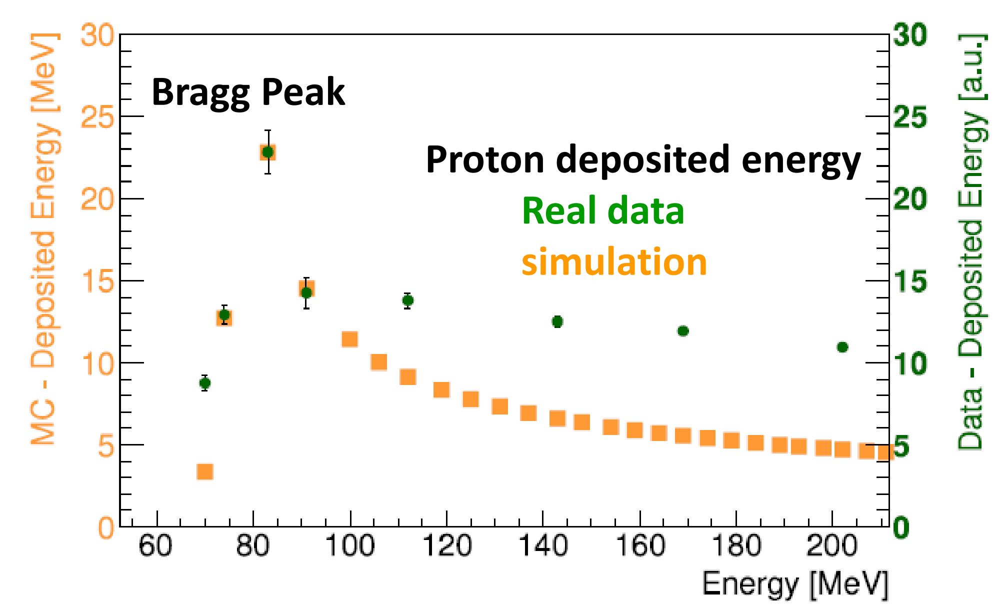
- amplified with a triple GEM intensifier
- acquired with CMOS Single Photon Avalanche Diode arrays

Dimension: 10 x 10 x 20 cm^3
Prototype: 4 x 4 x 4.8 cm^3

Many RO channel

fibers grouped

lower position resolution

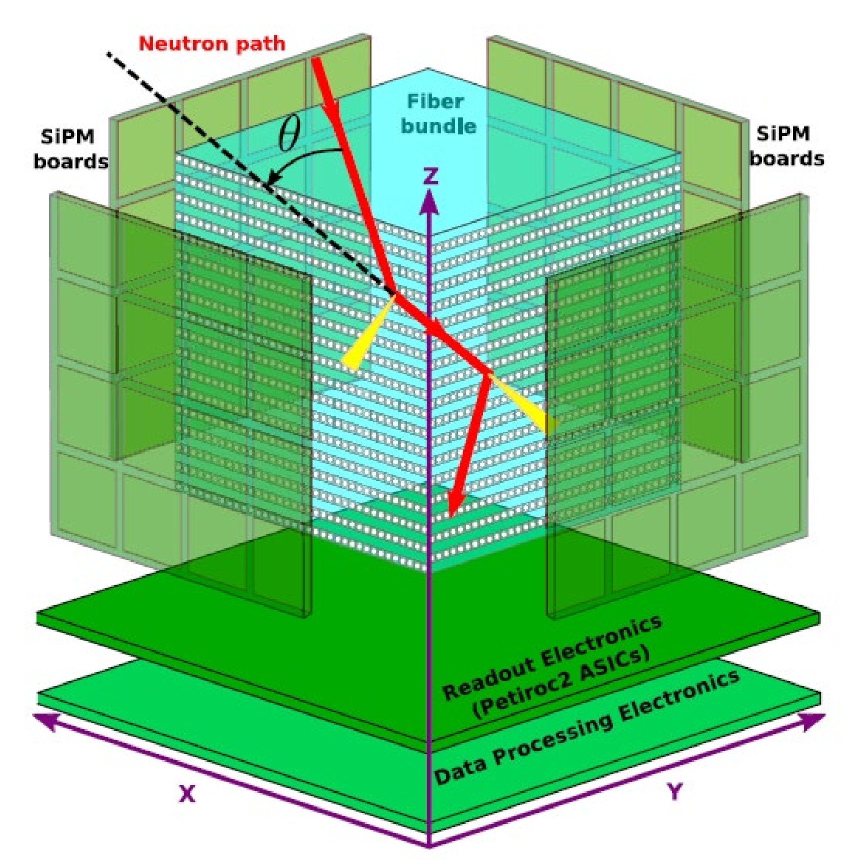


SOlar Neutron TRACking

Literature,2

G. A. De Nolfo et al, "SOlar Neutron TRACking (SONTRAC) Concept." (ICRC2019), PoS 36 (2019) 1074; 10.22323/1.358.1074
J.G. Mitchell et al, "Development of the Solar Neutron TRACking (SONTRAC) Concept" (ICRC2021), PoS 395 (2021) 1250; 10.22323/1.395.1250

32 layers of perpendicular scintillating fibers (1 mm)

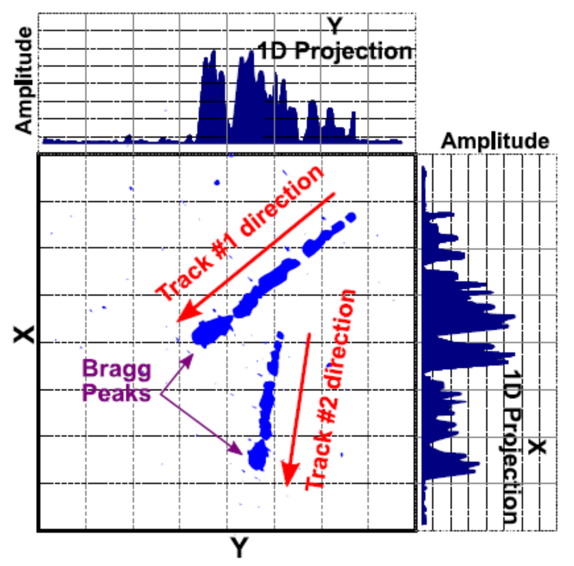


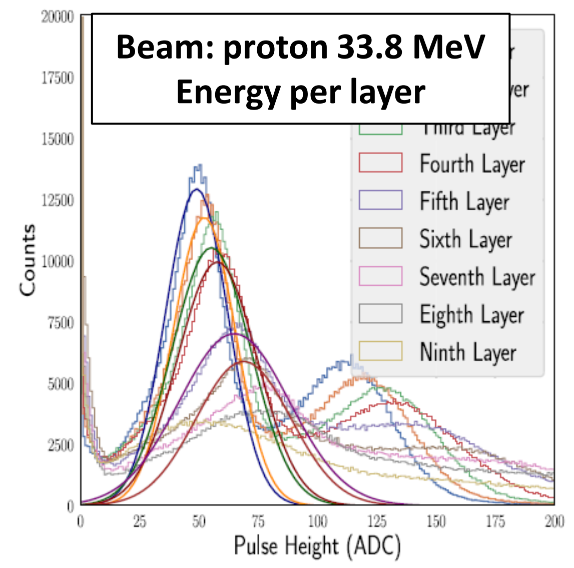
Light produced in fibers

- **acquired with SiPM**
- **RO system: 32-channel CAEN DT5550W**

neutron detectors placed or

- **in low Earth orbit (LEO)**
- **In Lunar Gateway (space station between earth and moon)**
- **In deep-space probes to the inner Heliosphere**





Literature,3

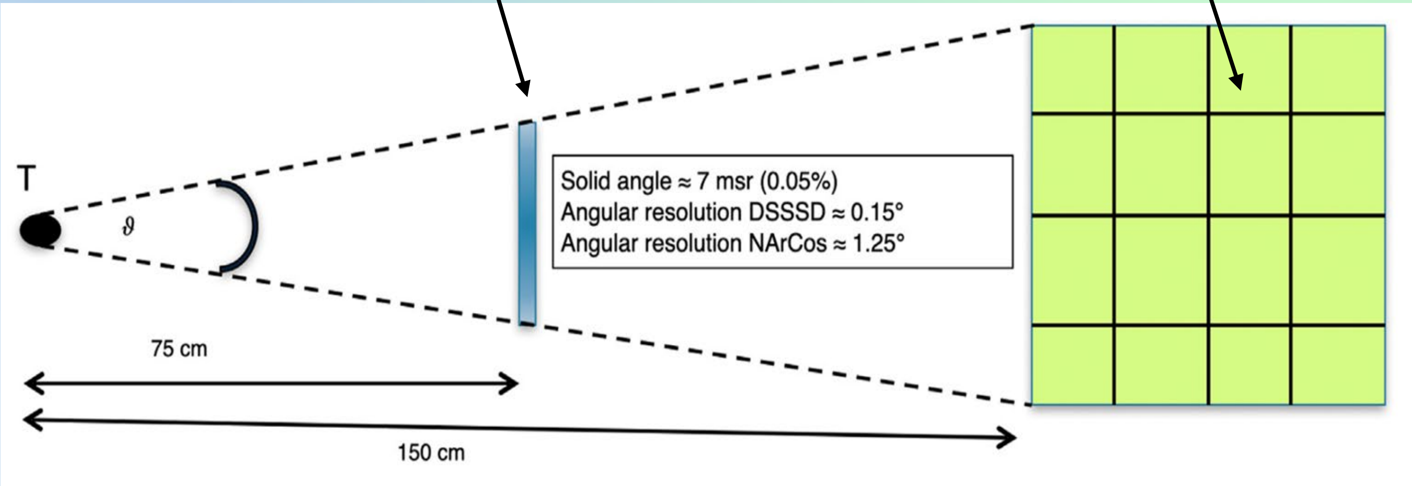
Neutron ARray for Correlation Studies (PRIN at LNS)

Pagano EV, et al. (2023), NArCoS: The new hodoscope for neutrons and charged particles. Front. Phys. 10:1051058. doi: 10.3389/fphy.2022.1051058

Neutrons detection via recoil proton technique
(only single scattering → fixed target experiment to determine neutron direction, tof to determine energy)

VETO
to discriminate primary protons from primary neutrons

array of unitary cells

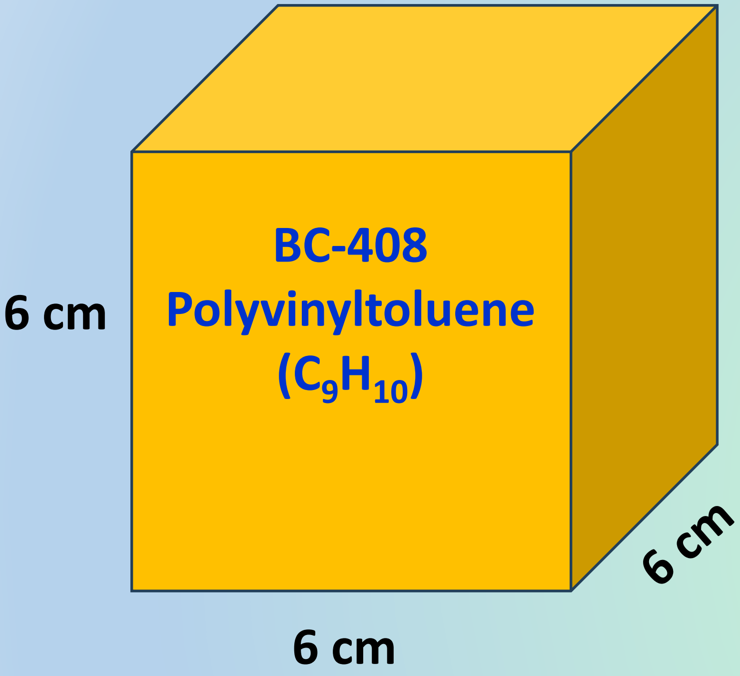


Energy range 5 – 50 MeV

Each cell consists of 3x3 cm EJ276G cube + SiPM + electronic readout

- **PSA** (pulse shape analysis) discriminate protons/neutrons from γ
- **VETO** discriminate neutrons from primary protons

RIPTIDE: plastic scintillator



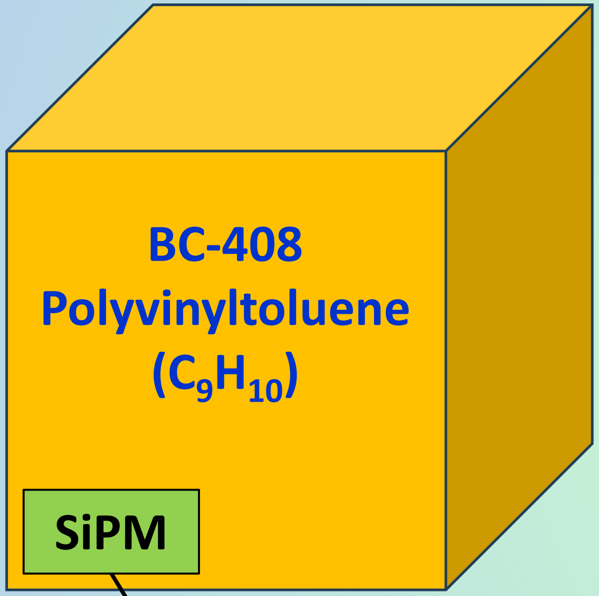
neutron energies: 3-50 MeV

proton ranges: 0.2 – 30 mm

Refractive index	1.58
Density	1.032 g/cm^3
Absorption length	200 cm
Scintillation yield	10^4 photon per MeV

	BC-408
Uscita in luce, % Antracene	68
Tempo di salita, ns	0.7
Tempo di decadimento, ns	1.8
Larghezza dell'impulso, FWHM, ns	2.2
λ del Max di Emissione, nm	408
No. di atomi di H per cm^3, (x10^{22})	5.21
No. di atomi di C per cm^3, (x10^{22})	4.74
Rapporto H:C	1.100
No. di elettroni, (x10^{23})	3.37

RIPTIDE: Trigger system

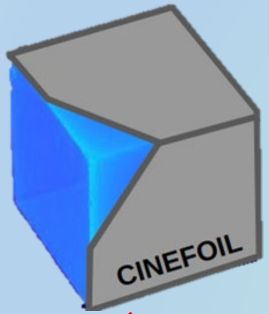


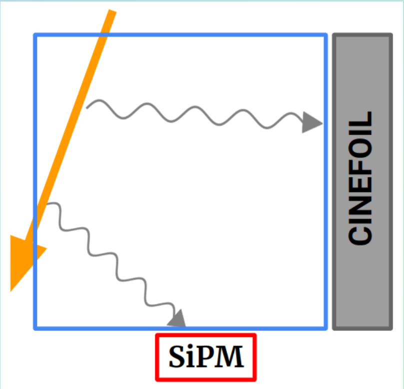
fast TRIGGER signal if something enters in the detector

Cube, SiPM and a system of electronic RO are already available

Tests done with cosmic rays

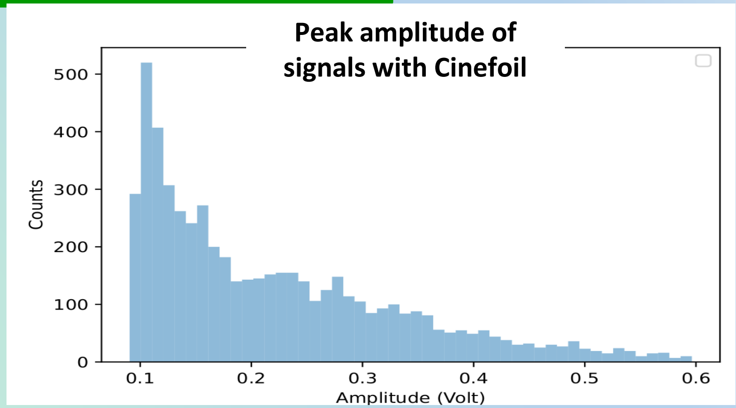
SiPM Characterization: light yield with cosmic rays

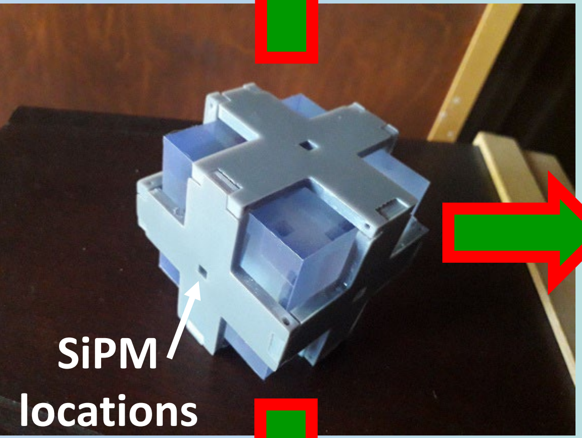




CINEFOIL:

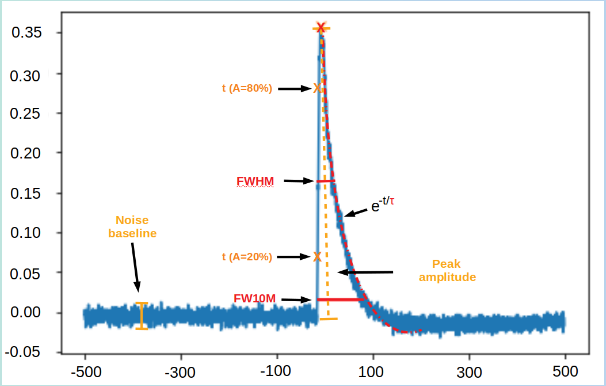
- Only direct light
- Lower signal
- Better time resolution

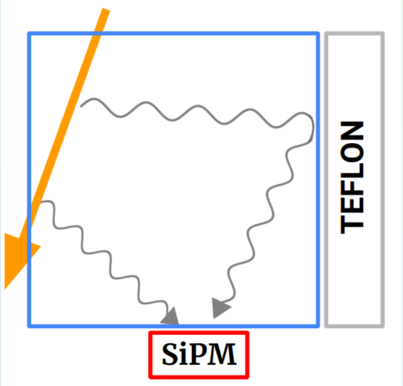




With or without amplifier?

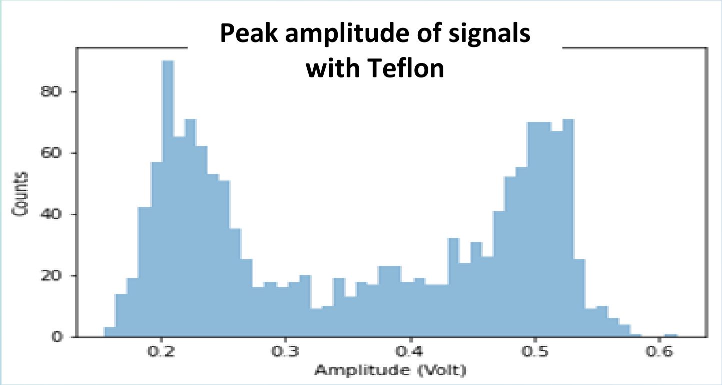
	Risetime (ns)	Decay time (ns)	FWHM (ns)	FW10M (ns)
CNA	3 ± 1	39 ± 4	150 ± 40	490 ± 80
CA	3 ± 1	39 ± 4	160 ± 40	490 ± 60
TNA	6 ± 3	42 ± 6	230 ± 30	530 ± 90
TA	5 ± 3	60 ± 15	310 ± 70	700 ± 130



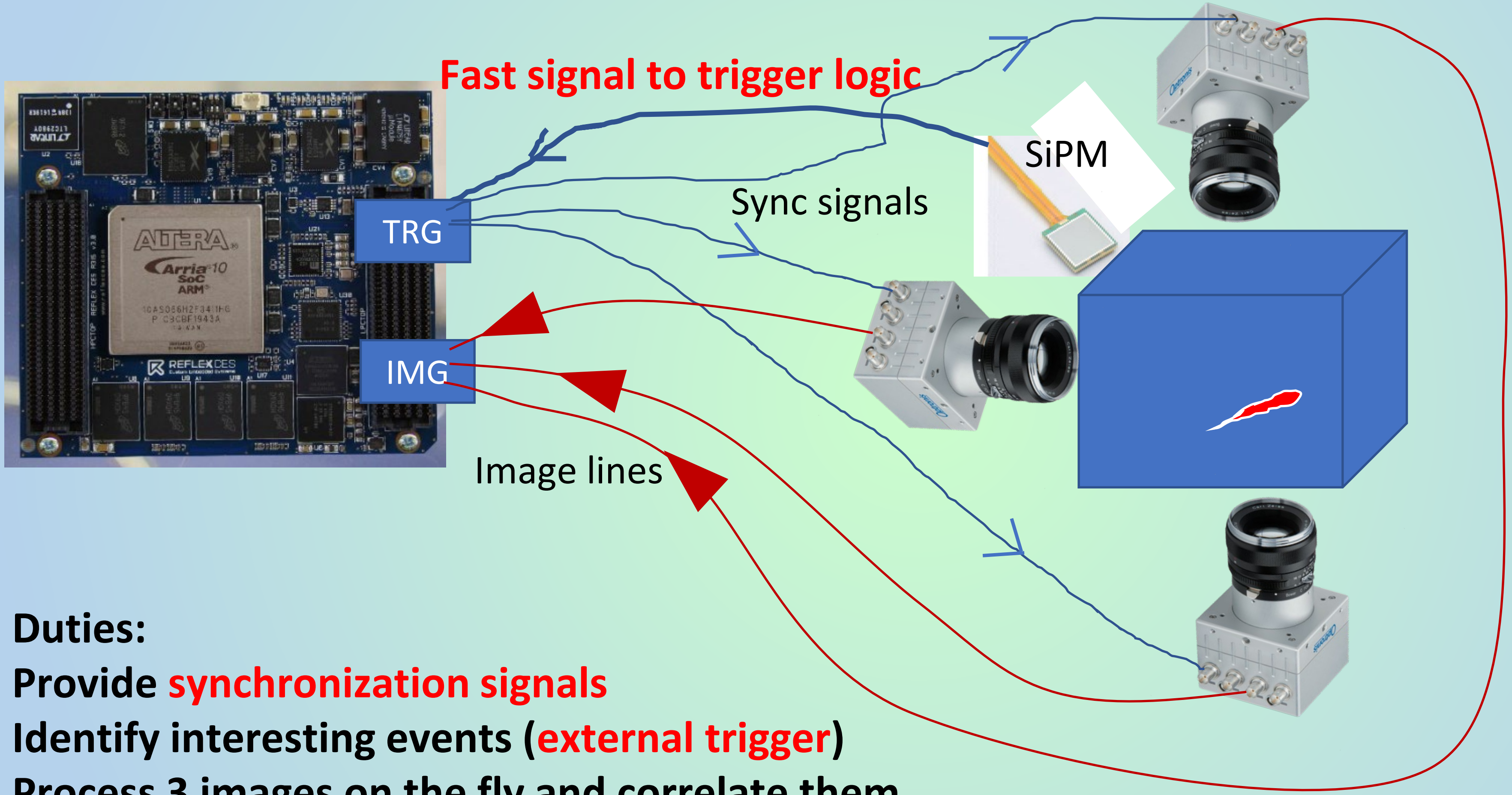


TEFLON:

- Direct and indirect light
- higher signal
- Worsen time resolution



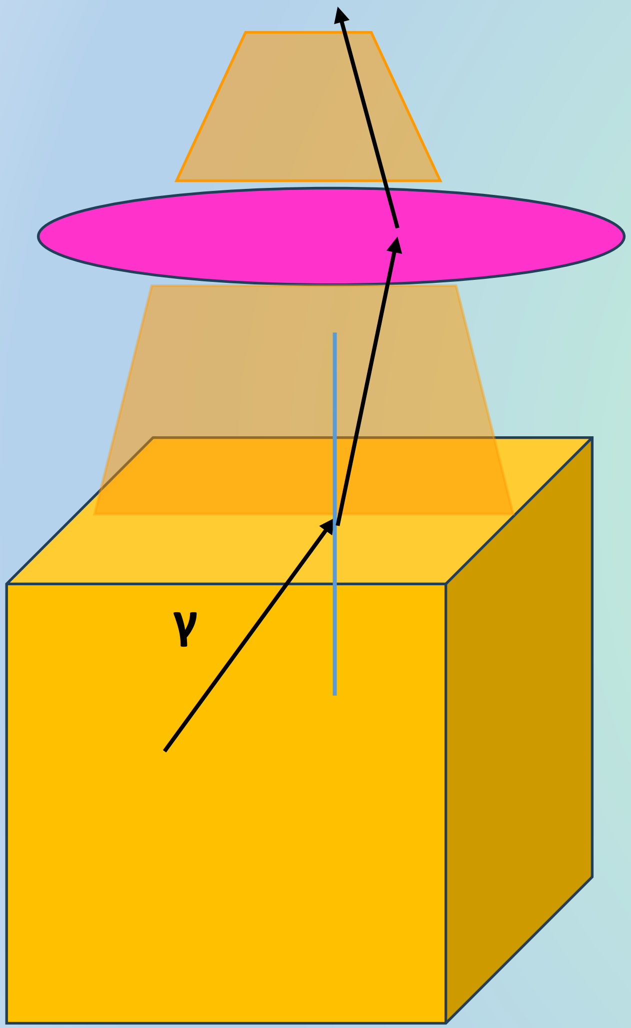
Trigger logic and Data collecting electronics



Number of cameras to be decided

Duties:
Provide synchronization signals
Identify interesting events (external trigger)
Process 3 images on the fly and correlate them
Store images with scattered protons
Measure energy (easy, ADC sums, cluster size)
and start & stop points (not so easy) → Use of FPGA+CPU SoC assembly

RIPTIDE: lens system



Lens system is necessary to reconstruct the photon direction

Each surface is unifomly illuminated

Without lens system is not possible to reconstruct the proton track

Crucial to simulate all the optic steps

Toy MC to simulate only optics

Apply optic system to GEANT simulation

Possible Sensor

Commercial CMOS

E30 F3.5
Macro
optics

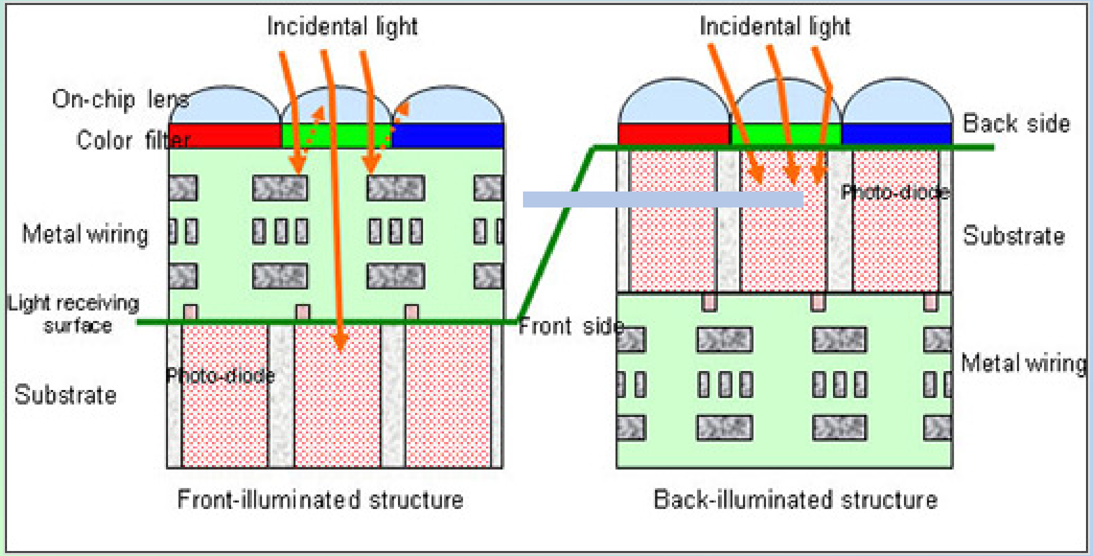
ASI
294MM
PRO

Sony IMX492 (IMX327)

16 fps (60 fps)

4k x 2.8 k pixels

14 bits adc, monochrome



Pro:

On the shelf! And in our lab!

Direct connection with a PC

Cont:

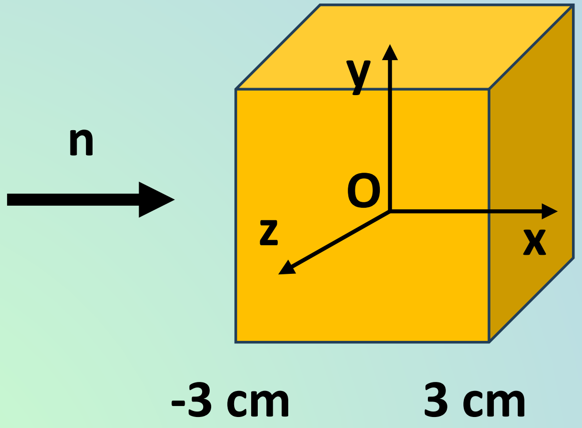
Low fps

No empty pixel suppression

High dead time during reading

Physics and detector Simulation

GEANT4 — A SIMULATION TOOLKIT



- Generated 10^6 neutrons and 10^6 protons
  - Initial proton position: concentric cube of 2 cm
  - Initial proton momentum: isotropcal emission
  - Initial neutron position: (-3.1, 0, 0) cm
  - Initial neutron momentum direction (1, 0, 0)
  - Initial kinetic Energy: 5, 10, 20, 50 , 100 MeV
- Cube geometry and material characteristics
- Transport Models
  - p and n derived from n-TOF results
  - Isotropically emission of 10^4 photons per MeV of proton

M.C. TOY

Optics simulation

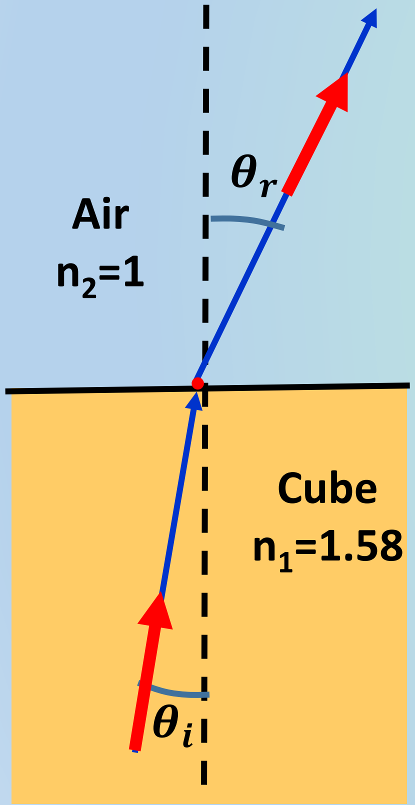
Image on sensors

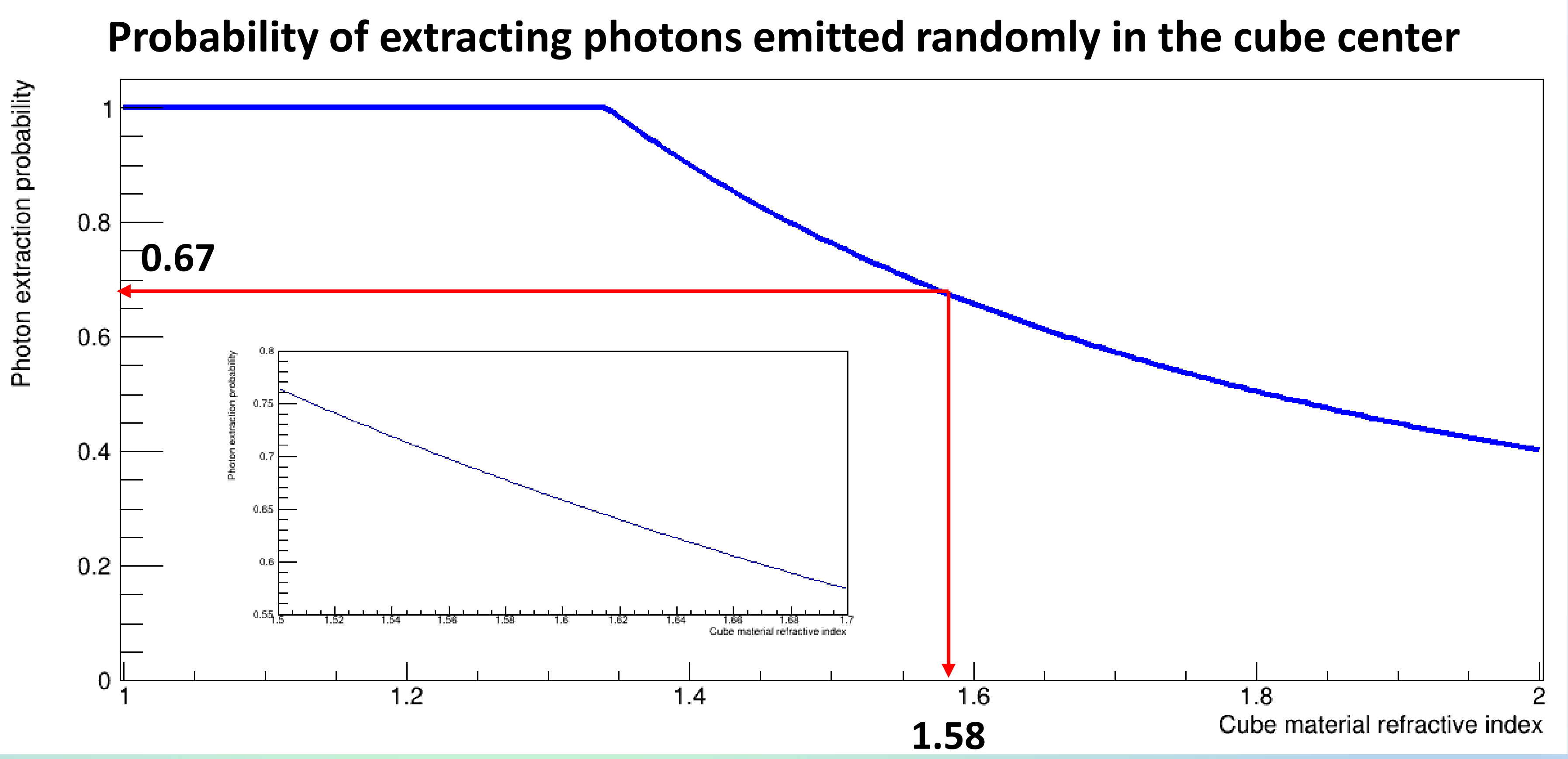
Reconstruction:
from 2 bidimensional images on sensors
→ Tridimensional Proton tracks

Toy MC simulation: photon transmission (Snell law)

$$\sin\theta_r = \frac{n_1}{n_2}\sin\theta_i$$

$$\theta_{max} = 39,3°$$





67% of photons not subject to total reflection

33% of photons lost due to total reflection

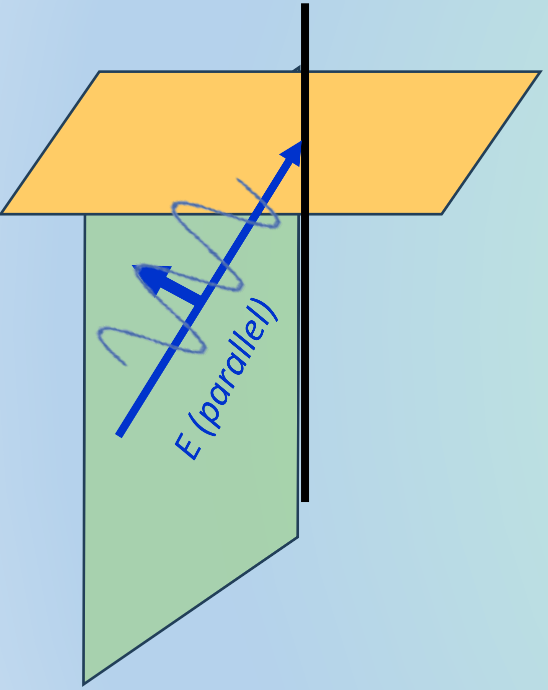
γ isotropically emitted in the center

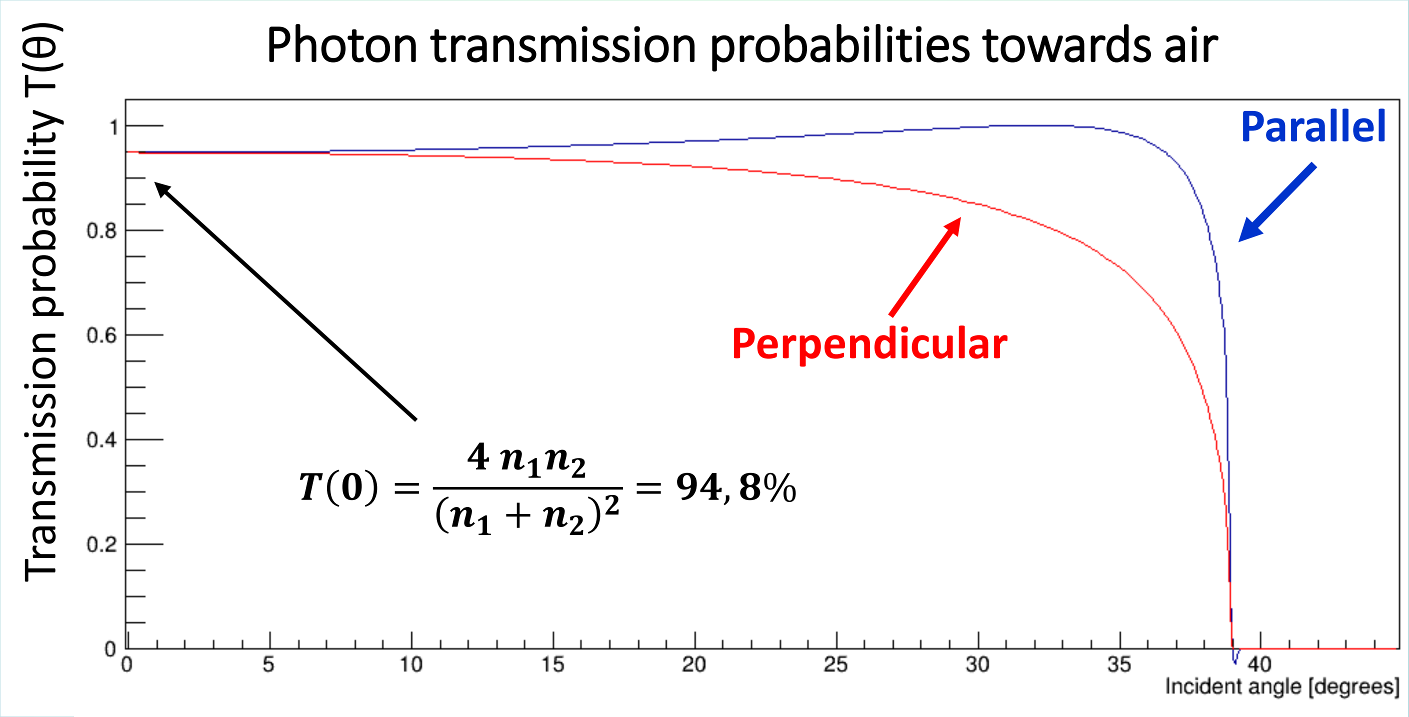
If $\theta > \theta_{max}$ on the first wall, $\theta > \theta_{max}$ on the all walls (γ doesn't exit) → low bkg → low intensity

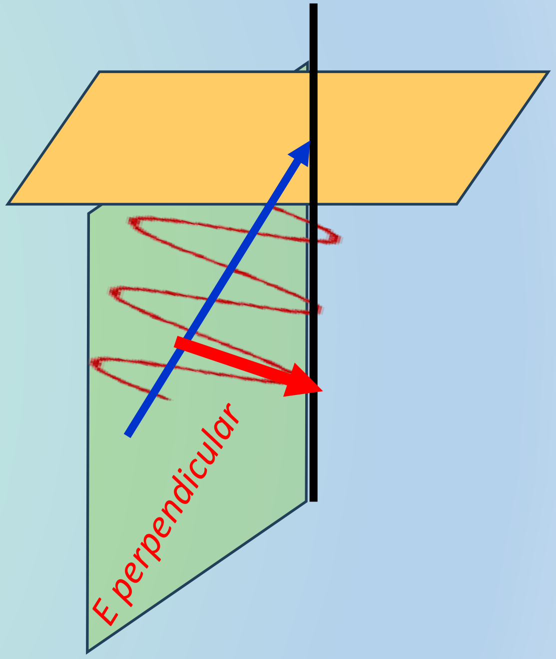
Toy MC simulation: photon transmission (Polarization)

γ has a random polarization that can be decomposed (50% parallel and 50% perpendicular)

parallel or perpendicular to the incident plane (plane having the photon momentum and the normal to the surface)







$$R = \left(\frac{n_1 \cos\theta_r - n_2 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i}\right)^2$$

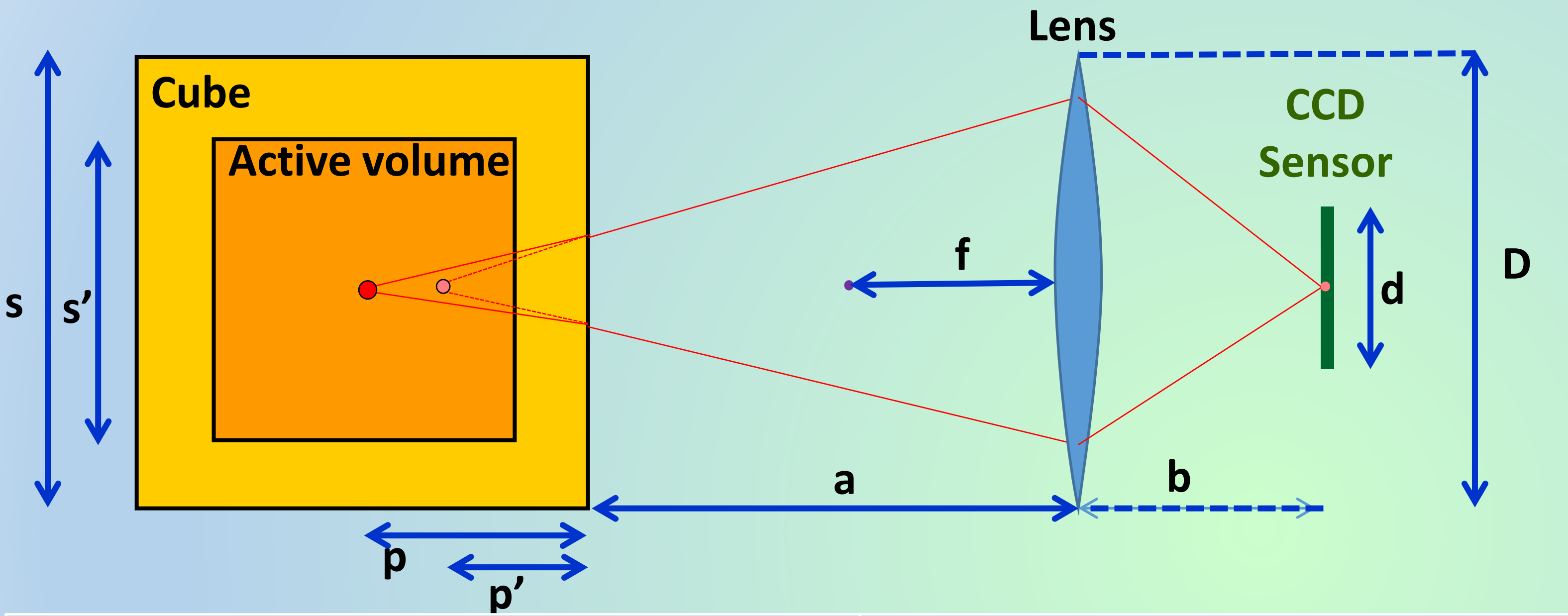
$$T = 1 - R = \frac{4 n_1 n_2 \cos\theta_r \cos\theta_i}{(n_1 \cos\theta_r + n_2 \cos\theta_i)^2}$$

T → Transmission
R → Reflection

$$R = \left(\frac{n_1 \cos\theta_i - n_2 \cos\theta_r}{n_1 \cos\theta_i + n_2 \cos\theta_r}\right)^2$$

$$T = 1 - R = \frac{4 n_1 n_2 \cos\theta_r \cos\theta_i}{(n_1 \cos\theta_i + n_2 \cos\theta_r)^2}$$

Optics scheme



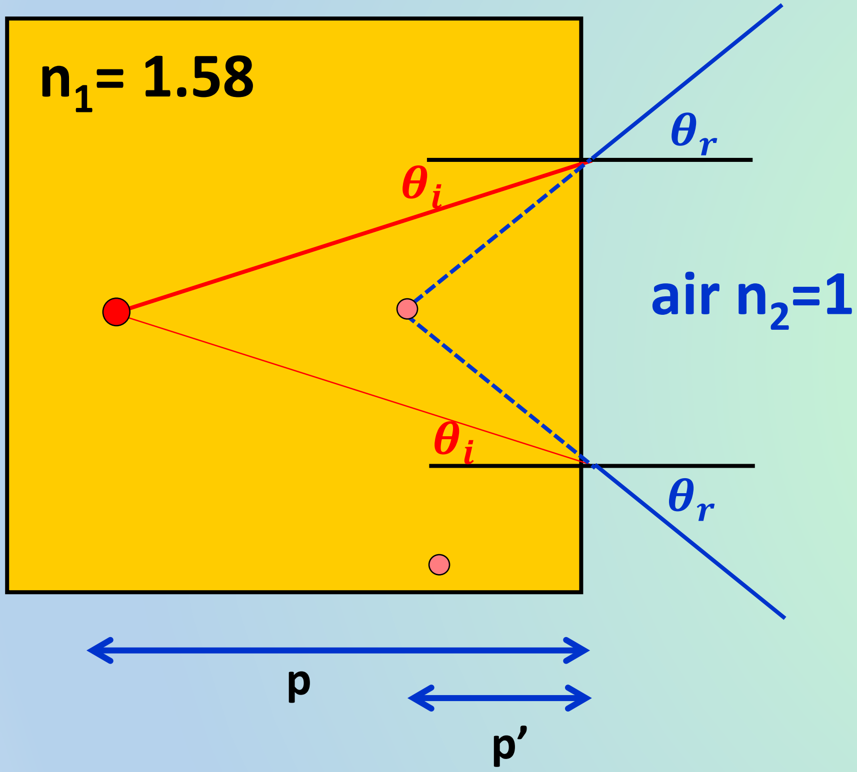
7 Parameters to fix	values
s: scintillator size	60 mm
s': side of the active cube	40 mm
d: side (not diagonal!) of the CCD sensor	20 mm
f: focal length of the lens	D/f highest possible (now D = 2f)
D: diameter of the lens	
a: position of the lens	
b: position of the sensor	

Those fixed on the common sense (obviously can be changed if needed)

D (f), a,b to be evaluated by simulation

The apparent source

As a spherical diopter
here is a plane (sphere with R → ∞)



$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

$$\rightarrow \frac{n_1}{p} + \frac{1}{-p'} = 0 \rightarrow p' = \frac{p}{n_1}$$

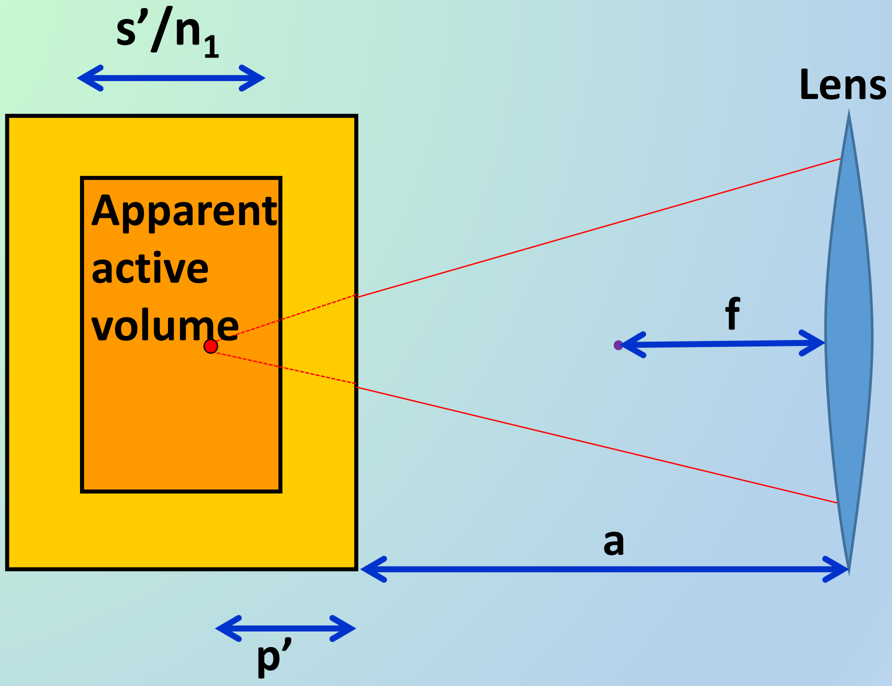
$p' = \frac{p}{n_1}$=18,9 mm

the source is seen by the optics shifted by 18.9 mm)

the optics see the cube «crushed» by a factor 1/n_1

Apparent active volume → Active volume/n_1

Longer field of view



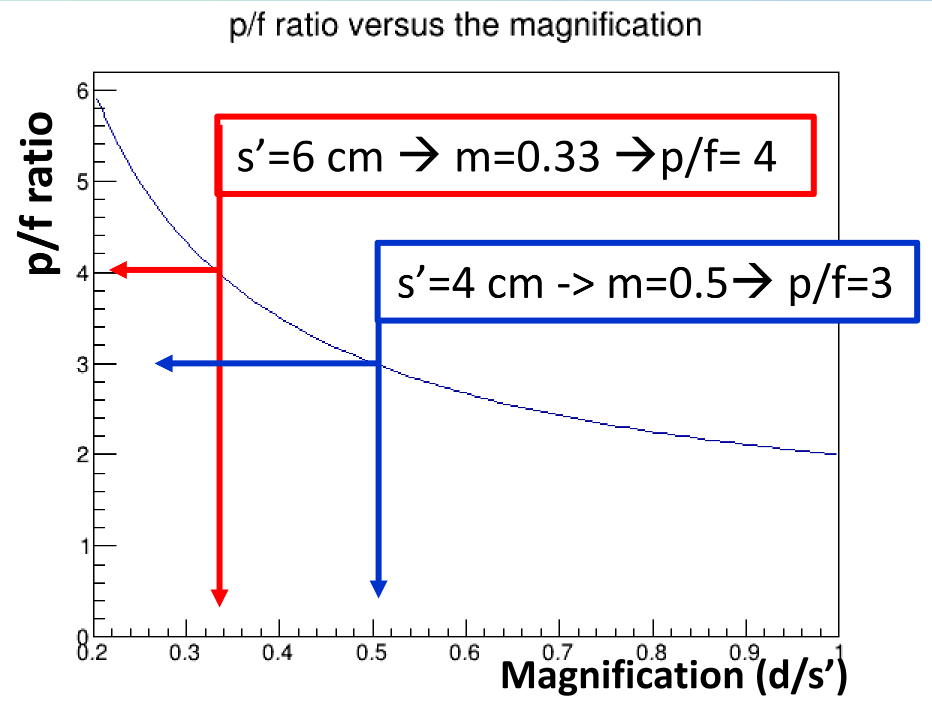
Lens magnification

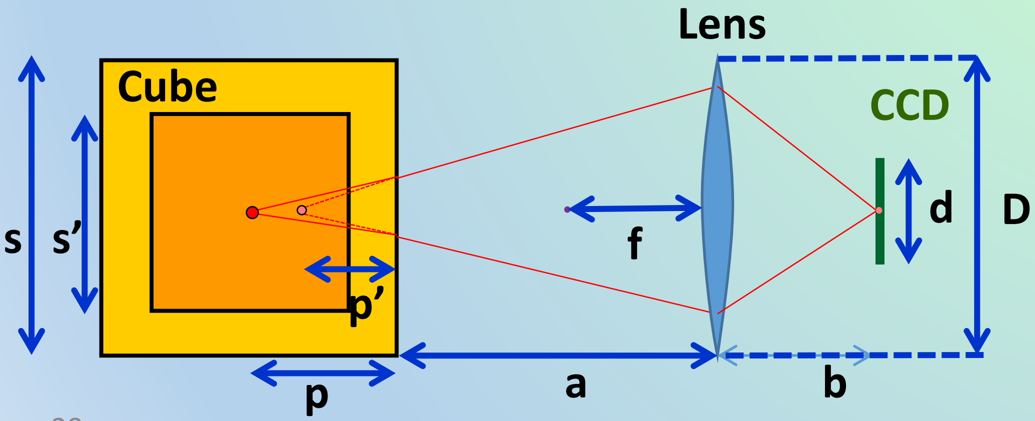
$$m = \frac{q}{p} = \frac{f}{p-f} = \frac{1}{\frac{p}{f} - 1}$$

and

$$m = \frac{d}{s'} = \frac{CCD\ sensor}{active\ cube\ side}$$

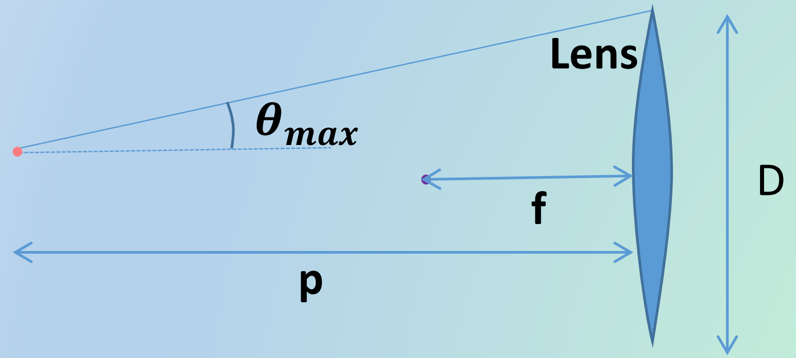
$$\frac{p}{f} = \frac{m+1}{m}$$





Different photon collection efficiency

Photon collection efficiency (γ emitted along the lens axis)



when D=2f

$$\tan\theta_{max} = \frac{D}{2p} = \frac{f}{p}$$

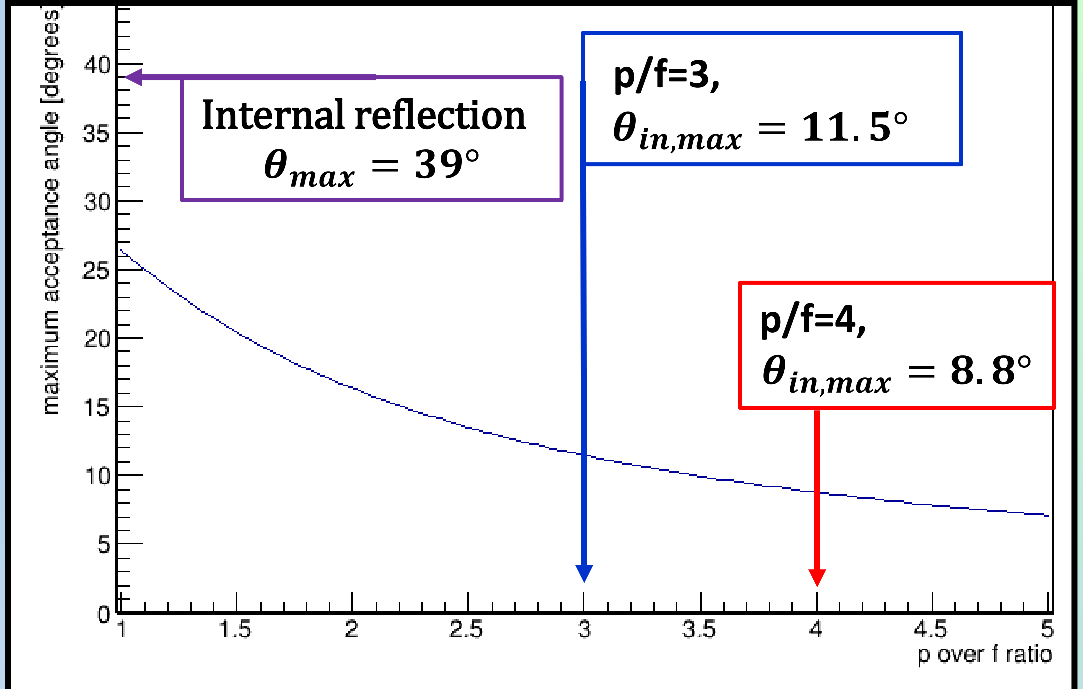
$$\Omega = 2\pi(1-\cos\theta_{max})$$

$$f(\Omega) = 3\ (1-\cos\theta_{max})$$

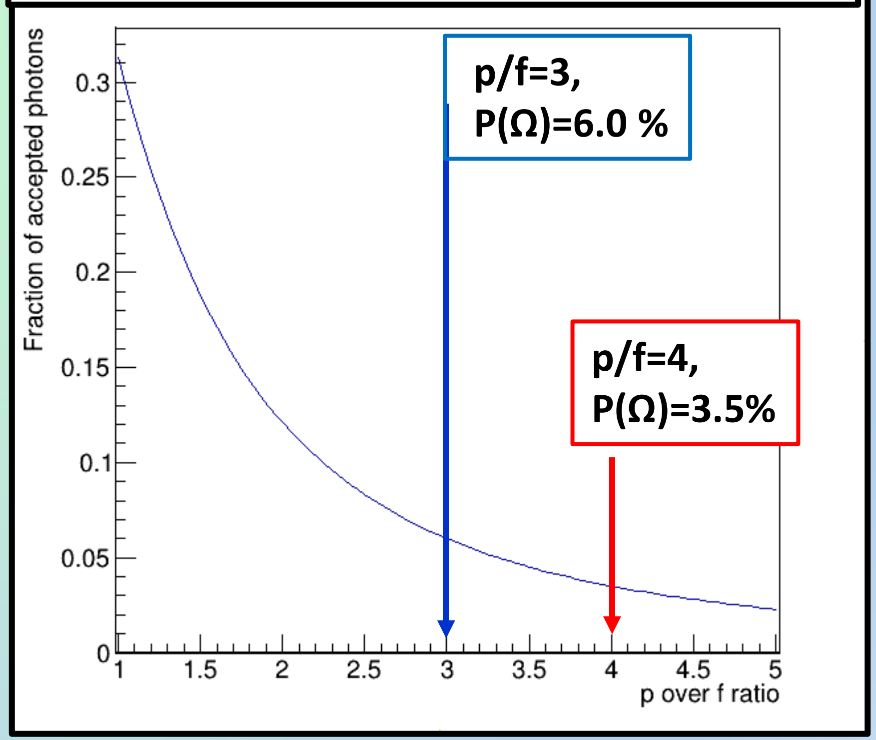
$$\theta_{in,max} = \theta_{max}/n_1$$

$$f(\Omega) = 3\ [1-\cos(\frac{f}{pn_1})]$$

Angle vs p/f ratio



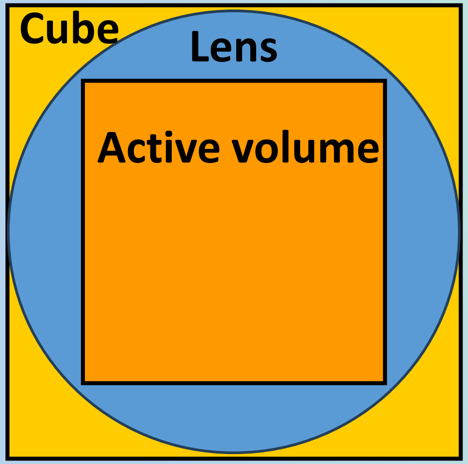
Acceptance vs p/f ratio



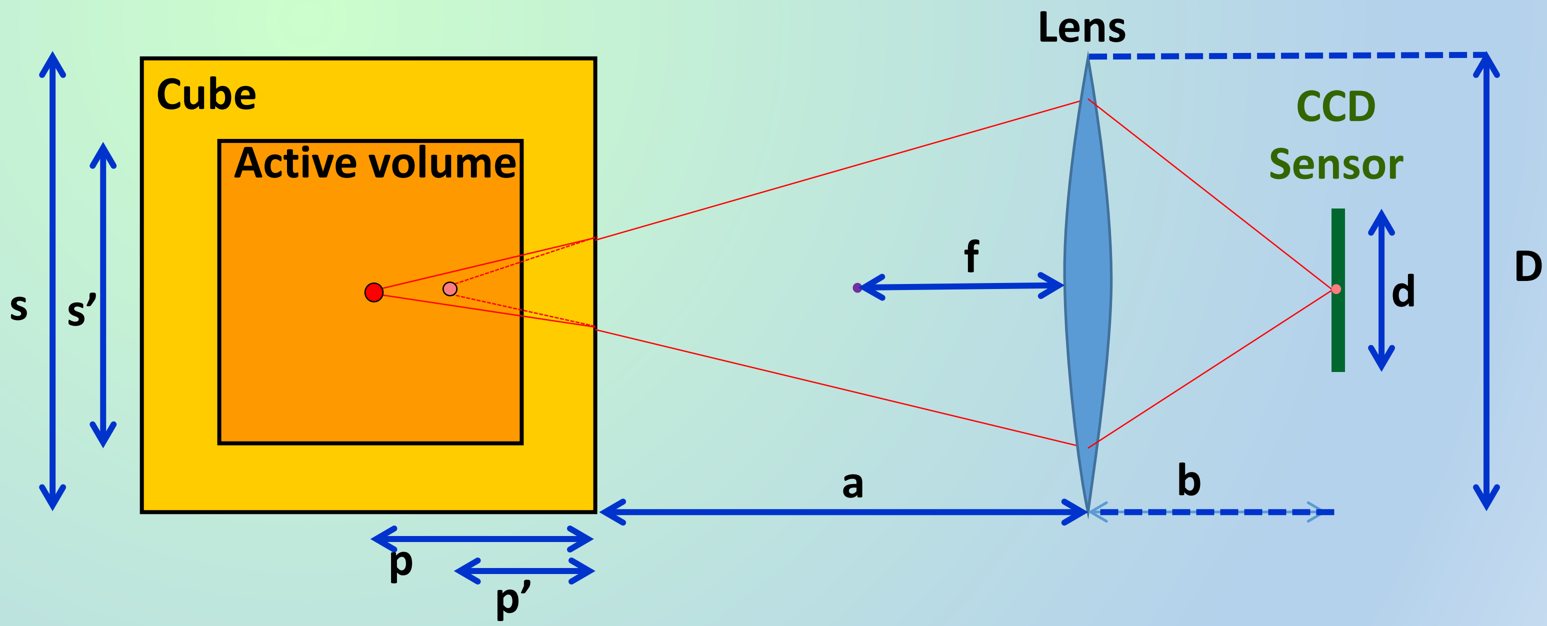
Final dimensions

to collect the light in the active volume we need a lens of similar size.

R from 2 to 4 cm (assume R=3 cm)



Parameter	values
s: scintillator size	60 mm
s’: side of the active cube	40 mm
d: side (not diagonal!) of the CCD sensor	20 mm
f: focal length of the lens	30 mm f = D/2
D: diameter of the lens	60 mm
a: position of the lens	71 mm a = p’’ – p’
b: position of the sensor	45 mm b = fp’’/(p’’-f)

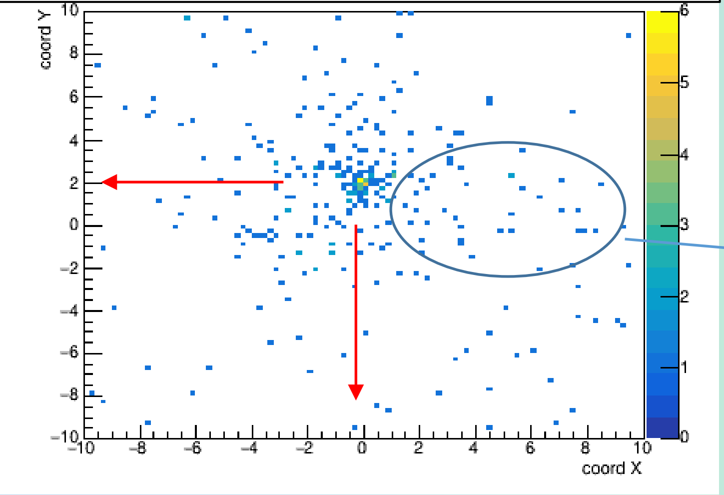


Simulation: Final dimension of the object ~30x30x10 cm^3

Position Resolution

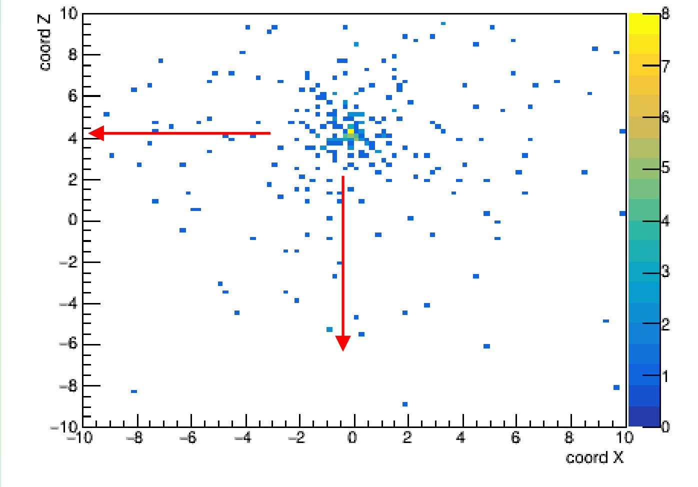
- photons generated randomly in the center of a cube (53x53x53 mm^3)
- Number of photons: 6.88x10^4
- Energy: 6.88 MeV

Face XY

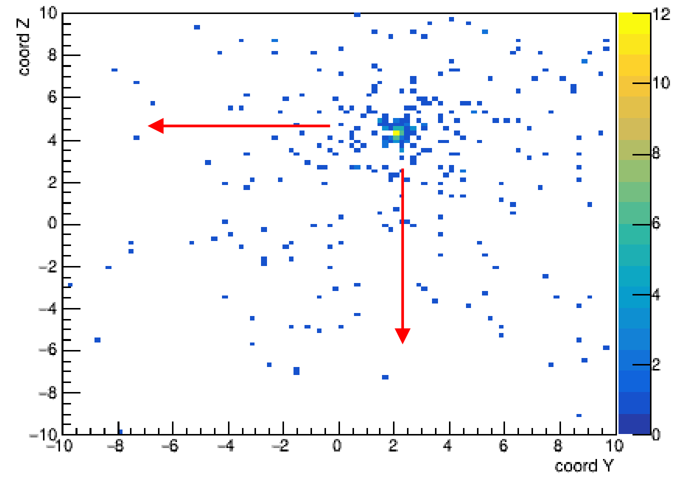


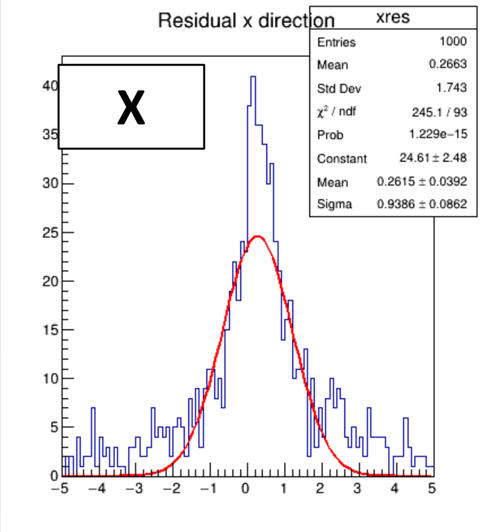
spherical aberration

Face XZ



Face YZ



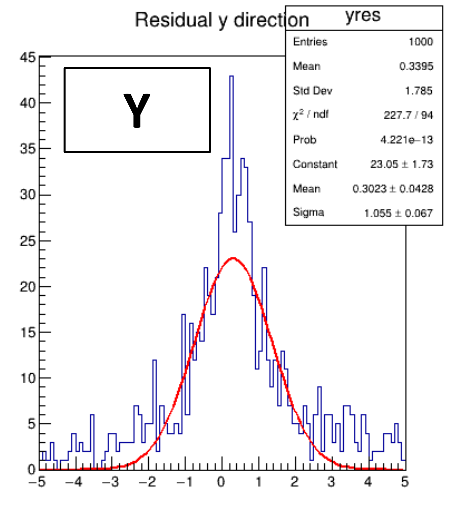


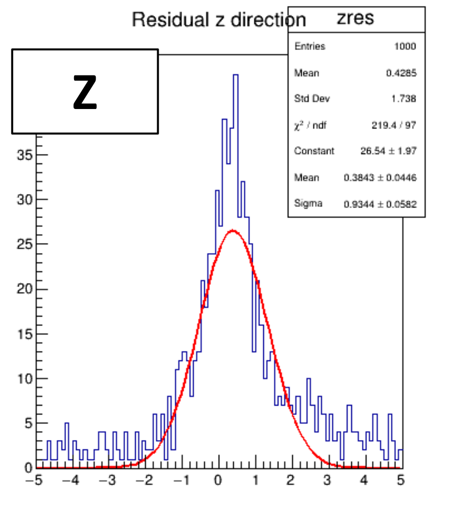
Position Reconstruction

Residuals

$$X_{estimated} = -X_{mean}/0.5$$
$$X_{res} = (X_{estimated} - X_{true})$$

Residuals 0.96 mm!

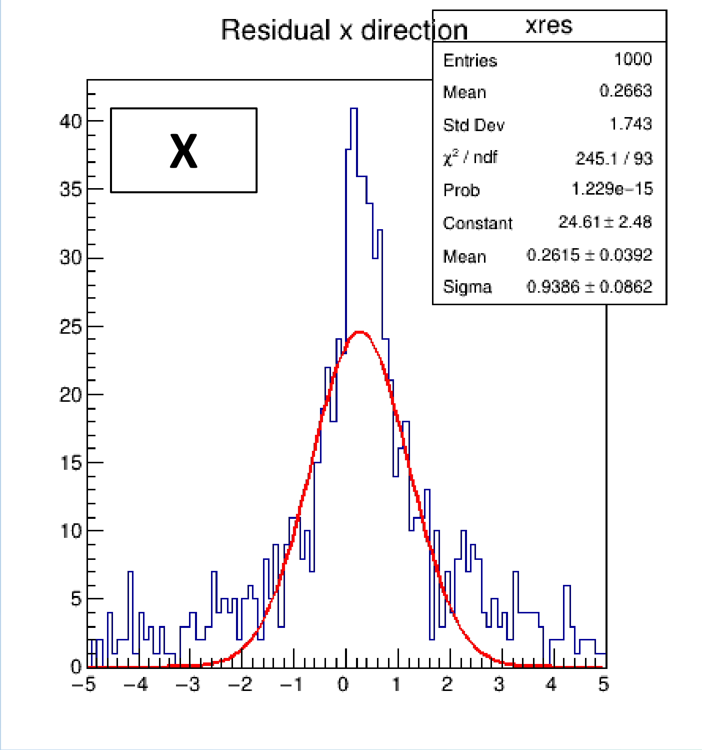




Position Resolution: variation of cube dimension

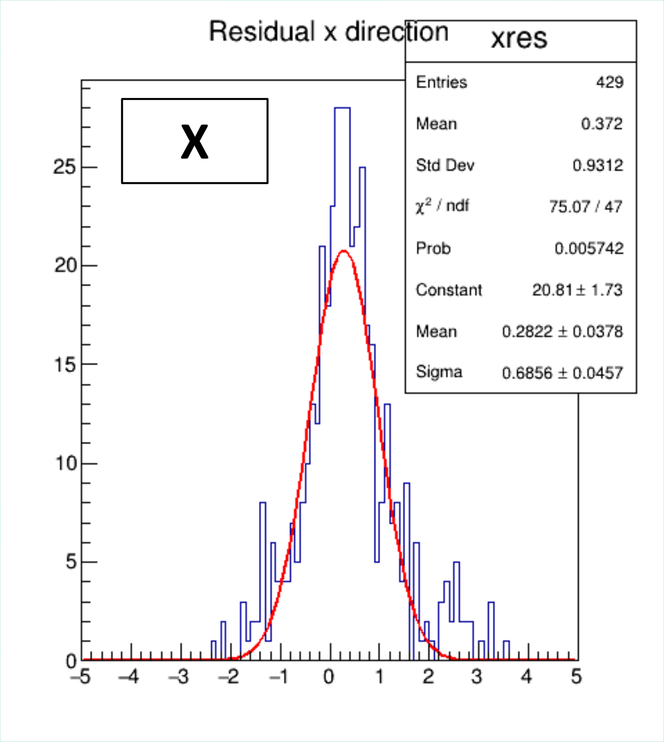
Position Reconstruction (the same for Y and Z)

cube (53x53x53 mm^3)



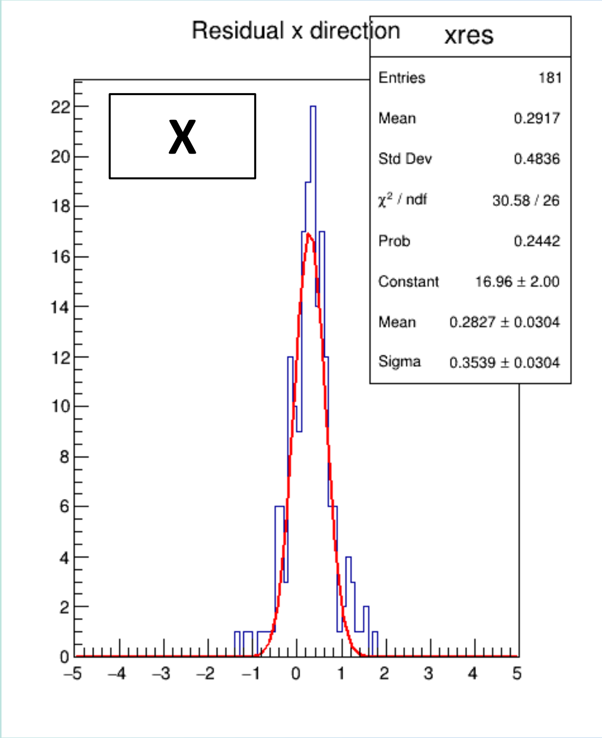
Residuals 0.96 mm!

cube (40x40x40 mm^3)



Residuals 0.68 mm!

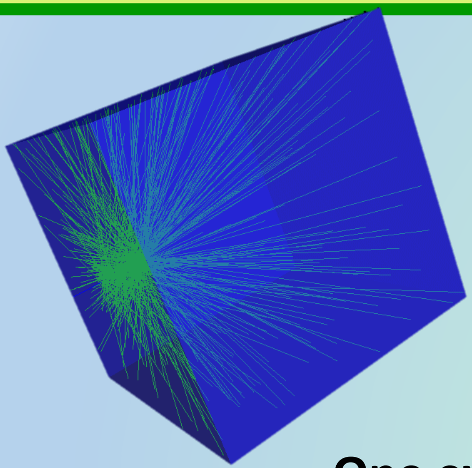
cube (30x30x30 mm^3)



Residuals 0.35 mm!

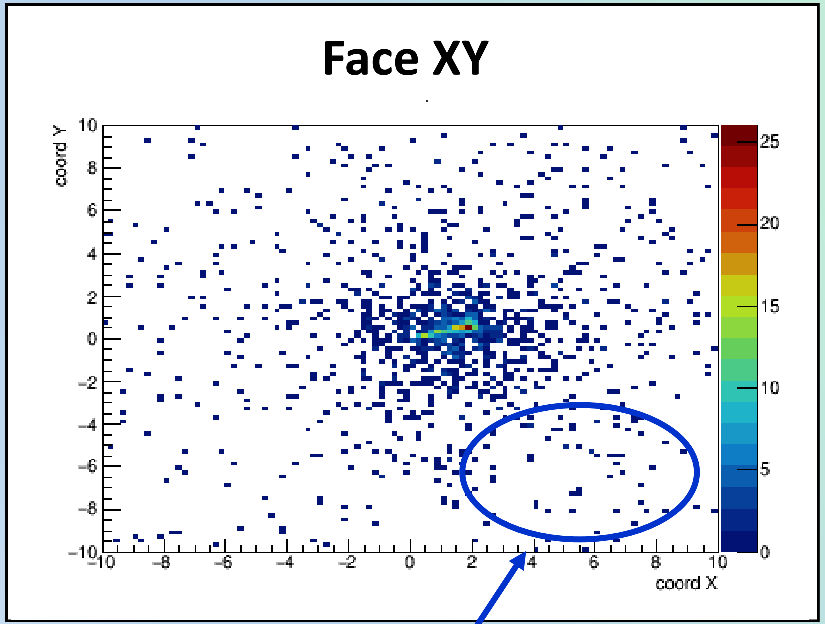
- **Decreasing the Cube dimension → improve the Position Reconstruction**
- **Decreasing the Cube dimension → decrease the detector efficiency**

Geant simulation

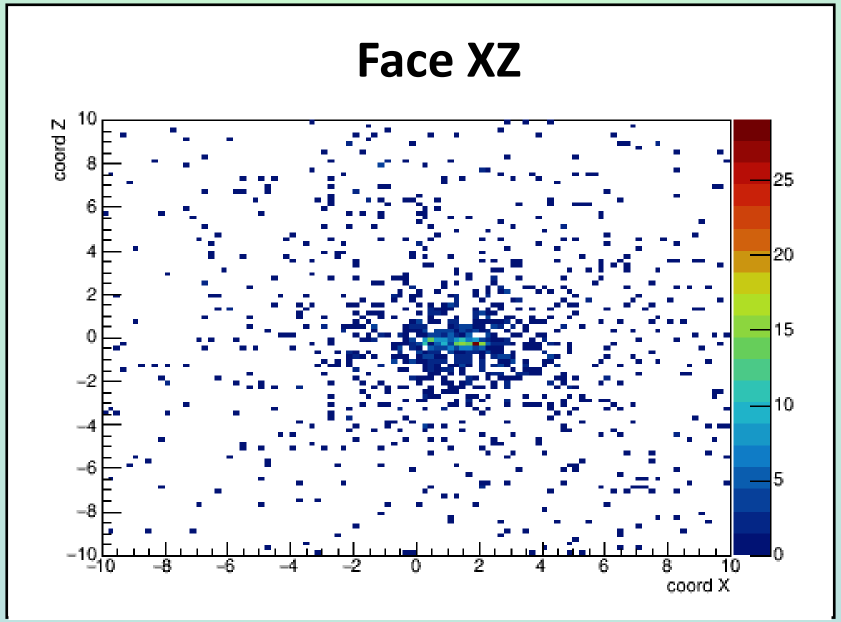


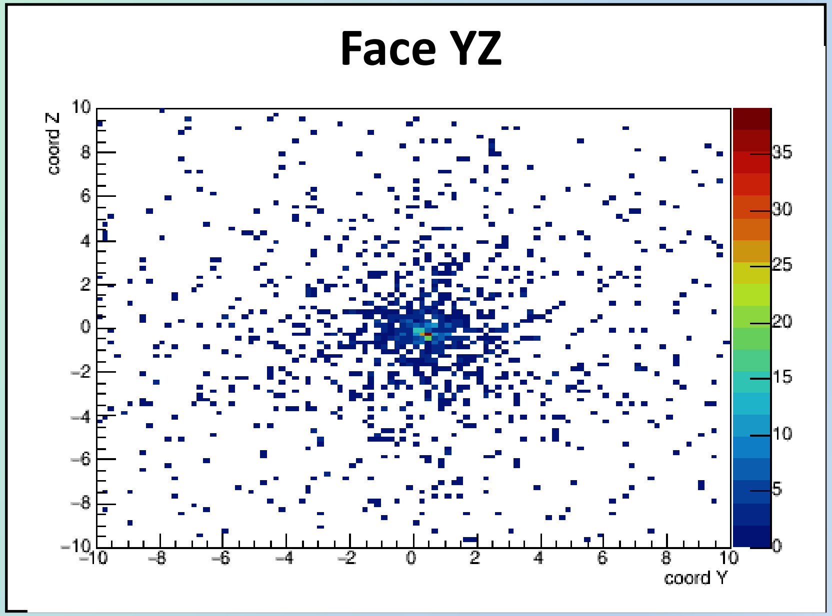
One event

- cube $60x60x60\ mm^3$
- protons generated isotropically in the center of a cube [-1:1] for X-Y-Z
- Energy: 30 MeV
- 10 k photons per MeV
- Material: only H
- Cube surface: total absorption (no reflection)
- Standard optics with p/f=3, f = 30 mm, R = 30 mm



spherical aberration



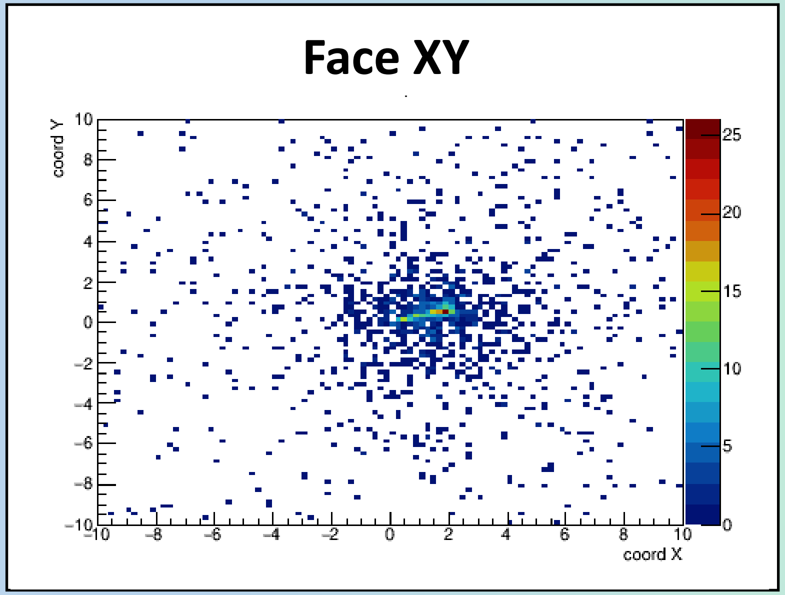


- About 1440 photons/view
- Track barely visible!

Geant simulation: variation of the radius of the lens

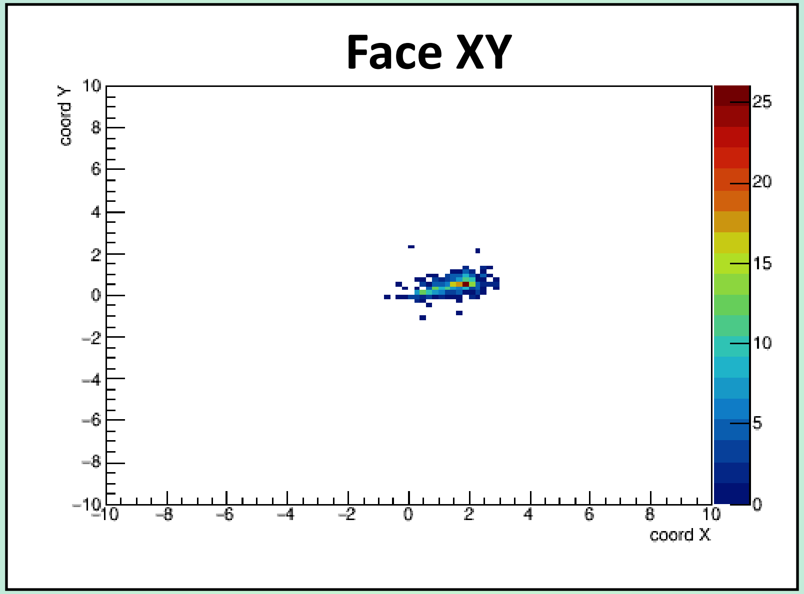
XY Projection (the same for the others)

p/f=3, f = 30 mm, R = 30 mm



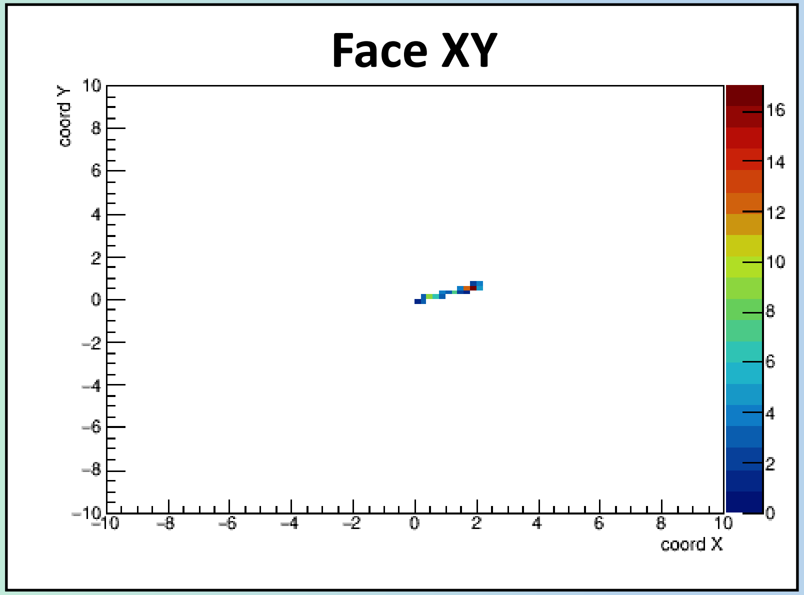
- **About 1440 photons/view**
- **Track barely visible!**

p/f=3, f = 30 mm, R = 10 mm



- **About 340 photons/view**
- **Track visible!**

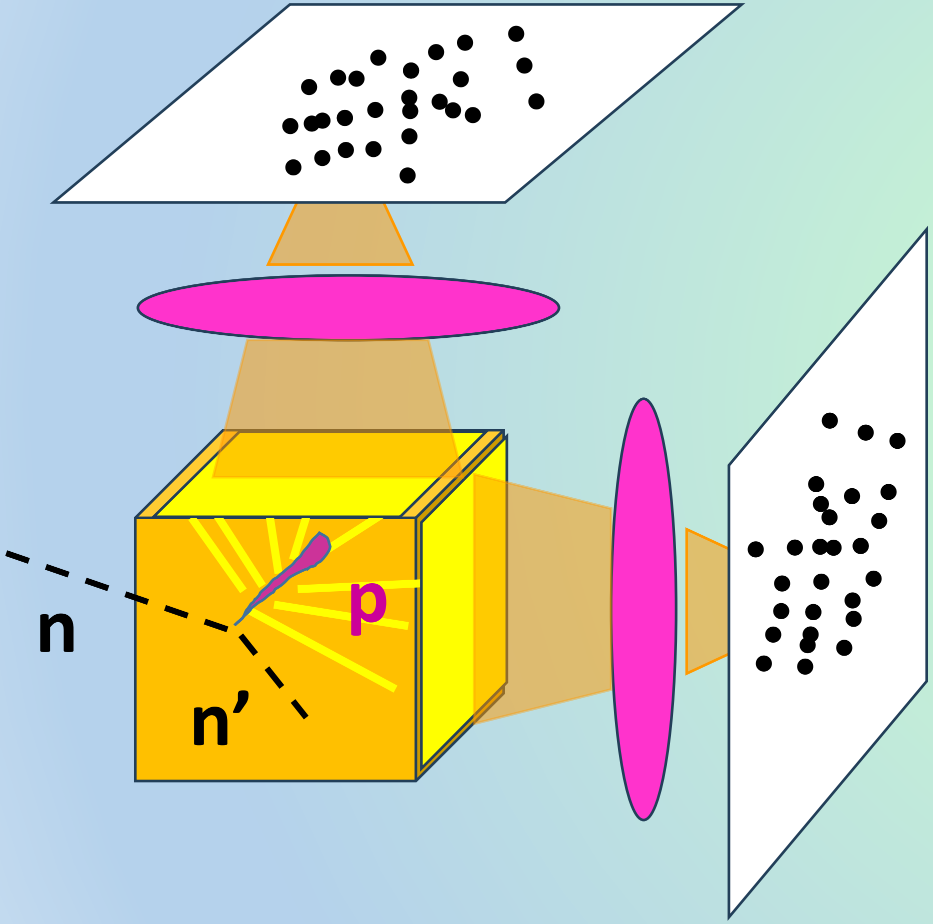
p/f=3, f = 30 mm, R = 5 mm



- **About 80 photons/view**
- **Track clearly visible!**

- **Decreasing the radius of the lens → decrease the spherical aberration → bkg decrease**
- **Decreasing the radius of the lens → decrease the light yield**

Tracks reconstruction



Requests:

- Minimum track lenght detectable ~ 0.2 mm → 3.5 MeV
- 10^4 photons per MeV of protons over the entire solid angle
- Scintillator covered by absorbing material to avoid internal light reflection → decrease the source of noise

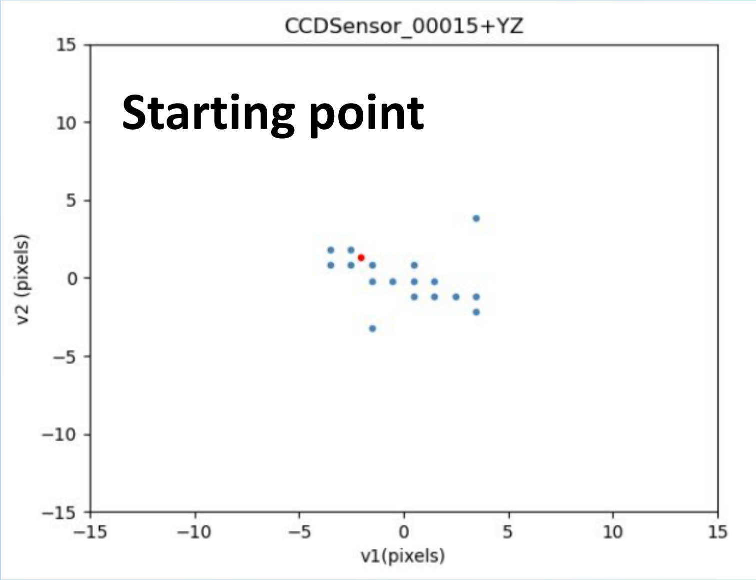
2 different approaches

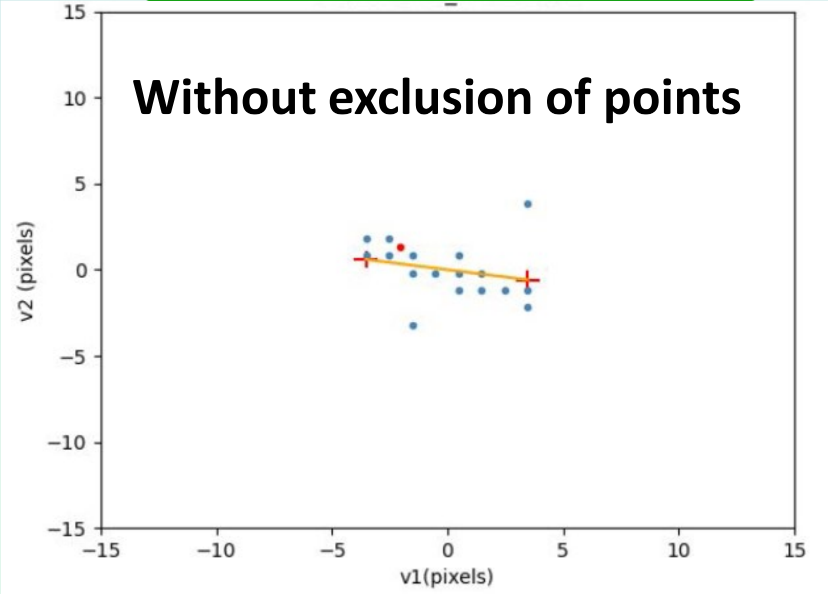
- Simple linear fit
  - Without exclusion of points
  - With exclusion of points
- Principal component analysis (PCA)

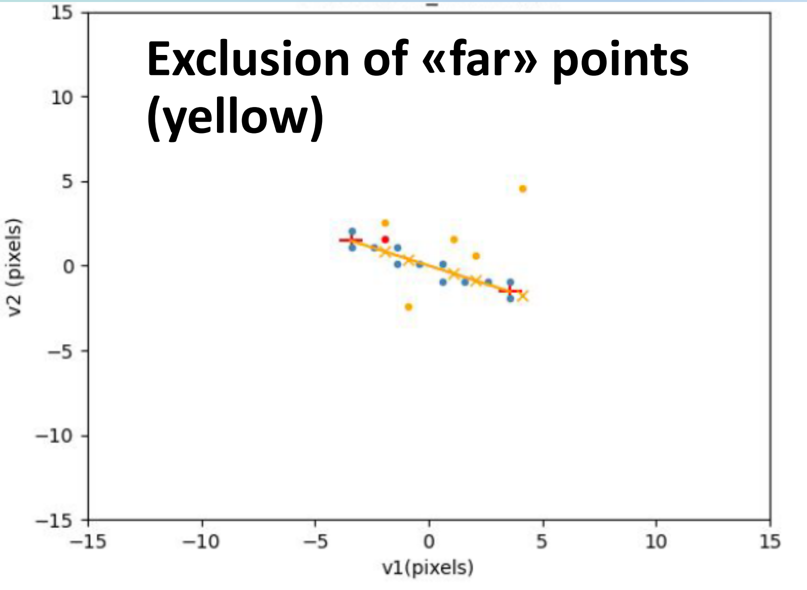
Radius of the Lens: 0.5 cm

CMOS pixel: 100x100

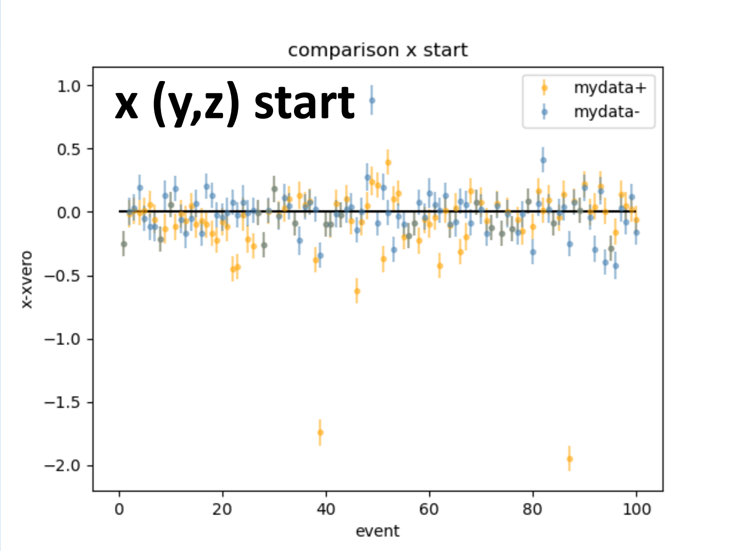
Linear fit

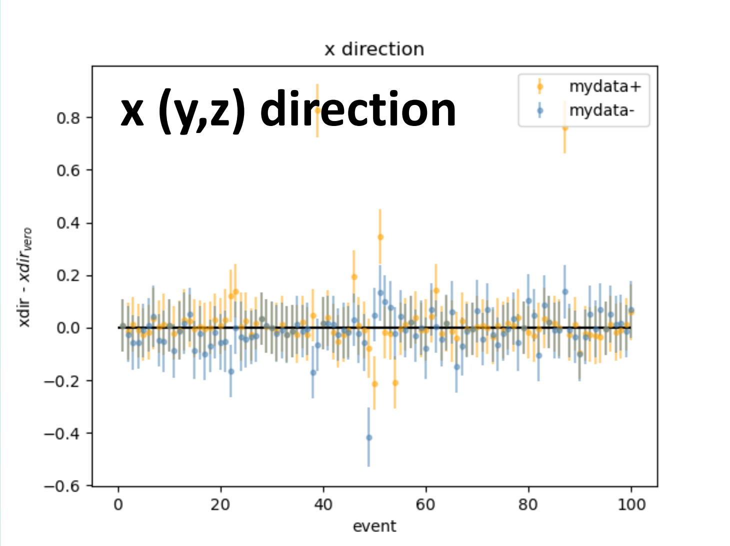


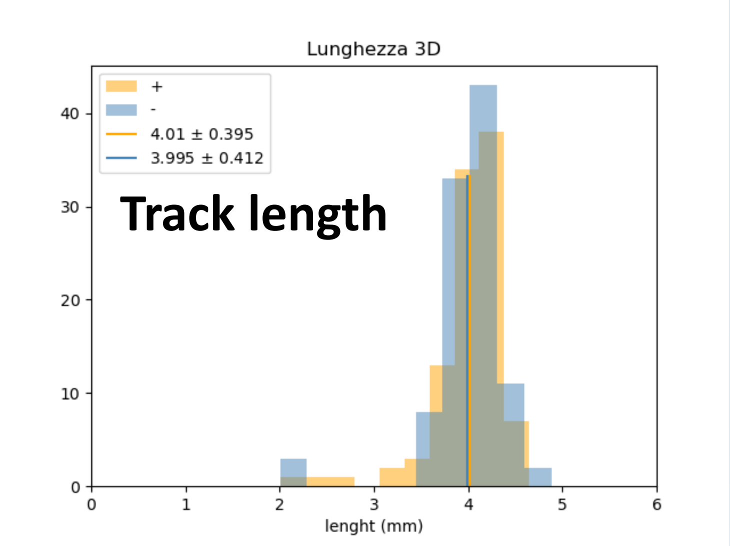




Residual (100 events)







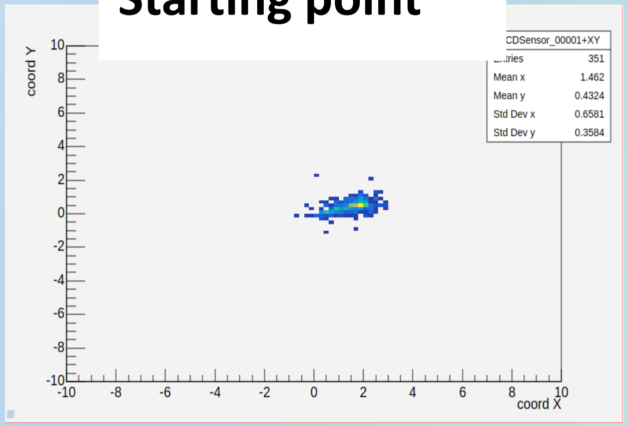
2 methods are compatible inside the error

Radius of the Lens: 1 cm

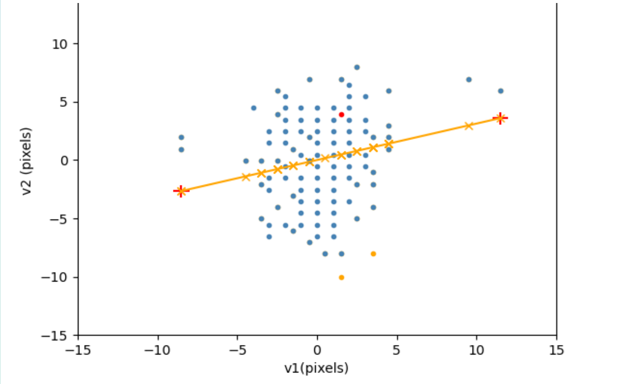
CMOS pixel: 100x100

Linear fit

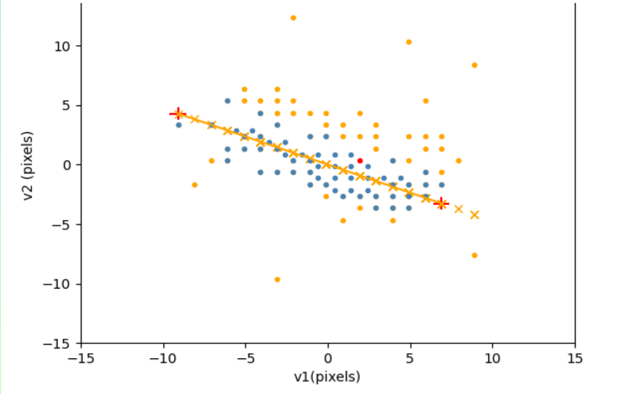
Starting point



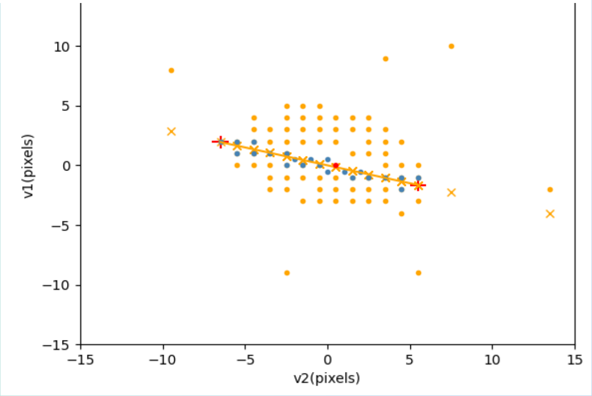
exclusion of points: thr =1



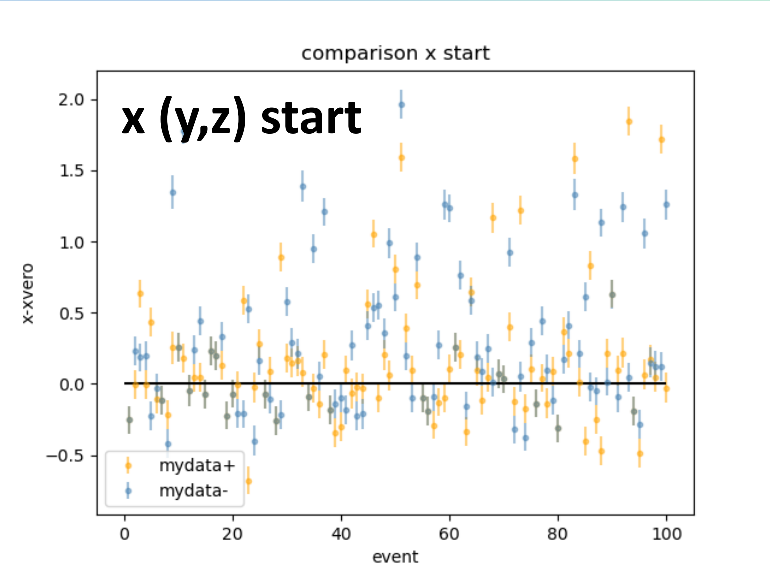
exclusion of points: thr =4

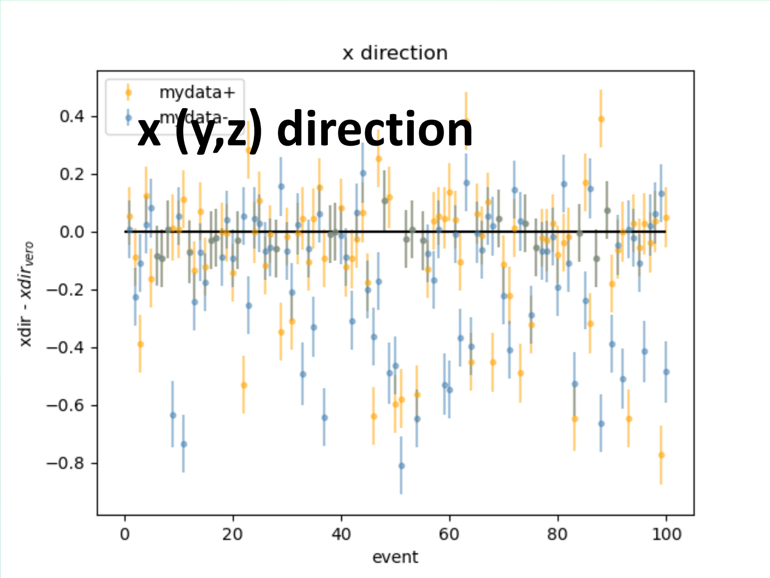


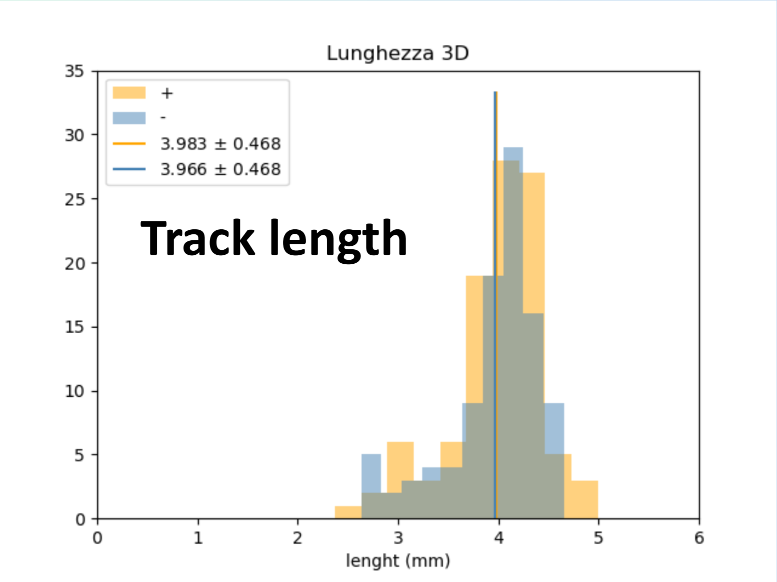
exclusion of points: thr =10



Residual





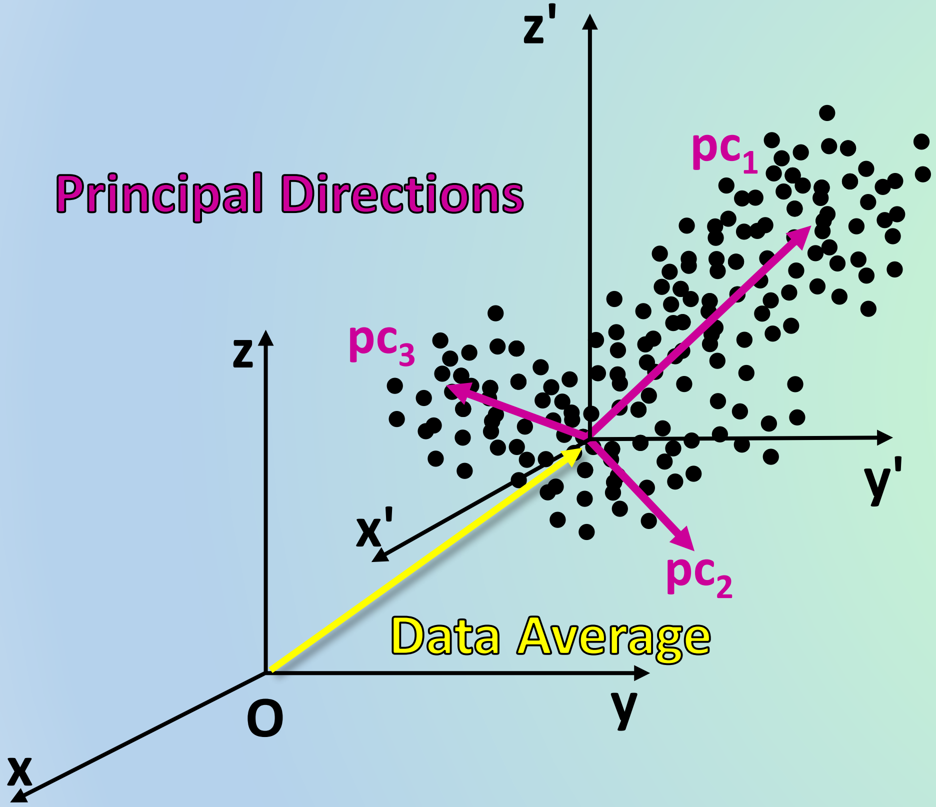


2 methods are compatible inside the error

PCA Analysis, 1

PCA (Principal Component Analysis) : machine learning tool supporting decisions and data analysis

In general → data sets are points (x_1, x_2, … , x_n) in the n-D space to discriminate/cluster



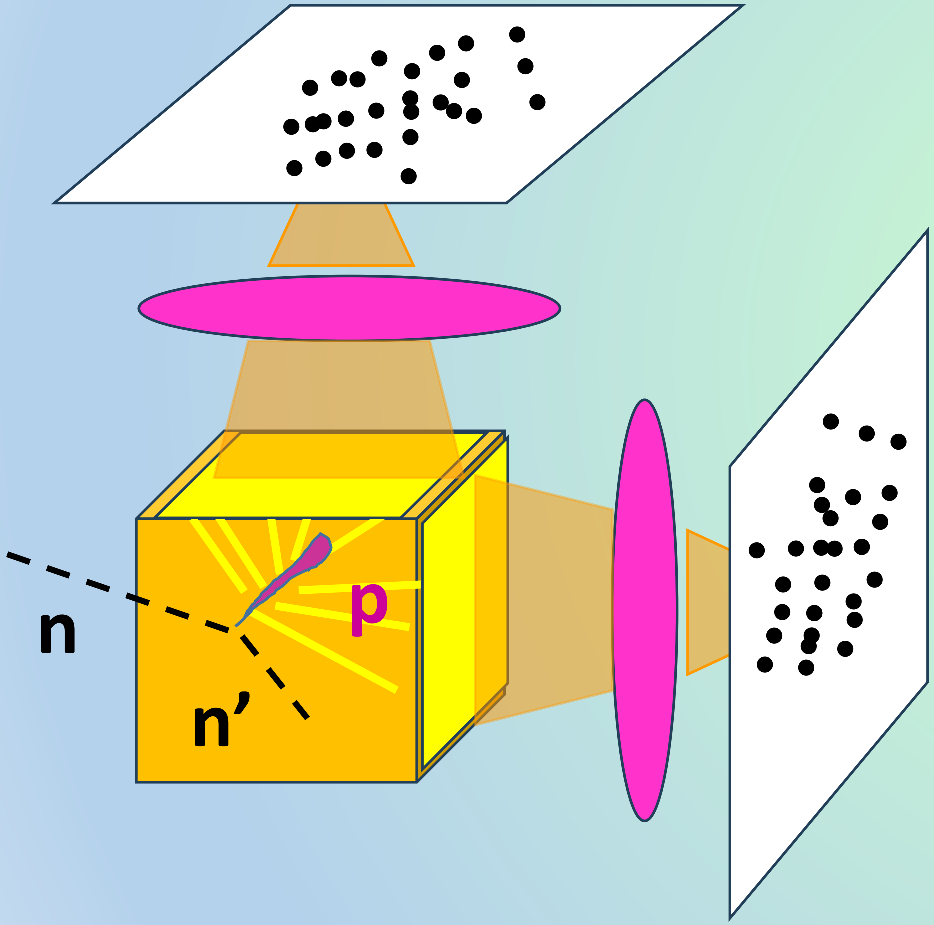
- O(xyz) Raw Data frame
- O'(x'y'z') Data referred to Average

PCA for Data Analysis	PCA for Particle Track Imaging

Clouds of data points
(here 3D space)
↓
Covariance matrix of data
↓
Diagonalization
↓
Finding "Principal" Directions
(distribution of data)
↓
3 eigenvectors and 3 eigenvalues
(maximum eigenvalue → prominent direction)

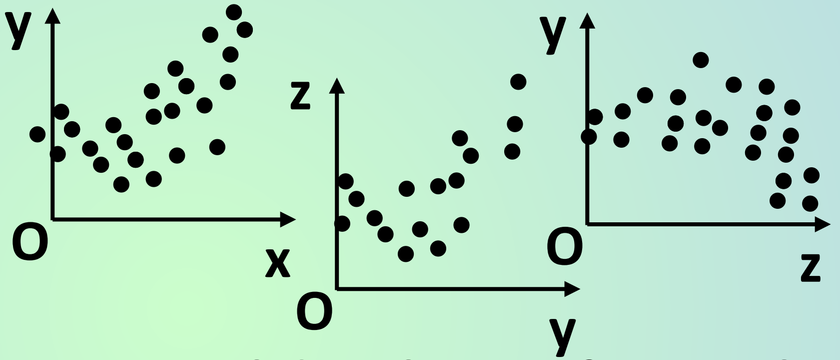
First eigenvector: <u>main tendency</u> in data/variables/params	First eigenvector: <u>Particle Track Direction</u> in detector volume

PCA Analysis, 2



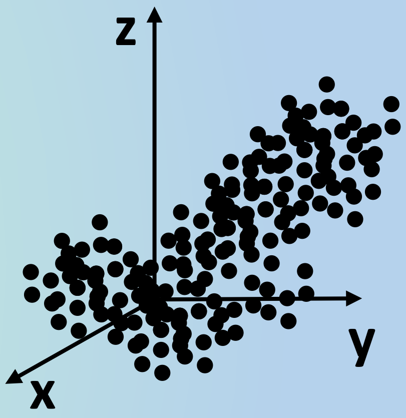
INPUT data for Principal Component Analysis

RIPTIDE (this case):
projection on cube faces



- marginal distribution for couples of variables (x,y) (y,z) (x,z)
- averages of data distributions

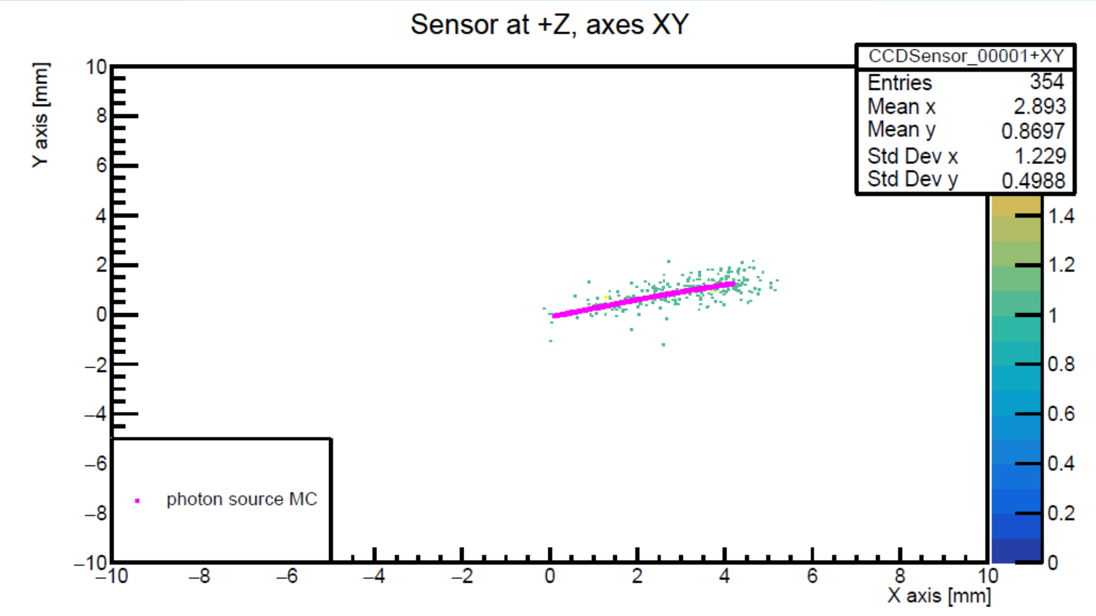
Data analysis (standard case):
raw data set

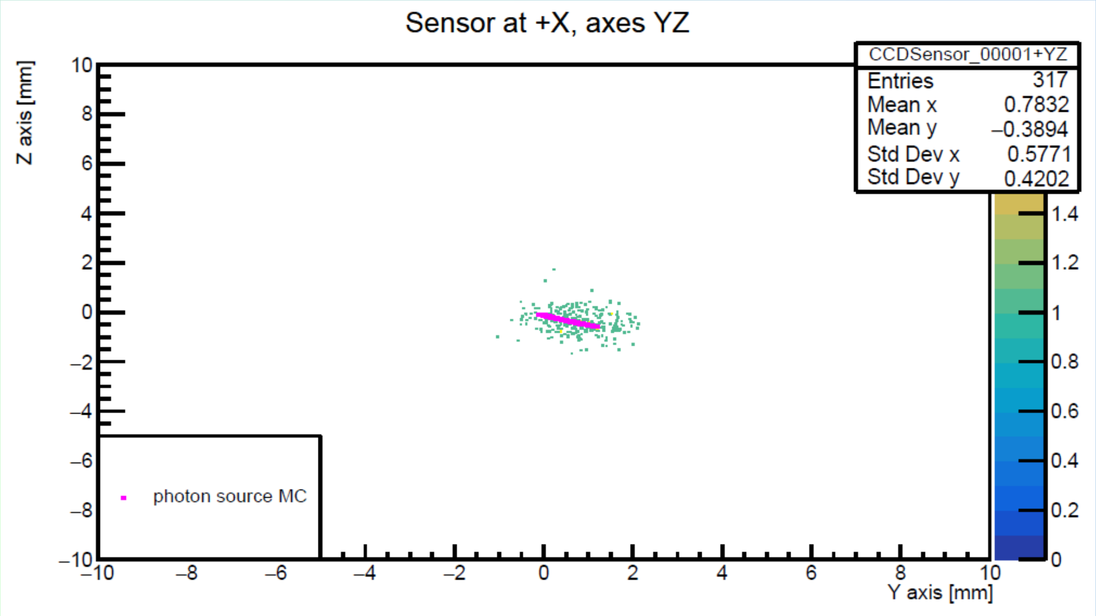


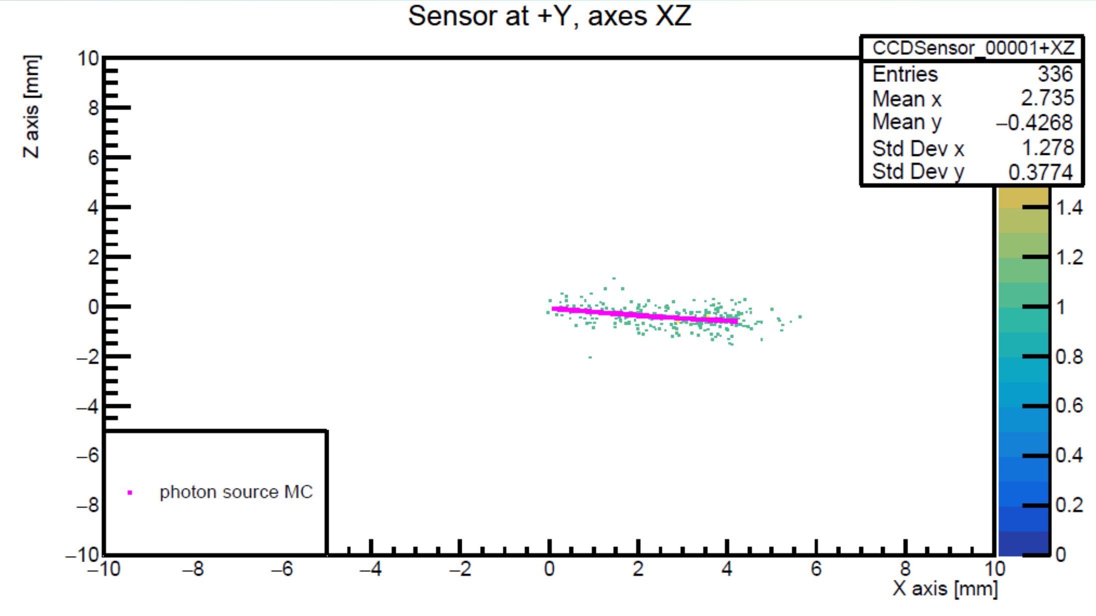
Covariance matrix & Data Average

Methodology studied and compared through MC simulations

Results with PCA analysis



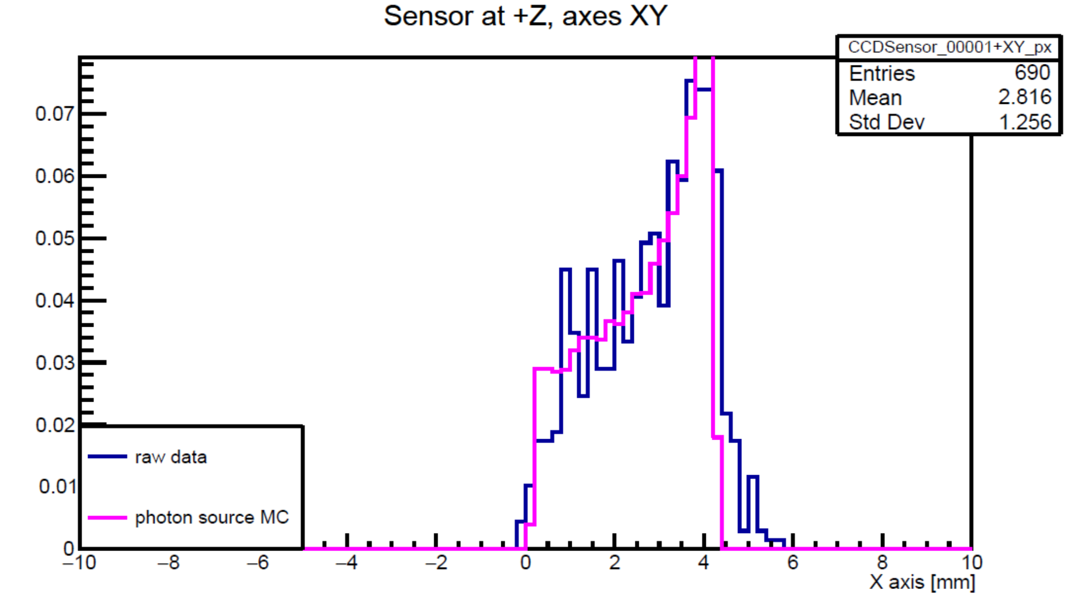


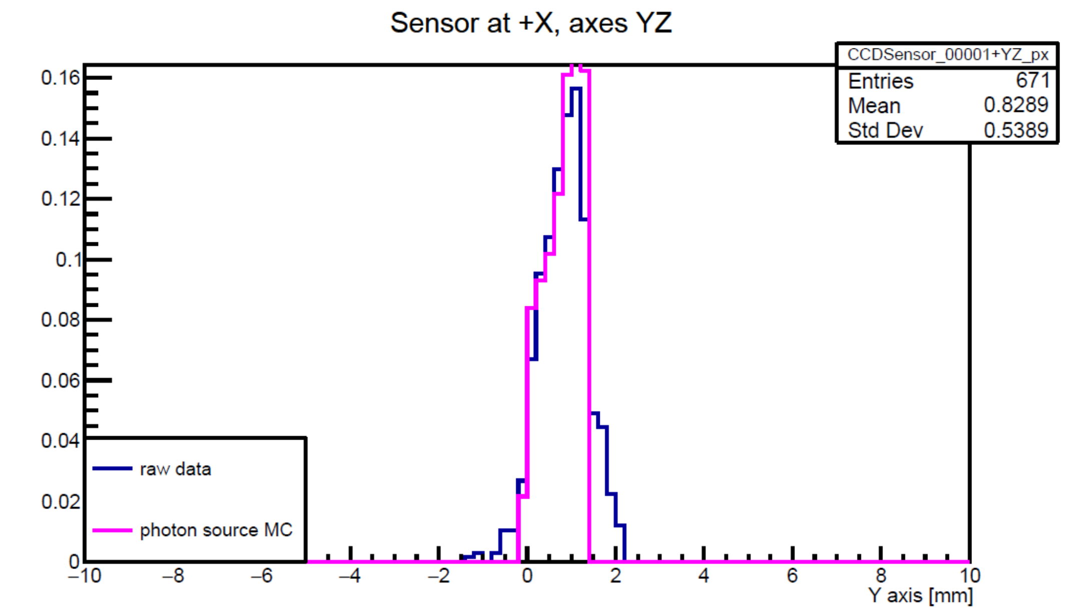


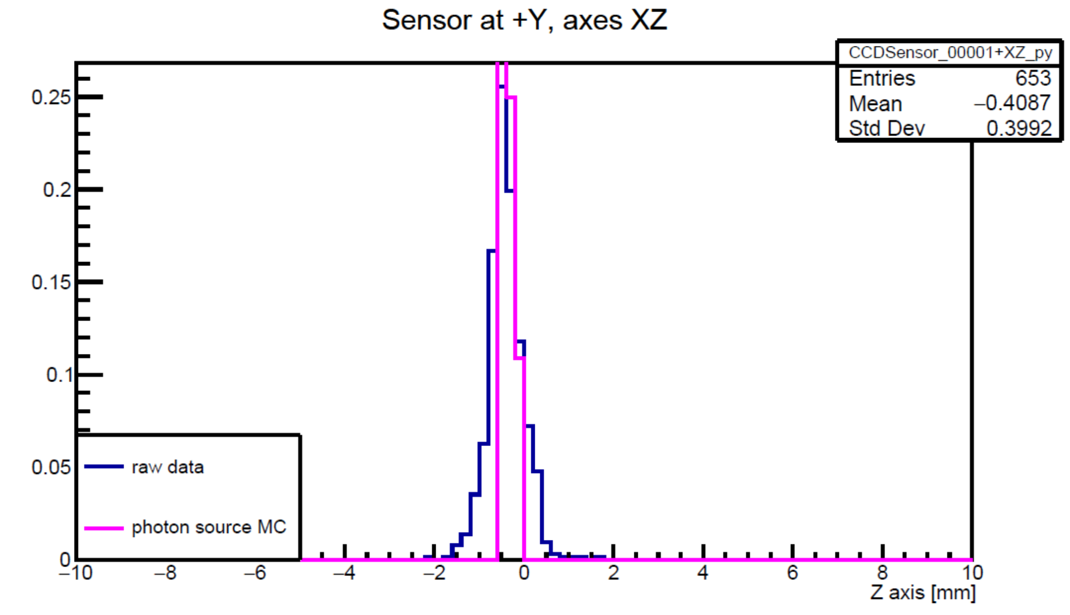
Proton track

- **30 MeV energy**
- **Generated in (2x2x2)cm^3 cube inside detector**
- **Direction isotropic**

Results with PCA analysis







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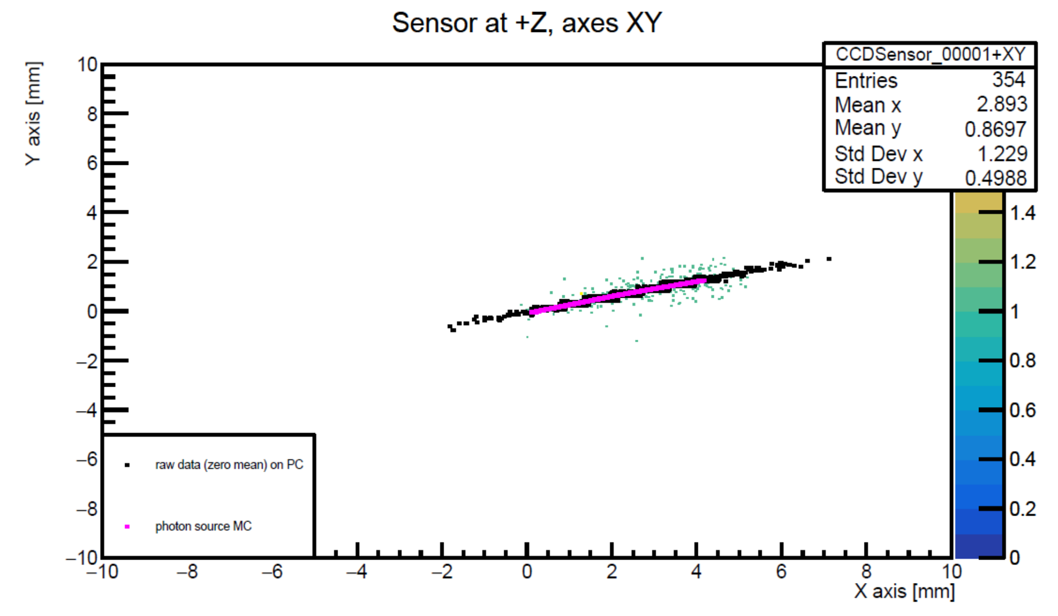

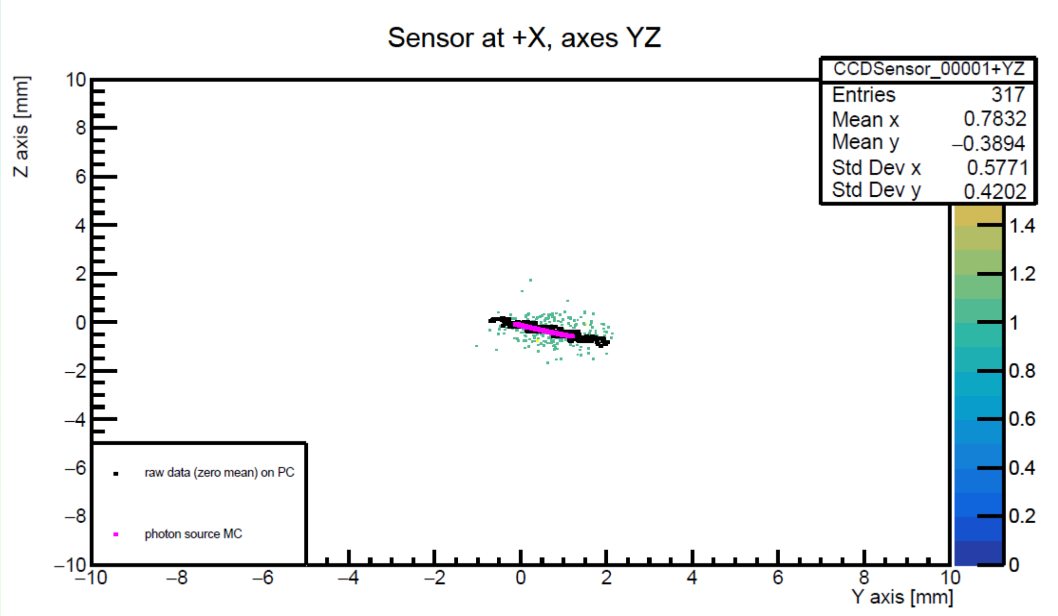

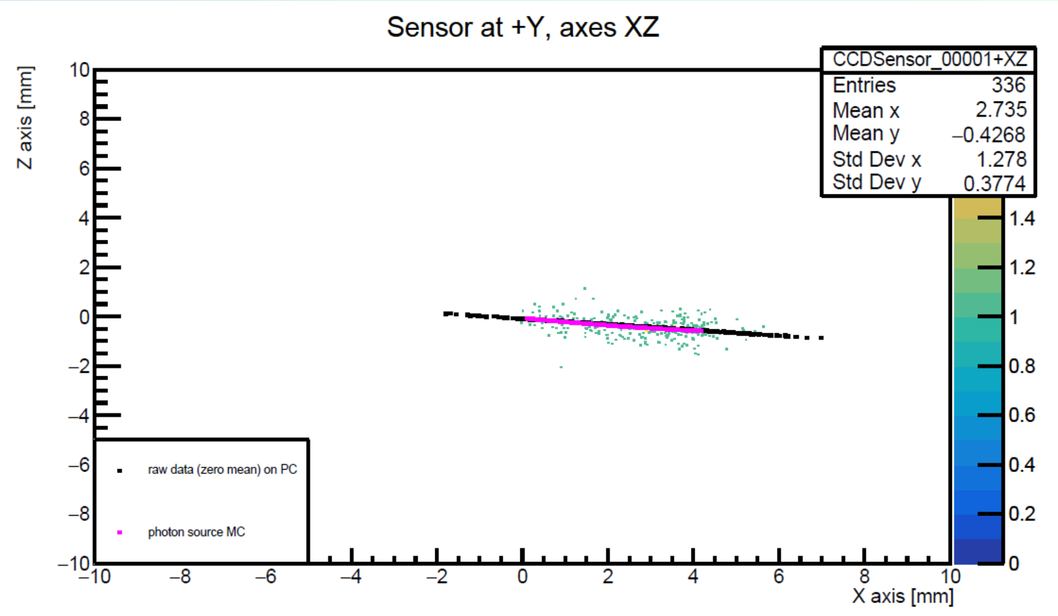

Proton track

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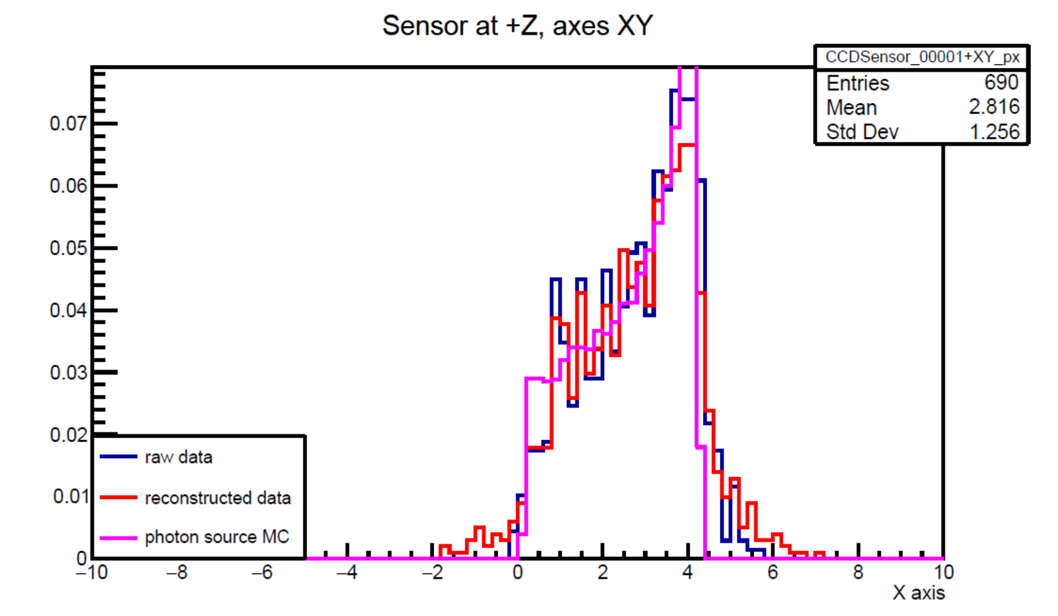
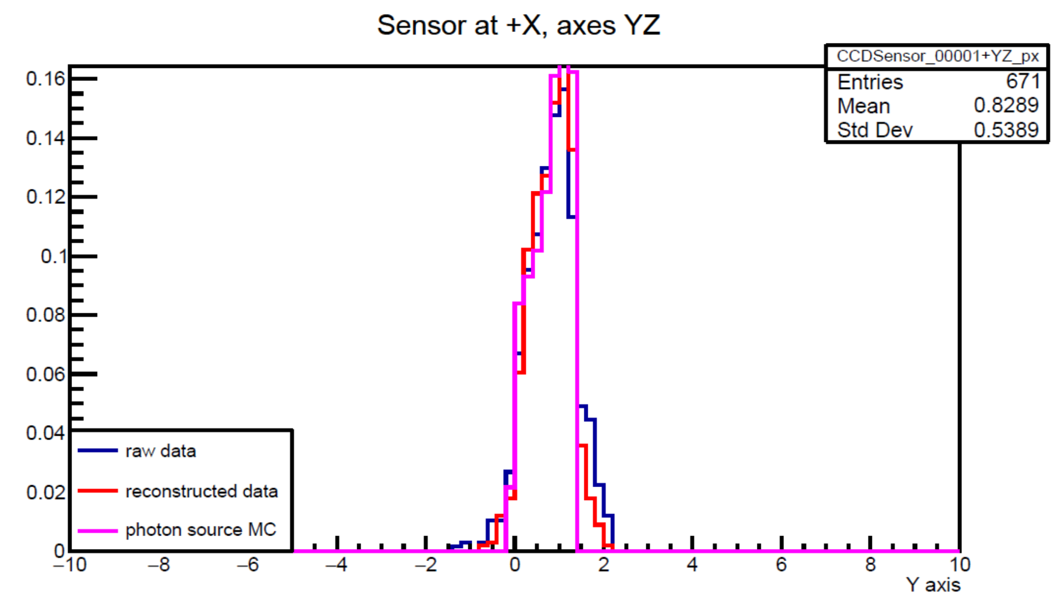
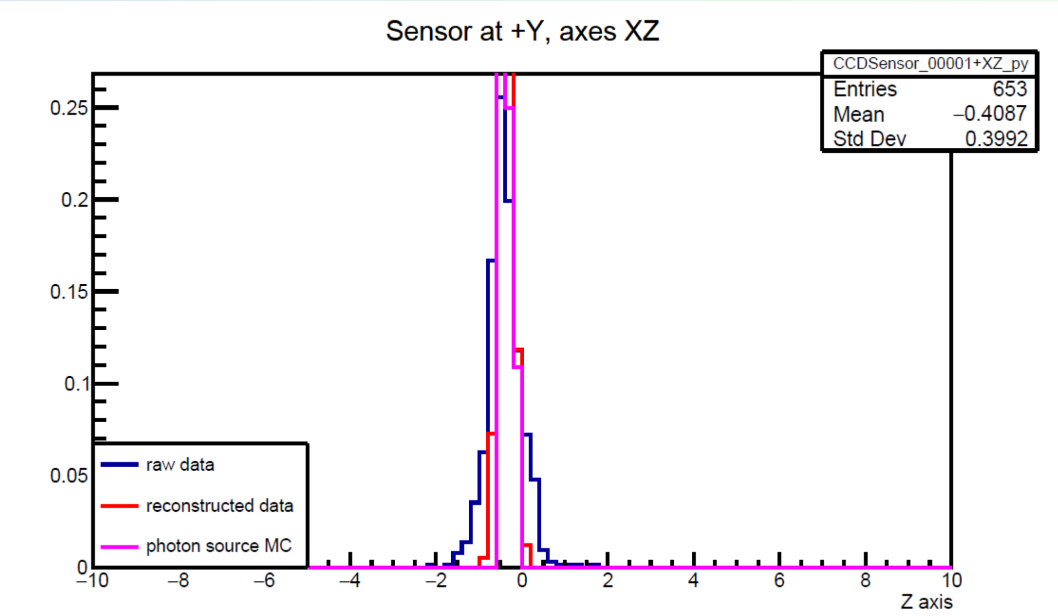
Results with PCA analysis



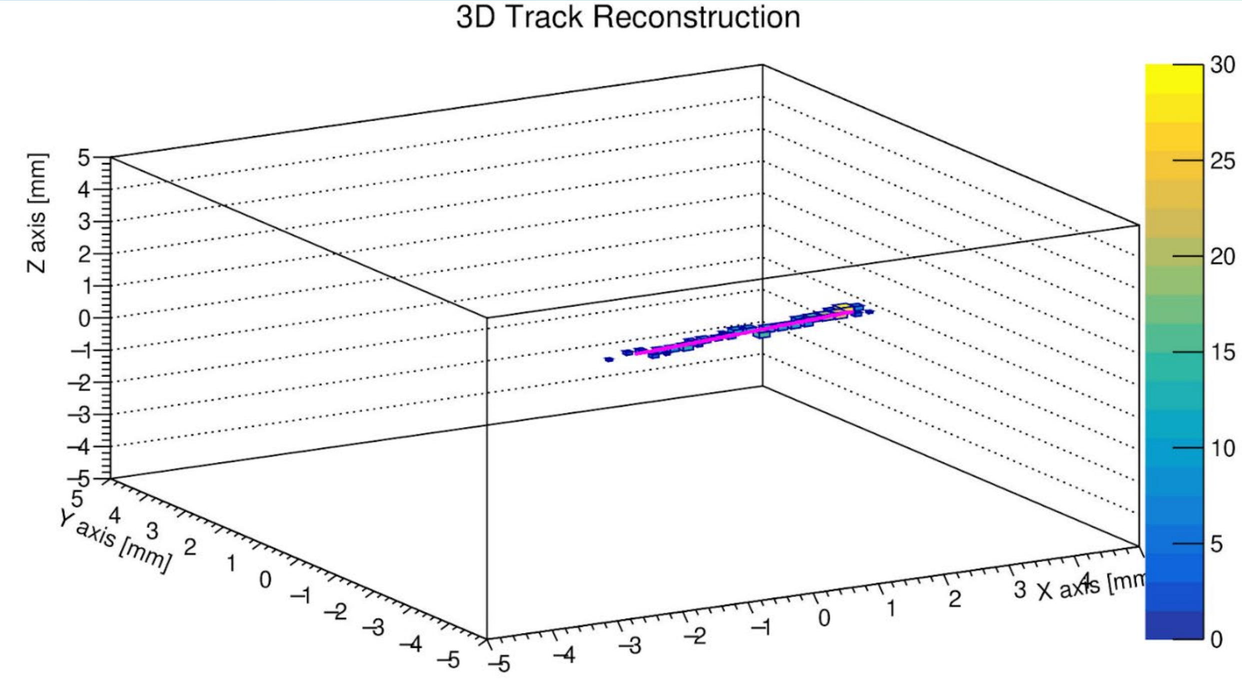




Proton track

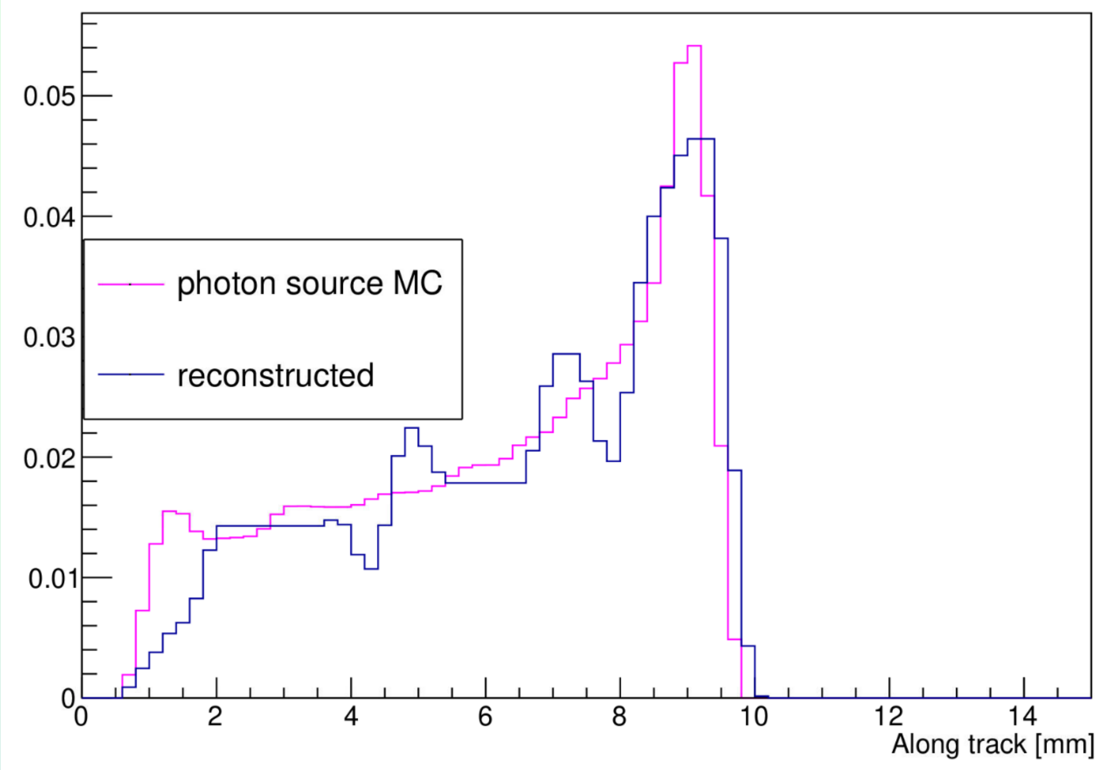
- 30 MeV energy
- Generated in (2x2x2)cm^3 cube inside detector
- Direction isotropic

Results with PCA analysis



Proton track

- **30 MeV energy**
- **Generated in (2x2x2)cm^3 cube inside detector**
- **Direction isotropic**



Proposal Summary

Fast neutron tracking based on n-p elastic scattering

Our knowdlege

- **GEANT4 Simulation**
  - p+BC408
  - n+BC408
  - Optical photons transport
- **Toy MC of a simple Optical System**
  - Systematics of optical parameters
  - Point light source
  - Proton source
- **Track Reconstruction**
  - Point interpolation
  - PCA

Challenge

- **Final Optical system**
  - Small aberration
  - High light collection
- **System geometry**
  - Use of only 2 cameras
  - compact detector
- **Working Prototype**
  - scintillation light photograph
  - Benchmarking of MC simulation
- **Track reconstruction**
  - Double scattering
  - New methods (AI)

Requests and milestones

CAPITOLO	DESCRIZIONE	2024	2025	2026
Apparati	2ND CMOS high frame rate camera (~CYCLONE 2000)	**7.5**	3RD CMOS: **7.5** (if required)	
Inventario	2 Canon RF 35mm F1.8 IS MACRO ST	**1.5**	MCP (if necessary) [**30**]	
Consumo	cables, connectors, supports	**1.0**	Laboratory metabolism: **2**	Laboratory metabolism: **2**
	black box to characterize light sensors	**1.0**		
	lens and mirrors	**1.0**		
Missioni	2 in-person meetings in Bologna	**1.0**	In person meetings: **1**	data takings: **5**
Totale		**13**	**[3-40]**	**7**

DATE	MILESTONES
31-12-2024	Definition of all the geometry except the image intensifier
31-12-2024	Light yield and multianode PMT measurements
31-12-2025	Reconstruction of the neutron kinematics in double scattering events
31-12-2025	First prototype realization (without the image intensifier)
31-12-2025	First laboratory tests with radioactive neutron source
31-12-2026	Ata taking with proton and neutron beams

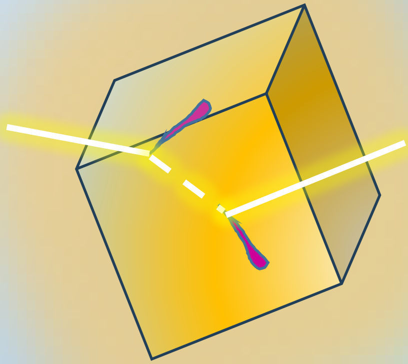
Duration: 3 years

- 2024: detector definition
- 2025: detector realization
- 2026: data taking

Bibliography

- Riptide: A. Musumarra et al, JINST 16 (2021) C12013-5
- Mondo: S.M. Valle et al, NIM A 845 (2017) 556
- Recoil proton: J. Hu et al, Sci. Rep. 8 (2018) 13363
- SONTRAC: G. A. De Nolfo et al, PoS 36 (2019) 1074
- N tracking: Z Wang, C Morris, NIM A 726 (2013) 145
- Master thesis of Claudia Pisanti
- P. Console Camprini et al. JINST 18 C01054
- M. Filipenko et al. Eur. Phys. J. C. (2014) 74:3131

Conclusions



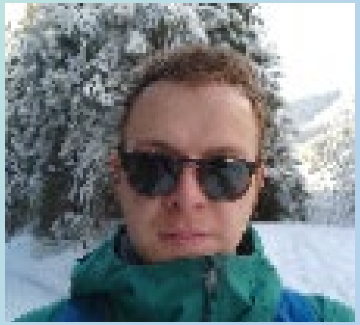
In our opinion the project is of extreme interest because:

- Useful in different physics fields (hadrontherapy, astrophysics, …)
- It is a new approach on neutron detection
- More applications can be identified
- Low cost of realization
- Realistic duration time (3 years) and manpower (3.8 FTE)



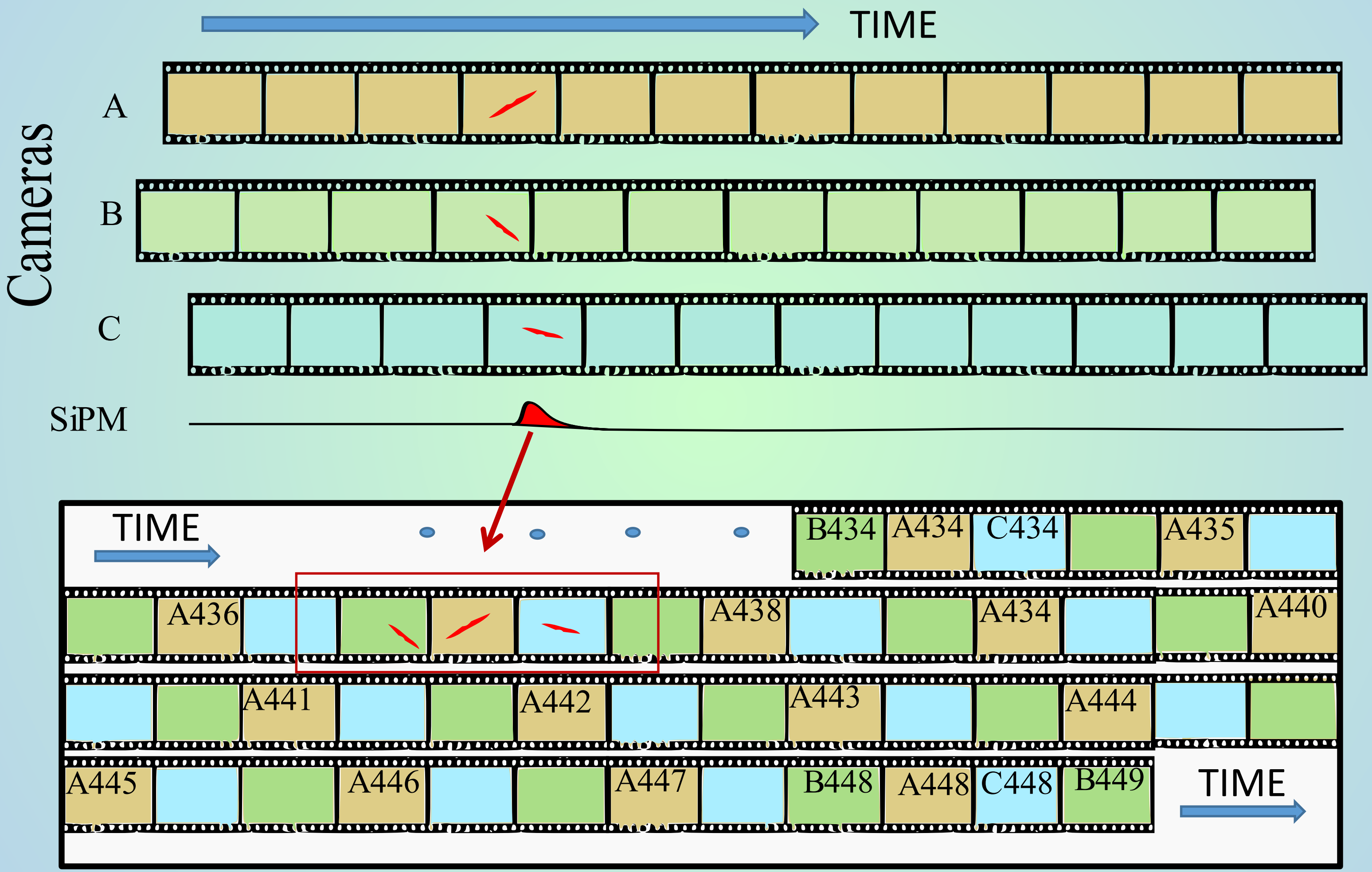





Backup slides

Sorting and triggering

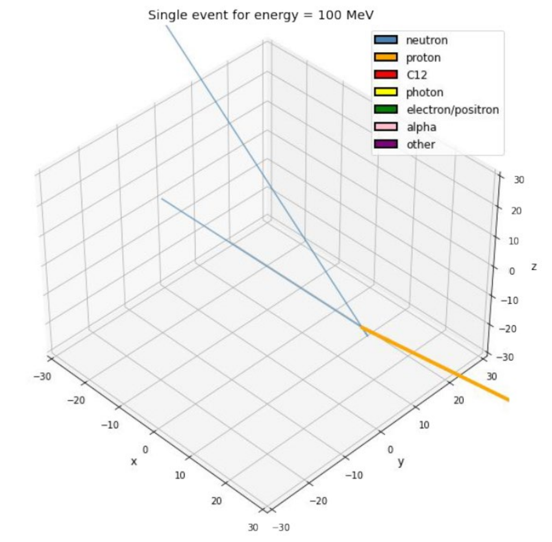


Circular buffer of time-sorted images

Simulation

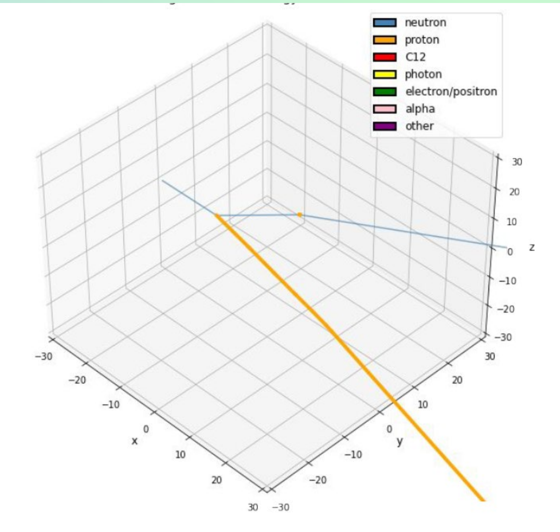
Percentage of exited protons after single scattering

Energia	Protoni usciti
5 MeV	0.490
10 MeV	0.509
20 MeV	0.590
50 MeV	0.654
100 MeV	0.743



Percentage of exited protons after double scattering

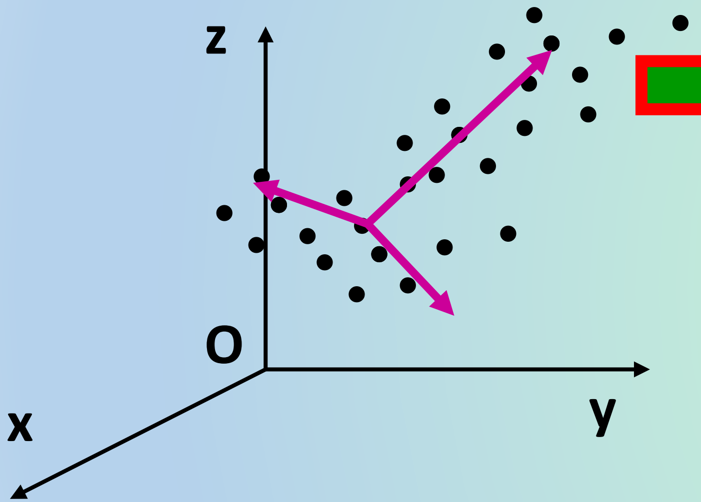
Energia	Protoni usciti
5 MeV	0.558
10 MeV	0.494
20 MeV	0.490
50 MeV	0.417
100 MeV	0.312



PCA Analysis, 1

In general (not our case) →

n points (x, y, z) in the space



Covariant matrix

$$\begin{pmatrix} <(x_i-<x>)^2> & <(x_i-<x>)(y_i-<y>)> & <(x_i-<x>)(z_i-<z>)> \\ <(y_i-<y>)(x_i-<x>)> & <(y_i-<y>)^2> & <(y_i-<y>)(z_i-<z>)> \\ <(z_i-<z>)(x_i-<x>)> & <(z_i-<z>)(y_i-<y>)> & <(z_i-<z>)^2> \end{pmatrix}$$

Diagonalization

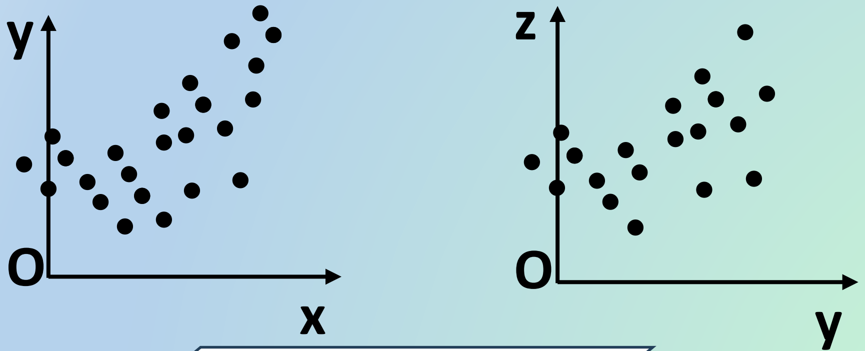
3 eigenvectors and 3 eigenvalues

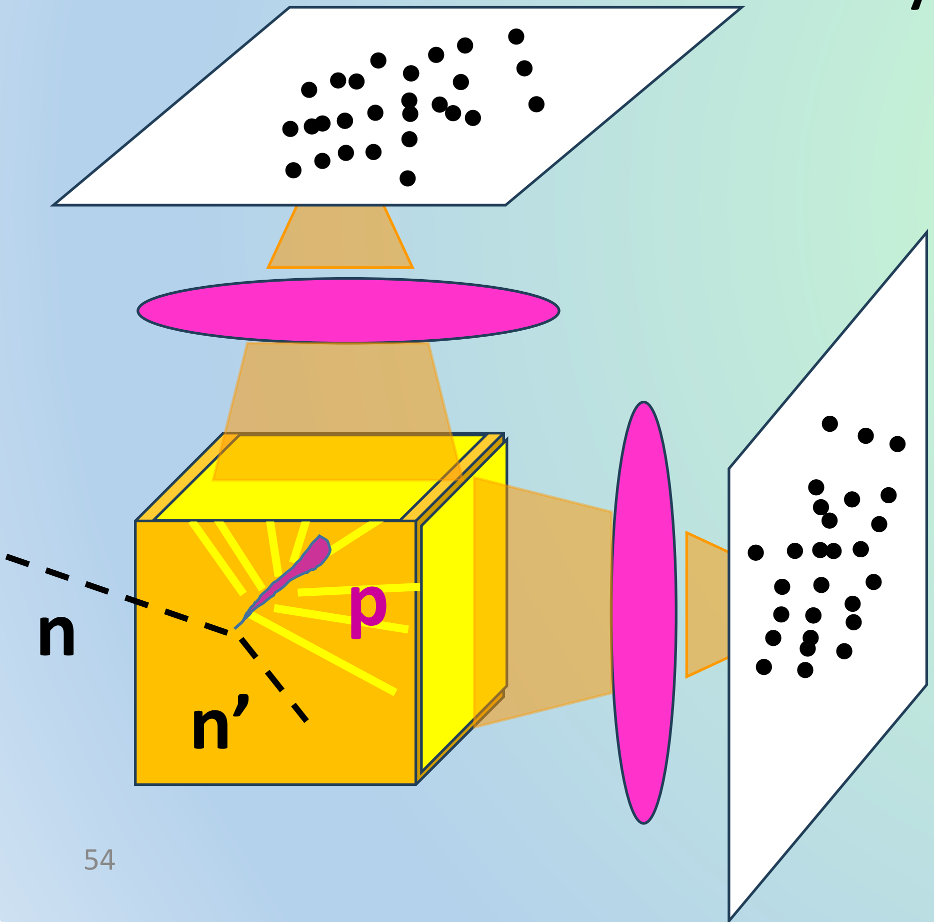
(maximum eigenvalue → principal direction)

Reduction of dimension
3n points → 3 vectors

Projecting points on principal eigenvector → Bragg Peak

PCA Analysis, 2





(x,y,z) → 2 couples (x, y) , (y,z), (x,z)

Projection on the plane (x,y,0), (0,y,z)

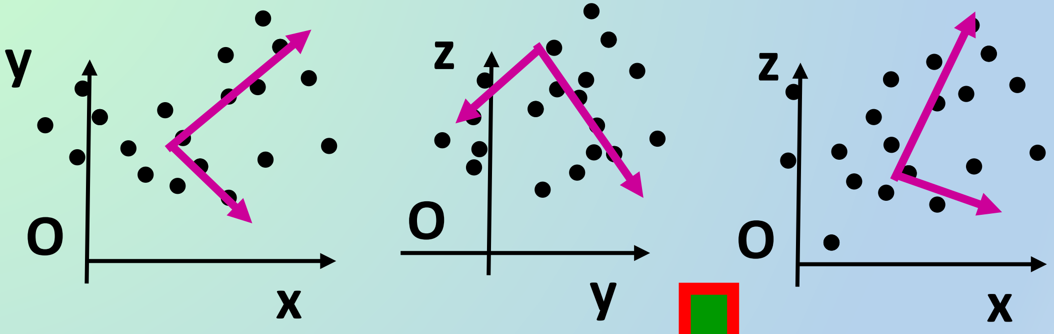
As before (projection on the 3 planes)

3 Covariant matrixes

$$\begin{pmatrix} <(x_i-<x>)^2> & <(x_i-<x>)(y_i-<y>)> \\ <(y_i-<y>)(x_i-<x>)> & <(y_i-<y>)^2> \end{pmatrix}$$

Diagonalization →

3 bidimensional eigenvectors



1 tridimensional eigenvector as plane intersection