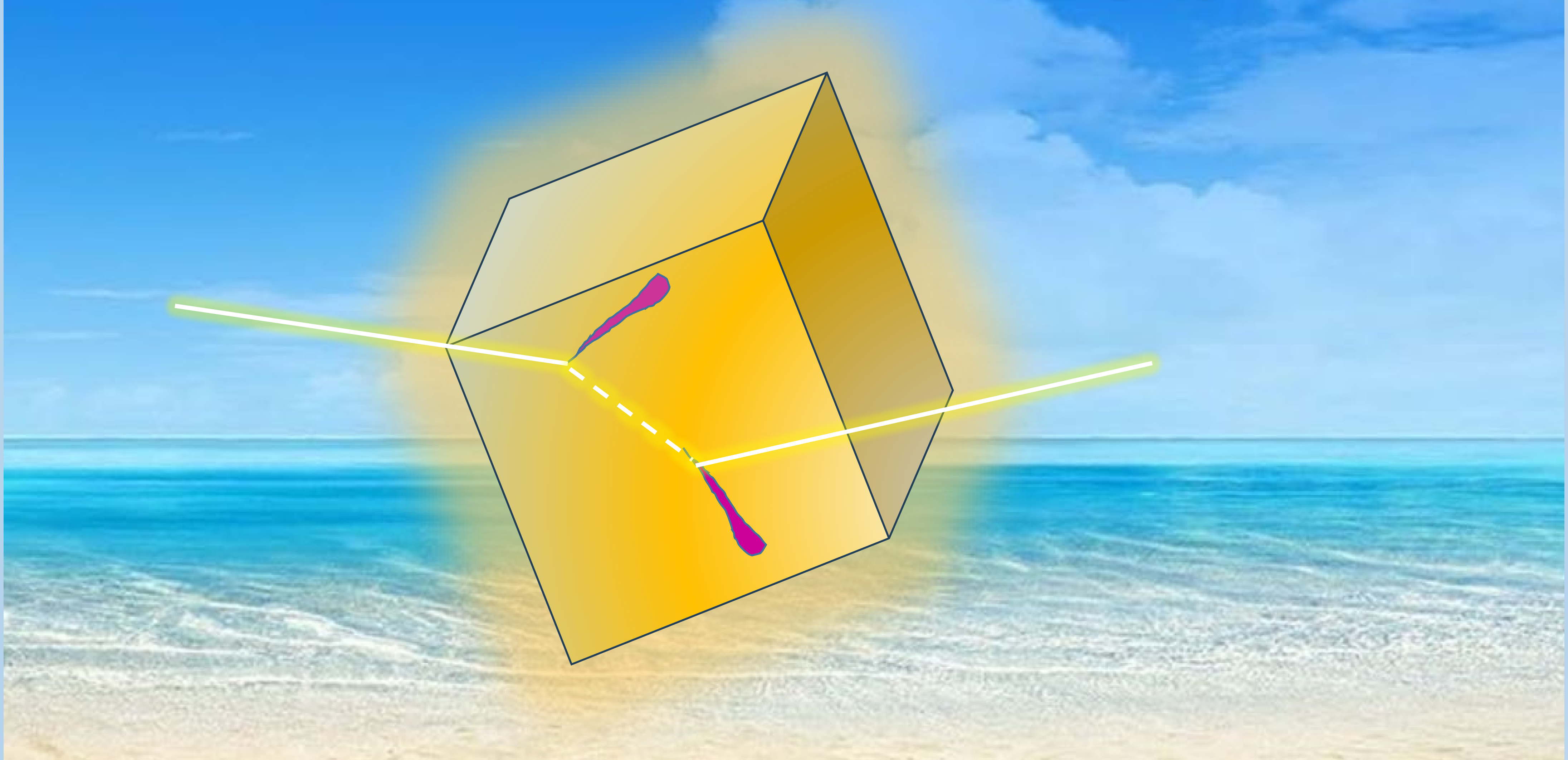
RIPTIDE: Recoil Proton Imaging Detector



Napoli, 25 Settembre riunione di CSN5, Roberto spighi

what

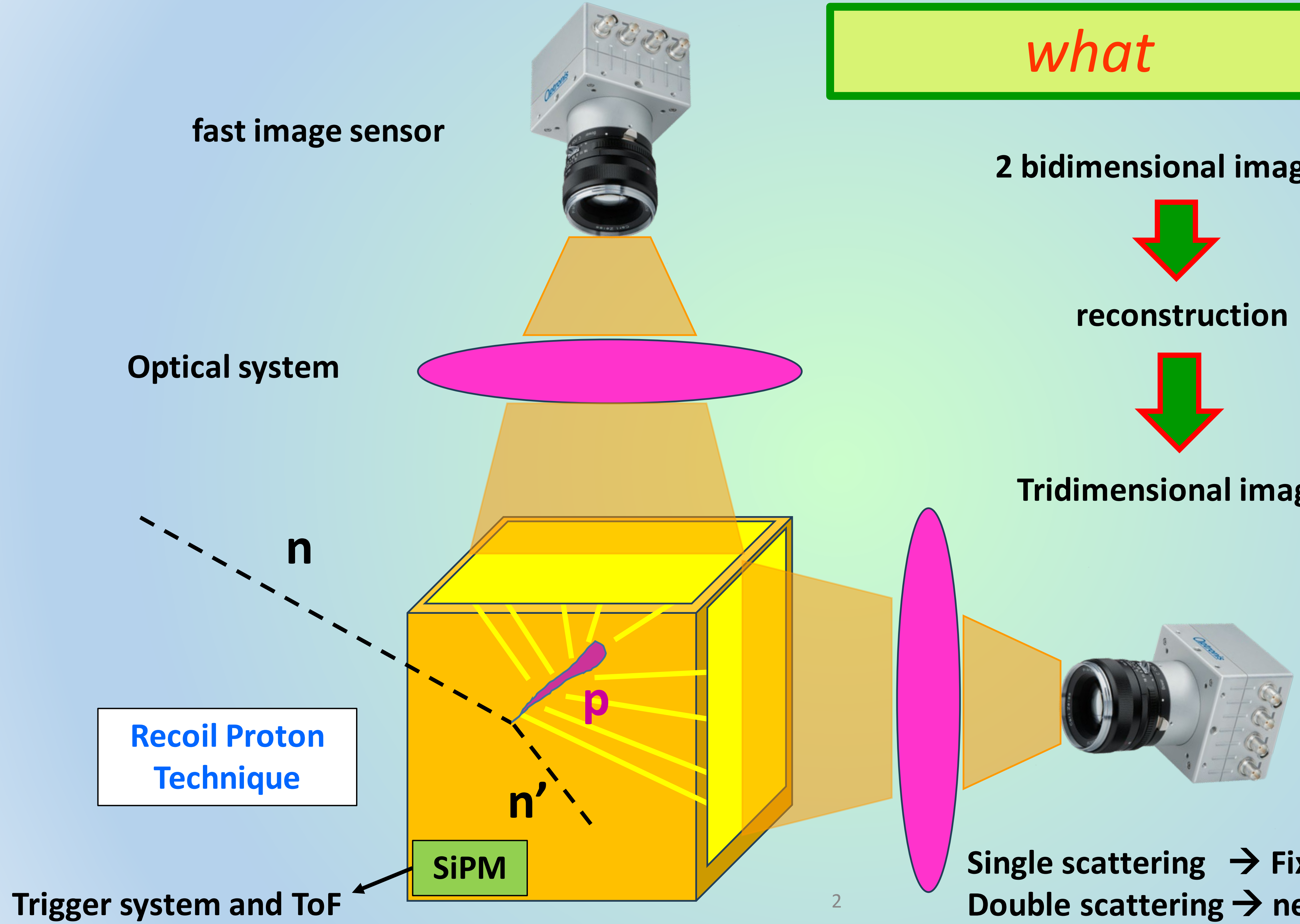
2 bidimensional images

↓

reconstruction

↓

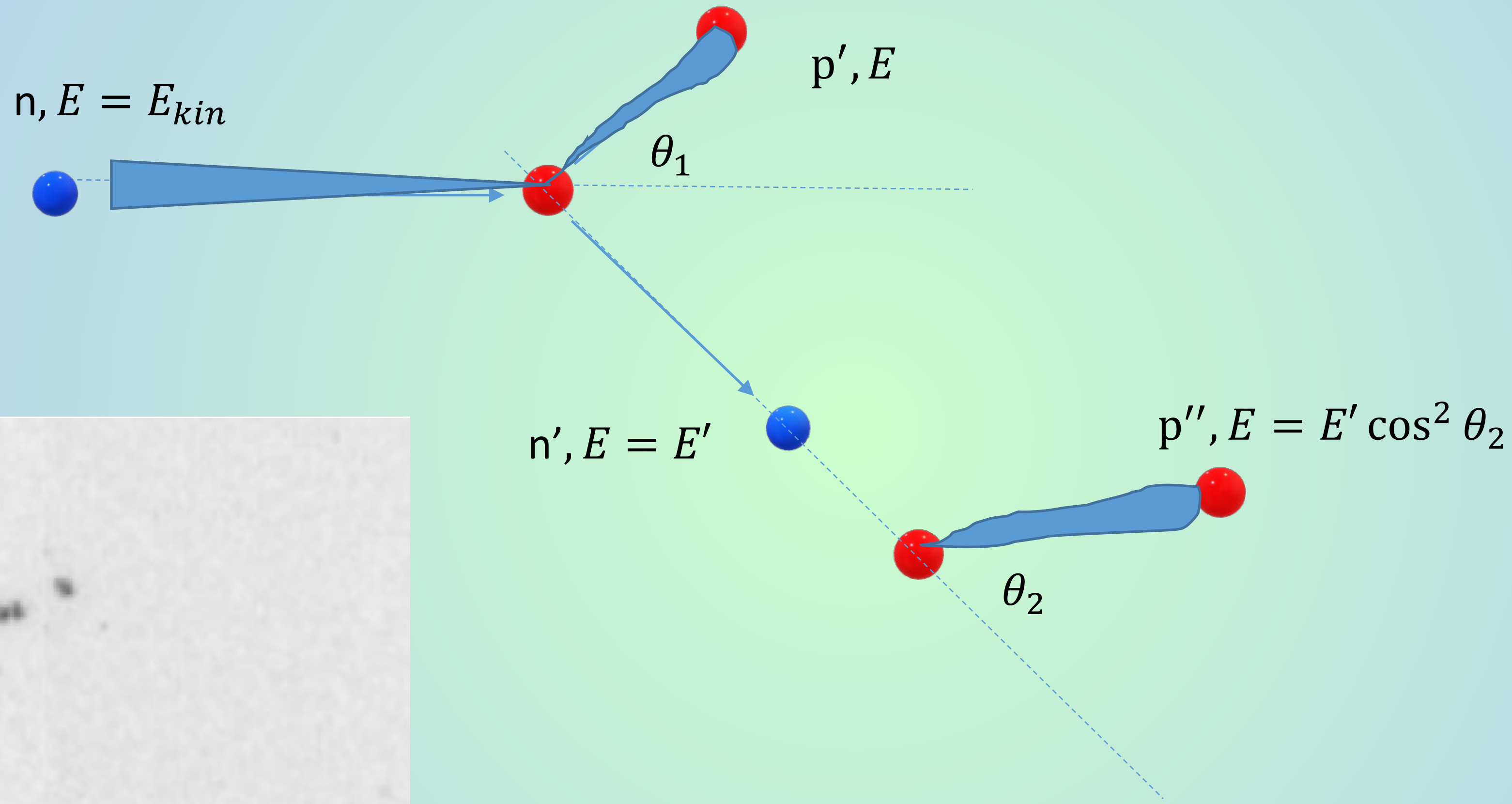
Tridimensional image



Single scattering → Fixed target experiment

Double scattering → neutron source not known

Metodology: Recoil proton Tecnique

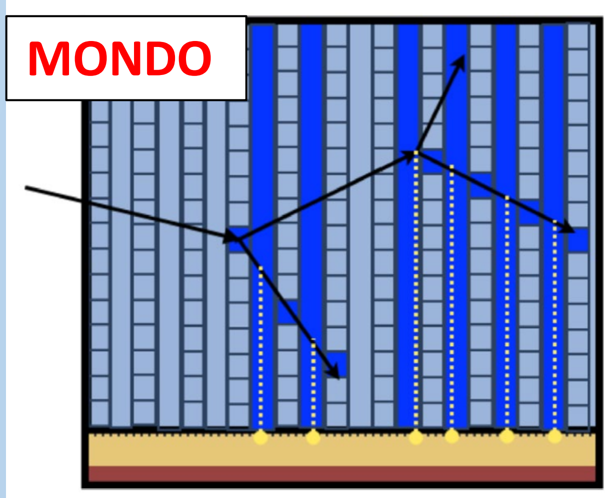


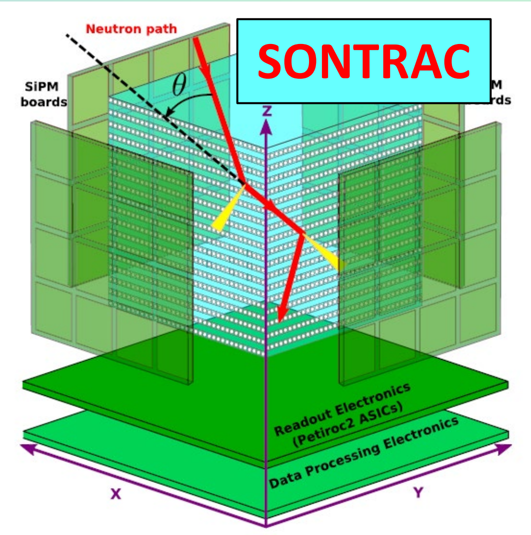
CCD image of a double scatter from a 65 MeV neutron incident from top

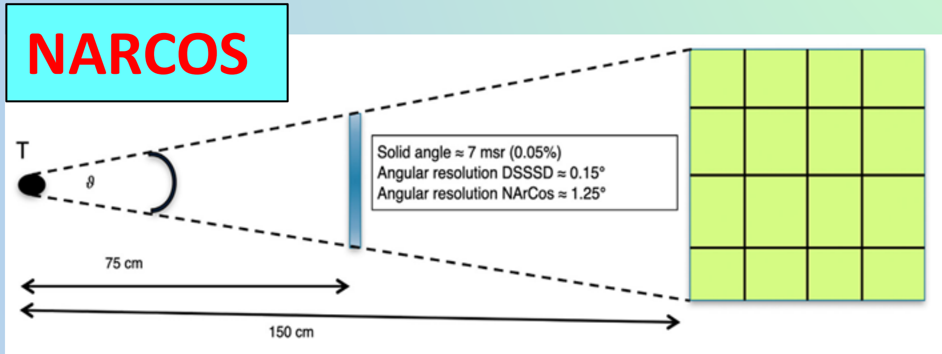
James M. Ryan, et al. «A Scintillating Plastic Fiber Tracking Detector for Neutron and Proton Imaging and Spectroscopy», the conference is available at University of new Empshire Scholar’s Repository, https://scholars.unh.edu/ssc/208

The bases of our project

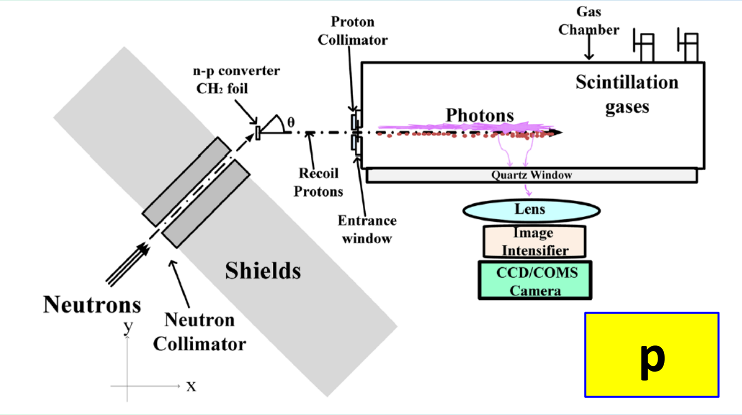
Neutron track Imaging with Single and Double scattering

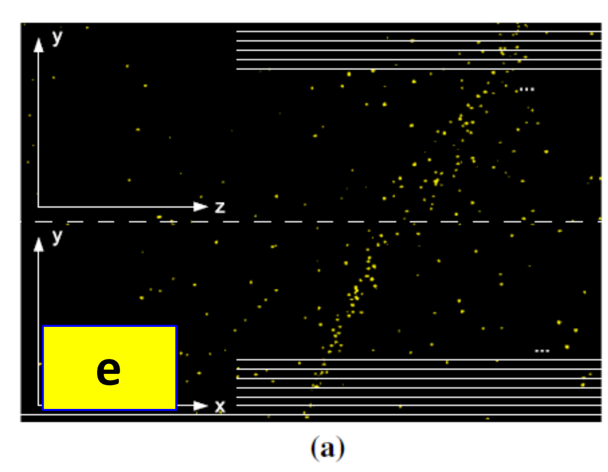


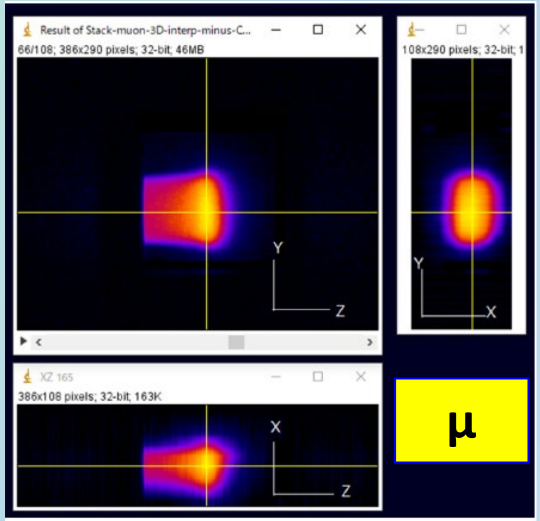




Optic system to «photograph» particles (p, e, μ)



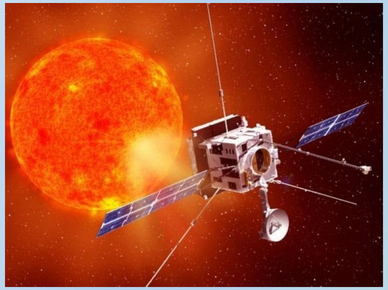




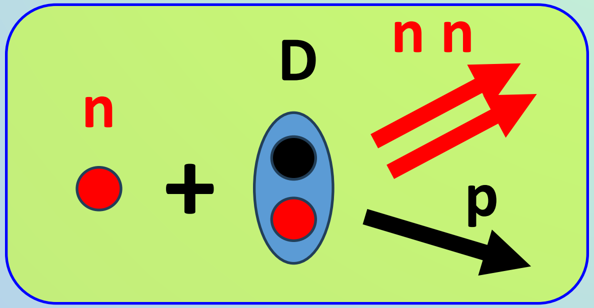
M. Marafini, *et al.*, Phys. Med. Biol. **62** (2017) 3299
G.A. de Nolfo, et al. NIMA 1054 (2023) 168352
E.V. Pagano, et al. Frontiers of physics, DOI 10.3389/fphy.2022.1051058

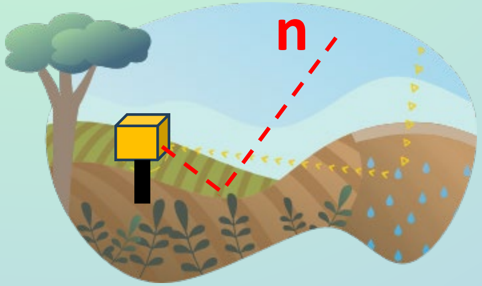
J. Hu et al, Sci. Rep. 8, 13363 (2018)
M. Filipenko et al. Eur. Phys. J. C (2014) 74:3131
S. Yamamoto, et al. NIMA 1015 (2021) 165768

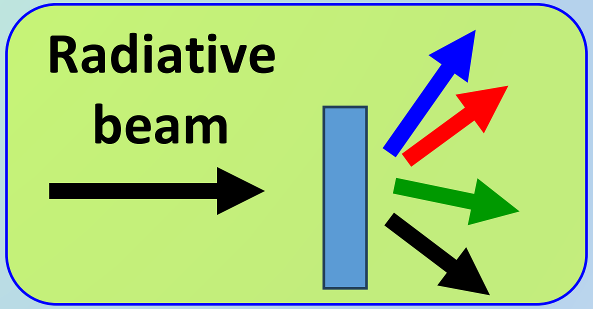
Possible applications



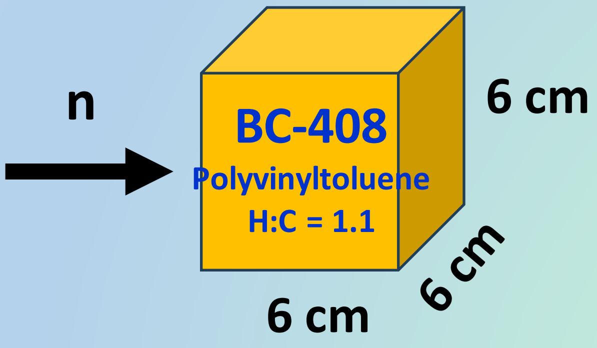
Application	Configuration (n. scattering)	Dimensions (cm x cm x cm)	Neutron energy (MeV)	Background	data taking (duration)	Experimental site
Solar neutrons	Double scattering	5x5x5 (SONTRAC)	10 – 50	Cosmic rays	months	satellite
Space radioprotection	Single scatt. (up – down)	~ 10x10x10	10 – 1000	Secondary particles + γ	weeks	Laboratory
Hadrontherapy radioprotection	Double scattering	10x10x20 (MONDO)	10 – 200	Secondary particles + γ	weeks	Laboratory
Nucl. Phys.: N-N scatt. length	Single scattering	6x6x6	10 – 50	Secondary particles + γ	weeks	Laboratory
Soil moisture	Single scatt. (up – down)	6x6x6	10 - 50	Cosmic rays	months	On the ground
Nucl. Phys.: Rad. beams	Single scattering	10x10x10	< 100	Secondary particles + γ	weeks	Laboratory
…	…	…	…	…	…	…







MC: n → scintillator



Simulation:

- probability of Single-double interaction
- Background estimation

Fss:

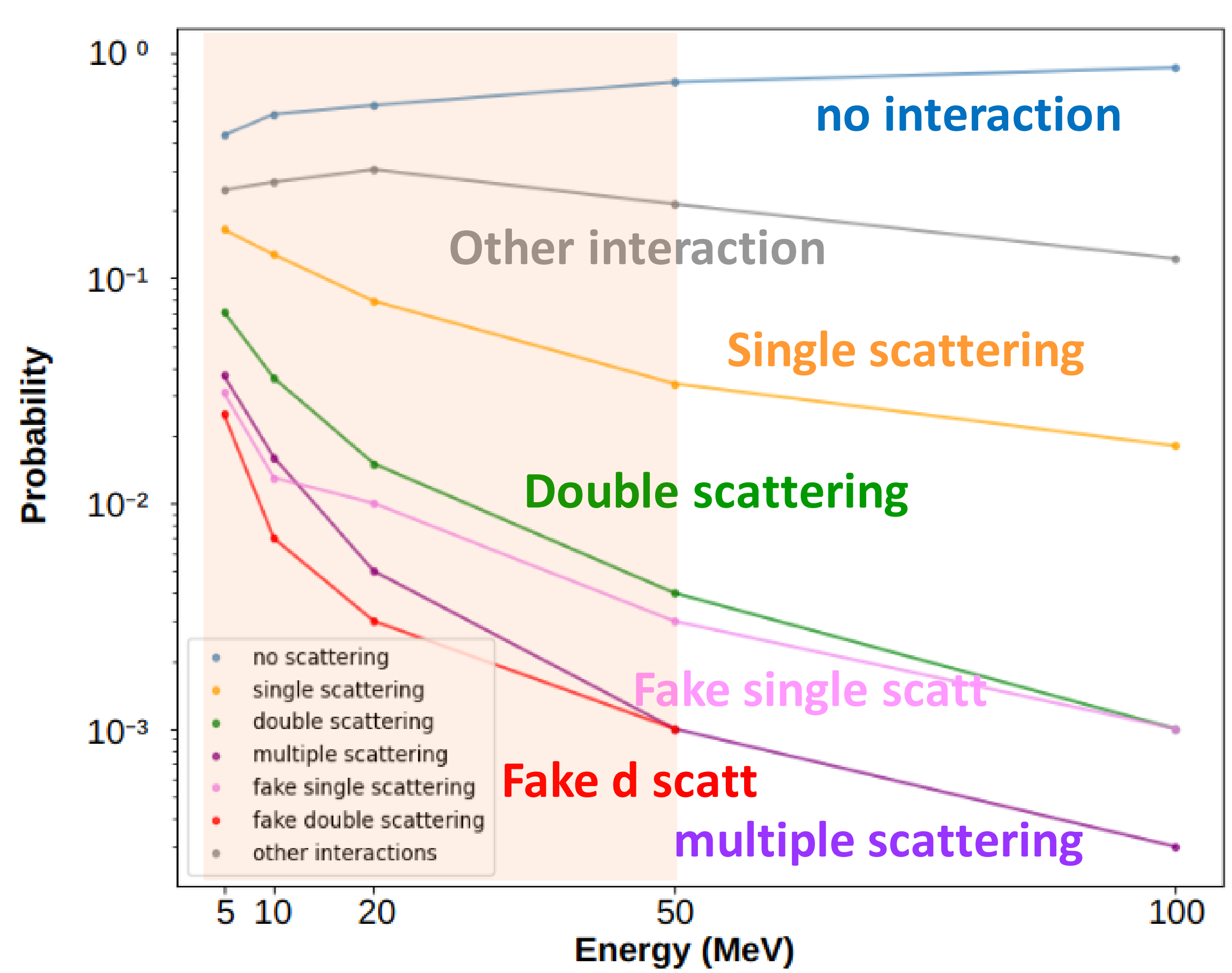
- scatt on C (not seen) and then on p

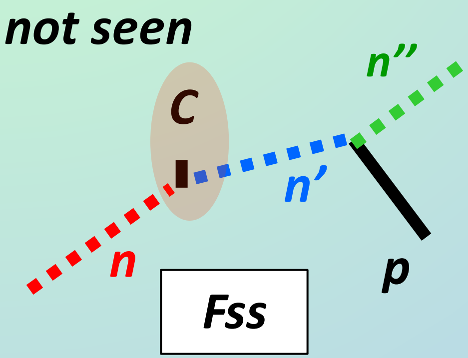
Fds:

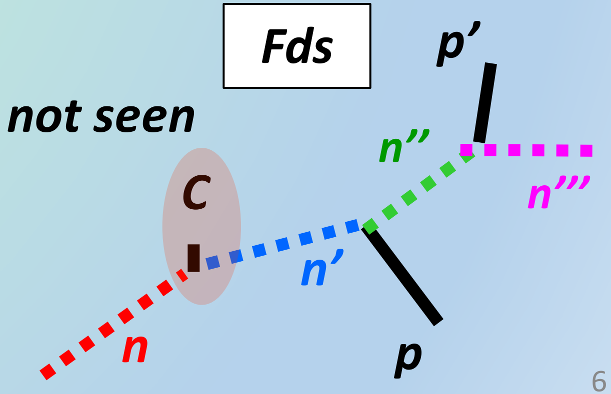
- scatt on C (not seen) and then on p and p
- Scatt on p, on C (not seen) and on p

n nteraction ~ 50%

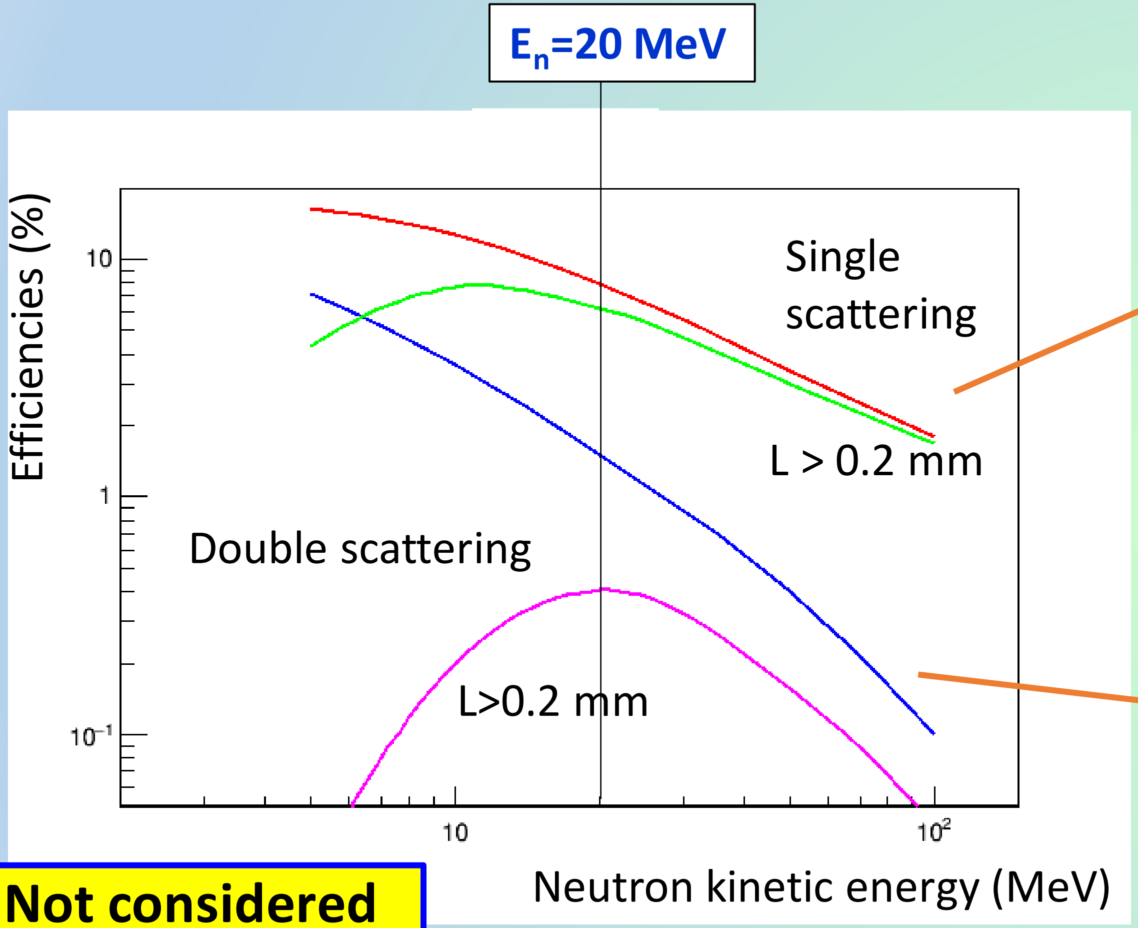
Low Bkg



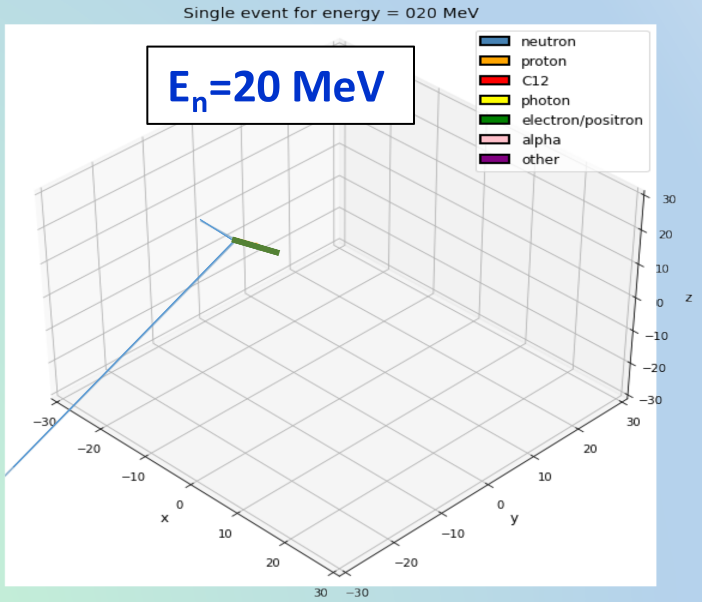




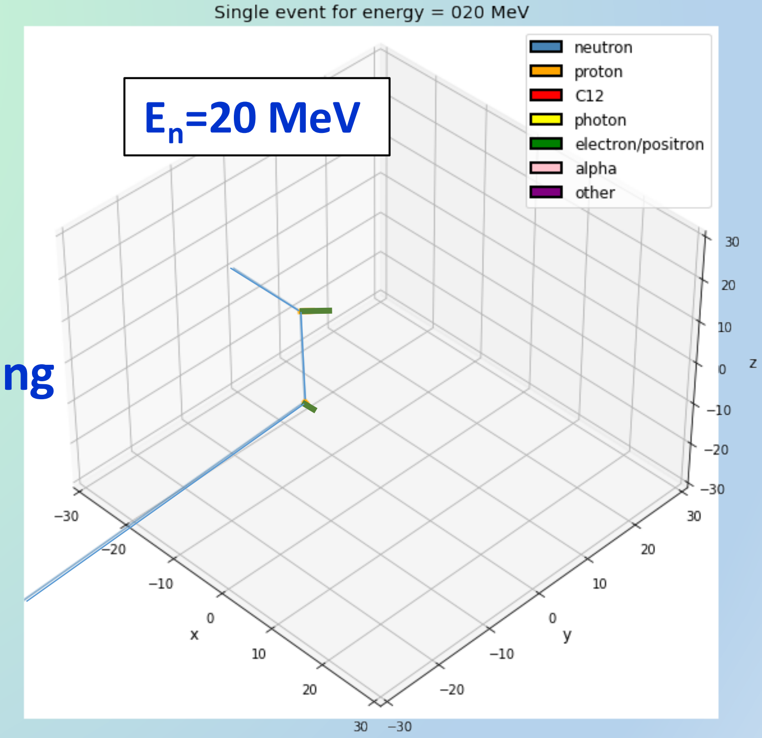
Interaction and detection efficiency



Single scattering



Double scattering



Not considered Optic efficiency

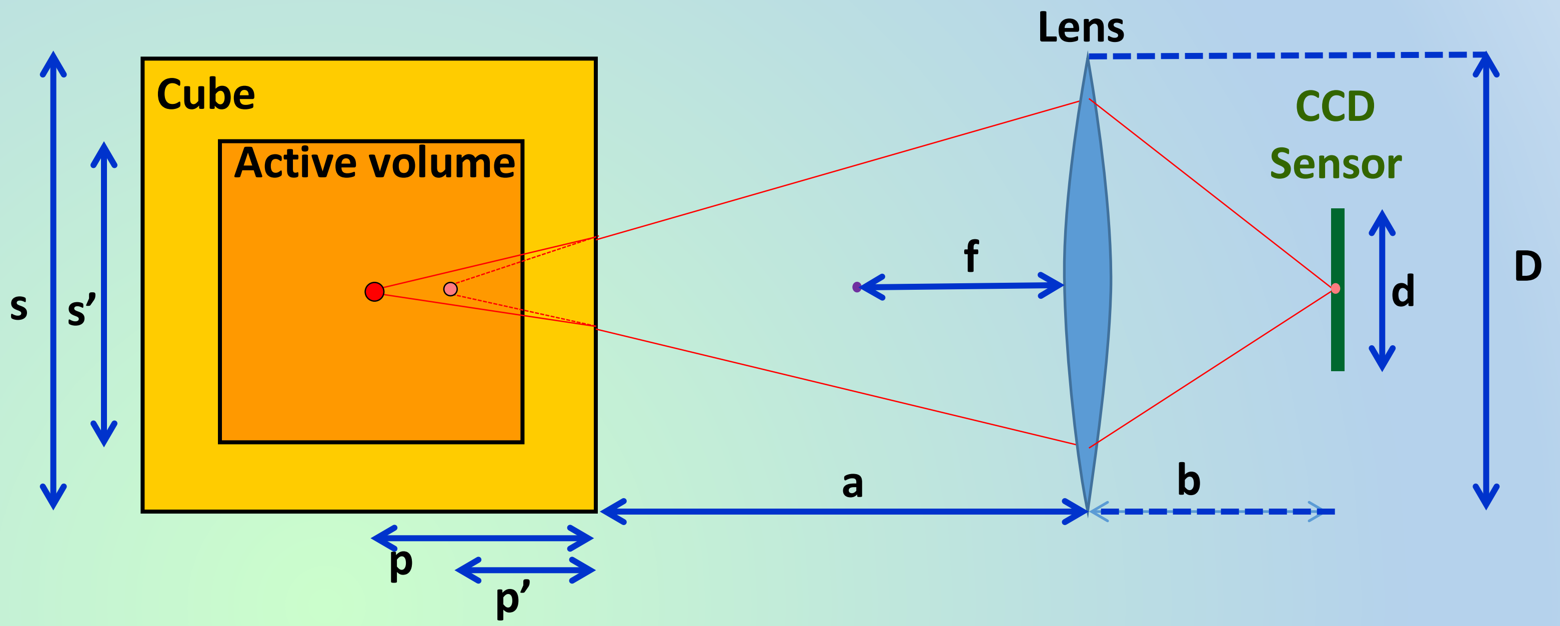
E_n = 20 MeV

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

7

Optic scheme

A lot of parameters to fix



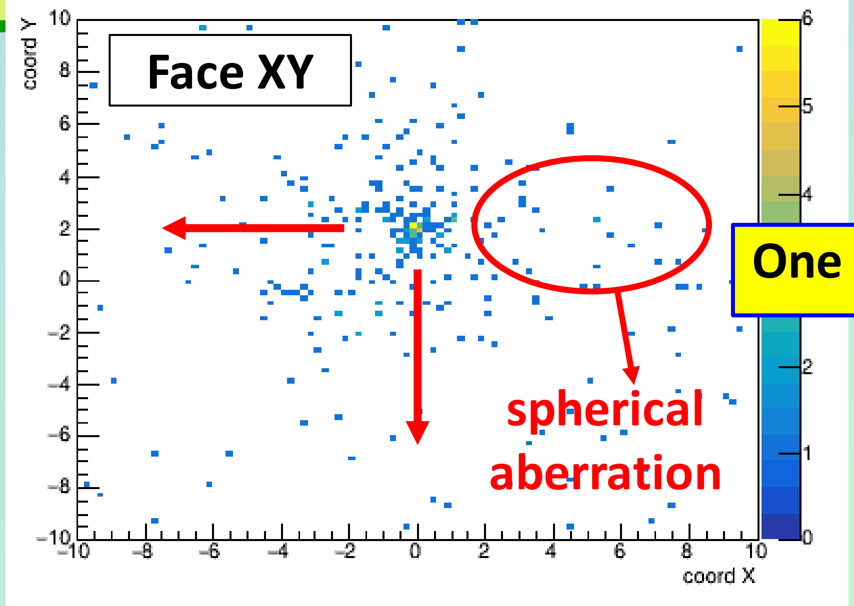
Parameter	values
s: scintillator size	60 mm
s’: side of the active cube	40 mm
d: side of the CCD sensor	20 mm
f: focal length of the lens	30 mm f = D/2
D: diameter of the lens	60 mm
a: position of the lens	71 mm a = p’’ – p’
b: position of the sensor	45 mm b = fp’’/(p’’-f)

Toy MC in order to have an idea of the optic dimension and performances

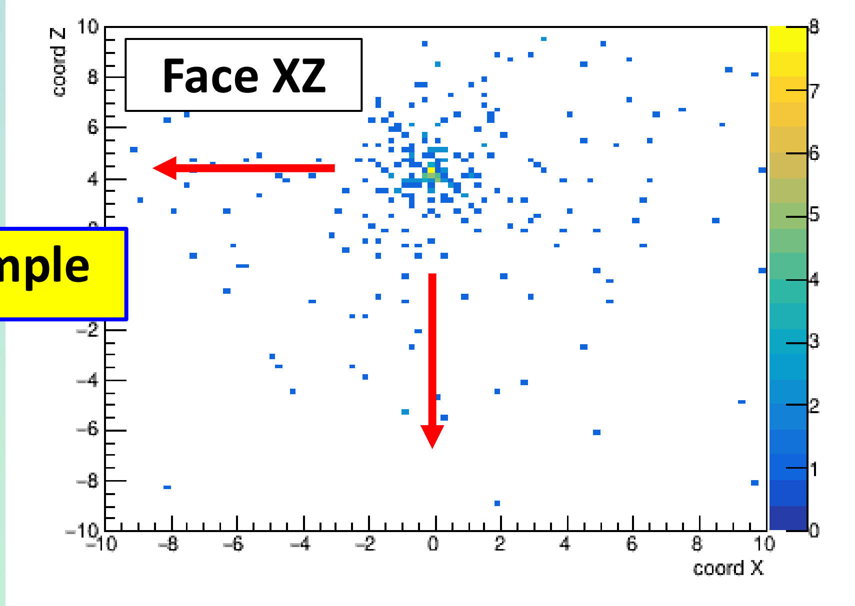
Photons simulation

- Pointlike sources in the cube
- Photons Isotropic direction
- \# of photons: 6.88×10^4
- Equivalent to 6.88 MeV p

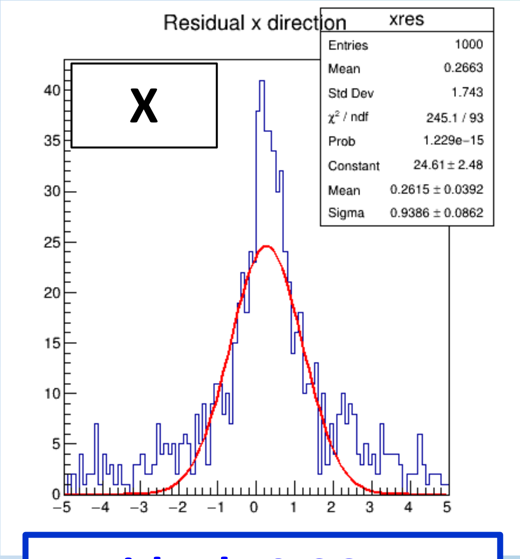
Cube 53x53x53 mm^3



One example

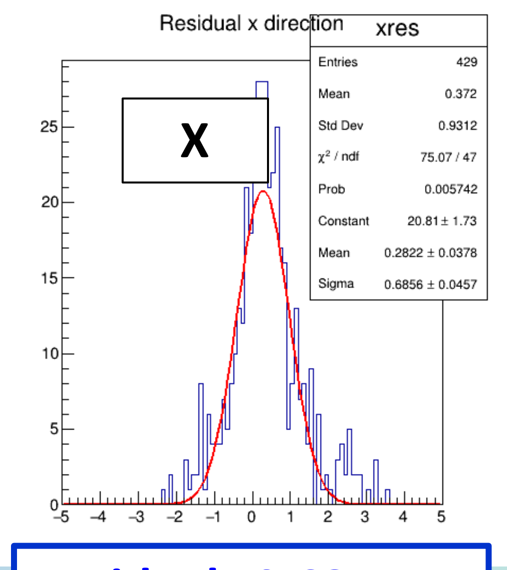


Cube 53x53x53 mm^3



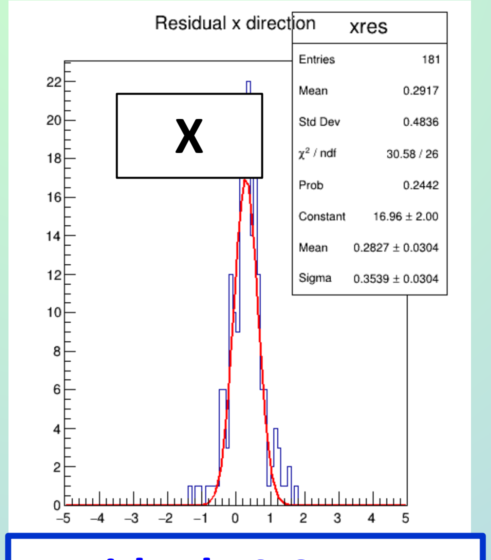
Residuals 0.96 mm

Cube 40x40x40 mm^3



Residuals 0.68 mm

cube 30x30x30 mm^3

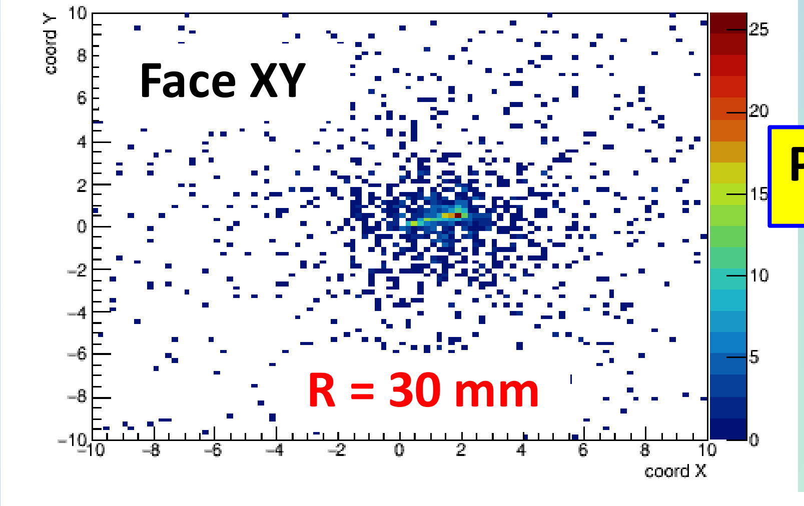


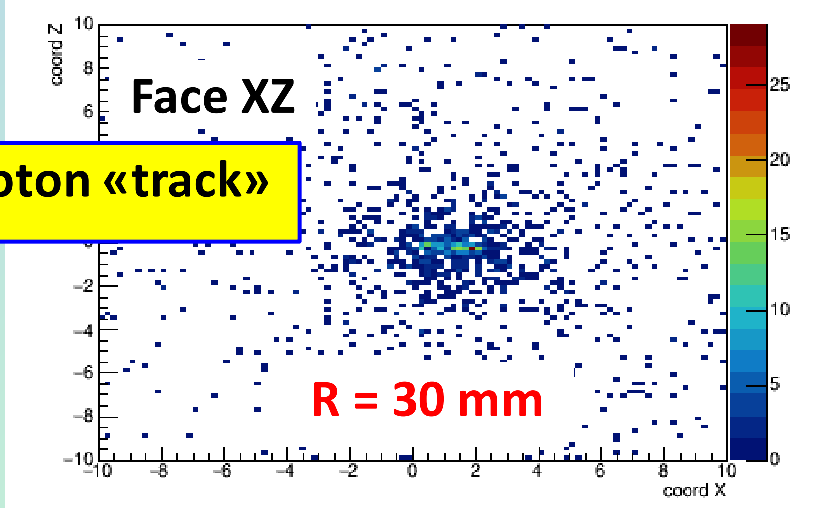
Residuals 0.35 mm

Decreasing Cube dimension
- improve Position Precision
- decrease detector efficiency

Protons simulation

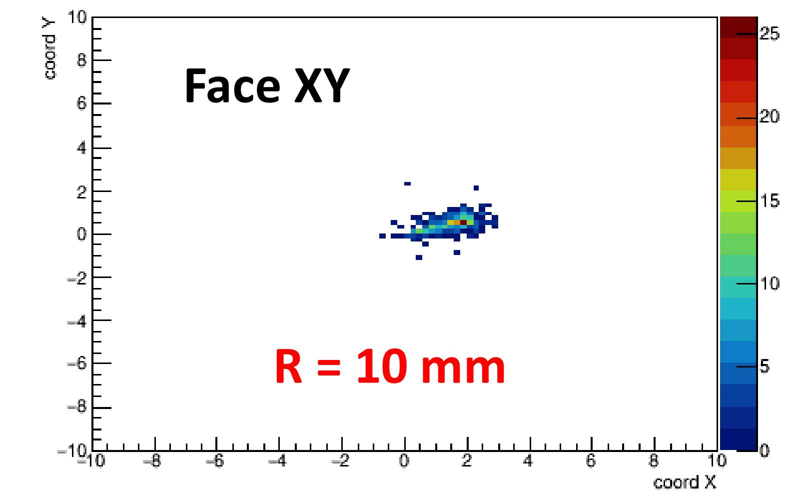
- Cilindric source
- Isotropic direction and position
- Energy: 30 MeV
- 10 k photons per MeV
- p/f=3, f = 30 mm



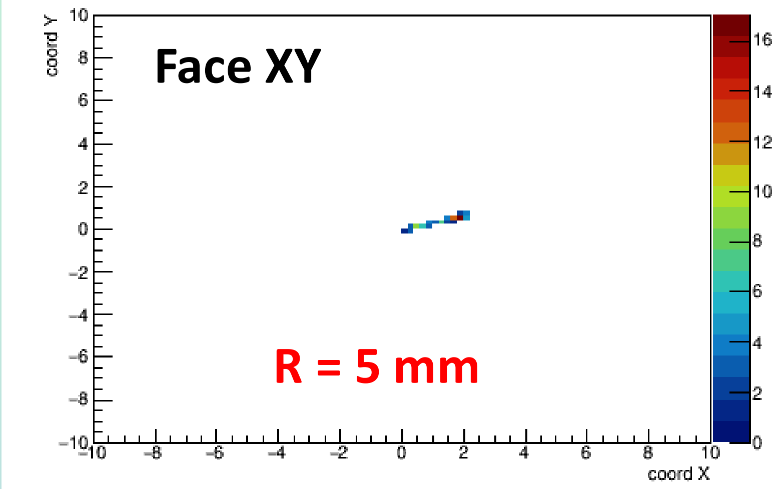


Proton «track»

- ~ 1440 photons/view
- Track barely visible



- ~ 340 photons/view
- Track visible



- ~ 80 photons/view
- Track clearly visible

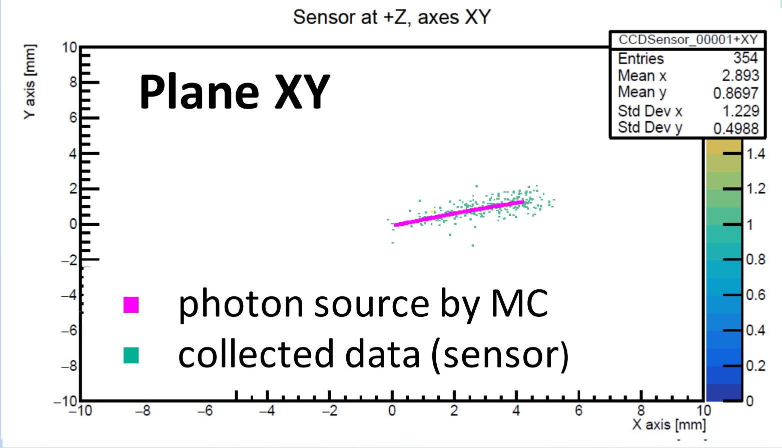
Decreasing the radius of the lens
- decrease spherical aberration
  - bkg decrease
- decrease light yield

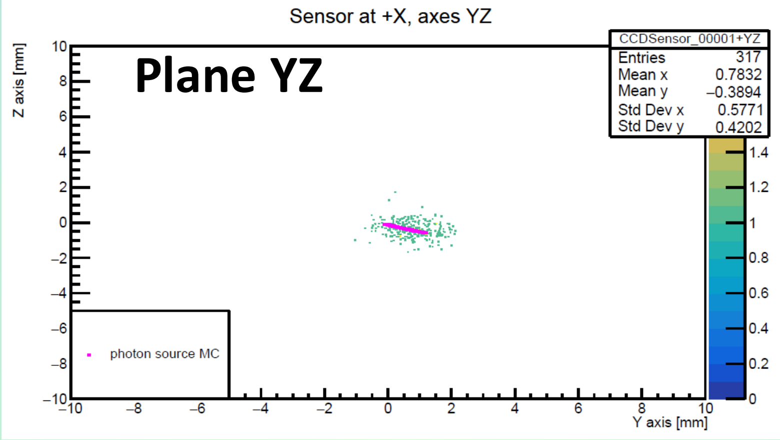
Tracks reconstruction

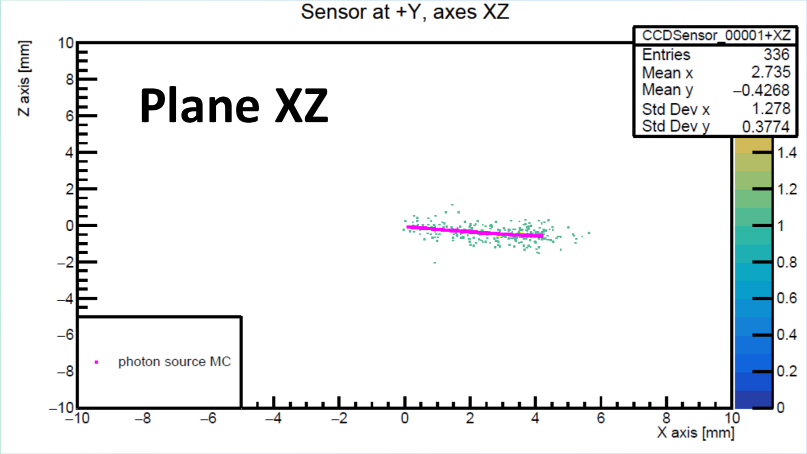
Source: 30 MeV protons

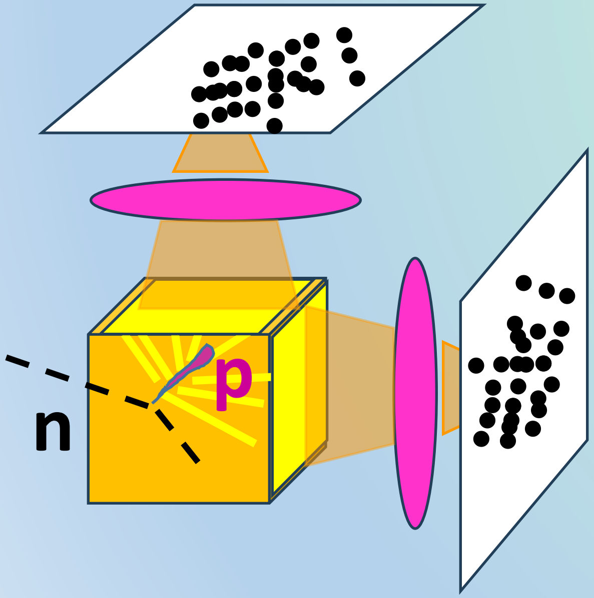
Generated in $(2x2x2)cm^3$

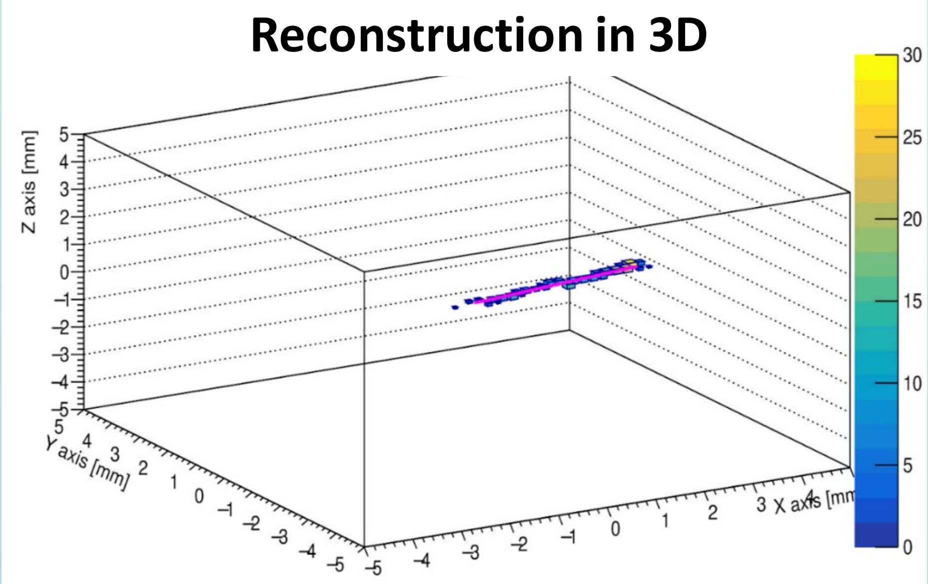
Isotropic Direction

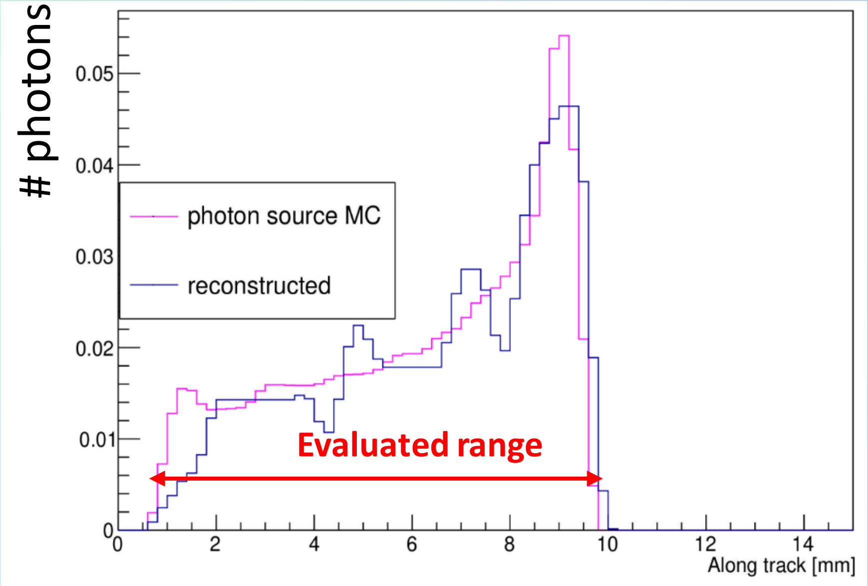












Summary

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
  - Pointlike 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)

GANT

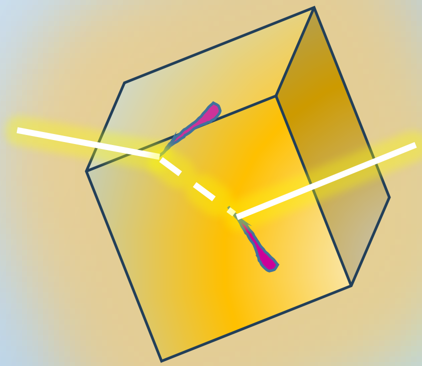
TASK ID	TASK TITLE	START DATE	END DATE	DURATION IN MONTHS	2024												2025												2026											
					Q1				Q2				Q3				Q1				Q2				Q3				Q1				Q2				Q3			
					Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Simulation & Analysis	01/01/2024	31/12/2025	24												M1												M5												
2	Optics	01/01/2024	30/06/2025	18												M2																								
3	Electronics & DAQ	01/07/2024	31/12/2025	18												M3						M4						M6												
4	Demonstrator	01/01/2025	31/12/2025	12																								M7												
5	Data Analysis	01/07/2025	31/12/2026	18																														M9						M11
6	Test	01/07/2025	30/06/2026	12																								M8						M10						

M1: Definition of all the geometry except the image intensifier
M2: Light yield and multianode PMT measurements
M3: Firmware for image acquisition
M4: Image acquisition with external trigger
M5: Reconstruction of the neutron kinematics in double scattering events
M6: Simultaneous acquisition from multiple cameras with external trigger
M7: First prototype realization (without the image intensifier)
M8: First laboratory tests with radioactive neutron source
M9: Analysis of radioactive source data
M10: Data taking with proton and neutron beams
M11: Track reconstruction from beam data

Requests & GANT

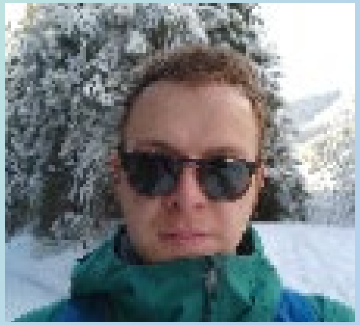
CAPITOLO	DESCRIZIONE	2024	2025	2026
Apparati	2ND CMOS high frame rate (~CYCLONE 2000)	**7.5**	3RD CMOS: **7.5** (if required)	
Inventario	2 Canon RF 35mm F1.8 IS MACRO ST	**1.5**	MCP (if necessary) [**30**]	
Consumo	cables, connectors, supports	**1.0**	Lab metabolism: **2**	Lab metab: **2**
	black box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

Conclusions



In our opinion the project is of extreme interest because:

- Useful in different physics fields (hadrontherapy, astrophysics, …)
- 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

Possible Sensor

Commercial CMOS

E30 F3.5
Macro
optics

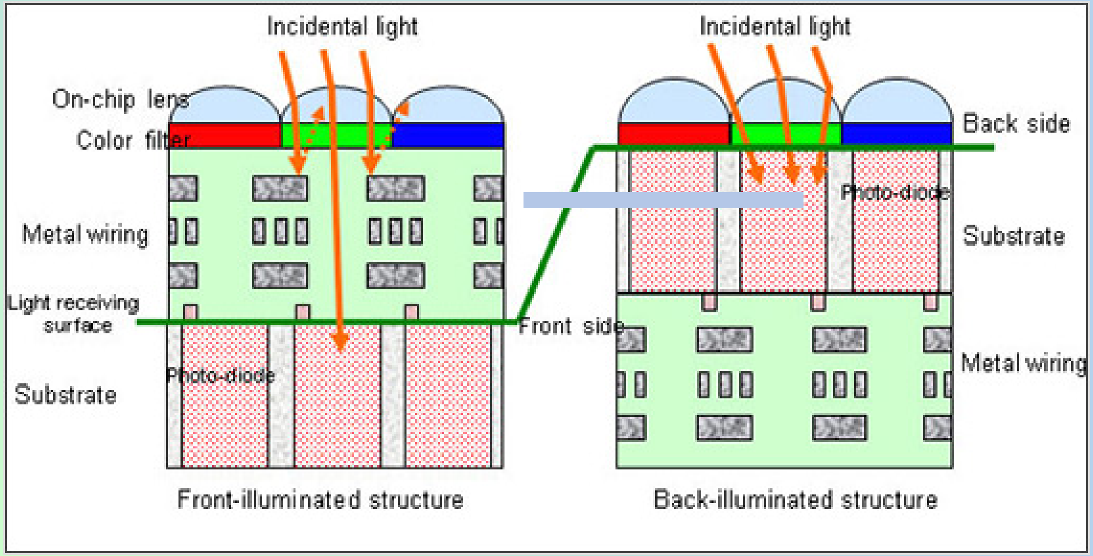
ASI
294MM
PRO

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

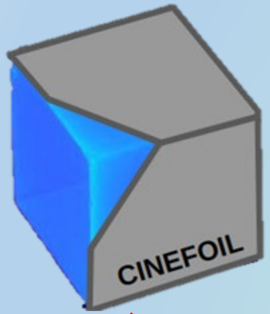
Cont:

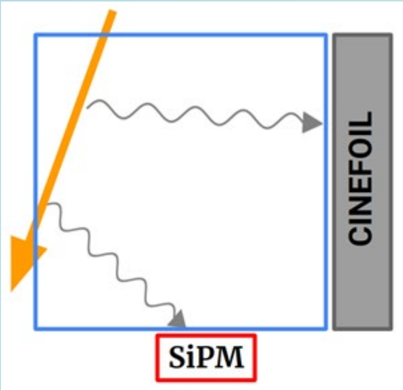
Low fps

No empty pixel suppression

High dead time during reading

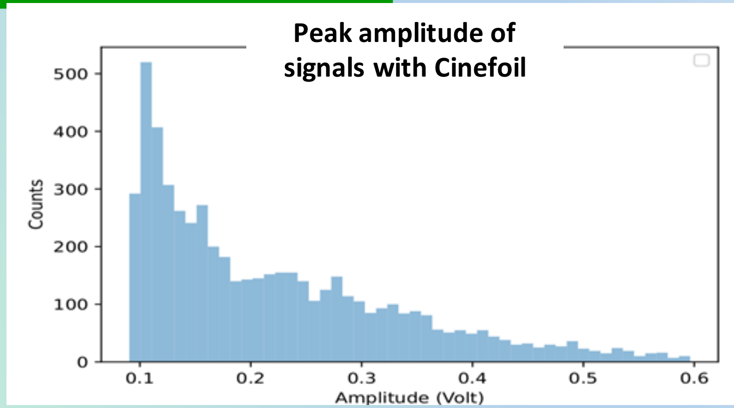
SiPM Characterization: light yield with cosmic rays

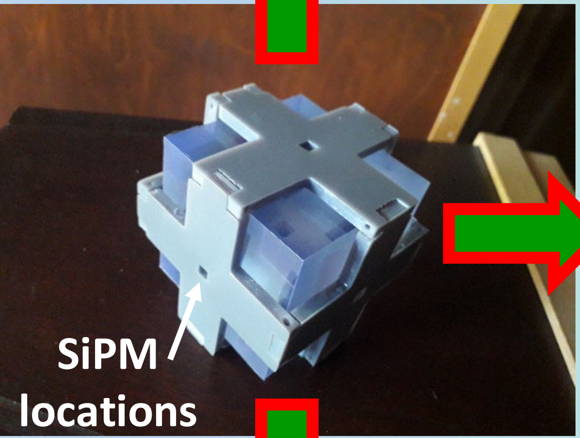




CINEFOIL:

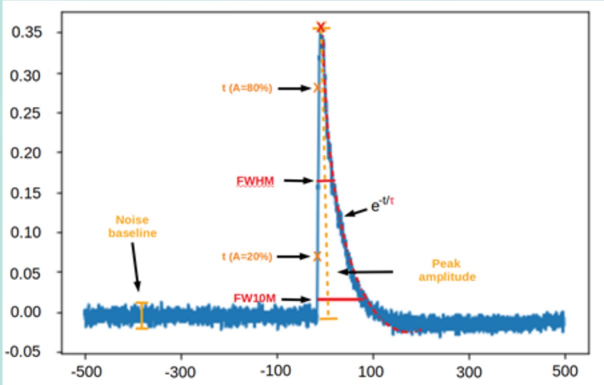
- Only direct light
- Lower signal
- Better time resolution

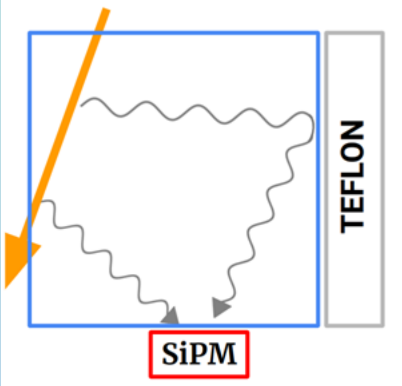




With or without amplifier?

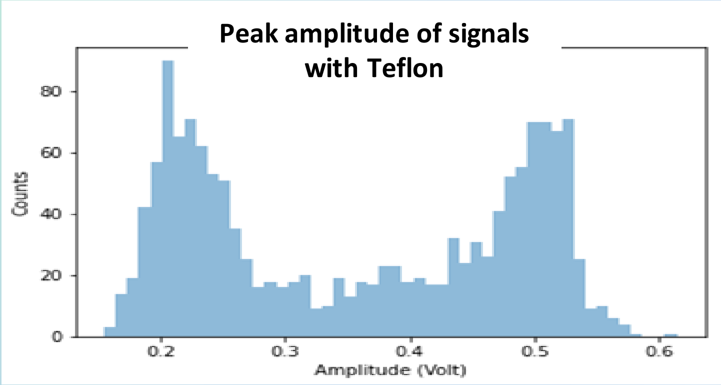
	Risetime (ns)	Decay time (ns)	FWHM (ns)	FW10M (ns)
CNA	3 ± 1	39 ± 4	150 ± 40	490 ± 80
CA	3 ± 1	39 ± 4	160 ± 40	490 ± 60
TNA	6 ± 3	42 ± 6	230 ± 30	530 ± 90
TA	5 ± 3	60 ± 15	310 ± 70	700 ± 130





TEFLON:

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

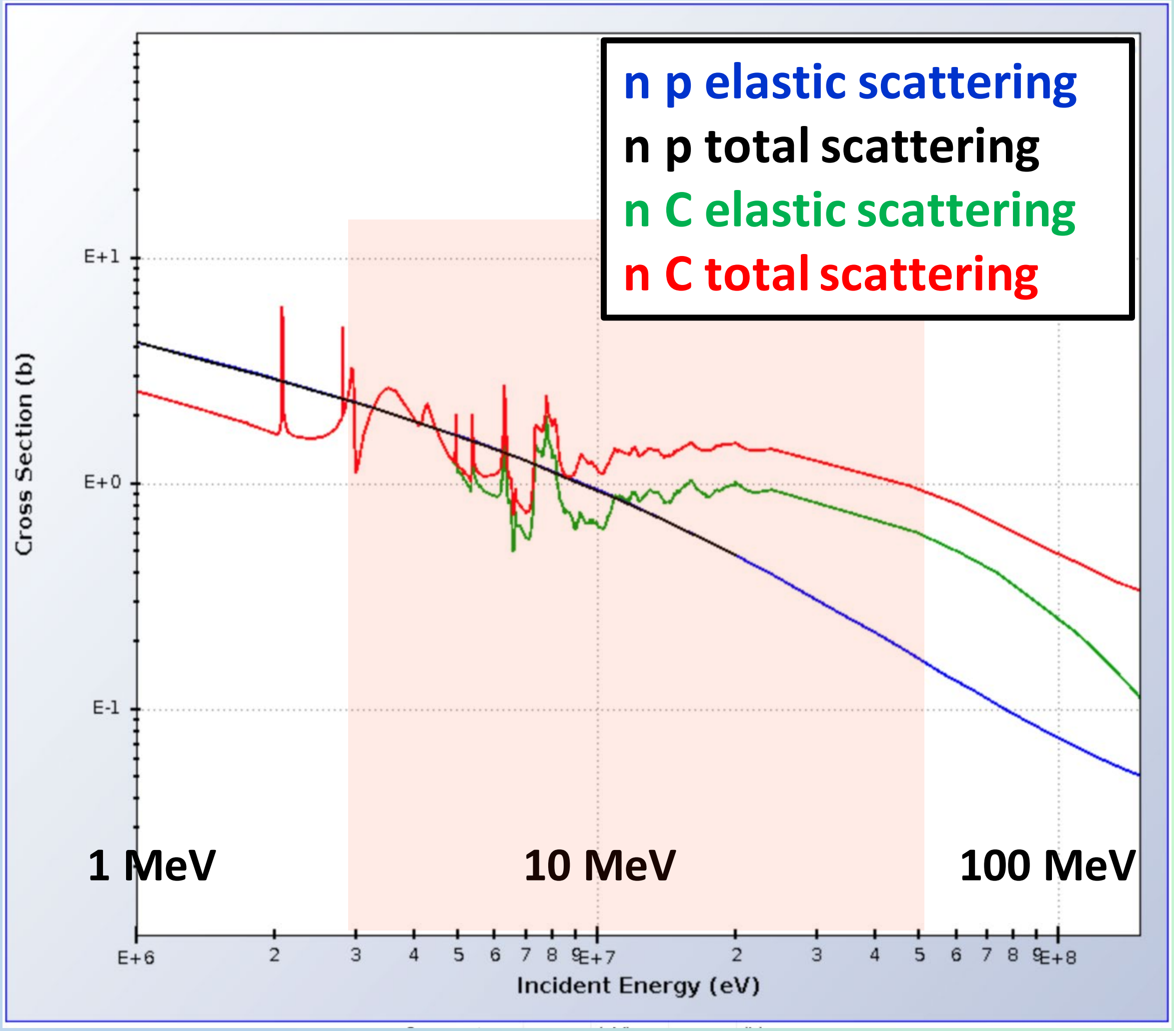


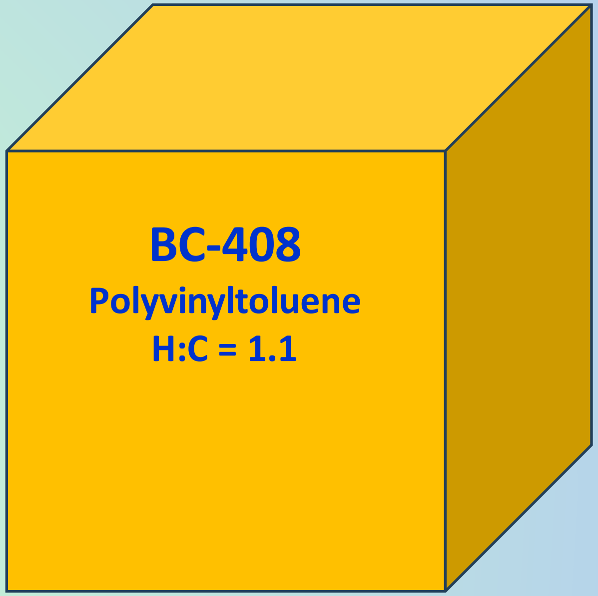
Group Members

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)

n in a plastic scintillator





Detection volume: $(6\ cm)^3$

neutron energies: 3-50 MeV

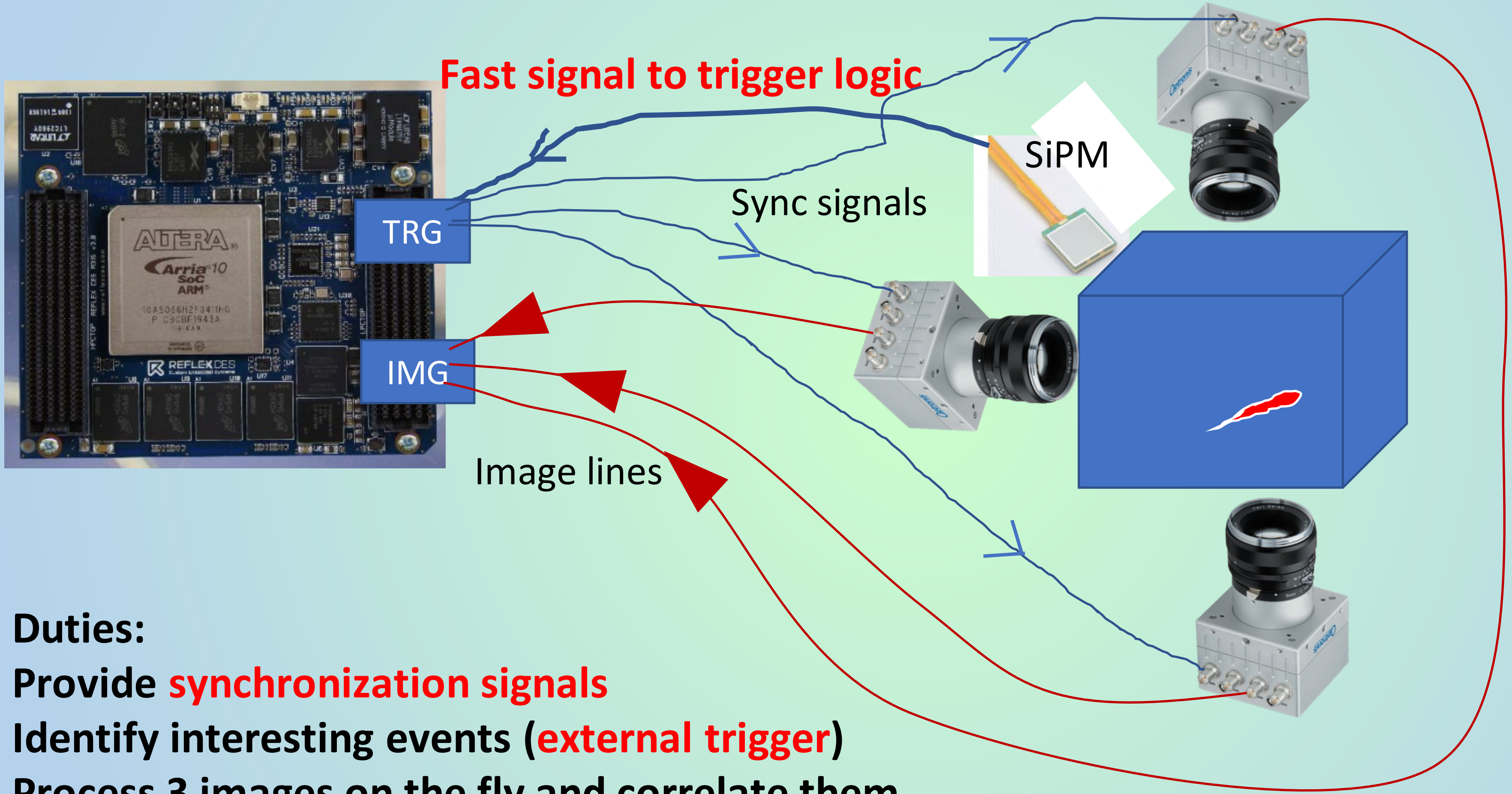
proton ranges: 0.2 – 30 mm

H:C = 1.1

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

but …

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

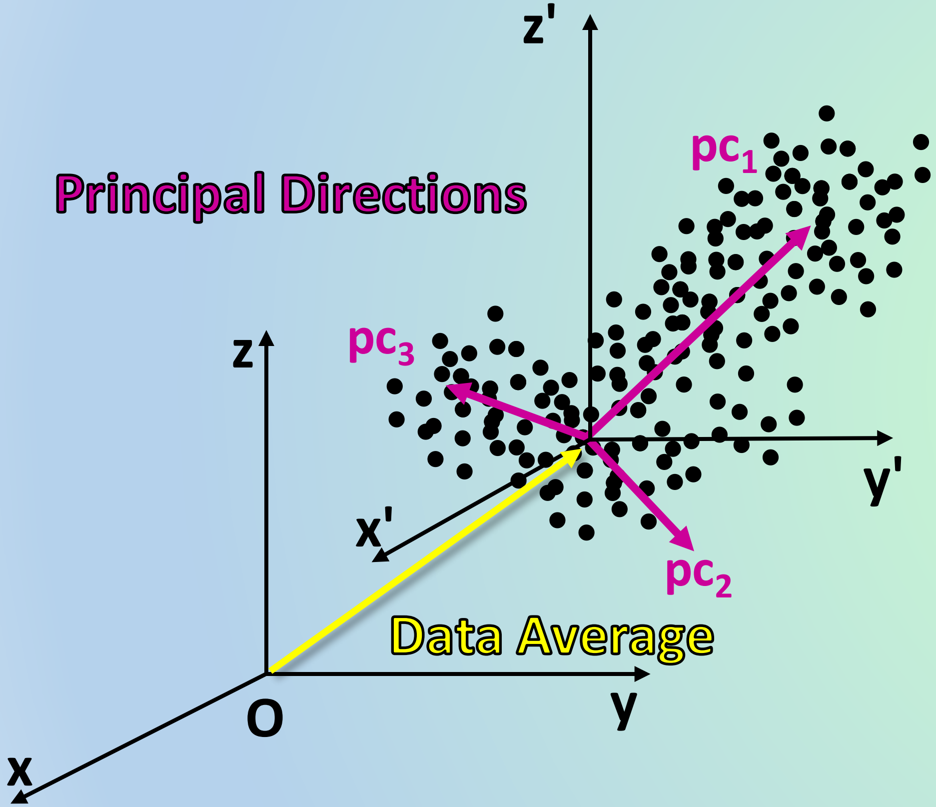
Measure energy (easy, ADC sums, cluster size)

and start & stop points (not so easy) → Use of FPGA+CPU SoC assembly

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

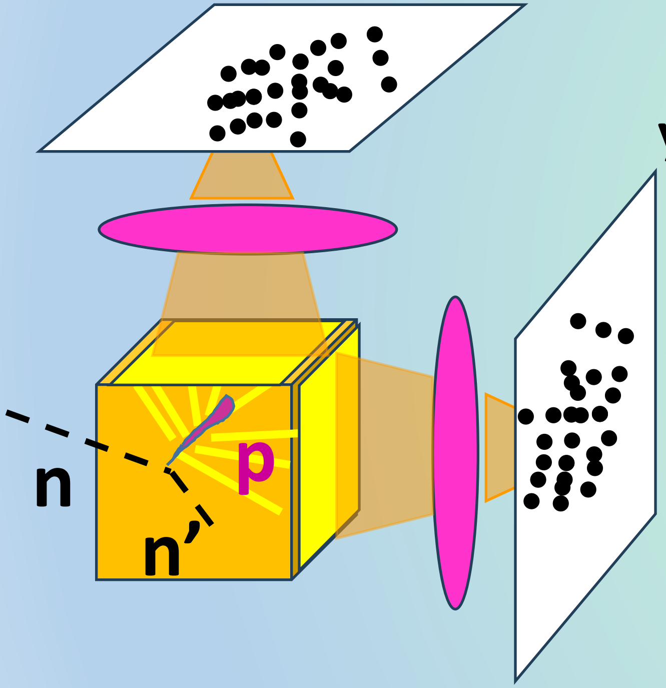
PCA Analysis, 2

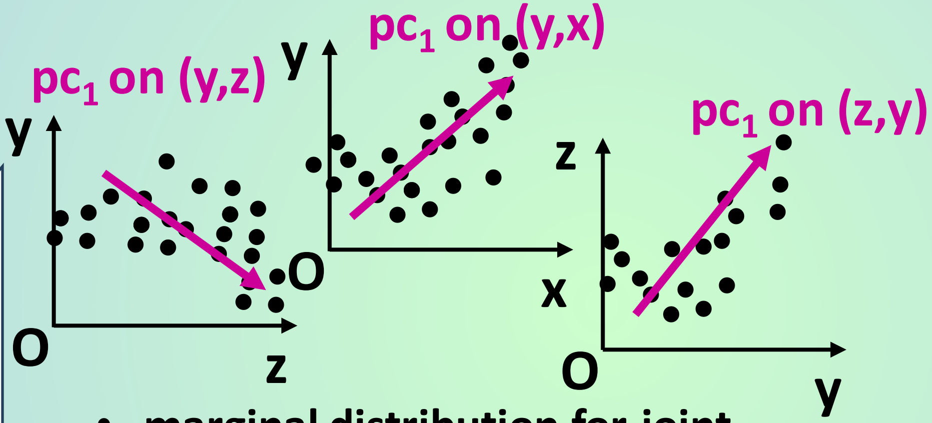
PCA for Particle Track Imaging – RIPTIDE case

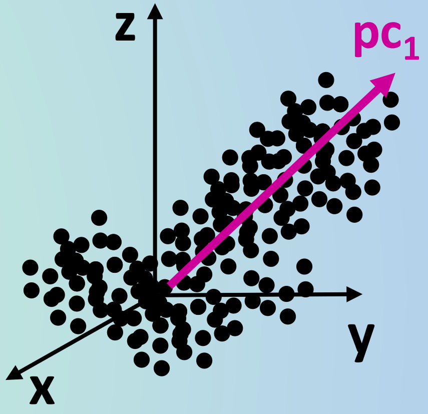
PCA for Data Analysis – standard case

INPUT: <u>projections on 2-3 cube faces</u>

INPUT: <u>raw data set</u>







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

Covariance matrix & Data Average

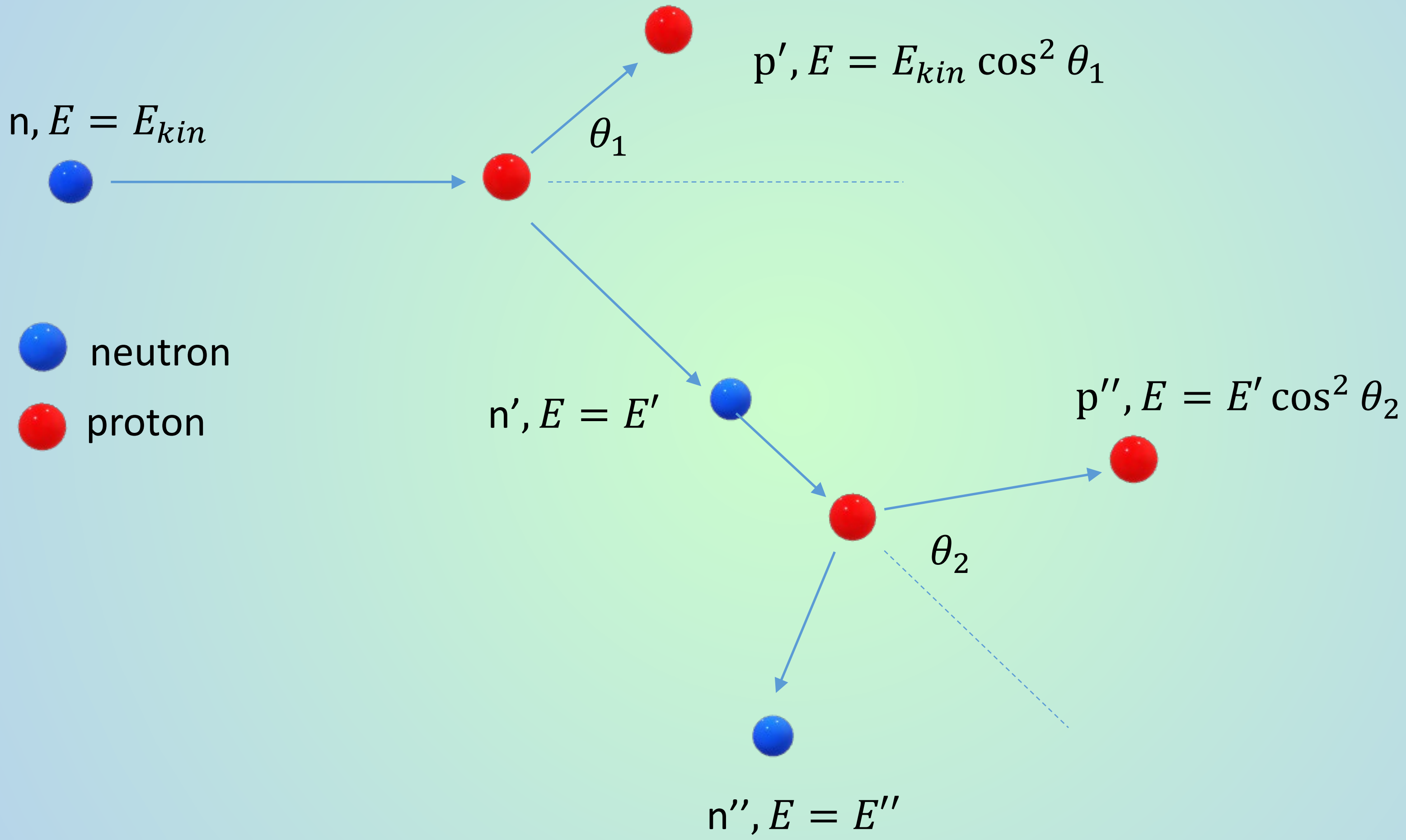
3D Principal Component: projected on each face

3D Principal Component

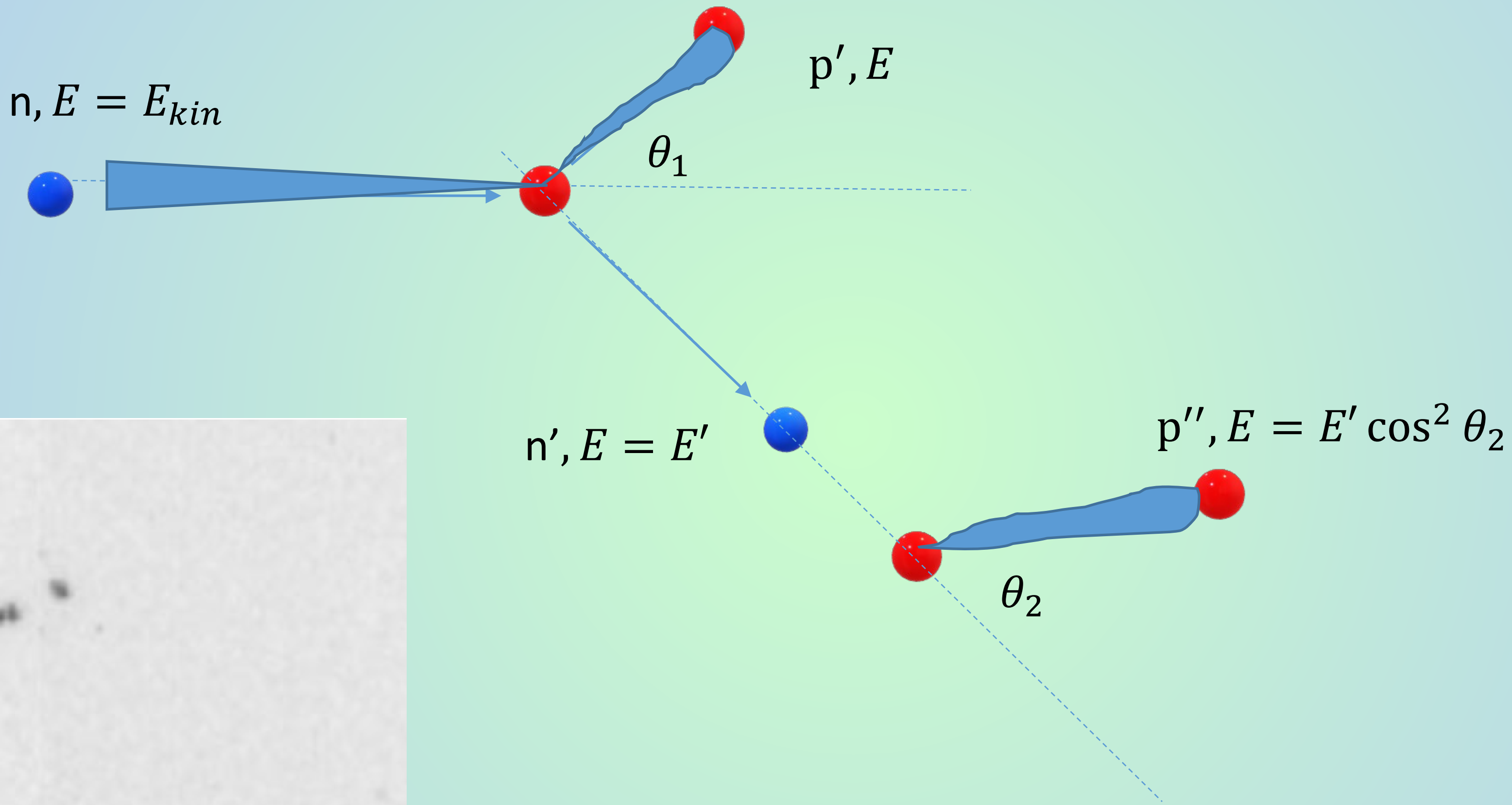
<u>Data compared with 2D projections</u>

<u>Data compared with Principal 3D</u>

Metodology: Recoil proton Tecnique



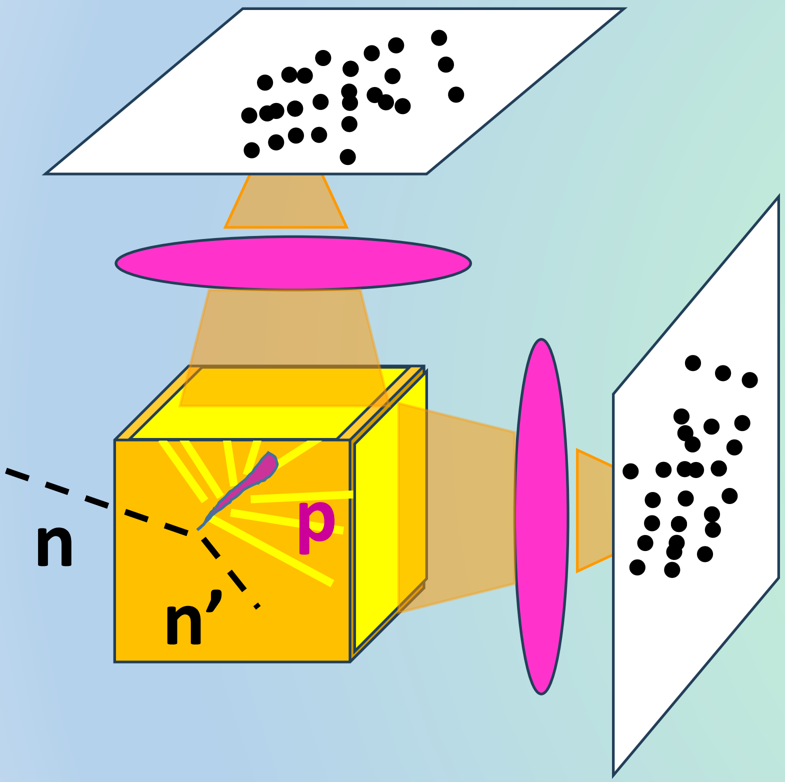
Metodology: Recoil proton Tecnique

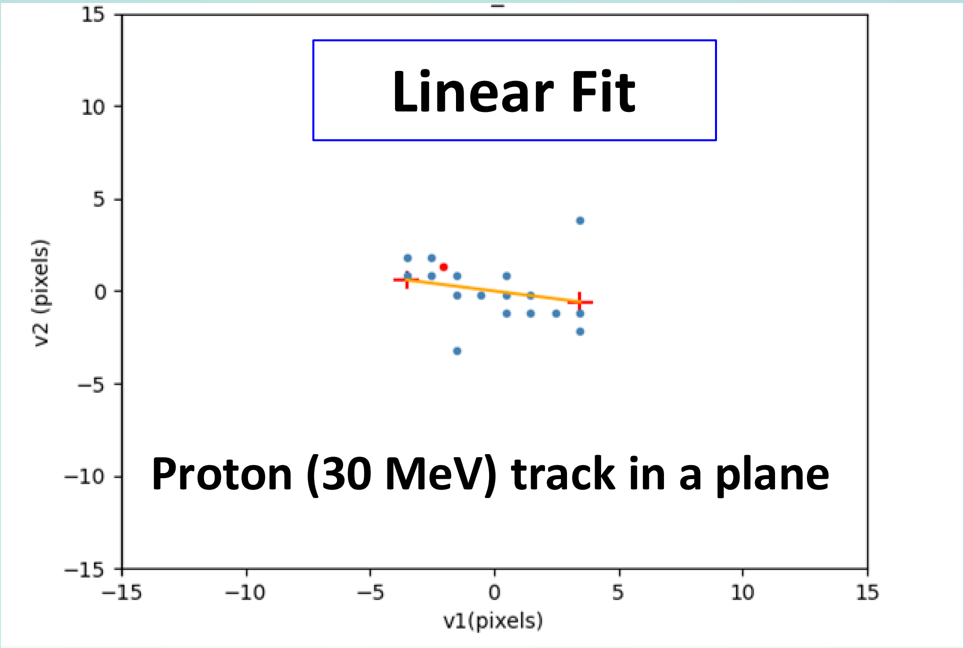


CCD image of a double scatter from a 65 MeV neutron incident from top

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

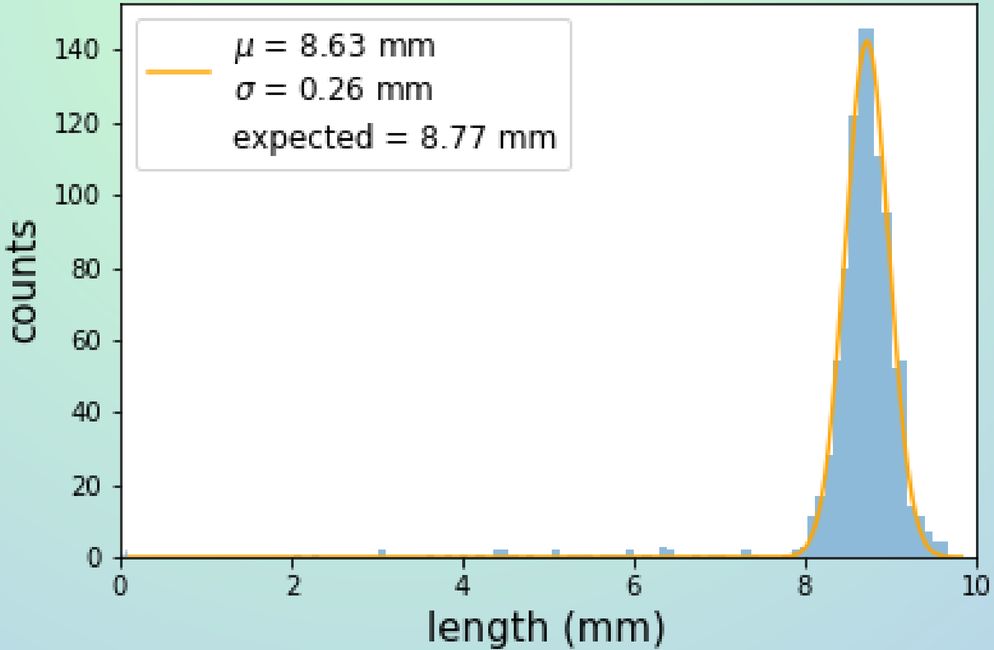
Tracks reconstruction





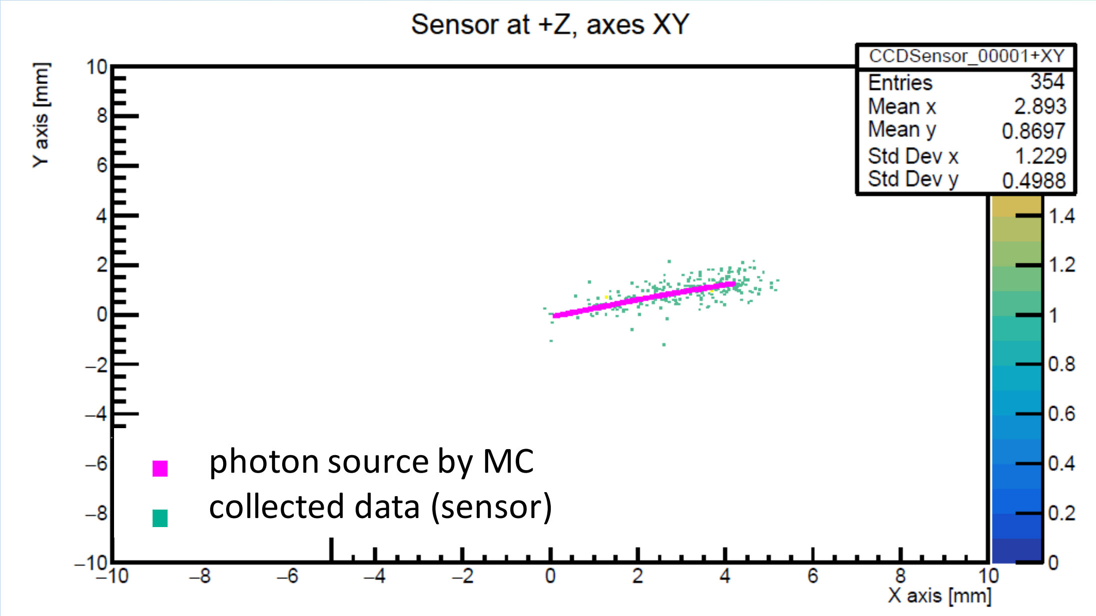
R = 0.5 cm

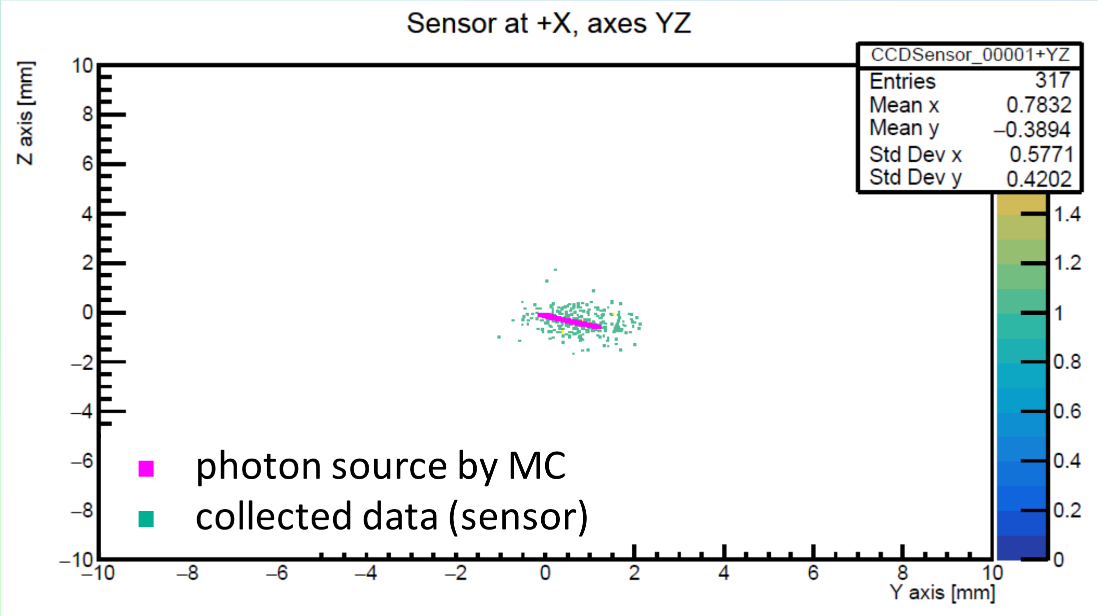
CMOS pixel: 100x100

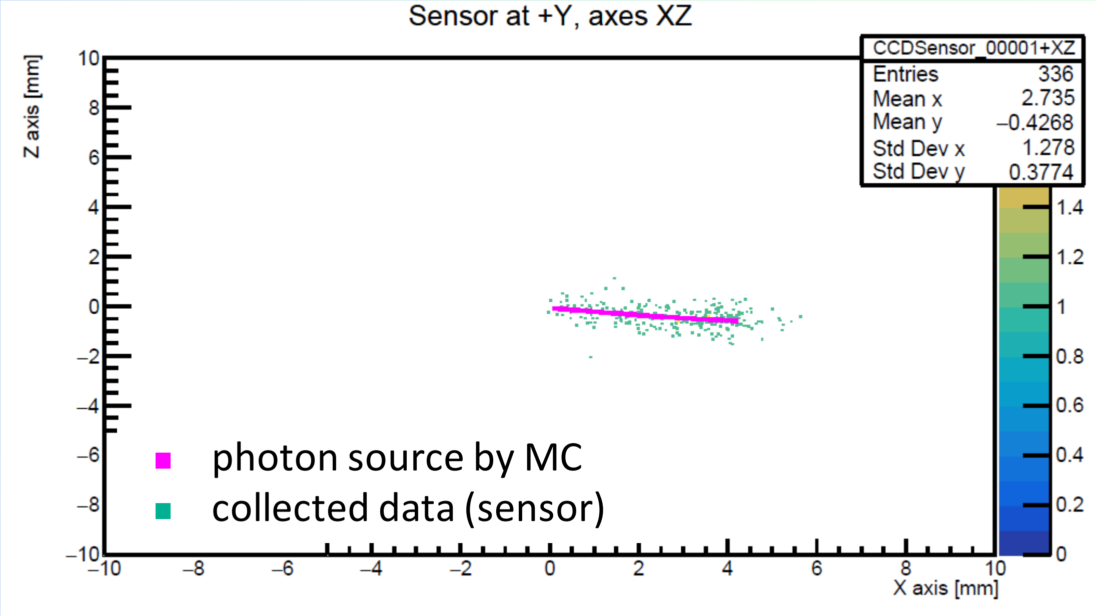


Track length precision
5%

Tracks from PCA analysis, 1



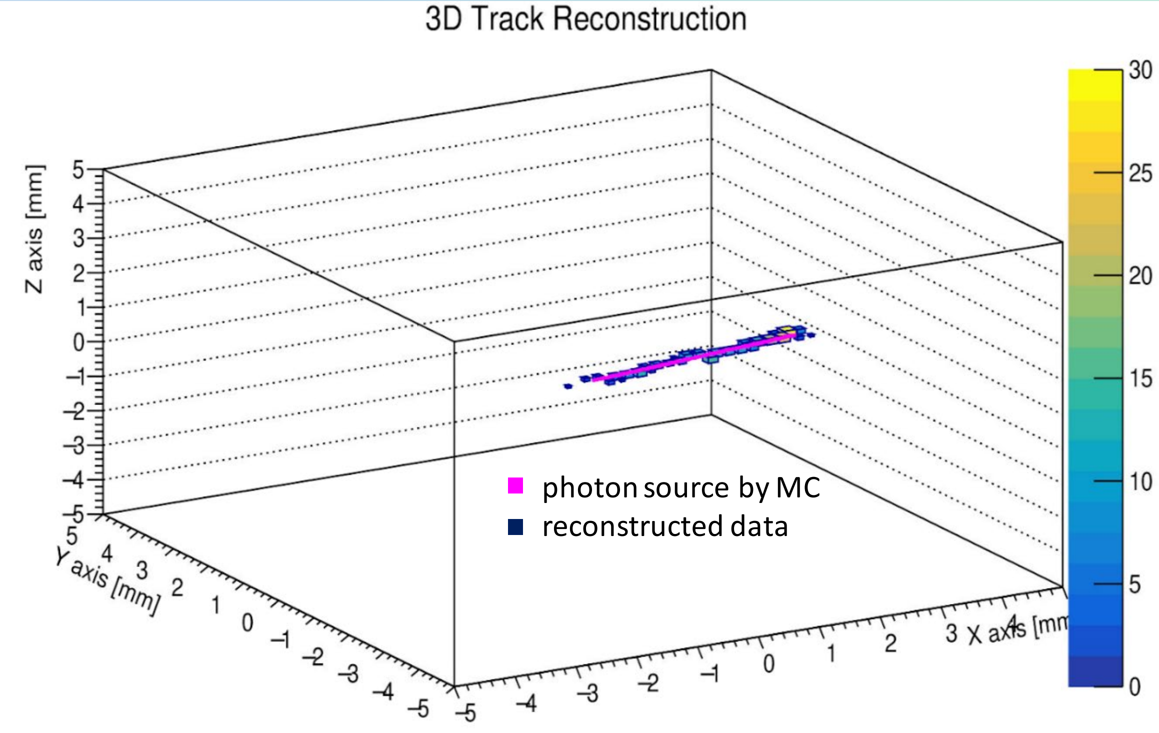


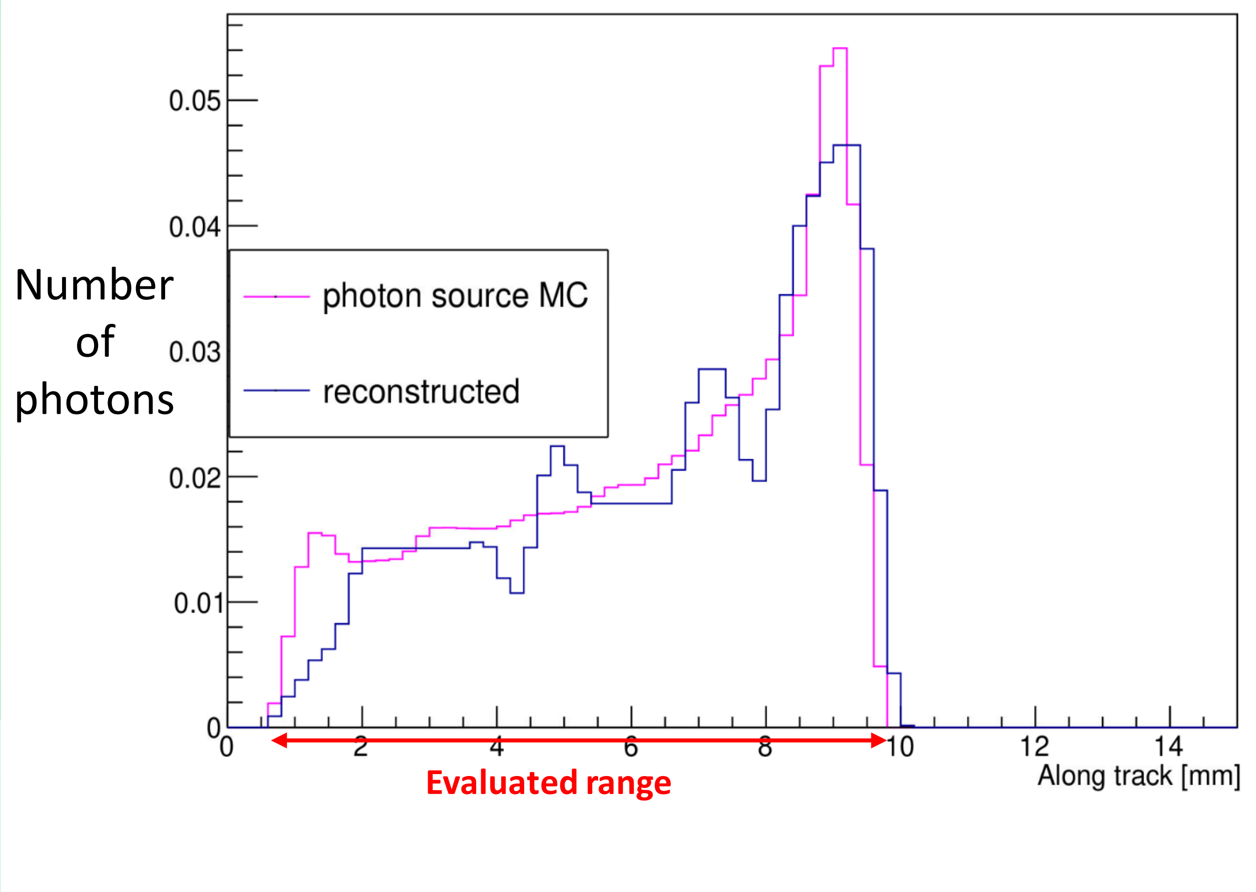


Source: 30 MeV protons

- **Generated in (2x2x2)cm^3 cube inside detector**
- **Isotropic Direction**

Tracks from PCA analysis, 2





<u>Source: 30 MeV protons</u>

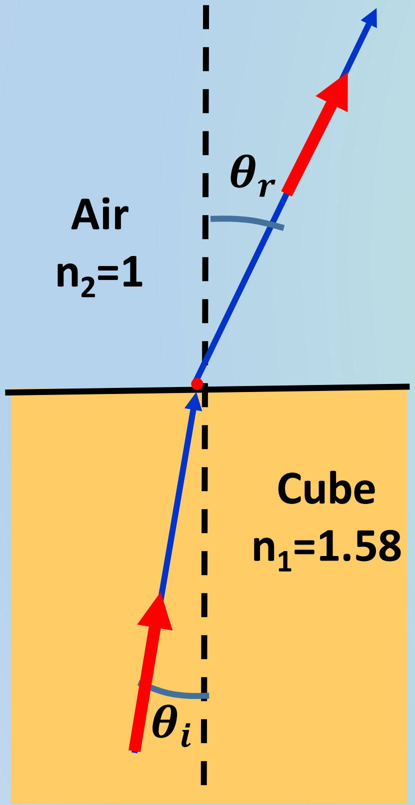
- **Generated in (2x2x2)cm^3 cube inside detector**
- **Isotropic Direction**

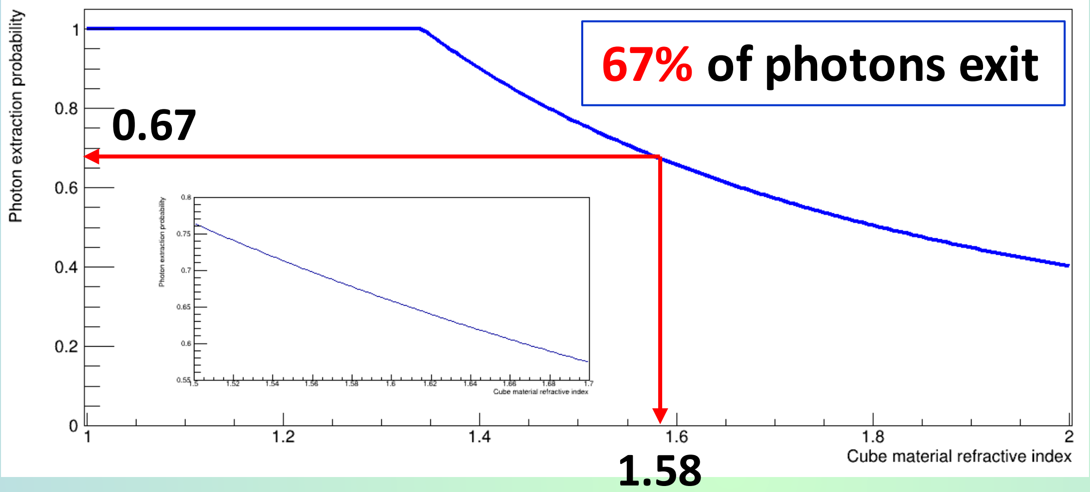
Toy MC: optic simulation

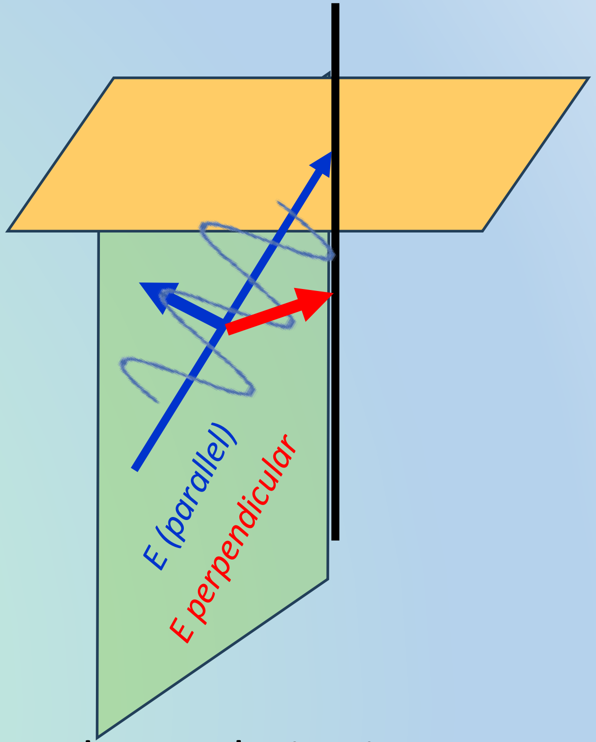
Snell law

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

$$\theta_{max} = 39,3°$$

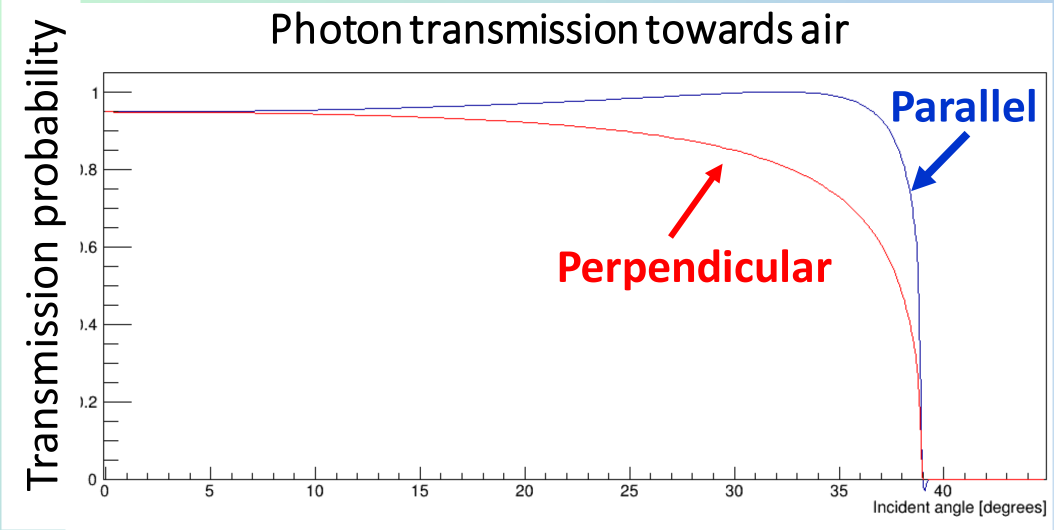






Photons → random polarization

Simulation: 50% parallel and 50% perpendicular



On average 95% of photons arrive to sensor