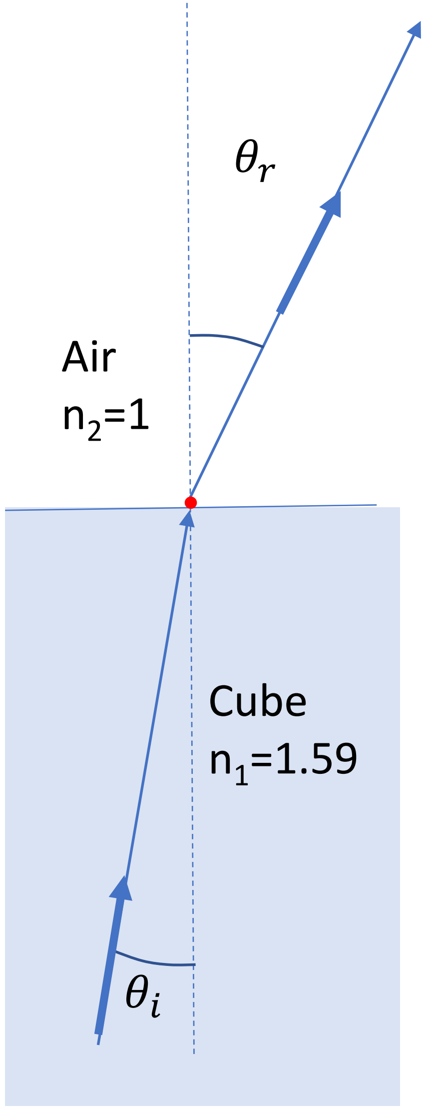
Riptide Optics

16/02/2023

Outline

- Recalling basic knowledge of optics
  (for my understanding & photon statistics)
- Riptide geometry, constraints & free parameters
- Proposed Riptide optics (first try)
- Toy MC simulations with light points
- Resolutions
- Geant simulations and first track images
- Summary

Refraction and total reflection



Snell law

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

for $\sin\theta_i > \frac{n_2}{n_1}$

There is no θ_r

since $\frac{n_1}{n_2}\sin\theta_i$ >1 →

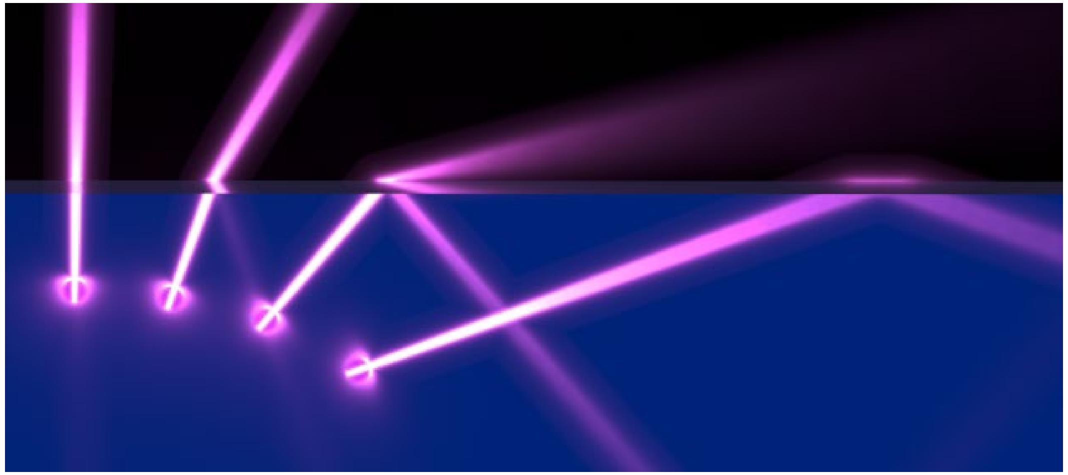
Total internal reflection

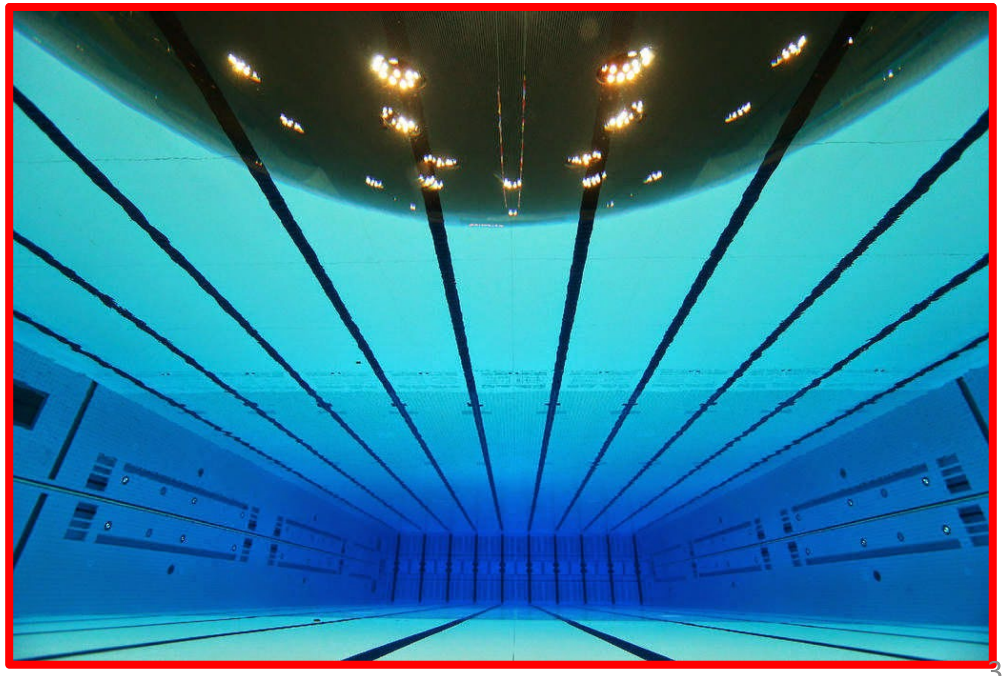
Polystirene

n=1.59, $\theta_{max} = 39{,}0°$

PolyVinilToluene

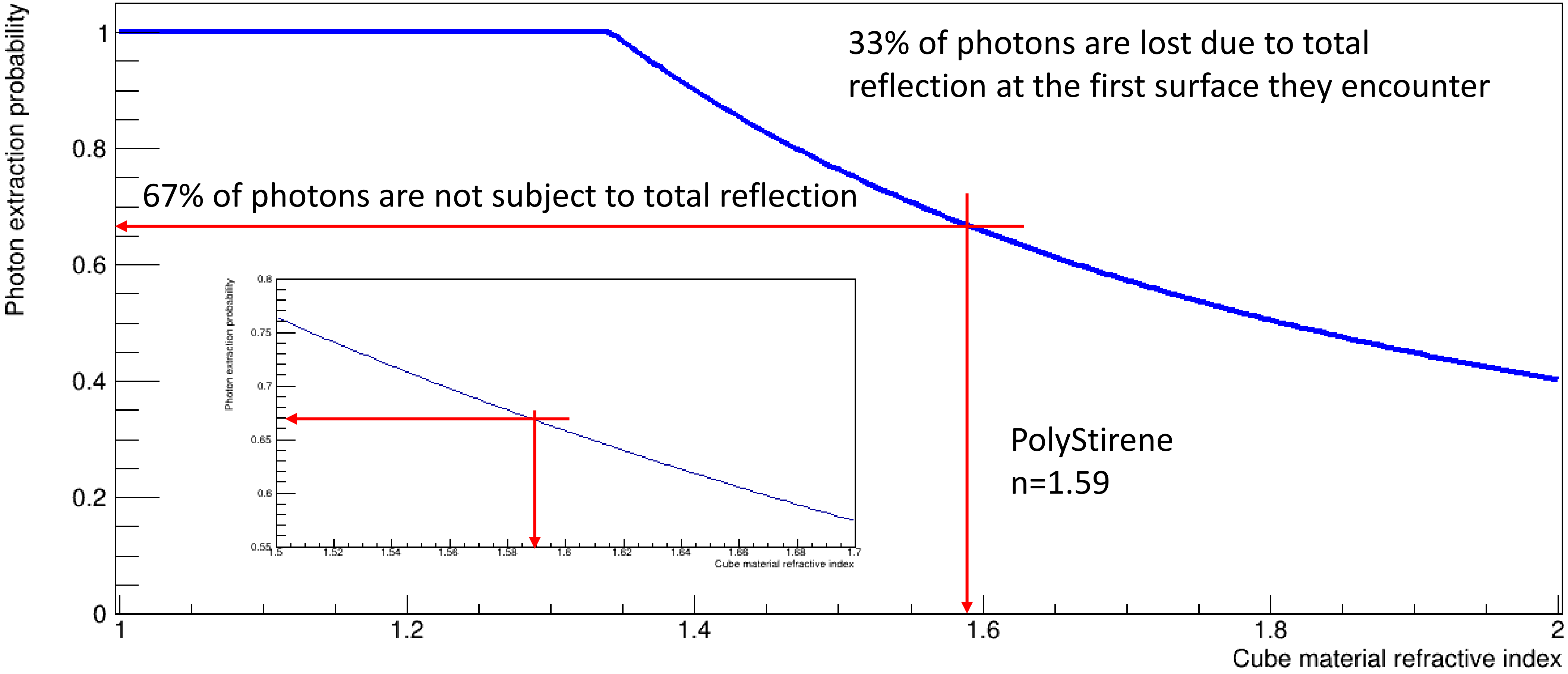
n=1.58, $\theta_{max} = 39{,}3°$





Total internal reflection traps some photons

Probability of extracting photons emitted randomly in the cube center



33% of photons are lost due to total reflection at the first surface they encounter

67% of photons are not subject to total reflection

PolyStirene
n=1.59

Partial internal reflection: Fresnel coefficients

The long story short: for incident angles different from 0, the reflection and transmission probabilities depend on the photon polarization with respect to the incident plane (i.e. the plane having the photon momentum and the normal to the surface). We distinguish between polarization **parallel** and **perpendicular** to the incident plane.

parallel

$$\begin{cases} E_{t\parallel} = \dfrac{2n_1 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i} E_{i\parallel} \\ E_{r\parallel} = \dfrac{n_1 \cos\theta_r - n_2 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i} E_{i\parallel} \end{cases}$$

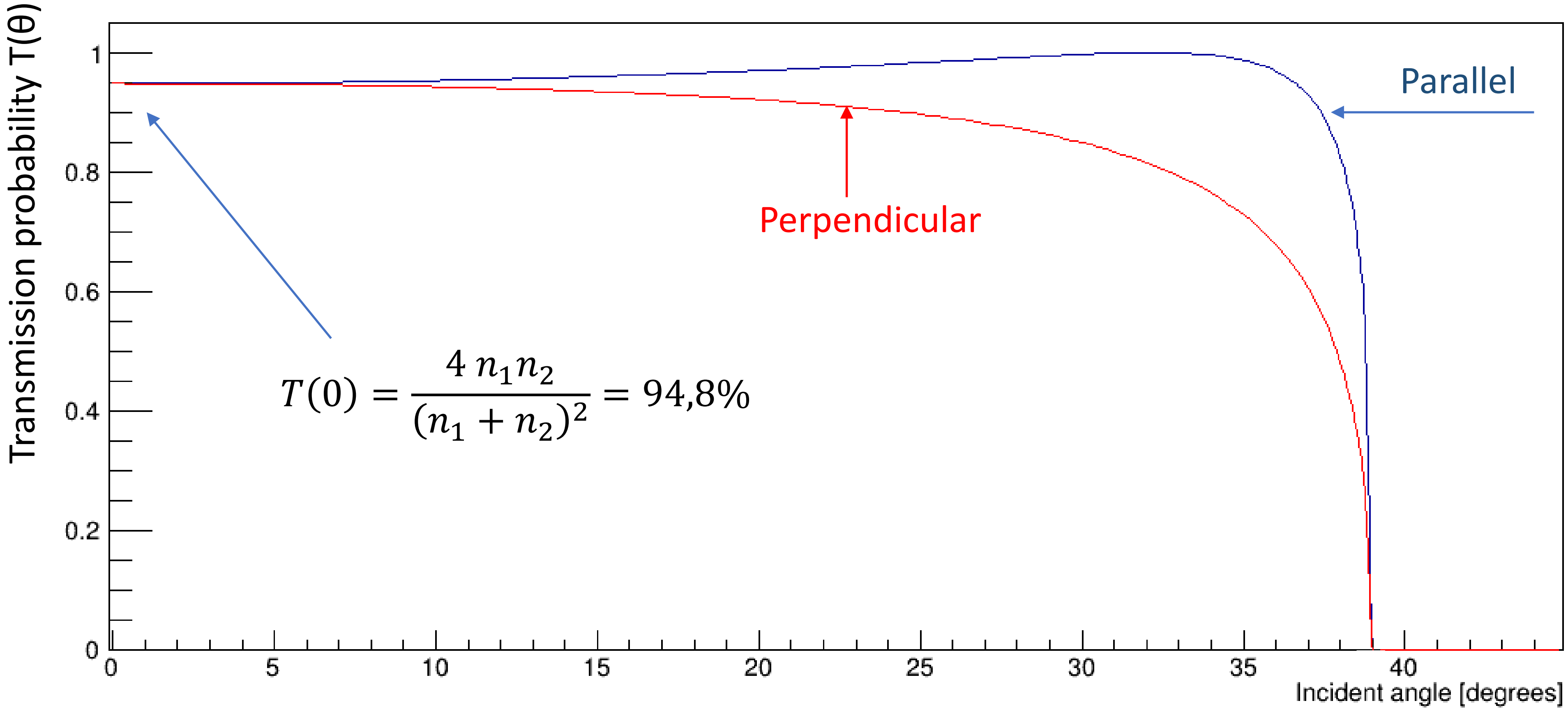
$$\begin{cases} R = \left(\dfrac{n_1 \cos\theta_r - n_2 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i}\right)^2 \\ T = 1 - R = \dfrac{4n_1 n_2 \cos\theta_r \cos\theta_i}{(n_1 \cos\theta_r + n_2 \cos\theta_i)^2} \end{cases}$$

perpendicular

$$\begin{cases} E_{t\perp} = \dfrac{2n_1 \cos\theta_i}{n_1 \cos\theta_i + n_2 \cos\theta_r} E_{i\perp} \\ E_{r\perp} = \dfrac{n_1 \cos\theta_i - n_2 \cos\theta_r}{n_1 \cos\theta_i + n_2 \cos\theta_r} E_{i\perp} \end{cases}$$

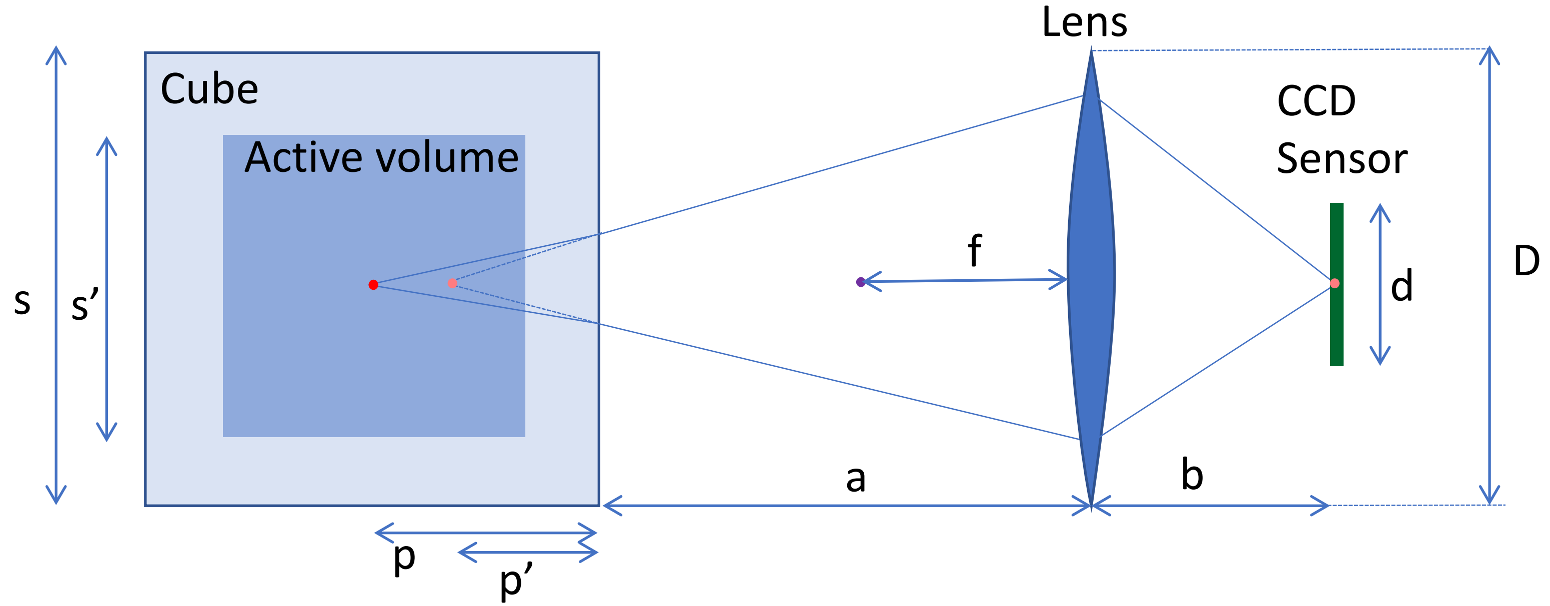
$$\begin{cases} R = \left(\dfrac{n_1 \cos\theta_i - n_2 \cos\theta_r}{n_1 \cos\theta_i + n_2 \cos\theta_r}\right)^2 \\ T = 1 - R = \dfrac{4n_1 n_2 \cos\theta_r \cos\theta_i}{(n_1 \cos\theta_i + n_2 \cos\theta_r)^2} \end{cases}$$

Photon transmission probabilities towards air



$$T(0) = \frac{4\,n_1 n_2}{(n_1 + n_2)^2} = 94{,}8\%$$

Optics schematics



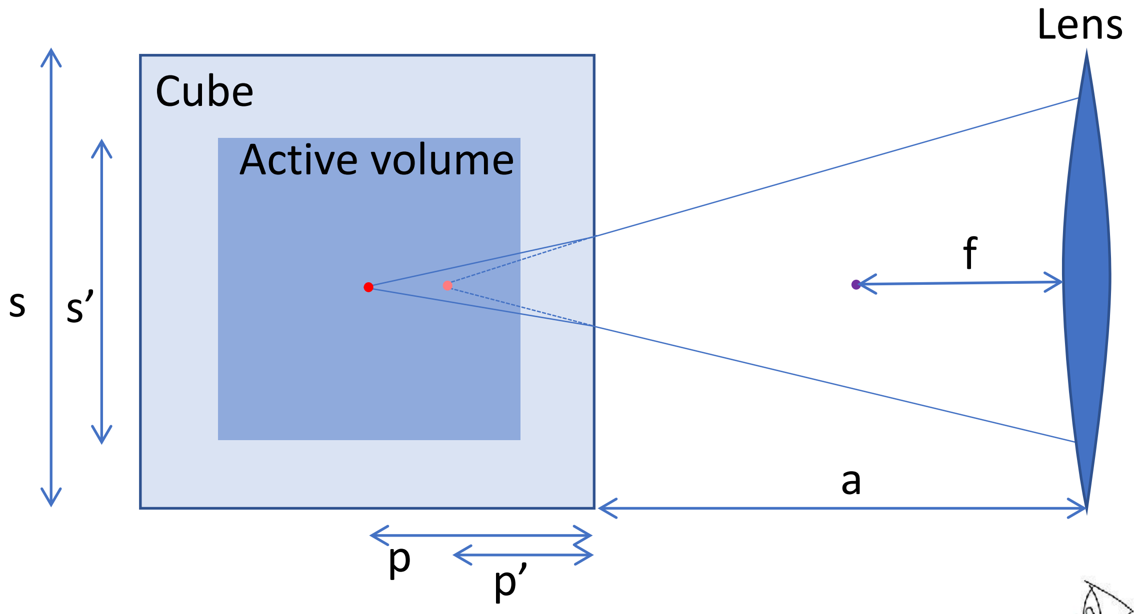
7 parameters to fix:

s: scintillator size
s': side of the active cube
d: side (not diagonal!) of the CCD sensor
f: focal length of the lens
D: diameter of the lens
a: position of the lens
b: position of the sensor

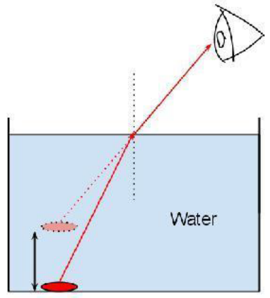
Some desidered parameter values:

s: fixed to 60 mm
s': highest possibile, reasonable 40 mm
d: fixed 20 mm
f: focal length of the lens
D: D/f highest possible (D = 2f as starting point)
a ?
b ?

Effect of the flat surface



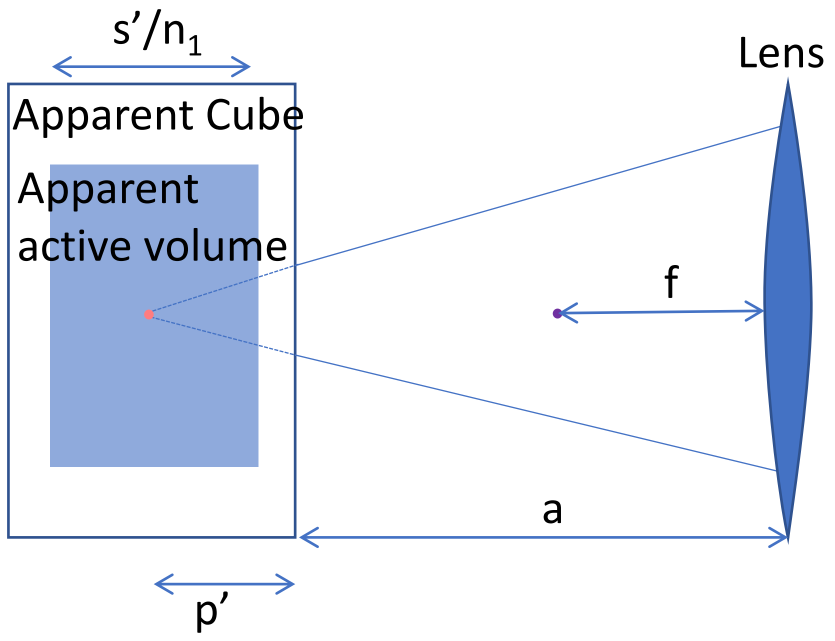
The flat surface acts as a sferical surface with an infinite radius



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

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

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



The overall effect is that the cube appears thinner, with a depth of s/n$_1$

This effect helps in having a longer field of view in the cube

Lens magnification

- Basic formulas:

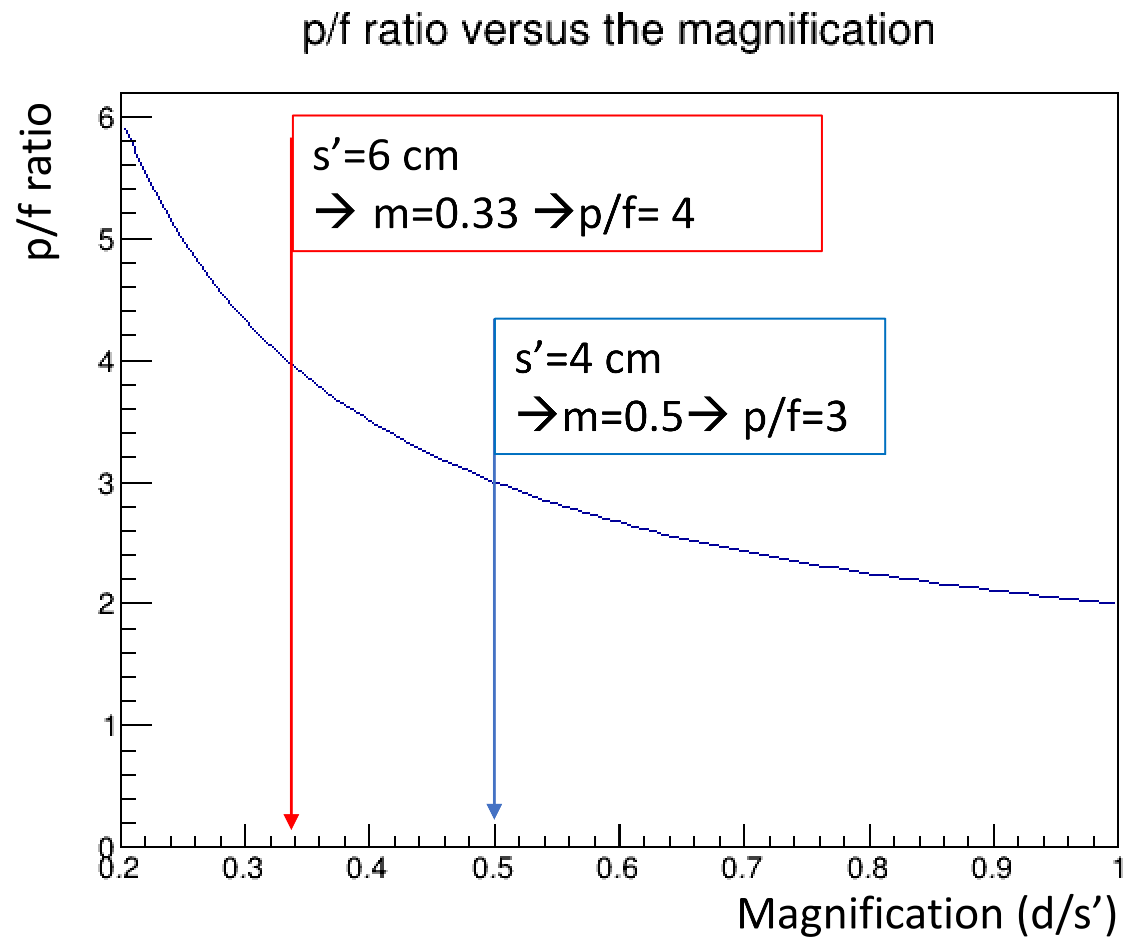
$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

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

Fixing magnification means to fix p/f

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

- RIPTIDE CUBE: $m=\frac{d}{s'}=\frac{CCD\ sensor\ side}{active\ cube\ side}$

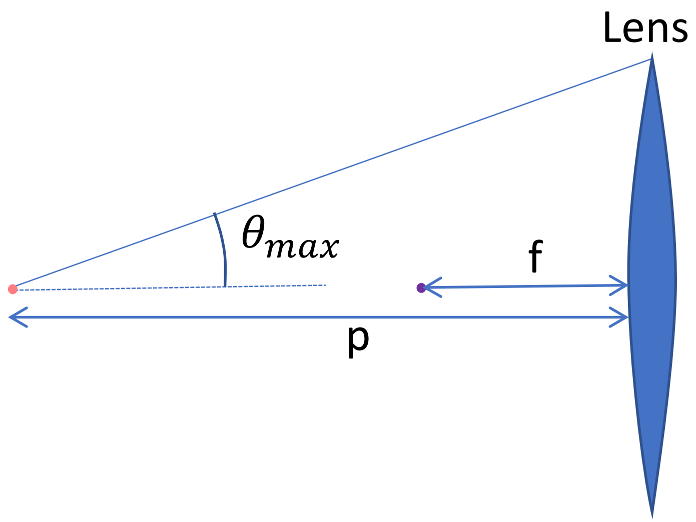


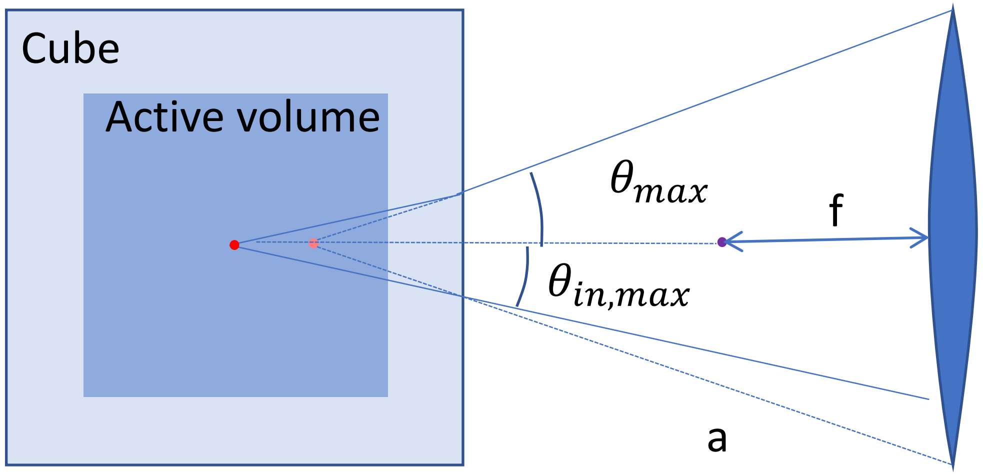
s'=6 cm
→ m=0.33 →p/f= 4

s'=4 cm
→m=0.5→ p/f=3

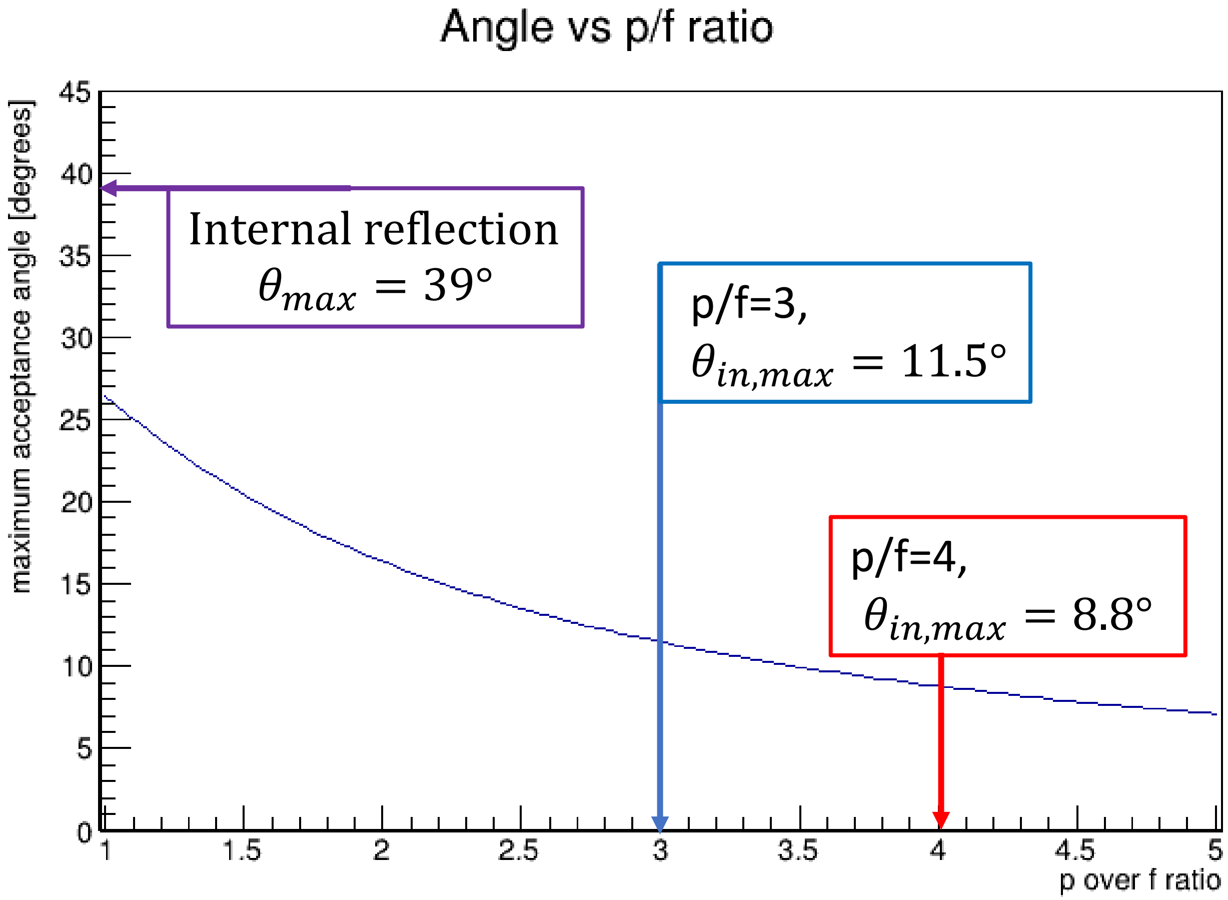
poor man's calculation on p/f effect

- p/f, when D=2f, defines the photon collection efficiency
- For photons produced along the lens axis
- $\tan\theta_{max} = \frac{D}{2p} = \frac{f}{p}$ $\Omega = 2\pi(1-\cos\theta_{max})$ $f(\Omega) = 3\,(1-\cos\theta_{max})$
- For photons produced inside the cube: $\theta_{in,max} = \theta_{max}/n_1$ → $f(\Omega) = 3\,[1-\cos(\frac{f}{pn_1})]$





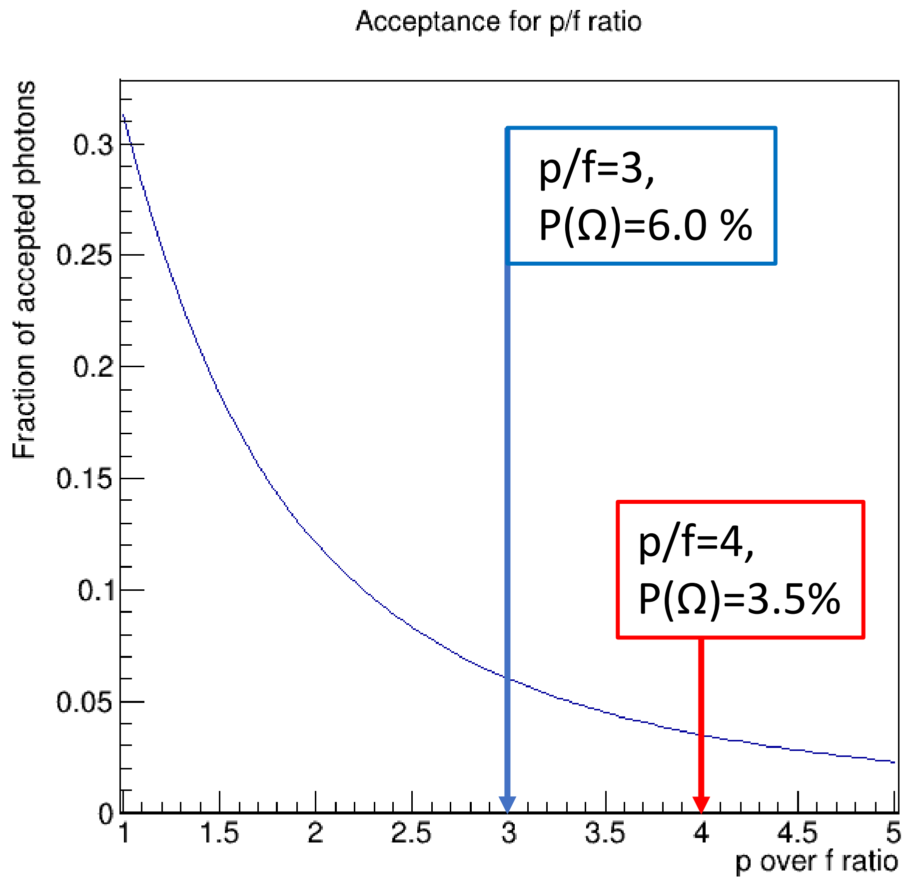
p/f plots


Angle vs p/f ratio

Internal reflection
$\theta_{max} = 39°$

p/f=3,
$\theta_{in,max} = 11.5°$

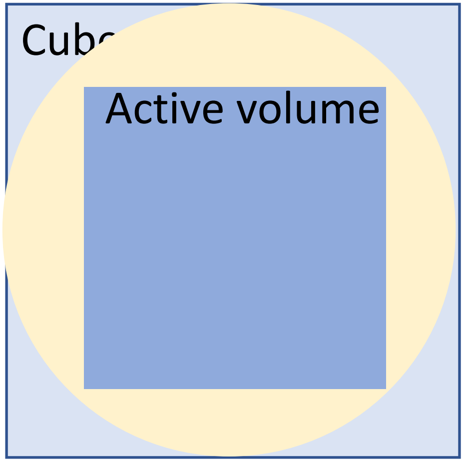
p/f=4,
$\theta_{in,max} = 8.8°$


Acceptance for p/f ratio

p/f=3,
P(Ω)=6.0 %

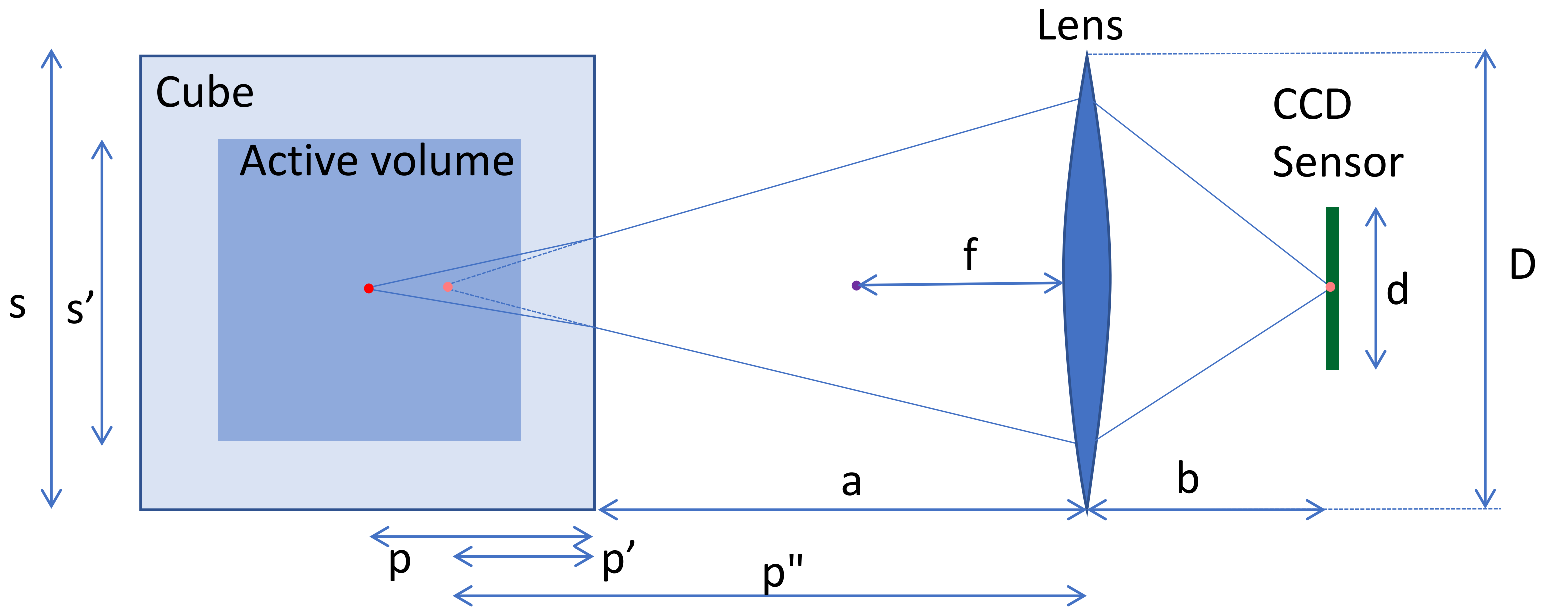
p/f=4,
P(Ω)=3.5%

Lens radius

- Up to now no information on the lens radius or diameter….
- To be able to collect efficiently the light in the active volume we need a lens of similar size.
- R from 2 to 4 cm. Lets assume R=3 cm.
- 

Collection efficiency close to the borders around 50%

Final dimensions



Some desidered parameter values:

s: fixed to 60 mm

s’: highest possibile,
reasonable 40 mm

d: fixed 20 mm

7 parameters to fix:

s: scintillator size

s’: side of the active cube

d: side (not diagonal!) of the CCD sensor

f: focal length of the lens

D: diameter of the lens

a: position of the lens

b: position of the sensor

Other parameters:

D: fixed equal to s, 60 cm

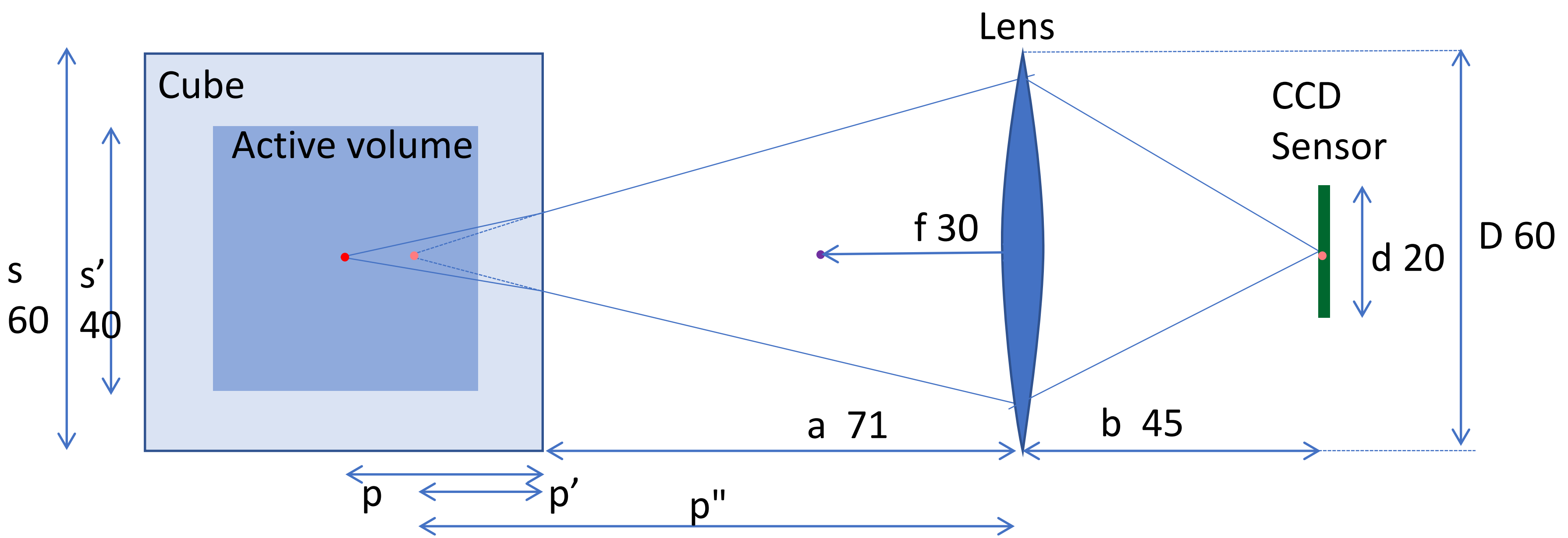
f=D/2 = 30 mm

p/f=3 → p’’=90 mm; p’=19 mm

→ **a=p’’-p’=71 mm**

→ **b= fp’’/(p’’-f)=45 mm**

Final dimensions (all numbers in mm)



Toy Monte Carlo

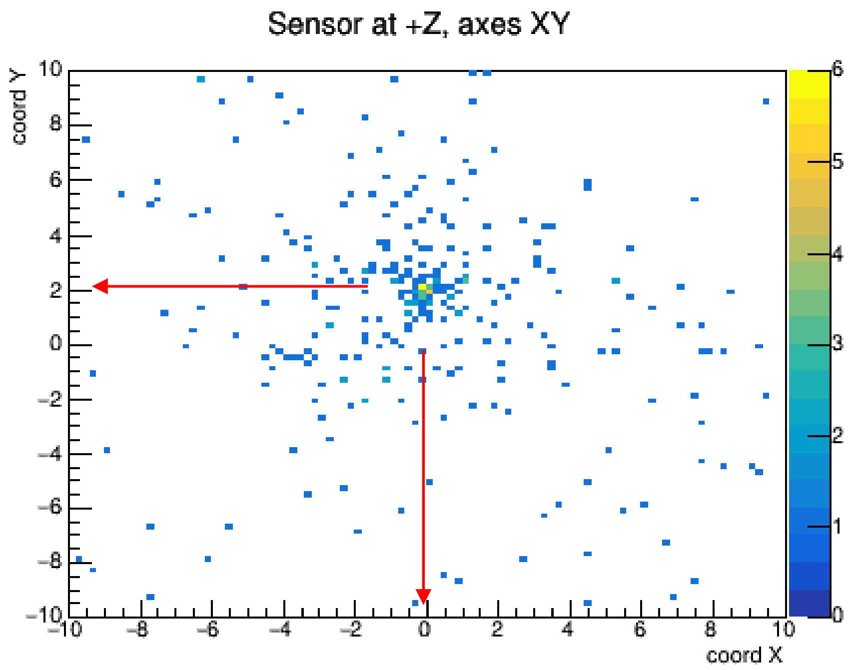
- A toy MC is used to generate optical photons in the set-up
- Position generated randomly in a cube 53x53x53 mm^3, centered in the origin
- Number of photons proportional to the energy (2-12 MeV, $10^4\gamma$/MeV)
- Photons are traced in the scintillator, towards the lens and till the CCD planes (6)
- Only photons entering into the sensors are stored

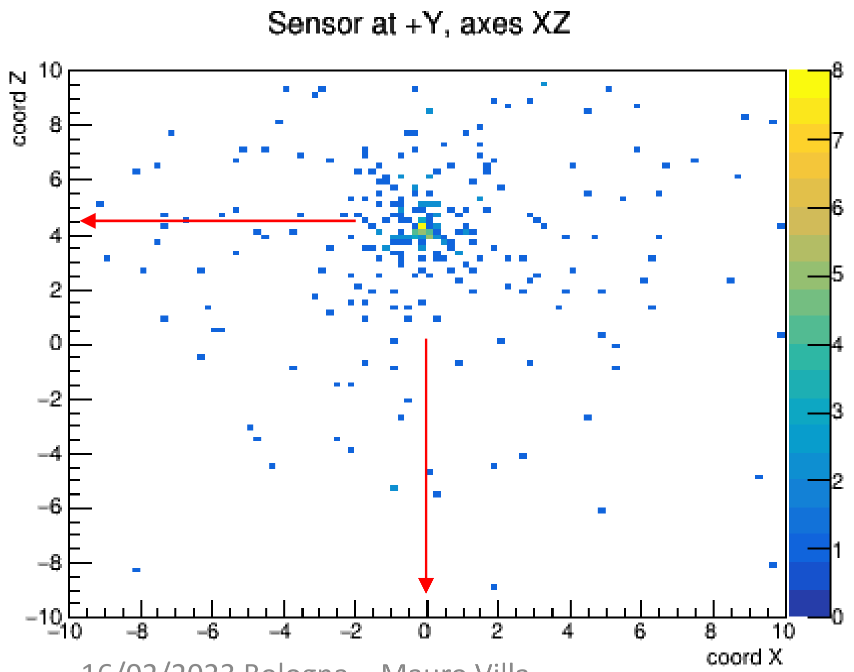
Example of a 3 view

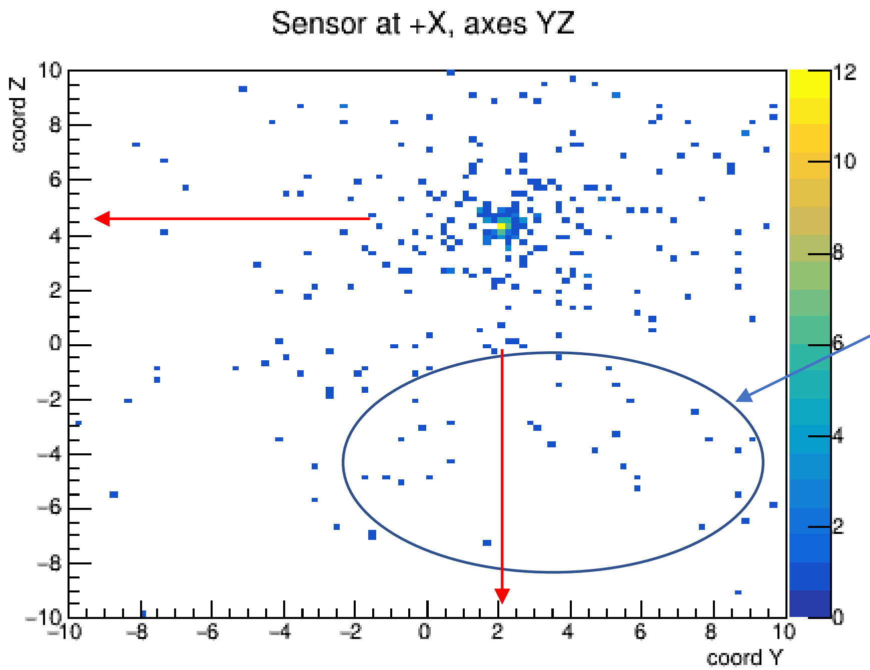
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)

Generation:
X = 0.07 mm
Y = -4.28 mm
Z = -8.75 mm

Energy: 6.88 MeV
#Photons: 68.8k







Faraway photons due to **spherical aberration**

Position reconstruction

- Poor man solution:
- Rebin CCD (100x100) in a 25x25 matrix;
- Isolate the highest pixel → extract pixel center coordinates (Up,Vp)
- In the 100x100 image define a region (20x20) centered in (Up,Vp)
- Evaluate mean, sigma of coordinates U and V in the region

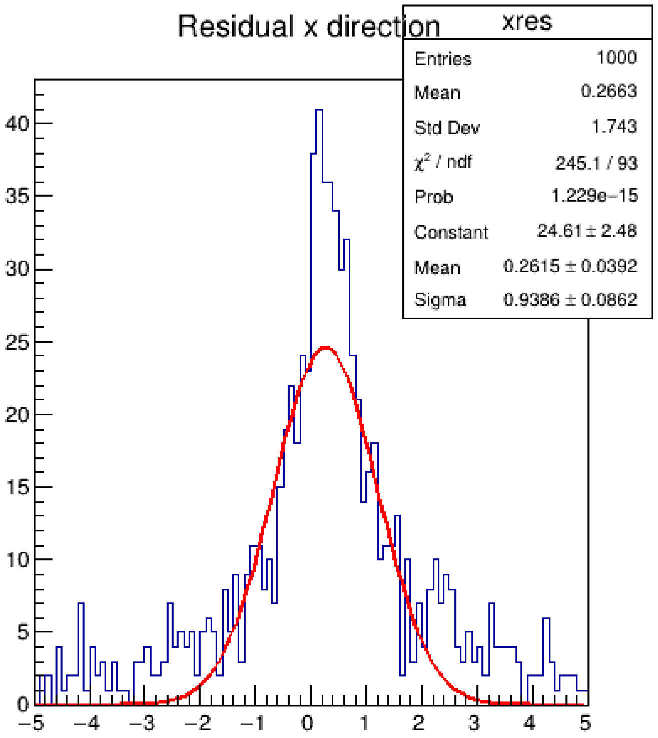
- Iterate over the three CCD images («+YZ», «+XZ», «+XY»)
- Find the mean value of X, Y, Z

Residuals for all generated points

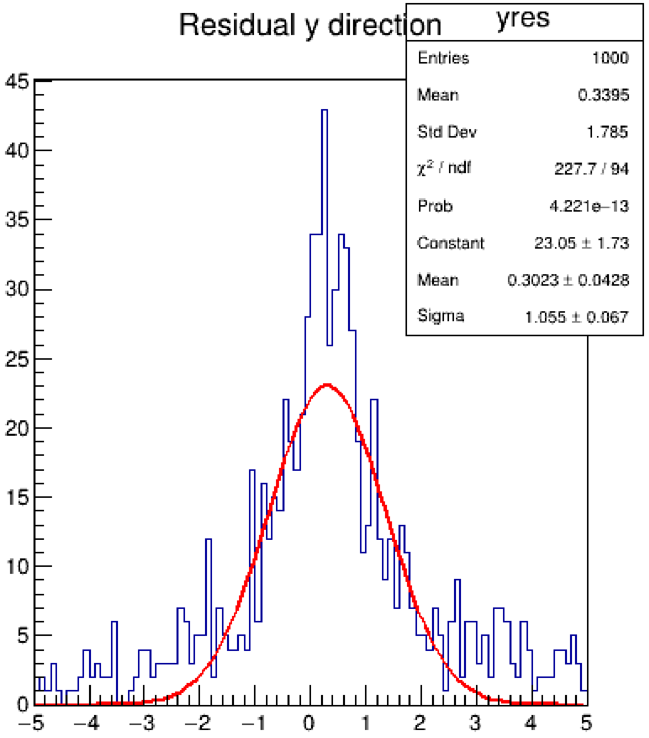
$X_{estimated} = -X_{mean}/0.5$
$X_{res} = (X_{estimated} - X_{true})$

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

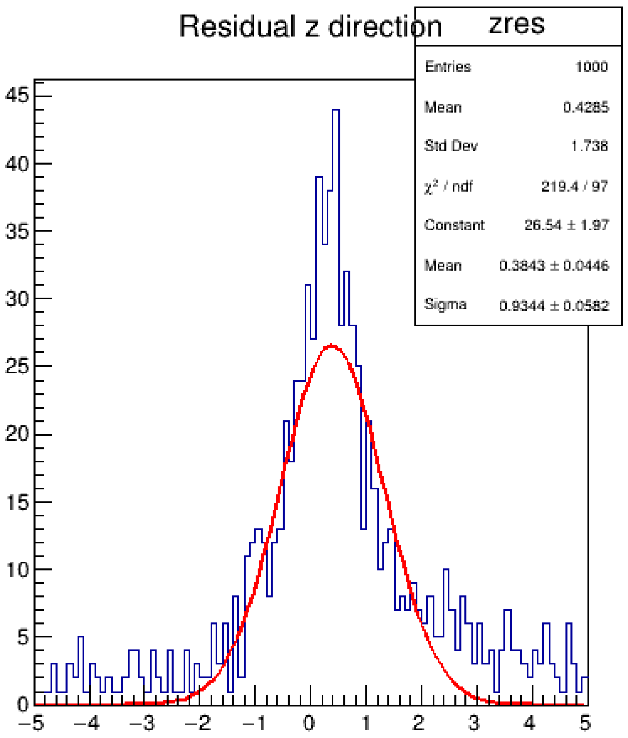
$Z_{estimated} = -Z_{mean}/0.5$
$Z_{res} = (Z_{estimated} - Z_{true})$



X_{res} (mm)



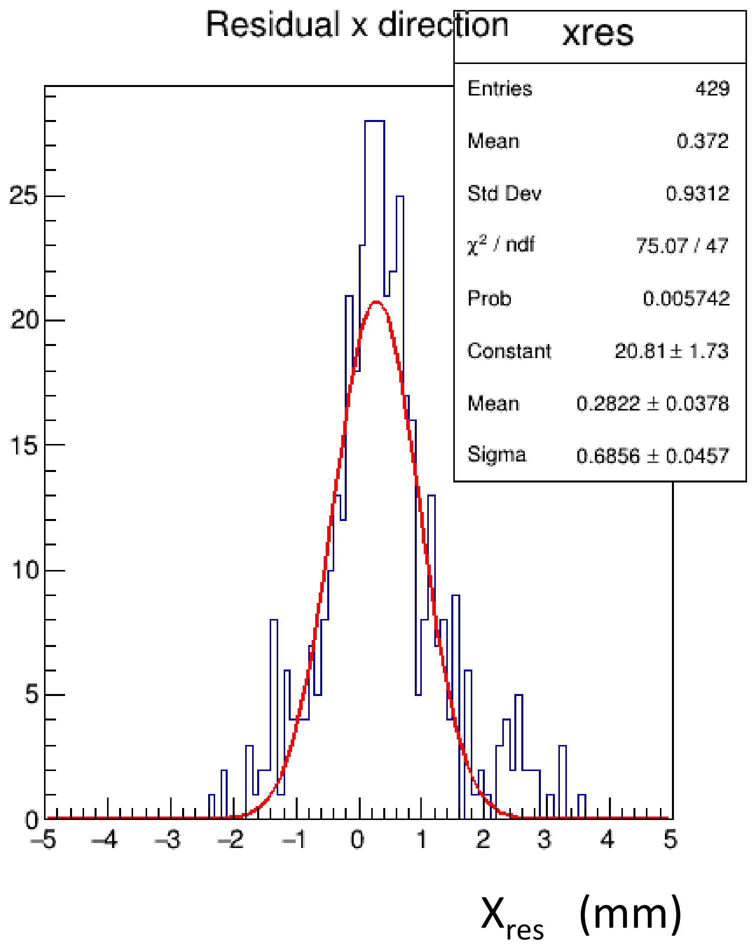
Y_{res} (mm)

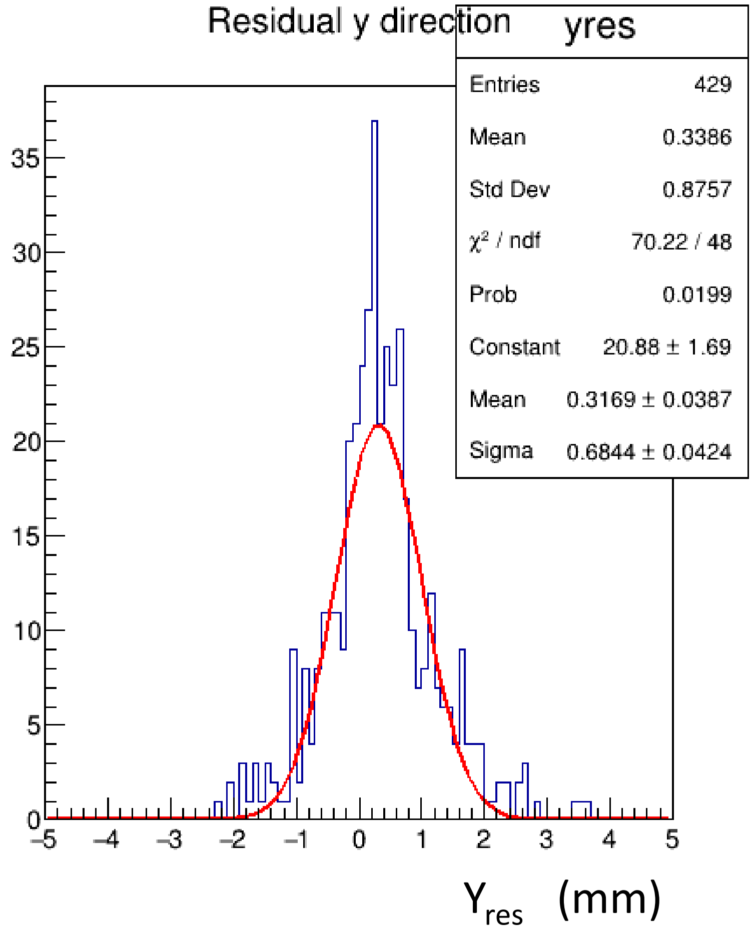


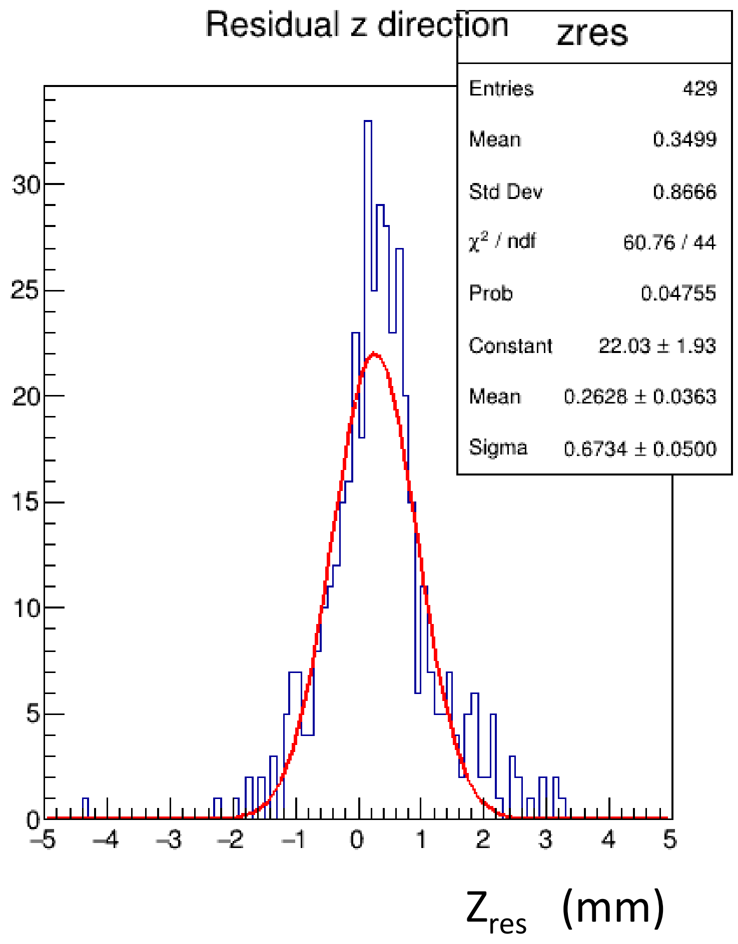
Z_{res} (mm)

Residuals 0.96 mm!

Residuals for generated points in a cube 40 mm side

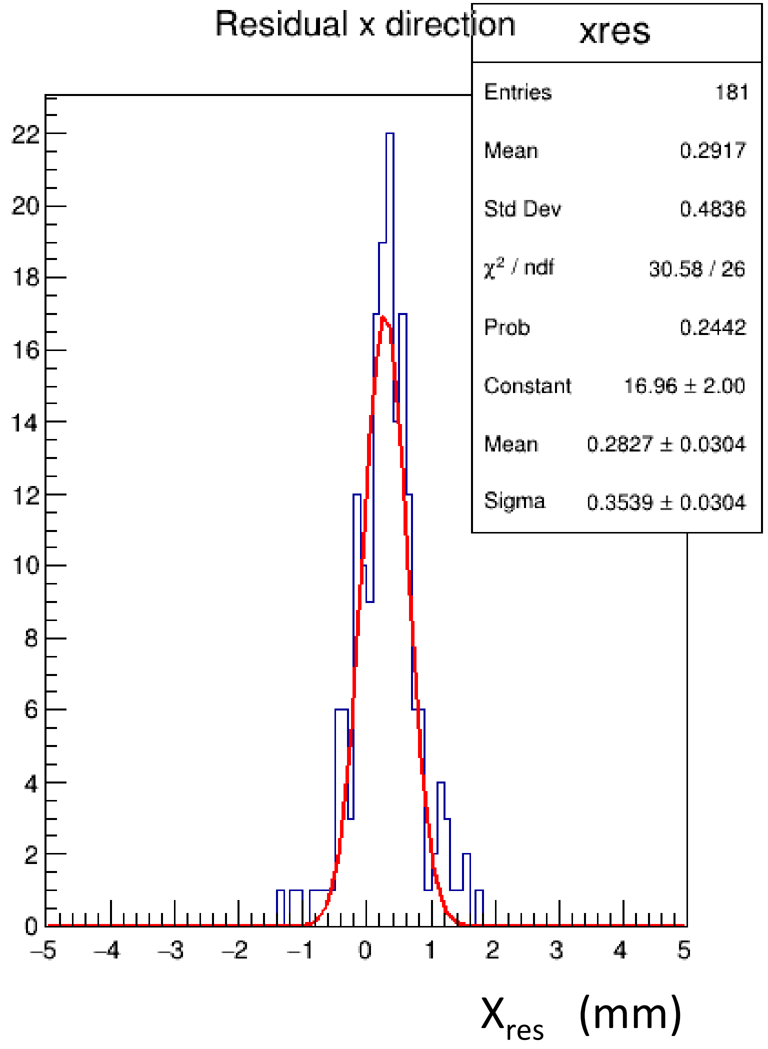


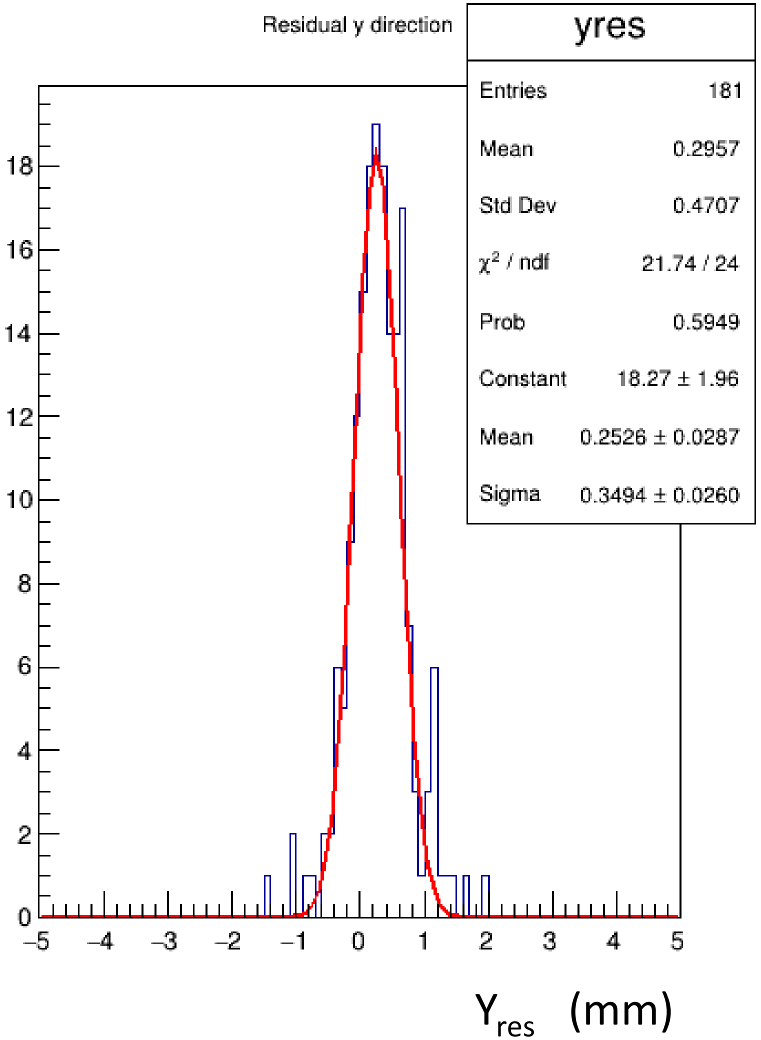


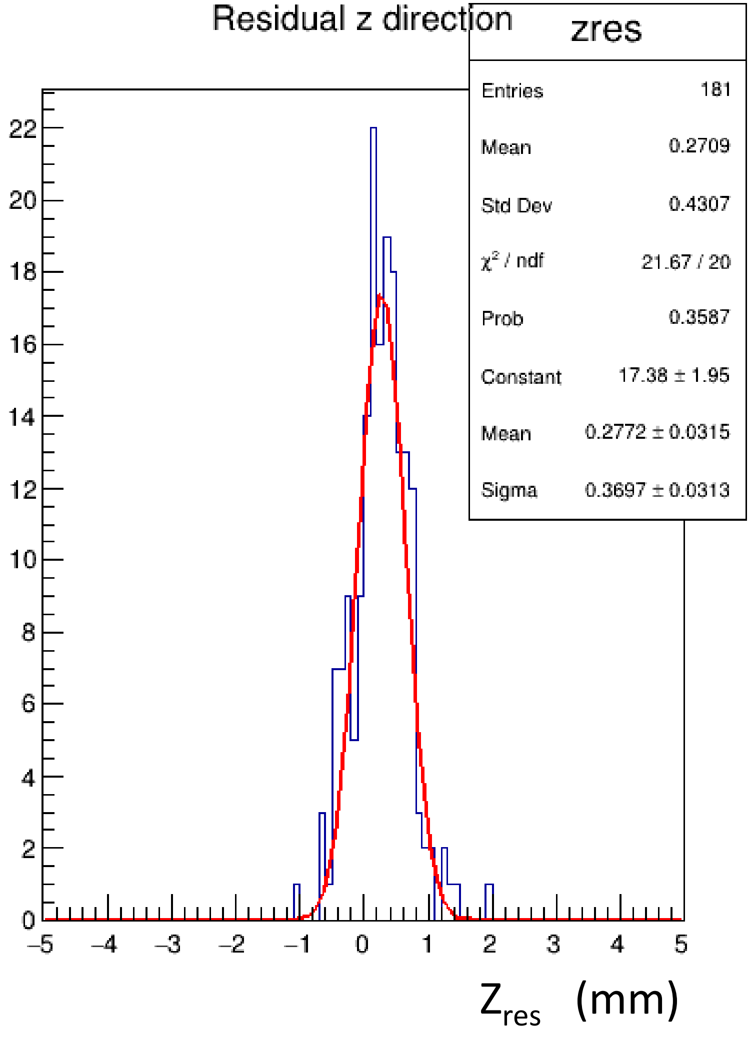


Residuals 0.68 mm!

Residuals for generated points in a cube 30 mm side



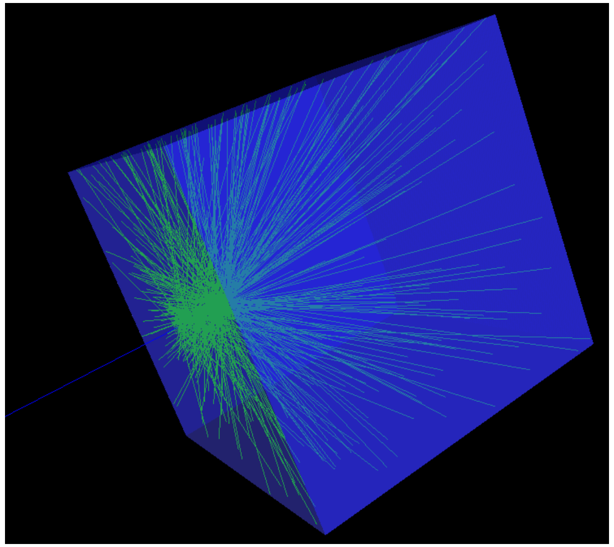




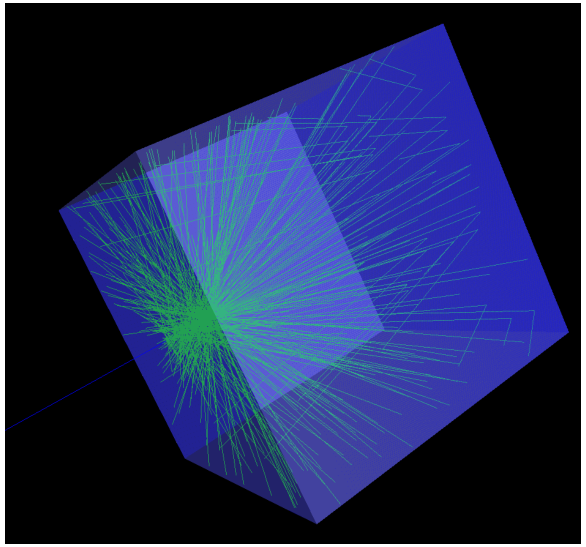
Residuals 0.35 mm!

Geant simulations

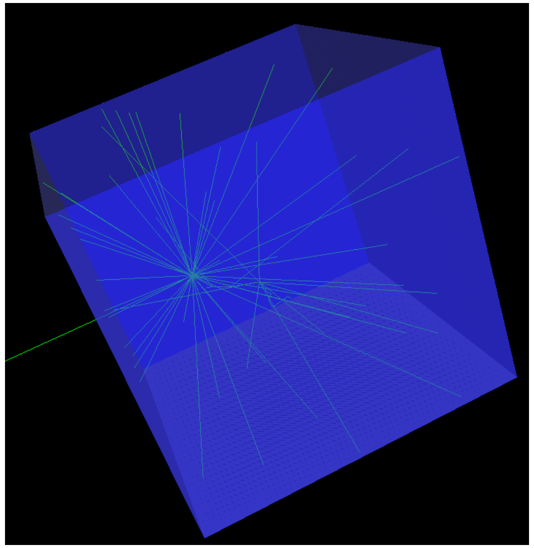
Studio qualitativo (produzione di 10 fotoni/MeV)



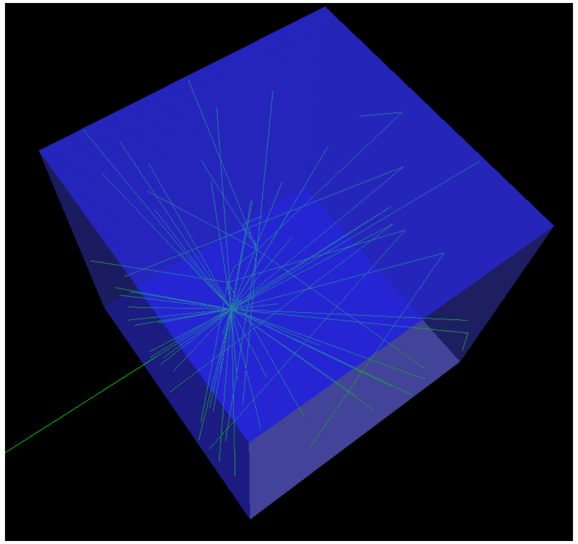
Fascio: protoni 50 MeV
(superficie cubo: assorbente)



Fascio: protoni 50 MeV
(superficie cubo: riflettente)



Fascio: neutroni 5 MeV
(superficie cubo: assorbente)



Fascio: neutroni 5 MeV
(superficie cubo: riflettente)

Studio quantitativo (produzione di 10.000 fotoni/MeV)

Sorgente

- protoni
- 30 MeV
- direzione isotropa
- generazione omogenea in cubo[-1,1]x[-1,1]x[-1,1]

CASO A: 30 eventi di sorgente
CASO B: 100 eventi di sorgente

Cubo di materiale 6x6x6 cm^3

Materiale scintillante: idrogeno puro

Parete esterna assorbente

Produzione di fotoni ottici = 10.000 fotoni/MeV

Risposte archiviate:

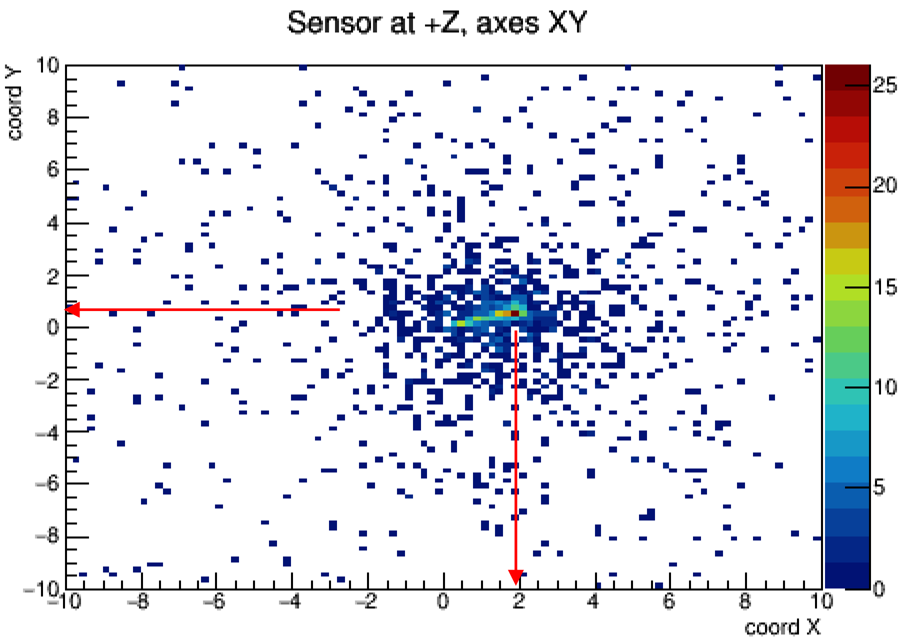
- **Coordinate di sorgente nello spazio delle fasi**
- **Coordinate di attraversamento di ogni fotoni ottico della superficie esterna (punto e versore quantità di moto)**

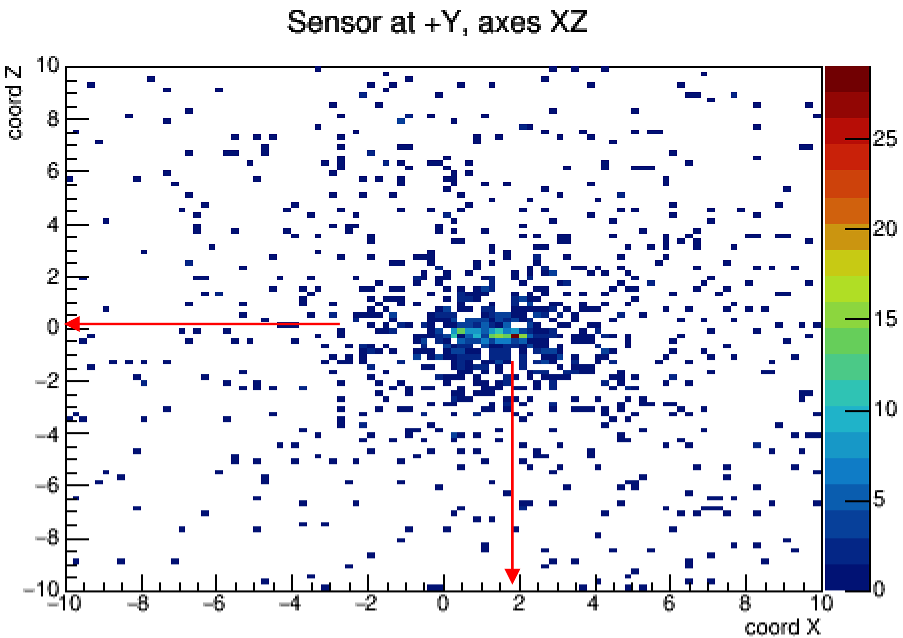
How Geant simulations are used

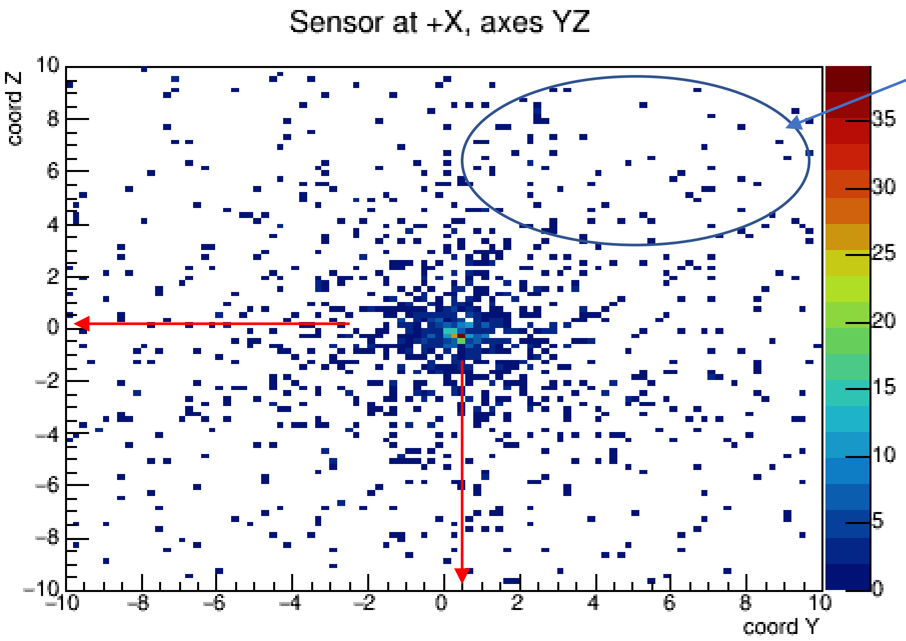
- Many informations for each event; used only the photon ones at the production point (not at the cube surfaces)
- Two samples: 30 and 100 events
- Full tracking of photons from the generation point till the 6 CCD sensors
- Geometry outside the Riptide cube can be changed easily

Geant simulation; Event #1

30 MeV proton events,
Random direction, random starting point
10k photons/MeV
«Standard optics with p/f=3, f = 30 mm, **R = 30 mm**»
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)


Sensor at +Z, axes XY


Sensor at +Y, axes XZ


Sensor at +X, axes YZ

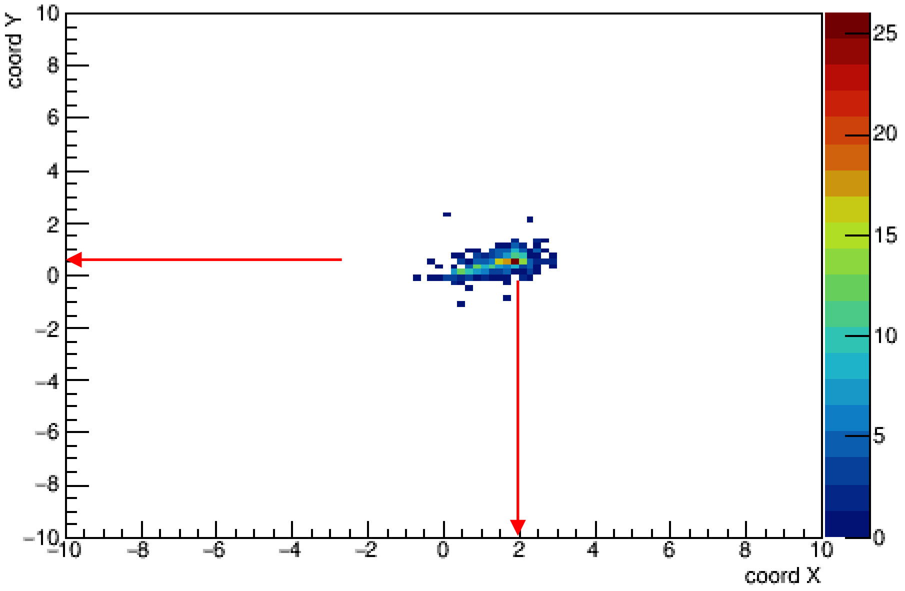
Faraway photons due to **spherical aberration**

About 1440 photons/view

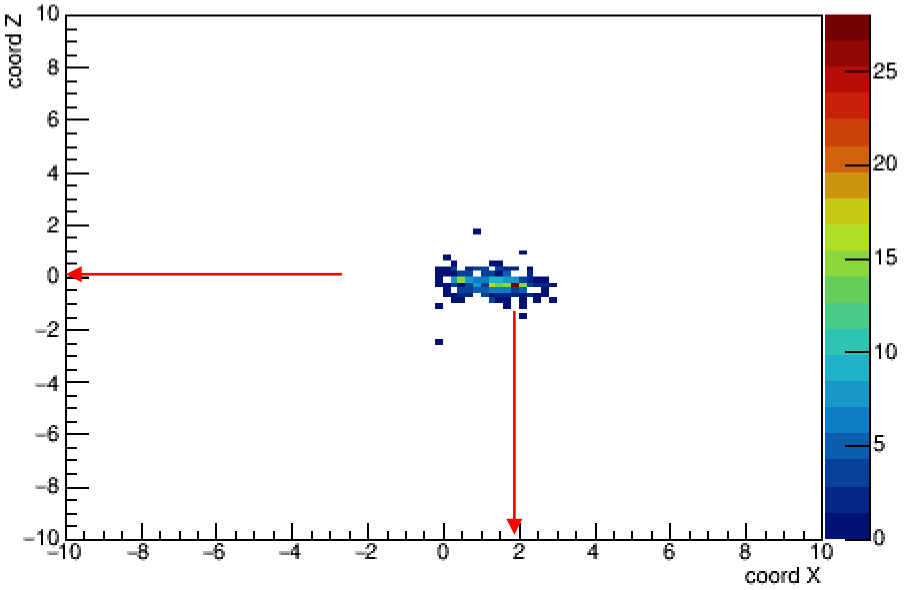
Track barely visible!

Geant simulation; Event #1

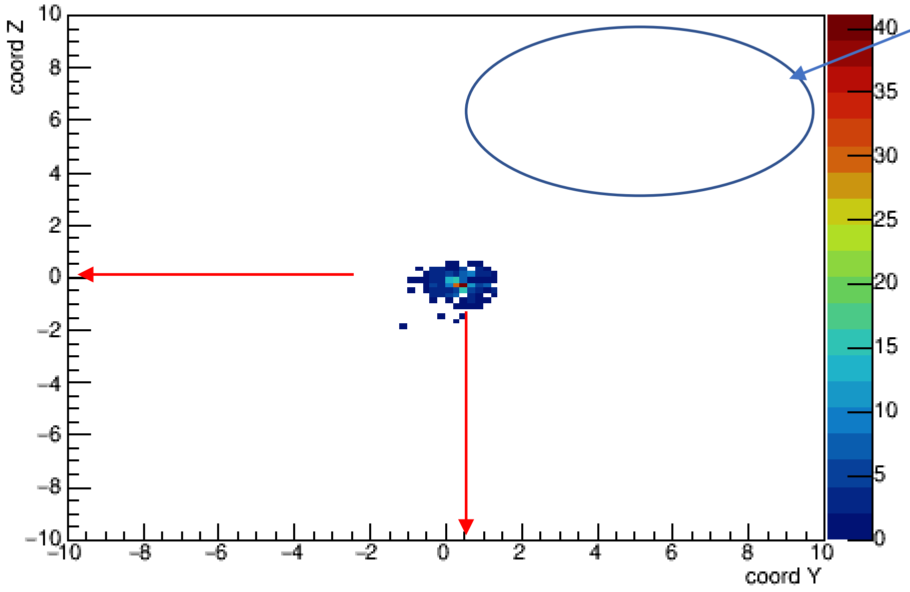
30 MeV proton events,
Random direction, random starting point
10k photons/MeV
«Standard optics with p/f=3, f = 30 mm, **R = 10 mm**»
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)



Sensor at +Z, axes XY



Sensor at +Y, axes XZ



Sensor at +X, axes YZ

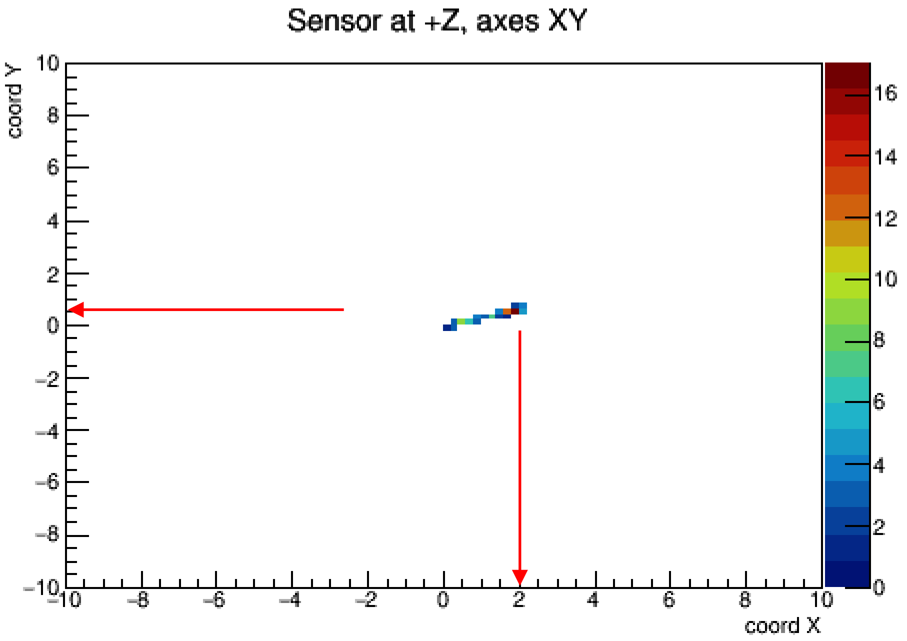
No faraway photons due to **spherical aberration**

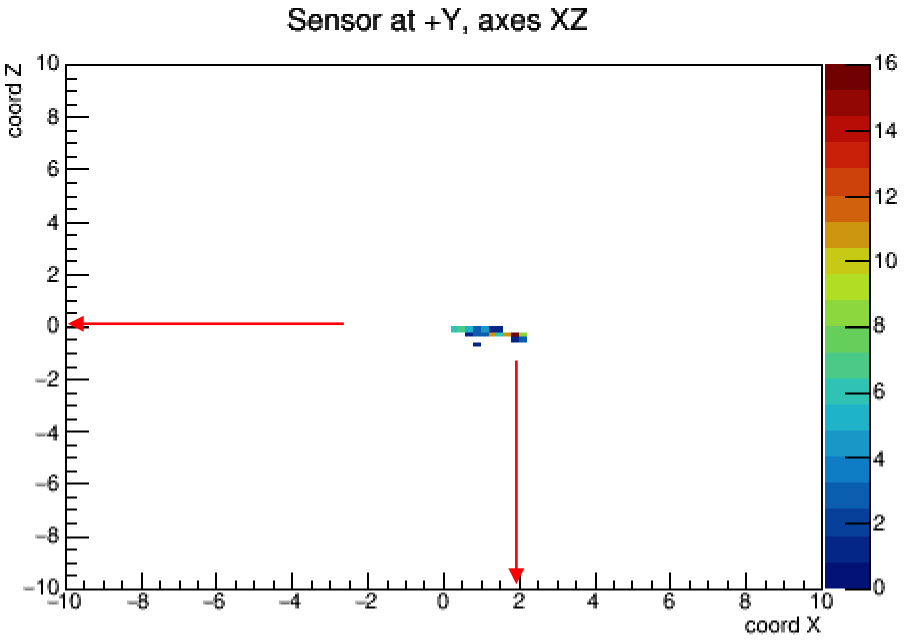
About 340 photons/view!

Track visible!

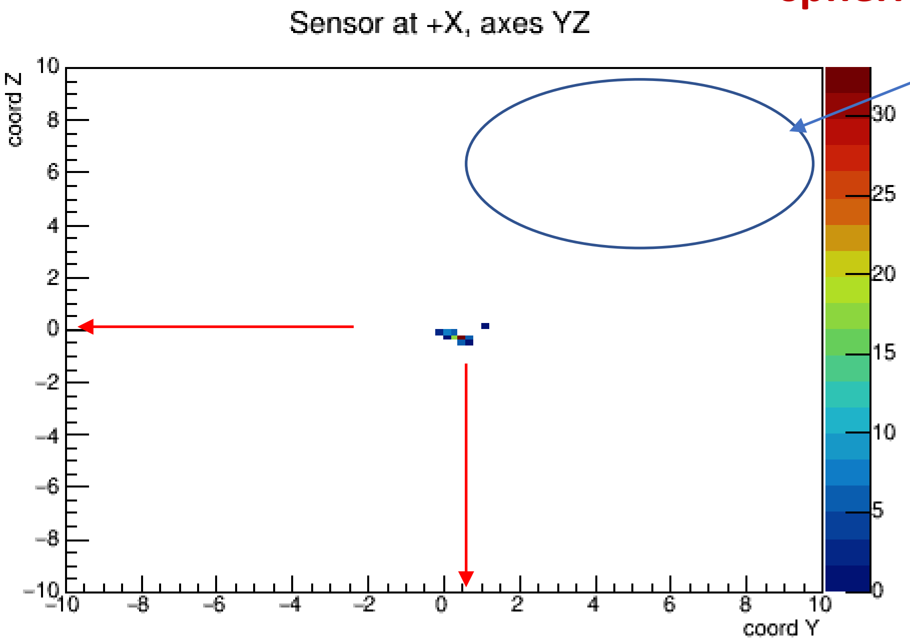
Geant simulation; Event #1

30 MeV proton events,
Random direction, random starting point
10k photons/MeV
«Standard optics with p/f=3, f = 30 mm, **R = 5 mm**»
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)


Sensor at +Z, axes XY


Sensor at +Y, axes XZ

No faraway photons due to **spherical aberration**

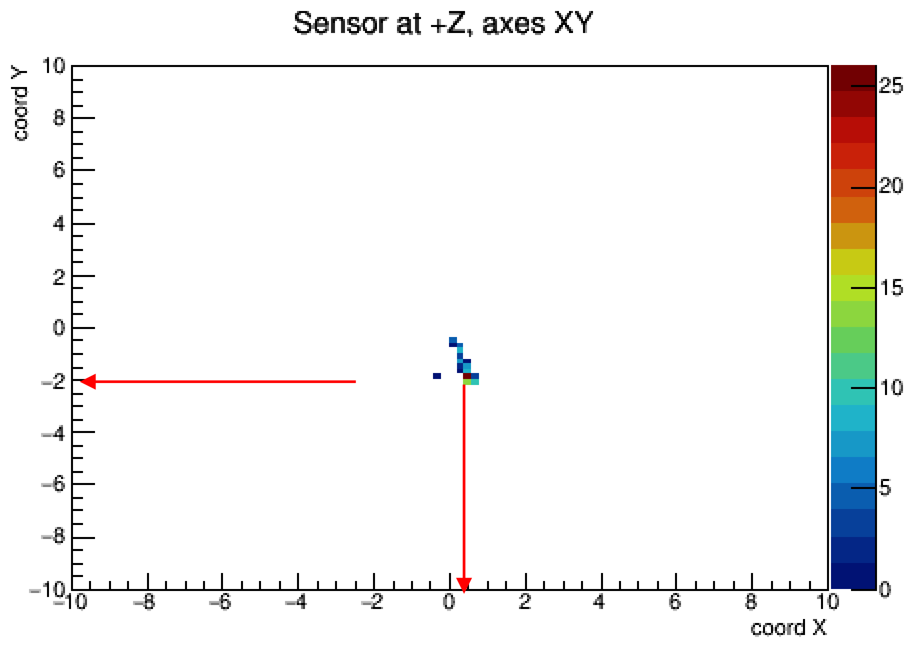

Sensor at +X, axes YZ

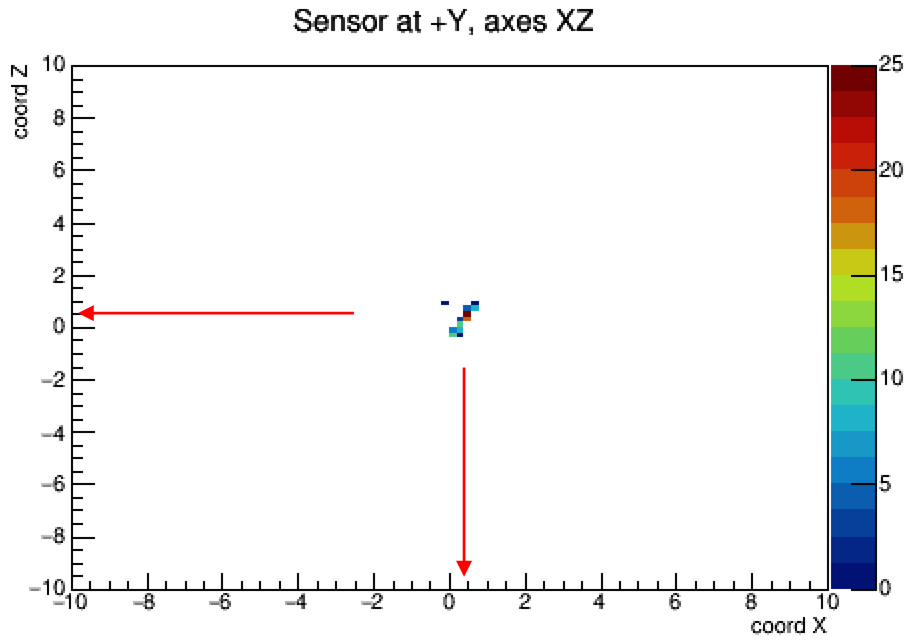
About 80 photons/view!

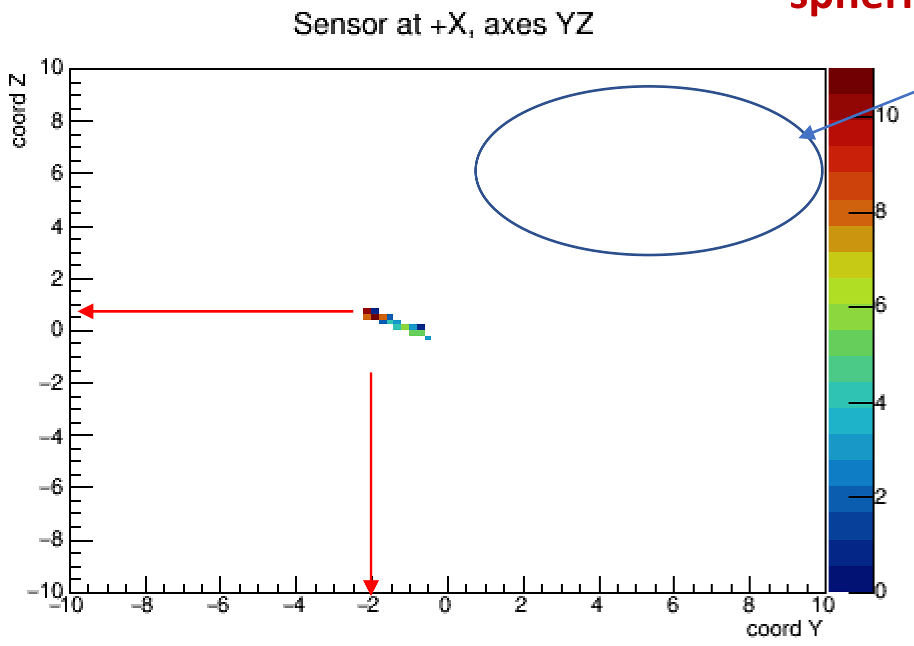
Track clearly visible!

Geant simulation; Event #2

30 MeV proton events,
Random direction, random starting point
10k photons/MeV
«Standard optics with p/f=3, f = 30 mm, **R = 5 mm**»
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)







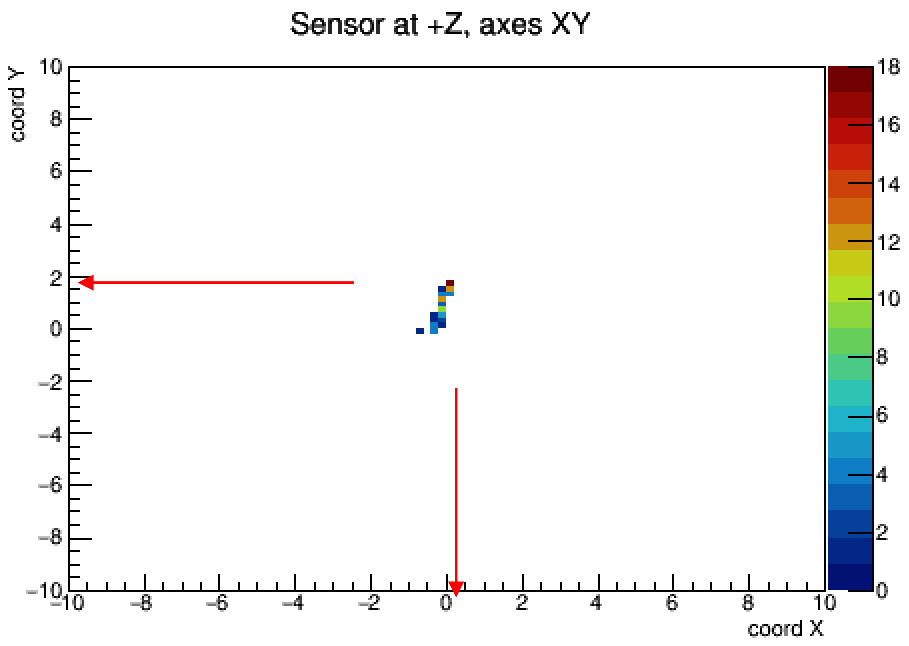
No faraway photons due to **spherical aberration**

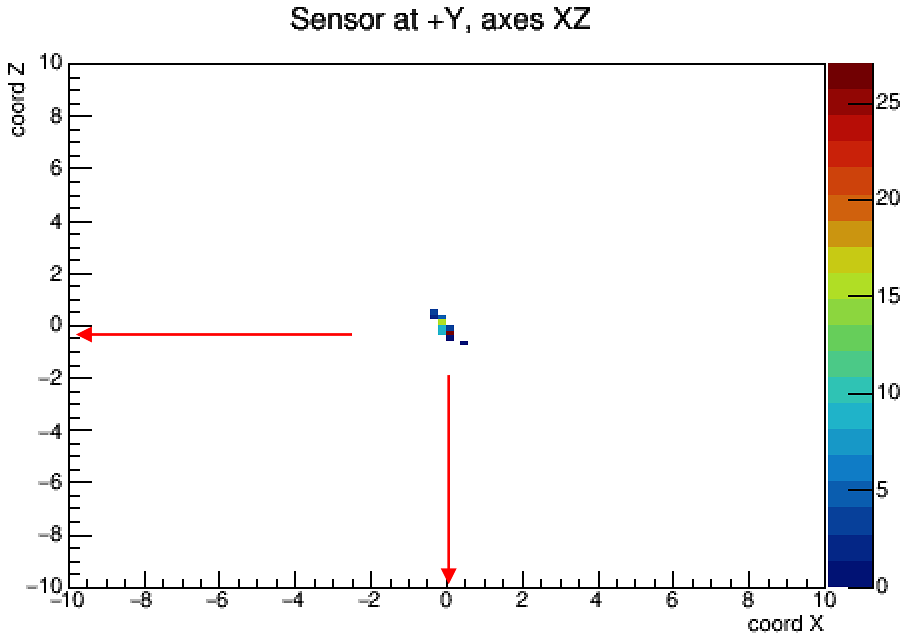
About 80 photons/view!

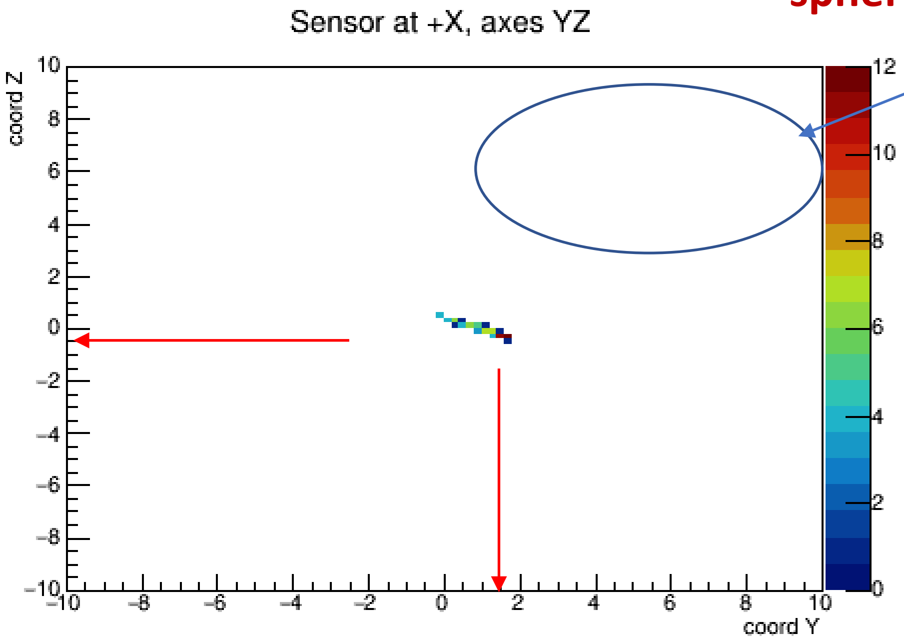
Track clearly visible!

Geant simulation; Event #3

30 MeV proton events,
Random direction, random starting point
10k photons/MeV
«Standard optics with p/f=3, f = 30 mm, **R = 5 mm**»
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)







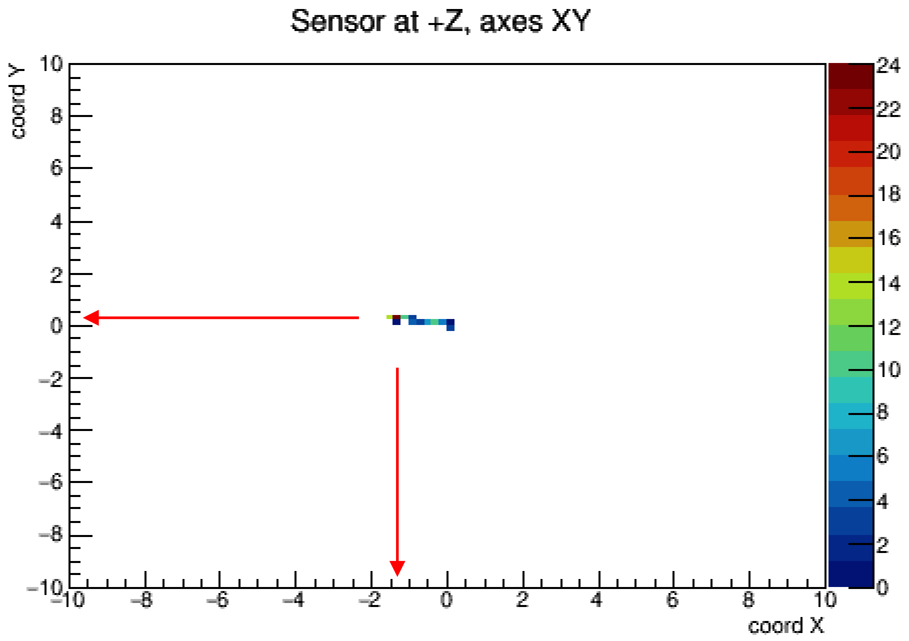
No faraway photons due to **spherical aberration**

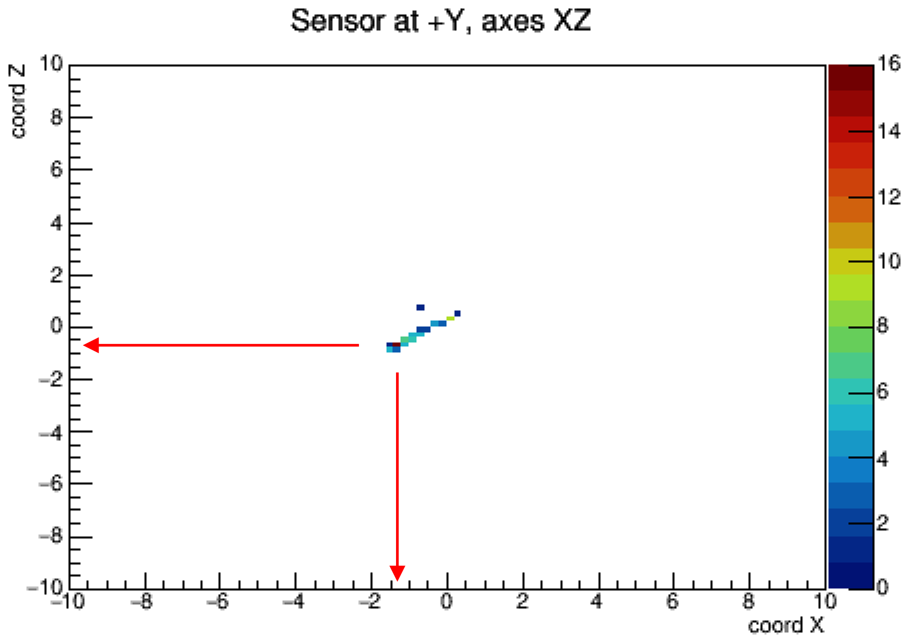
About 80 photons/view!

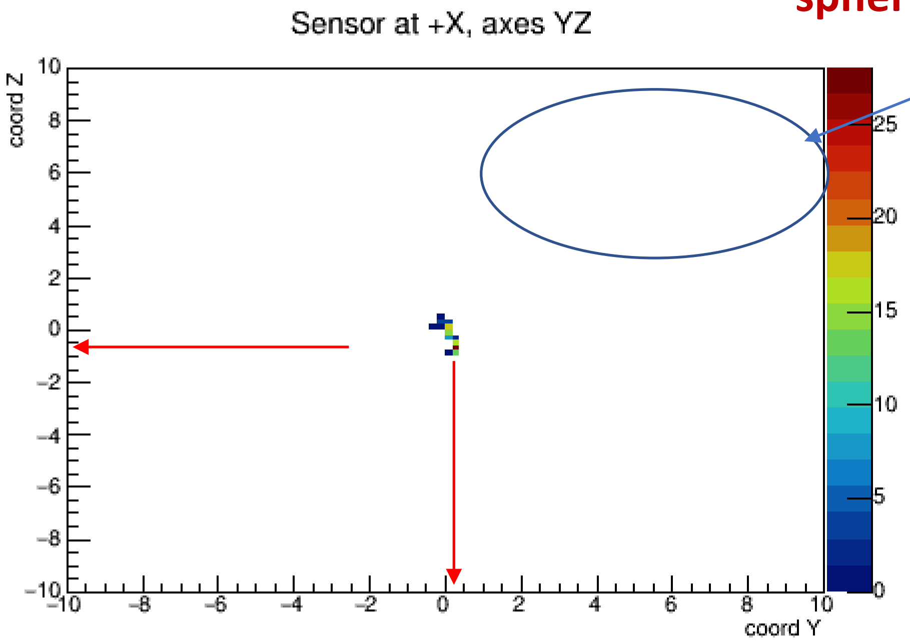
Track clearly visible!

Geant simulation; Event #4

30 MeV proton events,
Random direction, random starting point
10k photons/MeV
«Standard optics with p/f=3, f = 30 mm, **R = 5 mm**»
All units are in mm at the CCD position
(Lens: gain = 0.5, inverting)


Sensor at +Z, axes XY


Sensor at +Y, axes XZ


Sensor at +X, axes YZ

No faraway photons due to **spherical aberration**

About 80 photons/view!

Track clearly visible!

Summary

- A first optical study has been presented
- Good news:
  - First attempts on an optical scheme
  - Point resolutions of 0.35 mm can be achieved (best conditions)
  - Tracks can be seen clearly
- To be studied
  - Optimal R/f and optimal f. Ideally R = cube side/2
    - R=5mm and f=30 mm → R=30 mm → f=180 mm → p = 540 mm (from p/f=3)
  - Track reconstruction → Claudia, Patrizio
  - Position & energy resolution
  - Cube surfaces & material between cube surfaces and lenses
  - Overall efficiencies
- Next steps
  - MC studies with more single neutron tracks