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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

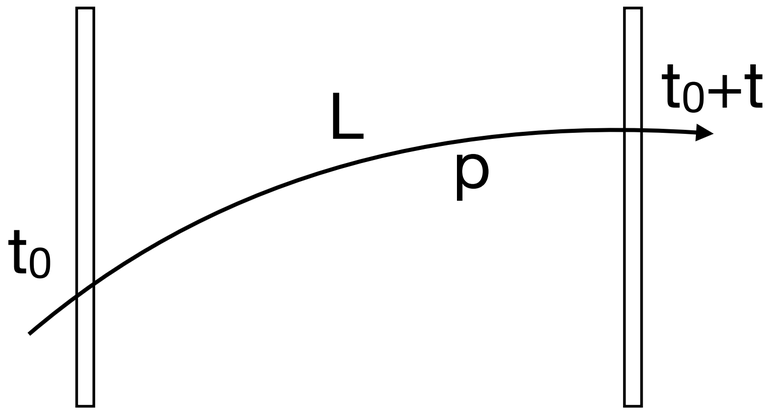
A 10 ps MCP-based time-of-flight detector

Mikhail Barnyakov
INFN Bologna

The 2026 International Workshop on the High-Energy Circular Electron-Positron Collider
21-26 October 2026, Shanghai, China

Introduction

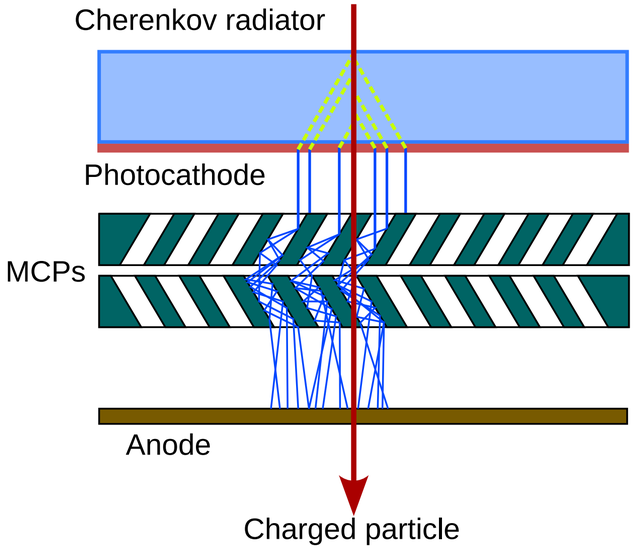
Particle identification by TOF measurement

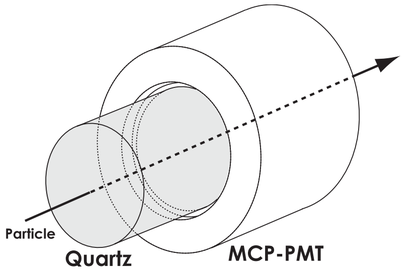


$$\frac{\mathrm{d}m}{m} = \frac{\mathrm{d}p}{p} + \gamma^2\left(\frac{\mathrm{d}t}{t} + \frac{\mathrm{d}L}{L}\right)$$

Time resolution is
the main limiting factor

Time resolution with microchannel plates





K.Inami et al.,"A 5 ps TOF-counter with an MCP–PMT", NIM A560(2006)303

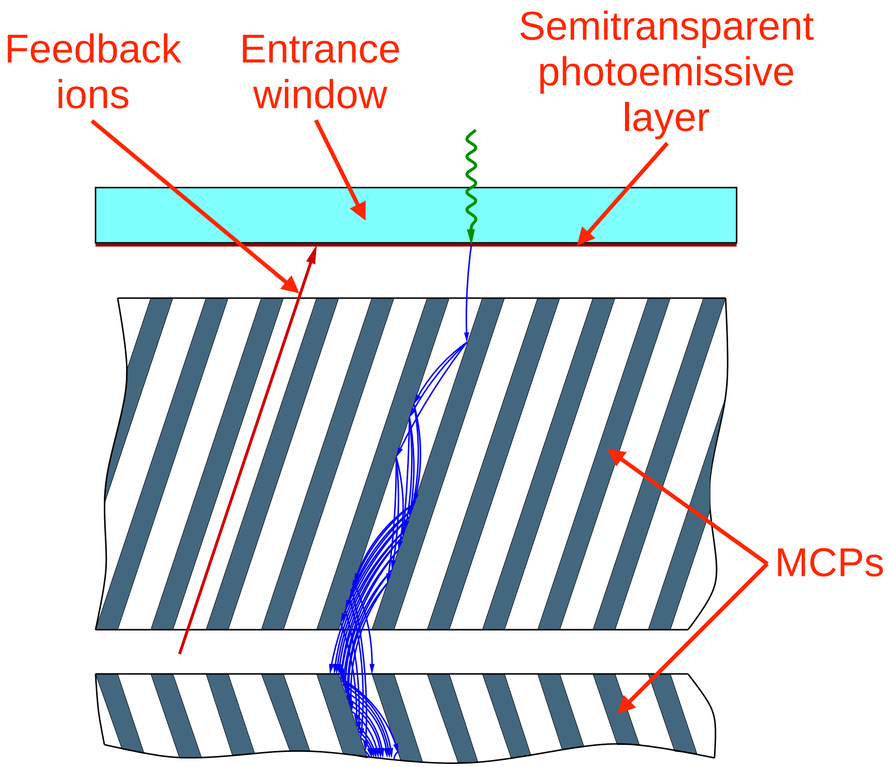
We are trying to improve this approach by:

- using robust CsI photocathode
- using photocathode geometries which improve lifetime

M. Barnyakov et al.,
JINST 21 (2026) C05021

Photocathode layouts

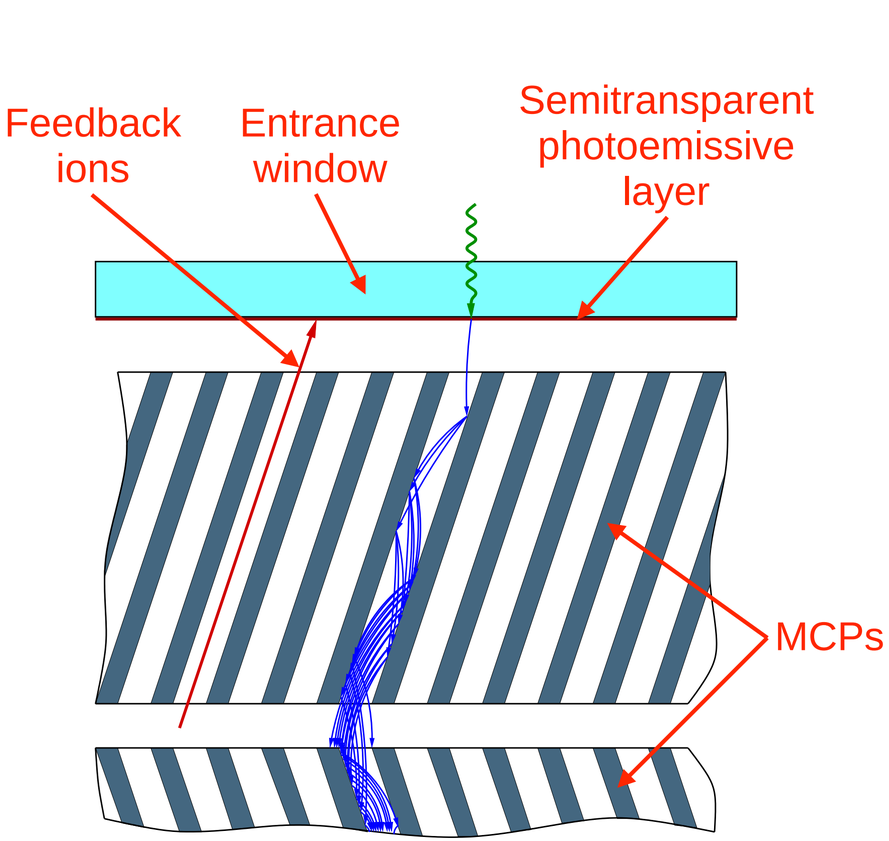
Semitransparent photocathode



Positive feedback ions from MCPs are the main cause of the photocathode ageing

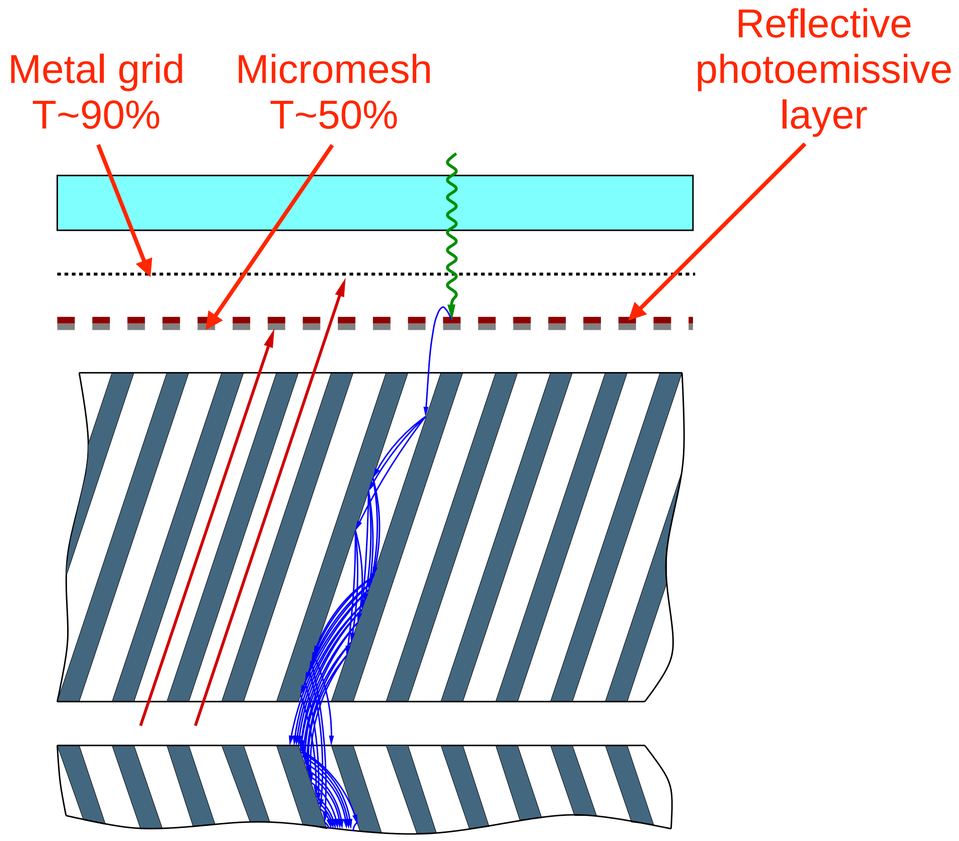
Photocathode layouts

Semitransparent photocathode



Positive feedback ions from MCPs are the main cause of the photocathode ageing

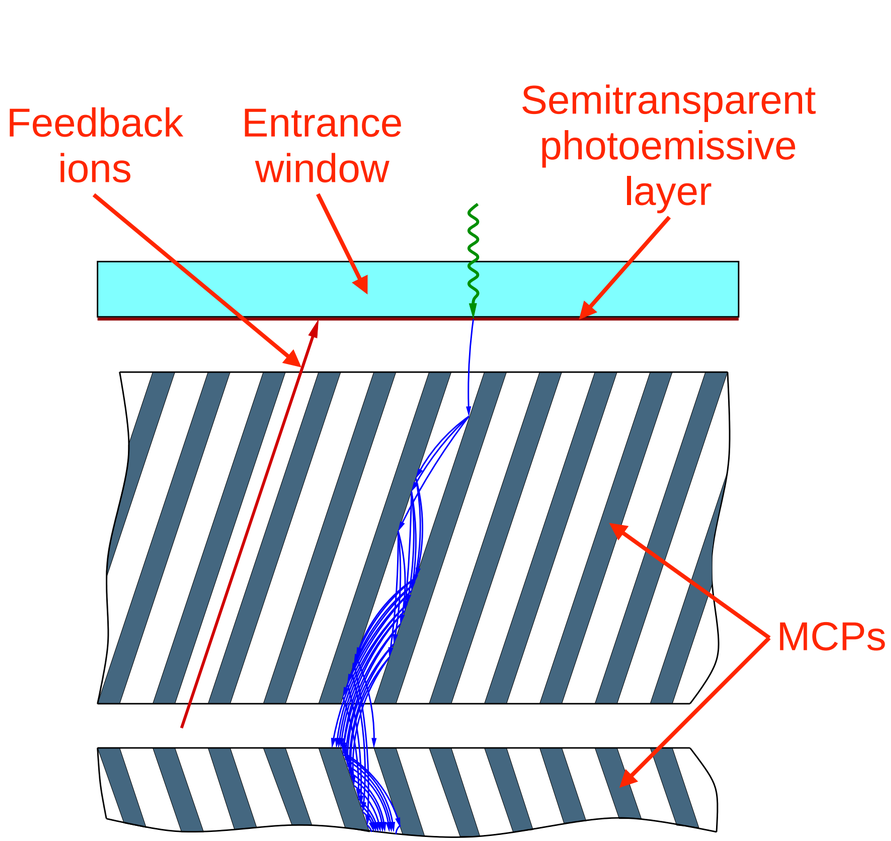
Mesh photocathode



George R. Carruthers, "Mesh-based semitransparent photocathodes," Appl. Opt. 14, 1667-1672 (1975)

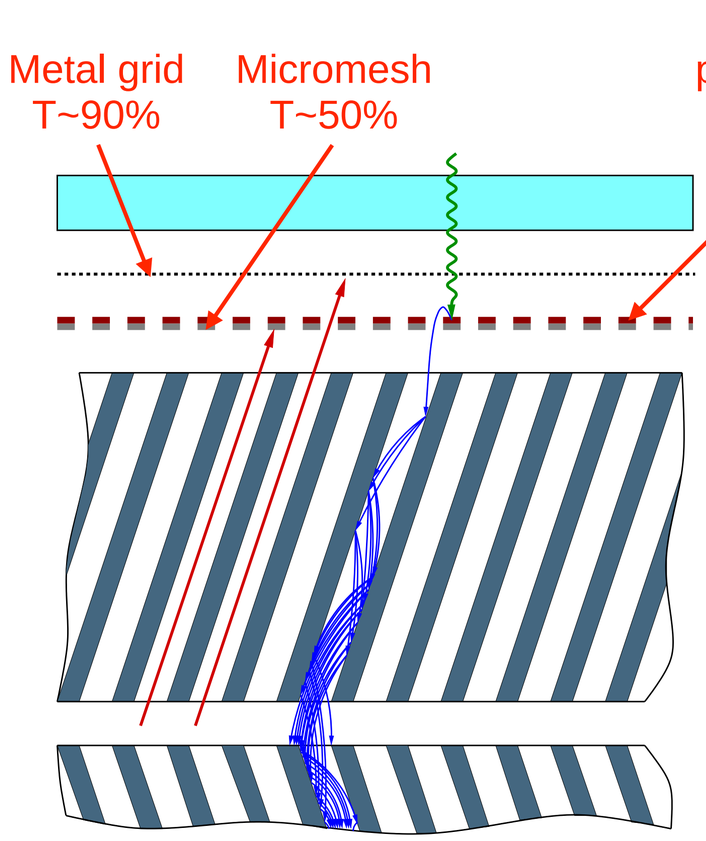
Photocathode layouts

Semitransparent photocathode



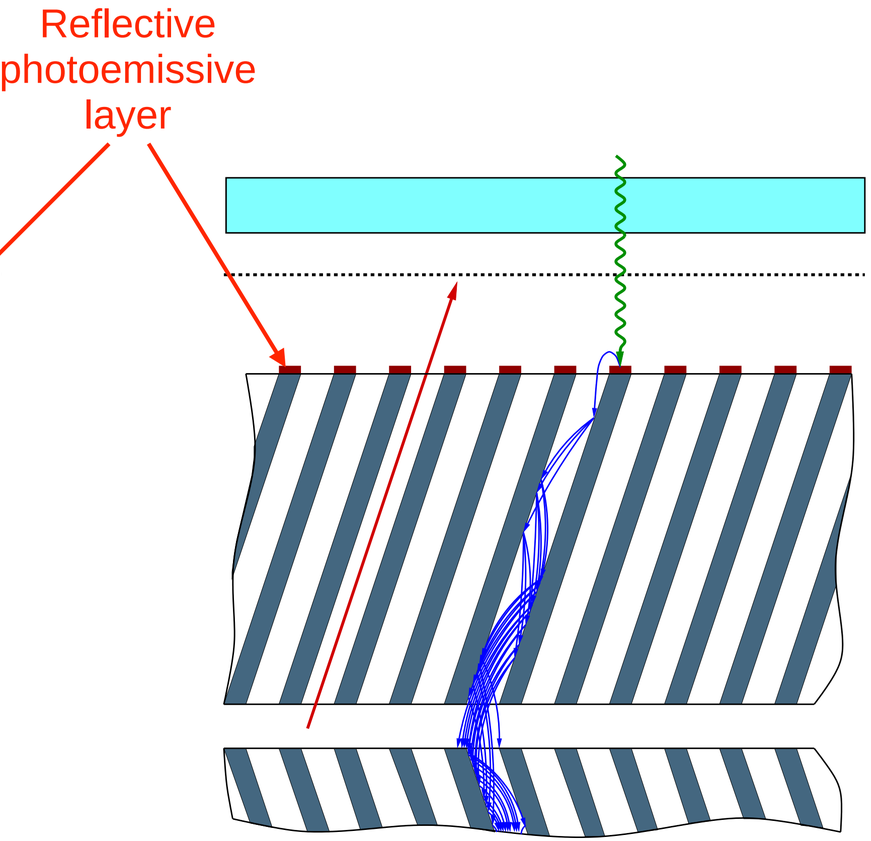
Positive feedback ions from MCPs are the main cause of the photocathode ageing

Mesh photocathode



George R. Carruthers, "Mesh-based semitransparent photocathodes," Appl. Opt. 14, 1667-1672 (1975)

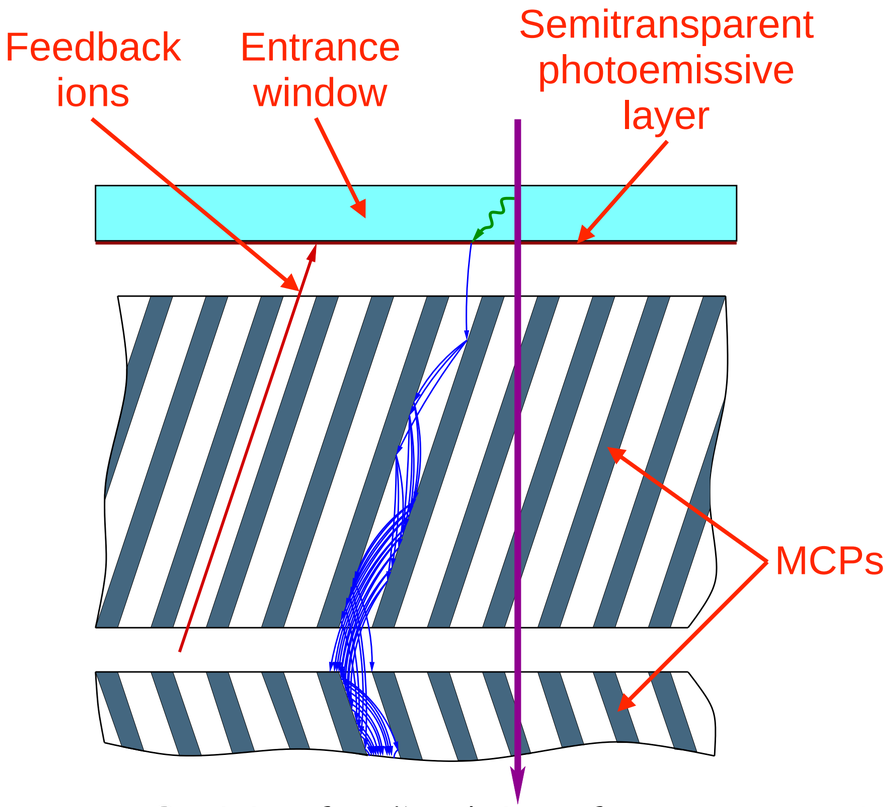
Photocathode on MCP



Used mainly to enhance the sensitivity of MCP for UV imaging application

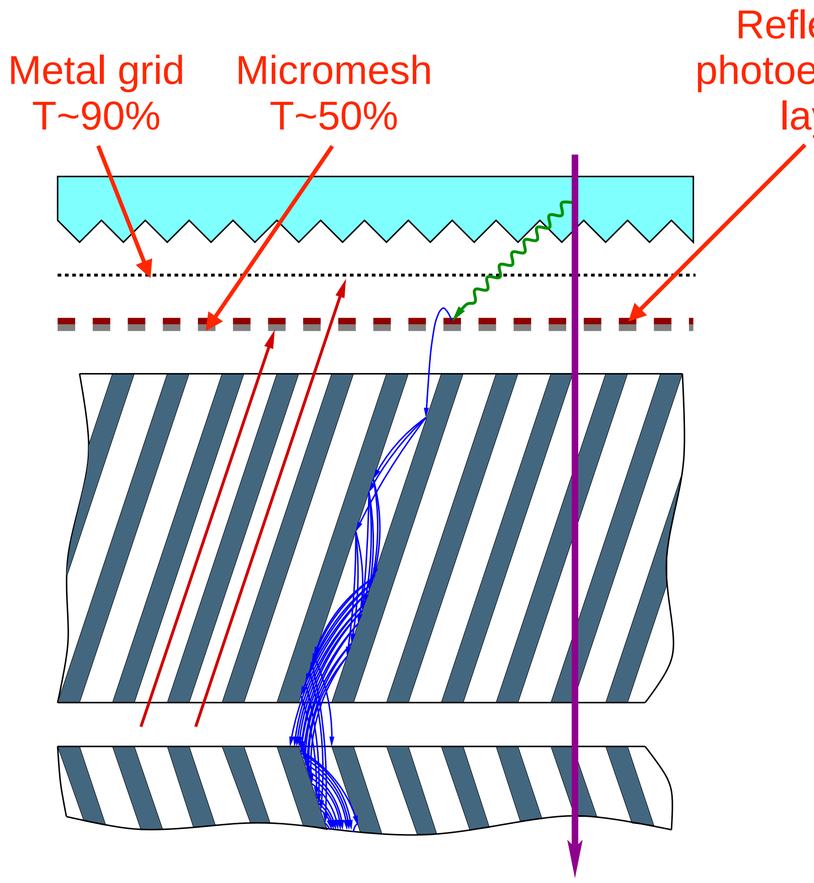
Photocathode layouts

Semitransparent photocathode



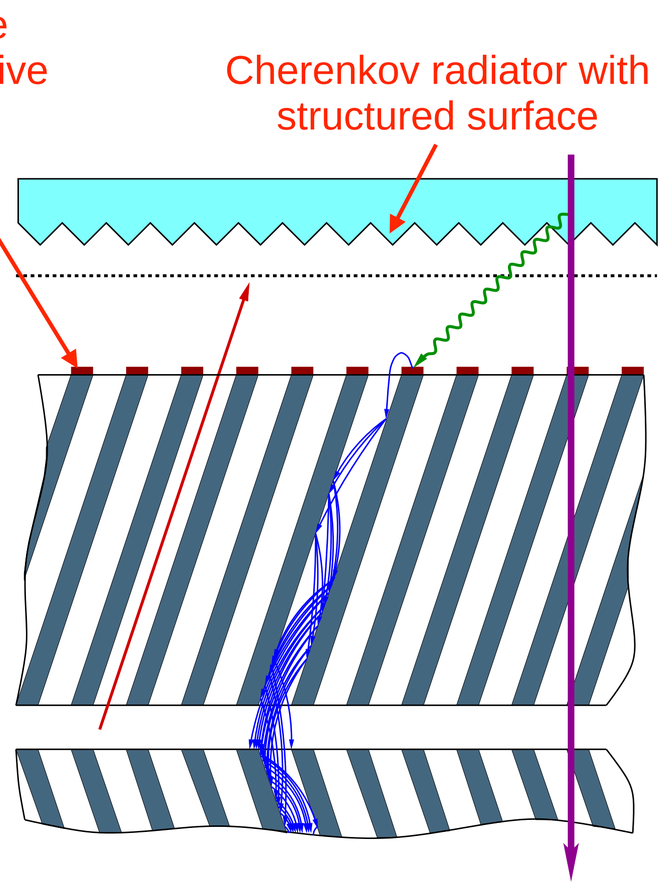
Positive feedback ions from MCPs are the main cause of the photocathode ageing

Mesh photocathode



George R. Carruthers, "Mesh-based semitransparent photocathodes," Appl. Opt. 14, 1667-1672 (1975)

Photocathode on MCP



Structured inner surface of the Cherenkov radiator to allow photons to escape

CsI photocathode

CsI photocathode pros:

- Easy to manufacture
- Easy to maintain and manipulate
- Can work in moderate vacuum
- May have longer lifetime due to better chemical stability (worth checking)

CsI photocathode cons:

- Needs VUV transparent optics
  => Cherenkov radiators made from MgF_2
- There is not a picosecond light source for VUV
  => time measurements with particle beam

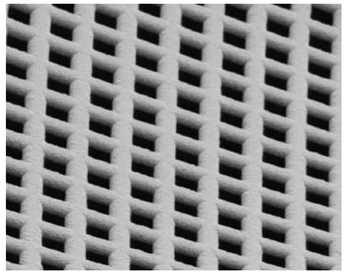
PVD setup in Bologna made by Zhengzhou CY Scientific Instrument Co., Ltd.:

- 4 resistive evaporators
- rotating sample table
- film thickness monitor

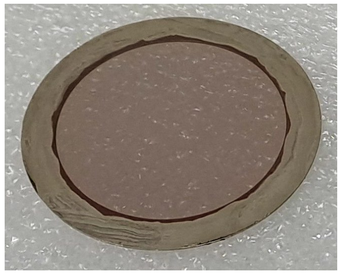


Mesh CsI photocathode

- CsI is deposited onto Ni meshes produced by Precision Eforming, LLC
- Mesh is bonded to the round frame of ⌀33 mm
- Best results are obtained for the mesh of 1000 lines per inch (□25 μm sell)
- CsI layer thickness 0.2 - 1 μm



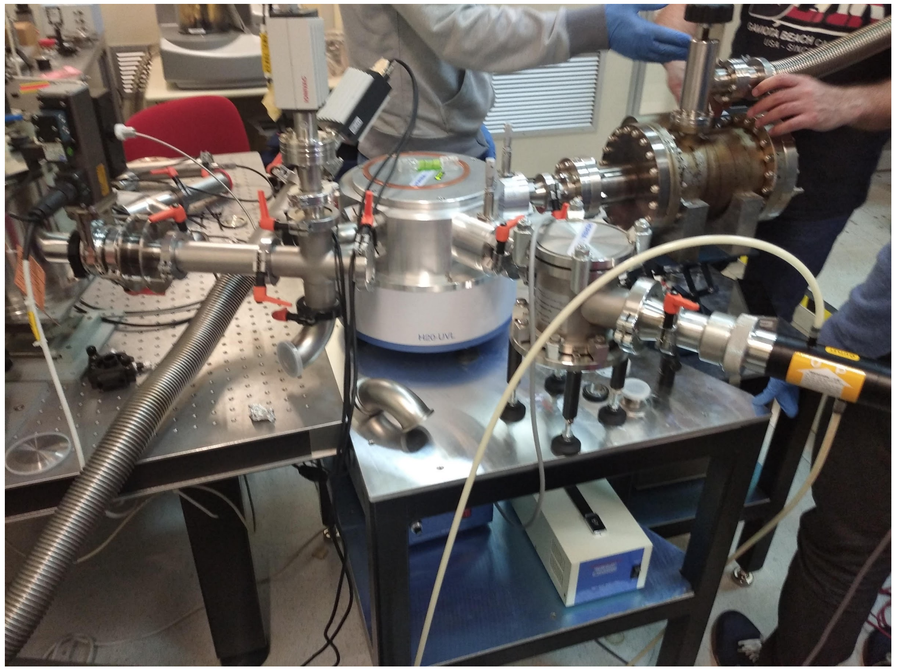
Microphotograph of an electroformed mesh

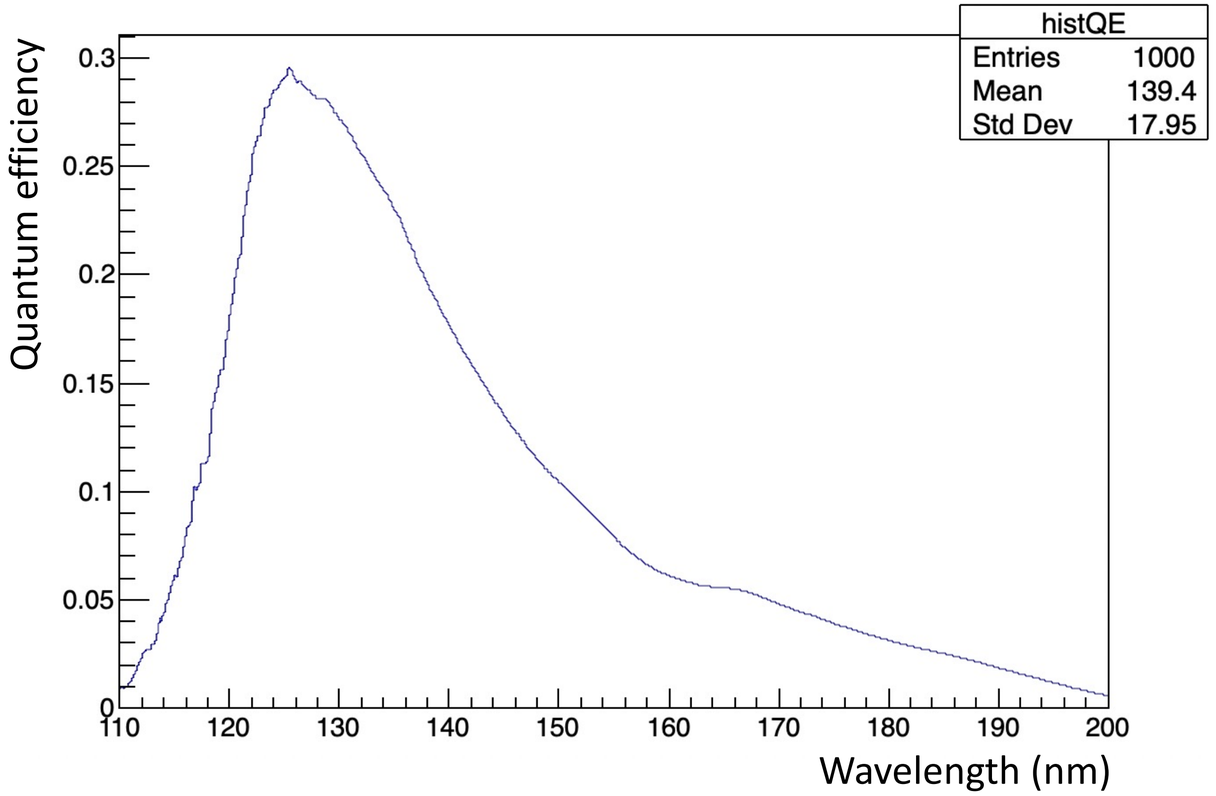


The mesh bonded to the frame

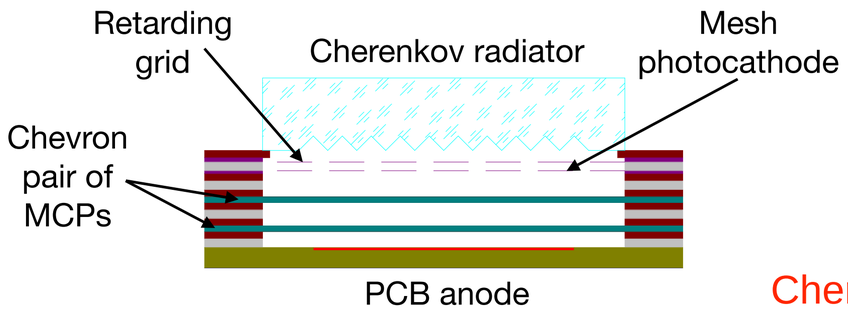
QE was measured at LNF using:

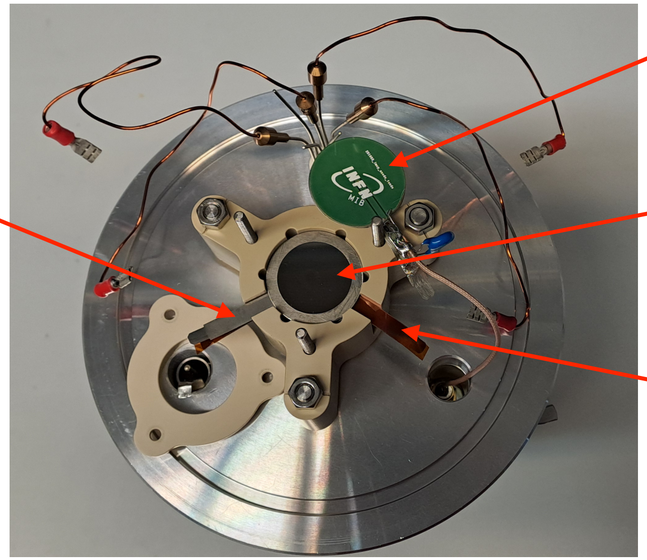
- vacuum monochromator Horiba H20-UVL
- deuterium lamp as a light source
- NIST calibrated Si photodiode

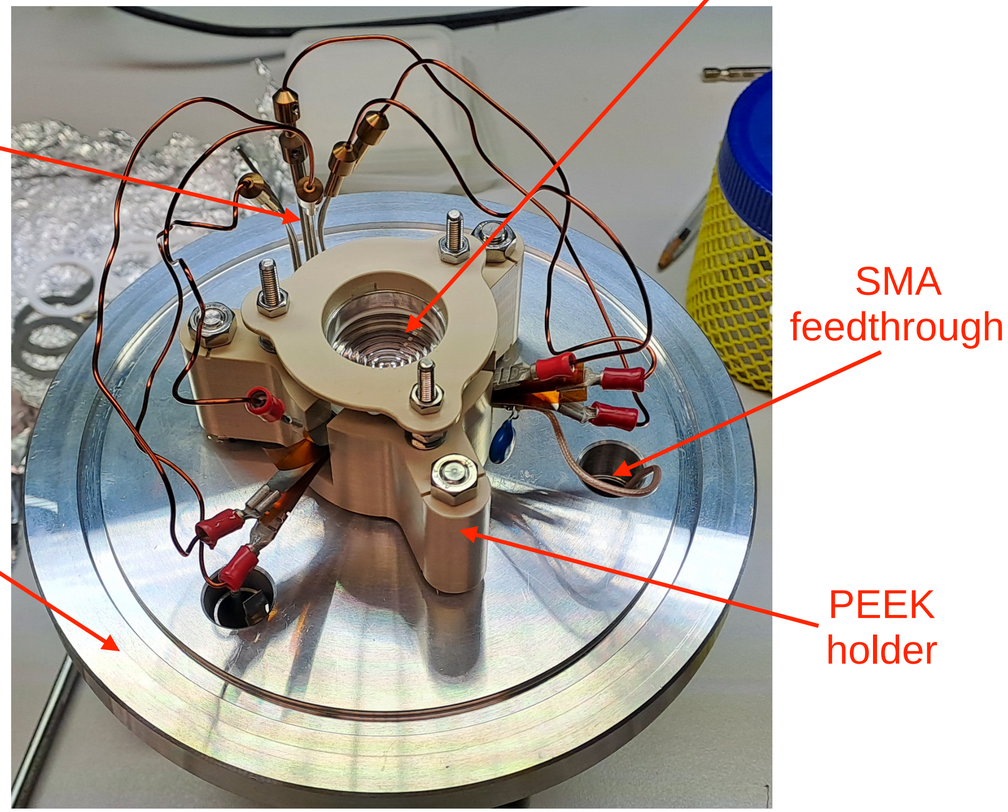


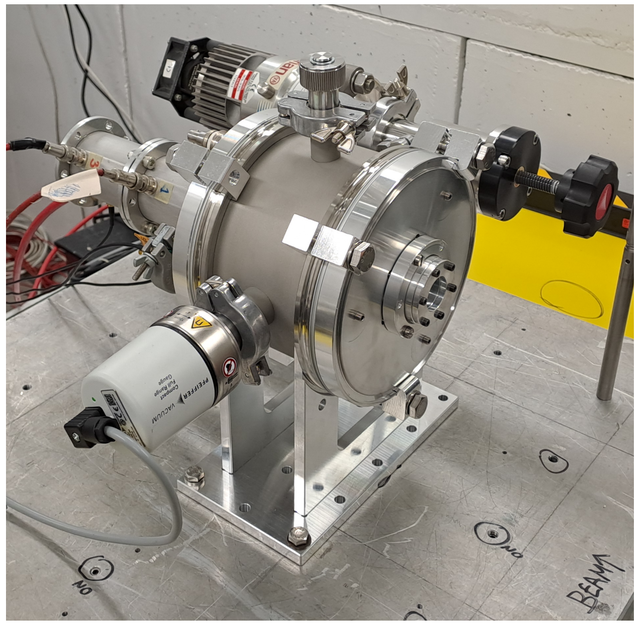


Prototype



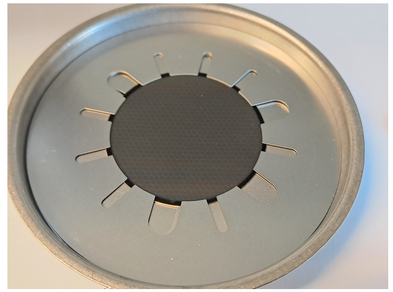






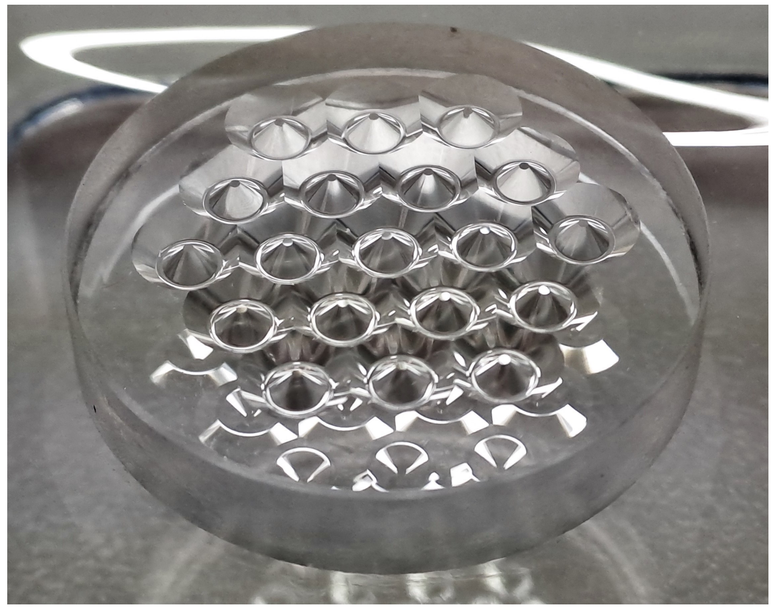
MCPs used:

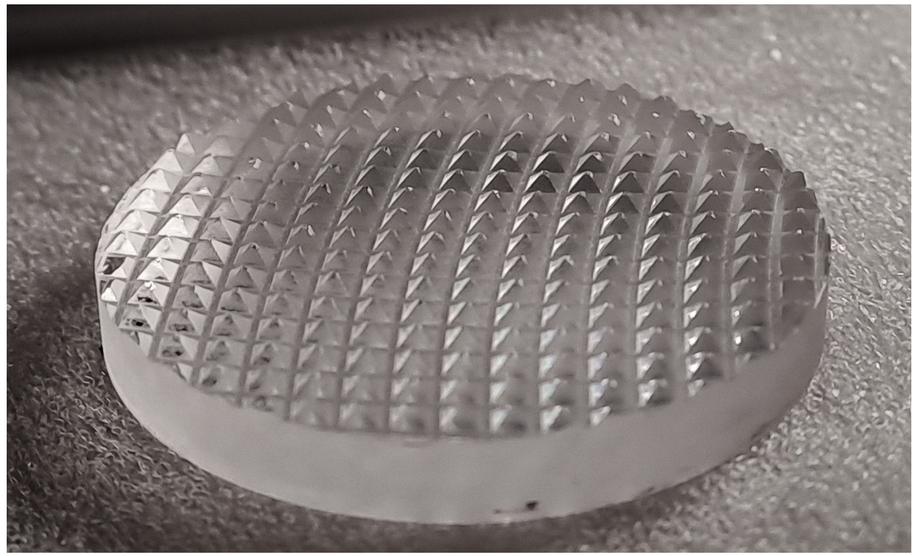
- 33 mm total diameter
- 10 μm pore diameter
- Incom (ALD) and Hamamatsu (lead glass) are tested



Cherenkov radiators

- Magnesium fluoride disks of 25 or 33 mm diameter and the thickness from 4 to 7 mm
- Surface is machined by Wielandts Upmt using diamond turning cut
- Structures with 2 mm pitch and 1 mm depth => 45° between surface and the particle track







Cones:
+ Good light output
- Slow/expense manufacturing

Pyramids:
+ Fast machining
- High probability of cracks
- Poor surface quality

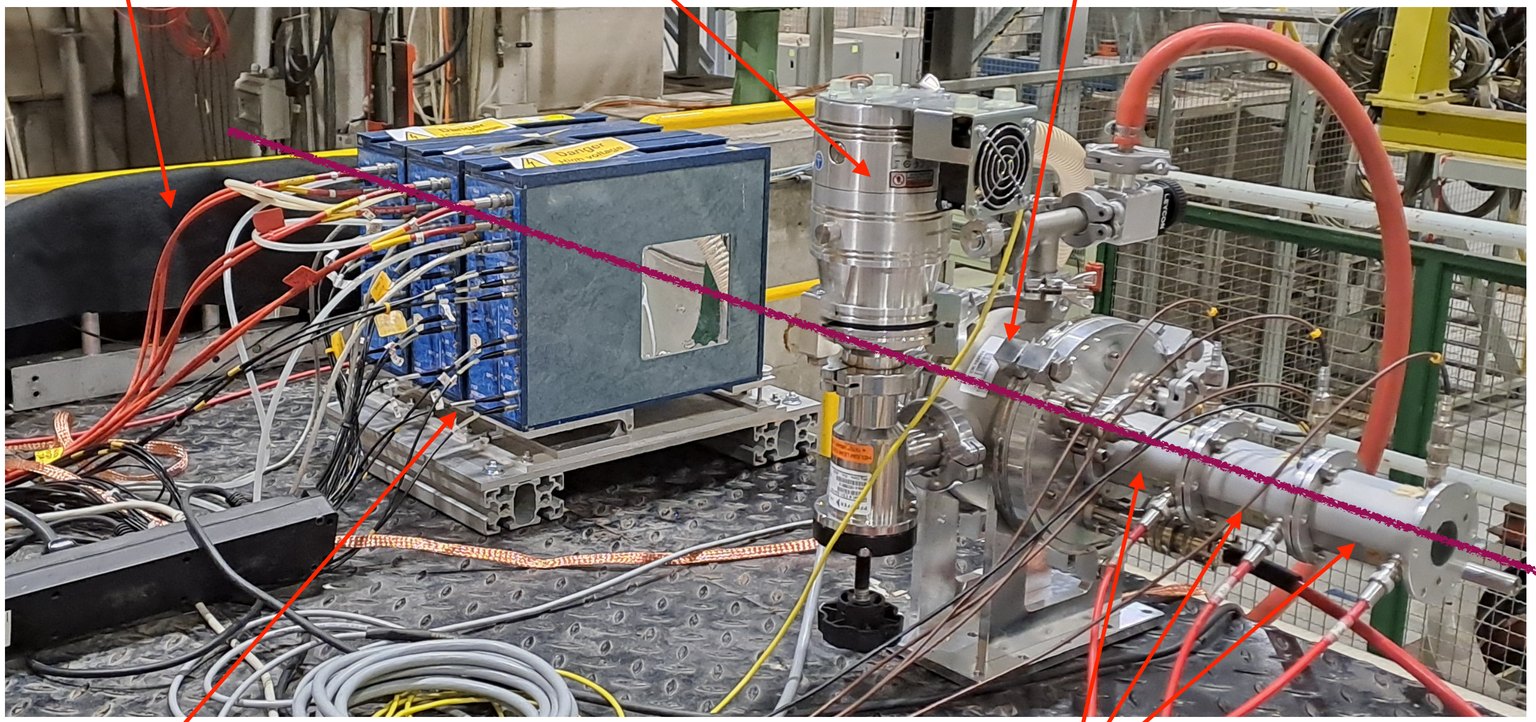
Circles:
+ Good light output
+ Reasonable manufacturing complexity

Test beam setup

Trigger counters

Turbo-molecular pump

Prototype (pressure ~5×10^{-6} mbar)



MIPs

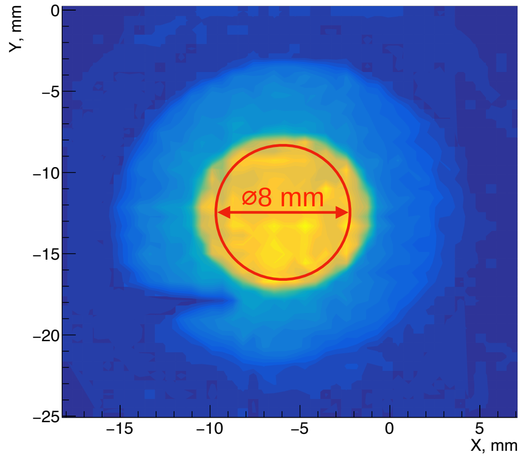
Latest test in October 2025 at SPS H8 with 180 GeV/c hadron beam (p^+, π^+)



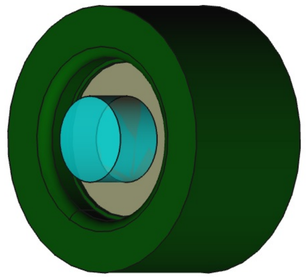
Signals are digitized by CAEN V1742 based on DRS4 chip:
- -500 MHz bandwidth
- -5 GS/s sampling
- -12 bit ADC

Intrinsic time resolution of properly calibrated DRS4 ~2 ps

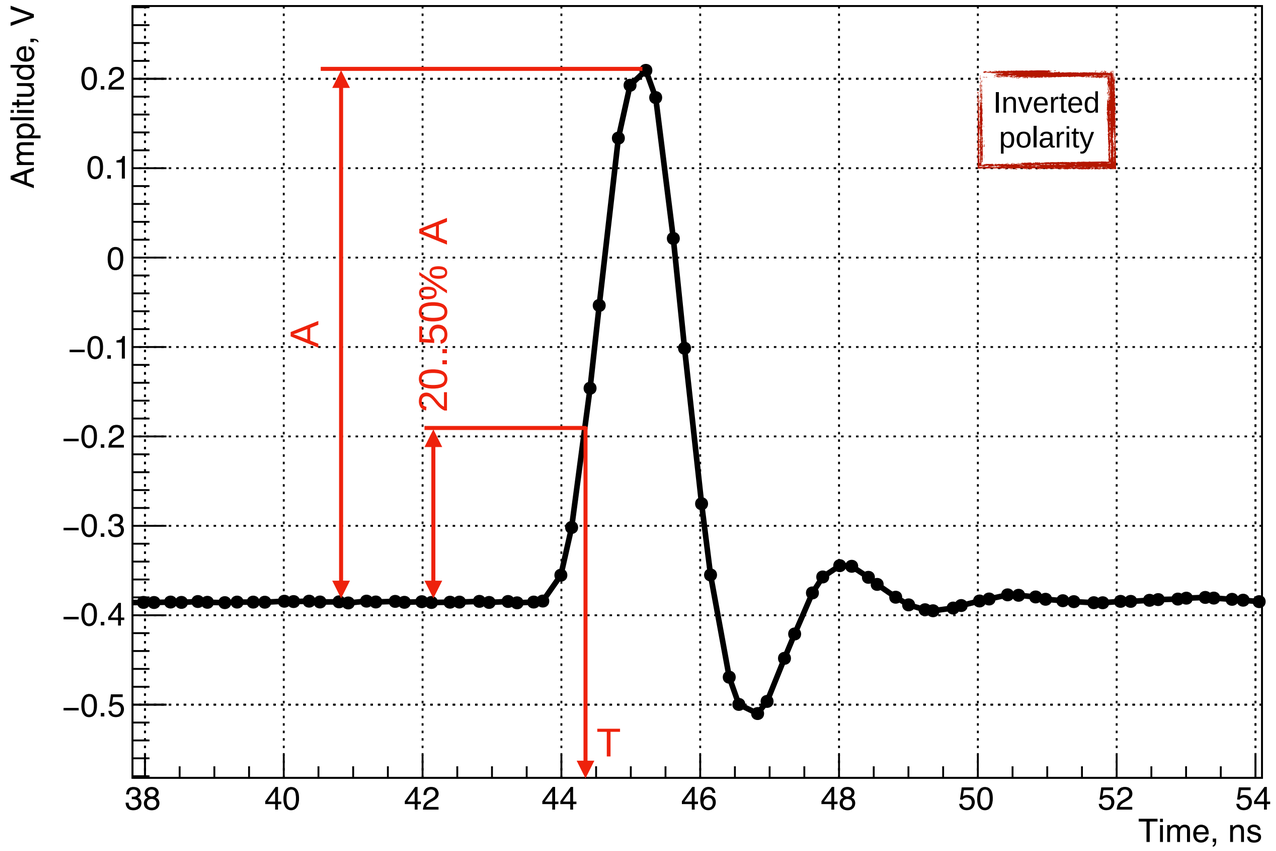
Delay wire chambers



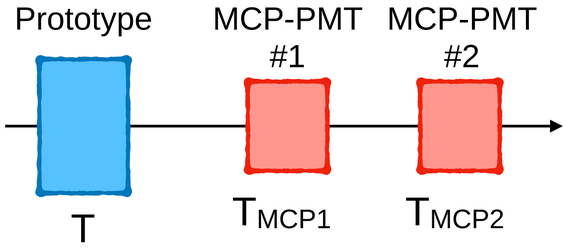
The MCP-PMTs coupled with PMMA radiator of ø10 mm for reference time measurement



Time measurement



- Time is measured by constant fraction discriminator algorithm
- Optimal CFD level is 20 to 50%

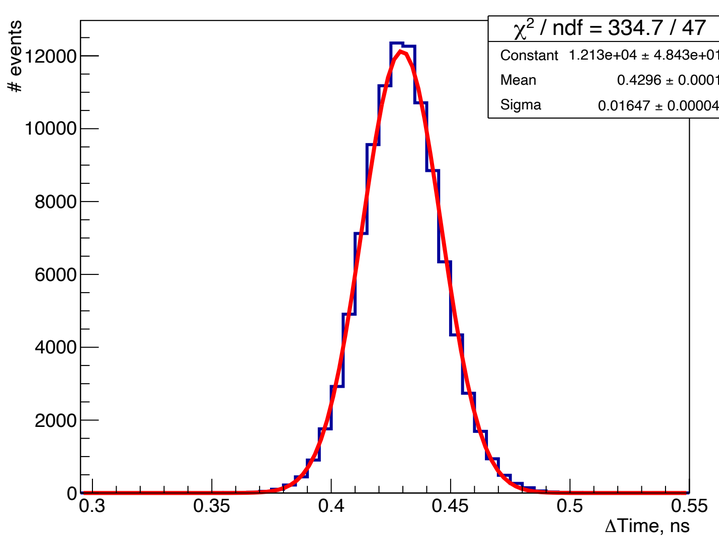


Using of two MCP-PMTs allows to evaluate the contribution of the reference time uncertainty to the measured time resolution of the prototype.

Prototype time with respect to the reference time: $T_{PROT} = T - T_{ref}$

Reference time: $T_{ref} = (T_{MCP1}+T_{MCP2}) / 2$

Dispersion of the time difference between two MCP-PMTs: $\sigma_{diff} \approx 16.5$ ps



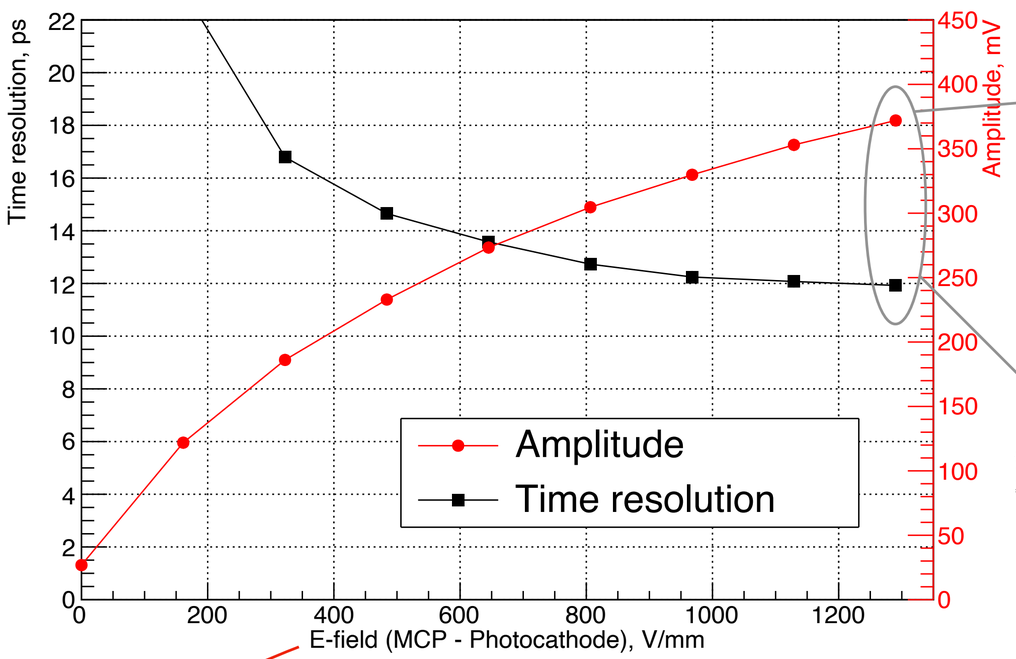
=> Time resolution of each (identical) MCP-PMT: $\sigma_{diff} / \sqrt{2}$

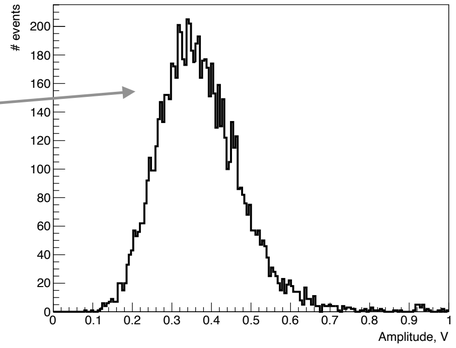
=> Time resolution of the reference time: $\sigma_{ref} = \sigma_{diff} / \sqrt{2} / \sqrt{2} \approx 8$ ps

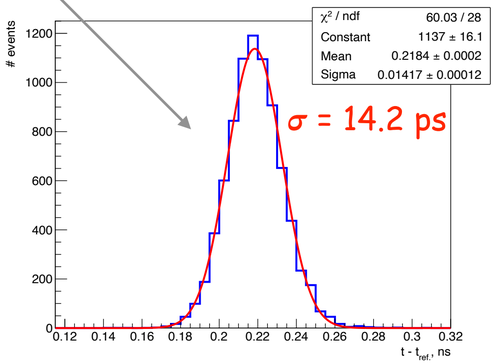
Subtraction of the reference time contribution to the intrinsic time resolution:

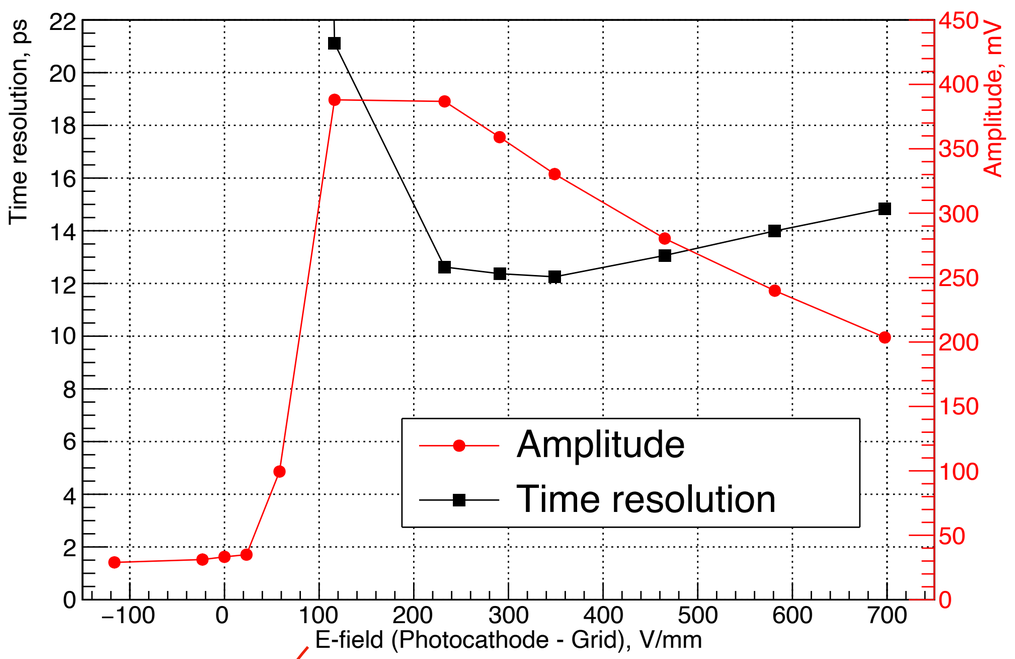
$$\sigma_{intrinsic} = \sqrt{\sigma_{PROT}^2 - \frac{\sigma_{diff}^2}{4}}$$

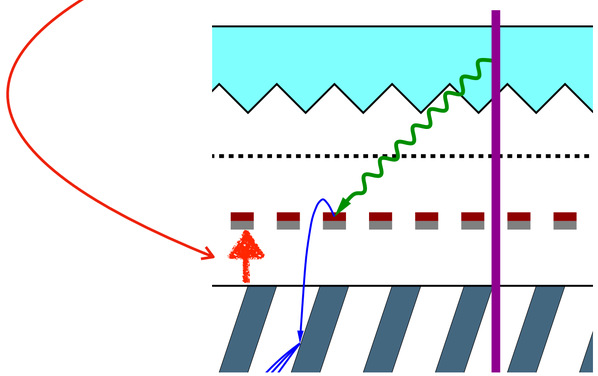
Test beam results - mesh photocathode

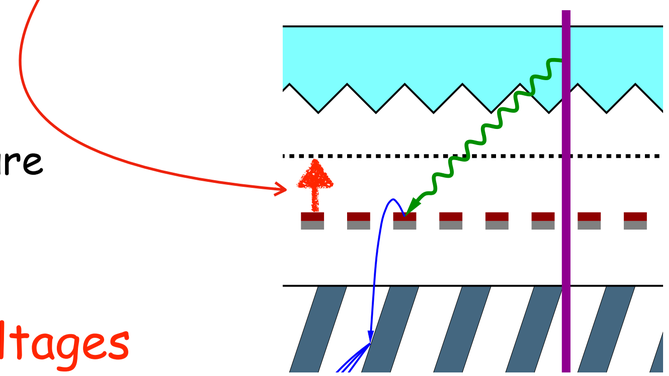








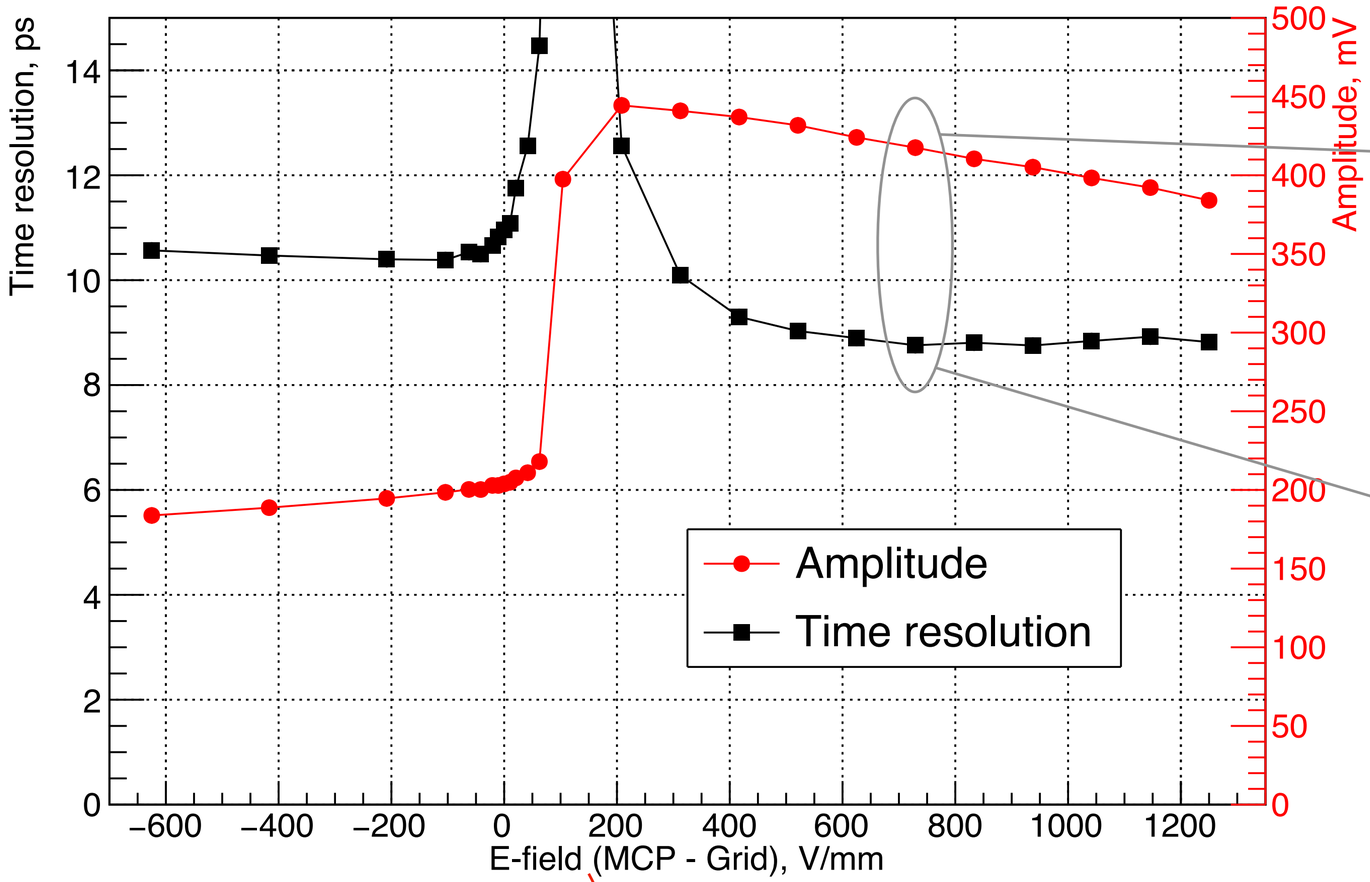


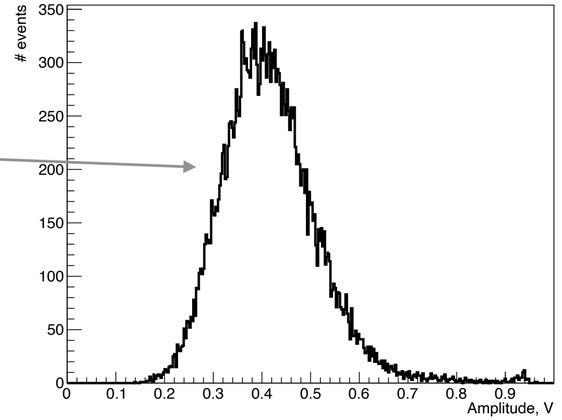


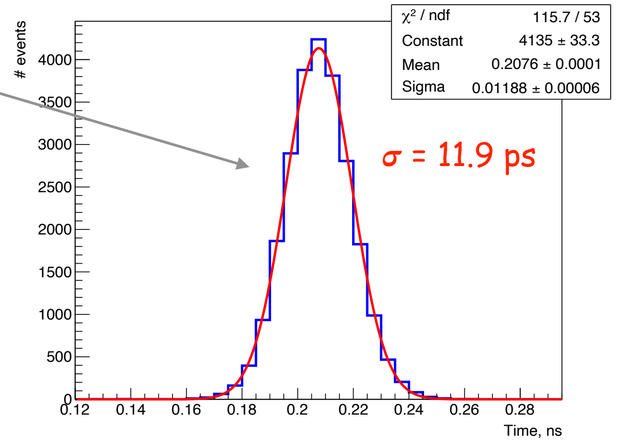
- 7 mm thick MgF_2 radiator with circular structure
- 1000 LPI mesh with 50% transparency

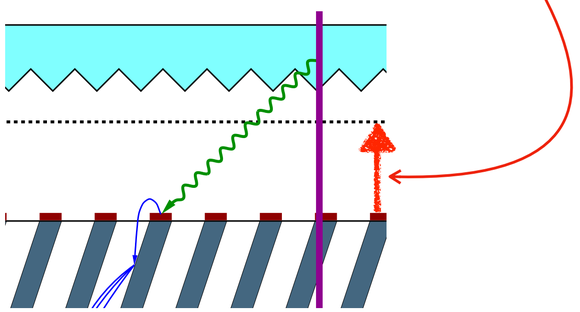
The time resolution is 12 ps at optimal voltages
(after subtraction of the reference time contribution)

Test beam results - photocathode on MCP





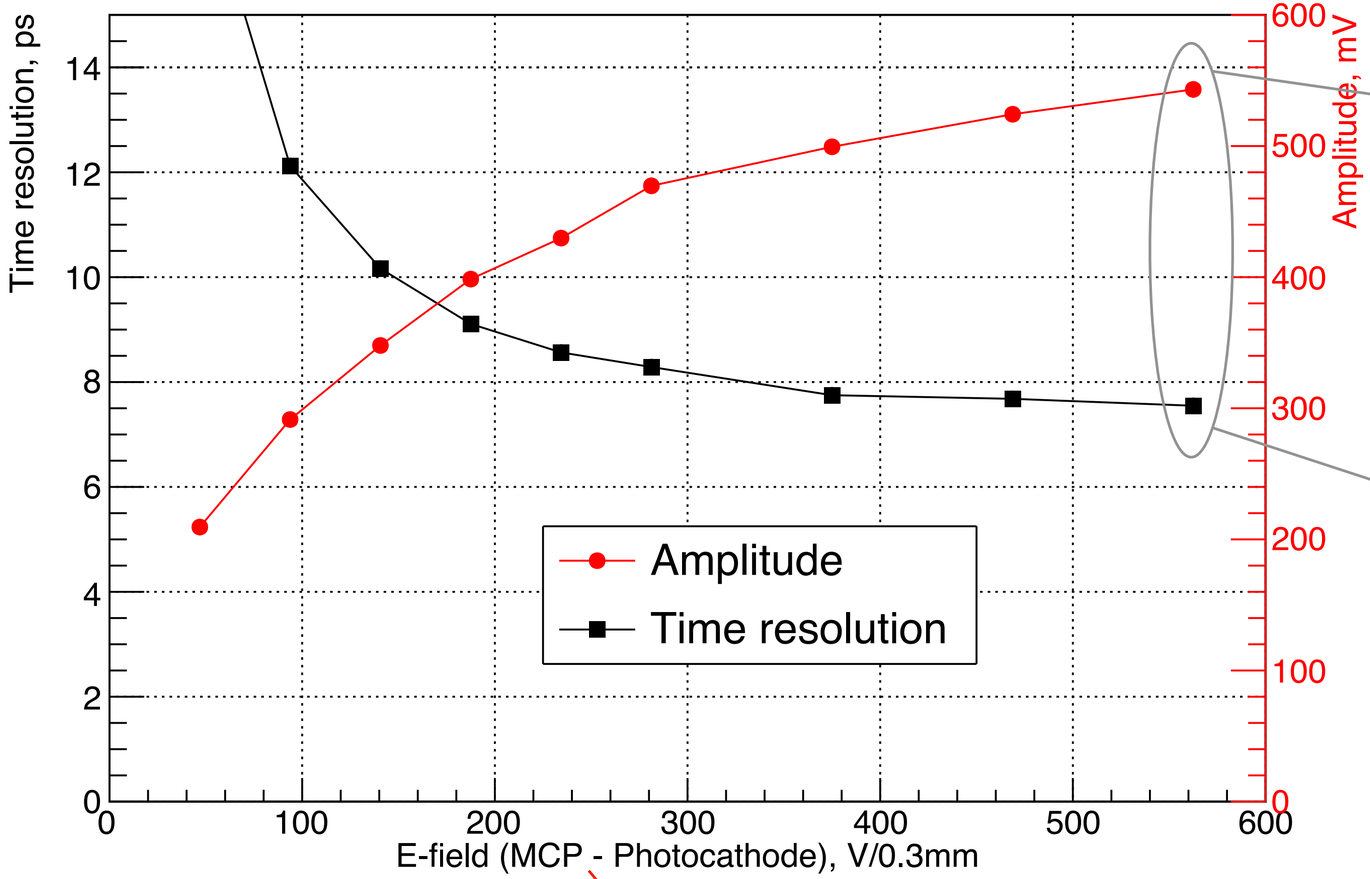


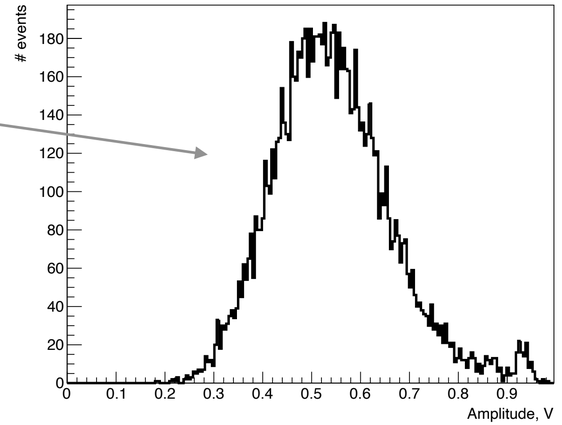


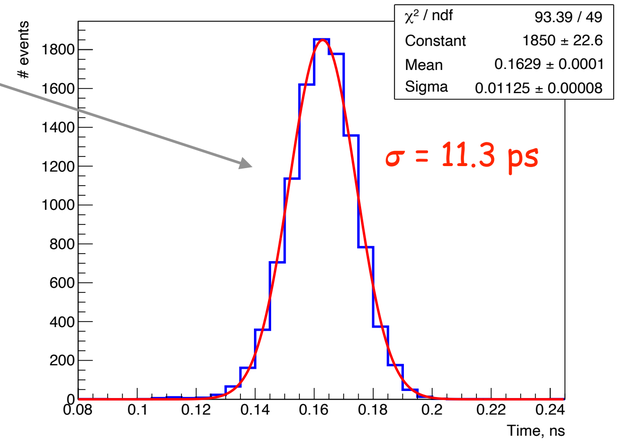
- 7 mm thick MgF_2 radiator with circular structure
- 1 μm of CsI on the MCP surface

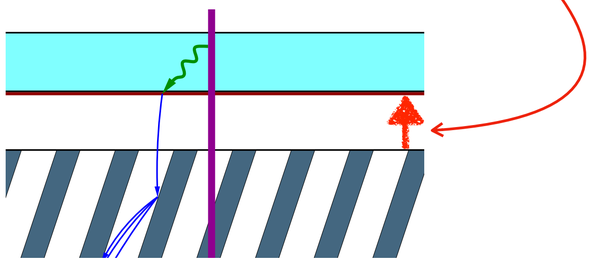
The time resolution is 9 ps at optimal voltage
(after subtraction of the reference time contribution)

Test beam results - semitransparent photocathode









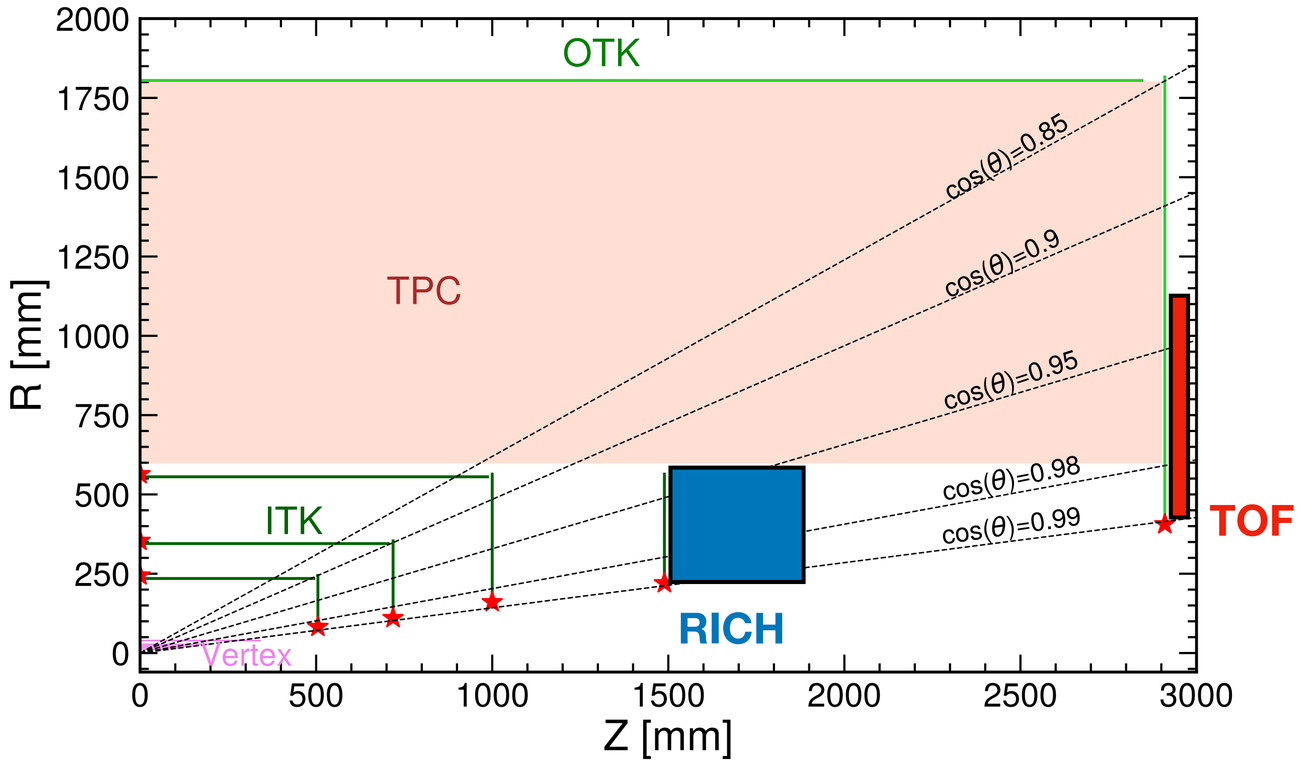
- 5 mm thick flat MgF_2 radiator
- 3 nm thick Cr electrode on the radiator
- 20 nm thick CsI photocathode

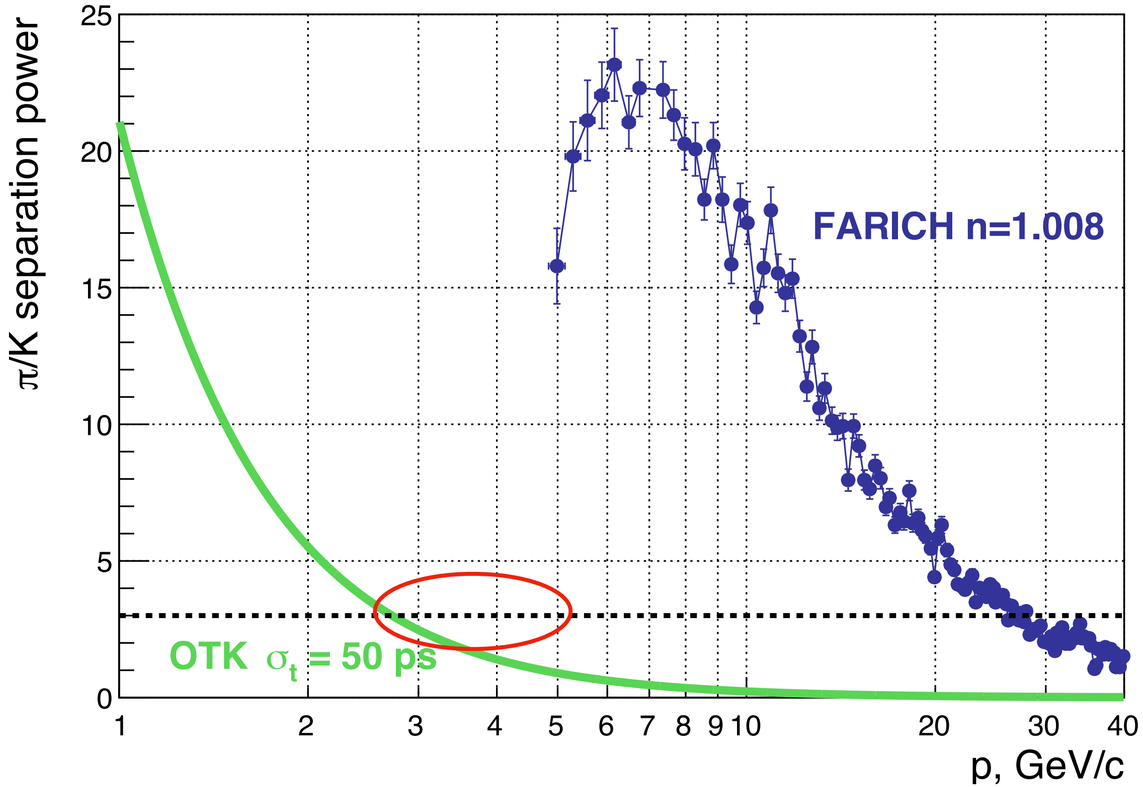
The time resolution is 7.6 ps for maximum voltage
(after subtraction of the reference time contribution)

Possible application at CEPC

To improve the PID at small polar angles the focusing aerogel RICH is proposed.
The aerogel refractive index 1.008 ⇒ no Cherenkov rings from kaons below ~5 GeV/c.

Fast TOF could be used for PID up to 5 GeV/c.

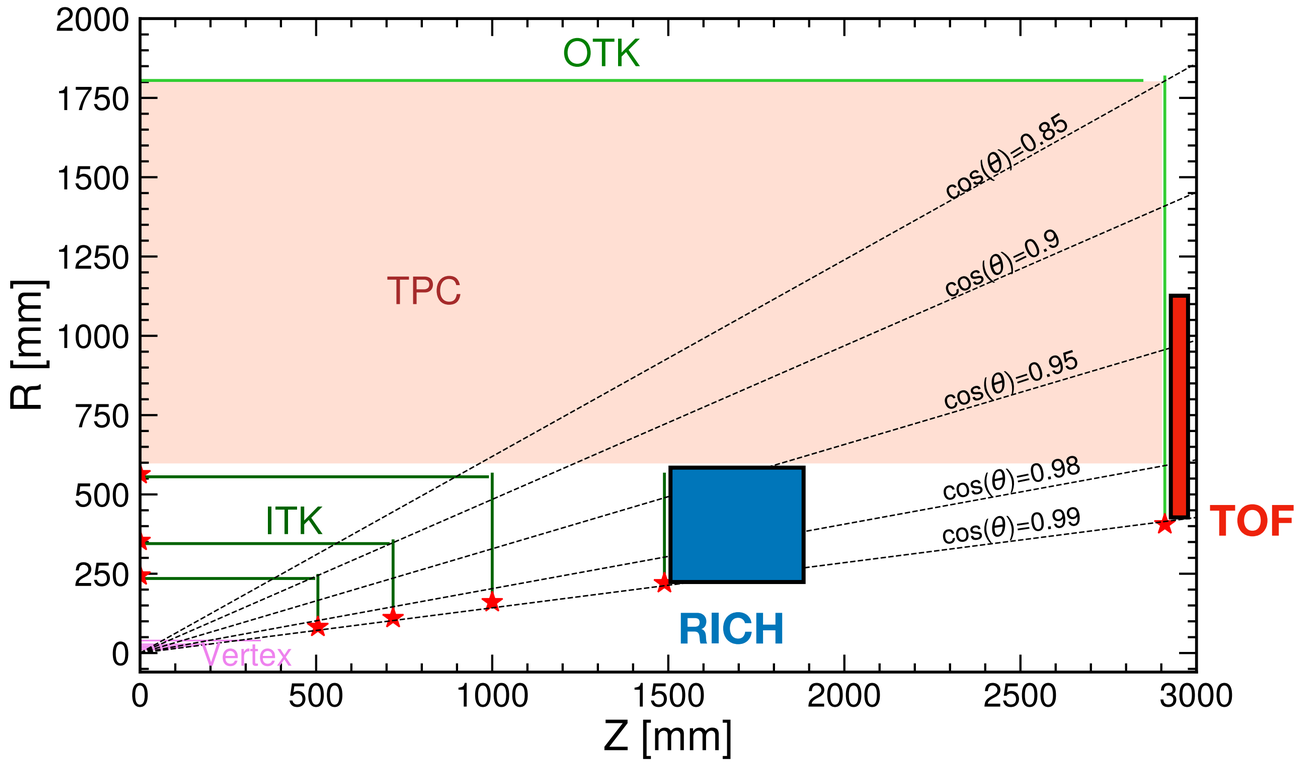


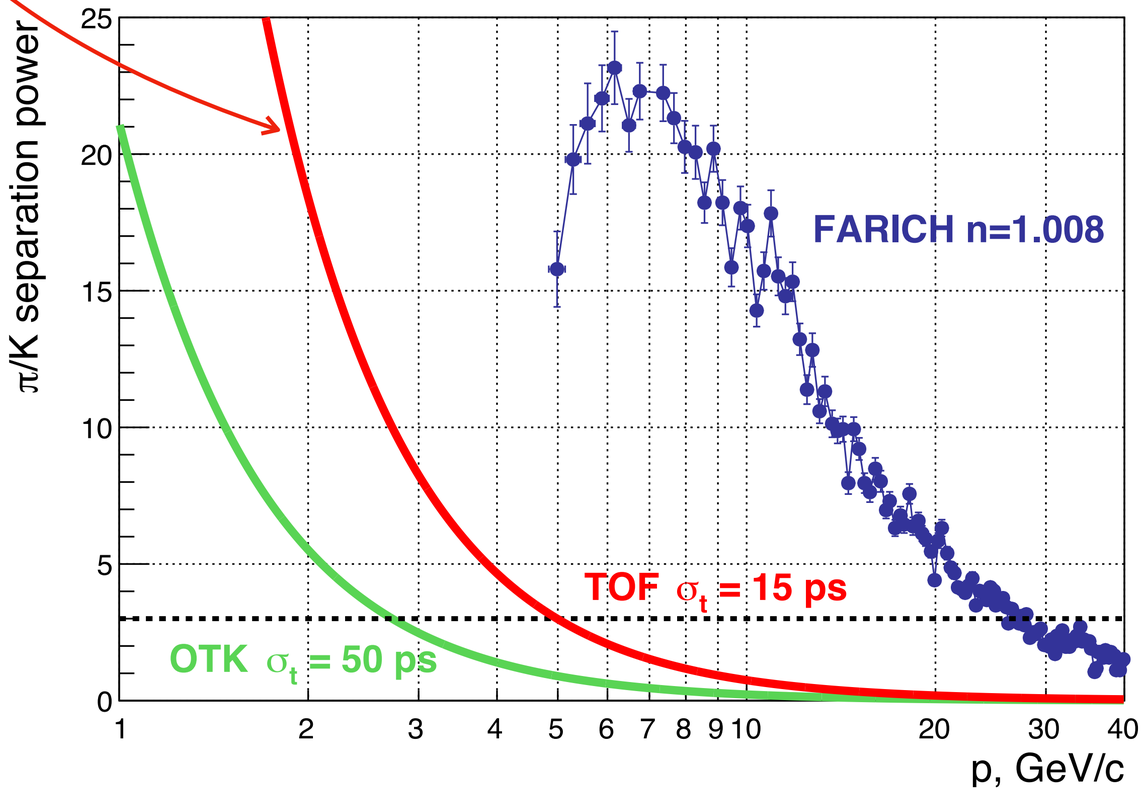


Possible application at CEPC

The TOF resolution is affected by the uncertainty of the interaction time due to the bunch length.

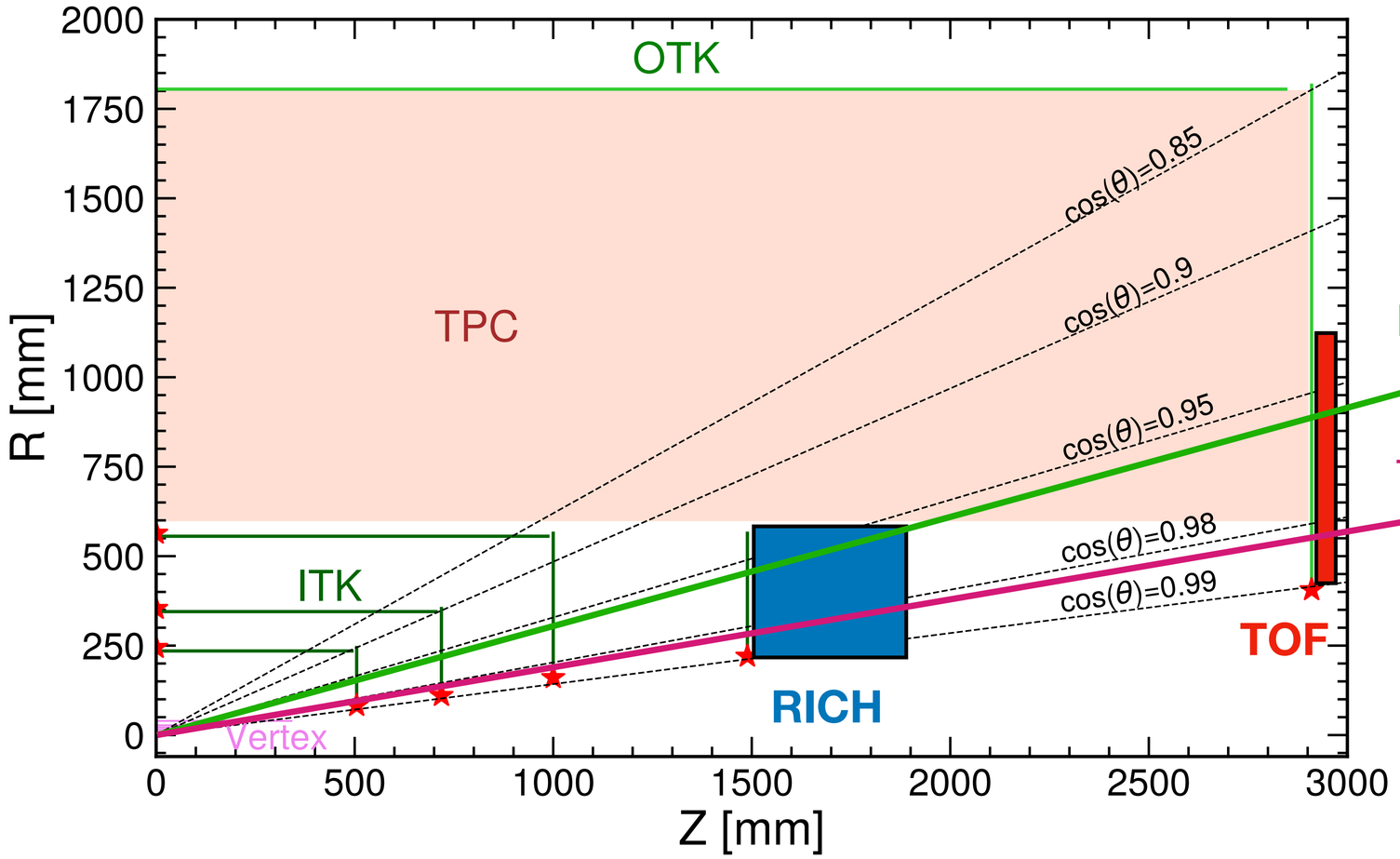
	Higgs	Z	W	$t\bar{t}$
Energy (GeV)	120	45.5	80	180
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Bunch crossing duration σ_t (ps)	13.7	29.0	16.3	9.7





Start time correction

If a second track from the same vertex is identified,
its time-of-flight can be used to evaluate the interaction time t_0.



Identified track ⇒ $t_0 = t - \frac{L}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2}$

Track to be identified using measured t_0

$\sigma_{t_0} \approx \sigma_t \approx 7.6$ ps ⇒ $\sigma_{tof} \approx 11$ ps

⇒ π/K separation up to ~5.8 GeV/c

Conclusions

- The prototype of MCP based time-of-flight detector with CsI photocathodes of different configurations has been made and tested.
- The intrinsic time resolution of 7.6 ps has been obtained for the semitransparent CsI photocathode deposited on a 5 mm thick MgF_2 window.
- Using a TOF detector with such a time resolution at the distance of 3 m from the interaction point would provide π/K separation up to momentum of 5 GeV/c.