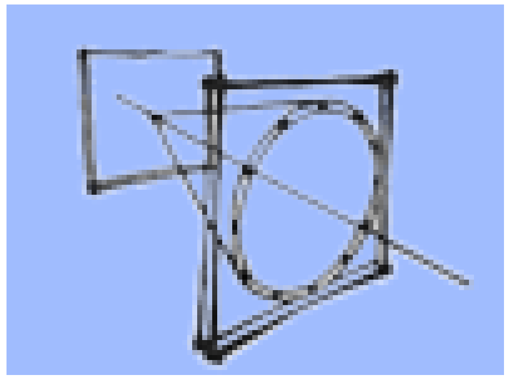
High Momentum PID at EIC

(in 10 years from now)

NOTE

in these slides, the reference is to π/K separation at 3 σ



INTRODUCTION

High-p h-PID at colliders, WHICH CHALLENGES ?

- **What is needed & related challenges:**

- Gaseous radiator ……………………. Short radiator length in spite of limited Ch. photon yield
  → the COMPACT RICH concept
- Focusing system (mirrors) .... Light support and substrate
- Wide phase space acceptance …. Extended systems complemented by low-p h-PID
- Detector in B-field region ………... Photon detectors effectively operating in B-field

- **Limited number of active RICHES for high p h-PID world-wide**

  - COMPASS
  - LHCb (2-counter system)

  } Wide phase space acceptance

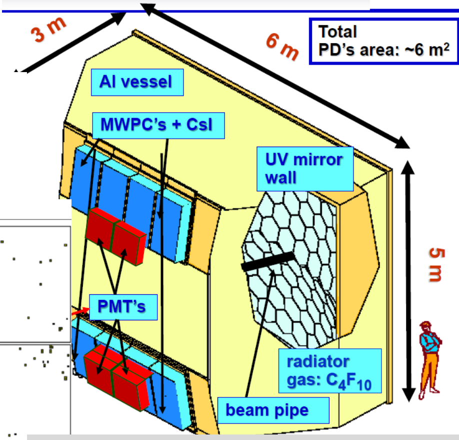
  - NA62

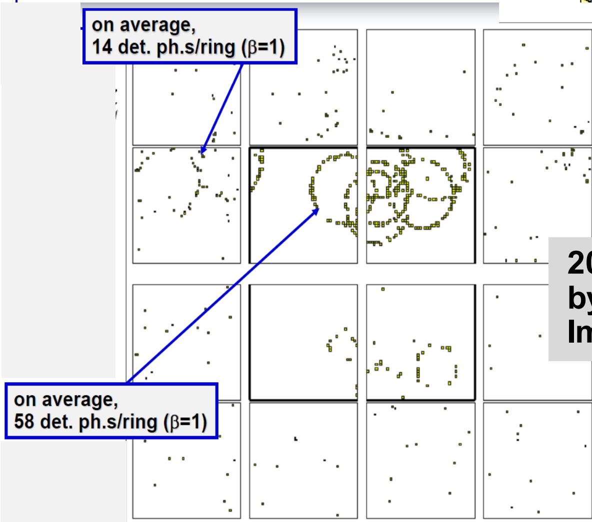
  small phase space acceptance

LESSONS FROM HIGH p RICHes IN OPERATION

COMPASS

C_4F_{10} - 3 m (n = 1.0015)



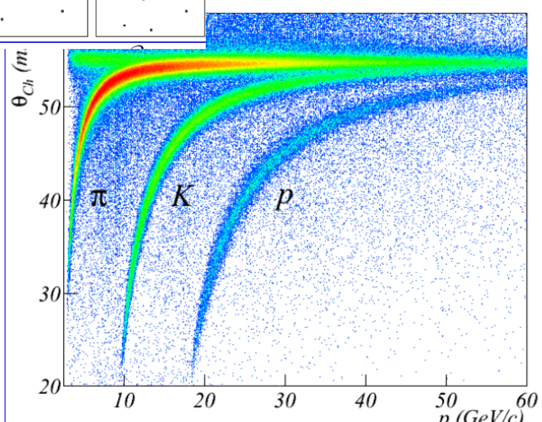


2016-2017: novel PDs by MPGD technologies: Improved detector stability

Effective QE range

CsI : 165-205 nm

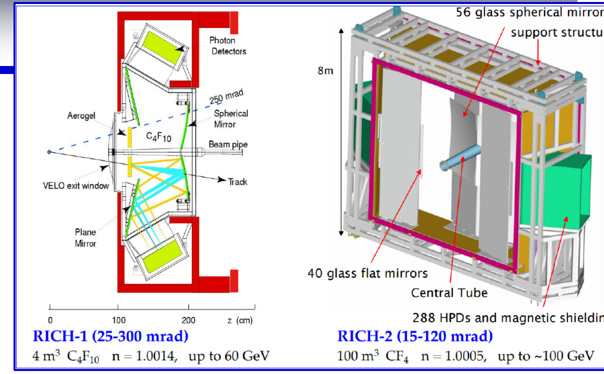
MAPMTs (UV extended window) : 200-650 nm



π-K separation, CL > 95% up to 45 GeV/c
π-K separation, CL > 90% up to 60 GeV/c

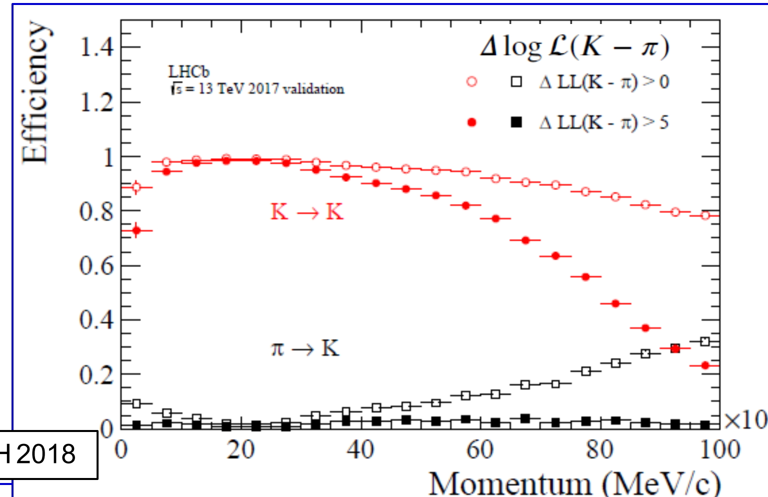
P. Abbon et al., NIMA 616 (2010) 21

LHCb



NIMA, 766 (2014) 245

Radiator	N_{pe} from data		N_{pe} from simulation	
	Tagged $D^0 \to K^- \pi^+$	$pp \to pp\mu^+\mu^-$	Calculated N_{pe}	True N_{pe}
Aerogel	5.0 ± 3.0	4.3 ± 0.9	8.0 ± 0.6	6.8 ± 0.3
C_4F_{10}	20.4 ± 0.1	24.5 ± 0.3	28.3 ± 0.6	29.5 ± 0.5
CF_4	15.8 ± 0.1	17.6 ± 0.2	22.7 ± 0.6	23.3 ± 0.5



S. Gambetta, RICH 2018

A FEW WORDS ABOUT SINGLE PHOTON DETECTORS

cont.

Time resolution (σ)

- PMTs, MAPMTs >/~ 0.3 ns
- MCP-PMT <100 ps
- SiPM <100 ps
- MWPCs >/~ 20 - 400 ns
  - FE dependent, ballistic deficit implications (*)
- MPGDs ~ 7-10 ns (INTRINSIC)

(*) COMPASS – Gassiplex 400 ns, ballistic def. 50%
APV25 20ns, ballistic def. 25%

Effective QE range

- Vacuum-based devices:
  λ > 300, 250, 200 nm
  [also solar-blind]
- Gaseous devices (CsI):
  λ < 205 nm

Operation in magnetic field

- PMTs, MAPMTs, HPMTs NO
- MCP-PMT YES
- MWPCs, MPGDs YES
- SiPM YES

COSTS

- Gaseous (*) - $ (0.2-0.4 M / m^2)
- MAPMTs - $$ (0.5-1 M / m^2)
- SiPM - $$ (0.8-1 M / m^2)
- MCP-PMT - $$$ (???)
  - LAPPD - $$ (0.8-1 M / m^2)

(*) gas system, mirrors more DEMANDING → expensive

Options for h-PID at high p in classical collider setups

"STANDARD" APPROCH

- 1 m-long radiator and visible light PDs
- *PDs: LAPPDs or SiPMs*
- C_4F_{10} (n = 1.0015, θ_max: 55 mrad)
  - π threshold : 2.5 GeV/c
  - K threshold : 9.0 GeV/c
  - n_det.ph.s (β=1) / 1m : ~ 20 - 30
  - To exploit PID up to 50 GeV/c : σ_C_ph < 1.5 mrad
- CF_4 (n = 1.0005, θ_max: 32 mrad)
  - π threshold : 4.4 GeV/c
  - K threshold : 15.6 GeV/c
  - n_det.ph.s (β=1) / 1m : ~ 10
  - to exploit PID up to 50 GeV/c : σ_C_ph < 0.9 mrad

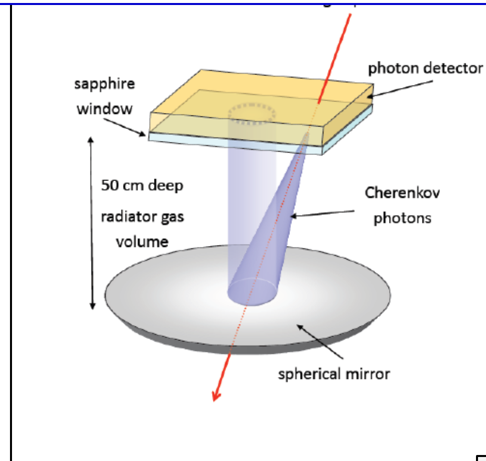
“HIGH PRESSURE” RICH

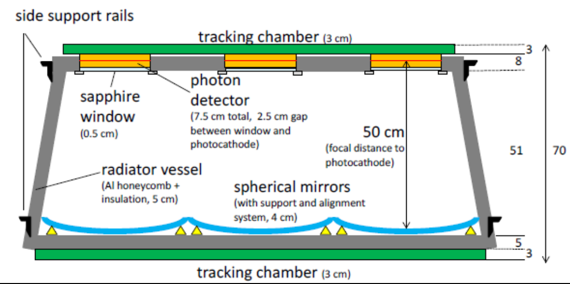
An option for ALICE HMPID upgrade (later abandoned)

A.G. Agócs et al. / Nuclear Instruments and Methods in Physics Research A 732 (2013) 361–365

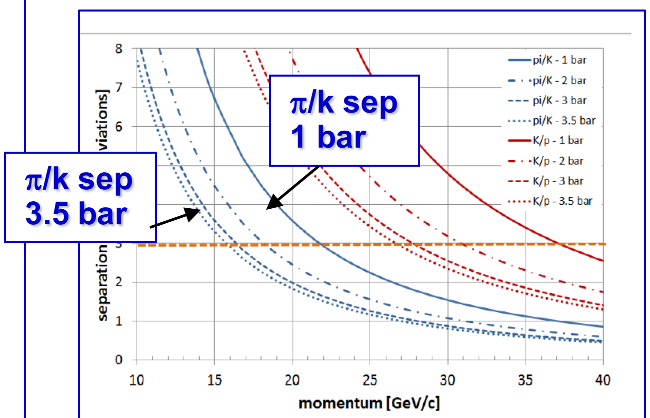
Details:
- Focusing RICH
- Radiator: 3.5 bar C_4F_8O (50 cm)
- Photon detector: CsI-MWPC (CH_4)
- Window: Sapphire
- Mirrors: 3x3

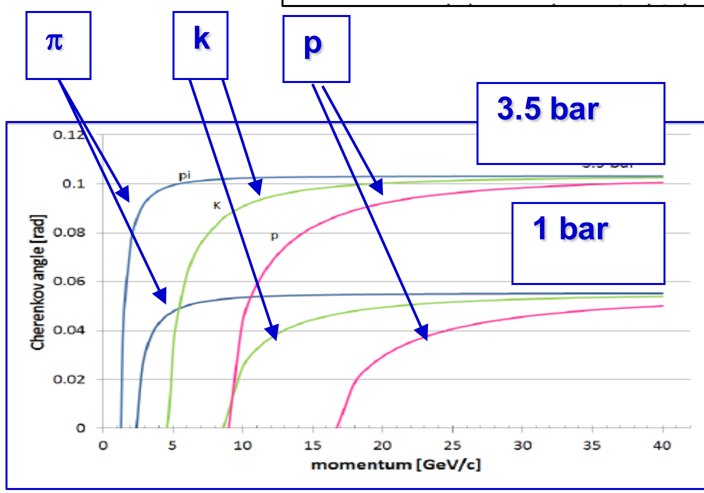
Goals:
- 1.5 mrad resolution
- p/K 3 σ sep. up to 25 GeV/c
- π/K sep. from 5 GeV/c
- π/K 3 σ sep. up to 16 GeV/c





Expected (simulations):





Test-beam :

n. of ph.s: 10 (saturation)

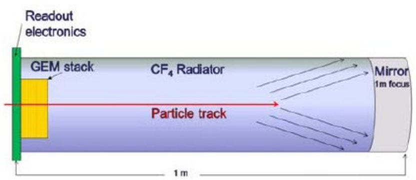
→ 20 ph.s per m

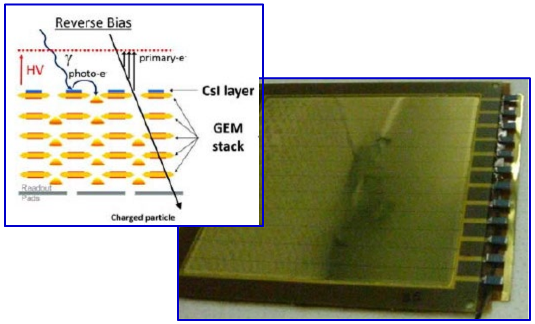
Reminder:
at 1 bar with MWPCs +CsI:
~ 5 ph.s per m

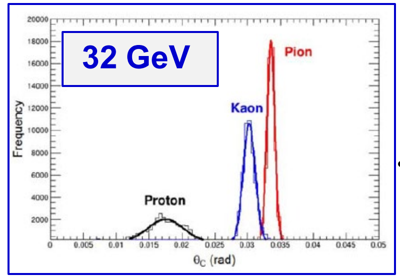
"WINDOWLESS" RICH

CF_4 windowless RICH concept, test-beam results

M. Blatnik et al., IEEE NS 62 (2015) 3256

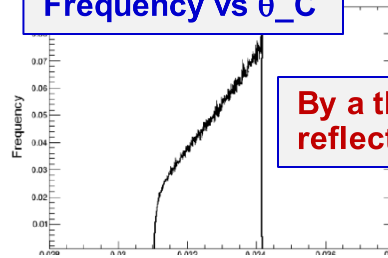






Pad-size ~ 5 mm

n_det_ph.s : 10



- 1 m-long radiator and gaseous PD
- Increased n. of detected photons with a wavelength range around 120 nm
  - 10 photons (as with visible PDs !)
- CF_4 (n = 1.0005, θ_max: 32 mrad)
  - π threshold : 4.4 GeV/c
  - K threshold : 15.6 GeV/c
  - n_det.ph.s (β=1) / 1m : ~ 12
  - Testbeam σ_C_ph : 1 mrad, where about ¼ from chromatic dispersion
  - to exploit PID up > 60 GeV/c : σ_C_ph < 0.7 mrad
- *High-tech, expensive mirrors, gas transparency issues at 120 nm*

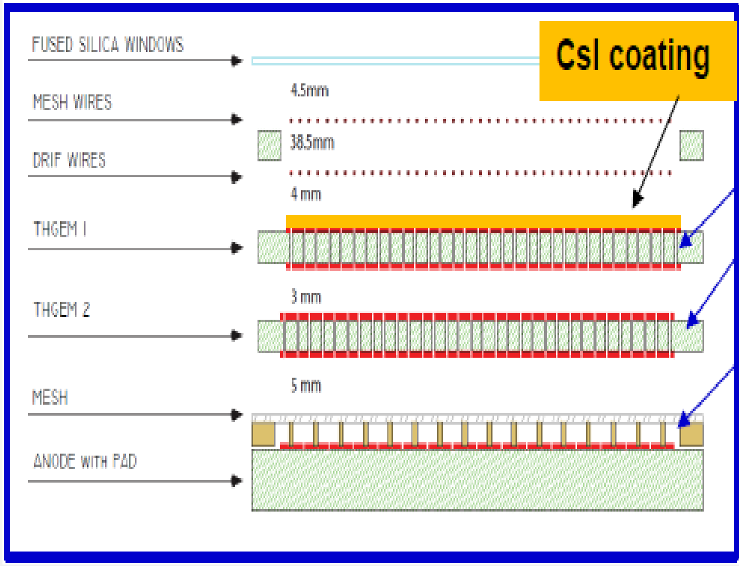
INFN ACTIVITY

Within eRD6

THE STARTING POINT

The novel gaseous single photon detectors of COMPASS RICH

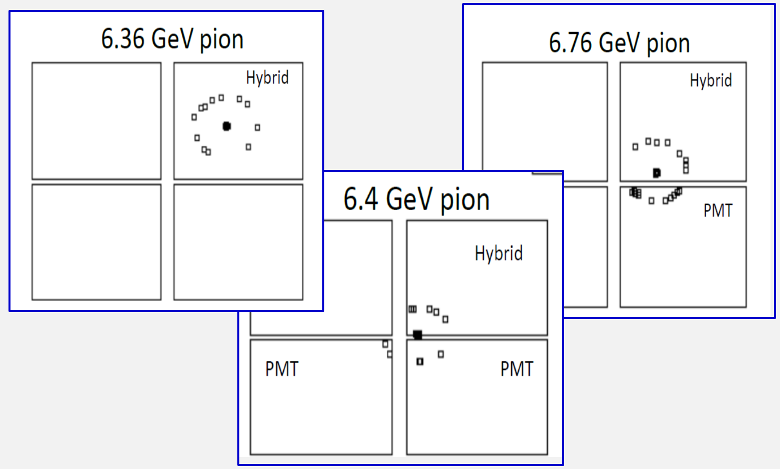
- Hybrid MPGD: 2 THGEMs + 1 MICROMEGAS



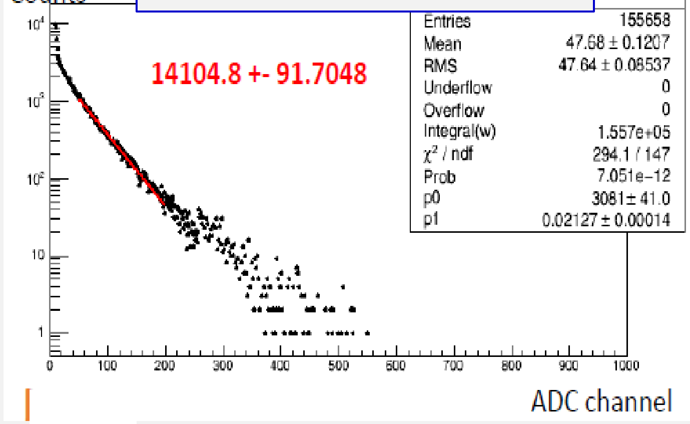
THGEMs

MICROMEGAS resistiva

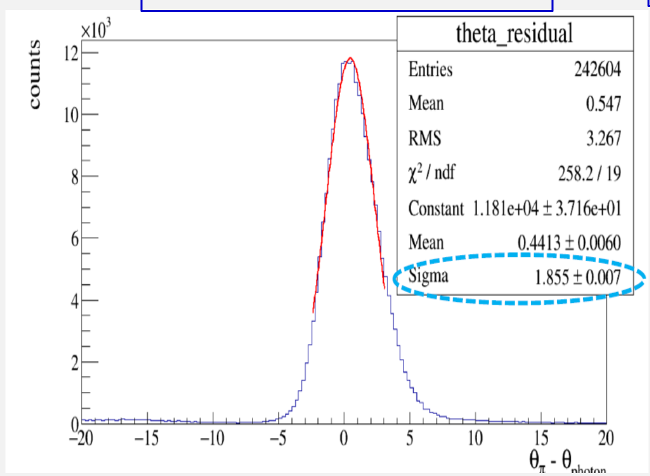
Event displays



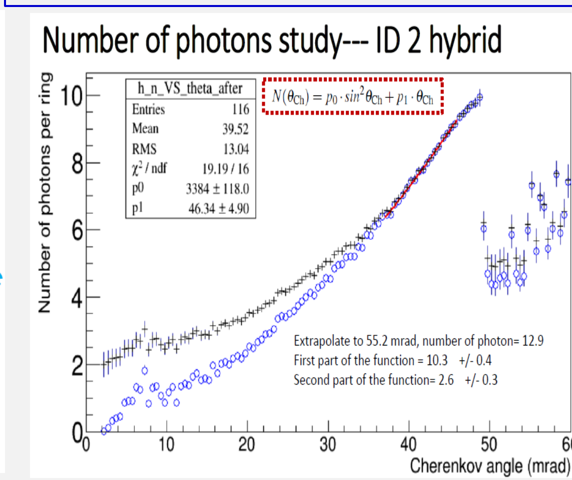
EFFECTIVE GAIN: 14 k



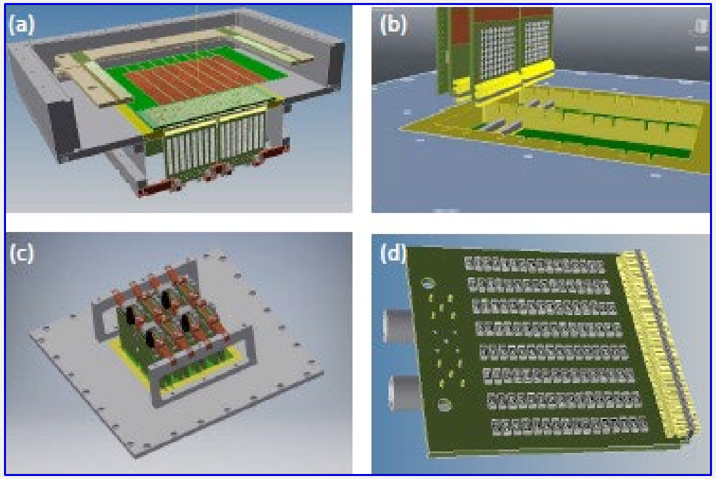
Resolution: 1.8 mrad

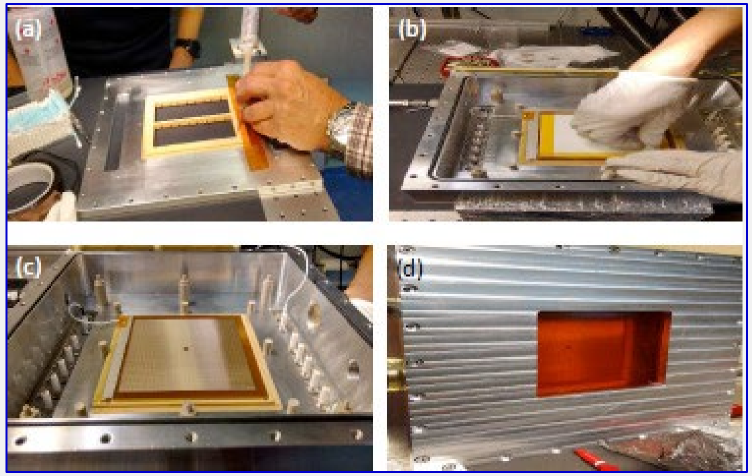


n. of photons/ring : 10-12 (β → 1)

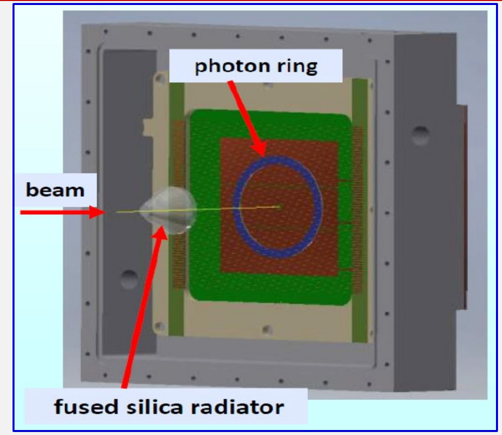


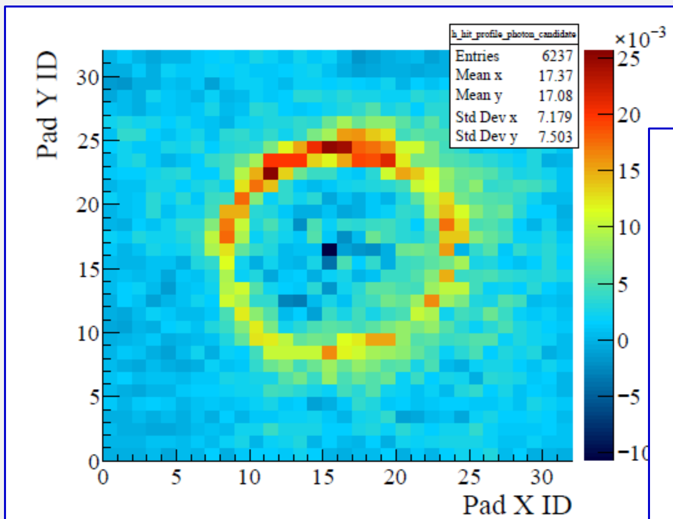
MOVING TOWARDS PAD-SIZE MINIATURIZATION



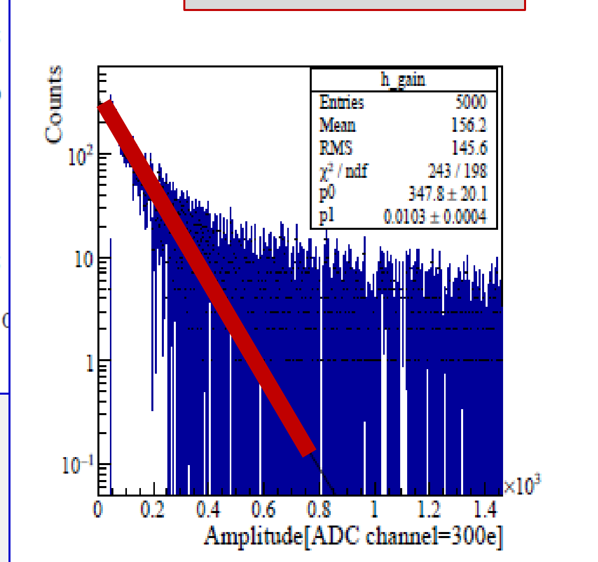


test-beam with quartz radiator

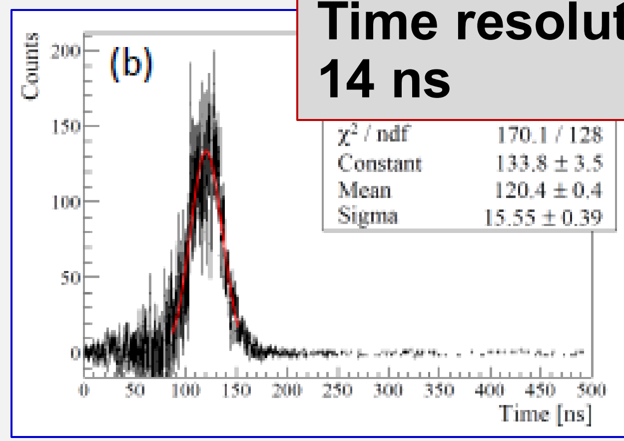




Gain ~ 30 k



Time resolution: 14 ns



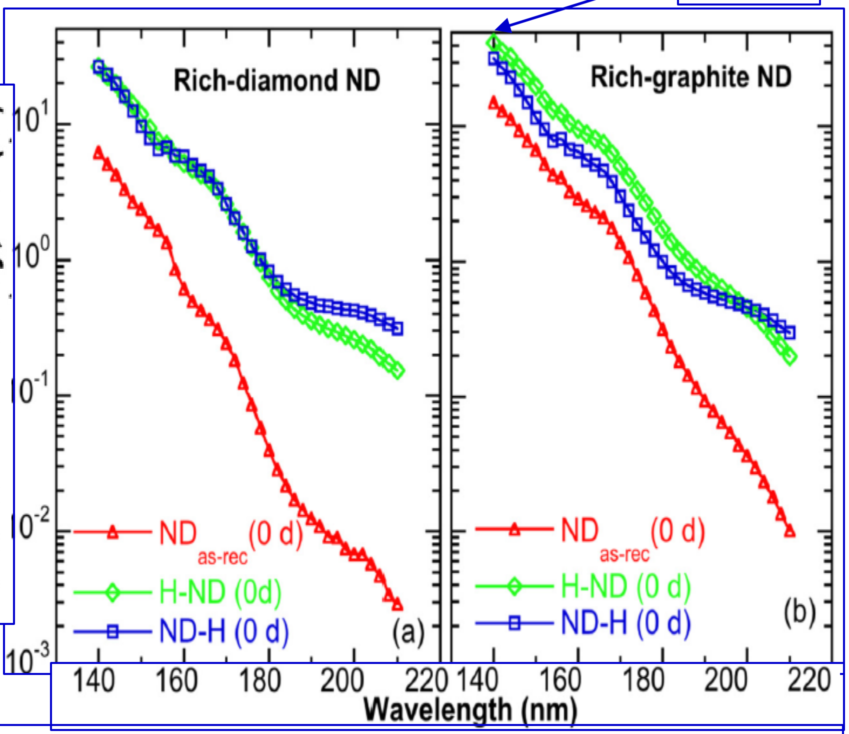
Noise still too high: we are at work to improve

NOVEL, ROBUST PHOTOCATHODES

HYDROGENATED NANO-DIAMOND powder

- **Starting point**

47 % (!)



L.Velardi, A.Valentini, G.Cicala, Diamond & Related Materials 76 (2017) 1

NEW :

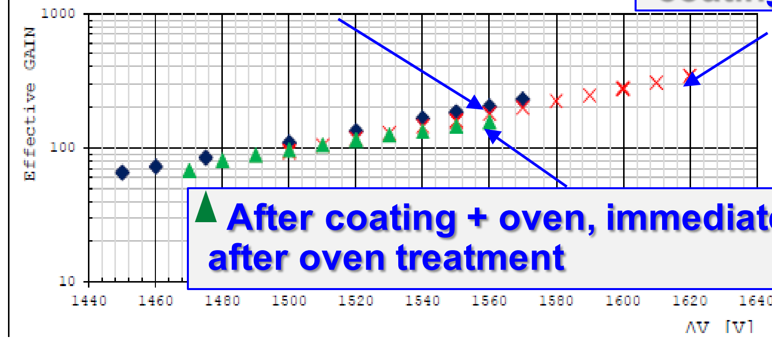
Photocatodes: diamon film obtained with Spray Technique making use of NC powder

- *Spray technique: T ~ 120˚C (instead of >800° as in standard techniques)*

Wide set of explorative studies

substrate type	sample label	coating material	number of spray shots
THGEM	TB IX	ND	300
THGEM	TB VIII	HND	140
THGEM	TB III	HND	43
THGEM	TB VII	HND	55
THGEM	TB XIX	HND	59
THGEM	TB XI	HND	250
disc	PBC1	ND	100
disc	PBC2	ND	100
disc	PBC3	ND	200
disc	PBC4	ND	200
disc	PBC5	ND	50
disc	PBC6	HND	50
disc	PBC9	HND	25
disc	PBC7	HND	50
disc	PBC10	HND	100
disc	PBC11	HND	200
[illegible]	[illegible]	HND	400

Unchanged performance of coated THGEMs

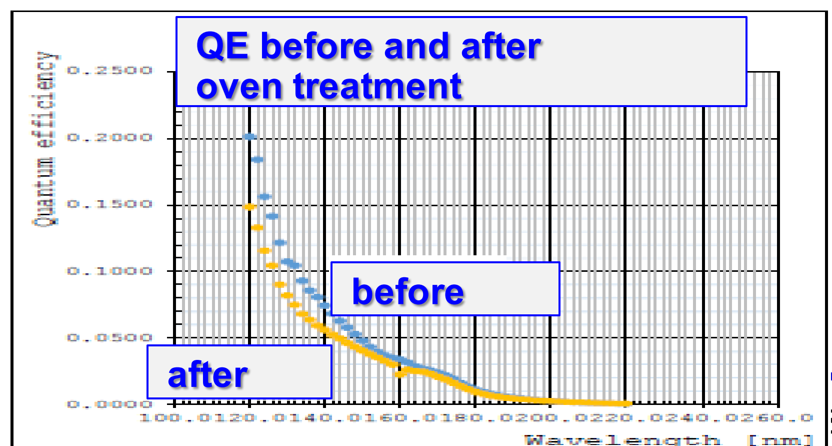


♦ After coating + oven, 1 month after oven treatment

x Before coating

▲ After coating + oven, immediately after oven treatment

QE check at the various coating stepos



QE before and after oven treatment

before

after

USE OF FLUOROCARBONS

In 10 year

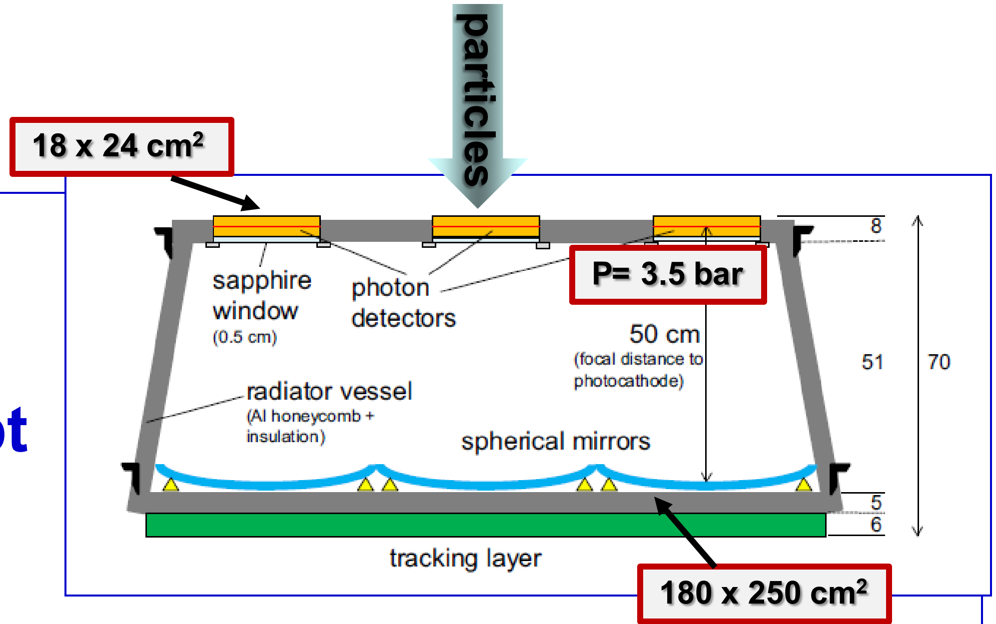
THE NOVEL ISSUE

- The current model are based on the use of fluorocarbons
  - Offering large Cherenkov photon rate with limited chromatic dispersion

- These gasses are not eco-friendly
  - They attack O_3
  - They have high Global Warming Potential values (100 y)
    - C_4F_{10}: 4800
    - CF_4 : 6500
    - CO_2 : 1 (by definition)
    - CH_4 : 86 (for comparison)

- **Other gas options?**
  - Not yet: The community starts only now addressing this aspect

ECO-FRIENDLY GASEOUS RICHES



- **2 very attractive ingredients in the ALICE VHPID concept**
  - **P > 1 bar**
    - **A handle to overcome the limitations of existing gasses: Take a "light gas" with limited chromaticity and make it "heavy"**
    - **A tunable detector**
  - **The overall design that results in isolated, small size PDs**
    - **Easier to build, easier to handle, easier to maintain**
    - **The PDs must be light**

PRESSURIZED Ar vs FLUOROCARBONS

Chromatic dispersion

gas	P (bar)	VISIBLE (bialkali with ext. UV glass window)						CsI & quartz window						CsI ~ 120 nm (windowless RICH)					
		(n-1) $*10^6$	σ (n-1) $*10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)	(n-1) $*10^6$	σ (n-1) $*10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)	(n-1) $*10^6$	σ (n-1) $*10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)
CF_4	1	497	11.5	31.5	0.4	**1.2**	**10.0**	545	7	33.0	0.2	**0.6**	**2.5**			33.2	0.83	**2.5**	**12.2**
C_4F_{10}	1	1367	46	52.3	0.9	**1.7**	**27.5**	1564	30.5	55.9	0.5	**1.0**	**7.2**						
Ar	1	294	10	24.2	0.4	**1.7**	**5.9**	340	7.5	26.1	0.3	**1.1**	**1.6**						
Ar	1.5	441	15	29.7	0.5	**1.7**	**8.9**	510	11	31.9	0.3	**1.1**	**2.3**						
Ar	2	588	19.5	34.3	0.6	**1.7**	**11.8**	580	14.5	34.1	0.4	**1.2**	**2.7**						
Ar	3	882	29.5	42.0	0.7	**1.7**	**17.7**	1020	22	45.1	0.5	**1.1**	**4.7**						
Ar	3.5	1029	34.5	45.3	0.8	**1.7**	**20.7**	1190	25.5	48.8	0.5	**1.1**	**5.5**						

Number of detected photons at β = 1 (scaling from yellow box)

PRESSURIZED Ar vs FLUOROCARBONS

gas	P (bar)	VISIBLE (bialkali with ext. UV glass window)						CsI & quartz window						CsI ~ 120 nm (windowless RICH)					
		$(n-1) \cdot 10^6$	$\sigma\,(n-1) \cdot 10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)	$(n-1) \cdot 10^6$	$\sigma\,(n-1) \cdot 10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)	$(n-1) \cdot 10^6$	$\sigma\,(n-1) \cdot 10^6$	θ_max (mbar)	σ_θ (mbar)	σ_θ / θ_max (chrom. only) (%)	n_ph/m (β = 1)
CF_4	1	497	11.5	31.5	0.4	**1.2**	**10.0**	545	[illegible]	[illegible]	[illegible]	**0.6**	**2.5**			33.2	0.83	**2.5**	**12.2**
C_4F_{10}	1	1367	46	52.3	0.9	**1.7**	**27.5**	1564	[illegible]	[illegible]	0.5	**1.0**	**7.2**						
Ar	1	294	10	24.2	0.4	**1.7**	**5.9**	340	[illegible]	[illegible]	0.3	**1.1**	**1.6**						
Ar	1.5	441	15	29.7	0.5	**1.7**	**8.9**	510	11	[illegible]	0.3	**1.1**	**2.3**						
Ar	2	588	19.5	34.3	0.6	**1.7**	**11.8**	580	[illegible]	34.1	0.4	**1.2**	**2.7**						
Ar	3	882	29.5	42.0	0.7	**1.7**	**17.7**	1020	[illegible]	45.1	0.5	**1.1**	**4.7**						
Ar	3.5	1029	34.5	45.3	0.8	**1.7**	**20.7**	1190	[illegible]	48.8	0.5	**1.1**	**5.5**						

Not enough photons

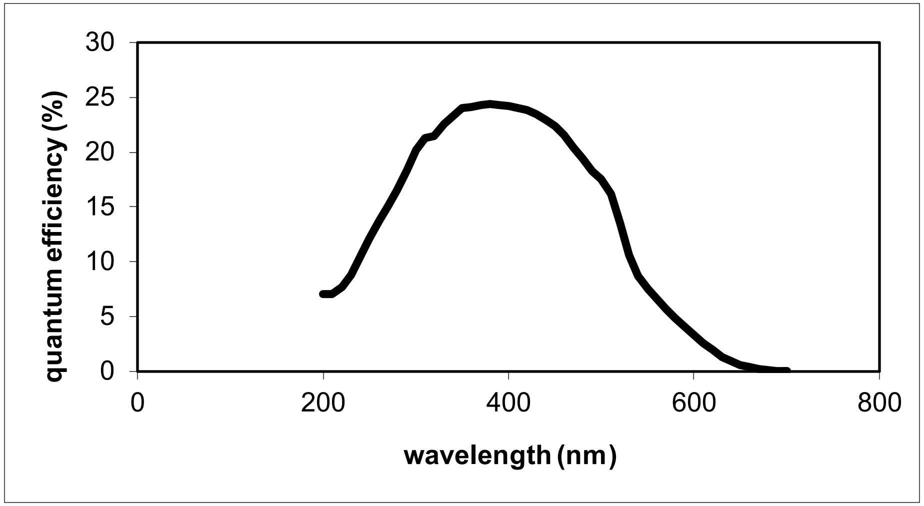
?

Promising: enough photons and Chromatic effect as for C_4F_{10}

The promising testbeam results with CF_4 suggest exploration here
If successful →
minimum material budget

SOME INPUTS USED 1/3

QE – Hamamatsu, MAPMT with UV extended window



The best quartz cuts here

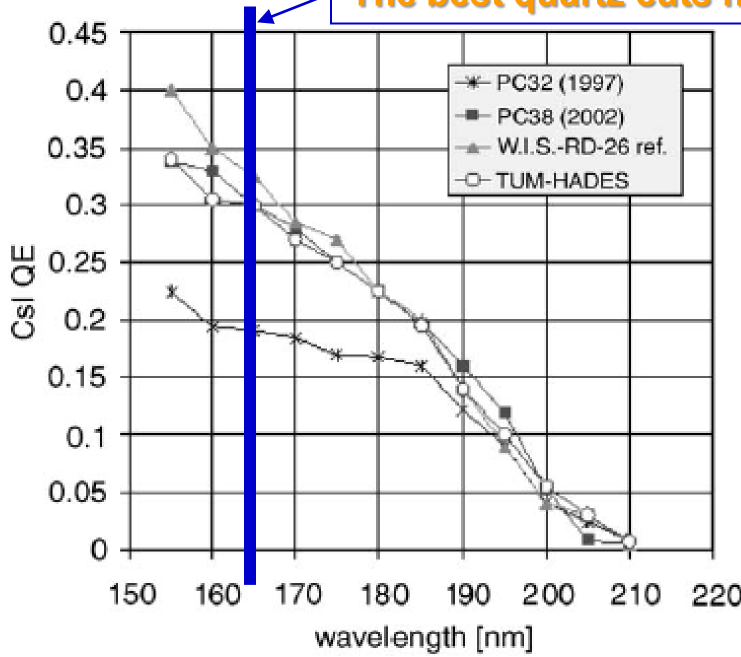
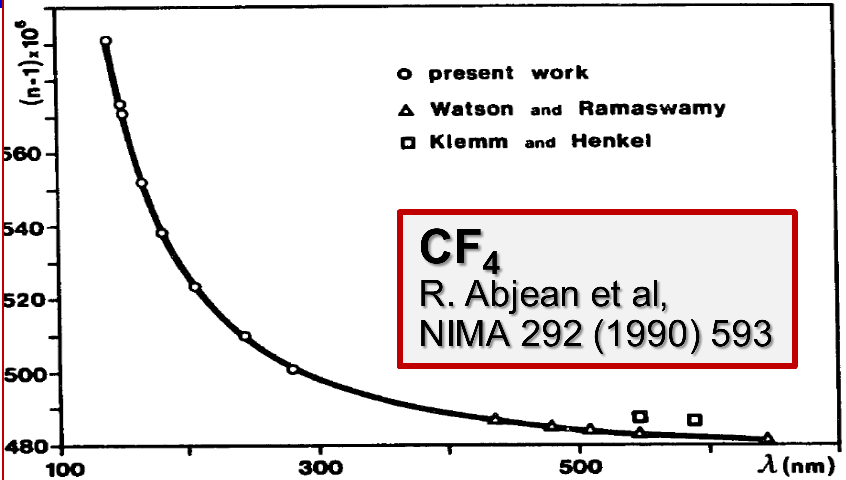


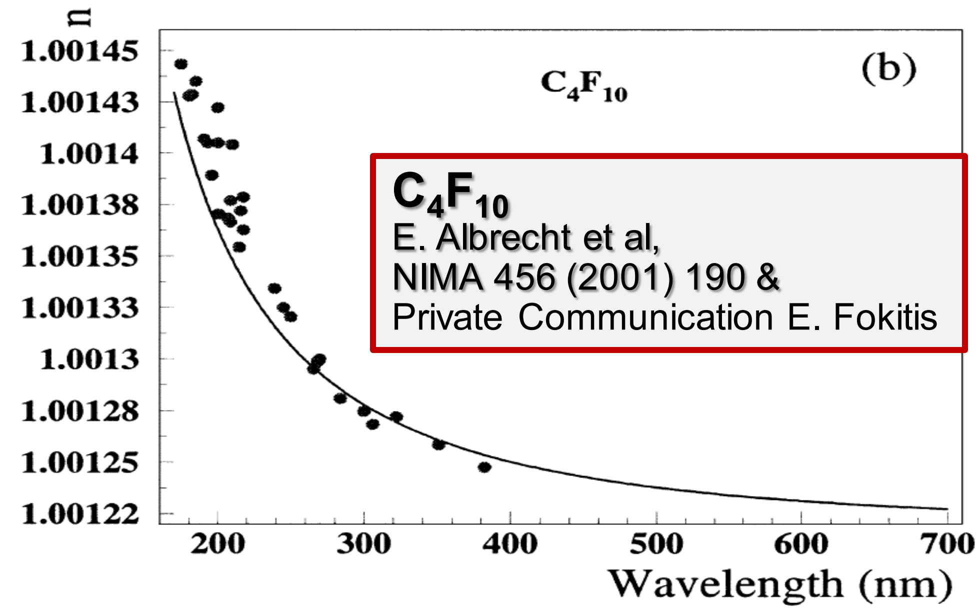
Fig. 1. The QE of CsI PCs produced at CERN for ALICE and at TUM for HADES, compared to that measured at the W.I.S. on small samples (reference for RD-26). PC32 is one of the four PCs equipping the ALICE-RICH prototype used in STAR at BNL.

A. Di Mauro, NIM A 525 (2004) 173.

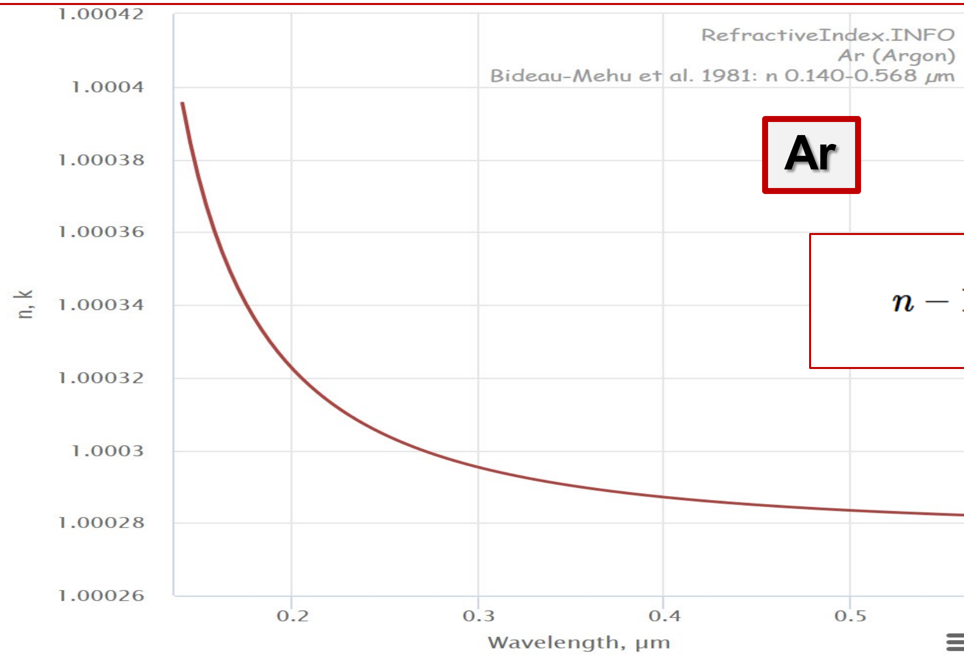
SOME INPUTS USED 2/3



CF_4
R. Abjean et al,
NIMA 292 (1990) 593



C_4F_{10}
E. Albrecht et al,
NIMA 456 (2001) 190 &
Private Communication E. Fokitis



Ar

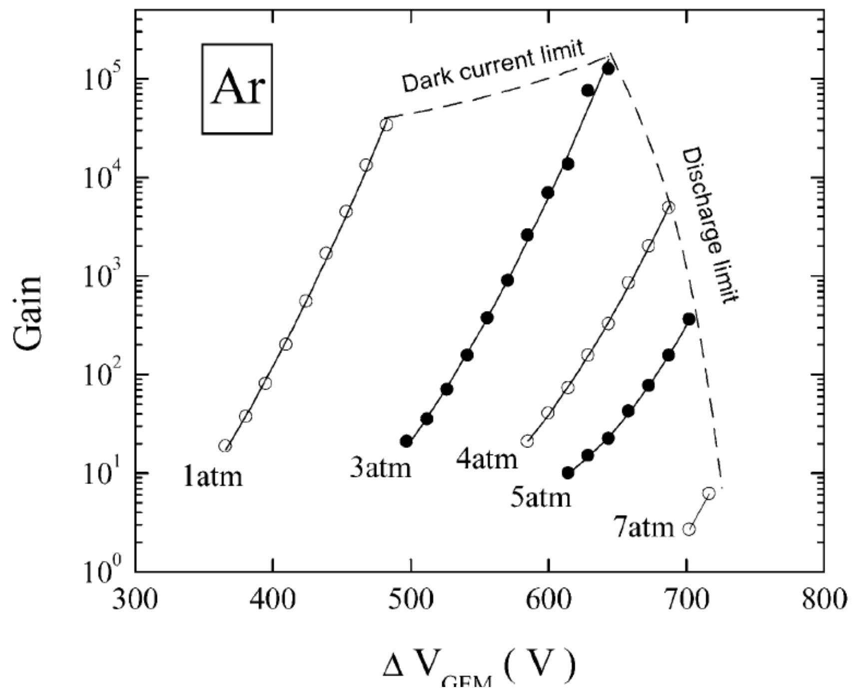
$$n-1=\frac{2.50141\times10^{-3}}{91.012-\lambda^{-2}}+\frac{5.00283\times10^{-4}}{87.892-\lambda^{-2}}+\frac{5.22343\times10^{-2}}{214.02-\lambda^{-2}}$$

These 2 poles are near 105 nm !

SOME INPUTS USED 3/3

QE – Hamamatsu, MAPM with UV extended windo

- **MPGD at high P, very limited literature, nevertheless:**
  - **Studies for a triple GEM (for double phase cryogenic detectors: at boiling point Ar density is 2.8 x density at normal conditions)**



A. Bondar et al. / Nuclear Instruments and Methods in Physics Research A 481 (2002) 200–203

For THGEMs, confirmed by the operation of the double phase DUNE prototype

SUMMARY

OPTIONS for h-PID at high-p needed at EIC

- **STANDARD APPROACH** (fluorocarbons + visible light PDs)
  - **Photon detectors to be established**
- **WINDOWLESS RICH** (CF_4 and MPGDs)
  - **Initiated with a successful test beam**
  - **PD developments within eRD6**
- **Ar RADIATOR @ HIGH P**(visible light PDs or windowless)
  - **Eco-friendly (possible future constrains)**
  - **Studies have to start**

Thank you !

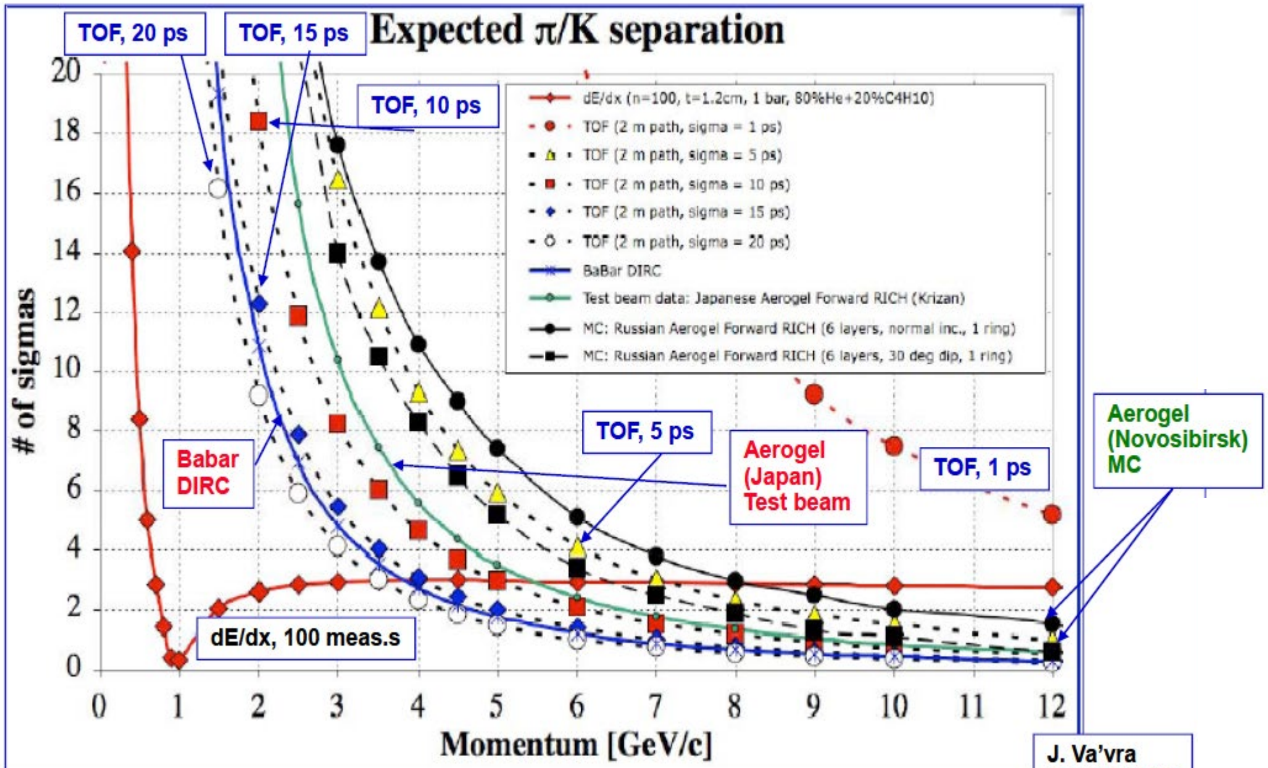
MORE INFORMATION

Dedicated R&D

ARE THERE NO-RICH OPTIONS? 1/2

TOF

2m lever arm assumed

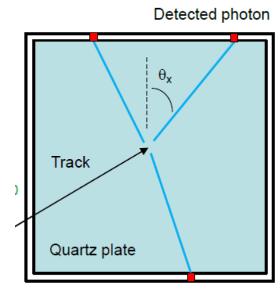


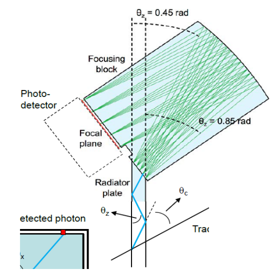
J. Va'vra @ RICH2007

TORCH : a DIRC for TOF

Overcoming:

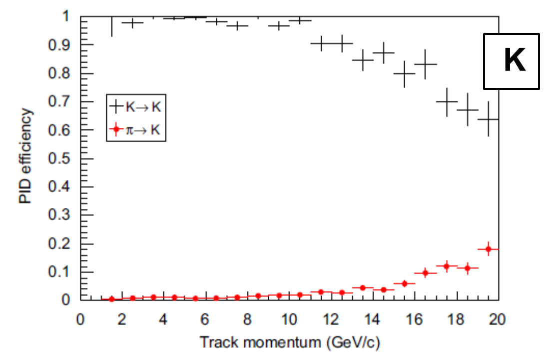
- the upper limit from θ_C saturation
- the time-resolution limit from single photon





MC
10 m
σ_t = 12.5 ps

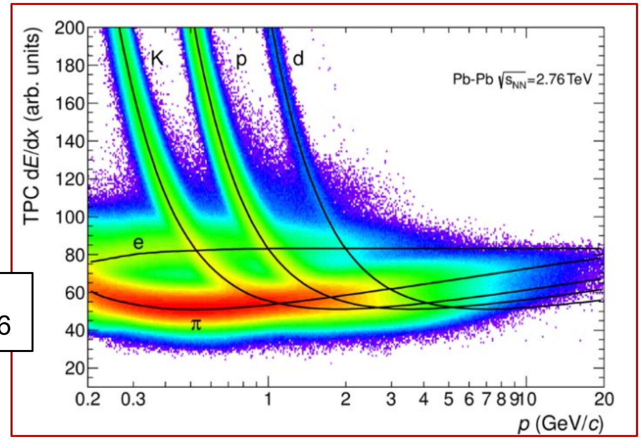
M.J.Charles, R. Forty, NIMA 639 (2011) 173



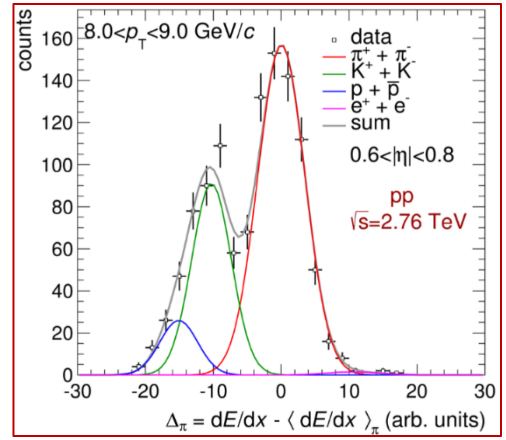
ARE THERE NO-RICH OPTIONS? 2/2

dE/dx

ALICE TPC (before upgrade)

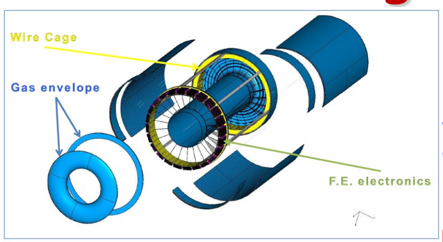


J. Alme et al., NIMA 622 (2010) 316

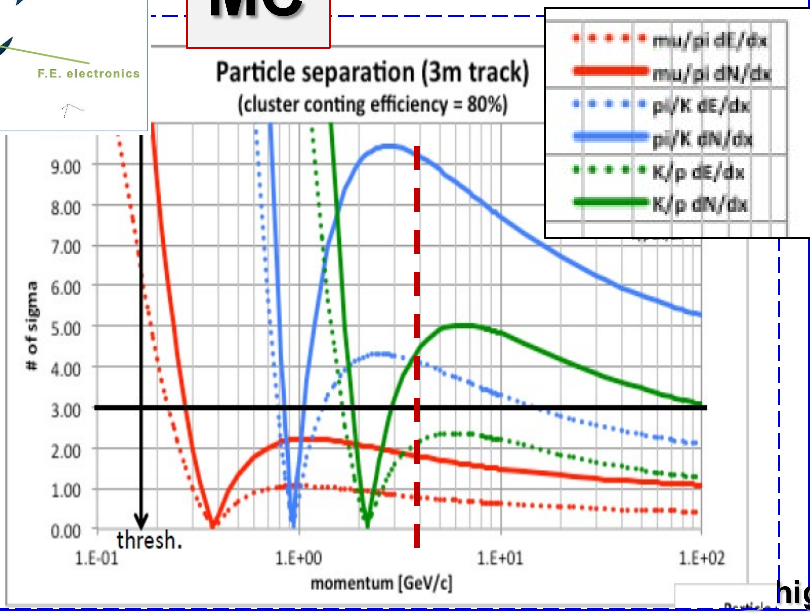


Cluster counting ?

DRIFT CHAMBER, 3 m long, gas: 90% He - 10% iC4H10



MC



F. Grancagnolo
INFN – Lecce, ITALY

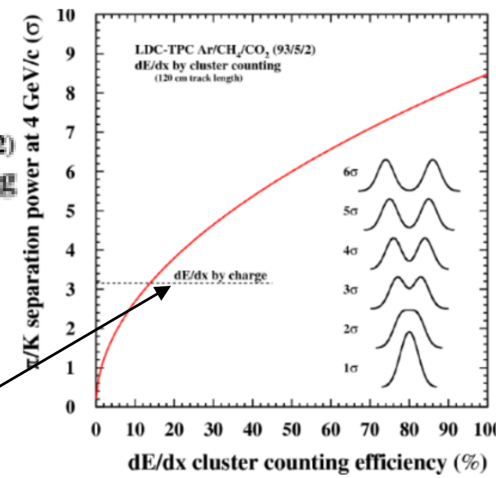
WG11 Detector Design Meeting
CERN
17 October 2016

Cluster counting in a TPC ?

namely, cluster counting with smearing due to diffusion

4 GeV/c K-π

LDC-TPC $Ar/CH_4/CO_2$ (93/5/2)
dE/dx by cluster counting
(120 cm track length)



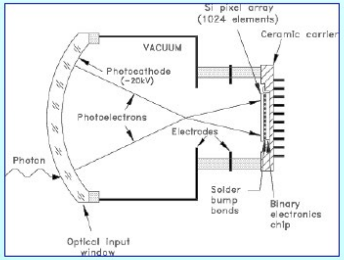
dE/dx

T. Hemmick, EICUG 2017

Addressing the photon detector issues

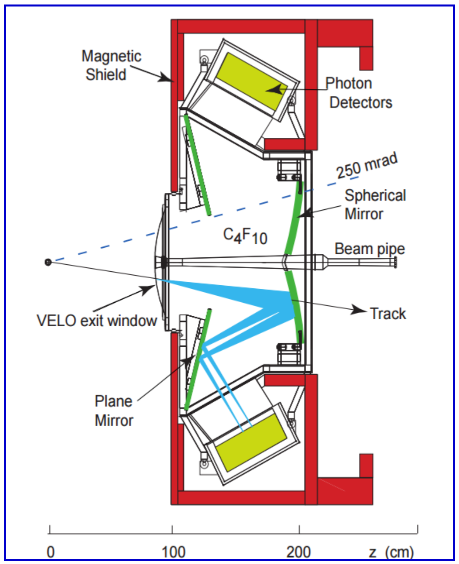
PMTs & MAGNETIC FIELD

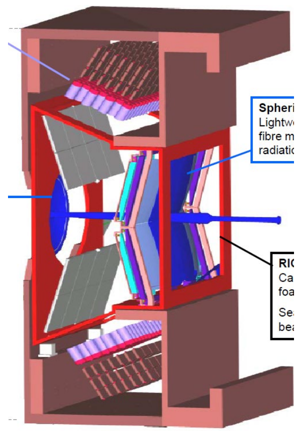
LHCb



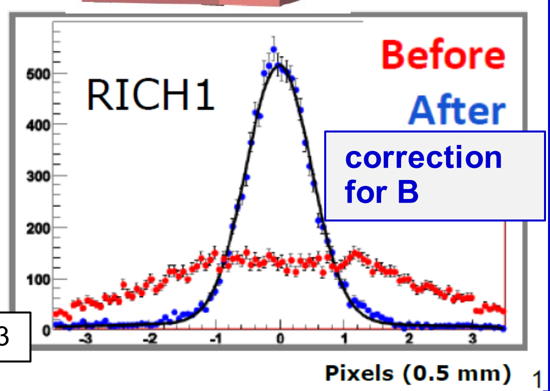
HPM, LHCb custom
1024 anods

Impressive mag. shielding





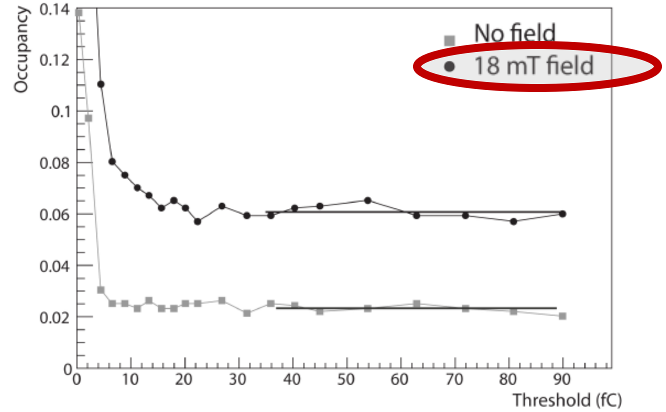
Nevertheless:



A. Papanestic, RICH 2013

COMPASS

P. Abbon et al., NIMA 616 (2010) 21



MAPMT type R7600-03-M16 by Hamamatsu

Individual soft iron shielding → B < 2 mT (external B ~ 20 mT)

ABOUT SINGLE PHOTON DETECTORS

3 families (grouping by technologies)

Vacuum based PDs

- **PMTS** (SELEX, Hermes, BaBar DIRC, NA62)
- **MAPMTs** (HeraB, COMPASS RICH-1 forward region, LHCb upgrade, GlueX, CLASS12, Panda forward-RICH)
- **Hybride PMTs** (LHCb)
- **HAPD** (BELLE II aerogel-RICH)
- **MCP-PMT** (BELLE II barrel: TOP detector)
- **LAPPDs – large size MCP-PMTs, development ongoing**

Gaseous PDs

- **Organic vapours - in practice only TMAE and TEA** (Delphi, OMEGA, SLD CRID, CLEO III, …)
- **CsI and open geometry** (HADES, COMPASS, ALICE, STAR, JLAB-HALL A)
- **CsI and MPGDs** (PHENIX HBD, no imaging, NEW: COMPASS RICH-1 2016-17 upgrade)

SiPMs

- **Silicon PMs** (not used so far in any experiment)
  - radiation hardness , intrinsic noise
  - cooling to moderate them → more material, complexity

A FEW WORDS ABOUT SINGLE PHOTON DETECTORS
cont.

Time resolution (σ)

- PMTs, MAPMTs >/~ 0.3 ns
- MCP-PMT <100 ps
- SiPM <100 ps
- MWPCs >/~ 20 - 400 ns
  - FE dependent, ballistic deficit implications (*)
- MPGDs ~ 7-10 ns (INTRINSIC)

(*) COMPASS – Gassiplex 400 ns, ballistic def. 50%
APV25 20ns, ballistic def. 25%

Effective QE range

- Vacuum-based devices:
  λ > 300, 250, 200 nm
  [also solar-blind]
- Gaseous devices (CsI):
  λ < 205 nm

Operation in magnetic field

- PMTs, MAPMTs, HPMTs NO
- MCP-PMT YES
- MWPCs, MPGDs YES
- SiPM YES

COSTS

- Gaseous (*) - \$ (0.2-0.4 M / m^2)
- MAPMTs - \$\$ (0.5-1 M / m^2)
- SiPM - \$\$ (0.8-1 M / m^2)
- MCP-PMT - \$\$\$ (???)
  - LAPPD - \$\$ (0.8-1 M / m^2)

(*) gas system, mirrors more DEMANDING → expensive

MORE ABOUT SINGLE PHOTON DETECTORS cont.

Any source of noise compromises PID efficiency and purity

- **Here shown making use of LHCb experience**

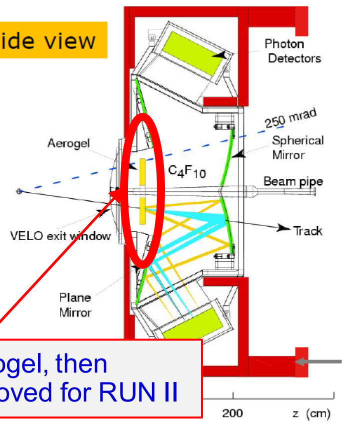
LHCb

RICH 1 — Acceptance 25-300 mrad

2 Detectors
3 Radiators

RICH 2 — Acceptance 15-120 mrad

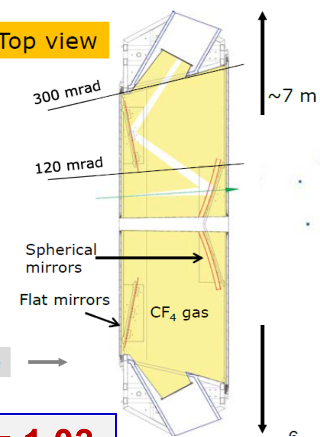
Side view



Aerogel, then removed for RUN II

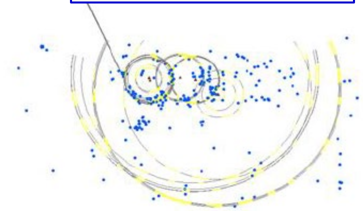
Note Scale Difference

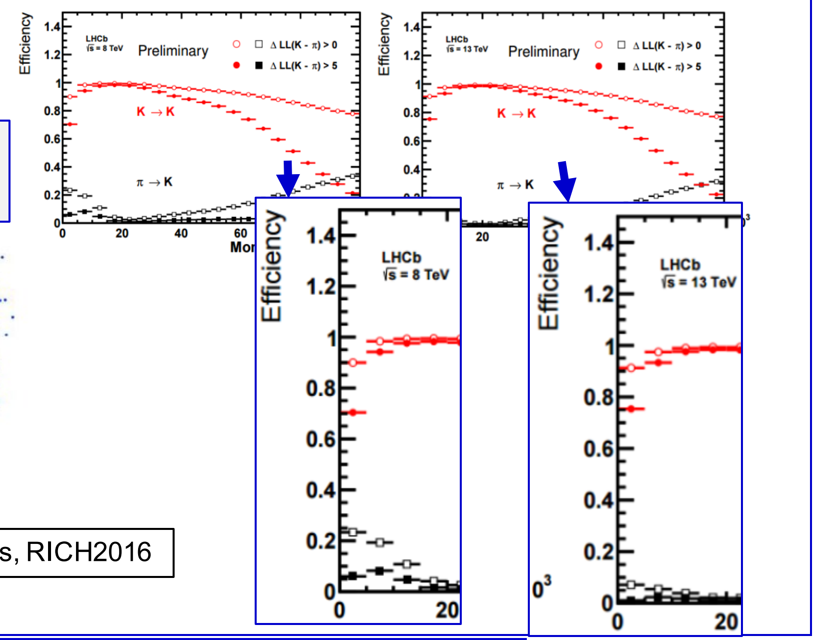
Top view



n = 1.03

Image RICH1 In RUN I





A. Papanestis, RICH2016

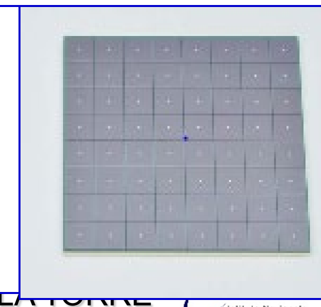
Aerogel rings very big

- Many photons, many track/photon combinations

Intrinsic noise rate, hits per m² in a time window of 10 ns

- **MAPMTs (cut to reject cross talk with only 5% photoelectron loss) ~0.1** (information source: COMPASS)
- **Gaseous (cut at 3 σ noise) : < 20** (information source: COMPASS)
- **SiPM (S13361-3050-08, room temperature, no ageing): 500** (information source: Hamamatsu data sheet)

MCCPs by Hamamatsu, 70% active area , Pixel size: 3 x 3 mm²



MAPMT : Gaseous : SiPM = 1 : 200 : 5000

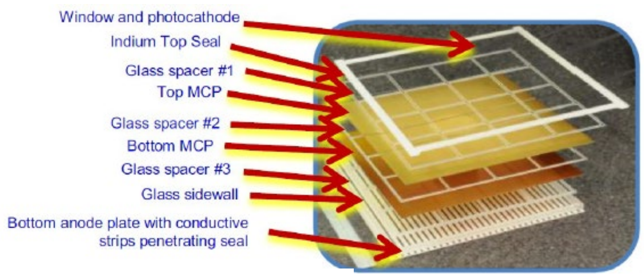
LAPPD, an OPTION ?

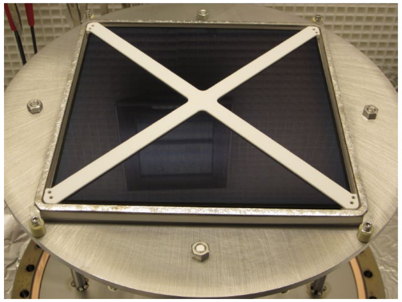
MINOT, Pisa Meeting 2018

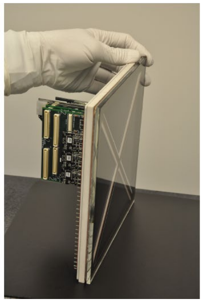
B.W. Adams et al., arXiv:1603.01843

LAPPD

(20x20 cm^2) MCP-PMTs







GEN I Strip r-o

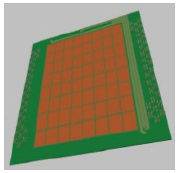
LAPPD #25 Performance Summary

Parameter	LAPPD 25
MCP resistance (Entry/Exit; MΩ)	10.7 / 14.2 MΩ at 875 V
QE	@365 nm: Max: 10%, Mean: 7.1%, s = 0.8% @455 nm: Mean: 10.2%
Gain	7.5×10^6 @ 850/950 V (entry/exit)
Dark rate (Single 13.5 cm2 strip)	9.5 Cts/s cm2 @ 50 volts on the P/C, 850 V/MCP, and Threshold of 7.6x105 gain
After pulses	Typical for MCP PMT – about 3.5%
Along-strip **Spatial Resolution** Cross-strip	2.8 mm RMS (measured as 33.4 psec) 1.3 mm RMS
Time Resolution	64 psec resolution TTS MCP Pulse Rise time: 850 psec, FWHM: 1.1 nsec

GEN II Capacitive Coupling

A thin metal DC ground plane is deposited onto the inside of the detector.

User-designed read-out elements



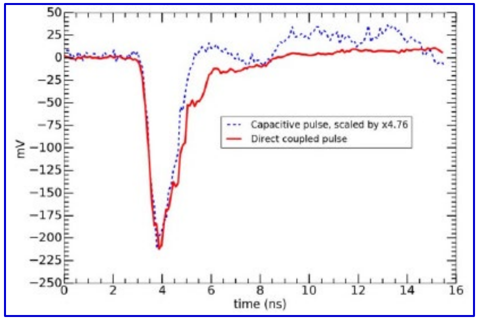


Table 1 - LAPPD Pricing Schedule (05-18-2019)

# Sold	Unit Price	Sales
1	$ 50,000	$ 50,000
2	$ 47,044	$ 94,088
3	$ 43,440	$ 130,319
4	$ 41,461	$ 165,842
5	$ 40,111	$ 200,557
6	$ 39,095	$ 234,571
7	$ 38,284	$ 267,988
8	$ 37,611	$ 300,890
9	$ 37,038	$ 333,343
10	$ 36,540	$ 365,398
20	$ 36,100	$ 721,995
50	$ 33,334	$ 1,666,694
75	$ 30,000	$ 2,250,007
100	$ 28,633	$ 2,863,335
300	$ 27,702	$ 8,310,468
500	$ 24,414	$ 12,206,898
750	$ 23,021	$ 17,265,691
1000	$ 21,972	$ 21,972,132

NEW

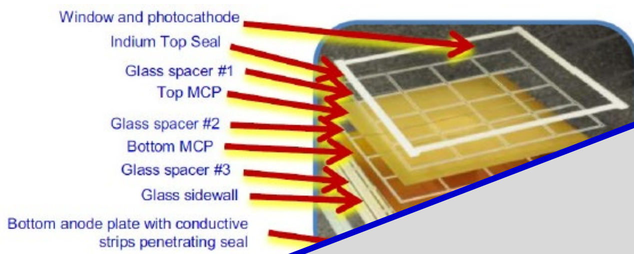
LAPPD, an OPTION ?

MINOT, Pisa Meeting 2018

B.W. Adams et al., arXiv:1603.01843

LAPPD

(20x20 cm^2) MCP-PMTs



LAPPD #25 Performance Sum

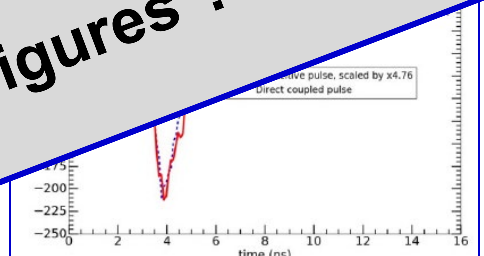
Parameter	
MCP resistance (Entry/Exit; MΩ)	
QE	

GEN I Strip-o

GEN

A thin m
plane is dep
inside of t

User-designe
out elements



OPEN QUESTIONS

1. **Will the development be continued up to full maturity?**
2. **What about the rate capability in the generation-2, namely the LAPPDs with resistive anode?**
3. **Cross-talk level with small pads ?**
4. **Ageing figures ?**

		88
		300,890
		$ 333,343
	36,540	$ 365,398
	$ 36,100	$ 721,995
50	$ 33,334	$ 1,666,694
75	$ 30,000	$ 2,250,007
100	$ 28,633	$ 2,863,335
300	$ 27,702	$ 8,310,468
500	$ 24,414	$ 12,206,898
750	$ 23,021	$ 17,265,691
1000	$ 21,972	$ 21,972,132

h-PID at HIGH p → RICH with GASEOUS RADIATOR

- **Cherenkov imaging detectors**
  - Gaseous RICH with focalization — p up to 50-100-300 GeV/c
  - Proximity focusing RICH — p up to 5-6 (8?) GeV/c
  - DIRC & DIRC derived schemes — p up to 5-6 GeV/c
- **TOF**
  - Classical (example: 4 m, 30 ps) — p up to 4-5 GeV/c
  - TORCH (DIRC-like TOF, 10 m 12.5 ps) — p up to ~15 GeV/c
- **dE/dx**
  - Traditional (example: ALICE TPC) — p up to 5-6 GeV/c
  - Cluster counting (example: MC for the CeeC IDEA concept, to be confirmed) — p up to >100 GeV/c