Anti-Deuteron identification in Space with Helium calorimeter

ADHD

(Anti Deuteron Helium Detector)

Advances in Space AstroParticle Physics 2023
Frontier technologies for particle measurements in space

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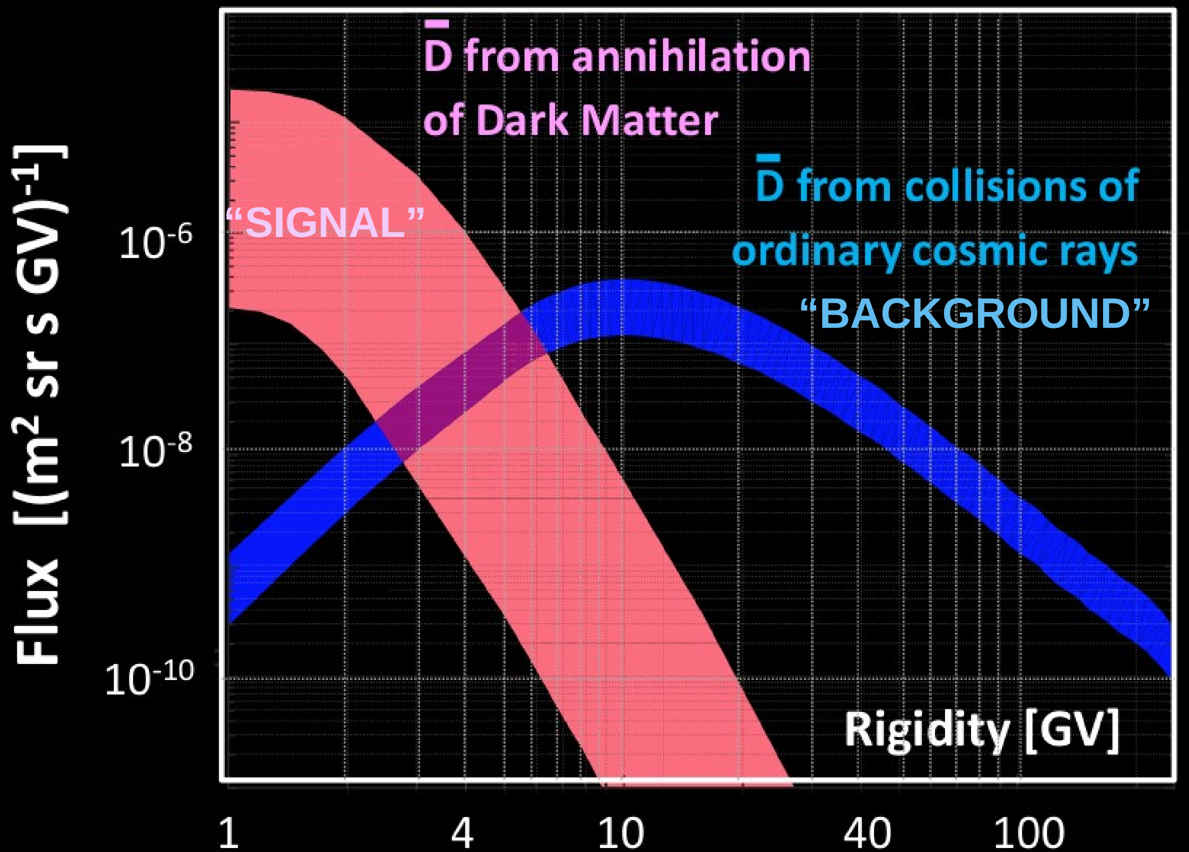
Anti Deuterons in Cosmic rays

Anti Deuterons have been proposed as an almost background free channel for Dark Matter indirect detection



■ Dark Matter model:
F. Donato et al., Phys. Rev. D, 62 (2000) 043003

■ Collisions of CR model
K. Blum et al., Phys. Rev. D 96 (2017) 103021)

The Anti Deuterons Flux is < 10^{-4} of the Antiproton Flux.

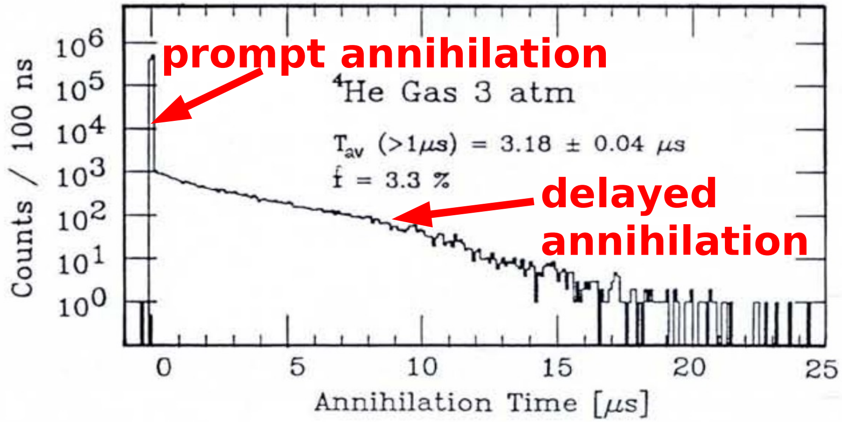
Additional background rejection needed

Helium metastable states

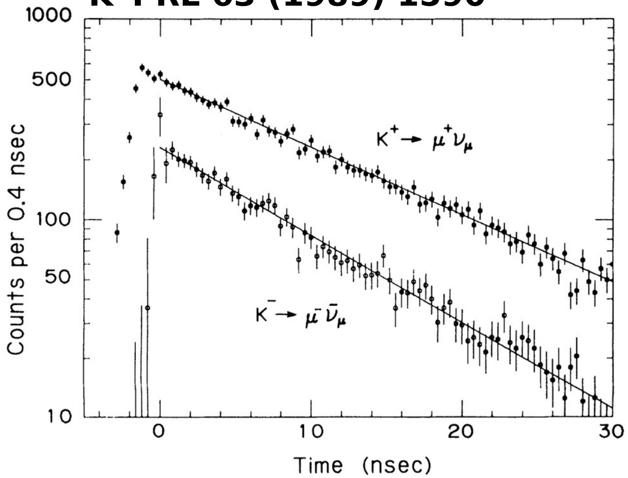
-In matter lifetime of stopped $\bar{p}$ is ~ps
-In liquid/gas He delayed annihilation: few μs
(~3.3% of the $\bar{p}$)(discovered @ KEK in 1991)

Observed also for K^- , π^- and expected for $\bar{D}$

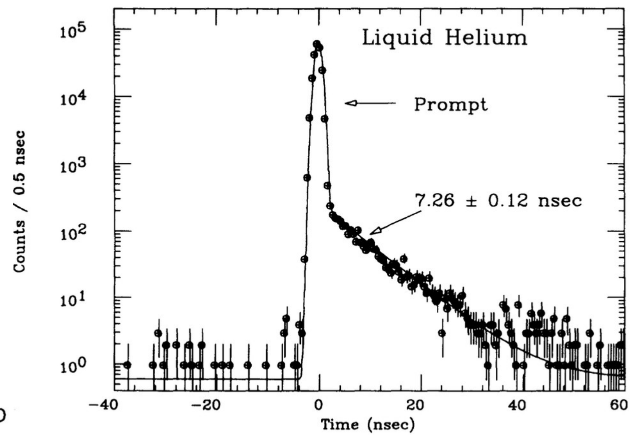
ASACUSA experiment at CERN use these metastable states to measure $\bar{p}$ mass



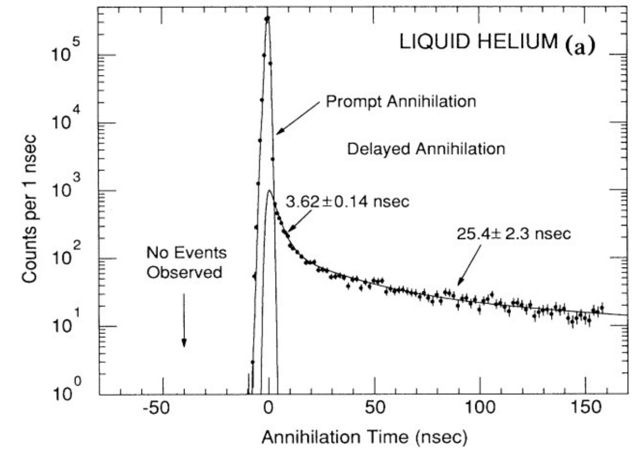
K^- PRL 63 (1989) 1590



π^- PhysRevA 45(1992)6202



$\bar{p}$ PRL 67 (1991) 1246



a signature for Z=-1 antimatter captures in He is a ~μs delayed energy release

Why He is a special target?

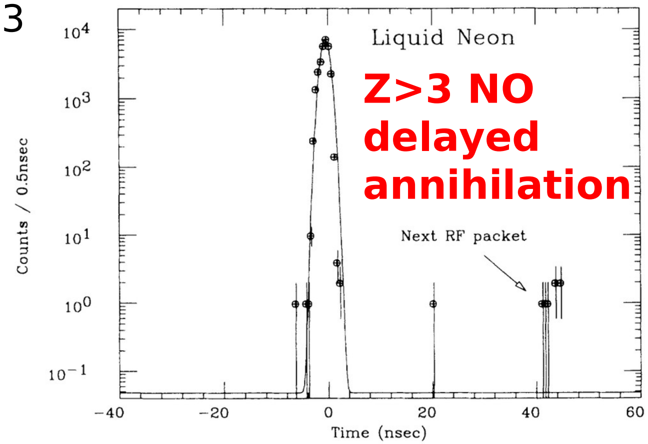
THEORY: Phys. Lett. 9 (1964) 65 PRL 23 (1969) 63

1) The electron is on 1s ground state, while the $\bar{p}$ (or also π^-,K^-,$\bar{d}$) occupies a **large n** level (~38 for $\bar{p}$) (~same bounding energy of the ejected e-)

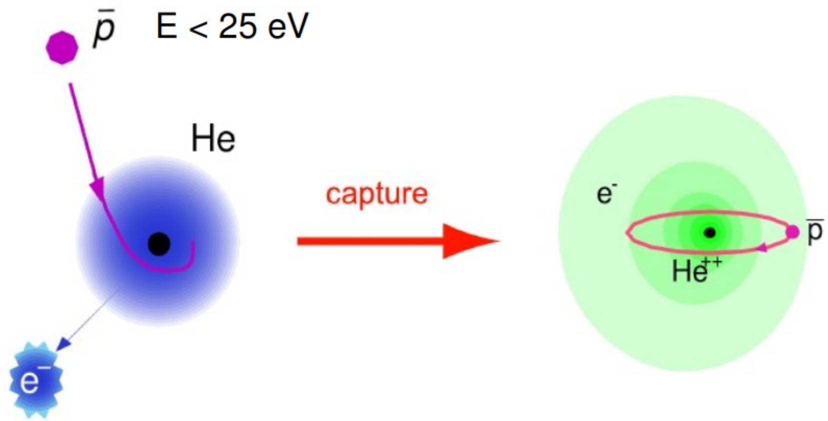
2) the Auger decay is suppressed as well, due to large level spacing of the remaining electron (~25 eV) compared to the small (~2 eV) n→n-1 level spacing of $\bar{p}$

3) the remaining electron in $\bar{p}$He suppresses the collisional Stark effect $(p\bar{p})_{nl} + H \Rightarrow (p\bar{p})_{nl'} + H$ (the main de-excitation channel for $p\bar{p}$ system)

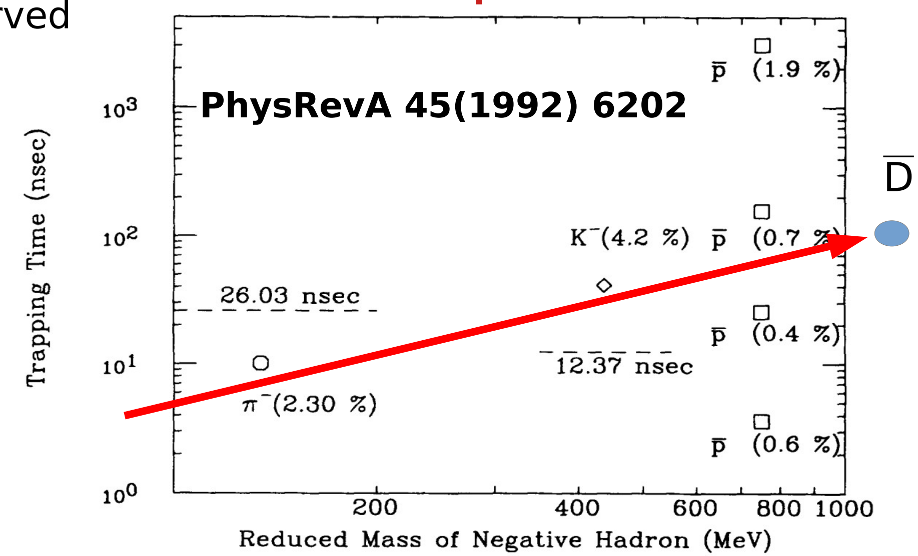
4) Metastability is not expected and not observed for Z>3



Metastability for Li^+ target? → still not found
(it could be a very interesting SOLID target)

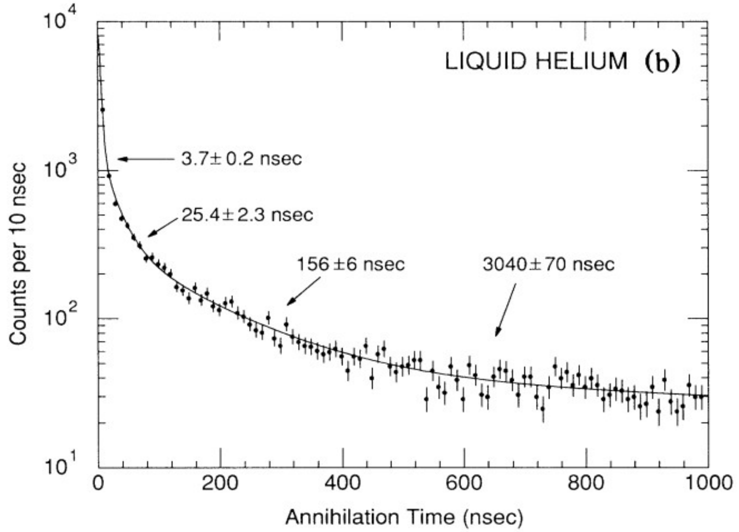


5) expected lifetime increases as squared of the reduced mass => **expected for antideuterium**



Lifetime & fraction vs pressure

Decay is NOT a single pure exponential:



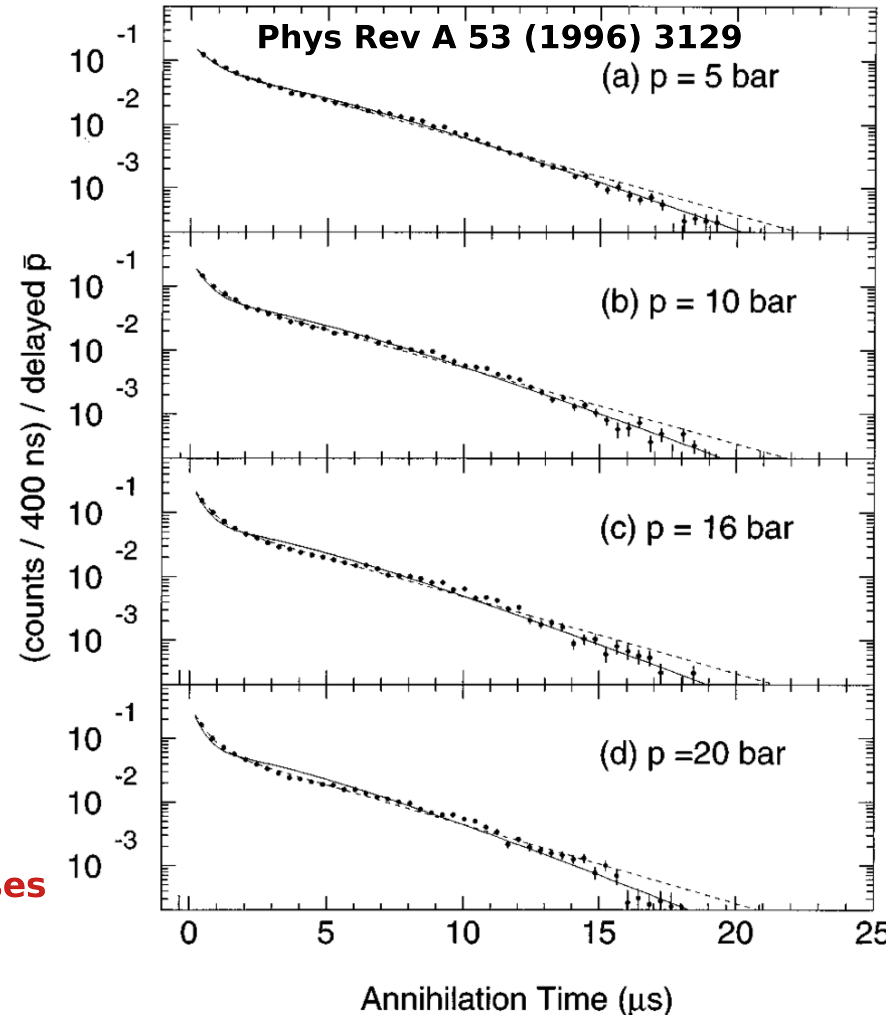
Roughly approximated by 2 components:
(slow and fast)

$$n(t) = A[f\lambda_f \exp(-\lambda_f t) + (1-f)\lambda_s \exp(-\lambda_s t)]$$

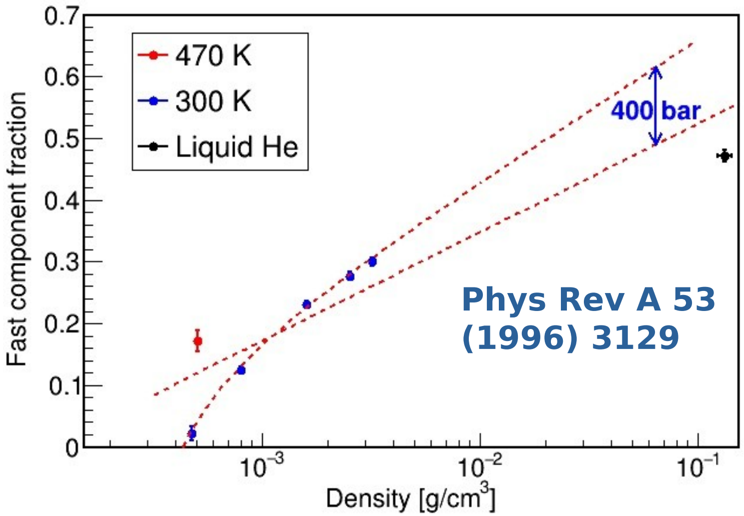
Gas impurities reduces the slow component

Increasing Pressure → Fast component increases

He @ room Temperature



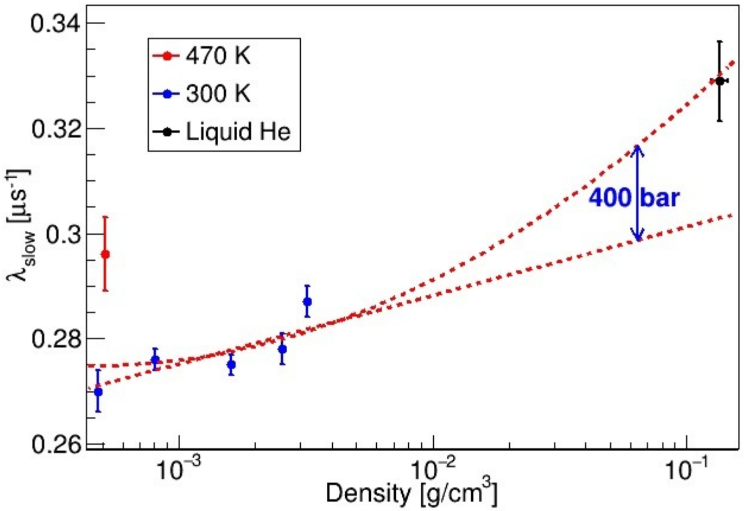
Lifetime & fraction @ 400 bar

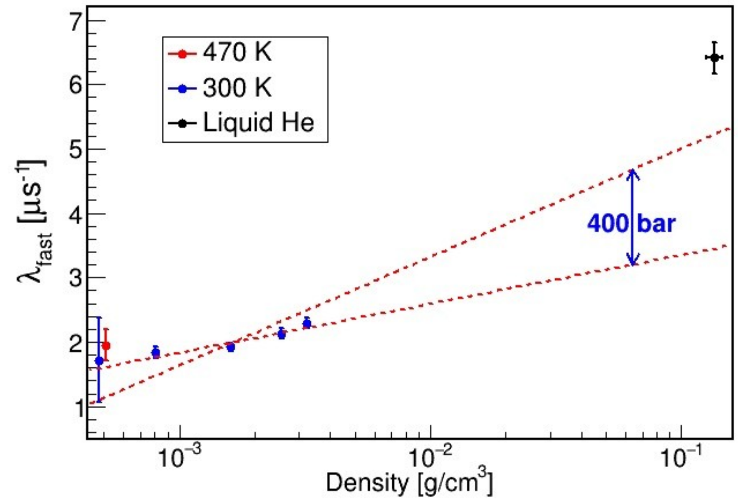


Existing measurements for He gas are scarce.
using the 2 components approximation:

$$n(t) = A[f\lambda_f \exp(-\lambda_f t) + (1-f)\lambda_s \exp(-\lambda_s t)]$$

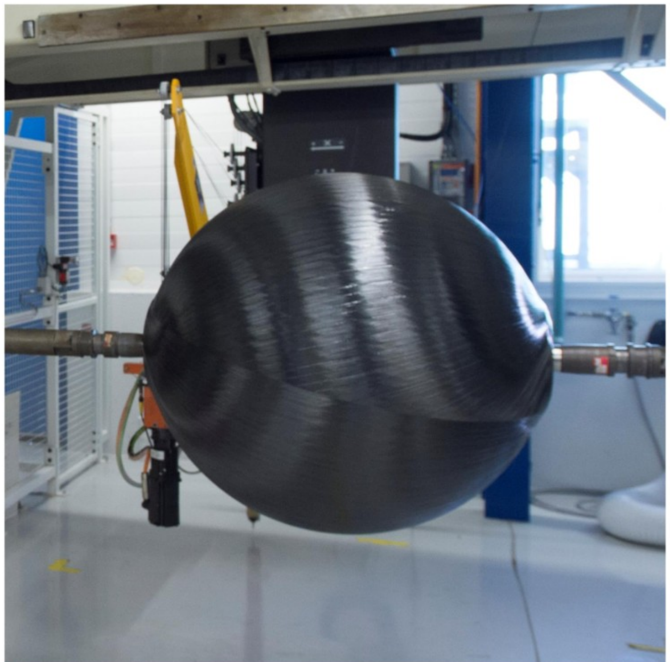
we can roughly extrapolate @ 400 bar & 300K:
A ~ 3.3% (no data found for P dependence of this)
f = 55±6%
λ_{slow} = 0.307±0.008 μs^{-1} => 3.26±0.08 μs
λ_{fast} = 4.0±0.8 μs^{-1} => 250±50ns





400 bar ⊘ = 90cm Helium tank: space qualified

arianeGROUP

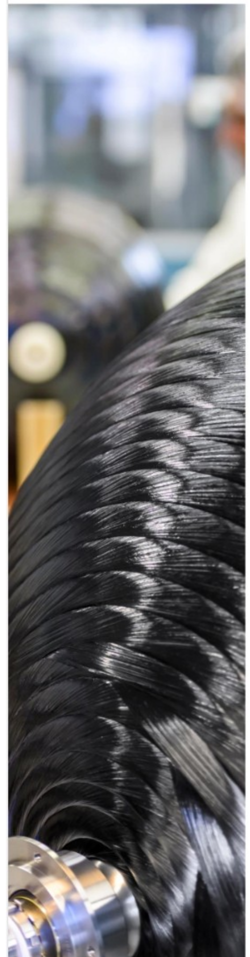


300L HELIUM TANK (MPCV)

HIGH PRESSURE TANKS PRODUCT LINE

- 108L Helium Tank (VEGA)
- **300L Helium Tank (MPCV)**
- Thermoplastic Liner Tank

Can be used for both applications, satellite or launcher.



300L HELIUM TANK (MPCV)

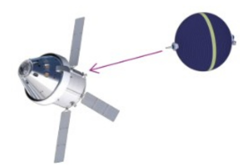
Application: Satellites & Launchers

ArianeGroup has developed and is qualifying a 300 Liters high pressure tank for MPCV (Multiple Purpose Crew Vehicule). This pressurant tank can also be used on launchers.

Characteristics	
Volume	300 Liters
MEOP	Bar 400 Safety factor 2
Burst pressure	> 800 bar
Mass	81 kg (without fixations)
External Diameter	865 mm

Our product:

- **Helium** Storage 300 L
- Developed from **Ariane 5** tank for ATV
- **Polar** Mounting
- **Manned flight** qualified (NASA)
- **ATV** : Flight Proven : (20 Tanks delivered)
- **MPCV :** Under Qualification (flight planed in 2019)



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Our activities are environmentally-friendly

A UNIQUE EXPERTISE TO SERVE OUR CUSTOMER NEEDS

- Customized solutions : gas, size, MEOP and interface
- Optimized for customers needs : mass, cost, safety and reliability
- ArianeGroup delivered more than 900 tanks without any failure

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www.ariane.group

P = 400 bar
⊘ = 87cm
M_{vessel} = 81kg
3.5g/cm²
M_{He}/M_{tot}=20% @400bar

Stored energy in the gas is ~14kg of TNT

a standard gas bottle would require >1cm of steel for such a size/pressure

310 bar ⌀ = 50cm Helium tank: ESA HeHPV project

https://artes.esa.int/projects/hehpv-helium-highpressure-vessel

Home / Projects / HeHPV (Helium High-Pressure Vessel)

HeHPV (Helium High-Pressure Vessel) - Qualification of a Helium High Pressure Tank

P = 310 bar

⌀ = 50cm → 50L

M_{vessel} = 10.8kg

Grammage 1.4g/cm^2

M_{He}/M_{tot}=16% @310bar

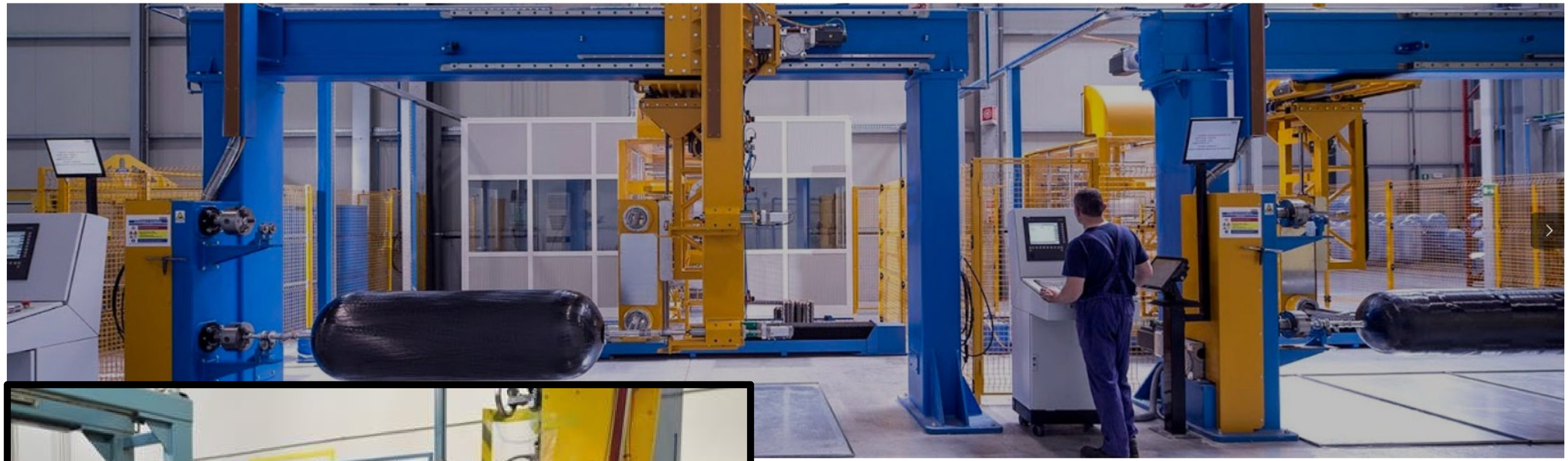
Objectives

The driving goal of the HeHPV programme is the development and qualification of a lightweight, high-performance, reliable yet cost-competitive helium tank for application in future spacecraft programmes. The applied approach enabled qualification via similarity of a volume range of 50-75 l, where the tank diameter is common for the entire range. Leak-before-burst (LBB) and burst testing with dedicated qualification models confirmed predicted failure modes and high margins of safety.

Existing and future market needs show high potential for such tanks, in particular for satellite systems, where helium tanks are required for the pressurisation of chemical propulsion systems.

Composite overwrapped pressure vessel (COPV)

Current typical application: H_2 storage tanks for automotive



Cylinders must be **light**

Faber relies on a unique +40 year track record which include a very comprehensive range of all Types of Cylinders (Type 1,2,3,4), eachone standing out for superior lightness, reliability and safety. The entire production process is controlled by Faber and performed in-house in one of our own dedicated plants. This ensures that Faber is capable of offering the right cylinder at a price that best fits the needs of our customers.

Faber company

(150km from Trento)

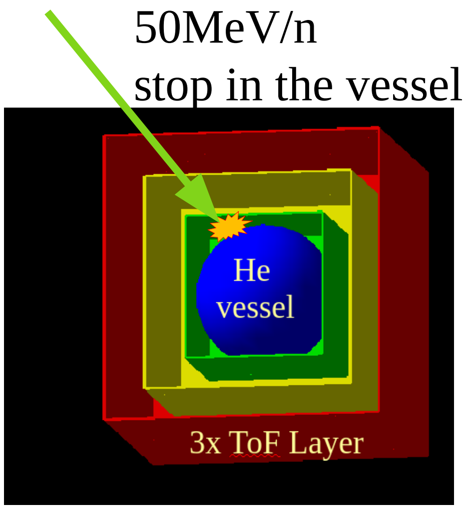
MC exercise with a SIMPLE geometry ⊘ = 90cm: Anti Deuteron He Detector (ADHD)

Preliminary Geant4 simulation:
Detector size: External ToF L = 1.5m;
ToF = 110 kg (4mm scintillator thickness)

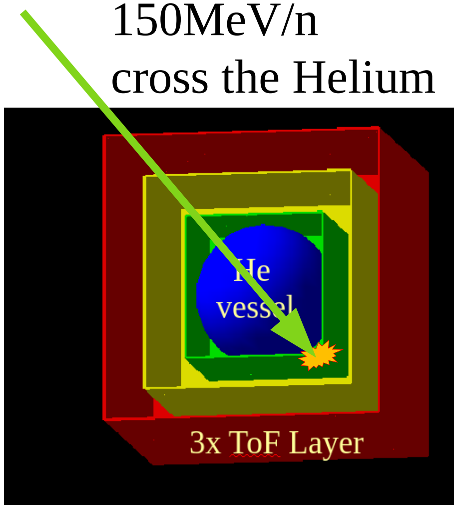
Vessel: ArianeGroup 300L@400bar = 100kg
$M_{He}/M_{detector}$= 10% (very naive, no structure here)

Kinetic energy range: 50-150 MeV/n
(threshold due to energy loss in vessel/ToF)

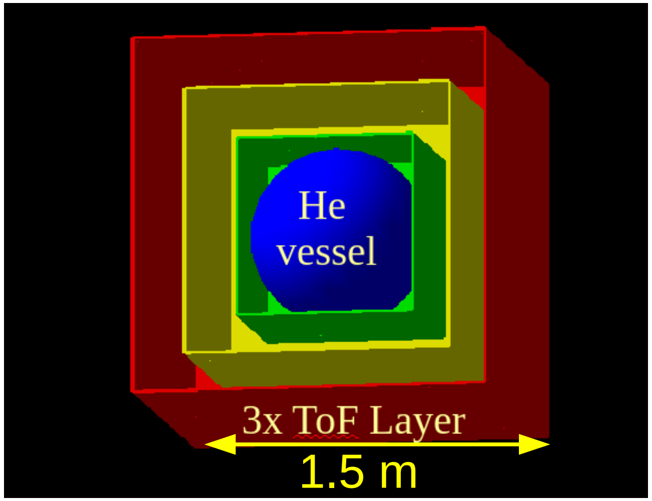
50MeV/n
stop in the vessel



150MeV/n
cross the Helium

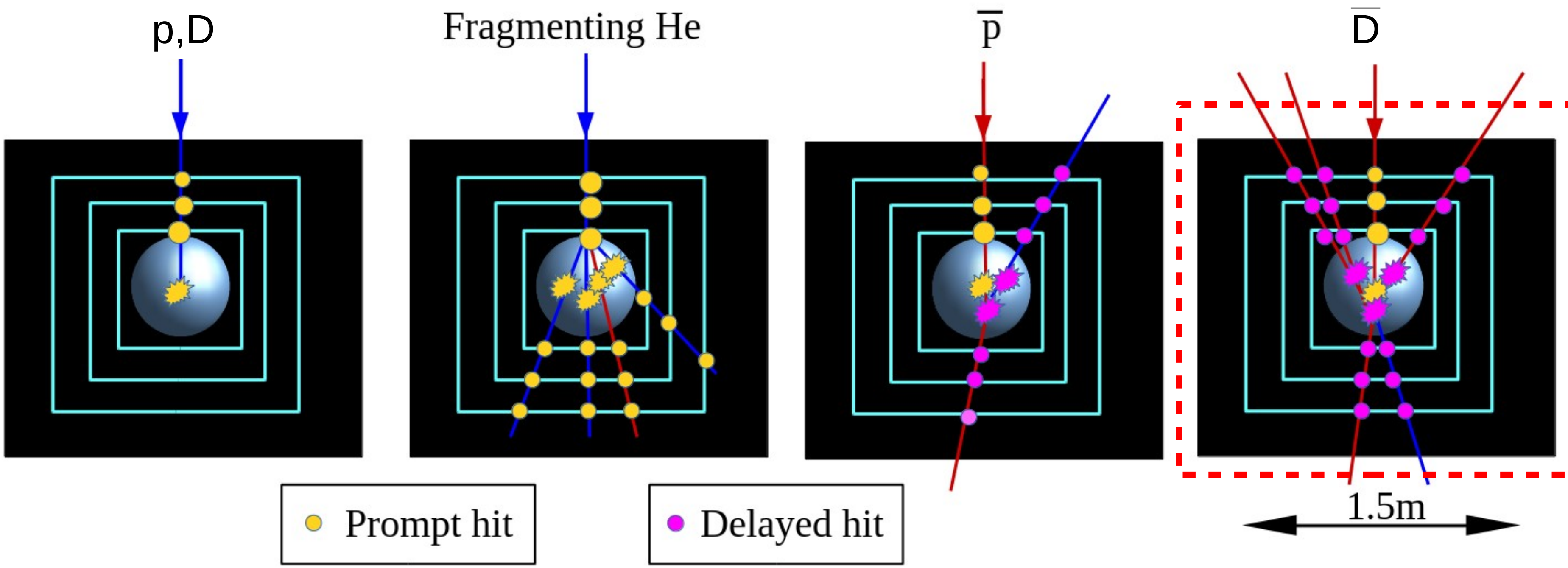


Simple Concept:
HeCalorimeter (scintillator)
3xTime of Flight (segmented) layers



**We need a light/thin vessel but we also want high Helium pressure and large vessel volume.
This imply a large force on the vessel walls and this is the main weakness of the ADHD concept.**

MC exercise with a SIMPLE geometry: Particle Identification



SIMPLE TRIGGER implementation:

A MIP release 10 MeV crossing HeCal diameter

1) Prompt HeCal Energy > 10MeV (reject MIPs)

2) only 3 prompt ToF hits (reject not stopping)

3) Delayed HeCal Energy >10MeV & <10μs (reject protons or nuclei stopping in HeCal)

AntiProton background rejection:

4) β_{ToF} vs HeCal E_{prompt}

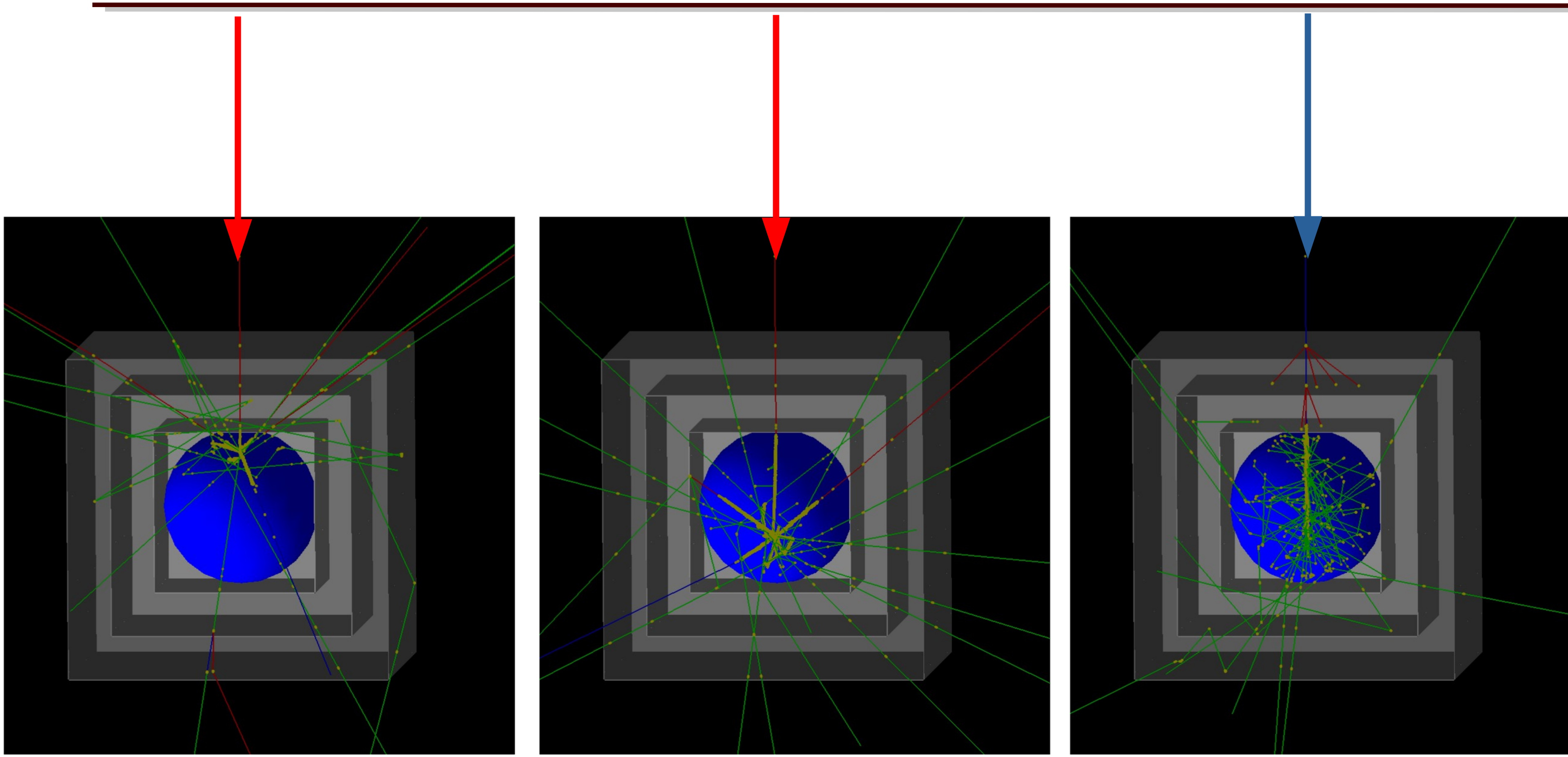
5) dE/dx ToF vs HeCal E_{prompt}

6) event topology (>3 delayed tracks)

7) HeCal E_{delay} > 350 MeV

GEANT4 event display

$\overline{\mathrm{D}}$ **(65MeV/n)** $\bar{p}$ **(230MeV)** **Carbon (600MeV/n)**



4 charged outgoing
(+ pair production)

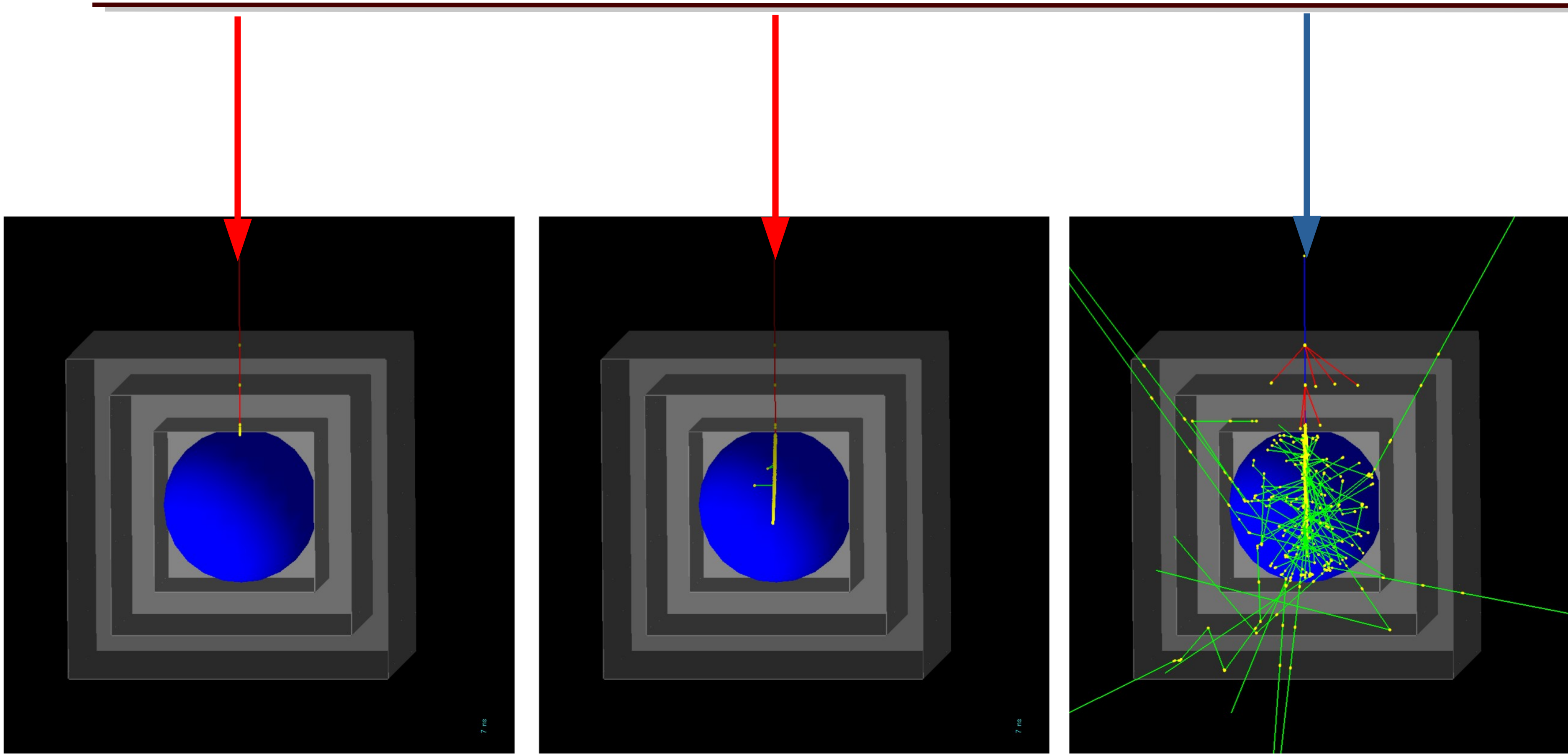
3 charged outgoing

0 charged outgoing

Negative **Positive** **Neutral** charges

[0-10] ns

$\bar{D}$ (65MeV/n) $\bar{p}$ (230MeV) Carbon (600MeV/n)



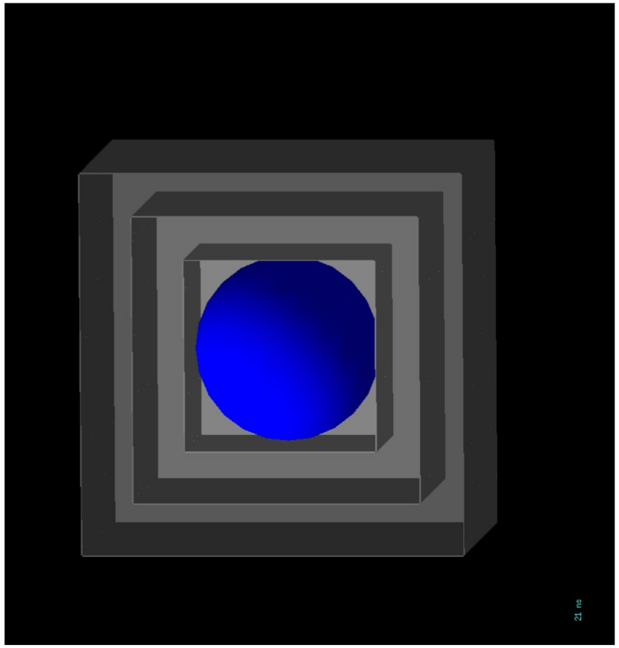
… ok it is slow …
prompt HeCal signal
3 hits in ToF

prompt HeCal signal
3 hits in ToF

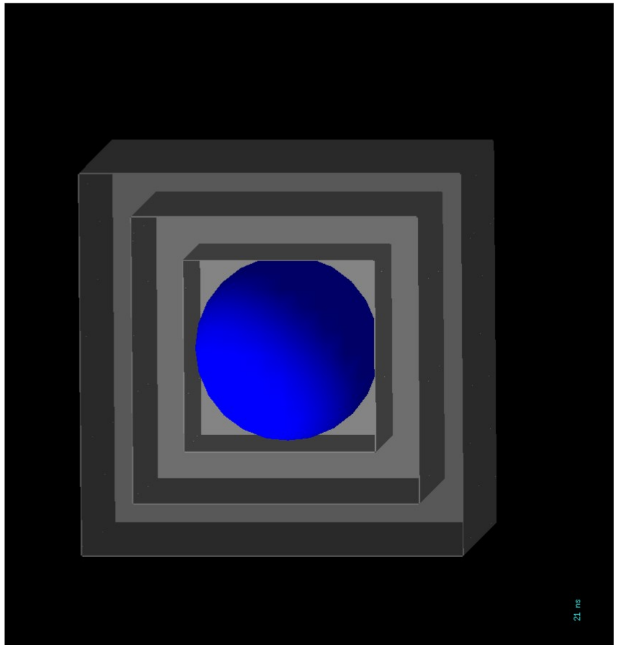
prompt HeCal signal
10 hits in ToF

[10-XX0] ns

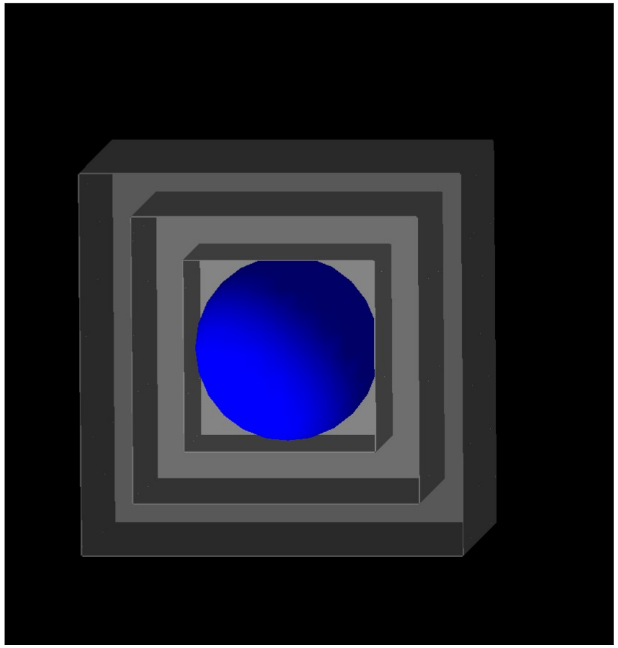
$\bar{D}$ (65MeV/n) | **$\bar{p}$ (230MeV)** | **Carbon (600MeV/n)**



Antideuteron orbiting He



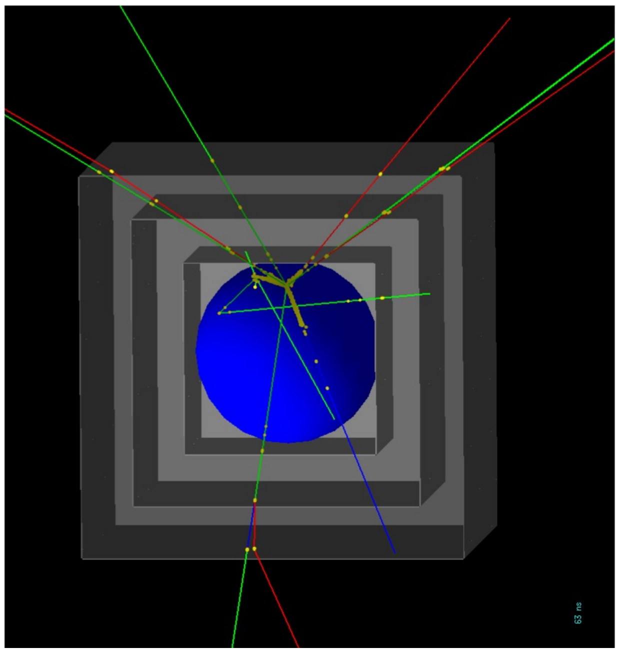
Antiproton orbiting He



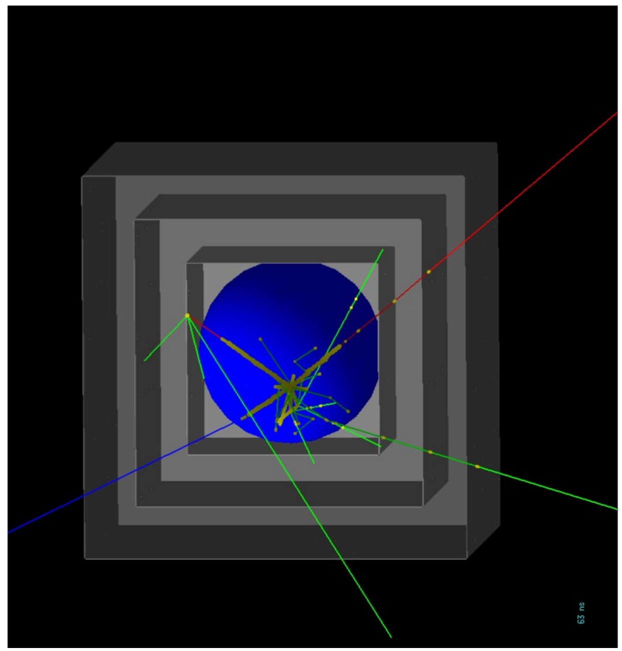
...nothing

[XX0-XX9] ns

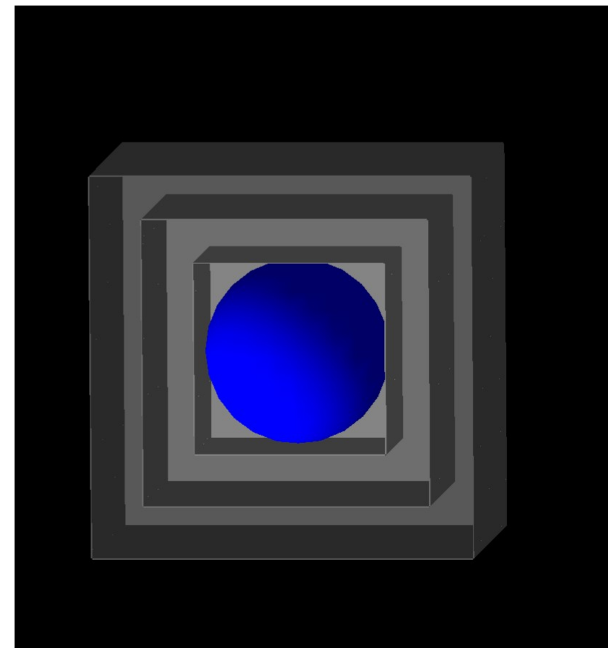
$\overline{\text{D}}$ (65MeV/n) | $\overline{\text{p}}$ (230MeV) | Carbon (600MeV/n)



Antideuteron annihilation

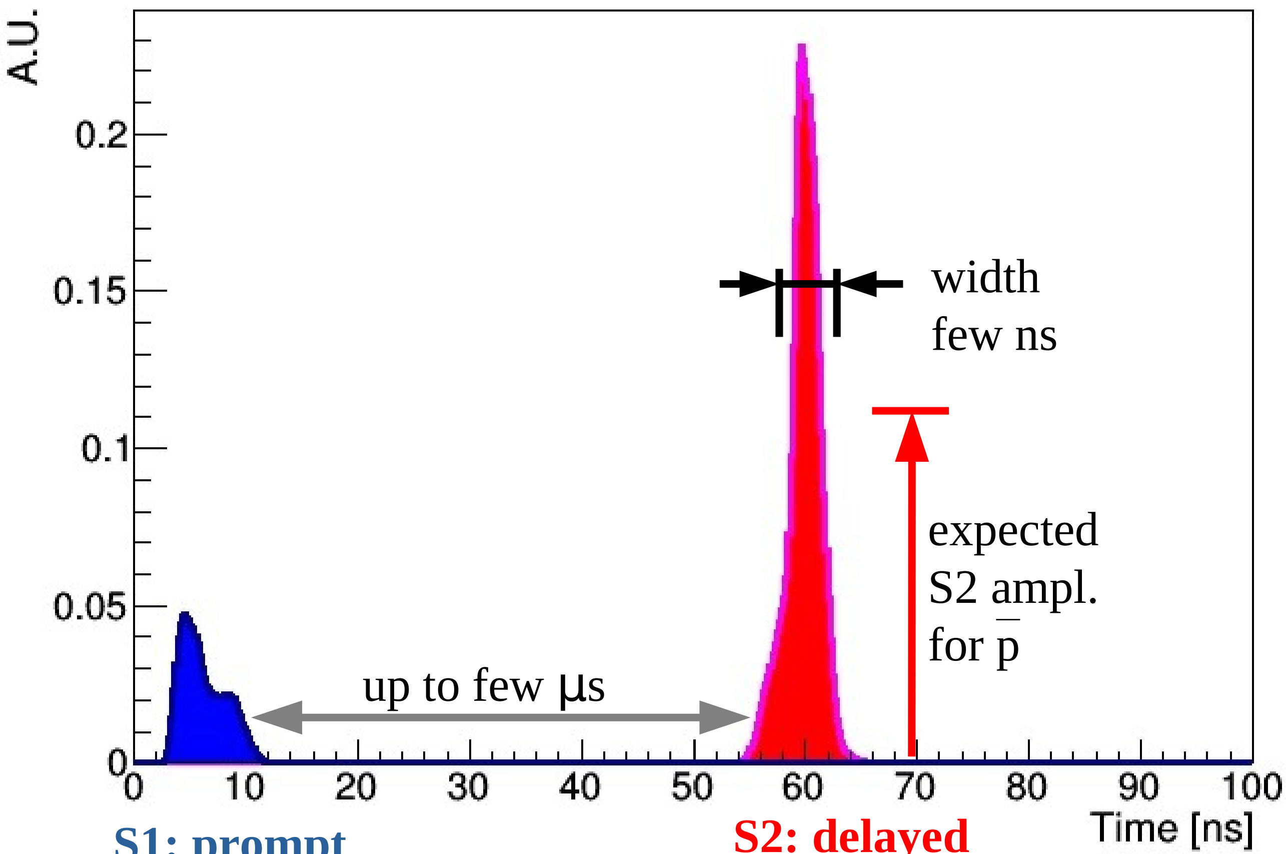


Antiproton annihilation



...nothing

Typical HeCal signature for $\bar{p}$ and $\bar{D}$

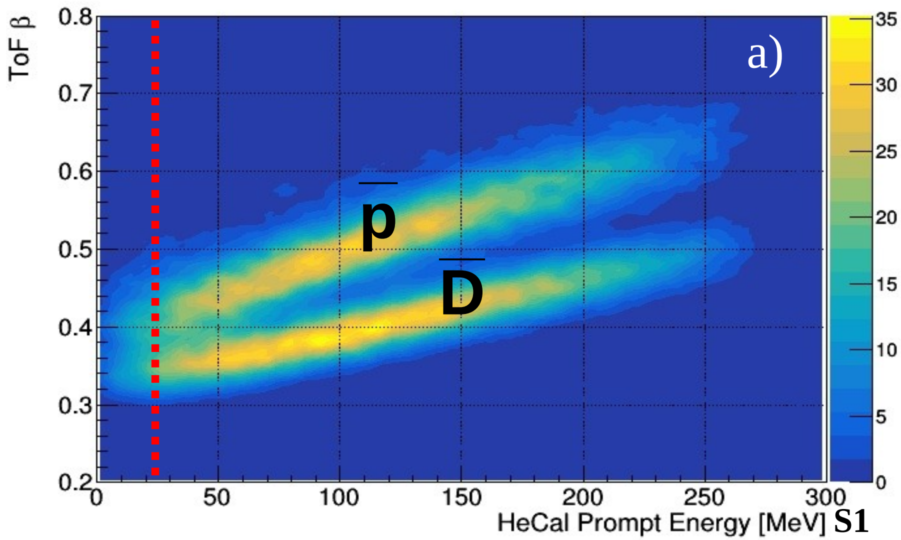


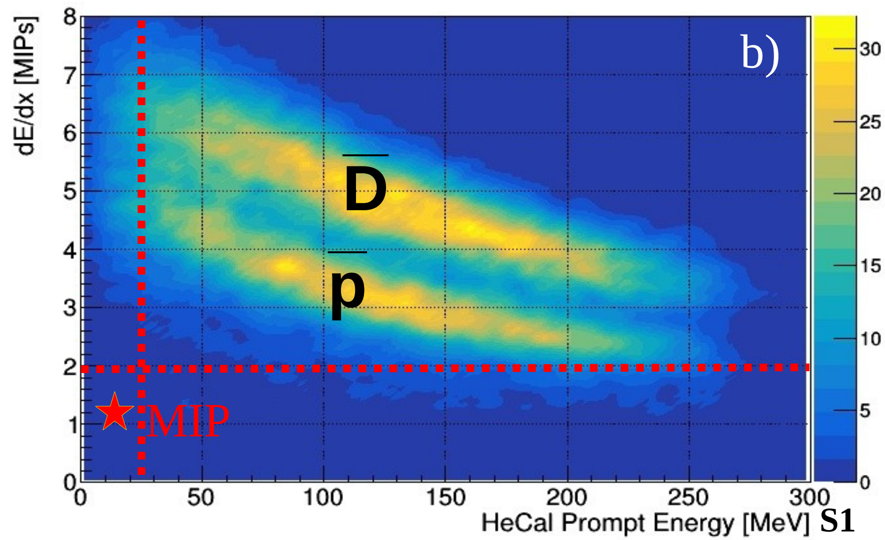
S1: prompt
$\bar{p}$ or $\bar{D}$
kinetic energy
(- energy loss)

S2: delayed
Charged π
Typ. S2 > S1
S2 and Ek not related

$\bar{p}/\bar{D}$ separation: prompt signal

★ MIP





ToF (30cm baseline & 4mm thickness):

β resolution 5% => $\sigma_{x/y}$ ~few cm & σ_T<0.1ns

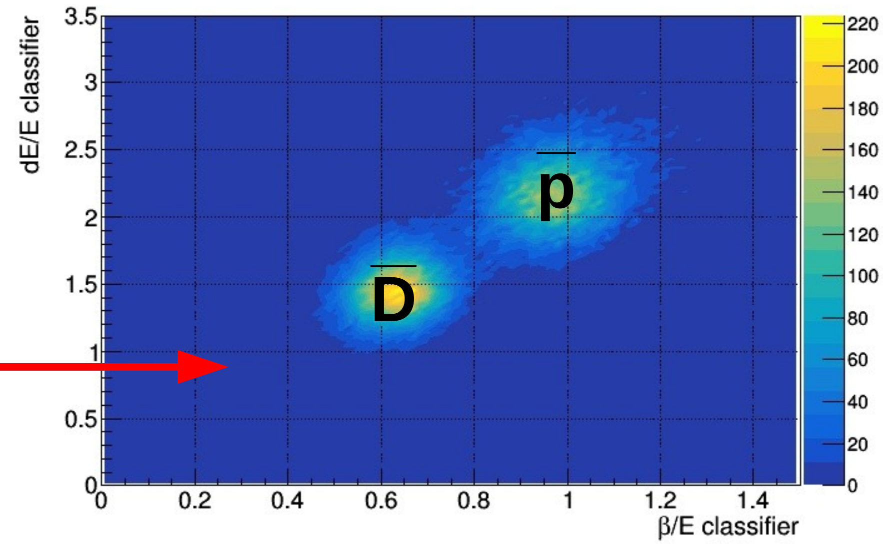
- ToF Energy resolution: 10%
- He Calorimeter Energy resolution: 10%

Parametrization of (**β** vs *E*) & *(dE/dx vs E)*

2 "independent" classifiers

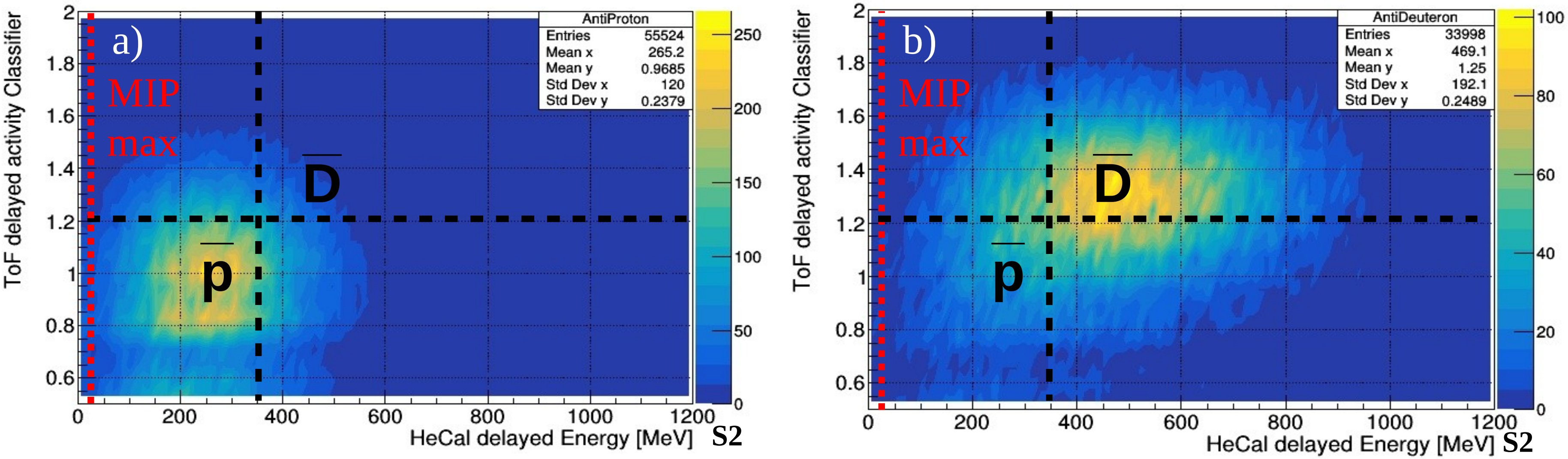
that can be combined to obtain an overall

"**Prompt signal classifier**"



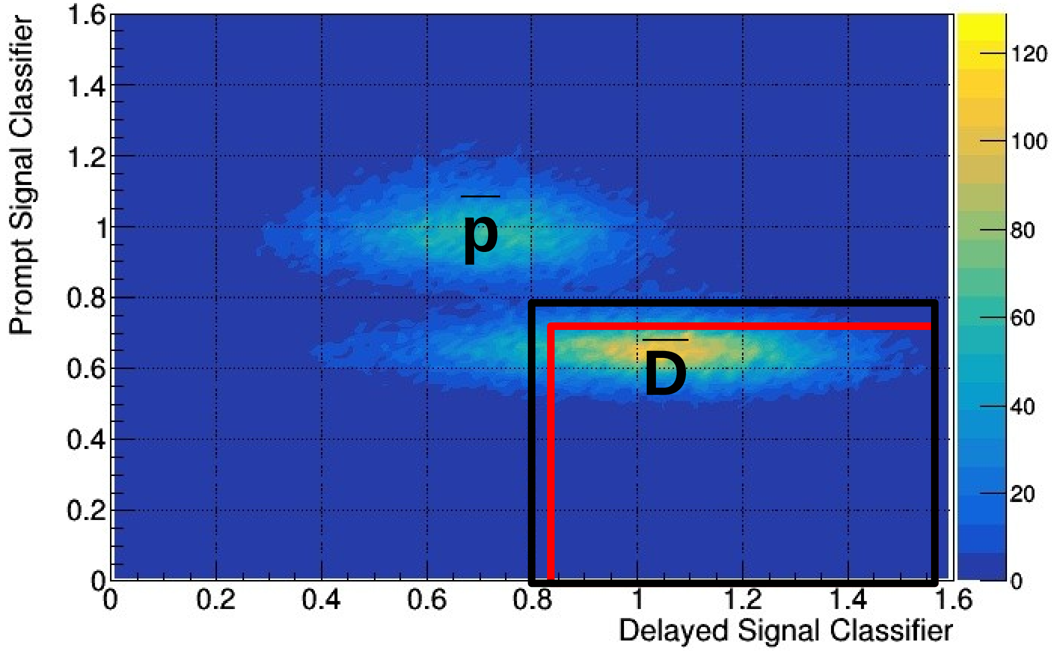
$\bar{p}/\bar{D}$ separation: delayed signal

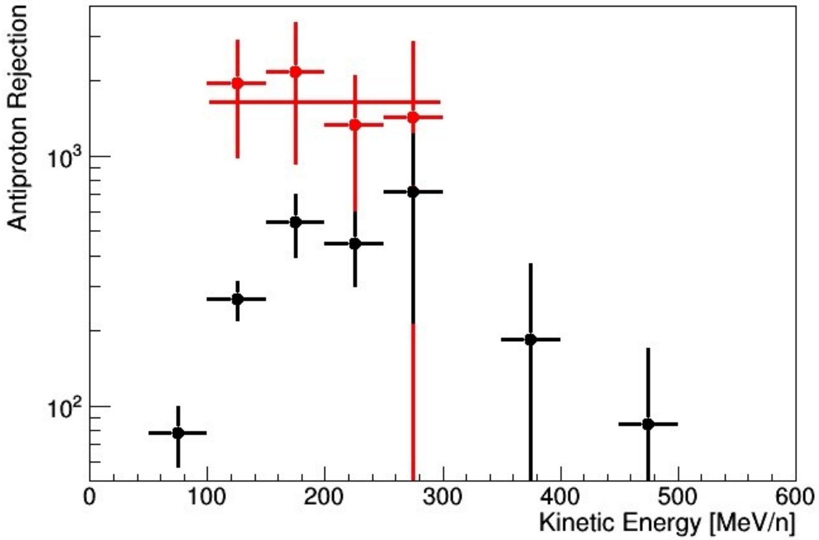
delayed signal amplitude is independent from Ekin: ~3 charged pion/antinucleon
-ToF delayed activity classifier = #ToF delayed hits ⊕ ToF delayed energy
(might improve with full track topology)

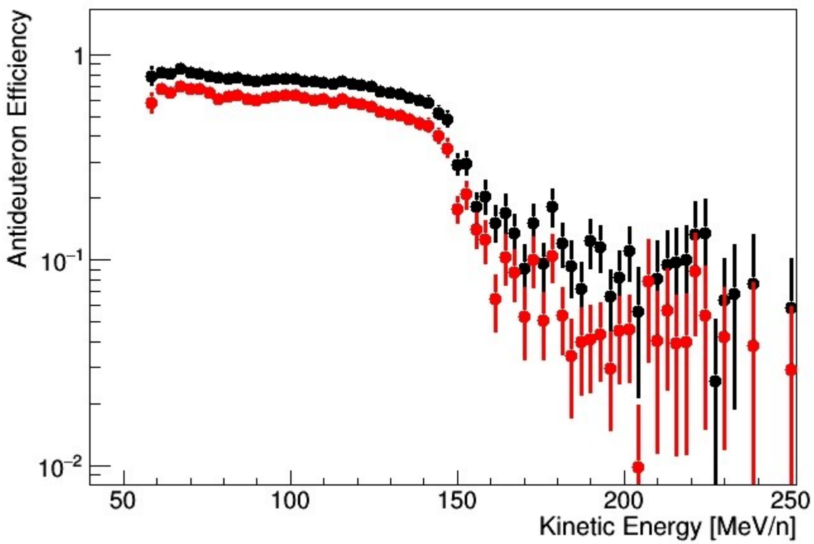


2 “independent” classifiers
that can be combined to obtain an overall
“**Delayed signal classifier**”

$\bar{p}/\bar{D}$ separation

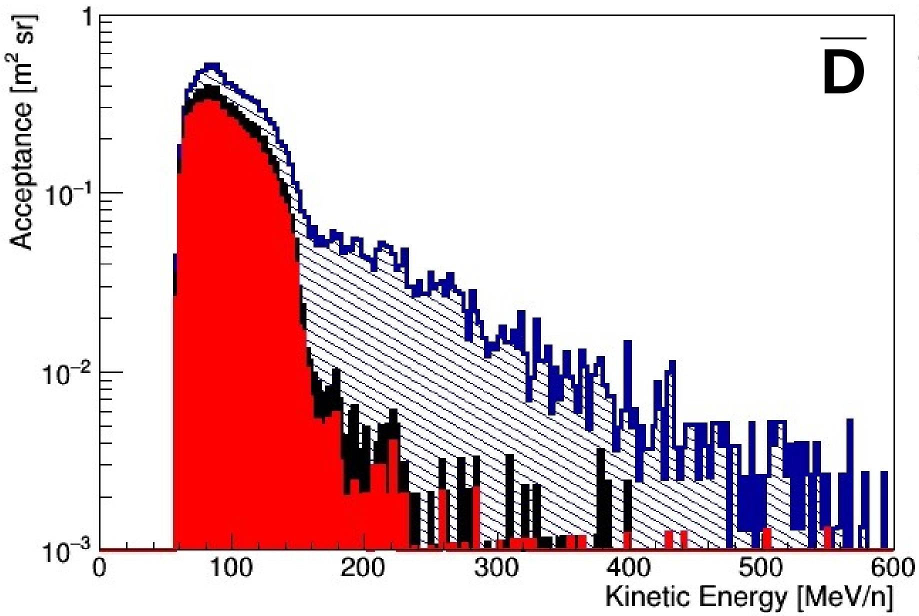


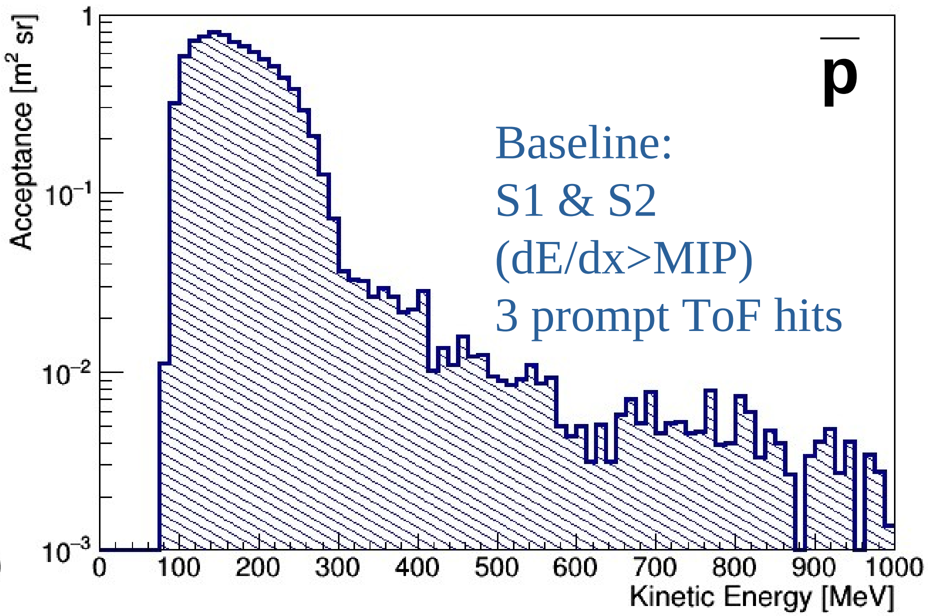




possibility to detect 1$\bar{D}$/1000 $\bar{p}$
($\bar{p}$ rejection 1500 @ 65% $\bar{d}$ efficiency)

$\bar{p}/\bar{d}$ acceptances

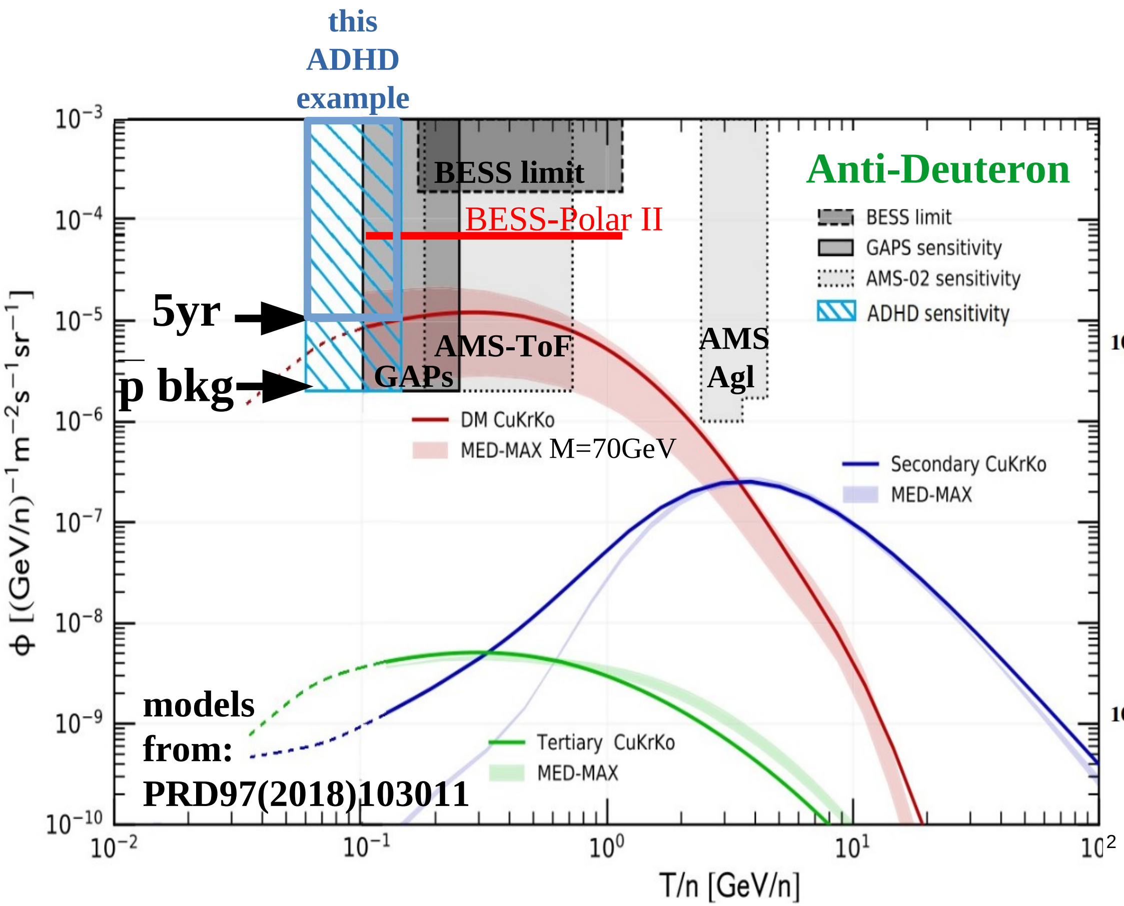


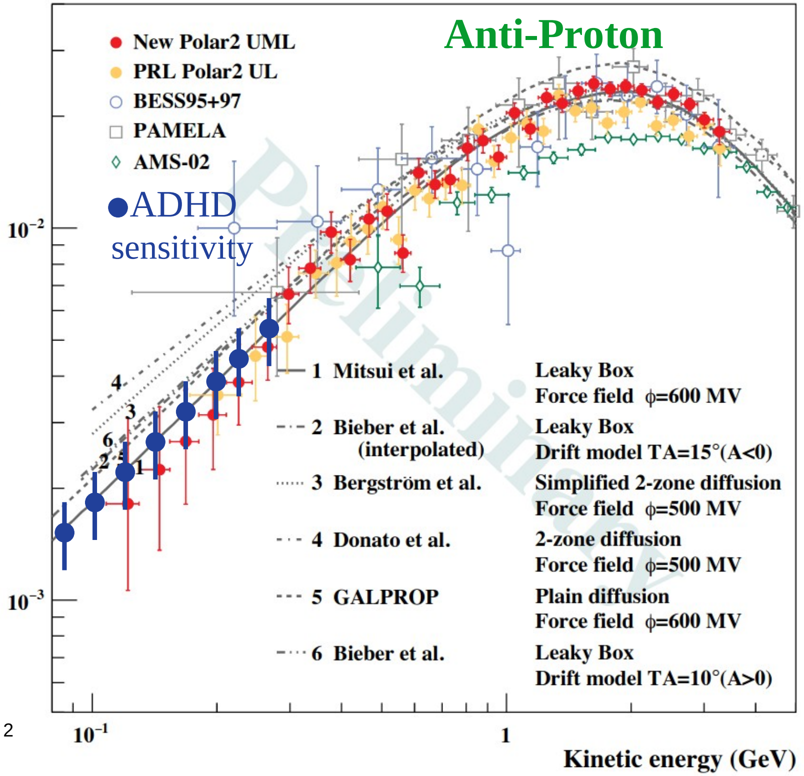


These have to be multiplied with the probability to form metastable states ~3.3%

Example of sensitivity/new measurements with 5yr data @ 0.2x0.033 m^2 sr:
-Antideuteron [50-150]MeV/n: ~10^{-5} (m^{2}s sr GeV/n)$^{-1}$ (<0.3 $\bar{p}$ background is expected)
-Antiproton: measurement in few bins in the range [100-300] MeV with < 10% error

planned sensitivity for this example (1 single ⌀ = 90cm COPV)





AMS02-GAPS-ADHD: different techniques, similar sensitivity, complementary Ek regions

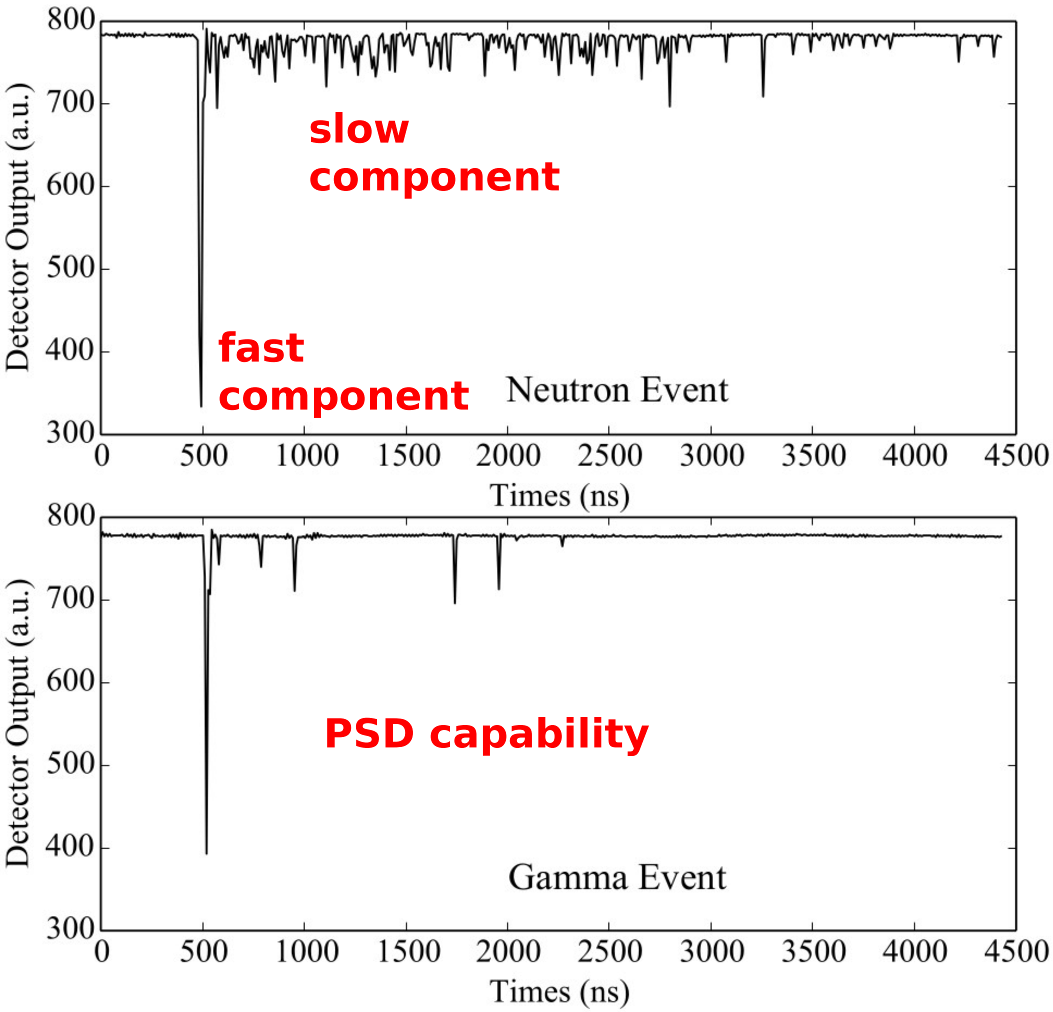
Join many signatures in a future/ultimate Antideuteron detector?

test of the performances of He calorimeter prototype with lab measurement @ INFN-TIFPA (no efforts to test the ToF)

we trust that a large ToF with σ_T<100ps is feasible

Large surface ToF detectors with few mm thickness are considered in many future projects (example AMS-100)

Scintillation in Helium



He as scintillator has a strong "fast" component (tens ns, 15000 ph/MeV)

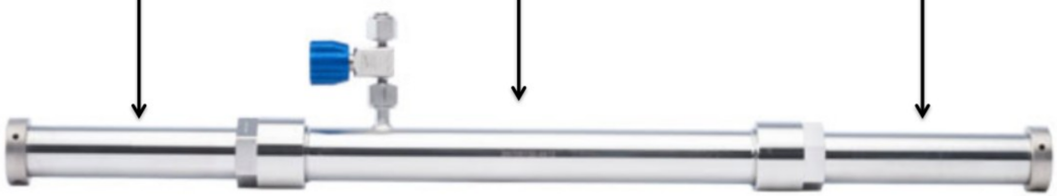
He is scintillating in VUV:
Vessel have to be PTFE coated with an organic phosphor that converted the wavelength of the scintillation light from 80 nm to 430 nm.

High pressure issue:
PMT cannot be used inside the high pressure vessel => use SiPM

TYPICAL USE:
Fast neutron monitor

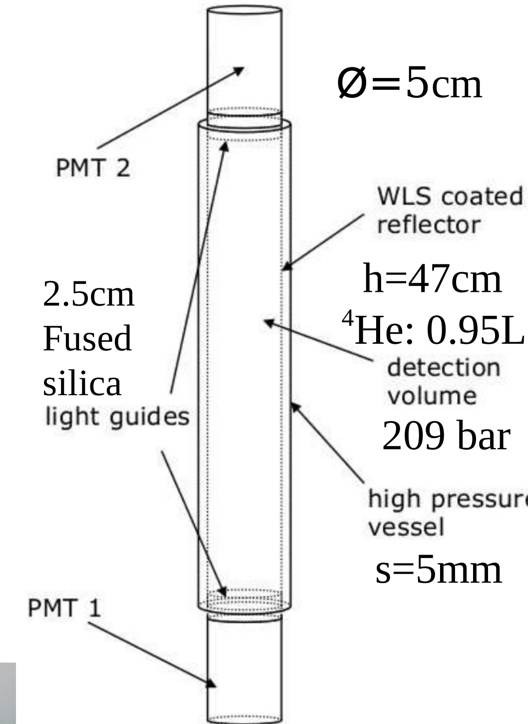
HeCal prototype based on ARKTIS B470 neutron detector 200 bar "cylinder" geometry

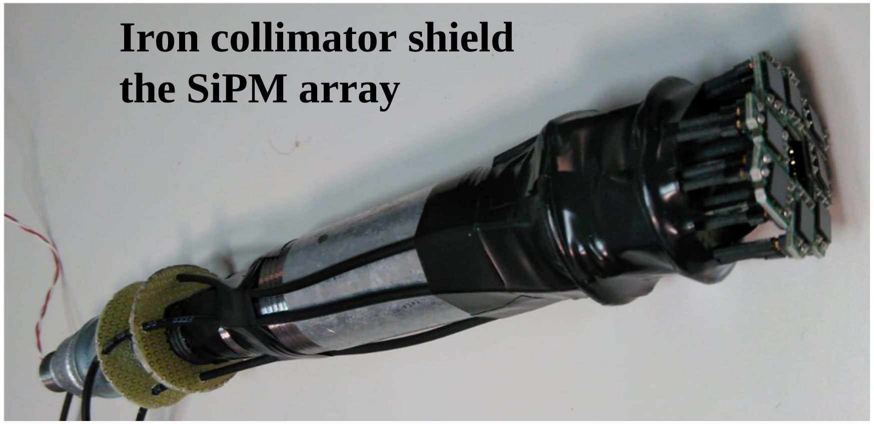
PMT 1 He **Volume** **PMT 2** => SiPM

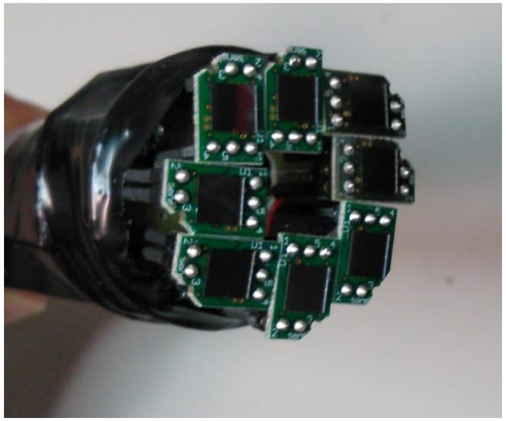


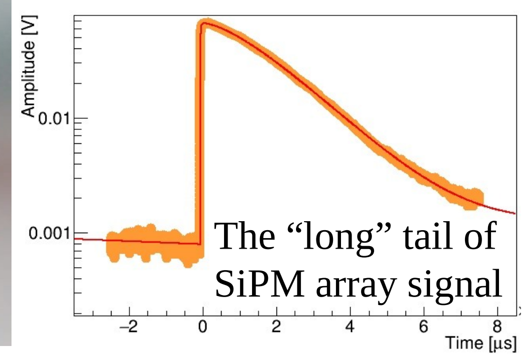
PMT1: Hamamatsu R580 Ø=38mm 27% Q.E.

To reduce material in front of the optical window, PMT2 was replaced with a SiPM circular array 8xSensL MicroFJ-60035 6x6mm^2 Fill Factor 65%



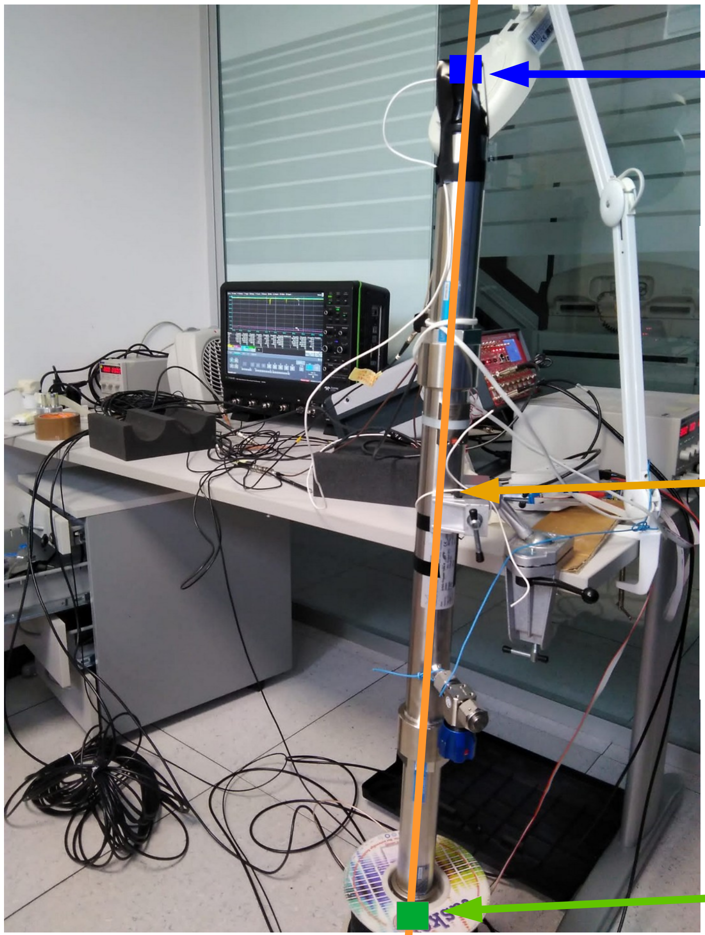






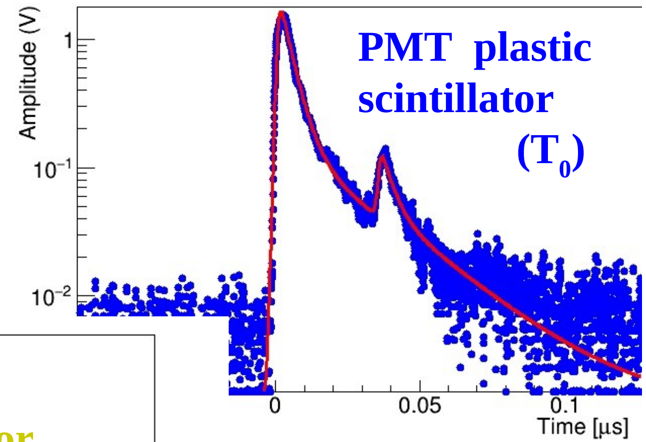
Vertical muon calibration @ TIFPA

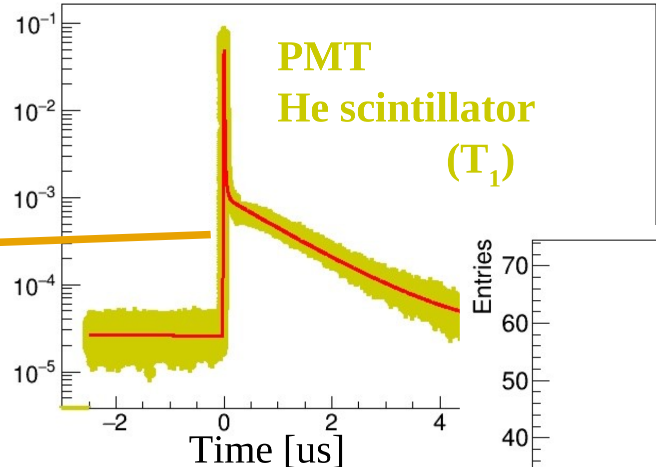
251muons/4months cross whole He volume L = 47cm => 3 MeV deposited

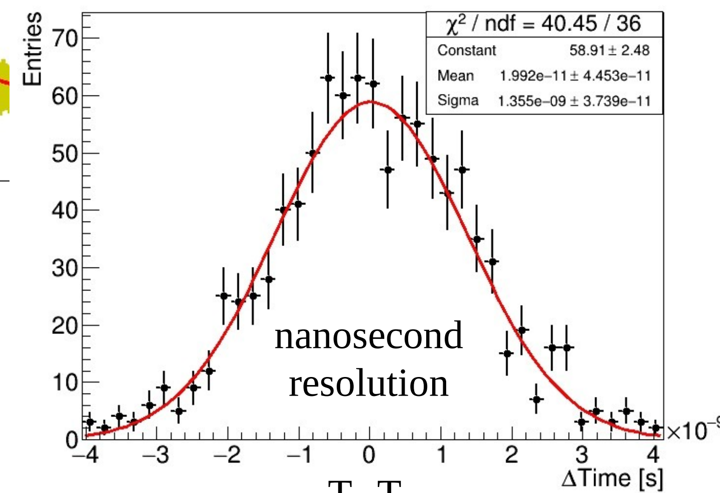


Top 4x0.8cm^2 plastic scint. T_0

Bottom 4x0.8cm^2 plastic scint. T_2

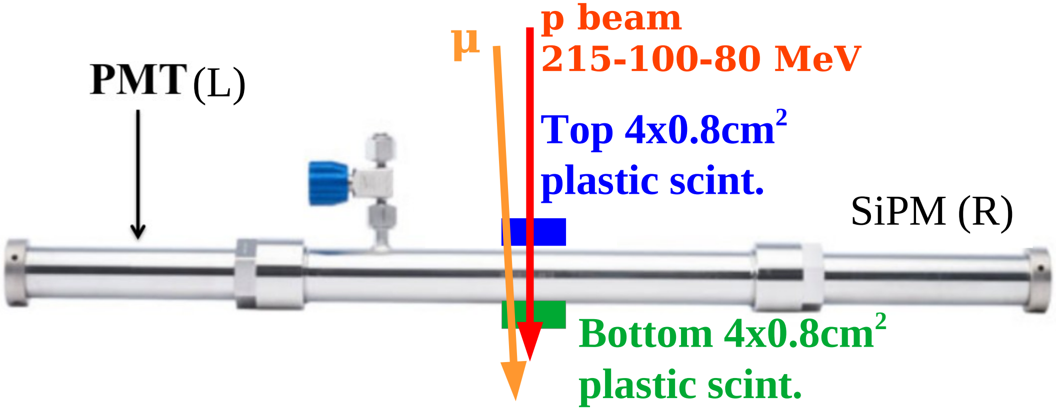






T_1-T_0

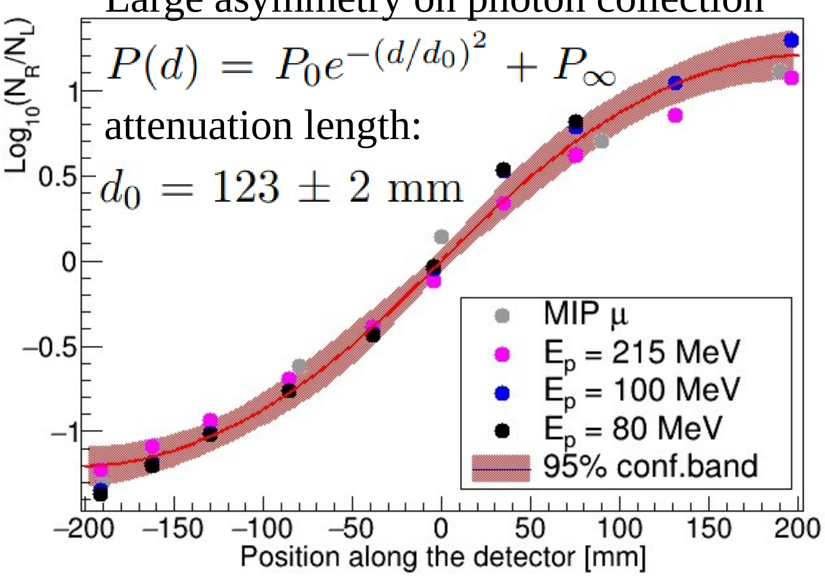
Muon/proton transversal calibrations



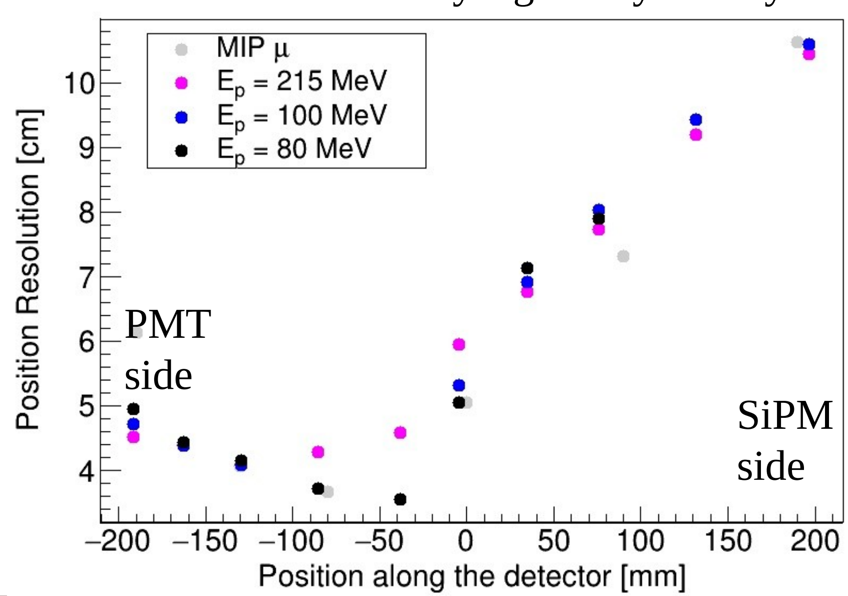
Test of 10 positions along the detector:

E_beam	E_deposited in He
Muon MIP	0.26 MeV
p 215 MeV	0.54 MeV
p 100 MeV	0.93 MeV
p 80 MeV	1.1 MeV

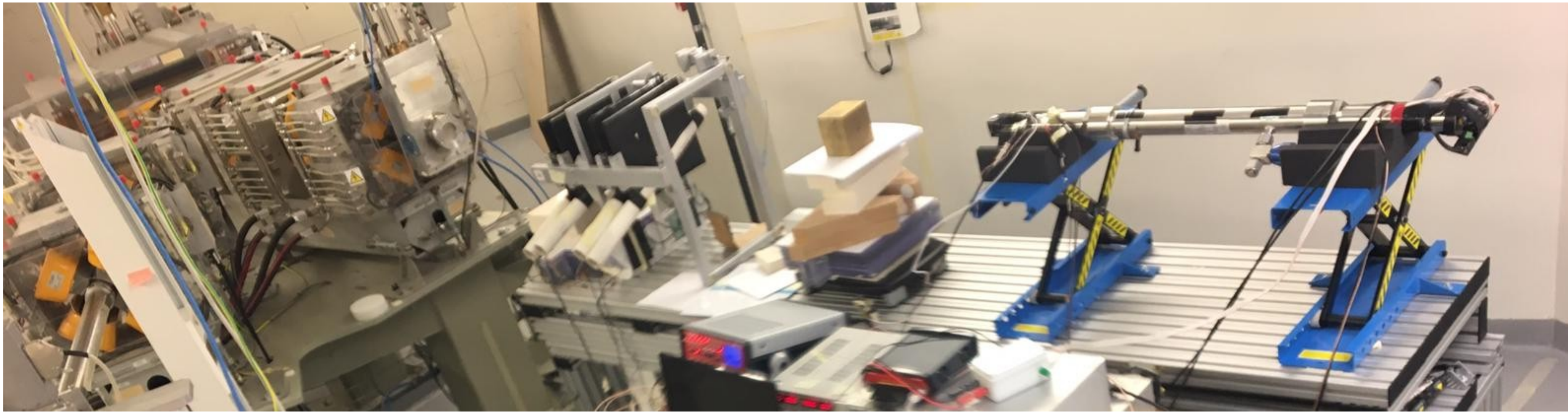
Large asymmetry on photon collection

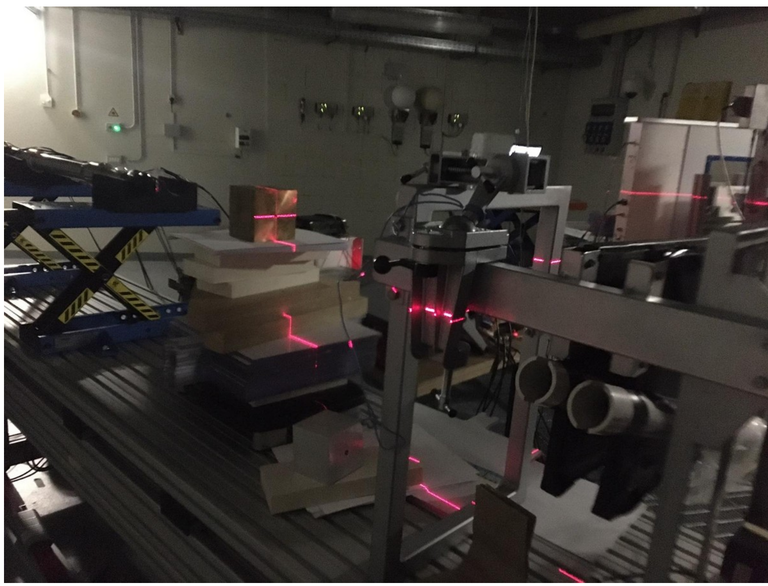


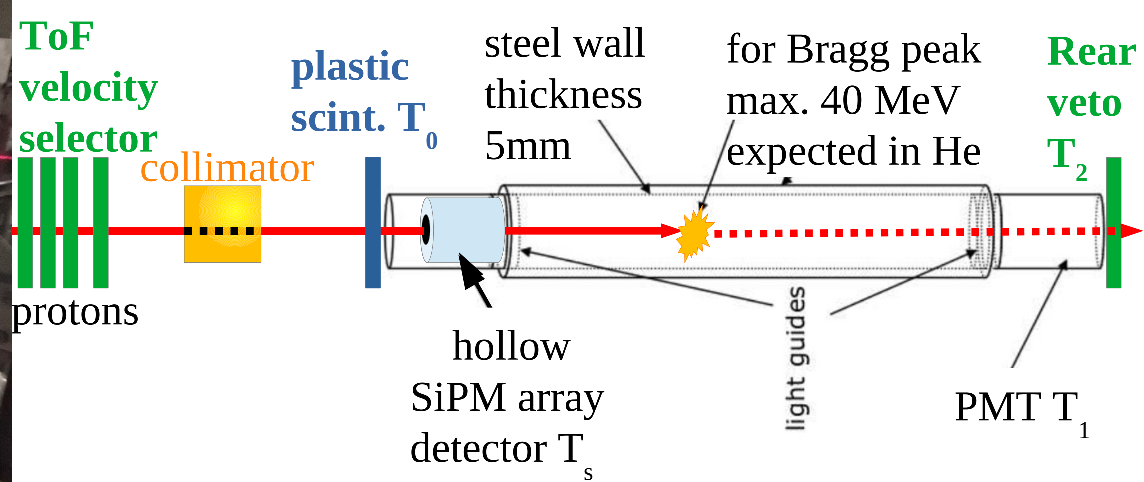
Position measured by signal asymmetry



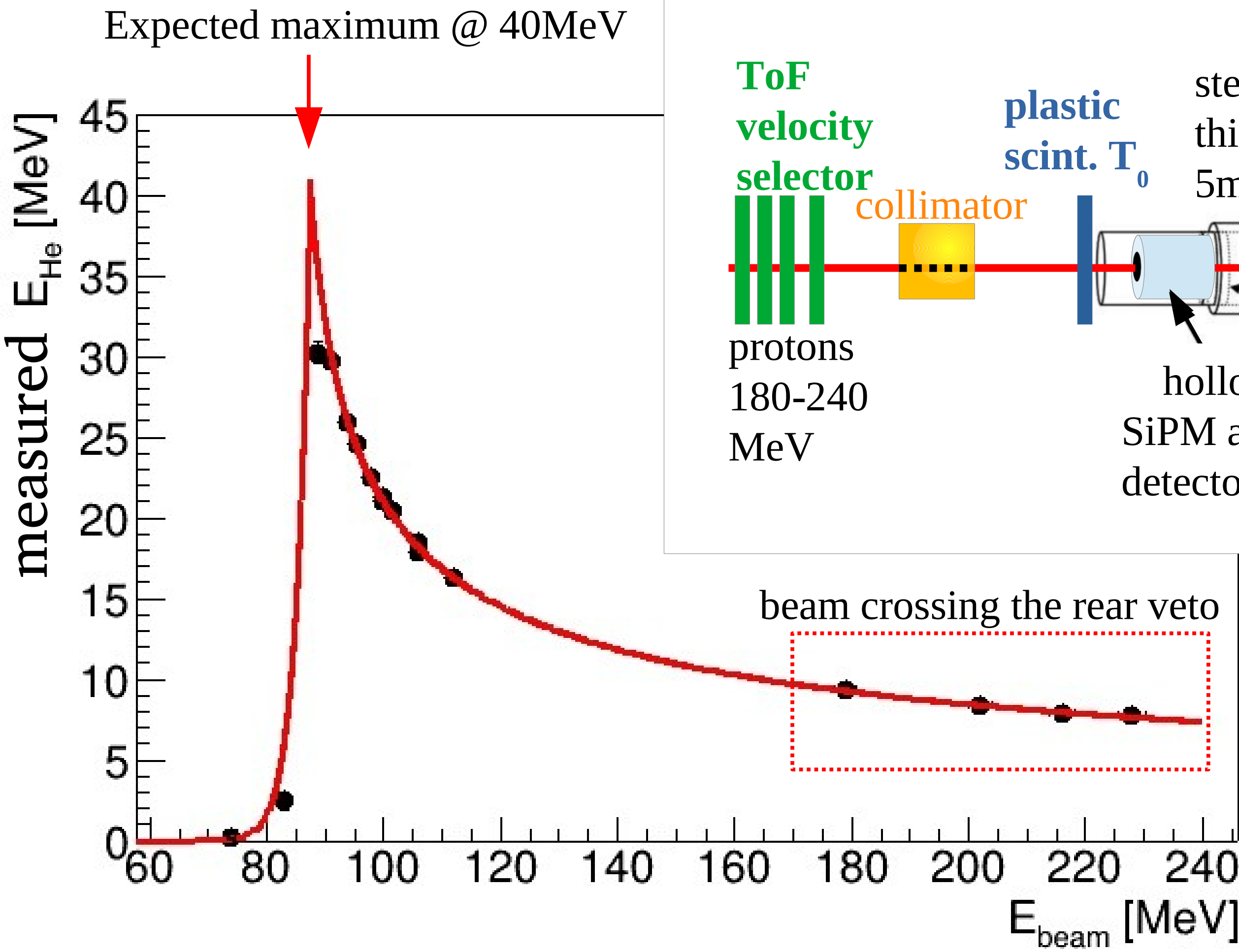
PROTONS (70-228MeV) @ TRENTO Proton-Therapy center

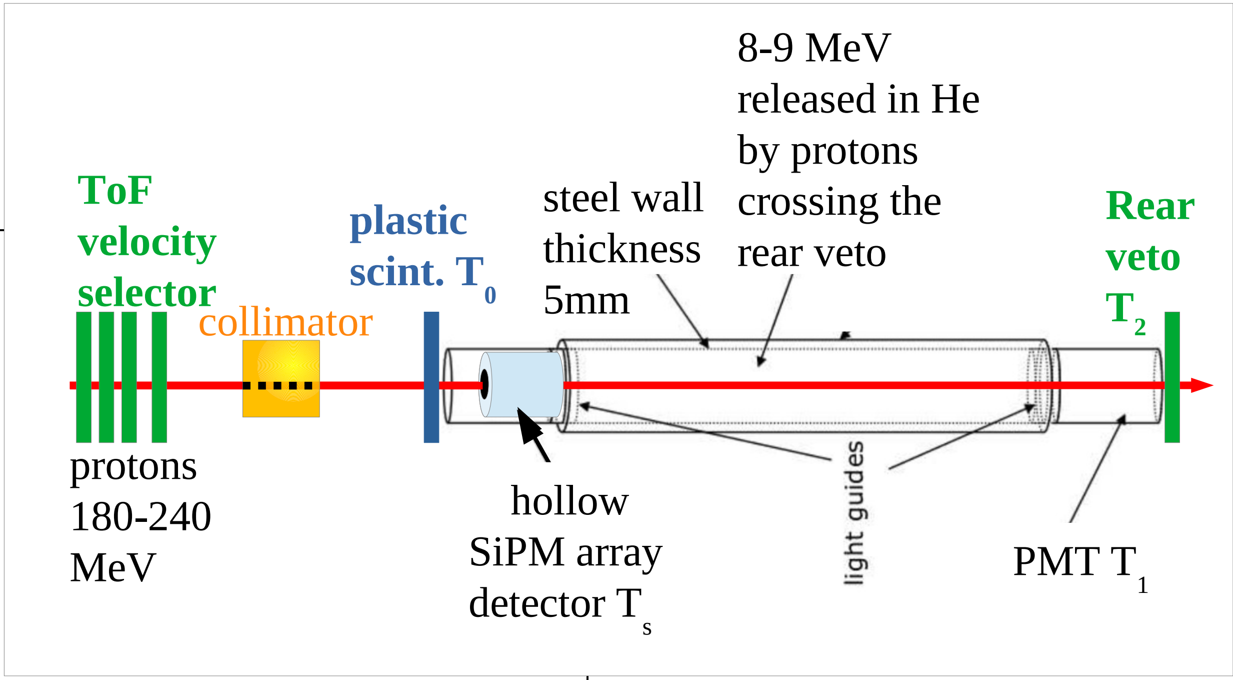






Proton Bragg peak in Helium



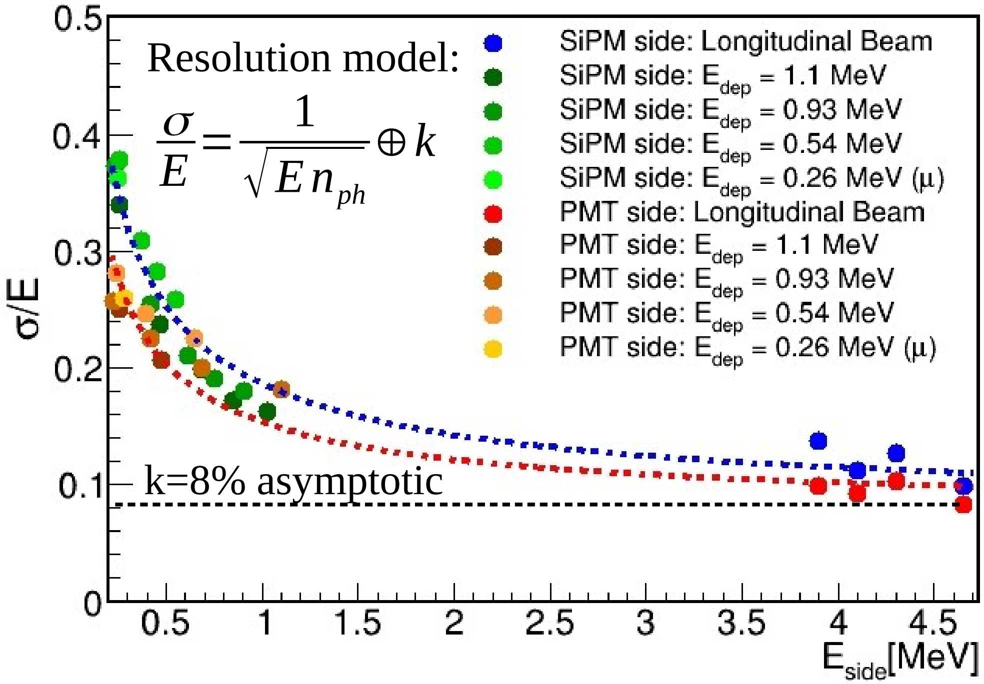


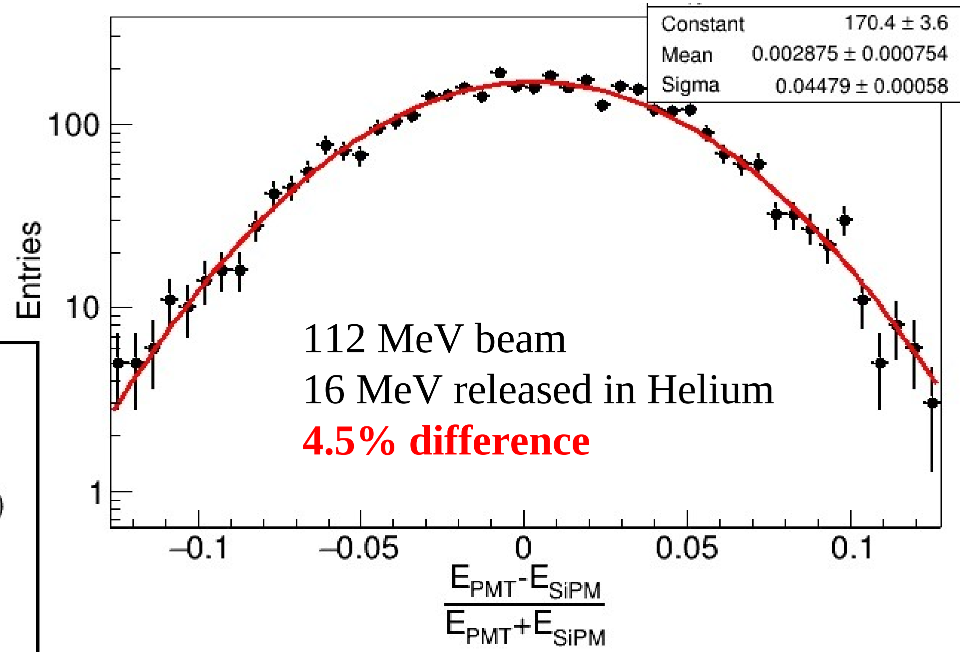
To control multiple scattering in 2.5cm SiO_2 (optical window) only protons with Ek>175 MeV that are crossing the rear veto (thus not hit the lateral steel wall) are considered to study detector time and energy resolutions.

Measured energy resolution

Use of 4 proton Ek crossing the whole detector:

E_Beam	<E_He>	E_deposited in He
228MeV	190 MeV	7.7 MeV
216MeV	175 MeV	7.9 MeV
202MeV	160 MeV	8.4 MeV
179MeV	140 MeV	9.3 MeV





SiPM side: n_{ph} = 34.5±1.6 ph.e/MeV

PMT side: n_{ph} = 56.4±4.1 ph.e/MeV

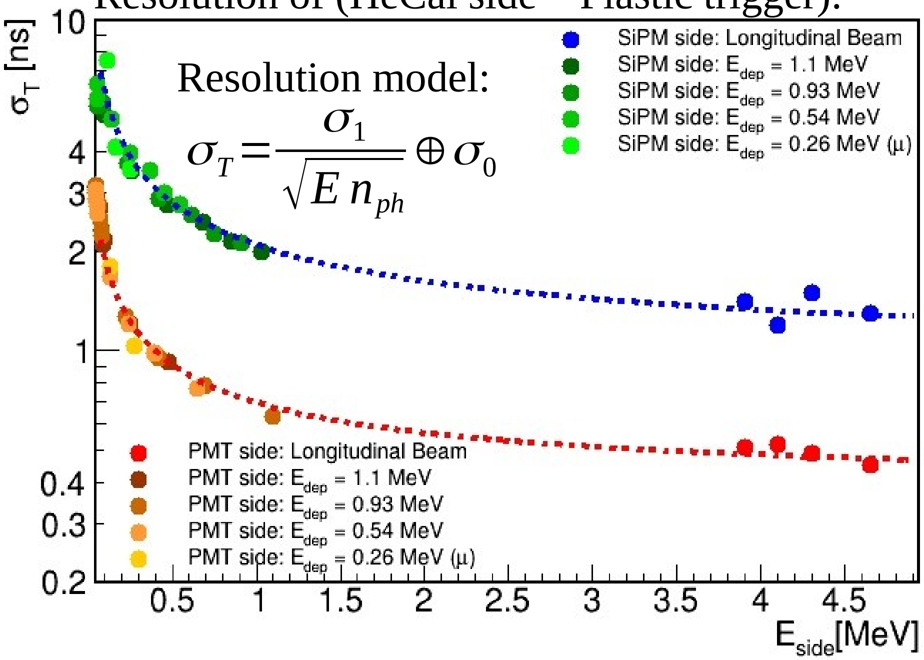
Ratio of n_{ph} PMT/SiPM = 1.63±0.14

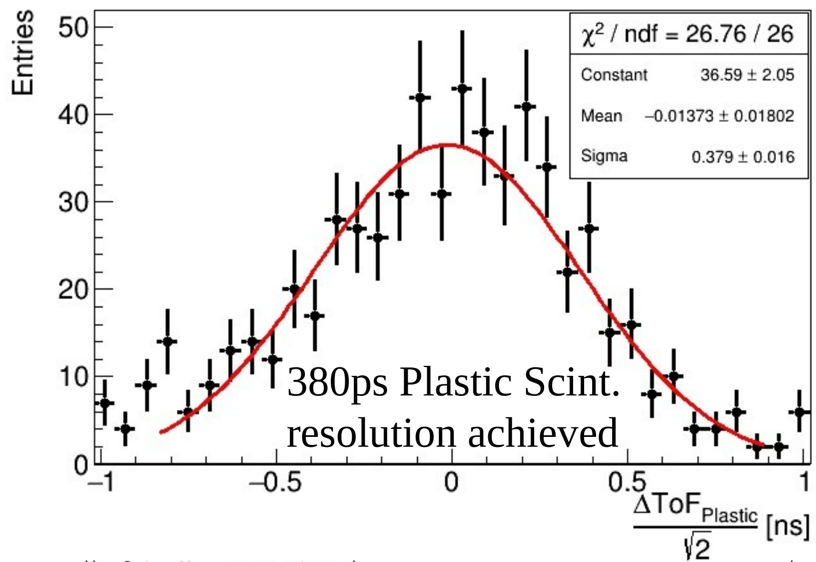
(expected ~1.3 by surface ratio x $PMT_{QE}/SiPM_{FillFactor}$

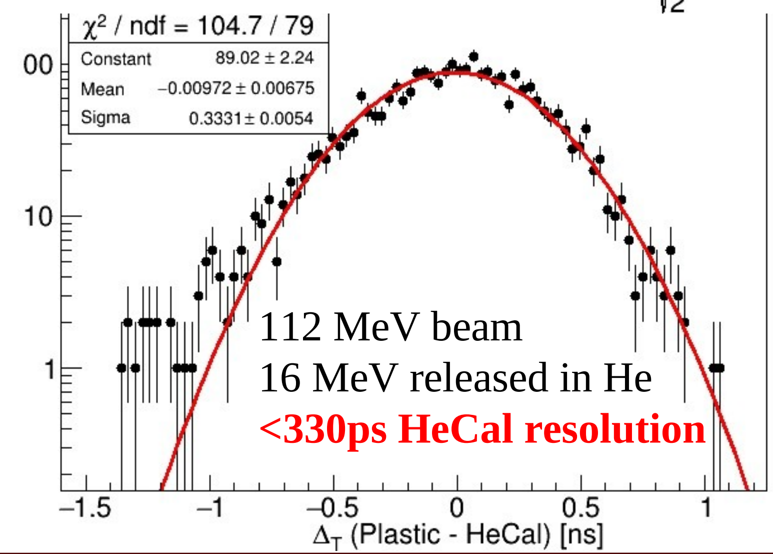
Energy resolution better than 10% achieved (ADHD goal)

Measured time resolutions

Resolution of (HeCal side – Plastic trigger):







SiPM side: σ_1 = 11.0±0.5 ns and σ_0 = 0.9±0.2 ns

PMT side: σ_1 = 4.4±0.2 ns and σ_0 = 0.39±0.03 ns

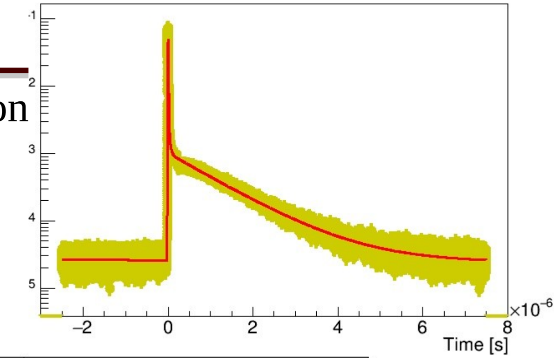
σ_1 can be interpreted as time uncertainty of single ph.e

σ_0 is the "asymptotic" time difference resolution.

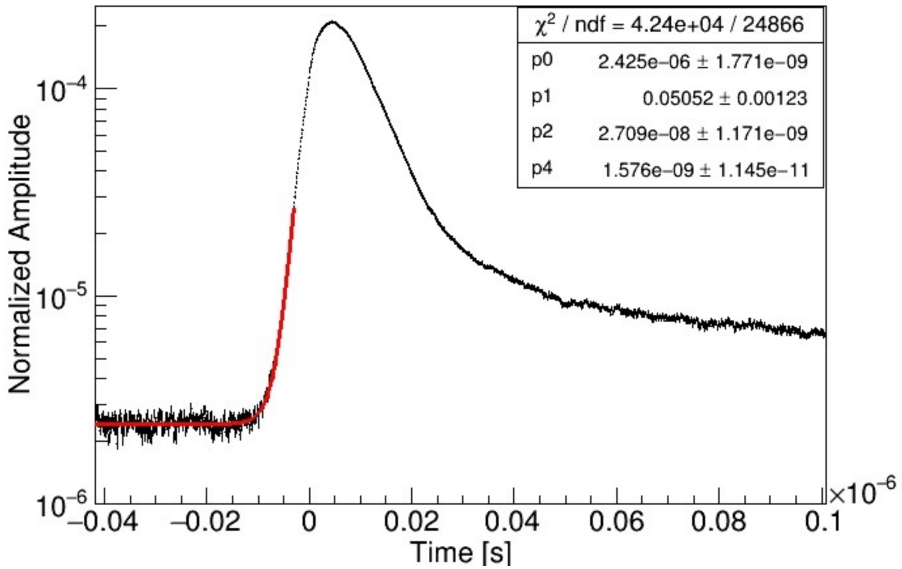
In the case of HeCal PMT side this is dominated by the time resolution of the Plastic scintillator (380 ps)

(**it is possible that ~300ps is a limit our 5Gs/s DAQ**)

Measurement of Helium Scintillation Components

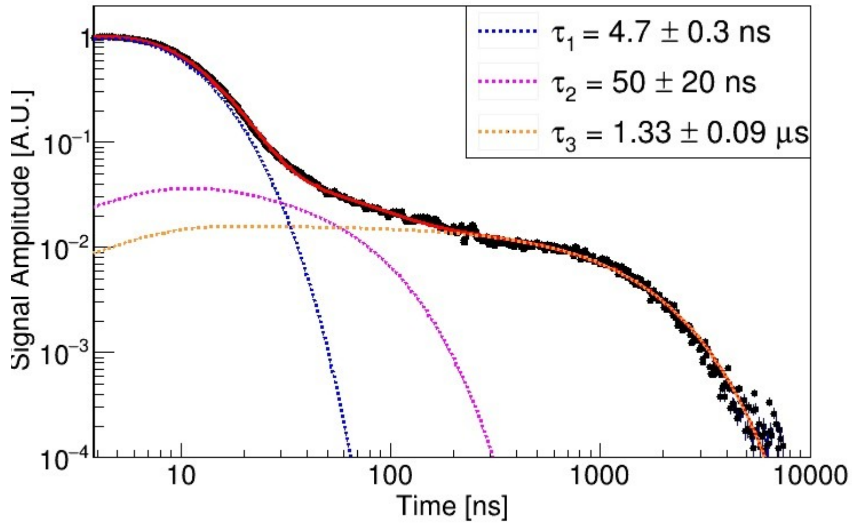


Waveform sampling @ 5Gs/s: Measurement of time structure of He scintillation
-Precise measurement of rise time and fast component decay time @ 200 bar
-First indication for a subdominant ~50ns decay component.



Fast exponential rise: τ_{grow} = 1.60±0.05ns

by comparison with the same DAQ we test a FNAL-NICADD plastic scintillator:
τ_{grow} = 0.37±0.07ns and τ_1 = 3.8±0.5ns
(and no evidence for τ_2 in this case)

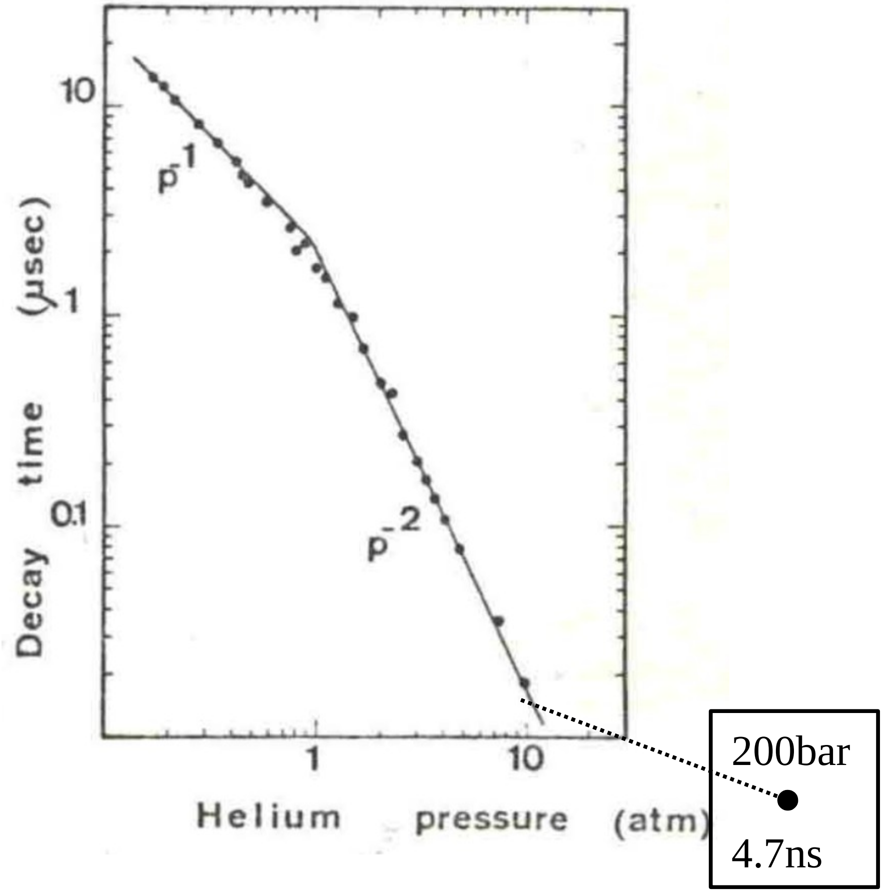


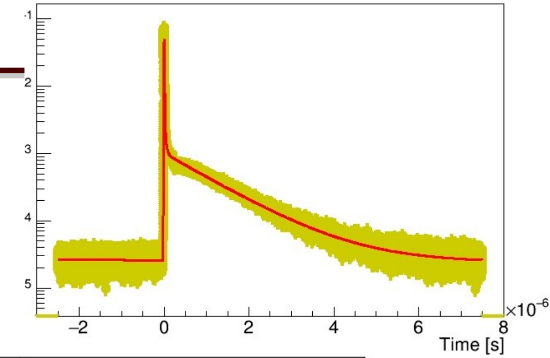
3 scintillation component: $\frac{N_1}{\tau_1} e^{-\frac{t}{\tau_1}} + \frac{N_2}{\tau_2} e^{-\frac{t}{\tau_2}} + \frac{N_3}{\tau_3} e^{-\frac{t}{\tau_3}}$

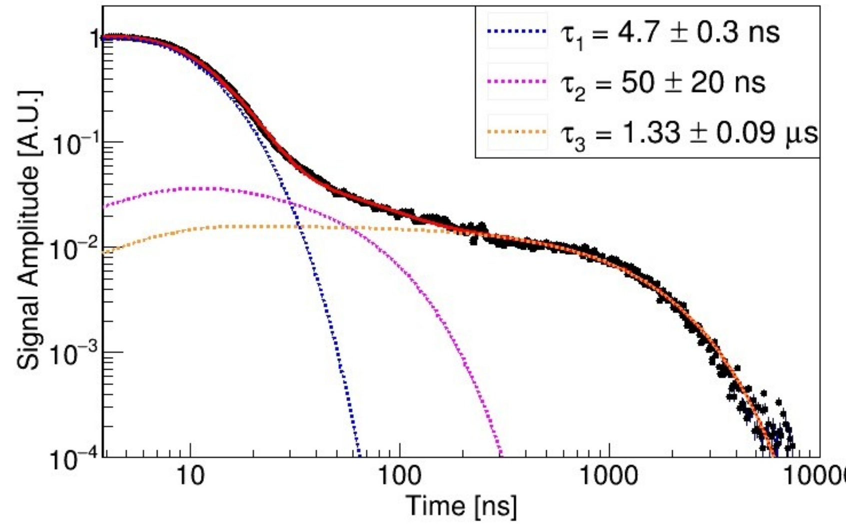
Measured ratios to fast component:
N_2/N_1 = (18±0.2±7)% (N_2 new indication)
N_3/N_1 = (70±7±15)% (N_3 well known)

Measurement of Helium Scintillation Components

Phys Lett A 28 (1968) 432
Past measurements of fast decay component at lower Helium pressure







3 scintillation component: $\frac{N_1}{\tau_1}e^{-\frac{t}{\tau_1}}+\frac{N_2}{\tau_2}e^{-\frac{t}{\tau_2}}+\frac{N_3}{\tau_3}e^{-\frac{t}{\tau_3}}$

Measured ratios to fast component:
$N_2/N_1 = (18\pm0.2\pm7)\%$ (N_2 new indication)
$N_3/N_1 = (70\pm7\pm15)\%$ (N_3 well known)

Plans for next 3 years:

Finanziato dall'Unione europea
NextGenerationEU

Ministero dell'Università e della Ricerca

Segretariato Generale

Direzione Generale della Ricerca

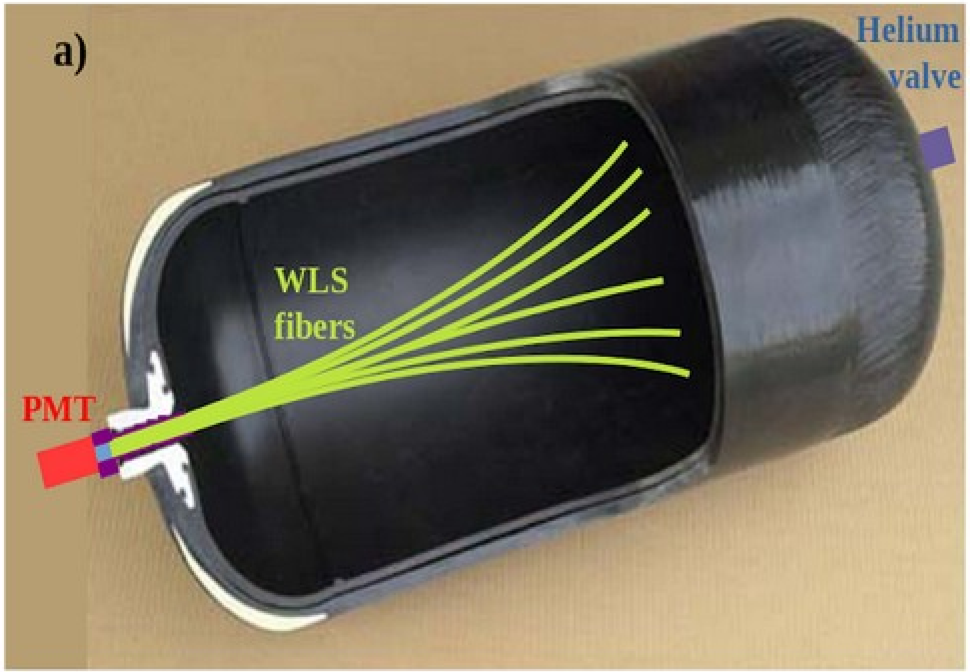
PRIN: PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE – Bando 2022
Prot. 2022LLCPMH

Pressurized Helium Scintillating Calorimeter for AntiMatter Identification

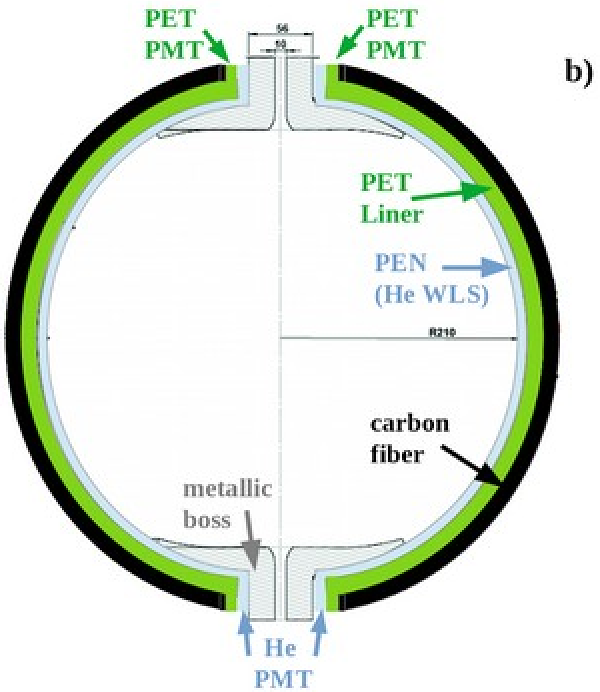
Project accepted: a specific PhD scholarship will be granted starting from Nov. 2023 (contact me if interested)

2024-2025 (PRIN project)

Development and test of HeCal prototype Based on commercial (automotive) COPV

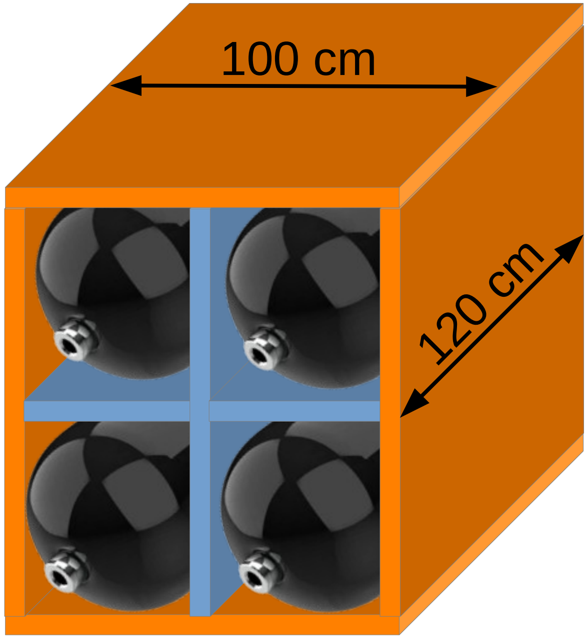


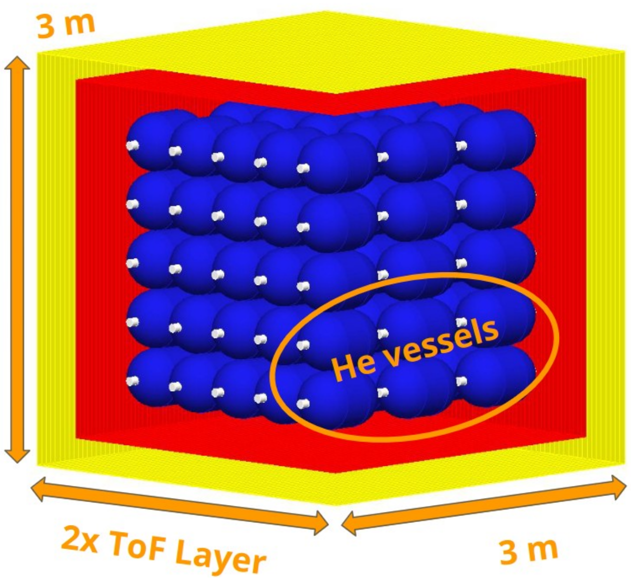
Development and test of a COPV including a "fast" scintillating layer in the vessel



PET and PEN are stronger than Copper and fast scintillating (6.8ns and 35 ns) (https://doi.org/10.3906/fiz-1912-9)

2026: ADHD demonstrator for a balloon launch
2x2x2 ⌀ = 50cm He modules





Thanks for your attention

and

Stay Tuned!

https://www.tifpa.infn.it/projects/adhd/