Probing Dark Matter with Antideuterons: Development of a Novel Double Annihilation Signature

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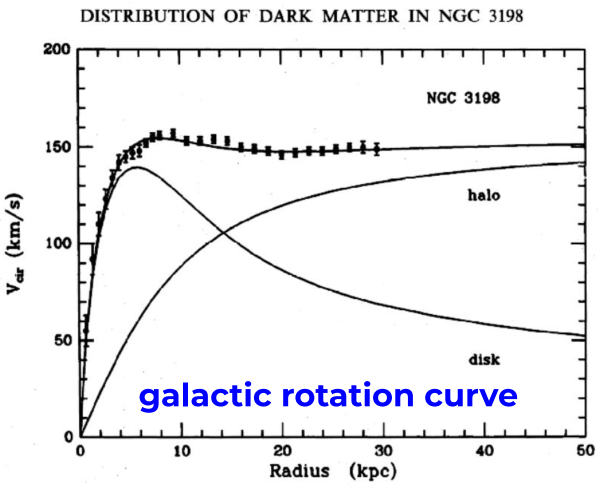
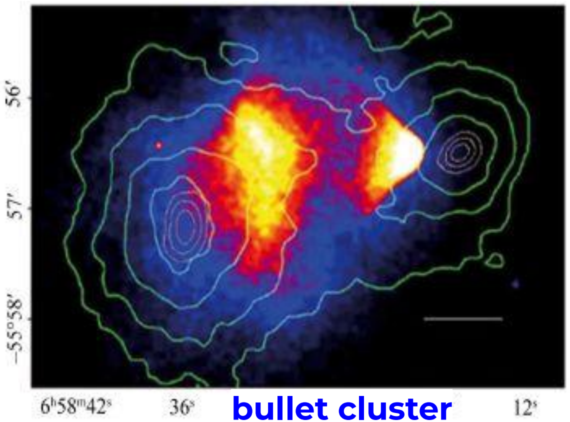
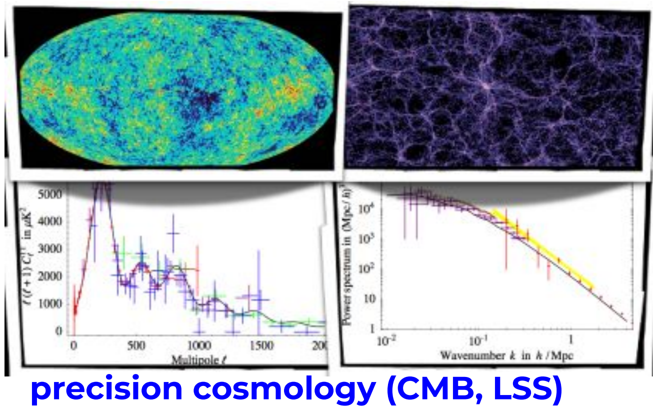
INFN
TIFPA Istituto Nazionale di Fisica Nucleare
ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE EMFCSC

Evidence of Dark Matter

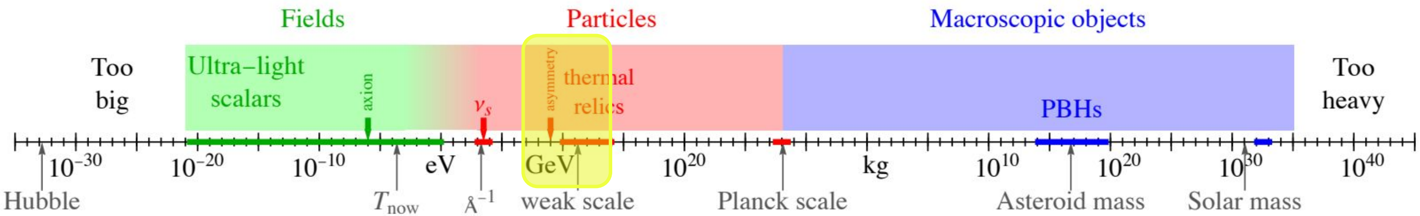
The successful standard cosmology theory (ΛCDM) predict existence of DM

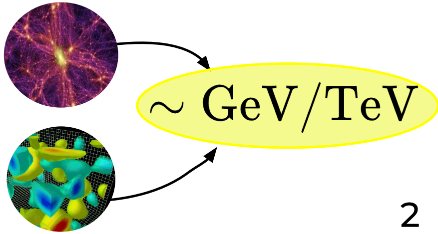






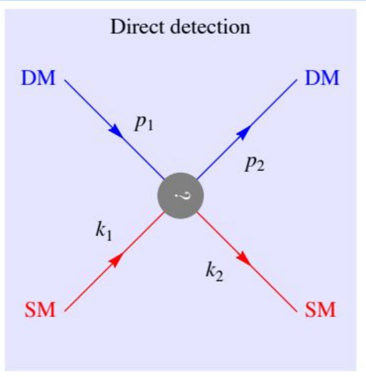
Allowed DM mass spans >90 orders of magnitude





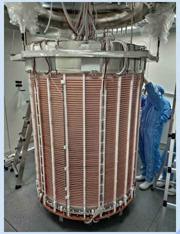
Particle DM searches

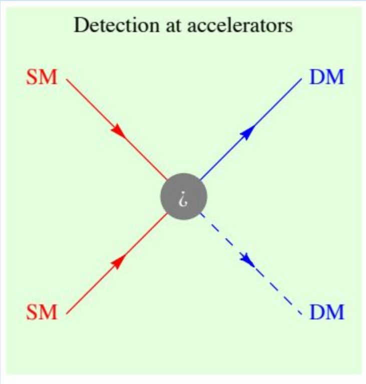
If DM is a weak-scale particle, we can hunt it from three directions simultaneously



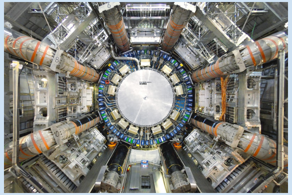
DM + nucleus scattering

XENONnT, LZ, PandaX

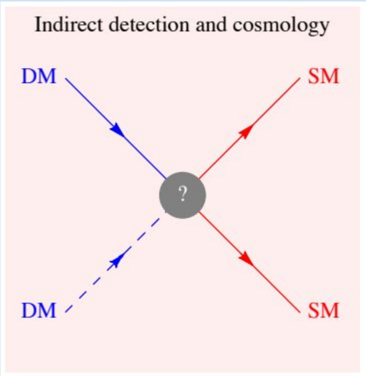




pair-production, missing energy



ATLAS, CMS



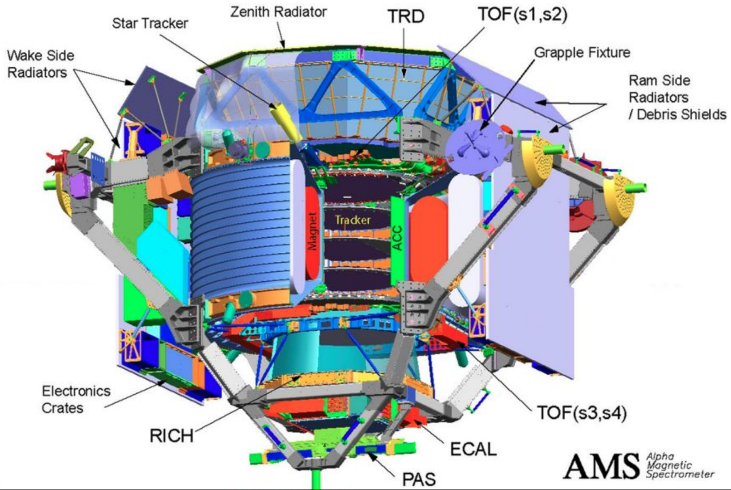
DM annihilation/decay products in CR

AMS02 *GAPS*

has $\overline{\mathrm{He}}$ detected in CR ? (still un-published)

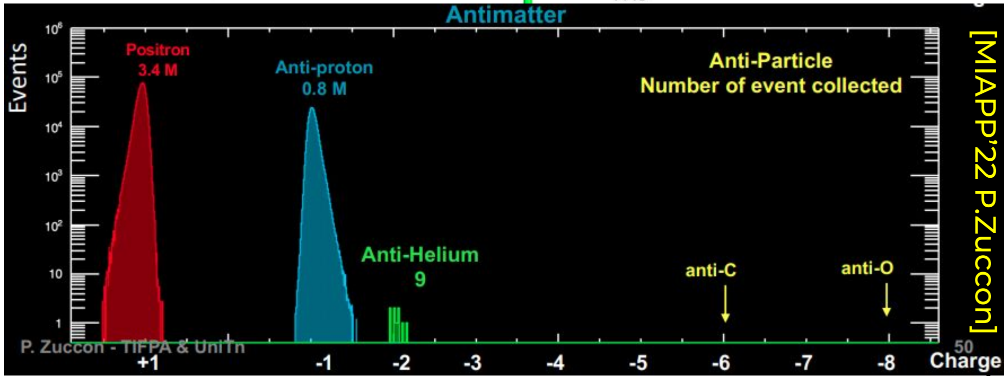
AMS-02

- magnetic spectrometer on the ISS since 2011
- silicon tracker + RICH + TOF + TRD + ECAL → identifies CR
- 250 billion events collected



Antihelium candidates (unpublished)

- ~10 antiHe events in 13 years
- No secondary expected
- Still low significance, if confirmed, no known astrophysical explanation

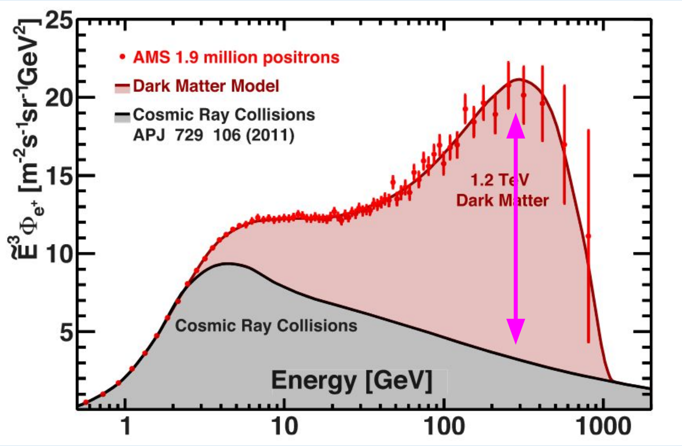


[MIAPP'22 P.Zuccon]

Antimatter in CR

positron

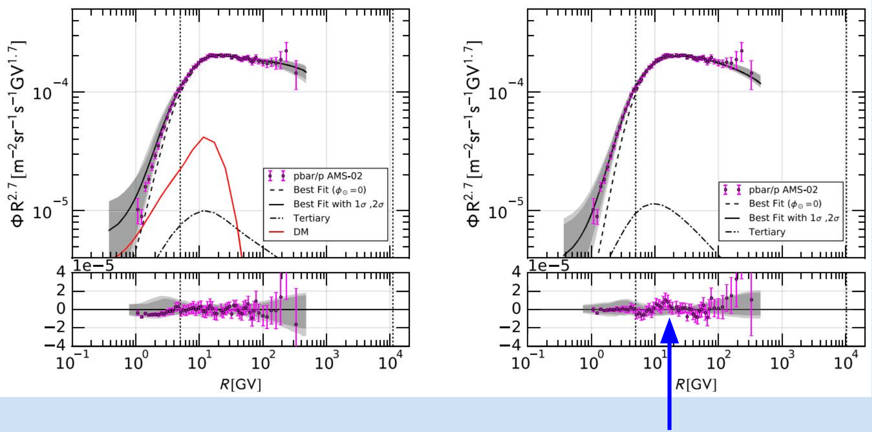
flux rising above ~10 GeV
screaming for unknown source



Pulsars can naturally inject hard e^+e^-,
now are the favored explanation

antiproton

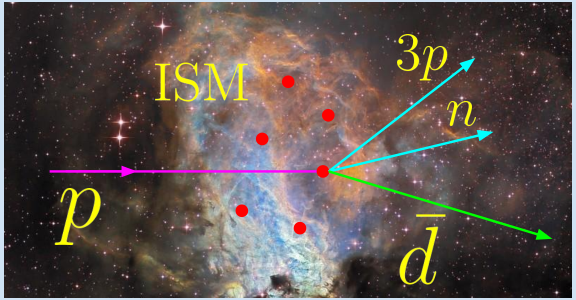
excess at ~10 GV,
pointing to a ~70 GeV WIMP



CR propagation uncertainties,
nuclear cross sections, and detector
systematics can absorb the excess

Low energy AntiD as smoking gun for indirect DM

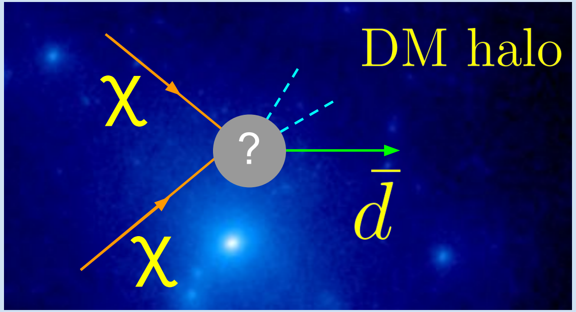
Astrophysical Background



Heavy final state + target at rest =
large minimum momentum of dBar

threshold energy T_p > 16 GeV
suppressed for T_{dBar} < 2 GeV/n

Dark Matter Signal



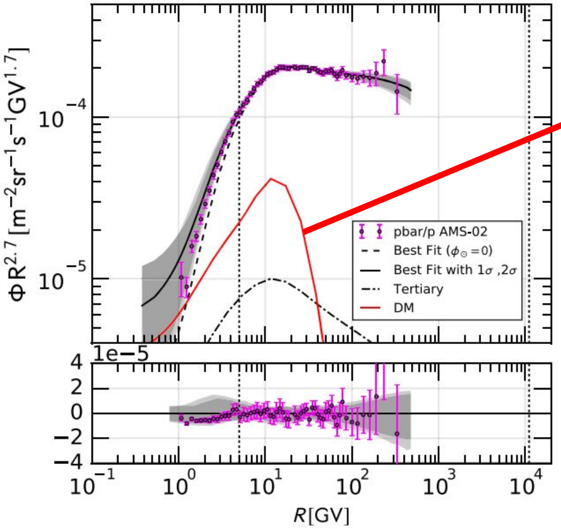
DM at rest → no boost + hadronizat =
dBar naturally slow

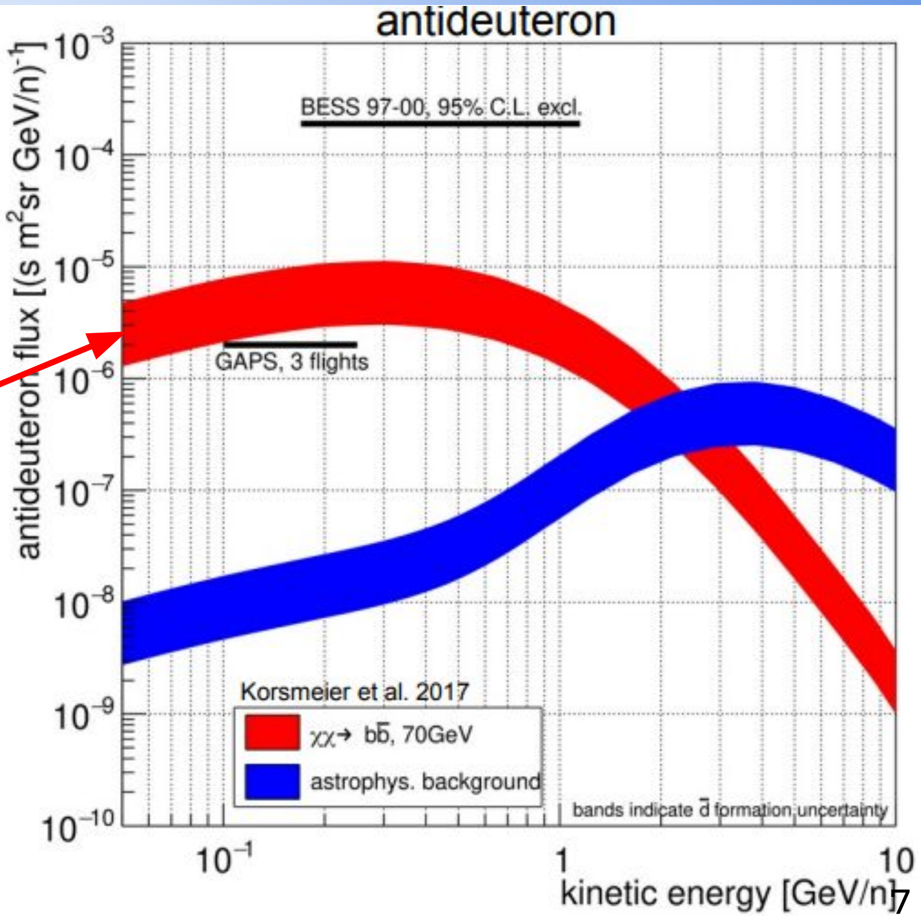
T_{dBar} ~ O(1) GeV/n
more M_χ → more hadrons, not faster one

AntiD smoking gun for indirect DM

"If the AMS-02 antiproton excess is real DM, what antideuteron flux does it predict and can GAPS/AMS see it?"

[Korsmeier, Donato, Fornengo, PRD 2018]



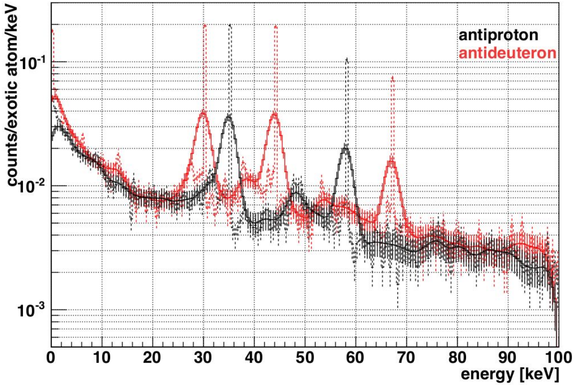


General AntiParticle Spectrometer (GAPS)

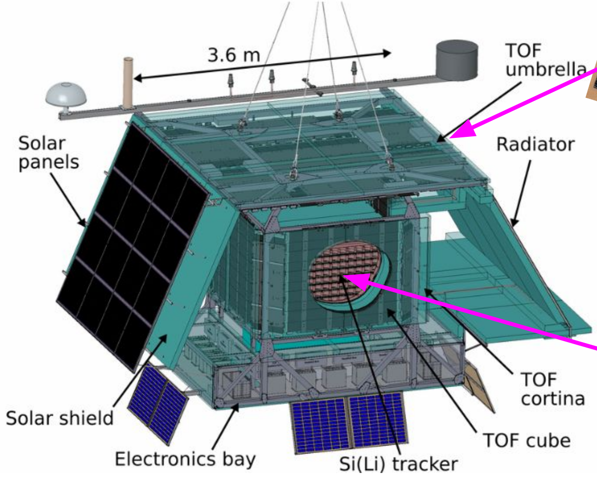
Detector: TOF + 10 x Si(Li) tracker layers (cooled -35°)

Signature:

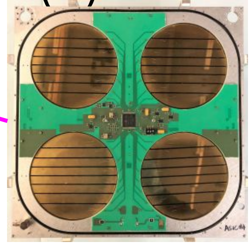
- annihilation products
- particle stopping depth
- exotic atomic X-rays (30-44-67 keV)

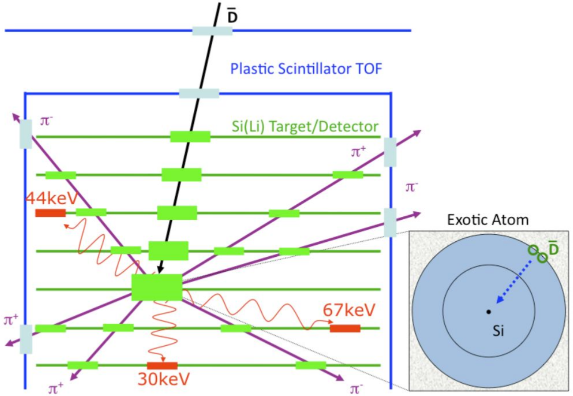


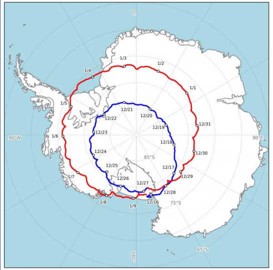
First Antarctic LDB flight Dec ‘25
(25 days, 2 South Pole laps, 500M+ events)



Si(Li) tracker

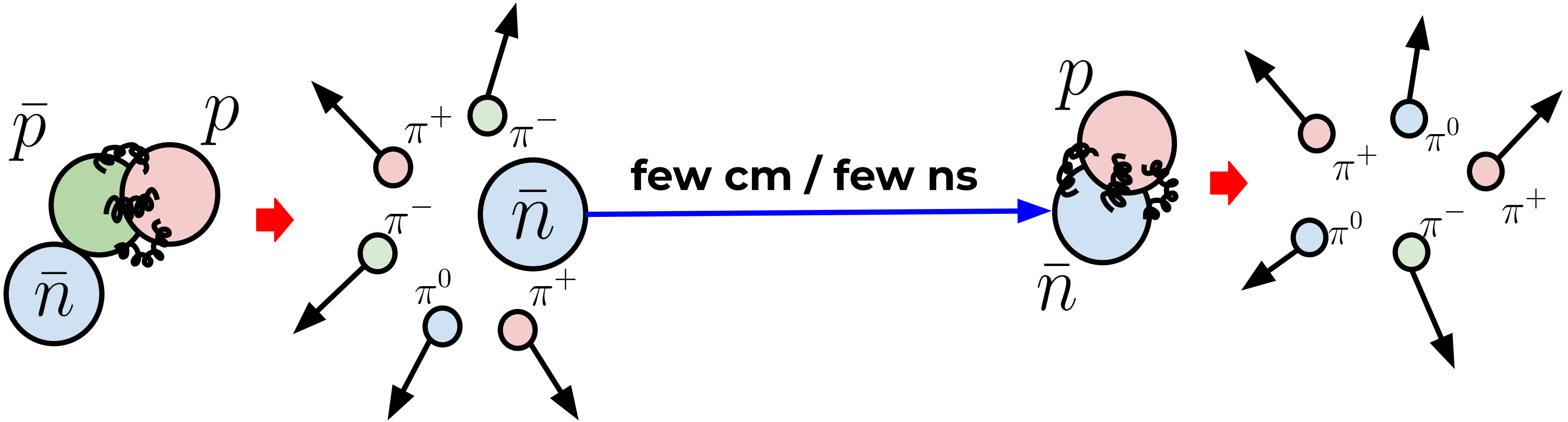






“Double pions star” signature

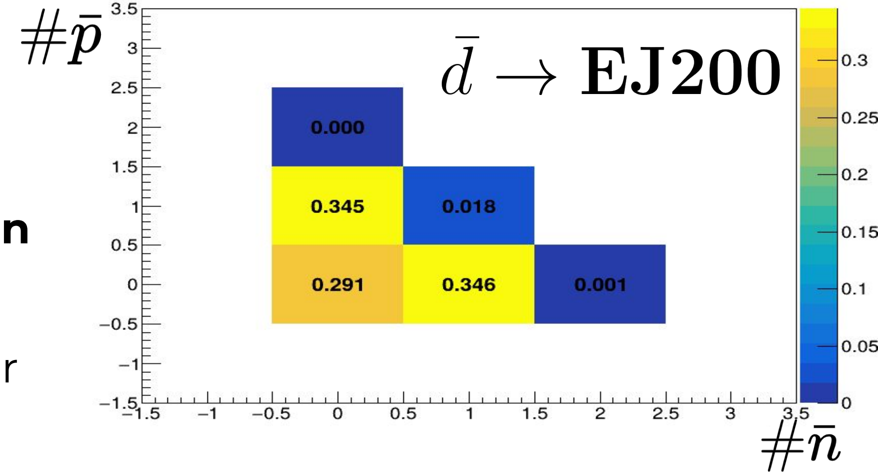
d-bar interacting with an **hydrogen** rich material produces two pion star, separated by few cm & few ns



A signature for d-bar is multiple pion stars

AntiD Annihilation in Plastic Scintillator

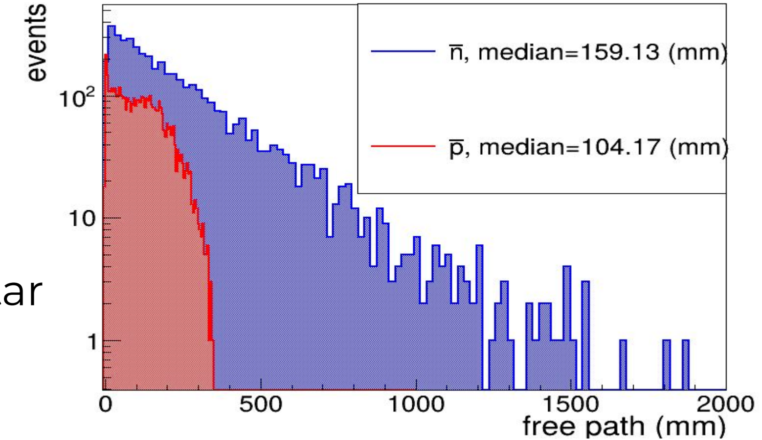
Geant4 simulation of antideuteron impinging on EJ200 at T = 0.2 GeV/n



Antinucleon Multiplicity after First Annihilation

- ~70% at least one recoiling antinucleon
- High survival probability enables double star

Free Path of the Recoiling Antinucleons



- Median free path: 15 cm (anti-n), 10 cm (anti-p)
- Macroscopic distances allow vertex separation
- Coarse-grained tracker could resolve double star signature

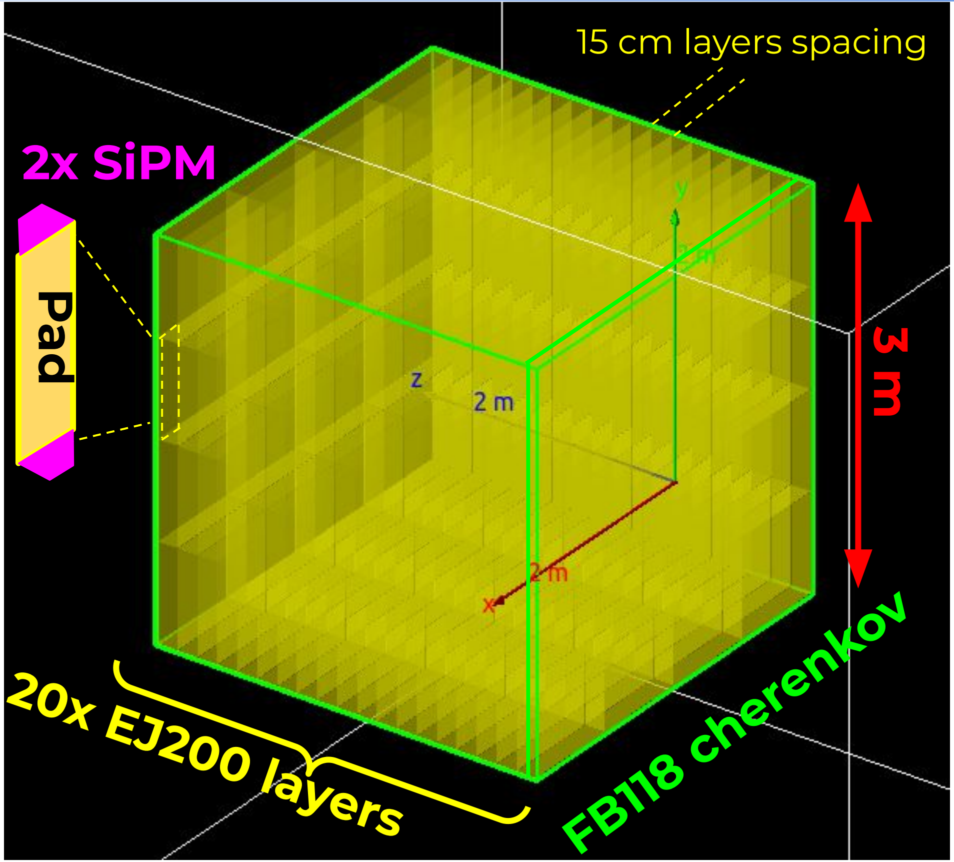
PLASTICAMI project: proposed design

A segmented plastic scintillator ToF detector with Cherenkov veto

- Volume: 3 x 3 x 3 m^3
- 30 x EJ200 5mm thick layers (20 planes + 10 lateral walls)
- segmented in pads (15 x 75 cm^2)
- external Cherenkov veto FB118 (ICRC poster https://indi.to/Lb8tZ)

- SiPM readout for each pad
- 4800 daq channels (ToF 300ps)

- Mass: 1.4Ton scint.(~ 2.5Ton payload)

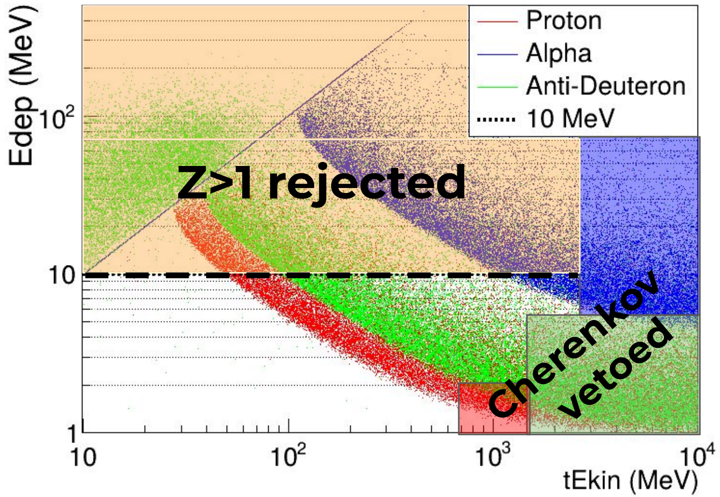


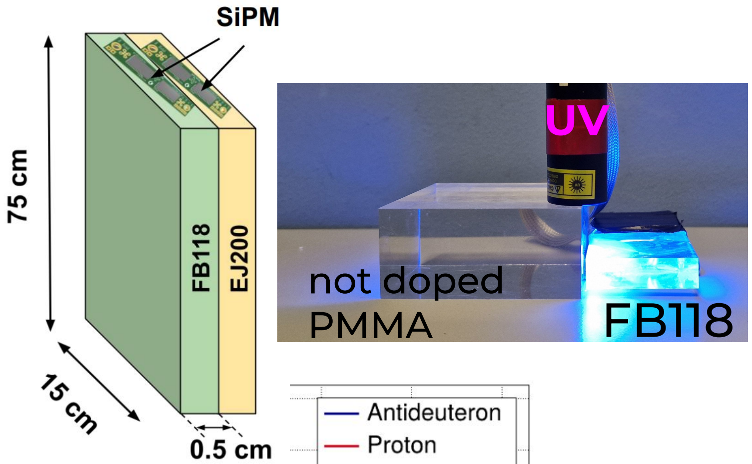
Trigger

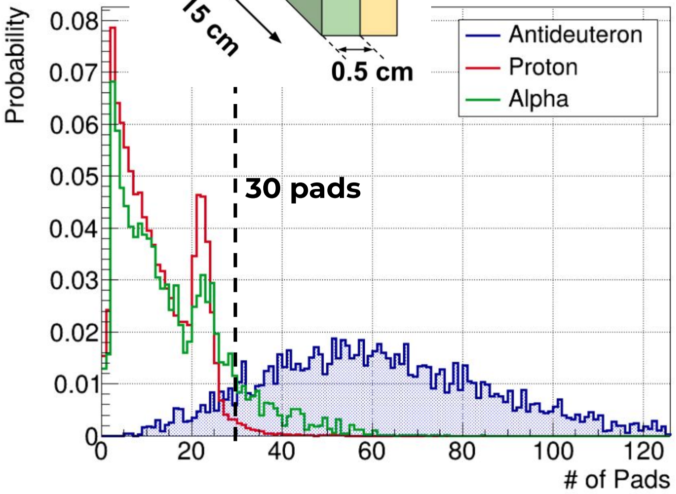
Three trigger levels:

- Cherenkov threshold (β < 0.8)
- dE/dX cut (< 10 MeV)
- Pads multiplicity in 50 [ns] (#Pads > 30)

trigger rate ~ 10^5 [Hz], dead time ~ 5%







“Double pions star” signature

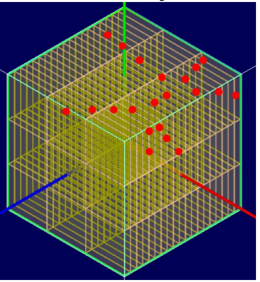
Double star condition:

$$\begin{cases} \Delta t > 2\text{ns} \\ |\Delta\vec{x}| > 15\text{cm} \end{cases}$$

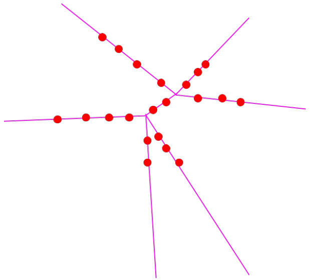
Reconstruction:

- Tracking + vertexing
- CNN/GNN
- Depth sensing (β vs Δz)

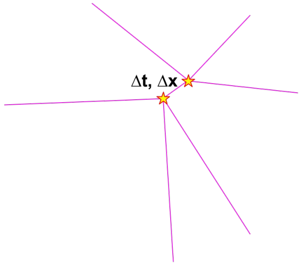
hits map

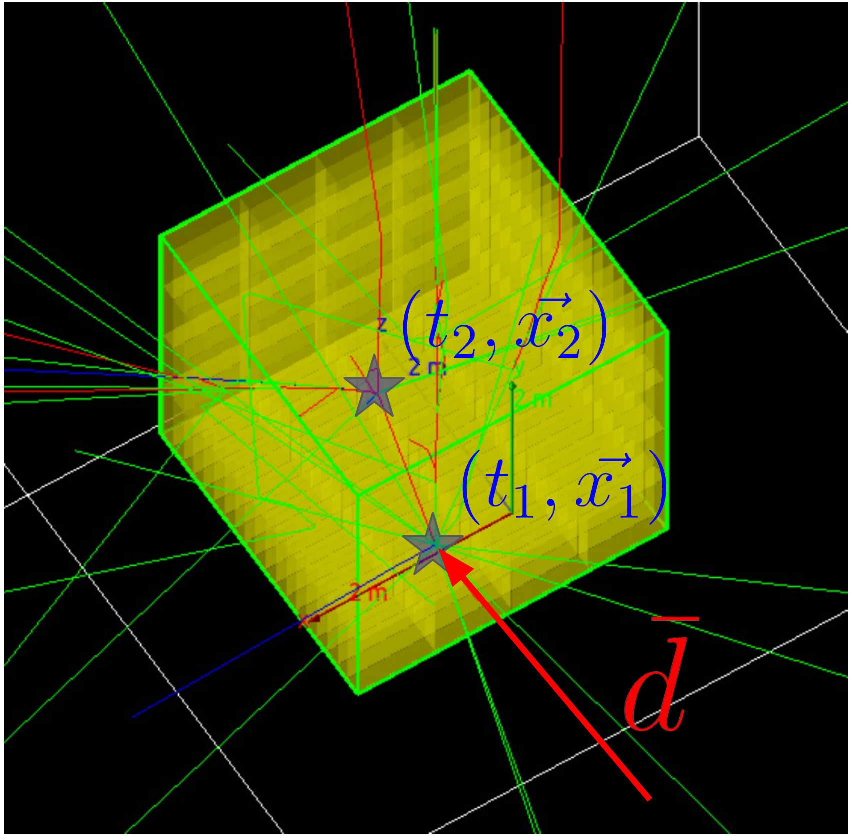


tracking



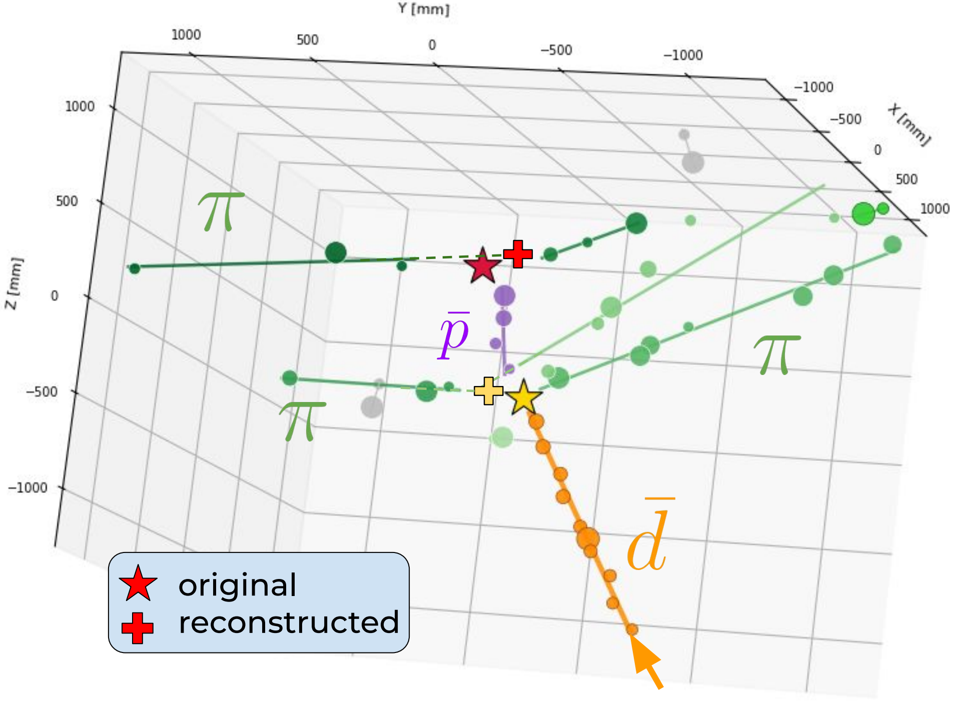
fit topology

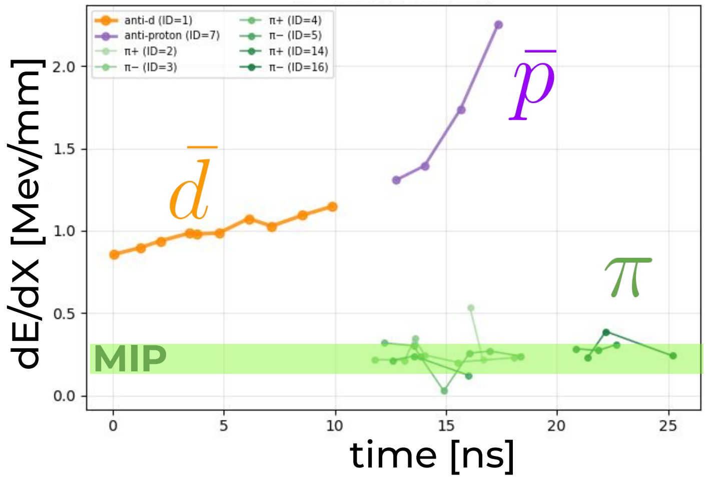




Event reconstruction

Reconstruction with realistic time/energy resolution and light attenuation





Tracking algorithm leverage:

- 4D hit (x, y, z, t, E)
- hermeticity
- dE/dX for PID

Acceptance

Acceptance conditions:

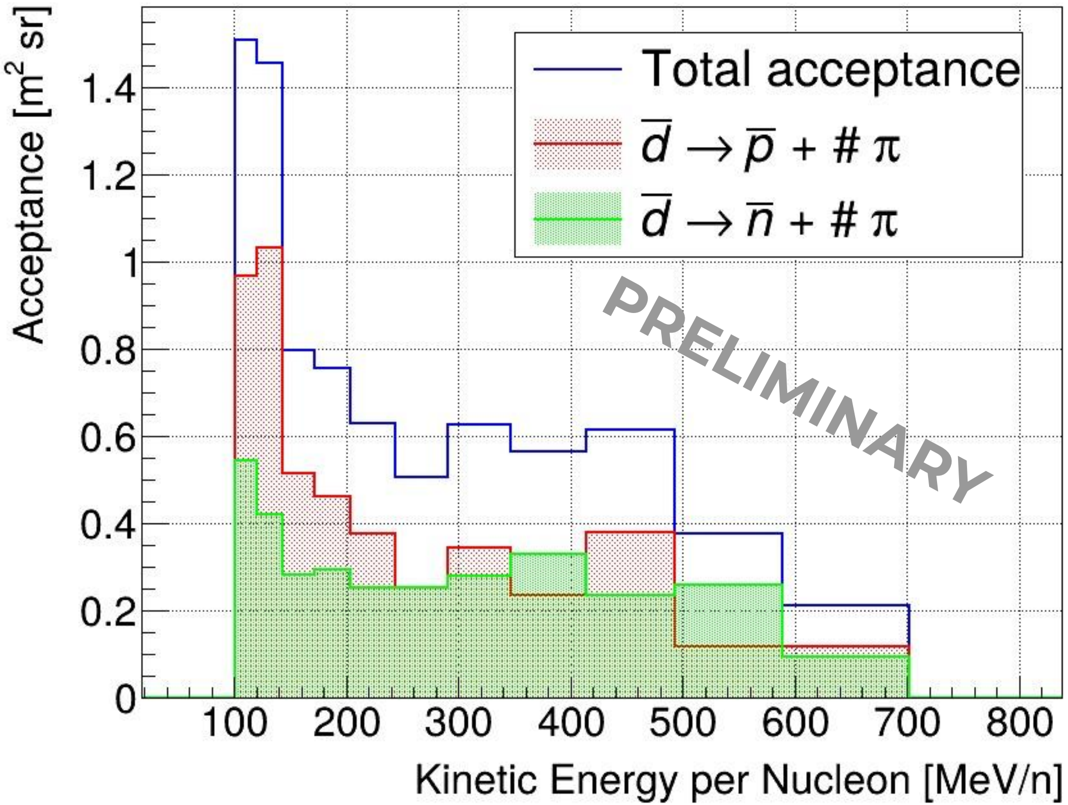
- **geomagn. cutoff** ~ 0.75

- **Trigger efficiency:**
dE/dX & Cherenkov
pad multiplicity

- ***d-bar* selections:**
fid. volume: 2.8x2.8x2.8 m^3

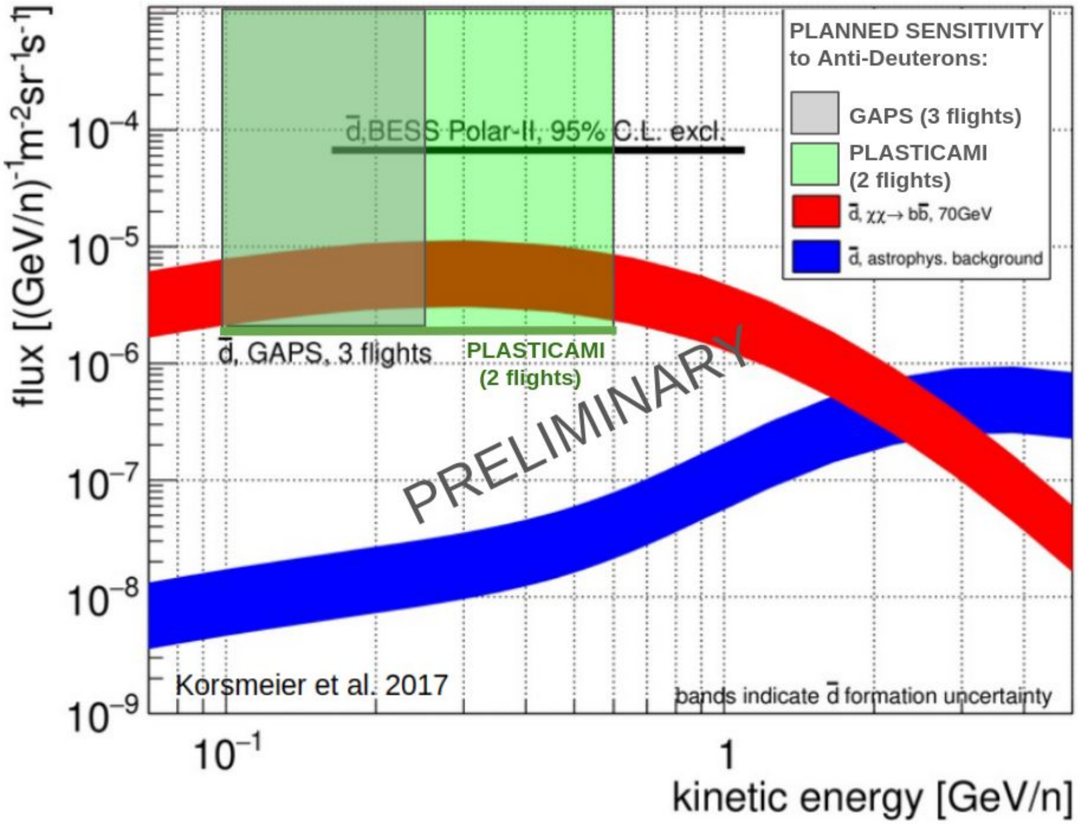
$$\begin{cases} \Delta t > 2\mathbf{ns} \\ |\Delta \vec{x}| > 15\mathbf{cm} \end{cases}$$

+ cautiously assumed a reconstruction eff. ~ 50%



Sensitivity: [100, 700] MeV/n

Sensitivity and conclusions

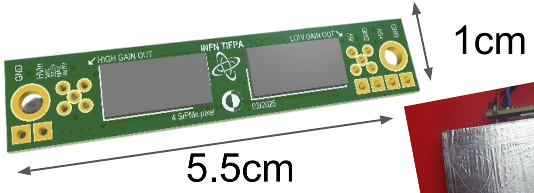


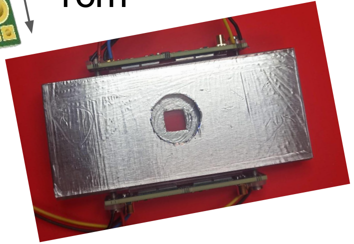
Based on the simple technology of plastic scintillators.

The PlastiCAMI approach seems very promising

Construction of a prototype detector ongoing @ INFN-TIFPA

1.44cm^2 SiPM fast readout:



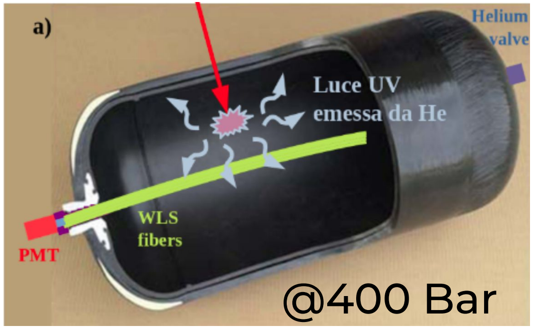


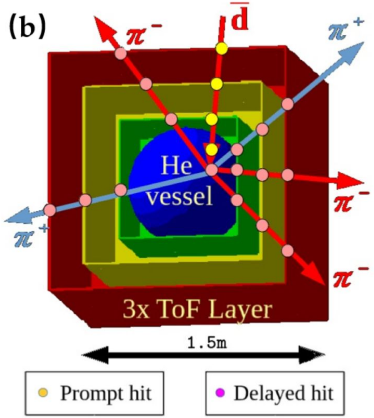
Backup

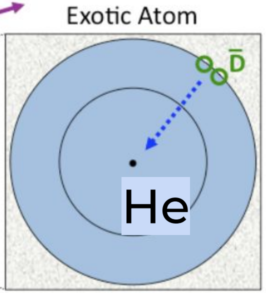
PHeSCAMI project

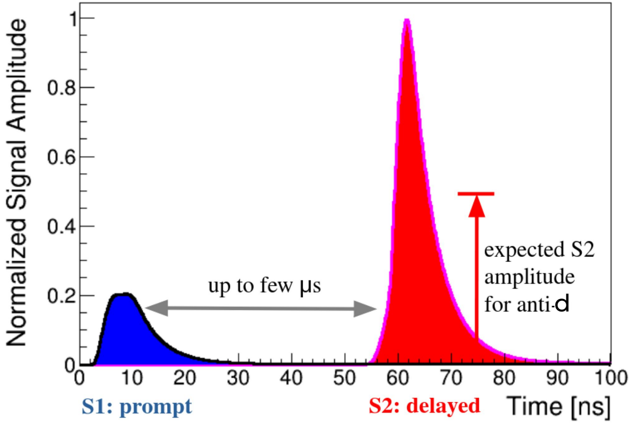
Detector: TOF + pressurized He scintillator

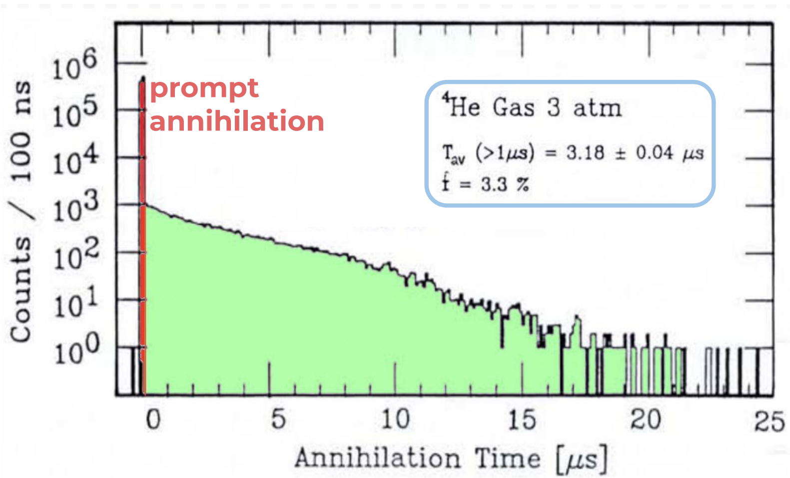
Signature: Delayed annihilation (μs) from metastable exotic He-antiD atoms, 3.3% captures long-lived states → prompt+delayed double-event





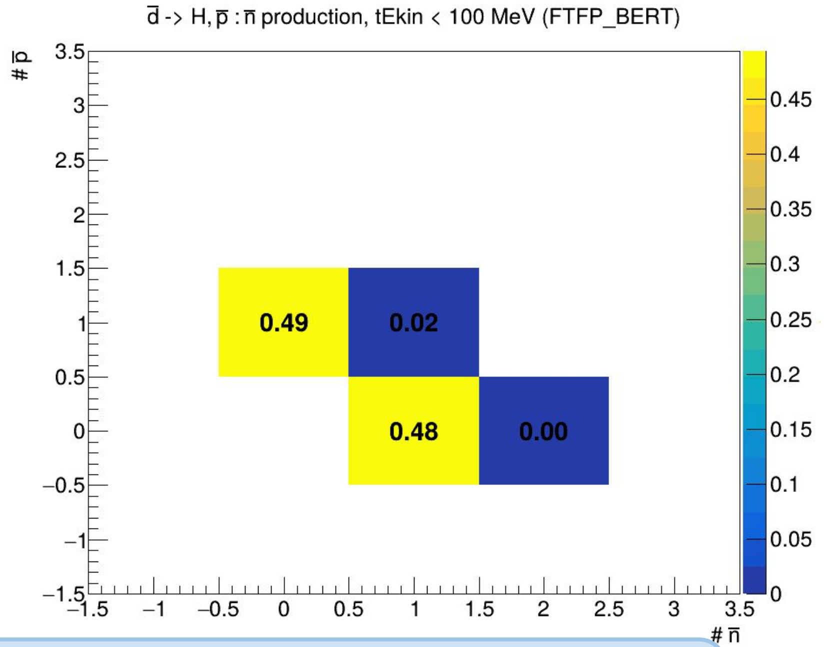






Prototype tested 20/23 (TIFPA), WLS validated '24, Fund 22/27, proposed for LDB

N-bar recoiling in $\bar{d} \to H$

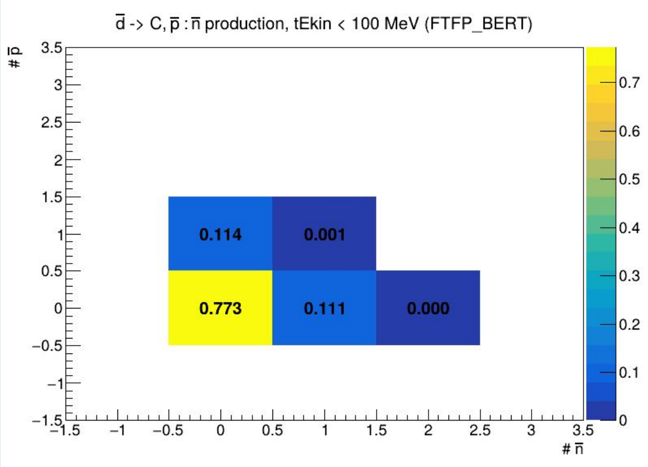


Geant4 simulation of ***d-bar*** on a ***H*** target predict same probability of ***p-bar/n-bar*** recoiling (~ 50%)

but *H* detectors in space are challenging as *He* ones: use plastic scintillator

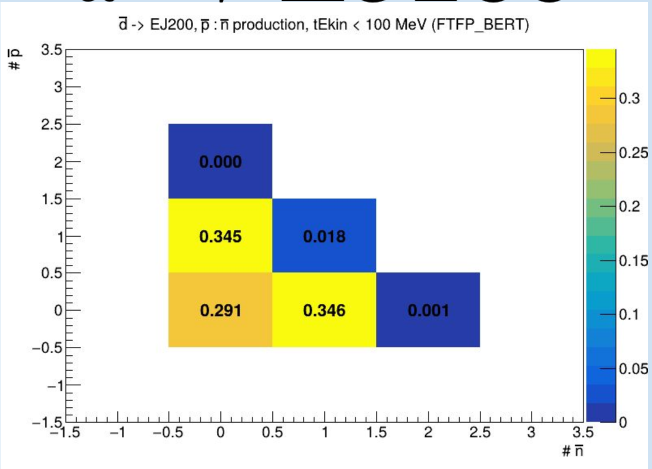
N-bar recoiling in plastic

$$\bar{d} \rightarrow C$$



Expected a major component of **complete *d-bar* annihilation** (some uncertainties on nuclear process)

$$\bar{d} \rightarrow \mathbf{EJ200}$$



Still presence of a 60% probability of ***N-bar*** recoil (some uncertainties on chemistry of exotic atoms)

N-bar recoil kinetic energy

ASTERIX studied the process:

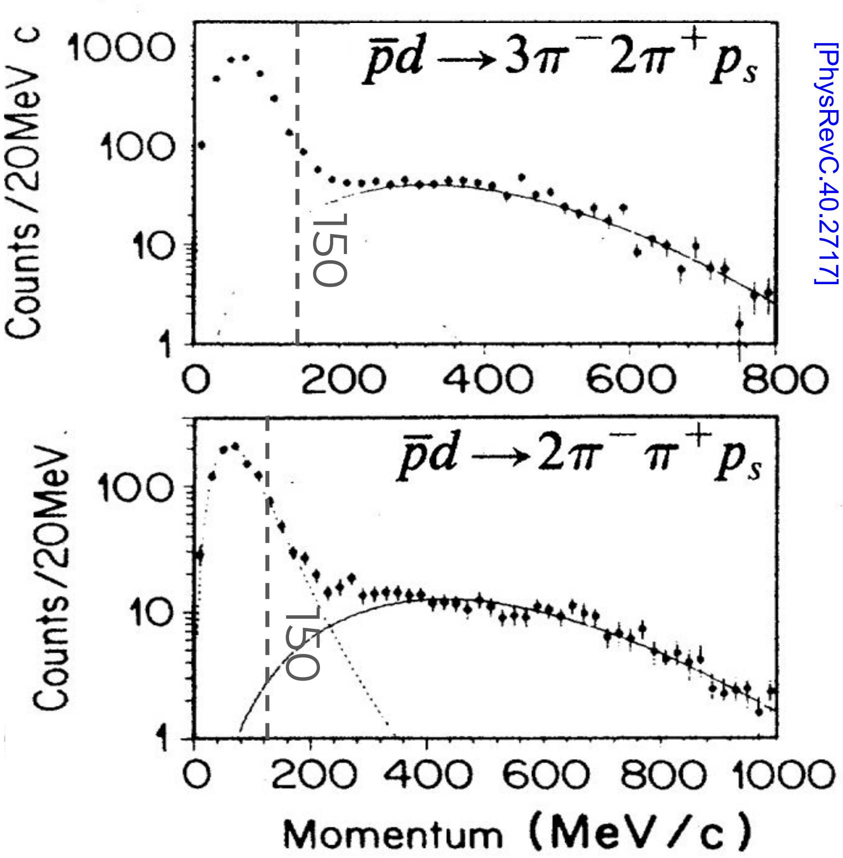
$$\boxed{\bar{p} \to d}$$

which is the mirror process of:

$$\boxed{\bar{d} \to p}$$

The mean of the momentum spectrum of recoiled *p* of these specific channels indicates that:

$$\boxed{E_K(p) \sim 10\mathrm{MeV}}$$

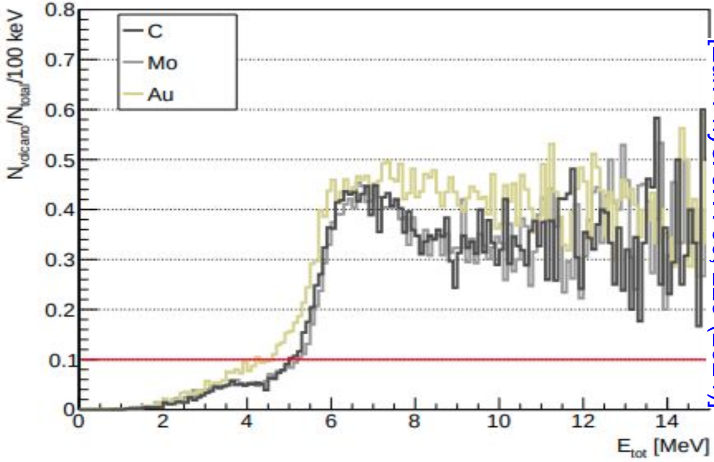


[PhysRevC.40.2717]

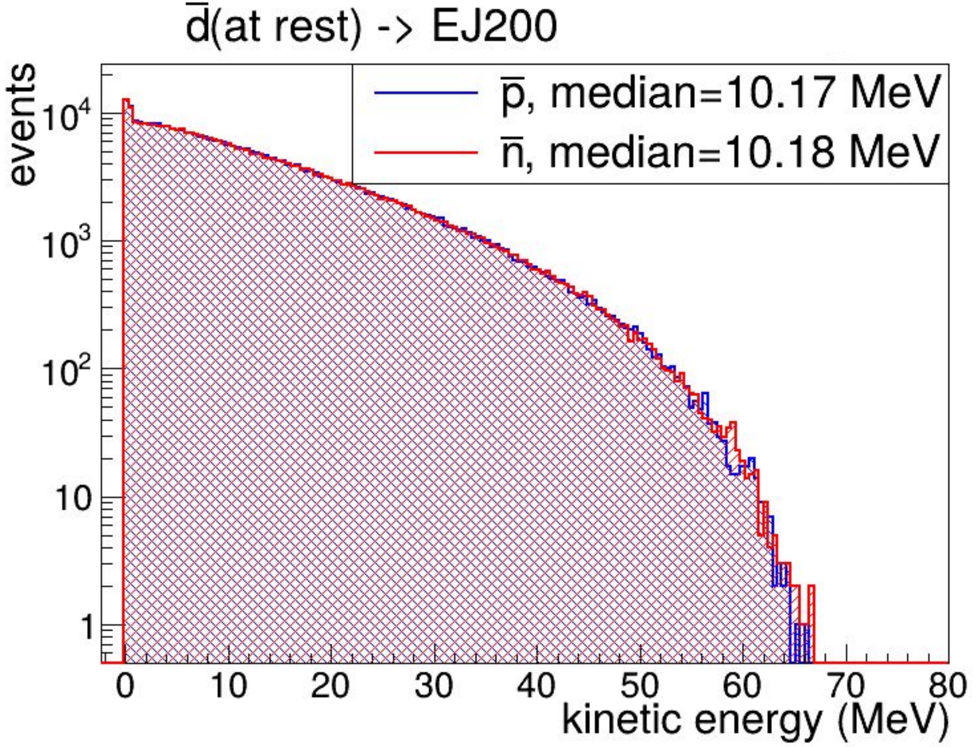
N-bar recoil kinetic energy

Geant4 kinetic energy of ***N-bar*** recoiled in plastic is of the same order of the direct measurements

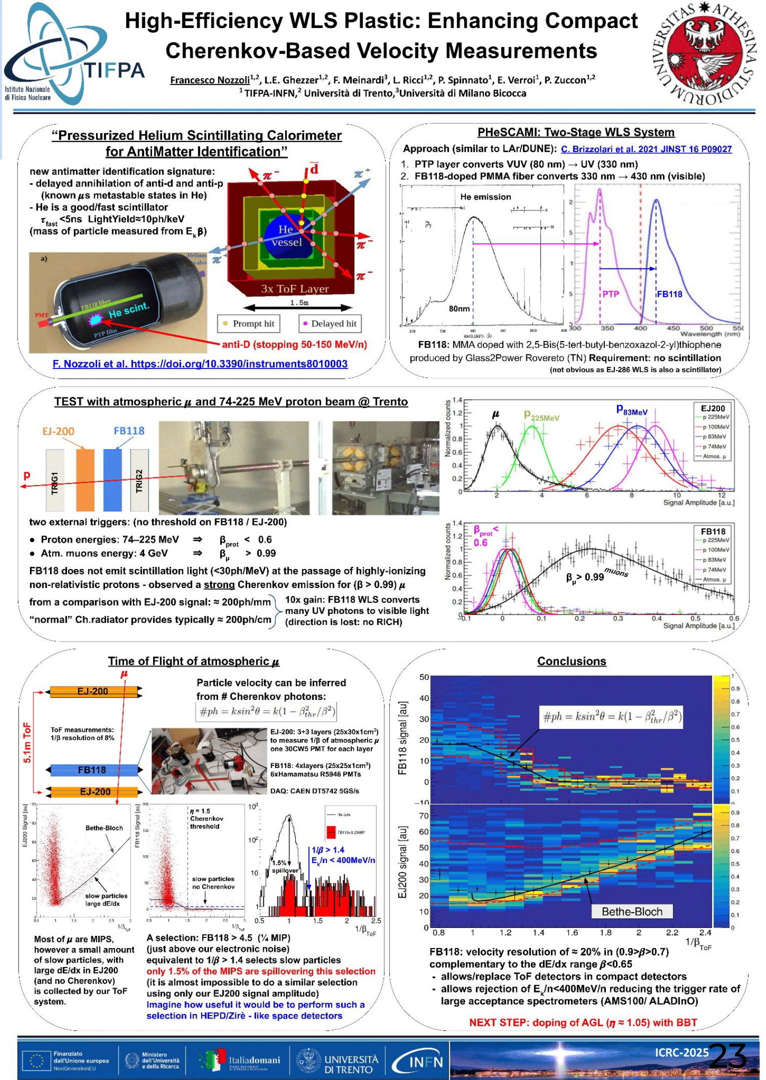
- ASTERIX
- nuclear prongs in *p-bar* annihilation of C, Mo, Au



[Eur. Phys. J. A 60, 225 (2024)]



Cherenkov veto



Power required by 4800 ToF channels

PETIROC 2A

SiPM read out for time of flight PET

Request a quote

Downloads

Weeroc website

Features

- **TRL Technology Readiness Level** 6 – Application prototype available
- **Detector Read-Out** SiPM, SiPM array
- **Number of Channel** 32
- **Signal Polarity** Positive or Negative
- **Fast trigger line**
- **Dynamic Range** 0-480 pC i.e. 3000 photoelectrons @ 10^6 SiPM gain
- **Fixed gain (40)** inverting voltage preamplifier
- **Slow shaper** with adjustable shaping time from 25 to 100 ns
- Charge measurements by Track&Hold
- Integral Non Linearity : 1% up to 2500 photoelectrons
- **40 ps bin Time to Amplitude converter** embedded in each channel
- **Power consumption** 6mW/channel

x 4800ch = 30W

Background: p pile-up and $\bar{p}$ annihilation

Background:

- p **pile-up**

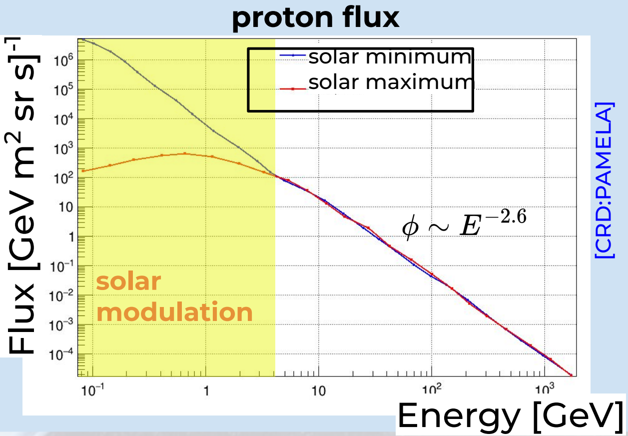
  during solar max, probability of a proton hit in a gate of 50 [ns] is:

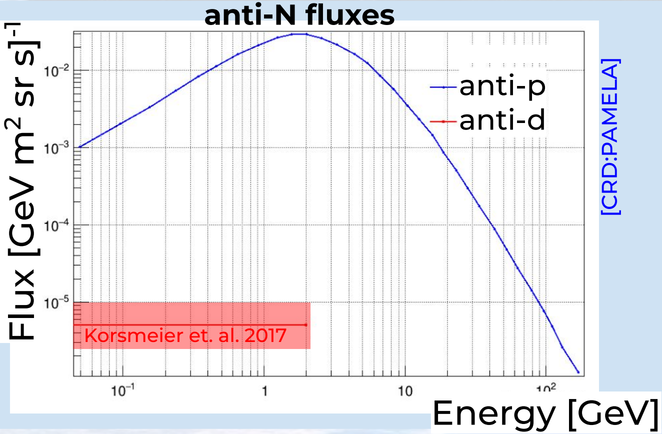
  P ~ 0.5%

- $\bar{p}$ **annihilation:**

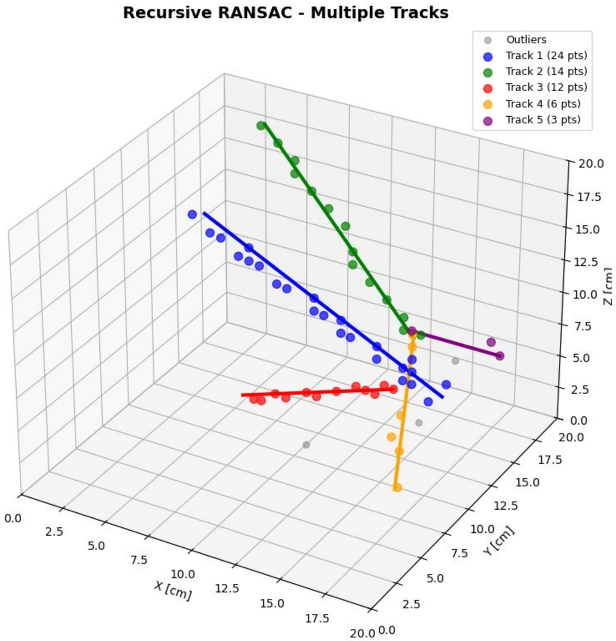
  antinucleon annihilation in the detector

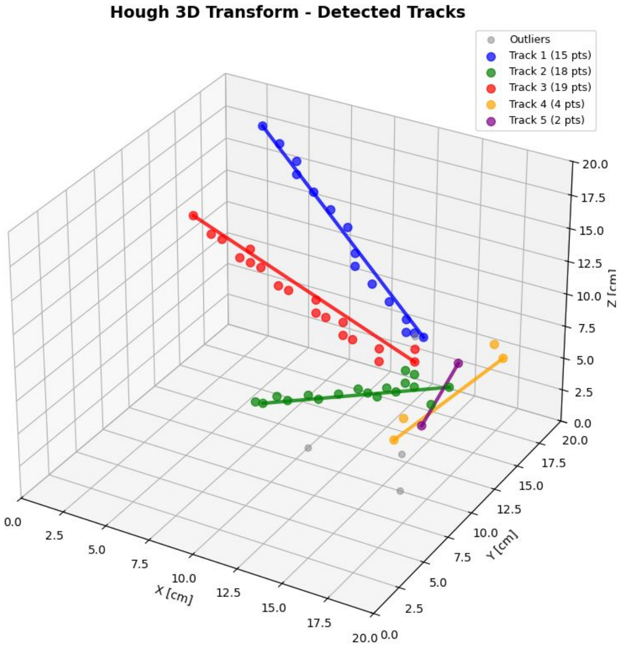
  antiP: 50 000 events/flight
  antiD: 50 events/flight





Classification: tracking





easy to integrate time information

difficult to integrate time information

Simulation: systematic

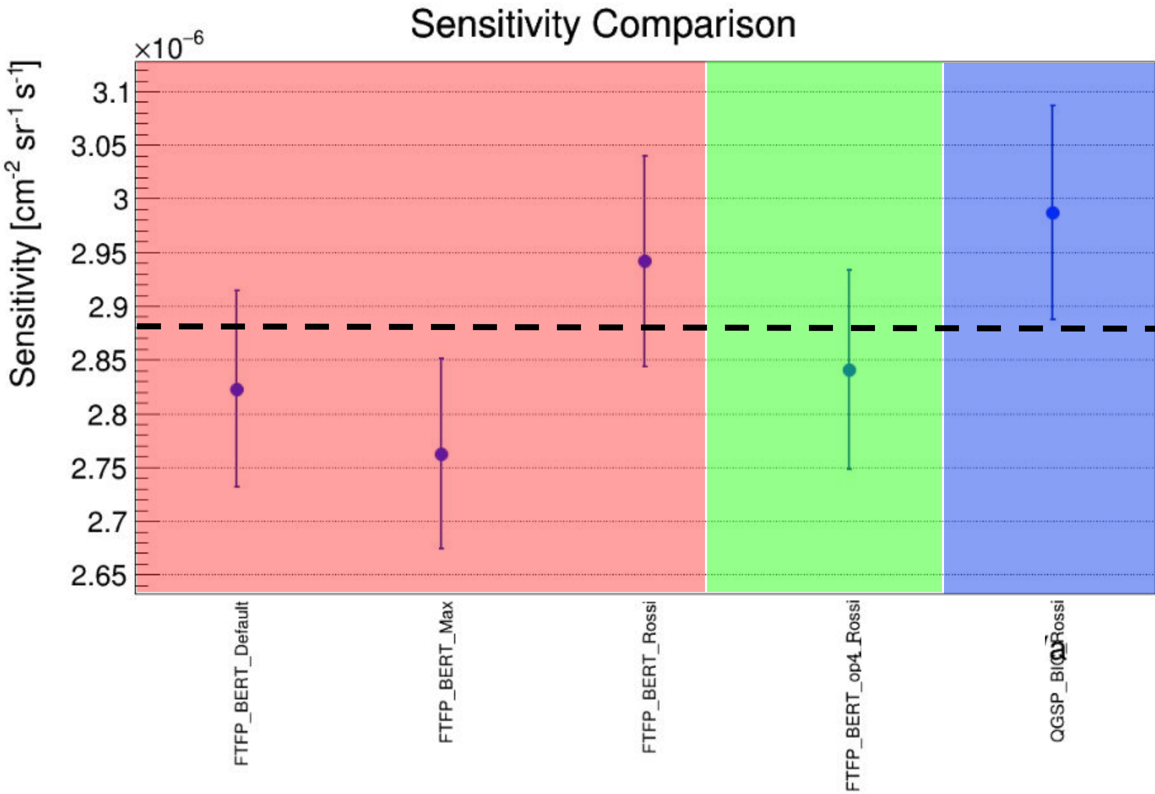
We verified the presence of systematic introduced by

PhysicsList:

- FTFP_BERT
- FTPT_BERT_op4
- QGSP_BIC

StepLimiter:

- Default
- “Rossi”
- Max



No systematic effect