Track detectors based on

straw drift tubes

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HEPD seminar
18.10.22

motivation

Large area tracker with a good spatial and/or momentum resolution

+ small material budged (minimal multiple scattering)

+ large area acceptance (unreachable for Si trackers)

sometimes

+ operation in vacuum (reliability + negligible leak rate)

+ operation in magnetic fields

+ ionization losses (dE/dx) allowing particle identification (thanks to proportional mode)

- limitations: rate capability – low and moderate rates, depends on the tracker length

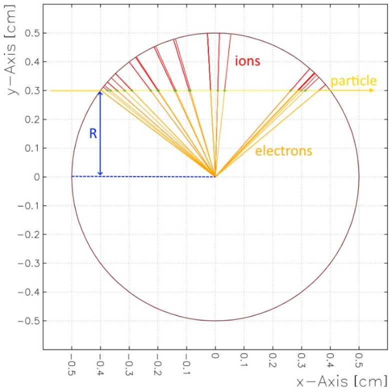
Straw tubes – operation principle

- thin wall drift tube of small (O(cm)) diameter

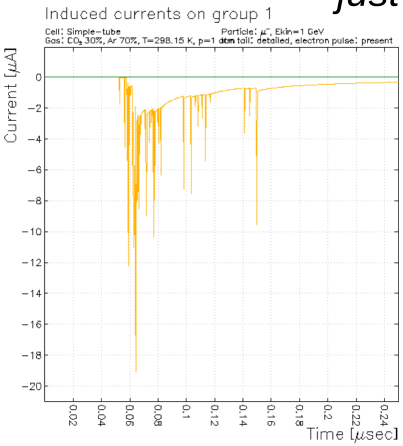
- proportional mode

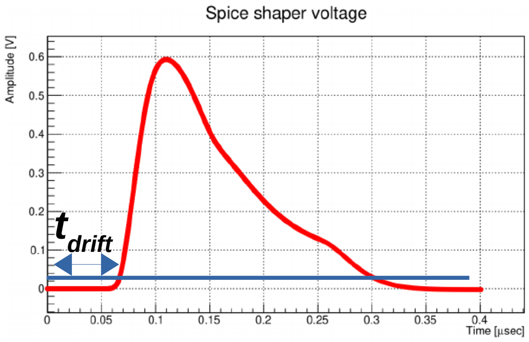
- drift time of ~first (or ~second) closest to anode electrons represents quite well the distance between the track of the ionizing particle ***R*** and anode wire

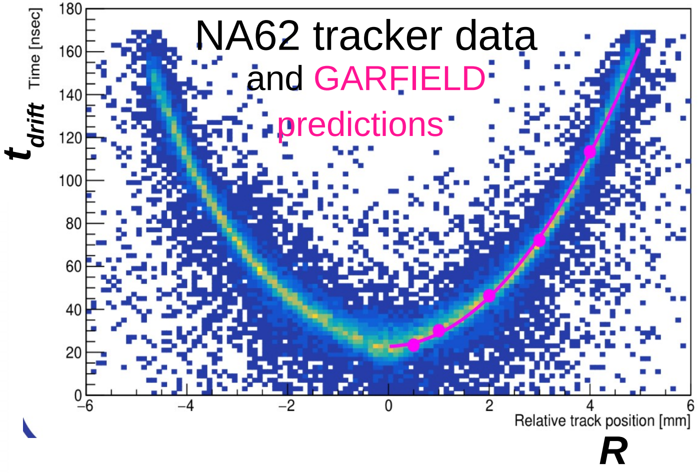
The drift time $\boldsymbol{t_{drift}}$ is measured as the difference between time $\boldsymbol{t_0}$ when an ionizing particle crossed the straw and the time when the induced straw signal exceeded a given threshold.



just for illustration



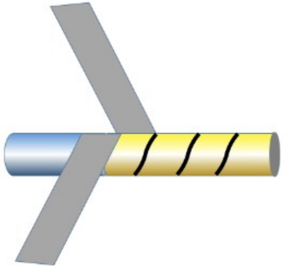


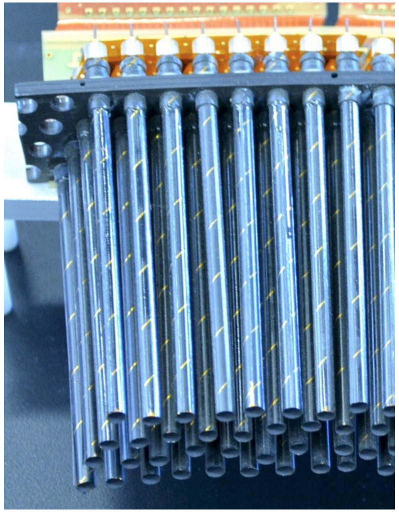


Technologies of the straws production

Winding

- **Atlas TRT**, LHCb OT, COMPASS, NA64,…
- Panda, Mu2e, ...



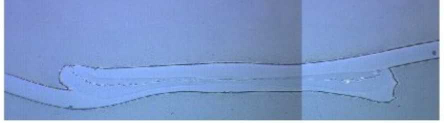


Ultrasonic welding

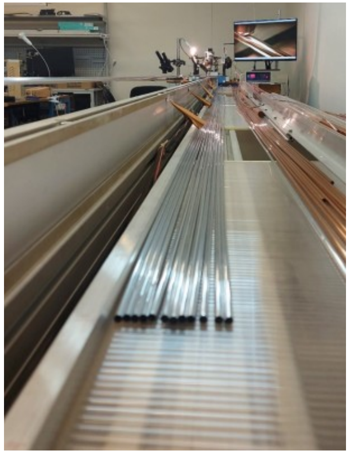
- NA62
- Comet, **SHiP**,

  Dune, **SPD**...

Weld seam (zoom x20 on a PC monitor)

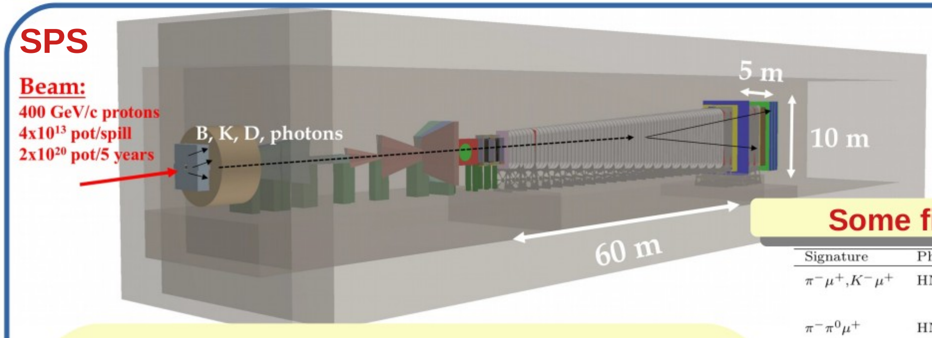


Cross-section of a welded seam



SHiP – Search for Hidden Particles

SHiP physics – search for new particles



- Signal: hidden particles from K, **D**, B decays with mass O(GeV)
  - HNL
  - Dark photon
  - Dark scalars
  - Axions and axion-like particles
  - …
- **Physics BG**: aiming o(1) event for $2x10^{20}$ proton on target (5 years) in a selected data sample (at least the HNL case) - "BG free experiment"

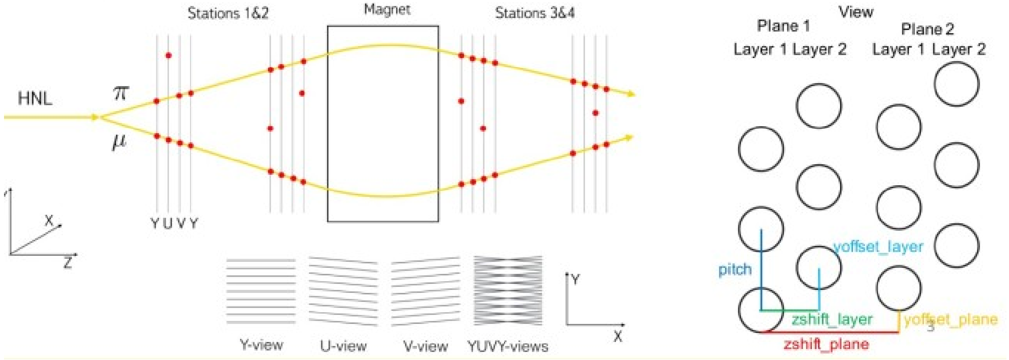
Some final states from TP

Signature	Physics	Backgrounds
$\pi^-\mu^+, K^-\mu^+$	HNL,NEU	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\pi^-\pi^0\mu^+$	HNL($\to \rho^-\mu^+$)	$K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$, $K_L^0 \to \pi^-\pi^+\pi^0$
π^-e^+, K^-e^+	HNL, NEU	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^0e^+$	HNL($\to \rho^-e^+$)	$K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$
$\mu^-e^+ + p^{miss}$	HNL,HP($\to \tau\tau$)	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$
$\mu^-\mu^+ + p^{miss}$	HNL,HP($\to \tau\tau$)	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+$	DP,PNGB,HP	RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$
$\mu^-\mu^+\gamma$	CS	$K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$
$e^-e^+ + p^{miss}$	HNL,HP	$K_L^0 \to \pi^-e^+\nu_e$
e^-e^+	DP,PNGB,HP	$K_L^0 \to \pi^-e^+\nu_e$
$\pi^-\pi^+$	DP,PNGB,HP	$K_L^0 \to \pi^-\mu^+\nu_\mu$, $K_L^0 \to \pi^-e^+\nu_e$ $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\pi^+$

RDM – random dimuon, HNL – Heavy Neutral Lepton, NEU – neutrolino, HP - Higgs Portal, DP – Dark Photon...

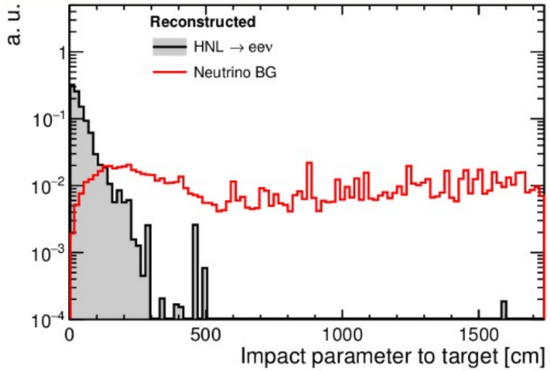
- **PNPI+Polytech** participates from the time of Technical Proposal (2015)
  - Main interest – Straw Tracker
    - Straw production
    - Simulation and reconstruction
    - TB participation and data analysis
    - Digital electronics and HV

SHiP Spectrometer Straw Tracker (SST)

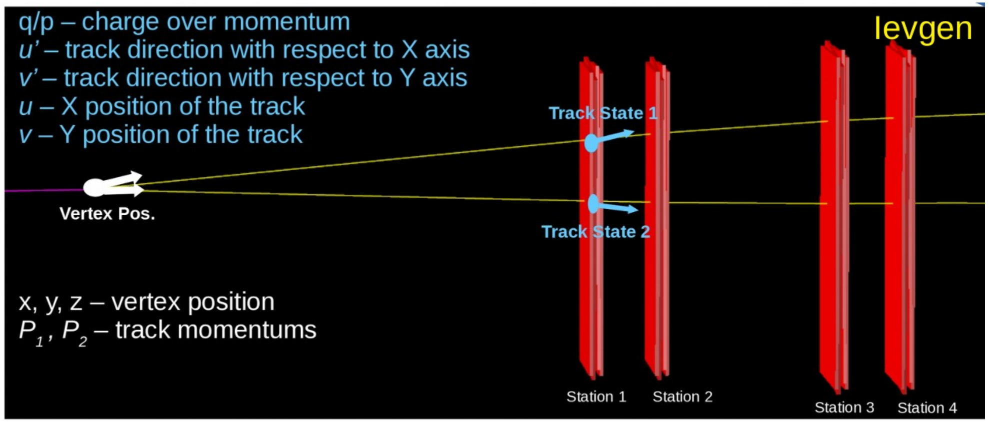


Z – not in scale – vertex in tens meters from the SST

- Ultra light straw stations operating in vacuum: 4 YUVY stations = ~20k straws
- Acceptance 5x10m^2 (=>4x10m^2)
- Straws of 20mm diameter, 30um diameter gold-plated tungsten wire
- Spacial resolution better than 120 um



input

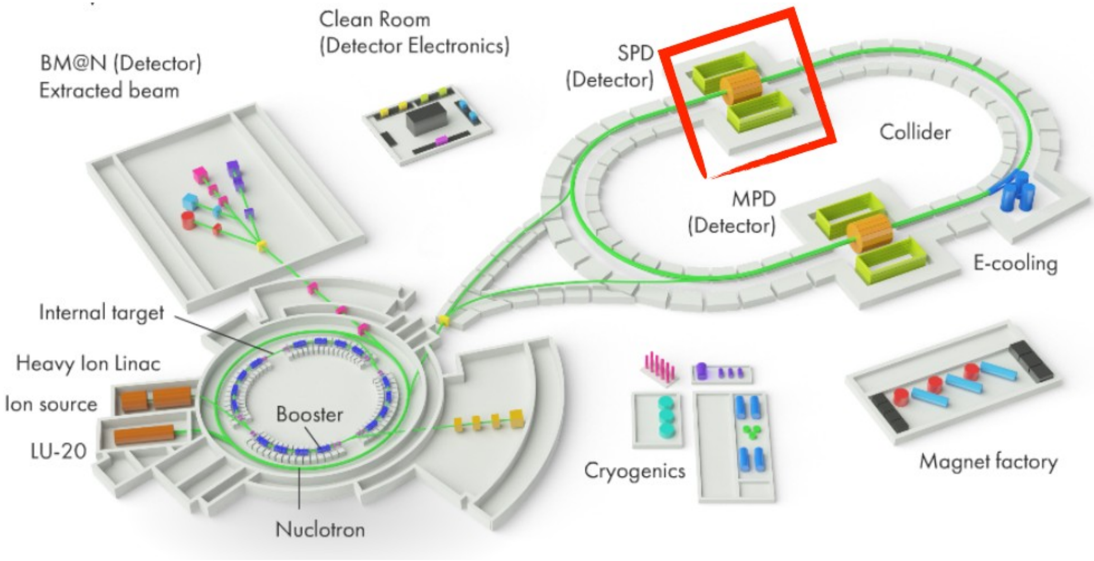


output

Tracking/vertexing parameters DOCA, IP, NDF and Chi2/NDF are powerful variables to distinguish BG and signal

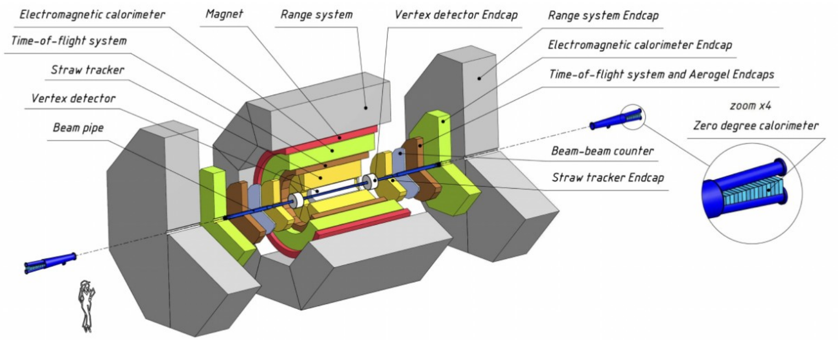
SPD – Spin Physics Detector

$$p^{\uparrow}p^{\uparrow}: \sqrt{s} \leq 27\ GeV$$
$$d^{\uparrow}d^{\uparrow}: \sqrt{s} \leq 13.5\ GeV$$
$$d^{\uparrow}p^{\uparrow}: \sqrt{s} \leq 19\ GeV$$

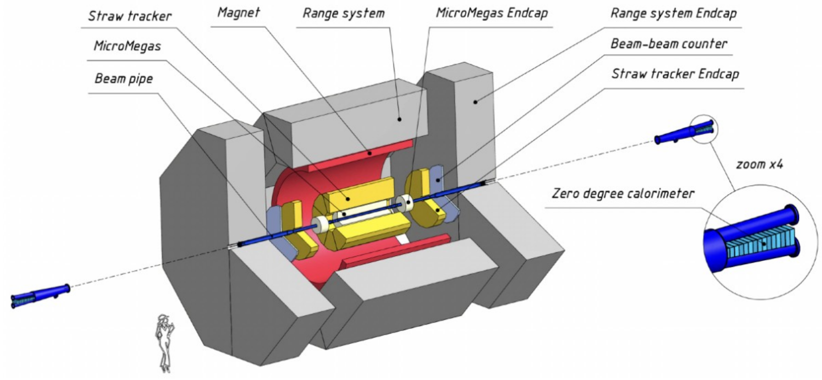


PNPI participation – physics, software, tracker

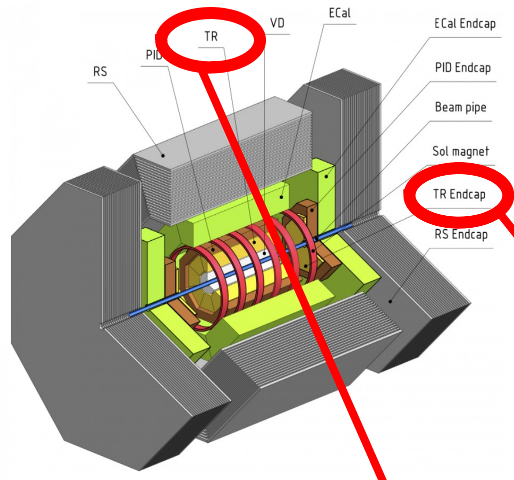
SPD detector



SPD detector – phase I



SPD tracker



The main tracking system of the SPD

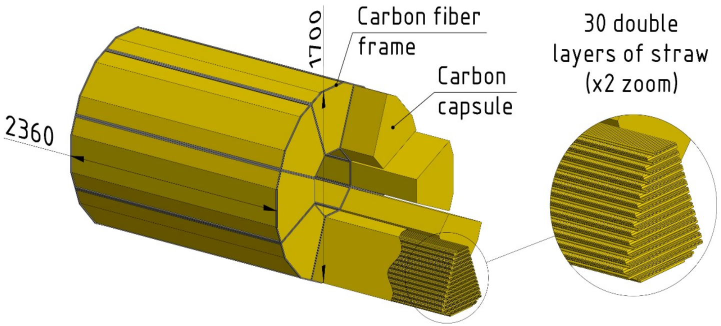
Straws:

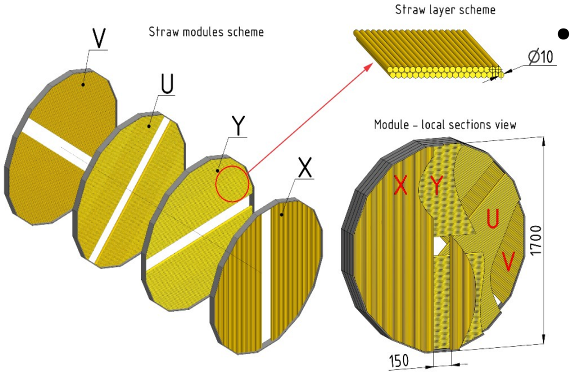
diameter 10mm

thickness 36um PET

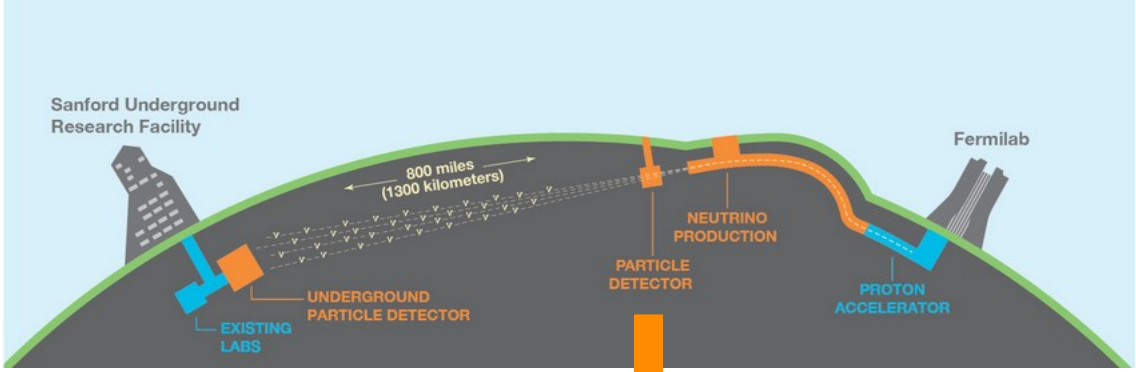
Spatial resolution ~150um

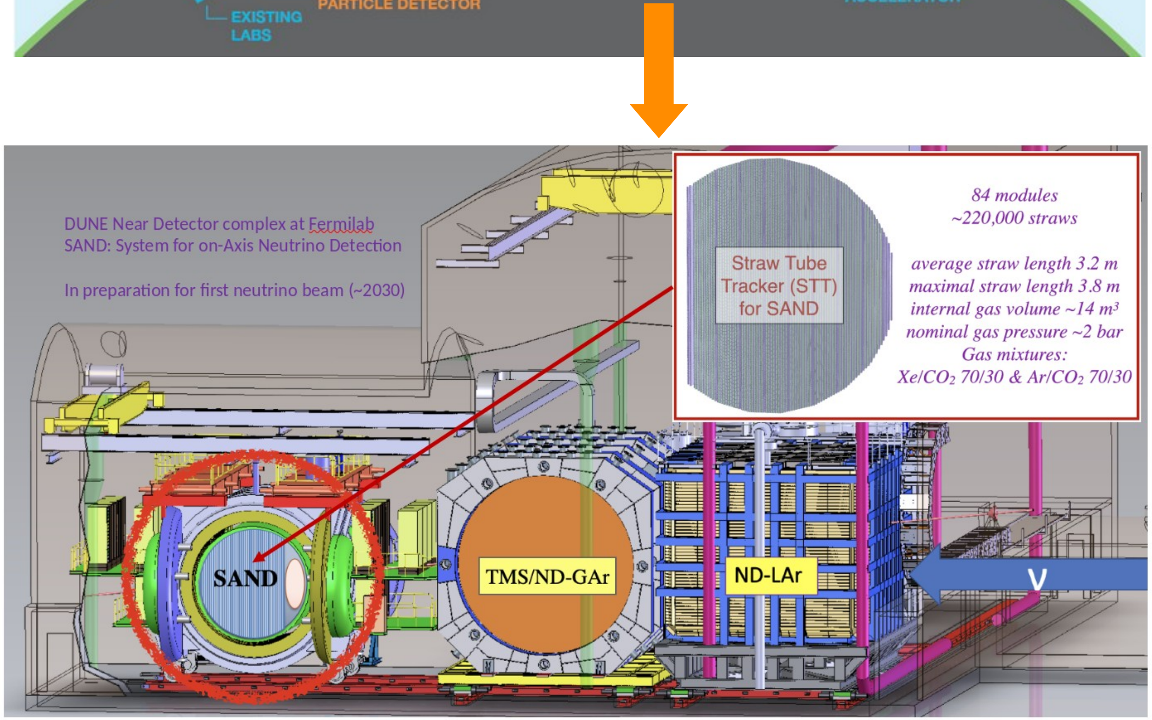
- Barrel (ultrasonic welding): 8 modules with up to 30 double-layers with the ZUV orientation = ~20k straws in total
- Endcaps (winding): 12 double-layers with the XYUV orientation
- Vast experience in straw production in JINR for several experiment: COMPASS, NA-62, NA-64, SVD-2; prototypes for: CREAM, SHiP, COMET, DUNE.



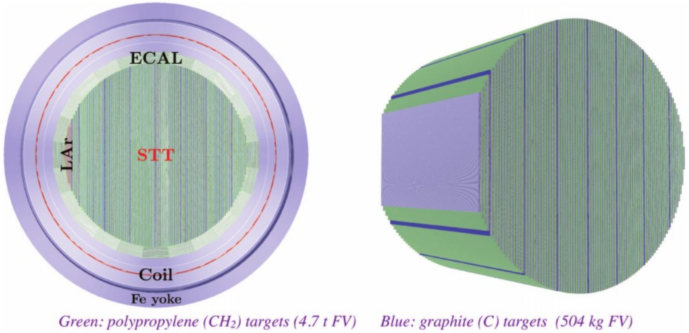


Deep Underground Neutrino Experiment (DUNE)





- Dune Straw Tube Tracker

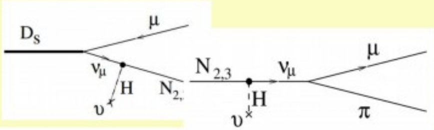


Beam monitoring (with ECAL) and neutrino flux measurements

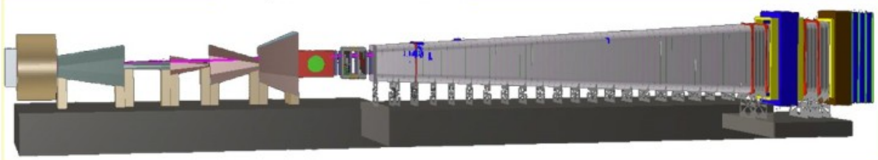
200k straws in total

Why we believe those trackers will work? NA62!

Initial SHiP detector concept is inspired by NA62

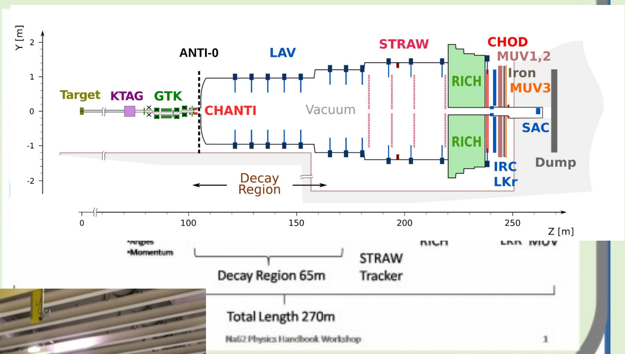


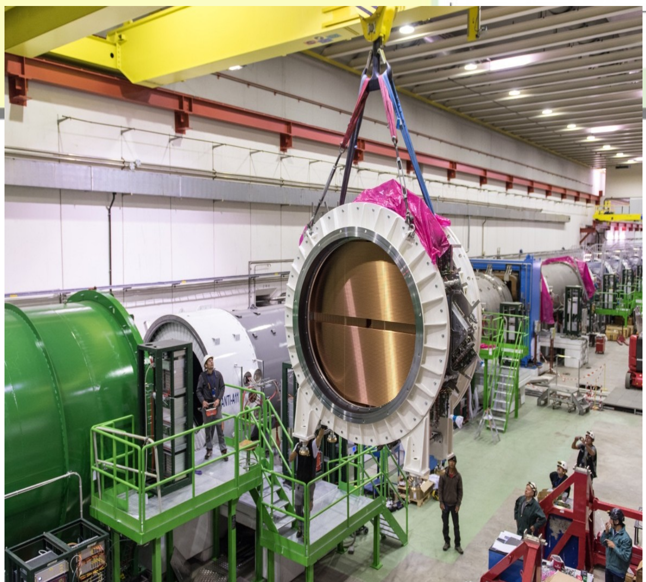
+ many other FS and other potential physics



NA62: rear kaon decays

$K^+ \rightarrow \pi^+ \nu\nu$

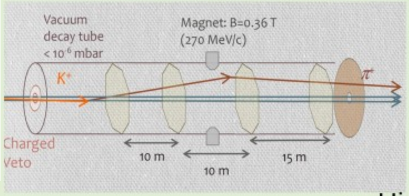


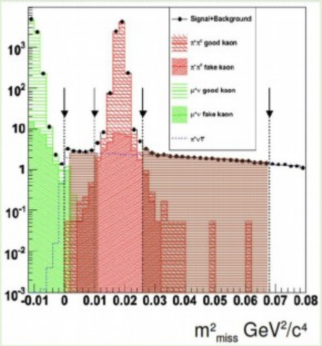


NA62:

4 straw tracker stations in vacuum

- Very good p resolution: $\sigma_p/p < 1\%$
- Angular resolution: $\sigma_\theta < 60\ \mu rad$
- Few radiation length: $< 4\times0.5\%\ X_0$
- High efficiency: > 99% hit efficiency
- High rate: 0.5 MHz in hottest area





- High rate operation
- multitrack event rejection
- extremely good momentum resolution

M. Raggi LNF

Hep-Mad 2011 Antananarivo 26-31 Aug 2011

Why we believe those trackers will work? NA62!

Current NA62 straw spectrometer:

- **Straw diameter: 9.8 mm**
  - Material: 36 μm thick PET
  - Plating: 50 nm copper + 20 nm gold
  - Wire: 30 μm tungsten wire
- **Gas: Ar+CO_2 (70:30)**
- **4 chambers, 7168 straws in vacuum**
  - 30 straw hits per track
- **Total material budget: 1.7% X_0**
  - Dominated by the PET (70%)
- **Single straw timing performance:**
  - Maximum drift time: 150 ns
  - Leading time resolution: 3-4 ns
  - Trailing time resolution: 30 ns

New straw detector, main features:

- Smaller straw diameter: 4.8 mm
  - Maximum drift time reduced to 80 ns
  - Trailing time resolution improved to 6 ns
- Keeping the 4 chambers layout, 21000 straws
  - Number of hits per track increased to 40
- Thinner straw material: 19 or 12 μm thick PET
- Lower total material budget: 1.0 – 1.5% X_0
  - Depending on the PET thickness option
  - Still dominated by the straw wall (60 – 70%)

How to readout future large straw trackers?

- SHiP ~20k channels, time (~ns), optional Q (signal vs noise, signal (mu) vs BG (e))
- DUNE ~200k channels, time (~ns), Q (PID)
- SPD ~20k channels, time (~ns), Q(PID)

  all – triggerless readouts

Possible solutions

- New development

  for example, SHiP SST/SBT common electronics

  https://indico.cern.ch/event/884132/contributions/3732240/attachments/1980538/3297968/20200203_Juelich_V1.pdf - D.Arutinov, SHiP electronics meeting 2020

- Existing solutions?

  VMM3/3a? http://cds.cern.ch/record/2693463/files/ATL-MUON-PROC-2019-009.pdf?version=1 - G.Iakovidis for ATLAS NSW - potentially matching performance

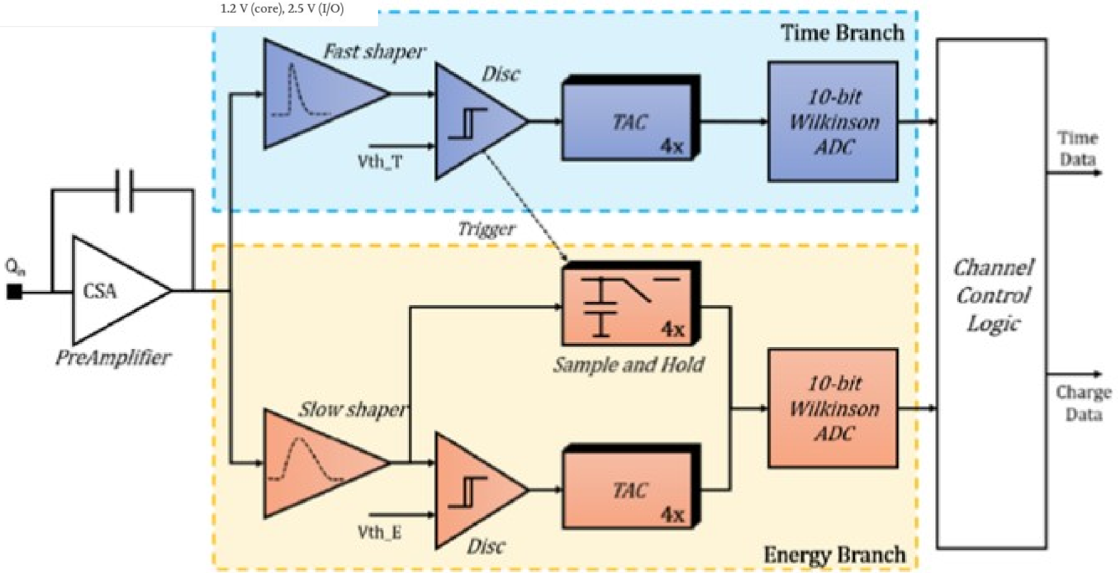
  - reasonable cost: ~1$/channel

  TIGER (BESIII GEM readout)- TIGER: A front-end ASIC for timing and energy measurements with radiation detectors A.Rivetti et al.

  - ...

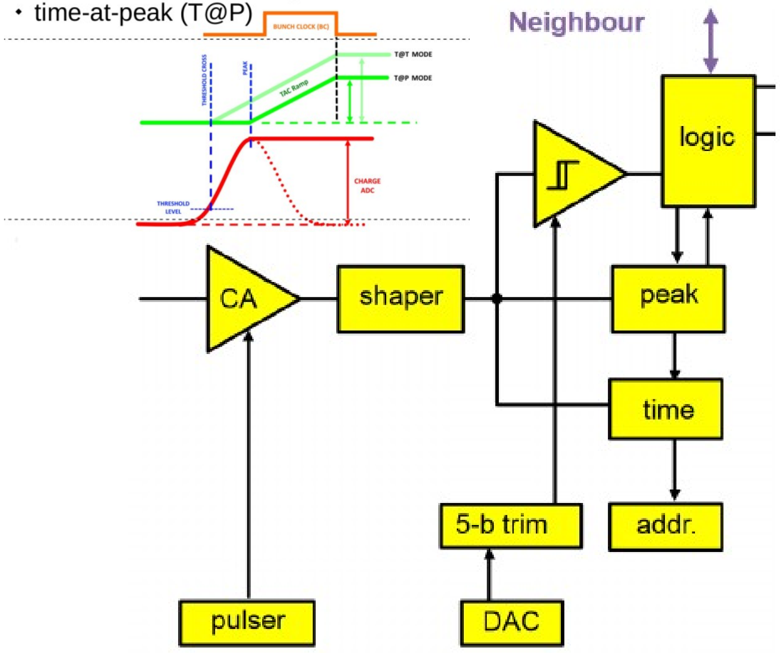
Input charge	1-50 fC
Input capacitance	Up to 100 pF
Data rate	10 kHz/ch
Non-linearity	< 1%
Charge collection Time	60 ns
Time resolution	< 10 ns (3 fC signal)
Power consumption	< 10 mW/ch
Technology	110 nm process
Power supply	1.2 V (core), 2.5 V (I/O)

TIGER vs VMM3



TIGER Architecture

- time-at-threshold (T@T)
- time-at-peak (T@P)



VMM3 Architecture

Main difference: tiger has two different shapers for Time and Energy measurements

Studies of VMM3/3a operating in T @ T mode

VMM3=>VMM3a : bug fix, high rate adaptation, flexibility for ATLAS NSW (MM and sTGC readout)

Widely operated in time-at-peak mode, we started to have look at time-at-threshold

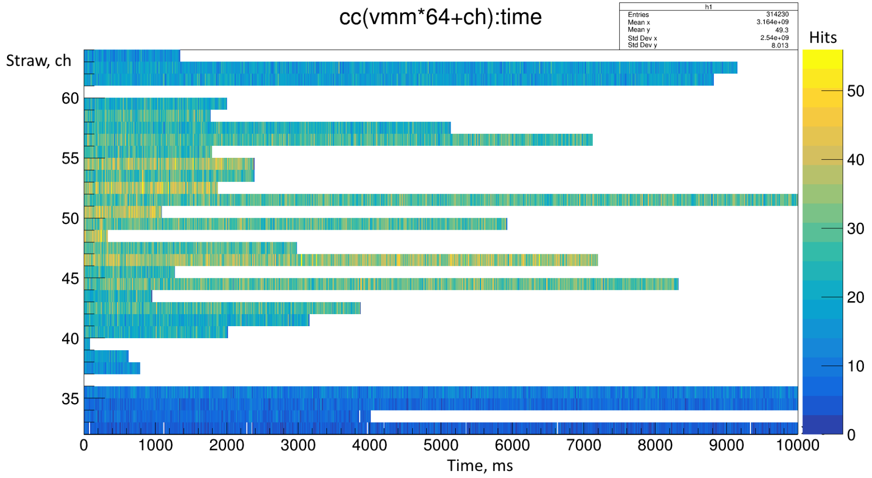
- Lab tests (VMM3a hybrids) – achievable time resolution ~1 ns (hardware)
- **Garfield + LTSpice simulation**
- Test Beams within RD51 – Oct 21 with VMM3a (RD51 hybrid), Apr-June + July 22 with VMM3(mu2e board)

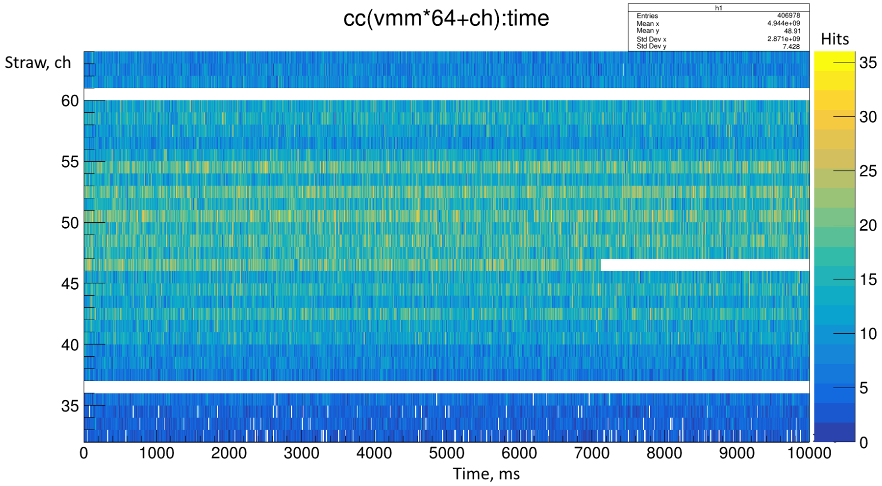
Measurements: VMM3a in T @ T

First observation during the October TB: “latching” channels

- Confirmed by lab tests. A possible explanation is an algorithmic problem in the cases when the time between the threshold crossing and signal peak is too short (<1 clock cycle). A consequence of high rate performance optimization for ATL-NSW??

- Confirmation: A comparison of operation stability with 40MHz and 80MHz clock frequency:





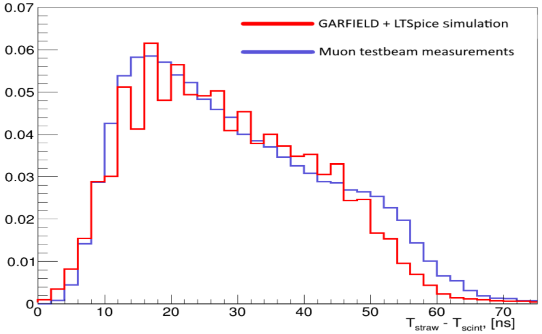
Measurements: VMM3 in T @ T

No such effect was found with the previous revision, VMM3:

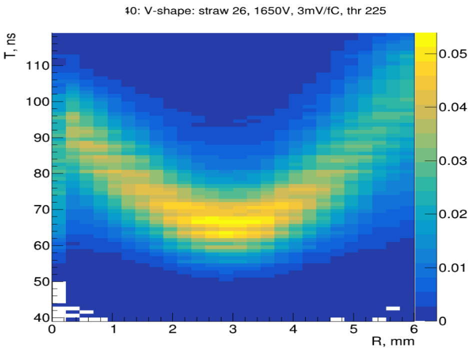
- the logic of the T@T mode slightly differs between VMM3 and VMM3a

Preliminary measurements result
Work in progress

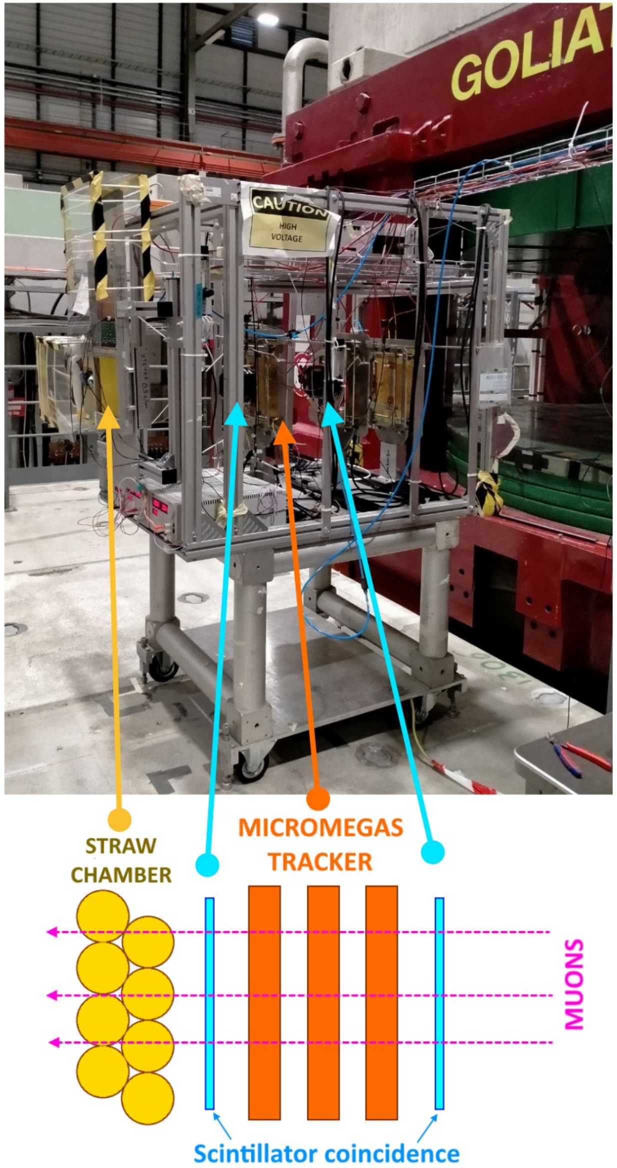
6mm straw,
D_{wire} = 30um,
HV = 1650V



Measured drift time distribution compared to Garfield + LTSpice simulation results



Measured ***r*(*time*$_{drift}$)** dependence
(reduced tracking information)



Summary of the TestBeam activities

Setup 1

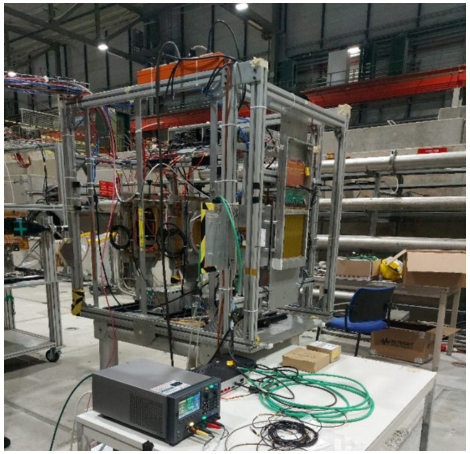
CERN, H4 (oct21)
4MM +straw station
VMM3a readout

Setup 2

CERN, H4 (spring+summer 22)
4MM +straw station
VMM3 readout (m2e board)
SRS +APV25 readout

Data analysis in progress…

Setup 3



CERN, H4 + H8 + H4 (summer + oct22)
4MM +straw station
TIGER readout
Data taking approaching… tomorrow

Summary

Starting from 2015 PNPI team actively participates in development of future trackers

- Contribution to SHiP SST (testbeam datataking and analysis, sim/reco software, conceptual design of digital electronics and development of the straw production station in PNPI)
- From 2020 - active participation in the SPD tracker development starting from the contribution to work on the reconstruction/simulation software and moving towards

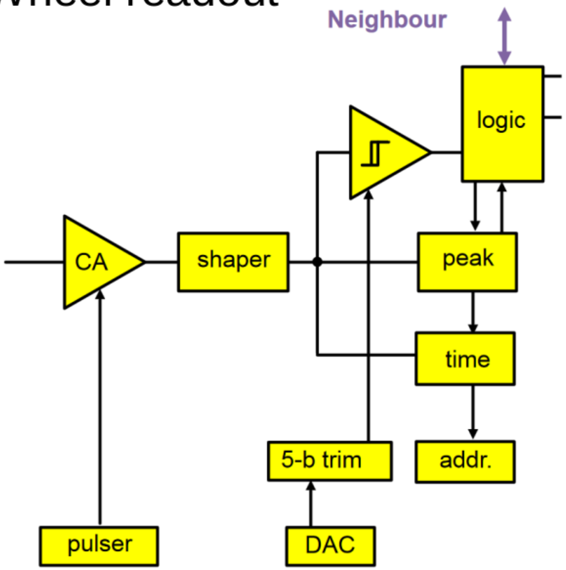
- General R&D on searches for optimal solution for optimal straw readout options
- Common work with JINR team
- Collaboration with RD 51, DUNE, NA62 and NA64
- Work ongoing...

backup

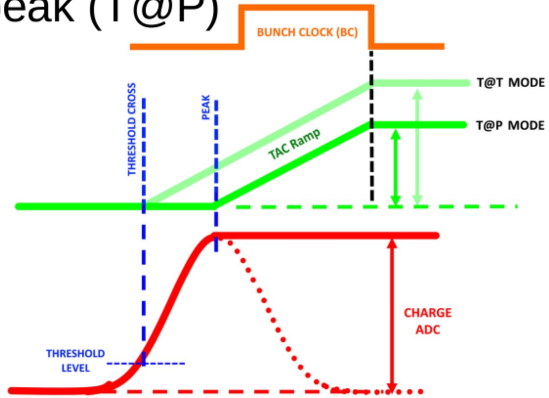
VMM3/3a in time-at-threshold mode

Multifunctional Application Specific Integrated Circuit (ASIC) VMM3 [ ]

- widely used as readout of micro-pattern gas detectors
- was a base for the production VMM3a version for the ATLAS New Small Wheel readout



- flexible settings of analogue input circuitry
- charge measurements (nominally 10b ADC)
- time measurements (nominally 8b TDC)
  - time-at-threshold (T@T)
  - time-at-peak (T@P)



Though VMM3/3a implements a precise time measurements of a threshold crossing (T@T), the most of applications measure signal peak time (T@P)