Straw Tube Tracker for SAND: Design and Overview

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for the SAND working group

Review of the DUNE Near Detector Design
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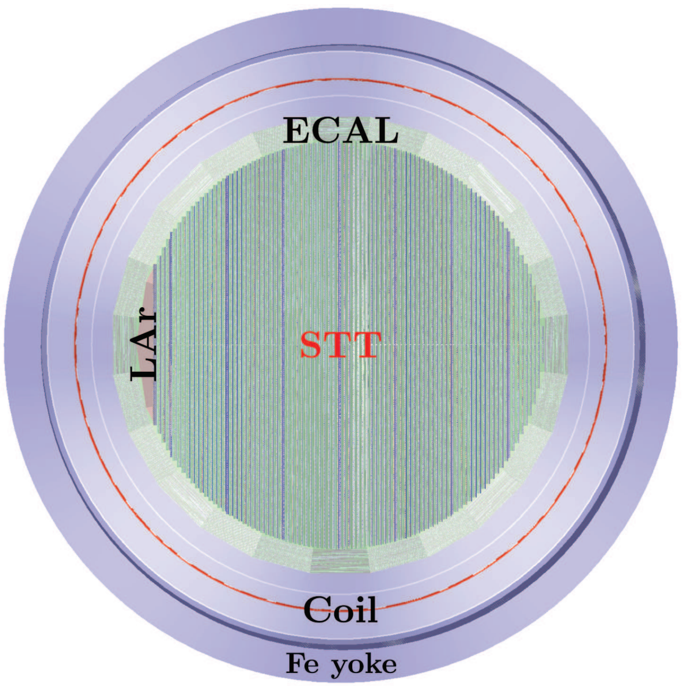
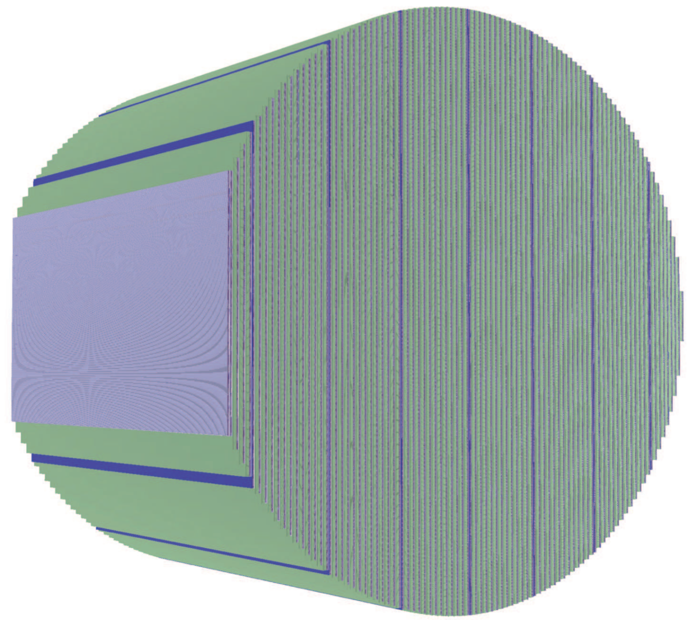
SAND WITH STRAW TUBE TRACKER

- *Detector configurations for the SAND inner tracker actively studied (CDR):*
  - *Thin LAr + 3DST + low-density tracker (either TPC or STT+targets);*
  - *Thin LAr + STT with multiple integrated targets;*

- *Description of full STT configuration with results of complete detector simulations, event reconstruction and physics performance is available in DocDb # 13262:*

  `https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=13262`





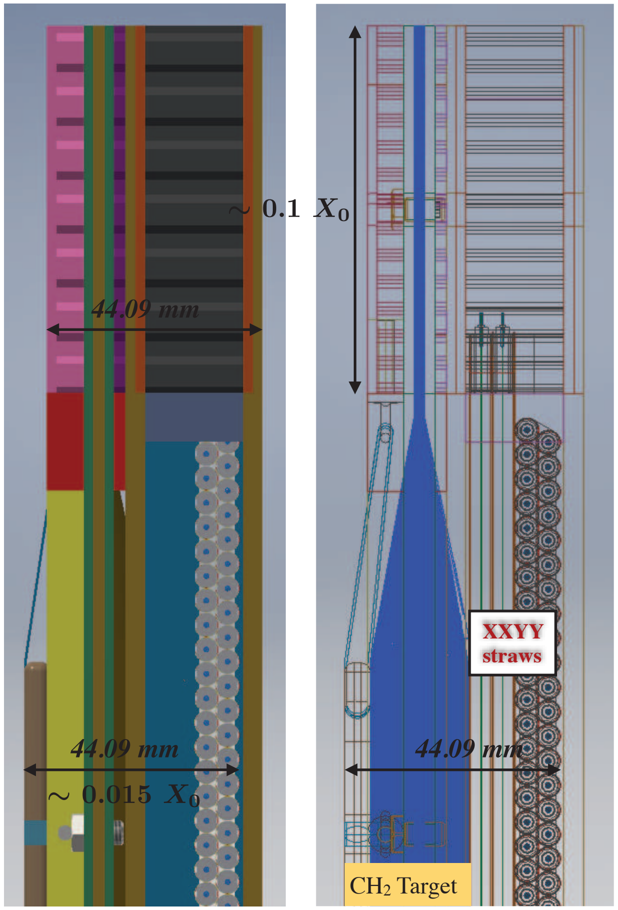
Green: polypropylene (CH_2) targets (4.7 t FV)   Blue: graphite (C) targets (504 kg FV)

A TOOL TO REDUCE SYSTEMATICS

✦ *STT designed to offer a control of ν-target(s) similar to $e^{\pm}$ DIS experiments:*

- *Typical ν-detectors: systematics from target composition & materials, limited target options;*
- *Possible accurate control of target(s) by separating target(s) from active detector(s);*
- *Thin targets spread out uniformly within tracker by keeping low density* $0.005 \leq \rho \leq 0.18$ *g/cm*^{3}.

$\Longrightarrow$ *STT can be considered a precision instrument fully tunable/configurable*

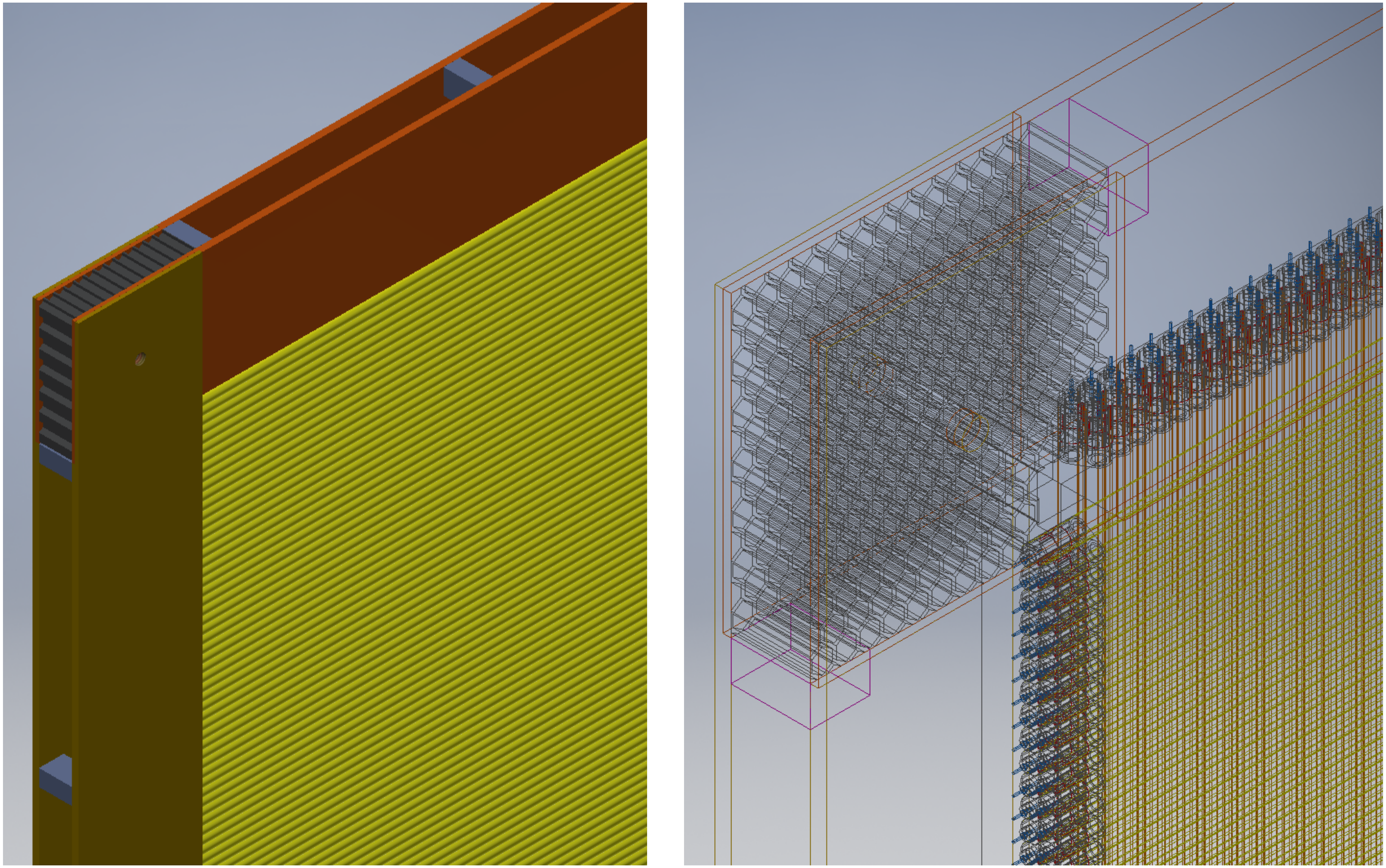


✦ *Targets (100% purity) account for $\sim 97\%$ of STT mass (straws 3%)*

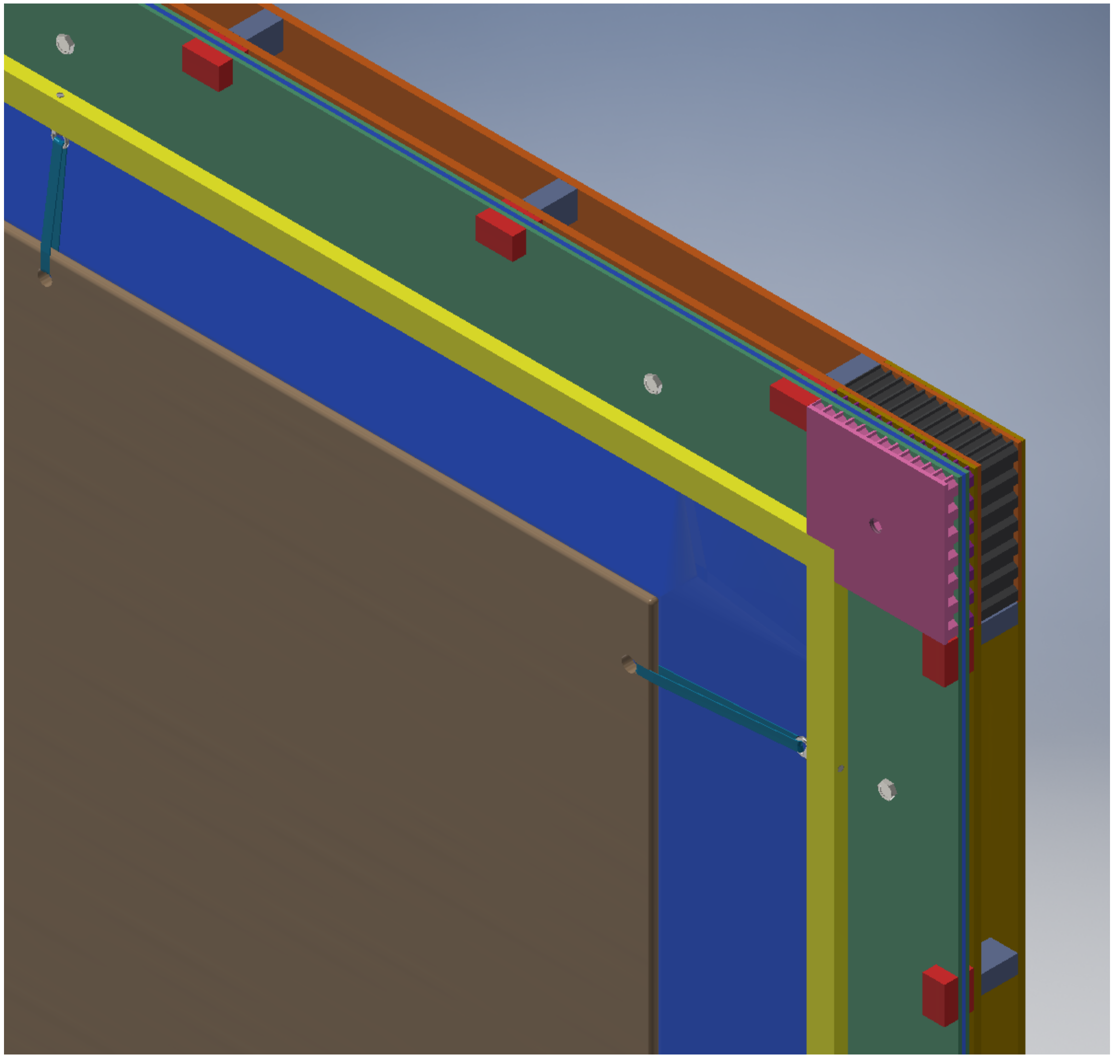
✦ *Separation from excellent vertex, angular & timing resolutions.*

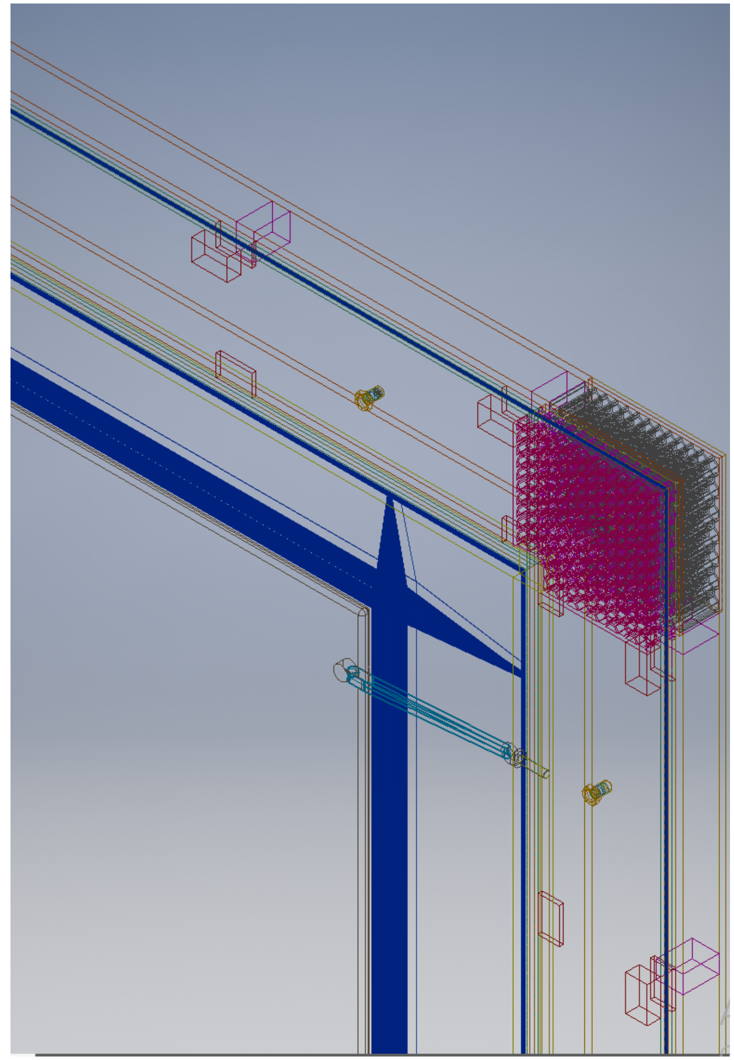
✦ *Thin targets can be replaced during data taking: C, Ca, Ar, Fe, Pb, etc.*

$\Longrightarrow$ *Optimized & engineered design, extensive performance studies*

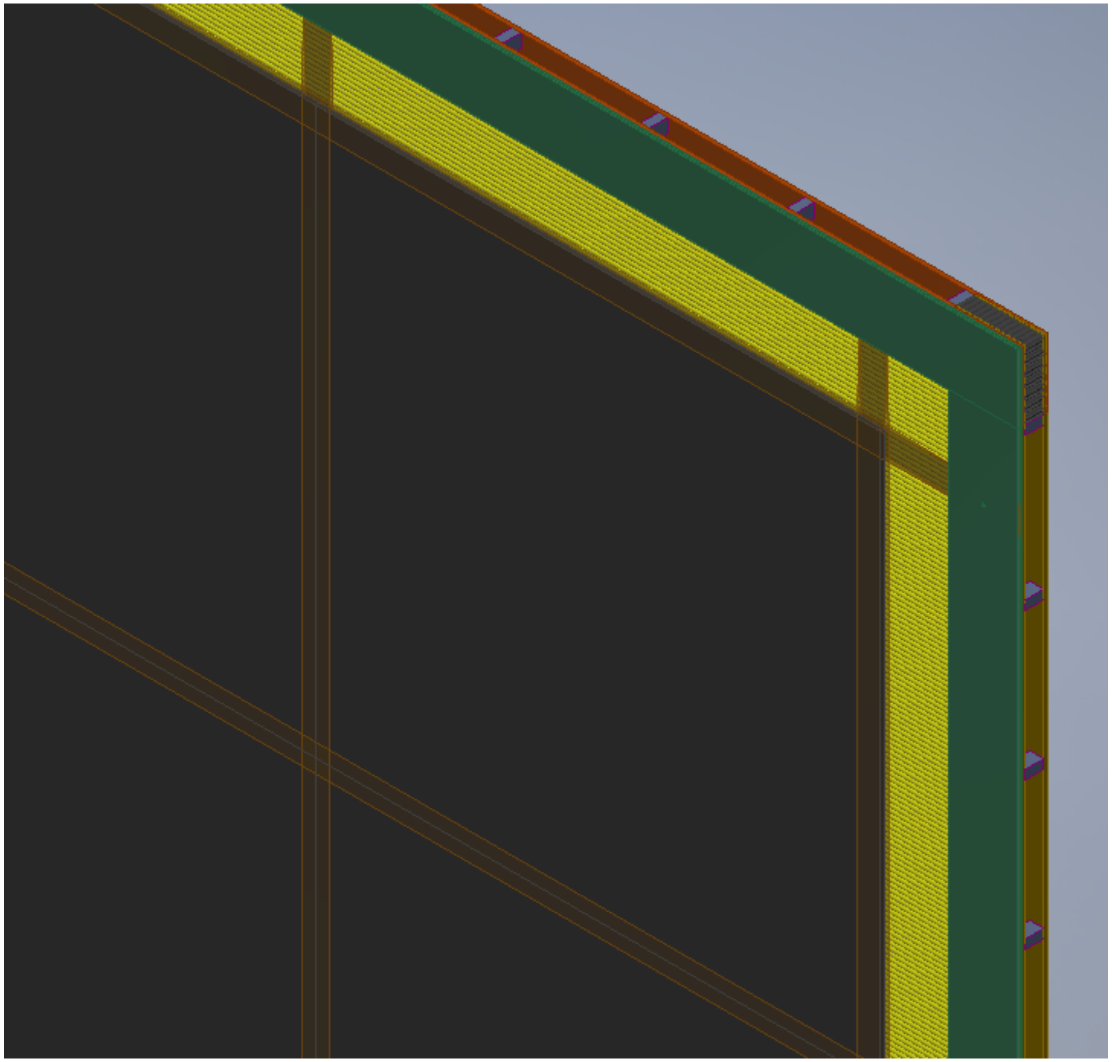


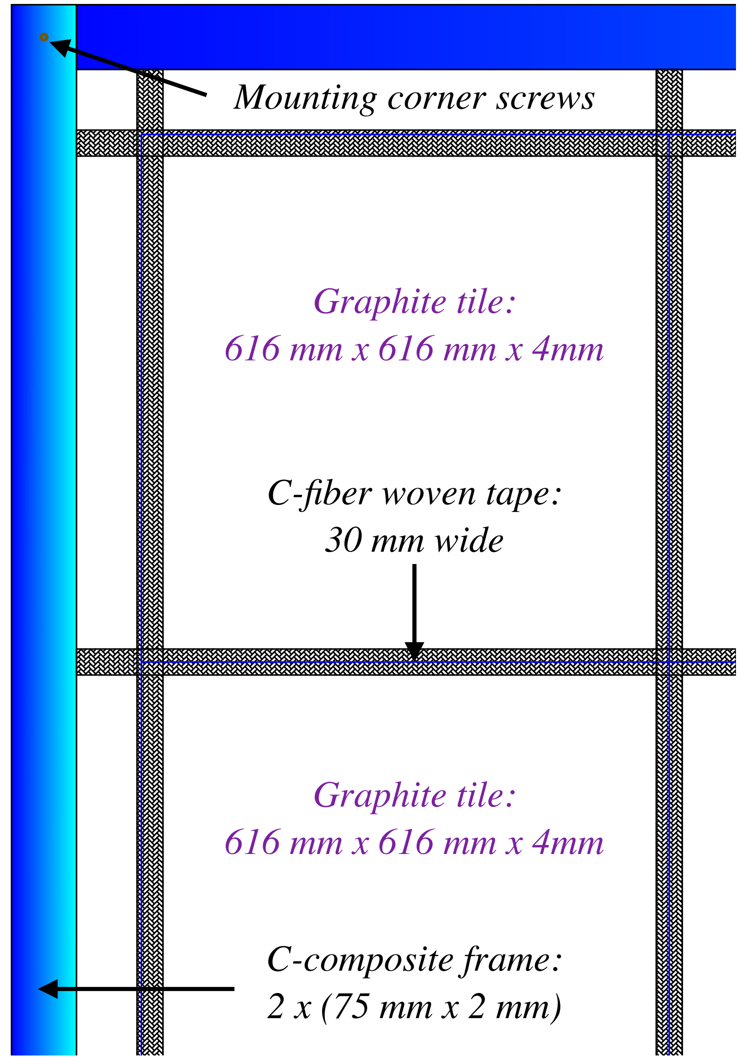
Target & radiator easily unmounted by removing 4 corner screws: density ~0.005 g/cm^3





Full module assembly with CH_2 target and radiator: maximal density ~0.18 g/cm^3

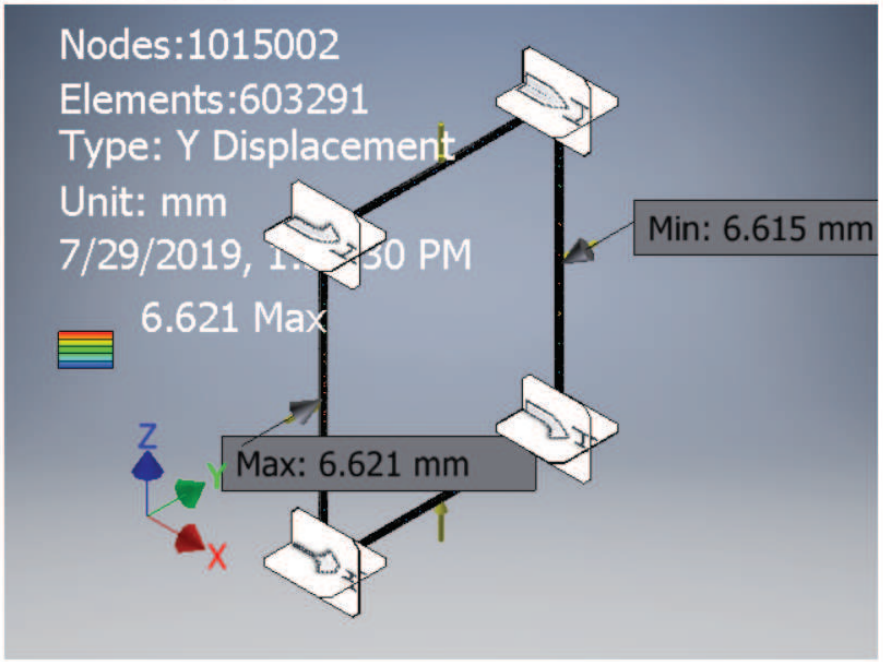




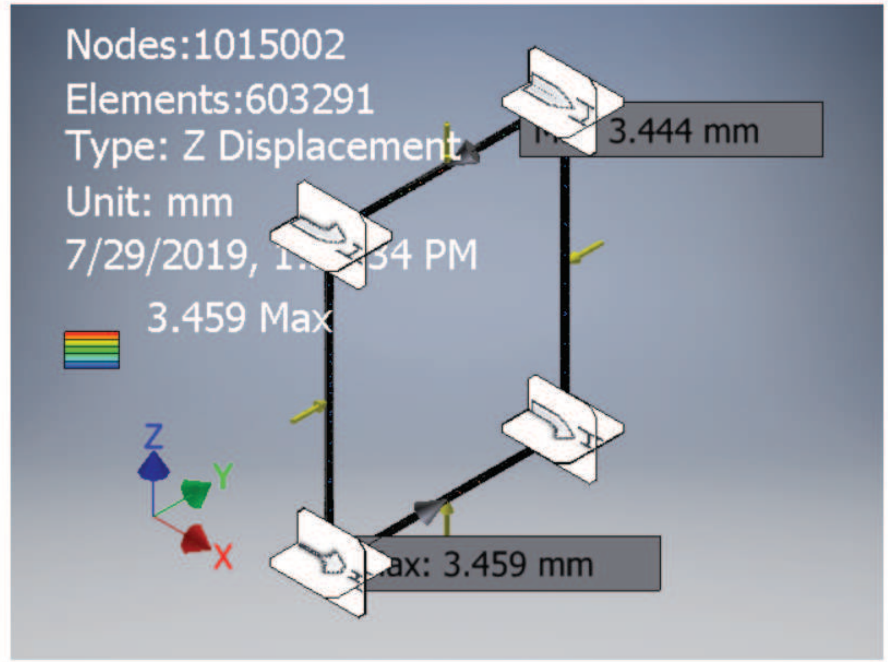
Full module assembly with graphite (C) target and XXYY straws

3D ENGINEERING MODEL & FE ANALYSIS

Y Displacement



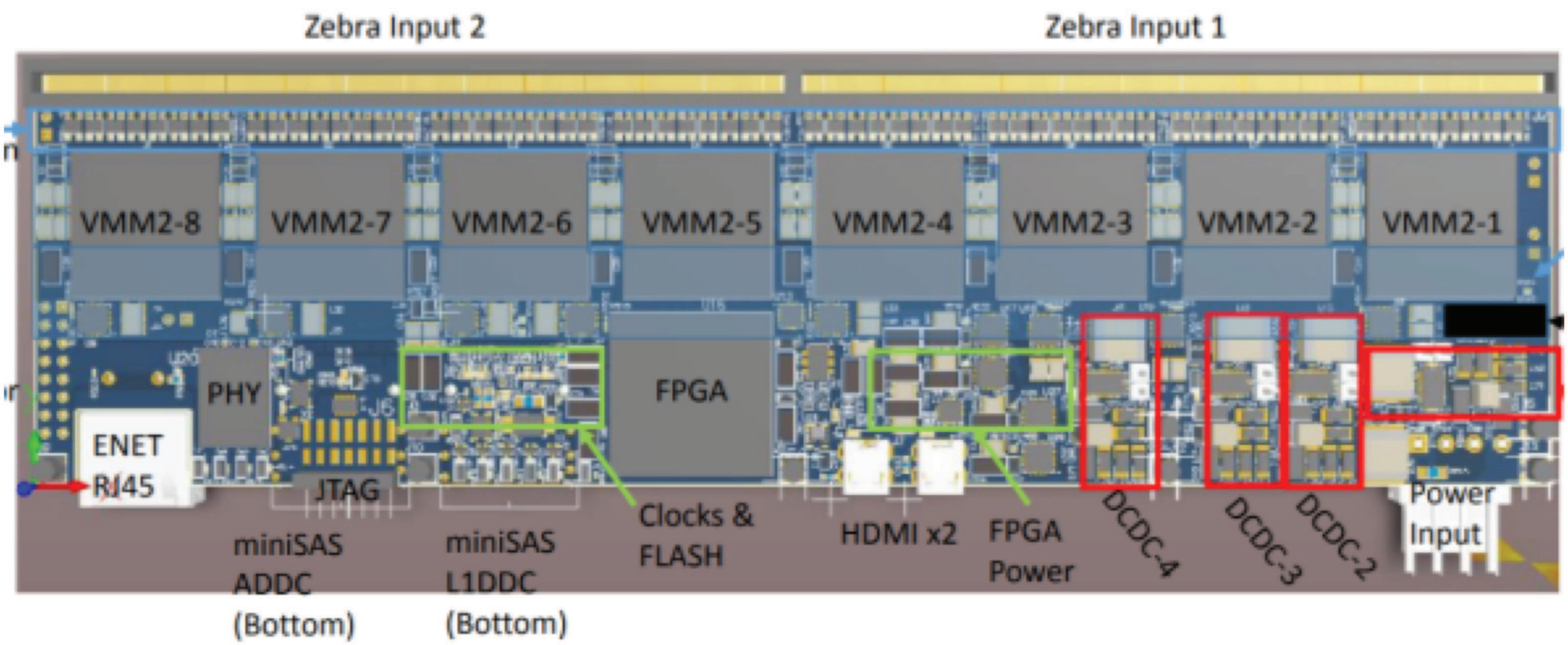
Z Displacement



- *Complete 3D CAD design of STT modules* with straws, radiator, CH_2 and C targets
  $\Longrightarrow$ *On average, C-composite frames add $\sim 0.1\ X_0$ of material $\perp$ to beam direction*
- *Detailed Finite Element (FE) analysis of deformations*
  $\Longrightarrow$ *Maximal deflections in central point of frames $\ll 1$ cm*

READOUT

- *Front-end (FE) electronics based on VMM3 ASICs* (BNL/CERN): 8 VMM3 per board
  $\Longrightarrow$ *Compact FE boards integrated into C-composite frames (off-the-shelf)*
- *Back-end (BE) electronics based on FELIX* system (ProtoDUNE & DUNE FD)
  $\Longrightarrow$ *FE board FPGAs transfer VMM3a data over gigabit links to the FELIX PCIe cards*



MMFE-8 FE board: 512 channels in 215mm x 60mm x 2.54mm, <10 W power

COST & SCHEDULE

- *Detailed STT cost estimate mostly based on vendor quotes from CAD drawings:*
  total cost **$6,875,361** *excluding manpower for module assembly & tests.*

- *Manpower required for module assembly and tests:*
  10 people to produce one STT module per month (average) ready for shipment.

- *Minimum of 3 sites to assemble & test the complete STT:*
  total of about 31 months required to complete all 92 STT modules (30 people).

- *A single straw production line per site with ultrasonic welding is enough:*
  with 3 lines all 231,834 straws in $<$ *26 months (100 straw/day, 12 people).*

$\Longrightarrow$ *Preliminary production plans exceed minimum required sites & lines*

STT FOR SAND

- *Groups with infrastructure & extensive experience in the construction of various straw detectors (ATLAS TRT, COMPASS, Mu2e, NA62, SHiP, COMET, etc.):*
  - *Georgian Technical University (GTU), Tbilisi, Georgia;*
  - *Joint Institure for Nuclear Reserach (JINR), Dubna, Russia (International Laboratory);*
  - *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia (HEP Laboratory).*

- *Several Indian institutions:*
  Indian Institute of Technology Guwahati (IITG); University of Hyderabad; Indian Institute of Technology Hyderabad; Jawaharlal Nehru University, New Delhi; University of Lucknow; Central University of South Bihar, possible BARC contribution
  [Annex-II between DAE (India) and DOE (USA) allocated $10M, request part of that for STT]

- *University of South Carolina, USA.*

- *Brookhaven National Laboratory (BNL), USA, for electronic readout.*

- *Belarusian State University, Minsk, Belarus.*

Legend: contributions to STT hardware

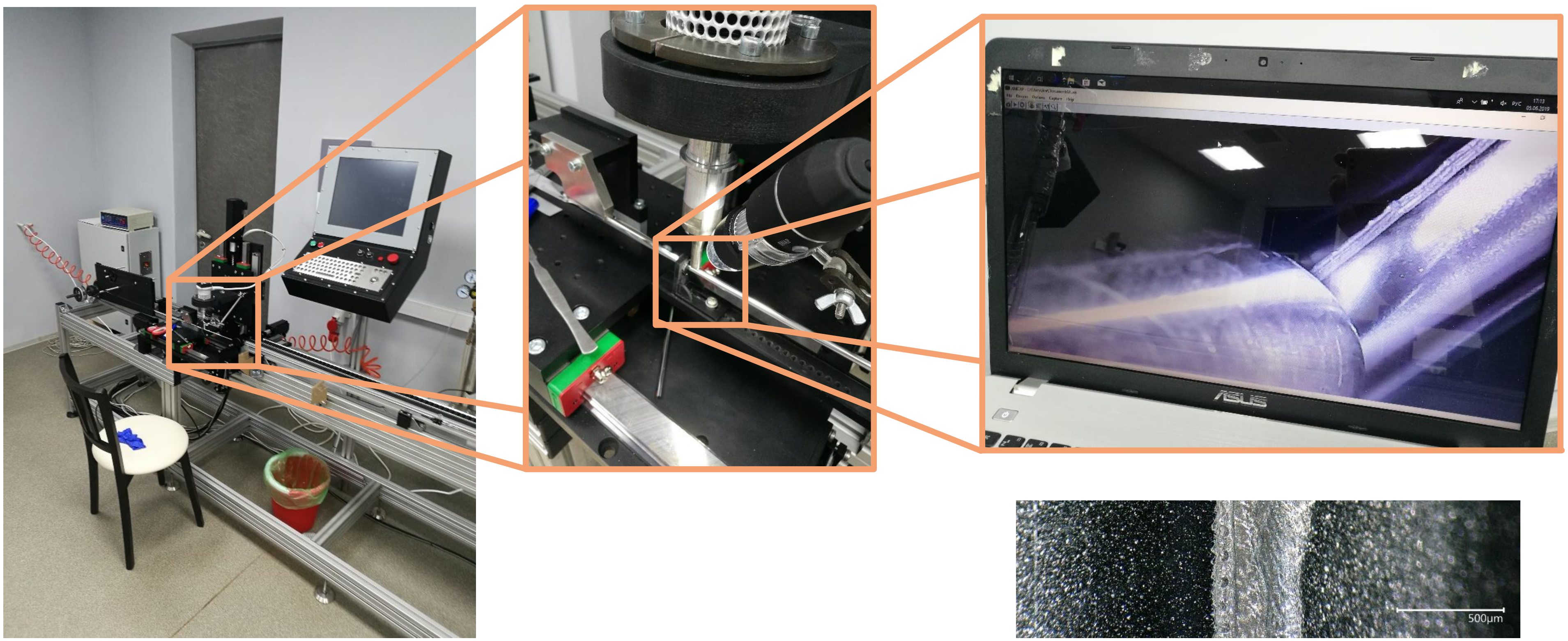
PROTOTYPING & TESTS

- *Same straws used in COMET and NA62 upgrade & off-the-shelf VMM3 readout: benefit from past and ongoing R&D for other projects.*

- *Straw production lines with ultrasonic welding existing / in preparation:*
  - *Existing GTU facility at JINR for COMET experiment (max straw length 2m);*
  - *Existing JINR facility for NA62/SHiP (max straw length 5m);*
  - *Existing PNPI facility (max straw length 5m);*
  - *Dedicated facility for STT production at GTU available by end of 2020 (max straw length 4m);*
  - *Dedicated facility for STT production planned at IIT Guwahati (max straw length 4m).*

- *USC secured more than enough ASIC chips (latest VMM3 revision, newly produced) to cover needs of entire prototyping and development phase (about 14,000 channels).*

- *Prototyping and test activity to validate the STT design until 2023 and actual detector construction from 2023 to 2026.*



Straw production line with ultrasonic welding operated by GTU

- *STT prototype being tested at JINR:*
  - *Small scale with 4 XXYY layers of straws built with ultrasonic welding at JINR;*
  - *Front-end electronic readout with VMM3(a) ASICS from Mu2e experiment (BNL);*
  - *Validate straw performance with VMM3(a) readout electronics.*

- *Extensive tests of straw properties by GTU, JINR, IIT Guwahati, PNPI:*
  - *Tension of straw walls & wires vs. operating conditions;*
  - *Detector stability over time, straw relaxation;*
  - *Overpressure operation and straw deformations;*
  - *Optimization of materials, small components, and welding process.*

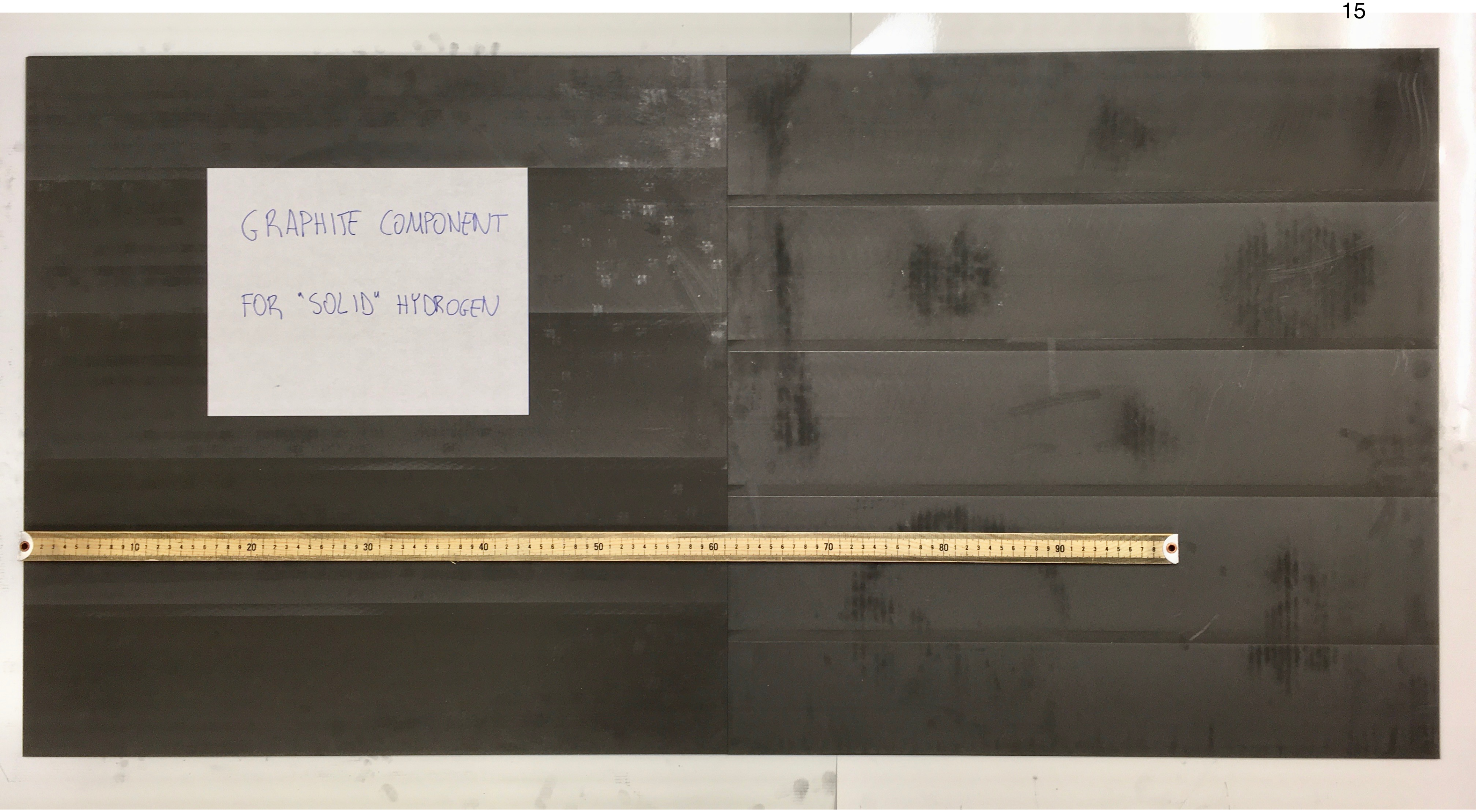
- *Prototype of graphite target being tested at USC:*
  - *Mechanical and chemical properties & target assembly;*
  - *Validate the design of the STT target modules.*

- *Build 1.6m $\times$ 1.6m prototype(s) with C-composite frames planned for STT, followed by a 4m long prototype to validate mechanical assembly & design of STT modules.*

- *Test-beam exposures of prototypes at CERN, possibly with very-low-energy beams.*

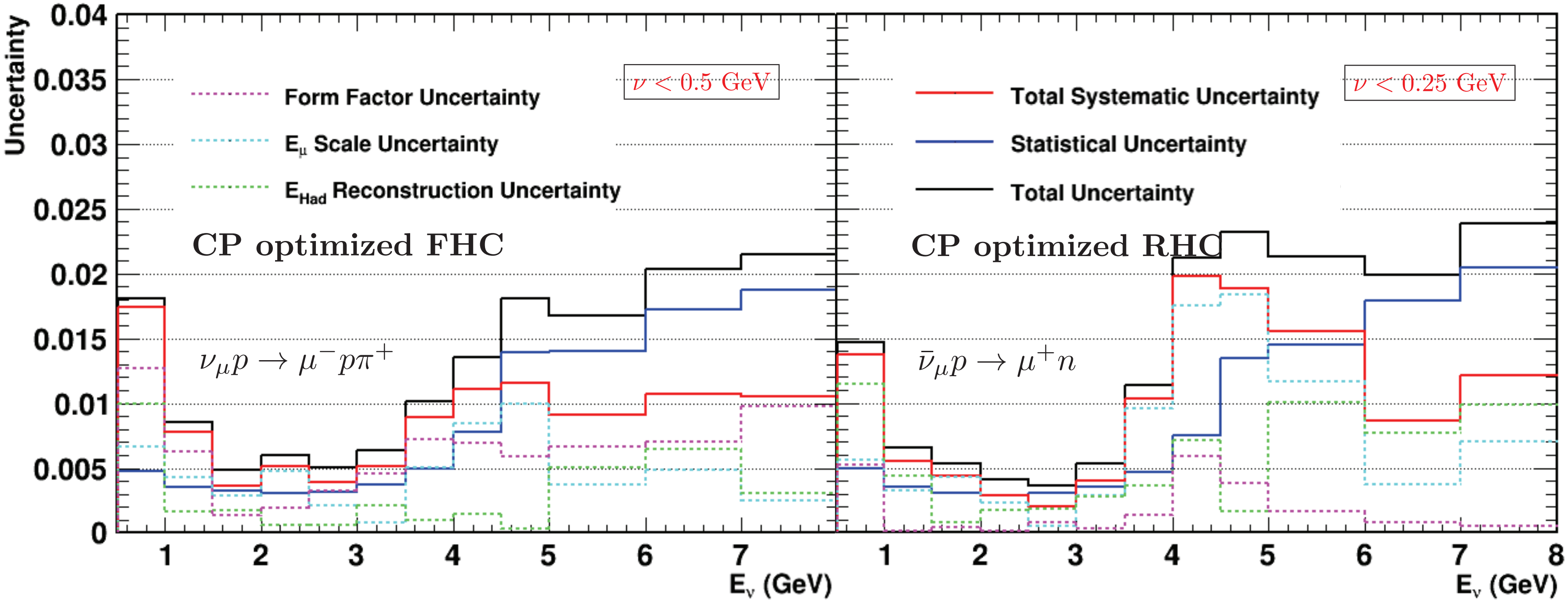
2.0 m and 5.0 m Straws

Production and test of 5m and 2m long straws (5mm diameter)
IIT Guwahati and JINR



Prototype of graphite target tested at USC:
2 machined tiles 612mm x 612mm x 4mm (isotropic graphite, purity 100 ppm)

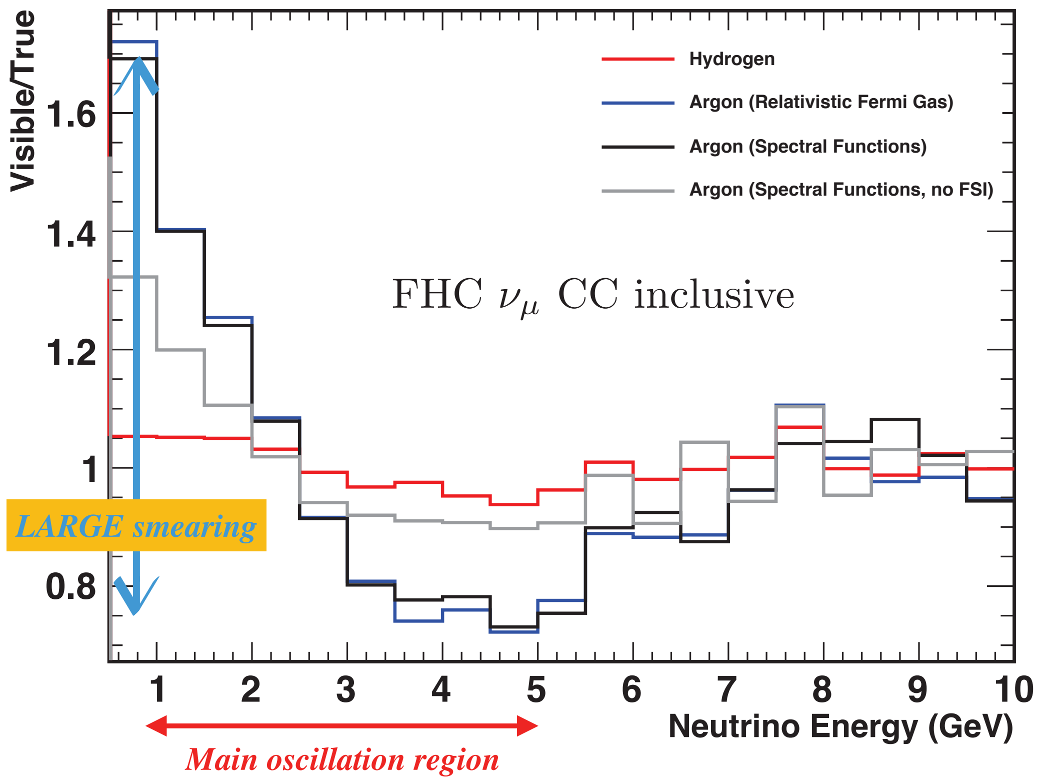
PRECISION FLUX MEASUREMENTS



- *103,000/year $\nu_\mu p \to \mu^- p \pi^+$ on H selected in STT with $\nu < 0.50$ GeV.*
- *131,000/year $\bar{\nu}_\mu p \to \mu^+ n$ on H selected in STT with $\nu < 0.25$ GeV.*

$\Longrightarrow$ *Relative ν_μ & $\bar{\nu}_\mu$ fluxes to $\sim$ 1% in one year for $1 < E_\nu < 4$ GeV*

CONSTRAINING NUCLEAR SMEARING IN Ar



Comparing Ar and H measurements within SAME detector imposes stringent constraints on the nuclear smearing in Ar

- ✦ *579,000/year ν_μ CC inclusive on H selected after subtracting 7% C bkgnd;*
- ✦ *333,000/year $\bar{\nu}_\mu$ CC inclusive on H selected after subtracting 16% C bkgnd.*

BROAD MEASUREMENT PROGRAM

✦ *Excellent beam monitoring with ECAL+STT with one week of data:*

- *Variations of horn current, water layer thickness, decay pipe radius, proton target density, proton beam radius, proton beam offset, horn 1 X shift, horn 1 Y shift with* $\Delta\chi^2 > 9$*;*
- *Change of beam direction of 0.13 mrad with* $\Delta\chi^2 > 9$ *(beam divergence 1.5 mrad).*

✦ *Precision flux measurements with STT:*

- *Relative* ν_μ *and* $\bar{\nu}_\mu$ *flux from* $\nu_\mu p \to \mu^- p \pi^+$ *and* $\bar{\nu}_\mu p \to \mu^+ n$ *on H with* $\nu < 0.5(0.25)$ *GeV:* $< 1\%$
- *Absolute* ν_μ *flux from* $\nu e^- \to \nu e^-$ *elastic scattering:* $\sim 2\%$
- *Absolute* $\bar{\nu}_\mu$ *flux from QE* $\bar{\nu}_\mu p \to \mu^+ n$ *on H with* $Q^2 < 0.05$ *GeV*^{2}*.*

✦ *Measurements of nuclear effects and constraints of nuclear smearing: H, C, Ar, etc.*

✦ *SAND with STT combined with the intensity and* $\nu(\bar{\nu})$ *spectra at LBNF enable a unique combination of physics measurements within the ND complex:*

- *No additional requirements with respect to the long-baseline analysis;*
- *Hundreds of diverse physics topics from precision measurements and searches for new physics, complementary to ongoing fixed-target, collider and nuclear physics efforts.*

$\Longrightarrow$ *Synergies with other components of the ND complex*

SUMMARY

✦ *SAND with STT satisfies and exceeds the ND requirements. It offers a control of ν targets similar to $e^{\pm}$ experiments & a fully tunable suite of various target materials.*
$\Longrightarrow$ *High resolution detector with momentum scale uncertainty <0.2%*

✦ *Realistic STT design based upon off-the-shelf technology developed for other experiments for both the straws and the electronic readout:*

- *A complete 3D CAD model of the detector with FE analysis of deformations exists;*
- *Cost estimate of the STT mostly based on vendor quotes from CAD drawings;*
- *A program of prototyping and tests is ongoing to validate the design and the electronic readout.*

✦ *Preliminary plans to produce the complete STT over a period of about 3 years.*

✦ *Concept of "solid" hydrogen target: high statistics $\mathcal{O}(10^6)$ samples of $\nu(\bar{\nu})$-hydrogen interactions, allowing precisions in the measurement of ν & $\bar{\nu}$ fluxes $< 1\%$.*

✦ *Detailed performance studies of SAND with STT available in DocDb # 13262: design, GEANT4/FLUKA, reconstruction, physics sensitivity studies, etc.*
https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=13262

Backup slides

STT CORE COSTS

Item	Cost (USD)	Comment
Procure straws	*1,534,593*	*Quote from Lamina Tubular Tech., UK*
Procure end plugs	*510,035*	*Cost from NA62, PANDA*
Procure wire spacers	*510,035*	*Cost from NA62, SHiP*
Procure crimping pins	*510,035*	*Cost from NA62, ATLAS TRT*
Procure anode wire	*243,658*	*Quote from Luma metall AB, Sweden*
Procure miscellaneous components	*123,000*	*Cost from NA62, ATLAS TRT*
Procure mechanics & C-fiber frames	*1,012,000*	*Quote from Bercella, Italy*
Procure STT tools	*569,000*	*Cost from other straw detectors*
Procure equipment & consumables	*100,000*	*Cost from other straw detectors*
Procure gas system	*515,000*	*Cost from ATLAS TRT*
Procure cooling system	*420,000*	*Cost from ATLAS TRT*
Procure radiator foils	*112,000*	*Quote from Bloomer Plastics, USA*
Procure polypropylene targets	*32,200*	*Quote from Boedeker Plastics, USA*
Procure graphite targets (ET10)	*49,400*	*Quote from Weaver Industries, USA*
Procure front-end electronics (VMM3)	*280,519*	*Quote from Fraunhofer/BNL*
Procure back-end electronics (FELIX)	*92,733*	*Cost from ProtoDUNE*
Procure HV components	*97,489*	*Quote from CAEN, Italy*
Procure LV components	*64,299*	*Quote from CAEN, Italy*
Procure distribution boards	*57,360*	*Cost from ATLAS NSW*
Procure cables & connectors	*62,310*	*Quote from CERN store*
Total	**6,875,361**	

ASSEMBLY & TESTS

✦ *Manpower required for assembly and tests:*
10 people to produce one STT module per month (average) ready for shipment.

✦ *Minimum of 3 sites to assemble & test the complete STT:*

- *Assume 10 people per site for a total of 30 people;*
- *Total of about 31 months required to complete all 92 STT modules;*
- *Need an assembly station and a station for acceptance tests per site to optimize work.*

✦ *A single straw production line per site with ultrasonic welding is enough:*

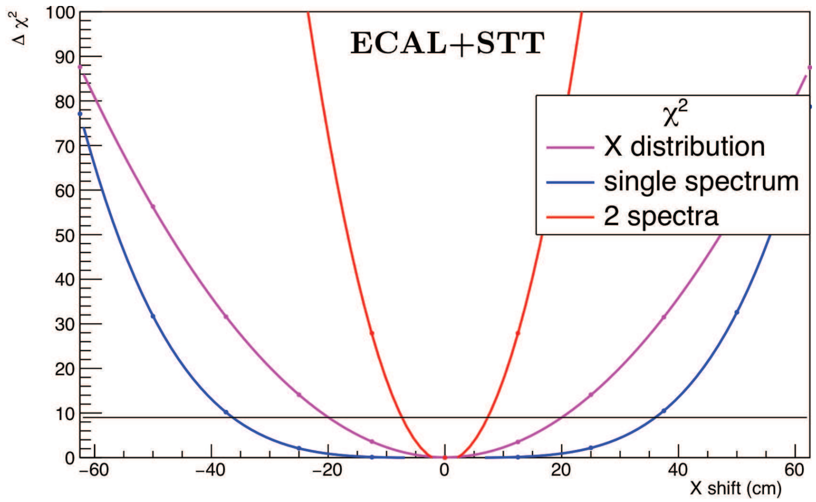
- *Existing production lines in operation at JINR, GTU/JINR, and PNPI easily replicable;*
- *Each production line can produce about 100 straws/day including quality control with 4 people;*
- *With 3 production lines (one per site) all the 231,834 STT straws can be produced in $<$ 26 months.*

$\Longrightarrow$ *In one month each site would produce 1.2 times the straws needed to assemble one module*

✦ *Minimum requirement: 3 production sites, each of them operated by 14 people and equipped with (i) straw production line; (ii) assembly station; (iii) test station.*

BEAM MONITORING WITH ECAL+STT

Beam parameter	*Variation*	*ECAL+STT* $\Delta\chi^2$
Proton target density	*+2%*	*19.6*
Proton beam radius	*+0.1 mm*	*37.4*
Proton beam offset X	*+0.45 mm*	*22.2*
Proton beam θ	*0.070 mrad*	*0.3*
Proton beam θ, ϕ	*0.07 mrad* θ*, 1.57* ϕ	*0.2*
Horn current	*+3 kA*	*105.6*
Water layer thickness	*+0.5 mm*	*22.2*
Decay pipe radius	*+0.1 m*	*48.1*
Horn 1 X shift	*+0.5 mm*	*14.6*
Horn 1 Y shift	*+0.5 mm*	*17.7*
Horn 2 X shift	*+0.5 mm*	*0.3*
Horn 2 Y shift	*+0.5 mm*	*0.2*



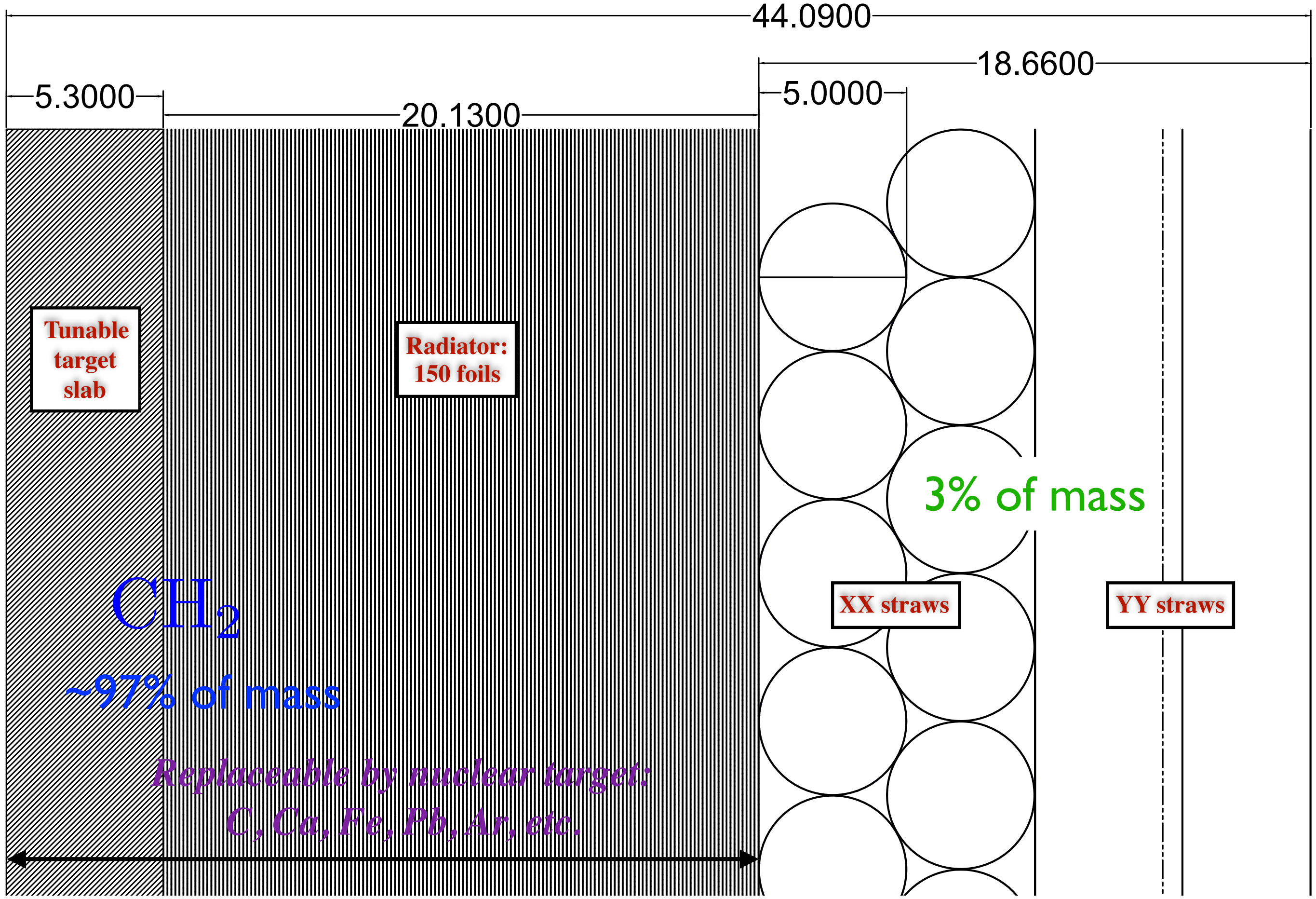
Sensitive to beam shifts of 7.4cm corresponding to 0.13 mrad

$\Longrightarrow$ *In one week* $(3.78 \times 10^{19}$ *pot) ECAL+STT sensitive to most variations with* $\Delta\chi^2 > 9$

STT BY NUMBERS

Number of straws	*231,834*
Total straw length (m)	*730,600*
Straw outer diameter (mm)	*5*
Average straw length (m)	*3.15*
Maximal straw length (m)	*3.83*
Total straw film area (m^2)	*11,470*
Total straw internal volume (m^3)	*14*
Total length of C-composite frames (m)	*1,205*
Number of modules	*92*
Number of modules with CH_2 target	*78*
Number of modules with graphite target	*7*
Number of straw planes	*368*
Number of FE boards	*453*
Number of HV channels	*368*
Number of LV channels	*114*

OPTIMIZED DESIGN OF STT MODULES



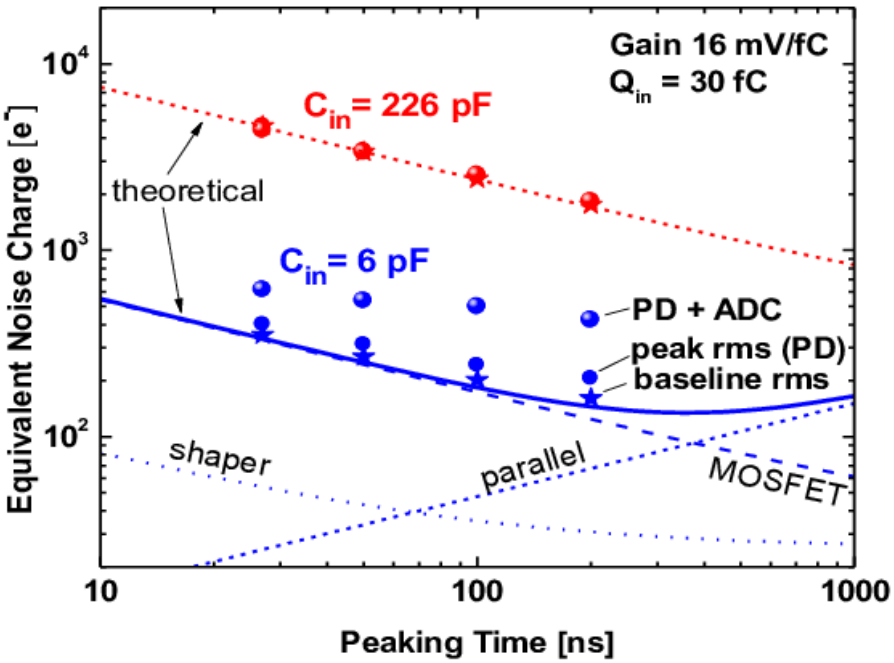
Total thickness $\sim 0.015 X_0$

READOUT & HV/LV

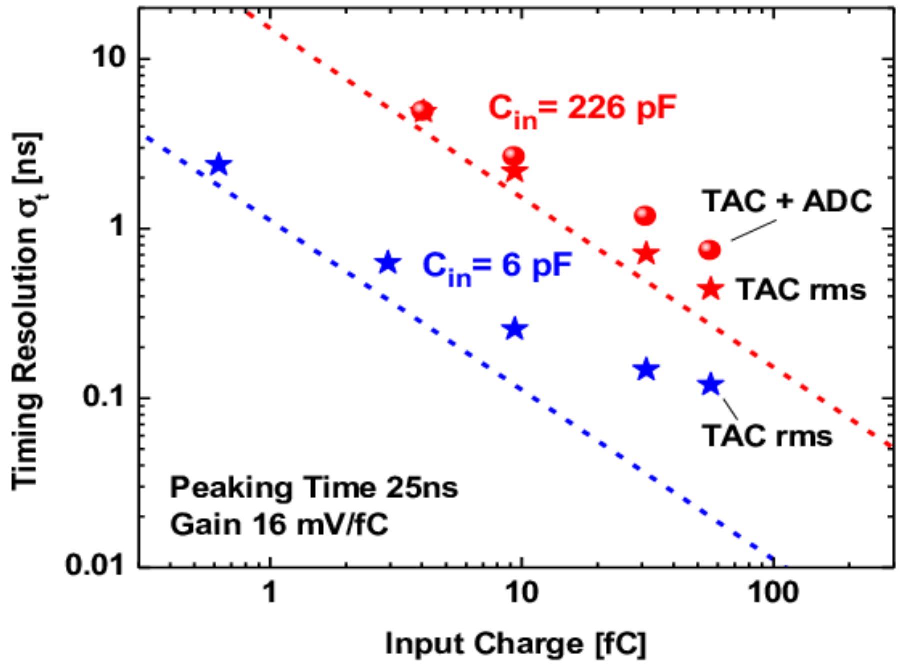
- *Front-end (FE) electronics based on VMM3 ASICs (BNL/CERN):*
  - *Off-the-shelf multi-purpose ASIC used by many modern experiments (ATLAS, STAR, SoLID, etc.);*
  - *Low-power, high performance 64 channel ASIC user configurable;*
  - *Compact FE boards integrated into C-composite frames with 8 VMM3 chips each, FPGA controlled;*
  - *Low per-channel cost and well established performance.*

- *Back-end (BE) electronics based on FELIX system:*
  - *Compatible with existing commodity electronics and platform used by ATLAS, PHENIX, etc.;*
  - *Same system used in ProtoDUNE and baseline option for DUNE FD;*
  - *FE board FPGAs transfer VMM3a data over gigabit links to the FELIX PCIe cards.*

- *HV & LV components:*
  - *HV maximal rating 1,500 V, LV maximal rating 12 V;*
  - *HV and LV boards share same mainframes (3 or 4 CAEN SY4527) to optimize power and space.*

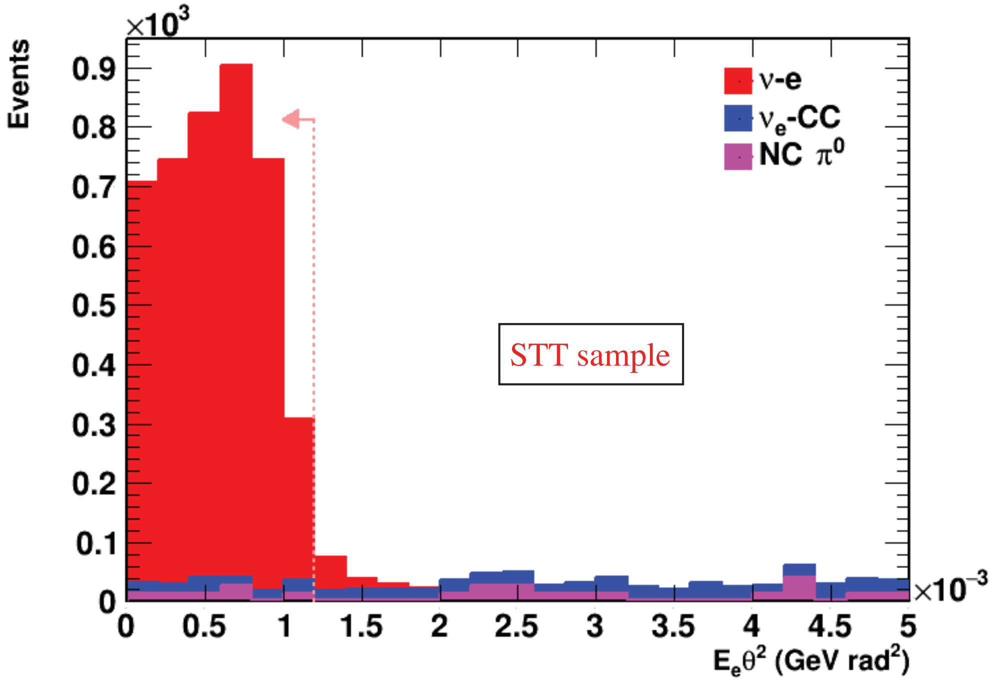


Gain 16 mV/fC
Q_in = 30 fC
C_in = 226 pF
C_in = 6 pF
theoretical
PD + ADC
peak rms (PD)
baseline rms
shaper
parallel
MOSFET
Equivalent Noise Charge [e⁻]
Peaking Time [ns]



C_in = 226 pF
C_in = 6 pF
TAC + ADC
TAC rms
TAC rms
Peaking Time 25ns
Gain 16 mV/fC
Timing Resolution σ_t [ns]
Input Charge [fC]

ABSOLUTE FLUX WITH $\nu e^- \to \nu e^-$ ELASTIC



1,046 (938) νe^-/year selected in FHC (RHC) beam from CH_2, C, Ar targets & straw mass

✦ *Excellent electron ID (TR $\sim 10^3$ π rejection), angular (~ 1.5 mrad) and E_e resolutions:*

Detector	*Signal*	ν_e *QE*	*NC* π^0	$\delta_{\rm stat}$	$\delta_{\rm syst}$	$\boldsymbol{\delta_{\rm tot}}$
STT FHC 5y on-axis	*5,814*	*3%*	*2%*	*1.3%*	*∼1%*	**∼ 1.7%**
ND-LAr FHC + DUNE-Prism (50%)	*18,715*	*11%*	*3%*	*0.7%*	*∼1.5%*	**∼ 1.7%**

$\Longrightarrow$ *Synergy between LAr (syst. dominated) & STT (stat. dominated) measurements*

GENERAL PURPOSE PHYSICS FACILITY

✦ *Possible to address the main limitations of neutrino experiments (statistics, control of targets & fluxes) largely reducing the precision gap with electron experiments.*

⟹ *Exploit the unique properties of the (anti)neutrino probe to study fundamental interactions & structure of nucleons and nuclei*

✦ *Turn the LBNF ND site into a general purpose $\nu\&\bar{\nu}$ physics facility with broad program complementary to ongoing fixed-target, collider and nuclear physics efforts:*

- *Measurement of $\sin^2\theta_W$ and electroweak physics;*
- *Precision tests of isospin physics & sum rules (Adler, GLS);*
- *Measurements of strangeness content of the nucleon $(s(x), \bar{s}(x), \Delta s$, etc.);*
- *Studies of QCD and structure of nucleons and nuclei;*
- *Precision tests of the structure of the weak current: PCAC, CVC;*
- *Measurement of nuclear physics and (anti)-neutrino-nucleus interactions; etc. .....*
- *Precision measurements as probes of New Physics (BSM);*
- *Searches for New Physics (BSM): sterile neutrinos, NSI, NHL, etc.....*

⟹ *Discovery potential & hundreds of diverse physics topics*

✦ *No additional requirements: same control of targets & fluxes to study LBL systematics*