Compact STT:
Design and Performance

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(on behalf of proponent institutions)

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CONTROL OF (ANTI)NEUTRINO TARGETS

✦ *Low-density, high-resolution Straw Tube Tracker gives control of configuration, chemical composition & mass of $\nu(\bar{\nu})$ target(s) like e-experiments*

- *Accurate measurement of $\nu(\bar{\nu})$-Hydrogen interactions from CH_2 & C subtraction and kinematic identification of $\nu(\bar{\nu})$-H (80-95% purity);*
- *Suite of nuclear targets: CH_2, C, Ar, Ca, etc. within SAME detector (same acceptance)*

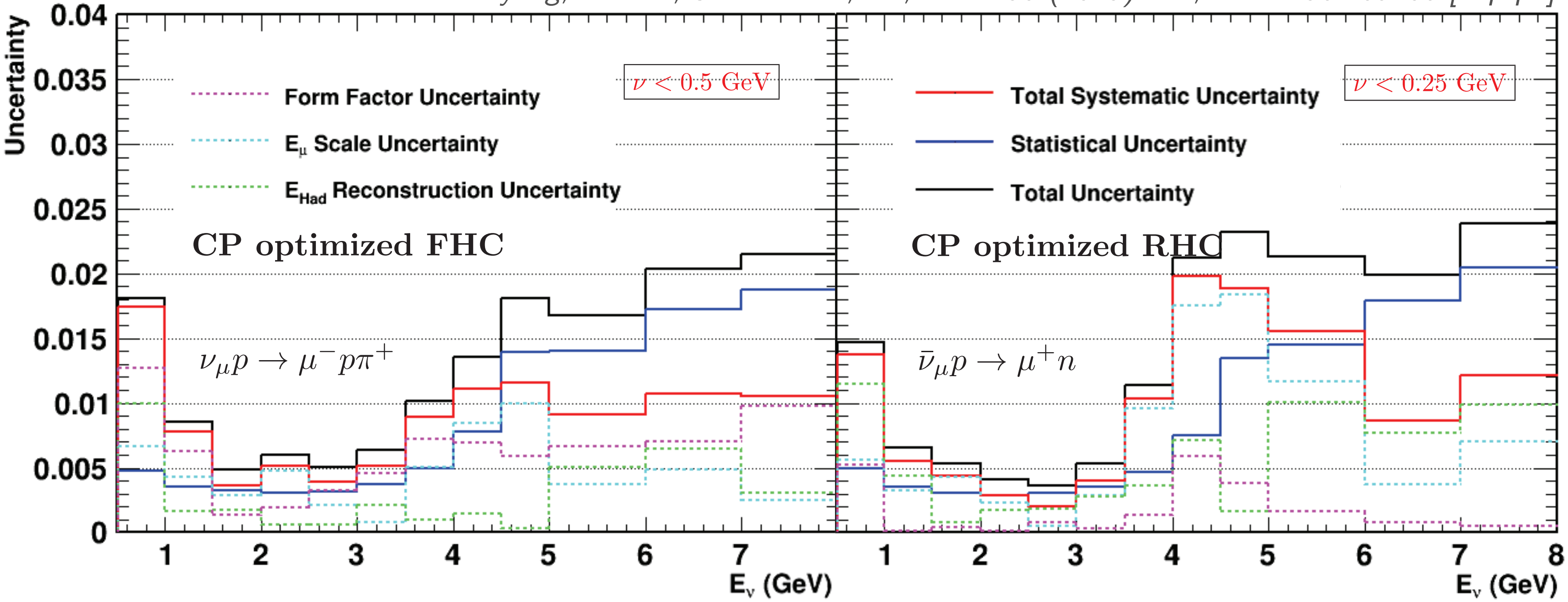
✦ *Modular design (flexible):*

- *Thin passive targets (100% chemical purity) physically separated from active tracker (straws);*
- *Tunable target mass & density by varying target thickness – targets >95% of STT mass – with average density $0.008 \leq \rho \leq 0.18\ g/cm^3$;*
- *A variety of dedicated thin ($< 0.1X_0$) targets can be installed & replaced during data taking;*
- *Allows use of hybrid targets including a 3DST module.*

$\Longrightarrow$ *Find optimal compromise between target mass (statistics) & resolution*

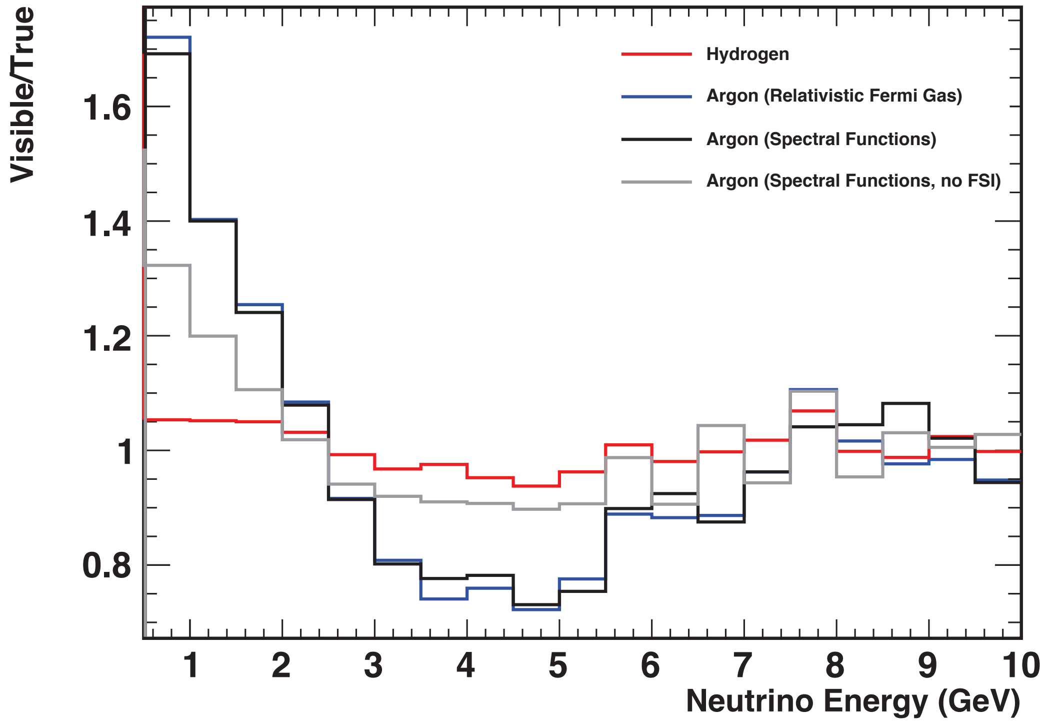
$\Longrightarrow$ *Excellent for quantifying the (anti)neutrino source (beam monitoring) & for precision measurements including rare processes*

H. Duyang, B. Guo, S.R. Mishra, RP, PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]



- *110,000/year $\nu_\mu p \to \mu^- p \pi^+$ on H selected in STT with $\nu < 0.50$ GeV.*
- *155,000/year $\bar{\nu}_\mu p \to \mu^+ n$ on H selected in STT with $\nu < 0.25$ GeV.*

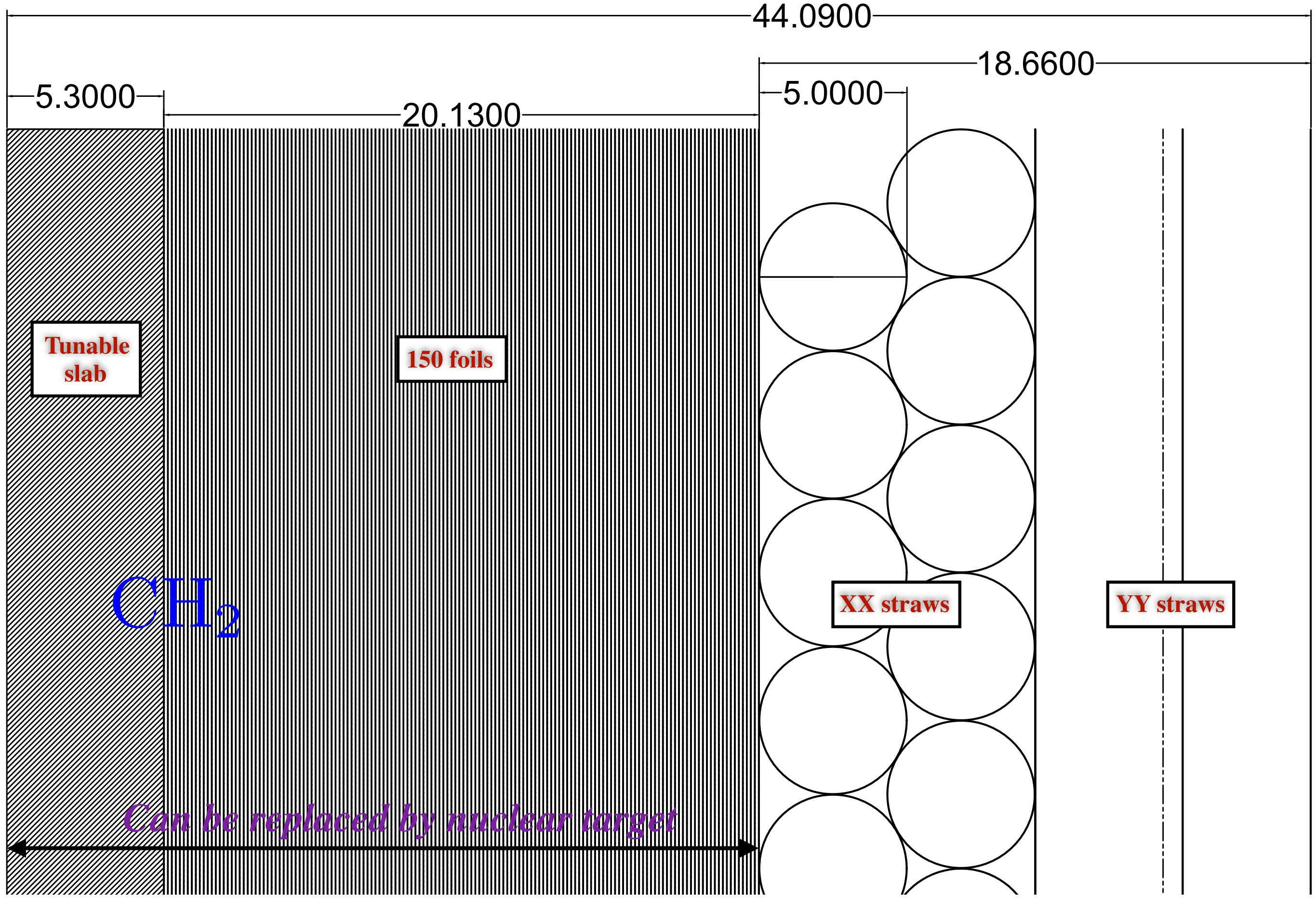
$\Longrightarrow$ *Measurement of relative ν_μ & $\bar{\nu}_\mu$ fluxes to $\sim$ 1% in one year for $1 < E_\nu < 4$ GeV*



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

- *623,000/year ν_μ-H CC inclusive selected in STT after subtracting 7% C bkgnd;*
- *384,000/year $\bar{\nu}_\mu$-H CC inclusive selected in STT after subtracting 16% C bkgnd.*

OPTIMIZED DESIGN OF STT MODULES



Total thickness $\sim 1.5\% X_0$

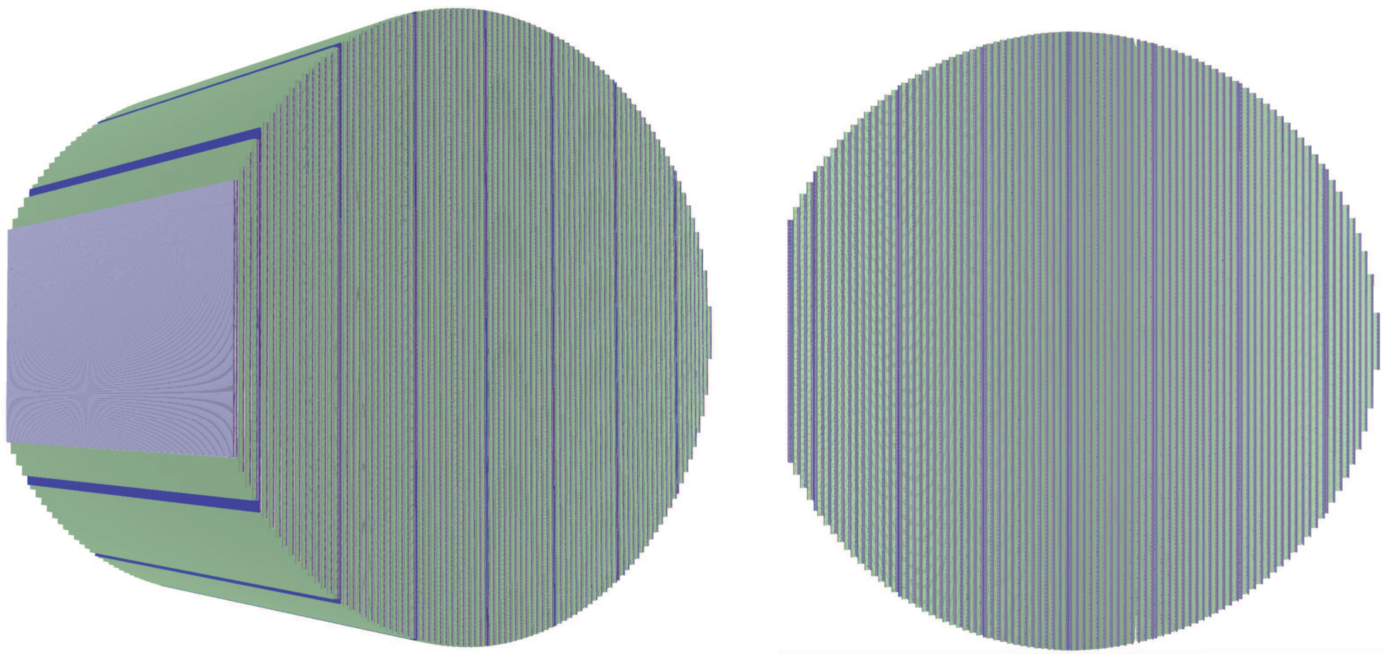
CH_2 & C DESIGNED TO HAVE SAME ACCEPTANCE

✦ *Default CH_2 and C (graphite) filling uniformly KLOE magnetic volume (∼43m^3):*

- *78 STT modules with CH_2 target & radiator: FV (20 cm from all edges) mass ∼* **4.7 t CH_2**;
- *7 STT modules with C (graphite) target with similar X_0 thickness: FV mass ∼* **504 kg C**;
- *231,834 straws: FV mass ∼ 262 (163) kg with 20 (12) μm walls: 4.8% (3.0%) of STT mass;*
- *Tracking modules without targets upstream and downstream of FV.*

$\Longrightarrow$ *Average density ~ 0.18 g/cm^3 & complete STT equivalent to $\sim 1.4\ X_0$*

✦ *Possible to install different materials: Ca, Fe, Pb, etc. + upstream LAr meniscus.*



Detailed GDML geometry available

COMBINED TRACKING & PARTICLE ID

✦ *Excellent angular, momentum & timing resolution:*

- *Low density design for accurate tracking;*
- $\delta\theta \sim$ *1-2 mrad*, $\delta p/p \sim$ *3-5% with default density* $\rho \sim 0.18$ *g/cm*^{3};
- *Time resolution* $\sim 1ns$, *can resolve beam structure & withstand high rates (max. drift* $\sim$ *50* ns*).*

✦ e^+/e^- *& other particle ID over the entire tracking volume:*

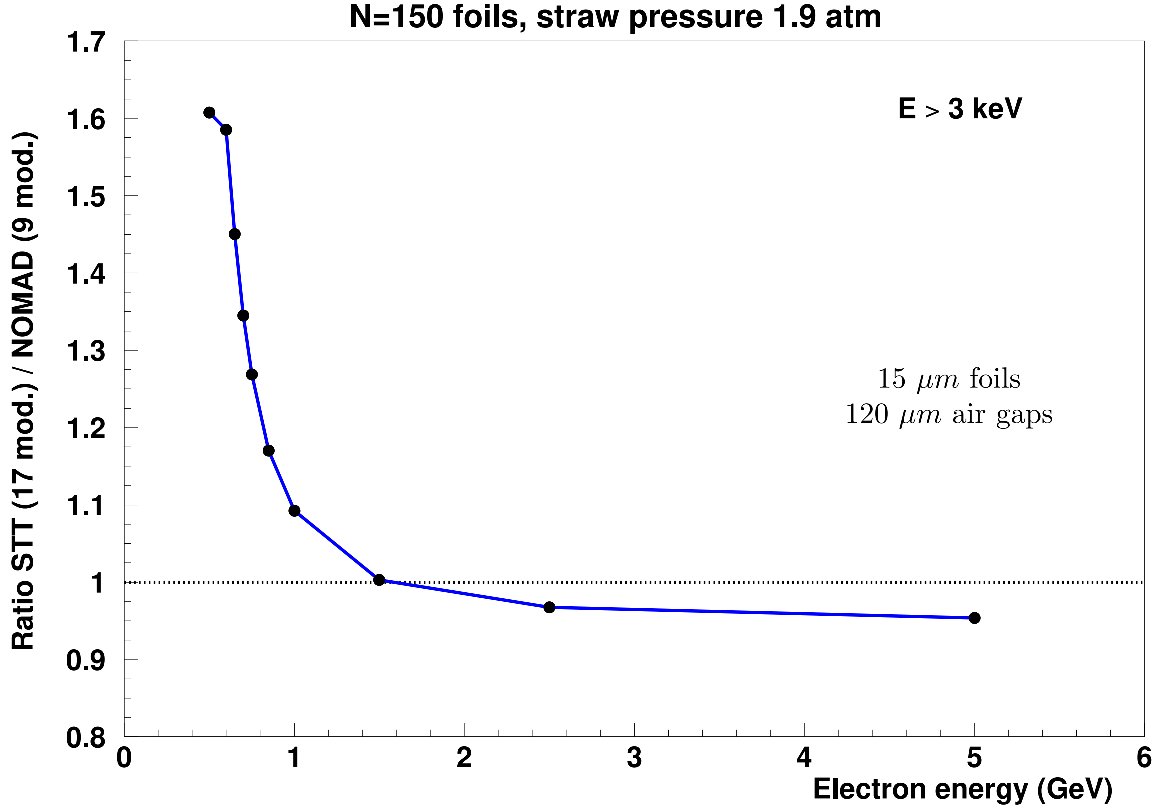
- *Electron ID with Transition Radiation (TR) and dE/dx* $\Longrightarrow \pi$ *rejection* $\sim 10^{-3}$;
- 4π *detection of* π^0 *from* γ *conversions* ($\sim 50\%$) *within the STT volume;*
- $p/\pi/K$ *ID with dE/dx and range.*

✦ *Accurate in-situ calibrations of momentum & angle reconstruction:*

- *Momentum scale from* $K_0 \to \pi^+\pi^-$ *in STT volume (264,000 in FHC);*
- *p reconstruction and identification, vertex, etc. from* $\Lambda \to p\pi^-$ *in STT volume (293,000 in FHC);*
- $e^\pm$ *reconstruction and identification from* $\gamma \to e^+e^-$ *in STT volume* (8×10^6 *in FHC).*

$\Longrightarrow$ *Momentum scale uncertainty* $< 0.2\%$ *(NOMAD)*

See docdb # 13262 and Paola's talk



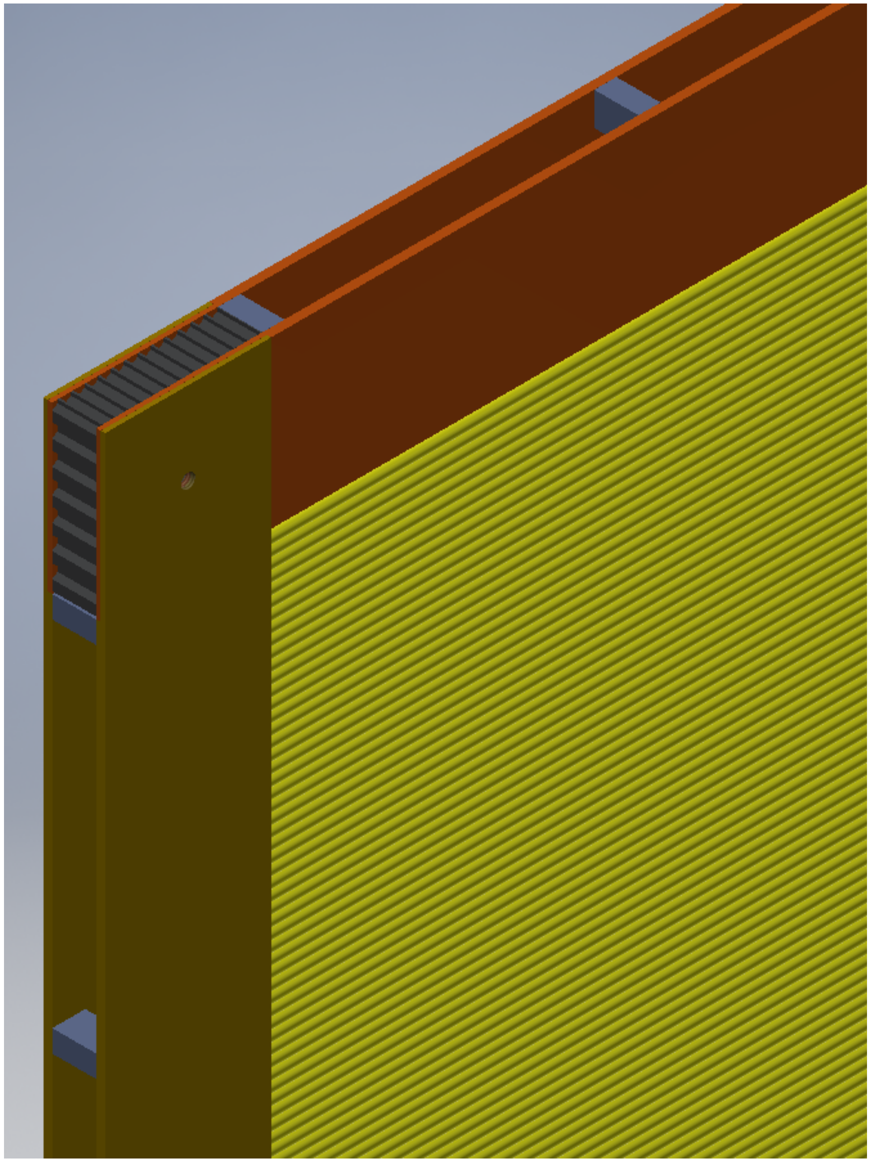
Radiator design optimized with simulations of Transition Radiation (TR)
TR performance (electron ID) in STT better than NOMAD at low energies

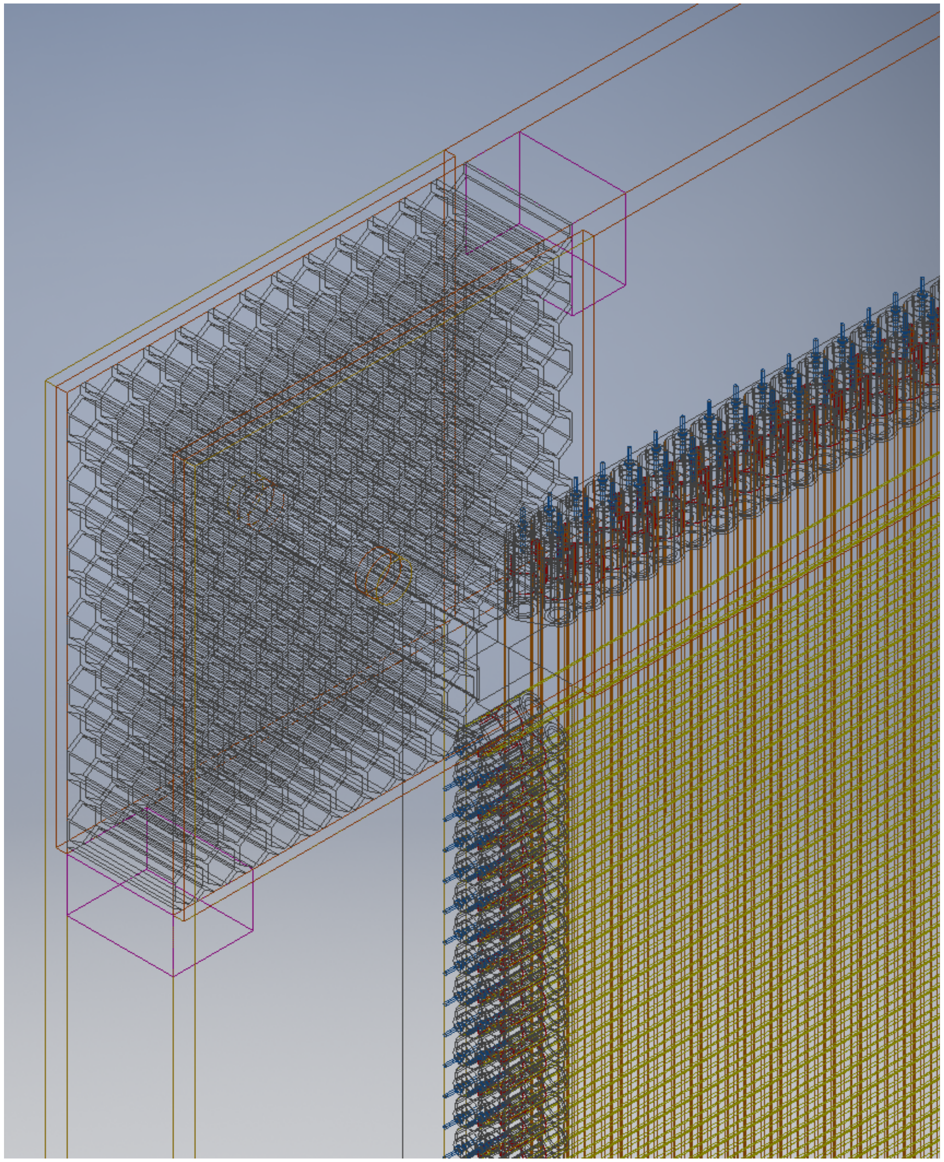
3D ENGINEERING MODEL

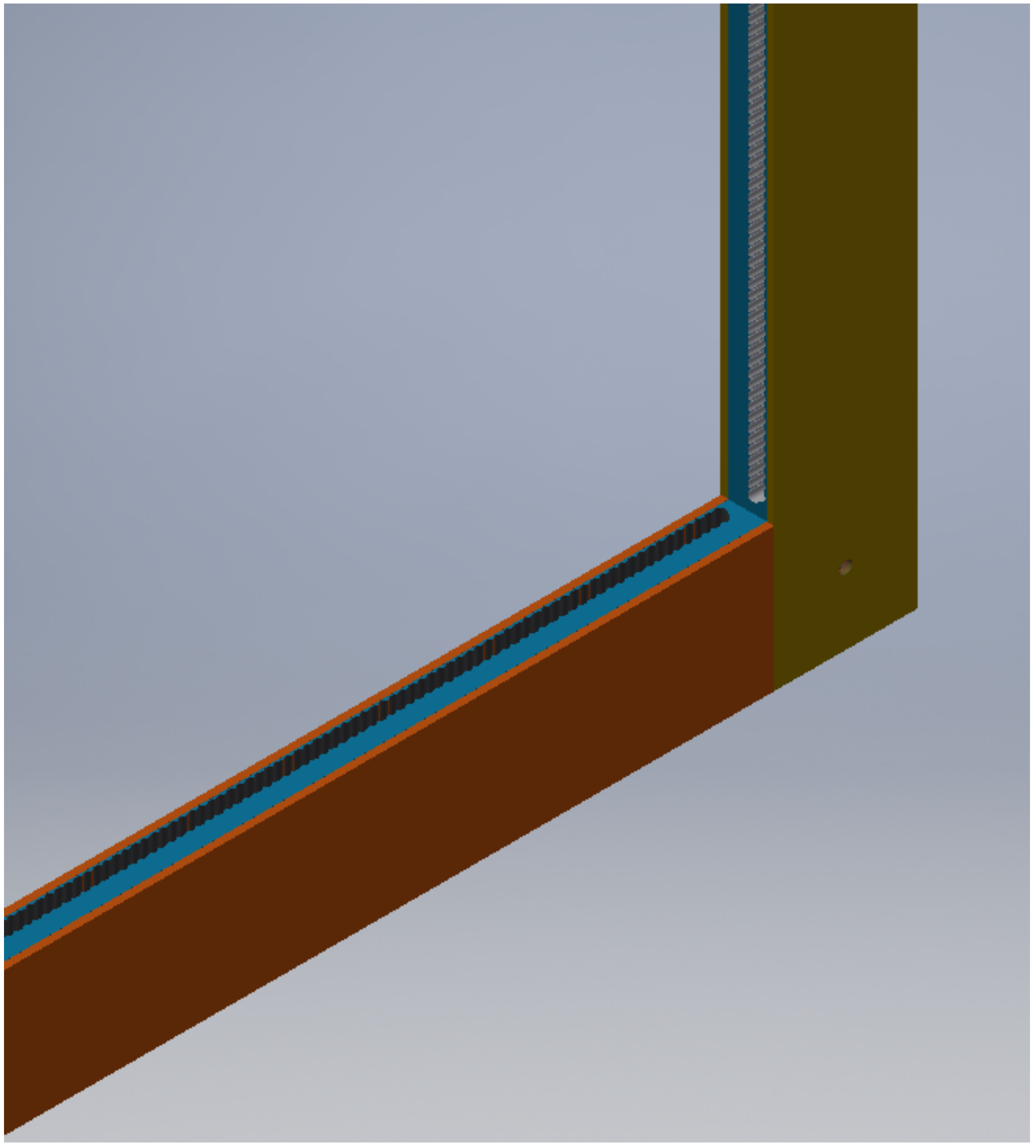
✦ *Complete 3D CAD design of STT modules with straws, radiator, and CH_2 target:*

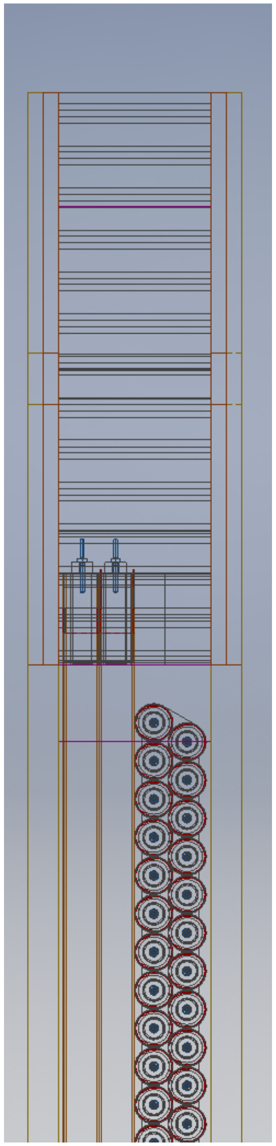
- *Self-supporting & withstanding internal pulls by straws;*
- *Minimize frame mass to avoid degradation of ECAL performance;*
- *Radiator & target easily mounted/unmounted without affecting the mechanical stability;*
- *Realistic implementation including all elements: straws, coatings, wires, end-plugs, screws, etc.*
- *Main frame material C-composite with Young's modulus 175 GPa.*

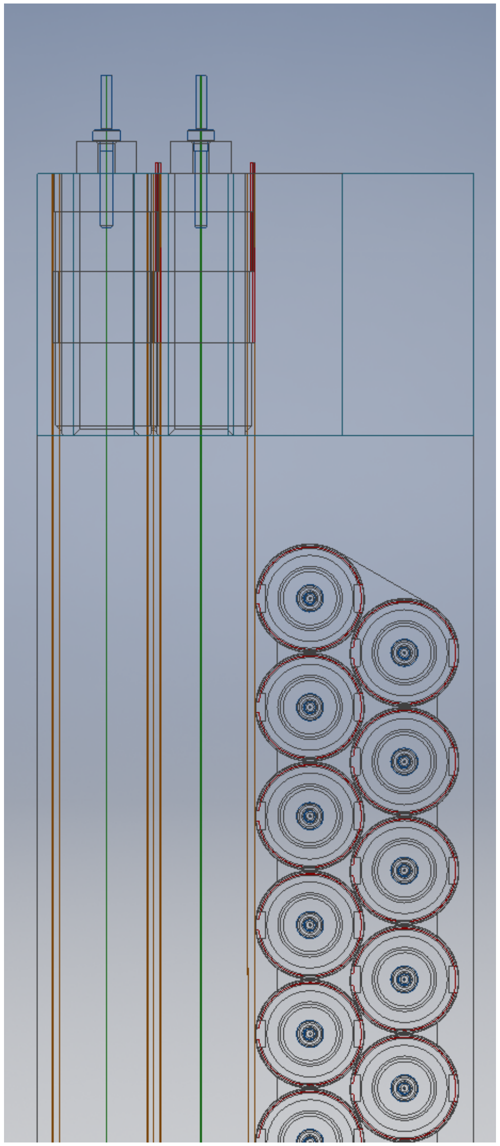
$\Longrightarrow$ *On average, frames add only $\sim 0.1\ X_0$ of material $\perp$ to beam direction*

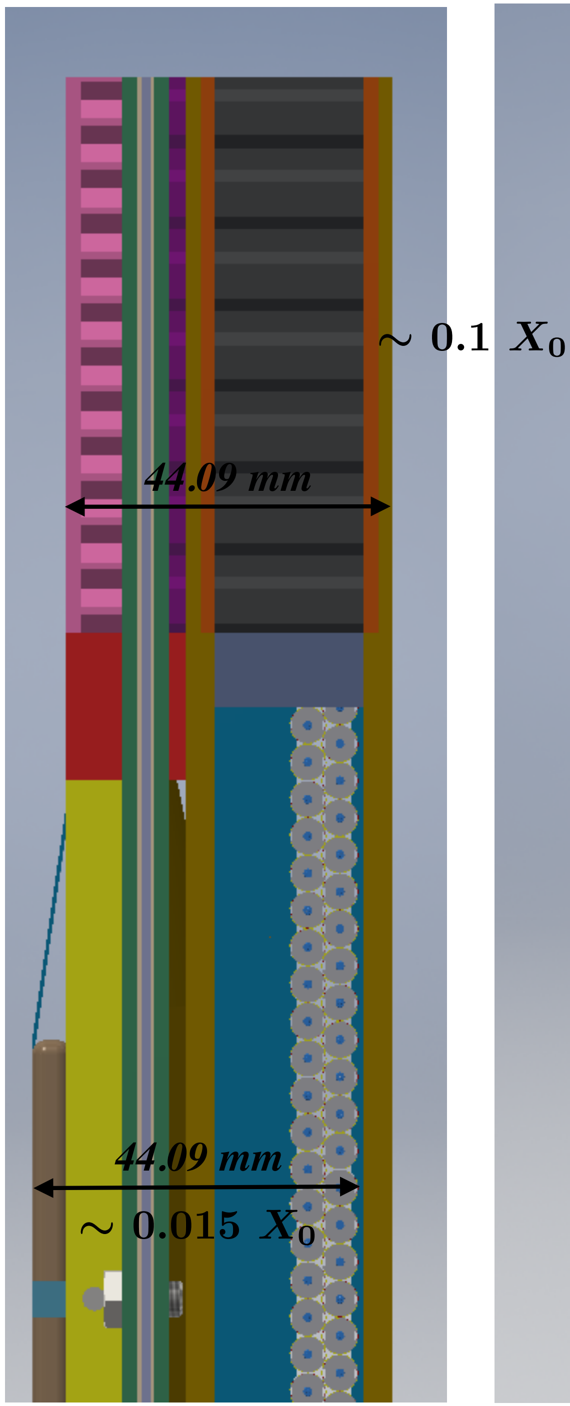


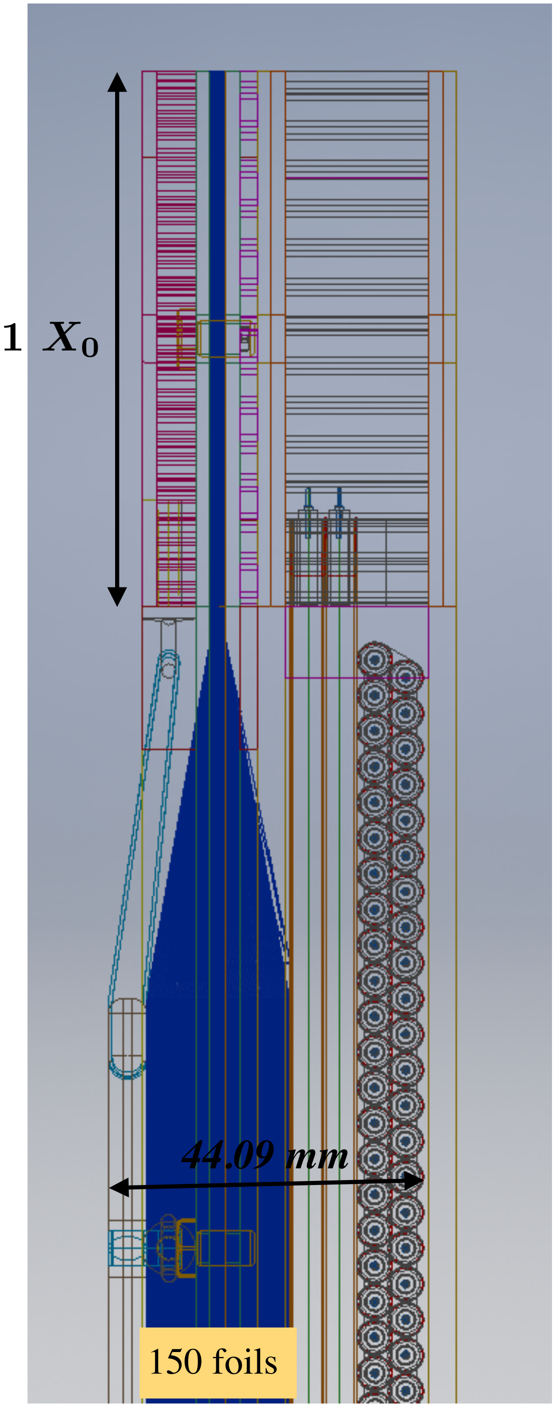


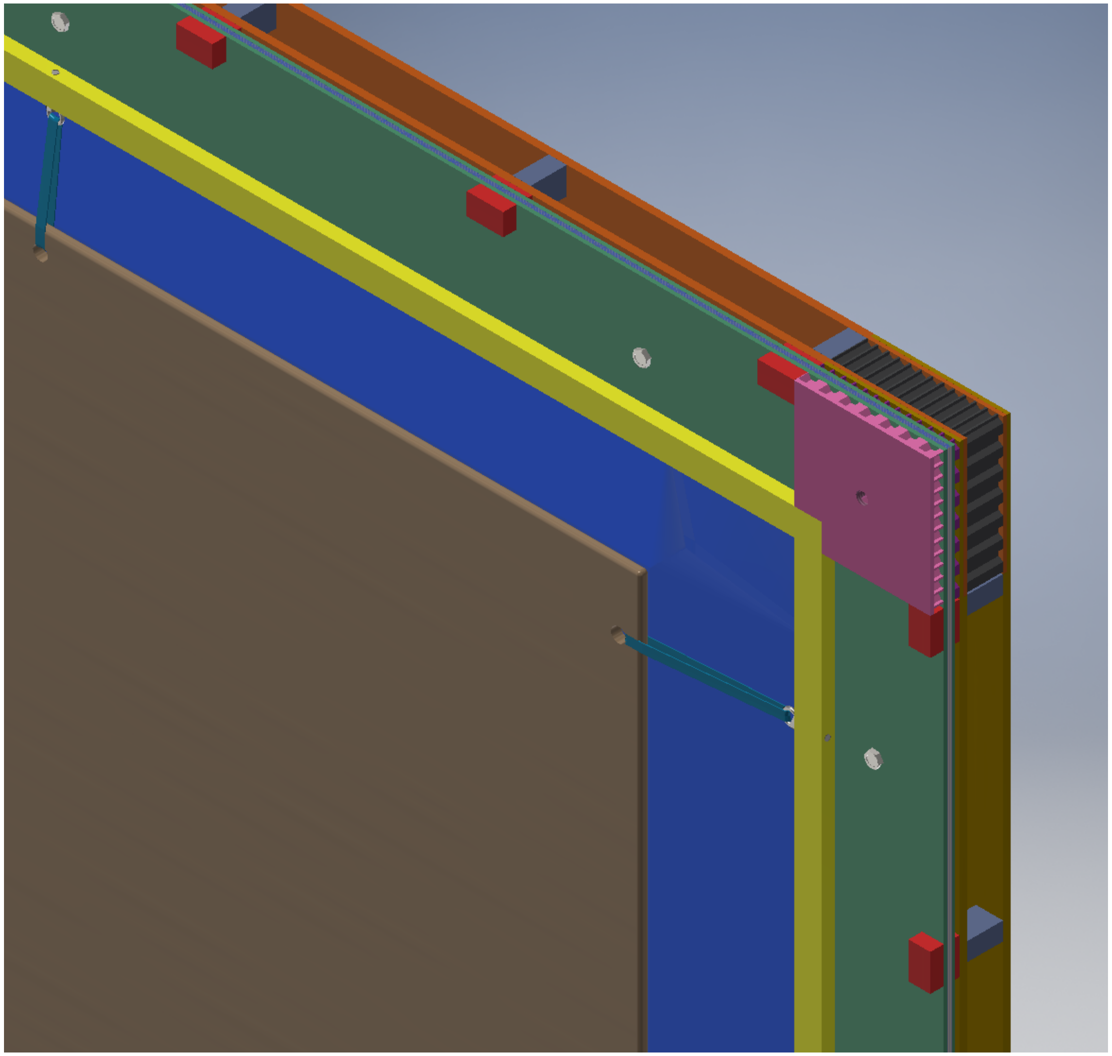


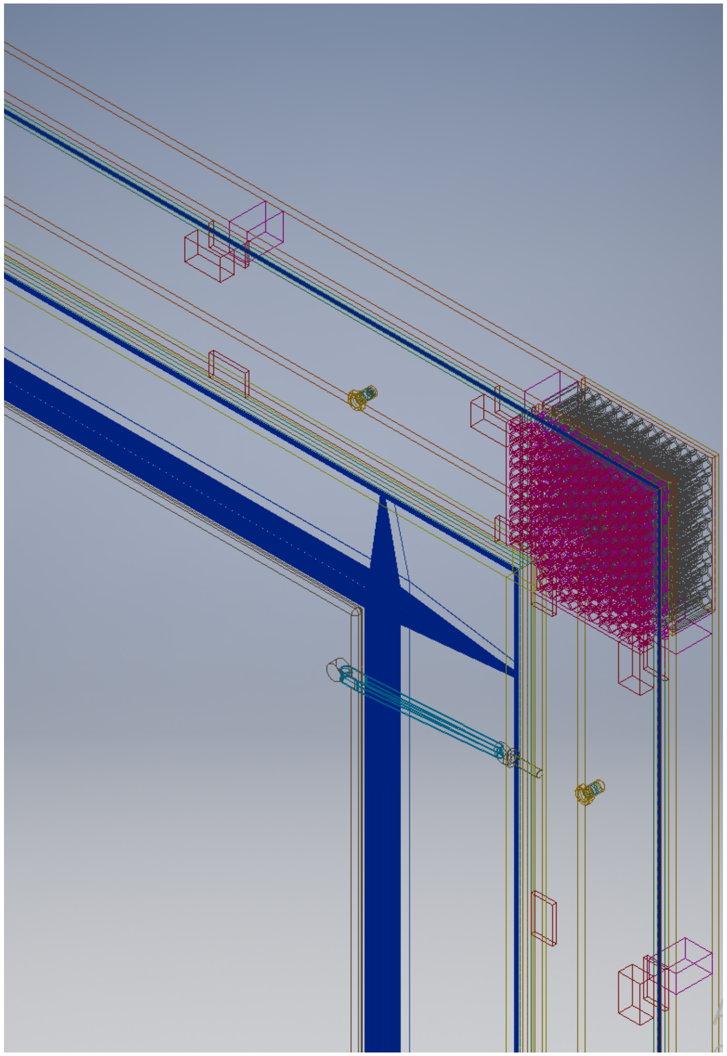





$\sim 0.1\ X_0$
44.09 mm
44.09 mm
$\sim 0.015\ X_0$


44.09 mm
150 foils





3D ENGINEERING MODEL & FE ANALYSIS

✦ *Complete 3D CAD design of STT modules with straws, radiator, and CH_2 target:*

- *Self-supporting & withstanding internal pulls by straws;*
- *Minimize frame mass to avoid degradation of ECAL performance;*
- *Radiator & target easily mounted/unmounted without affecting the mechanical stability;*
- *Realistic implementation including all elements: straws, coatings, wires, end-plugs, screws, etc.*
- *Main frame material C-composite with Young's modulus 175 GPa.*

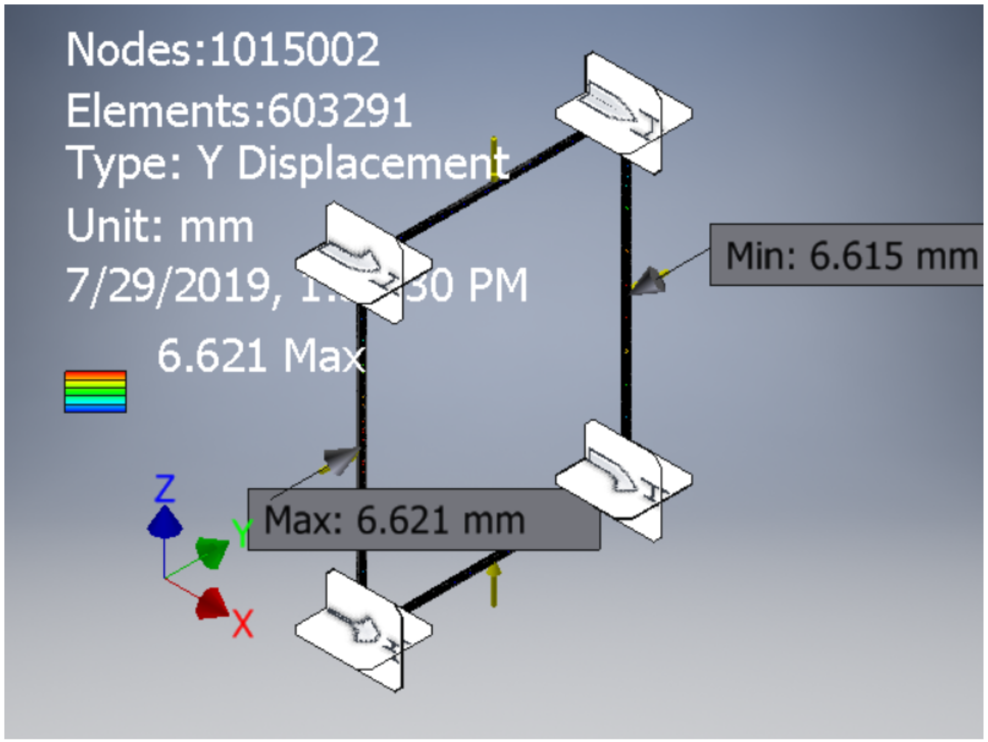
$\Longrightarrow$ *On average, frames add only $\sim 0.1\ X_0$ of material $\perp$ to beam direction*

✦ *Detailed Finite Element (FE) analysis of deformations:*

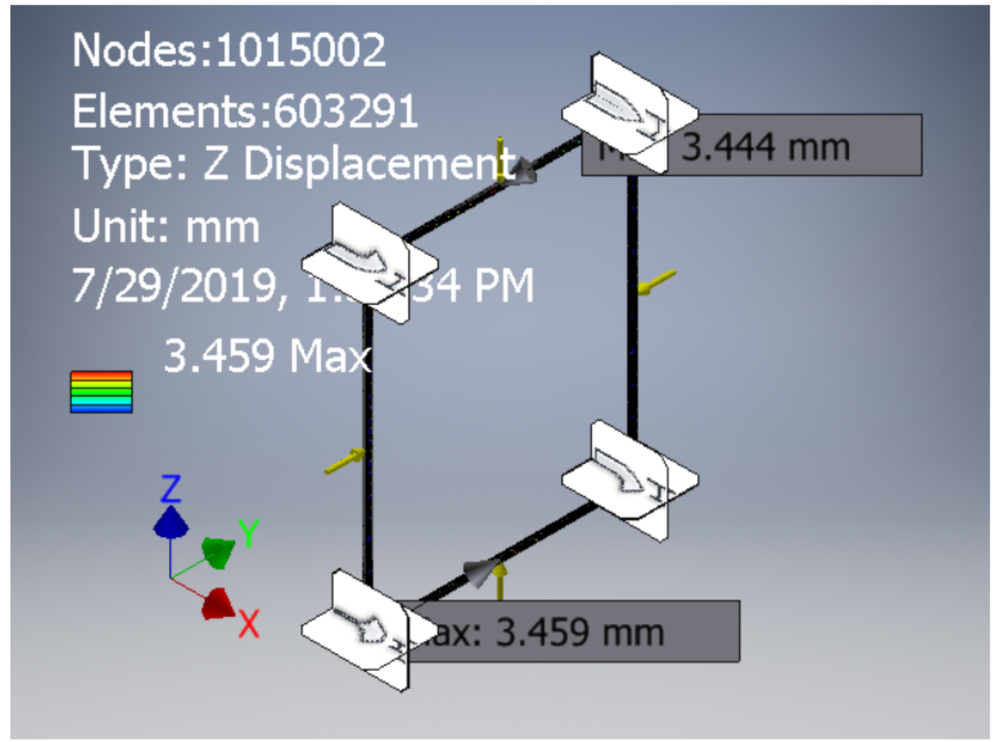
- *Assume worst case: central STT module 400 cm $\times$ 338 cm;*
- *Internal gas overpressure (1.9 atm) & XXYY straw assembly substantially reduce tension on frames;*
- *Wire tension 50g $+$ straw pre-tension of 200g: total 250g/straw;*
- *Forces applied by each straw: uniformly distributed across frame elements.*

$\Longrightarrow$ *Maximal deflections in central point of frames $\ll 1$ cm*

Y Displacement



Z Displacement



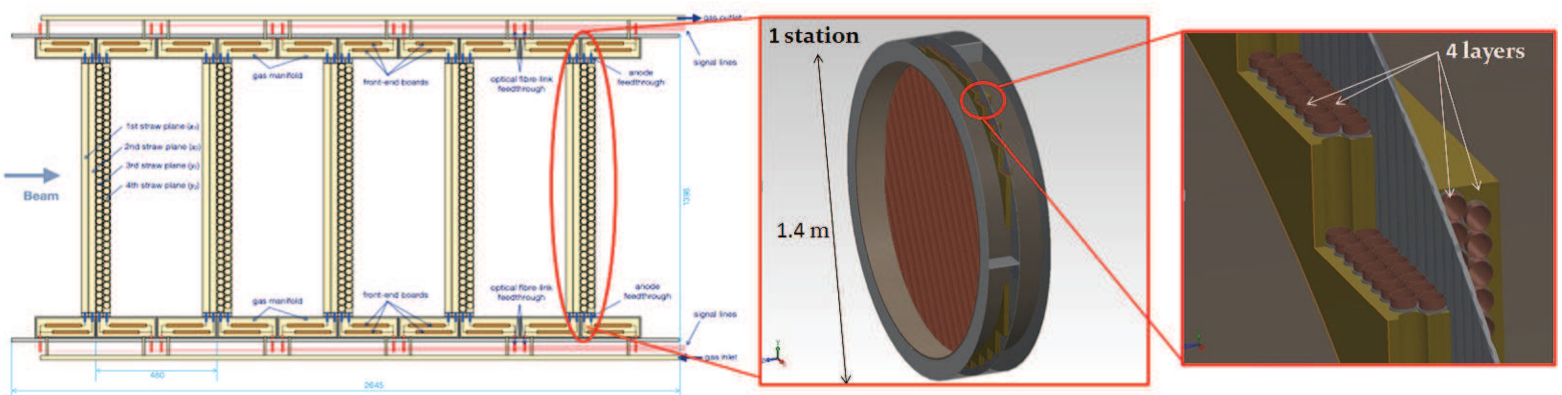
Detailed Finite Element Analysis of deformations

SIMILAR REQUIREMENTS AS ONGOING PROJECTS

- *STT technology used by existing/planned COMET, PANDA, Mu2e, NA62, SHiP, etc.*
  $\Longrightarrow$ *Benefit from common R&D and prototyping during pre-production phase*

- *Existing straw production line by GTU group at JINR Dubna for COMET:*
  - *COMET based upon same 4 XXYY layer design as updated STT modules;*
  - *Ultrasonic welding technology allows thin straw walls: existing prototypes 12 μm walls, 2m long;*
  - *Can operate overpressure (COMET in vacuum), similar conditions as in STT $\sim$ 1.9atm;*
  - *Each production line can produce 100-150 straws/day including quality control.*

- *Possible to produce complete STT with 3 production sites replicating existing COMET technology, assuming up to 3 straw production lines per site ($\sim$ one year).*



Straw production line with ultrasonic welding operated by the GTU group at JINR Dubna for the COMET experiment

COMPACT STT FOR SAND-DUNE

- *Large groups with infrastructure & extensive experience in the construction of various straw detectors (ATLAS TRT, COMPASS, Mu2e, NA62, SHiP, COMET, etc.):*
  - *Joint Institute for Nuclear Reserach (JINR), Dubna, Russia (International Laboratory);*
  - *Georgian Technical University (GTU), Tbilisi, Georgia;*
  - *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia (HEP Laboratory).*
- *Brookhaven National Laboratory (BNL) for electronic readout.*
- *University of South Carolina, USA.*
- *Belarusian State University, Minsk, Belarus.*
- *Interest from Indian institutions:*
  Indian Institute of Technology Guwahati (IITG); Jawaharlal Nehru University, New Delhi; University of Lucknow; University of Jammu; Banaras Hindu University.
- *Substantial interest from different physics communities in the non-oscillation physics program enabled by the STT within the KLOE magnet (docdb # 13262)*

  $\Longrightarrow$ *A rapidly growing community expanding the DUNE scientific base*

ONGOING R&D ACTIVITIES

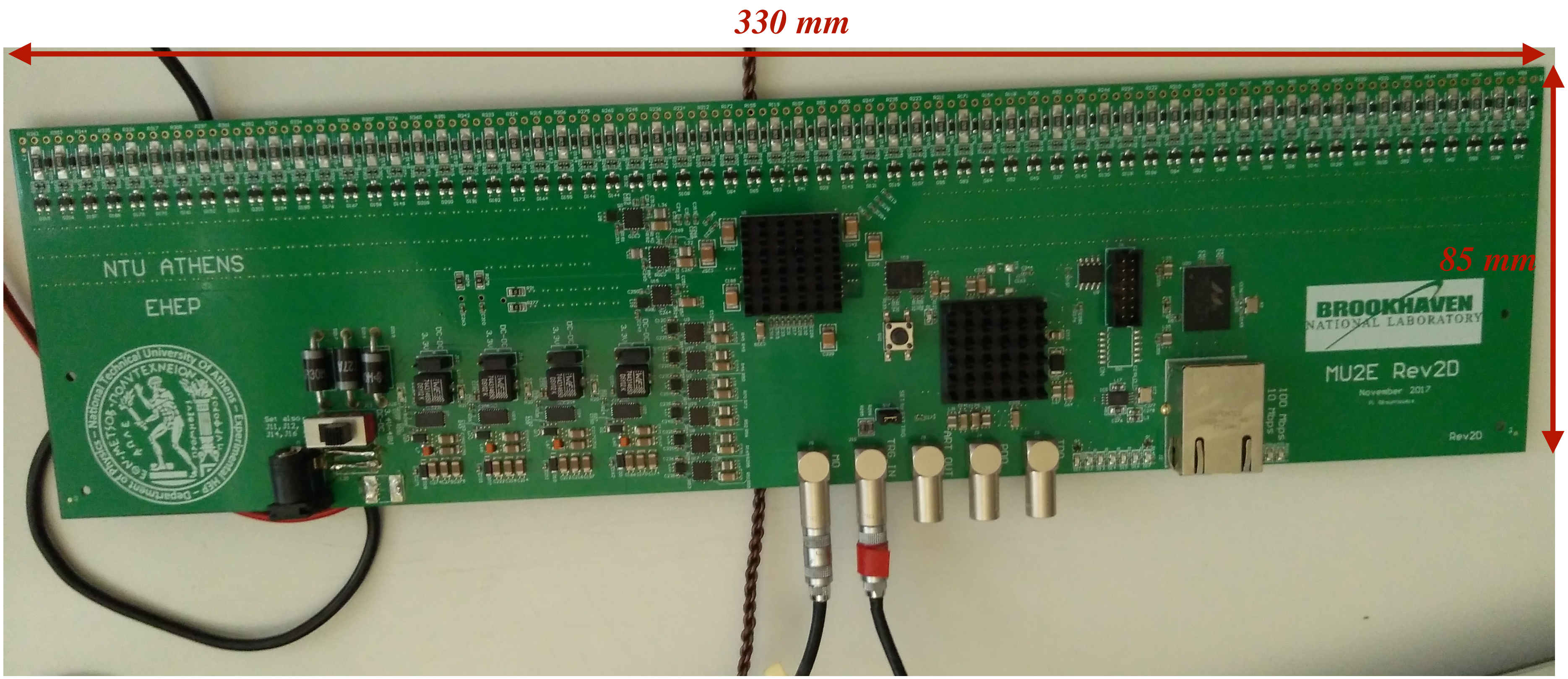
✦ *STT prototype to be built & tested in October-November 2019 at JINR:*

- *Small scale with 4 XXYY layers of straws built with ultrasonic welding at JINR;*
- *Front-end electronic readout with VMM3(a) ASICS from BNL;*
- *BNL boards and DAQ currently being tested at CERN (JINR, BNL);*
- *Mechanical assembly of XXYY straws;*
- *Validate straw performance with VMM3(a) readout electronics;*
- *Identify requirements for further developments of STT readout.*

✦ *Extensive tests of straw properties by GTU group at JINR for COMET:*

- *Tension of straw walls & wires vs. operating conditions;*
- *Detector stability over time, straw relaxation;*
- *Overpressure operation and straw deformations;*
- *Optimization of materials & welding process.*

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



VMM3 (and VMM3a) front-end readout boards being tested (JINR, BNL)

PRECISION ON-AXIS BEAM MONITORING

- *Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on Hydrogen*: $< 1\%$
  $\nu < 0.5$ *GeV* *flattens cross-sections reducing uncertainties on E_ν dependence.*

- *Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on Hydrogen*: $< 1\%$
  $\nu < 0.25$ *GeV*: *uncertainties comparable to relative ν_μ flux from $\nu_\mu p \to \mu^- p \pi^+$ on H.*

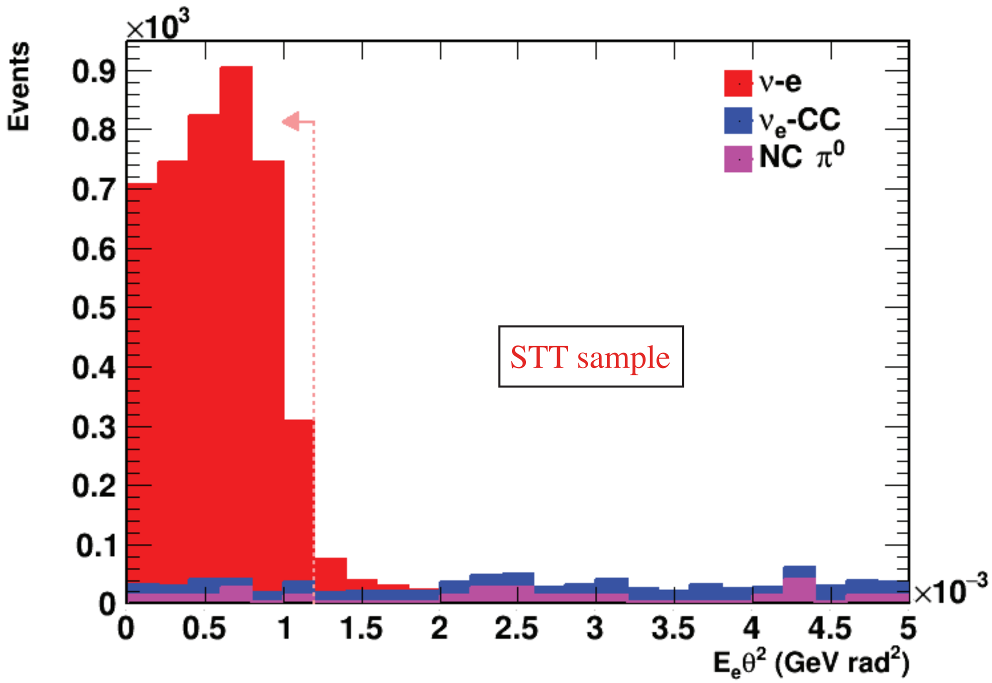
- *Absolute $\bar{\nu}_\mu$ flux from QE $\bar{\nu}_\mu p \to \mu^+ n$ on H with $Q^2 \sim 0$ (neutron β decay)*

- *Absolute ν_μ flux from $\nu e^- \to \nu e^-$ elastic scattering*: $\sim 2\%$
  $\Longrightarrow$ *Complementary to measurement in LAr TPC with small systematics*

- *Ratio of ν_e/ν_μ AND $\bar{\nu}_e/\bar{\nu}_\mu$ vs. E_ν from CH_2 (& H) targets*
  $\Longrightarrow$ *Excellent $e^\pm$ charge measurement and $e^\pm$ identification ($\sim$ 90k $\bar{\nu}_e$ CC in FHC)*

- *Determination of parent $\mu/\pi/K$ distributions from $\nu(\bar{\nu})$-H (& CH_2) at low-ν*
  $\Longrightarrow$ *Direct in-situ measurement for flux extrapolation to FD*

- *Stability of beam profile vs. E_ν and (x,y) over fiducial area 298 cm $\times$ 360 cm.*
  $\Longrightarrow$ *Total fiducial mass of 5.5 t uniformly filling the magnetic volume*

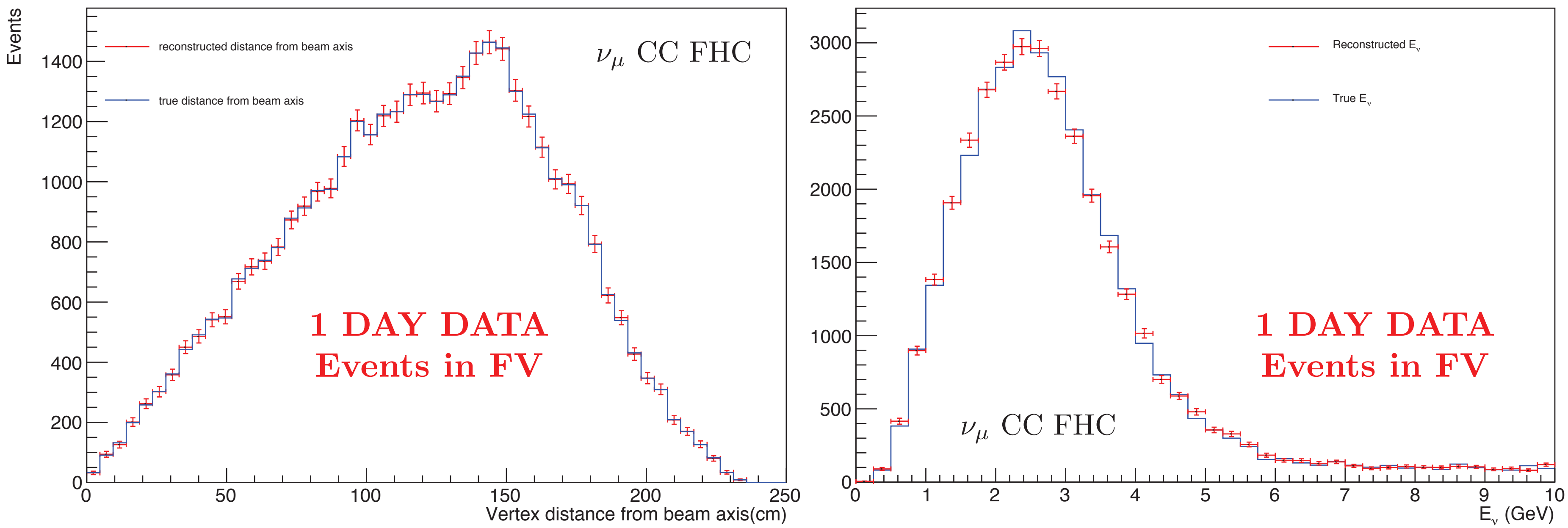


1,046 (938) νe^-/year selected in FHC (RHC) beam from CH_2, C, Ar targets & straw mass

✦ *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%**
LAr FHC + DUNE-Prism (50%)	11,229	11%	3%	0.9%	~1.5%	**~ 1.7%**

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



- ✦ *37,000/day ν_μ CC FHC & 14,000/day $\bar{\nu}_\mu$ CC RHC on CH_2, C, and straws in FV.*
- ✦ *Uniform filling of KLOE allows beam monitoring of (E_ν, r) up to $r \sim 250$ cm.*

  $\Longrightarrow$ *On-axis monitoring of beam stability & focusing in real time*

CONSTRAINING NUCLEAR SMEARING

$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu \, \boxed{\Phi(E_\nu)} \, P_{osc}(E_\nu) \, \boxed{\sigma_X(E_\nu)} \, \boxed{R_{phys}(E_\nu, E_{vis})} \, \boxed{R_{det}(E_{vis}, E_{rec})}$$

$\Phi(E_\nu) \rightarrow$ **~1% in H** $\sigma_X(E_\nu) \rightarrow F_i(Q^2)$ $R_{phys}(E_\nu, E_{vis}) \rightarrow R_{phys} \equiv I$

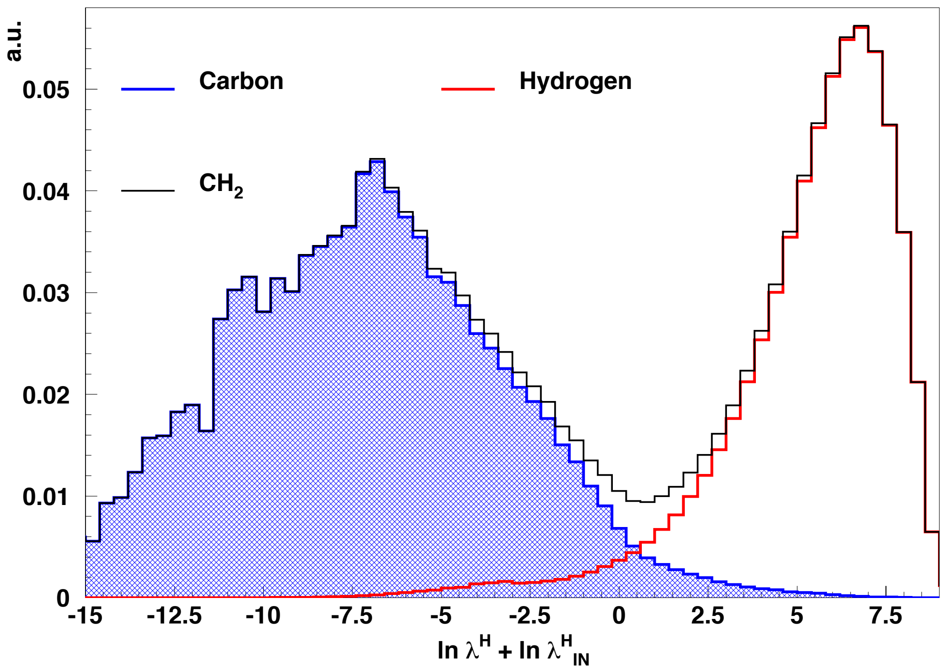
✦ *Hydrogen only target offering missing information to reduce systematics:*

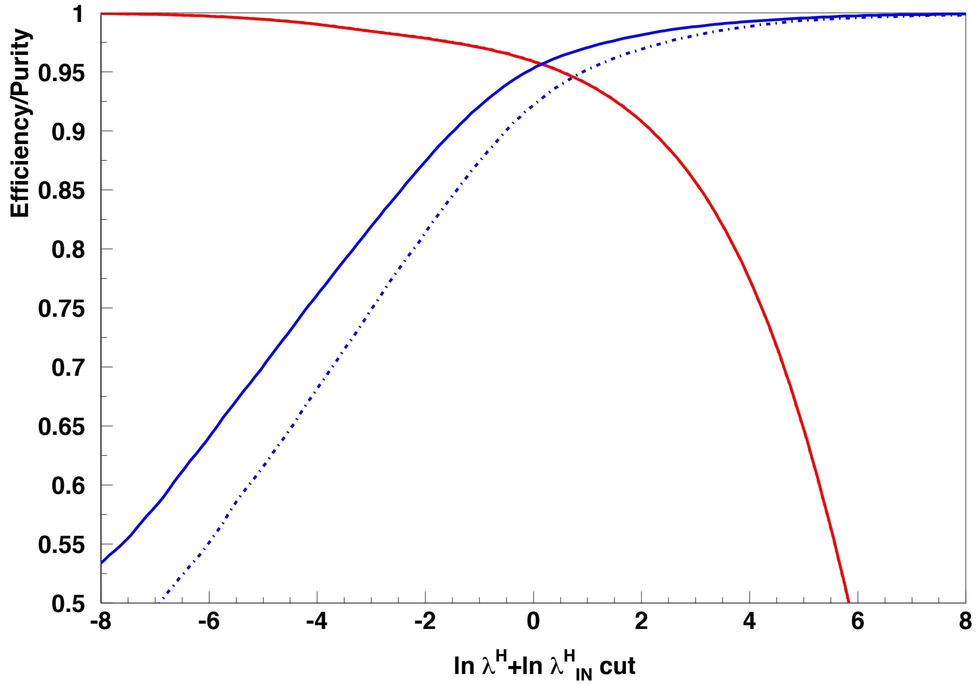
- *Constraining the nuclear smearing $\sigma_X R_{phys}$ from direct comparison of Ar and H targets;*
- *Calibration of the (anti)neutrino energy scale.*

✦ *Providing necessary redundancy against MC/model & unexpected discrepancies:*

- *Ar detectors alone (even ideal) cannot resolve $\sigma_X R_{phys} R_{det}$ & related systematics;*
- *DUNE-Prism alone sensitive to (beam) model & tuning to resolve off-axis discrepancies.*

$\Longrightarrow$ *Synergy between DUNE-Prism and Hydrogen measurements in STT to resolve systematics from beam modeling & nuclear smearing*





Selection of $\nu_\mu p \to \mu^- p \pi^+$ *and* $\bar{\nu}_\mu p \to \mu^+ p \pi^-$ *processes*

*H. Duyang, B. Guo, S. Mishra, and RP, arXiv:1809.08752**v2** [hep-ph]*

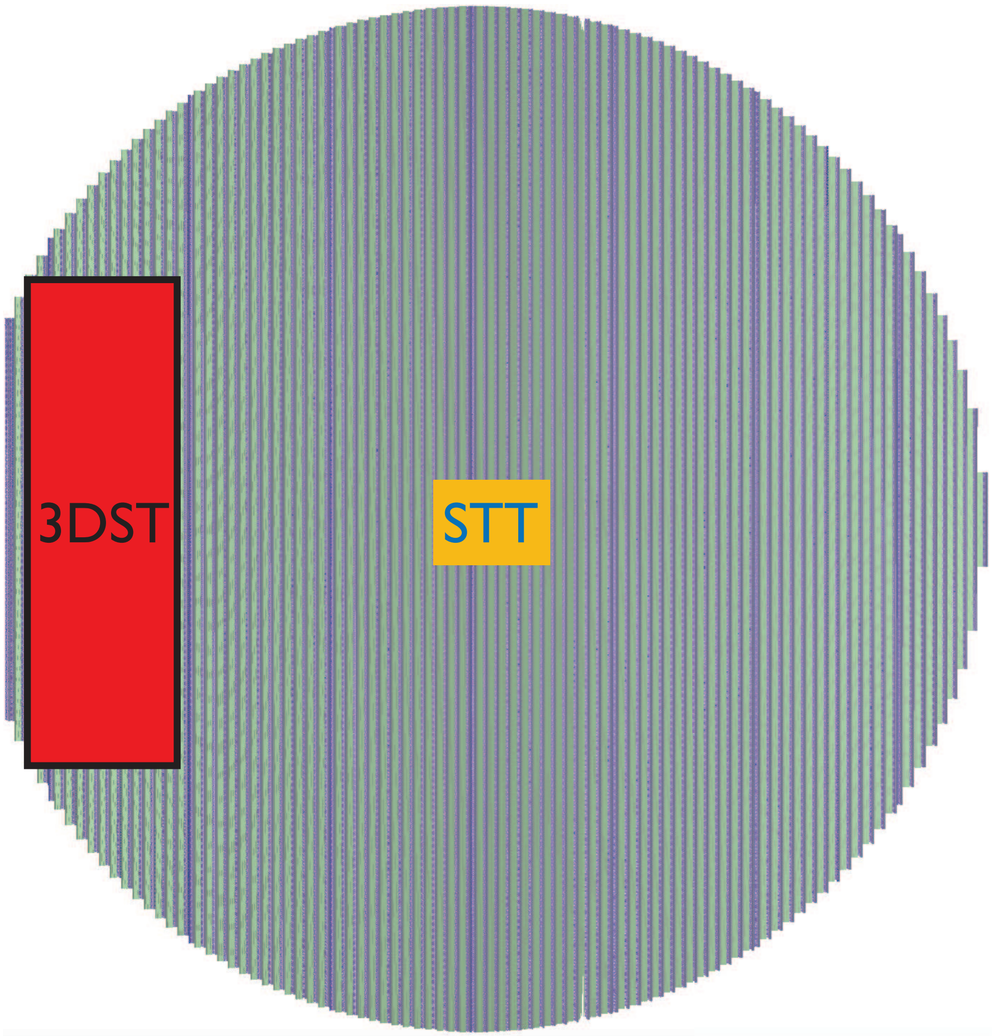
Process	ν_μ-H CC $\mu^- p\pi^+$	$\mu^- p\pi^+ X$	$\mu^- n\pi^+\pi^+ X$	Inclusive	$\bar{\nu}_\mu$-H CC $\mu^+ p\pi^-$	$\mu^+ n\pi^0$	$\mu^+ n$	$\mu^+ p\pi^- X$	$\mu^+ n\pi\pi X$	Inclusive
Eff. ε	96%	89%	75%	93%	94%	84%	75%	85%	82%	80%
Purity	95%	93%	70%	93%	95%	84%	80%	94%	84%	84%

TABLE I. Efficiency ε and purity for the kinematic selection of H interactions from the CH_2 plastic target using the likelihood ratio $\ln\lambda^{\rm H}+\ln\lambda^{\rm H}_{\rm IN}$ or $\ln\lambda^{\rm H}_4+\ln\lambda^{\rm H}_{\rm IN}$. For the $\mu^+ n$ QE topologies $\ln\lambda^{\rm H}_{\rm QE}$ is used instead. The cuts applied for each channel are chosen to maximize the sensitivity defined as $S/\sqrt{S+B}$, where S is the H signal and B the C background. The CC inclusive samples are obtained from the combination of the corresponding exclusive channels.

Process	ν_μ-H CC, $\varepsilon \equiv 75\%$ $\mu^- p\pi^+$	$\mu^- p\pi^+ X$	$\mu^- n\pi^+\pi^+ X$	Inclusive	$\bar{\nu}_\mu$-H CC, $\varepsilon \equiv 75\%$ $\mu^+ p\pi^-$	$\mu^+ n\pi^0$	$\mu^+ n$	$\mu^+ p\pi^- X$	$\mu^+ n\pi\pi X$	Inclusive
Purity	99%	99%	70%	98%	99%	90%	80%	98%	90%	86%

TABLE II. Purity achieved with the kinematic selection of H interactions from the CH_2 plastic target using a cut on the likelihood ratio $\ln\lambda^{\rm H}+\ln\lambda^{\rm H}_{\rm IN}$ or $\ln\lambda^{\rm H}_4+\ln\lambda^{\rm H}_{\rm IN}$ resulting in the fixed H signal efficiency ε specified. For the $\mu^+ n$ QE topologies $\ln\lambda^{\rm H}_{\rm QE}$ is used instead. For illustration purpose, the value of the efficiency is chosen as the lowest among the ones listed in Tab. I for individual topologies. The CC inclusive samples are obtained from the combination of the corresponding exclusive channels.

STUDY/EVALUATE HYBRID CONFIGURATIONS



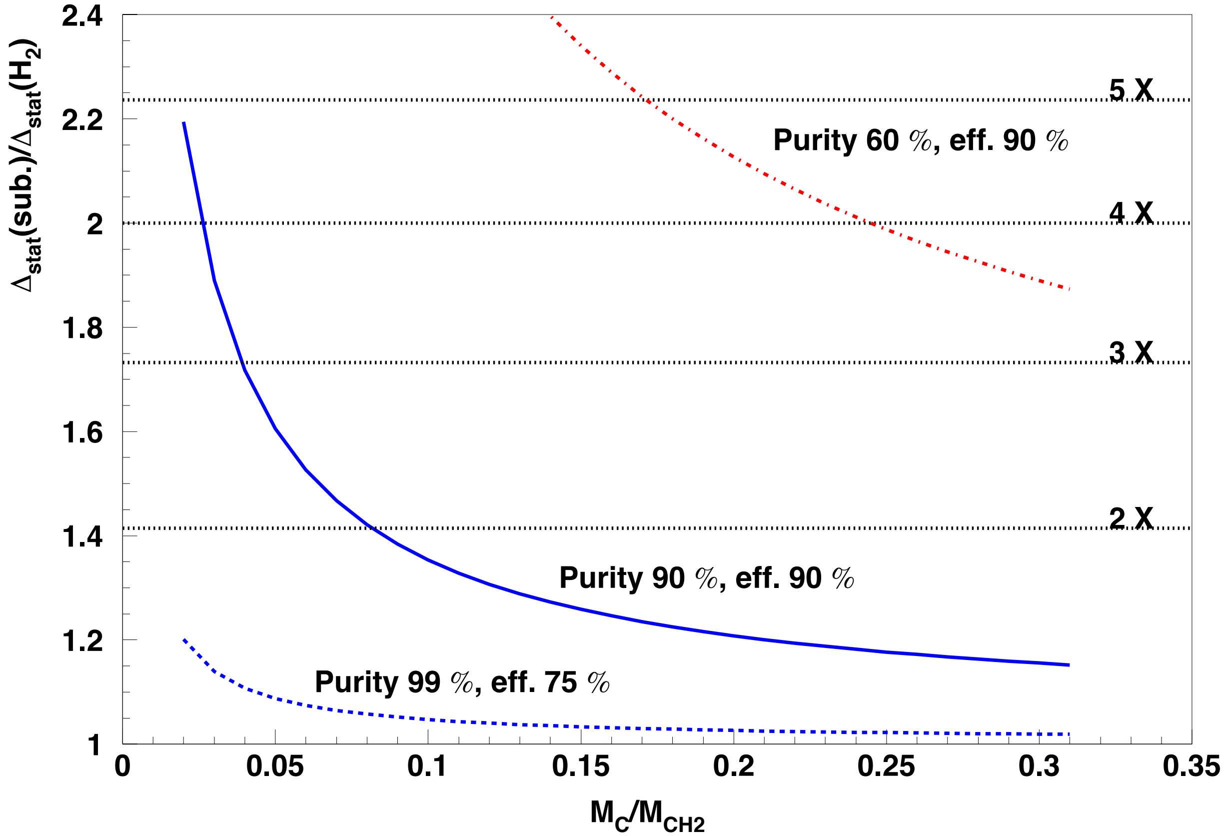
- *Consider different design options to understand the physics potential of possible hybrid detectors including 3DST & STT.*
- *Need to study benefits vs. limitations of various options for the main ND physics measurements.*
- *Useful to use common simulation framework & benchmark developed in docdb # 13262*

  $\Longrightarrow$ *See talk by Paola*

Backup slides

CC process	CH_2 target	H target	CH_2 selected	C bkgnd	H selected
$\nu_\mu p \to \mu^- p \pi^+$	5,615,000	2,453,000	2,305,000	115,000	2,190,000
$\nu_\mu p \to \mu^- p \pi^+ X$	11,444,000	955,000	877,000	61,000	816,000
$\nu_\mu p \to \mu^- n \pi^+ \pi^+ X$	3,533,000	183,000	158,000	48,000	110,000
ν_μ CC inclusive	34,900,000	3,591,000	3,340,000	224,000	3,116,000
$\bar{\nu}_\mu p \to \mu^+ n$	4,450,000	1,688,000	1,274,000	255,000	1,019,000
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	827,000	372,000	342,000	17,000	325,000
$\bar{\nu}_\mu p \to \mu^+ n \pi^0$	791,000	366,000	295,000	48,000	247,000
$\bar{\nu}_\mu p \to \mu^+ p \pi^- X$	2,270,000	176,000	153,000	9,000	144,000
$\bar{\nu}_\mu p \to \mu^+ n \pi \pi X$	2,324,000	280,000	220,000	35,000	185,000
$\bar{\nu}_\mu$ CC inclusive	13,000,000	2,882,000	2,284,000	364,000	1,920,000

TABLE III. Number of events expected in the selection of all the various processes on H with the default low energy (anti)neutrino beams available at the LBNF [1, 2], assuming 5+5 years of data taking with the neutrino and antineutrino beams. The first two columns (CH_2 and H targets) refer to the initial statistics, while the last three include all selection cuts described in this paper (Sec. III and Tab. I). For the CH_2 and C targets the numbers refer to the given final state topologies originated from either p or n interactions. The fifth column shows the total residual C background to be subtracted from the corresponding CH_2 selected samples. We use a ratio $M_C/M_{C/CH_2} = 0.12$ to measure the C backgrounds from the graphite targets. See the text for details.



$$N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_{C/CH_2}}{M_C}$$

Data-driven subtraction of small backgrounds (model-independent)