An analysis of photons collected from tagged cosmic-ray muons in ProtoDUNE-SP

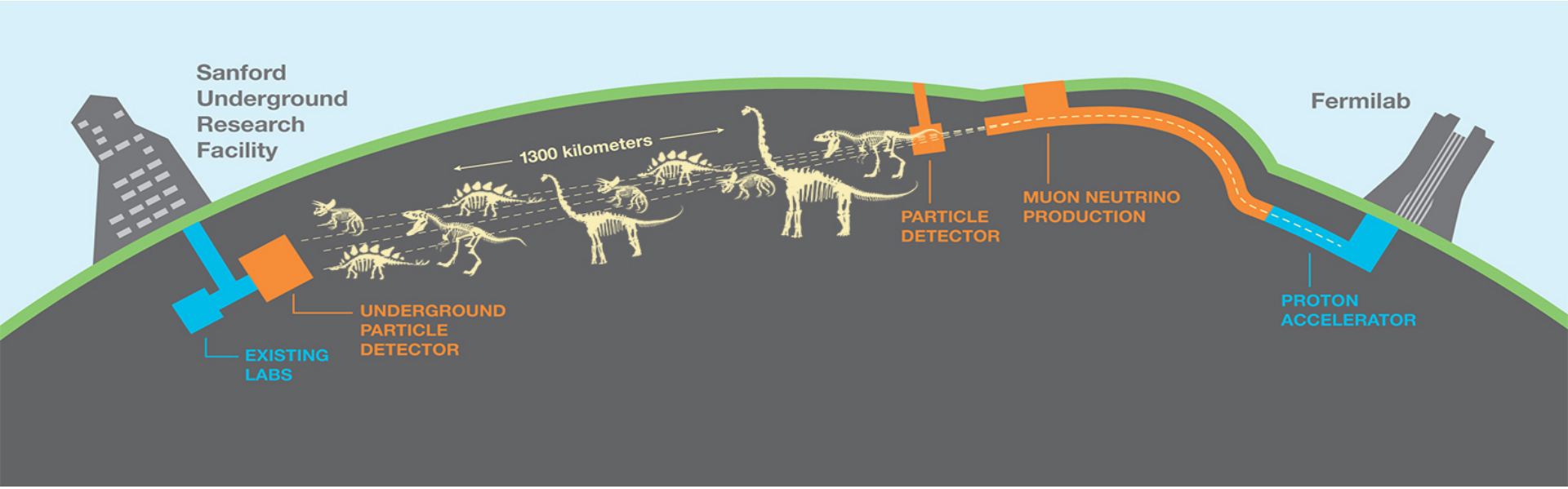
Bryan Ramson (on behalf of the DUNE collaboration)

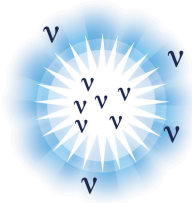
Fermilab Seminar

October 29, 2020

Introduction—(What is DUNE?)

The Fermilab Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillations experiment.





Will measure with greater precision:

- leptonic CP-violation (δ_{CP},Δ**L=0**?)
- Neutrino oscillation (θ_{13}, and θ_{23})
- Neutrino mass hierarchy (**NH** or **IH**)

Will observe or further constrain:

- Proton Decay (Δ**B=0?** Δ**(B-L)?,GUT)**

Will observe:

- Core-collapse/supernova burst neutrinos

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Background—(Neutrino Oscillations)

Neutrino Oscillations: Example of leptonic CP-violation, demonstration of possible mechanism for matter/anti-matter asymmetry.

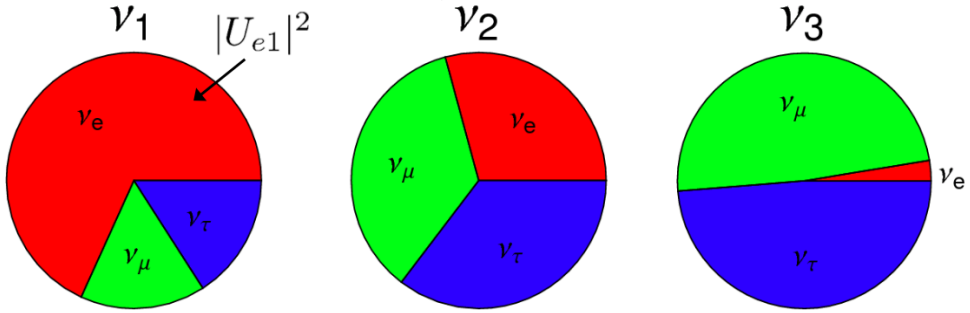
$$\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L} \gamma^\mu \nu_{\alpha L} + \mathrm{h.c.} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha L} \gamma^\mu \sum_{i=1,2,3} U_{\alpha i}\, \nu_{iL} + \mathrm{h.c.}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

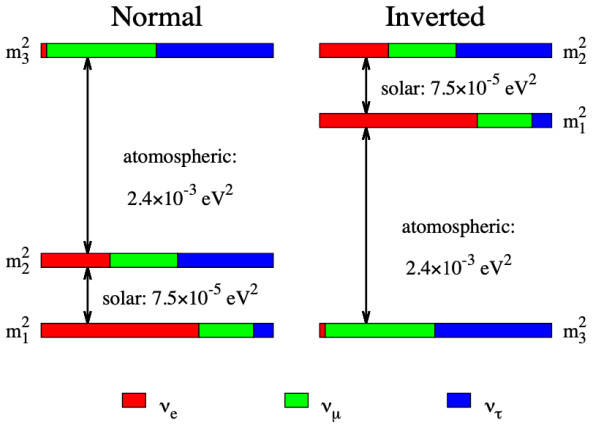
PMNS Matrix = Atmospheric × Reactor × Solar

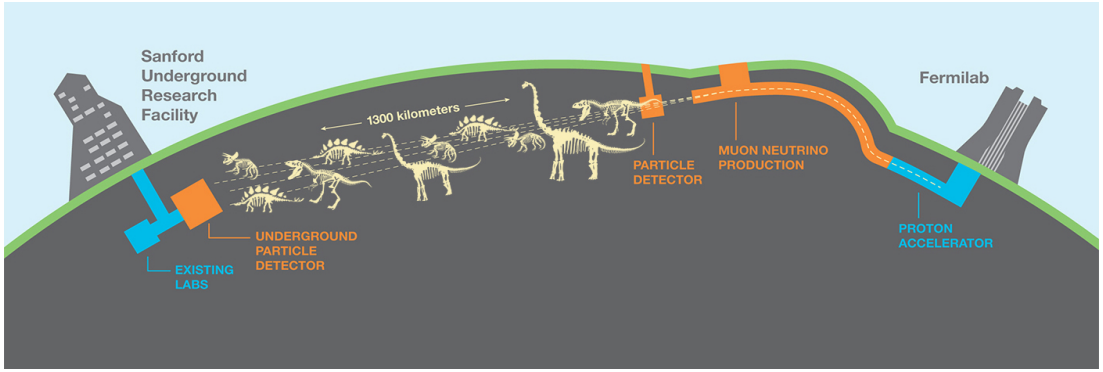
$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(Lake Louise Winter Institute, Winter, 2017)



(JUNO, Miramonti, 2018)





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- Neutrino oscillation ($\boldsymbol{\theta_{12}}$,$\boldsymbol{\theta_{23}}$)
- leptonic CP-violation $\boldsymbol{\delta_{CP}}$ ($\boldsymbol{\Delta}$**L=0**?)
- Neutrino mass hierarchy (**NH** or **IH**)

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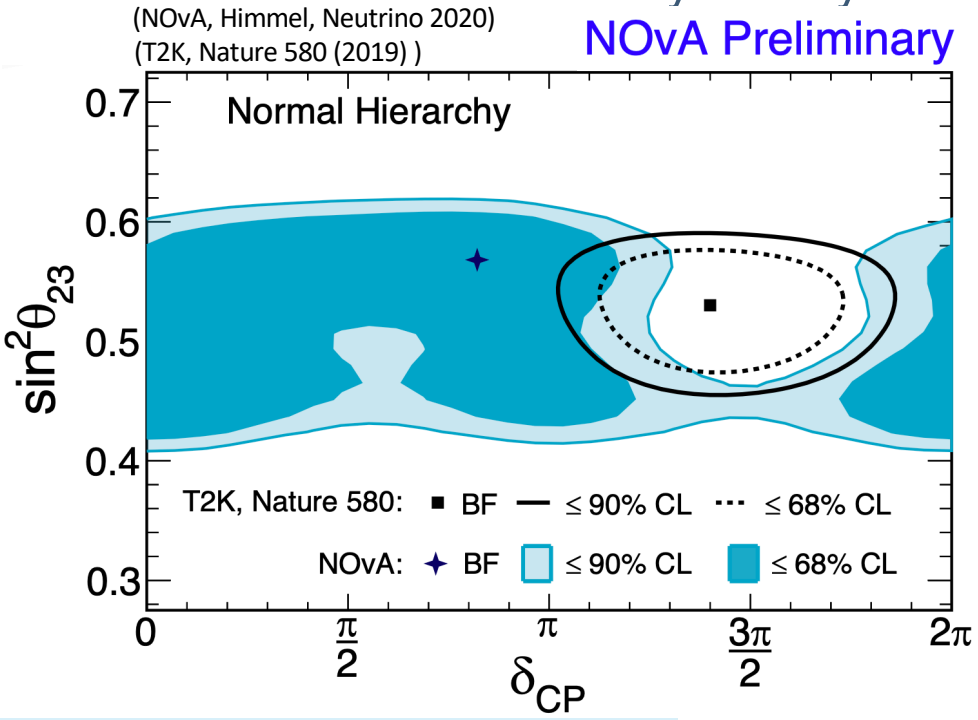
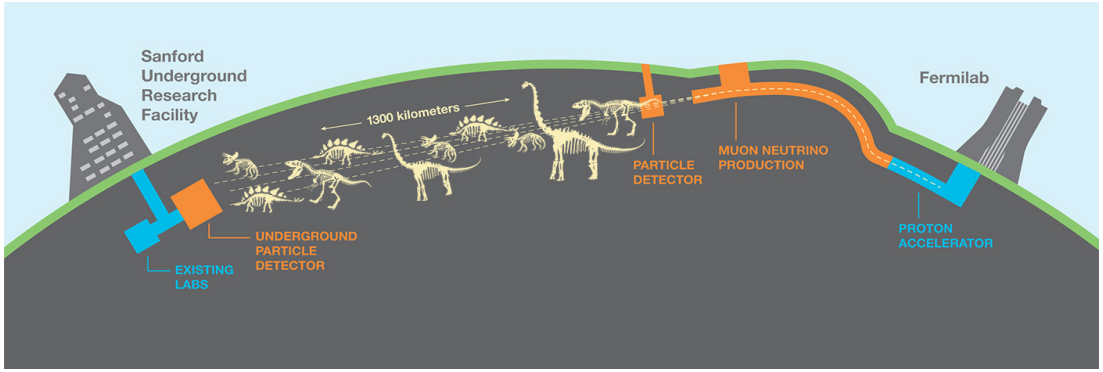
Background—(Neutrino Oscillations)

Neutrino Oscillations: Example of leptonic CP-violation, demonstration of possible mechanism for matter/anti-matter asymmetry.

Both favor Normal Hierarchy!



NOvA and T2K are in mild tension with each other!



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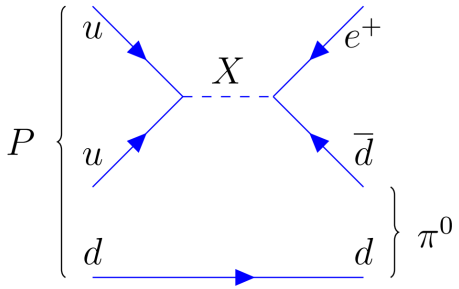
Background—(Proton Decay)

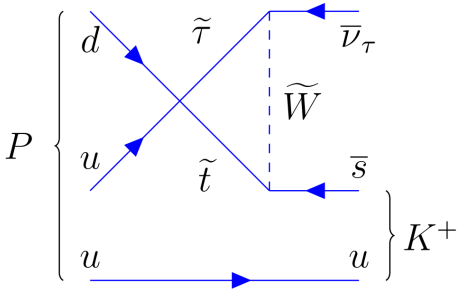
Proton Decay: Statements about GUT!

Most popular, accessible theories:

arXiv:1512.06148

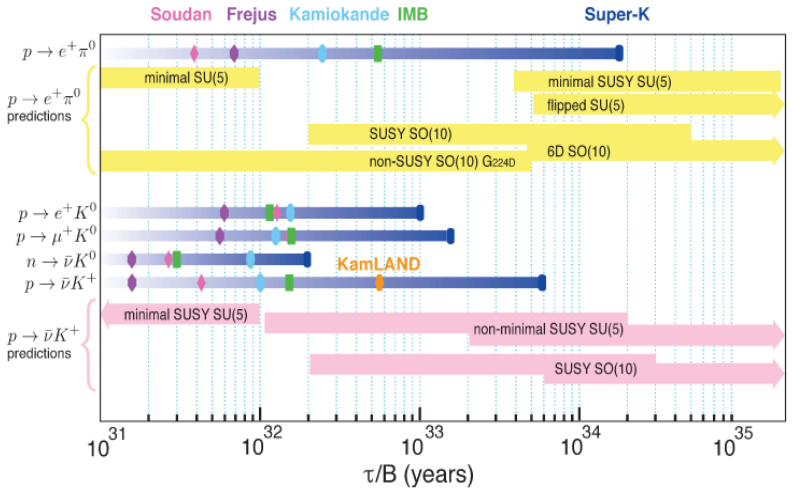


SU(5) Gauge-Mediated GUT

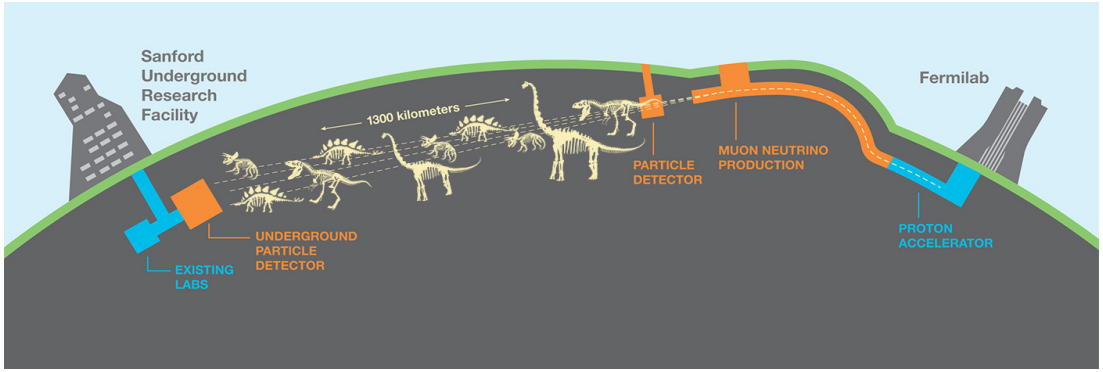


Supersymmetric GUT

arXiv:2002.02967



About ~5.5 × 10^{32} nucleons at DUNE FD



Will observe or further constrain:

- Proton Decay (***ΔB=0?***)

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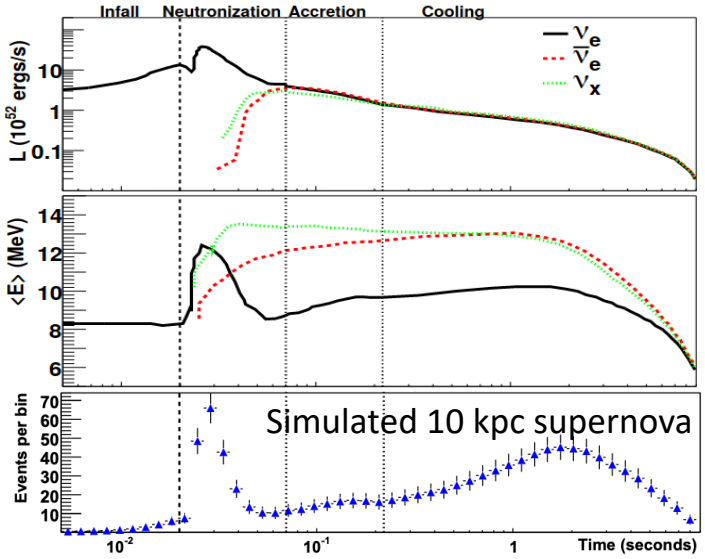
Background—(Supernova Bursts)

Rare measurements of supernova bursts!

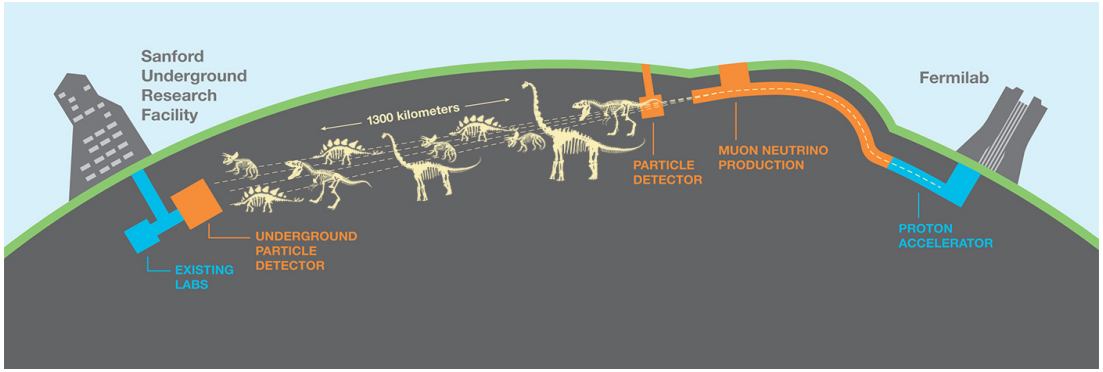


SN 1987A (Wikipedia)

- Events are rare, neutrinos are in the few to tens of MeV
- SN1987A produced 25 events across world neutrino detectors

arXiv:1804.01877

Neutrino signal evolves over time and is related to SN structure!



If lucky, will observe:

- Core-collapse/supernova burst neutrinos

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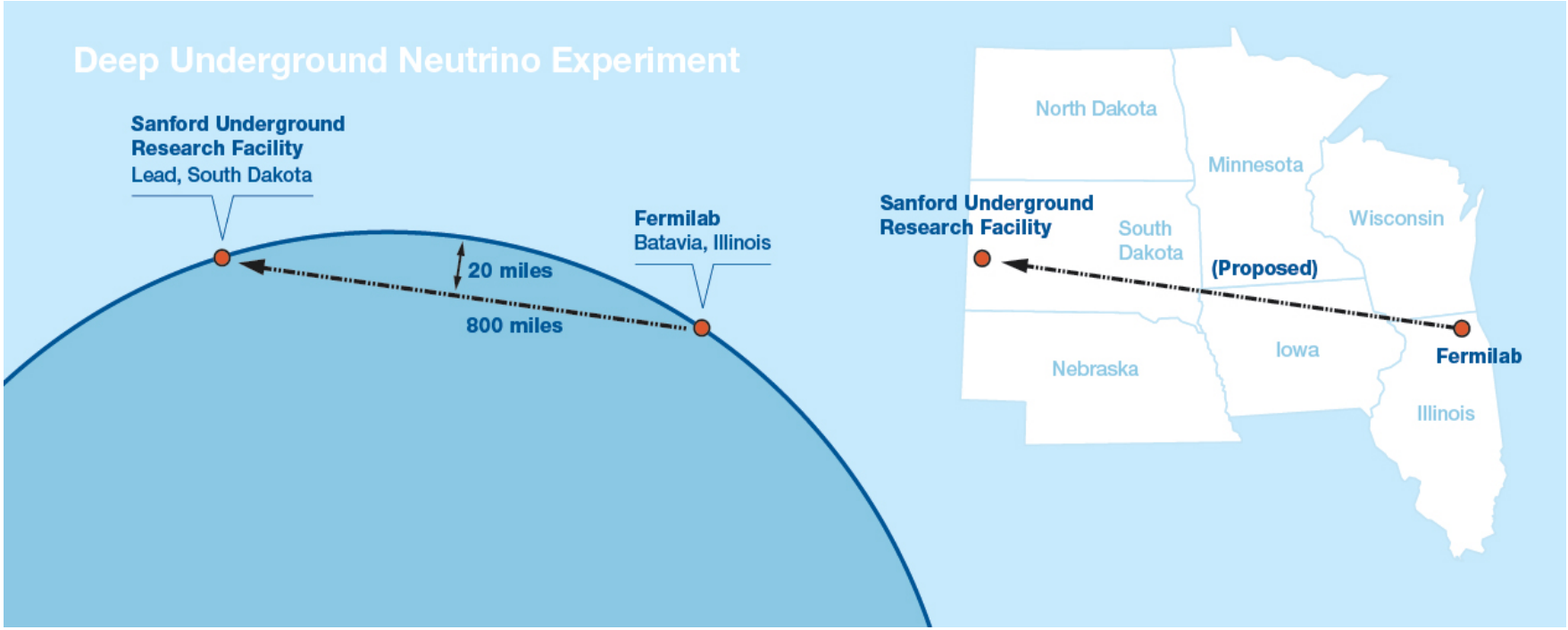
The DUNE Detectors

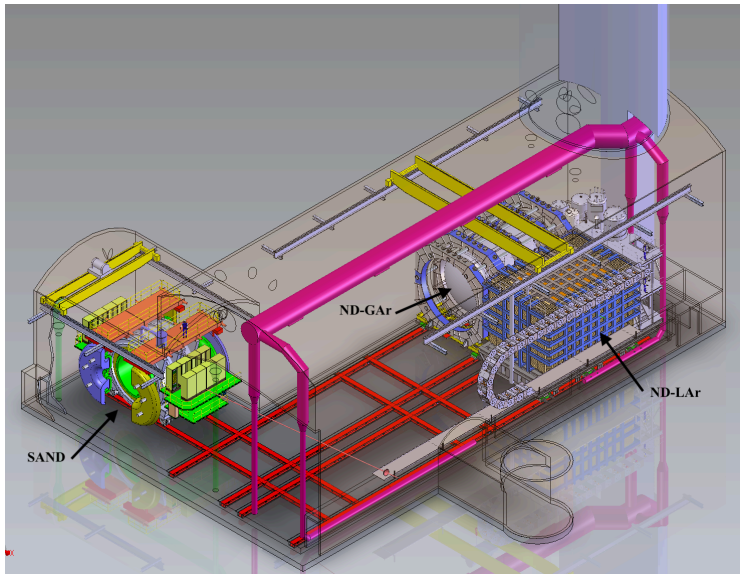
DUNE is a multi-detector Long-Baseline Neutrino Oscillations Experiment.

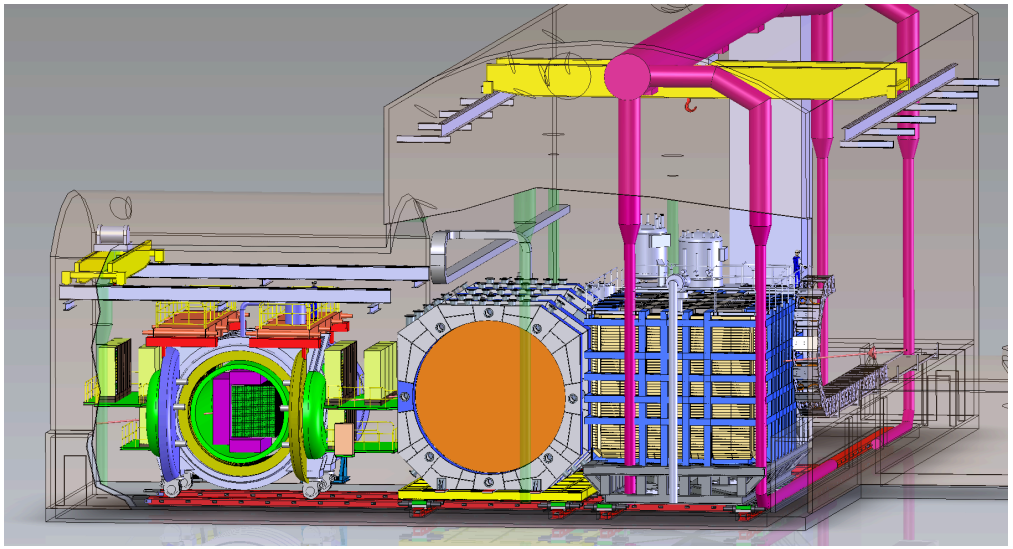


Detector baseline is 800 miles with 20 miles maximum depth, enhances sensitivity to the neutrino matter effect!

The DUNE Near Detector

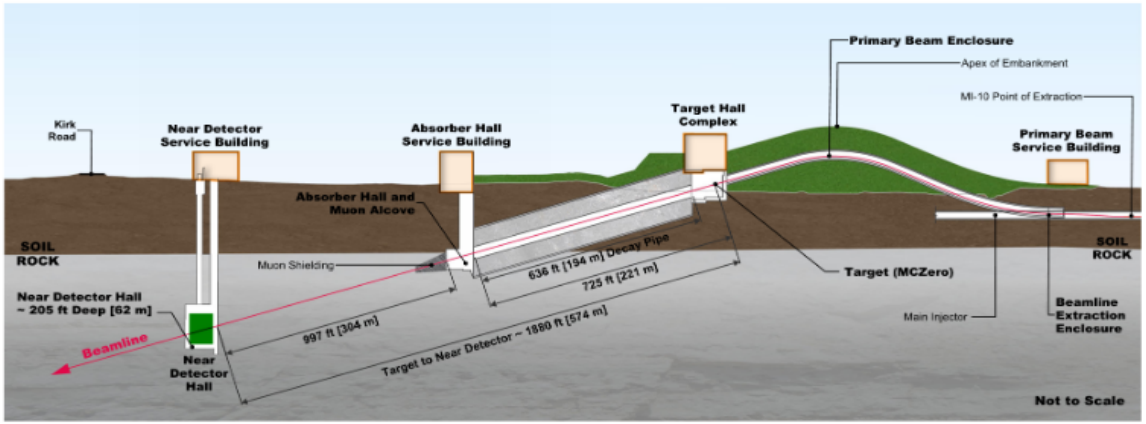
DUNE is a multi-detector Long-Baseline Neutrino Oscillations Experiment.

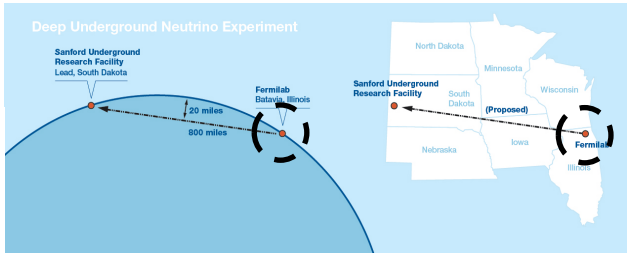




Near Detector Hall ~62 meters underground

arXiv:2002.02967





Near-Detector Hall to constrain observation systematics!

- Gaseous Argon ND (ND-GAr)
- Liquid Argon ND (ND-LAr)
- System for on-axis Neutrino Detection (SAND)

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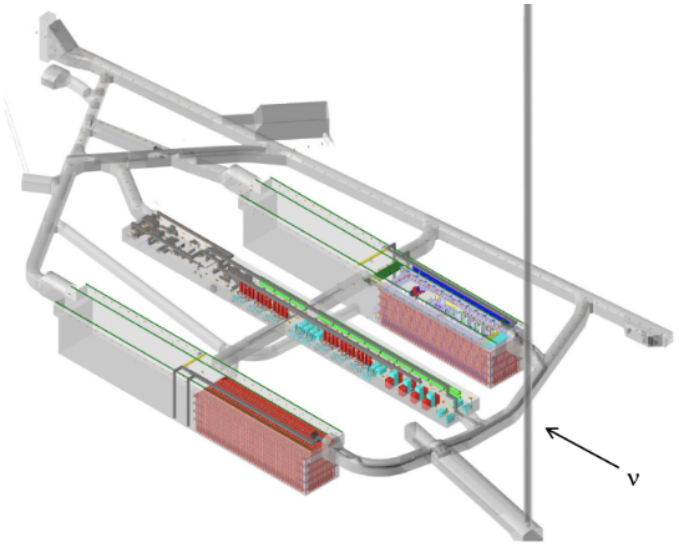
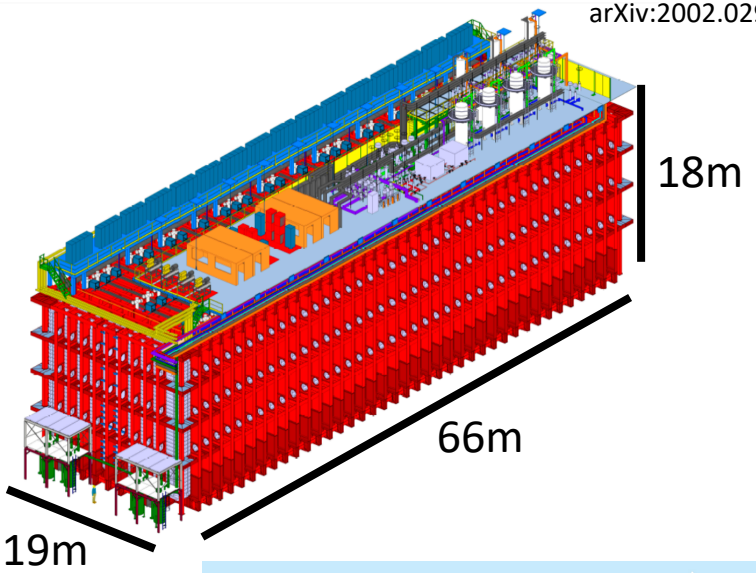
The DUNE Far Detector

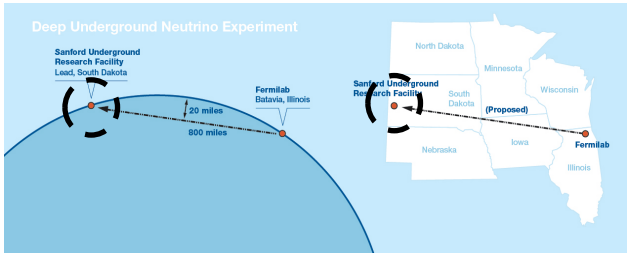
DUNE is a multi-detector Long-Baseline Neutrino Oscillations Experiment.



arXiv:2002.02967



Far Detector Hall ~1.5 km underground



Far-Detector designed to observe physics:

- 4-17 kt Fiducial Volume
- 1st & 2nd Modules planned to be Single Phase
- Possible "Module of Opportunity"

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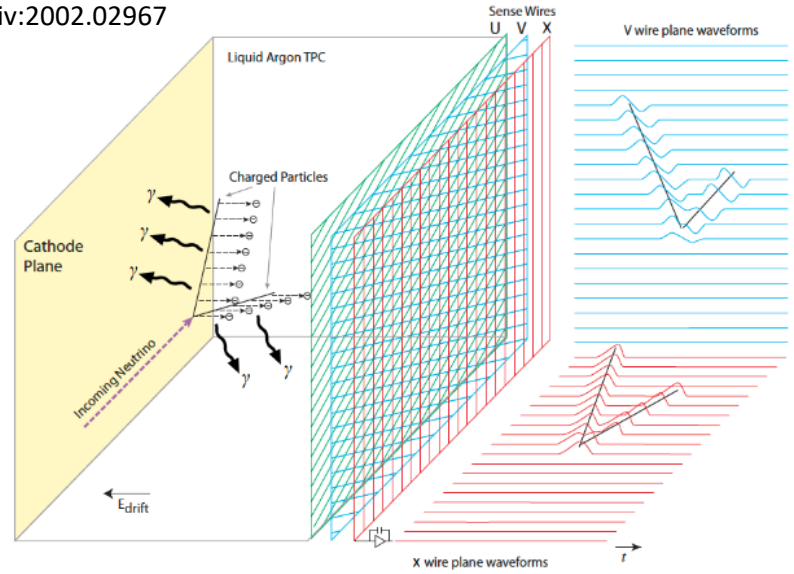
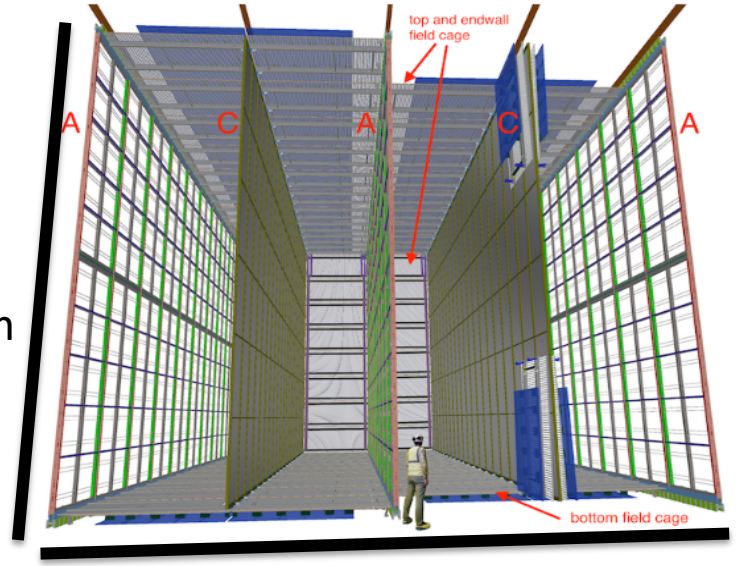
DUNE FD Single Phase (SP)

Single Phase Detector Details:

arXiv:2002.02967





”Drift” Action

Far-Detector Module Details:

- 3.6 m drift @ 500 V/cm
  - Implies 180 kV Field Total
- Modular Electric Field Cage
  - 600 Cathode Plane Assemblies (CPAs)
  - 150 Anode Plane Assemblies (APAs)
- Photon Detectors embedded in APAs

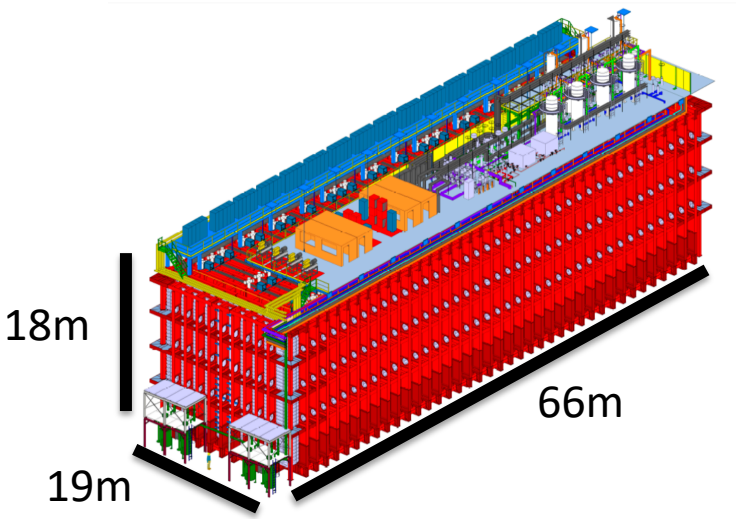
Photon Detection System:

- Photon Detectors embedded in unused APA space
  - Each APA has 10 Photon Detectors
- 1500 total detectors per SP module
- Primary detector will be X-ARAPUCA

Liquid Argon purity is very important!

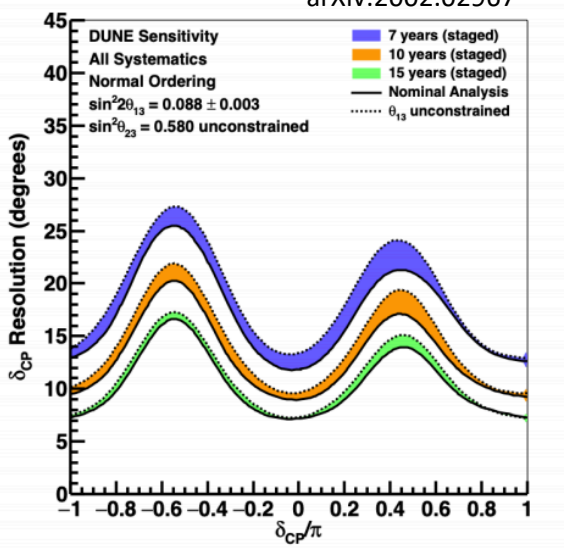
Projected Oscillations Sensitivities

Required operation for physics.



Detector Parameter	DUNE Specification
Average E-Field	250 V/cm (Minimum) 500 V/cm (Nominal)
LAr e^- Lifetime	> 3 ms
TPC+CE Noise Signal-to-Noise <SNR>	< 1000 e^- ENC
CE Dead Channels	< 1%
PDS Light Yield	> 0.5 Photons/MeV @ 3.6 m (Minimum)
PDS Time Resolution	< 100 ns

arXiv:2002.02967



Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{CP} = -\pi/2$)	1
5σ mass ordering (100% of δ_{CP} values)	2
3σ CPV ($\delta_{CP} = -\pi/2$)	3
3σ CPV (50% of δ_{CP} values)	5
5σ CPV ($\delta_{CP} = -\pi/2$)	7
5σ CPV (50% of δ_{CP} values)	10
3σ CPV (75% of δ_{CP} values)	13
δ_{CP} resolution of 10 degrees ($\delta_{CP} = 0$)	8
δ_{CP} resolution of 20 degrees ($\delta_{CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ resolution of 0.004	15

FD Photon Detection System: Uncertainties in LAr

Uncertainty in the scintillation medium!

A well functioning PDS system provides many benefits to the DUNE mission:

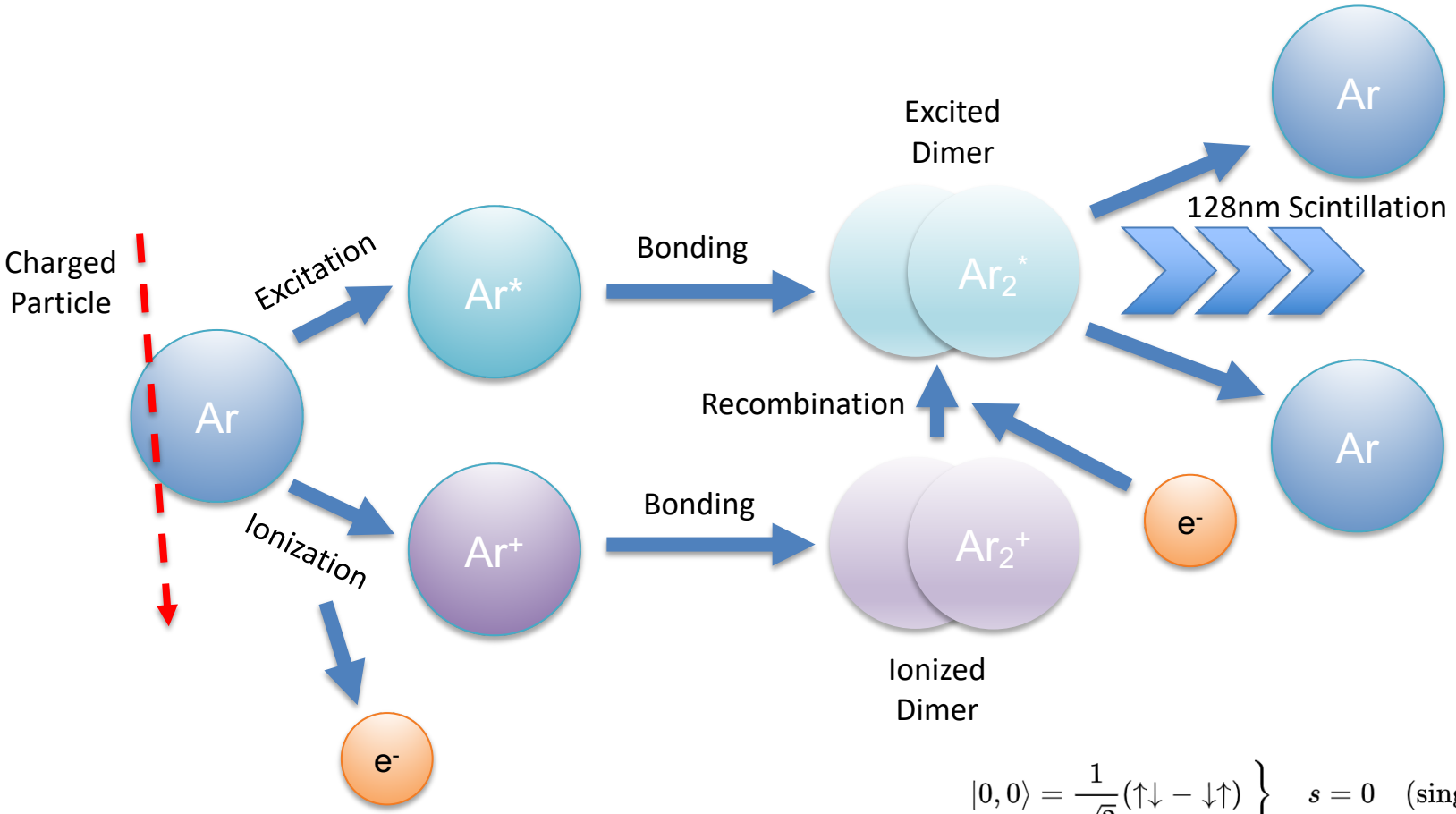
- Detector wide timing resolution improves by a factor of 1000!
- ~50% of interaction energy produces scintillation light, additional handle on reconstruction systematics
- Necessary for “t0” on proton decay and supernova burst events.

…but propagation of Vacuum UV Light in the medium is not well understood!

Precision understanding of scintillation and scattering in Liquid Argon medium is very beneficial to the DUNE mission!

Light Propagation in LAr

Light Scintillation Mechanism.



Dimers can form with *aligned* or *anti-aligned* spins

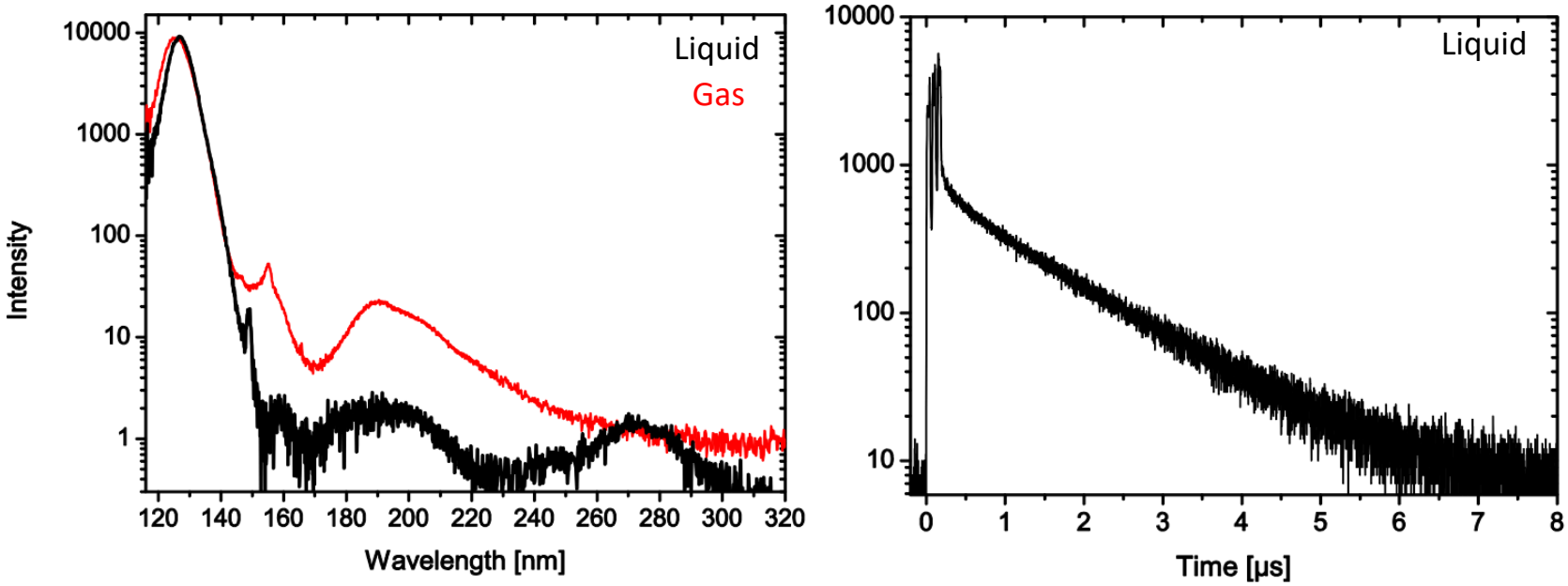
$$|0,0\rangle = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow) \quad s = 0 \quad \text{(singlet)}$$

$$\left.\begin{aligned} |1,1\rangle &= \uparrow\uparrow \\ |1,0\rangle &= \tfrac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow) \\ |1,-1\rangle &= \downarrow\downarrow \end{aligned}\right\} \quad s = 1 \quad \text{(triplet)}$$

Light Propagation in LAr

Light Scintillation Properties.

(Heindl et al., EPL 91 62002, 2010)

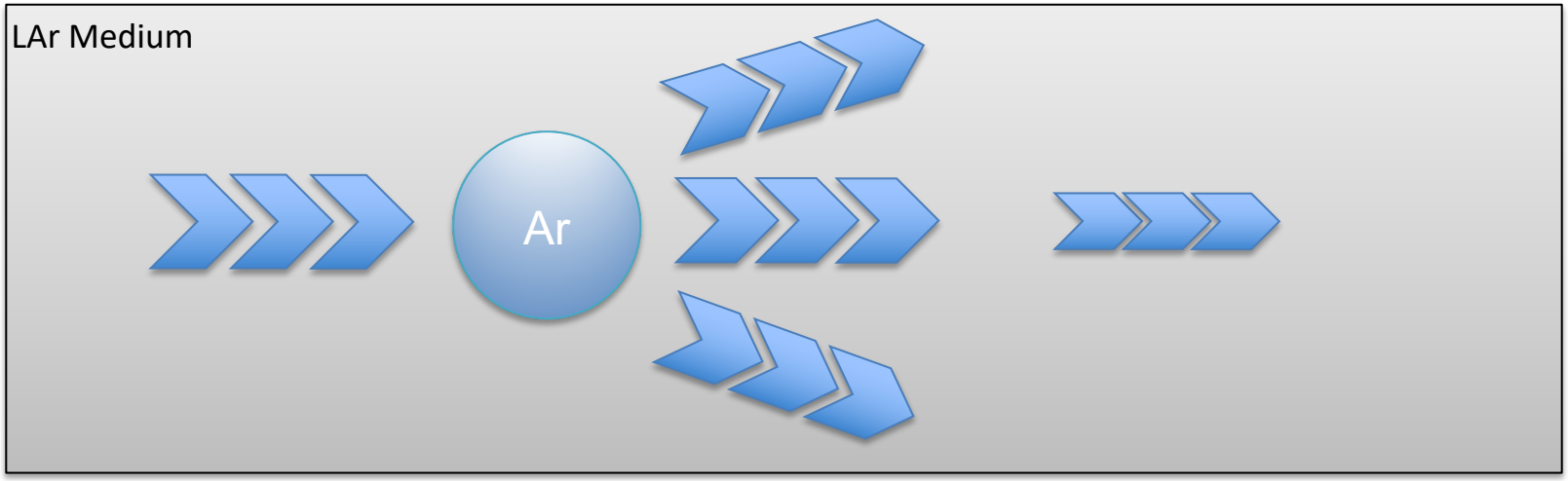


Light Production

- Majority of scintillated light produced at 128 nm through short-lived excimer (excited dimer)
- Scintillation time constants depend on excimer decay from singlet (6 ns) or triplet (1.6 us) states
- Generated light is isotropic and unpolarized
- About 40,000 photons/MeV, 26,000 photons/MeV in nominal field

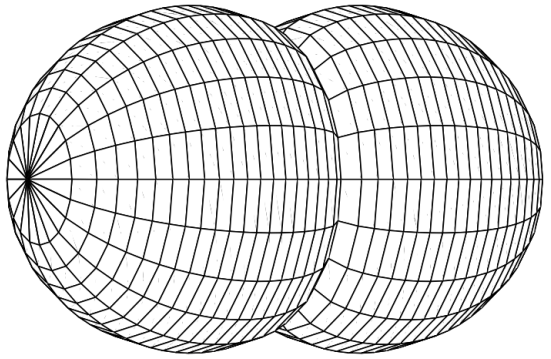
Light Propagation in LAr

Propagation and Scattering of scintillation light!



VUV light also undergoes Rayleigh scattering in the medium

$$I = \frac{I_0}{r^2}\alpha^2\left(\frac{2\pi}{\lambda}\right)^4\frac{1+\cos^2\Theta}{2} \rightarrow I = I_0 e^{-\frac{x}{\Lambda}}$$



(Liou, 2002)

Tension in measurements and calculation

- Ishida et al (1997) report 66 cm with 5% uncertainty.
- Calvo et al (ArDM Collaboration) (2016) report 52 cm with 13.5% uncertainty.
- Seidel et al (2002) calculate 90 cm.
- Babicz et al (2020) measure 99.9 with 1% uncertainty.

DUNE FD SP Prototype—What is ProtoDUNE-SP?

The ProtoDUNE project is two full scale prototypes of different DUNE FD Modules with proton beam from the CERN SPS. The first, ProtoDUNE-SP is based on the SP Module design with full scale parts.

ProtoDUNE-SP consists of:

- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Photon Detection System (PDS)
- Cosmic-Ray Tagger (CRT)

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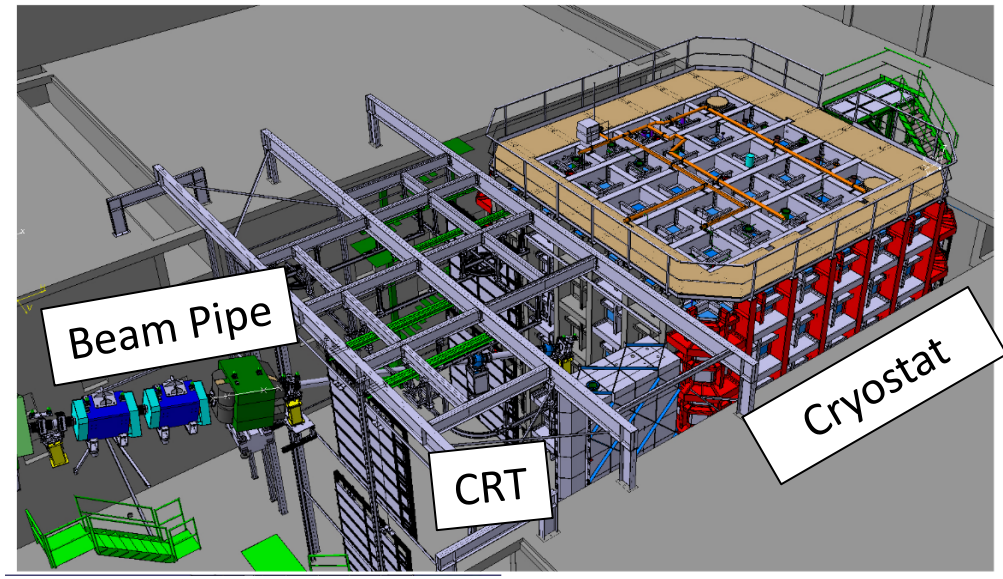

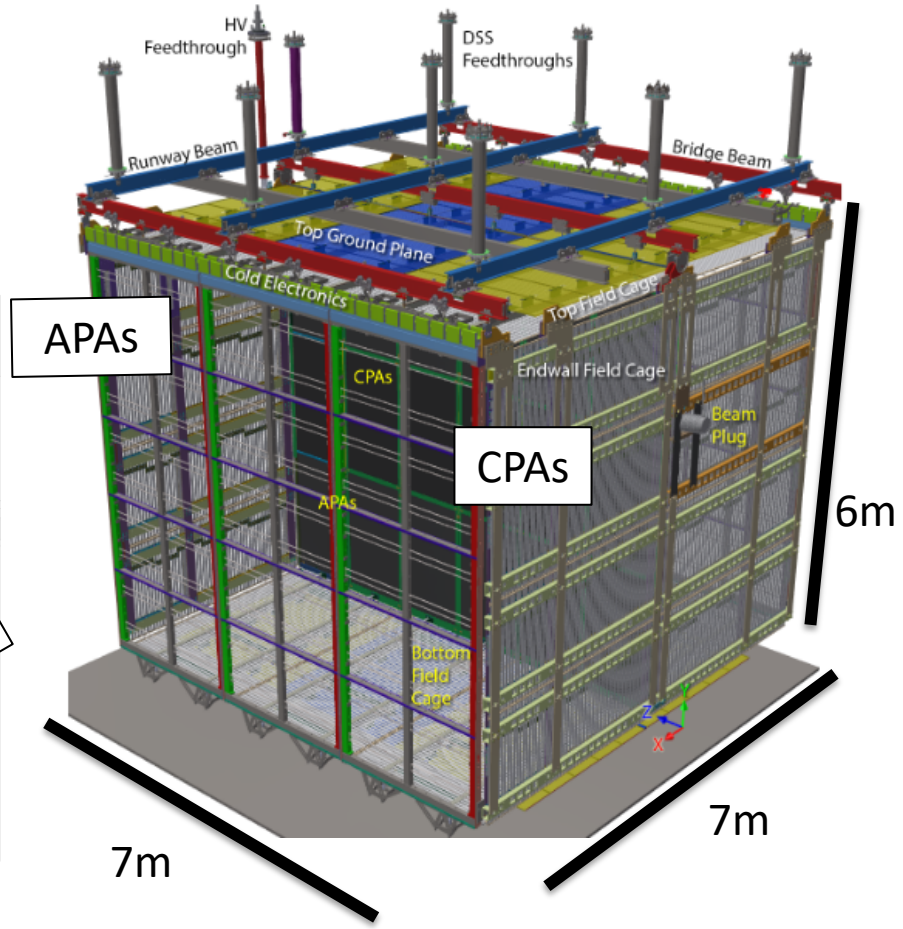

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DUNE FD SP Prototype—Tertiary CERN SPS Beam

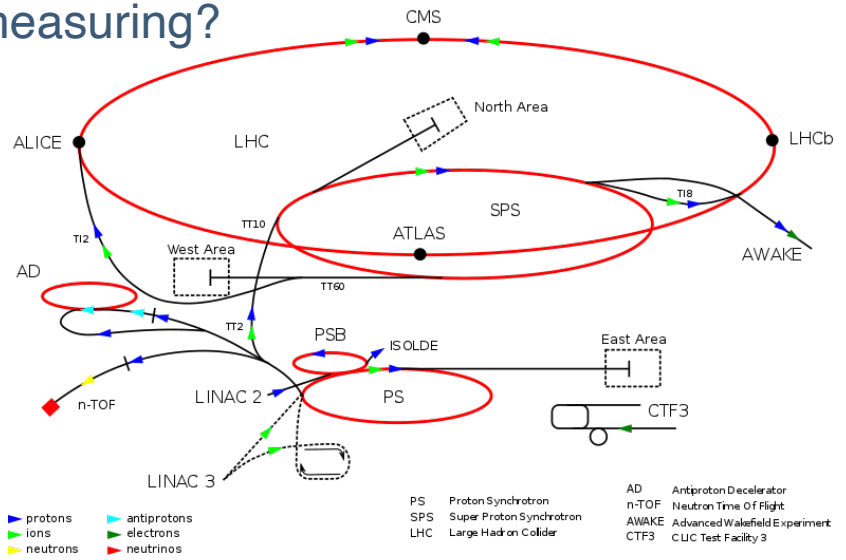
How do we know what particles we're measuring?

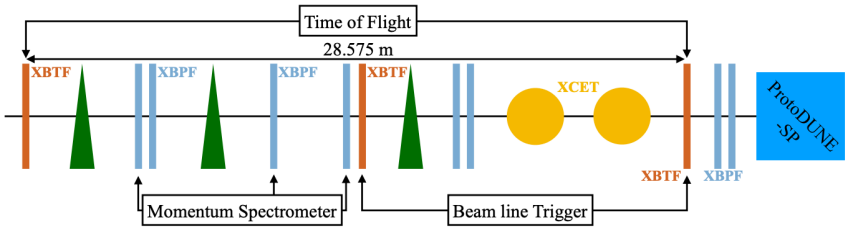
ProtoDUNE-SP consists of:

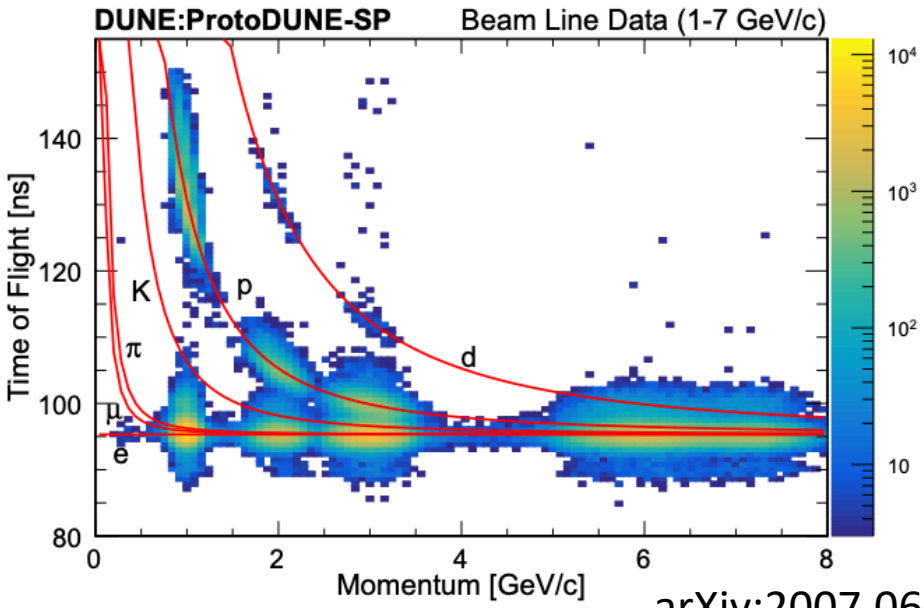
- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)

CERN SPS Beam:

- Protons from 400 GeV CERN SPS
- Incident on Beryllium Target
- Secondary Beam is 80 GeV
- Incident on secondary target
- 0.3-7 GeV H4-VLE Beam







arXiv:2007.06722

Fermilab DUNE

DUNE FD SP Prototype—Single Phase LArTPC

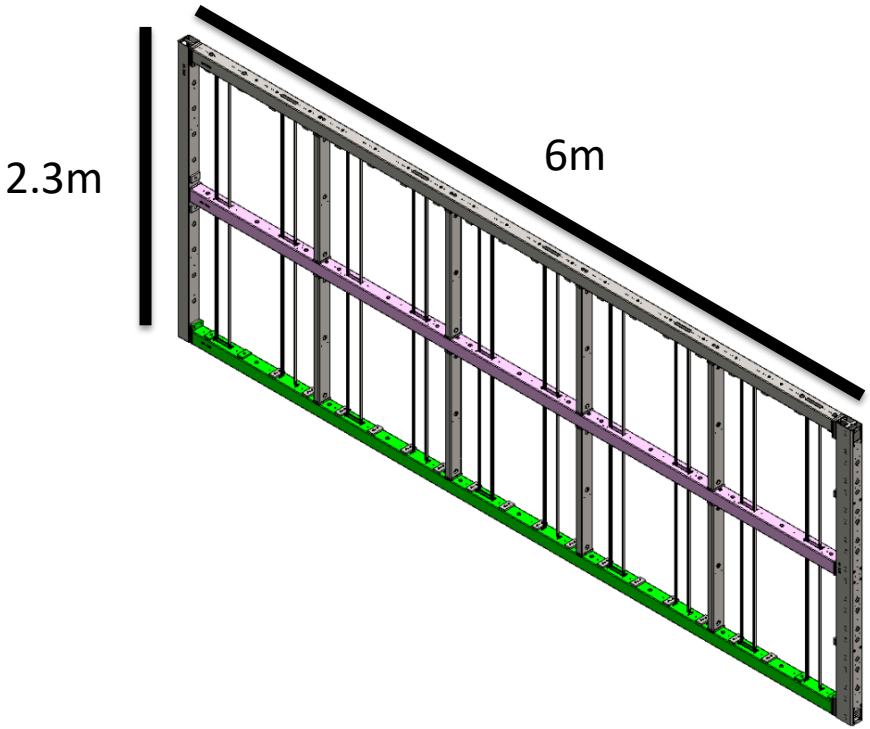
How are we providing a uniform electric field?

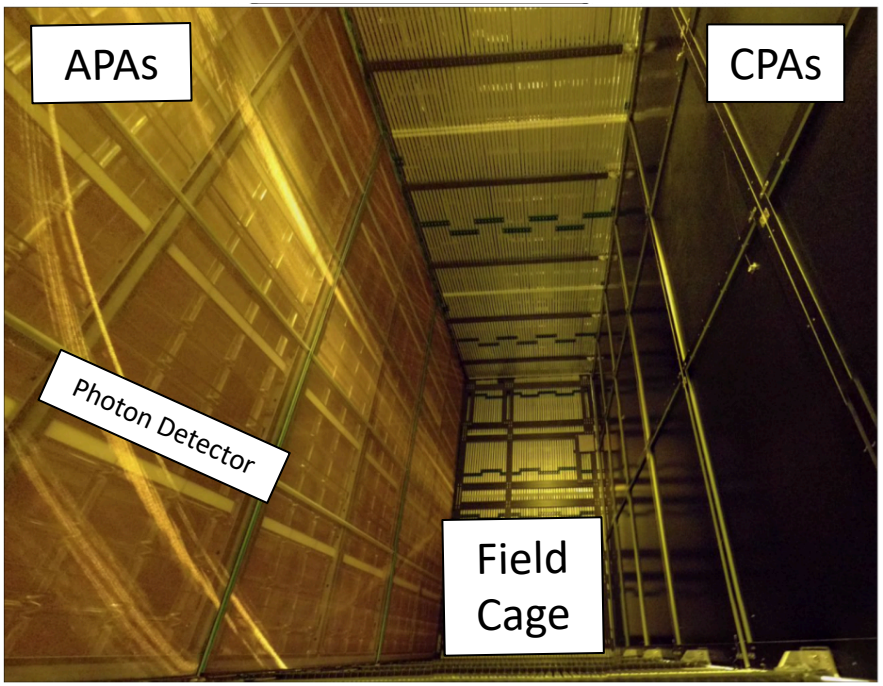
ProtoDUNE-SP consists of:

- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)

Single Phase LArTPC

- Consists of DUNE FD SP Module Design
- 6 APAs and 18 CPAs
- Dual 3.6m Drift Volumes
- 500 V/cm, 180 kV per volume (WR)





Fermilab DUNE

DUNE FD SP Prototype—Single Phase LArTPC

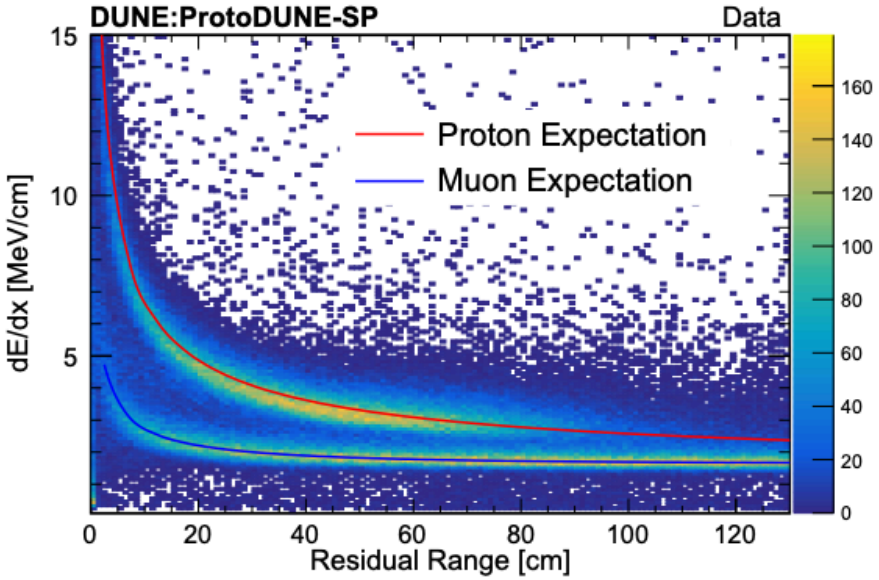
Can we reconstruct particles?

ProtoDUNE-SP consists of:

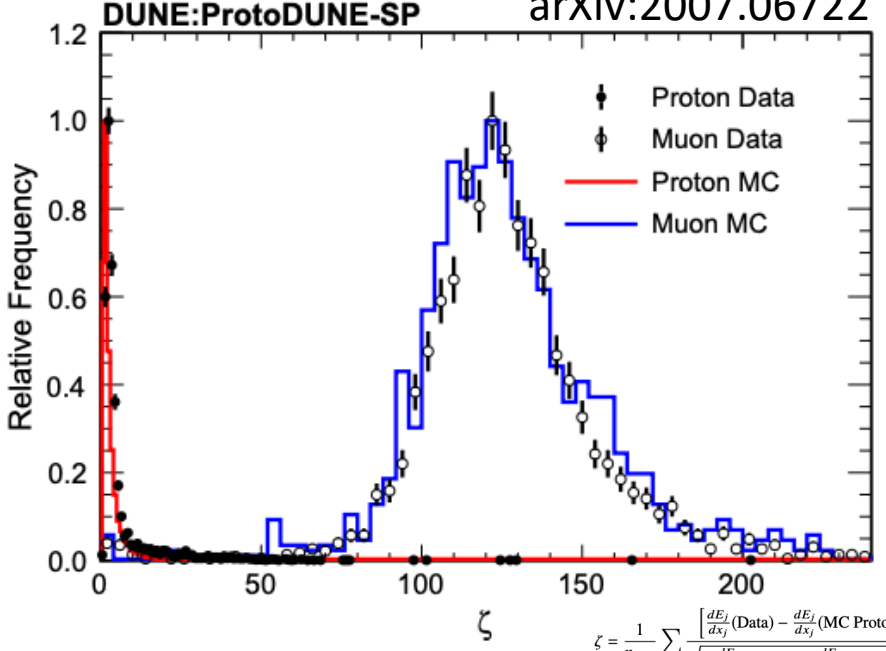
- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)

Single Phase LArTPC

- ~10.5ms average electron lifetime
  - (as high as 89 ms)
- Pandora used for particle and event reconstruction
- 0.5 microsecond resolution



arXiv:2007.06722



$$\zeta = \frac{1}{n_{\mathrm{DoF}}} \sum_j \frac{\left[\frac{dE_j}{dx_j}(\mathrm{Data}) - \frac{dE_j}{dx_j}(\mathrm{MC\ Proton})\right]^2}{\sqrt{\delta^2 \frac{dE_j}{dx_j}(\mathrm{Data}) + \delta^2 \frac{dE_j}{dx_j}(\mathrm{MC\ Proton})}},$$

Effective demonstration of particle ID through energy loss!

Fermilab DUNE

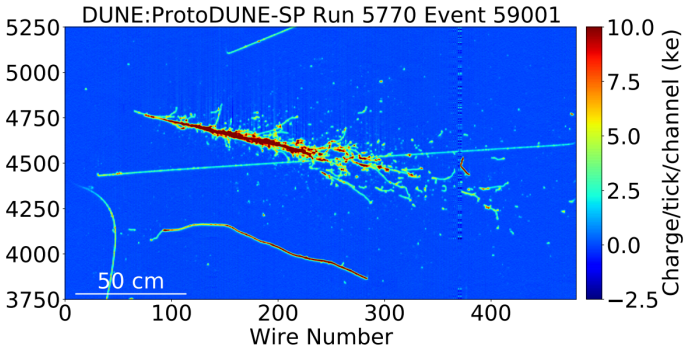
DUNE FD SP Prototype—Single Phase LArTPC

Can we reconstruct particles and events?

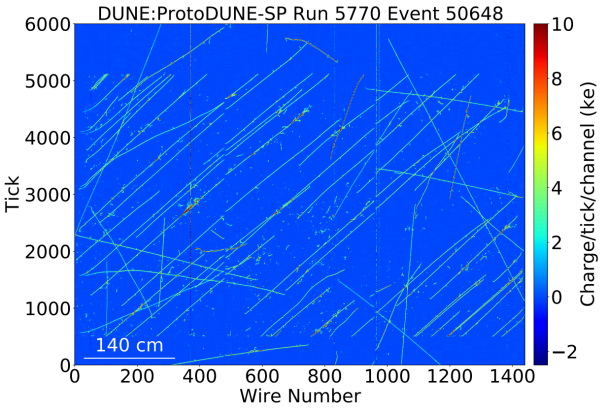
ProtoDUNE-SP consists of:

- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)

6 GeV Electron Candidate



Cosmic Ray Muon Shower

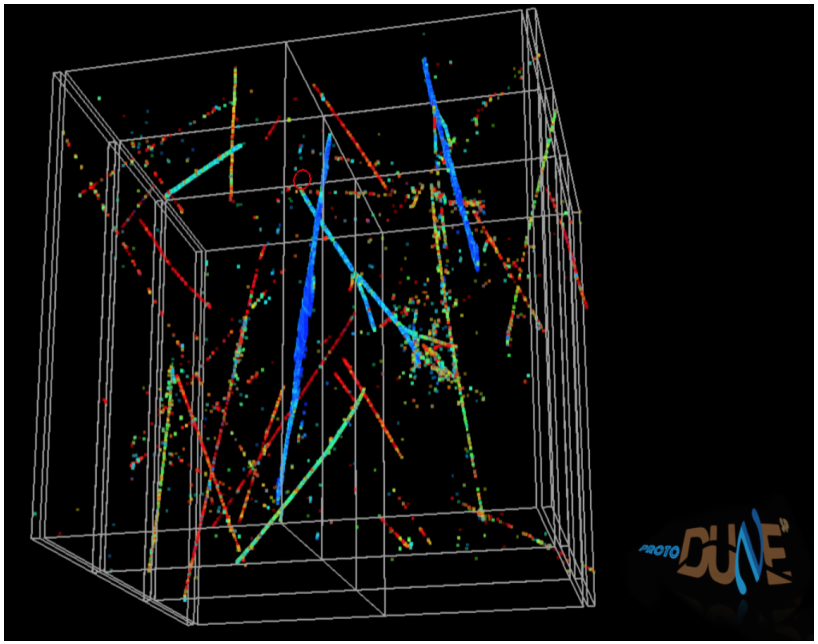


Color Corresponds to Charge Deposited

Single Phase LArTPC

- ~10.5ms average electron lifetime
  - (as high as 89 ms)
- Pandora used for particle and event reconstruction
- 0.5 microsecond resolution

3D Reconstruction



Color Corresponds to Timing of Track

arXiv:2007.06722

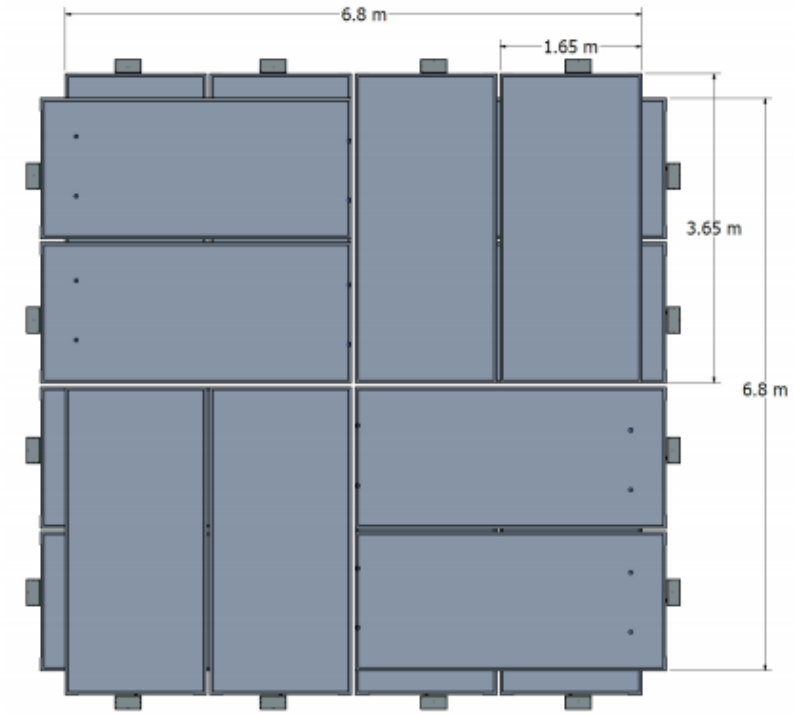
Fermilab DUNE

DUNE FD SP Prototype—Tagging Cosmic-Rays!

Additional Triggers?

ProtoDUNE-SP consists of:

- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)



arXiv:2007.06722

Cosmic Ray Tagger

- 32 modules
  - 64-5 cm x 365 cm strips per module
- 20 ns resolution
  - 60 ns trigger coincidence
- 10m upstream stagger

Fermilab DUNE

DUNE FD SP Prototype—Tagging Cosmic-Rays!

Triggering coincidences?

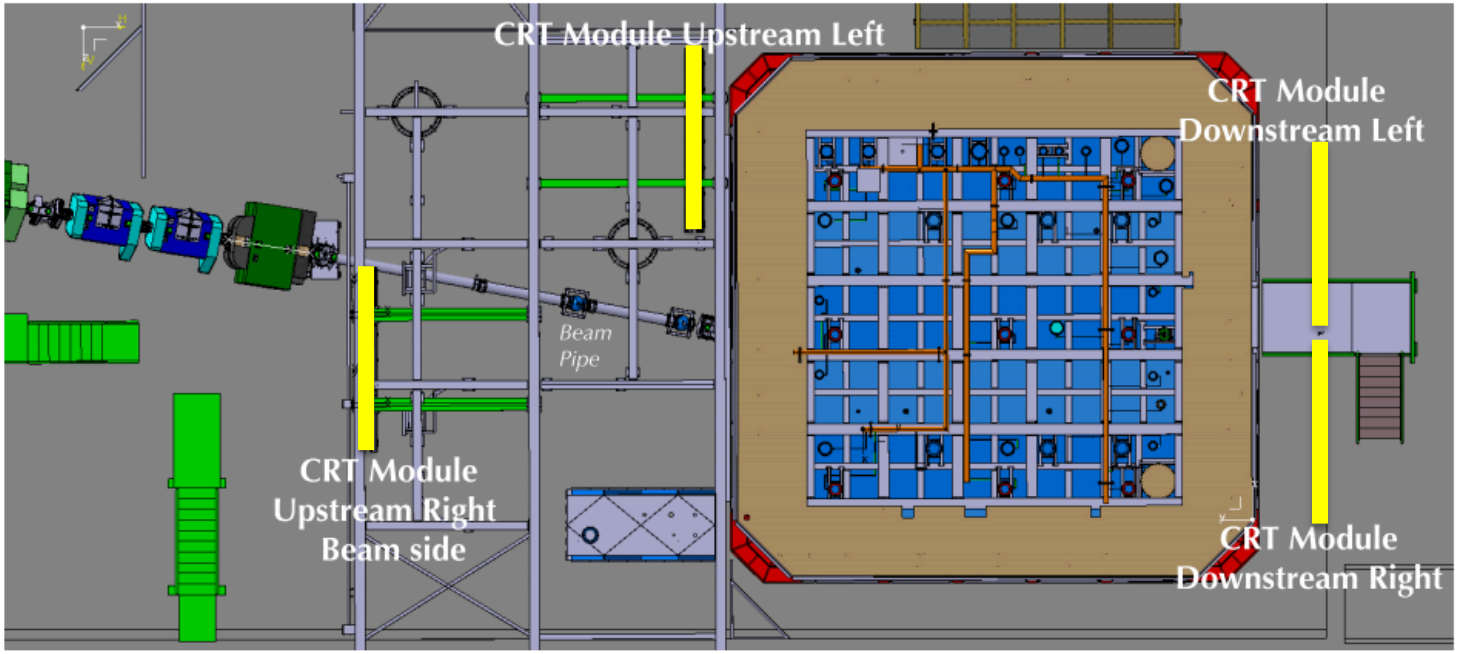
ProtoDUNE-SP consists of:

- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)

Cosmic Ray Tagger

- 32 modules
  - 64-5 cm x 365 cm strips per module
- 20 ns resolution
  - 60 ns trigger coincidence
- 10m upstream stagger

Interesting effects on trigger acceptance! arXiv:2007.06722

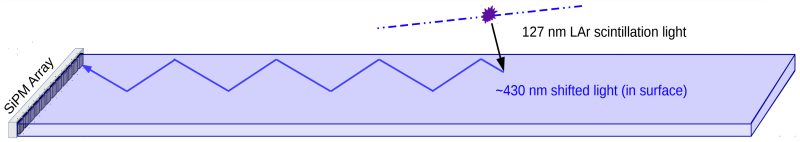


DUNE FD SP Prototype—Photon Detection System

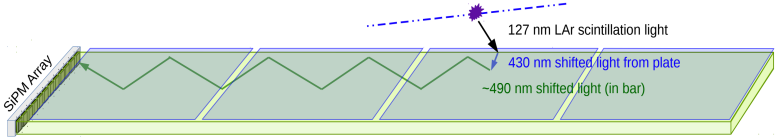
Testing new technologies!

ProtoDUNE-SP consists of:

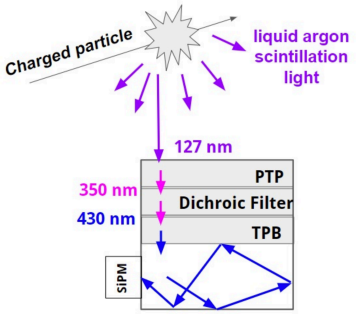
- Tertiary CERN SPS Beam
- Single-Phase LArTPC
- Cosmic-Ray Tagger (CRT)
- Photon Detection System (PDS)



”Dip-Coated” (DC) Type Collector × 29



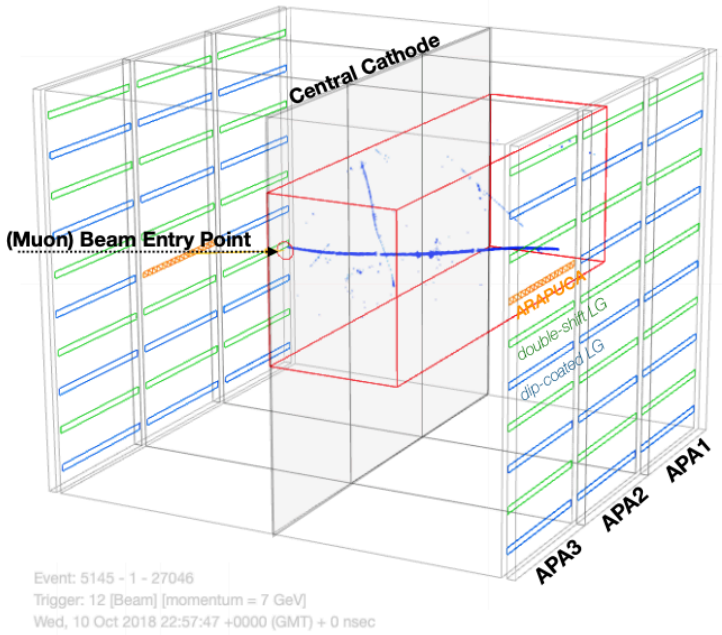
”Double-Shifted” (DS) Type Collector × 29



ARAPUCA Concept

Photon Detection System

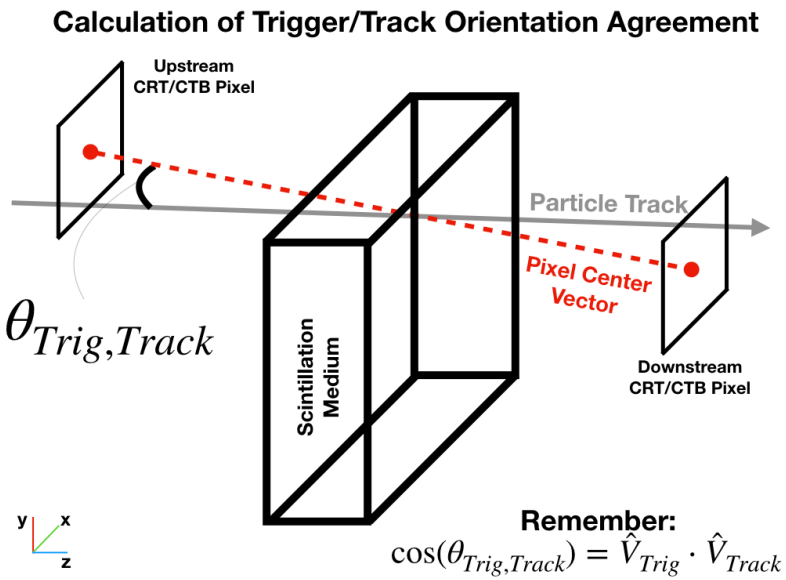
- Photon Detector Technology Demonstration
  - 60 Photon Detectors
  - 3 Photon Collector Technologies
    - 29 Dip Coated Light Guide Detectors
    - 29 Double Shift Light Guide Detectors
    - **2 S-ARAPUCAs**
  - 2 Photon Sensors Manufactures
    - SensL & Hamamatsu



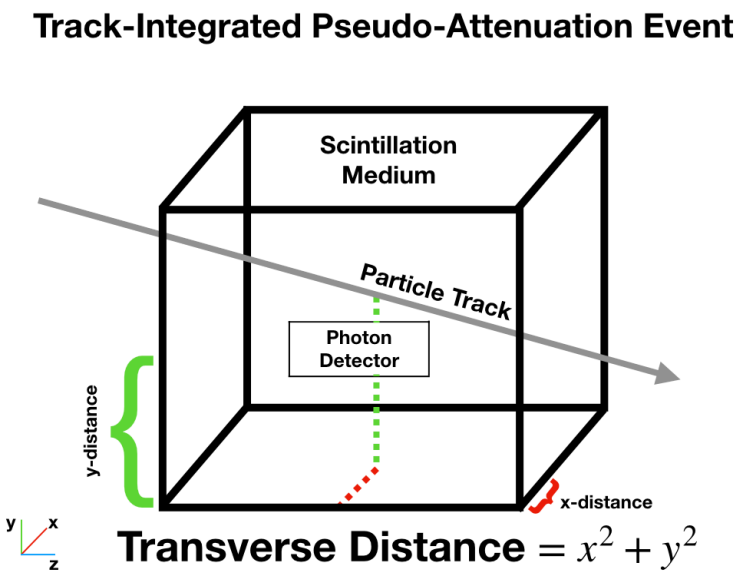
Probing Attenuation in ProtoDUNE-SP

Coordinating all three ProtoDUNE-SP subsystems!

Steps 1 & 2

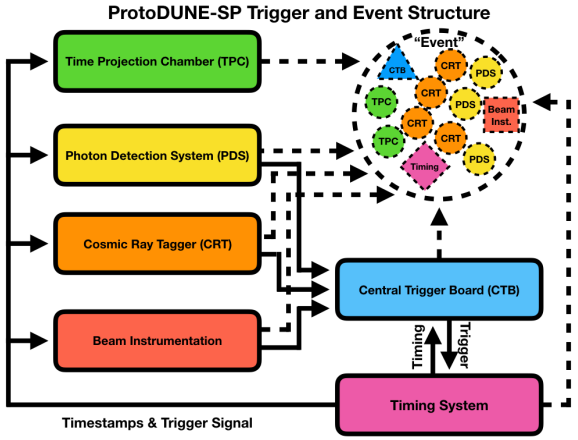


Steps 3 & 4



Cosmic Ray Collection Scheme

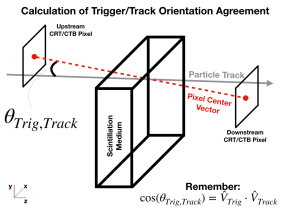
1. Look for throughgoing muons with 60 ns coincidences through the CRT.
2. Use reconstructed track vector agreement through pixels centers to confirm trigger.
3. Use reconstructed light to examine attenuation in the medium.
4. Compare to simulation.



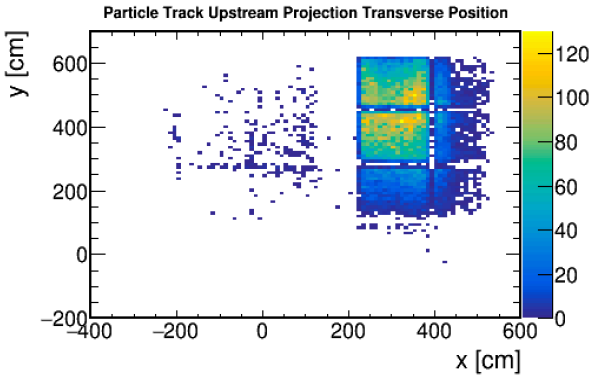
Fermilab DUNE

Probing Attenuation in ProtoDUNE-SP

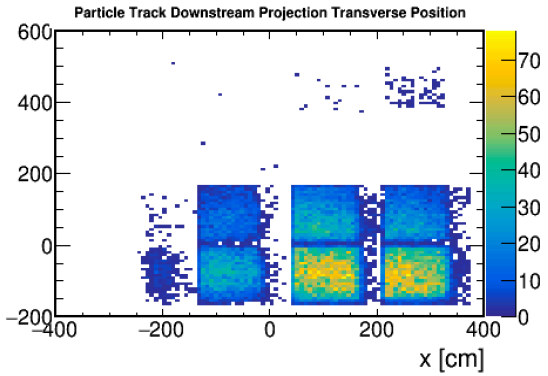
Collected triggers



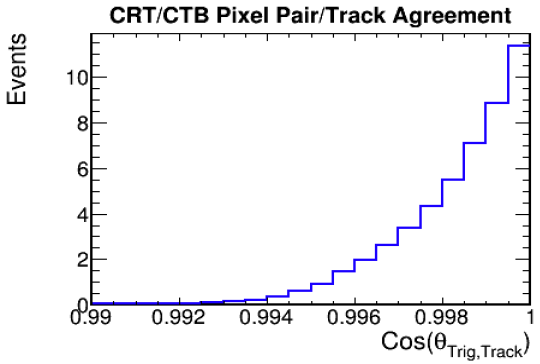
Upstream



Downstream



Pixel/Track agreement impossible beyond 7.5 degrees or $\cos(\theta) > .991$

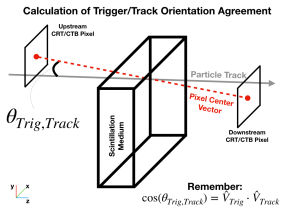


Track Collection

- 1.13 million candidate events from cosmic data period of November 2018 to February 2019
- 10m beam right offset for CRT makes trigger incompatible with throughgoing particles on that side
- About 43 thousand events with proper agreement and light signals!

Probing Attenuation in ProtoDUNE-SP

Collected triggers



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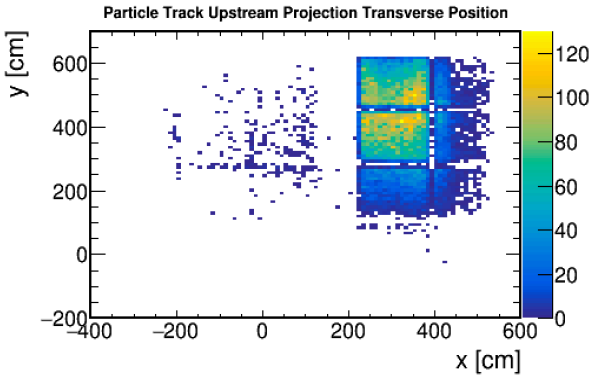
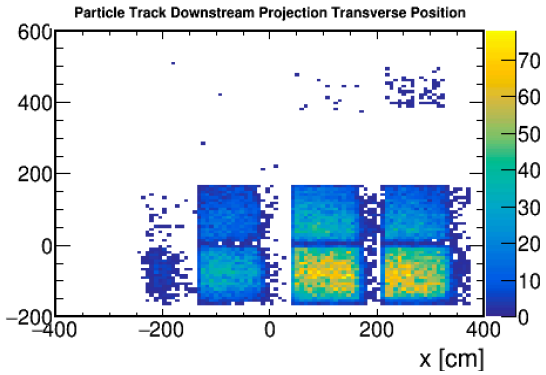
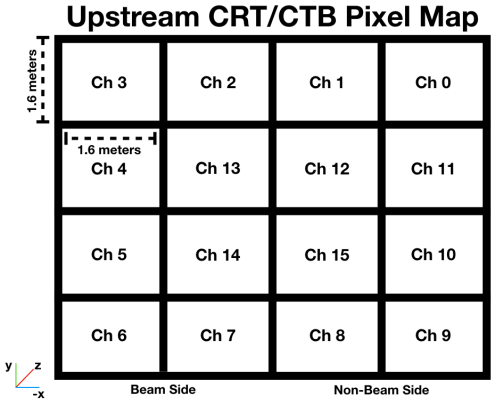
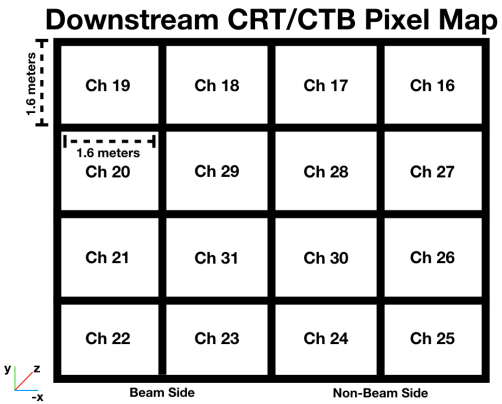


Downstream







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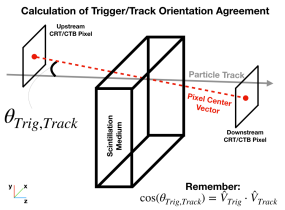
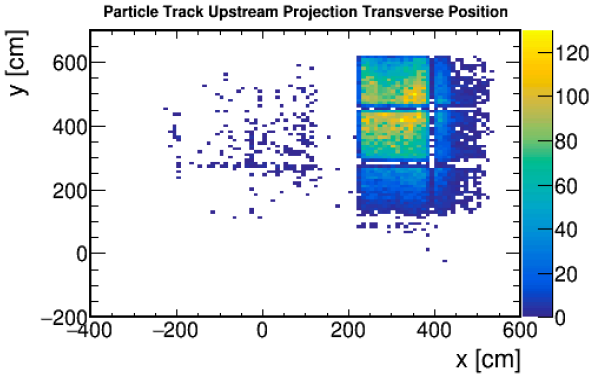
Probing Attenuation in ProtoDUNE-SP

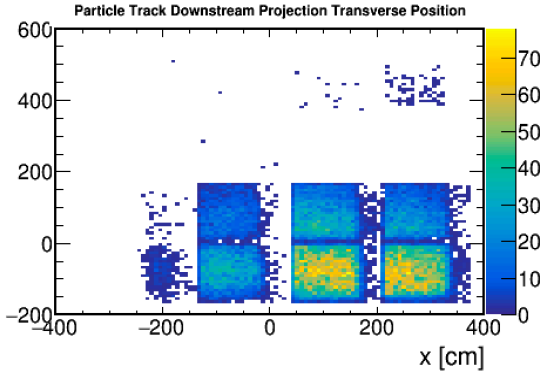
Collected triggers

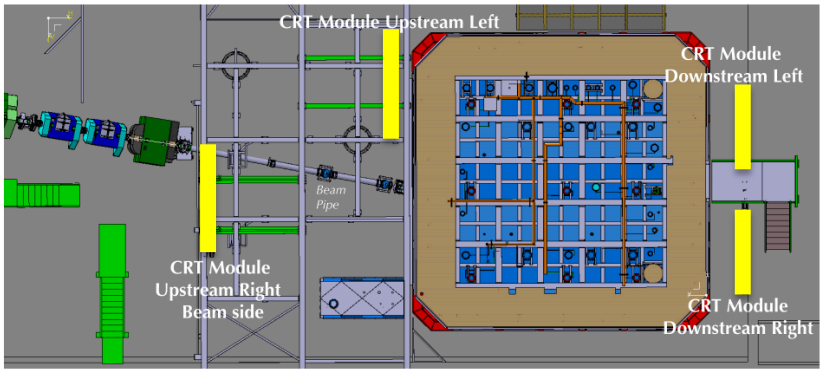


Upstream



Downstream





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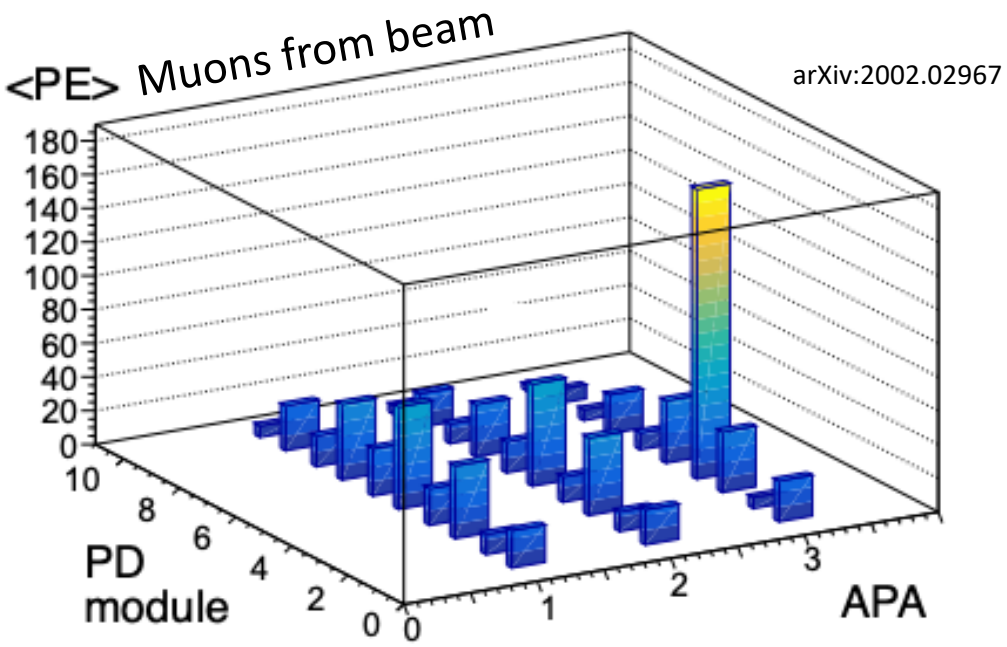
Probing Attenuation in ProtoDUNE-SP

Analysis of collected photons.

*Efficiency analysis derived from beam data and simulation

Nº of PDS elements examined	Detector Type	Efficiency
8	ARAPUCA cell	$\tilde{\epsilon}_A = (2.00 \pm 0.25)$ %
4	ARAPUCA cell (double area)	$\tilde{\epsilon}_{A2} = (1.06 \pm 0.09)$ %
10	Double-shift module	$\tilde{\epsilon}_{DS} = (0.21 \pm 0.03)$ %
9	Dip-coated module	$\tilde{\epsilon}_{DC} = (0.08 \pm 0.02)$ %

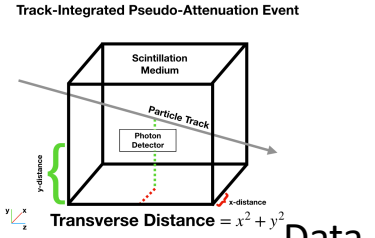


arXiv:2002.02967

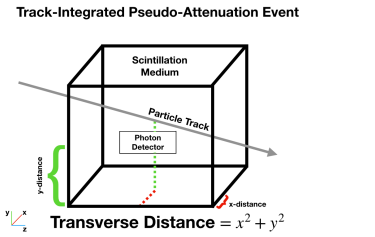
S-ARAPUCA between 5 and 10 times more efficient than competing technologies and in central location on non-beam side.

Probing Attenuation in ProtoDUNE-SP

Analysis of collected photons.



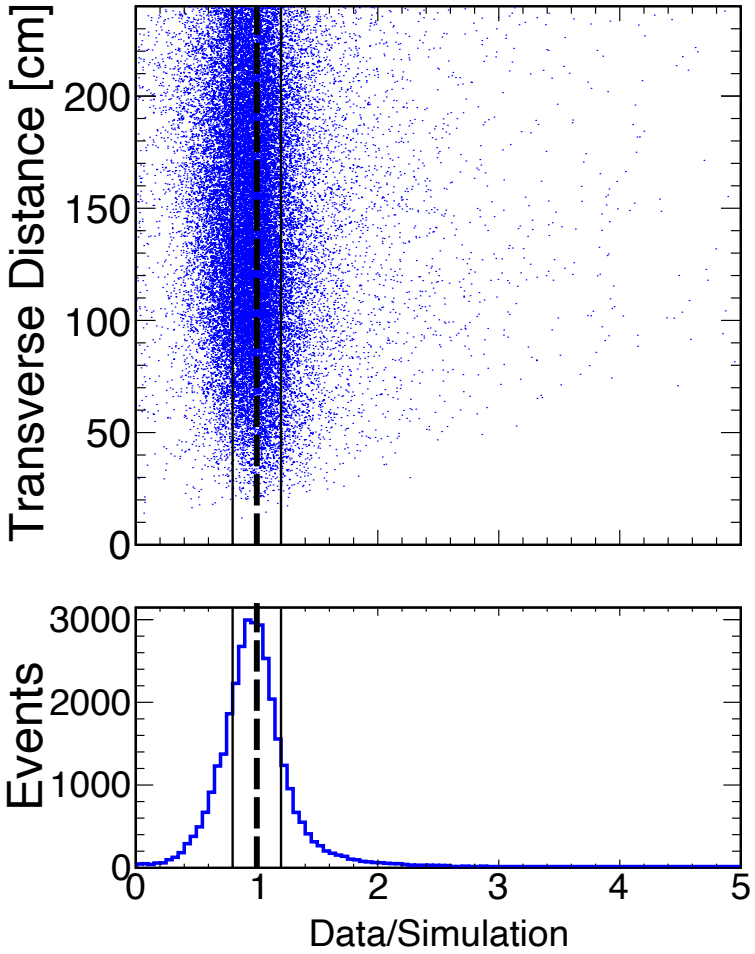
Data_i



Simulation_i

=

arXiv:2007.06722



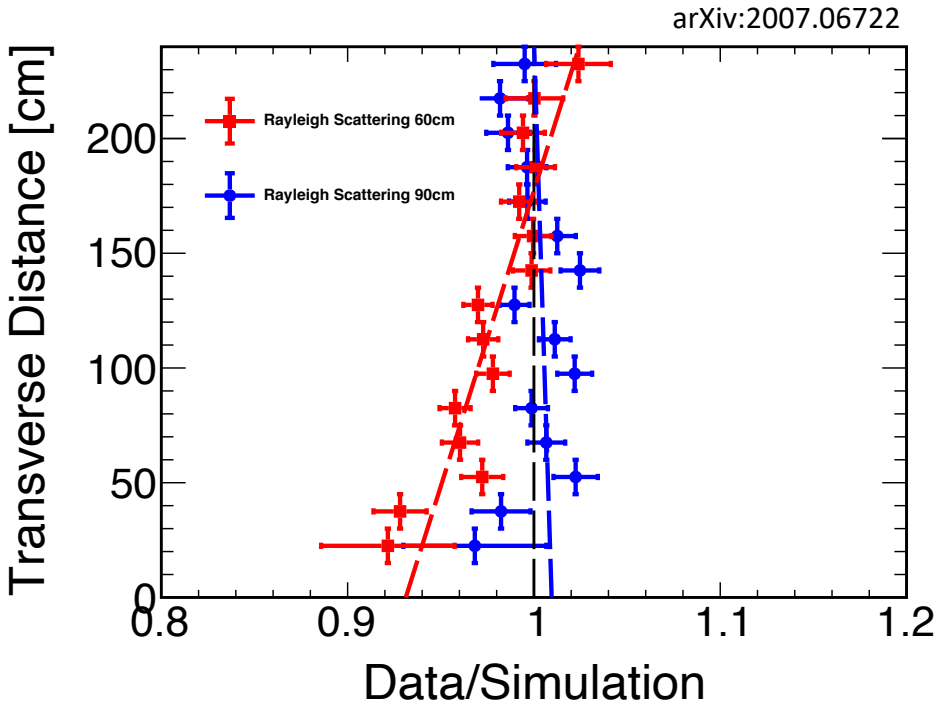
1σ agreement at 18.6% with Rayleigh Scattering at 90 cm

Data-driven simulation using radial distance measurement from beam left S-ARAPUCA agrees with data after normalization!

Fermilab DUNE

Probing Attenuation in ProtoDUNE-SP

Choosing Rayleigh scattering length for simulation.



Difference between two comparisons show about 5% on average *but grows exponentially with distance*

Using same data driven simulation method at 90 cm and 60 cm Rayleigh scattering, *data prefer 90 cm <u>regardless of normalization</u>!*

Summary & Conclusions

ProtoDUNE-SP is a successful fully operational prototype of a DUNE FD SP Module

Design goals for single phase detector achieved!

Detector Parameter	DUNE Specification	ProtoDUNE Operation
Average E-Field	250 V/cm (Minimum) 500 V/cm (Nominal)	500 V/cm (Everywhere)
LAr e^- Lifetime	> 3 ms	10.5 ms (Average) >89 ms (Maximum)
TPC+CE Noise Signal-to-Noise <SNR>	< 1000 e^- ENC	(C) 550 e, (I) 650 e ENC (C) 48.7, (I) 21.2 (w/CNR)
CE Dead Channels	< 1%	0.2%
PDS Light Yield	> 0.5 Photons/MeV @ 3.6 m	1.9 Photons/MeV @ 3.3 m
PDS Time Resolution	< 100 ns	< 14 ns

Using all three subsystems, a measurement of attenuation of light in the medium was attempted, data prefer 90 cm Rayleigh Scattering length.

Current Work

Improvements on the light system

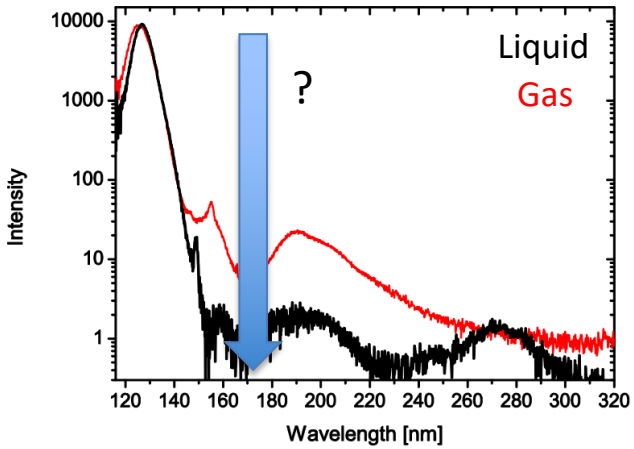
ProtoDUNE-SP has been contaminated and doped!

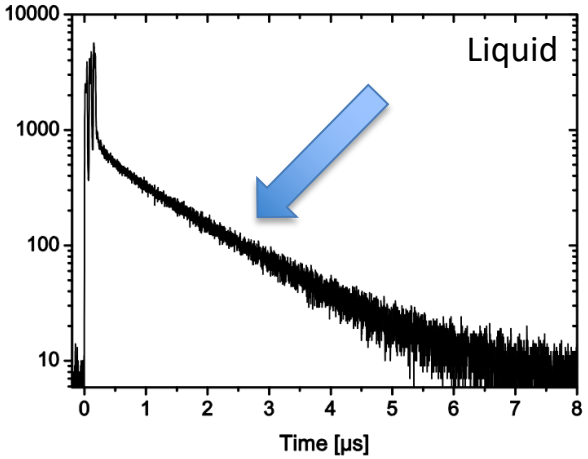
Air (Nitrogen & Oxygen) quenches light, but the addition of ~ppm liquid Xenon *may* recover it!

$$I = \frac{I_0}{r^2}\alpha^2\left(\frac{2\pi}{\lambda}\right)^4\frac{1+\cos^2\Theta}{2}$$

Xenon also scatters less (I_{Xe}/I_{Ar} ~ .29)

(Heindl et al., EPL 91 62002, 2010)





Improvement of light production and collection through Xenon?