Double calorimetry in the DUNE Far Detectors

Giulia Brunetti
29/10/2024

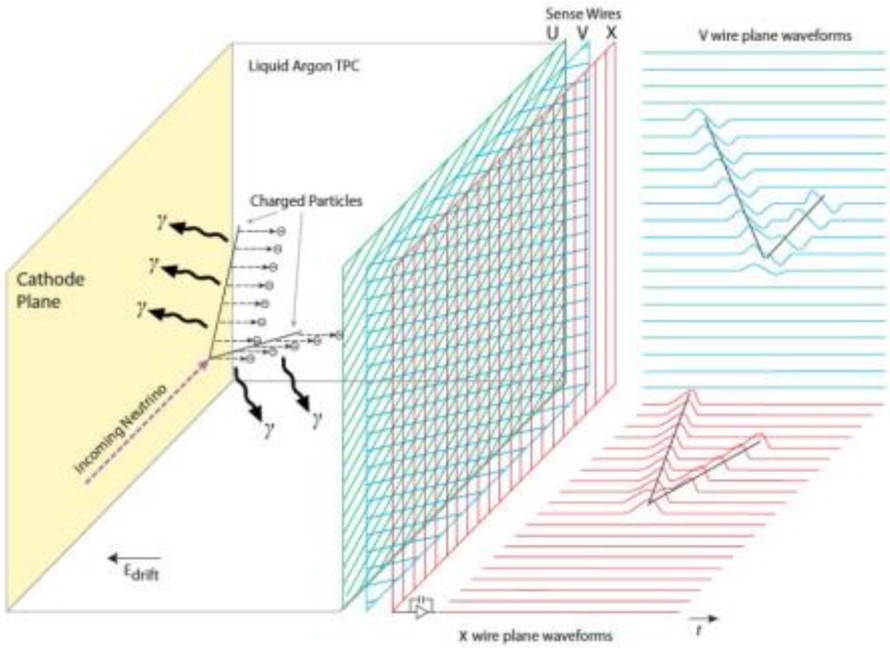
Liquid Argon TPC

Two observables generated from **energy deposition by particles in liquid Argon**:

- **CHARGE** → Ionization electrons, drift to the anode: precise imaging
- **LIGHT** → VUV scintillation photons (λ=128nm): precise event timing

→ Two independent readout systems:

- Anodic charge readout
    - → FD-HD: wire charge readout
    - → FD-VD: PCB charge readout
- Photo Detection System (PDS)
    - → X-ARAPUCA Concept

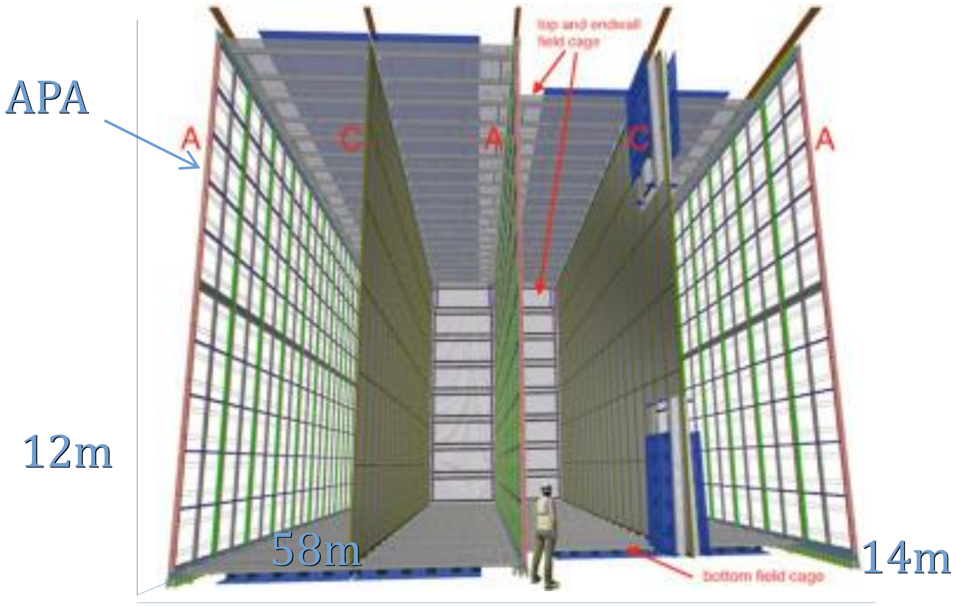


Double Calorimetry: Charge+Light

- The key strength of DUNE is the ability to measure the oscillation patterns of neutrinos over a range of energies spanning the first and second oscillation maxima: coordinated analysis of the reconstructed ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ energy spectra in near and far detectors
- **Energy resolution directly impacts DUNE sensitivity to CPV and Mass Ordering**

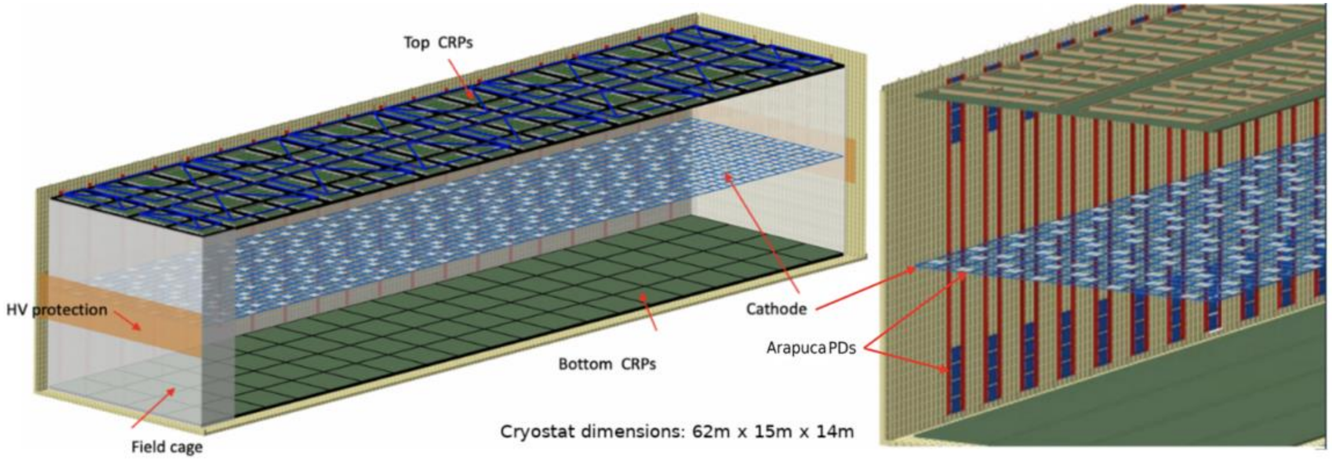
FD1

- **Four 3.2 m Horizontal Drift regions**: alternated Anode and Cathode Plane Assemblies
- **Charge readout with wires** in Anode Planes Assembly (150 APA, 6x2.3m)
- E_{field} = 500 V/cm
- **PDS**: 10 modules for APA = in total 1500 modules in FD-1, 4 channels per module. 1 Module 2092x118x23 mm^3 = 4 supercells 488x100x8 mm^3



FD2

- **Two 6 m Vertical Drift regions**
- **Charge readout with PCB planes** (160 CRPs, 3x3.4m)
- E_{field} = 450 V/cm , 300 kV on Cathode
- **PDS** modules mounted on the cathode and on the cryostat walls:
  - Square geometry: dimension 65x65 cm^2
  - A single large WLS light guide plane
  - Light readout by 160 SiPMs mounted on flexible strips
- **Xenon doped LAr**



The Photo-detection System
LAr VUV Light detection

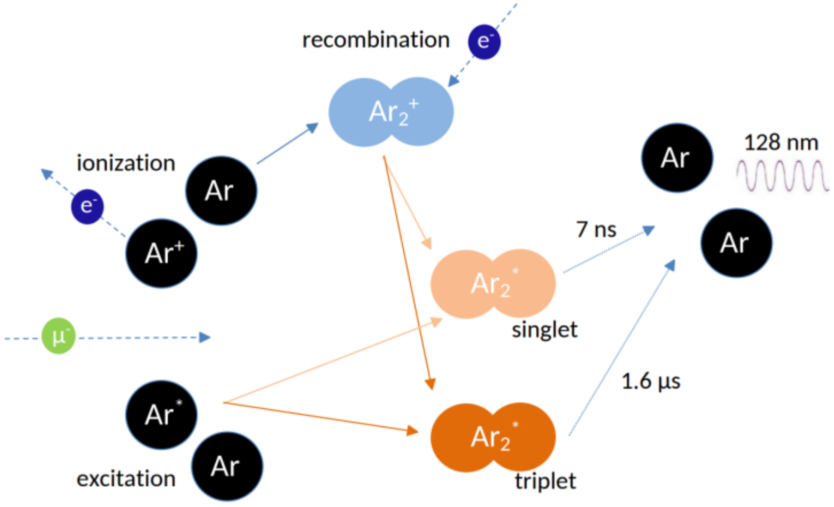
Scintillation light is:

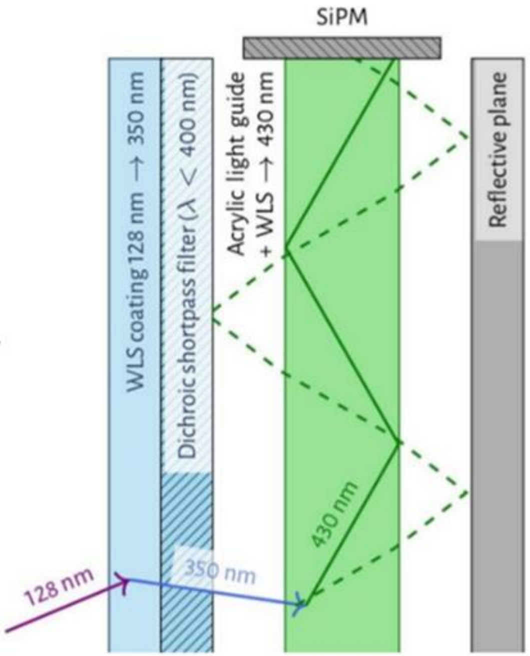
- **Abudant**: 25k photons/MeV @ 500V/cm → combined with charge signal improves calorimetry
- **Fast:** fast component τ=7 ns → provides event t_0, crucial for triggering non-beam events

Detection of Light in a DUNE TPC: **X-ARAPUCA**

The core of the device is the **dichroic filter**: a multilayer interference film highly transparent for wavelength below a cutoff and highly reflective above it

- VUV photons converted to longer wavelength (WLS)
- Visible light is trapped inside a module, a fraction is conveyed to Photomultipliers (SiPM)





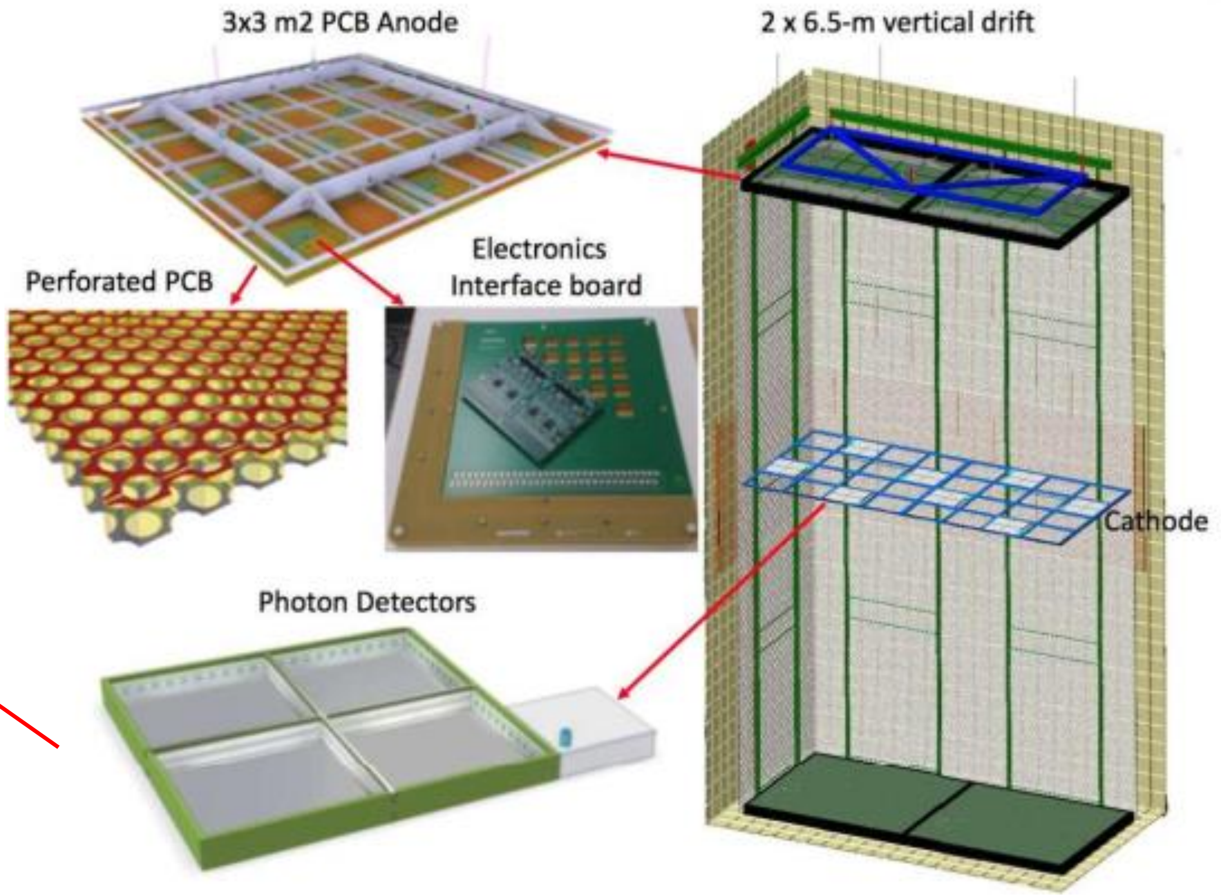
Reflective box equipped with an entrance window, two photon downshifting stages, one dichroic filter and one light guide coupled to SiPM

ProtoDUNE Vertical Drift: FD2 Technology

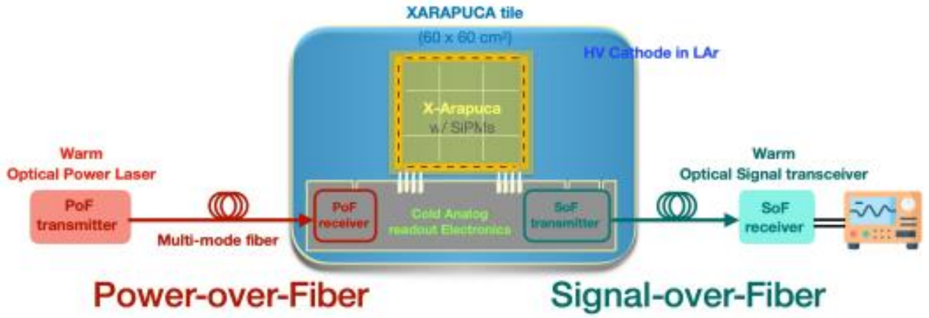
FD2 Vertical Drift technology

- Drift Length doubled → ~ 6m, drift vertical w/ cathode in the middle, cold electronics and PDS
- Xe-Doping

Eur. Phys. J. C 82, 618 (2022)

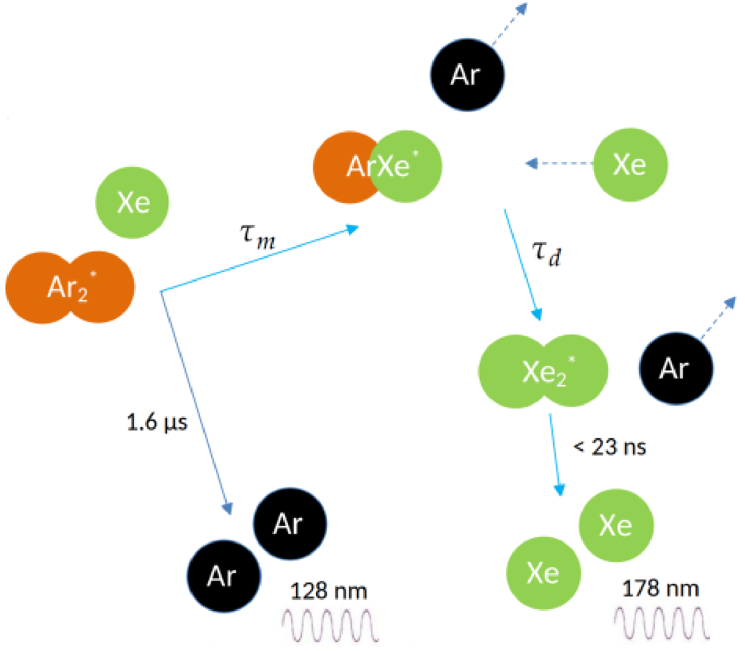


X-ARAPUCA in the Cathode (300 kV!) and outside the field cage. To overcome the challenge of powering and reading SiPMs in a 300kV electric field → **PoF** (Power Over Fibers): Power through optical fibers converted to DC at cold, good performance and durability



ProtoDUNE Vertical Drift: FD2 Technology

Light Uniformity and Light Yield improved with **Xenon doping**



Time constants of these processes are inversely proportional to the rate constant and to the Xe concentration (→ increasing the Xe concentration enhances the wavelength shifting efficiency until reaching saturation effects)

- Xenon added to LAr → Xe atoms can interact with Argon excimers creating an ArXe excited dimer
- Dimer comes across a Xe atom resulting in the creation of Xe^*_2 that decays very fast (<23 ns) emitting 178 nm photons:
  - LAr transparent to its own light, but VUV γ scatter Rayleigh on Ar
  - Larger Rayleigh scattering length for 178 nm photons (~9m vs 1m for 128 nm photons) → better light uniformity & LY

→ Light Collection enhanced in the FD-VD, important for double-calorimetry analyses

Double Calorimetry: Charge+Light

The energy deposited in the detector goes into 2 observables: **Charge and Light**

- **Using only the charge**→standard reconstruction of deposited energy in a LArTPC, only the electrons that escape e^--ion recombination and successfully drift to the anode can be used: a correction must be applied to account for the charge lost:

Energy from Charge only:

$$E_Q = Q^* R / W_{ion}$$

R=Recombination Factor = electron recombination survival probability.
Depends on the E_{field} and local ionization charge density *dQ/dx* → difficult to determine at all deposition sites, particularly for EM showers → use of an average value
$\mathbf{W_{ion}}$=ionization work function

- **Adding the light**: charge and light are anticorrelated and their sum is directly proportional to the deposited energy:

Energy from Charge+Light:

$$E_{QL} = W_{ph}\,(Q+L)$$

$\mathbf{W_{ph}}$=19.5 eV = average amount of energy deposited by a charged particle to produce an ion or exciton. Related to $\mathbf{W_{ion}}$ through the excitation ratio α: W_{ion}=23.6eV=(1-α)*W_{ph}

Charge: $\mathbf{Q} = N_i R = \mathbf{N_e}$

Light: $\mathbf{L} = N_{ex} + N_i (1-R) = \mathbf{N_\gamma}$

$\mathbf{Q+L} = N_i+N_{ex} = \mathbf{\Delta E / W_{ph}}$

→ We can perform a calorimetric measurement by-passing the correction for recombination that is no longer necessary and improve energy resolution

Double Calorimetry: Charge+Light

So we need:

Q = N_e = Number of ionization electrons **calculated from reconstructed charge**

L = N_γ = Number of scintillation photons **calculated from reconstructed photo-e$^-$ in the optical detectors**

$$Q = C_e^{cal} \sum_i q_i e^{t_i/\tau_e}$$

$q_i e^{t_i/\tau_e}$ = charge corrected by electron lifetime = Sum of all collection plane hits corrected by electron lifetime

C_e^{cal} = ADC to electron calibration constant

$$L = \frac{Total\,PE}{QE \cdot F_{vis}}$$

$Total\,PE$ = reconstructed photo-electrons of the event

QE = photo-detection efficiency

$F_{vis} = \frac{\sum_i f_{vis(p_i)} \cdot q_i}{\sum_i q_i}$ = Charge weighted visibility function of the event, gives the expected photons @ the optical detector w.r.t the photons emitted in position p_i by the passing particle
→ We need a **Visibility Map** of the detector!

Light Simulation

1) **Production**: phenomenological model that modifies the Birks' charge recombination model and provides the anticorrelation between light and charge and its dependence with dE/dx and E_{field} :
$Q(dE/dx, E_{field}) + L(dE/dx, E_{field}) = N_i + N_{ex}$ N_i, N_{ex} = model input parameters, with current numerical values extracted from data
2022 JINST 17 C07009

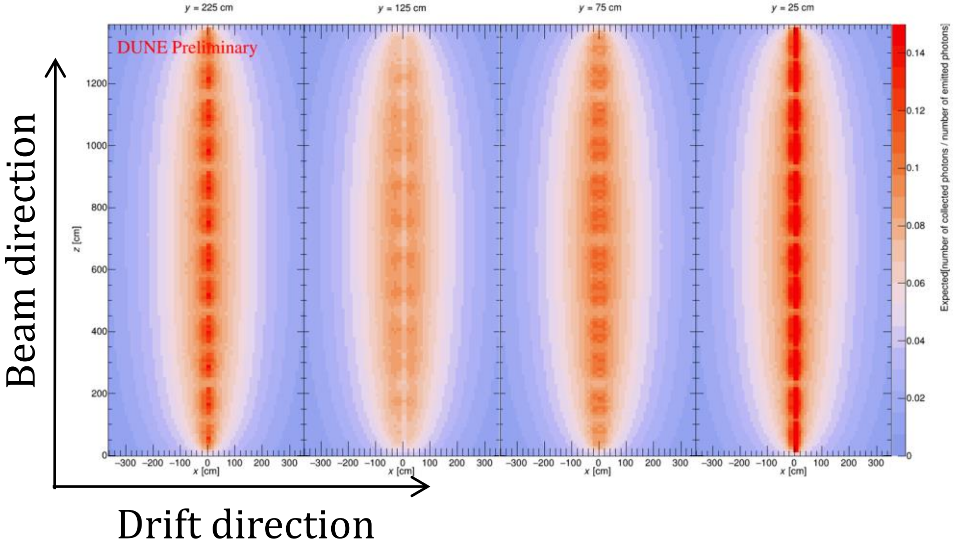
2) **Propagation**: tracking individual photons in Geant4 is prohibitive → Semi-analytical model that predicts hits on a PDS module from scintillation photons produced: factorize geometry (Ω), absorption and Reyleigh scatterin
Effective parametrization calibrated on heavy Geant4 simulations
Eur. Phys. J. C 81, 349 (2021)

3) **Digitization**:
   - For each p.e., a waveform is created (shape modelled on direct measurements)
   - Waveforms filtered to deconvolve detector response and scintillation time profile

Visibility Maps: Gives $f_{vis}(p_i)$ = the expected photons @ the optical detector w.r.t the photons emitted in position p_i by the passing particles

Visibility Map from semi-analitycal model corresponding to a fraction of FD1

Visibility at different Y

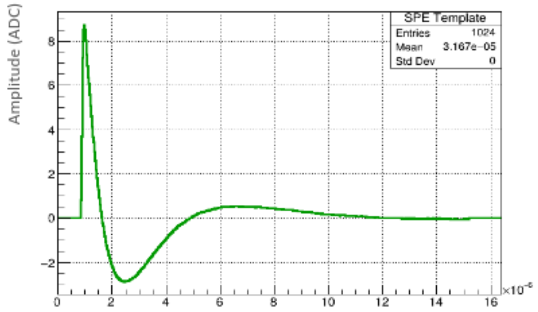


Light Simulation (PDS @ MiB)

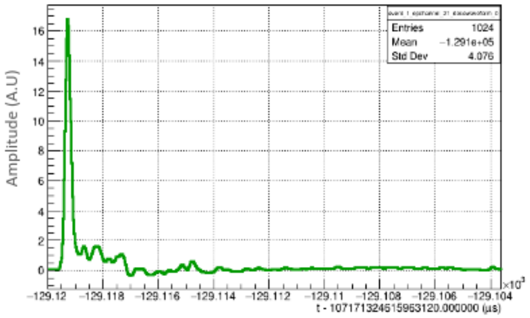
D. Guffanti, M. Delgado, F. Bramati, F. Galizzi

- New! “**PhotonVisibilityExport” Module**
  - Map generation also for a single OpDet
  - Pull request to include it in *duneopdet*

- Study of Trigger Rate of ProtoDune-HD PDS
- LArSoft Digitizer Module: realistic modelling of SiPM response
- LArSoft Deconvolution Module: undershoot removal and PDS signal reconstruction improvement

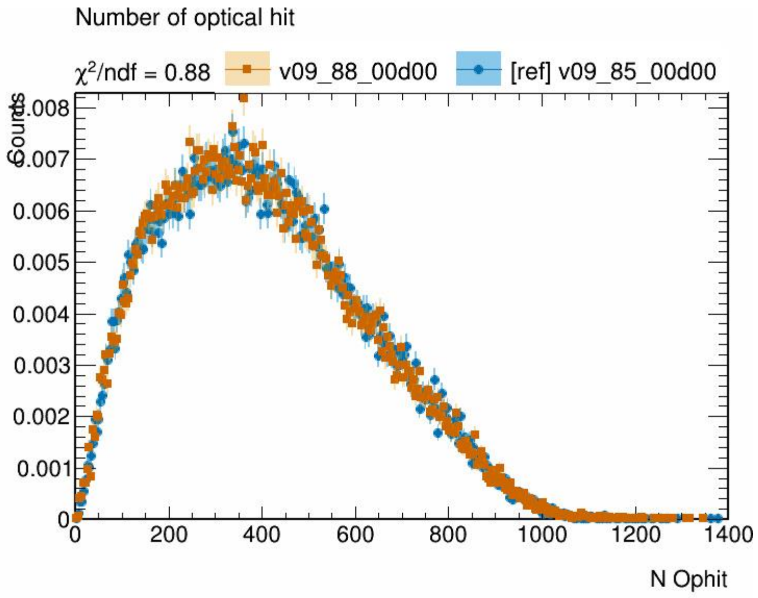


Digitalization Stage



Deconvolution "Wiener"/"Gauss"

- **PDS Automatic Validation**
  https://indico.fnal.gov/event/60082/contributions/291446/attachments/178329/243058/gff-pds-ci.pdf
  DUNE Continuous Integration (lar_ci): PDS integration w/ automatic validation w.r.t. reference dataset



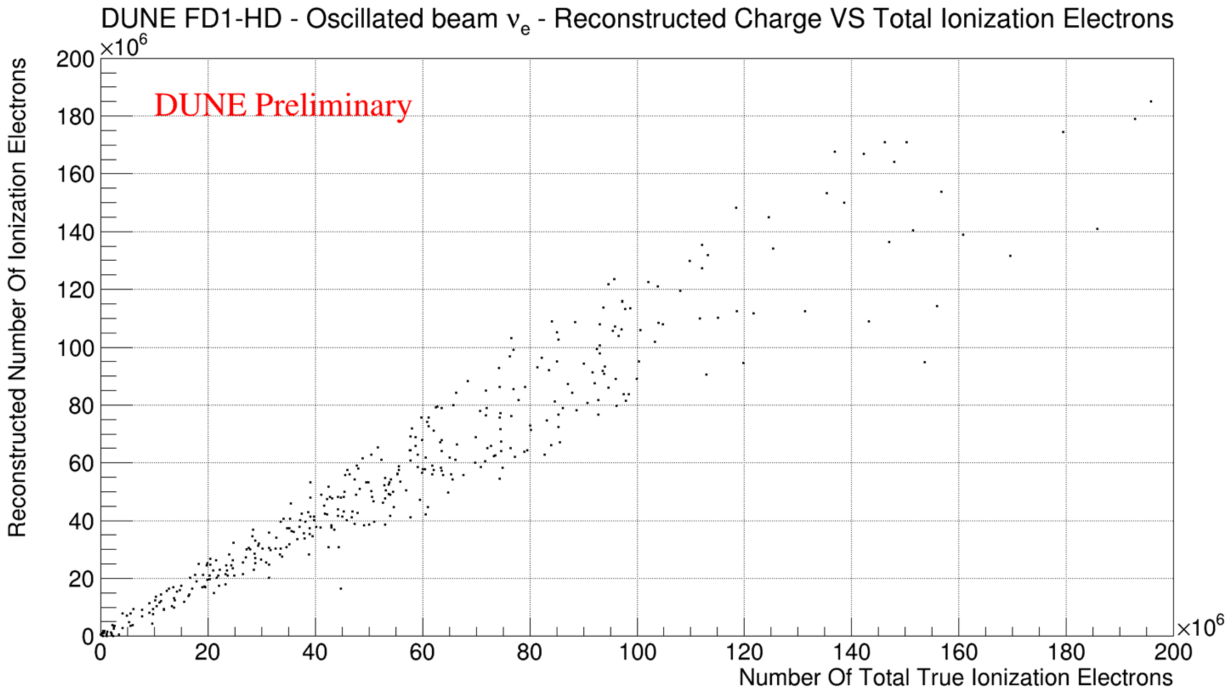
DUNE Far Dector Horizontal Drift – Beam ν_e

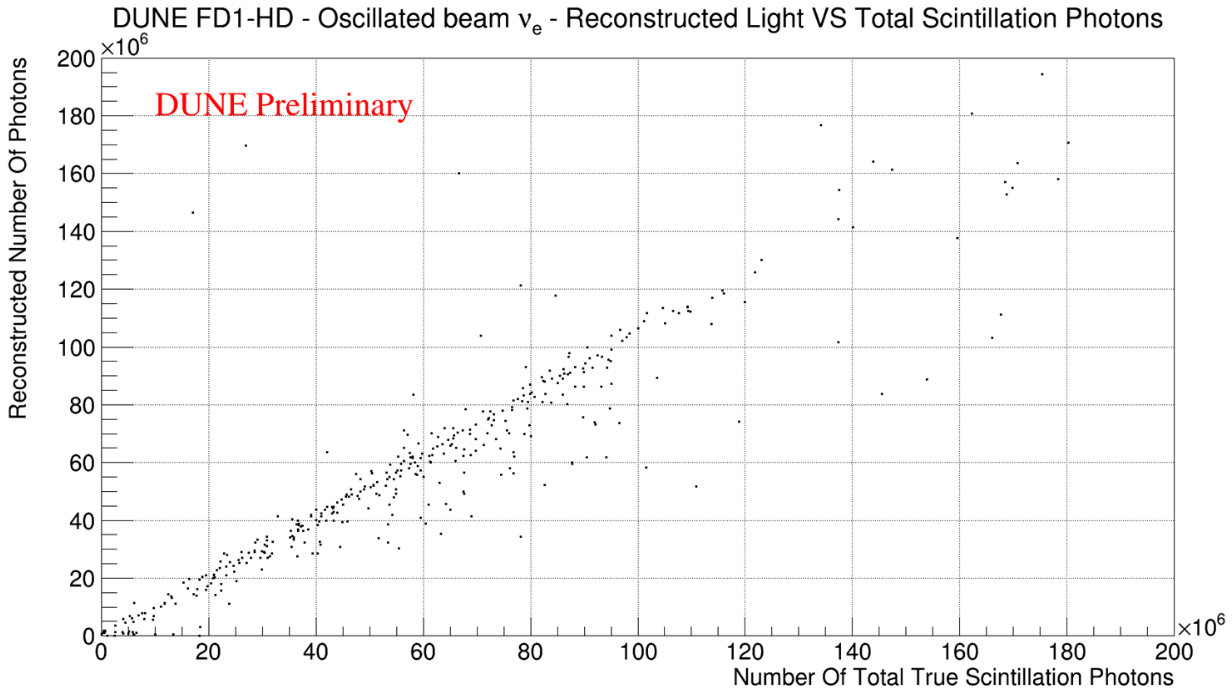
Preliminary studies with beam neutrinos simulated events in the DUNE FD1-HD

Simulation of DUNE-FD1 beam events: 500 beam ν_e . Selecting evts with spacepoints in fiducial volume

- all collection plane charge hits
- all PE reconstructed

Calculation of Q & L →
should correspond to Nb of e^- and γ generated in LAr

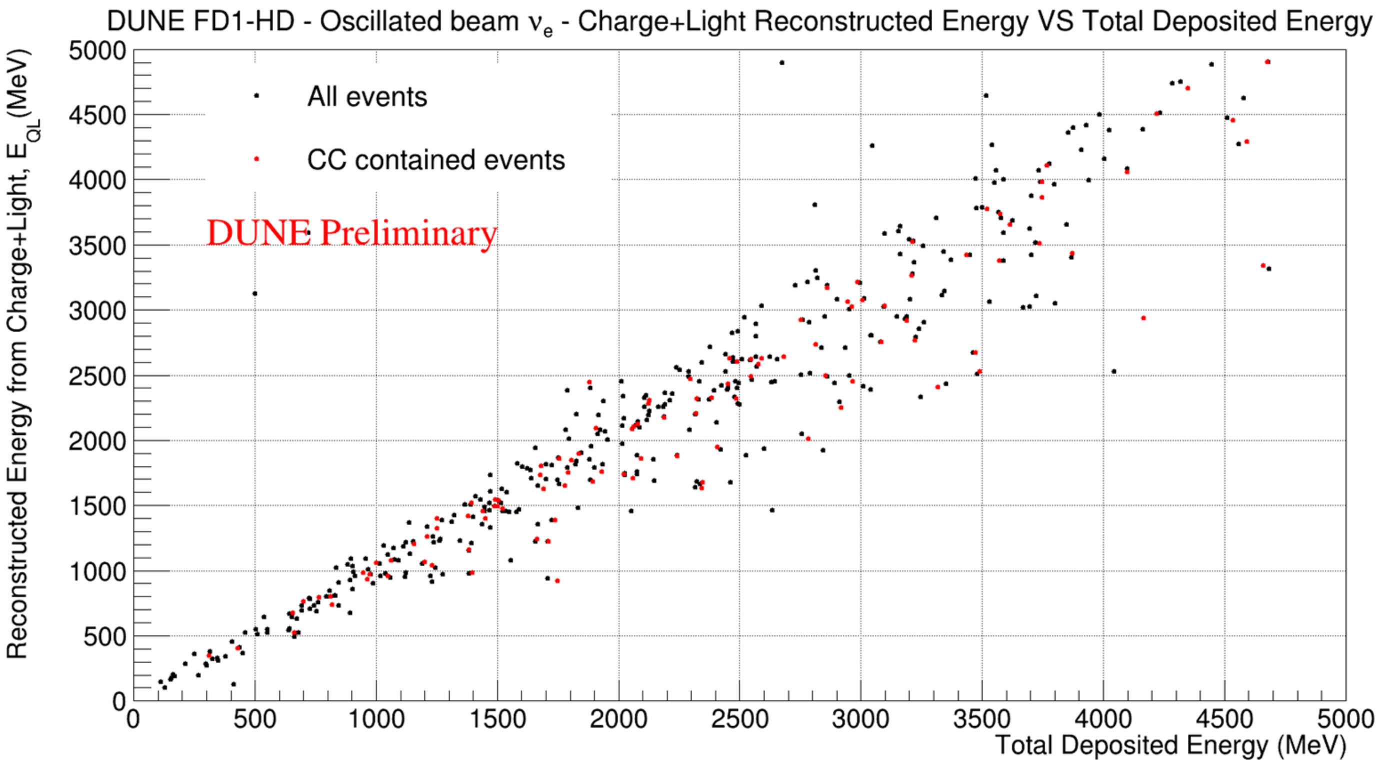

DUNE FD1-HD - Oscillated beam ν_e - Reconstructed Charge VS Total Ionization Electrons


DUNE FD1-HD - Oscillated beam ν_e - Reconstructed Light VS Total Scintillation Photons

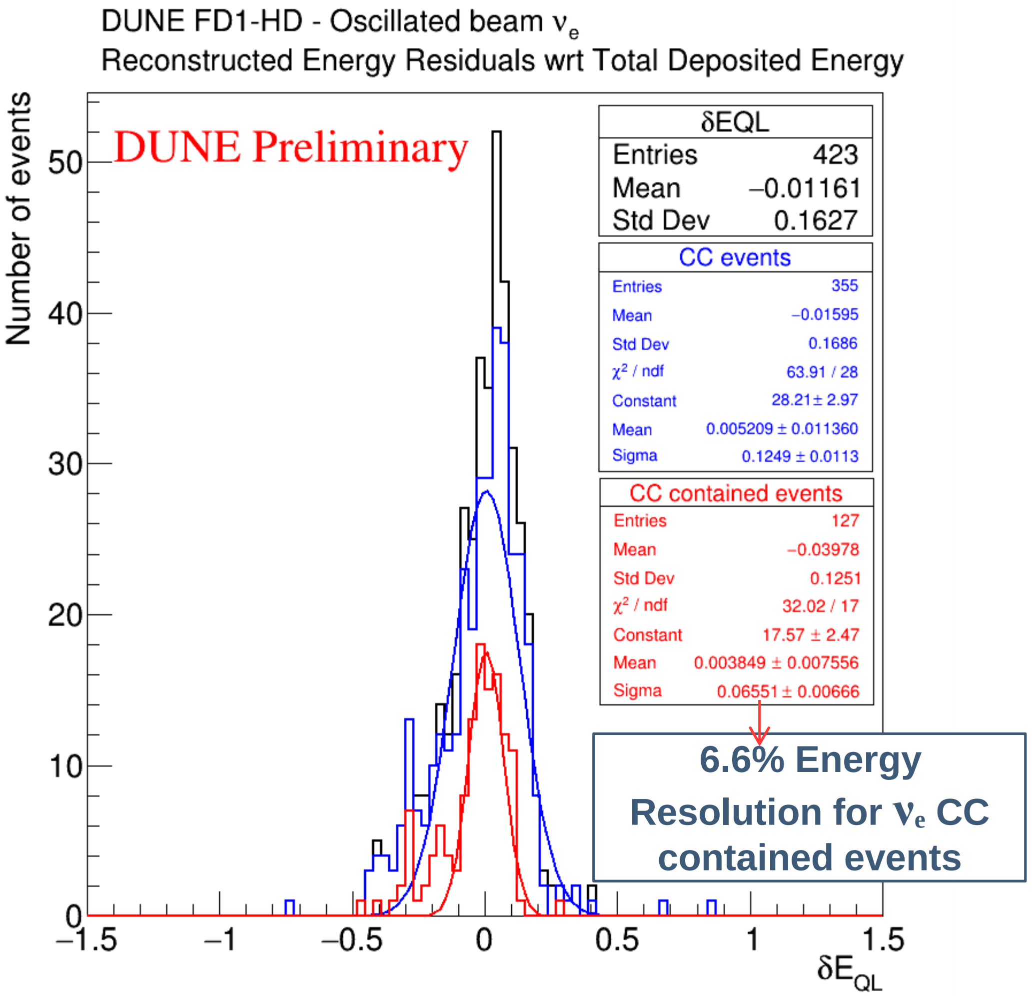
DUNE Far Dector Horizontal Drift – E_{QL}

Reconstructed event Energy from Charge & Light: $E_{QL} = W_{ph}(Q+L)$

→ Comparison to Total Deposited Energy



DUNE FD1-HD - Oscillated beam ν_e - Charge+Light Reconstructed Energy VS Total Deposited Energy



DUNE FD1-HD - Oscillated beam ν_e

Reconstructed Energy Residuals wrt Total Deposited Energy

6.6% Energy Resolution for ν_e CC contained events

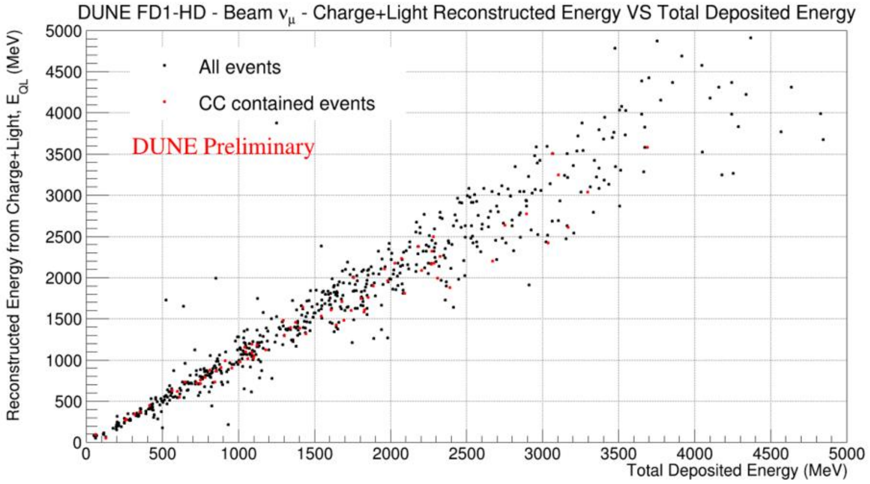
DUNE Far Dector Horizontal Drift – Beam ν_μ & $\overline{\nu_\mu}$

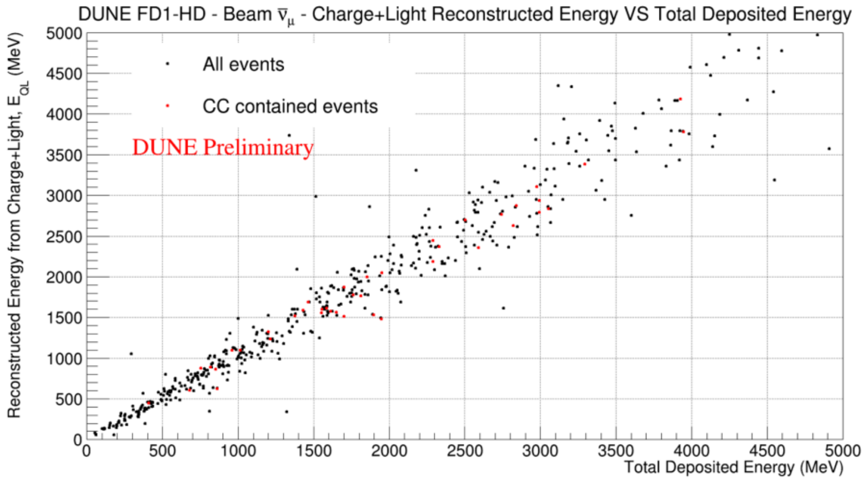
E_{QL} & comparison to Total Deposited Energy

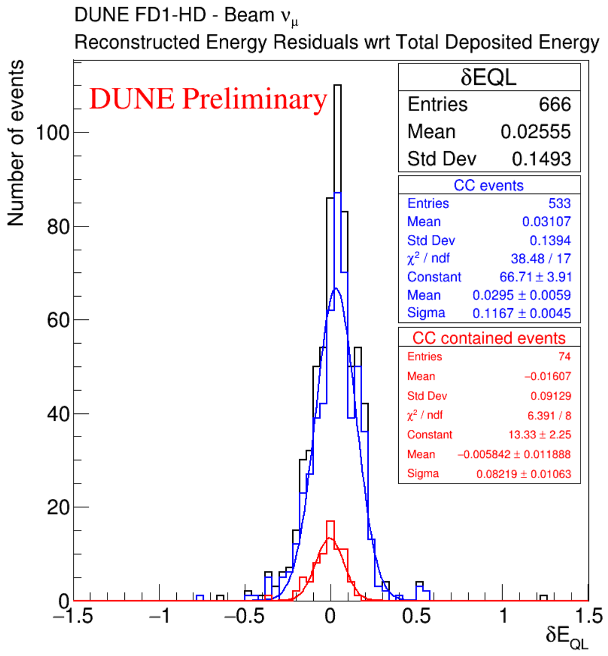
DUNE-FD1 simulated beam events:

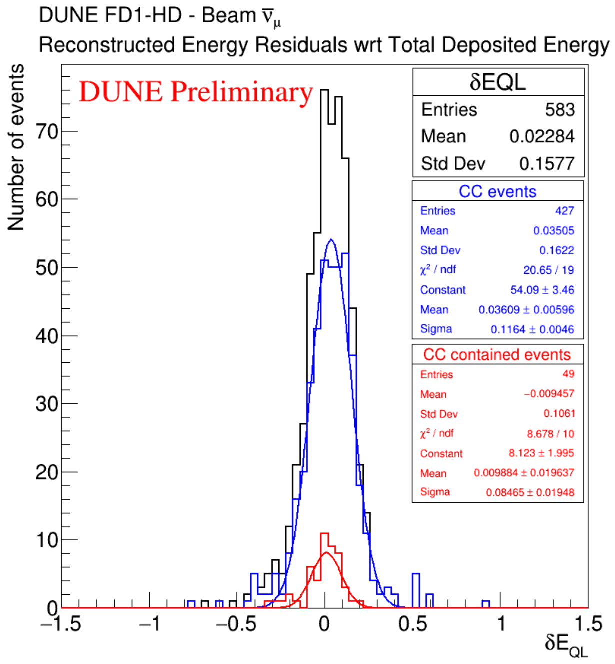
- 700 beam ν_μ & beam $\overline{\nu_\mu}$

- **Energy Resolution:**
  - **ν_μ CC contained ~ 8.2%**
  - **$\overline{\nu_\mu}$ CC contained ~ 8.5%**









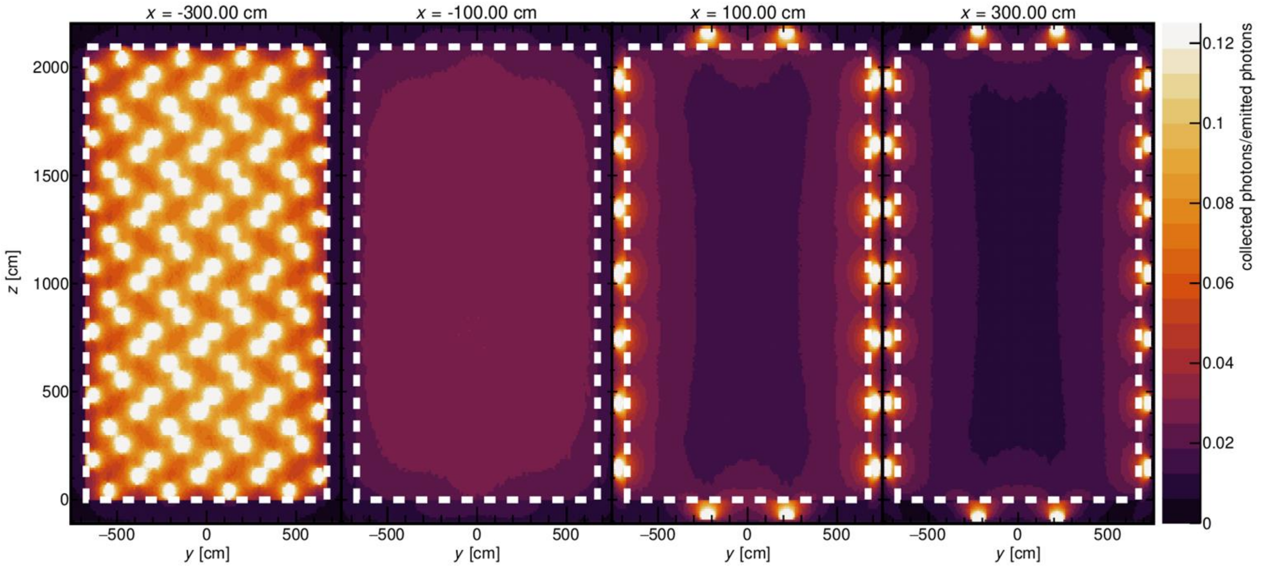
DUNE Far Dector Vertical Drift – Simulated Events

- 1000 beam ν_e with
  - FD-Vertical Drift, Geometry 1x8x14_3view_30deg
  - Light Model: Semianalytical
- Containment cut: pandora spacepoints of the event in fiducial volume: $|x| < 315$, $|y| < 662.3$, $10.5 < z < 2081$ cm
- Beam ν_e Stats: 77% CC, 36% CC contained
- Visibility Map obtained from semi-analytical considering **0.3 Ar + 0.53 Xe**
- LY in VD:

Ar Corrections: fast component 0.65,
slow component 0.65 * 0.31

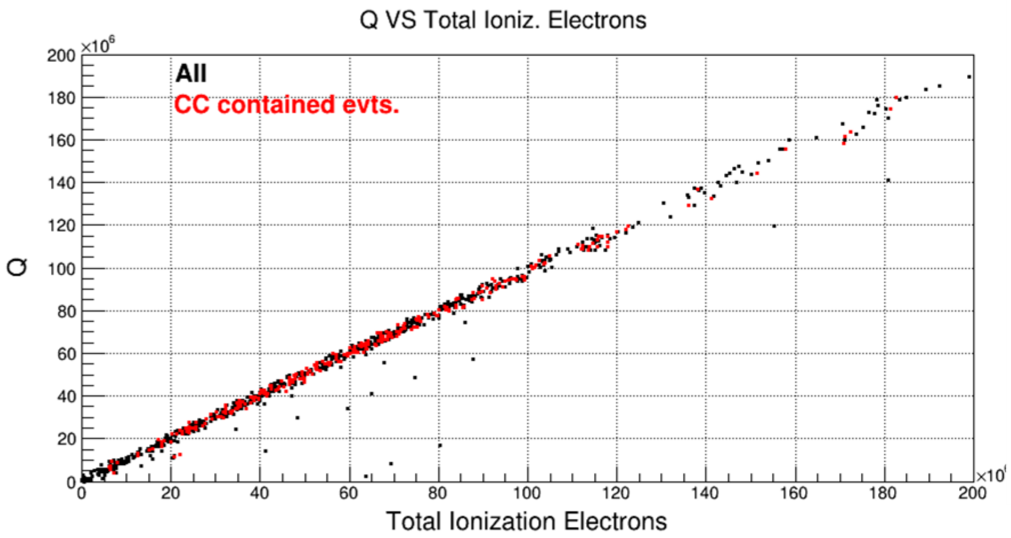
Xe Corrections: fast component 0,
slow component 0.69

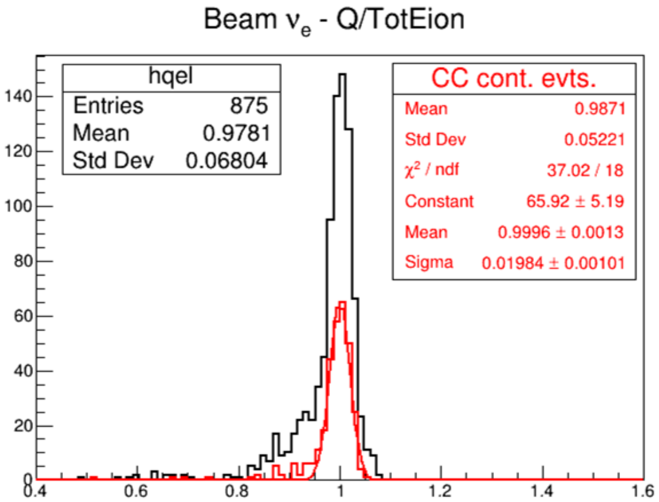
The Light Map



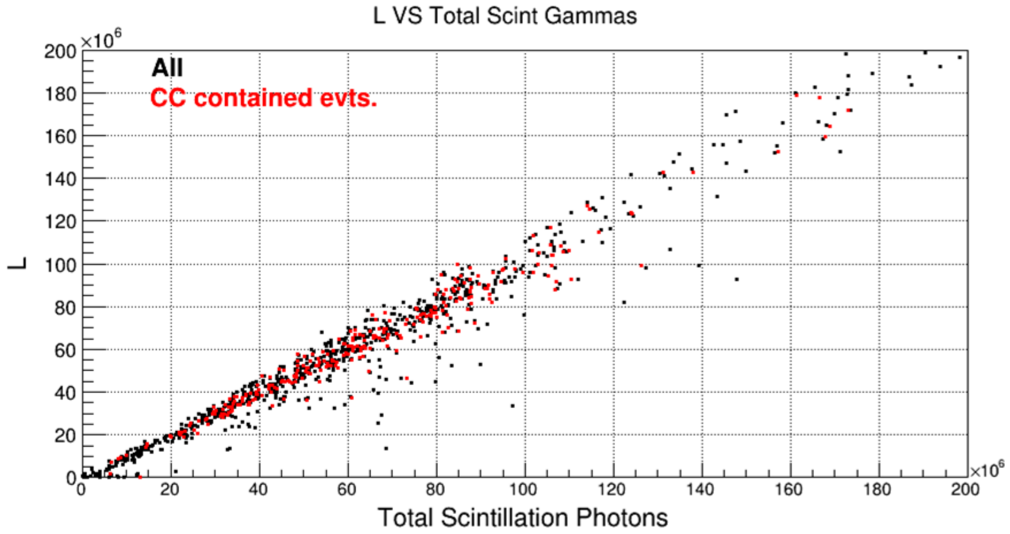
DUNE Far Dector Vertical Drift – Q & L

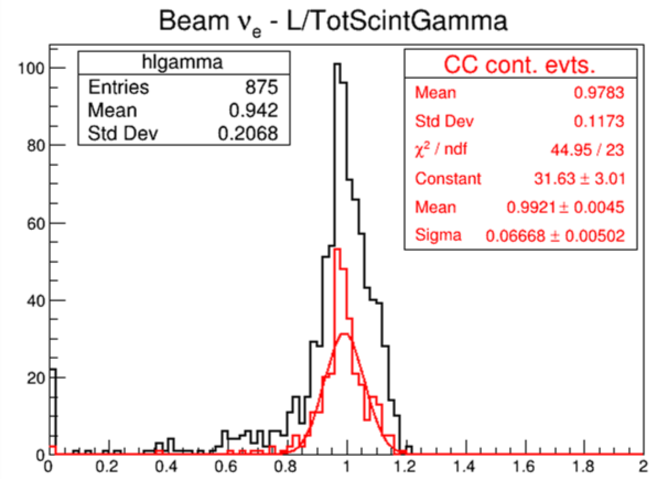
- Q VS Ionization Electrons





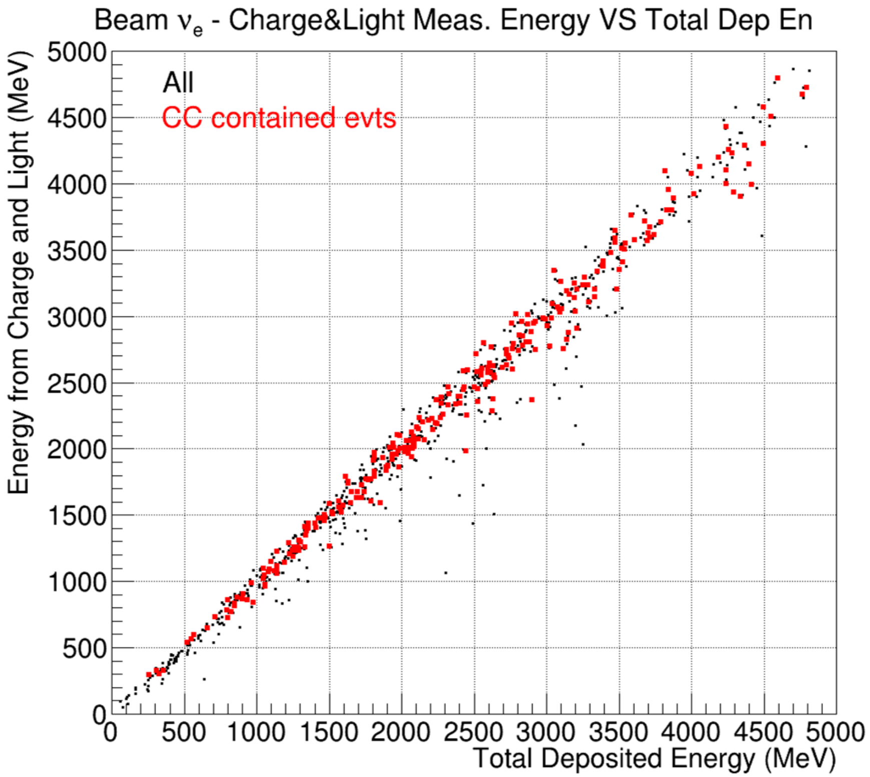
- L VS Scintillation Gammas

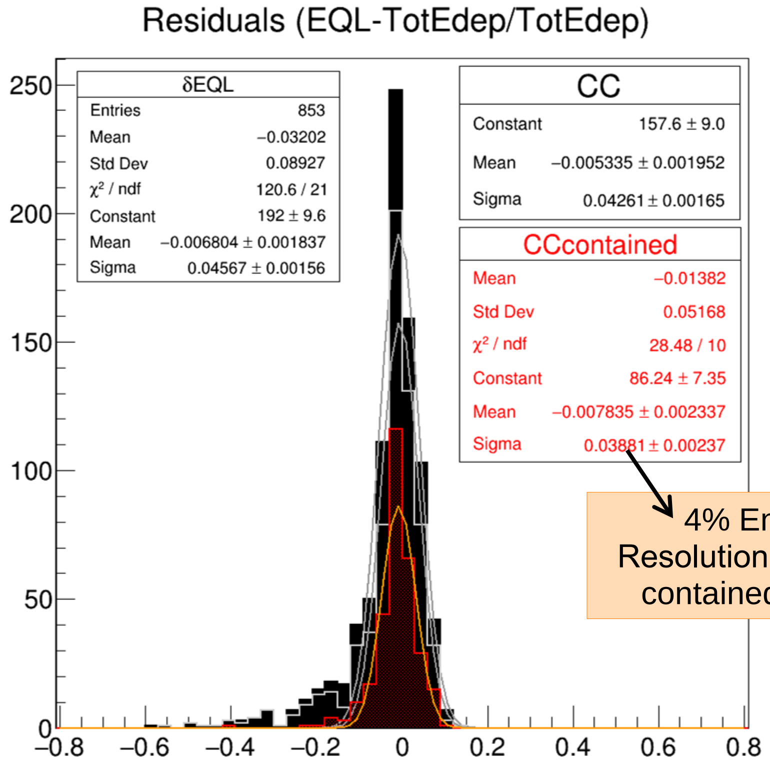




DUNE Far Dector Vertical Drift – E_{QL}

Reconstructed event Energy from Charge & Light:
$E_{QL} = W_{ph}\,(Q+L)$ → Comparison to Total Deposited Energy





4% Energy Resolution for ν_e CC contained events

Conclusions

- DUNE detectors are kton **LArTPCs**, collection of VUV LAr scintillation photons is an integral aspect of the technology
- **Double Calorimetry**: Combining Charge and Light allows to reconstruct the deposited energy in LAr
  - by-passing the correction for recombination of ionization electrons
  - Can improve the energy resolution

Preliminary results on simulated beam events in DUNE FD1:

σ_E CC contained on Total Deposited Energy**: 6.6 % ν_e, 8.2% ν_μ and 8.5% $\overline{\nu_\mu}$**

in DUNE FD2:

σ_E CC contained on Total Deposited Energy: **4% ν_e**

- Milano-Bicocca actively involved in many PDS activities, simulations and analyses!

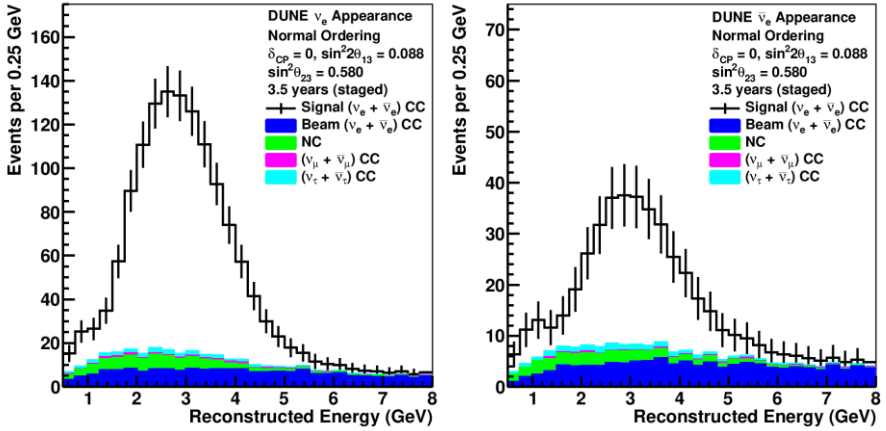
See tomorrow's presentations!

Back ups

Double Calorimetry: Charge+Light

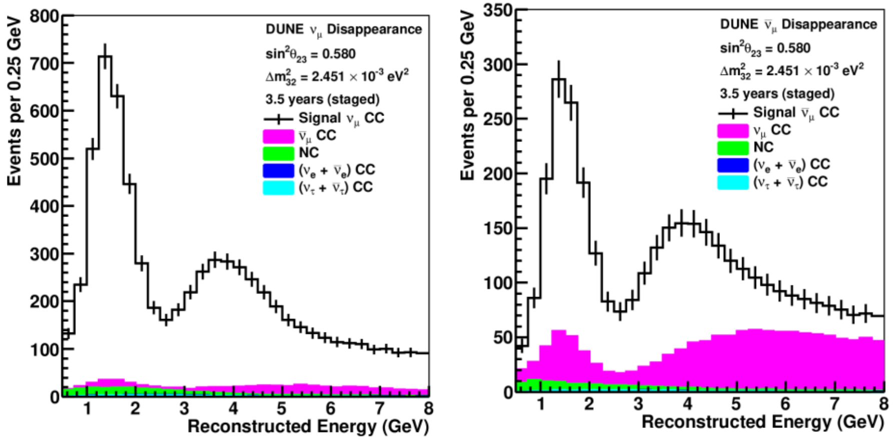
- The key strength of DUNE is the ability to measure the oscillation patterns of neutrinos over a range of energies spanning the first and second oscillation maxima: coordinated analysis of the reconstructed ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ energy spectra in near and far detectors
- **Energy resolution directly impacts DUNE sensitivity to CPV and Mass Ordering**

Neutrinos Antineutrinos

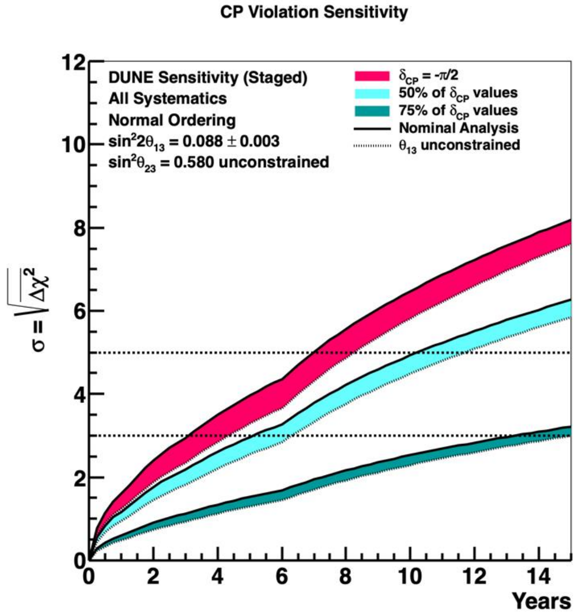


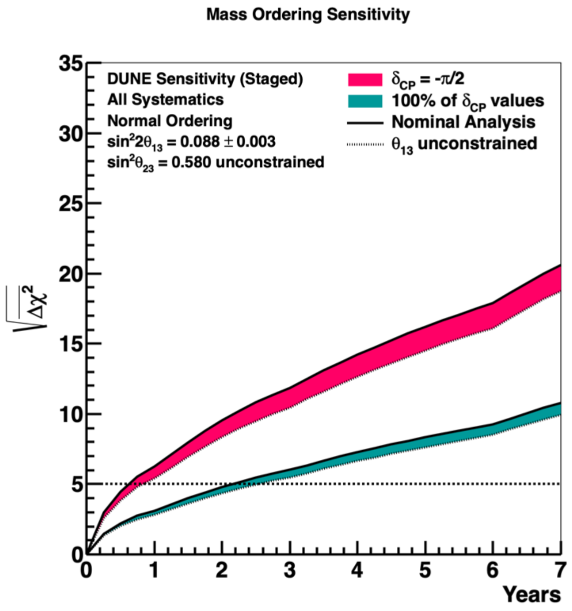
ν_e Appearance

Neutrinos Antineutrinos



ν_μ Disappearance

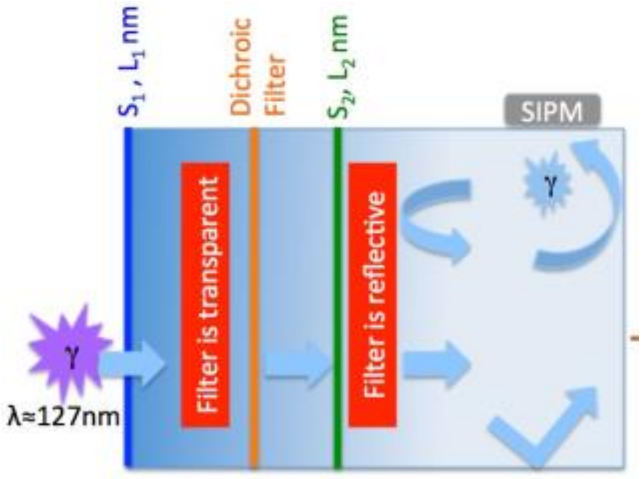


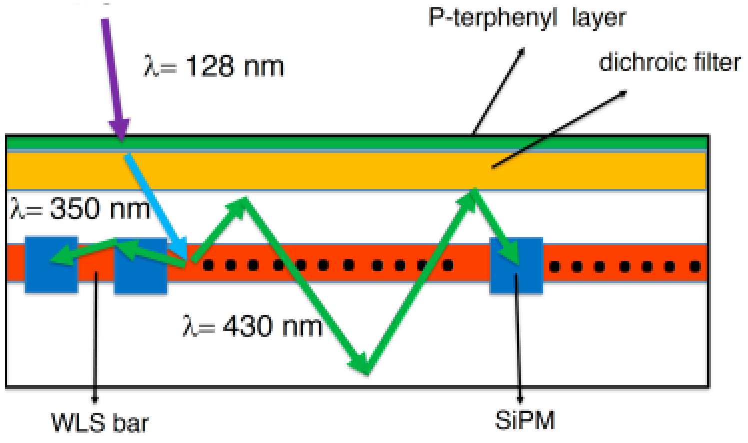


The Photo-detection System
LAr VUV Light detection: X-Arapuca

X-ARAPUCA Concept: trap photons in a box with highly reflective internal surfaces

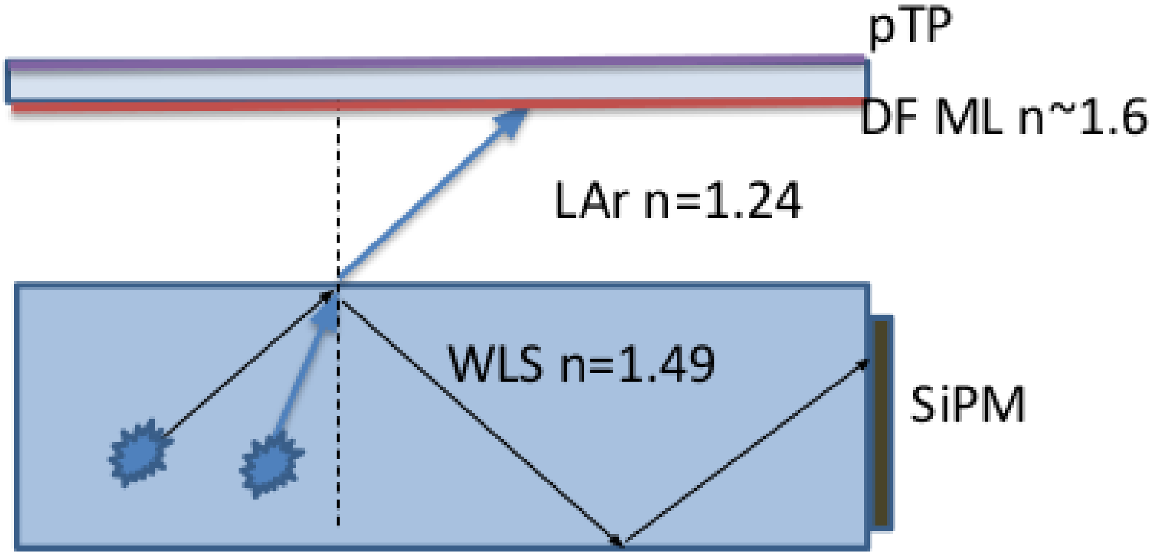
- The core of the device is the **dichroic filter**: a multilayer interference film which is highly transparent for wavelength below a cutoff and highly reflective above it
- VUV scintillation light produced in LAr →
- PTP shifter deposited on the dichroic external side converts VUV light to a wavelenght < dichroic cutoff (**light transmitted**)
- The internal WLS bar converts the primary shifted photons to a wavelenght > dichroic cutoff (**light is trapped**)
- After reflections the photons can be detected by SiPM positioned laterally with respect to the WLS plane





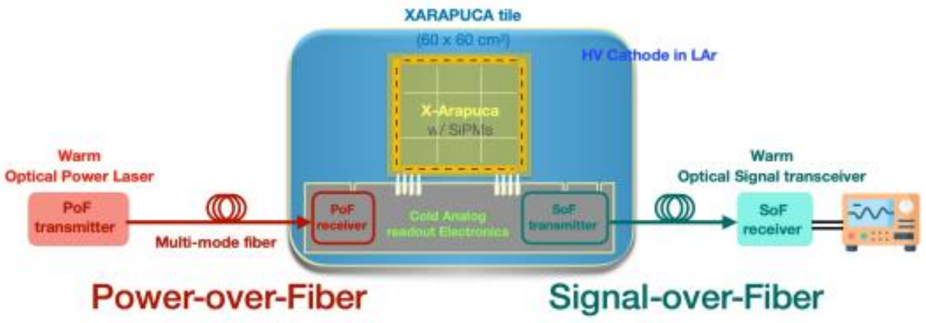
Dichroic Filters

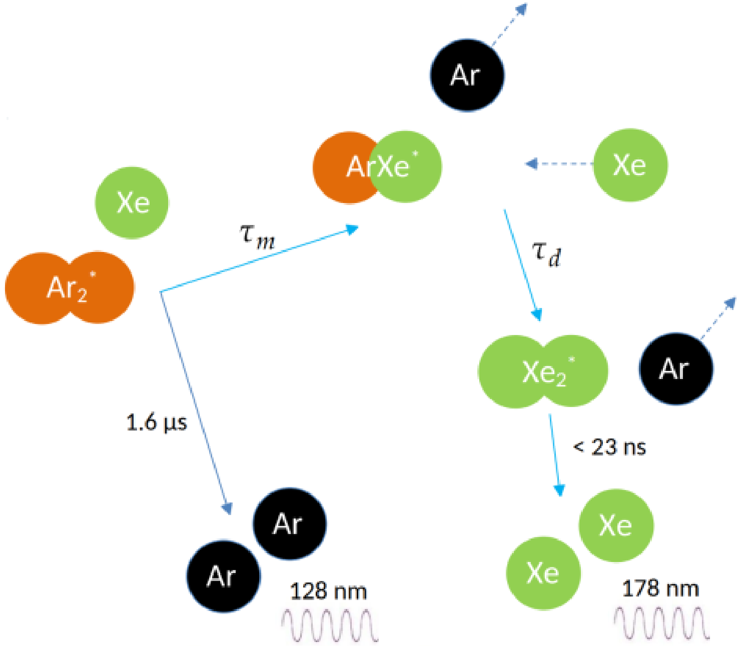
- made of thin film multilayer coatings on a glass/fused silica substrate. They act as Fabry-Perot interferometer to selectively transmit/reflect light.
- For Large volume LAr detectors → Large area DF (minimize optical window dead areas) → challenge: pTP coating uniformity
- The glass window is coated with a primary WLS (pTP) to downshift the 128 nm light to ~350 nm



- Filters have been optimized to operate in LAr (@45°)
- Higher transmittance in the pTP emission range
- Higher reflectivity in the light guide WLS chromophore emission range
- But narrower reflectivity window

ProtoDUNE Vertical Drift - PDS





- A new technology to overcome the challenge of powering and reading SiPMs in a 300kV electric field: the **Power over Fibers (PoF)**: Power through optical fibers converted to DC at cold, good performance and durability
- ProtoDUNE-VD now installed @ CERN with novel PoF X-ARAPUCA
  - Major R&D effort (cold-box tests, design optimization,definition of VD PDS baseline towards FD2)
  - PDE of VD PDS membrane modules recently validated w/ a dedicated measurement (~2% preliminary), will be performed also for the PoF modules

•**Xenon Doping:** 178 nm wavelength photons

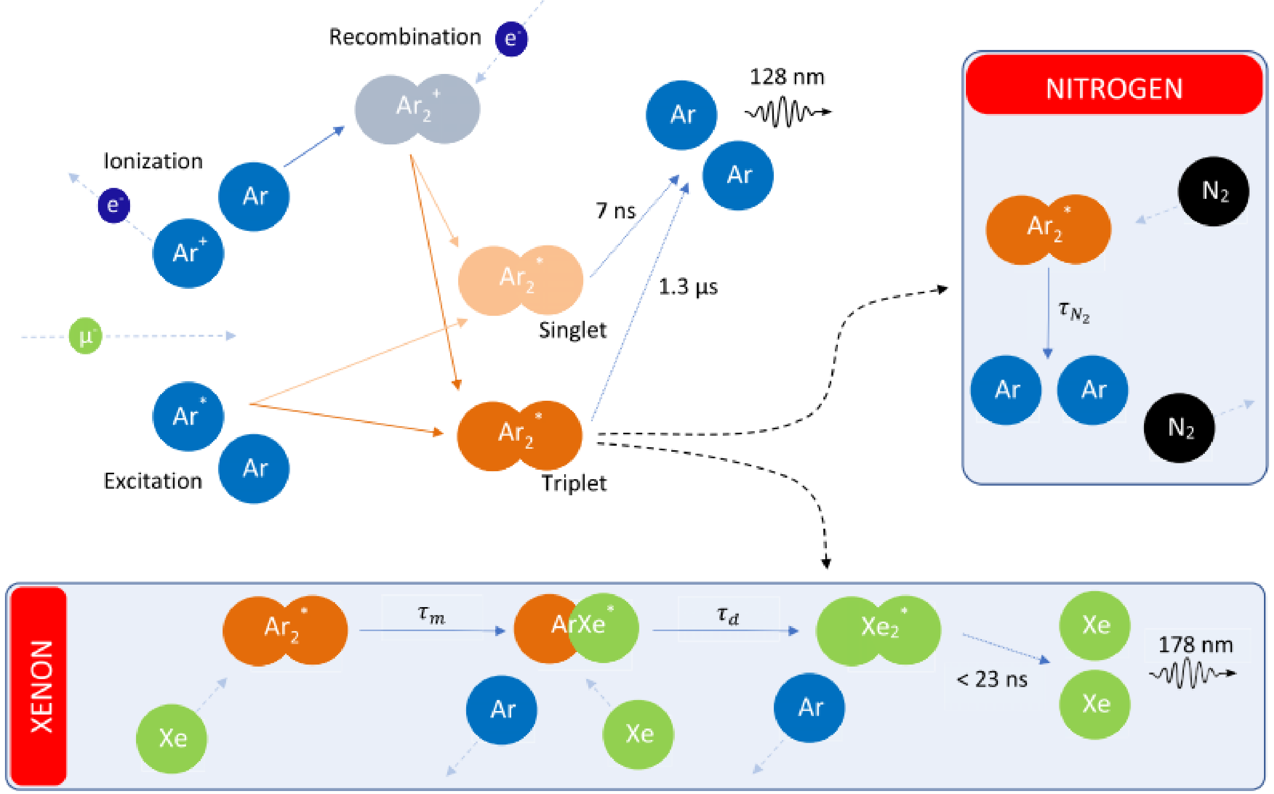
- LAr transparent to its own light, but VUV γ scatter Rayleigh on Ar
- Larger Rayleigh scattering length for 178 nm photons (~9m vs 1m for 128 nm photons) → better light uniformity & LY
- Xenon doping successfully tested with:
  - ProtoDUNE-DP (GAr+LAr) (5.8 ppm) → Eur. Phys. J. C (2022) 82:618
  - A dedicated run of protoDUNE-SP(18.8 ppm, 13.5 kg): 2 Xe-light sensitive XA (1 Xe-only, 1 Ar+Xe) succesfully tested, 95% of light lost due to N_2 pollution recovered

Xe Doping

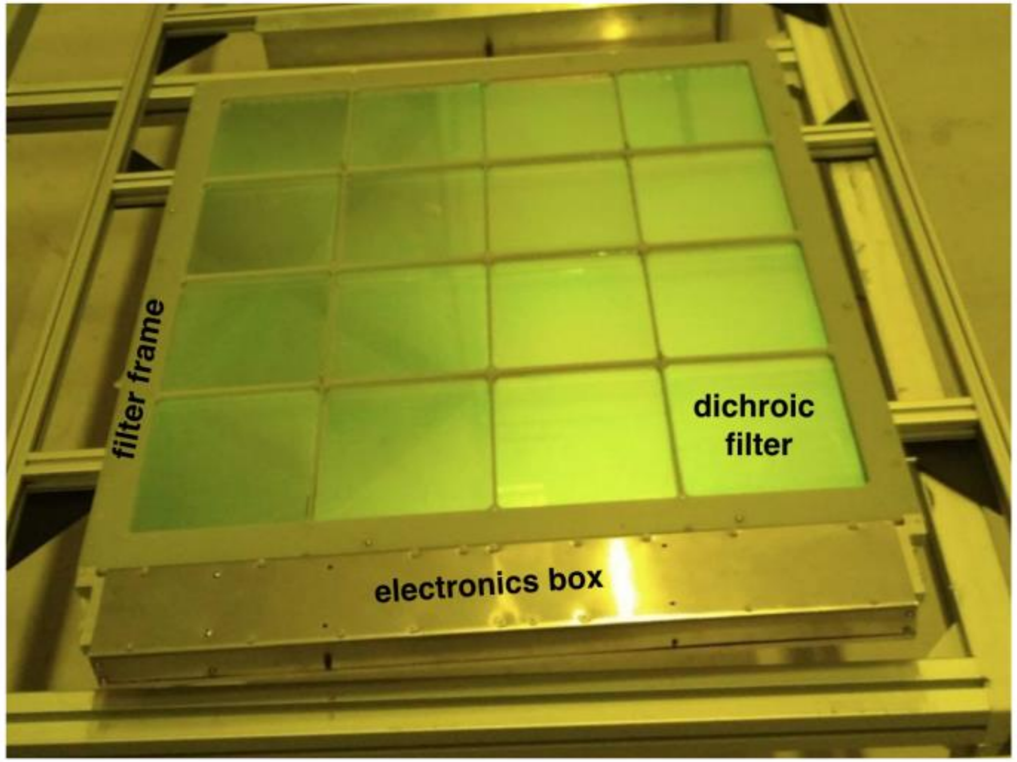
- Xenon added to LAr → Xe atoms can interact with Argon excimers creating an ArXe excited dimer
- Dimer comes across a Xe atom resulting in the creation of Xe^*_2 that decays very fast (<23 ns) emitting 178 nm photons.

The time constants of these processes are inversely proportional to the rate constant and to the Xe concentration (→ increasing the Xe concentration enhances the wavelength shifting efficiency until reaching saturation effects)

- The presence of pollutants like N_2 can reduce the light by quenching. This process is more efficient as the time scale becomes faster, i.e. at larger nitrogen concentrations.
- Xenon becomes a direct concurrent in the process since its reaction rate constant is larger than the one of N_2, the light can be recovered with the wavelength shifting mechanism



FD2 – Vertical Drift X-ARAPUCA



Same technology but different SiPM coverage and dimensions, WLS plate dimensions 60.7x60.7x0.4 cm^3:

- Maximize photon detection
  - SiPM-WLS coupling
  - optimize Optical Path and plate thickness vs attenuation length i.e. dye concentration
  - new dichroic filters
- Maximize active area
  - larger dichroic filters
- PDE measurements of the large area X-Arapuca are being performed at different sites: INFN Naples, CIEMAT (Madrid)

SiPMs & WLS

- **SiPM to WLS coupling**
  - To minimize gap between SiPM and WLS in LAr → SiPMs on flex circuits + spring loaded mount to compensate WLS shrinking (~1% i.e. 6 mm)
  - Also tested SiPM fitting in dimple cuts (flat or cylindrical) machined at the edges of WLS
- **WLS attenuation length (λ_{att})**
  - For PMMA based WLS in LAr, the critical angle for light trapping at the surfaces is $56° = \theta_c$. For $\theta > \theta_c$ light is trapped and guided by TIR to SiPMs
  - Due to multiple reflections the optical path inside large size WLS may reach a couple of meters → dye concentration tailored to FD2 size and optical path → optimization driven by simulations