FD3 PDS Simulation: Status and Needs

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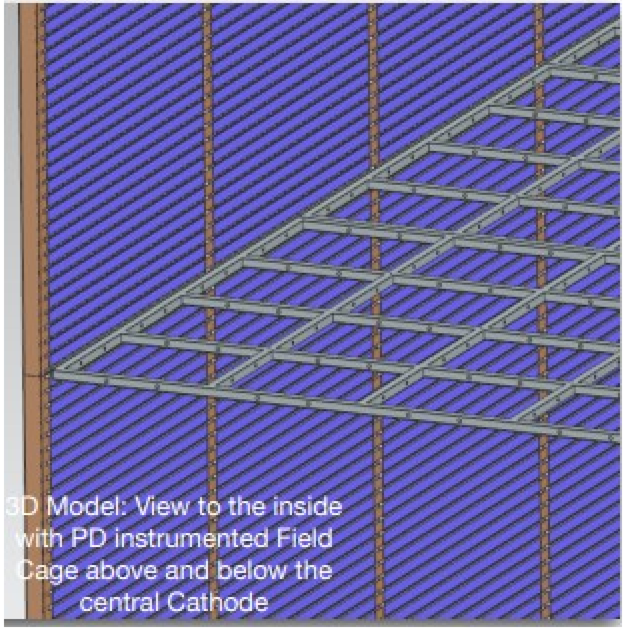
DUNE FD3 Mini-Workshop Toward a Combined Photon Detection and Field Cage System

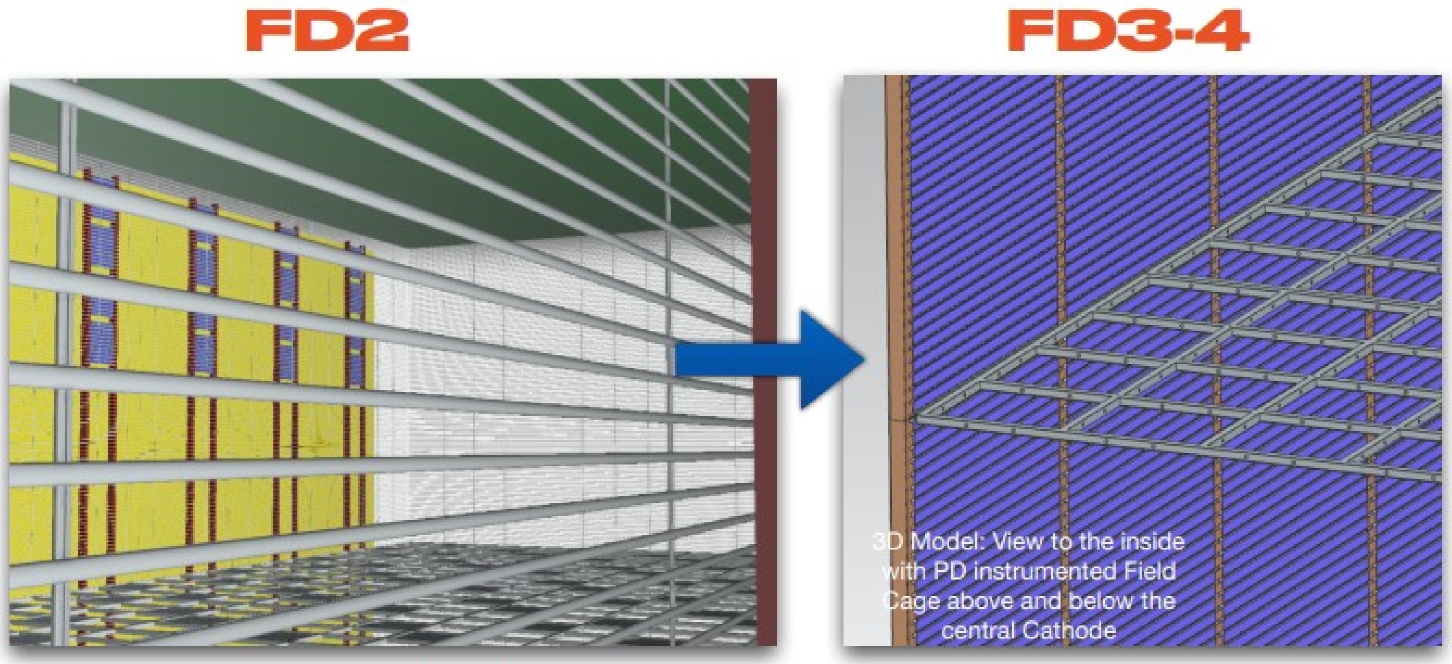
June 26 2023



Monte Carlo Simulations

- Important tool for experiments
  - Evaluation of design choices
  - Sensitivity studies
  - Quantification of systematic errors
  - Development of analysis methods
- Allows for robustness in predictions made
- Aids the decision making processes related to the experiment's design
- Allow the development of reconstruction algorithms ahead of experimental data and comparison with MC truth

Building on the Vertical drift PDS experience

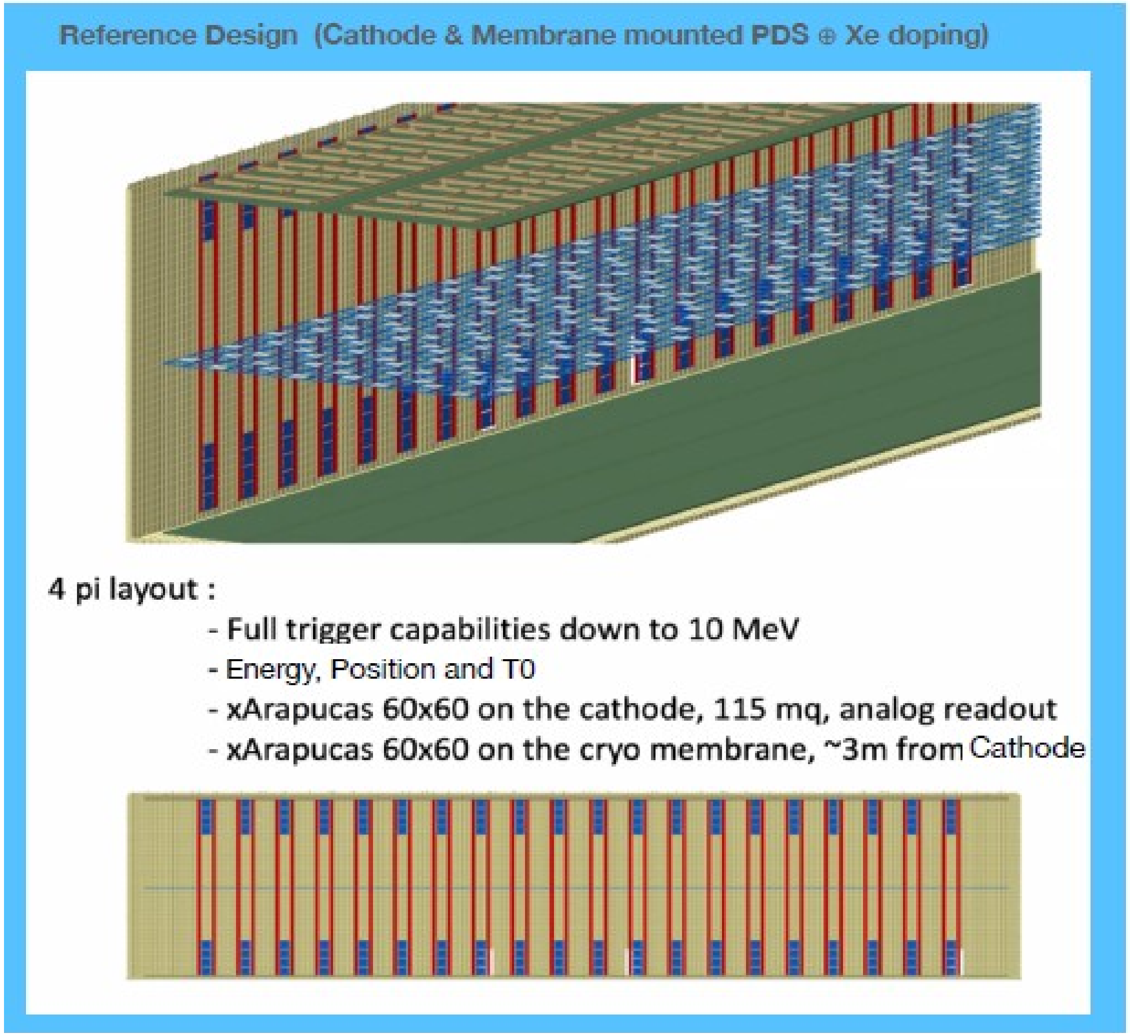


FC - 70% T

View of the FD2 Lower Volume from behind the FC, as seen by the Membrane PD modules

- Naturally expand x10 optical coverage (wrt FD2 PDS)
- Provide optimal mechanical frame structure for xARAPUCA bars in between (reduce fabrication & installation complexity (and costs))
- Retain FC electrical functionality for TPC

Vertical Drift PDS



PD Active Optical Coverage onto 5 sides

(w/ modified FC - 70% T)

+

PD Passive Optical Coverage (reflector) on the Anode side

+

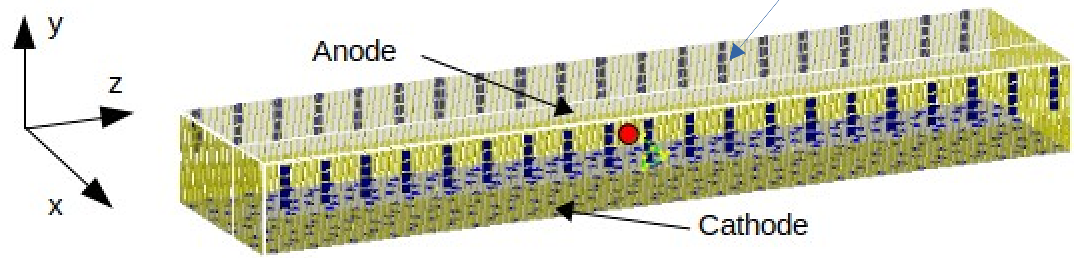
Xe doping

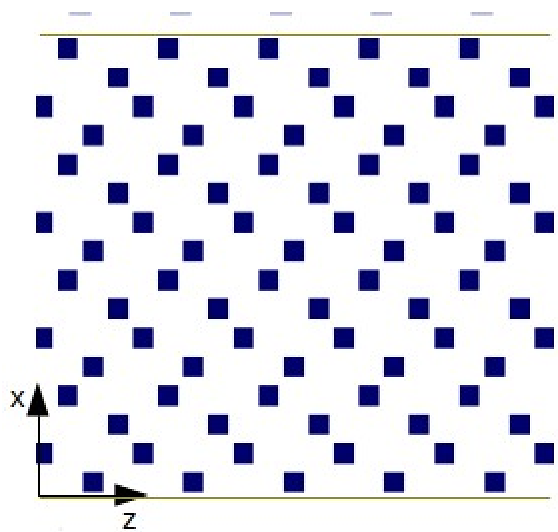
VD Standalone Geant4 Simulation

- FC structure
- Semi-transparent Cathode: T = 80%
- Anode R=20% (Xe)
- Rayleigh scattering*
  λ_{Ar} = 99.9 cm,
  λ_{Xe} = 8.5 m
- Abs length
  Abs_{Ar} = 20 m,
  Abs_{Xe} = 80 m

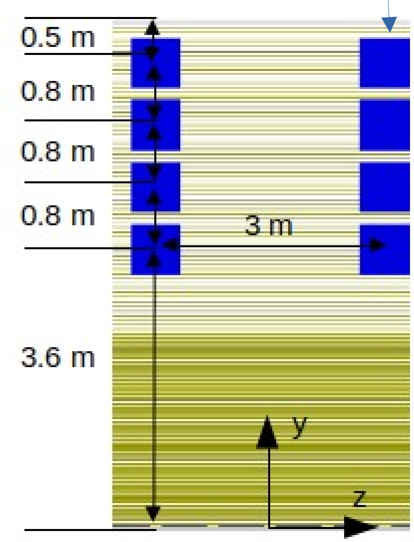
Top VD volume

PDs 60 cm behind FC





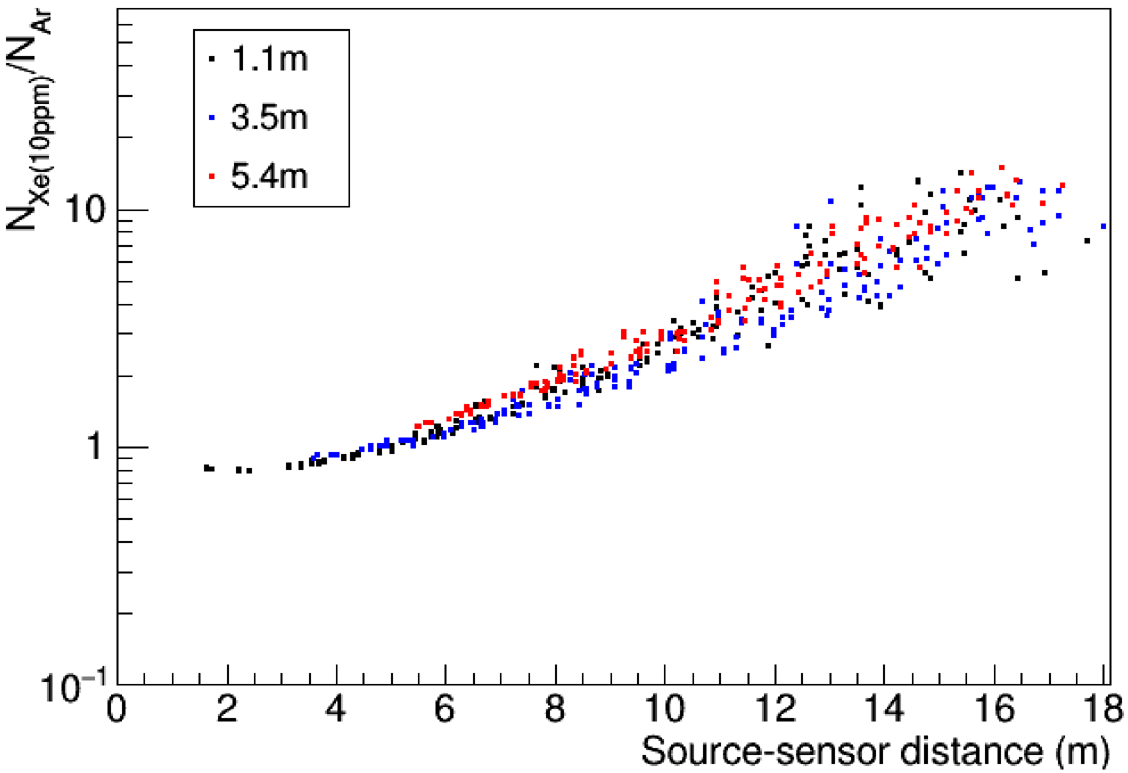
Top view: Arapucas over cathode



F. Marinho, LP

VD Standalone Geant4 Simulation

- Effect of Xe doping
  - Improves detection at large distances
  - Increases LY uniformity across large volumes



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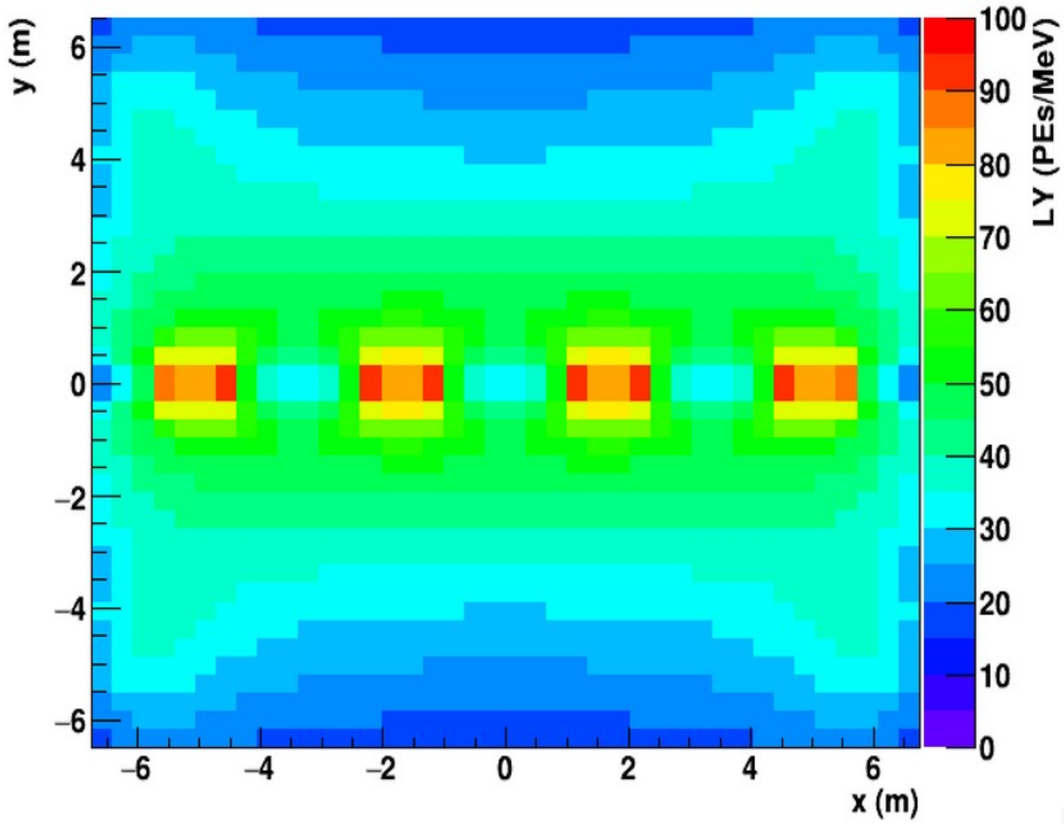
VD PDS: Light Yield Map

- 25000 photons per MeV of energy deposited
  - 70% for Xe
  - 30% for Ar
- 3% detection efficiency

$LY_{total} = 0.31\ LY_{LAr} + 0.53\ LY_{Xe}$

- $\langle LY \rangle = 38$ PE/MeV
- $LY_{Min} = 16$ PE/MeV

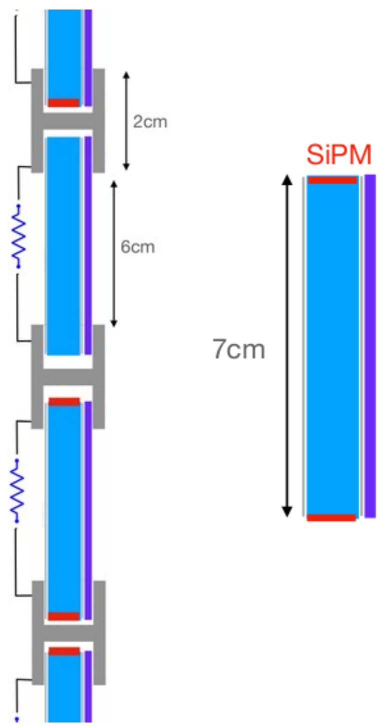
Ar + Xe (10 ppm)



H. Amar, F. Cavanna, F. Marinho, LP, M. Sorel

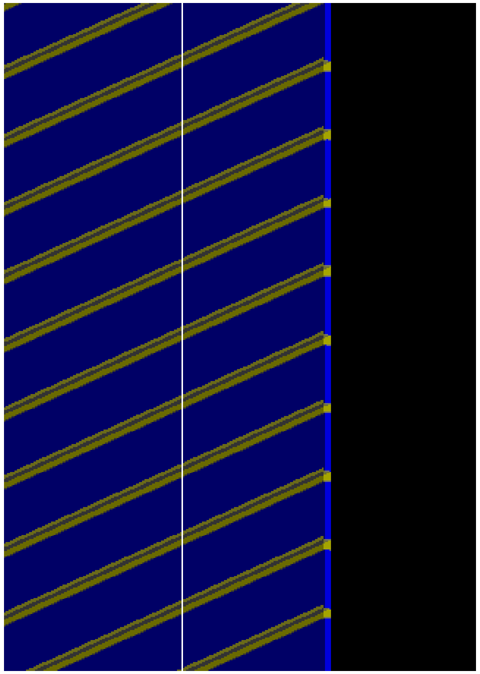
FD3 Proposal Standalone Geant4 Simulation

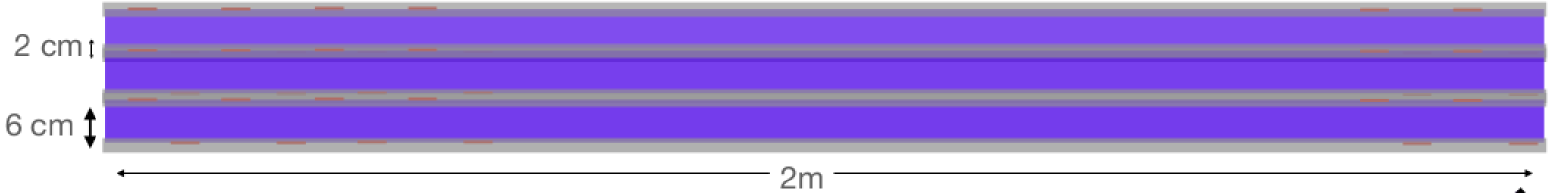
- Same optical properties as for VD simulations
- LAr refractive index, Rayleigh scattering, absorption
- Reflectivity of membrane, anode, cage field, etc
- **PTP emitted photons are also tracked**



Full volume
No FC vertical beam support

X-Arapuca in blue
FC profiles in yellow





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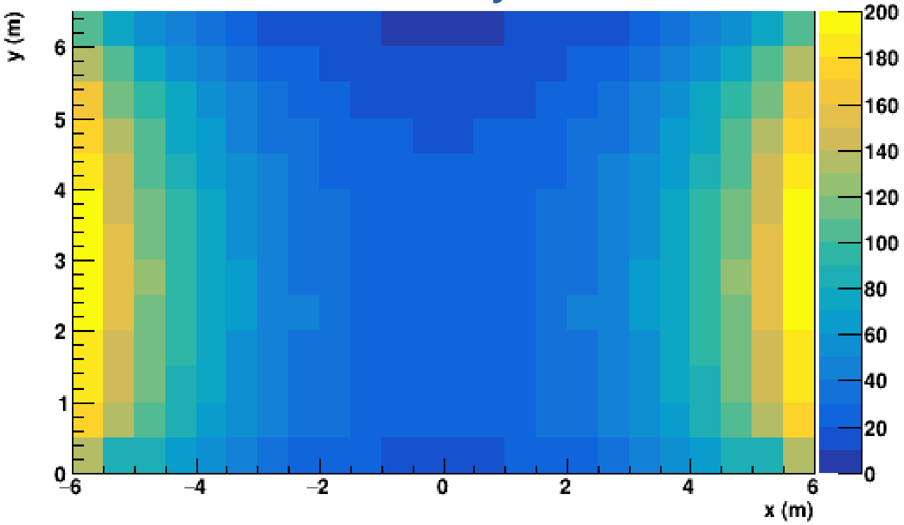
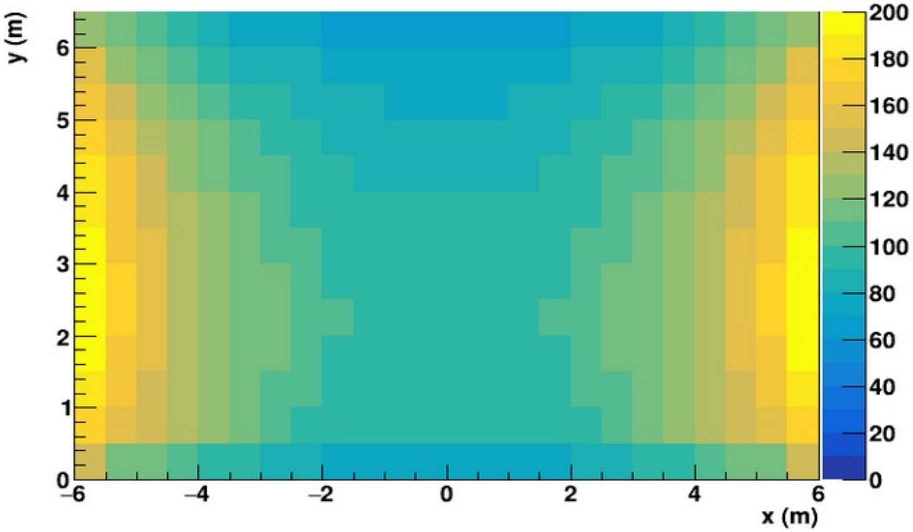
FD3 Proposal Standalone Geant4 Simulation

- Effect of Xe doping

Ar only



Ar + Xe



(Top volume only)

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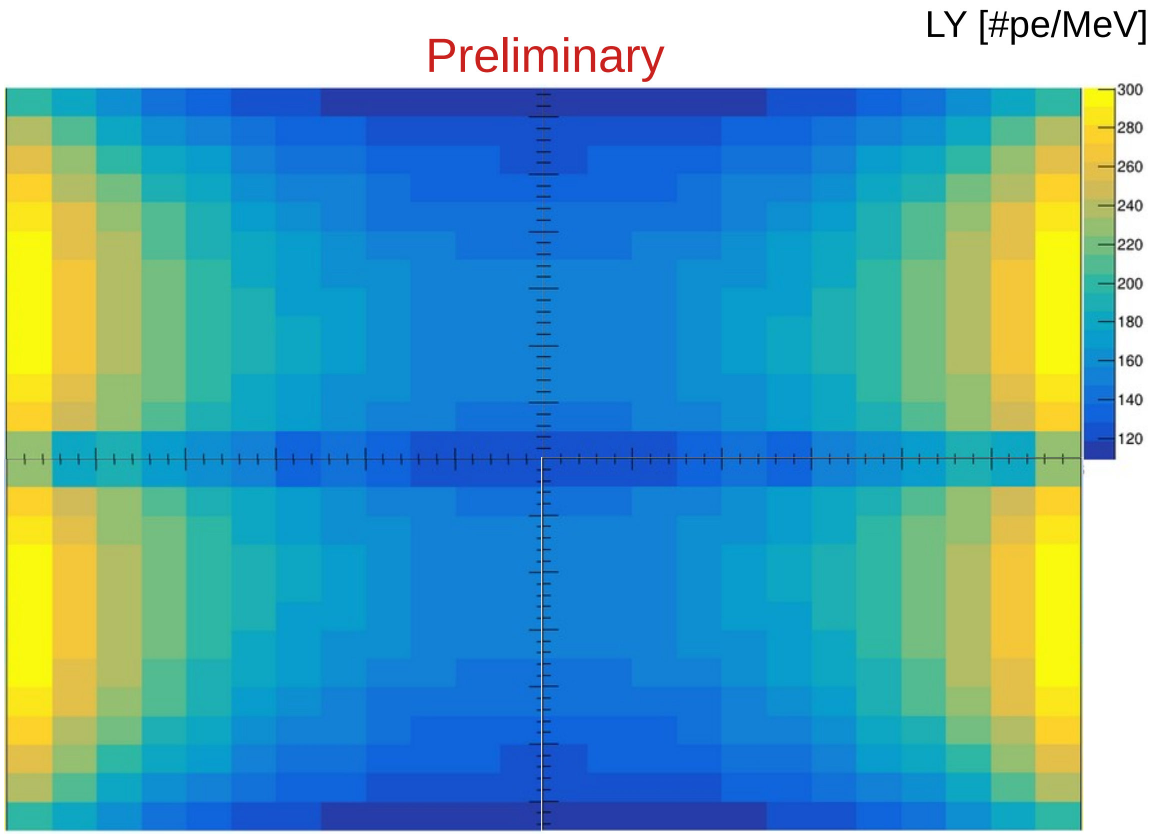
FD3 Proposal Light Yield Map

- Sensors efficiency: 2 %
- 25000 photons/MeV deposited
- All sensors detecting any level of light for evaluation
- No cut on #pe applied

$\langle LY \rangle$ = 181 PE/MeV

LY_{Min} = 128 PE/MeV

Preliminary



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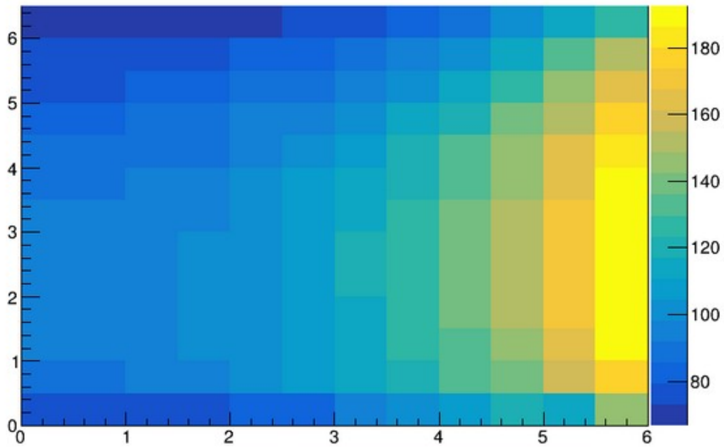
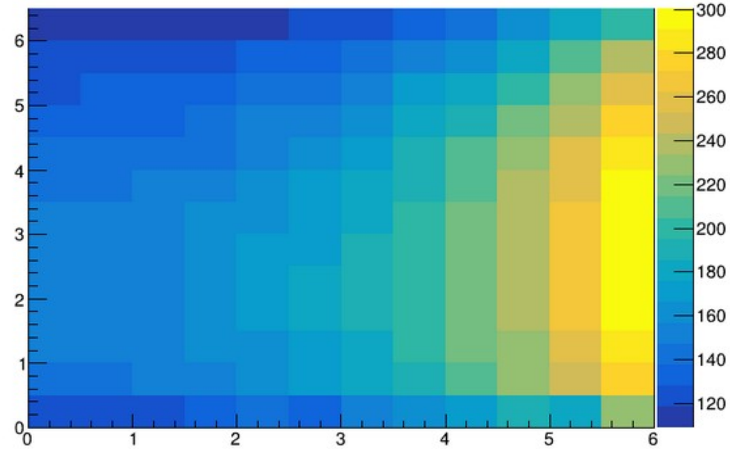
FD3 Light Yield Map: Impact of PTP backscattered light

Preliminary

LY$_{total}$ [#pe/MeV]



No backward emission

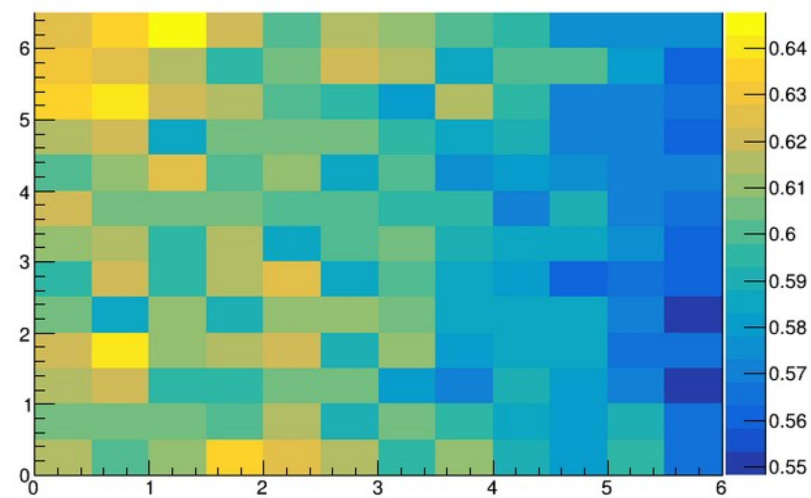


Including backward emission

- Total light yield increase due to backward ptp emissions

  Increase: $(LY_{total}^{ptp} / LY_{total}^{no\ ptp}) - 1$

- Percentage ~60 %



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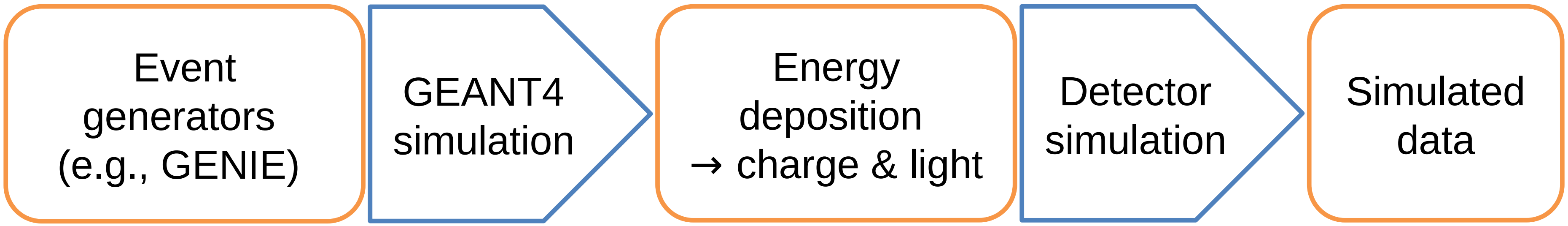
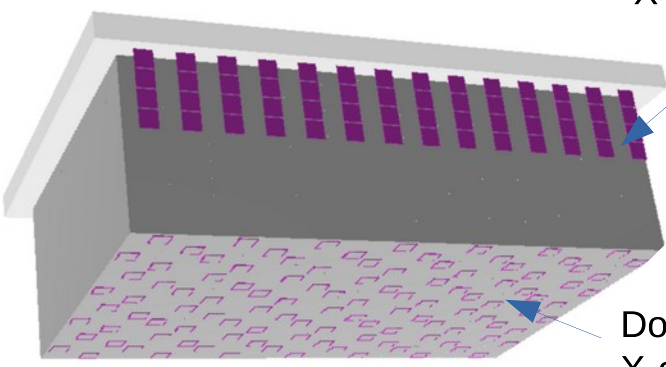
PDS Simulation Flow in LArSoft

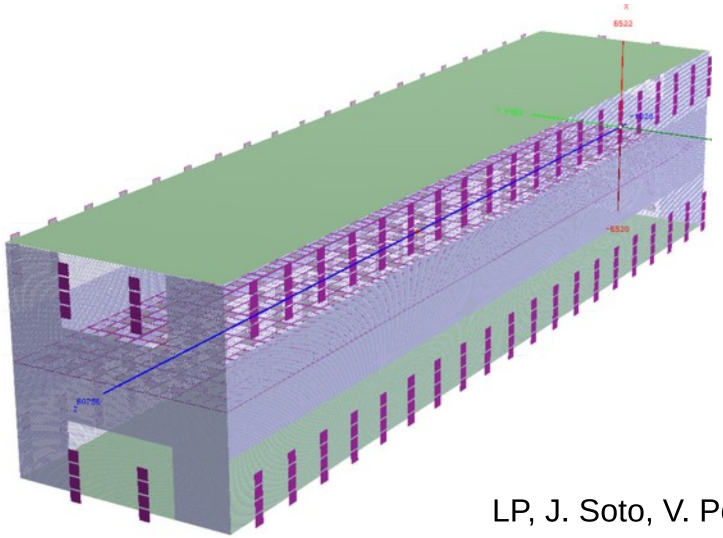


- Simulation implemented within common LArSoft framework
- GEANT4 tracks primary particles and their daughters through the detector geometry → energy depositions → number of ionization electrons and scintillation photons
- Detector simulation :
  - Photon hits in PDS according to “visibility” of the given volume element + convolution with electronics → digitized waveforms

Building on the VD PDS experience: LArSoft

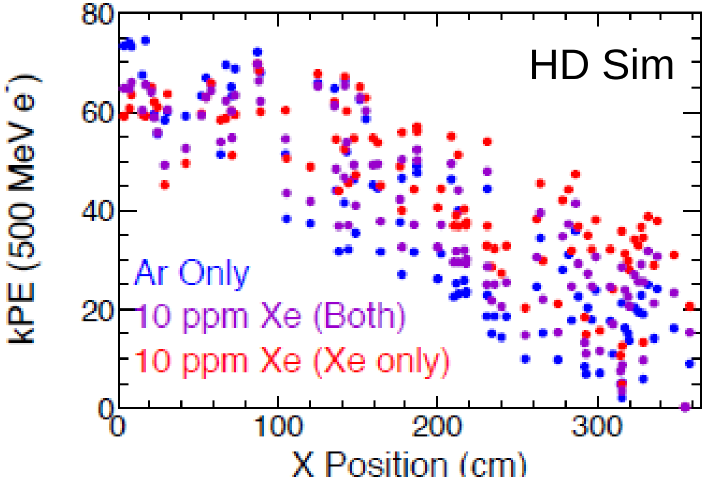
- Geometry





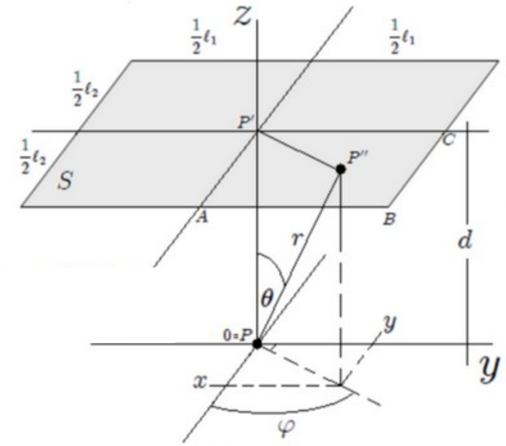
LP, J. Soto, V. Pec

- Simulation of Xe-doped Light:
  - Ar e Xe light in the same job with separately light yields (QEs)

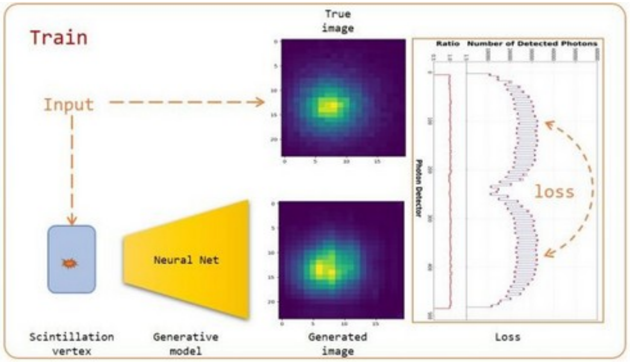


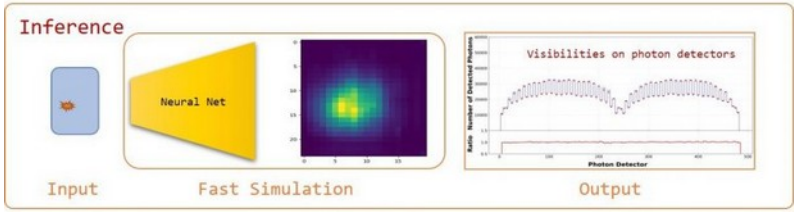
A. Himmel, W. Mu, B. Behera

VD PDS in LArSoft

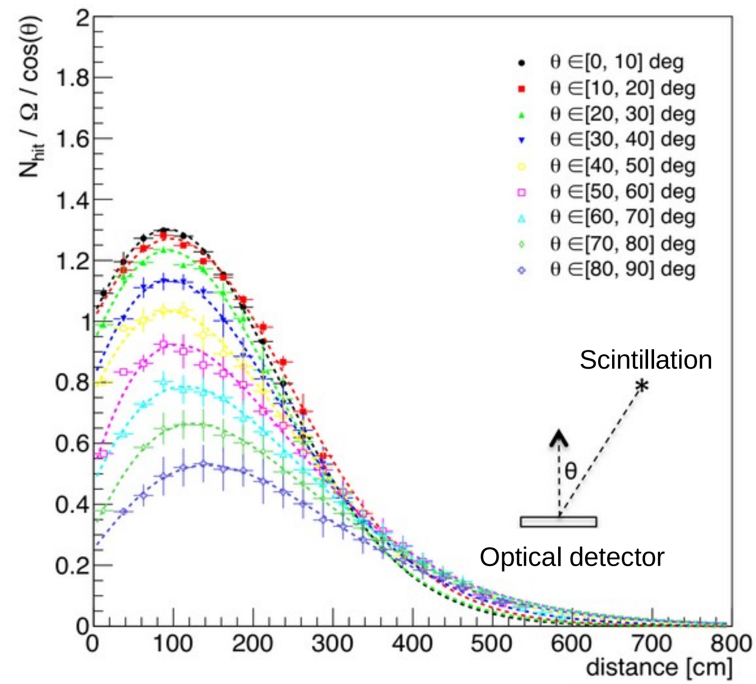


- **Fast light simulation**
  - semi-analytic model → parameterization according to PD-source distance and relative angle
  - Computable graph → generative NN trained on full optical G4 sample





W. Mu, A. Himmel

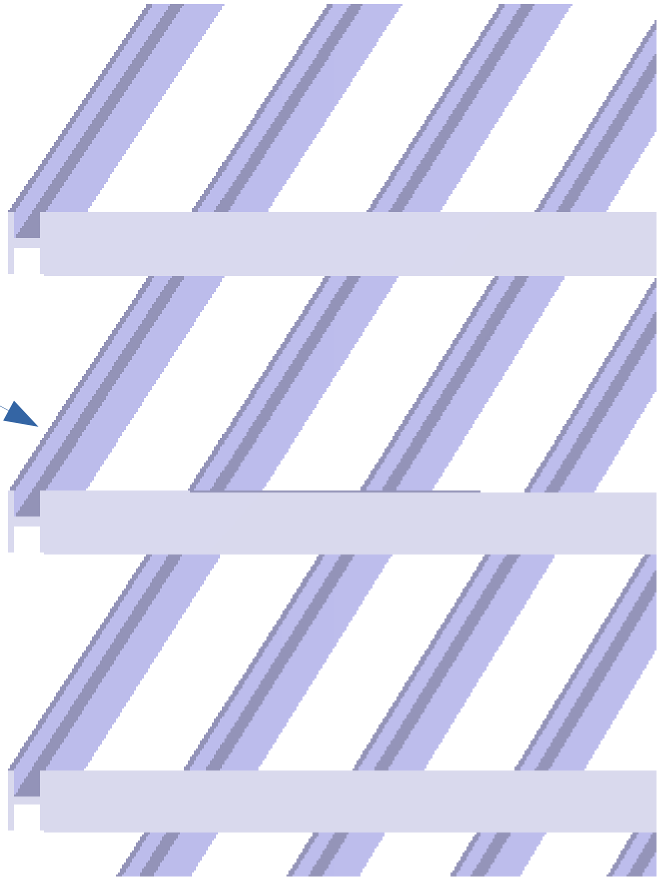


J. Li, P. Green, A. Szelc

FD3 Proposal PDS in LArSoft

- Geometry on the way

H-shaped Field Cage
profiles in place



- Need to include PTP emission

H. Amar, J. Soto

Module 3 Proposal Simulation To-do list

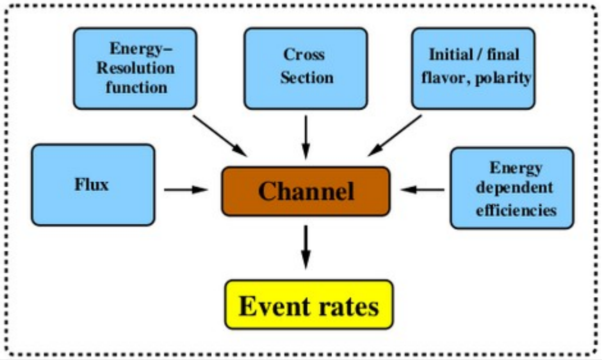
- Simulation of the new Arapuca design
- Improve Geant4 Standalone Simulation
  - Greater PD granularity
  - Other general improvements to geometry (e.g. include vertical FC bars)
  - Preliminary studies on system's capabilities
- Implement full LArSoft simulation
  - Geometry being implemented
  - Fast optical sim
  - Digitizer stage
  - Reconstruction

Summary:

- Current simulation efforts:
  - Geant4 Standalone Simulation
    - Tool for improving PDS performance and evaluating design options
    - Preliminary information on
      - Position and energy resolution
      - Trigger capabilities
      - Timing studies
  - LArSoft Tools
      - Detailed physics studies including the impact of backgrounds

BACKUP

Possible Impact of a better PDS E resolution



- Calorimetry for beam events → impact on oscillation studies

$$n_a = N\,\epsilon_a \int_0^\infty dE\,\phi(E) P_{3\nu}^{\rm osc}(E)\sigma(E) \int_{E_a-\Delta E_a/2}^{E_a+\Delta E_a/2} dE^{\rm rec} R(E, E^{\rm rec})$$

energy resolution function

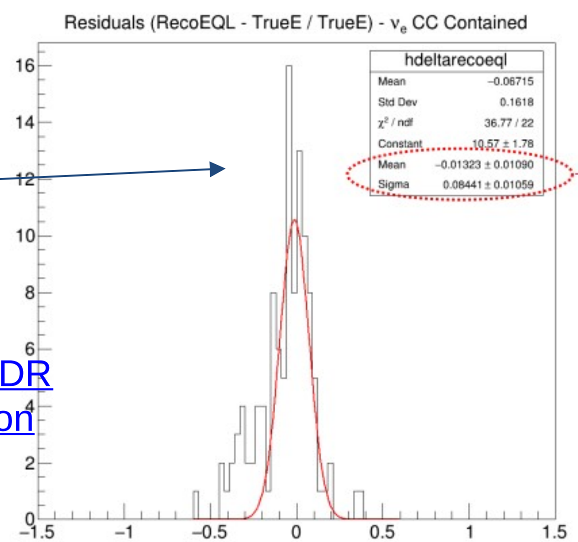
  - Neutrino energy resolution at the far detector is ∼15 to 20%, depending on lepton flavor and reconstruction method [1]
  - Preliminary studies in FD1 combining charge and light signals [2]

Charge: $Q = N_e = N_i R$

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

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

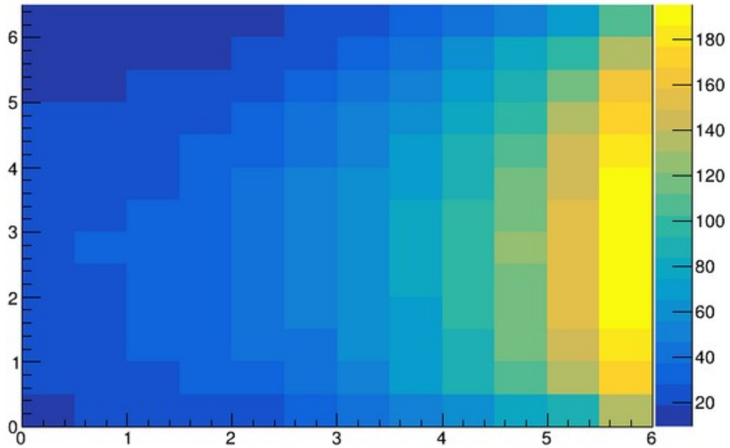
No dependence on recombination factor



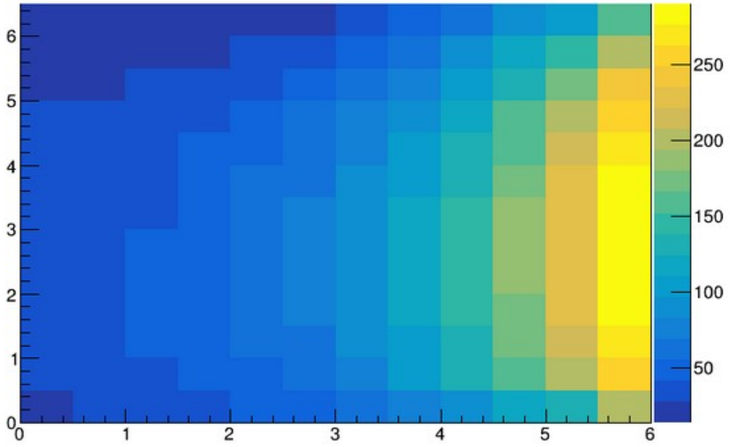
8% overall energy resolution for ν_e CC events

[1] Experiment Simulation Configurations Approximating DUNE TDR
[2] G. Brunetti, M. Torti, D. Guffanti, FD Sim/Reco WG presentation

LY_{LAr} [#pe/MeV]



No backward emission

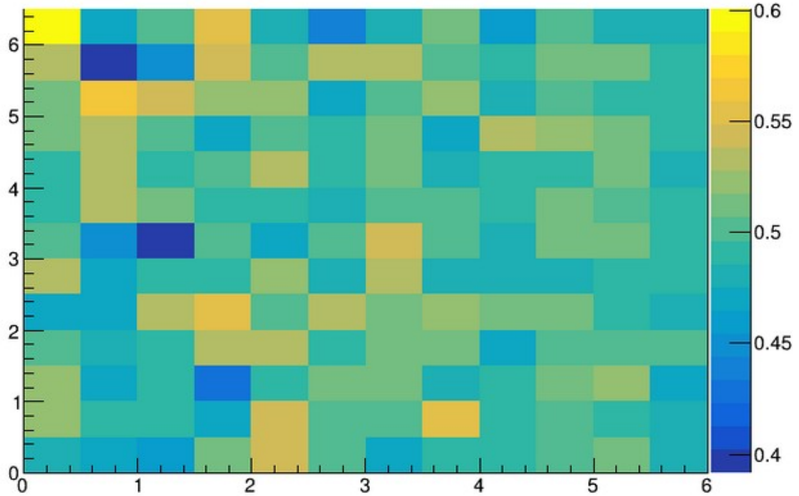


Including backward emission

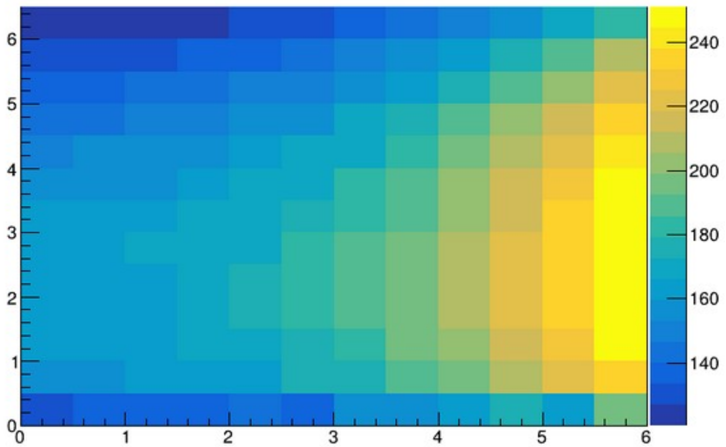
- Direct LAr light yield contribution increase due to backward ptp emissions

  Increase: $(LY_{LAr}^{ptp} / LY_{LAr}^{no\ ptp}) - 1$

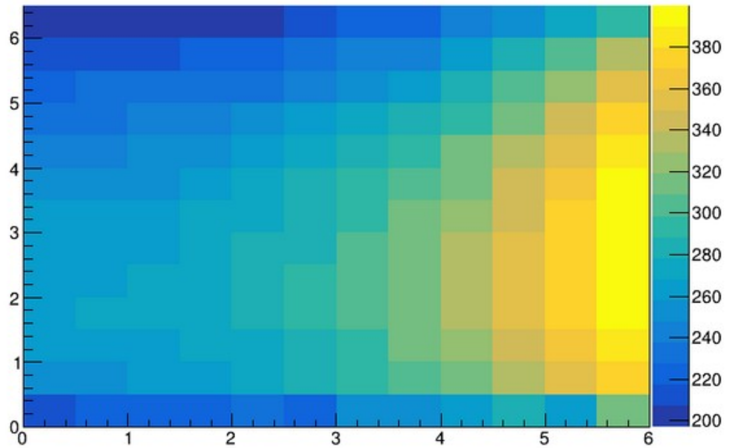
- Percentage ~50 %
  - uniform across volume



LY_{Xe} [#pe/MeV]



No backward emission

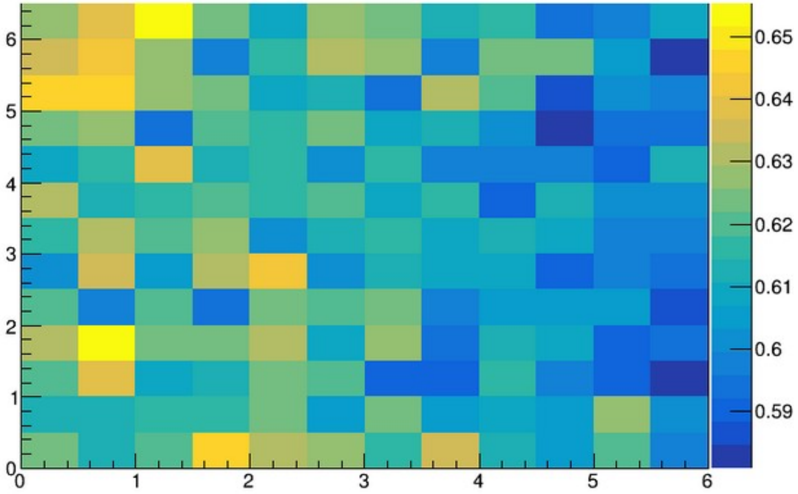


Including backward emission

- Xe doping light yield contribution increase due to backward ptp emissions

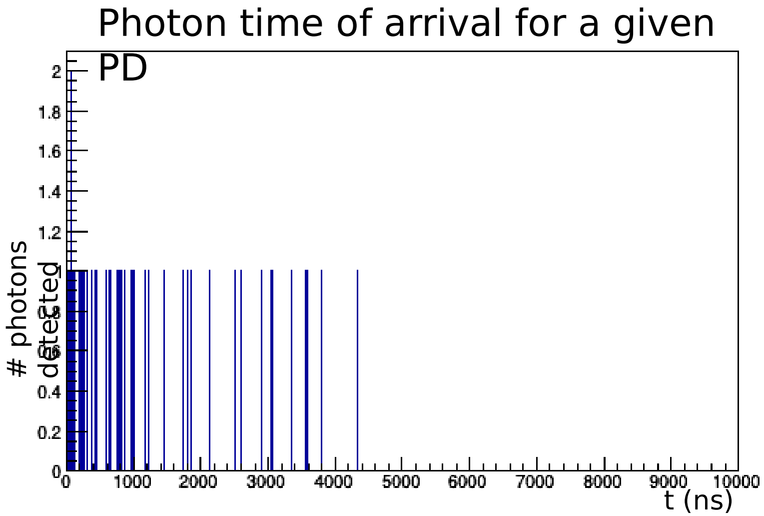
  Increase: $(LY_{Xe}^{ptp} / LY_{Xe}^{no\ ptp}) - 1$

- Percentage >60 %
- Higher impact noticed closer to the lower LY region

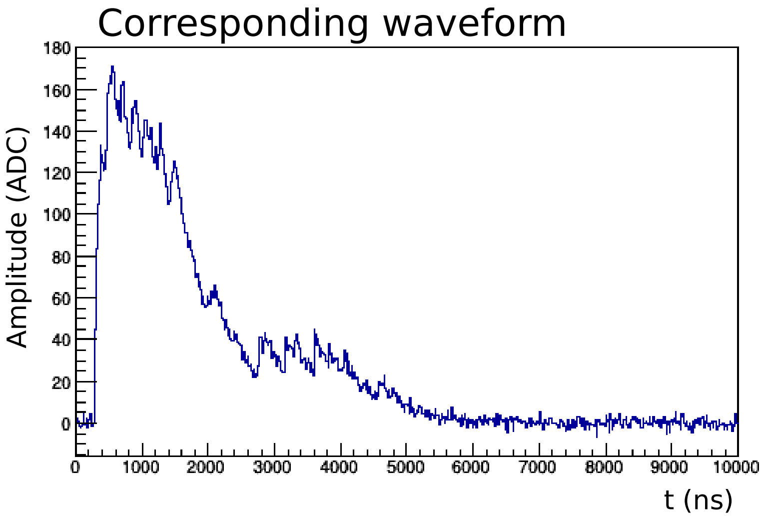


VD Time Information in the Reference Design

- Optical waveforms taking into account
  - Emission time (Ar and Xe)
  - Propagation time
  - X-ARAPUCA QE
  - X-ARAPUCA shifters
  - SiPM (single PE profile, crosstalk...)



- Detector performance studies
  - Timing resolution
  - Digitizer requirements (dynamic range, sampling frequency...)
  - Improving position resolution



F. Marinho

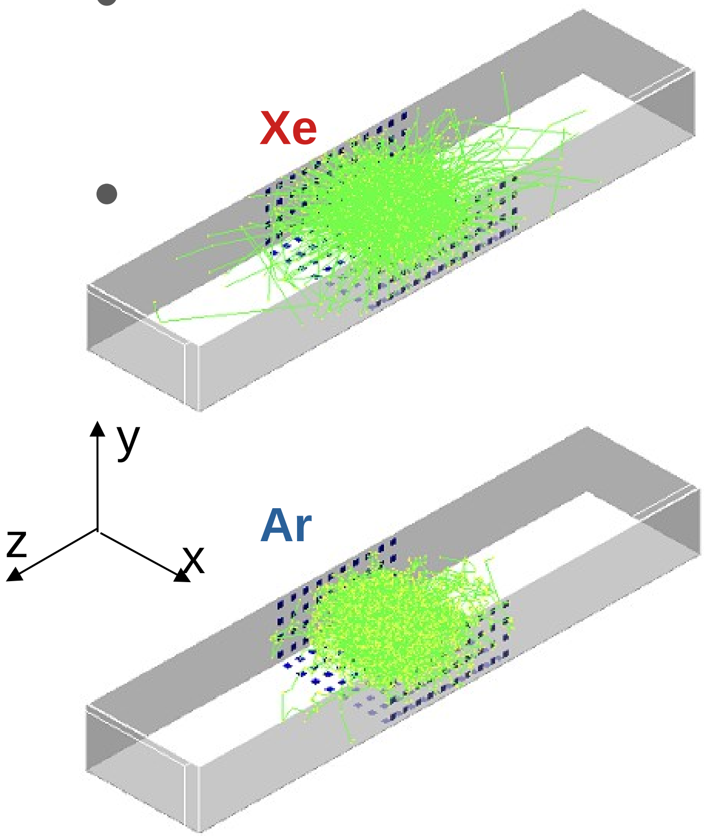
HD Single Phase PDS Requirements

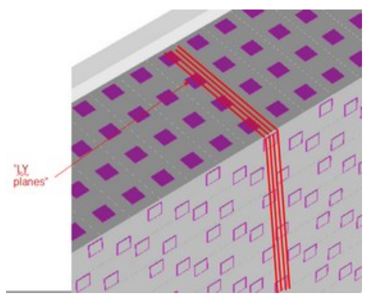
Label	Description	Specification (Goal)	Rationale	Validation
SP-FD-3	Light yield	$>$ 20 PE/MeV (avg), $>$ 0.5 PE/MeV (min)	Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV SN νs, and allows tagging of $> 99\,\%$ of nucleon decay backgrounds with light at all points in detector.	Supernova and nucleon decay events in the FD with full simulation and reconstruction.
SP-FD-4	Time resolution	$< 1\,\mu s$ ($< 100\,ns$)	Enables 1 mm position resolution for 10 MeV SNB candidate events for instantaneous rate $< 1\,m^{-3}ms^{-1}$.	
SP-FD-15	LAr nitrogen contamination	$< 25\,ppm$	Maintain 0.5 PE/MeV PDS sensitivity required for triggering proton decay near cathode.	In situ measurement
SP-PDS-2	Spatial localization in y-z plane	$< 2.5\,m$	Enables accurate matching of PD and TPC signals.	SNB neutrino and NDK simulation in the FD

- Current taken as guidelines

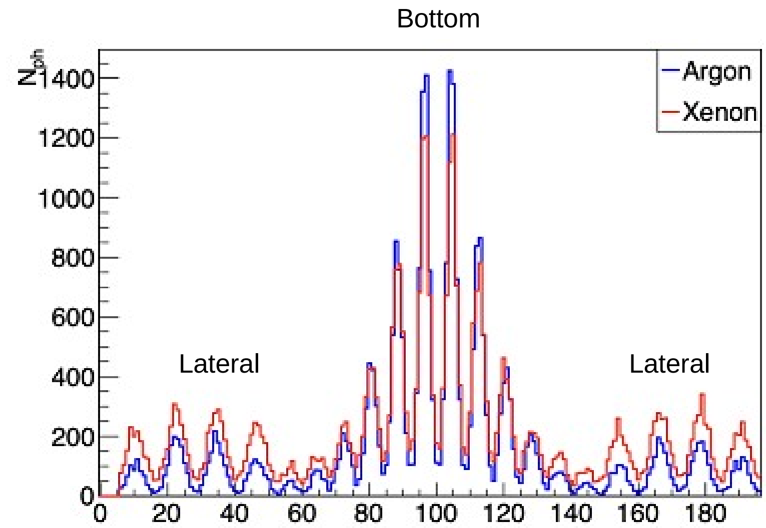
VD Reference Design Simulation

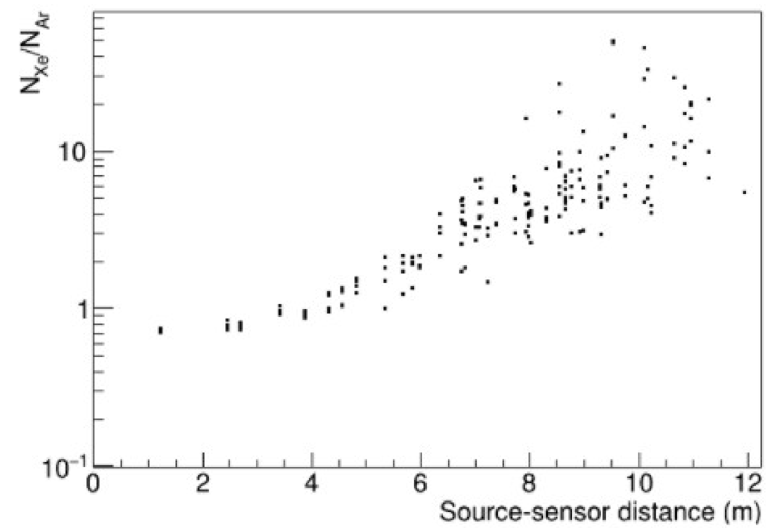
192 tiles in ~1/6
VDrift volume





Photons per PD:





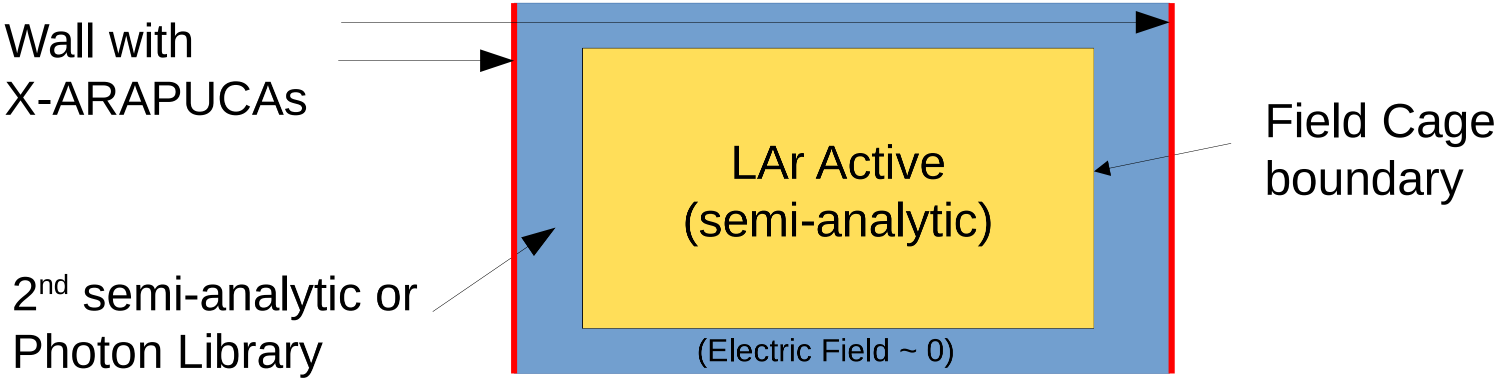
Fast Light Sim in Vertical Drift

- LAr Active volume
  - Semi-analytic model

- Volume outside the Field Cage
  - Hybrid model (Optical library outside active volume)

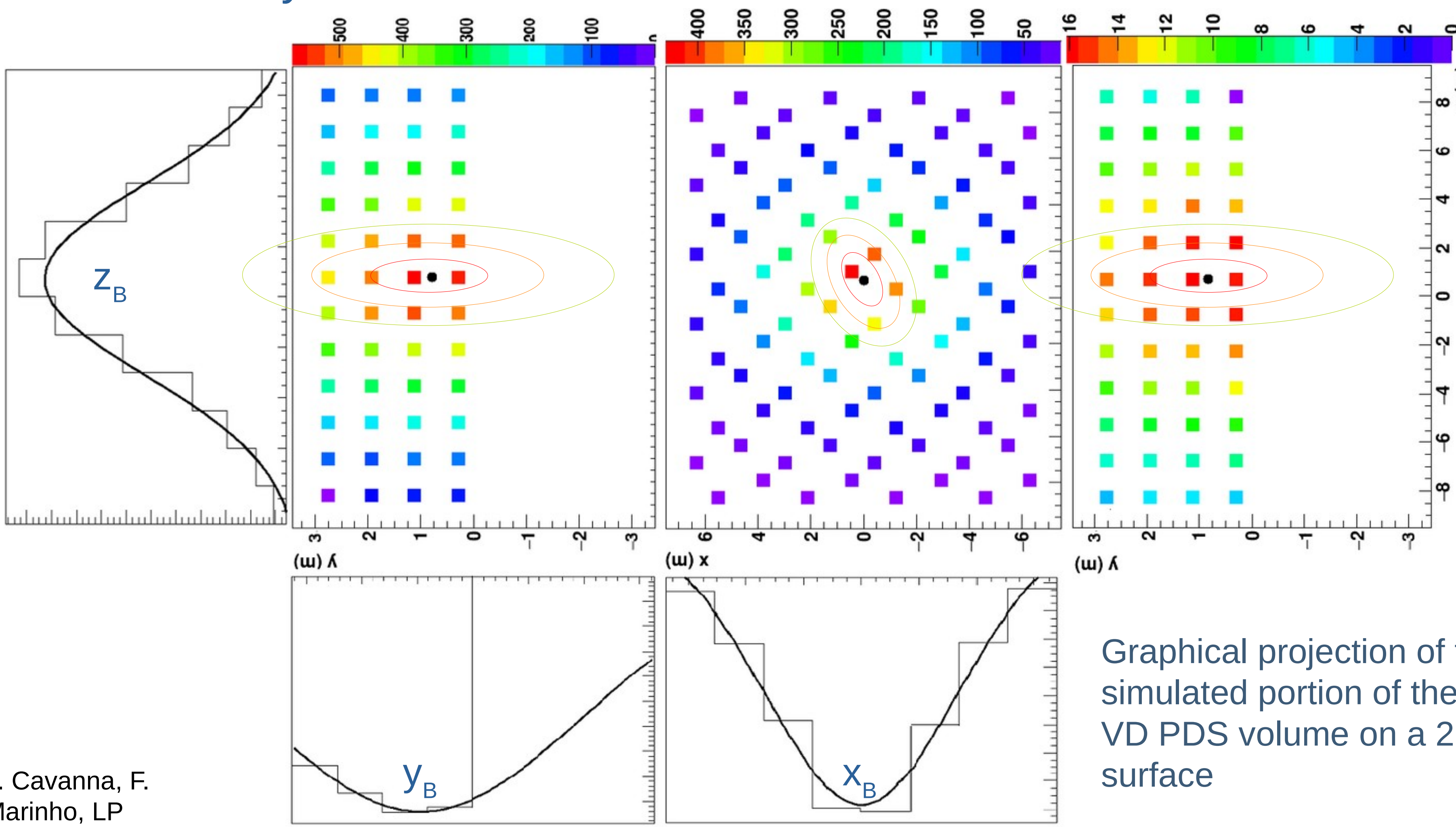
OR

  - Second set of parameters for semi-analytic model



VD Position Resolution in the Reference Design

- From barycenter determination

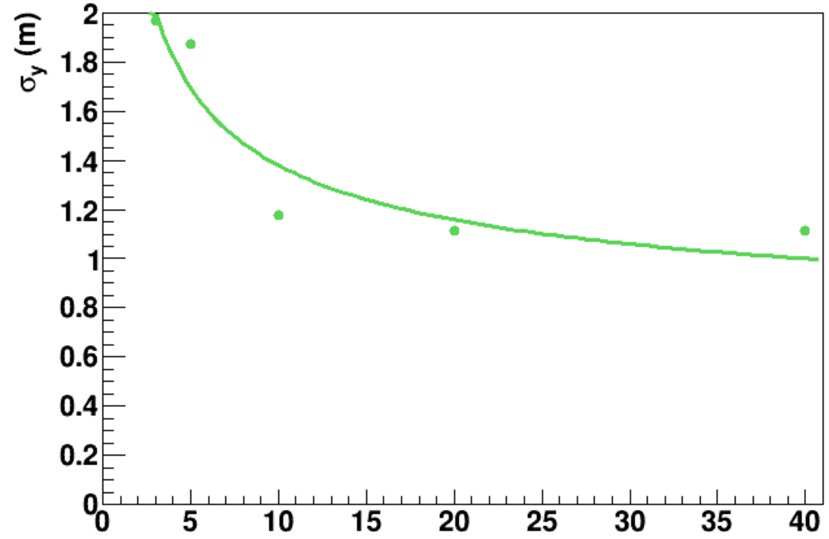


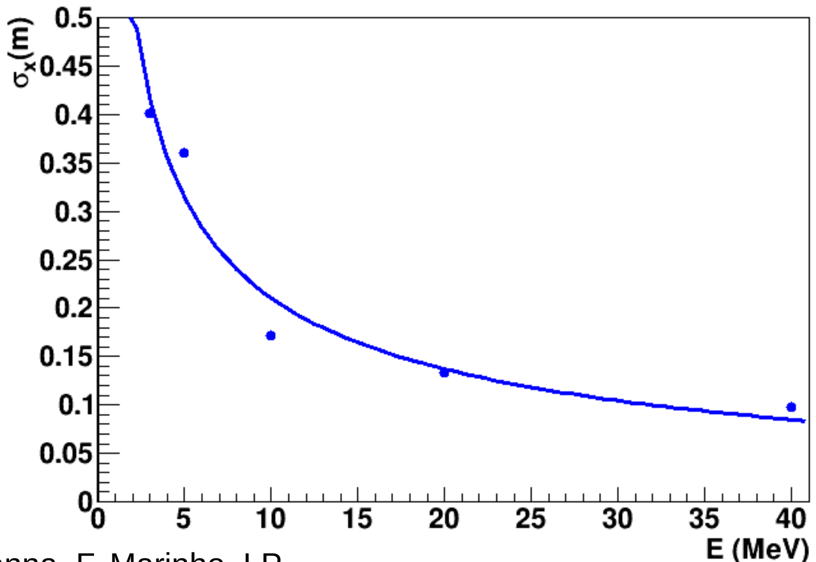
Graphical projection of the simulated portion of the VD PDS volume on a 2D surface

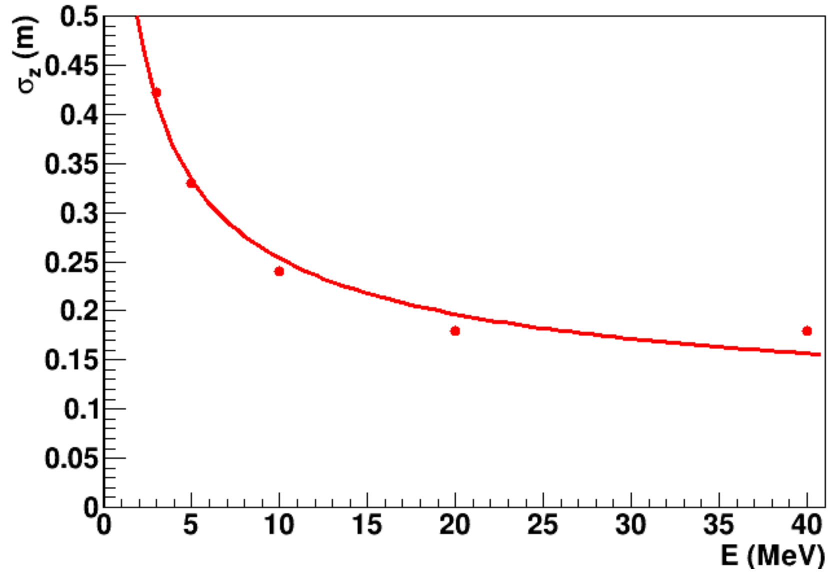
F. Cavanna, F. Marinho, LP

VD Position Resolution in the Reference Design

- Resolution propto 1/sqrt(E)
- Good position resolution in x and z
- In y: less photons
  - Expect improvements with timing and/or cathode information







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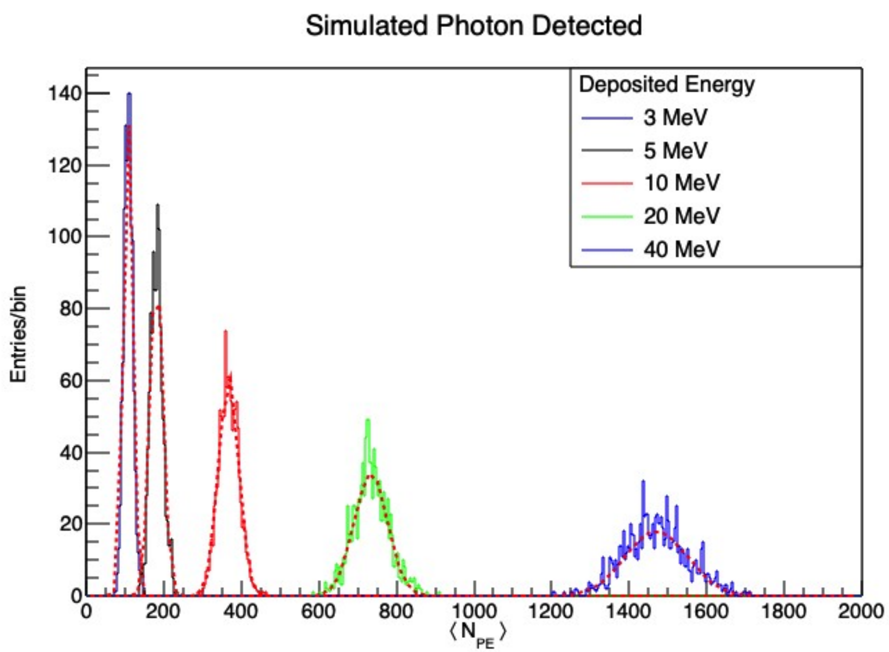
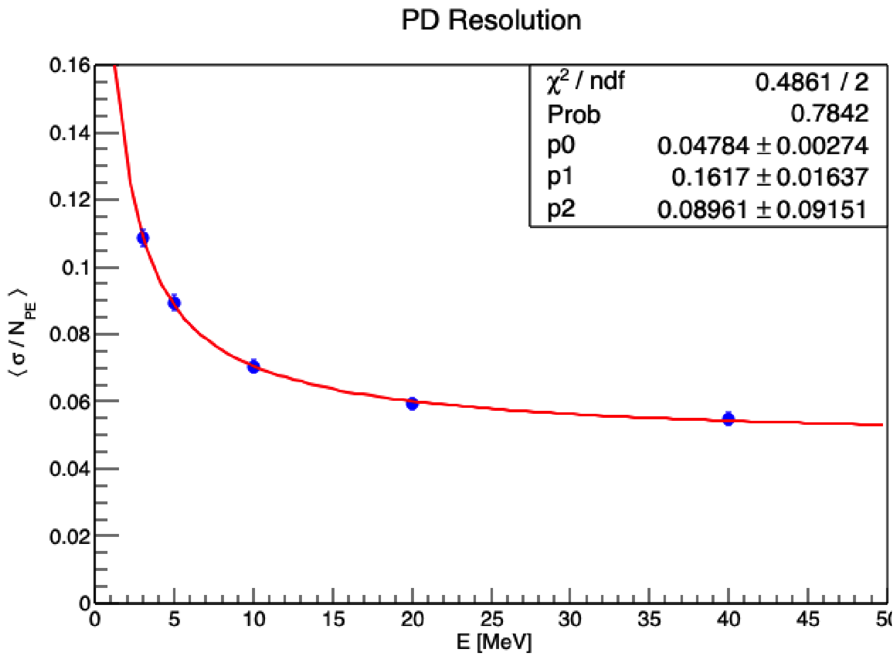
VD Energy Resolution in the Reference Design

- Point-like source at the center of top volume
  - Uncertainty on energy calibration (p0)
  - Statistical fluctuation (p1) on the number of detected PEs
  - Noise term (p2)





F. Cavanna, F. Marinho, LP, D. Totani

VD Preliminary Dynamic Range Studies

- 6 GeV e- shower @ 0.5m from cathode
- Pure LAr, λabsorption = 50m