Impact of Photosensitive Dopants on DUNE Physics Program

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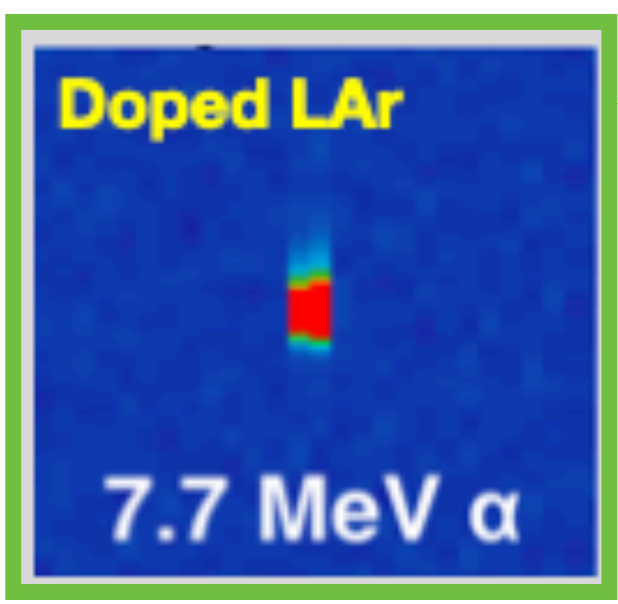
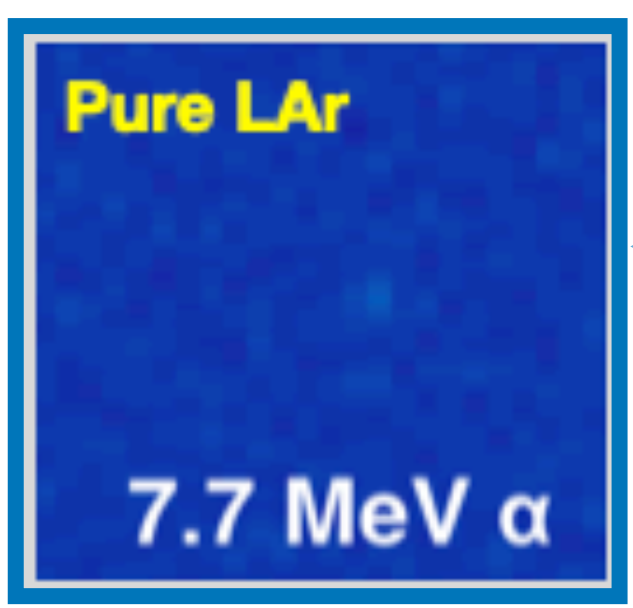
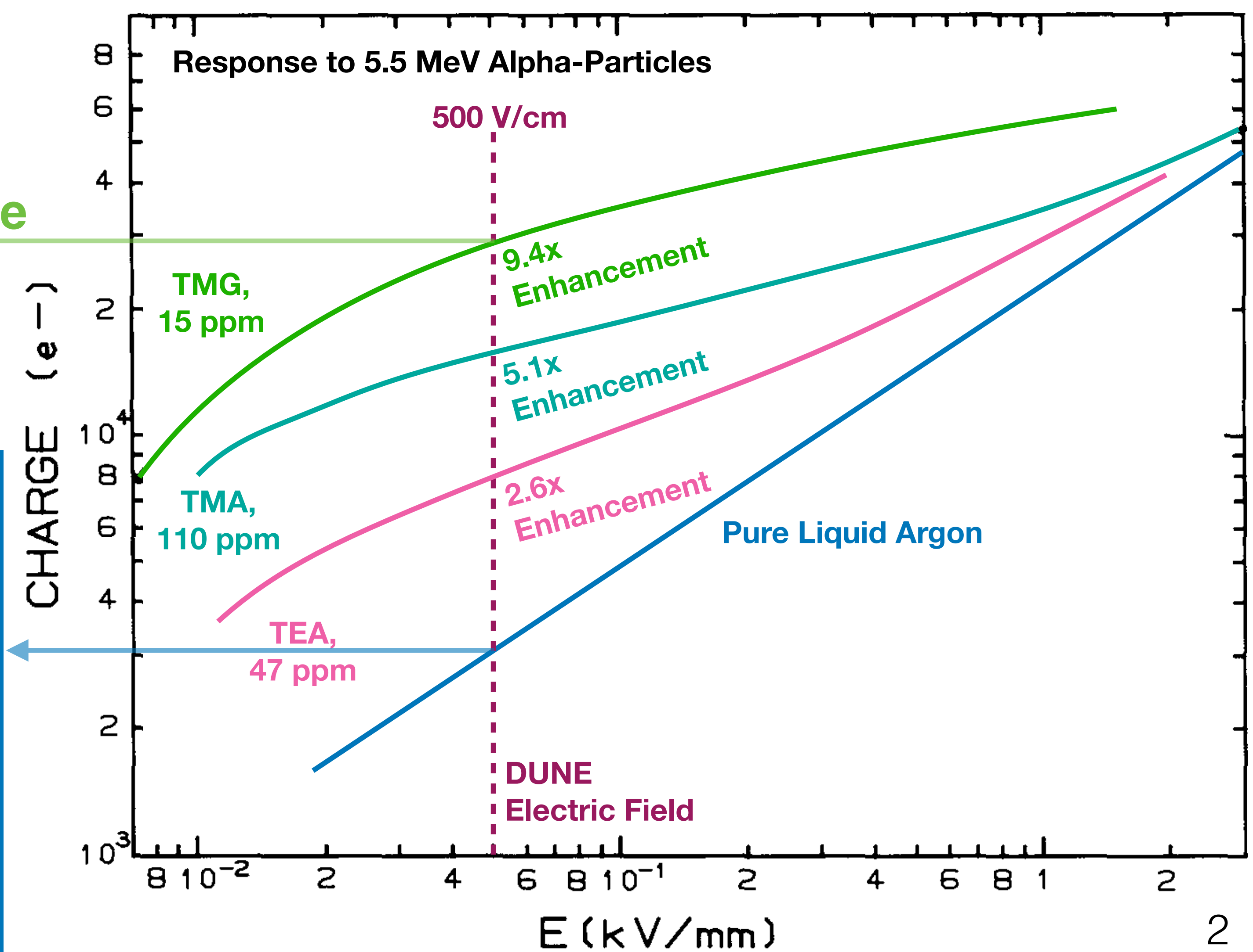
Photosensitive Dopants

- Dopants convert isotropic UV light into directional charge
  - Past demonstrations have shown ~60% of light is converted to charge
  - A huge increase in the information collected about the scintillation channel
- Only requires doping to the ppm level with a hydrocarbon
  - No negative impact on electron drift characteristics



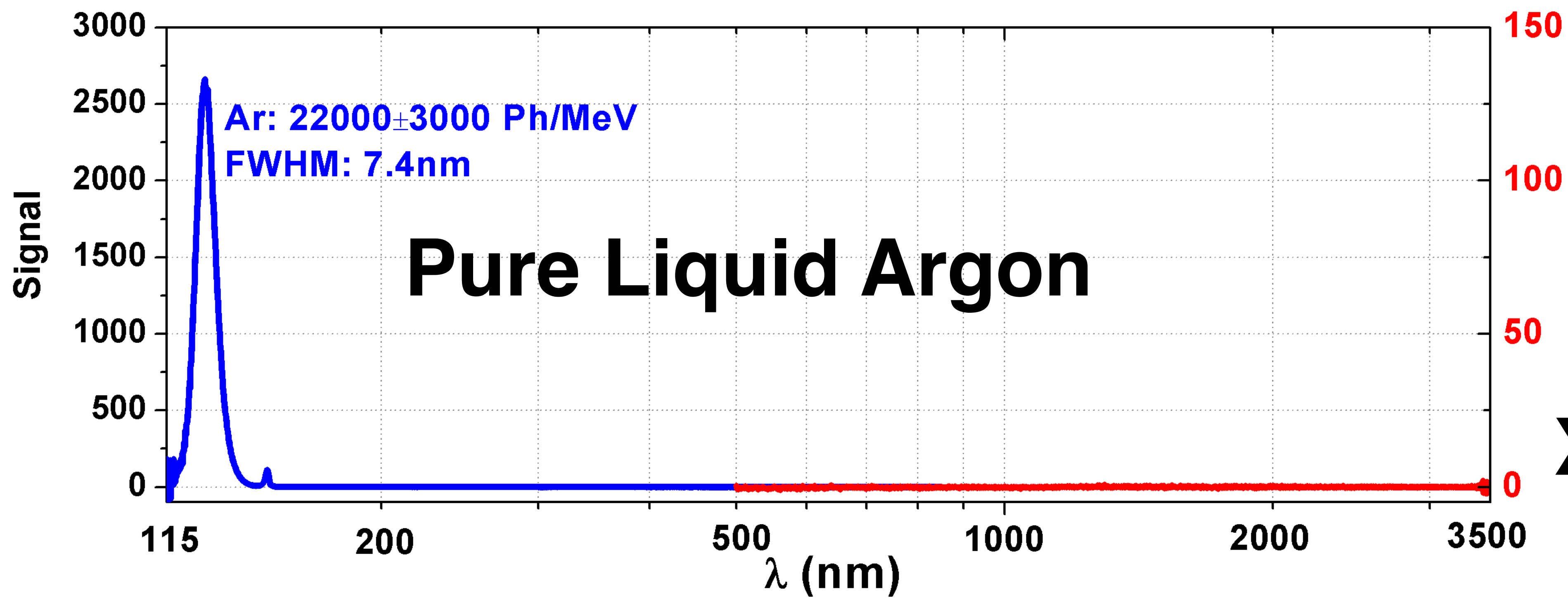
Light turned to charge





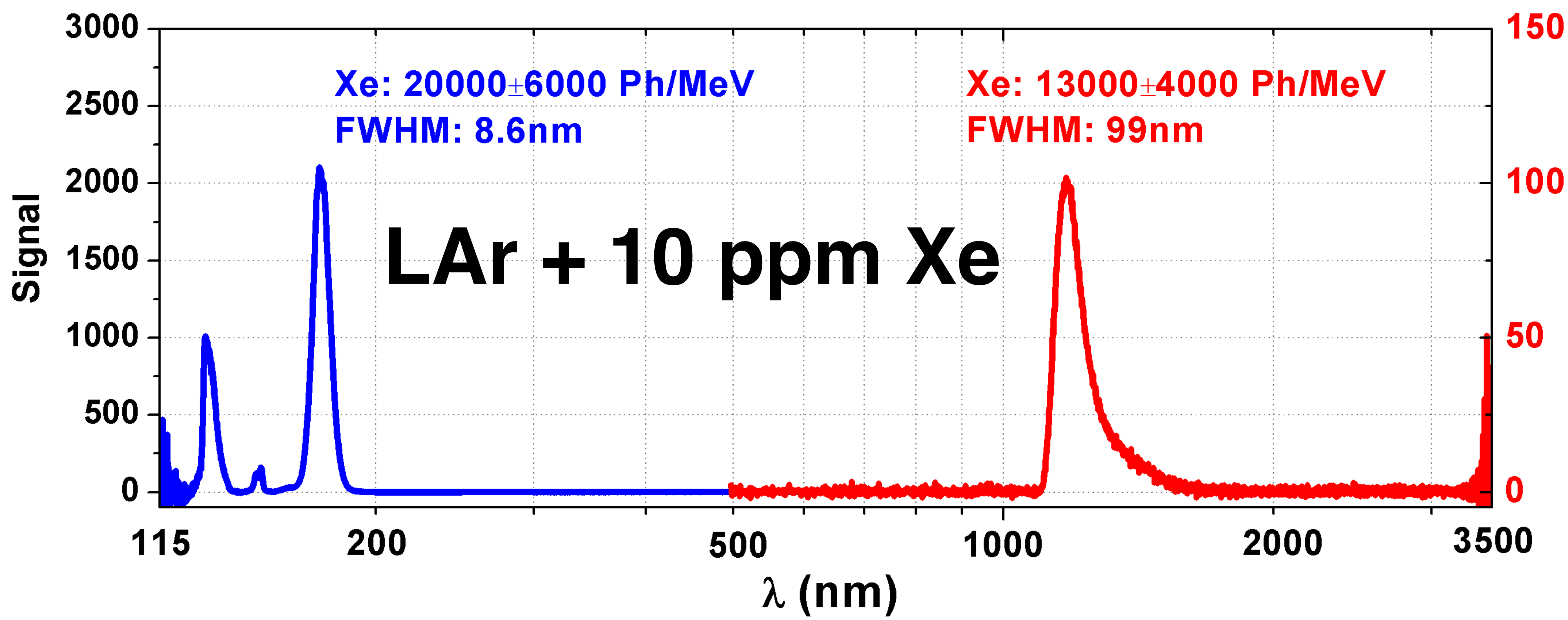
Same simulated alpha event!

Can One Trigger Such a LArTPC?



Xenon doped LAr creates IR light!

A. Neumeier et al., Europhys. Lett. 109 12001 (2015)



IR light won't ionize dopant

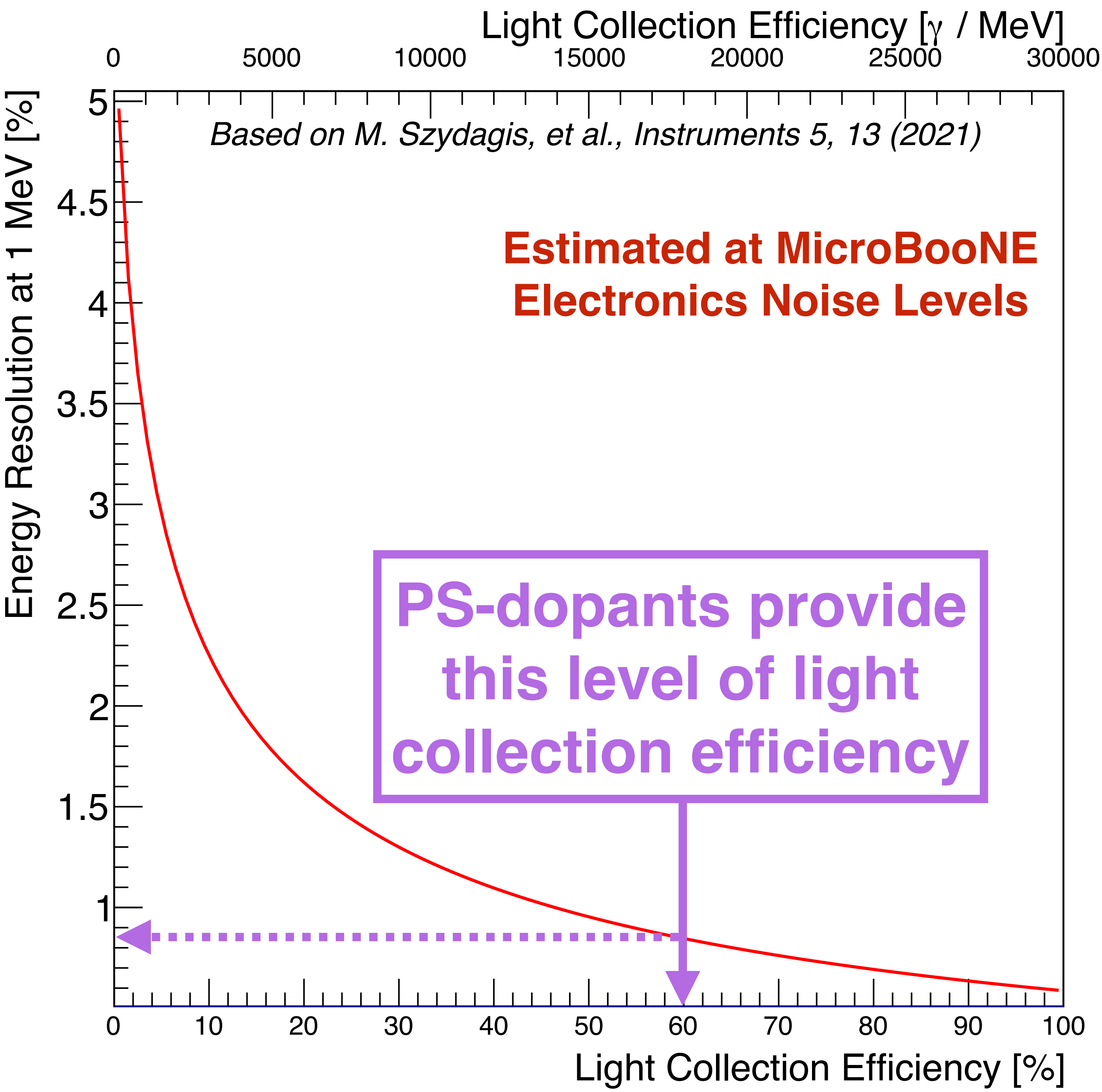
Can be used for triggering

Detector Concept

- To achieve this one would need to dope a Far Detector module with a few ppm of xenon and a PS-dopant
  - Doping a full 17-kton FD module would cost O($700,000)
  - Could be even cheaper without xenon, but this would mean no taggable light signals
- These dopants can work equally well with any single-phase charge readout (CRPs, pixels, etc.)
- One could forego light detectors completely, resulting in additional cost savings
  - Using the beam timing one can achieve 10 μs timing resolution for accelerator neutrinos
  - For supernova neutrinos, drift time provides ms-scale timing resolution
  - Both of which could be sufficient

Impact on Low Energy Electrons, Theory

- Measuring particle energies calorimetrically is improved by combining light & charge
- PS-dopants can enable the conversion of 60% of the light to charge
- This allows light+charge calorimetry directly from the ionization signals
- This is expected to enable 1% level energy resolution for low-energy electrons



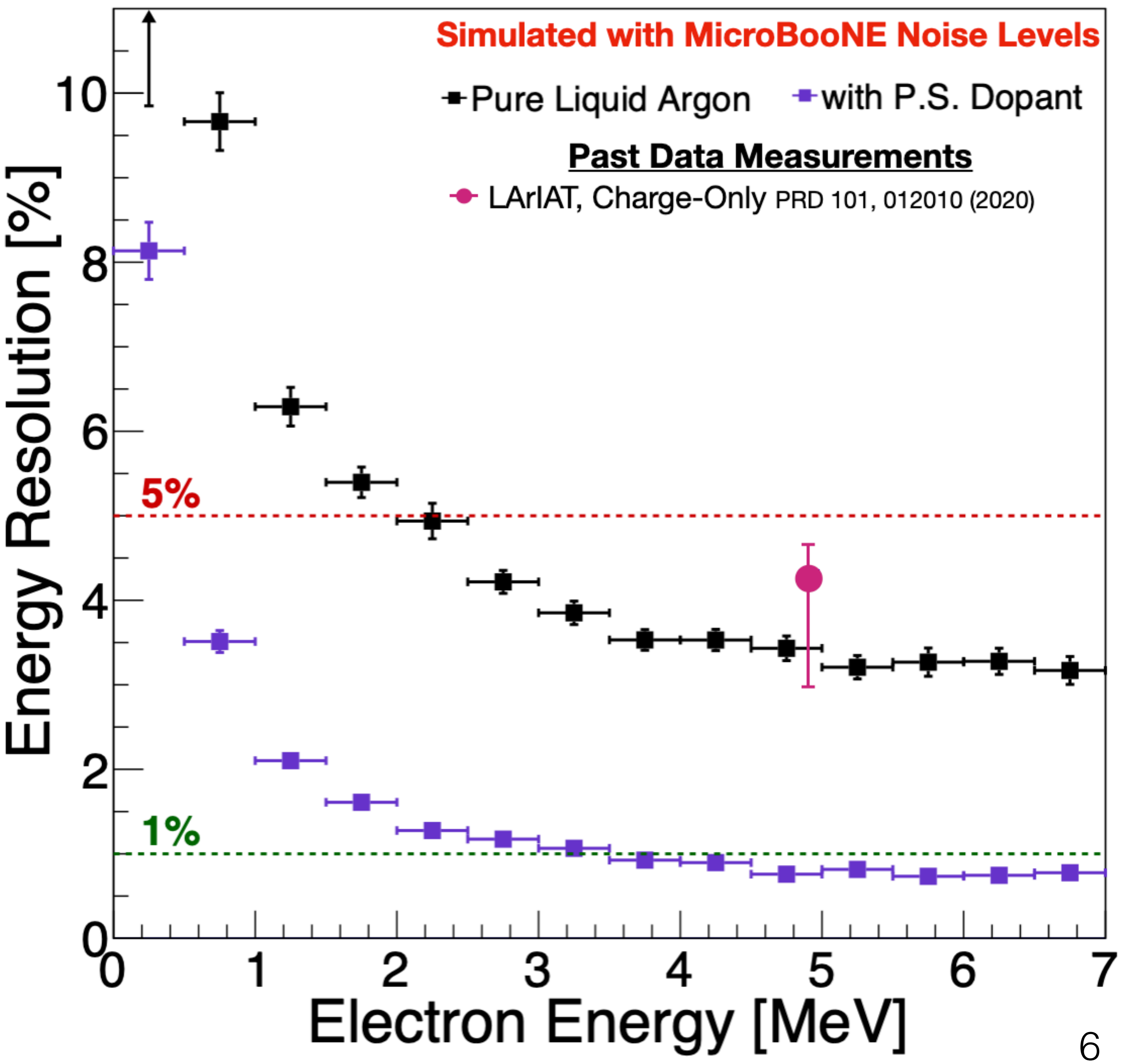
Impact on Low Energy Electrons, Full Simulation

- Tested in a full LArSoft LArTPC detector simulation with real noise, signal simulation, signal processing, and reconstruction

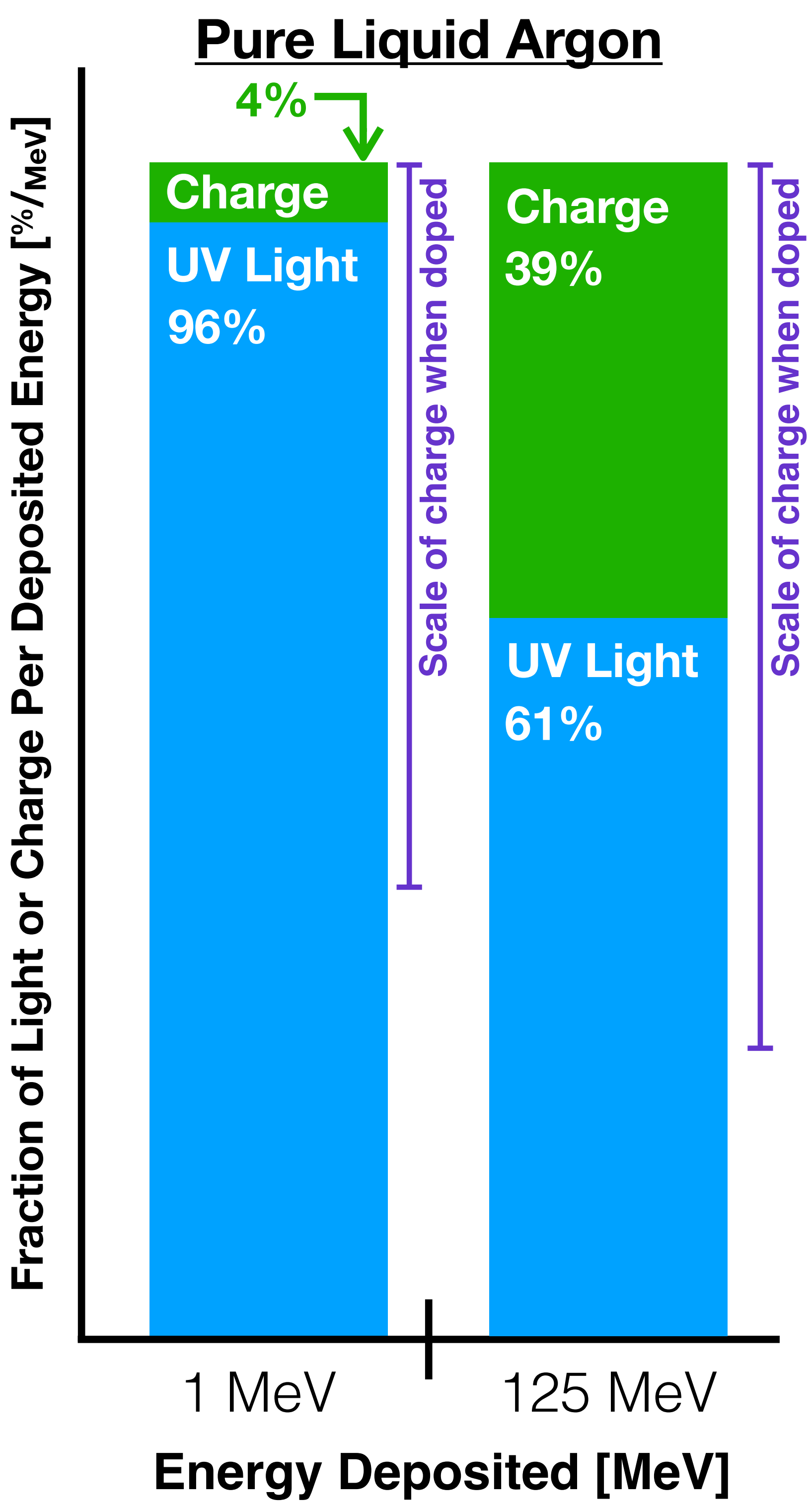
- The estimated energy resolution for pure argon was validated against results from LArIAT

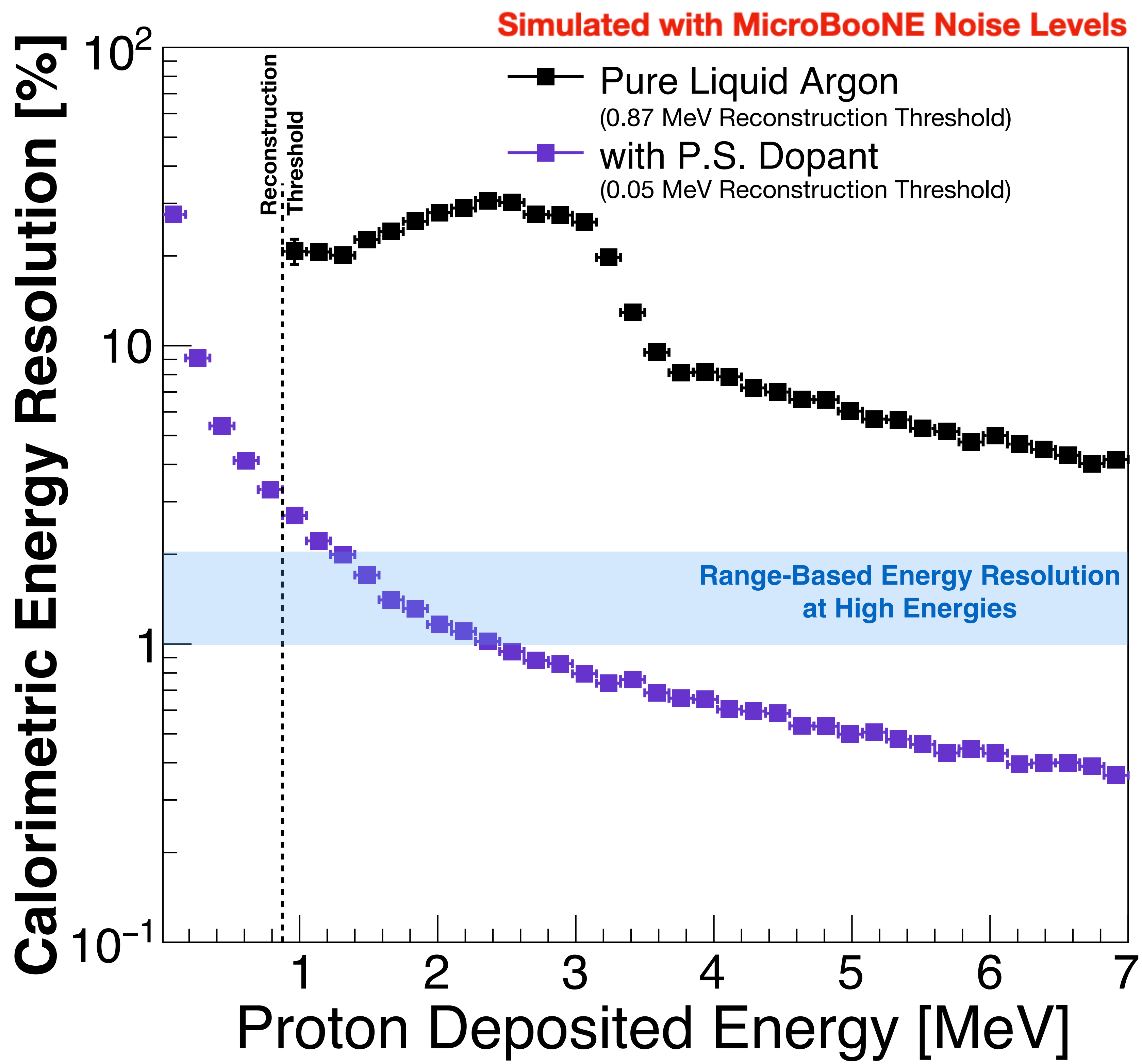
- When simulating PS-dopant we find the energy resolution improve substantially

Based on full detector simulation and full reconstruction with realistic noise



Impact on Hadrons

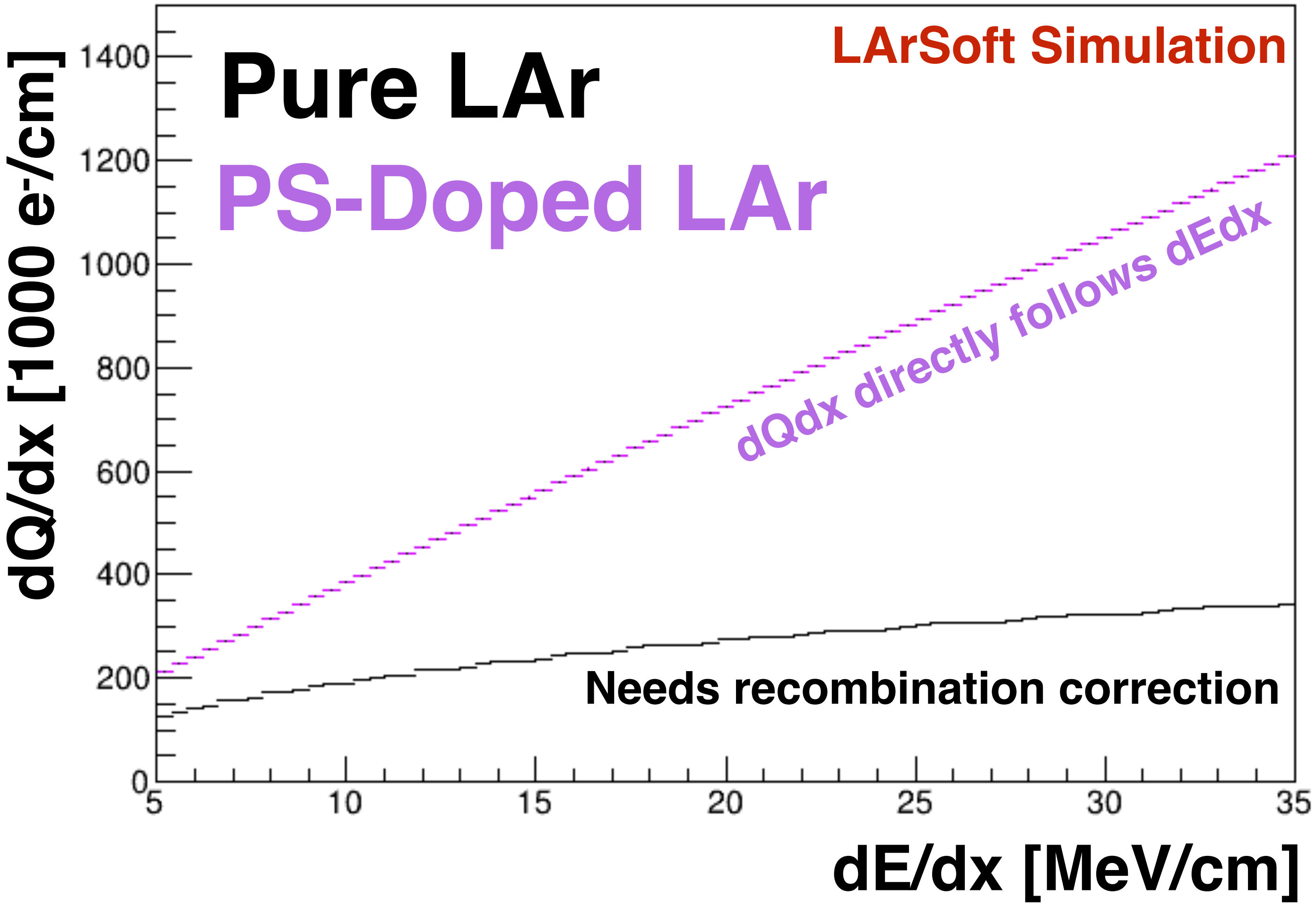


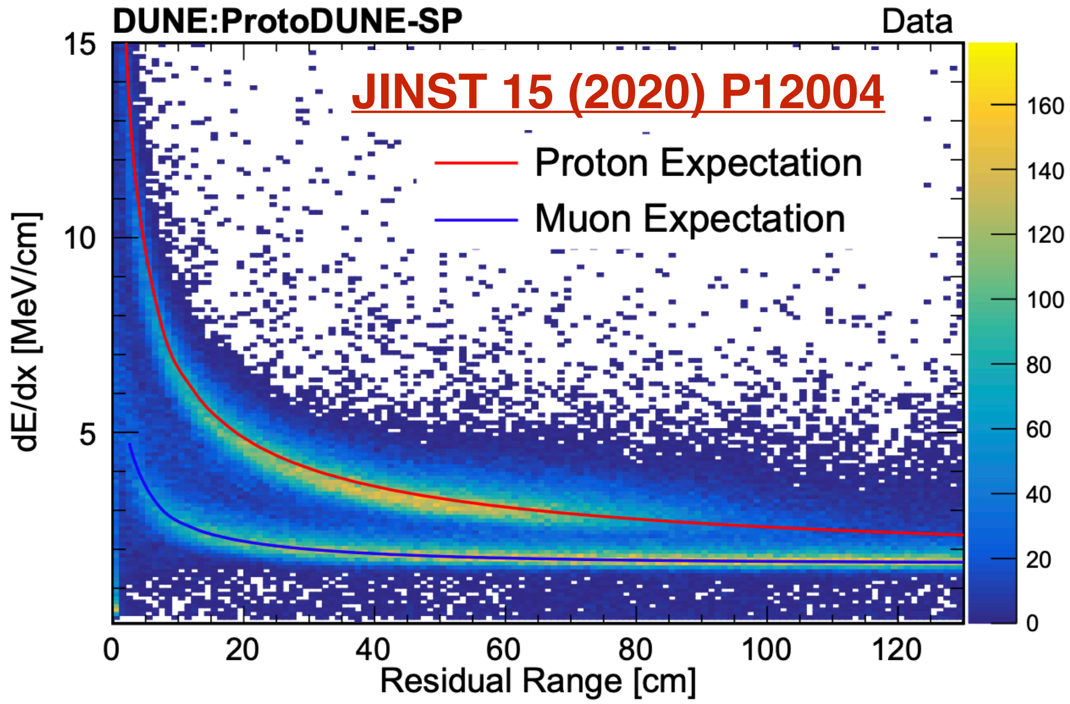


Impact on Recombination

- In pure LAr the amount of charge-to-light ratio changes as more energy is deposited
  - We measure dQ/dx and infer dE/dx by applying recombination corrections
- When PS-dopants are introduced the amount of charge is linear with the energy deposited
  - **This improves energy reconstruction and particle-ID capabilities**

Based on Stopping Protons



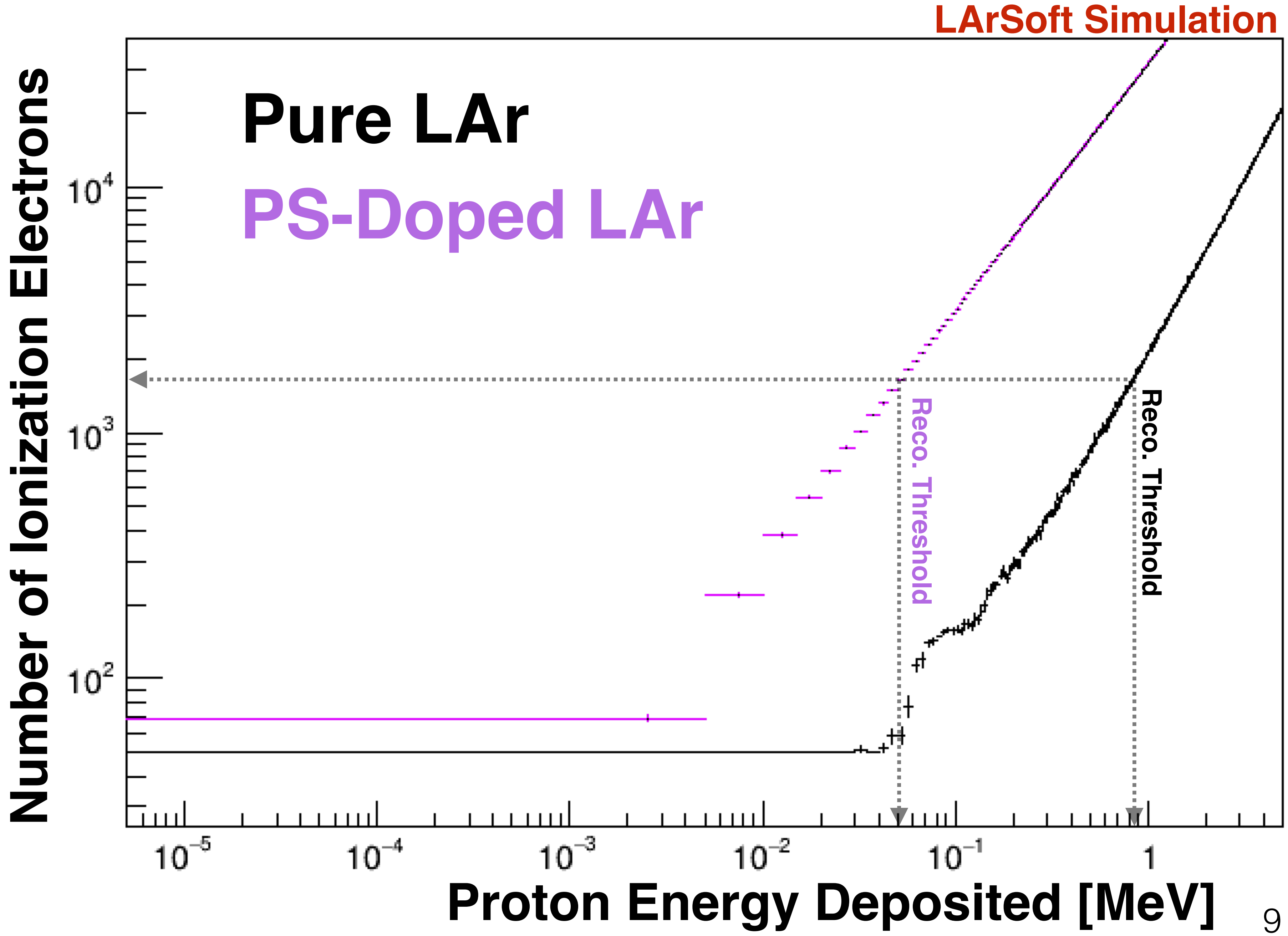


Hadronic Detection Thresholds

- The full detector simulation also demonstrated a reduced threshold for detecting low energy protons (>17x)

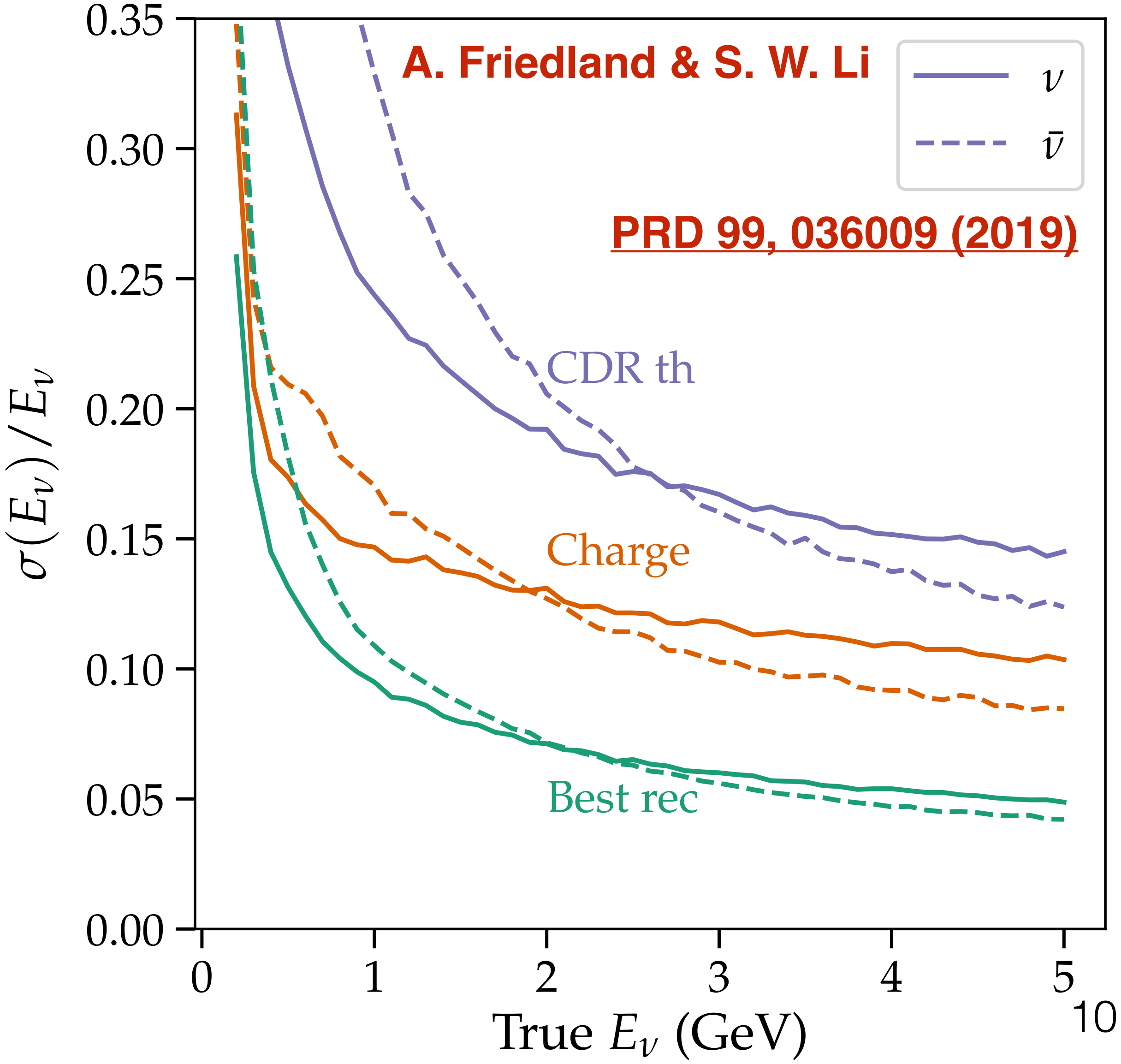
- In pure LAr protons were unable to be detected below 0.87 MeV

- In PS-doped LAr protons were unable to be detected below 0.05 MeV



Reconstructing Neutrino Interactions

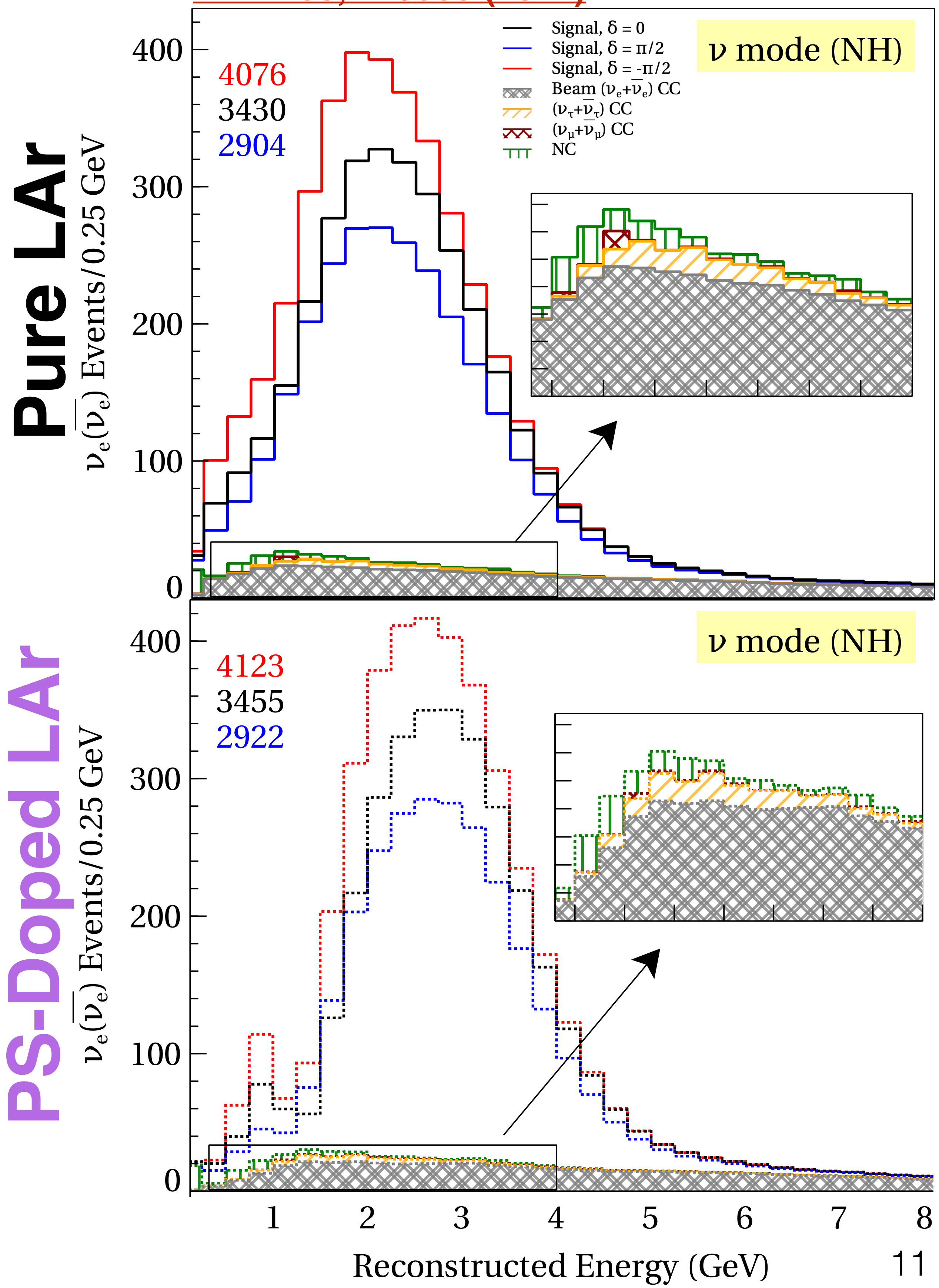
- Dopants improve reconstruction in two ways:
    - Particle energy reco. (no need for recombination corrections)
    - Reduced thresholds (proton threshold drops 7.5x)
- **Will directly improve neutrino energy reconstruction**
- Friedland and Li studied the impact of these effects on reconstructing E_ν
    - **"Charge"** - Lower thresholds
    - **"Best rec"** - Perfectly applied recombination correction
- Energy resolution improves by >2x across a broad range of energy



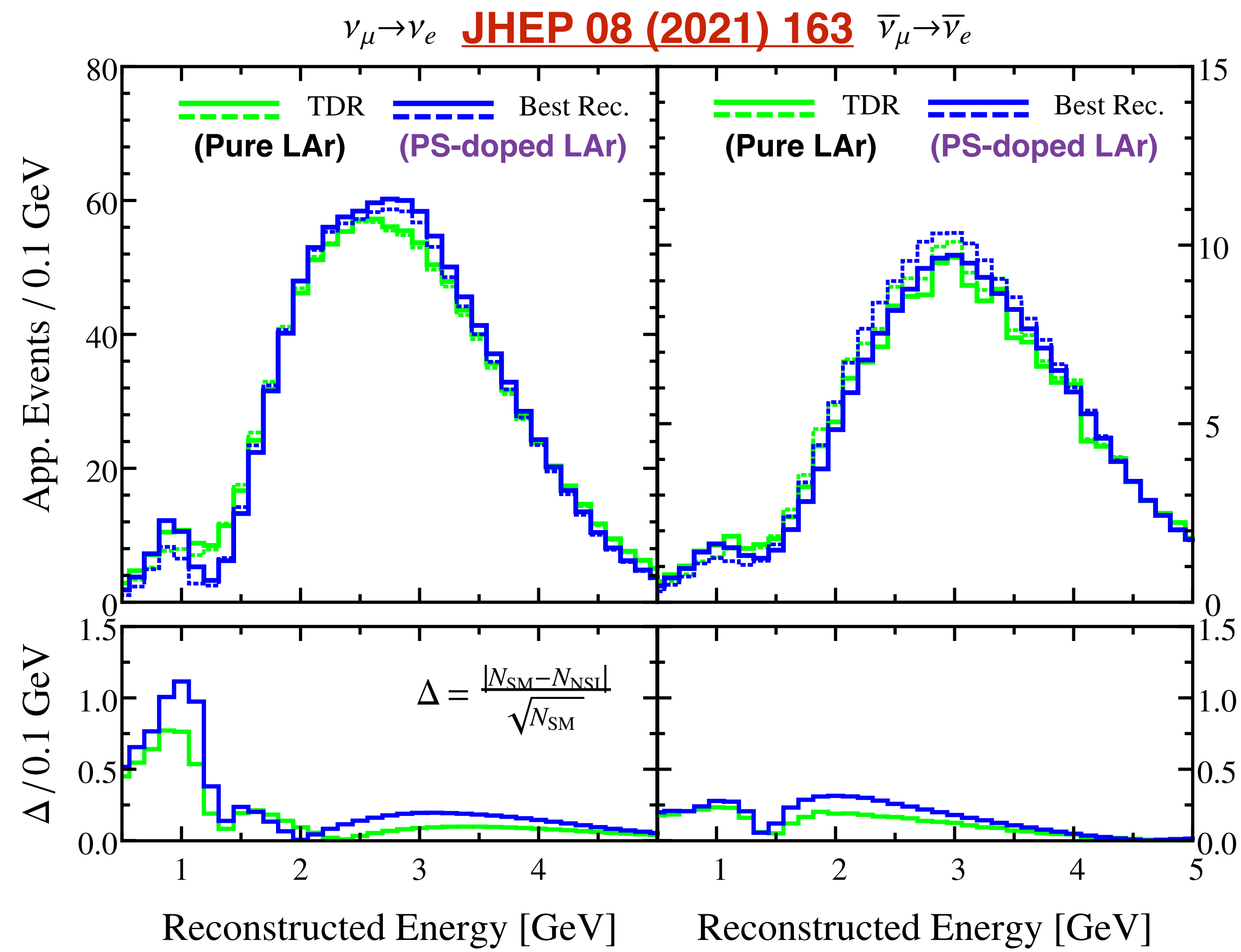
Impact on Neutrino Oscillation Measurements

- These plots demonstrate the impact of using the previous slides energy resolutions when studying DUNE neutrino oscillations
- The second oscillation maximum becomes very clear at the lowest energies
- This paper found a 9% increase in the δ_{CP} discovery potential and better precision in measuring δ_{CP}, reducing the uncertainty from ±15° to ±11° at -110°

PRD 103, 116003 (2021)

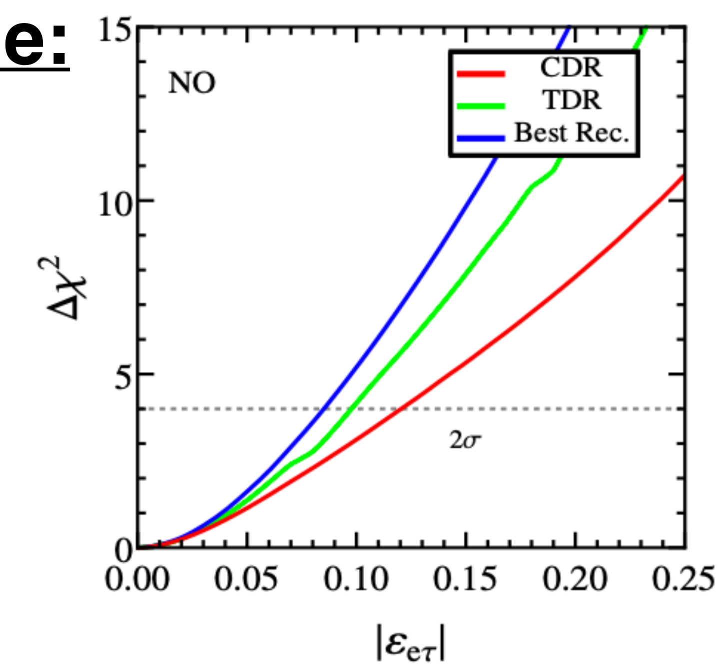


Impact on Non-standard Neutrino Interactions



- These improvements extend also to measuring non-standard neutrino interactions
  - Break degeneracies with standard oscillations
  - Improves limits of NSI parameters

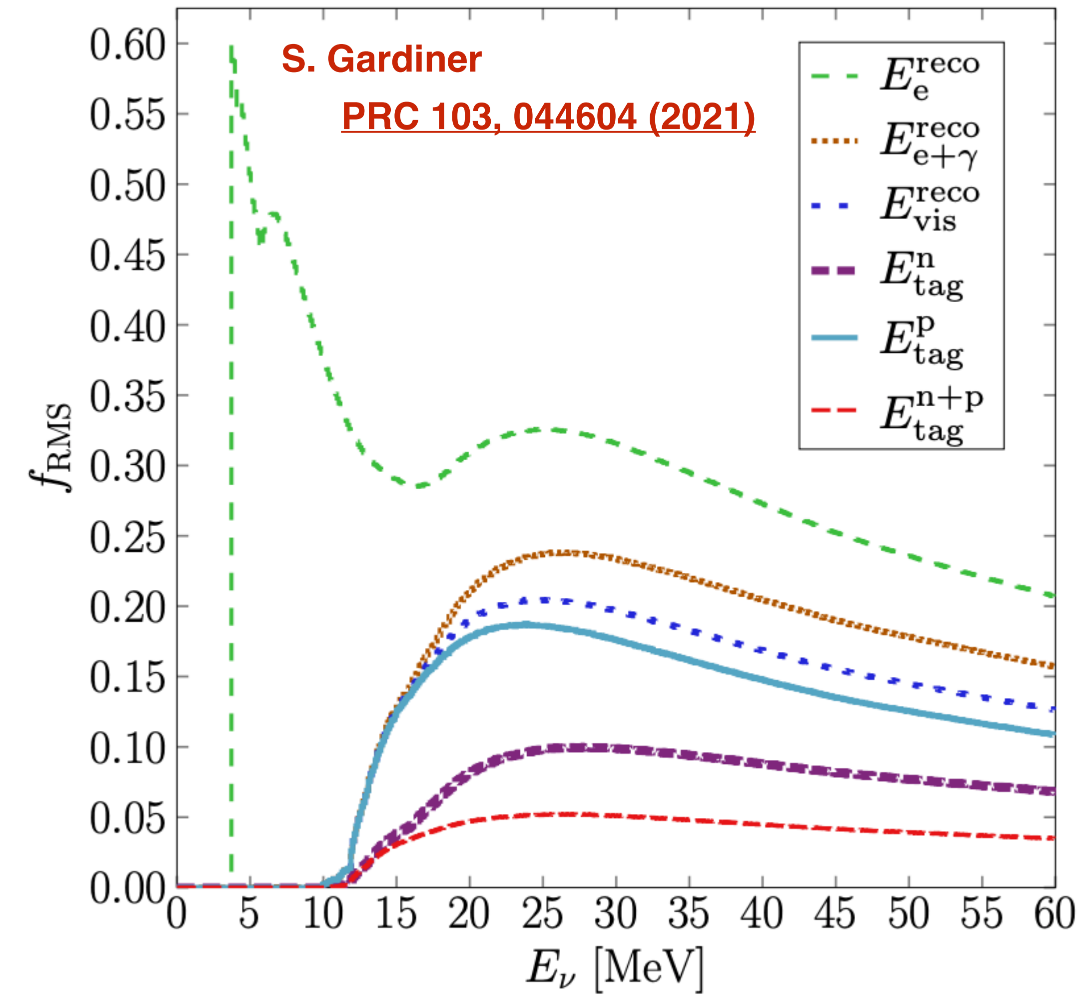
Example:

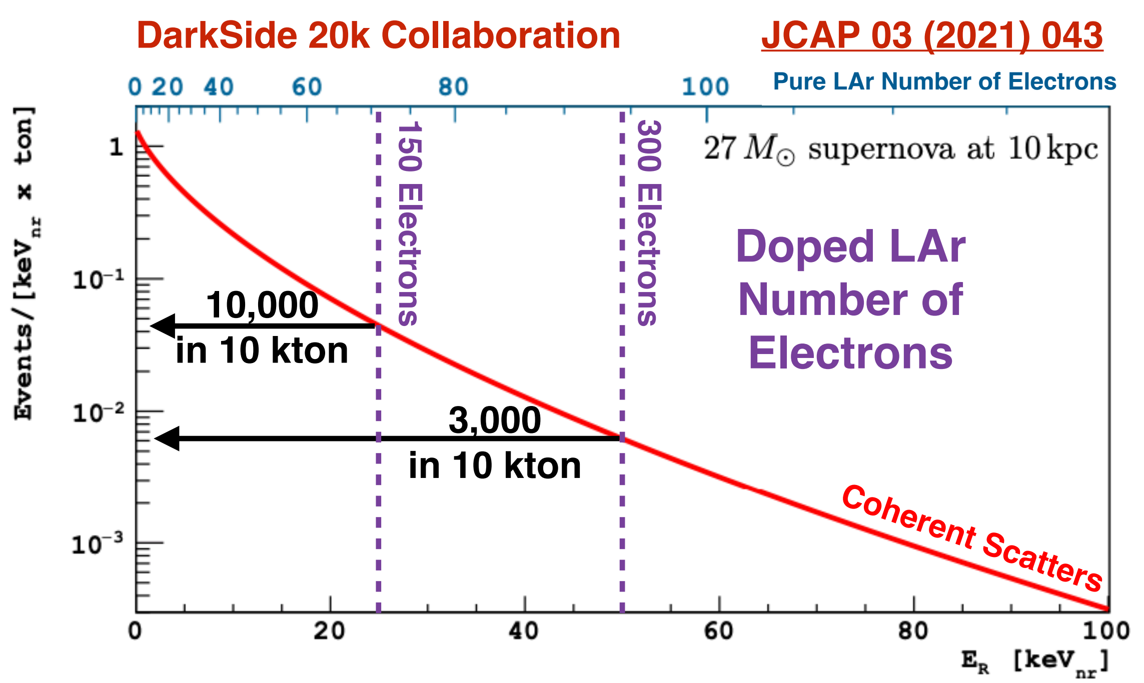


- Increasing constraints on $|\varepsilon_{e\mu}|$ by 10%, $|\varepsilon_{e\tau}|$ by 11%, and $|\varepsilon_{\mu\tau}|$ by 4%

Supernova Neutrino Physics

- When studying supernova neutrinos photosensitive dopants help primarily by lowering thresholds
- Tagging protons would improve CC-elastic discrimination which can improve pointing resolution
- Reconstructing charged-current interactions are largely limited by being able to tag the proton and neutron scatters
  - Being able to simply tag their existence increases your energy resolution substantially
- CEvNS from supernovas will also benefit from the high efficiency light-to-charge conversion
  - 25 keVnr would create ~150 ionization electrons which might be able to be resolved in a VD-style or pixelated readout





(Thanks to J. Zettlemoyer)

Conclusions

- PS-dopants provide a broad enhancement in the physics capabilities of LArTPCs
    - Low cost (<$700,000), works with any charge readout, could forego light detectors
    - Coupling this with xenon doping could allow infrared light to be used for triggering
- This is done by converting the UV light to charge
    - This removes the need for recombination corrections
    - Lowers thresholds
    - Improves energy reconstruction
- Based on detailed simulations this improves:
    - MeV-scale energy resolution by 5x
    - GeV-scale neutrino energy resolution by 2x
    - Supernova neutrino energy resolution by >5x and pointing resolution
    - When coupled to a low noise readouts, could enable sensitivity to coherent neutrino scatters from supernova

Back-ups

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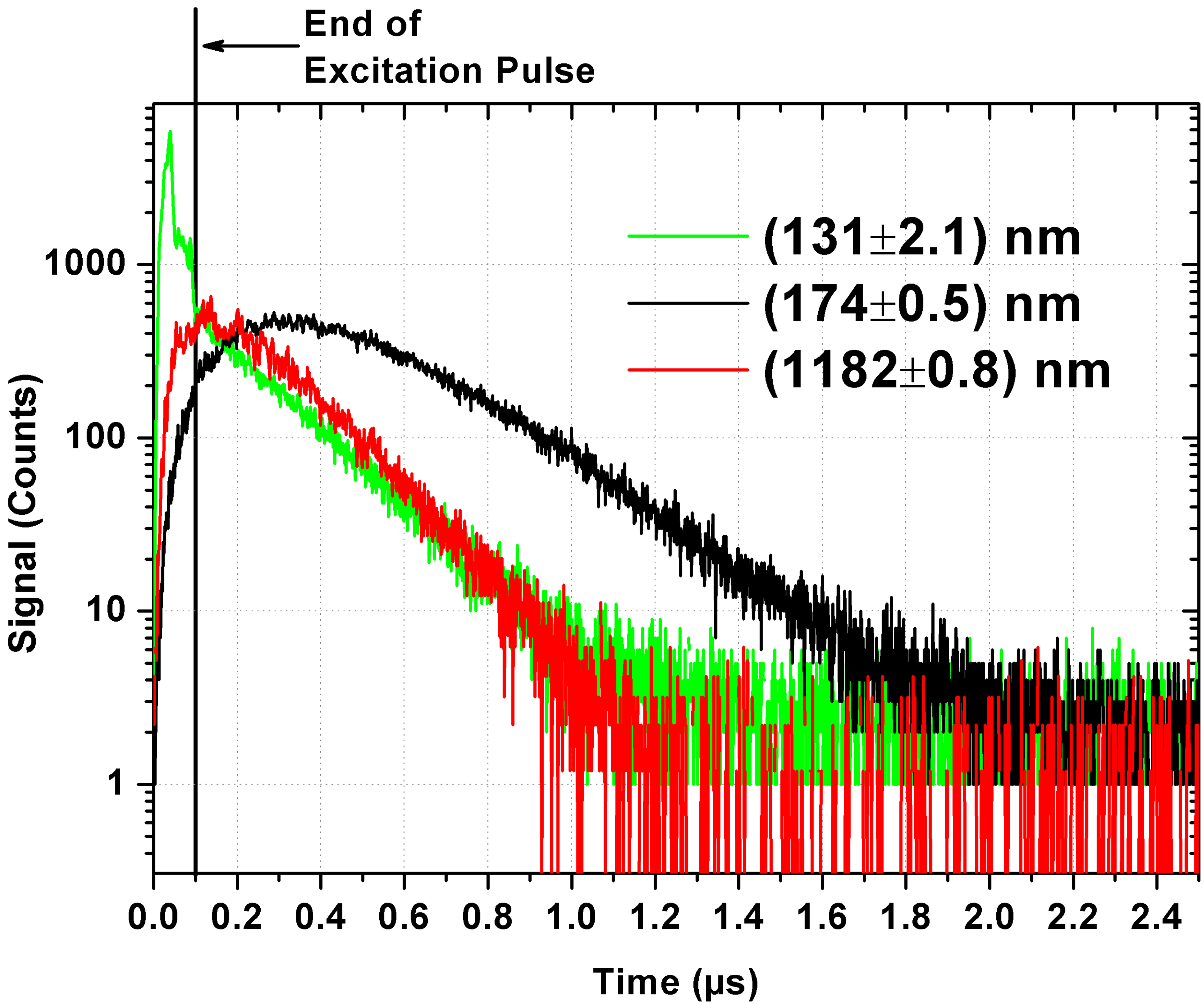

End of
Excitation Pulse
(131±2.1) nm
(174±0.5) nm
(1182±0.8) nm
1000
100
10
1
Signal (Counts)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Time (μs)

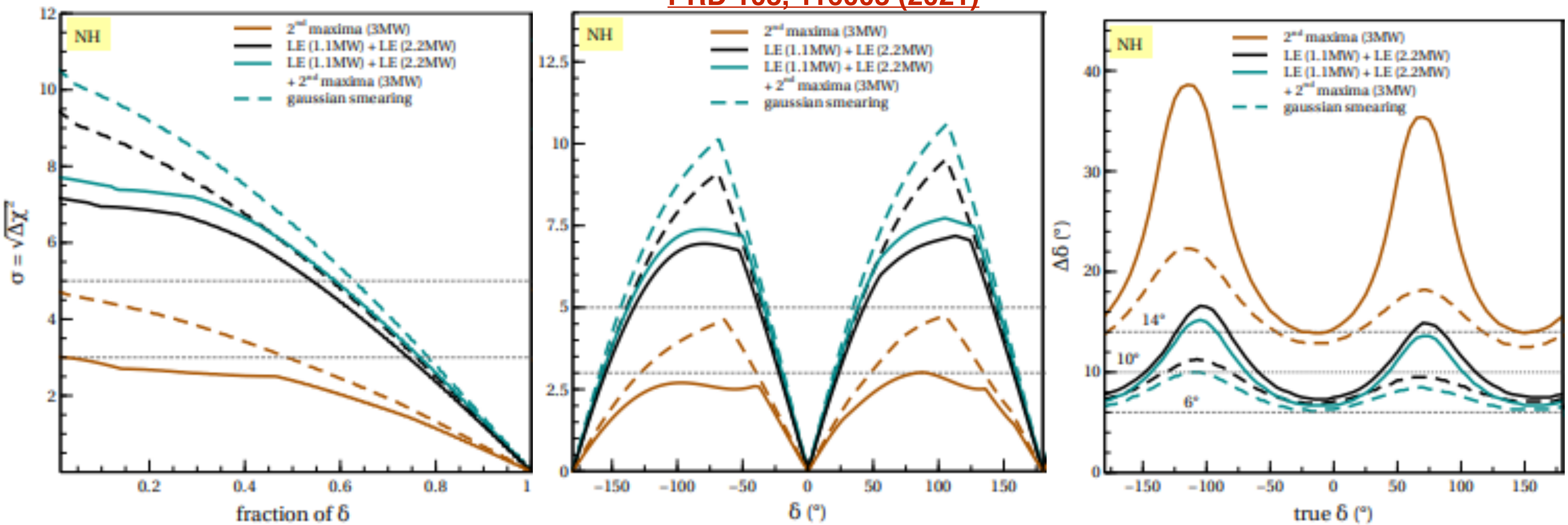
Freidland and Li Thresholds

TABLE I. Detection thresholds according to the DUNE CDR document [5]. The values given correspond to the kinetic energy of each particle.

	p	$\pi^{\pm}$	γ	μ	e	others
Thresholds (MeV)	50	100	30	30	30	50

Impact of PS-dopants on δCP

PRD 103, 116003 (2021)



Compare Black (Pure LAr) to Dotted Black (PS-Doped LAr)