Nanoparticle-enhanced photosensors for UV light detection

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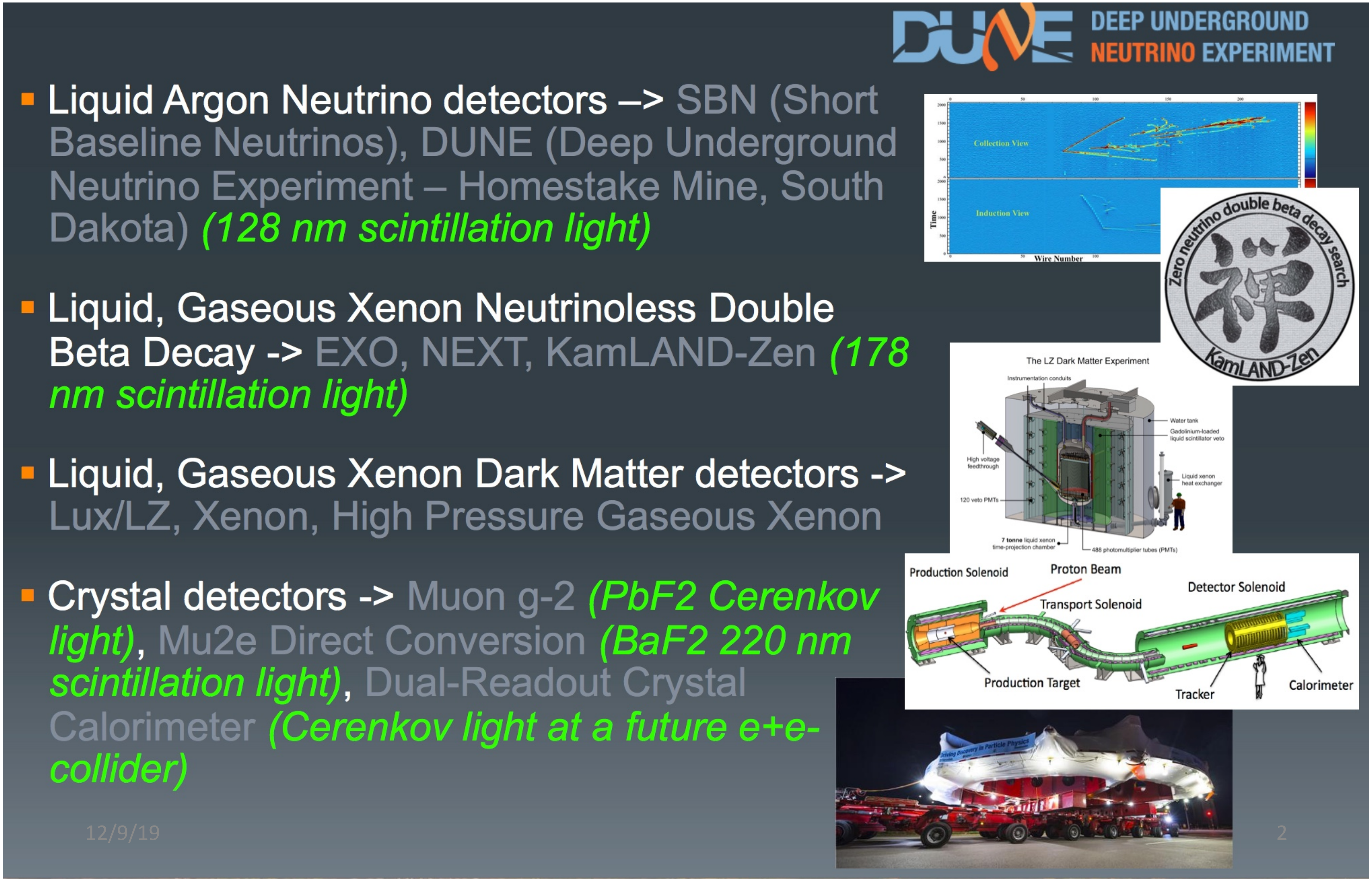
Motivation



- Liquid Argon Neutrino detectors –> SBN (Short Baseline Neutrinos), DUNE (Deep Underground Neutrino Experiment – Homestake Mine, South Dakota) *(128 nm scintillation light)*
- Liquid, Gaseous Xenon Neutrinoless Double Beta Decay -> EXO, NEXT, KamLAND-Zen *(178 nm scintillation light)*
- Liquid, Gaseous Xenon Dark Matter detectors -> Lux/LZ, Xenon, High Pressure Gaseous Xenon
- Crystal detectors -> Muon g-2 *(PbF2 Cerenkov light)*, Mu2e Direct Conversion *(BaF2 220 nm scintillation light)*, Dual-Readout Crystal Calorimeter *(Cerenkov light at a future e+e- collider)*

Quantum Confinement

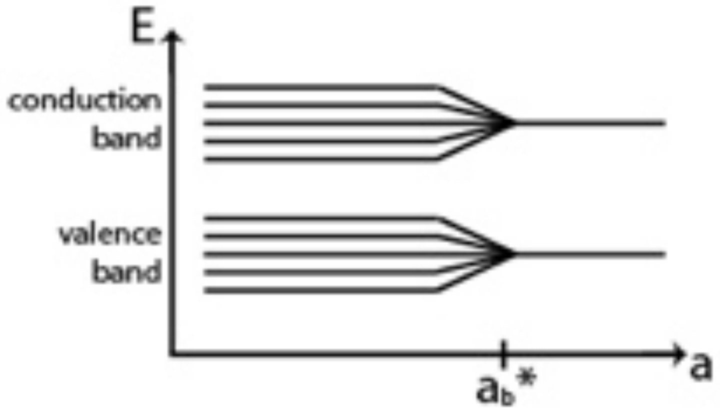
- If the size of the nanoparticle is smaller than the electron wavelength :

  -> Quantum Confinement condition

    - ✓ Larger energy gap
    - ✓ Splitting of energy levels
    - ✓ Strong transitions

  -> Tunable electronic and optical properties if nanoparticle size typically <10 nm

- Occurs on atomic/molecular level –> *higher intensity, efficiency* than bulk material

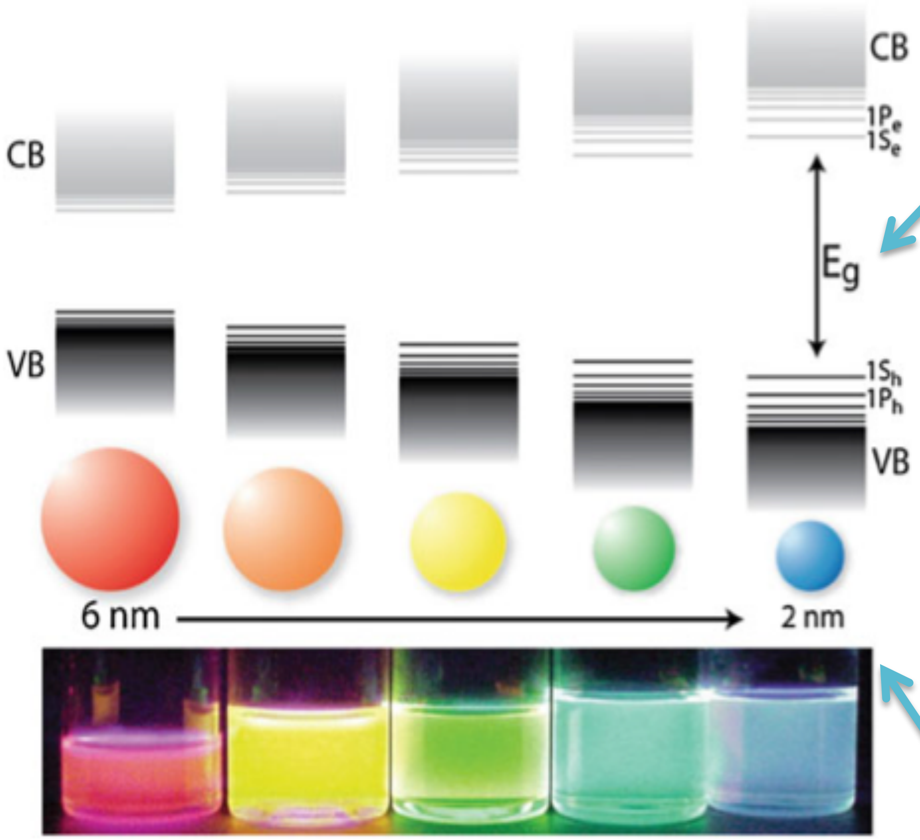


Energy level splitting vs size (a); a_b^* is exciton Bohr radius

Happens in the Sun - quantum confinement dominates -> many energy level splittings -> continuous to make white light

Nanoparticles - Quantum Confinement

Quantum Confinement changes material properties when particle size < electron wavelength



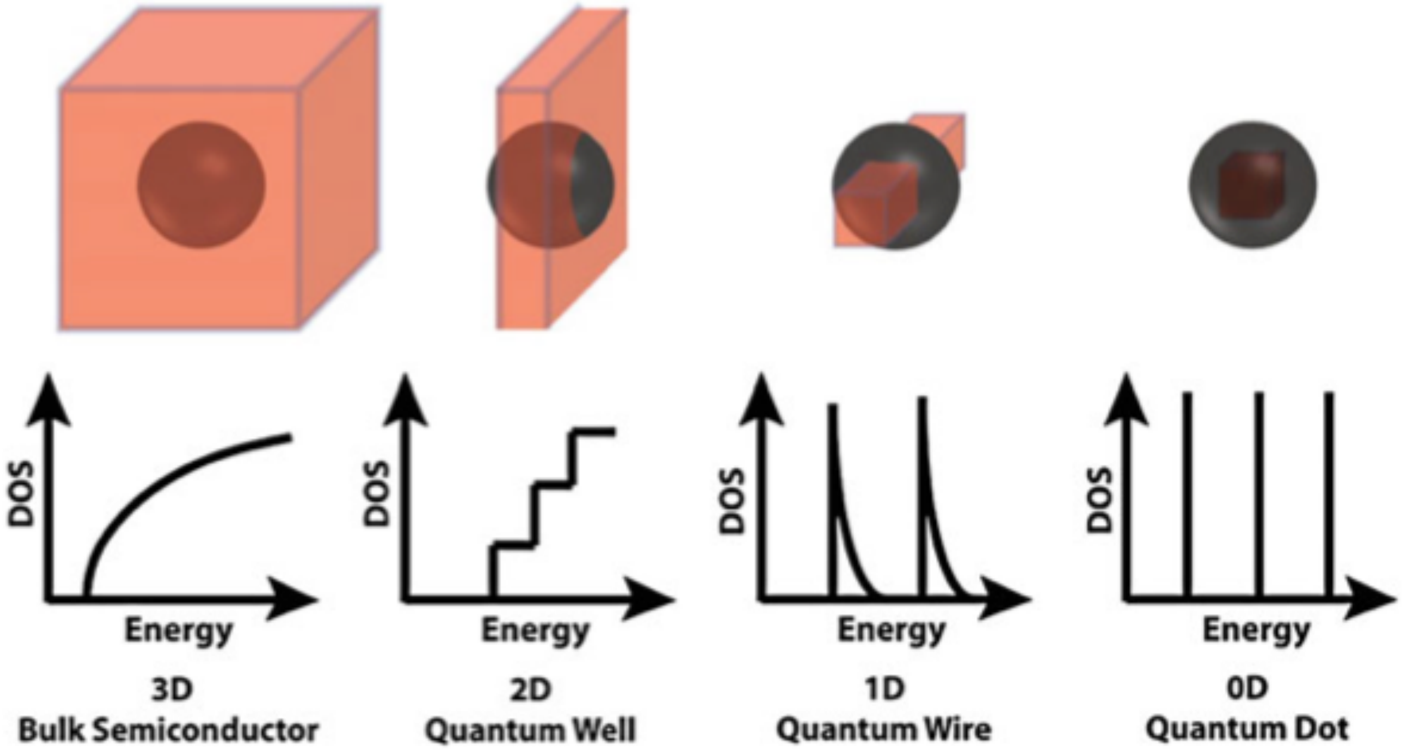
Eg increases with decreasing particle size -> ***UV photon absorption***

Discrete energy levels form at the band-edges

Stokes Shift is difference between absorption and emission wavelength

Emission wavelength decreases with decreasing size -> ***tunability***

Terminology of nanoparticle dimensionality



- Dimensions shown as rectangular solids
- Electron wavelength *(Exciton Bohr diameter)* represented by the sphere
- Plots show Density of States (DOS) vs Energy
- Dimensionality – 3D is bulk material -> 0D is *Quantum Dot*

Recent Developments at ANL + Collaborators

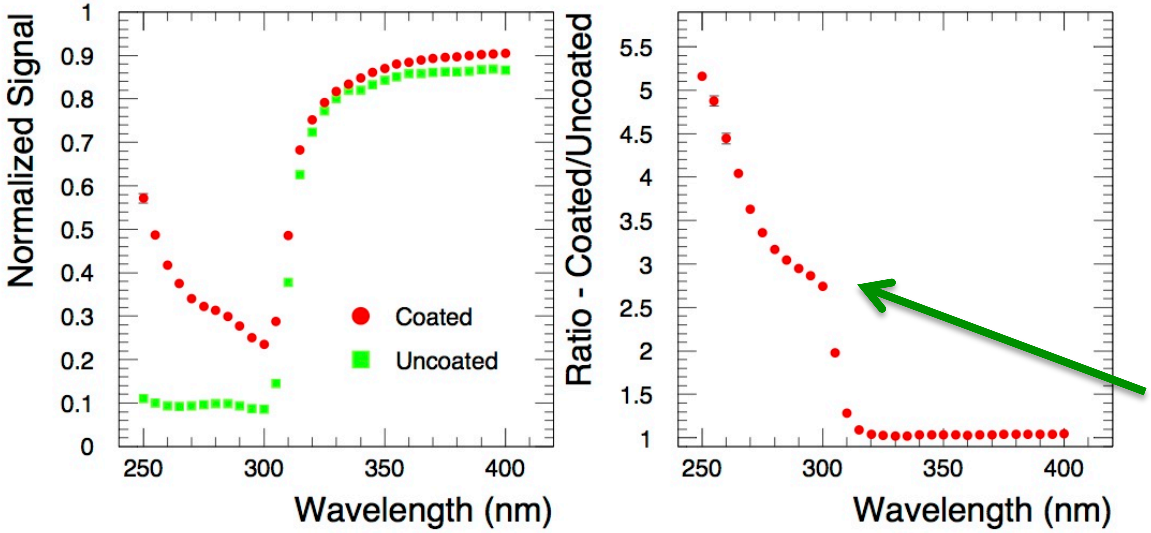
- Scientific Reports article – July, 2018
  - Contact: CytoViva, Inc. (measurement instrumentation) – currently working closely with Wei Chen at UTA on methods/devices for nanoparticle diagnostics
- Future publication of nanoparticle candidate for BaF2 crystal readout – test optimized cookie with monochromator, spectrophotometer
  - Patented candidate for Mu2e calorimeter upgrade (BaF2 UV readout)
- Technology Commercialization Fund: passed 1st round of pre-proposal – full proposal due Dec 12; strong group behind proposal
  - ANLHEP - intial testing, characterization
  - ANLAMD – atomic layer deposition techniques for film production
  - ANLNST - timing, size, etc. studies of nano candidates
  - UTA - selection/production of nano candidates in many forms
  - Solgro, Inc. - coatings for greenhouse panels, plant growth testing – ***provider of non-Federal matching funds for full proposal***
- Current SBIR with CapSym, Inc.

  - Nanoparticle wavelength shifters for Argon, Xenon

Testing Tools at ANL

- Low wavelength filter-based vacuum/N2 atmosphere testing device (under development)
- PYTHON macros to calculate relevant quantities − electron wavelength, fermi energy, band gap enhancement, etc.
  - predict whether a candidate will show QC effects
  - used in our SR article to successfully explain observations
- Scanning monochromator − good down to ~200 nm, need N2 environment to eliminate fluctuations down to ~160 nm (window limit)
- Spectrophotometer − try Ocean instrument in our next publication
- ANLNST (NanoSciende and Technology Division)
  - measurements of timing of Stokes Shift, other nano diagnostics
  - Simulation code to predict nanoparticle properties

Initial Nanoparticle sample tests



Si nanoparticle coating on plastic film (U of I partner)

Published result:

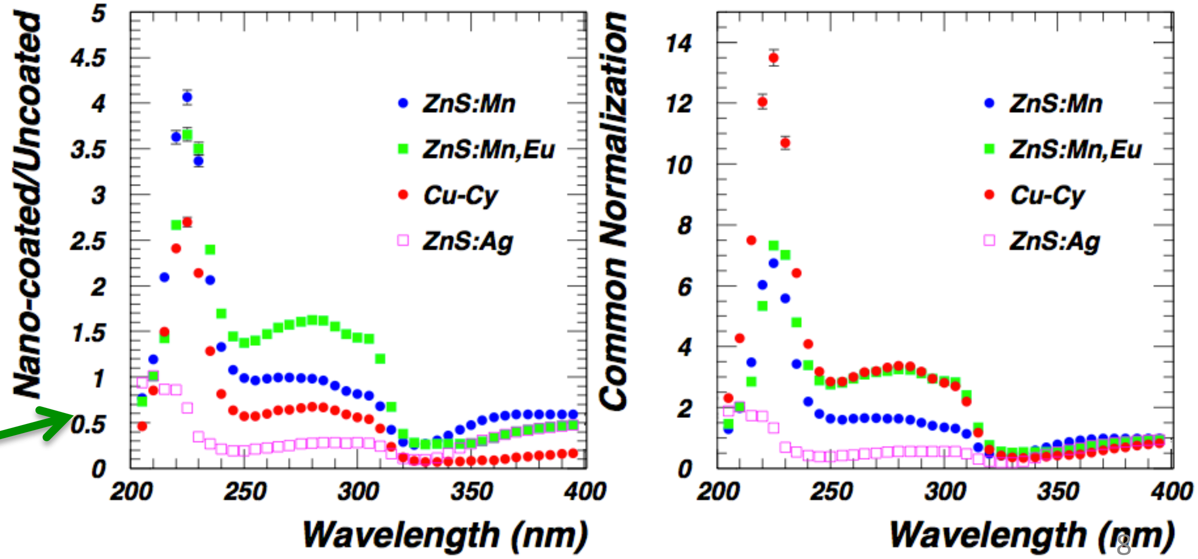
JINST 10 05008 (2015)

Enhanced response:
250 nm < λ < 300 nm

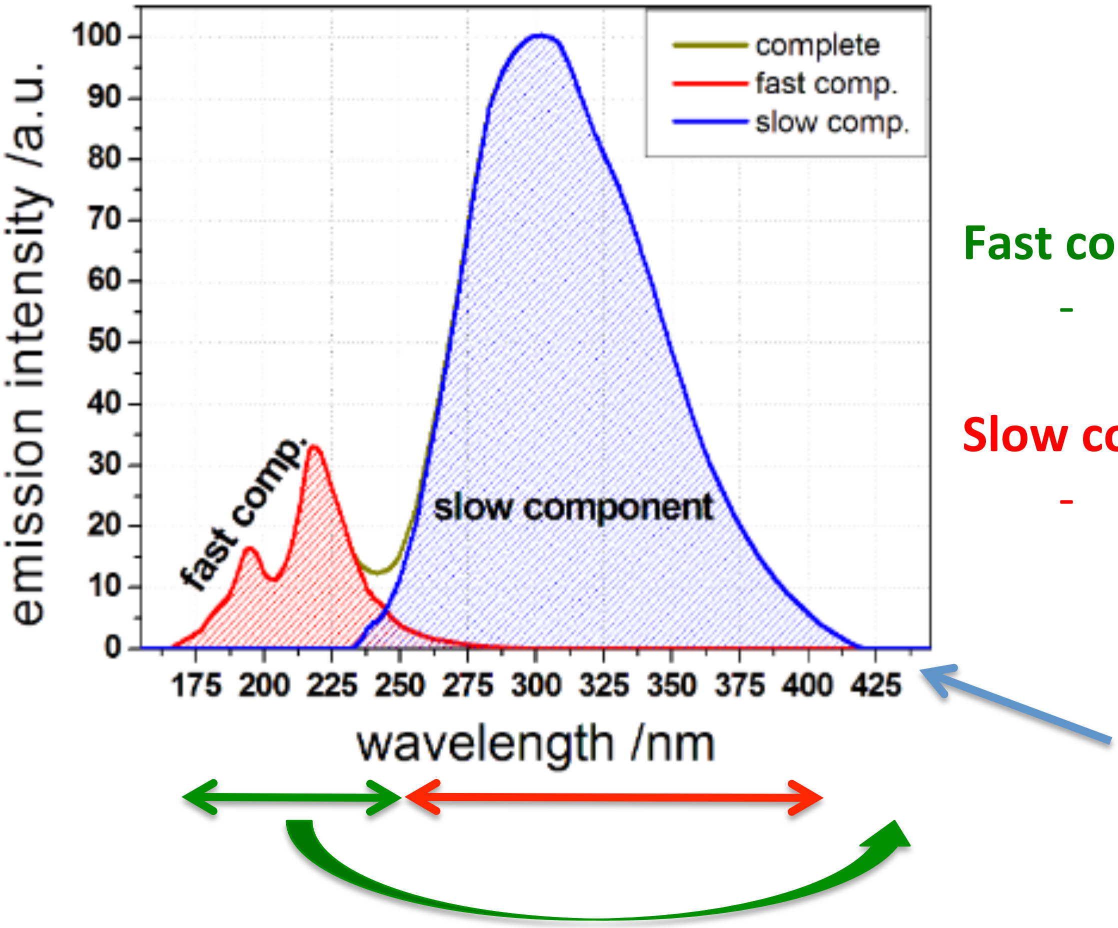
Nanoparticles deposited on clear plastic tape (UTA partner)

Published result:
SR 8:10515 (2018)

Enhanced response for ¾ samples:
200 nm < λ < 250 nm



BaF2 Crystal Readout – Mu2e Upgrade



Fast components (195, 224 nm)

- **Decay time ~1 ns**

Slow component (250 -> 400 nm)

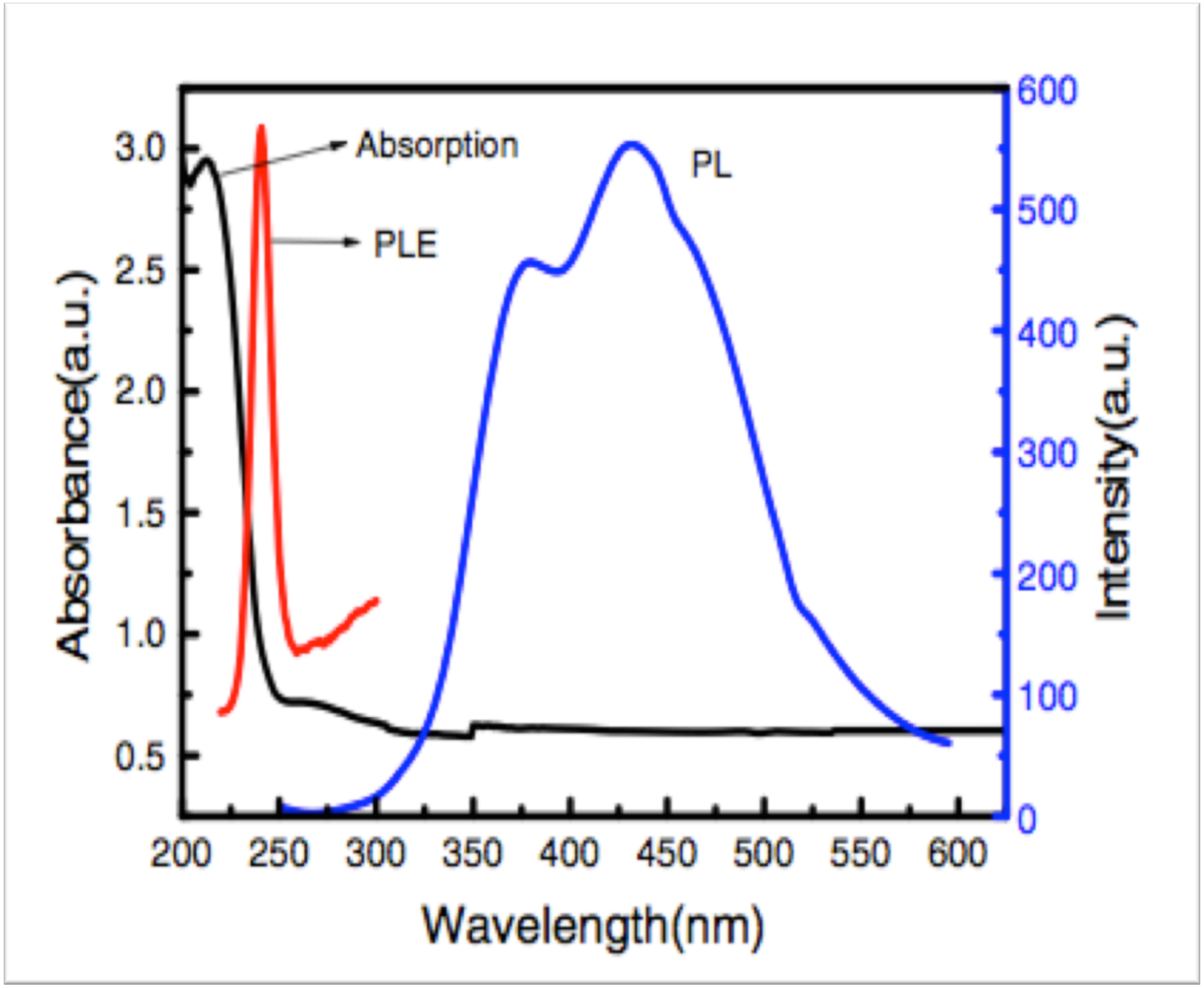
- **Decay time ~650 ns**

SiPM peak sensitivity
(425 nm)

Absorption, then Stokes shift over slow component to sensor

no sensitivity for slow component!

Absorption/emission of nanoparticle candidate



Absorption:

strong < 250 nm

weak > 250 nm

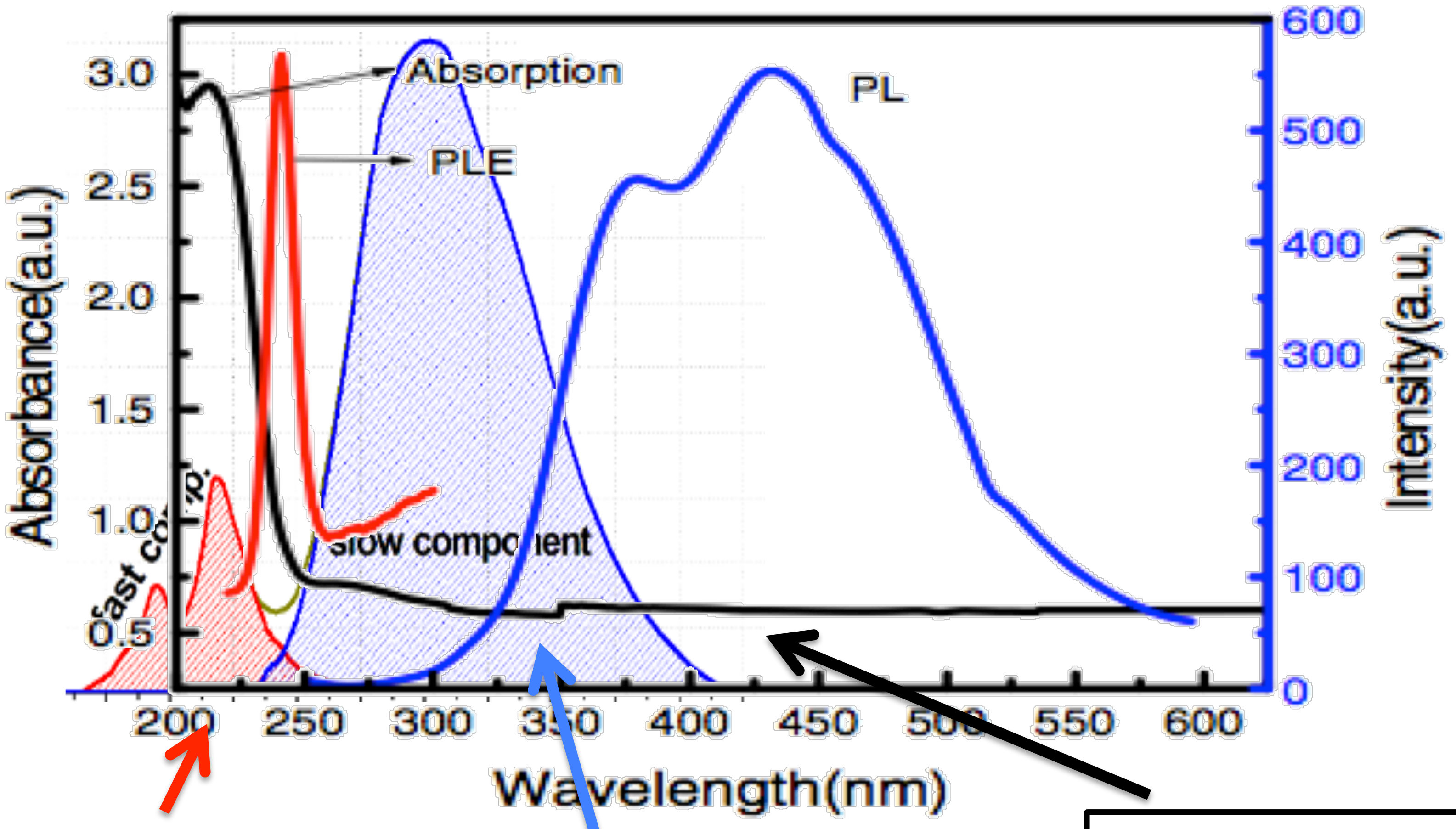
Emission:

300 nm < λ < 600 nm

Stokes Shift:

~200 nm peak-to-peak

Nanoparticle candidate for BaF2 Readout



195, 224 nm emission of BaF2

absorption peak of nanoparticle

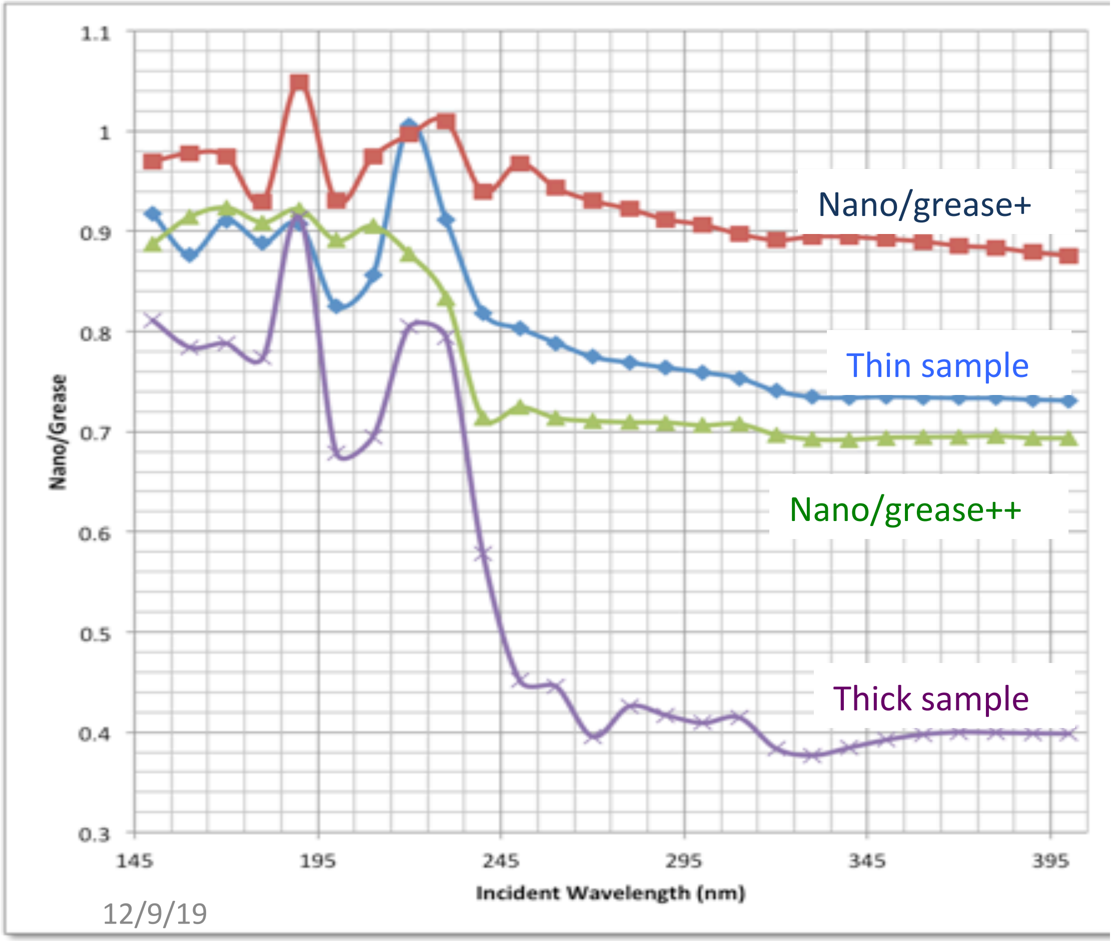
Little absorption for wavelengths >250 nm

Overlap of slow component and nanoparticle emission:

1) wave-shift to longer wavelength, or 2) resin coating on the SiPM

Nanoparticle Response

Tested a nanoparticle sample made at UTA by *mixing nanoparticles in UV-transparent grease (DOW-Corning)*

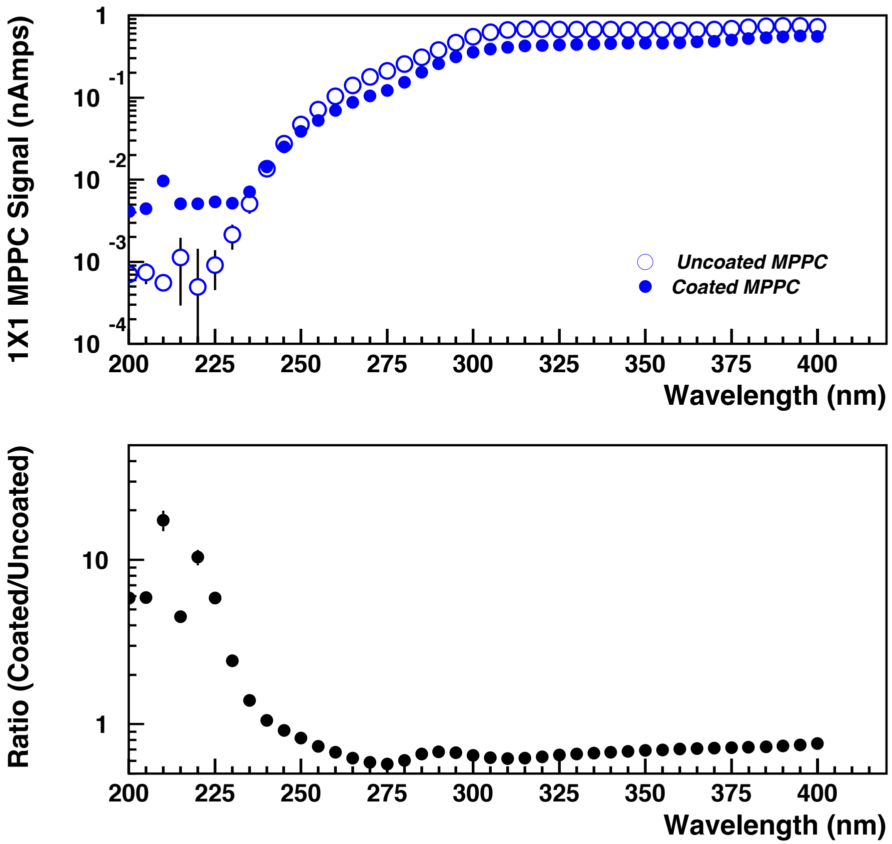


Compare blue, purple − it appears that passing through more nanoparticles helps − small reduction in the peak at 220 nm and a larger reduction in the signal > 245 nm.

-> determine the amount of nanoparticles in the grease by optimizing the 220/300 ratio for maximum rejection of light >250 nm.

-> Ratio of 220/300 for purple (thick) sample is ~2/1

A different nanoparticle candidate



UTA nanoparticles *deposited directly on the resin (face) of the SiPM*

Enhanced response of coated SiPM seen in the wavelength range from 200 nm − 240 nm compared to uncoated sensor

Without any optimization, ratio of coated to uncoated in the 200 − 240 nm range is ~factor of 10 greater than in the region > 250 nm!

We have tested at least 2 nanoparticle candidates which show sensitivity in the desired wavelength range and, in addition, much reduced sensitivity without the need for additional filters in the wavelength range > 250 nm

Plans for BaF_2 220 nm Readout

- Optimize thickness, nanoparticle concentration in DOW-Corning grease for best signal to noise (220 nm / 300 nm) ratio using monochromator
- Test this on a BaF_2 crystal with muons
- Find a binder that can contain nanoparticles at the optimal concentration and thickness that makes a *soft cookie for placement between a crystal and a sensor (SiPM)*
  - Siloxane epoxy (same properties as DOW-Corning grease?)
  - *3M hardener + DOW grease + nanoparticles -> soft cookie for crystal face recently accomplished*
- *Or, a hard, permanent coating for a crystal face*
- Produce nanoparticle/sensor combination for Mu2e BaF_2 Calorimeter

Motivation: Homogeneous, Dual-Readout Calorimetry

- Development of clear, dense crystals (PbWO, BGO, PbF, . . .) with both scintillator and cerenkov response
  -> Cerenkov response is prompt, short λ
  -> Scintillator response has longer time, longer λ

7-9 g/cc densities -> 5-6 λ_I total absorption crystal calorimetry in, e.g., CDF barrel calorimeter volume

- Development of photodetectors (SiPM, APD, . . .)
  -> for scintillator response, small area (1 mm^2) SiPMs
  -> for cerenkov response, development of (thin) large area (~1 inch^2) detectors *

On-crystal photodetectors -> highly segmented and granular calorimeter

Cerenkov/scintillator response ratio correction optimizes energy resolution of calorimeter objects

Resulting high-purity particle shower content per calorimeter cell

-> Use of PFA algorithms to categorize clusters

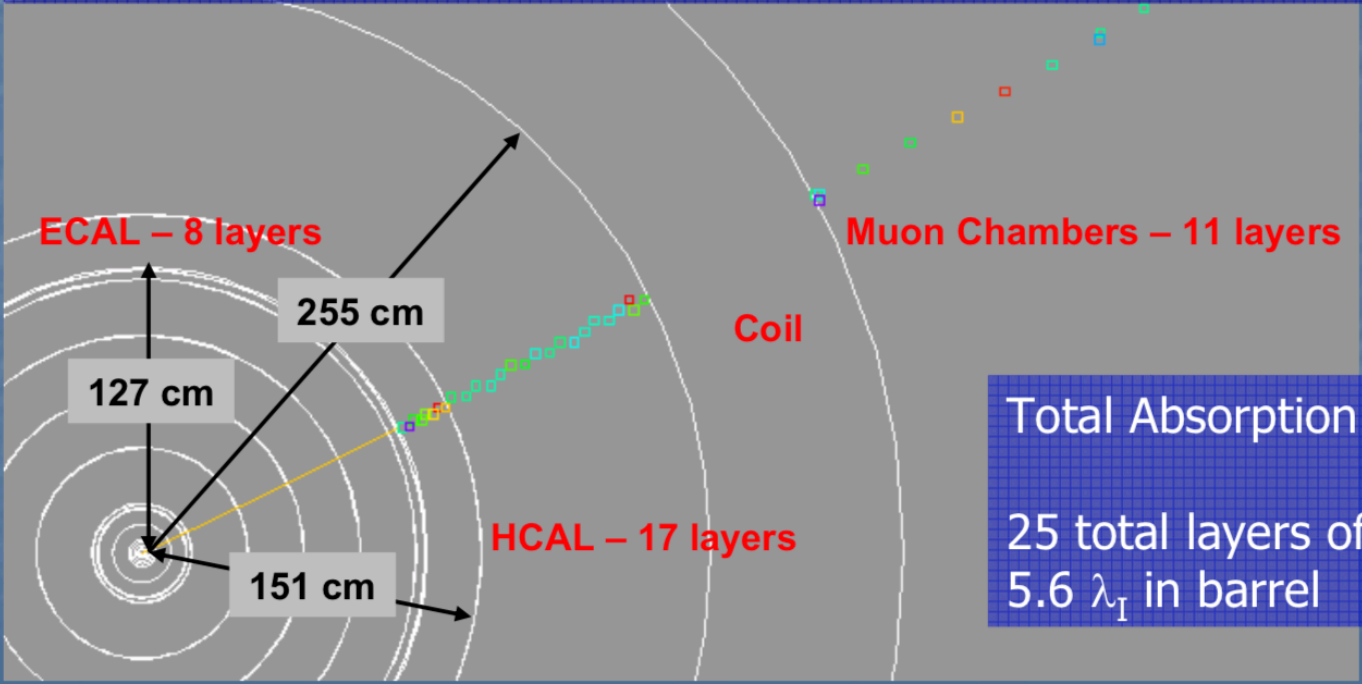
** Nanoparticle-infused cookie on crystal sides!*

Dual Readout Calorimeter Detector Parameters

Dual Readout Calorimeter *in SiD02* Shell (Barrel and EC)*

DR ECAL
3 cm x 3 cm x 3 cm BGO
8 layers – 21.4 X_0 (1.1 λ_I)
127 cm IR – 151 cm OR
Scin/Ceren analog hits

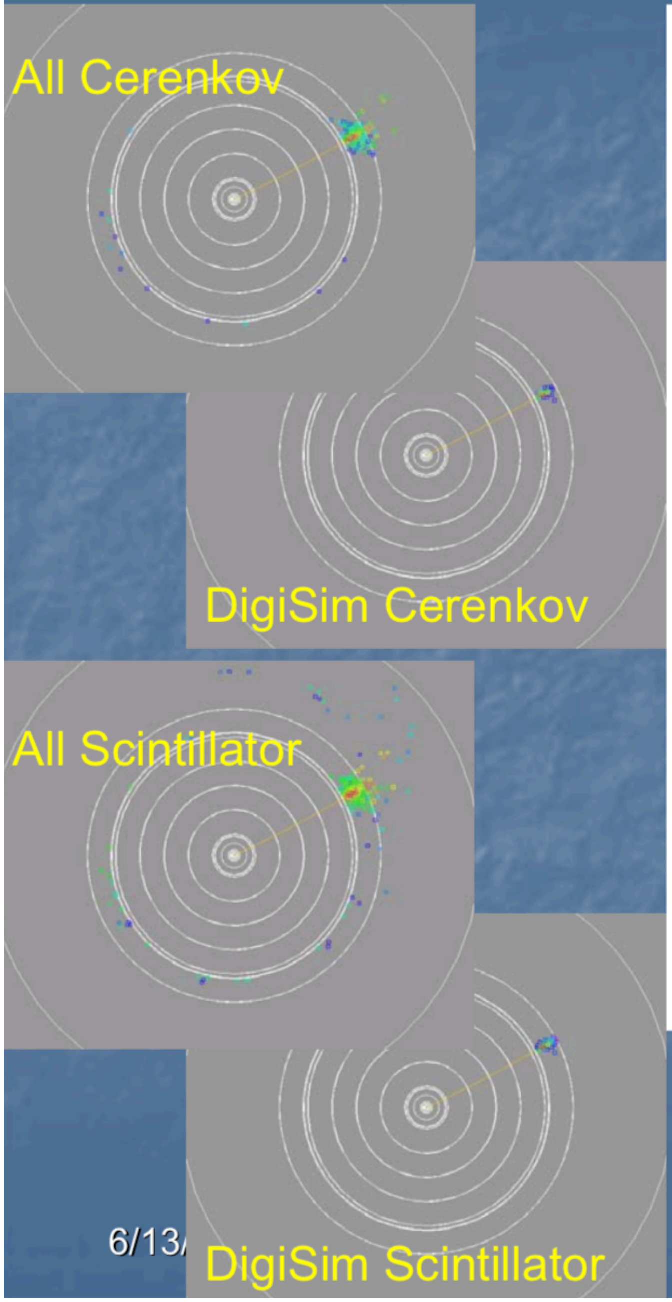
DR HCAL
5 cm x 5 cm x 6 cm BGO
17 layers – 4.6 λ_I
151 cm IR – 253 cm OR
Scin/Ceren analog hits

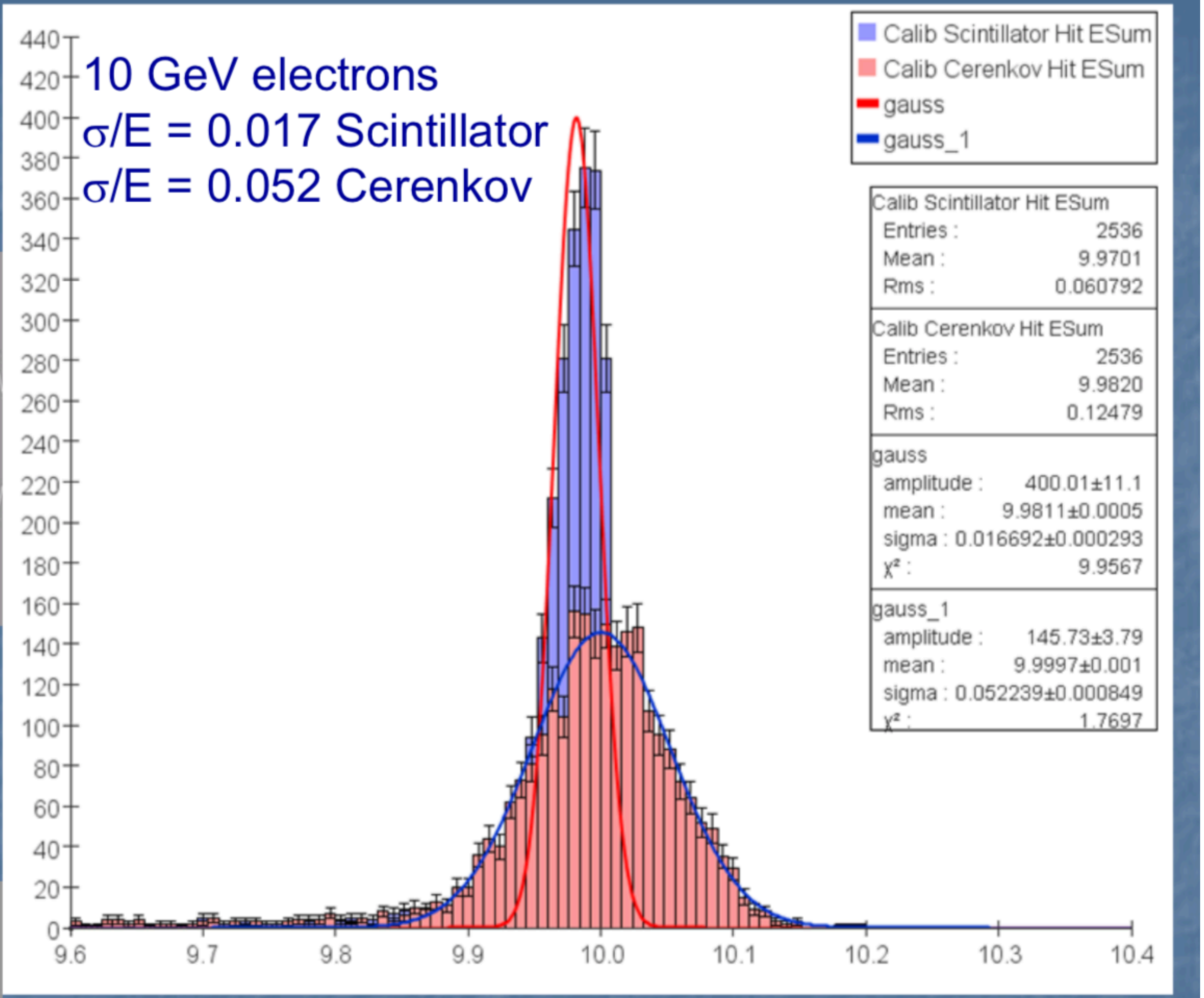


Total Absorption Crystal Calorimeter

25 total layers of BGO
5.6 λ_I in barrel

Electron Calibration for Scintillator, Cerenkov

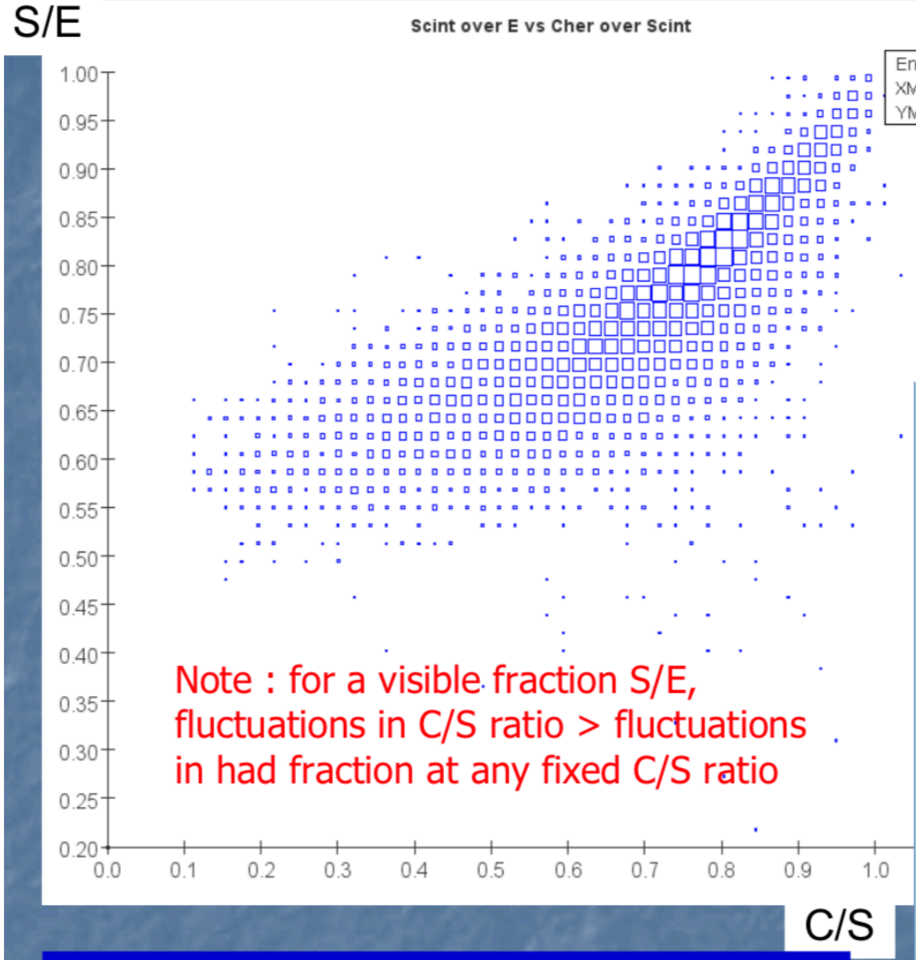




$S = 1.004 \times s_{raw}$

$C = 7692 \times c_{raw}$

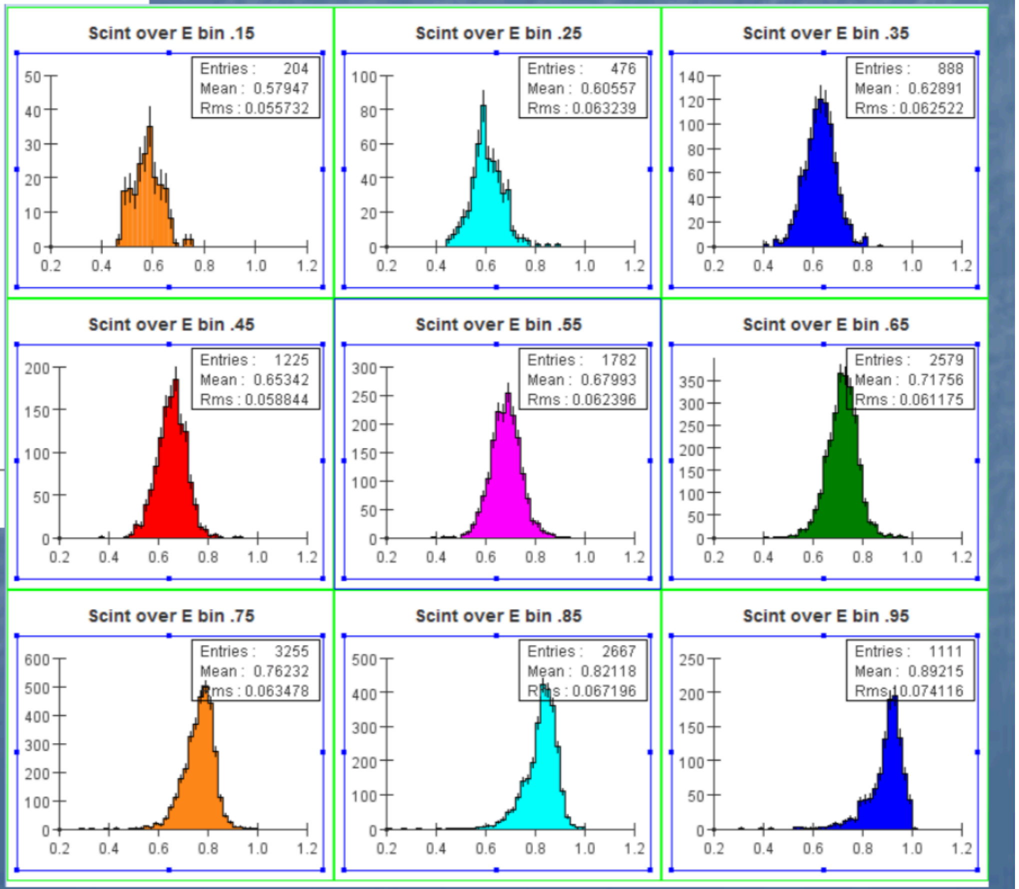
Cerenkov/Scintillator Correction for Hadrons



Note : for a visible fraction S/E, fluctuations in C/S ratio > fluctuations in had fraction at any fixed C/S ratio

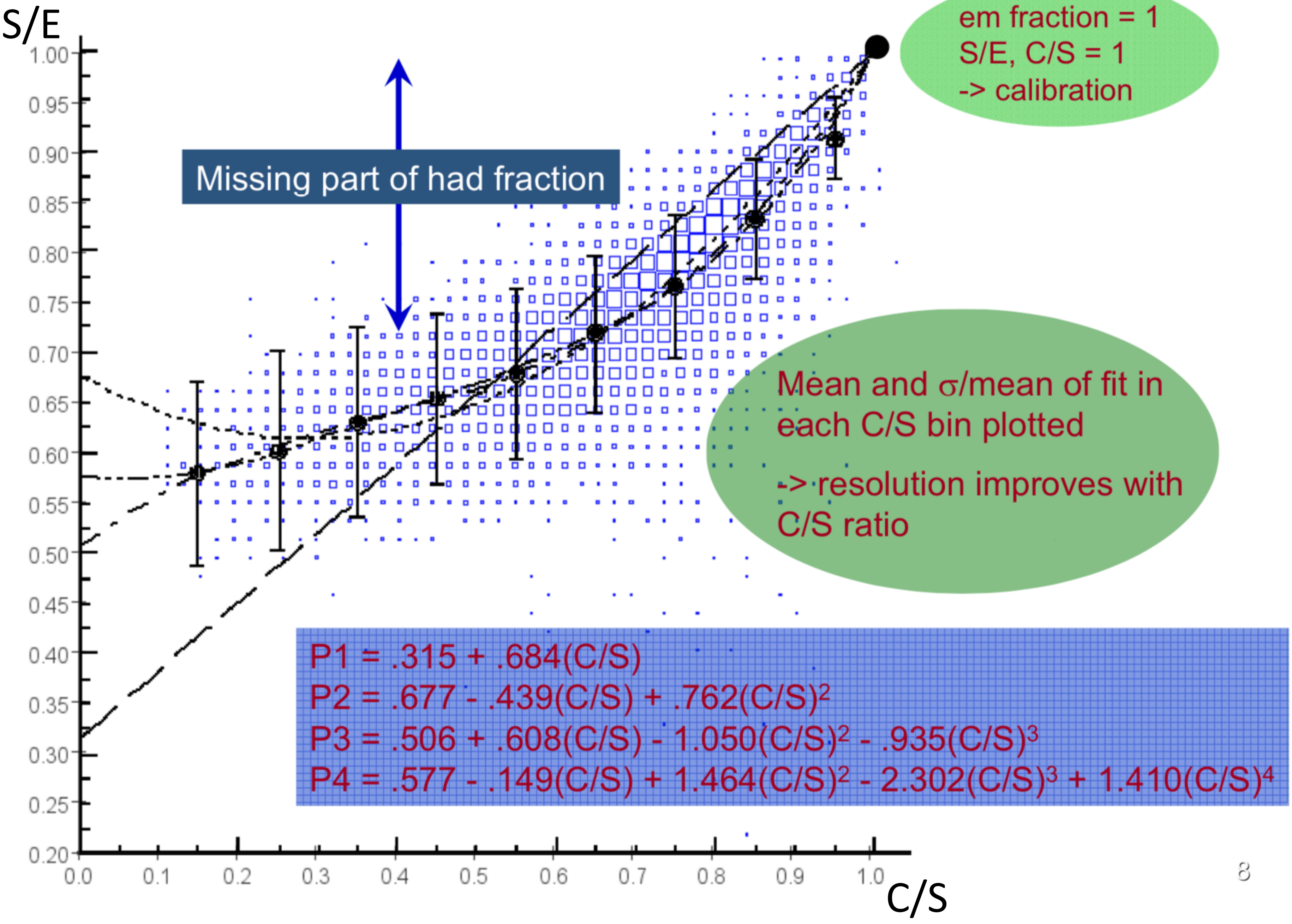
5, 10, 20, 50, 100 GeV pions

S/E slices in C/S bins



S (e calibrated scintillator response)
-> em and had visible energy
C (e calibrated cerenkov response)
-> mostly em part of shower
C/S ~ em fraction of visible energy
S/E = total fraction of energy seen

Polynomial Correction Functions : E = S/Pn



Missing part of had fraction

em fraction = 1
S/E, C/S = 1
-> calibration

Mean and σ/mean of fit in each C/S bin plotted

-> resolution improves with C/S ratio

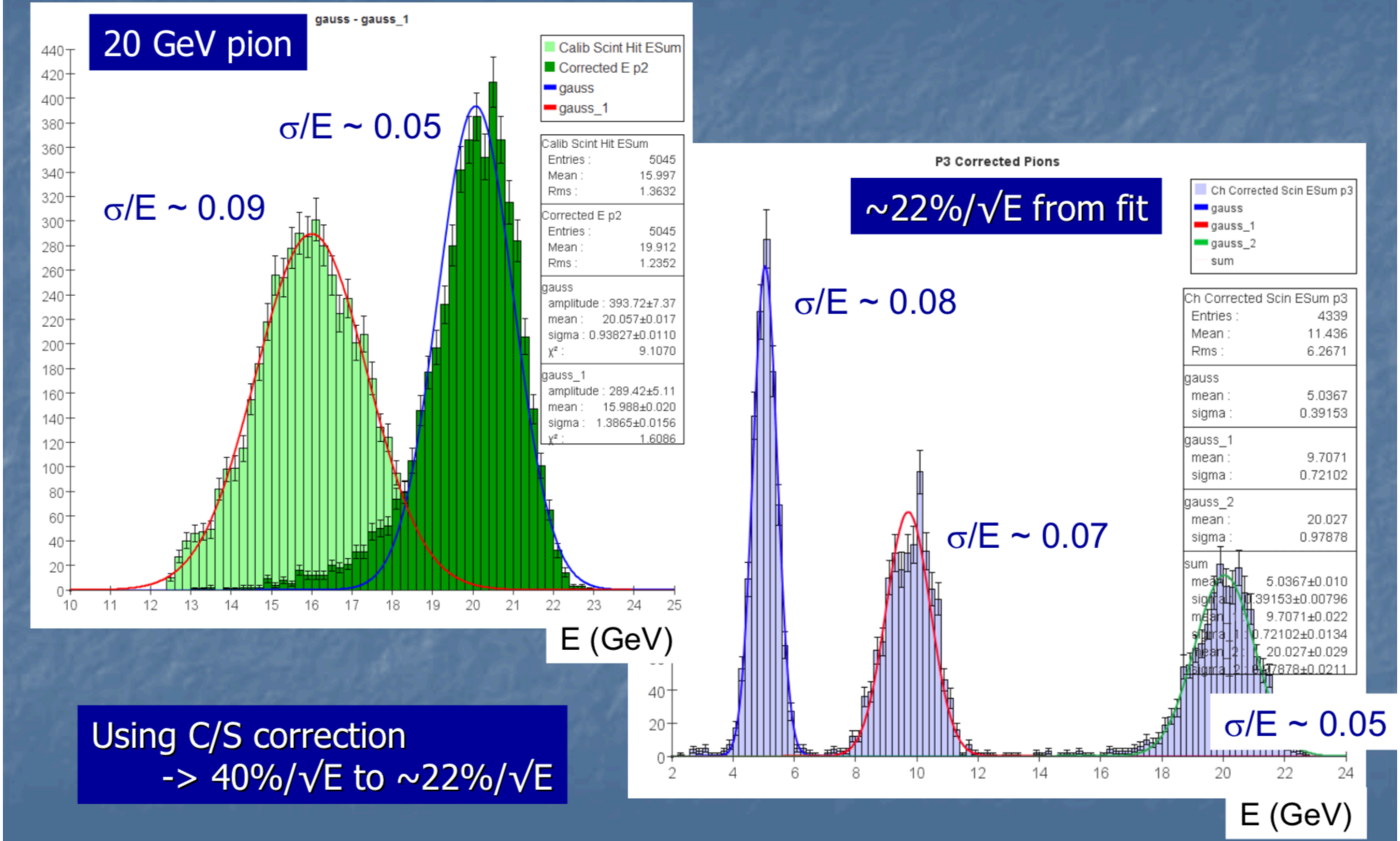
$P1 = .315 + .684(C/S)$

$P2 = .677 - .439(C/S) + .762(C/S)^2$

$P3 = .506 + .608(C/S) - 1.050(C/S)^2 - .935(C/S)^3$

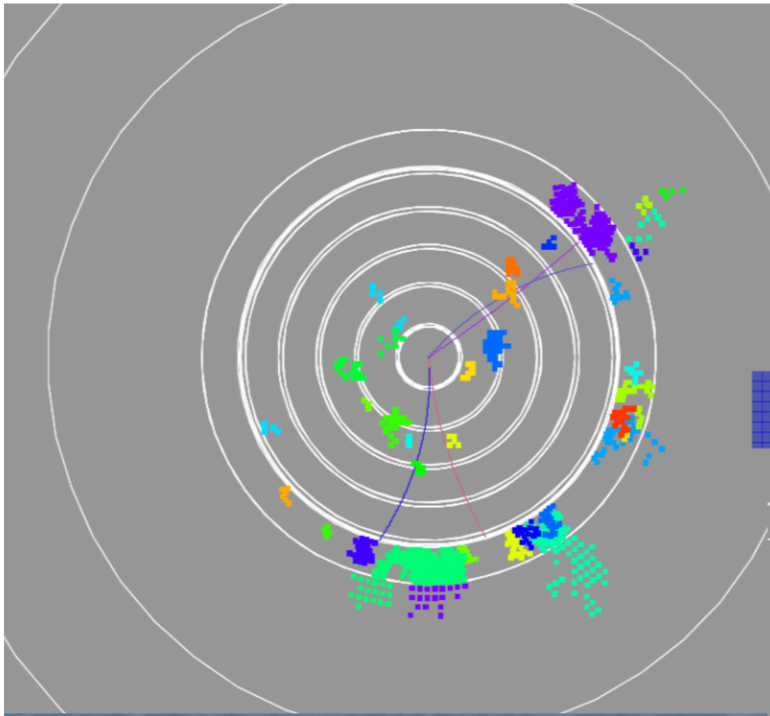
$P4 = .577 - .149(C/S) + 1.464(C/S)^2 - 2.302(C/S)^3 + 1.410(C/S)^4$

Corrected Pion Scintillator signal using Polynomials

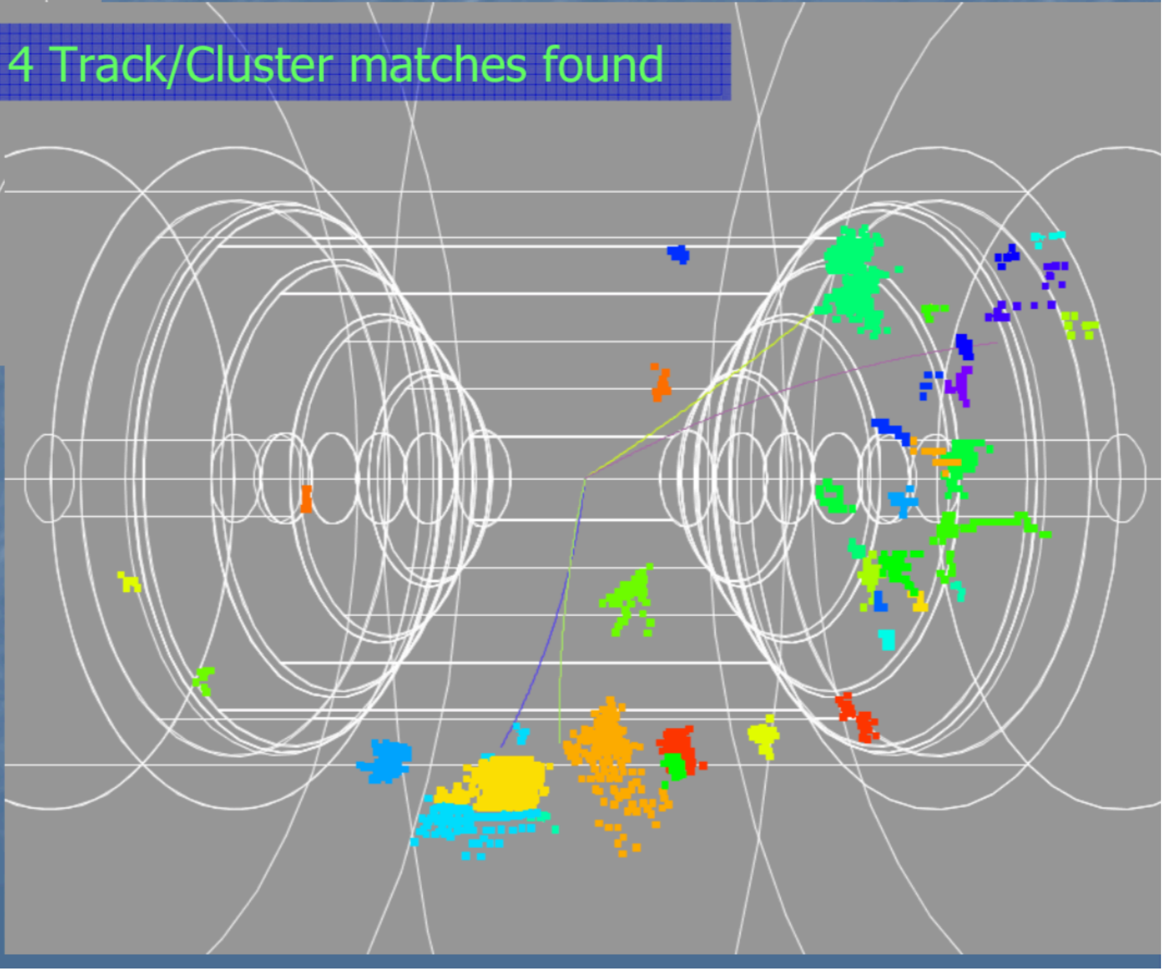


Using C/S correction
-> 40%/√E to ~22%/√E

Particle Flow + C/S correction



e^+e^- -> ZZ -> ννqq @ 500 GeV



4 Track/Cluster matches found

PFA Tracks + C/S-corrected
Cluster RPs

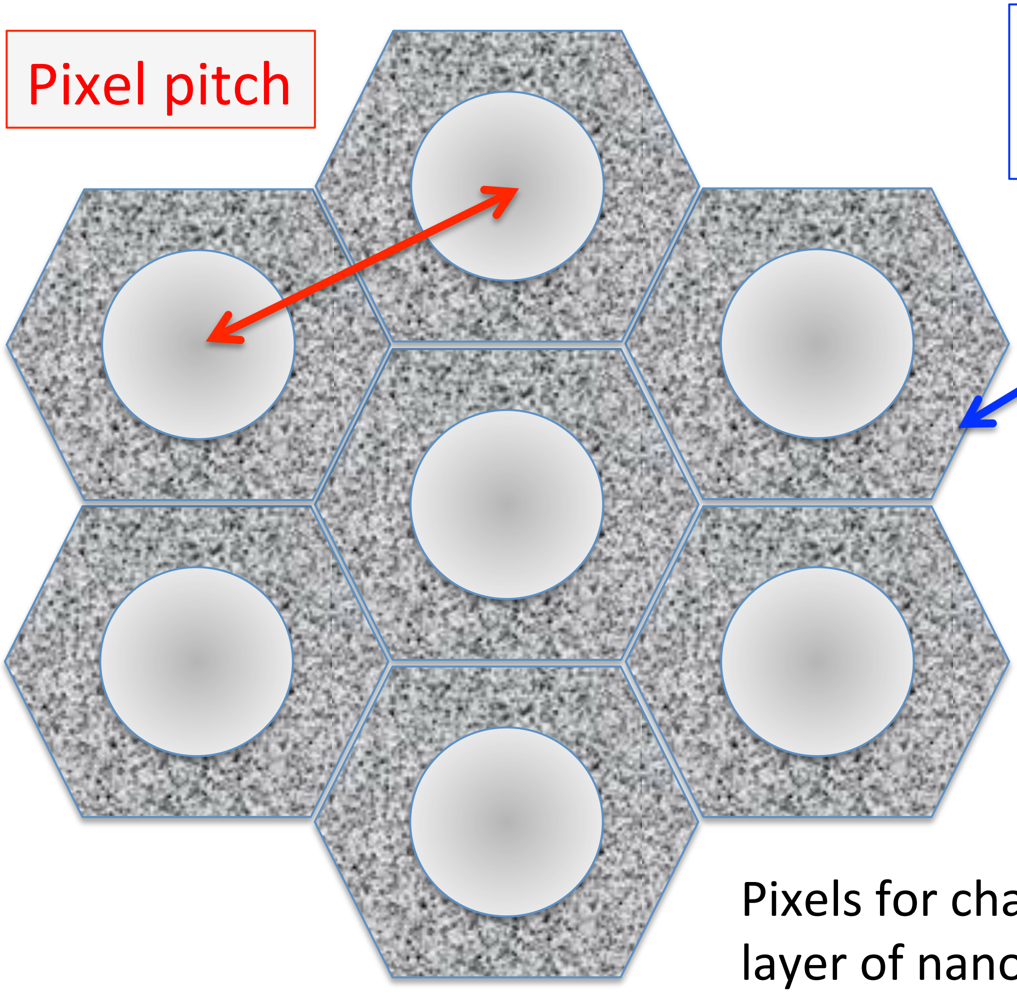
PFA-Enhanced

Future Pixel APA for DUNE (4th detector)

Nanoparticle idea for photon detection on a pixel APA

- Need plane with 2D pixels (metal charge collector) and photon sensors
- Idea − photon sensors form the plane with charge collection pixels isolated within the photon sensors
- Pixel plane is made of a substrate material with nanoplatelets deposited on the substrate, readout on the back side (outside of TPC)
- Nanoplatelets absorb VUV photons, generate electrons − direct conversion of photons to current (possibly no separate photosensor)
- *Current SBIR* to identify nano candidates sensitive to 128 nm and 175 nm −> form into nanoplatelets -> direct signal
- *Keep in mind − doping Argon with hundreds of ppm Xenon converts all 128 nm light to 175 nm − may already have suitable candidates to start incorporating into nanoplatelets (to be tested in pDuNE)*

Qpix plane inside Field Cage



Pixel pitch

Nanoplatelet layer for photon detection

Nanoplatelets

- ✓ UV absorption to electron current (ANL NST Division)

Pixels for charge collection surrounded by layer of nanoparticles

- UV -> Visible -> photosensor -> readout
- Or, possibly UV -> electron current -> readout

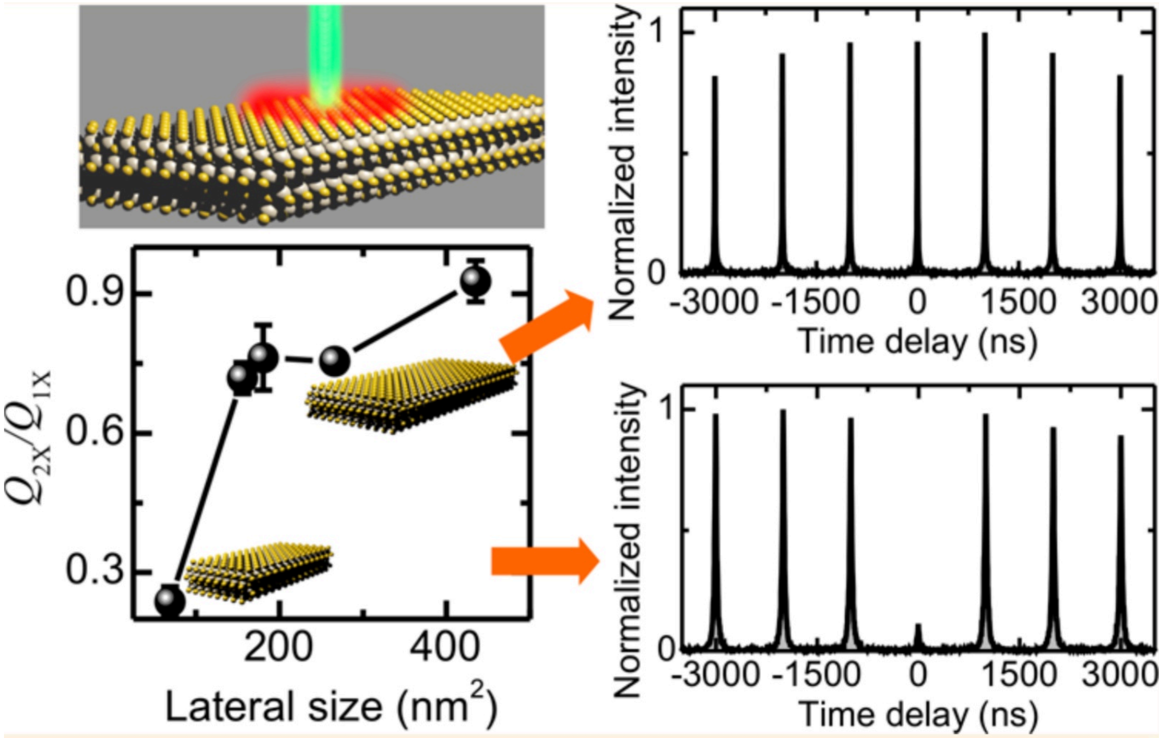
ANL NST - Nanoplatelets

Alternative form for readout of crystal:

- Nanoplatelet (1-dimension smaller than λ_e) deposited on crystal surface

- Amplification of signal when lateral size increases (multiple signal response shows up at 0 ns time delay)

- Collaboration between CNM and ANLHEP (joint LDRD proposal submitted)



Work at ANL Center for Nanoscale Materials

Published: ACS Nano 2017, 11, 9119-9127

Potential Nanosensors, Applications, Customers

Detector	App	Absorbed λ (nm)	Emitted λ (nm)	Nano Candidates	Customers
Argon	Coating	125	425	CdTe	HEP(DUNE, SBN)
Xenon	Coating	178	425	CdTe	HEP, NP(Dark Matter, 0νββ)
Water	Coating	125-300	425	CdTe, LaF3:Ce	HEP(ANNIE)
BaF2 Xstal	Cookie, Surface	220	425	LaYO, CuCy, ZnS:Mn, ZnS:Mn-Eu, CdTe	HEP(Mu2e)
PbF2 Xstal	Cookie, Surface	200-300	425	Si, LaYO, LaF3:Ce, CdTe	HEP, NP(g-2, DRCal)
CsI, CeF3, CeBr3, LaCl3, LaBr3 Xstals	Cookie, Surface	300-371	425	LaF3:Ce	Medical
Plastic Lens	Infusion, Coating	300-400	425-550	LaF3:Ce	Night Vision, Defense
Window Glass	Infusion, Coating	300-400	425-550	LaF3:Ce	Homes, Businesses, Greenhouses

Some other interesting Apps

- UV Night Vision
  - Use reflected UV light in 300-400 nm range to enhance vision in low light conditions
  - UV tag identifiers
- Enhanced plant growth
  - Match light in greenhouses to the dual absorption peaks of chlorophyll
  - Nanoparticle spray for crops in fields!
  - Pending TCF (DOE) proposal
- Window glass lighting
  - Nanoparticle-infused window glass lights interior spaces
  - No power required
  - Planned tests at ANL glass shop

Nanoparticle-enhanced Night Vision

From **Science**Daily

Bats Scan The Rainforest With UV-Eyes

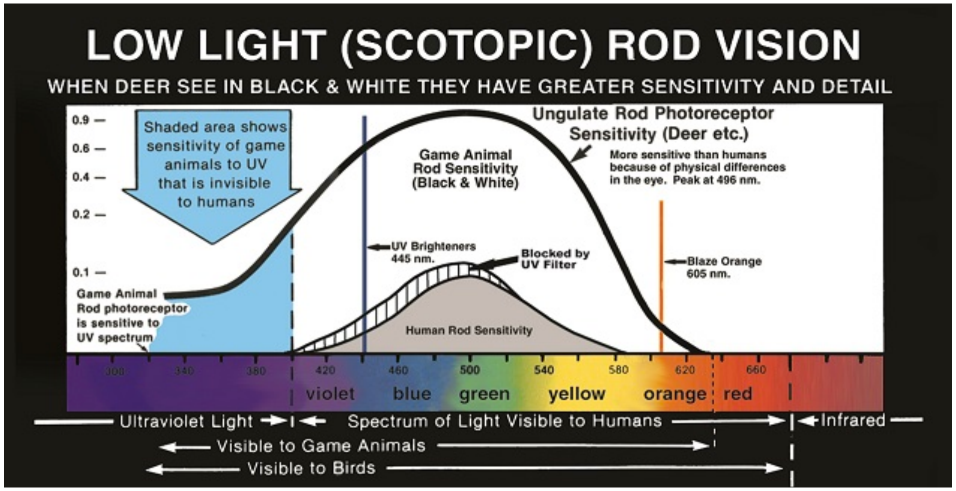
“Bats from Central and South America that live on nectar from flowers can see ultraviolet light (Nature, 9 October 2003).”

“There is little light at night. But compared to daylight, the colour spectrum is shifted towards short, UV-wavelengths.”

“Interestingly, bats achieve an absorption efficiency in the UV bandwidth of nearly 50 percent of their photoreceptors major peak of absorbance (alpha-band). *This is nearly five times the value expected from in-vitro measurements of beta-band absorption in rhodopsin molecules.* Whether this indicates a *novel mechanism for light perception* in the bats eye that is still unkown for mammals remains open.”

-> High efficiency for UV absorption is a characteristic of quantum confinement in nanoparticles – *Bat eye rods are coated with nanoparticles!?*

. . . and Deer

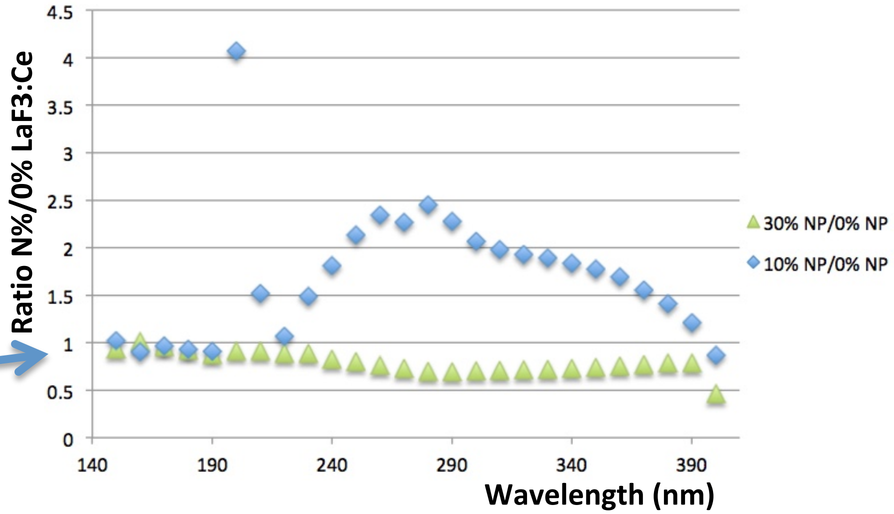


. . . and now Us!

LaF3:Ce nanoparticles in transparent polycarbonate buttons (contacts)

Enhancement for 10% LaF3:Ce:

230 nm < λ < 390 nm



Enhancing Plant Growth

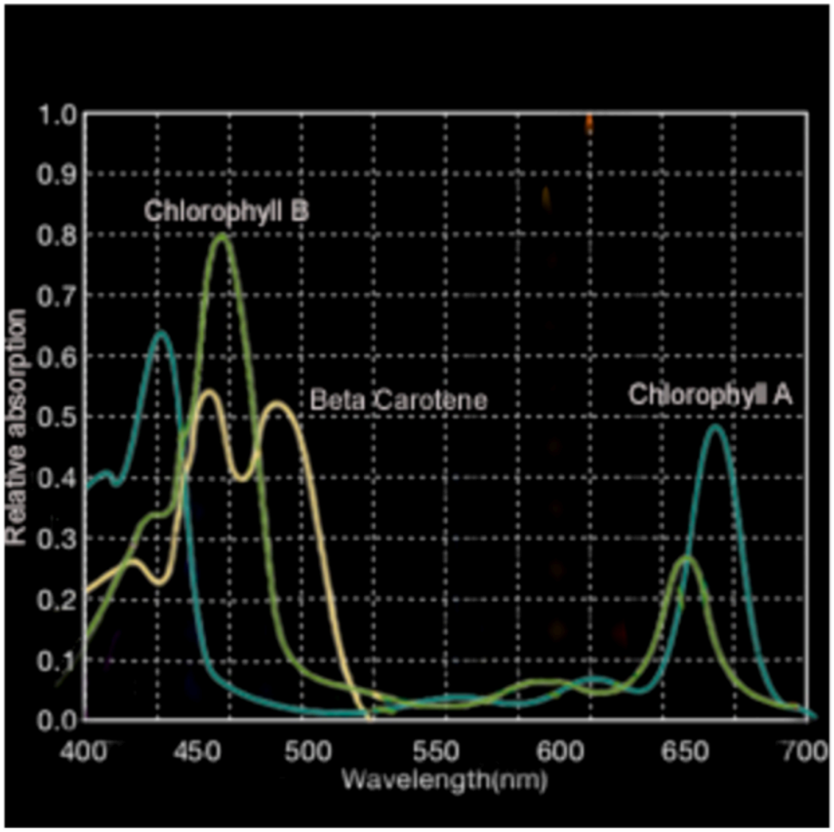


Fig. 1: Absorption Spectrum Chlorophyll A, B and Beta-Carotene

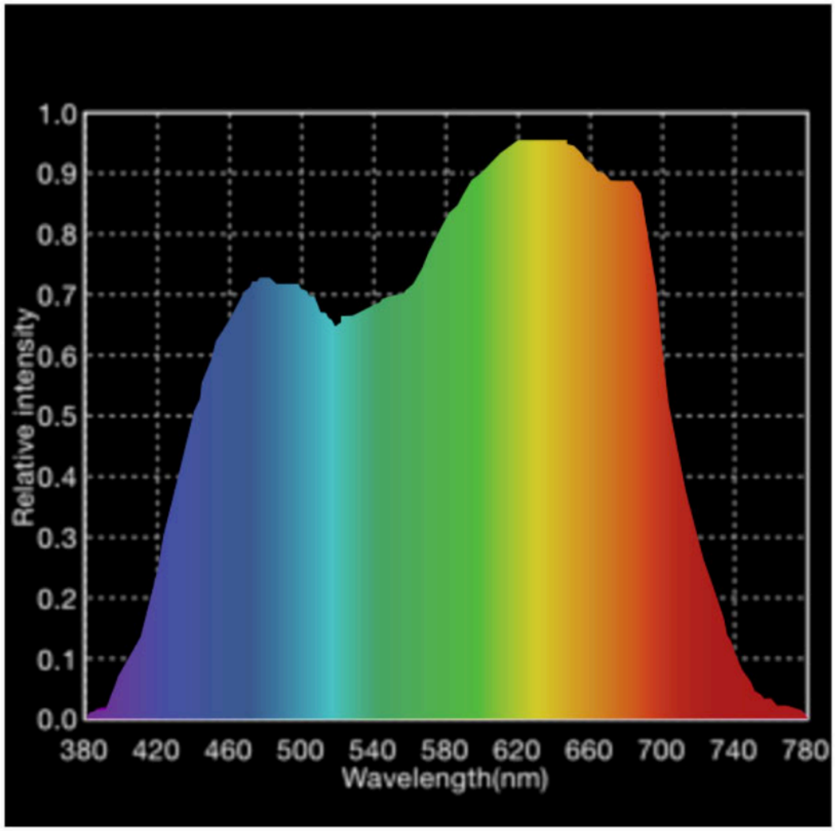
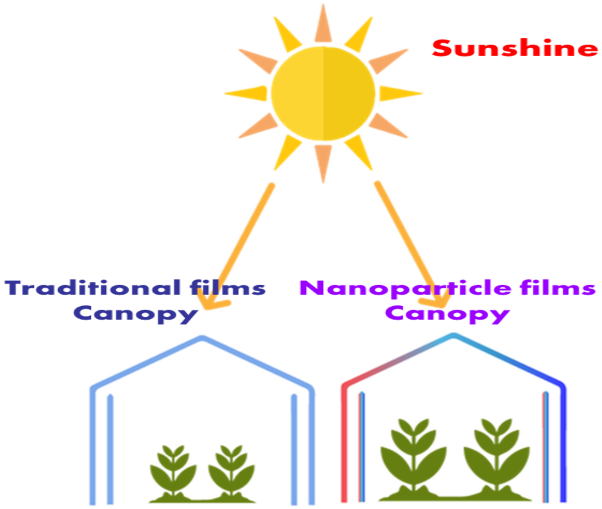


Fig. 2: Action Spectrum

Questions? / Fragen?

Solgro, Inc. Results



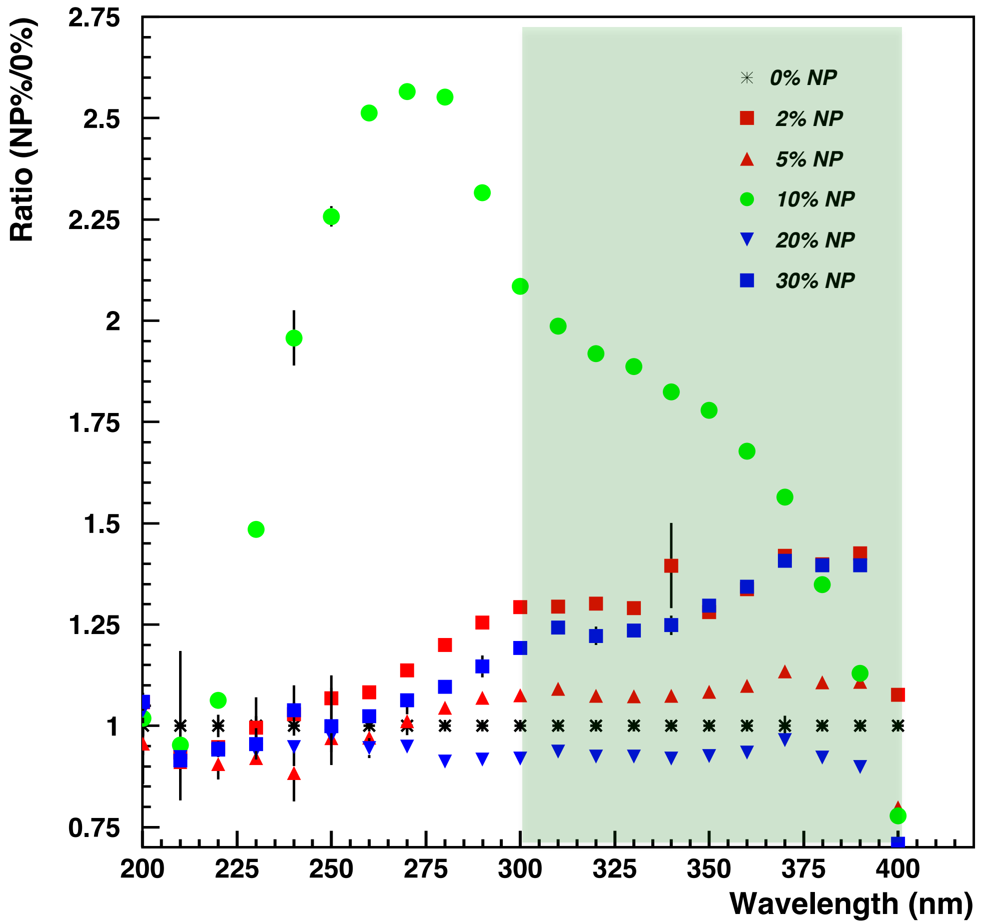
Nanoparticle application:

- Use 2 different nano candidates to convert UV to blue and UV and green to red
- Nano candidates in plastic film
- First results show dramatic increase under nano film section!

Also

- Bioelectricity production from plant-based fuel cells!
- Using other nanoparticle to filter unwanted IR -> lower temp in greenhouse

Nanoparticle candidate for window glass



- Enhanced response for 10% concentration of nanoparticle candidate in range 300 – 400 nm
- Infuse into window glass, chose nanoparticle size so that emitted wavelength is ~470 nm (peak of solar light spectrum)
- At least 10% more usable light! – more in low light conditions