Test beam study of SiPM-on-tile configurations for the CMS HGCAL

(arXiv/2102.08499)

Michael Krohn

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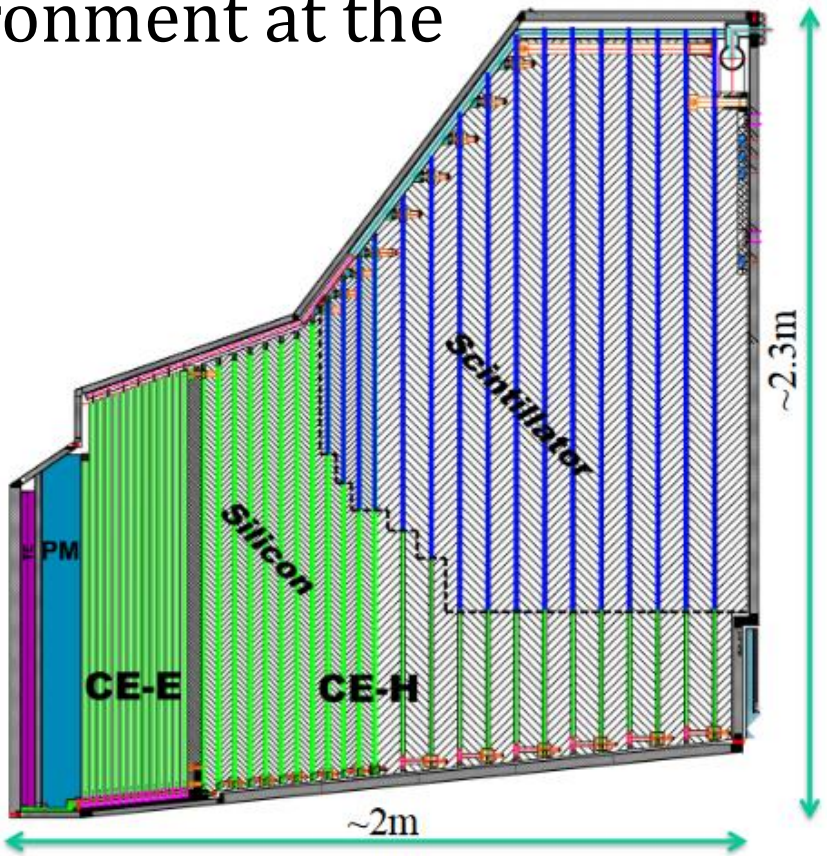
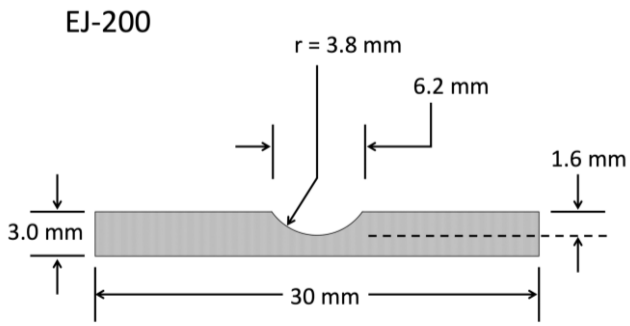
HGCAL at the HL-LHC

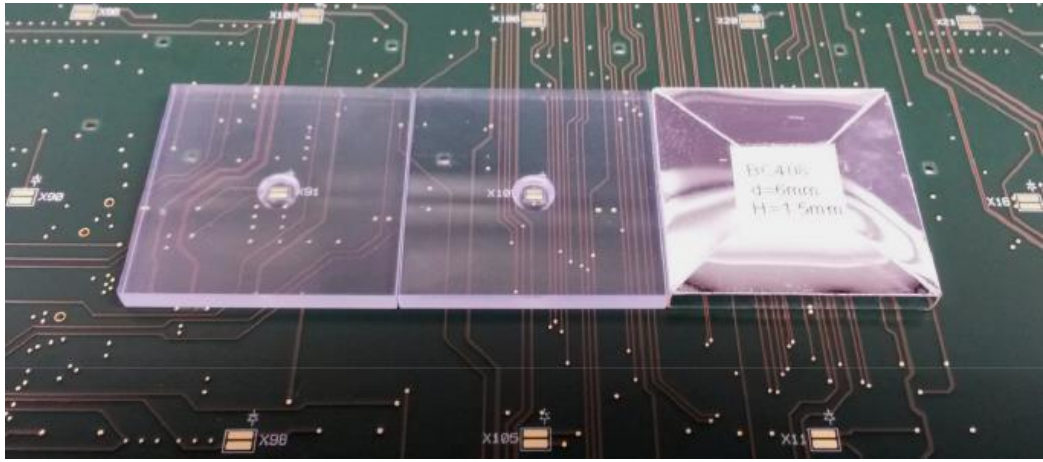
- CMS **endcap** will operate in an unprecedented radiation environment at the HL-LHC
  - Doses up to 2 MGy
- High Granularity Calorimeter (**HGCAL**): **replacement of CMS endcap calorimeters**
  - A 5D (imaging) calorimeter using particle flow
  - **Silicon sensors** in the CE-E and high radiation region of CE-H
  - Scintillator section composed of **SiPM-on-tile** design in regions where radiation fields allow



SiPM-on-Tile Design

- Developed for the Calorimeter for Linear Collider Experiment (CALICE)
  - **Individually wrapped** plastic scintillator tiles placed on SiPMs
  - **Dimple** in scintillator provides mechanical space for SiPM and improves uniformity of response across tile
  - Allow for calibration of individual tiles

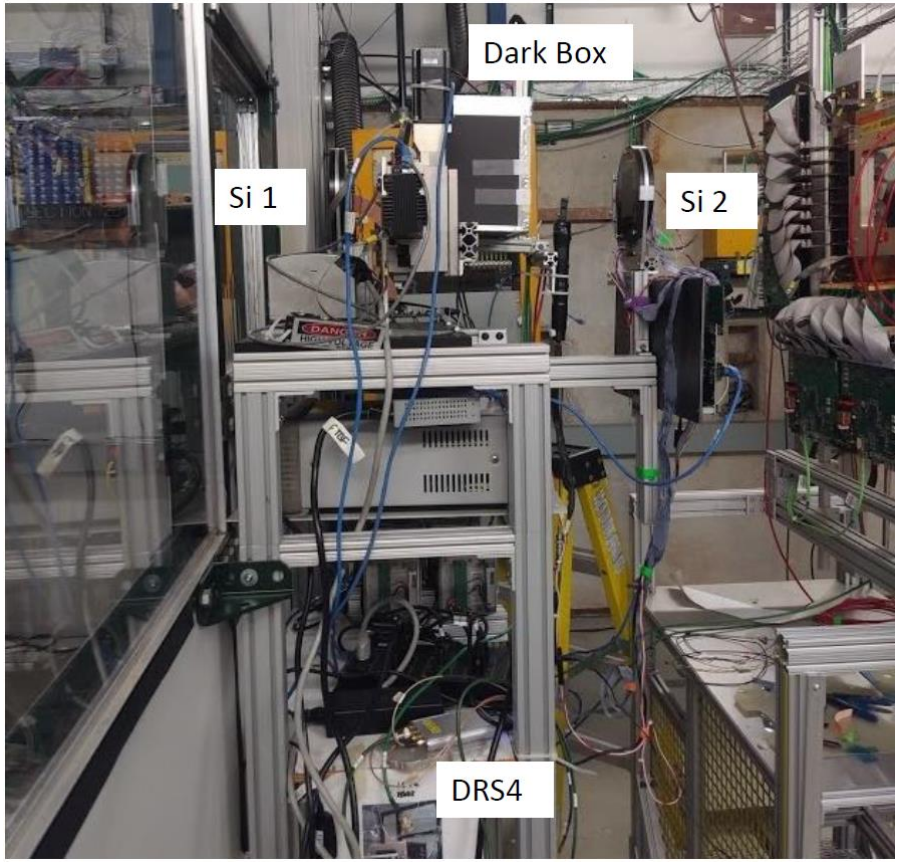


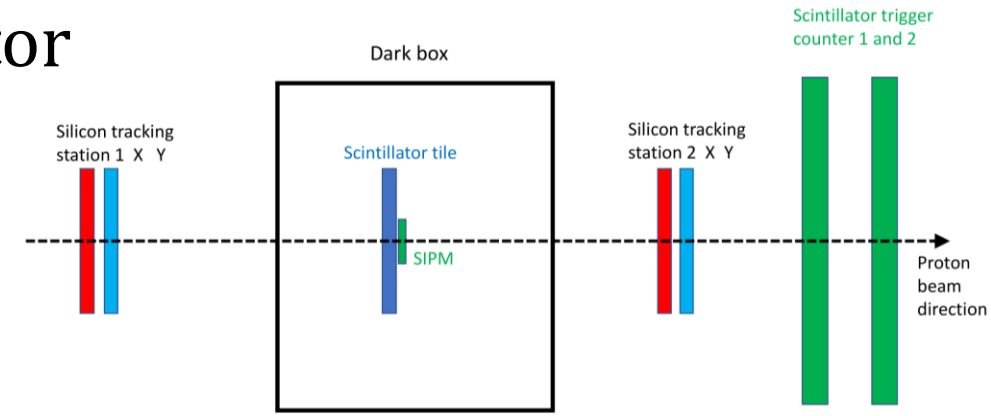


Test Beam

Test Beam Setup

- FNAL beam conditions
  - **120 GeV protons**
  - Beam spot ~4cm diameter, $\sigma = 1.5$cm in x and y
- Planes of Si strip tracking detectors placed on either side of sample black box
- Trigger provided by a coincidence of 2 scintillator counters
  - ~1k triggers/spill
- Temperature sensor in black box





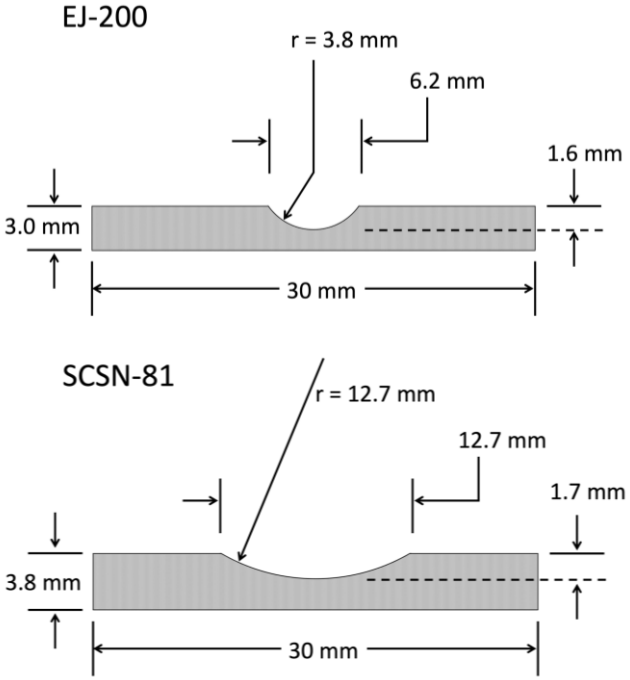
SiPMs

White silk screen

- **S13360-1350**
  - Historical reference to compare with previous measurements
  - Breakdown voltage = 51.76V
- **S14160-1315**
  - Best representative of SiPMs in HGCAL: Hamamatsu S14160 series will be used
  - Breakdown voltage = 38.31V

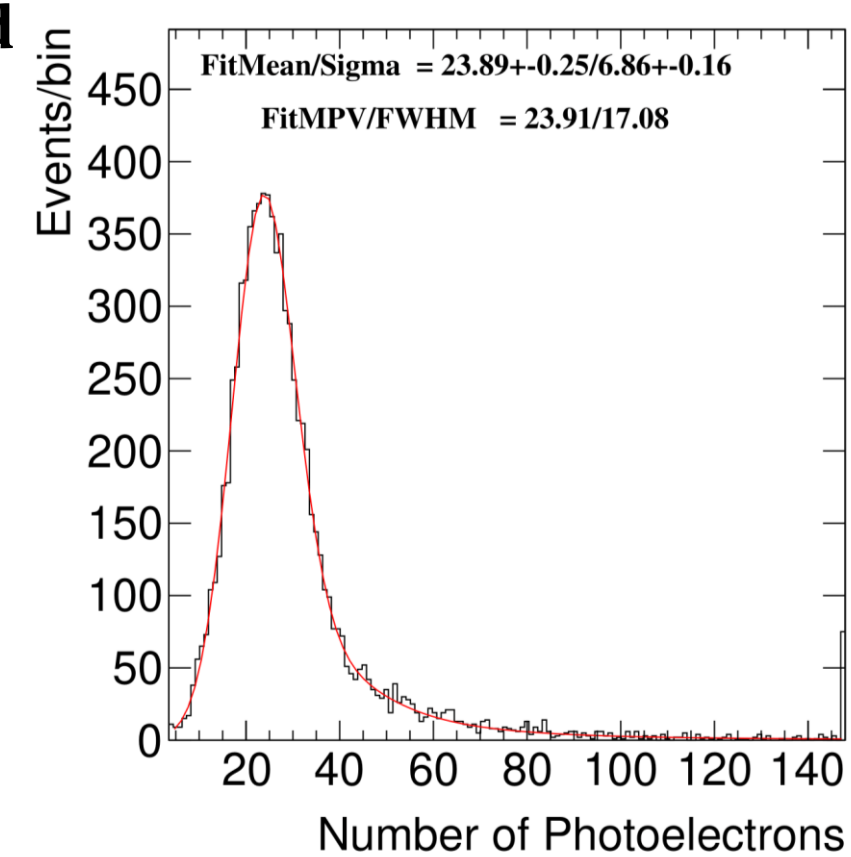
Scintillator Tiles

- $3 \times 3\text{cm}^2$ tiles
  - 3.8 mm thick **SCSN-81** (Polystrene-based scintillator)
  - 3 mm thick **EJ-200** (Polyvinyltoluene-based scintillator)
- Various transverse sized EJ-200 tiles ranging from $2.3 \times 2.3 - 5.5 \times 5.5\text{cm}^2$
- Tyvek and ESR wrappings



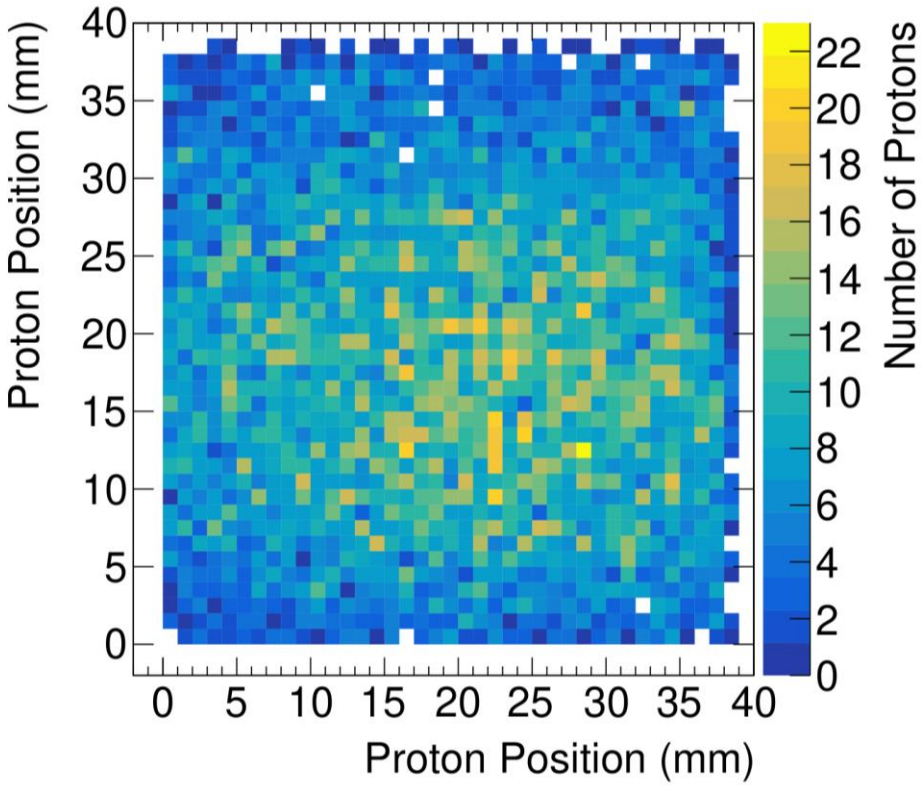
Light Yield Determination

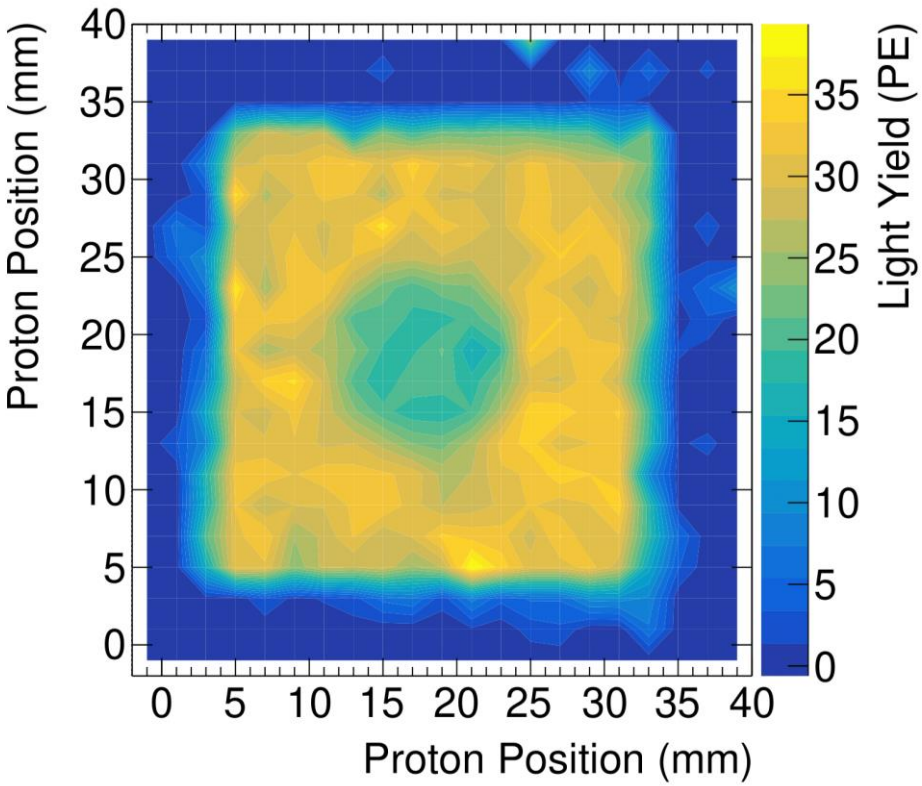
- Fit the MIP yield distribution with the convolution of a **Gaussian and Landau**
  - Gaussian models low light yield region
  - Landau models high light yield tail
- MPV used as a figure of merit
- $\pm$**3% systematic uncertainty** on the MPV MIP yield derived from multiple different measurements of the exact same tile over the course of the test beam



Tile Uniformity

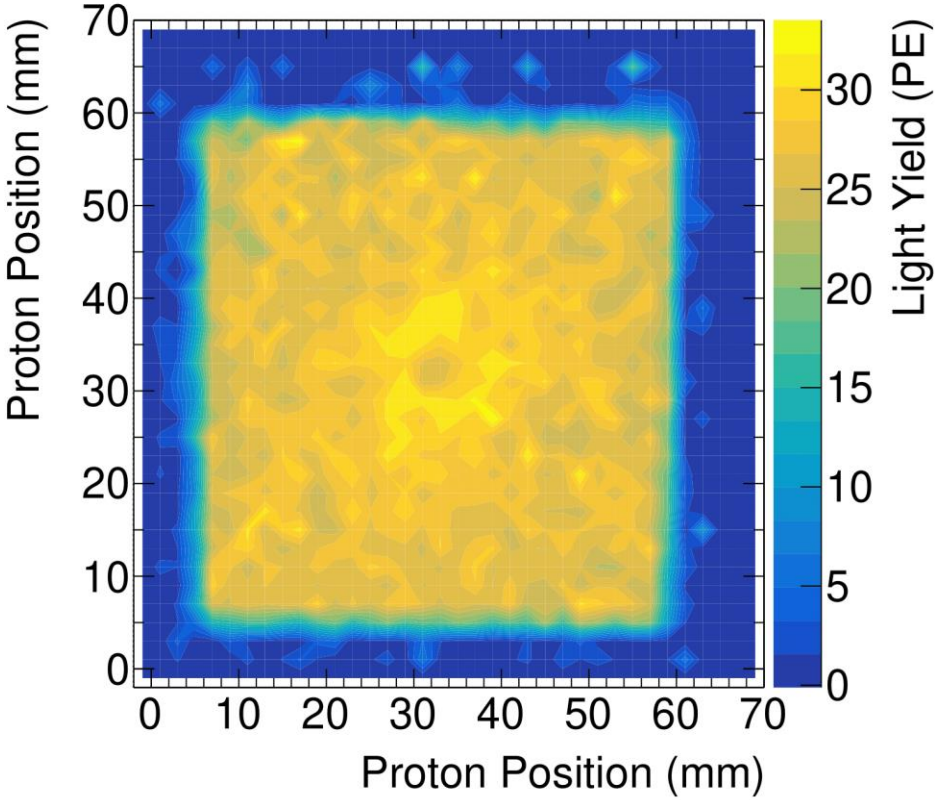
- Analysis technique provides response positions with a resolution of ~1 mm
- Special tile with a large, 12.7 mm diameter, dimple shows our measurements are sensitive to it

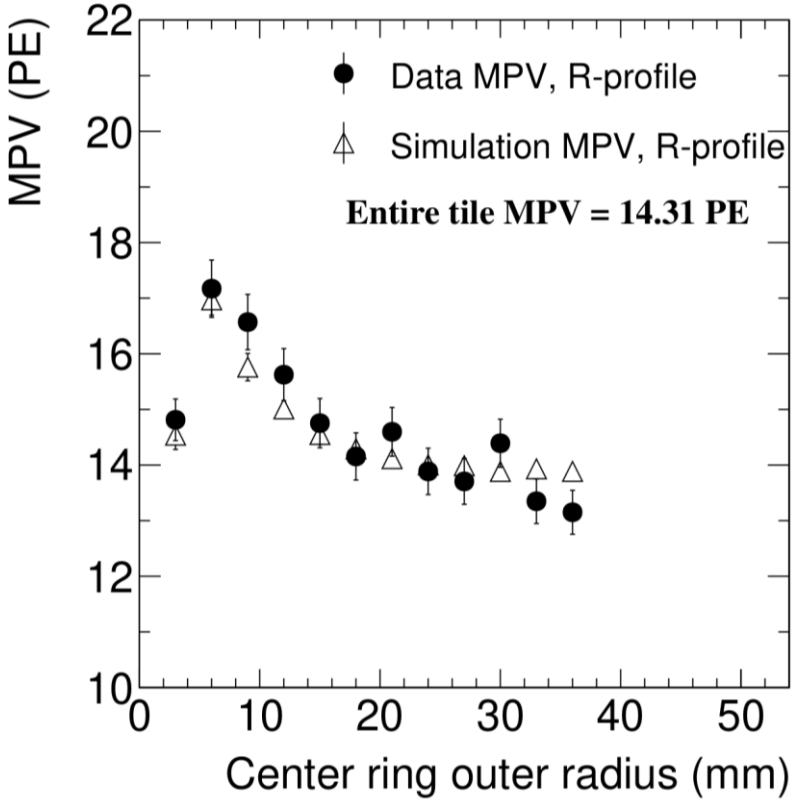




Tile Uniformity – 5.5 × 5.5cm^2 EJ-200 tile

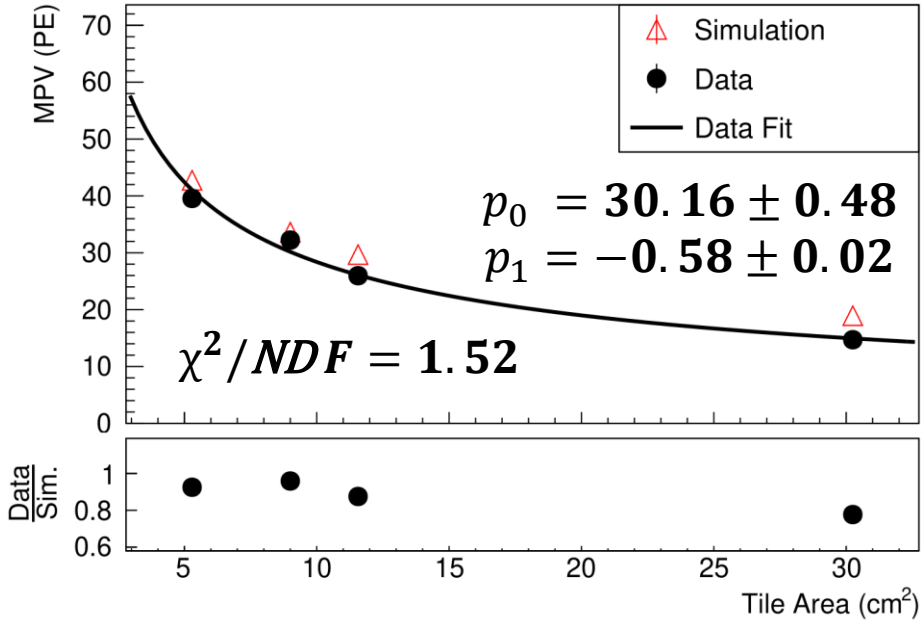
- Good agreement between data and simulation
  - Based on tile profile, SiPM centered approximately exactly
- Light yield varies by ~20% depending on annular region





Light Yield vs Tile Area

- MIP yield measurements for different sized tiles ranging across planned sizes for HGCAL
  - EJ200 scintillator wrapped in ESR, 3 mm thick. S13360 on white silkscreen with $V_{op} = 54.26\text{V}$
- χ^2 fit to data: $\text{MPV} = p_0(\text{Tile Area}/9cm^2)^{p_1}$
- Confirm LY $\sim 1/\sqrt{\text{Tile Area}}$ relation

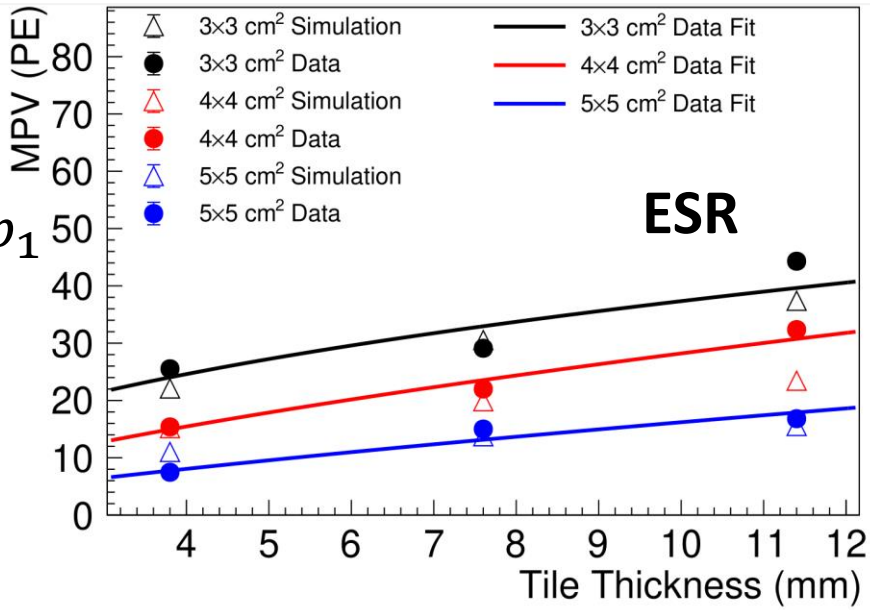


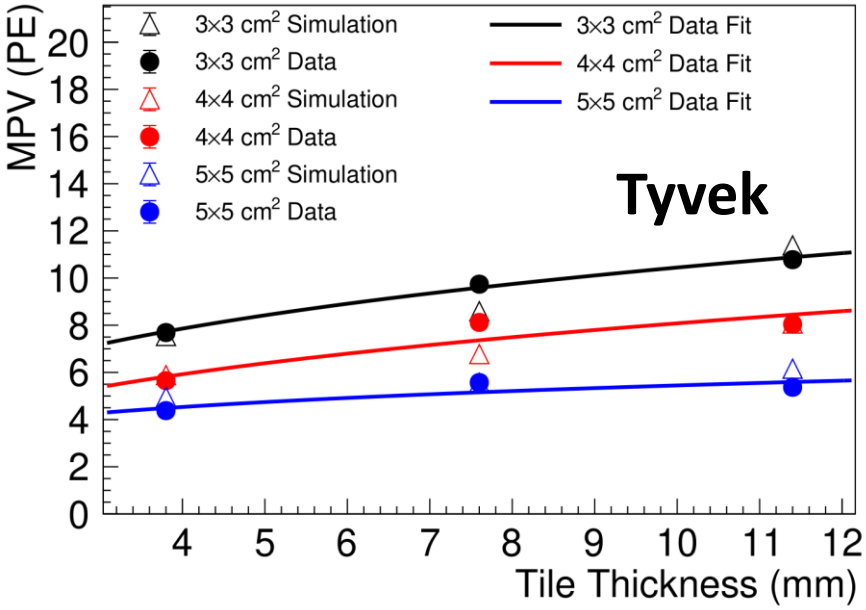
Light Yield vs Tile Thickness

- χ^2 fit to data: MPV = $p_0(\text{Tile Thickness}/3.8mm)^{p_1}$

SCSN-81 tile area, mm	Wrapping	p_0 fit values	p_1 fit values
30.0×30.0	ESR	24.03 ± 0.74	0.45 ± 0.04
30.0×30.0	Tyvek®	7.73 ± 0.22	0.31 ± 0.04
40.0×40.0	ESR	14.95 ± 0.44	0.66 ± 0.04
40.0×40.0	Tyvek®	5.82 ± 0.16	0.34 ± 0.04
50.0×50.0	ESR	7.76 ± 0.21	0.76 ± 0.04
50.0×50.0	Tyvek®	4.49 ± 0.13	0.20 ± 0.04

- Light yield has a greater increase as tile thickness increases for ESR wrapped tiles compared to Tyvek wrapped tiles





Tile Thickness – ESR vs Tyvek

- ESR wrapping increases light yield by (1.7 – 4.1)x compared to Tyvek wrapping depending on tiles size
  - Thicker and smaller area tiles benefit most from ESR

SCSN-81 tile dimensions, mm	ESR/Tyvek® light yield MPV ratio
$30.0 \times 30.0 \times 3.8$	3.32 ± 0.30
$30.0 \times 30.0 \times 7.6$	2.99 ± 0.27
$30.0 \times 30.0 \times 11.4$	4.11 ± 0.37
$40.0 \times 40.0 \times 3.8$	2.72 ± 0.25
$40.0 \times 40.0 \times 7.6$	2.63 ± 0.24
$40.0 \times 40.0 \times 11.4$	4.03 ± 0.37
$50.0 \times 50.0 \times 3.8$	1.71 ± 0.16
$50.0 \times 50.0 \times 7.6$	2.65 ± 0.24
$50.0 \times 50.0 \times 11.4$	3.15 ± 0.29

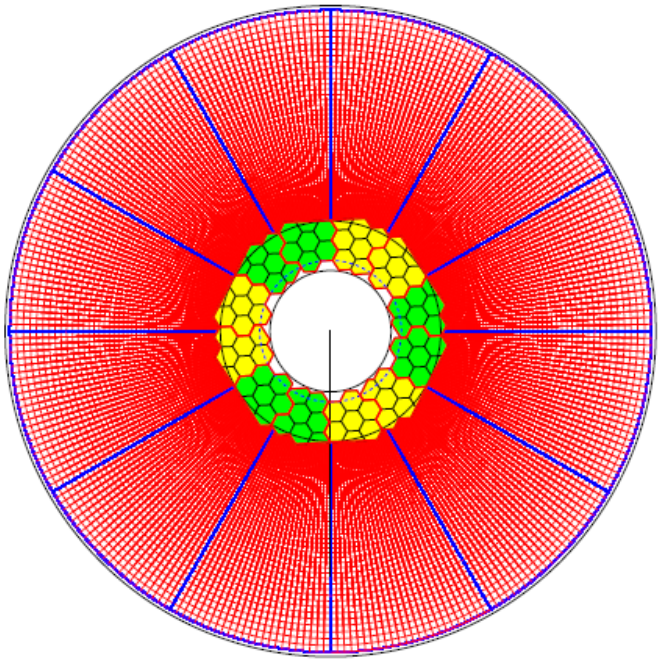
Summary

- Characterized uniformity for a variety of SiPM-on-tile configurations
- Measured light yield proportional to $\frac{1}{\sqrt{\text{Tile Area}}}$, for tile sizes ranging from smallest to largest planned tiles for the HGCAL
- ESR wrapping increases light yield by $(1.7 - 4.1)$x compared to Tyvek
- Can view studies in more detail in paper submitted to JINST: [arXiv/2102.08499]

Backup

Scintillator Geometries

- Tiles arranged in $r - \varphi$ grid, with sizes ranging from $4 - 30\ cm^2$
- Magnitude of MIP signal $\sim \frac{1}{\sqrt{\text{Tile Area}}}$
  - Smaller sized tiles at small radii
    - High light yield where the radiation damage is highest
  - Larger tiles at large radii
    - Larger area per channel



SiPM Photodetectors

Table 7.9: Measured characteristics of the HE upgrade silicon photomultipliers.

SiPM parameter	S10943-4732
Pixel pitch (μm)	15
Diameter of sensitive area (mm)	2.8
Operating temperature (°C)	24
V_{BR} (V)	≈65
Operating voltage (V)	V_{BR} + 4
Dark current (nA)	150
Photodetection efficiency at 550 nm (%)	30
Capacitance (pF)	215
Gain	3.5×10^5
Pixel recovery time (ns)	≈10
Excess noise factor	1.18
Optical cross-talk (%)	17
After pulses (%)	<2%
dV_{BR}/dT (mV/°C)	58.5
Temperature sensitivity (%/°C)	3
Voltage sensitivity (%/V)	50

Scintillator Material

- Polyvinyltoluene-based scintillator (PVT)
  - Higher light yield
  - Ex: EJ-200, EJ-260, EJ-262

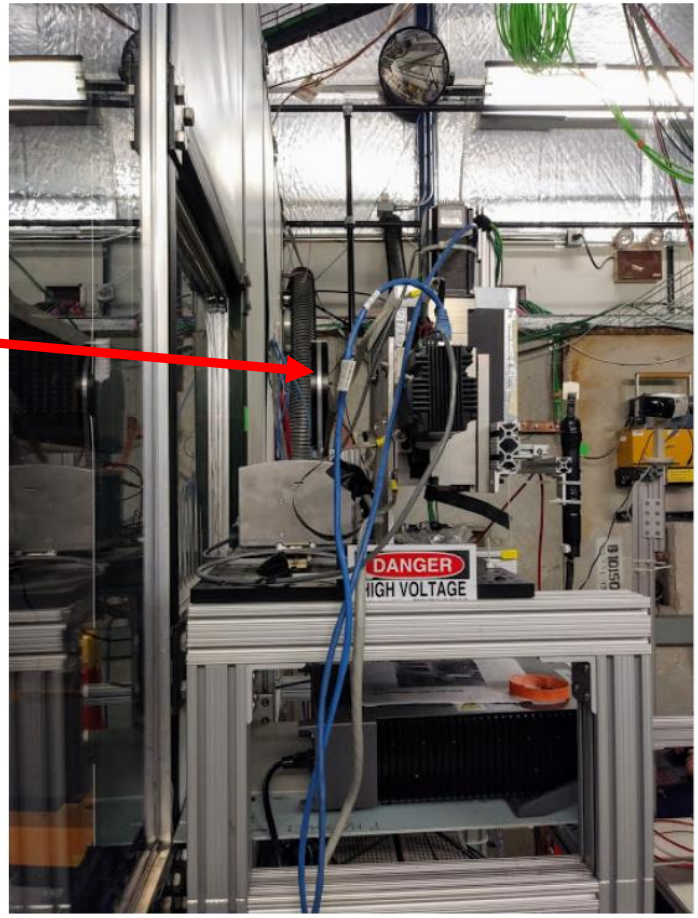
- Polystrene-based scintillators (PS)
  - Produced economically with injection molding techniques
  - Ex: SC-301, SCSN81

	EJ-200	BC-408	IHEP SC-301
Base material	PVT	PVT	PS
Light output (% anthracene)	64	64	60
Scintillation efficiency γ/MeV	9000	9000	8500
Wavelength of max. emission (nm)	425	425	420
Rise time (ns)	0.9	0.9	1.4
Decay time (ns)	2.1	2.1	2.5
CTE (K^{-1})	78×10^{-6}	78×10^{-6}	70×10^{-6}

Testbeam Setup

Side View Beam direction

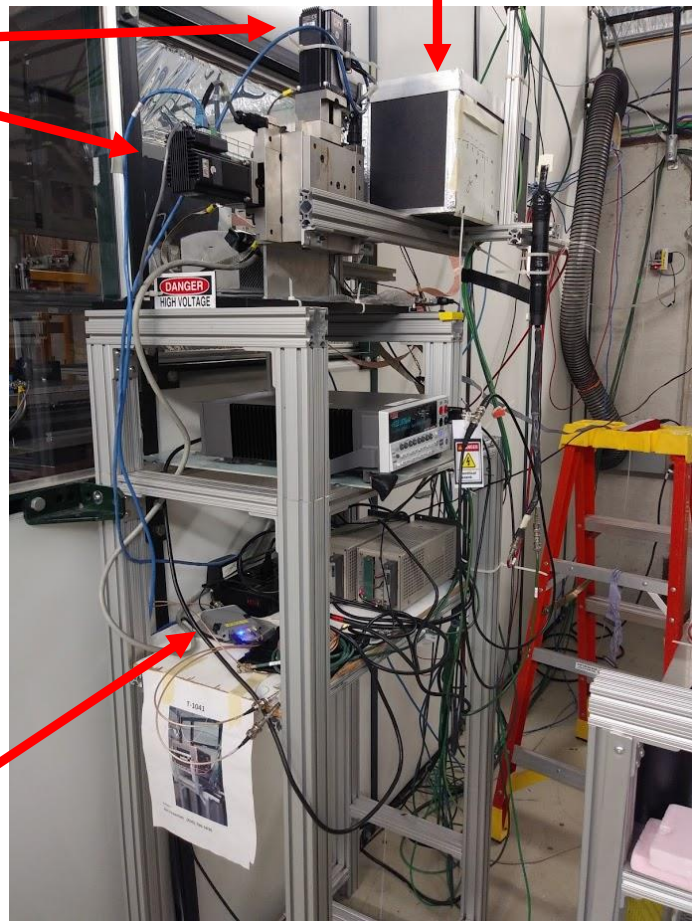
X,Y planes of Si



Dark box for sample

X, Y motors

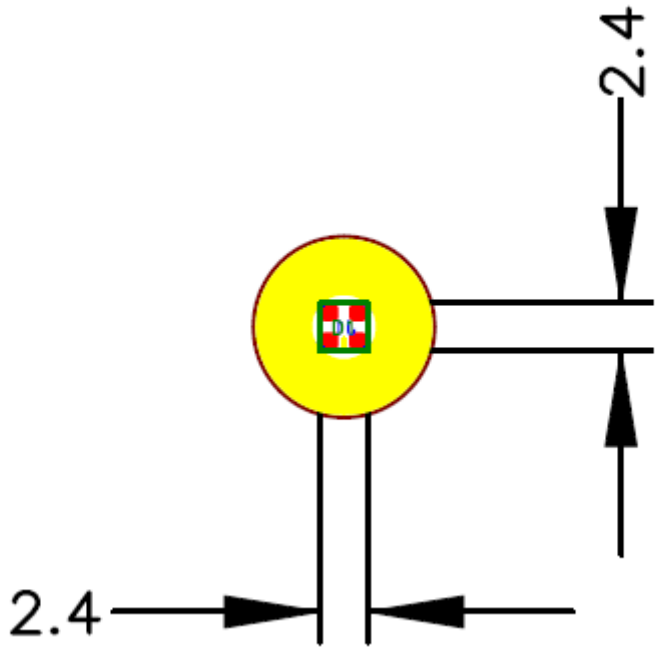
DRS4

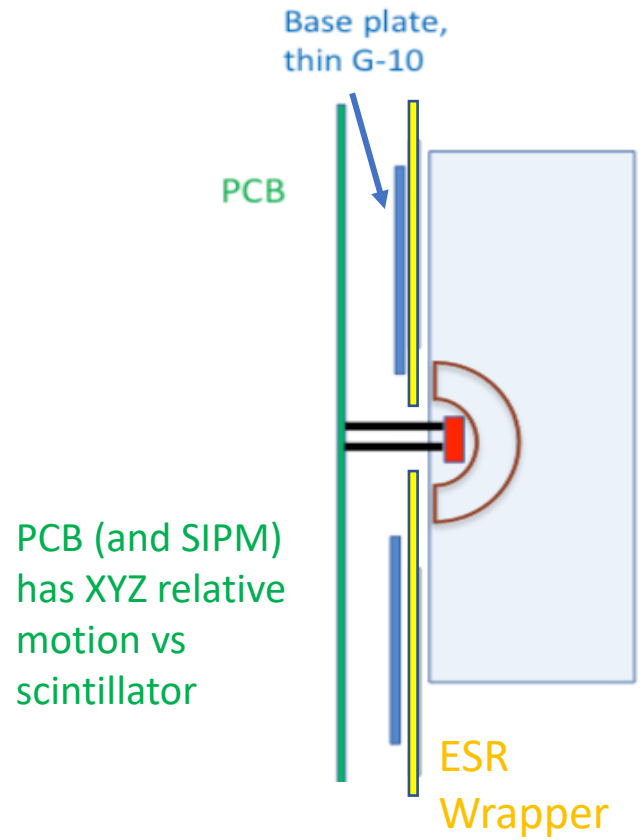


- 2nd tracker plane added for February testbeam

Testboard and Sample Setup

Board diameter = 9 mm

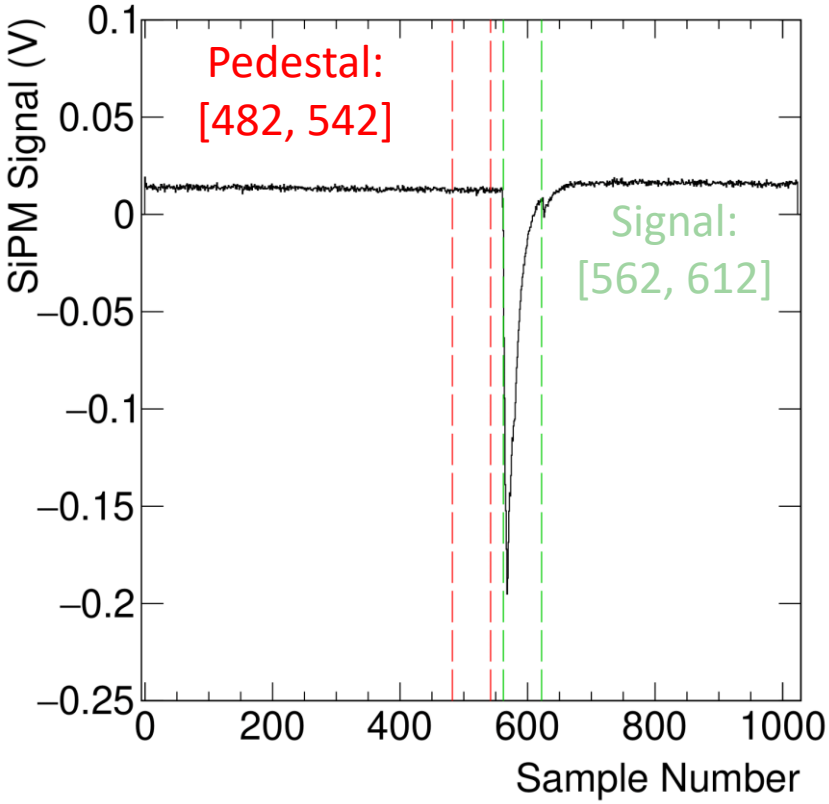




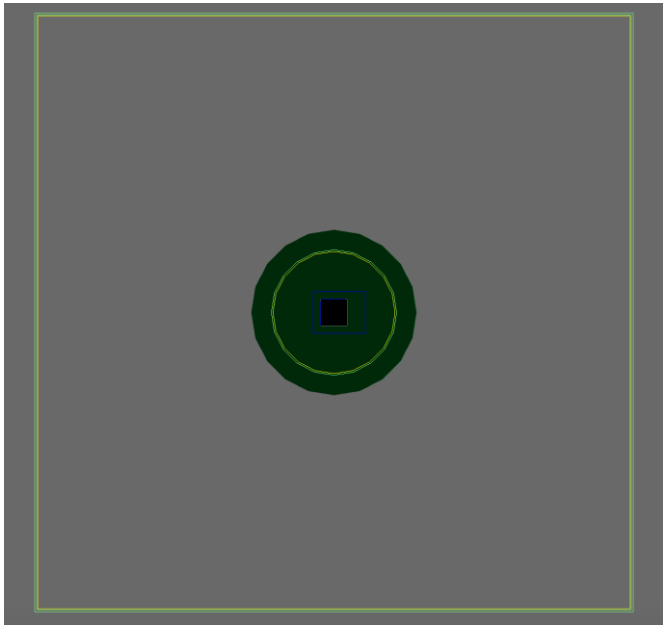
- Boards being produced with white silk screen

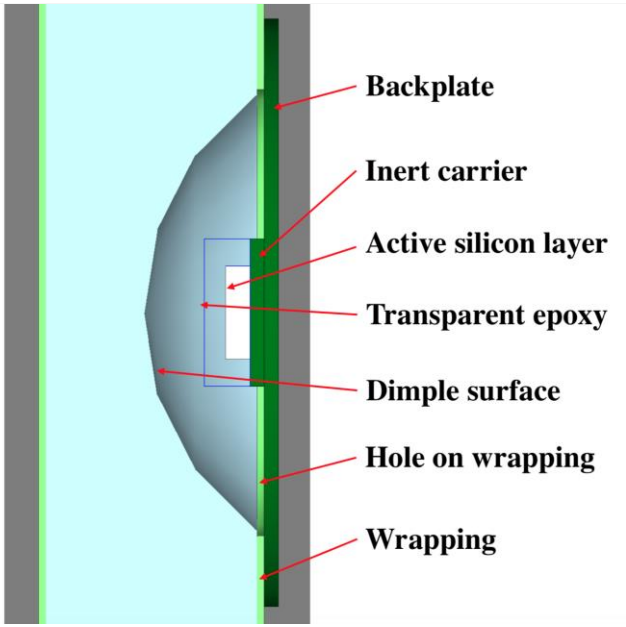
DAQ Setup

- DRS4 waveform digitizer
  - 16 bit ADC
  - 1 ns sampling period
- OTSDAQ framework
  - Configure DRS4 board and the silicon strip trackers
  - Provide triggers for both systems
- Light output measured as integral of waveform pulse
  - Integrated 60 samples near pulse max, starting at 0.25 of pulse max
  - Pre-amplitude region used for pedestal evaluation



Simulation



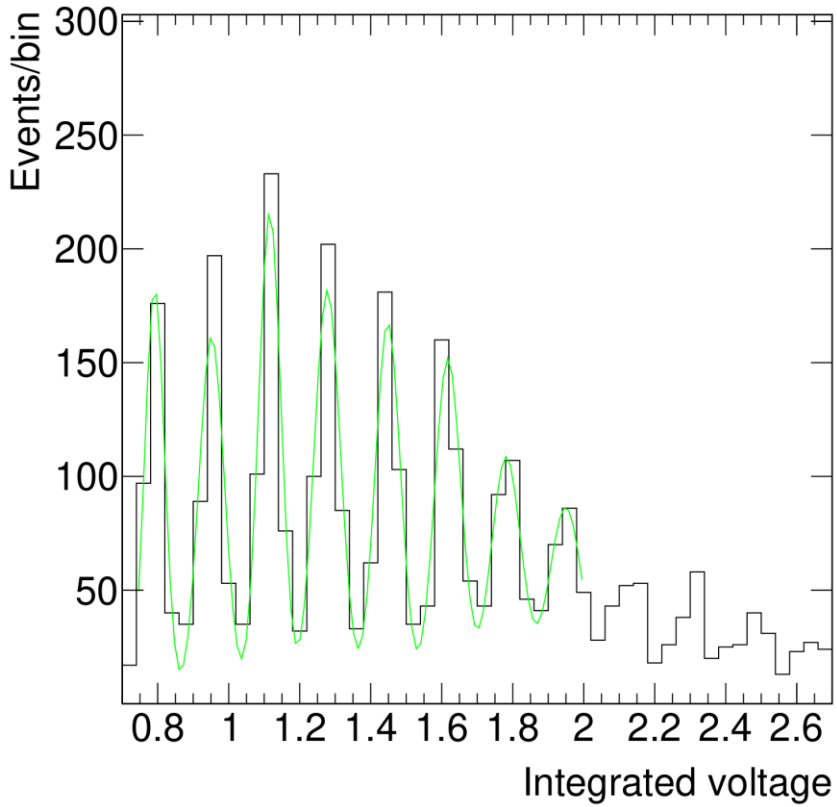


- GEANT4 based simulation composition
  - Tile with dimple
  - SiPM sitting on a back plane
- Simulated protons uniformly distributed across the tile's surface
  - Scintillating efficiency:
    - **EJ200**: 10 photons/keV, **SCSN-81**: 8.7 photons/keV

SiPM Calibration

- Collect 10-20k waveforms from a low light yield tile

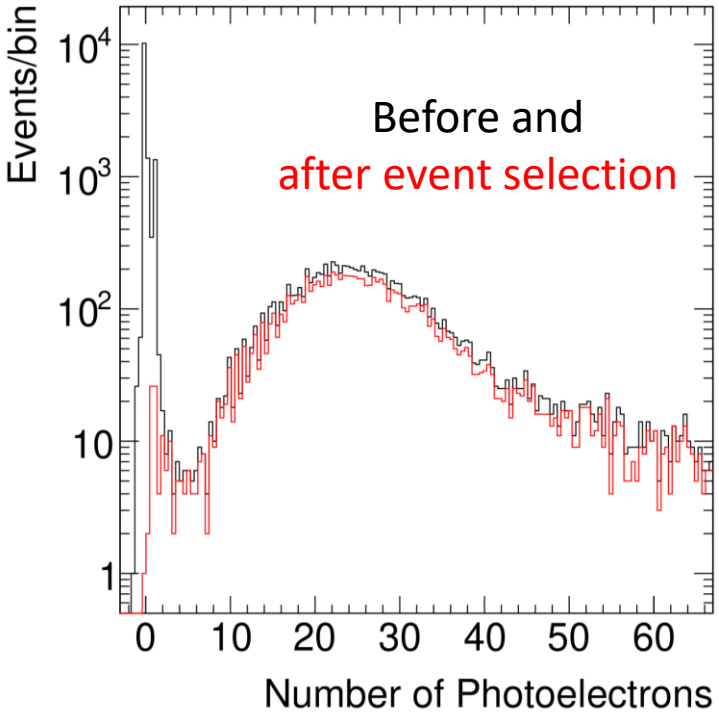
- Fit the first 7 peaks with the sum of Gaussian curves
  - Mean distance between peak is the extracted conversion factor



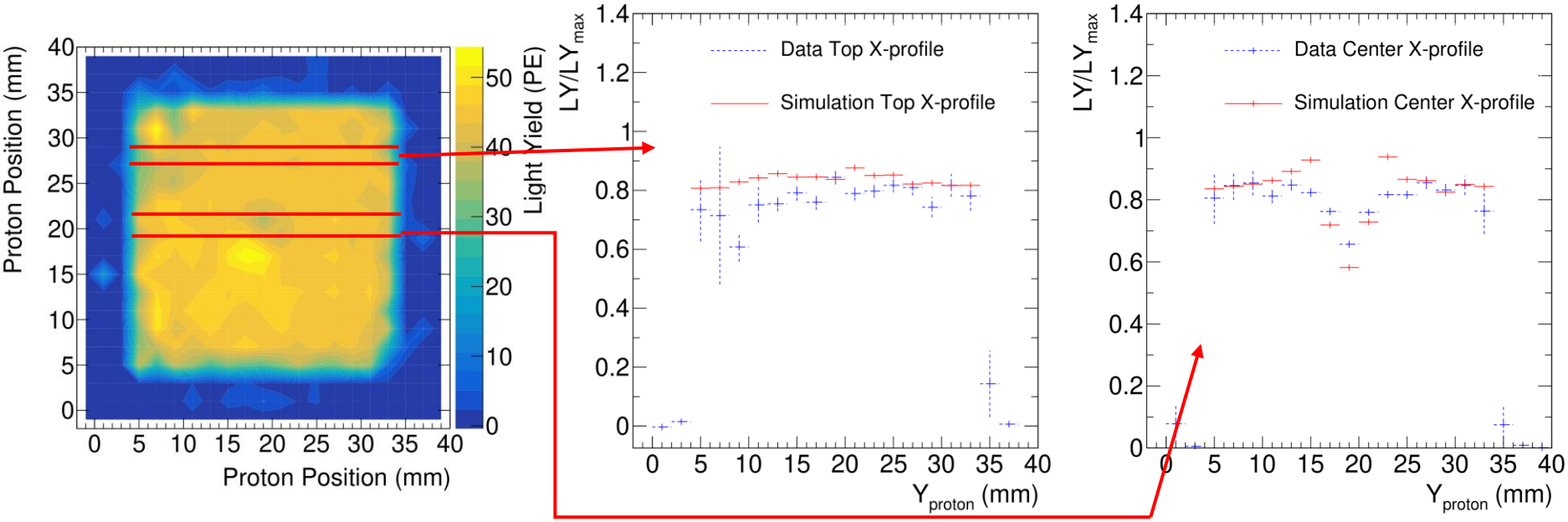
Gain
$= 0.165$
$\pm 0.001\ PE/V_I$

Event Selection

- Matching trigger number for DRS4 and tracker data
- **Clean waveform**
  - Falling edge required to reach 0.25 of maximum
  - Pre-signal region required to at least be the size of the wave form integration region
- **Noise suppression**
  - Pulse required to have amplitude above 10 mV
- **Clean tracker data**
  - Upstream tracker station required to have hits in both x and y planes, but no more than 2 strips in each

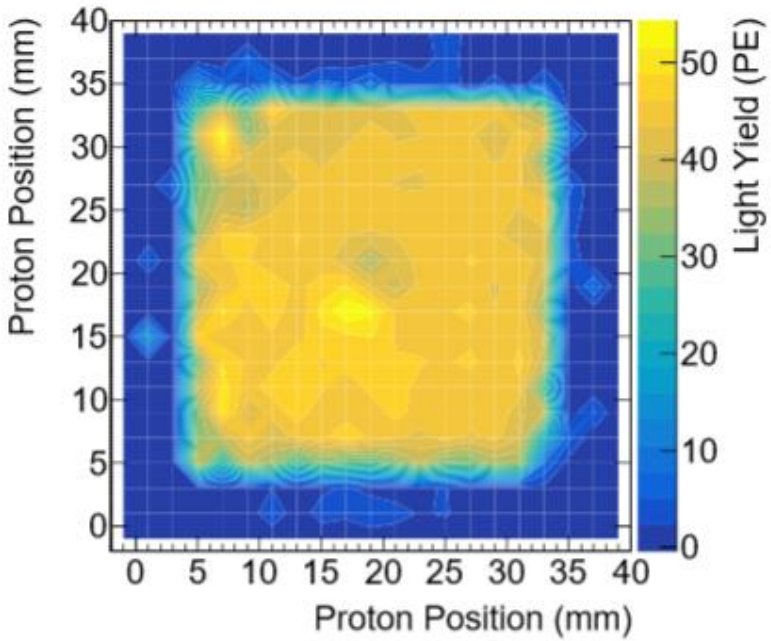


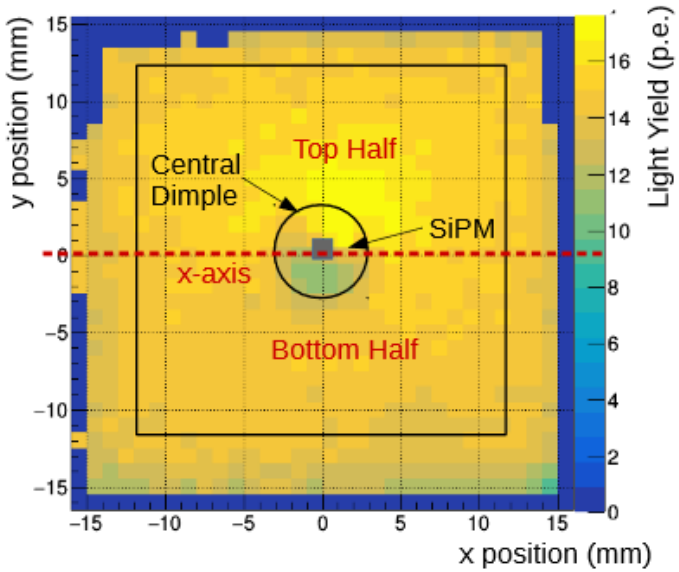
Tile Uniformity – 3x3cm EJ-200 tile



- ~15-25% decrease in LY in dimple region compared to rest of tile
  - Dimple radius = 3.1mm
- Fairly good agreement between data and simulation
  - Disagreement just outside of dimple → due to misaligned SiPM (backup)

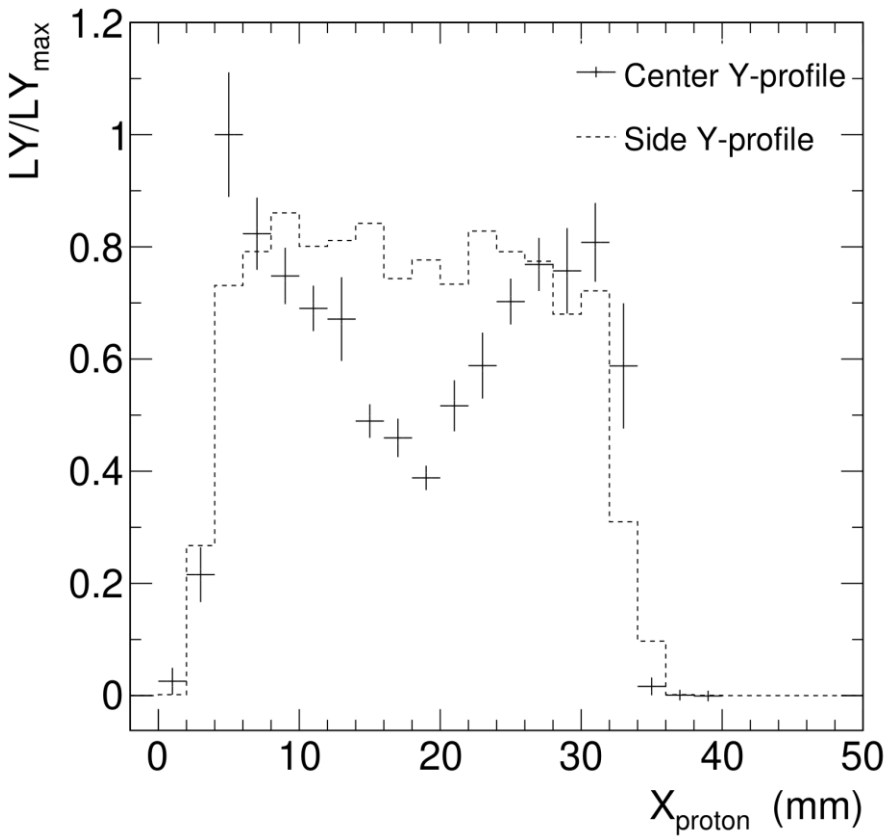
Tile Uniformity – 3x3cm EJ-200 tile

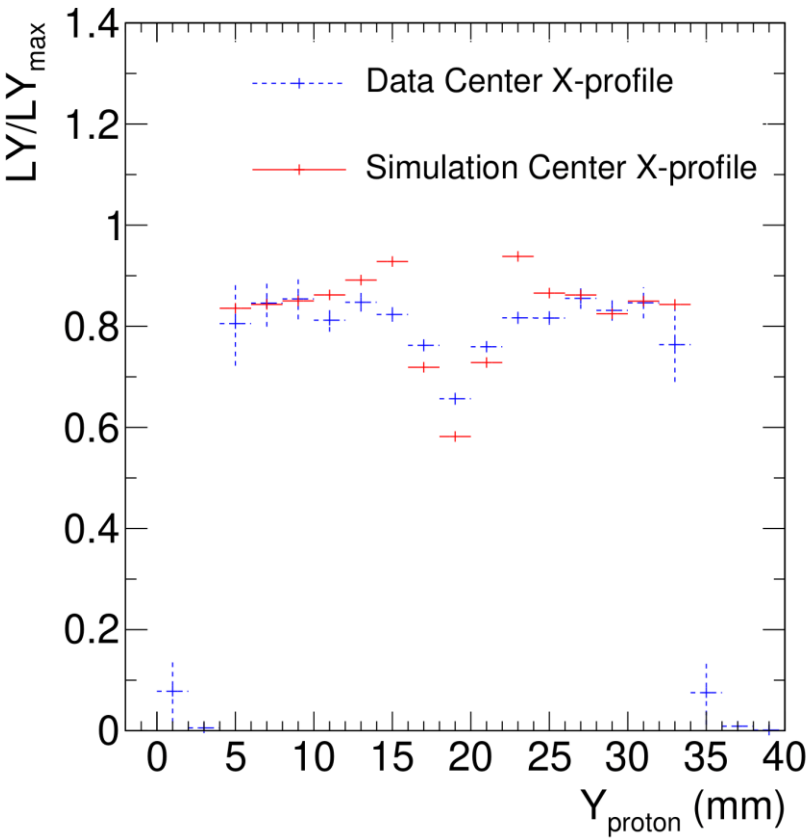




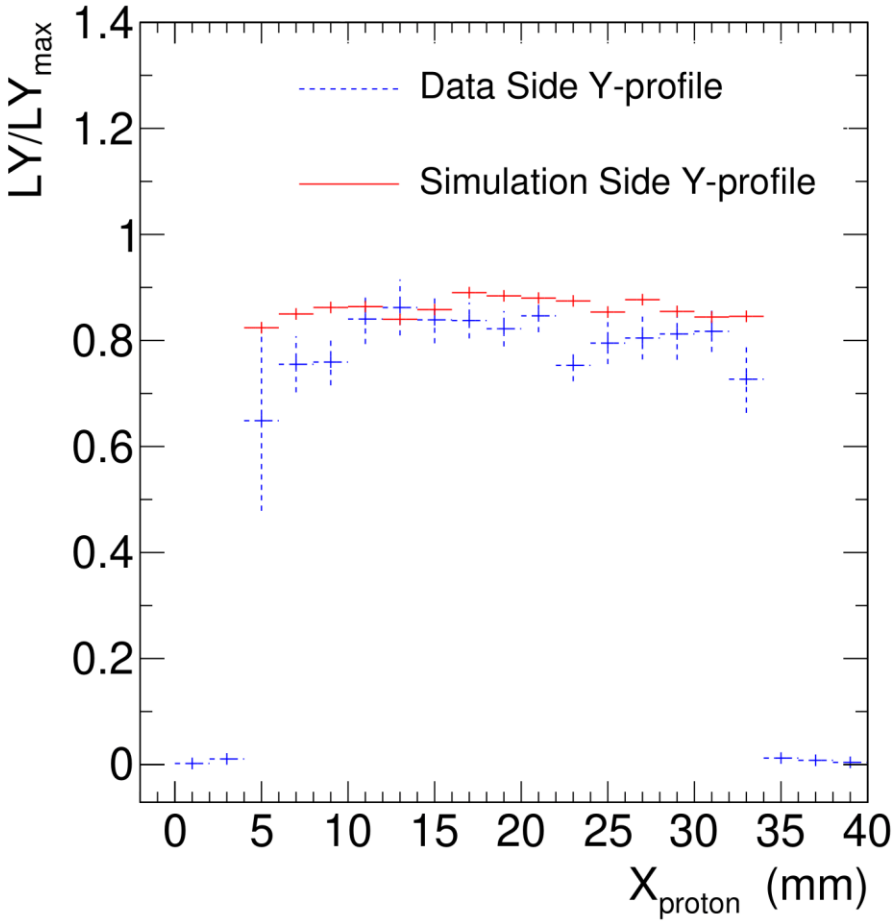
- Silva and Simon publication (link) studied asymmetry in SiPM-on-tile light yield vs misaligned SiPM
  - Discrepancy between data and simulation on previous slide due to misaligned SiPM

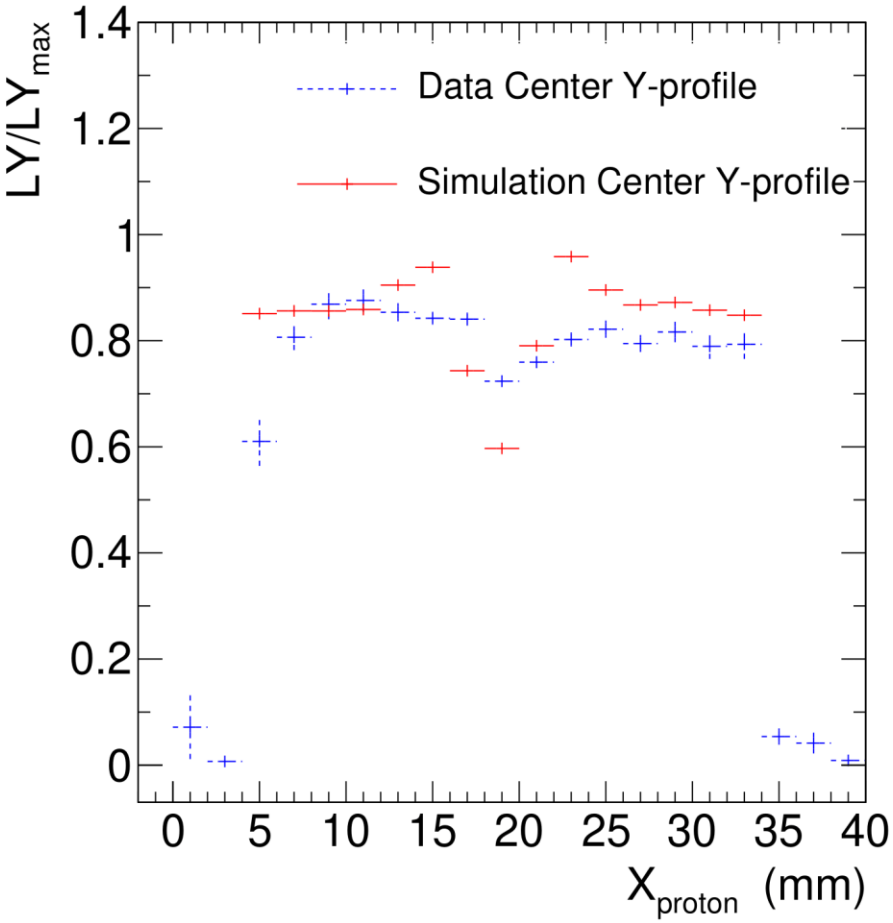
Tile Uniformity – 3x3cm SCSN-81 tile





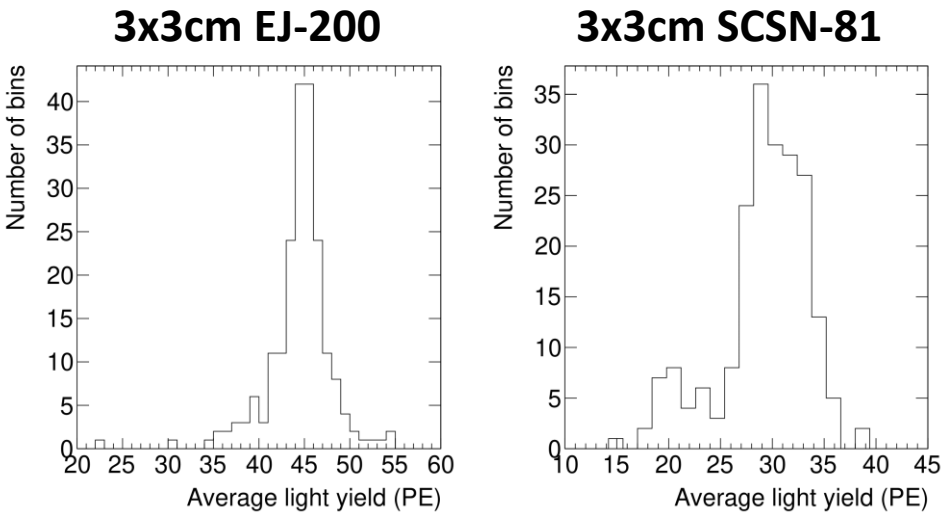
Tile Uniformity – 3x3cm EJ-200 tile





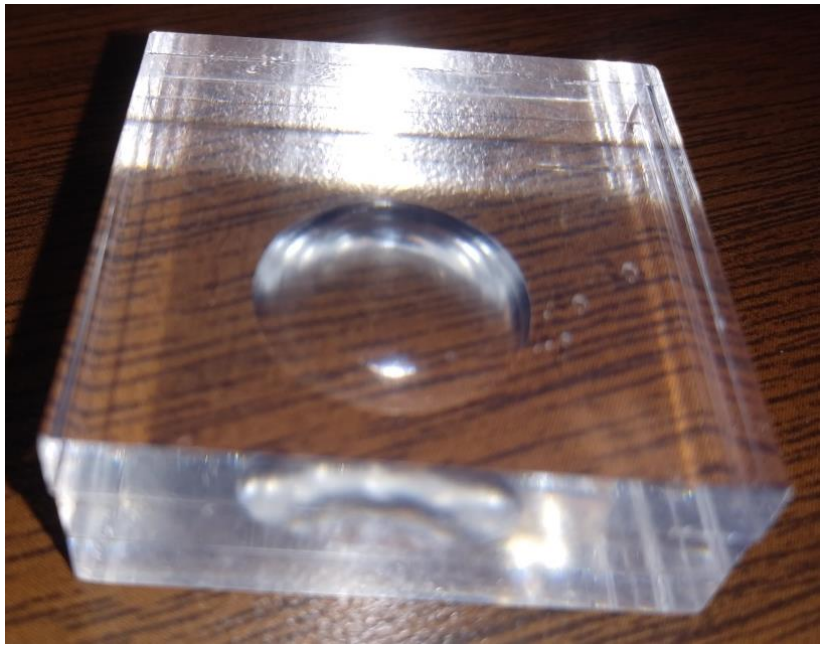
Quantifing Tile Uniformity

- Split tile into 2x2mm bins
- Calculated RMS/mean for average light in all bins
- Simulated the light response across a perfectly uniform tile, assuming a Poisson distribution with average LY of 30 PE
- $Non - Uniformity = \frac{\mathrm{RMS/mean}_{tile}}{\mathrm{RMS/mean}_{uniform}} - 1$



Tile	Non-Uniformity
EJ-200 2.3×2.3	0.14 ± 0.03
EJ-200 3.0×3.0	0.39 ± 0.05
EJ-200 3.4×3.4	0.61 ± 0.05
EJ-200 5.5×5.5	0.40 ± 0.04
SCSN-81 3.0×3.0	1.58 ± 0.11

Light Yield vs Tile Thickness

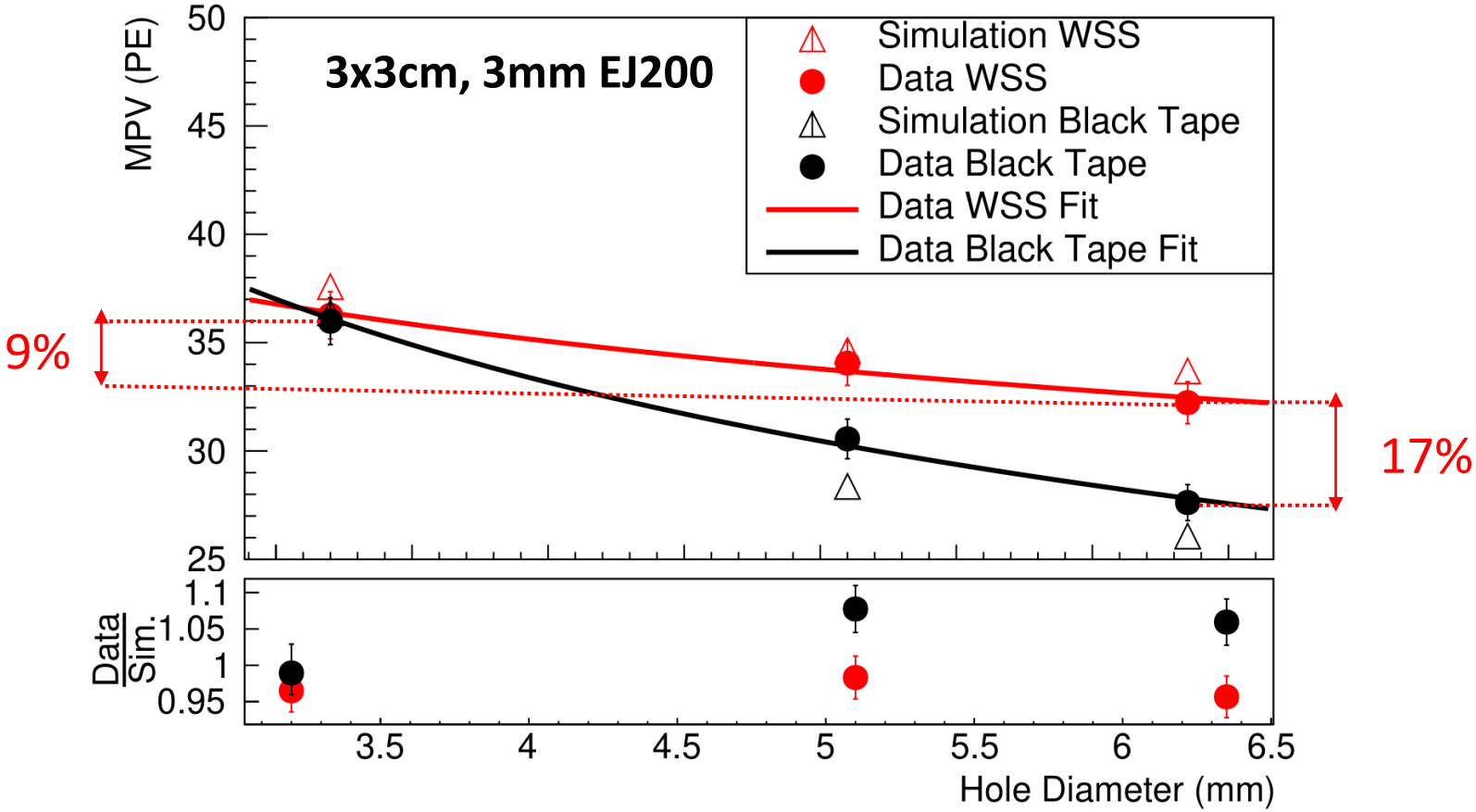


- Stacked 3.8 mm thick, SCSN81 tiles
  - One tile per stack had a dimple machined in it
  - Optical grease used to couple layers together
  - Hand-wrapped Tyvek and ESR

Hole Size Studies

- 3x3cm EJ-200 wrapped in ESR with SiPM 13360 on white silk screen
  - Dimple diameter is roughly ¼ in
  - Placed ESR with smaller holes cut in it over SiPM to simulate smaller holes
  - Covered white silk screen with black tape to negate its effects

Hole Size of ESR Wrapper



- White silkscreen increases the light yield by up to 17% compared to black tape
- With SiPM on white silkscreen, light yield increases by ~9% as hole in ESR wrapping shrinks from 6.3 mm to 3.2 mm diameter

SiPM Insertion Distance Study

- 3x3cm EJ200 wrapped in ESR with SiPM 13360
  - Nominal – SiPM fully above dowel bin board. "Aligned with tile bottom"
  - 1mm recessed - SiPM pulled slightly out of dimple, so that it's flush with dowel bin board
  - Large dependence on SiPM insertion distance

Nominal SiPM height

Run	MPV	FWHM	Mean(L+G fit)
Nominal	33.85	17.15	33.61 ± 0.18
1mm recessed	21.47	13.23	20.87 ± 0.27

Light Output (PE) Summary