# Building a Tracking Detector for the P2 Experiment

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SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Cluster of Excellence PRISMA Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

# The P2 Experiment: Overview

## The Idea

Precision measurement of the weak mixing angle at low $Q^2$

## Motivation

- Fundamental quantity of the Standard Model
- Sensitive for New Physics

## Method

- Measure parity-violating asymmetry in electron-proton scattering
- **M**ainz **E**nergy-recovery **S**uperconducting **A**ccelerator (MESA)

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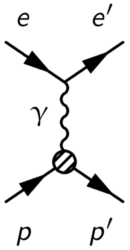
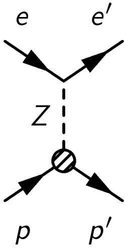
# The Weak Mixing Angle $\theta_W$ in the Standard Model (SM)

## Definition

$\tan\theta_W = \frac{g}{g'}$ with $SU(2)_L \times U(1)_Y$ gauge couplings $g$, $g'$

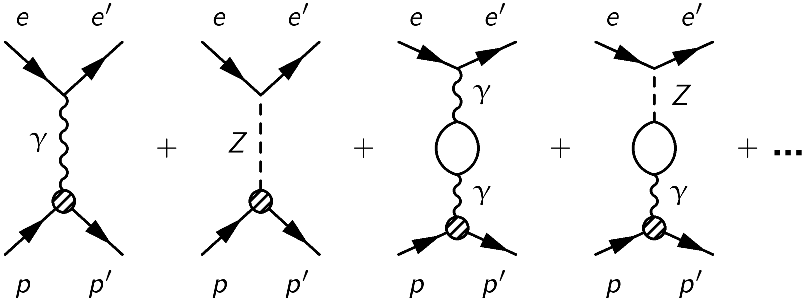



Proton electric charge
$+1$



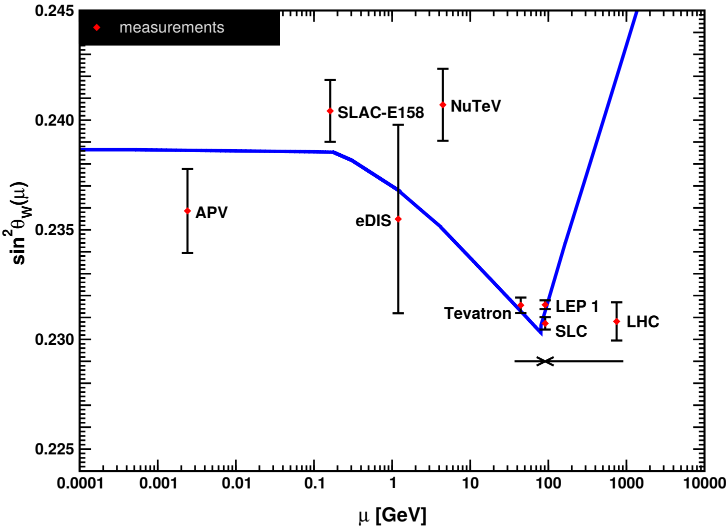

Proton weak charge
$1 - 4\sin^2\theta_W$

# Scale dependence of $\sin^2\theta_W$

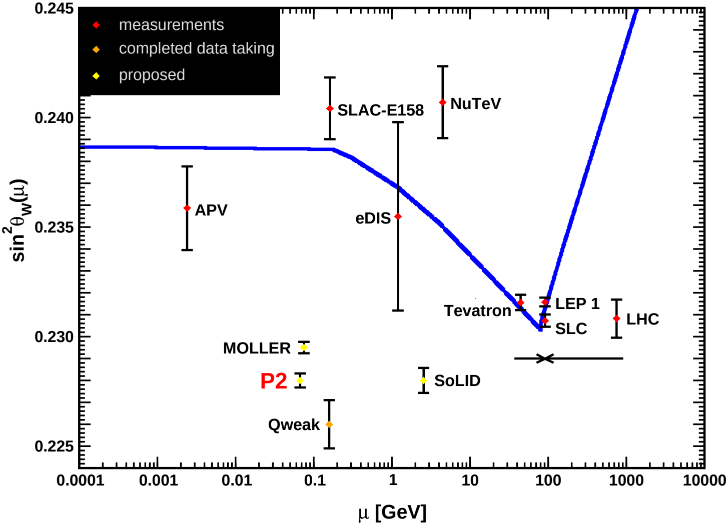



Absorb radiative corrections into effective, scale-dependent ("running") $\sin^2\theta_W(Q^2)$

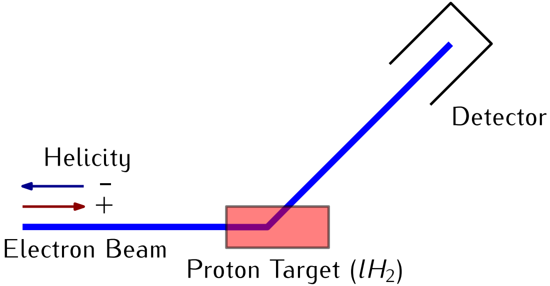
# Running $\sin^2\theta_W$ Measurements



# Running $\sin^2\theta_W$ Measurements



# Measure $\sin^2\theta_W$ via Parity Violating ep-Scattering



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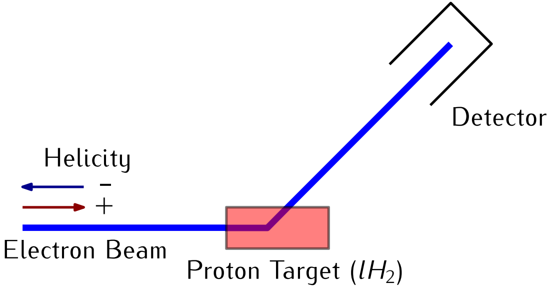
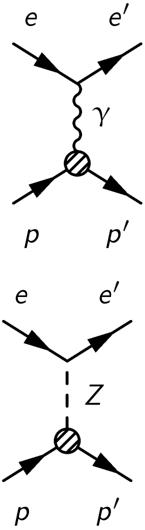
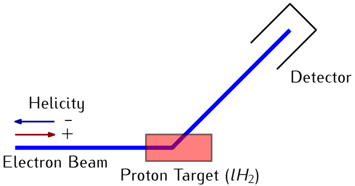



## Parity violating asymmetry

- Photon exchange parity invariant
- Z-boson exchange violates parity!
- $A_{\mathrm{PV}} \equiv \frac{N_- - N_+}{N_- + N_+}$
- Flip helicity and count!

# Measure $A_{PV}$ in ep-Scattering




- $A_{PV} \equiv \frac{N_- - N_+}{N_- + N_+} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(1 - 4\sin^2\theta_W - F(Q^2)\right)$
  - $Q^2$ = momentum transfer
  - $F(Q^2)$ = proton form factor

- Need very high statistics and precise control of systematics
  - $150\,\mu A$ beam current, 10 000 h measuring time
  - 60 cm liquid hydrogen target for high luminosity
  - MESA beam
    - $E = 155\,\mathrm{MeV}$
    - Highly polarized ($\geqslant 85\,\%$), flip helicity at 1 kHz
    - Low helicity-correlated uncertainties

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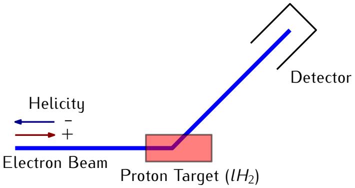


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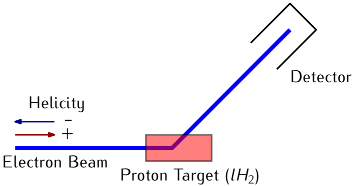


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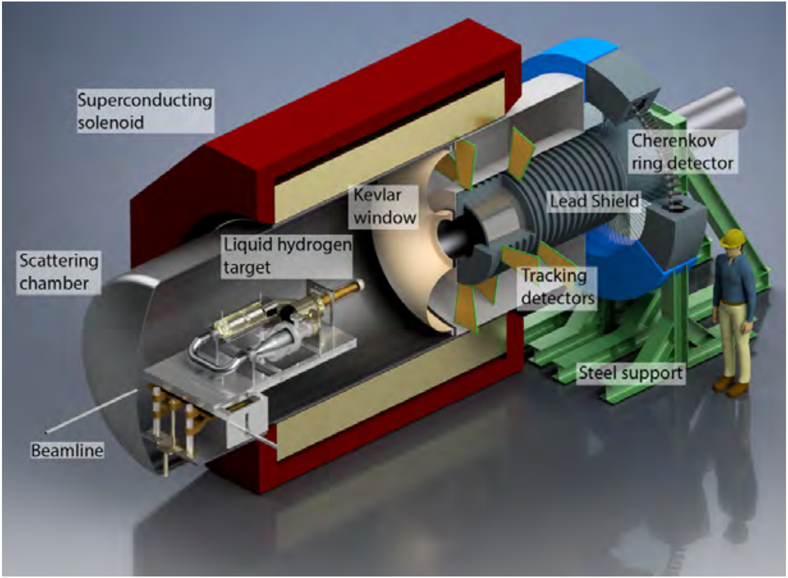
  - $150\,\mu A$ beam current, $10\,000\,\mathrm{h}$ measuring time
  - $60\,\mathrm{cm}$ liquid hydrogen target for high luminosity
  - MESA beam
    - $E = 155\,\mathrm{MeV}$
    - Highly polarized ($\geqslant 85\,\%$), flip helicity at $1\,\mathrm{kHz}$
    - Low helicity-correlated uncertainties $\leqslant 0.1\,\mathrm{ppb}$

$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} \sim 0.14\,\%$$

# P2 Detector Layout



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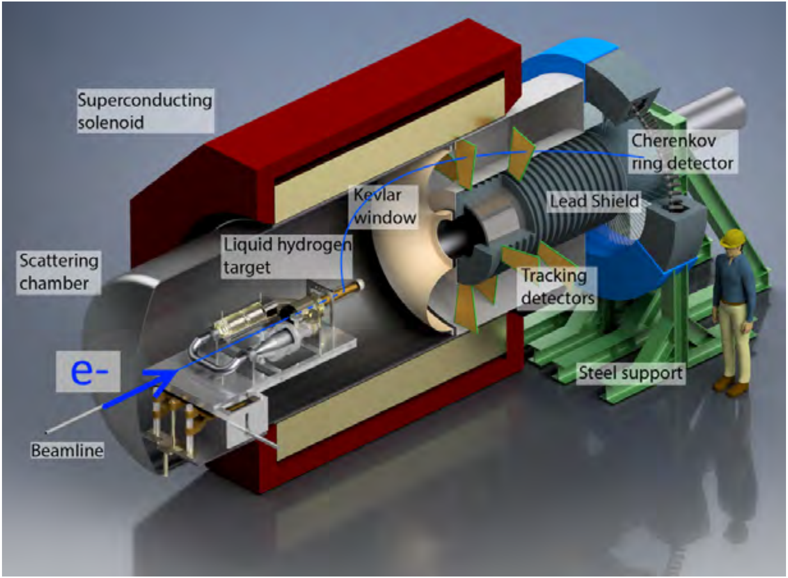

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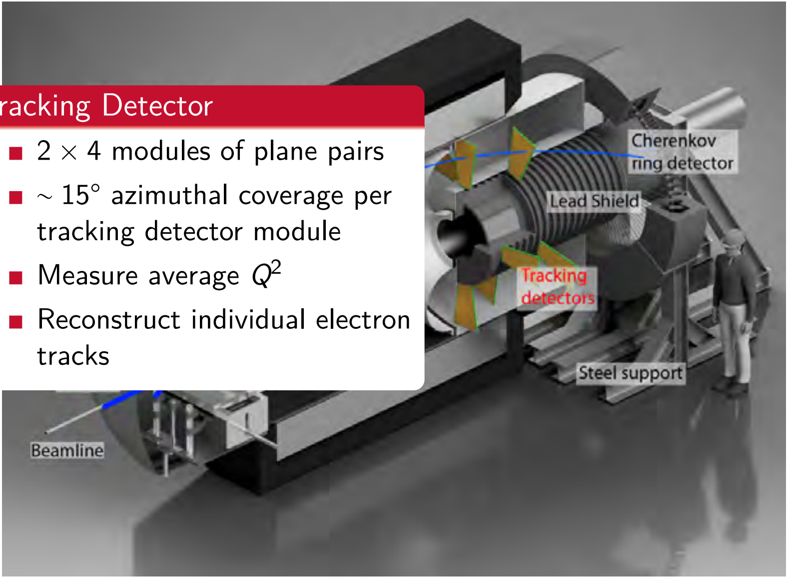
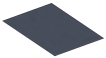



## Tracking Detector

- $2 \times 4$ modules of plane pairs
- $\sim 15^\circ$ azimuthal coverage per tracking detector module
- Measure average $Q^2$
- Reconstruct individual electron tracks

# Silicon Pixel Chips

- High Voltage Monolithic Active Pixel Sensors
- Silicon thinned to 50 $\mu m$
- Size about 2x2$cm$ per chip
- Power dissipation about 1W/Chip



1 Chip

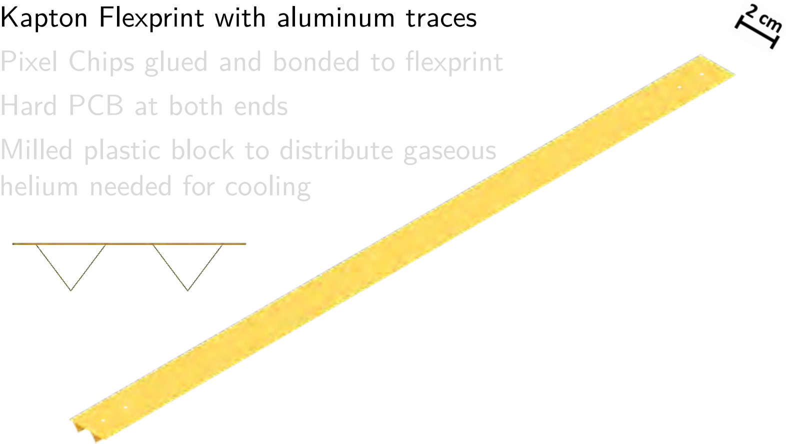
# Silicon Pixel Chips

- High Voltage Monolithic Active Pixel Sensors
- Silicon thinned to 50 $\mu m$
- Size about 2x2$cm$ per chip
- Power dissipation about 1W/Chip

14 Chips

# Strip Assembly

- Kapton Strip with two V-folds for mechanical stability and for cooling
- Kapton Flexprint with aluminum traces
- Pixel Chips glued and bonded to flexprint
- Hard PCB at both ends
- Milled plastic block to distribute gaseous helium needed for cooling



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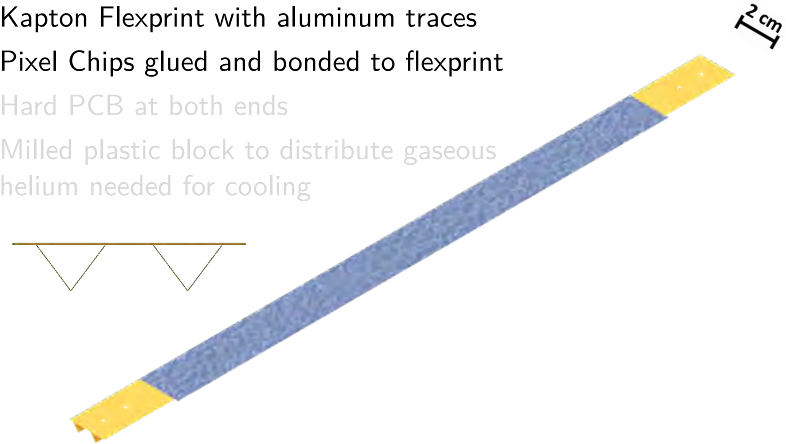

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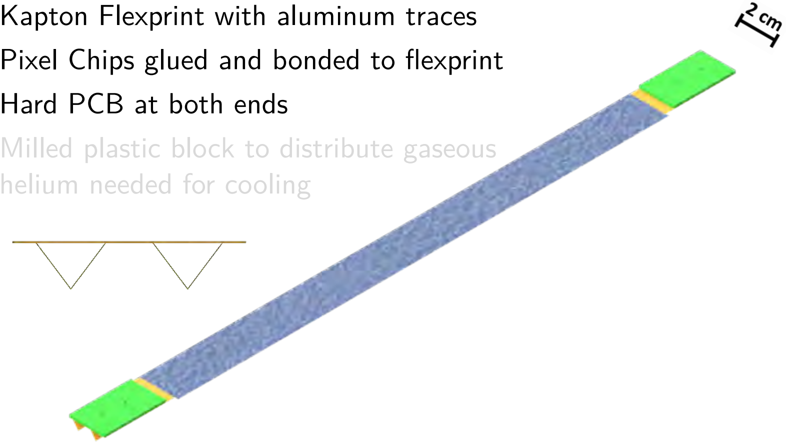

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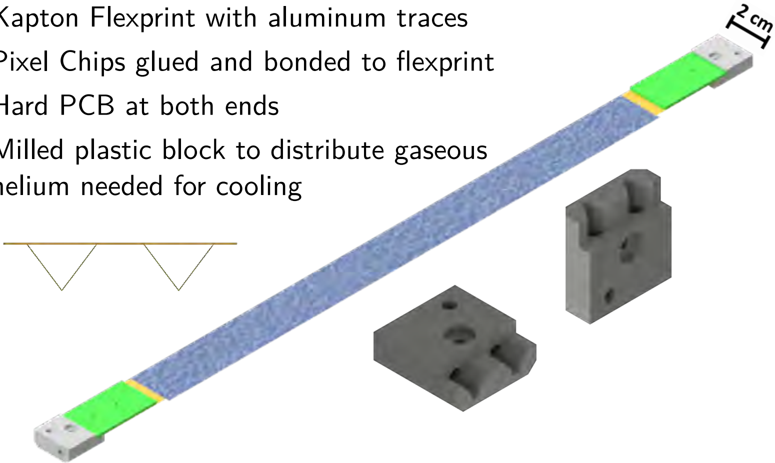
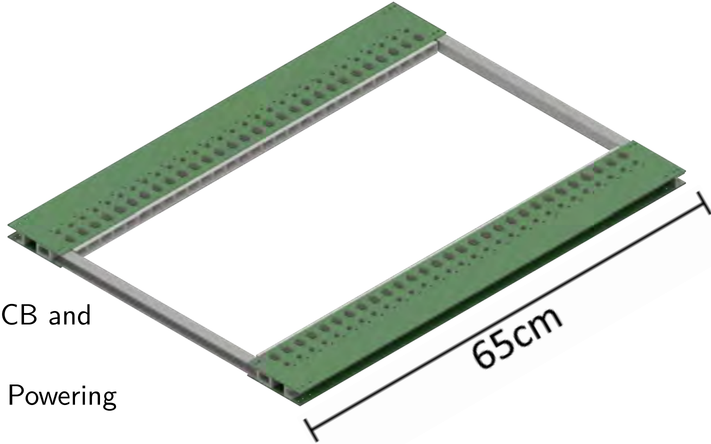


# Tracking Detector Module




- Sandwich of PCB and Cooling pipes
- Electronics for Powering and Readout
- Strips mounted via Samtec Interposer

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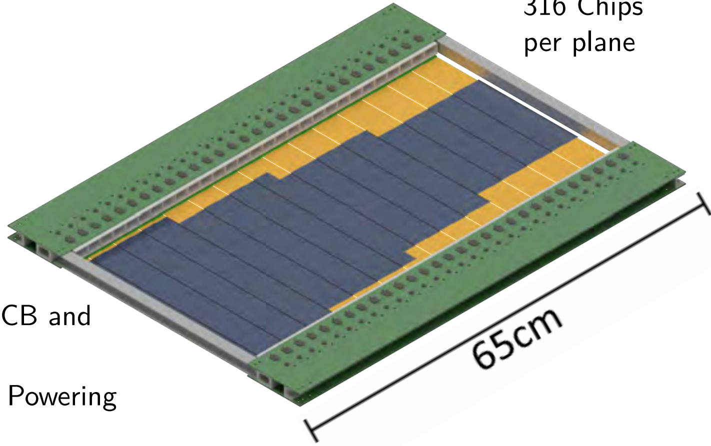


316 Chips per plane

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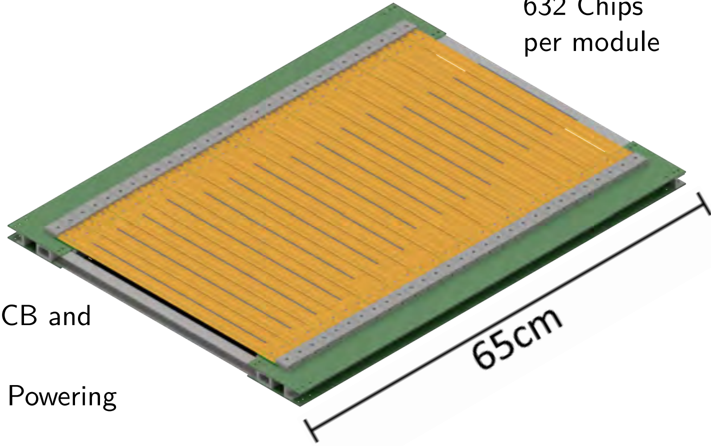
# Tracking Detector Module

632 Chips
per module

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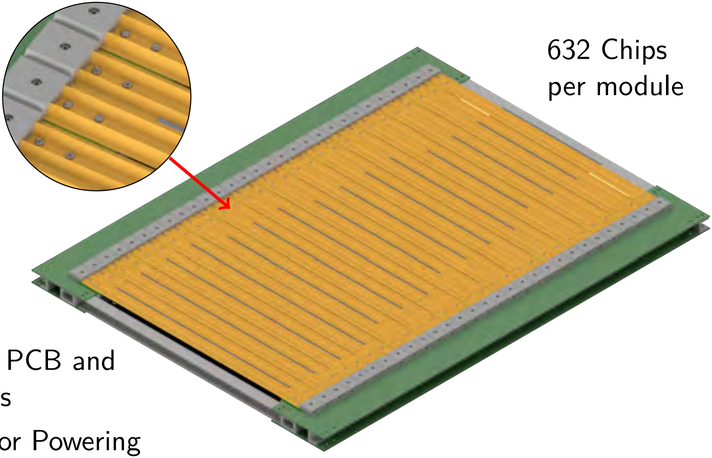

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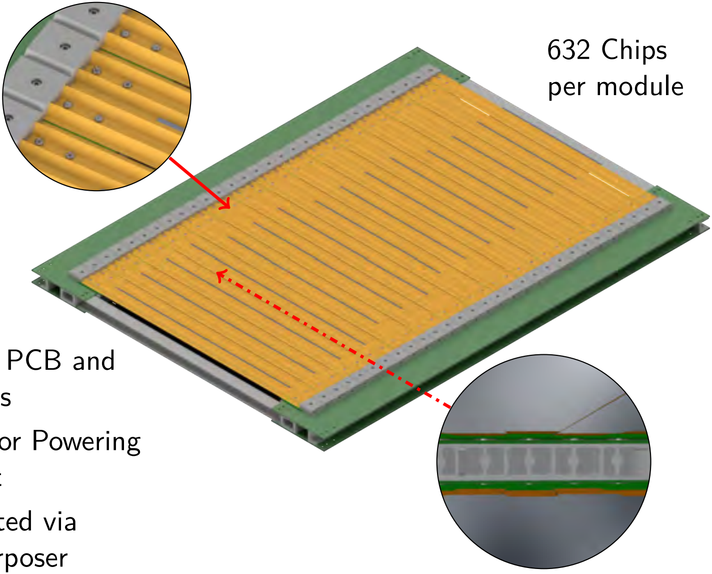

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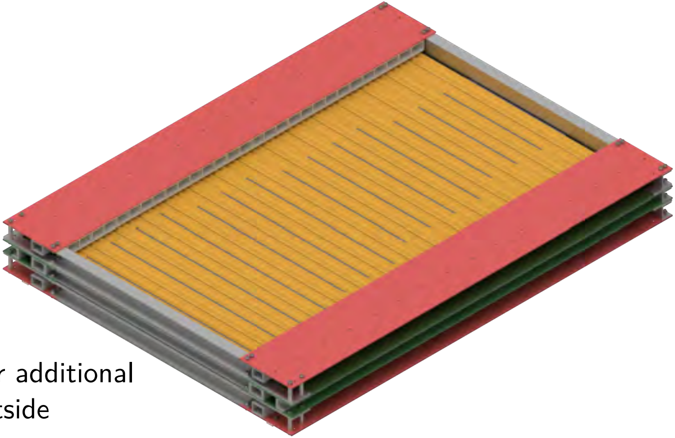

- Outer frame for additional helium flow outside
- Closed with foil to guide helium flow

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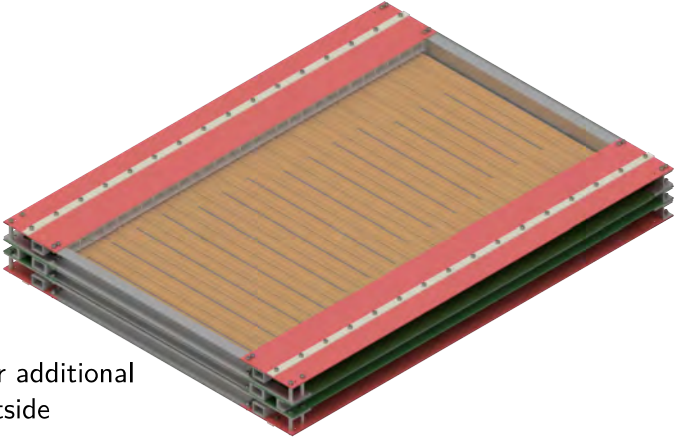

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# Strip Connection

## Requirements

- Reliable connection
- Fast signal transmission
- Power transmission
- Alignment
- (Easily) exchangeable

- Samtec® ZA8 Interposer
  - high density, low profile board-to-board interconnect
  - 1mm height
  - 0.8mm pitch
  - Compression contacts on top, solder balls on bottom

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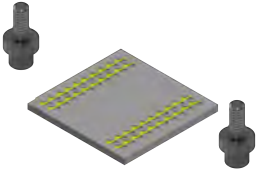

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<u>Testboard</u>

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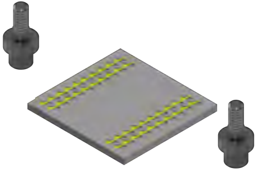
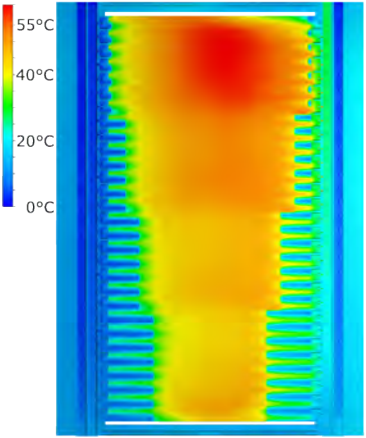


# Cooling

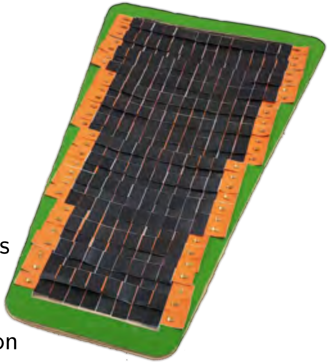
- Gaseous Helium cooling
- Tracker placed in helium atmosphere
- Helium flow
  - through V-folds
  - between planes
  - over the planes
- Expected heat production $\sim 1\,W$ per chip (632 Chips)
- Maximum operating temperature $\leqslant 70\,^{\circ}\mathrm{C}$




1.6W/chip, 42l/s helium flow

# Summary and Conclusions

- P2 Experiment
  - Measure $\sin^2\theta_W$ at low $Q^2$ in parity violating ep-scattering
  - $A_{PV}$ measurement with integrating Cherenkov detectors
- Tracking Detector
  - $Q^2$ Measurement and systematic studies
  - Low material budget
  - Very high (background) particle rates
  - Detailed track finding and reconstruction studies ongoing
  - Development of mechanical layout started

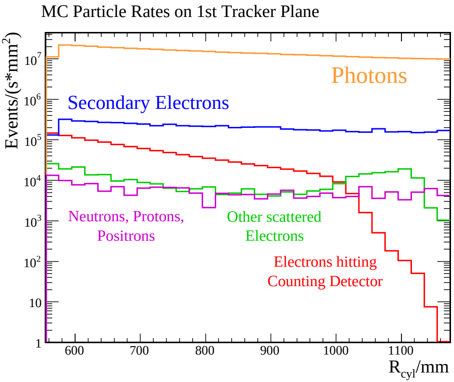


Thank you for your attention.

Backup

# Challenges for the Tracking Detector

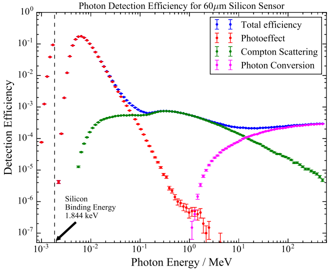
- Very high particle rates at full beam intensity
  - $\mathcal{O}(10^{15})$ beam electrons per second
  - Large amount of background, mostly bremsstrahlung photons



# Test the Detector Response to Photons

## Photon Background

- Continuous bremsstrahlung energy spectrum
- Photoelectric Effect
- Compton Scattering
- Pair Creation




- Radioactive Sources
  First result: $\eta \sim 29\%$@6 keV (Fe55)
- MAMI beamtest for higher photon energies

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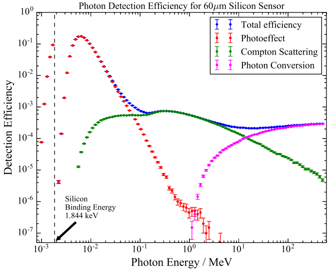

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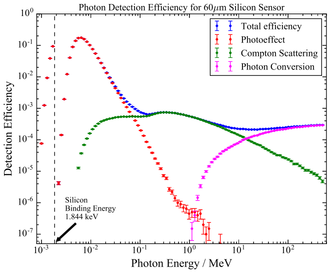
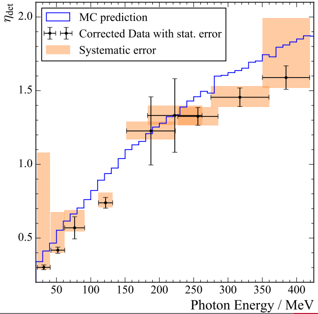


# ZA8 Interposer

- Tested Device
  - 10x10 pins
  - 0.8 mm pitch
  - 1mm thickness
  - Single Compression

- Ratings

**3.0 TESTING**

**3.1 Current Rating:** 0.9A (Ten Pins Powered 1x10)
**3.2 Voltage Rating:** 110 VAC
**3.3 Operating Temperature Range:** -55°C to +105°C
**3.4 Operating Humidity Range:** Up to 95% (Per EIA-364-31)
**3.5 Electrical:**

| ITEM | TEST CONDITION | REQUIREMENT | STATUS |
|---|---|---|---|
| Withstanding Voltage | EIA-364-20 (No Flashover, Sparkover, or Breakdown) | 335 VAC | Pass |
| Insulation Resistance | EIA-364-21 (1000 MΩ minimum) | 45,000 MΩ | Pass |
| Contact Resistance (LLCR) | EIA-364-23 | Δ 15 mΩ maximum (Samtec defined)/ No damage | Pass |

**3.6 Mechanical:**

| ITEM | TEST CONDITION | REQUIREMENT | STATUS |
|---|---|---|---|
| Durability | EIA-364-09C | 25 cycles | Pass |

**4.0 HIGH SPEED PERFORMANCE**

**4.1** Based on a 3 dB insertion loss

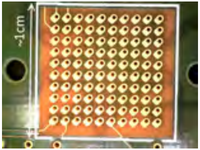
| Stack Height | Single-Ended Signaling | Differential Pair Signaling |
|---|---|---|
| 1mm | 10.2 GHz / 20.4 Gbps | 20 GHz / 40 Gbps |

**4.2 System Impedance:** 50 ohm for single-ended and 100 ohm for differential pair

http://suddendocs.samtec.com/productspecs/za8.pdf

# Test Board

- HSMC Connector
- 7 differential pairs
  - 4 pairs
    HSMC → interposer →
    Top board loop →
    interposer → HSMC
  - 1 pair HSMC→ SMA out
  - 2 pairs
    HSMC → interposer →
    Top board loop →
    interposer → SMA out
- 20 LED's on top board to quickly test 40 connections
- Power plane on both boards for current rating tests




# Pinout

| | A | B | C | D | E | F | G | H | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | G1 | DP1_in | GND | DP1_out | VCC | VCC | VCC | DP4_out | VDD4 | G4 |
| 2 | GND | DP1_in | GND | DP1_out | VDD1 | VCC | VCC | DP4_out | VDD5 | G5 |
| 3 | GND | GND | G2 | VDD14 | DP6_in | VDD2 | VDD3 | VDD6 | VCC | VCC |
| 4 | GND | DP2_in | G3 | VDD15 | DP6_in | VDD17 | VDD7 | VCC | VCC | VCC |
| 5 | G15 | DP2_in | G14 | DP3_in | VDD16 | DP6_out_sma | VDD8 | DP4_in | G6 | G7 |
| 6 | VCC | VCC | G16 | DP3_in | DP3_out | DP6_out_sma | VDD9 | DP4_in | G9 | G8 |
| 7 | VCC | DP2_out | G17 | VDD18 | DP3_out | VDD20 | VDD12 | VDD10 | VCC | VCC |
| 8 | VCC | DP2_out | GND | VDD19 | G20 | VDD13 | G13 | GND | VCC | VCC |
| 9 | G18 | GND | GND | DP5_out_sma | GND | DP5_in | GND | GND | VDD11 | G10 |
| 10 | G19 | GND | GND | DP5_out_sma | GND | DP5_in | GND | GND | G12 | G11 |
| 11 | | | | | | | | | | |
| 12 | VCC = +1.8V, linked, max. 8A | | | | | | | | | |
| 13 | VDD* = +3.3V, individually connected | | | | | | | | | |
| 14 | GND = Ground, linked | | | | | | | | | |
| 15 | G* = Ground, individually connected | | | | | | | | | |
| 16 | DP = differential pair | | | | | | | | | |

# Connection Reliability

- 2 top boards with LED's mounted
- 3 bottom boards with HSMC connector assembled
- Several plugging and un-plugging cycles with different board combinations
- No broken connection found yet

# BER test

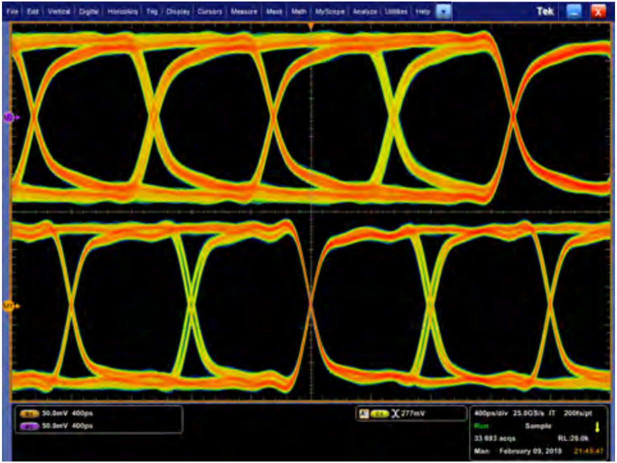
- $2.5\,\mathrm{Gbit/s}$
- Test with all 4 pairs which are routed to the HMSC connector on both ends
- No error found in $1.25 \cdot 10^{15}$ transmitted bits per channel

Show in table: Current | Min..Max | Best

| Link Alias | Status | Bits tested | BER | Test pattern |
|---|---|---|---|---|
| ...0_address_0 | Running | 1.2554E15 | 0 | PRBS31 |
| ...0_address_1 | Running | 1.2555E15 | 0 | PRBS31 |
| ...0_address_2 | Running | 1.2554E15 | 0 | PRBS31 |
| ...0_address_3 | Running | 1.2554E15 | 0 | PRBS31 |

# Eye diagram

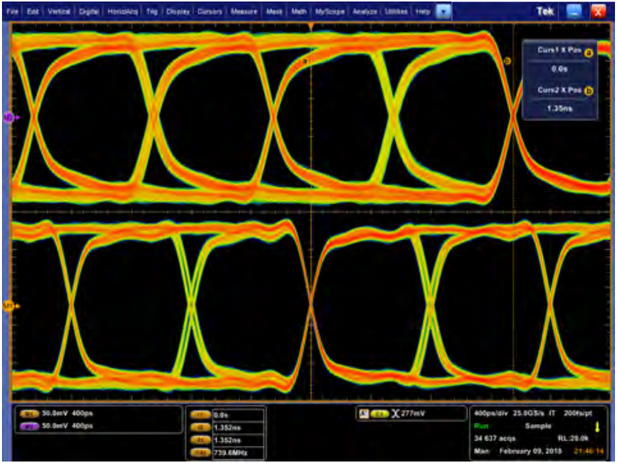
Top: Differential Pair 5
Bottom: Differential Pair 1 directly from FPGA




- 1.25 Gbps
- Eye diagram for signal after interposer sufficiently wide opened
- Time difference of 1.35 ns does not fit to trace length difference of 18 cm!

# Eye diagram

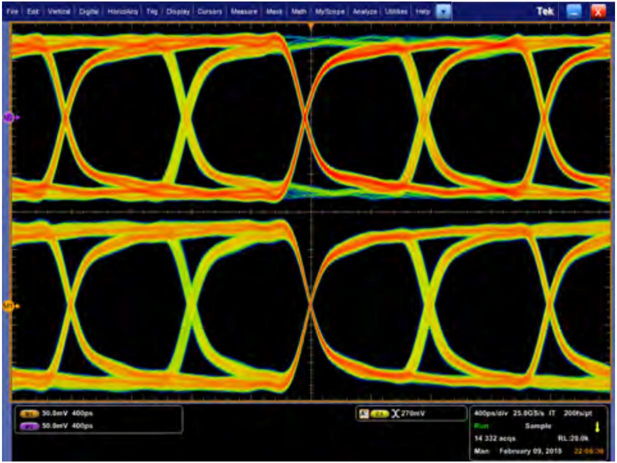
Top: Differential Pair 5
Bottom: Differential Pair 1 directly from FPGA



- 1.25 Gbps
- Eye diagram for signal after interposer sufficiently wide opened
- Time difference of $1.35\,\mathrm{ns}$ does not fit to trace length difference of $18\,\mathrm{cm}$!

# Eye diagram

Top: Differential Pair 6
Bottom: Differential Pair 5




- Why are there non-transitioning lines?
- Both Eye diagrams sufficiently wide opened
- Time difference of $0.04\,\mathrm{ns}$ does not fit to trace length difference of $2.8\,\mathrm{cm}$!

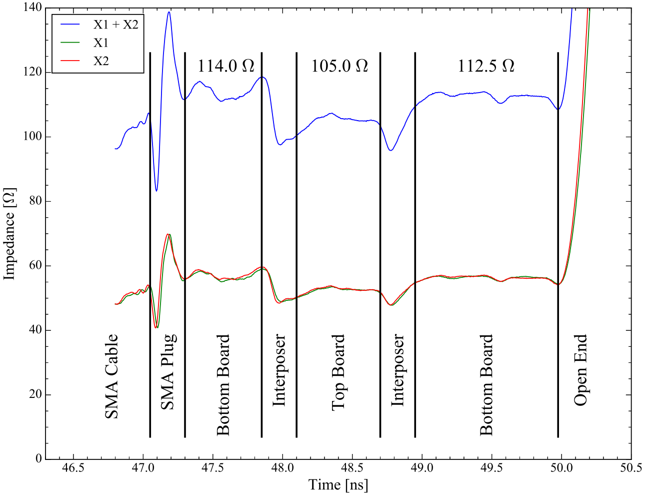
JG|U

# Eye Diagram Statistics

| | Direct Transmission | Interposer |
|---|---|---|
| Width [ps] | | |
| - mean | 725.05 | 700.88 |
| - std. dev. | 4.98 | 5.34 |
| - max | 740.20 | 717.28 |
| - min | 685.61 | 660.52 |
| Height (transitioning) [ps] | | |
| -mean | 179.72 | 145.34 |
| -std. dev | 0.51 | 1.06 |
| -max | 181.46 | 148.95 |
| -min | 177.01 | 139.35 |
| Height (non-transitioning) [ps] | | |
| -mean | 202.82 | 185.84 |
| -std. dev | 0.56 | 0.96 |
| -max | 204.86 | 189.06 |
| -min | 199.51 | 180.39 |
| Rise Time (10% $\rightarrow$ 90%) [ps] | | |
| -mean | 201.38 | 298.40 |
| -std. dev | 7.38 | 42.87 |
| -max | 309.44 | 524.25 |
| -min | 175.47 | 208.31 |
| Fall Time (90% $\rightarrow$ 10%) [ps] | | |
| -mean | 207.09 | 295.55 |
| -std. dev. | 8.97 | 35.50 |
| -max | 297.30 | 531.83 |
| -min | 179.21 | 208.79 |

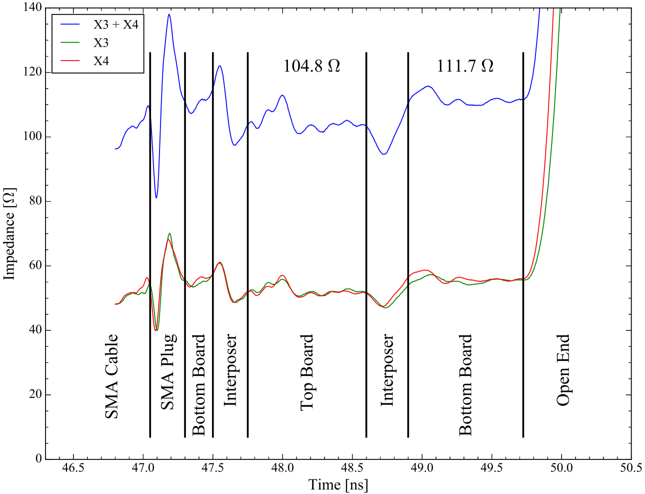
# TDR Impedance Measurement

## Differential Pair 5

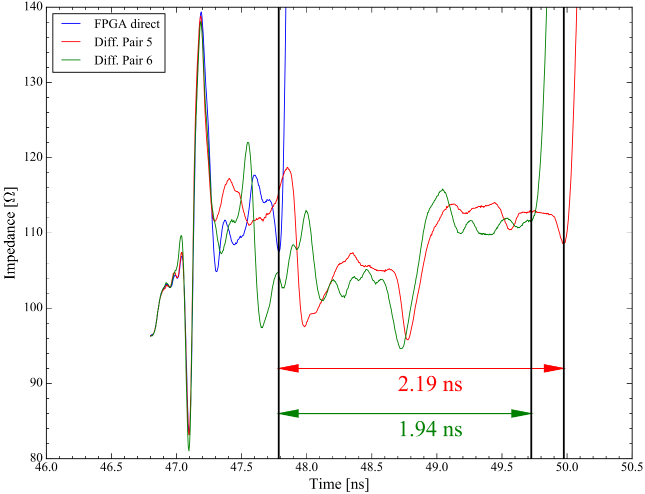


# TDR Impedance Measurement

## Differential Pair 6



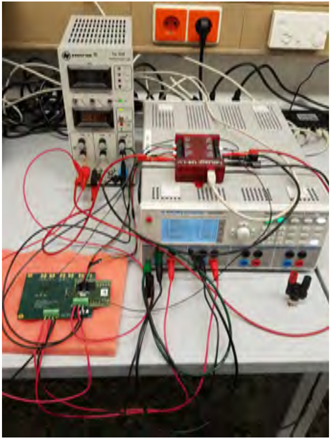
# TDR Time Measurement




- Length difference
  - DP5 - DP0: 18.0 cm
  - DP6 -DP0: 15.2 cm

# Setup

- CMOS temperature sensor glued on top and bottom board opposite to interposer
- 2 channels of HMP4040
- Readout and Load control via LabJack
- 1.8 V Supply voltage



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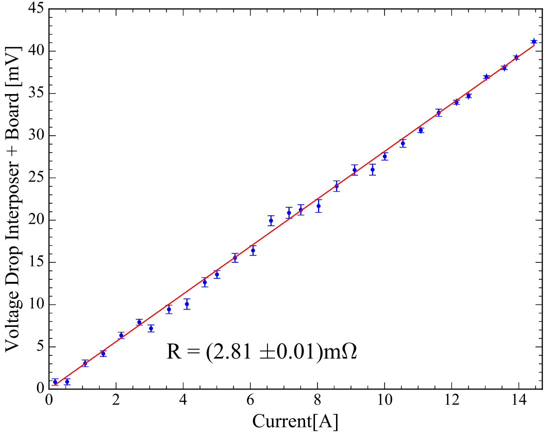
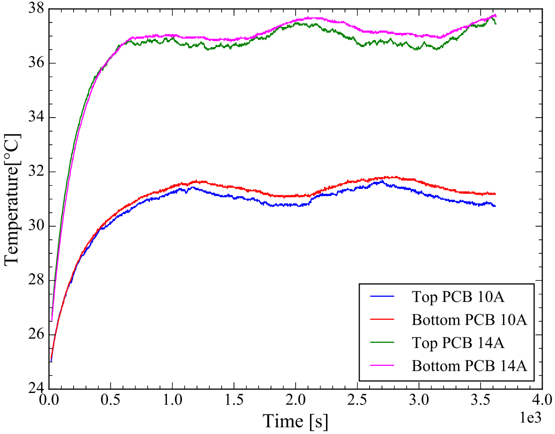
# Voltage Drop



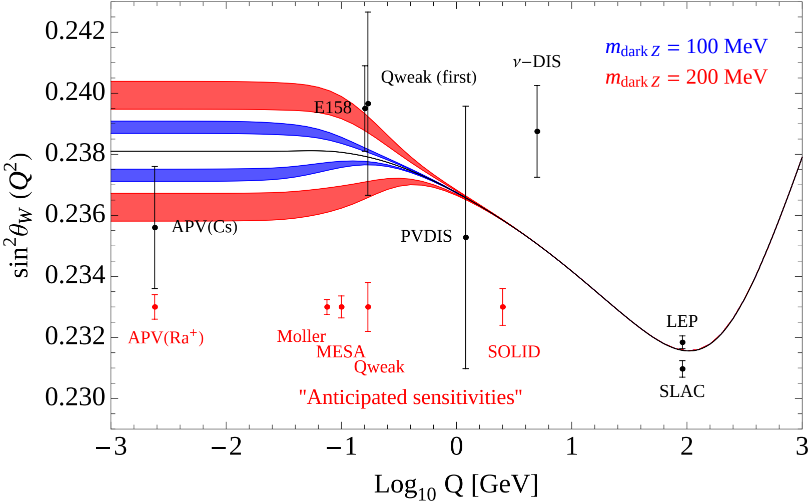
# Temperature



JG|U

## Sensitivity to New Physics

Hooman Davoudiasl, Hye-Sung Lee, and William J. Marciano
Phys. Rev. D 89, 095006



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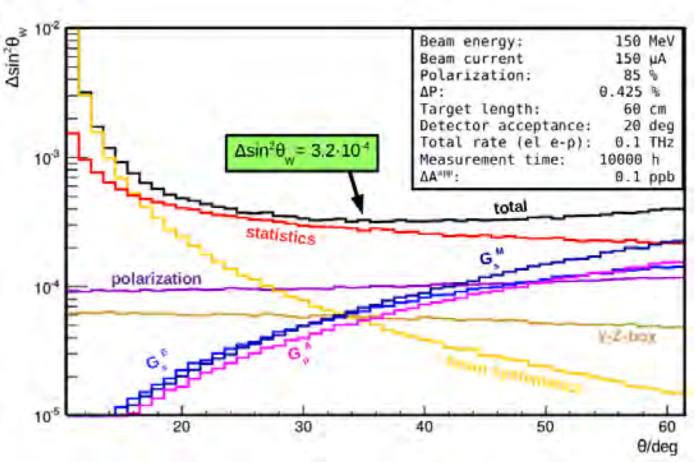
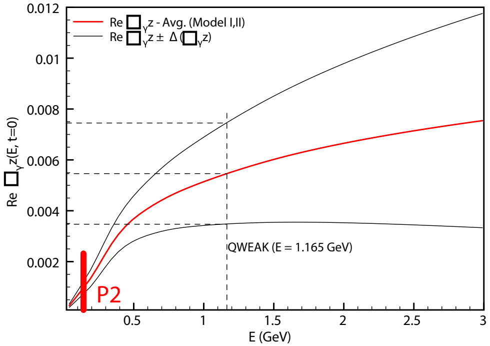
## Beam Stability Requirements

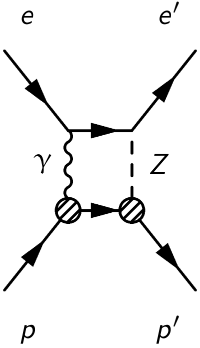
| | Achieved at MAMI | $A_{PV}$ uncertainty | requirement |
|---|---|---|---|
| Energy fluctuation | $0.04\,\mathrm{eV}$ | $< 0.1\,\mathrm{ppb}$ | ok! |
| Position fluctuation | $3\,\mathrm{nm}$ | $5\,\mathrm{ppb}$ | $0.13\,\mathrm{nm}$ |
| Angle fluctuation | $0.5\,\mathrm{nrad}$ | $3\,\mathrm{ppb}$ | $0.06\,\mathrm{nrad}$ |
| Intensity fluctuation | $14\,\mathrm{ppb}$ | $4\,\mathrm{ppb}$ | $0.36\,\mathrm{ppb}$ |

# Systematic Uncertainties



# $\gamma/Z$-box processes uncertainty contribution



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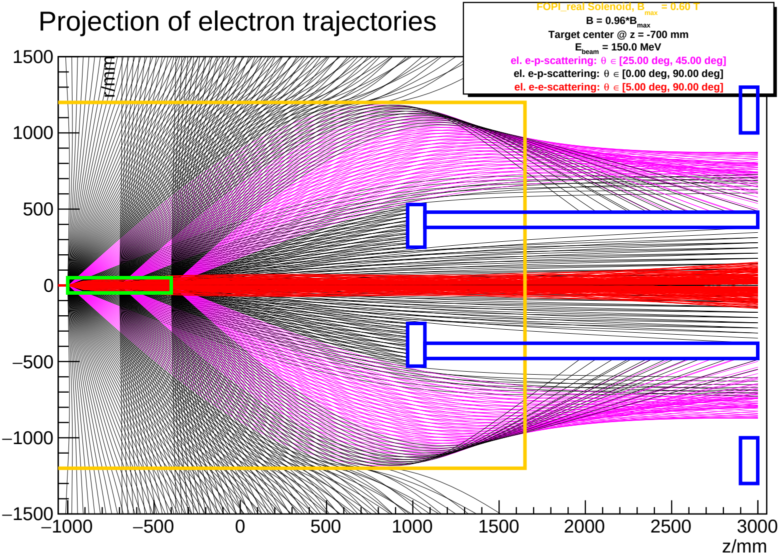
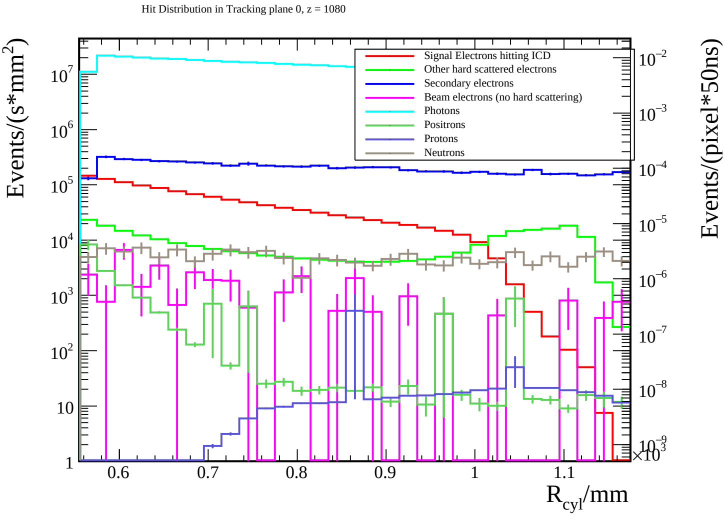
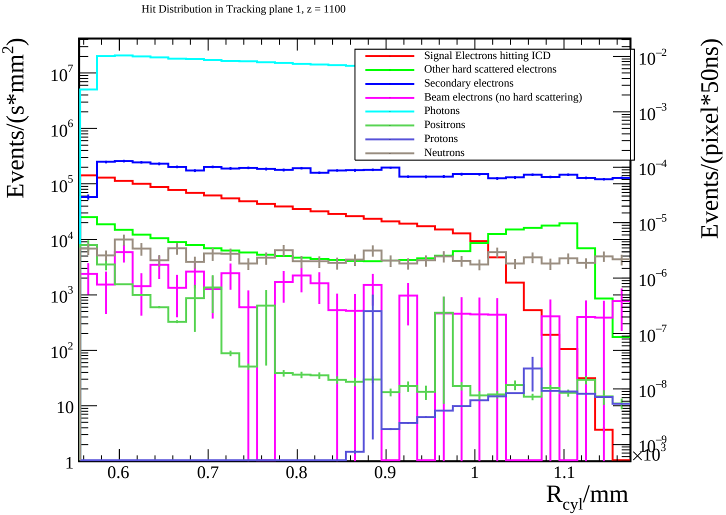
# Projection of Expected Electron Trajectories



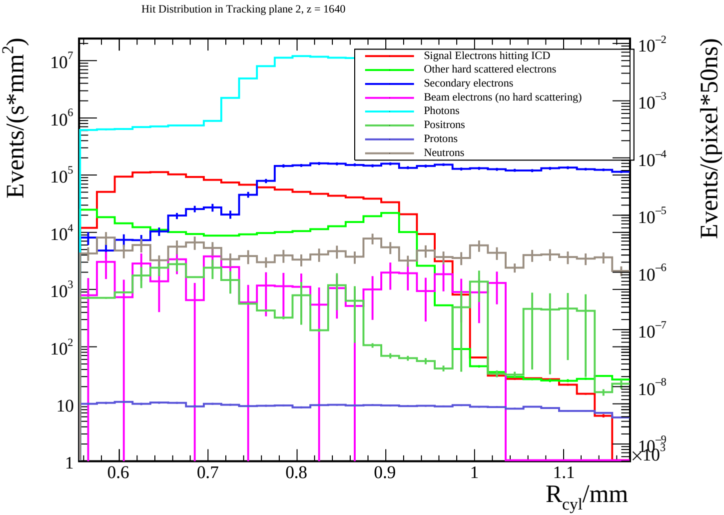
# Expected Particle Rates on First Plane



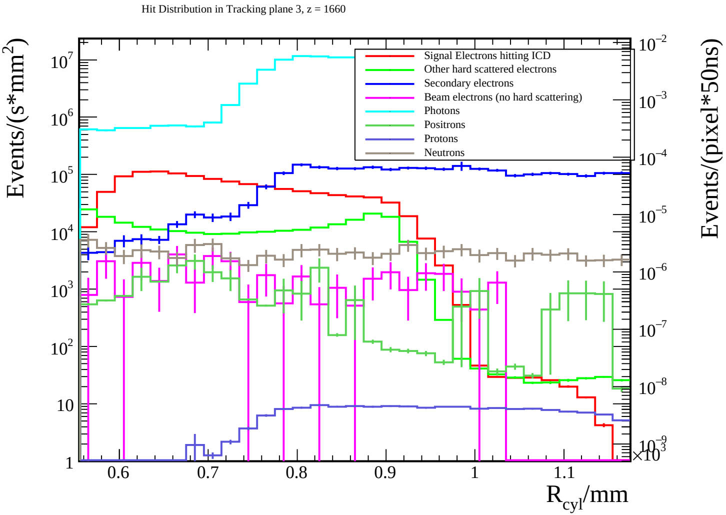
# Expected Particle Rates on Second Plane



# Expected Particle Rates on Third Plane



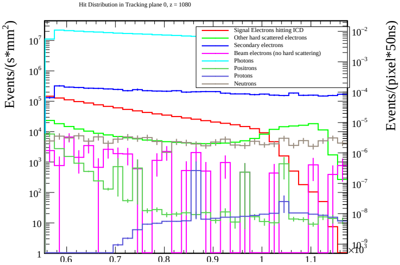
# Expected Particle Rates on Fourth Plane

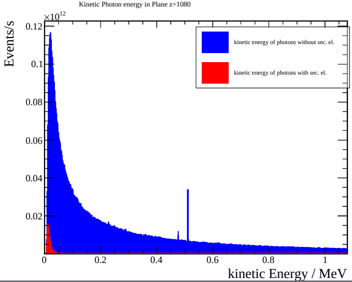


# Photon Background

- Continuous bremsstrahlung energy distribution
- Secondary electrons mainly produced by photo-effect
- Low detection rate of higher energetic photons
- Reduced rate of secondary electrons on "covered" plane
- Detailed investigation of detector response to low energy photons needed

## First Tracker Plane

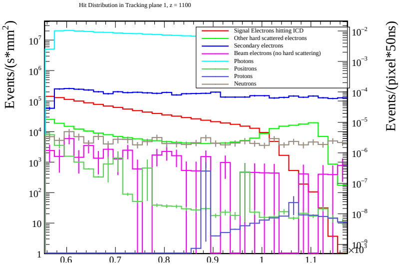


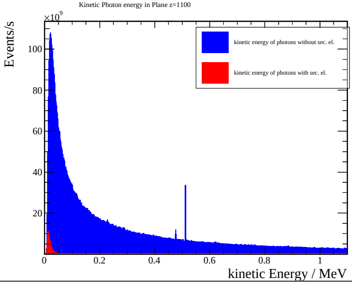



# Photon Background

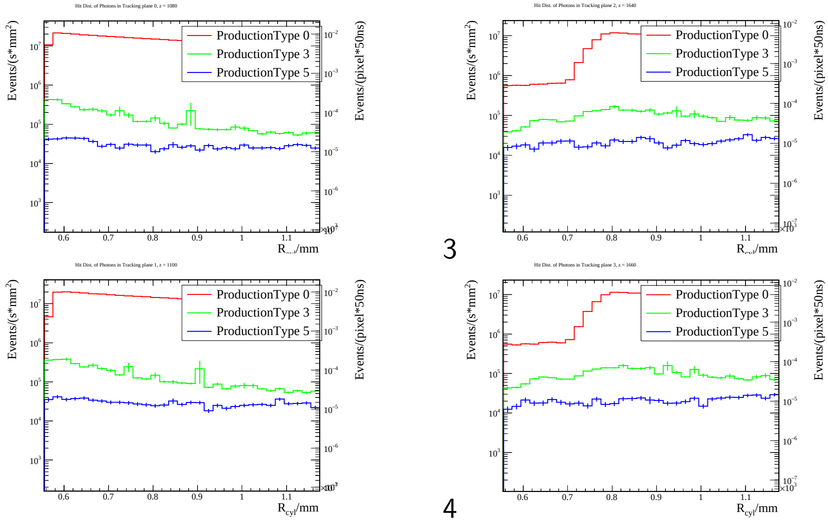
- Continuous bremsstrahlung energy distribution
- Secondary electrons mainly produced by photo-effect
- Low detection rate of higher energetic photons
- Reduced rate of secondary electrons on “covered” plane
- Detailed investigation of detector response to low energy photons needed

## Second Tracker Plane



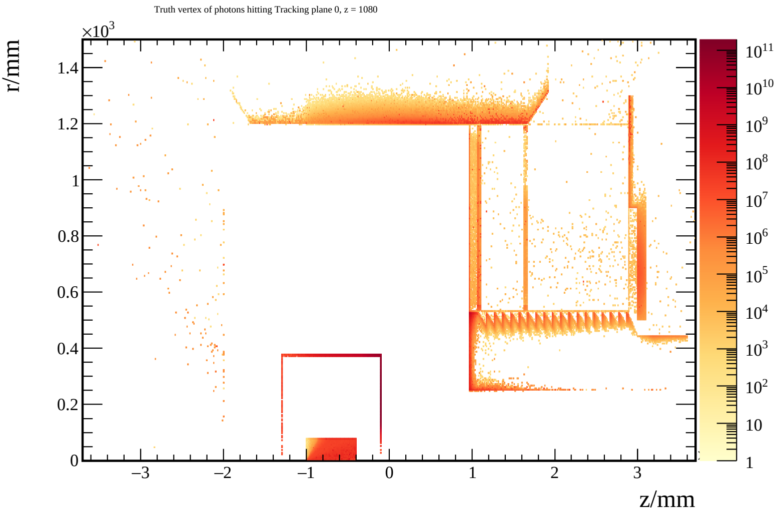



# Photon Production Processes

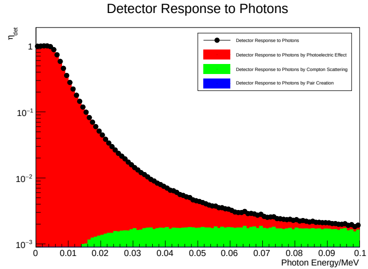


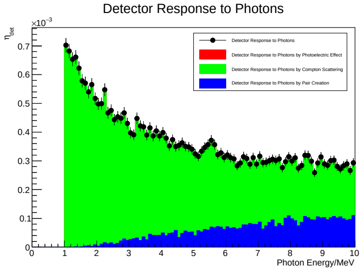

process encoding: 0 = bremsstrahlung in the target, 3 = bremsstrahlung in other detector parts, 5 = pair annihilation

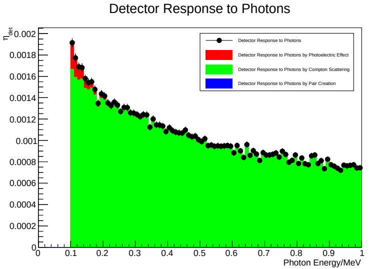
# Photon Vertices

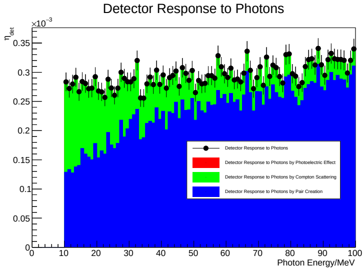


# MC Detector Response to Photons

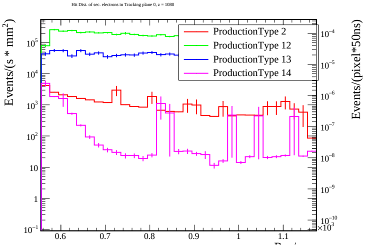


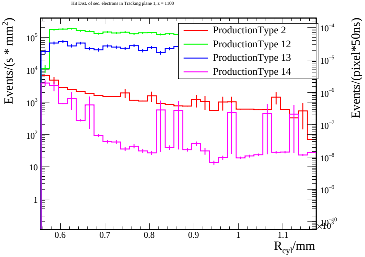



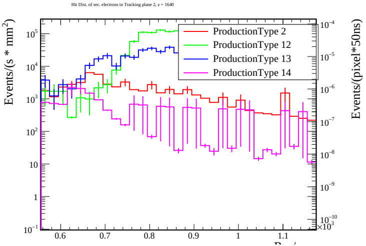
# Secondary Electrons Production Processes



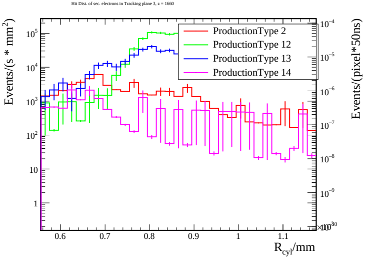

1




2




3

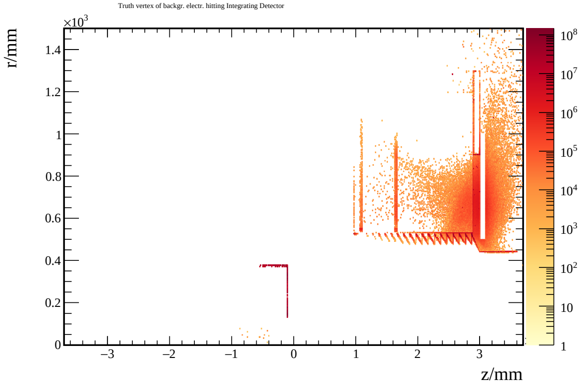



4

Process encoding: 2 = ionisation, 12 = Photoeffect, 13 = Compton Scattering, 14 = Pair creation

# Background Electrons Hitting Integrating Cherenkov Detector

## Production Vertices



# Additional Electron Loss due to Segmented Tracker Layers