THE SHIP *SPLITCAL* ELECTROMAGNETIC CALORIMETER

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DESY

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SHiP
Search for Hidden Particles

PRISMA+
Cluster of Excellence

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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The SHiP Case

Where are all the new **dark-matter particles?**

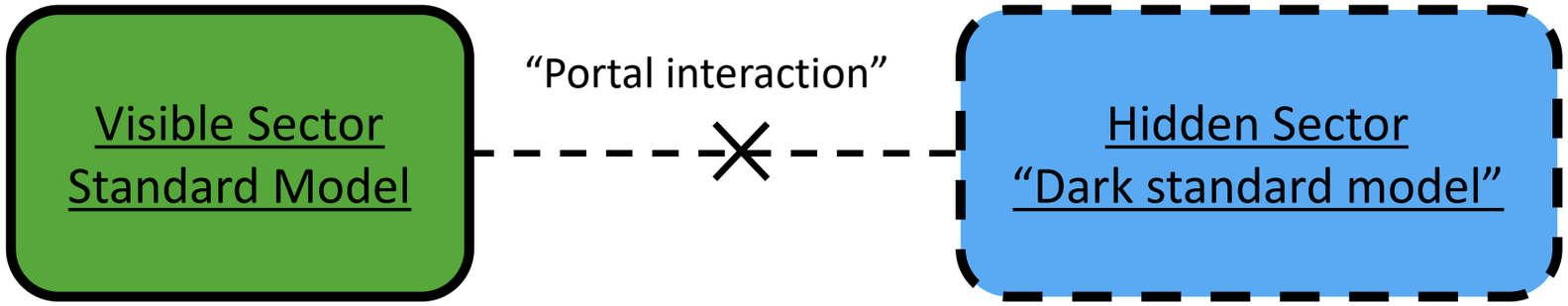
Two possibilities why we have not detected them yet:

- They are ***very massive.***
- They have ***no*** or ***very feeble couplings*** to SM particles.

➜ ***„Hidden Sector“***

Hidden Sector may be accessible in ***high-intensity experiments*** via sufficiently light particles which also couple to SM particles.

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$

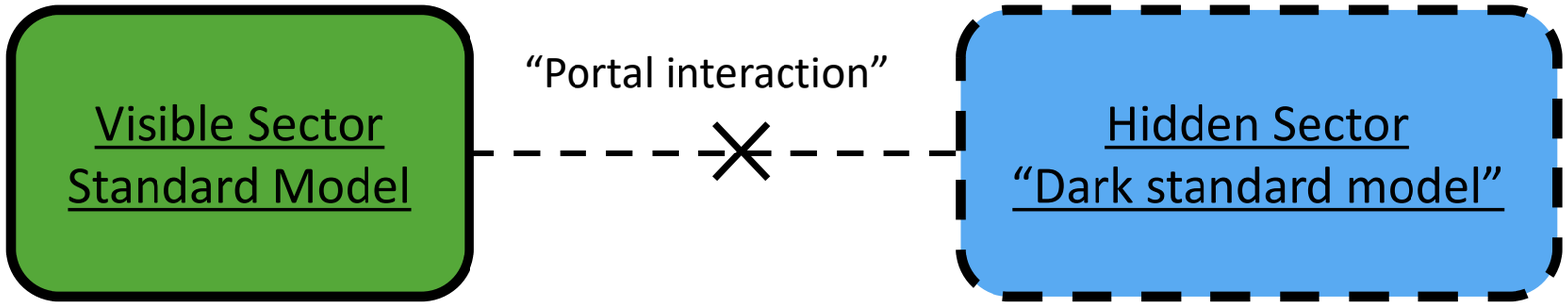


The SHiP Case

The dynamics of the ***Hidden Sector*** may drive the dynamics of the ***Visible Sector*** via renormalizable interactions (**„Portals“**) and be responsible for

- Dark Matter — scalar or fermionic
- Neutrino oscillations
- Baryon asymmetry
- Higgs mass
- …

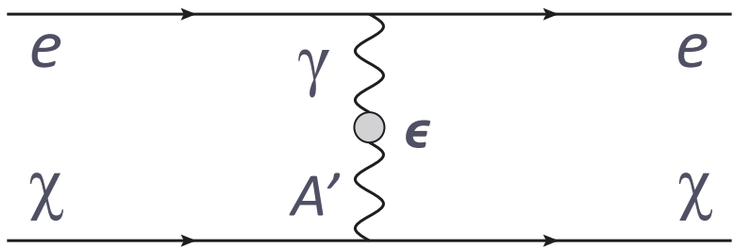
$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



Portals to the Hidden Sector

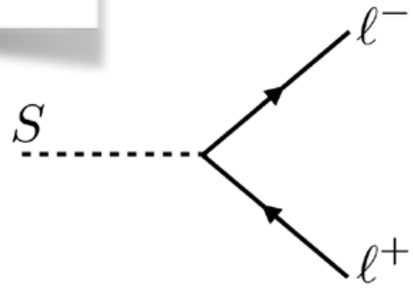
- **Vector portal („*Dark Photons (DPs)*“):**
  - Fields A'_μ with strength $F'_{\mu\nu}$, mixing with coupling ϵ with electroweak field $F_Y^{\mu\nu}$.

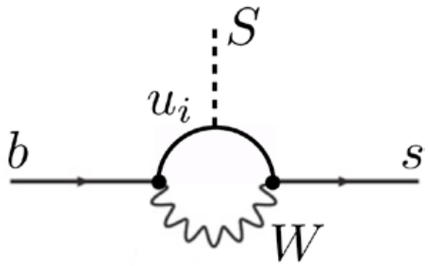
$$\mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$



- **Scalar portal:**
  - New scalar particles S, which couple to the square $|\phi|^2$ of the Higgs field.

$$\mathcal{L}_{\text{Scalar portal}} = (\lambda_i S_i^2 + g_i S_i)(\Phi^\dagger \Phi)$$

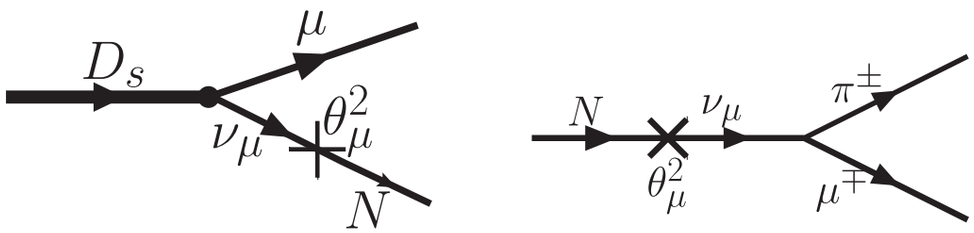




Portals to the Hidden Sector

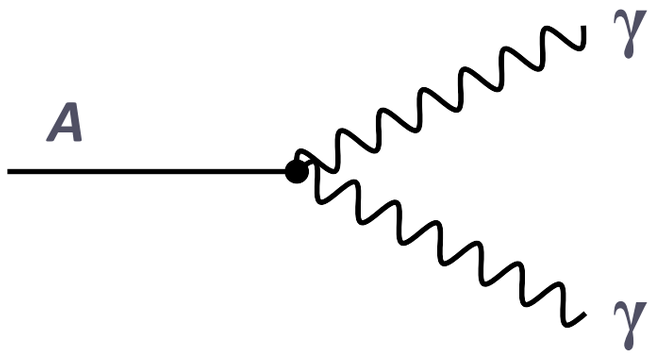
- **Neutrino portal („*Heavy Neutral Leptons (HNLs)*“):**
  - New neutral singlet fermions N_I with Yukawa coupling $F_{\alpha I}$ to *SU(2)* lepton doublets L_α.

$$\mathcal{L}_{\text{Neutrino portal}} = F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{\Phi})N_I$$



- **Other, non-renormalizable couplings:**
  - Example: *Pseudo-scalar* ***Axion-like particles A (ALPs)***, which couple to two photons.

$$\mathcal{L}_{\text{A}} = \frac{A}{4f_A}\epsilon^{\mu\nu\lambda\rho}F_{\mu\nu}F_{\lambda\rho}$$



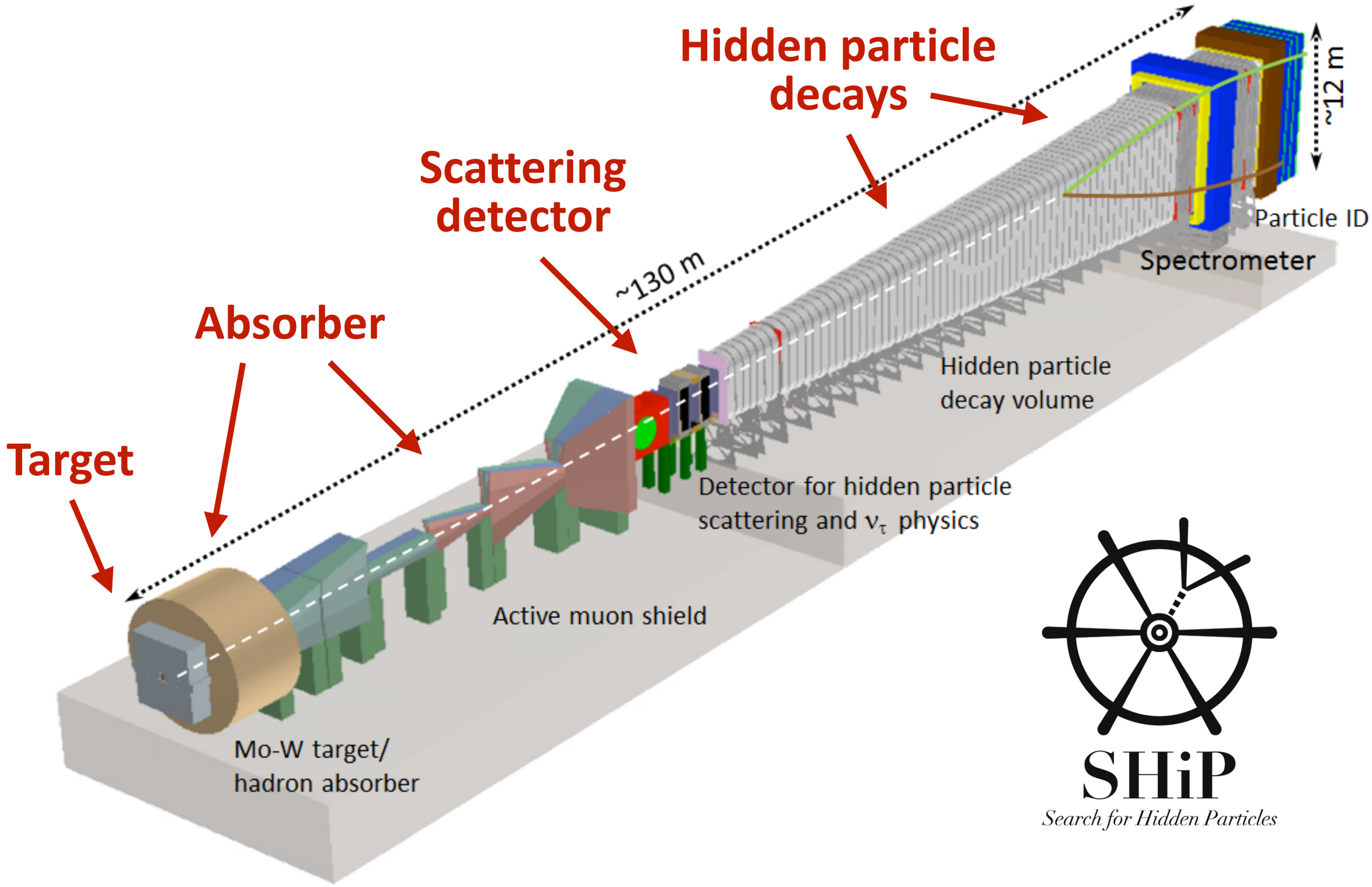
What do we look for in SHiP?

Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino	$\ell^+\ell^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

- **All kinds of final states:**
  - **Two-track** with hadrons, muons, electrons, with and without photons.
  - Also neutral events with **photons only** (e.g. ***ALP*** → γγ).

Multipurpose detector

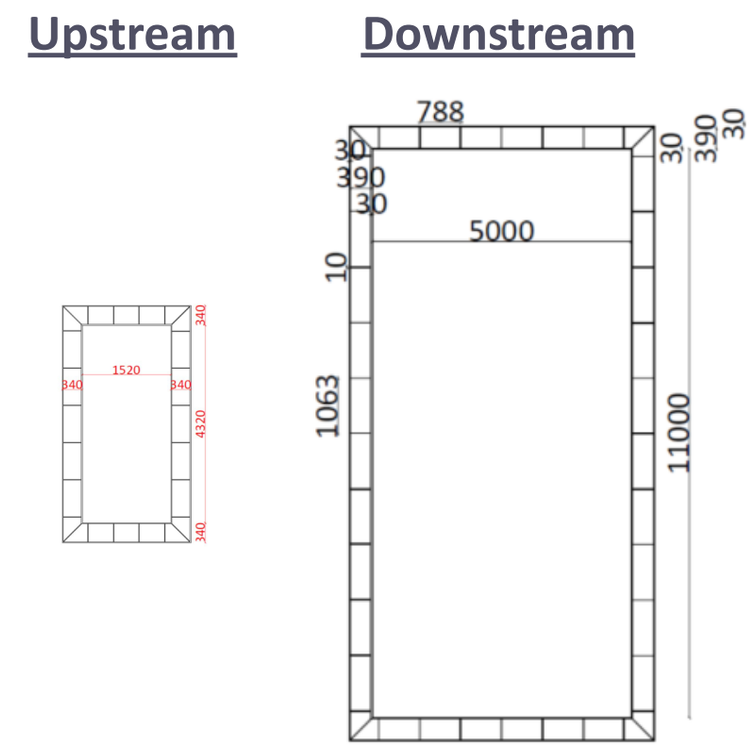
The SHiP Setup



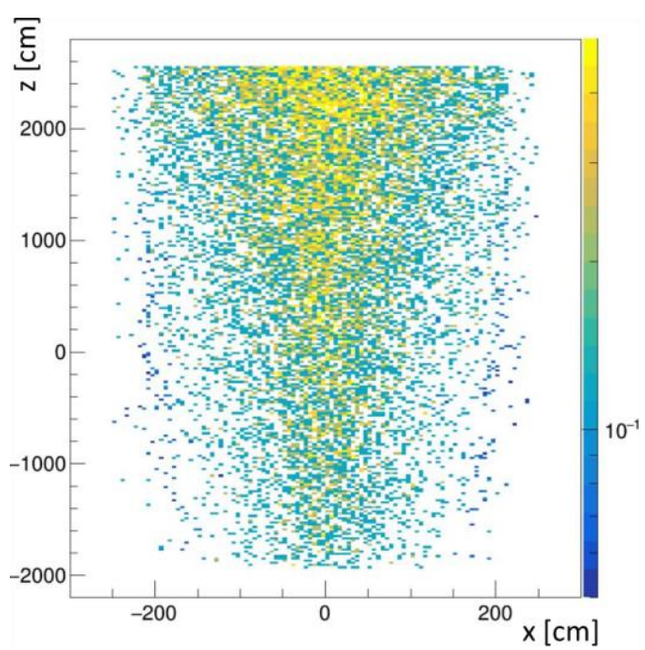
SHiP
Search for Hidden Particles

Decay Vessel

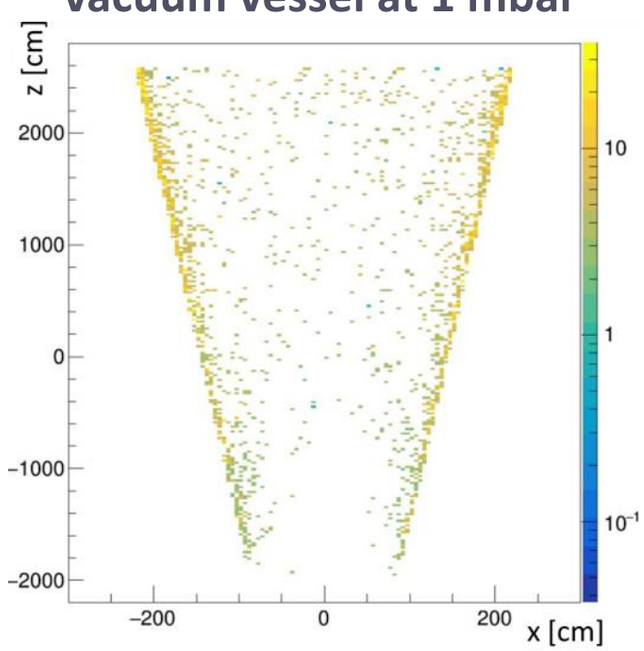
- **50 m long decay volume** for hidden-sector particles.
- Under **vacuum (10^{-3} bar)** to **suppress neutrino interactions** with air or gas.

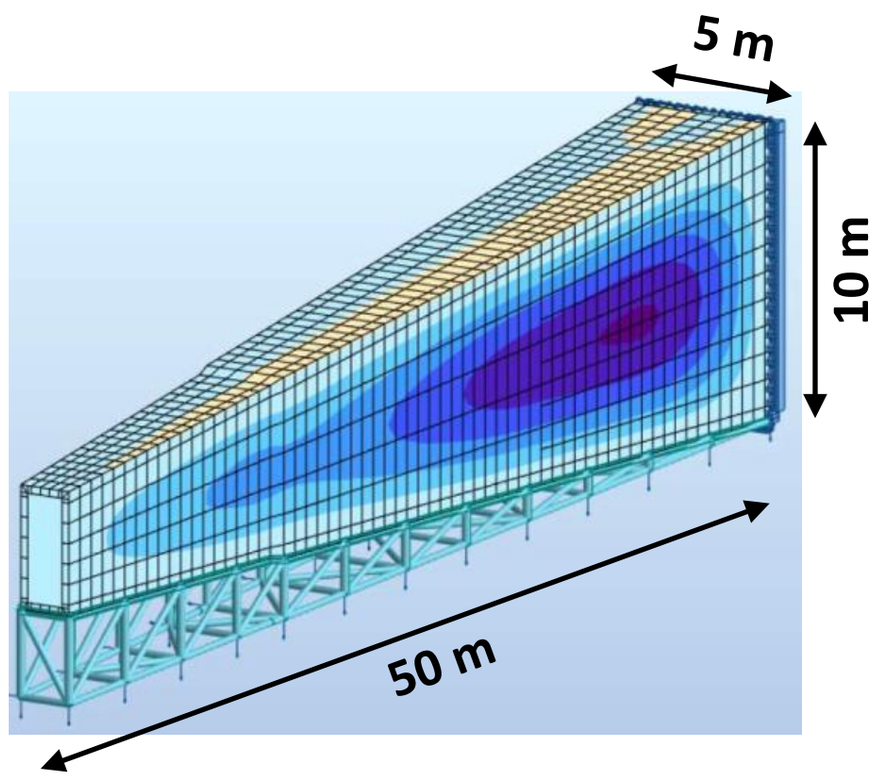


ν interactions in air



ν interactions in vacuum vessel at 1 mbar





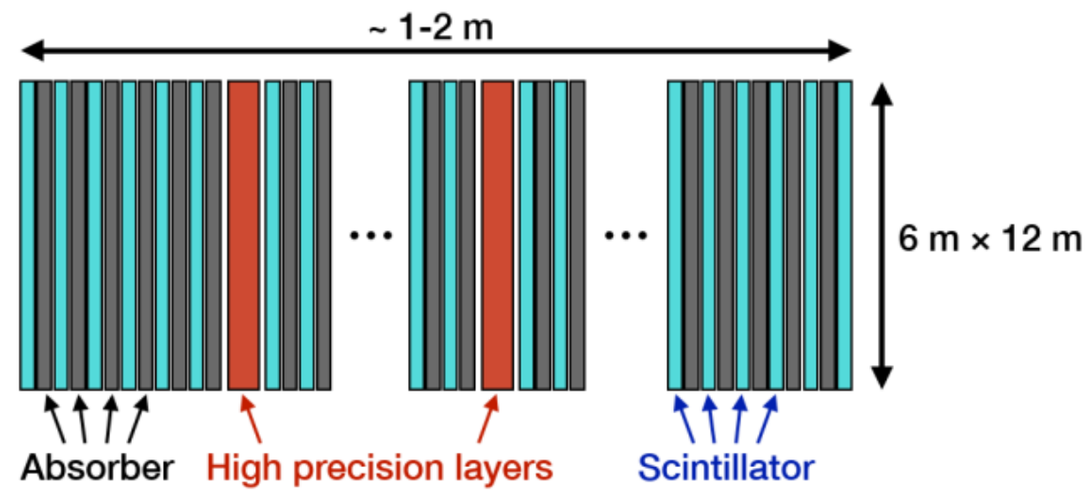
Electromagnetic Calorimeter (SplitCAL)

The **ECAL** shall serve several purposes:

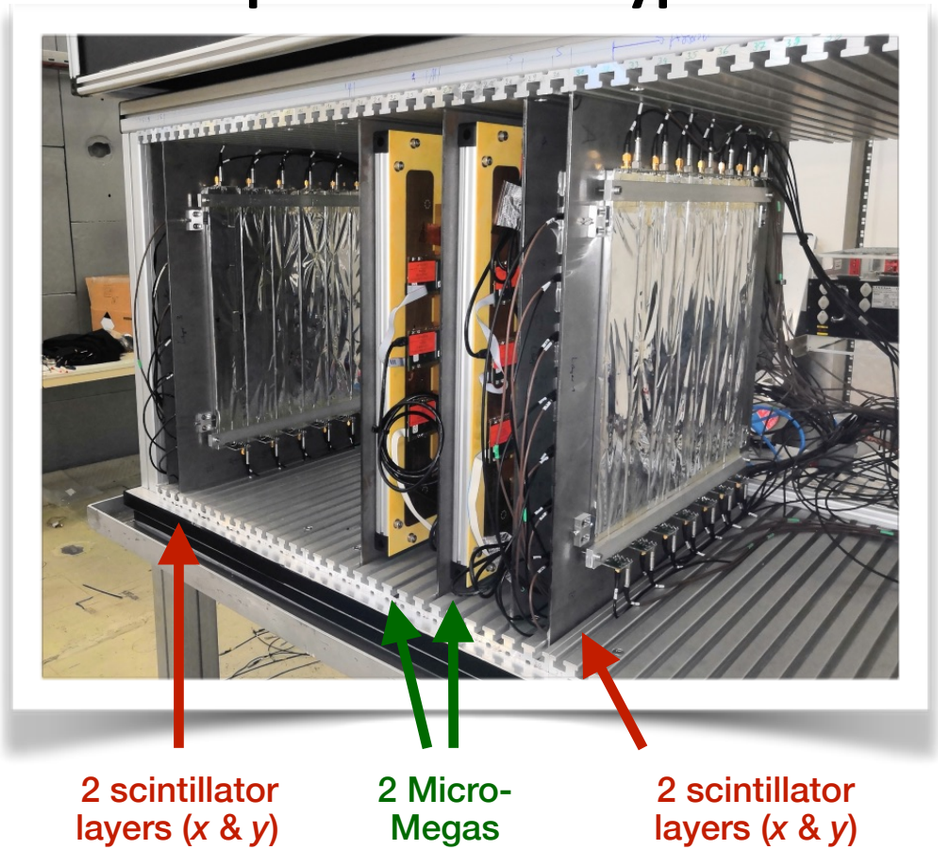
- **Energy measurement** of electrons & photons.
- **Particle ID** of electrons, muons and hadrons.
- **Photon direction** for $A \rightarrow \gamma\gamma$ reconstruction.

„SplitCAL“:

- **Scintillator ECAL.**
- **High-precision layers** for shower direction (e.g. MicroMegas).

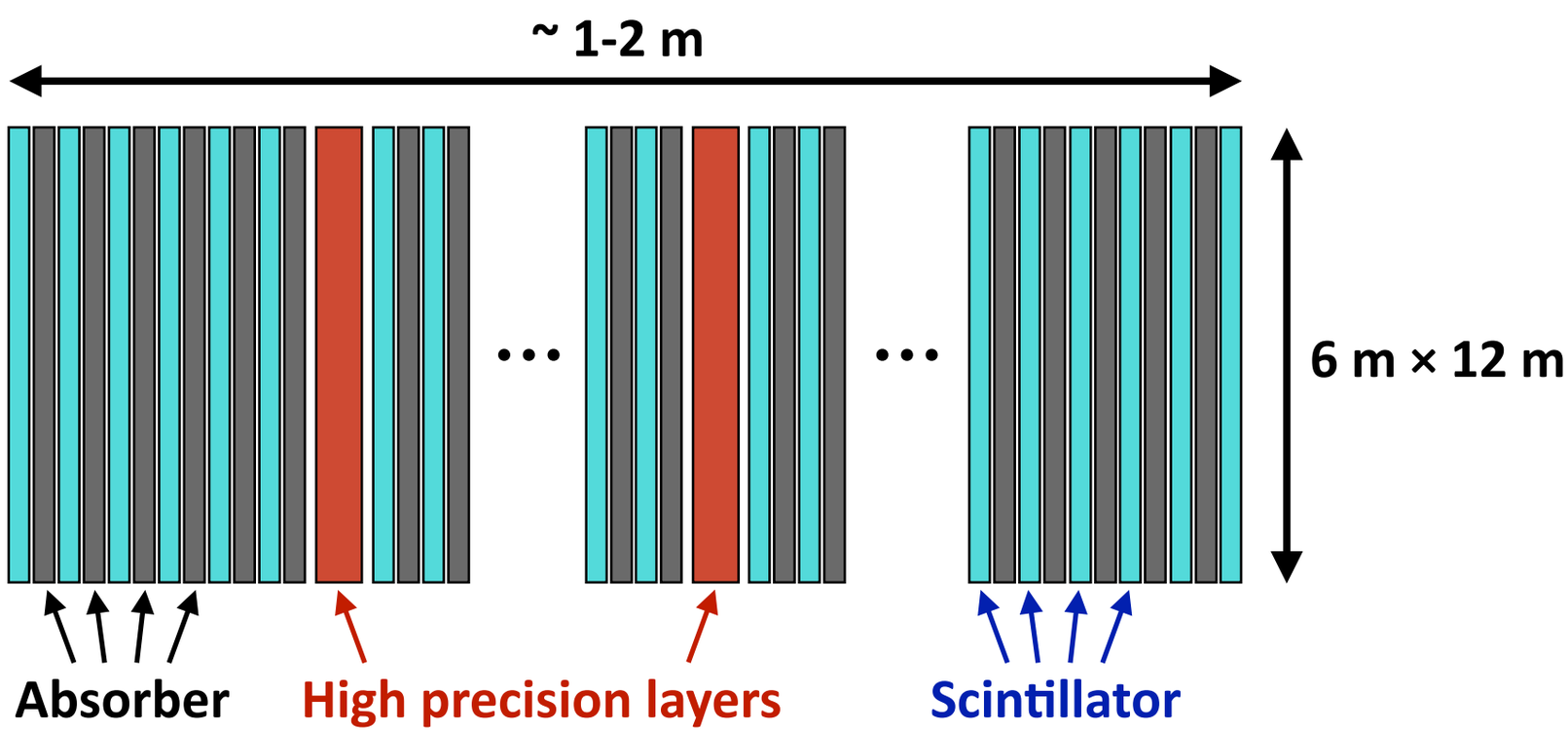


SplitCAL Prototype



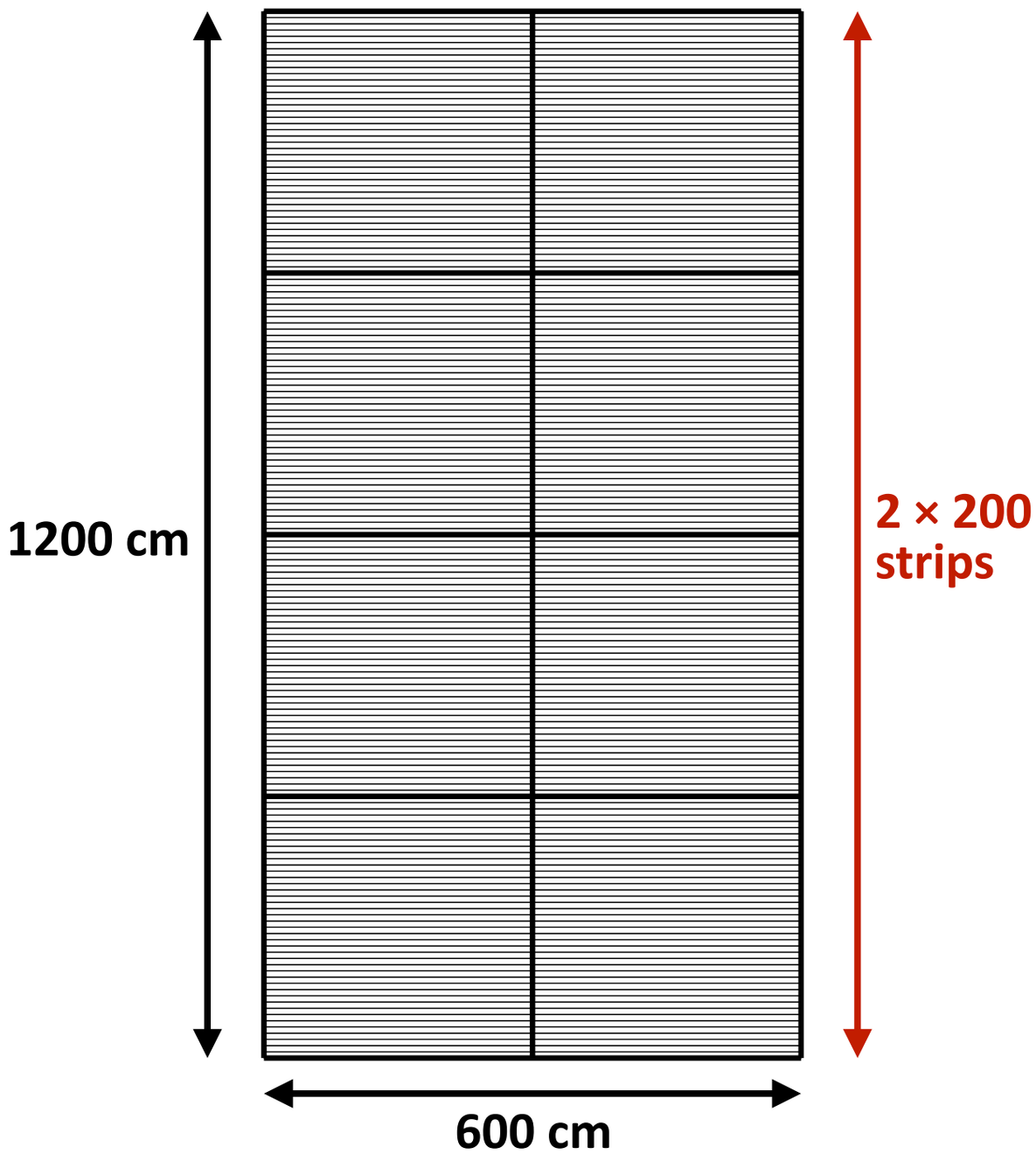
SplitCAL Design

- **Large absorber planes** of 6 m × 12 m cross section
- About **40-50 scintillating planes** (20-25 X_0).
  Strip orientation alternating in *x* and *y* and WLS fibre readout.
- **2 or 3 high precision layers** for measurements of the shower development ➜ **photon direction in $X \rightarrow \gamma\gamma$ decays.**

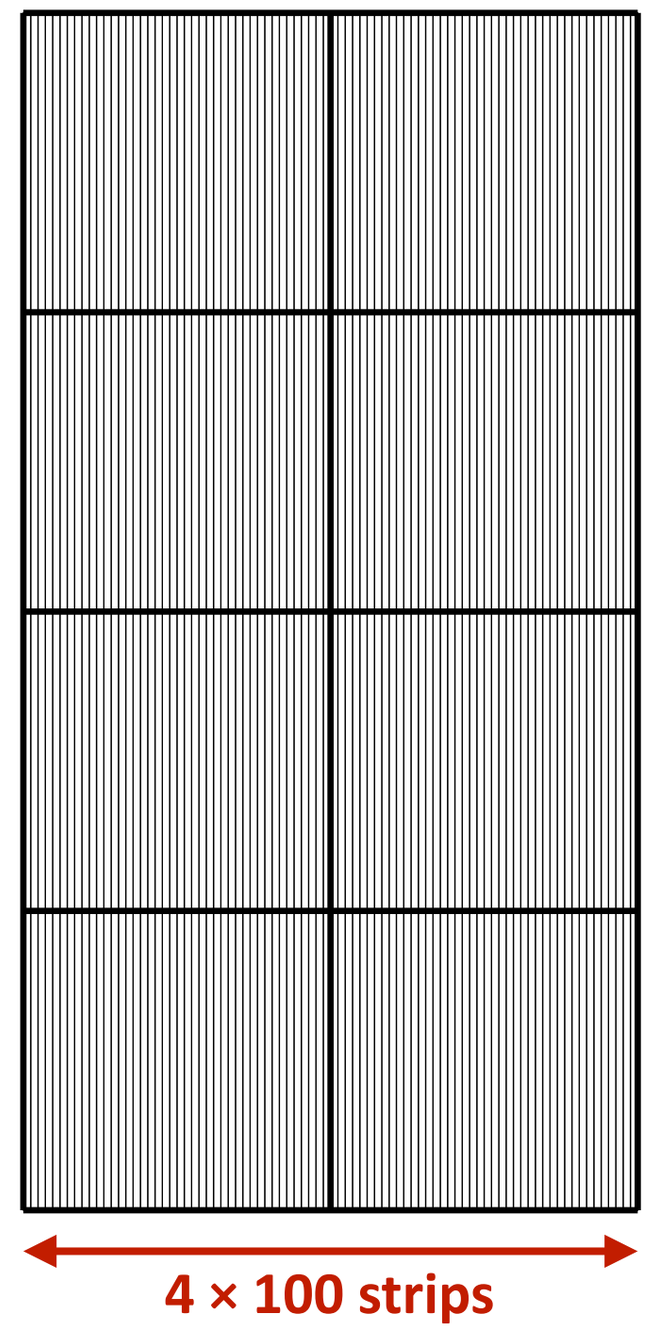


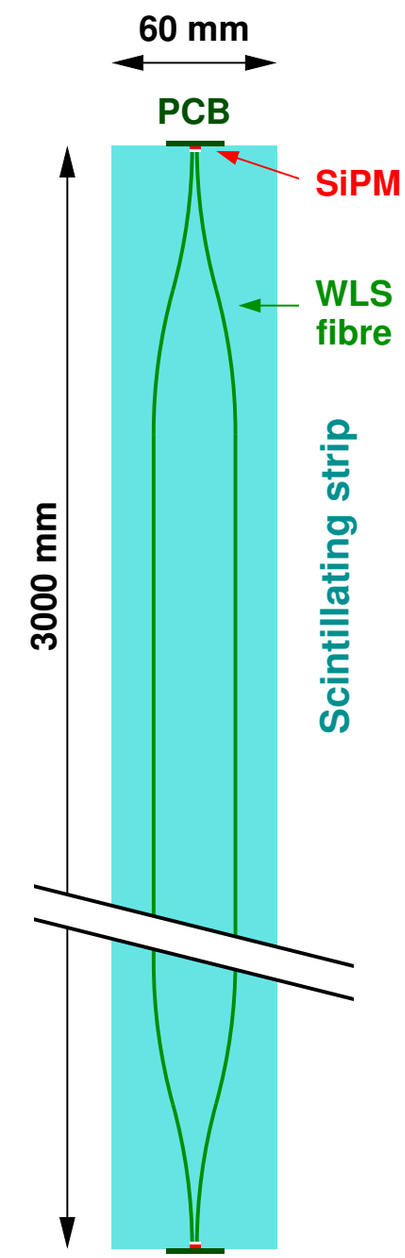
Layout of Scintillating Layers

Horizontal layer



Vertical layer





Basic Scintillator-ECAL Parameters

Assumptions for the basic parameters of the scintillator ECAL:

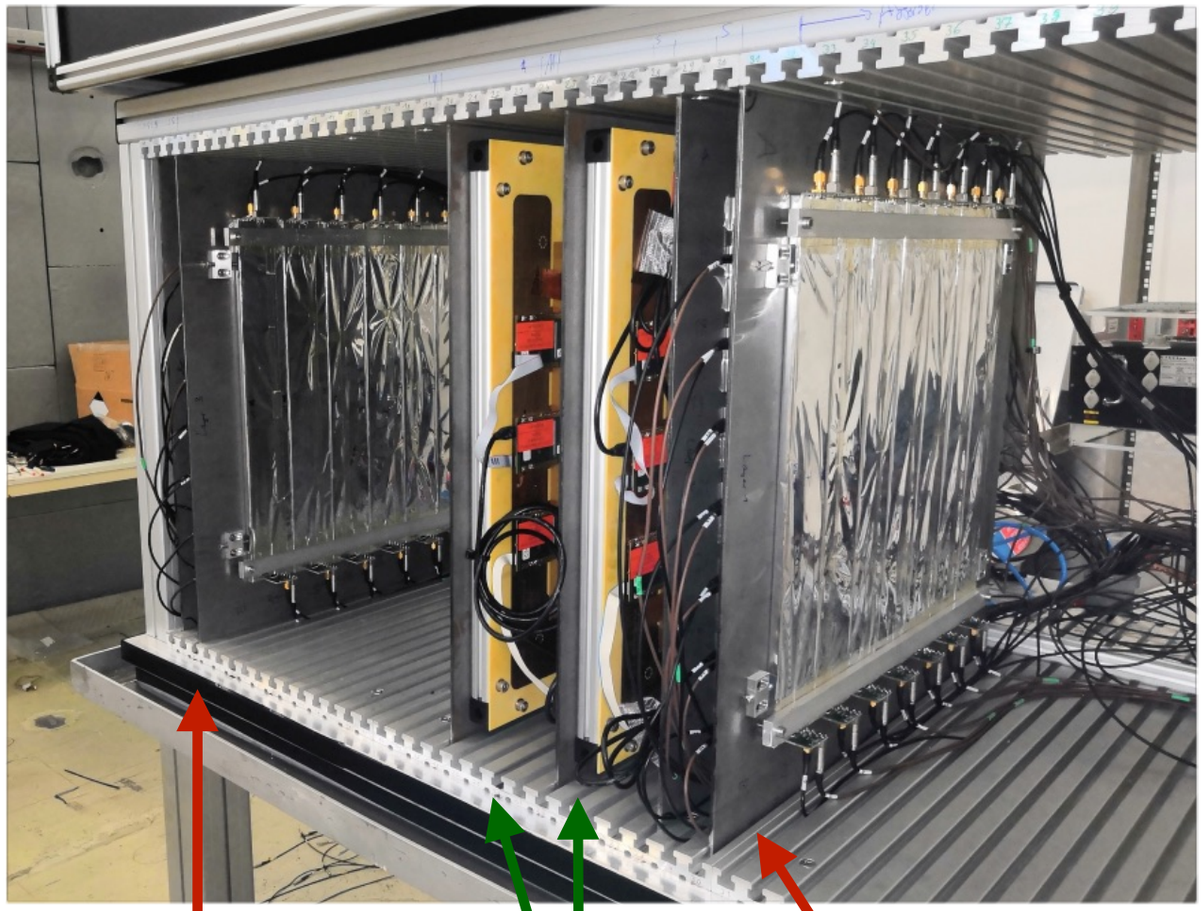
- **Depth:** **25 X_0** (could probably be less, e.g. 20 X_0)
- **# of layers:** **50** (or 40 for length of 20 X_0)
- **Front face:** **6 m × 12 m = 72 m²**
- **Absorber:** **Lead** (X_0 = 0.56 cm) or **iron** (X_0 = 1.76 cm).

  ➜ Total weight: **115 tons** (Fe: 248 tons)
- **Scintillators:** **400 strips** (3 m × 6 cm × 1 cm) **/ plane** ➜ **20 000 strips**
- **Fibres:** 2 × 20 000 × 3 m = **120 km**
- **SiPMs:** 2 × 20 000 = **40 000** (and same number of readout channels)

SplitCAL Prototype

SplitCAL Prototype

No additional absorber layers

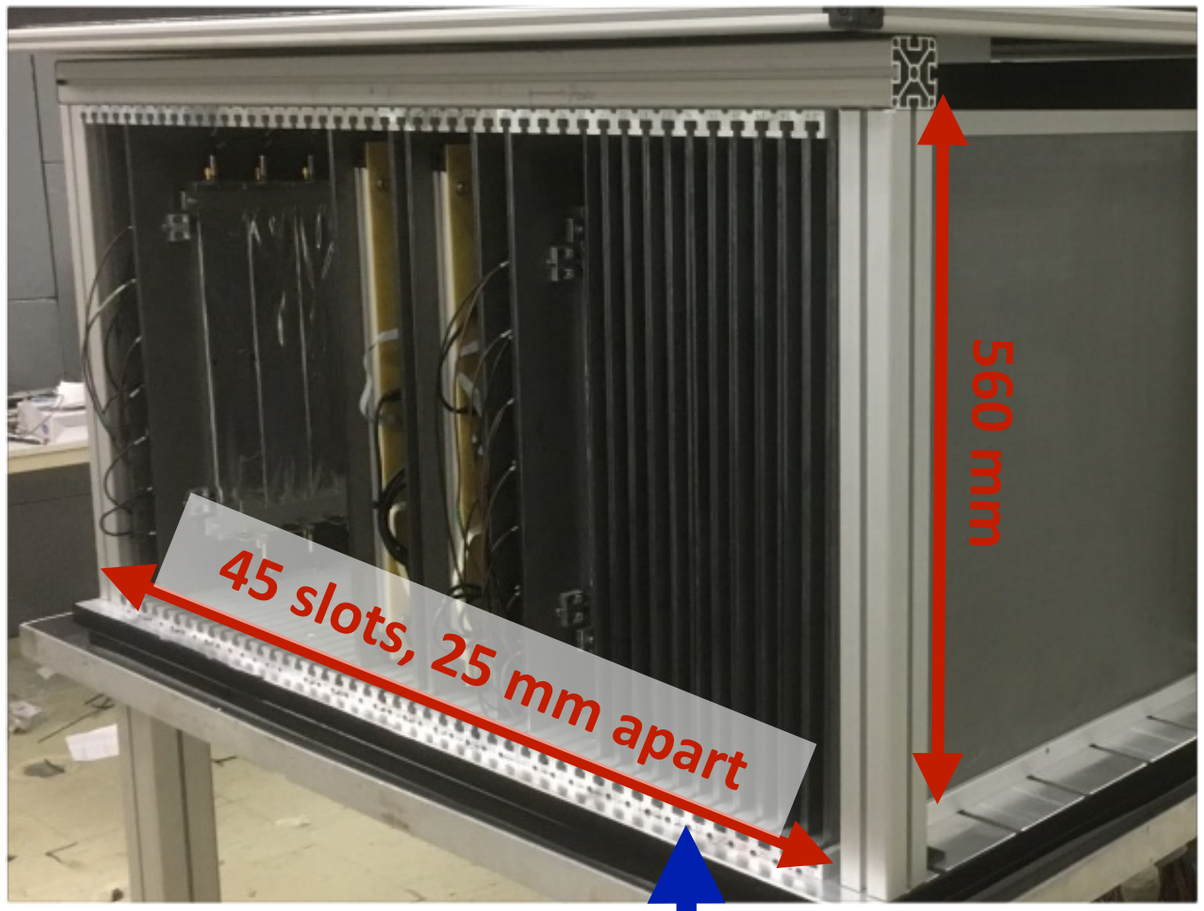


2 scintillator layers (*x* & *y*)

2 Micro-Megas

2 scintillator layers (*x* & *y*)

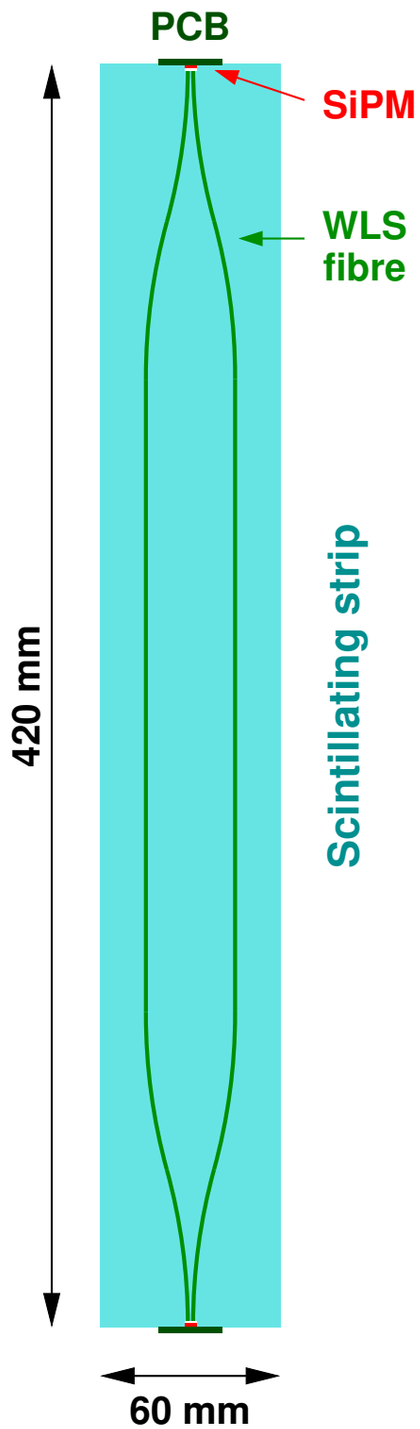
With absorber layers in front



22 absorber layers (≈ 5 X_0)

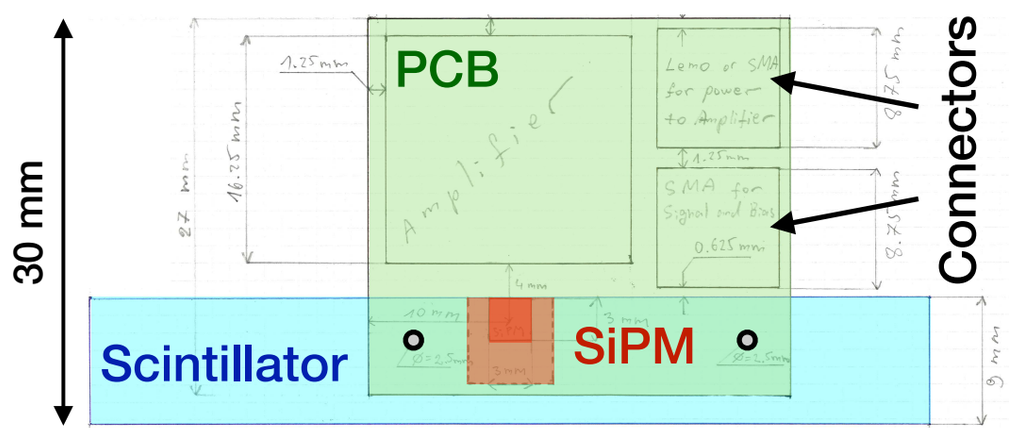
All kinds of setups easily possible.

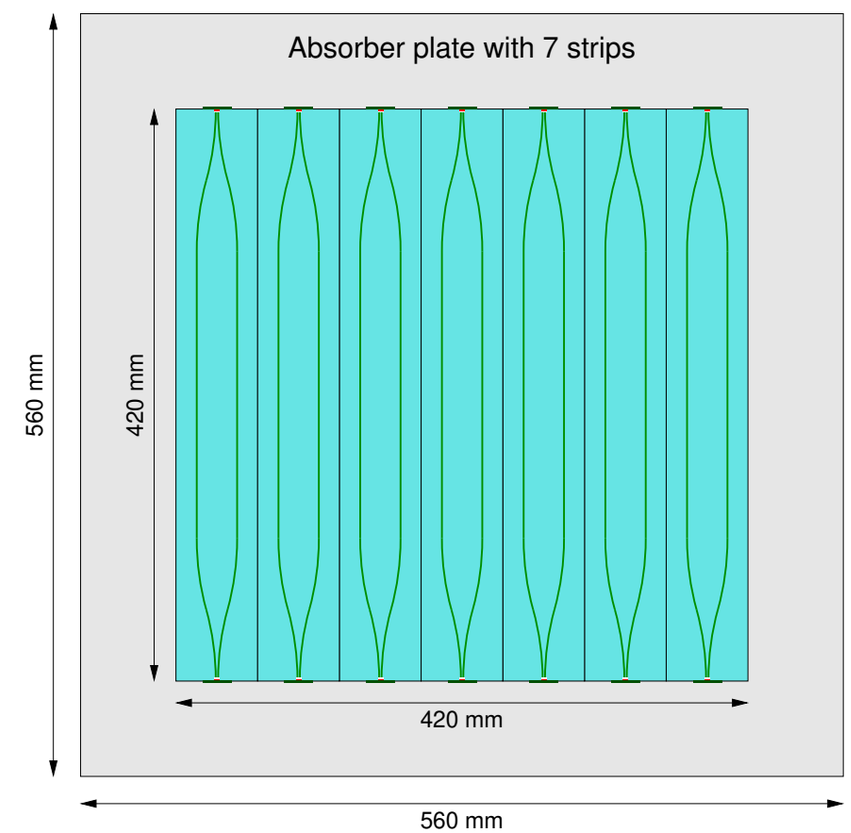
Scintillating Planes



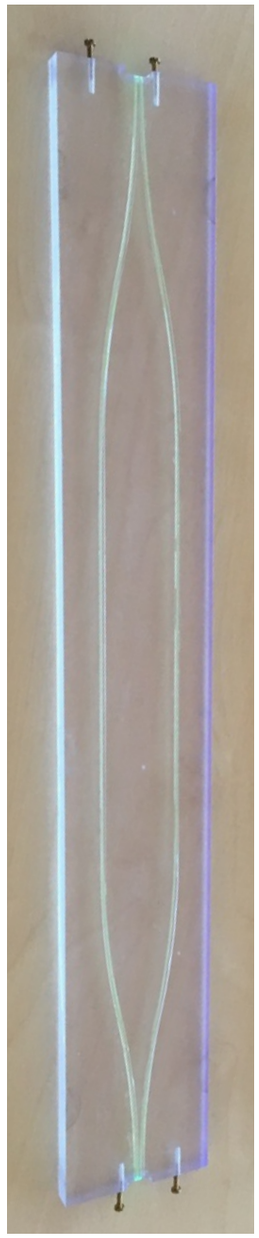
Each scintillating plane consists of one absorber plate, with 7 scintillating strips mounted.

- Double-sided readout ➜ 2 × 7 = 14 chan/plane.
- 2 horizontal & 2 vertical planes.
- SiPMs, preamps, and bias voltage mounted on a single PCB on the front faces of the strips.





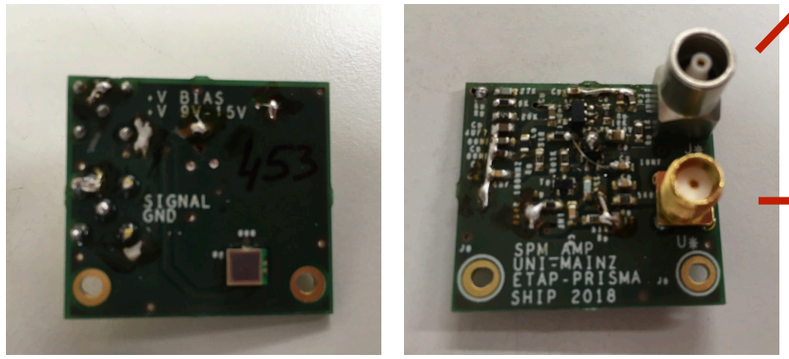
Scintillating Planes



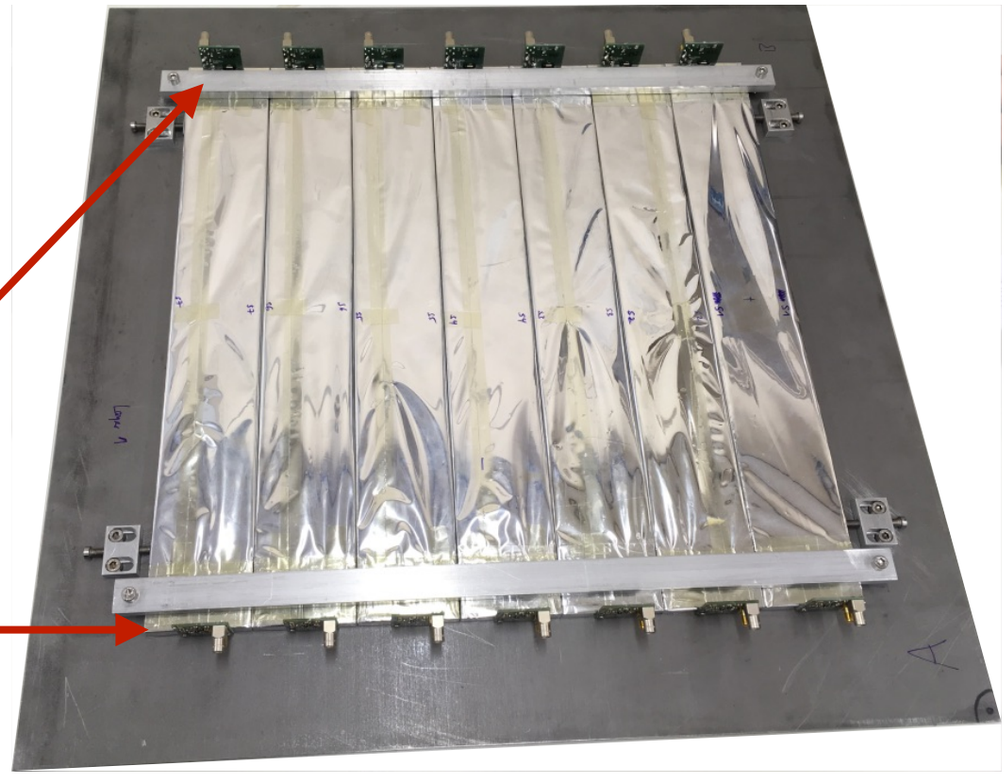
Scintillating strip

Each scintillating plane consists of one absorber plate, with 7 scintillating strips mounted.

- Double-sided readout ➜ 2 × 7 = 14 chan/plane.
- 2 horizontal & 2 vertical planes.
- SiPMs, preamps, and bias voltage mounted on a single PCB on the front faces of the strips.



SiPM with preamplifier



Absorber plate with 7 strips

SiPMs

Two types of SiPMs used:

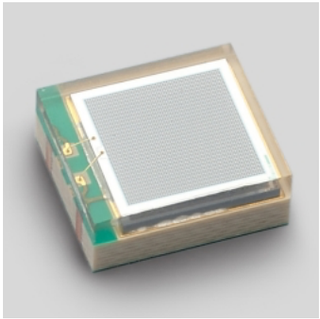
- **Hamamatsu S13360-3025PE**

  $3 \times 3\ mm^2$, 25 µm pitch, 14400 pixels.
  Used with WLS fibres of 1.2 mm diameter.

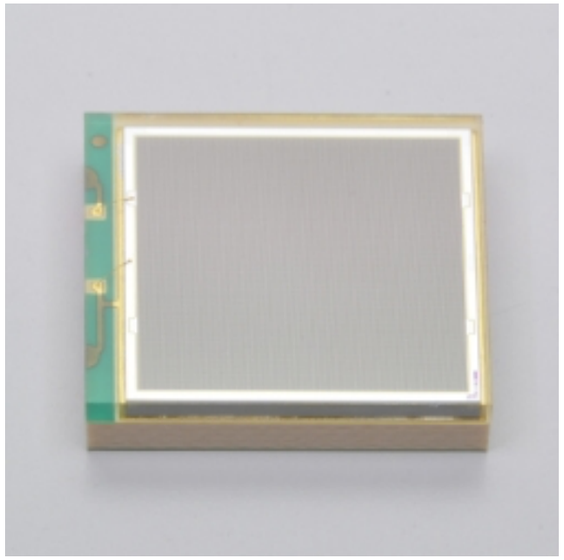
- **Hamamatsu S13360-6050PE**

  $6 \times 6\ mm^2$, 50 µm pitch, 14400 pixels.
  Used with WLS fibres of 2.0 mm diameter.

Large number of pixels necessary for dynamic range between MIPs and electron showers.



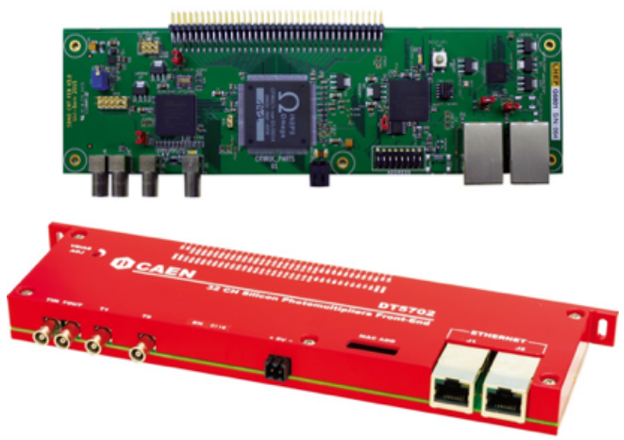
S13360-3025PE



S13360-3025PE

Prototype Scintillator Readout

- **Preamps directly at the SIPMs.**
  - Amplify signal for transmission through ≈ 4 m of coaxial cables.
- **Front-end electronics:**
  - Shaping and digitization of SiPM pulses.
  - Two **CAEN DT5702** modules
    - Each 32 channels with individual V_{bias}.
    - Multiplexed output, QDC functionality.
      - ROOT based DAQ software.
      - Very sensitive input, amplified signal needs to be downsized.



CAEN DT5702

Towards the final Readout

- **Prototype readout far too expensive** (and clumsy) for $\mathcal{O}$(40k) channels.
- **Better: ASICs close to SiPMs** for signal collection and digitization.

  Requirements:

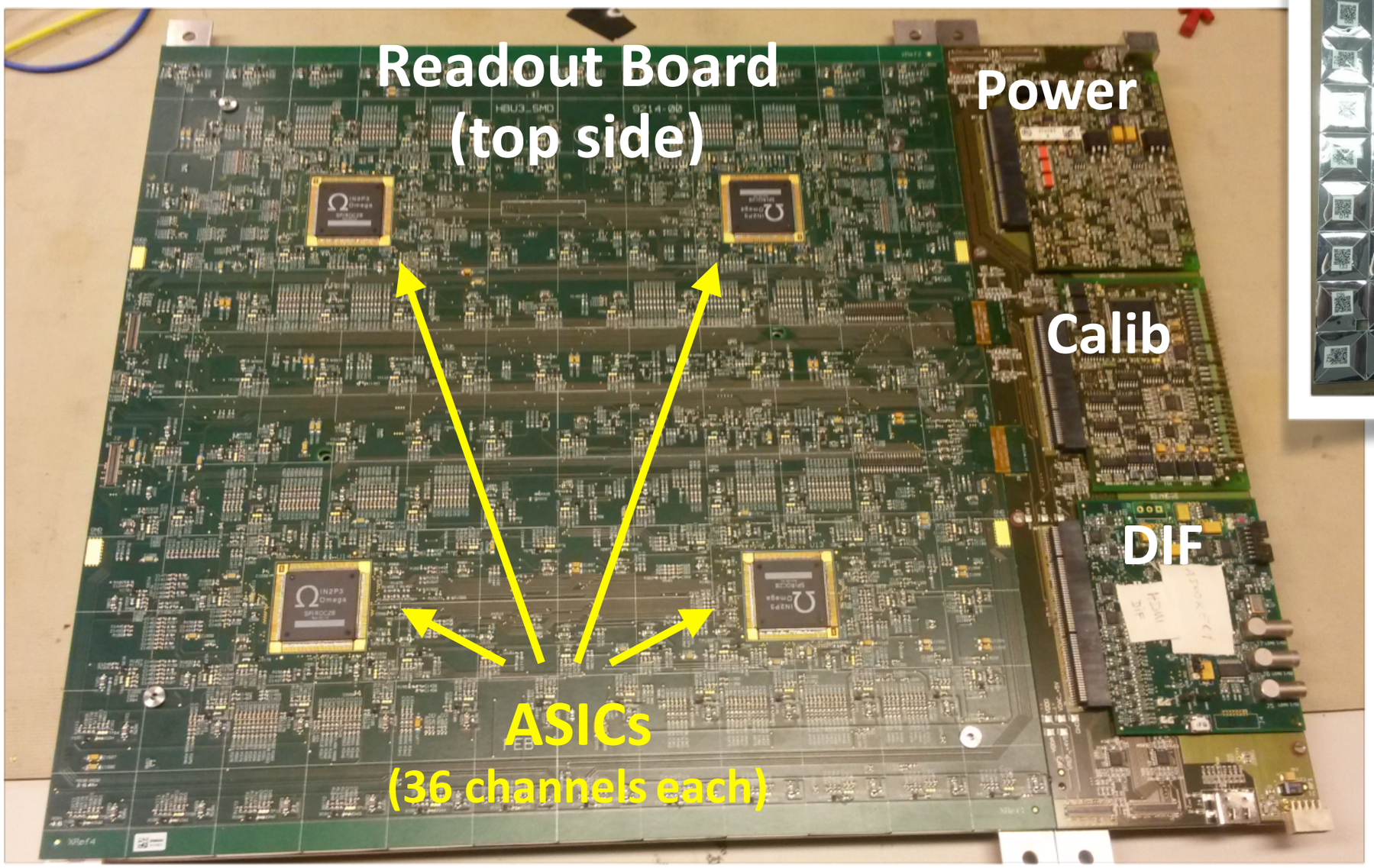
  - Large dynamic range (MIPs as well as e.m. showers).
  - Low rate.
  - SiPM calibration (temperature variations!).
  - Multiplexed digital output because of very many channels.

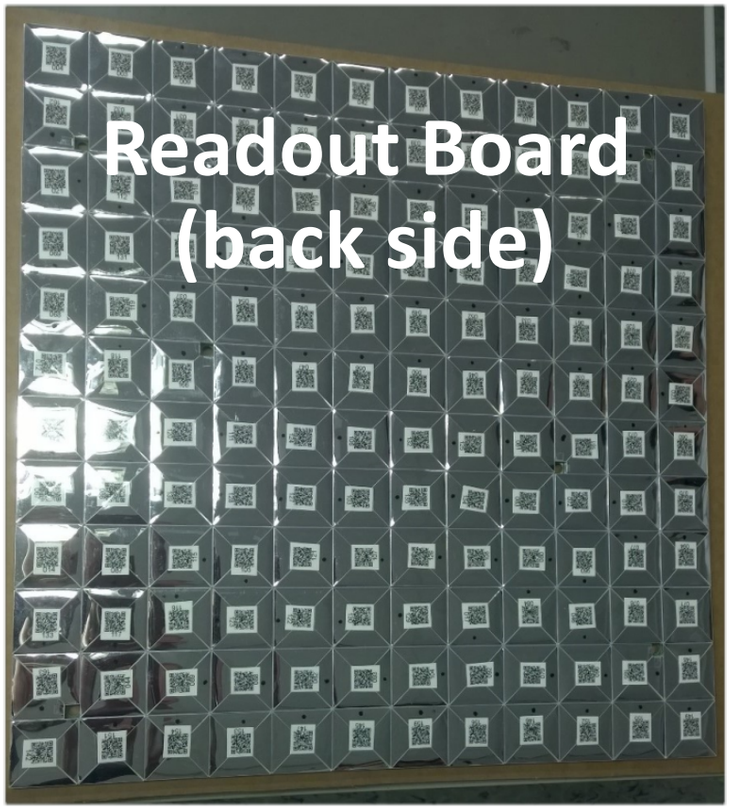
➜ Very similar requirements as for calorimeters at the ILC.

➜ Look at Calice AHCAL design.

Towards the final Readout

Calice AHCAL readout board (144 channels)

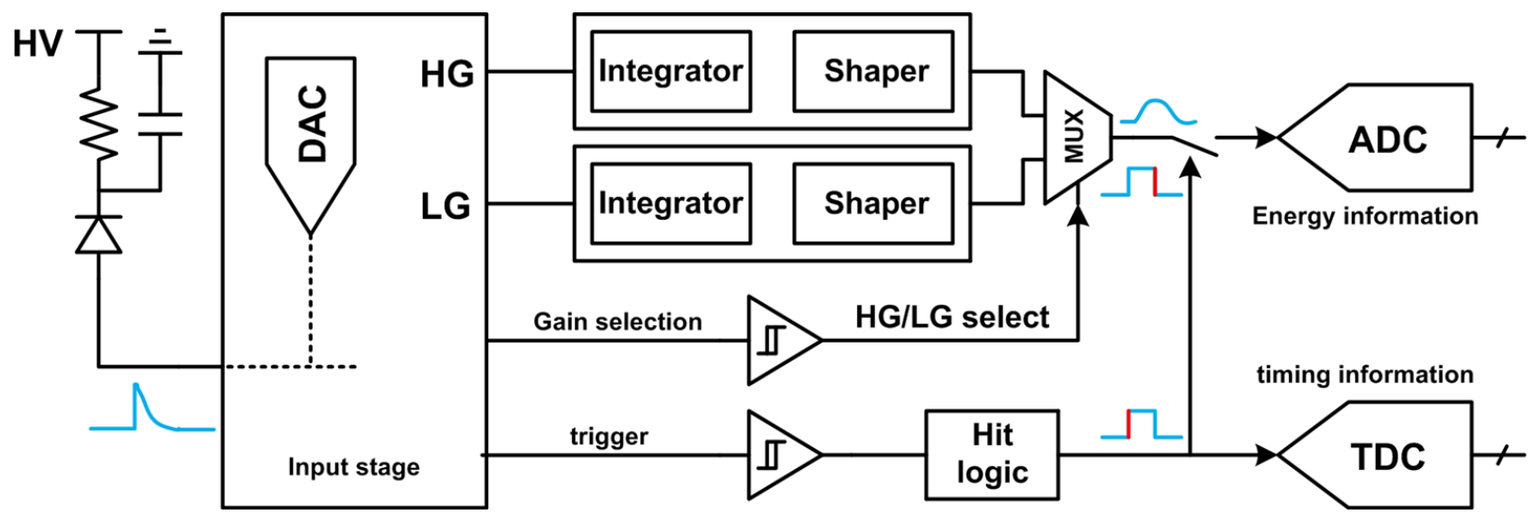


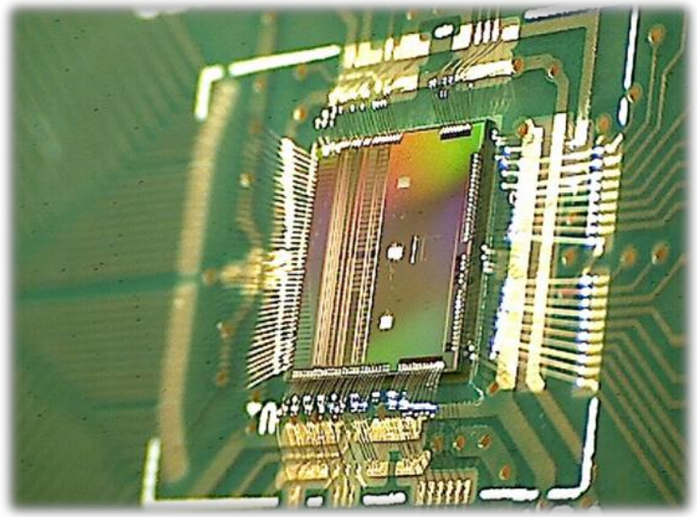


Towards the final Readout

Two working ASICs for Calice readout (very similar properties):

- **SPIROC** (v.2E), OMEGA/IN2P3-CNRS
- **KLauS** (v.5), Uni Heidelberg





(Z. Yuan)

Towards the final Readout

Two working ASICs for Calice readout (very similar properties):

- **SPIROC** (v.2E), OMEGA/IN2P3-CNRS
- **KLauS** (v.5), Uni Heidelberg
- Both ASICs are suitable (may even have too much functionality).
  - ➜ Going to evaluate the KLauS chip from Heidelberg.

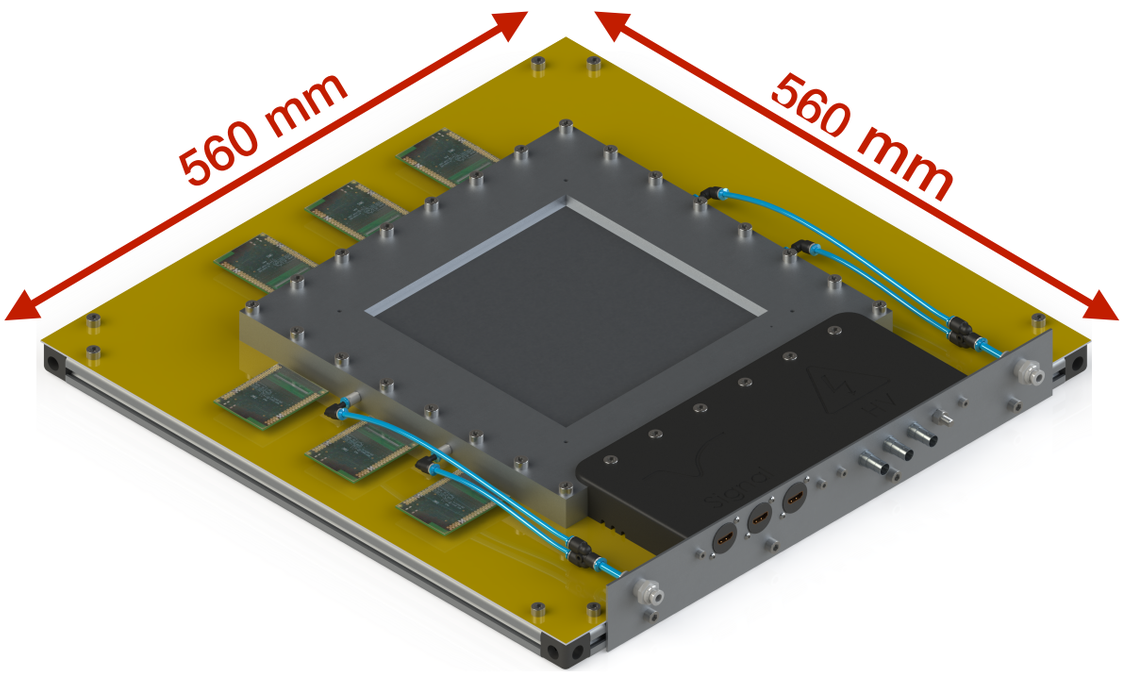
Open question:

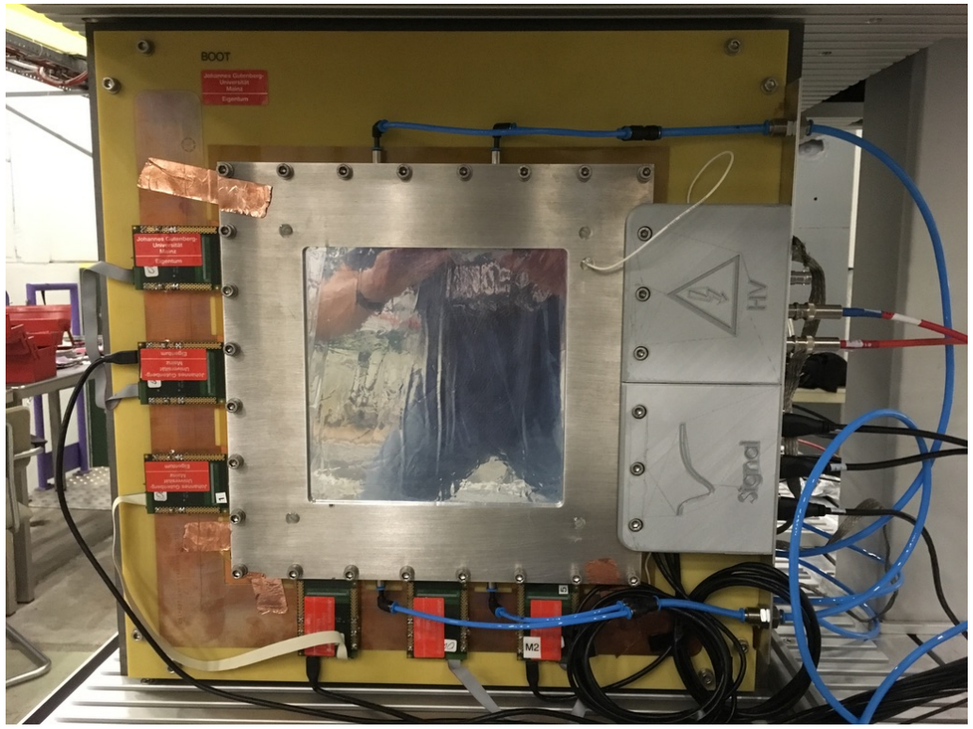
- **Integration into very different layout of SHiP ECAL.**

High-Precision Layers

Two MicroMegas chambers with **18 × 18 cm²** active area.

- Each MicroMegas contains a double-layer with *x* and *y* strips, mounted on one absorber plate.
- **Strip pitch = 500 µm** ➜ **360 strips** in each view.
- Readout with custom ASICs (APV) and external trigger.





Main Open Questions

SiPM-WLS fibre coupling:

- Secure, efficient and repeatable coupling.
  Some ideas (e.g. diffusors), but more R&D needed.

SiPM Readout:

- Main difficulty: Dynamic range MIP → EM shower
- Try to use an existing ASIC and possibly adapt existing electronic.

Mechanics:

- Integration of scintillators and absorbers.
  Keep in mind the size!

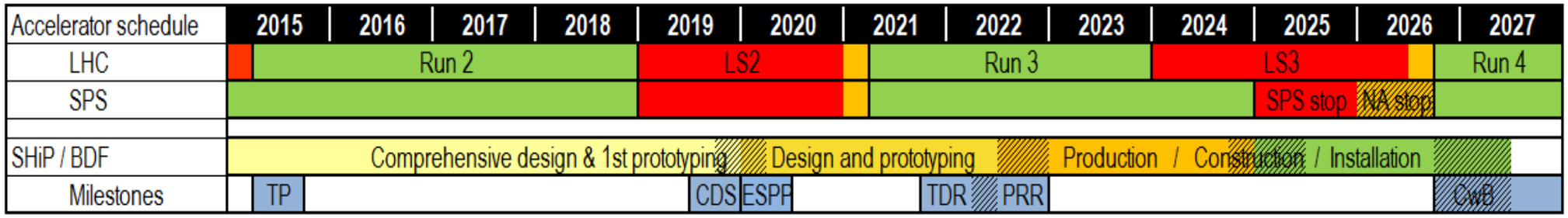
Conclusions

***SplitCAL* for the SHiP experiment**

- **Absorber-scintillator sandwich** for energy measurement.
  - **Long scintillating strips** with WLS fibre readout.
  - Light readout with **SiPMs, large dynamic range required.**
- **High-precision layers** for photon directions
  - **MicroMegas,** similar to new ATLAS muon chambers.

Timeline for SHiP

- **Decision for approval awaited for 2020.**
- In case of approval: **Start planned for 2026.**

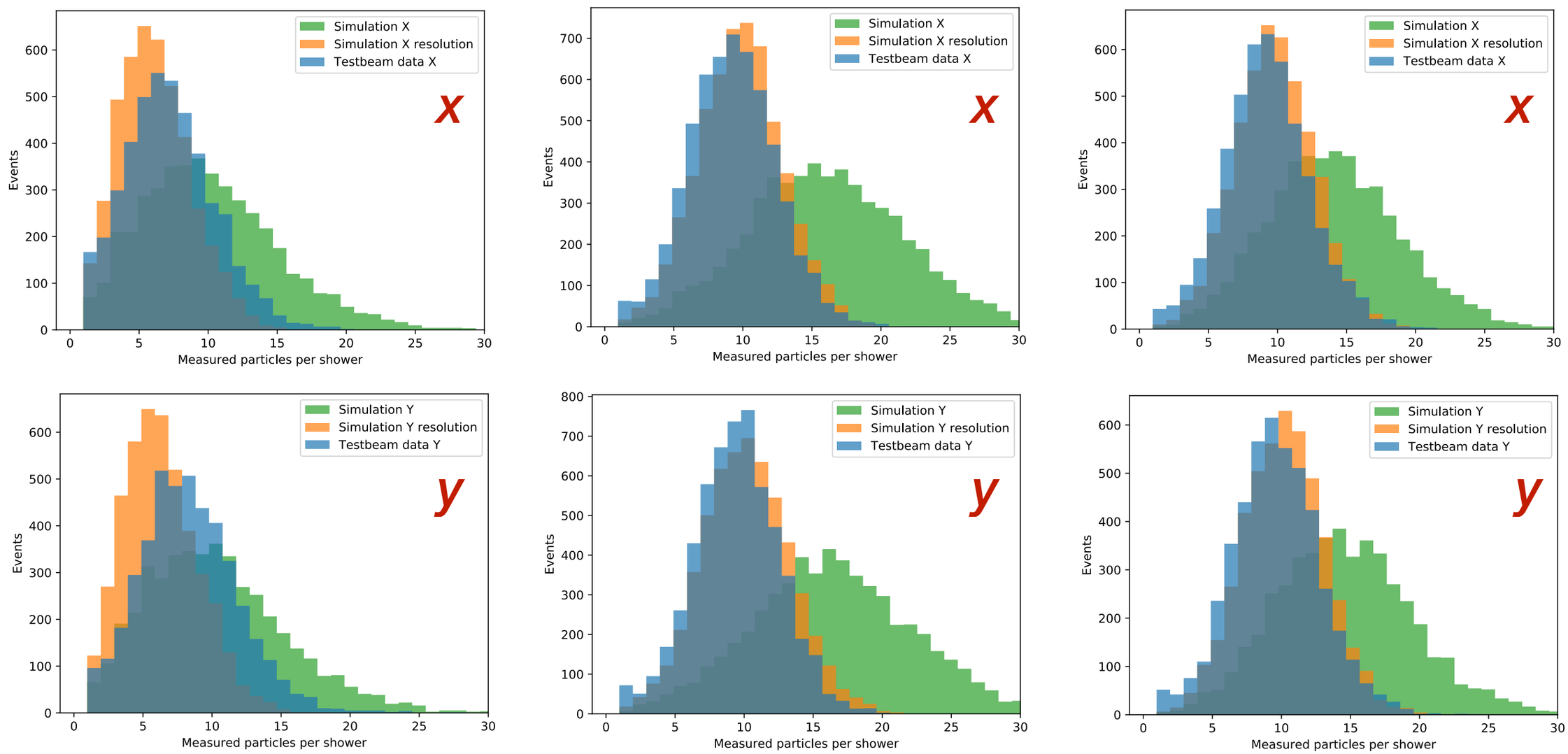


Backup

Test Beam Results for High-Precision Layers

Average number of measured particles:

2.1 X_0 | **3.9 X_0** | **5.7 X_0**

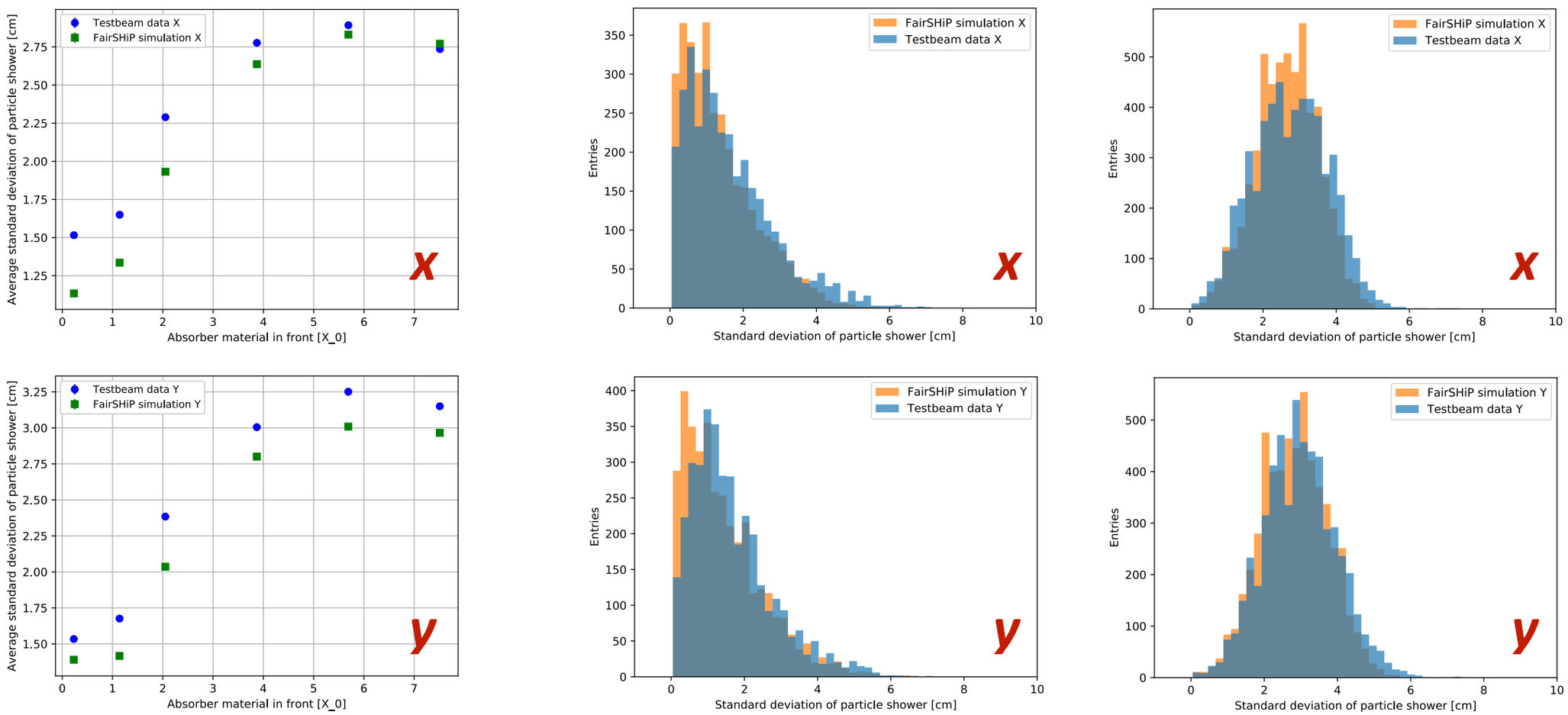


Test Beam Results for High-Precision Layers

Shower width (excluding single-particle events):

- Good agreement between measurement and simulation, only some additional noise seen in real data.

1.1 X_0 **3.9 X_0**

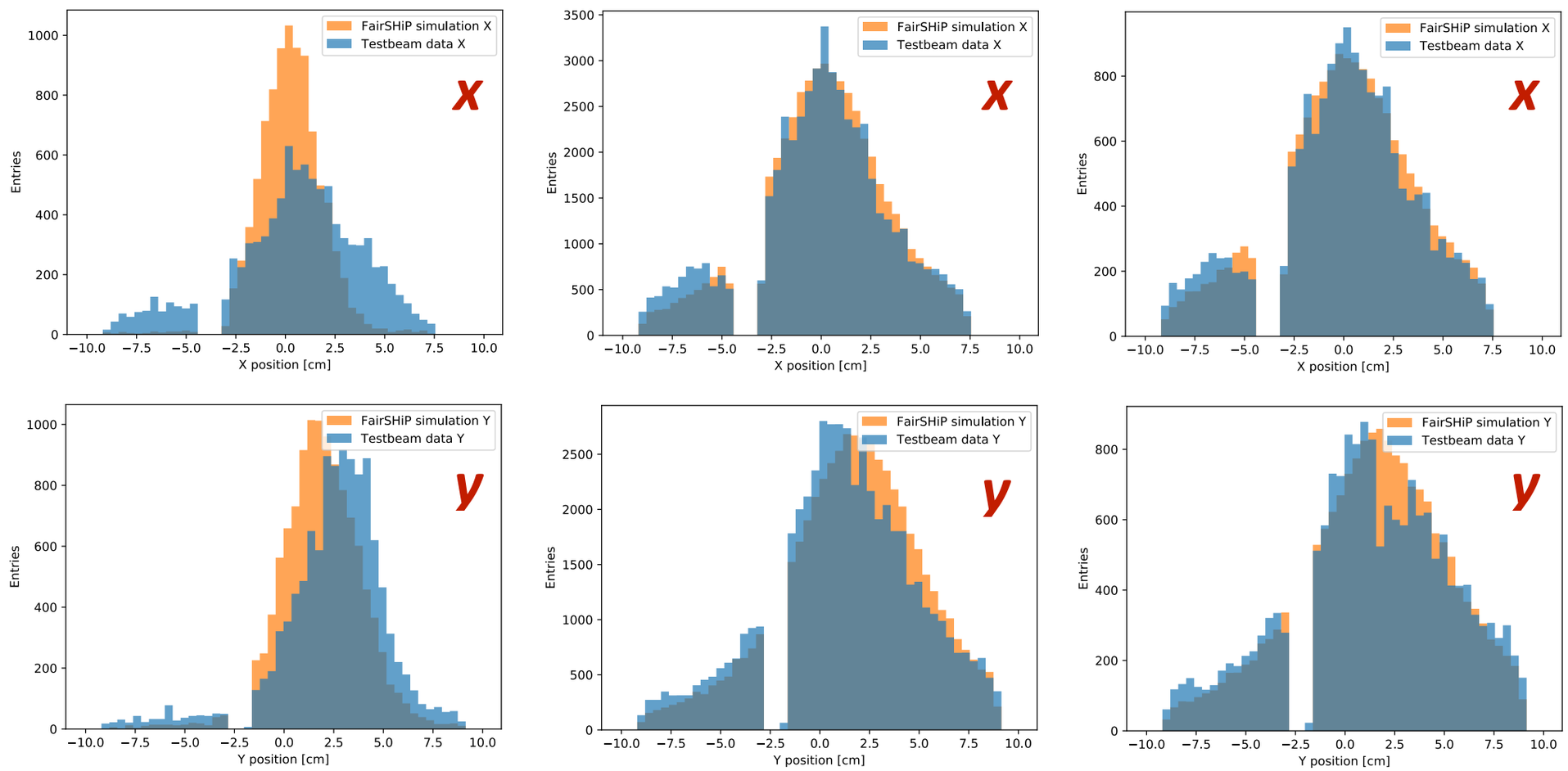


Test Beam Results for High-Precision Layers

Measured hit distributions:

- Absolute distributions agree fairly well,
  considering the difficulty to simulate the beam profile.

0.2 X_0 **3.9 X_0** **7.5 X_0**



Test Beam Results for High-Precision Layers

Measured hit distributions:

- Better: adjusted position = mean(2nd MM) – mean(1st MM)
  - ➜ again very good agreement apart from residual noise.

0.2 X_0 **2.1 X_0** **5.7 X_0**