Development of high-precision calorimeters for the SHiP experiment at CERN SPS

EPPG seminar, Ghent University

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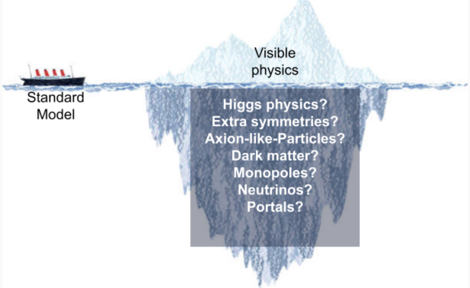
Outline

- The Standard Model and its limits
- The Search for Hidden Particles
- Neutrino physics at SHiP and high granularity layers
- Downstream calorimetry at SHiP and high precision layers
- Conclusion

The Standard Model

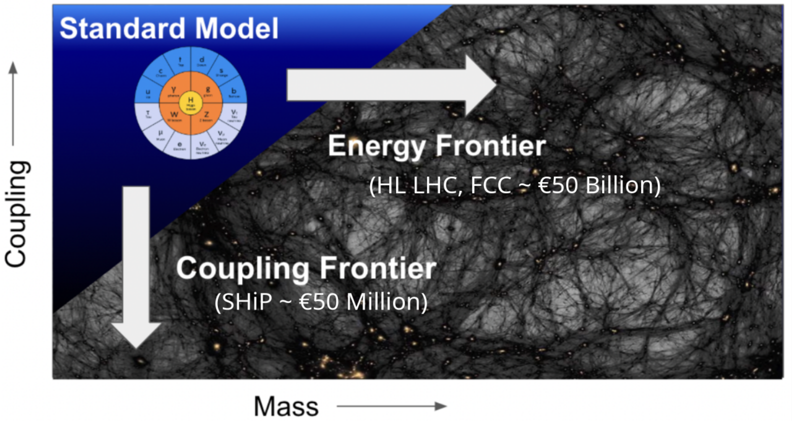
- Complete, renormalisable theory which looks like it could be consistent all the way up to the Planck scale $\mathcal{O}(10^{18}\ \text{GeV})$
- Fully consistent with nearly all experimental data
- Some problems remain however:
    - Gauge hierarchy problem: why is the Higgs so light?
    - Neutrino oscillations: why are neutrinos so light? Where does their mass come from?
    - Inconsistency with the current state of the universe: baryogenesis in the early universe requires more CP violation
    - Is unable to explain gravity and the existence of dark matter

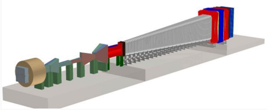


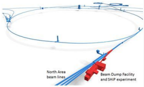
Beyond the Standard Model: where to sail?

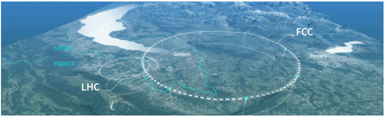
New physics is either:

1. Too heavy to have been seen (∼TeV or more: SUSY neutralino, resonant leptogenensis HNL...)
2. Too weakly interacting to have been seen (much less than even neutrinos: hidden sector mediator, oscillation leptogenensis HNL...)





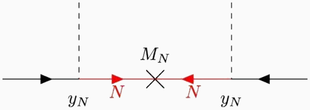


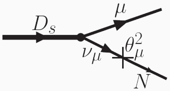


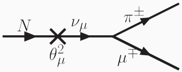
Beyond the Standard Model: what to look for (examples)

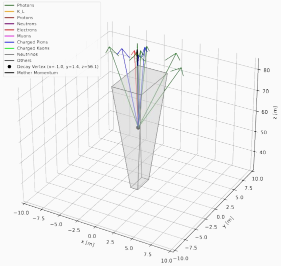
Heavy neutral leptons:

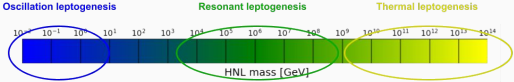
- Right-handed neutrinos
- Explain neutrino mass scale (type I seesaw)
- Allow leptogenesis





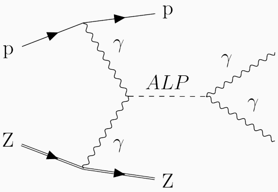


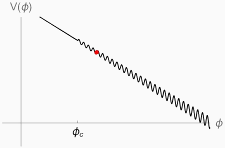


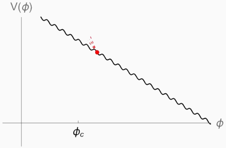


Axion-like-Particles:

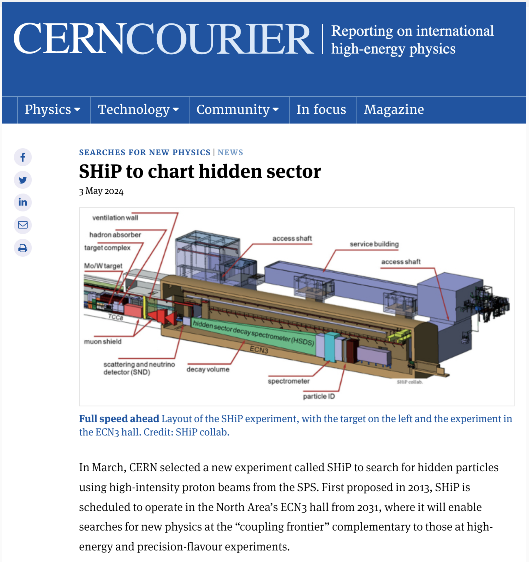
- Generic (pseudo-) Nambu-Goldstone boson emerging from broken global symmetries
- May offer a relaxation solution to the hierarchy problem
- May mediate interactions to a Hidden Sector







Beyond the Standard Model: how to sail?



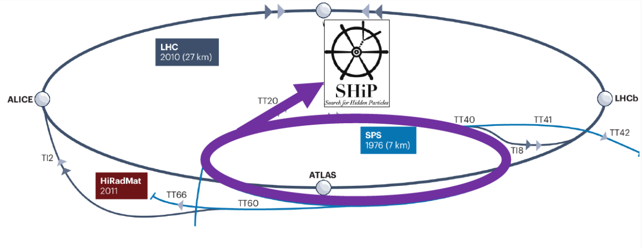
SEARCHES FOR NEW PHYSICS | NEWS

SHiP to chart hidden sector

3 May 2024

Full speed ahead Layout of the SHiP experiment, with the target on the left and the experiment in the ECN3 hall. Credit: SHiP collab.

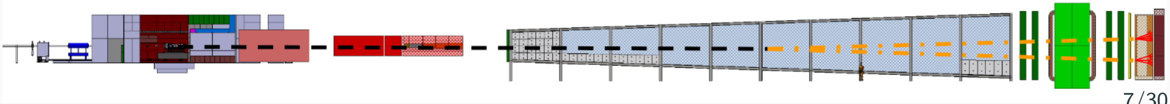
In March, CERN selected a new experiment called SHiP to search for hidden particles using high-intensity proton beams from the SPS. First proposed in 2013, SHiP is scheduled to operate in the North Area's ECN3 hall from 2031, where it will enable searches for new physics at the "coupling frontier" complementary to those at high-energy and precision-flavour experiments.



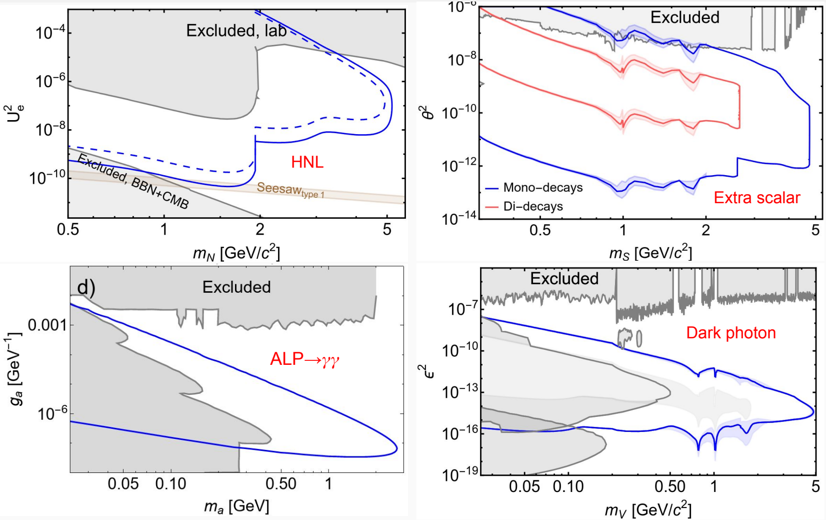
- SHiP/NA67 experiment approved in March 2024
- Use SPS accelerator proton to fire protons on target
    - Facility already under construction
    - Data taking begins in 2031

Beyond the Standard Model: the SHiP experiment

- High-intensity beam dump experiment: 6×10^{20} protons on target over 15 years
- Globally unique physics potential: large D and B meson fluxes
- Sensitivity to a broad variety of Feebly Interacting Particles (FIPs)
  - HNLs
  - Axion-like-particles (ALPs)
  - Dark scalar Higgs-like particles
  - Dark photons
  - Light dark matter (LDM)
- Unprecedented measurements of ν_τ, F_4 and F_5, flavour physics, lepton universality and many more
- Will operate in a zero-background environment

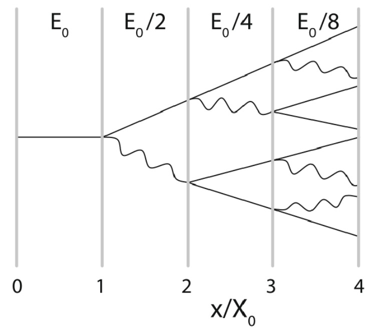


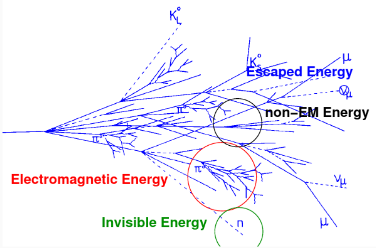
SHiP: where can we sail?



Interlude: introduction to calorimetry

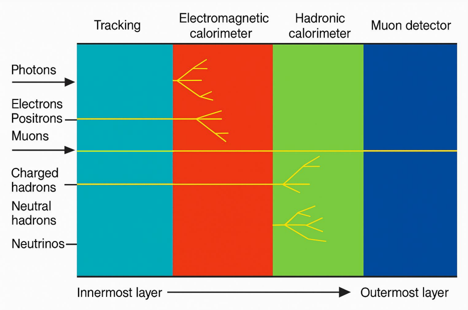
- Particle detectors determine what (particle identification), where (tracking), when (timing), how (physics process) and how much (energy measurement).
- Calorimeters are generalists, they can measure each of these variables with an emphasis however on what and how much
- Calorimeters are *destructive* detectors and function with some combination of sensitive and passive material
- They come in two greater variants: electromagnetic calorimeters (ECAL) and hadronic calorimeter



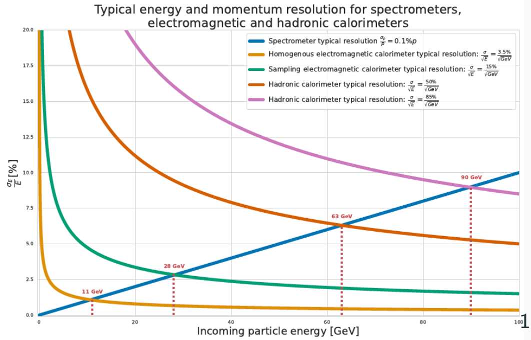


Interlude: introduction to calorimetry

- They have unique particle identification capabilities
    - Signal identification and background suppression
- Their relative energy resolution *improves* with greater energy $\propto \frac{1}{\sqrt{E}}$

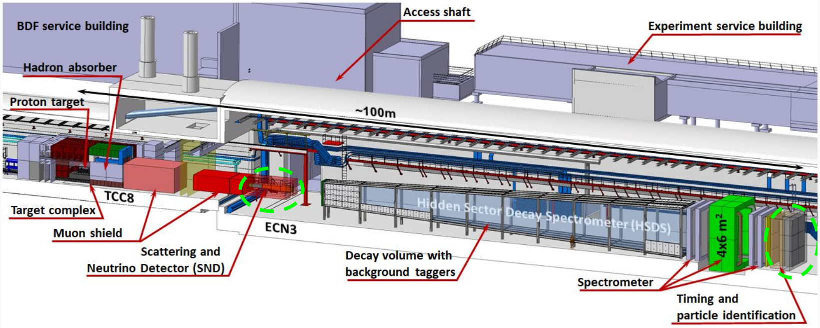


- Calorimeters are challenging because
    - Great diversity in available technologies (scintillators, liquid noble gases, semiconductors, cherenkov...)
    - Mechanical integration is difficult


Typical energy and momentum resolution for spectrometers, electromagnetic and hadronic calorimeters

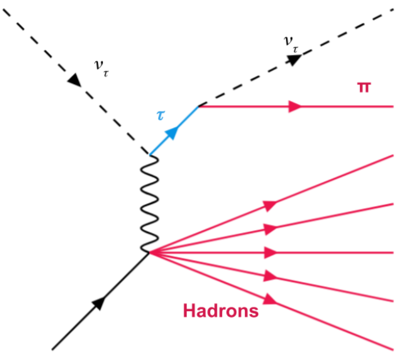
Calorimetry at SHiP

- SHiP is equipped with two calorimeter systems
  - The SND@SHiP calorimeter
    - Used in the observation of LDM and ν
    - Embedded into the muon shield
  - The Particle identification detector calorimeter
    - Sampling ECAL with excellent angular resolution for neutral final states
    - HCAL to discriminate muons and hadrons in a wide momentum range



ν_τ physics at SND@SHiP

- Experimental signature of a ν_τ:
  - *Double-kink* topology from ν_τ interaction and τ decay
  - Missing p_T carried by outgoing ν_τ
- BDF/SHiP produces a very large ν_τ sample through $\mathrm{D_s} \rightarrow \tau\nu_\tau$ with $\sigma_{\text{stat}} < 1\,\%$ for all neutrino flavours
- Will mark the beginning of ν_τ phenomenology!
- Measurement accuracy is determined by systematic uncertainty $\sim 5\,\%$ in all ν fluxes, dominated by uncertainty in the cascade charm production in the thick SHiP tungsten target

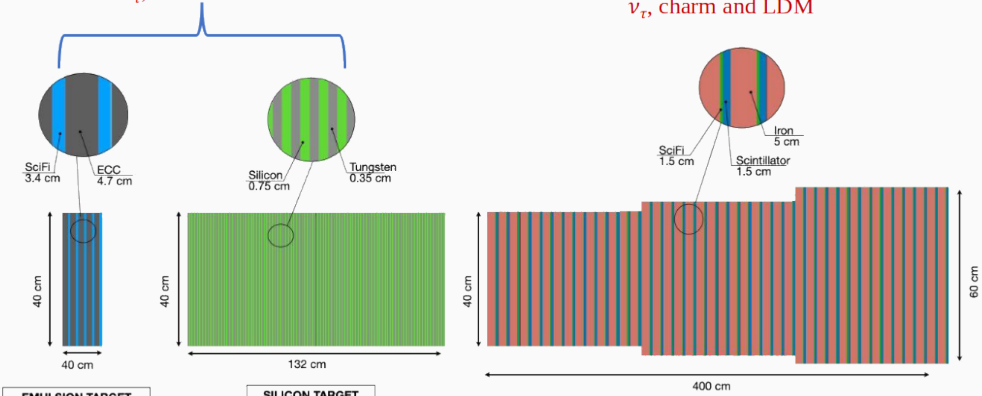


	<E> [GeV]	beam dump	<E> [GeV]	SND target acceptance	<E> [GeV]	CC DIS interactions
N_{ν_μ}	2.6	5.4×10^{18}	8.4	1.5×10^{17}	40	8.0×10^{6}
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	6.8	1.2×10^{17}	33	1.8×10^{6}
N_{ν_e}	6.3	4.1×10^{17}	30	1.3×10^{16}	63	2.8×10^{6}
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	22	9.3×10^{15}	49	5.9×10^{5}
N_{ν_τ}	9.0	2.6×10^{16}	22	1.0×10^{15}	54	8.8×10^{4}
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	32	1.0×10^{15}	74	6.1×10^{4}

Calorimetry at SND@SHiP

High-precision VTX detector
ν_τ, charm and LDM

Magnetised tracking calorimeter (MTC)
ν_τ, charm and LDM



EMULSION TARGET			
ECC	5	Tungsten	180
		Emulsion	180
SciFi	5		
Weight	0.5 ton		

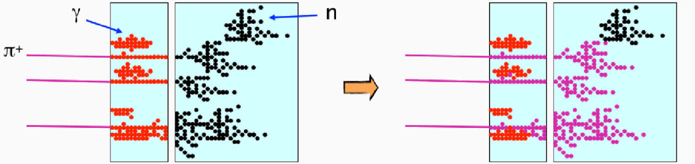
SILICON TARGET	
Tungsten	120
Silicon	120
Weight	1.2 ton

MAGNETIC HCAL	
Iron	42
Scintillator	42
SciFi	42
Weight	2.5 ton

10 λ → ~2m Fe
40 slabs, 5 cm each
Rounded to 42

Calorimetry at SND@SHiP

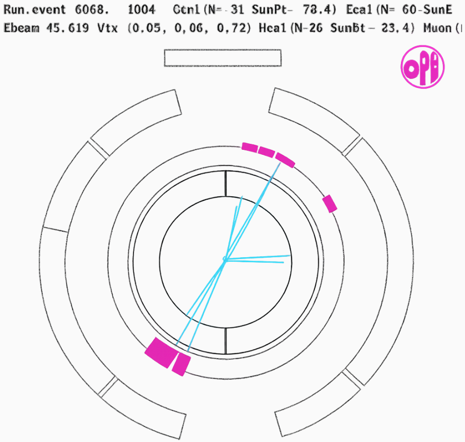
- Require a massive neutrino target to maximise neutrino interaction rates
- Reconstruction of neutrino interaction vertex
  - EM-showers (ν_e) to be reconstructed with modest energy resolution but good vertex/angular resolution
  - Muon identification and momentum measurement requires a magnetised absorber with tracking capabilities (ν_μ)
  - Hadronic energy measurement (ν_e, ν_μ, ν_τ)
  - τ decay vertex reconstruction → need a vertex detector (similar to SND@LHC)
- Particle flow capabilities



$E_{JET} = E_{ECAL} + E_{HCAL}$ $\quad$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

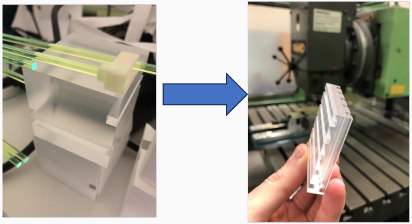
The power of particle flow (here in OPAL)

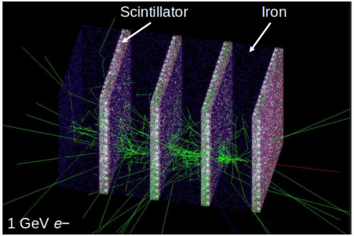
- $\mathrm{Z}^0 \rightarrow$ hadrons
    - $\sim$ 33 particles
    - $\sim$ 20 charged
    - $\sim$ 10 $X \rightarrow \gamma\gamma$
    - 3 $\mathrm{n}, \mathrm{K}^0_\mathrm{L}$
- Distributing the energy evenly in two jets
    - $E_\text{jet} = (60.6\%_\text{track} + (30.3\%_\text{em} + (9.1\%_\text{had})E_\text{jet}$
    - $E_\text{jet} = 10 \times 2.76\,\text{GeV}_\text{track} + 13.82\,\text{GeV}_\text{em} + 4.15\,\text{GeV}_\text{had}$
    - $\frac{\Delta E_\text{jet}}{E_\text{jet}} = 0.005\% \oplus 0.8\% \oplus 2.2\% = 2.4\%$ using particle flow
    - $\frac{\Delta E_\text{jet}}{E_\text{jet}} = 0.8\% \oplus 6.2\%$ without
    - 3.4% mass resolution with particle flow, 8.8% without



High Granularity layers at SND@SHiP

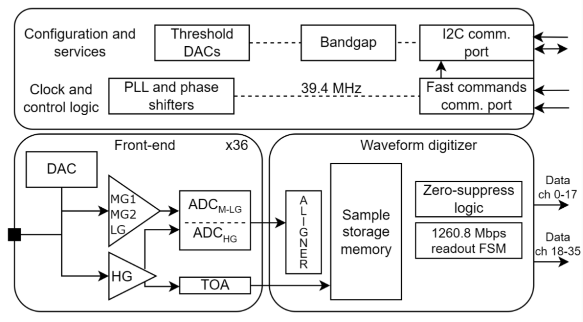
- Use the dismantled SoLiD experiment's scintillator cubes and convert them into tiles and integrate into the MTC as high granularity layers (HGLs)
    - Tiles are traversed by WLS fibres and readout by SiPMs
    - Allows the reconstruction of shower topology with good energy resolution
- Simulation and optimisation of the HGLs
    - Determine and optimise sensitivity of the proposed design
- Build of a scalable HGL prototype in 2026
    - Evaluate reconstruction and timing capabilities in test beams
    - Implementation of particle flow algorithms





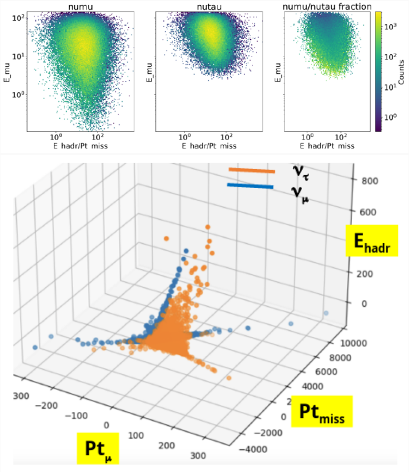
High Granularity layers at SND@SHiP: readout electronics

- Require large dynamic range, good timing resolution and operation in a triggerless environment
- Preferred option: CALOROC1b ASIC
  - CMS-HKROC-like backend
  - 36 channels
  - 10-bit 40 MHz ADC
  - 25 ps TDC
  - 4 gain levels
  - Parallel channel readout



ν_τ reconstruction using HGLs

- Main background to ν_τ reconstruction: ν_μ interactions (CC for τ leptonic decays and NC for hadronic decays)
- Current ML algorithms uses
  - Missing energy w.r.t. ν_τ direction of flight
  - Muon momentum → use HGLs to complement SciFi
  - Hadron energy → particle flow
- Require $\frac{\text{Signal}}{\text{Background}} \sim 10$ → optimisation → better use of HGLs on the model of CALICE AHCAL
- Enables LFU study in neutrino interactions $\sigma_{\text{stat}\oplus\text{syst}} \sim 3\%$ in $\frac{\nu_e}{\nu_\mu}$, $\frac{\nu_e}{\nu_\tau}$ and $\frac{\nu_\mu}{\nu_\tau}$
- Measurement of neutirno σ_{DIS} up to $100\,\text{GeV}$ → $E_\nu < 10\,\text{GeV}$ as an input to DUNE, higher energies to cosmic neutrinos, $\sigma_{\text{stat}\oplus\text{syst}} 5\,\%$

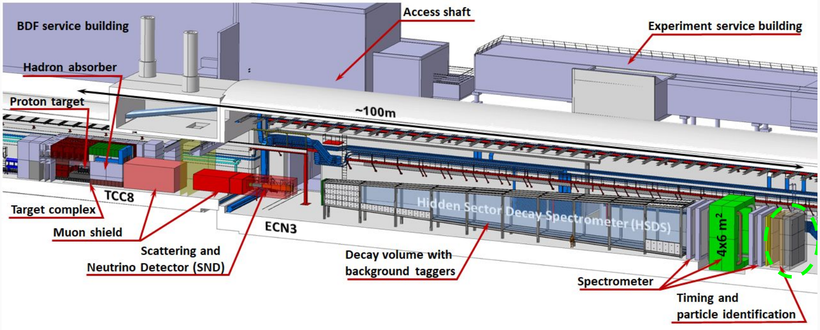


HGL summary

- HGLs are necessary to improve the (hadronic) energy resolution of the SND
- Based around existing materials and technologies
- To be studied
    - Particle identification capabilities in simulation
    - Energy resolution optimisation using particle flow algorithms
    - Prototype assembly using SoLiD cubes and WLS fibres
    - Readout electronics and integration into the wider detector

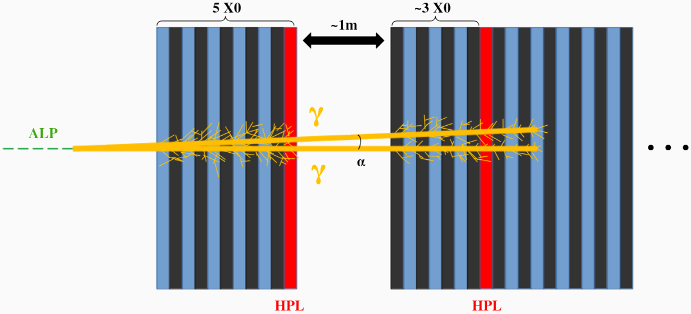
High precision calorimetry for FIP searches

- PID detector is composed of two calorimeter systems: ECAL (SplitCal) and HCAL
- Designed to discrminate $\mathrm{e}/\mu/\pi$ in particular
- Needs to enable reconstruction of neutral final states (ALP$\rightarrow \gamma\gamma$, heavy HNL decays, dark photon decays...)
- For this ECAL requires excellent angular resolution



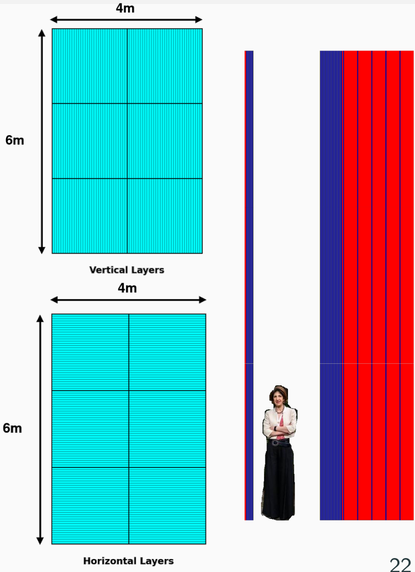
SplitCal base design

- Mixed technology sandwich sampling calorimeter
- Aims at shower and MIP reconstruction
- Plastic scintillator bars (EJ200) used for energy reconstructing layers
- Uses 2-3 High Precision Layers (HPLs) to reconstruct shower directionality
- 20 X_0 depth for shower containement
- Weighs ~ 30t



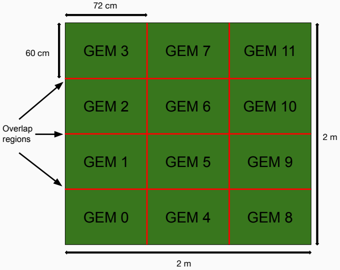
SplitCal base design

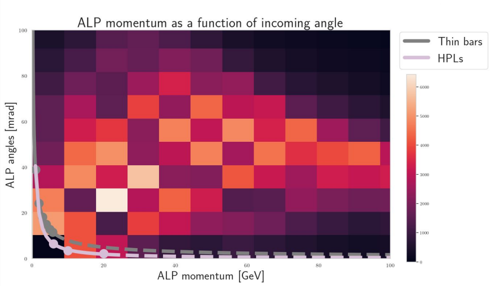
- Detector is built in 6 *hexants*
- Each hexant has three main components:
  - Absorber (Pb for ECAL, Fe for HCAL)
  - Scintillator bars (some mixture of $1 \times 200 \times 6\,\mathrm{cm}^3$ and $1 \times 200 \times 1\,\mathrm{cm}^3$) readout by SiPMs
  - High Precision Layers based on GEMs
- Segmentation → 18 modules in total
- Each module is built separately
- Readout philosophy: each module is readout independently



High-precision layers

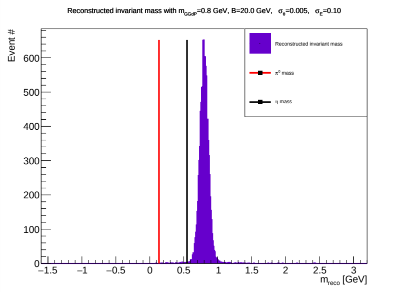
- Triple GEMs are ideal as HPLs
  - Good position resolution
  - Fairly cheap per unit area
  - Rather low rate: expected $\sim 50\,\text{kHz}$ detector-wide
- 70-30% Ar-CO_2
- Allows to reconstruct shower directionality
- Complementarity with the Spectrometer for hard muons
- Yields excellent invariant mass and vertex resolution



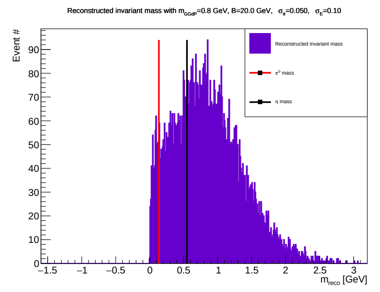


Detector characteristics in model independent $X \to \gamma\gamma$ decays

- Angular resolution is crucial in the reconstruction of neutral final states
- Essential to distinguish from π^0 and η backgrounds
- Necessary to filter out EM debris background



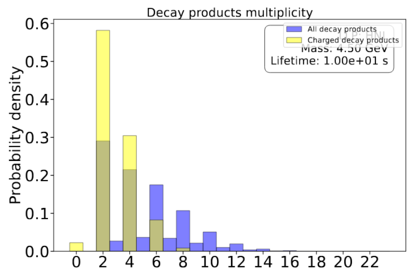
$$m_{X\gamma\gamma} = 800\,\text{MeV},\ p_z = 20\,\text{GeV},\ \sigma_\theta = 5\,\text{mrad},\ \sigma_E = \frac{10\%}{\sqrt{E}}.$$

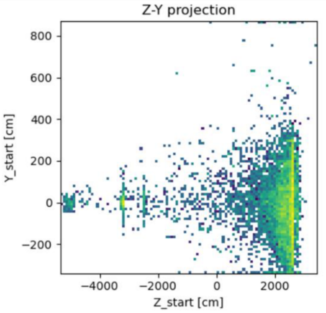


$$m_{X\gamma\gamma} = 800\,\text{MeV},\ p_z = 20\,\text{GeV},\ \sigma_\theta = 50\,\text{mrad},\ \sigma_E = \frac{10\%}{\sqrt{E}}.$$

HPL optimisation in simulation

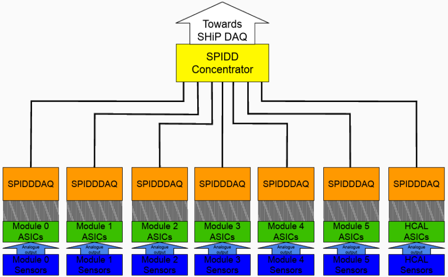
- Garfield evaluation of GEM performance for EM showers (estimated up to $\sim 28\,000$ primary electrons in a shower!)
- How many HPLs are needed?
- Optimal HPL positions within the detector
- Physics studies
  - HNL decays with neutrals in final state
  - Dark photon decays
  - Improved ALP decay analysis
  - Filtering of background
- Contribution to vertex resolution
  - Needed for signal and background





Calorimeter readout and electronics

- Readout is to be fully triggerless → requires little dead-time
- Try to digitise analogue signals as close as possible to the sensors
- Scintillator SiPMs readout by the CALOROC1b
- HPLs use SRS based on the 10bit VMM3a
  - Apparently some issues with first 3 bits
  - Do we need a large dynamic range?
- Rely on FPGA (Xilinx ZYNC or Versal) on SPIDDDAQ boards (to be designed) to assign timestamps
  - Convert bitstreams to ethernet
- Slow and fast control architecture to be designed



Towards SHiP DAQ

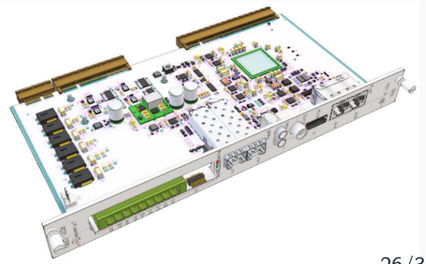
SPIDD Concentrator

SPIDDDAQ SPIDDDAQ SPIDDDAQ SPIDDDAQ SPIDDDAQ SPIDDDAQ SPIDDDAQ

Module 0 ASICs | Module 1 ASICs | Module 2 ASICs | Module 3 ASICs | Module 4 ASICs | Module 5 ASICs | HCAL ASICs

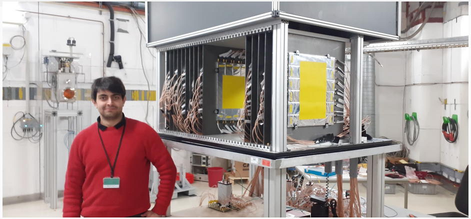
Analogue output

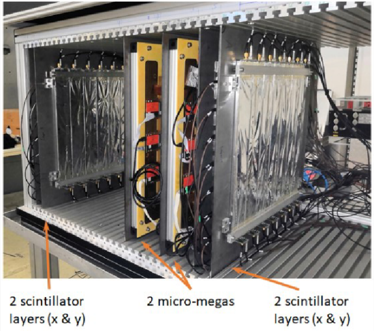
Module 0 Sensors | Module 1 Sensors | Module 2 Sensors | Module 3 Sensors | Module 4 Sensors | Module 5 Sensors | HCAL Sensors



Calorimeter prototyping

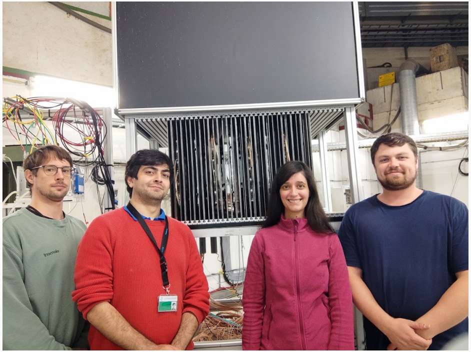
- On the scintillator side, significant prototyping has been done already
- A prototype of hybrid GEM-scintillator calorimeter should be devised and built in 2026
    - SRS system to be used and integrated with prototype scintillator redout electronics
- Test at SPS in 2026, at the same time as the HGL optimised prototype
- Compare performance to simulation
- A second prototype to be built and tested using optimised electronics and mechanical integration at DESY in 2027/28





SplitCal summary

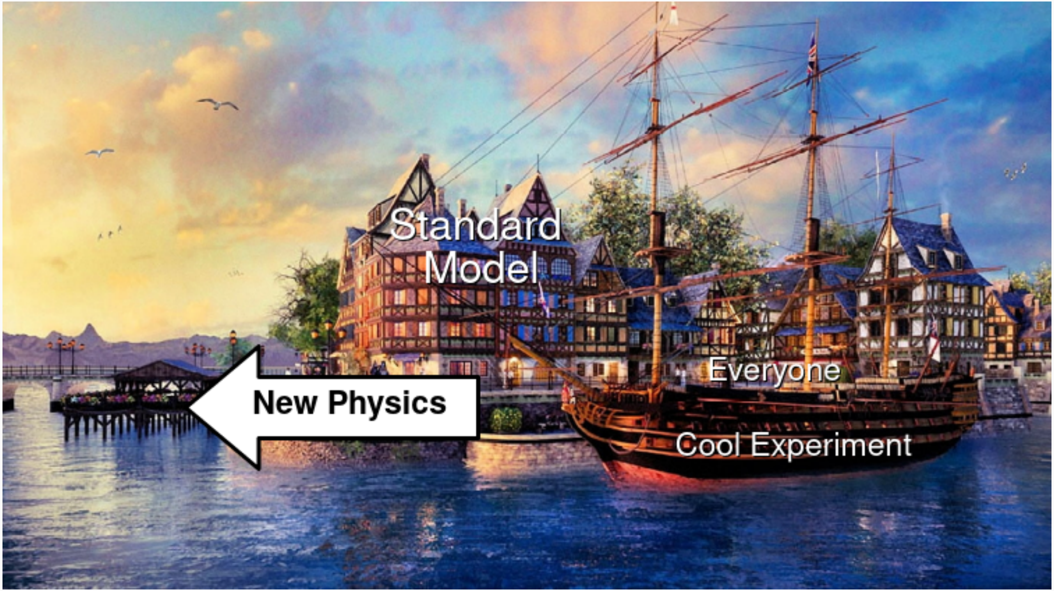
- Significant simulation studies need to be conducted to evaluate detector requirements and performance w.r.t. signal and background
- Integration of HPLs into the detector to be done
- Readout electronics and DAQ scheme to be designed
- Would lead to building 2-3 prototypes
- Evaluation of HPL performance to be done in test beams
- Work closely with the rest of the PID group on these items



Conclusion

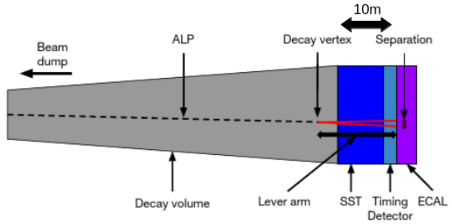
- BDF/SHiP has a wide and unique physics program as a beam dump experiment
- Calorimetry features prominantly in SHiP
    - Magnetised tracking calorimeter → High Granularity Layers
    - PID detector → High Precision Layers
- Opens the way for unprecedented sensitivity at the intensity frontier
- Wide simulation program on detector design and physics performance to be done
- Developments on detector build, integration and readout to be pursued
- 15 years of new physics searches!

All aboard!

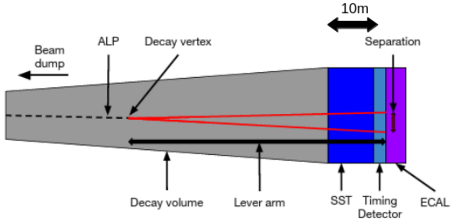


Backup: $\gamma\gamma$ separability

- Separation crucial for $\gamma\gamma$ → no separation, no signal!
  - Needs to be verified
- Separability generally favoured by lower boost, higher mass and shorter lifetimes
- In the following Separation assumed possible if both showers separated by at least $2R_\mathrm{M}$ ($3.2\,$cm in lead). The decay taken at end of the decay vessel, with the ECAL $10\,$m downstream. Consistent with NA62 separation selection.

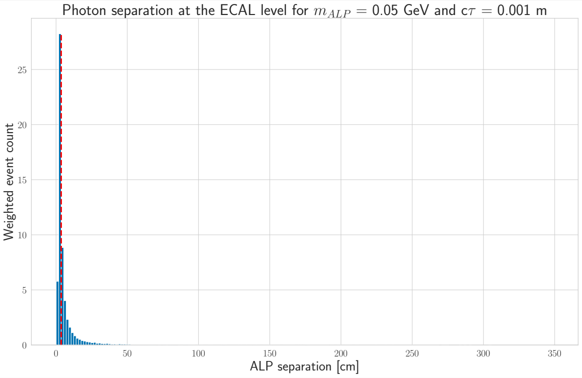


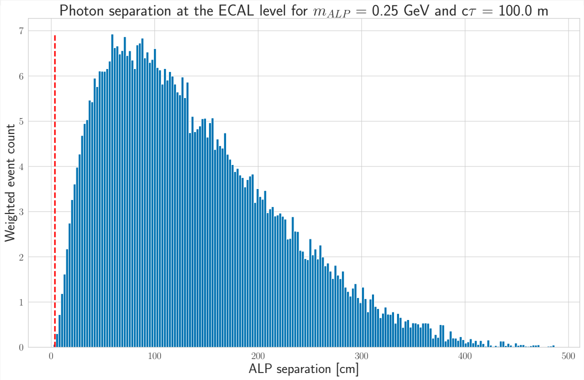
(a) Effect of a short lever arm for a late decaying ALP in particle separation: the separation is reduced.



(b) Effect of a long lever arm for an early decaying ALP in particle separation: the separation is increased.

Backup: $\gamma\gamma$ separability



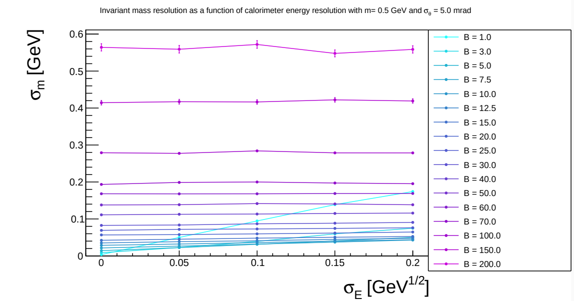


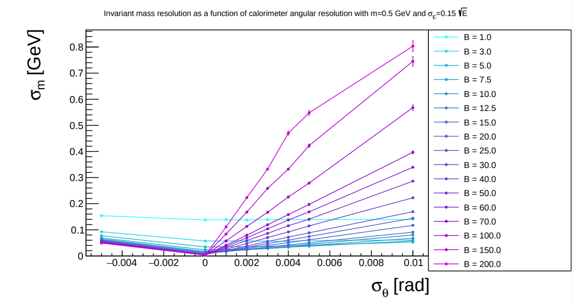
$m_{\text{ALP}} = 50\,\text{MeV}$ mass and $c\tau = 1\,\text{mm}$

$m_{\text{ALP}} = 250\,\text{MeV}$ mass and $c\tau = 100\,\text{m}$

ALP$\rightarrow\gamma\gamma$ separation ensured almost everywhere, only under tension in $m_{\text{ALP}} = 50\,\text{MeV}$ mass and $c\tau = 1\,\text{mm}$ (and the distance to the end of the DV will probably be longer + we can probably implement better separation techniques).

Backup: Detector characteristics in model independent $X \rightarrow \gamma\gamma$ decays

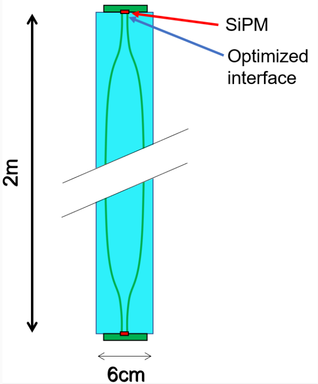

Invariant mass resolution as a function of calorimeter energy resolution with m= 0.5 GeV and σ_θ = 5.0 mrad

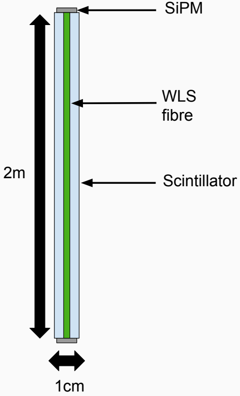

Invariant mass resolution as a function of calorimeter angular resolution with m=0.5 GeV and σ_E=0.15 $\sqrt{E}$

→ angular resolution valuable in all circumstances, value degrades at low boost, energy resolution becomes especially valuable for low B!

Backup: SHiP PID Detector: scintillators

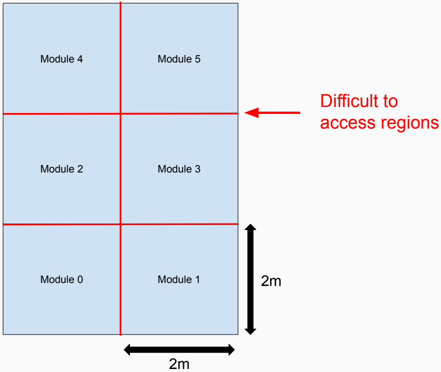
- Two scintillator bar types in proportions to be determined (between 15 360 and 96 000 channels)
  - Each bar type has a corresponding SiPM:
    - (ECAL+HCAL) Wide bars: large $6 \times 6\,\text{mm}^2 SiPMs$, many pixels, large signals (up to $\mathcal{O}(100s)$mV), large capacitance (up to $\mathcal{O}(2\,\text{nF})$). Baseline: S14160-6050HS SiPM, Broadcom/FBK SiPMs to be studied
    - (ECAL) Thin bars: smaller $\sim 1.3 \times 1.3\,\text{mm}^2$ SiPMs, fewer pixels, smaller signals (up to $\mathcal{O}(10s)$mV), smaller capacitance (up to $\mathcal{O}(10s)$pF). Baseline: S13360-1325PE SiPM.





Backup: the problem of dead space and ease of access

- (Known) concerns were pointed out in our mechanical design
  - One of the largest fixed target calorimeters ever conceived
- Experiment will run for ∼ 15 years, there will be problems
- In the current (basic) configuration, three main issues
  - Difficulty to cool (cooling needs are being reassessed, still probably needed)
  - Difficult channel access → cassette scheme? Layer-wide of module wise?
  - Dead regions → Need to be minimised absolutely
- All three points are related
- Thought of a few alleyways to try to resolve these issues



Backup: people at the moment

Role	**Person**	**Comments**
Project leader	Walter Bonivento	_
Integration/Installation	Matei Climescu/Rainer Wanke	Soon hopefully also Frank Steeg
Power/Control/Readout/Monitoring	Matei Climescu	_
Software	Matei Climescu/Walter Bonivento	_
Safety	Matei Climescu	_
CAD	Matei Climescu	Hopefully someone else soon (Fabian, Frank?)
GEMs/HPLs	Matei Climescu/Kirill Skovpen	Treated separately for now, will integrate
Test Beam	Sebastian Ritter/Claudia Delogu/Matei Climescu	_