New physics search with SHiP at CERN

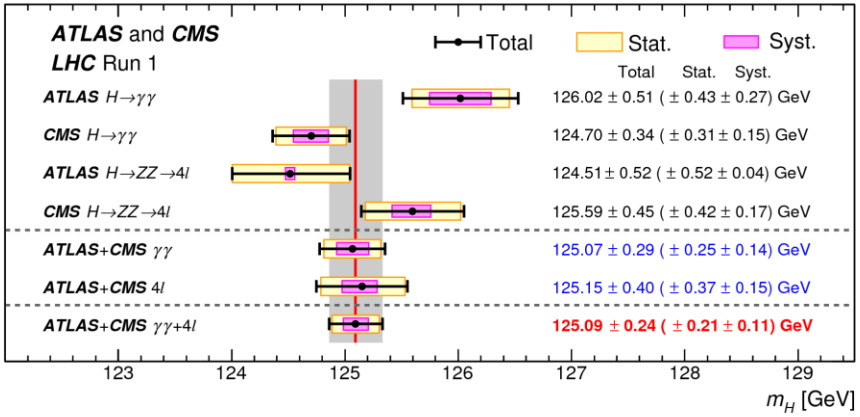
Vladimir Shevchenko

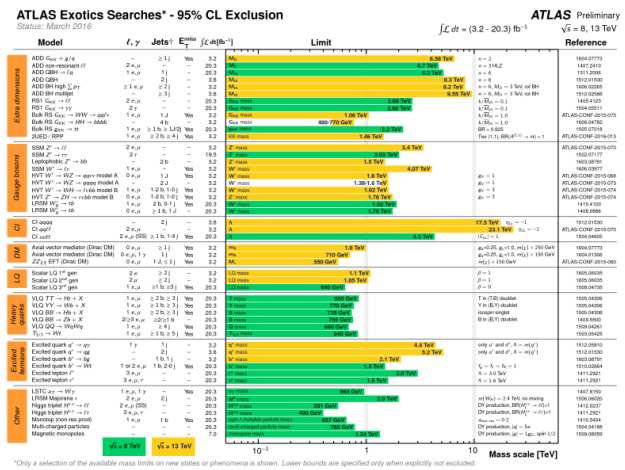
NRC «Kurchatov Institute»
NUST «MISiS»
on behalf of the SHiP collaboration

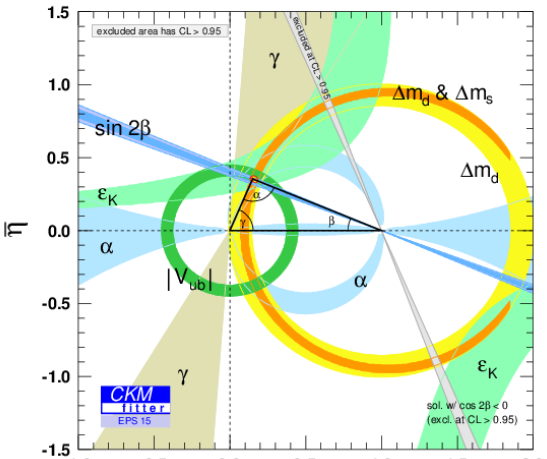
ICNFP 2019

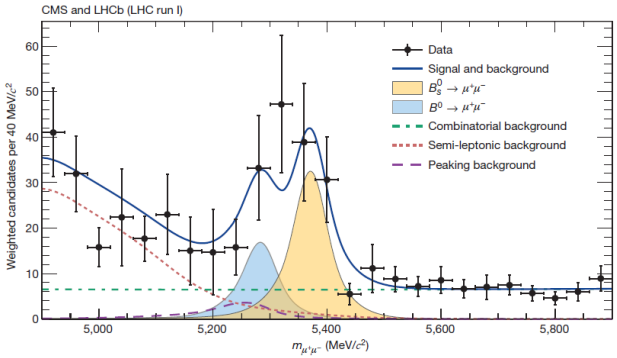
Present status of HEP

Triumph of the Standard Model: Higgs boson, flavour physics, rare decays and **nothing beyond..**









At the same time we are sure (not from LHC) that ***there is physics*** beyond the **SM**:

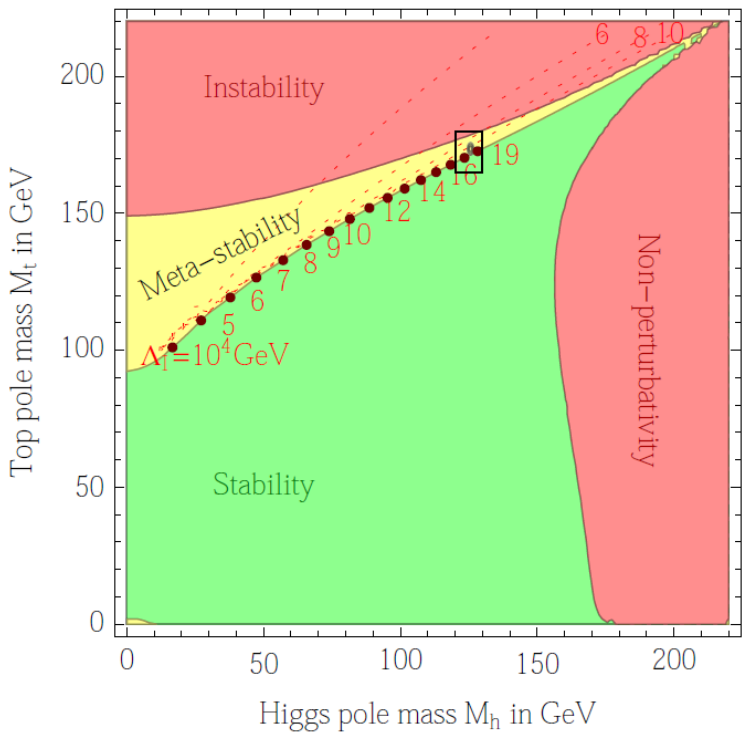
- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- ...

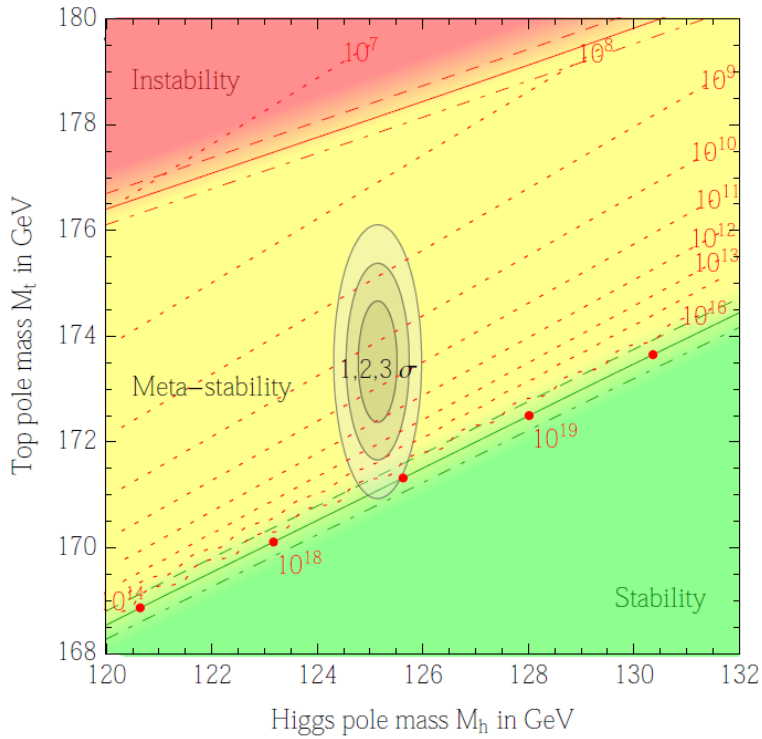
Besides that, there are many «why» and «how» in the **SM**:

- How is EW scale so smaller than UV scale?
- Why hierarchy between **SM** scales?
- Why are lefts doublets and rights singlets?
- Why 3 generations? Why CKM hierarchy & CP?
- ...

Observable Higgs mass corresponds to metastability of the SM vacuum

(from arXiv:1307.3536)





(I. V. Krive, A. D. Linde, N. Cabibbo, L. Maiani, G. Parisi, R. Petronzio, M.Lindner, H.B.Nielsen, C.Froggatt, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, A. Strumia, J. R. Espinosa, M. Quiros, G.Altarelli and many others)

Strong hint to **NO** New Physics up to the Planck scale.

Standard Model Criticality Prediction: Top mass 173 ± 5 GeV and Higgs mass 135 ± 9 GeV.

C.D. Froggatt

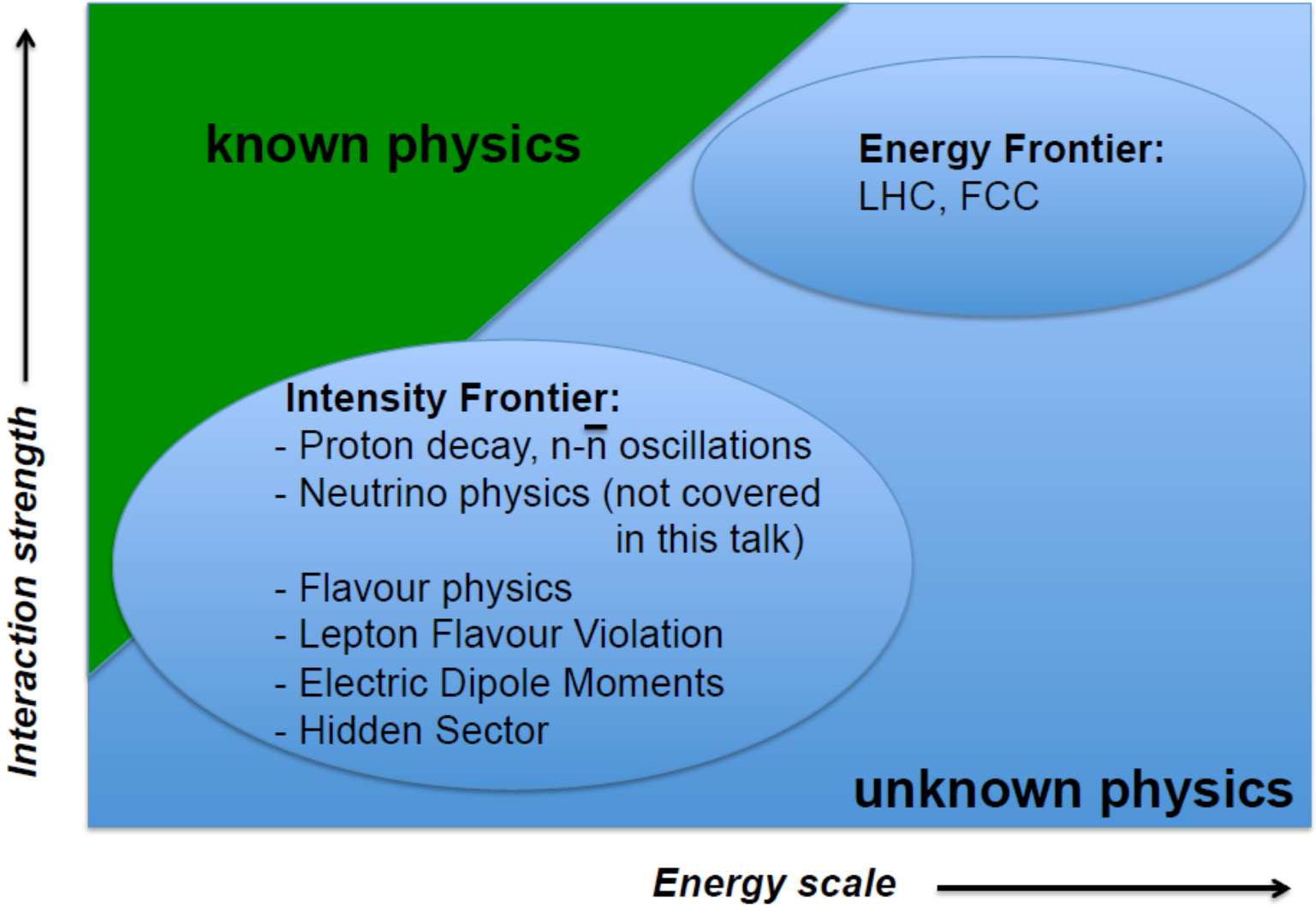
Department of Physics and Astronomy
Glasgow University, Glasgow G12 8QQ, Scotland

H.B. Nielsen

The Niels Bohr Institute
Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

Abstract

Imposing the constraint that the Standard Model effective Higgs potential should have two degenerate minima (vacua), one of which should be - order of magnitudewise - at the Planck scale, leads to the top mass being 173 ± 5 GeV and the Higgs mass 135 ± 9 GeV. This requirement of the degeneracy of different phases is a special case of what we call the multiple point criticality principle. In the present work we use the Standard Model all the way to the Planck scale, and do not introduce supersymmetry or any extension of the Standard Model gauge group. A possible model to explain the multiple point criticality principle is lack of locality fundamentally.



Revival of interest to NP searches on Intensity Frontier

Search for Hidden Particles (SHiP) experiment

Fixed target beam dump type experiment @SPS CERN

- **4×10^{13}** protons @ **400** GeV, **2×10^{20}** pot in **5** years
  - ✓ **10^{18} charm mesons**
  - ✓ **10^{14} beauty mesons**
  - ✓ **10^{16} tau leptons**

- Large vacuum detector volume

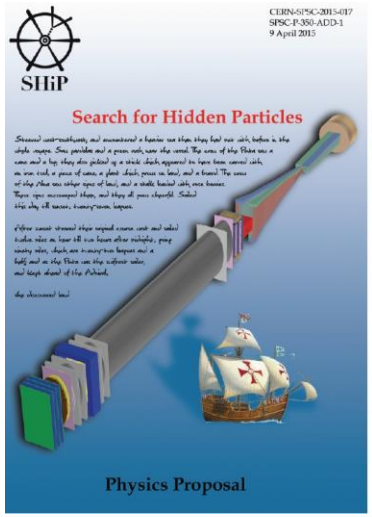
To reduce neutrino interactions and to give hidden particles space to fly

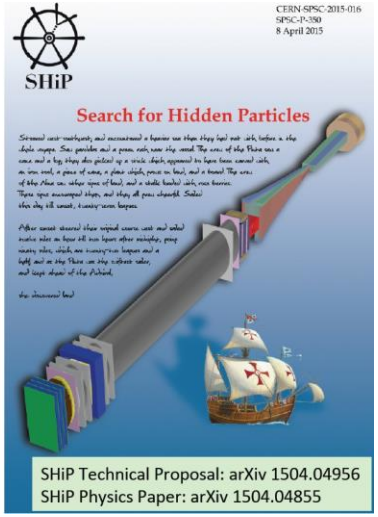
- Active muon shield

To deflect muons at short distances in order to put detector close to the target (HS particles may have large $\mathbf{p_T}$)

2013: Expression of Interest submitted
2015: Technical and Physics proposals
2016: Recommendation by CERN SPSC to proceed to CDR
2018: CDR by the Beam Dump Facility group published
2019: CDR to be submitted

~290 authors, 54 institutes, 18 countries





Portal framework for BSM physics

$$L = L_{SM} + L_{HS} + L_{portal}$$

Visible (SM) matter ⟷ Hidden Sector (HS)

contains Dark Matter and can have very complicated structure

The lowest dimensional renormalizable portals in the SM are:

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

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What HS particle is SHiP looking for?

- Heavy neutral leptons

Could explain SM neutrino masses (via seesaw), Dark Matter, Baryon Asymmetry.
Seen in weak semi-leptonic decays of hadrons, W, Z.

- «Dark Photons»

Addition of **U(1)** gauge group to SM, kinetic mixing with **γ** and Z
Seen in bremsstrahlung, light neutral meson decays, quark annihilation

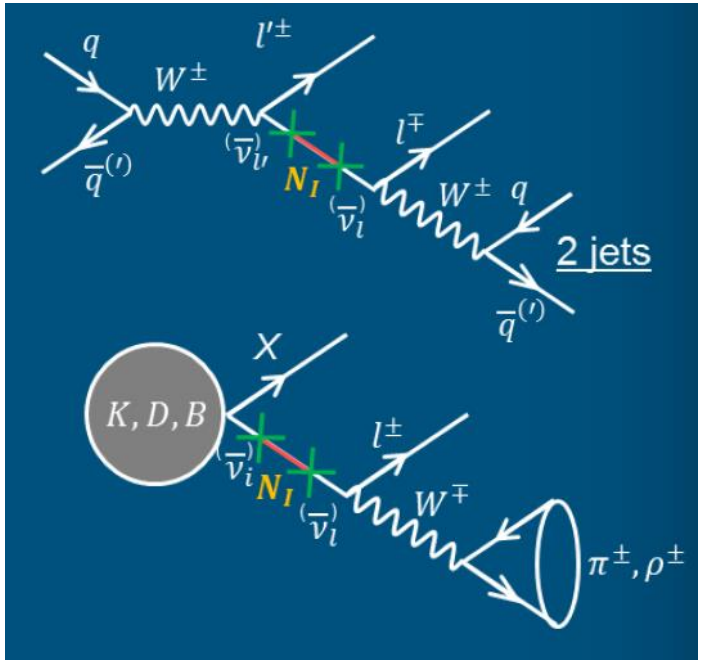
- (Light) Dark Matter

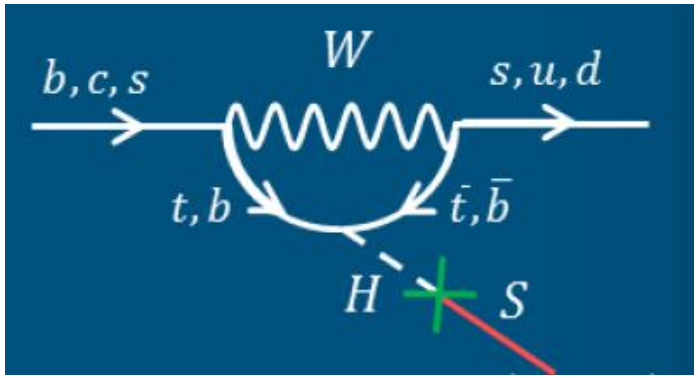
Stable or very long-lived particles

- «Dark Higgses»

Neutral singlet scalars that couple to the SM Higgs field

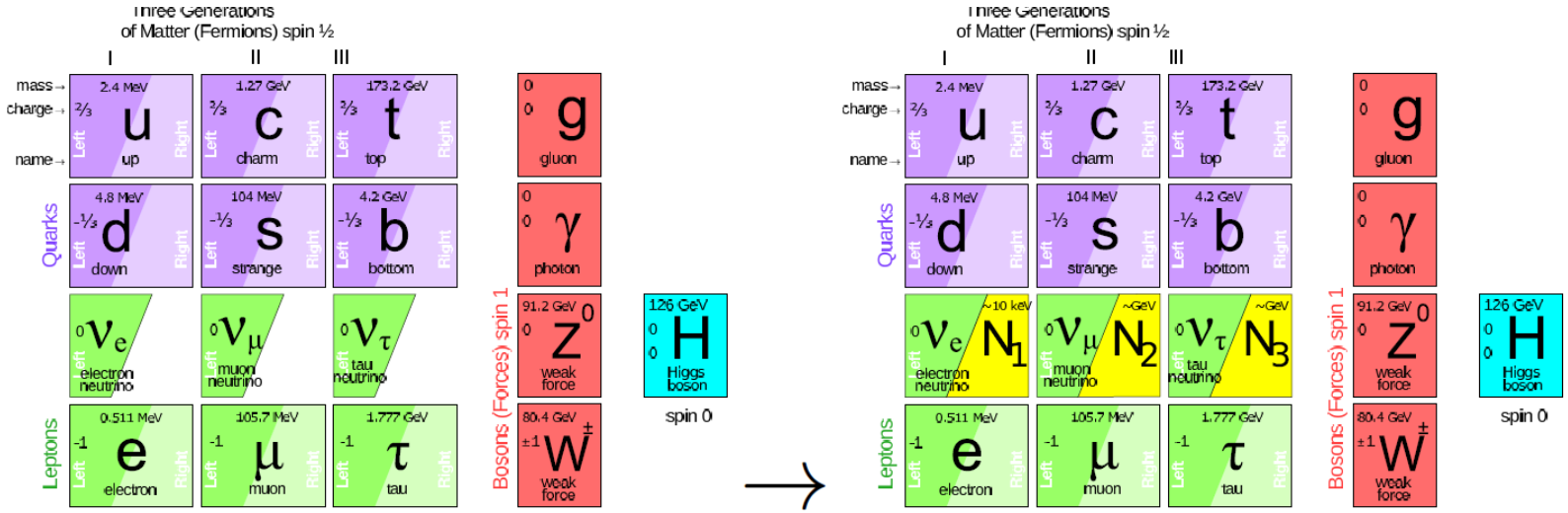
- Axion-like particles





Most interest has been attracted so far to the neutrino portal (heavy neutral leptons). General renormalizable type I see-saw Lagrangian with 3 HNLs:

$$L = L_{SM} + \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\Phi\bar{N}_I L_\alpha - \frac{M_I}{2}\bar{N}_I^c N_I + \text{h.c.}$$



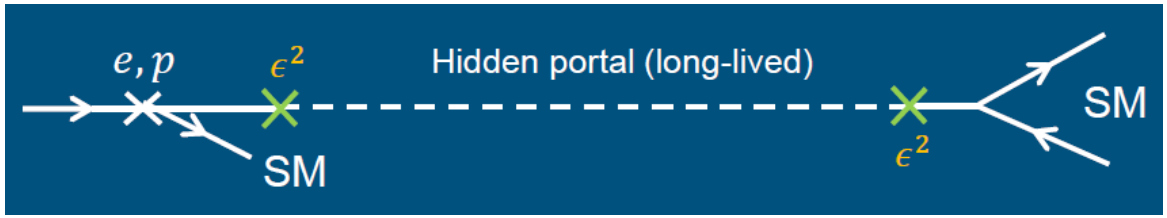
N_1 with mass $\mathcal{O}$(keV) – dark matter

N_2 , N_3 with mass $\mathcal{O}$(GeV) – neutrino masses via see-saw and baryon asymmetry

(T.Asaka, M.Shaposhnikov, '05; D.Gorbunov, M.Shaposhnikov, '07; etc)

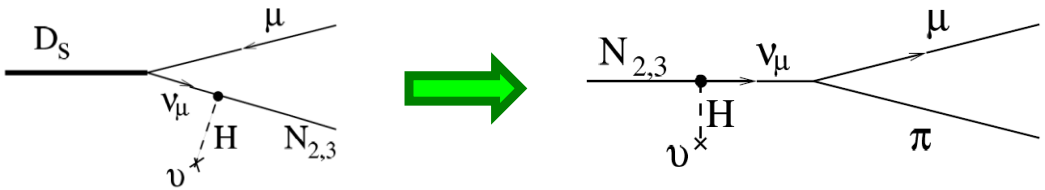
Difference (and complementarity) between direct and indirect searches

Direct:

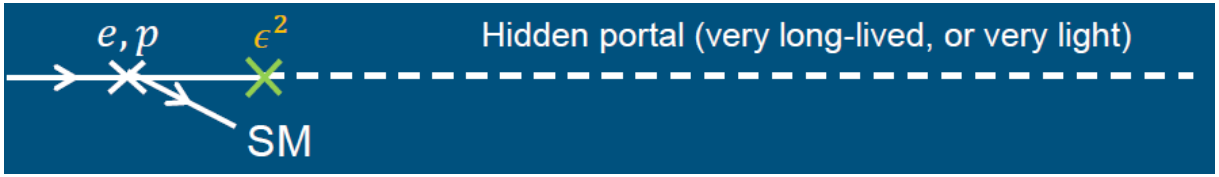


Clean decay signature ("displaced vertex)
Allow identification of the model (portal type)
But: probability $\propto \epsilon^4$

Case of SHiP



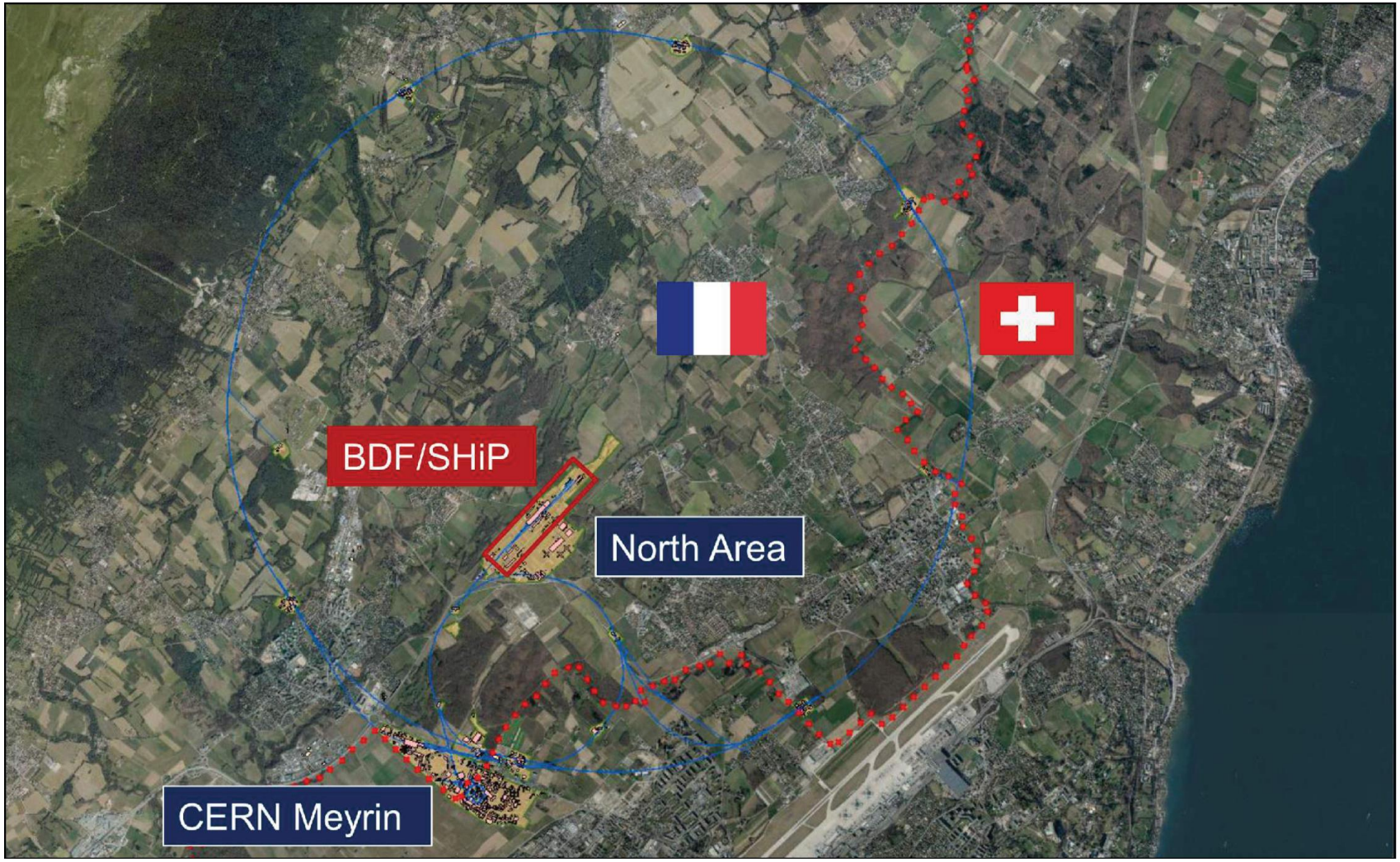
Indirect:



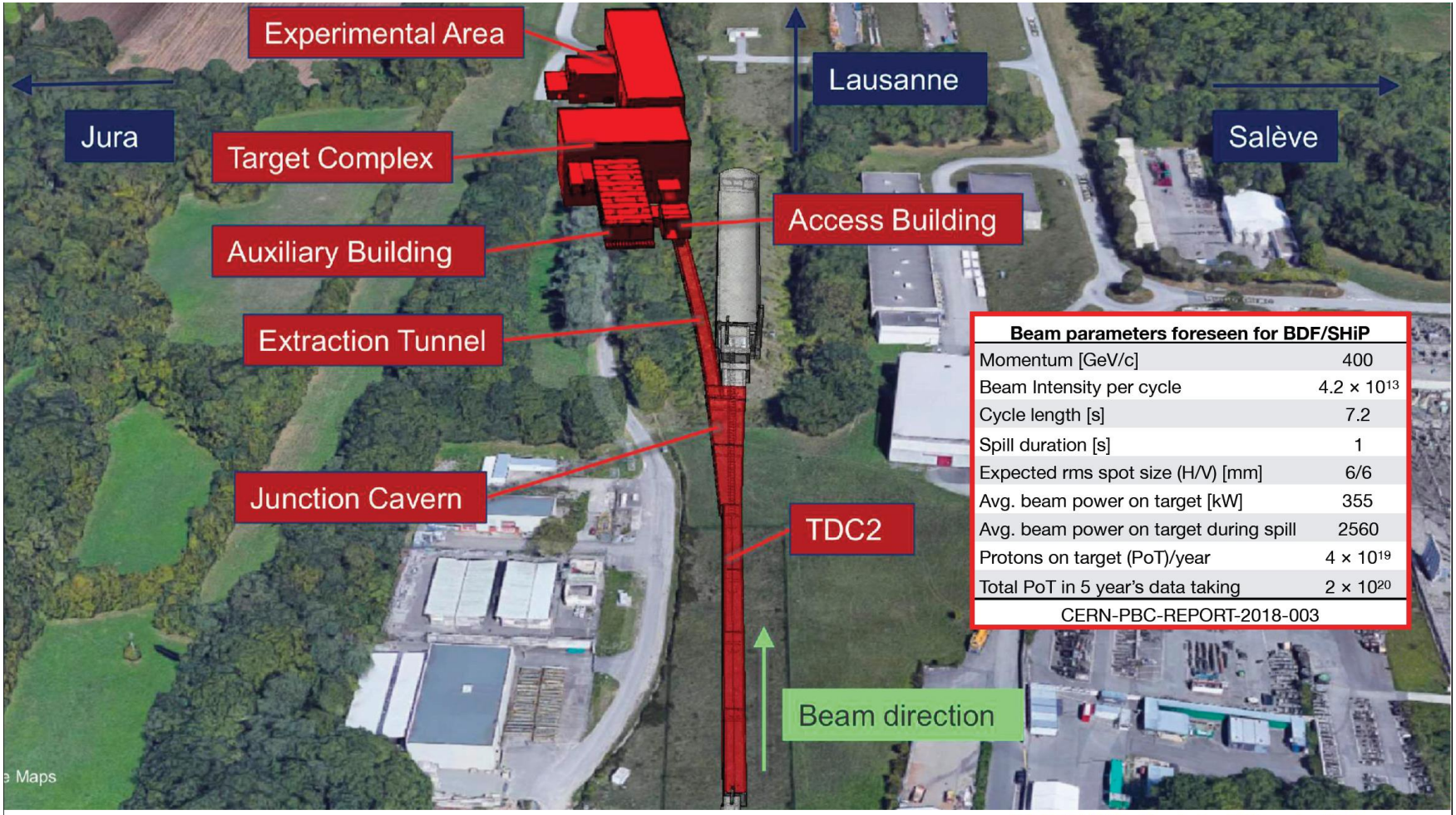
Hidden particles escape detector
Missing energy/momentum/mass
Probability $\propto \epsilon^2$

Highest possible intensity on target vs zero background in the detector

SHiP setup: Beam Dump Facility @ CERN



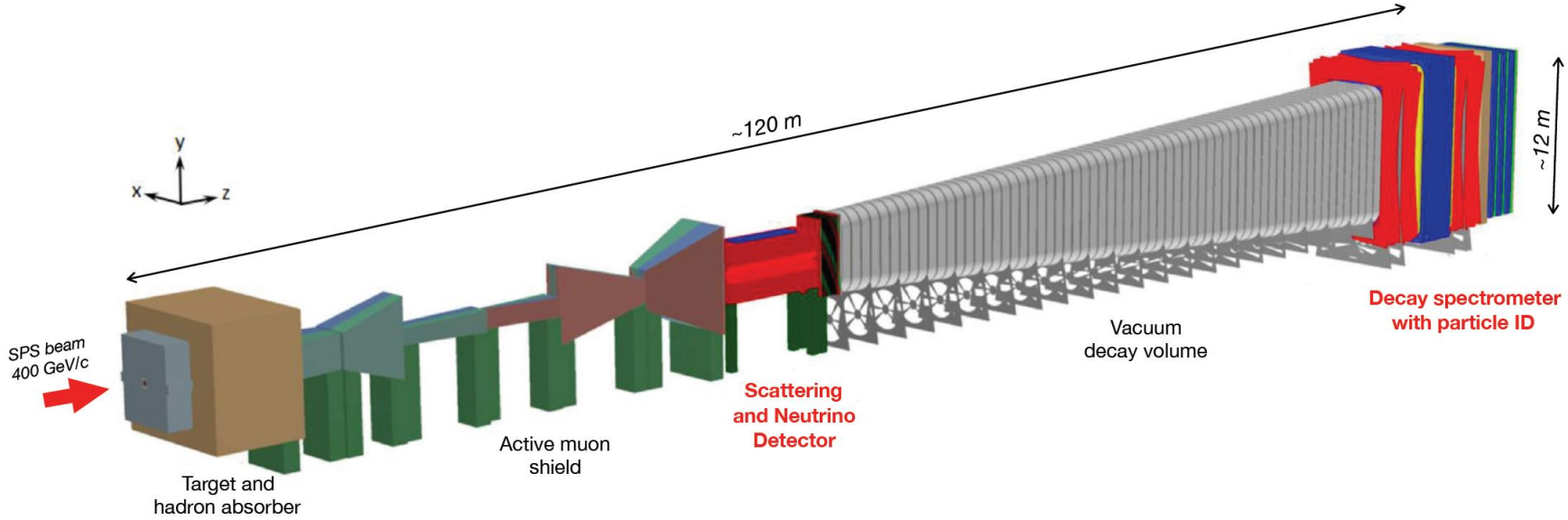
Beam Dump Facility @ North Area

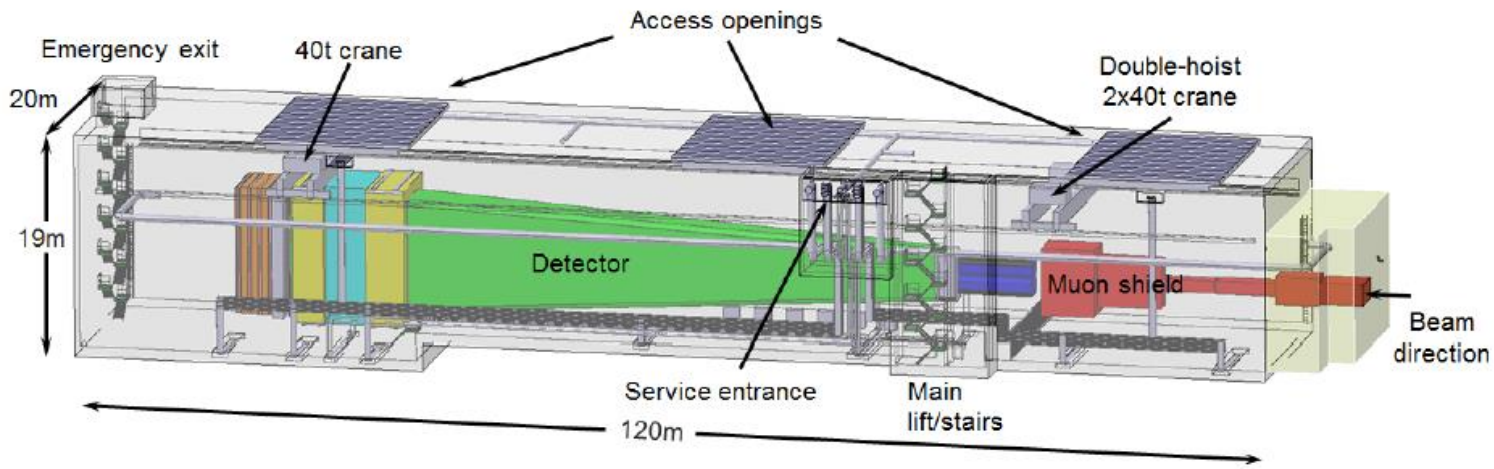


Beam parameters foreseen for BDF/SHiP	
Momentum [GeV/c]	400
Beam Intensity per cycle	4.2×10^{13}
Cycle length [s]	7.2
Spill duration [s]	1
Expected rms spot size (H/V) [mm]	6/6
Avg. beam power on target [kW]	355
Avg. beam power on target during spill	2560
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}
CERN-PBC-REPORT-2018-003	

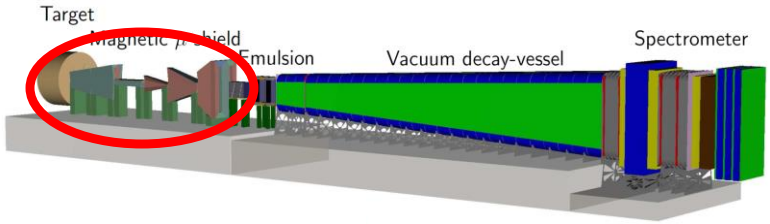
EDMS 2044415 L. Dougherty - 07 November 2018

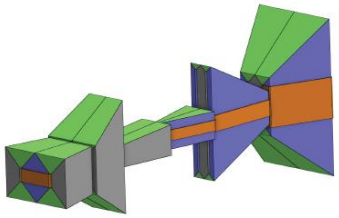
SHiP general layout



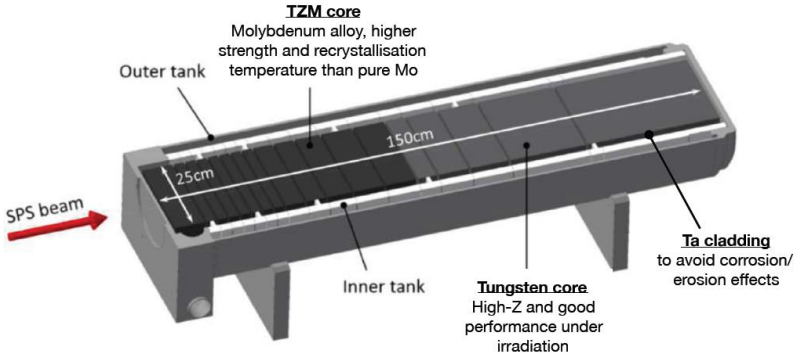


Target and active muon shield

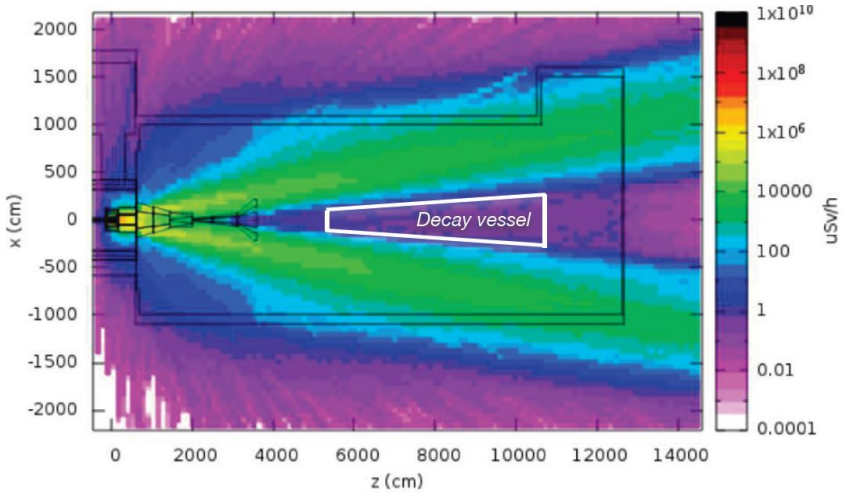




- **4x10^{13}** p / 7sec → **355** kW average, **2.6** MW during **1** sec spill – water cooled to dissipate
- **Target** – to maximize production of charm**. ~12λ_{int}** -long segmented; high-**Z** hybrid solution composed of **Mo** alloy (TZM) & pure **W**
- **Shield** – designed to reduce muon flux as **10^{11}** → **2.5× 10^{4}** ; assembled of **0.3 mm** grain-oriented (GO) steel sheets; magnetic field **1.7 T**

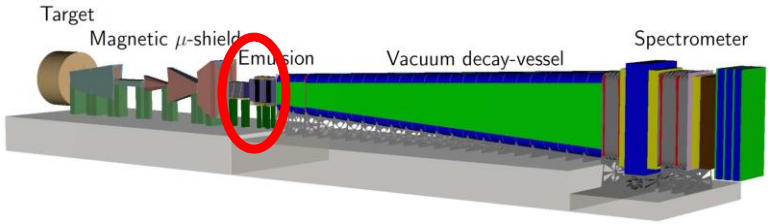


JINST 13 (2018) no.10, P10011

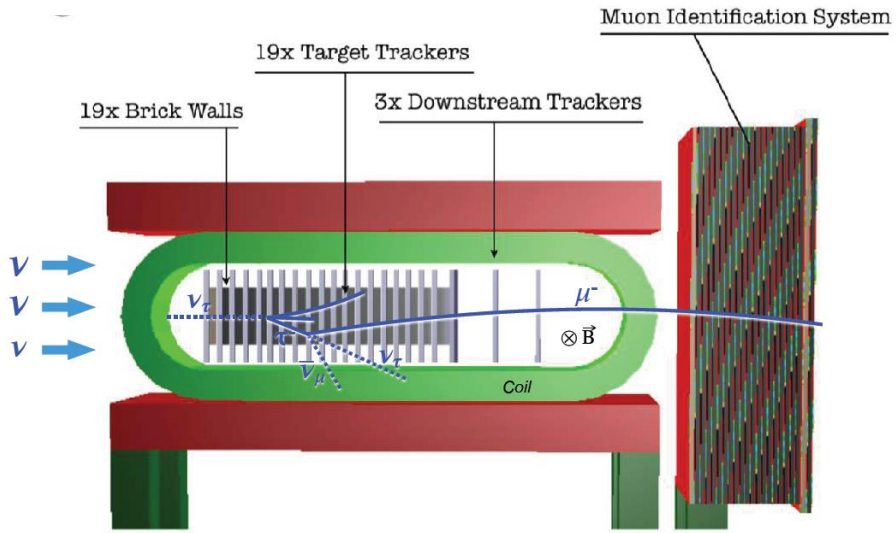


JINST 12 (2017) no.5, P05011

Scattering and neutrino detector



OPERA – like design



- emulsion detector with 12 SciFi tracker planes for time stamp
- muon identification
- magnetic field **1.25 T** – info on particles' electric charge

SM Physics

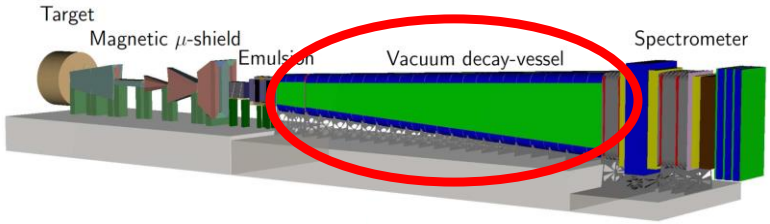
- physics of τ-(anti)neutrino physics, **N~10^4**
- first observation of τ-antineutrino
- structure functions $F_4(x,Q^2)$ and $F_5(x,Q^2)$
- ν-N DIS physics
- ν_τ magnetic moment

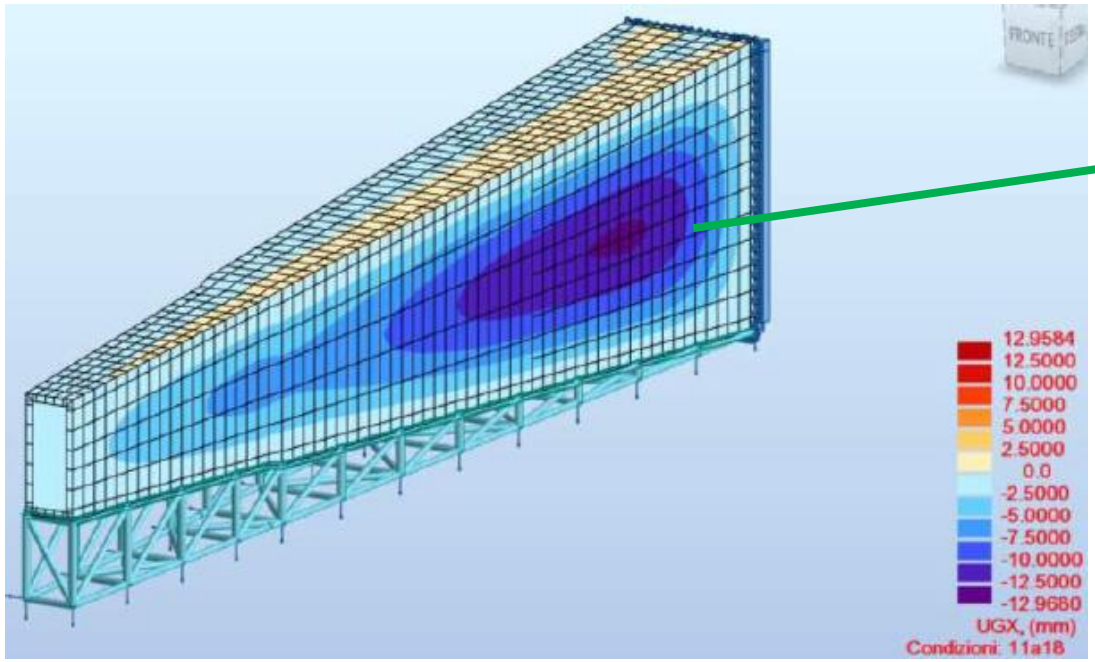
Hidden sector physics

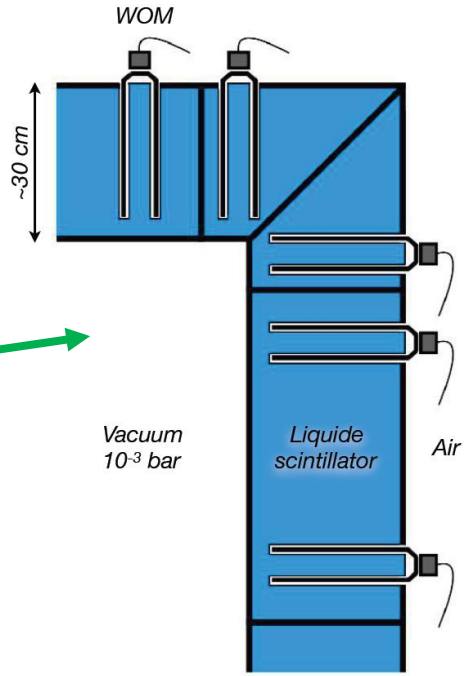
- Light dark matter search via electron scattering

(see Antonia Di Crescenzo's talk on ICNFP 2019)

Vacuum decay vessel



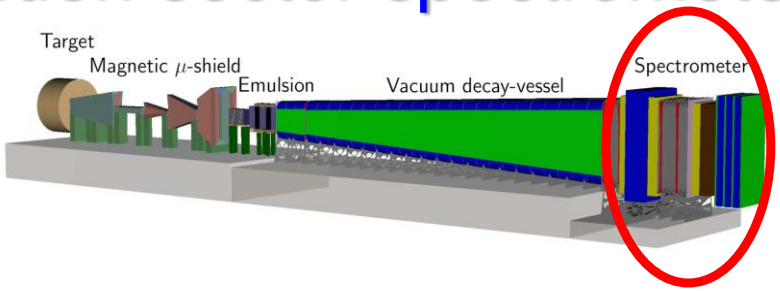


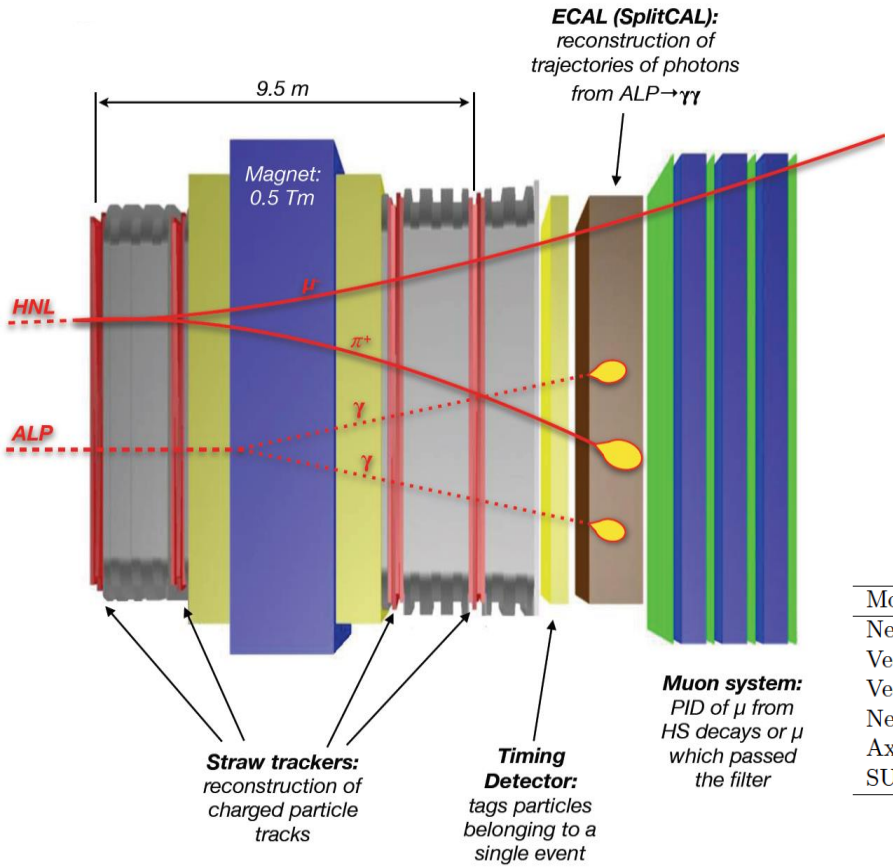


Length: **50 m**
Downstream size: **6×11 m**

Liquid scintillator based surrounding background tagger, tagging charged particles entering decay volume and tagging **ν** and **μ** interactions in the vacuum chamber walls

Hidden sector spectrometer





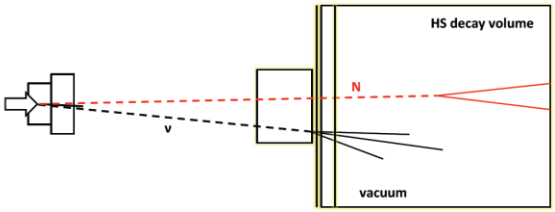
- precise reconstruction of decay vertices produced by charged particles
- precise timing **(< 0.1 ns)** to reject background
- magnetic field **0.5-1.0 Tm**
- particle identification

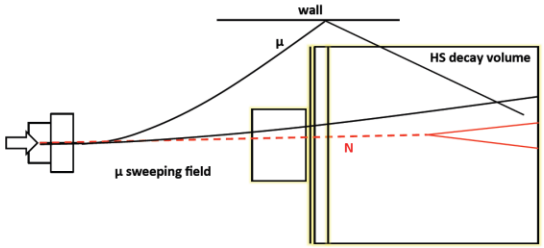
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino,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

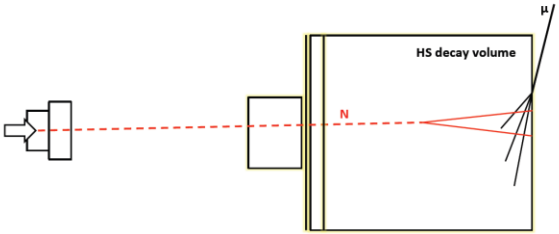
Simulation status and background studies

Mature software framework using **Pythia6, Pythia8, Genie, Geant4**

- Cascade production of heavy flavours
- Validation on data from **NA62** and Hyperon
- Validation using two dedicated experiments in summer 2018 at SPS:
  - muon flux measurement with target replica accumulated **10^{11}** pot;
  - charm cross-section measurement with a target prototype





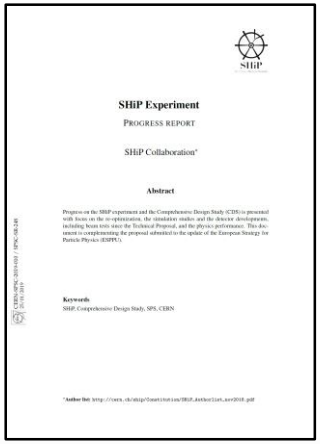


Background summary:

Background source	Expected events
Neutrino background	< 1
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon Combinatorial	4.2×10^{-2}

Backgrounds redundantly shown to be < 1, even for partially reconstructed signal

Prototyping



SHiP Experiment

PROGRESS REPORT

SHiP Collaboration*

Abstract

Progress on the SHiP experiment and the Comprehensive Design Study (CDS) is presented with focus on the re-optimization, the simulation studies and the detector developments, including beam tests since the Technical Proposal, and the physics performance. This document is complementing the proposal submitted to the update of the European Strategy for Particle Physics (ESPPU).

Keywords

SHiP, Comprehensive Design Study, SPS, CERN

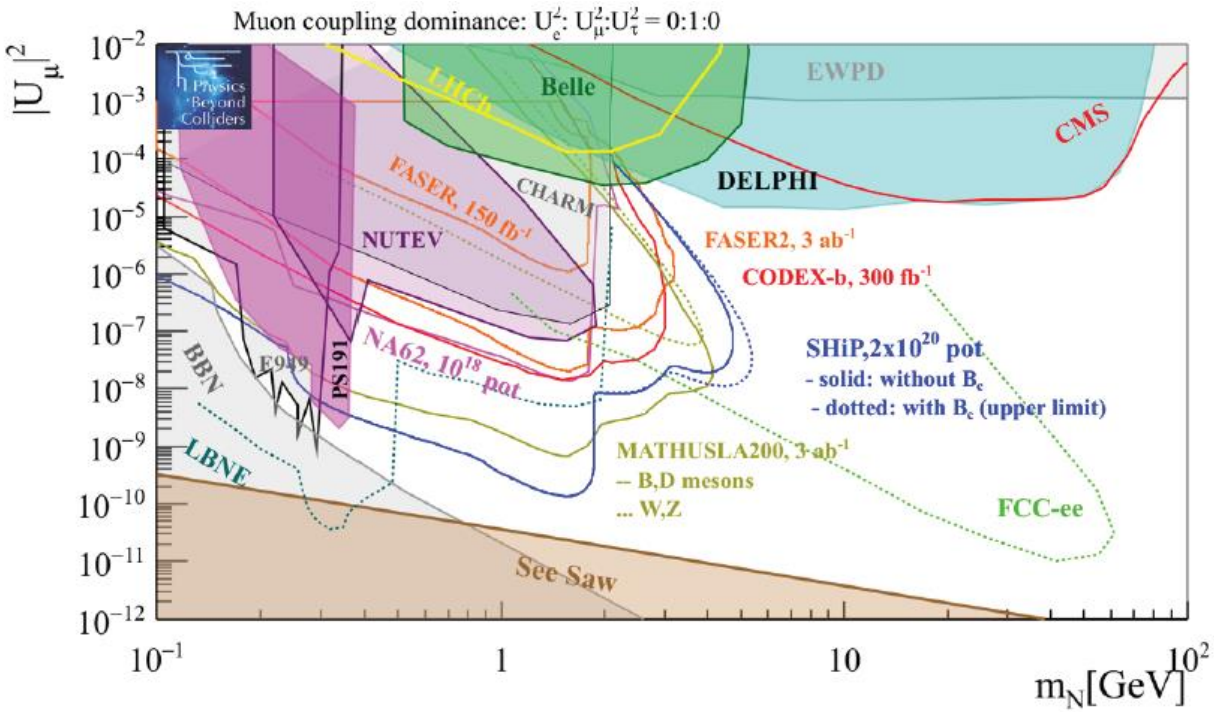
*Author list: http://cern.ch/ship/Constitution/SHiP_Authorlist_nov2018.pdf

Various prototypes have been produced and tested (and more are in progress) in order to check and prove experiment's sub-detectors concept.

(see SHiP Experiment progress report, CERN-SPSC-2019-010 / SPSC-SR-248; 25/01/2019)

SHiP sensitivity – HNL

(sensitivity plots from CERN-PBC-REPORT-2018-007)



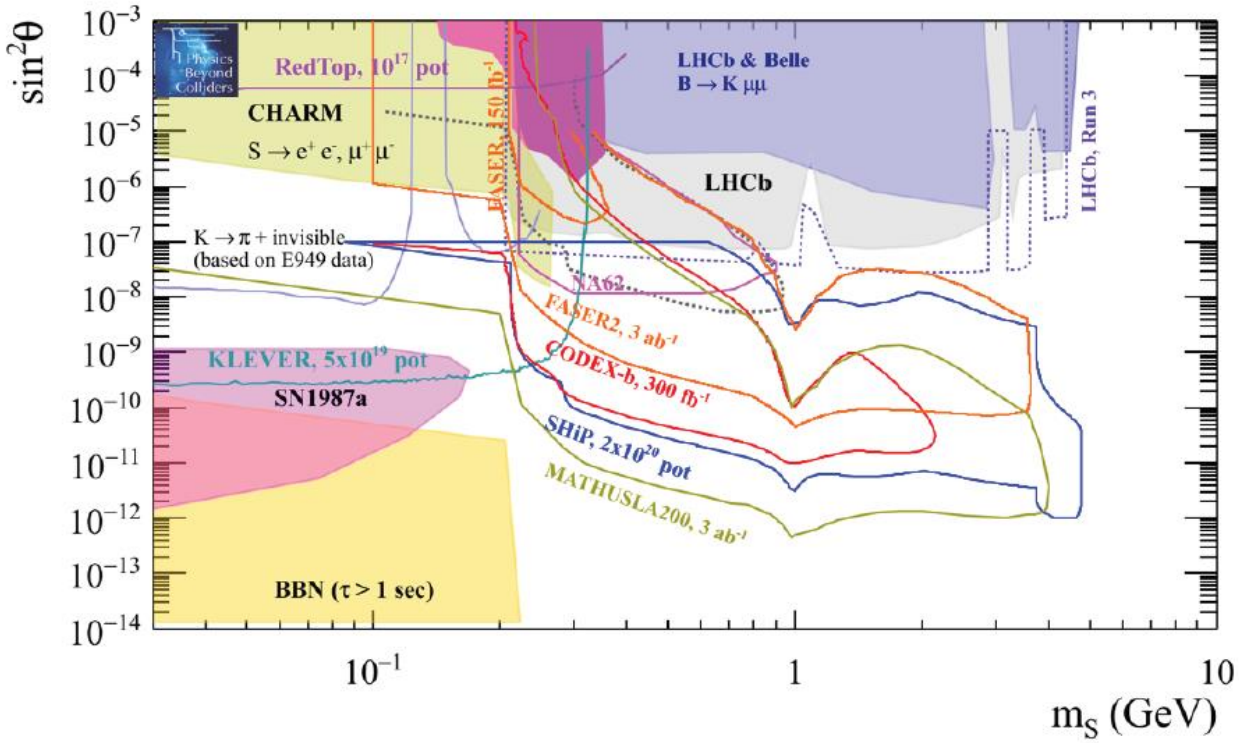
$M_{HNL} < M_B$:
SHiP will have much better sensitivity than LHCb & Belle-II

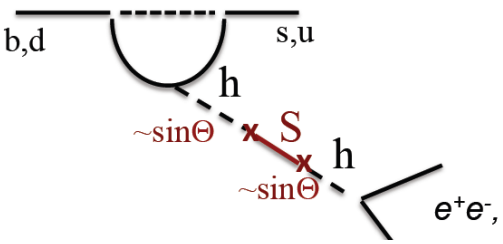
$M_B < M_{HNL} < M_Z$:
FCC in ee-mode

$M_{HNL} < M_Z$:
HL-HE LHC

SHiP covers most of parameter space below B-mass.
Moving down towards the ultimate see-saw limit.

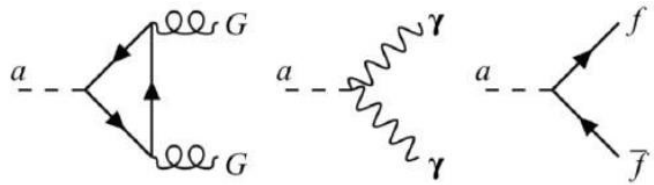
SHiP sensitivity – scalars

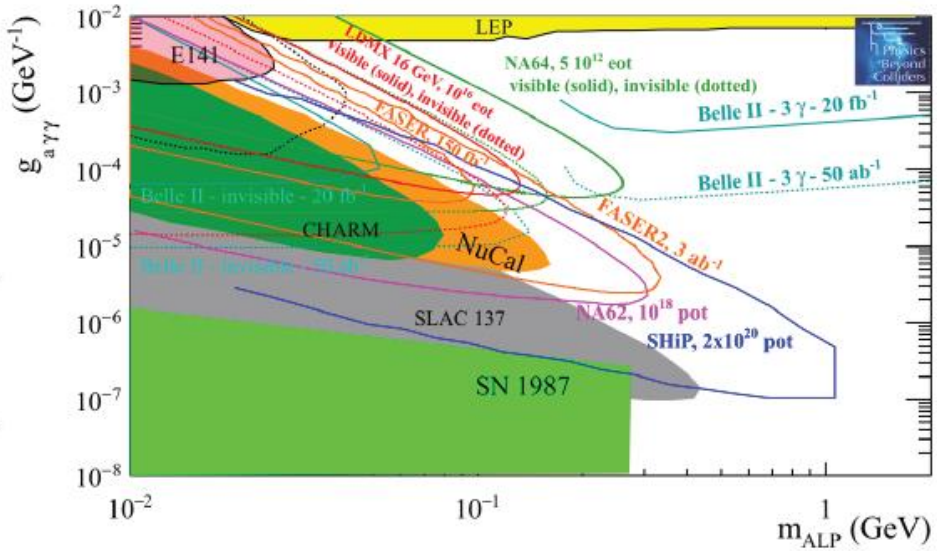




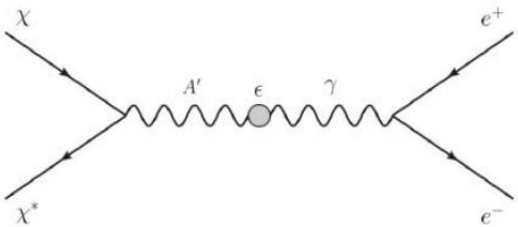
SHiP sensitivity – vectors and axions

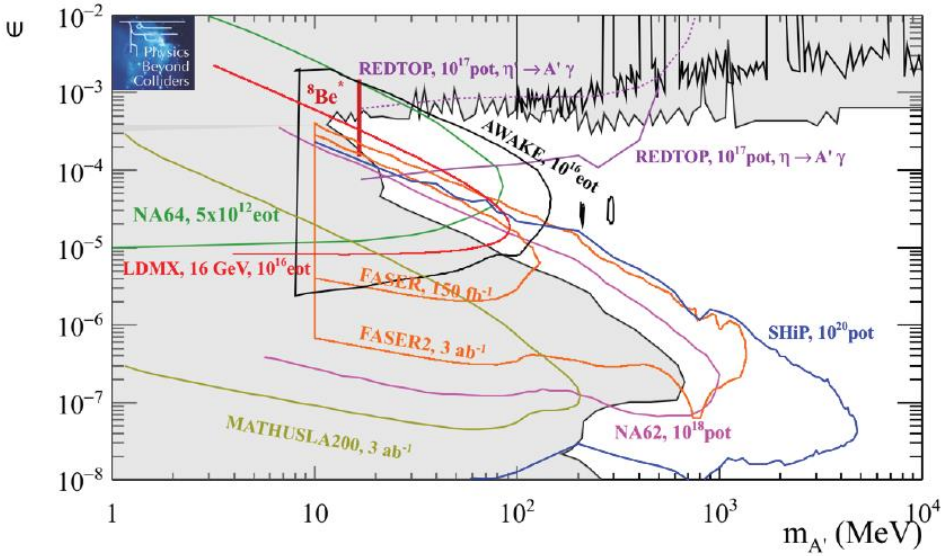
Axion portal:





Vector portal:

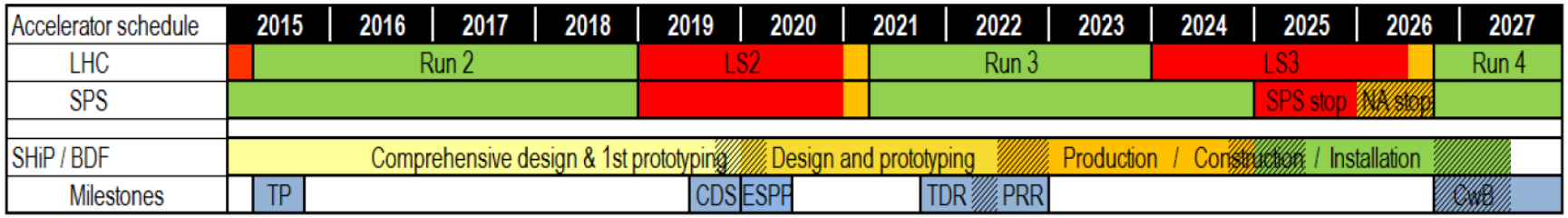




Conclusion

- Search for Hidden Particles (**SHiP**) experiment – exploration of the Intensity Frontier
- Beam Dump Facility (BDF) – new infrastructure in the North Area of CERN SPS: extraction tunnel, target complex, experimental area
- Physics case – direct search for feebly interacting particles: Heavy Neutral Leptons, vector, scalar, axion portals to the Hidden Sector
- SHiP CDS report submission November 2019
  finalize analyses of updated detector performances (simulation, test beams);
  include description of parts that were left out in the progress report;
  include results of the DESY test beam 2019 and measurement etc
- Preparation of the Technical Design Report (TDR) by the end of 2022

7 years between approval and the first run



Post-conclusion

We need a clue where New Physics is

The word «clue» derives from «clew», an Old English word for a ball of string. It came to mean ‘a hint that aids a solution’ through allusion to the Greek legend of Theseus.

The same story is with the Russian word «клубок», which means a ball of thread.

Notice that Ariadne’s string could not help Theseus to find the Minotaur in the Labyrinth, but was extremely helpful to follow the right way out.

«The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being. But the big questions of our field remain wide open (hierarchy problem, flavour, neutrinos, DM, BAU, etc.).This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias(es).»

M. Mangano