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Electron and proton beams for Dark Sector Searches at the CERN North Area

Note dedicated talks relevant to Dark sector at the CERN NA:
- ✓ *NA62 M. Mirra & M. Raggi*
- ✓ *SHiP L. Fabri*
- ✓ *NA64 M. Hosgen*

Scientific strategy: three pillars (based on ESPP)

Fabiola Gianotti

Full exploitation of the LHC:

- ❑ successful operation of the nominal LHC (Run 2, LS2, Run 3)
- ❑ construction and installation of LHC upgrades: LIU (LHC Injectors Upgrade) and HL-LHC

Scientific diversity programme serving a broad community:

- ❑ ongoing experiments and facilities at Booster, PS, SPS and their upgrades (ELENA, HIE-ISOLDE)
- ❑ participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through CERN Neutrino Platform

Preparation of CERN's future:

- ❑ vibrant accelerator R&D programme exploiting CERN's strengths and uniqueness (including superconducting high-field magnets, AWAKE, etc.)
- ❑ design studies for future accelerators: CLIC, FCC (includes HE-LHC*)
- ❑ future opportunities of diversity programme (new): "Physics Beyond Colliders" Study Group

(*) HE-LHC: FCC-hh dipole technology (~16 T) in LHC tunnel → $\sqrt{s}$ ~ 30 TeV

Important milestone: update of the European Strategy for Particle Physics (ESPP): ~ 2019-2020

Standard Model is great but it is not a complete theory

Experimental facts of BSM physics

- *Neutrino masses & oscillations*
- *Baryon Asymmetry of the Universe (BAU)*
- *The nature of non-baryonic Dark Matter (DM)*

SHiP Physics Paper: 1504.04855

Many theoretical ideas, including those which predict new light particles, and which can be tested experimentally

CERN "Physics Beyond Colliders" Study Group established in March 2016

Mandate
Explore opportunities offered by the (very rich) CERN accelerator complex to address outstanding questions in particle physics through projects:

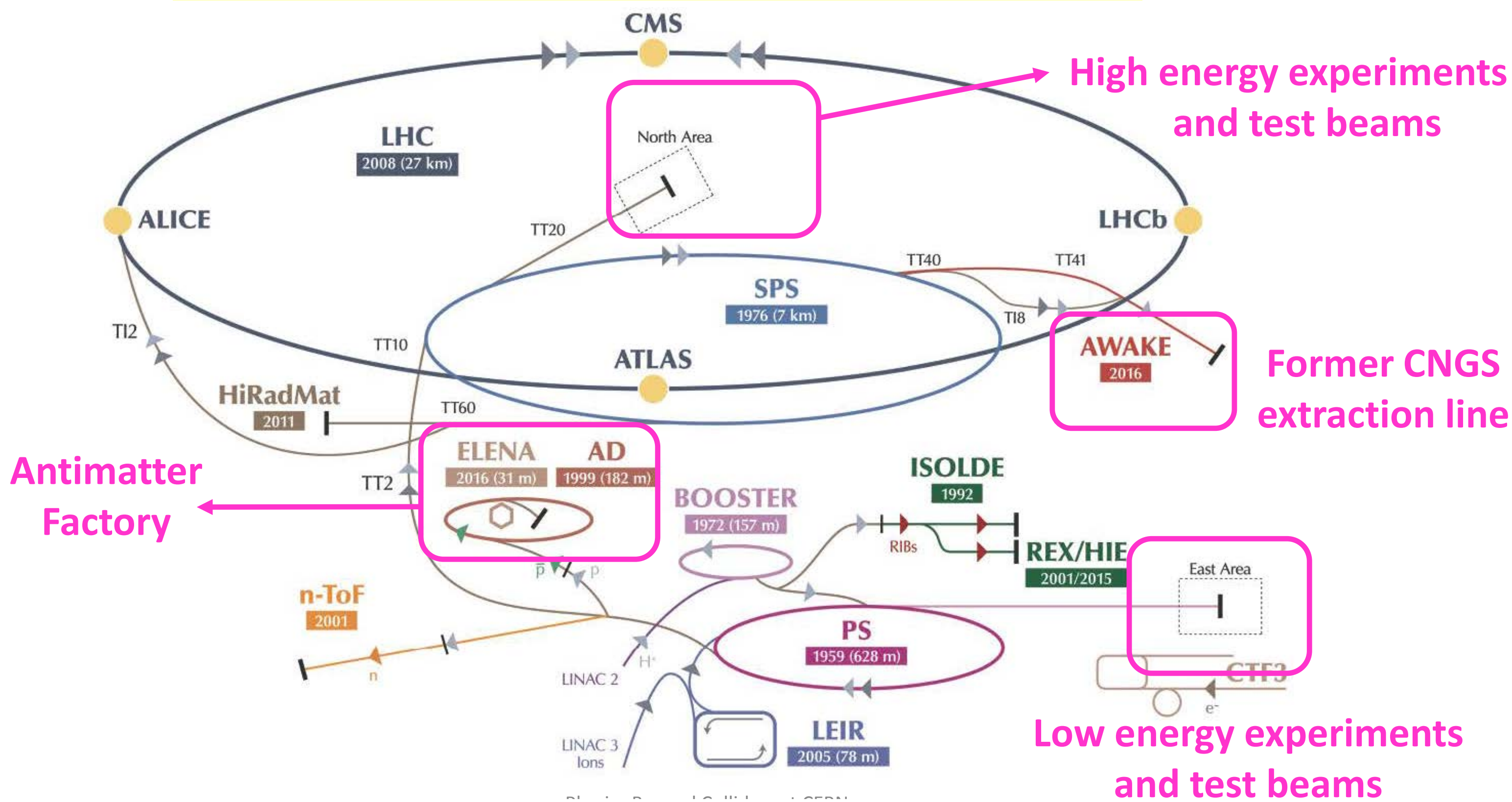
❑ complementary to high-energy colliders (studied at CERN: HE-LHC, CLIC, FCC)
→ we know there is new physics, we don't know where it is → we need to be as broad as possible in our exploratory approach

❑ exploiting the unique capabilities of CERN accelerator complex and infrastructure and complementary to other efforts in the world:
→ optimise the resources of the discipline globally

Search for Hidden Sector at the CERN SPS proton (NA62 & SHiP) and electron (NA64) beams

Thanks to stable LHC operation and long lifetime of the LHC beams significant fraction of the SPS protons, and its time, are available for physics at the North Area !

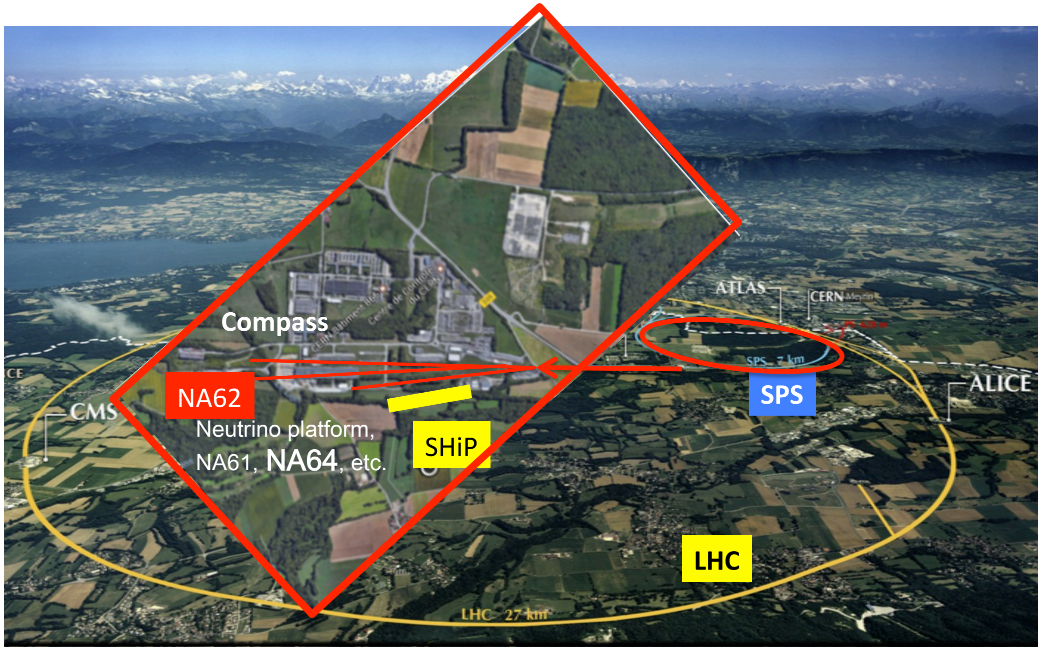
THE PRESENT CERN ACCELERATOR COMPLEX



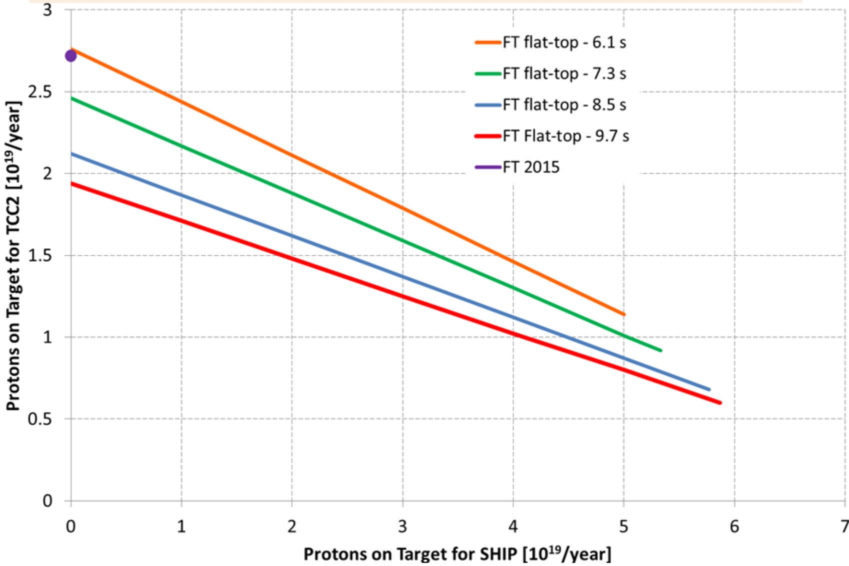
Nominal year of the SPS operation → 200 days with typical machine availability ~80%; 20% of the SPS physics time to run LHC and 80% - to run fix target programme

The Fixed-target facility at the SPS: Prevessin North Area site

Very intense proton beam with highest in the world energy delivered to fixed target exp. at CERN SPS. ***The aim is to deliver with $4{\times}10^{13}$ protons / spill (at slow extraction)***



Sharing of pot between current fixed target exp. and planned Beam Dump Facility (BDF)



Proposed implementation is based on minimal modification to the current SPS complex

Search for Hidden Sector (HS)
or very weakly interacting NP

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

Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

Naturally accommodates Dark Matter
(may have rich structure)

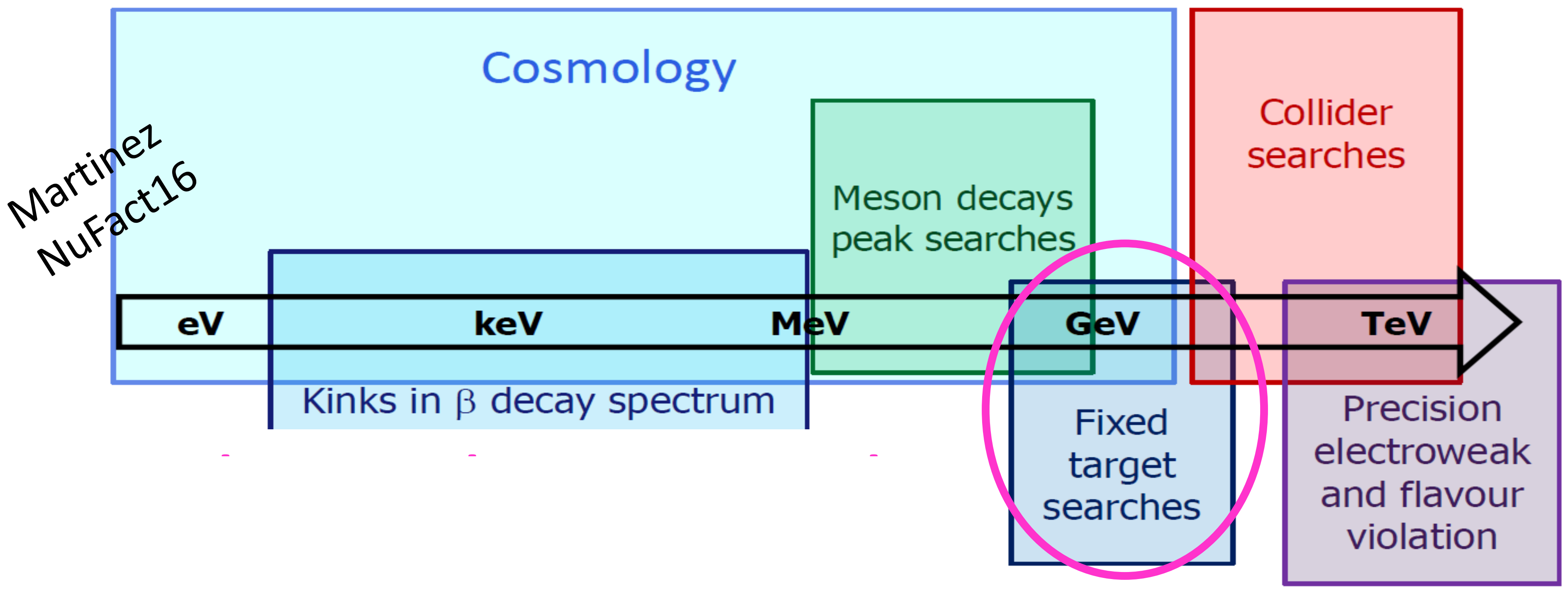
✓ *HS production and decay rates are strongly suppressed relative to SM*
  - *Production branching ratios $O(10^{-10})$*
  - *Long-lived objects*
  - *Interact very weakly with matter*

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+ \rightarrow \pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Full reconstruction and PID are essential to minimize model dependence

Experimental challenge is background suppression

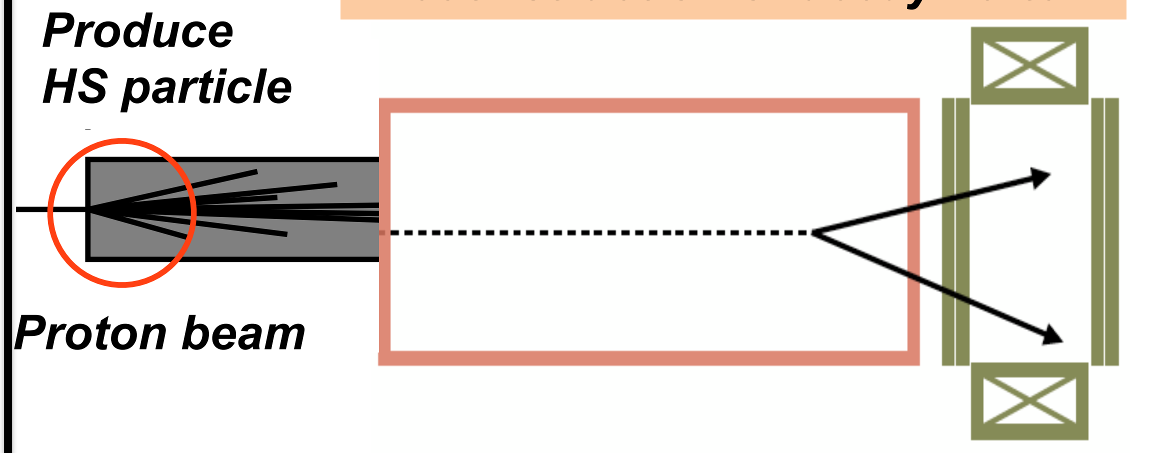
Search for Dark Sector at fixed target is complementary to many other searches



Two strategies at CERN SPS

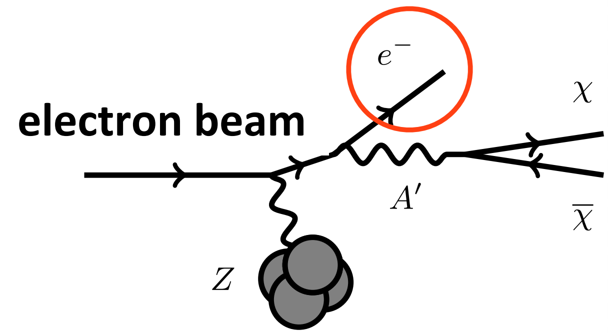
Direct observation (SHiP & NA62)

Reconstruction of decay vertex

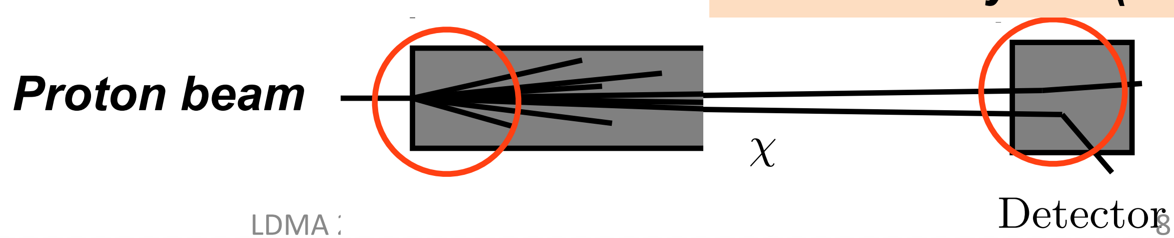


Indirect detection (SHiP & NA64)

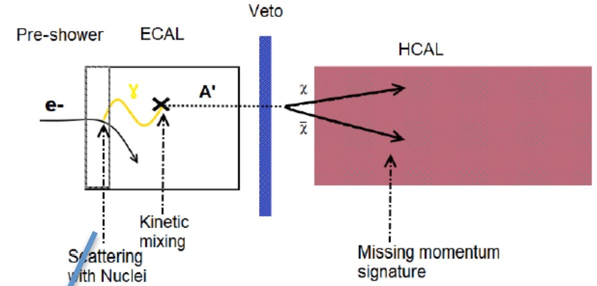
Missing energy technique (NA64)

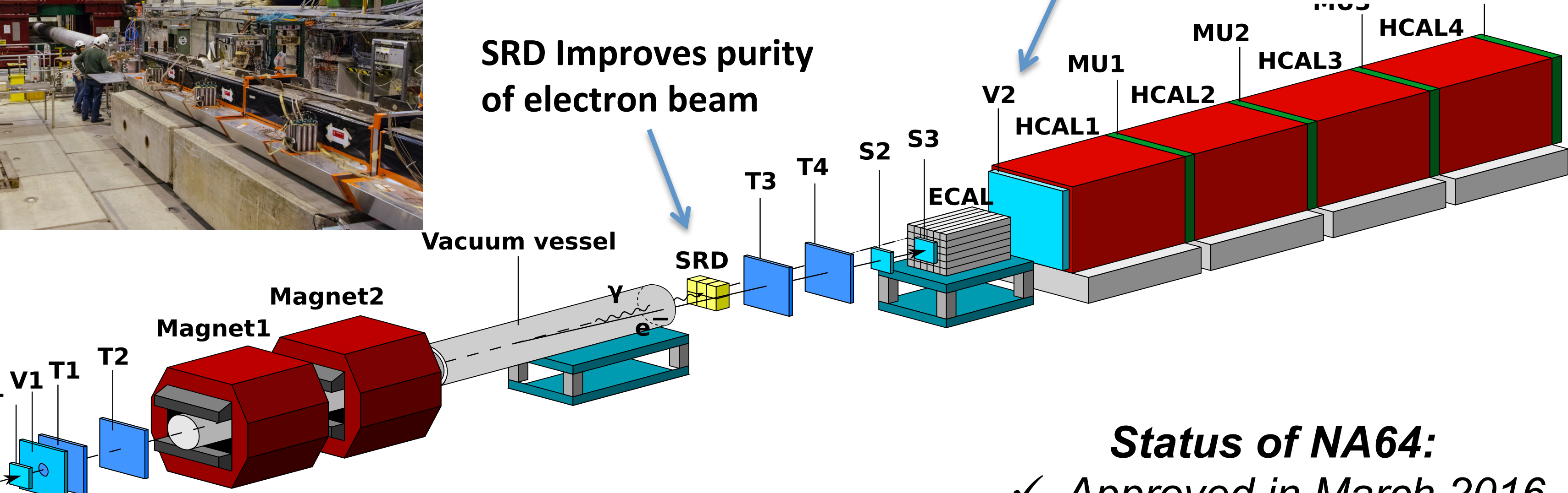


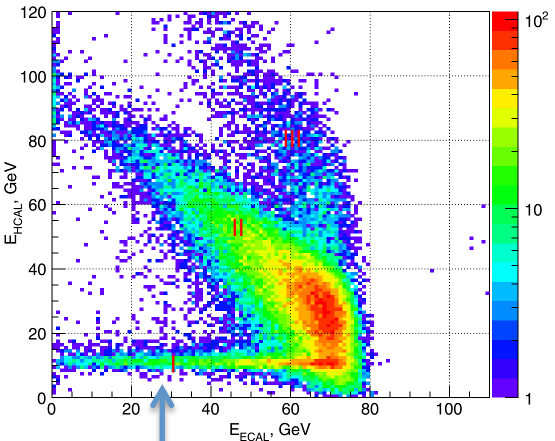
Scattering technique, electron or nuclei scattered by DM (SHiP)



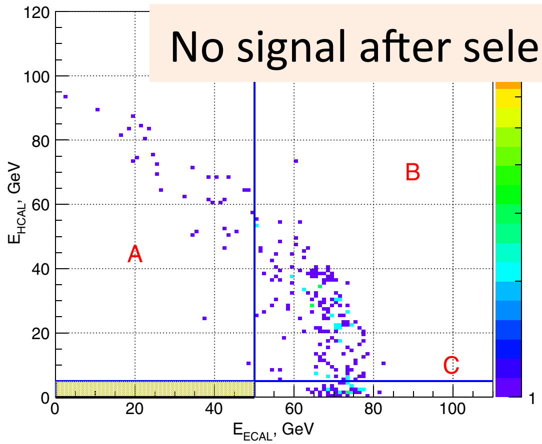
NA-64: *search for HS at electron beam in events with missing energy*







QED $\mu^+\mu^-$ to calibrate MC



Status of NA64:

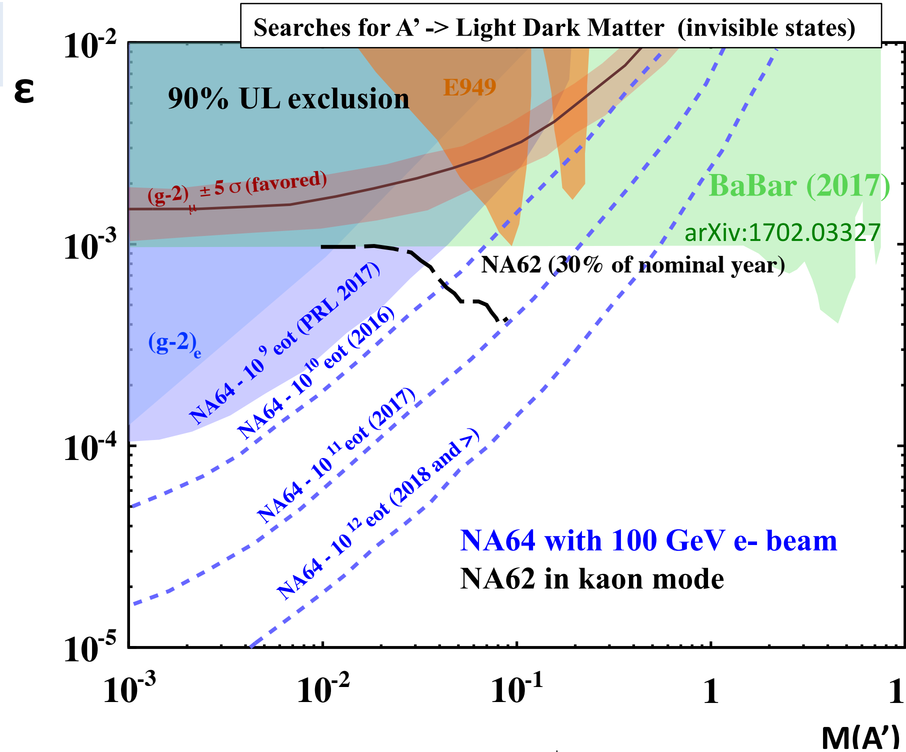
- ✓ *Approved in March 2016*
- ✓ *Two successful runs in 2016 with 4×10^{10} eot collected running at 5×10^{6} e^- / spill*
- ✓ *Plans for 2017:*
  Improve electron tagging
  Run at (7-8)$\times10^{6}$ e^- / spill
  to collect (2-3)$\times10^{11}$ eot

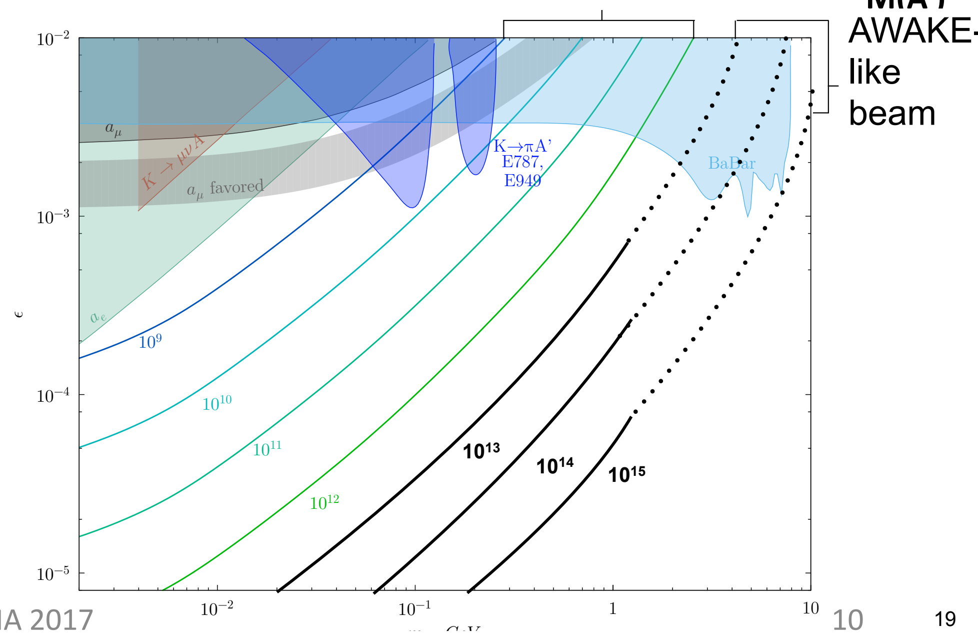
NA-64 prospects @ electron beam

Three stage physics programme:

- ✓ ***Phase I** (2017-2018)*
  Continue data taking with "standard" 100 GeV electron beam at H4
  Collect few ×10^{11} eot
- ✓ ***Phase II***
  ×10 integrated intensity to fully explore NA64 potential
  Collect O(10^{13}) eot
- ✓ ***Phase III***
  Use AWAKE-like electron beam (intrinsically pure): 10^9 e^- / spill
  → 500 times higher than current NA64/SPS secondary beam
  Different beam energies or higher intensities may be possible

AWAKE had successful beam data in 2016 → establishment of plasma modulation. Goal for 2017 → first acceleration of plasma



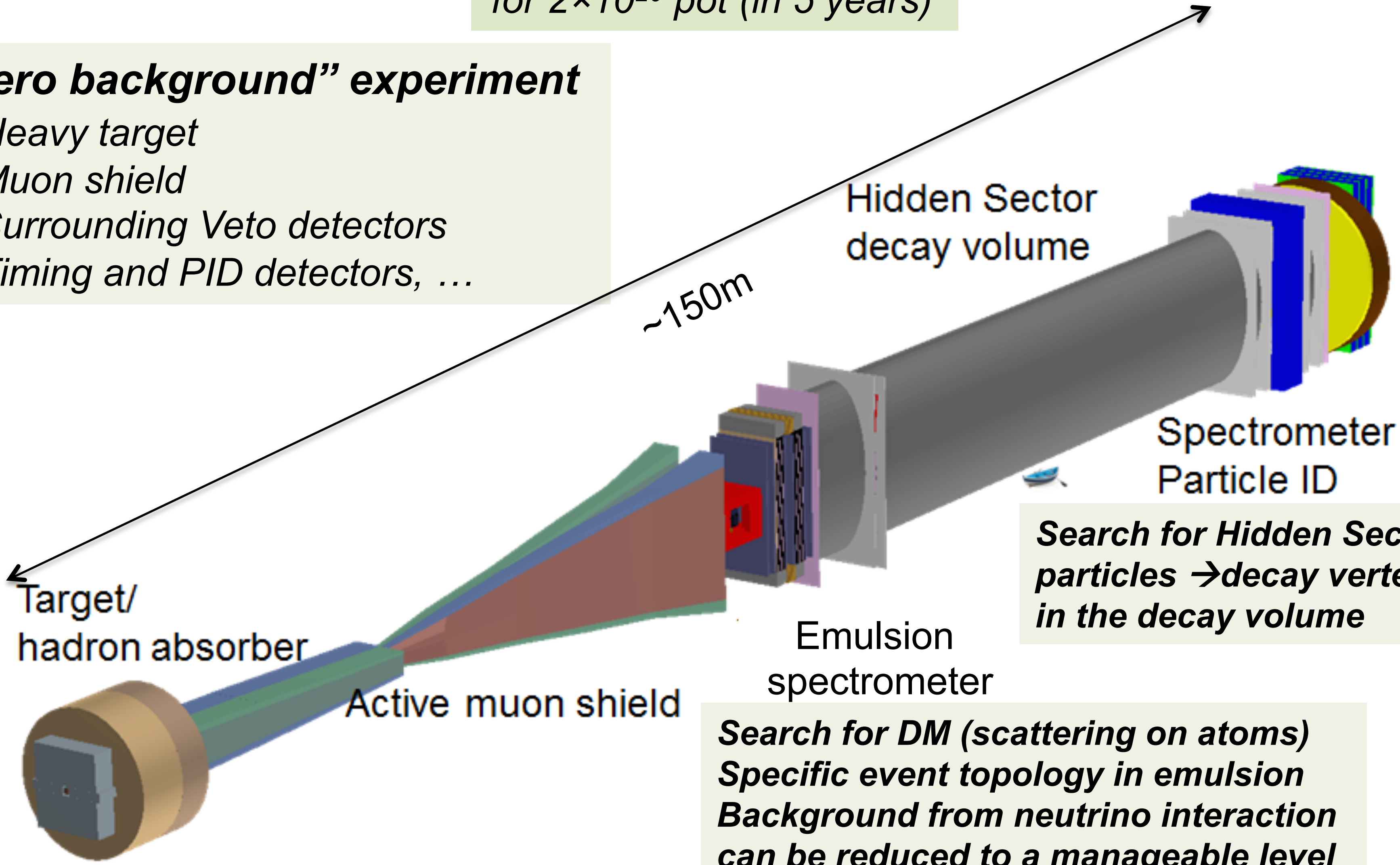


The SHiP experiment at SPS
(to search for HS particles with O(10 GeV) masses)

SHiP Technical Proposal: 1504.04956

>10^{18} D, >10^{16} τ, >10^{20} γ for 2×10^{20} pot (in 5 years)

"Zero background" experiment
- *Heavy target*
- *Muon shield*
- *Surrounding Veto detectors*
- *Timing and PID detectors, …*

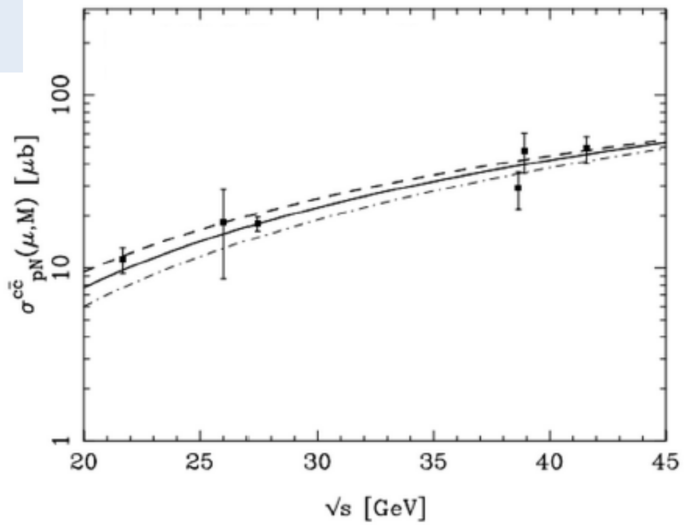


Search for Hidden Sector particles →decay vertex in the decay volume

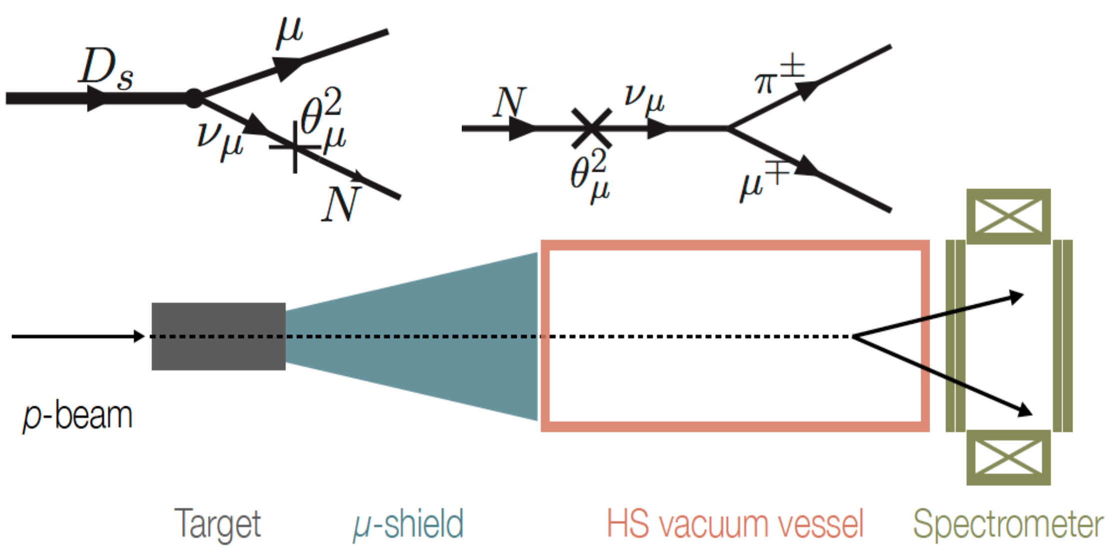
Search for DM (scattering on atoms)
Specific event topology in emulsion
Background from neutrino interaction can be reduced to a manageable level

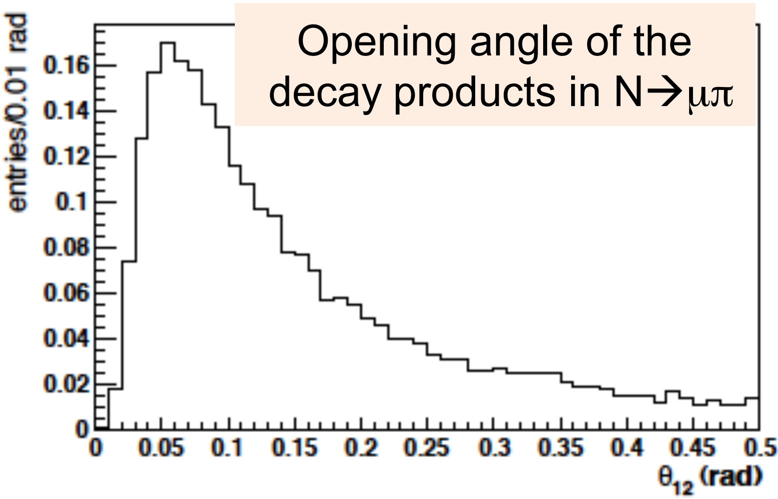
General experimental requirements
to search for HS at beam dump experiment

- ✓ *Search for HS particles in Heavy Flavour decays*
  Charm (and beauty) cross-sections strongly depend on the beam energy



- ✓ *HS produced in charm and beauty decays have significant P_T*





Detector must be placed close to the target to maximize geometrical acceptance. Effective (and "short") muon shield is the key element to reduce muon-induced backgrounds

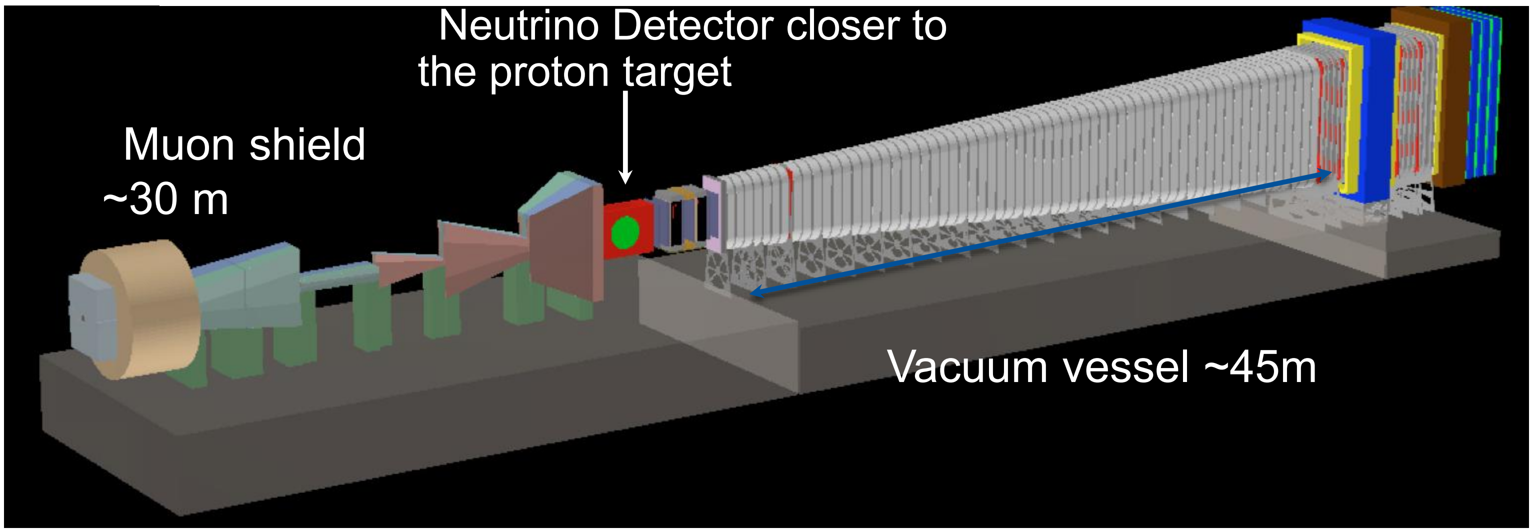
Brief history and current status of SHiP

- ✓ *Letter Of Intent - October 2013*
- ✓ *Technical Proposal & Physics Paper - April 2015*
- ✓ *Reviewed by the SPSC and CERN RB by March 2016, and recommended to prepare a Comprehensive Design Study (CDS) by 2018*
  → Input to the European strategy consultation to take a decision about approval of SHiP in 2019/2020

CDS will improve SHiP TP version *respecting cost constraints*

Main goals of the SHiP optimization for the CDS

- ✓ *Further optimization of the target*
- ✓ *Configuration of the muon shield, including magnetization of the hadron stopper (**MC to be validated with data**)*
- ✓ *Shape, dimension and evacuation of the decay volume*

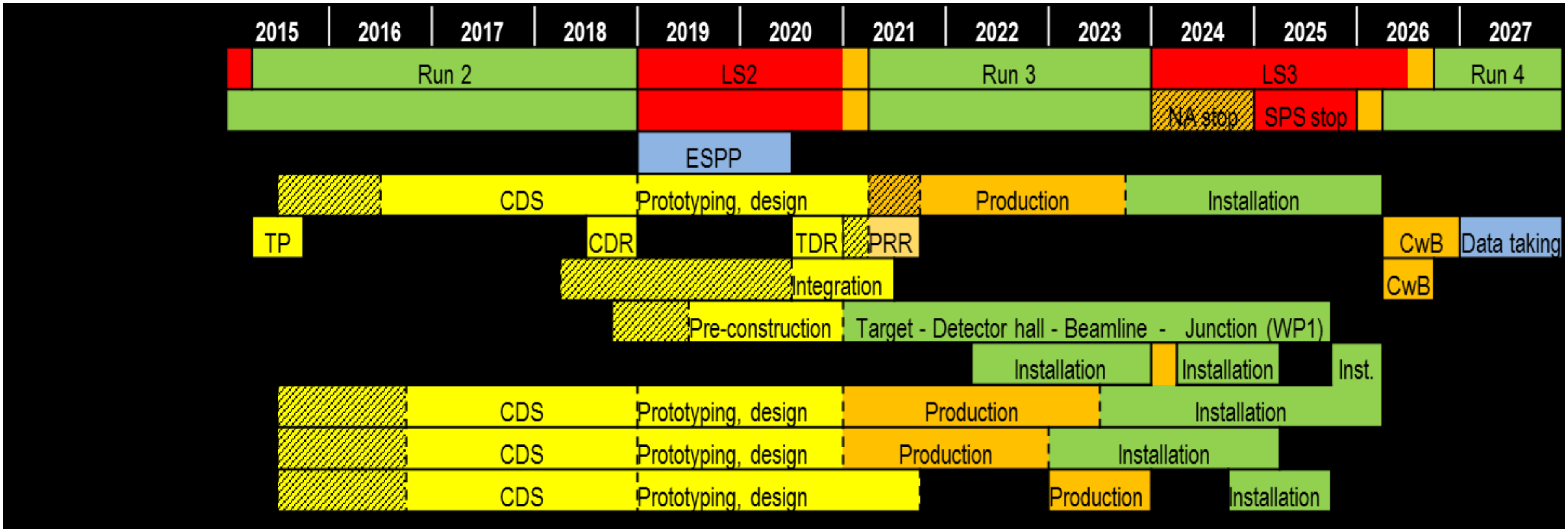


- ✓ *Optimization of the emulsion detector to search for LDM*
- ✓ *Optimization of physics performance for various sub-detectors*
- ✓ *Revisit detector technologies, including new sub-detectors, to further consolidate background rejection and extend PID*

Updated background estimates and signal sensitivities, and cost

- ✓ *Contribution from the secondary interactions in the target improves signal yield by ~50% (**to be validated with data)***

Global SHiP schedule



- ✓ ***Planning very well aligned with***
  - *Update of European strategy 2019/2020*
  - *Accelerator schedule (to be followed closely)*
  - *Production Readiness Reviews (PRR) 2020Q1 →*
  - *Construction / production 2020 →*
  - *Data taking (pilot run) 2026 (start of LHC Run 4)*

- ✓ ***Main current priority: Comprehensive Design Study by 2018***

NA62 plans to search for HS (2021-2023)

T. Spadaro
PBC, March 2017

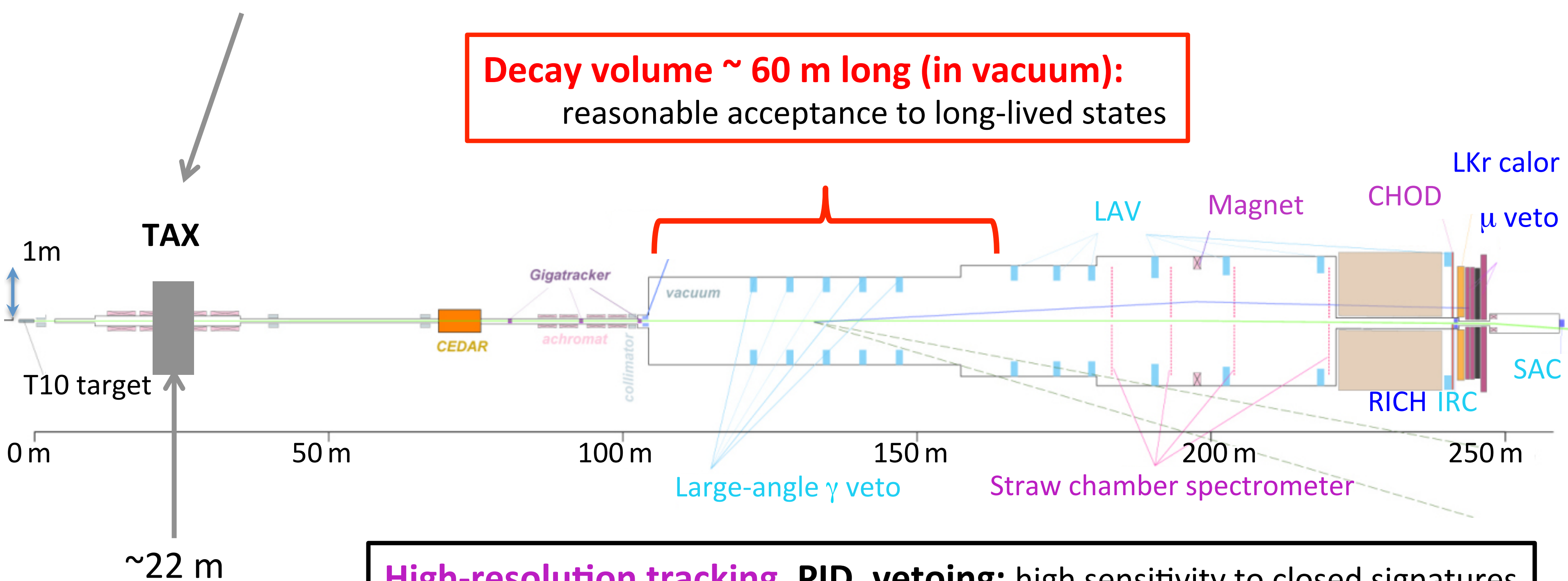
High-intensity 400-GeV proton beam → boost charm/beauty, other meson production

10^{18} POT / nominal year: 10^{12} POT/sec on spill, 3.5-s/16.8 s, 100 days/year, 60% run efficiency

10^{15} $D_{(S)}$, 10^{14} K, 10^{18} $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95

Compact beam dump: ~11 λ_I Cu-based beam-defining collimator (TAX)
radioprotection-compliant even if target removed

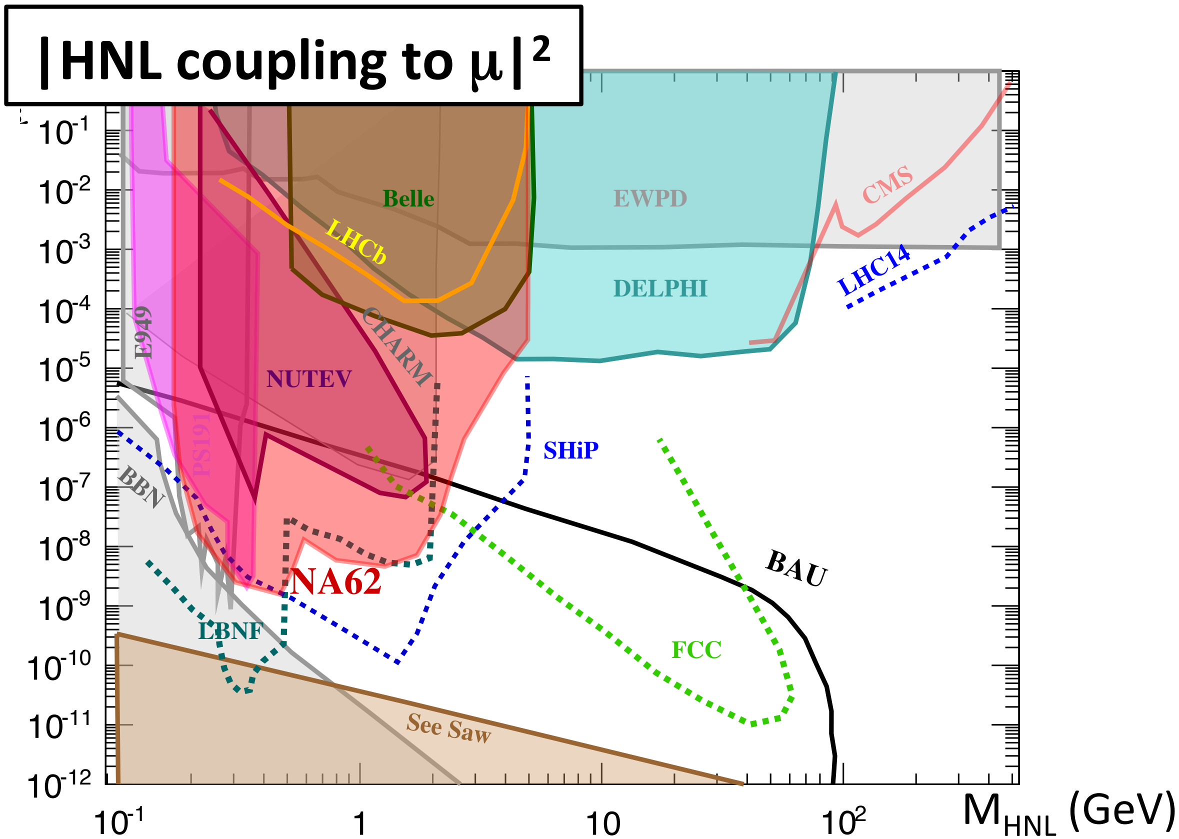
Decay volume ~ 60 m long (in vacuum):
reasonable acceptance to long-lived states



High-resolution tracking, PID, vetoing: high sensitivity to closed signatures

Future prospects and comparison with other facilities

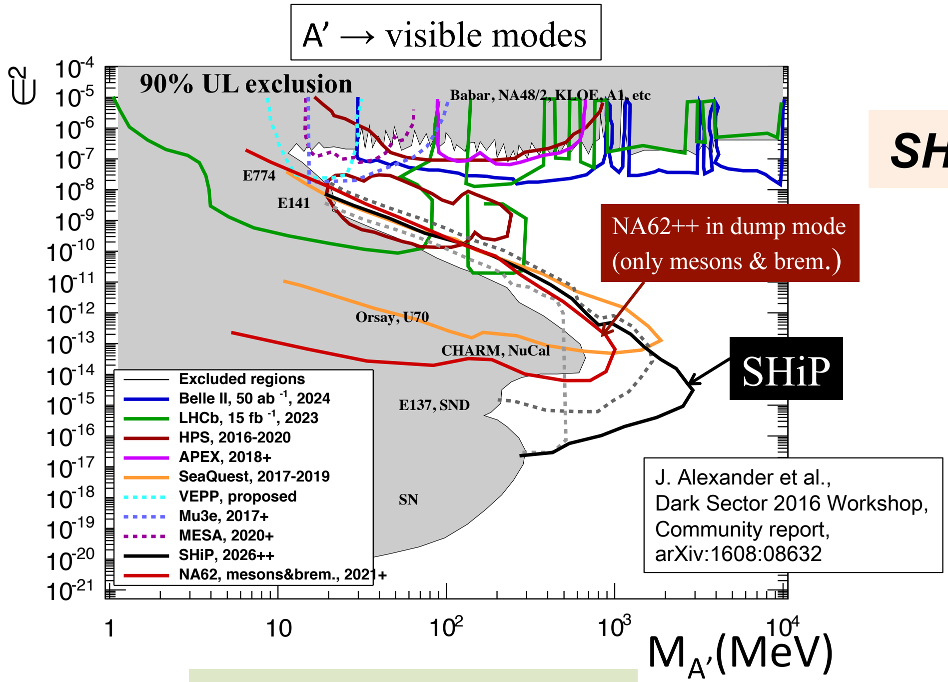
HNLs:



- ✓ $M_{HNL} < M_b$ *LHCb, Belle2*
  SHiP will have much better sensitivity
- ✓ $M_b < M_{HNL} < M_Z$ ***FCC in e^+e^- mode*** *(improvements are also expected from ATLAS / CMS)*
- ✓ $M_{HNL} > M_Z$ ***Prerogative of ATLAS/CMS @ HL LHC***

SHiP will also have the best prospects for HS particles produced in heavy flavour decays, e.g. hidden scalars

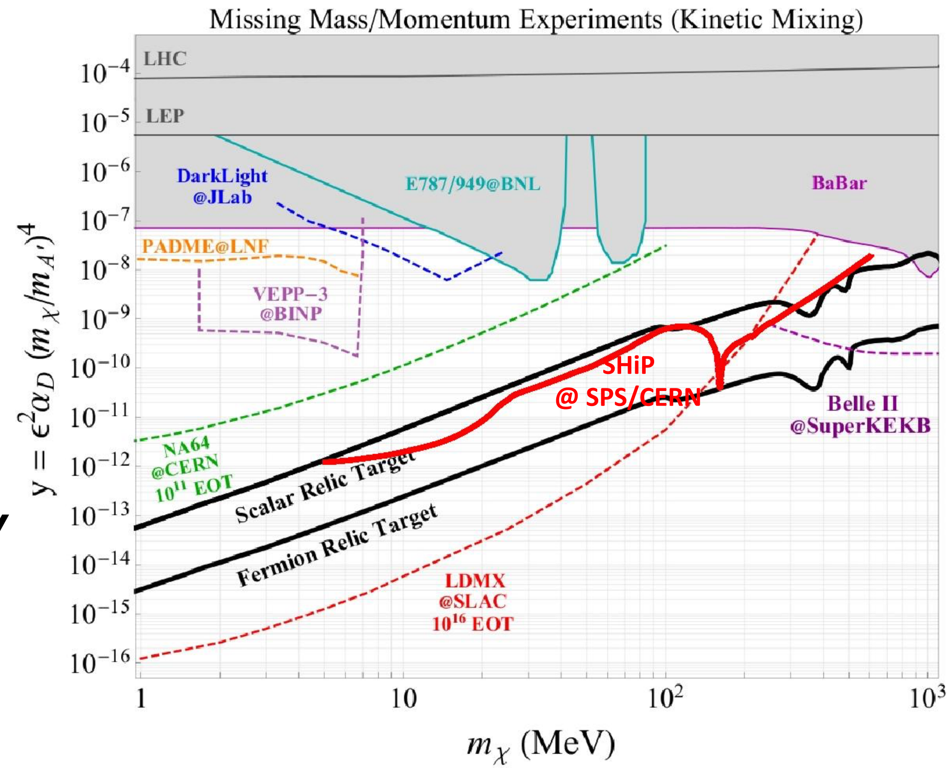
Future prospects and comparison with other facilities



Dark photons:

SHiP is unique up to O(10GeV) and $\varepsilon^2 < 10^{-11}$

$M_{A'}/M_\chi=3$



Light Dark Matter

Detection via scattering

- ***SHiP has unique potential for M_χ <1GeV***
- *BDX in JLab may have a competitive sensitivity for M_χ <10 MeV*

Missing mass / energy technique

- *Belle II – comparable to SHiP for M_χ>0.5 GeV with 50 ab^{-1} provided that low energy mono-photon is implemented*
- *LDMX (under discussion at SLAC) has the best prospects for M_χ< 100 MeV Time scale is unclear.*

Dark sectors 2016: 1608.08632

Conclusions

- ✓ ***Physics case to search for Dark Sector is very timely !***
  No NP finding at LHC, *but many theoretical models offer a solution for the BSM experimental facts with light very weakly-interacting particles**. Must be tested !***

- ✓ ***CERN is ideal place to search for Dark Sector at high energy and high intensity SPS beams.*** *Two complementary strategies are being explored, direct observation (ShiP & NA62) and indirect detection using missing energy technique (NA64) and scattering technique (SHiP)*

- ✓ ***NA64 is currently taking data at electron beam at H4 / NA and have unique sensitivity.*** *Future prospects are highly competitive with similar projects in the world*

- ✓ ***SHiP is an ideal experiment to search for new phenomena in < O(10 GeV) range in "no background" environment***
  Complementarity between two detection techniques:
  - *Reconstruction of the decay vertices in the decay volume*
  - *Detection of interactions with atoms in the emulsion spectrometer*

- ✓ ***The rich physics programme to search for Dark Sector at the SPS North Area at CERN nicely complements searches for NP at the LHC***

SHiP at CERN @ 400 GeV vs US-SHiP at Fermilab @ 120 GeV

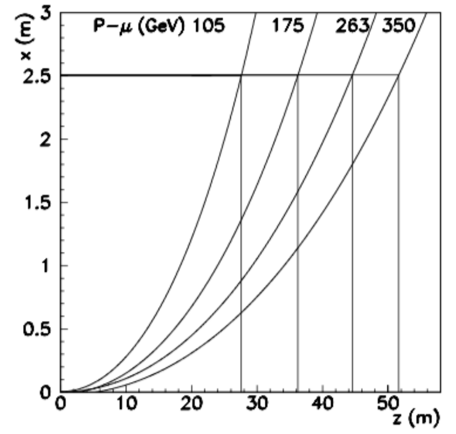
Assume:

- *Hypothetical detector US-SHiP has similar size to the SHiP detector*
- *Slow beam extraction (*)*
- *The target with the same material (*)*
- *Full background suppression*
- ***Dedicated to US-SHiP operation (in conflict with neutrino programme)***

(*) – technical feasibility to be demonstrated for US-SHiP

	SHiP	US-SHiP 40 m long and at 37 m from the target
N_{pot} / year delivered at ~1s extraction	4×10^{19}	$\sim5.3\times10^{20}$
$\sigma_{cc}(E_{beam})$, au	1	1/7
Detector acceptance (E), au	1	0.6

Trajectory of m in Fe(1.8T)



- ✓ ***Similar performance for HS produced in charm decays***
  Sensitivity for HS produced in B decay is severely compromised, σ_{bb} (120/400) = 625
- ✓ ***Really poor prospects for tau neutrino physics at 120 GeV beam energy***
- ✓ ***SPS @ 400 GeV is ideal to perform the physics programme of SHiP***