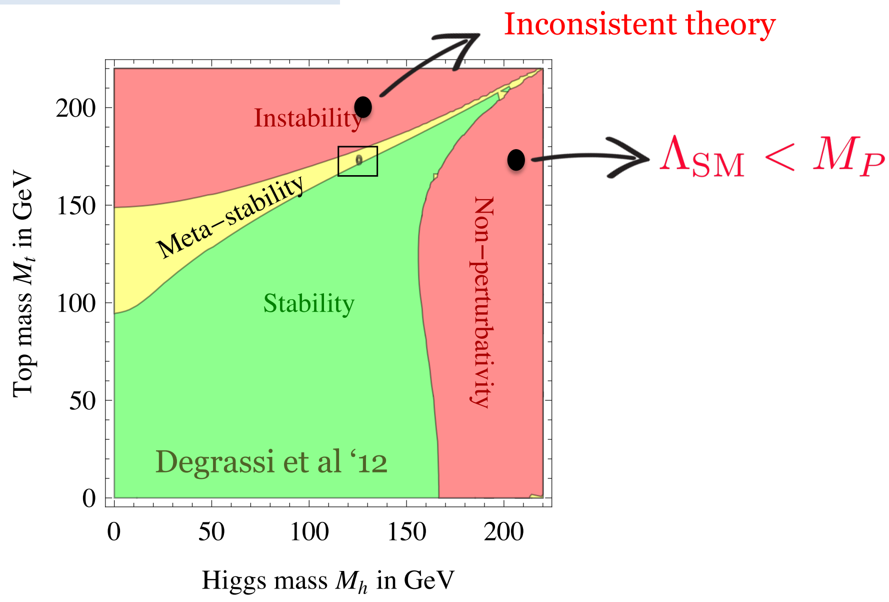
Andrey Golutvin
Imperial College London

The SHiP Physics case

Standard Model is great but it is not a complete theory

Higgs discovery made the SM complete (with only a marginal evidence (<2σ) for the SM vacuum metastability) → SM is a self-consistent FT all the way up to Planck scale



Experimental facts of BSM physics

- *Neutrino masses & oscillations*
- *The nature of non-baryonic Dark Matter*
- *Excess of matter over antimatter in the Universe*

Theoretical shortcomings

Gap between Fermi and Planck scales, Dark Energy, connection to gravity, resolution of the strong CP problem, divergence of the Higgs mass, the pattern of masses and mixings in the quark and lepton sectors, …

No clear guidance at the scale of New Physics

Physics landscape today

1. Direct searches for NP by ATLAS and CMS have not been successful so far

→ Parameter space for popular BSM models is decreasing rapidly, but only 10% of the complete HL-LHC data set has been delivered so far

→ NP discovery still may happen

2. LHCb reported intriguing hints for the violation of Lepton Flavour Universality

in $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to se^+e^-$ / $b \to s\mu^+\mu^-$ decays

→ Clear evidence of BSM physics if substantiated with further studies

But even then it will not be possible to determine NP scale with certainty

Many models predict enhanced LFV effects (some close to the current experimental limits) in decays of τ lepton (recently proposed TauFV experiment)

3. Significant efforts in neutrino physics did also not ameliorate our knowledge about NP scale. Neutrino masses and oscillations can be accounted in SM extended by two sterile neutrinos of essentially any mass

4. DM: no evidence for WIMP in GeV-TeV mass range neither in direct nor in indirect searches → Light DM? May also be a super heavy DM

Scale of NP: See-saw generation of neutrino masses

Most elegant way to incorporate non-zero neutrino mass to the SM Lagrangian is given by the see-saw formula:

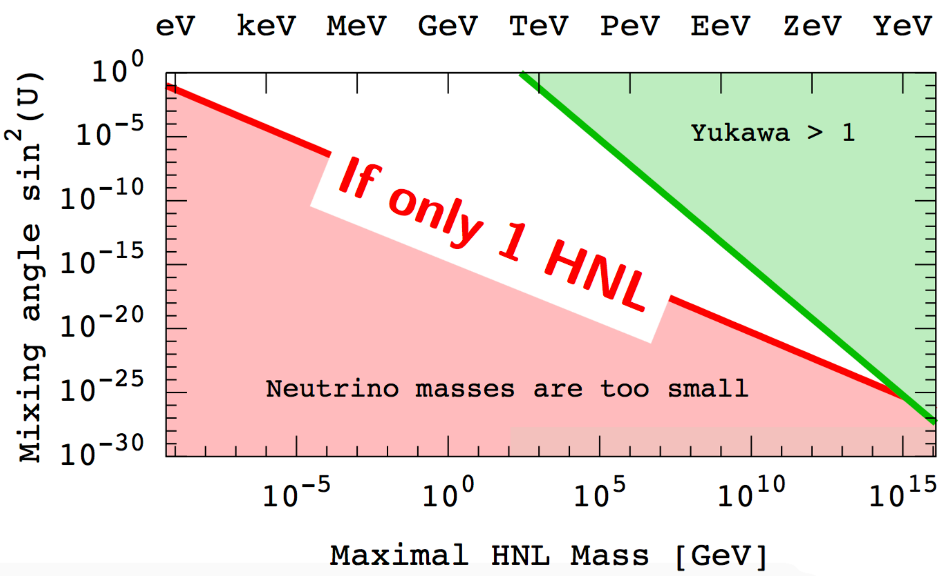
$$m_\nu = \frac{m_D^2}{M}$$

where $m_D \sim Y_{I\alpha} < \phi >$ *- typical value of the Dirac mass term and M is Majorana mass term*

Example:

For M ~ 1 GeV and m_ν ~ 0.05 eV it results in m_D ~ 10 keV and Yukawa coupling ~ 10^{-7}

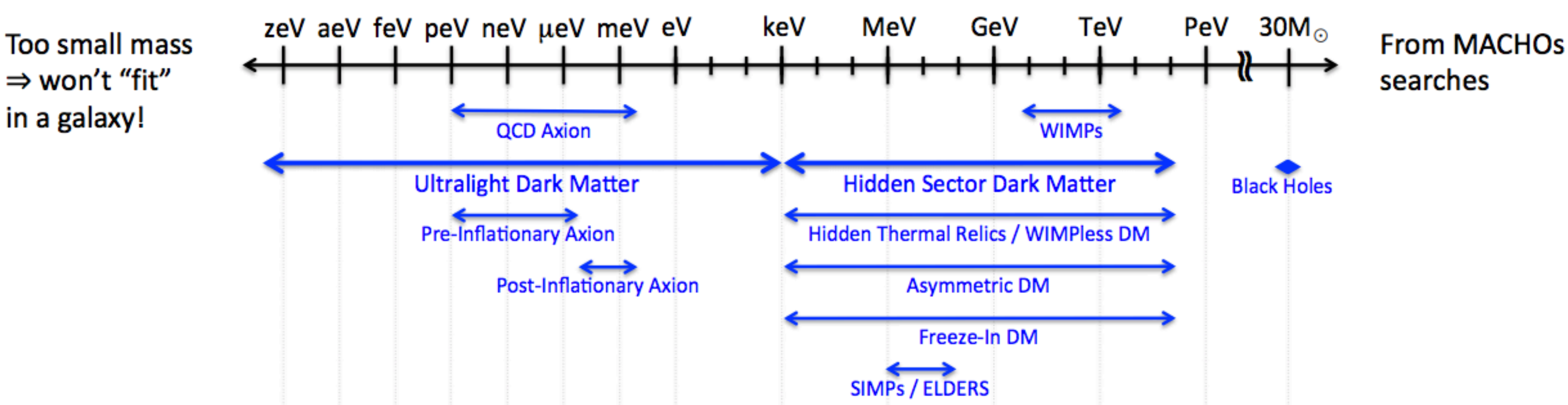
Smallness of the neutrino mass hints either on very large M or very small $Y_{I\alpha}$



Scale of NP: Dark Matter

European Strategy Update

Dark Matter Candidates: Very little clue on mass scales



Slide from H.Murayama from ESPPU

The prediction for the mass scale of Dark Matter particles spans from 10^{-22} eV (ALPs) to 10^{20} GeV (Wimpzillas, Q-balls)

BSM theories with a new energy scale
(which may also contain "light" particles)

We know that new particles exist

- Neutrino masses and oscillations

  Scale of new physics:
  from 10^{-9} GeV to 10^{15} GeV

- Dark matter

  Scale of new physics:
  from 10^{-30} GeV to M_P

- Baryon asymmetry of the Universe

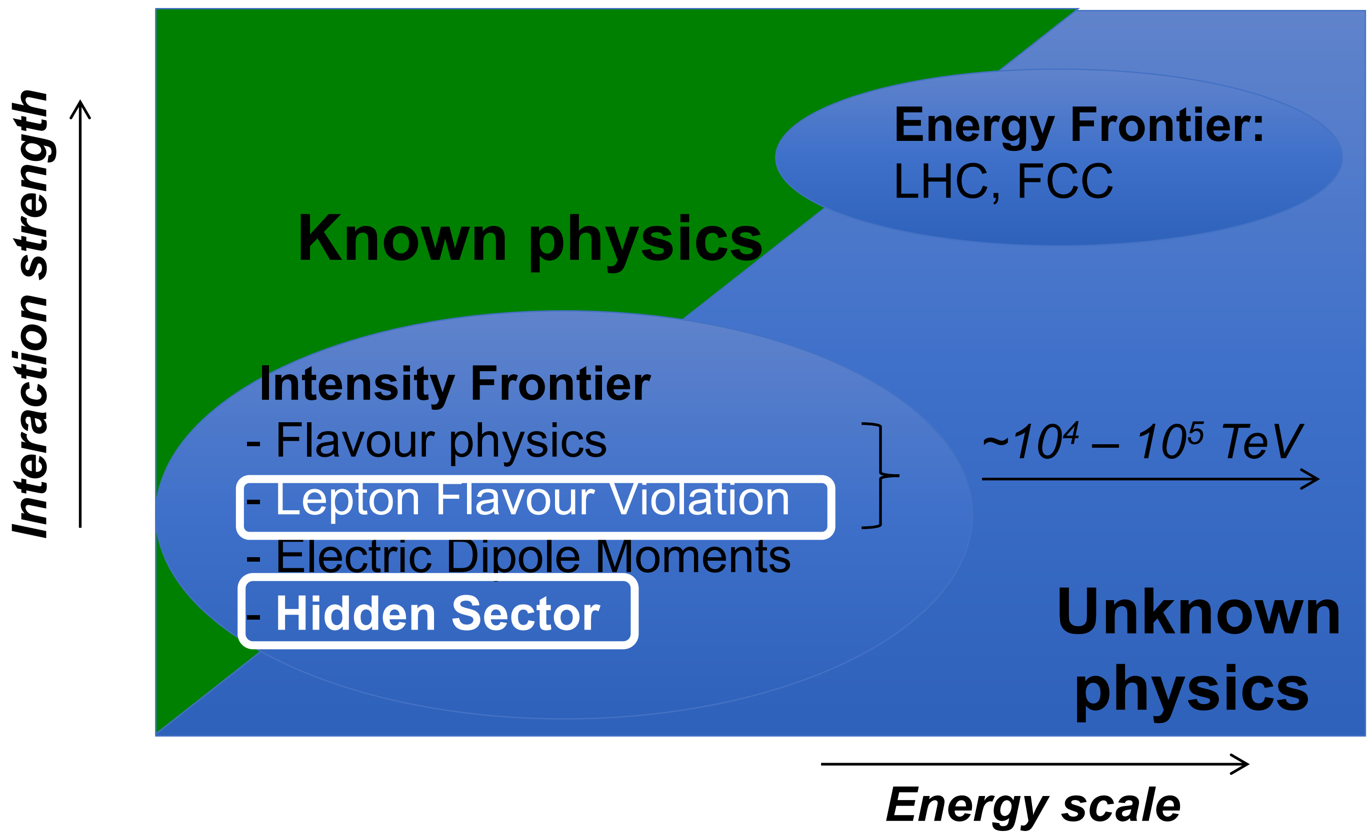
  Scale of new physics:
  from 10^{-3} GeV to 10^{15} GeV

- ✓ *We know that there are new particles*
- ✓ *We do not know what they are*
- ✓ *There is no guaranteed discovery anymore/no leading theoretical model*
- ✓ ***Diversity** of experimental program is crucial*

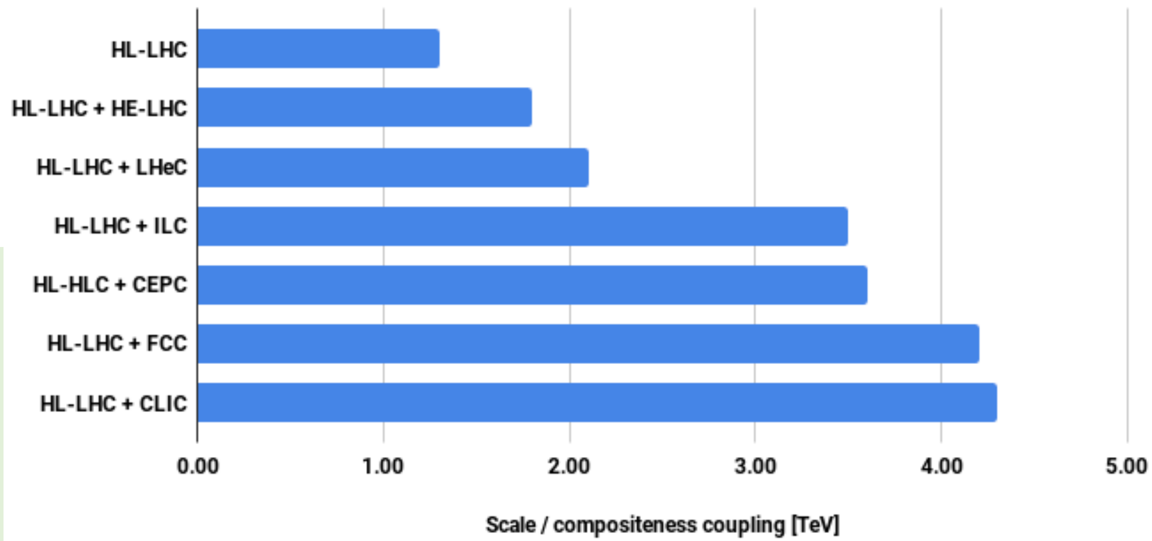
So, there is always a good reason to increase the energy (even √s > 14 TeV) and intensity, even if the scale of NP happens to be inaccessible directly. LHC is also one of the best machines at the Intensity Frontier !

Quest for New Physics

- ✓ *Higgs discovery made the SM complete*
- ✓ *SM s a great theory but does not represent the full picture*
- ✓ *NP should exist but we have no definitive predictions on the masses and coupling constants of NP particles*

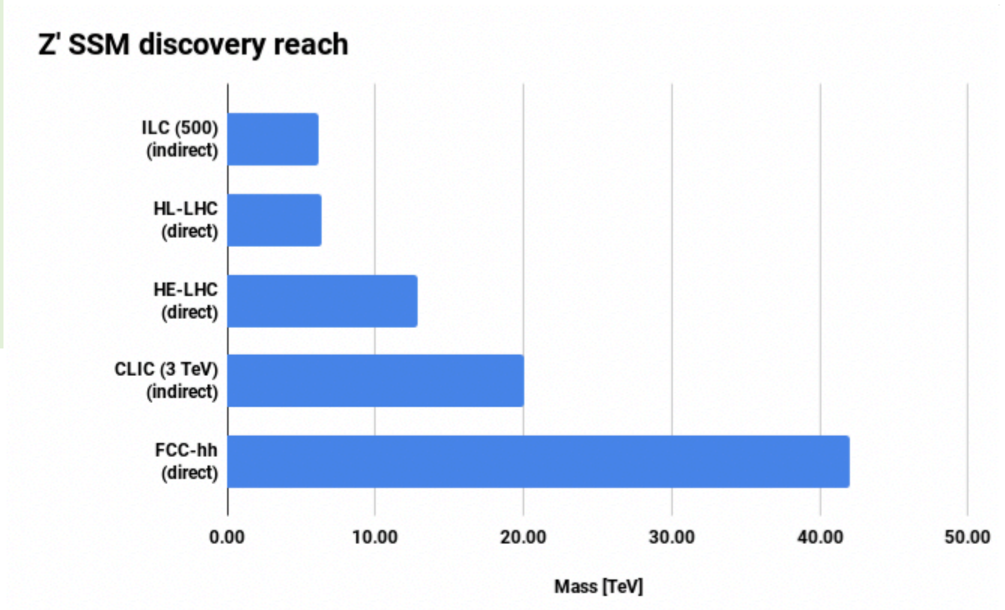


BSM reach at the Energy Frontier



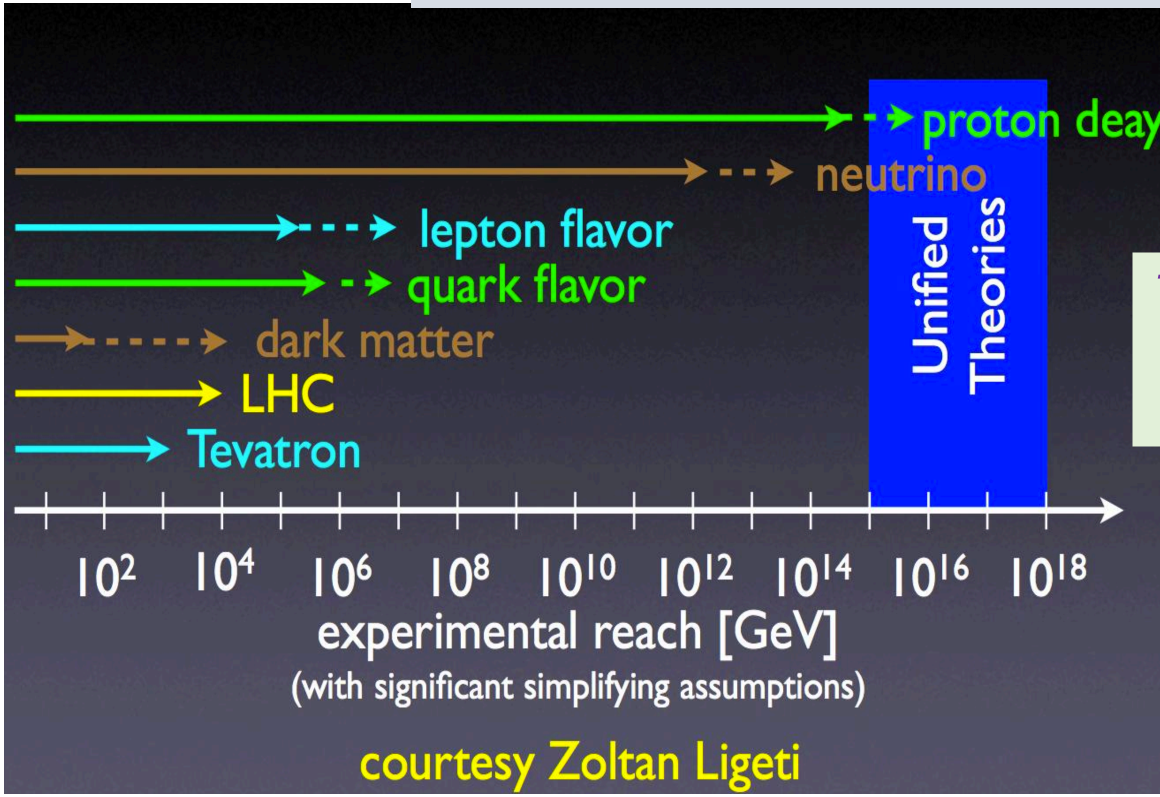
Fundamental questions from EPPSU/Granada:

- ✓ *To what extent can we tell whether the Higgs is fundamental or composite?*
- ✓ *Are there new interactions of new particles around or above the EW-scale?*



BSM can be directly explored up to ~50 TeV

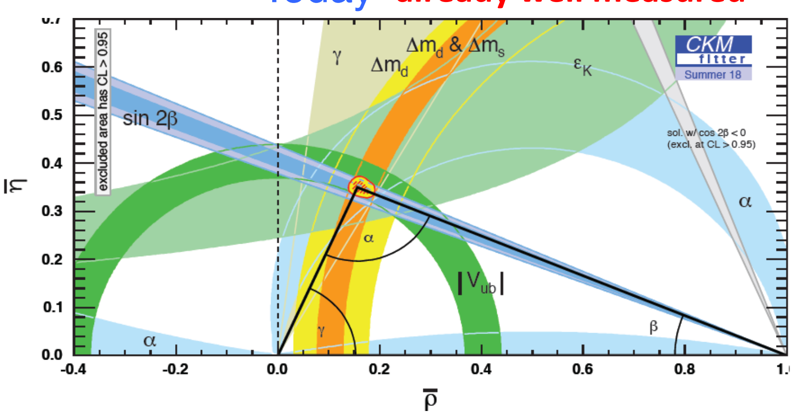
Exploration power of the Intensity Frontier



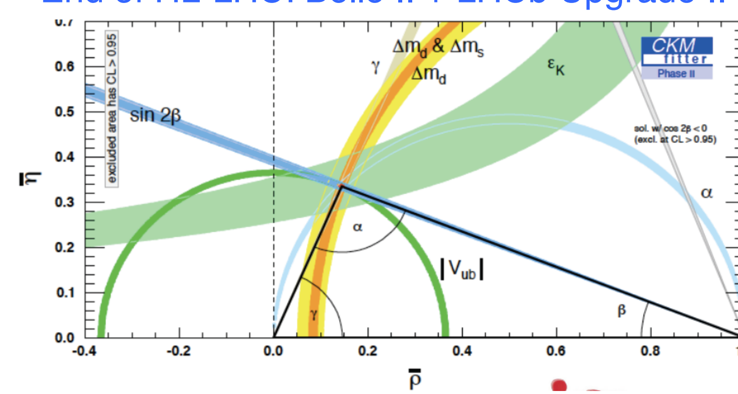
The scale of strongly coupled NP ($\Lambda > 10^3$ TeV for 10^{-2} coupling) is well above direct reach

CKM prospects in b(c)-decays *from EPPSU/Granada*

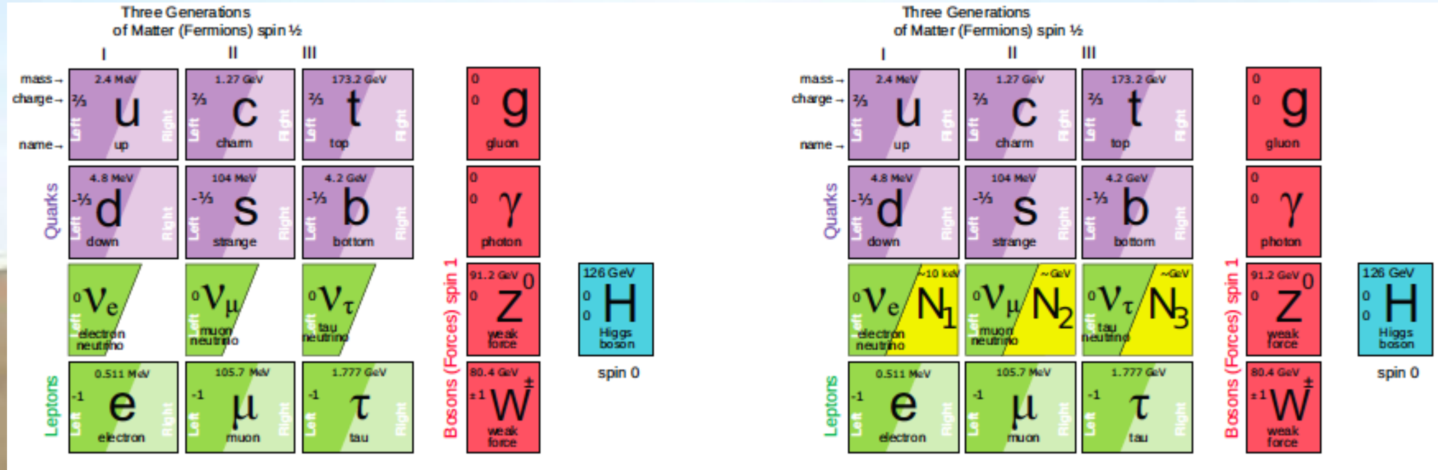
Today **already well measured**



End of HL-LHC: Belle II + LHCb Upgrade II



BSM theories with no NP between Fermi and Planck scales



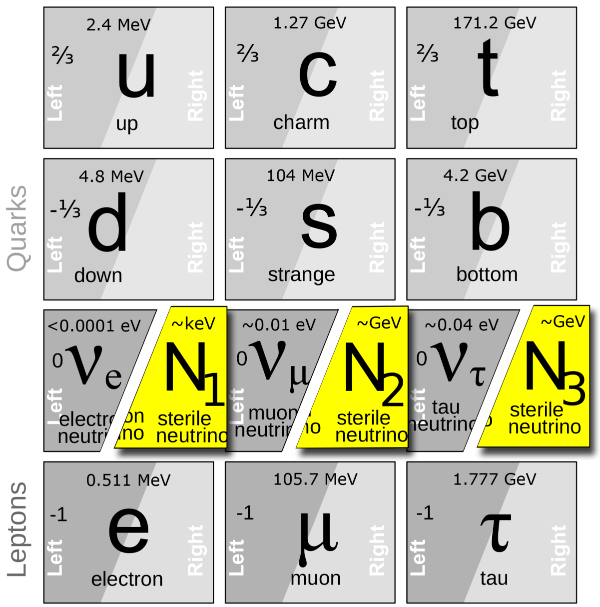
Gravity and EW scale may be connected via tunneling transition ?

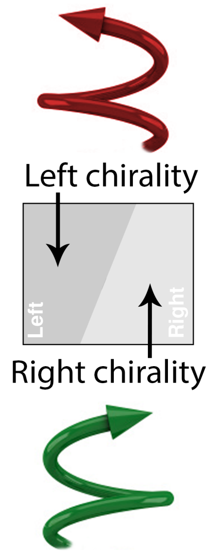
$M^2_H = M^2_P \times e^{-S}$ with S=72 (arXiv 1803.08907; 1804.06376)

10

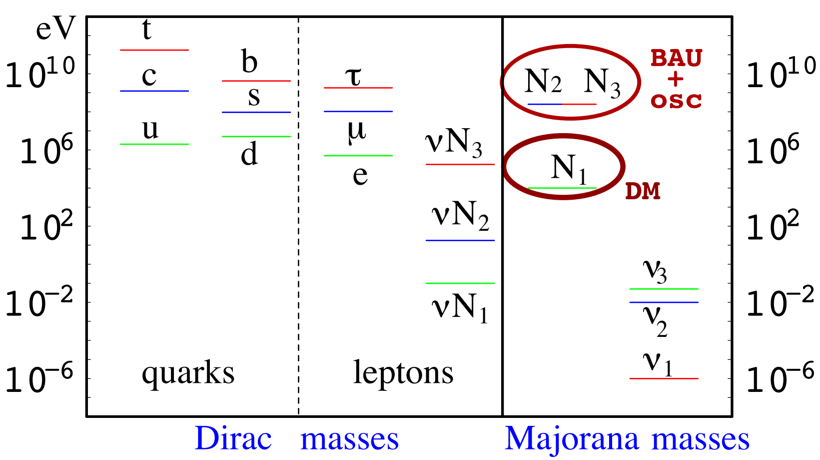
νMSM (T.Asaka, M.Shaposhnikov PL B620 (2005) 17) explains all experimental evidences of the BSM physics at once by adding 3 Heavy Neutral Leptons (HNL): N_1, N_2 and N_3

νMSM provides explanation to all experimental facts of BSM





- **Neutrino oscillations:** particles N_2, N_3
- **Baryon asymmetry:** same particles N_2, N_3
  - masses $\geq O(100) MeV$
- **Dark matter:** particle N_1
  - mass $1 - 50$ keV
- **Inflation:** Higgs field coupled to gravity
  - Inflationary parameters for $M_{\text{Higgs}} \sim 126$ GeV in perfect agreement with observations



- **Neutrino Minimal Standard Model (νMSM)**
- Masses of right-handed neutrinos as of other order of masses of other leptons
- Yukawas as those of electron or smaller
- **Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]**

Models with Hidden Sector
(attract currently more attention)

Many theoretical models (portal models) predict new massive light particles which can be tested experimentally

SHiP Physics Paper – Rep.Progr.Phys.79(2016) 124201 (137pp),
SLAC Dark Sector Workshop 2016: Community Report – arXiv: 1608.08632,
Maryland Dark Sector Workshop 2017: Cosmic Visions – arXiv:1707.04591
Report by Physics Beyond Collider (PBC) study group – to be published

Two types of Hidden Particles:

- ✓ ***Light Dark Matter (LDM)***
- ✓ ***Portals (mediators) to Hidden Sector (HS):***
  - *Heavy Neutral Leptons (spin ½, coupling coefficient U^2)*
  - *Dark photons (spin 1, coupling coefficient ε)*
  - *Dark scalars (spin 0, coupling coefficient $\sin\theta^2$)*
  - *Special case (non-renormalizable) Axion Like Particles (ALP)*

Portal operators

- dim 2: Hypercharge U(1) field, $B_{\mu\nu}$: vector portal. New particle - dark photon; renormalisable coupling - kinetic mixing

$$\varepsilon B_{\mu\nu} F'^{\mu\nu}$$

- dim 2: Higgs field, $H^{\dagger}H$: Higgs portal. New particle - "dark" scalar; renormalisable couplings

$$(\alpha_1 S + \alpha S^2)H^{\dagger}H$$

- dim 5/2: Higgs-lepton, $H^{T} L$: neutrino portal. New particles - Heavy Neutral Leptons, HNL; renormalizable couplings

$$y\ H\ N\ L$$

- dim 4: New particles - ALPs (axion like particles), pseudo-scalars: axion portal. Non-renormalizable couplings of the ALPS a to the operators

$$G_{\mu\nu}\tilde{G}^{\mu\nu} \quad \partial_{\mu}J^{\mu}, \text{ etc}$$

suppressed by the coupling Fa.

Properties of Hidden Particles

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

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*
- *May decay to various final states*

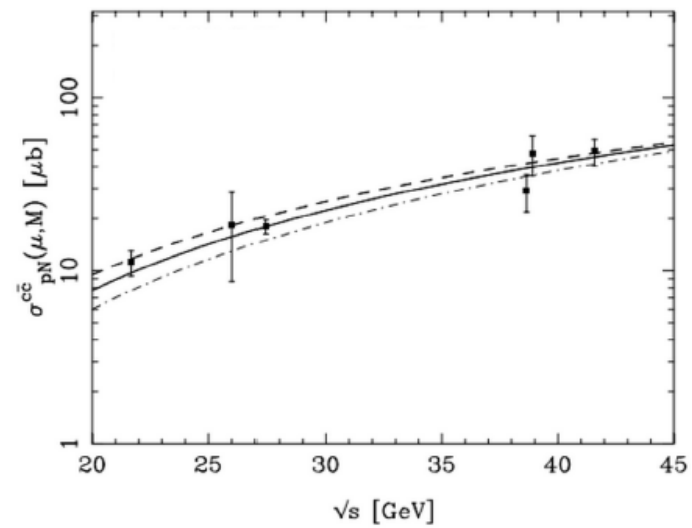
Portal models	*Final states*
HNL	$l^+\pi^-$, l^+K^-, $l^+\rho^-$
Vector, scalar, axion portals	l^+l^-
HNL	$l^+l^-\nu$
Axion portal	$\gamma\gamma$

Full reconstruction and PID are essential to minimize model dependence

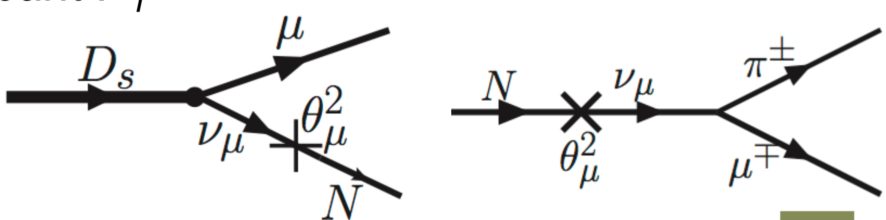
Experimental challenge is background suppression

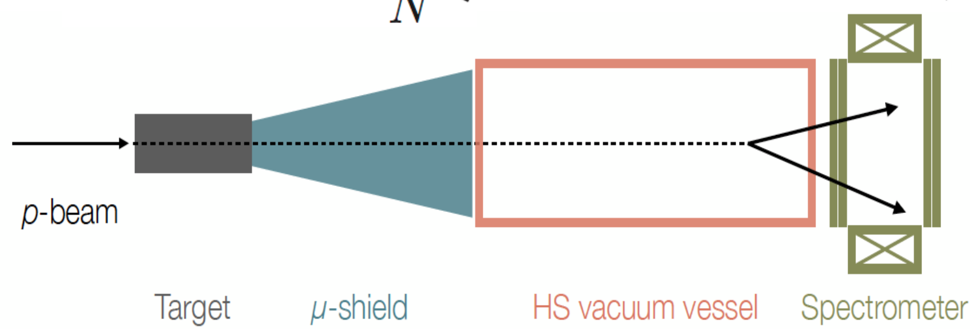
General experimental requirements
to search for decaying Hidden Particles

- ✓ *Particle beam with maximal intensity*
- ✓ *Search for HS particles in Heavy Flavour decays*
  Charm (and beauty) cross-sections strongly depend on the beam energy.
  At CERN SPS: σ(pp→ssbar X)/σ(pp→ X) ~ 0.15
  σ(pp→ccbar X)/σ(pp→ X) ~ 2 10^{-3}
  σ(pp→bbbar X)/σ(pp→ X) ~ 1.6 10^{-7}



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

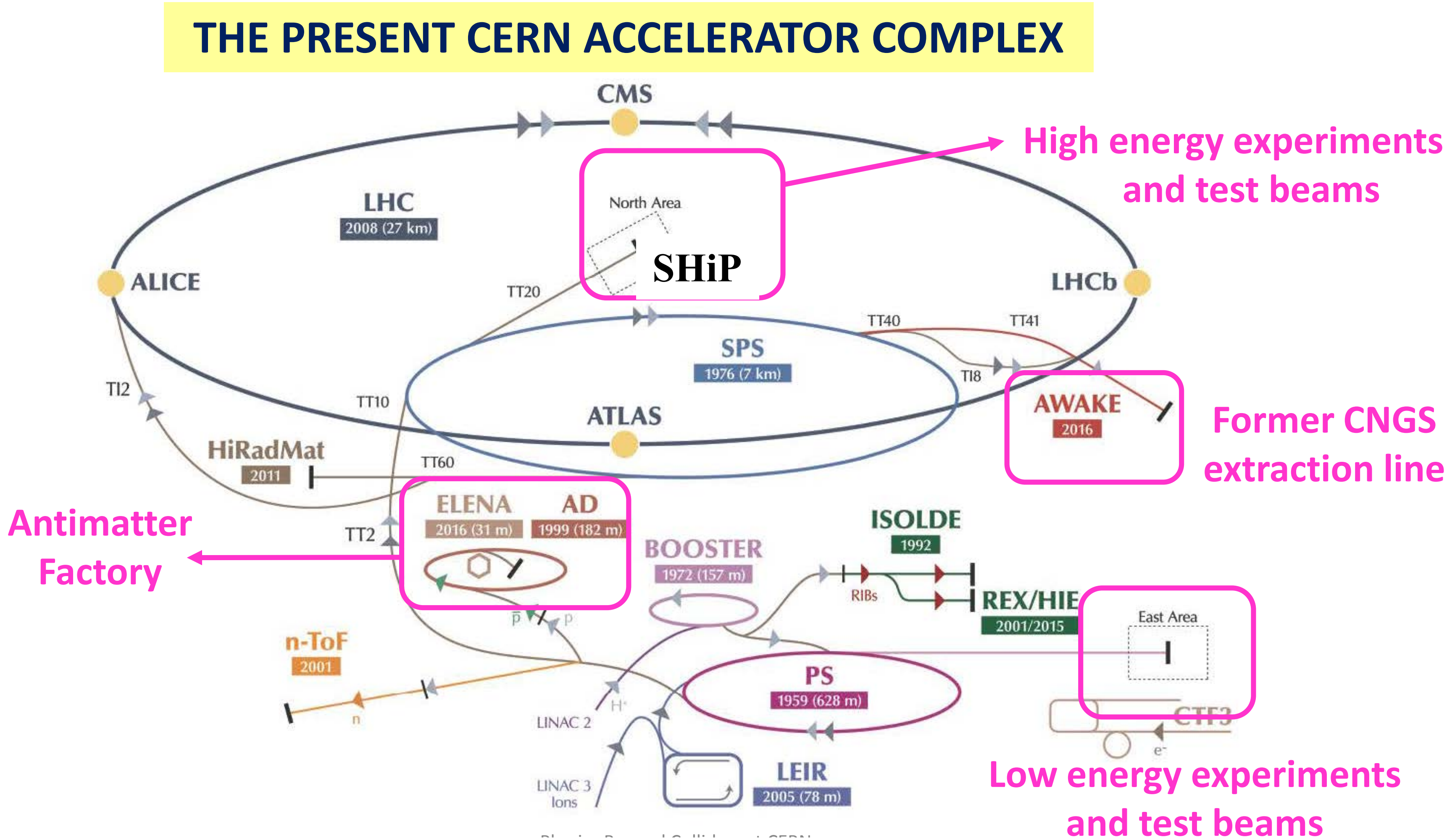




Long decay volume and large geometrical acceptance of the spectrometer are essential to maximize detection efficiency

Detector must be placed close to the target to maximize geometrical acceptance
Effective (and “short”) muon shield is essential to reduce muon-induced backgrounds

The highest intensity can actually be achieved at the LHC's injector: SPS



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

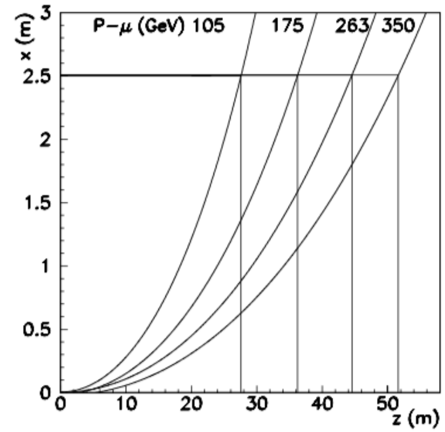
SHiP at CERN @ 400 GeV vs XXX at Fermilab @ 120 GeV

Assume:

- Hypothetical detector XXX has similar size to the SHiP detector
- Slow beam extraction (*)
- The target with the same material (*)
- Full background suppression
- Dedicated to XXX operation (in conflict with neutrino programme)
(*) – technical feasibility to be demonstrated for XXX

	SHiP	XXX 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

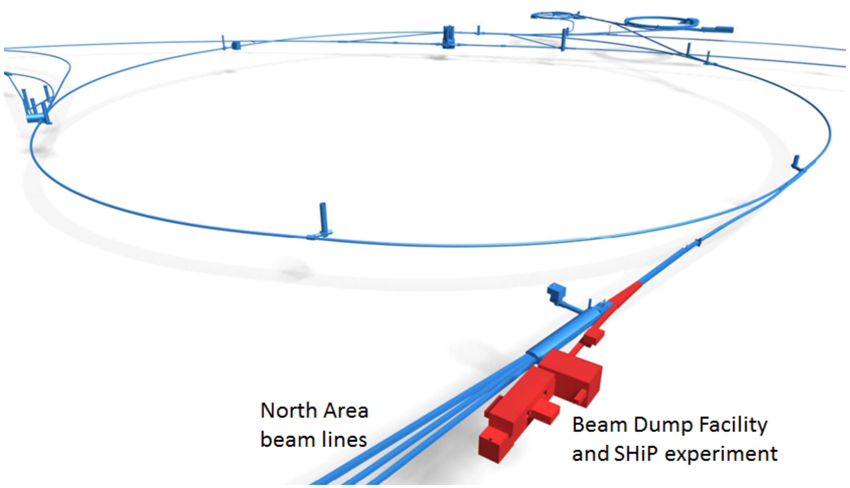
Trajectory of m in Fe(1.8T)

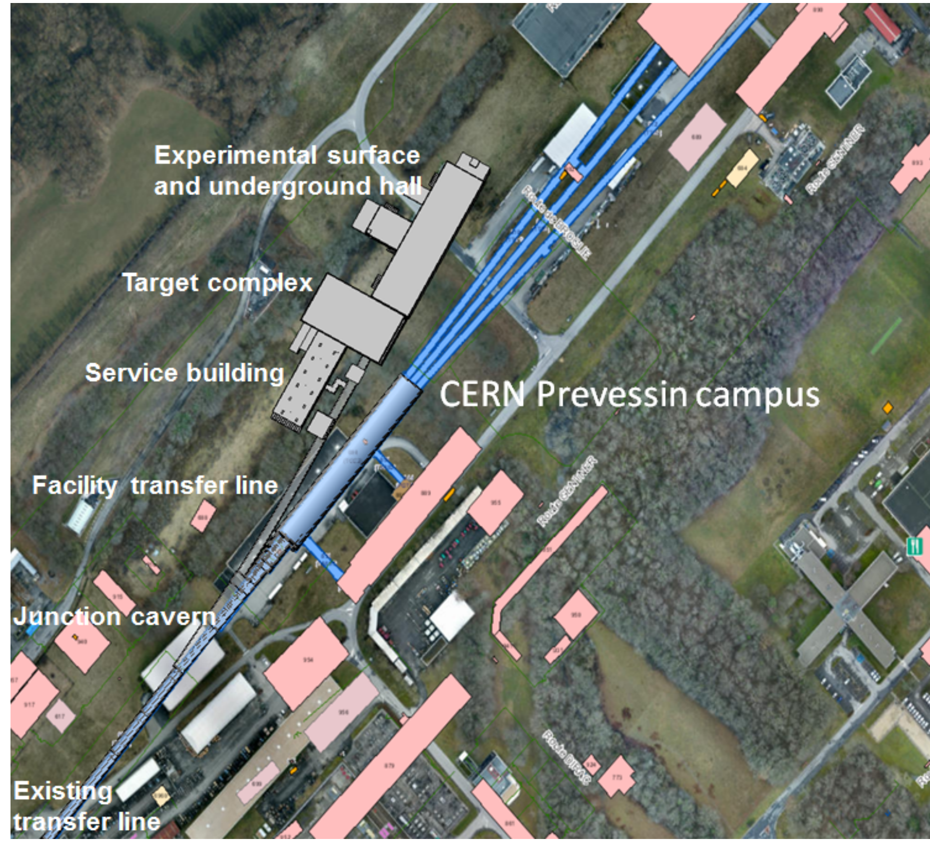


- ✓ ***Similar performance for HS produced in charm decays***
  Sensitivity for HS produced in B decay is severely compromised, σ_{bb} (120/400) = 625
- ✓ ***Really poor prospects for tau neutrino physics at 120 GeV beam energy***
- ✓ ***SPS @ 400 GeV is ideal to perform the physics programme of SHiP***

Beam Dump Facility (BDF) at CERN

✓ ***Location at CERN***
New 400 GeV proton beam line branched off the splitter section of the SPS transfer line to the North Area



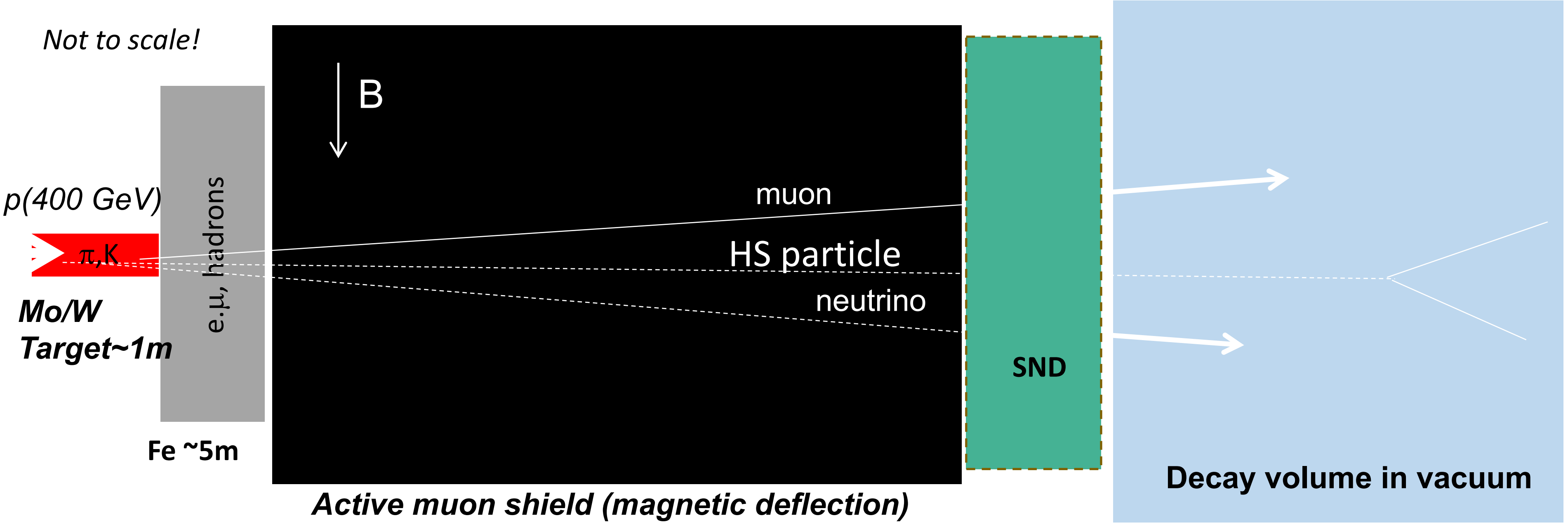


✓ ***Proton yield and beam delivery***
- *Nominal beam intensity* 4×10^{13} *pot per spill*
- *Baseline scenario: annual yield of* 4×10^{19} *pot to the BDF, and* 10^{19} *pot to the other experiments in the North Area, while respecting HL-LHC requirements*
- *SHiP sensitivities assume* 5×10^{20} *pot in five years of nominal operation*

SHiP beam-line
(incompatible with conventional neutrino facility)

Initial reduction of beam induced backgrounds

- *Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in π/K → $\mu\nu$ decays (short λ_{int})*
- *Hadron absorber*
- *Effective muon shield (without shield: muon rate ~10^{11} per spill of 5×10^{13} pot)*
- *Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector*



Multidimensional optimization: *beam energy, beam intensity, background conditions and detector acceptance*

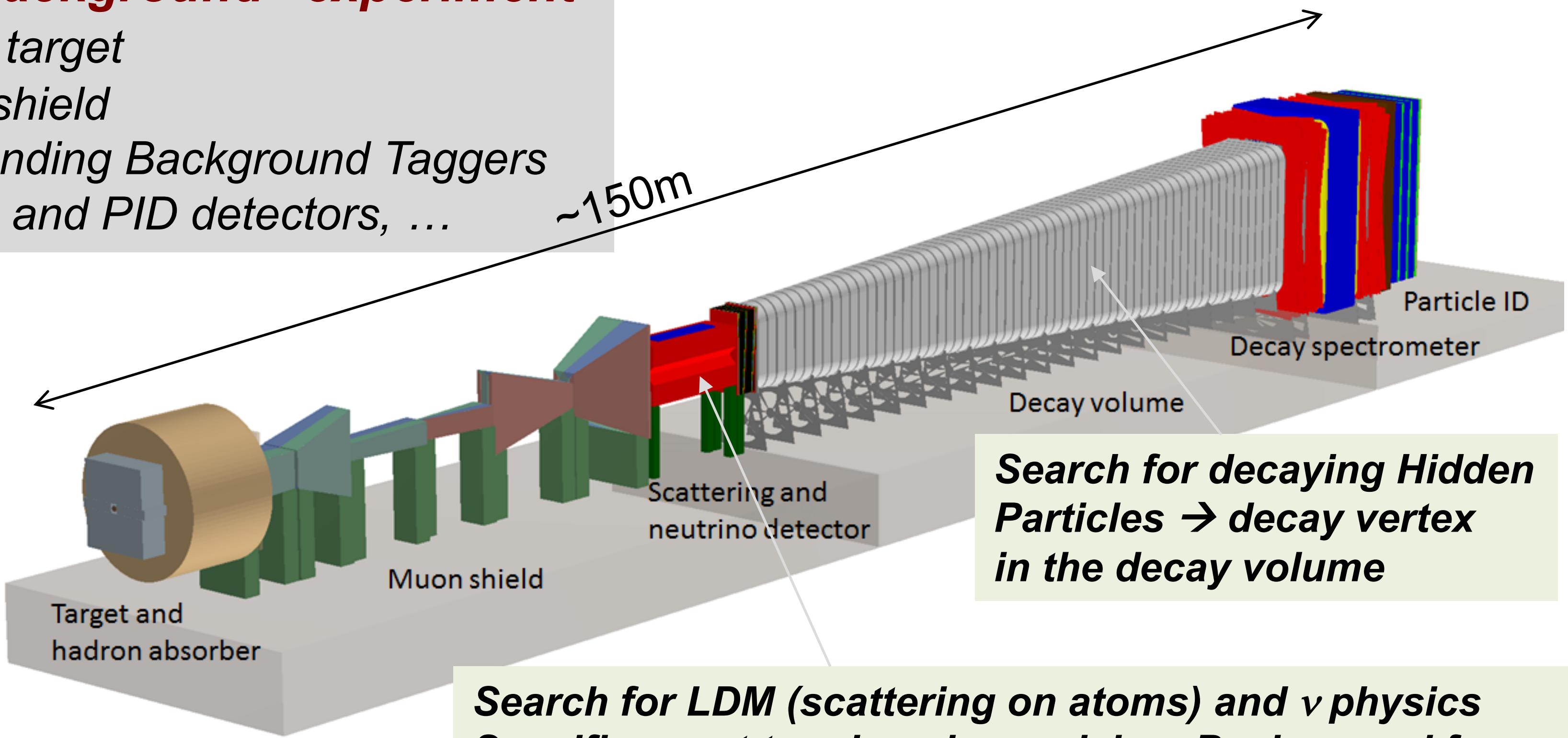
SHiP detector at BDF/CERN

SHiP Technical Proposal: 1504.04956

$>10^{18}$ D, $>10^{16}\tau$, $>5\times10^{15}$ ν_τ for 2×10^{20} pot (in 5 years)

"Zero background" experiment

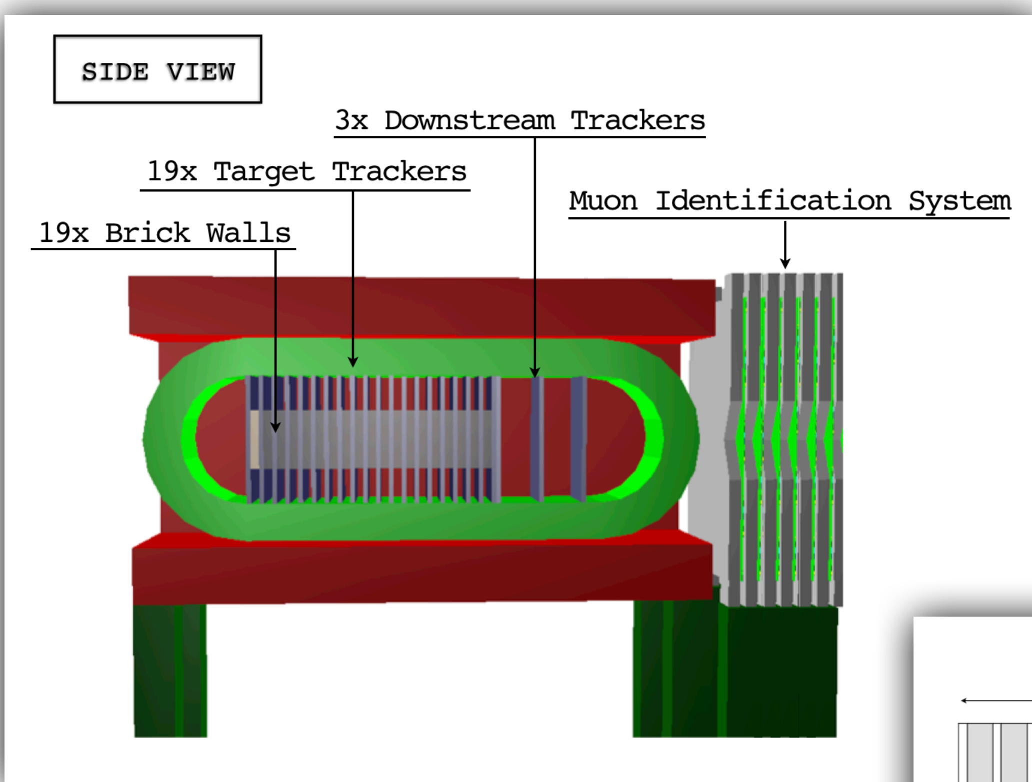
- *Heavy target*
- *Muon shield*
- *Surrounding Background Taggers*
- *Timing and PID detectors, …*



Search for decaying Hidden Particles → decay vertex in the decay volume

Search for LDM (scattering on atoms) and ν physics Specific event topology in emulsion. Background from neutrino interaction for LDM searches can be reduced to a manageable level

SHiP Scattering and Neutrino Detector (SND)



REQUIREMENTS:

High spatial resolution to observe the τ decay (~1 mm)

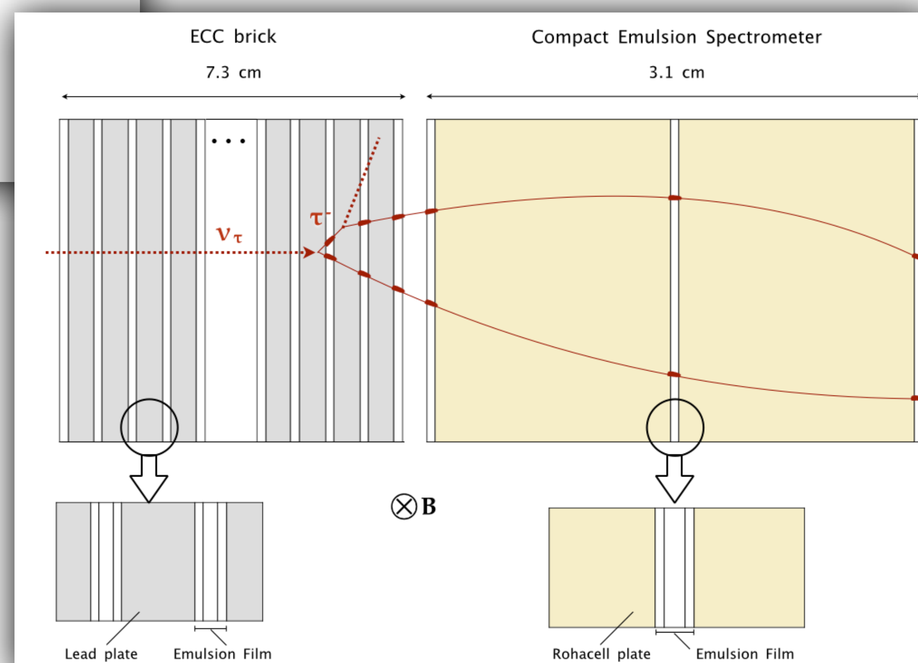
*→ **EMULSION FILMS***

Electronic detectors to give "time" resolution to emulsions

*→ **TARGET TRACKER PLANES***

Magnetized target to measure the charge of τ products

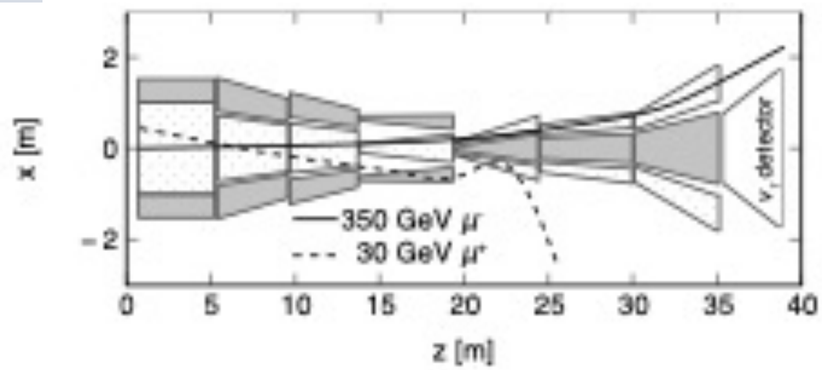
*→ **MAGNET***



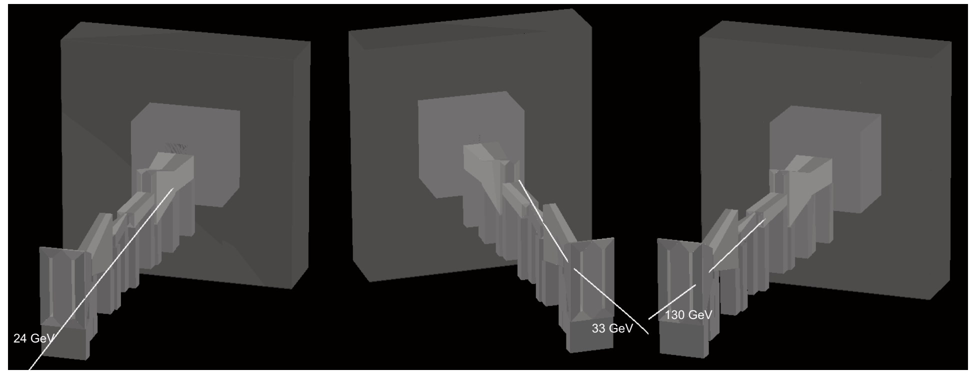
- ✓ *The Emulsion Target exploits the **Emulsion Cloud Chamber (ECC)** technology*
- ✓ *Sensitive Trackers: nuclear emulsions*
- ✓ *Passive material: lead plates*

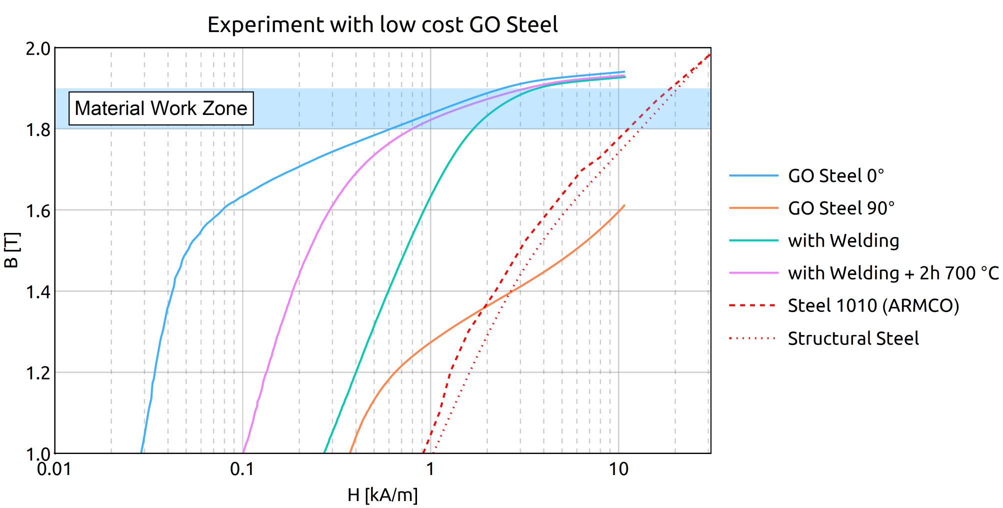
Active Muon Shield

- ✓ *Shield is entirely based on magnetic sweeping*
- ✓ *Initial muon flux ~10^{11} muons / sec*
- ✓ *Residual flux ~50 kHz → negligible occupancy!*

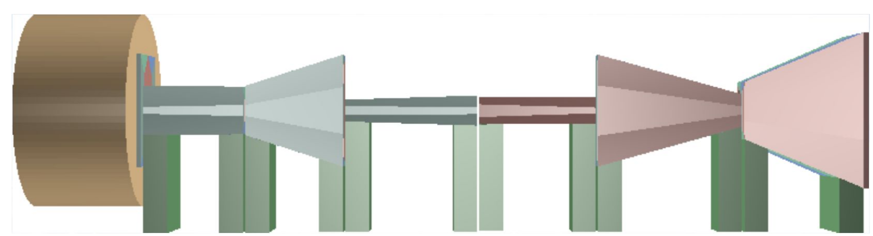


***Huge object:** 5m high, 40m long, Weight ~1500 tons, made of 300 mkm thick sheets of GO steel to achieve 1.8 T field*





Shape optimised using Machine Learning technique



Decaying Hidden Particles

- ***Neutrino portal***
  LFV final states → HNL signal can easily be discriminated against other portals

- ***Vector portal***
- ***Scalar portal***
- ***ALP***

  Note:
  Identical final states with charged particles
  (but different BRs of decay channels
  and different kinematics of decay products)
  → Need significant statistics to discriminate between portals

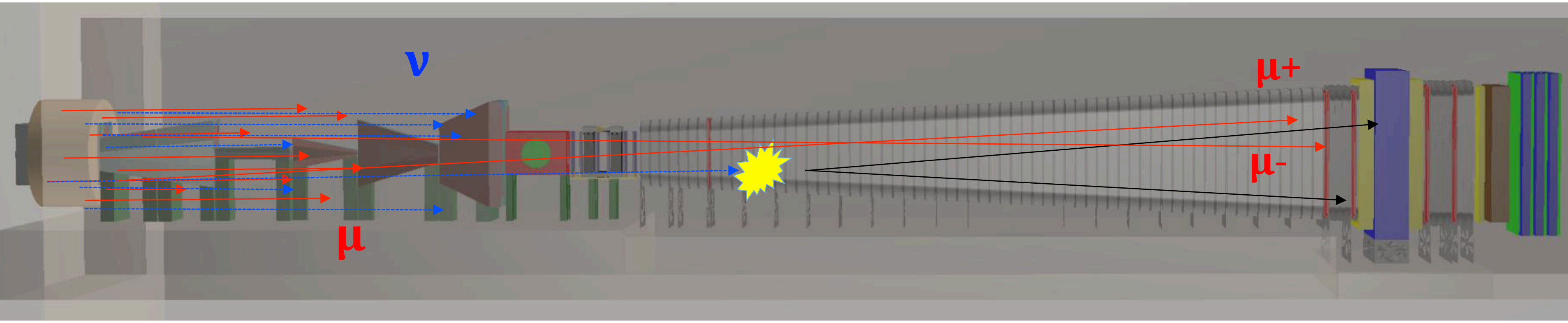
  ALPs can decay to the 2-photon final state with sizeable BR
  → Electromagnetic calorimeter is essential to distinguish between ALP signal and dark photon, or dark scalar

Event selection for decaying Hidden Particles

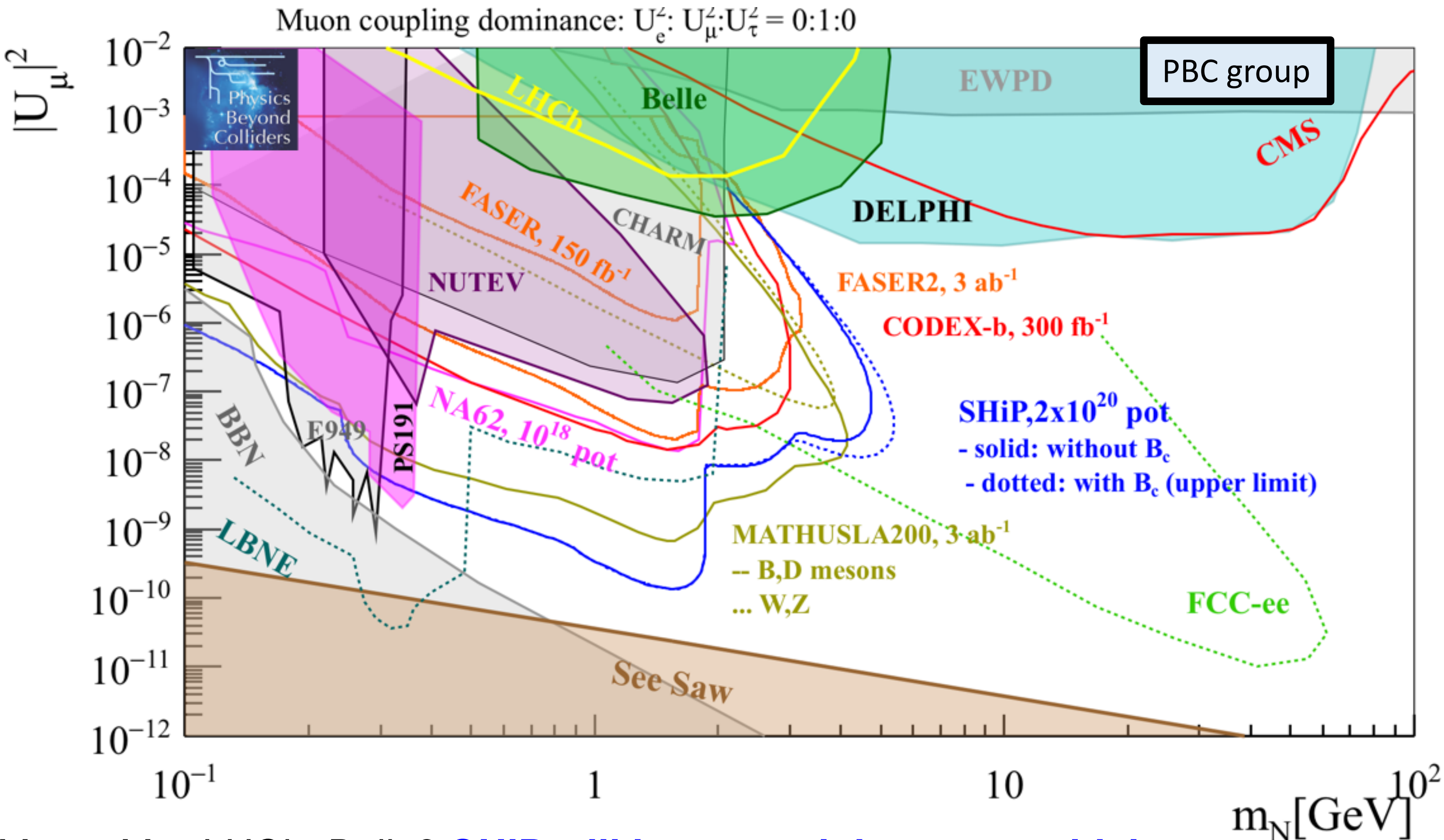
- ✓ *Event selection is based on very high signal efficiency and redundant background suppression*
- ✓ ***All HS models require an isolated vertex in the decay volume***
- ✓ ***Common selection based on IP cut wrt target to ensure model independent search***
- ✓ ***Redundancy cuts:***
  - *- Veto criteria from the taggers*
  - *- PID cuts*
  - *- Time coincidence cut (to reject combinatorial background)*

Three main classes of background:

- ***Neutrino induced***] *interactions in the SND and the walls of decay volume*
- ***Muon inelastic***] *and surrounding infrastructure*
- ***Combinatorial muon*** *from muons survived the muon shield and entered the decay volume*



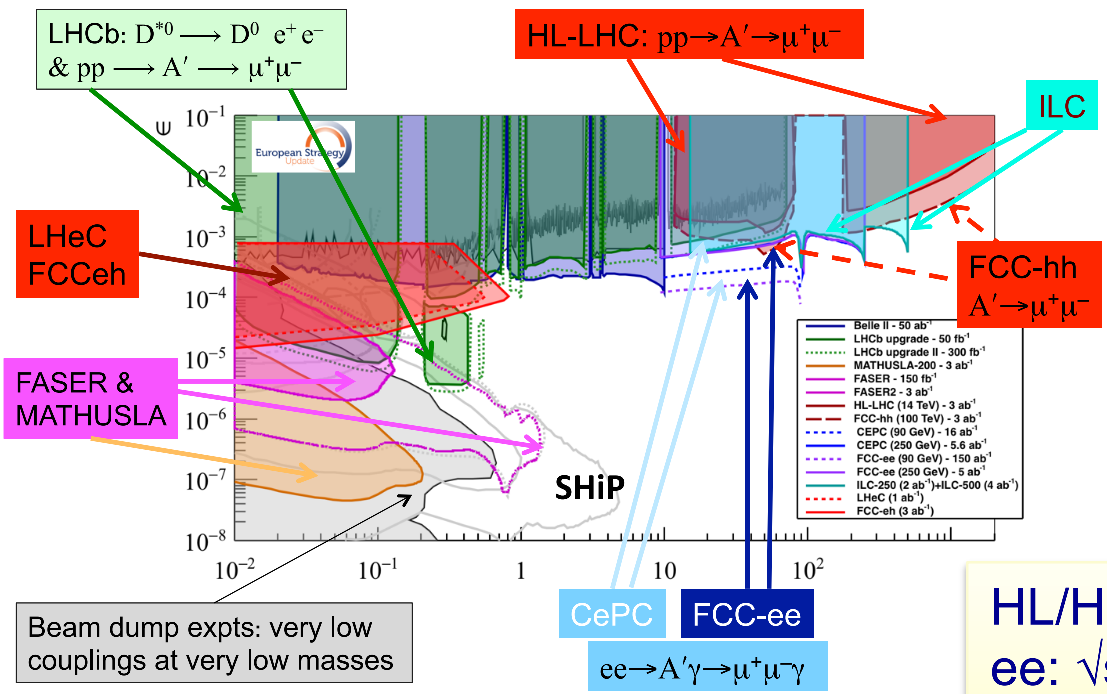
How (and where) to search for HNL (νMSM)



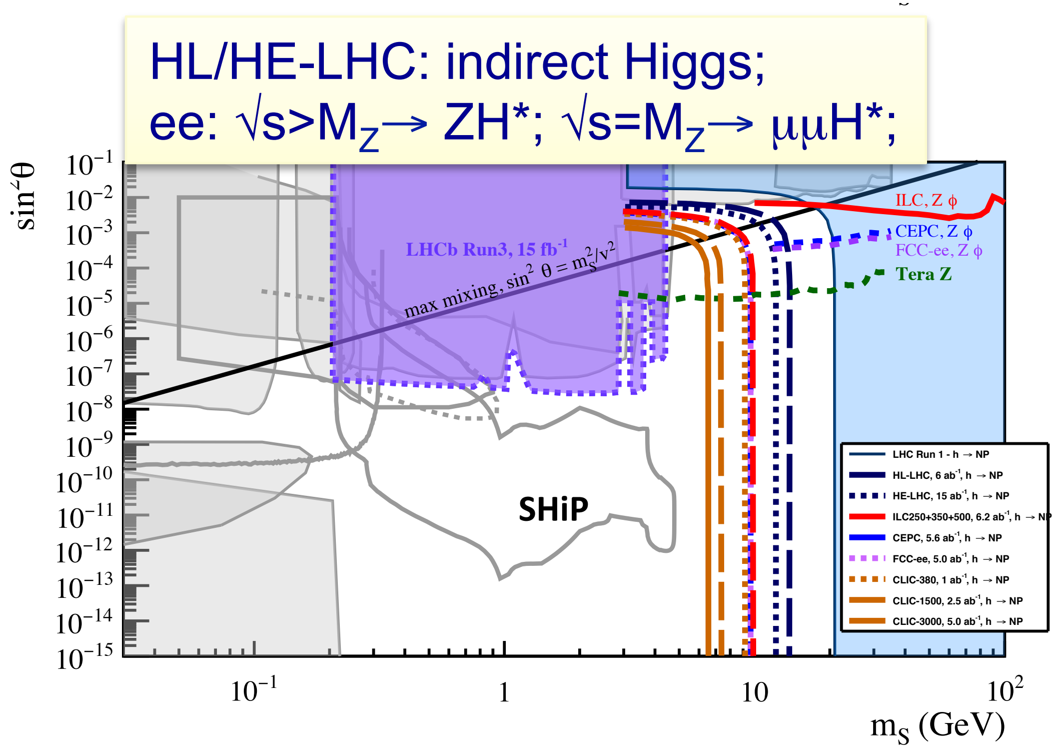
- ✓ $M_{HNL} < M_b$ LHCb, Belle2 **SHiP will have much better sensitivity**
- ✓ $M_b < M_{HNL} < M_Z$ **FCC in e^+e^- mode** *(improvements are also expected from ATLAS / CMS)*
- ✓ $M_{HNL} > M_Z$ **Prerogative of ATLAS/CMS @ HL LHC**

SHiP sensitivity covers large area of parameter space below B mass moving down towards ultimate see-saw limit

How (and where) to search for dark photon/scalar

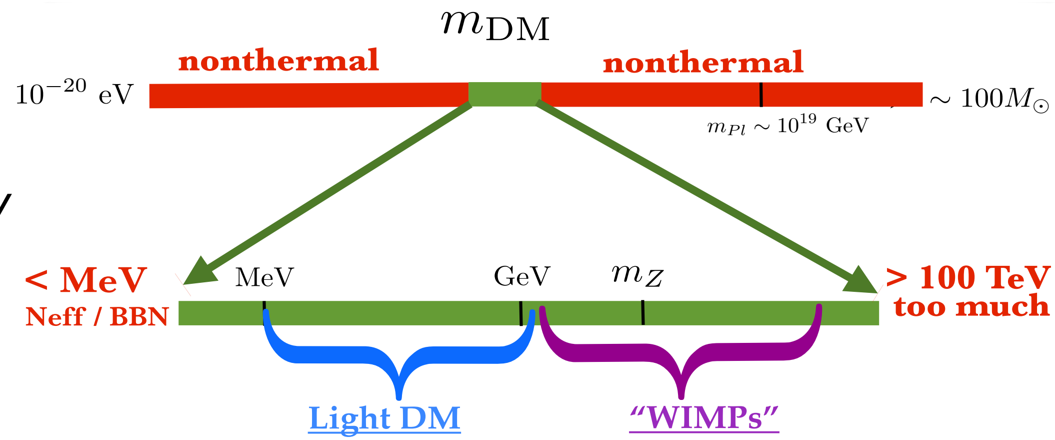


Important part of physics programme at LHC and future colliders

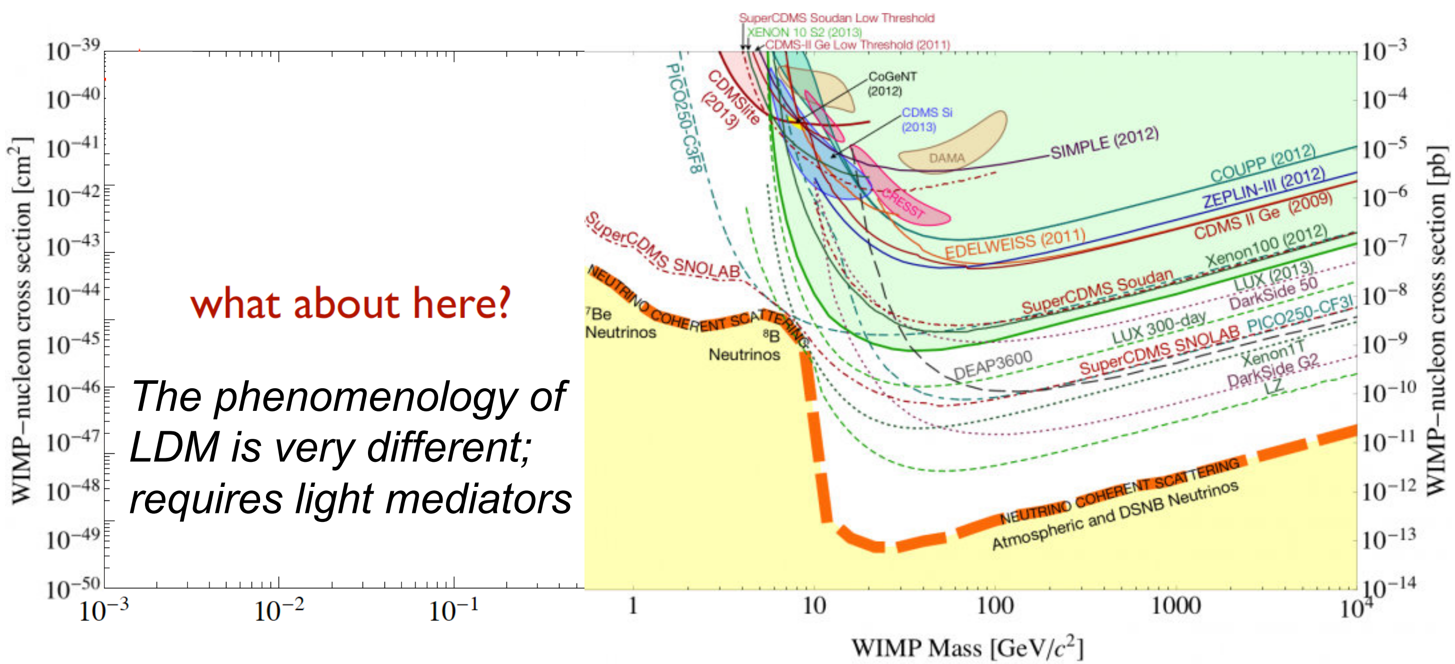


***SHiP sensitivity is unique at small masses** (up to O(5 GeV))*
and very low ε, sin²θ

Light Dark Matter search



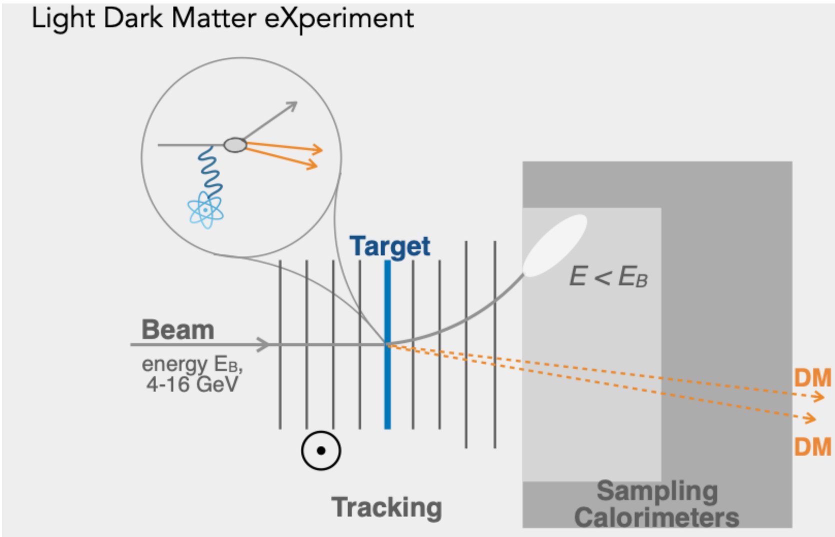
Assuming thermal equilibrium in early universe narrows down the search mass interval



- ✓ *Limited sensitivity for slow galactical DM search at low masses*
- ✓ *Essential to explore a sub-GeV range for LDM*
- ✓ *High intensity beam-dump experiments can play the key role here*

Complementary techniques of searching for relativistic LDM produced at electron and proton beams

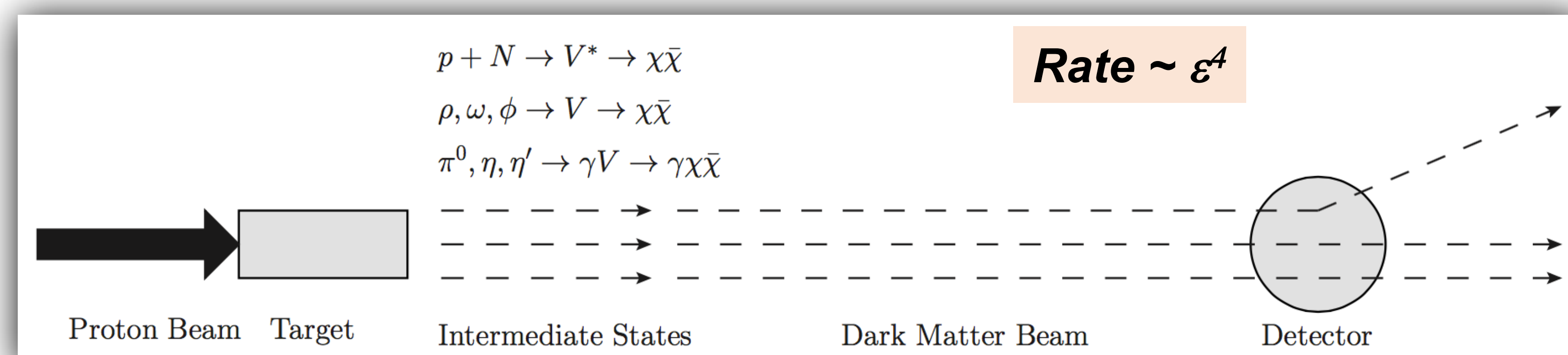
- ✓ *Missing energy & missing (transverse) momentum technique at electron beam → model dependent, applicable only to DM produced in dark photon decays*



Rate ~ ε^2

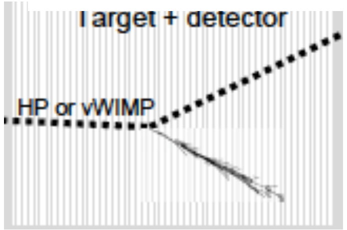
LDMX at SLAC will individually measure up to 10^{16} electrons on target

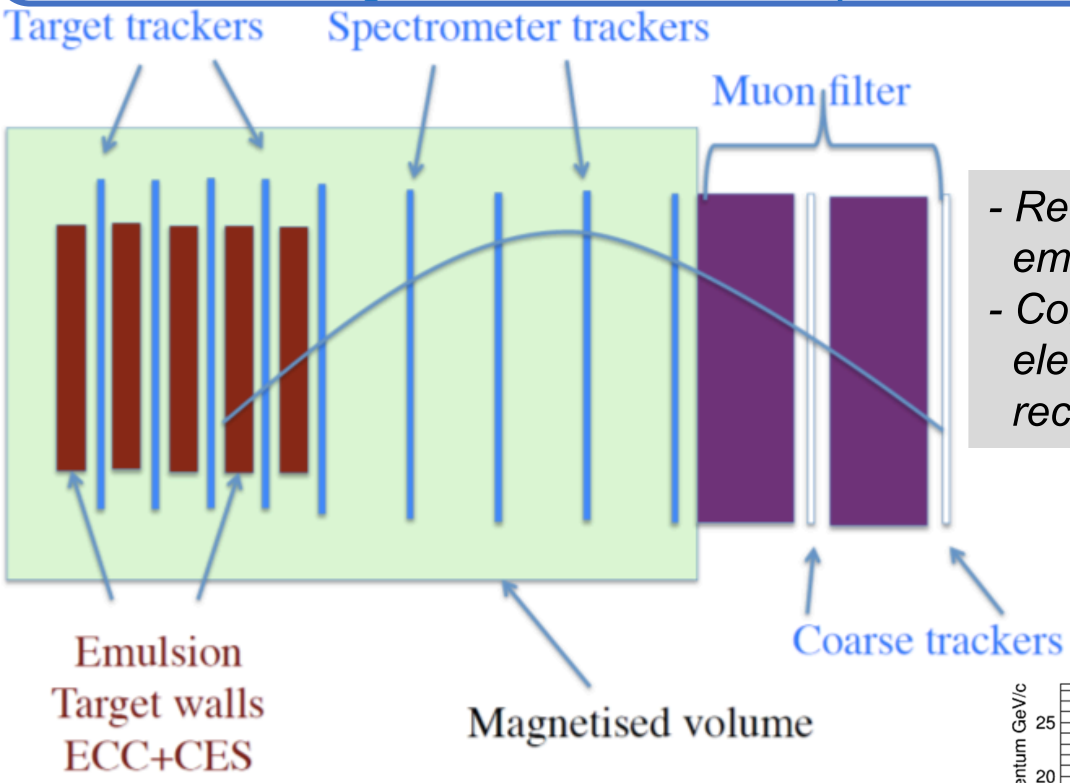
- ✓ *Missing mass technique (Belle II) → requires dedicated low energy mono-photon trigger*
- ✓ *LDM scattering at proton beam dump (SHiP)*



Search for Light Dark Matter

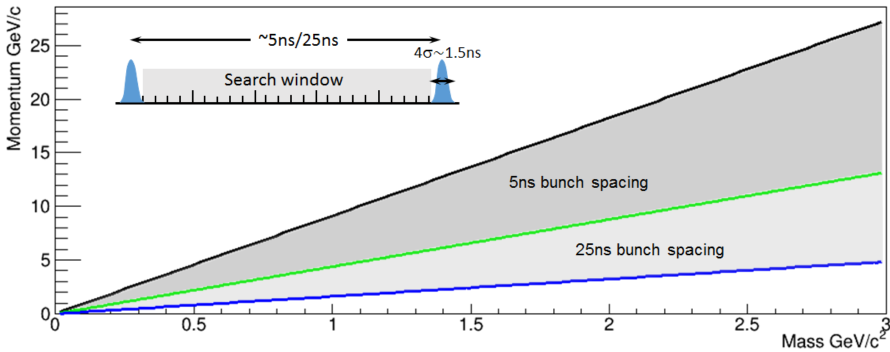
LDM can scatter on atoms of the dense material of the SHiP Scattering and Neutrino Detector (SND)
→ *detection signature: EM shower (or nuclei recoil)*





- *Reconstruction of the EM showers in emulsion demonstrated with OPERA data*
- *Complement emulsion detector with fast electronic Target Tracker to improve electron reconstruction*

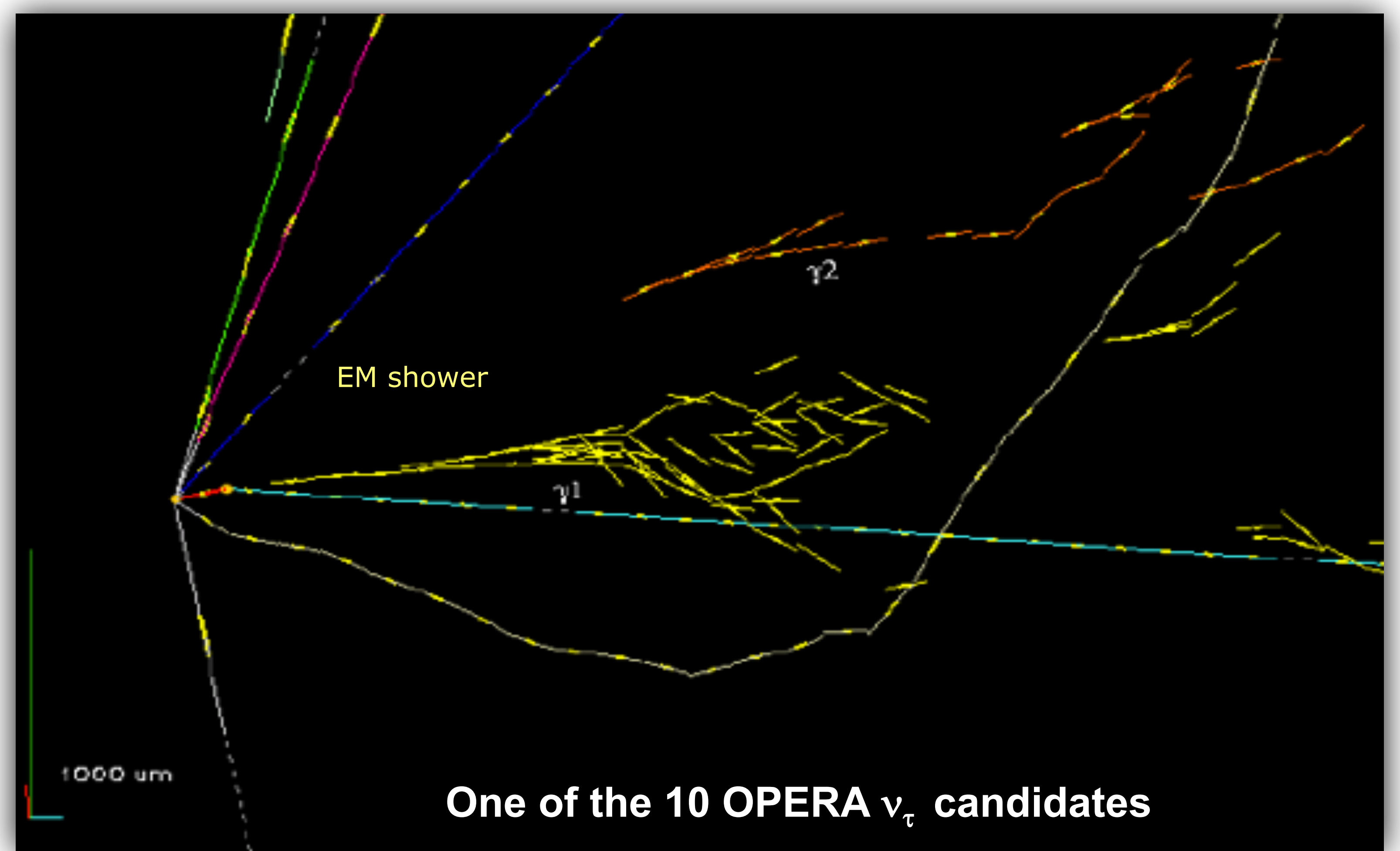
<u>Under study:</u> Elimination of the neutrino background by ToF operating with the SPS bunched beam: 4σ/spacing = 1.5ns / (5 or 25ns) & ~40 m distance from the target → ***Requires 0.5 ns time resolution of the Target Tracker***



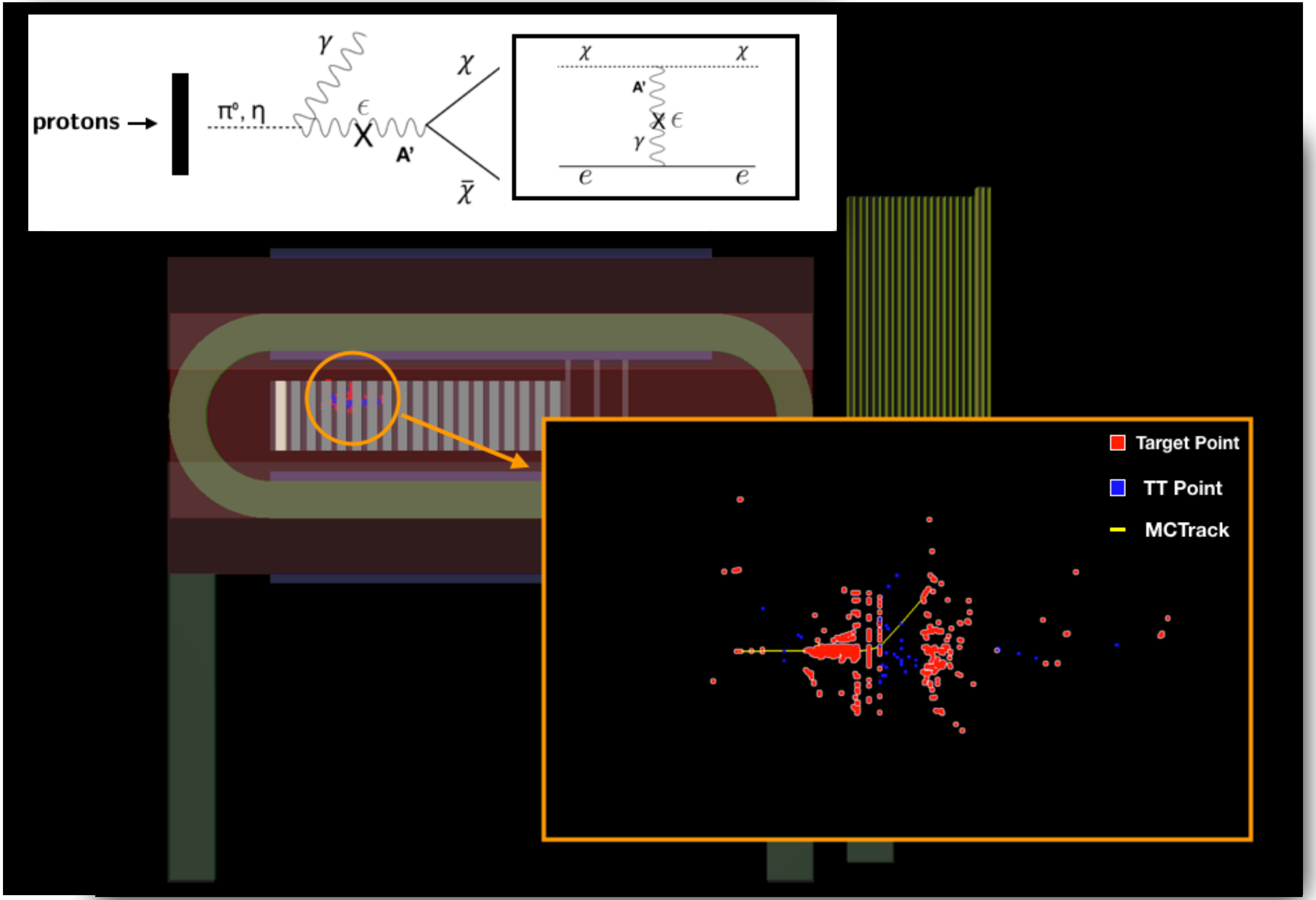
29

LDM detection in the emulsion target

- ***Electron identification:*** *electromagnetic shower reconstruction with calorimetric technique (emulsion + TT → $\sigma_E/E \sim 20\%/\sqrt{E}$)*
- *Angular resolution:* ***mrad***
- ***Micrometric precision*** *in vertices and track reconstruction → precision isolation around LDM interaction vertex*

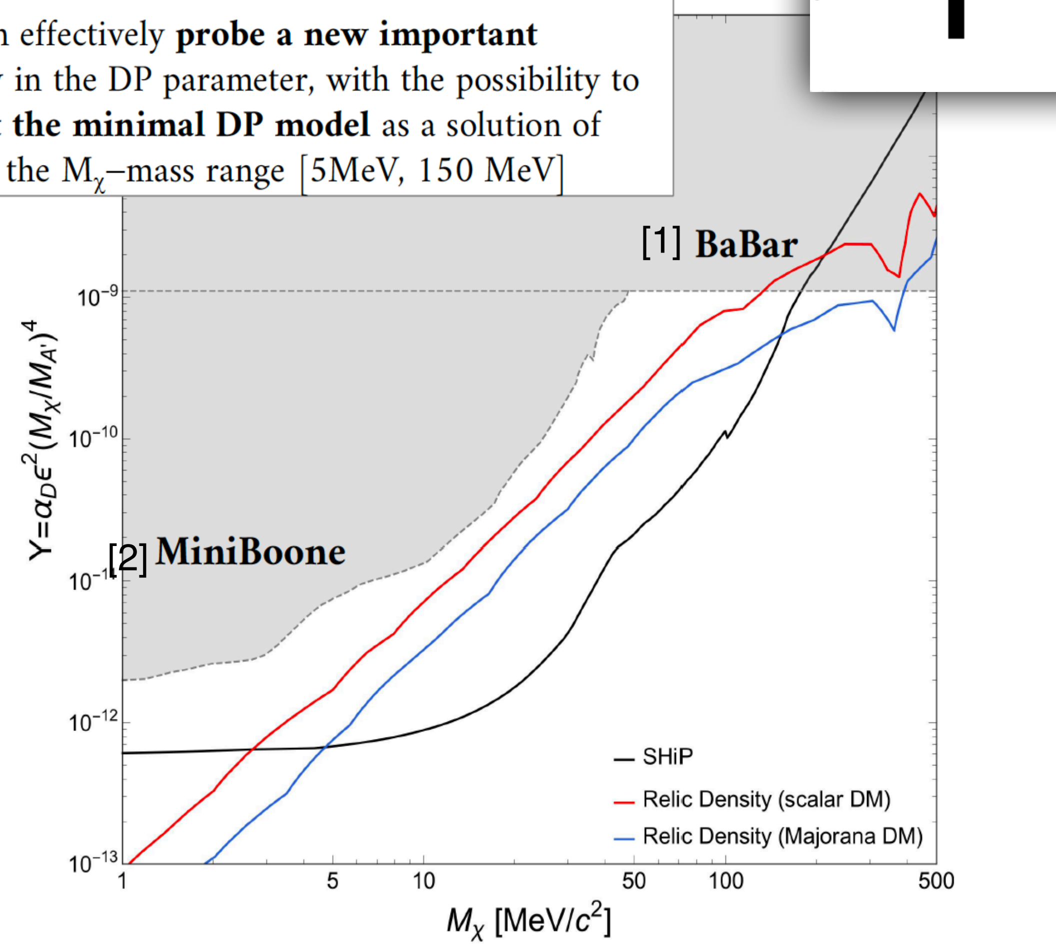


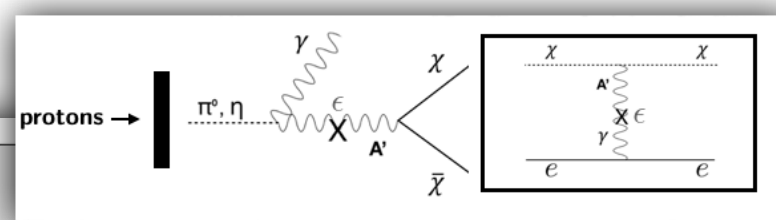
LDM signal events in the emulsion target



SHiP sensitivity to LDM

SHiP can effectively **probe a new important window** in the DP parameter, with the possibility to **rule out the minimal DP model** as a solution of TDM in the M_χ–mass range [5MeV, 150 MeV]





Benchmark model

$$\alpha_D = 0.1 \qquad \left(\frac{M_\chi}{M_{A'}}\right) = \frac{1}{3}$$

$$Y = \alpha_D \epsilon^2 \left(\frac{M_\chi}{M_{A'}}\right)^4$$

[1] arXiv:1702.03327

[2] arXiv:1807.06137

SND@LHC

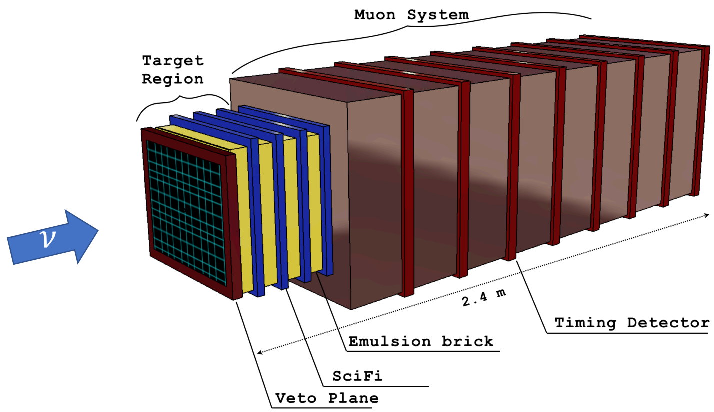
To operate at LHC in the TI18 cavern (~500 m away from the ATLAS IP)

Detector layout

SciFi: σ ~60 μm
TT-emulsion matching
Energy measurement

Plastic scintillator bars
Muon tagging
σ_t <100ps

ECC+SciFi = Wall
4 walls in the target, 380 kg
8 stations for the muon id
On average 9 λ_{int}



Detector optimized to see ν_e, ν_μ and ν_τ

Expected neutrino interactions

Neutrino flavour	Neutrino Flux (incident)	CC Interactions Initial config	CC Interactions Updated config
ν_μ	4.6×10^{11}	62	975
ν_e	5.9×10^{10}	21	332
ν_τ	3.0×10^{9}	1	18
$\bar{\nu}_\mu$	4.0×10^{11}	27	429
$\bar{\nu}_e$	6.2×10^{10}	11	174
$\bar{\nu}_\tau$	2.9×10^{9}	0	7
TOT	9.87×10^{11}	122	1935

Most of them from charm decays

25 fb^{-1}

150 fb^{-1}
Target mass: 850 kg

Incremental detector installation: *(will probably be revised)*

- Emulsion bricks, SciFi, Veto Plane ready by end of 2020
- Four planes of Scintillator bars ready by mid 2021
- Additional four planes of Scintillator bars ready by end of 2021
- After 2022 replace the emulsion target every ~25 fb^{-1}

✓ *SND@LHC EoI submitted to LHCC in mid. February*
✓ *Currently under discussions*

SHiP Collaboration: brief history and future steps

SHIP is currently a collaboration of 54 institutes (out of which 4 associate institutes), including >250 physicists from 18 countries, plus CERN and JINR

- ✓ *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 2019*
- ✓ *SHiP Progress report and CDS report submitted to SPSC in 2019*
  → *Input to the European Strategy consultation, which will hopefully help to take a decision about construction of SHiP in 2020*

SHiP is ready to go for TDR (see Richard's talk)

Conclusions

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

- ✓ ***BDF @ CERN is ideal place to search for Hidden Particles at high energy and high intensity SPS beams.*** *Two complementary strategies are being explored at SHiP, direct observation of the HS decay vertex and LDM detection via its scattering on atoms*

- ✓ ***The rich physics programme to search for Hidden Particles and LFV τ decays at BDF nicely complements searches for NP at the energy frontier and in flavour physics at CERN***