Physics Beyond Colliders

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ALEGRO Workshop
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Acknowledgements: Gaia Lanfranchi

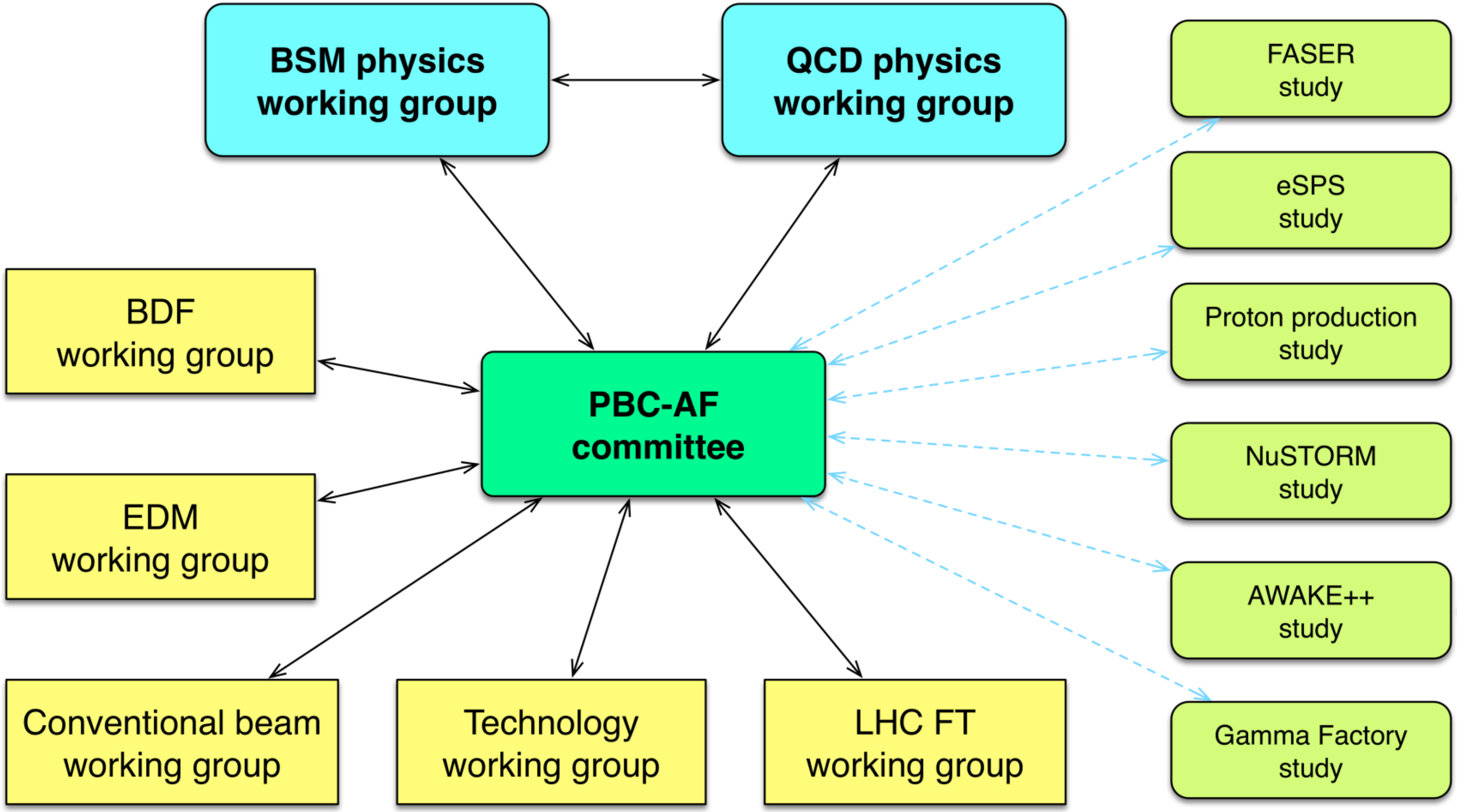
PBC - aim of the exercise

- Maximize physics reach of existing complex
  - New facilities exploiting existing complex
  - Novel exploitation of existing facilities
  - Provide support for novel off-site facilities
  - Harness the existing expertise and resources

Within the limits posed by an already vibrant and diverse physics program!

And evaluate these options motivation and competitiveness in a world wide scape

PBC structure



See Steinar

See Edda

- **Budget line (fellows, material)**
- **Fellows: Civil Engineering, Integration, Beam Transfer, Radiation Protection, CV, Target development, Accelerator physics, Magnets**

Physics Beyond Colliders: BSM experimental programme

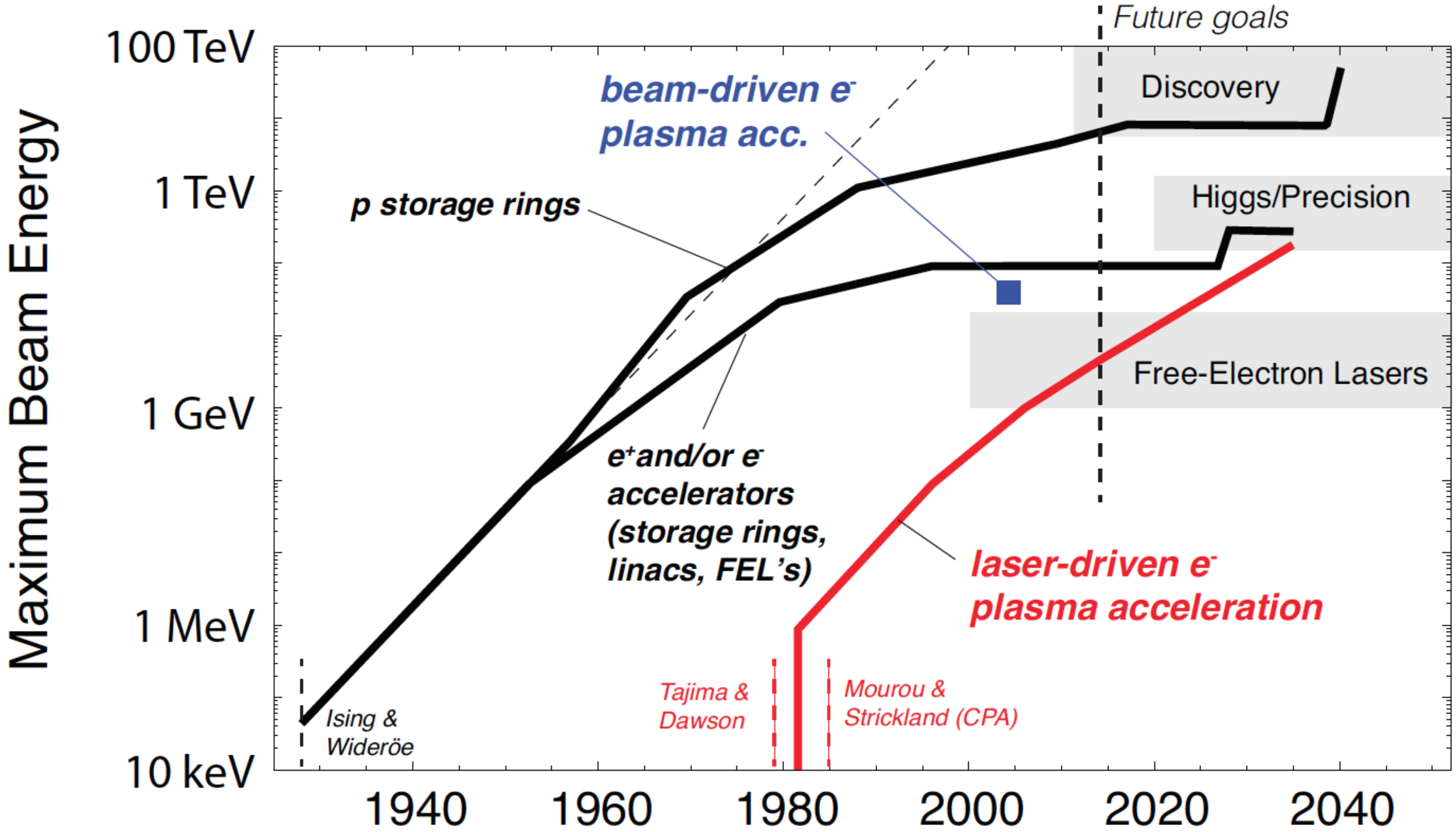
The projects considered in the BSM WG have been classified in the terms of sensitivity to benchmark cases in a given mass range. Since the TeV scale is very well explored at the LHC, we focus on:

sub-eV range: search for axions, Axion-like particles with:
- gluon coupling: protons and deuteron EDMs or in charmed baryons MDMs/EDMs
- photon coupling with axion helioscopes or laboratory experiments (LSW).

MeV-GeV range: search for RH neutrinos below the EW scale, Axion-Like Particles, Light Dark Matter and corresponding light mediators (Dark Photons, Dark Scalars, etc) at extracted beams or at the LHC interaction points.

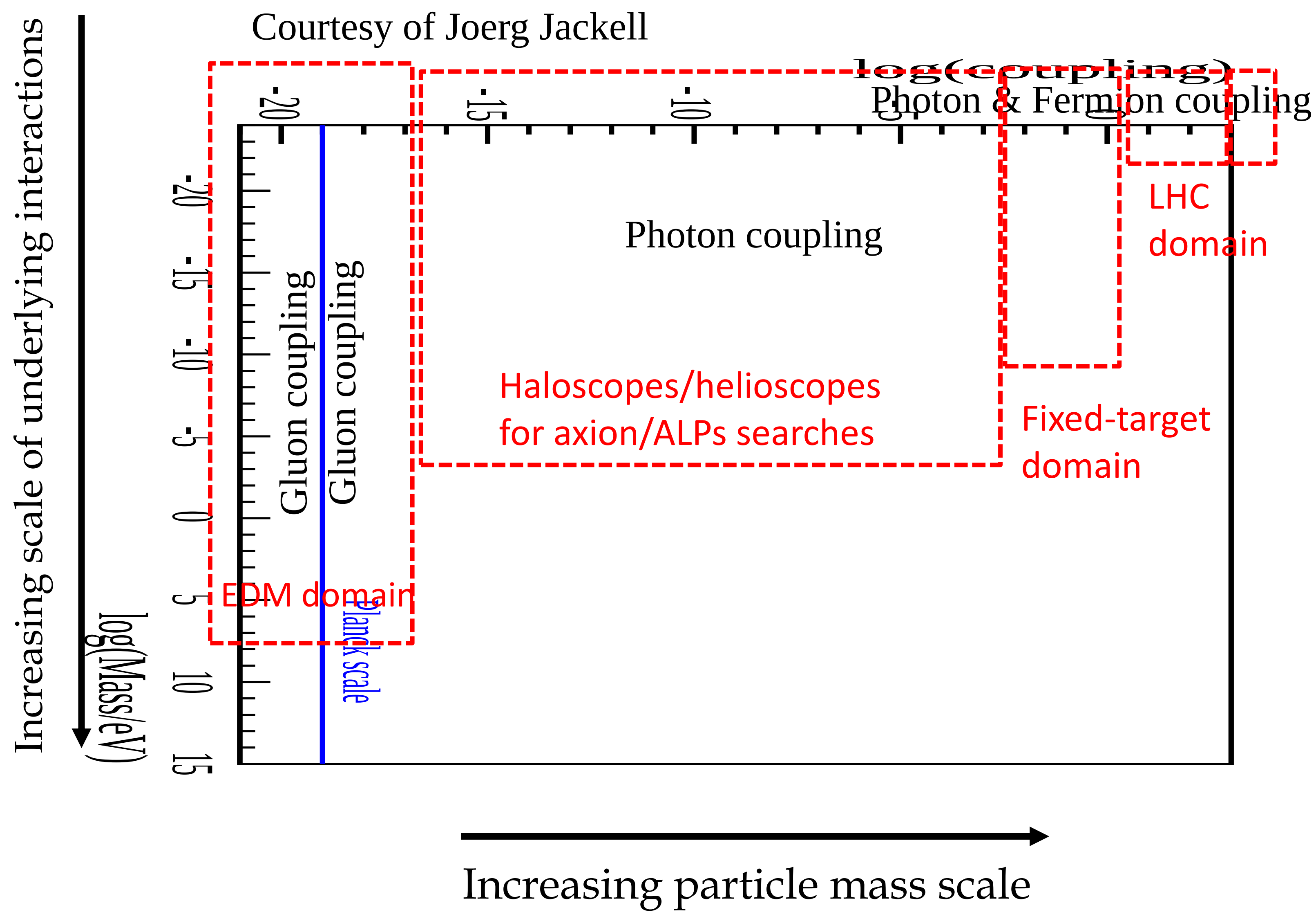
>>TeV range:
Search for NP in clean and very rare flavor processes or in EDMs as probe of > 100 TeV NP scales, if originated by new sources of CPV.

Physics landscape



Ralph Assmann

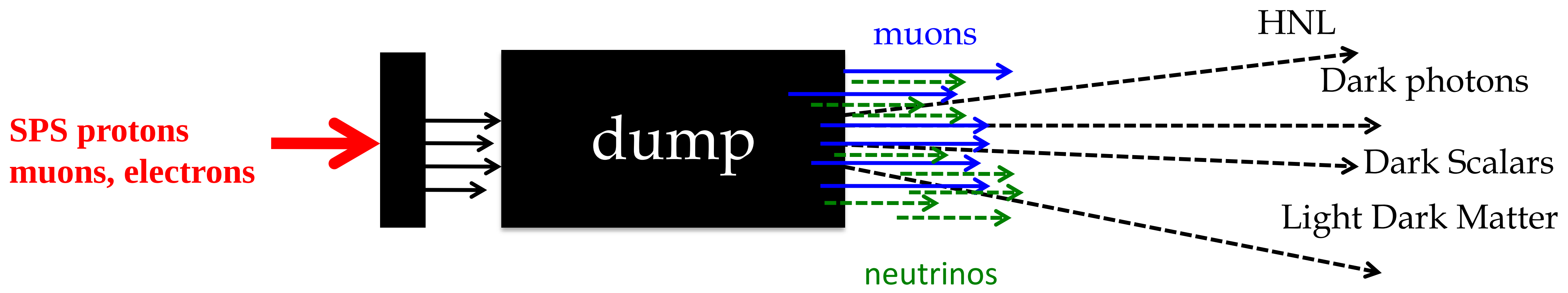
Starting to quantify a comprehensive picture



Projects considered in the BSM WG

Proposal	physics case	beam line	beam type	beam yield
sub-eV range:				
IAXO	axions/ALPs (photon coupling)	–	axions from sun	–
ALPS-III	axions/ALPs (photon coupling)	laboratory	LSW	–
CPEDM	p, d EDM,	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons MDMs, EDMs	LHCb IP	7 TeV p	–
MeV-GeV range:				
SHiP	ALPs, Dark Photons, Dark Scalars, LDM, HNLs	BDF	400 GeV p	$2 \cdot 10^{20}$/5 years
NA62^{++}	ALPs (photon, fermion coupling) Dark Photons, Dark Scalars, HNLs	K12	400 GeV p	up to $3 \cdot 10^{18}$/year
NA64^{++}	ALPs (which couplings?) Dark Photons, Dark Scalars, LDM	H4	100 GeV e^-	$5 \cdot 10^{12}$ eot/year
	$+ L_\mu - L_\tau$	M2	160 GeV μ	$10^{12} - 10^{13}$ mot/year
	+ CP, CPT, leptophobic DM	H2-H8, T9	$\sim$ 40 GeV π, K, p	$5 \cdot 10^{12}$/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8 (SLAC) -16 (eSPS) GeV e^-	$10^{16} - 10^{18}$ eot/year
RedTop	Dark Photon, Dark scalar	CERN PS	1.8 or 3.5 GeV	10^{17} pot
MATHUSLA	Dark Scalar, Dark Photon, HNLs,..	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
FASER	Dark Photon, Dark Scalar, ALPs	ATLAS IP	14 TeV p	3000 fb^{-1}
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
Codex-b	Dark Scalar, Dark Photons, ...	LHCb IP	14 TeV p	300 fb^{-1}
> TeV range:				
KLEVER	$K_L \to \pi^0 \nu \bar{\nu}$	P42	400 GeV p	$5 \cdot 10^{19}$ pot /5 years
TauFV	LFV τ decays	BDF	400 GeV p	5% of the SHiP yield

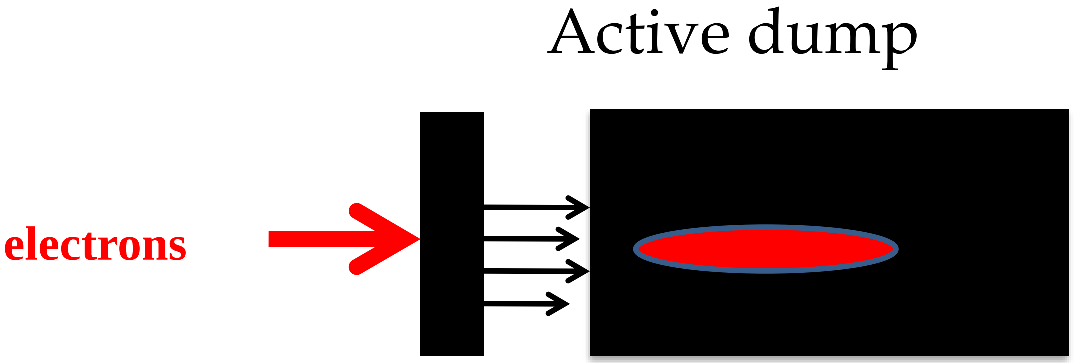
Search for long-lived particles in the MeV-GeV range with "DUMP" experiments



Technique used by NA62^{++}, SHiP, NA64^{++}
(and indirectly also by MATHUSLA, FASER, CodexB, MilliQan)

Search for long-lived particles in the MeV-GeV range: "ACTIVE DUMP" experiments

Any discrepancy between the energy of the electron measured before and in the active dump would be sign of the production of some non-interacting particles, as for example Dark Matter

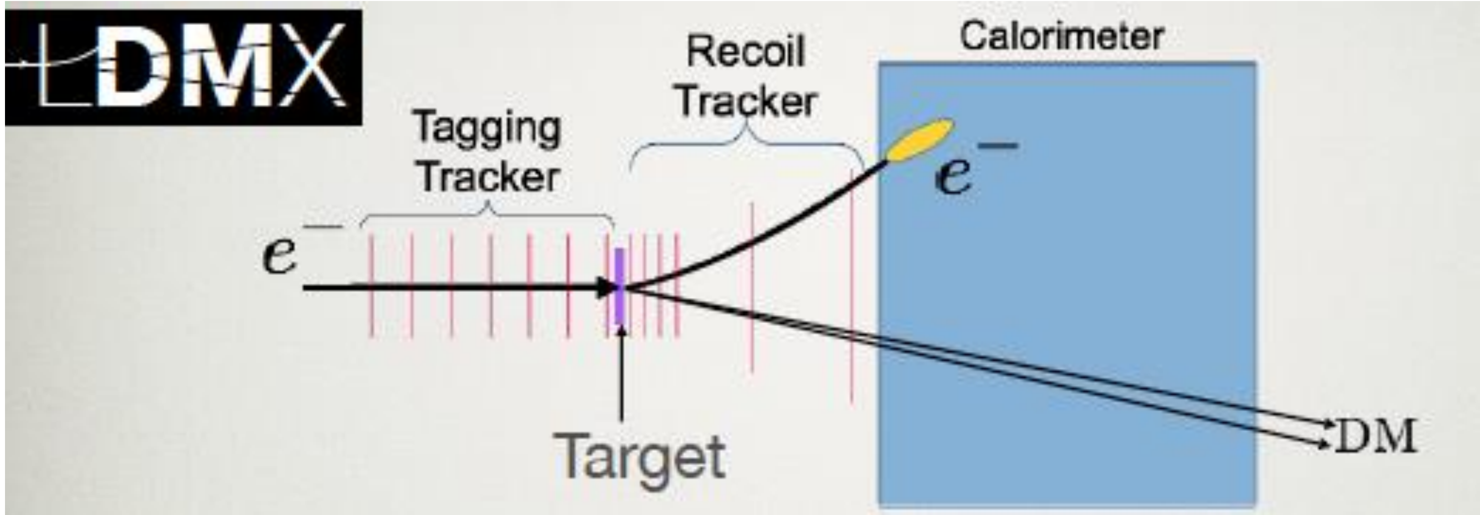


Missing Energy technique mainly used by NA64

electromagnetic calorimeter serves as an active beam dump

Search for long-lived particles in the MeV-GeV range : “MISSING MOMENTUM” technique

Missing momentum:
any discrepancy between the momentum of the electron/muon measured before and after the target would be sign of the production of some non-interacting particle, as for example Dark Matter



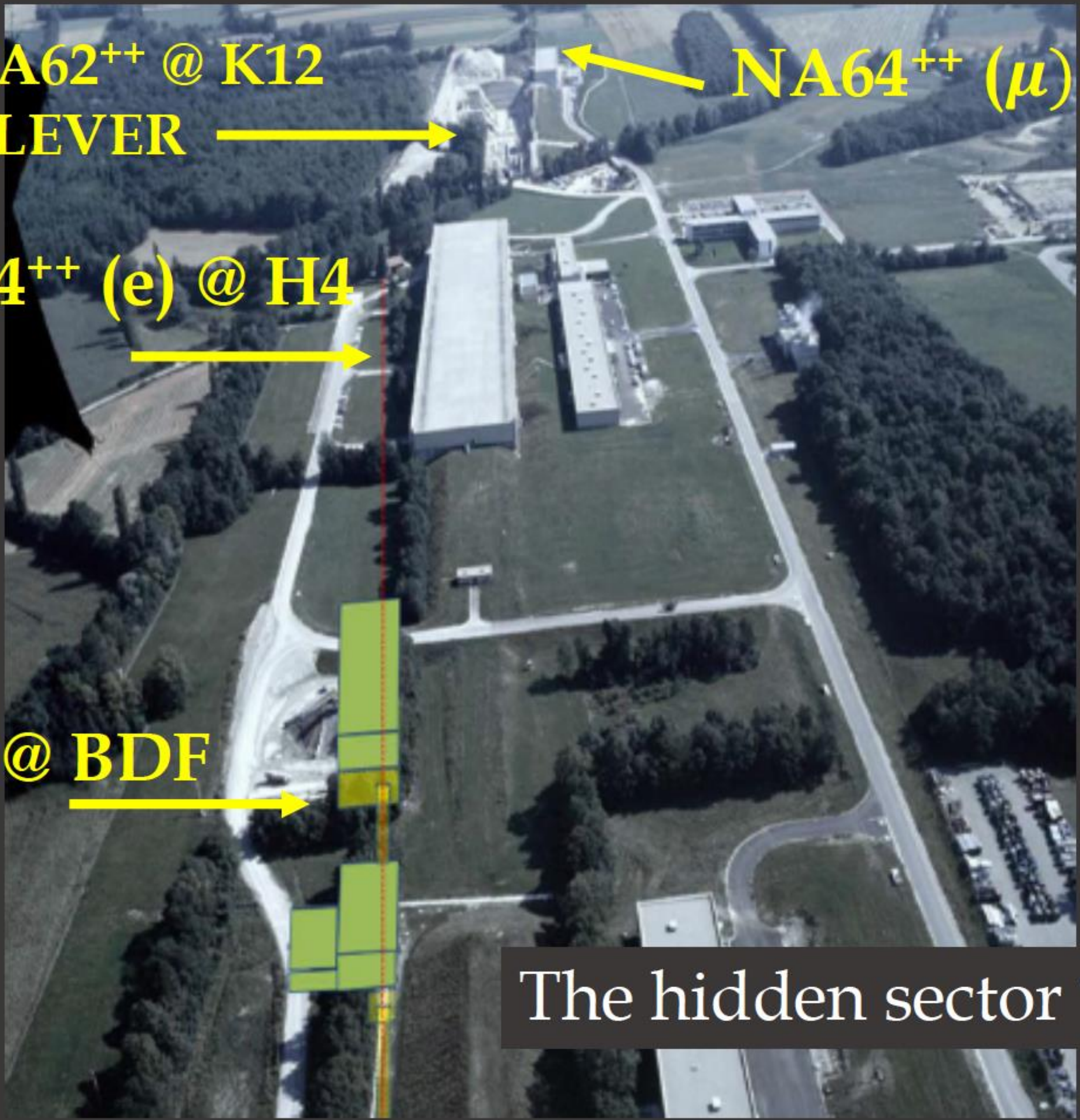
Missing momentum technique mostly used by e.g. LDMX @ eSPS

PBC accelerator side - main themes

- Exploitation of SPS/North Area (HSC)
  - options, required developments, compatibility
- Novel approaches
  - Gamma Factory, EDM storage ring, AWAKE++, eSPS
- LHC
  - Long Lived Particles, LHC-FT
- Technology
  - various options (VMB, LSW, IAXO…)

- Studies clearly at different stages
- Nothing too radical - such as a new proton driver (SPL, PS2 etc.)…
- Appropriate given the medium to long term priorities of the lab

Aerial picture of the North Area



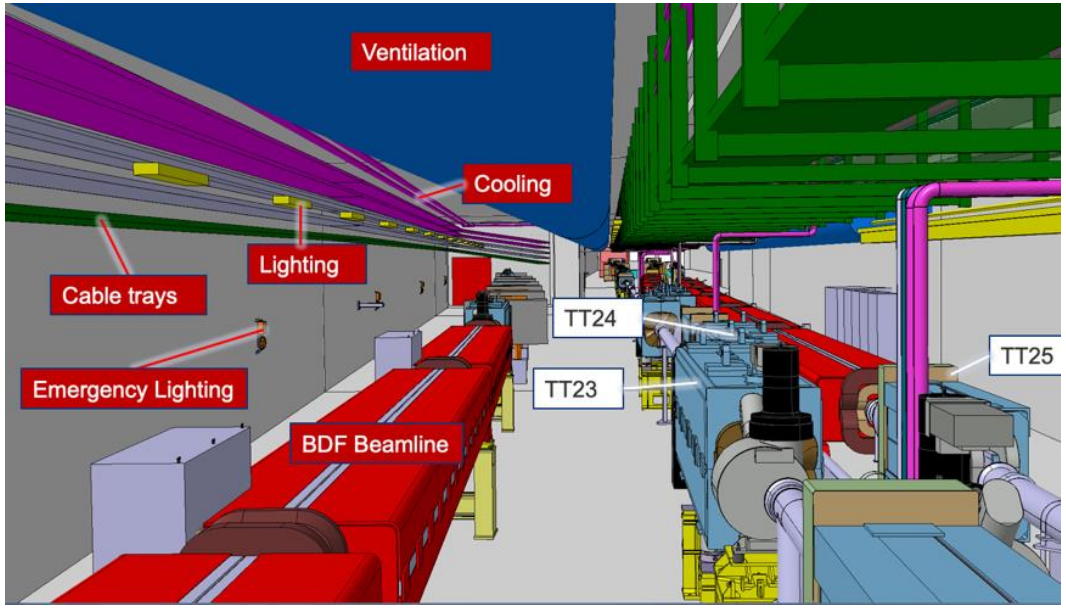
HSC

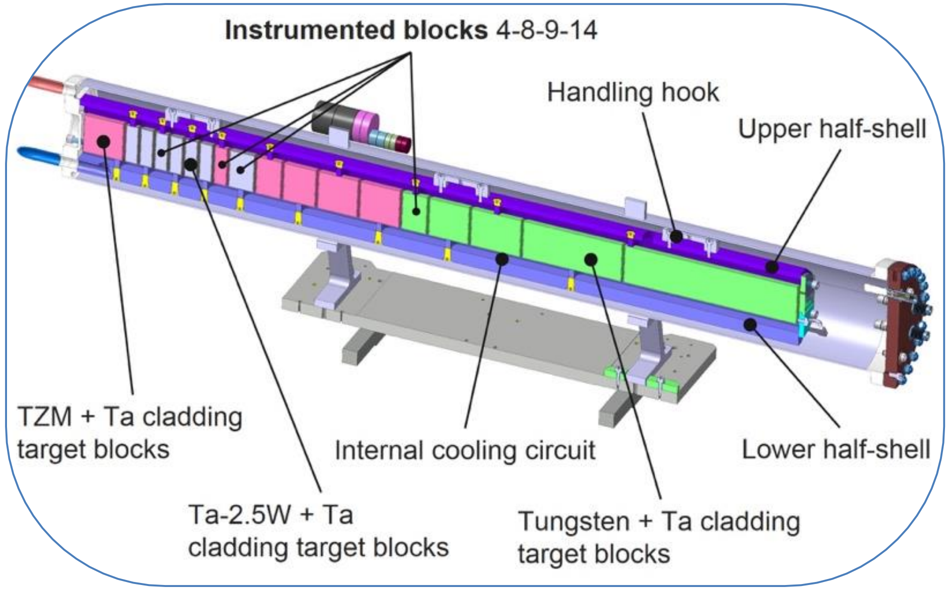
The hidden sector "campus"

Gaia Lanfranchi

BDF (SHiP, tauFV)

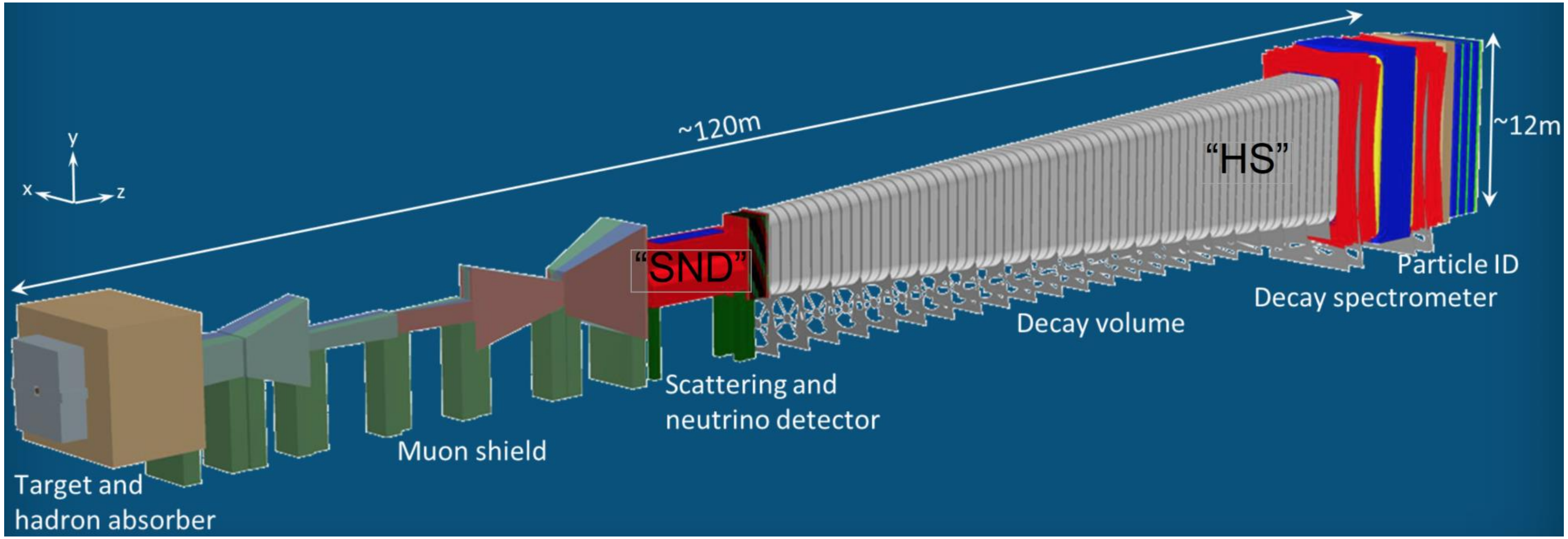
- Comprehensive Design Study in preparation
- Technically feasible, operationally interesting
- Time-line: ideally start CE before LS3
- Material cost: ~160 MCHF





SHiP@BDF

Beam:
400 GeV/c protons
$4x10^{13}$ pot/spill
$2x10^{20}$ pot/5 years



Physics cased based on $2x10^{20}$ protons on target (5 years of nominal operation)
Signal yields from $>10^{18}$ D mesons, $>10^{16}$ tau, $>10^{21}$ photons (>100 MeV)

Dual detector system:

1. Search for HS decays ("HS detector")
2. Neutrino physics and search for LDM recoil signatures ("SND")

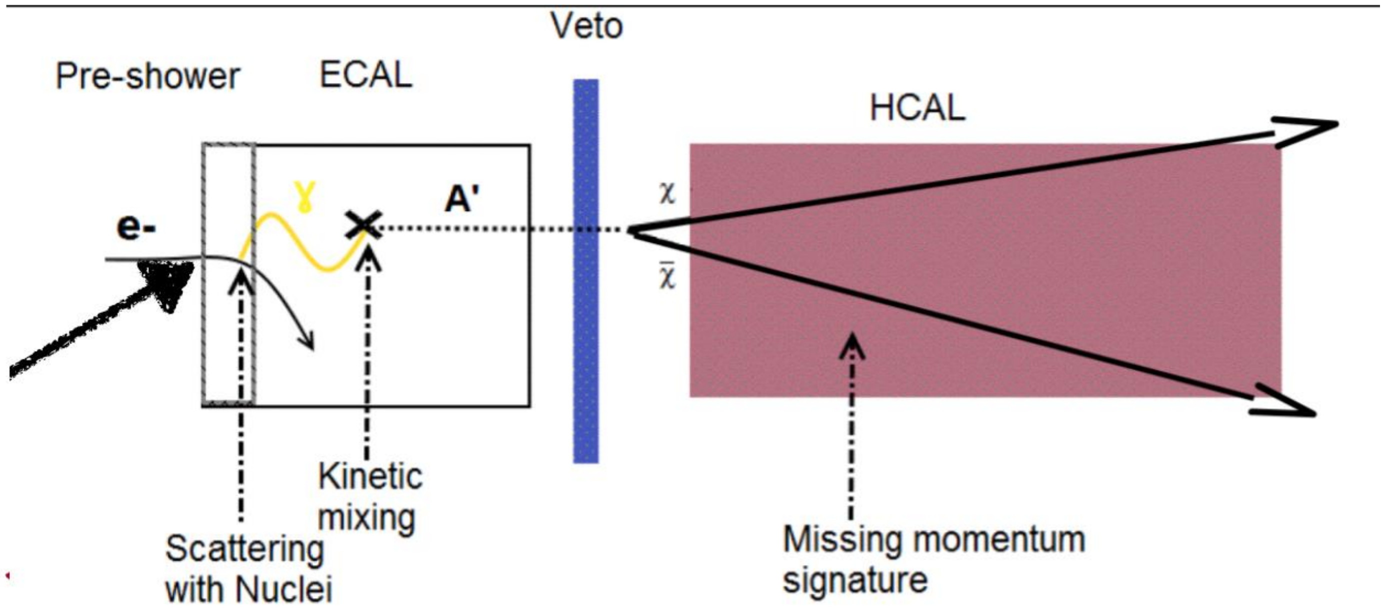
NA64^{++}: electrons, muons and hadrons

Proposal to extend the physics programme after LS2:

NA64++ (electrons): extension beyond 2021 to accumulate up to $5\text{x}10^{12}$ eot in H4

NA64++ (muons): use the 100-160 GeV muon beam in COMPASS area to study hidden sector with muon couplings. Very complementary to Dark Sector with electron couplings

NA64++ ($K_{L,S}$, π^0, η, η' → invisible): produced via charge exchange reactions $\pi(K)\ p \rightarrow M^0\ n + E_{miss}$

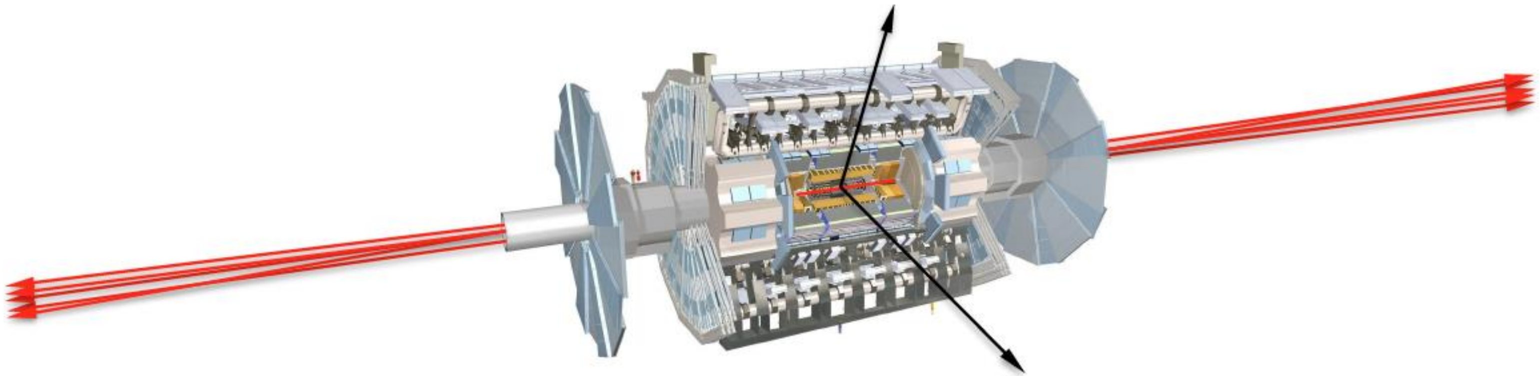


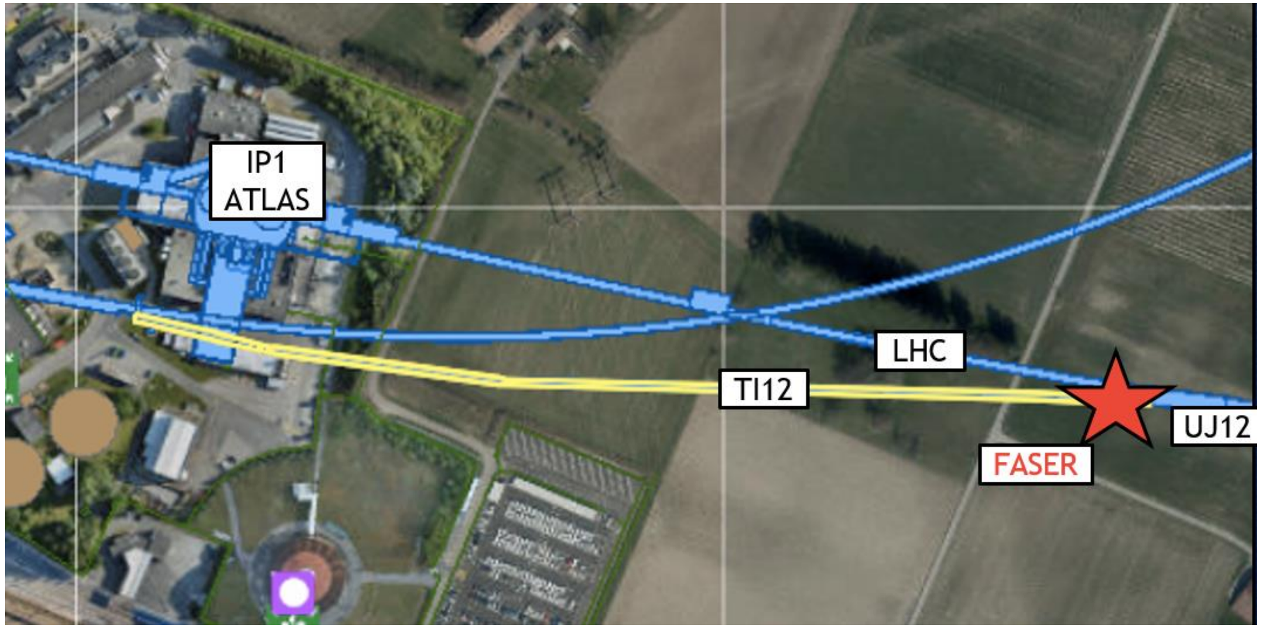
Worldwide interest

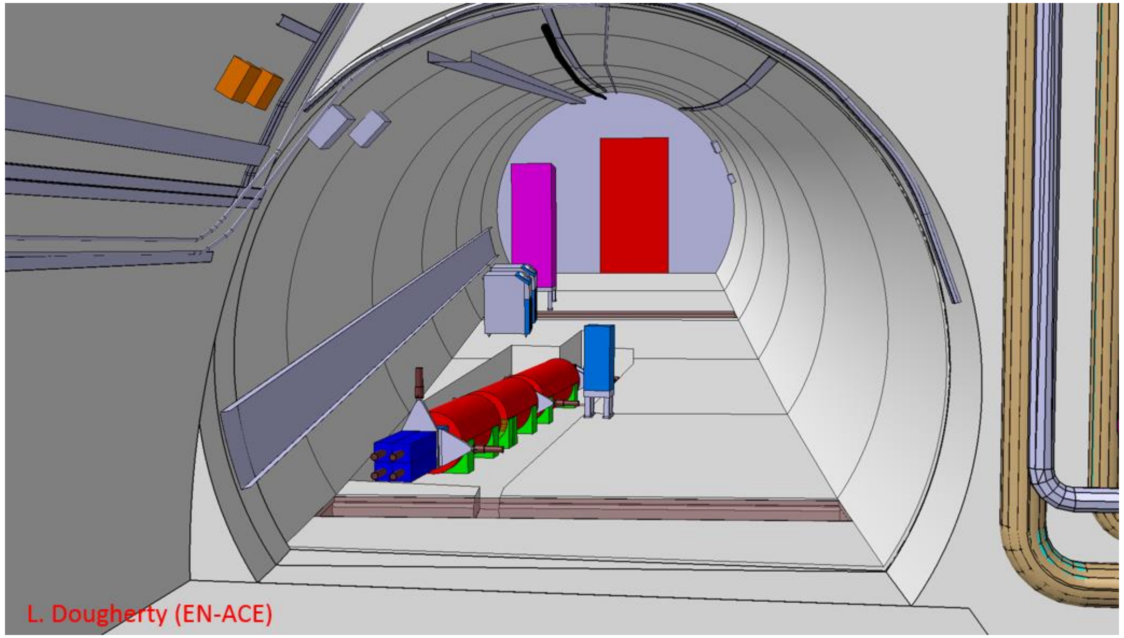
			Energy	PoT/EoT
NA62++	p	Direct LDM search (beam dump mode)	400 GeV	1e18
SHiP	p	Direct LDM search	400 GeV	2e20
MiniBoone	p	Direct LDM search (beam dump mode)	8 GeV	1.9e20
SeaQuest	p	Direct LDM search	120 GeV	1e18 -1e20
HPS	e	Direct Dark Photon Search	2.3 GeV	
APEX	e	Direct Dark Photon Search	6 – 12 GeV	
DarkLight	e	Direct Dark Photon Search	100 MeV	
BDX	e	Direct LDM search	11 GeV	1e22
NA64(++)	e	Missing energy	100 GeV	5e10
LDMX	e	Missing energy/momentum	16 GeV	1.6e16
PADME	e+	Missing mass	550 MeV	1e13
AWAKE50	e	Direct LDM search	50 GeV	1e16

LHC-LLP

Approval for installation of FASER 1 in LS2 granted





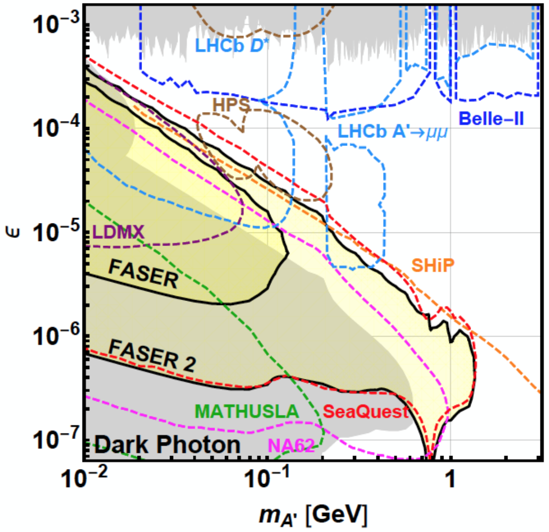


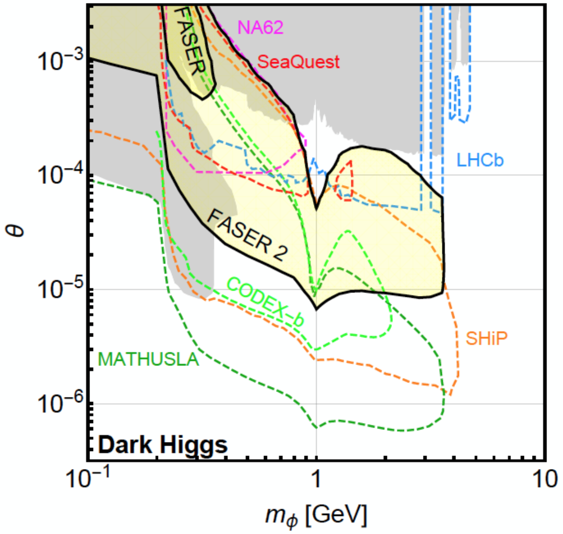
FASER's Physics Potential

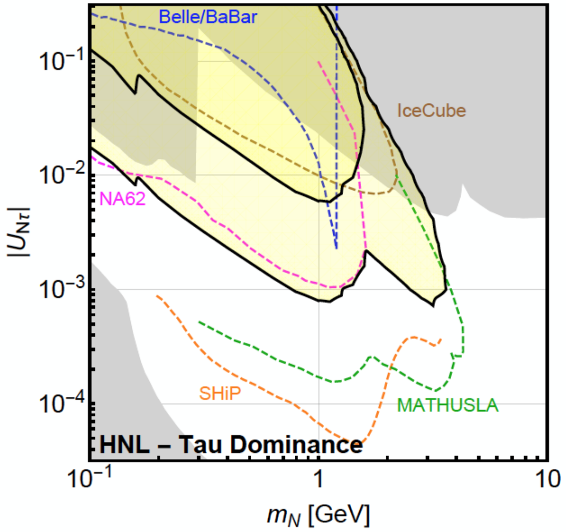
LLP Searches at FASER

- FASER has a full physics program: Dark photon, dark Higgs, HNL, ALPs

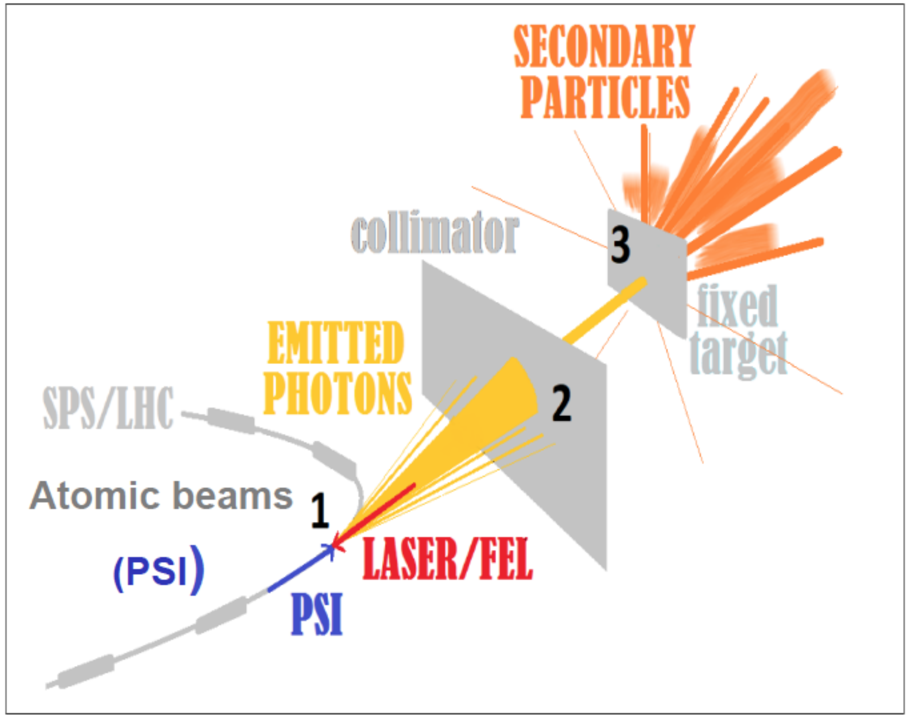
Dark Photon	Dark Higgs	HNL
$\epsilon F^{\mu\nu} F'_{\mu\nu}$	$\epsilon \lvert H \rvert^2 \phi^2$	$y L H N$
[1708.09389]	[1710.09387]	[1801.08947]







Gamma Factory research tools:
primary and secondary beams



primary beams:

- partially stripped ions
- electron beam (for LHC)
- gamma rays

secondary beam sources:

- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

collider schemes:

$\gamma-\gamma$ collisions,
E_{CM} = 0.1 – 800 MeV

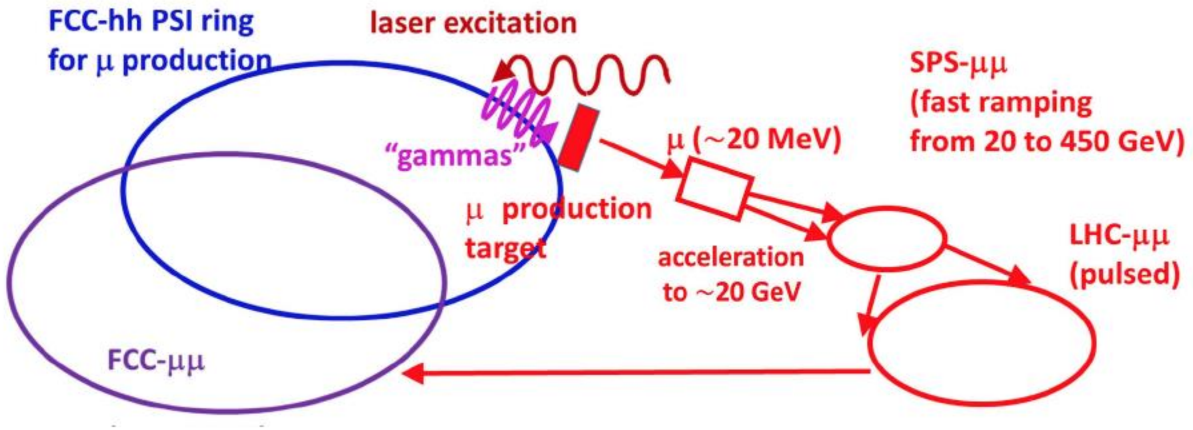
$\gamma-\gamma_L$ collisions,
E_{CM} = 1 – 100 keV

γ–p(A), ep(A) collisions,
E_{CM} = 4 – 200 GeV

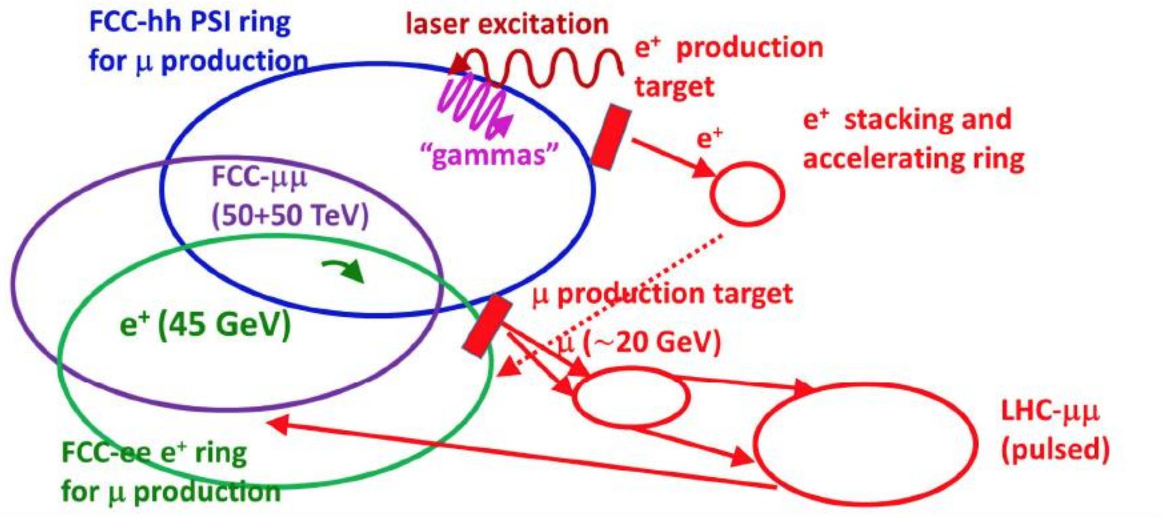
PSI to top energy in LHC in 2018, Proof-of-principle in SPS under development

F. Zimmermann – Muon collider workshop, 2018 - Padova

100 TeV μ collider FCC-μμ with FCC-hh PSI $\mu^{\pm}$ production



100 TeV μ collider FCC-μμ with FCC-hh PSI e^{+}
& FCC-ee $\mu^{\pm}$ production



Interesting times!