EPPSU Open Symposium, Granada, May 13-16, 2019

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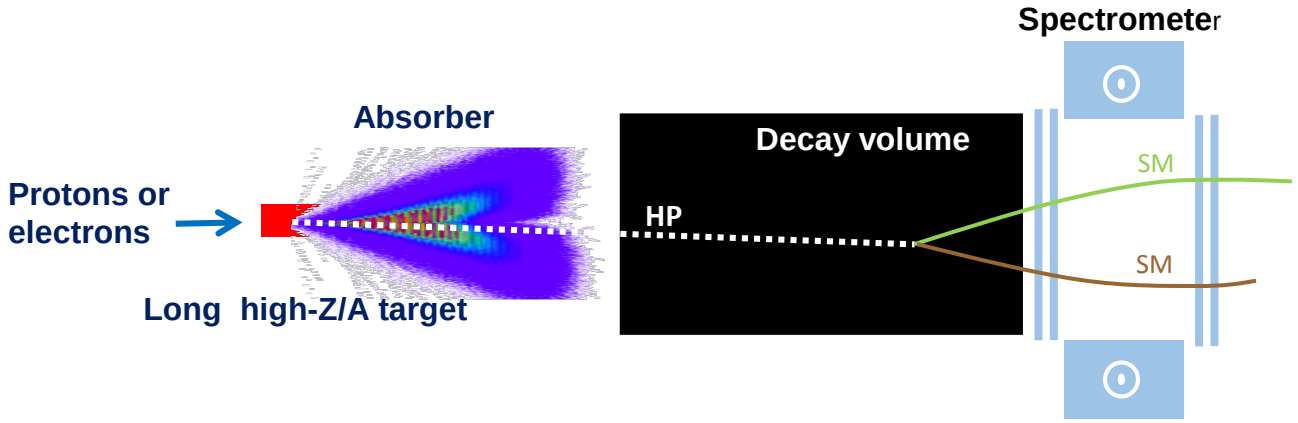
DARK SECTOR SEARCHES WITH BEAM DUMPS
Experimental Perspective

Based mainly on the Physics Beyond Colliders study (input #42)
PBC BSM Working Group Report: arXiv:1901.09966
PBC Summary Report: arXiv:1902.00260

+ credit to the Collaborations for many plots shown here

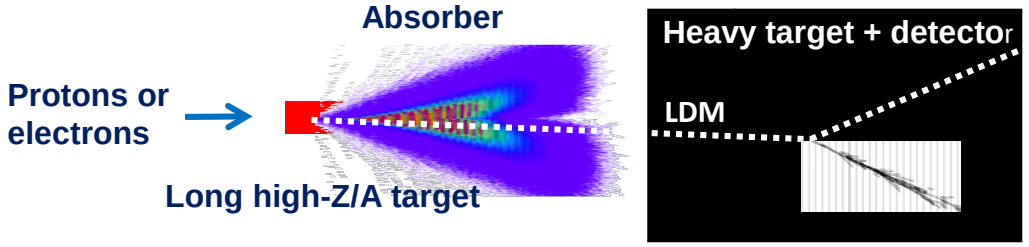
EXPERIMENTAL METHODS



Visible decay to SM particles

$signal \propto \epsilon^4$

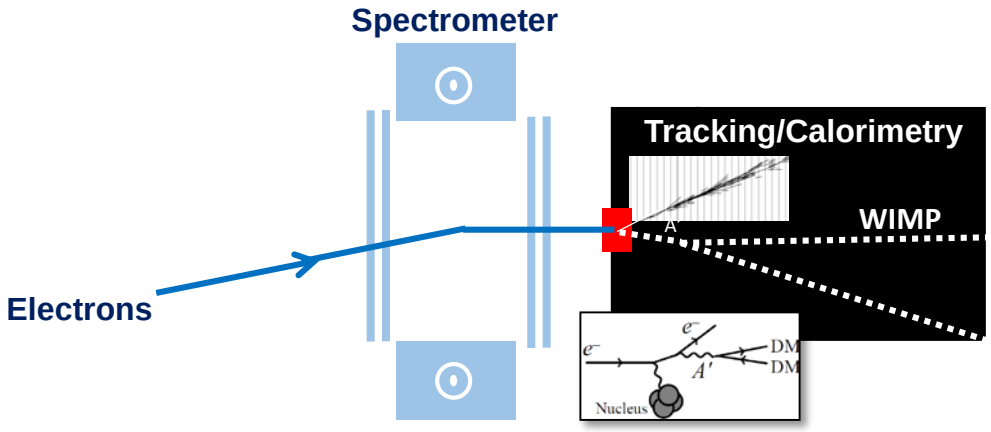
Critical: BG control



Recoil e/N from rescattering

$signal \propto \epsilon^4$

Critical: BG control



Missing energy from invisible decays

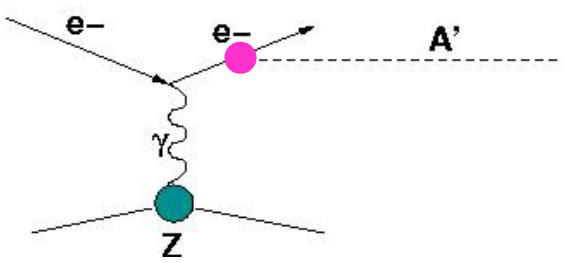
$signal \propto \epsilon^2$

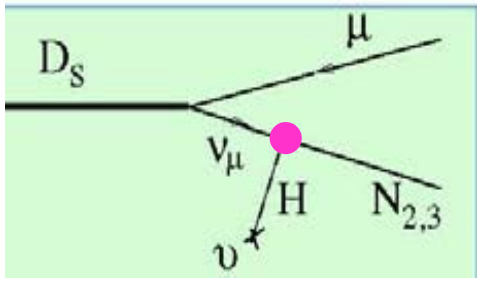
Critical: initial particle and pileup control

Graphics Courtesy Richard Jacobson

NB: reach in (m,ε) depends on many parameters:
beam energy & intensity, decay length, signatures, background …

MAIN PRODUCTION MODES





Primakov/Bremstrahlung:

Mass reach mainly in sub-GeV domain, weakly dependent on beam energy

Meson decays:

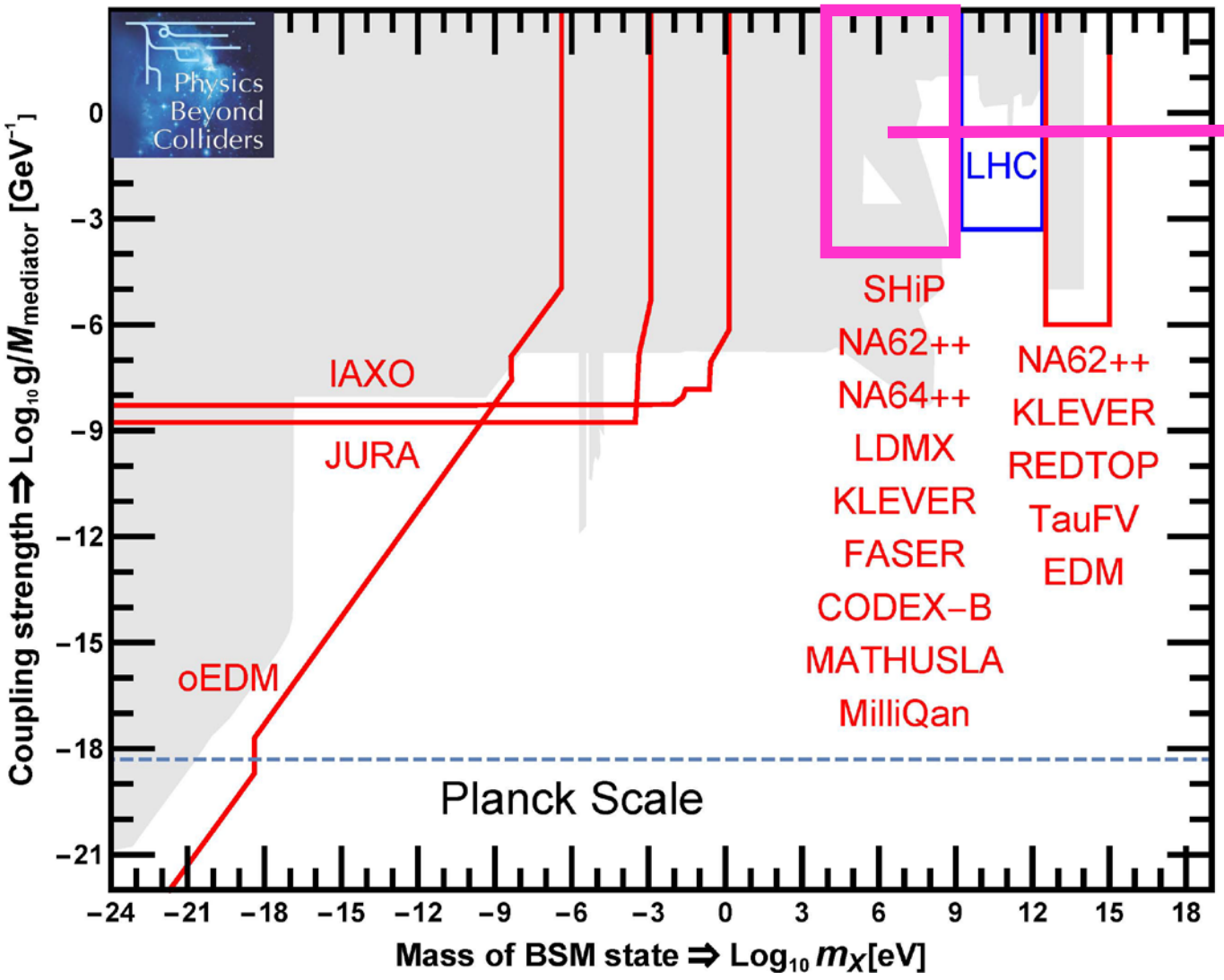
Mass reach in multi-GeV domain dependent on accessible meson mass thresholds (K,D,B)

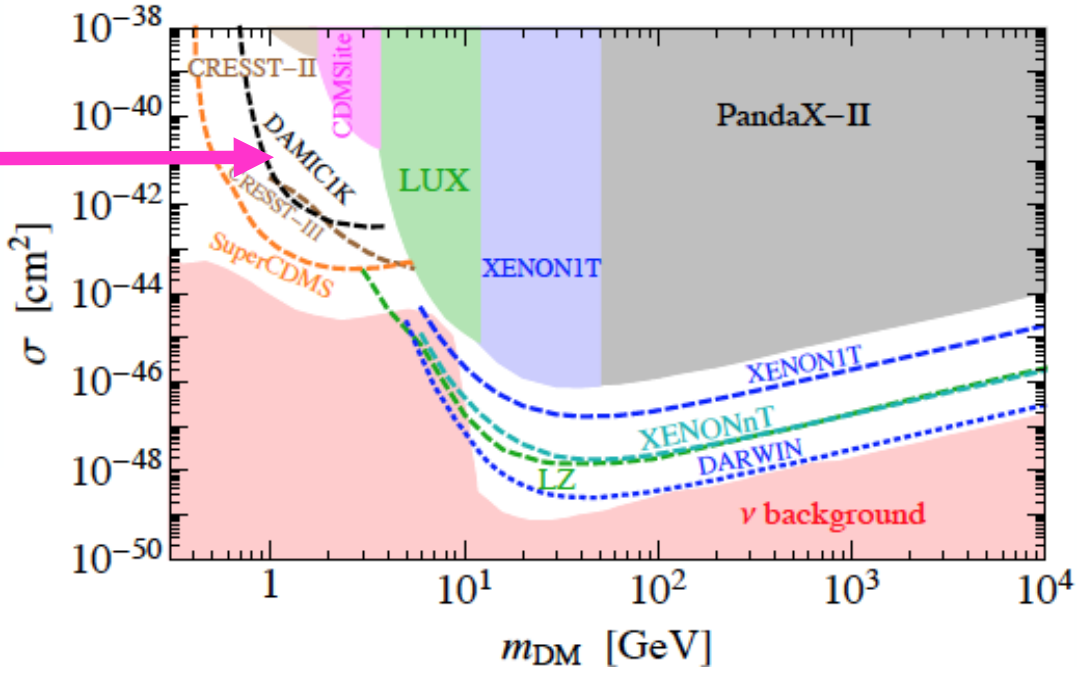
EXPERIMENTAL SIGNATURES

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	$\gamma\gamma$

+ recoil particles or missing energy for rescattering / missing energy methods

REACH OF FIXED-TARGET BEAMDUMPS IN GLOBAL LANDSCAPE





Specific reach in the MeV-GeV domain:

- **where direct WIMP searches are less efficient**
- **complementary to domains accessible with other methods**

MAIN PAST BEAM DUMP PROJECTS

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
E137 @SLAC	80's	e 20 GeV	$2\ 10^{20}$	recoil e	DP, ALPs
E141 @SLAC	80's	e 9 GeV	$2\ 10^{15}$	visible e^+e^-	DP, ALPs
E774 @FNAL	80's	e 275 GeV	$5.2\ 10^{9}$	visible e^+e^-	DP
NuTeV @FNAL	90's	p 800 GeV	$2\ 10^{18}$	visible μ	HNL
NUCAL @Serpukhov	80's	p 70 GeV	$1.7\ 10^{18}$	visible $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$	DP, DS, ALPs
PS191 @CERN	80's	p 19 GeV	$0.8\ 10^{19}$	visible	HNL
CHARM @CERN	80's	p 400 GeV	$2.4\ 10^{18}$	visible $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$	DP, DS, HNL

NB: most past beam dumps were "cheap" by-products of other experiments

MAIN CURRENT BEAM DUMP PROJECTS OUTSIDE CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
HPS @JLAB	2016-20	e 2-6 GeV	~10^{20}	visible e^+e^-	DP, ALPs
APEX @JLAB	2018-19	e 1-4.5 GeV	~10^{20}	visible e^+e^-	DP, ALPs
BDX @JLAB	~2022	e 12 GeV	~10^{22}	recoil e	DP, ALPs
LDMX @SLAC	> 2022	e 4-8 GeV	2 10^{16}	invisible	DP, ALPs
MiniBooNe @FNAL	2013-14	p 8 GeV	1.8 10^{20}	recoil e, N	DP
SBND @FNAL	>2020	p 8 GeV	6 10^{20}	recoil Ar	DP
SEAQUEST @FNAL	2021-30	p 120 GeV	$10^{18} \rightarrow 10^{20}$	visible e^+e^-	DP, DS, HNL
LBND @FNAL	>2025	p 120 GeV	~10^{21}	recoil e, N	DP, DS, HNL

Recent dedicated experiments demonstrate a regain of interest for beam dumps

Flavour factories (BELLE II, …) have also some sensitivity from exotic decays

BEAM DUMP PROJECTS AT CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
NA64++(e)	2015-24	e 100 GeV	~5 10^{12}	invisible & visible e^+e^-	DP, ALPs
eSPS/LDMX	> 2026	e 16 GeV	10^{16}	invisible	DP, ALPs
AWAKE++	> 2026	e ~50 GeV	~10^{15}	visible e^+e^-	DP, ALPs
NA62++	> 2022	p 400 GeV	10^{18}	visible	DP, DS, HNL, ALPs
SHiP	> 2026	p 400 GeV	2 10^{20}	recoil & visible	DP, DS, HNL, ALPs
NA64++(μ)	> 2022	μ 160 GeV	5 10^{13}	invisible	DZ_μ, ALPs

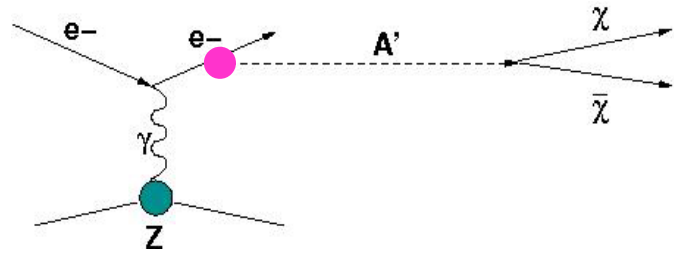
NB: CERN offers unique opportunities with both lepton and hadron beams

LHCb and LHC-LLP dedicated projects (FASER, milliQan, CODEX-b, MATHUSLA) have also sensitivity in similar mass range

"Cheap" setup implemented in 2015 on H4 e test beam

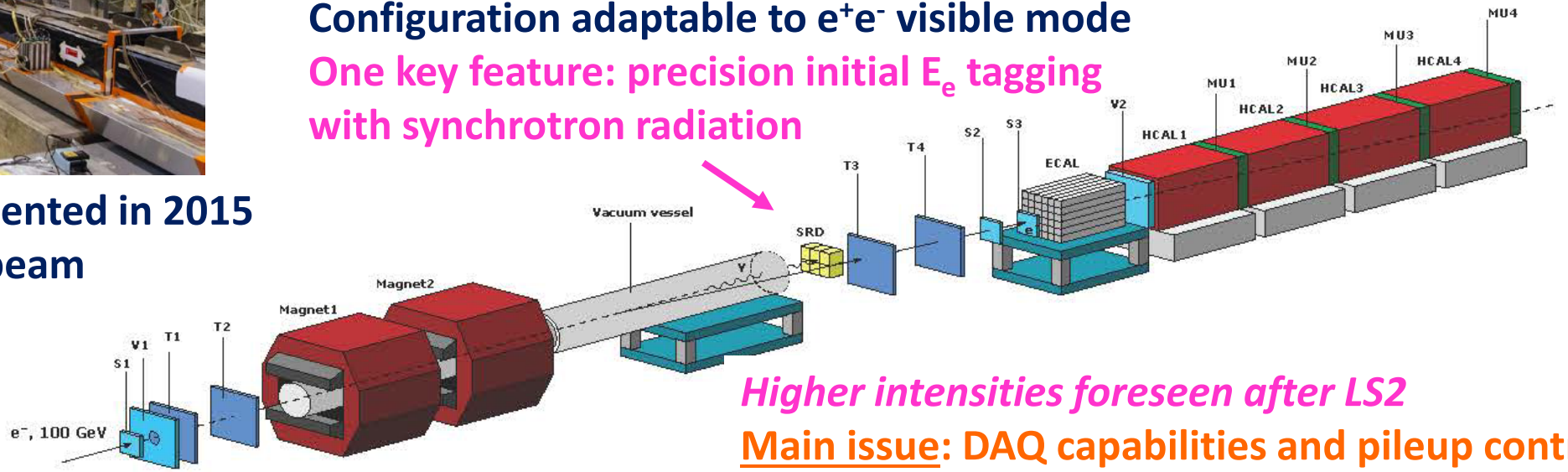
NA64++

Dark Photon search from invisible decays with missing energy



Configuration adaptable to e^+e^- visible mode

One key feature: precision initial E_e tagging with synchrotron radiation



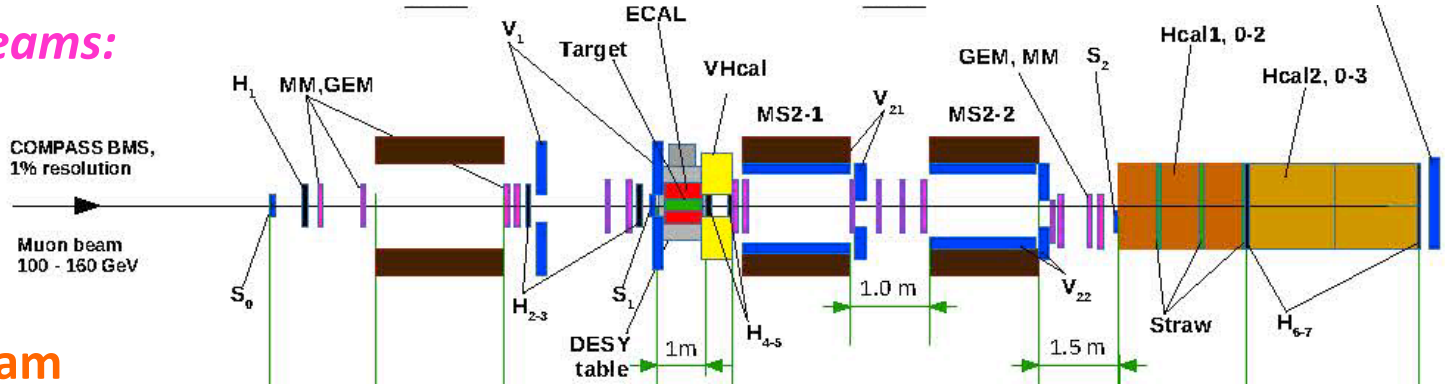
Higher intensities foreseen after LS2

Main issue: DAQ capabilities and pileup control

Wish also to extend the method to μ / hadron beams:

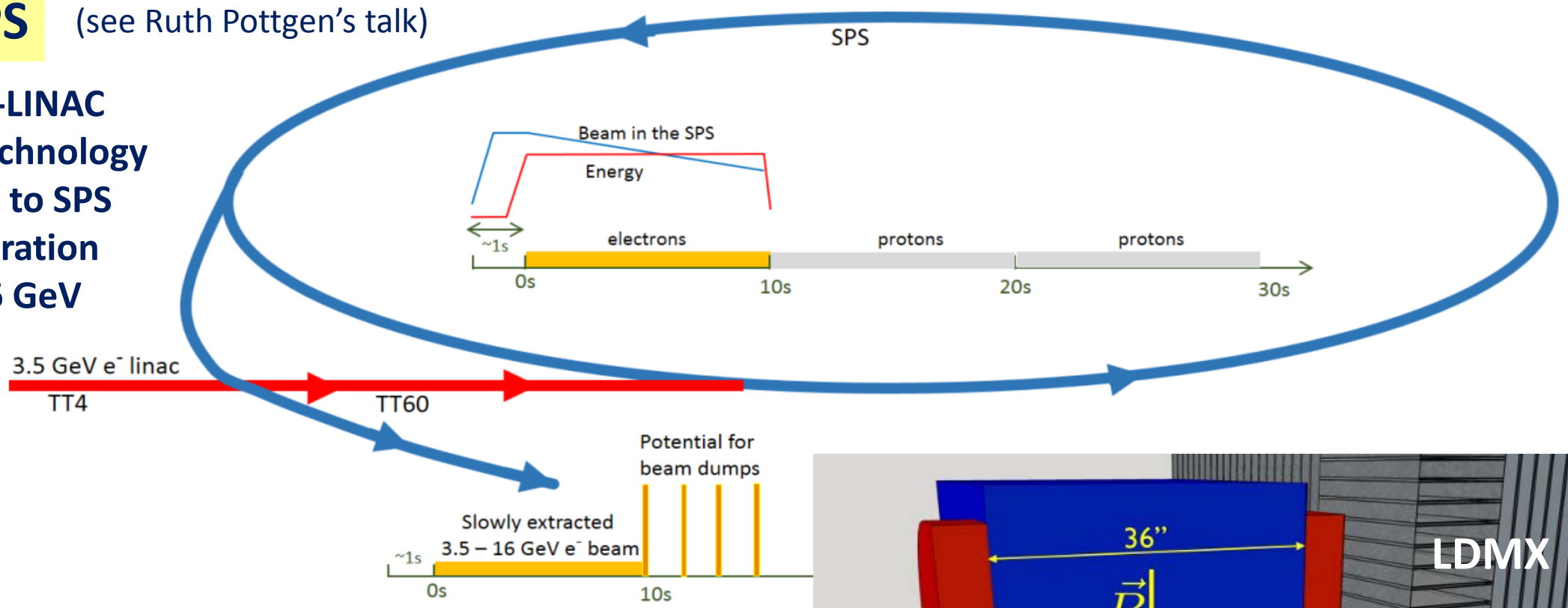
- **Few months of μ beam would test a $(g-2)_\mu$ interpretation**
- **Few years of μ beam would improve limits on millicharged particles**

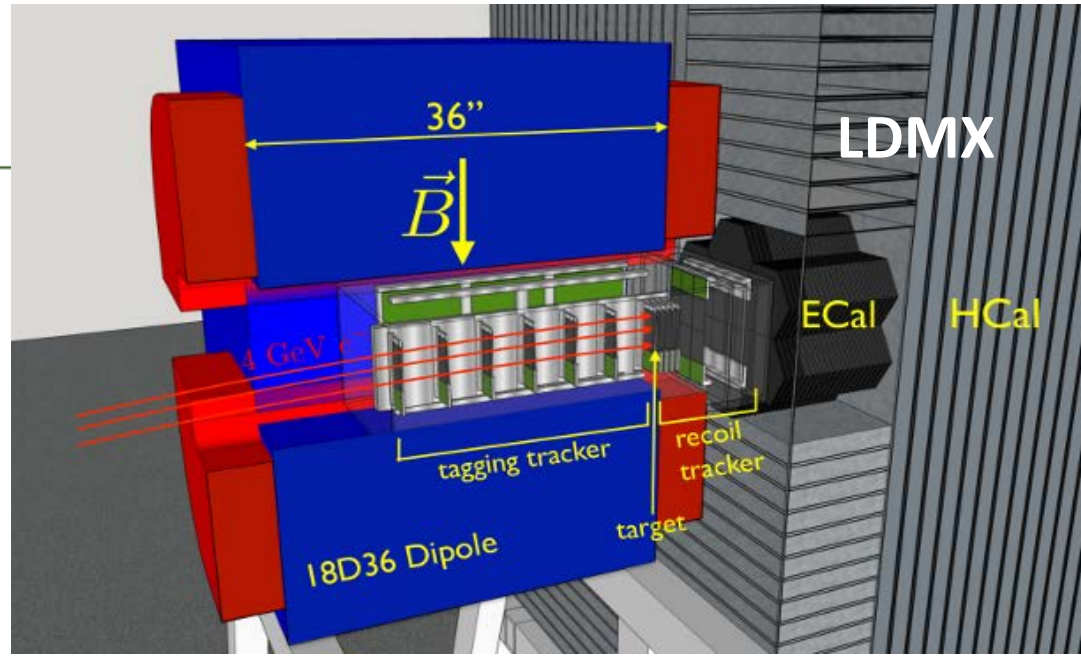
Main issue: competition with COMPASS on μ beam



eSPS (see Ruth Pottgen's talk)

3.5 GeV e-LINAC with CLIC technology connected to SPS for acceleration up to 16 GeV



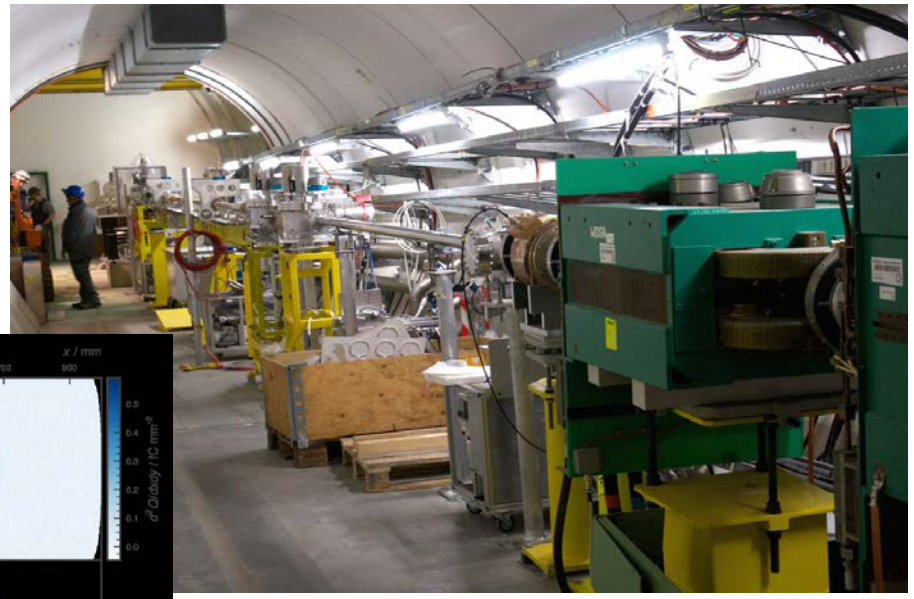


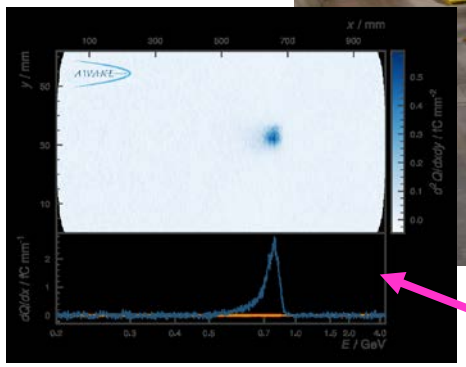
Slow extraction of up to ~10^{16} e/year
if 1/3 of SPS duty cycle reserved to project

Would allow hidden sector searches
in the invisible mode with a LDMX-like detector

AWAKE++

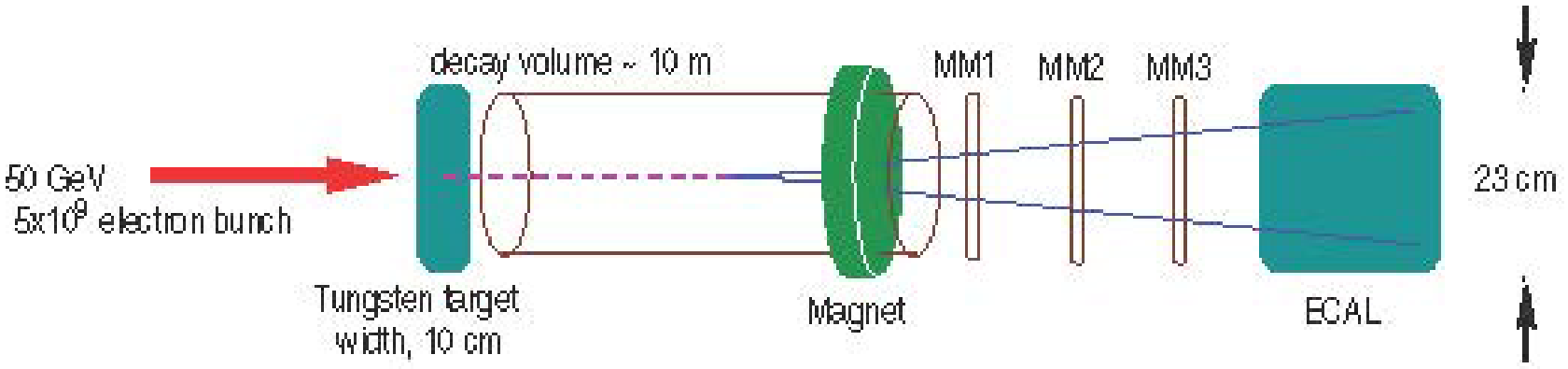
R&D for electron acceleration with a plasma cell excited by proton bunches





First accelerated e seen in 2018 (~2 GeV) - Phase 2 (~10 GeV) in preparation for run3

Could provide ~10^{15} ~50 GeV pulsed e's/year in the post-LS3 era for e^+e^- visible searches by an experiment located in the CNGS decay tunnel



NA62 BEAM DUMP

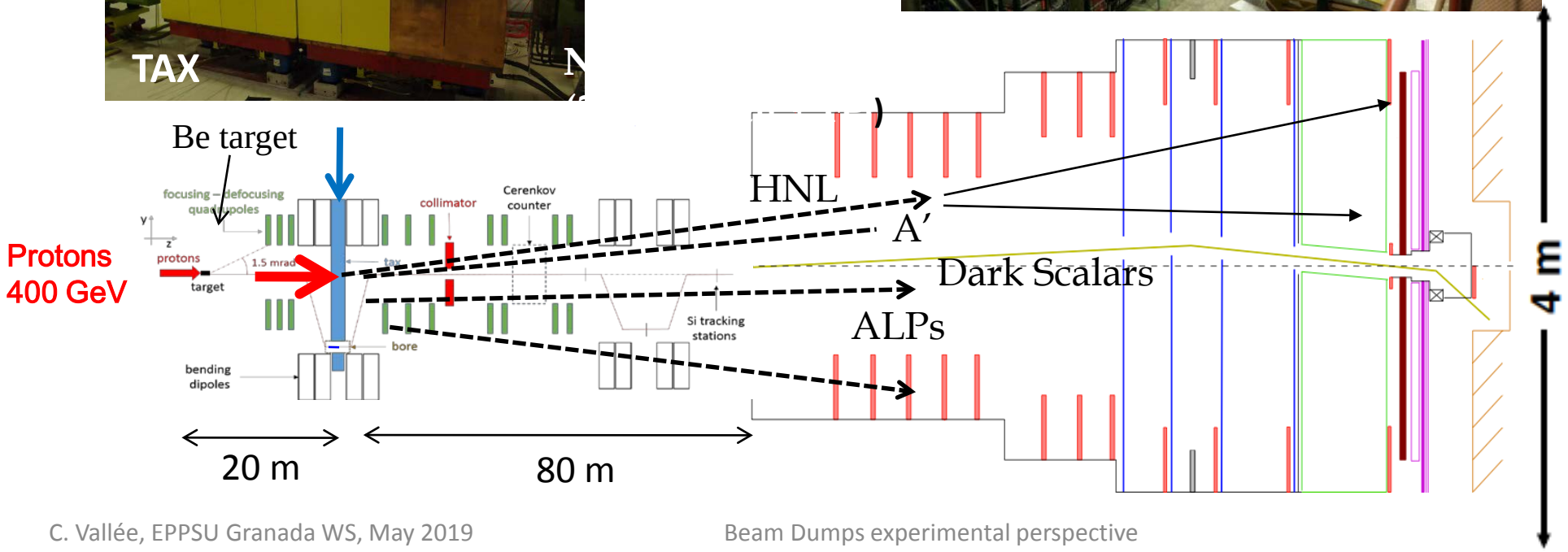
Reminder: main NA62 goal is ultra-rare decay $K^+ \rightarrow \pi^+ \nu\nu$

Successful data taking since 2016, more needed after LS2 to reach goal of ~100 events

Some data taking in beam dump mode under consideration during run 3

Achieved by closing the TAX collimator

1 year would correspond to ~10^{18} PoT



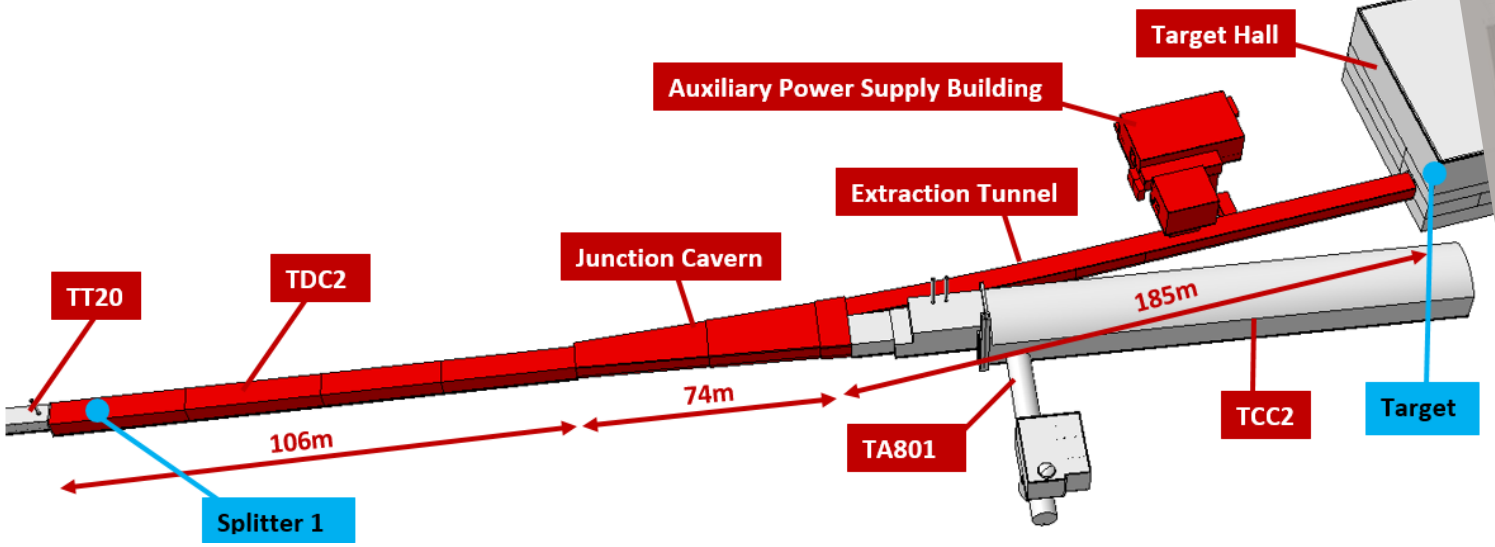
Instrumentation of NA62 decay vessel well adapted to searches in visible mode

BEAM DUMP FACILITY & SHiP

BDF: (see Mike Lamont's talk)

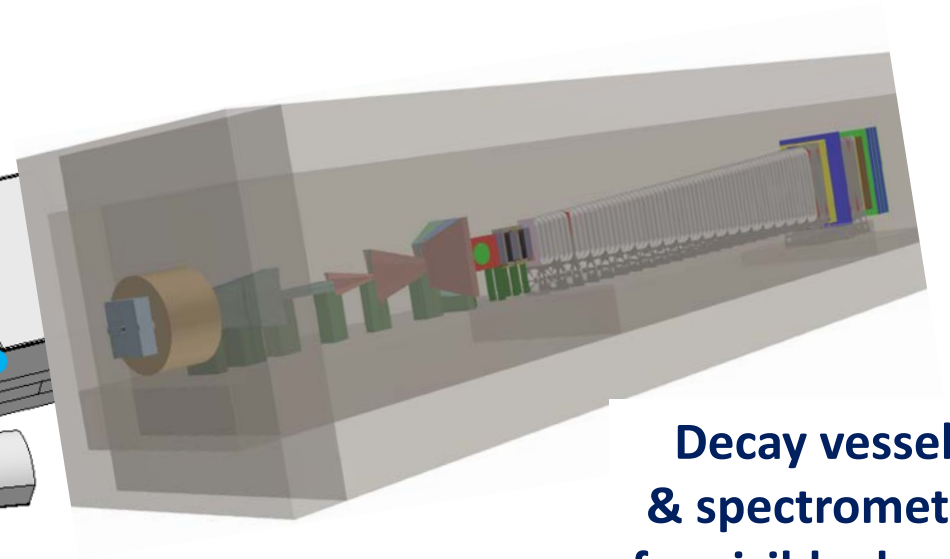
Comprehensive Design Study done:
critical points under control
(slow extraction losses/target complex/μ shielding)

Conceptual Design Report foreseen for end of EPPSU
Project mature for an implementation decision



SHiP (see Elena Graverini's talk)

A state-of-the-art dual spectrometer for hidden sector searches in a beam dump



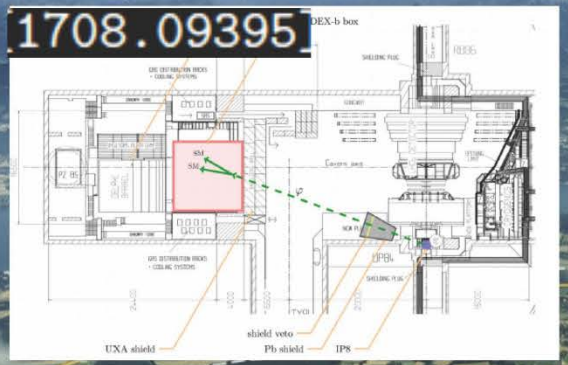
Decay vessel & spectrometer for visible decays

Emulsion spectrometer for DM scattering + ν_τ physics

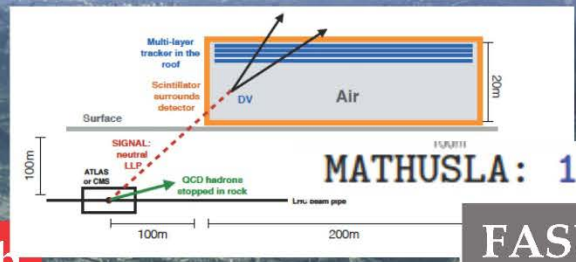
LHC-LLP DEDICATED PROJECTS

MilliQan, MATHUSLA, FASER, Codex-b @ the LHC IPs

Codex-b @ LHCb IP

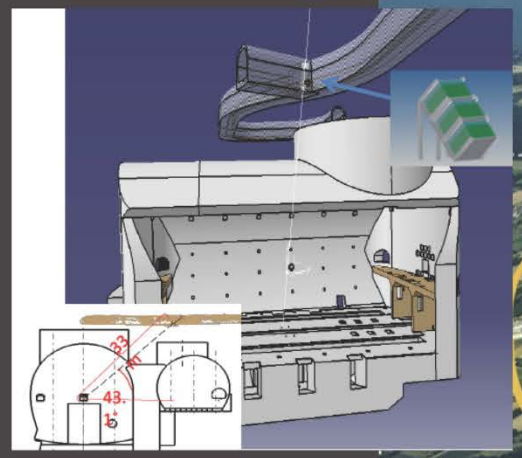


MATHUSLA @ ATLAS or CMS IPs



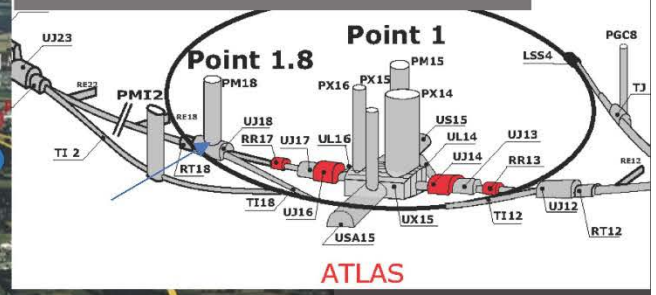
MATHUSLA: 1606.06298

MilliQan @ CMS IP



MilliQan: 1607.04669

FASER @ ATLAS IP



FASER: 1708.09389

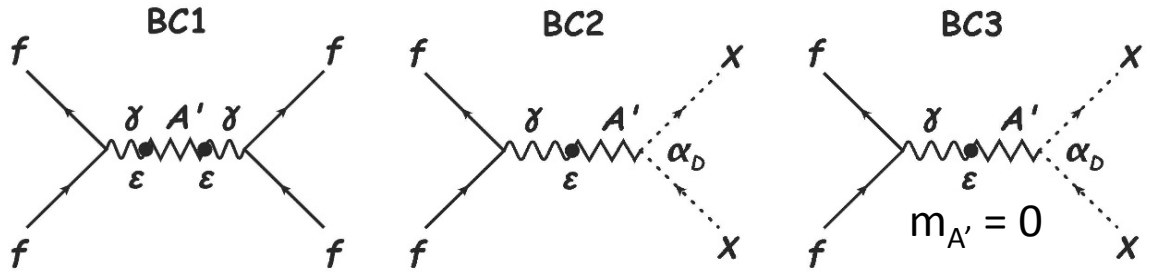
Phase I recently approved for run 3

NB: all "small scale" projects except MATHUSLA

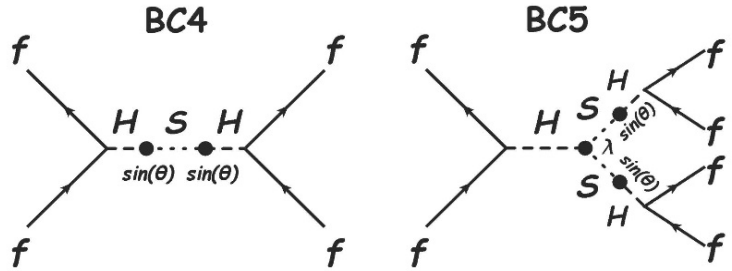
PBC BENCHMARK MODELS FOR HIDDEN SECTOR

defined to compare reach of projects under same assumptions

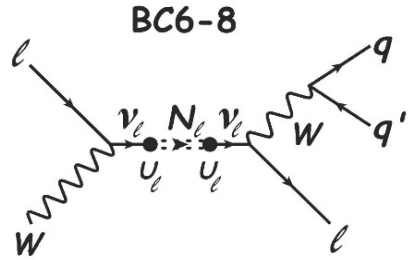
Dark Photons, Dark Matter & millicharged particles



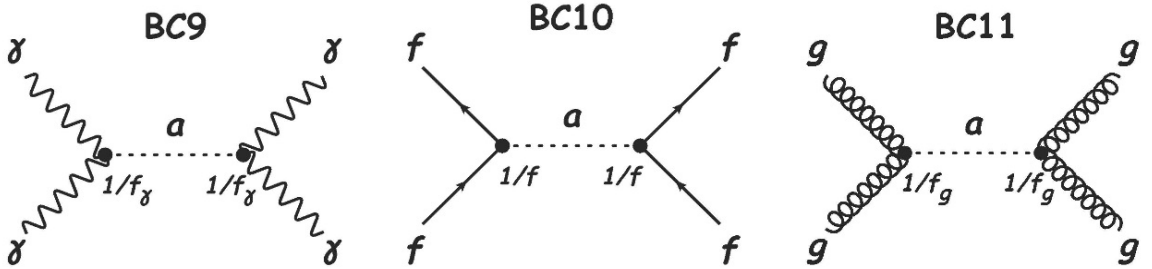
Dark Scalars



Heavy Neutral Leptons



Axion-Like Particles

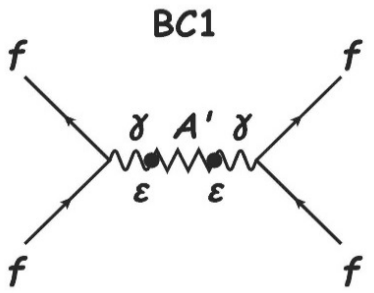


Physics Beyond Colliders

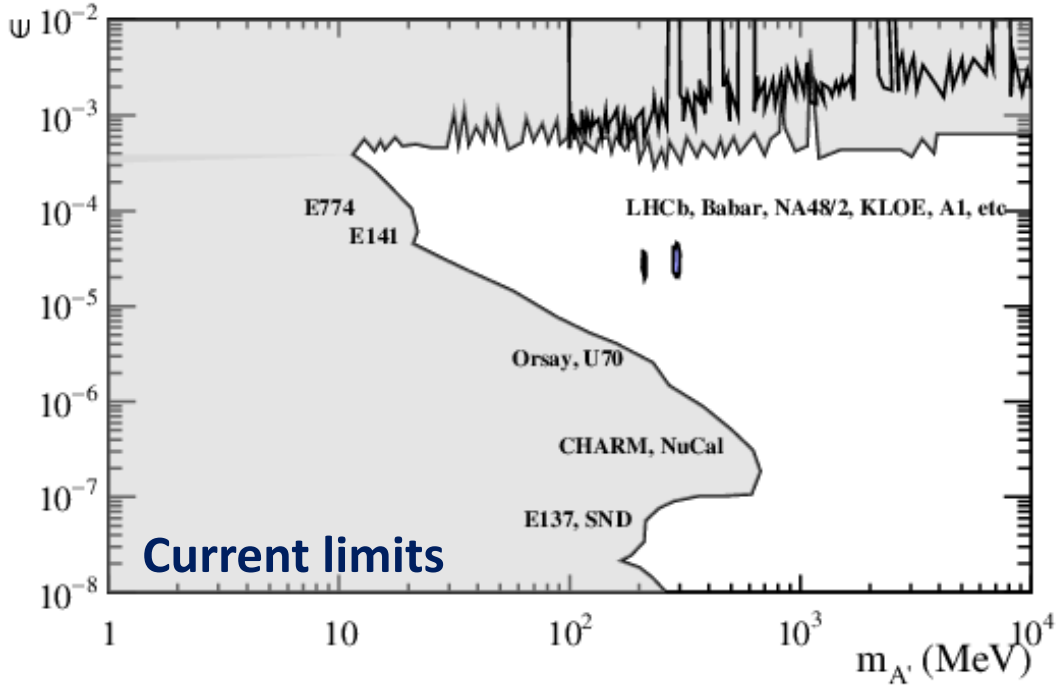
Warning:
the sensitivity estimations have different levels of maturity among projects

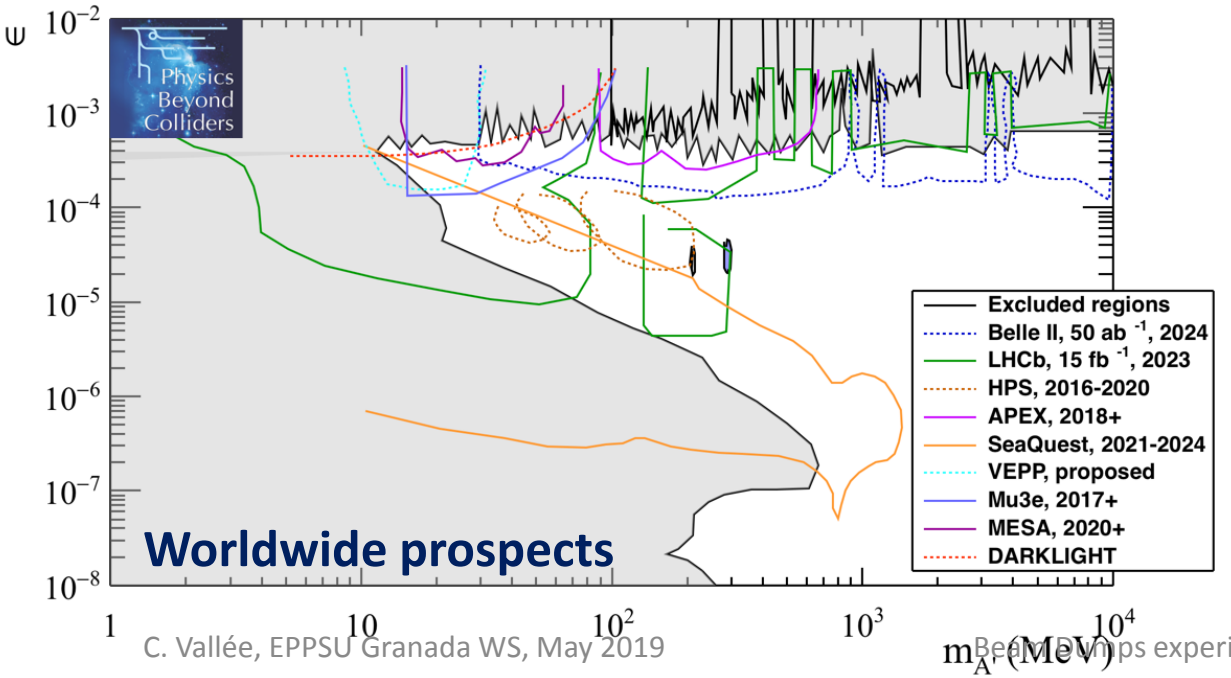
Project	Background	Efficiency	Inputs
NA62++	0-BG assumed	partly included	10^{16} PoT run in BD mode
KLEVER	partly included	included	fast simulation
REDTOP	included	included	full simulation
NA64++(e)	included	included	real data
NA64++(μ)	0-BG assumed	100 % assumed	M2 μ beamtest
eSPS/LDMX	included	included	full simulation at 4 GeV
AWAKE++	0-BG assumed	100 % assumed	toy model
SHiP	0-BG assumed	included	full simulation
CODEX-b	0-BG assumed	included	full simulation
FASER	0-BG assumed	100 % assumed	BG simulations & in situ measurements
MATHUSLA200	0-BG assumed	100 % assumed	cosmic & LHC BG fluxes
milliQan	included	included	full simulation

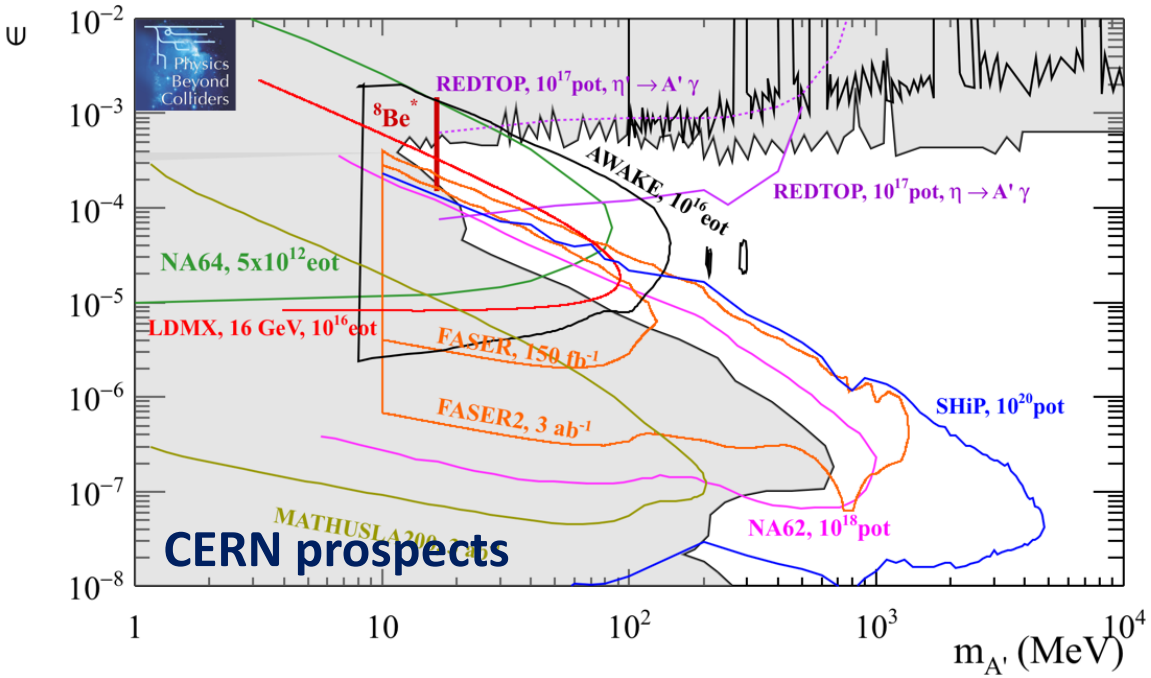
Dark Photon visible mode



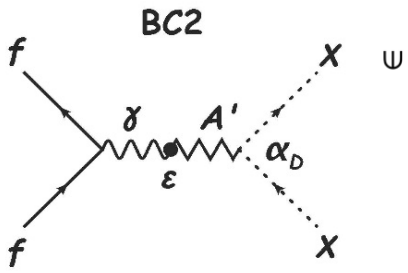
- Most studied in the past
- Current limits still dominated by old projects
- Strong revived worldwide competition to NA62++, AWAKE++ and FASER for this channel
- Unique reach of SHiP at high mass/low coupling



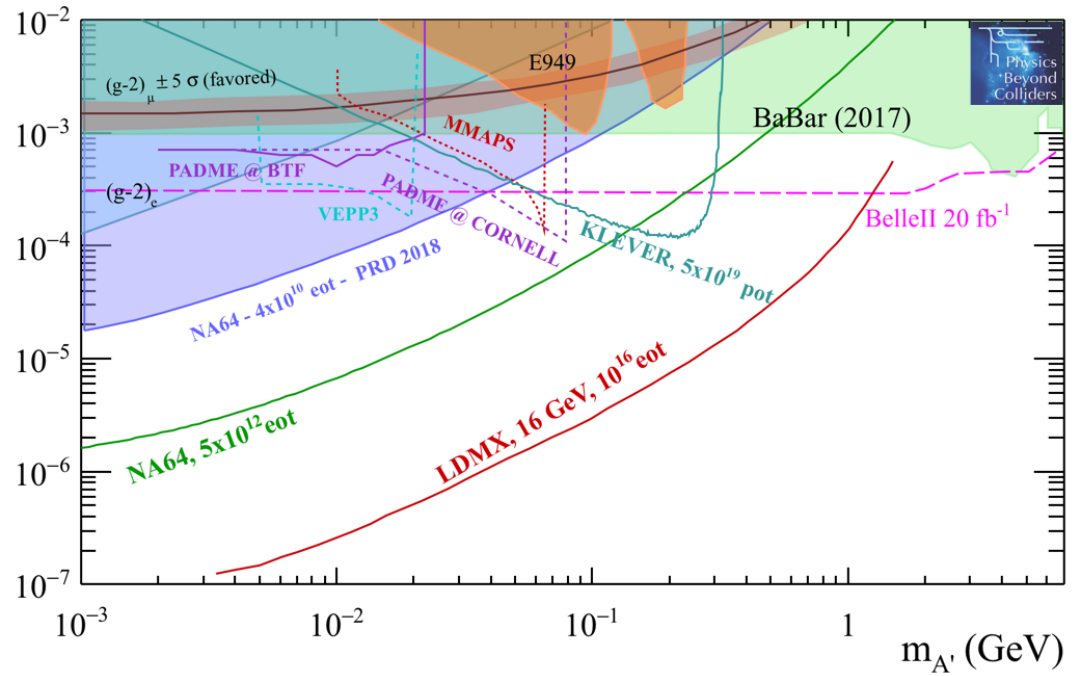


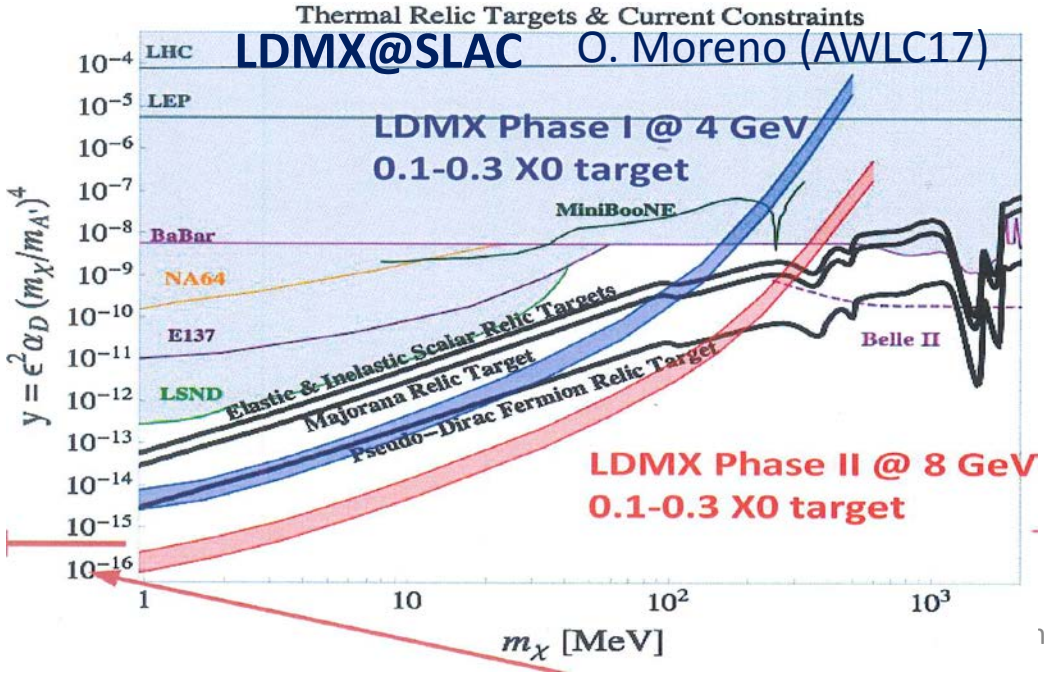


Dark Photon invisible mode



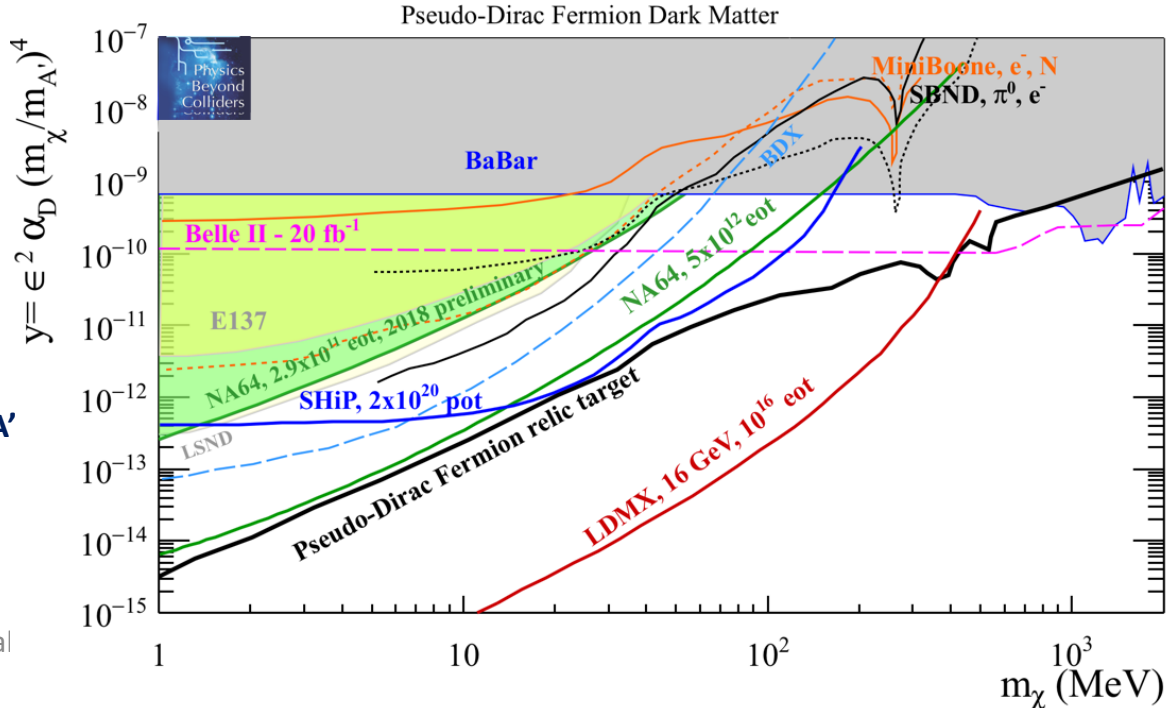
- **Unique NA64++(e) short term opportunity to explore the relevant DM parameter space**
- **Significantly higher reach of LDMX@eSPS, to be put in regard with a possible faster&cheaper implementation of LDMX at SLAC** ***(pending approval of LCLS-II beam extraction)***



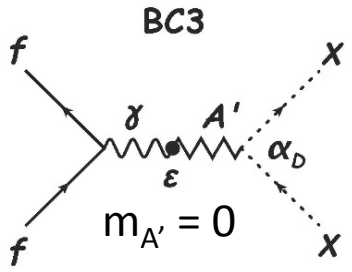


$\alpha_D = 0.1$

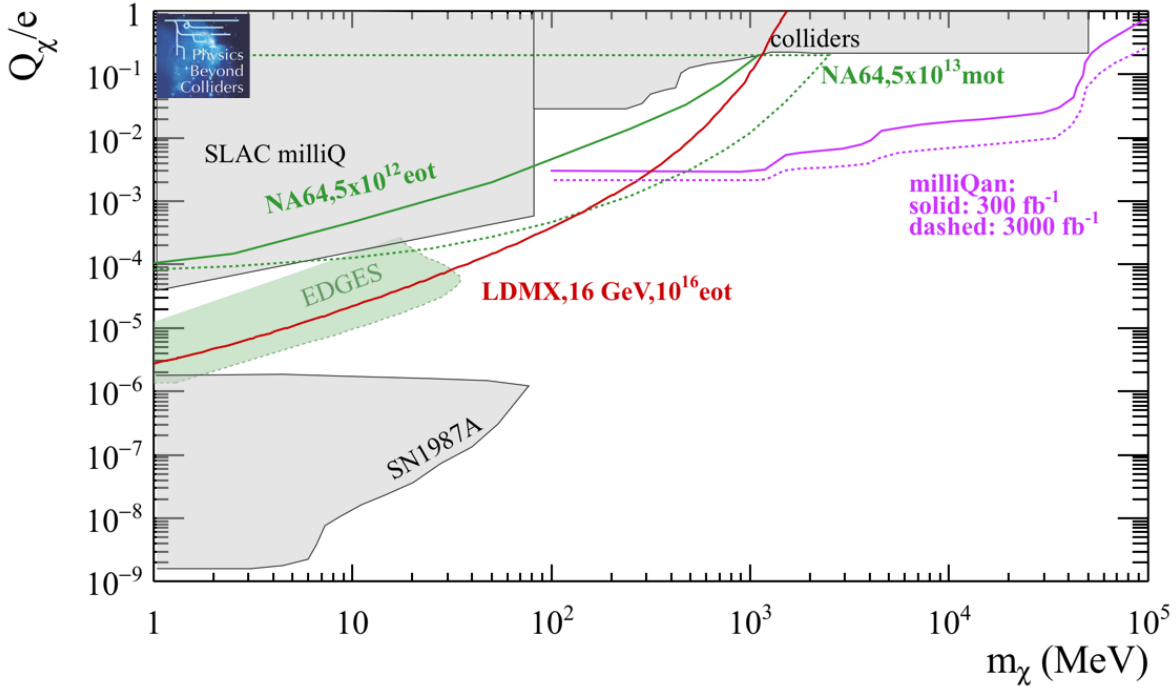
$m_\chi = 1/3\ m_{A'}$



Dumps experimental

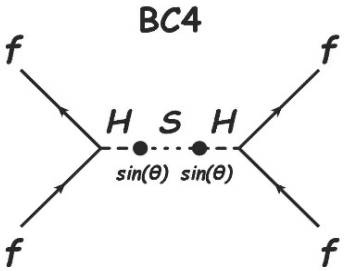


Millicharged Particles

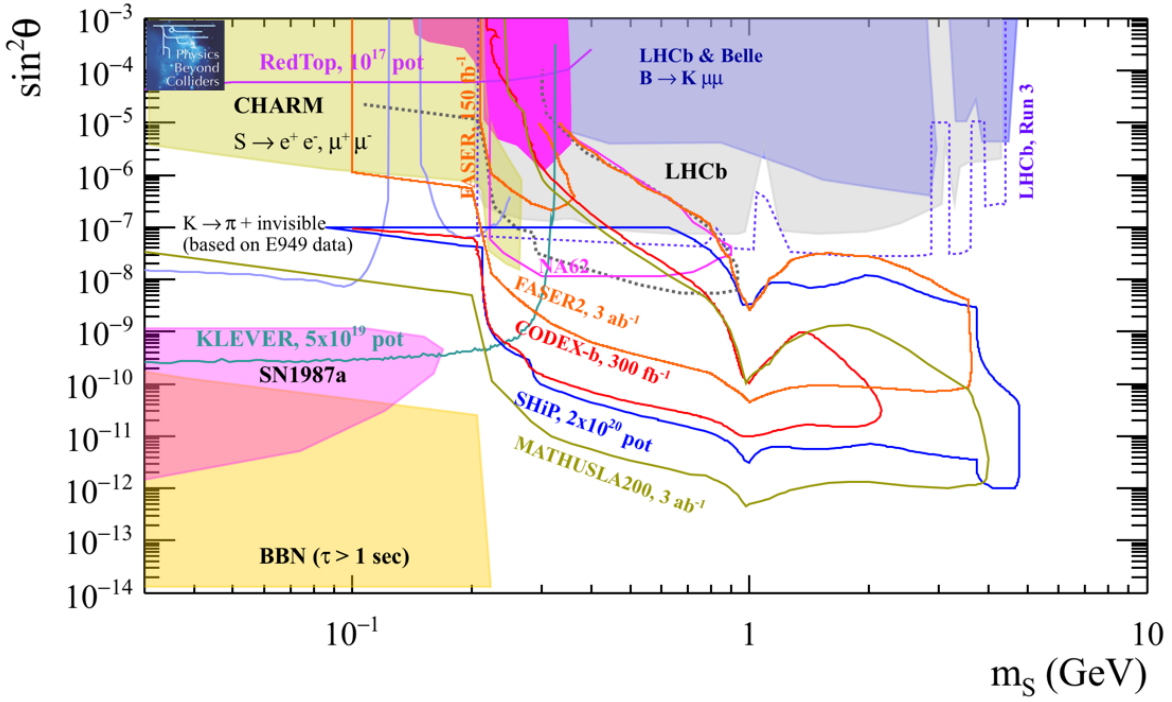


Strong competition of milliQan to a long run of NA64++(μ).

A short term few-months run could still be of interest for $(g-2)_\mu$



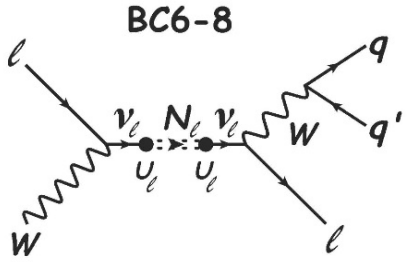
Dark Scalars



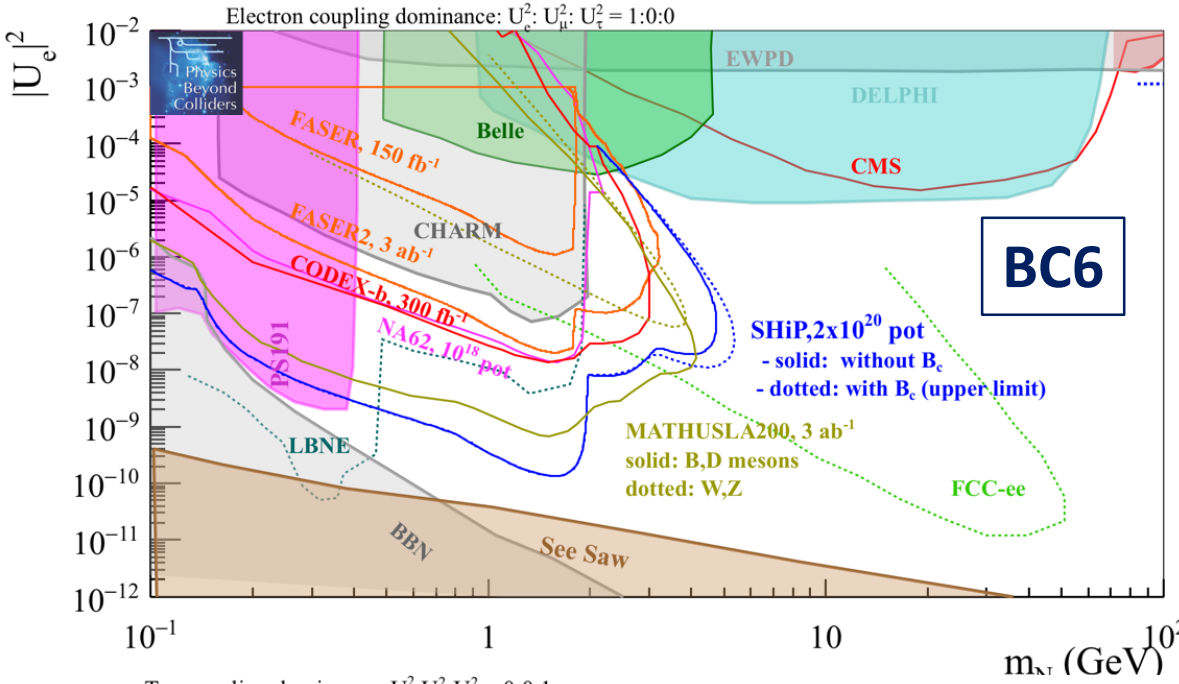
Complementary reach of projects in term of couplings.

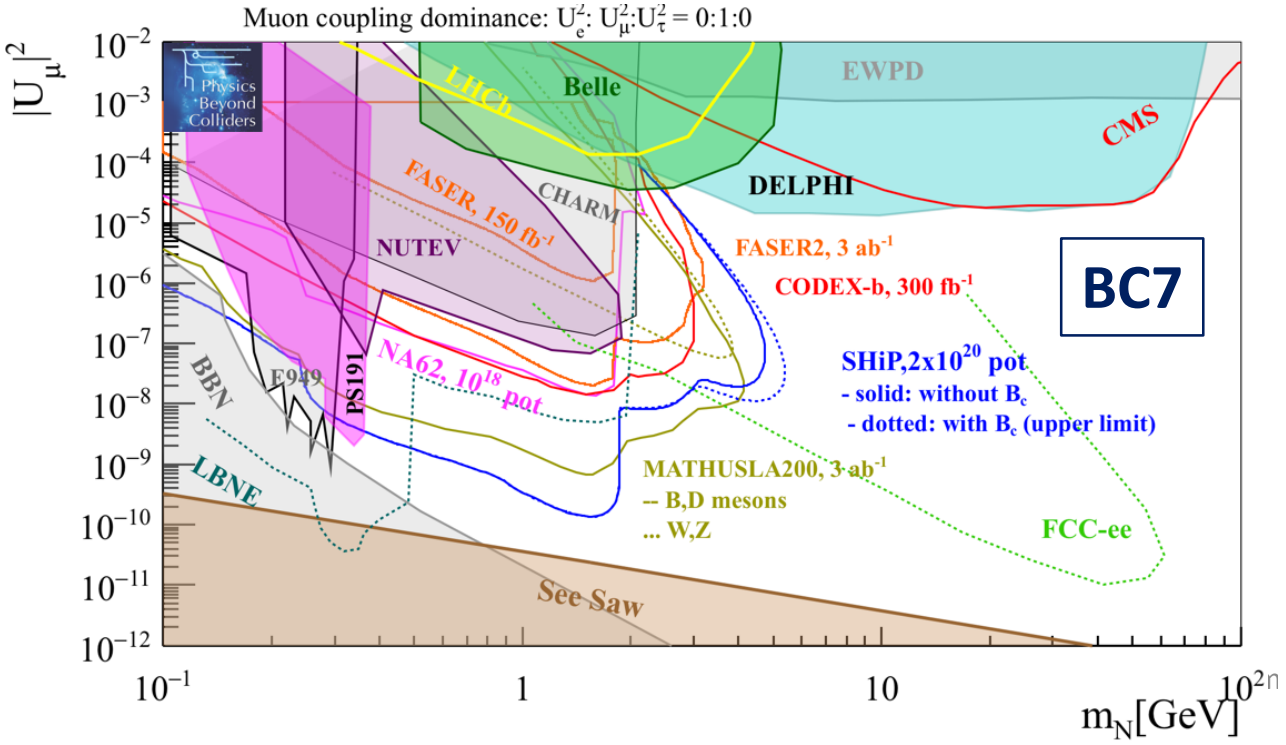
Mass reach fixed by meson masses

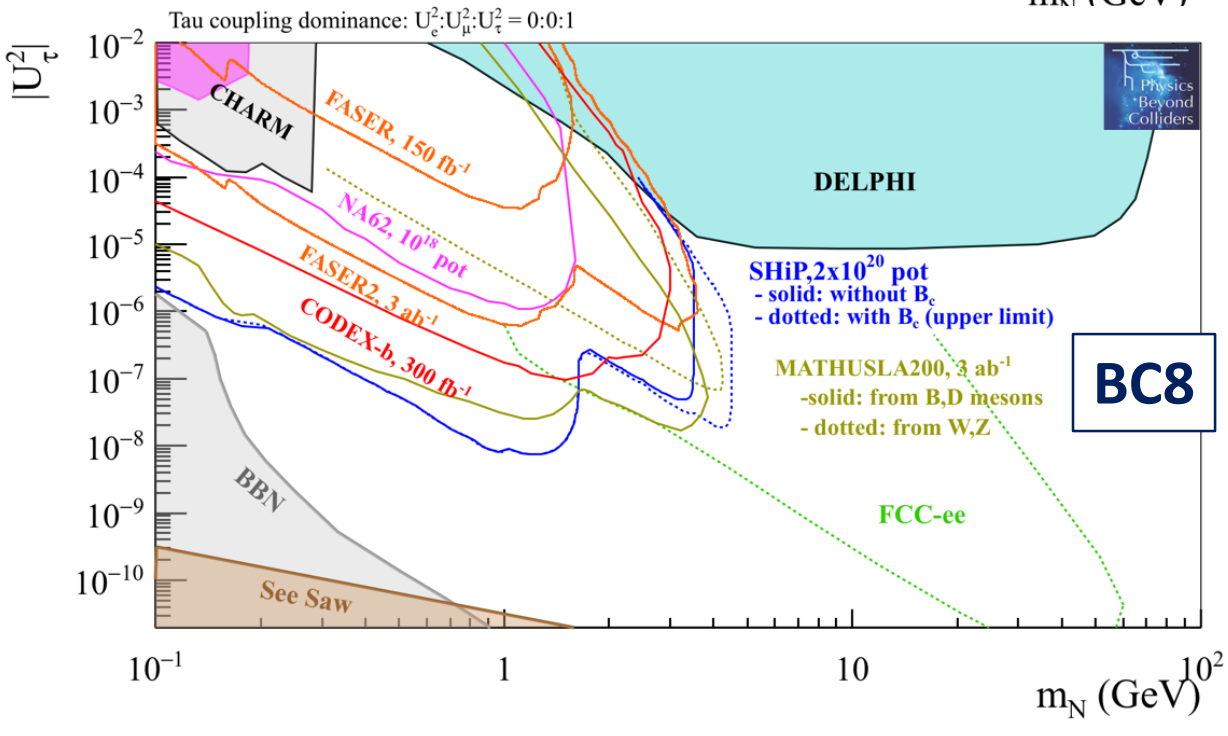
DARK FERMIONS (HNL's)



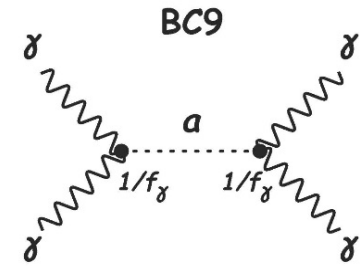
- **Unique short term opportunity to explore a significant parameter space with NA62 Beam Dump and FASER**
- **SHiP has the highest reach on the long term**

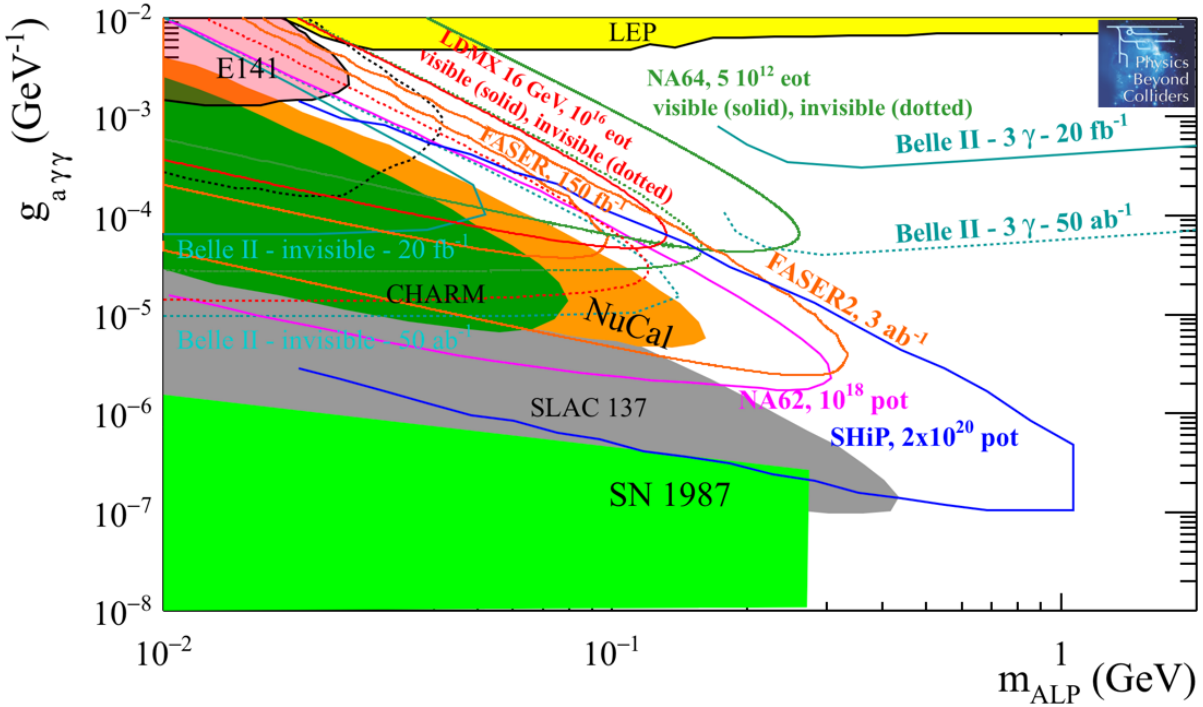


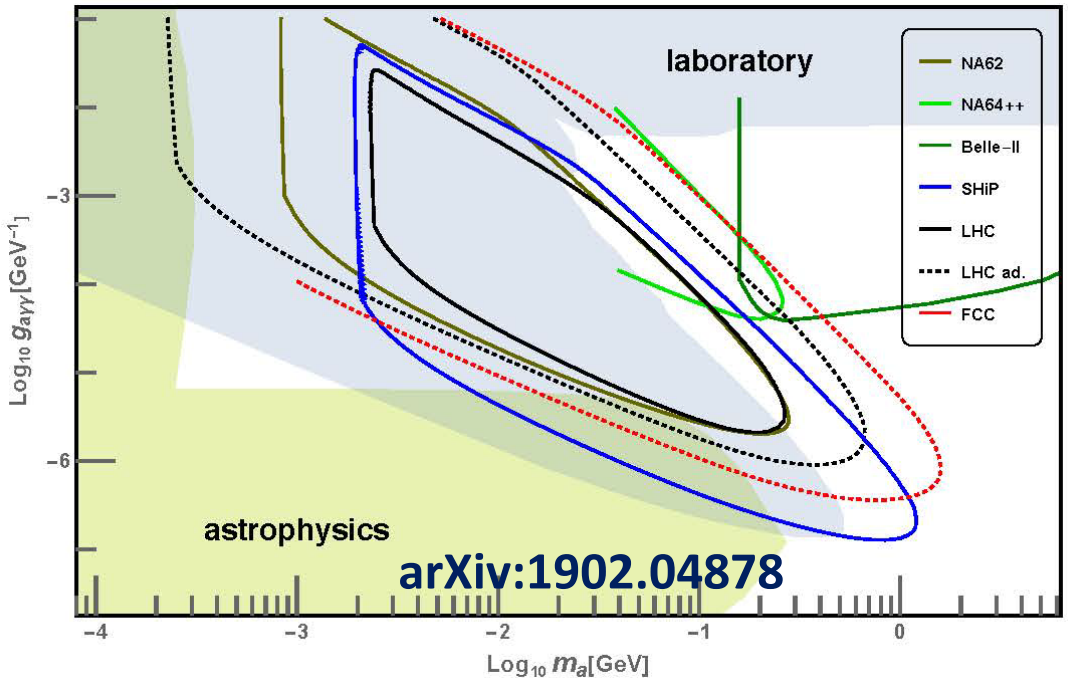




ALPS IN BEAMDUMPS







Similar reach as for visible A'
(similar signatures γγ and e^+e^-)

NB: Exploratory study of higher energy beam dump potential (LHC/FCC)
→ no real breakthrough:
SPS seems to offer a quite optimal energy-intensity mix in the present context

SUMMARY & OUTLOOK

Recent regain of interest in beam dumps worldwide

Unique short term windows of opportunity at CERN
for Dark Photons with NA64++ and for HNLs with a NA62 Beam Dump option

SPS offers close to optimal parameters for a state-of-the-art
Beam Dump Facility with a unique reach in the long term

New high-intensity e-beams @ CERN should be considered
in regard of existing opportunities elsewhere
JLAB / SLAC LCLS-II / DESY XFEL

ADDITIONAL SLIDE

LEVEL OF READINESS OF THE CERN BEAM DUMP PROJECTS

Quote:	A B C	ready need upgrade to be built	ready under design need R&D	adequate to strengthen to be built	< 10 M€ 10-50 M€ > 50 M€	Run 3 Run 4 Run 5
Project	**Physics highlight**	**Beam requirement**	**Detector maturity**	**Collaboration**	**Cost beam+det**	**Earliest operation**
NA61++	QGP Charm	B	B	A	A	A
COMPASS+	R_p & QCD	A	B	A	A	A
COMPASS++	QCD	B	B	B	B	B
MUonE	HVP(g-2)$_\mu$	A	B	B	A	A
LHC-FT	QCD	A	B	B	A	A
LHC-FT++	spin/MM/EDM	A	C	B	A	B
NA60++	QGP phase	C	B	C	B	B
DIRAC++	chiral QCD	C	B	C	B	B
NA62++	dark sector	B	A	A	A	A
KLEVER	$K^0 \to \pi^0 \nu\bar{\nu}$	B	C	B	B	B
NA64++	dark photon	A	B	A	A	A
SHiP	dark sector & ν_τ	C	B	A	C	B
TauFV	$\tau \to 3\mu$	C	C	B	C	C
REDTOP	η decays	B	C	B	B	B
EDM ring	p EDM	C	C	B	C	C
eSPS	dark photon	C	B	B	C	B
AWAKE++	dark photon	C	B	A	B	B
nuSTORM	$\sigma(\nu)$	C	C	B	C	B
γ-Factory	high rate γ	C	C	C	-	C