Physics Beyond Colliders

Accelerators – close-out

Mike Lamont

"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

⬇

Enrich and diversify CERN's future scientific programme

Goal is to involve interested worldwide community, and to create synergies with other laboratories and institutions in Europe (and beyond).
Note: interesting ideas may emerge from these studies which do not need to be realised at CERN.

- ❑ Overall coordinators: Joerg Jaeckel (Heidelberg; theory), Mike Lamont (CERN; accelerator), Claude Vallée (CPPM and DESY; experimental physics)
- ❑ Kick-off meeting 6-7 September 2016
- ❑ Final report by end 2018 → in time for update of European Strategy

Briefing book

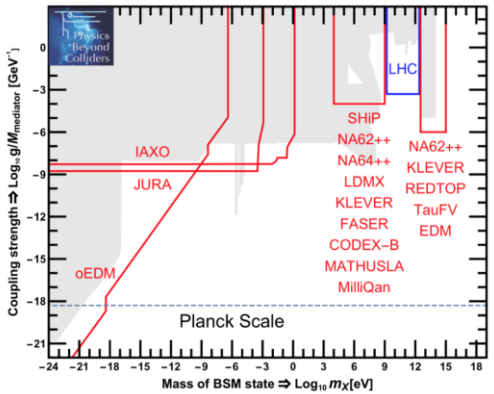
- 2) Theoretical Overview
- 3) Electroweak Physics
- 4) Strong Interactions
- 5) Flavour Physics
- 6) Neutrino Physics
- 7) Cosmic Messengers
- 8) Beyond the Standard Model
- 9) Dark Matter and Dark Sectors
- 10) Accelerator Science and Technology
- 11) Instrumentation and Computing

Dark Matter and Dark Sectors - quote

- Vacuum over large volumes, cryogenics (+), photosensors, liquid argon detectors, design and operation of complex experiments—including software and data processing—are common themes within and beyond the communities engaged in DM and DS searches.
- Technological challenges related to these topics can benefit from new and existing platforms for joint discussion and collaboration.
- The expertise present at CERN as the hub for the current largest collider programme worldwide, together with the expertise of other large European National labs and the complementary expertise of innovative small-scale experiments, can stimulate knowledge transfer and add guidance and coherence to the overall DM programme.

Accelerator Science and Technology

- Mixed bag
  - Technology, EW sector, high energy, Muon Colliders, Plasma…
- Accelerators Beyond colliders
  - Accelerator-based Neutrino Beams
    - *"nSTORM represents a very promising approach with great potential to boost R&D toward energy frontier muon colliders."*
  - BSM Searches with Accelerators
    - basically PBC with due reference to initiatives elsewhere



Proposal	Main Physics Cases	Beam Line	Beam Type	Beam Yield
sub-eV mass range::				
IAXO	Axions/ALPs (photon coupling)	–	axions from sun	–
JURA	Axions/ALPs (photon coupling)	laboratory	eV photons	–
CPEDM	p, d EDMs	EDM ring	p, d	–
	Axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons EDMs	LHCb IP	7 TeV p	–
MeV-GeV mass range:				
SHiP	ALPs, Dark Photons, Dark Scalars LDM, HNLs, lepto-phobic DM, ..	BDF, SPS	400 GeV p	2×10^{20}/5 years
NA62++	ALPs, Dark Photons, Dark Scalars, HNLs	K12, SPS	400 GeV p	up to 3×10^{18}/year
NA64++	ALPs, Dark Photons, Dark Scalars, LDM	H4, SPS	100 GeV e^-	5×10^{12} eot/year
	+ $L_\mu - L_\tau$	M2, SPS	160 GeV μ	10^{12}-10^{13} mot/year
	+ CP, CPT, leptophobic DM	H2–H8, T9	40 GeV π, K, p	5×10^{12}/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8(SLAC)-16(eSPS) GeV e^-	10^{16}-10^{18} eot/year
AWAKE++	Dark Photon	AWAKE beam	30-50 GeV e^-	10^{16} eot/year
RedTop	Dark Photon, Dark scalar, ALPs	CERN PS	1.8 or 3.5 GeV p	10^{17} pot
MATHUSLA200	weak-scale LLPs, Dark Scalar, Dark Photon, ALPs, HNLs	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
FASER	Dark Photon, Dark Scalar, ALPs, HNLs, B–L gauge bosons	ATLAS IP	14 TeV p	3000 fb^{-1}
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
CODEX-b	Dark Scalar, HNLs, ALPs, LDM, Higgs decays	LHCb IP	14 TeV p	300 fb^{-1}
» TeV mass range:				
KLEVER	$K_L \to \pi^0 \nu \bar{\nu}$	P42/K12	400 GeV p	5×10^{19} pot/5 years
TauFV	LFV τ decays	BDF	400 GeV p	O(2%) of the BDF proton yield
CPEDM	p, d oEDMs	EDM ring	p, d	–
	Axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons MDMs, EDMs	LHCb IP	7 TeV p	

BB Intro - quotes

- Accelerator-based beam-dump and fixed-target experiments can perform sensitive and comprehensive searches of sub-GeV DM and its associated dark sector mediators. They will broadly test models of thermal light DM that are as yet underexplored.
- Europe has the opportunity to play a leading role in the searches for DM by fully exploiting the opportunities offered by the CERN facilities, such as the SPS, the potential Beam Dump Facility (BDF), and the LHC itself, and by supporting the programme of searches for axions to be hosted at other European institutions.

Given that the spotlight was elsewhere, PBC appears to have made its case well – reflected in recent presentations

ECFA-EPS Special Session

Toward the Update of the European Particle Physics Strategy

Welcome	*Jorgen D'Hondt*	
Overview of the ESPP Open Symposium	*Halina Abramowicz*	
ICC - Auditorium, Ghent	14:35 - 15:05	
Technology path towards future colliders	*Caterina Biscari et al.*	
ICC - Auditorium, Ghent	15:05 - 15:35	
Community challenges and opportunities for detector R&D	*Ariella Cattai*	
ICC - Auditorium, Ghent	15:35 - 16:05	
Higgs at Future Colliders	*Christophe Grojean*	
ICC - Auditorium, Ghent	16:05 - 16:35	
Coffee break		
Physics Beyond Colliders	*Claude Vallee*	
ICC - Auditorium, Ghent	17:00 - 17:30	
Synergies between astroparticle, particle and nuclear physics	*Caterina Doglioni*	
ICC - Auditorium, Ghent	17:30 - 18:00	
Computing and Software challenges	*Graeme A Stewart*	
ICC - Auditorium, Ghent	18:00 - 18:30	

Halina Abramowicz

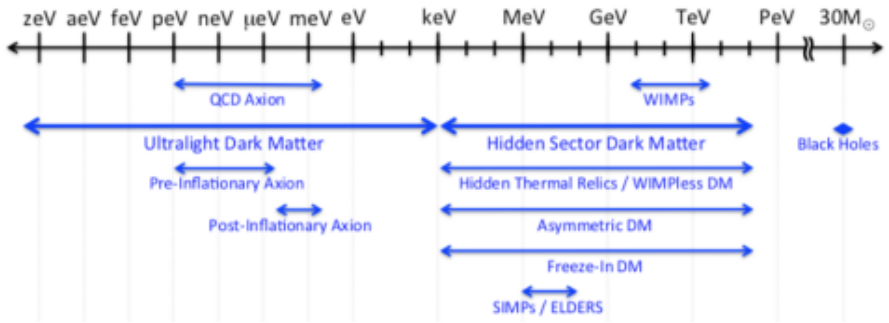
European Strategy Update

Report from Open Symposium in Granada

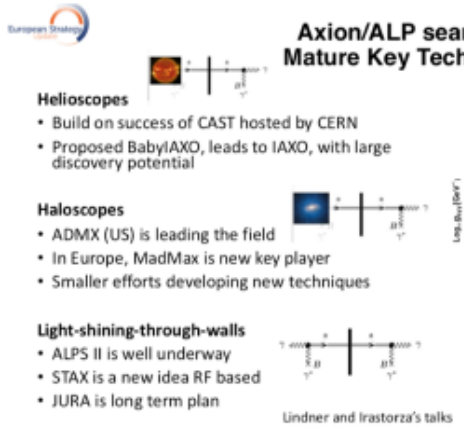
Dark matter/Dark sector

- Dark Matter
  - What if dark matter is light?
- Dark Sector
  - Search for dark photon

Too small mass ⇒ won't "fit" in a galaxy!



From MACHOs searches



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

"Small scale" projects

CERN based

ID	Name	Timeline	Cost
12	SHiP	Physics in 2027	70 MCHF
129	SPS BDF	Available 2027	156.3 MCHF
17	n_TOF	---	
36	Dark sector with primary electron beam @ CERN	eSPS commissioning 2024 (5 years after decision)	79.5 MCHF
39	EPIC / ISOLDE	Commissioning 2027	101 MCHF
58	AWAKE++	Installation in LS3	---
110	Next-generation LHC HI exp.	R&D etc. ongoing; installation during LS4 (2030)	150 MCHF
151	BSM searches with HI collisions at LHC	---	No significant investment
143	QCD facility at M2 beamline at SPS	---	10-20 MCHF
153	KLEVER	Installation 2025 (LS3)	38.95 MEUR
75	REDTOP	---	50 M$
75 / 94	LHC-LLP with MATHUSLA etc.		< 100 MCHF
	NA60++	3 years R&D, 2 years construction; data taking after LS3	15-25 M€
118	MUonE		< 10 M€
	COMPASS++	After LS3 operation	10-20 M€
154	NuStorm	Component construction starting >8 years from now	160 MCHF

Elsewhere

76	J-PARC	---	---
93	NICA @ JINR	Multi-phase setup; operational 2025?	465 M$
14	Complex Nevod	2019-26	24.6 MCHF
49	Super-Tau-Charm Factory	Operation 2029	415 MEUR
137	Short baseline neutrinos at FNAL	Physics with LArTPC end of 2020	---
30	Large-scale neutrino detectors in Russia	Full setup ready 2027	265 MEUR
124	Neutrino beam Protvino → ORCA	2018 construction start; 2027 (35) phase 1 (2) data taking	---
158	Opportunities in acc.-based neutrinos in Japan	T2K running beyond 2021; HyperK far detector construction beginning 2020.	---
64	Gravitational waves / Einstein Telescope	5 years construction	O(1000 MEUR)
11	SuperKEKB/Belle II	operation until ~2027	---
74	Electron-ion collider science and technoloy	---	---

List not complete – work in progress

THE MAIN PBC MESSAGES TO THE EPPSU

FOR CERN PROJECTS

LHC Fixed-Target opens a worldwide unique domain to both SF and QGP measurements

Requires support for full exploitation of its potential on the LHC lifetime

A SPS Beam Dump Facility would cover a worldwide unique domain for hidden sector searches complementary to high-energy colliders and non-accelerator experiments

A mid-size project now mature for an implementation decision

FOR PROJECTS OUTSIDE CERN

Support is required to fully exploit the potential of National Labs for both non-accelerator projects (e.g. IAXO) and precision physics (e.g. pEDM R&D)

The particle physics potential of the new European facilities such as ESS and DESY XFEL requires support to be fully exploited in the long term.

Avenues towards the discovery of new physics

Jorgen D'Hondt Muon Collider Workshop Oct 9-11

	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
precision frontier	H couplings to few % ν mass/mixing/nature QGP phase-transition b/c-physics	H couplings to % EW & QCD & top QGP vs Lattice QCD b/c/τ-physics	H couplings to ‰ H self-coupling to % proton structure di-boson processes
breaking the SM	next-gen K-beams proton precision e & n EDM lepton flavor (μ→e)	p EDM storage rings	rare top decays small-x physics
direct searches	Beam Dump Facility eSPS (light DM) Long-Lived Signals / ALPs DM vs neutrino floor	heavy neutral lepton	new high-mass part. next-gen hidden exp. low-mass DM

Hopefully the main message will come through

This is what we should be doing in the medium term!

Well motivated, competitive, cost-effective options, making good use of CERN's existing complex, beams, and expertise.

Rare decays and precise measurements
KLEVER ($K^0_L \rightarrow \pi^0 \nu\nu$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP (η decays)
MUonE (hadronic vacuum polarization for ($g\text{-}2_\mu$))
EDM proton storage ring

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

Other facilities:
γ-factory from Partially Stripped Ions;
nuSTORM

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, crystals) in ALICE & LHCb

Hidden sector with "beam dumps"
NA64++ (e,μ)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

For small erections may be finished by their first architects;
grand ones, true ones, ever leave the copestone to posterity.
God keep me from ever completing anything...

Oh, Time, Strength, Cash and Patience!

Herman Melville

Phase 1 – short term (1-2 years)

	Goal	Required PBC Support
BDF	Approval for TDR	Target, Beam Transfer, some material
TauFV	Feasibility study/CDR	CE, Integration, Beam Transfer, Target, RP
eSPS	CDR	CE, Integration, Beam Transfer
Conv. Beams	Proposal development	Personnel
LHC-FT crystals	Bent crystal developments	[Personnel, material]
LHC-FT gas	Development/deployment	[Machine side support for implementation]
Gamma Factory	Proof of Principle tech. proposal	Beam Transfer, Integration, material
Technology	Proposal development	Personnel
EDM	Approval for CDR for prototype ring	Continued CERN involvement - personnel
nuSTORM	Towards CDR	CE, Integration, Beam Transfer, Target, RP
LHC-LLP	Development/deployment	CE, Integration, accelerator side support
AWAKE++	Continued feasibility	Personnel

Accelerator side – no mandate after mid- 2020– but a line in MTP and it appears to make sense to plough on

Further down the road

- Big ones
  - BDF, eSPS, nuSTORM, EDM looking to enter next phase (CDR, TDR)
- Conventional beams
  - support required but normal processes apply (SPSC)
- LHC FT, Gamma Factory
  - resources for implementation in shorter term
- LHC LLP
  - individual experiments, support for CE, Integration etc.
- Technology
  - interesting options – support required

Pending approvals for the individual initiatives
Down selection might have to be considered.

North Area/SPS	Status	Deploy	Cost	Physics
BDF/SHiP,tauFV	CDS	LS3+	C6	Hidden Sector
eSPS/LDMX	→CDS	<LS3	C5	DM
nuSTORM	Feasibility	LS4+	C6	Neutrinos
CB/KLEVER	EoI	LS3+	C3	Precision
CB/COMPASS-RFSB	EoI/proposal	LS3+	C4	QCD
NA62++	Studies	Run 3	C1	Hidden Sector
NA64++	OP	Run 3	C1	DM
MUonE	Proposal	Run 3	C2	g-2
LHC				
LHC FT - gas	TP	Run 3	C1	PDF,DY,spin
LHC FT - crystal	prototype	Run 3	C2	MDM/EDM
FASER	TP/approval	Run 3	C2	LLP
MATHUSLA	LOI	LS3	C5	LLP
CODEX-b	LOI	LS3	C3	LLP
milliQan	demo	Run 3	C2	LLP
ANIBUS	proposal	Run 4	C3	LLP
NOVEL				
Gamma Factory PoP	→CDR	Run 3	C2	PSI/Laser
pEDM protype	proposal	2022	C4	EDM
AWAKE++	exploratory	LS3+	C4	DM
PS				
REDTOP	proposal	LS3+	C3	BSM+
TECHNOLOGY				
VMB	LOI	Run 3	C2	VMB
BabyJURA, JURA1, JURA 2	proposal	2023	C2,C2,C4	ALPs
BabyIAXO/IAXO	advanced	2023	C3,C4	Axions

C1	< few 100 kCHF
C2	From few 100 KCHF to 1-2 MCHF
C3	From 1-2 to 5-10 MCHF
C4	~10-50 MCHF
C5	> 50 MCHF
C6	> 150 MCHF

Summary

- Assuming ESPP approbation for the “diversity program”
- Continued generic PBC support in the short/medium term with appropriate funding (CB, EDM, LLP, Tech…)
- Next stage approval for any of the big ones
  - will require the injection of dedicated resources
  - down selection might be necessary
- Go/no-go on smaller proposals (gamma factory PoP…)
  - dedicated resources if approved

Thanks!

BDF	Marco Calviani, Brennan Goddard, Richard Jacobsson
Conventional beams	Lau Gatignon, Markus Brugger
Protons post LIU	Giovanni Rumulo, Hannes Bartosik, Eirini Koukovini Platia
LHC FT	Massi Ferro-Luzzi, Stefano Redaelli
EDM	Hans Ströher, Yannis Semertzidis, Christian Carli
Gamma factory	Witek Krasny, Reyes Alemany, Brennan Goddard
Technology	Andre Siemko, Babette Döbrich
AWAKE++	Edda Gschwendtner, Matthew Wing
nuSTORM	Ken Long, Jonathan Gall
FASER	Jamie Boyd, Brian Peterson
eSPS	Steinar Stapnes, Lyn Evans, Thorsten Akesson

HSE-RP	Mirko	Casolino	**BDF/PBC** Radiation Protection
HSE-RP	Daniel	Bjorkman	BDF/PBC Radiation Protection
EN-CV	Pietro	Avigni	Target and target complex
EN-MME	Josep	Busom Descarrega	Target and target complex
EN-STI	Edmundo	Lopez Sola	Target and target complex
EN-STI	Joao Pedro	Canhoto Espadanal	Target and target complex
EN-EA	Pablo	Santos Díaz	**BDF/PBC** Integration
EN-EA	Liam	Dougherty	**BDF/PBC** Integration
EN-EA	Marcel	Rosenthal	Conventional beams
EP-ADO	Nikolay	Bykovskiy	**PBC** Technology (IAXO)
BE-ABP	Malek	Haj Tahar	**PBC** EDM
BE-ABP	Eirini	Koukovini Platia	**PBC** Complex performance
SMB-SE	Jonathan	Gall	**BDF/PBC** Civil engineering
TE-ABT	Yann	Dutheil	**BDF/PBC** extraction/beamline
TE-MSC	Jakub	Kurdej	Splitter design

Huge thanks to the conveners and the members of the working groups for their uptake and collaboration – always in addition to existing workloads and with only limited injection of additional resources.