Physics Beyond Colliders @ CERN

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Precision Science Workshop · 9 April 2018

long version at https://doi.org/10.5281/zenodo.1117970

Physics Beyond Colliders Annual Workshop
CERN · 21–22 November 2017

Study Group mandated by CERN Management to prepare the next European HEP strategy update (2019-20). Explore the opportunities offered by the CERN accelerator complex and infrastructure to get new insights into some of today's outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. The focus is on fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that may require different types of experiments.

Time scale: next two decades

Jörg Jaeckel · Mike Lamont · Claude Vallée

238 participants · 51 presentations

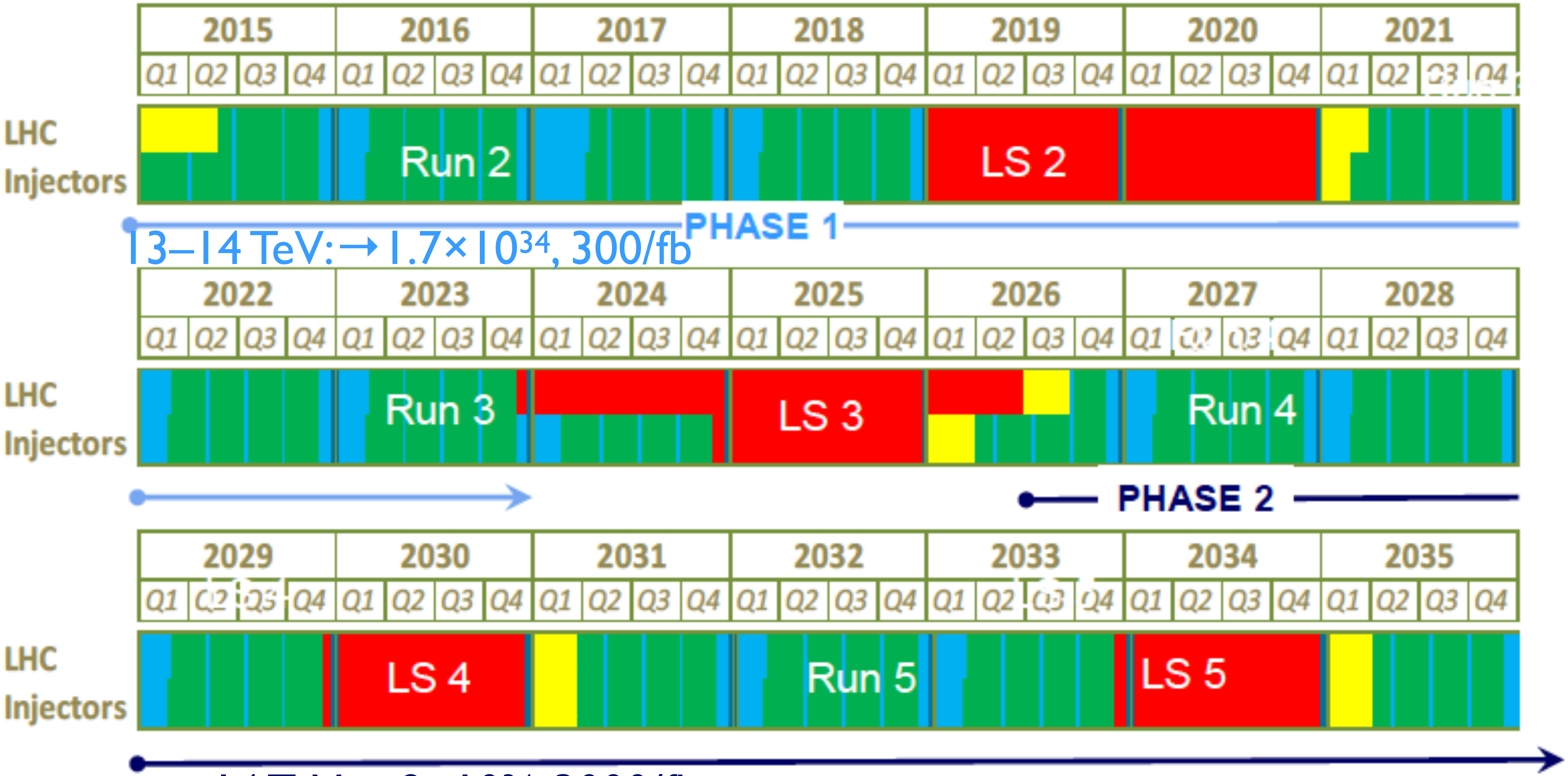
https://home.cern/about/experiments

Approved Experiments reviewed by the SPS and PS Experiments Committee (SPSC), Status Sept. 2016			
Experiment		**Description**	**Comment**
AD2 (ATRAP)	AD	Precise laser or microwave spectroscopy of trapped antihydrogen	
AD3 (ASACUSA)		Atomic Spectroscopy And Collisions Using Slow Antiprotons	
AD4 (ACE)		Relative Biological Effectiveness of Antiproton Annihilation	finished data taking
AD5 (ALPHA)		Antihydrogen spectroscopy	
AD6 (AEGIS)		Testing gravity with antimatter	
AD7 (GBAR)		Testing gravity with antimatter	
AD8 (BASE)		Comparisons of the fundamental properties of antiprotons and protons	
PS212 (DIRAC)	PS	Observation of mesonic atoms and tests of low energy QCD	finished data taking
PS215 (CLOUD)		Influence of galactic cosmic rays (GCRs) on aerosols and clouds	
NA58 (COMPASS)	SPS	Study of hadron structure and hadron spectroscopy	
NA61 (SHINE)		Strong interactions, neutrinos and cosmic rays	
NA62		Measuring rare kaon decays	
NA63		Electromagnetic Processes in strong Crystalline Fields	
NA64		Search for dark sectors in missing energy events	
UA9 (CRYSTAL)		Crystal Channeling	
AWAKE		Advanced Proton-Driven Plasma Wakefield Acceleration Experiment	
WA104 (NP01)	Neutrino Facility	Refurbishment of the ICARUS Detector	
ProtoDUNE-DP (NP02)		Prototype of a Double-Phase Liquid Argon TPC for DUNE	
ProtoDUNE-SP (NP04)		Prototype of a Single-Phase Liquid Argon TPC for DUNE	
Baby MIND (NP05)		Prototype of a Magnetized Iron Neutrino Detector	
CAST	non-accel. Experiments	Search for Axions and Axion-like particles	
OSQAR		Search for QED vacuum magnetic birefringence, Axions and photon Regeneration	
CNGS1 (OPERA)	CNGS	Neutrino oscillation experiment at LNGS	finished data taking
CNGS2 (ICARUS)		Neutrino oscillation experiment at LNGS	finished data taking

CERN 20-year schedule

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- **Long Shutdown (LS)**
- Beam commissioning
- Technical stop



13–14 TeV: → 1.7×10^{34}, 300/fb

14 TeV: → 2×10^{34}, 3000/fb

**outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015*

RESOURCES FOR ACCELERATOR ACTIVITIES

PBC study now officially included in the CERN Mid Term Plan

37. Physics Beyond Collider (PBC)

Goals	Physics Beyond Colliders (PBC) is an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments. A kick-off workshop was held in September 2016 identified a number of areas of interest. Following this meeting and consultation with the relevant communities, the study team has defined the structure and the main activities of the group and appointed conveners of thematic working groups. The scientific findings will be collected in a report to be delivered by the end of 2018. This document will also serve as input to the next update of the European Strategy for Particle Physics. Under the auspices of the PBC study are the feasibility studies for the SPS Beam Dump Facility (BDF). Resources for these studies were included in the 2016 MTP.
2018 targets	The key deliverable of the Physics Beyond Colliders study is a document summarizing the feasibility and science case of the options. This document is to be provided to the update of the European Strategy for Particle Physics, the process for which is scheduled to take place in 2019.
Future prospects & longer term	The long-term vision for the exploitation of the accelerator complex is to be explored. Backed by strong physics case, initiatives pursued could provide a valuable to complement to CERN's collider program.

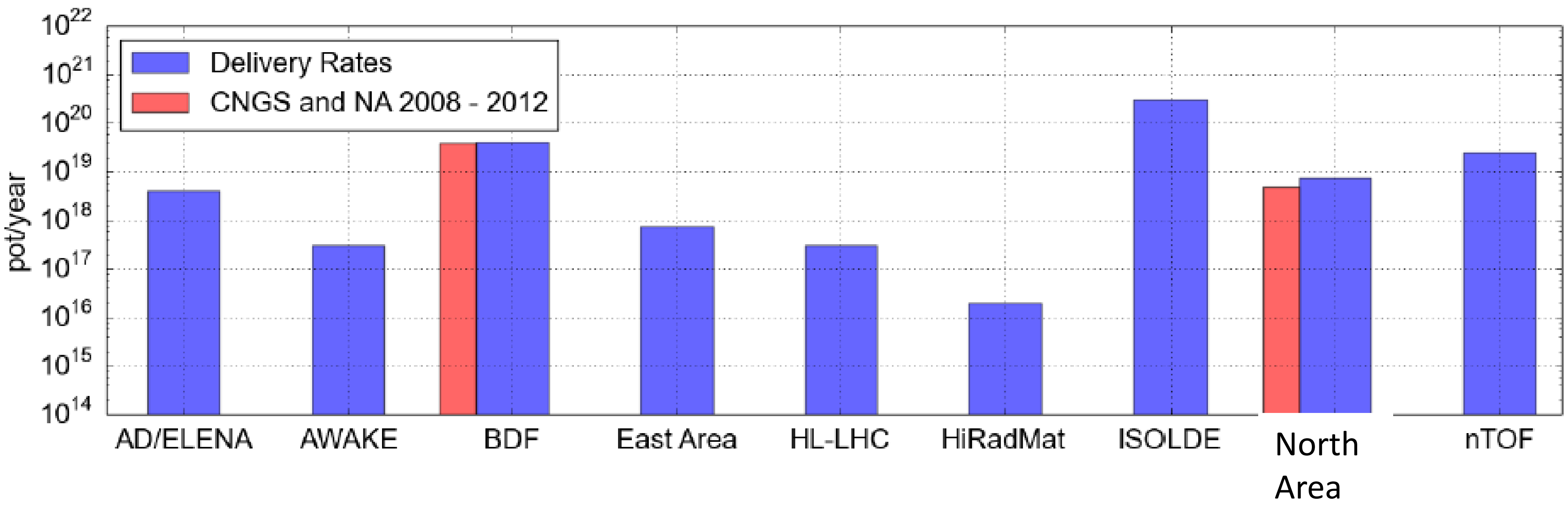
- Resources have been assigned – our thanks to the directorate
- 12 fellows at present (9 with BDF) plus some material

… + many contributions from external institutes associated to the projects

CERN Medium-Term Plan

Complex already heavily solicited

- LHC will continue to dominate
- Diverse forward looking program already in place!

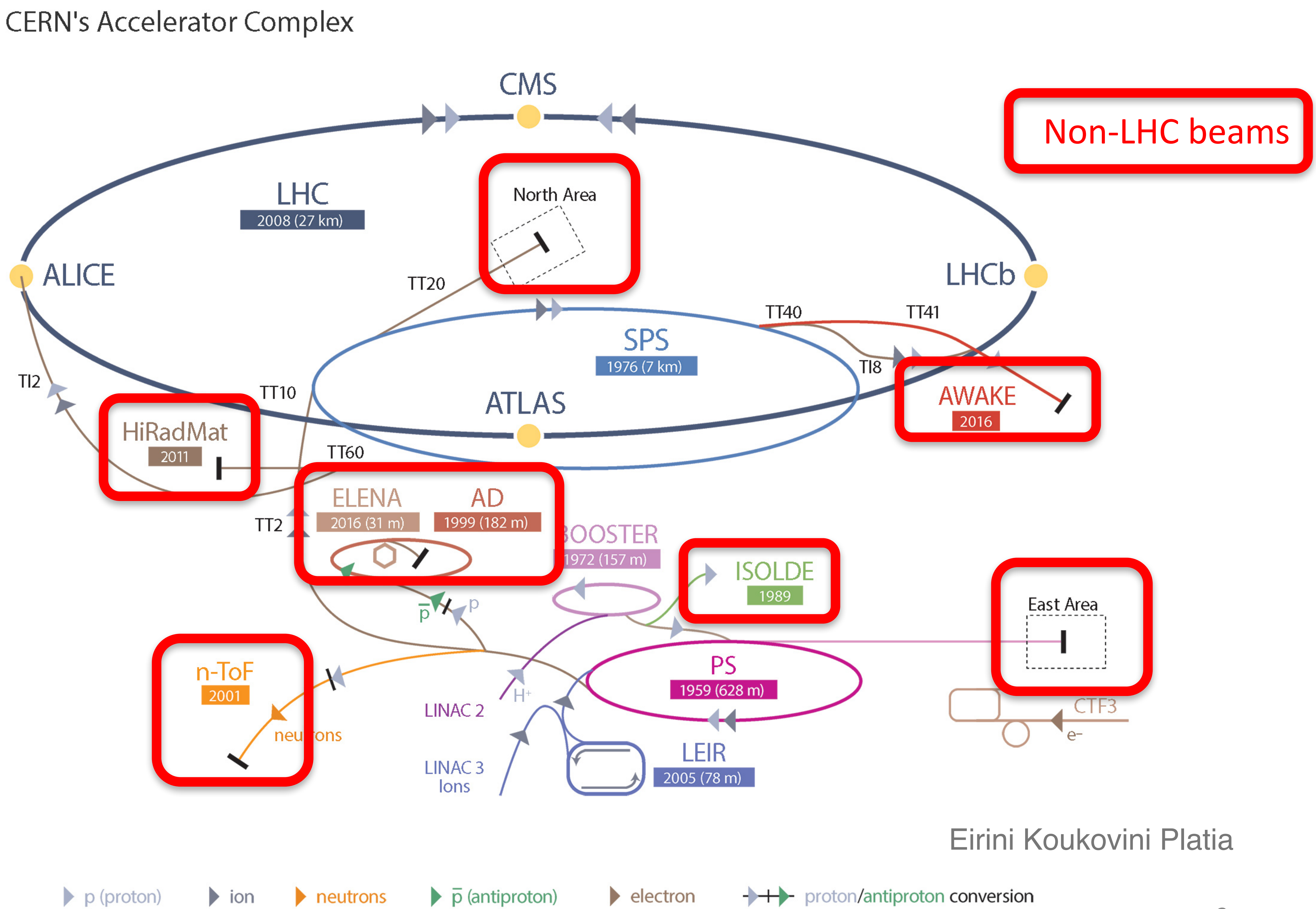


Compare Fermilab now:

NOνA 5.5×10^{20} · BNB 3×10^{20} · μ Campus 1.4×10^{20} · Test Beams …

Current capacity $\approx 1.3\times10^{21}$

CERN accelerator complex



Eirini Koukovini Platia

PBC DELIVERABLES in short

One main overview document supplemented by :

Accelerator documents:

Beam Dump Facility	:	Conceptual Design of the BDF
EDM ring	:	Fully developed feasibility study including preliminary costing
Conventional beams	:	Study beam upgrades for extended or new fixed target projects
LHC Fixed Target	:	Conceptual design of LHC internal crystal and gaseous targets
Technology	:	Evaluation of possible CERN contributions to non-acc. projects
Complex performance	:	Injector complex performance after LIU
AWAKE++	:	Exploratory study of possible applications of the AWAKE concept
NuSTORM	:	Updated broad outline of a possible implementation at CERN
Gamma Factory	:	Exploratory study of the concept feasibility

BSM and QCD context documents with for each proposed project:

Evaluation of the physics case in the worldwide context
Possible further optimization of the detector
For new projects: investigation of the uniqueness of CERN siting

NB: no arbitration between projects to be done by PBC !

SHiP

Detector developments

Significant progress in technology developments, e.g.

<u>Timing Detector</u>
1. Plastic scintillator +SIPM
2. MRPC
- Test beam 2017 w. electronics
- Demonstrated σ_t<100ps

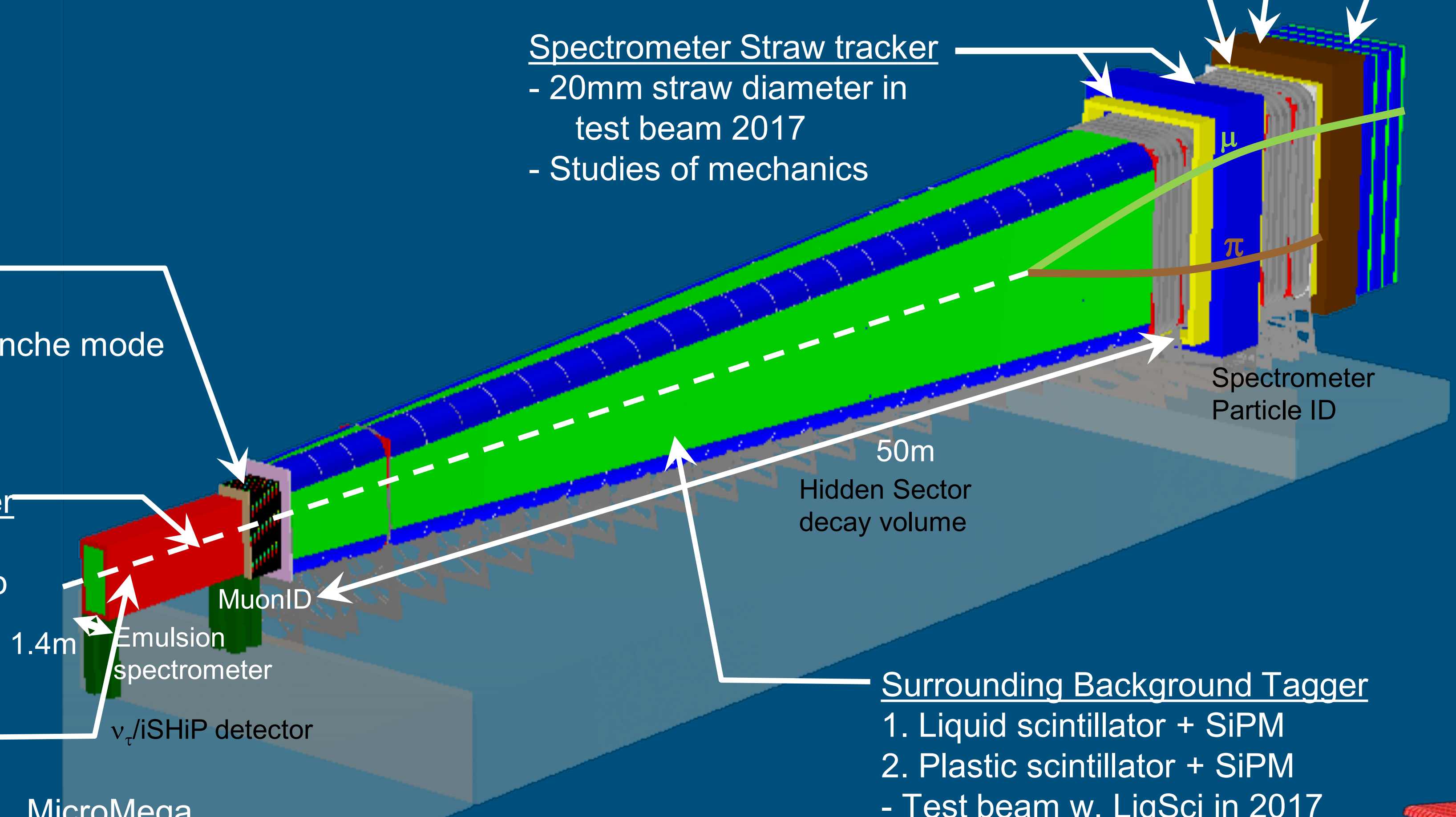
<u>ECAL/HCAL</u>
- Sandwich calorimeter w. scintillating bars+SiPM
- High-precision layers for directionality for ALP→$\gamma\gamma$
- Test beam 2018

<u>MUON</u>
1. Scintilating bars+SiPM
2. Scintillatig tiles+SIPM
- Option 1 validated in test bea
- Option 2 in 2018

<u>Spectrometer Straw tracker</u>
- 20mm straw diameter in test beam 2017
- Studies of mechanics

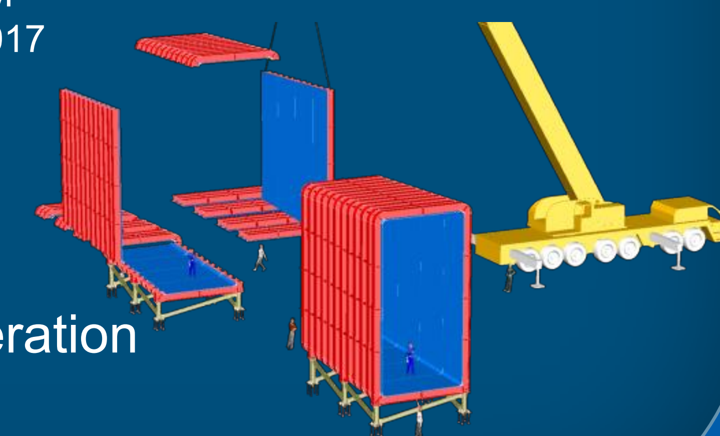
<u>Upstream MuonID</u>
- RPC
- Optimized for avalanche mode

<u>Spectrometer tracker</u>
- SciFi
- Synergy with LHCb



<u>Target tracker</u>
1. SciFi
2. GEM,μRWELL, MicroMega
– μRWELL w. μTPC mode in test beam 2017
- GEM and MicroMega in earlier test beams

<u>Surrounding Background Tagger</u>
1. Liquid scintillator + SiPM
2. Plastic scintillator + SiPM
- Test beam w. LiqSci in 2017



In addition:

- Specification of infrastructure and services for assembly, installation and operation
- Evaluation of safety aspects

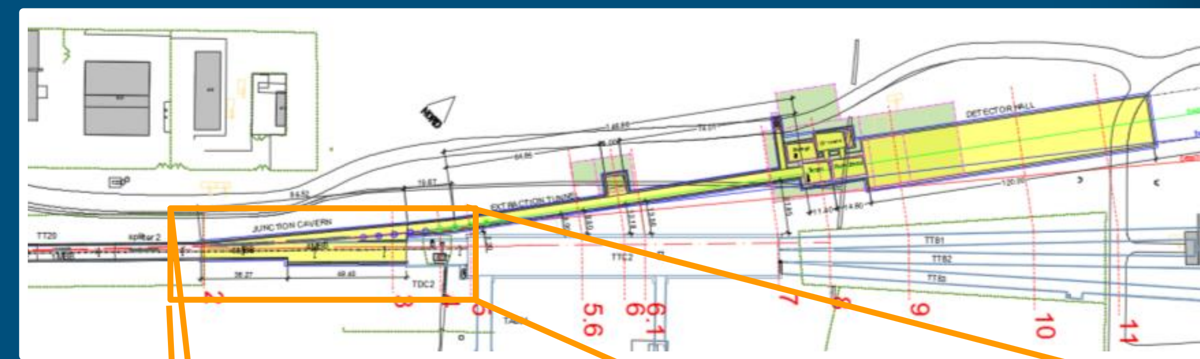
τ → 3μ at SHIP Facility: "τSHiP"

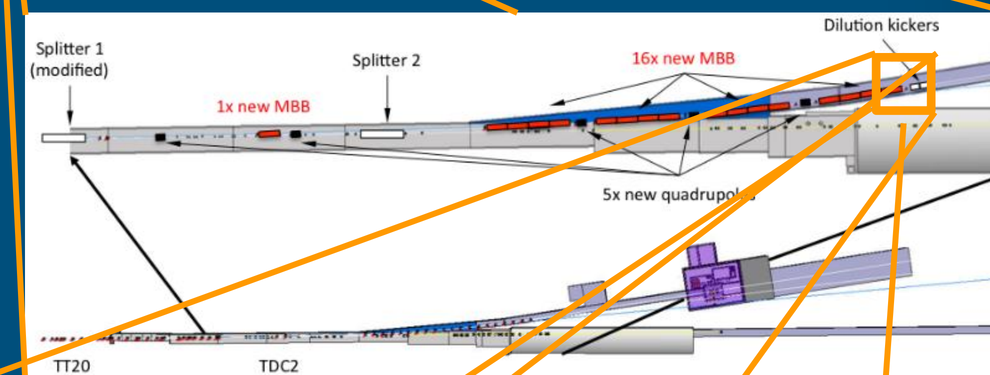
Resumed studies of LFV τ → 3μ at SHIP

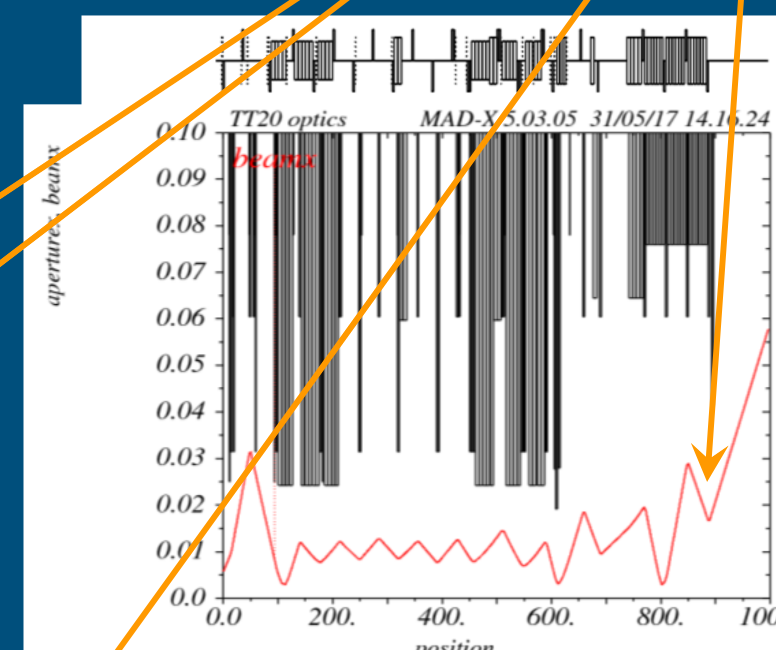
Opportunity already explored in SHiP Physics Proposal
(Rep. Prog. Phys. 79 (2016) 124201)

- Parallel operation with ν/iSHiP and dSHiP most efficient!
- With 5×10^{13} τ decays in vacuum from 1% of 2×10^{20} pot on SHiP main target : U.L. on BR(τ → 3μ) ~ 10^{-10} or better
- Also opportunity for $D \to \mu\mu, \ldots$
- Challenges
  - Radiological aspects 1% beam loss
  - Entire facility to be moved downstream by 20m
  - Main backgrounds: $D_s \to \eta(\mu^+\mu^-\gamma)\mu^-\nu_\mu$ and combinatorial background from muons produced in η, ρ, ω decays
  - → Very interesting and challenging technologically
    - → Synergy with future upgrades of LHCb tracking and calorimetry

(Radiological aspects and moving the facility downstream: Not yet subject of facility studies)

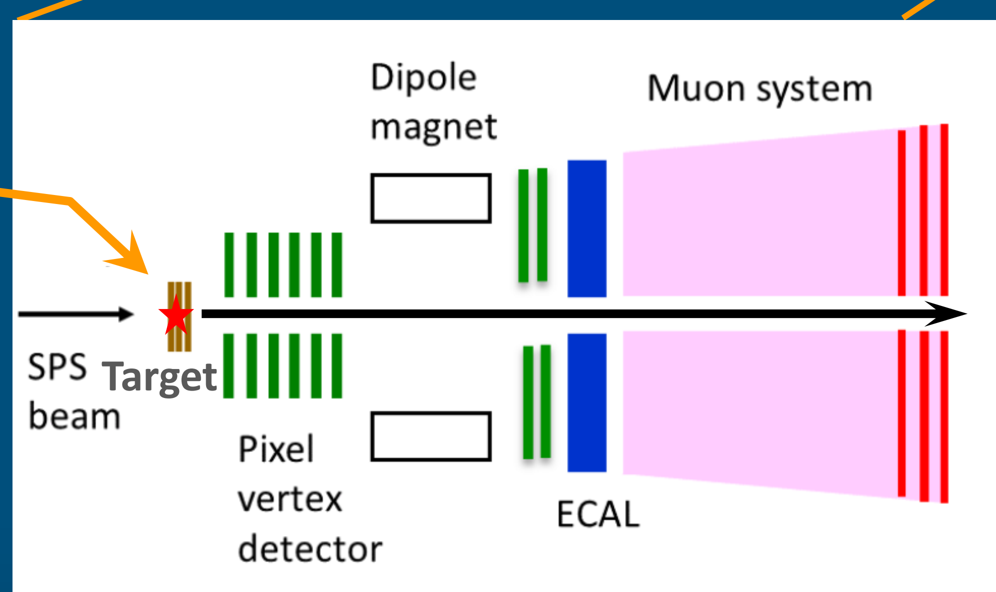




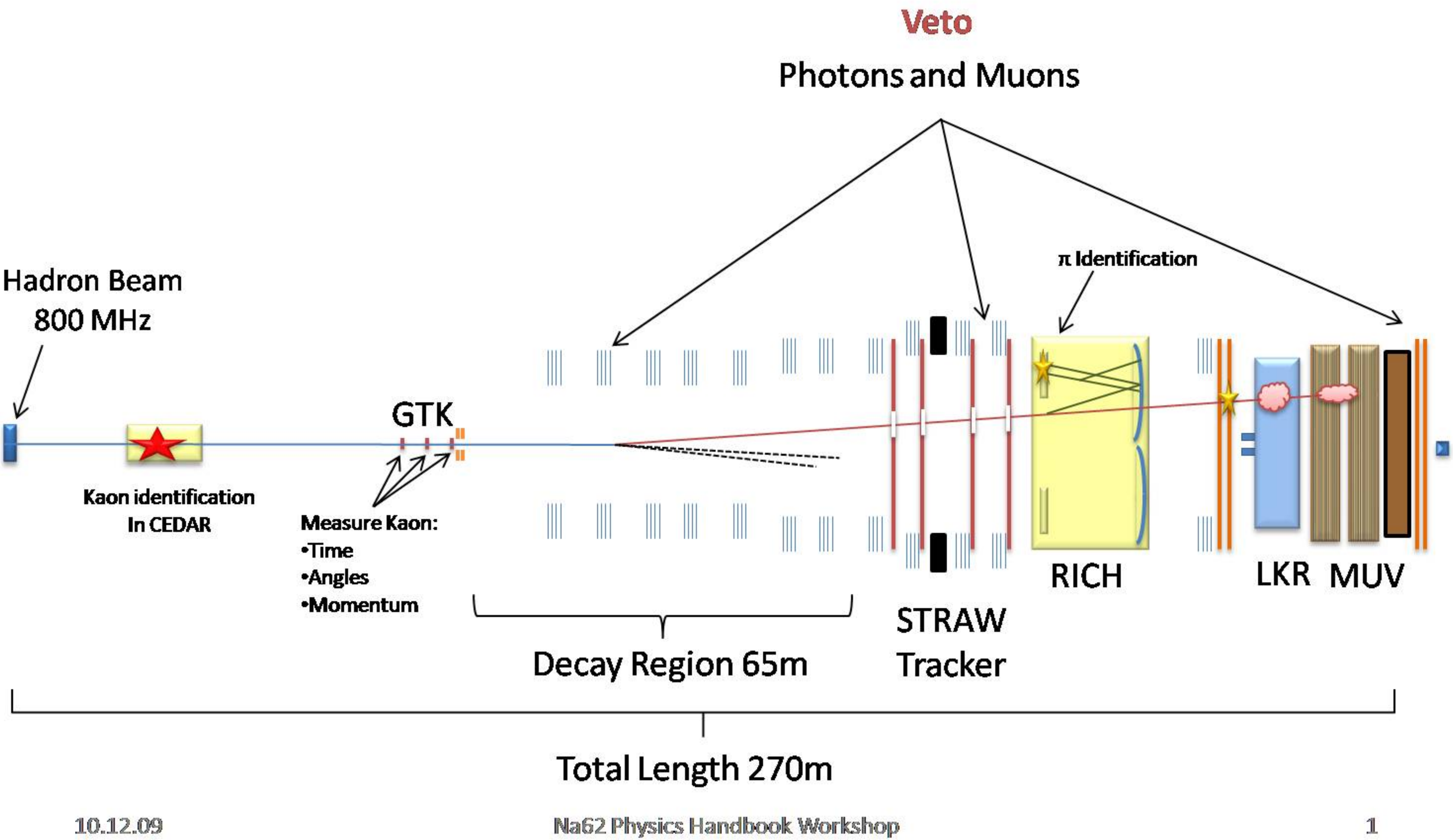


6σ beam envelope incl. 5 mm orbit deviation and 10% beta beating → RMS 3mm

E.g. 1mm W (multiple) target system intercepting 1% of 2×10^{20} pot



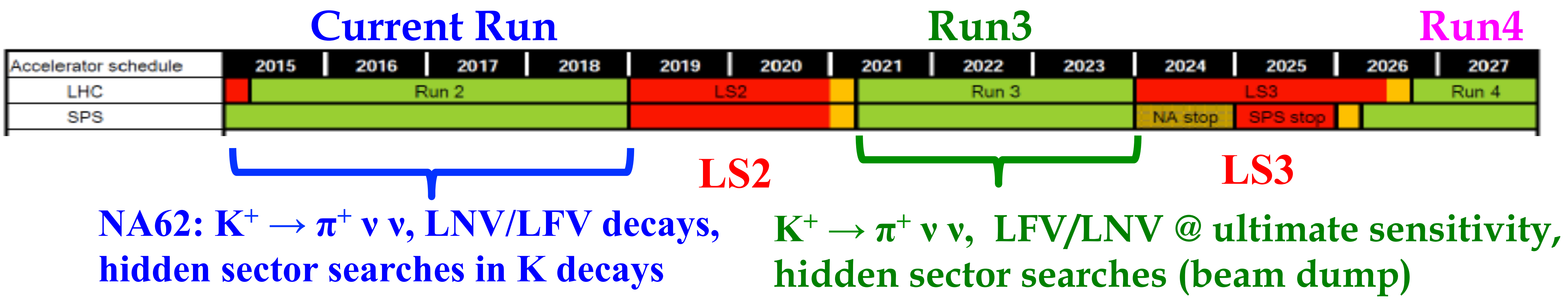
NA62 goal: O(100) $K^+ \to \pi^+ \nu \bar{\nu}$



Physics at NA62 in Run 3

A rich field to be explored with minimal upgrades to the present setup

0. **Run to refine $\pi\nu\nu$ measurement:** need, duration, setup depend on **measurement scenario**
1. **Present K^+ beam setup + trigger upgrades:** unprecedented LFV/LNV sensitivities from K^+/π^0
2. **10^{18} POT in "beam-dump" mode:** NP searches for MeV-GeV mass hidden-sector candidates



Conclusions: physics at NA62 after LS2

Assuming fulfillment of main goal, BR(K-> $\pi\nu\nu$), a broad physics program at NA62 after LS2

1. Present K^+ beam and dedicated triggers :

- **LFV and LNV to SES ~ 10^{-12} from K and π^0 decays**
- **Ultra-rare/forbidden π^0 decays**

2. Year-long data-taking (10^{18} POT) in beam dump mode provides sensitivity to NP models:

- **Dark photons, Heavy Neutral Leptons, Axion-like particles, Dark scalars, etc.**

Expected sensitivity superior to that from other initiatives in the same time range

Data demonstrate background rejection for 2-track searches @4x10^{15} POT's

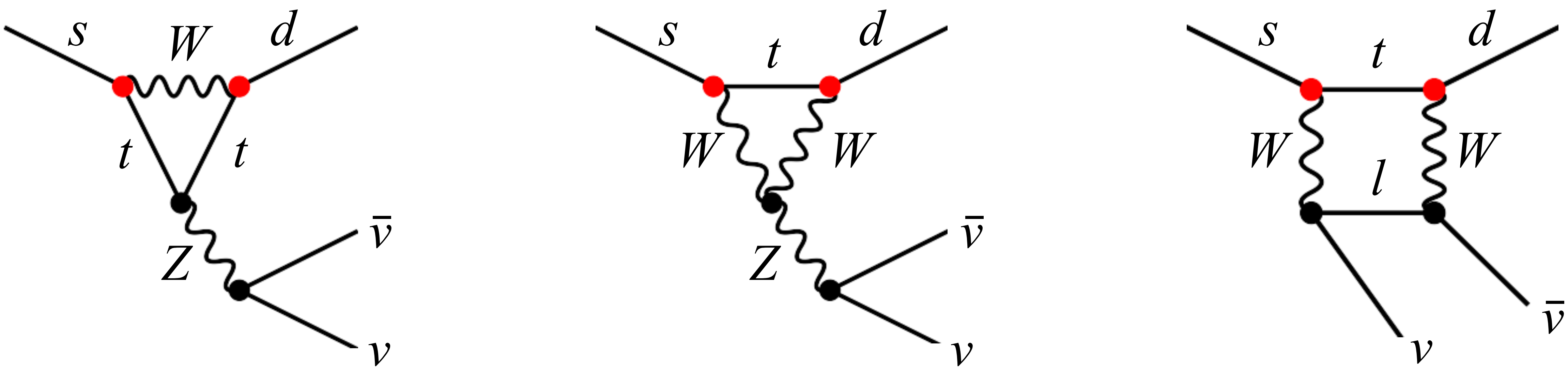
The current NA62 run will be exploited to:

- **evaluate bkg rejection up to ~10^{16} -- 10^{17} POT's**
- **potentially achieve first results (ALP -> $\gamma\gamma$ search, etc.)**
- **optimize design for future beam-dump mode**

$K \to \pi\nu\nu$ in the Standard Model

KLEVER

FCNC processes dominated by Z-penguin and box amplitudes:



Extremely rare decays with rates very precisely predicted in SM:

•Hard GIM mechanism + pattern of CKM suppression ($V_{ts}{}^* V_{td}$)

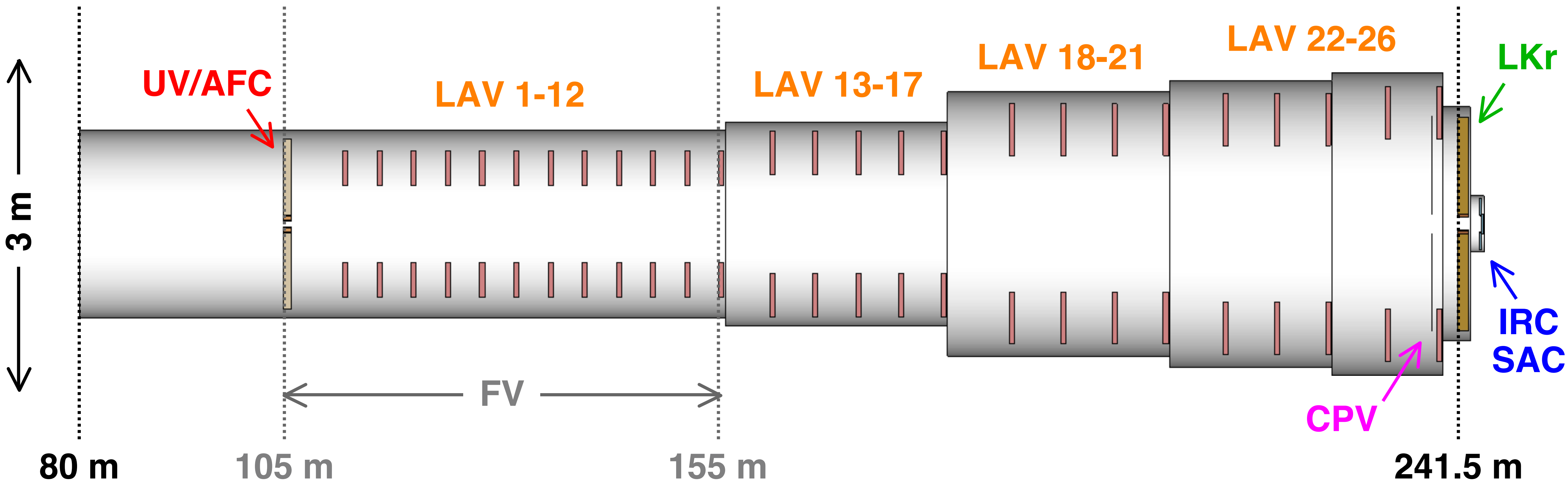
•No long-distance contributions from amplitudes with intermediate photons

•Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

	SM predicted rates Buras et al, JHEP 1511*	**Experimental status**
$K^+ \to \pi^+\nu\bar{\nu}$	**BR = (8.4 ± 1.0) × 10^{-11}**	**BR = (17.3 $^{+11.5}_{-10.5}$) × 10^{-11}** Stopped K^+, 7 events observed BNL 787/949, PRD79 (2009)
$K_L \to \pi^0\nu\bar{\nu}$	**BR = (3.4 ± 0.6) × 10^{-11}**	**BR < 2600 × 10^{-11} 90%CL** KEK 391a, PRD81 (2010)

* Tree-level determinations of CKM matrix elements

An experiment to measure $K_L \to \pi^0 \nu\bar{\nu}$ KLEVER



Target sensitivity:

5 years starting Run 4

~60 SM $K_L \to \pi^0\nu\nu$

S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

Main detector/veto systems:

UV/AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 liquid-krypton calorimeter
IRC/SAC	Small-angle vetoes
CPV	Charged-particle veto

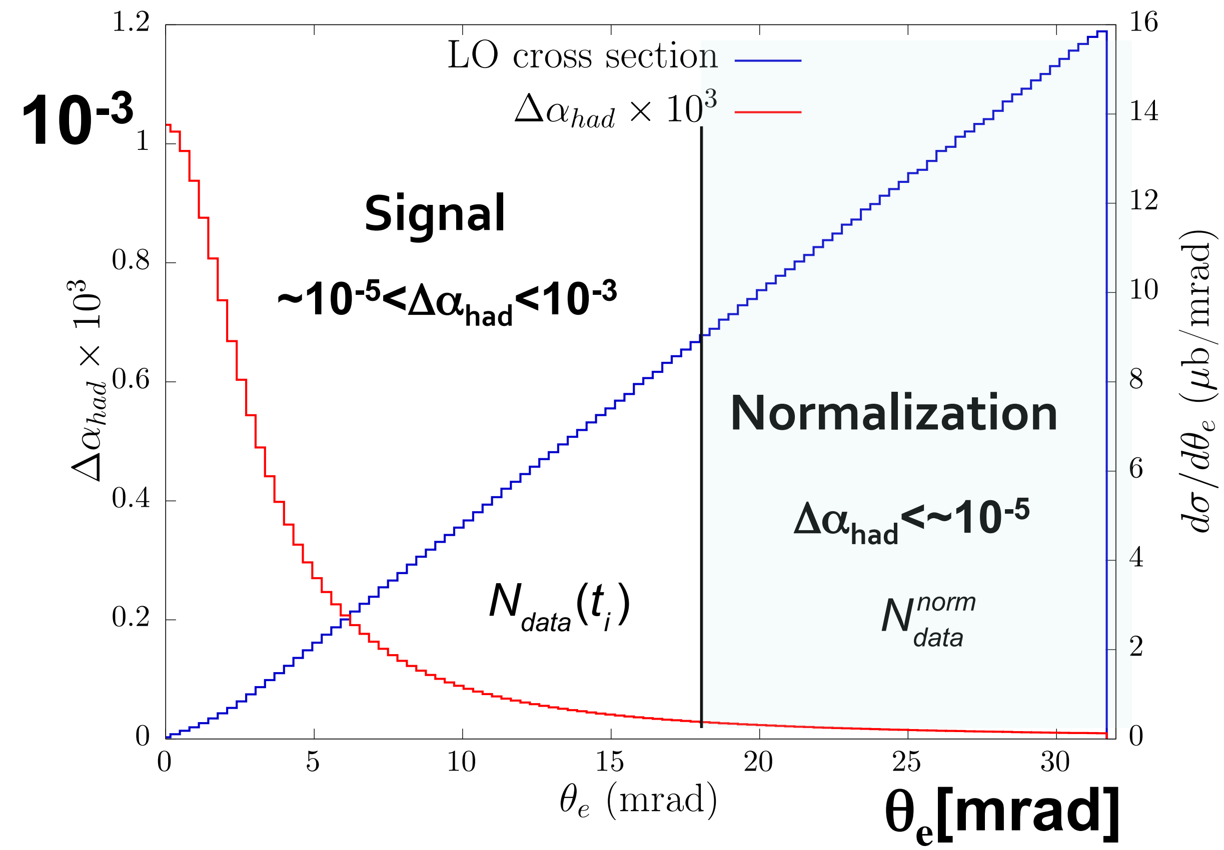
MUonE :
measuring a_μ^{HLO} in the spacelike region

- a_μ^{HLO} can be obtained as integral on $\Delta\alpha_{had}$ (t) for t<0

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}(t(x))dx$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

t momentum transfer in the reaction

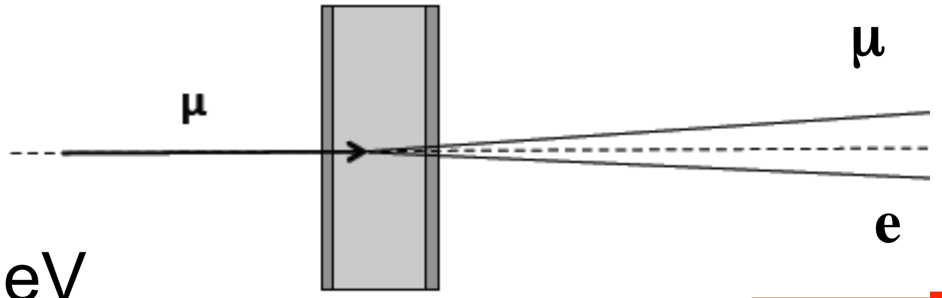


- $\Delta\alpha_{had}$ (t) (t<0) from μ-e elastic scattering using a high energy muon beam (E~150 GeV) on electron low-Z target

$$\frac{N_{data}(t_i)}{N^0_{MC}(t_i)} = \boxed{\frac{N_{data}(t_i)}{N^{norm}_{data}}} \times \boxed{\frac{\sigma^{0,norm}_{MC}}{\sigma^0_{MC}(t_i)}} \sim 1-2(\Delta\alpha_{lep}(t_i)+\Delta\alpha_{had}(t_i))$$

Ratio of the theoretical cross section (with no VP)

Ratio of data $N_{signal}(t)/N_{normalization}$



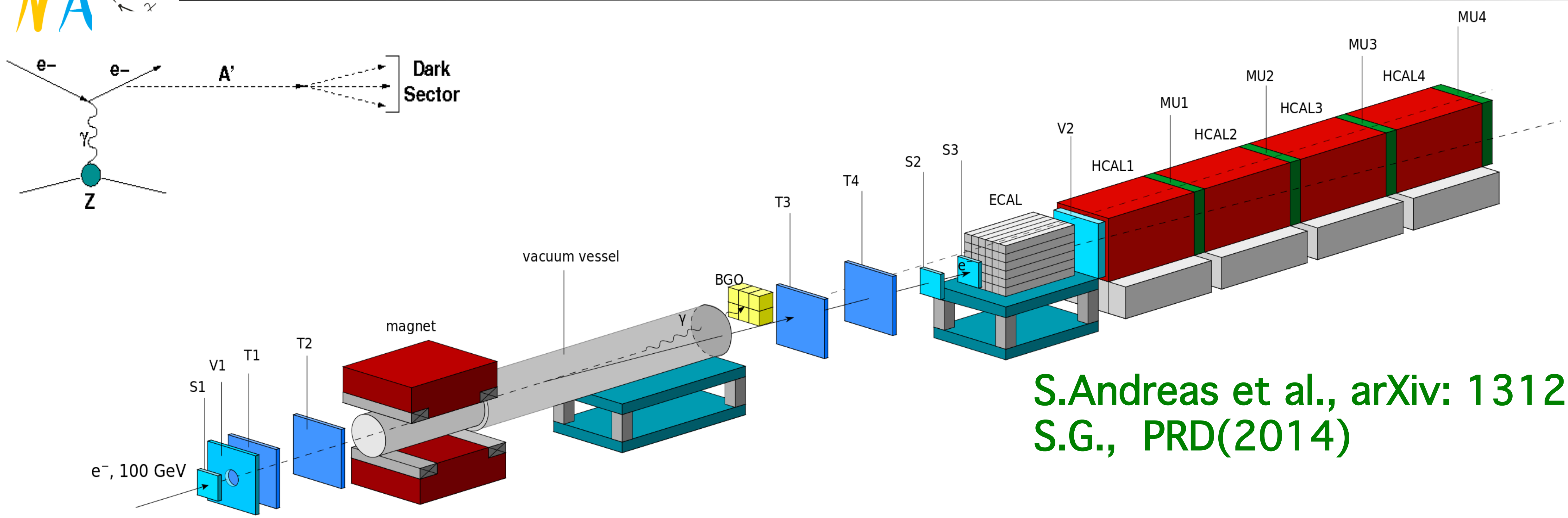
150 GeV

target

a_μ^{HLO} at 0.3% → These two ratios should be known at 10^{-5}

Search for A´->invisible decays at the CERN SPS

4.



S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

Main components :

- clean 100 GeV e- beam
- e- tagging: tracker+SRD
- fully hermetic ECAL+HCAL

Signature:

- in: 100 GeV e- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

Summary of NA64++ Physics Prospects beyond LS2

Beam and process	Motivation	Required number of POT
1. $e^- Z$		
✧ A´-> invisible ✧ X(16.7), A´ -> e^+e^- ✧ pseudoscalar ->invisible ✧ a -> $\gamma\gamma$ ✧ milli-Q	S,V mediator of light DM production ^{8}Be anomaly, Leptonic pseudogoldstone, ALP decays, miii-Q	~5x10^{12} EOT ~5x10^{12} EOT
2. $\mu^- Z$		
✧ $Z_{\mu\tau}$ -> $\nu\nu$, $\mu^+\mu^-$ ✧ pseudoscalar -> invisible ✧ μ->τ conversion	$(g-2)_\mu$, New gauged symmetry L_μ-L_τ. Leptonic pseudo-goldstone, LFV	10^{12}-10^{13} MOT
3. π (K) p-> M^0 n + E_{miss}		
✧ K_L-> invisible ✧ K_S-> invisible ✧ π^0, η , η -> invisible	NHL, $\phi\phi$, Bell-Steinberger Unitarity, CP, CPT symmetry	~5x10^{12} P(K)OT
4. p A -> X+ E_{miss}		
✧ leptophobic X	~ GeV DM	~5x10^{12} POT

Summary

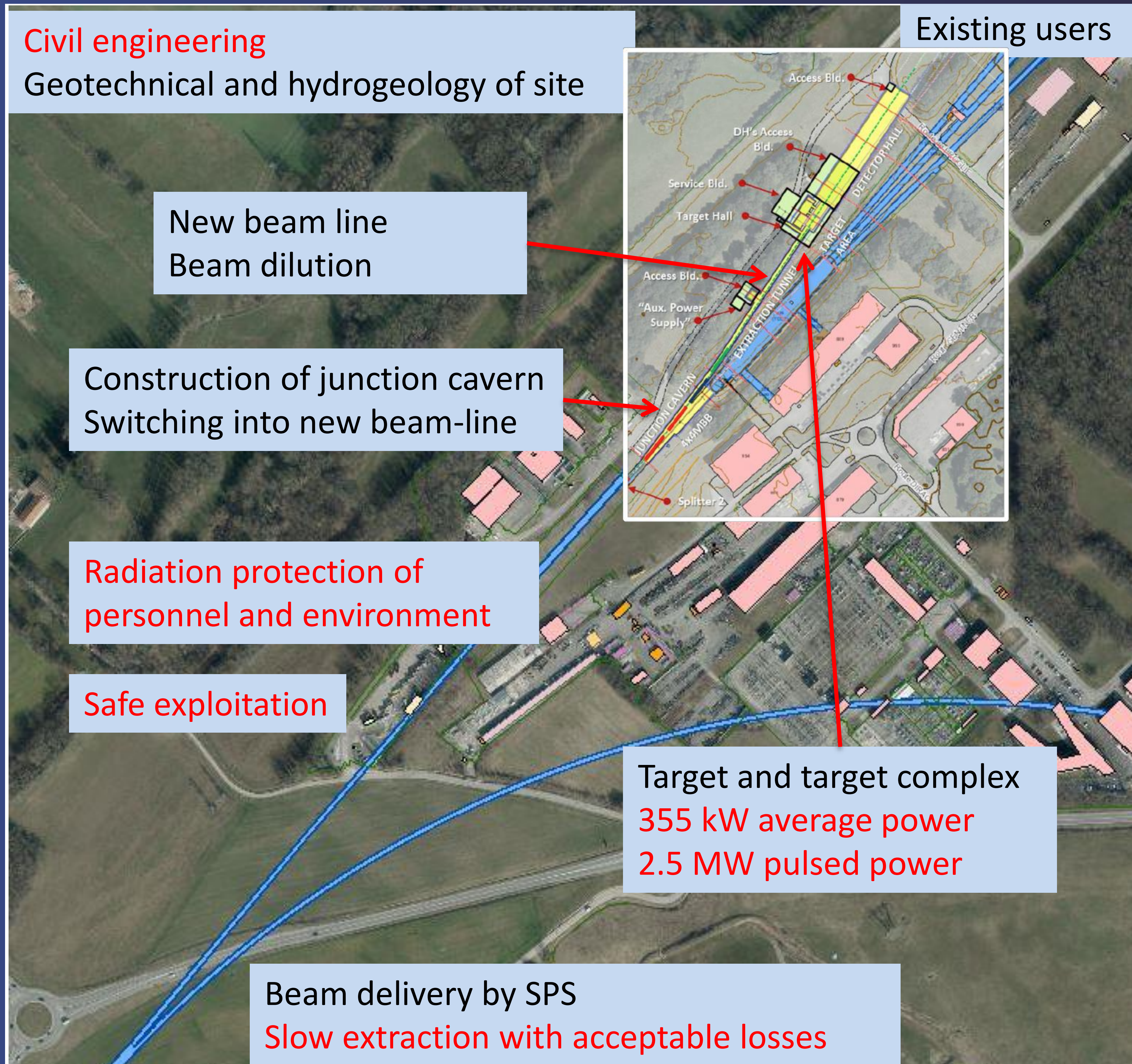
New physics (dark sector, new symmetries, hidden particles, ..) at a scale of the visible sector can be effectively probed with the NA64 approach by using e, μ , π , K, and p beams at CERN in the medium term future. The physics results promise to be rich, and might be unexpected.

NA64++ provisional time schedule

2016 I 2017 I 2018 I 2019 I 2020 I 2021 I 2022 I 2023 I 2024 I 2025 I 2026 I 2027 I

Beam					
e^-, H4 →	$(g-2)_\mu$, 8Be, Dark Sector	LS2	8Be, Dark Sector	LS3	Dark Sector
μ^-, M2 →	Proposal, Preparation	g_μ-2, Dark sector, m-τ	LS3	Dark sector, m-τ	
π^-, K^-, H2-H8,T9 →	Proposal	$\pi^0,\eta,\eta',K_L \to inv$	LS3	$\pi^0,\eta,\eta',K_S,K_L \to inv$	

Beam Dump Facility Design (TDR end 2021)



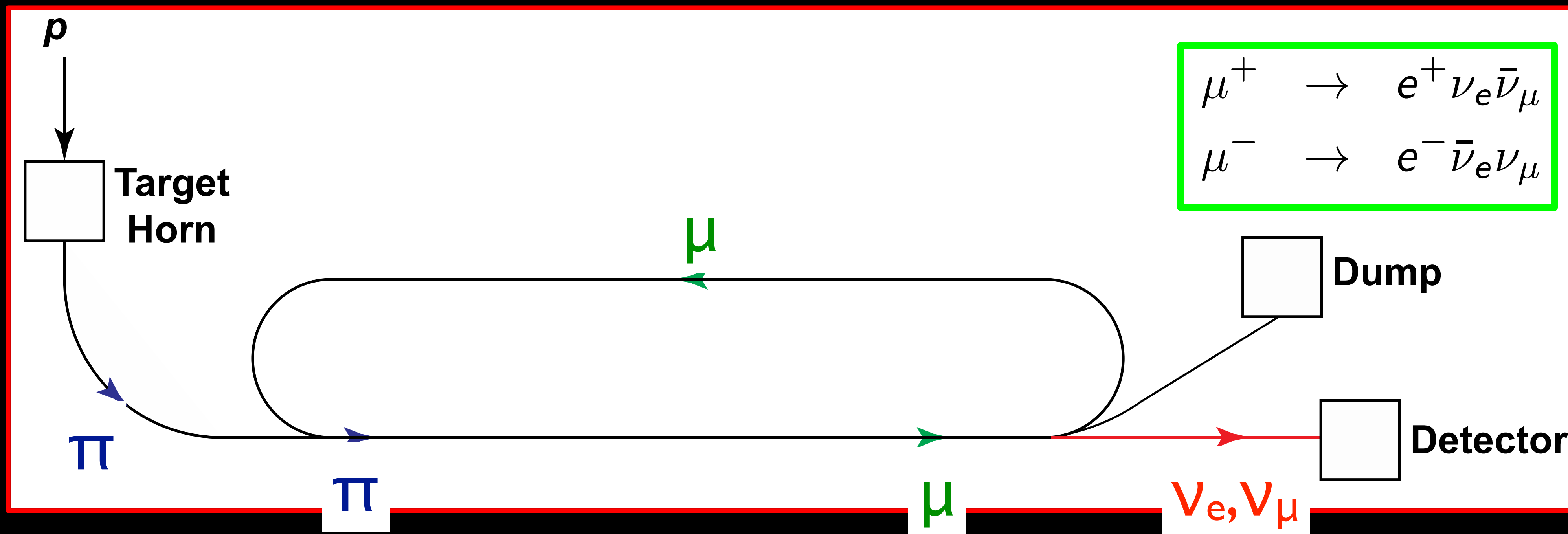
REDTOP Key Points

- Yield of $2x10^{13}$ η mesons/year (x-section >10 mbarns in the 2 GeV beam energy region)
  - Possibly $2x10^{11}$ η' mesons/years in a second phase
- 4π detector coverage (almost)
- Very small width (1.3 keV) overconstraints events → low background
- 3 (5) "golden" channels (will be described in details in the proposal)
  - But at least ~20 interesting channels (simmetry violations, new particles and forces searches, precision measurements)

Dark photon search: $\eta \rightarrow \gamma(A' \rightarrow$ lepton pairs)

Light scalar search: $\eta \rightarrow \pi^0(H \rightarrow$ lepton pairs)

Neutrinos from stored muons



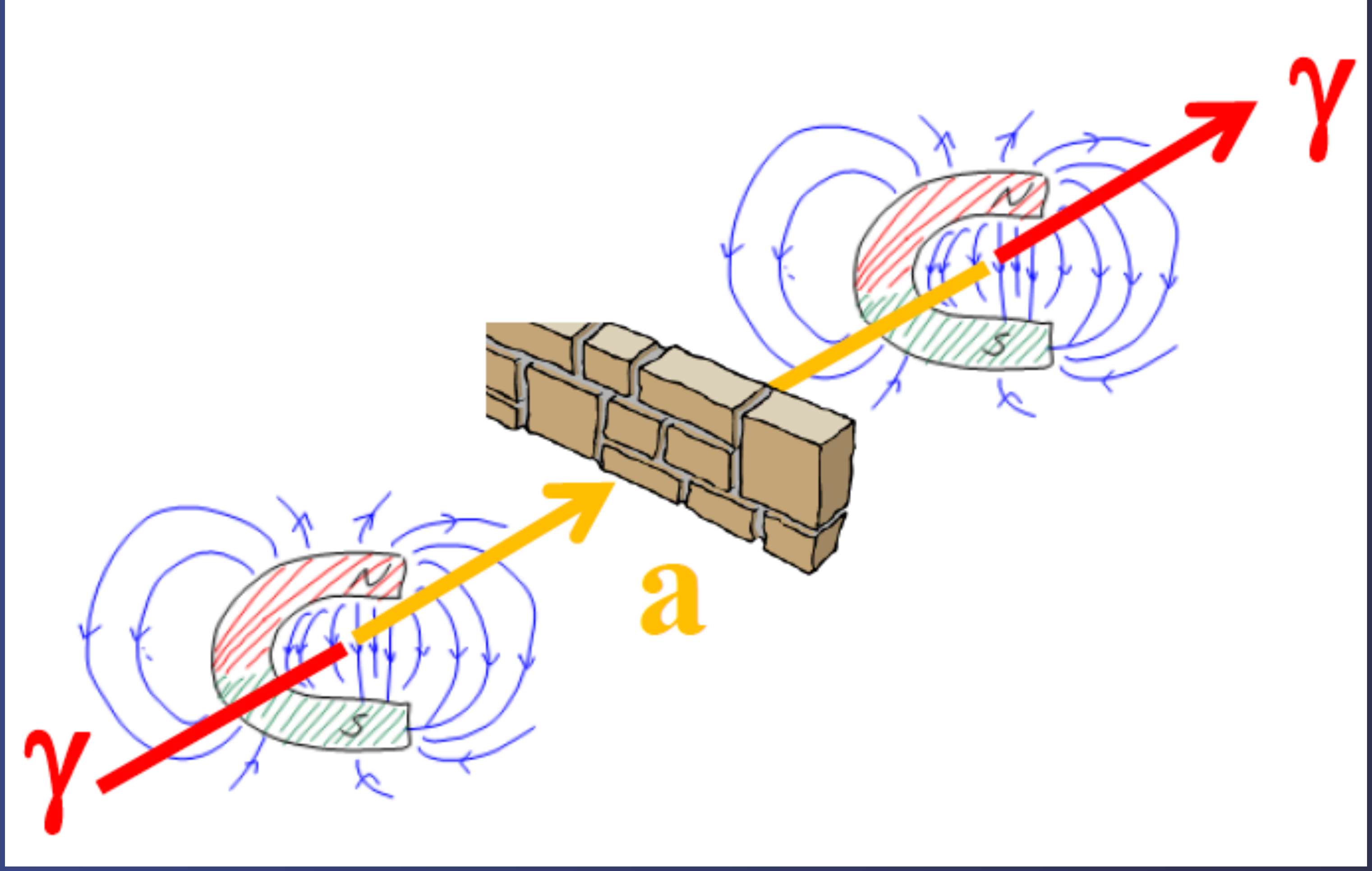
- **Scientific objectives:**
  1. %-level ($\nu_e N$)cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- **Precise neutrino flux:**
  - Normalisation: < 1%
  - Energy/flavour precise
- $\pi \rightarrow$ ➚injection pass:
  - "Flash" of ν_μ

2

3. Nucleon structure, ν-nucleus

Axion & Axion-like particle searches



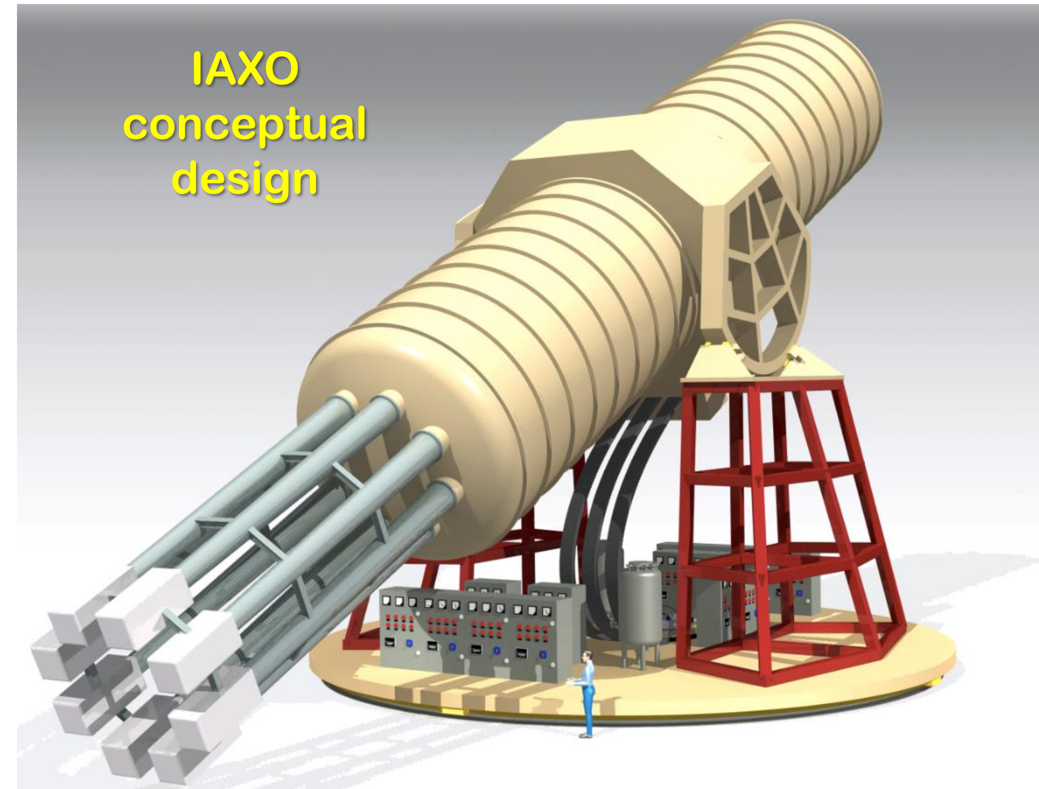
A. Lindner: ALPS-II at DESY
20 straightened HERA dipoles (5.8 T)

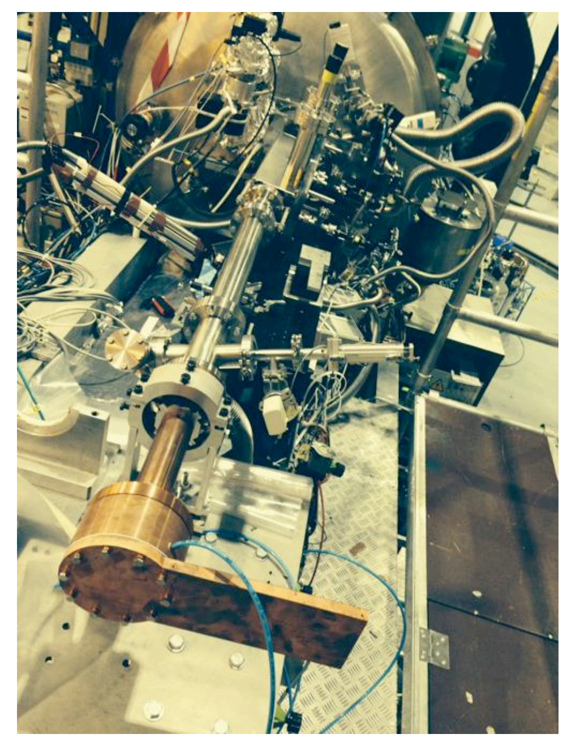
P. Spagnolo: NEXT—very intense, low-energy (30 GHz) γ source

G. Zavattini: Light propagation in external field (super PVLAS)

IAXO experiment reminder

- Next generation "axion helioscope" after CAST
- Purpose-built large-scale magnet
  - >300 times larger B^2L^2A than CAST magnet
  - Toroid geometry
  - 8 conversion bores of 60 cm Ø, ~20 m long
- Detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background techniques for detectors
  - Optics based on slumped-glass technique used in NuStar
- ~50% Sun-tracking time
- Large magnetic volume available for additional "axion" physics (e.g. DM setups)





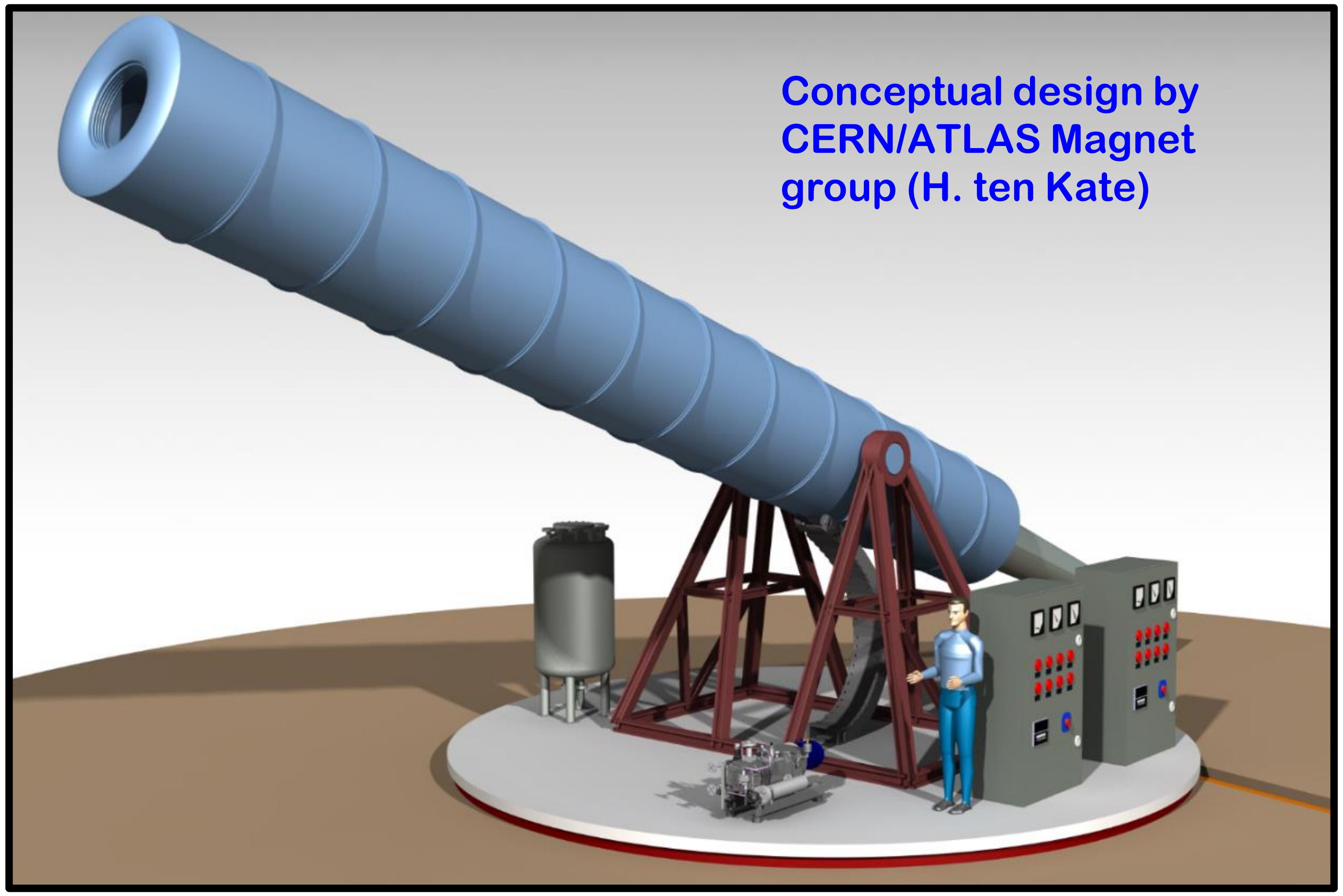
IAXO pathfinder system at CAST

In operation in 2014-15

Last CAST results published in Nature Physics last May
Nature Phys. 13 (2017) 584-590

BabyIAXO

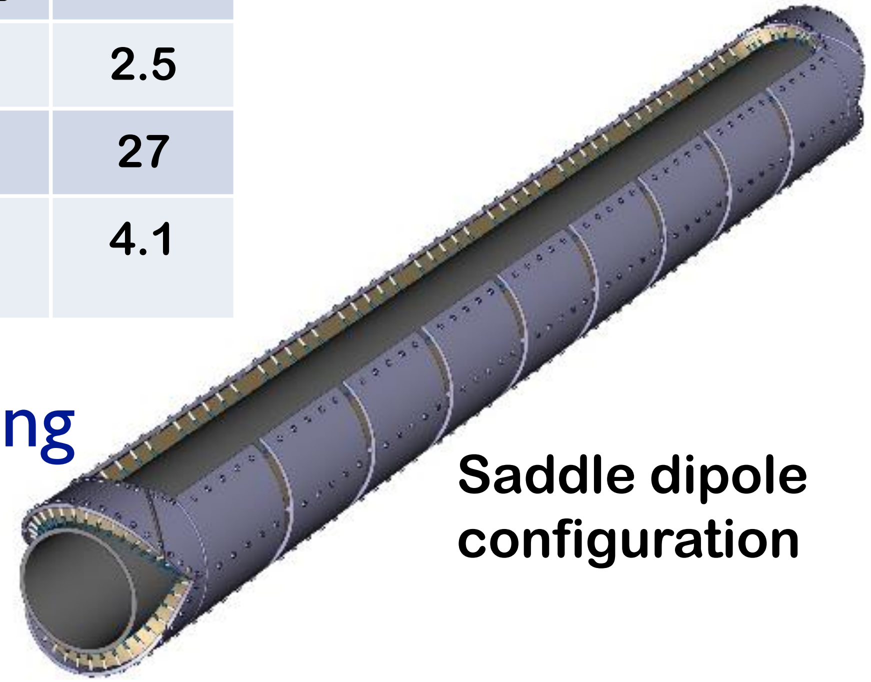
- Single bore magnet
- Bore dimensions similar to full IAXO bores → detection line representative of final ones.
- New magnet configuration (saddle dipole). Potential to go to higher B.
- Test & improve all systems. Risk mitigation for full IAXO
- Produce relevant physics
- More staged access to funds
- Move earlier to "experiment mode"



Free bore [m]	0.6
Magnetic length [m]	10
Field in bore [T]	2.5
Stored energy [MJ]	27
Peak field [T]	4.1

10x CAST MFOM

DESY, INR consider hosting



Saddle dipole configuration

- BabyIAXO CDR finished. Moving to Technical Design

What is Fermilab doing to plan a future,
and shape the next P5?

What should we be doing
(to engage the wider community)?

How might we work with the
Physics Beyond Colliders
initiative?