Physics Beyond Colliders Annual Workshop

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Fermi National Accelerator Laboratory

Fermilab Theory Seminar · 12 December 2017

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

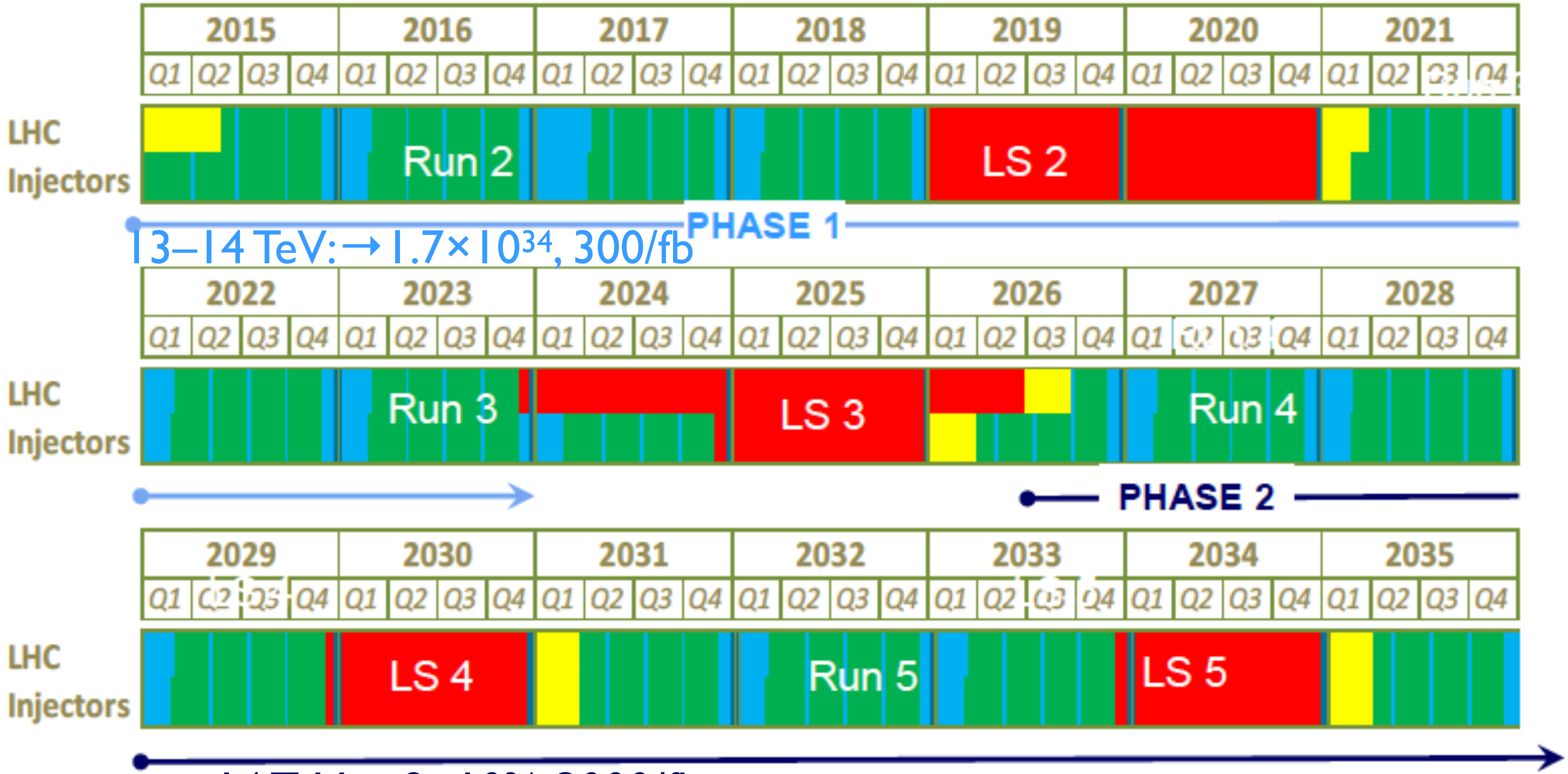
Approved Experiments reviewed by the SPS and PS Experiments Committee (SPSC), Status Sept. 2016			
Experiment		**Description**	**Comment**
AD2 (ATRAP)	AD	Precise laser or microwave spectroscopy of trapped antihydrogen	
AD3 (ASACUSA)		Atomic Spectroscopy And Collisions Using Slow Antiprotons	
AD4 (ACE)		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



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.

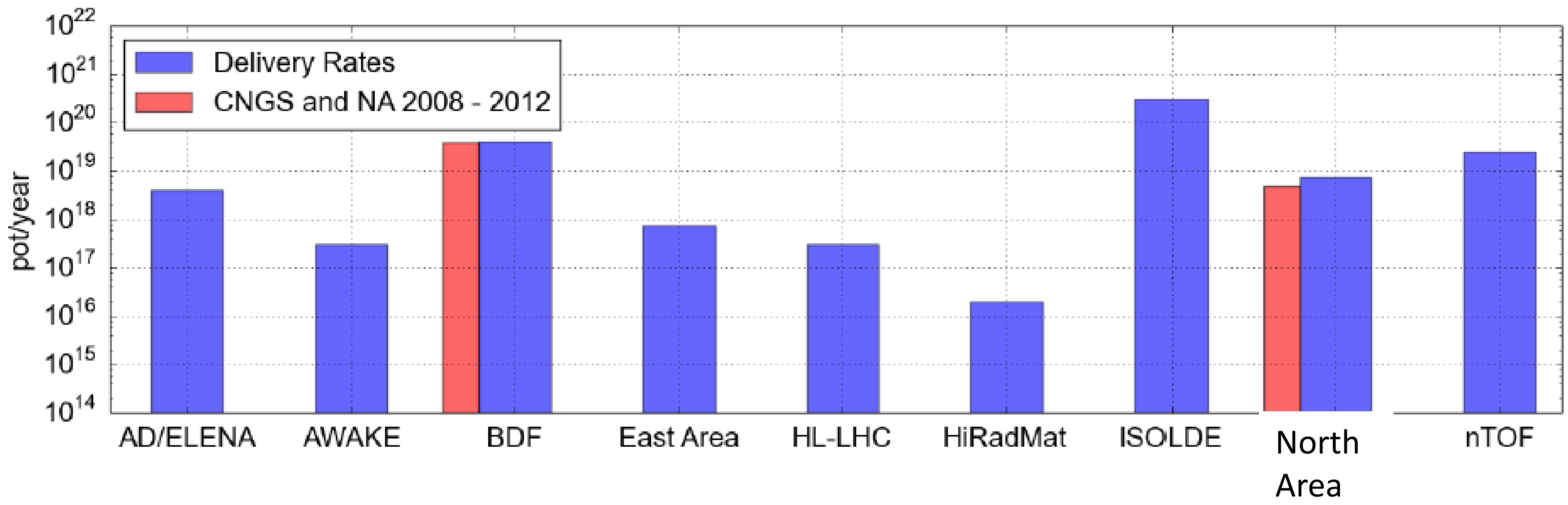
- Resources have been assigned – our thanks to the directorate
- 12 fellows at present (9 with BDF) plus some material

… + 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!

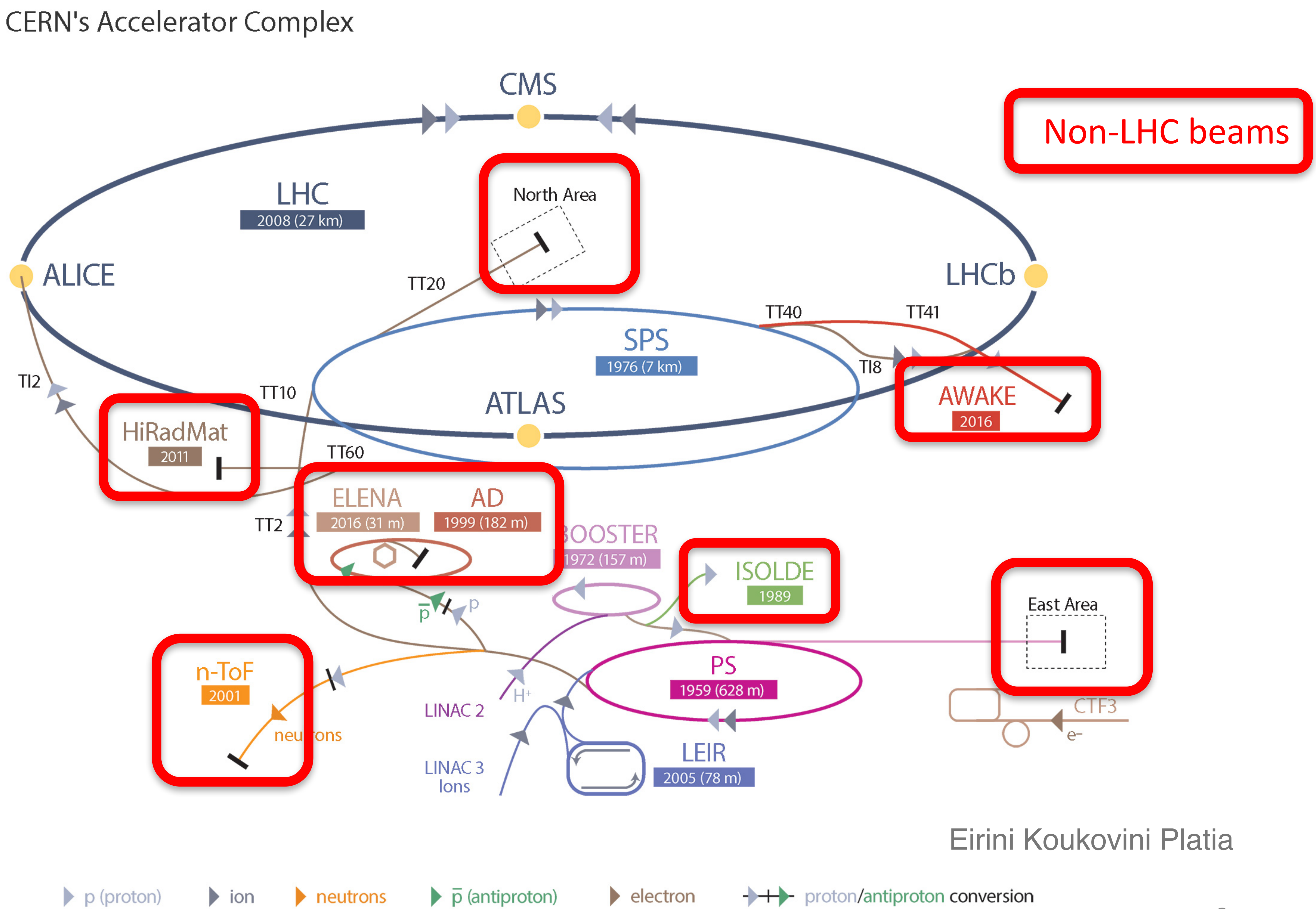


Compare Fermilab now:

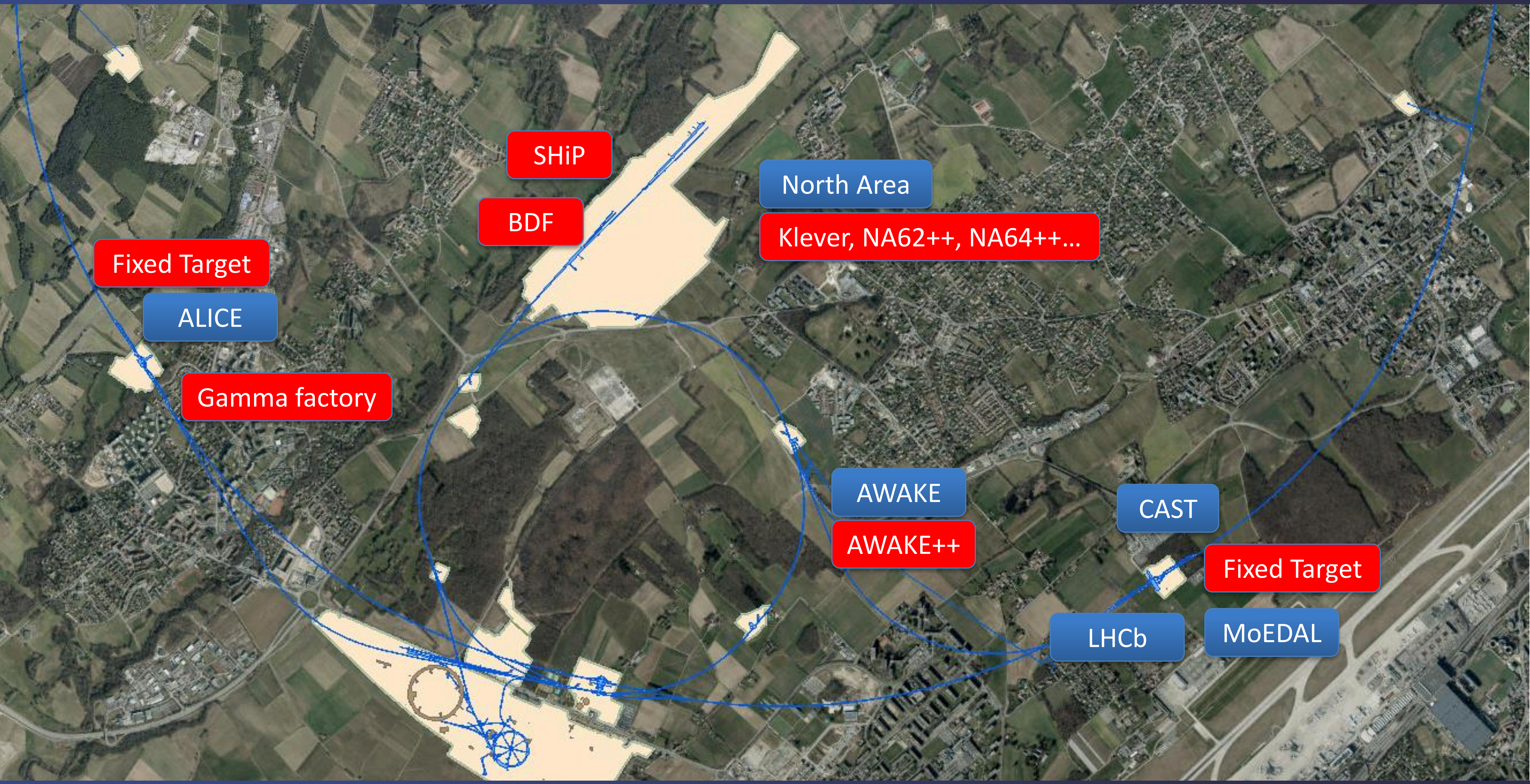
NOvA 5.5×10^{20} · BNB 3×10^{20} · μ Campus 1.4×10^{20} · Test Beams …

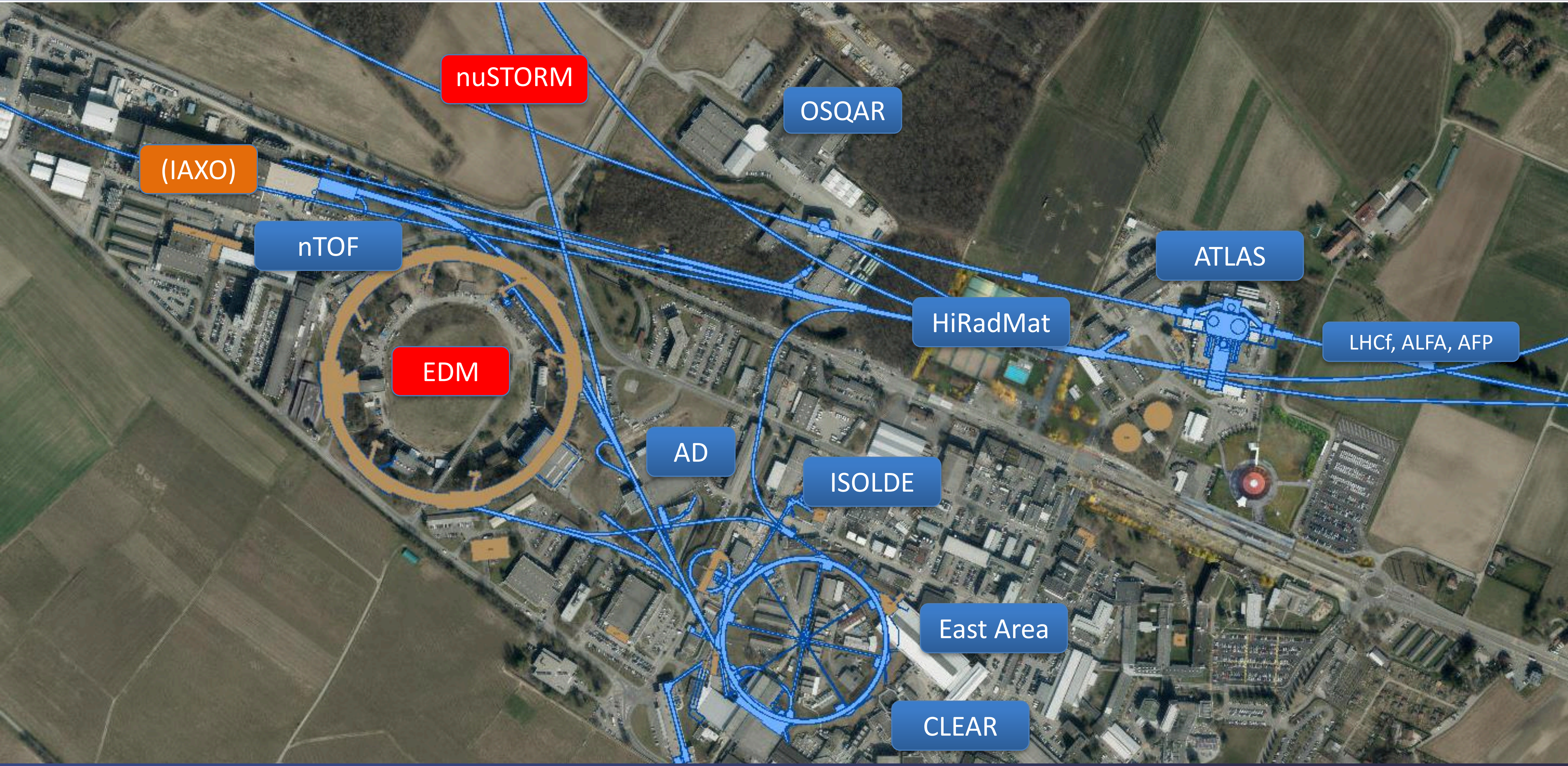
Current capacity $\approx 1.3\times10^{21}$

CERN accelerator complex

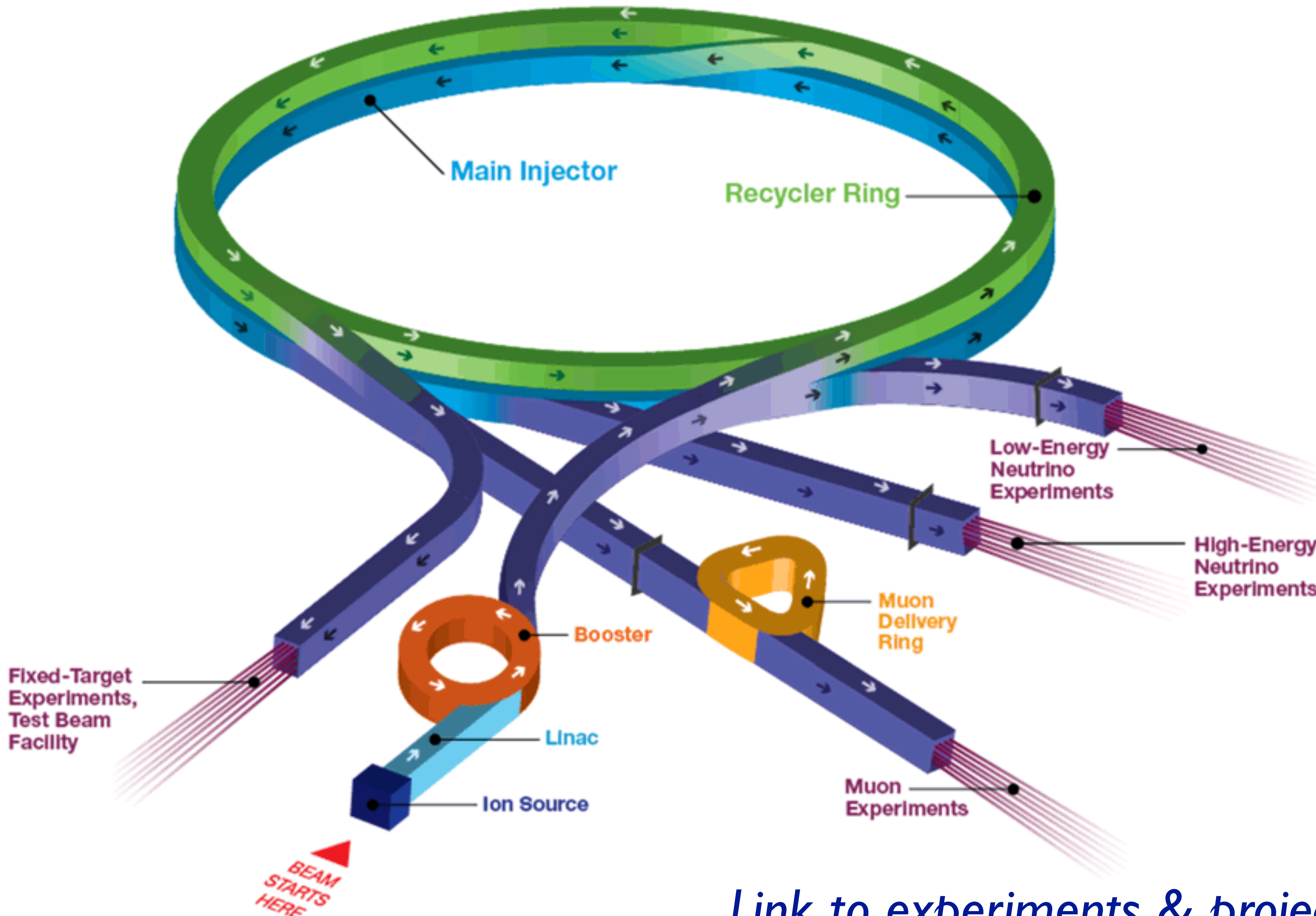


Eirini Koukovini Platia


SHiP
BDF
North Area
Klever, NA62++, NA64++...
Fixed Target
ALICE
Gamma factory
AWAKE
AWAKE++
CAST
Fixed Target
LHCb
MoEDAL


nuSTORM
OSQAR
(IAXO)
nTOF
ATLAS
HiRadMat
LHCf, ALFA, AFP
EDM
AD
ISOLDE
East Area
CLEAR

Fermilab Accelerator Complex



Link to experiments & projects

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 !

A MATTER OF GROWING INTEREST WITHIN THE COMMUNITY

e.g. ICFA Seminar, 6-9 Nov. 2017, Ottawa

Topics covered: **large overlap with PBC study**

- Neutrinos, double beta decay
- Dark matter: wimps, axions, dark photons…
- Nuclear theory, nuclear astrophysics,
- Ions, DIS, QCD
- Flavour
- Dipole moments
- Cosmology: CMB, dark energy
- Advanced accelerators, table-top experiments, quantum materials
- LHC, future colliders, technology

Fermilab

2013

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DMA Convener),[7] Jeremy Mardon (DD Convener),[8] David Morrissey (RDS Convener),[9] Tim Nelson (Organizer),[5,§] Maxim Perelstein (VDP Convener),[1] Matt Pyle (DD Convener),[10] Adam Ritz (DMA Convener),[11] Philip Schuster (Organizer),[5,6,¶] Brian Shuve (RDS Convener),[5] Natalia Toro (Organizer),[5,6,**] Richard G Van De Water (DMA Convener),[12] Daniel Akerib,[5,13] Haipeng An,[3] Konrad Aniol,[14] Isaac J. Arnquist,[15] David M. Asner,[15] Henning O. Back,[15] Keith Baker,[16] Nathan Baltzell,[17] Dipanwita Banerjee,[18] Brian Batell,[19] Daniel Bauer,[7] James Beacham,[20] Jay Benesch,[17] James Bjorken,[5] Nikita

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC

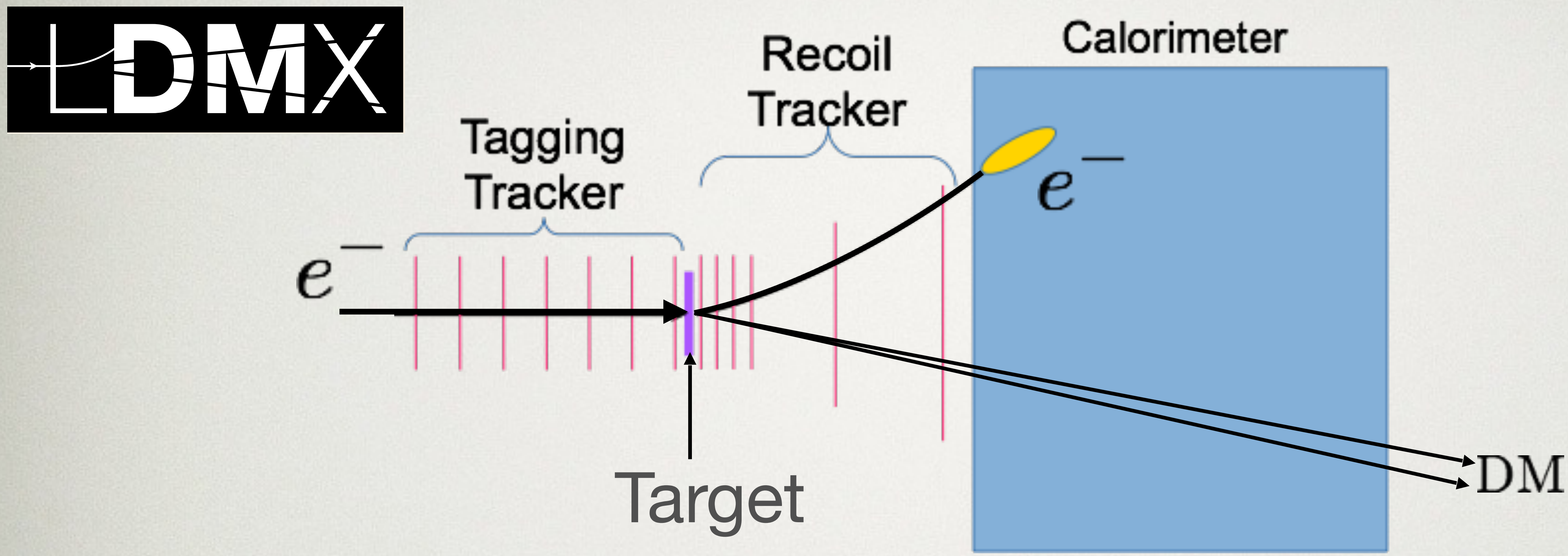
Theorists' motivations, ideas, wishes

Philip Schuster: *Hidden Sector with e^- beam*
sub-GeV dark matter; LDMX

Jörg Jaeckel : *BSM working group*
Axion-like particles, pseudo-Goldstone bosons, etc.

Kickoff Workshop, September 2016
M. Shaposhnikov · New physics below the Fermi scale
M. Pospelov · EDMs & precision $(g-2)_\mu$
A. Ringwald · Axions, ALPs: Astro/cosmo motivations, tests
C. Burrage · Detecting dark energy by atom interferometry
P. Graham · Precision measurement for particle physics

Basic Concept & Beam Requirements



- ✦ Electron beam impinging on target:
  - multi-GeV electrons
  - 1-200 MHz bunch spacing
  - Ultra-low O(1-5) electrons per bunch

Implementation at CERN?
10^{16} e^-/year: 10 GeV,
1–10 e^-/bunch per 5–25 ns
Stapnes talk

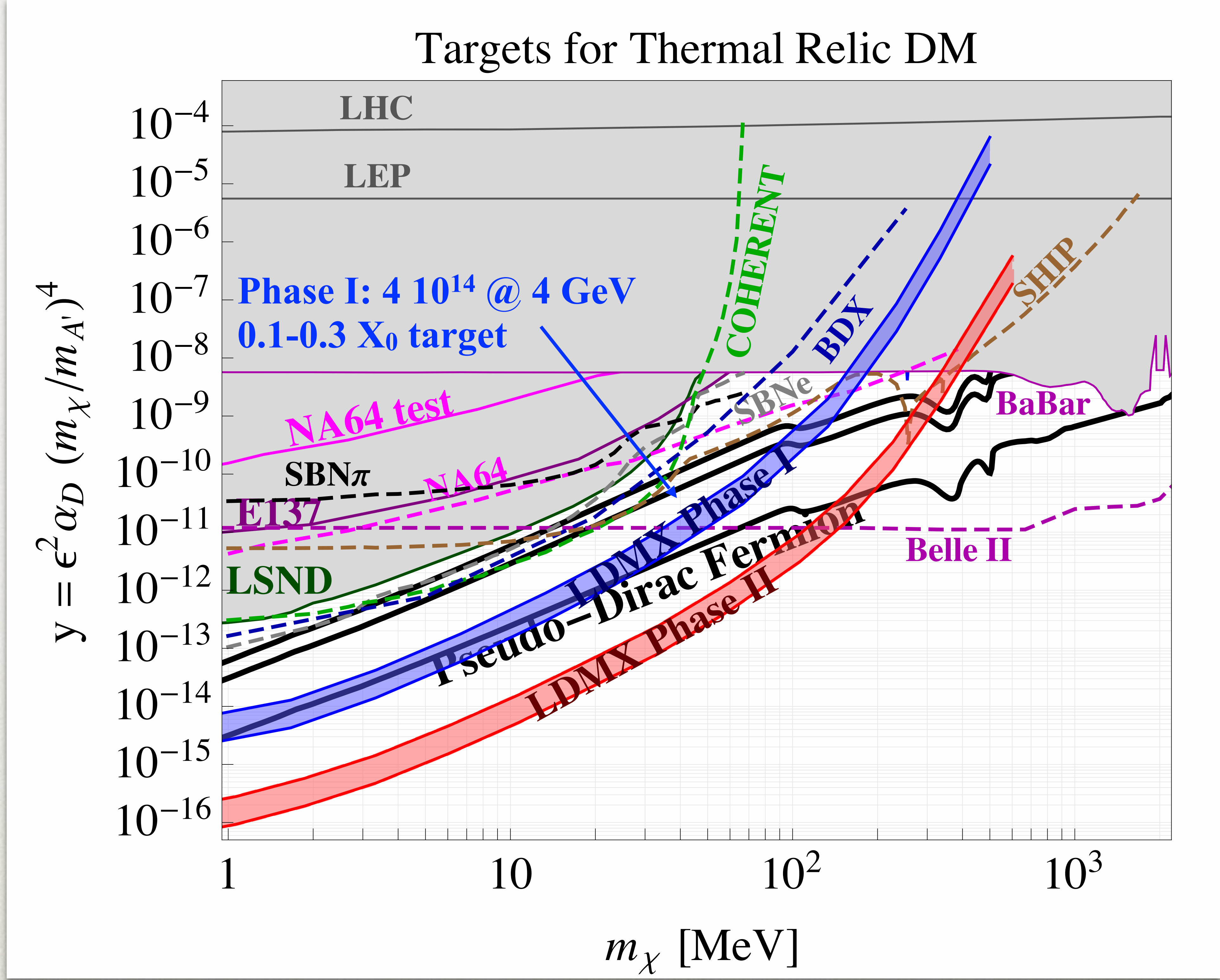
- ✦ Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field
- ✦ Reject events with visible particles carrying remaining energy
  - Deep, highly segmented calorimeter

LDMX Sensitivity

Phase I: Based on 40 MHz "single electron" rate

Phase II: Based on handling O(5) electrons per bunch, fully exploit granularity and faster detectors + requires new trigger

Designing for 4-8 GeV (proposed) DASEL beam at SLAC, or 11 GeV beam at Jefferson Lab. See backup.



Unique potential to reach all thermal DM milestones at masses below ~200 MeV

SHiP

Detector developments

Significant progress in technology developments, e.g.

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

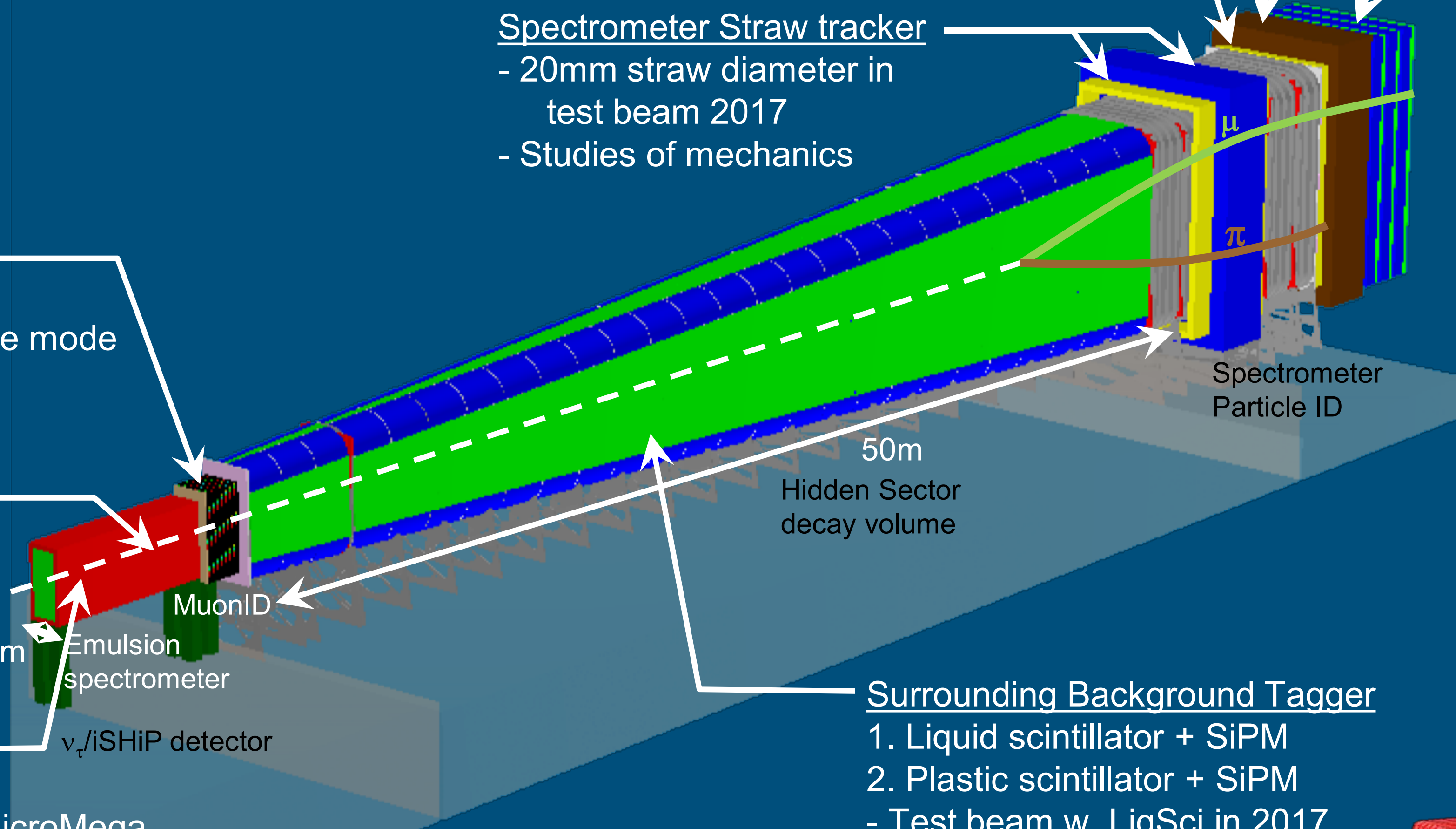
Timing Detector
1. Plastic scintillator +SIPM
2. MRPC
- Test beam 2017 w. electronics
- Demonstrated σ_t<100ps

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

Spectrometer Straw tracker
- 20mm straw diameter in test beam 2017
- Studies of mechanics

Upstream MuonID
- RPC
- Optimized for avalanche mode

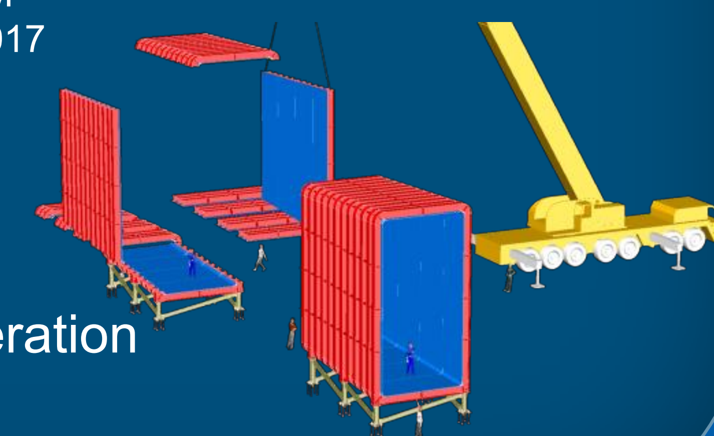
Spectrometer tracker
- SciFi
- Synergy with LHCb



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

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

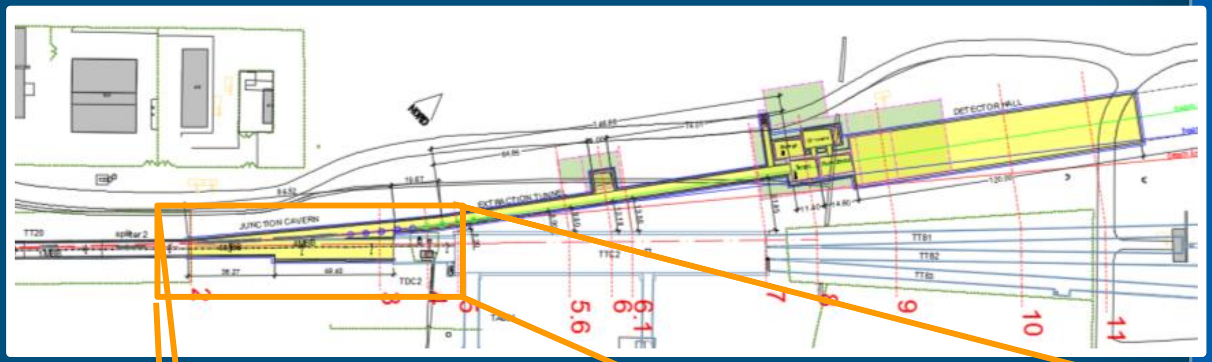
In addition:
- Specification of infrastructure and services for assembly, installation and operation
- Evaluation of safety aspects



τ → 3μ at SHIP Facility: "τSHiP"

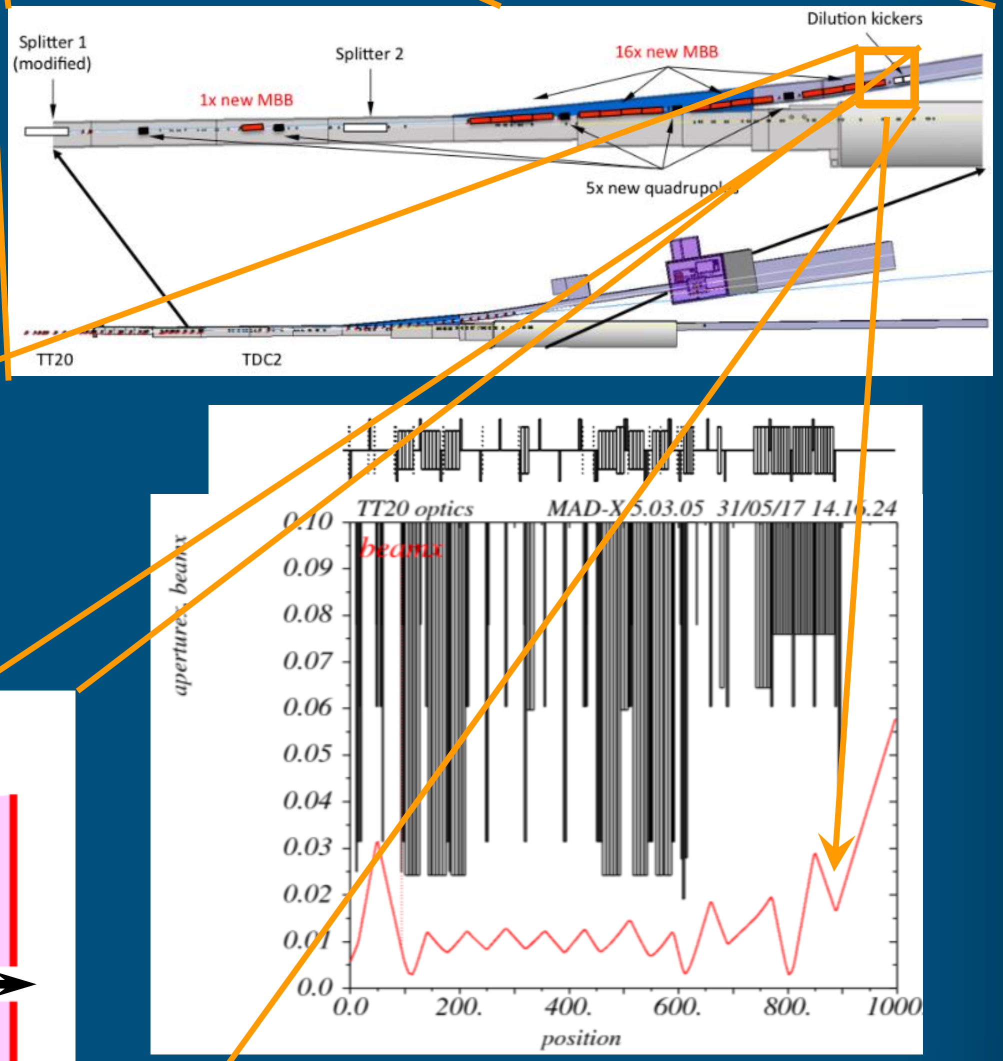
Resumed studies of LFV τ → 3μ at SHIP

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



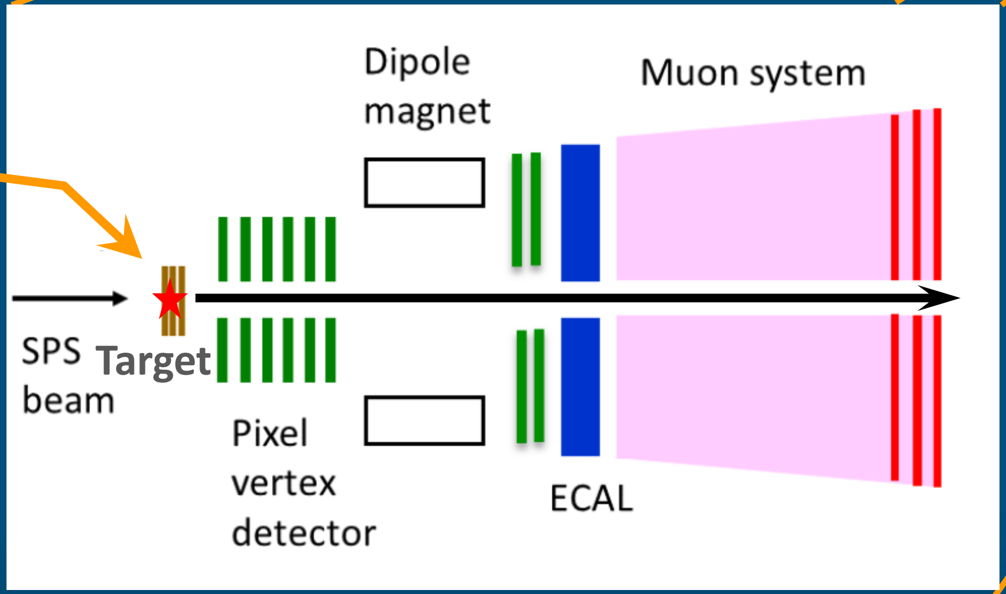
- → Parallel operation with ν/iSHiP and dSHiP most efficient!
- → With 5×10^{13} τ decays in vacuum from 1% of 2×10^{20} pot on SHiP main target : U.L. on BR(τ → 3μ) ~ 10^{-10} or better
- → Also opportunity for $D \to \mu\mu,\ldots$
- ⊙ Challenges
  - Radiological aspects 1% beam loss
  - Entire facility to be moved downstream by 20m

    } Not yet subject of facility studies
  - 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



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

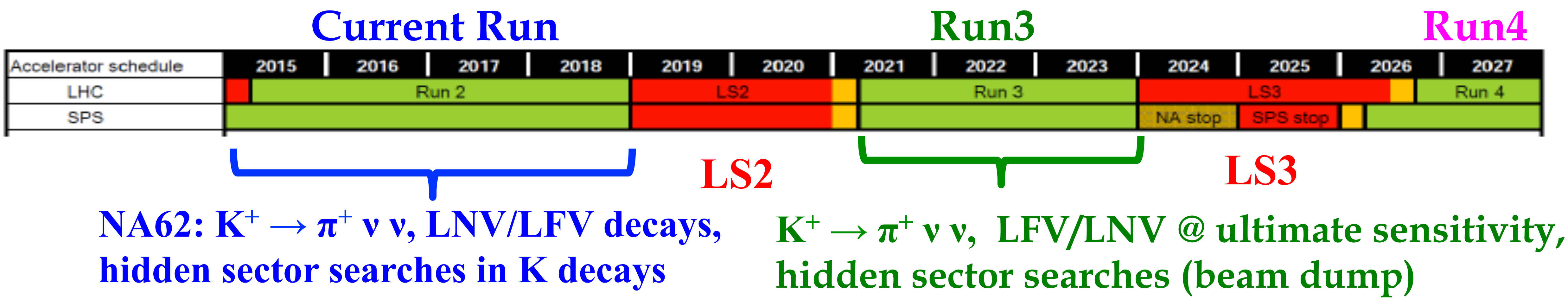
E.g. 1mm W (multiple) target system intercepting 1% of 2×10^{20} pot



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($K\to\pi\nu\nu$), 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.**

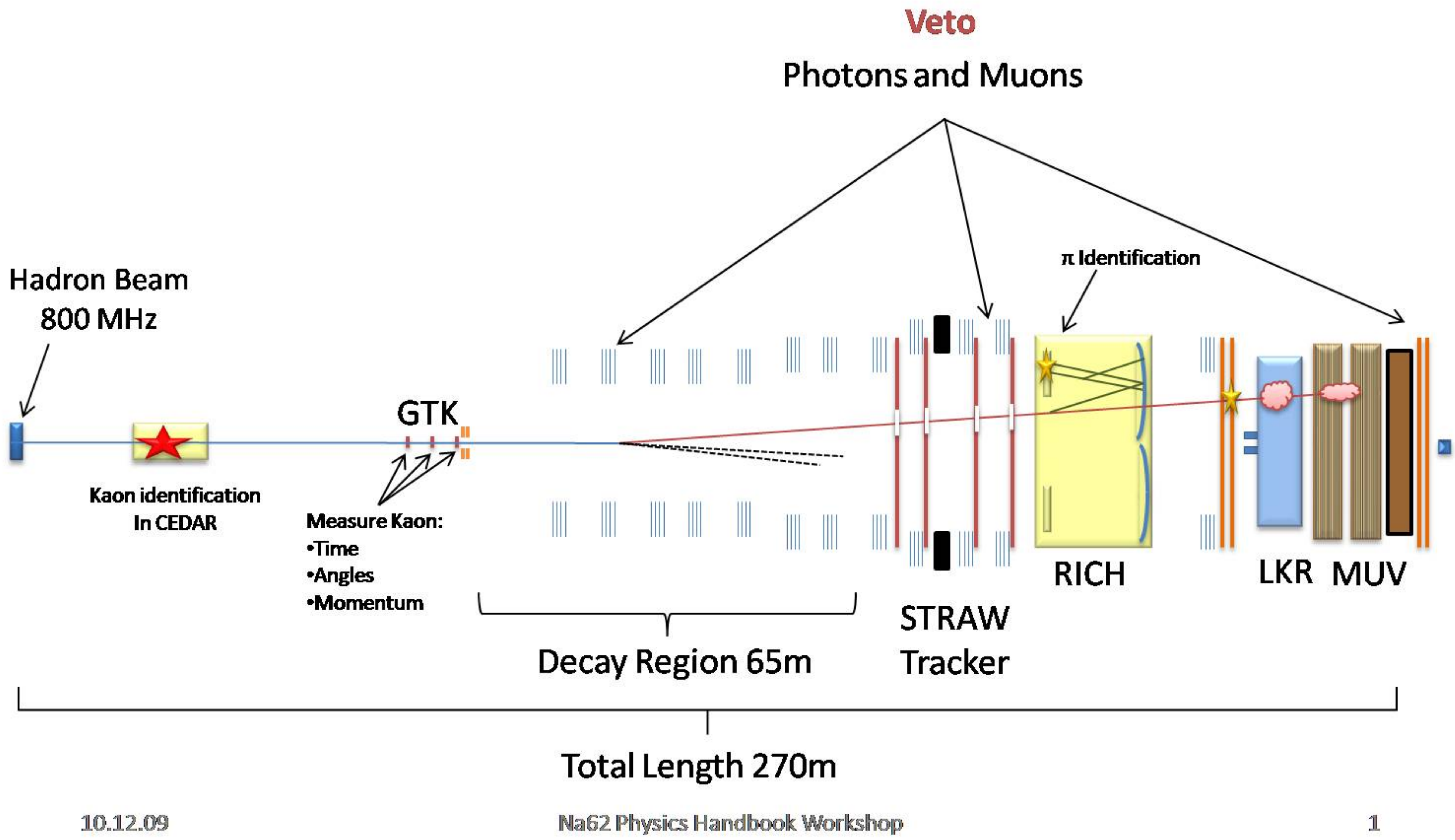
Expected sensitivity superior to that from other initiatives in the same time range

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

The current NA62 run will be exploited to:

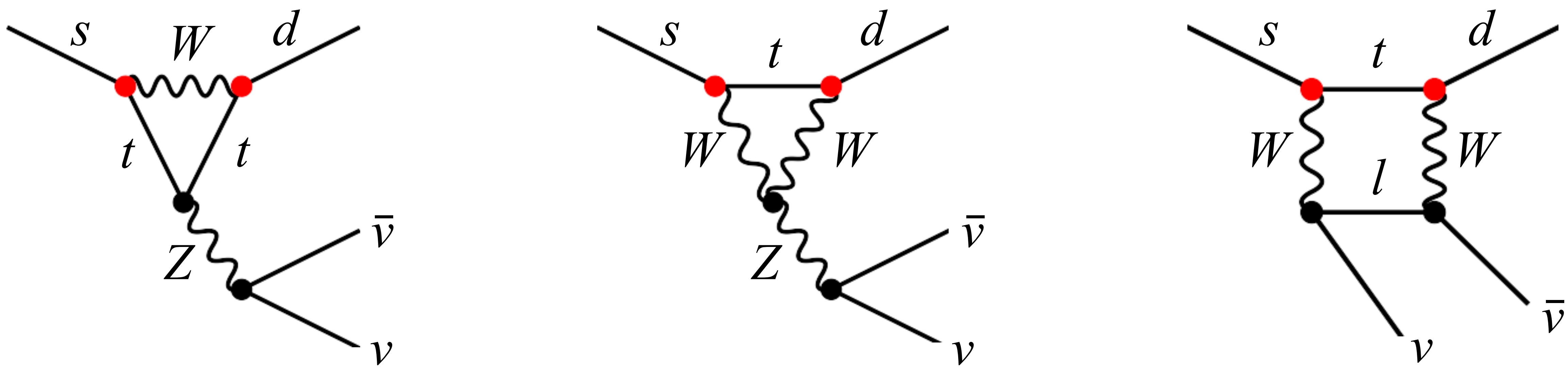
- **evaluate bkg rejection up to ~10^{16} -- 10^{17} POT's**
- **potentially achieve first results (ALP -> $\gamma\gamma$ search, etc.)**
- **optimize design for future beam-dump mode**

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



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

FCNC processes dominated by Z-penguin and box amplitudes:



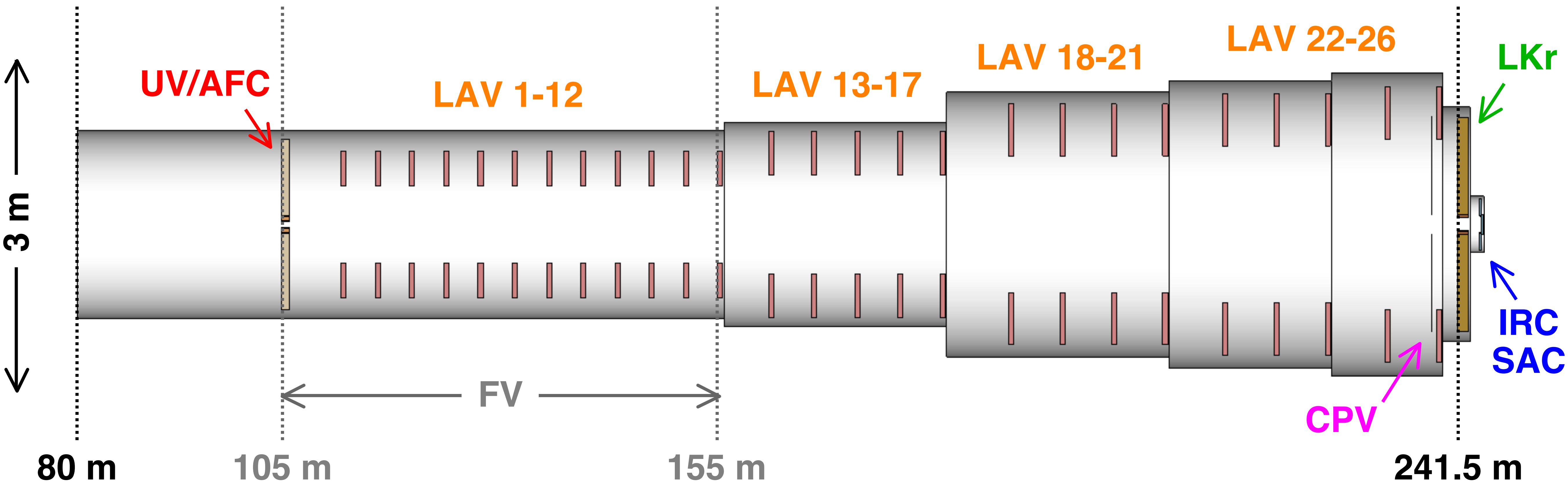
Extremely rare decays with rates very precisely predicted in SM:

- 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**
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	**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)
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	**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

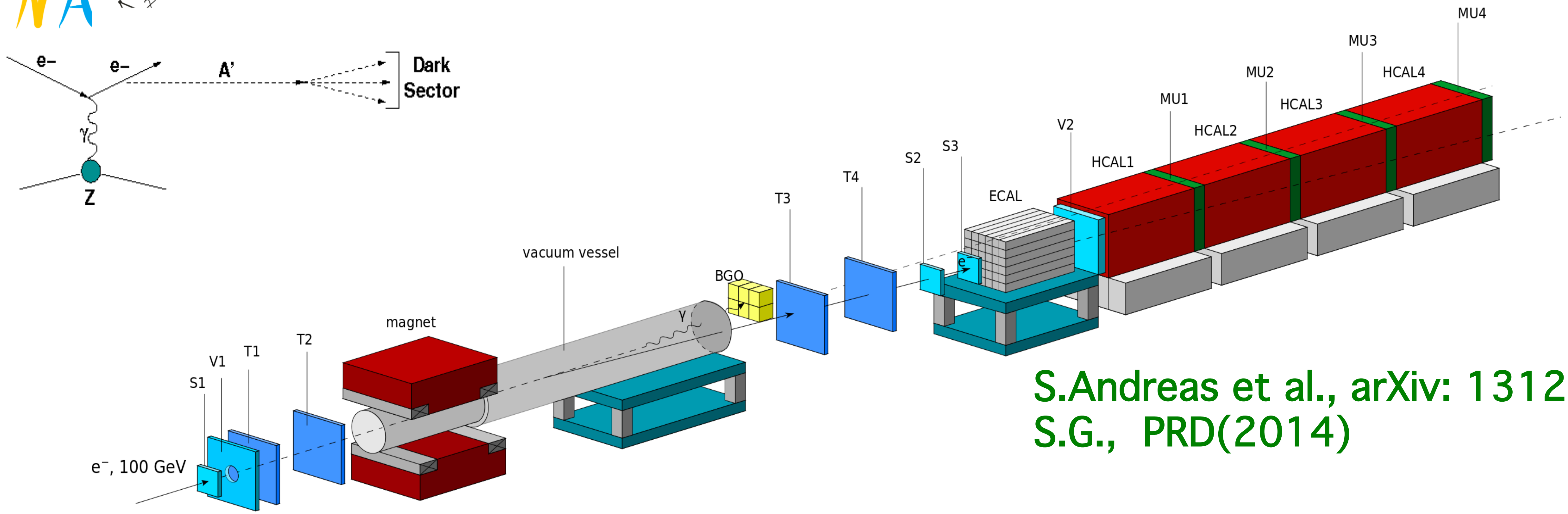
~60 SM $K_L \to \pi^0 \nu\nu$
S/B ~ 1

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

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



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	~$5\text{x}10^{12}$ EOT ~$5\text{x}10^{12}$ 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	~$5\text{x}10^{12}$ P(K)OT
4. p A -> X+ E_{miss}		
✧ leptophobic X	~ GeV DM	~$5\text{x}10^{12}$ 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.

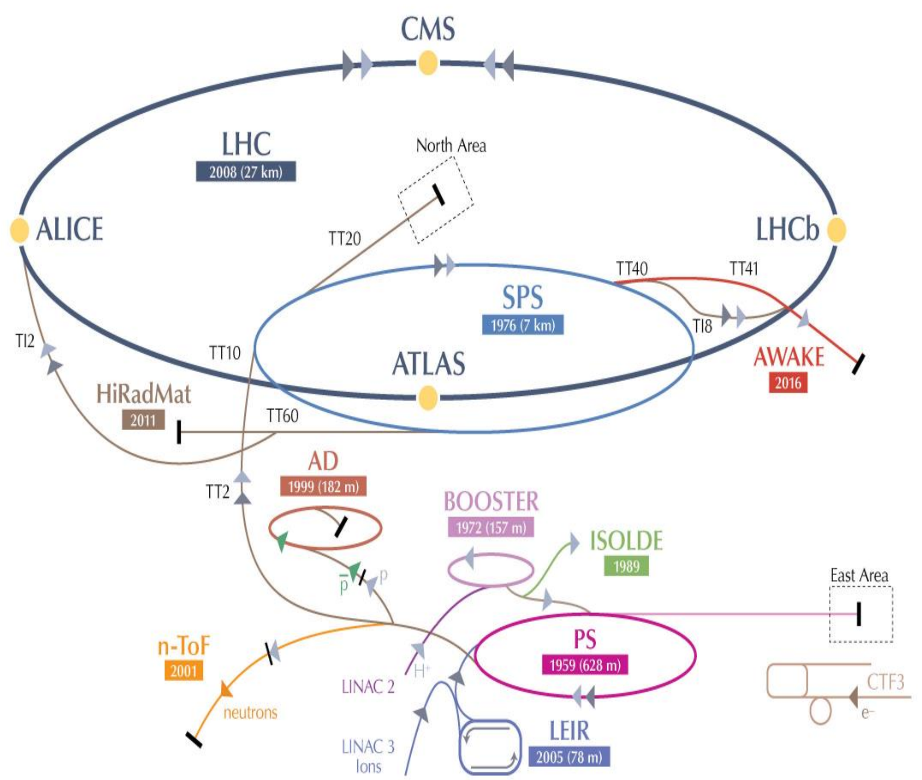
NA64++ provisional time schedule

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	$\pi^0,\eta,\eta',K_S,K_L \to inv$

AWAKE

Introduction



AWAKE: Advanced Proton driven Plasma Wakefield Experiment

- First facility that investigates the use of plasma wakefields driven by a proton beam to accelerate electrons to high energies at GeV level.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators
- Collaboration of 18 institutes and 2 associate members.
- Approved in 2013
- First beam in 2016

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022/23/24
Proton and laser beam-line	Study, Design, Procurement, Component preparation		Installation	Commissioning	Data taking RUN 1		Long Shutdown 2 24 months		Data taking RUN 2	
Experimental area	Modification, Civil Engineering and installation; Study, Design, Procurement, Component preparation				Phase 1					
e^- source and beam-line	Studies, design		Fabrication	Installation	Commissioning	Phase 2				

Run 1 – until LS2 of the LHC.

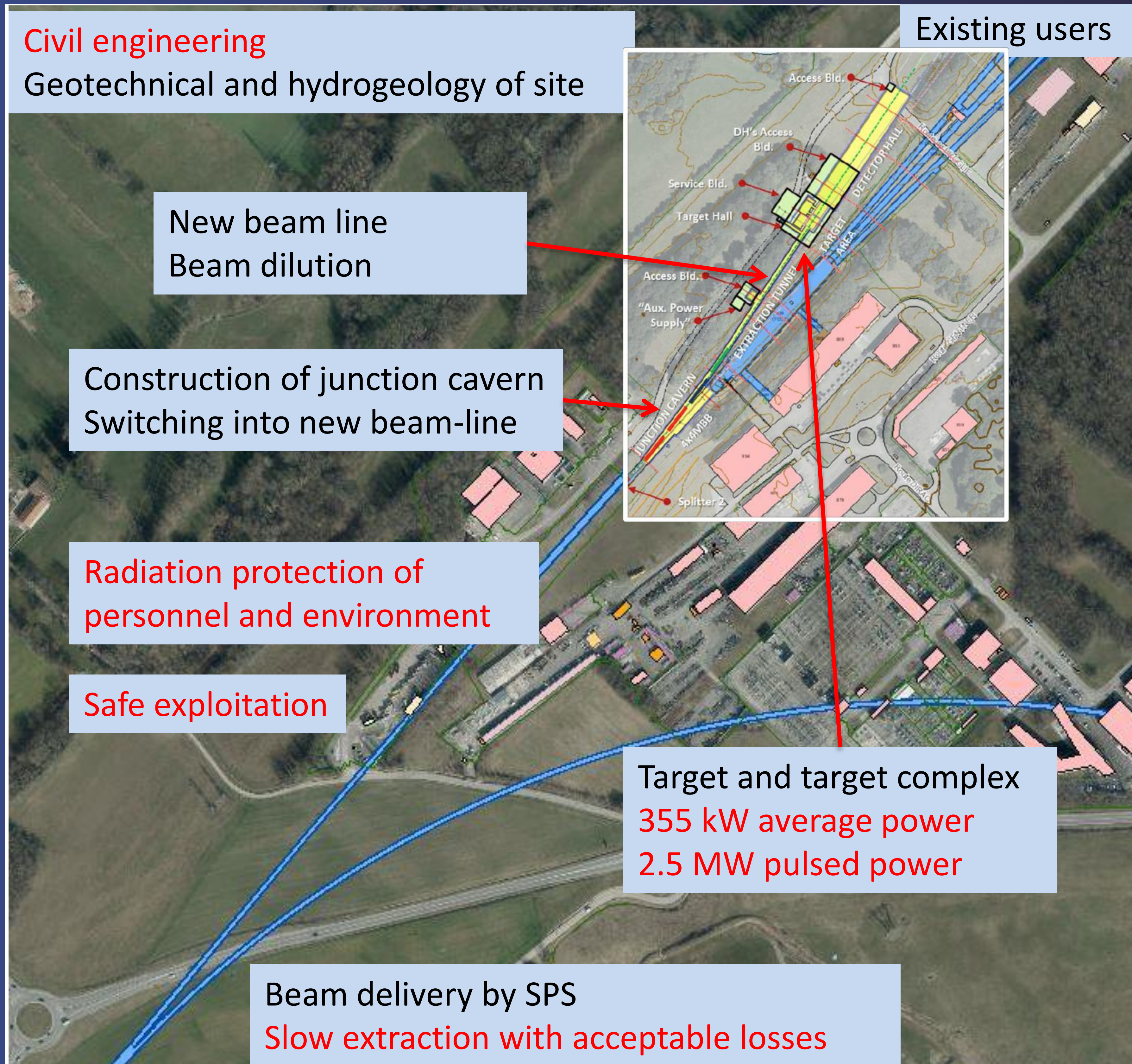
After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

After Run 2: kick off particle physics driven applications

3

Run 2 goal: 5–10 GeV e– in 10–20 m plasma

Beam Dump Facility Design (TDR end 2021)



Civil engineering
Geotechnical and hydrogeology of site

Existing users

New beam line
Beam dilution

Construction of junction cavern
Switching into new beam-line

Radiation protection of personnel and environment

Safe exploitation

Target and target complex
355 kW average power
2.5 MW pulsed power

Beam delivery by SPS
Slow extraction with acceptable losses

Directional dark-matter detection using a carbon nanotube forest

A. Polosa

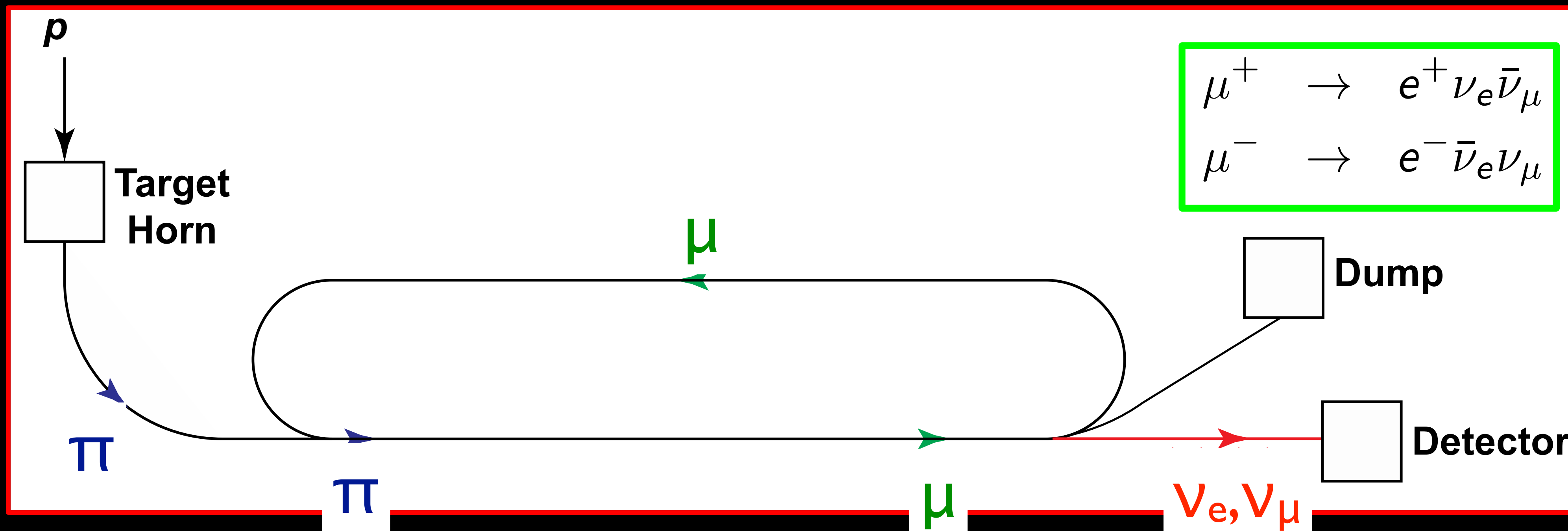
REDTOP Key Points

- 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: $\eta \to \gamma(A' \to$ lepton pairs)

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

Neutrinos from stored muons

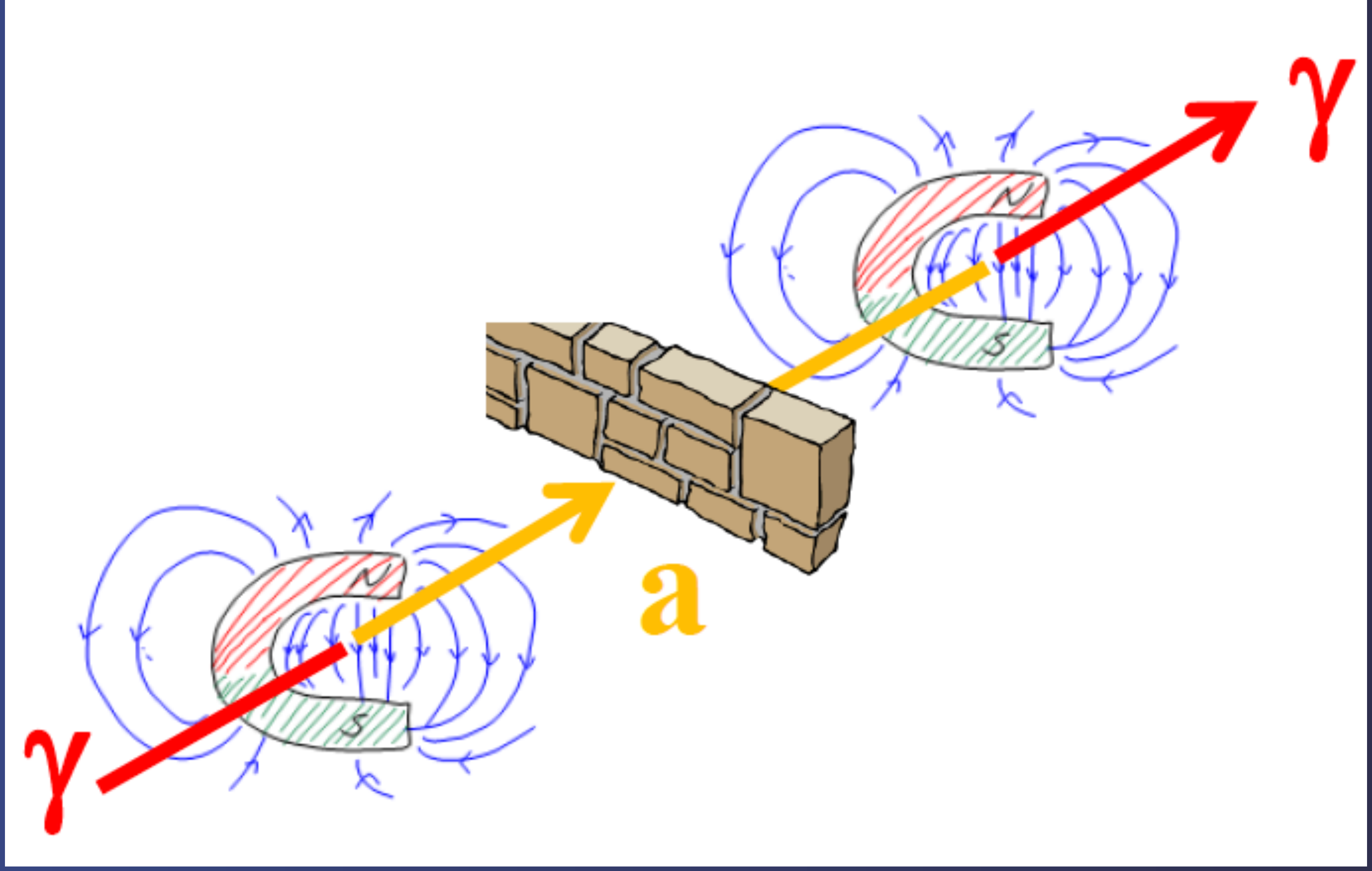


- **Scientific objectives:**
  1. %-level $(\nu_e N)$cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- **Precise neutrino flux:**
  – Normalisation: < 1%
  – Energy/flavour precise
- **π → ↗injection pass:**
  – "Flash" of ν_μ

3. Nucleon structure, ν-nucleus

Axion & Axion-like particle searches



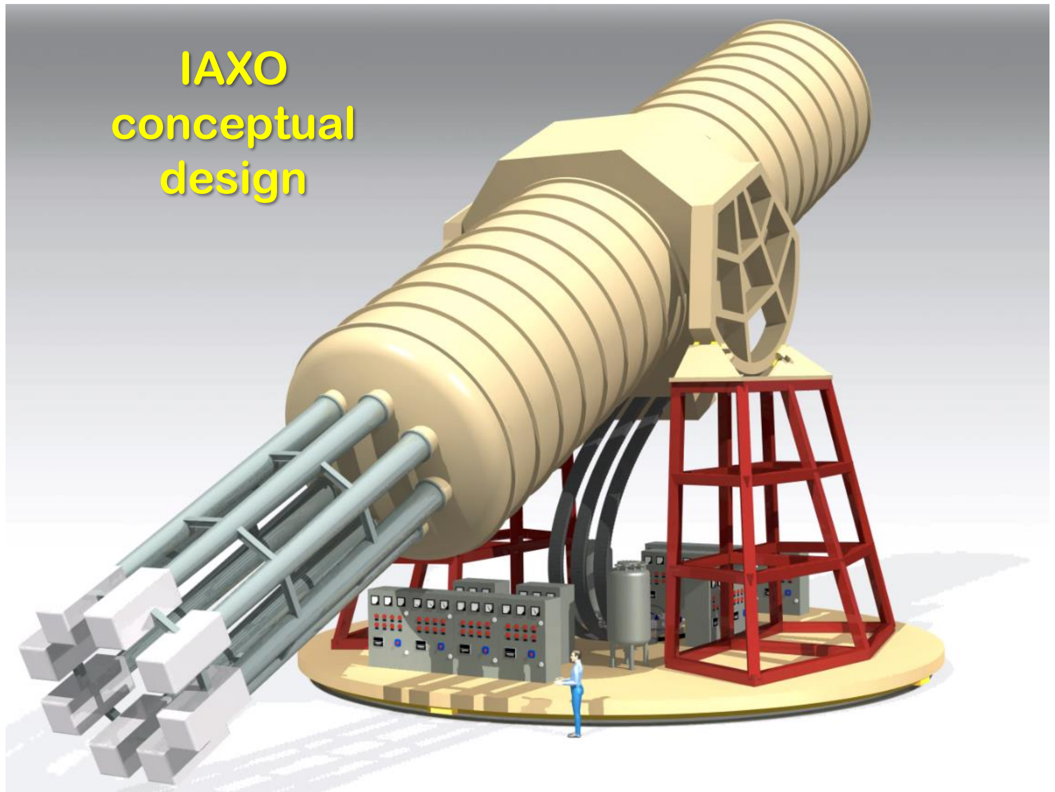
A. Lindner: ALPS-II at DESY
20 straightened HERA dipoles (5.8 T)

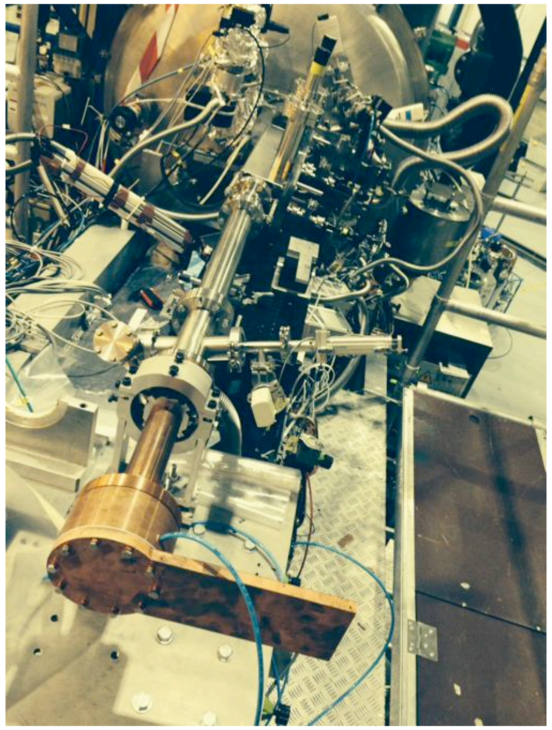
P. Spagnolo: NEXT—very intense, low-energy (30 GHz) γ source

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)





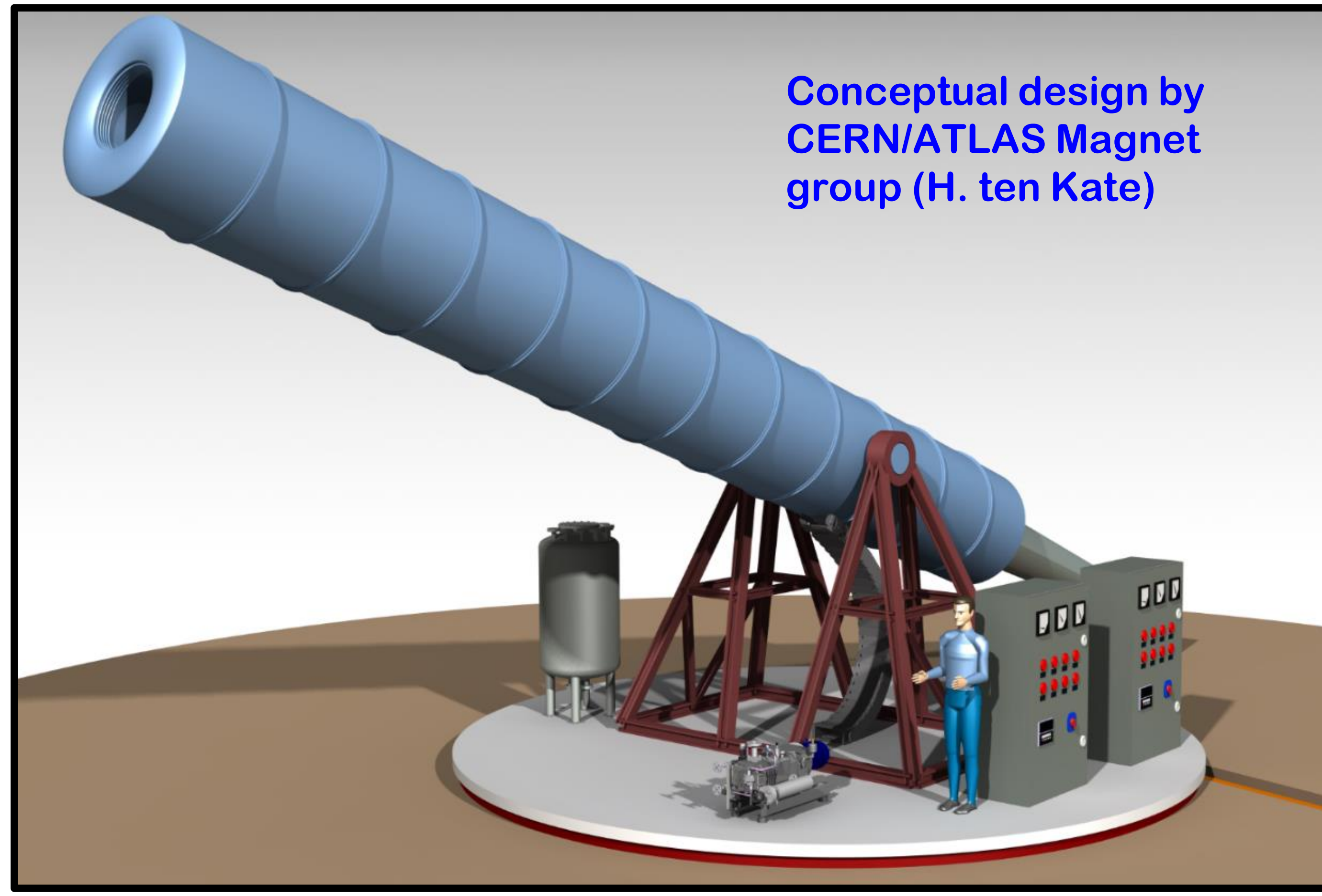
IAXO pathfinder system at CAST

In operation in 2014-15

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

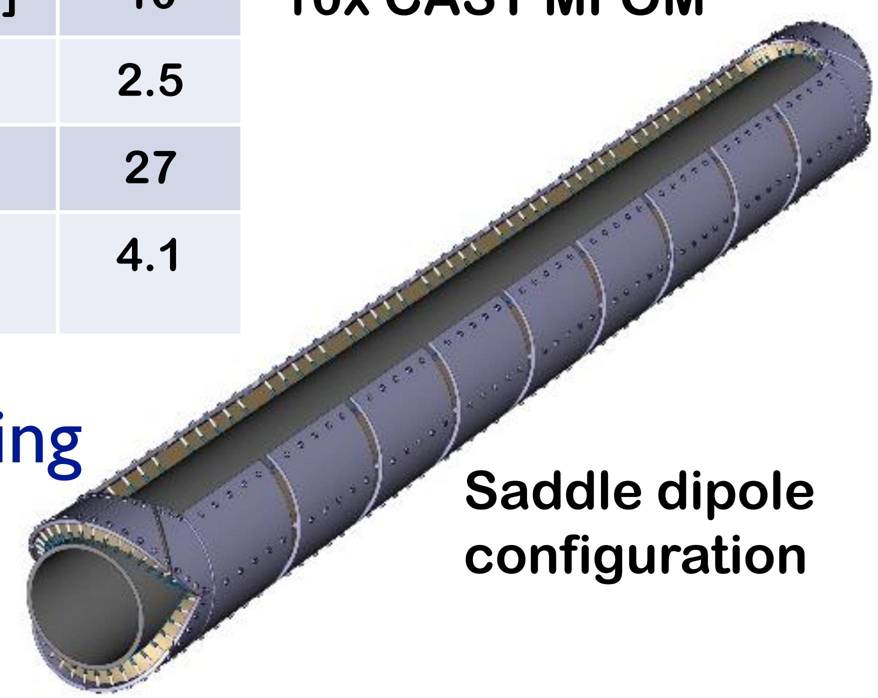
BabyIAXO

- 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



Saddle dipole configuration

DESY, INR consider hosting

- BabyIAXO CDR finished. Moving to Technical Design

LUXE: Laser Und XFEL.EU Experiment (M. Wing)

- **Strong-field QED is a new physical regime which needs to be investigated.**
  - We may see something new and unexpected or
  - Confirm and understand predictions which go back ~ 80 years
  - Understand and apply knowledge to systems where this occurs, e.g. neutron stars, high energy colliders
- **Propose to set up an experiment using XFEL.EU electron beam and measure physics above the Schwinger critical field.**
- Initial investigations and consideration of pioneering E144 experiment suggest we will be able to be well above the Schwinger field.
- **Embarking on feasibility/design study of machine, laser, experimental setup**
  - Simulation of experimental setup, optimisation, parameters, e.g. laser, beam size.
  - Spectrometer detector designs.
  - Theoretical calculations and physics simulations.
  - Evaluate that experiment is parasitic to XFEL.EU.
- **Plan to host a workshop next spring/summer to gather interest and develop further.**
- People welcome to join.

$$E_{\text{crit}} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16}\ \text{V/cm}$$

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

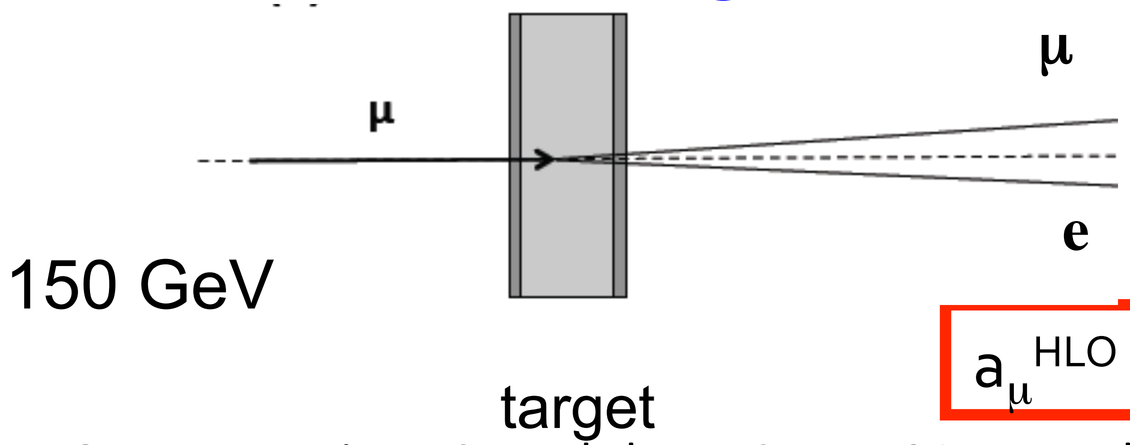
- a_μ^{HLO} can be obtained as integral on $\Delta\alpha_{had}$ (t) for t<0

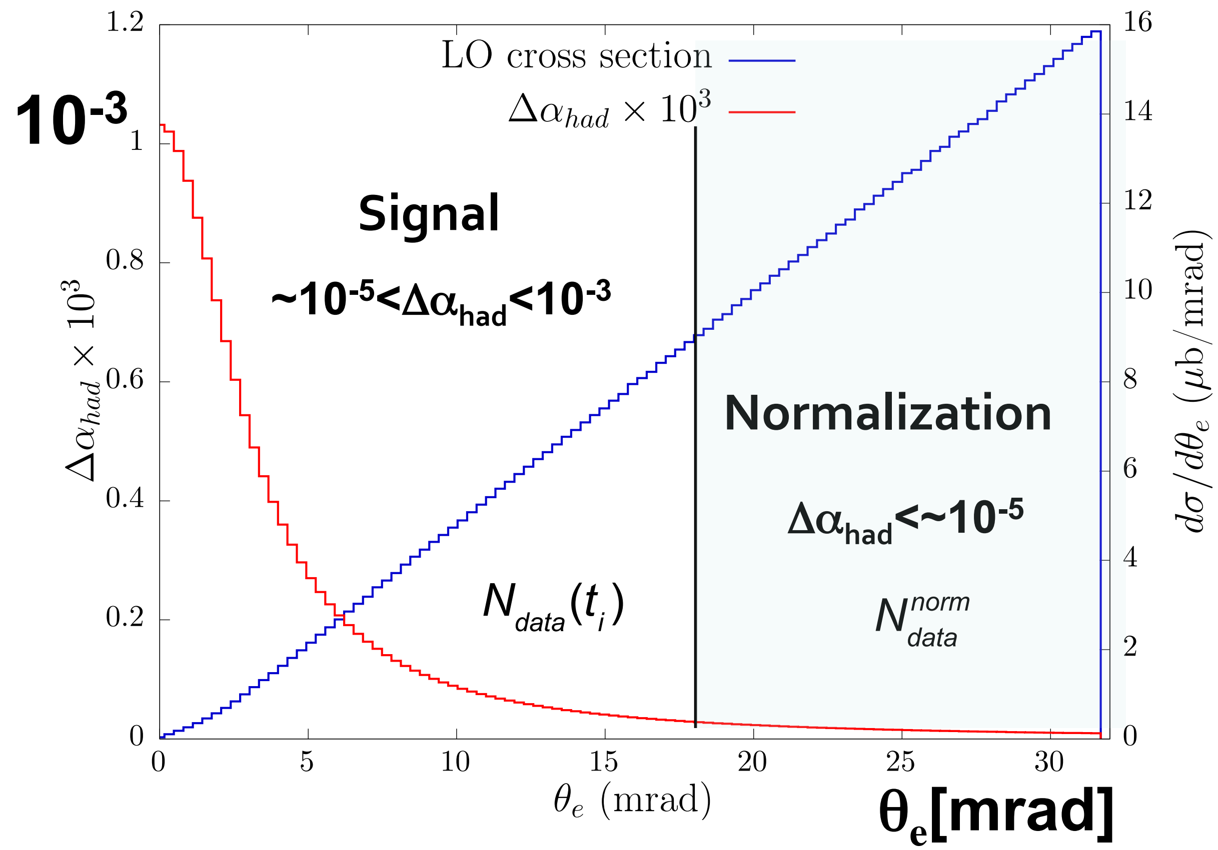
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}(t(x))dx$$

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

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 $N_{signal}(t)/N_{normalization}$

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

Theory

- QED NLO MC generator with full mass dependence has been developed (Pavia group)

- First results obtained for the NNLO box diagrams contributing to mu-e scattering in QED (Padova group)

1709.07435

Master integrals for the NNLO virtual corrections to μe scattering in QED: the planar graphs

Pierpaolo Mastrolia,[a,b] Massimo Passera,[b] Amedeo Primo,[a,b] Ulrich Schubert[c]

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[b] *INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

[c] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*

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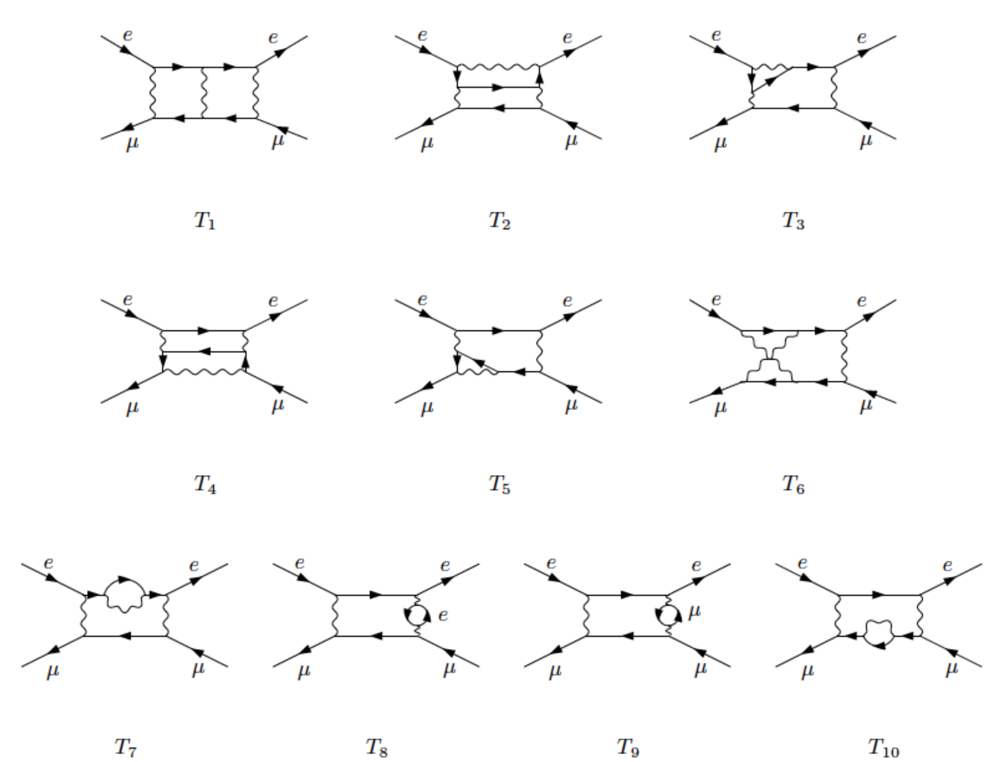


- An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)

Theory

- A kick-off theory meeting has been held in Padova last September: https://agenda.infn.it/internalPage.py?pageId=0&confId=13774 .

Muon-electron scattering: Theory kickoff workshop

4-5 September 2017
Padova

Europe/Rome timezone

- A Topical workshop on the theoretical aspects of mu-e scattering will take place next February at MITP, Mainz https://indico.mitp.uni-mainz.de/event/128/ with many experts

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

mitp Mainz Institute for Theoretical Physics

The Evaluation of the Leading Hadronic Contribution to the Muon Anomalous Magnetic Moment

19-23 February 2018
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

Organization

PBC LHC FIXED TARGET

PBC Home | LHC FT in Indico | Resources

Several proposals for fixed-target experiments at the LHC are being actively studied by physics communities. For example, the use of splitting of beam halos from the core with bent crystals for internal targets and the use of internal gas (possibly polarised) or solid targets. The working group will address the technical feasibility and impacts on the LHC machine with the aim of bringing together the various initiatives (UA9, LHC collimation team, AFTER collaboration, ...) and presenting a report to the update of the European Strategy for Particle Physics (ESPP).

Caveats:

- Resources:
  - No resources created for this scope
  - Thus, based on "best effort" of a few people
- Several proposals mention LHCb as a possible place to perform their experiment. This does **not** imply that LHCb has approved these proposals.

Ongoing work. No conclusions drawn yet.

Conclusions

AFTER

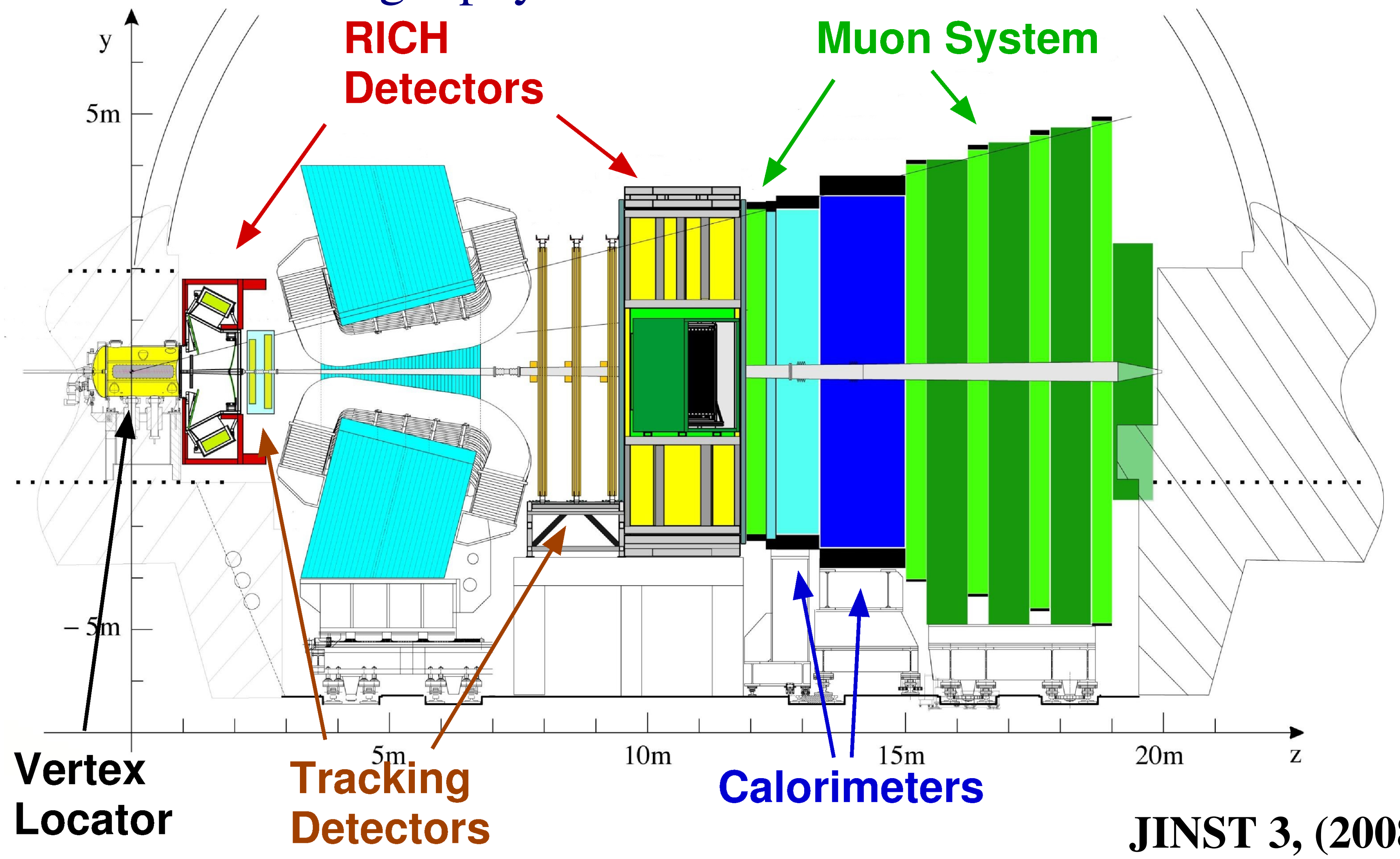
- THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC

  S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

  - The high *x* frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, new rapidity domain and new probes
- 2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-Jet, ...
- Based on fast simulations, the AFTER@LHC study group has made FoMs for LHCb and ALICE in the FT mode which clearly support a full physics program
- In synergy with & under the advice of the PBC, we now prepare a document on the fixed-target physics at the LHC
- However, even for FoMs based on fast simulations, we will need to imagine a coherent data-taking plan (pH, pA, PbA, PbH) given allocatable bandwidths, ...

The LHCb Detector

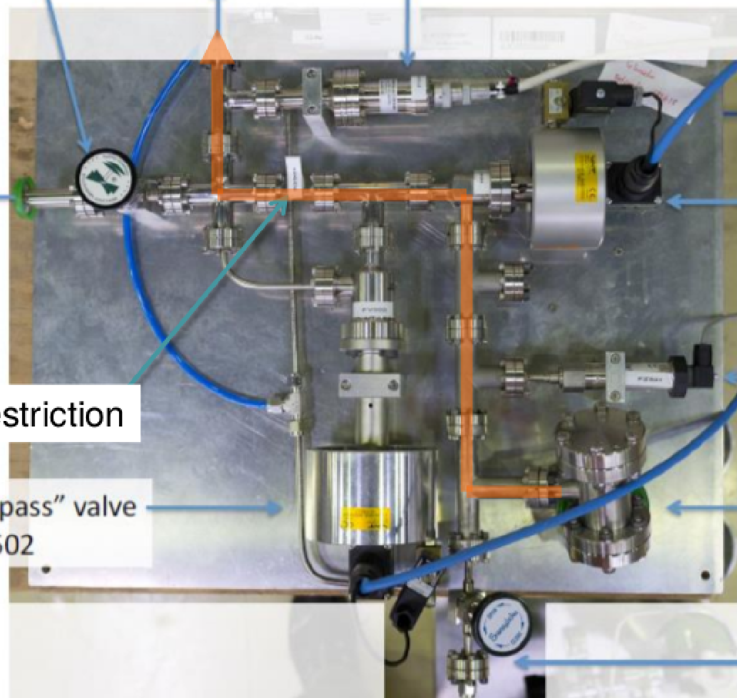
- LHCb is the LHC experiment with "fixed-target like" geometry very well suited for... fixed target physics!



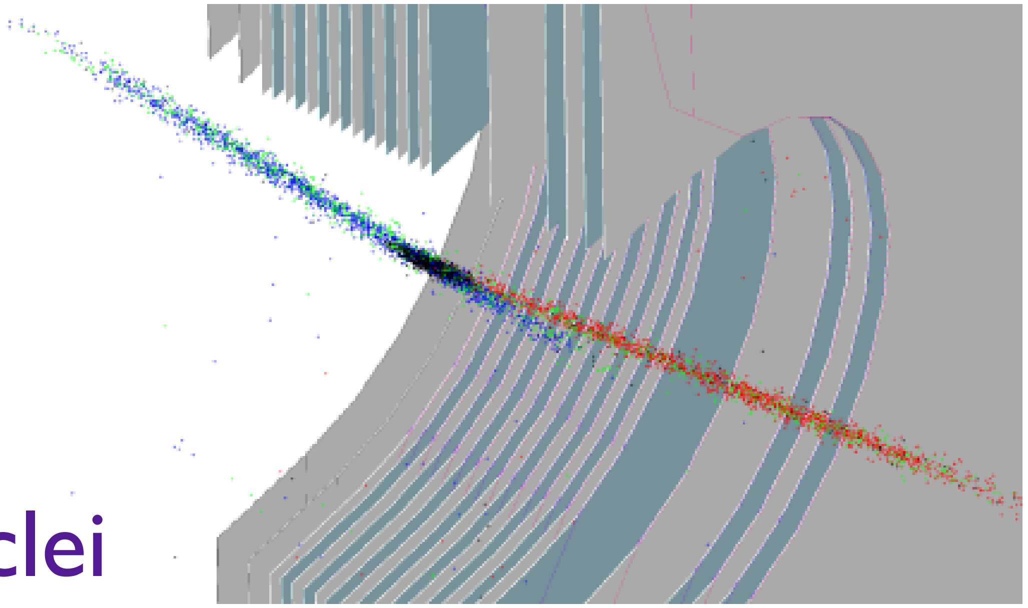
JINST 3, (2008) S08005

- fully instrumented in the pseudorapidity range $2 < \eta < 5$
- excellent vertexing, tracking, PID
- flexible trigger with high bandwidth: hardware level up to 1 MHz, software level with offline-quality event reconstruction

SMOG: the LHCb internal gas target



- The System for Measuring Overlap with Gas (SMOG) allows to inject small amount of noble gas (He, Ne, Ar, ...) inside the LHC beam around ($\sim \pm 20$ m) the LHCb collision region
  Expected pressure $\sim 2 \times 10^{-7}$ mbar

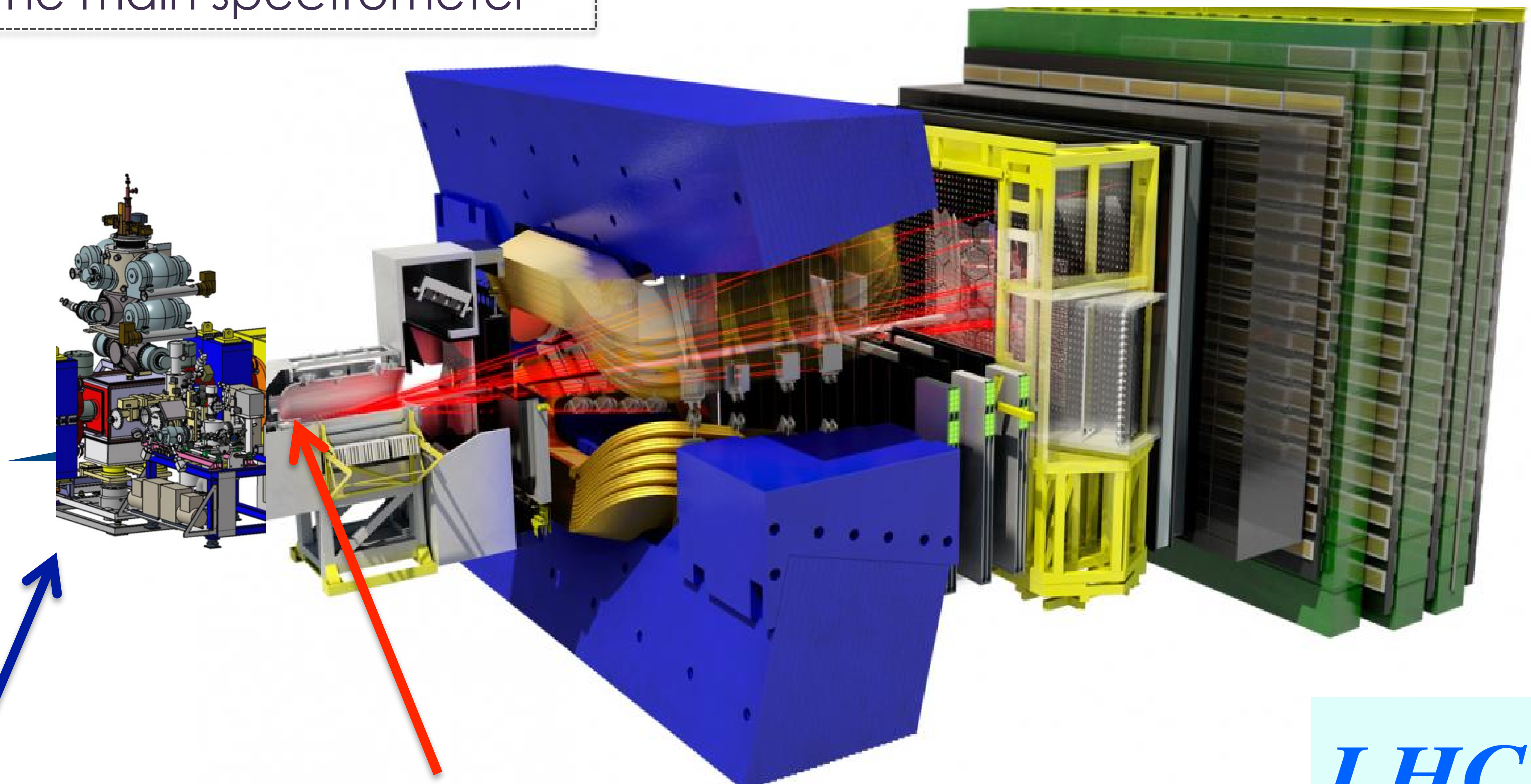


- Originally conceived for the luminosity determination with beam gas imaging **JINST 9, (2014) P12005**
- Became the LHCb internal gas target for a rich and varied fixed target physics program

Charm production on various nuclei as input to cosmic-ray simulations

Unpolarised+ Polarised Gas Target

N.B. No changes are requested to the main spectrometer



ALICE in fixed-target mode?

PHYSICS MOTIVATIONS

ALICE

- ❑ Physics Opportunities of a Fixed-Target Experiment using the LHC Beams developped in several publications of the AFTER@LHC study group

S. J. Brodsky et al., Phys. Rept. 522 , 239 (2013), 1202.6585
J. Lansberg et al, Special Issue in Adv. High Energy Phys.,Vol 2015
A. B. Kurepin et al., Physics of Atomic Nuclei, 74, (2011), 446

- ❑ Three main physics goals identified:

  - ❖ Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon and nucleus

    Structure of nucleon and nuclei at large-x poorly known
    Study possible gluon EMC effect in nuclei
    Existence of possible non-perturbative source of c and b quarks in the proton : useful for high-energy neutrino and CR physics

  - ❖ Advance our understanding of the dynamics and spin of gluons inside polarised nucleons. *with a polarised target*

    Limited understanding of nucleon spin structure
    Test TMD factorization formalism

  - ❖ Study heavy-ion collisions between SPS and RHIC energies towards large rapidities

    Explore the longitudinal expansion of QGP formation
    Study collectivity in small systems with new probes (heavy quarks)
    Test factorization of CNM effects (Drell-Yan)

TARGET TECHNOLOGIES AND LUMINOSITIES

- Feasibility of using an internal gas target at the LHC demonstrated by LHC Collaboration with the SMOG system
  Limited running time (pumping system limited), no target polarization, only low density noble gases, typical L_{int} ~ few to O(100) nb^{-1} in pA

- Storage Cell gas target (HERMES experiment like target) can permit to increase the gas density by several orders of magnitude
  Gas densities reached with a storage cell already too large for ALICE data taking capabilities

- Gas jet option (H-jet polarimeter at RHIC like) : already provides large gas densities compatible with ALICE setup

- Another way of making fixed target collisions compatible with the ALICE setup is to use an internal solid target (coupled to a bent crystal)

- Integrated luminosity over one LHC year compatible with an ALICE setup

System	Internal wire (5 mm thick *)		
	L_{int}	σ_{inel}	Inelastic Rate
p + Solid H	130 pb^{-1}	~ 27 mb	350 kHz
p + W (37-185 µm)	1.2 - 5.9 pb^{-1}	~ 1.7 b	200kHz - 1 MHz
p + Pb (71-357 µm)	1.2 - 5.9 pb^{-1}	~1.8 b	200kHz - 1 MHz
Pb + Solid H	2.6 nb^{-1}	~ 1.8 b	4.7 kHz
Pb + W (Pb)	3.2 (1.6) nb^{-1}	6.9 (7.2) b	22 (12) kHz

* Unless specified

System	Gas Jet option / Storage Cell with « levelled» gas pressure		
	L_{int}	σ_{inel}	Inelastic Rate
p + H↑	45 pb^{-1}	~ 27 mb	100 kHz
p + H_2	450 pb^{-1}	~ 27 mb	1 Mhz
p + Xe	1.5 – 7.7 pb^{-1}	~ 1.3 b	200 kHz – 1 MHz
Pb + Xe	8.1 nb^{-1}	~ 6.2 b	50 kHz

6

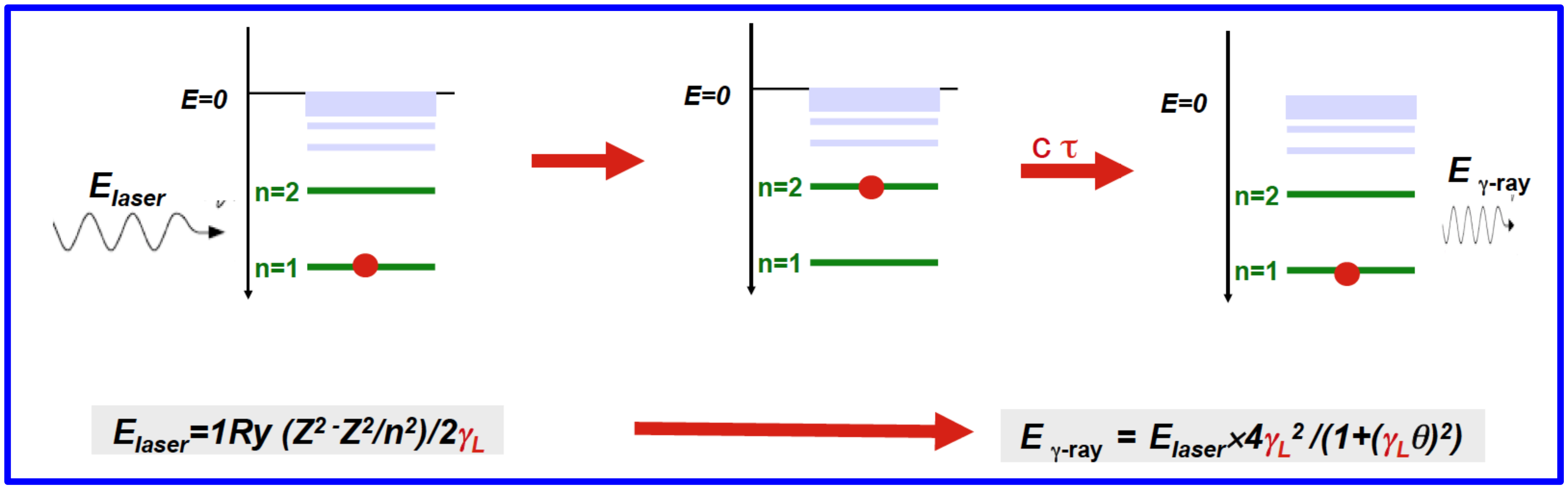
Bent-crystal measurements of intrinsic moments

Work is going on in several directions and several new results since last PBC

- ✓ Improving and reinforcing the physics case (see also F. Martinez Vidal talk)
- ✓ Studying **the setup in LHC** from machine point of view (see also M. Ferro-Luzzi talk)
- ✓ Performing the **tests in SPS** (as from the LOI 2016) in order to demonstrate the feasibility of the **double crystal + target** and studies the background prior to the insertion to LHC [WORK INSIDE UA9]
- ✓ Performing the **feasibility studies of EDM and MDM measurement using LHCb detector** [WORK mainly INSIDE LHCb – see also F. Martinz Vidal talk]

Gamma Factory Project scope

- *Accelerate and store beams of highly ionised atoms (Partially Stripped Ions – PSI) and excite their atomic degrees of freedom, by laser photons to form high intensity primary beams of gamma rays and, in turn, secondary beams of polarised leptons, neutrinos, neutrons and radioactive ions.*

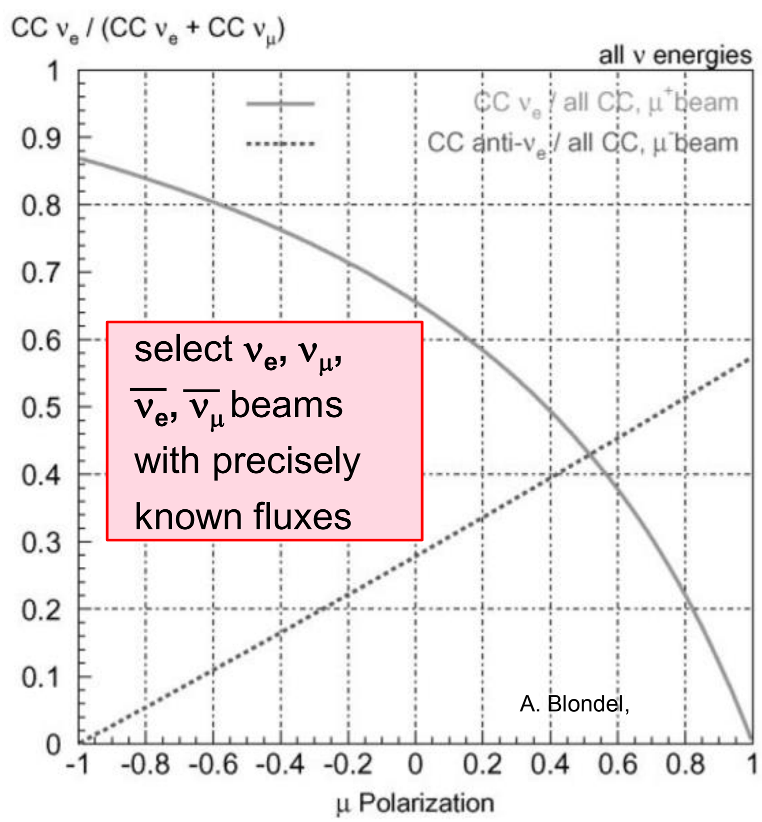


- *Provide a new, highly efficient scheme of transforming the accelerator RF power (selectively) to the above primary and secondary beams trying to achieve a leap, by several orders of magnitude, in their intensity and/or brightness, with respect to the existing facilities.*

SPS studies with Xe^{+39}

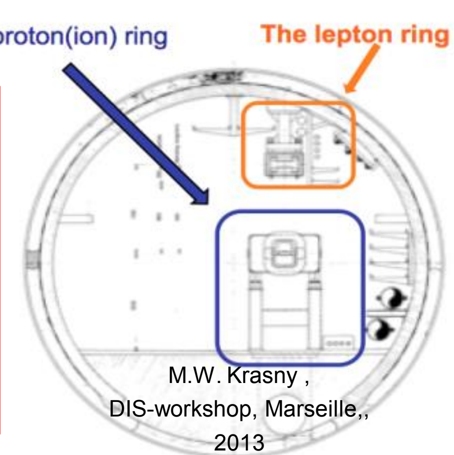
Promises of GF research tools - examples

Low emittance, high intensity polarised positron and muon source for:
(1) ν-factory, (2) muon collider and (3) lepton-proton collider

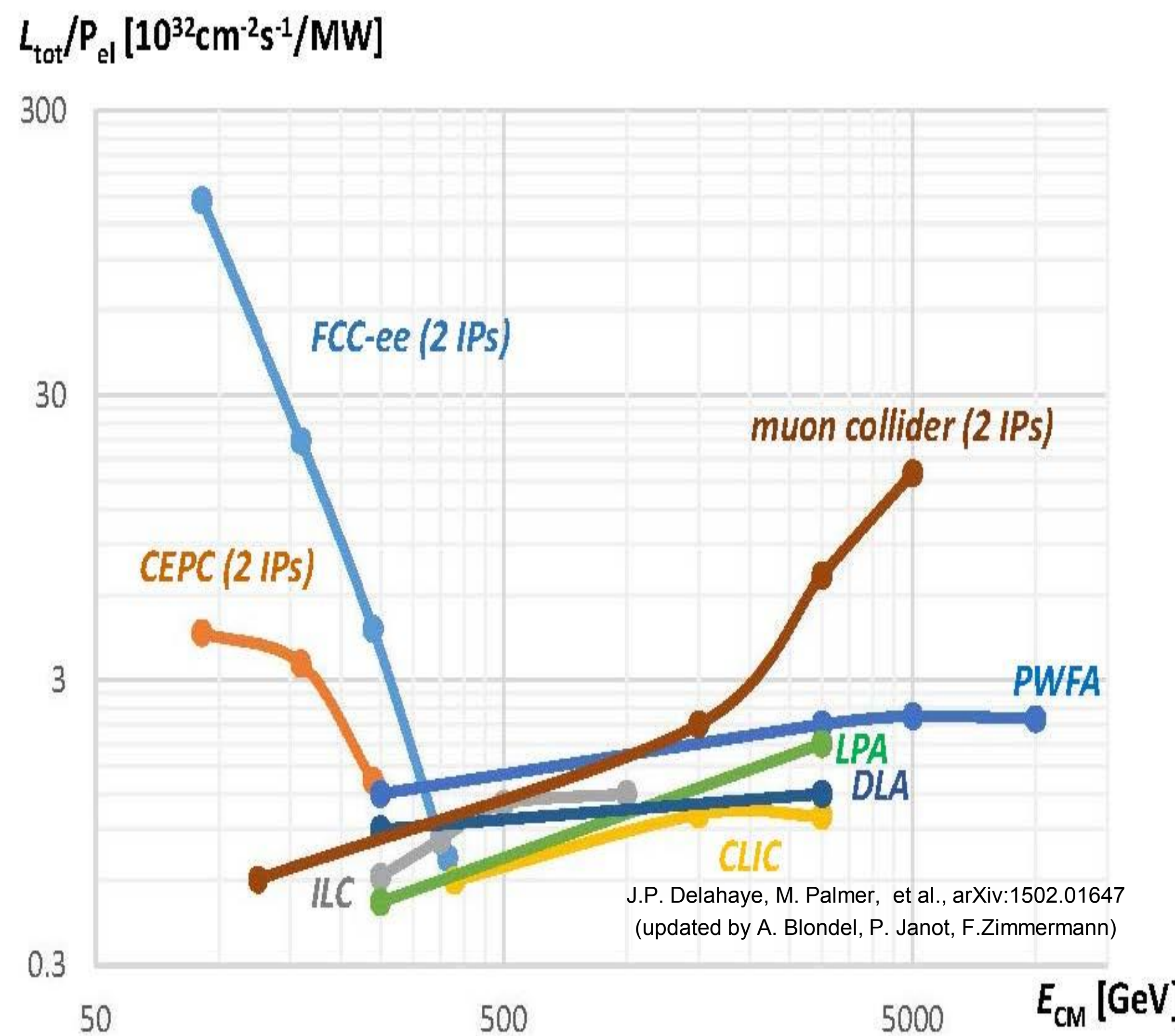


select ν_e, ν_μ, $\overline{\nu}_e$, $\overline{\nu}_\mu$ beams with precisely known fluxes

Polarised e^+ and e^- for the "LHC precision support" DIS scattering program, μ^+ and μ^- for the TeV region Lepton-Proton collider



The SPS tunnel



For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption

4

EDMs

More QCD

Nuclear β-decay

. . .

Next steps:

Form working groups

Work

Solicit new ideas

Work

Prepare Yellow report(s) … 2018

Present to European Strategy Update

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?