Imperial College London – October 18, 2017
Claude Vallée (CPPM/DESY)

Status and Prospects of PHYSICS BEYOND COLLIDERS at CERN

Study Group mandated by the CERN Management
to prepare the next European HEP strategy update (2019-20)
coordination: J. Jäckel, M. Lamont, C.V.

Excerpt from the PBC mandate:
"Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world."
Time scale: next 2 decades
pbc.web.cern.ch

PBC EVENTS

KICK-OFF WORKSHOP, CERN, Sept. 6-7, 2016

> 300 registered participants, 3/4 from outside CERN

<u>Agenda</u> :

1. **Theorists wishes**
2. **Accelerator complex opportunities**
3. **Potential future of existing programs**
4. **New ideas: Call for abstracts → 33 abstracts submitted, 20 selected for presentations**

Talks on invitation

1st GENERAL WORKING GROUP MEETING, CERN, March 1-2, 2017

Identification of main issues to be studied

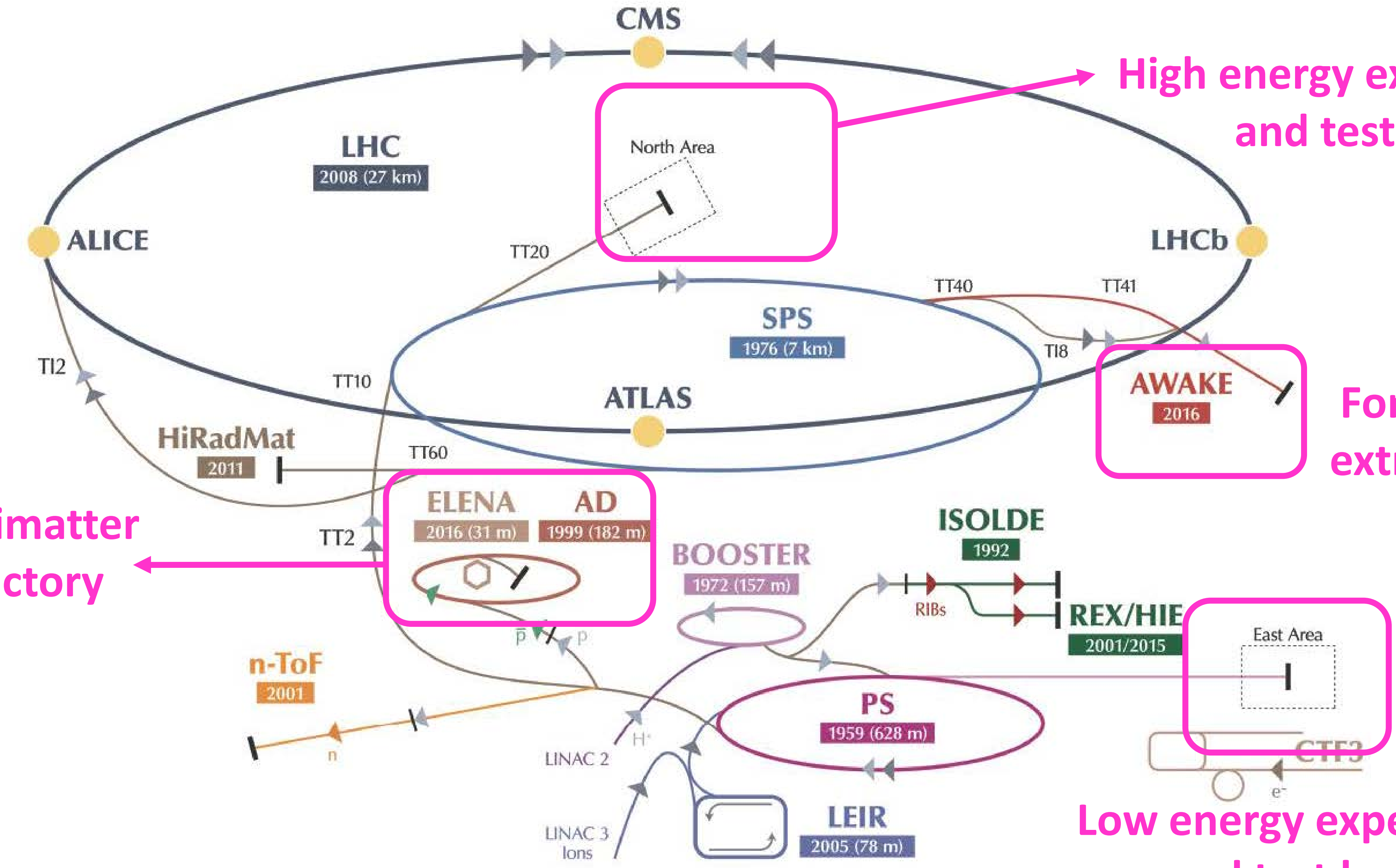
FOLLOW-UP OPEN WORKSHOP scheduled at CERN on November 21-22, 2017

https://indico.cern.ch/event/644287/

Progress on projects and new call for abstracts

NB: credit to Collaborations for the plots shown in this presentation

THE CERN ACCELERATOR COMPLEX



High energy experiments and test beams

Former CNGS extraction line

Antimatter Factory

Low energy experiments and test beams

A DECADE OF VIBRANT "DIVERSITY" PHYSICS AT CERN !

~1000 physicists on ~20 experiments

completed	full swing	expanding	starting	?
CNGS (ν) DIRAC (QCD)	COMPASS (QCD) NA61 (QCD)	ANTIMATTER FACTORY (CPT)	NA62 & NA64 (DM) ν Platform (det. R&D) AWAKE (acc. R&D)	PBC

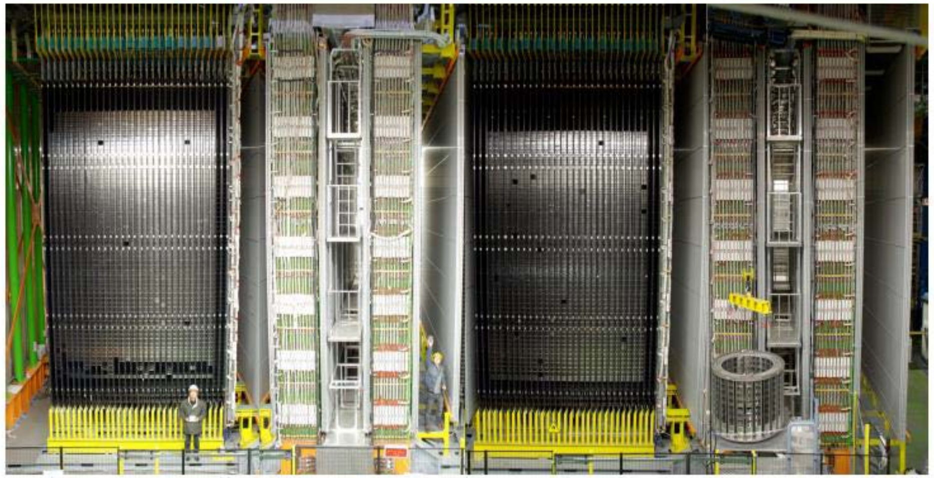
…+ CAST, OSQAR, etc…

Recent stop of major programs (e.g. CNGS) leaves room to new significant initiatives

CNGS

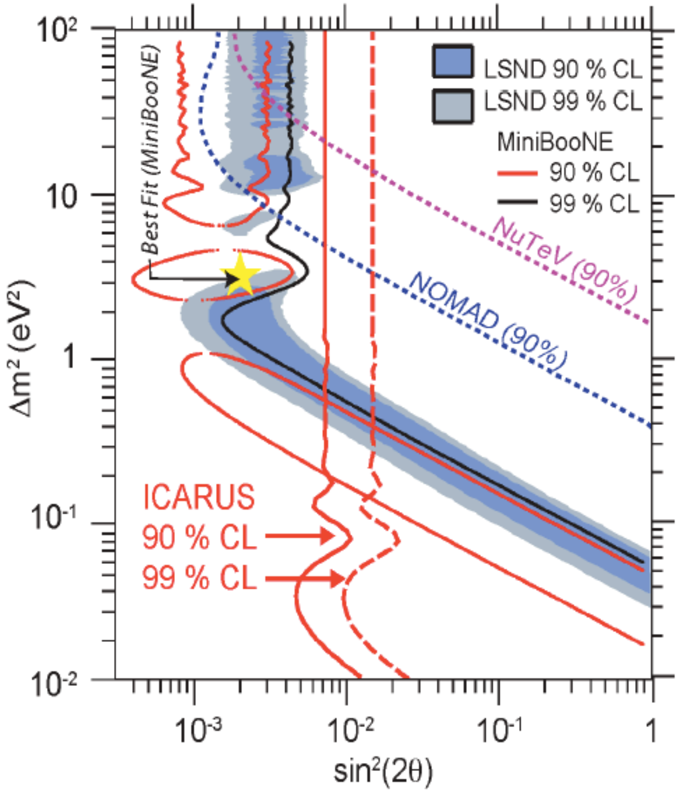
CERN ν_μ beam to Gran Sasso (CNGS) optimized for ν_τ appearance (E_ν~ 17 GeV)

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006	—	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001	—	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	—	0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	—	—	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5



OPERA: establishment of $\nu_\mu \to \nu_\tau$ oscillation

ICARUS: limits on sterile neutrinos



NEUTRINO PLATFORM

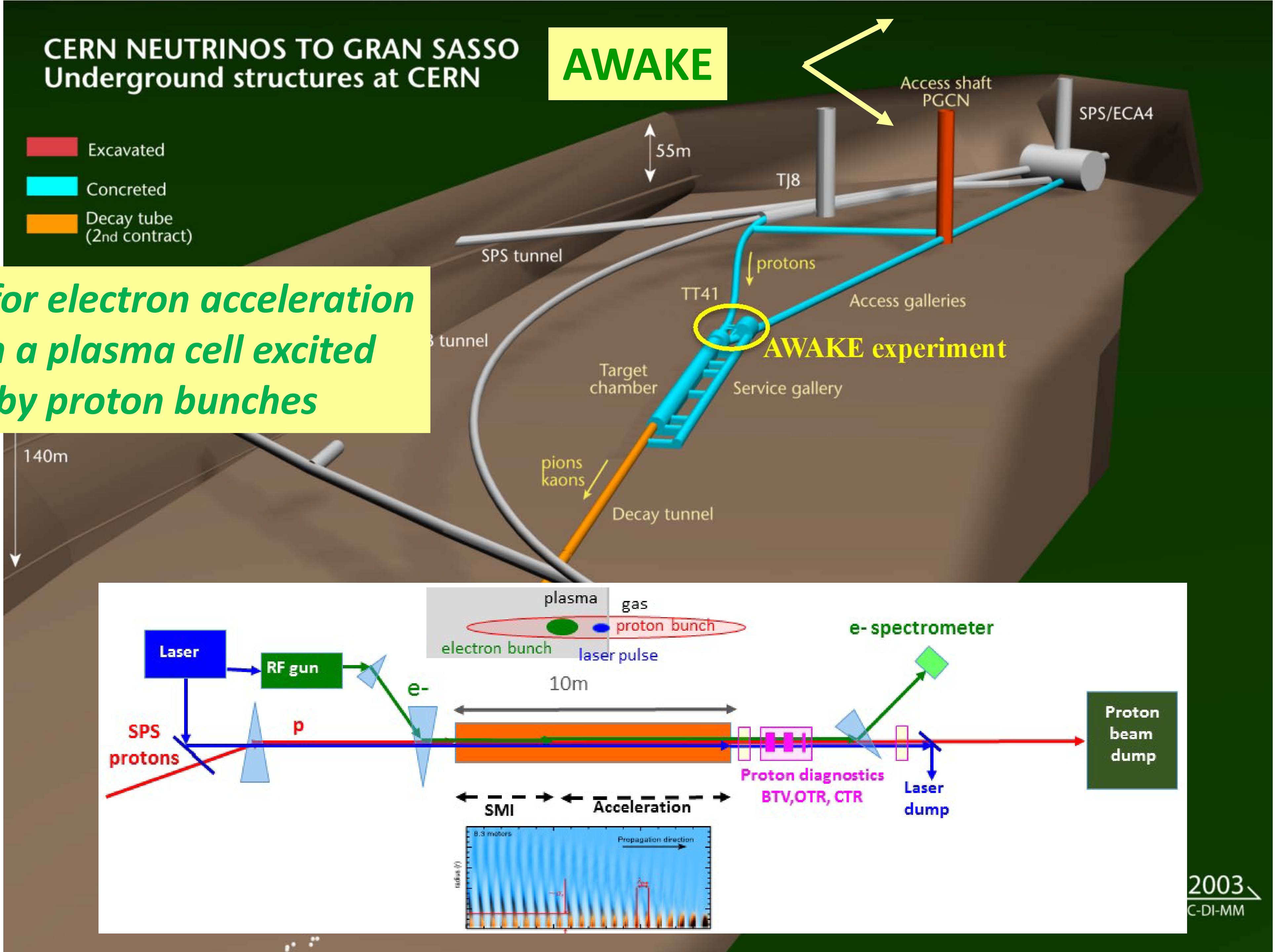
DUNE LAr-TPC engineering prototypes to be calibrated in low energy beams in a North Hall extension

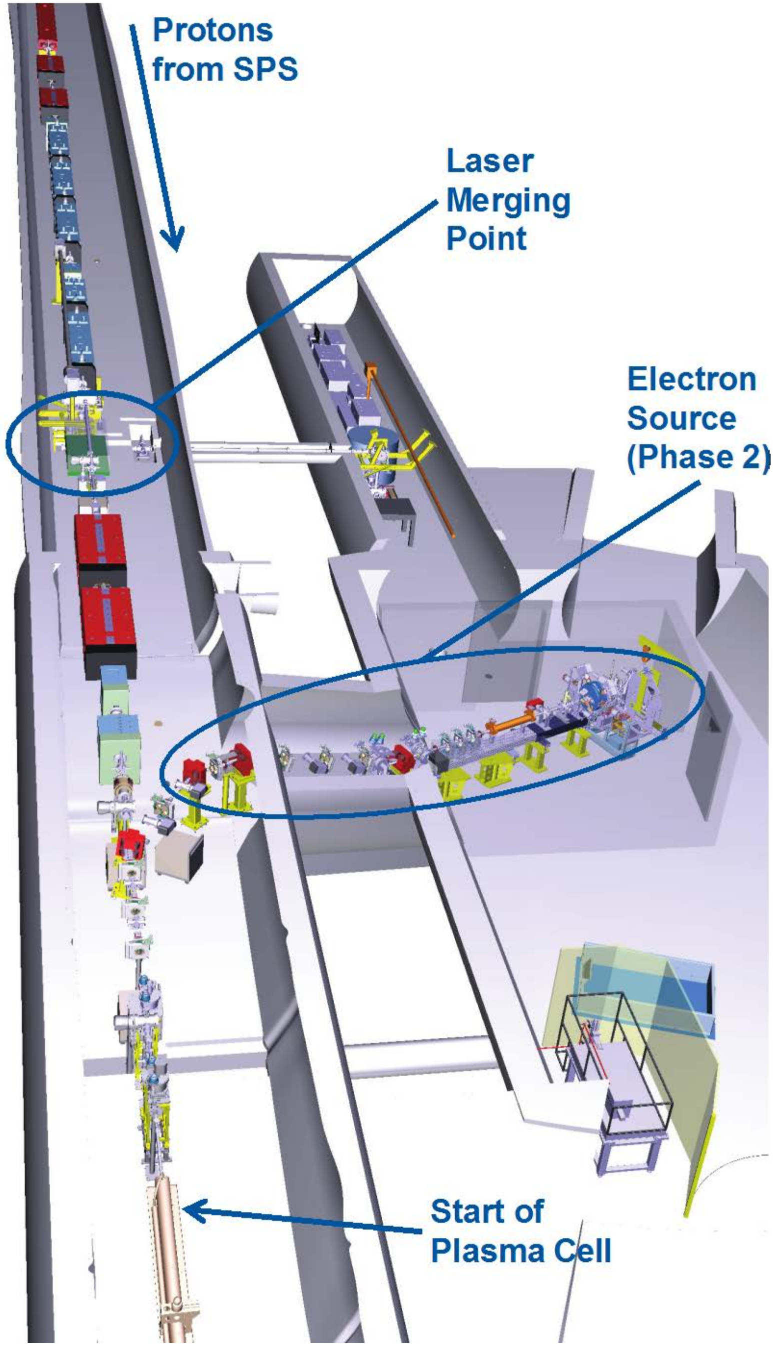
Prototypes being assembled in hall extension. ***Tight schedule to take beam data before LS2***

NB: technology could also be on interest for future DM projects at CERN

AWAKE

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



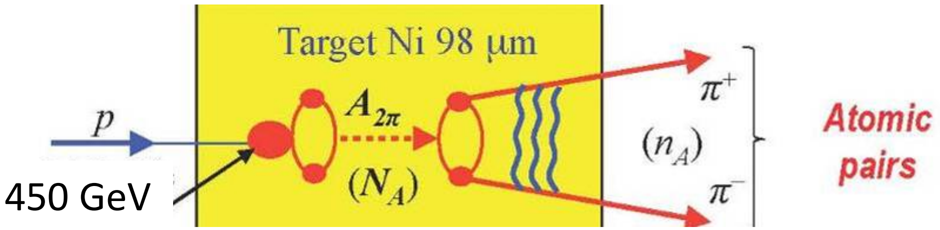


AWAKE successful first beam data end 2016
with the establishment of plasma modulation

Goal for 2017/18 is first electron acceleration
Post-LS2 program under preparation

A project of interest for future
high E / high I electron beams

DIRAC @ PS

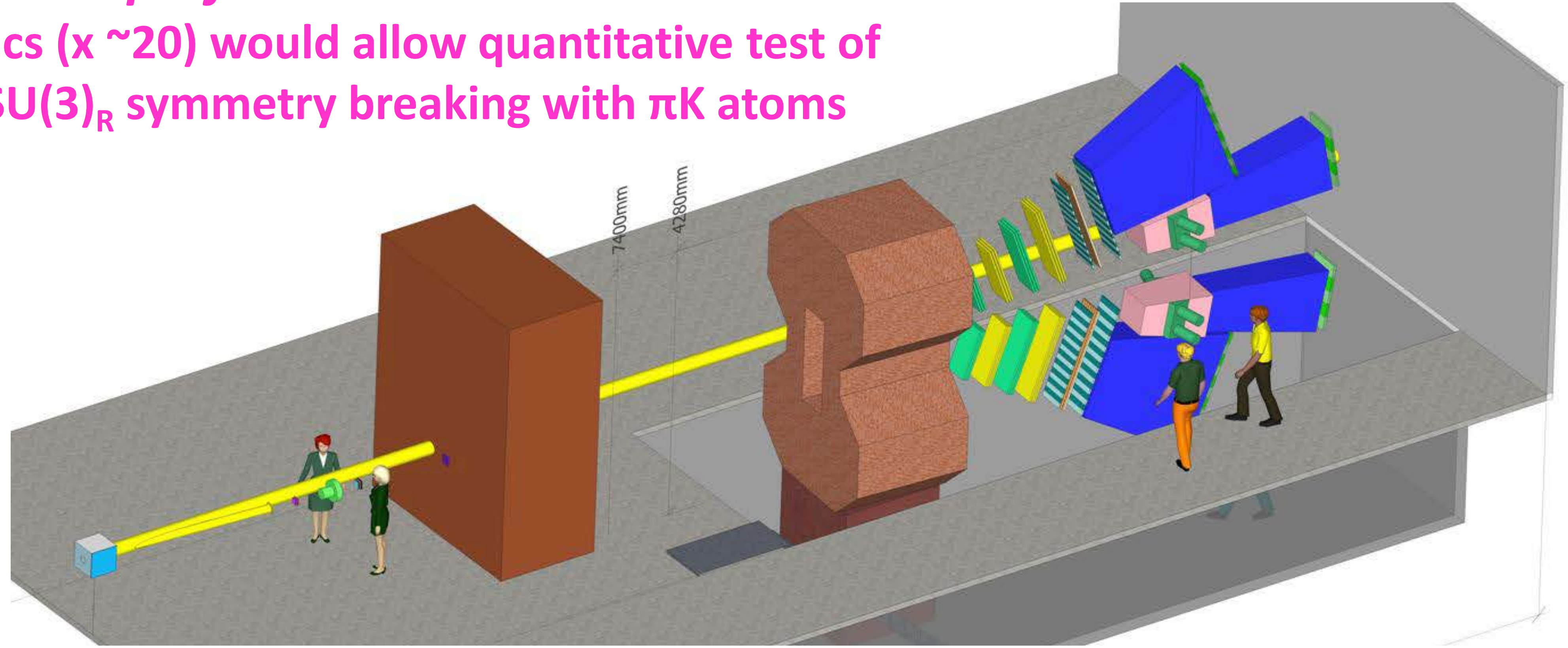


Low E perturbative chiral QCD with mesonic atoms:

Discovery of πK atoms and metastable ππ atoms

AFTER LS2: wish to perform similar studies at SPS:

Increased statistics (x ~20) would allow quantitative test of chiral $SU(3)_L \times SU(3)_R$ symmetry breaking with πK atoms



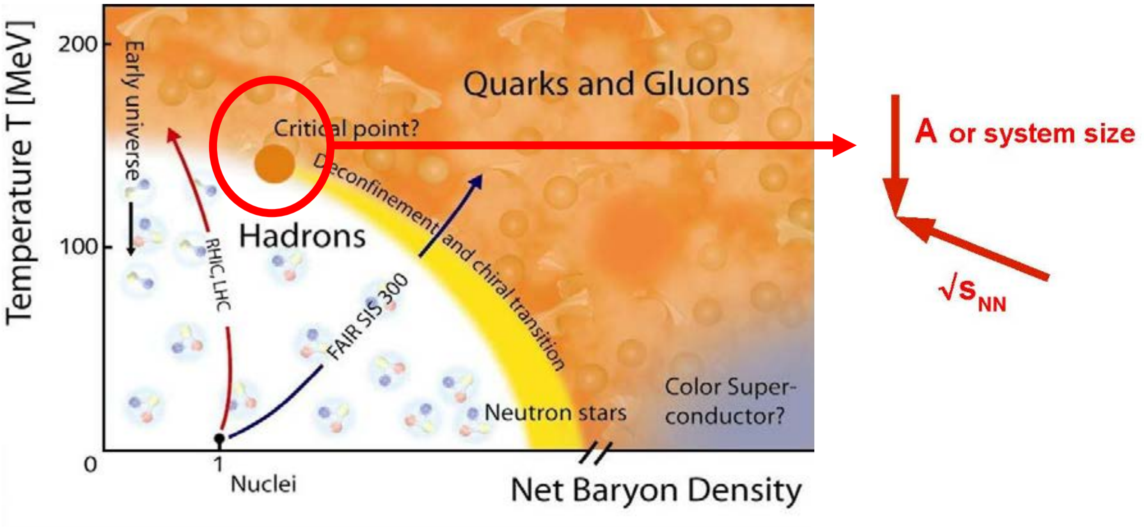
Main issues: siting at CERN and strength of Collaboration

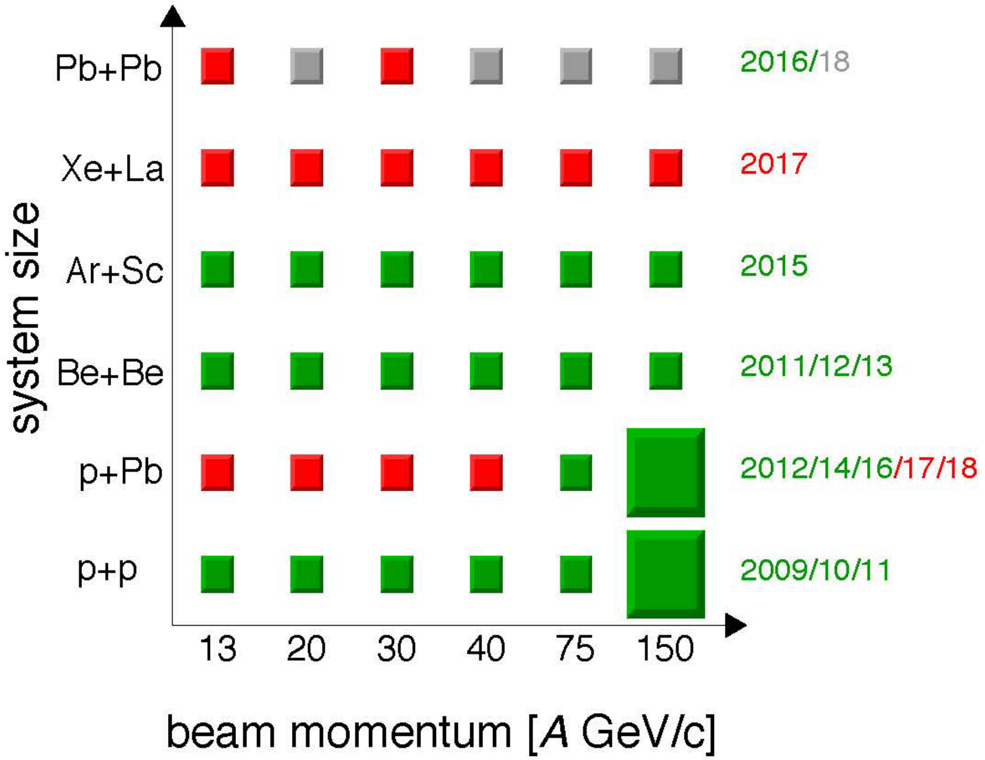
NA61/SHINE

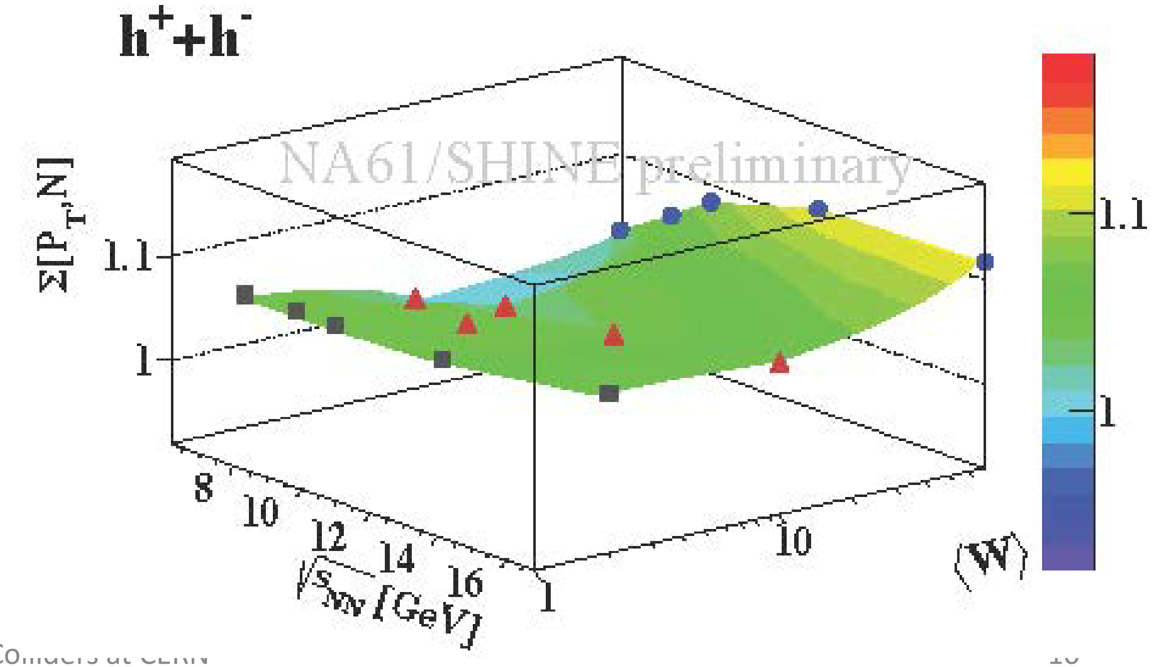
Search for QCD Critical Point by scan in the (T, μ_B) plane

Scan to be completed until LS2

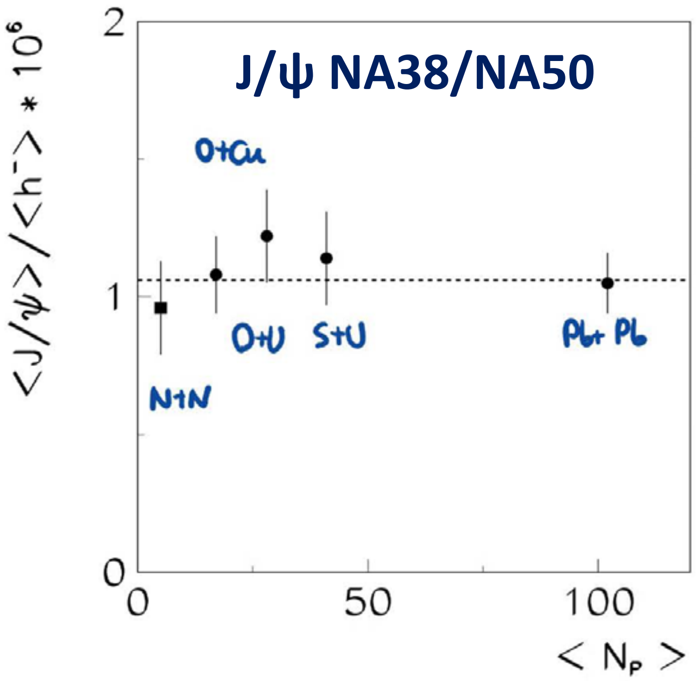
No indication of CP yet

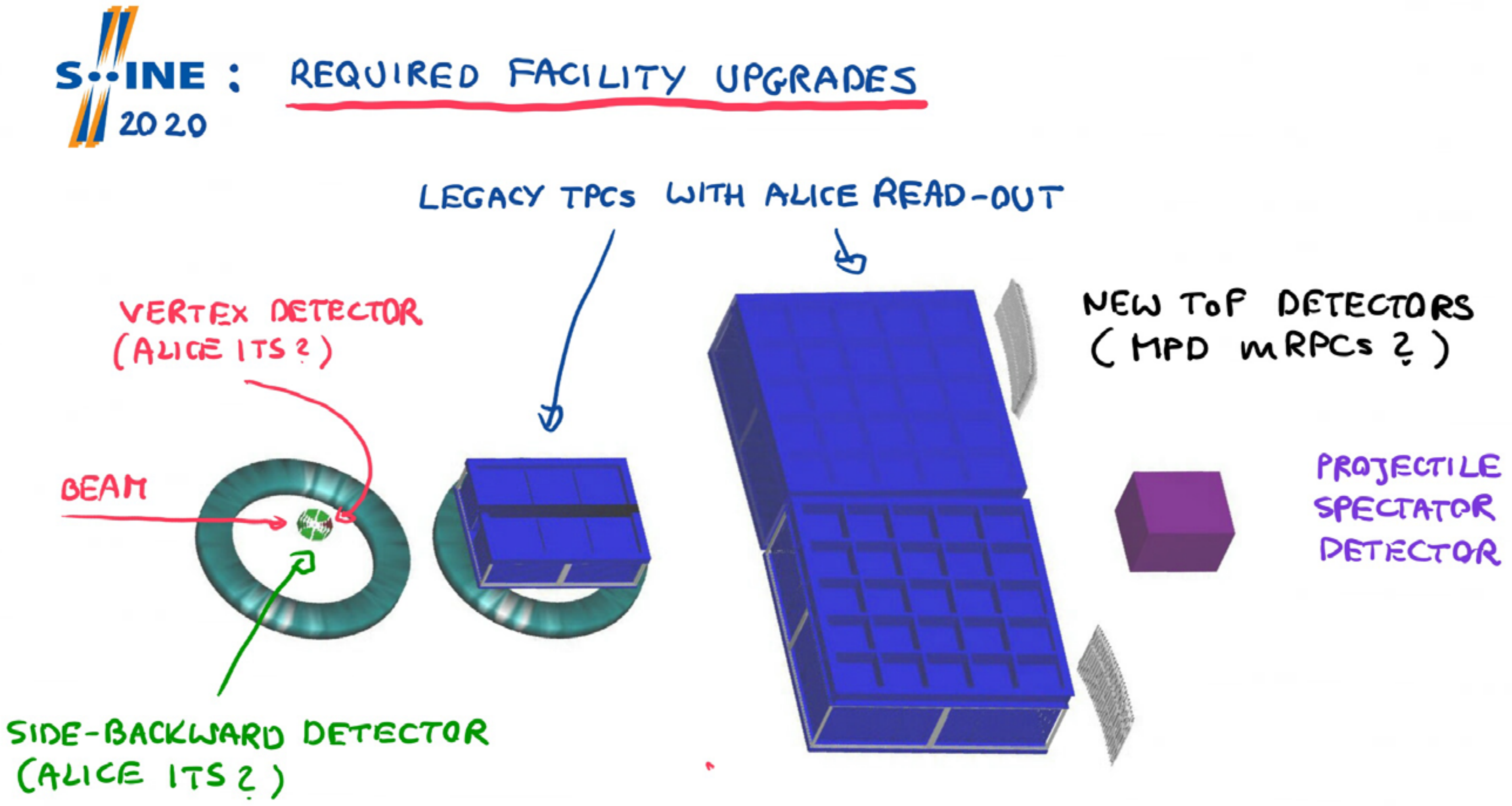






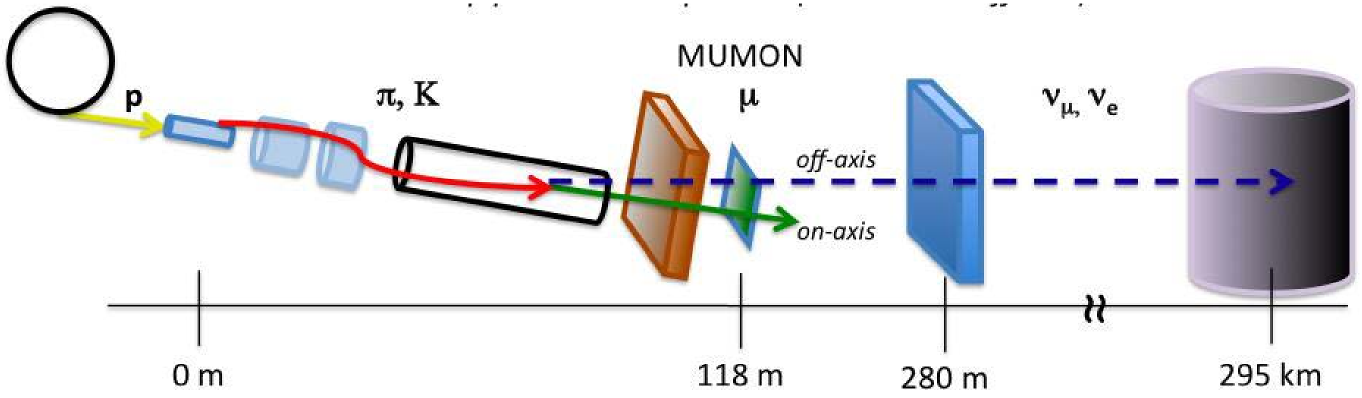
AFTER LS2:
wish to further study QCD deconfinement with open charm





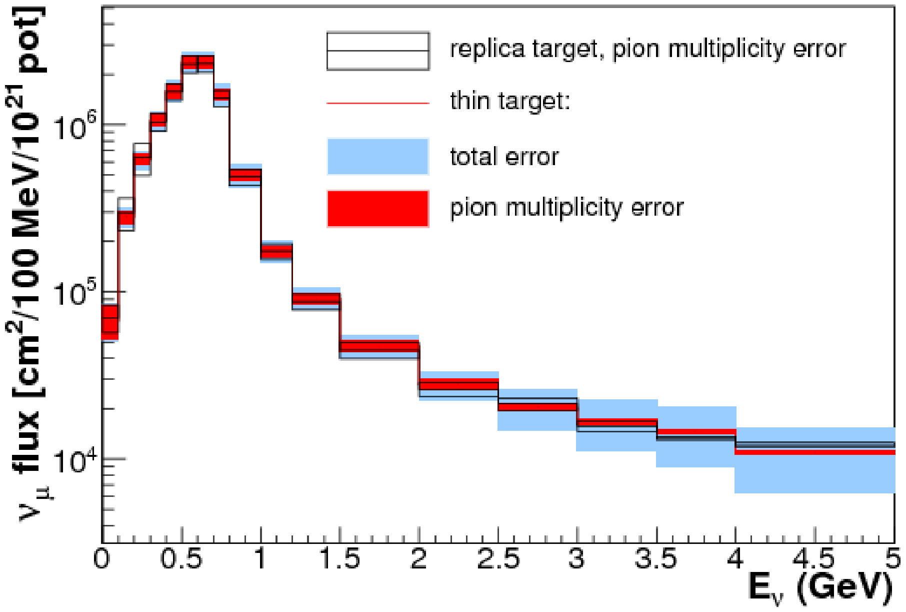
Would allow to disentangle statistical/dynamical models in complement of J/ψ data from NA38/NA50

<u>Main issues</u>: factor 10 increase in beam intensity and high rate data taking

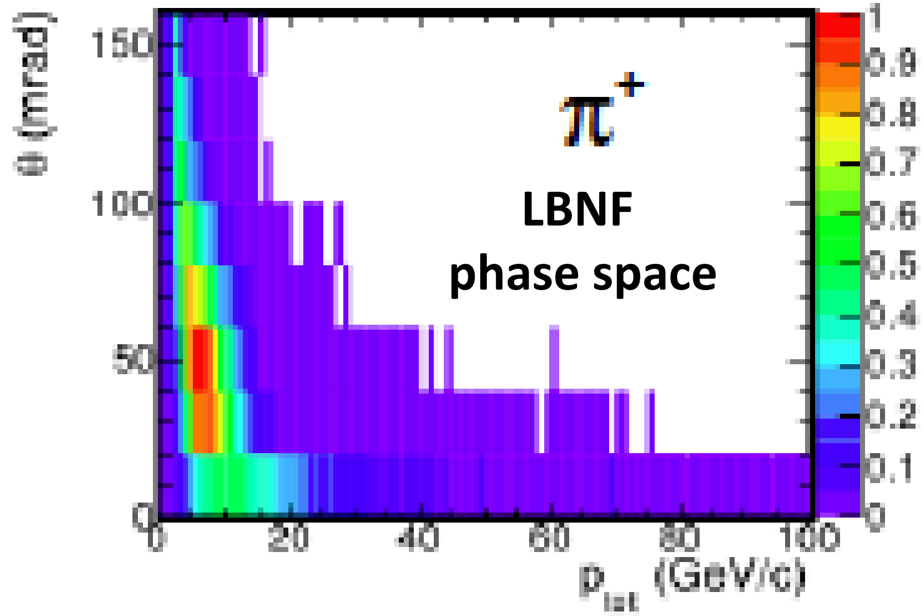


NA61 large acceptance TPC also unique to constrain ν beam fluxes

Heavily used by T2K with p-C and p-replica target data



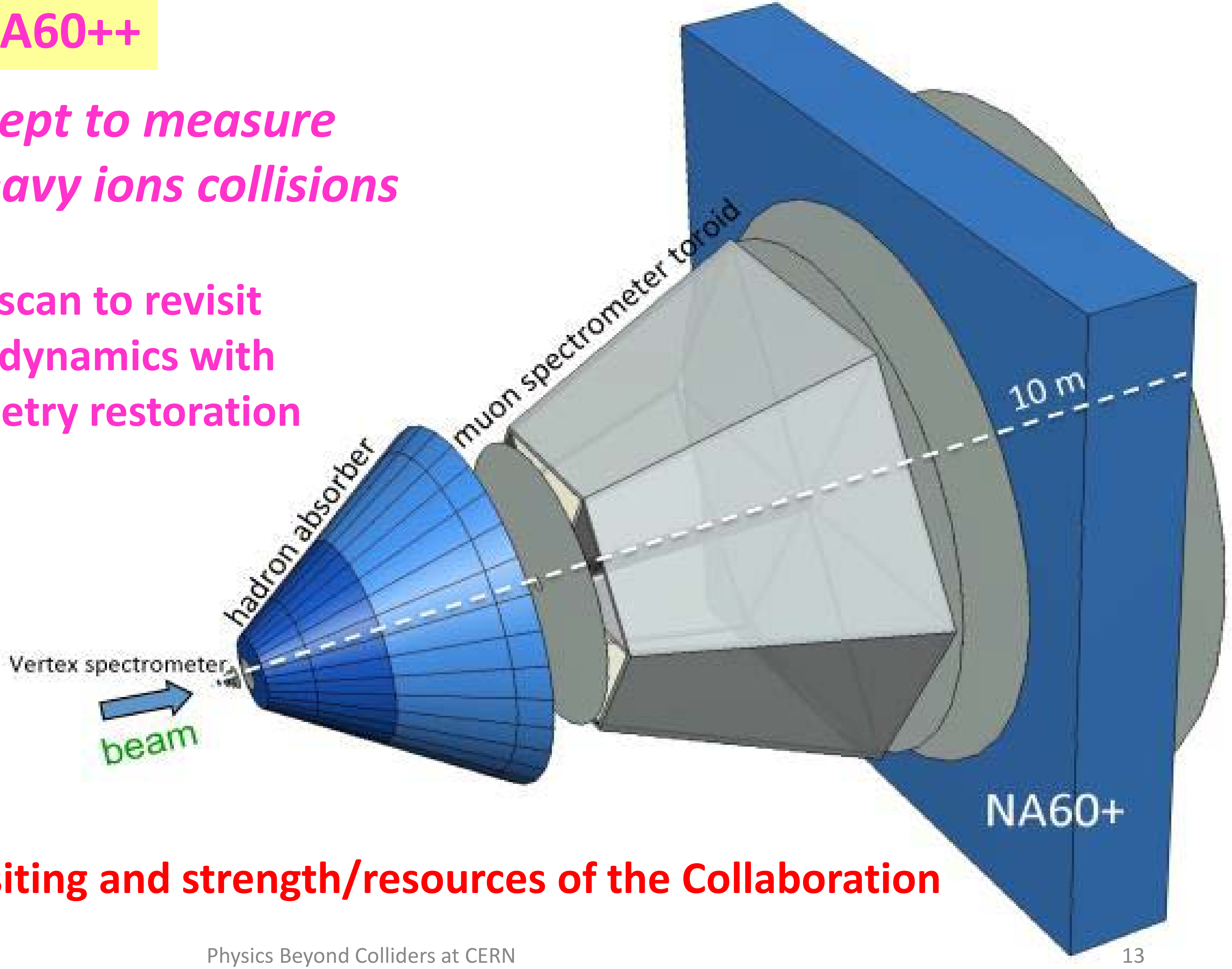
Similar program starting with the US for LBNF



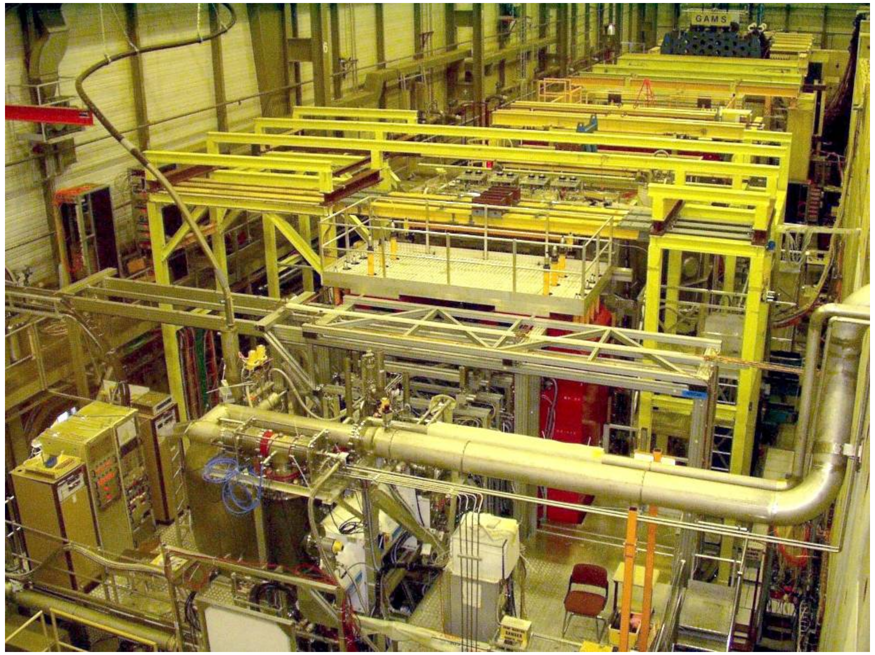
New idea: NA60++

Revival of NA60 concept to measure low mass dimuons in heavy ions collisions

New feature: energy scan to revisit QCD phase transition dynamics with a focus on chiral symmetry restoration



<u>Main issues</u>: Experiment siting and strength/resources of the Collaboration

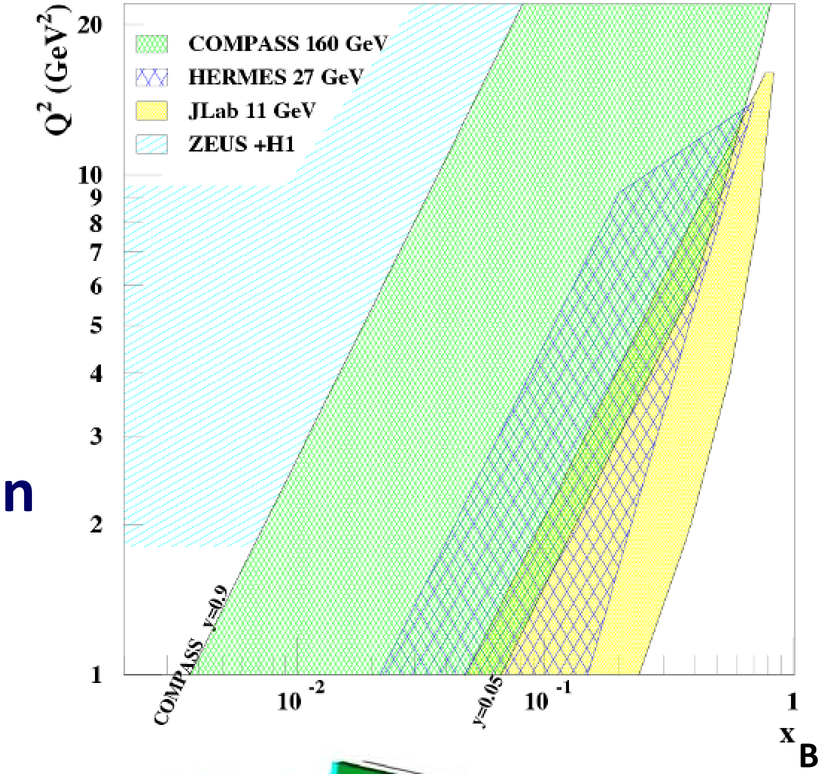


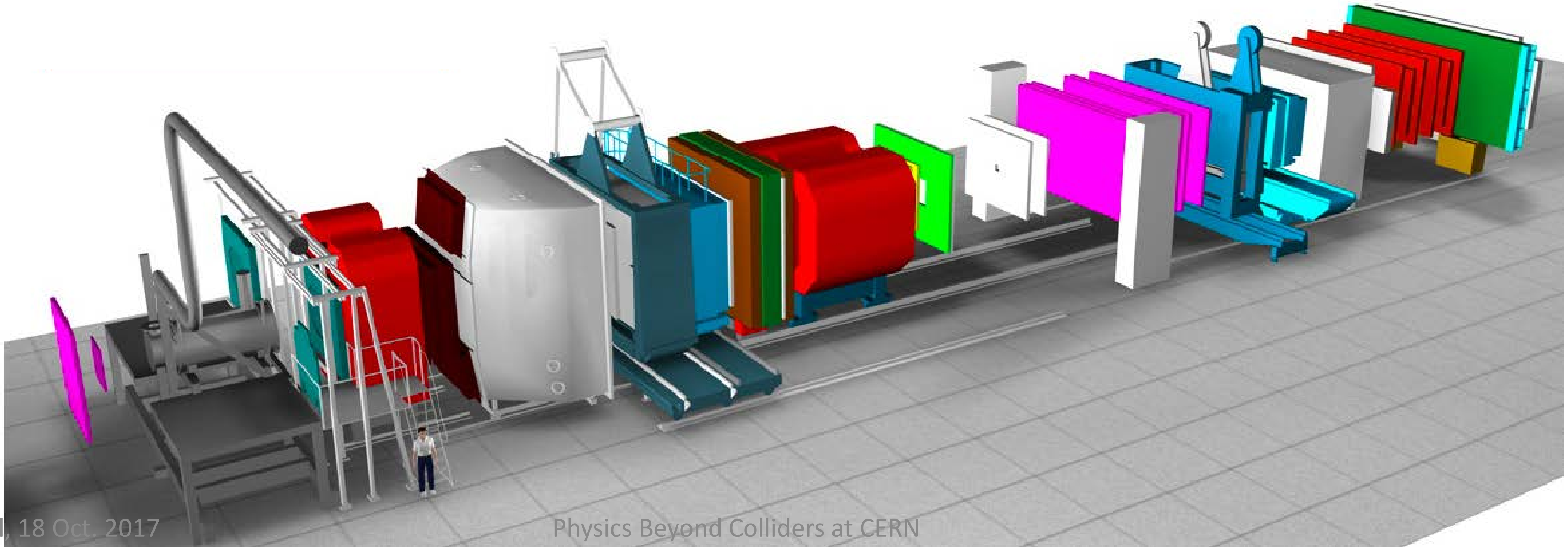
COMPASS

→

→

a large acceptance spectrometer in the intermediate x-domain between H1/ZEUS and HERMES/JLAB

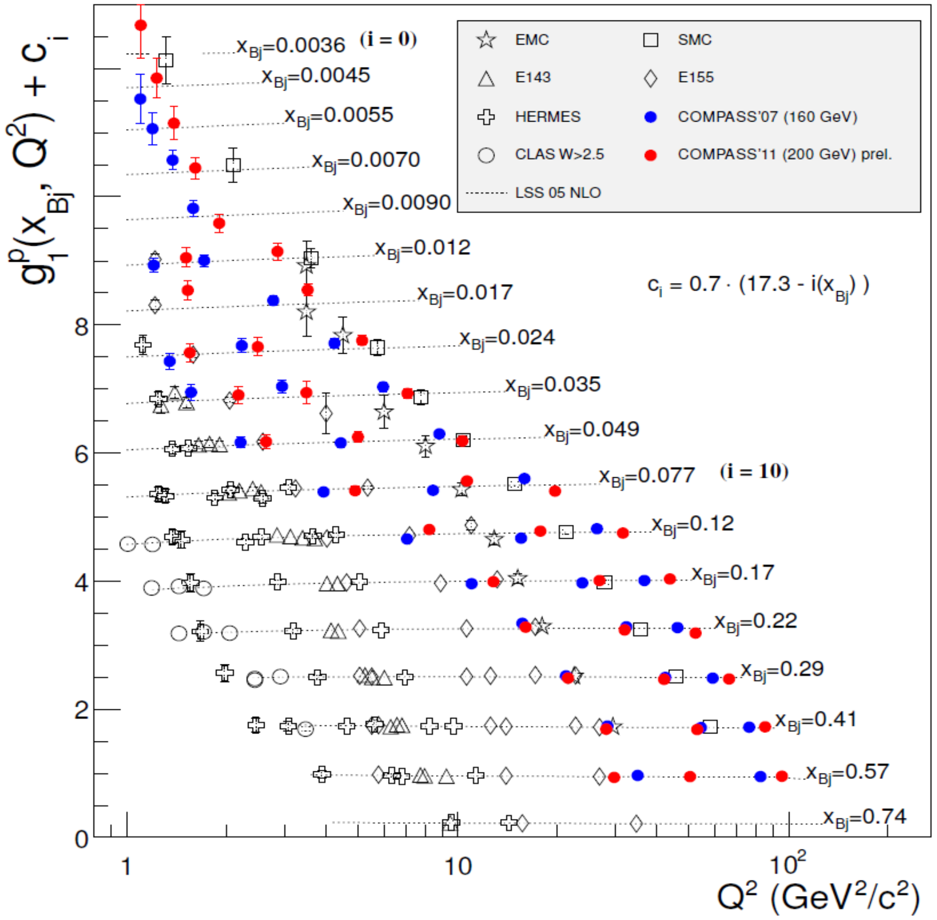




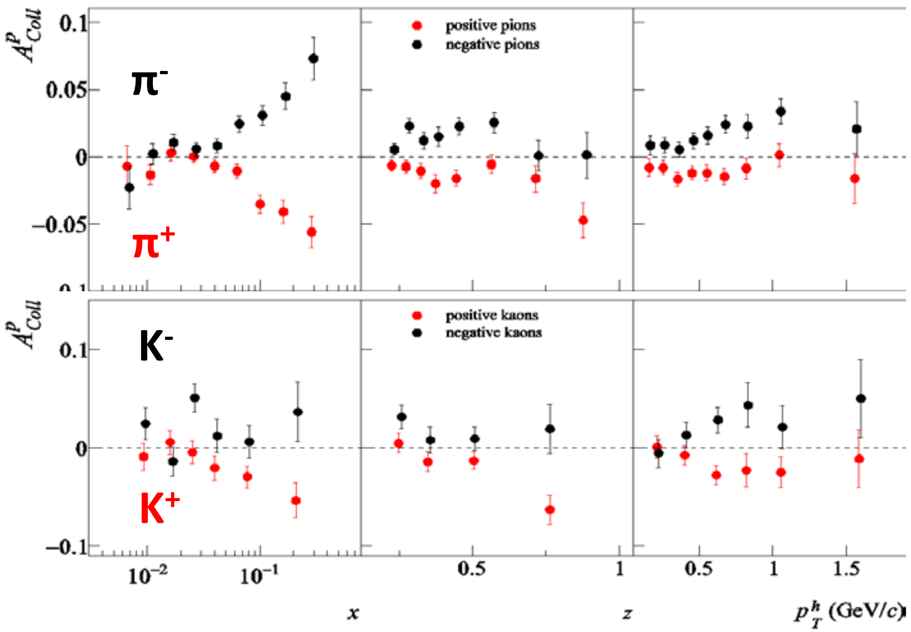
COMPASS I

Muon beam data taking completed in 2012, focused on quark spin contribution to proton spin

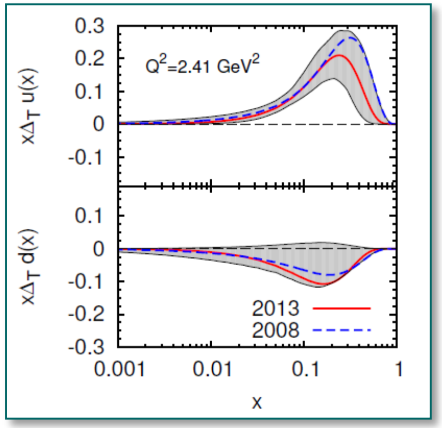
Longitudinal spin ⟷ **Transverse spin**



Improved precision on g_1 at low x

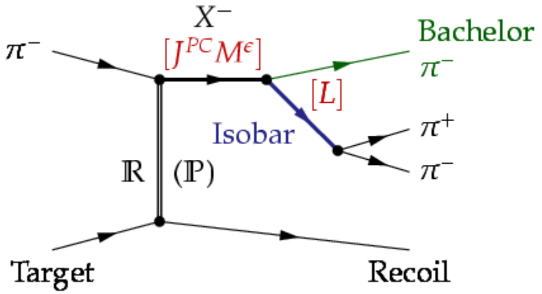


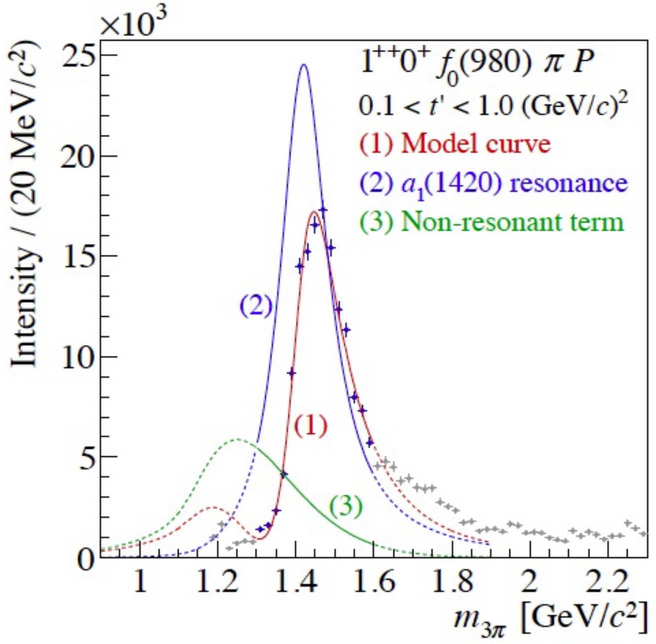
Non-zero transversity in proton confirmed



COMPASS I(+II) : SPECTROSCOPY AND PRIMAKOV

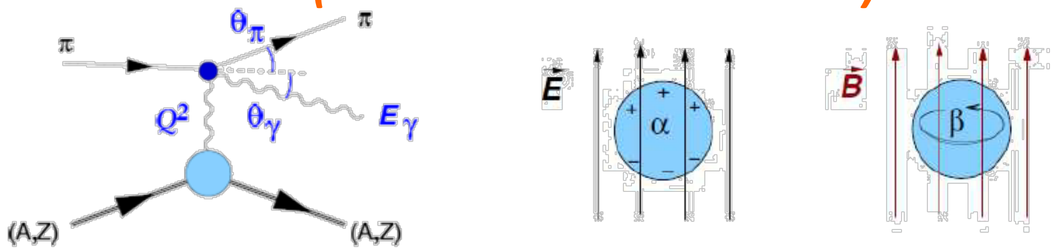
New isovector meson $a_1(1420)\ 1^{++}$

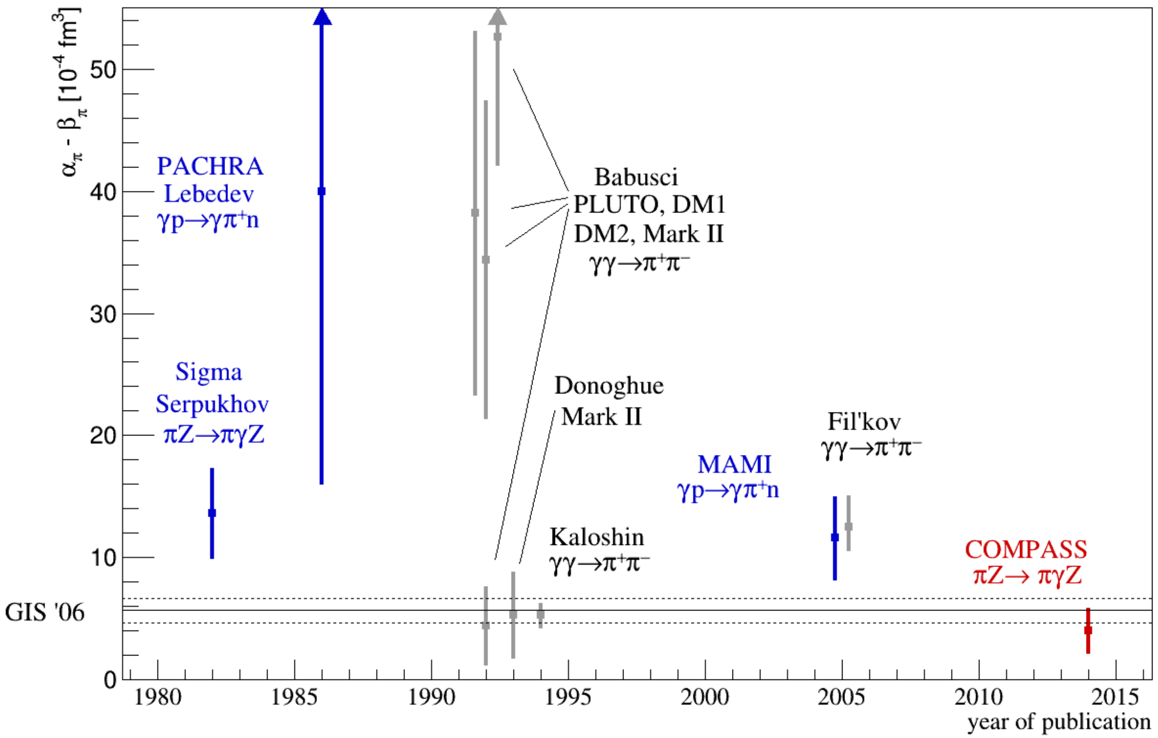




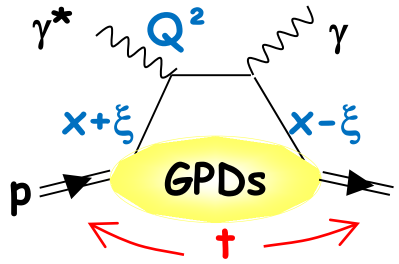
Pion polarizability with 2009 Primakov data

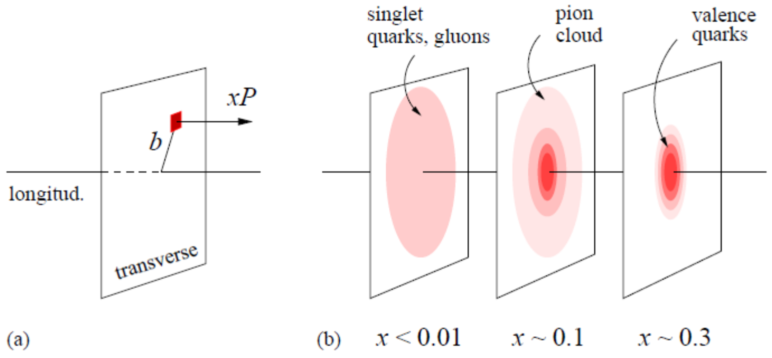
(to be x 5 with 2012 data)

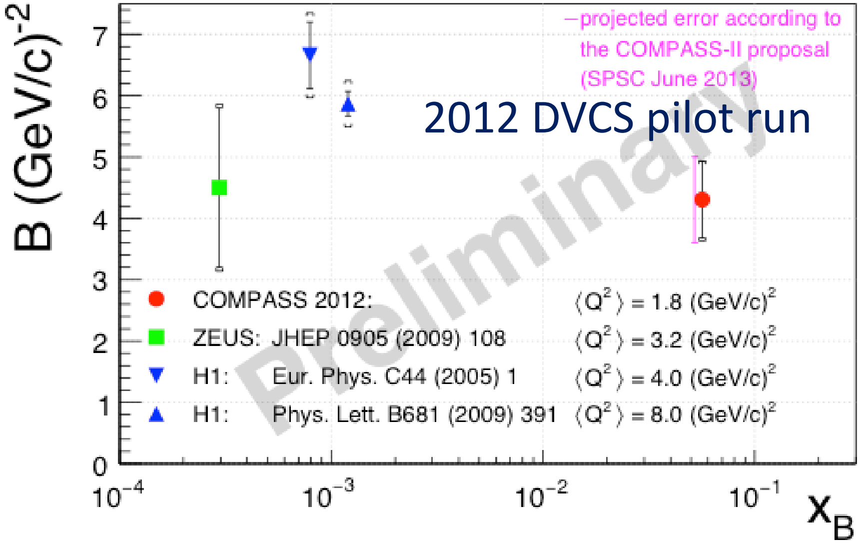




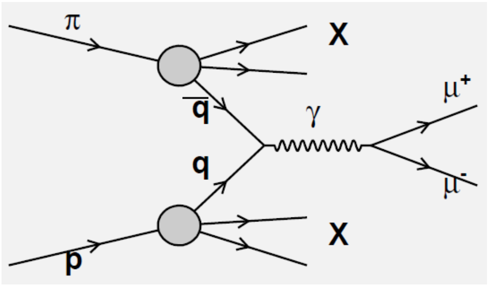
COMPASS II (2014-18)

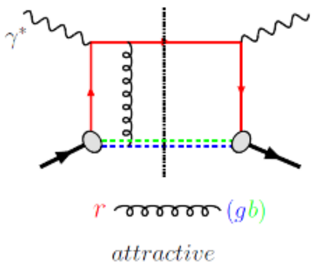


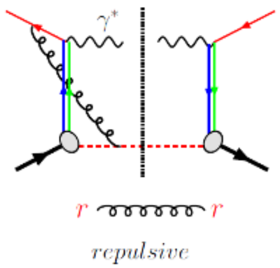


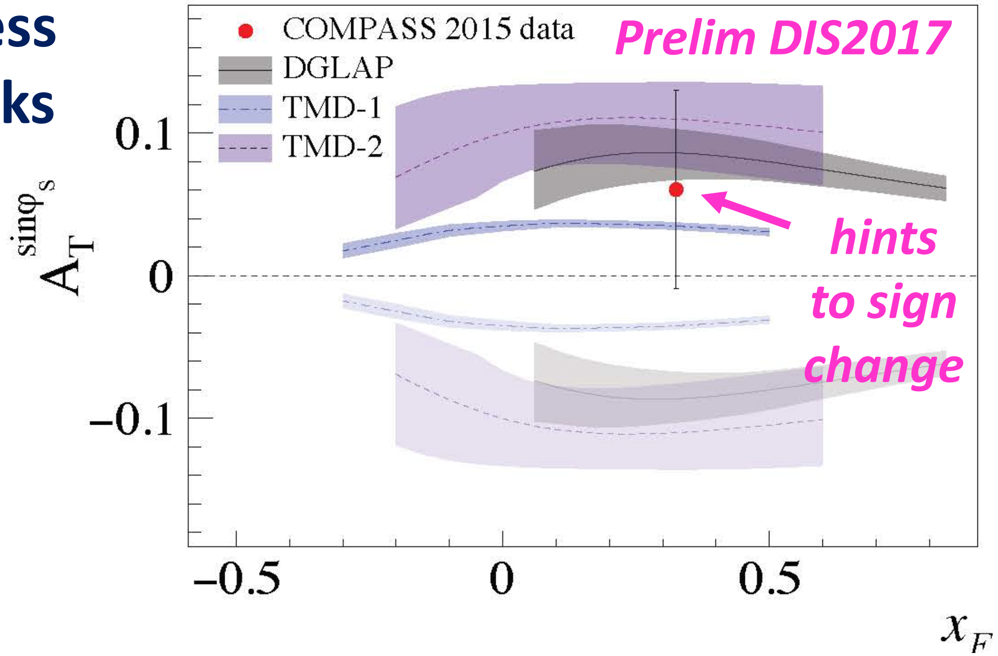


<u>2016-17: DVCS</u> : proton tomography with access to orbital momentum of quarks





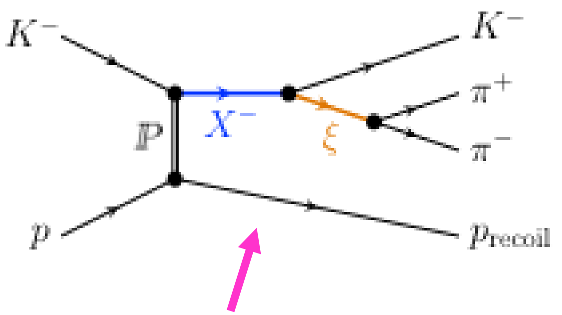




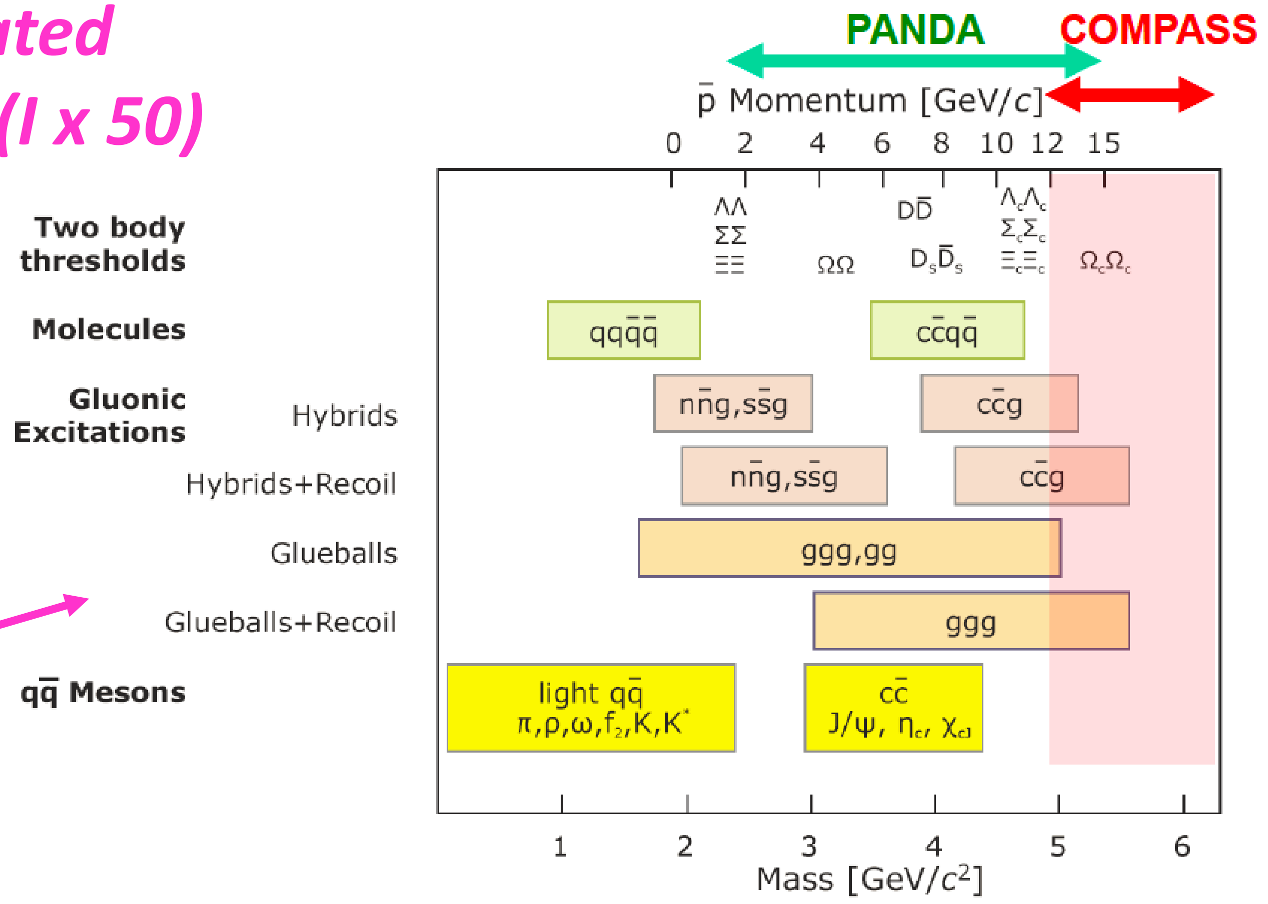
<u>2014+15+18: DY</u> : Transverse Momentum Dependent (TMD) QCD effects in the valence regime

Measurement complementary to SiDIS : opposite asymmetries expected

AFTER LS2: wish RF separated antiproton and kaon beams (I x 50)



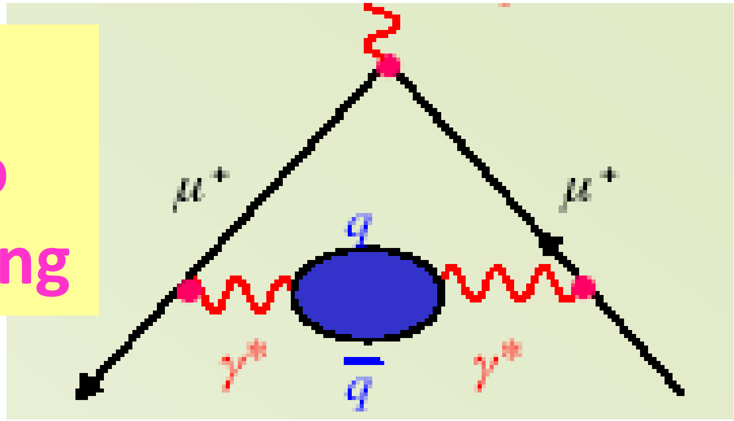
- High statistics strange meson spectroscopy
- Exotic states spectroscopy complementary to LHCb/PANDA
- Kaon and antiproton structure



DY statistics	NH_3	Al (7cm)	W	NA3	NA10	E537	E615
K^- beam	14,000	2,800	29,600	700			
$\bar{p}$ beam	15,750	2,750	22,500			387	

Main issues: Competition, cost of RF separated beam, Collaboration long term support

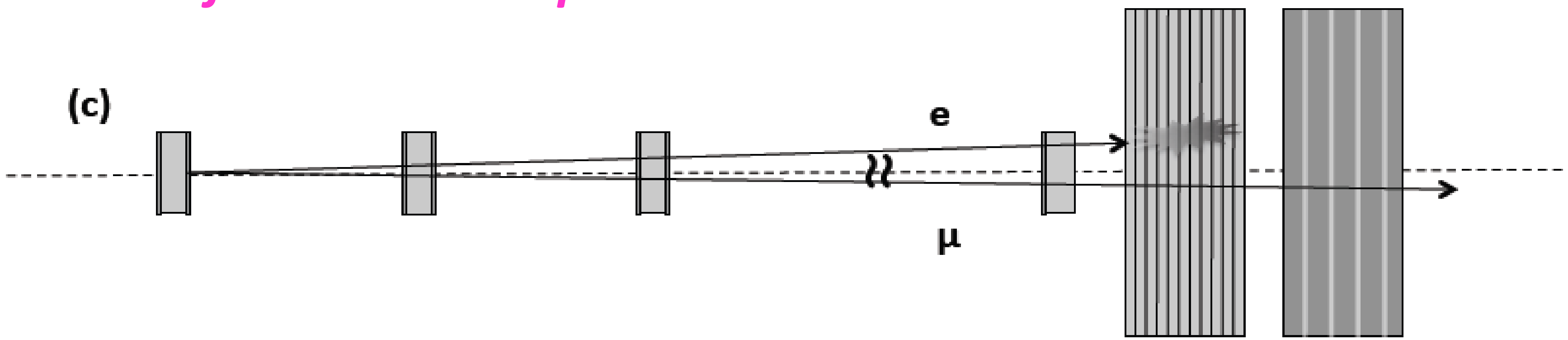
New idea: "MU-E" experiment: direct measurement of the dominant contribution to the theoretical error on $(g-2)_\mu$ from μ-e elastic scattering



Vacuum polarisation

High statistics space-like measurement could reduce by factor 2 the current error derived from time-like processes

μ beam
150 GeV

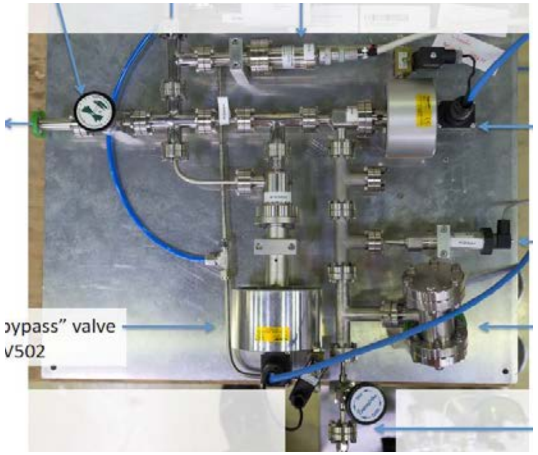


Full t range accessible thanks to high energy μ beam boost, self normalized measurement
Might be feasible with reasonable resources within the (modified) COMPASS setup

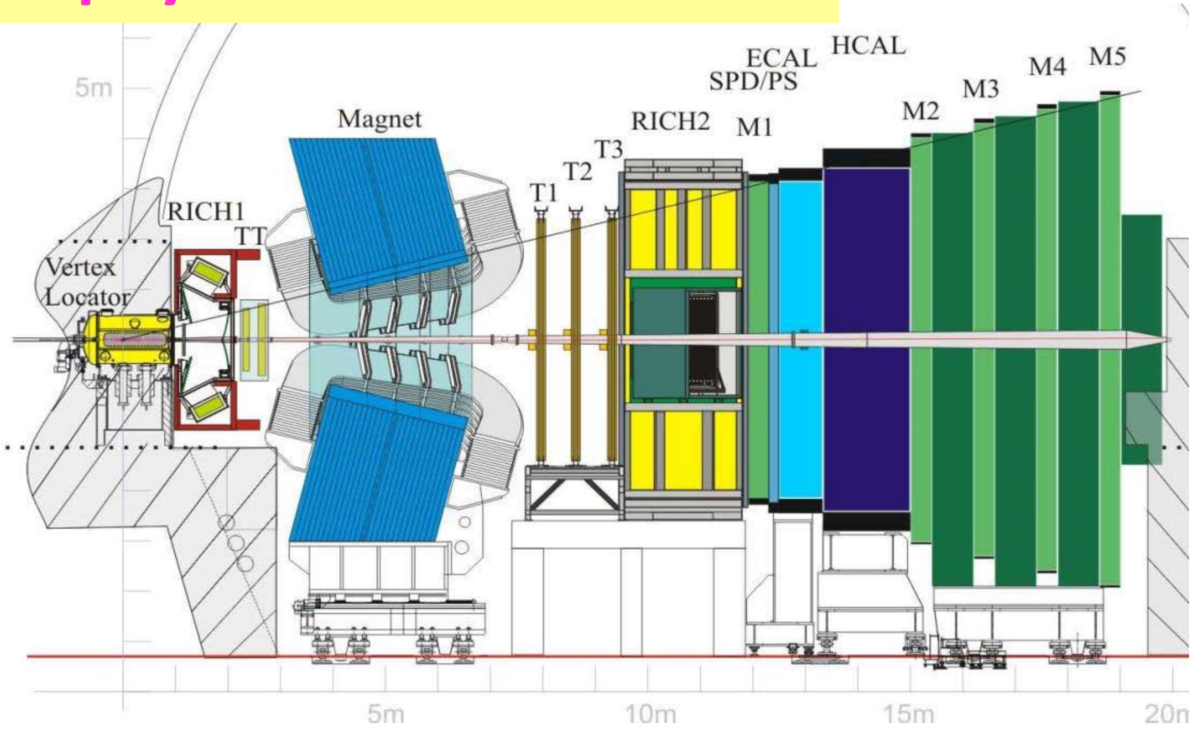
<u>Main issue</u>: systematic effects (control needed at 10^{-5} level)

New idea: Fixed Target physics with LHC beams

Internal gas target (LHCb, AFTER)

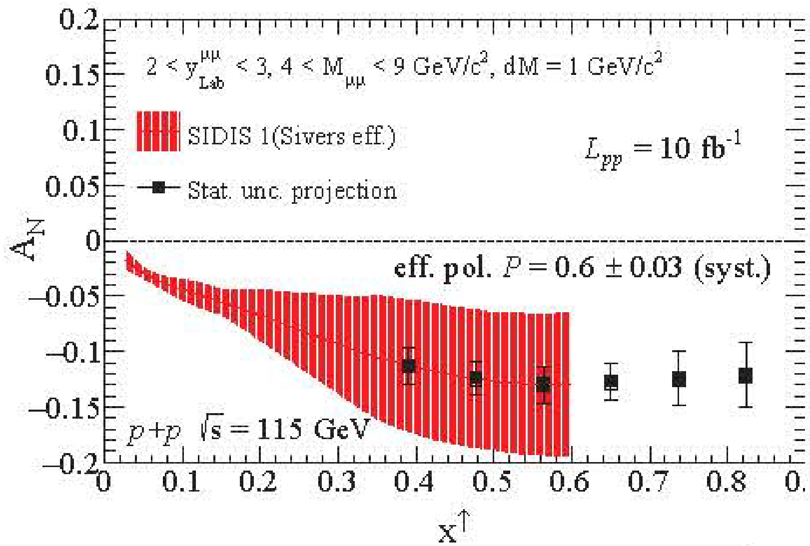


Upstream of LHCb and/or ALICE



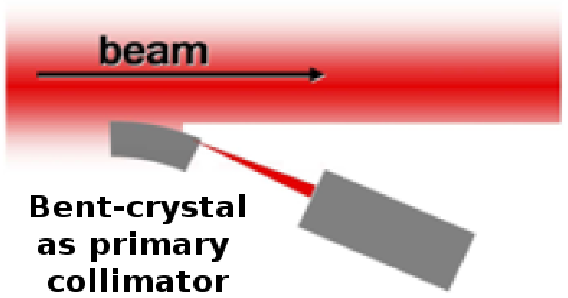
e.g. SMOG or polarized HERMES-like

p-p: High precision TMD measurements (polarized target) and charm at high x
p-A: Nuclear PDFs



New idea: Fixed Target physics with LHC beams cont'd

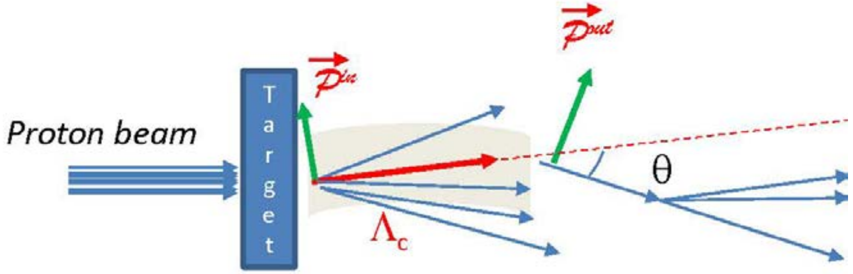
Crystal extraction

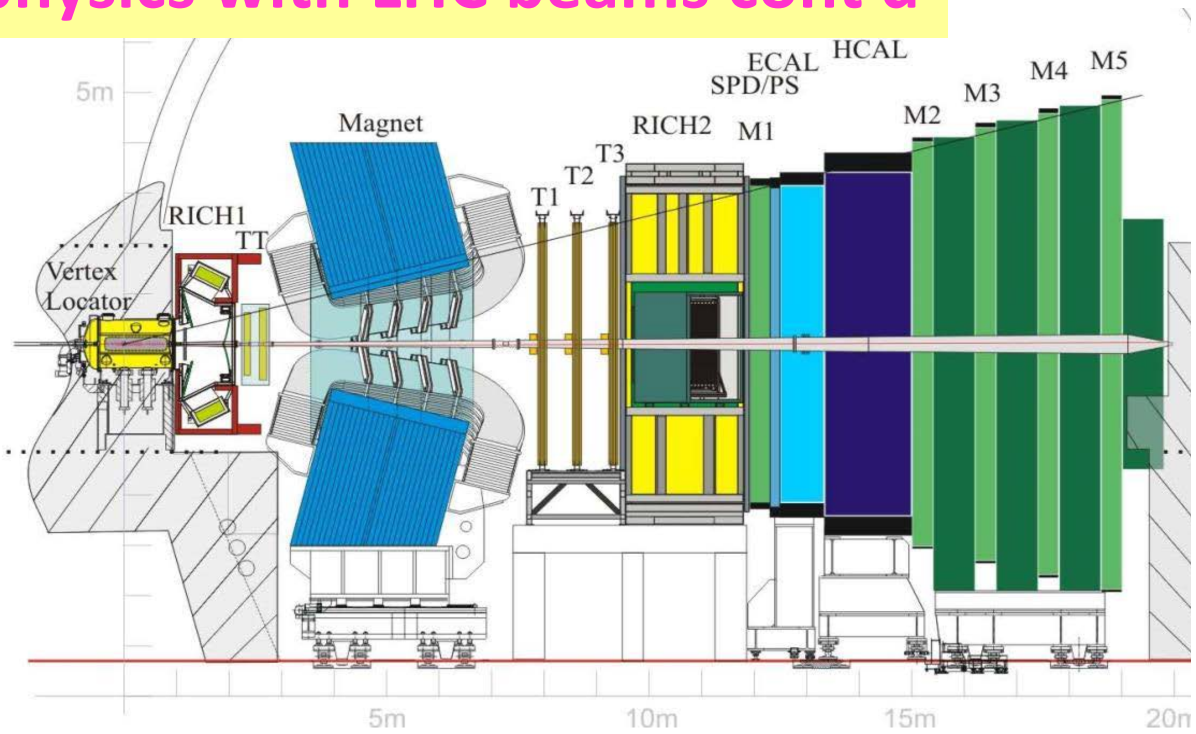


UA9

Upstream of LHCb and/or ALICE

$$\frac{dN_i}{N_{0i}\, d\cos\theta_i} = \frac{1}{2}\left(1+\alpha P_i \cos_i\theta_i\right)$$



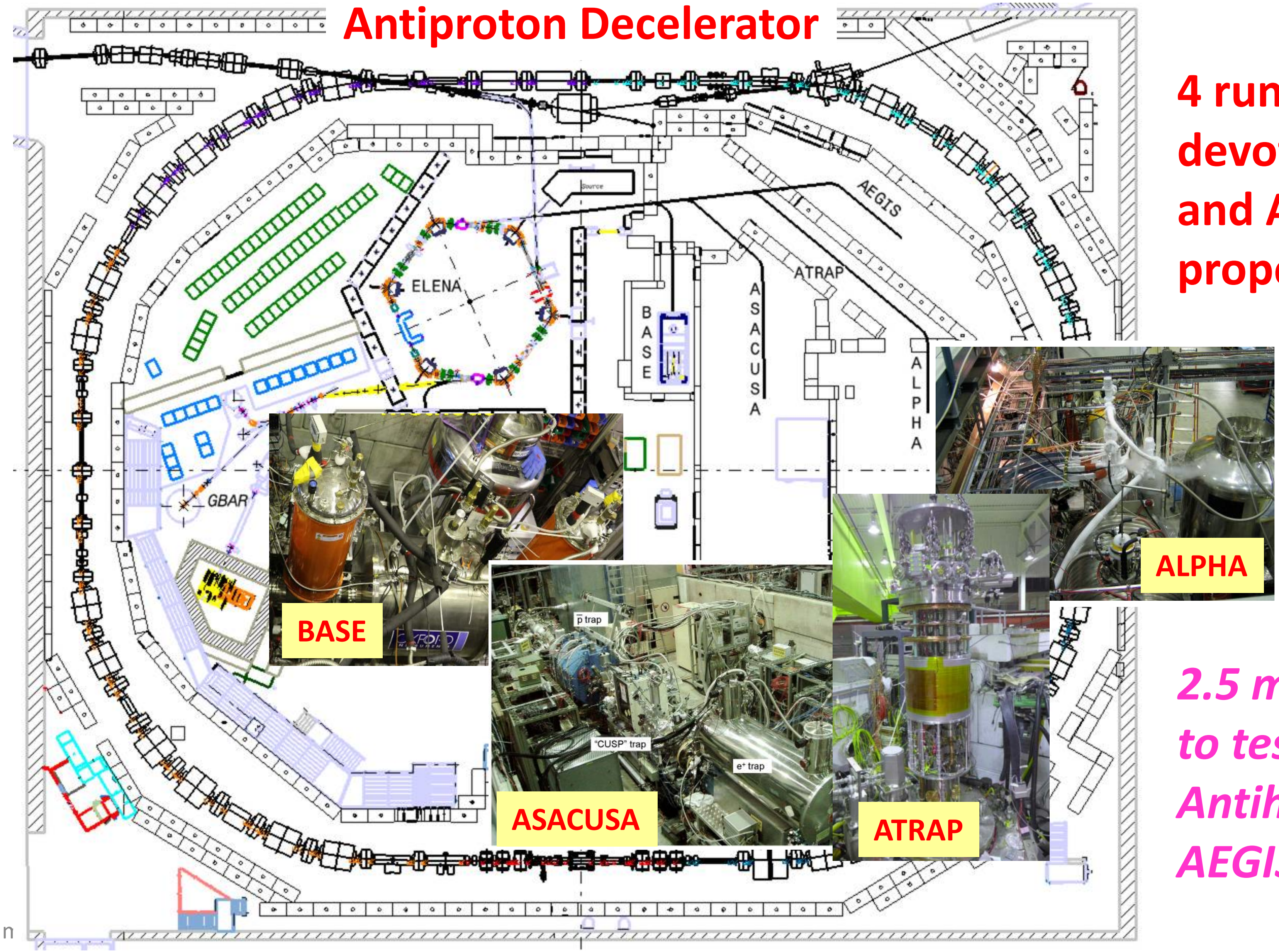


Proposed for measurement of magnetic and electric moments of short lived baryons

Could test anomalous moments of heavy quarks

<u>Main issue of LHC internal fixed targets</u>: compatibility with other LHC programs/goals

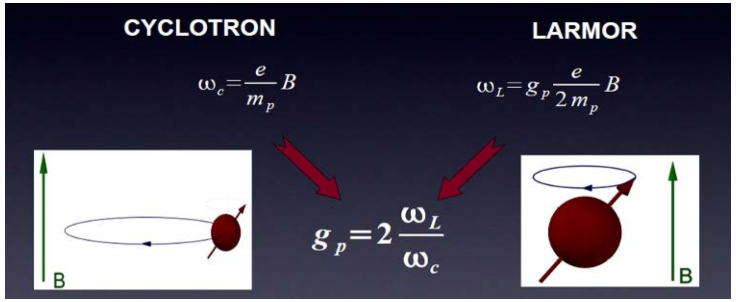
ANTIMATTER FACTORY

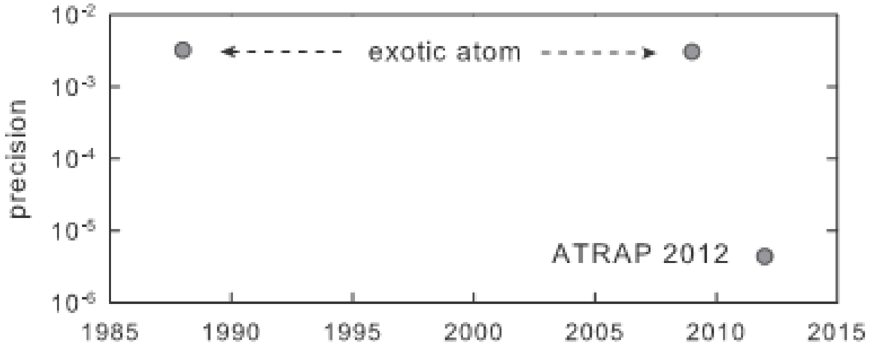


4 running experiments devoted to Antiproton and Antihydrogen properties

2.5 more in preparation to test gravity of Antihydrogen: AEGIS/GBAR/ALPHA-g

Antiproton Properties

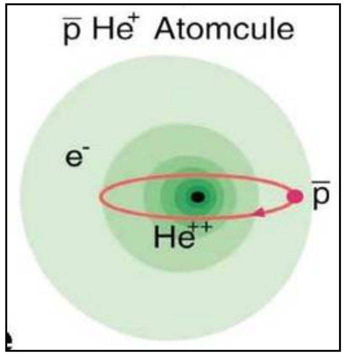


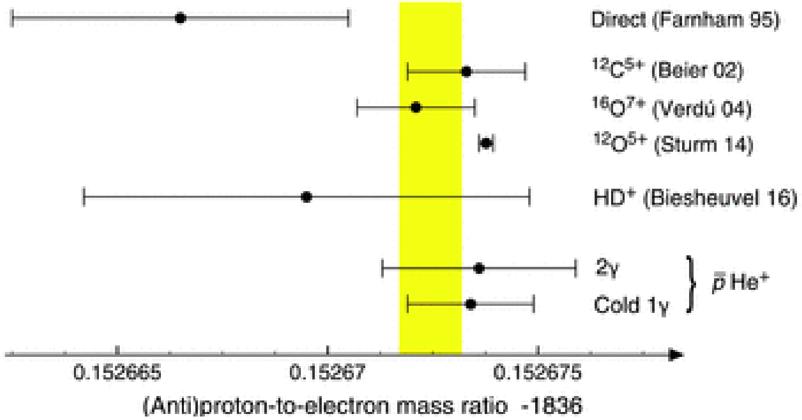


Magnetic moment:

ATRAP gain in precision of ~3 orders of magnitude using new method with single trapped antiproton

Significant improvement expected soon from BASE





Mass:

Regular ASACUSA progress with cold 1- and 2-photon spectroscopy of antiprotonic Helium

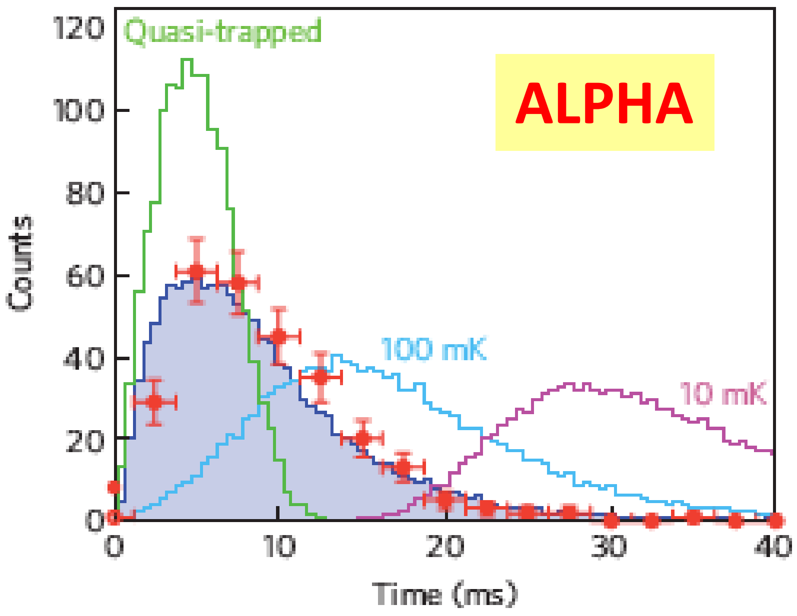
$$\boxed{\frac{(-q/m)_{\bar{p}}}{(q/m)_{p}} - 1 = 1(69) \times 10^{-12}}$$

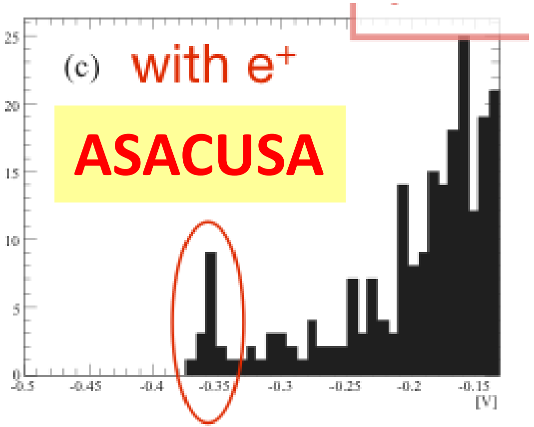
Charge/Mass:

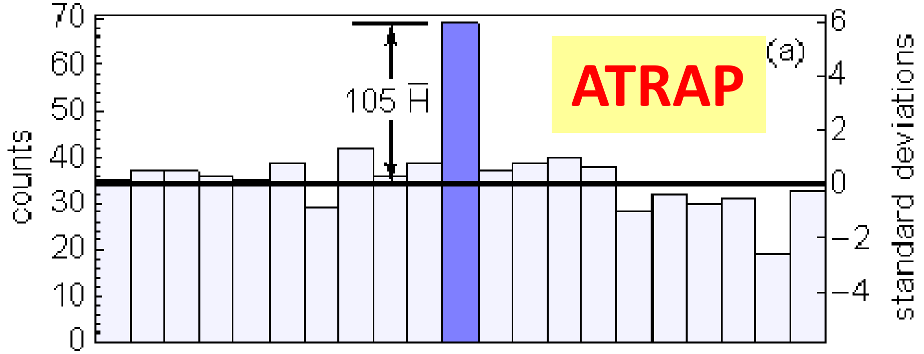
High precision BASE measurement with cyclotron frequency

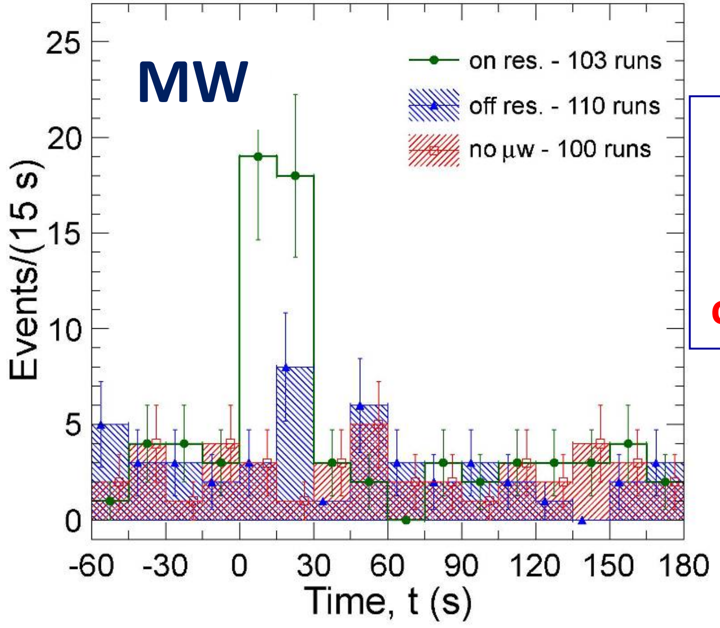
Antihydrogen Properties

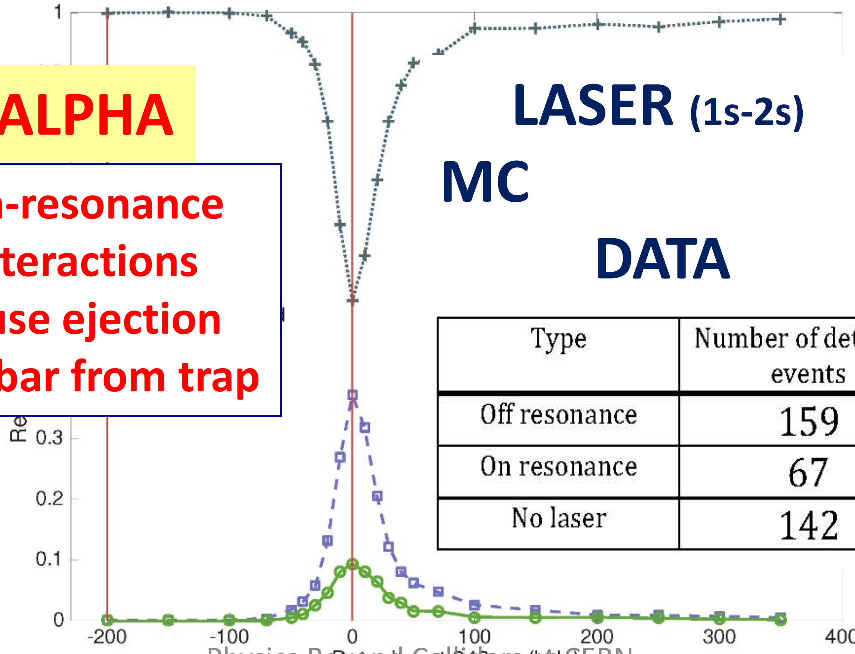
Hbar trapping established by 3 experiments











On-resonance interactions cause ejection of Hbar from trap

Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

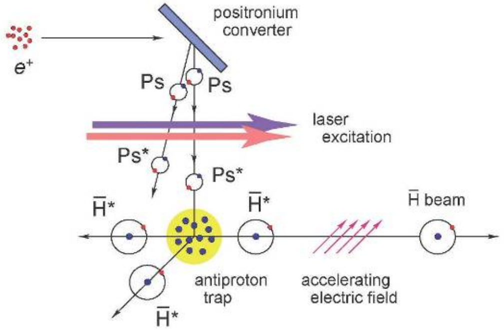
First Hbar microwave and laser spectroscopy performed by ALPHA

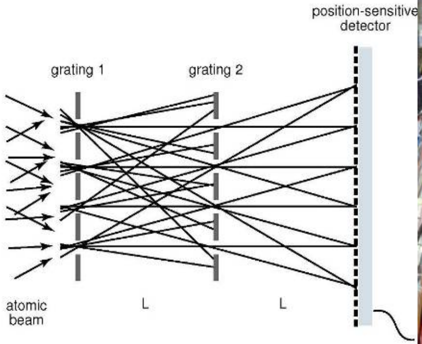
Antihydrogen Properties cont'd: gravitation

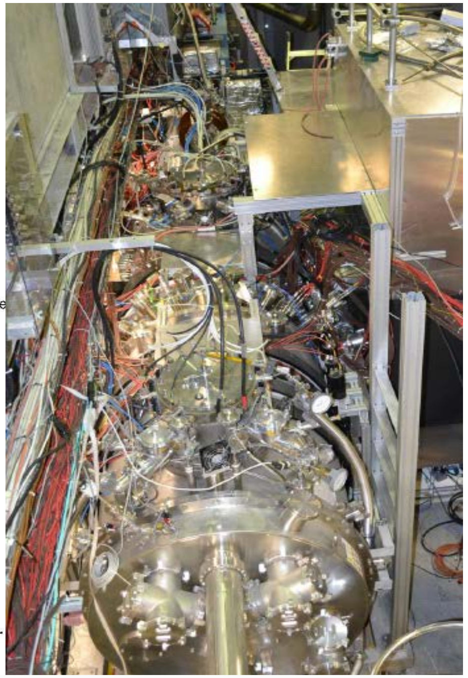
2.5 experiments now devoted to a direct measurement

AEGIS

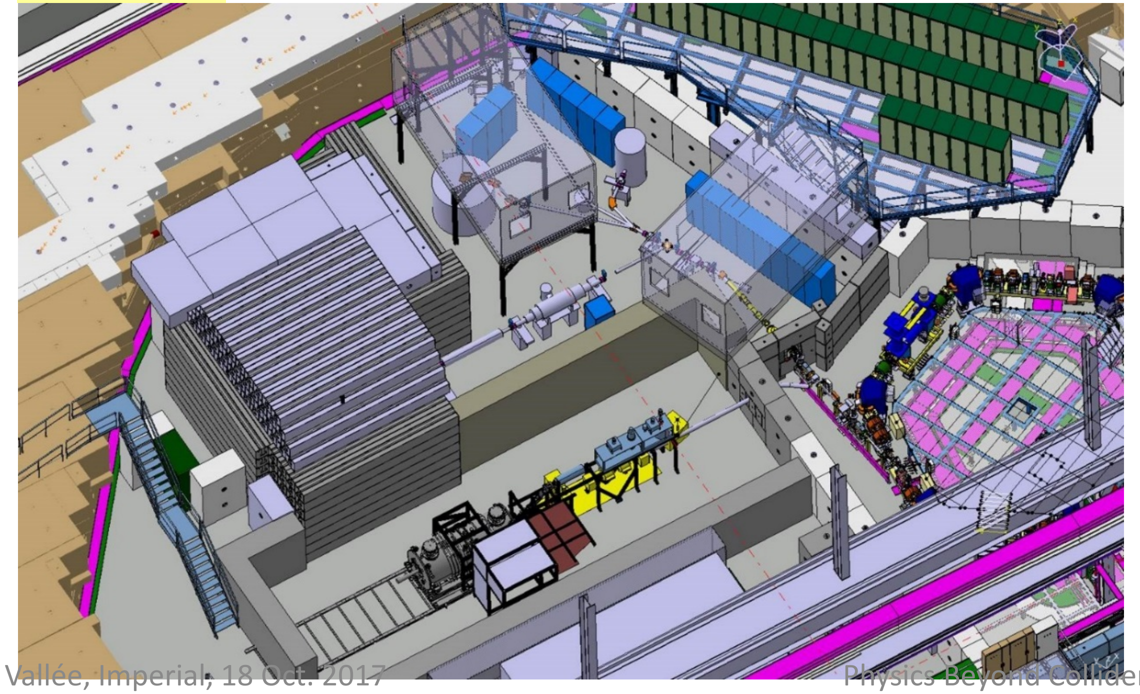
in-flight deviation of Hbar atoms by gravitation

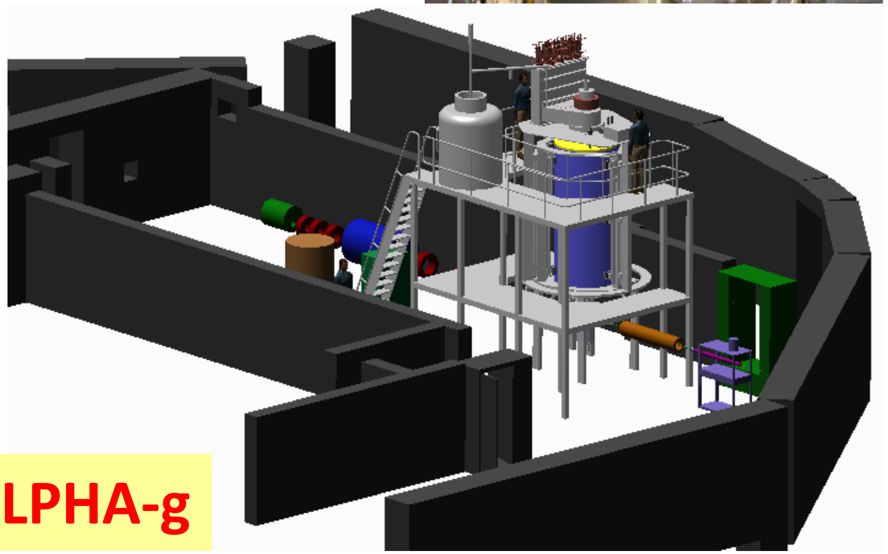






GBAR: Hbar free fall using ELENA





ALPHA-g

Statistical method for a first measurement of the sign

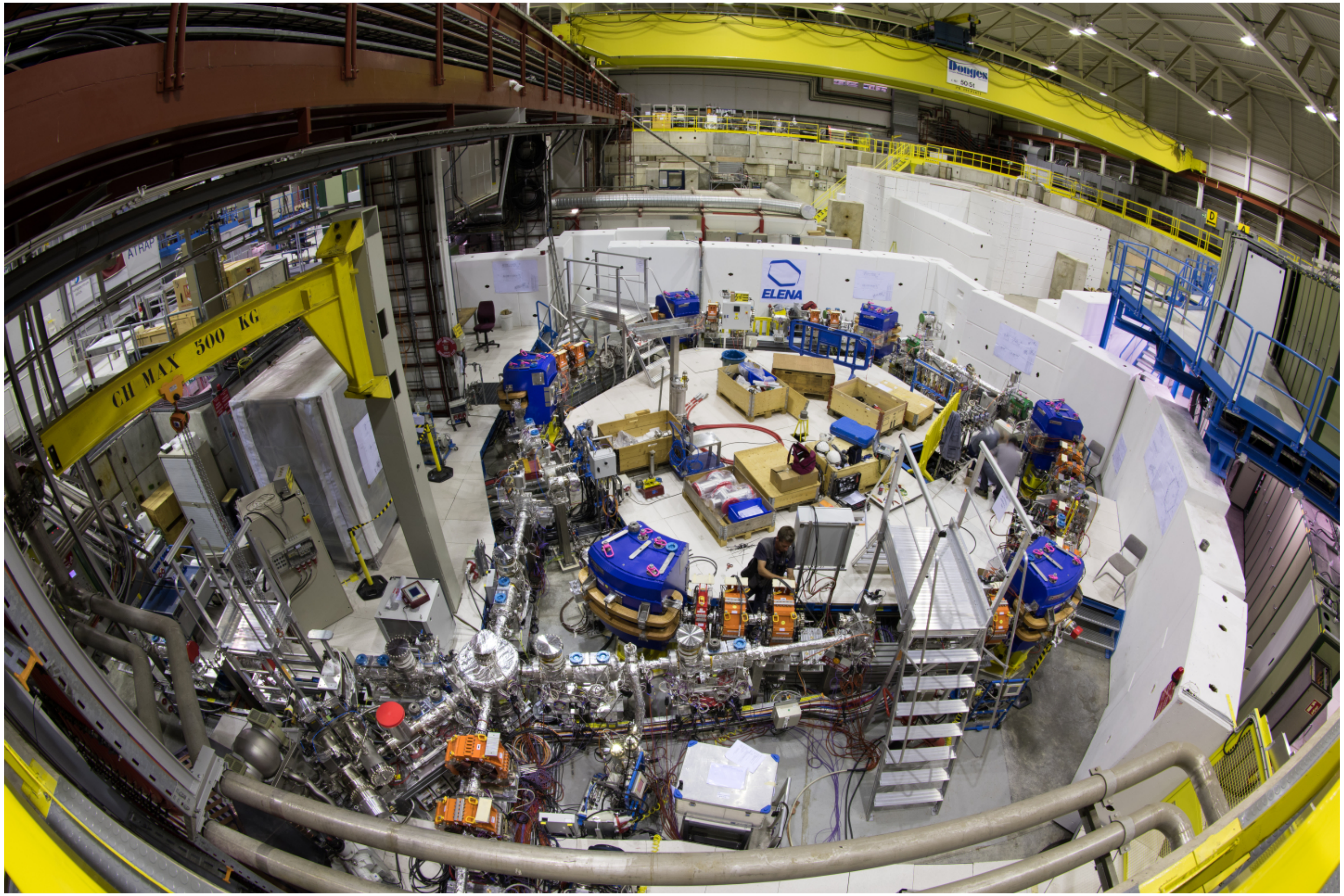
AFTER LS2: ELENA

Further deceleration of antiprotons from 5 MeV to 100 KeV kinetic energy

Will increase by 2 orders of magnitude the antiproton trapping efficiency

Under commissioning for first connection to GBAR in 2017

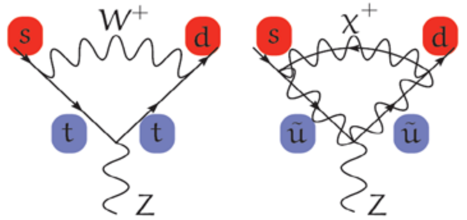
Secures antimatter physics for the next decade



$\boxed{K \to \pi\nu\bar{\nu}}$ (*BR ~ 10^{-11}*)

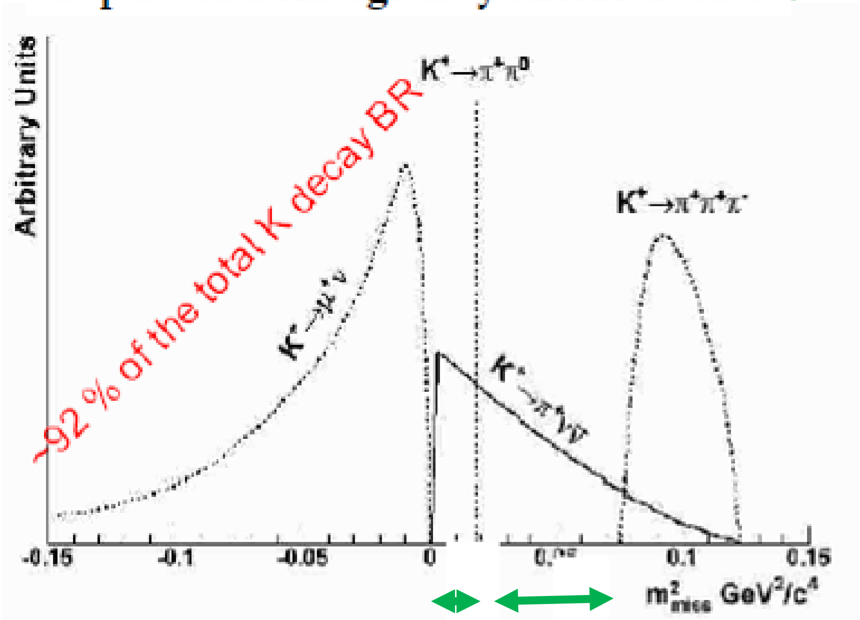
NA62

Rare K decays

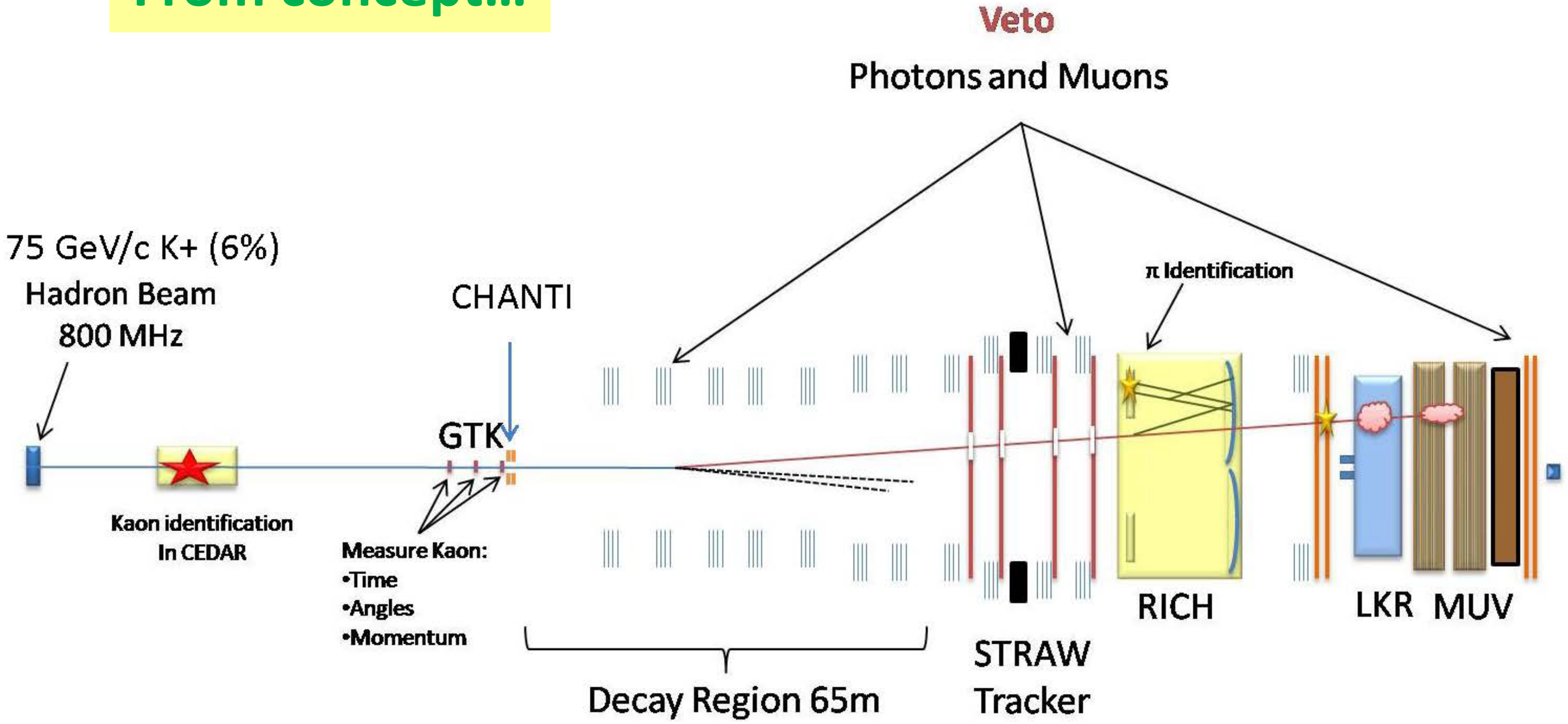


From concept…

Separated from signal by kinematic cuts



Signal regions

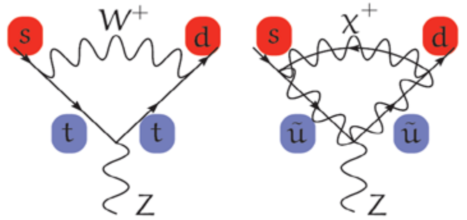


1 GHz 75 GeV unseparated beam, 11 MHz K^+ decays in detector

$\boxed{K \to \pi\nu\bar{\nu}}$ (*BR ~ 10^{-10}*)

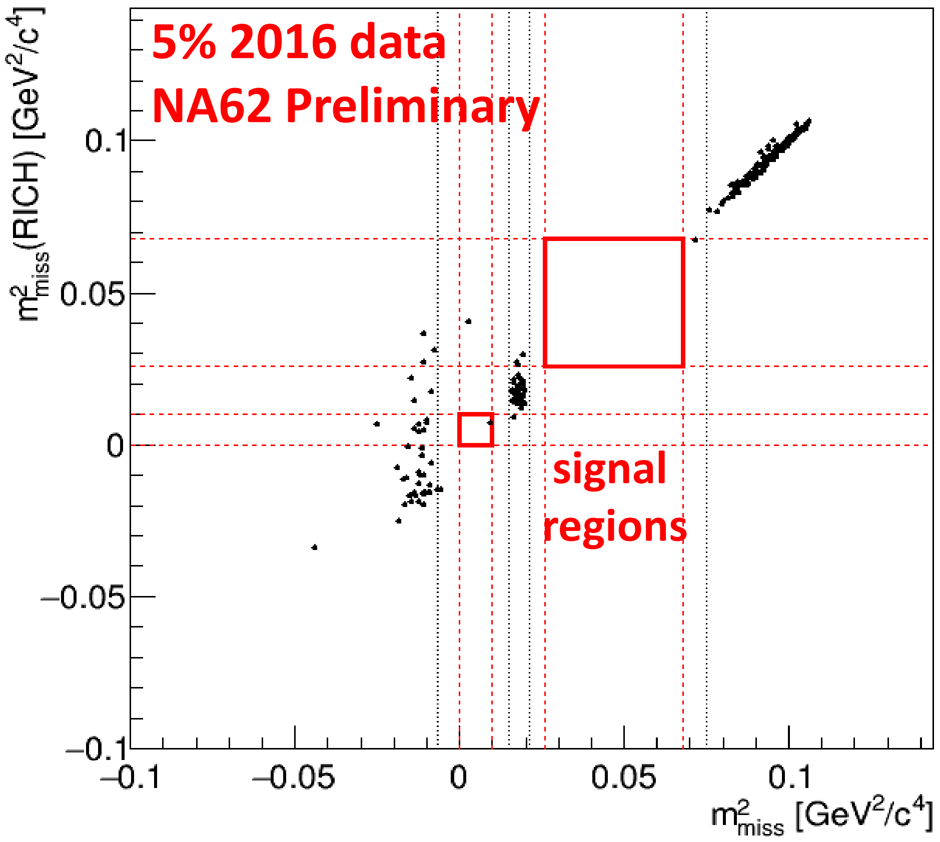
NA62

Rare K decays



...to reality !

After many years of intensive construction and commissioning



Detector fully operational in 2016, first year of quasi-nominal operation

Signal regions: ~100 evts expected until LS2

New idea: K° → π°νν rare decay (KLEVER)

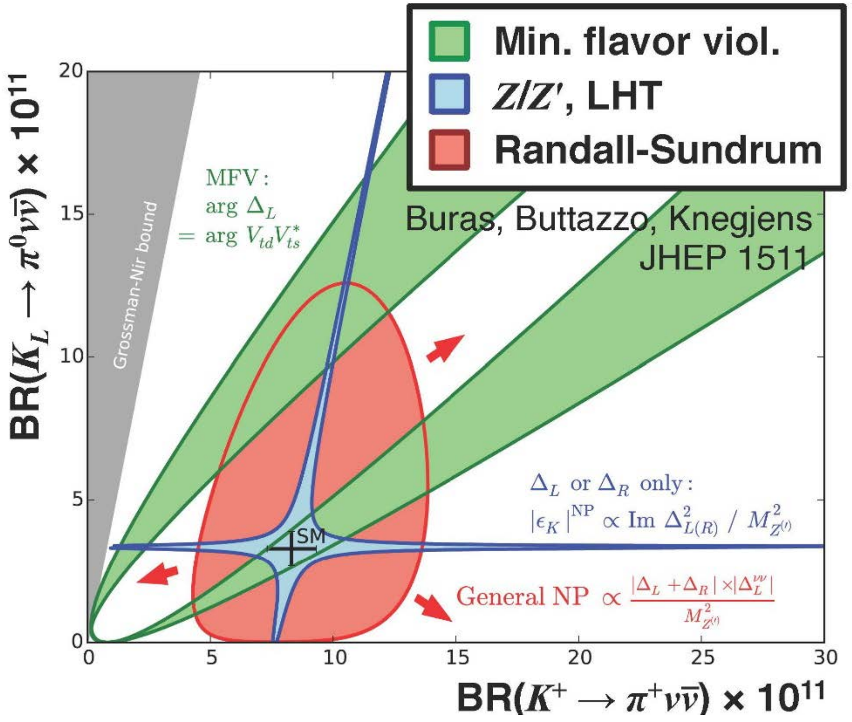
K^0 decays complementary to K^+ decays for the CKM matrix and BSM searches.

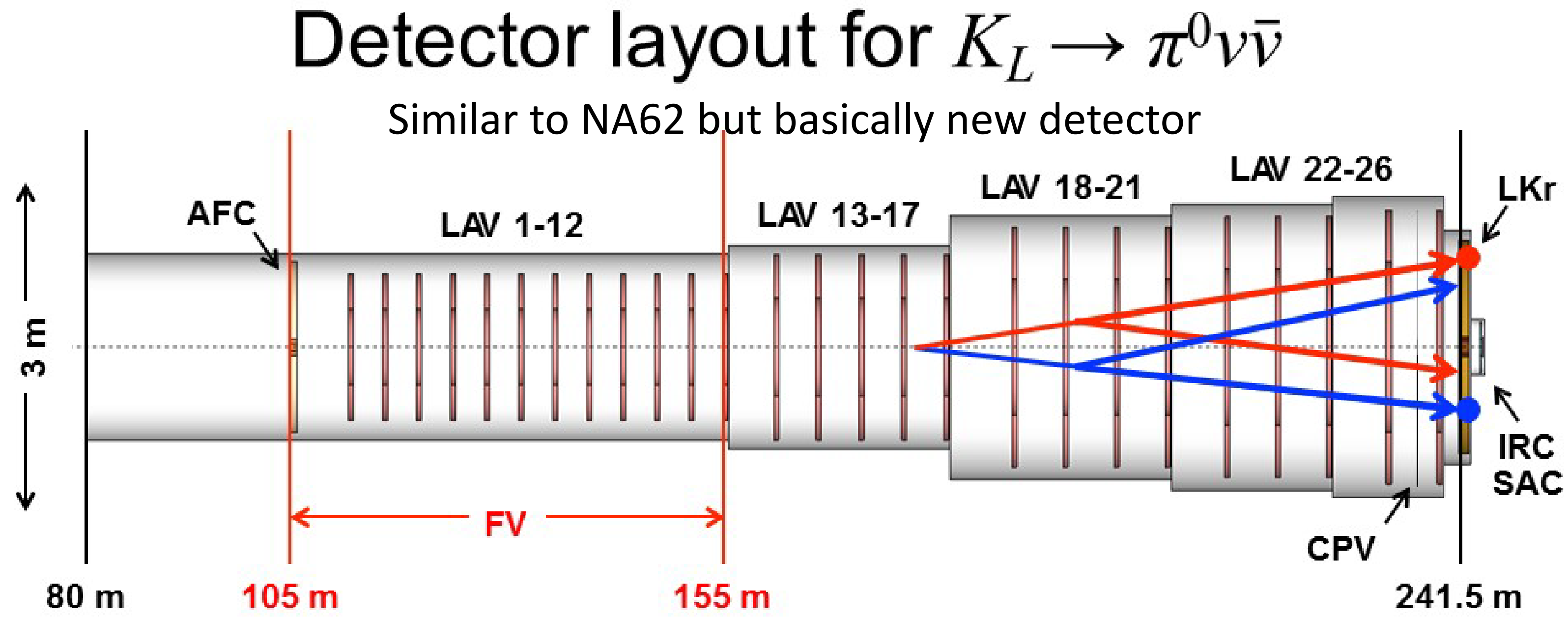
Would require a new high intensity K° beam.

~50 events could be collected with a similar but basically new detector.

Competition from starting KOTO at JPARC:

few evts expected in coming years, upgrade by factor ~10 foreseen > 2025





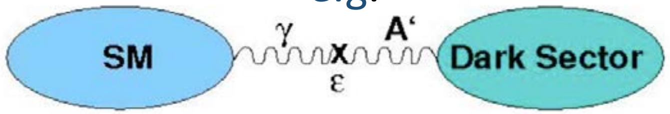
Main issues: actual sensitivity vs competition, cost of new beam and upgraded detector

Intermezzo: the Hidden Sector

$$L = L_{SM} + L_{mediator} + L_{HS}$$

Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino
e.g.



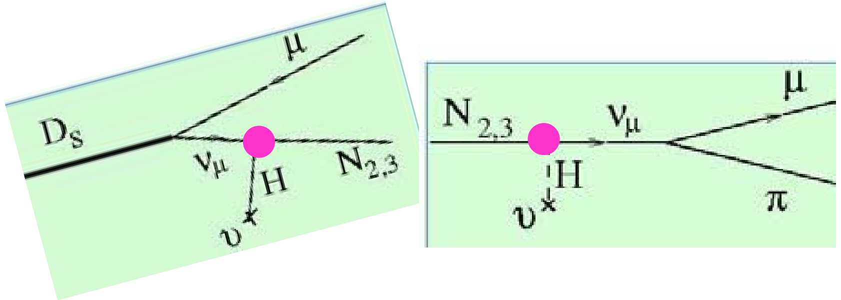
Hidden Sector

Naturally accommodates Dark Matter
(may have rich structure)

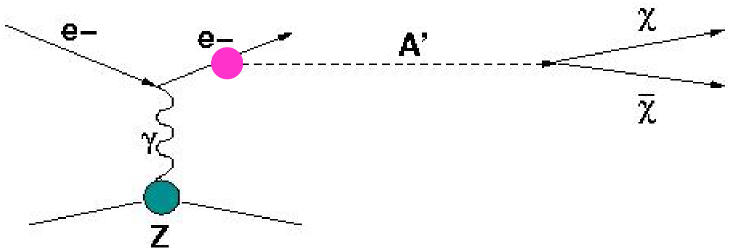
- *Long-lived objects*
- *Interact very weakly with matter*

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+\to\pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

Intermezzo cont'd: the Hidden Sector



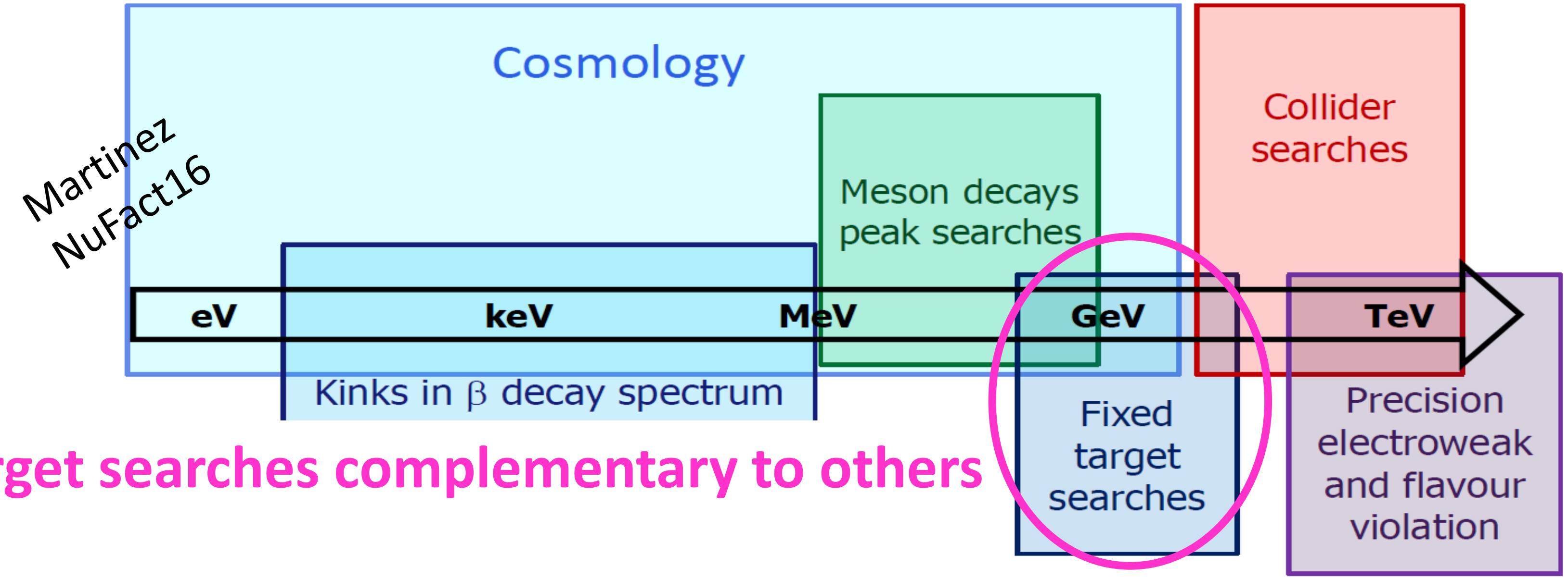
2 methods



Production + decay of new particle:
2 couplings → needs high intensity

Invisible decay of new particle:
accommodates lower intensity

A similar situation as the search for neutrino oscillations in the 70 – 80's:
do not know if they exist and where they stand !

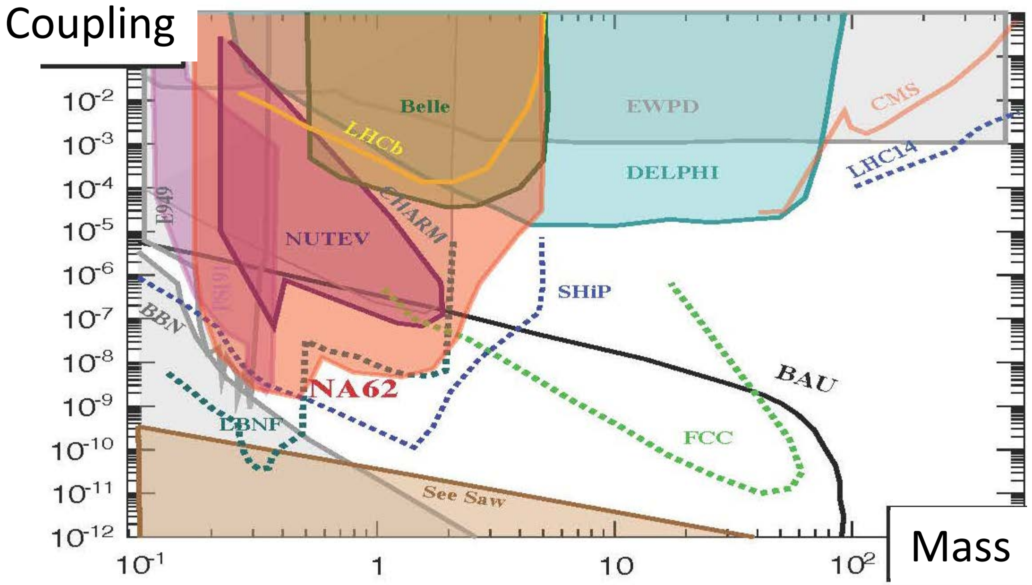


Fixed Target searches complementary to others

AFTER LS2 : NA62++

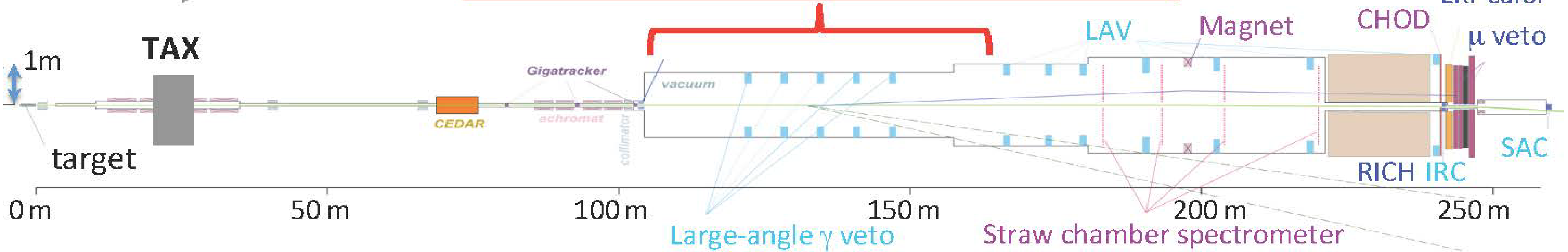
Wish to run ~1 year in beam dump mode to look for Heavy Neutral Leptons

→ possible intermediate step towards a more ambitious beam dump facility



Compact beam dump: ~11 λ_I Cu-based beam-defining collimator (TAX)
radioprotection-compliant even if target removed

Decay volume ~ 60 m long (in vacuum):
reasonable acceptance to long-lived states

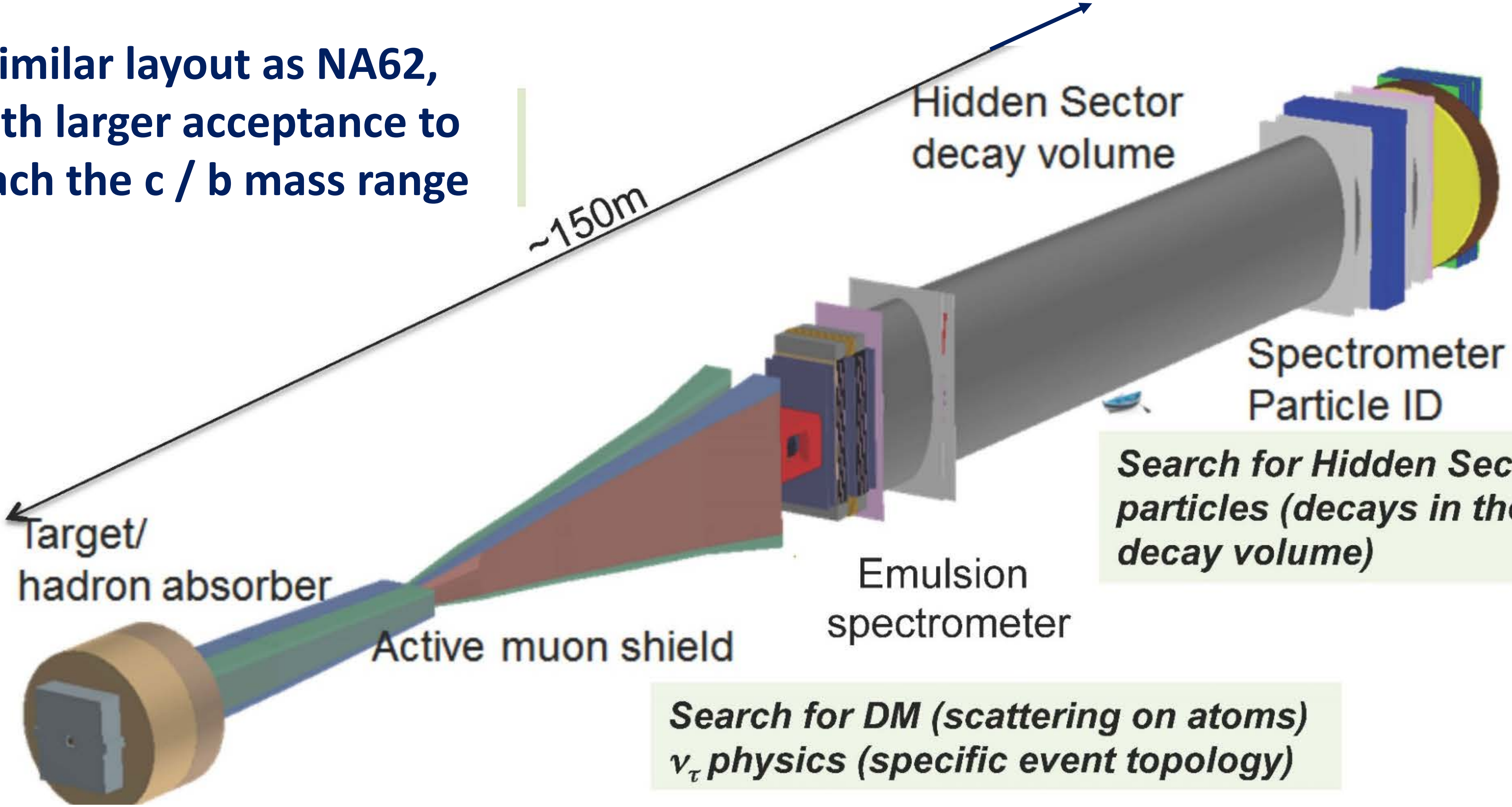


SHiP

Flagship program for a comprehensive investigation of the Hidden Sector in the few GeV domain

Exploits the unique high-E/ high-I SPS features

Similar layout as NA62, with larger acceptance to reach the c / b mass range

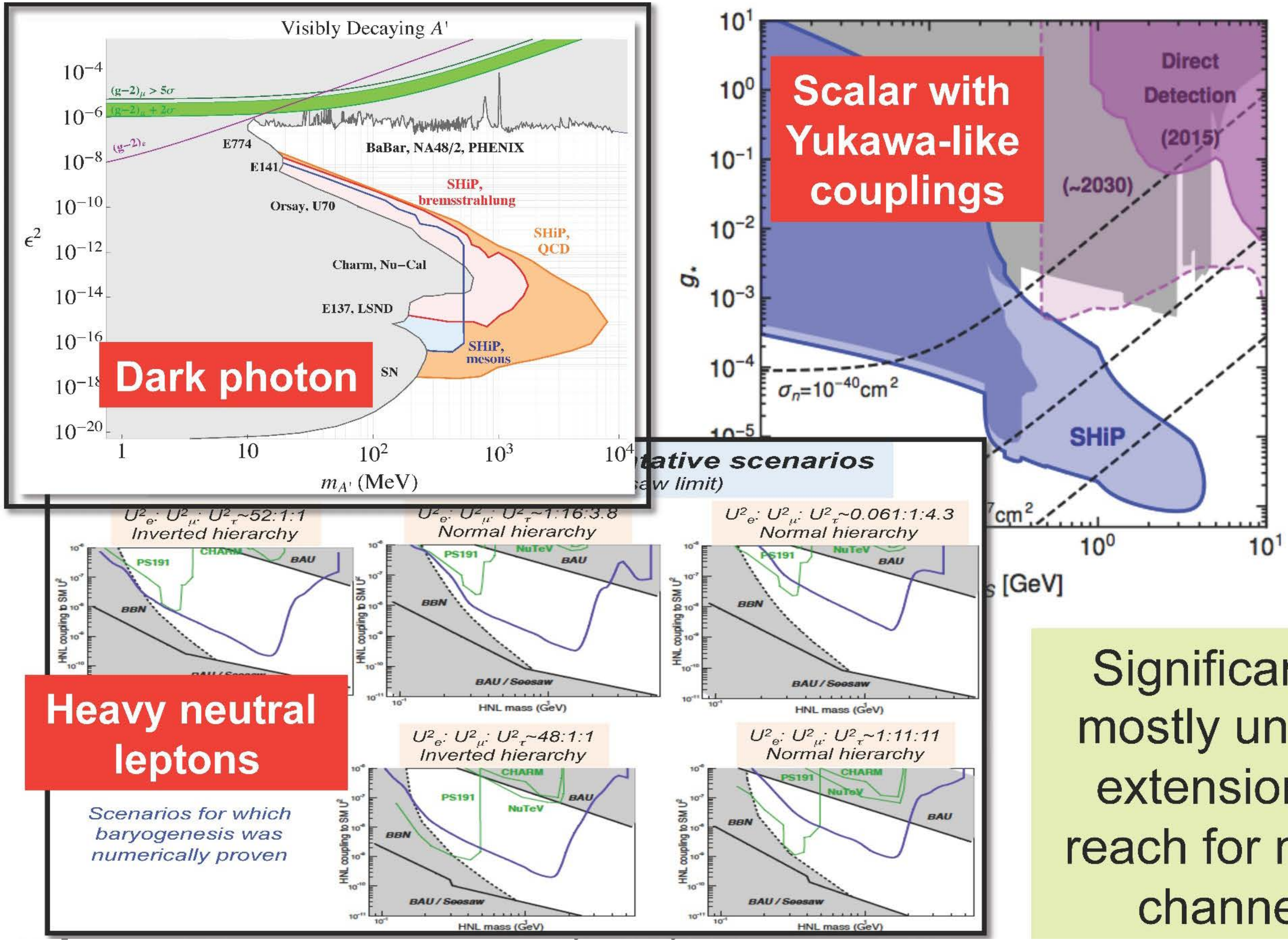


Search for Hidden Sector particles (decays in the decay volume)

Search for DM (scattering on atoms)
ν_τ physics (specific event topology)

C.

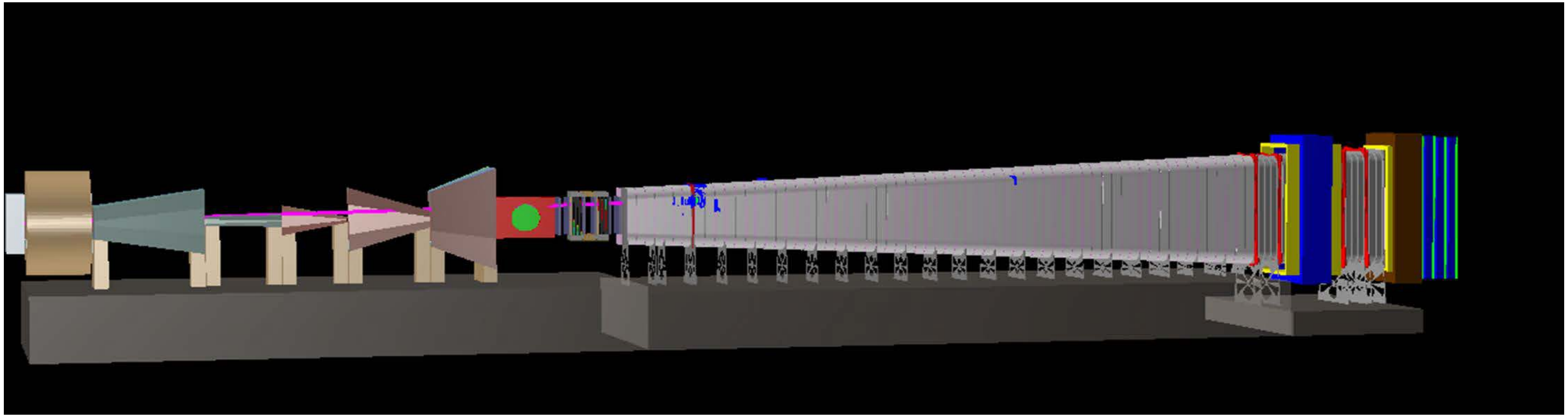
SHiP physics reach



Significant & mostly unique extension of reach for many channels

SHiP optimisation

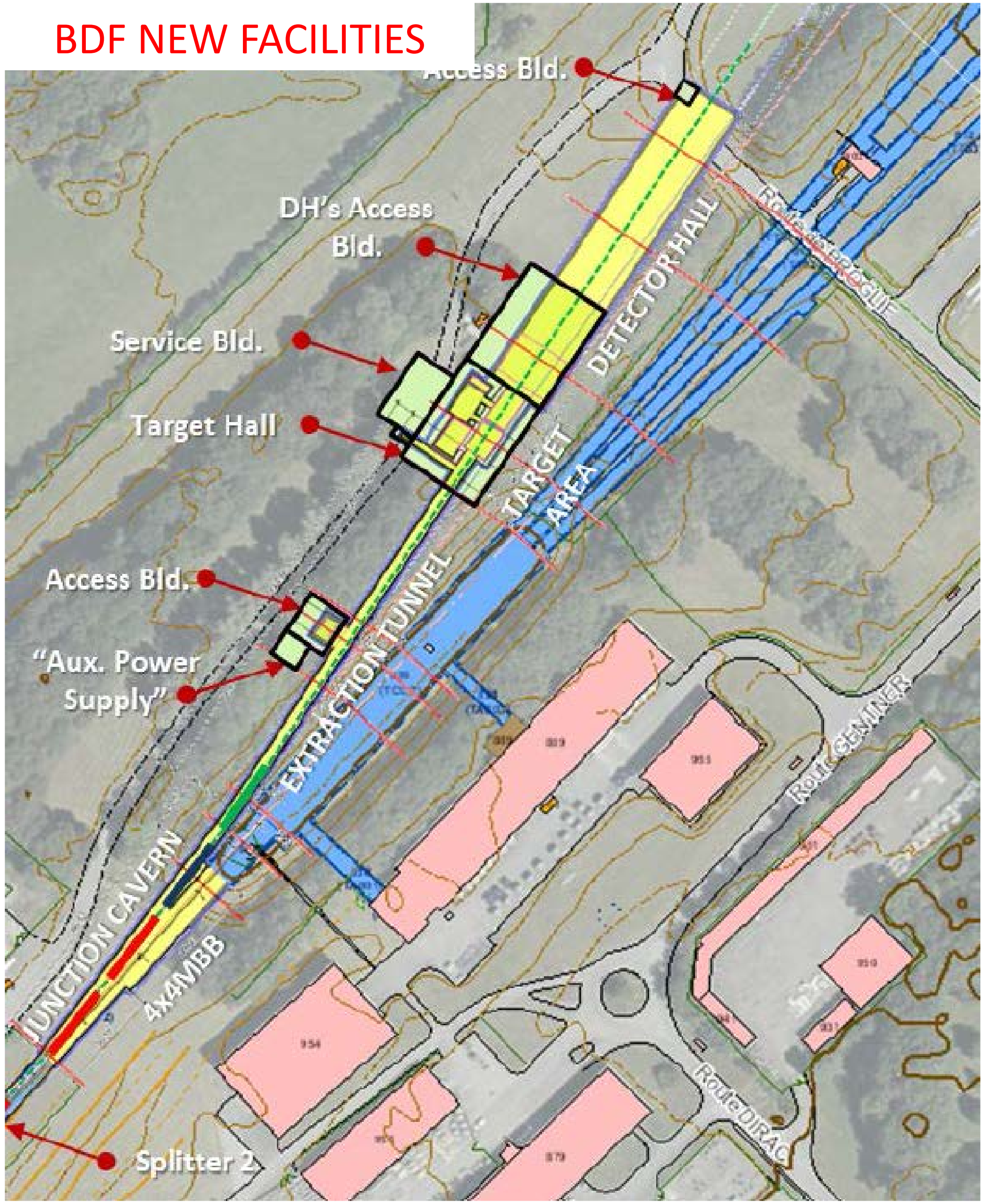
Comprehensive Design Study ongoing



Magnetized hadron absorber → shorter muon shielding and high acceptance.
Muon yields and charm cross sections to be measured in test beams.
Background estimations can benefit from NA62 data.

Main issue: maximize physics reach to justify high investment of a new beamdump facility

BDF NEW FACILITIES

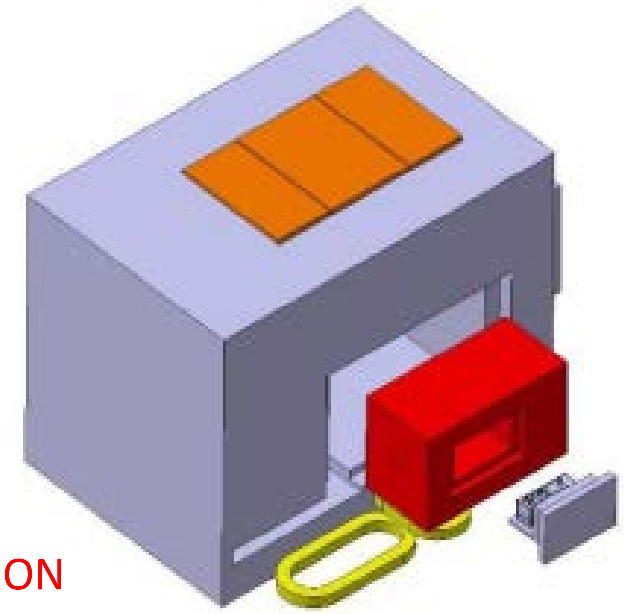


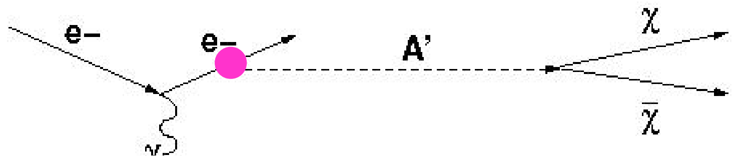
BEAM DUMP FACILITY

Conceptual design ongoing at CERN.
Foreseen to be sited close to the North Area

An opportunity for a new post-CNGS high intensity general facility at CERN

TARGET STATION

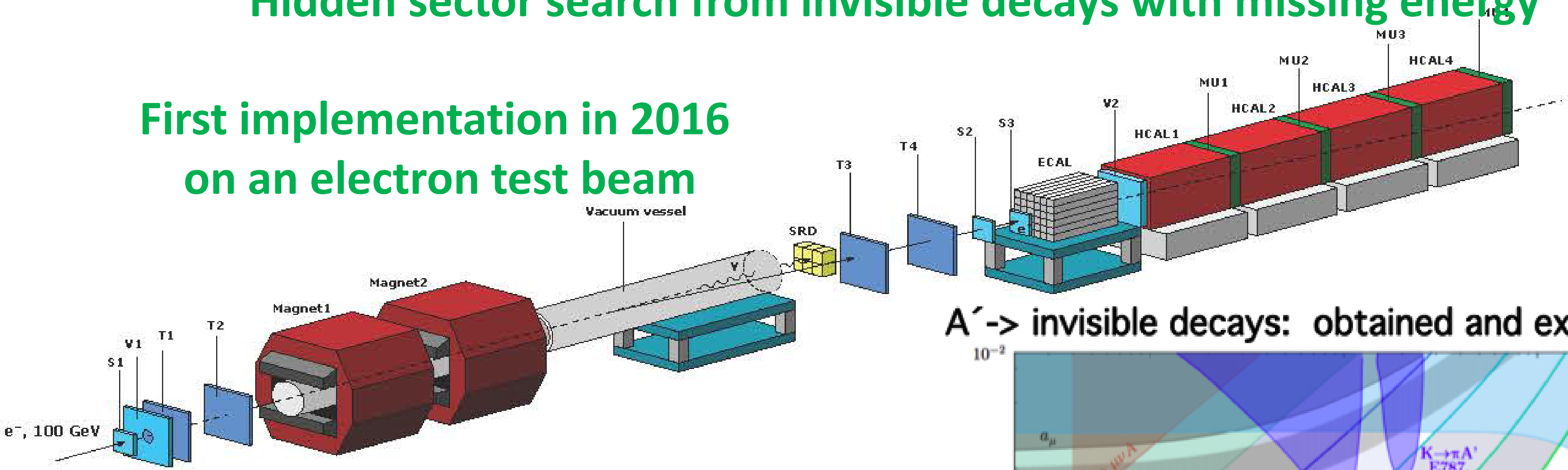




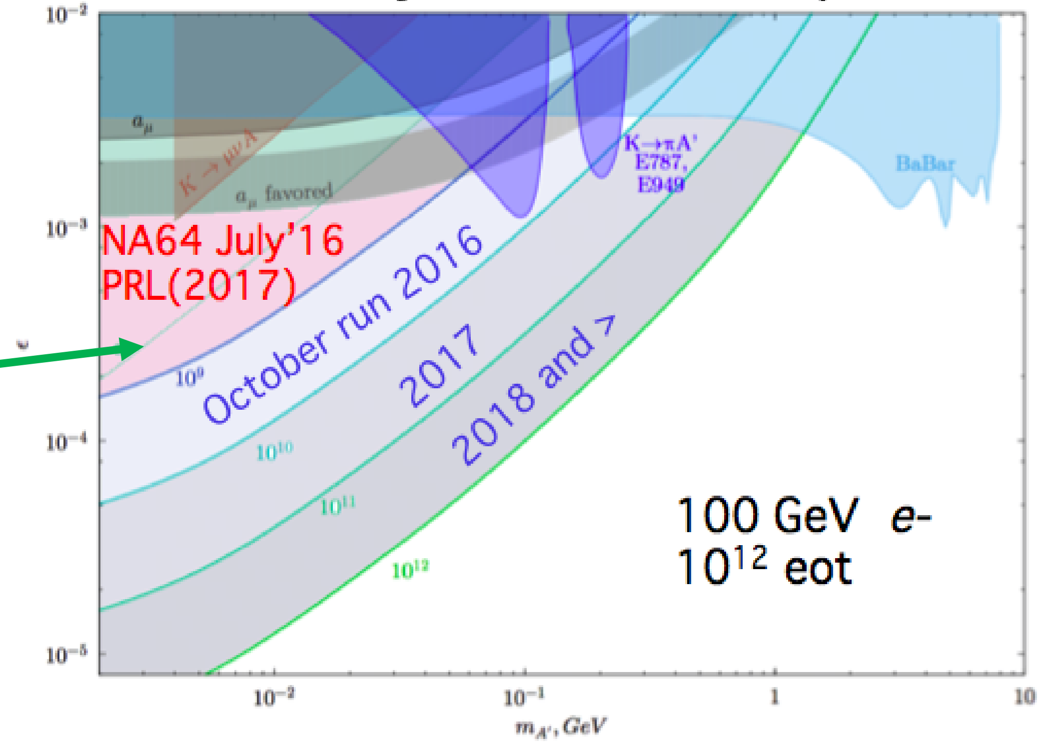
NA64

Hidden sector search from invisible decays with missing energy

First implementation in 2016 on an electron test beam



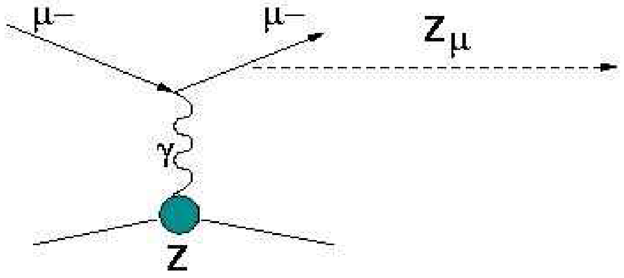
A´-> invisible decays: obtained and expected limits

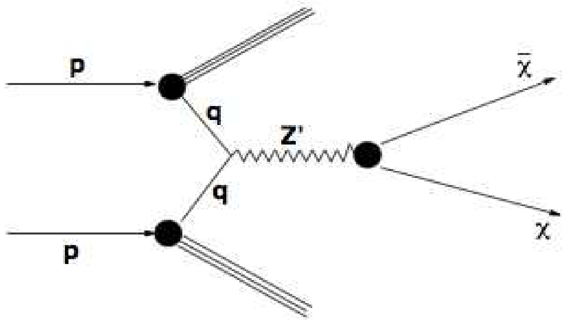


Exclusion of $(g-2)_\mu$ interpretation with 1 day of data taking confirms the potential of the method ***(more data under analysis)***

AFTER LS2: NA64++

Wish to extend the method to μ / π / K / p beams



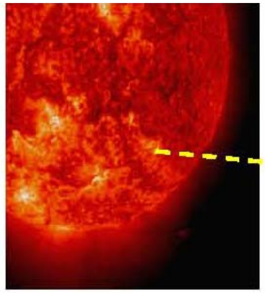


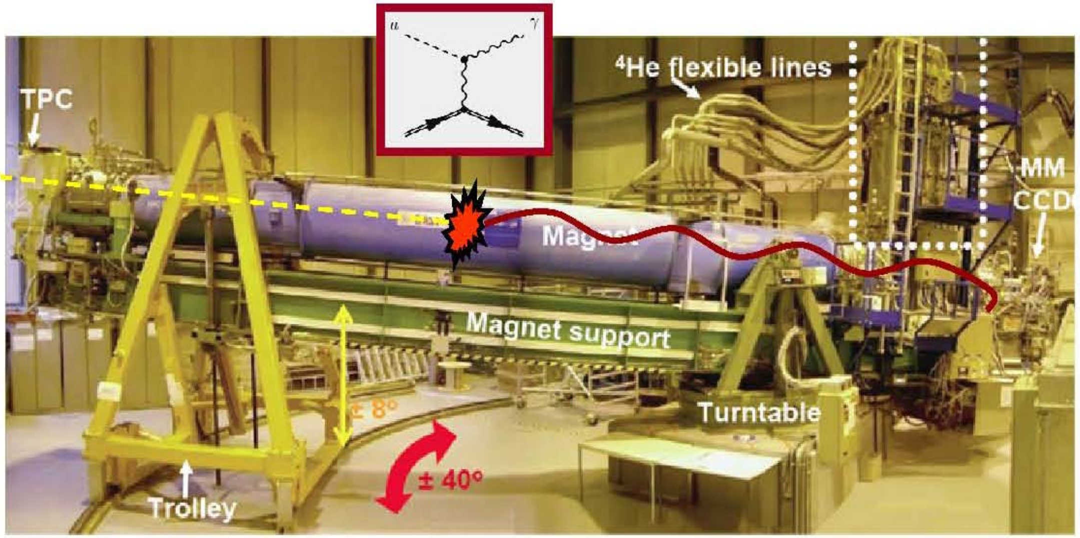
Process	New Physics	Sensitivity
1. $e^-Z \to e^-Z + E_{miss}$		
✧ $A' \to e^+e^-$ ✧ $A' \to$ invisible ✧ alps ✧ milli-Q	Dark Sector: Dark Photons and DM New light states (V,S) weakly coupled to e- ^{8}Be excess	$10^{-3} < \varepsilon < 10^{-6}$ $M_{A'} \sim$ sub-GeV mQ $< 10^{-5}$-10^{-7} e $M_{mQ} \sim$ sub-GeV
2. $\mu^- Z \to \mu^- Z + E_{miss}$		
✧ $Z_\mu \to \nu\nu,\ \mu^+\mu^-$ ✧ a_μ ✧ $\mu \to \tau$ conversion	$(g-2)_\mu$ anomaly, New Z_μ from L_μ-L_τ gauged symm., scalars coupled to μ LFV	$\alpha_\mu < 10^{-11}$-10^{-9} $\sigma_{\mu\tau}/\sigma_\mu < 10^{-9}$-$10^{-8}$
3. π (K)p-> $M^0 n + E_{miss}$		
✧ $K_L \to$ invisible ✧ $K_S \to$ invisible ✧ $\pi^0, \eta, \eta' \to$ invisible	CP, CPT symmetry Bell-Steinberger Unitarity, new WC particles: NHL, $\phi\phi$, VV	Br $< 10^{-8}$-10^{-6}, Complementary to $K \to \pi\nu\nu$ Br $< 10^{-8}$-10^{-7}
4. $pA \to Z' + E_{miss}$		
✧ leptophobic Z´	~ GeV DM	$\sigma_{Z'} < 10^{-7}$-10^{-8} /p

Main issues: e beam intensity and CERN siting for other beams

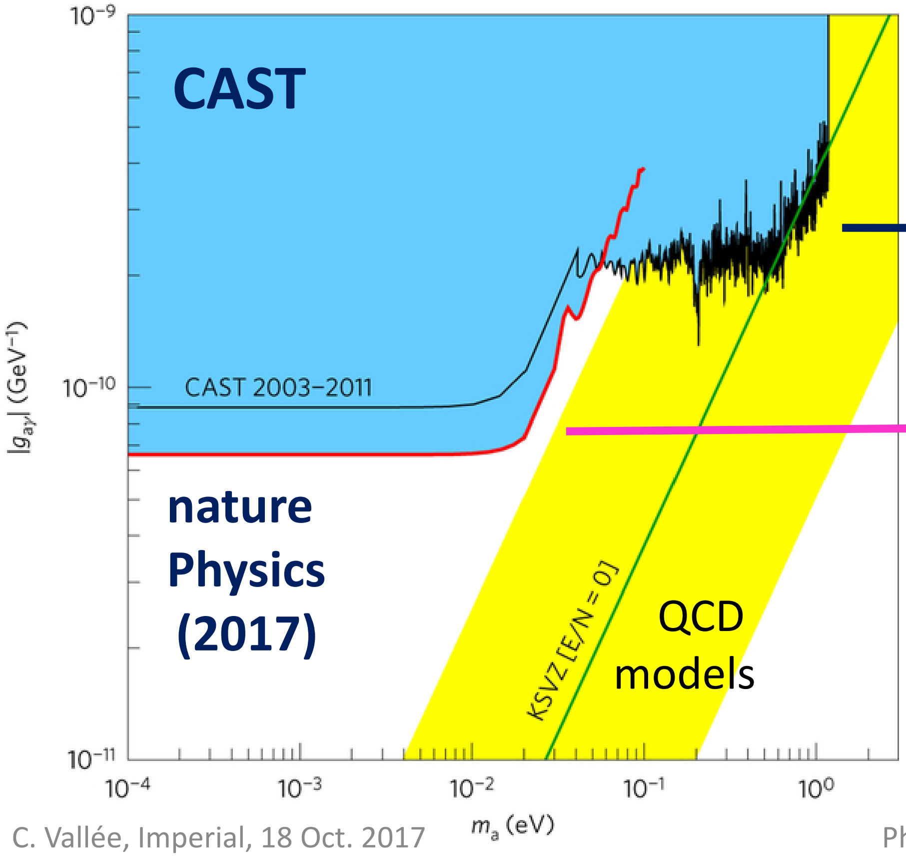
Another possible source of hidden particles:

Axions from the sun





CAST: Instrumented LHC magnet pointed to the sun to convert Axions into X rays



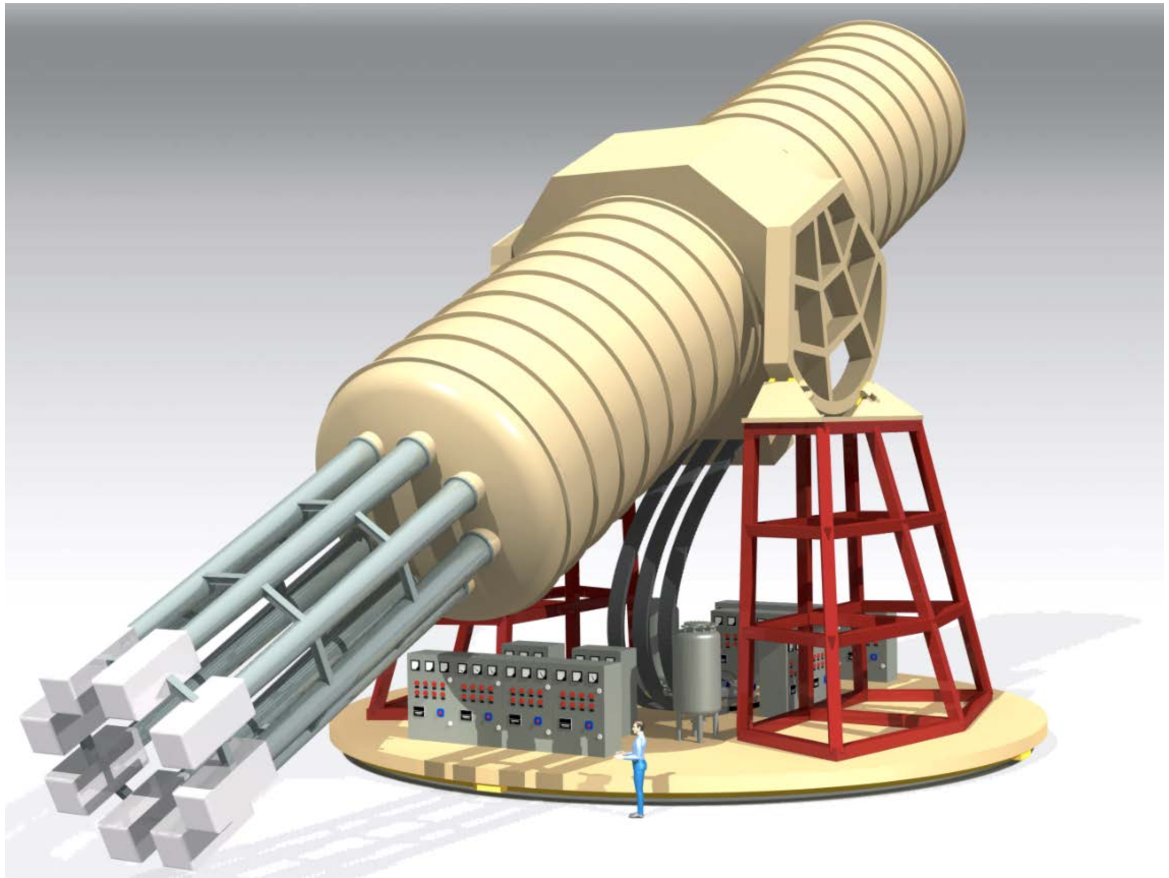
^{3}He and ^{4}He scans completed, start to bite into QCD models

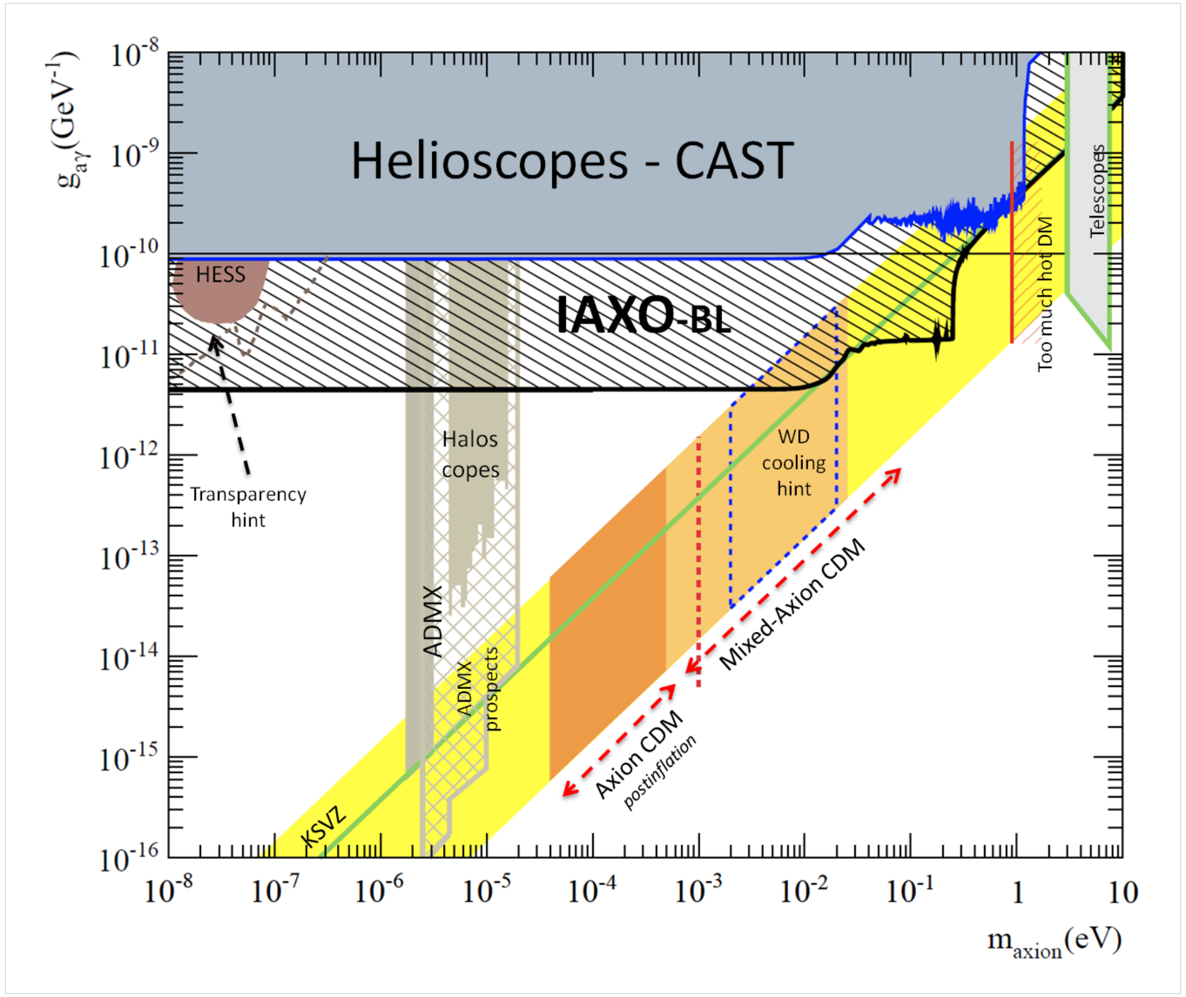
Vacuum runs continued with “IAXO pathfinder” detection system

R&D on new detection techniques going on CAST CERN setup

New idea: IAXO

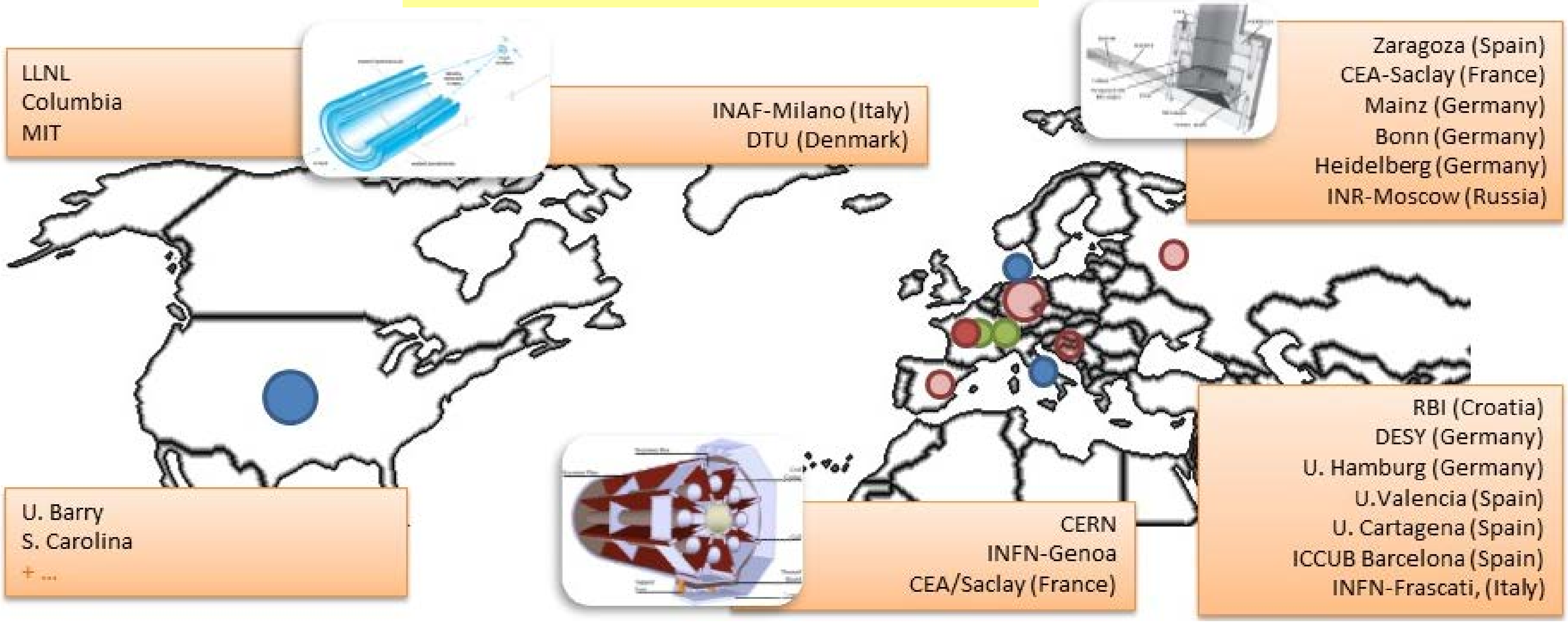
Next generation Axion Helioscope beyond CAST





Wish to profit from CERN magnet expertise (ATLAS-like large bore toroid)

IAXO TDR preparation



Collaboration formally founded in July 2017, funding being secured to prepare TDR.

Prototypes of IAXO detector under preparation,

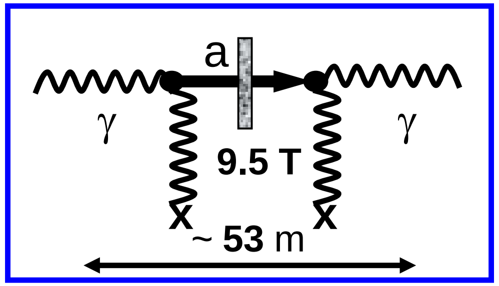
Support from CERN for magnet design granted within PBC

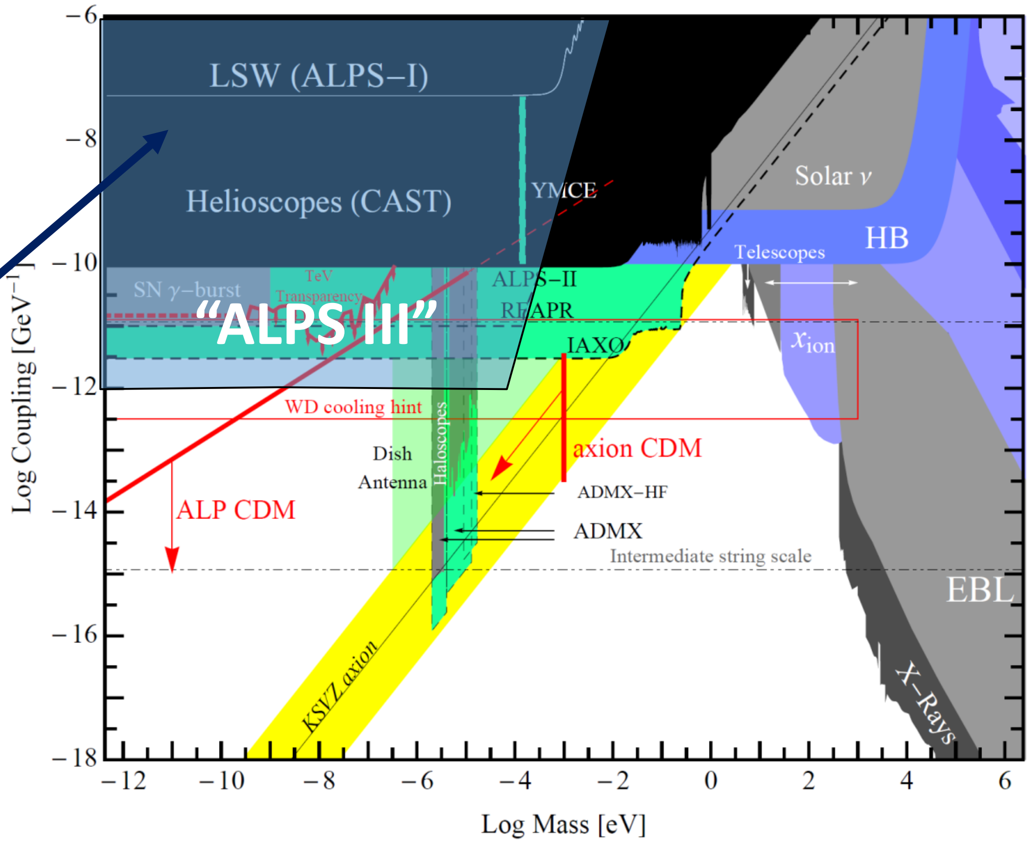
Baby-IAXO intermediate option may offer optimal sensitivity/cost ratio

<u>Main IAXO issues</u>: Collaboration strengthening and helioscope siting (DESY interest)

Laboratory Axions: "ALPS III"

Light shining through a wall





Comparable limits obtained by OSQAR@CERN and ALPS@DESY

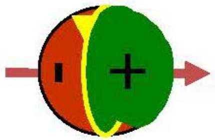
ALPSII@DESY under construction

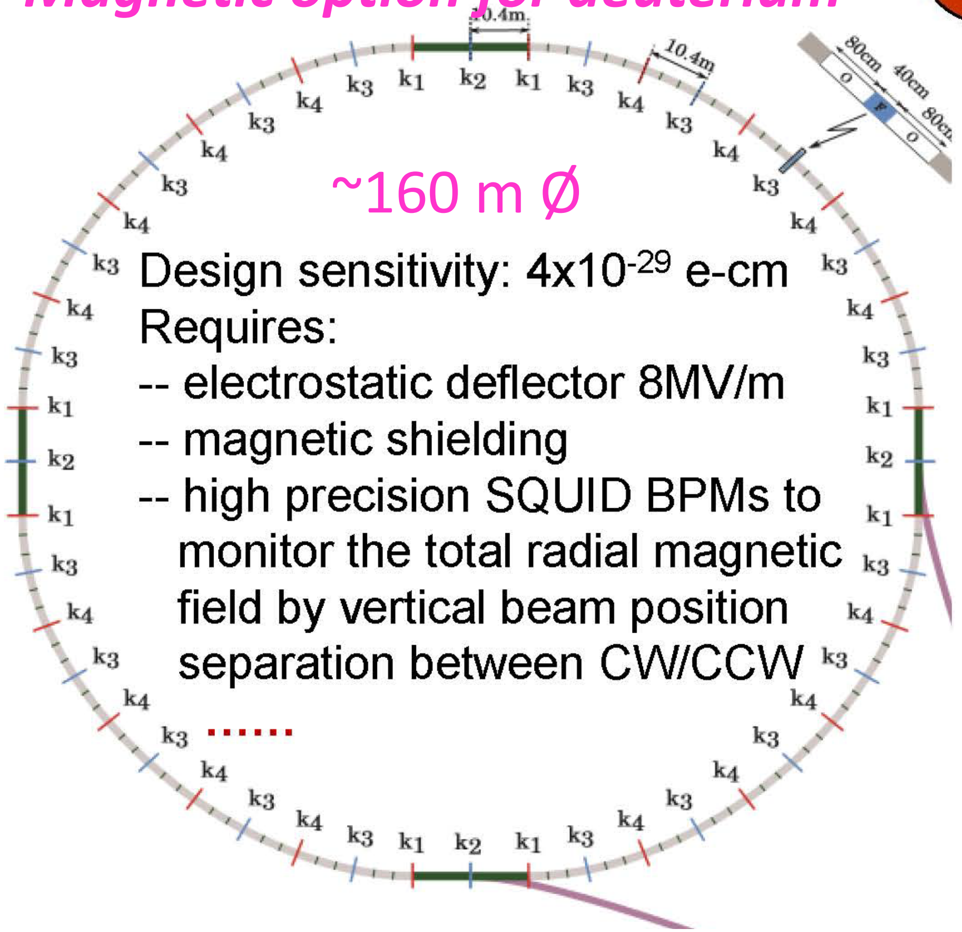
Dipole	Aperture [mm]	Field strength [T]	LSW experiment	Number of used dipoles
HERA (straightened)	50	5.3	ALPS II (DESY)	20
LHC	40	9.0	OSQAR (CERN)	2
"FCC"	100 (40)	13 (20)	"ALPS III"	

A combined project ("ALPS III") could benefit from CERN high field magnet developments

New idea: Storage Ring for proton/deuterium EDM

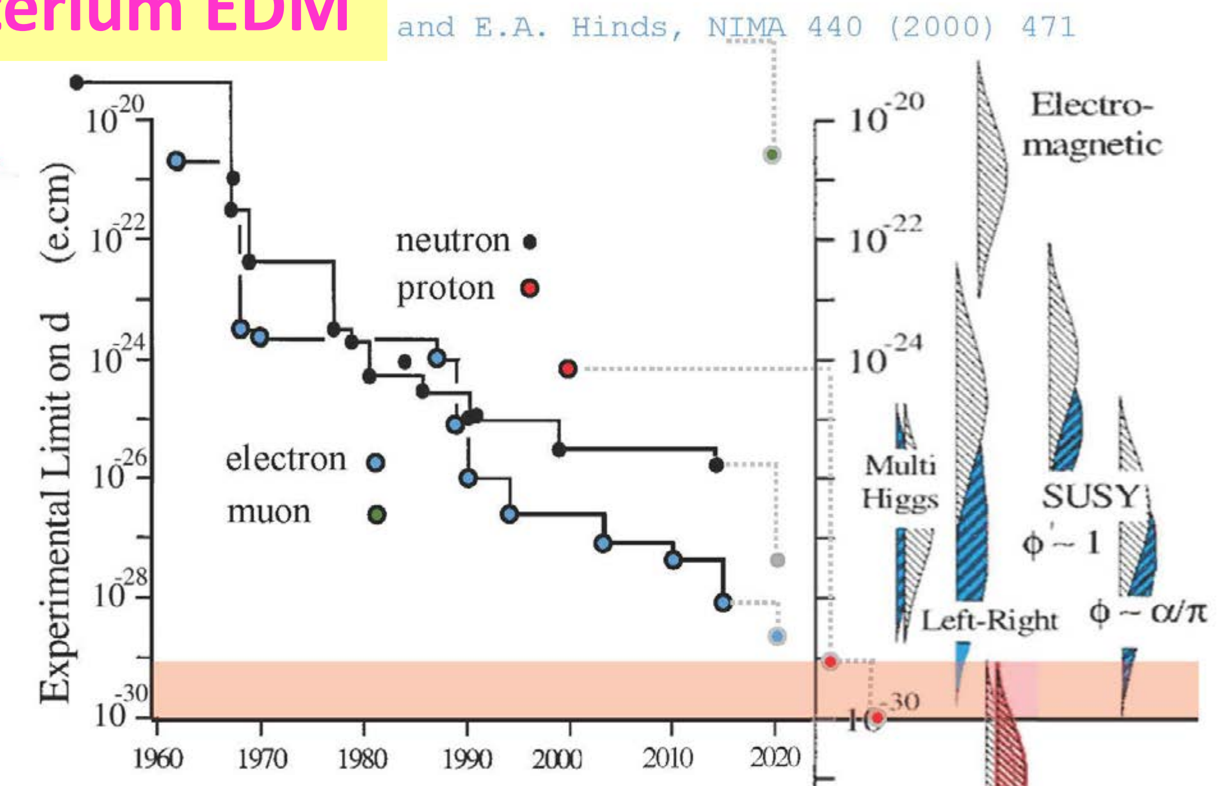
Electrostatic option for proton
Magnetic option for deuterium

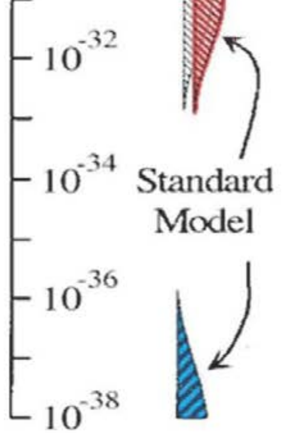




~160 m Ø

Design sensitivity: 4×10^{-29} e-cm
Requires:
-- electrostatic deflector 8MV/m
-- magnetic shielding
-- high precision SQUID BPMs to monitor the total radial magnetic field by vertical beam position separation between CW/CCW
……





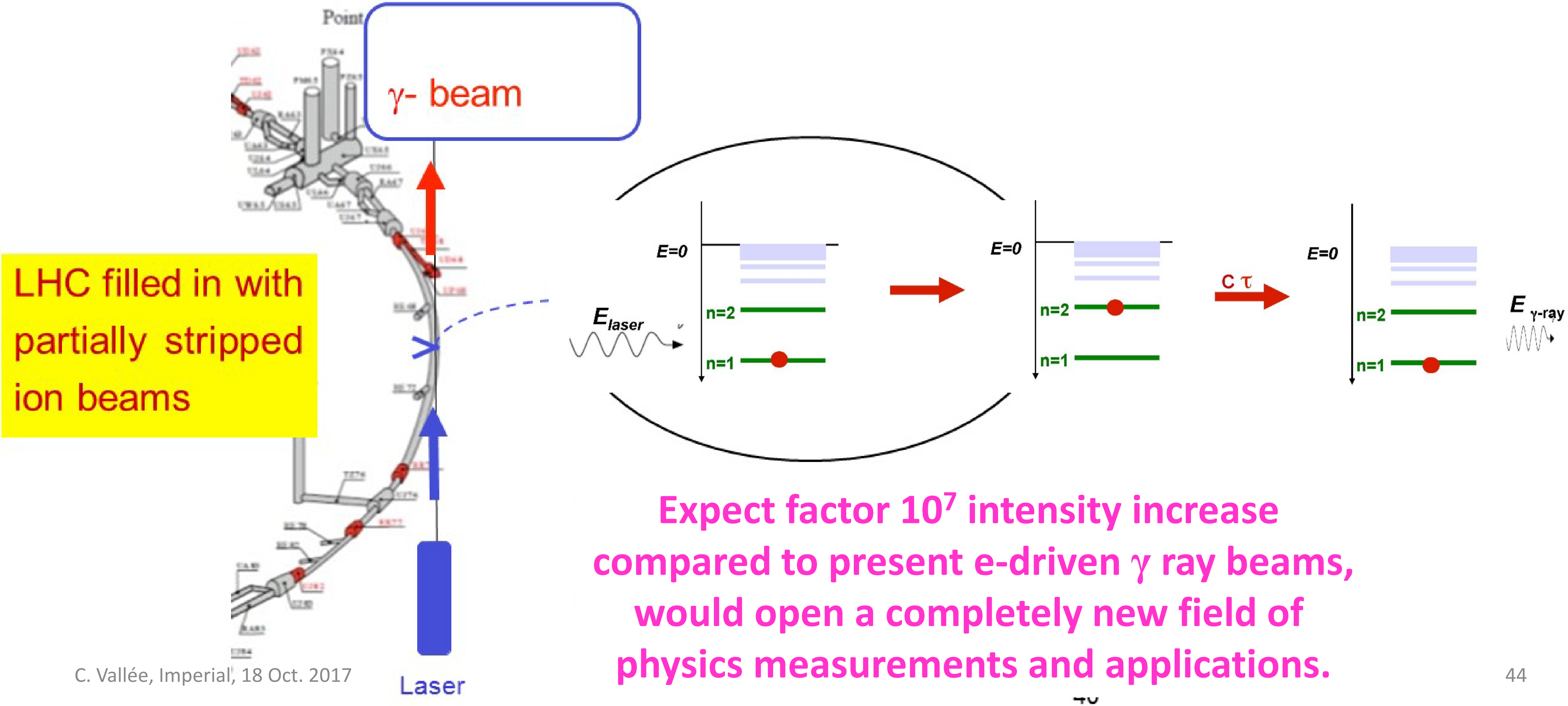
10^{-29} e-cm sensitivity would correspond to 100 TeV for new physics energy scale

Ring design ongoing by CERN with srEDM and JEDI collaborations

<u>Main issue</u>: control of systematic effects (e.g. B fields)

New idea: Gamma Factory

Use LHC beam to convert laser photons into 0.1 - 400 MeV γ rays

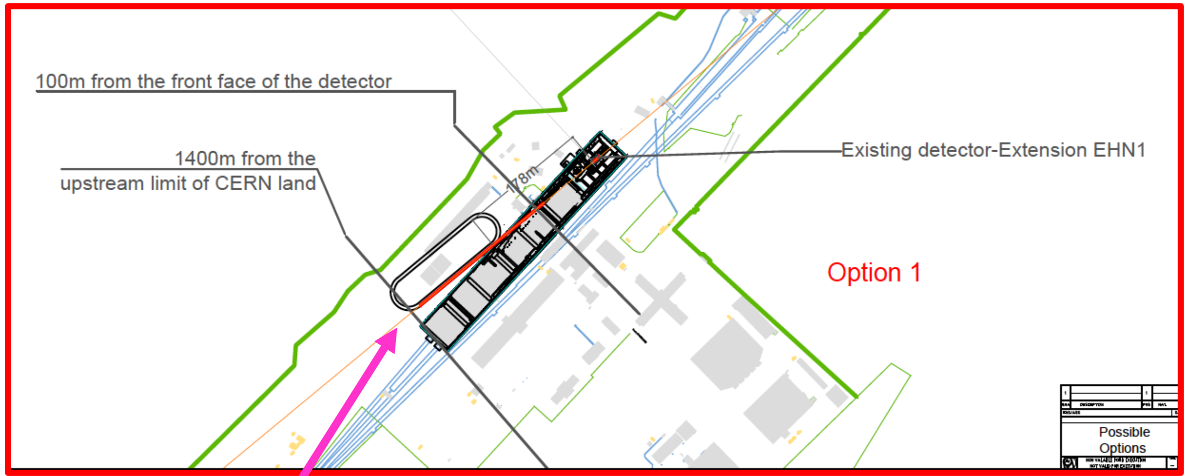


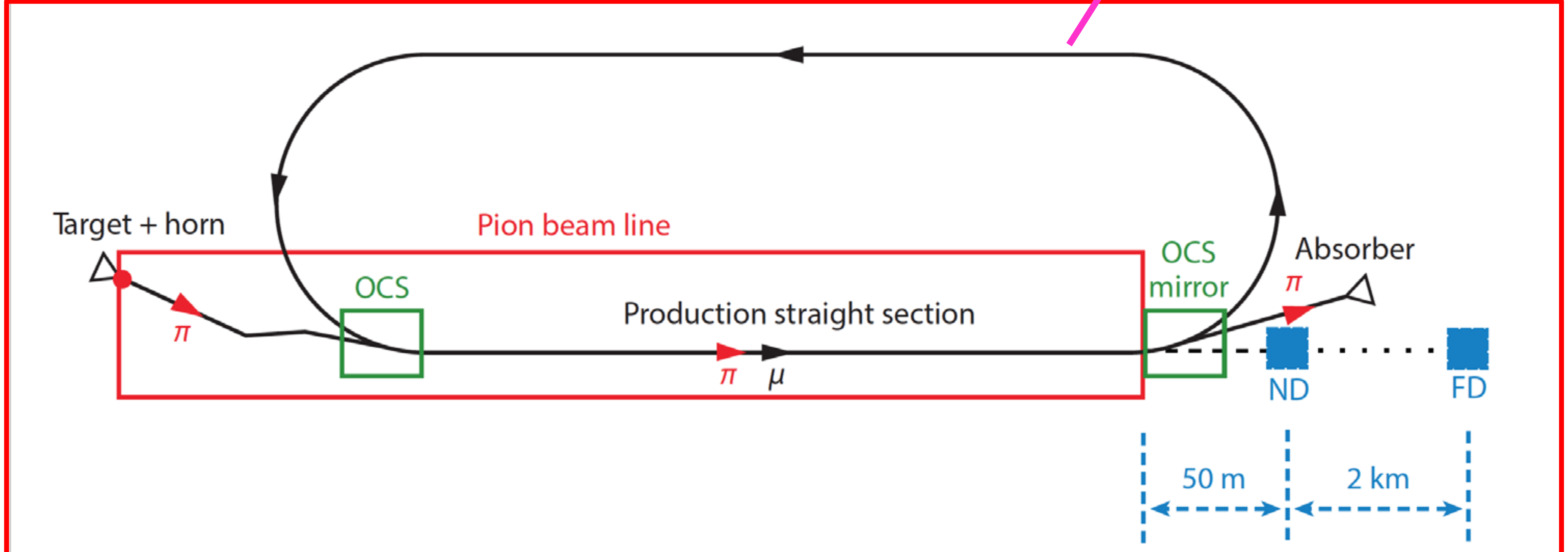
Expect factor 10^7 intensity increase compared to present e-driven γ ray beams, would open a completely new field of physics measurements and applications.

NuSTORM

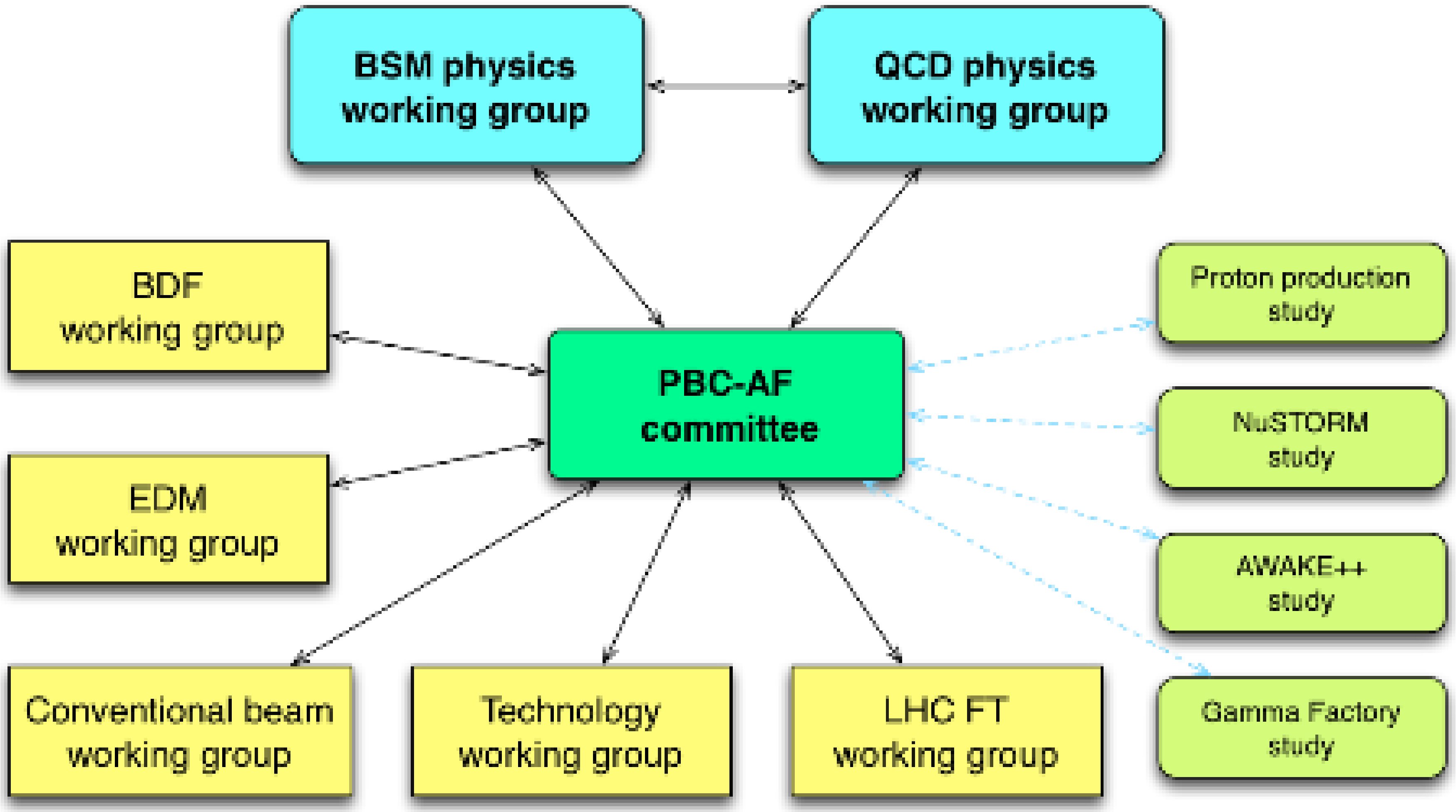
Well controlled ν beam from a μ storage ring.

Would allow precise σ(ν) measurements.
Also a path towards a ν factory or a μ collider.





PBC WORKING GROUP STRUCTURE



Organisation and follow-up of activities documented on http://pbc.web.cern.ch/

PBC DELIVERABLES

One main overview document supplemented by CDR/CDS
at a level of details matched to the maturity of the projects
To be submitted end 2018 as input to the next European Particle Physics strategy update

NB: no arbitration between projects to be done by PBC
Guidelines will come later from the Strategy update

One of the main added values of PBC: a forum for exchanges
between communities with similar motivations, under CERN "umbrella":
SHiP/NA62, COMPASS/LHC-FT, COMPASS/MUE,
NA60/NA61/LHC-FT, JEDI/srEDM, OSQAR/ALPS, etc…

ADDITIONAL SLIDES

ACCELERATOR SUB GROUPS DELIVERABLES

Subgroups:		Deliverable:
Beam Dump Facility	:	Technical feasibility of BDF as input to SHiP CDS
EDM ring	:	Fully developed feasibility study incl. preliminary costing
Conventional beams	:	Study upgrades for NA62++, NA64++, COMPASS++, DIRAC++ beams
LHC Fixed Target	:	CDR putting together UA9, LHC Collimation, AFTER…
Technology	:	Evaluation of possible CERN contributions to non-acc. projects

Studies:

Complex performance	:	Performance plan in LIU era and exploration of new proton driver
AWAKE	:	Exploratory study of possible applications of AWAKE concept
NuSTORM	:	Broad outline of possible implementation at CERN
Gamma Factory	:	Exploratory study incl. initial tests

PHYSICS SUB GROUPS DELIVERABLES

Deliverables 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

BSM subgroup : SHiP/NA64++/NA62++/IAXO/LSW/EDM …

QCD subgroup : COMPASS++/μ-e/LHC-FT/DIRAC+/NA60++/NA61++ …