Workshop on LHCb Heavy Ion and Fixed Target Physics
CERN – Jan. 9-10, 2017

Claude Vallée (CPPM/DESY)

Status and Prospects of Fixed Target Physics at CERN

… a major item of the Physics Beyond Colliders 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 KICK-OFF WORKSHOP

held at CERN on Sept. 6-7th
https://indico.cern.ch/event/523655/

> 300 registered participants, 3/4 from outside CERN

AGENDA :

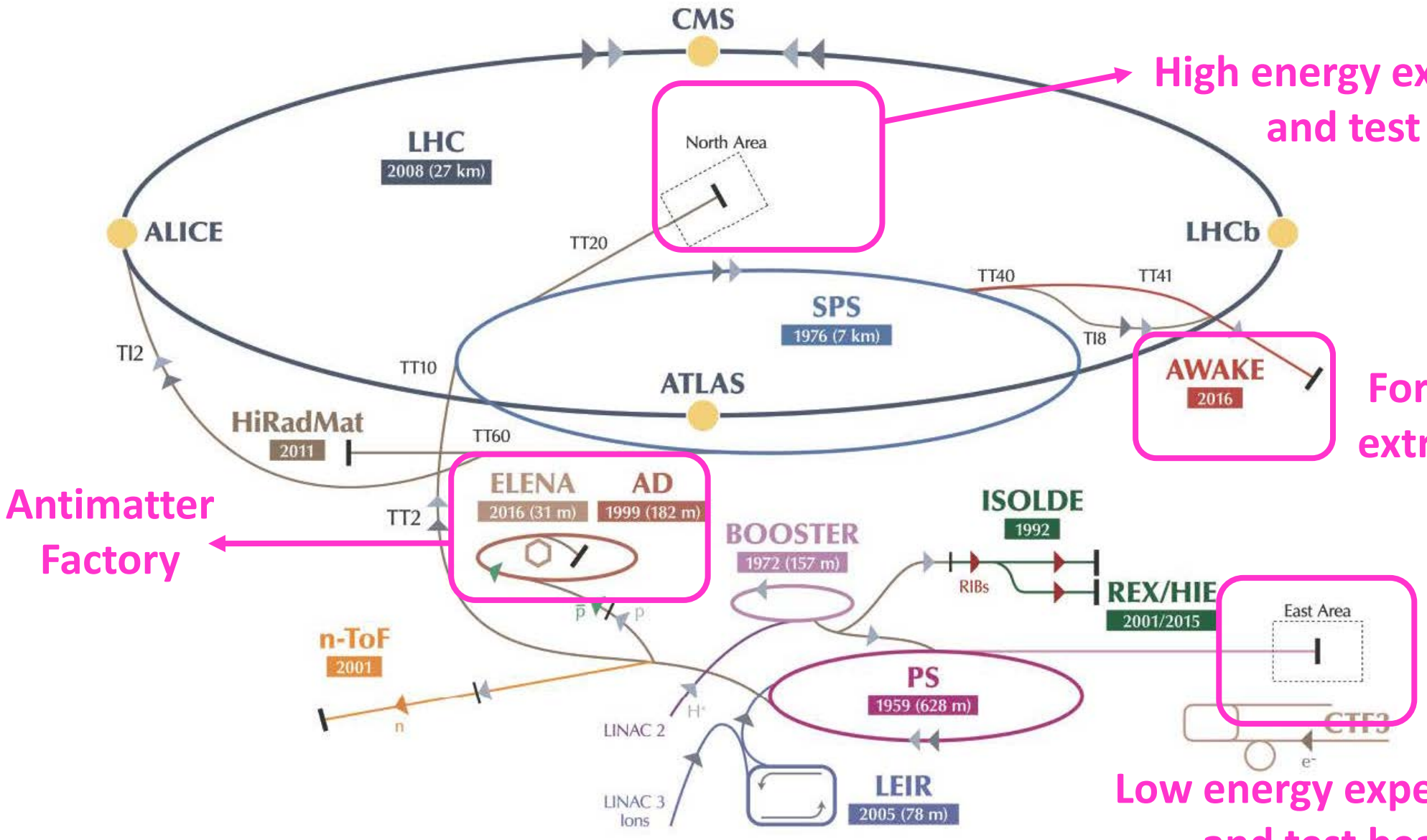
1. **Theorists wishes**
2. **Accelerator complex opportunities**
3. **Potential future of existing programs**

Talks on invitation

4. **New ideas: Call for abstracts → 33 abstracts submitted, 20 selected for presentations**

 NB: credit to all speakers and collaborations for the plots shown in this presentation

THE CERN ACCELERATOR COMPLEX



High energy experiments and test beams

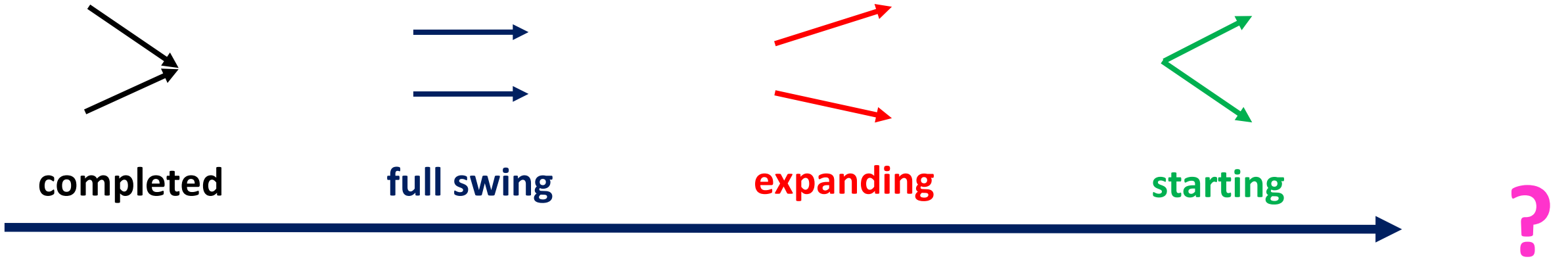
Former CNGS extraction line

Antimatter Factory

Low energy experiments and test beams

A DECADE OF VIBRANT "DIVERSITY" PHYSICS !

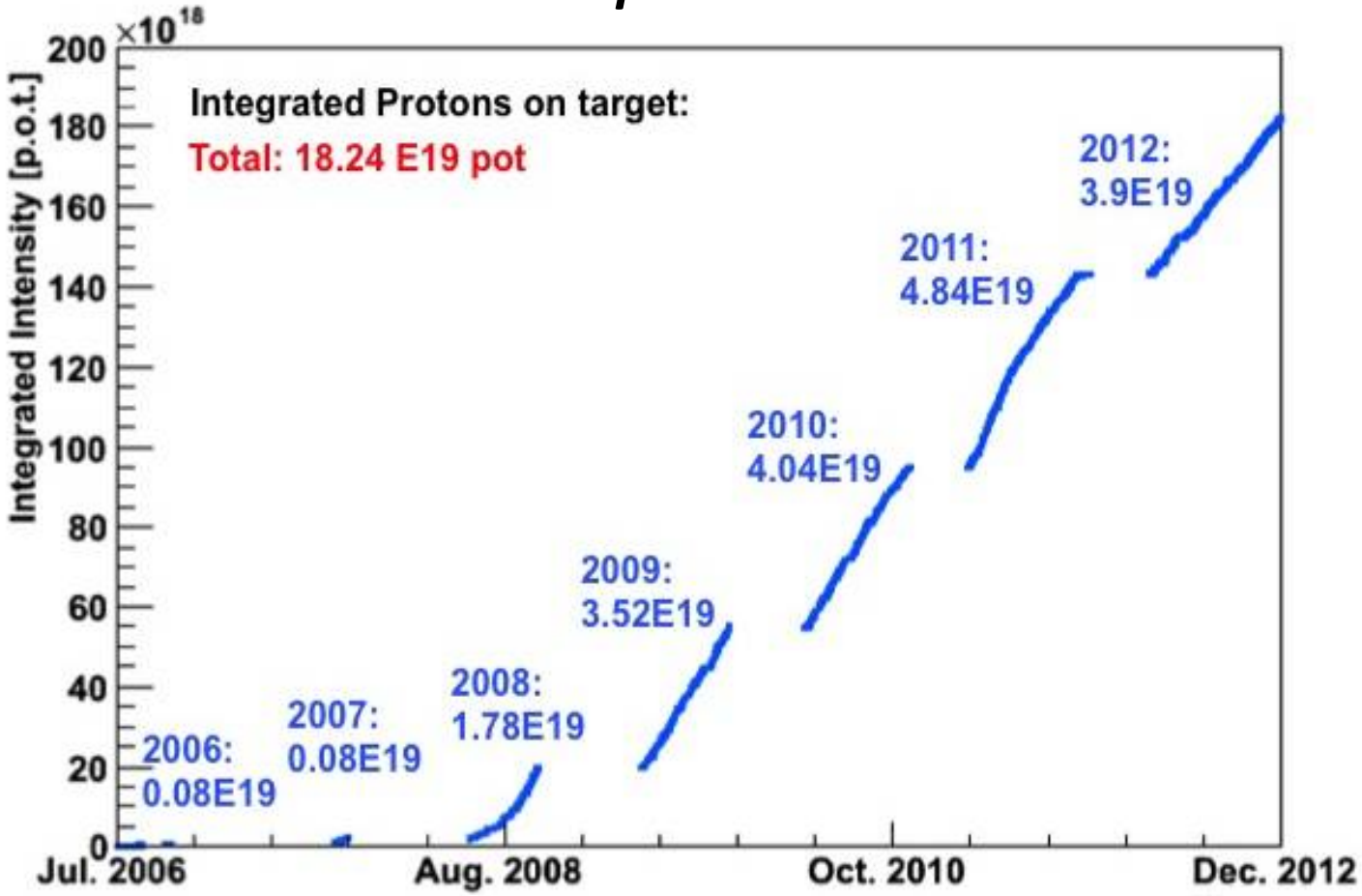
~1000 physicists on ~20 experiments



CNGS

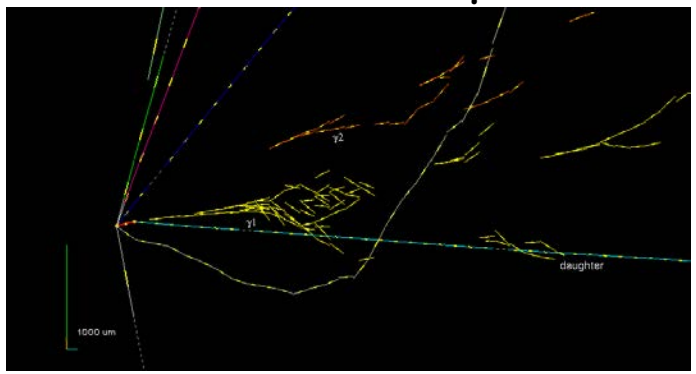
CERN ν_μ beam to Gran Sasso (CNGS) optimized for ν_τ appearance (E_ν~ 17 GeV)

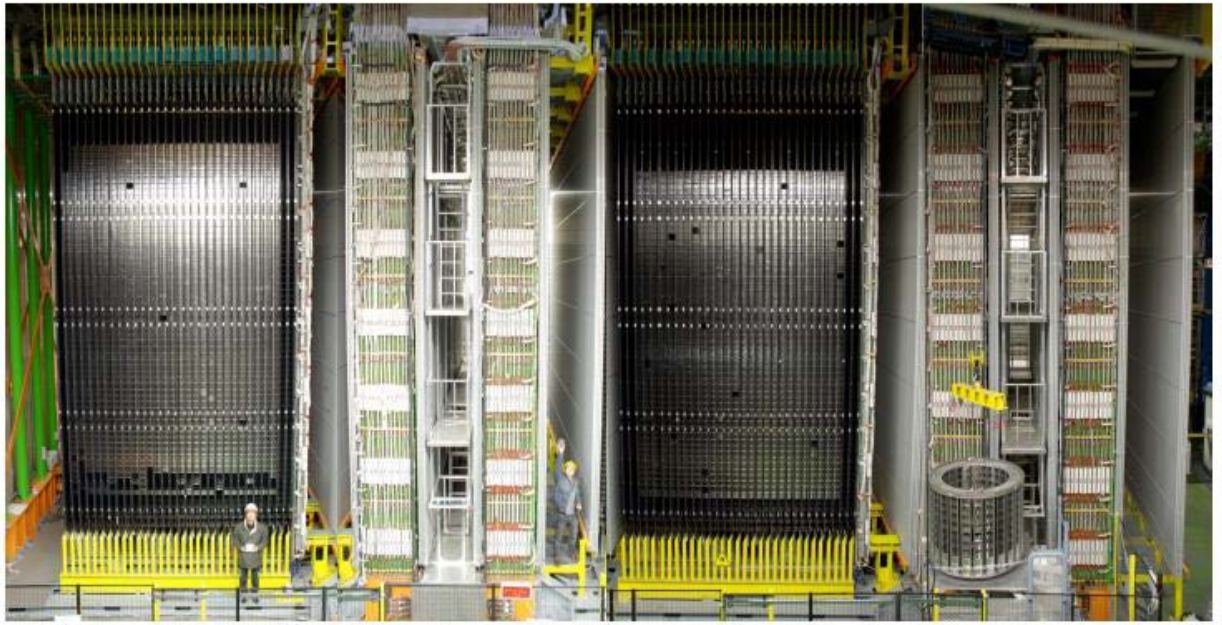
Successful completion of the beam operation in 2012 !

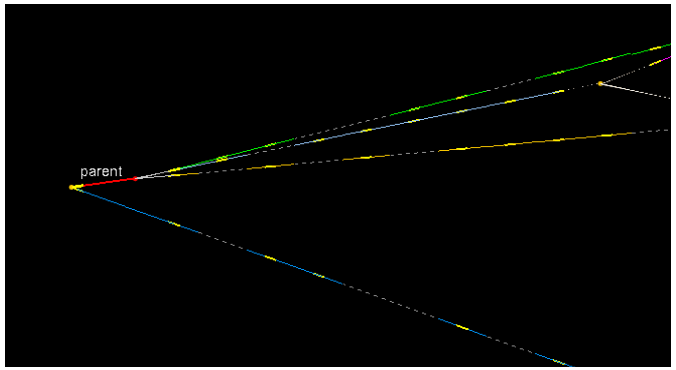


OPERA

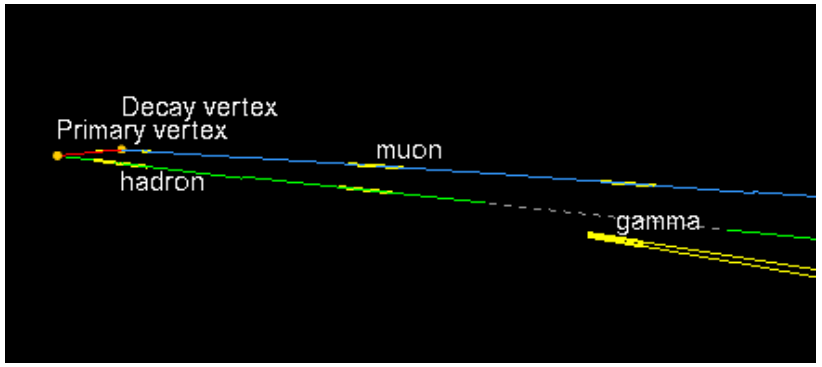
establishment of ν_τ appearance in ν_μ oscillations

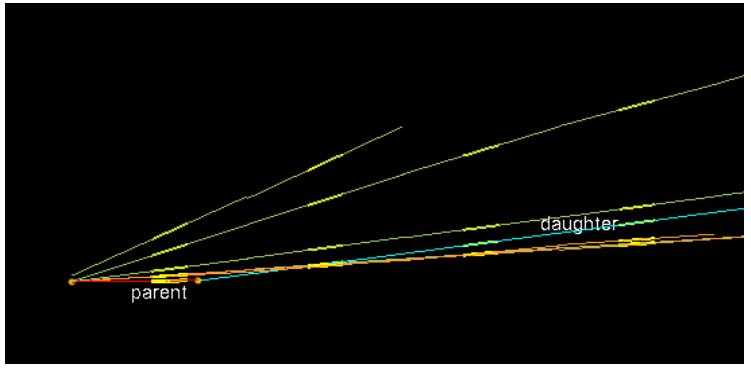


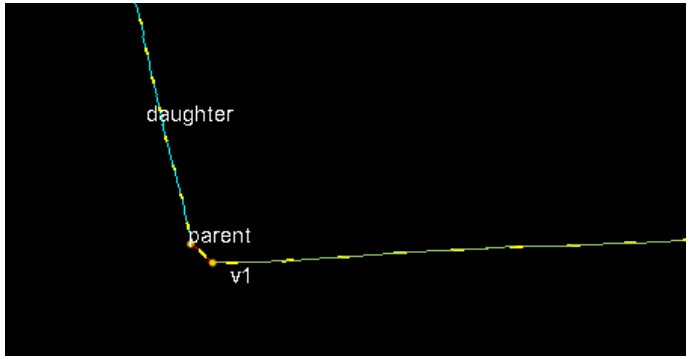




Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006	–	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001	–	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	–	0.0002 ± 0.0001	0.004 ± 0.001	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 ± 0.000	0.25 ± 0.05	2.64 ± 0.53	5



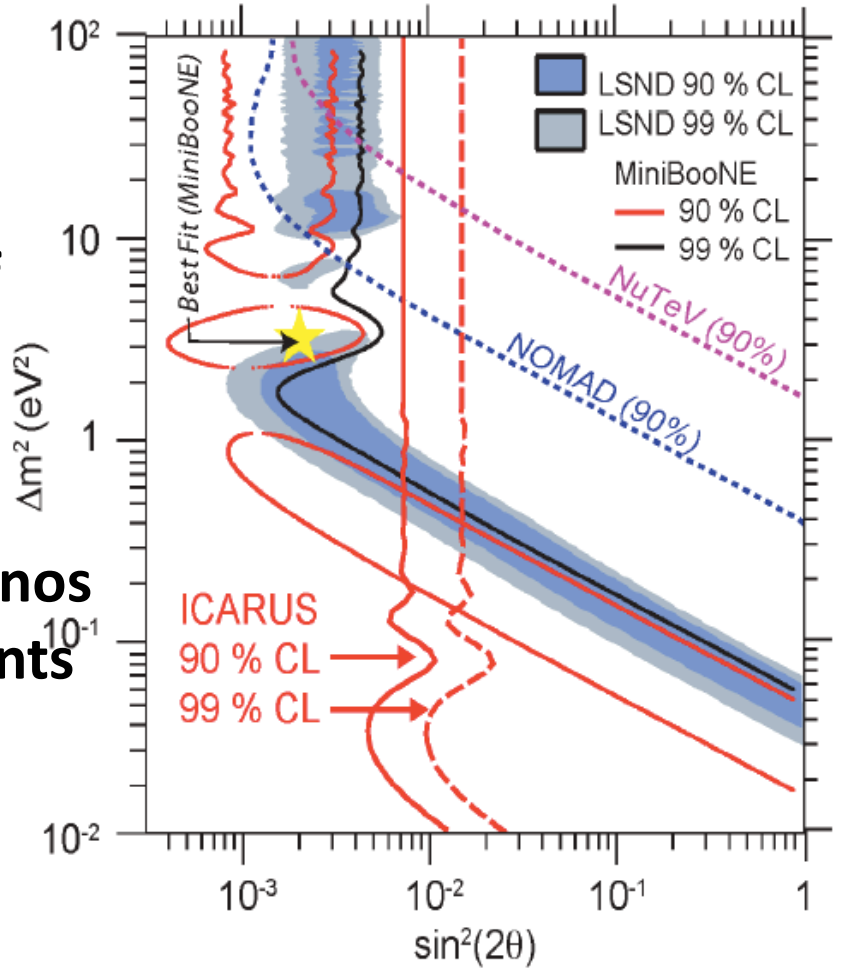


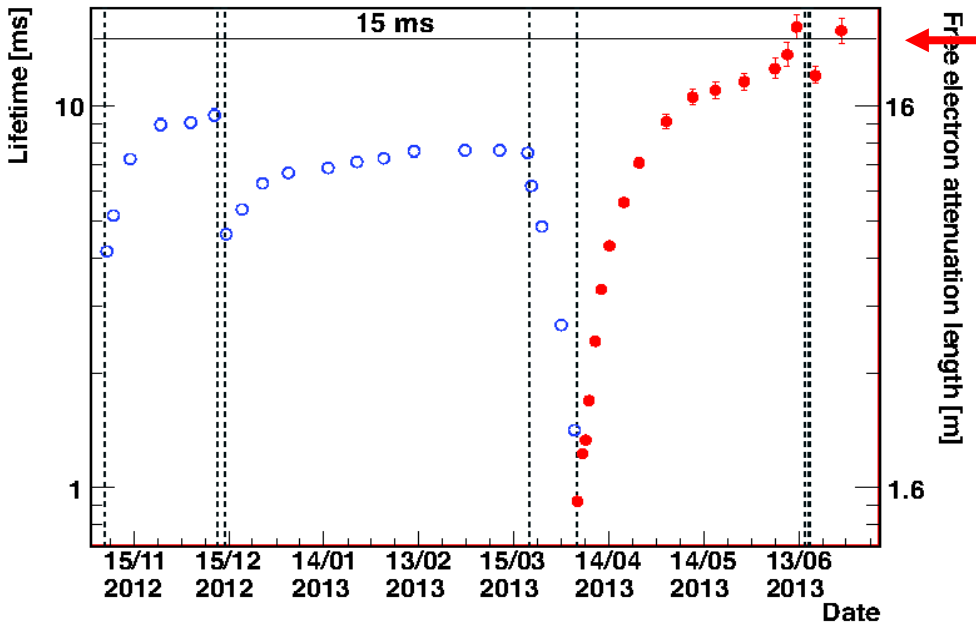


ICARUS

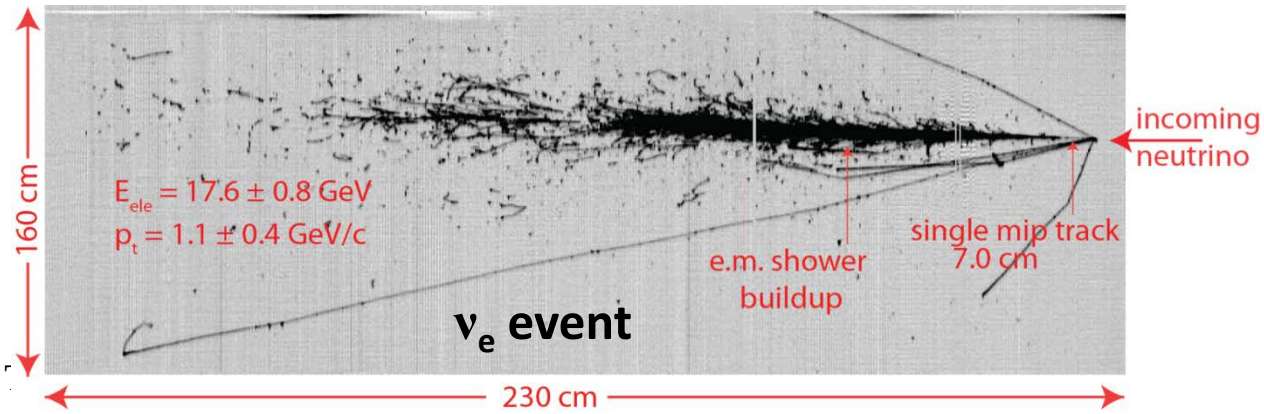
Proof of concept of a large LAr TPC

Limits on sterile neutrinos from analysis of ν_e events





High LAr Purity reached

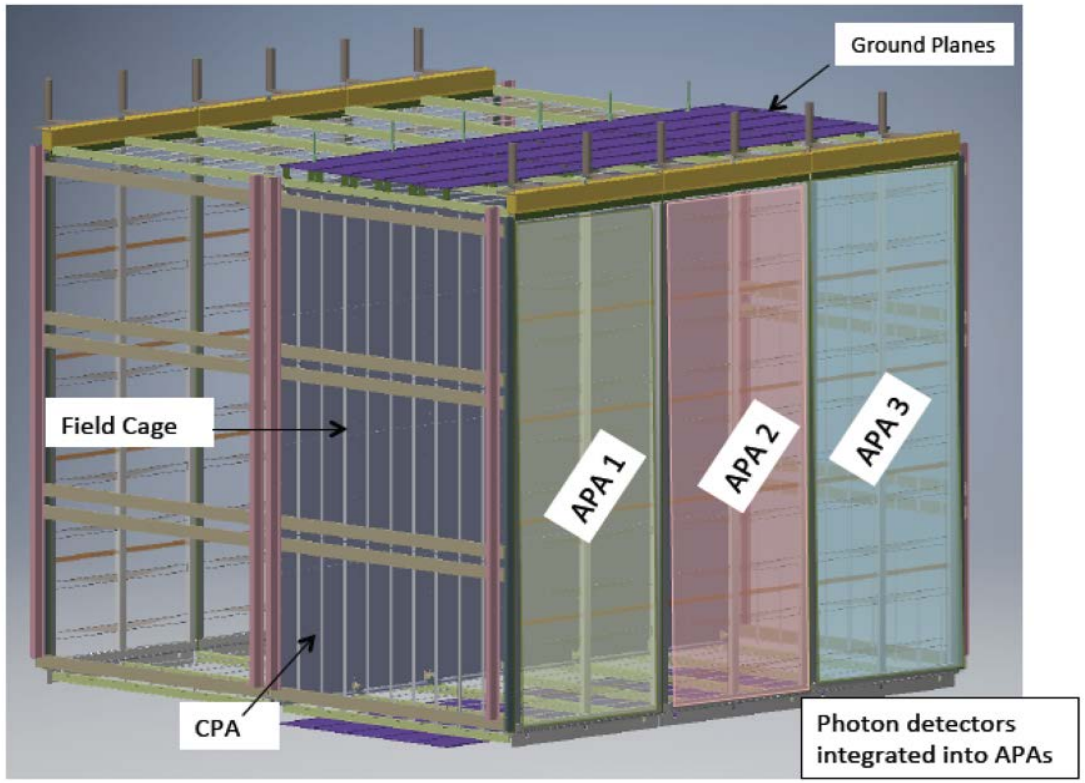


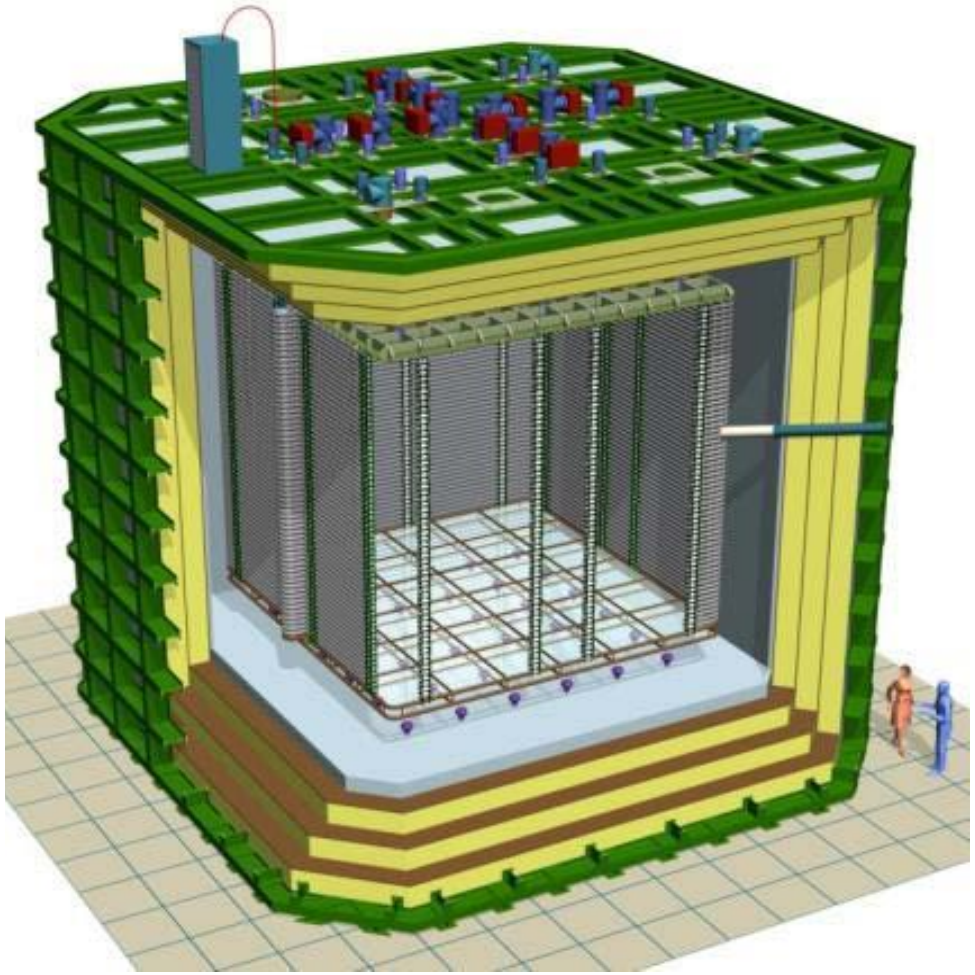
ν_e event

ure of Fixed

NEUTRINO PLATFORM

Large engineering detectors for DUNE



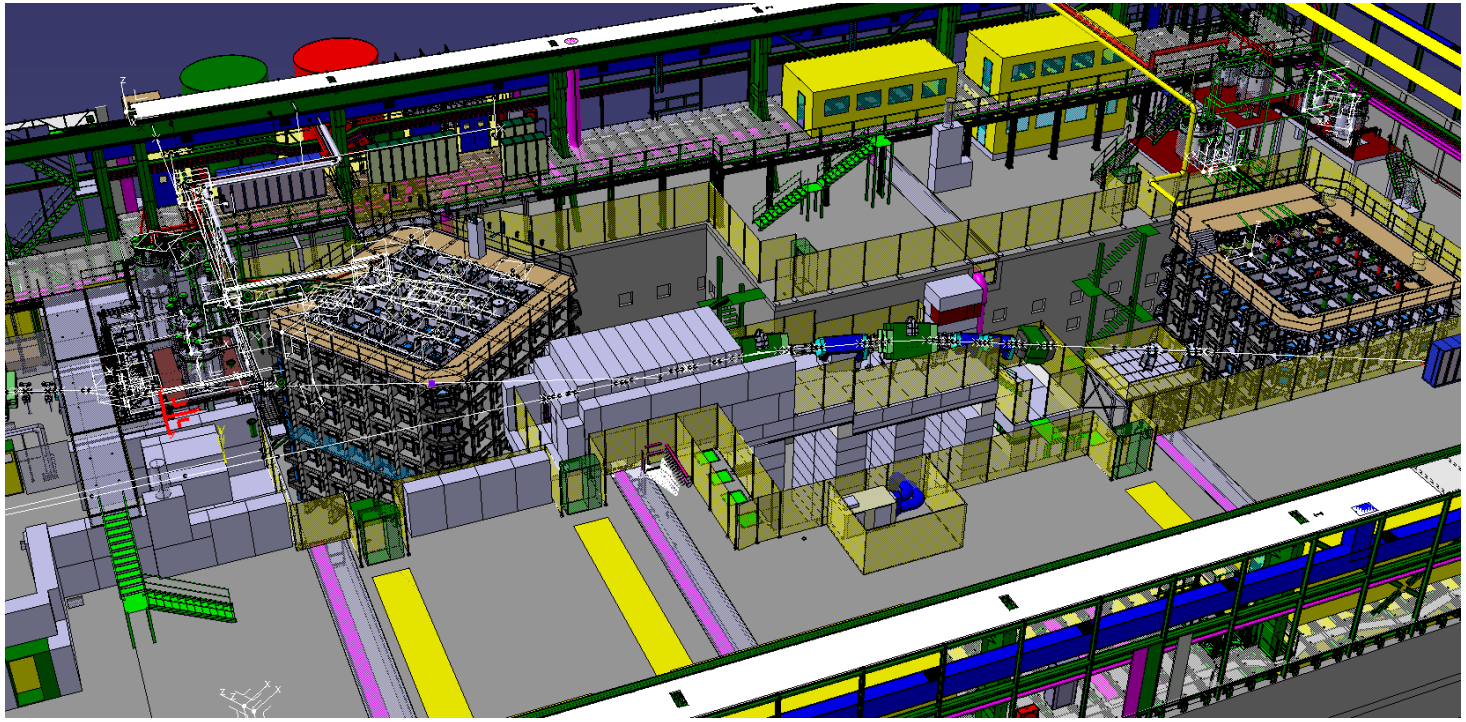


Single Phase:
ProtoDUNE-SP

Double Phase:
ProtoDUNE-DP

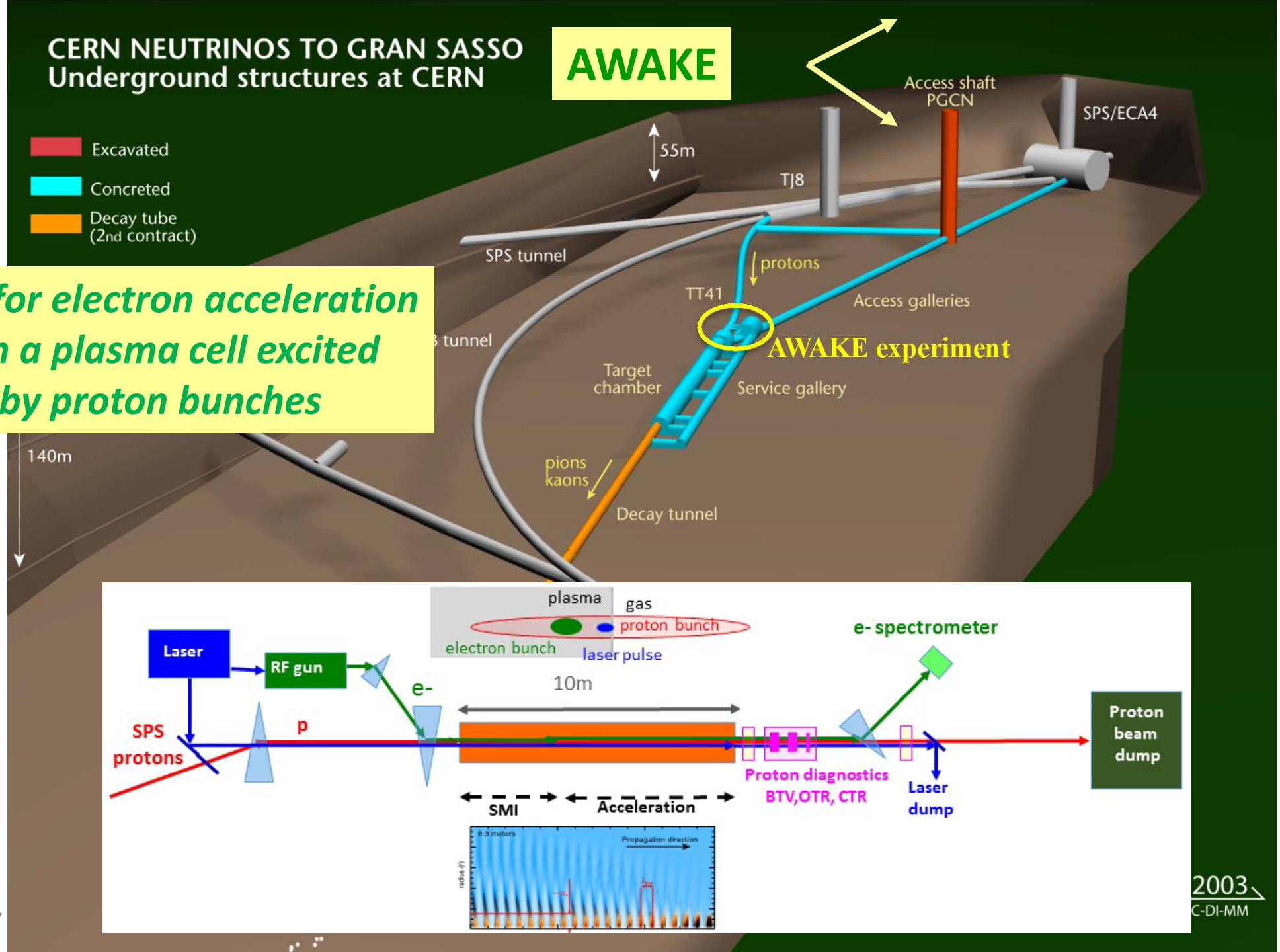
NEUTRINO PLATFORM

Engineering prototypes to be calibrated in low energy beams in a North Hall extension

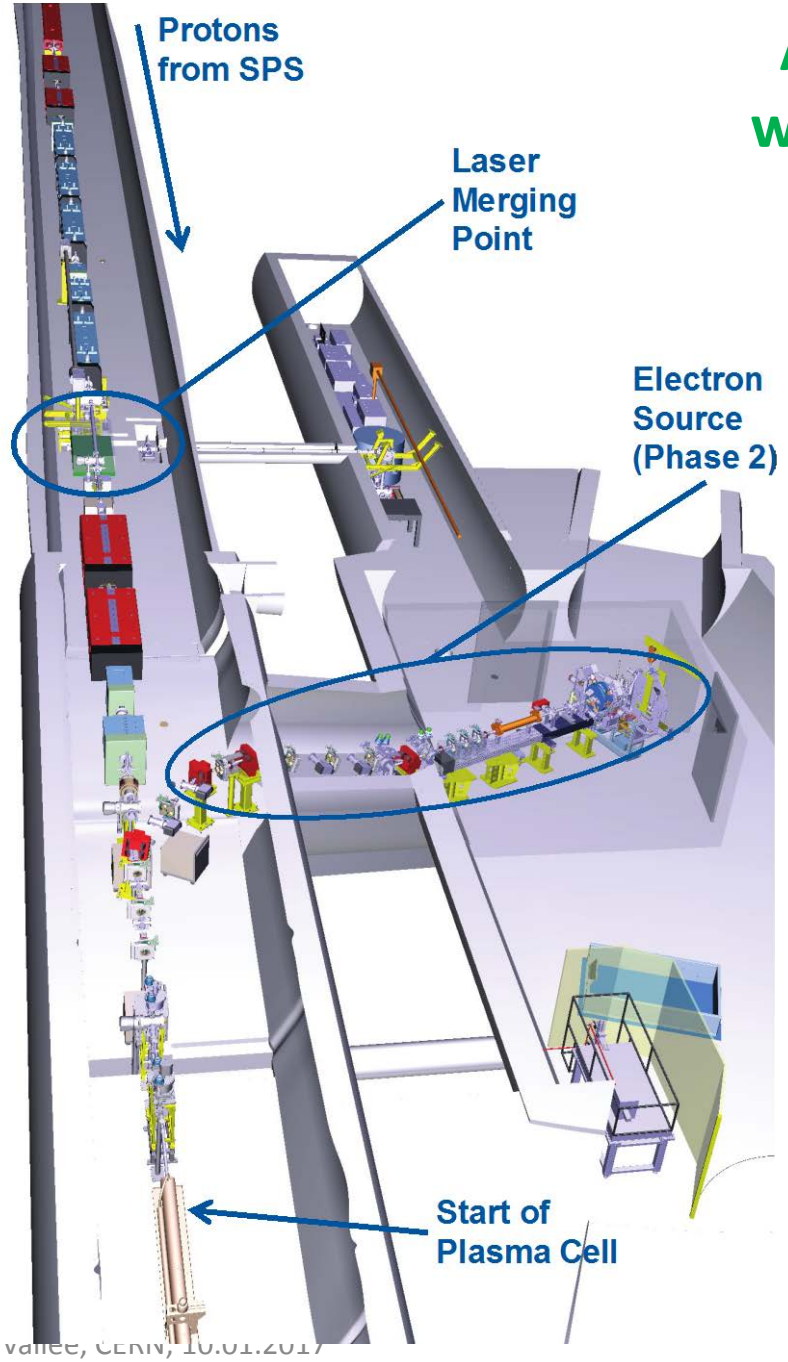


Hall extension ready

But tight schedule to take beam data before LS2



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



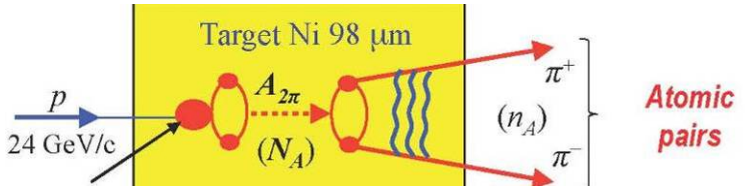
AWAKE successful first beam data end 2016 with the establishment of plasma modulation

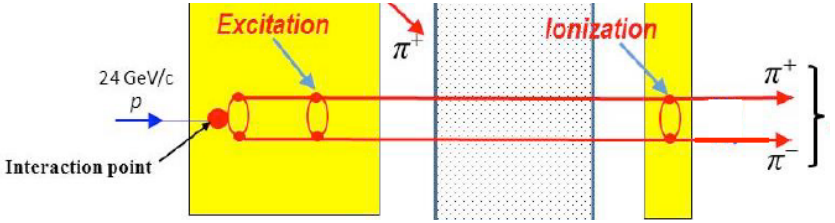
Goal for 2017 is first electron acceleration

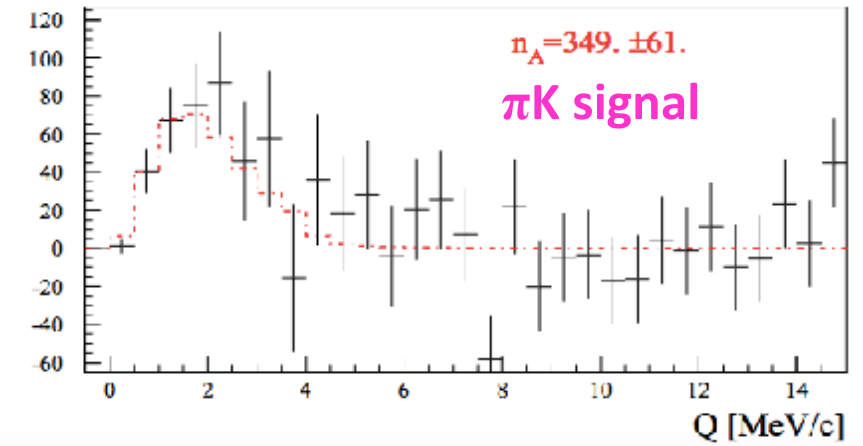
A project of interest for future high E / high I electron beams

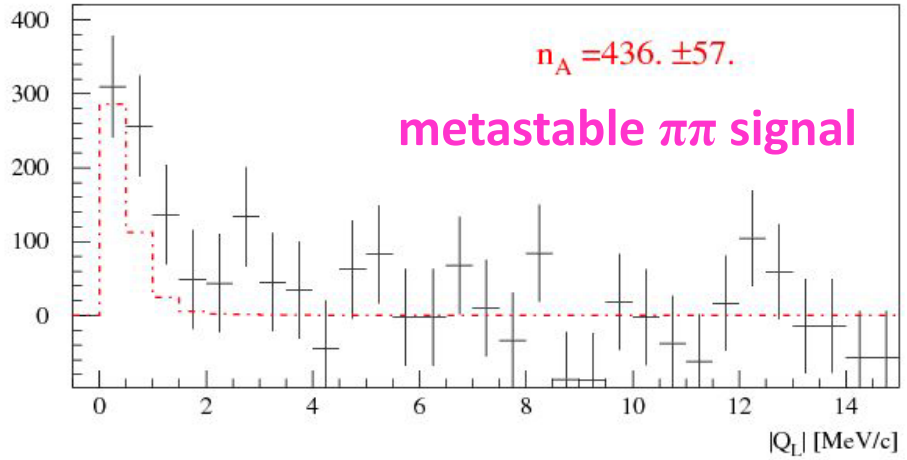
DIRAC @ PS

Low E perturbative chiral QCD with mesonic atoms:
Discovery of πK atoms and metastable ππ atoms



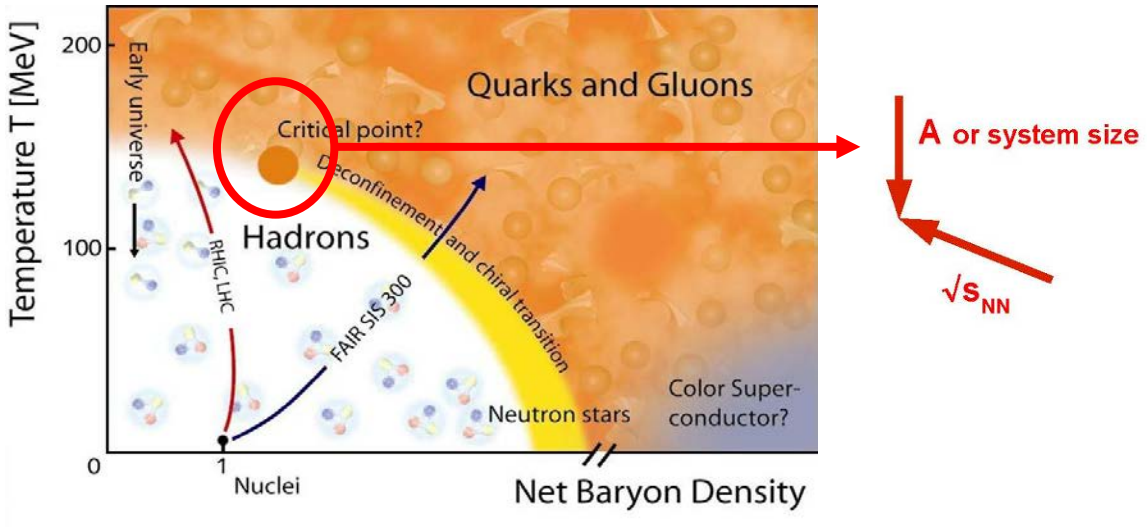






AFTER LS2: wish to perform similar studies at SPS (statistics x ~20)

would allow quantitative test of chiral $SU(3)_L$ x $SU(3)_R$ symmetry breaking

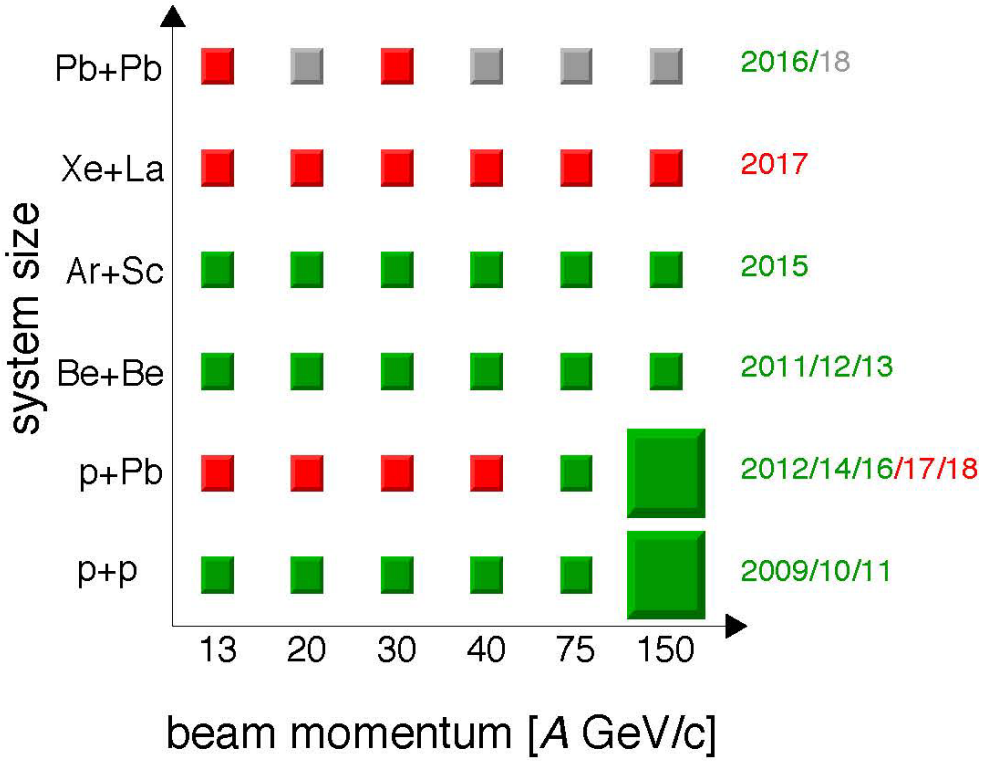


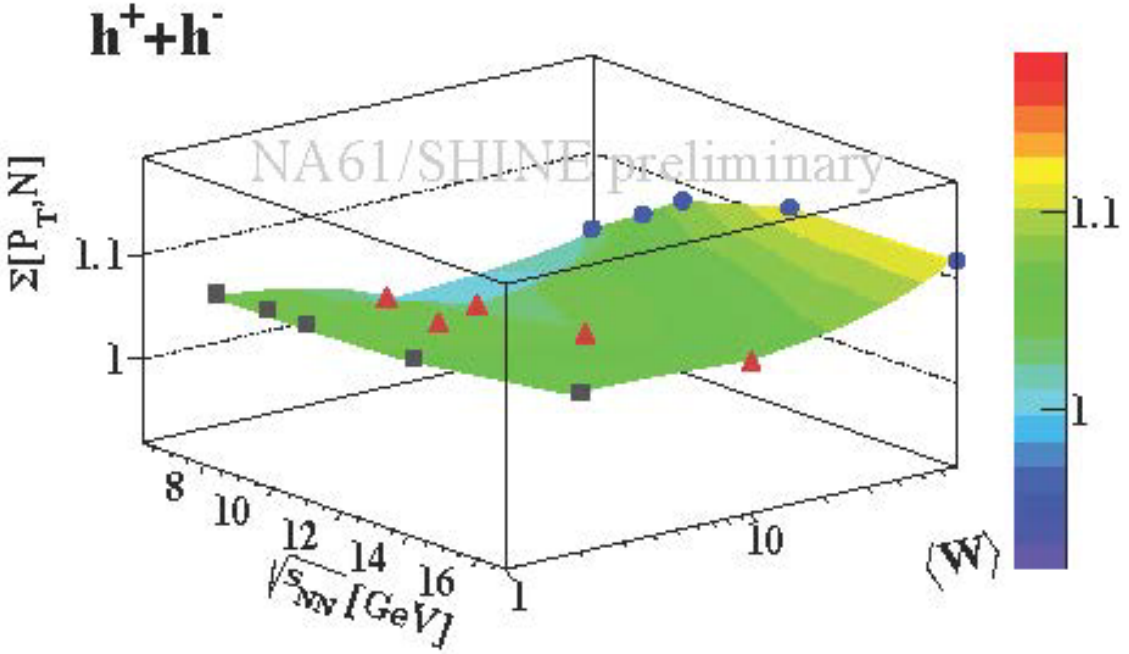
NA61/SHINE

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

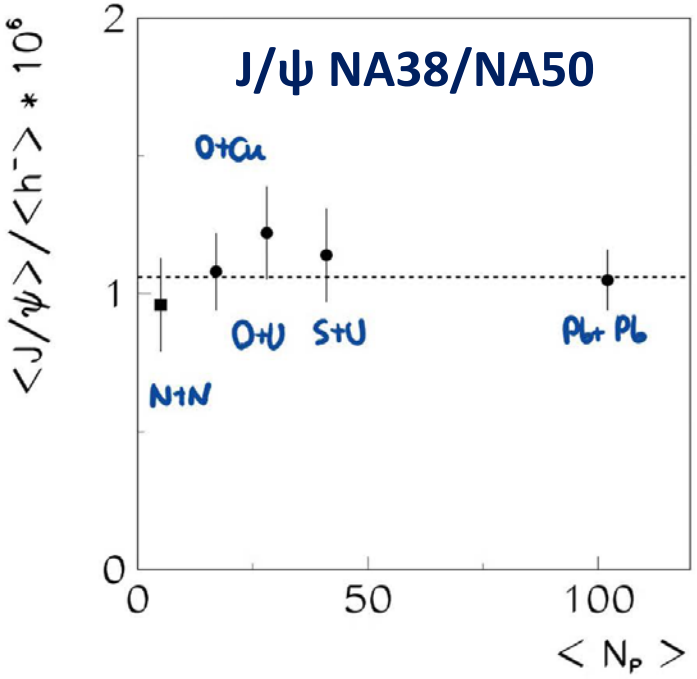
Scan to be completed until LS2

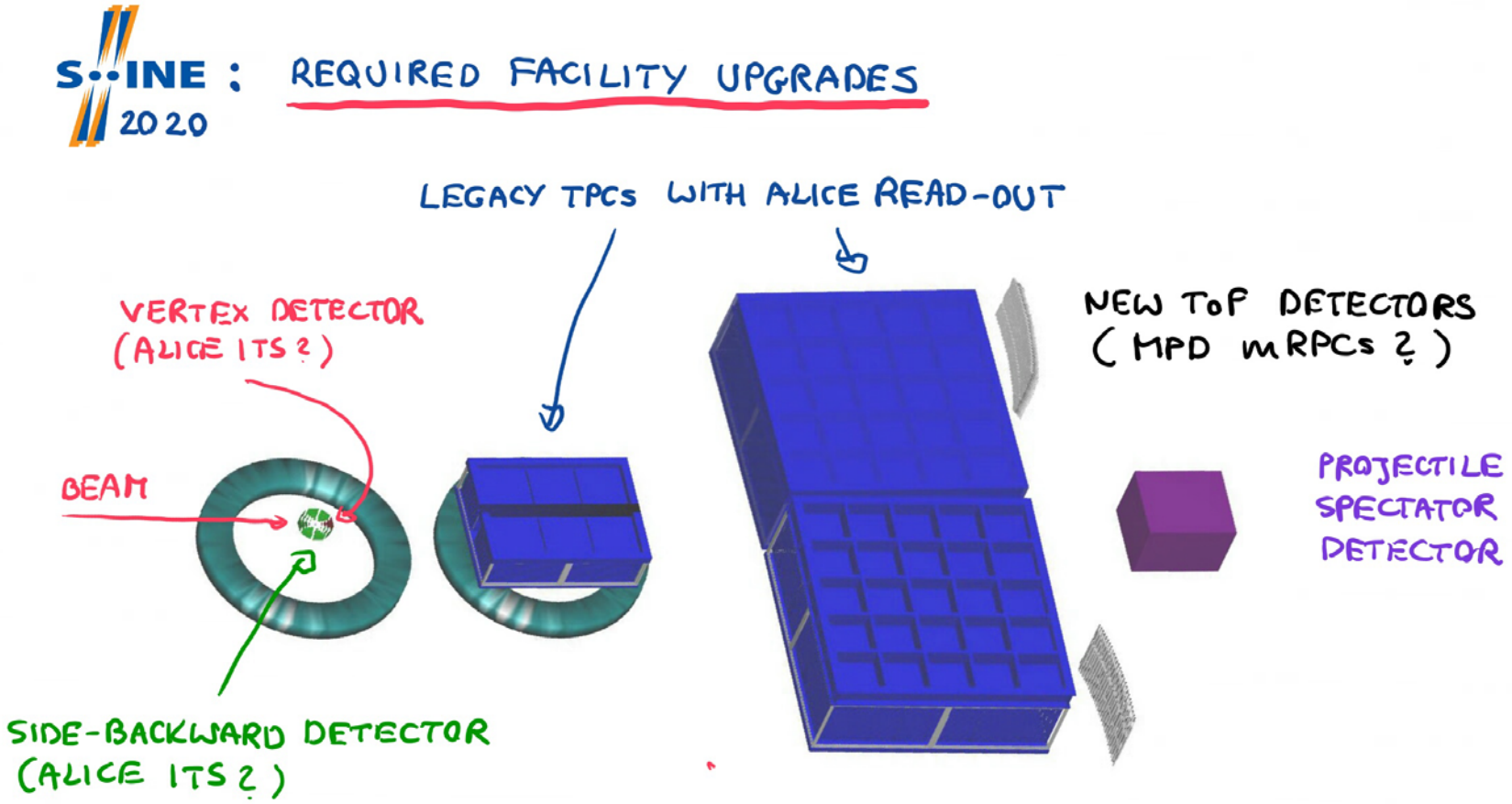
No indication of CP yet



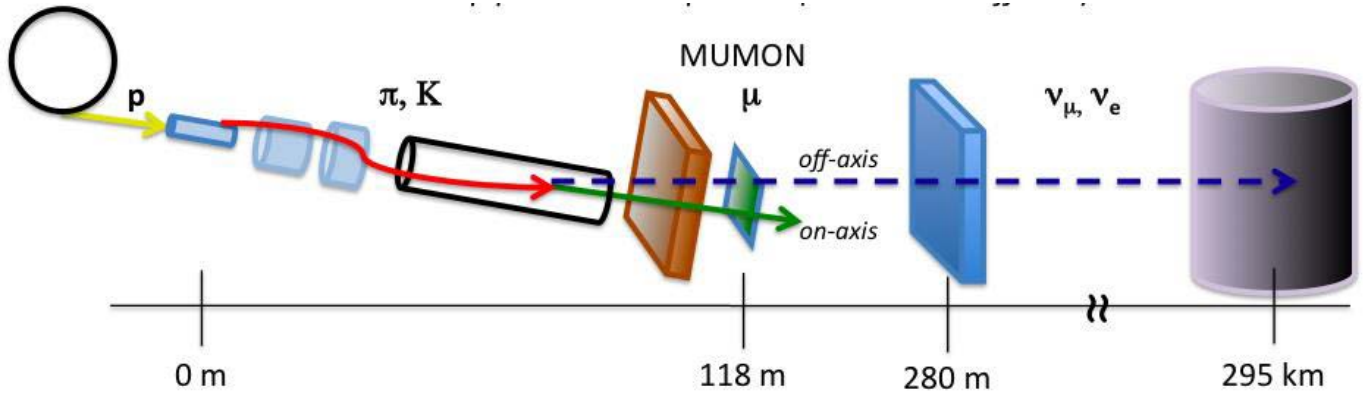


AFTER LS2:
wish to further study QCD deconfinement with open charm



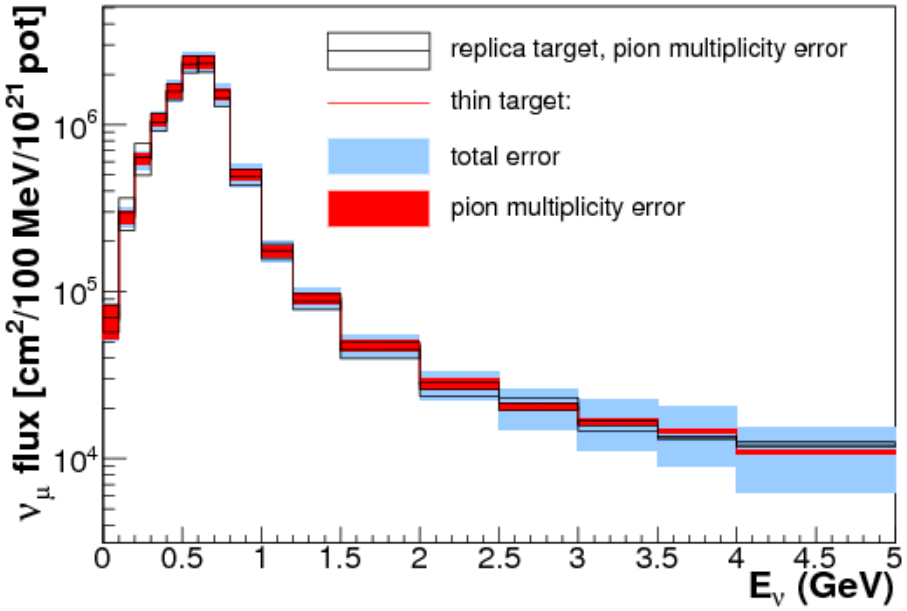


Would allow to disentangle statistical/dynamical models in complement of J/ψ data from NA38/NA50

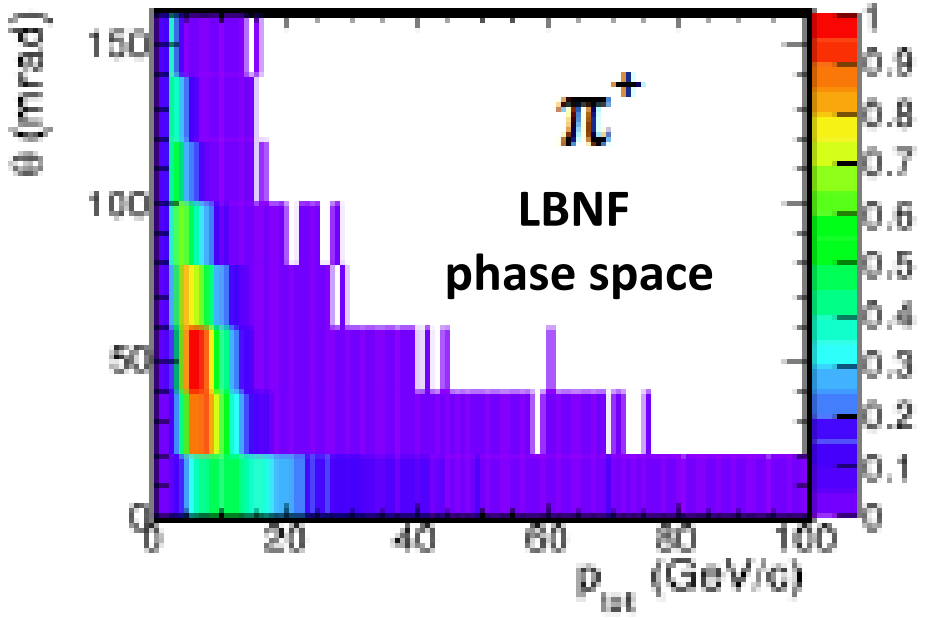


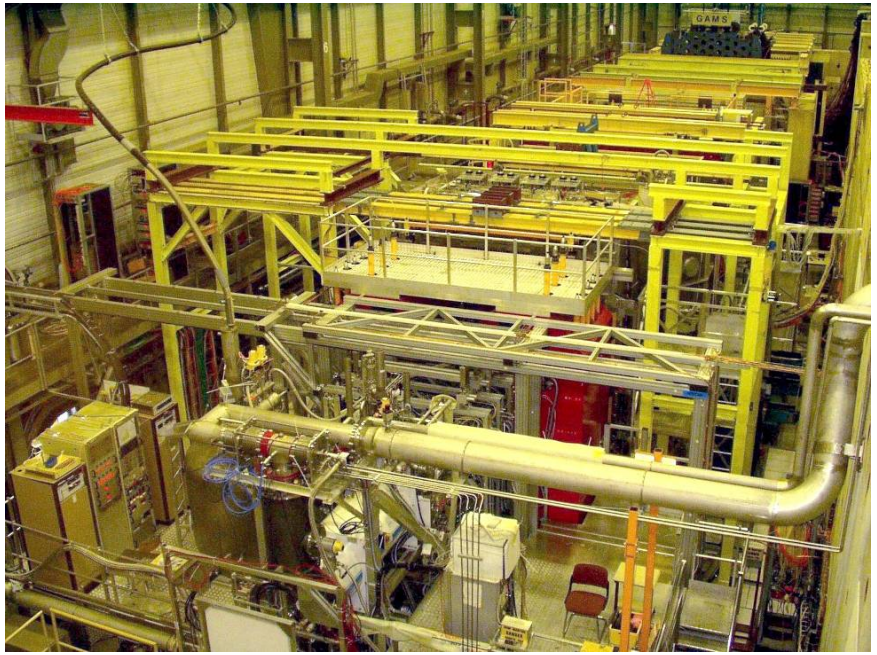
NA61 large acceptance TPC also unique to constrain ν beam fluxes

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

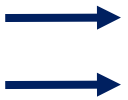


Similar program starting with the US for LBNF

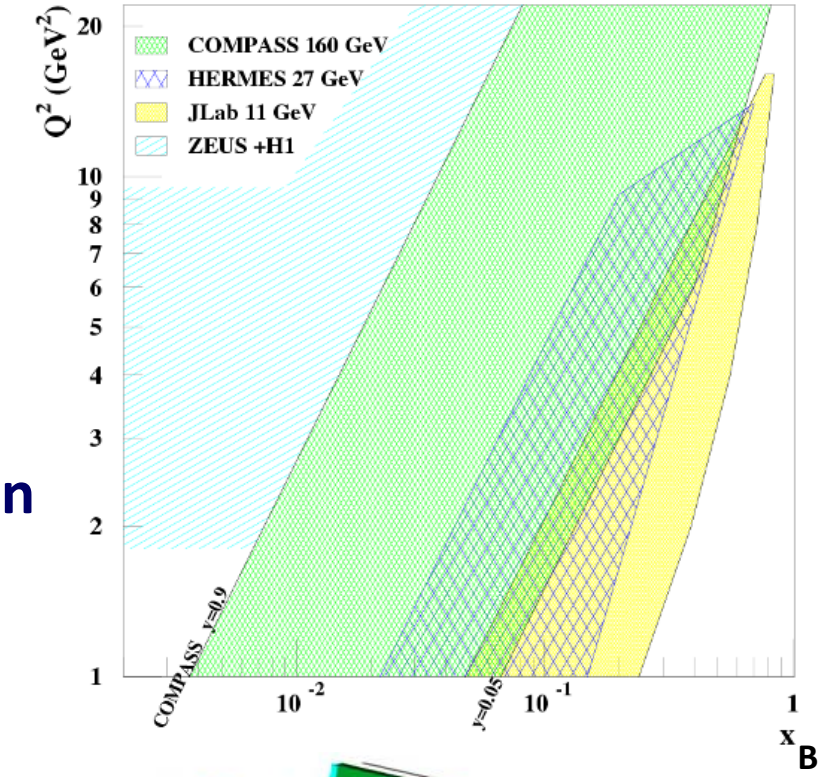


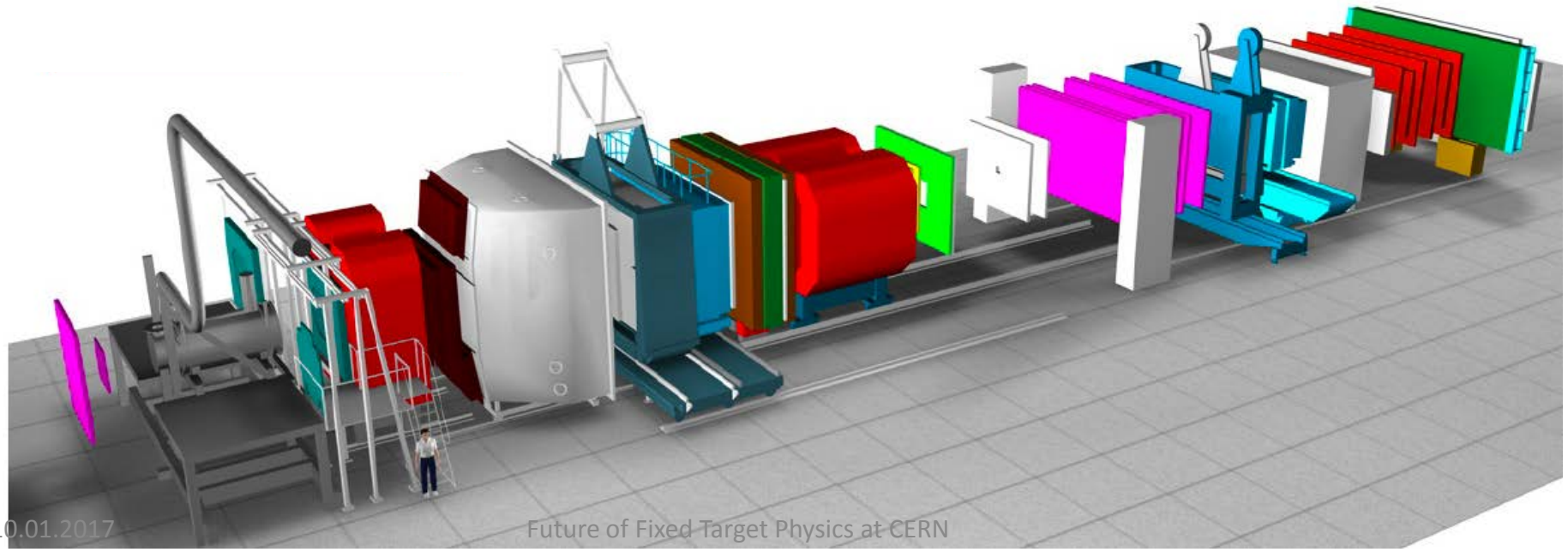


COMPASS



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

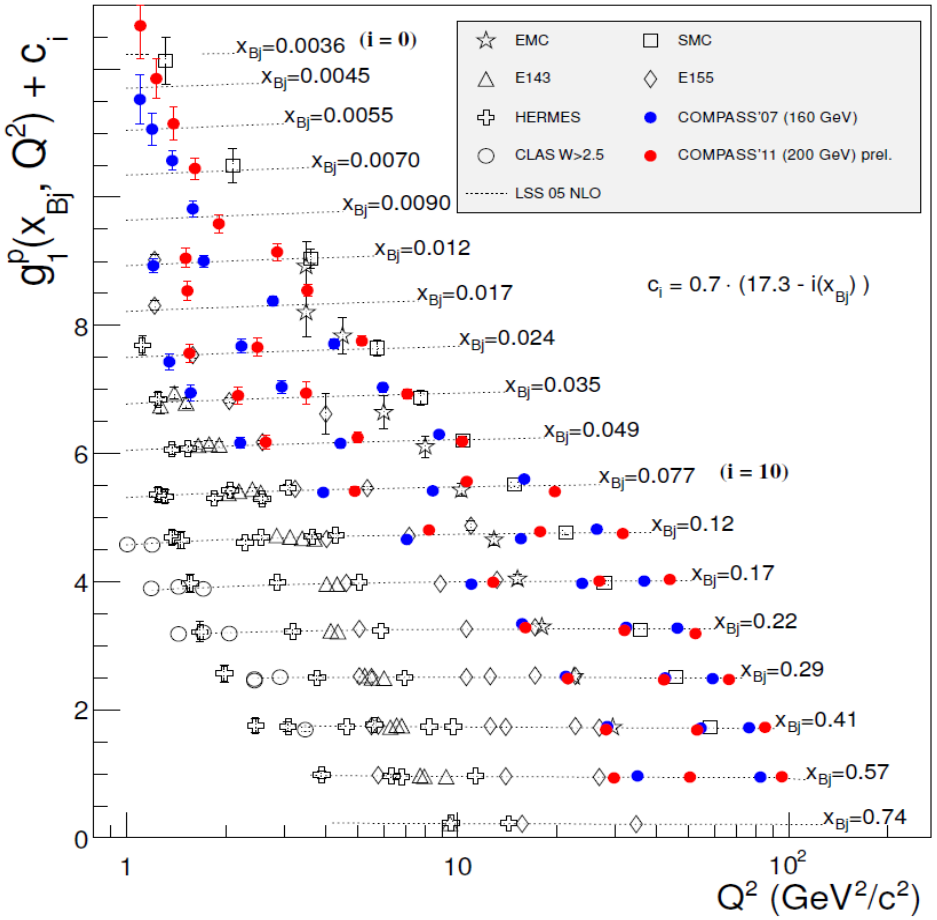




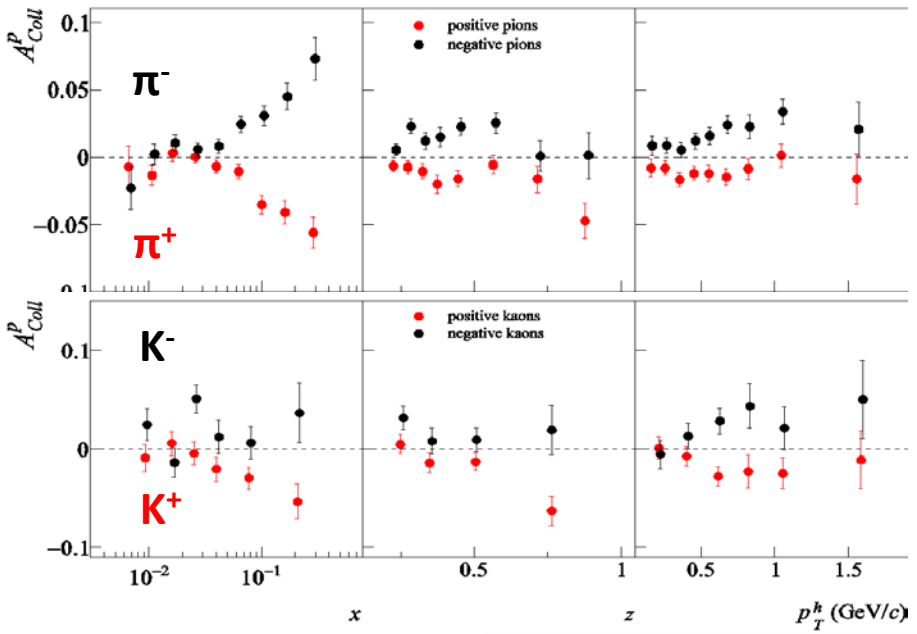
COMPASS I

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

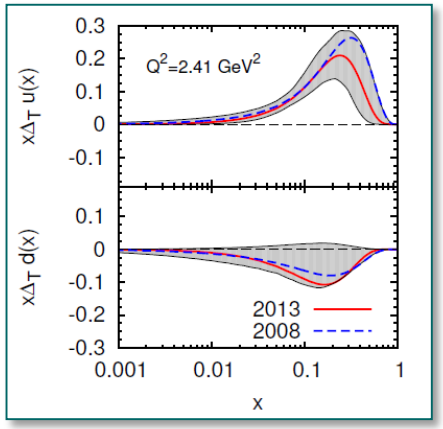
Longitudinal spin ⟷ **Transverse spin**



Improved precision on g_1 at low x

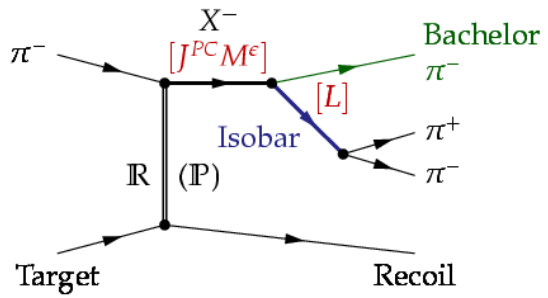


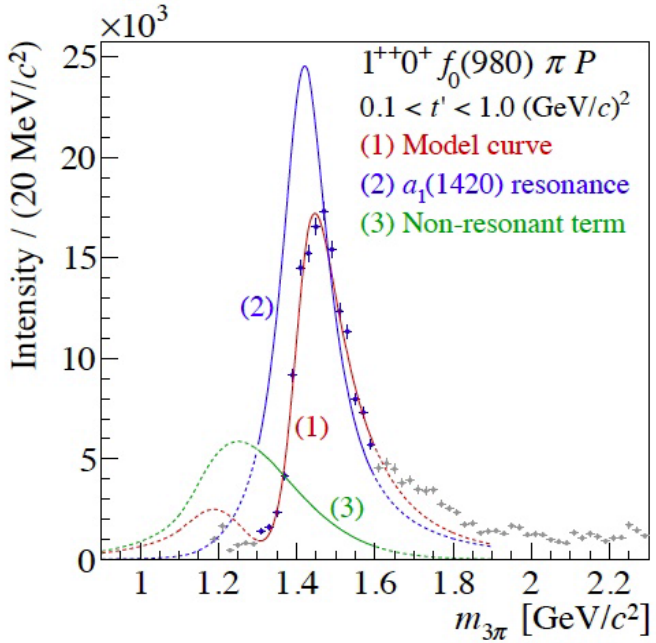
Non-zero transversity in proton confirmed



COMPASS I(+II) : SPECTROSCOPY AND PRIMAKOV

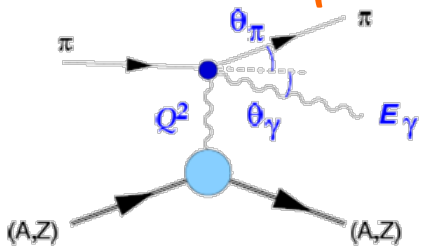
New isovector meson $a_1(1420)$ 1^{++}

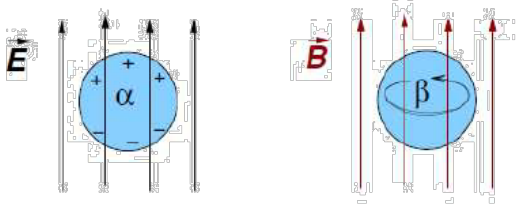


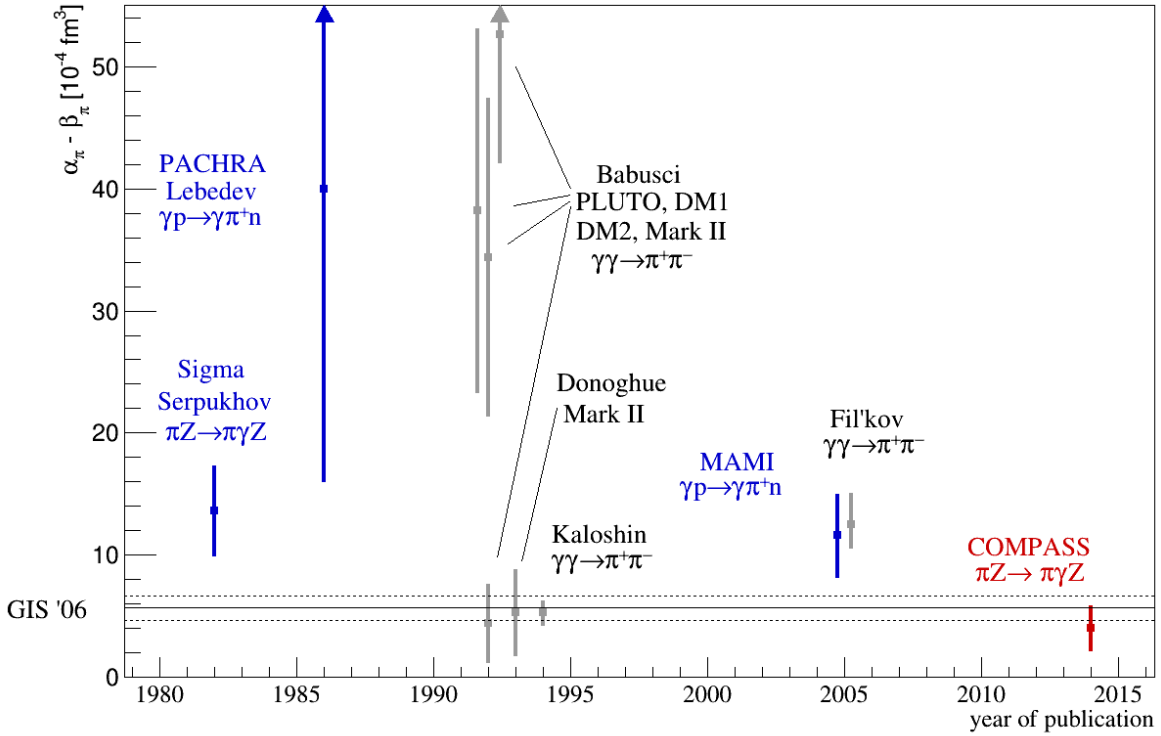


Pion polarizability with 2009 Primakov data

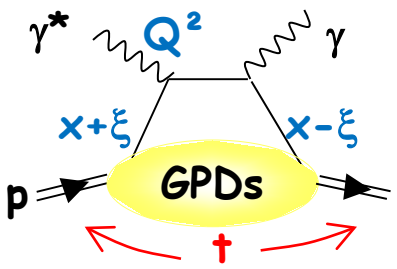
(to be x 5 with 2012 data)

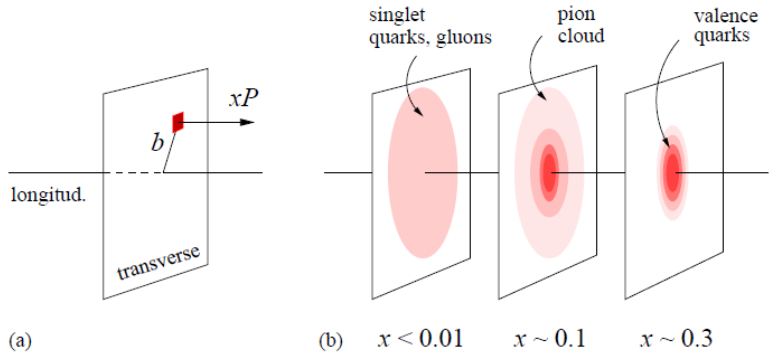


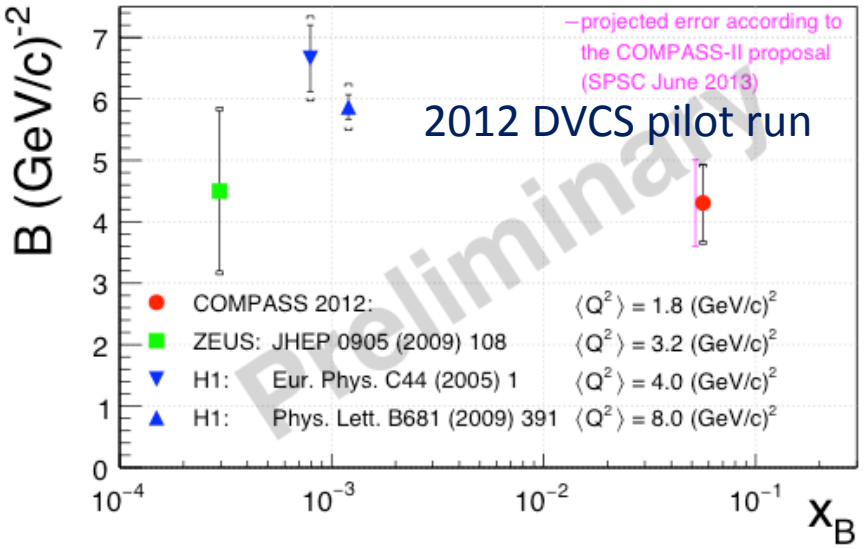




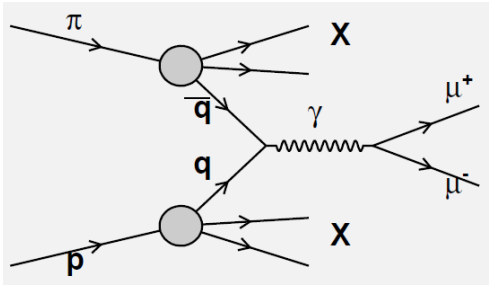
COMPASS II (2014-18)

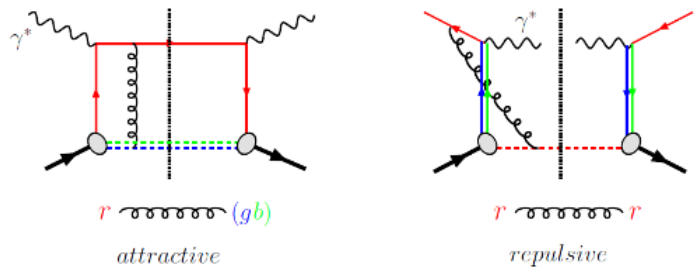


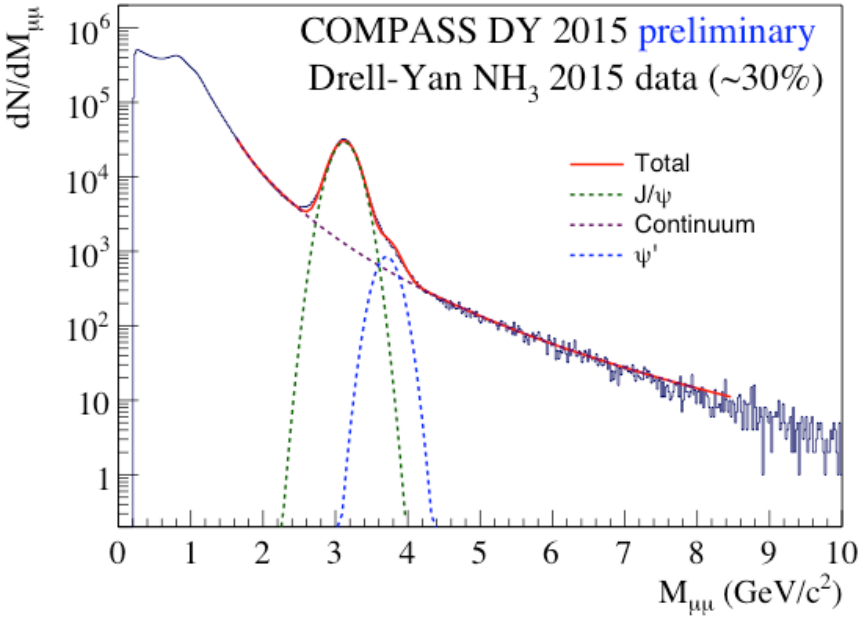




2016-17: DVCS : proton tomography with access to orbital momentum of quarks



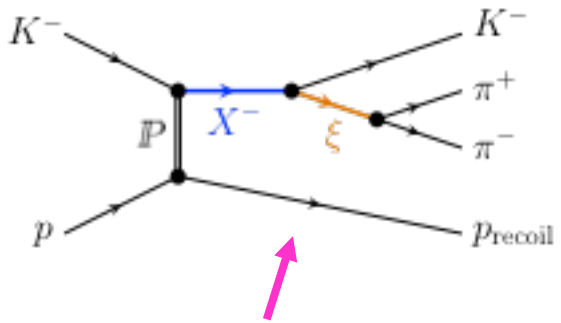




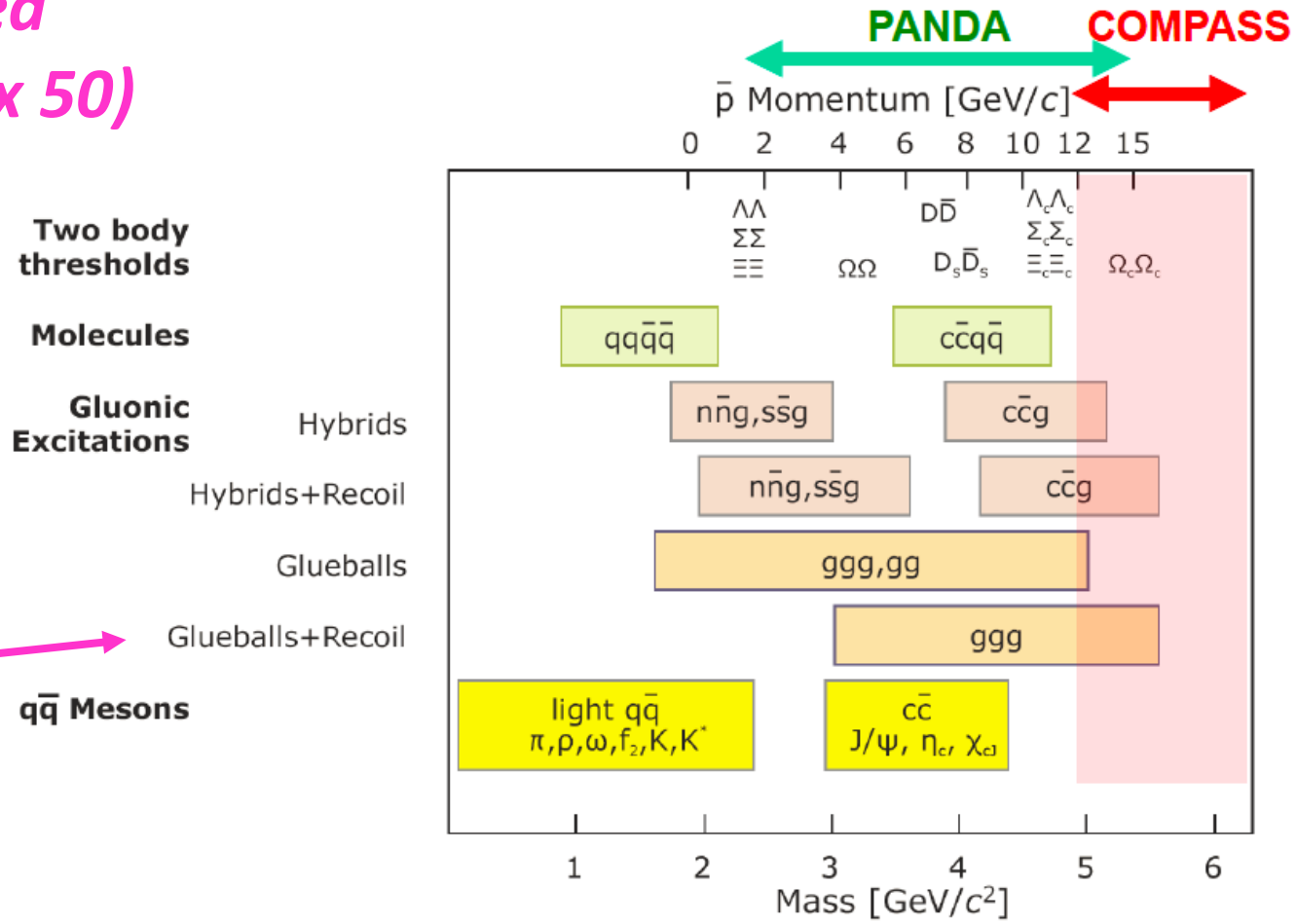
2014+15+18: DY : *Transverse Momentum Dependent (TMD) QCD effects in the valence regime*

Measurement complementary to SiDIS : opposite asymmetries expected

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



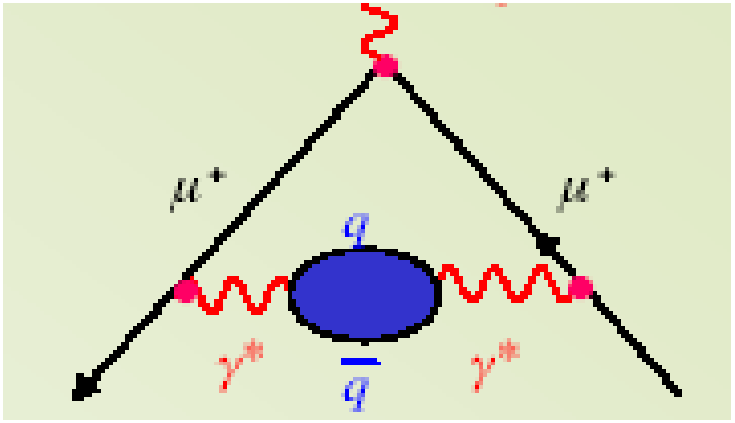
- High statistics strange meson spectroscopy
- Exotic states spectroscopy complementary to LHCb
- Kaon and antiproton structure



DY statistics

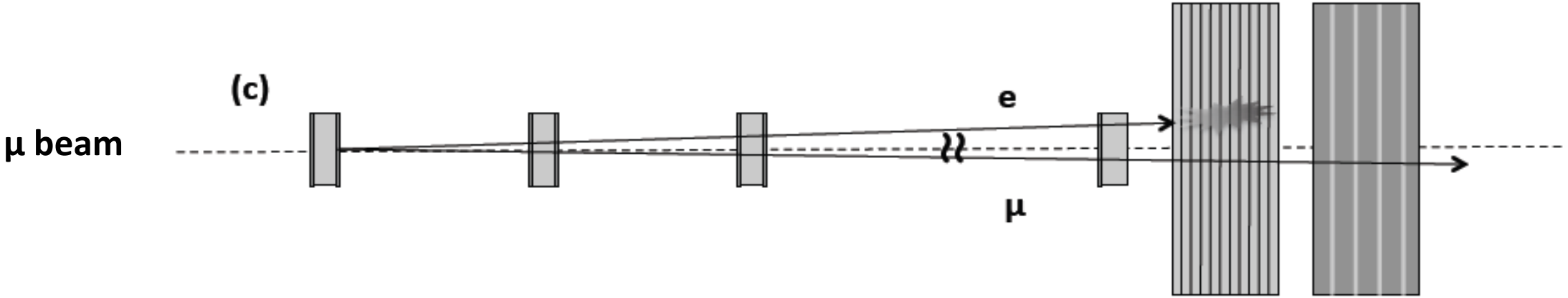
	NH_3	Al (7cm)	W	NA3	NA10	E537	E615
K^- beam	14,000	2,800	29,600	700			
$\bar{p}$ beam	15,750	2,750	22,500			387	

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



Vacuum polarisation

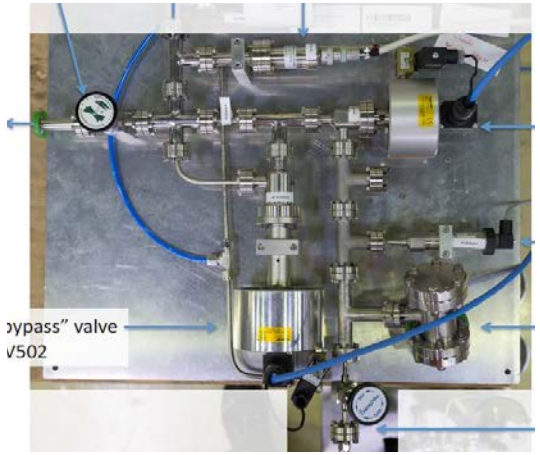
High statistics space-like measurement could reduce by factor 2 the current error derived from time-like processes



Might be feasible with reasonable resources within the (modified) COMPASS setup

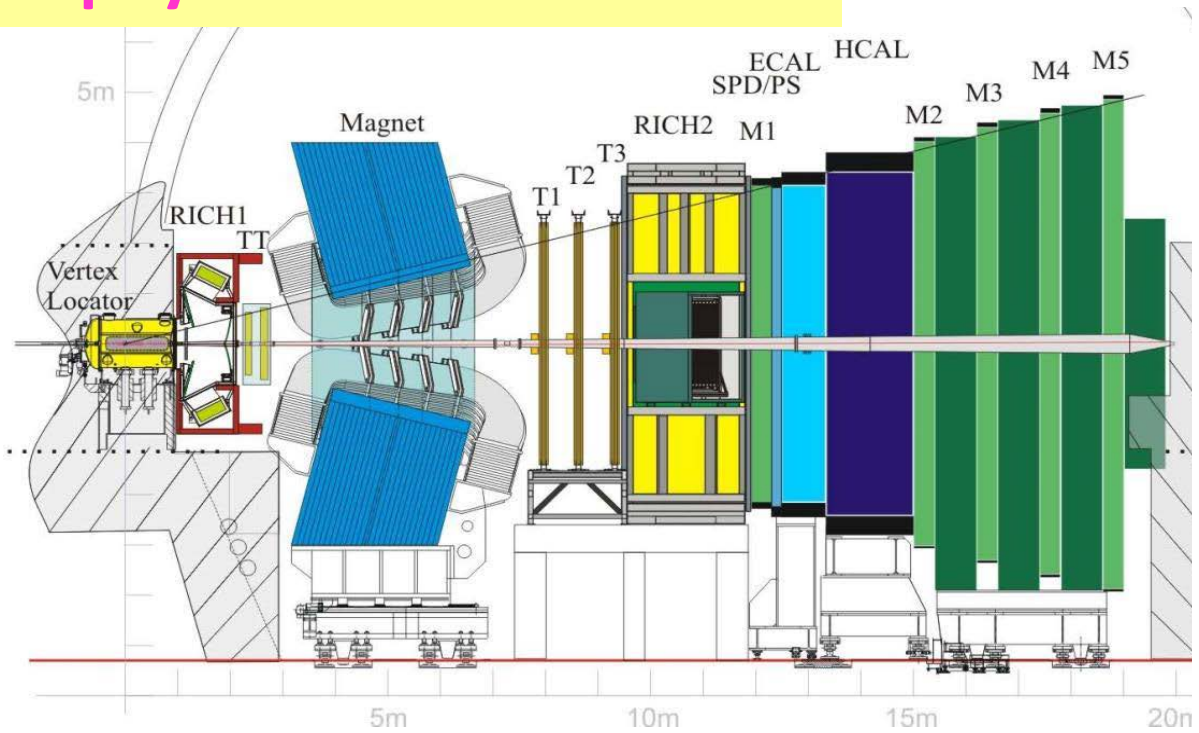
New idea: Fixed Target physics with LHC beams

Internal gas target (AFTER)



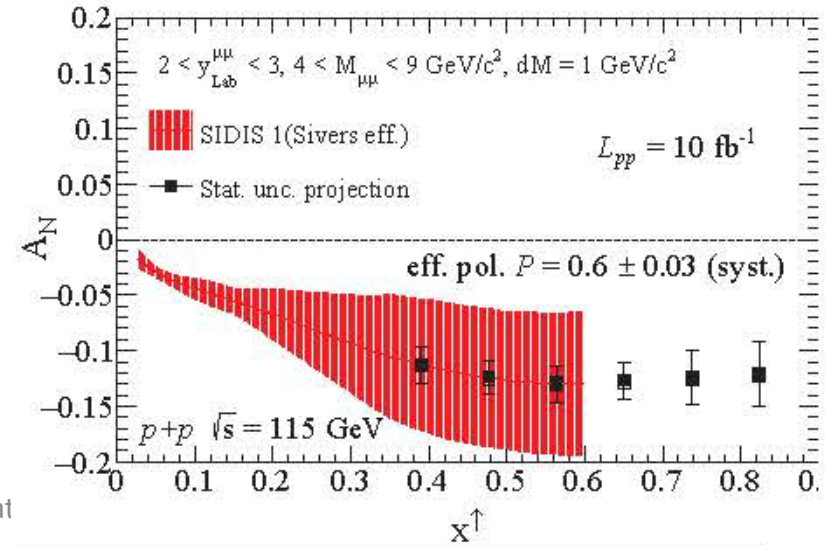
e.g. SMOG

Upstream of LHCb and/or ALICE



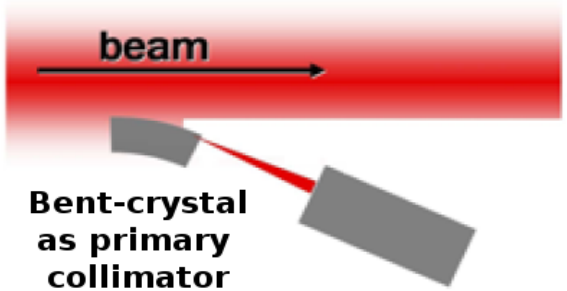
p-p: High precision TMD measurements (polarized target) and charm at high x

p-A: Nuclear PDFs



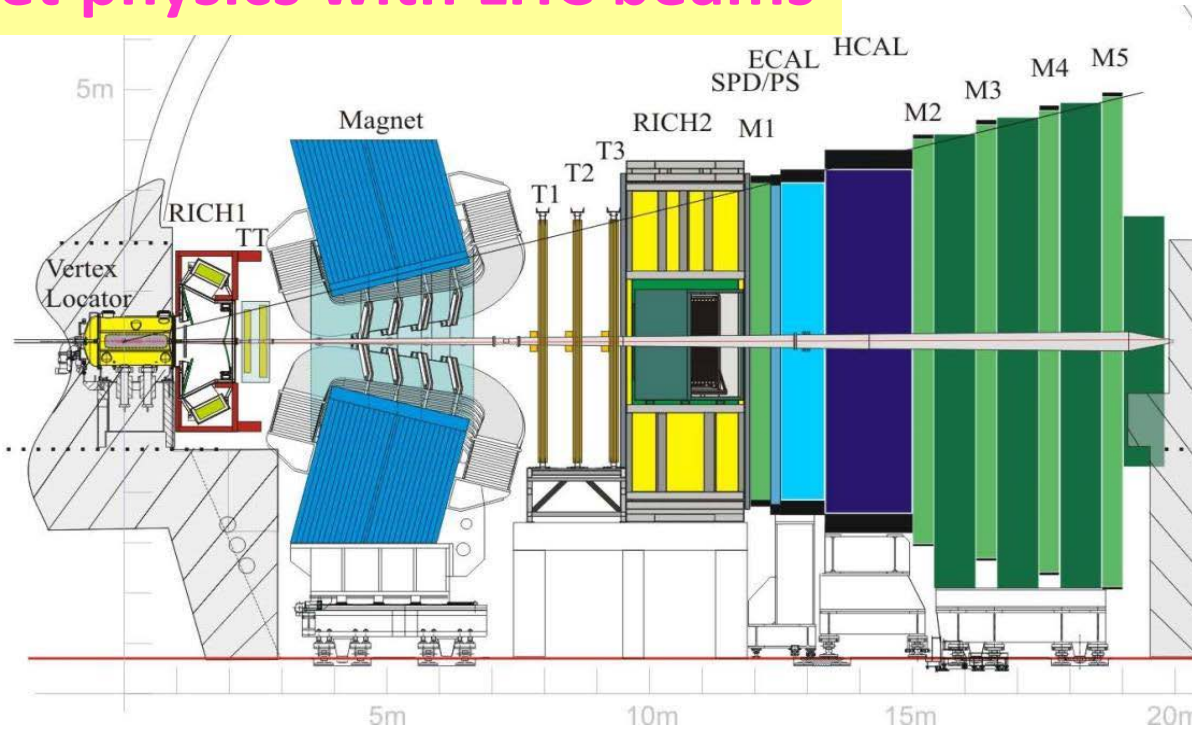
New idea: Fixed Target physics with LHC beams

Crystal extraction

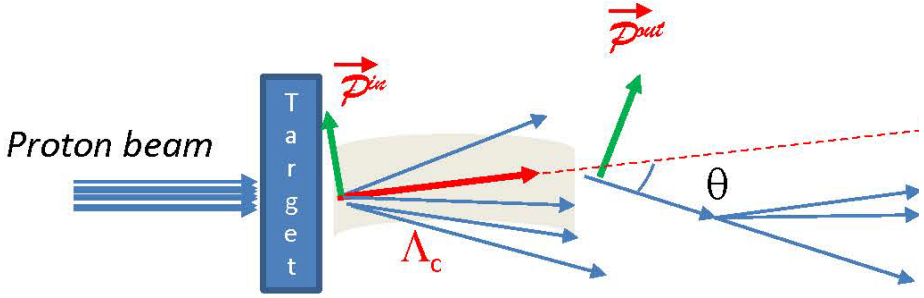


UA9

Upstream of LHCb and/or ALICE



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

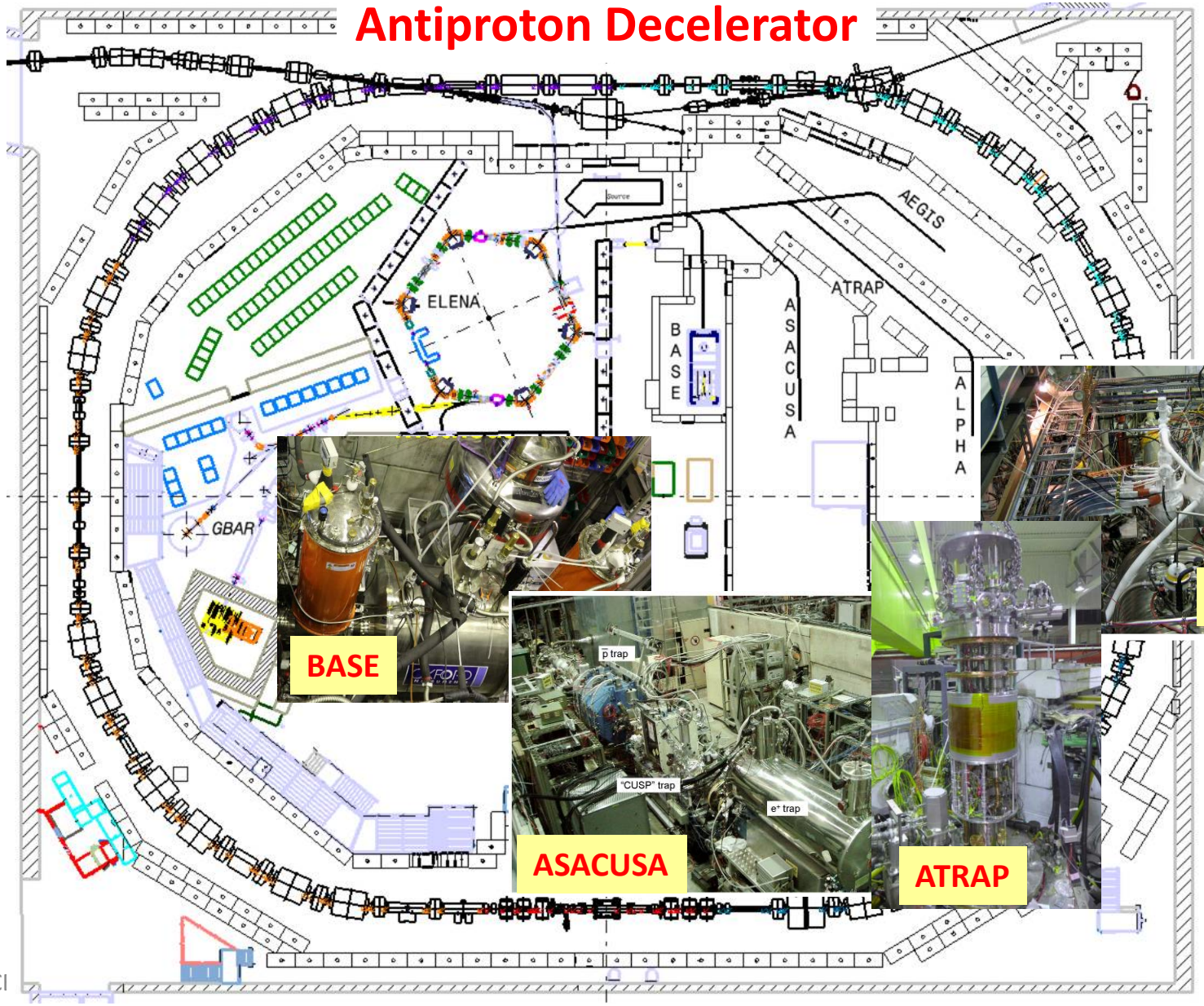


Proposed for measurement of magnetic moments of short lived baryons

Could test anomalous magnetic moments of heavy quarks

ANTIMATTER FACTORY

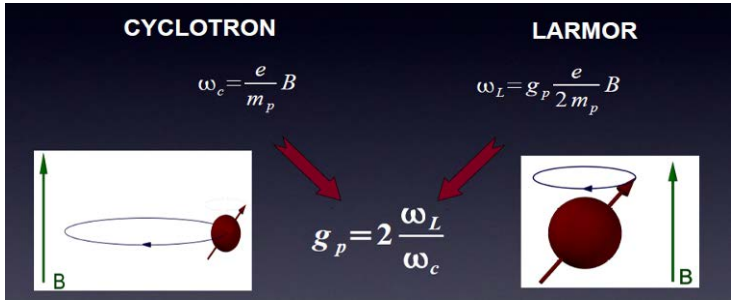
Antiproton Decelerator

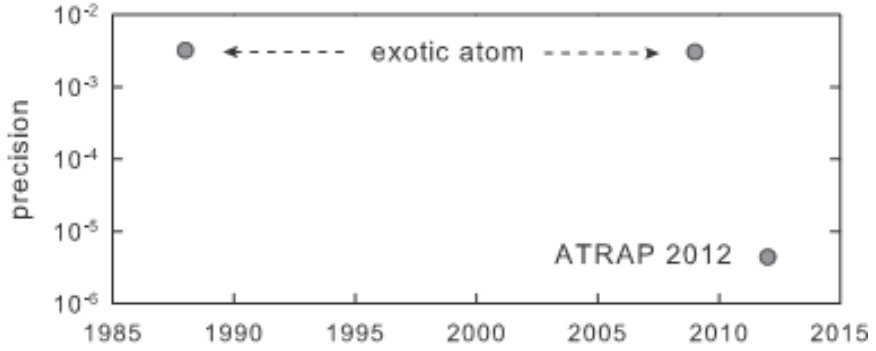


4 running experiments devoted to Antiproton and Antihydrogen properties

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

Antiproton Properties

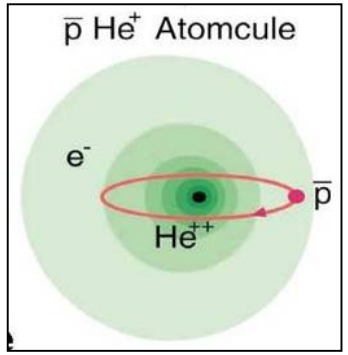


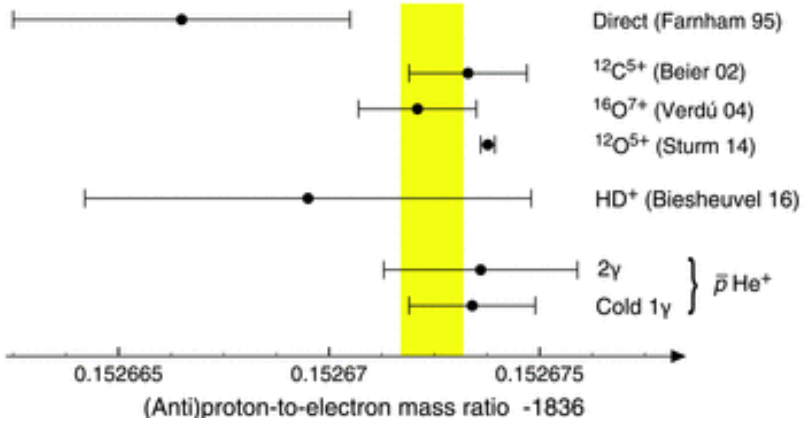


Magnetic moment:

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

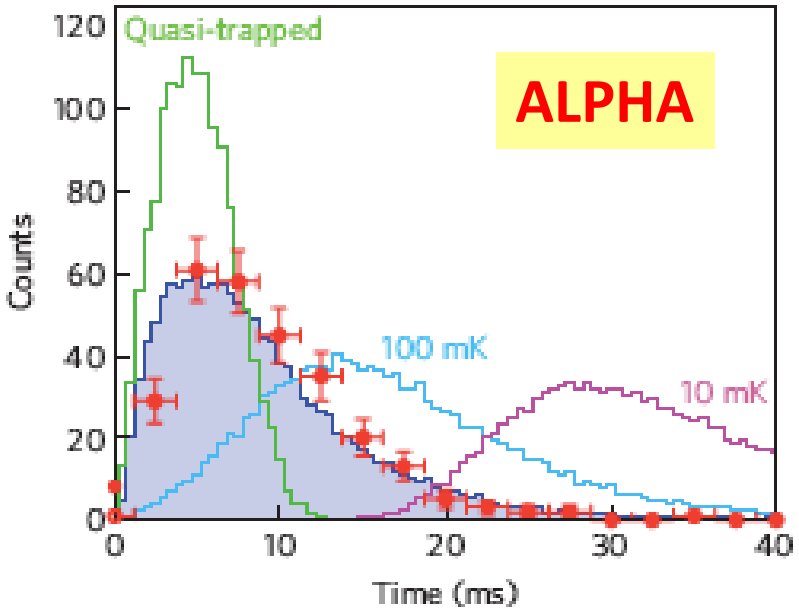
$$\frac{(-q/m)_{\bar{p}}}{(q/m)_{p}} - 1 = 1(69) \times 10^{-12}$$

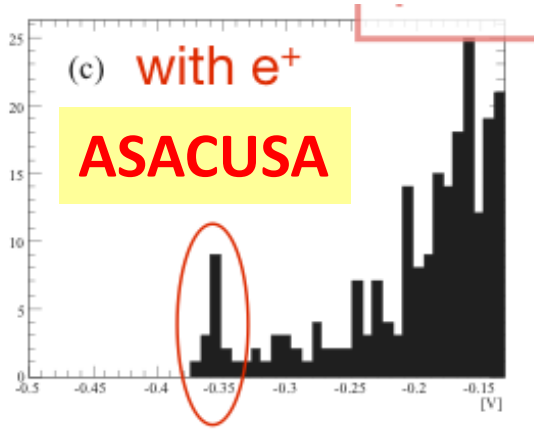
Charge/Mass:

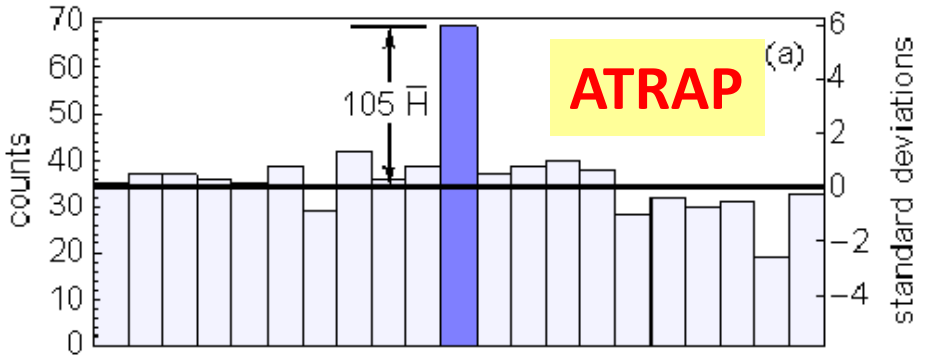
High precision BASE measurement with cyclotron frequency

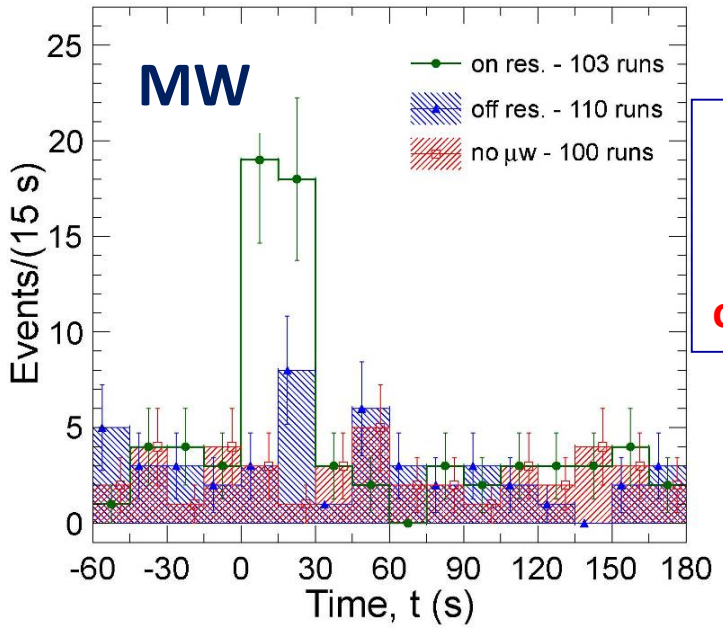
Antihydrogen Properties

Hbar trapping established by 3 experiments



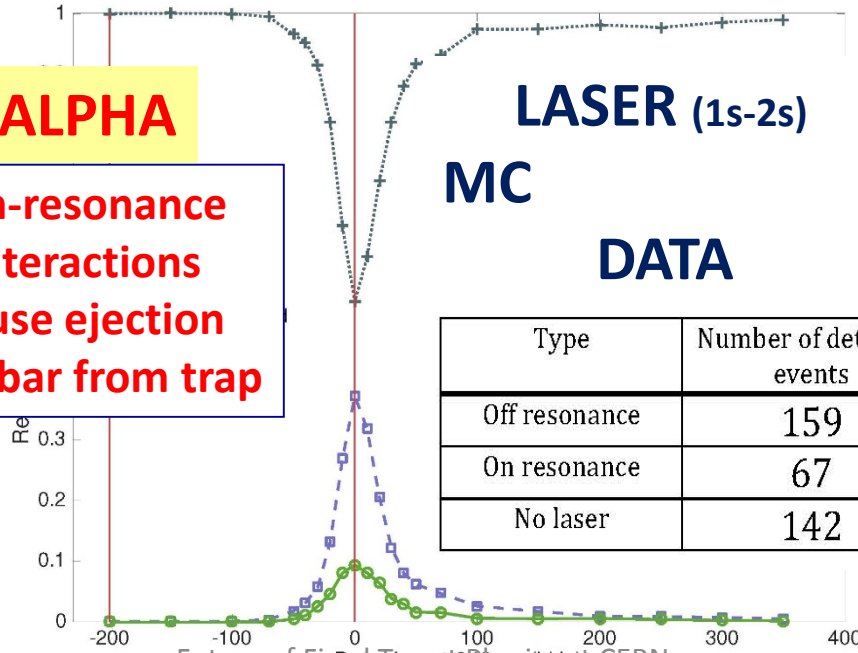






ALPHA

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

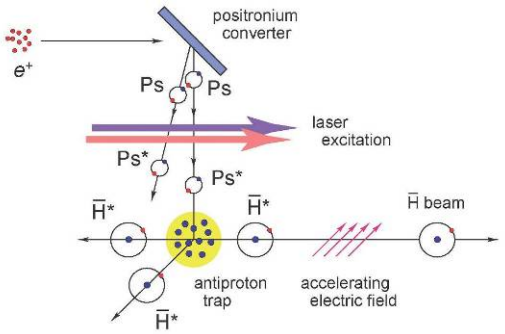
First Hbar microwave and laser spectroscopy performed by ALPHA

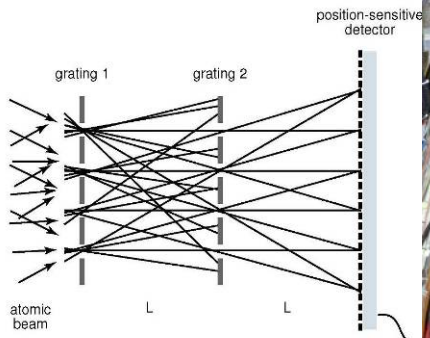
Antihydrogen Properties cont'd: gravitation

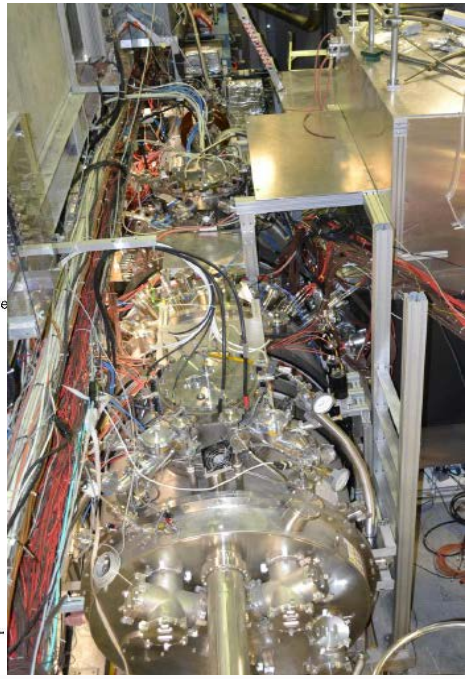
2.5 experiments now devoted to a direct measurement

AEGIS

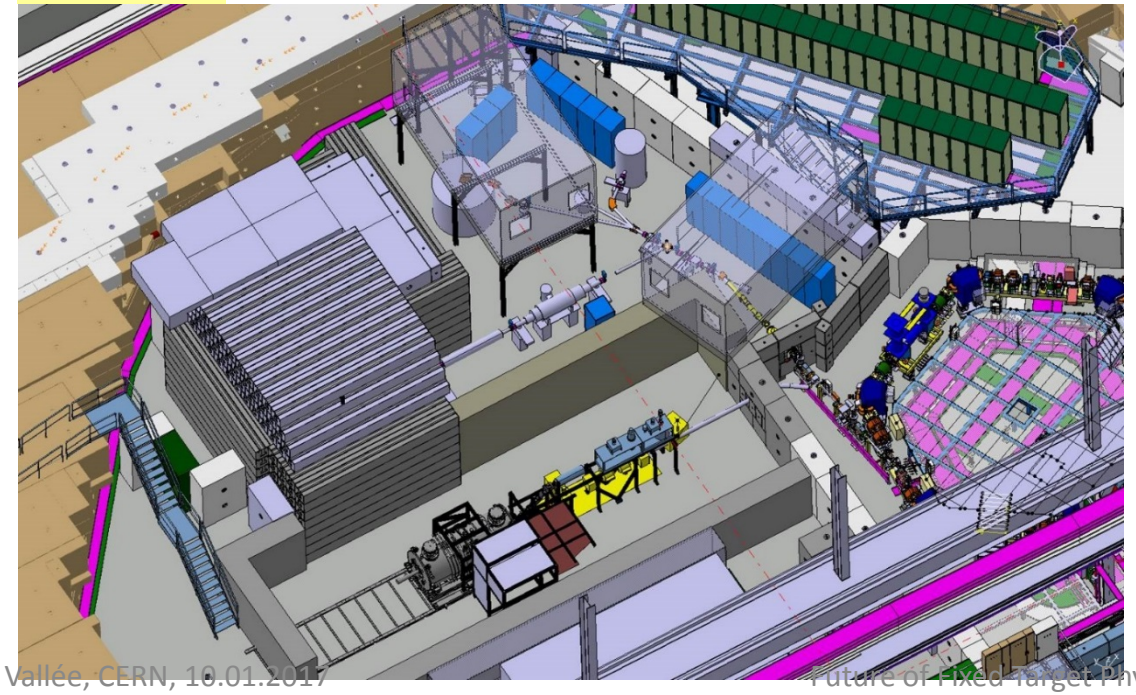
in-flight deviation of
Hbar atoms by gravitation

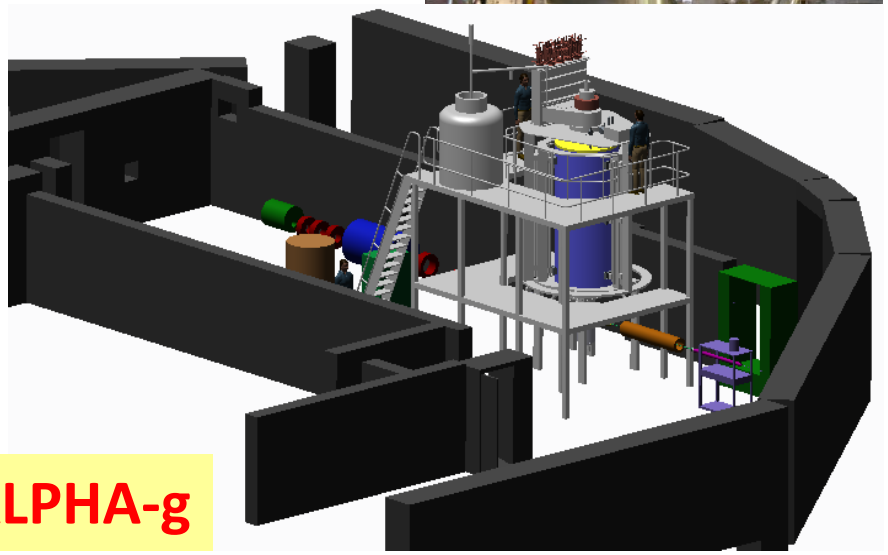






GBAR: Hbar free fall using ELENA





ALPHA-g

Statistical method
for a first measurement of the sign

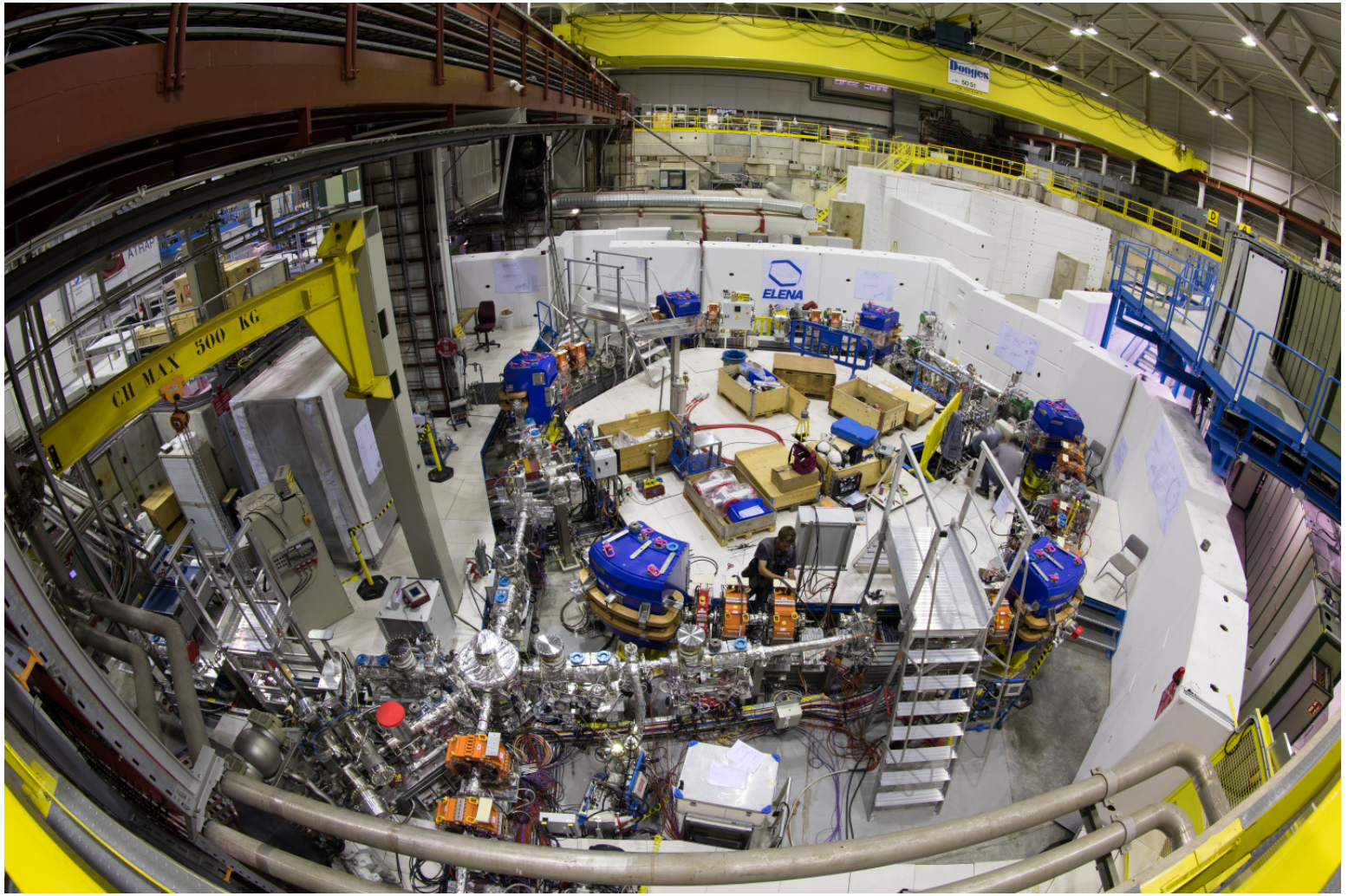
AFTER LS2: ELENA

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

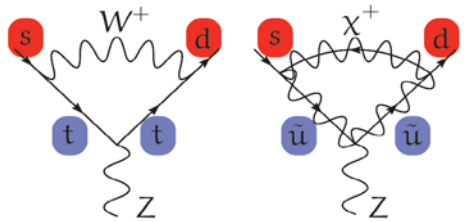
Secures antimatter physics for the next decade



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

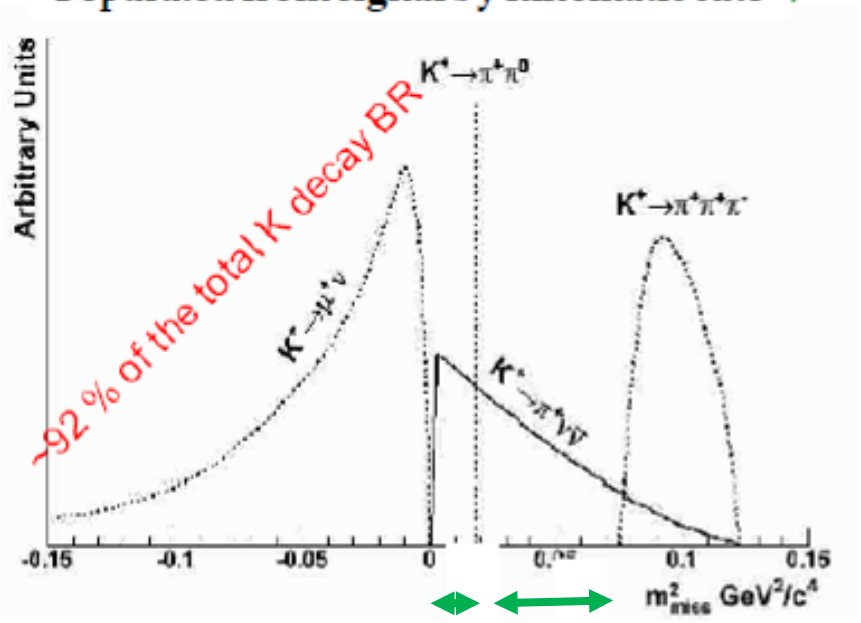
NA62

Rare K decays

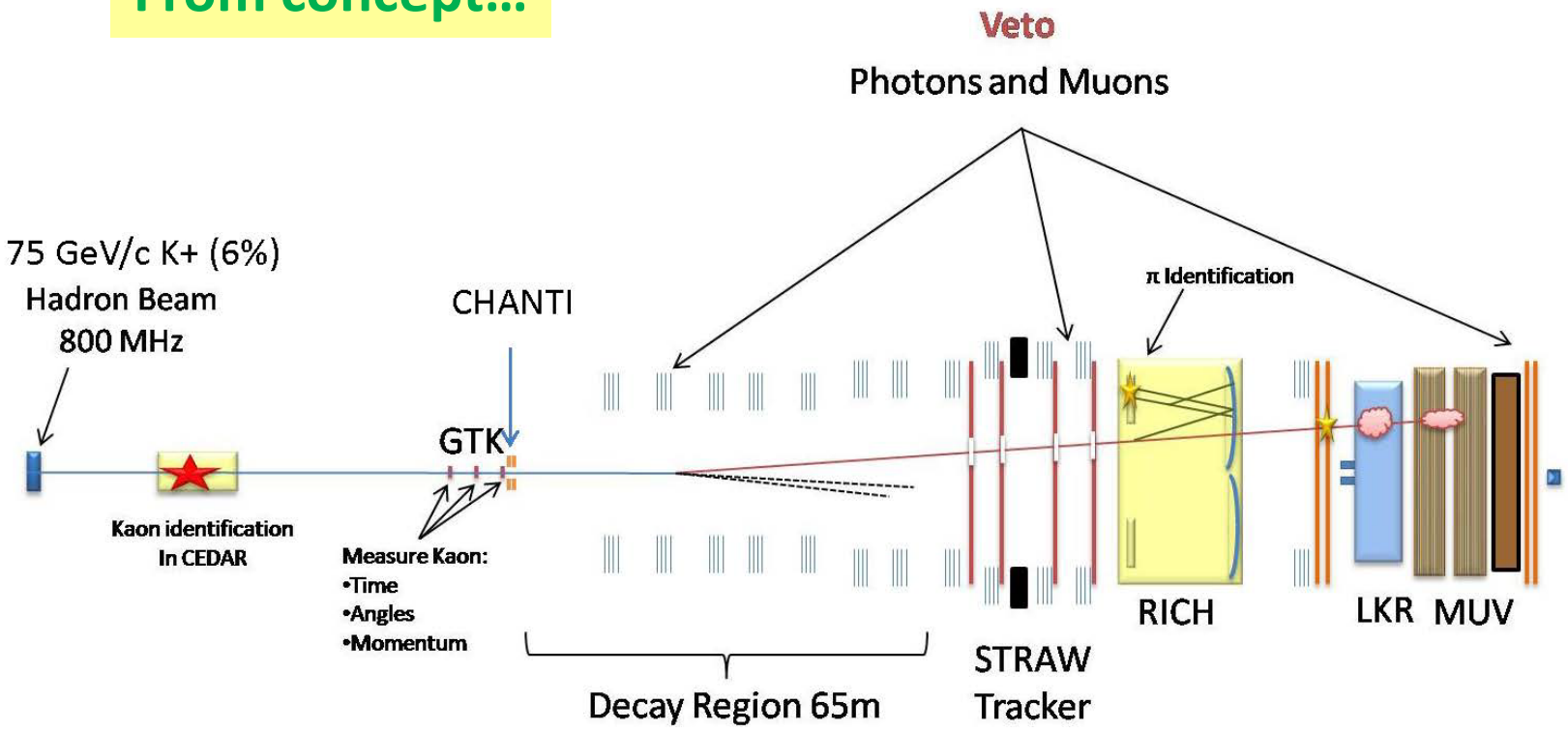


From concept…

Separated from signal by kinematic cuts :



Signal regions

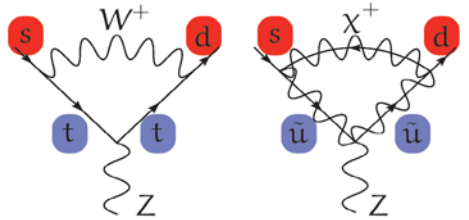


1 GHz 75 GeV unseparated beam,
11 MHz K^+ decays in detector

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

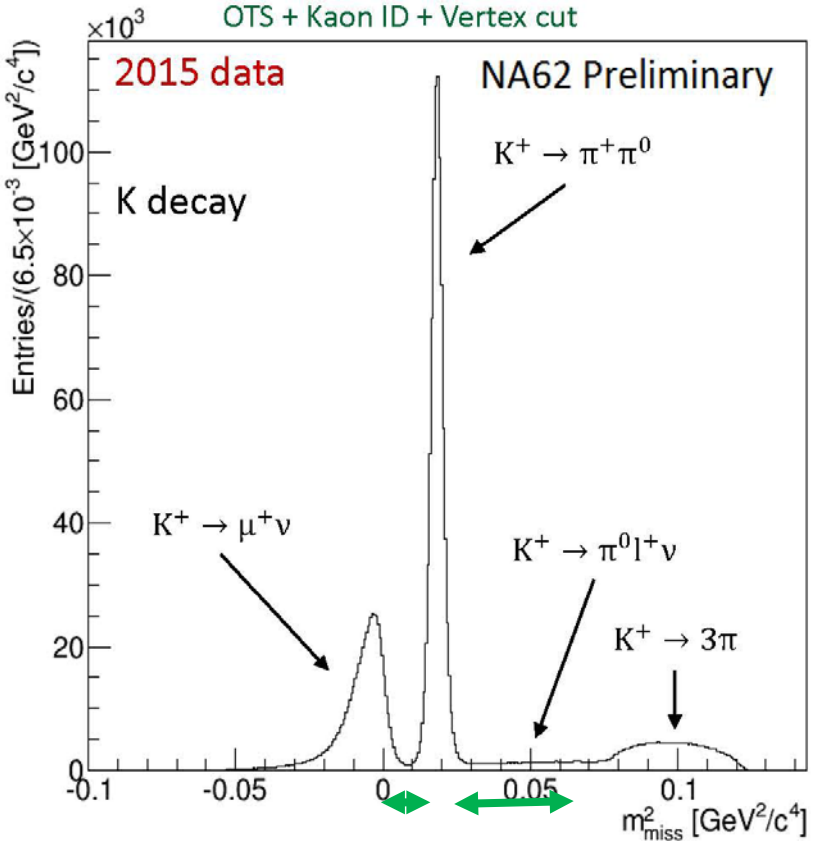
NA62

Rare K decays



…to reality !

After many years of intensive construction and commissioning



Signal regions: ~100 evts expected until LS2

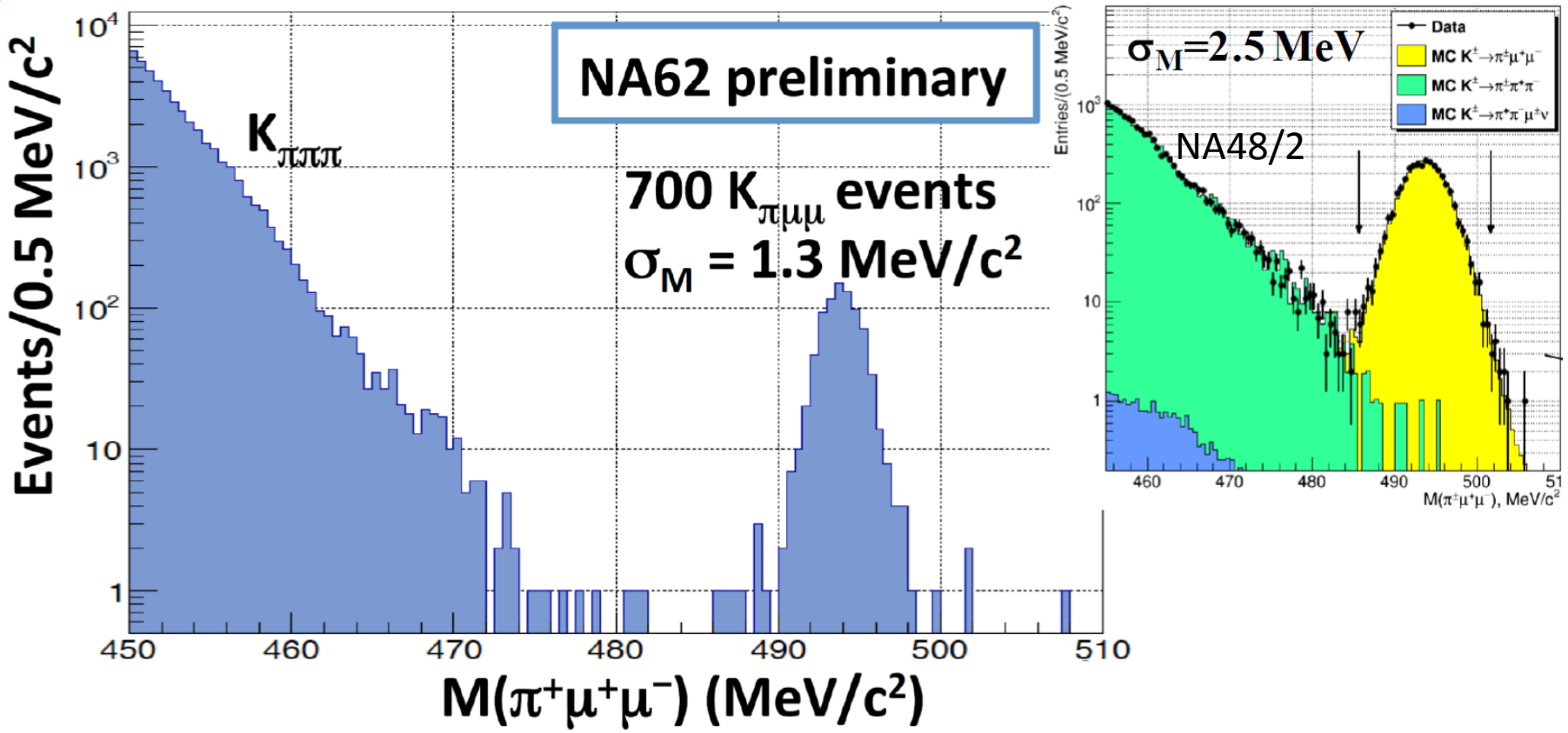
Detector fully operational in 2016, first year of quasi-nominal operation

First look at NA62 2016 Data

Slide shown at CKM2016 2 months ago…

Dimuon trigger, few % of the data, BR~9 10^{-8}

$$K^+ \to \pi^+ \mu^+ \mu^-$$



Mass resolution better by a factor ~2 with respect to NA48/2

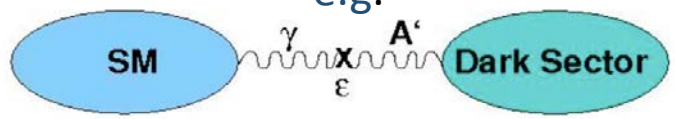
Intermezzo: the Hidden Sector

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

Visible Sector

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

e.g.



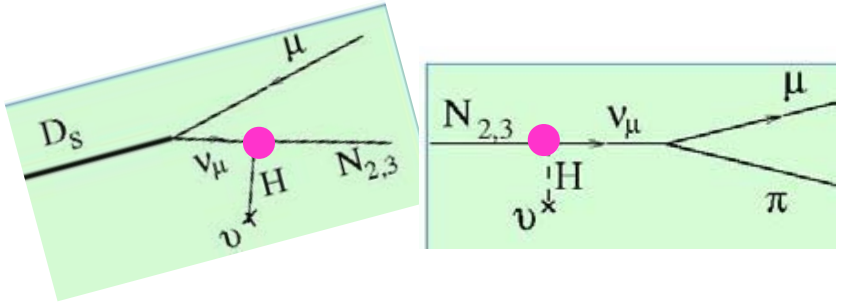
Hidden Sector

Naturally accommodates Dark Matter
(may have rich structure)

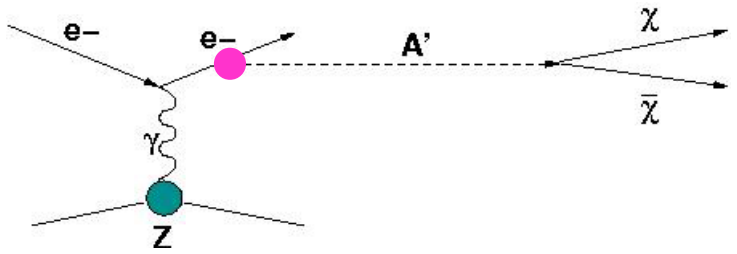
- *Long-lived objects*
- *Interact very weakly with matter*

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

Intermezzo cont'd: the Hidden Sector



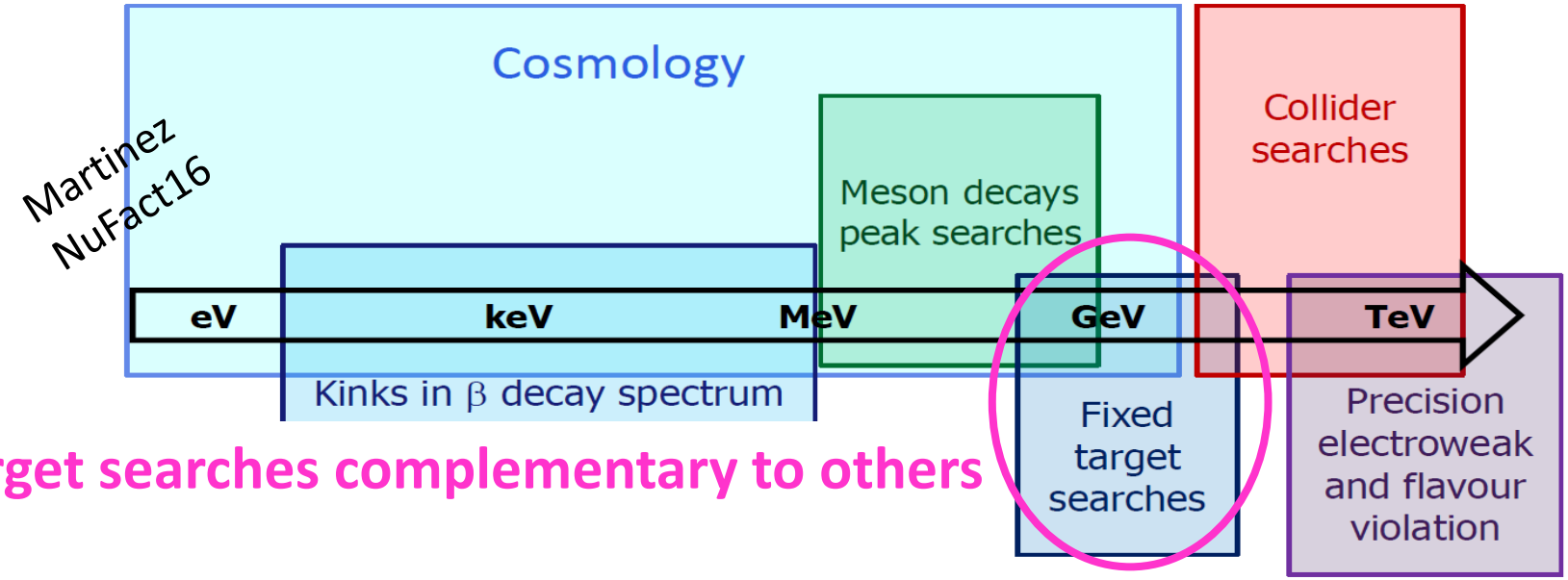
2 methods



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 !

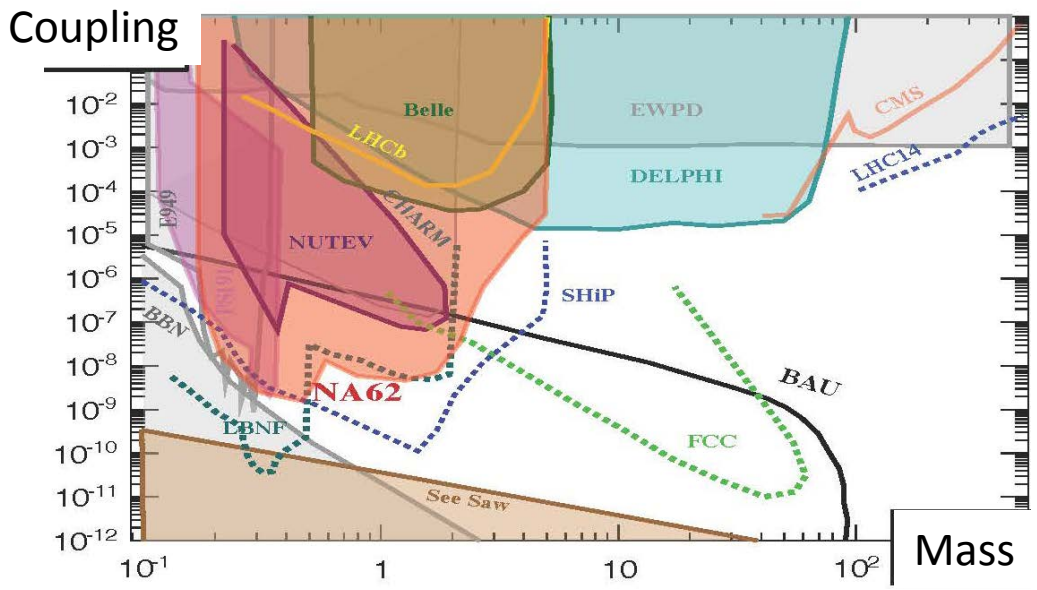


Fixed Target searches complementary to others

AFTER LS2 : NA62+

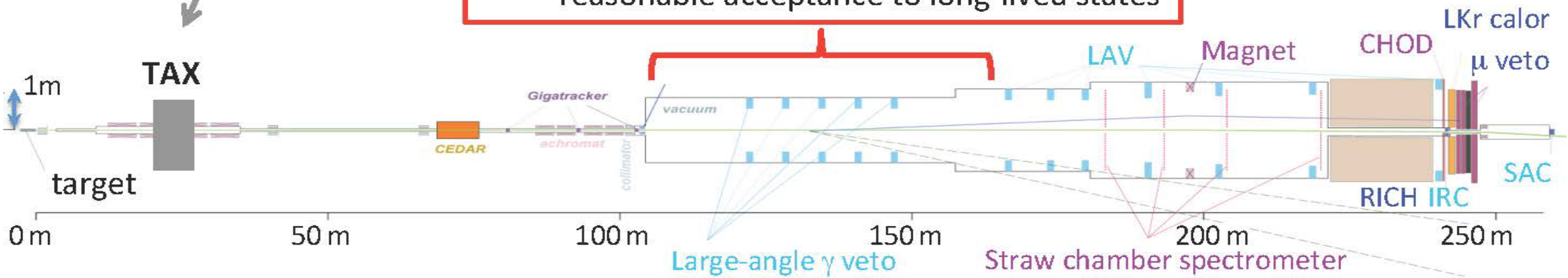
Wish to run ~1 year in beam dump mode to look for Heavy Neutral Leptons

→ 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



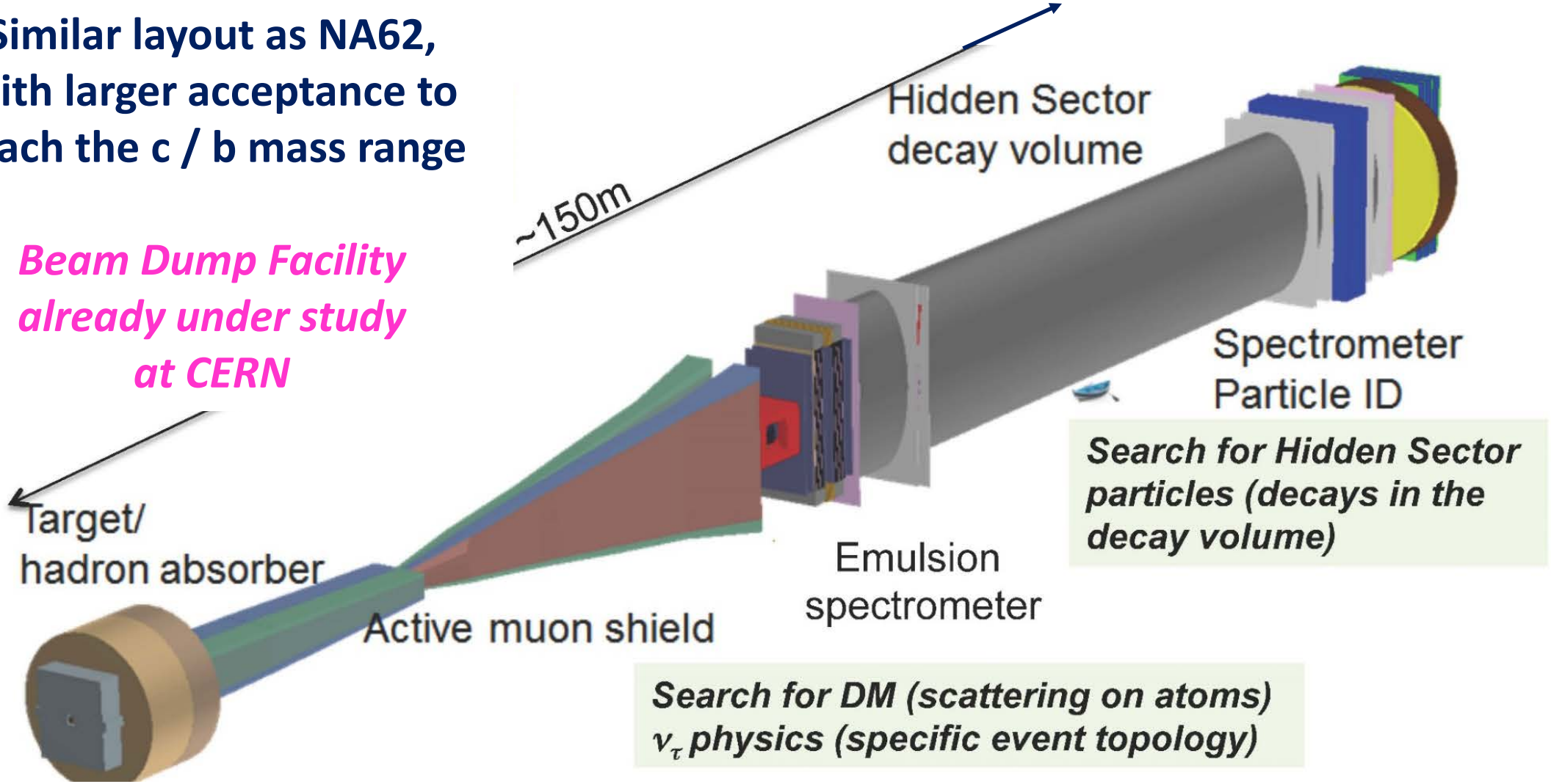
SHiP

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

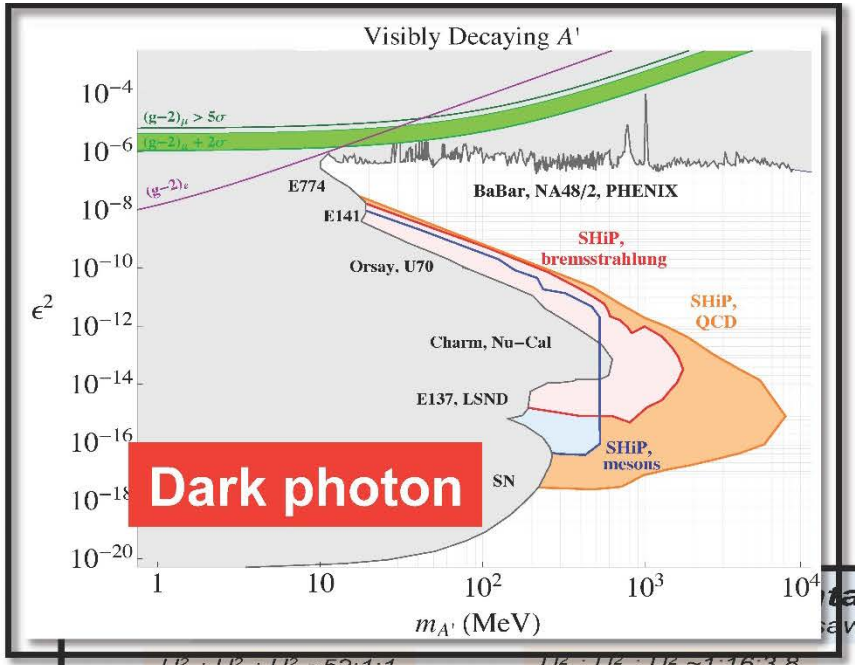
Beam Dump Facility already under study at CERN



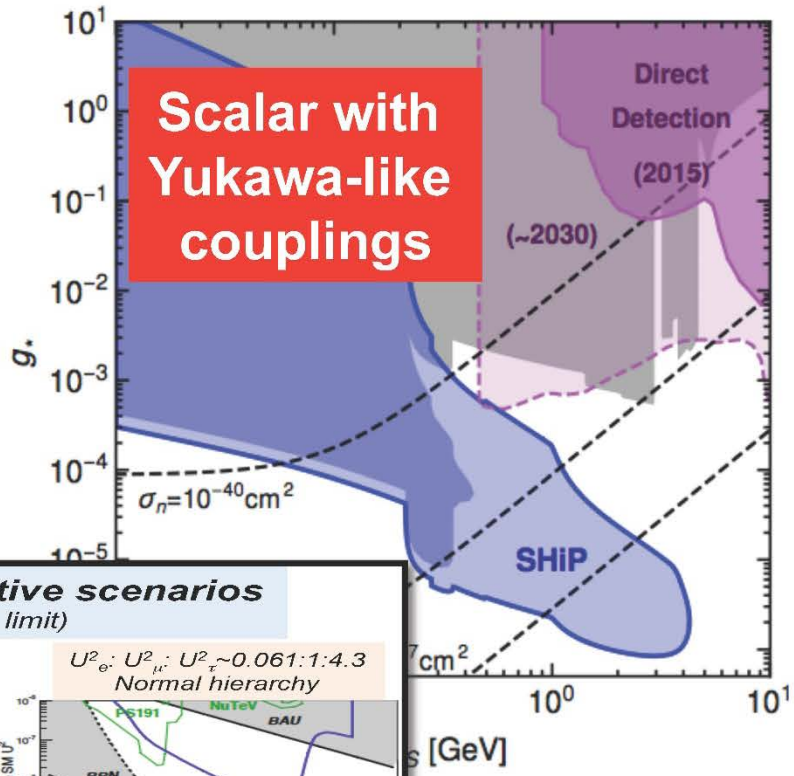
Search for Hidden Sector particles (decays in the decay volume)

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

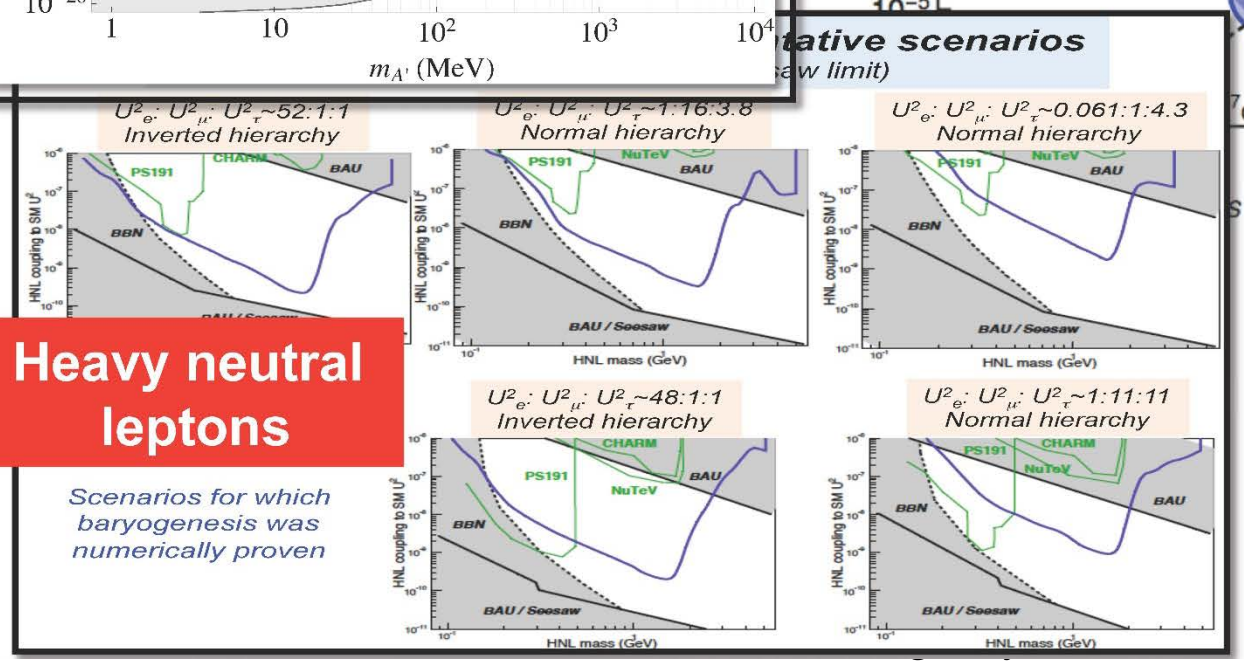
SHiP physics reach



Dark photon



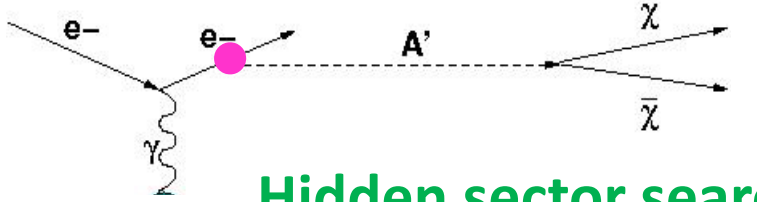
Scalar with Yukawa-like couplings



Heavy neutral leptons

Scenarios for which baryogenesis was numerically proven

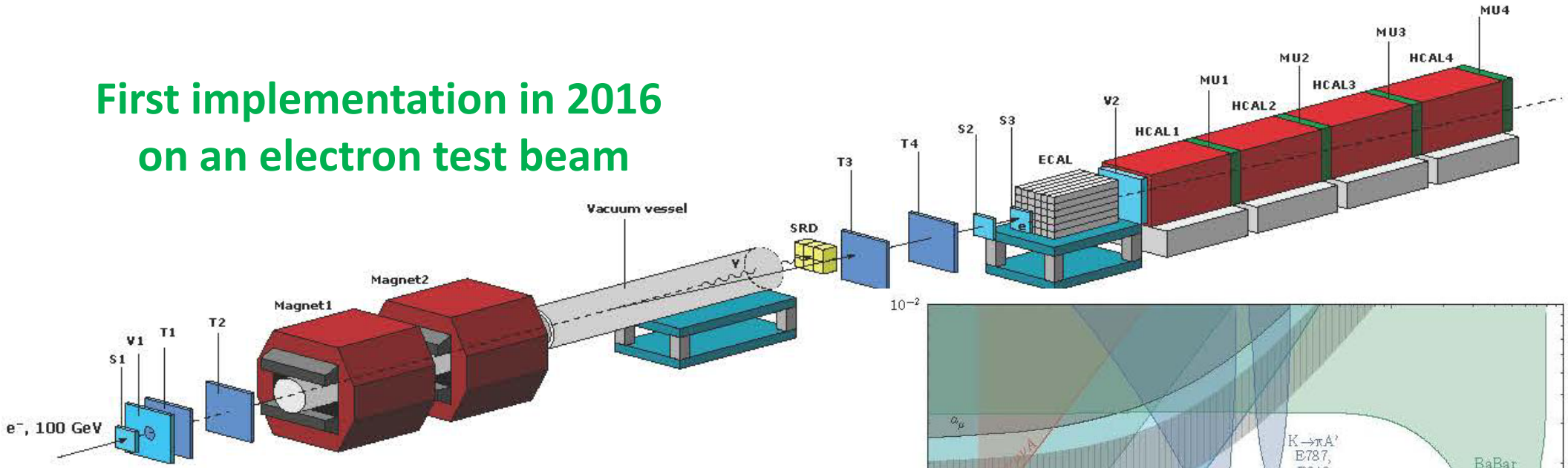
Significant & mostly unique extension of reach for many channels



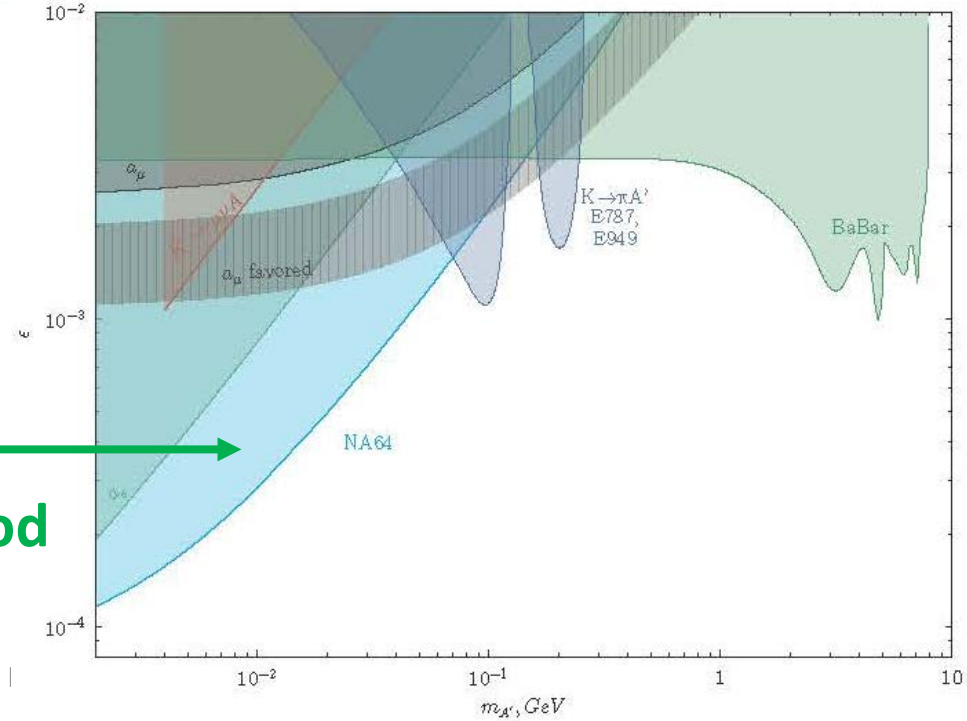
NA64

Hidden sector search from invisible decays with missing energy

First implementation in 2016
on an electron test beam

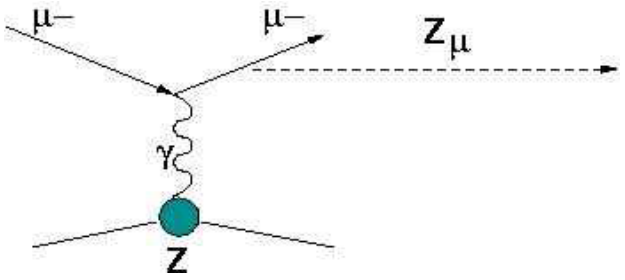


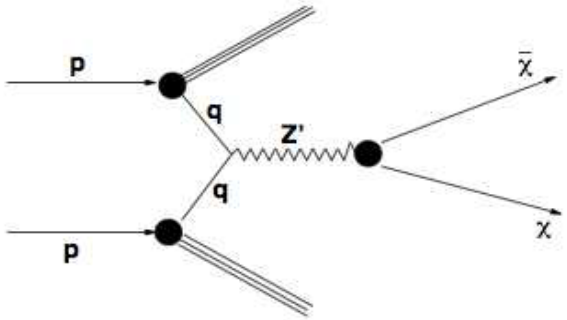
Exclusion of $(g\text{-}2)_\mu$ interpretation
with 1 day of data taking
confirms the potential of the method
(more data under analysis)



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 Sectors: Dark Photons and DM $(g-2)_\mu$ new particles, Charge Quantization	$10^{-3} < \varepsilon < 10^{-6}$ $M_{A'} \sim$ sub-GeV $e' < 10^{-5}$-10^{-7}
2. $\mu^- Z \to \mu^- Z + E_{miss}$		
✧ $Z_\mu \to \nu\nu$, $\mu^+\mu^-$ ✧ μ->τ conversion	New gauged symmetry $L_\mu - L_\tau$ and leptonic forces LFV	$\alpha_\mu < 10^{-11}$-10^{-9} $\sigma < 10^{-9}$-$10^{-8}/\mu$
3. $\pi(K)p \to M^0 n + E_{miss}$		
✧ $K_L \to$ invisible ✧ $K_S \to$ invisible ✧ π^0, η, $\eta' \to$ invisible	CP, CPT symmetry B-S Unitarity, new particles: NHL, ϕϕ, VV	Br $< 10^{-8}$-10^{-6}, comple- mentary to K->πνν Br$< 10^{-8}$-10^{-7}
4. $pA \to X + E_{miss}$		
✧ leptophobic X	~ GeV DM	$\sigma < 10^{-7}$-10^{-8} /p

PHYSICS BEYOND COLLIDERS ORGANISATION

Working Groups structure and membership defined :

- **Accelerator WG to study possible implementation of the projects at CERN.**
  Core members: CERN accelerator people + projects proponents

- **Physics WG to study the physics case in worldwide context and optimize the projects**
  Core members: theorists&experimentalists + projects proponents

NB1: Working Groups will be open to persons willing to contribute.
Core members will warrant adequate expertise and follow-up of the activities.

NB2: List of projects will stay open to new ideas and may evolve.

ACCELERATOR WORKING GROUP STRUCTURE

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 WORKING GROUP STRUCTURE

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

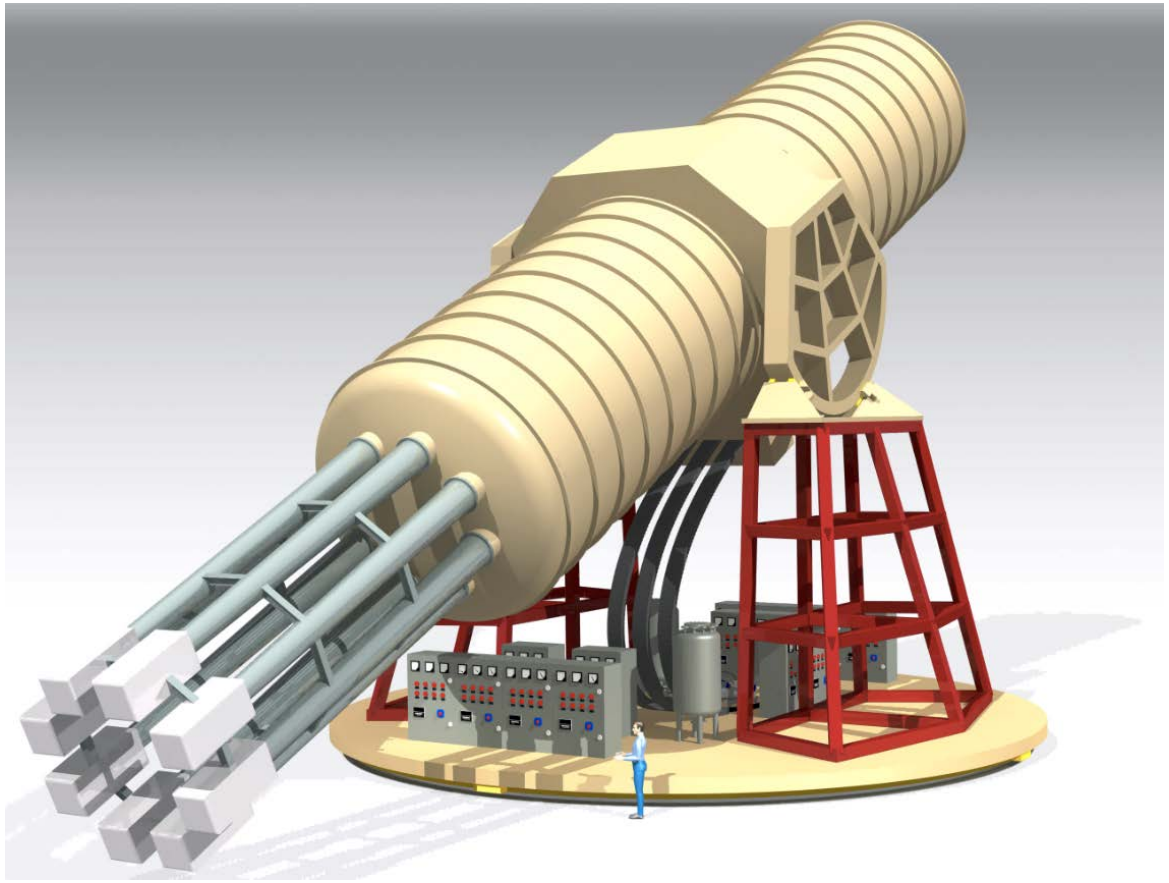
BSM subgroup : SHiP/NA64+/NA62+/IAXO/OSQAR-ALPS-III/EDM …

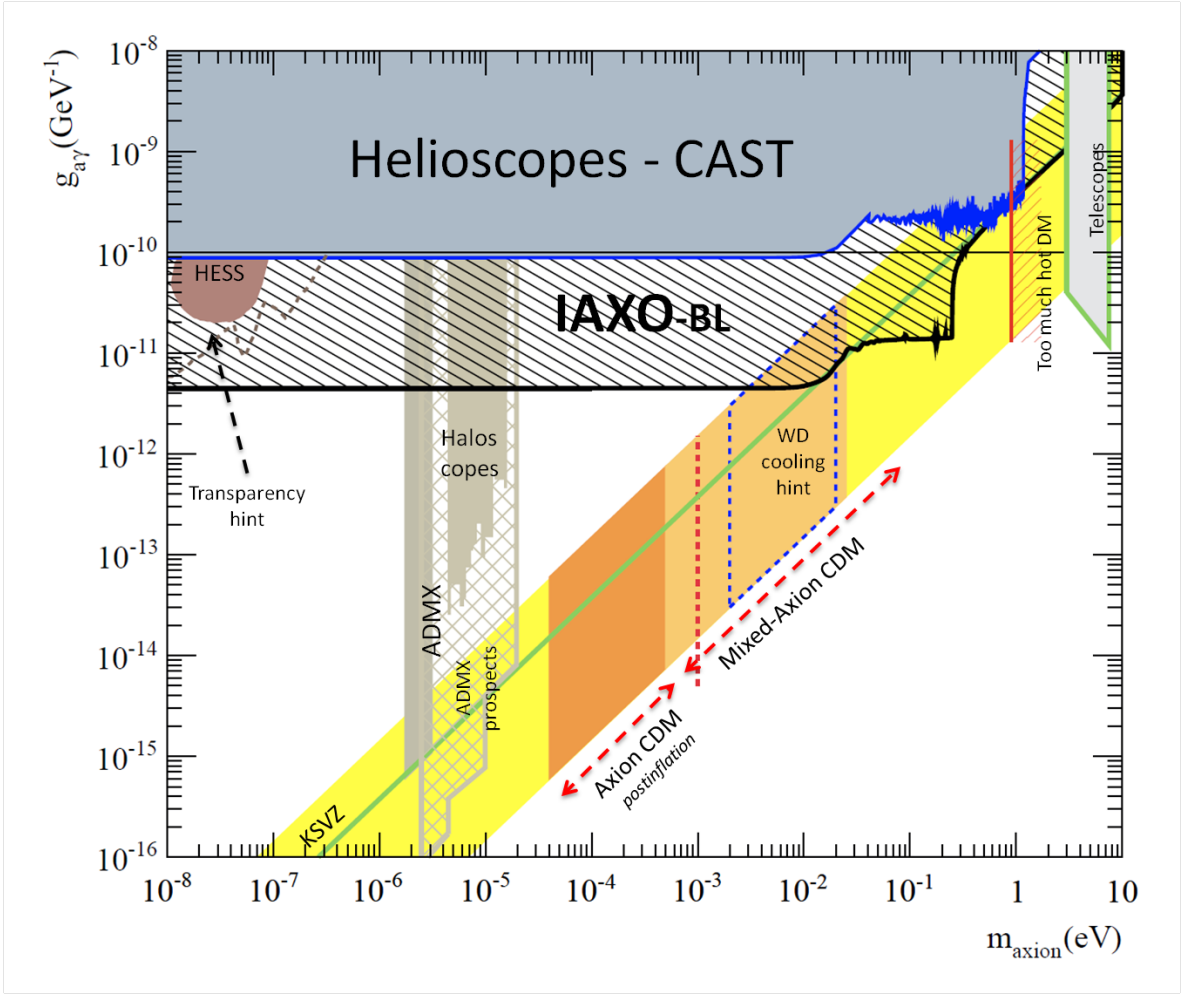
QCD subgroup : COMPASS+/μ-e/LHC-FT/DIRAC+/NA60+/NA61+ …

ADDITIONAL SLIDES:
NON-FIXED TARGET PBC PROJECTS

New idea: IAXO

Next generation Axion Helioscope beyond CAST

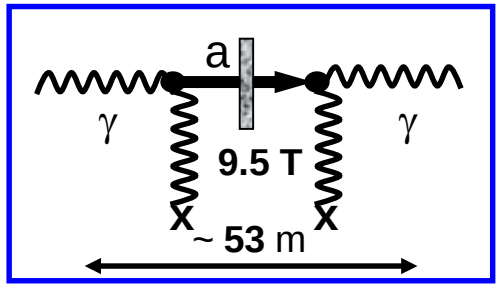


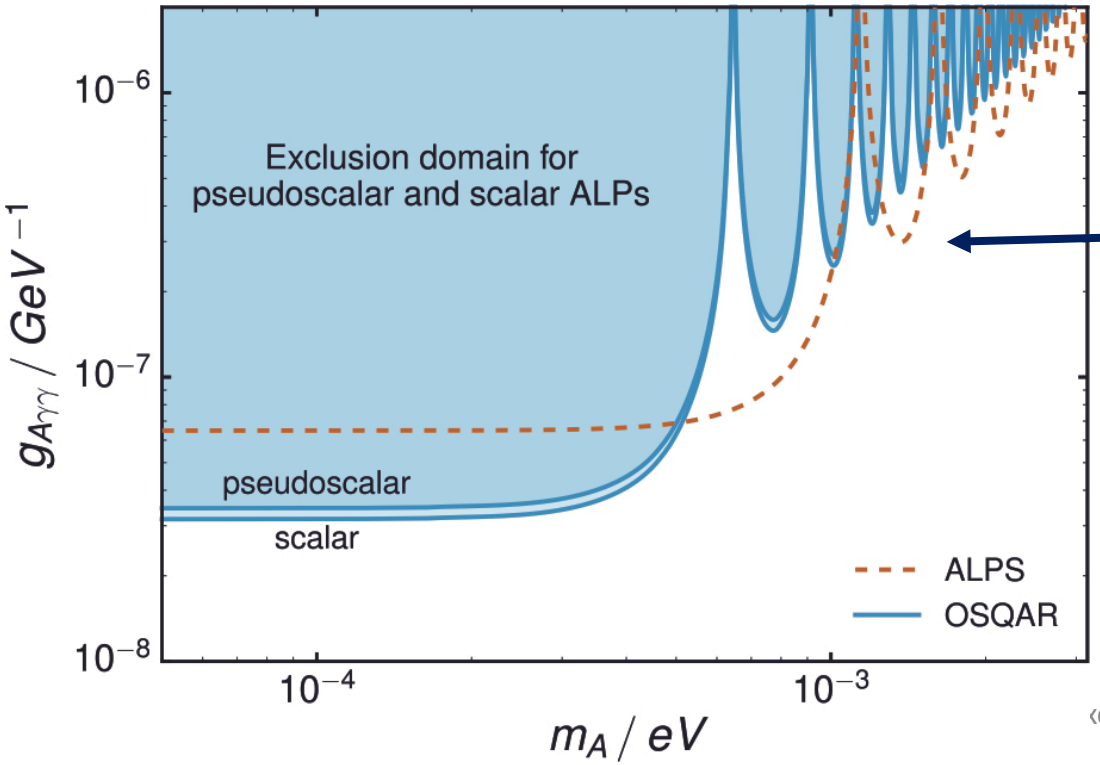


Wish to profit from CERN magnet expertise (ATLAS-like large bore toroid)

Laboratory Axions: OSQAR/ALPS

Light shining through a wall



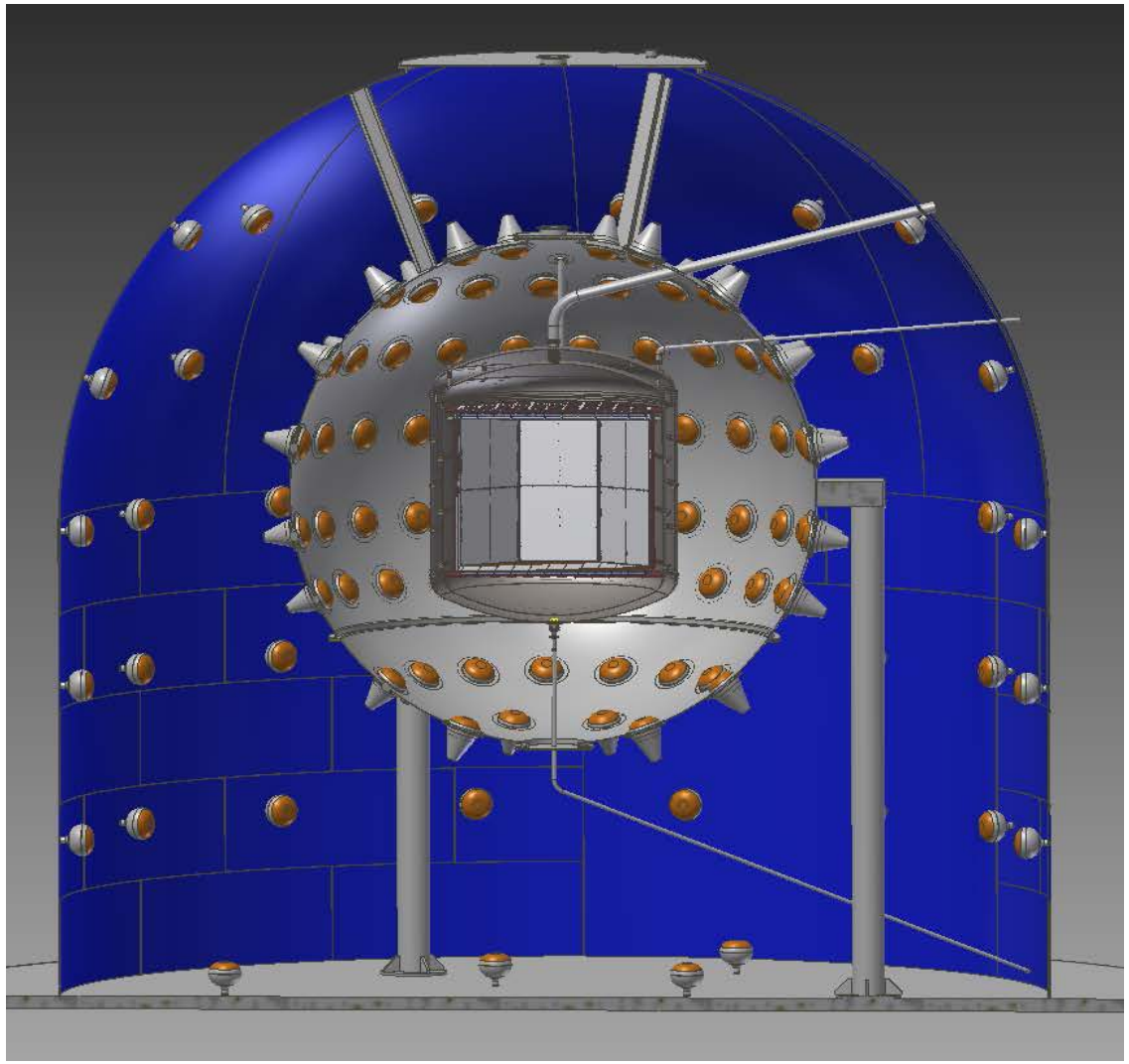


Comparable limits obtained by OSQAR@CERN and ALPS@DESY

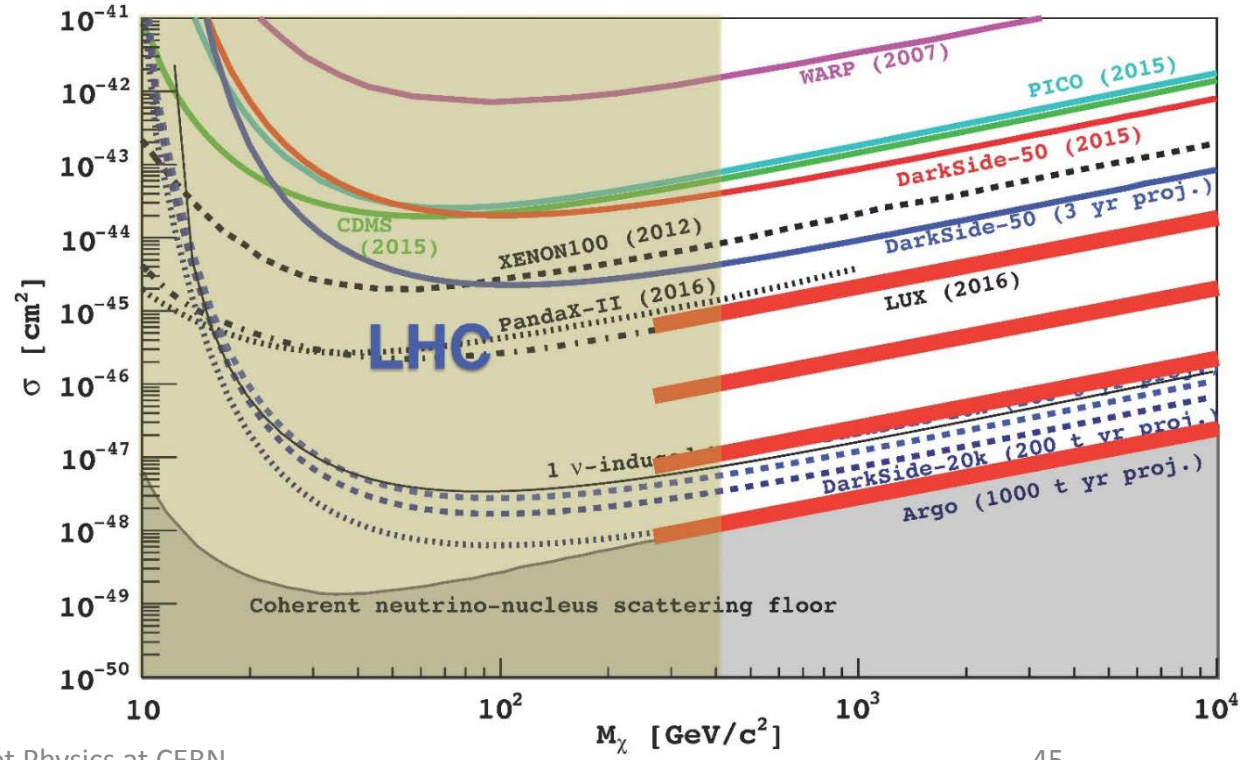
A combined project ("ALPS III") could benefit from CERN high field magnet developments

New idea: DARKSIDE@LNGS

"Ultimate" WIMP search with depleted LAr double phase TPC

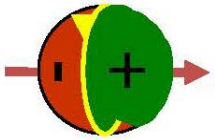


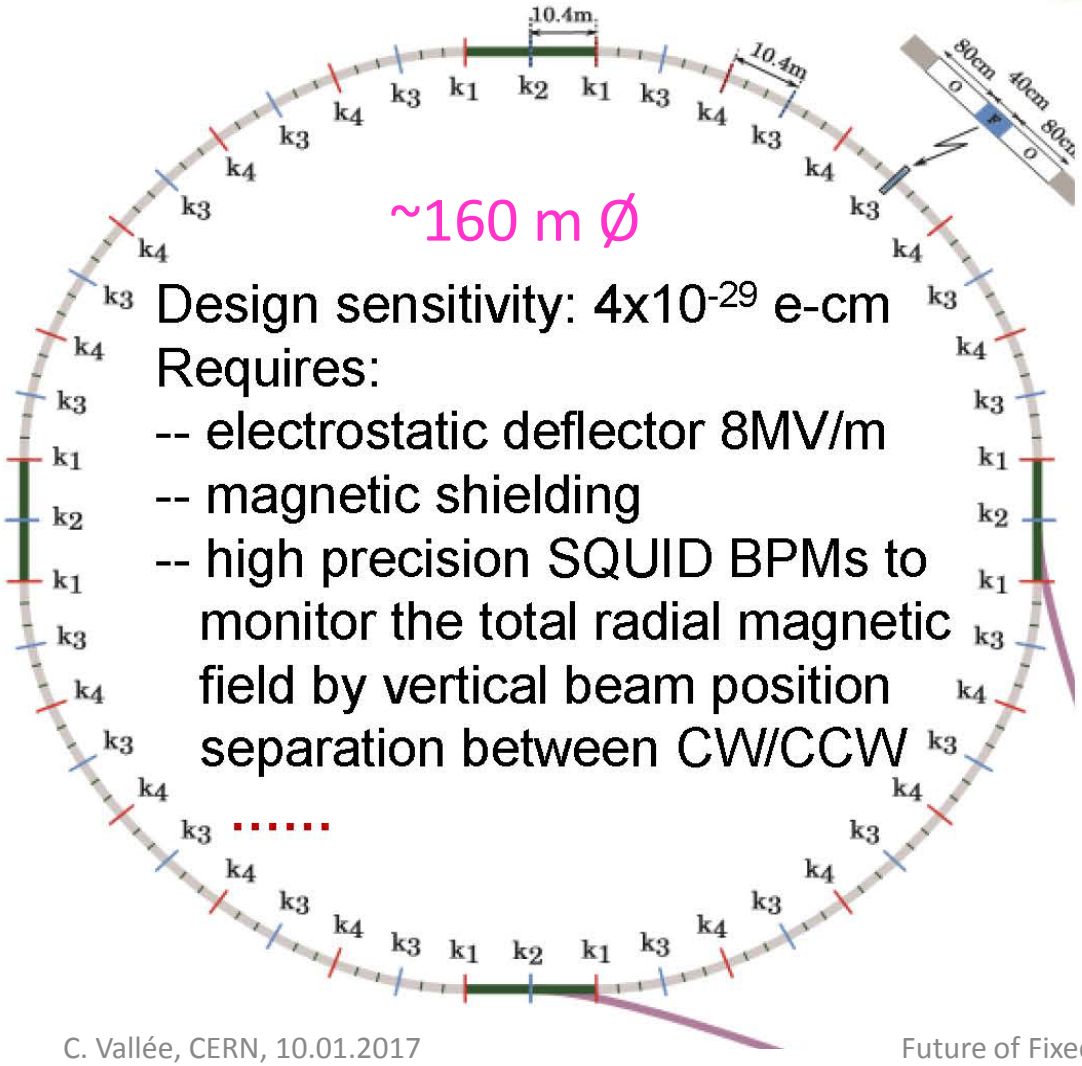
Wish to exploit synergies with CERN on LAr, cryogeny, low noise SiPMs, etc…



New idea: Storage Ring for proton EDM

incl. electrostatic option
applicable to proton only

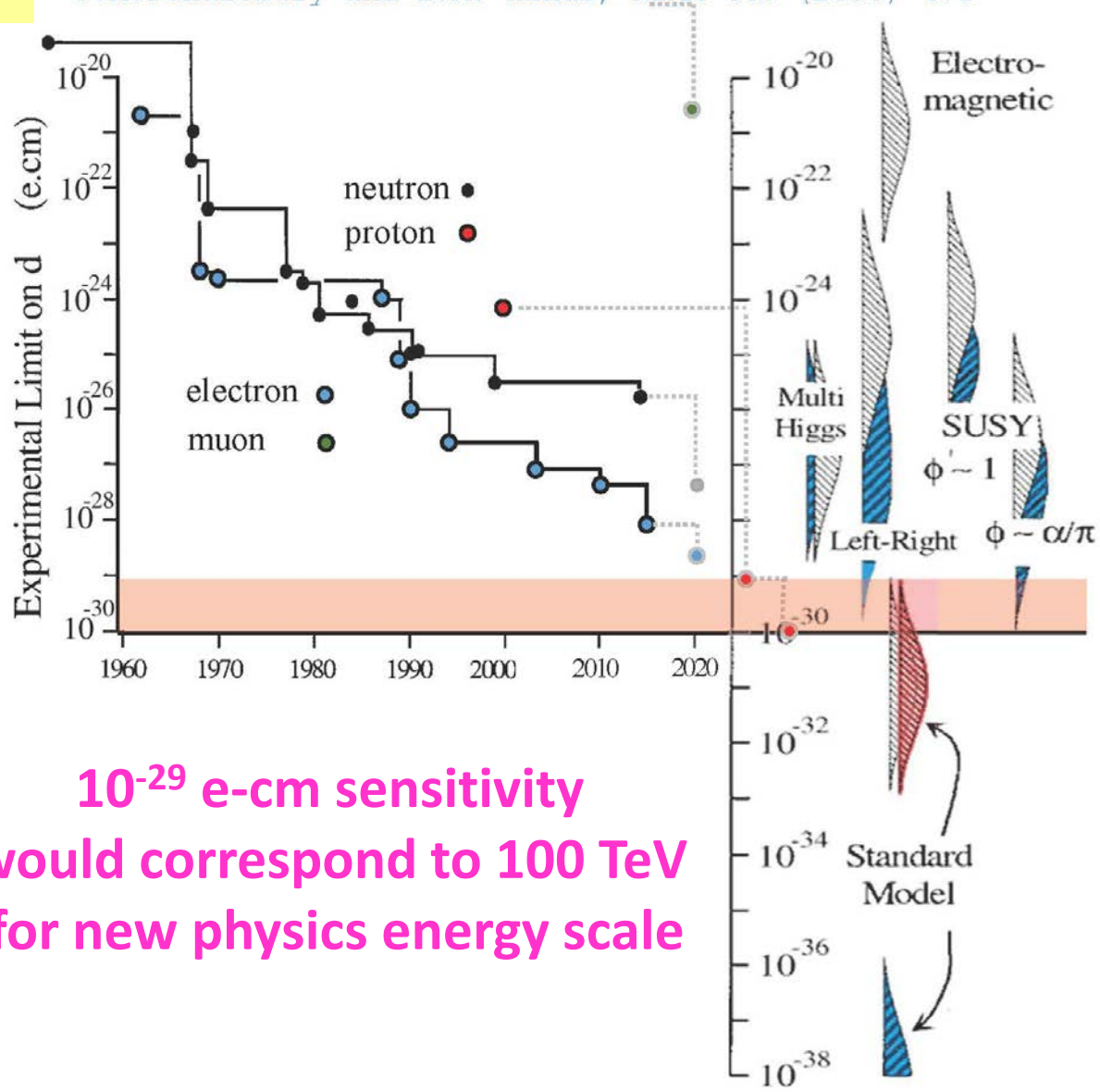




~160 m Ø

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
.....

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

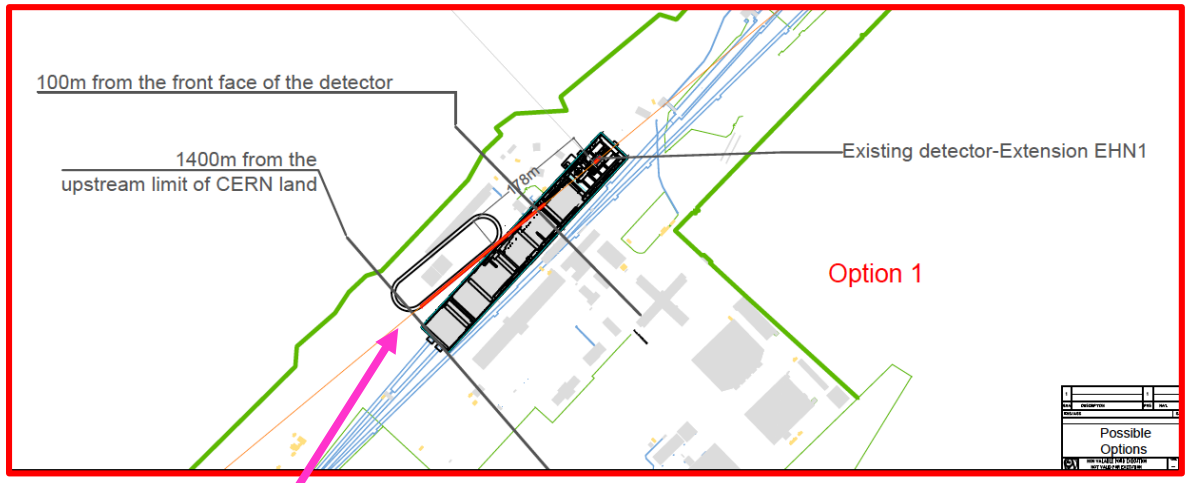


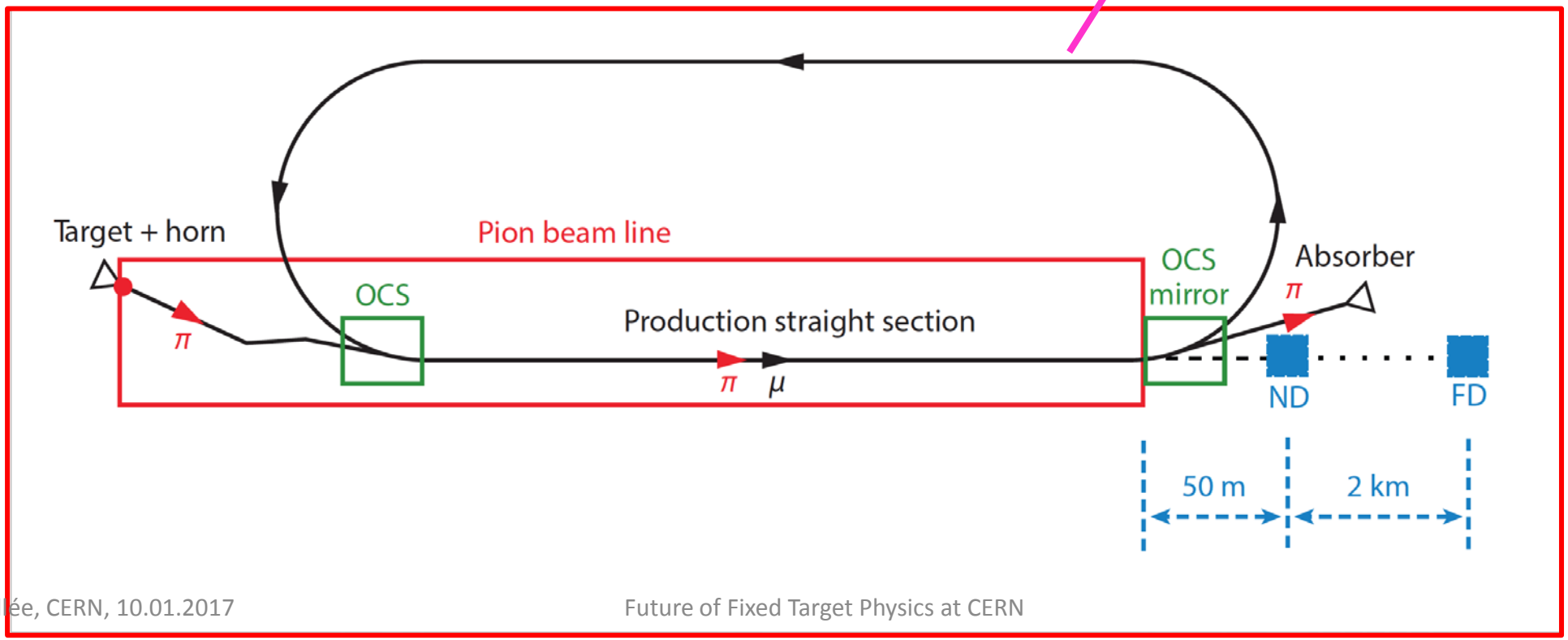
10^{-29} e-cm sensitivity would correspond to 100 TeV for new physics energy scale

New idea: NuSTORM

Well controlled ν beam from a μ storage ring.

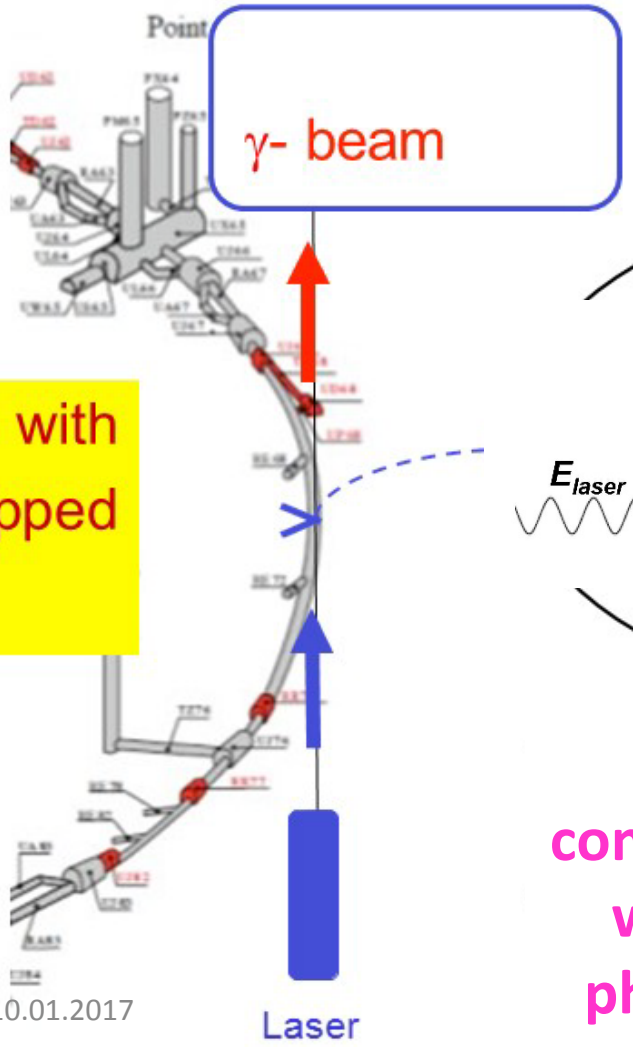
Would allow precise σ(ν) measurements.
Also a path towards a ν factory or a μ collider.



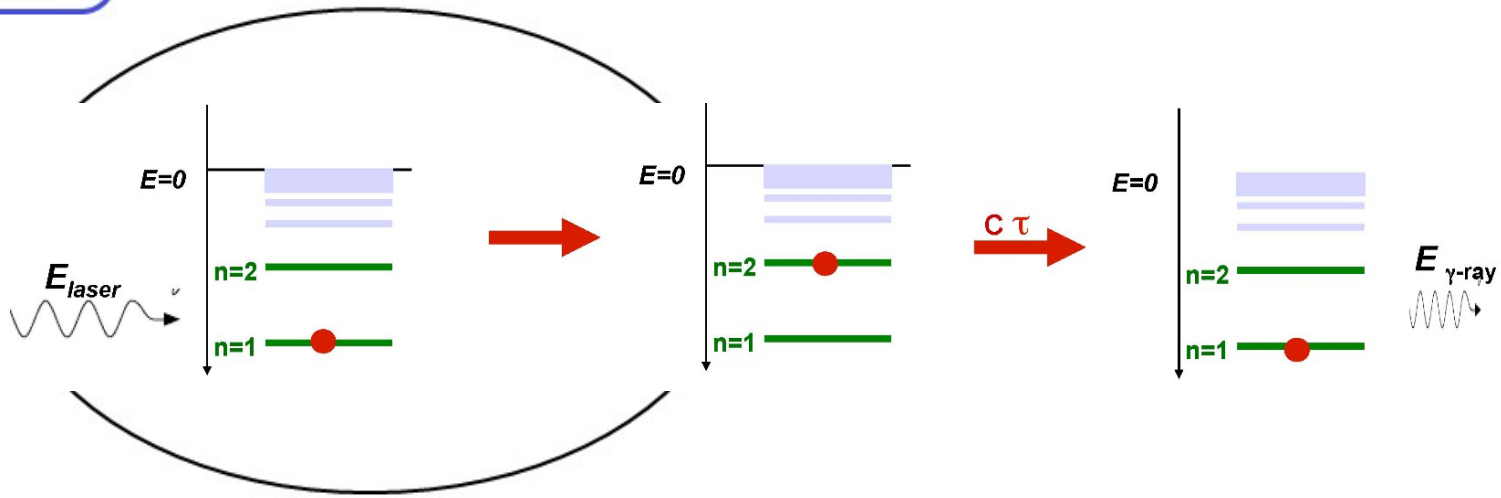


New idea: Gamma Factory

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



LHC filled in with partially stripped ion beams



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.