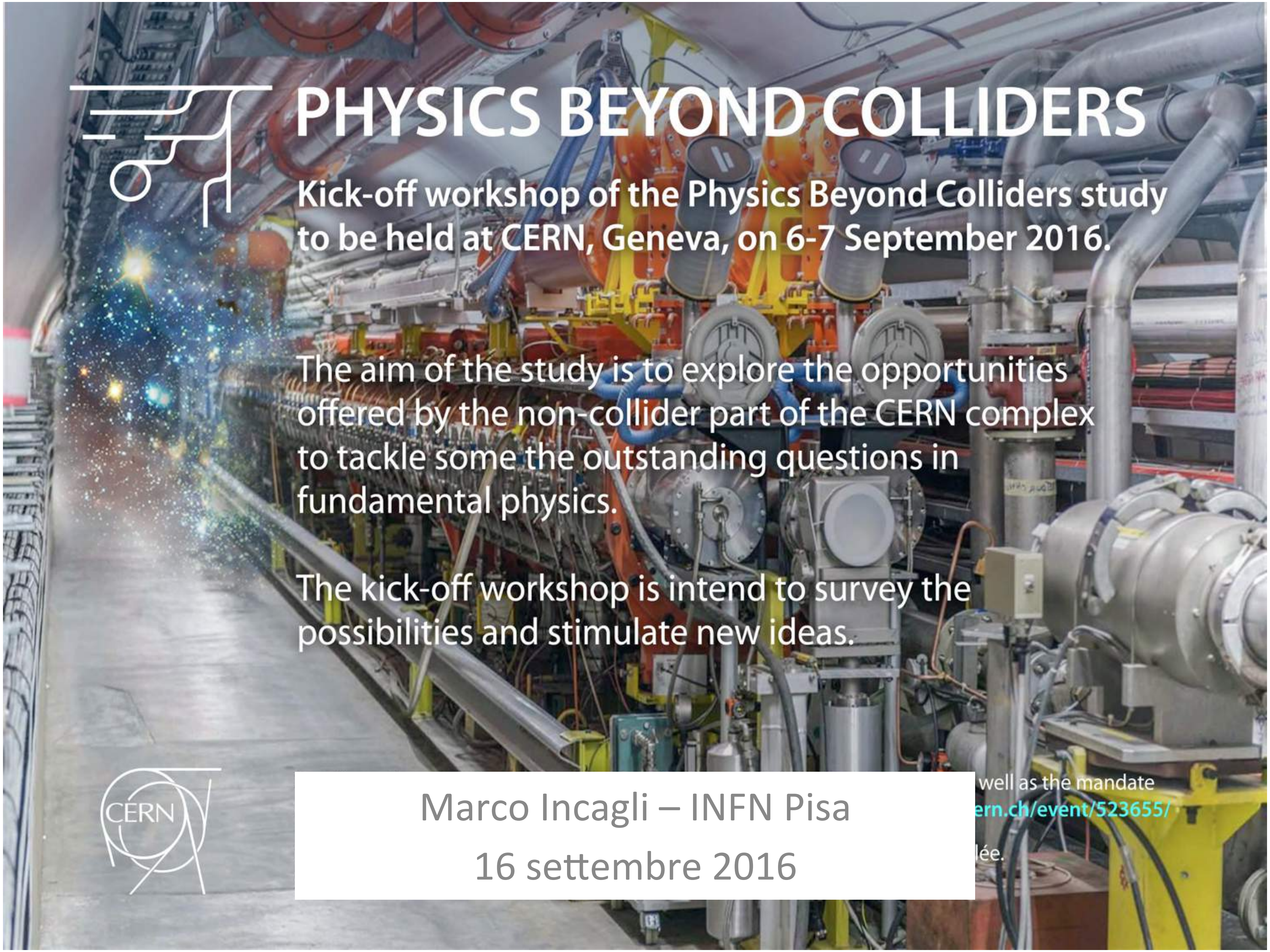



Marco Incagli – INFN Pisa

16 settembre 2016

# Struttura del workshop

- **Session 1**: *Theorists motivations, ideas and wishes*
  - ... direct and indirect searches for new particles (axions, dark photons, HNL, etc...), as well as testing symmetries and interactions...
- **Session 2**: *Accelerator and infrastructure opportunities at CERN*
  - ... upgrades of the CERN complex. Anticipated topics include proton yields in the LINAC4 era, beam dump facilities, fixed target options, and non-accelerator options. Novel ideas such as proton drivers, muon rings, EDM rings will be explored.
- **Session 3**: *Potential future of existing programmes*
  - The main experimental collaborations other than LHC currently operating at CERN will present their views for their mid-term and long-term future.
- **Session 4**: *New experimental ideas*
  - This session will be the focus of the workshop and aims at collecting ideas from the community for new experimental programmes exploiting the unique features of CERN.

# Questo report: approccio "sperimentale"

1. k->pnn + neutrini right handed
2. Dark sector with missing energy
3. QCD, misure di sezione d'urto
4. EDM + (g-2)
5. Antimatter experiments
6. Beam facilities: gamma factories + Awake
7. Esperimenti non agli acceleratori: axions, Kwisp, DarkSide

# 1 – k->$\pi\nu\nu$ e dark sector

NA62

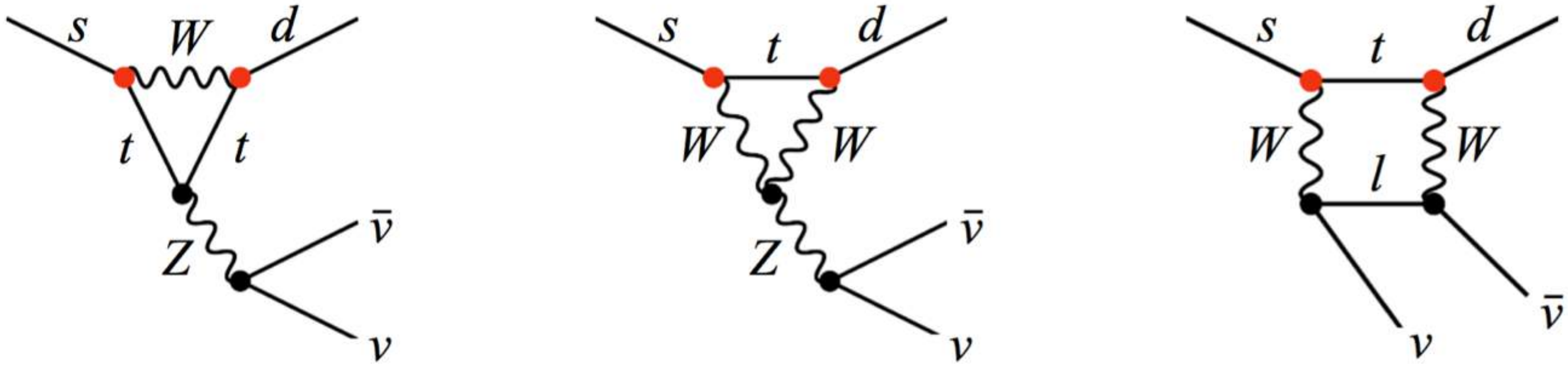
KLEVER ($K_L$->$\pi_0\nu\nu$)

SHIP

(ma perche' sono messi insieme?)

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

* Tree-level determinations of CKM matrix elements

# $K \to \pi\nu\bar{\nu}$ and the unitarity triangle

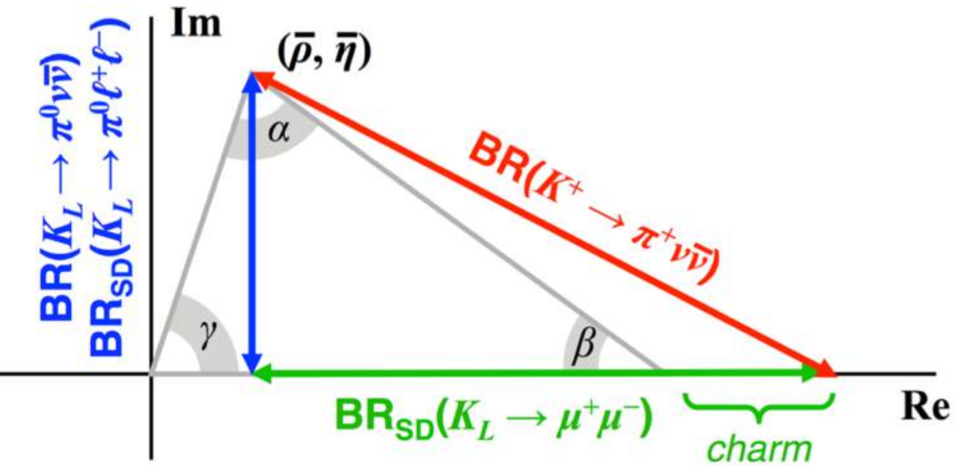
**Dominant uncertainties for SM BRs are from CKM matrix elements**

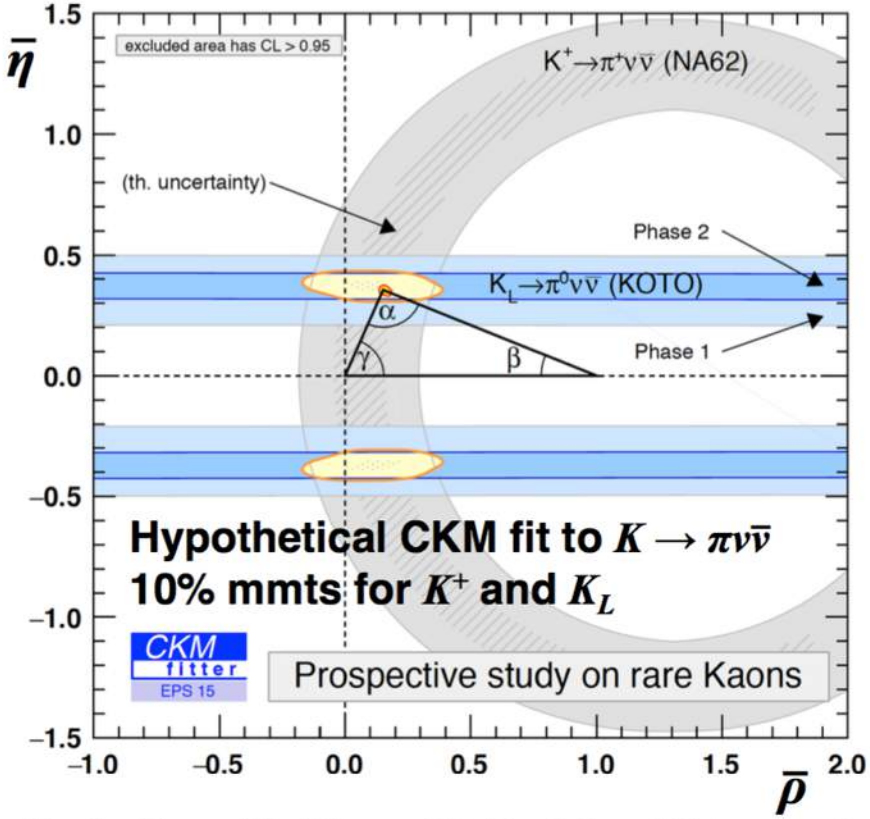
$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

Buras et al.,
JHEP 1511

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

- Intrinsic theory uncertainties ~ few percent
- BR measurements for both $K^+$ and $K_L$ determine the unitarity triangle independently from $B$ inputs
  - Overconstrain CKM matrix → reveal NP?



# Decadimento carico: NA62

**Run in 2015:**

Commissioning of L0 trigger

Run up to nominal intensity, 3.3 $10^{12}$ POT/spill, 3.5-s effective-length spill

**Running in 2016:**

Stable running at 20% of the nominal beam intensity

**Data already collected: sensitivity to BR($K \rightarrow \pi\nu\nu$) up to $10^{-9}$**

**End of 2016:** reach SM-expectation sensitivity, **O($10^{-10}$)**

**End of 2017 run:** improve (by much) on present state of the art (BNL measurement)

**End of 2018 run:** measurement of BR at 10%

# $K_L \to \pi^0 \nu\bar{\nu}$: experimental considerations

**Essential signature: 2$\gamma$ with unbalanced $p_\perp$ + nothing else!**

All other $K_L$ decays have ≥ 2 extra $\gamma$s or ≥ 2 tracks to veto

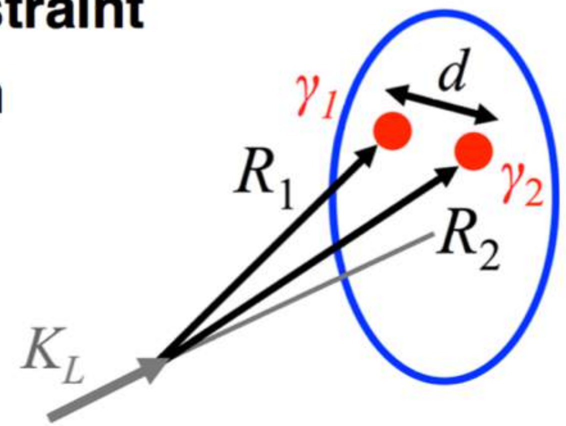
(Exception: $K_L \to \gamma\gamma$, not a big problem since $p_\perp = 0$)

**$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint**

Generally used to reconstruct vertex position

$$m_{\pi^0}^2 = 2E_1E_2\,(1-\cos\theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

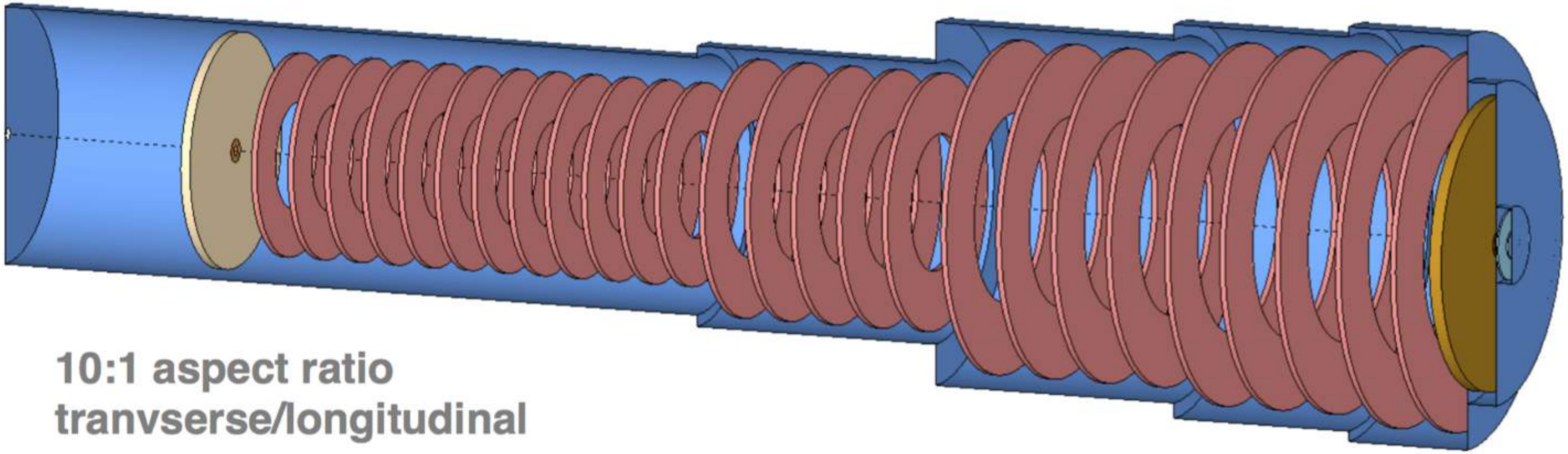



**Main backgrounds:**

**$K_L \to \pi^0\pi^0$ with 2 lost $\gamma$s**
**BR = 8.65 × $10^{-4}$** → Hermetic veto, including beam exit

$n$ + gas $\to X\pi^0, X\eta$ → High vacuum decay region

# Detector layout for $K_L \rightarrow \pi^0 \nu\bar{\nu}$




**Roughly same vacuum tank layout and fiducial volume as NA62**

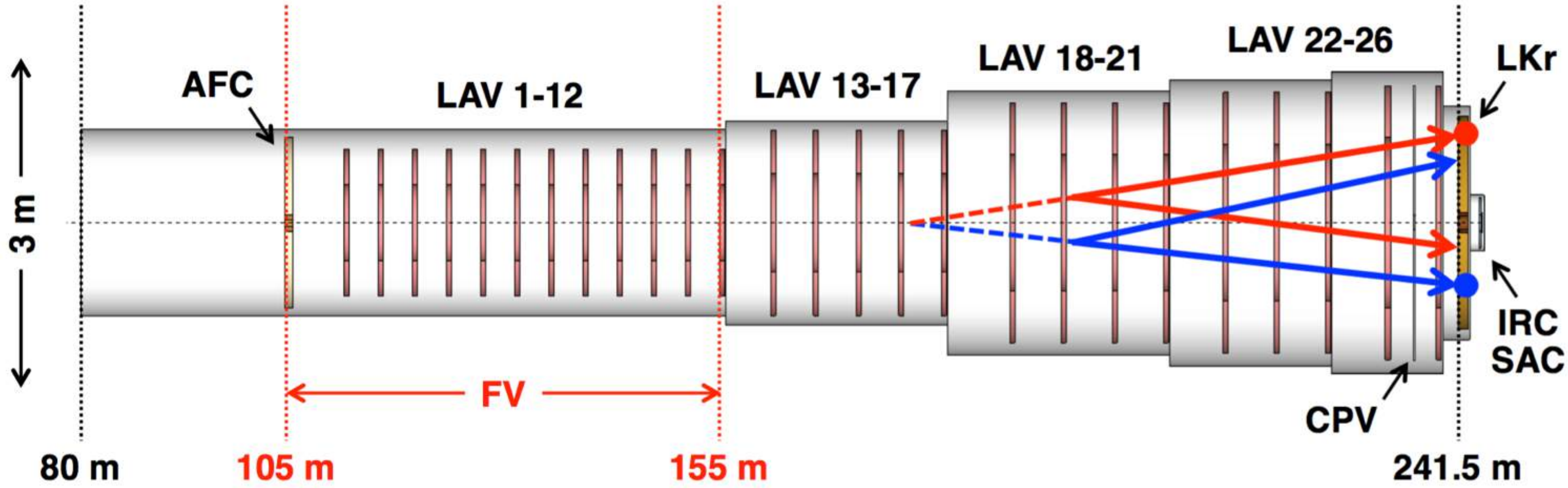
- Upstream edge of vacuum tank 20 m in front of AFC
- FV starts ~105 m downstream of target – decay away $\Lambda$, $K_S$
- About 2.2% of $K_L$ in beam decay in FV

**Possible to re-use NA48 LKr calorimeter (?)**

**26 new large-angle photon veto stations (LAV), coverage to 100 mrad**

**New small-angle photon veto detectors (IRC/SAC)**

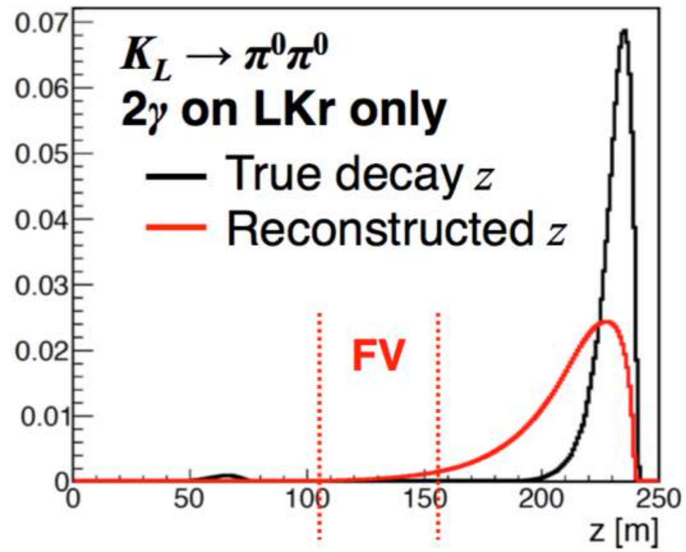
# Detector layout for $K_L \to \pi^0 \nu \bar{\nu}$



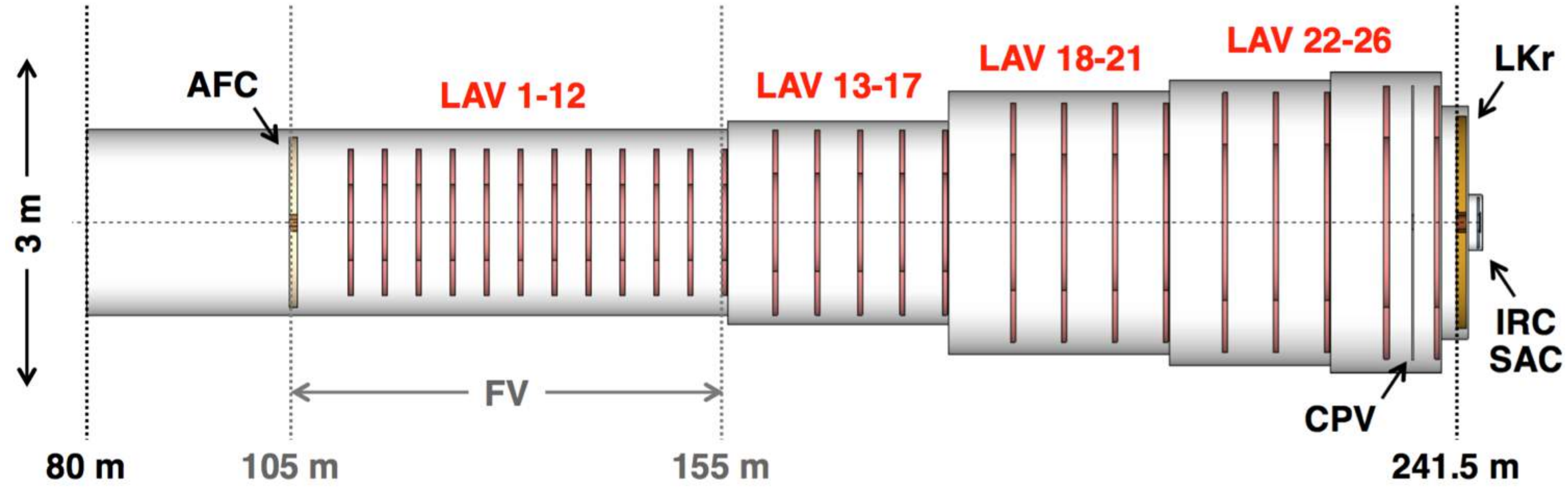

**Vacuum tank layout and FV similar to NA62**

**90-m distance from FV to LKr significantly helps background rejection**

- Most $K_L \to \pi^0\pi^0$ decays with lost photons occur just upstream of the LKr
- "$\pi^0$s" from mispaired $\gamma$s are mainly reconstructed downstream of FV



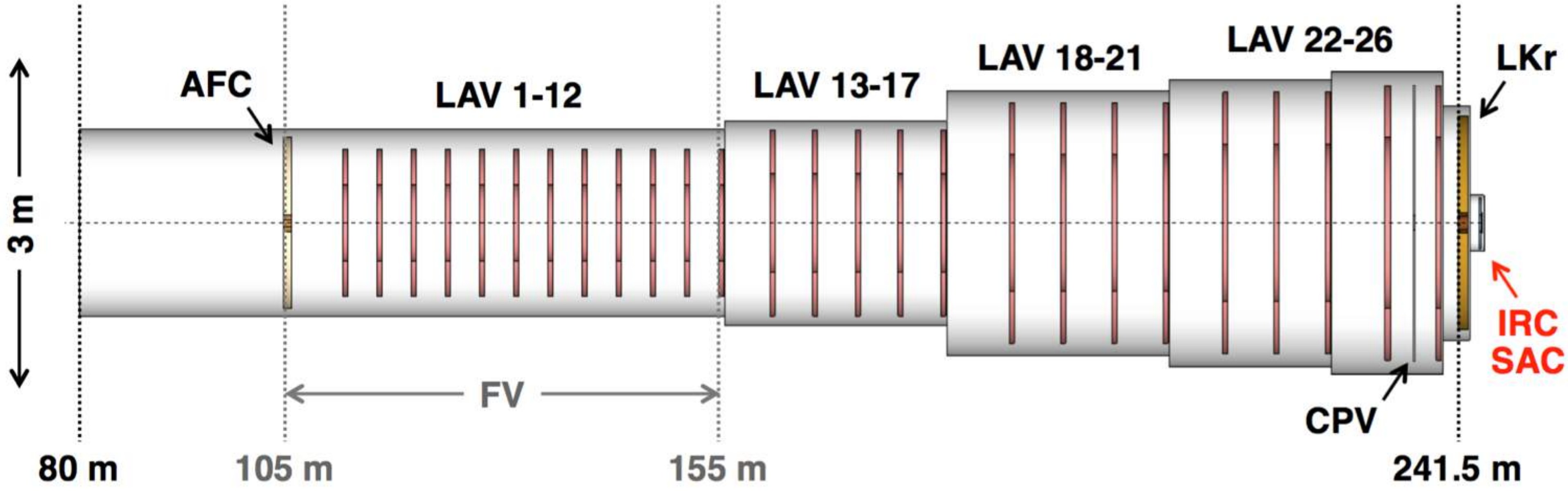
# Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$




**26 new large-angle photon veto stations (LAV)**

- 5 sizes, sensitive radius 0.9 to 1.6 m, at intervals of 4 to 6 m
- Hermetic coverage out to 100 mrad for $E_\gamma$ down to ~100 MeV
- Baseline technology: Lead/scintillator tile with WLS readout
  Based on design of CKM VVS
  Assumed efficiency based on E949 and CKM VVS experience

# Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$




**Small-angle photon veto systems (IRC, SAC)**

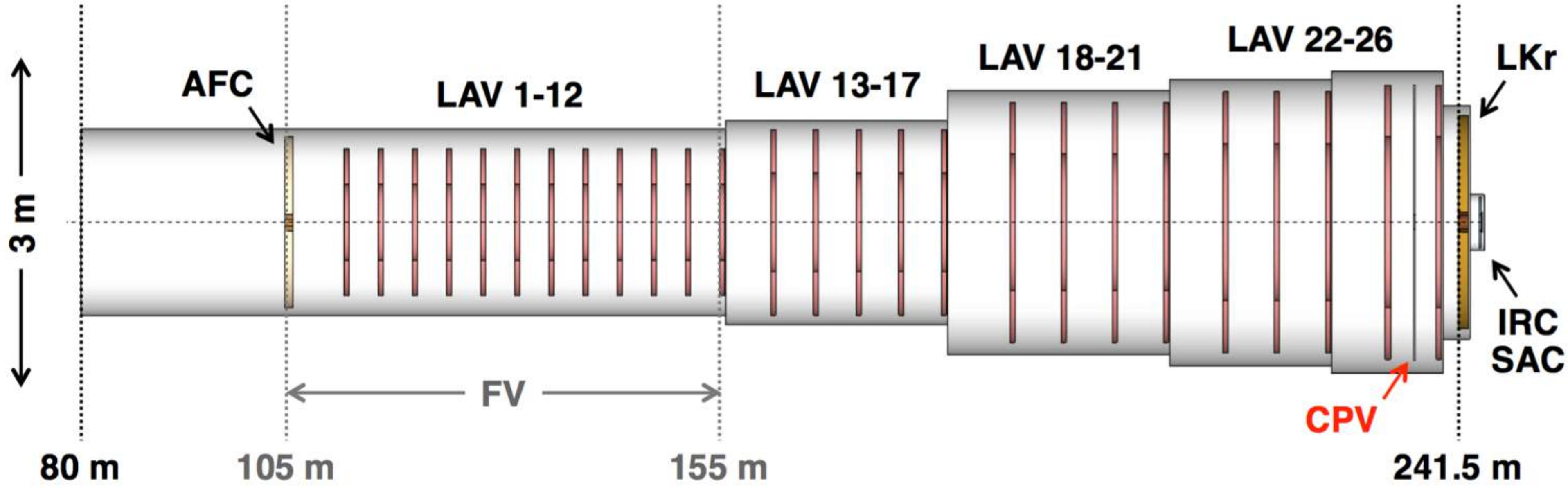
- Reject high-energy $\gamma$s from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 3 GHz of beam neutrons

| | Rate (MHz) | Req. $1-\varepsilon$ |
|---|---|---|
| $\gamma, E > 5$ GeV | **230** | **$10^{-2}$** |
| $\gamma, E > 30$ GeV | **20** | **$10^{-4}$** |
| $n$ | **3000** | **–** |

**Baseline solution:**

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber

# Detector layout for $K_L \to \pi^0 \nu \bar{\nu}$




**Charged particle rejection**

- **Charged particle vetoes (CPV):** Scintillating tiles, 5 m upstream of LKr
- **Re-use NA62 hadronic calorimeters** (MUV1/2, not shown)
  Ratio of hadronic/total energy effective to identify $\pi$ showers
- **LKr shower profile:** Use cluster RMS to identify and reject $\pi$

# $K_L \to \pi^0 \nu\bar{\nu}$ sensitivity summary

| Channel | Simulated statistics | Events found | Expected in 5 yrs* |
|---|---|---|---|
| $K_L \to \pi^0 \nu\bar{\nu}$ | 100k yr | 1.94M | **97** |
| $K_L \to \pi^0\pi^0$ | 5 yr | 111 | **111** |
| $K_L \to \pi^0\pi^0\pi^0$<br>All bkg evts from cluster fusion<br>Upstream decays not yet included | 1 yr | 3 | **15** |
| $K_L \to \gamma\gamma$<br>$p_\perp$ cut very effective | 3 yr | 0 | **0** |
| $K_L \to$ **charged** | **thought to be reducible** | | |

*Must subtract 35% for $K_L$ losses in dump $\gamma$ converter

**~ 60 SM $K_L \to \pi^0 \nu\bar{\nu}$ in 5 years with $S/B \sim 1$**

**Background study incomplete!**

$\pi^0$ from interactions of halo neutrons on residual gas, detector materials

Radiative $K_L$ decays, $K_S$/hyperon decays

# Hidden sector at NA62: motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics:

**search for non-gravitational interactions DM-SM**

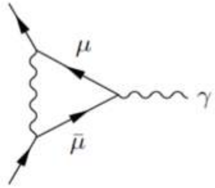
**A mediator of a hidden sector might exist**, inducing DM-SM field **(feeble)** interactions

many possible dynamics: vector (A', aka dark photon), neutrino (HNL), axial (ALP a), scalar..

**Various experimental hints** for hidden sector at MeV-GeV, e.g., $a_\mu$ 3.5-$\sigma$ discrepancy:

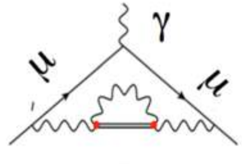
Might be due to a dark photon A' ...

A'




[Okun, Holdom]

...or to an ALP a enhancing light-by-light?




a

[Marciano, et al. arXiv:1607.01022]

**Model dependence: experimentally driven approach**

**Feeble interaction:** ultra-suppressed production rate, **very** long-lived states

E.g.: 1-GeV mass HNL, $\tau \sim 10^{-5}$--$10^{-2}$ s, decay length ~ 10--10000 Km at SPS energies, suppression at production $10^{-7}$--$10^{-10}$

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

# New Physics below the Fermi Scale

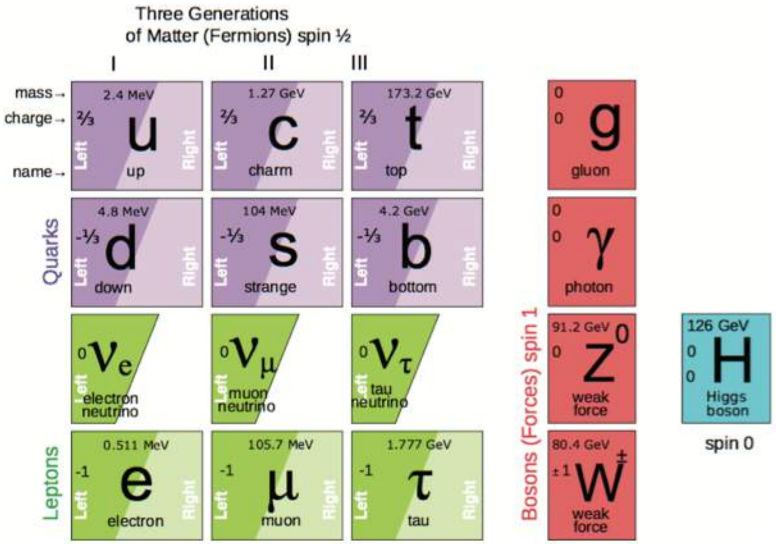
Mikhail Shaposhnikov

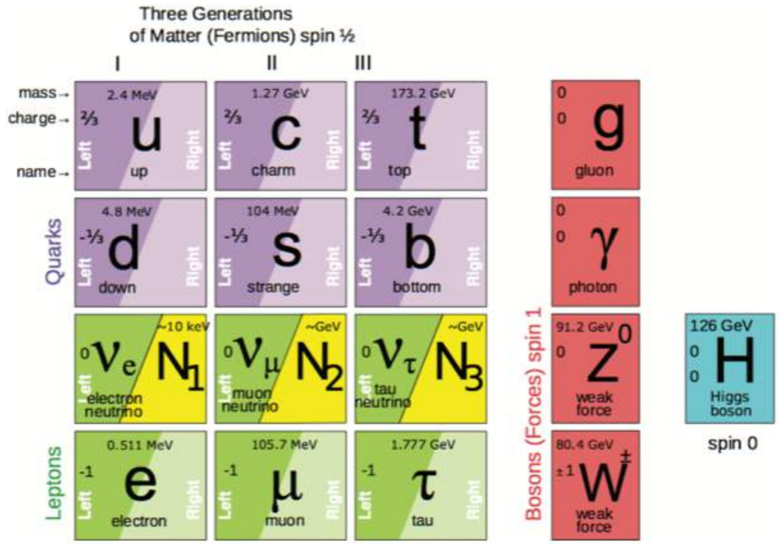
CERN
Physics
Beyond
Colliders

# Superweakly interacting new physics below the Fermi scale

- Light messengers between the SM and heavy sectors such as SUSY, extra dimensions, new strong dynamics.
- Light Dark matter and/or light particles in the hidden sector
- Absence of new particle thresholds between the Fermi and Planck scales? Then all the experimental BSM problems should be explained by light particles.

# An example: $\nu$MSM




N = Heavy Neutral Lepton - HNL, Majorana fermion

Role of $N_1$ with mass in keV region: dark matter

Role of $N_2,\ N_3$ with mass in 100 MeV – 100 GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, $Z$ and $W$ and inflate the Universe.

For comprehensive study of possibilities at CERN SPS see:

**IOP** Publishing

Reports on Progress in Physics

Rep. Prog. Phys. **00** (2016) 000000 (137pp)

UNCORRECTED PROOF

**Report on Progress**

# A facility to search for hidden particles at the CERN SPS: the SHiP physics case

Sergey Alekhin[1,2], Wolfgang Altmannshofer[3], Takehiko Asaka[4], Brian Batell[5], Fedor Bezrukov[6,7], Kyrylo Bondarenko[8], Alexey Boyarsky[8,68], Ki-Young Choi[9], Cristóbal Corral[10], Nathaniel Craig[11], David Curtin[12], Sacha Davidson[13,14], André de Gouvêa[15], Stefano Dell'Oro[16], Patrick deNiverville[17], P S Bhupal Dev[18], Herbi Dreiner[19], Marco Drewes[20], Shintaro Eijima[21], Rouven Essig[22], Anthony Fradette[17], Björn Garbrecht[20], Belen Gavela[23], Gian F Giudice[5], Mark D Goodsell[24,25], Dmitry Gorbunov[26,27], Stefania Gori[3], Christophe Grojean[28,29,69], Alberto Guffanti[30], Thomas Hambye[31], Steen H Hansen[32], Juan Carlos Helo[10,33], Pilar Hernandez[34], Alejandro Ibarra[20], Artem Ivashko[8,35], Eder Izaguirre[3], Joerg Jaeckel[36,69], Yu Seon Jeong[37], Felix Kahlhoefer[29], Yonatan Kahn[38], Andrey Katz[5,39,40], Choong Sun Kim[37], Sergey Kovalenko[10], Gordan Krnjaic[3], Valery E Lyubovitskij[41,42,43], Simone Marcocci[16], Matthew Mccullough[5], David McKeen[44], Guenakh Mitselmakher[45], Sven-Olaf Moch[46], Rabindra N Mohapatra[47], David E Morrissey[48], Maksym Ovchynnikov[35], Emmanuel Paschos[49], Apostolos Pilaftsis[18], Maxim Pospelov[3,17,69], Mary Hall Reno[50], Andreas Ringwald[29], Adam Ritz[17], Leszek Roszkowski[51], Valery Rubakov[26], Oleg Ruchayskiy[21,52,68], Ingo Schienbein[53], Daniel Schmeier[19], Kai Schmidt-Hoberg[29], Pedro Schwaller[5], Goran Senjanovic[54,55], Osamu Seto[56], Mikhail Shaposhnikov[21,68,69], Lesya Shchutska[45,69], Jessie Shelton[57], Robert Shrock[58], Brian Shuve[3], Michael Spannowsky[59], Andy Spray[60], Florian Staub[5], Daniel Stolarski[5], Matt Strassler[40], Vladimir Tello[54], Francesco Tramontano[61,62,69], Anurag Tripathi[61], Sean Tulin[63], Francesco Vissani[16,64], Martin W Winkler[65] and Kathryn M Zurek[66,67]

# NA62 perfectly suited for hidden sector searches

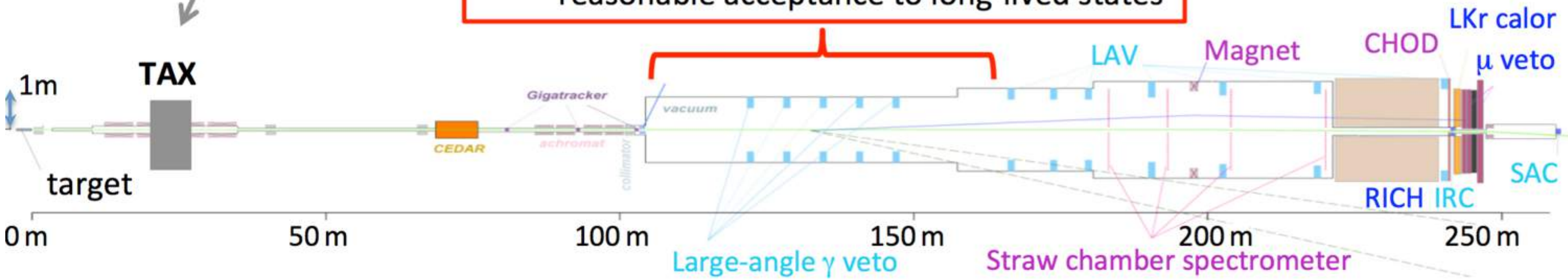
**High-intensity 400-GeV proton beam →** boost charm/beauty, other meson production

**$10^{18}$ POT / nominal year:** $10^{12}$ POT/sec on spill, 3.5-s/16.8 s, 100 days/year, 60% run efficiency

**$10^{15}$ $D_{(S)}$, $10^{14}$ K, $10^{18}$ $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95 (& B mesons, too)**

**Compact beam dump:** ~11 $\lambda_I$ 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

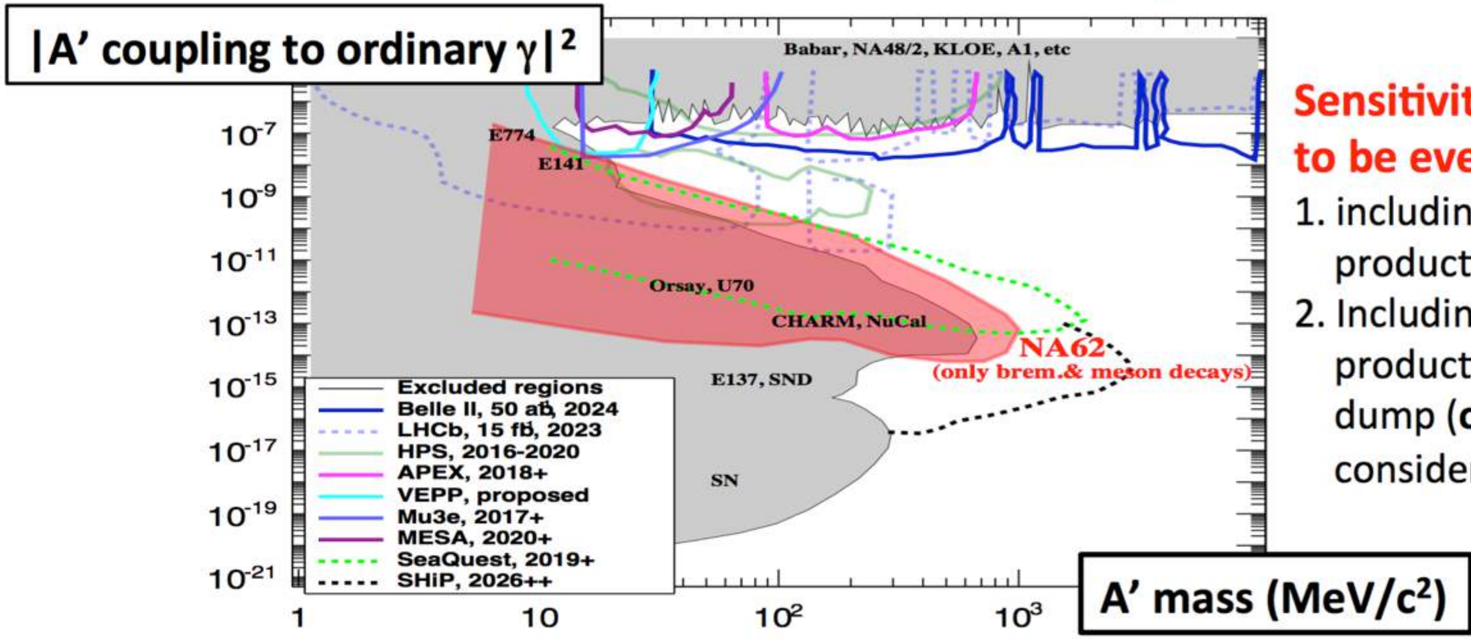



**High-resolution tracking, PID, vetoing:** high sensitivity to closed signatures

# Search for visible decays of long-lived A'

**Assume $2 \times 10^{18}$ 400-GeV POT:**

search for displaced, dilepton decays of dark photons, A' → ee, μμ
include trigger/acceptance/selection efficiency
assume zero-background, evaluate expected 90%-CL exclusion plot



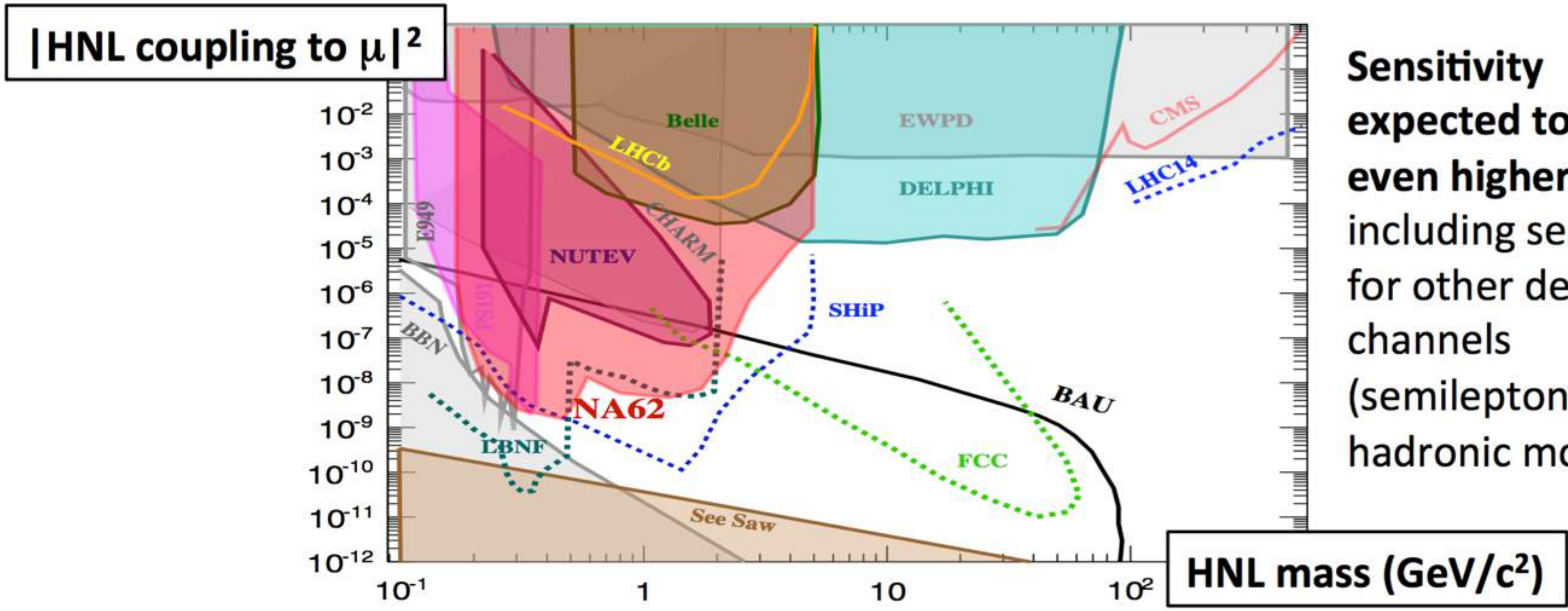

**Sensitivity expected to be even higher:**

1. including direct QCD production of A'
2. Including A' production in the dump (**only target** considered here)

# Search for visible decays of heavy neutral leptons

**Assume 2 $10^{18}$ 400-GeV POT:**

search for displaced, leptonic decays HNL → $\pi e$, $\pi\mu$
include trigger/acceptance/selection efficiency
assume zero-background, evaluate expected 90%-CL exclusion plot




**Sensitivity expected to be even higher** after including search for other decay channels (semileptonic, hadronic modes)

# commento

- misure di SHIP (molto) migliori di quelli di NA62 sia come statistica che come controllo del fondo
- ... ma quelle di NA62 possono essere fatte 10 anni prima ad un costo inferiore di ~100M !
- naturalmente l'utilizzo di NA62 come rivelatore per "hidden sector" ritarda lo sviluppo del progetto sui K neutri
- (penso che) una decisione sara' presa nel 2018 anche alla luce della quantita' di dati raccolti nel canale carico

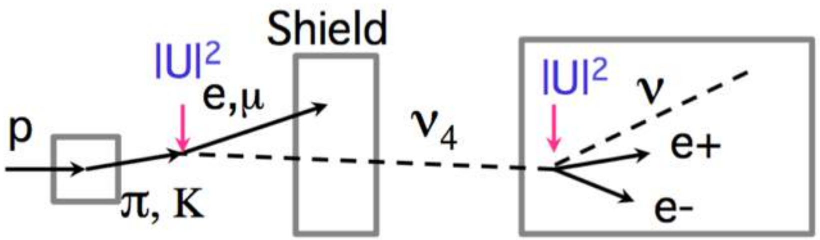
# 2 – Dark sector with missing energy

NA64

# NA64 approach to search for new physics

The NA64 is a new fixed-target experiment aiming to search for dark photon A´->invisible decays at the CERN SPS with a new approach: the active beam dump combined with missing energy technique.

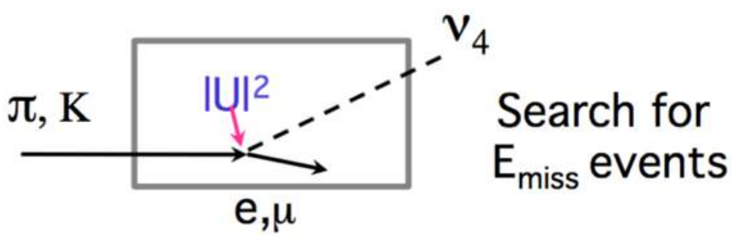
**Beam dump:** ⟵ Complementary to each other ⟶ **NA64 approach:**




Sensitivity ~$|U|^4$

e.g. SHIP, A. Golutvin talk

active beam dump + $E_{miss}$

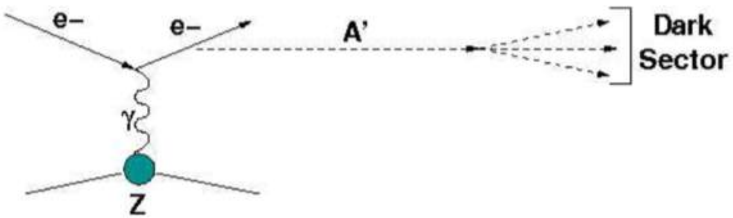



Sensitivity~$|U|^2$

Goal of the talk: to show that this approach allows a sensitive probe of "light new physics" (dark sector physics, new symmetries, new WI sub-GeV particles coupled to e, μ, q's) by using e, $\mu$, $\pi$, K, and p beams from existing facilities at CERN.

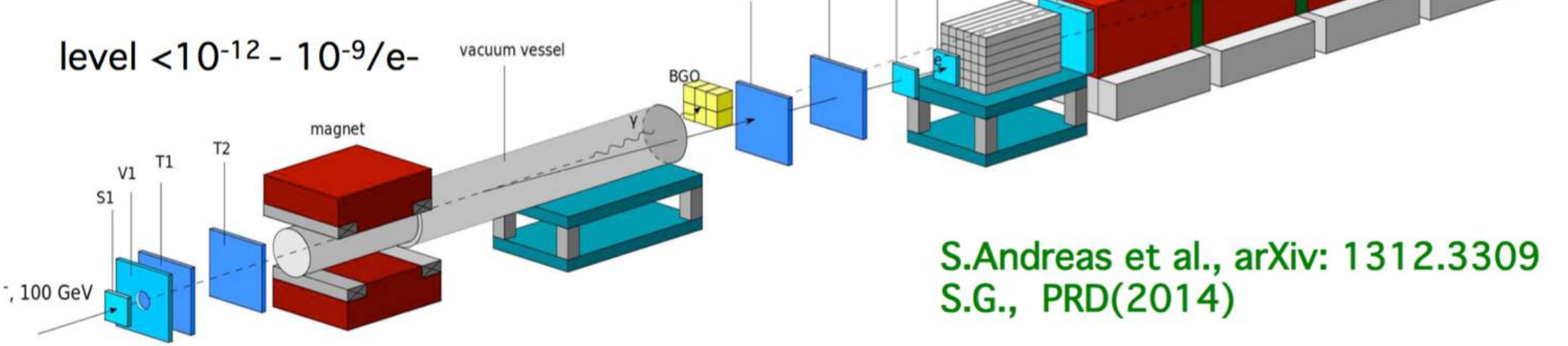
# esempio con fasci di elettroni

## Source of A´s:




## Invisible decay of invisible state!

level $<10^{-12} - 10^{-9}$/e-




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

**Main components :**

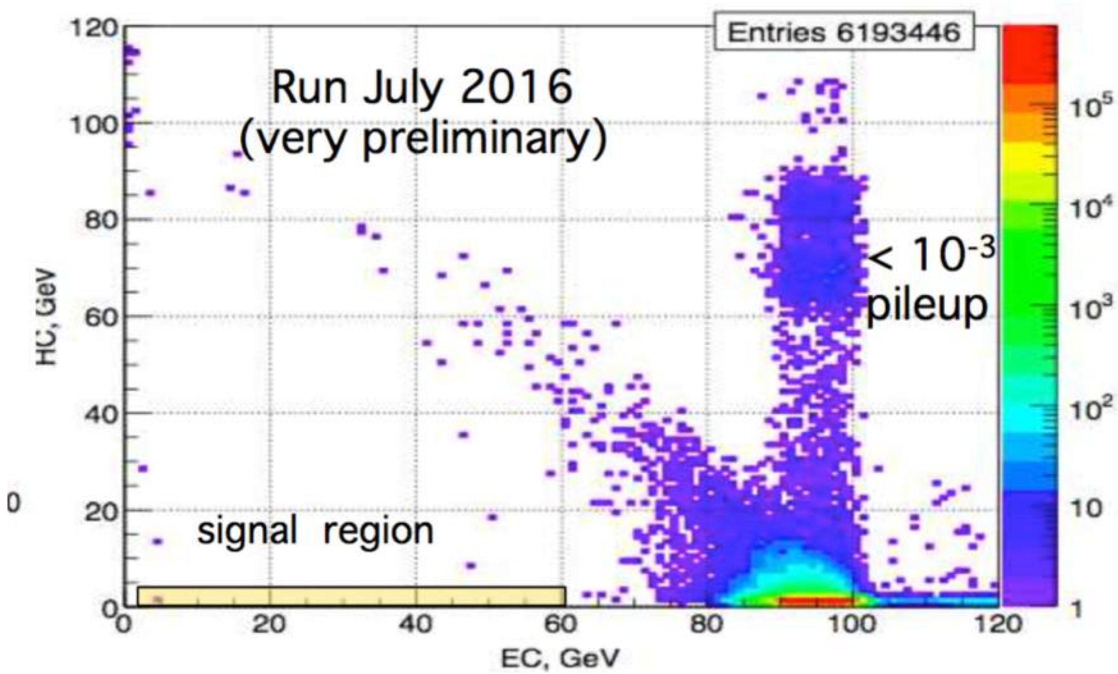
- clean, mono-energ. 100 GeV e- beam
- e- tagging system: MM/GEM/Straw tracker + SRD (BGO, LYSO; Pb-SC)
- $4\pi$ fully hermetic ECAL+ HCAL

**Signature:**

- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ $\varepsilon^2$
- same signature for milli-q, APLs, ....

# Esperimento NA64

- la qualita' e l'intensita' del fascio di ingresso sono fondamentali -> vedi in seguito proposta di AWAKE
- al momento si usa il fascio della North Area
- plot di energia rilasciata nel calorimetro adronico (HC) vs calorimetro elettromagnetico (EC)

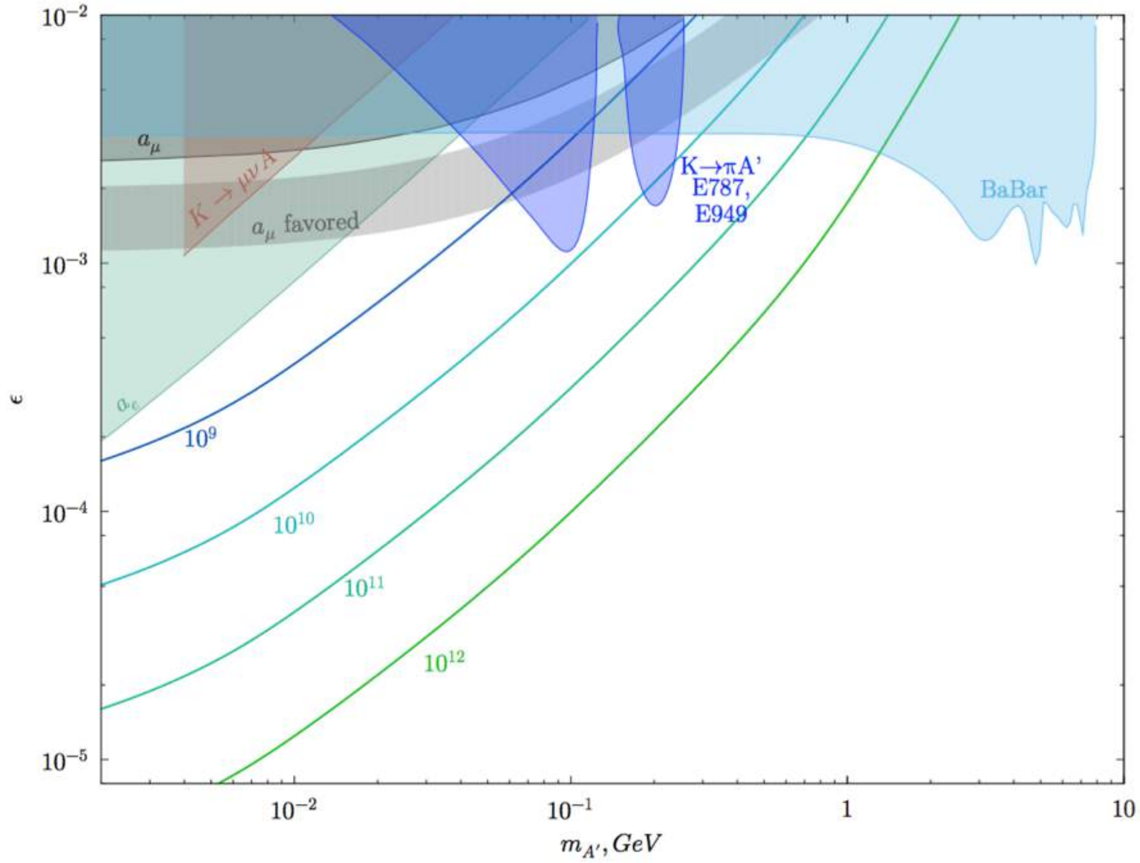


# Summary of background sources for A´-> invisible



| Source | Expected level | Comment |
|---|---|---|
| Beam contamination | | |
| - $\pi$ , $p$, $\mu$ reactions and punchthroughs,... - $e^-$ low energy tail due to bremss., $\pi$ , $\mu$ -decays in flight... | $< 10^{-13}$-$10^{-12}$ <br> $< 10^{-12}$ | Impurity < 1% high precision MM tracker + $e^-$ SR photon tag |
| Detector | | |
| ECAL+HCAL energy resolution, transverse hermeticity, holes, dead material, cracks... | $<10^{-13}$ | Full upstream coverage |
| Physical | | |
| - hadron electroproduction, e.g. $e^-A \to e^-A^* + n,\pi,\rho,J/\psi$– - n punchthrough, $\mu$ inefficiency - WI process: $e^- Z \to e^- Z\nu\nu$ | $< 10^{-13}$ <br> $< 10^{-13}$ | HERA ep-data (H1 Collaboration) WI $\sigma$ estimated. |
| Total | $< 10^{-12}$ | |

- il regime di esclusione dipende fondamentalmente dal numero di "electrons on target" ....
- .... nel caso ottimistico di "zero background"!
- (non ho studiato in maniera approfondita l'esperimento, ma le stime fatte sembrano un po' approssimative)



# 3 – QCD, misure di sezione d'urto

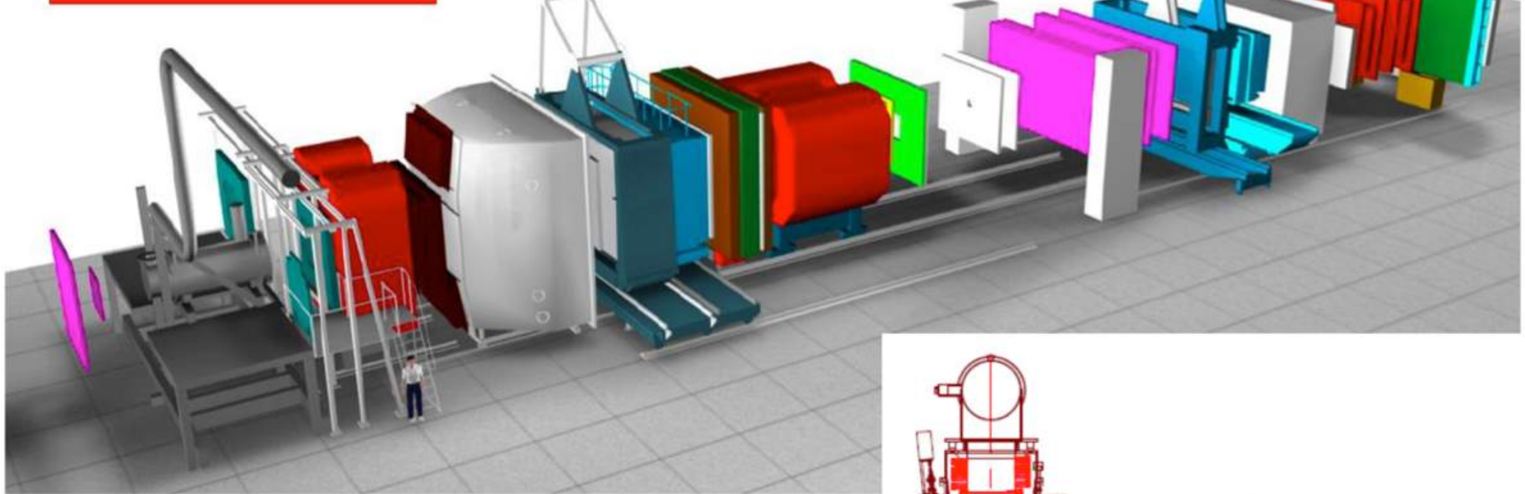
COMPASS (m, e, hadron beams)

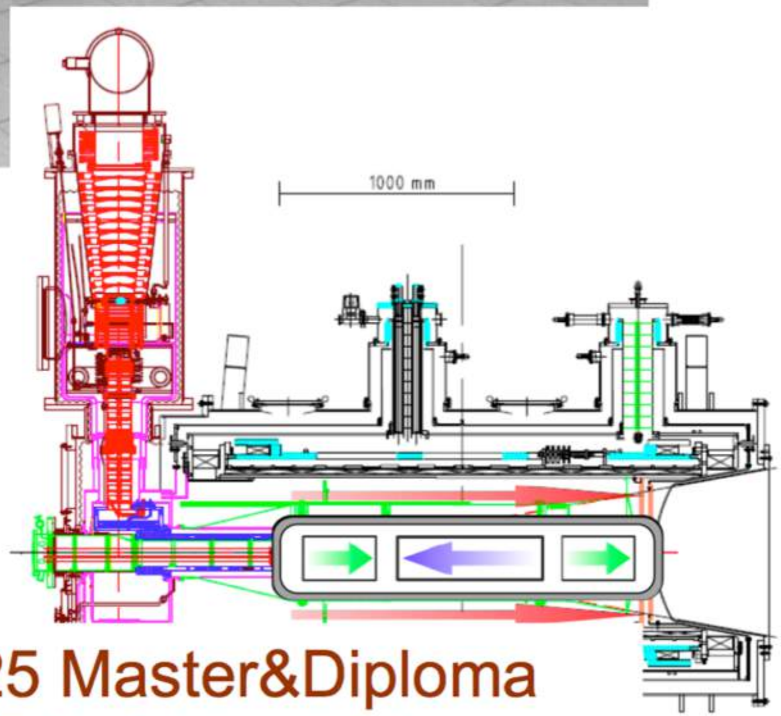
NA61/SHINE (hadron and nuclear beams)

Fixed target @ LHC

# COMPASS Spectrometer at SPS M2 beam line (CERN)

**COMPASS**






Universal and flexible apparatus.
Most important features of the two-stage COMPASS Spectrometer:

1. Muon, electron or hadron beams with the momentum range 20-250 GeV and intensities up to $10^8$ particles per second
2. Solid state polarised targets ($NH_3$ or $^6LiD$) as well as liquid hydrogen target and nuclear targets
3. Ad
syst

~240 physicists (~60 PhD, ~25 Master&Diploma students), 12 countries + CERN, 24 institutions

# Beyond 2020 dedicated Workshop

This week – regular annual COMPASS Workshop (IWHSS'16 Kloster Seeon)

## COMPASS beyond 2020 Workshop

21 Mar 2016, 08:05 → 22 Mar 2016, 17:10 Europe/Zurich

222-R-001 (CERN)

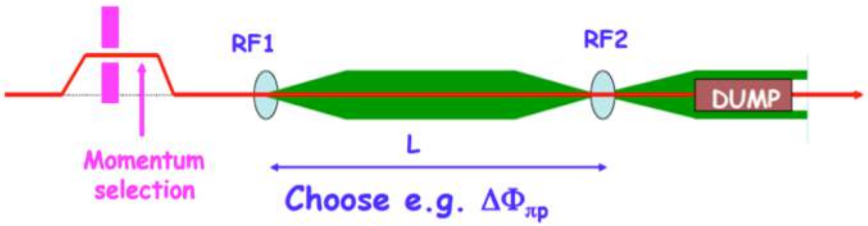
**Description** The goal of the workshop is to explore hadron physics opportunities for fixed-target COMPASS-like experiments at CERN beyond 2020 (CERN Long Shutdown 2 2019-2020). The programme comprises

- Reviews of the various physics domains: TMDs, GPDs, FFs, spectroscopy, exotics, tests of ChPT, astrophysics

- Reviews of physics results expected in the next 10 years from major labs around the world

- Good attendance (>100 physicists), large interest
- 11 "outside" review talks – Jefferson Lab, RHIC, Fermilab, KEK (Japan) BEPC II (IHEP, Beijing), NICA (JINR, Dubna), CERN (After, LHCb), GSI (Panda), J-PARC (Japan), EIC – China;
- 7 COMPASS talks (chronol.) – SIDIS, GPDs, Chiral Dynamics, astrophysics (dark matter), Drell-Yan, hadron spectroscopy;
- 2 "round-table"-like discussions on possible future with hadron and muon beams;
- Outcome of the Workshop:
    - RF Separated antiproton/kaon beam would provide a unique opportunity for future fixed target COMPASS-like program at CERN
    - Existing muon and hadron beam allows to extend current COMPASS program by doing unique or first class measurements of exclusive processes, SIDIS and Drell-Yan

# RF separated antiproton/kaon beam




$\Delta\Phi = 2\pi\ (L\ f\ /\ c)\ (\beta_1^{-1} - \beta_2^{-1})$ with $\beta_1^{-1} - \beta_2^{-1} = (m_1^2 - m_2^2)/2p^2$

"Normal" $h^-$ beam composition:
~97% (π) ~2.5%(K) ~0.5% (pbar)

Assumptions:

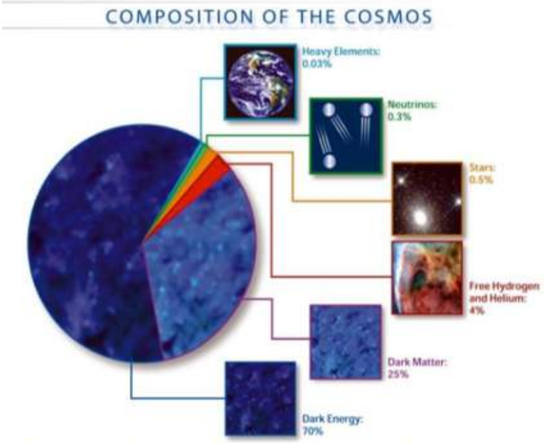
– $8 \times 10^7$ antiprotons for $10^{13}$ ppp (10 seconds) (optimistic estimate by Lau Gatignon);
– we assume here $4 \times 10^{13}$ protons.

Antiprotons RF separated beam: $3.2 \times 10^7$ /s - Gain is a factor of 50 compared to the standard $h^-$ beam for Drell-Yan experiment (~1% of $h^-$ beam $6 \times 10^7$ /s dominated by $\pi^-$)

Using the same assumption for RF separated kaon beam, possible kaon beam intensity is $8 \times 10^6$ /s - Gain is a factor of 80 compared to to the standard "spectroscopy" $h^-$ beam

**High intensity RF separated beam will provide unique opportunities for Hadron Spectroscopy and Drell-Yan physics**

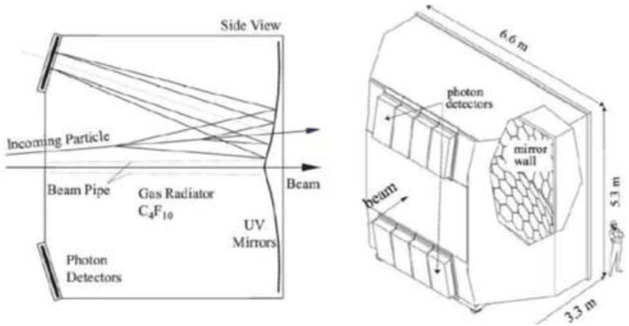
# Astrophysics – search for dark matter,
## contribution from COMPASS

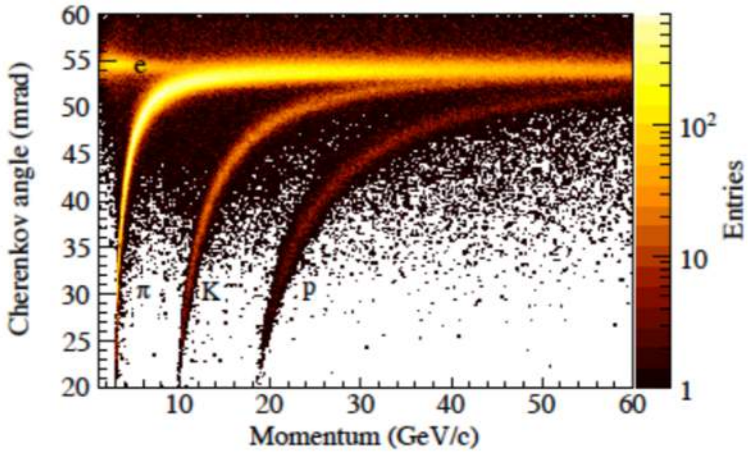



- New AMS(2) data – the antiparticle flux is well known now (few % pres.);
- Two type of processes contribute – SM interactions (proton on the ISM with the production for example antiprotons in the f.s.) and contribution from dark particle – antiparticle annihilation;
- In order to detect a possible excess in the antiparticles flux a good knowledge of inclusive cross sections of p-He interaction with antiparticles in the f.s. is a must, currently the typical precision is of 30-50%.

Thus the primary goal is to measure inclusive antiproton (positron, gamma) production cross section in a wide kinematical range with the precision <10%. **Compared to NA49 COMPASS have factor ~1000** as luminosity. COMPASS:

- Proton beam energy range 50-250 GeV
- Secondary particles identification:
  - Antiprotons (RICH)
  - Positrons and Gamma (ECals)

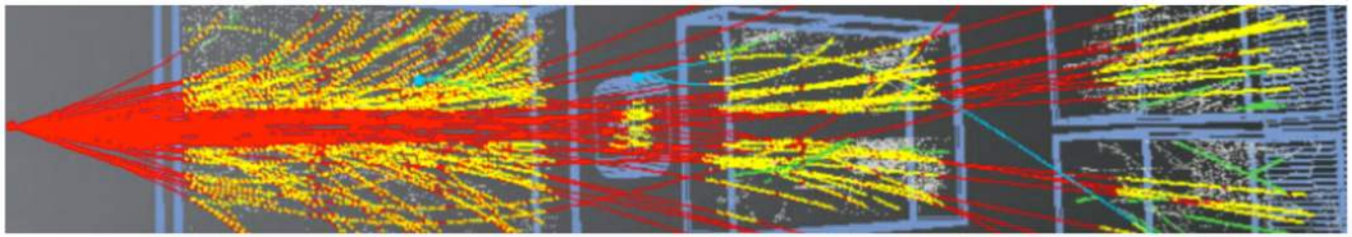


# NA61/SHINE: PHYSICS AND FACILITY BEYOND 2020

M. GAZDZICKI FOR NA61/SHINE

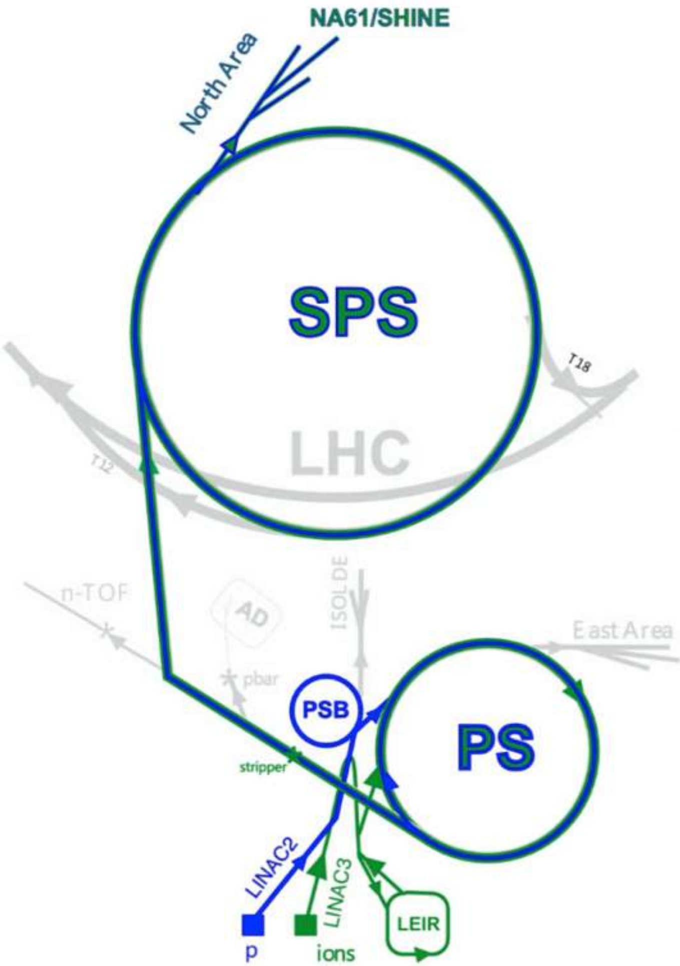
- NA61/SHINE: PHYSICS AND FACILITY
- IDEAS FOR MEASUREMENTS BEYOND 2020



S··INE

CERN

# SHINE FACILITY: BEAMS



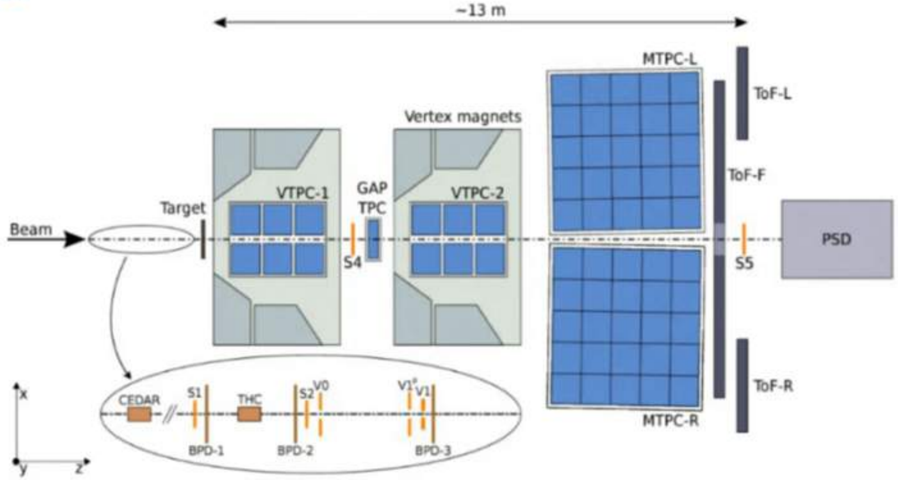

PRIMARY BEAMS:

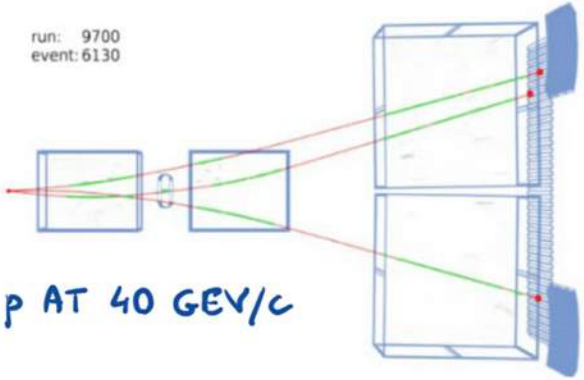
- PROTONS AT 400 GEV/c
- IONS (Ar, Xe, Pb) AT 13A-150A GEV/c

SECONDARY BEAMS:

- HADRONS ($\pi^{+/-}$, $K^{+/-}$, $p/\bar{p}$) AT 13-400 GEV/c
- IONS (Be) AT 13A-150A GEV/c

# SHINE FACILITY: DETECTOR




p+p AT 40 GEV/c

- A LARGE ACCEPTANCE (≈ 50%) HADRON SPECTROMETER
- BEAM PARTICLES MEASURED BY COUNTERS AND MWPCs
- CHARGE PARTICLES MEASURED BY 5 (+2) TPCs
- PID VIA dE/dx IN TPCs AND tof IN 3 ToF DETECTORS
- ENERGY OF PROJECTILE SPECTATORS MEASURED IN PSD
- PRECISE VERTEXING VIA SMALL ACCEPTANCE VERTEX DETECTOR

JINST 9 (2014) P06005

## IDEAS FOR MEASURMENTS BEYOND 2020

KEY QUESTIONS / REQUESTED MEASUREMENTS:

- STRONG INTERACTIONS:
  STATISTICAL VS DYNAMICAL MODELS
  (NON-LOCAL VS LOCAL PARTICLE PRODUCTION)
  / OPEN CHARM, CUMULATIVE HADRONS, FLUCTUATIONS IN ≈FULL ACCEPTANCE

- NEUTRINOS:
  INITIAL NEUTRINO FLUX FOR DUNE
  / HADRON YIELDS FROM THE SURFACE OF THE DUNE REPLICA TARGET

# COMPASS + NA61/SHINE

- in generale si nota un interesse nell'estendere le misure di "precisione" di sezioni d'urto adroniche
- questo e' spinto dalla richiesta di varie comunita':
  - astroparticle
  - neutrini
  - interazioni di QCD
  - sviluppo di MC
  - ...

# The fixed-target mode with TeV beams: why and what for ?

**4 decisive features**

- accessing the high $x$ frontier $[|x_F| \equiv \frac{|p_z|}{p_{z\,\max}} \to 1]$
- achieving high luminosities,
- varying the atomic mass of the target almost at will,
- polarising the target.

**3 physics cases**

- High-$x$ gluon, antiquark and heavy-quark content in the nucleon & nucleus
- Transverse dynamics and spin of gluons inside (un)polarised nucleons
- Heavy-ion physics between SPS & RHIC energies towards large rapidities

All this can be realised at CERN in a parasitic mode with the most energetic beams ever !

Nota: all (past) colliders with $E_p \geq 100$ GeV have had a fixed-target program (Tevatron, HERA, SPS, RHIC)

# 4 – EDM + (g-2)

EDM storage ring

misura della sezione d'urto adronica per g-2

# EDMs and precision g-2 as a window into New Physics

Maxim Pospelov
Perimeter Institute/U of Victoria

Purcell and Ramsey (1949) ("How do we know that strong interactions conserve parity?" $\longrightarrow |d_n| < 3 \times 10^{-18} e\text{cm}$.)

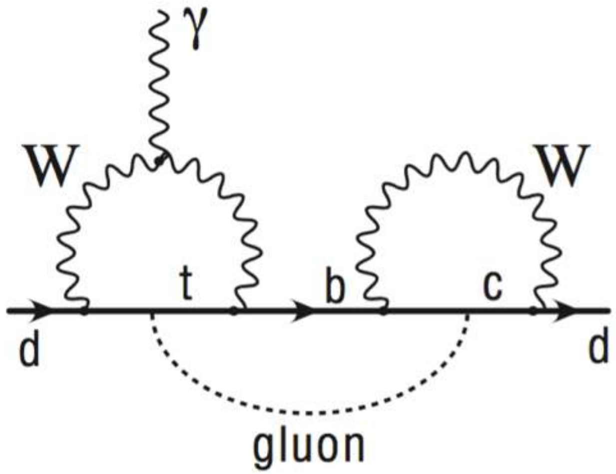
$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$d \neq 0$ means that both P and T are broken. If CPT holds then CP is broken as well.

CPT is based on locality, Lorentz invariance and spin-statistics = very safe assumption.

*search for EDM = search for CP violation, if CPT holds*

# EDMs from CKM




CKM phase generates tiny EDMs:

$$d_d \sim \mathrm{Im}(V_{tb}V^*_{td}V_{cd}V^*_{cb})\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$
$$< 10^{-33} e\text{cm}$$

Direct quark EDMs identically vanish at 1 and 2 loop levels (Shabalin, 1981). 3-loop EDMs are calculated by Khriplovich.

$d_e$ first appears at 4 loops (Khriplovich, MP, 1991) $< 10^{-37}$ cm

$d_n$ is dominated by long distance effects but does not exceed $10^{-31}$

# CP violation from the Theta term

- If CKM gave too small an EDM, there is a much bigger source of CP violation in the flavor conserving channel - theta term

Energy of QCD vacuum depends on $\theta$-angle:

$$E(\bar{\theta}) = -\frac{1}{2}\bar{\theta}^2 m_* \langle \bar{q}q \rangle + \mathcal{O}(\bar{\theta}^4, m_*^2)$$

where $\langle \bar{q}q \rangle$ is the quark vacuum condensate and $m_*$ is the reduced quark mass, $m_* = \frac{m_u m_d}{m_u + m_d}$. In CP-odd channel,

$$d_n \sim e \frac{\bar{\theta} m_*}{\Lambda_{\mathrm{had}}^2} \sim \bar{\theta} \cdot (6 \times 10^{-17})\, e\,\mathrm{cm}$$

Strong CP problem = naturalness problem = Why $|\bar{\theta}| < 10^{-9}$ when it could have been $\bar{\theta} \sim O(1)$? $\bar{\theta}$ can keep "memory" of CP violation at Planck scale and beyond. Suggested solutions

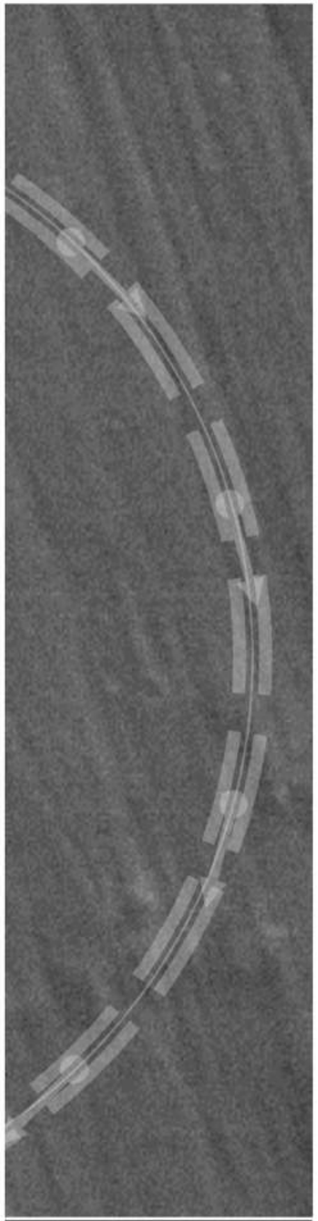
Axions or clever symmetry for keeping theta=0; $m_u$=0…

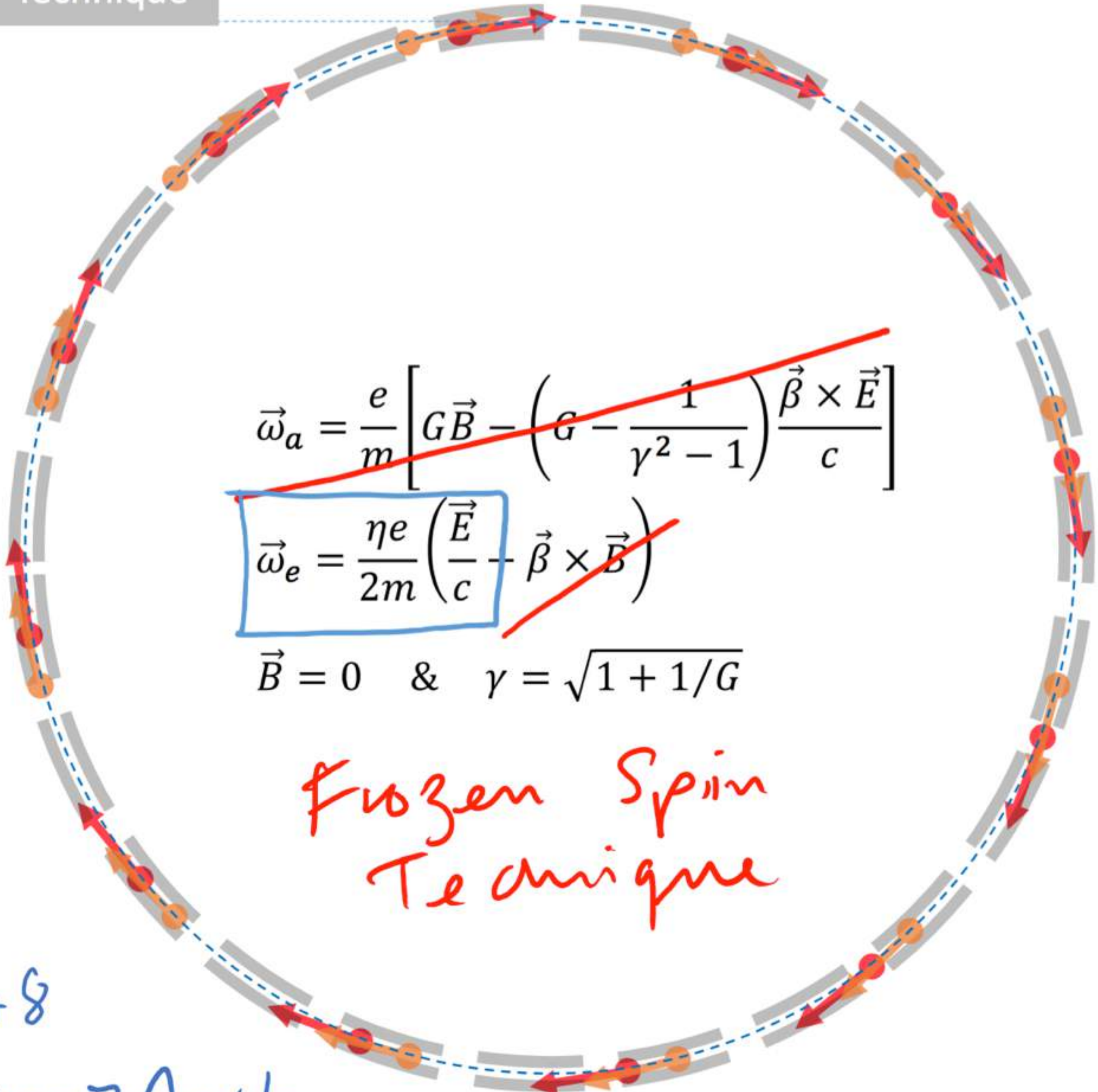
# Come misurare un EDM

- neutrone: precessione di Larmor dello spin in presenza di campo elettrico+magnetico parallelo e antiparallelo; adesso si usano Ultra Cold Neutrons (UCN) ed un campo magnetico oscillante oltre ai due **E+B** paralleli e antiparalleli
- nuclei (quark): nuclei pesanti (Tl, PbF, Hg, ...) vengono polarizzati, intrappolati (e.g. Penning trap) e sottoposti ad un campo elettrico
- protone, deuterio, (eventualmente) muone: intrappolare la particella in uno *storage ring* e combinare effetti di campo magnetico ed elettrico sui momenti magnetici ed elettrici della particella per osservare la precessione dello spin rispetto all'impulso ***p***

$$H = -\mu \vec{B} \cdot \vec{s} - d\vec{E} \cdot \vec{s}$$

## Technique





$$\vec{\omega}_a = \frac{e}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

$$\vec{\omega}_e = \frac{\eta e}{2m}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)$$

$$\vec{B} = 0 \quad \& \quad \gamma = \sqrt{1 + 1/G}$$

Frozen Spin Technique

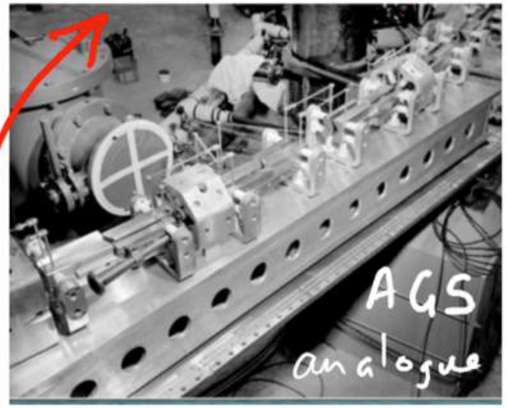
$\gamma = 1.248$

$p = 0.7007$ GeV/c

# Feasibility all-electric ring

faster & cheaper

- Two technical reviews have been performed BNL: Dec 2009, March 2011
- Fermilab review. Lebedev "concept sound"
- First all-electric ring: AGS-analogue ('53-'57)




There were electrostatic quadrupoles and sextupoles, a single gap rf system, a pickup electrode system and the other appurtenances necessary to an accelerator. The Electron Analogue is the only electrostatic alternating gradient, strong focusing, synchrotron ever built and, as such, occupies a unique place in particle accelerator history. M. Plotkin '91

Ring radius 4.7m

Proposed-built 1953-57

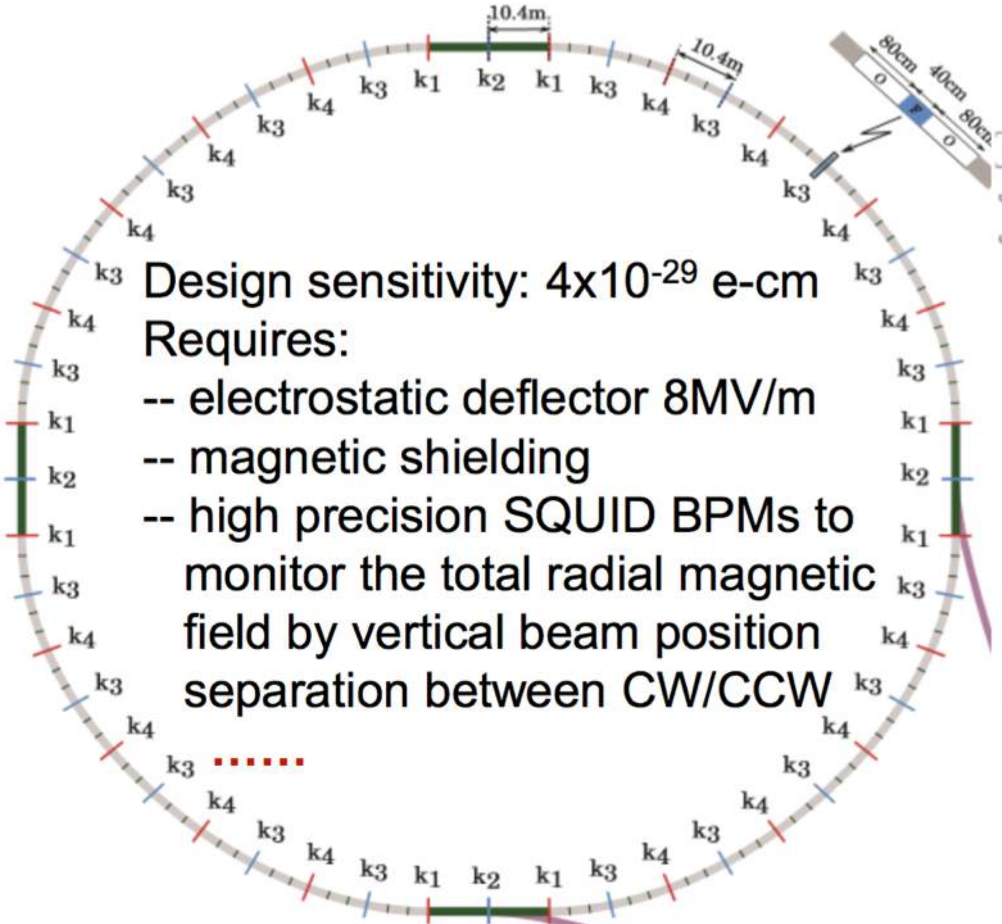
- Heidelberg Cryogenic Storage Ring:

  (expertise in collab.)

# pEDM Storage Ring

Mei Bai – JULICH, Aachen

## Pure Electrostatic Storage Ring for proton EDM




Design sensitivity: $4 \times 10^{-29}$ e-cm

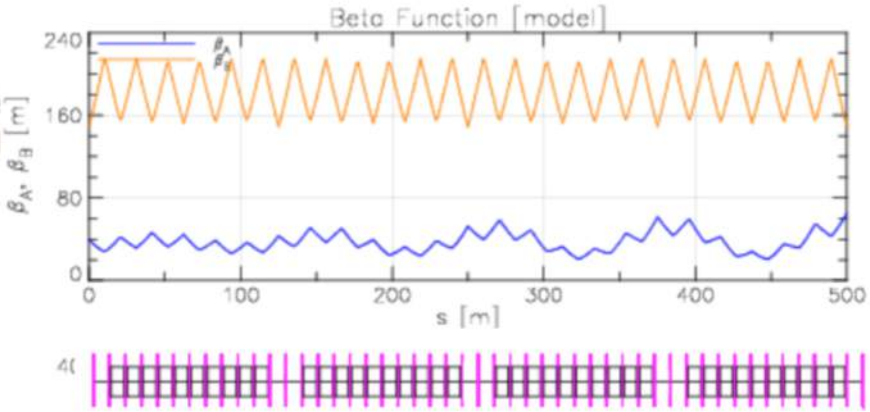
Requires:

-- 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

......




| | |
|---|---|
| Bending radius | 52.3 m |
| circumference | 500 m |
| Electrode spacing | 3 cm |
| Deflector shape | cylindrical |
| Harmonic, RF[MHz] | 100, 35.878 |
| $Q_x$, $Q_y$ | 2.42, 0.44 |
| $\varepsilon_x$ , $\varepsilon_y$ [mm-mrad] | 17, 3.2 |
| maximum $\frac{dp}{p}$ | $4.6 \times 10^{-4}$ |
| Dispersion, max [m] | 30 m |

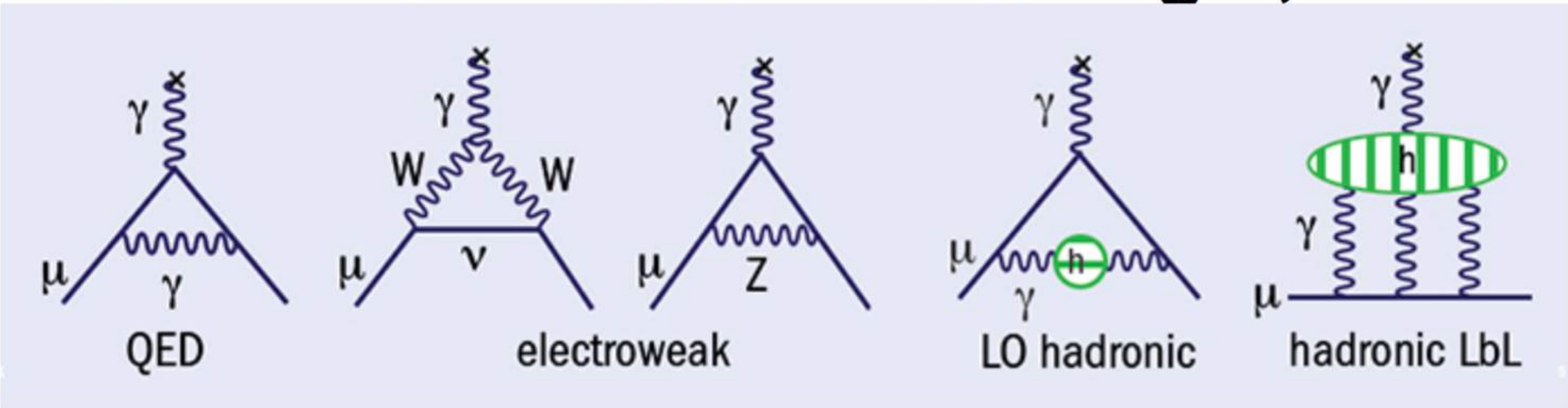
V. Anastassopulos et al, https://arxiv.org/abs/1502.04317

FORSCHUNGSZENTRUM

# Summary

- Storage ring based EDM search offers fantastic physics
- Significant effort and progress are made worldwide
  - Experimental demonstration of long spin coherence time
  - The new low magnetic field shielding
  - High efficient polarimeter for deuteron beam that enabled key spin manipulations
  - Many others …
- For the implementation of the EDM ring, things to consider
  - the progress of the ongoing R&D efforts worldwide
  - scenarios that allow the search of EDM of multiple ion species for fully understand the CP violation
  - and with this in mind, a staged approach for reaching the holy grail of $10^{-29}$ e-cm or better sensitivity may benefit the community, both physics and accelerator, in the long run

# Theoretical status of muon g-2, SM




The history of theoretical calculations goes very far in the past. Back to Schwinger's result, $a_\mu^{\text{1-loop QED}} = \alpha / (2\pi)$

Currently, the QED calculations are carried out to four-loop order,

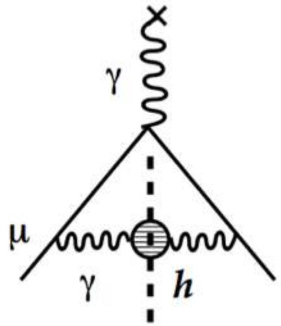
$$a_\mu^{\mathrm{QED}} = 116584718.08(15) \cdot 10^{-11}$$

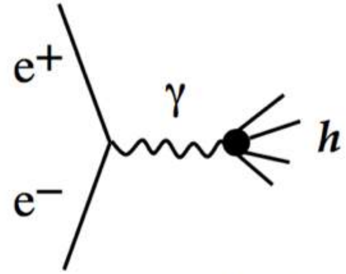
Electroweak calculations are also under control,

$$a_\mu^{\mathrm{EW}} = (154 \pm 2) \cdot 10^{-11}$$

Hadronic contributions: A. vacuum polarization B. "light-by-light"

For A. unitarity + analyticity comes to rescue:




$$a_\mu^{\text{had, LO VP}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, \sigma^0_{\text{had}}(s) K(s)$$

$$a_\mu^{\text{had, LO VP}} = (694.91 \pm 3.72_{\text{exp}} \pm 2.10_{\text{rad}}) \cdot 10^{-10}\,.$$

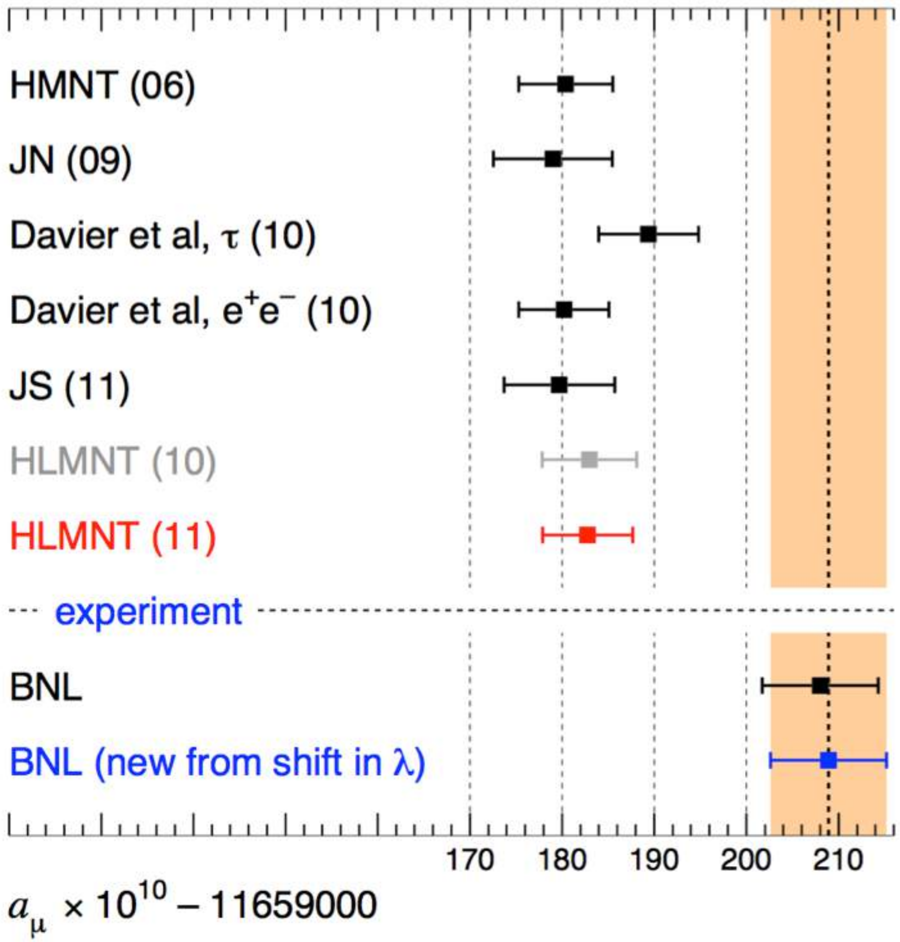
For B. some hadronic model calculations are necessary at this points (loops of heavy quarks + loops of light mesons, e.g. pions)

Recent evaluations give $a_\mu^{\text{had, l-by-l}} = (10.5 \pm 2.6) \cdot 10^{-10}$

$a_\mu^{\text{had, l-by-l}} = (11.6 \pm 4.0) \cdot 10^{-10}$

# Summary of the current discrepancy

From Hagiwara et al. (2011)




There is a theoretical "deficit" of $3\times10^{-9}$, and the tension is ~ 3.5 $\sigma$

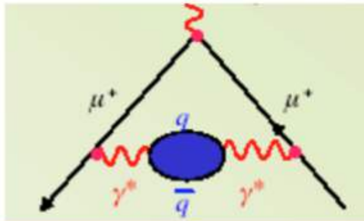
# Future: new experiment at Fermilab

Repeat of the BNL experiment with the same storage ring, but much enhanced intensities, and improved monitoring of the magnetic field.

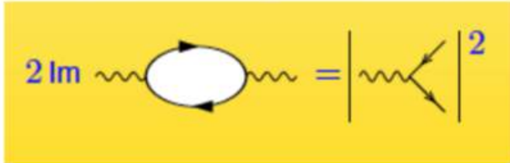
Goal: *shrink the size of the experimental errors by a factor of ~4.*

# $a_\mu^{HLO}$ calculation, traditional way: time-like data

$a_\mu$=(g-2)/2



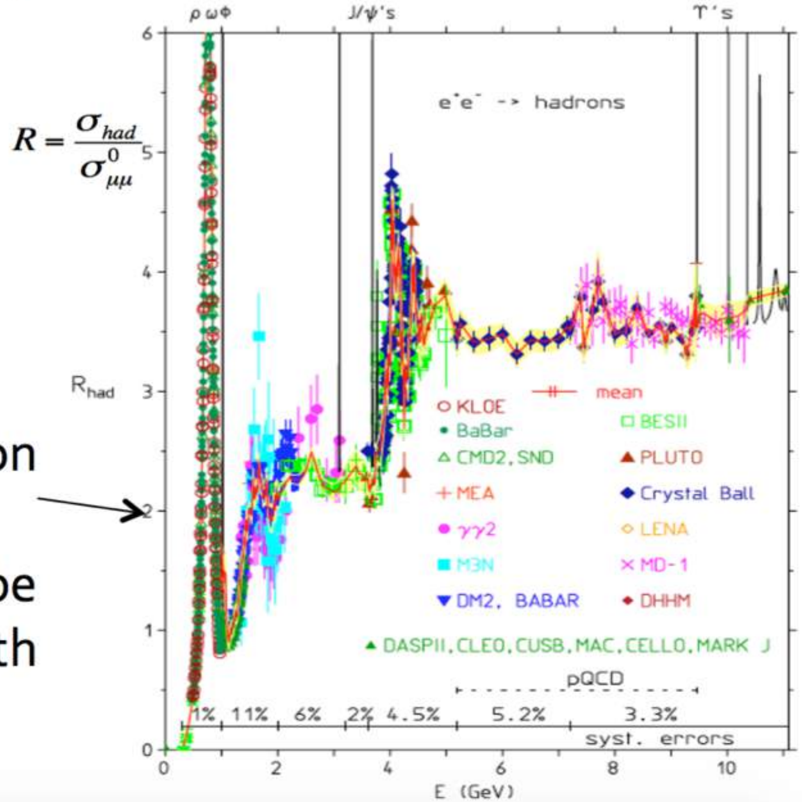

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to hadr}(s)K(s)ds$$




$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s} \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\mathrm{Im}\,\Pi_{had}(s)$$

Traditional way: based on precise experimental (time-like) data:

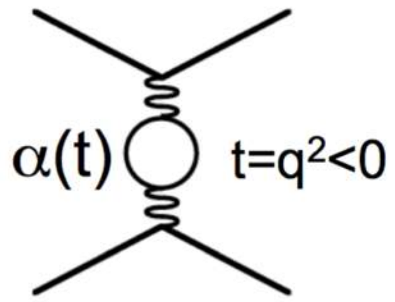
**$a_\mu^{HLO}$ = (692.3±4.2)$10^{-10}$** (DHMZ)




- Main contribution in the low energy region (**highly fluctuating!**)
- Current precision at 0.6% → needs to be reduced by a factor **~2** to be competitive with the new **g-2** experiments

# Alternative approach: $a_\mu^{HLO}$ from space-like region

[*C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni*
Phys.Lett. B746 (2015) 325-32]

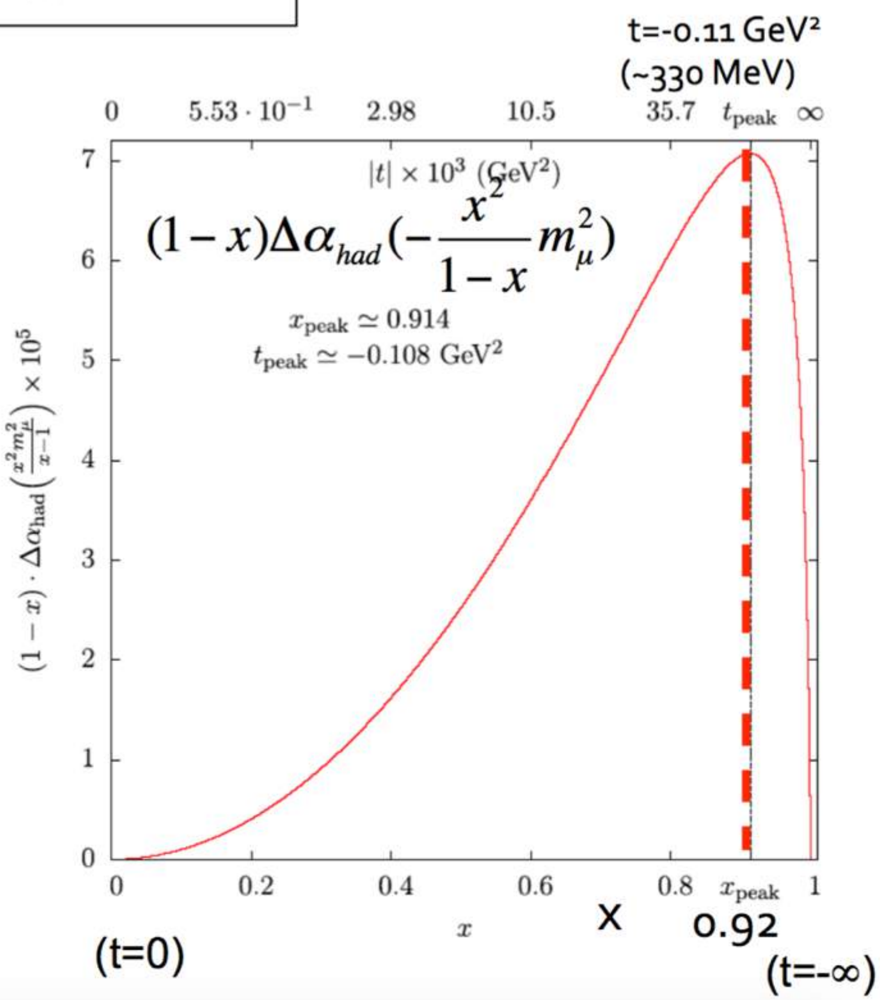



$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$

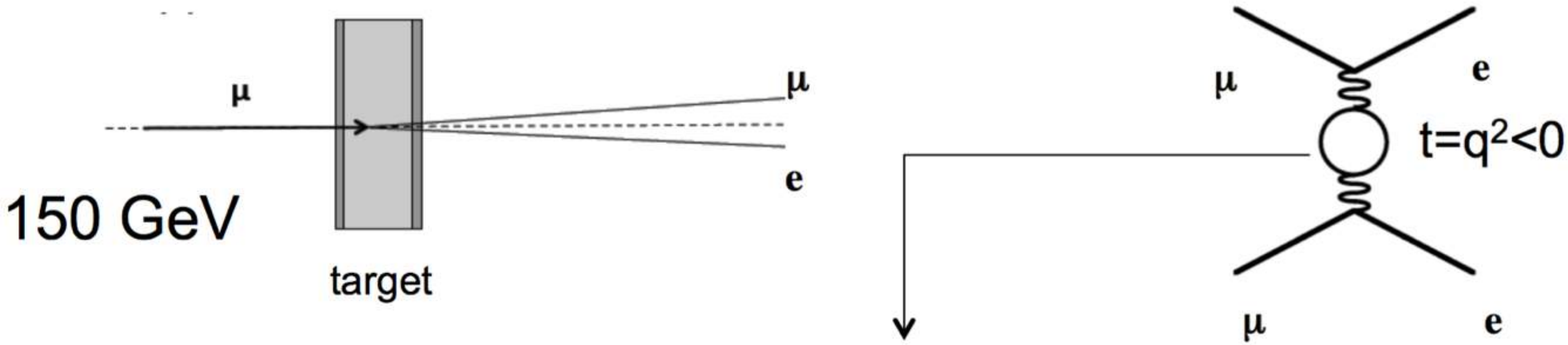
$$t = \frac{x^2 m_\mu^2}{x-1} \quad 0 \le -t < +\infty$$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \quad 0 \le x < 1;$$

- **$a_\mu^{HLO}$ is given by the integral of the curve** (smooth behaviour)
- **It requires a measurement of** the hadronic contribution to the effective electromagnetic coupling in the space-like region **$\Delta\alpha_{had}$(t) (t=q²<0)**
- **It enhances** the contribution from **low** q² region (below 0.11 GeV²)
- **Its precision** is determined by the **uncertainty** on $\Delta\alpha_{had}$ (t) in this region

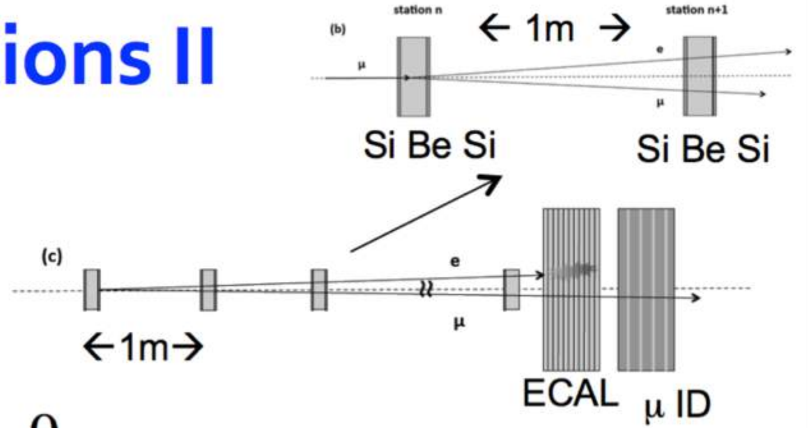


## $\Delta\alpha_{had}(t)$ can be measured with high energy muon beam (E~150 GeV) on electron low-Z target, through the elastic scattering $\mu e \rightarrow \mu e$




$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

# Detector considerations II



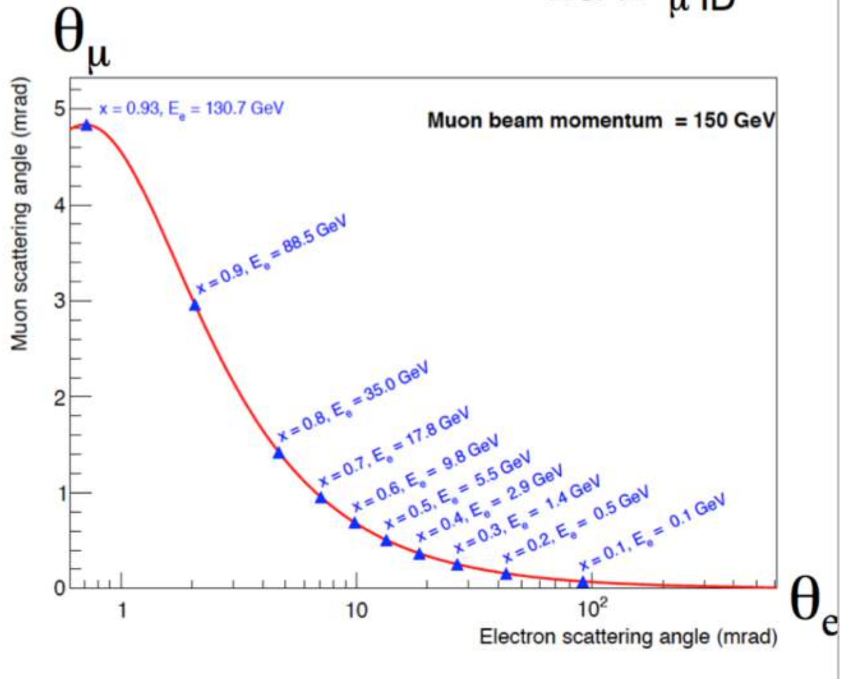

- Modular apparatus: 20 layers of 3 cm Be (target), each coupled to 1 m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle

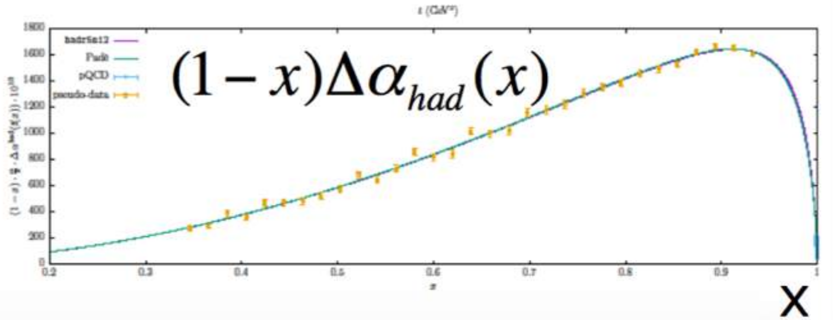
- The $t=q^2<0$ of the interaction is determined by the electron (or muon) scattering angle (a` la NA7)

- ECAL and μ Detector located downstream to solve PID ambiguity below 5 mrad. Above that, angular measurement gives correct PID

- It provides uniform full acceptance, with the potential to keep the systematic errors at $10^{-5}$ (main effect is the multiple scattering for normalization which can be studied by data)

- **Statistical considerations show that a 0.3% error can be achieved on $a_\mu^{HLO}$ in 2 years of data taking with $2\times10^7$ μ/s**



- la misura puo' essere fatta al fascio di $\mu$ del Cern (M2) che fornisce $2*10^7$ $\mu$/sec
  - con il fascio dedicato, l'errore statistico della misura e' 0.3% in 2 anni di presa dati
  - piccolo problema: sullo stesso fascio c'e' Compass!
- La parte piu' delicata e' la targhetta:
  - alto Z aumenta interazioni (=statistica) ma anche multiple scattering e background
  - 20 bersagli di Berillio (2cm) equipaggiato con Silicio per il tracking
  - puo' essere fatta una proof of concept con una stazione per verificare la fattibilita'

# 5 – antimateria, antiidrogeno

# Probing Fundamental Physics with Antimatter


Stefan Ulmer (BASE)

for the

AD-Collaborations


ATRAP

# Strategy and Physics Motivation

- Precise comparisons of the fundamental properties of **simple baryonic matter/antimatter** conjugates at **low energy** and with **high precision**.
- Such comparisons provide stringent tests of CPT invariance.
- Simple systems can be understood, and understanding provides sensitivity with respect to deviations.

**matter sector**

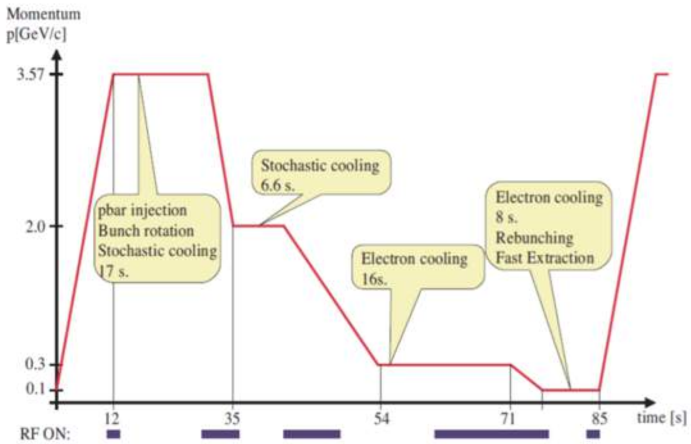
| | |
|---|---|
| proton lifetime (direct) | >1.67 e34 y |
| proton m | 90 p.p.t. |
| proton magn. moment | 3.3 p.p.b. |
| hydrogen 1S/2S | 0.004 p.p.t. |
| hydrogen GSHFS | 0.7 p.p.t. |

**antimatter sector**

| | |
|---|---|
| antiproton lifetime | >1.2 y |
| antiproton m | 90 p.p.t. |
| antiproton m. moment | 4.4 p.p.m. |
| antihydrogen 1S/2S | ? |
| antihydrogen GSHFS | ? |

ALPHA
BASE
ATRAP
GBAR
AEgIS

# Methods – the antiproton decelerator

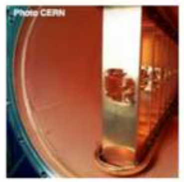




AD provides: 30.000.000 antiprotons at 5.3 MeV each 120s

- Degrading / RFQ-D
- Catching
- Electron Cooling and kickout
- Compression

resistive cooling –> particles at 8ueV

**bridge 6 orders of magnitude within a few 100s**

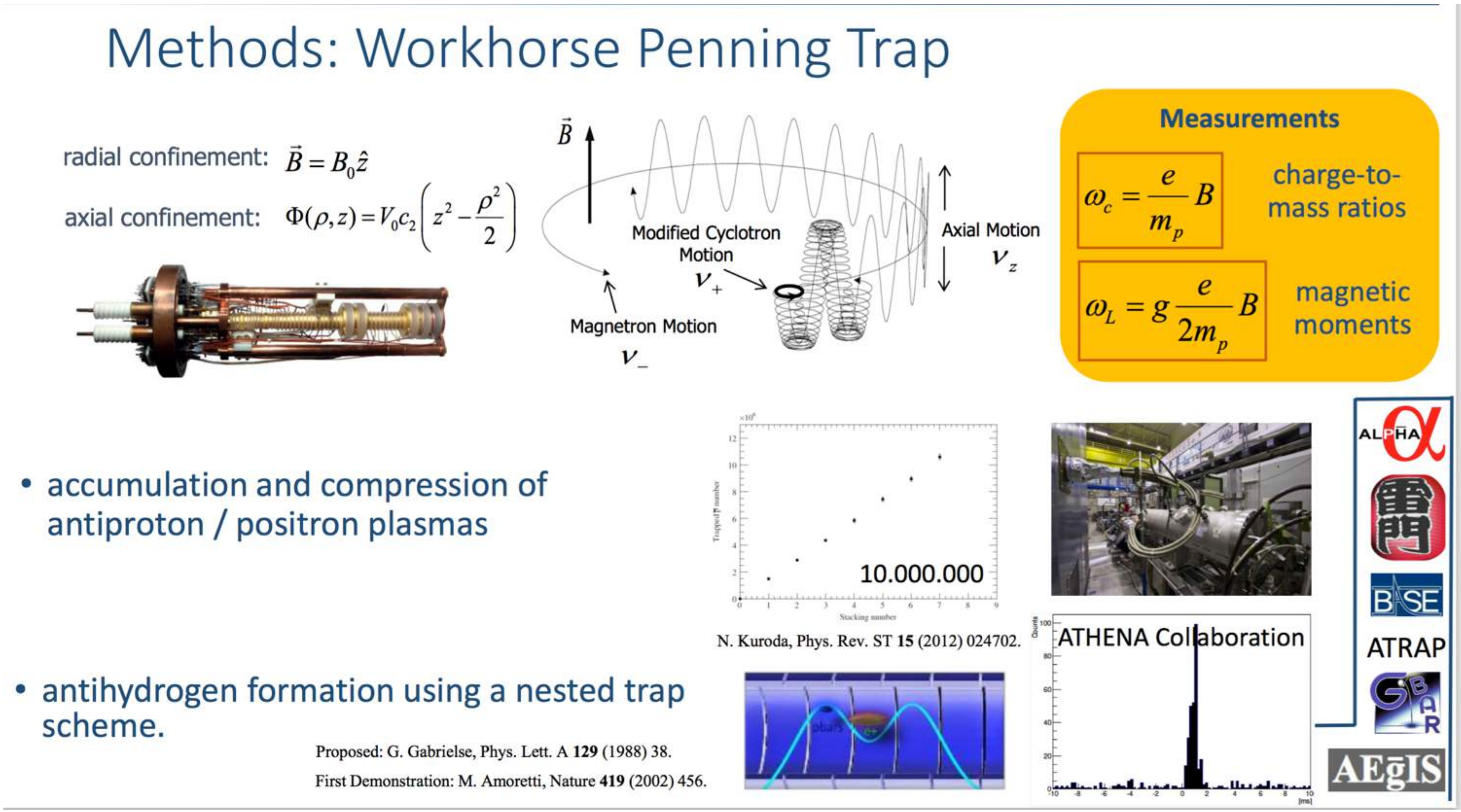



**work pioneered by the TRAP collaboration**

Catching: G. Gabrielse et al, PRL 57, 2504 (1986)
Cooling: G. Gabrielse et al, PRL 63, 1360 (1989)
Measurement: G. Gabrielse et al, PRL 65, 1317 (1990)

ATRAP

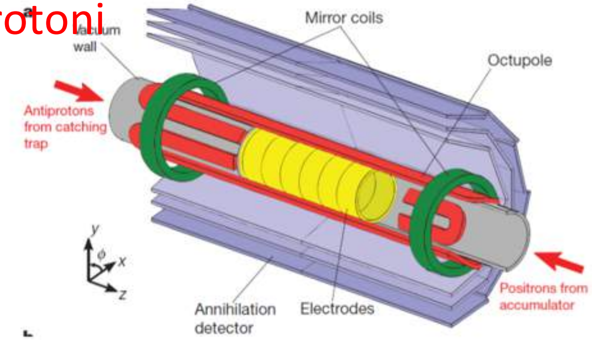
# plasma di anti-protoni e positroni



# produzione di anti-idrogeno

## Physics Measurements

anti-protoni




positroni

- Antihydrogen 1S/2S laser spectroscopy in magnetic trap.
- Hydrogen in trap: 5 p.p.t.
- Trapping via atomic magnetic moment, Challenge: shallow trap (0.5 K)

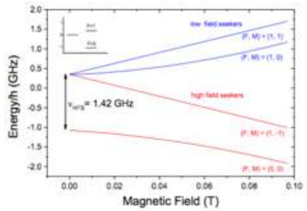
C. L. Cesar, Phys. Rev. Lett. **77** (1996) 255.

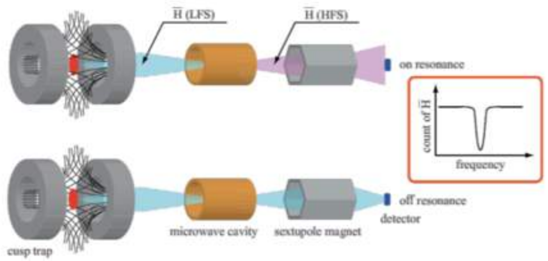
- Antihydrogen beam spectroscopy (ASACUSA Scheme)

1ppb

$$\nu_{HF} = \frac{16}{3} \cdot \mathrm{Ry} \cdot \alpha^2 c \cdot \left( \frac{1}{1+\frac{m_e}{m_p}} \right)^3 \cdot \frac{m_e}{m_p} \cdot \frac{\mu_e}{\mu_B} \cdot \frac{\mu_p}{\mu_N} \cdot (1 + \delta_{str} + \delta_{QED})$$

<1ppb




ALPHA

ATRAP

- extract antiproton magnetic moment
- probe antiproton substructure
- Test SME coefficients

Achieved 3.3 p.p.b. using hydrogen beam (Widmann Group in ASACUSA)

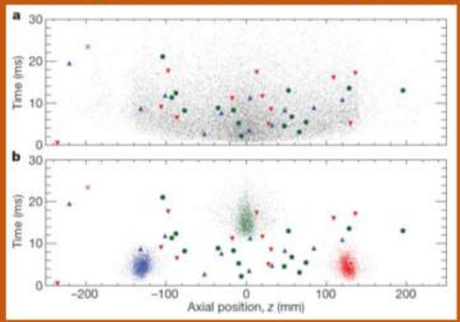
A. Mohri and Y. Yamazaki, Europhys. Lett. **63** (2003) 207.

AEgIS

# risultati gia' prodotti

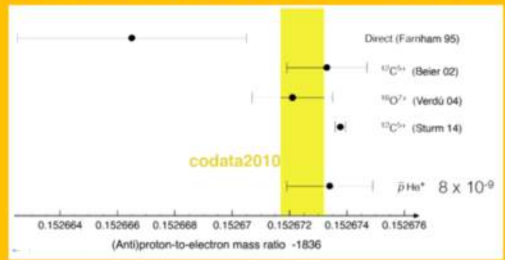
## Highlights – CPT Sector

### trapped antihydrogen




ALPHA, Nature 468, (2010) 674.
sim. res. ATRAP, PRL (2012)

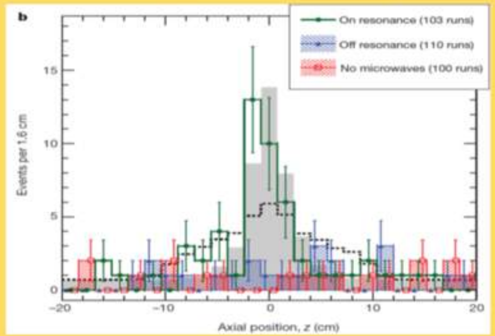
### antiproton/electron mass ratio




2-photon spectroscopy of anti-protonic helium / 8 p.p.b.

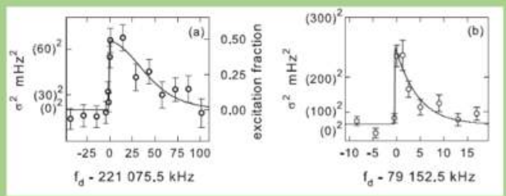
ASACUSA, Nature **484** (2011) 475.

### «rf-spectroscopy»




ALPHA, Nature 483, (2012) 442.

### antiproton mag. moment




4.4 p.p.m. measurement using single Penning trap technique

ATRAP, Phys. Rev. Lett **110** (2013) 130810

### Antihydrogen Beam

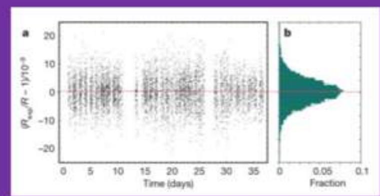
**Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.**

| | Scheme 1 | Scheme 2 | Background |
|---|---|---|---|
| Measurement time (s) | 4,950 | 2,100 | 1,550 |
| Double coincidence events, $N_t$ | 1,149 | 487 | 352 |
| Events above the threshold (40 MeV), $N_{>40}$ | 99 | 29 | 6 |
| *Z*-value (profile likelihood ratio) ($\sigma$) | 5.0 | 3.2 | — |
| *Z*-value (ratio of Poisson means) ($\sigma$) | 4.8 | 3.0 | — |

Major step towards planned antihydrogen spectroscopy.

ASACUSA, Nature Comm. **3** (2014) 475.

### antiproton/proton Q/M ratio




69 p.p.t. measurement using two particle Penning trap technique

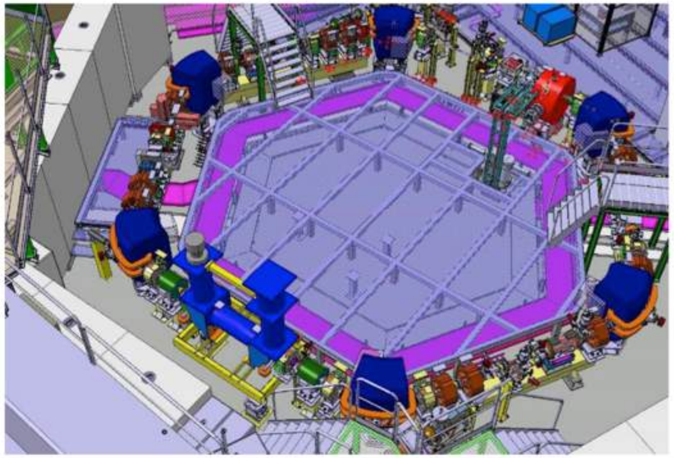
BASE, Nature **493** (2014) 502.

# Per il futuro: modifica del sistema di rallentamento dei positroni e degli anti-protoni -> citato ma non descritto!

## ELENA

- Antiprotons are caught in Penning traps using degraders – 99.9% of particles are lost.
- ELENA provides antiprotons decelerated to 100keV – compared to the AD – at improved beam emittance.
- Degrading at low particle energies is much more efficient

| Experiment | ELENA Gain Factor |
|---|---|
| ALPHA | 100 |
| ATRAP | 100 |
| ASACUSA | 10 |
| AEgIS | 100 |



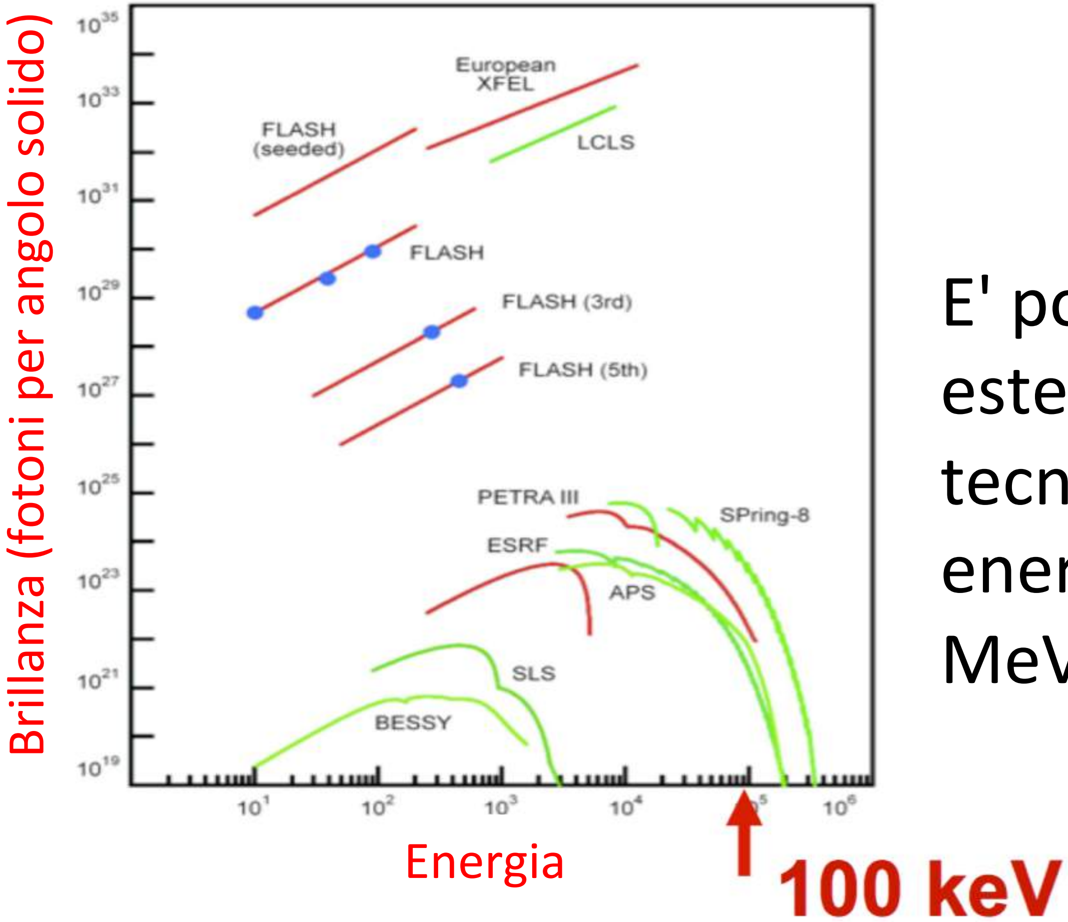
- **ELENA will be able to deliver beams almost simultaneously to all experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone**

Provides bright future perspective for antiproton-physics at CERN

# 6 – beam facilities

- gamma factory
- Awake

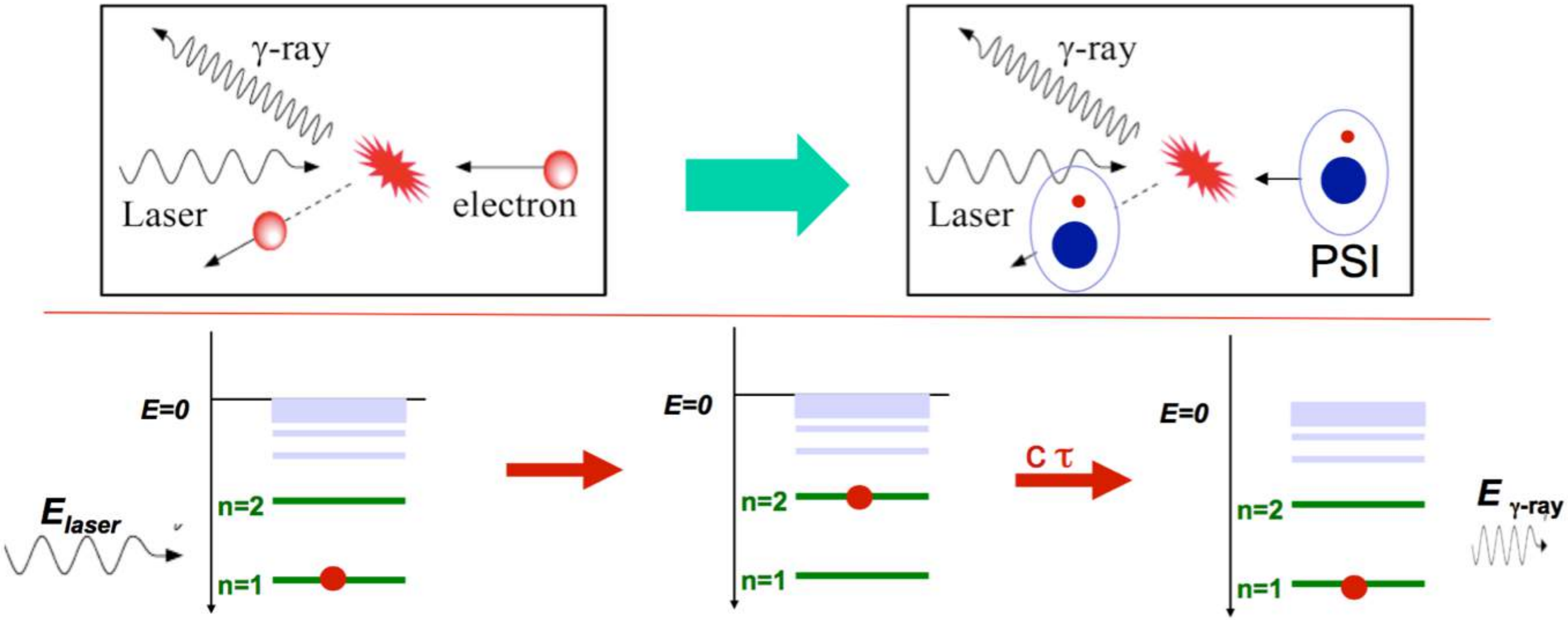
# X-ray factories




Energies up to ~ 100 keV

E' possibile estendere questa tecnologia a energie di 1-100 MeV?

# Simple Idea: replace an Electron beam by a Partially Stripped Ion (PSI) beam




$E_{laser} = 1Ry\,(Z^2 - Z^2/n^2)/2\gamma_L$ → $E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^{\,2}/(1+(\gamma_L\theta)^2)$

*Note:* $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

8

# "Tuning" dell'energia

$$\nu_i^{max} \longrightarrow (4\,\gamma_L^2)\,\nu_i$$

$\gamma_L$ =E/M - Lorentz factor for the ion beam

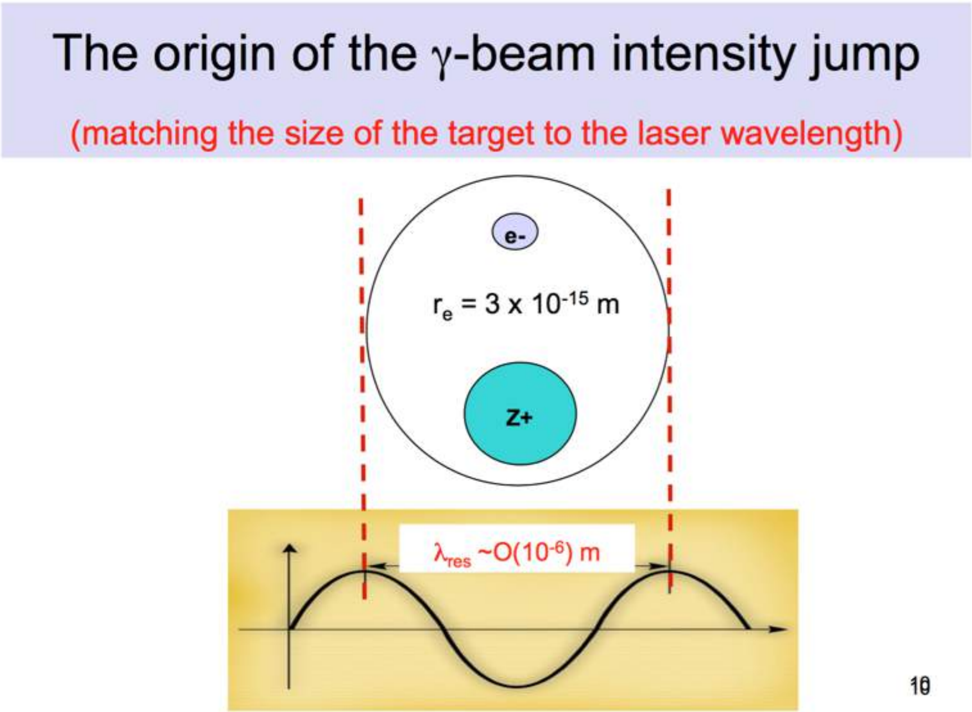
*The tuning of the PSI beam energy (SPS or LHC), the choice of the ion type, and the number of left electrons and of the laser type allows to tune the $\gamma$-ray energy in the requisite energy domain of 100 keV – 400 MeV.*

*Example (maximal energy):*

*LHC,* $Pb^{80+}$ *ion,* $\gamma_L$ = 2887, n=1→2, $\lambda_{laser}$ = 104.4 nm, $E_\gamma$ (max) = 396 MeV

9

# Intensita' del fascio




Sezioni d'urto:

- elettroni

$$\sigma_e \approx r_e^2 \approx 10^{-25} cm^2$$

- PSI

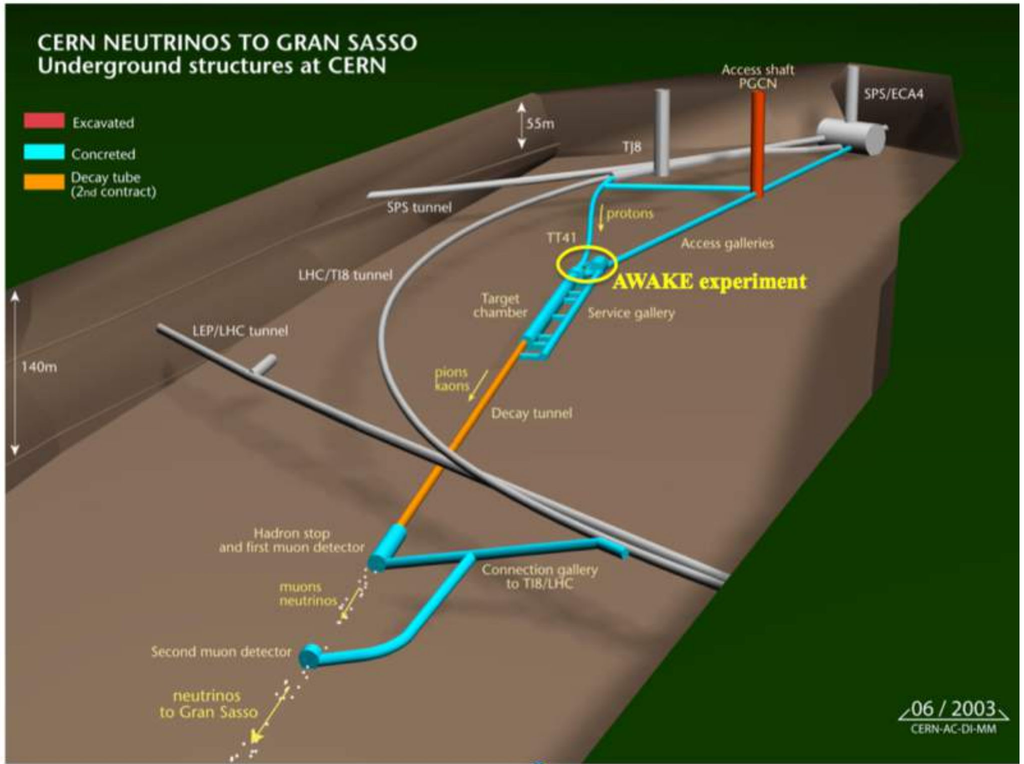
$$\sigma_{PSI} \approx \lambda_{res}^2 \approx 10^{-18} - 10^{-16} cm^2$$

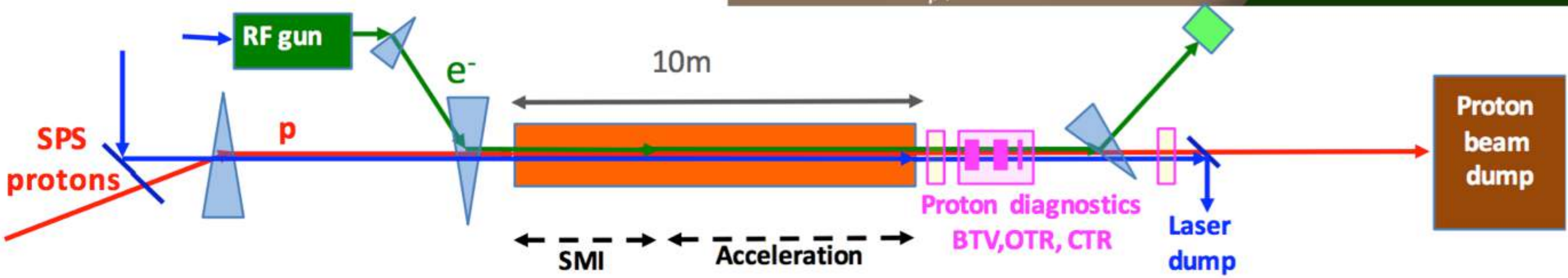
- brillanza aumentata di 7-9 ordini di grandezza

# Fascio di elettroni O(50GeV) di alta purezza e intensita'

## AWAKE: proton driven plasma wakefield experiment

- Demonstration experiment to show effect for first time and obtain *GV/m* gradients.
- Use *400 GeV* SPS proton bunches with high charge.
- To start running this year and first phase to continue to LS2.
- Apply scheme to particle physics experiments leading to shorter or higher energy accelerators.



# Physics behind AWAKE

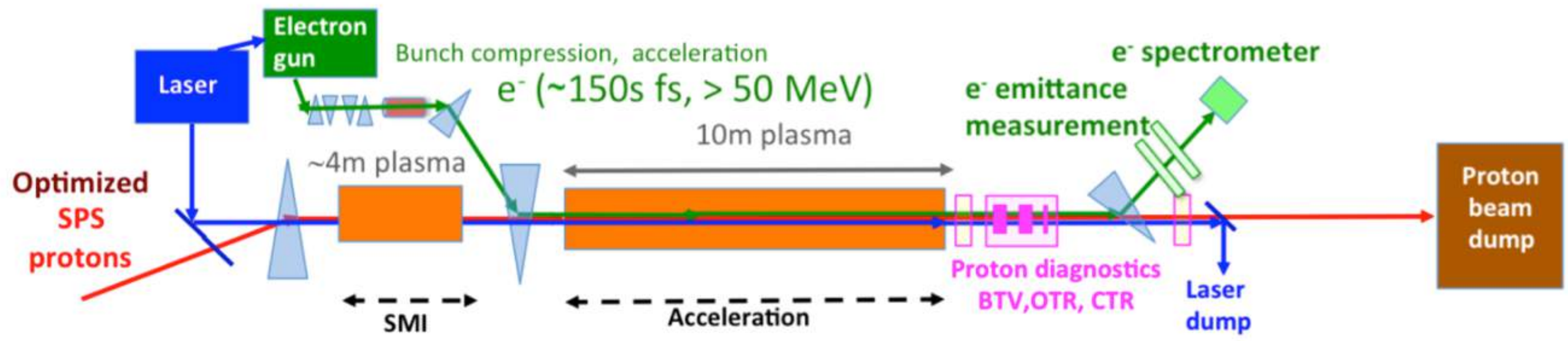
A plasma wakefield is a type of wave generated by particles travelling through a plasma. AWAKE will send proton beams through plasma cells to generate these fields. By harnessing wakefields, physicists may be able to produce accelerator gradients hundreds of times higher than those achieved in current radiofrequency cavities. This would allow future colliders to achieve higher energies over shorter distances than is possible today.

Usando protoni dell'SPS → elettroni di ~50 GeV
Usando protoni di LHC → elettroni di ~2 TeV

Test attuali svolti con SPS

# AWAKE Run 2

- Preparing AWAKE Run 2, after LS2 and before LS3.
  - Accelerate electron bunch to higher energies.
  - Demonstrate beam quality preservation.
  - Demonstrate scalability of plasma sources.




Preliminary Run 2 electron beam parameters

| Parameter | Value |
|---|---|
| Acc. gradient | >0.5 GV/m |
| Energy gain | 10 GeV |
| Injection energy | $\gtrsim$ 50 MeV |
| Bunch length, rms | 40–60 $\mu$m (120–180 fs) |
| Peak current | 200–400 A |
| Bunch charge | 67–200 pC |
| Final energy spread, rms | few % |
| Final emittance | $\lesssim$ 10 $\mu$m |

- Are there physics experiments that require an electron beam of up to *O(50 GeV)* ?
- Use bunches from SPS with *3.5 × $10^{11}$ protons* every *~ 5 s*.
- Using the LHC beam as a driver, *TeV* electron beams are possible.

E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008).

# Possible physics experiments

- Use of electron beam for test-beam campaigns.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Also accelerator test facility.
  - Variation of energy.
  - Provide pure electron beam.
- Fixed-target experiments using electron beams, e.g. deep inelastic scattering.
  - Measurements at high *x* with higher statistics than previous experiments.
  - Polarised beams and spin structure of the nucleon.
- **Search for dark photons à la NA64**
  - Consider beam-dump and counting experiments.
- **High energy electron−proton collider**
  - A low-luminosity LHeC-type experiment.
  - A very high energy electron−proton collider.

This is not a definitive list, but a quick brainstorm and people are invited to think of other possible uses/applications/experiments.

# 7 – esperimenti non agli acceleratori

ALPS

IAXO (seguito di CAST)

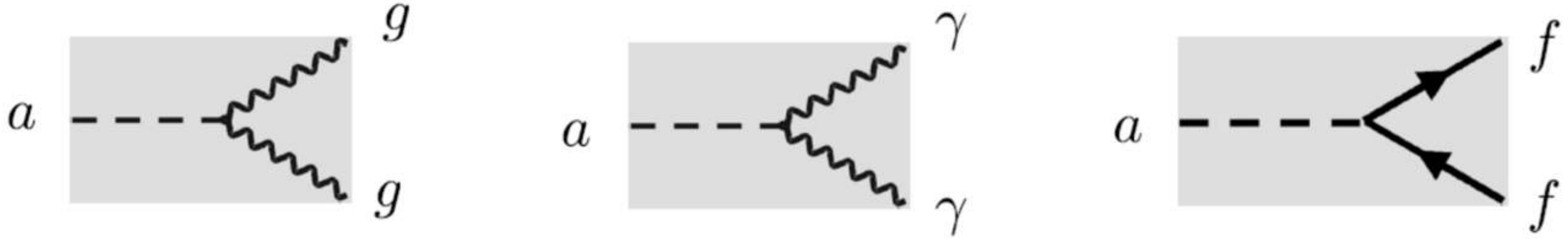
KWISP

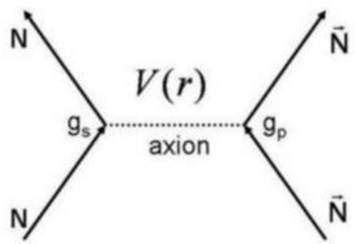
DARK-SIDE

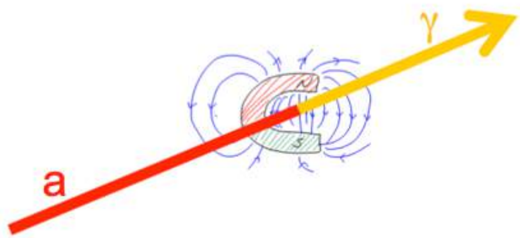
# Axion and axion-like-particle (ALP) couplings

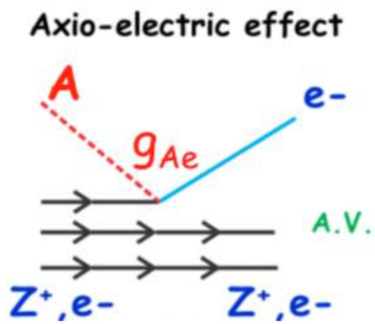
- Axion and other Nambu-Goldstone bosons arising from spontaneous breakdown of global symmetries are theoretically well-motivated very weakly interacting slim (ultra-light) particles.
  The coefficients are determined by specific ultraviolet extension of SM.

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f\gamma^\mu\gamma_5\psi_f$$



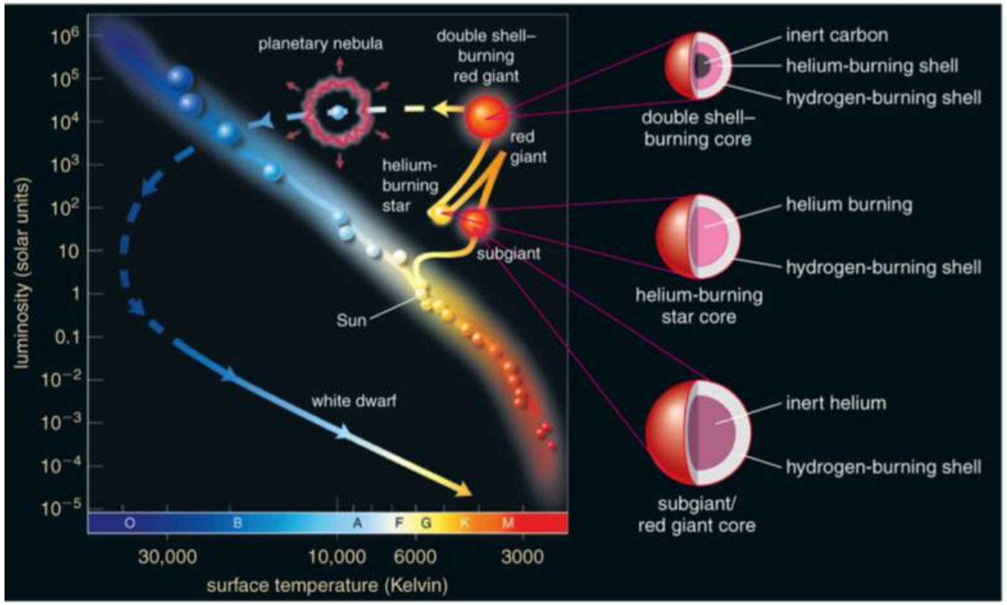



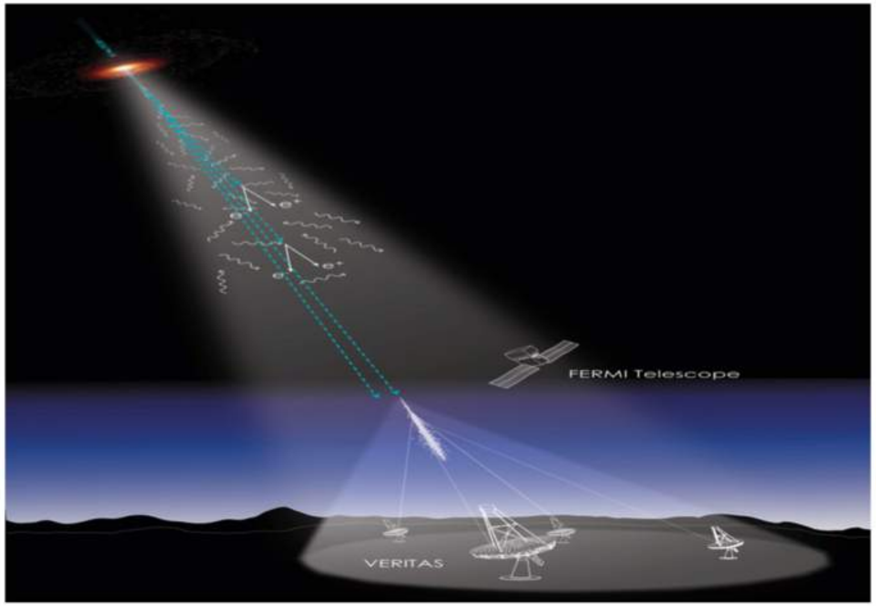



# Astro-Hints on Axion/ALPs?

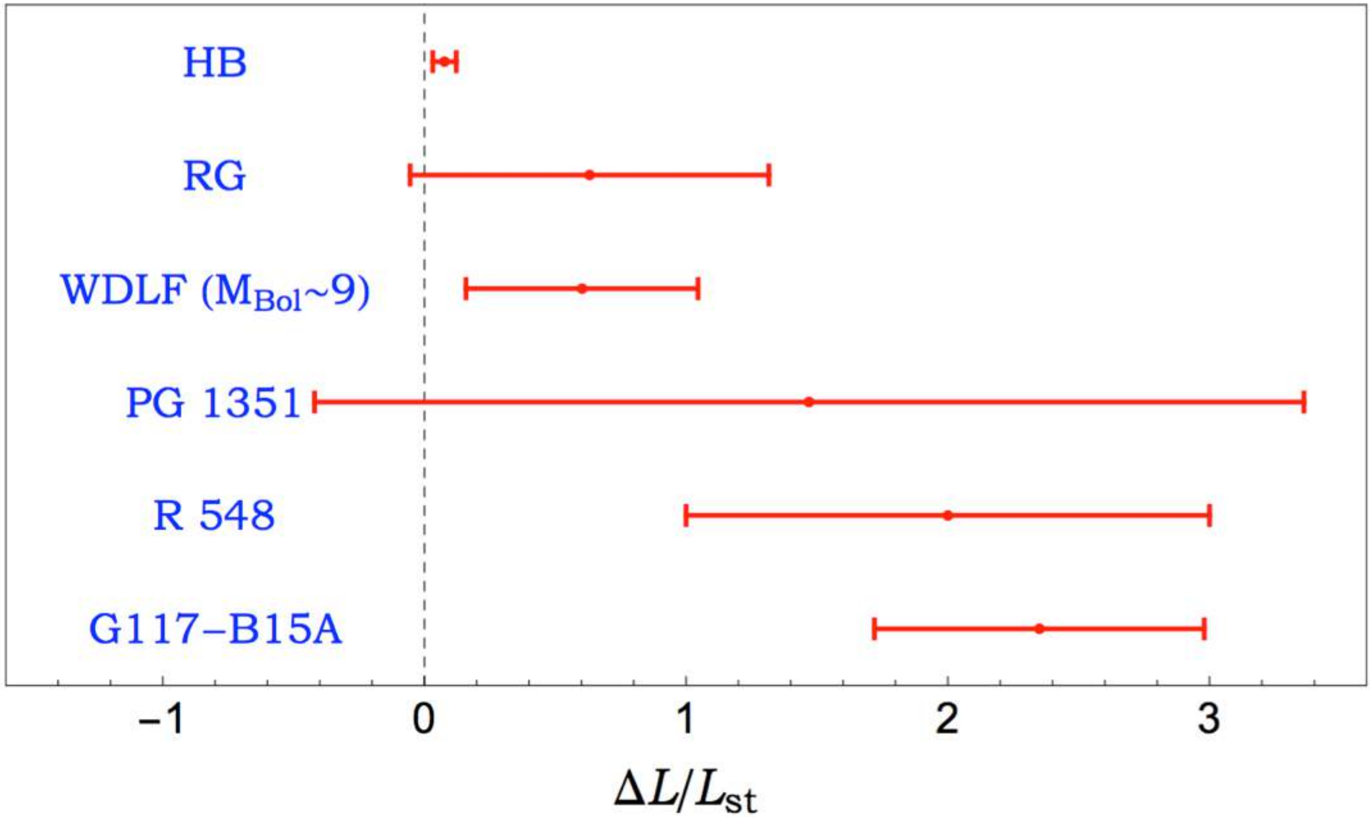
- Modest hints for
  - excessive energy losses of stars in various evolutionary stages,
  - photon-ALP conversion in astrophysical magnetic fields



# Hints of Axion/ALP Energy Losses of Stars?

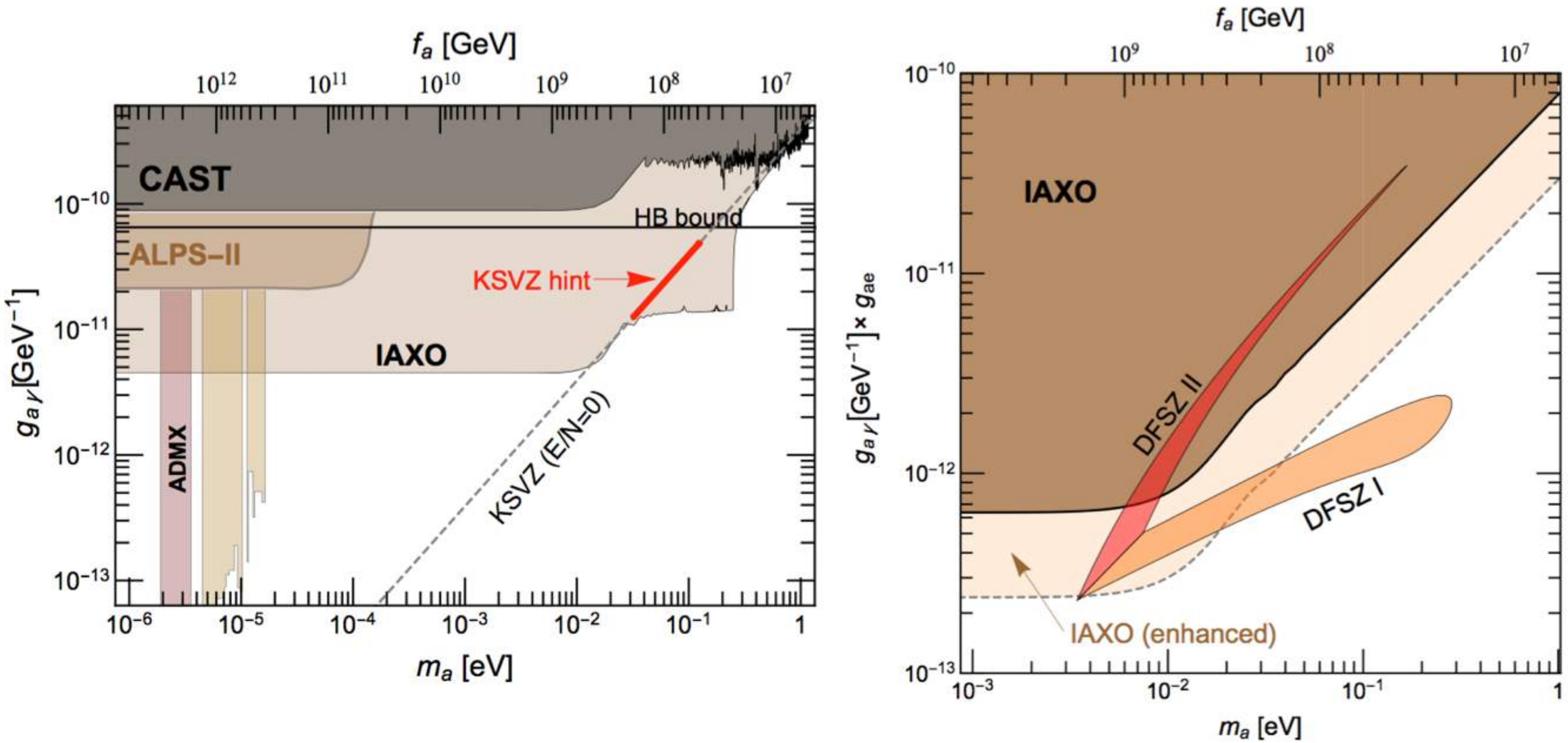
> Excessive energy losses of HBs, RGs and WDs:




[Giannotti,Irastorza,Redondo,AR, arXiv:1512.08108]

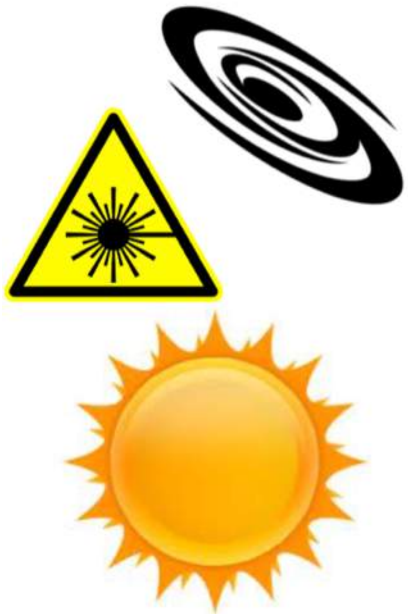
# Hints of Axion/ALP Energy Losses of Stars?

> Excessive energy losses of HBs, RGs and WDs can all be explained at one stroke by production and emission of axion/ALP with coupling both to electrons and photons, e.g. in specific axion models:




[Giannotti,Irastorza,Redondo,AR, in preparation]

# Tecniche di ricerca degli assioni



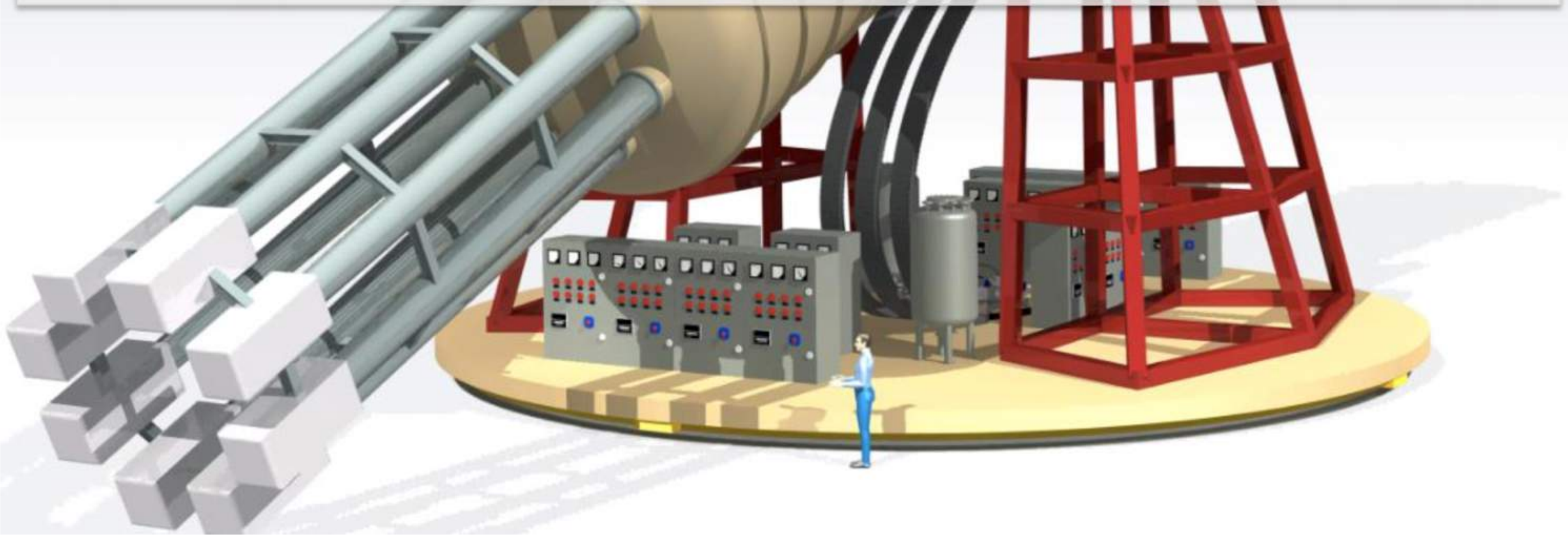
| Source | Experiments | Model & Cosmology dependency | Technology |
|---|---|---|---|
| Relic axions | ADMX, ADMX-HF, Casper, CAPP, ... | High | New ideas emerging, Active R&D going on,... |
| Lab axions | ALPS, OSQAR, fifth force exps,... | Very low | |
| Solar axions | SUMICO, CAST, IAXO | Low | Ready for large scale experiment |

- Helioscopes → do not rely on the axion being the dominant DM component. Solar axion emission robust prediction
- Helioscopes → No R&D needed. Technology mature enough for a large scale experiment (IAXO)
- Large complementarity with other detection strategies

# Physics case, prospects and status of the International AXion Observatory IAXO

Igor G. Irastorza (U. Zaragoza)
on behalf of the IAXO collaboration

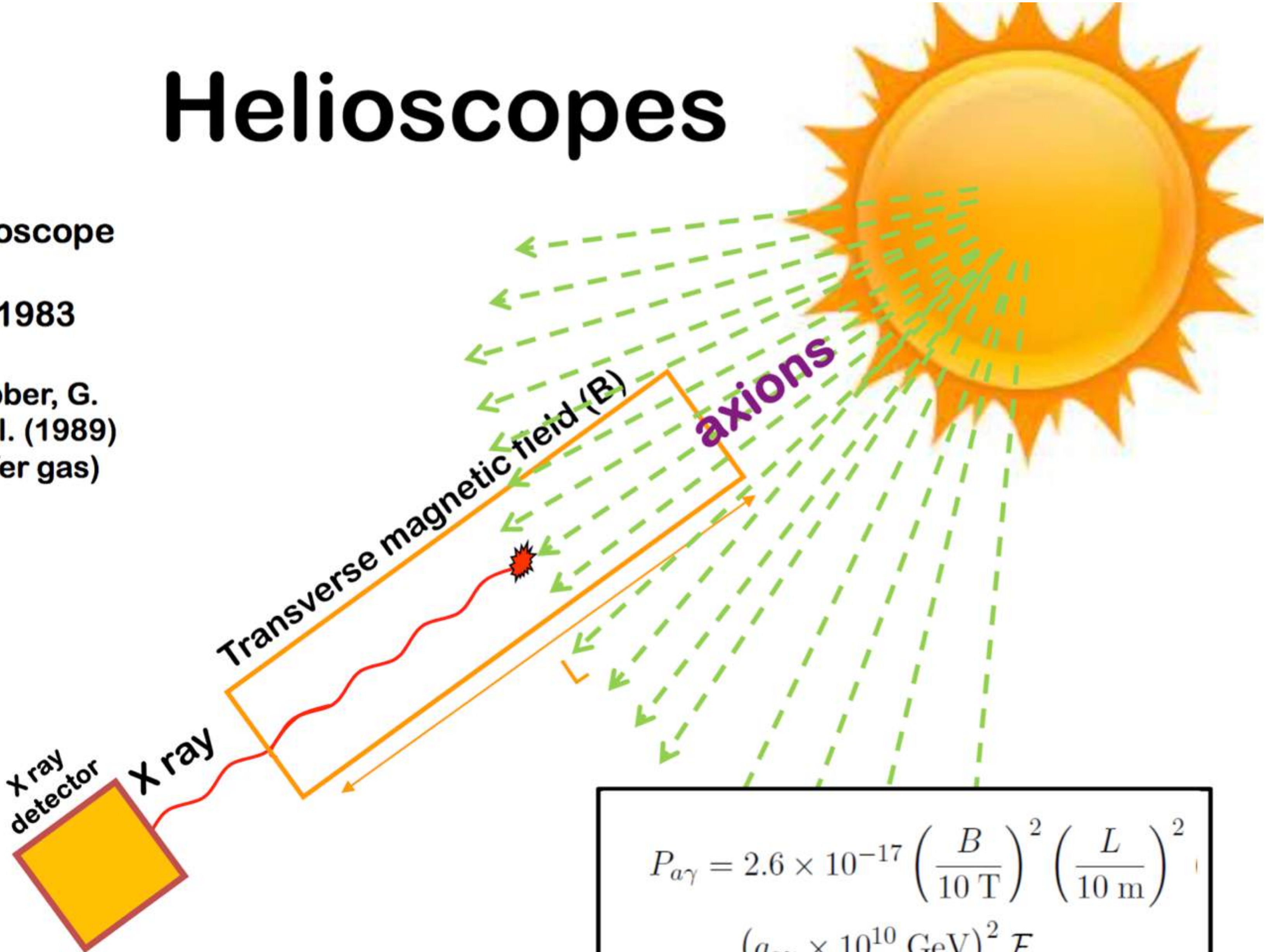
Beyond Colliders, CERN, September 7th 2016



# Helioscopes

**Axion helioscope concept**
**P. Sikivie, 1983**

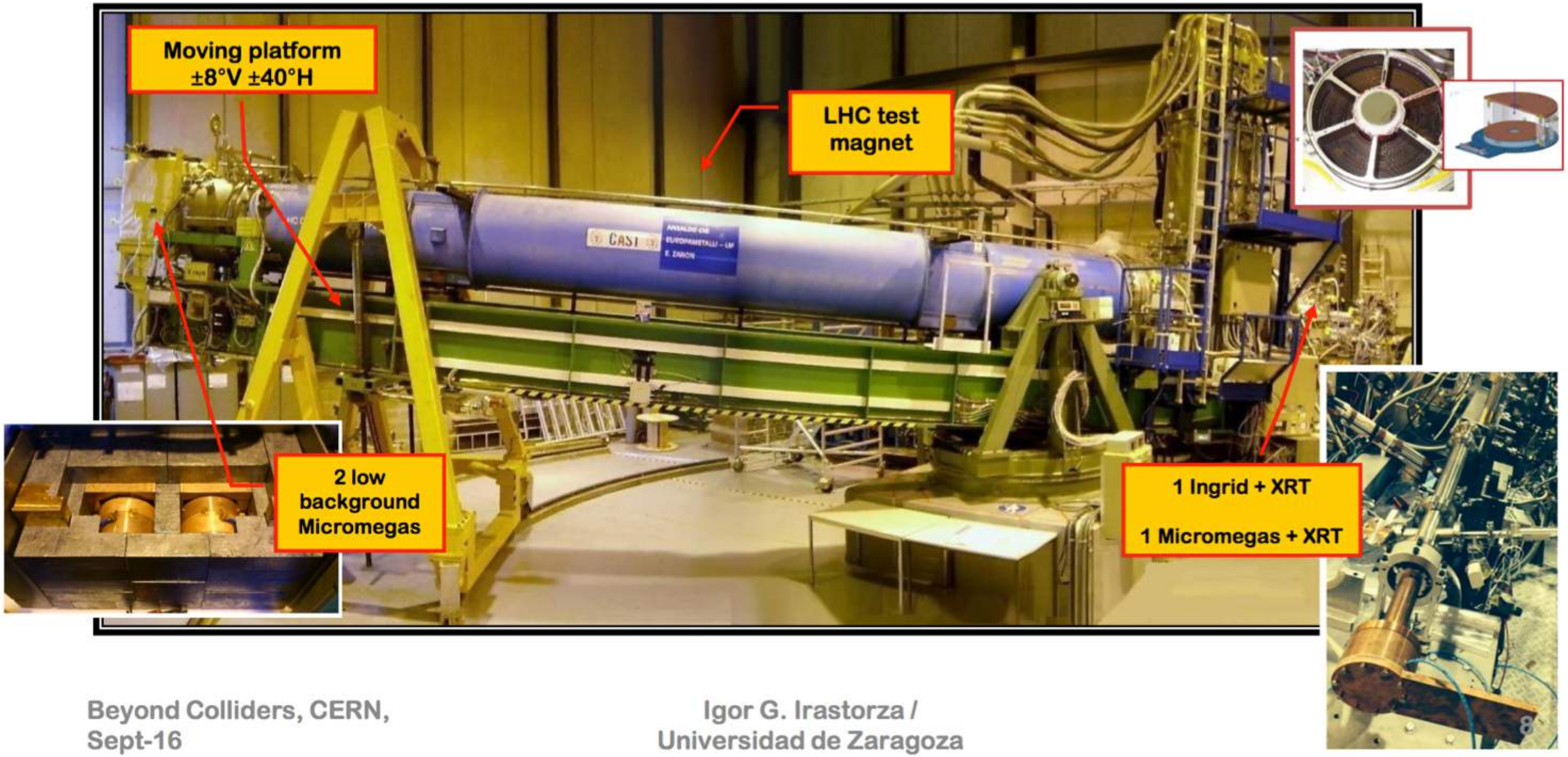
**+ K. van Bibber, G. Raffelt, et al. (1989) (use of buffer gas)**




$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \mathrm{GeV}\right)^2 \mathcal{F}$$

# CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 2 X ray telescopes to increase signal/noise ratio.

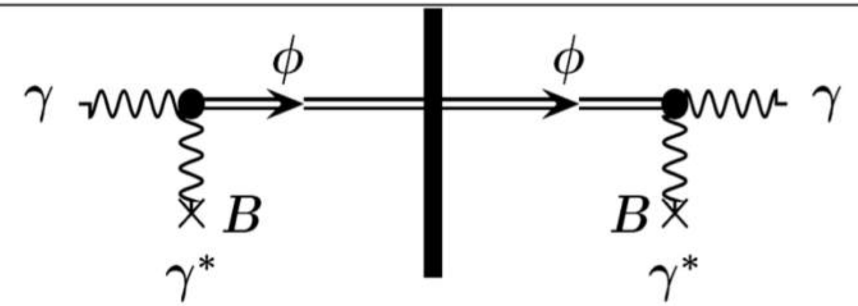


# How to look for ALPs …

… by exploiting their coupling to photons:

- WISPs pass any barrier and could make

## light-shining-through-a-wall.




Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

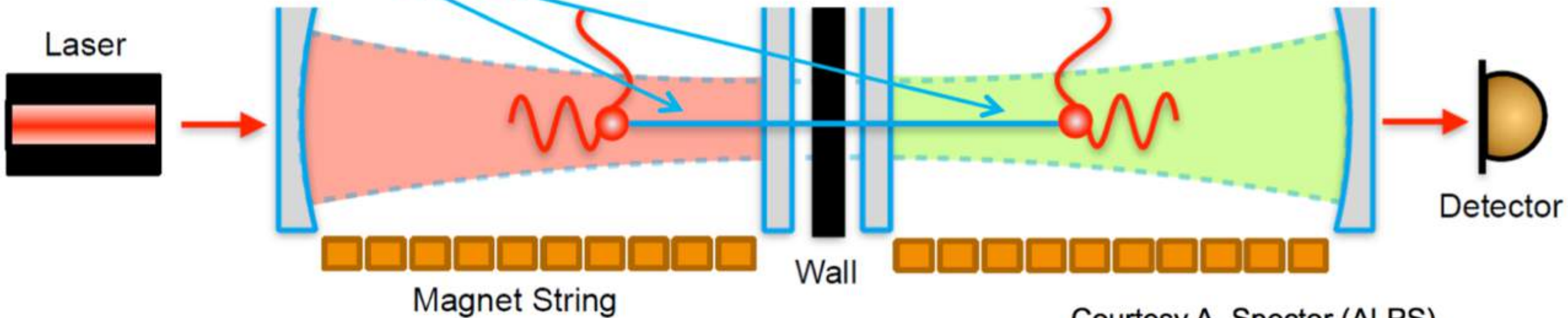
Axions, axion-like particles

$$P_{\gamma\to\phi}(B,\ell,q) = \frac{1}{4}\,(g\,B\,\ell)^2\;F(q\ell) \qquad F(q\ell) = \left[\frac{\sin\left(\frac{1}{2}q\ell\right)}{\frac{1}{2}q\ell}\right]^2$$

***$q = p_\gamma - p_\Phi$***
***l: length of B field***

Ruolo del CERN: magnete

$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1T}\frac{l}{10m}\right)^4$$




Courtesy A. Spector (ALPS)

- Use long strings of strong dipole magnets.
- Implement optical resonators to recycle the light before the wall and to boost the re-conversion of ALPs to photons behind the wall.
- The maximal length is given by the aperture of the magnets and the beam shape of the resonating mode in the optical resonators.
- The maximal circulating light power before the wall is given by the damage threshold of the mirrors and the beam spot size.

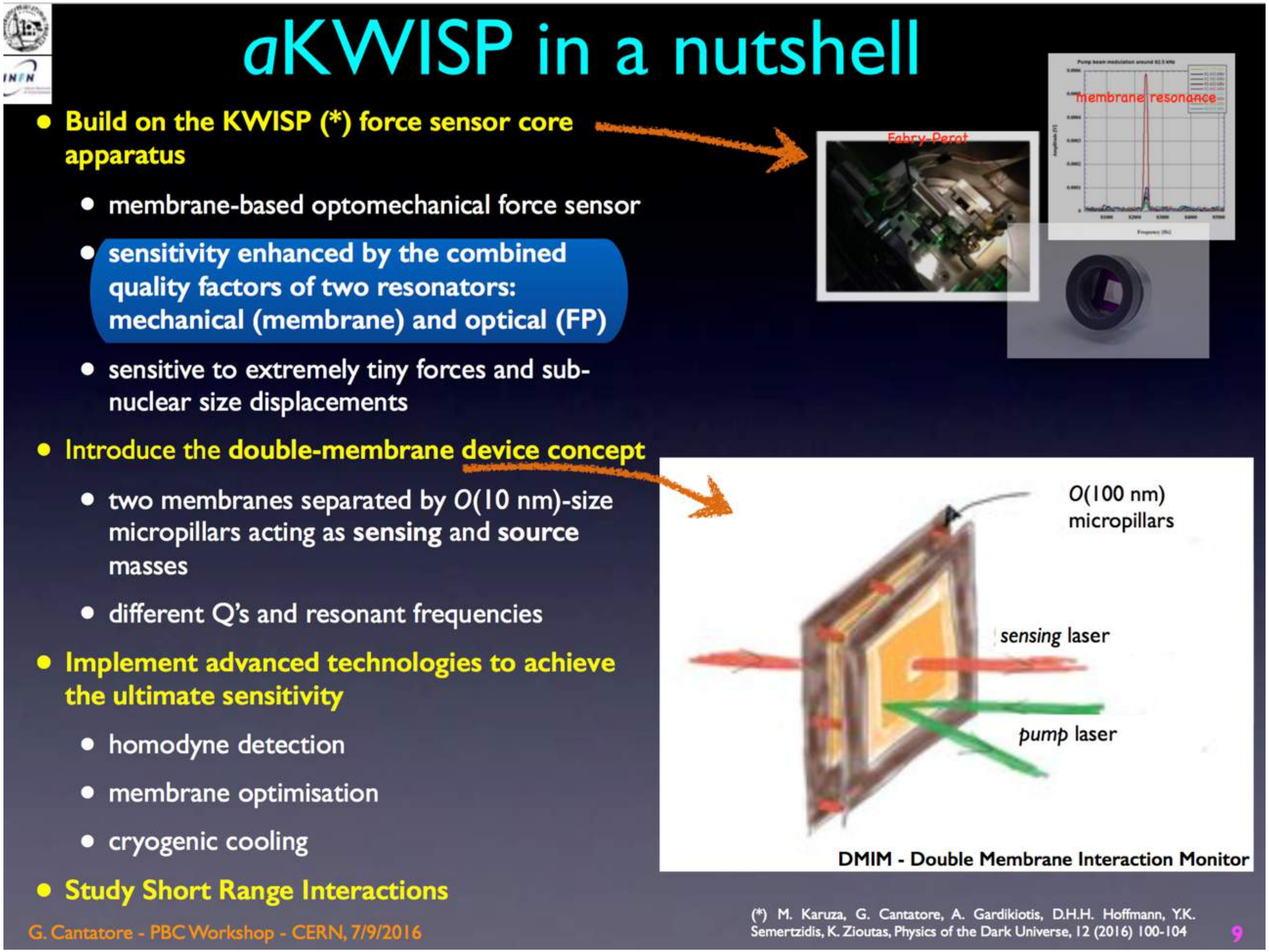
# To-take-home

- Accelerator dipole magnets under development at CERN could be the basis of an “ultimate” light-shining-through-a-wall experiment mainly searching for axion-like particles.

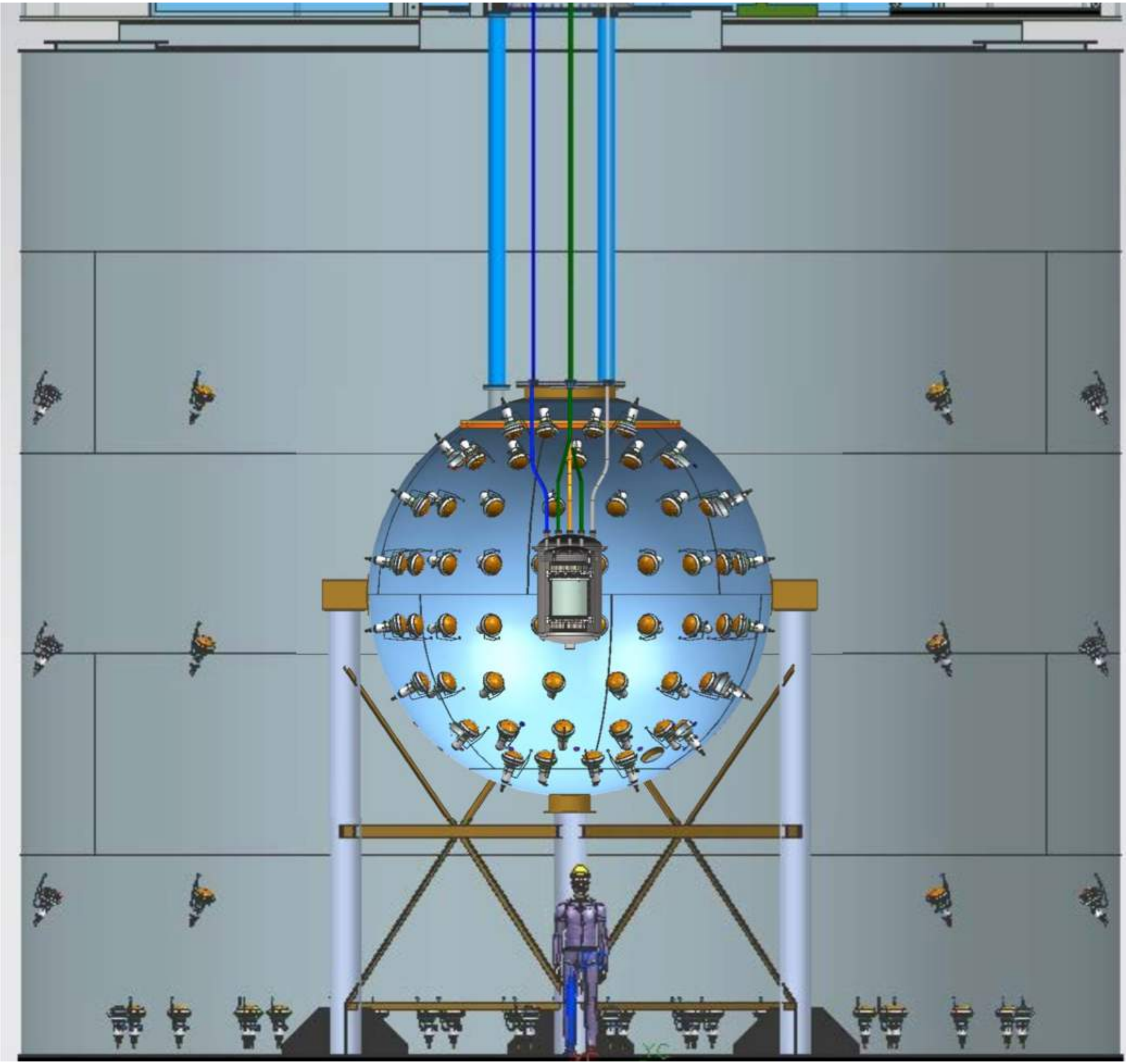
- The costs of such an experiment would be dominated by the costs of the magnet strings.
  - The costs probably strongly correlate with decisions on future accelerator projects.

- Considering the development of the physics case for axion-like particles in the recent years, experiments have to move from the niche *“make best use of existing equipment built for something else”* to more dedicated installations:
  - IAXO and “ALPS III”.

- studi odi forze a short range (~verifica di 1/r^2 a distanze ~110-100nm)
- non mi e' chiaro cosa c'entri il Cern



10 m Height
11 m Diameter
1,000 Tonnes
Water Cherenkov
Muon Veto



Ruolo del Cern: costruire presso il Cern un prototipo di 1 tonnellata

# Kickoff - general points

- Four sessions
  - **Theorists' motivations**, ideas and wishes
  - **Accelerator and infrastructure** opportunities
  - **Potential future of existing programs**
  - **New experiment ideas**

- **Avoided a top-down approach**
- **With the aim of getting ideas on the table**
- **No commitment at this stage! Goal is to provide input to European Strategy Update (ESU)**

# Conclusions

- Considerable potential for novel exploitation of existing complex
  - Cleary need to evaluate, prioritize, and commit resources where appropriate
- Some compelling new ideas at varying degrees of maturity
  - Evaluate, select, develop, report
  - Continue exploration of new ideas
- Possible collaboration with other labs to be explored

Foresee PBC follow-up meeting next year