The CERN Experimental Programme

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SMARTHEP School on Collider Physics & ML
University of Geneva
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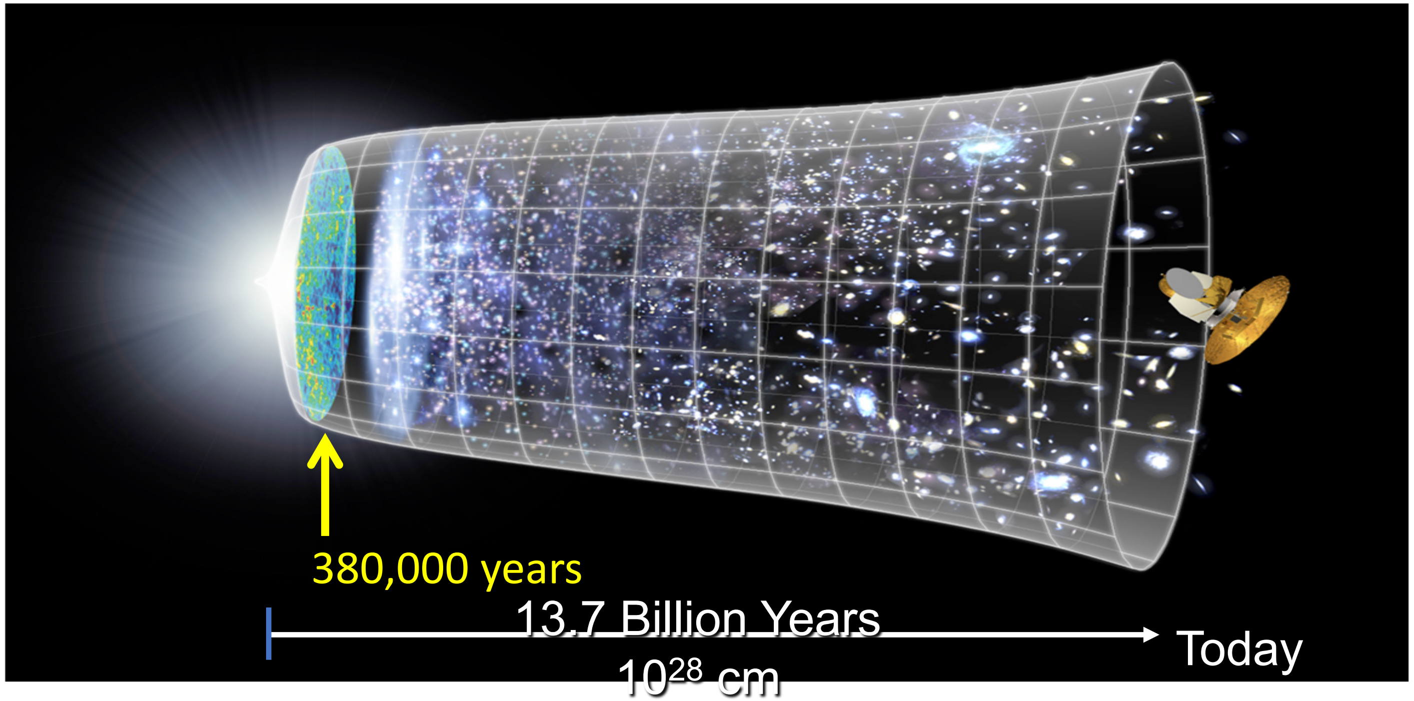
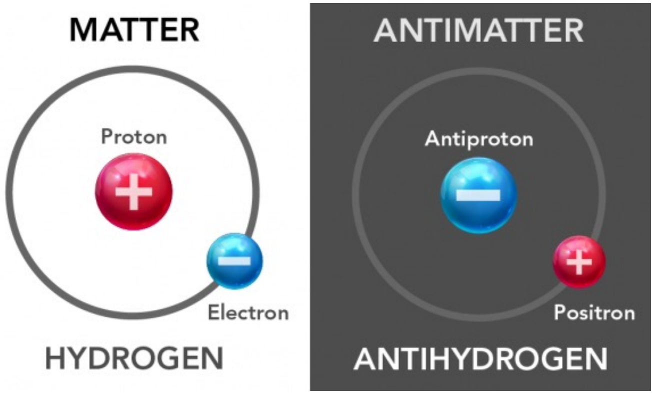
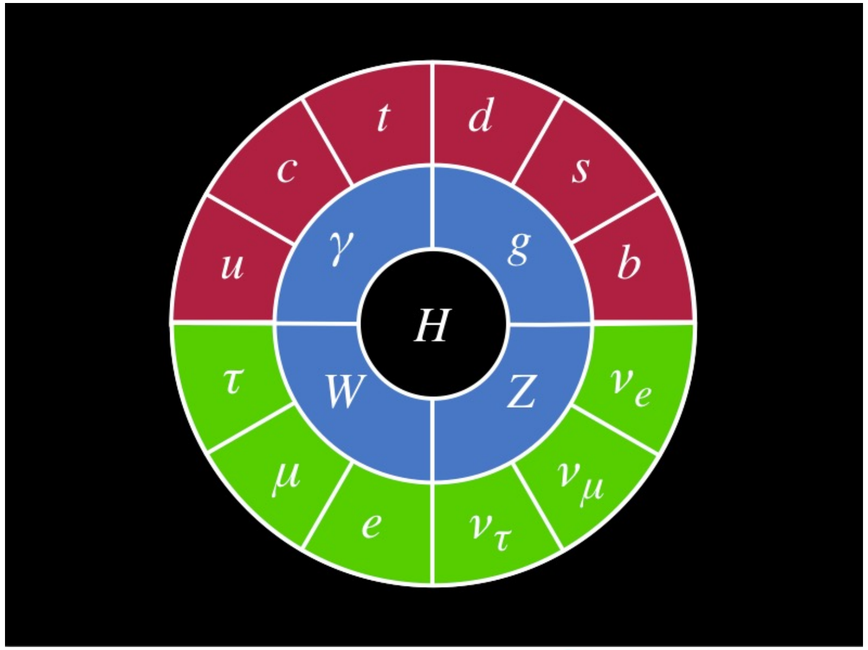






SMARTHEP
REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY

CERN Mandate

The CERN mandate is setout in the CERN convention (from 1953!) which says (amongst other things):

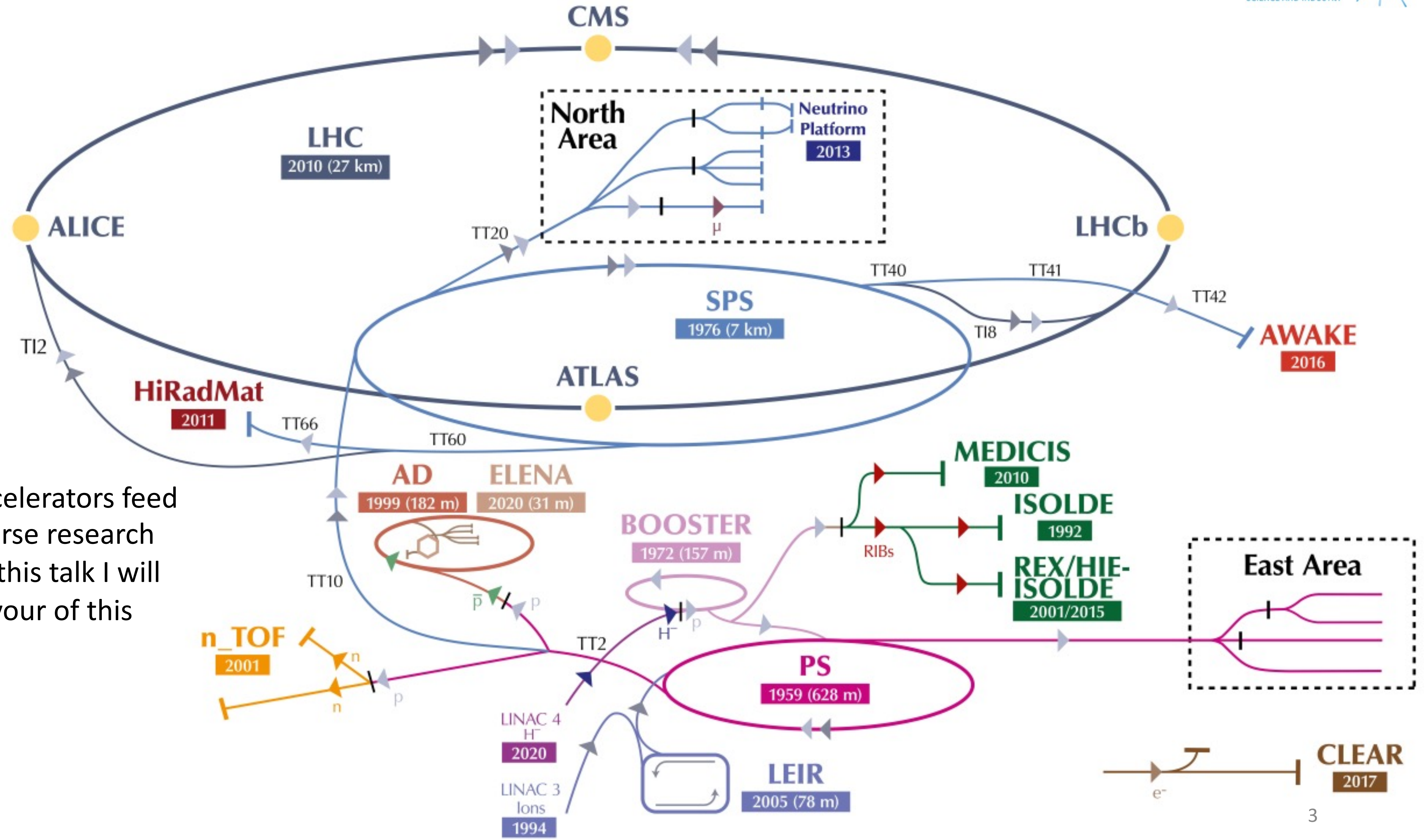
ARTICLE II : Purposes

1. The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available.
2. The Organization shall, in the collaboration referred to in paragraph 1 above, confine its activities to the following:
    1. the construction and operation of one or more international laboratories (hereinafter referred to as "the Laboratories ") for research on high-energy particles, including work in the field of cosmic rays; each Laboratory shall include:
        i. one or more particle accelerators;
        ii. the necessary ancillary apparatus for use in the research programmes carried out by means of the machines referred to in (i) above;
        iii. the necessary buildings to contain the equipment referred to in (i) and (ii) above and for the administration of the Organization and the fulfilment of its other functions;

Physics, and CERN, has evolved in the 70 years since then, but CERN still focuses on fundamental research, in the domains of particle and nuclear physics, including both experimental and theoretical research, and R&D for future projects.

From: https://council.web.cern.ch/en/content/convention-establishment-european-organization-nuclear-research

Today, the CERN research programme is shaped by the unique accelerator complex that exists at CERN



These set of accelerators feed a huge and diverse research programme. In this talk I will try to give a flavour of this programme.

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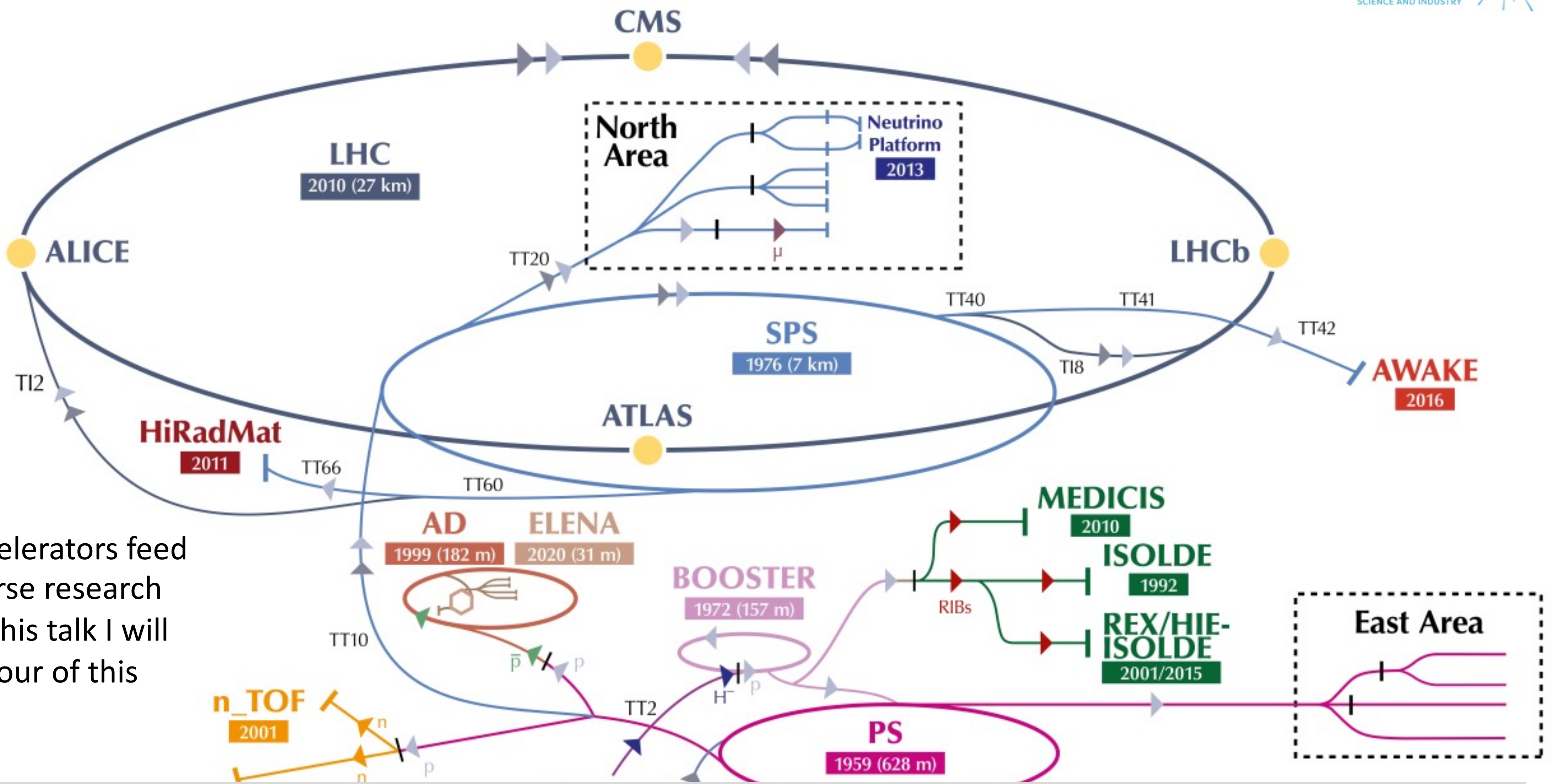


These set of accelerators feed a huge and diverse research programme. In this talk I will try to give a flavour of this programme.

Disclaimers:
- Unfortunatley due to time, I will not be able to cover everything. Apologise if your favourite experiment is missed.
- I am (by far) not an expert on everything discussed here.

Some outstanding questions in fundamental physics

What is the origin of the masses of the elementary particles (quarks, electrons, …) ?

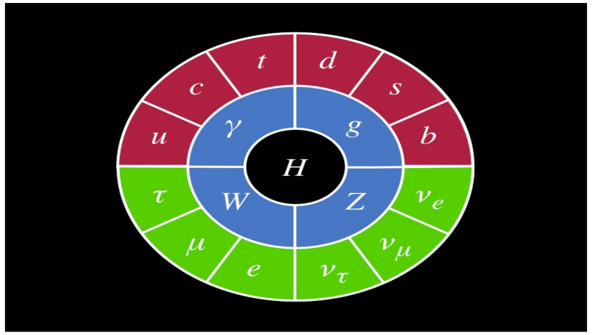
95% of the universe is unknown (dark): e.g. 25% of dark matter

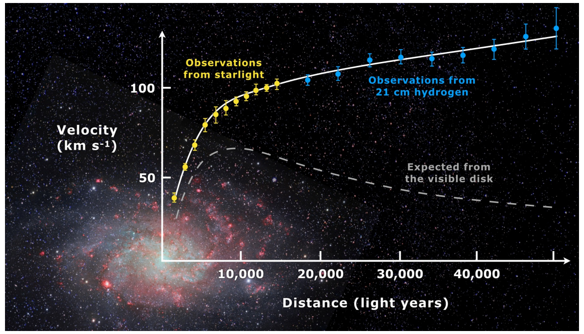
Why is there so little antimatter in the universe ?

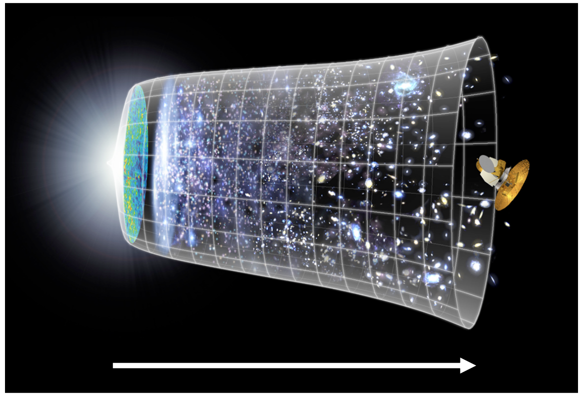
What are the features of the primordial plasma permeating the universe ~10 μs after the Big Bang ?

Are there other forces in addition to the known four ?

Etc. etc.



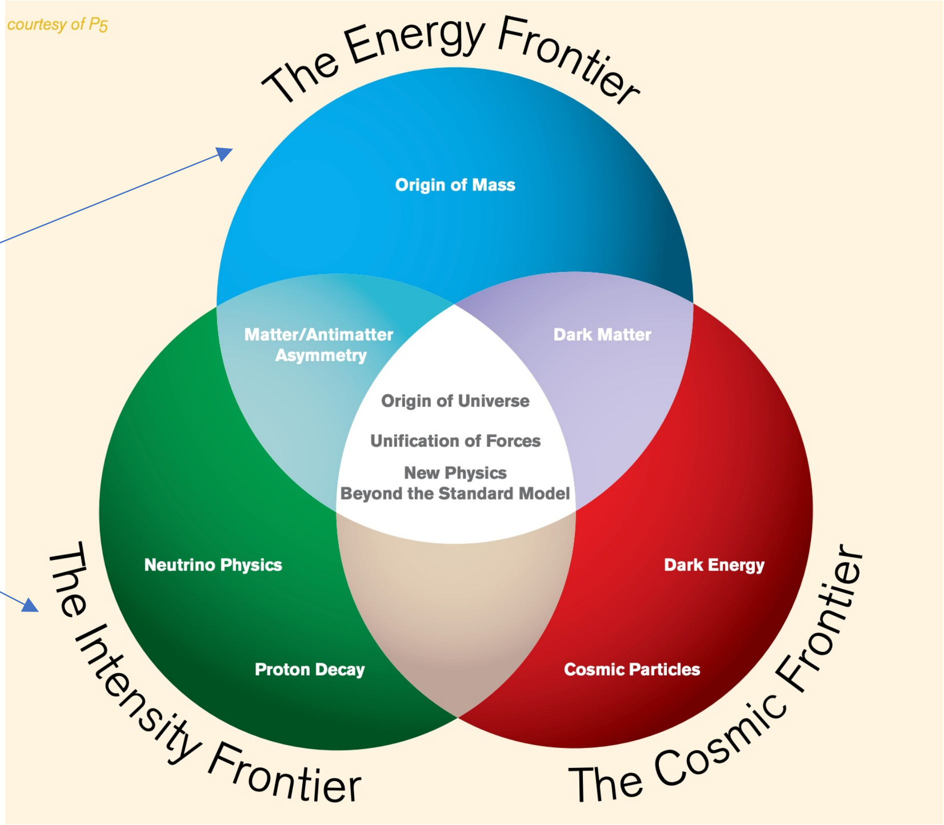




Particle Beams at CERN

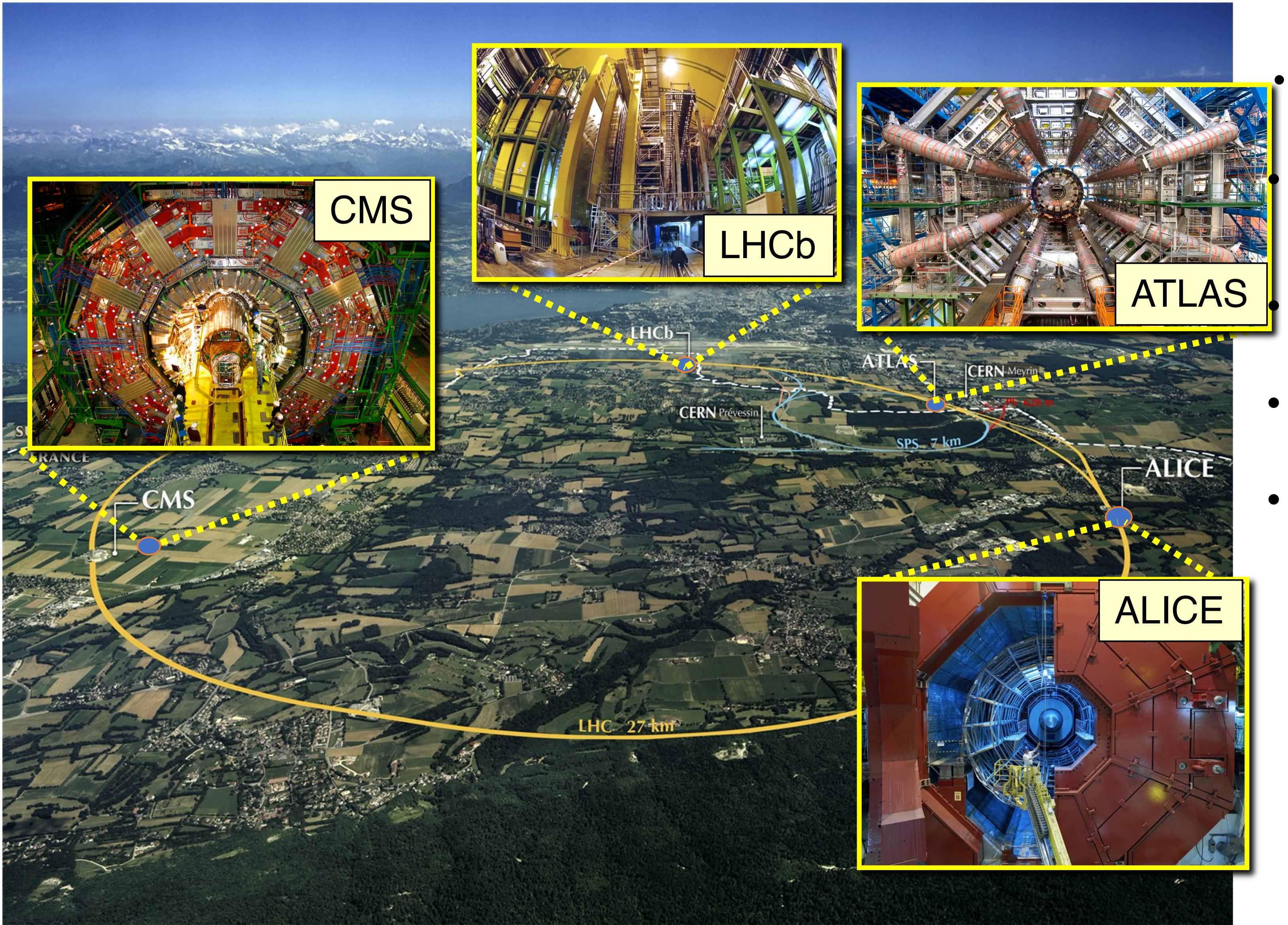
Some of these questions can be addressed using particle beams.
Broadly speaking particle beams are used in 3 ways at CERN:

- **Particle collider**
  - 2 counter rotating beams are collided together
  - Gives the highest collision energy
  - Best for for studying heavy (new) particles
- **Fixed target:**
  - A particle beam is steered into a 'fixed target' (or beam dump)
  - Gives the highest rate of particles
  - Best for studying rare processes with light particles
- **Particle decelerator:**
  - A particle beam is decelerated, or cooled
  - Allows to 'trap' anti-matter particles or rare nuclear isotopes



Particle beams at CERN include protons, muons, electrons, pions, different types of heavy ions (Pb, O, Ar, Xe, …), anti-protons, as well as various short lived radioactive isotopes.
The beams span an energy range from <10 keV (ELENA) -> 7 TeV (LHC) (over 8 orders of magnitude!).

The Large Hadron Collider

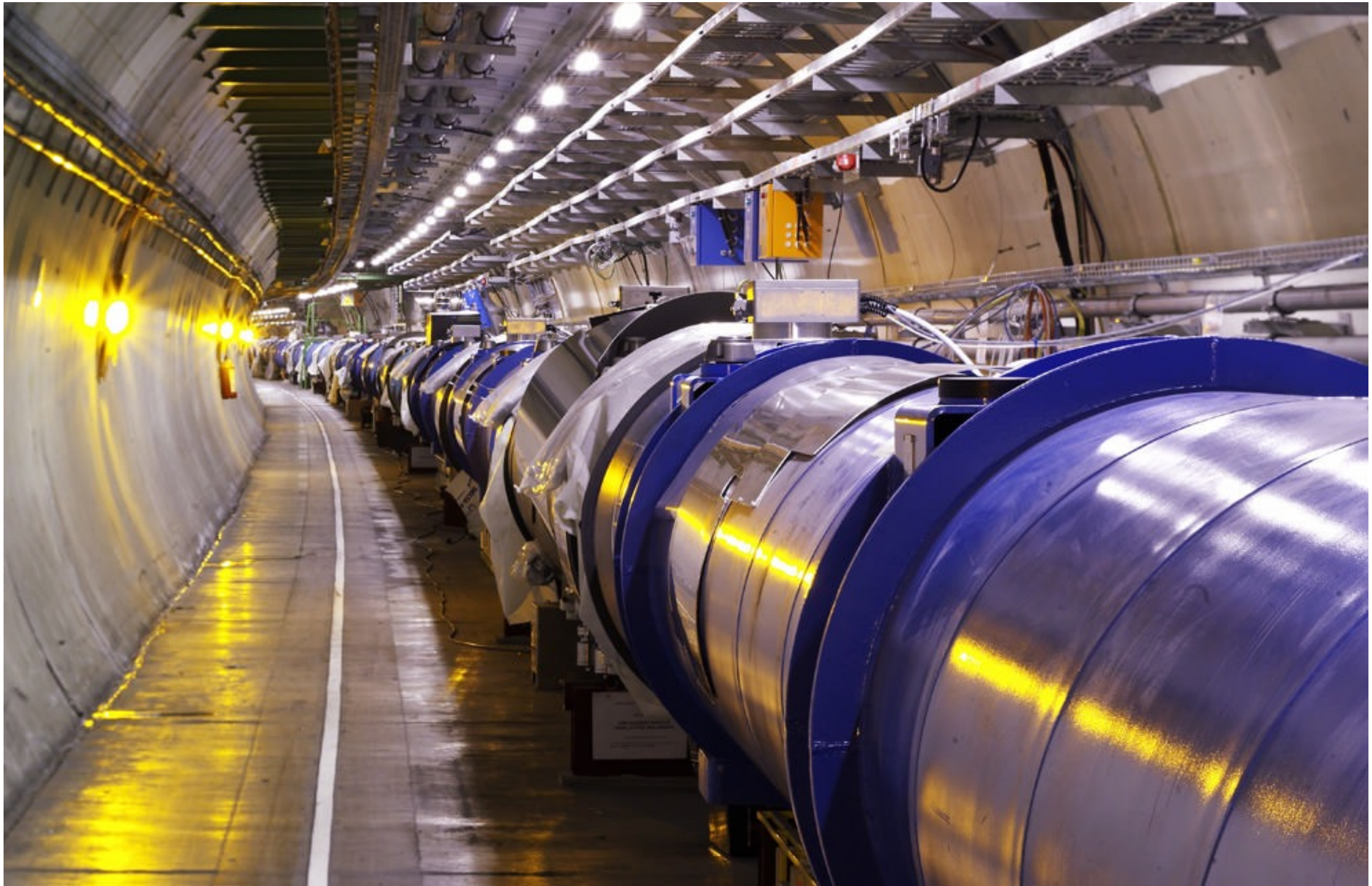


- The LHC collides protons at ~14 TeV with very high luminosity
- For 1 month a year it collides fully stripped Pb ions
- General purpose detectors (ATLAS/CMS)
  - Higgs, Top, electroweak, QCD, Searches for heavy new particles (SUSY, exotics)
- Flavour physics (LHCb)
  - B-physics / CP violation
- Heavy ion (ALICE)
  - Quark Gluon Plasma
- Small experiments:
  - Neutrinos: FASER/SND@LHC (New for 2023)
  - Search for exotic particles: MoEDAL/FASER/SND@LHC
  - Total cross section measurement: TOTEM*
  - Forward particle production (input for cosmic ray physics): LHCf*

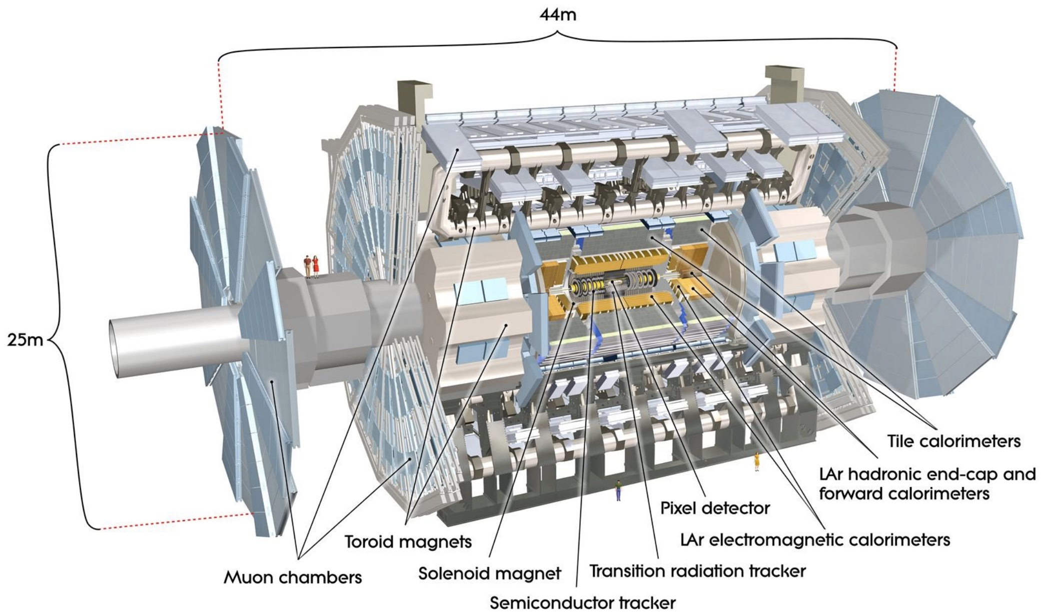
* - take data in special LHC runs

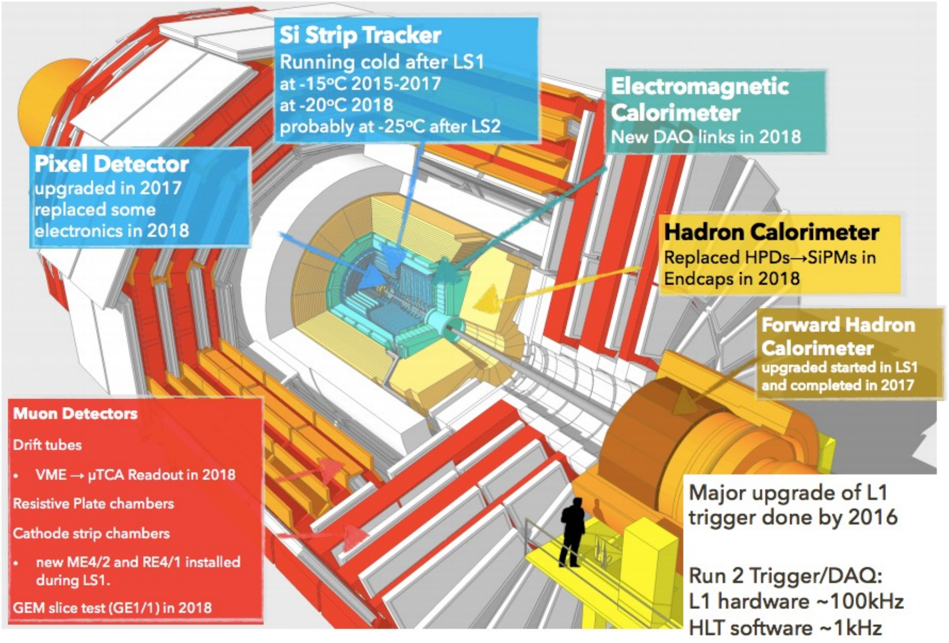
LHC: 26.7km, ~7 TeV

Started physics in 2010



ATLAS/CMS Experiments





ATLAS and CMS designed to do the same physics – 2 experiments to cross check each others results.

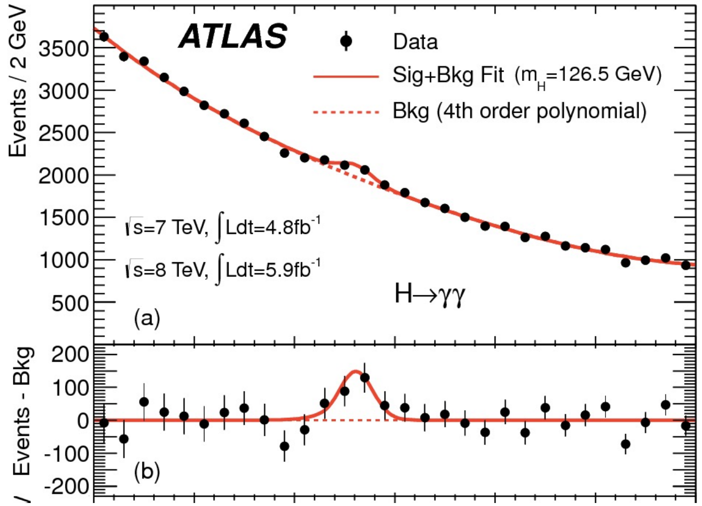
The experiments have been taking high energy data since 2010.

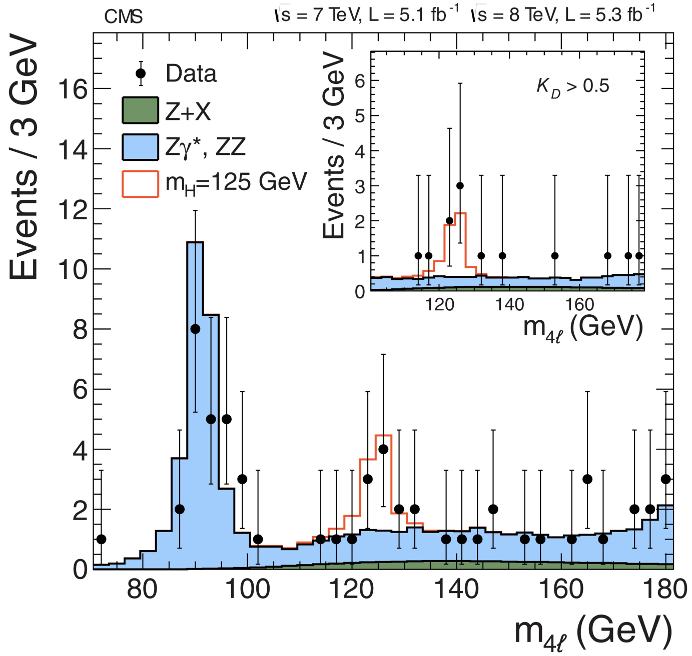
Discovery of the Higgs Boson in 2012 a milestone in particle physics.

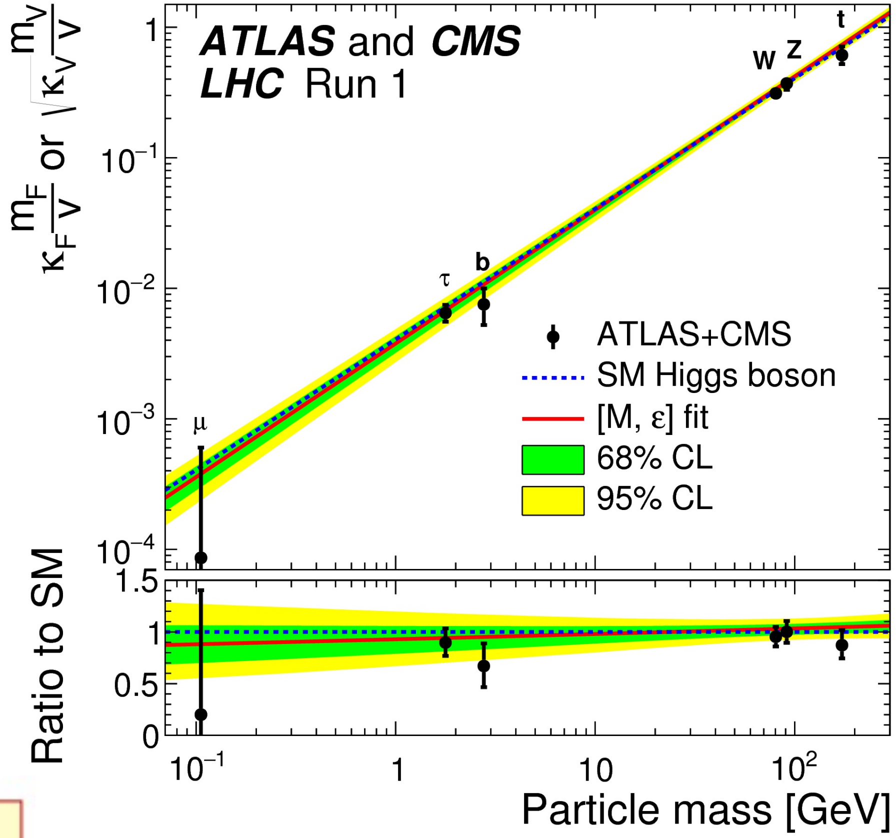
Completed the Standard Model but leaves many questions unanswered!

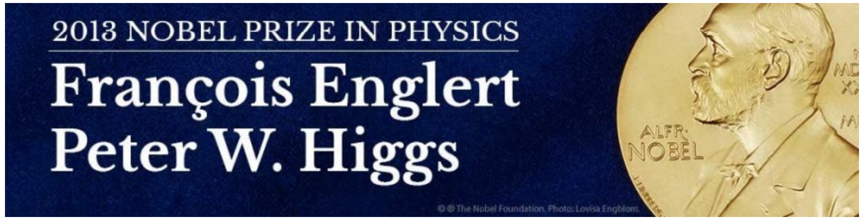
Many searches for heavy physics beyond the Standard Model, unfortunately nothing seen!

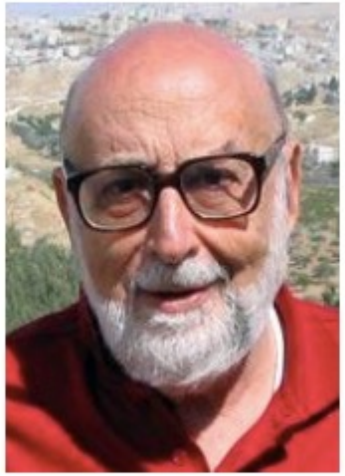
ATLAS/CMS: Higgs Discovery at LHC

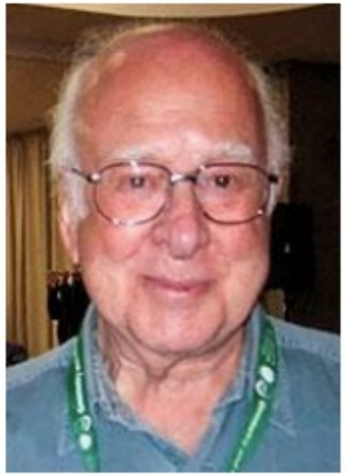












"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Now detailed studies confirm SM higgs like behaviour at the ~10% level. Full LHC dataset will improve this to the few-% level.

(What the Higgs tells us)

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

This equation neatly sums up our current understanding of fundamental particles and forces.

Gauge interactions, well studied in last 50 years

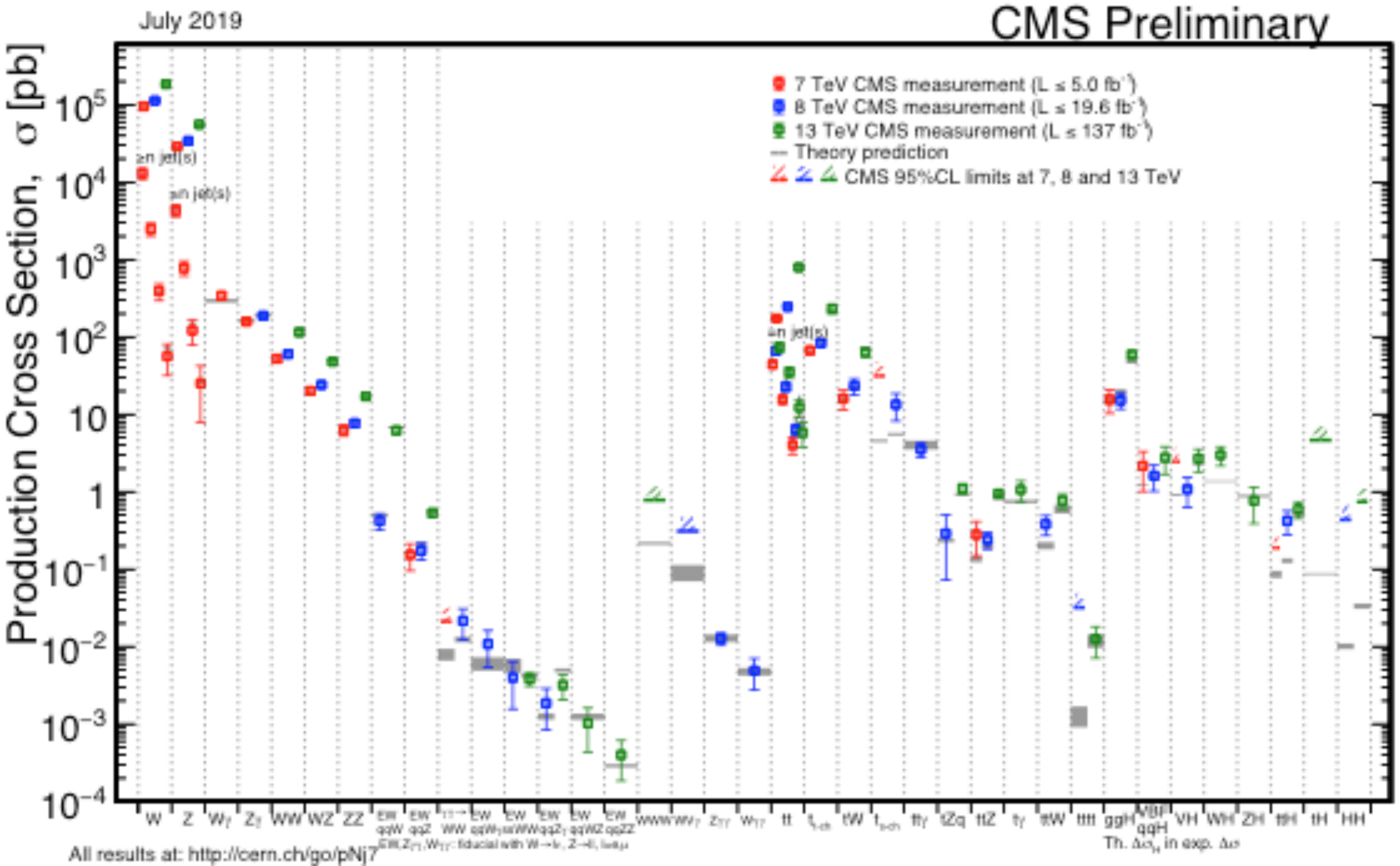
Yukawa coupling (Higgs to fermions) not a gauge interaction. Never studied before. Higgs coupling to fermions is the first time we can really study this!

Higgs potential. Need HH production to study this!

Higgs coupling to vector bosons. Gauge interaction with scalars. Similar to what we have seen before.

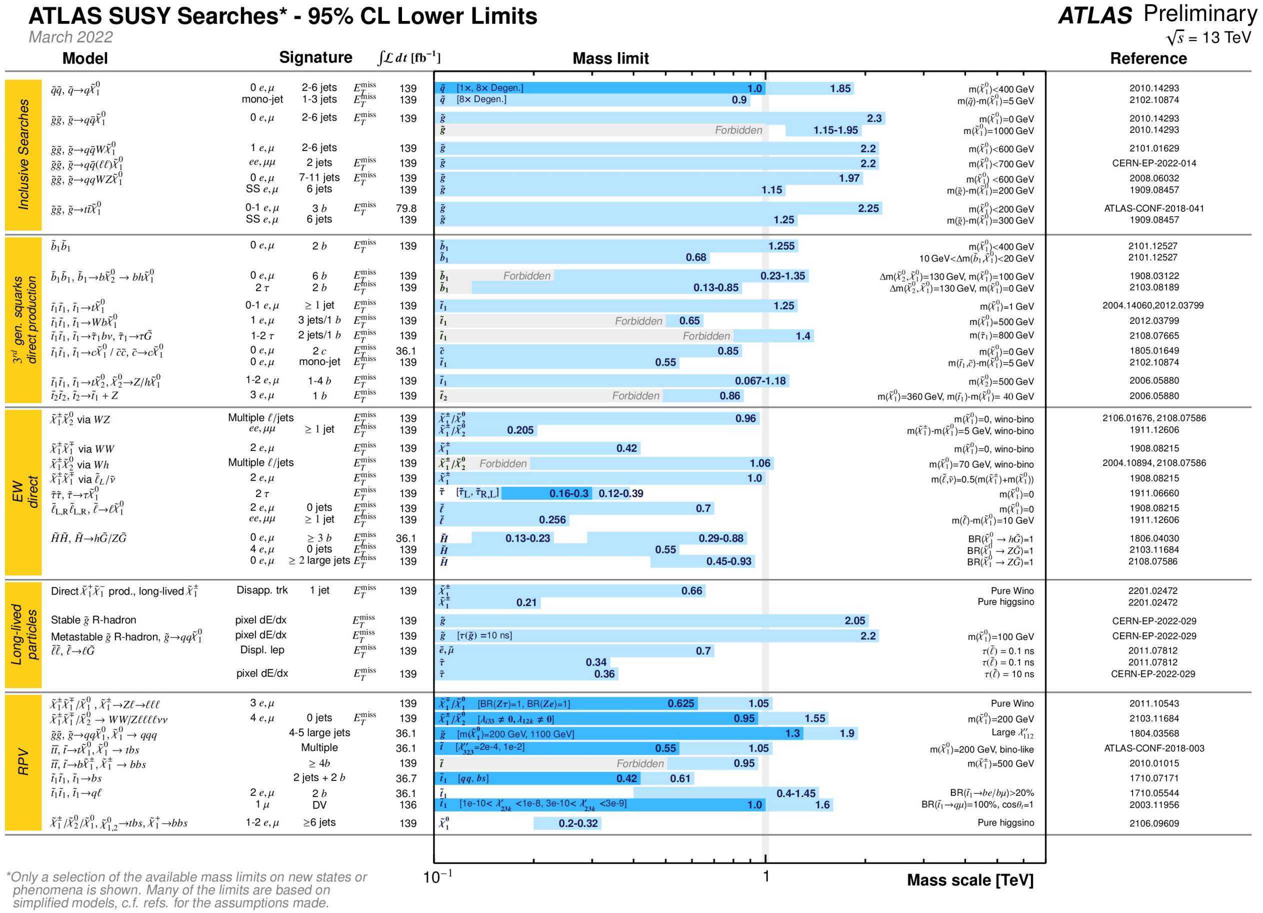
ATLAS/CMS: Standard Model Measurements

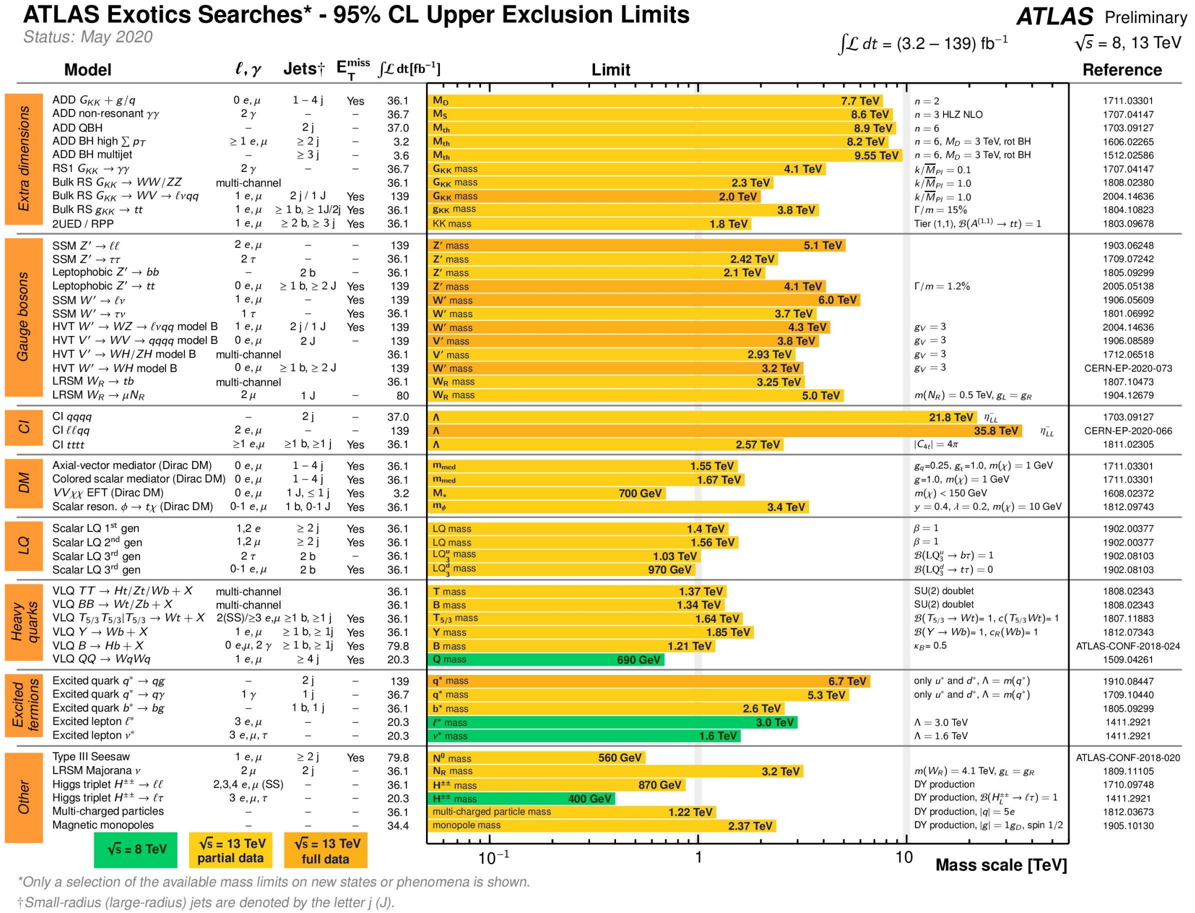
ATLAS/CMS have a large programme of SM cross section measurements, including very precise W,Z and top cross-sections, di-boson, jet cross sections etc… Cover 9 orders of magnitude in cross-section!



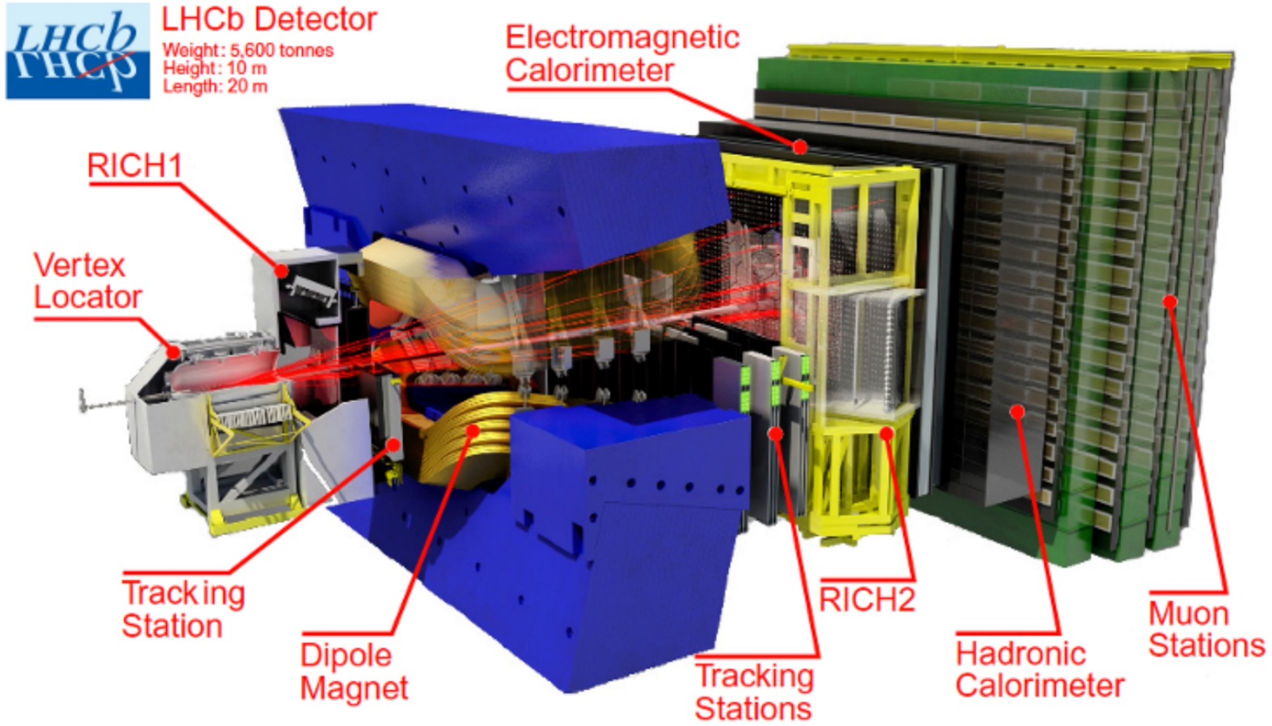
ATLAS/CMS: Beyond Standard Model Searches

ATLAS/CMS have carried out a huge number of searches for new particles/phenomena – unfortunately with no direct evidence for physics beyond the Standard Model.





LHCb Experiment

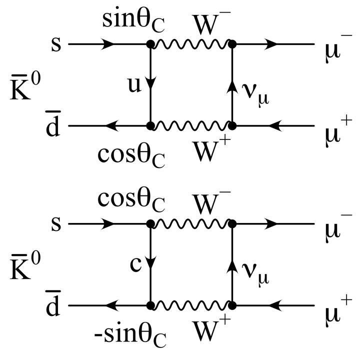


LHCb is dedicated to flavour physics studies. Optimized to study B-hadron decays at the LHC, with physics goals of:

- Study CP violation in B sector, multiple independent measurements of SM CP violating parameters
- Study rare B meson decays sensitive to possible new particles in loops

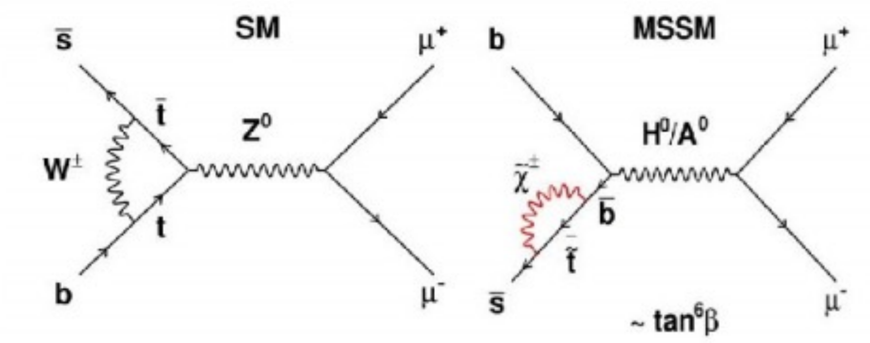
Evidence of new particles can show up in indirect "precision" measurements (with heavy new particles can enter via loop diagrams) before being directly produced at high energy colliders. Heavy new particles can enter via loop diagrams:

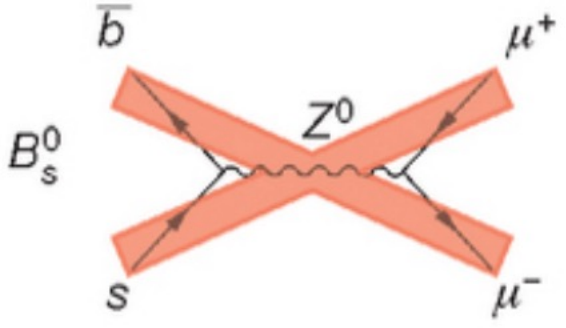
- GIM mechanism before discovery of the charm quark
- CP violation and CKM before discovery of beauty and top quarks
- Neutral current before discovery of the Z boson



LHCb: Rare decays

Bs->$\mu^+\mu^-$ decay very rare decay in SM, with possible large enhancement with New Physics (e.g. SUSY):





Theoretically clean.
Flavour changing neutral current.
Loop and helicity suppressed in SM.

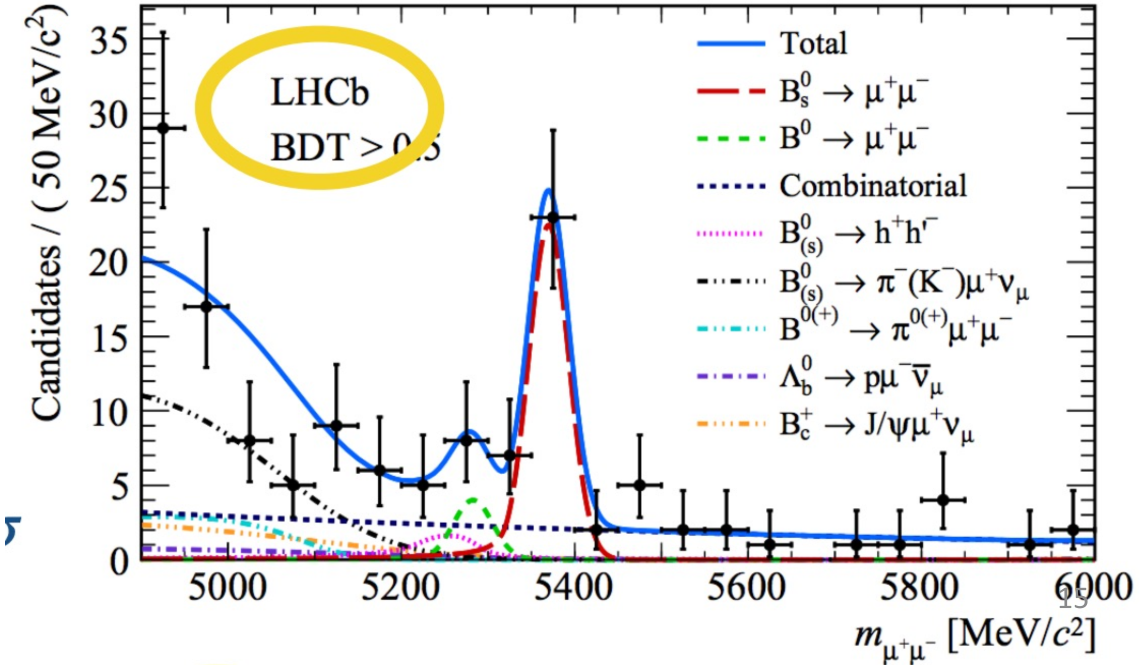
$$BR(B_s \rightarrow \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \rightarrow \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

Latest result from LHCb:

$$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ @ } 95\,\% \text{ CL}$$

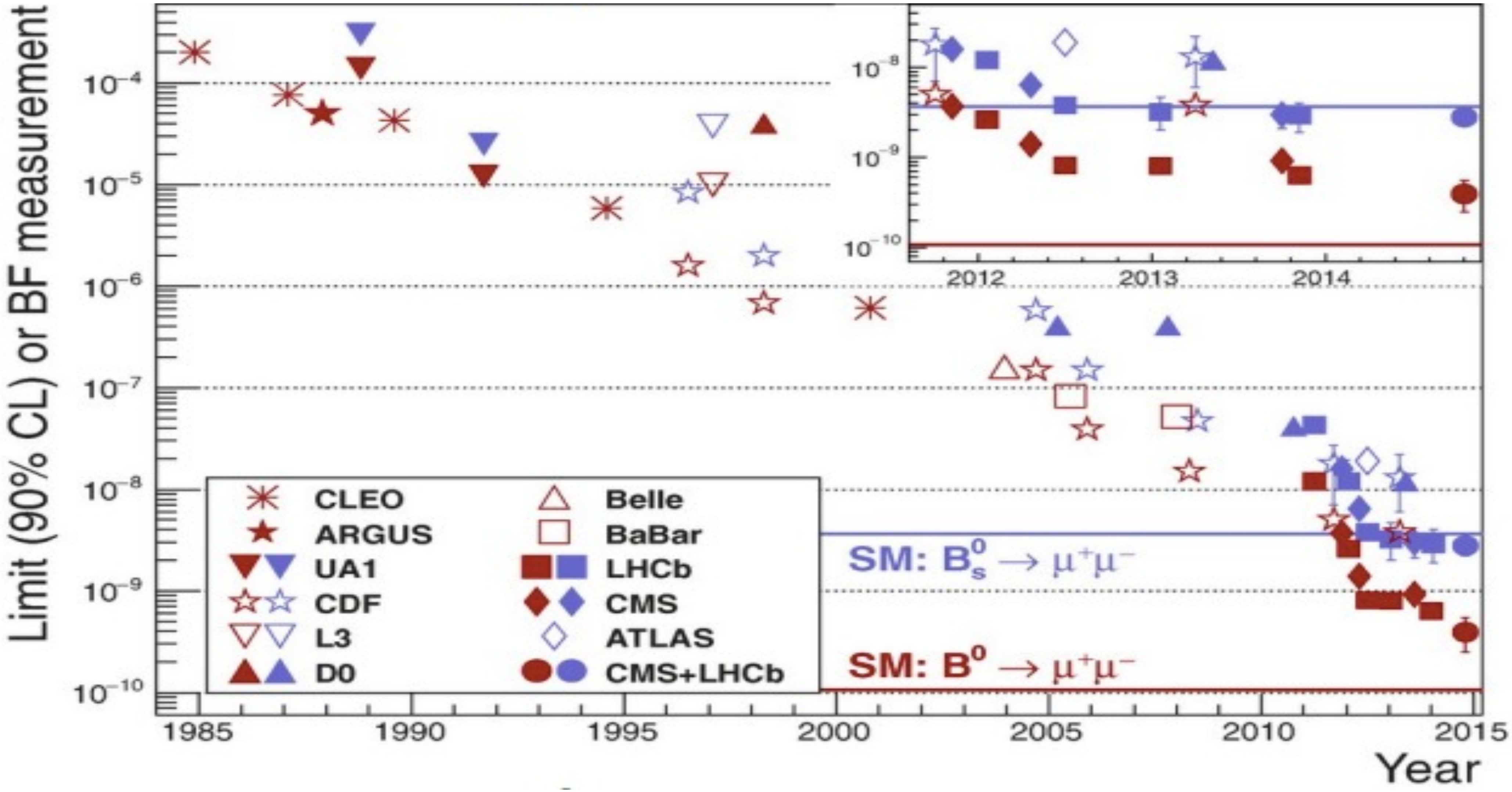
7.8σ



LHCb: Rare decays

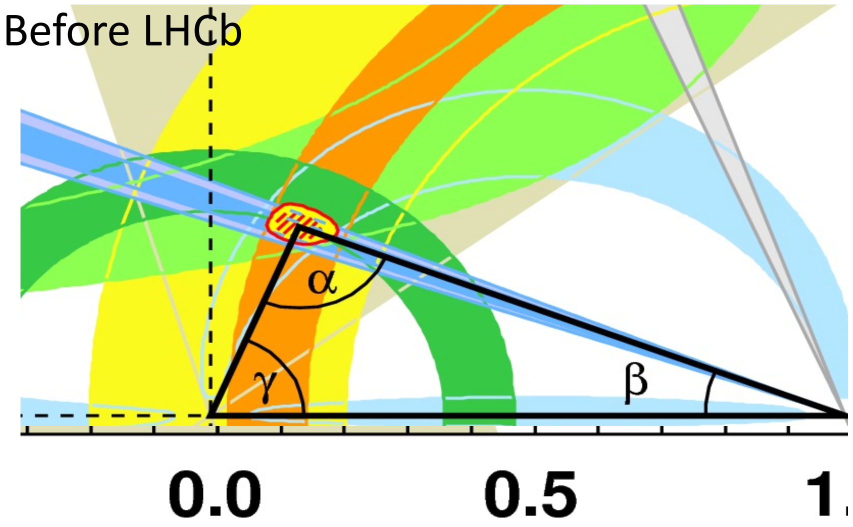
Bs->$\mu^+\mu^-$ decay very rare decay in SM, with possible large enhancement with New Physics (e.g. SUSY):

Long history of searches for this decay, finally disocvered at the LHC after more than 25 years!

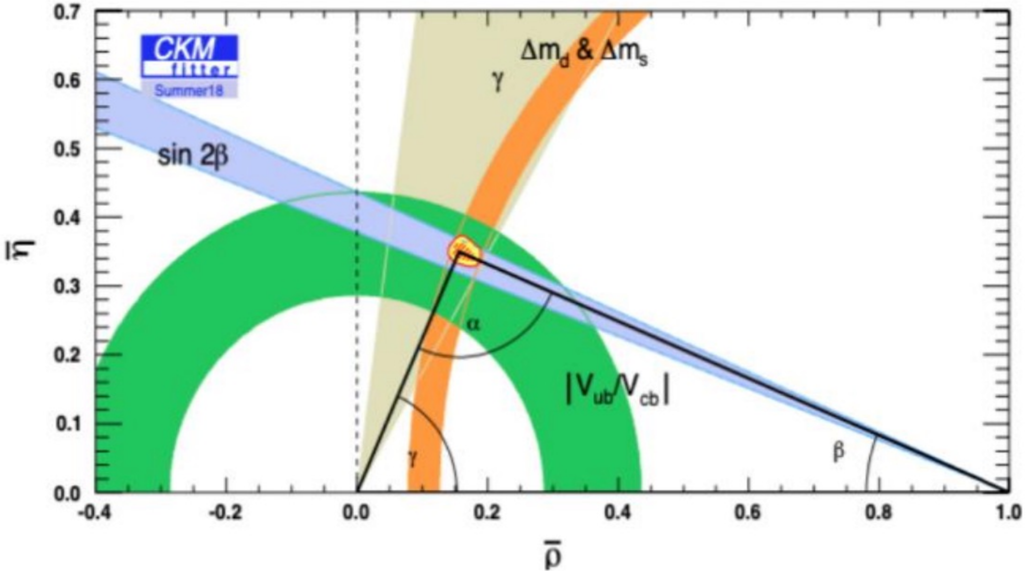


LHCb: CP Violation

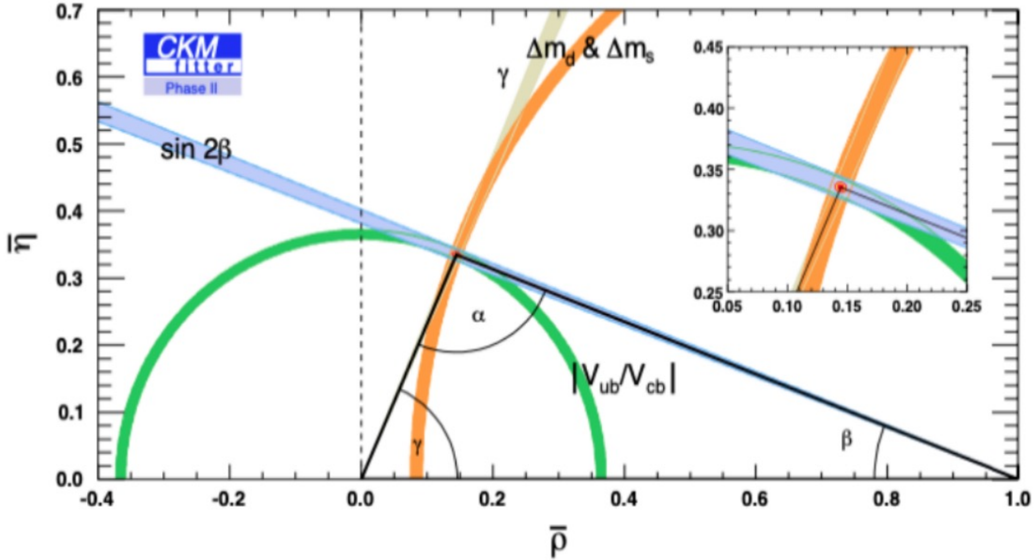
CP violation needed to explain the observed matter/anti-matter asymmetry in the universe.
Naturally occurs in the Standard Model with 3 generations of quarks (complex phase in quark mixing matrix).
However, measured level of CP violation in SM by far too small to explain the observed asymmetry.
Studied in detail by multiple measurements to overconstrain the CKM “Unitarity Triangle” – LHCb has given a huge improvement in the precision, and a possible future upgrade would bring a big gain in sensitivity.



LHCb only, end of 2018

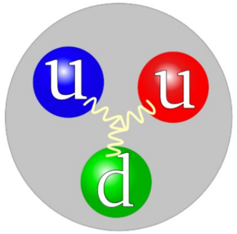


LHCb Upgrade II + LQCD improvement

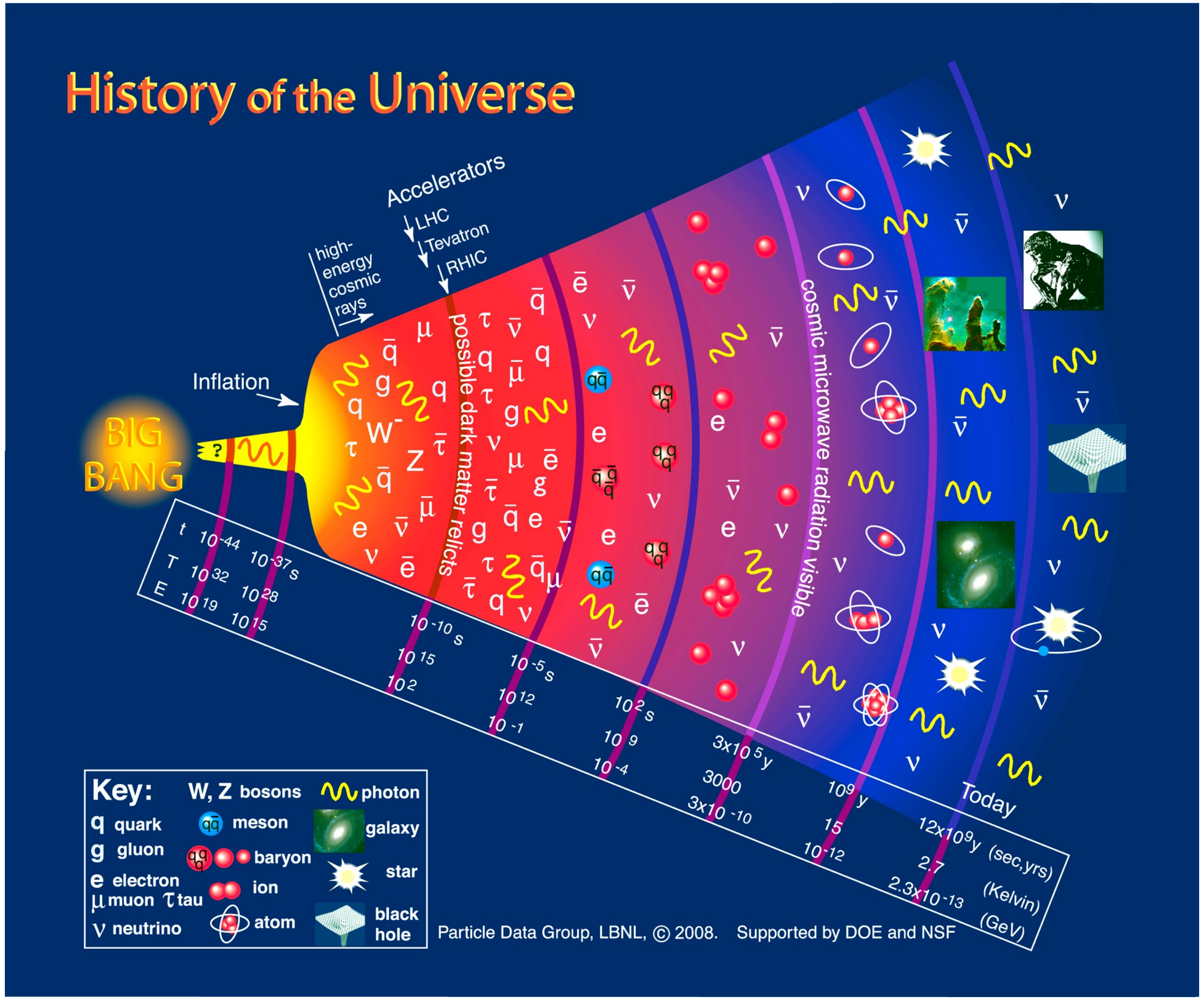


ALICE – Heavy Ion Physics at the LHC

- We think that during first few μs:
  - quarks not trapped inside hadrons
  - but free in a deconfined phase -> Quark-Gluon Plasma (QGP)
- Around 10 μs:
  - T ~ 170 MeV (~ 2 10^{12} K)
  - quarks and gluons recombine quark epoch -> hadron epoch
- Although the Higgs gives mass to fundamental particles nearly all atomic mass (~99%) is dynamically generated by QCD confinement
  - Mass of uud quarks ~ 10 MeV
  - Mass of proton ~ 938 MeV



- By colliding heavy ions at very high energies can reach energy densities that should form the QGP
- Evidence of QGP formation already from previous (lower enegy) experiments at BNL-RHIC and the CERN-SPS but LHC allows much more detailed studies
- ALICE experiment dedicated for heavy ion physics



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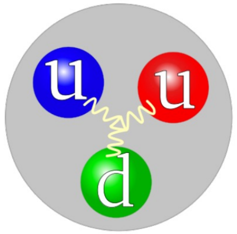

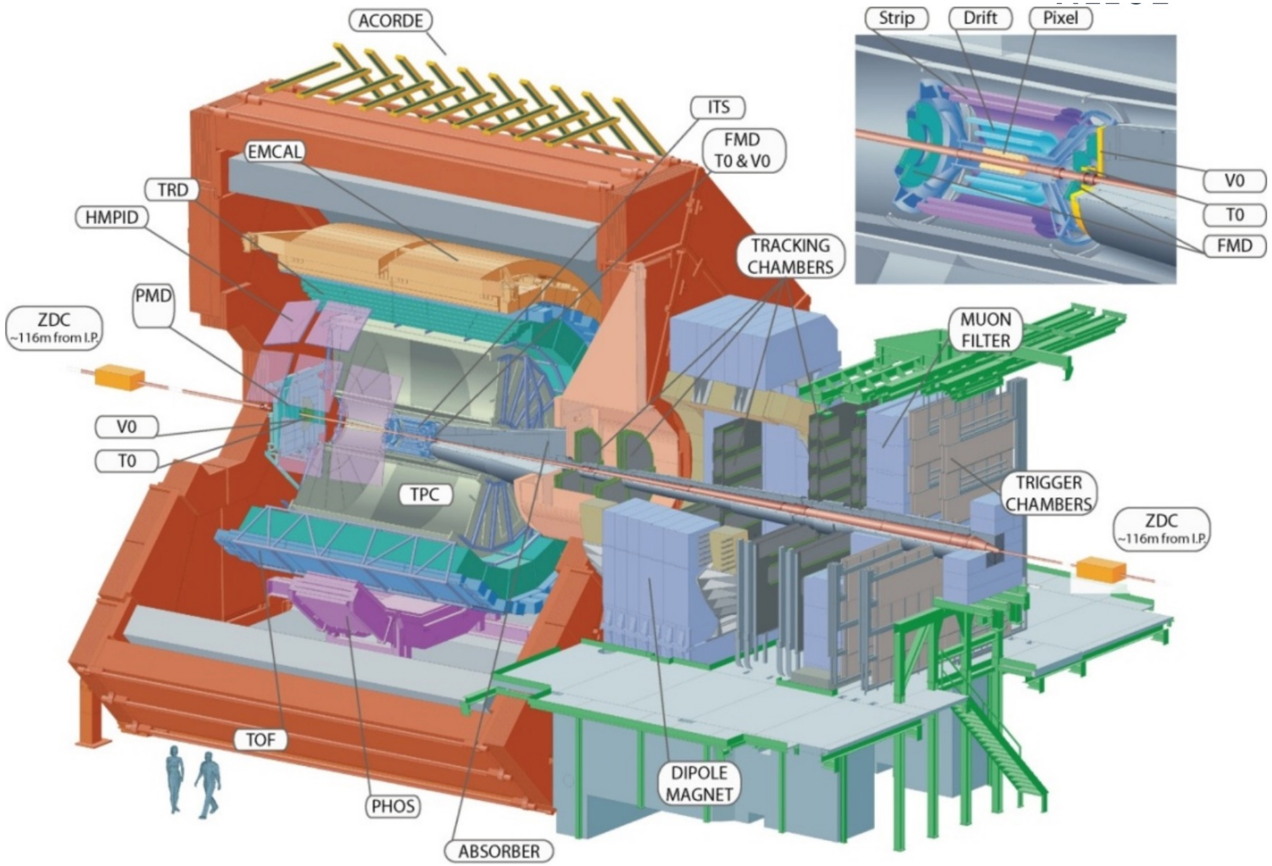

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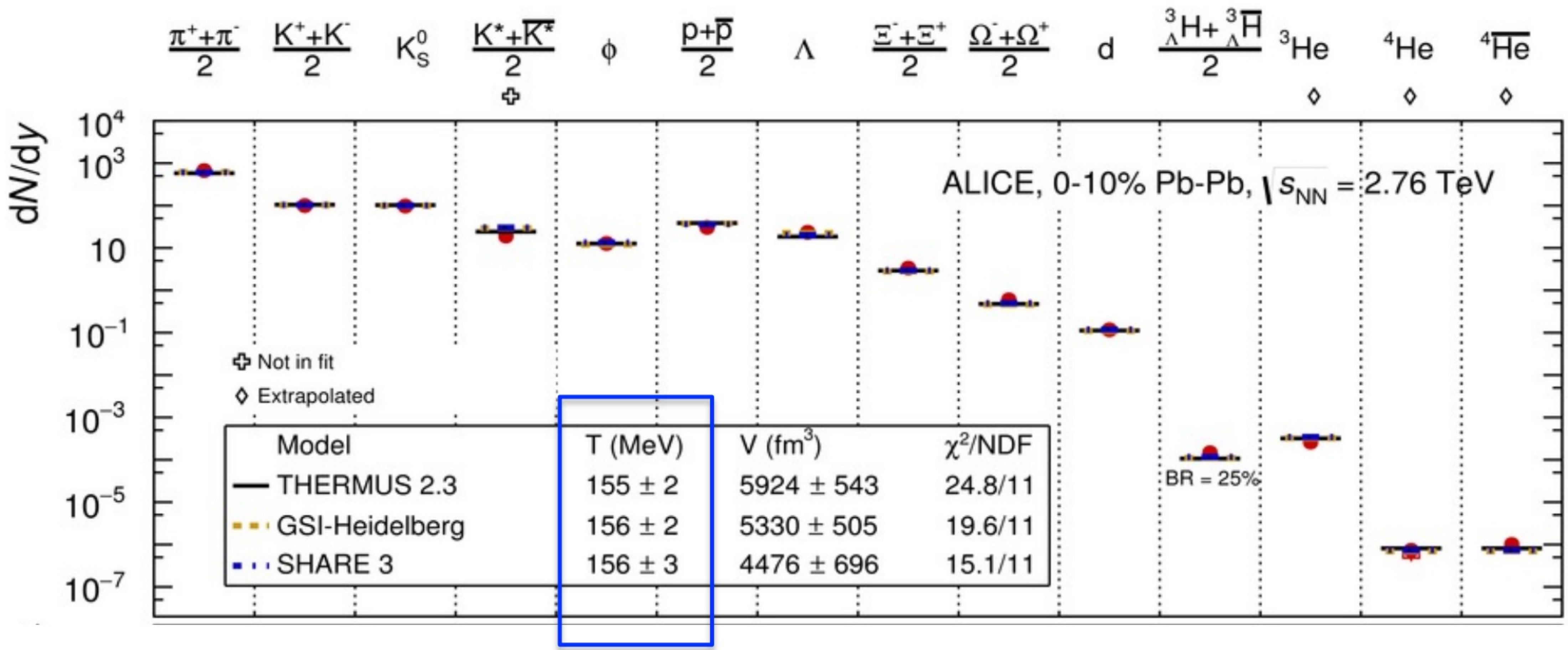
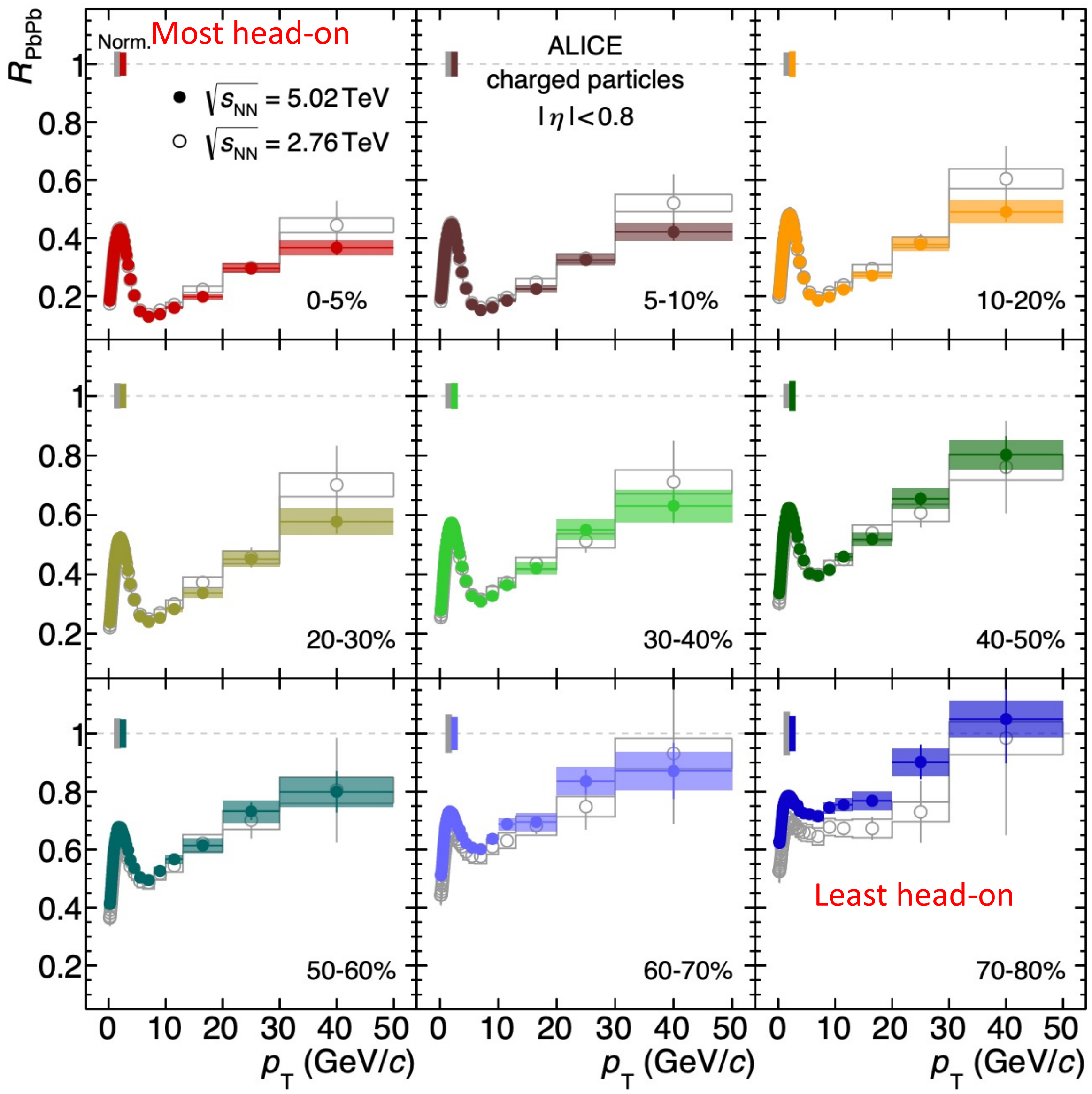
Detector optimized for excellent particle identification (both for stable and decaying particles).

ALICE – Example physics

Fitting the measured yields of different hadron types, can extract the transition temperature ~160 MeV

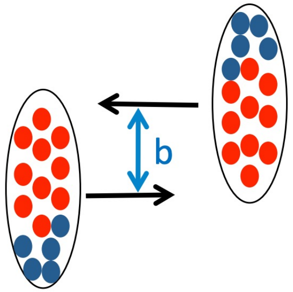


ALICE – Example physics



Nuclear modification factor: $$R_{AA} = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{pp}}$$

- Compare charged particle energy distribution for Pb-Pb collisions with proton-proton collisions.
- Plot for different "centrality" of the ion collisions (a measure of how head-on the ions collide).

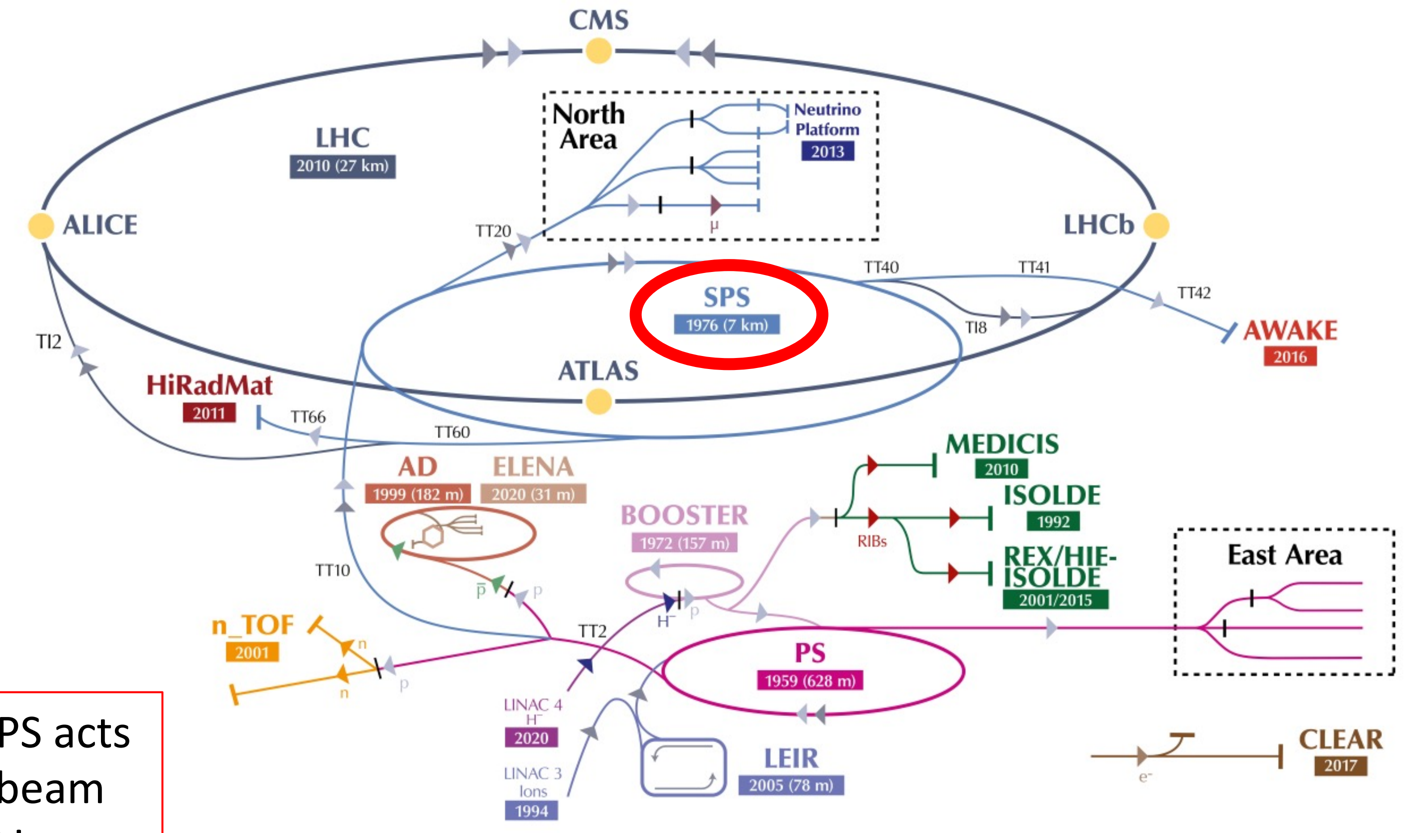


- Sensitive to energy loss of partons in QGP before hadronization.
- Clear quenching of parton energy due to propagation through the QGP, stronger effect for head-on collisions.

ATLAS, CMS and LHCb also contribute to heavy ion physics with Pb-Pb collisions at the LHC.

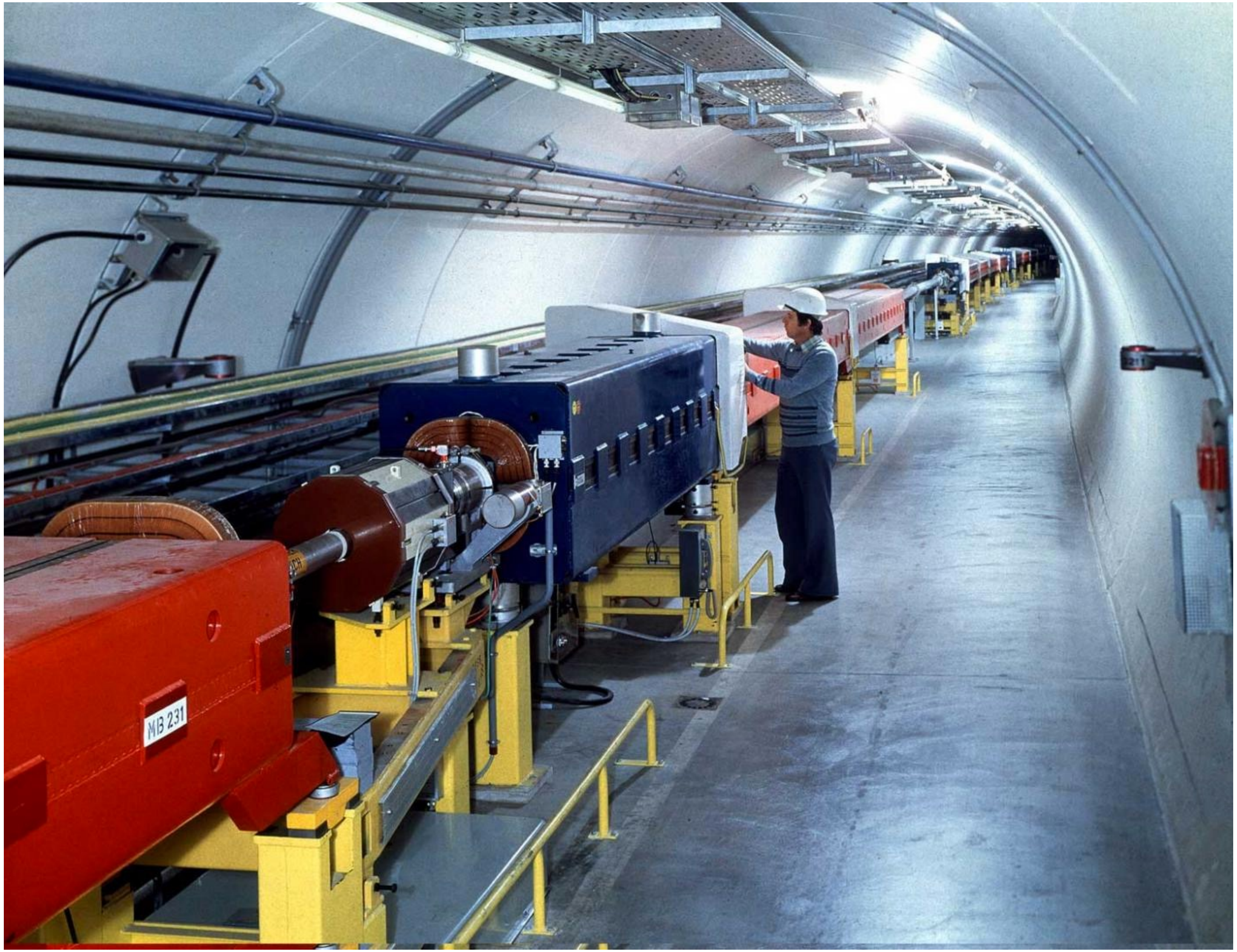
SPS Experiments

- Fixed target of high energy (up to 450 GeV) proton, or heavy ion beams, or secondary e, μ, π beams
- SPS experiments are situated in the CERN “North Area” and are therfore given an NA number!
- QCD (NA58/COMPASS)
  - Hadronization
- Heavy ion (NA61/SHINE)
  - Quark gluon plasma
- Flavour physics (NA62)
  - Rare kaon decays
- NA63
  - Radiation in strong electromagnetic fields
- Light dark matter searches (NA64)
  - Missing mass searches
- Ds production NA65
  - Input for future Tau neutrino experiments



As well as the experimental programme above the SPS acts as the injector of protons into the LHC, and delivers beam for short testbeams for detector calibration and R&D!

Super Proton Synchrotron (SPS) 450GeV, 6.9km



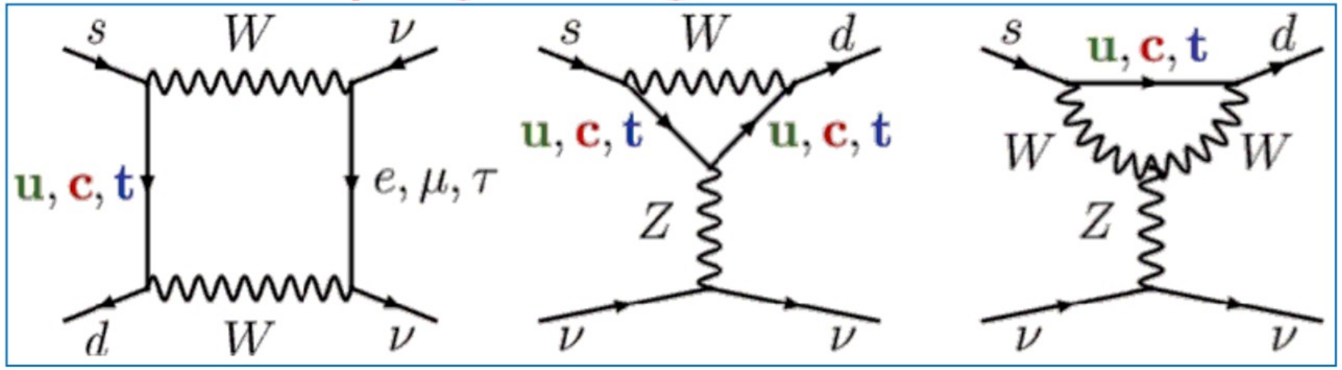
First operation in 1976

NA62 rare kaon decay search

NA62 dedicated experiment to measure the decay: $K^+ \to \pi^+ \nu \bar{\nu}$

Very rare, branching fraction < 10^{-10} predicted with good accuracy ($\mathcal{O}$(5%))
Very sensitive to possible new particles entering in the loops (similar to LHCb).

SM: box and penguin diagrams

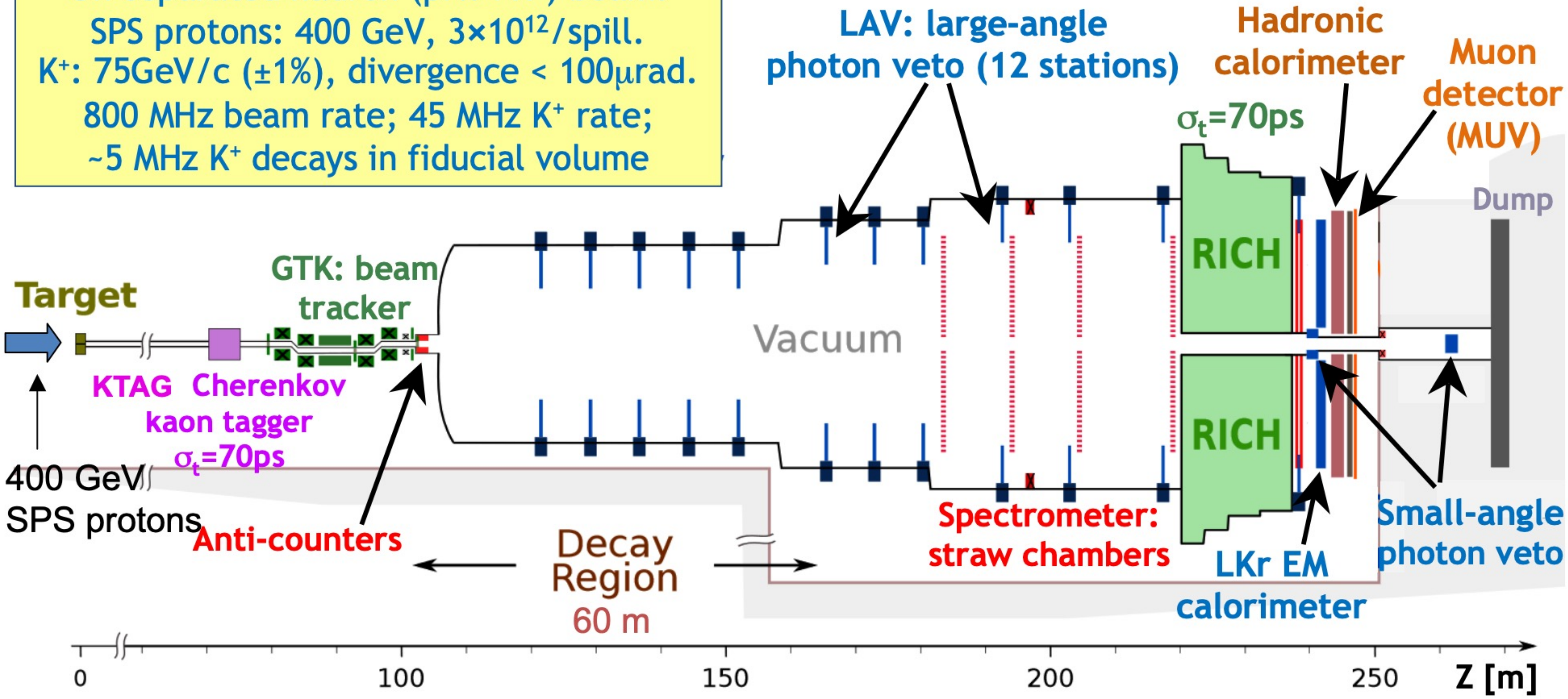


Experimental challenges:
- Signal very rare, need lots of Kaons
  - 3x10^{12} p/spill, 800MHz beam rate => 5MHz of K+ decays in detector volume
- Backgrounds many orders of magnitude larger than signal
  - Need excellent background reduction
- Neutrinos undetected
  - Detector needs to have very good coverage to be able to veto backgrounds from missing particles

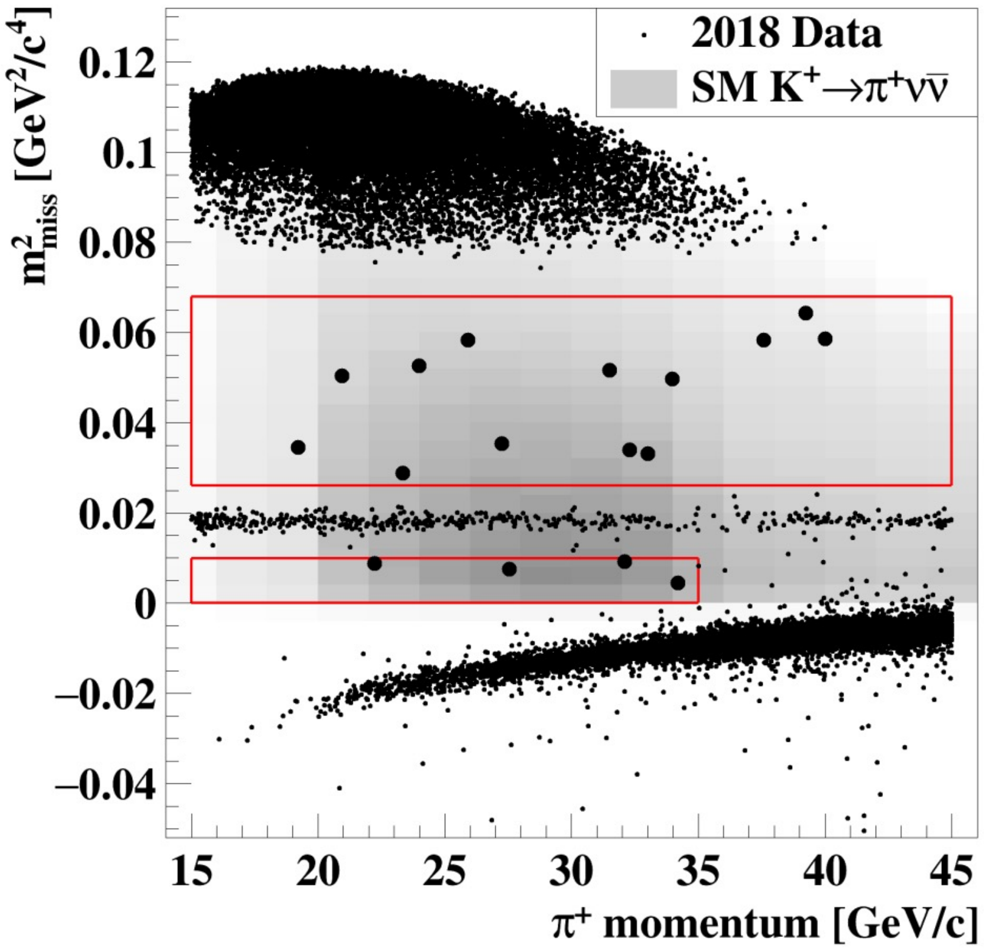
The NA62 experiment

NA62 collaboration, JINST 12 (2017) P05025

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
800 MHz beam rate; 45 MHz K^+ rate;
~5 MHz K^+ decays in fiducial volume



NA62 rare kaon decays search



Recent result (using data collected in 2016,2017 and 2018).
Signal events separated by background using kinematic variables.

$$N_{obs}(2016 + 2017 + 2018) = 20$$

$$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{sys} \pm 1.19_{ext}$$

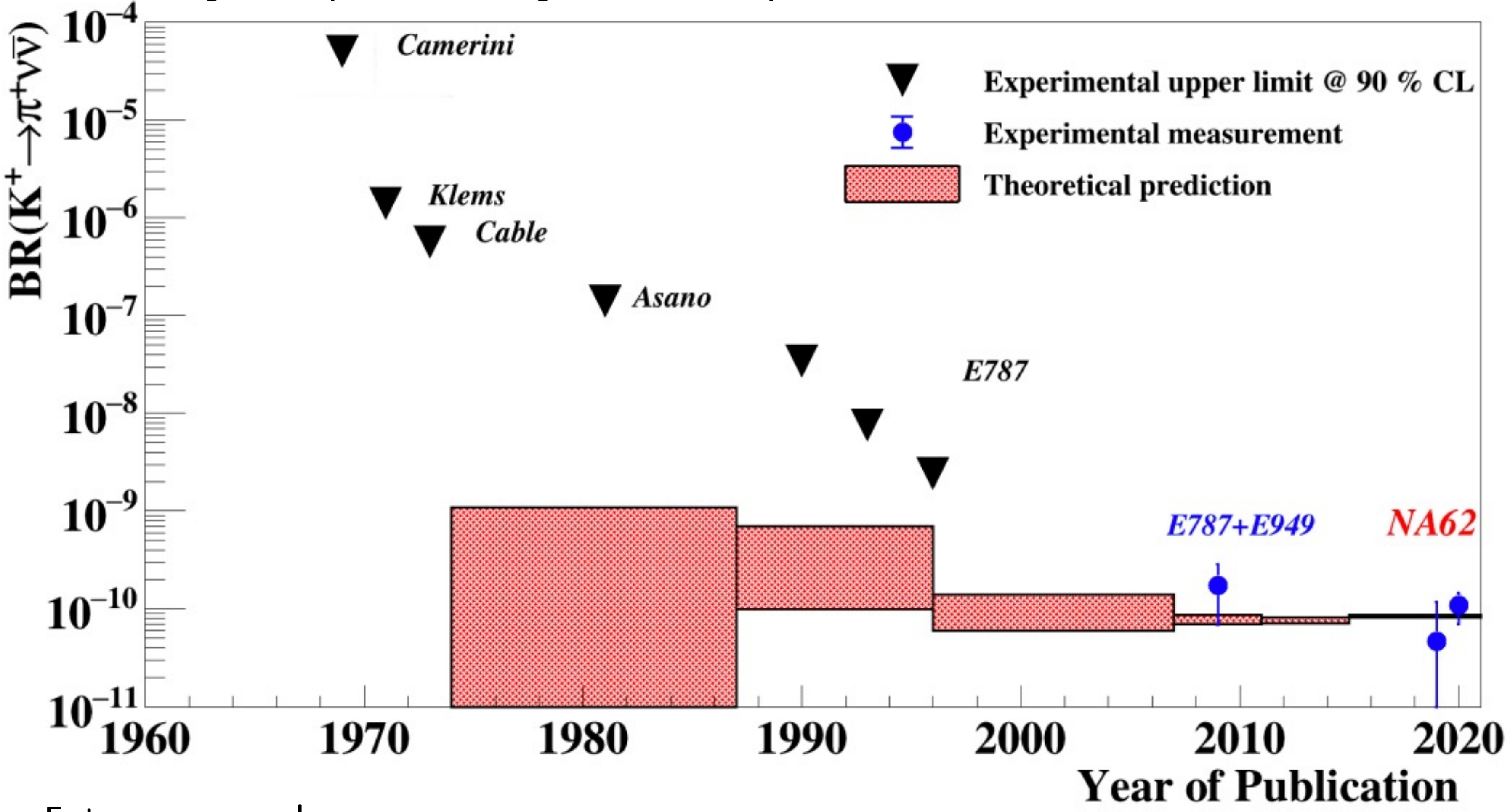
$$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$$

$$Br(K^+ \rightarrow \pi^+\nu\nu) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{sys}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

3.4σ significance

NA62 rare kaon decays search

Long history of searching for this decay.



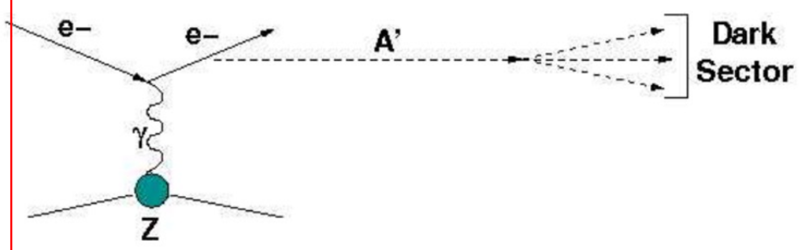
Future proposal:

- to measure branching fraction with 5% precision (same level as the theoretical uncertainty),
- then to measure related (but experimentally more challenging) decay modes: $K_L \to \pi^0 \nu \bar{\nu}$

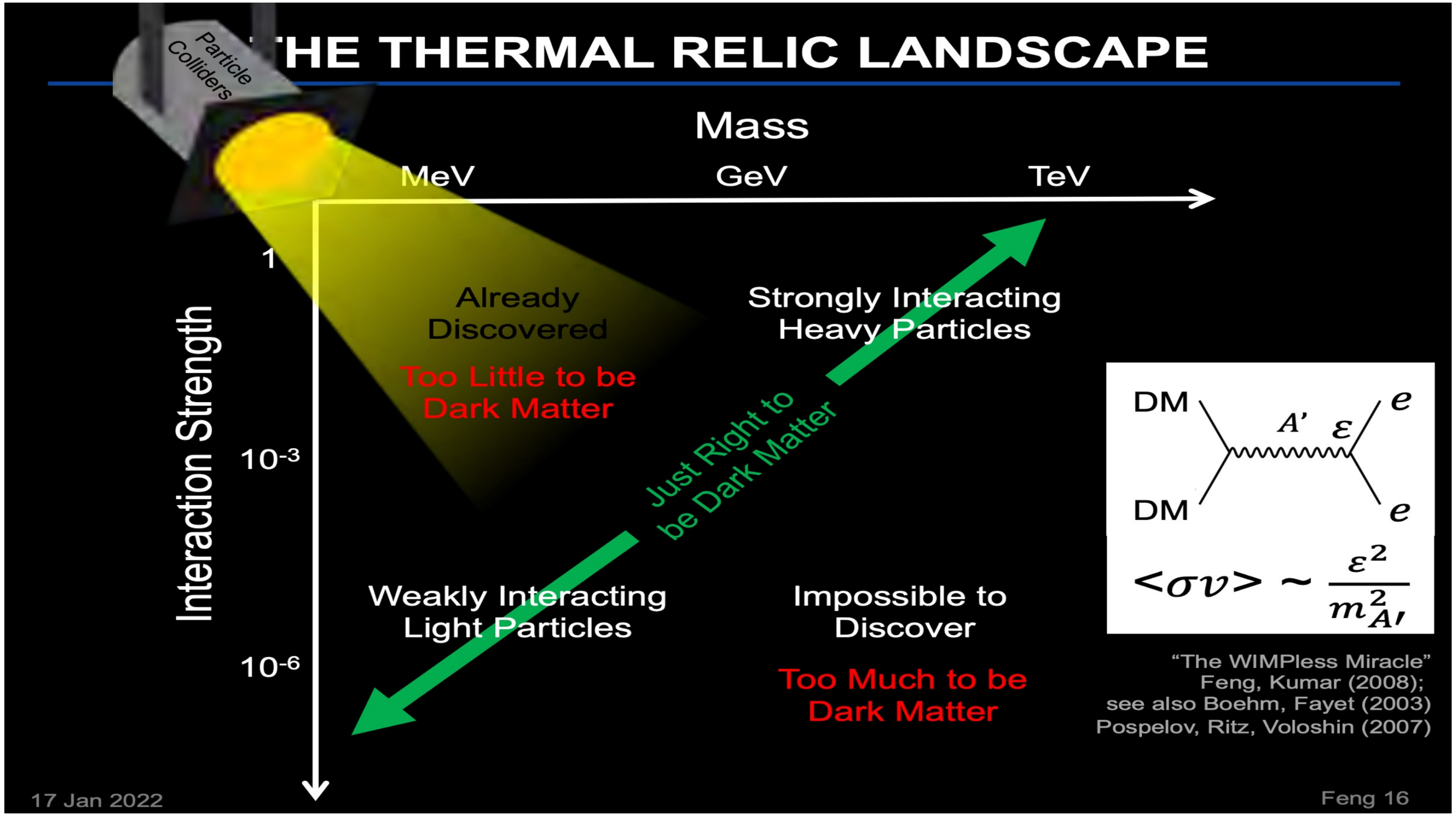
NA64 dark sector search

- Dark photon (A’) can act as a mediator between dark matter and the SM particles
  - Needed to give the observed DM relic density
- In much of viable paramater space these are light (m<1 GeV) with very weak coupling (ε~10^{-5})

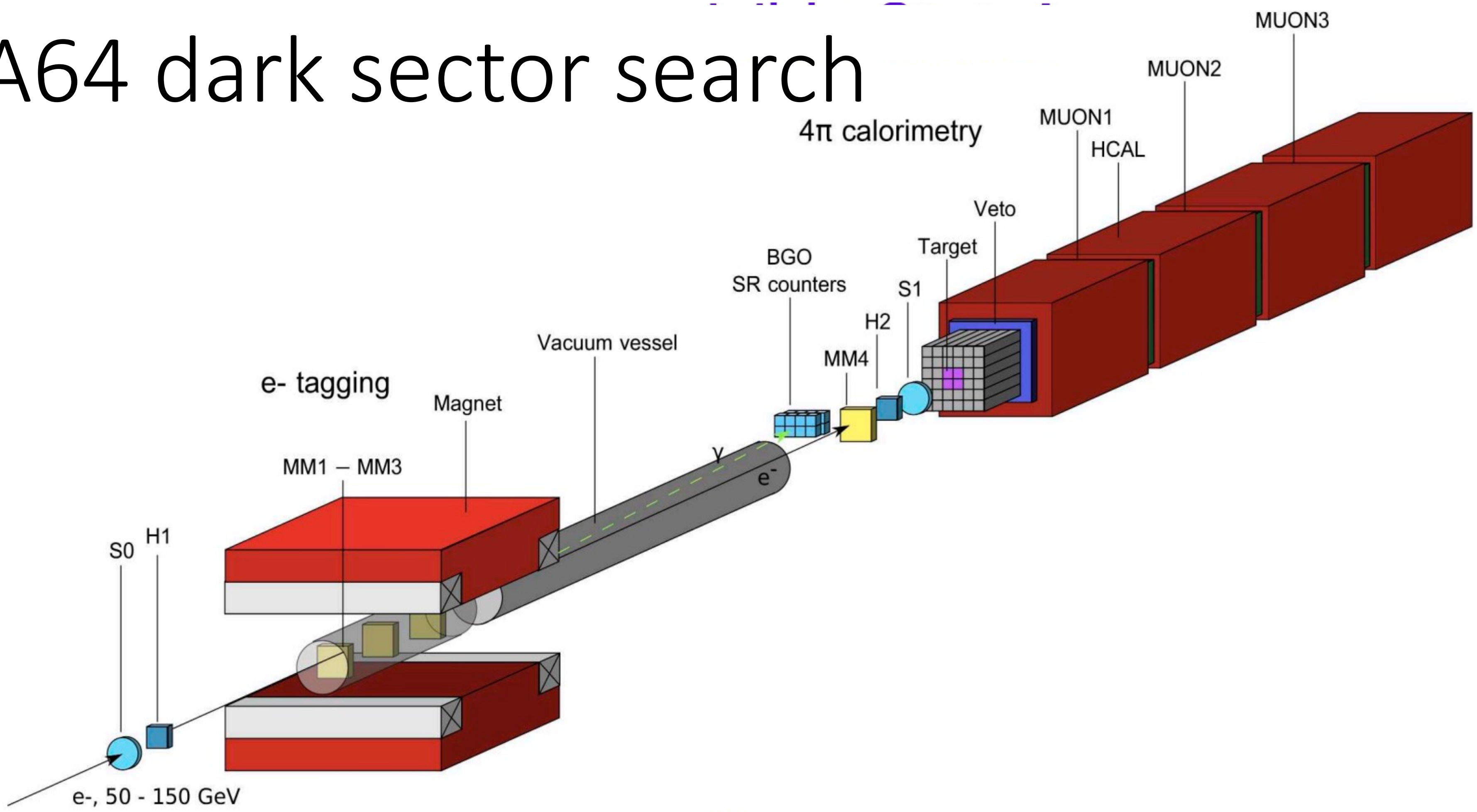
NA64 uses the SPS electron beam to look for A’ being radiated from the electron in a target, and decaying to invisible dark matter particles:



The experiment searches for “missing energy” due to the A’.
For relevant signal parameter speace, expect 1 A’ per 10^9 – 10^{12} electrons.



NA64 dark sector search



3 main components :

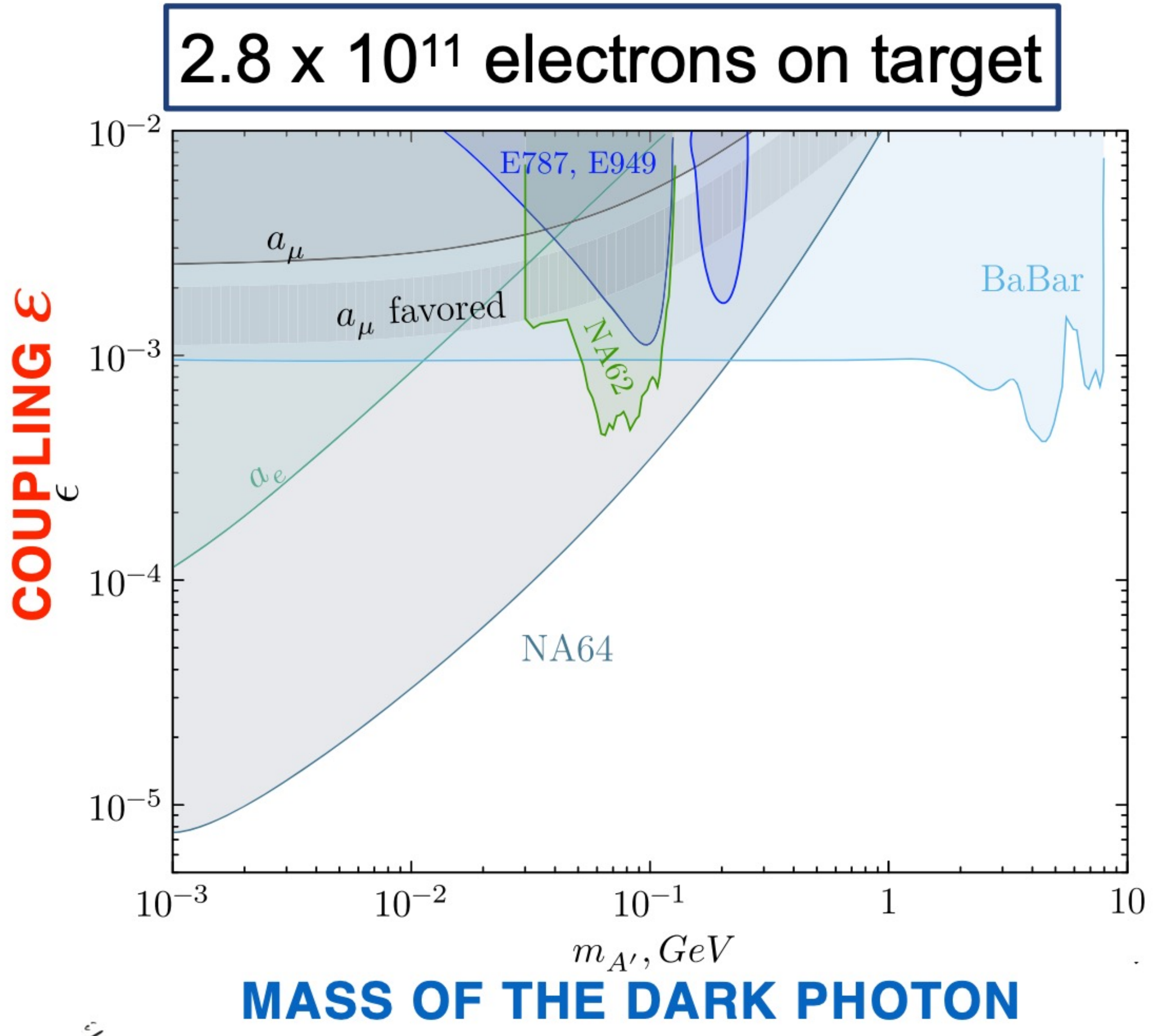
- clean, mono-energ. 100 GeV e- beam
- e- tagging system: MM tracker + SR
- 4π fully hermetic ECAL+ HCAL

Signature:

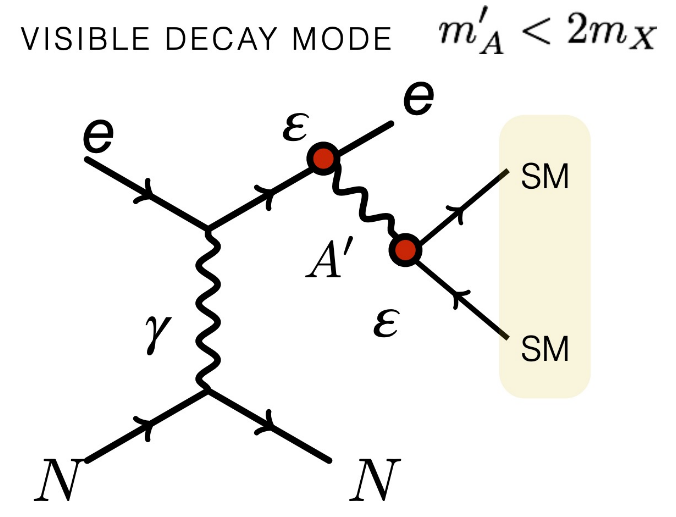
- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ ε^2

NA64 dark sector search

No signal seen, but NA64 sets world leading limits on invisible A' decays in much of the parameter space.

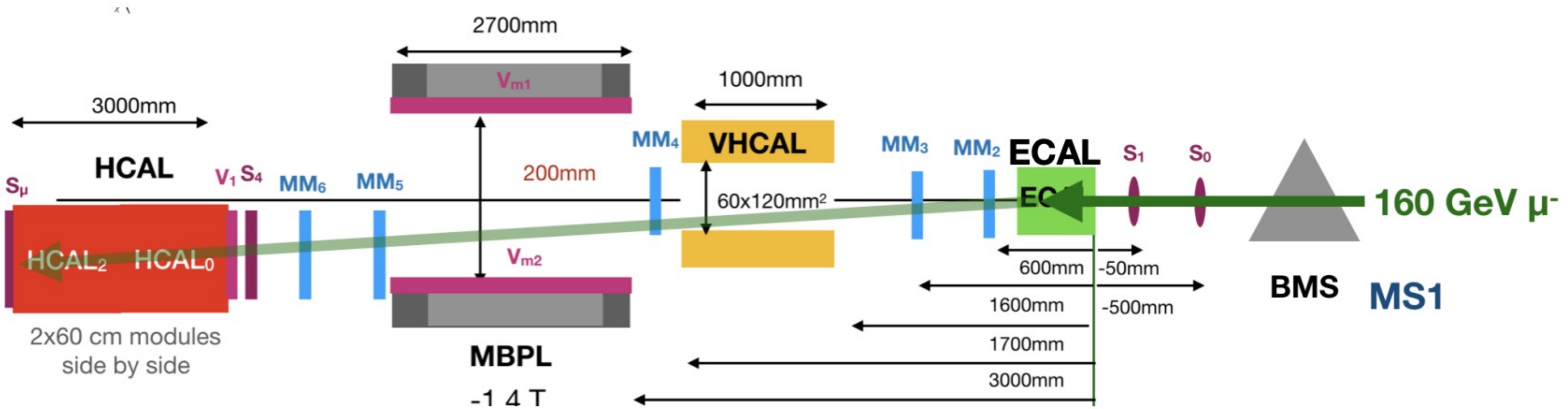


NA64 can also search for visible decays of the A' – e.g



NA64 dark sector search

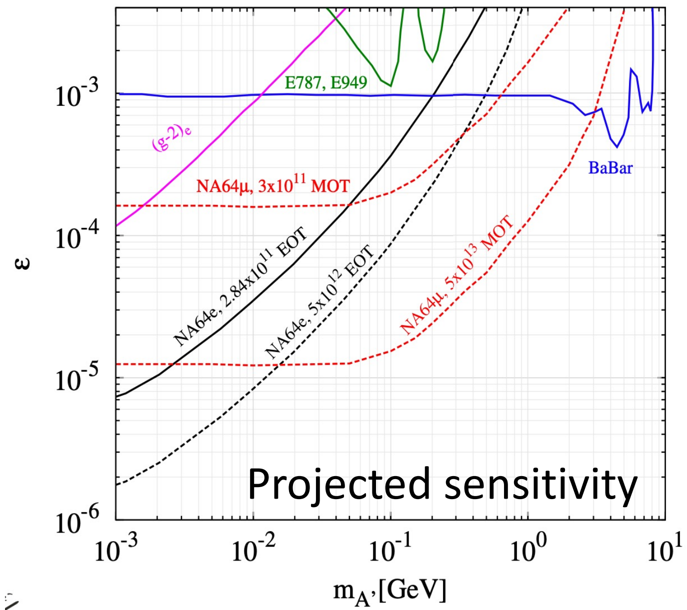
Possible future update, use muon beam to look for dark sector particles that couple predominatly to muons. Motivated by muon g-2 anomaly.



Signature:
1) Tagged 160 GeV incoming muon
2) Scattered muon with <80 GeV
3) No activity in HCAL

Signal production and decay:

$$\mu + Z \rightarrow \mu + Z + A', A' \rightarrow \chi\bar{\chi}$$

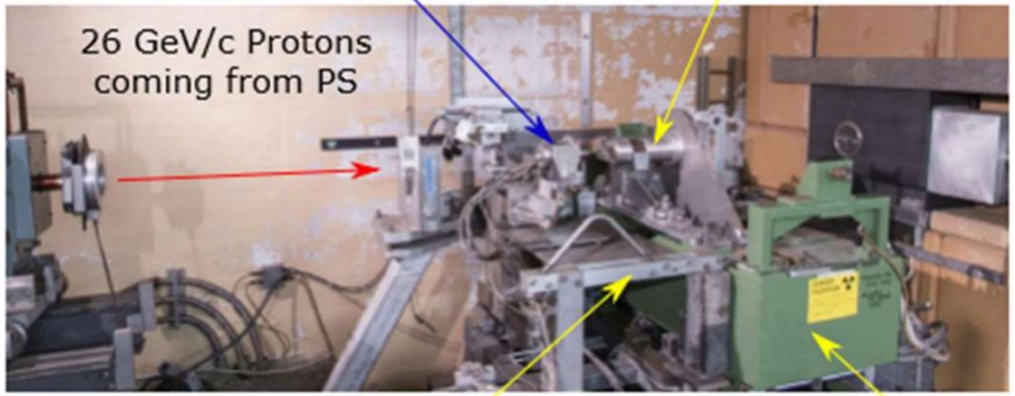


PS (Proton Synchrontron): 26GeV, 628m

1959

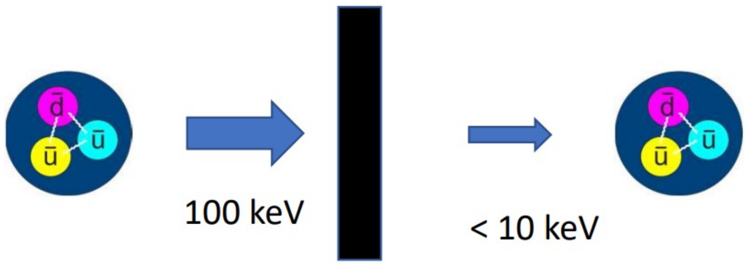
The Antiproton Decelerator (AD) experiments

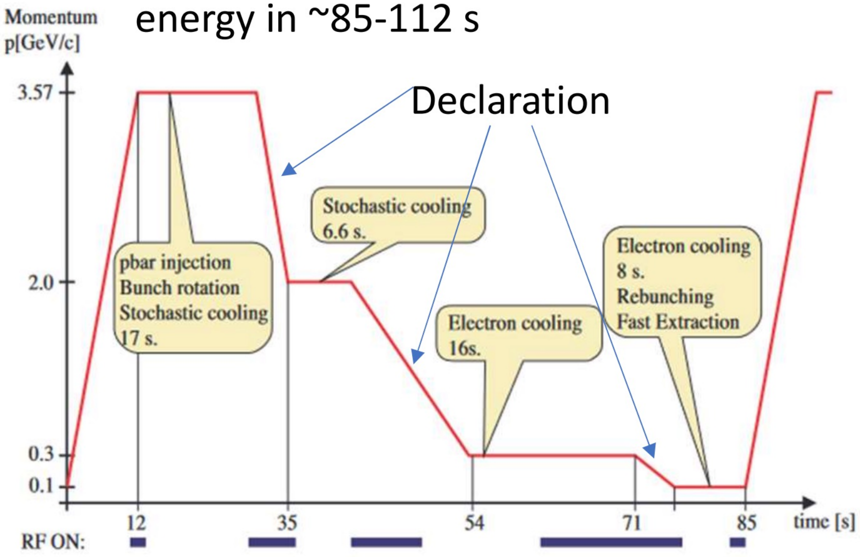
- Unlike other CERN accelerators, the AD decelerates anti-protons to reduce their kinetic energy so they can be used for anti-matter studies and to make anti-atoms
- Anti-protons produced by colliding protons on a target:

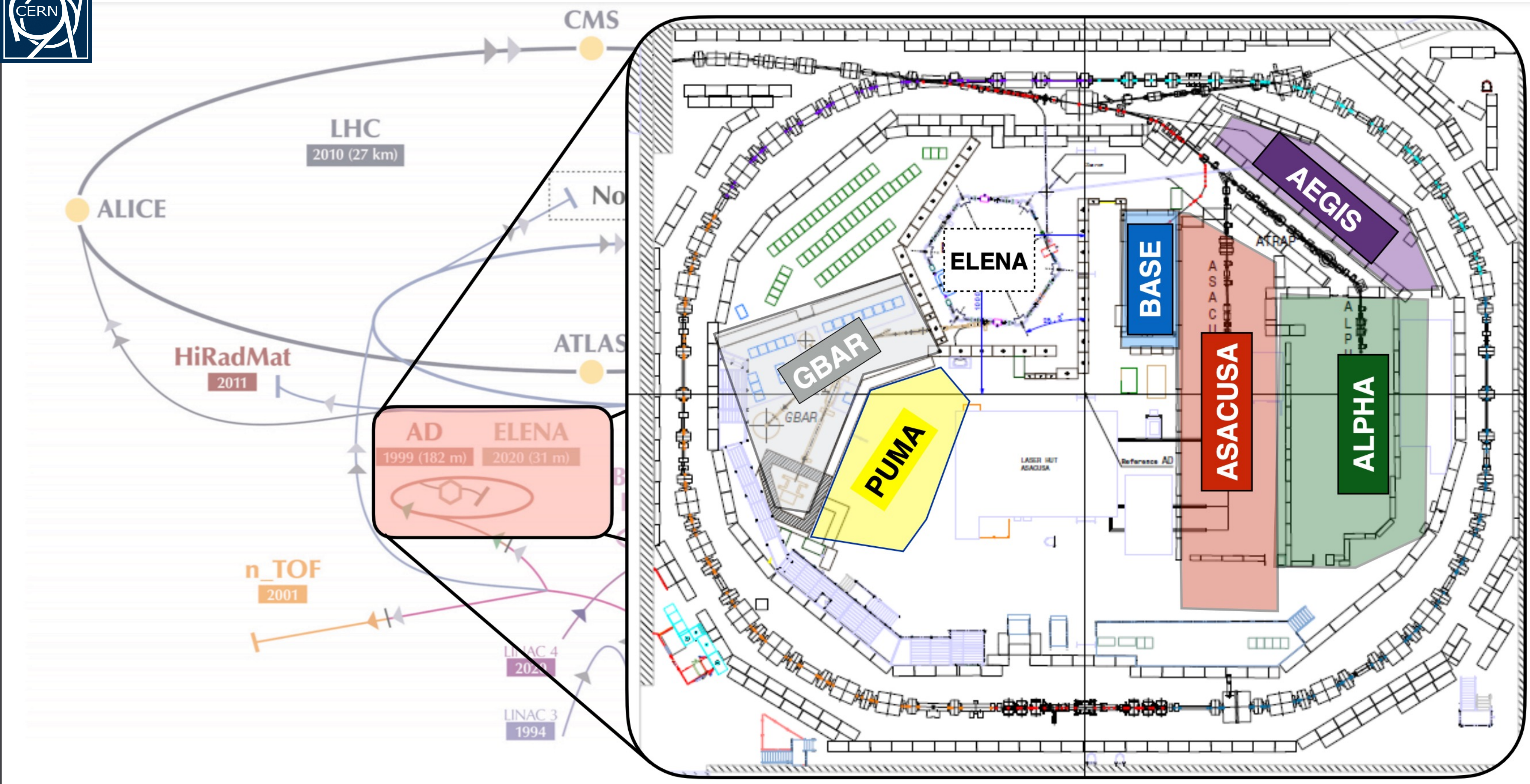


$$p + \text{nucleus} \rightarrow \text{Excited nucleus} + p + \bar{p} + \text{other particles}$$

Antiprotons produced at ~3.6 GeV
Using a combination of stochastic cooling and electron cooling the beam energy is reduced to 100 MeV in the AD, and then to 100 kev in the (new) ELENA ring. Final energy reduced to <10kev by passing beam through degrader foil.






CMS
LHC
2010 (27 km)
ALICE
HiRadMat
2011
ATLAS
AD
1999 (182 m)
ELENA
2020 (31 m)
n_TOF
2001
LINAC 3
1994
ELENA
BASE
AEGIS
GBAR
PUMA
ASACUSA
ALPHA
ATRAP

Taken from: https://indico.cern.ch/event/1132623/attachments/2469990/4259769/Antimatter%20Slides.pdf

What's the cost of a gram of antimatter?

In 2018

Electricity used cost 67 million Swiss Franc, and uses 1.25 TWh per year when running

10% spent on Proton Synchrotron, AD takes ~2.4 s/112 s= 2% of cycles

Costs ~130,000 CHF in electricity per year to produce antiprotons

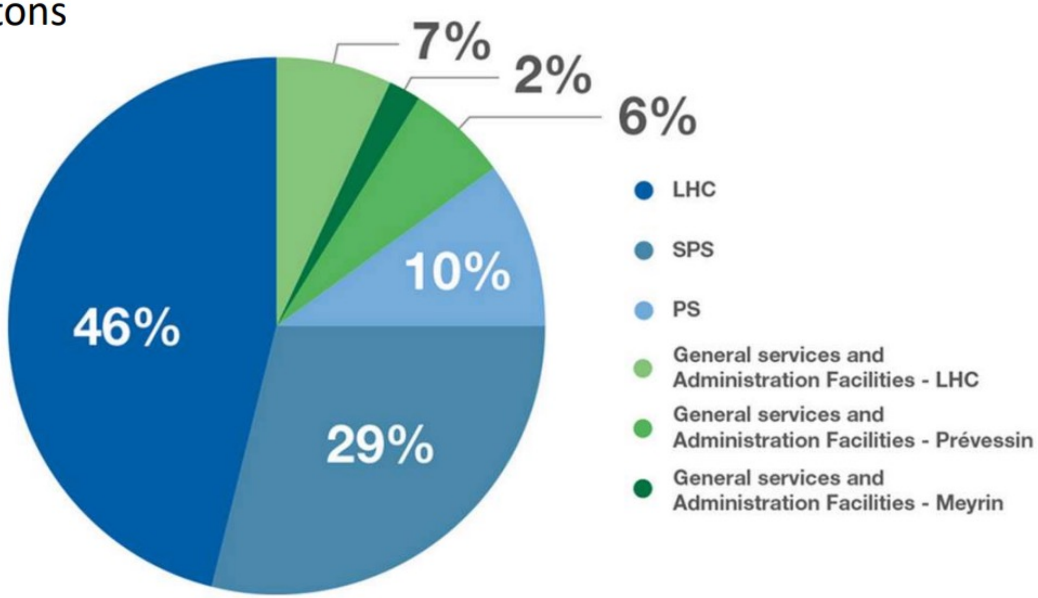
~10 trillion antiprotons produced per year ~12 picograms

Cost per gram ~**8000 trillion Swiss Franc (100x world GDP/y)**

- Not including people to operate the machine!

Not a cheap way to make lots of antimatter

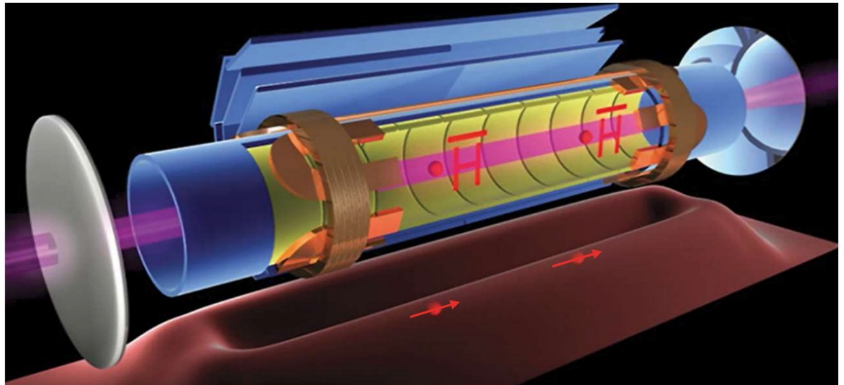
Or looking at it another way – cost per particle
12 nano Swiss Francs or 40 cents per shot



CERN Financial Budget 2018
https://hse.cern/environment-report-2017-2018/energy

The Antiproton Decelerator (AD) experiments

- Scientific goal to look for evidence of violation of CPT symmetry
  - Comparing fundamental properties of anti-matter and matter
- Several experiments using different techniques AEgIS, ALPHA, ASACUSA, BASE and GBAR
  - Very experimentally challenging!
  - Different techniques across experiments:
    - Positron source
    - Anti-hydrogen creation
    - Trapping method
    - Measurement methods

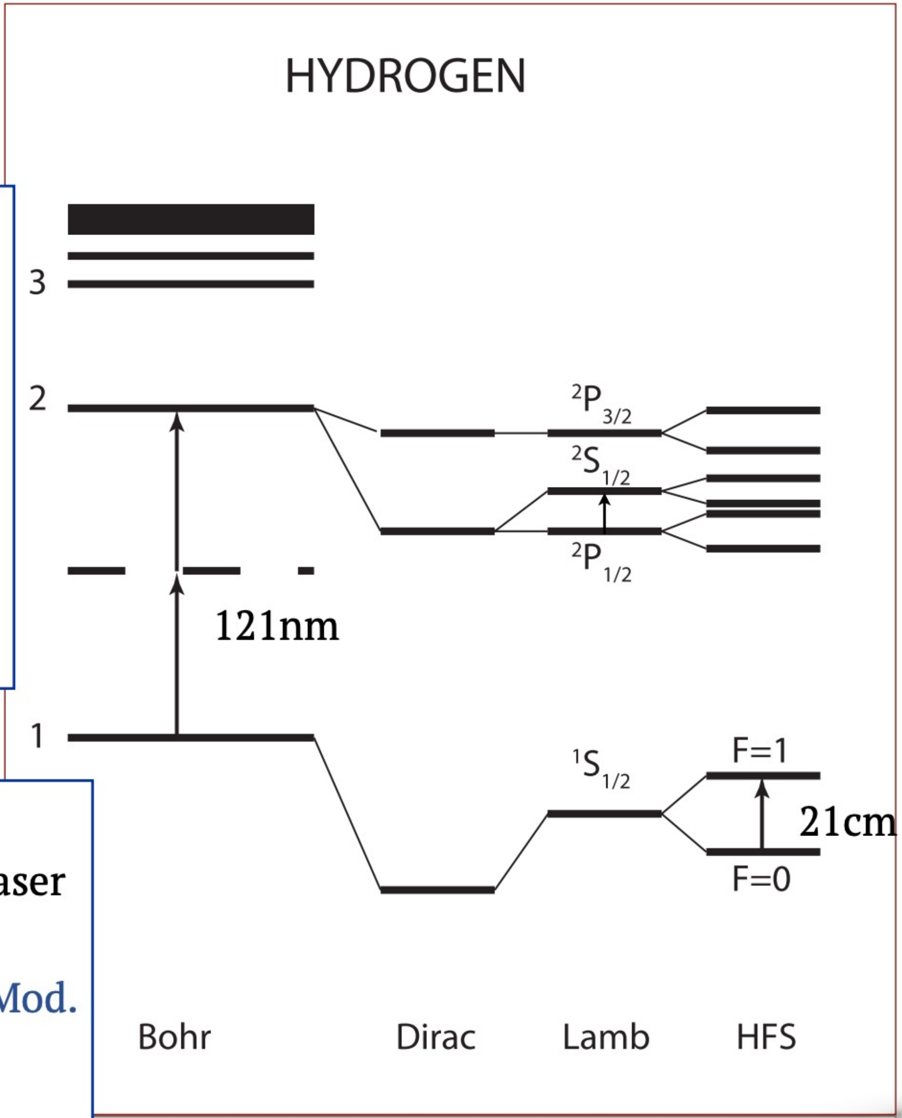

Cryogenic UV buildup cavity, Lasers + Penning traps- hard!!!

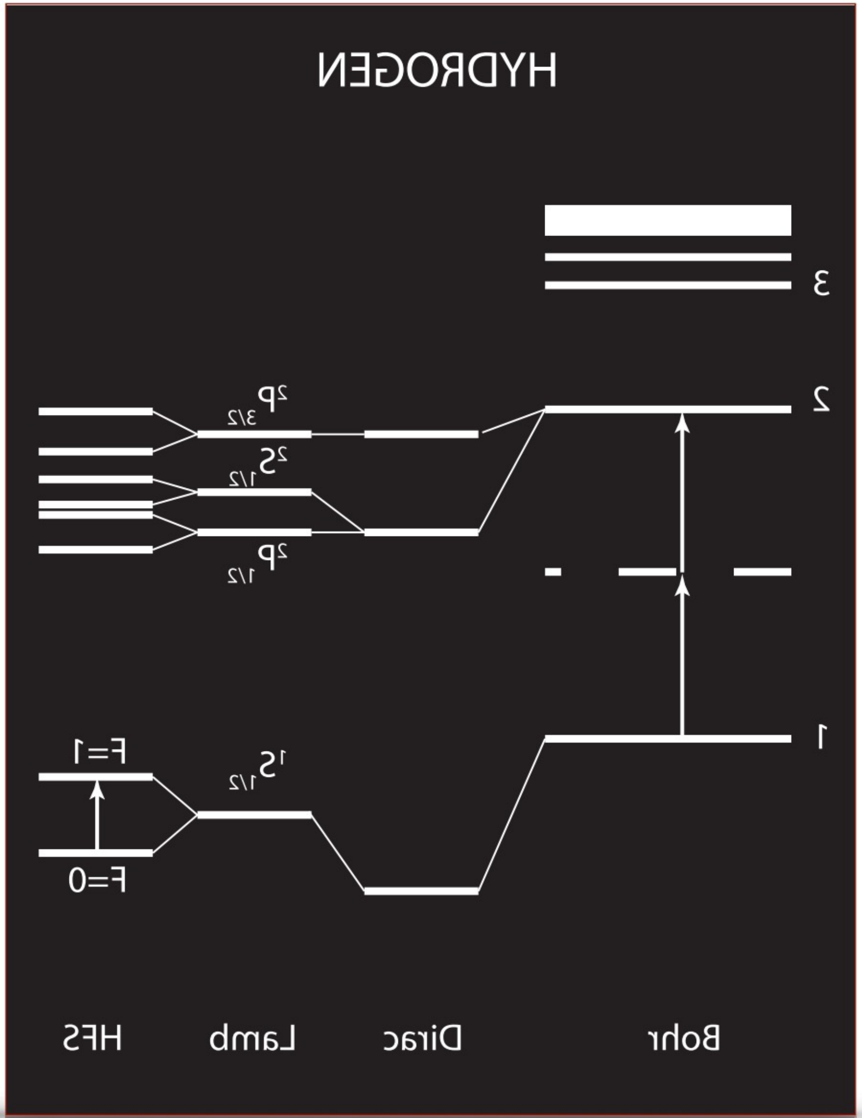
- New efforts to transport trapped cold anti-protons / anti-hydrogen
  - Transport anti-hydrogen to quieter location for measurement since fluctuating magnetic background in experimental area limits precision for spectroscopy (BASE-STEP experiment)
  - Transport to anti-protons to ISOLDE to study neutron rich nuclei via antiproton annihilation (PUMA experiment)

1

Antihydrogen spectroscopy

1S-2S: two photon transition
4×10^{-15} (~10 Hz) in a cold (~6K) atomic beam
G. Parthey et al. Phys. Rev. Lett. 107 (2011)





hyperfine splitting measurement in maser
$\sim 10^{-12}$ (~1 mHz)
Ramsey, N. F. Rev. Mod. Phys. 62, 541–552 (1990).

Antihydrogen spectroscopy

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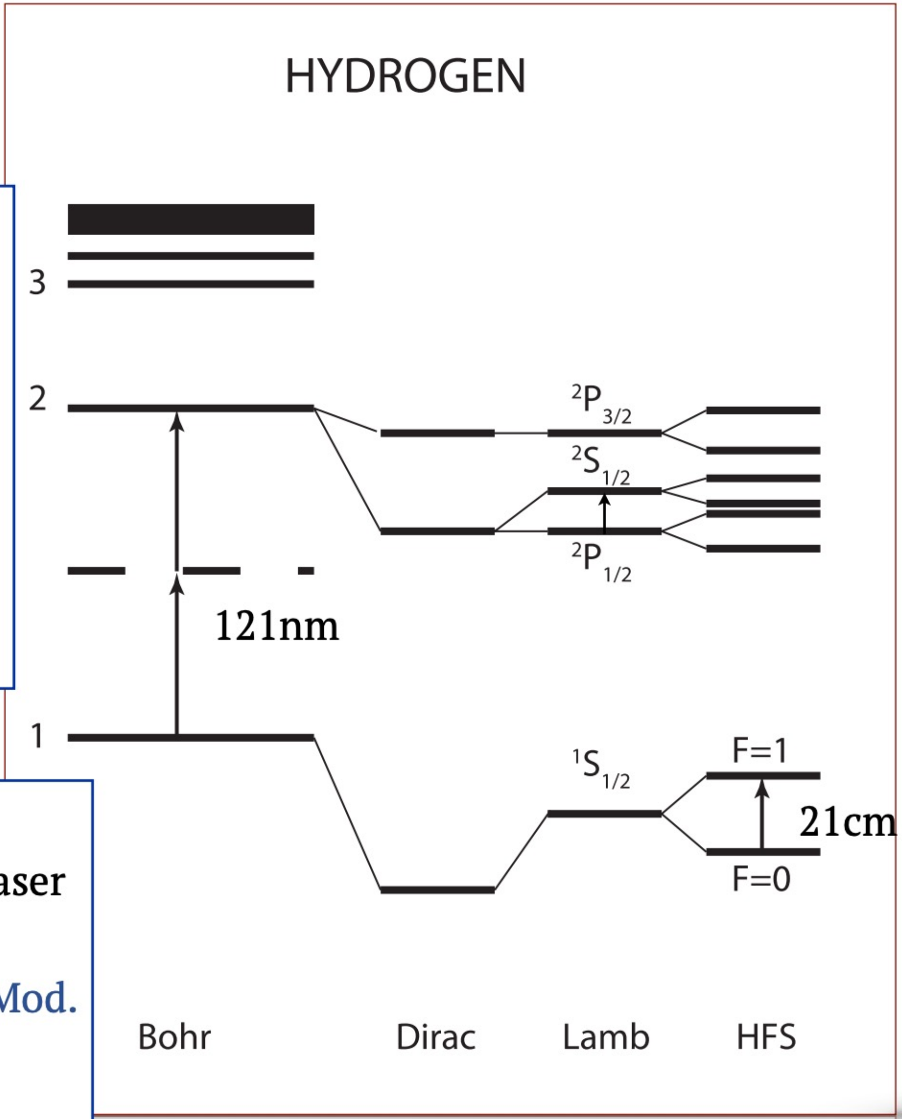

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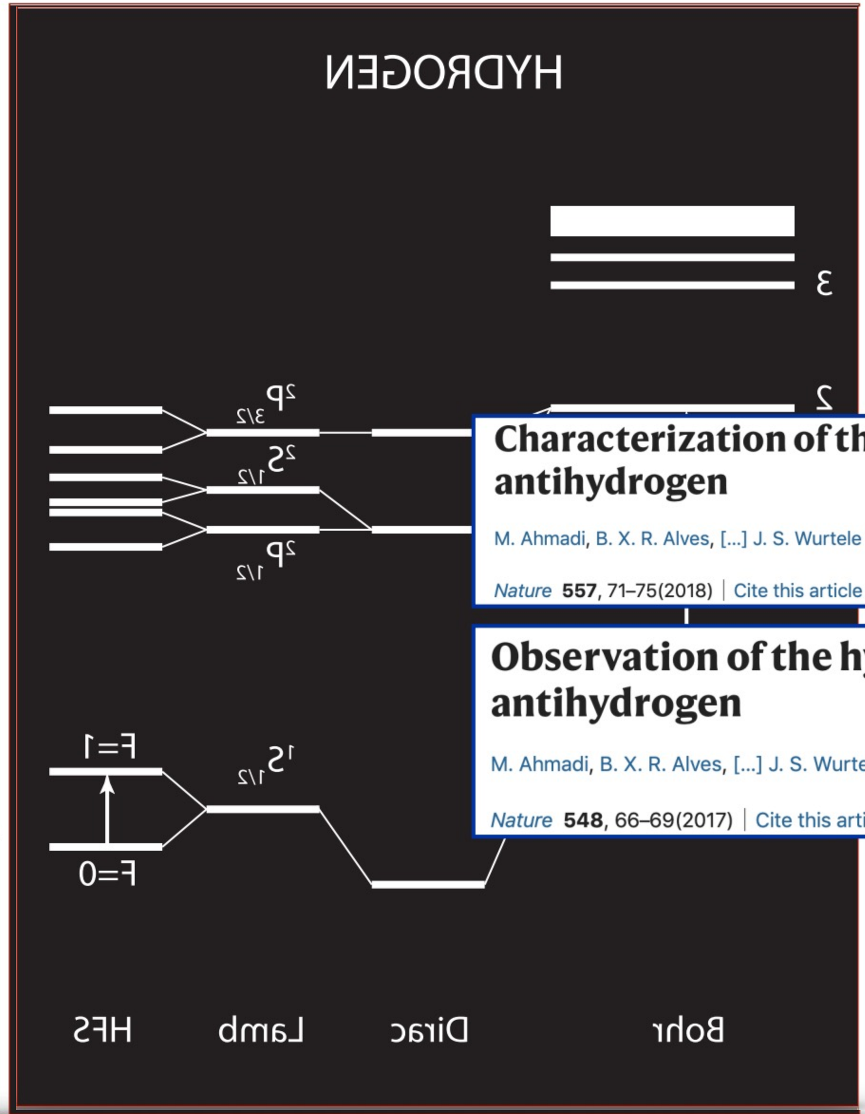


Characterization of the 1S–2S transition in antihydrogen $\sim 2 \times 10^{-12}$
M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele
Nature **557**, 71–75(2018) | Cite this article

Observation of the hyperfine spectrum of antihydrogen $\sim 5 \times 10^{-4}$
M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele
Nature **548**, 66–69(2017) | Cite this article

ALPHA Collaboration

Impressive precision on spectral lines measurements!

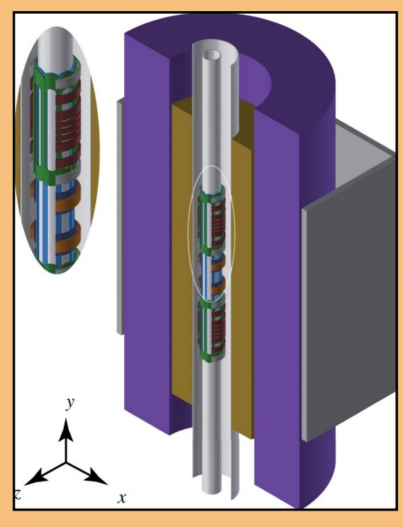
Planned gravity measurements with antihydrogen atoms

Plurality of approaches

VERTICAL TRAP

- increase up/down sensitivity (up to 1.3m trapping range)
- much improved field control

Sign measurement planned soon
1% targeted $\bar{H}$ cooling to ~20 mK and advanced magnetometry

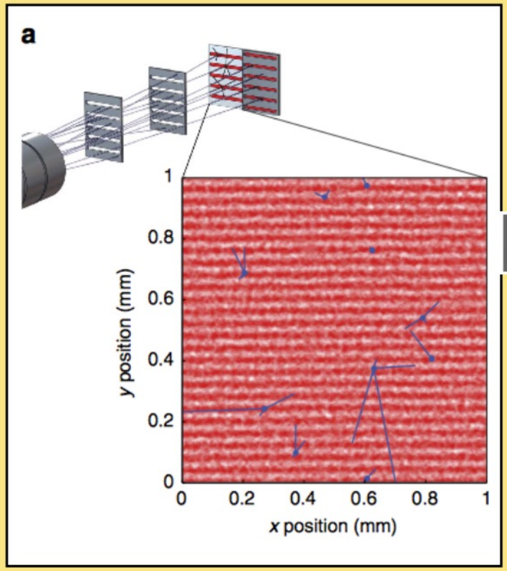


(ALPHA-g)

$\bar{H}$ BEAM

- Sensitivity to ~10 µm deflection needed
- cold antiproton translates in cold $\bar{H}$ thanks to CE mechanism

Sign measurement targeted



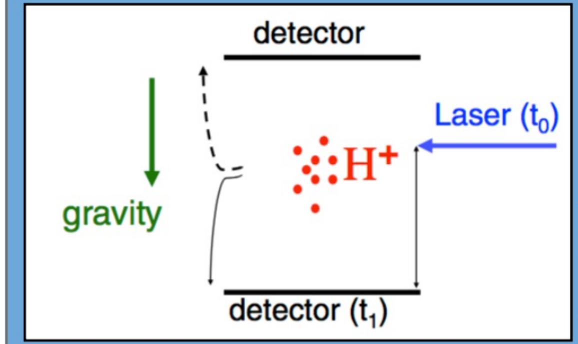
AEgIS

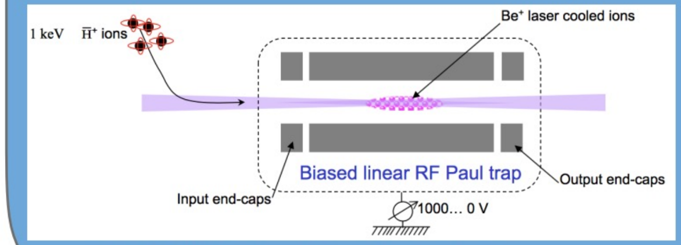
S. Aghion et al. Nature Communications 5 (2014) 4538

$\bar{H}^{+}$ BEAM

- Cooling below 1 m/s : Sympathetic cooling of $\bar{H}^{+}$
- opens new horizons

1% measurement targeted



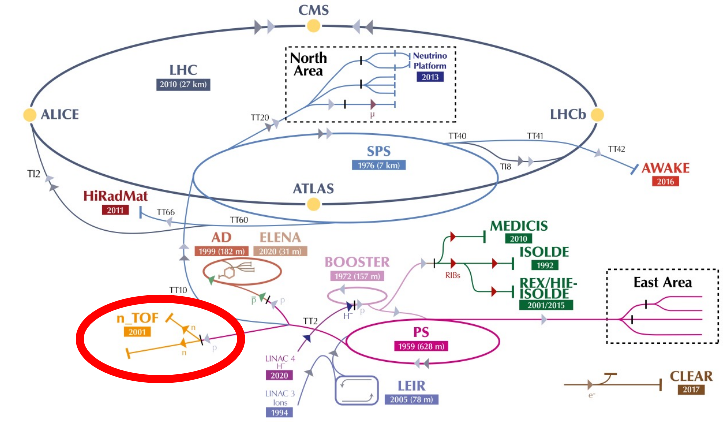


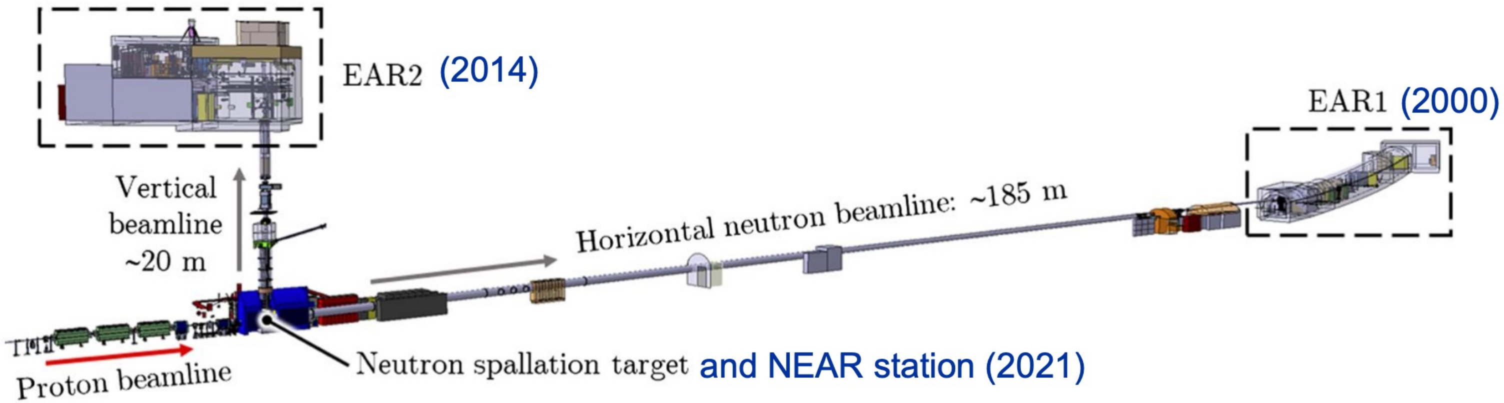
e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

Remember even if fundamental anti-particles interact differentally with gravity, most of the mass of the atoms/anti-atoms comes from QCD confinement effects. Anti-atoms will not fall “up”.

N-TOF

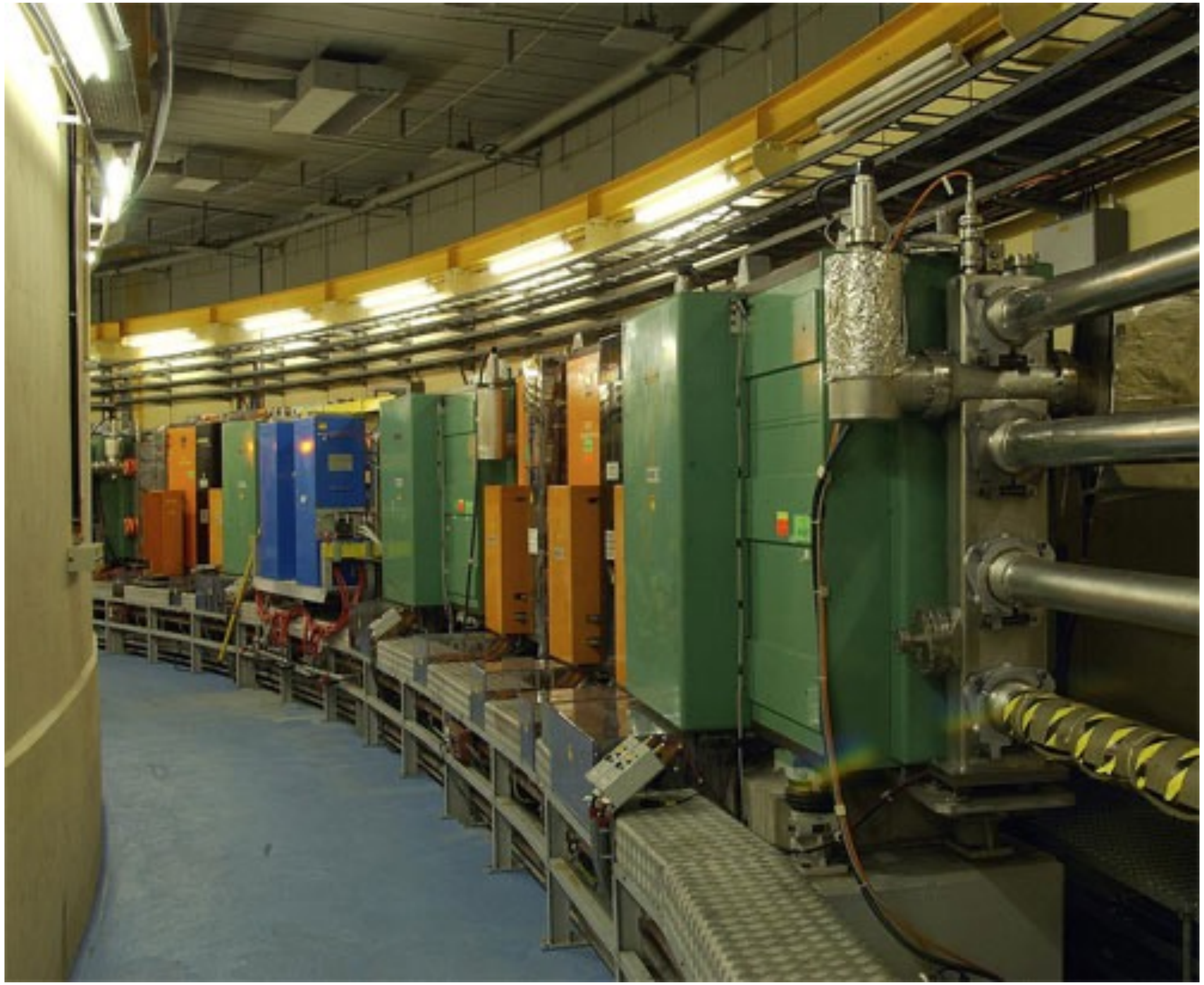
- Neutron time-of-flight (N-TOF) facility for high accuracy neutron-induced cross-section measurements
  - Focused on neutron astrophysics, nuclear technology, medical
- 20 GeV/c proton beam from the Proton Synchrotron (PS) strikes an actively cooled pure-lead neutron spallation target
- Produced neutrons are water-moderated to produce a spectrum that covers 11 orders of magnitude in energy from GeV down to meV
- Measured nuclear reaction rates very important for:
  - Big-bang nucleosynthesis (relevant for Li anomaly) and stellar evolution
  - The development of nuclear-energy technology, including possible future beam driven reactors





PSB (The Booster)

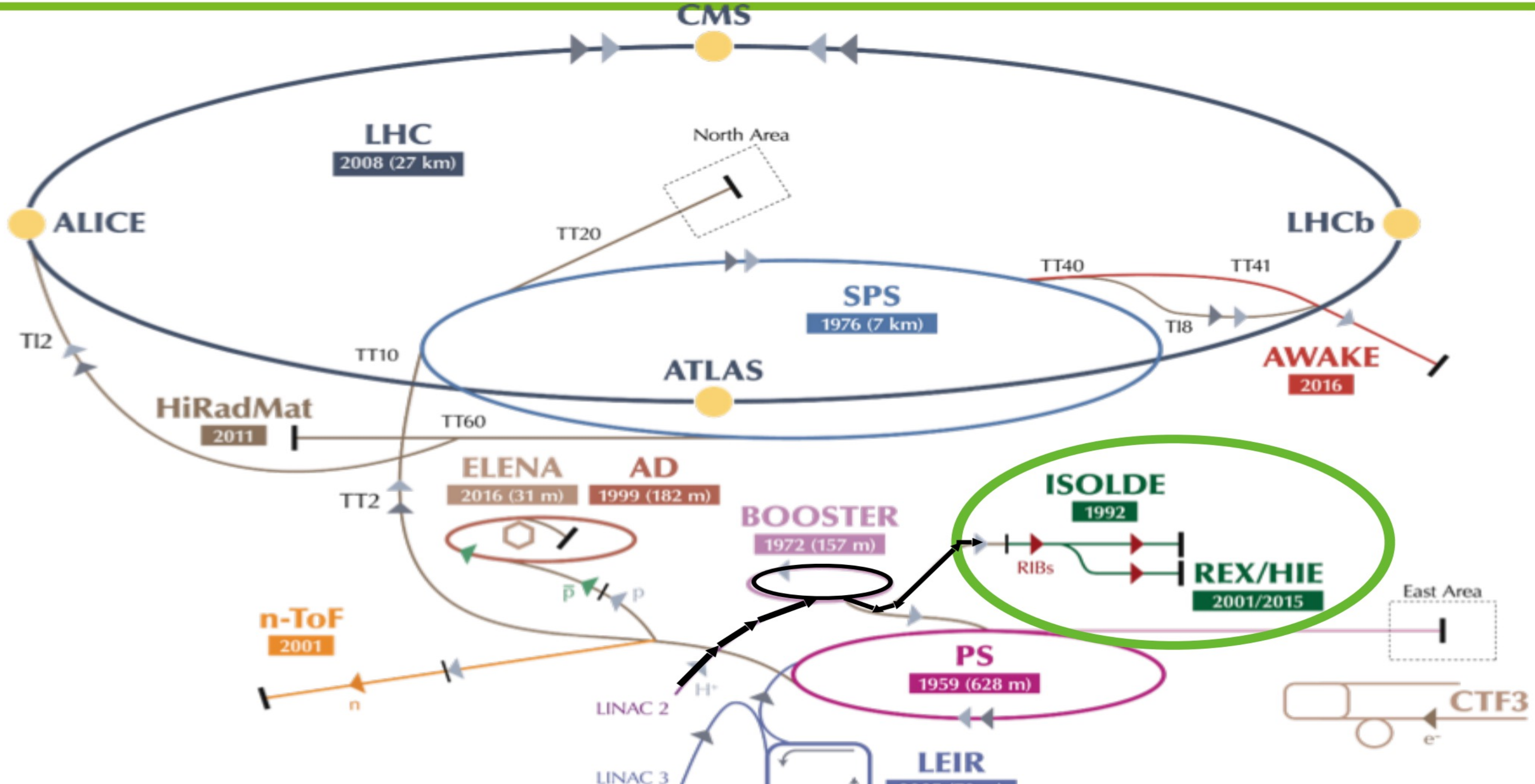
1972



157m (4 rings)

1.4 GeV

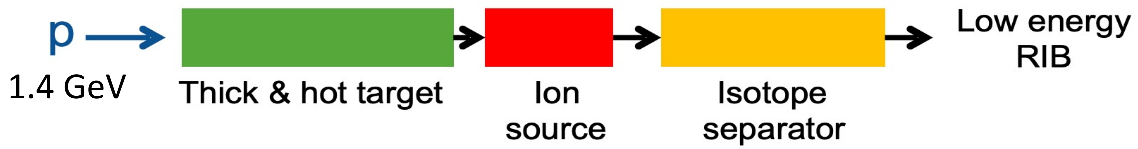
ISOLDE at CERN

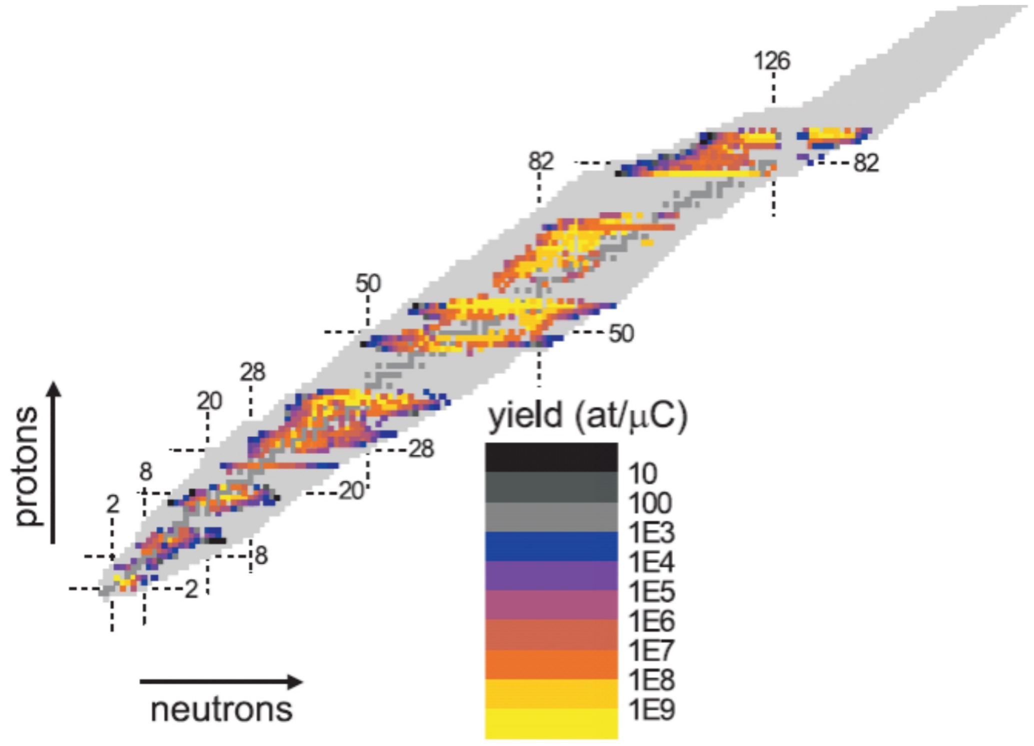


- 1.4 GeV protons (~92% speed of light)
- 50% of CERN's protons

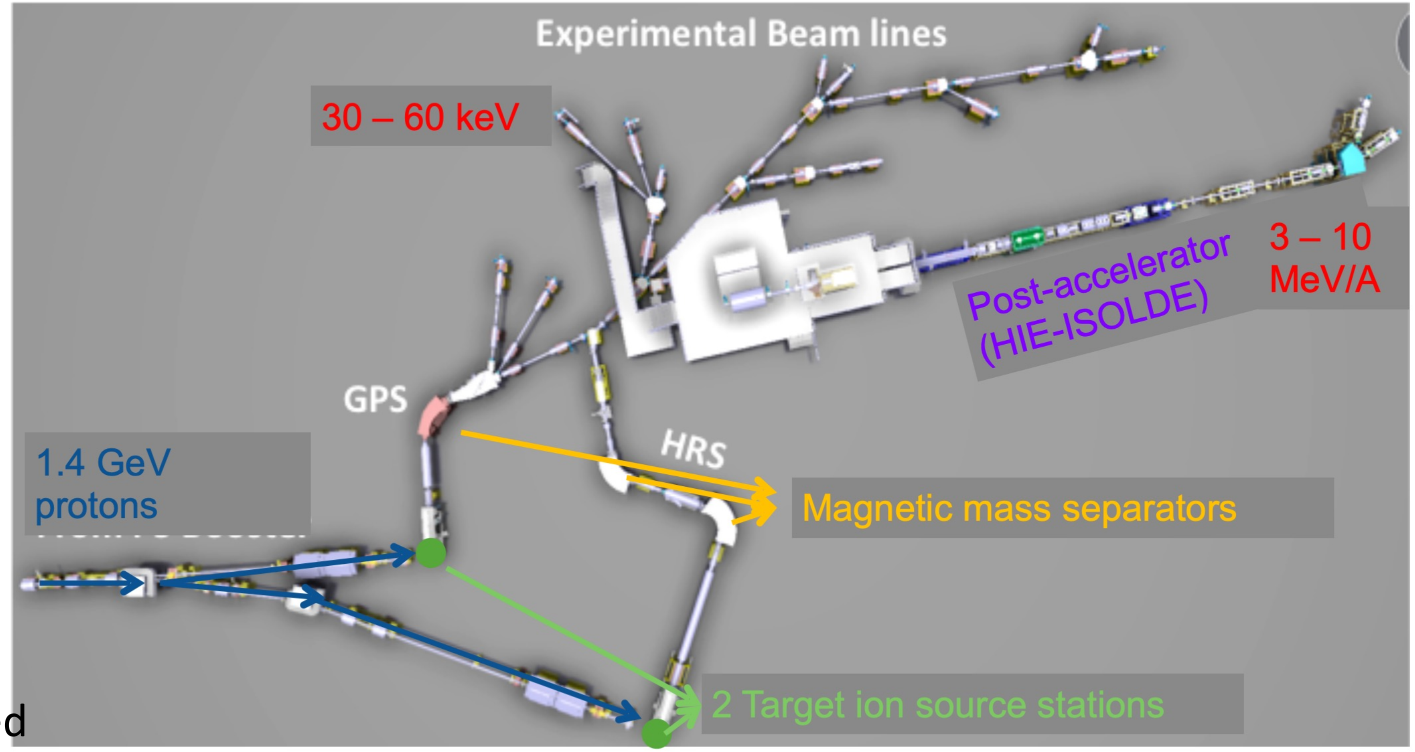
ISOLDE: Radioactive Ion Beams (RIB)

- Isotope Separator On-line Device (ISOLDE) Facility at CERN
- Produces rare radioactive isotopes



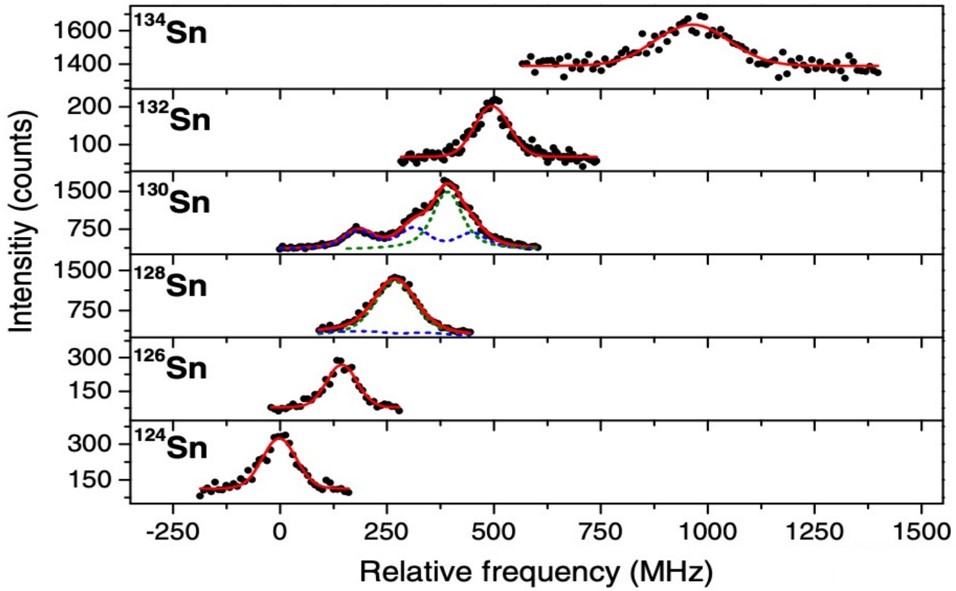


1300 isotope of more than 70 chemical elements produced



Experiments at ISOLDE

- ISOLDE beams used by many experiments
- Covering:
    - Fundamental nuclear physics
    - Solid state physics
    - Bio-physics
- MEDICIS facility produces non-conventional radioisotope for medical research
- Nuclear physics measurements include:
    - Mass measurements of isotopes
    - Laser spectroscopy of nuclear energy levels
    - Measurement of nuclear charge radii



Example of physics highlight: towards a nuclear clock at ISOLDE

Over past 60 years, unit of time (second) defined using atomic clocks, i.e. transition (~ 9 GHz) between two hyperfine levels of ground state of cold ^{133}Cs atoms. Precision: 10^{-16} (1s in 300 million years).

Nuclear clocks are potentially more precise than atomic clocks, due higher transition frequency (optical region) and less sensitivity to external perturbations. They are also excellent quantum sensors.

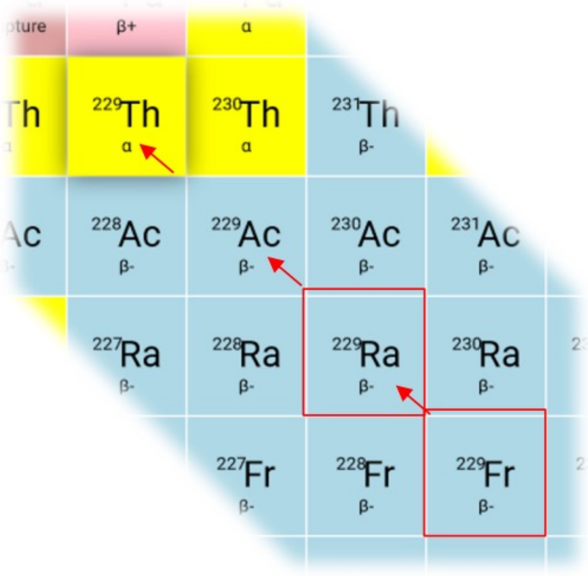
^{229}Th is currently best candidate for a nuclear clock: first excited state (^{229m}Th) is at only ~ 8 eV from ground state and has long half time (→ narrow spectral line)

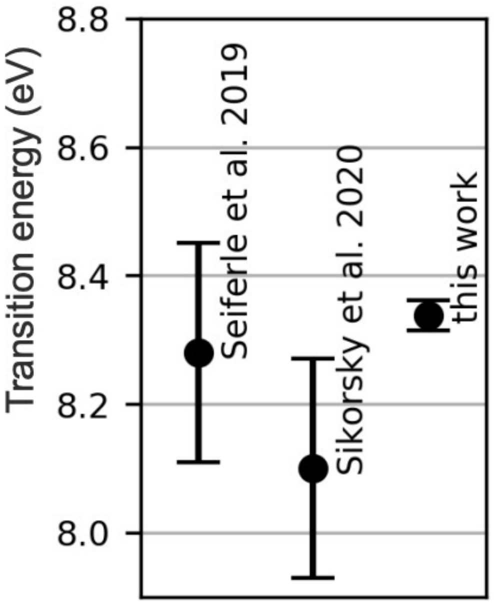
Tirolf, Seiferle, von der Wense

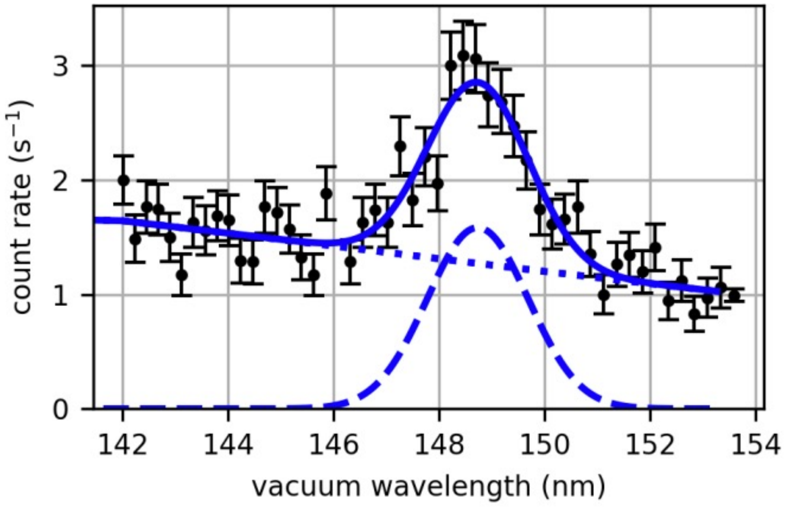
CERN COURIER
Volume 62 Number 5 September/October 2022

Experiment at ISOLDE in 2022: ^{229m}Th produced using β-decay of a ^{229}Fr - ^{229}Ra beam implanted into CaF_2 and MgF_2 crystals. Radiative decays of ^{229}Th observed for the first time → allowed precise measurement of transition energy (essential for laser excitation of the clock) and confirmed "long" lifetime of ^{229m}Th state

KU LEUVEN

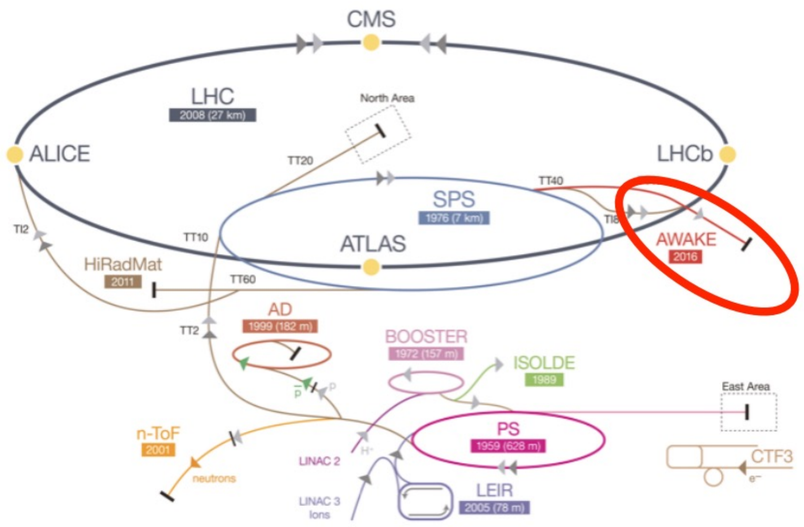






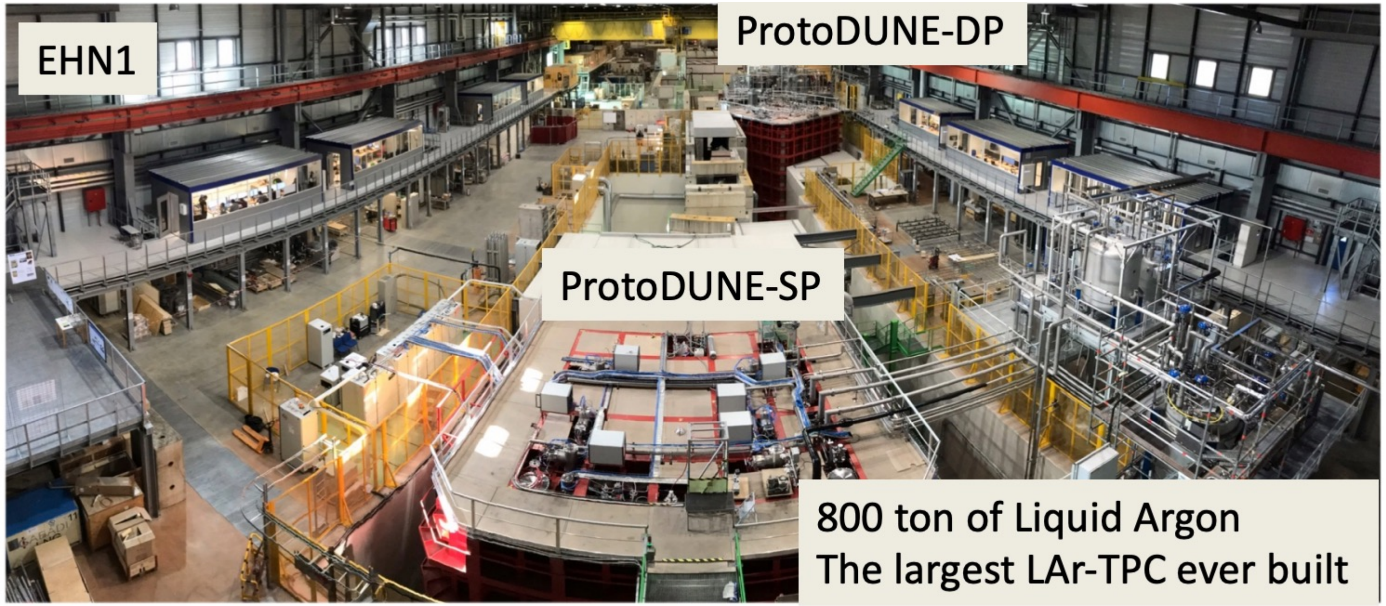
R&D

- CERN has a strong R&D programme covering experimental and accelerator physics
- AWAKE is a proof-of-principle experiment that uses plasma to accelerate particles to high energies over short distances
  - In principle plasma wakefields can generate acceleration gradients hundreds of times higher than those achieved in current radiofrequency cavities
  - AWAKE uses protons from the SPS to create plasma wakefields in a 10m long plasma cell. This is then used to accelerate an electron “witness” beam up to a few GeV
    - 19MeV -> 2 GeV acceleration achieved in 2018
  - Could be used to make future high energy e+e- colliders much smaller and affordable!

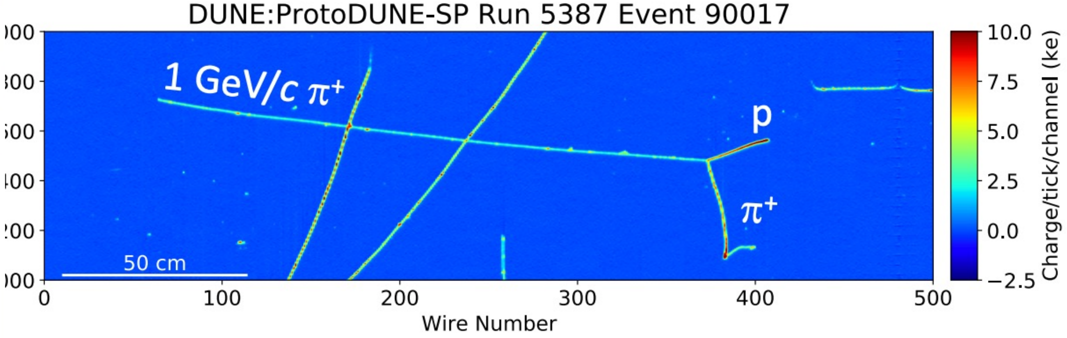


R&D

- CERN has a strong R&D programme covering experimental and accelerator physics
- Proto-Dune is an R&D effort to build the first very large scale LAr TPC detectors for neutrino physics
  - LAr TPC technology first proposed in 1977 by C.Rubbia for neutrino physics,
  - LAr used as both the target for neutrino interaction, and the active detection medium (scintillation and ionisation)
  - Proto-Dune is O(1ktonne) but is actually a small scale protype of the final DUNE experiment detectors (which will be 4x10ktonne detectors)



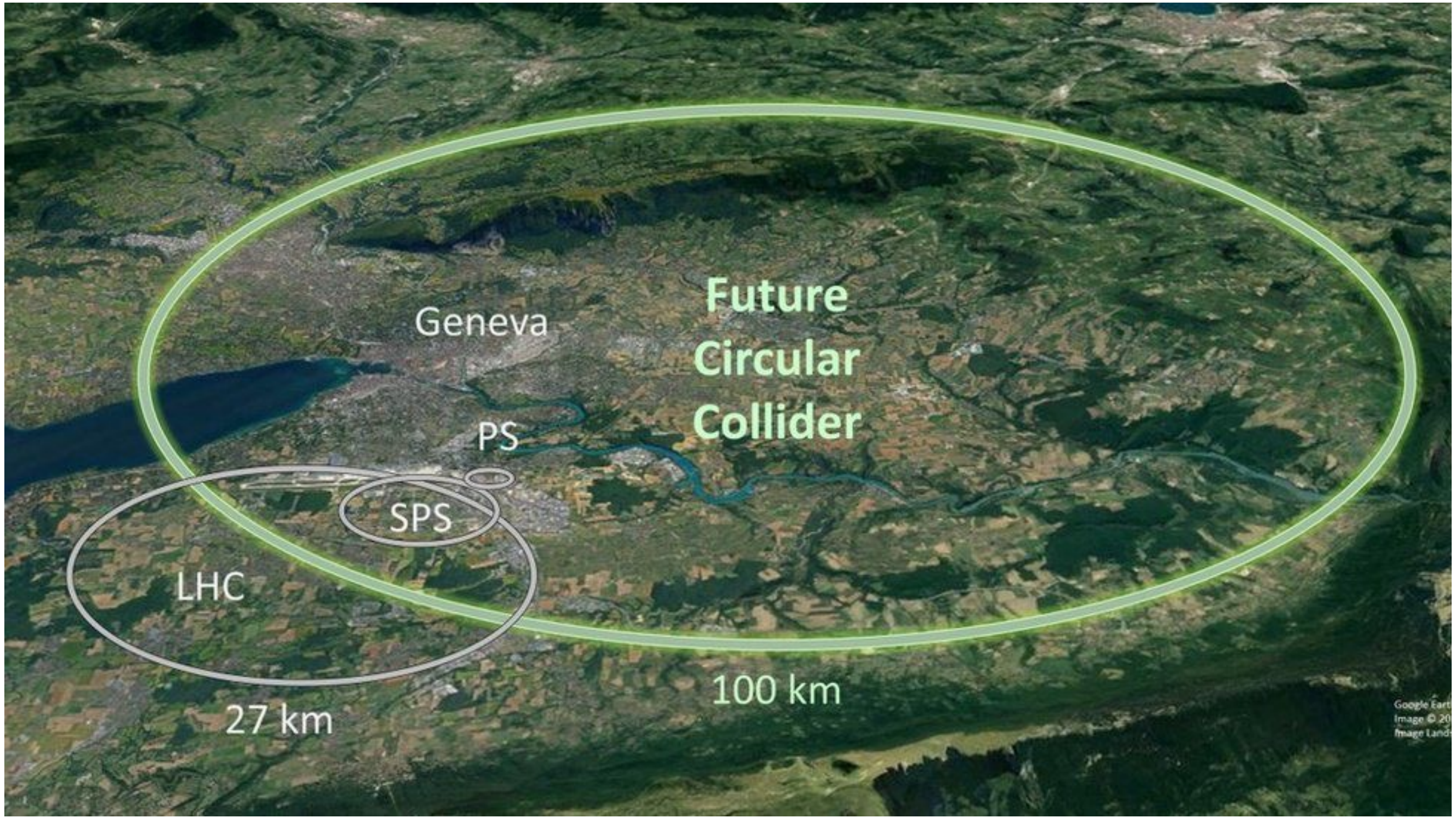
Protodune performance studies with particle beams from the SPS



Longterm future projects

- CERN is currently studying the possibilities of a new larger accelerator, the Future Circular Collider (FCC)
- Plan 100km ring with up to 100 TeV collision energy (~7x LHC)

Idea is an initial phase of e+e- collisions at an energy to study Higgs production.
Followed by a proton-proton collider at the highest energy.
Requires new superconducting magnet technology to reach this energy, CERN is leading a large R&D effort into such magnets.
Many challenges (both financial and technical).



Conclusions

- CERN has an extremely broad scientific research programme covering high-energy and nuclear fundamental physics research as well as applied science, and R&D
- The CERN experiments are carrying out cutting edge research in many areas with results relevant across a broad range of physics (cosmology, astronomy etc…)
- The programme is driven by the unique and flexible CERN accelerator complex
  - Many interleaved machines providing an incredibly diverse set of beam species and energies
    - Crucial parts of the chain were built more than 60 (PS) and 40 (SPS) years ago but still providing worlds best beam for many experiments
    - Operated by an extremely competent and creative group of accelerator physicists and engineers
- CERN is currently looking at future medium and large-scale projects

- Enjoy you research!

Acknowledgements

- For this talk I have borrowed material from the following:
  - "Antimatter in the lab" J. Devlin, CERN Summer student lectures 2022
  - "Nuclear Physics at CERN" S. Malbrunot, CERN Summer student lectures 2022
  - "Heavy Ions" F. Bellini, CERN Summer student lectures 2022
  - (All summer student lectures are available here: https://summer-timetable.web.cern.ch/)
- And presentations by:
  - F. Gianotti, M. Pepe-Altarelli, G. Salam, F. Antinori, P. Crivelli, T. Yang, C. Lazzeroni, P. Muggli
- Many thanks!

The Source (+ RF Quadrupole: 750keV)