DESY Tuesday Seminar, 11.3.2008 and
Physikalisches Seminar Zeuthen, 12.3.2008

The Physics Program at the PS & SPS: CERN's Unique Scientific Breadth

Christoph Rembser, CERN

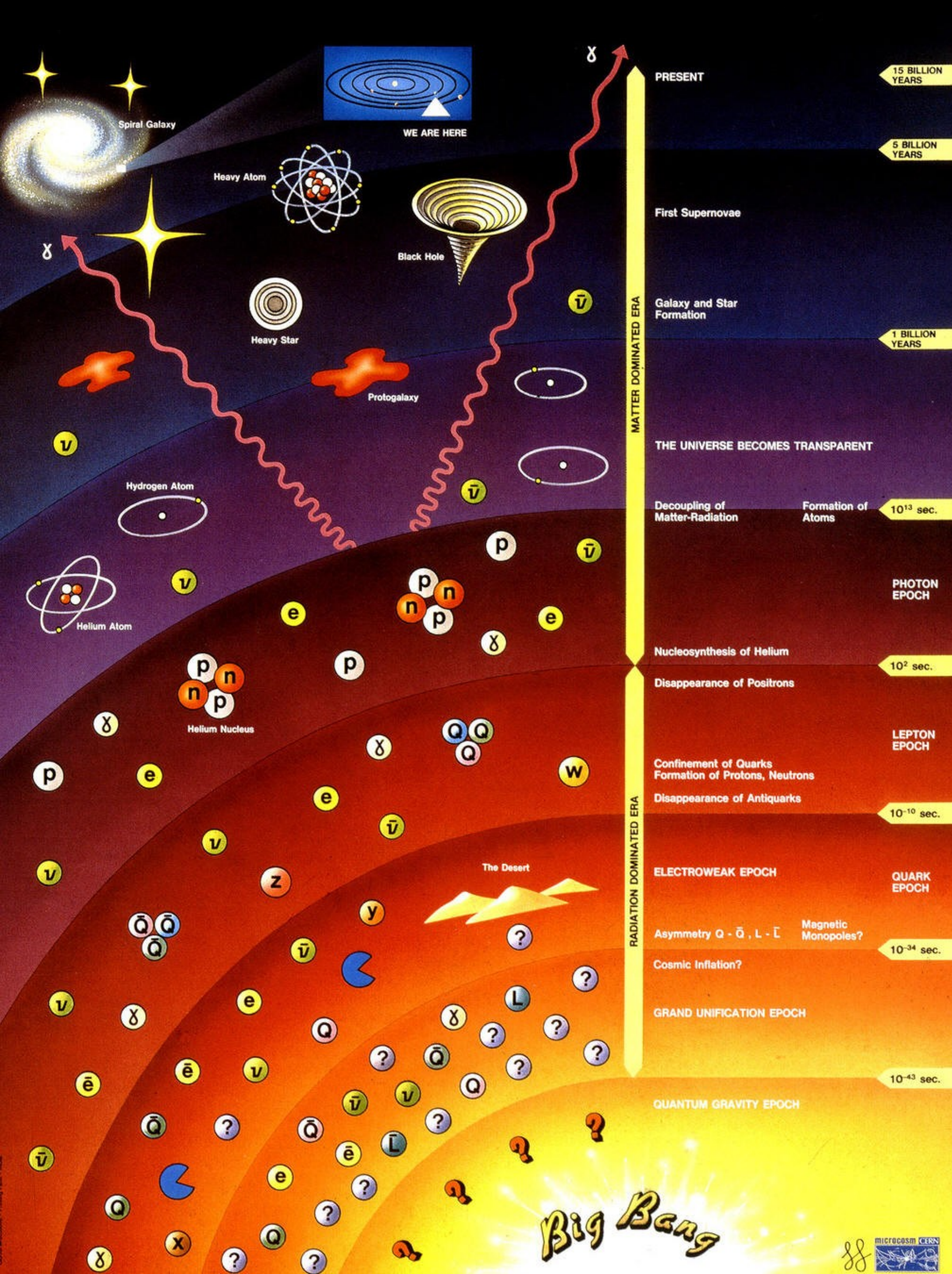
Abstract

While the main focus over the past years has shifted towards flagship experiments at colliders, a rich and exciting physics program is still carried out at the CERN Proton-Synchrotron (PS) and Super-Proton-Synchrotron (SPS) attracting large scientific communities from the various fields of physics.

In my talk I will introduce the CERN PS and SPS accelerators which are successfully and efficiently operating since many years and which are providing a wide range of different particle beams.

This beams with energies up to 450GeV are used in various experimental facilities like the Antiproton Decelerator, the Neutron Time-of-Flight facility, the PS and SPS experimental areas or at the CNGS beamline which provides a beam of high-energy neutrinos to the Gran Sasso laboratory about 730km away from CERN. I will present an overview on the physics program of CERNs "lower energy" accelerators and will report on its experiments.

As from this year onwards the PS and SPS also serve as injectors for the Large Hadron Collider LHC, I will review their operation modes and possible machine upgrades which will ensure to keep CERN's unique scientific breadth and that the experiments at the PS and SPS will remain an important and indispensable part of the laboratories activities.



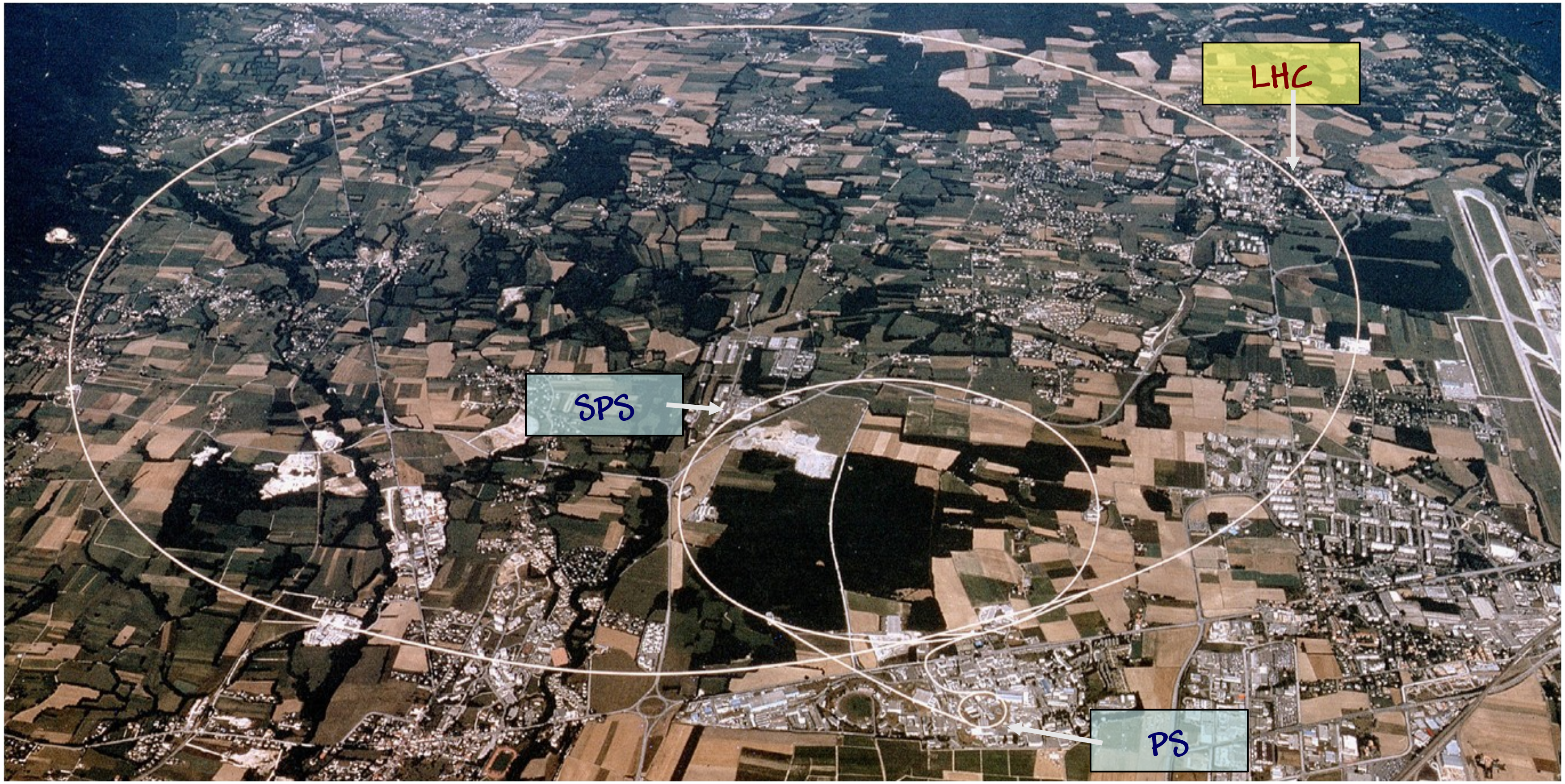
This talk:
deeper understanding our existing world at the PS & SPS and its experiments (DIRAC, CLOUD, AD, COMPASS, CNGS, NA6x ...)

The Physics Program at the PS & SPS: CERN's Unique Scientific Breadth

by Christoph Rembser, CERN-PH

NOT covered:
getting closer in understanding the]origin of our universe at the LHC and its experiments (ATLAS, CMS, LHCb, ALICE, TOTEM, LHCf)

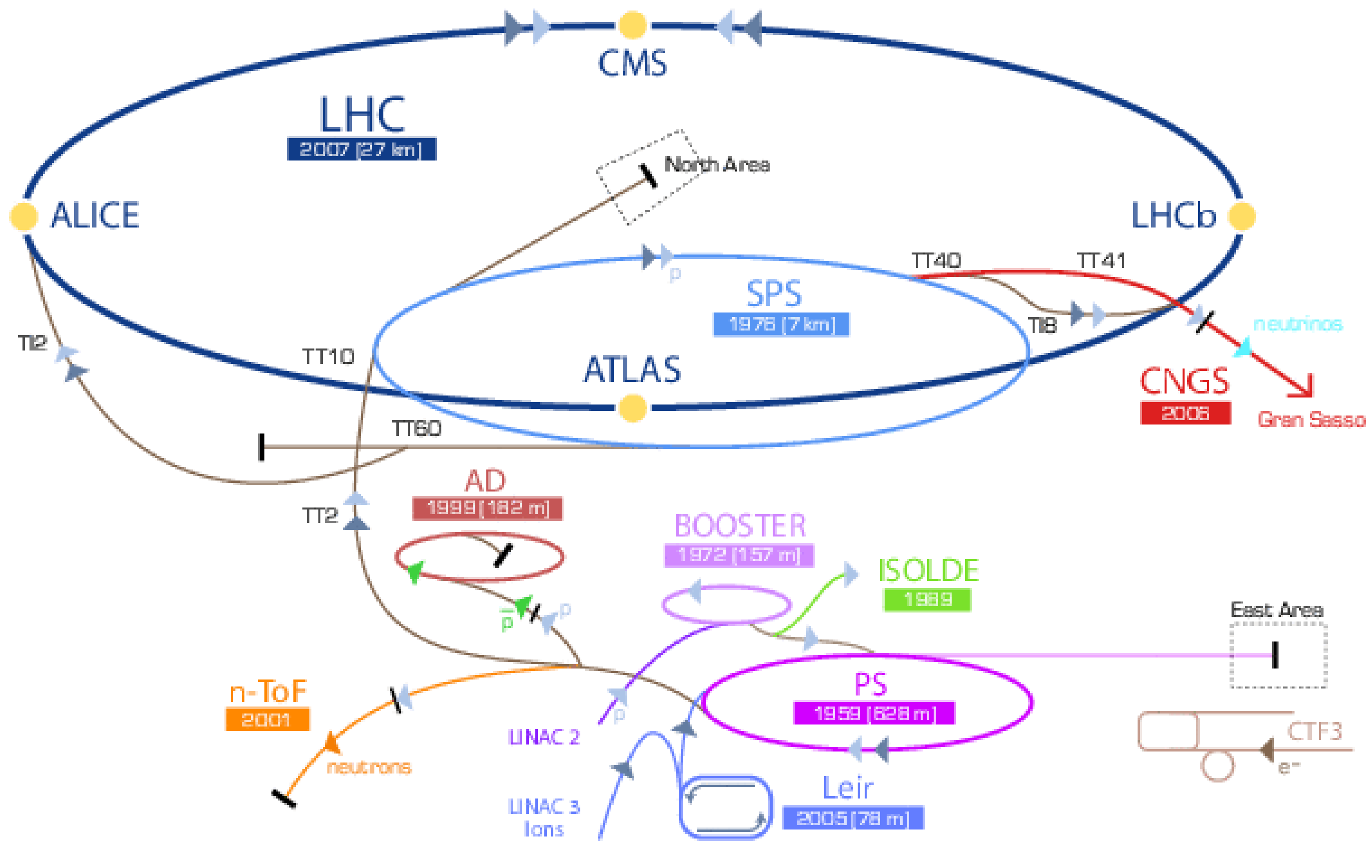
CERN: the World's Most Complete Accelerator Complex (not to scale)



CERN: in total >9000 users, representing >500 universities & institutes, more than 80 nationalities; most working at CERN's flagship: the Large Hadron Collider **LHC**...

...but also ~2500 users perform >**50 experiments and beam tests** at the Proton Synchrotron **PS** and Super-Proton Synchrotron **SPS** ⇒ **this talk**

CERN: the World's Most Complete Accelerator Complex (not to scale)



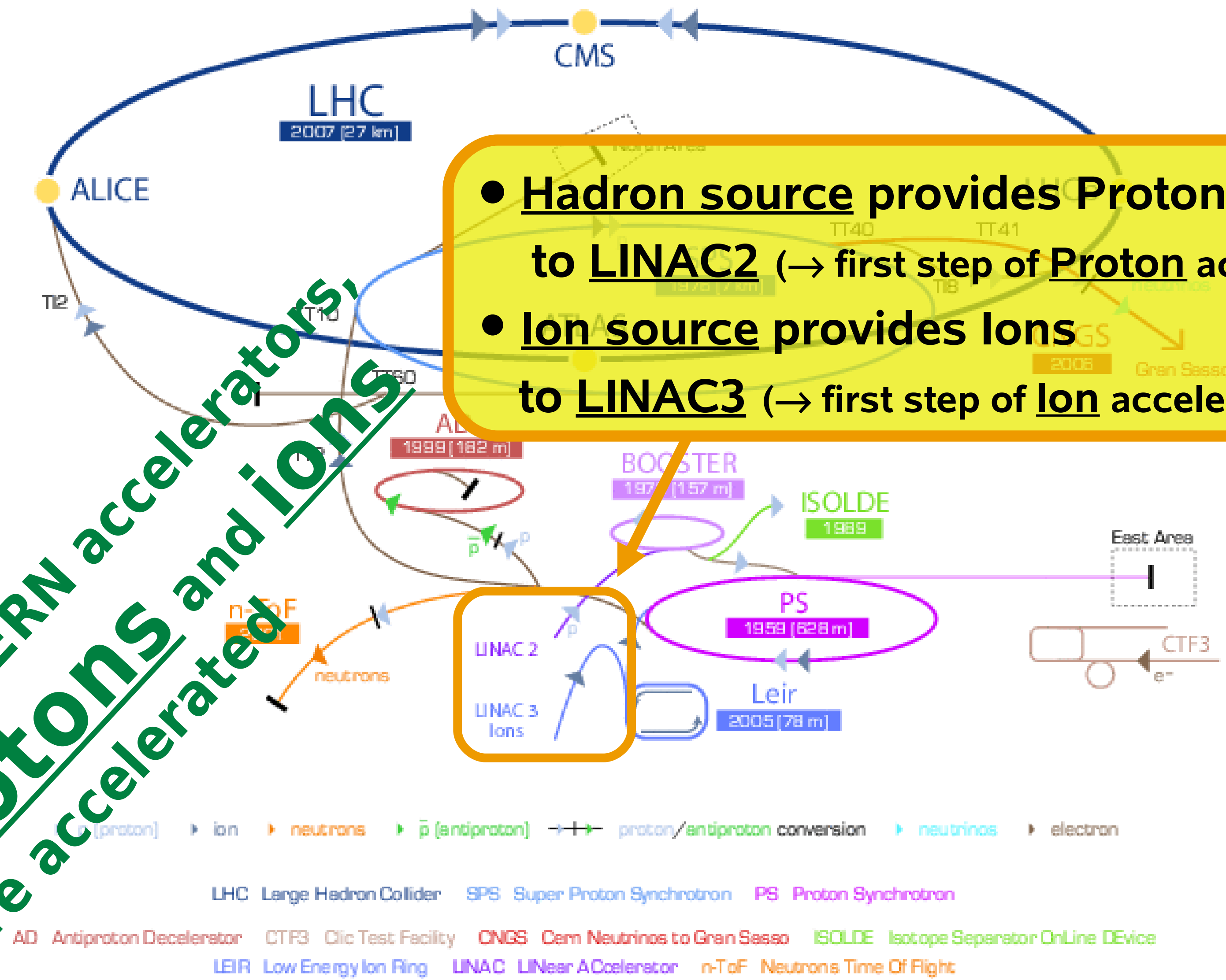
p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

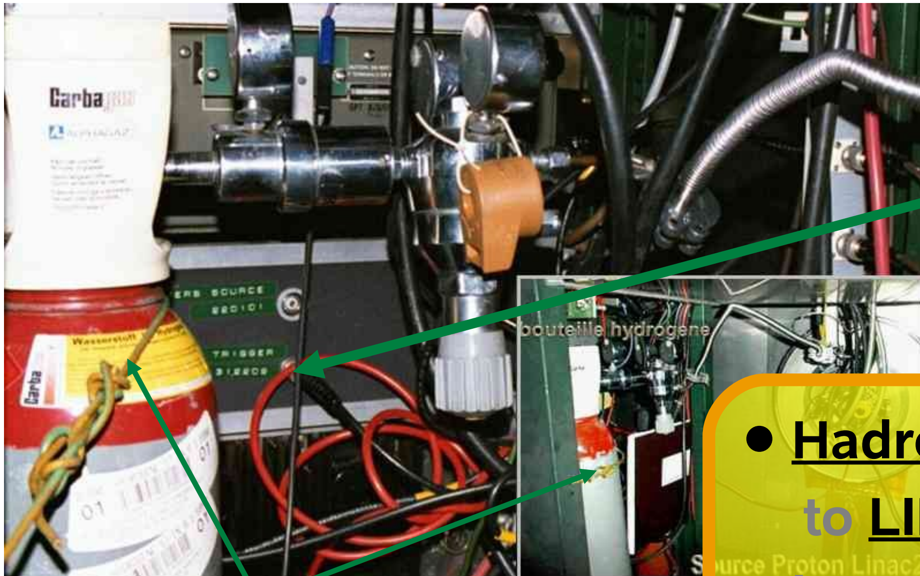
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

CERN: the World's Most Complete Accelerator Complex (not to scale)



- **Hadron source provides Protons to LINAC2** (→ first step of **Proton** acceleration)
- **Ion source provides Ions to LINAC3** (→ first step of **Ion** acceleration)

In the CERN accelerators, protons and ions are accelerated



"protons from the bottle"

The CERN Proton source:

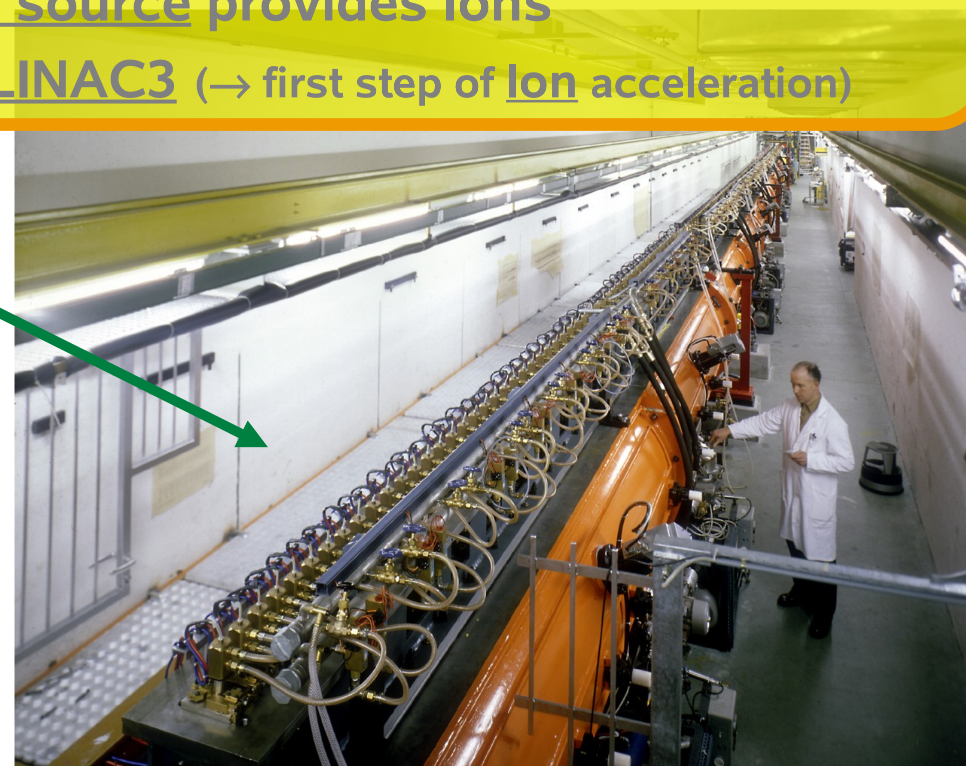
Hydrogen is "stripped" in duoplasmatron, protons are extracted at **92keV** (beam current: 250 - 320mA). Before injection to the LINAC2, protons are accelerated to **750keV** by Radio Frequency Quadrupoles

- **<u>Hadron source</u>** provides Protons to **<u>LINAC2</u>** (→ first step of <u>Proton</u> acceleration)
- <u>Ion source</u> provides Ions to <u>LINAC3</u> (→ first step of <u>Ion</u> acceleration)

The CERN Proton LINAC2 (1978):

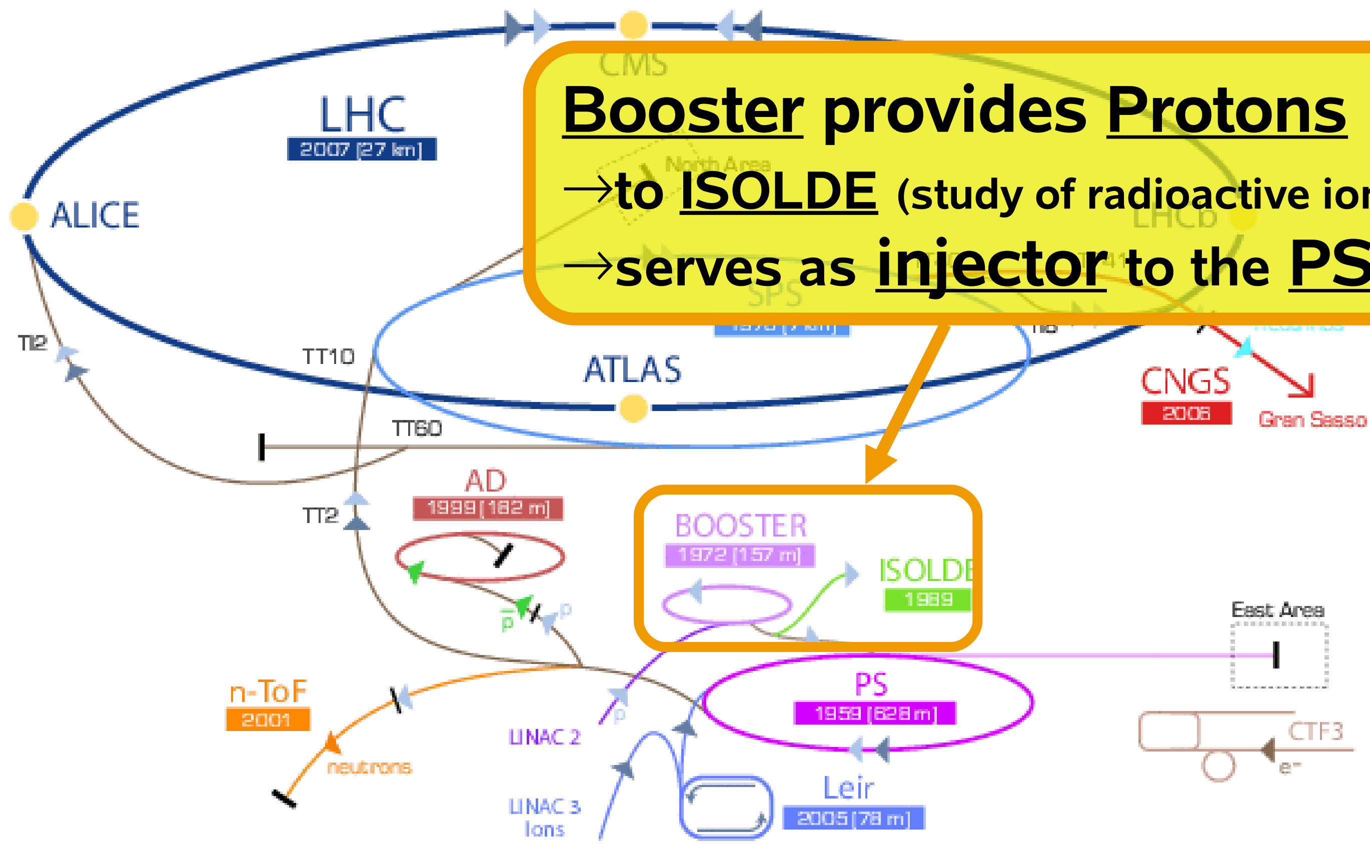
Protons from the source are accelerated to **50MeV** with intensities between 150mA (design) and 180mA (needed for LHC).

N.B.: A new LINAC (LINAC4) is currently in preparation, start of operation ~2011.



CERN: the World's Most Complete Accelerator Complex (not to scale)

The path of the protons:



<u>Booster</u> provides <u>Protons</u>

→to <u>ISOLDE</u> (study of radioactive ion beams)

→serves as <u>injector</u> to the <u>PS</u>

p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

ISOLDE (1989): production of a large variety of radioactive ion beams for different experiments, e.g. nuclear and atomic physics, solid-state physics, life sciences and material science. Radioactive nuclides are produced in thick high-temperature targets via spallation, fission or fragmentation reactions. Until now more than 600 isotopes of more than 60 elements (Z=2 to 88) have been produced with intensities up to 10^{11} ions per second.

C.R.: not an expert on ISOLDE physics, different user community → skip details...

Booster provides Protons

→to **ISOLDE** (study of radioactive ion beams)

→serves as **injector** to the **PS**

PS Booster (1972):

4 superimposed rings accelerate 4 times 1.05 x 10^{12} protons from 50 MeV up to **1.4 GeV**. A Booster cycle lasts **1.2 s** (→ defines the **heart beat** of the CERN accelerator complex)

CERN: the World's Most Complete Accelerator Complex (not to scale)

The path of the protons:

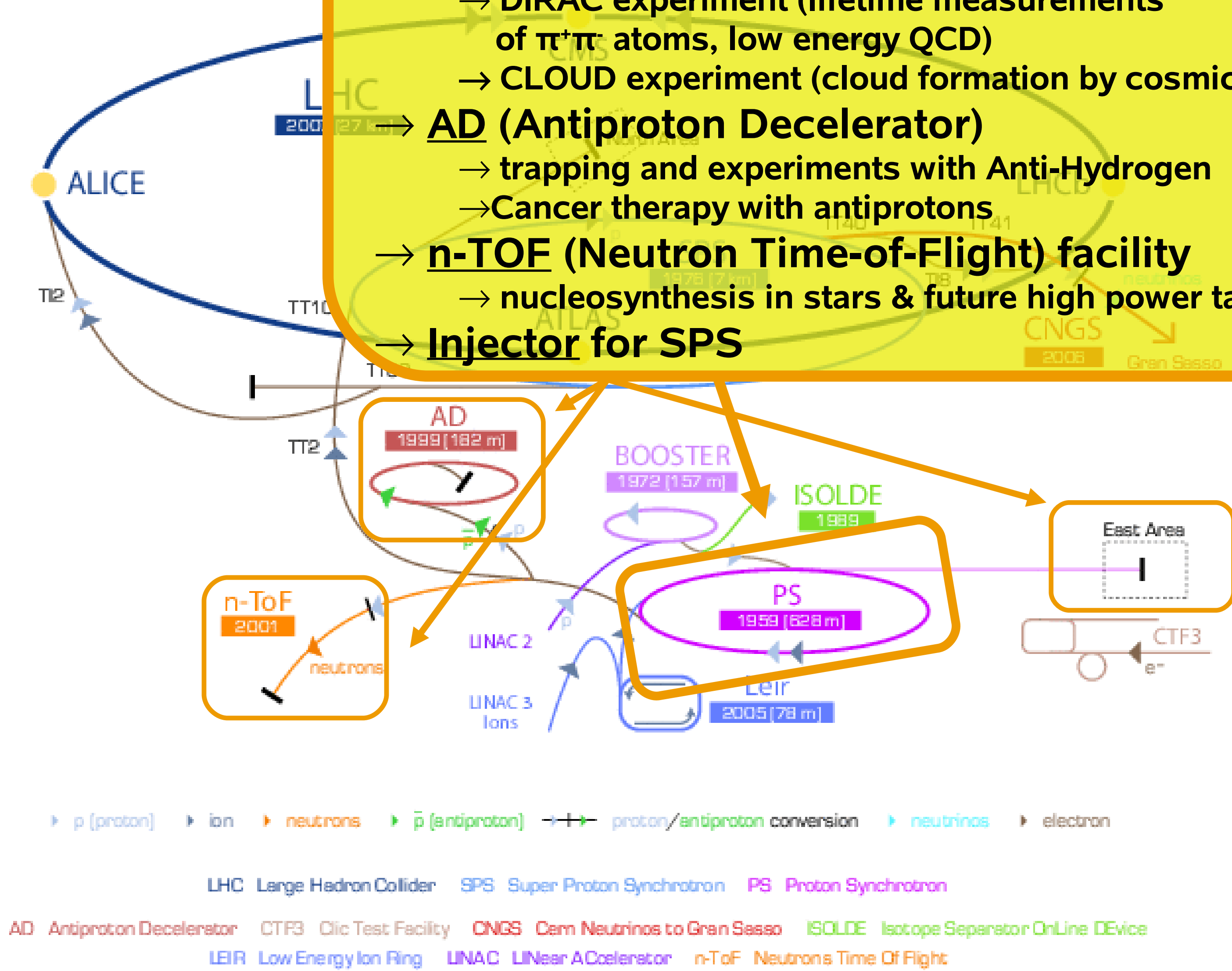
PS (Proton Synchrotron) provides Protons to

→ **East Area**
- → beam tests for detector studies/calibration
- → Irradiation facility for material studies
- → DIRAC experiment (lifetime measurements of $\pi^+\pi^-$ atoms, low energy QCD)
- → CLOUD experiment (cloud formation by cosmic rays)

→ **AD (Antiproton Decelerator)**
- → trapping and experiments with Anti-Hydrogen
- → Cancer therapy with antiprotons

→ **n-TOF (Neutron Time-of-Flight) facility**
- → nucleosynthesis in stars & future high power targets

→ **Injector for SPS**

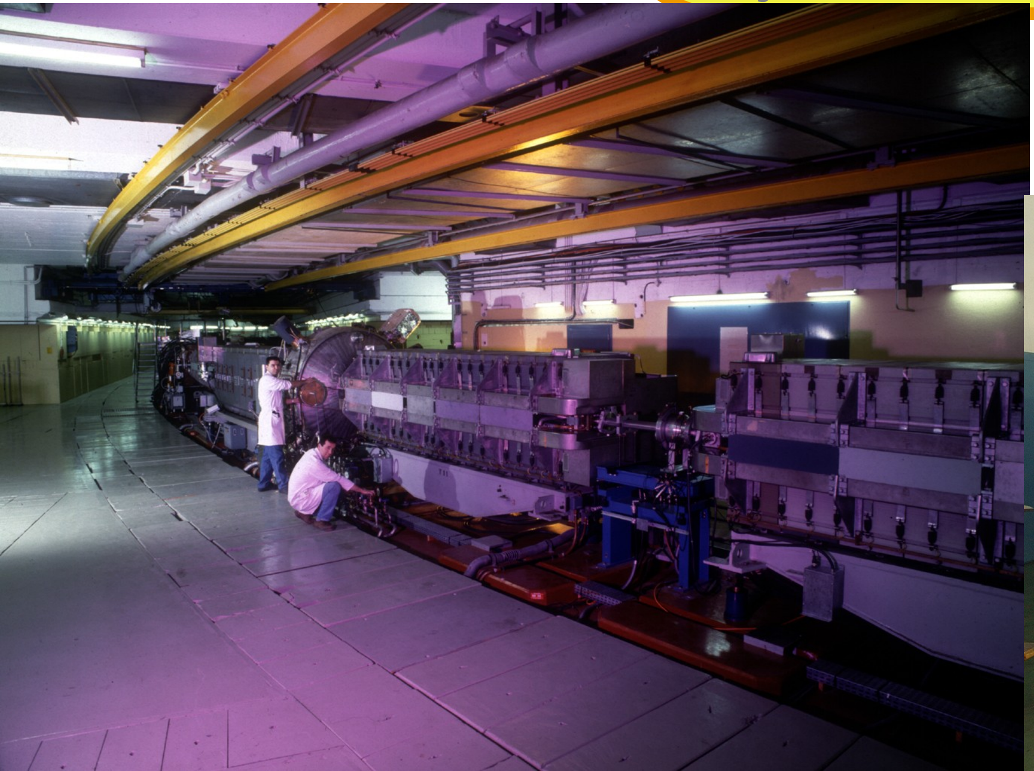


The CERN Proton Synchrotron (PS, 1959):
filled by 2 batches from Booster, ramping protons up to **26GeV**, maximum $1.4x10^{13}$ protons per pulse.

PS (Proton Synchrotron) provides Protons to

- → East Area
  - → beam tests for detector studies/calibration
  - → Irradiation facility for material studies
  - → DIRAC experiment (lifetime measurements of $\pi^+\pi^-$ atoms, low energy QCD)
  - → CLOUD experiment (cloud formation by cosmic rays)
- → AD (Antiproton Decelerator)
  - → trapping and experiments with Anti-Hydrogen
  - →Cancer therapy with antiprotons
- → n-TOF (Neutron Time-of-Flight) facility
  - → nucleosynthesis in stars & future high power targets
- → Injector for SPS

View into the PS tunnel



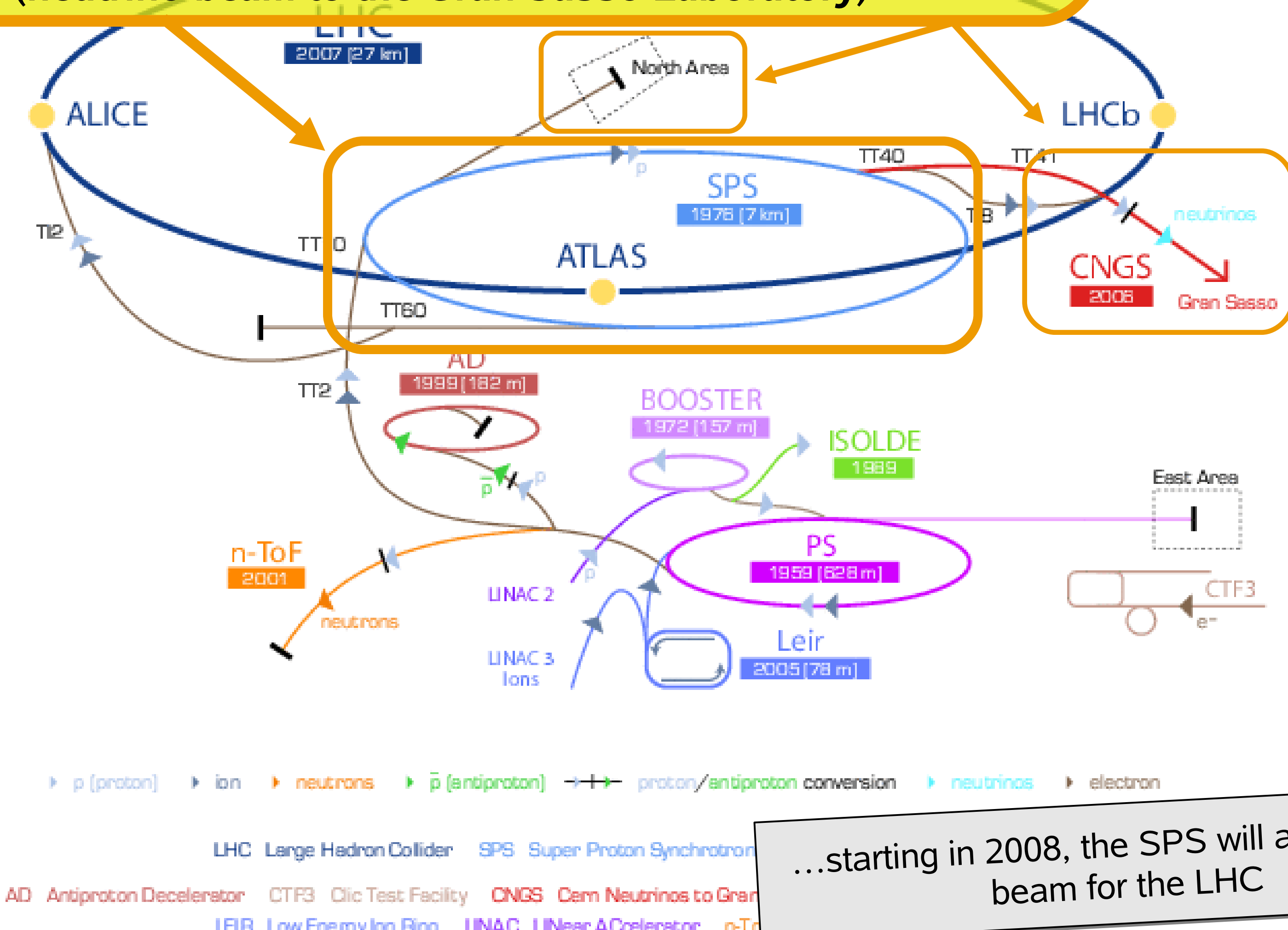
The PS magnets power supply: a

CERN: the World's Most Complete Accelerator Complex (not to scale)

The path of the

<u>SPS</u> (Super Proton Synchrotron) provides Protons to
→ <u>North Area</u>
- → beam tests for detector studies/calibration, material studies
- → COMPASS experiment (hadron spectroscopy)
- → NA48 experiment to study rare kaon decays, NA61, NA63

→ <u>CNGS</u> (neutrino beam to the Gran Sasso Laboratory)

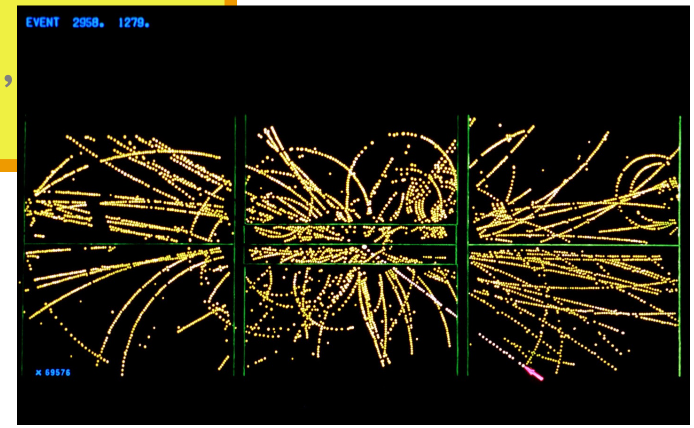


…starting in 2008, the SPS will also provide beam for the LHC

SPS (Super Proton Synchrotron) provides Protons to

→ North Area
- → beam tests for detector studies/calibration, material studies
- → COMPASS experiment (hadron spectroscopy)
- → NA62 experiment to study rare kaon decays, NA61, ...

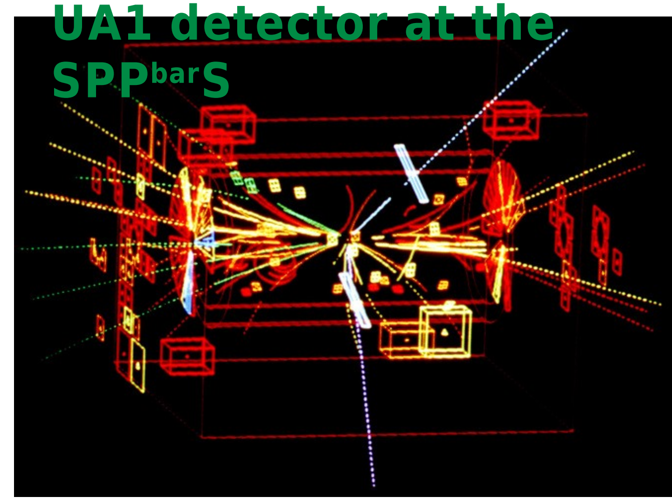
→ CNGS (neutrino beam to the Gran Sasso Laboratory)



The CERN SPS (1976) accelerates protons up to **450GeV** with intensities up to 10^{11} protons per bunch. In 1981 upgraded to a proton-antiproton collider ($SPP^{bar}S$) using stochastic cooling

View into the SPS tunnel

Observations of first W+/- event (1982) and Z0 event (1983) with the UA1 detector at the $SPP^{bar}S$



SPS (Super Proton Synchrotron) provides Protons to

→ **North Area**

→ beam tests for detector studies/calibration, material studies

→ COMPASS experiment (hadron spectroscopy)

→ NA62 experiment to study rare kaon decays, NA61, NA62

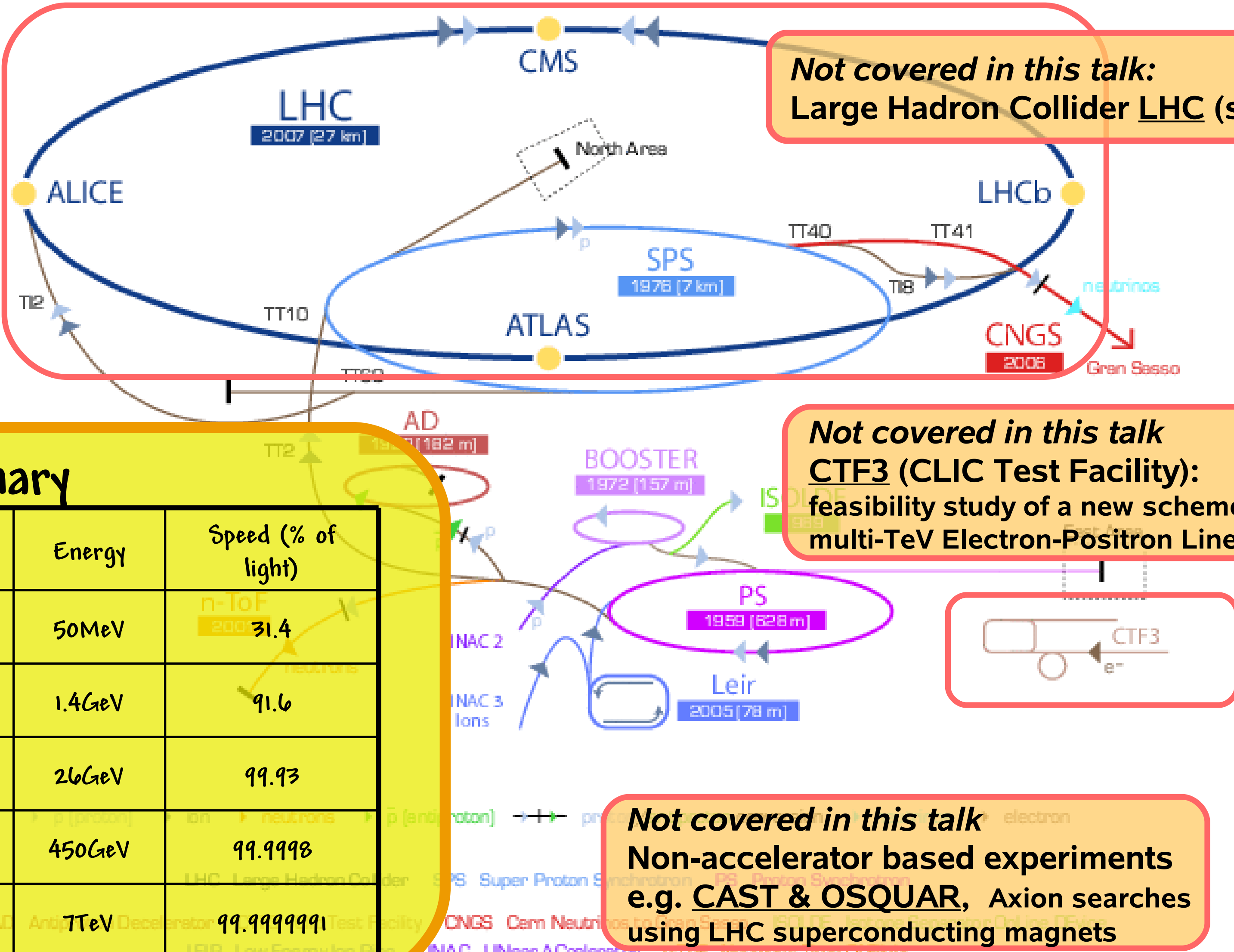
→ CNGS (neutrino beam to the Gran Sasso Laboratory)

At the CERN PS/SPS: 9 test beam lines with more than one experimental zone per line

CERN Testbeams:
at the PS/SPS about 2500 physicists from all over the world and from many experiments (HEP, space experiments, astroparticle physics, material science …) come to CERN to test and calibrate their detectors. CERN provides unique facilities with the worlds highest energy test beams (p, e, π, μ, K, ions up to 450GeV)

…prominent "DESY" users of the beam tests over the last years: CALICE, DESY-Telescope…

CERN: the World's Most Complete Accelerator Complex (not to scale)



Not covered in this talk:
Large Hadron Collider LHC (start 2008)

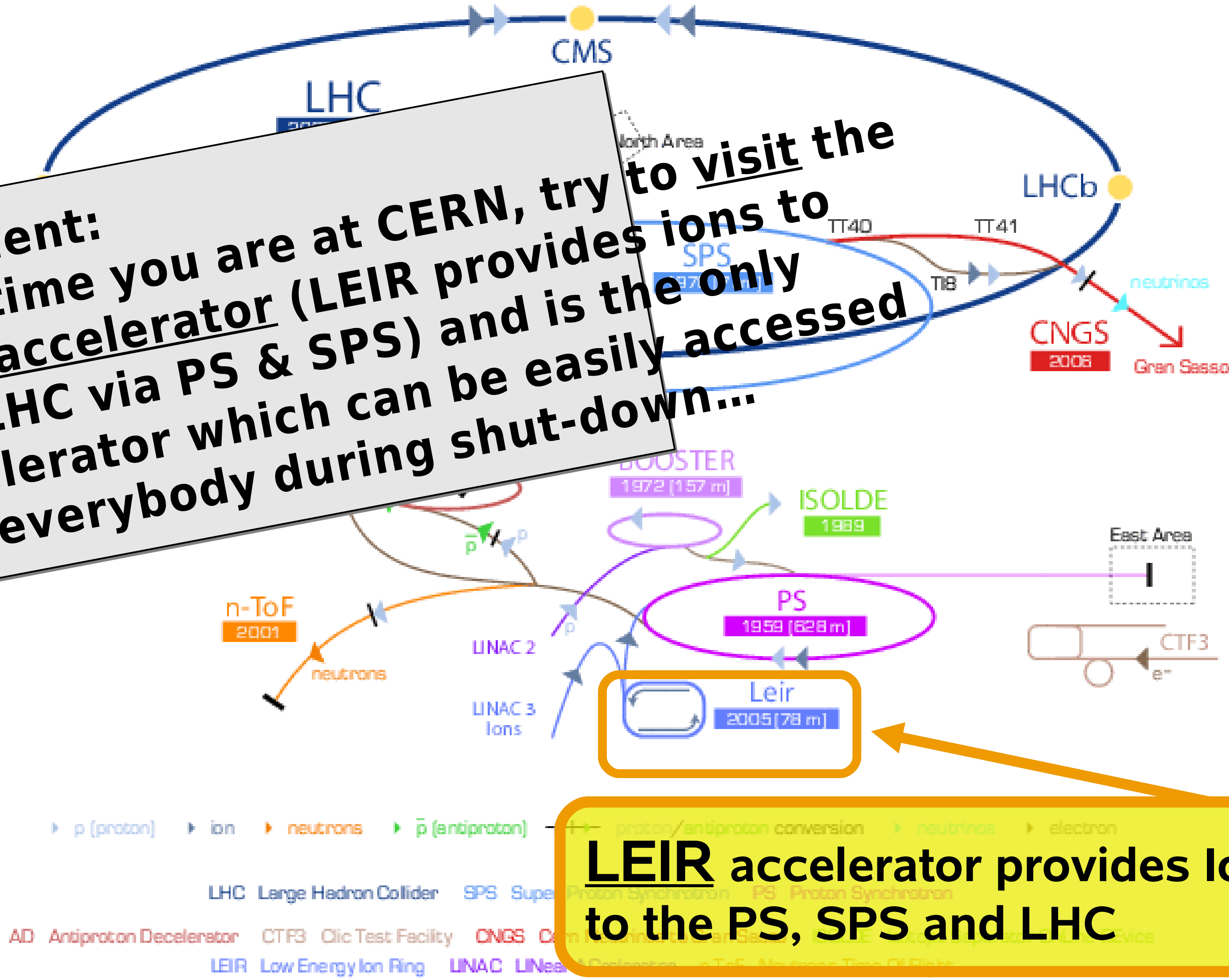
Not covered in this talk
CTF3 (CLIC Test Facility):
feasibility study of a new scheme for a multi-TeV Electron-Positron Linear Collider

Not covered in this talk
Non-accelerator based experiments
e.g. CAST & OSQUAR, Axion searches using LHC superconducting magnets

Summary

	Energy	Speed (% of light)
LINAC2	50MeV	31.4
Booster	1.4GeV	91.6
PS	26GeV	99.93
SPS	450GeV	99.9998
LHC	7TeV	99.9999991

CERN: the World's Most Complete Accelerator Complex (not to scale)



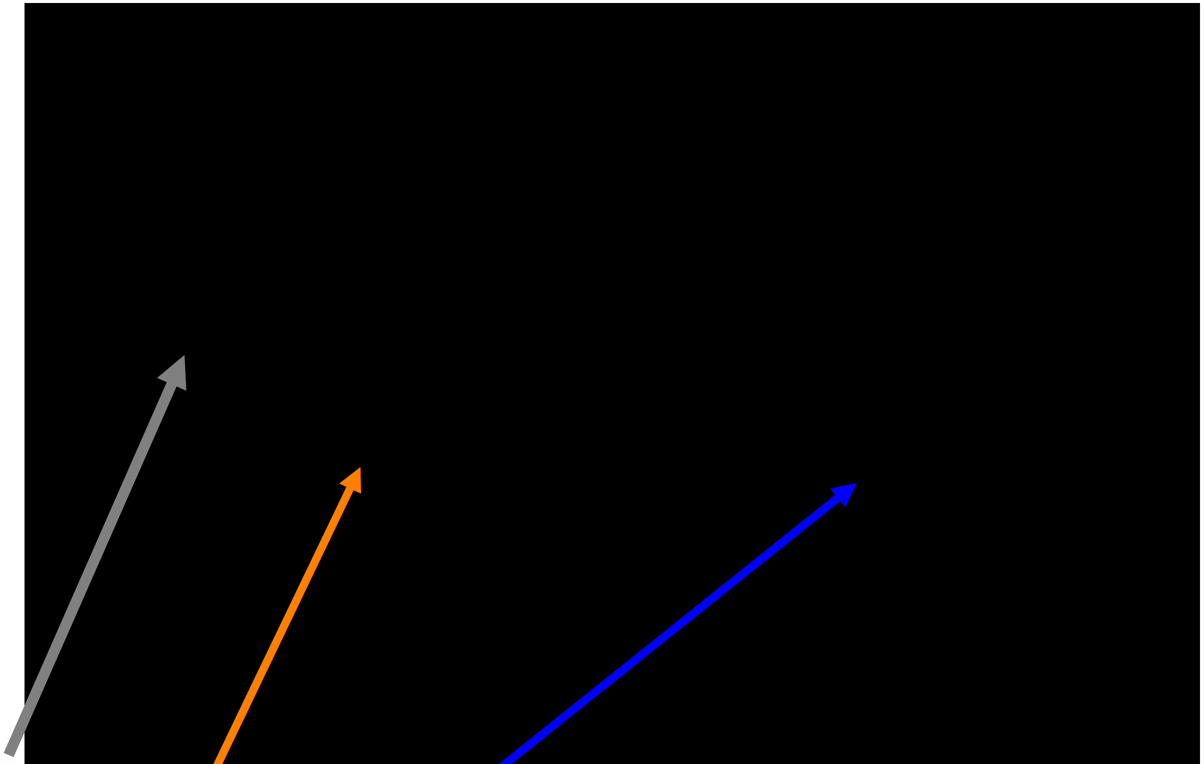
Comment:
next time you are at CERN, try to visit the LEIR accelerator (LEIR provides ions to the LHC via PS & SPS) and is the only accelerator which can be easily accessed For everybody during shut-down…

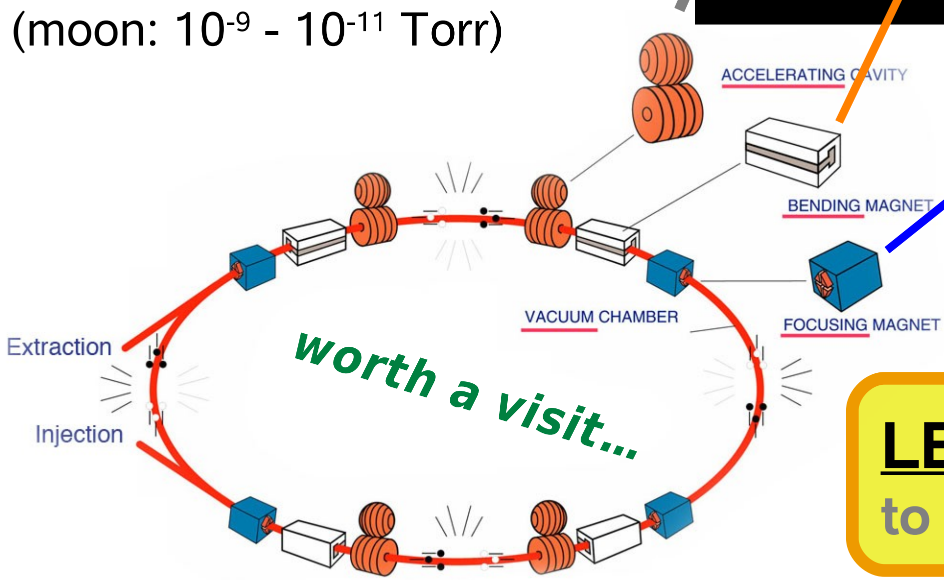
LEIR accelerator provides Ions to the PS, SPS and LHC

The Low Energy Ion Ring **LEIR** (2006):

Ions from the LINAC3 injected with 4.2MeV per nucleon are accumulated up to 10^9 ions per fill, and accelerated to **14.8MeV per nucleon**.

To guarantee good beam quality for the LHC ion beam (small emmittance) the vaccum for LEIR has to be extremly good: $\sim 10^{-12}$ Torr (moon: 10^{-9} - 10^{-11} Torr)

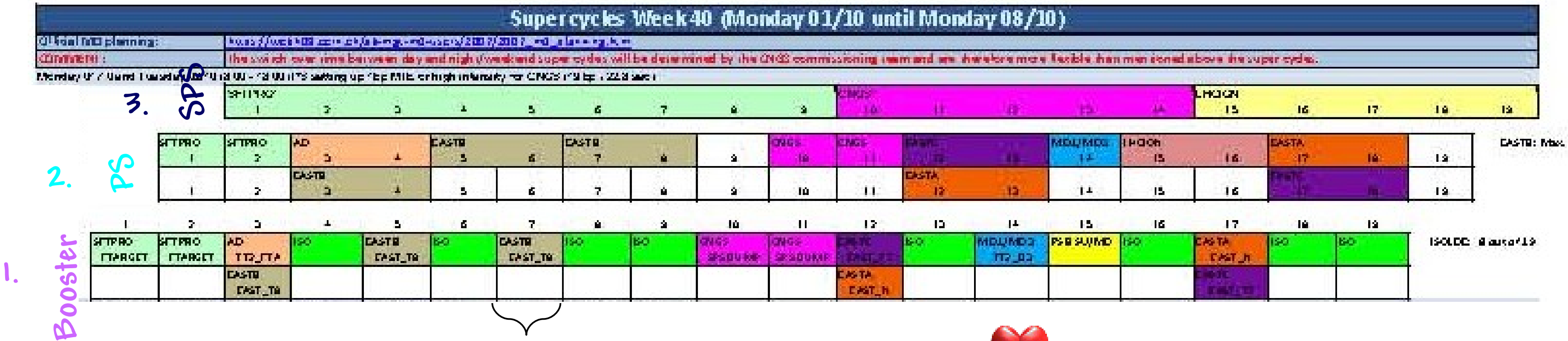




LEIR can accelerate a number of different ion species.
Start of LHC ion operation is foreseen for 2009 with Pb ions.

LEIR accelerator provides Ions to the PS, SPS and LHC

How beams are distributed: Super-Cycles



1 basic period = 1.2s = "CERN's heartbeat"

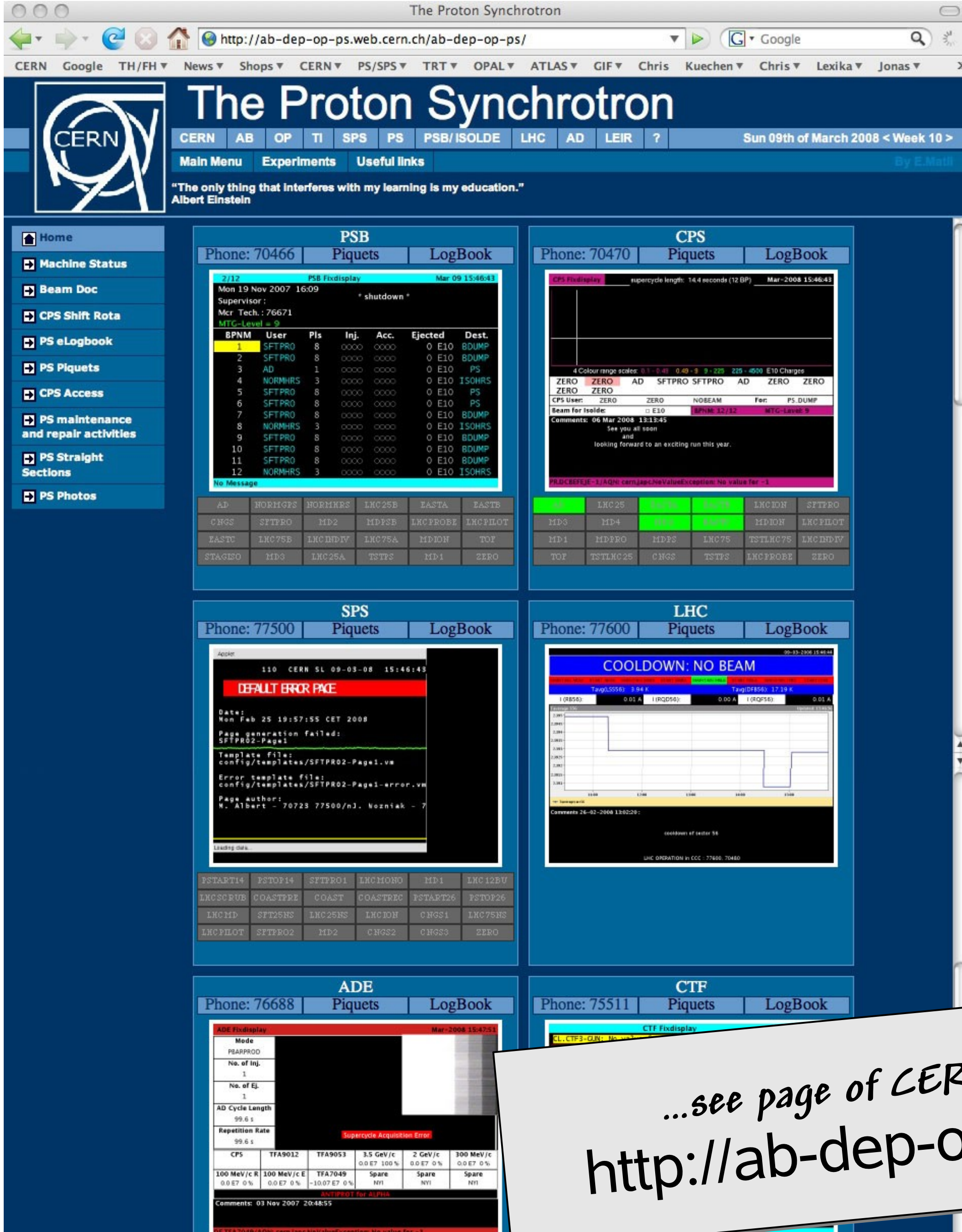
- Booster provides beam each 1.2s (=1 basic period bp) to **PS** or **ISOLDE** Each shot is allocated to a specific "user", thus different beam conditions
- PS provides beam to AD, East Area, nTOF (slow extraction, 2.4s) or SPS (fast extraction, 1.2s)
- SPS provides beam to North Area (9bp), CNGS (5bp), LHC (here: LHCIons, 5bp)

⇒ After certain numbers of basic periods (here: 19bp = 22.8s) the sequence is repeated; sequence is called **Super-Cycle**

⇒ The distribution of the various beams to the different users is **very flexible**, can be changed within seconds (PS)/minutes (SPS)

(Example above: Super Cycle Mon Oct 1 2007)

Comment: Protons and Ions can be delivered within the same Super-Cycle



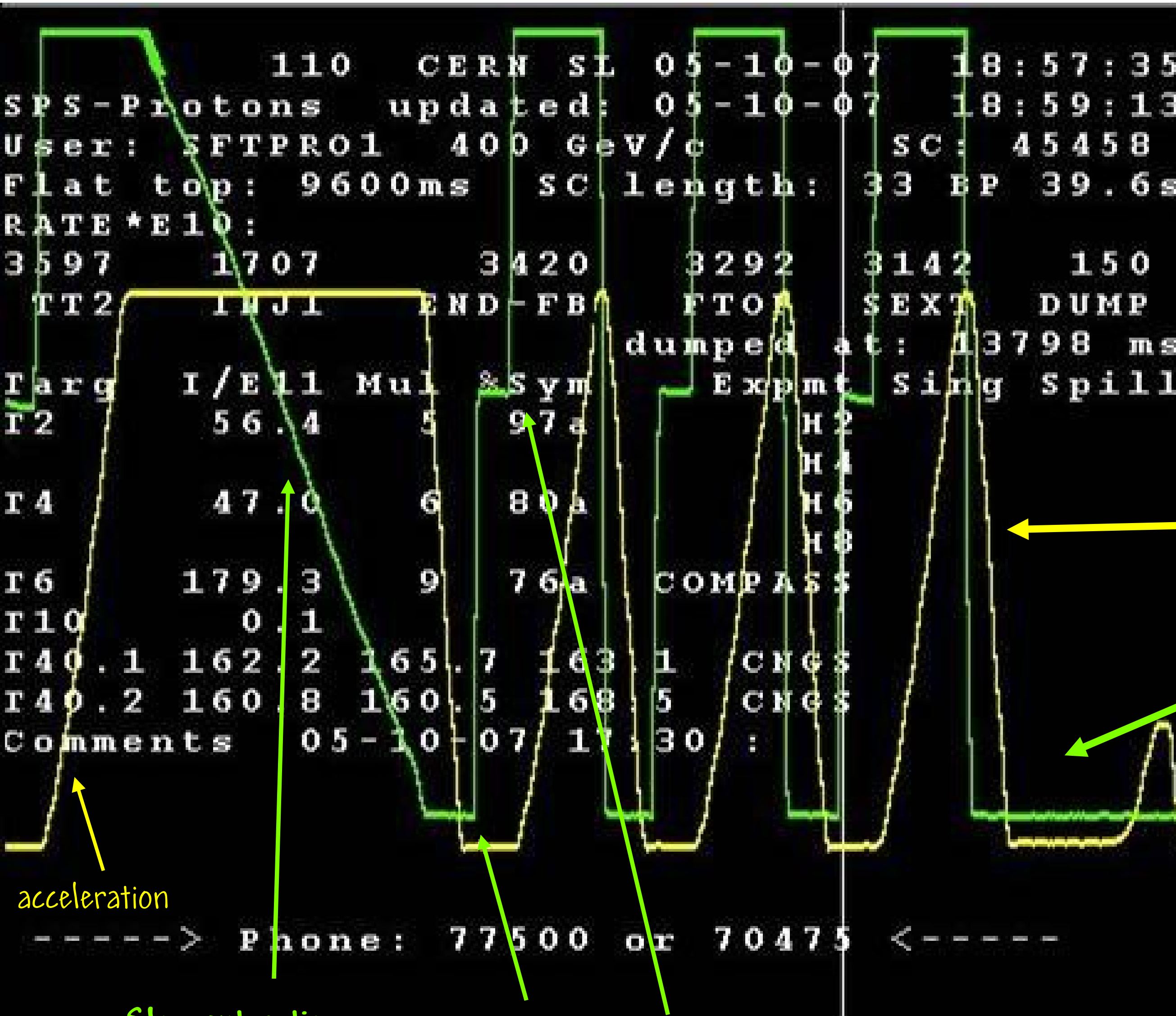
Overview on Status of all CERN Accelerators

- Very interesting, especially during LHC start-up..., provides status of
  - → Booster
  - → PS (=CPS)
  - → SPS
  - → LHC
  - → AD (=ADE)
  - → CLIC Test Facility (=CTF)
  - → LEIR

...see page of CERN Accelerator Operations Group at
http://ab-dep-op.web.cern.ch/ab-dep-op/

A typical SPS Super-Cycle in 2007...

or "what you always see on the TV screens in the CERN corridors"



Example (Oct 5 2007):

A Super Cycle in the SPS with

→1 pulse to North Area

→3 pulses to CNGS;

duration is 33bp (=39.6s)

SPS magnet current

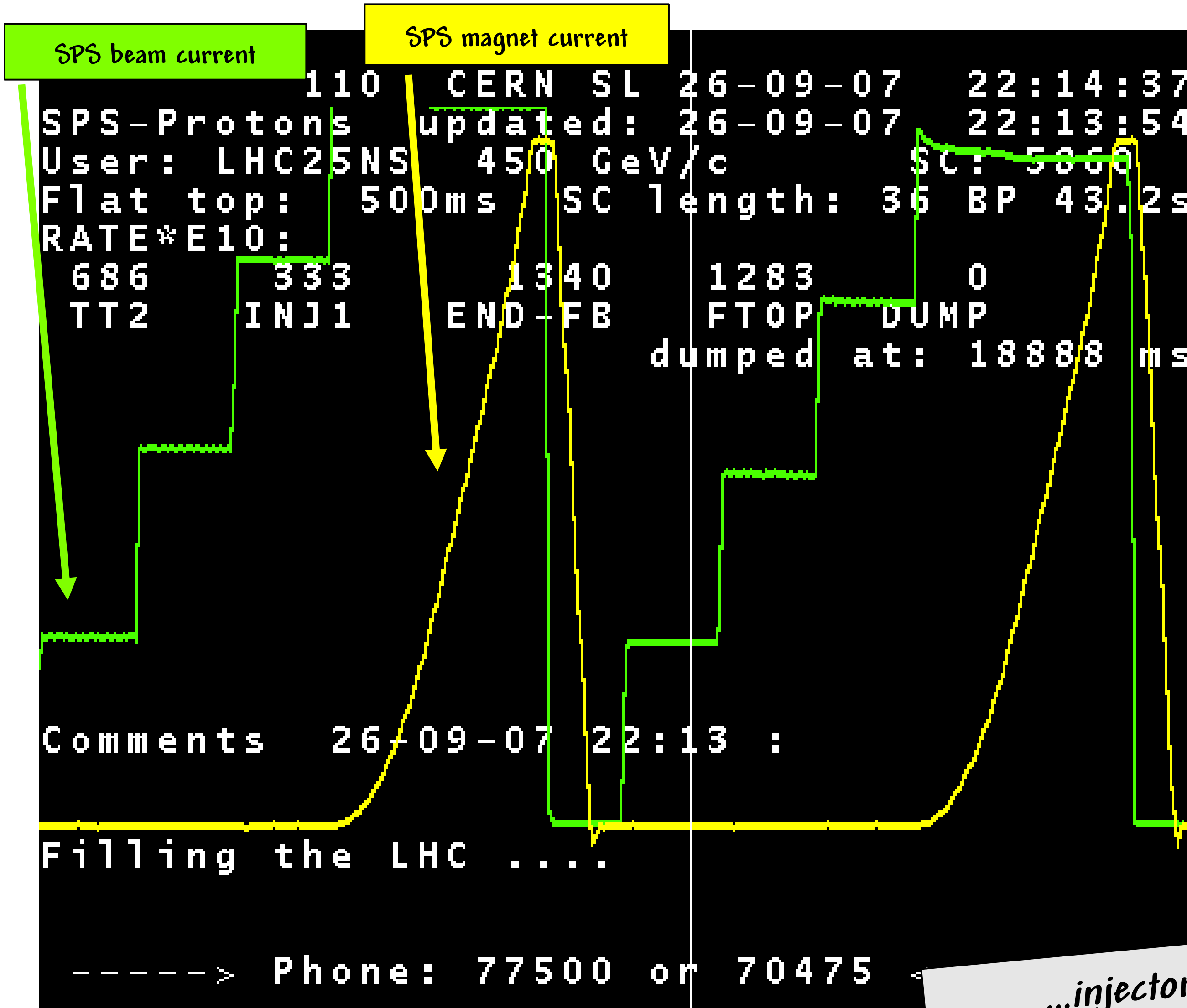
SPS beam current

8 x extraction from PS to SPS (8 basic periods out of 33bp

⇒ 25bp for other users...)

time →

...and another one, preparing for LHC...



Screenshot SPS Page !
Sept 26 2007

4 batches with 72 bunches each, half of nominal LHC beam intensity extracted to dumps in transfer lines, interleaved operation (ring1 and ring2)

...injector accelerators at CERN are ready for the LHC

The Experiments in 2006, 2007, 2008

Example: 2007 SPS Users Sched

24-Oct-2007 — **2007 SPS Fixed Target Programme** — Version 3.25

Colour code: blue (dark shading) = not yet allocated ; yellow (light shading) = not allocatable or Machine Development

	P1A	P1B	P2	P3	P4	P5
	21 2 May 23 May	26 23 May 18 Jun	37 18 Jun 25 Jul	41 25 Jul 4 Sep	36 4 Sep 10 Oct	33 10 Oct 12 Nov
T2 -H2		2; CMS ZDC 11; 4	CMS 9; CMS Combined 28	CMS Combined 14; CMS 12; CMS CASTOR 14	PHENIX 9; 6; 8; NA61 13	NA61 19; 7; 7
T2 -H4		2; 16	DREAM 7; 0; DREAM 8; ECC 7; AMS RE1 14	CMS ECAL 29; LHCf 11	LHCf 7; CMS ECAL 22; U BRAN 7	NA63 26; EA MD 4; 3
T4 -H6		2; EA MD 5; 4; CERF 7	EA MD 5; 4; RD42 7; CALICE 21	CALICE 28; RD42 13	9; 6; ALICE EMCAL & ZDC 21	SILC R&D 12; 7; RD42 7; 7
T4 -H8		2; RD22 16	2; TOTEM 7; 7; TOTEM 7; ATLAS BCM 7; 7	14; E BRAN 7; TOTEM 7; CMS BRM 13	TOTEM 7; 8; DESY 7; RD22 13	ATLAS 3DSI 7; ATLAS RP 12; RD22 14
T4 -P0		2	NA62 37	NA62 41	NA62 36	NA62 33
T6 -M2		2; COMPASS 16	COMPASS 37	COMPASS 41	COMPASS 36	COMPASS 33
CNGS					CNGS 23	CNGS 19

- **Physics Experiments at the PS**
  - → East Area: DIRAC, CLOUD
  - → AD: ASUACUSA, ATRAP and ALPHA, AD4
  - → N-TOF: MERIT
- **Physics Experiments at the SPS**
  - → North Area: COMPASS, NA61, NA62, NA63
  - → CNGS: OPERA

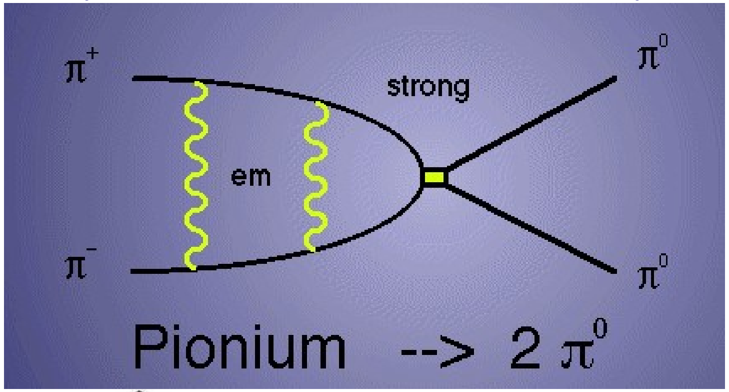
Other 42 users:
Beam tests for detector development, calibration and test (e.g. Satellite based experiments)

Do we understand the strong Force?

- Theory to describe strong interaction: Quantum Chromo Dynamic QCD
- QCD is quite advanced, e.g. precise prediction of lifetime of $\pi^+\pi^-$ atoms

→ need experimental tests: done by DIRAC

- $\pi^+\pi^-$ (Pionium) atoms: formed by interaction of proton beam in target, Coulomb attraction if 2 pions get closer than few fm



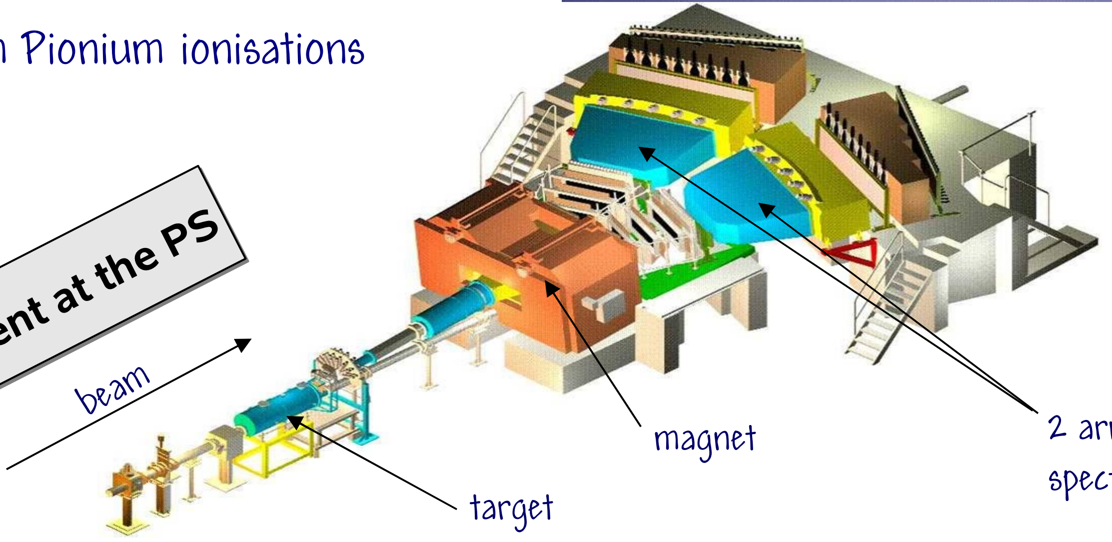
- Pionium: decays 99.6% to $\pi^0\pi^0$

  (but π^0 can not be seen by detector, decay products in beam direction...)

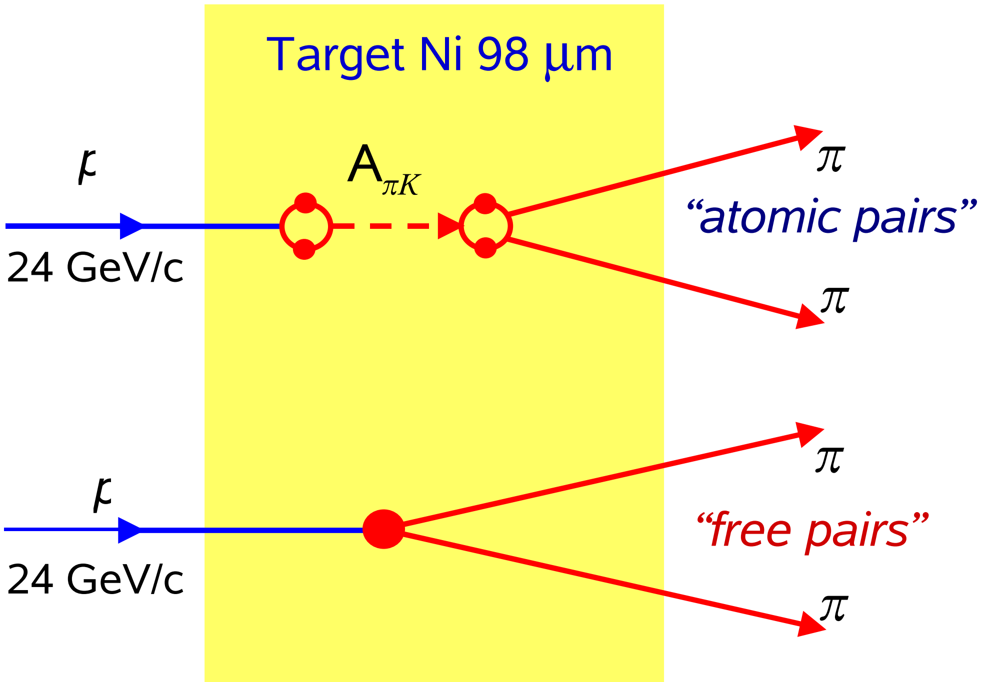
- **Trick**: Pionium ionisation *(=break-up)* probability is proportional to Pionium lifetime

⇒ Measure $\pi^+\pi^-$ pairs from Pionium ionisations

The DIRAC Experiment at the PS



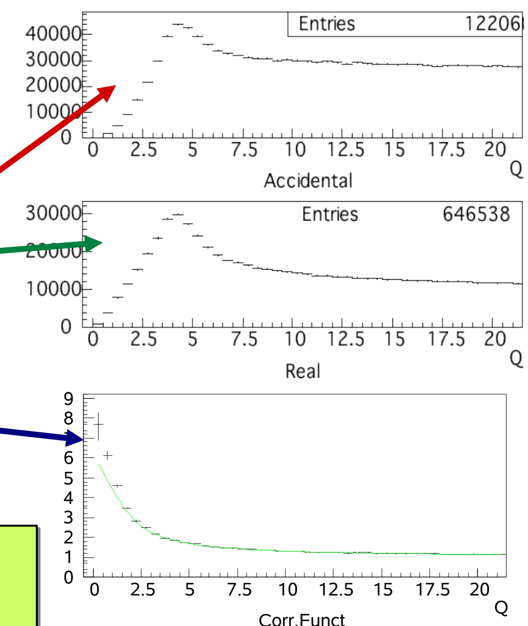
DIRAC or how to measure $\pi^+\pi^-$ Atoms



- **Atomic pairs** characterised by small opening angles
- Time corellated pions, observed left/right arm of spectrometer
- Relatively small pair momenta <3GeV
- Background: free pairs from hadron production

Methode to extract atomic pairs:

- Spectra of relative momenta for accidental events (=background) is fitted to spectra for time correlated pairs (background + signal)
- Difference gives spectrum for **atomic pairs**
- Derive result:

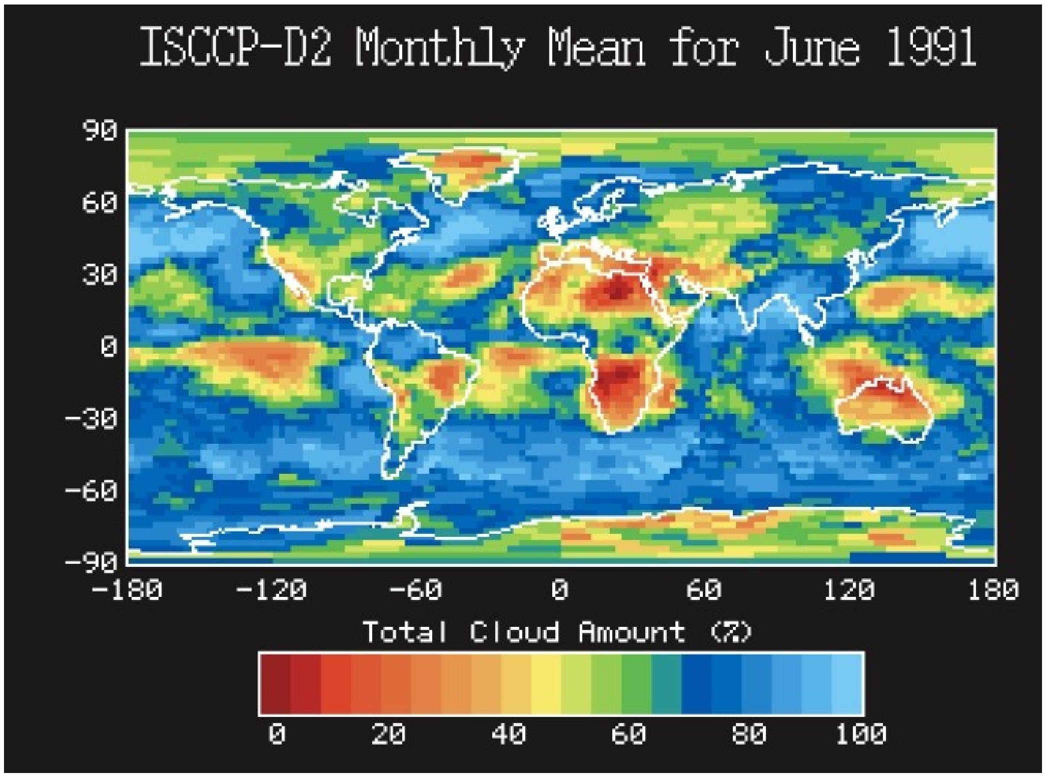


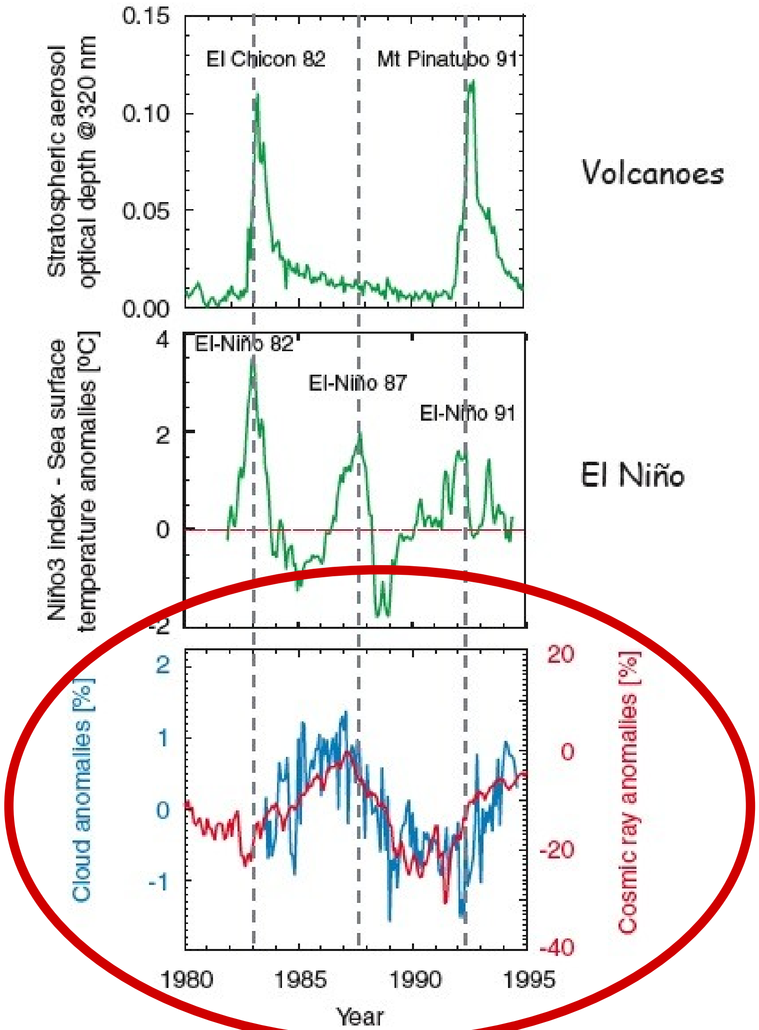
...but error still 20%, need more data

τ = 2.91 fs (pred.: 2.9 fs)

Let's talk about the Weather (CLOUD)

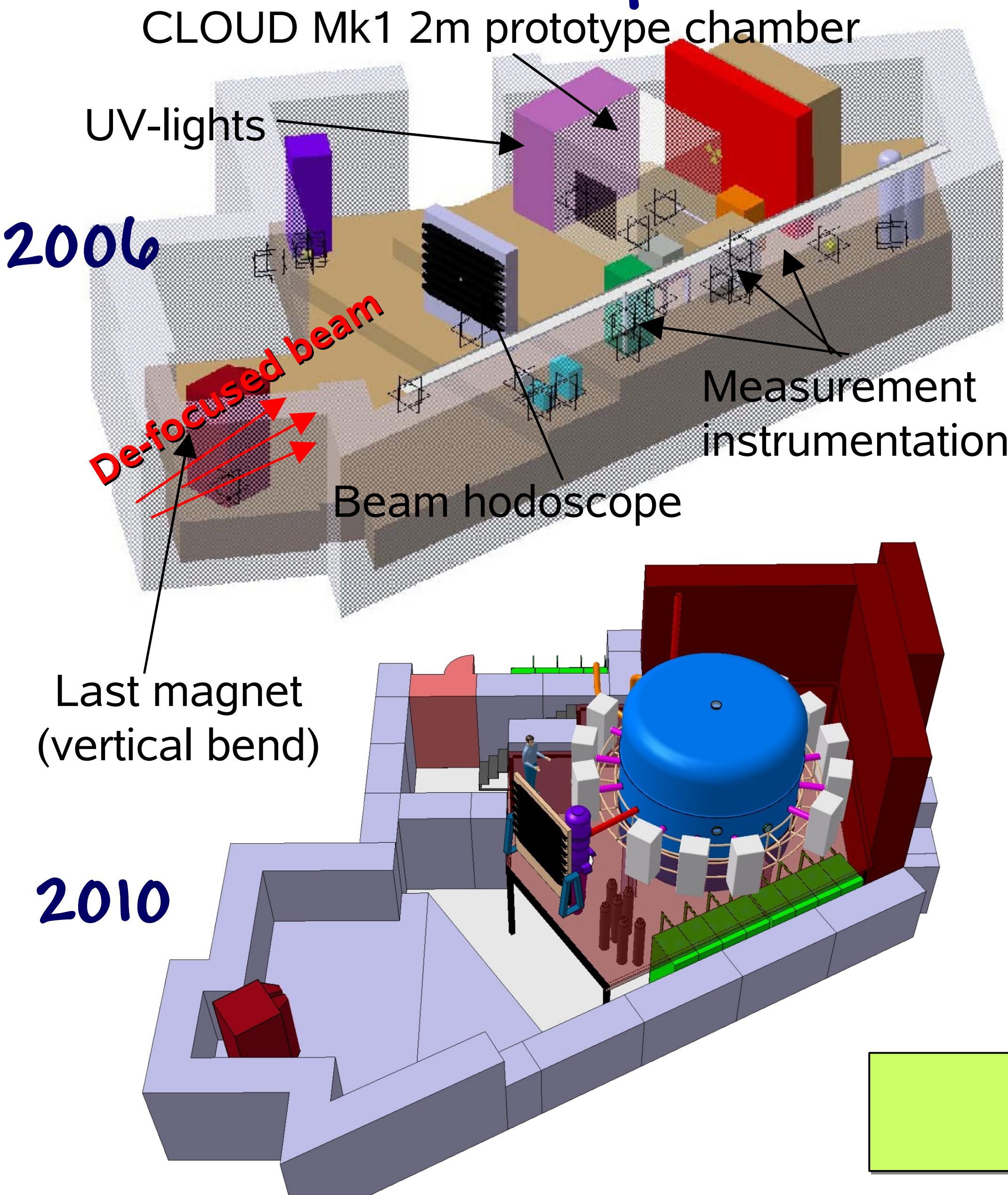
- Observations of density of clouds by satellites and measurement of cosmic rays suggest a correlation between cosmic rays and our weather…





The CLOUD Experiment at the PS

CLOUD: Study of the Atmosphere at CERN...



Link between cosmic rays and clouds not yet established/understood
Ions may grow via clusters to form aerosol which may become condensation nuclei...

The CLOUD Experiment:

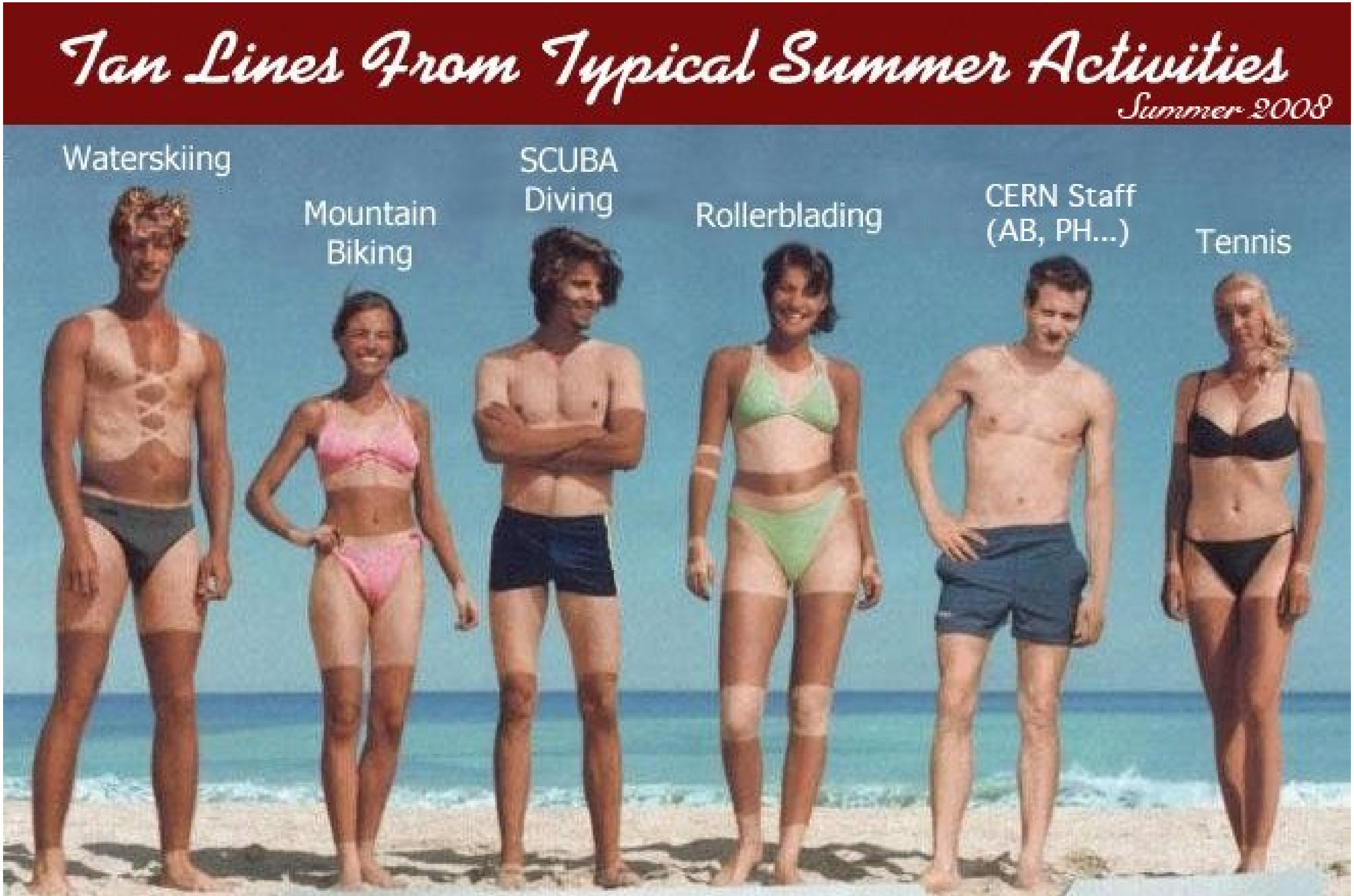
- reproduce cosmic ray conditions throughout troposphere and stratosphere

- study and understand how cloud nuclei are formed

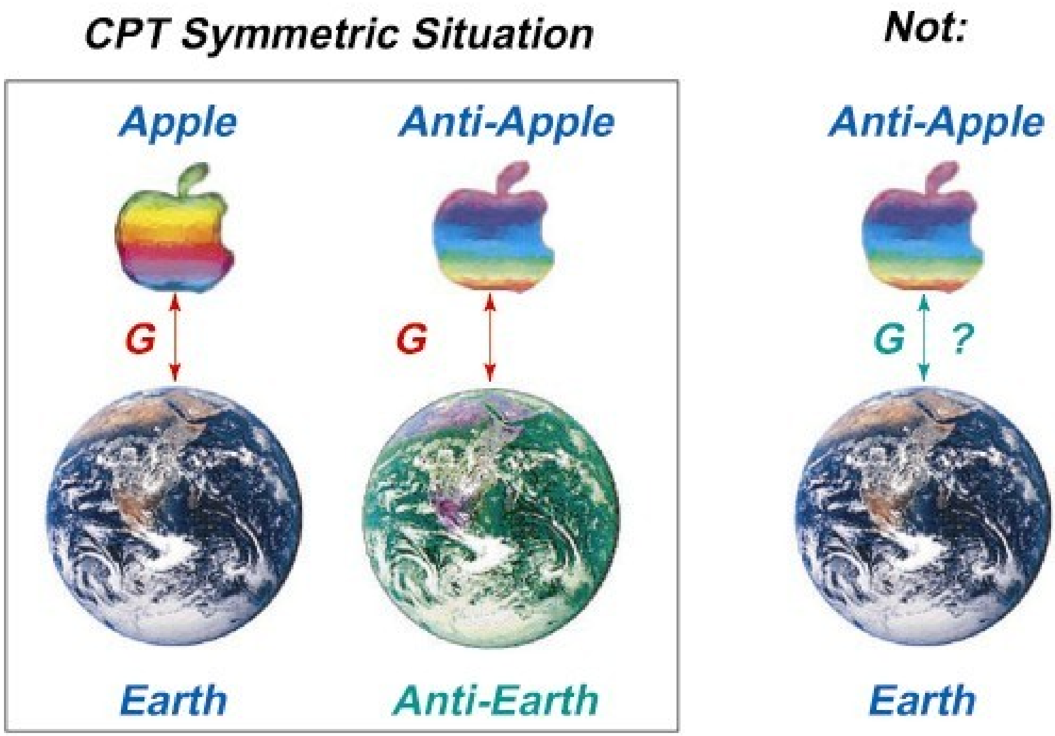
→ 3 GeV pions spread over 1.8x1.8m, 1-100kHz rate

Final Set-up ready 2010

Depending on CLOUDs:



What about Gravity? (AD)



AD = Antiproton Decelerator

- How does antimatter behave in gravitational fields?

⇒ need electrically neutral antimatter to test...

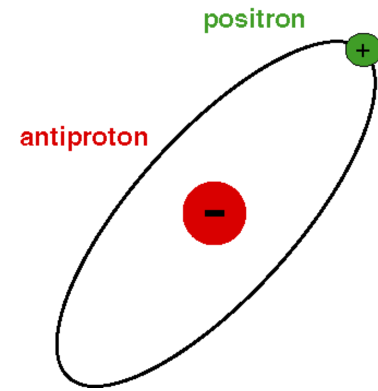
⇒ Does antimatter behave exactly like matter?

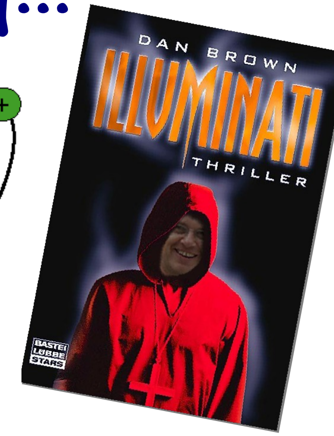
⇒ E.g. does it decay to the same antiparticles with same decay rate as matter?

⇒ At Big Bang, the same amount of matter/antimatter was produced; what happened to antimatter? Is there a difference between the two?

The ASACUSA, ATRAP and ALPHA Experiment at the AD

AD - CERN's Antimatter Factory...

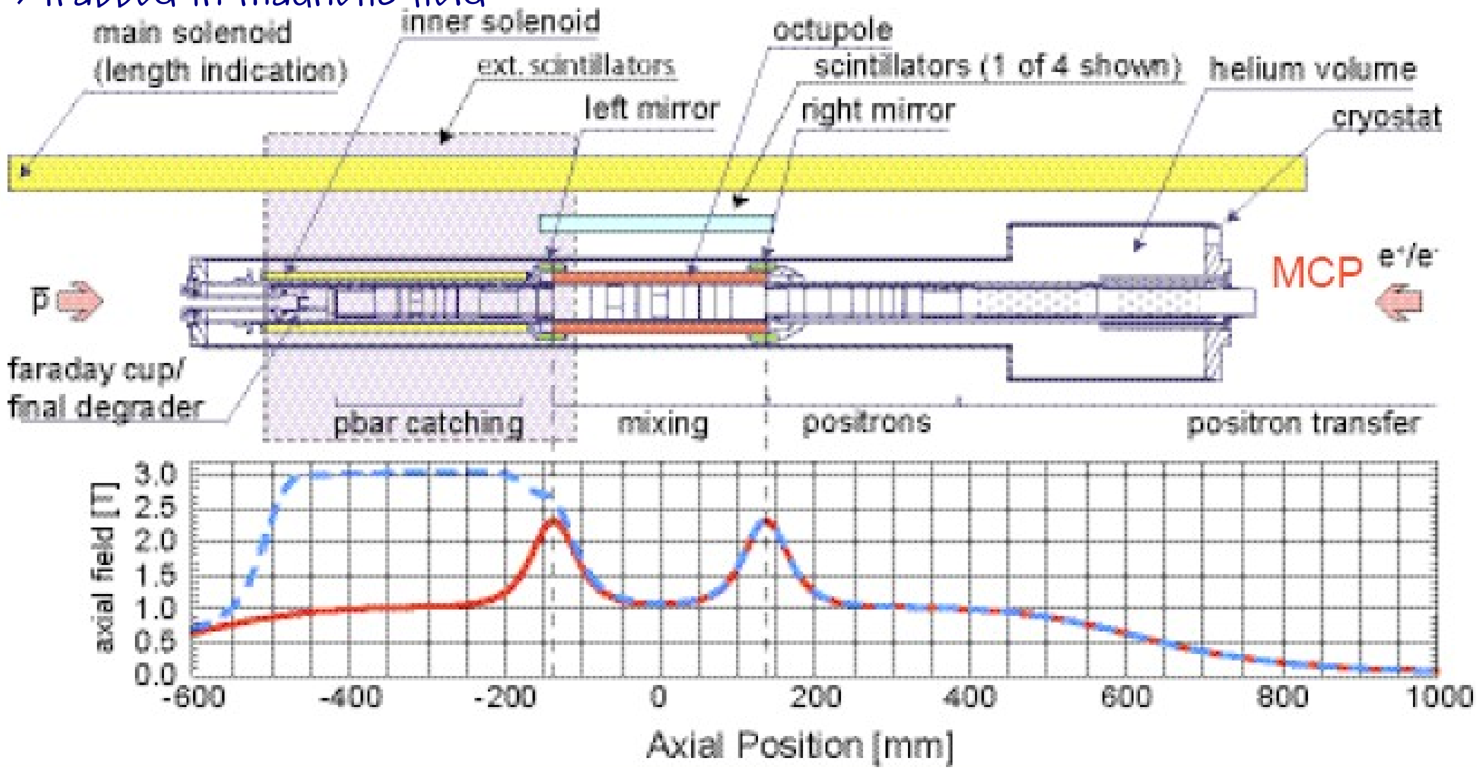




- Production and study of Anti-Hydrogen atoms
  - → need antiprotons from AD
  - → need positrons from Na^{22}
- How they find together?

(works only with cold particles)

- → trapped in magnetic field



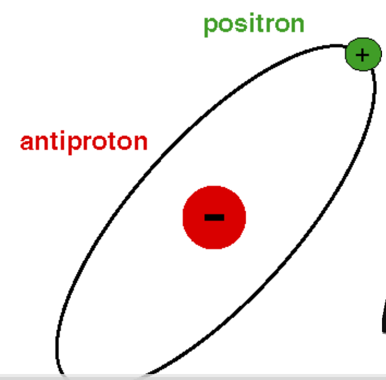
Example: The ALPHA Experiment

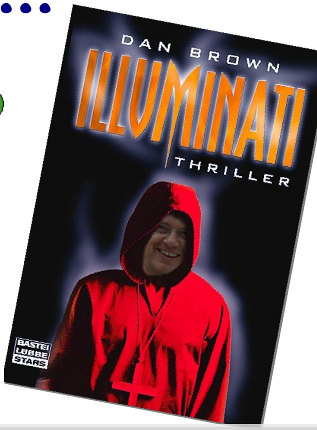
AD - CERN's Antimatter Factory...

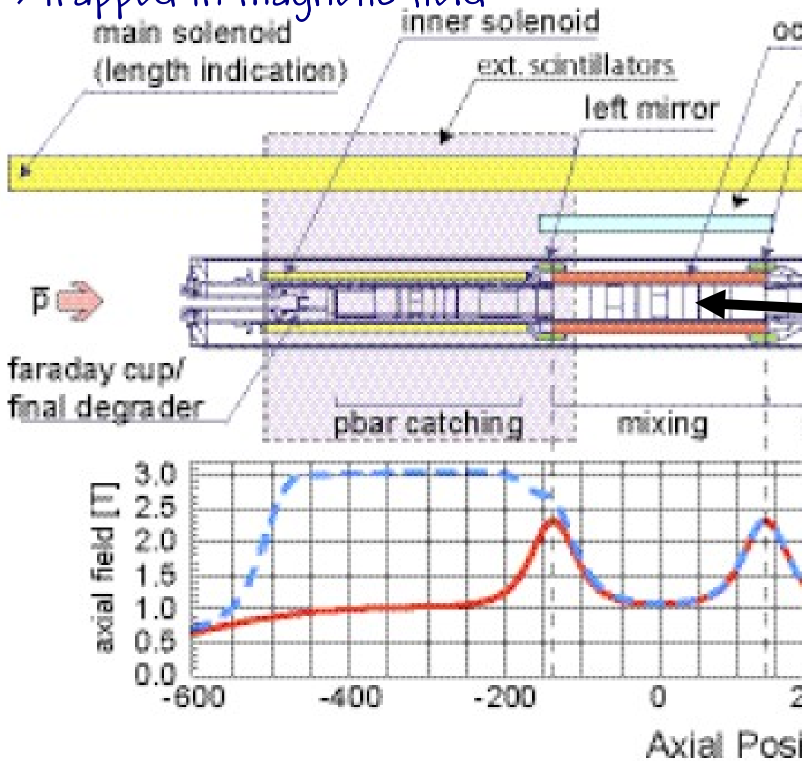
- Production and study of Anti-Hydrogen atoms
  - → need antiprotons from AD
  - → need positrons from Na^{22}
- How they find together?

(works only with cold particles)

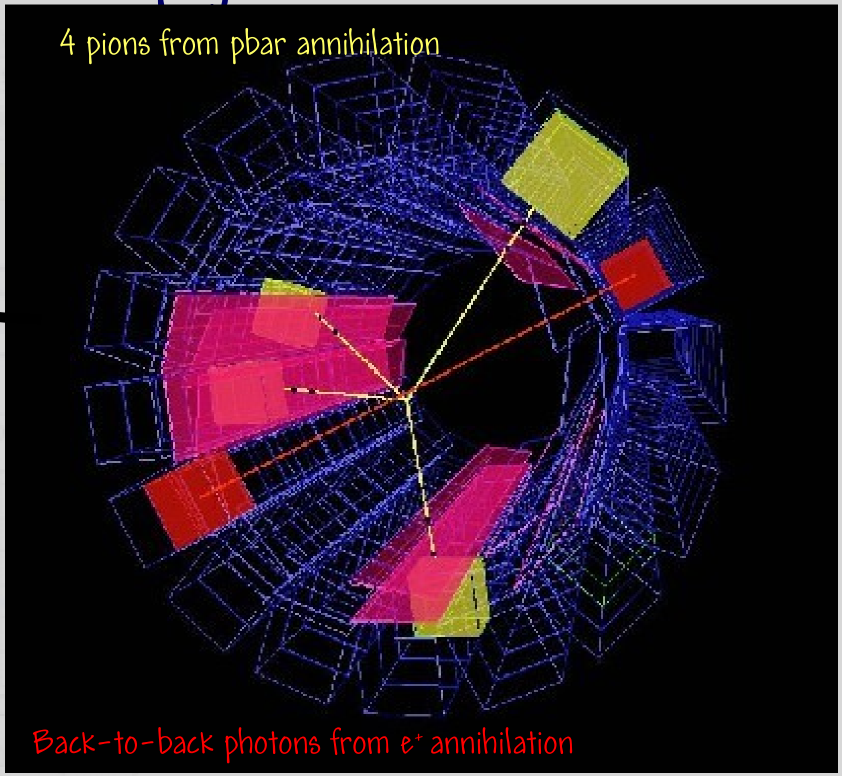
→ trapped in magnetic field







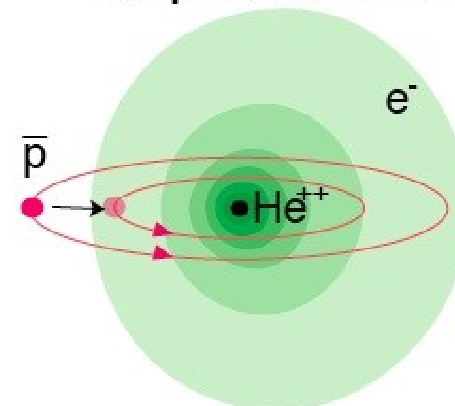
Identifying Hbar annihilations:



AD - still some way to go...

- Experiments ATRAP, ALPHA:
  - → Manage to create O(100) anti-hydrogen / second (for 10^5 antiprotons trapped)
- Challenges: do something with anti-hydrogen...
  - → let it fall down (or up?)
  - → laser spectroscopy...
- Experiment ASACUSA
  - → Specialised on spectroscopy of antiprotonic Helium
  - → interesting results in 2006
    - E.g. determination of value of anti-p/e mass ratio

Antiprotonic Helium



$$\frac{M_{\bar{p}}}{m_e} = 1836.152674(5)$$

ASACUSA 2006
Hori et al., PRL 96, 243401 (2006)

$$\frac{M_p}{m_e} = 1836.1526675(39)$$

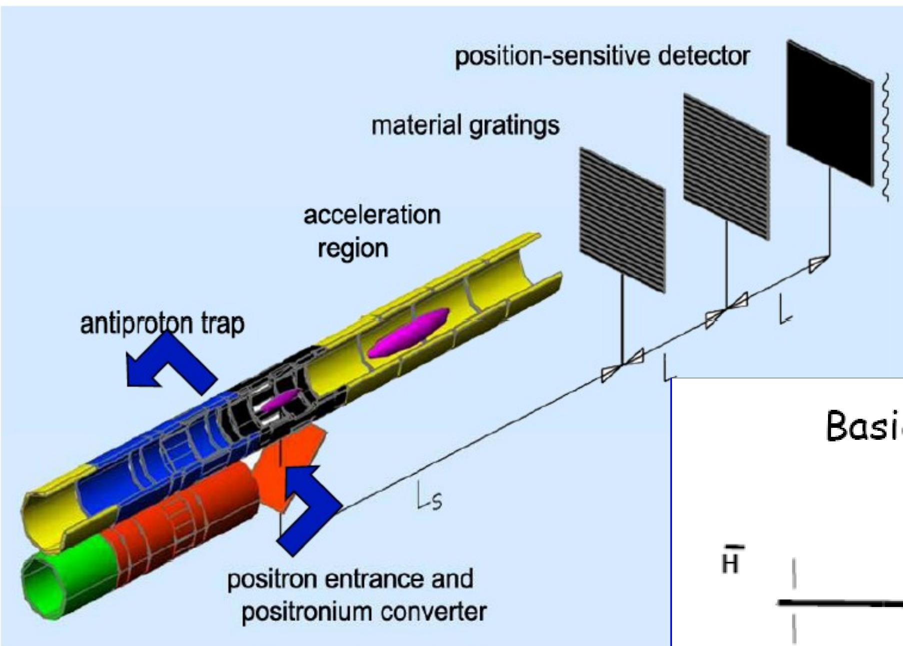
CODATA 98

$$\frac{M_p}{m_e} = 1836.15267261(85)$$

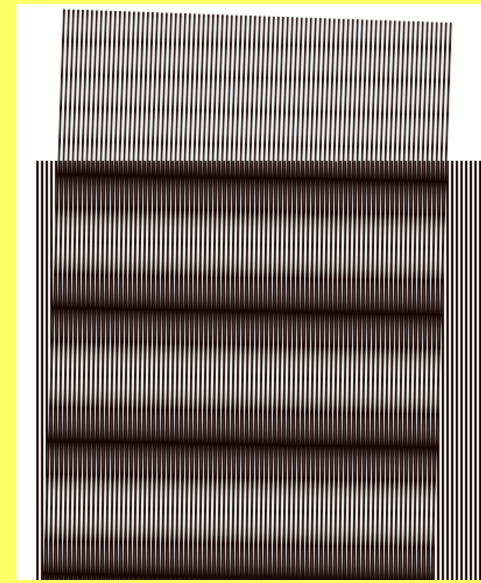
CODATA 2002

A different Ansatz to learn about Gravity: the AEGIS Experiment at the AD

- Produce Anti-Hydrogen **beam**...
- ...flighing for 1m at a few 100m/s...
- ...expect a deflection by gravity of about 20µm...
- ...use **Moire-Interferometer** to check deflection

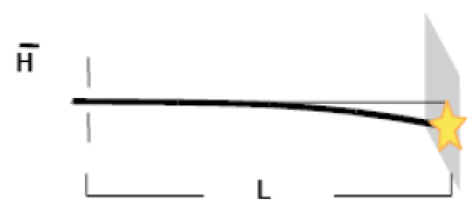


A ntimatter
E xperiment:
G ravity
I nterferometry
S pectroscopy



"A Moiré pattern, formed by two sets of parallel lines, one set inclined at an angle of 5° to the other"

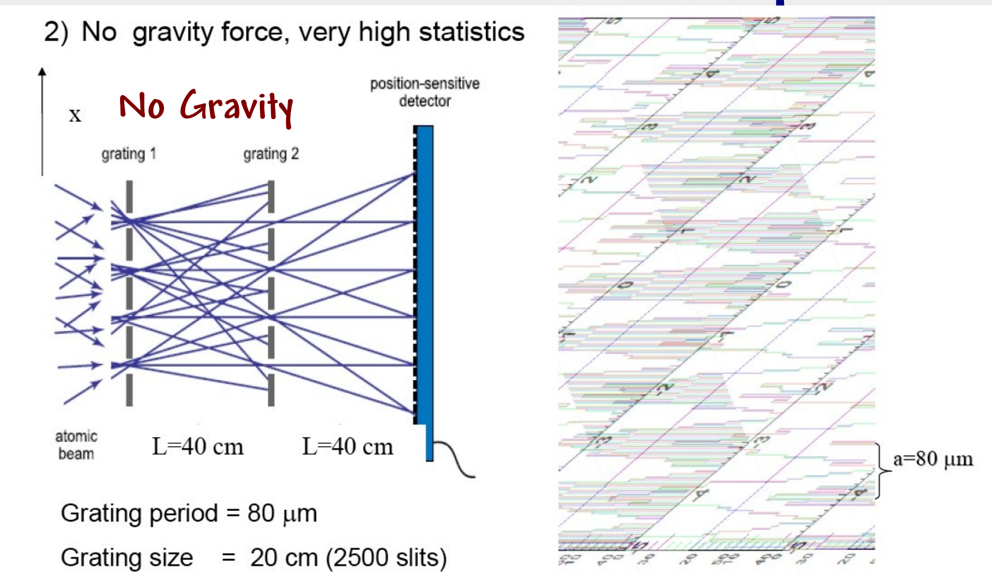
Basic principle:

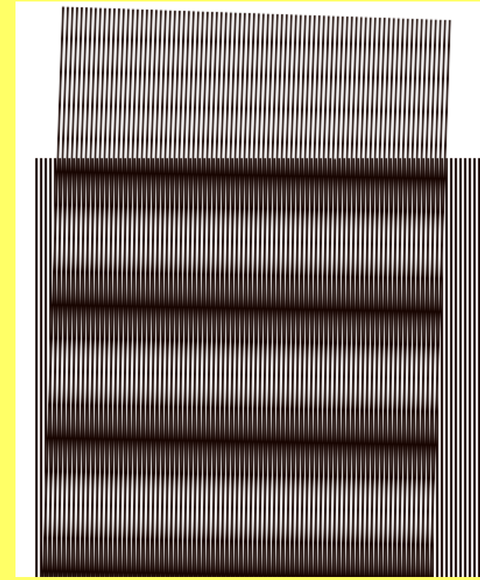


$$h = \frac{g}{2} \bullet \left(\frac{L}{v_h}\right)^2$$

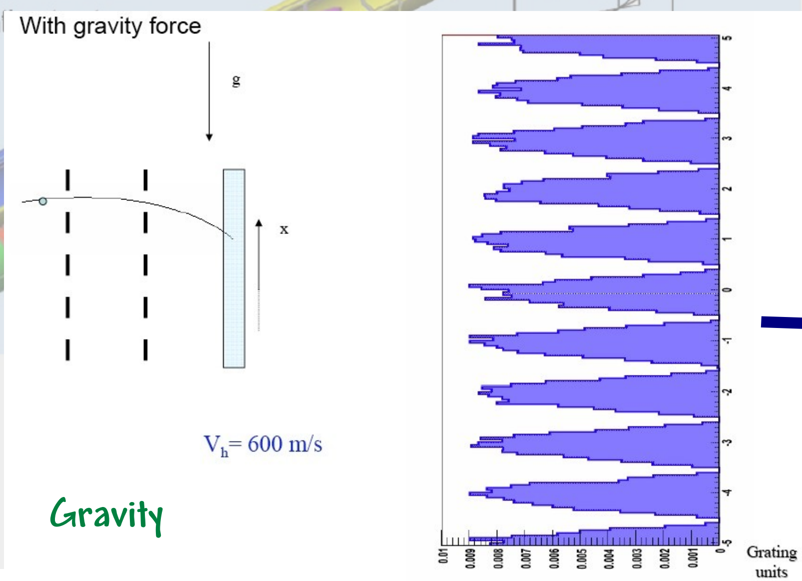
⇒ AEGIS: plans for data taking 2009 - 2012

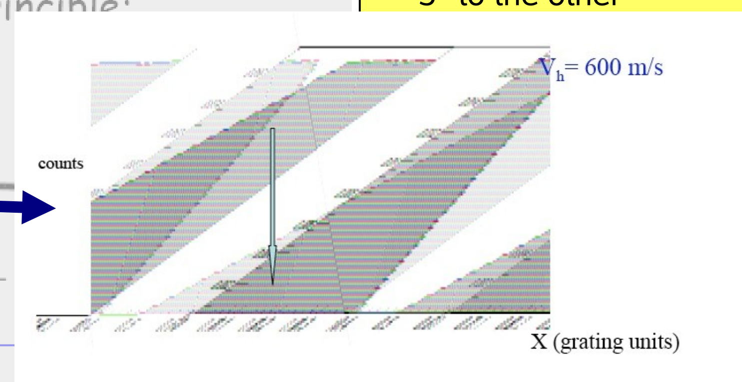
A different Ansatz to learn about Gravity: the AEGIS Experiment at the AD





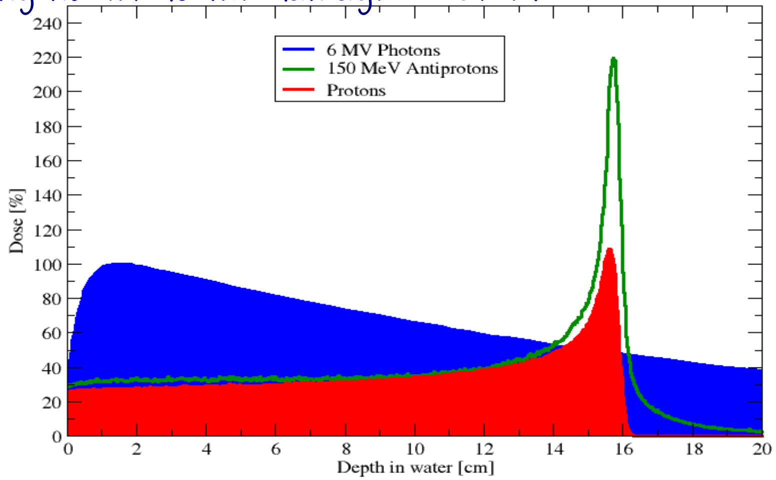
"A Moiré pattern, formed by two sets of parallel lines, one set inclined at an angle of 5° to the other"

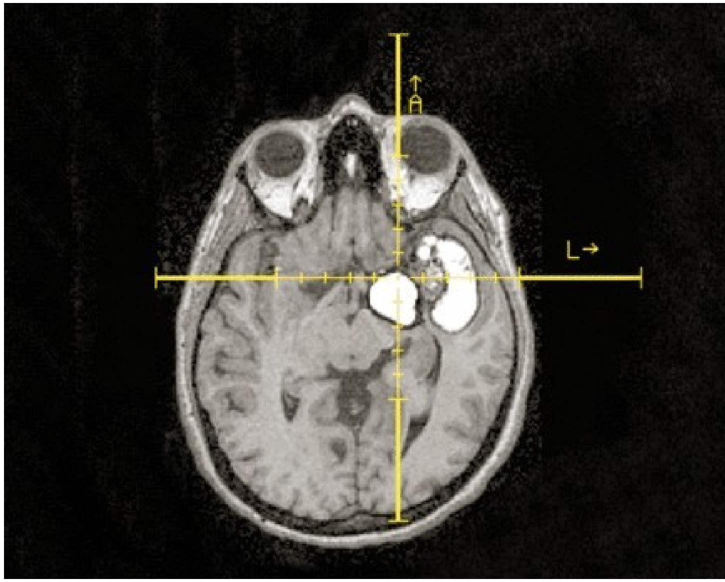




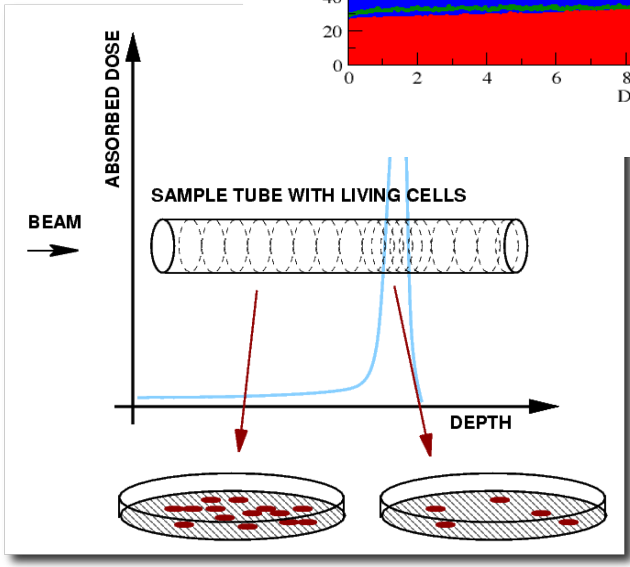
AD4/ACE-Cancer Therapy with Antiprotons?

- The quest: hit the tumor, save surrounding tissue
- Antiproton annihilation:
  - → Energy = 2 x mp ~1.88GeV
  - → Most of energy carried away by π, γ
  - → Recoiling nuclei do the damage ~ 30MeV
- The idea:



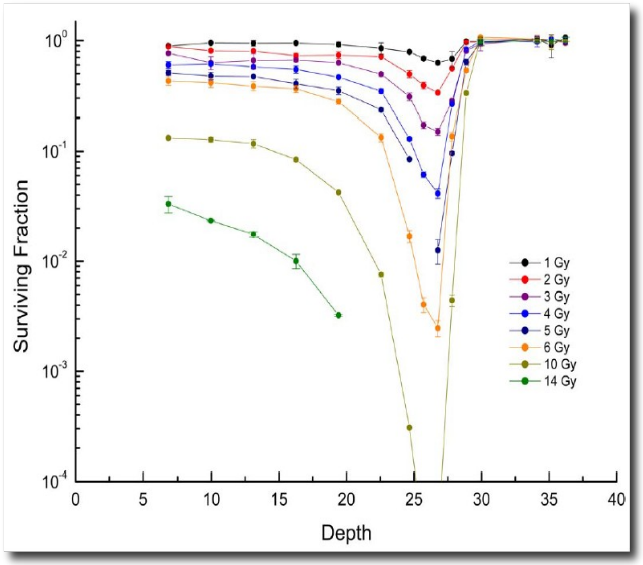


- Set-up:



Still some way to go!
→Need cross-check with carbon ions
→Need better dose measurements...
→T.b.c. > 2008

- First results:



From Particles to Elements...

Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

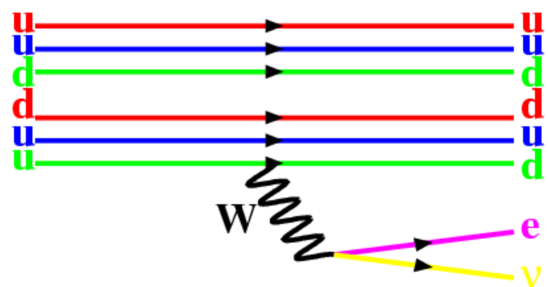
Legend - click to find out more...

H - gas **Li - solid** **Br - liquid** **Tc - synthetic**

- Non-Metals
- Transition Metals
- Rare Earth Metals
- Halogens
- Alkali Metals
- Alkali Earth Metals
- Other Metals
- Inert Elements

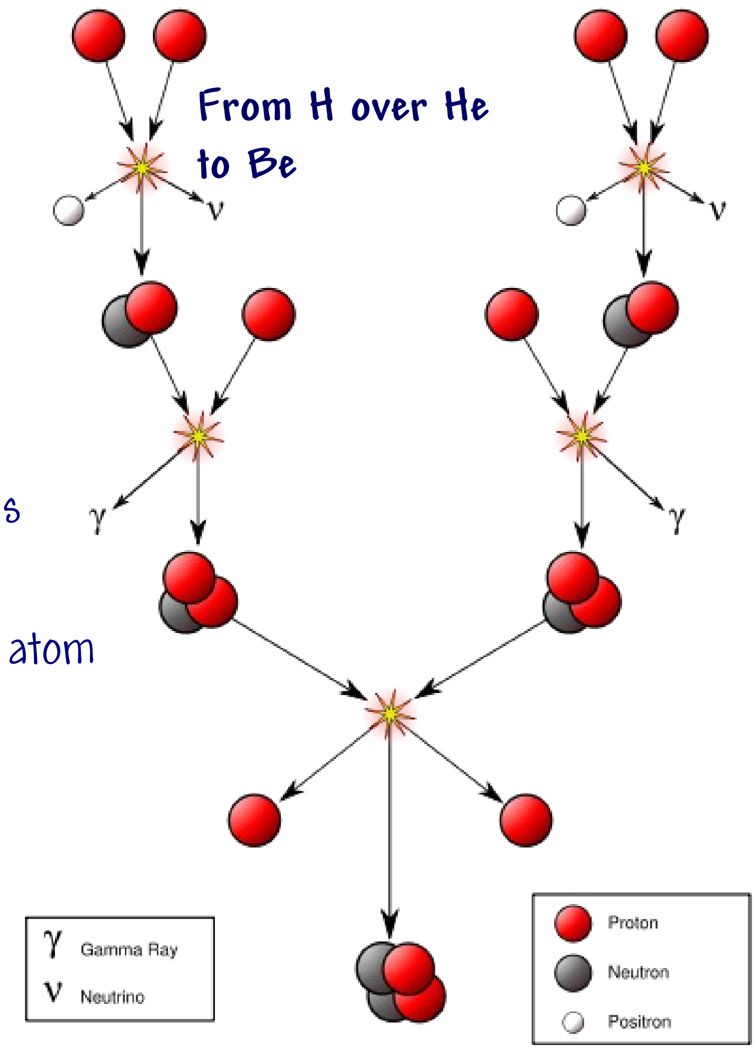
Chemical Elements in the Universe

- Chemical elements up to Iron are produced in stars by fusion
  - → fundamental process:
    - ∀ β+ decay of a proton to a neutron



- For elements bigger than Fe (26 protons, 30 neutrons) this process stops
  - →difficult for a proton (=charged particle) to enter the atom and reach nucleus

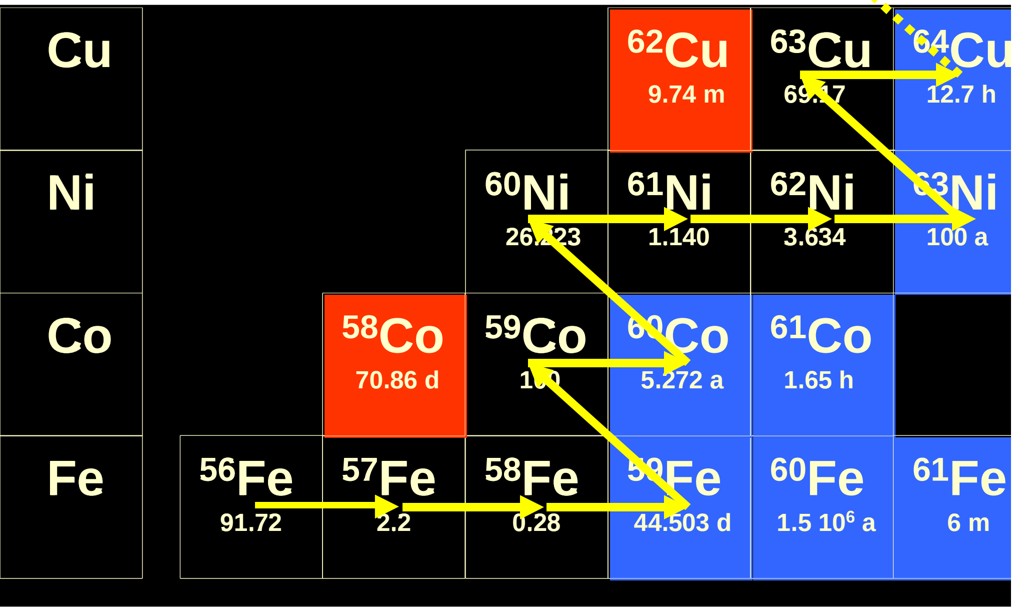
- **Where and how heavy elements are produced?**

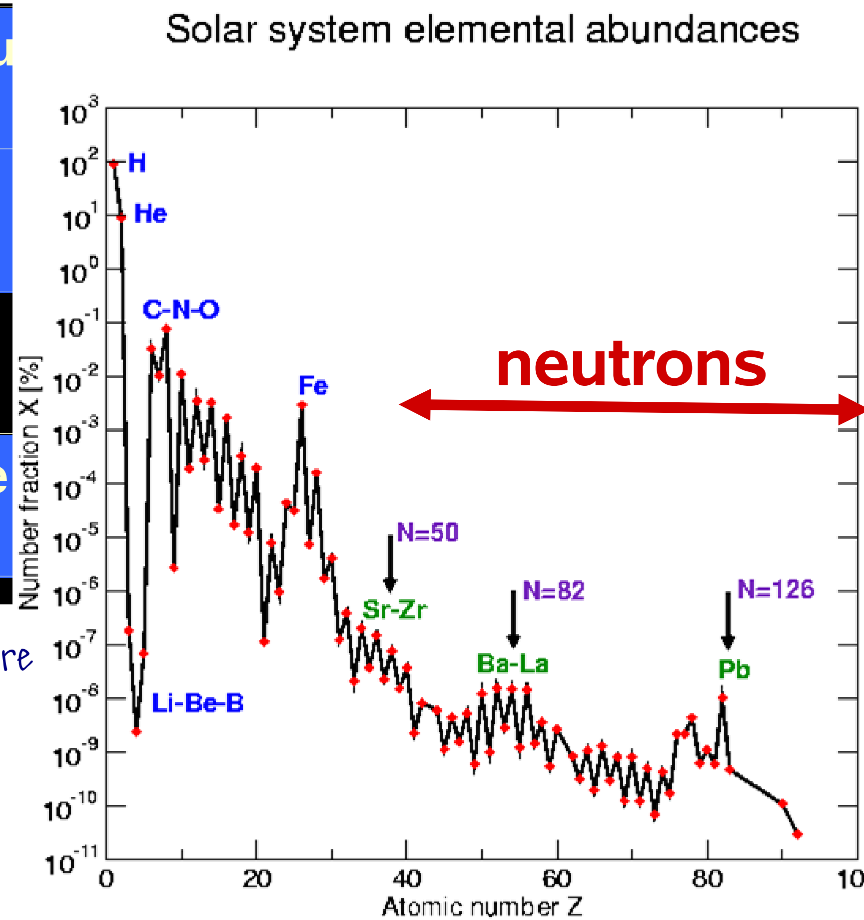


Nucleosynthesis in Stars: the s-Process

(s = slow neutron capture)

- Half of the elements are produced via slow neutron capture in stars
  - → neutrons (electricaly neutral enter the nucleus)
  - → followed by β- decay of a neutron to a proton

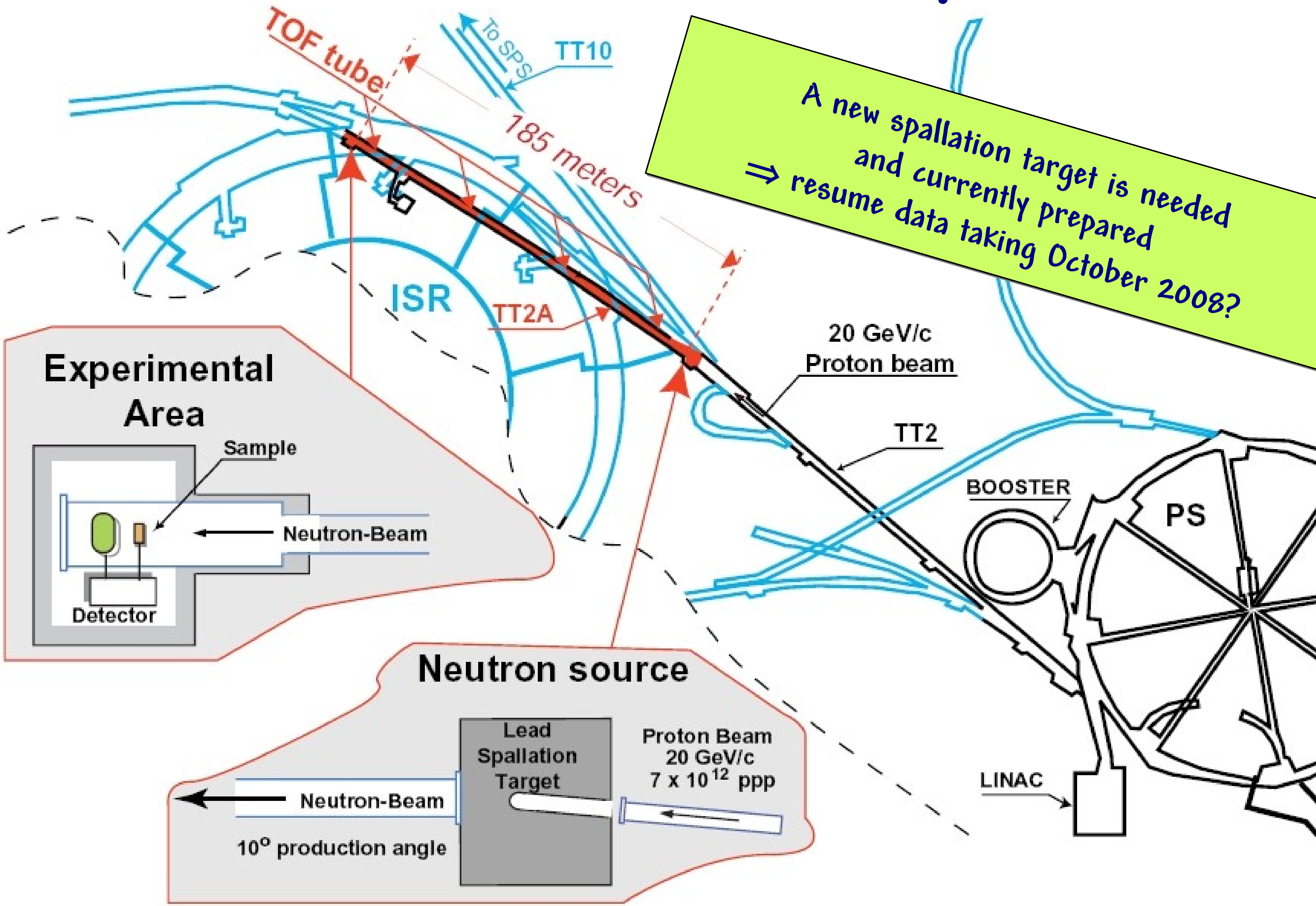




- The measurement of the neutron capture cross sections are key ingredients to understand s-process nucleosynthesis

⇒ **will be explored by n-TOF**

The n-TOF Facility



A new spallation target is needed and currently prepared
⇒ resume data taking October 2008?

Targets for High Power Beams

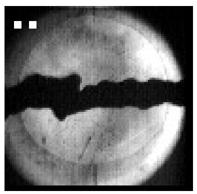
- Future applications at accelerators require targets in high power proton beams (several MW, now in use < 1MW)
  - → Intense neutrino beams,
  - → Studies of rare processes initiated by muons,
  - → Studies of materials for spallation sources with neutron beams
  - → Accelerator production of tritium,
  - → Transmutation of nuclear waste...
- Technical challenges for targets:
  - → Survival of components against
    - **melting/vaporisation**
    - **beam induced pressure waves**
    - **radiation damages**
- Solution
  - → **Flowing liquid target** in form of a **free jet** at the interaction region with the beam

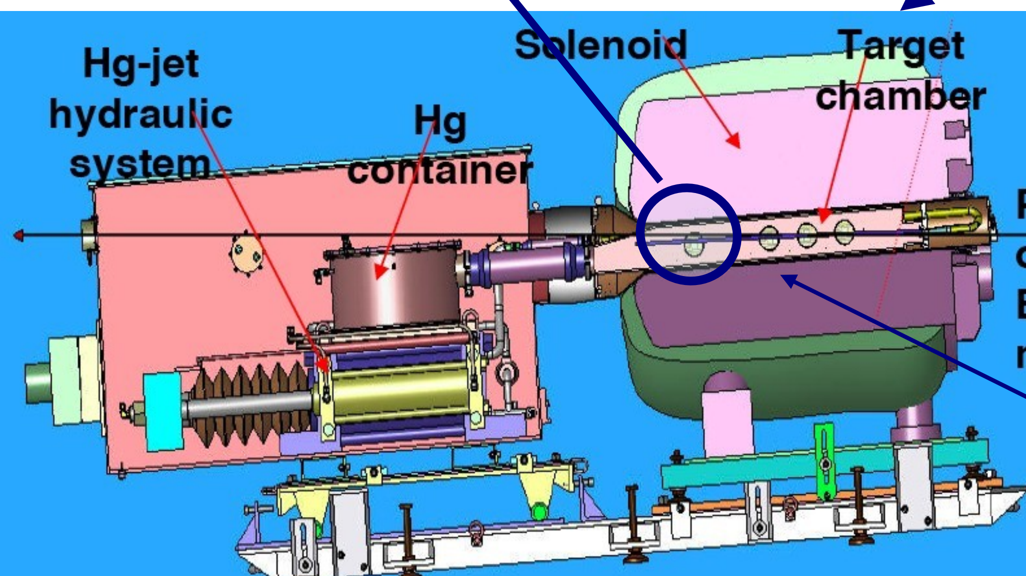
⇒ The **MERIT** (**MER**cury **I**ntense **T**arget) experiment

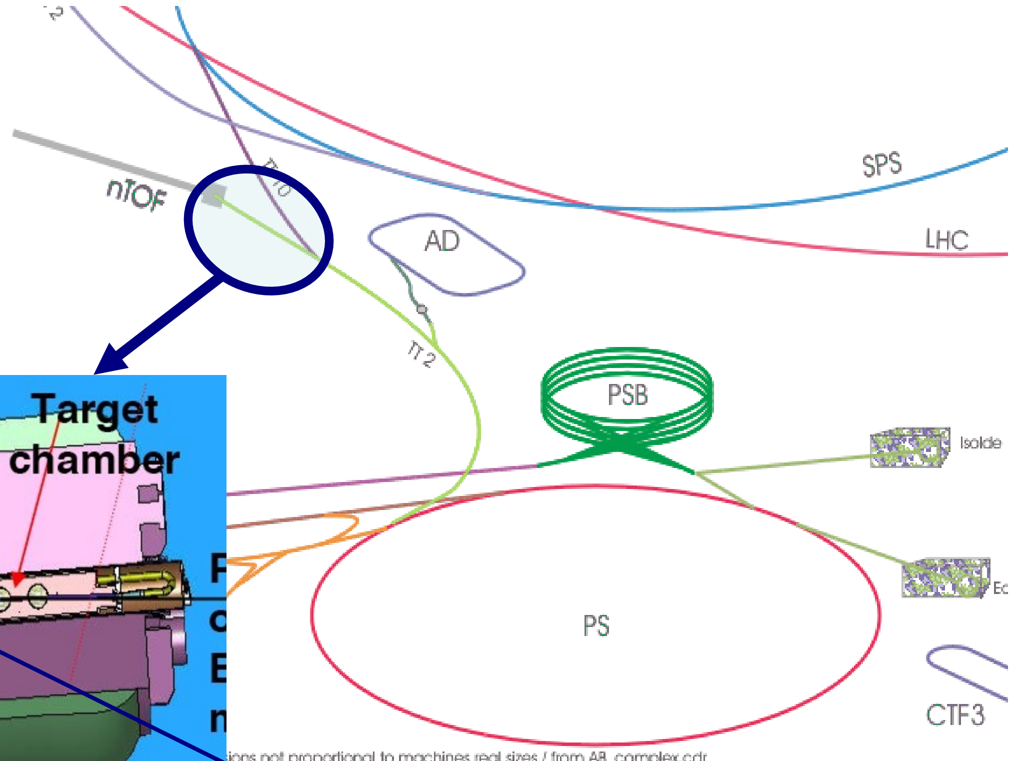
The MERIT Experiment

- Proof-of-principle test of a free mercury jet target inside a 15-T capture solenoid magnet;
- Located in nTOF proton line, requires only ~100 fast-extracted PS high-intensity pulses

View through window onto target







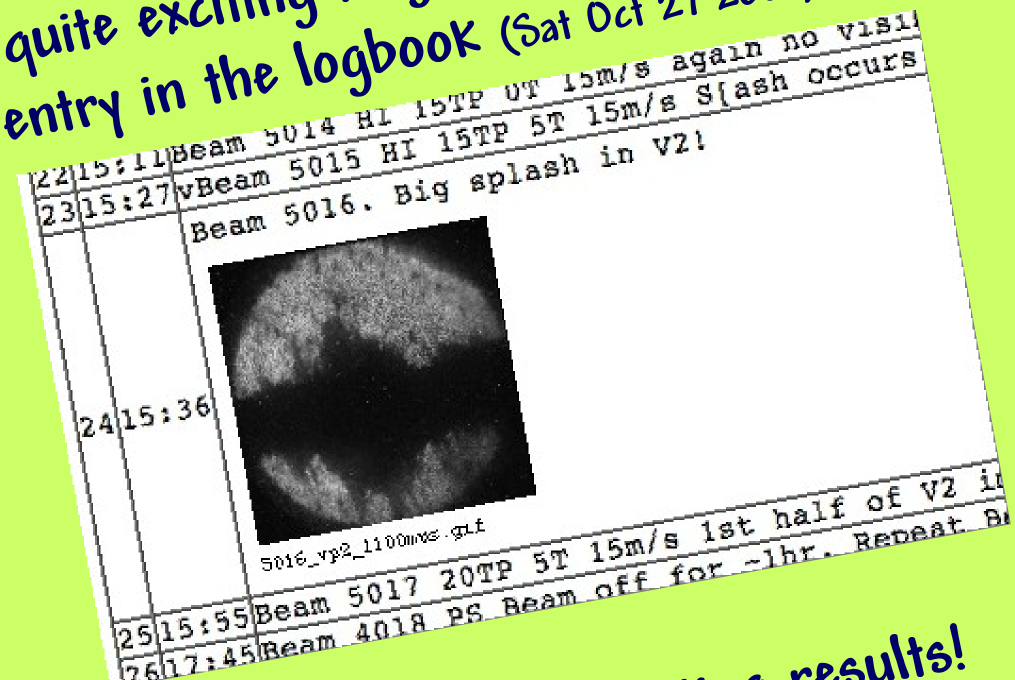
Main tools & detectors:
high speed cameras...

The MERIT Experiment at the nTOF line

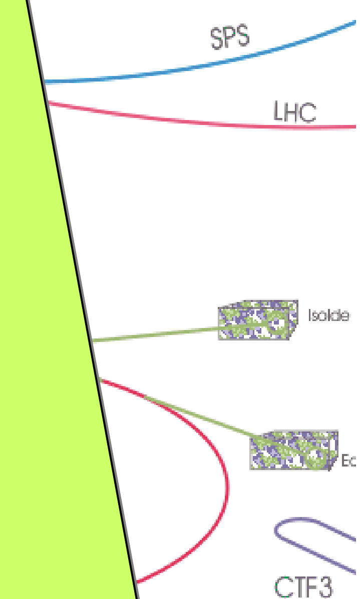
The MERIT Experiment

- Proof-of-principle test of a free mercury jet tar... solenoid magnet;
- Located in nTOF proton li... ...tensity pulses

MERIT successfully finished in 2007...
Was quite exciting to get it going...
e.g. entry in the logbook (Sat Oct 27 2007)



Looking forward for interesting results!

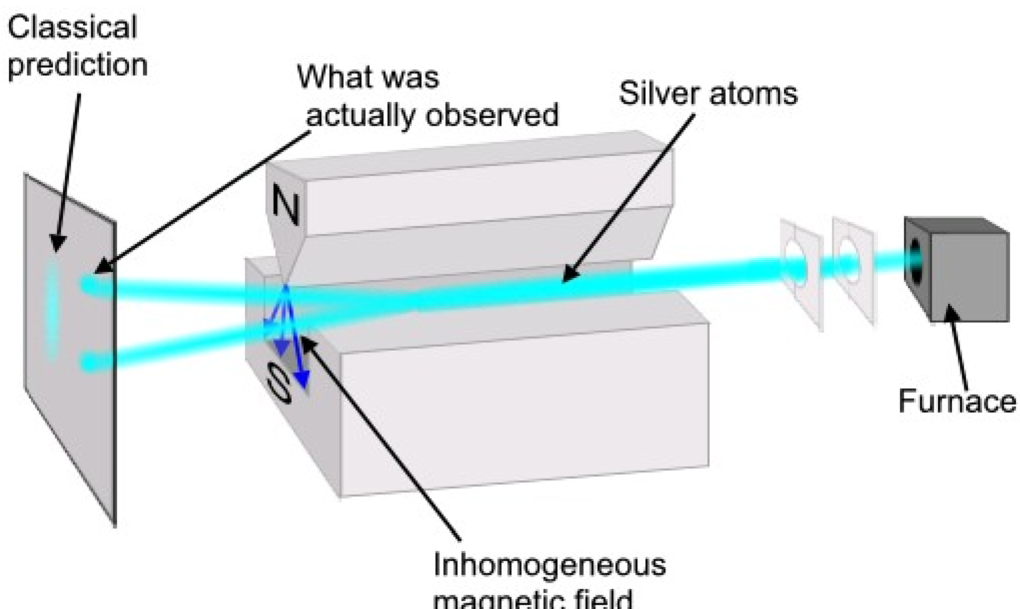


The MERIT Experiment at the nTOF line

The Spin

An important Property of Elementary Particles

- The spin is an intrinsic property of a particle, like its charge, its mass
- Quantum Mechanics: angular momentum of particle is quantised
  → magnitude S can only take values of $S = \hbar\sqrt{s(s+1)}$,
- First observation by Stern & Gerlach 1922:



- beam of electrically neutral particles is influenced by magnetic field!!!

⇒ silver atoms exist in two states!!! (spin 1/2 & spin -1/2)

Fermions: spin 1/2

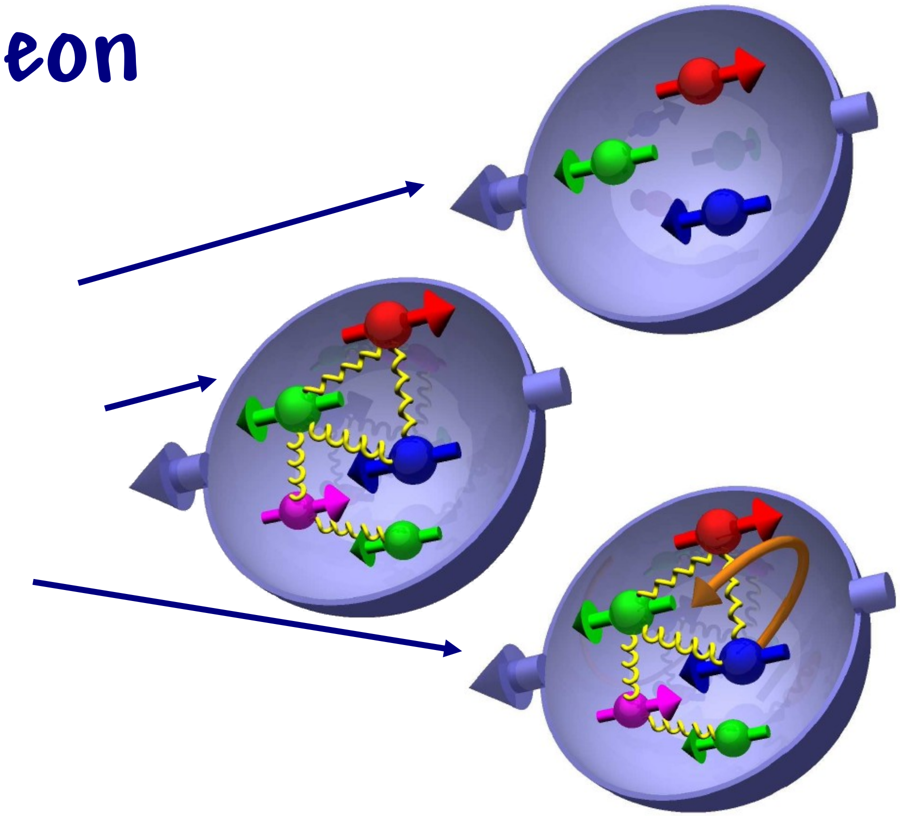
Bosons: spin 0, 1

- spin is a fundamental property of particles (Pauli Prinziple)

⇒ do we understand the spin of compound objects, e.g. **proton spin**???

The Spin of the Nucleon

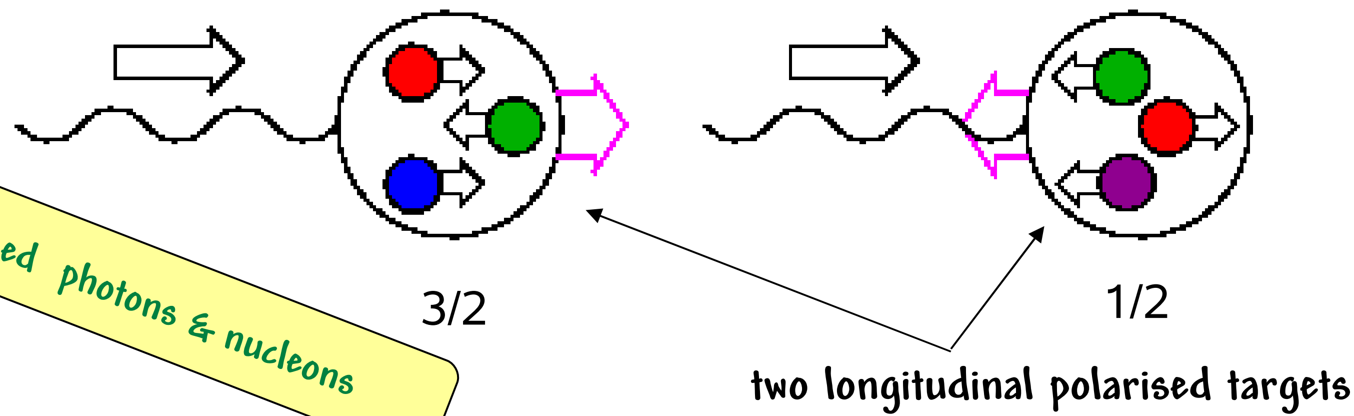
- Contributions to the spin of the proton
  - → naive QPM: only valence quarks Δq_v
    QPM = Quark Parton Model
  - → QCD: sea quarks and gluons $\Delta q_{s,}$ ΔG
    QCD = Quantum Chromo Dynamic
  - → orbital angular momentum L_q, L_g
- Spin of proton = 1/2
  - → naive QPM: 1/2 = 1/2 - 1/2 + 1/2
  - → otherwise, with $\Delta\Sigma = \Delta u + \Delta d + \Delta s$



$$1/2 = 1/2 \cdot \Delta\Sigma + 1 \cdot \Delta G + \langle L_z \rangle$$

How to measure ΔΣ (COMPASS)

- Incoming (polarised) muon radiates (polarised) photon (photoabsorption)



need polarised photons & nucleons

- only quarks with opposite helicity can absorb the polarised photon via spin-flip
- Measure "deflected" muon, count interactions with target 1 or 2

$$\frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}}$$

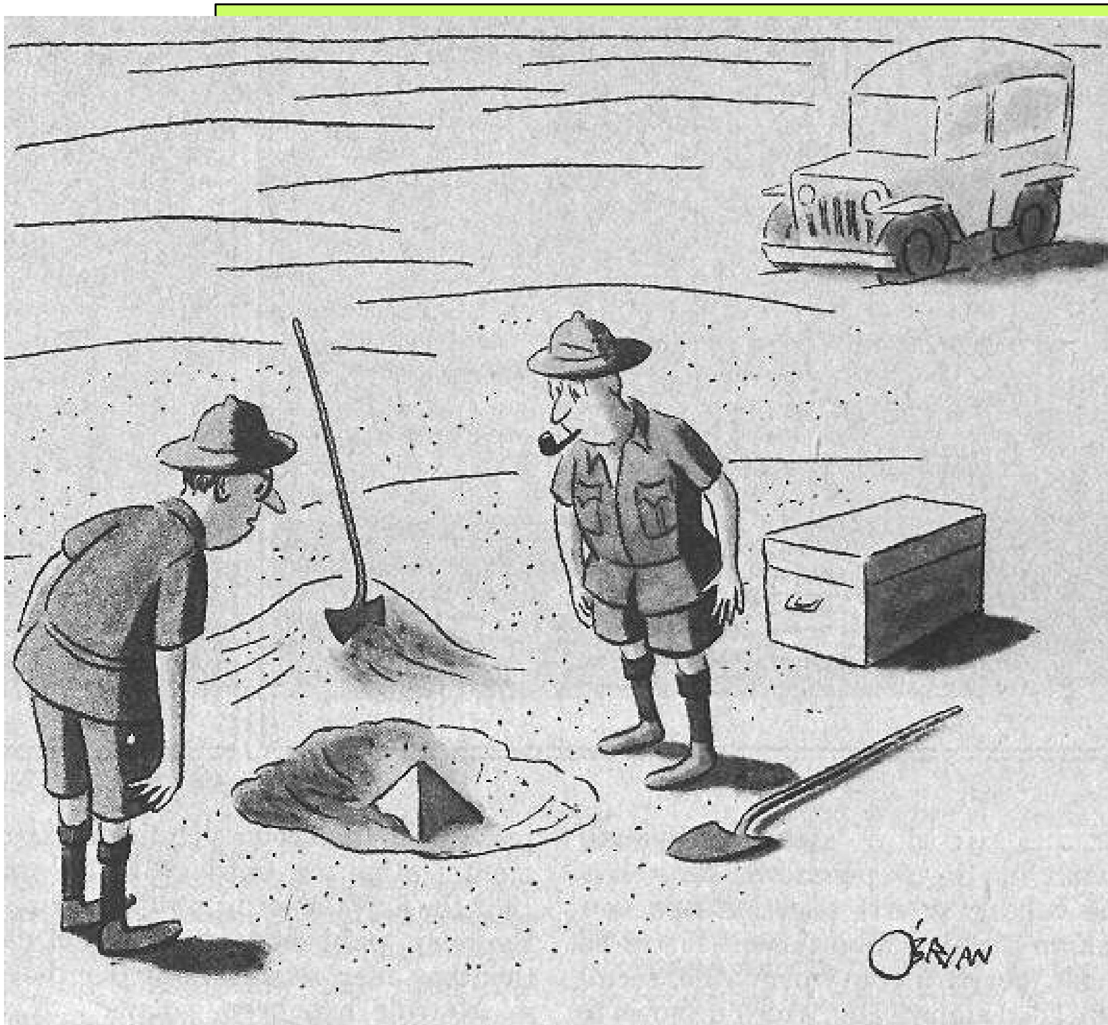
Asymmetry measurement (difference / sum) ⇒no systematics, e.g. particle flux

⇒ Number of quarks in polarisation direction of nucleon:

Result: ΔΣ ~ 0.25 (=fraction of contribution to proton spin by quarks)

...what else contributes???

...what else contributes???



"This could be the discovery of the century. Depending, of course, on how far down it goes."

$\langle L_z \rangle$

(unknown)^2

nge

some theories predict VERY high contributions, but shielded and canceled by higher sea quark contributions

Result: $\Delta G \sim 0.06$
VERY SMALL!!!
To be continued...

Probing the Standard Model with Precision Measurements, NA62

- Standard Model of particles predicts
  → Production rates, decay modes and branching ratios of particles
- Is the Standard Model correct? Is there new physics?
- E.g. looking for the decay $K^+ \rightarrow \pi^+ \nu\nu$ (NA62 experiment)
  → Prediction by theory:

$$BR(K^+ \quad \pi^+ \nu\bar{\nu}) = (8.0 \quad 1.1) \quad 10^{-11}$$
$$BR(K^0_L \quad \pi^0 \nu\bar{\nu}) = (3.0 \quad 0.6) \quad 10^{-11}$$

(Buras et al. 04)

→ Prediction by other hot&sexy theories (e.g. Supersymmetry, SUSY)

→ $BR(K^+ \rightarrow \pi^+ \nu\nu) = 40 \times 10^{-11}$

→ $BR(K^+ \rightarrow \pi^0 \nu\nu) = 50 \times 10^{-11}$

2008 - 2010

⇒ **NA62** *(former NA48-3/P326)*
might open window for new physics
(...before the LHC does?)

A First Try: NA62 in 2007

- Measure $R_K = \Gamma(K \rightarrow e\nu) / \Gamma(K \rightarrow \mu\nu)$
- Standard Model predictions: $R_K(SM) = (2.472 +/- 0.001) \times 10^{-5}$

  → but variations of order 1% may be present from contributions by SUSY effects (max. effect up to -3.2%) in specific models
- World average (PDG): $R_K = (2.44 +/- 0.11) \times 10^{-5}$ from 3 experiments (1972, 1975, 1976, few hundred events each...)

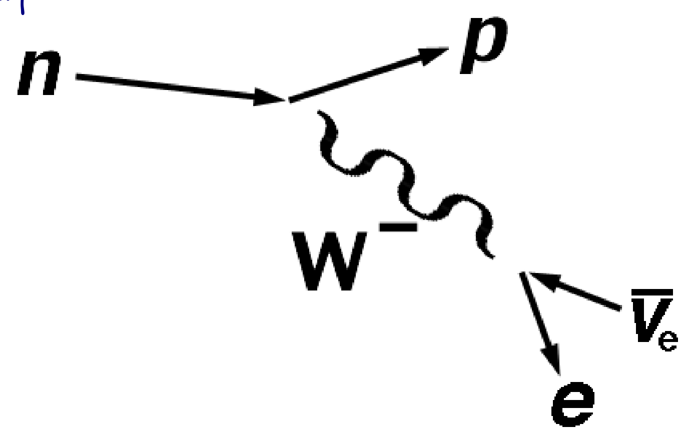
- In 2007, NA62 collected about 110000 events, expect stat. error ~0.3%, total error ~0.35%

⇒ NA62 successfully took data in 2007...

... results will be interesting!

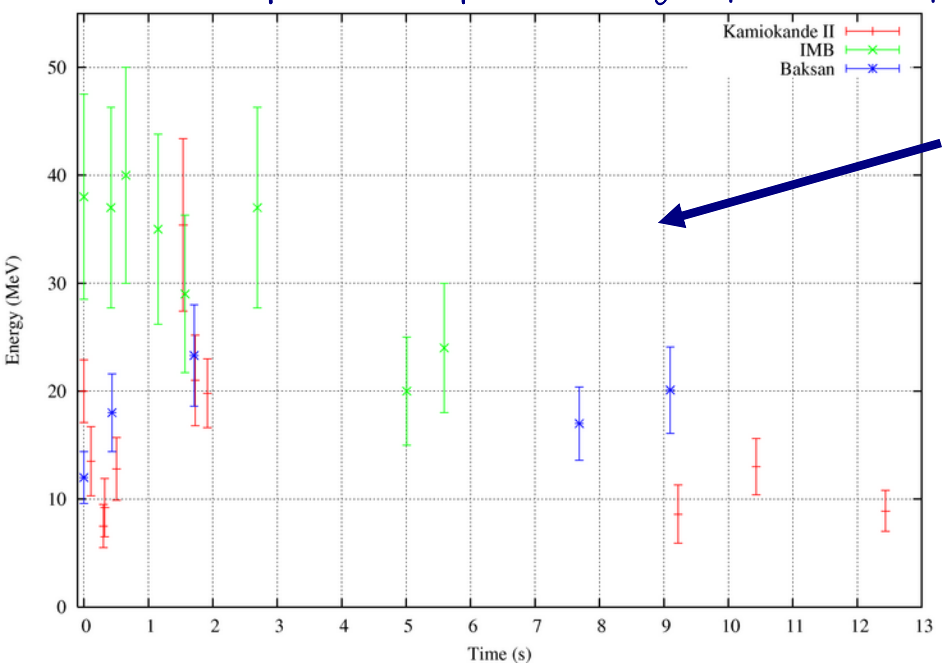
What about Neutrinos Masses???

- Neutrino "invented" 1930 by W. Pauli to explain neutron decay
  - → Neutrino (ν) is only weakly interacting
    - thus escapes direct detection…
  - → Pauli assumed precisely zero neutrino mass



⇒ **Is this true???**

- (indirect) approach to measure neutrino masses:
  - → Supernova explosions (e.g. explosion of super giant Sanduleak 1987)



- Detectors measure arrival time and energy of neutrinos from the Supernova
- if neutrinos have mass, they travel with v<c, depending on mass and energy

⇒ from non-observation of energy/time dependence: derive **limits on neutrino mass** ***(but limits still consistent with m=0!!!)***

Neutrino Oscillations (CNGS)

→ a neutrino created with specific flavour (e, μ, τ) can later be measured to have different flavour

→ probability measuring specific flavour oscillates periodically as neutrino propagates

→ **oscillation implies that neutrino has a mass**

- oscillation of solar neutrinos have been observed by different experiments

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2 2\theta \sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

→ Particular interest:

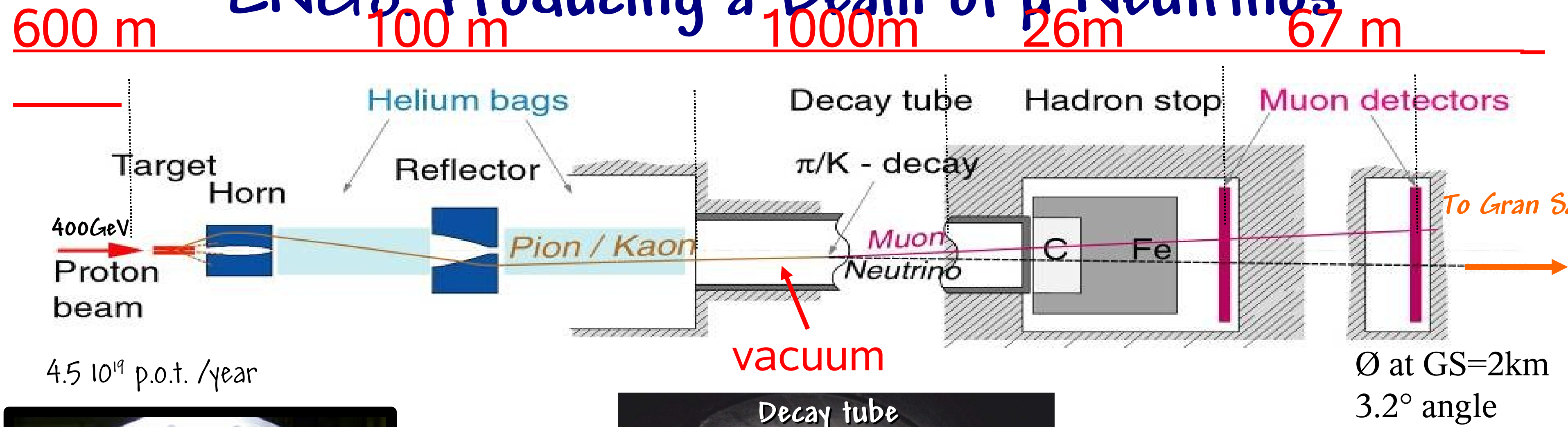
- information on the strength of flavour changing described by the Maki-Nakagawa-Sakata (MNS) matrix (similar to CKM matrix describing flavour mixing...)

→ **CNGS** produces beam of muon neutrinos ν_μ, detectors are searching for tau neutrinos ν_τ (= appearance expe

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

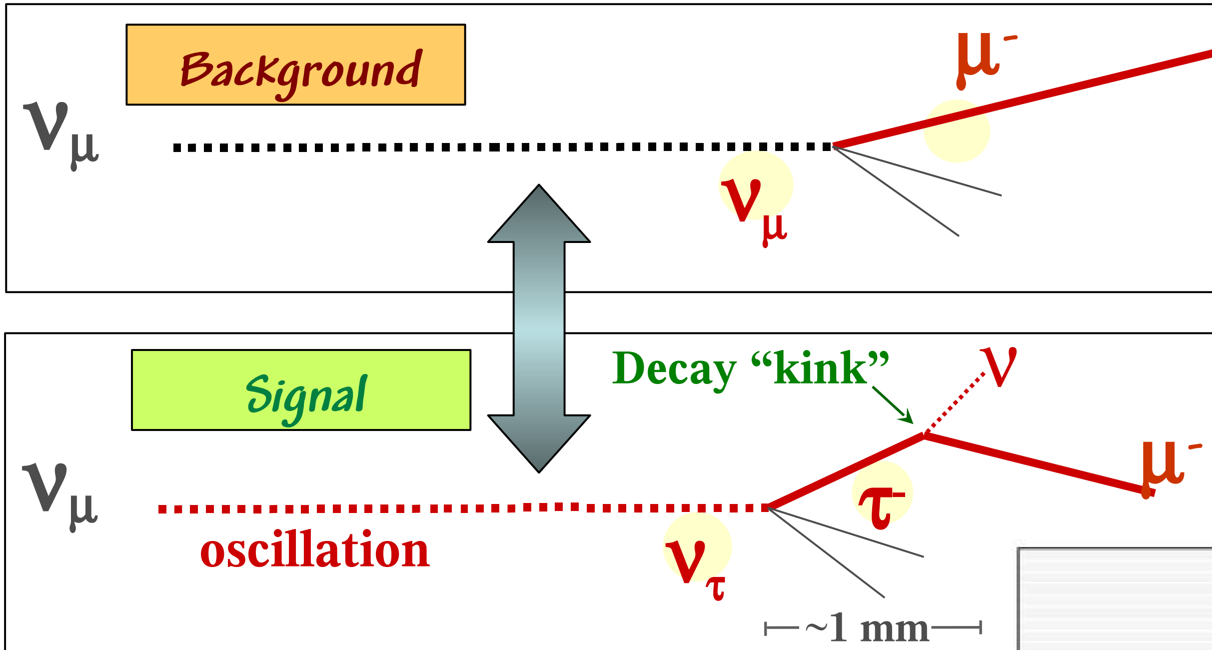
→ **expected sensitivity** to mass difference **Δm^2** between ν_μ and ν_τ of **$10^{-3}eV^2$** ⇒ observe in 5 years **~10-20 ν_τ events**, depending on Δm^2 (1.9-3.0 x $10^{-3}eV^2$) over ~1 exp. background event

CNGS: Producing a Beam of μ Neutrinos

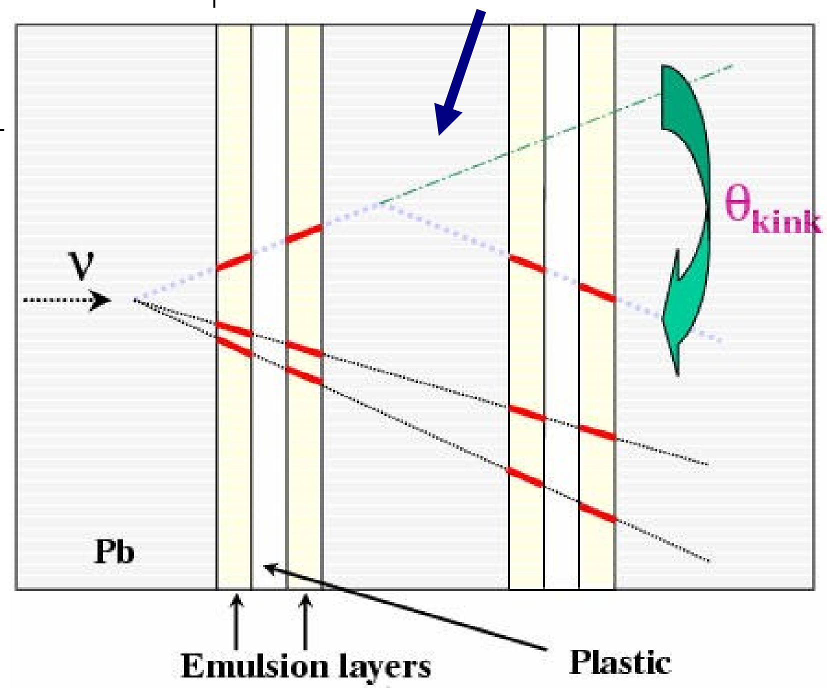


- Civil engineering completed (June ´03)
- Hadron stopper and decay tube installed (June ´04)
- Target section completed in 2006 (first CNGS beam in August 2006)

The OPERA Experiment: Detection of ν_τ CC interactions and direct observation of τ decays



OPERA concept:
Observe CC interactions in lead target (1 mm thick plates) and detect τ's in emulsion films
(~155000 bricks, ~10x10x20cm3, 57 emulsion layers each)



What the brick cannot do:

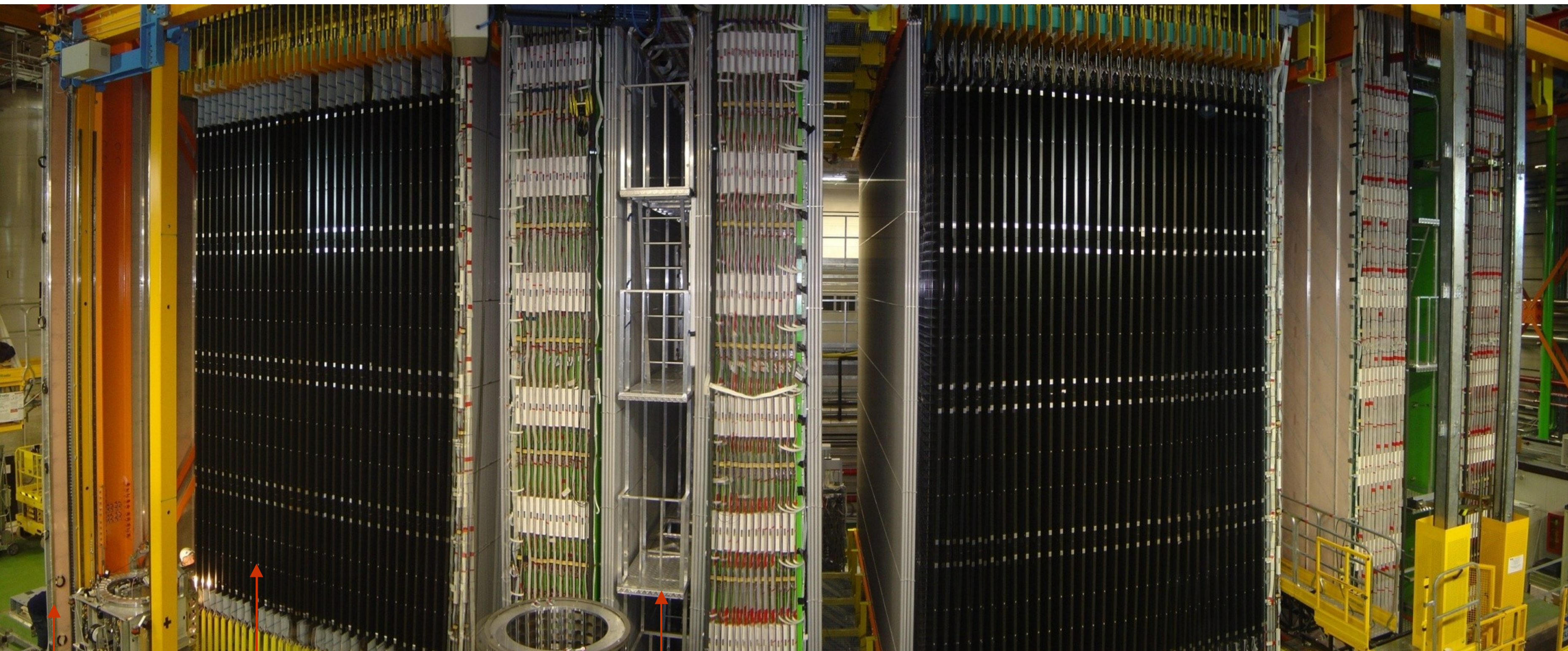
- trigger for a neutrino interaction
- muon identification and momentum/charge measurement

$\Rightarrow$ need a hybrid detector

A Photo of the OPERA Experiment

20 m

SM1 SM2



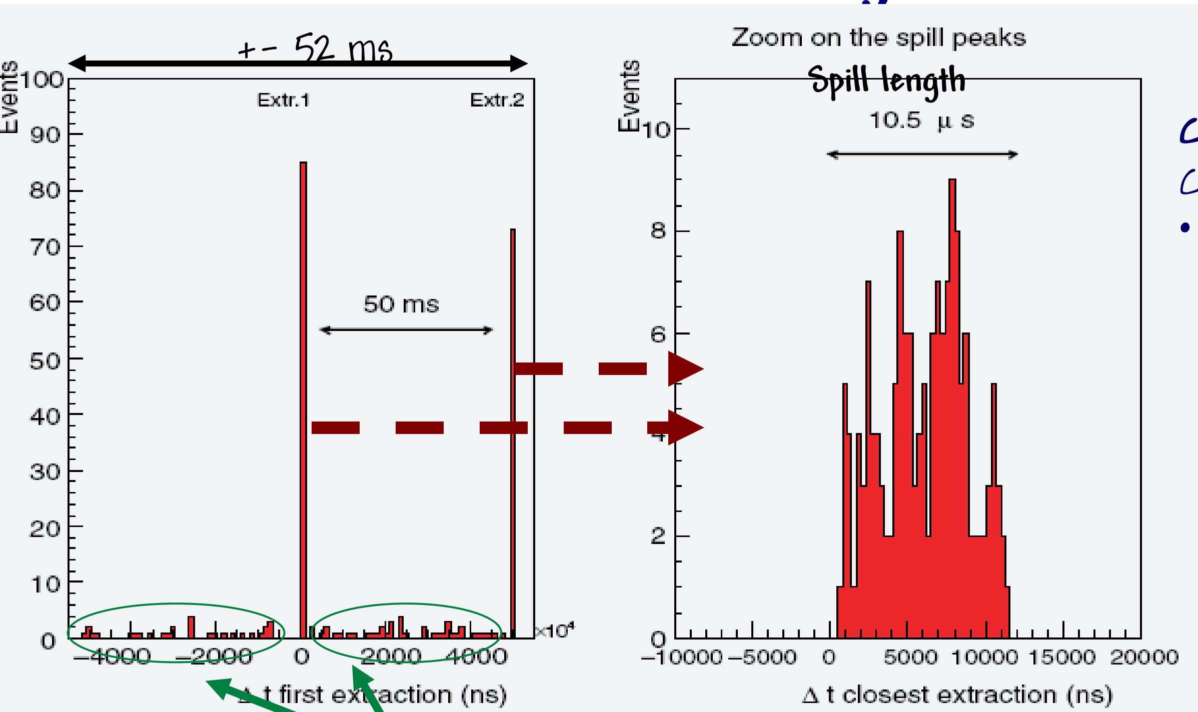
10 m

Veto

Target tracker

Spectrometer:
XPC, HPT, RPC, magnet

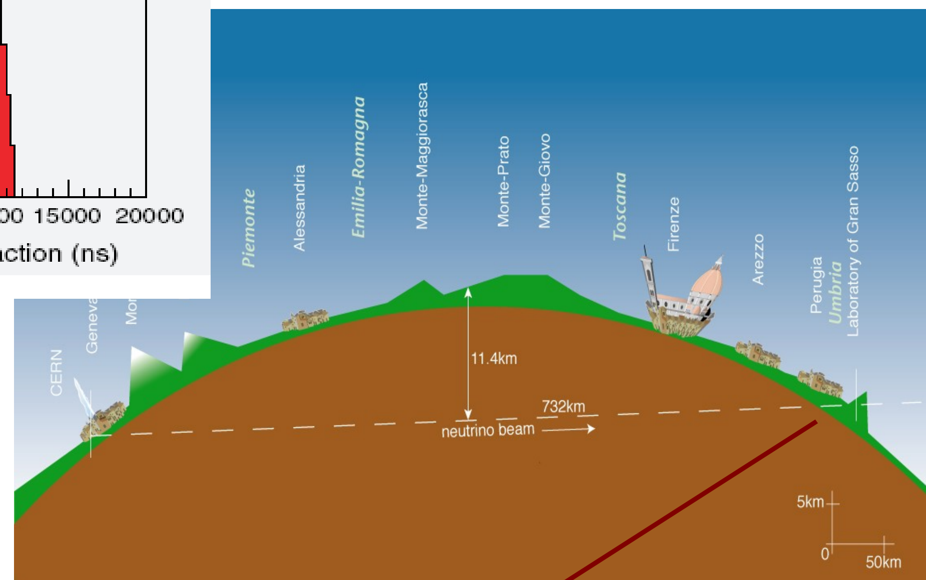
CNGS Commissioning and first events in OPERA

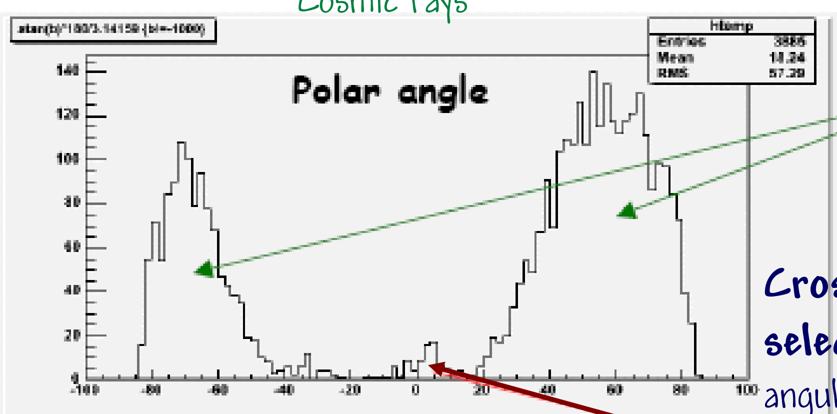


Cross-check and selection of events from CERN by OPERA using timing information

- spill structure of the SPS should be seen!

Cosmic rays





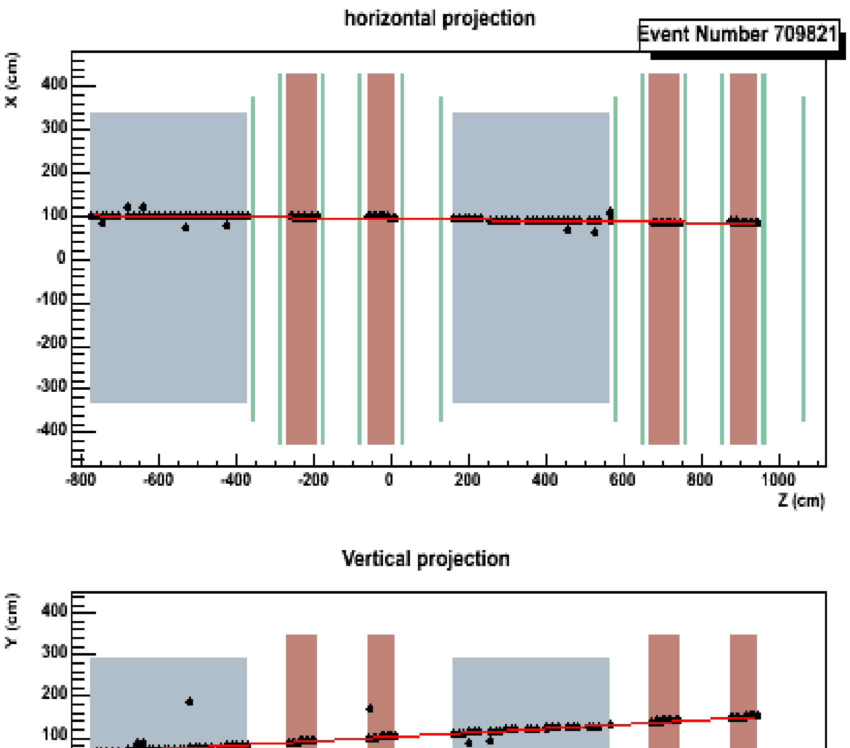
Cosmic rays

Cross-check and event selection:
angular distribution

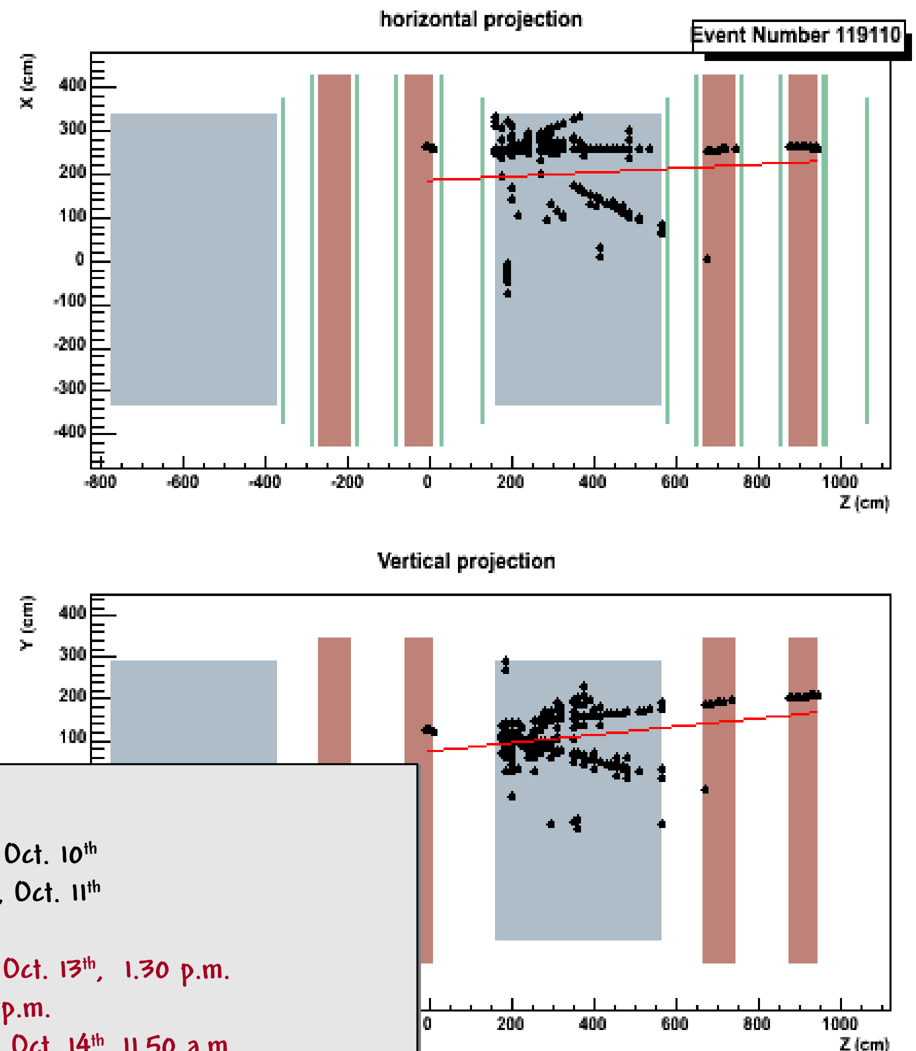
Signal: events coming 3.5deg from below (...from CERN!)

Beam Events

CC event originated upstream of the detector (BOREXINO, rocks)



CC event originated in the first magnet

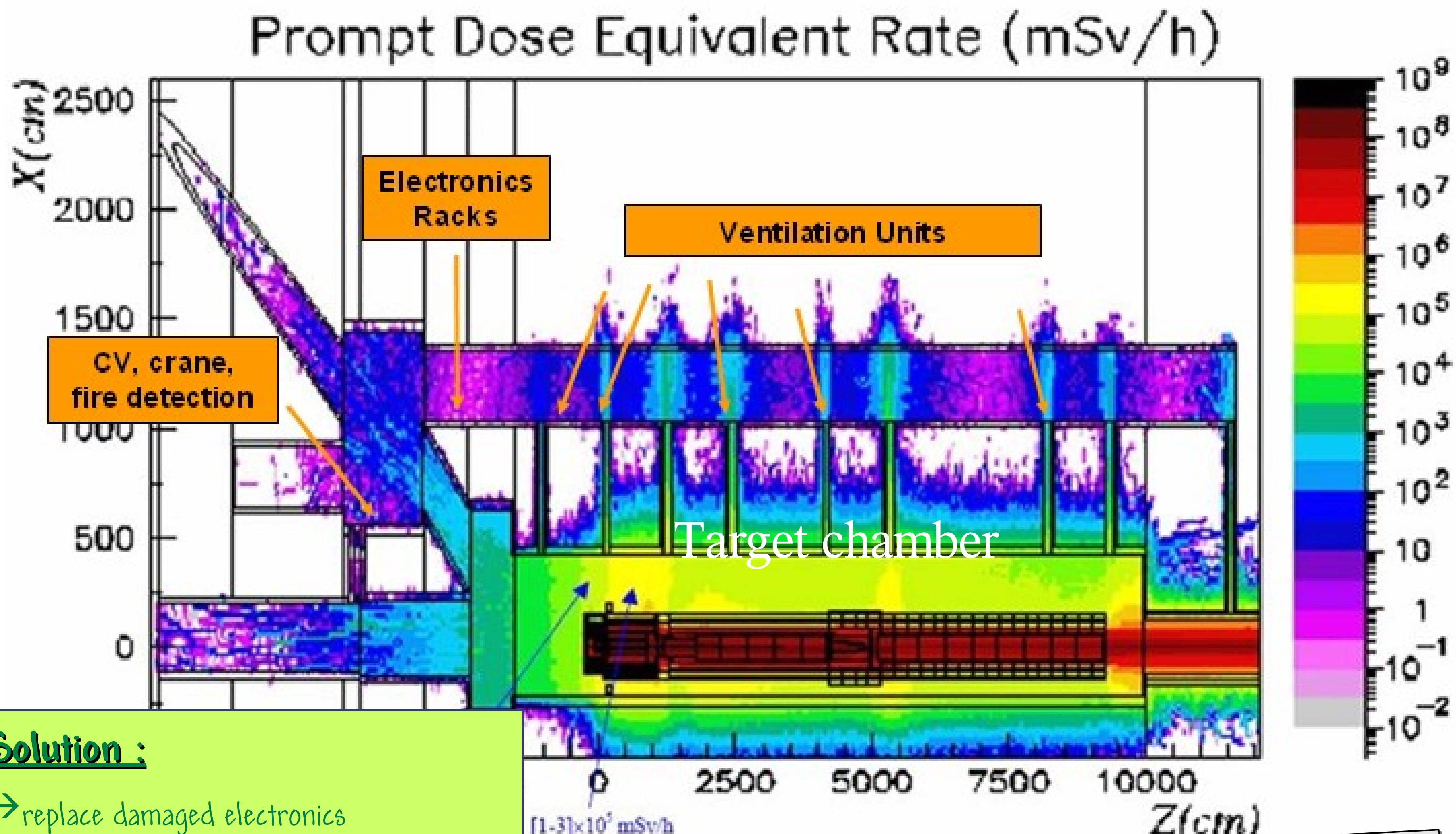


Time scale for brick analysis:

CS film development	Wed., Oct. 10th
Brick film development	Thurs., Oct. 11th
CS scanning	Fri., Oct. 12th
Brick transportation LNGS → BARI	Sat., Oct. 13th, 1.30 p.m.
CS scanning predictions LNGS → BARI	Sat., Oct. 13th, 2.52 p.m.
SB started	Sun., Oct. 14th, 11.50 a.m.
Track disappearance	Sun., Oct. 14th, 5.25 p.m.
Quasi-online reconstruction and event confirmation	Sun., Oct. 14th, 5.42 p.m.

CNGS Problem in 2007

- CNGS commissioning run stopped 5 days earlier → failure of electronics of ventilation units because of radiation damages...



Solution :

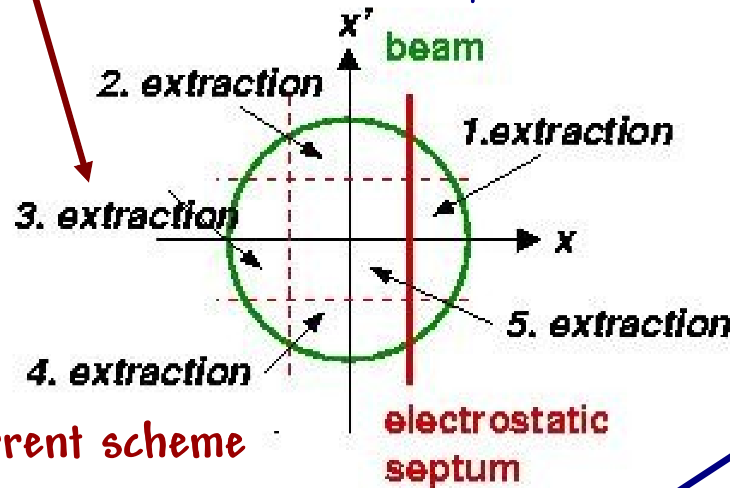
→replace damaged electronics

→find another place for ventilation control units

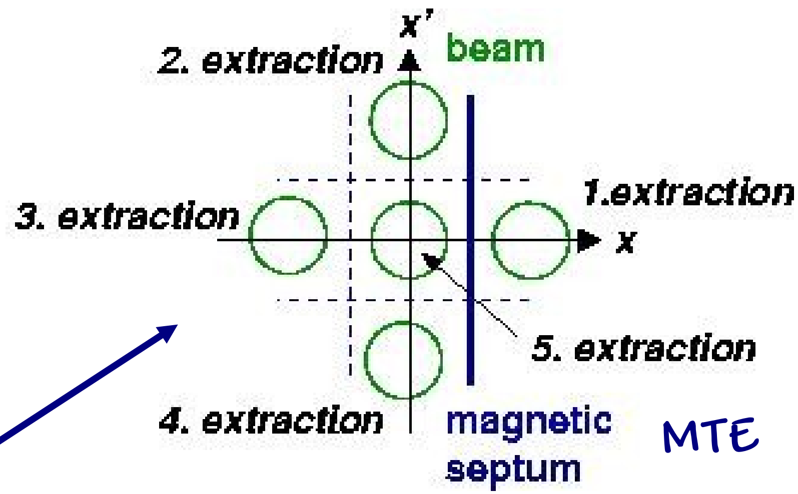
... lesson learned:
LHC equipment is checked to prevent similar problems...

Extraction of high intensity beams: a challenge for the machines...

- **Current extraction scheme** of high intensity CNGS beam from the PS to the SPS causes lot of radiation (electrostatic septum)



Current scheme



MTE

- **New scheme, multi-turn-extraction (MTE)** will start operating in 2008: much less radiation (magnetic septum)!!!!

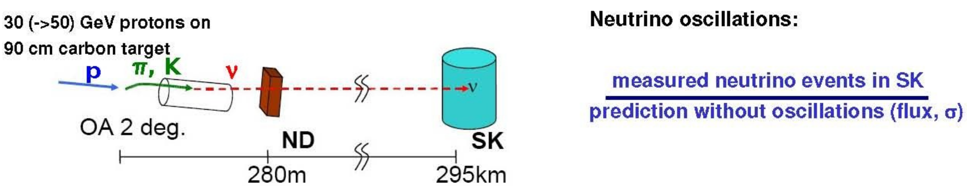
  additional PS hardware, main parts:
  - Sextupole, octopole to introduce non-linearities and to create **islands** (=capture)
  - Kickers, for extraction

Comment: MTE is a great idea and challenging!
The scheme is used at accelerators for the first time…

Neutrino Flux: Do we understand what we are doing? NA61 is checking using SPS beam!!!

- Measurement of neutrino oscillations requires precise number of detected neutrinos normalised to **prediction without oscillation**
- E.g. for T2K (search for ν_e appearance, ν_μ disappearance):

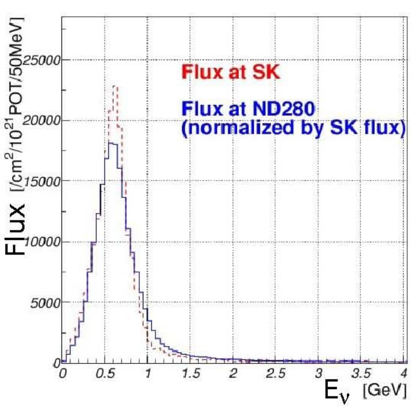
T2K Scheme:



-there exist no measurements of hadron production off carbon with 30 GeV protons
-there is no secondary particle flux measurement from the T2K target
-the near detector flux is not identical to far detector flux
→ the far/near ratio depends on the hadron production on the T2K target and thus
→ the resulting uncertainty are not well known
→ neutrino interactions cross sections can not be measured

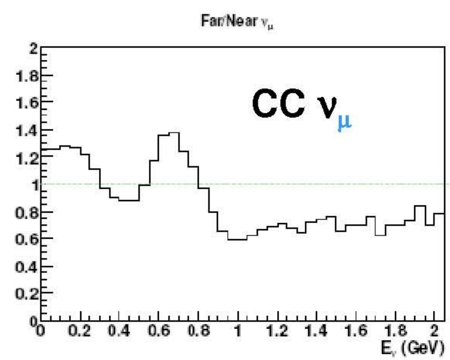
- Experiments will measure the production (yield, cross section) of secondary hadrons

→ Goal: **high precision** O(1%) for various targets and energies *(old data from 1970s, errors ~15%)*



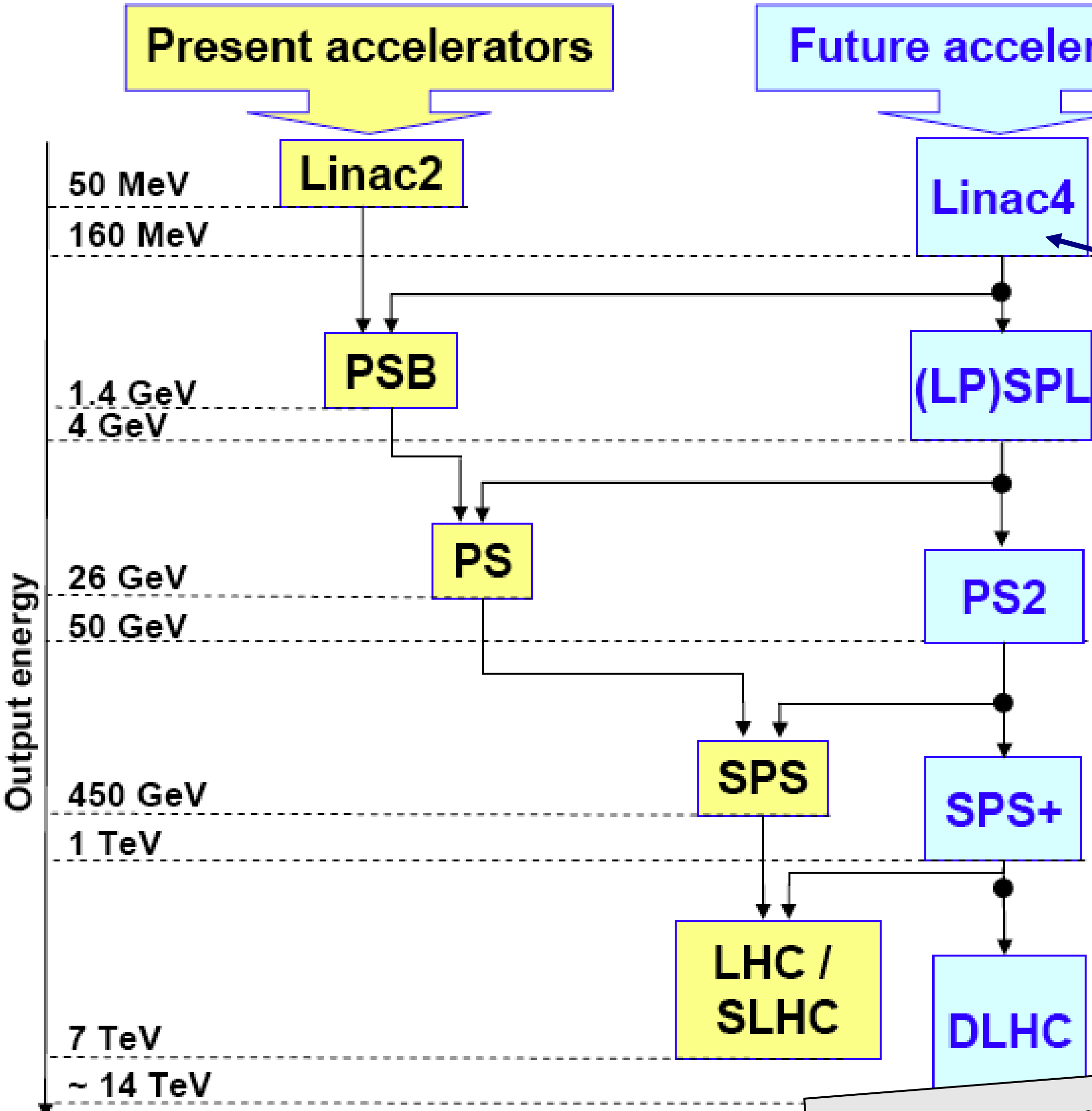
← ν_μ flux (important for disappearance)

far/near ratio is not flat →



Comment: Important "service" measurements ⇒ impact on many fields (neutrinos, air shower experiments, ...)

The Future



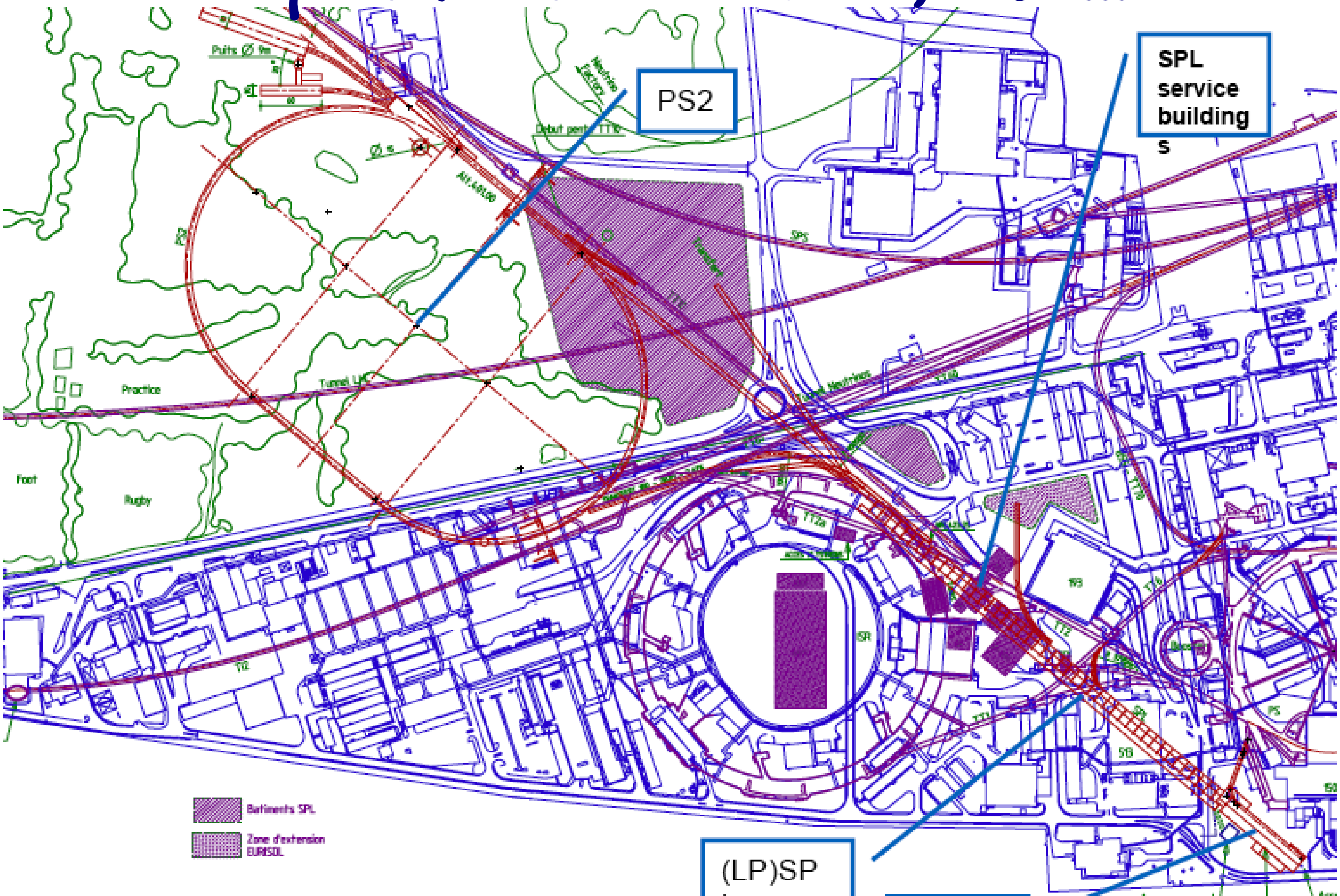
CERN priorities:

- Consolidation and upgrade of LHC injectors
  → Start with new LINAC (~2011)
- LHC upgrade and maximum performance injectors
- …

(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Comment: New ideas for new experiments could profit from new injectors!!!

Layout for the LINAC4, PS2...



- <u>Linac4 will be built at its "final" location</u>

...a short word on test beams at CERN and around the World

Laboratory	# beamlines	Particles	Energy Range	Diagnostics	Availability
CERN PS	4	p (prim.) e, h, μ (sec.)	26 GeV 1-15 GeV	Cherenkov, TOF, MWPC	continuous except winter shut down, Duty cycle depends on SPS Super Cycle (@ SPS 15% - 30%)
CERN SPS	4	P (prim.) e, h, μ (sec.) e, h tertiary	400 GeV 10 - <400 GeV 2 – 10 GeV	Cherenkov, CEDAR, TOF, MWPC	
DESY	3	e (prim.) e (sec.)	7 GeV 1 – 6 GeV	no external beam diagnostics	>3 months per year
Fermilab	1	p (prim.) p, K, π, e, μ (sec.)	120 GeV 1 – 85 GeV	Cherenkov, TOF, MWPC, SiStrips, Pixels	continuous (5%), except summer shutdown
Frascati	1	e	25 – 750 MeV		6 months per year
IHEP Beijing	3	e (prim.) e, p, π (sec.)	1.1 – 1.5 GeV (prim.) 0.4 – 1.2 GeV (sec.)	Cherenkov, TOF, MWPC	continuous after March 2008
IHEP Protvino	4	P (prim.) p, K, π, μ	70 GeV 1 – 45 GeV	Cherenkov, TOF, MWPC	one month, twice per year
J-Parc					available in 2009
KEK Fuji	1	e (prim.) e (sec.)	8 GeV 0.5 – 3.4 GeV		available autumn 2007, ~240 days/year
LBNL	1	e (prim.) p n	1.5 GeV < 55 MeV < 30 MeV	Pixel telescope	continuous
SLAC	1	e (prim.) e, p, π (sec.)	28.5 GeV 1 – 20 GeV		parasitic to PEPII, non-concurrent with LCLS

CERN continues to provide beams of many particles over a wide energy range (1 - 450 GeV @ PS & SPS)

→ excellent support, well established infrastructure

→ high duty cycle

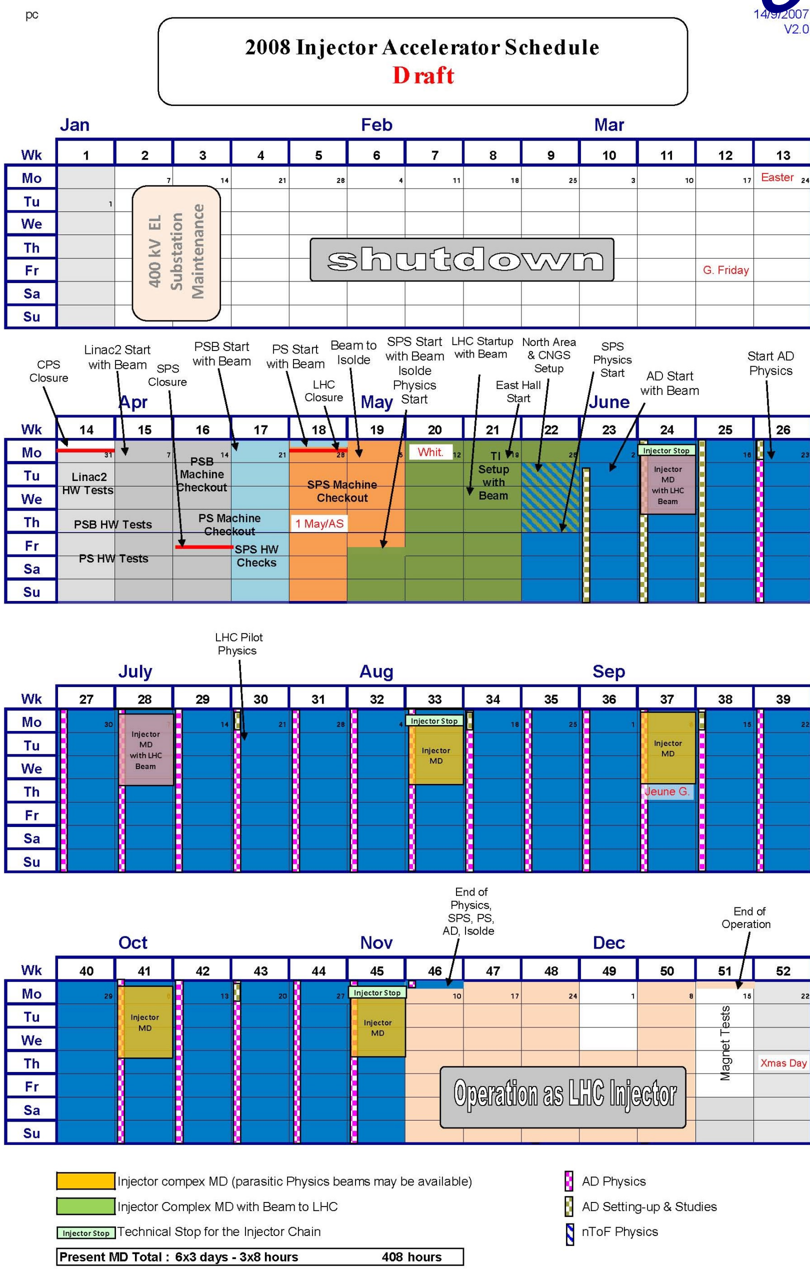
→ "simple" to get beam time

Other beam tests with particle energies <30GeV:

Fermilab: 1 (new) beam line, can be used 5% of accelerator on time

IHEP Protvino: 4 beam lines, two months per year

Summary



- **Rich Physics Program** at the CERN **PS** and **SPS** accelerators:
  - → High efficiency and very good performance of the machines
  - → Unique experimental facilities and excellent service/support by the CERN teams for all colleagues and users
  - ⇒ Large communities from different fields in HEP community continue to use and profit from the existing facilities

- **Looking forward** to the year **2008**:
  - → PS physics start May 19 2008...
  - → SPS physics start May 29 2008...
  - → AD physics start June 23 2008...
  - → LHC start in summer...

...it will be again an exciting year for physics!!!!

...see you at CERN!!!