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CERN Academic
Lectures
May 2008

Energy isn't Everything
CERN's Fixed Target Niche

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Abstract

Fixed target physics at CERN remains an essential part of the laboratory's scientific programme and horizon. In recent years fixed target and decay physics using CERN's unique accelerator and beam facilities continues to enable unique experiments to be undertaken. An overview is presented of the status of this physics and, wherever appropriate, of its future.

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Energy isn't Everything
CERN's Fixed Target Niche

1. Overview: the program
2. Nuclear Matter and QCD Degrees of Freedom
3. Low Energy Hadronic Physics
4. *K*-decay Physics
5. Understanding anti-matter
6. The spin-structure of the Nucleon
7. Scalar Fields ?
8. Neutrino Physics @ CERN
9. Onwards

"I cannot choose the best. The best chooses me." Rabindranath Tagore

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1. Overview: the programme

- heavy ion programme @ SPS

1. **NA49** Large Acceptance Hadron Detection for an Investigation of Pb-induced Reactions at the CERN SPS *completing*
2. **NA60** Study of Prompt Dimuon and Charm Production with Proton and Heavy Ion Beams at the CERN SPS *completing*
3. **NA61** Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS *data-taking*

- nucleon spin structure and hadronic physics @ SPS

NA58 **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy *data taking*

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Overview: the programme

- AD programme

1. AD-2(**ATRAP**) Cold Antihydrogen for Precise Laser Spectroscopy *data taking*
2. AD-3(**ASACUSA**) Atomic Spectroscopy and Collisions using Slow Antiprotons *data taking*
3. AD-4(**ACE**) Relative Biological Effectiveness and Peripheral Damage of Antiproton Annihilation *data taking*
4. AD-5(**ALPHA**) Antihydrogen Laser Physics Apparatus *constructing and commissioning*

- particle astrophysics

CAST A Solar Axion Search Using a decommissioned LHC Test Magnet *data taking*

Overview: the programme

- *K*-decay @SPS

1. **NA48.2** Precision Measurement of Charged Kaon Decay Parameters with an Extended NA48 Setup *completing*
2. **P136** R&D Programme for a measurement of $K \rightarrow \pi \nu\nu$ *on-going*
3. **NA62** Measurement of the ratio $K^+ \rightarrow e\nu / K^+ \rightarrow \mu\nu$ *analysing*

- PS programme

1. PS212 (**DIRAC**) Lifetime Measurements of pi+ pi- Atoms to Test Low-Energy QCD Predictions *data taking*
2. PS214 (**HARP**) Hadron Production for the Neutrino Factory and for the Atmospheric Neutrino Flux *completing*
3. PS215 (**CLOUD**) A Study of the Link between Cosmic Rays and Clouds with a Cloud Chamber at the CERN PS *construction and commissioning*

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Overview: the programme

- CNGS programme

1. CNGS1 (**OPERA**) An Appearance Experiment to Search for $\nu_\mu \rightarrow \nu_\tau$ Oscillations in the CNGS Beam
   construction and commissioning
2. CNGS2(**ICARUS**) A search programme for explicit ν-oscillations *construction and commissioning*

- "photon science"

  OSQAR: Photon Regeneration, the QED vacuum, and scalar fields *construction, commissioning, data taking*

- Coherent QED, and Accelerator Science?

  EM Processes in Strong Crystalline Fields *data taking*

What follows is necessarily limited and to my personal taste !

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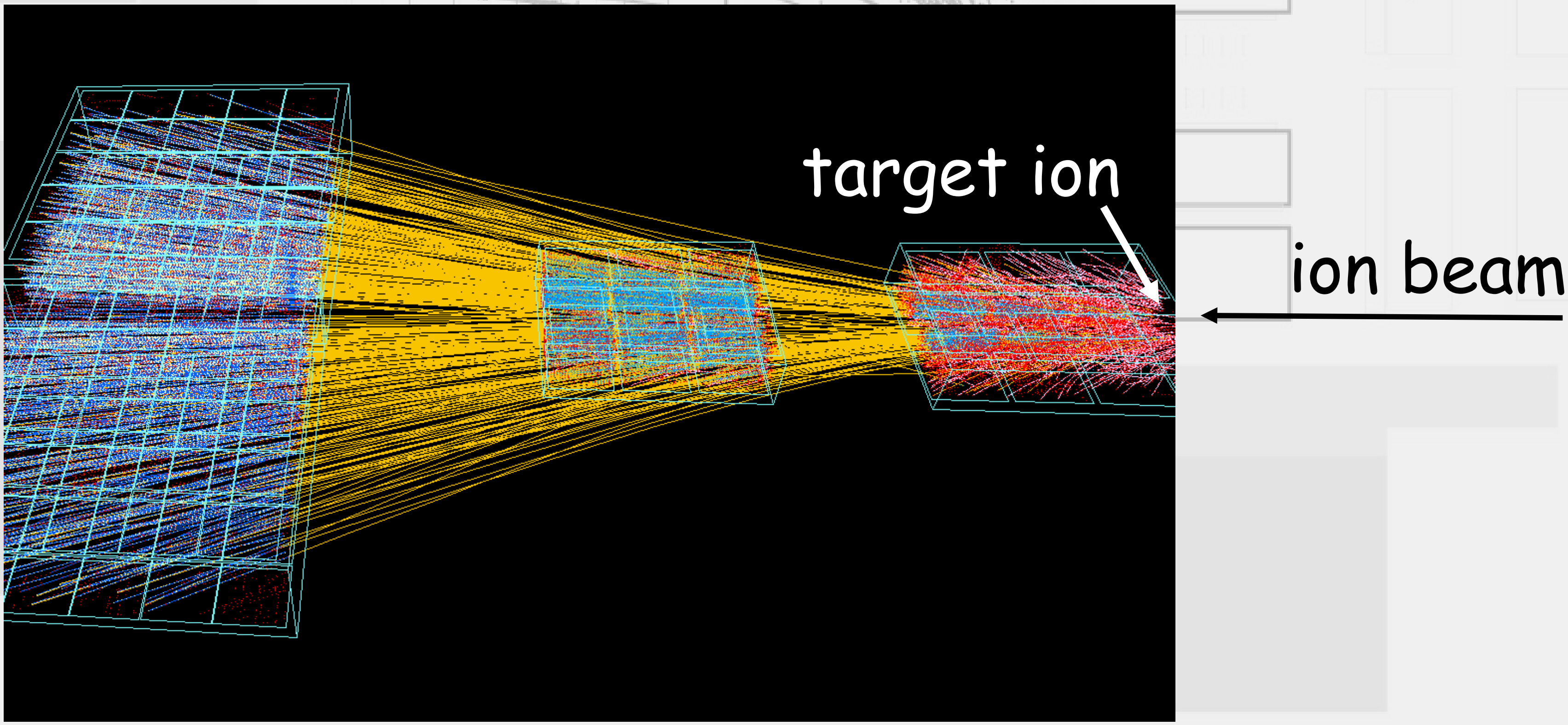
2. Nuclear Matter and Degrees of Freedom

- heavy ion FT physics
  - study of matter at extreme energy density
  - search for state of quasi-free partons
    quarks and gluons → quark-gluon plasma (QGP) ?



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Nuclear Matter

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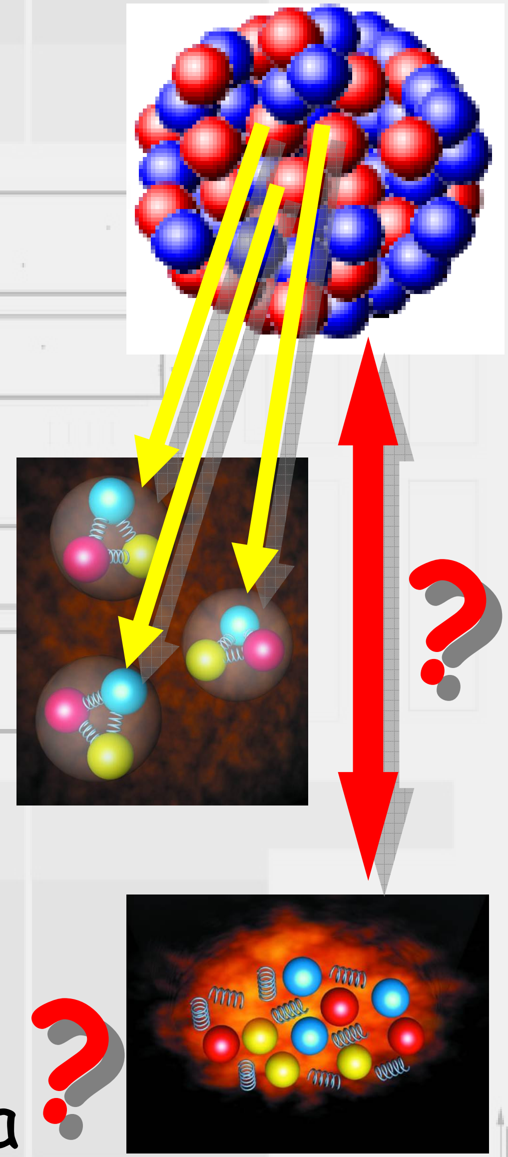
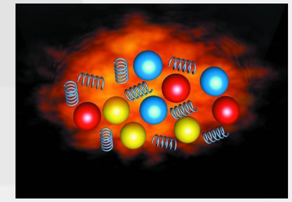
- nuclear matter @ BE (~ MeV) scale
  - colour confinement of QCD d.f.
    → bound state colour singlet (1_c)
    → nucleon d.f.
    → strong (> EM) nuclear force
    saturates → fluid
    $R = 1.25 A^{1/3}$ fm
    1 nucleon per 8 fm^3
    → internucleon force ≲ 1-2 fm
    → independent particle shell



- nuclear matter and QCD d.f

  nucleon phase (confined) ↔ (energy) parton phase (deconfined)
  Quark-Gluon Plasma

Nuclear Matter as QGP?



- Quark-Gluon Plasma
  - partonic (coloured) d.f.
  - low $T \leftarrow$ overlap nucleons $\leftarrow$ pressure: cold QGP
    neutron star ?
  - higher $T \leftarrow$ heating $\leftarrow$ energy: hot QGP
    $\rightarrow q\bar{q}gg... \rightarrow$ hadrons
  - plasma $\leftarrow$ quasi-free $q\ \bar{q}\ g$
    $\leftarrow q\ \bar{q}\ g$ colour screened by other colour
  - "predicted" feature of chromodynamics (SM)
    non-perturbative (lattice)
  - finite T field theory $\rightarrow$ Universe $\leq 10^{-4}$ s

↳ vital piece of the SM of the Universe

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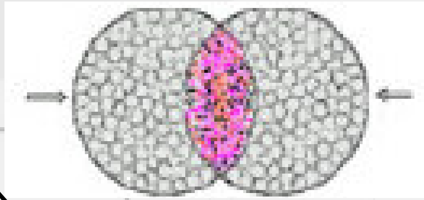
QGP from Ion Collisions ?

courtesy NA49

- hot QGP expectation/phenomenology

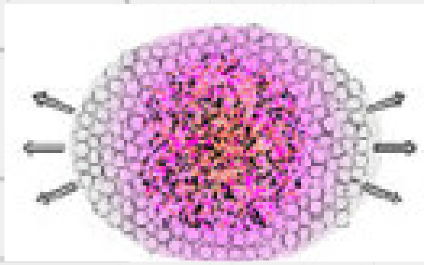
1. microscopic nucleon collisions



$qqq\ q\bar{q}\ g \rightarrow$ pre-equil$^{\underline{m}}$ parton state

net mom$^{\underline{m}}$ along beam $\leftrightarrow$

2. parton re-scattering $\rightarrow$ thermal



$q\ \bar{q}\ g \rightarrow$ pre-equ$^{\underline{m}}$ parton state

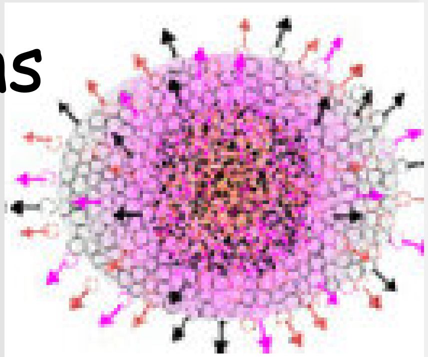
mom$^{\underline{m}}$ equi-partition

$u\ \bar{u}\ d\ \bar{d}\ s\ \bar{s}$ equi-partition

few GeV/fm^3 $\rightarrow$ QGP @ high T?

3. QGP (?) expands and cools $\rightarrow$ hadrons

(if QGP) phase transition



4. hadrons re-scatter and interact

dilution

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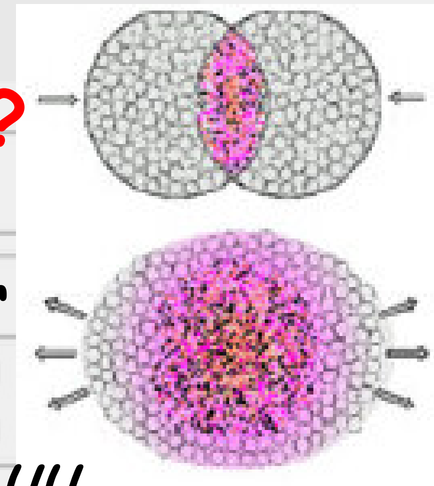
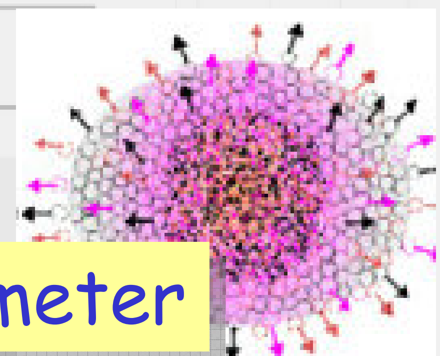
QGP Signatures ?

courtesy NA49

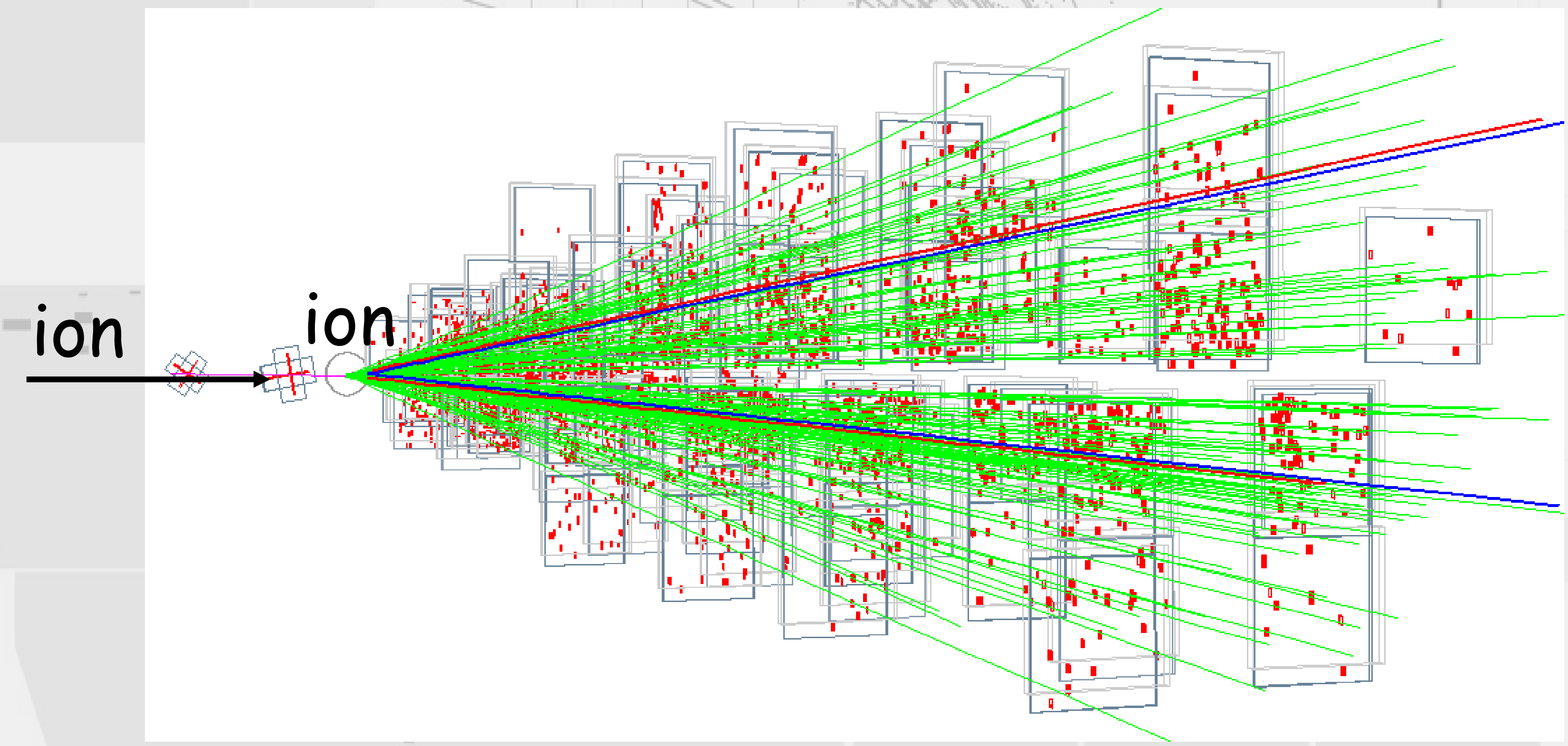


- hot QGP experiment: high energy AA
  - microscopic nucleon collisions
    + parton re-scattering → thermal QGP?
    ↳ enhanced γ (black body) → detector
    enhanced $e\ \mu$ (black body) → detector
    suppressed $J/\psi\ \ \psi'$ → detector
    ρ-resonance distortion $q\bar{q}\,/\,\pi\pi \to \rho \to \mu\mu$
  - QGP(?) expands and cools → hadrons
    + hadrons re-scatter and interact
    ↳ re-scattering preserves light flavours
    hadron flavour mix → **hadron thermometer**
    → T_c @ QGP-hadron phase change ?
    → μ_B@ QGP-hadron phase change ?



Experiment

- heavy ion FT physics
  - *InIn PbPb AuAu* and *pA* physics with high multiplicity tracking



  - LHC technology synergy (NA60)

NA60

Third generation experiment which focuses on particular QGP signatures difficult to access at colliders (RHIC)

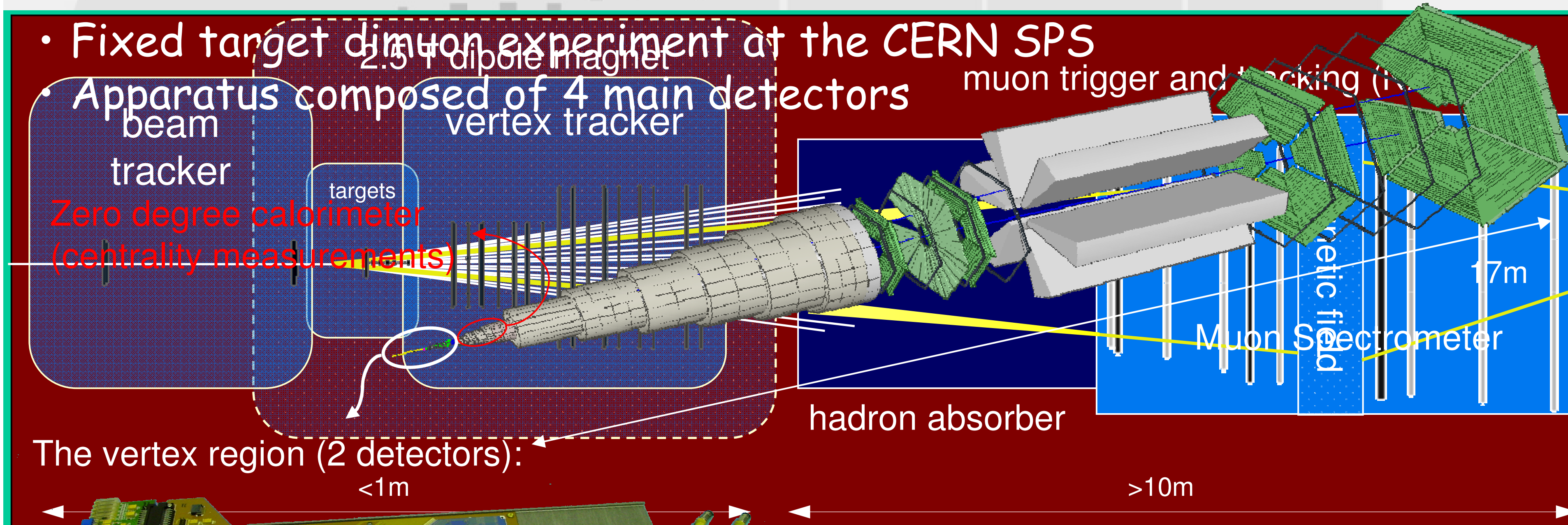
Properties of the possible phase transition assessed through a study of muon pair production with unprecedented precision

Investigated QGP signatures:

- ρ meson: mass and decay width sensitive to chiral symmetry restoration
- J/ψ meson: production sensitive to onset of deconfinement
- Continuum muon pairs: thermal radiation from the plasma

NA60

- Fixed target dimuon experiment at the CERN SPS
- Apparatus composed of 4 main detectors



Concept of NA60: place a *silicon tracking telescope* in the vertex region to measure the muons *before* they suffer multiple scattering in the absorber and *match* them (in both angles and momentum) to the tracks measured in the spectrometer

Origin of muons can be accurately determined
Improved dimuon mass resolution
(~20 MeV/c^2 at ω instead of 80 MeV/c^2)

High luminosity $\mu\mu$ experiment:
possible with radiation tolerant detectors and high speed DAQ

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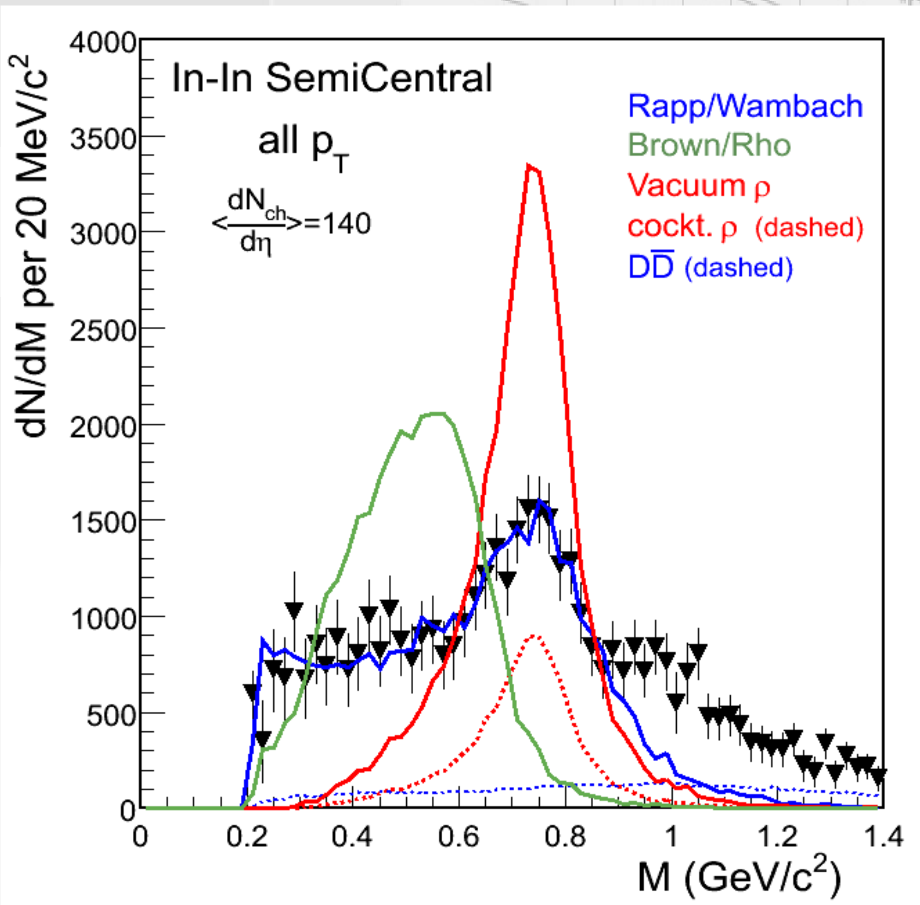
NA60

ρ yield largely dominated by the process $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$

For the first time in-medium properties of the ρ meson assessed quantitatively

towards asymptotically free *q* and *g* in QCD



No change in mass (BR), only strong broadening (RW) observed

Connection with chiral symmetry restoration under investigation

Which processes contribute to $m_{\mu\mu}$ > 1 GeV?

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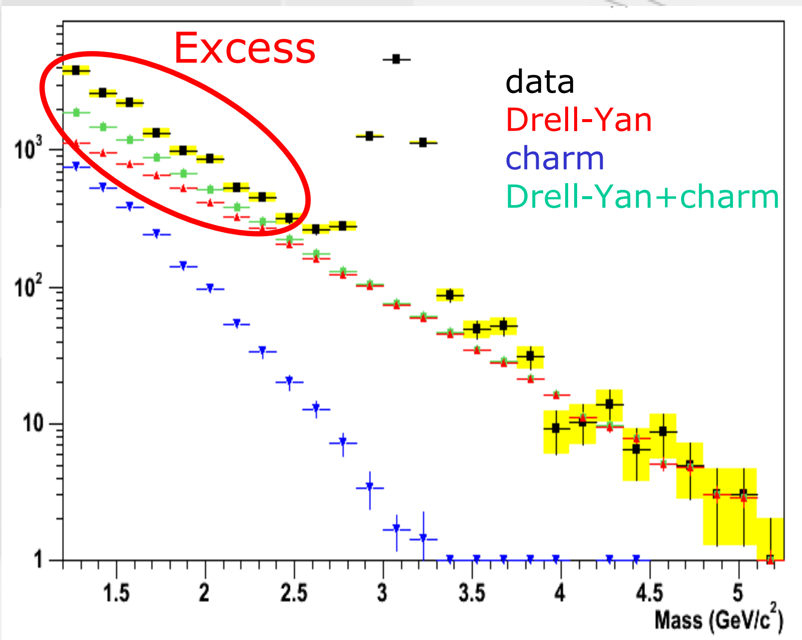
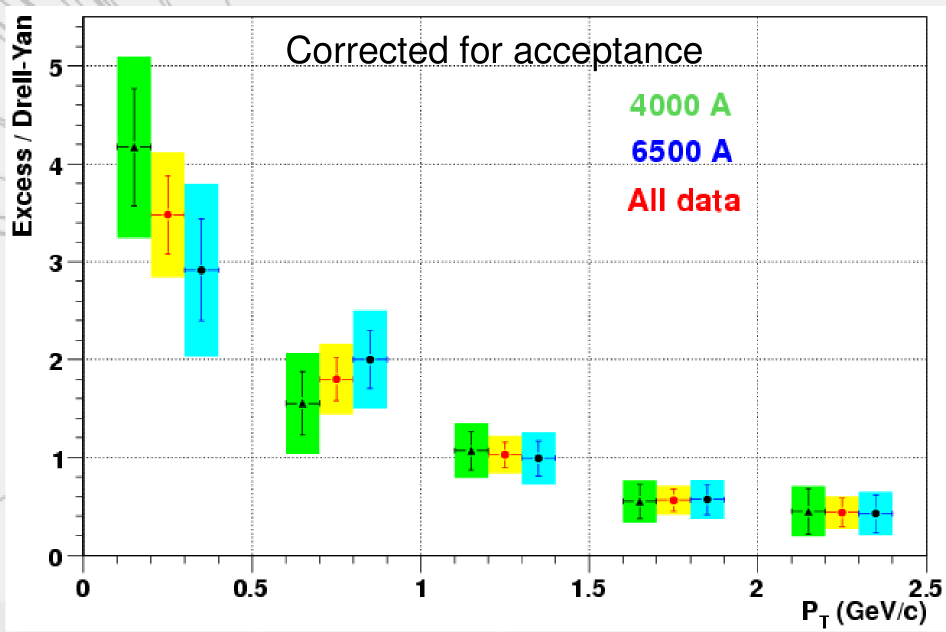
NA60

Clear μμ excess over expected Charm and Drell-Yan yields observed

Enhanced open charm excluded by precise measurement of muon track offset with respect to the primary interaction point





Excess qualitatively different from Drell-Yan (strongly concentrated at low p_T)

Looks related to a soft process like $q\bar{q}$ annihilation in a deconfined phase or multipion annihilation $\Rightarrow$ Thermal radiation

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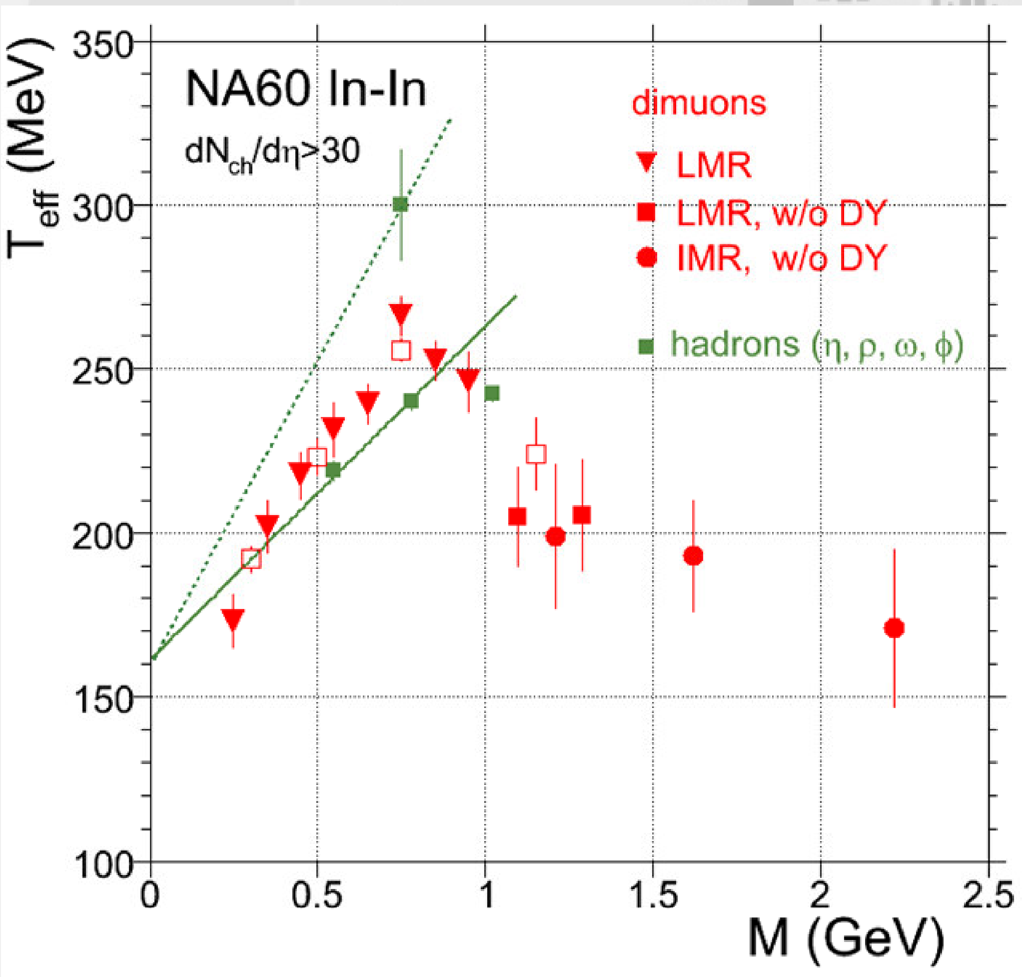
NA60



Strong rise of T_{eff} with dimuon mass, followed by a sudden drop for M>1 GeV

Rise consistent with collective motion (radial flow) of a hadronic source (here $\pi\pi \rightarrow \rho \rightarrow \mu\mu$)

Drop signals sudden transition to low-flow source, i.e. source of partonic origin (here $qq \rightarrow \mu\mu$)

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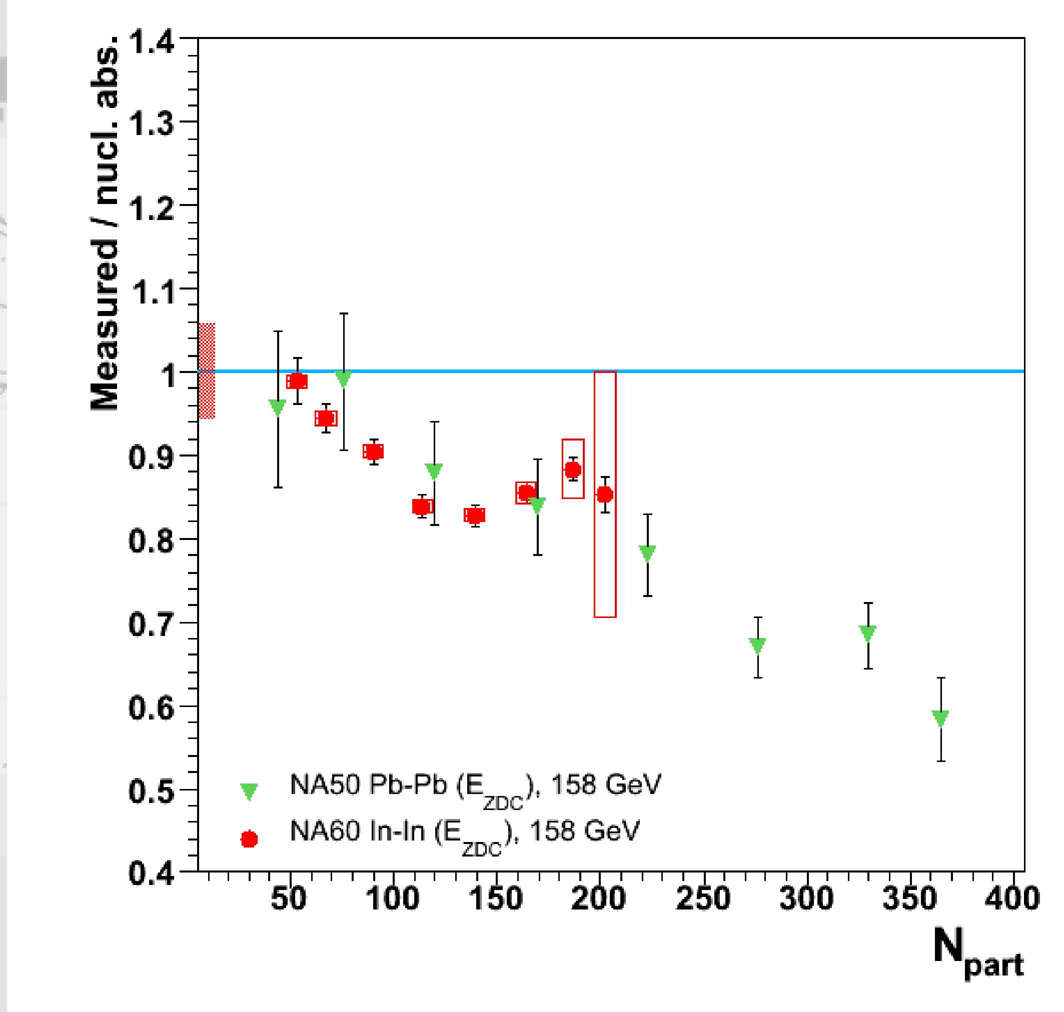
NA60

Anomalous suppression detected in Indium-Indium starting at N_{part} ~ 80, corresponding to an energy density ~ 1.5 GeV/fm^3

Centrality dependence of J/Y suppression determined by NA60 much more precisely than previous measurements

J/Y suppression marking the onset of deconfinement?



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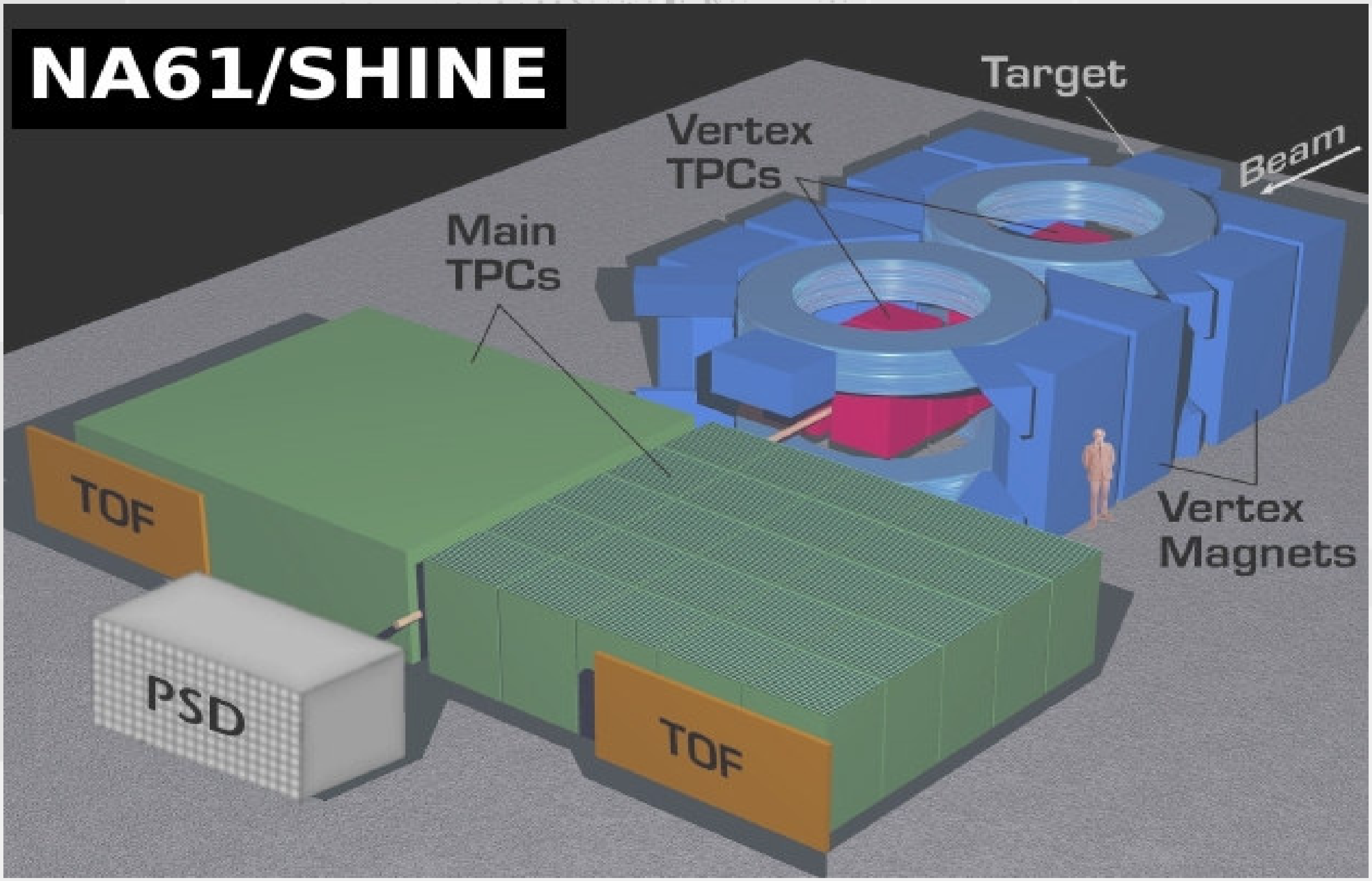
NA49

- noble gentleman of ion physics
  - matamorphosing into the future !



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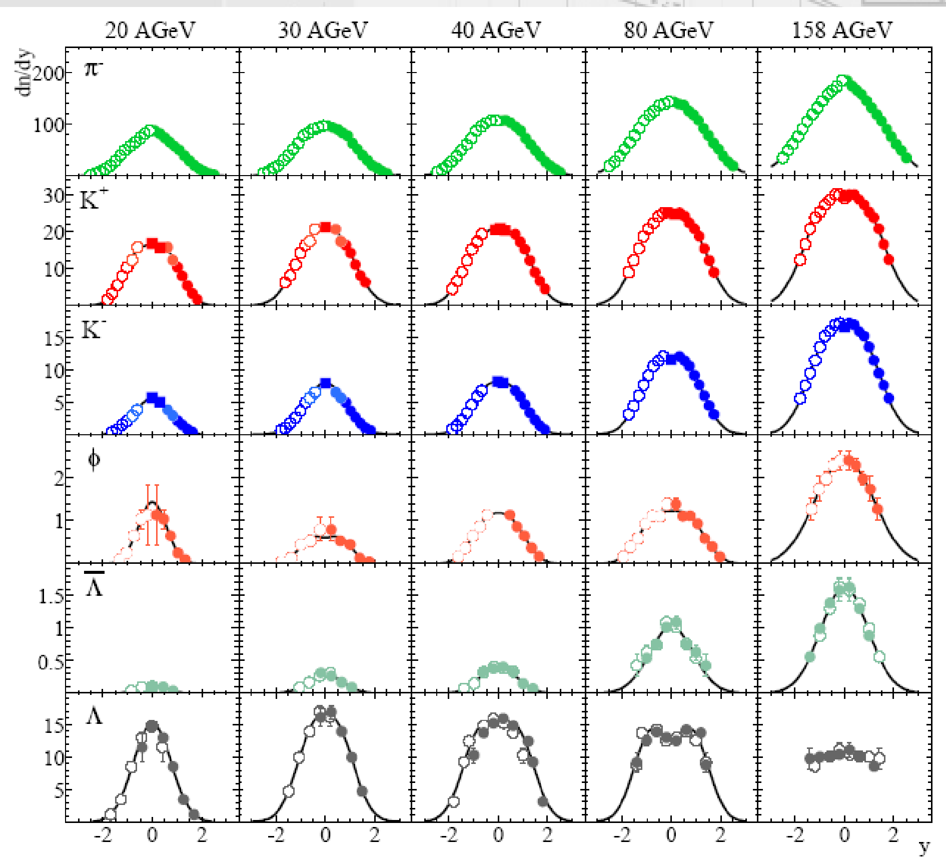
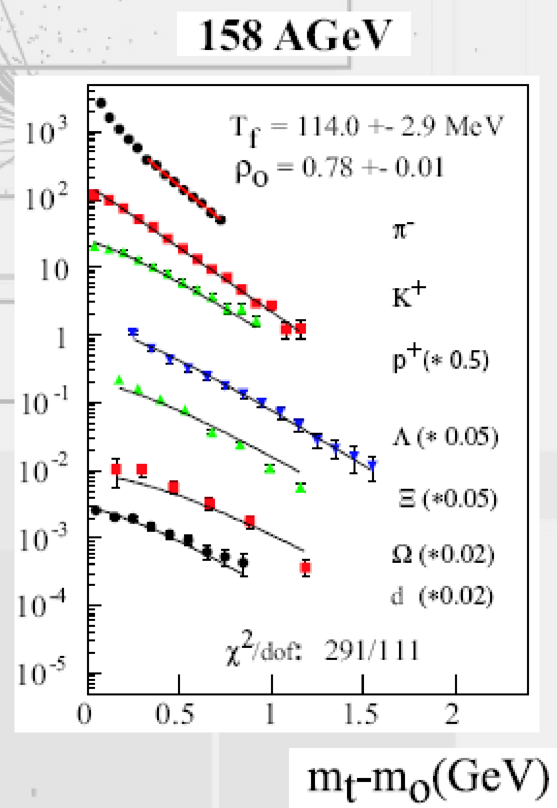
NA49

- yields and momentum spectra →
properties of the matter created in collisions

longitudinal momentum (rapidity) spectra



transverse momentum spectra



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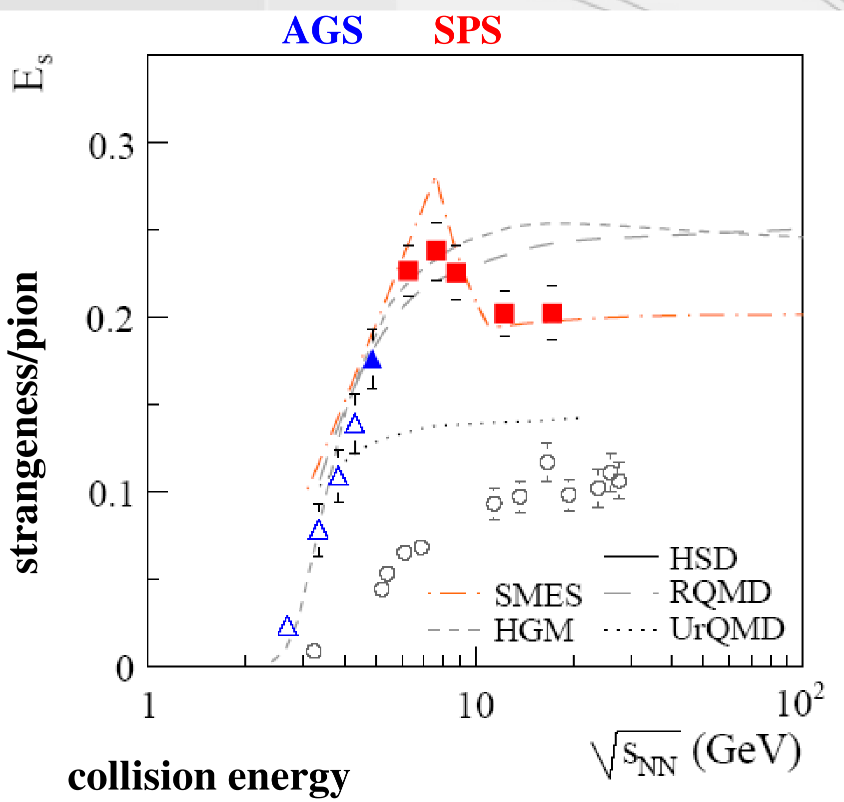
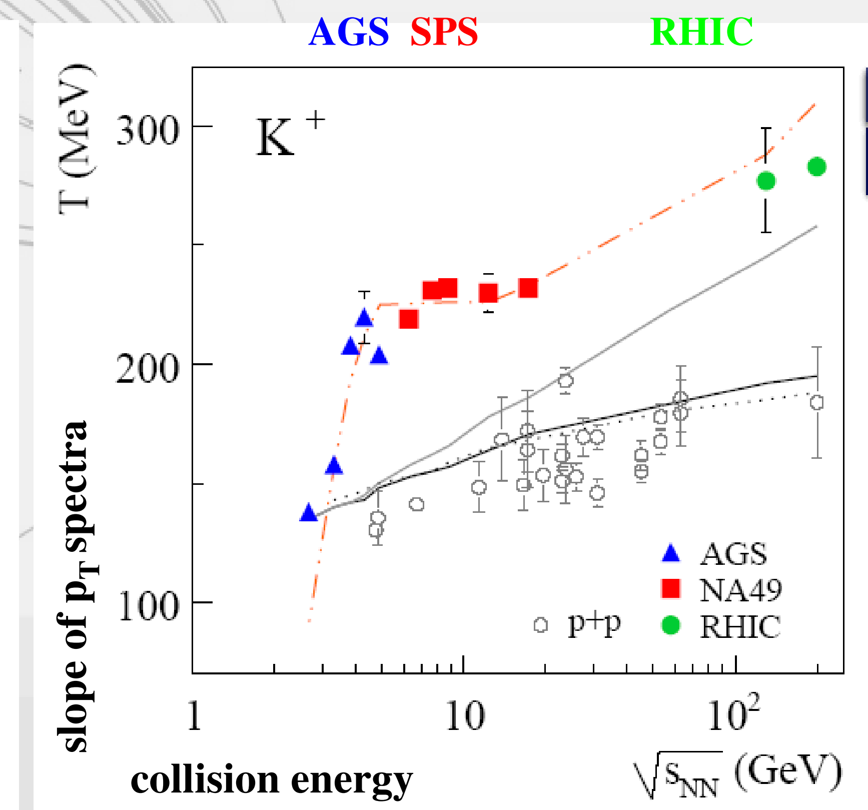
NA49

- central Pb+Pb collisions
  hadron gas (AGS) ↔ QGP (SPS/RHIC) ?





- models without deconfinement fail

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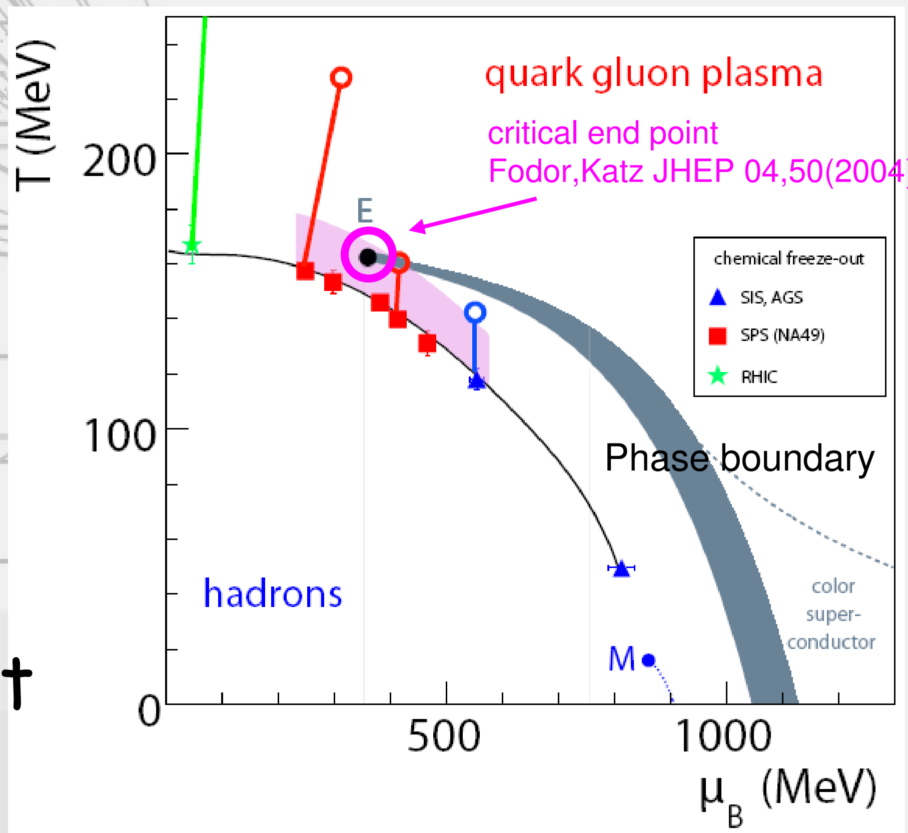
NA49

- matter in central *PbPb* collisions at SPS ?
  - fit hadron gas model to particle yields

F.Becattini et al, PRC69 (2004) 024905)



- QCD → 1^{st} order phase transition + critical point

- hadron condensation
  ~ QCD-lattice critical point

- confinemen ↔ phase equilibria ← QGP ?

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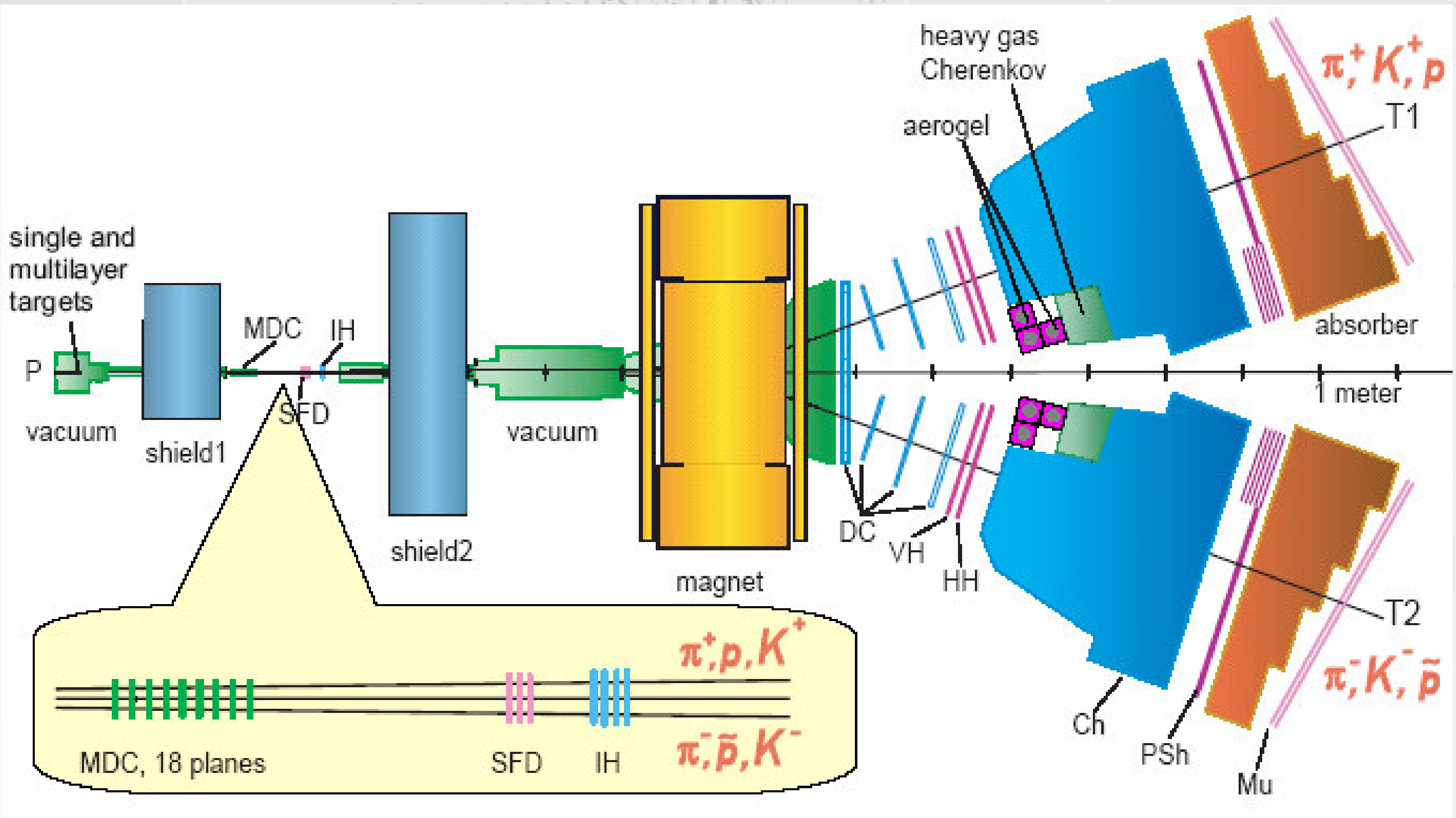
Ion Physics @ CERN

- heavy ion FT physics
  - SPS fixed target
    - equilibrating deconfined QCD
      - dilepton excess: flow $\pi\pi \to \rho \; M \leq M_\rho$ ✔
      - $qq \to \rho \; M > M_\rho$ ✔
      - J/ψ suppression ✔
      - ρ distortion: to be understood ✔
    - hadron condensation:
      - strangeness/$\pi \to$ models with deconfinement
      - hadron thermometer (fireball + data) ✔
    - $\to$ phase transition to QGP?

↳ unique future ion physics @ CERN FT + LHC (+ RHIC @ BNL)

3. Low Energy Hadronic Physics

- DIRAC: precision low mass di-meson spectrometer $\pi\pi$ and $K\pi$ scattering lengths



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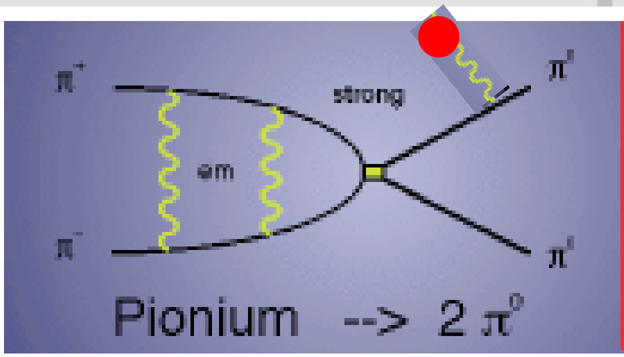
Low Energy Hadron Physics: DIRAC



Pionium or $A_{2\pi}$ can be produced in the interaction of a 24 GeV/c proton beam with nuclear targets (eg. Ni). These exotic atoms originate from Coulomb attraction in the final state, when the relative distance between 2 pions is of the order of few fm.

The **aim** of **DIRAC** is to detect $\pi^+\pi^-$ **pairs** originating from $A_{2\pi}$-BREAKUP (ionization) in the same nuclear target: These so-called "atomic pairs" are characterized by small opening angles (< 3 mrad) and small relative pair momenta **Q < 3 MeV/c**.

The detection of "atomic pairs" allows to determine the $\underline{A_{2\pi}\text{ BREAKUP probability}}$, which is a function of the $A_{2\pi}$ LIFETIME.

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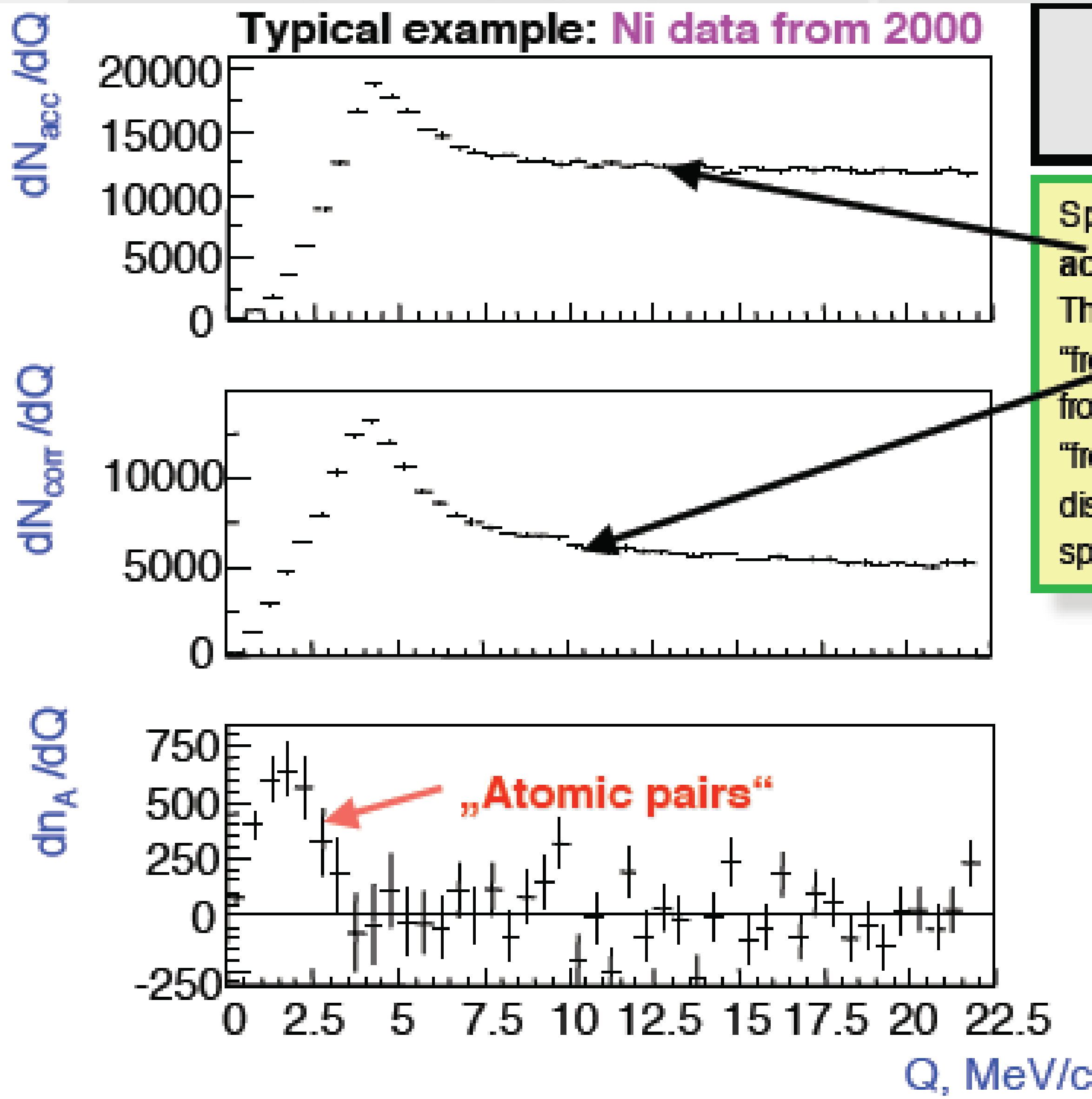
Low Energy Hadron Physics: DIRAC

Typical example: Ni data from 2000



„Accidental“ & „correlated“ pairs:

Spectra of $\pi^+\pi^-$ relative momenta Q for accidental and time-correlated pairs. The latter sample dN_{corr}/dQ contains mainly "free" and few "atomic" (Q < 4 MeV/c) pairs from pionium ionization. For Q > 4 MeV/c the "free pair" spectrum dN_{free}/dQ is fitted by a distribution, based on the "accidental pair" spectrum.

Method

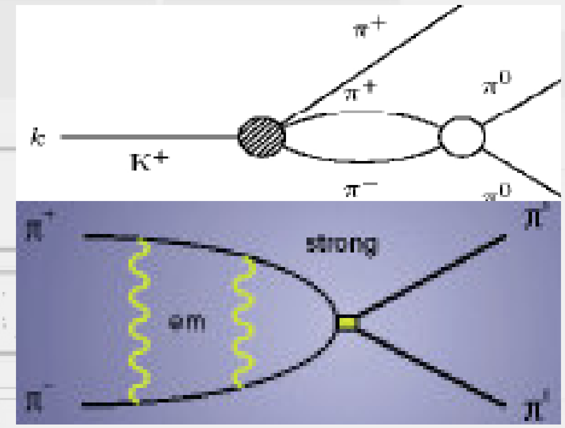
Effect ⇒ "Atomic pairs":
Difference between the spectra dN_{corr}/dQ observed and dN_{free}/dQ predicted for all Q: → Residual pairs. The excess at low Q is the **signal** for "atomic pairs", i.e. $\pi^+\pi^-$ pairs from pionium ionization.

Low Energy Hadron Physics: DIRAC

- measuring low energy $\pi\pi$ scattering
  - *K*-decay

    isospin amplitudes: a_0 and a_2
  - pionium → $\pi\pi$

    isospin amplitude comb$^{\underline{n}}$: a_0 - a_2



- measuring low energy $K\pi$ scattering
  - "kapionium" → $K\pi$

    isospin amplitude comb$^{\underline{n}}$: a_1 – a_3
- at low energy potential structure not resolved

→ scattering length a_s

$$\sigma = \frac{4\pi}{k^2}\sin^2\delta_s = 4\pi a_s^2$$

↳ important test of QCD at low energy

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Low Energy Hadron Physics: DIRAC

Low-energy QCD predictions for $\pi\pi$ scattering lengths (s-wave):

$a_0 = 0.220 \pm 2.3\%$ $a_2 = -0.0444 \pm 2.3\%$ $a_0 - a_2 = 0.265 \pm 1.5\%$

Experiments

*) using Roy equations

$K \to \pi^+\pi^- e^+\nu_e (K_{e4})$:

1) 1977 Geneva-Saclay: (PR D15, 574) $a_0 = 0.28 \pm 18\%$ *)

2) 2001 E865 / BNL: (PRL 87, 221801) $a_0 = 0.203 \pm 16\%$ *)

$a_2 = -0.055 \pm 42\%$

3) 2008 NA48 / 2: (EPJ C54, 411) $a_0 = 0.233 \pm 7\%(stat) \pm 3\%(sys) = \ldots \pm 7.5\%$ *)

$a_2 = 0.0471 \pm 23\%(stat) \pm 8\%(sys)$

$K \to \pi^0\pi^0\pi^+$:

2006 NA48 / 2: (PL B633, 173) $a_0 - a_2 = 0.268 \pm 3.7\%(stat) \pm 1.5\%(sys) \pm 4.8\%(ext) = \ldots \pm 6.2\%$

Low Energy Hadron Physics: DIRAC

Low-energy QCD predictions for scattering lengths (s-wave):

ππ: $a_0 - a_2 = 0.265 \pm 1.5\%$ *πK:* $a_1 - a_3 = 0.24$ (1−loop) $a_1 - a_3 = 0.269 \pm 6\%\ (RS)$

Experiments

$A_{2\pi}$ lifetime:

1) 2005 **DIRAC**: (PL B619, 50) $a_0 - a_2 = 0.264 \pm 7.5\%(stat) \pm {}^{3}_{8}\%(sys) = \ldots \pm {}^{8}_{11}\%$

...based on 2001 data (6530 observed atoms)

2) 2008 **DIRAC**: preliminary $a_0 - a_2 = 0.268 \pm 4.5\%(stat) \pm {}^{1.9}_{2.2}\%(sys) = \ldots \pm {}^{4.9}_{5.0}\%$

...from major part 2001-03 data (13390 observed atoms)

3) >2008 **DIRAC**: $a_0 - a_2 = \ldots \pm 2\%(stat) \pm 1\%(sys) \pm 1\%(th) = \ldots \pm 2.4\%$

...after data collection in **2008 & 2009**

$A_{\pi K}$ lifetime:

>2008 **DIRAC**: $a_1 - a_3 = \ldots \pm 10\%\,(stat)$

...after data collection in **2008 & 2009**

↳ on the way to checking chromodynamic χPT

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4. *K*-decay Physics

- direct $\not{CP}$ in K^0 rare decays
- semi-leptonic decays

NA48: ε'/ε	1997
ε'/ε	1998
ε'/ε	1999
no spectrometer: K_L / NA48/1 K_S	2000
ε'/ε lower inst. intensity	2001
NA48/1: K_S	2002
NA48/2: $K^{\pm}$	2003
NA48/2: $K^{\pm}$	2004
NA62: K^+	2007

- $K^0_{S,L}$ in neutral final states
- K^0_S rare decays
- neutral hyperon radiative and semi-leptonic decays
- search for direct $\not{CP}$ in $K^{\pm}$
- $\pi\pi$ scattering
- lepton universality

Courtesy A Ceccucci

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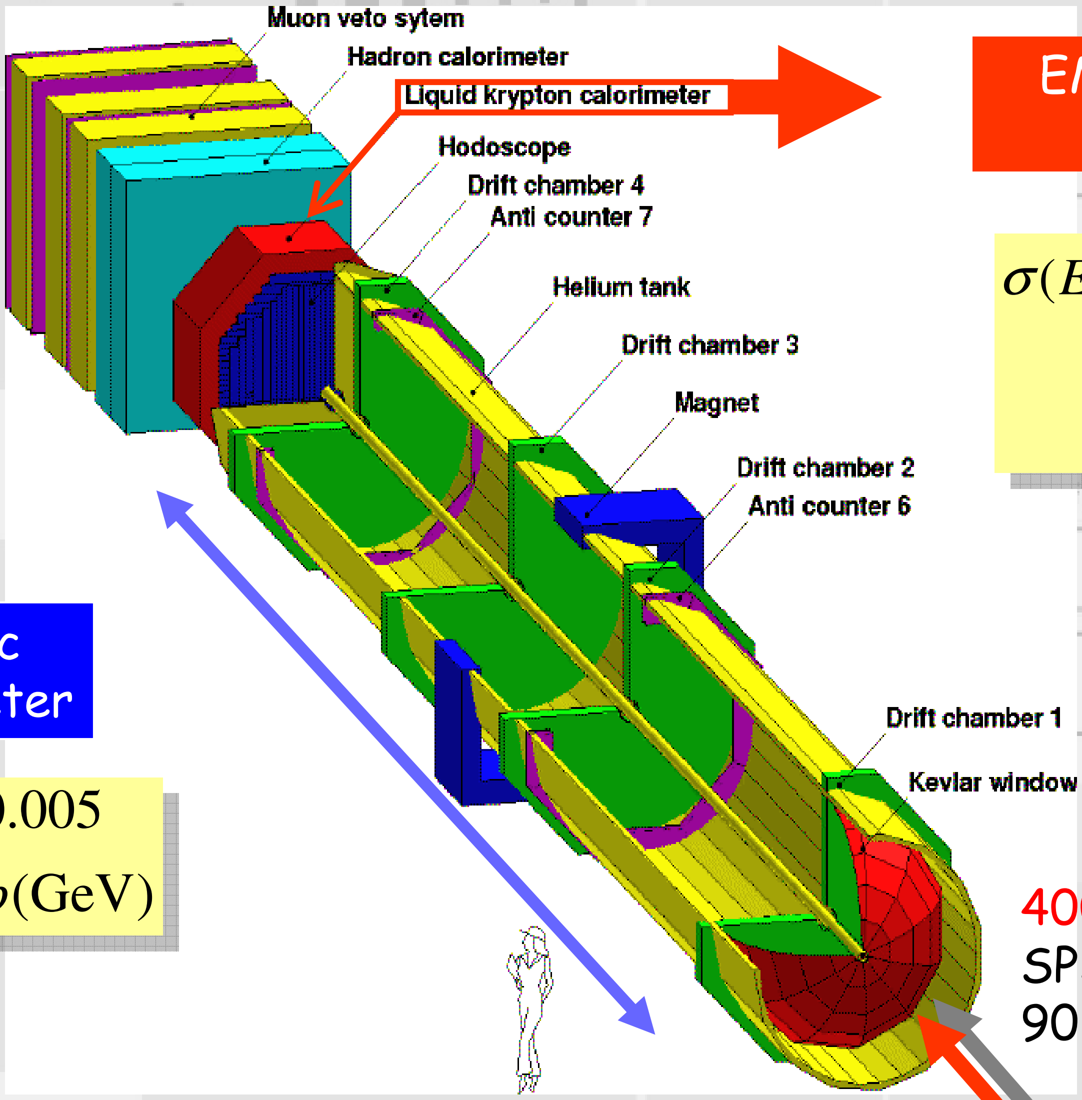
NA48



EM Calorimeter (LKr)

$$\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09\ /E \oplus 0.0042$$

magnetic spectrometer

$$\sigma(p)/p = 0.005 \oplus 0.000\,09\, p(\text{GeV})$$

400 GeV/c protons from SPS on Be target
90 m long decay tank

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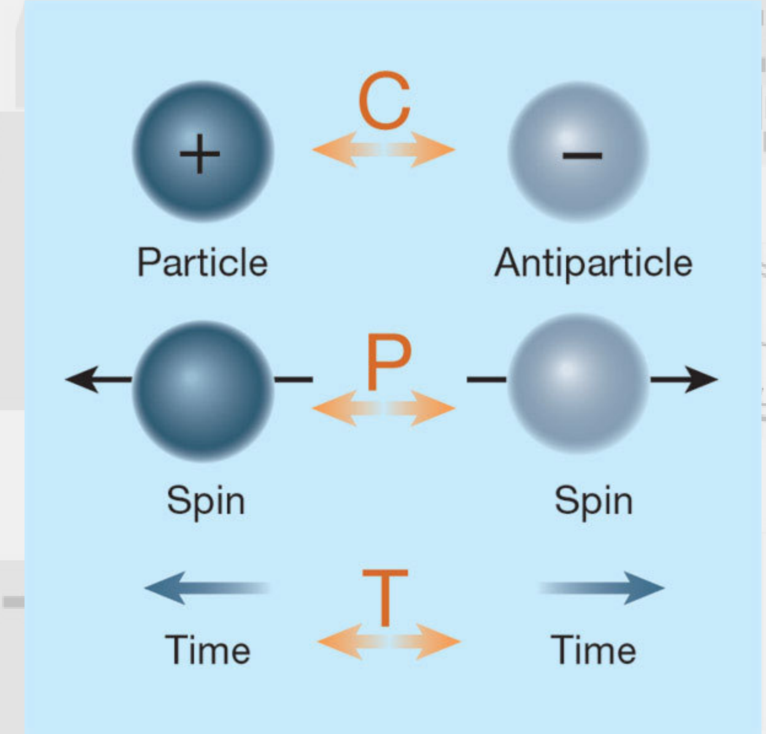
Discrete Symmetries



L. Landau, 1957: "As is well known, the unusual properties of *K*-mesons have created a perplexing situation in modern physics…. Invariance of the interactions with respect to combined inversion (CP) leaves space completely symmetrical….

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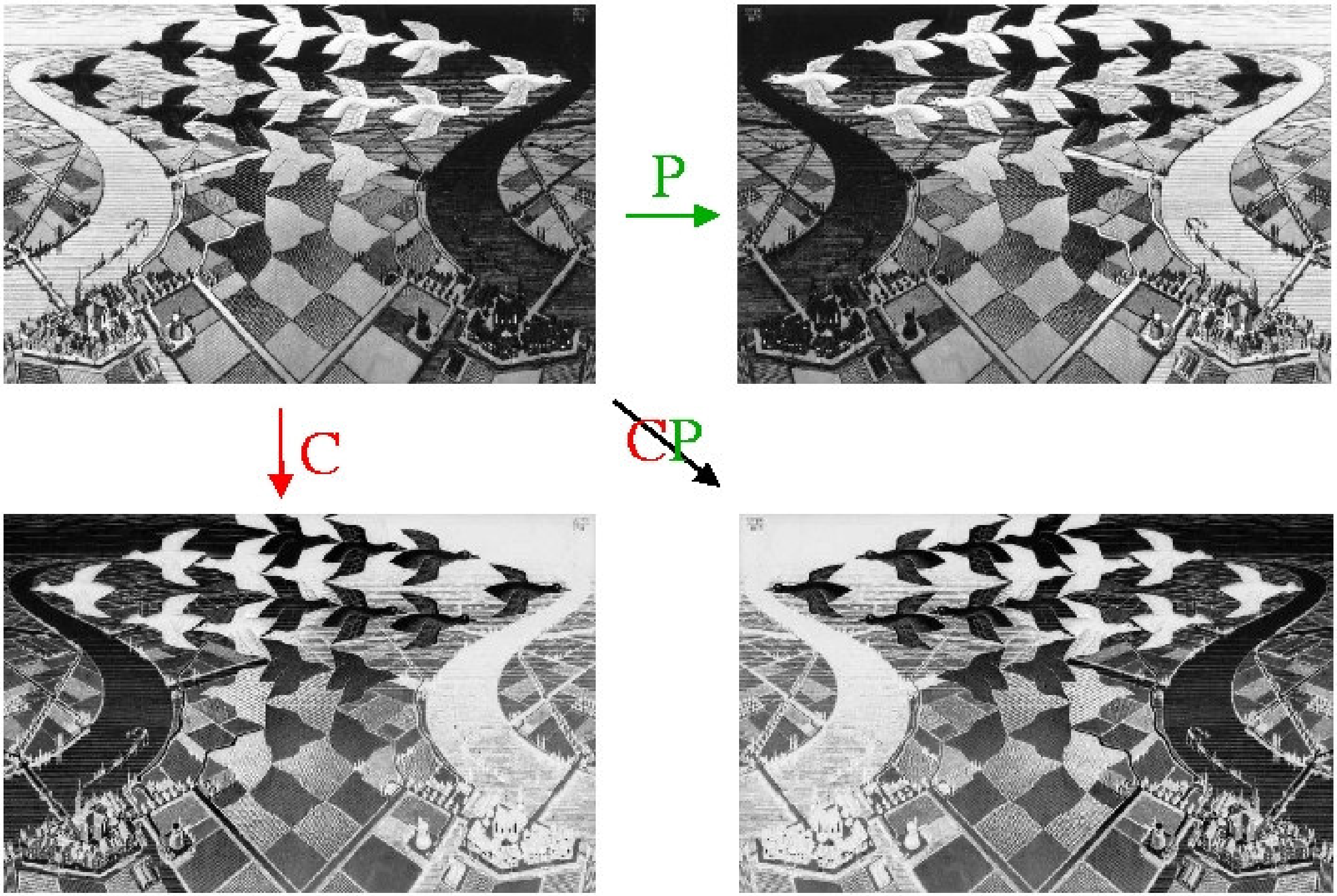
CP Violation



From Gino Isidori:
http://scienzapertutti.lnf.infn.it/P1/schedaCP.html

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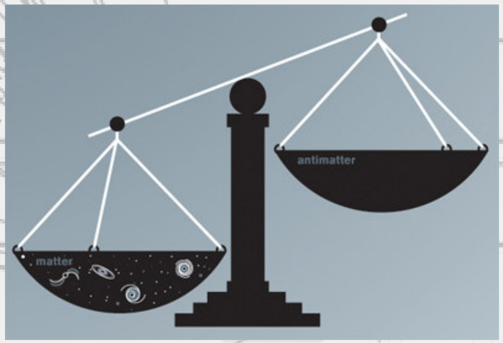
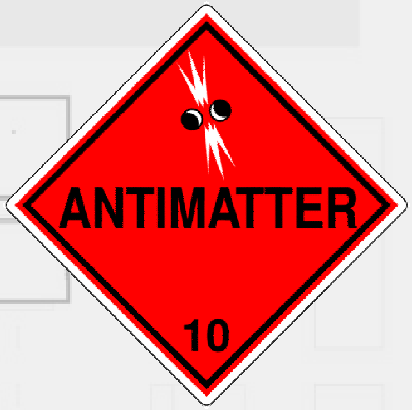
Sakharov Conditions

- matter ~ antimatter
  where has all the antimatter gone?
- early Universe $\frac{n_q - n_{\bar{q}}}{n_q}$
  $\rightarrow$ today $\frac{n_B}{\gamma} \sim 10^{-9}$





- Sakharov Conditions (1967)
  for a Matter Anti-Matter imbalance:
  - baryon number violation
  - non-equilibrium (at some stage)
  - $\not{C}$ & $\not{CP}$

  What is at the origin of $\not{CP}$?

What is (the origin of) $\not{C}P$?

- discovery of $\not{C}P$ (BNL 1964)
  - indirect: $R(K^0 \to \overline{K^0}) \neq R(\overline{K^0} \to K^0)$
- super-weak interaction (Wolfenstein)
  - only in indirect (kaon oscillations)
  - not in decays
  - no other plausible experimental effect
- 3 q generations (Kobayashi & Maskawa, 1973)
  (2 q generations no phase $\to CP$
  3 q generations 1 (complex) phase $\to \not{C}P$)
  - before c-quark discovery
  - 3 q generations direct $\to \varepsilon'/\varepsilon \neq 0$ in K-decay
    $\to \not{C}P$ in B-decay

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What is (the origin of) $\not{C}\not{P}$?

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- direct $\not{C}P$

$$\left.\begin{array}{c}(\pi^+\pi^-)\\(\pi^0\pi^0)\end{array}\right\}\ CP = +1$$

subtle differences between K_L and K_s decays to 2π due to different contributions from I=0 and I=2

INDIRECT CPV	DIRECT CPV

$$\frac{A(K_L\to\pi^0\pi^0)}{A(K_S\to\pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\frac{A(K_L\to\pi^+\pi^-)}{A(K_S\to\pi^+\pi^-)} = \varepsilon + \varepsilon'$$

$$\langle 2\pi\,|\,K_L\rangle = \varepsilon\langle 2\pi\,|\,K_1\rangle + \langle 2\pi\,|\,K_2\rangle$$

$\varepsilon' \neq 0$ particle and antiparticle decay rates differ:

$$\frac{\Gamma\left(K^0\to\pi^+\pi^-\right)-\Gamma\left(\overline{K^0}\to\pi^+\pi^-\right)}{\Gamma\left(K^0\to\pi^+\pi^-\right)+\Gamma\left(\overline{K^0}\to\pi^+\pi^-\right)} = 2\mathrm{Re}\left(\varepsilon'\right)$$

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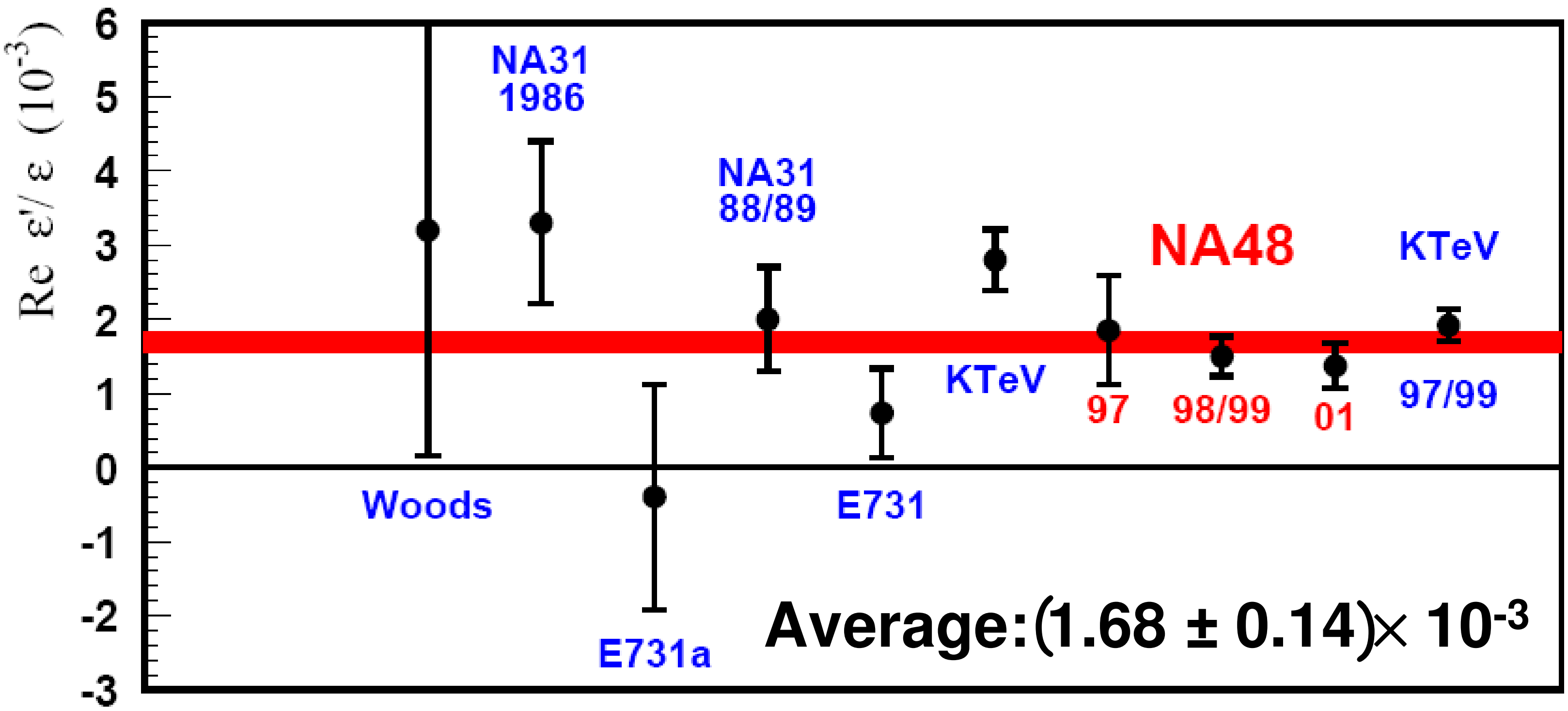
Direct $\not{C}P$: Re ε'/ε

$$R = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right)}{\Gamma\left(K_S \to \pi^0\pi^0\right)} \Big/ \frac{\Gamma\left(K_L \to \pi^+\pi^-\right)}{\Gamma\left(K_S \to \pi^+\pi^-\right)} \approx 1 - 6\ \mathrm{Re}\left(\varepsilon'/\varepsilon\right)$$



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NA48/2

- search for direct $\not{C}P$ in $K \to \pi\pi\pi$
  - precision measurement of Dalitz Plot $|M(u,v)|^2$

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$$

$$u = (s_3 - s_0)/m_\pi^2 \quad v = (s_2 - s_1)/m_\pi^2$$

$$s_i = (p_K - p_{\pi i})^2 \qquad i = 3 \text{ for } \pi \text{ with odd charge}$$

$$s_0 = (s_1 + s_2 + s_3)/3$$

$$A_g = (g^+ - g^-)/(g^+ + g^-) \sim \Delta g / 2g$$

- $A_g > 10^{-5} \to$ direct $\not{C}P$ beyond SM
- narrow-band 60 GeV/c achromatic beam
- concurrently collect K^+ and K^- decays

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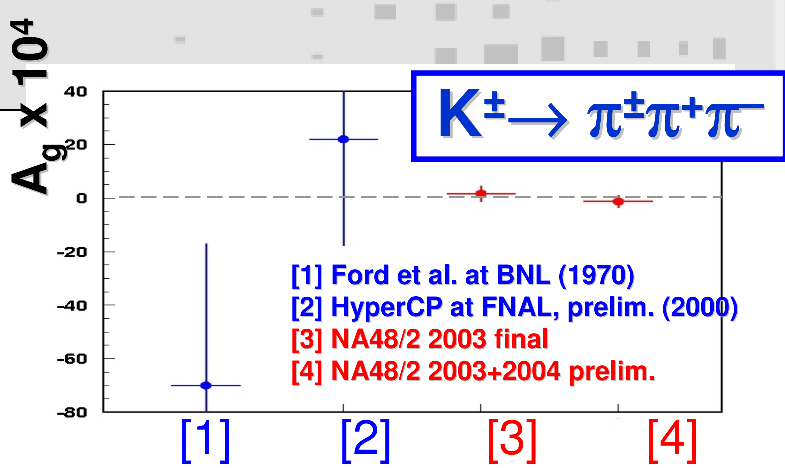
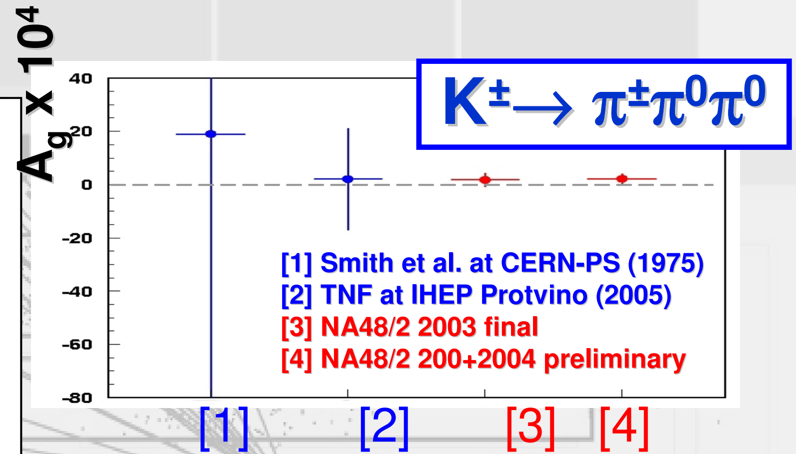
NA48/2

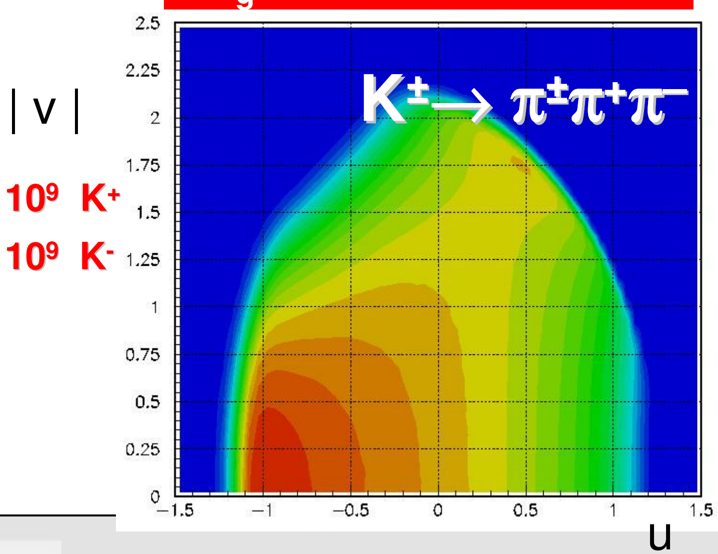




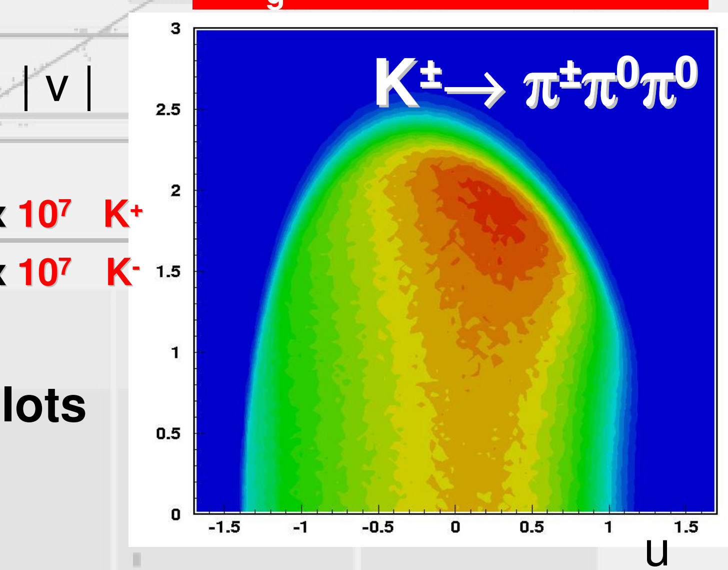
$A^c_g = (-1.5 \pm 2.1) \times 10^{-4}$

$A^n_g = (1.8 \pm 1.8) \times 10^{-4}$

2.0×10^9 K^+
1.1×10^9 K^-



5.9×10^7 K^+
3.2×10^7 K^-



Dalitz Plots

- no signature BSM

hep-ex:07070697

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$C\!\!\!/P$ and Quark Mixing: Outlook

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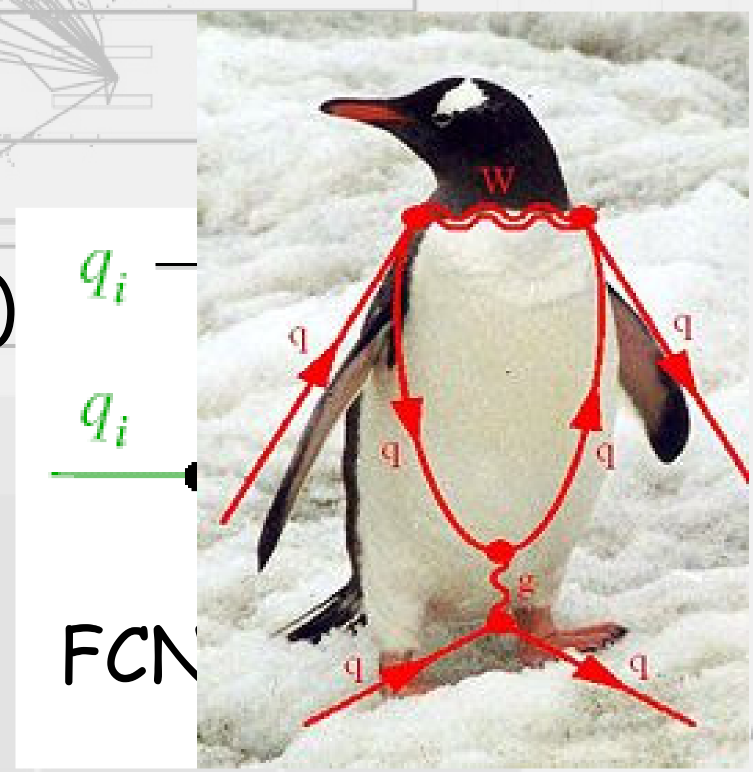
- NA48/2 has closed another window of opportunity
- current observations of $C\!\!\!/P$ (*K* & *B* decay + mixing)
  ← complex phase in CKM
- precise probes for SM deviations ?
  - ultra-rare *K*-decay
  - no SM “tree” (FCNC)
  - short distance dynamics
- experimental challenge (P326)
  BR~ 10^{-10} to 10^{-11}

$K^+ \to \pi^+ \nu \nu$	$K^0_L \to \pi^0 \nu \nu$
$K^0_L \to \pi^0 e^+ e^-$	$K^0_L \to \pi^0 \mu^+ \mu^-$

- ±10% crucial ↔ LHC physics



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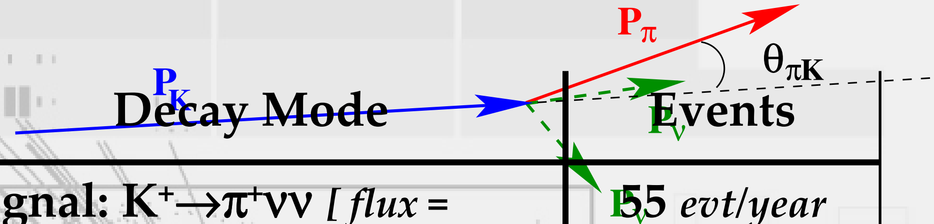
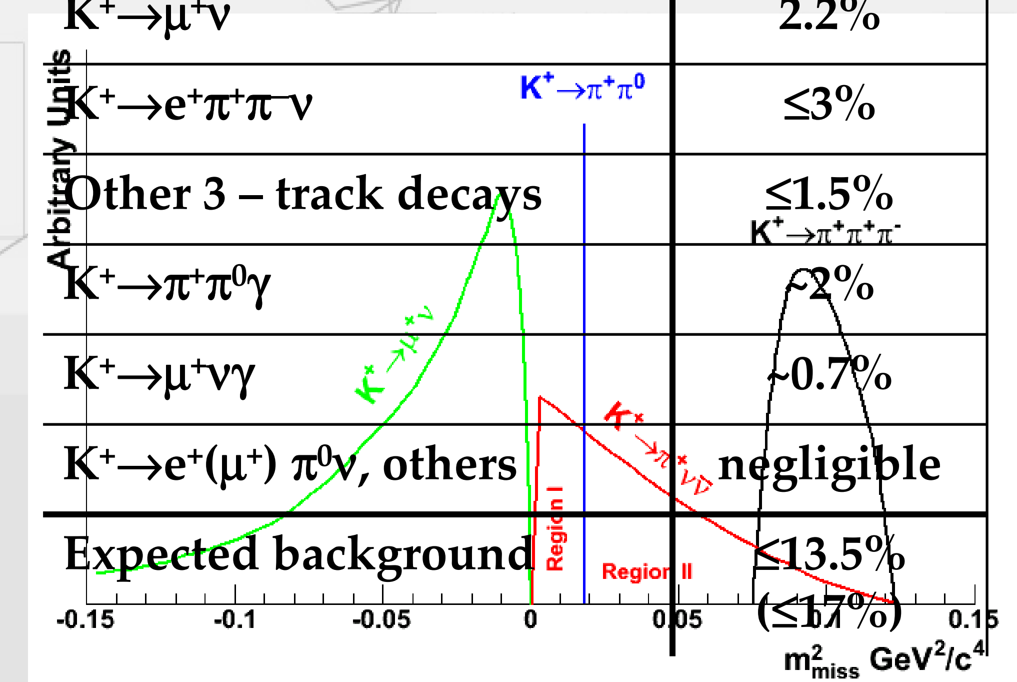
P326: preparing for $K\rightarrow\pi\nu\bar{\nu}$

- experimental method
  - kinematic rejection
  - photon vetoes reject $K^+\rightarrow\pi^+\pi^0$
  - PID (RICH) reject $K^+\rightarrow\mu^+\nu$



$$m^2_{miss} \simeq m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta^2_{\pi K}$$

Decay Mode	Events
Signal: $K^+\rightarrow\pi^+\nu\nu$ *[flux = 4.8×10^12 decay/year]*	55 *evt/year*
$K^+\rightarrow\pi^+\pi^0$ *[$\eta_{\pi 0}$ = 2×10^-8 (3.5×10^-8)]*	4.3% (7.5%)
$K^+\rightarrow\mu^+\nu$	2.2%
$K^+\rightarrow e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+\rightarrow\pi^+\pi^0\gamma$	~2%
$K^+\rightarrow\mu^+\nu\gamma$	~0.7%
$K^+\rightarrow e^+(\mu^+)\ \pi^0\nu$, others	negligible
Expected background	≤13.5% (≤17%)



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P326: preparing for $K \rightarrow \pi\nu\nu$

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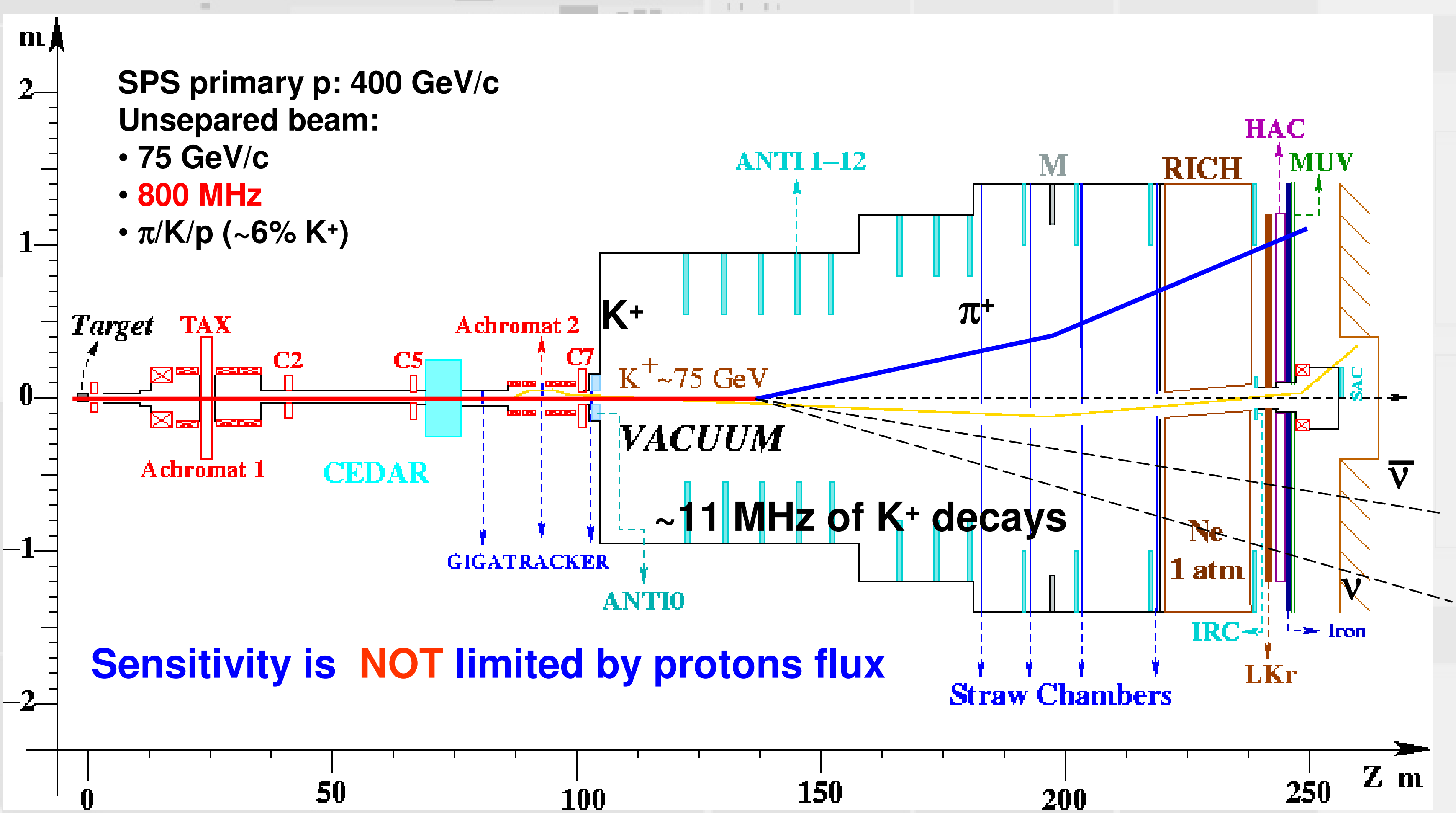

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Interlude: BSM with Chirality

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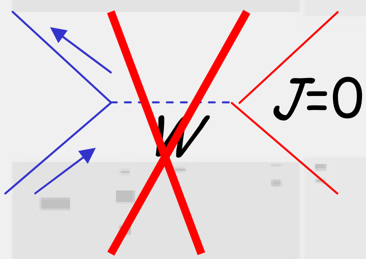
- NA62: precision (~0.5%) measurement of

  $R_K = \Gamma(K^+ \to e^+ \nu)/\Gamma(K^+ \to \mu^+ \nu)$ < 3% ?

  - old favourite … in modern context

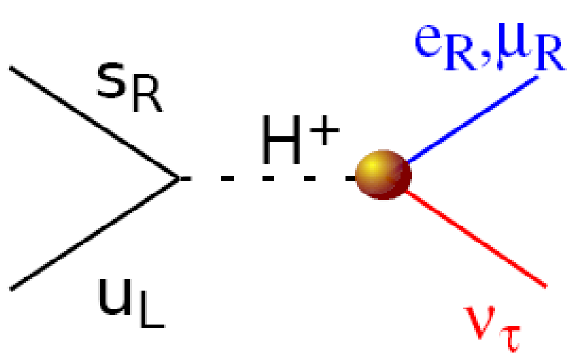
L-fermions



helicity suppression of SM

≡ lepton universality

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}, \quad i = e, \mu, \tau$$



$$eH^\pm\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500\text{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\,SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

Masiero, Paradisi, Petronzio, hep-ph/0511289 PRD74,(2006)

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R_K now

$$R_M = \frac{\Gamma(M \to e\nu(\gamma))}{\Gamma(M \to \mu\nu(\gamma))} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{1-\left(\frac{m_e}{m_M}\right)^2}{1-\left(\frac{m_\mu}{m_M}\right)^2}\right)^2 \times (1+\delta R_M)$$

The latest SM theoretical predictions:

R_π = (1.2352 ± 0.0001) × 10^{-4}

R_K = (2.477 ± 0.001) × 10^{-5}

$\pi \to e\nu$

$R^{\exp\pi}_{e/\mu}\ (\pm 0.4\%)$

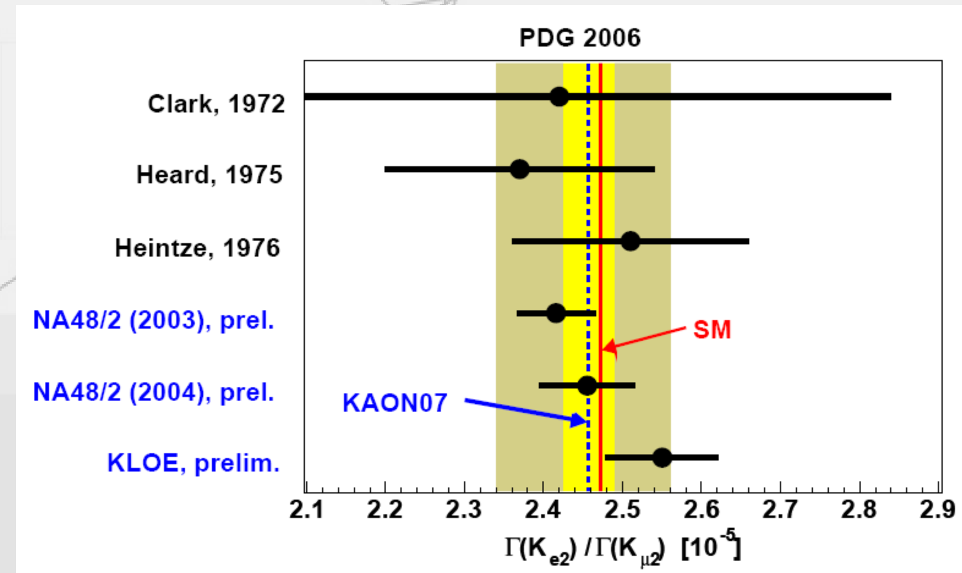
$1.2265(34)(44)x10^{-4}$ TRIUMF (1992)

$1.2346(35)(36)x10^{-4}$ PSI (1993)

New experiments planned at TRIUMF and PSI to reach <0.1% on R_π

Experimental Situation before NA62

$$R_K = 2.457 \pm 0.032 \times 10^{-5}$$



- analysing 2007 data

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Precision *K*-decay > 2008

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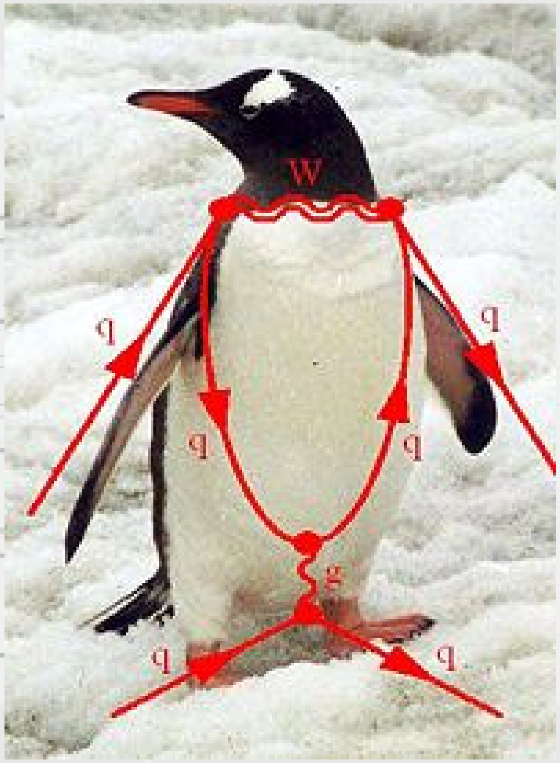
- precise probes for SM deviations ?
  - ultra-rare *K*-decay
  - no SM "tree" (FCNC)
  - short distance dynamics



- experimental challenge (P326)
  BR~ 10^{-10} to 10^{-11}

$K^+ \to \pi^+ \nu \nu$	$K^o{}_L \to \pi^0 \nu \nu$
$K^o{}_L \to \pi^0 e^+ e^-$	$K^o{}_L \to \pi^0 \mu^+ \mu^-$

  - ±10% crucial ↔ LHC physics
  - rare *K*-decay + *B* ↔ LHC physics ?
- rare *B* + *K* decay for multi-TeV ?

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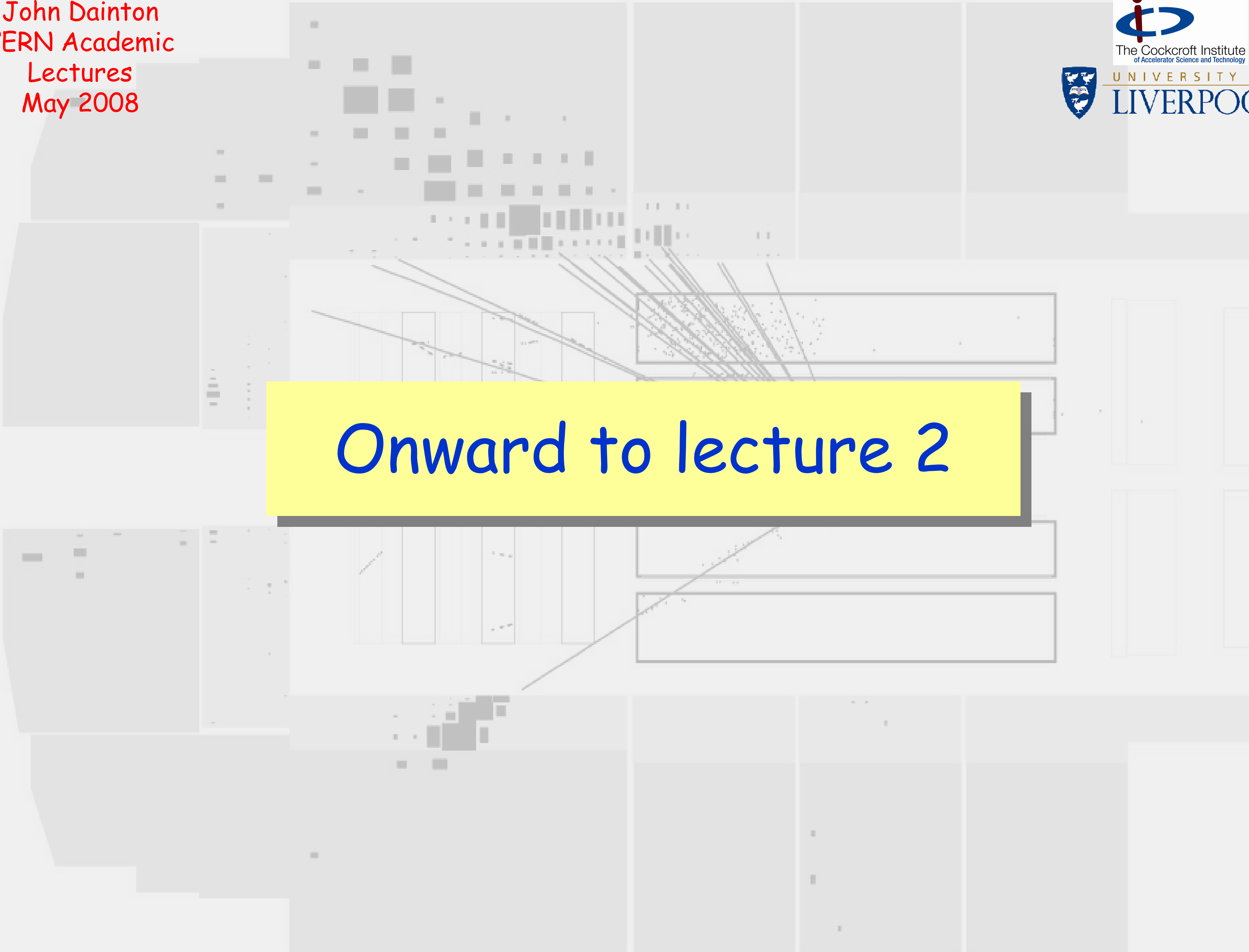

Onward to lecture 2

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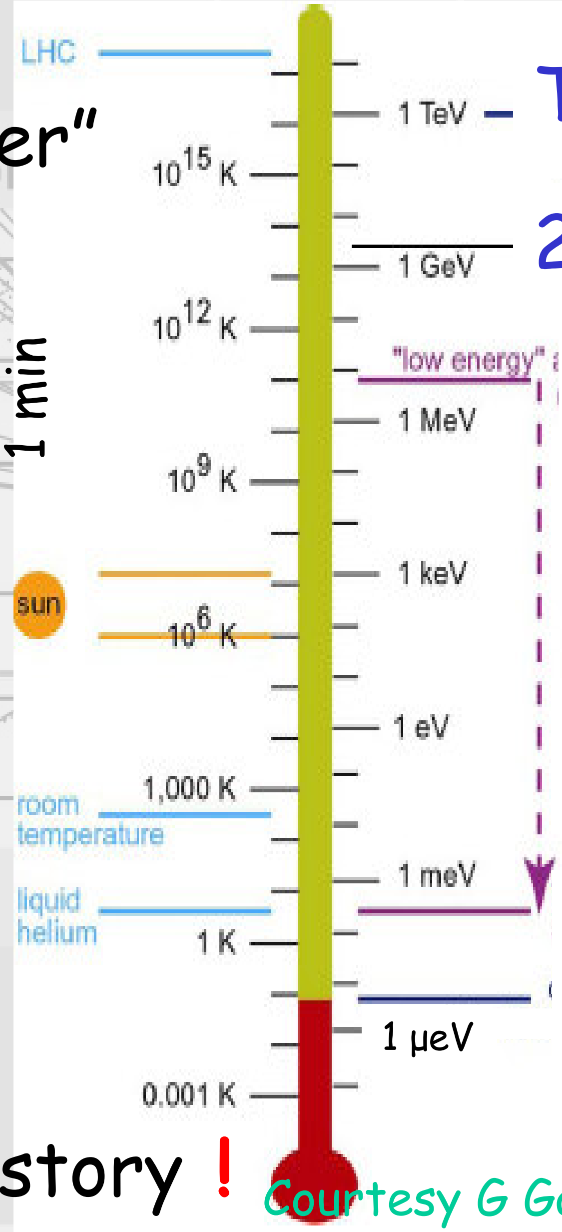
5. Understanding Anti-matter

- cold anti-protons $\bar{p}$
  - "manufacturing anti-matter"
    PS $p \rightarrow \bar{p}p$ 10^{-6}/collision
    deceleration + cooling
    stochastic + electron
    extraction @ ~ 0.1c
    1 min
  - 2002 thousands $\bar{H}$



Terascale

$2m_pc^2$

LEAR+AD

x10^{10}

trap
1 e^-
cyclotron

… (some say) the rest is history !

Courtesy G Gabrielse Harvard

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Manufacturing $\bar{p}$: AD

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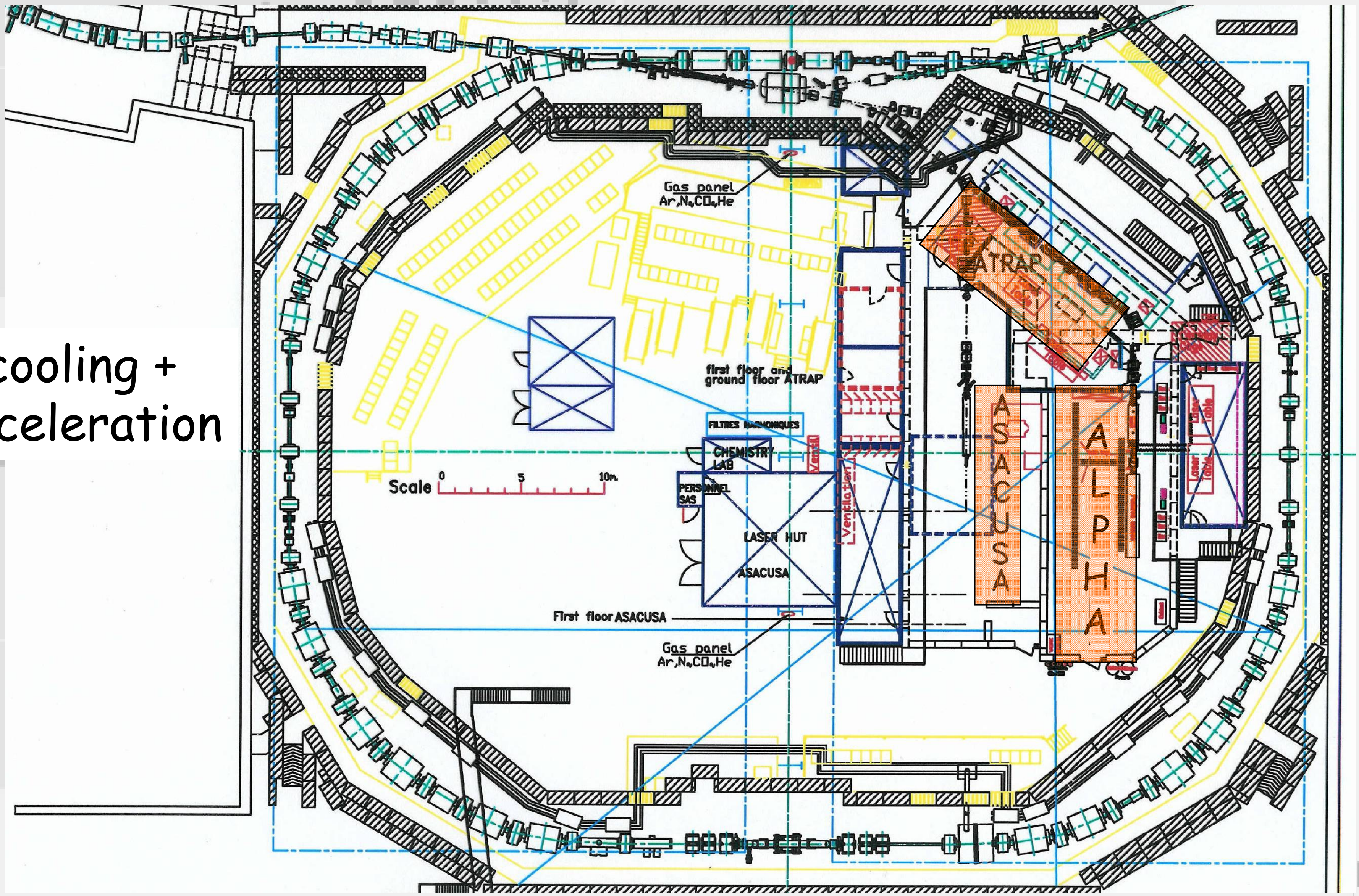
cooling + deceleration



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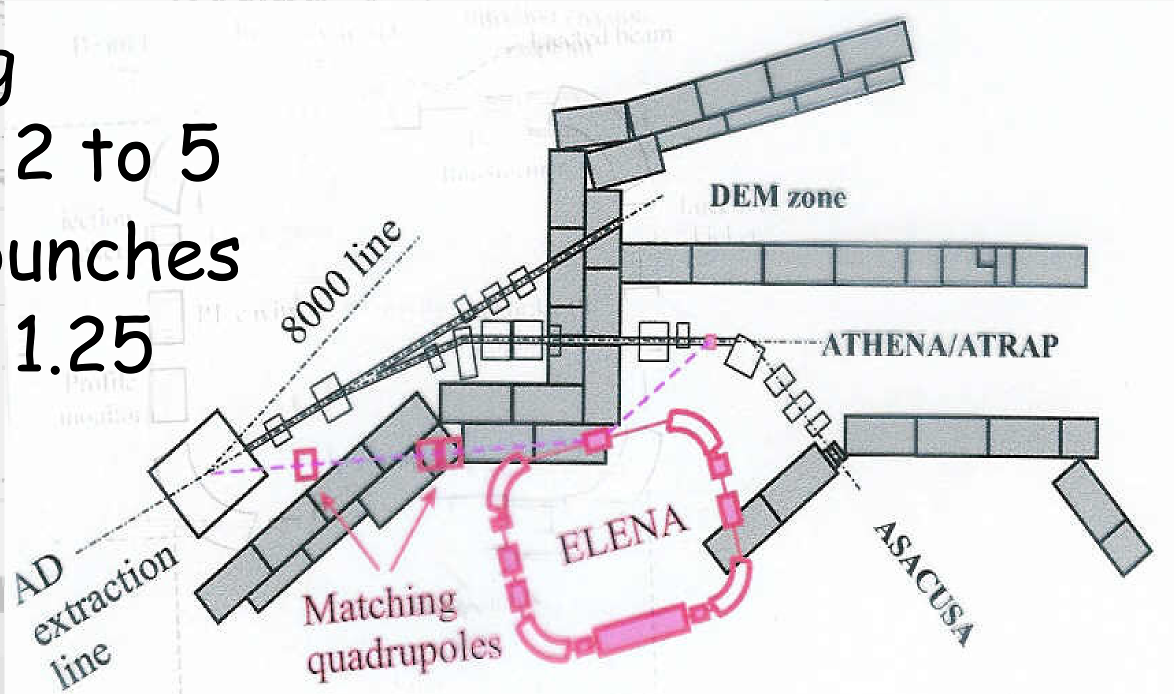
Delivering $\bar{p}$: AD

- modified extraction
- degrader foils → RFQD for ATRAP + ALPHA
- injection stacking
  → intensity x 2 to 5
- PS beam 4 → 5 bunches
  → intensity x 1.25



- decelerator ring ELENA

↳ 5.3 MeV → $KE_{\bar{p}}$ → 100 KeV ?

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Trapping $\bar{p}$

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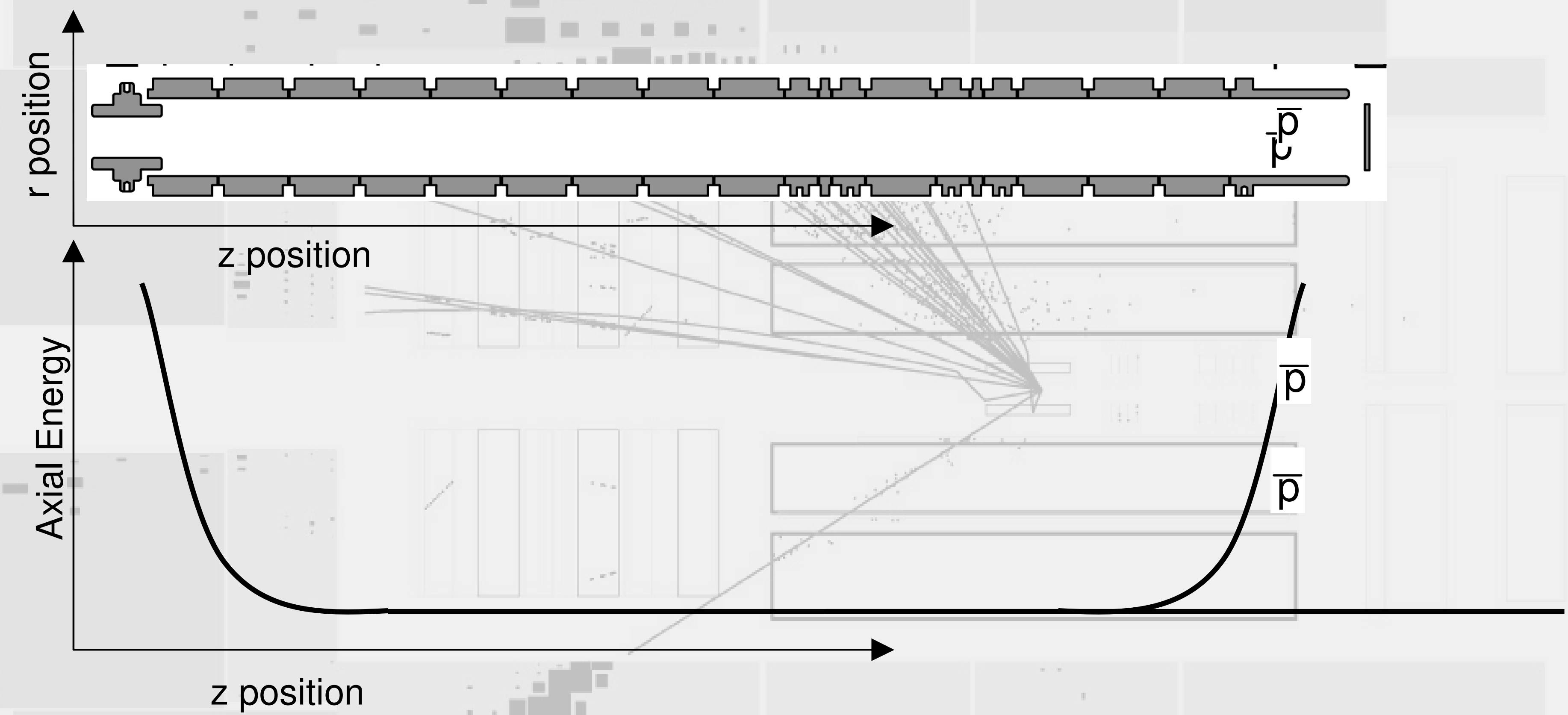

"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor,
H. Kalinowsky, J. Haas, and W. Kells;
Phys. Rev. Lett. 57, 2504 (1986).

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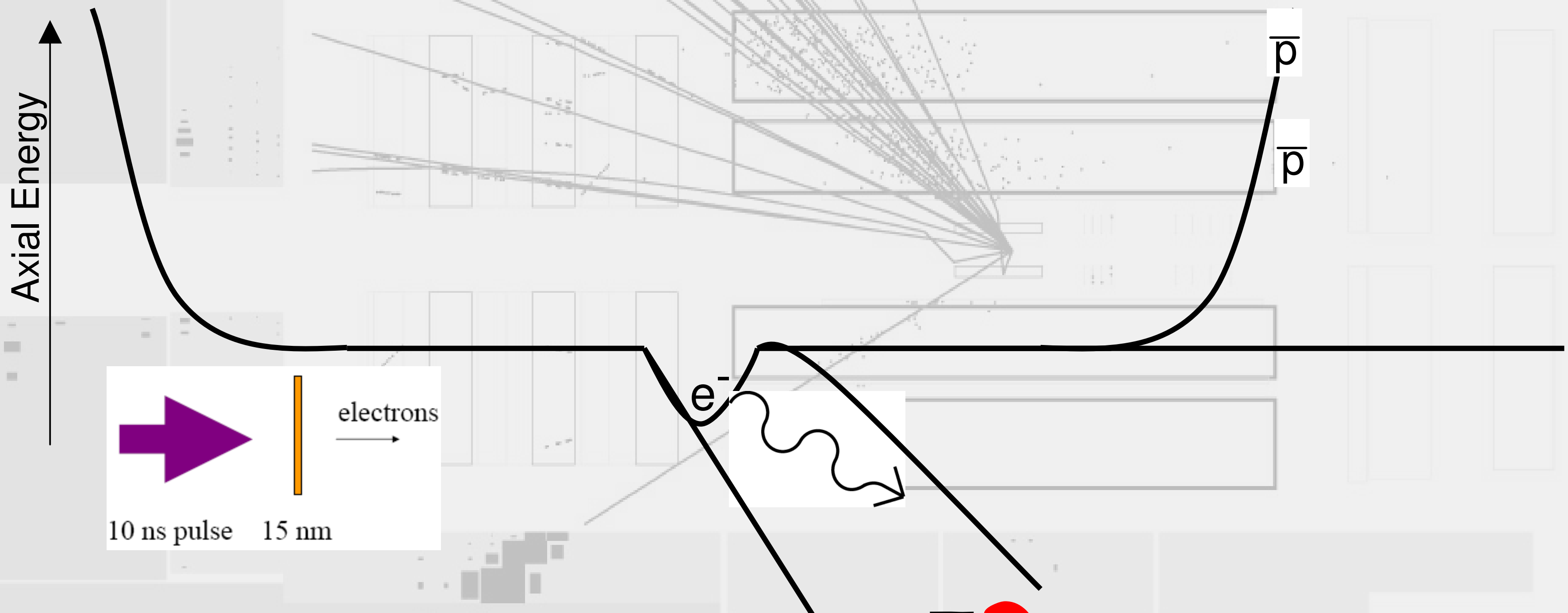
Cooling $\bar{p}$

- cool $\bar{p}$ via collisions with e
- e radiate away excess energy

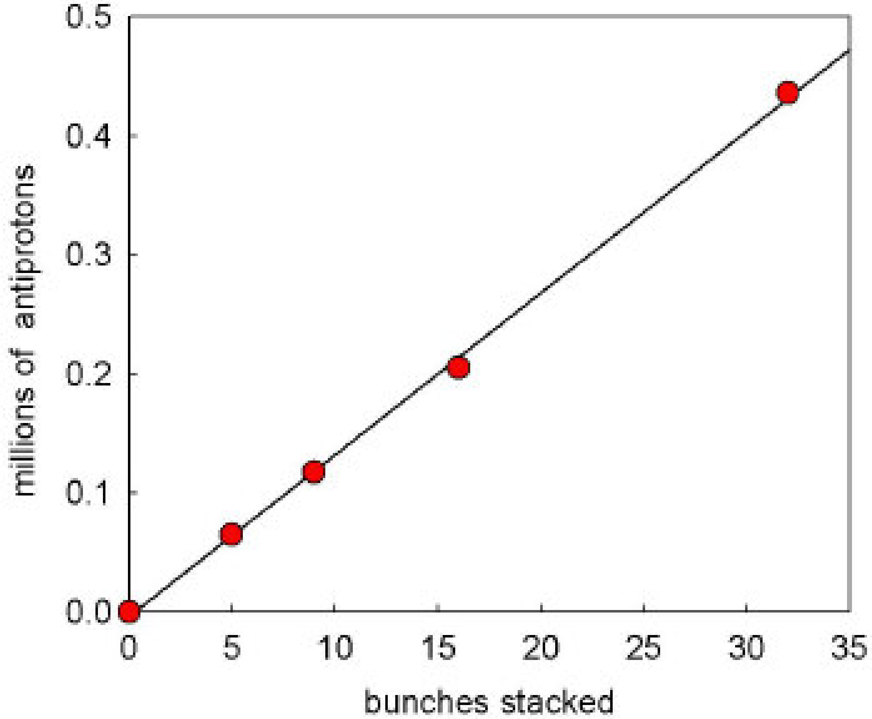


↳ cool and condense with $e^+ \rightarrow \bar{H}$?

"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells; Phys. Rev. Lett. 63, 1360 (1989).

Trapping $\bar{p}$

Accumulating Antiprotons – just a matter of time



Can stack this number in a single well, for more need multiple wells

ATRAP's good vacuum $< 5 \times 10^{-17}$ Torr allows such stacking
(ATHENA and ASACUSA use stacking but with less bunches)

First Demonstration – Antiprotons Stacked in a Trap
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells
Phys. Rev. Lett. 63, 1360 (1989)

"Stacking of Cold Antiprotons"
ATRAP
Phys. Lett. B **548,** 140 (2002)

Understanding Anti-matter

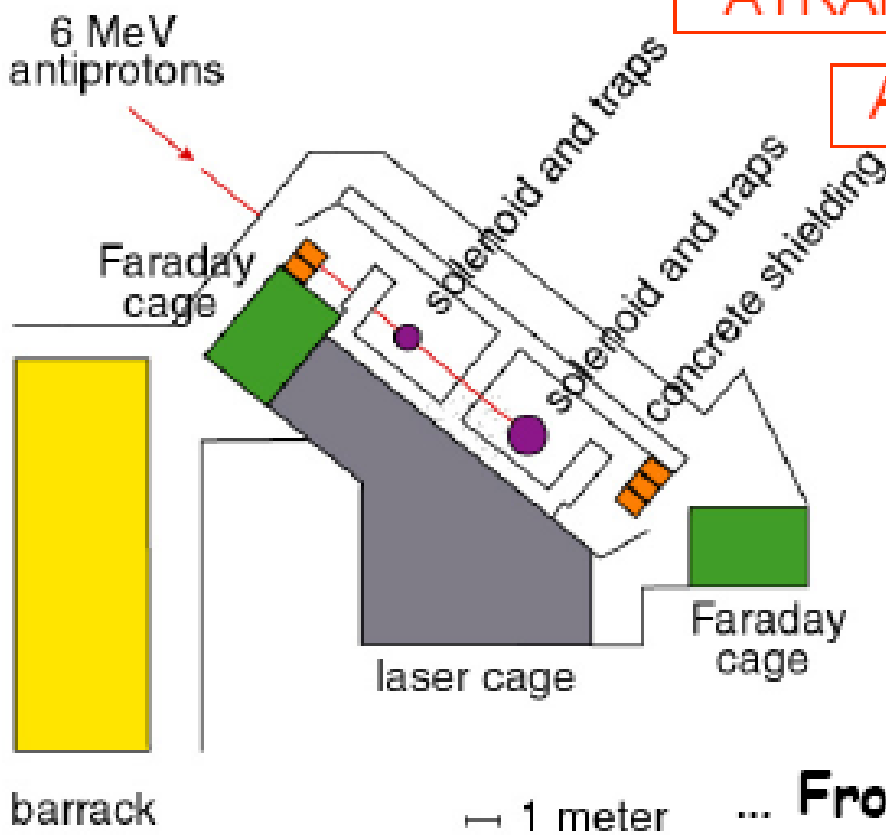
Apparatus and Goals:

... nested pbar and e+
Penning traps, 4K electrons
and stacked pbar

Compare H and Hbar ...
- CPT tests via spectroscopy
- Gravitational acceleration
- CERN AD is unique facility!

ATRAP I (→ 2004)

ATRAP II (2006→)



- new solenoid
- larger apparatus .. many more Hbar
- room for laser access
- room for magnetic traps
- room for annihilation imaging

... From demonstration to factory

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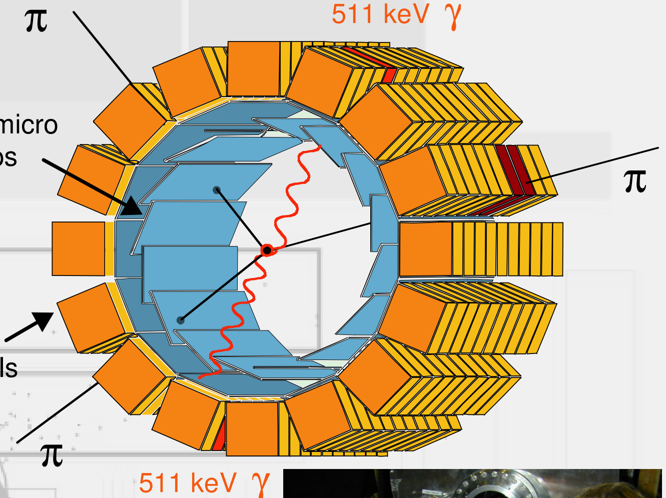
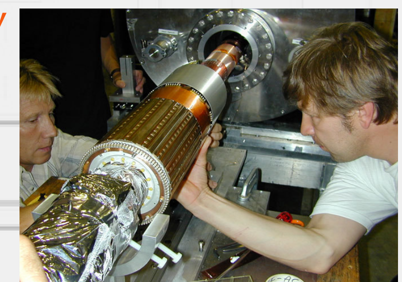
Making $\bar{H}$

- $\bar{H}$ made at non-relativistic energy
  - excited anti-atom $n \sim 30$
- $\bar{H}$ annihilations detected
  - ATHENA ($\rightarrow$ ALPHA)

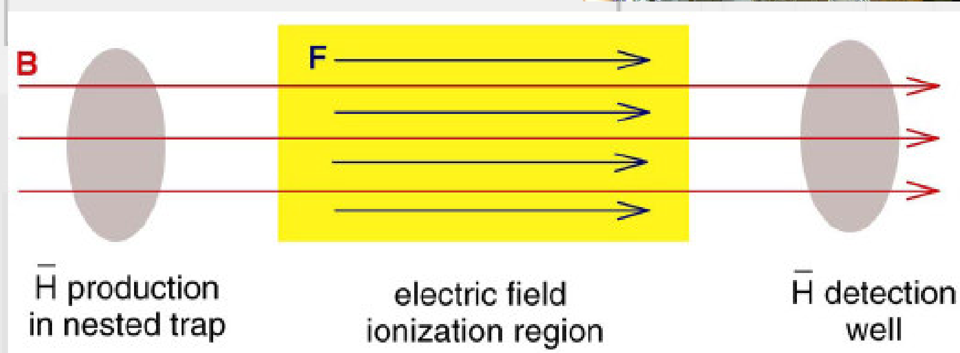
    $\bar{H}(\bar{p}e^{+})$ + matter $\rightarrow \pi^{+}\pi^{-} + \gamma\gamma$





- $\bar{H}$ stripped $\rightarrow$ velocity
  - ATRAP

    $\bar{H}(\bar{p}e^{+}) + E\text{-field} \rightarrow \bar{p} + e^{+}$



↳ produce $\bar{H}$ at $n = 1, 2$?

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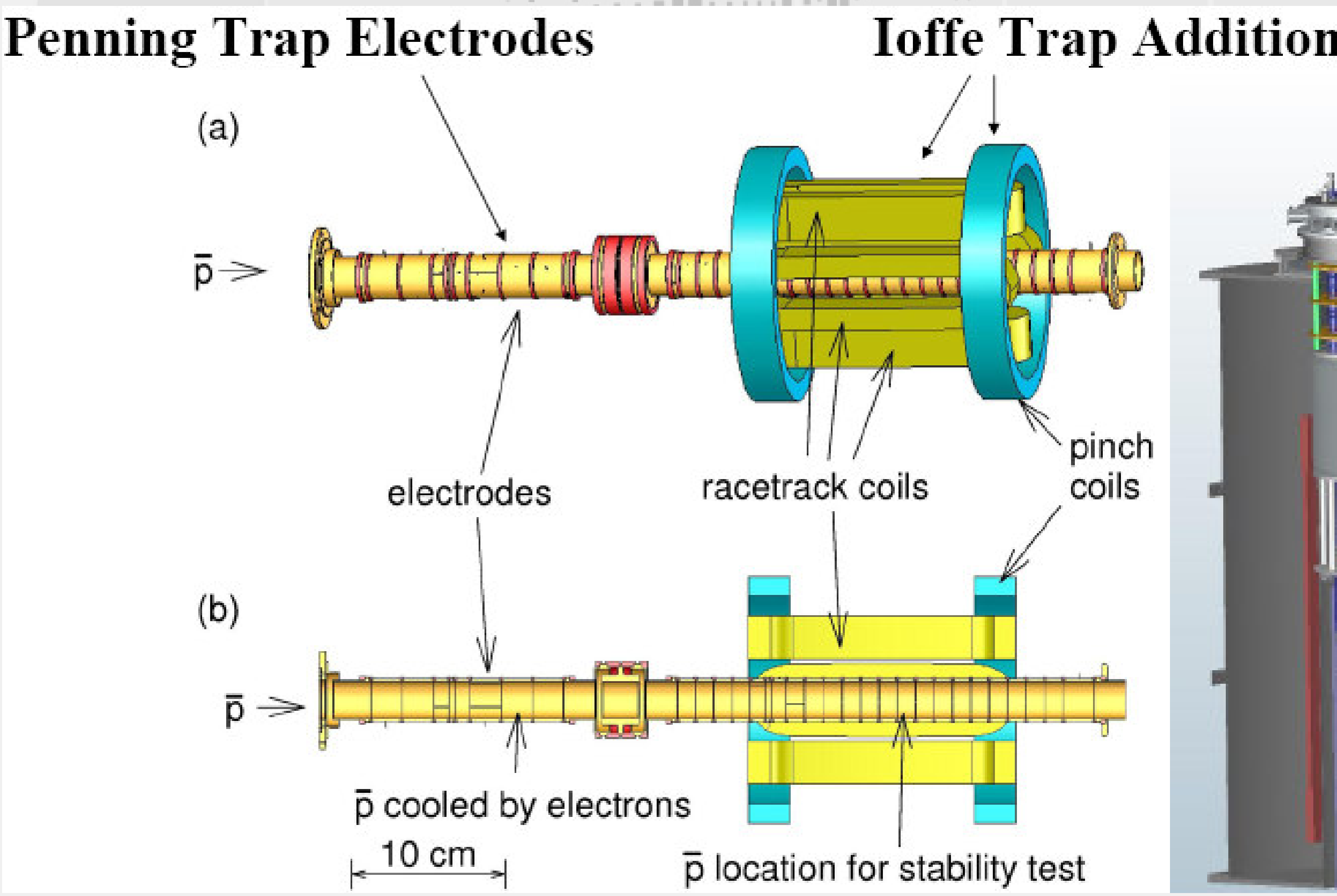
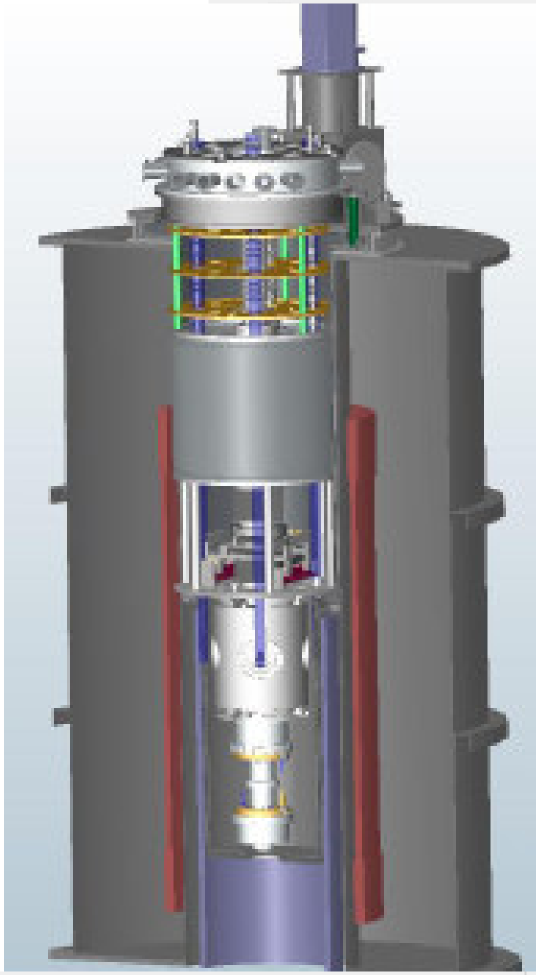
ATRAP

- trap both $\bar{p}$ and $\bar{H}$





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ALPHA

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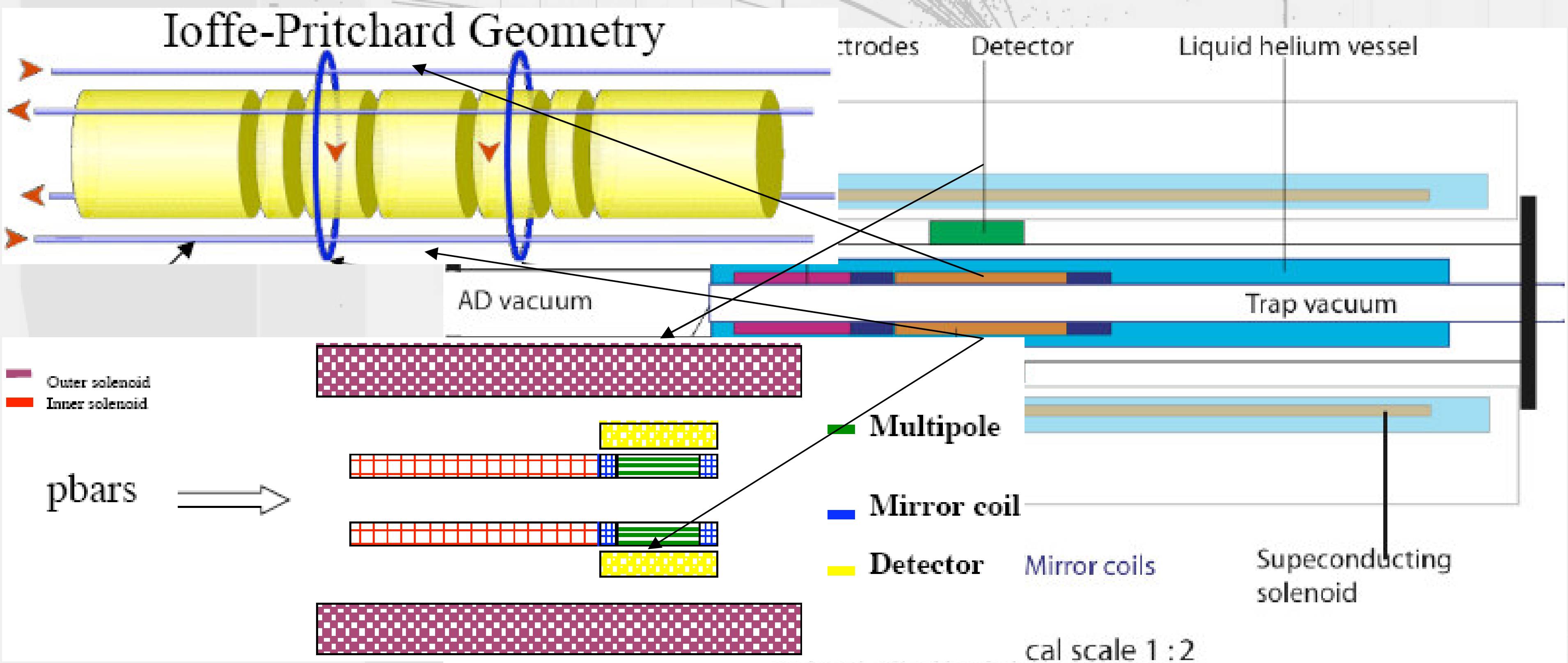
- Anti-hydrogen Laser PHysics Apparatus
  - $1s\,2s$ 2-photon $\bar{H}$ spectroscopy (cf H for ~~CPT~~)
  - trap neutral $\bar{H}$
  - detect $\bar{H}$ annihilation → charged particles



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ALPHA: $\bar{H}$ Trap

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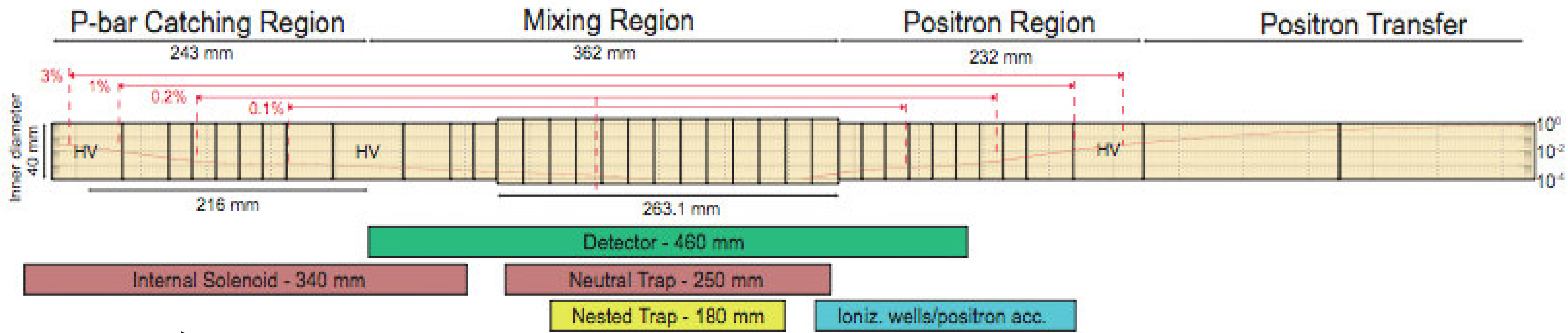
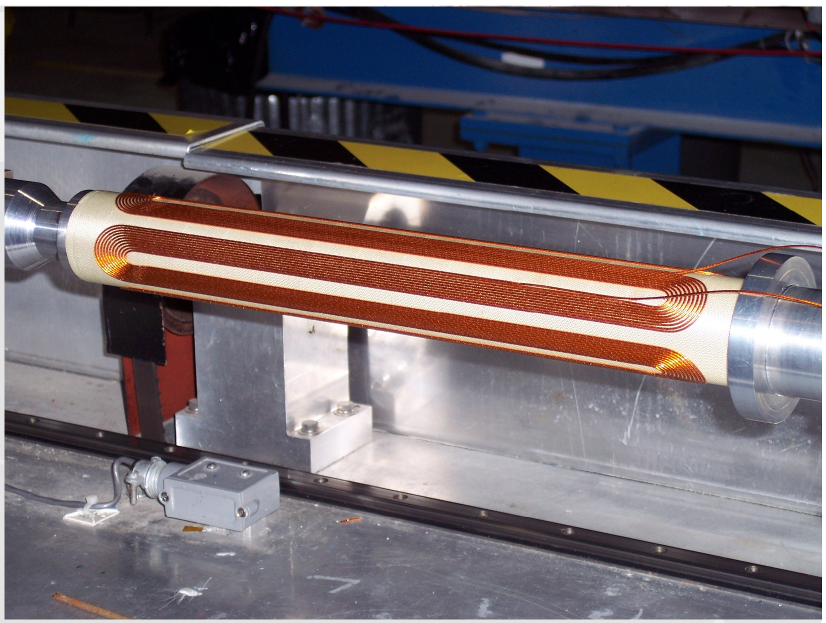
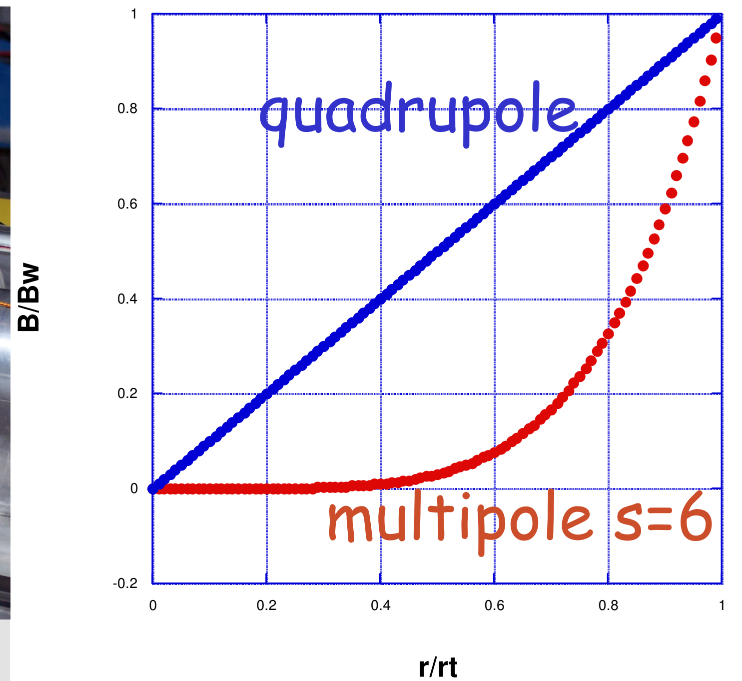


$\bar{p}$ →





- all inside solenoid

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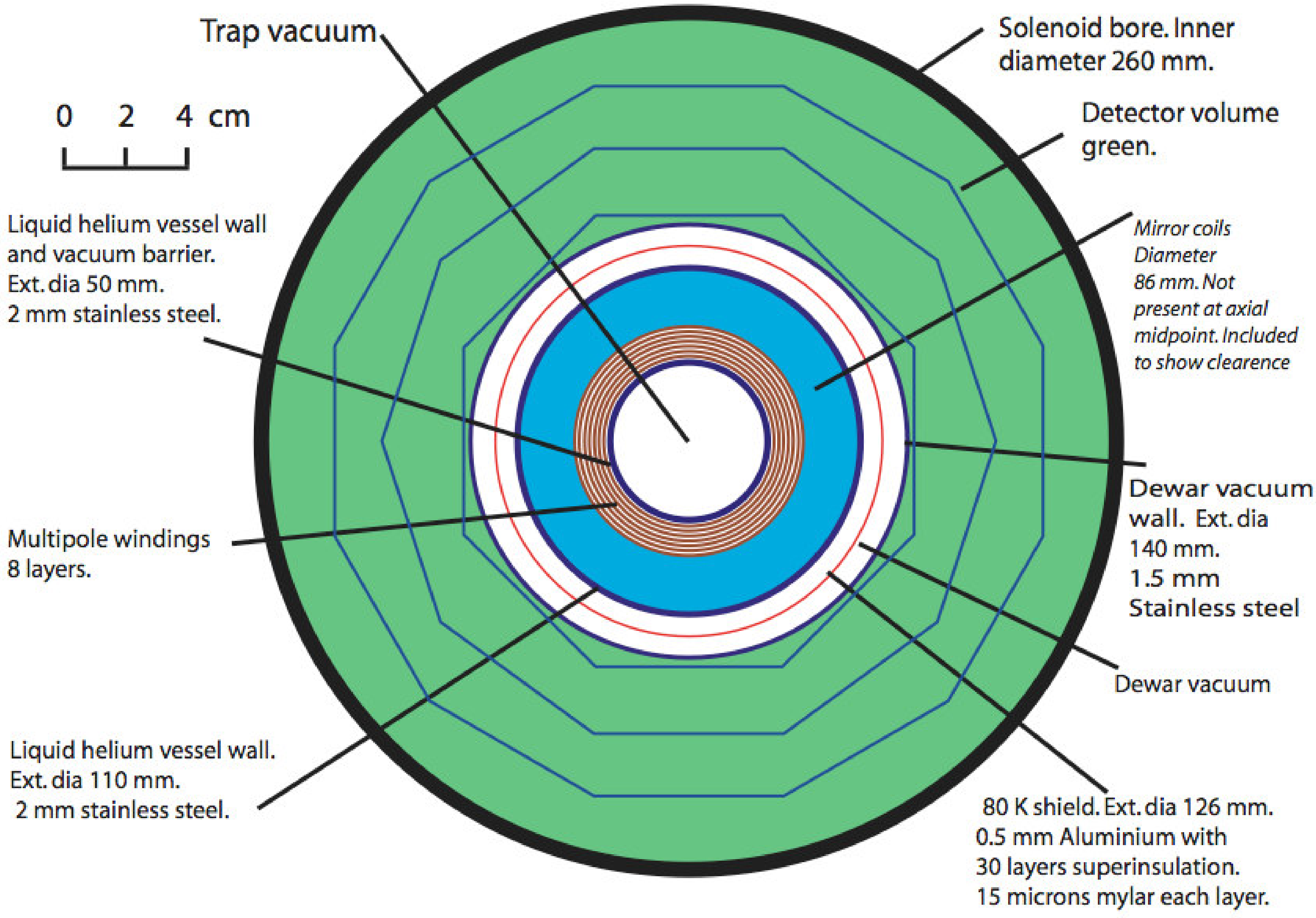
ALPHA: detector



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ALPHA: B_z-field

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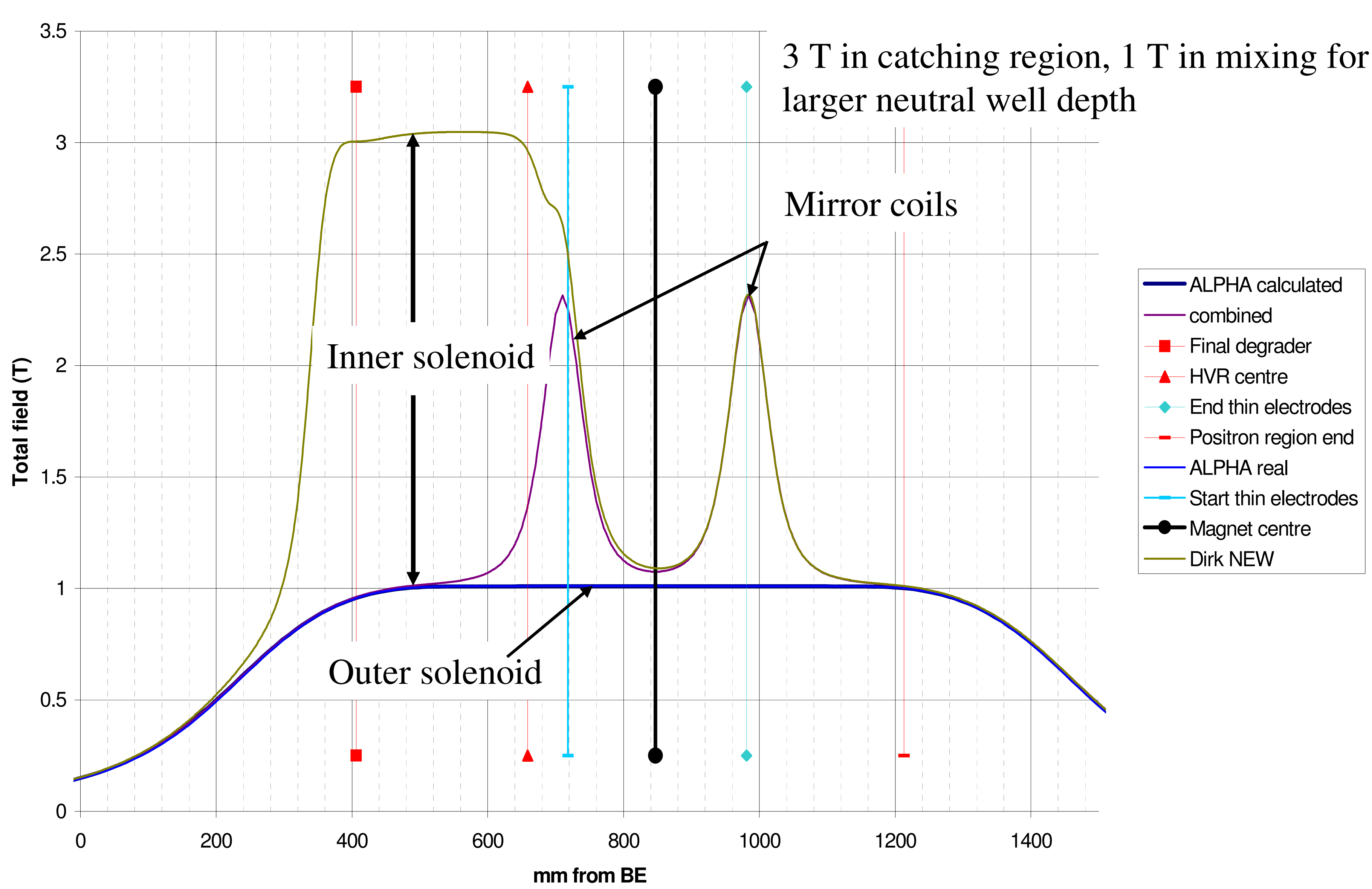

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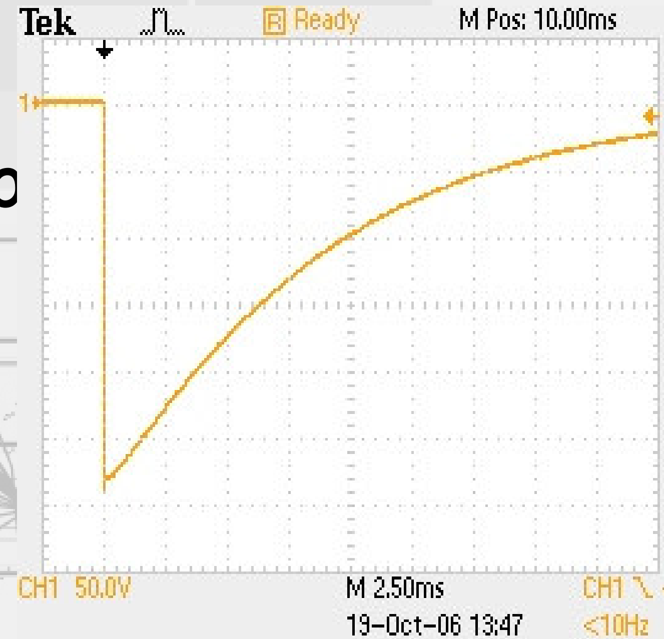
ALPHA: multipole $\bar{H}$ trapping ?

1. 2 to 8 AD shots → trap
2. $\bar{p}$ + e → mixing region + ramp up o
   A in 45 s)
3. inject p to nested well
   → mix with e^+
4. after mixing dump charged with
   E- fields
5. dump magnetic trap
6. annihilation events from escaping neutral $\bar{H}$?



Octupole current

$$2.3 \times 10^6\ \bar{p} + 5.6 \times 10^9\ e^+ \rightarrow ?$$

- analysing many such cycles

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ASACUSA: Anti-protonic *He*

- precision laser spectroscopy of $\bar{p}\,{}^3He^+$ $\bar{p}\,{}^4He^+$

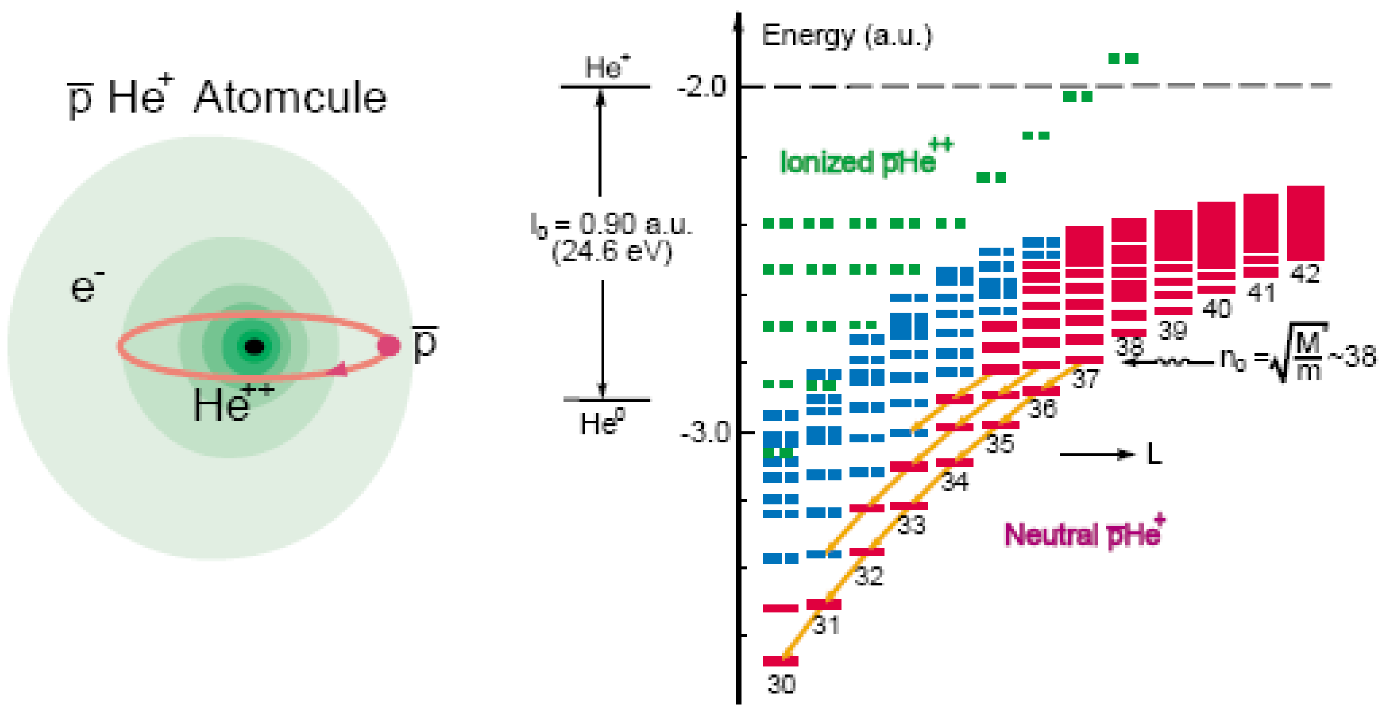

Fig. 1. (a) The structure of the $\bar{p}He^+$ atomcule, in which the $\bar{p}$ with large-(n, l) quantum numbers circulates in a localized orbit around the He^{2+} nucleus, while the electron occupies the distributed 1s state. (b) The level scheme of large-(n, l) states of the $\bar{p}He^+$ atomcule. The solid bars indicate radiation-dominated metastable states, while the broken lines are for Auger-dominated short-lived states, The significance of this categorization will be explained below. The ionized $\bar{p}He^{2+}$ states are also shown by dotted lines. From Ref. [2].

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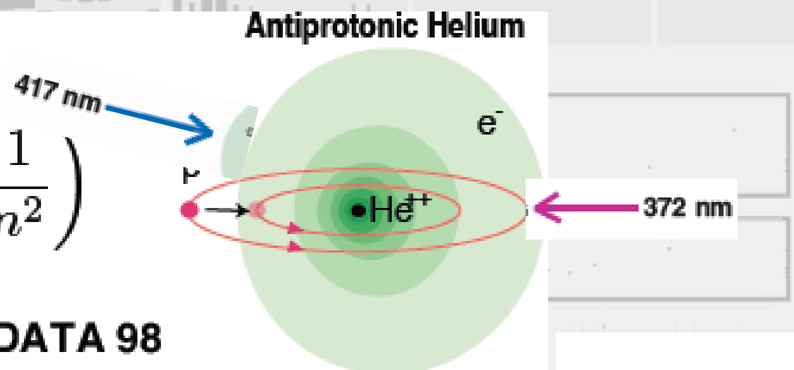
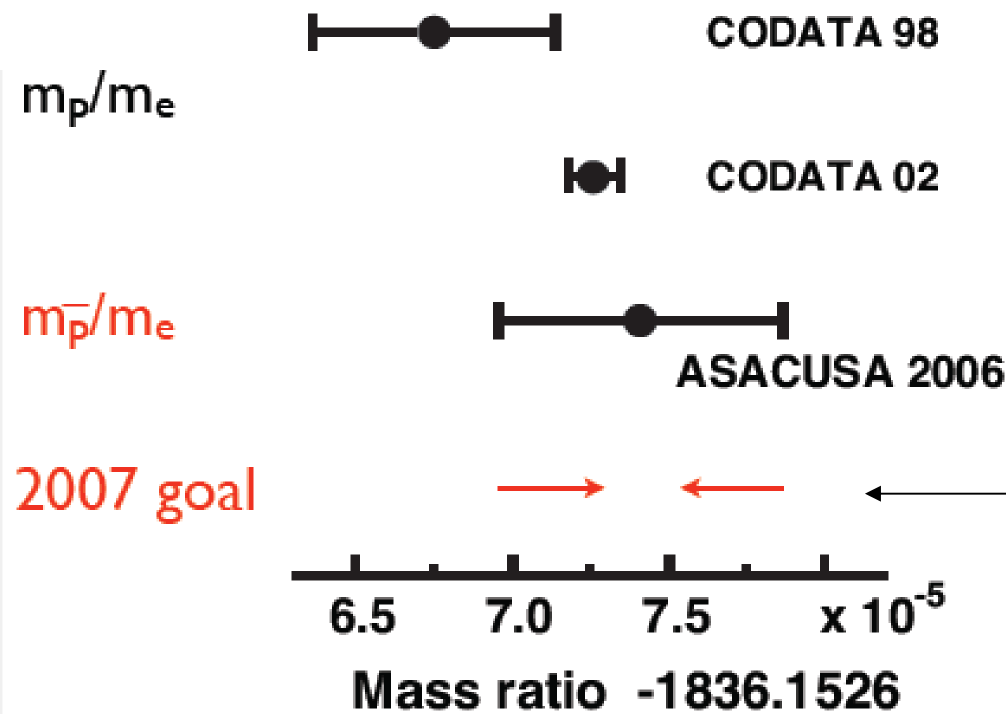
ASACUSA: Anti-protonic *He*

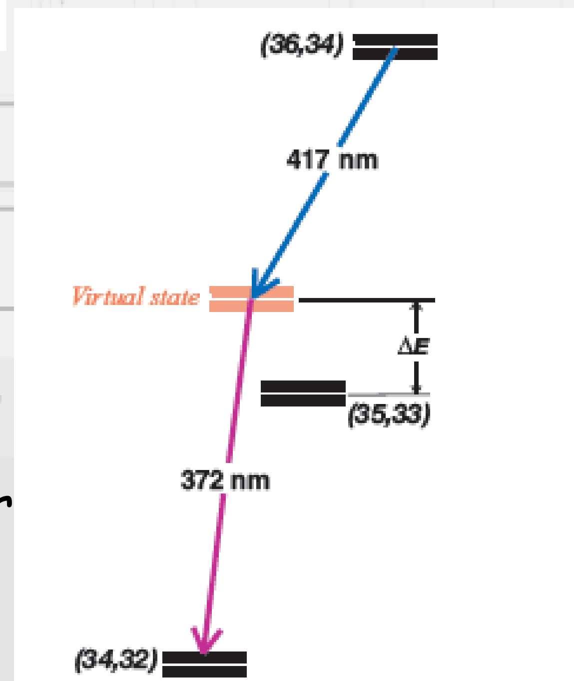
- $\bar{p}He^{+} \rightarrow \bar{p}/e$ mass ratio

$$\Delta\nu_{n,\ell\rightarrow n',\ell'} = Rc\frac{m^*_{\bar{p}}}{m_e}Z^2_{\text{eff}}\left(\frac{1}{n'^2}-\frac{1}{n^2}\right)$$





2-photon sub-Doppler



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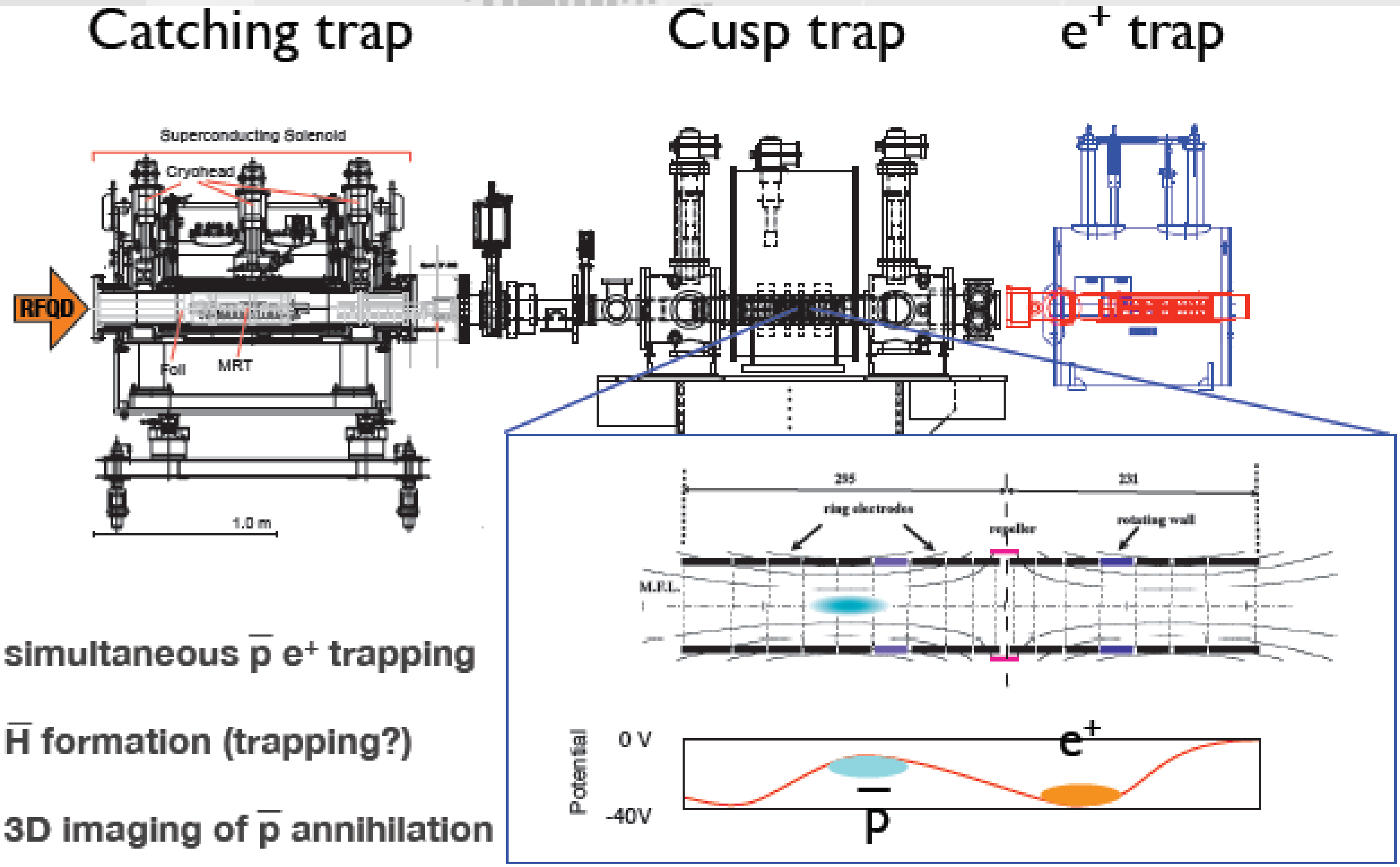
ASACUSA

- catch, cool, compress $\bar{p}$



simultaneous $\bar{p}$ e^+ trapping

$\bar{H}$ formation (trapping?)

3D imaging of $\bar{p}$ annihilation

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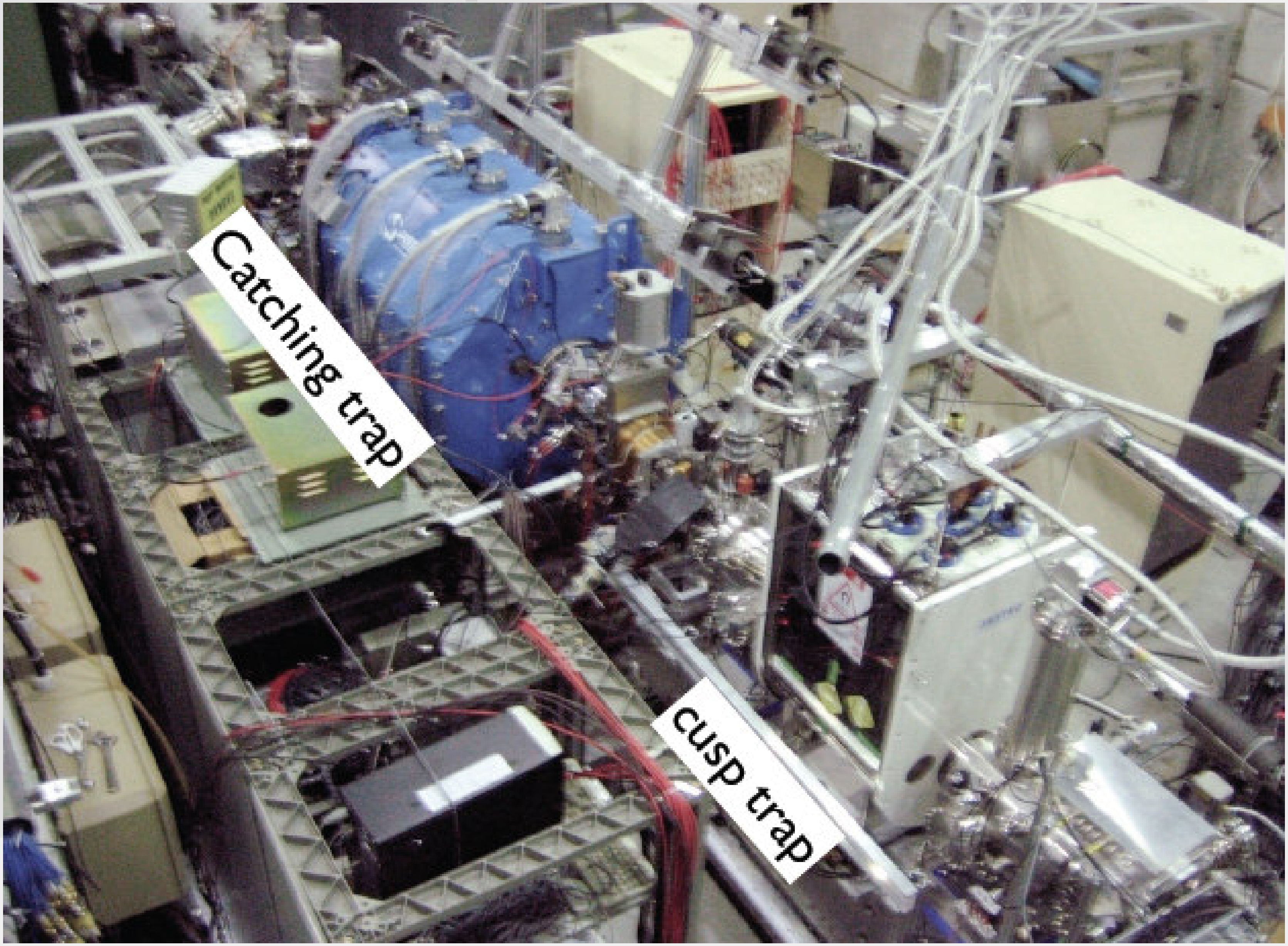
ASACUSA



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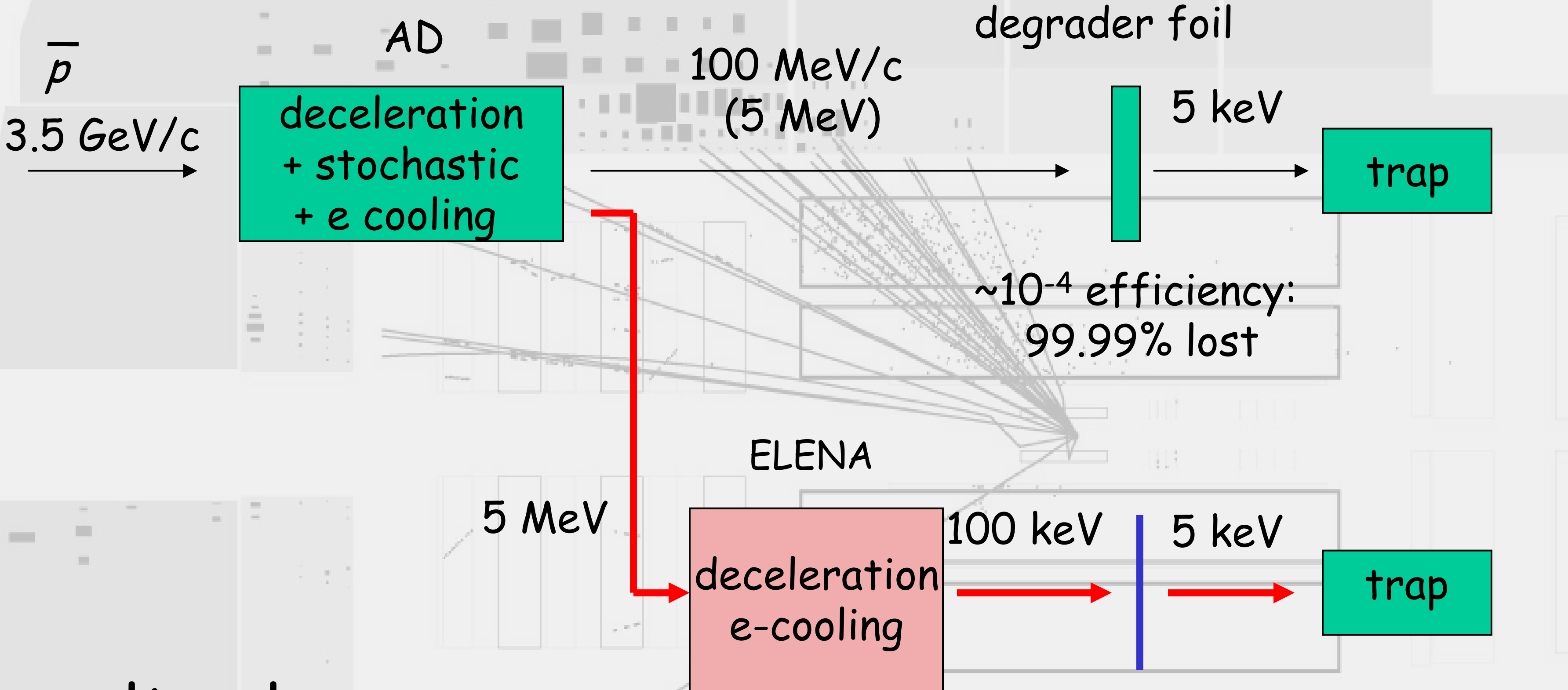
ELENA?



- ultra-low energy
- compressed phase space
- x 10^4 $\bar{p}$
- international collaborators ?

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ELENA

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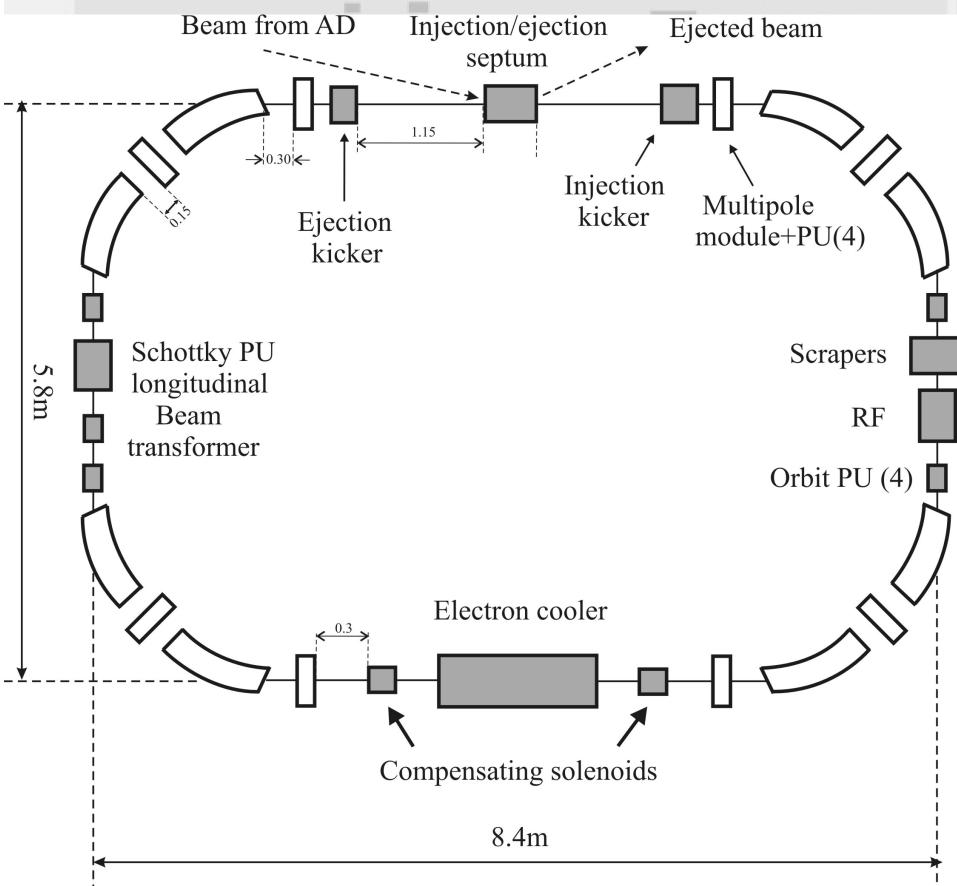

ELENA layout

Momentum, MeV/c	100 – 13.7
Energy, MeV	5.3 - 0.1
Circumference, m	26.062
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitation by space charge	1.1 107
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Expected cooling time at 100 keV, sec	1
Required vacuum* for $\Delta\ \varepsilon$ =0.5 π mm mrad/s,Torr	3*10-12
IBS blow up times for bunched beam* (ε x,y=5 π mm mrad, Δ p/p=1 10-3), s	1.1 / -9.1 / 0.85
* No electron cooling is assumed	

ELENA basic parameters

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6. Spin in Hadronic Structure

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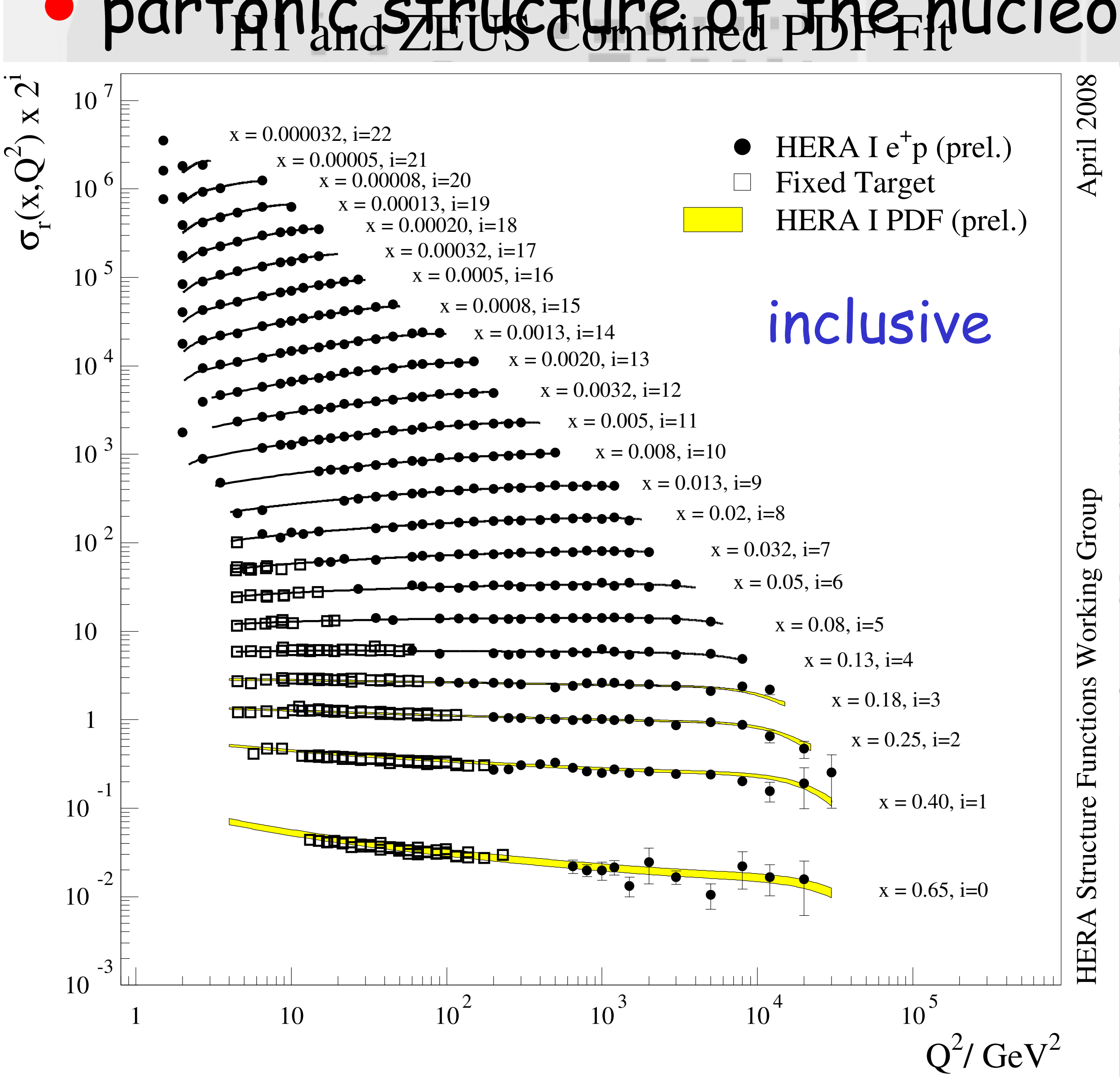
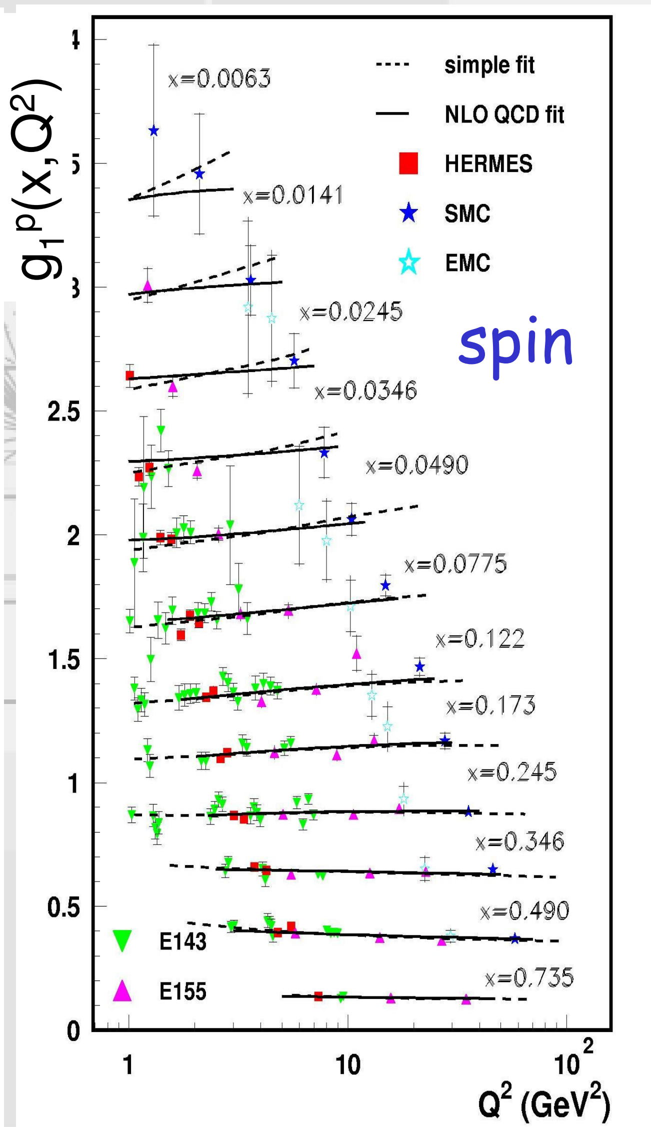
- partonic structure of the nucleon





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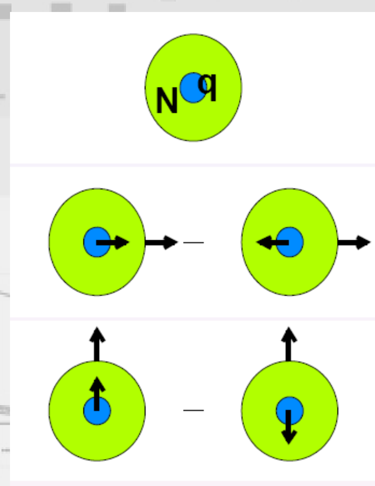
Parton Distribution Functions

q, g

$\Delta q, \Delta g$

$\Delta_T q$



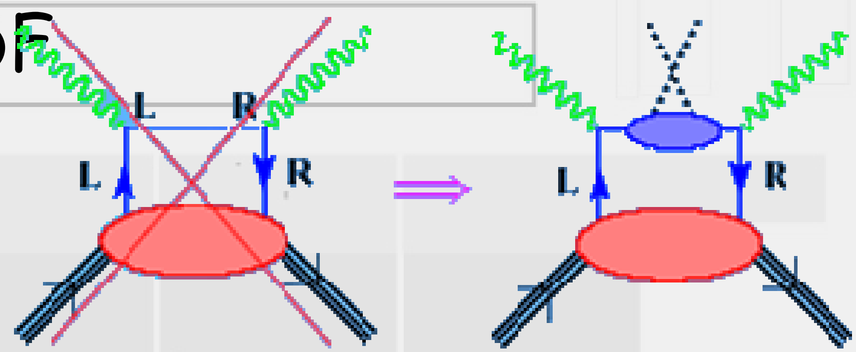
momentum

helicity

transversity (alias h_1)

$\Delta_T q(x)$

- 3 "twist-2" PDFs
- transversity chiral-odd PDF
- in semi-inclusive DIS if coupled to a chiral-odd fragmentaion function
- Soffer bound:



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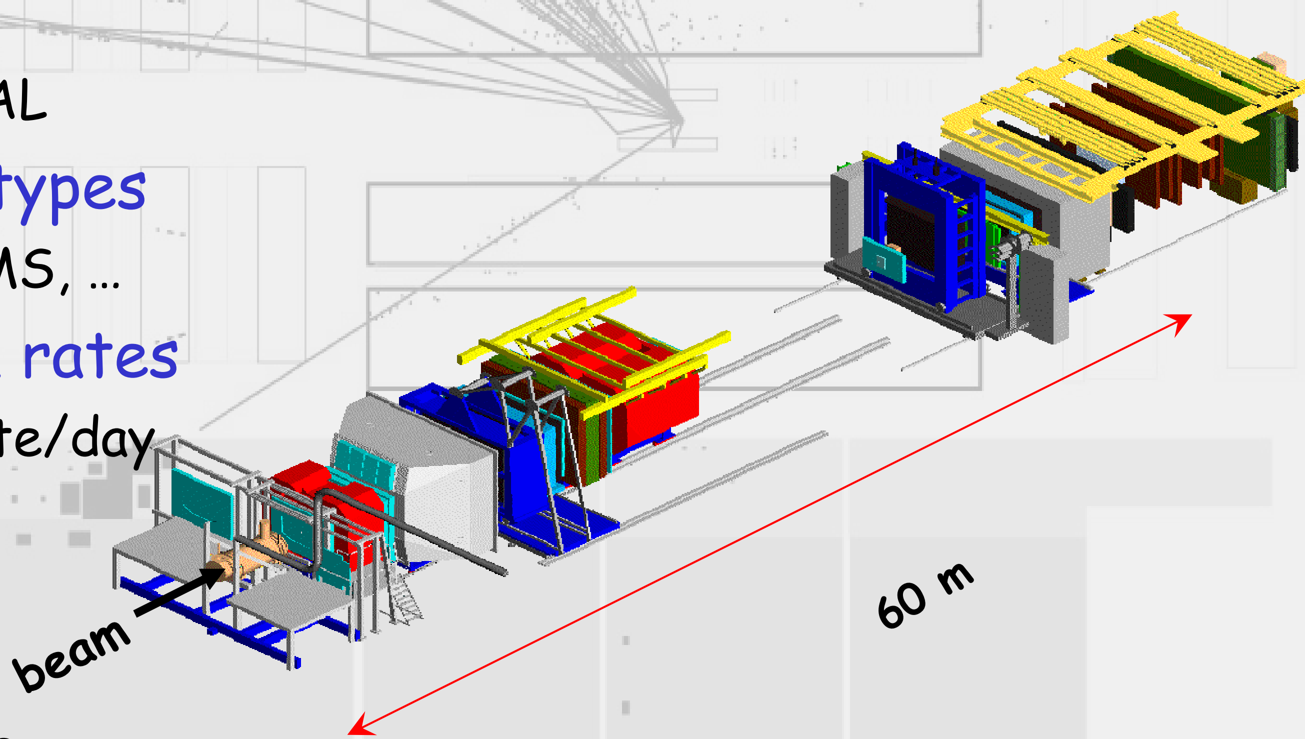
COMPASS

- 250 physicists from 10 countries
- fixed-target experiment at unique SPS beam-line
  - muons (160 GeV/c), pions (<280 GeV)
- world-largest polarised solid-state target
- full particle ID
  - RICH, ECAL, HCAL
- novel detector types
  - Micromegas, GEMS, …
- LHC-grade data rates
  - presently 8 TByte/day
- data taking
  - start 2002
  - muons till 2007
  - pion beam ≥ 2008



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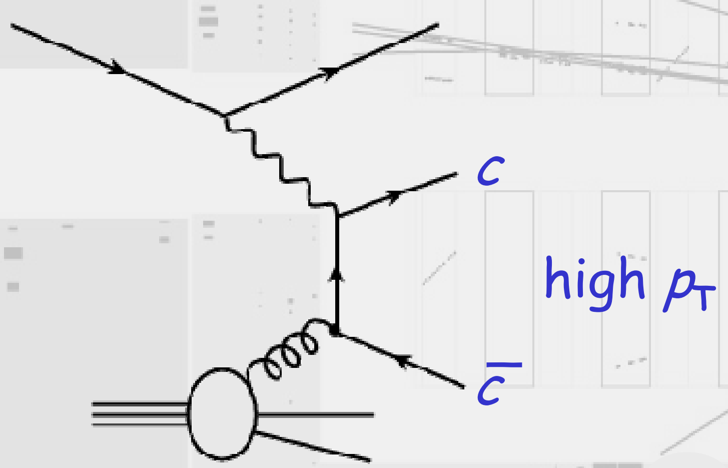
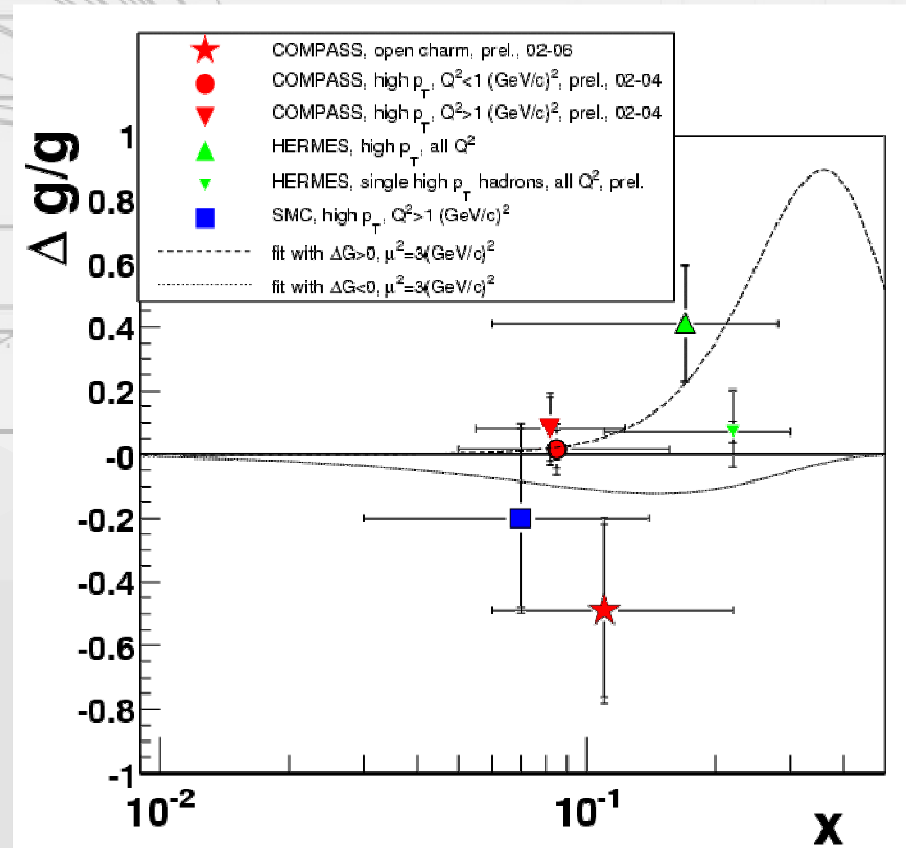
Gluon Spin Polarisation $\Delta g / g$

- nucleon spin puzzle (CERN EMC 1980s)
  - $S_z \sim 0.3q + ?$
  - gluon contribution shows up in $\Delta g / g$



$$\Delta G = \int_0^\infty g(x)\mathrm{d}x$$

↳ large ΔG unlikely ?

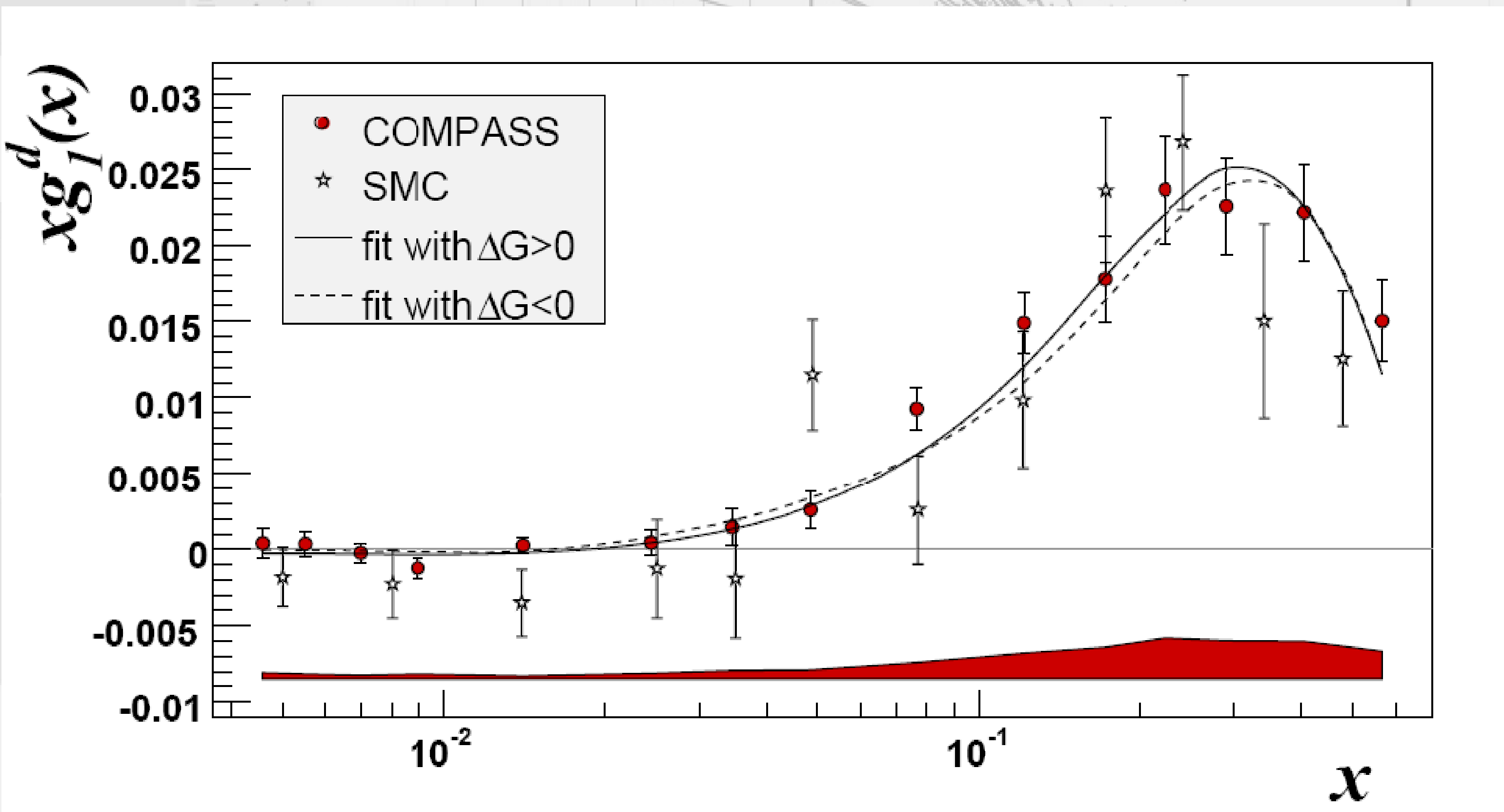


Quark spin in Nucleon

- quark contribution to spin $\Delta\Sigma$ from $g_1(x)$

  precise measurement of g_1^d at low x

$$\Delta\Sigma = 0.3 \pm 0.02$$



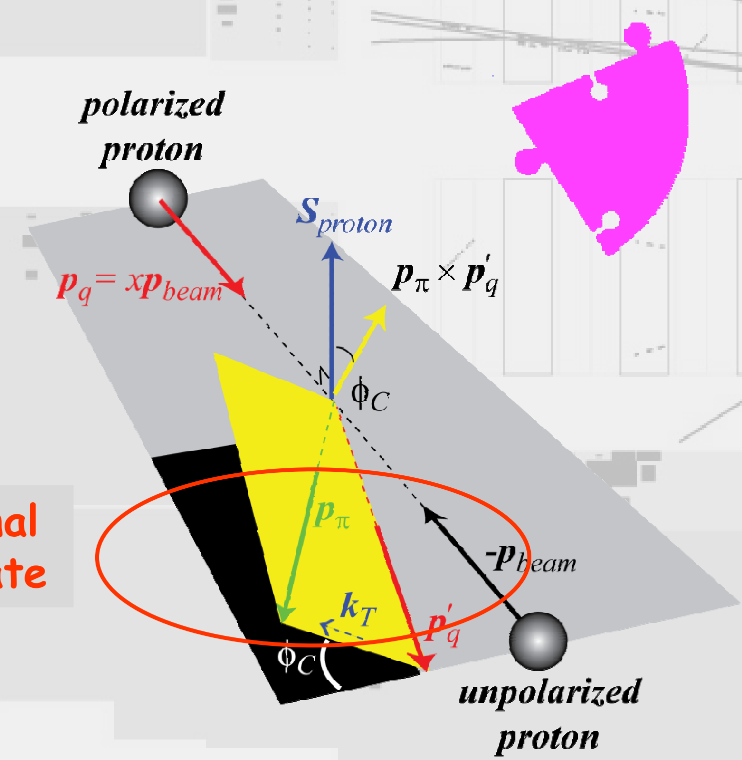
Single-spin asymmetry

Collins/Heppelmann mechanism

transverse quark polarization and *spin-dependent fragmentation* (transversity)

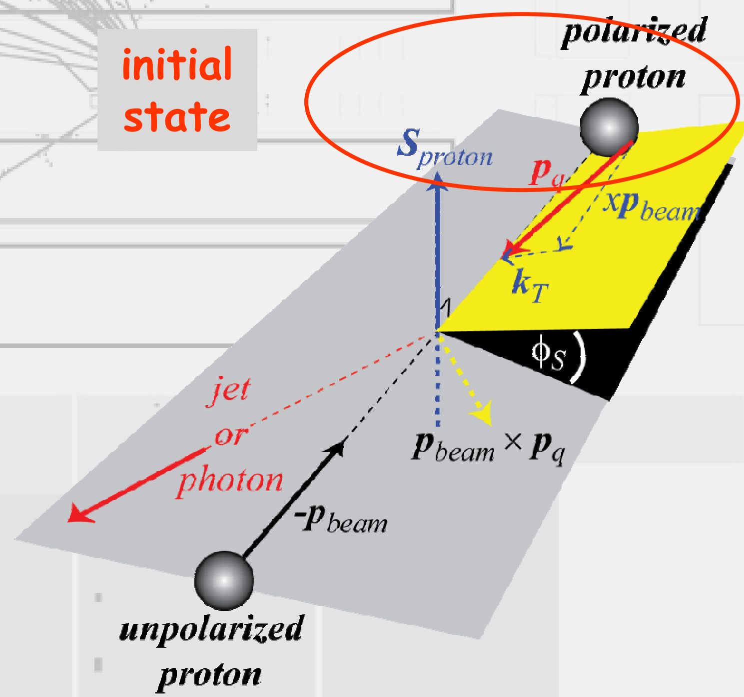
Sivers mechanism

spin-correlated transverse momentum k_T (orbital motion)



final state

initial state



from L. Bland

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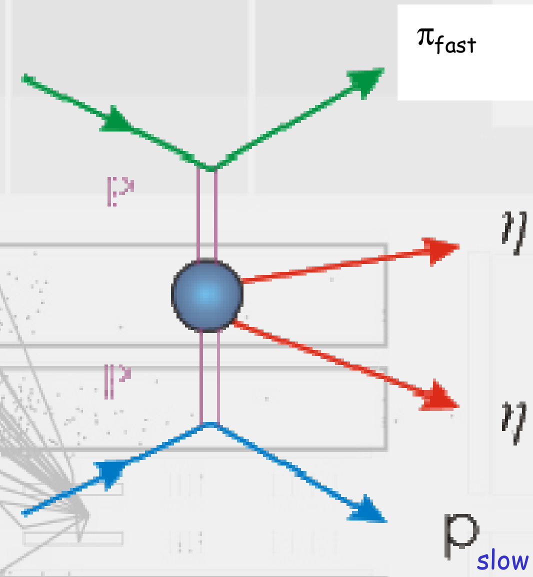
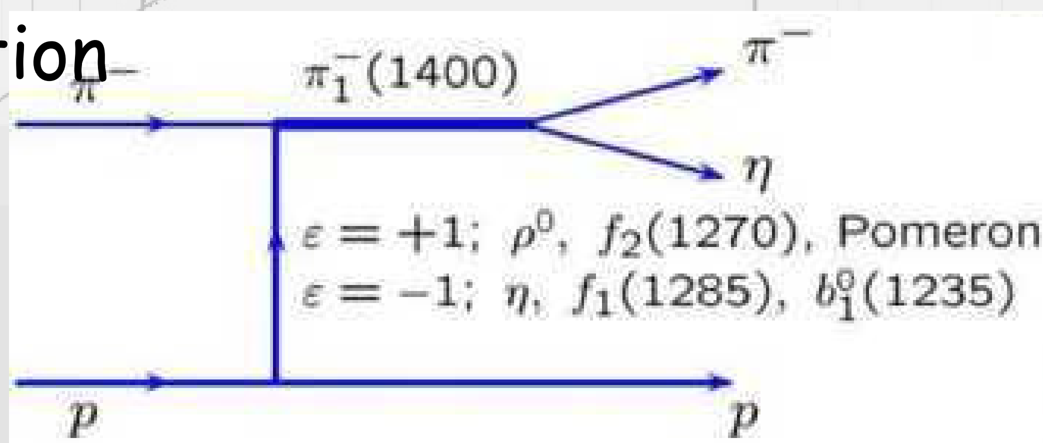
COMPASS: Hadron Physics

- hadron beam ≥ 2008
  190 GeV/c π K
  + hydrogen target



- central kinematics
  glueballs

- diffractive dissociation
  hybrids,
  exotic quantum numbers



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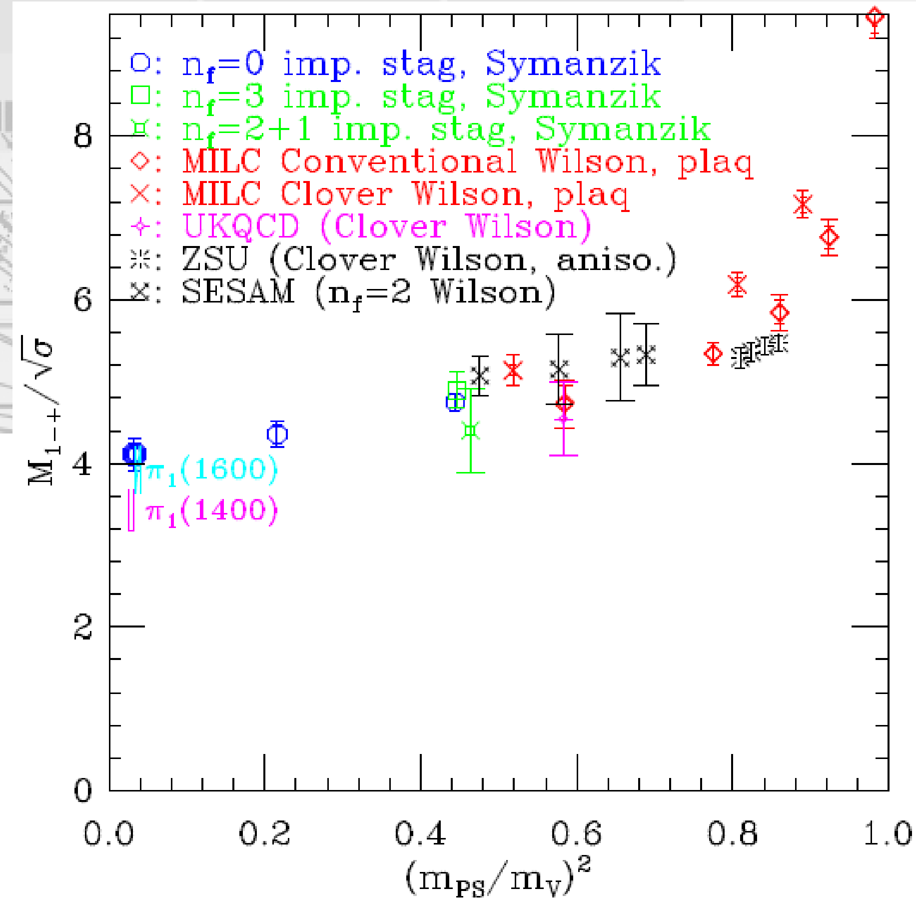
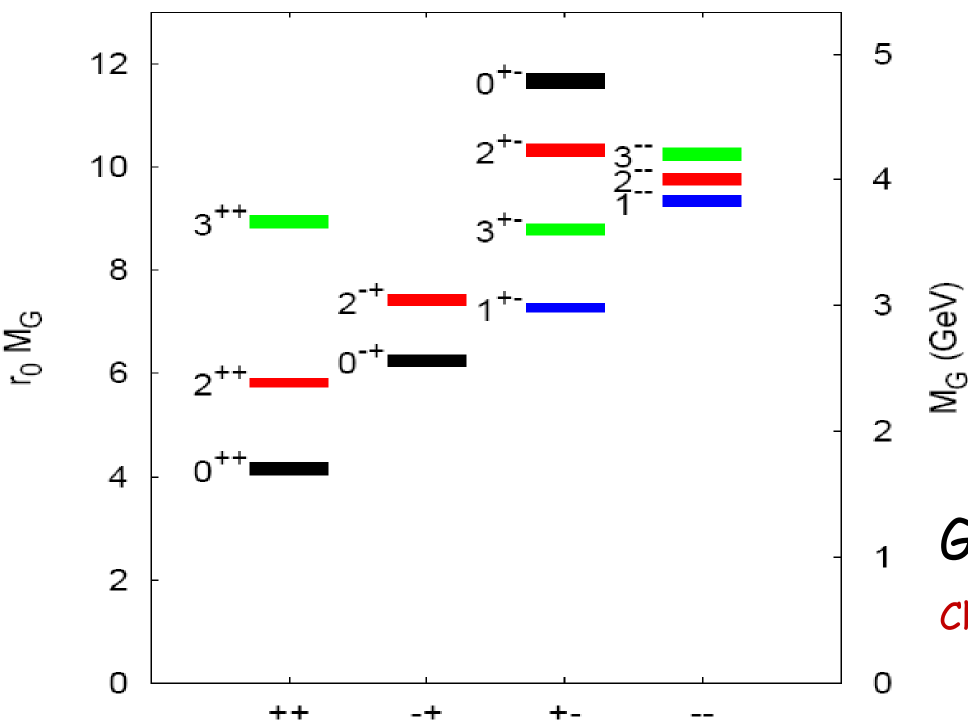
QCD-Lattice Motivation

- quenched QCD-2007

  M(hybrid-*uu*): 1.8 GeV

  M(hybrid-*ss*): 2.1 GeV





Glueball spectrum lattice

Chen et al., PRD73 2006

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7. Scalar fields

- the strong CP problem
  - no ~~CP~~ in QCD
  - no QCD phase $\bar{\Theta}$
  - Peccei-Quinn mechanism

    $\bar{\Theta} \rightarrow$ SSB field $\leftarrow$ axion (low mass scalar)
- experiment
  - Vacuum Magnetic Birefringence (PVLAS OSQAR)
  - photoproduction in Sun: $\gamma\gamma \rightarrow$ axion (CAST CERN)
  - DM galaxy halo: axion $\rightarrow$ μwave γ tunable cavity (ADMX LLRL)
  - "light shining thru walls" $\gamma\gamma \rightarrow$ axion $\rightarrow \gamma\gamma$ FEL

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Axion ?

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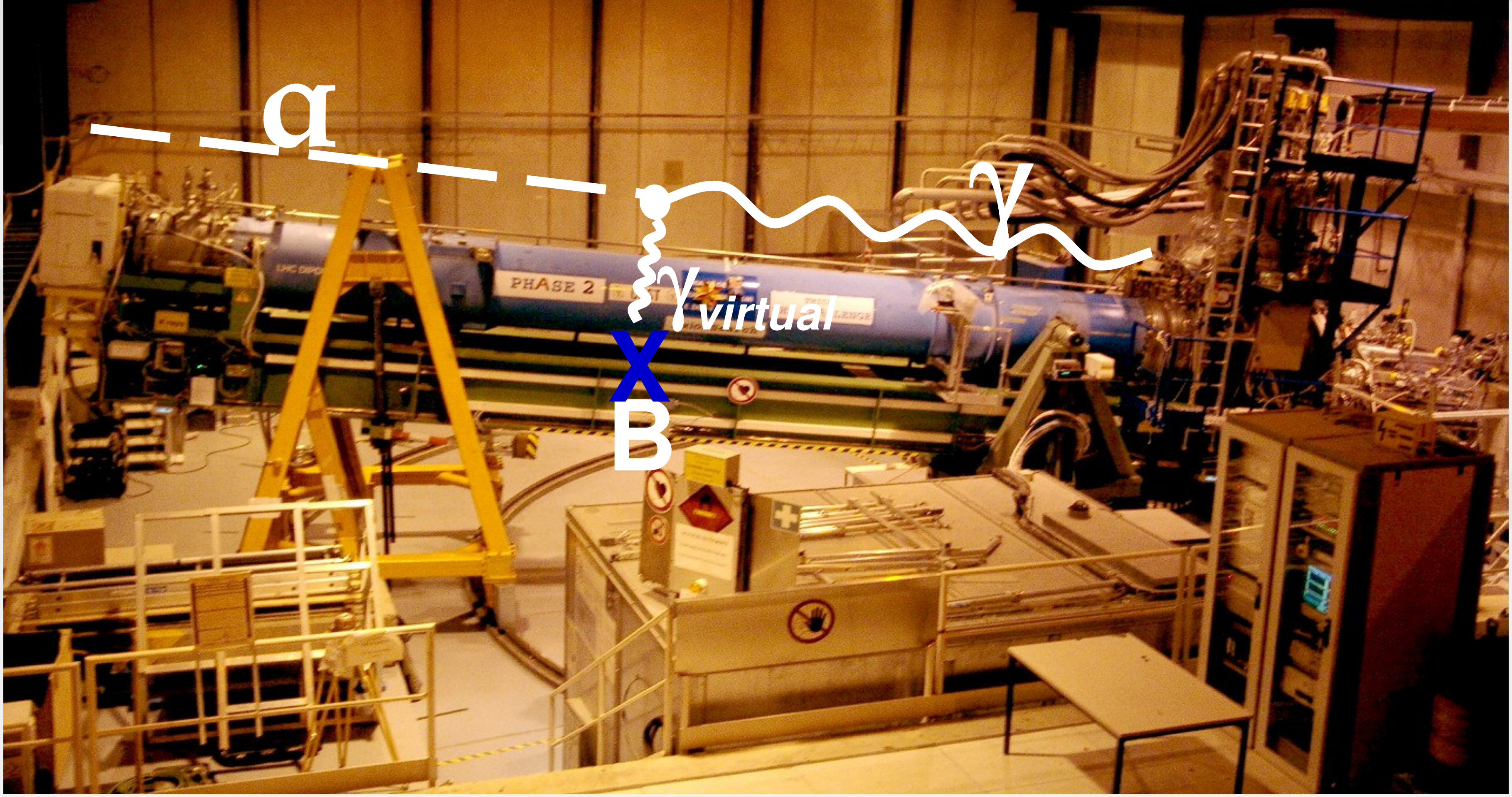
- CAST
  - inverse Primakoff of solar axion



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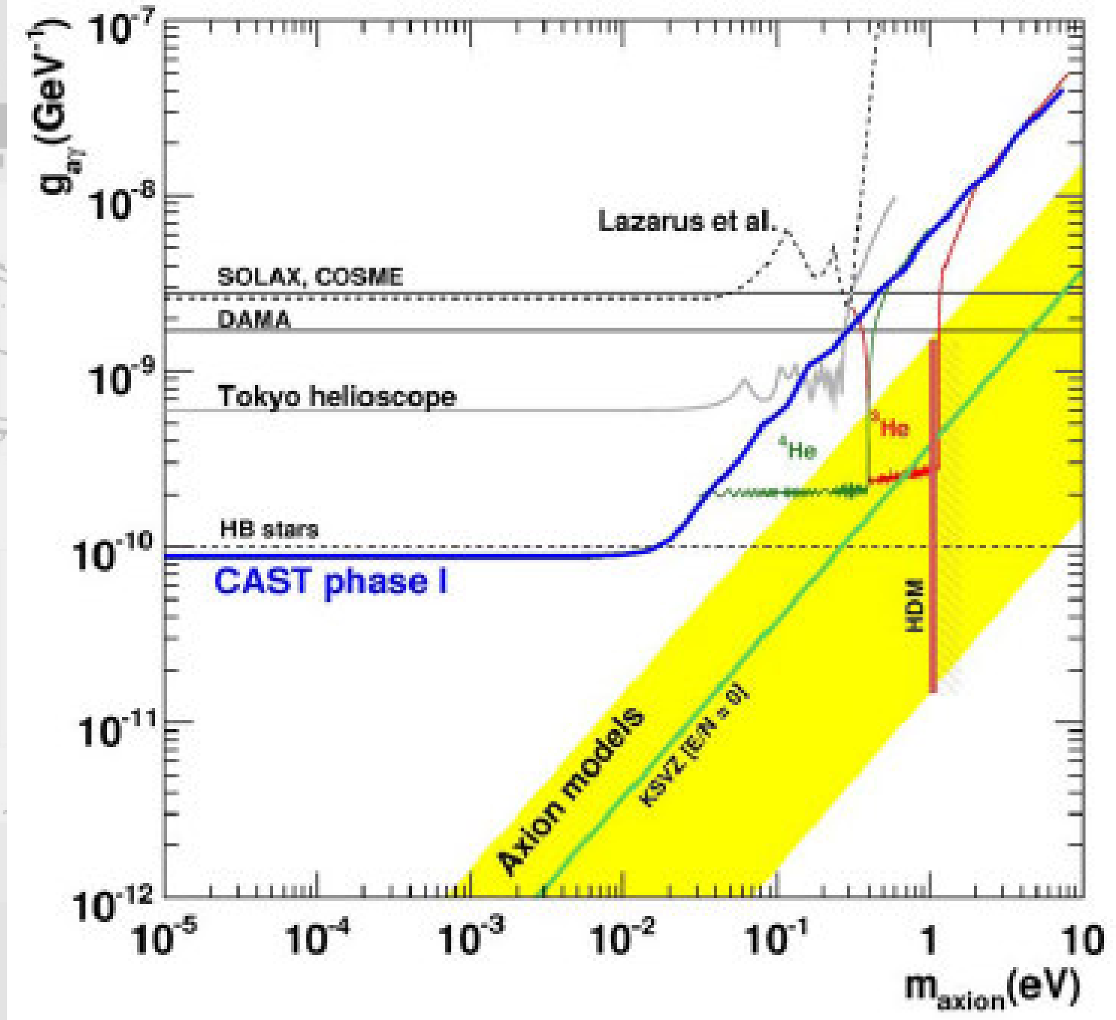
Axion ?

- PVLAS

- pressure density
  → refractive index
  → larger m_{axion}

- *He* data-taking underway
  → > hot dark matter limit



↳ CAST: unique sensitivity

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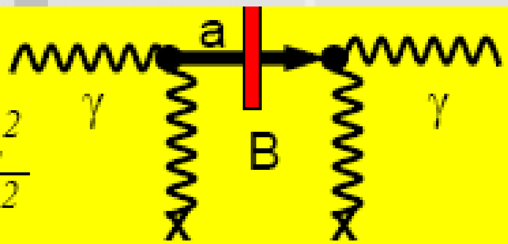
Axion ?

- photon regeneration – OSQAR

P. Sikivie, PRL 51 (1983) 11415

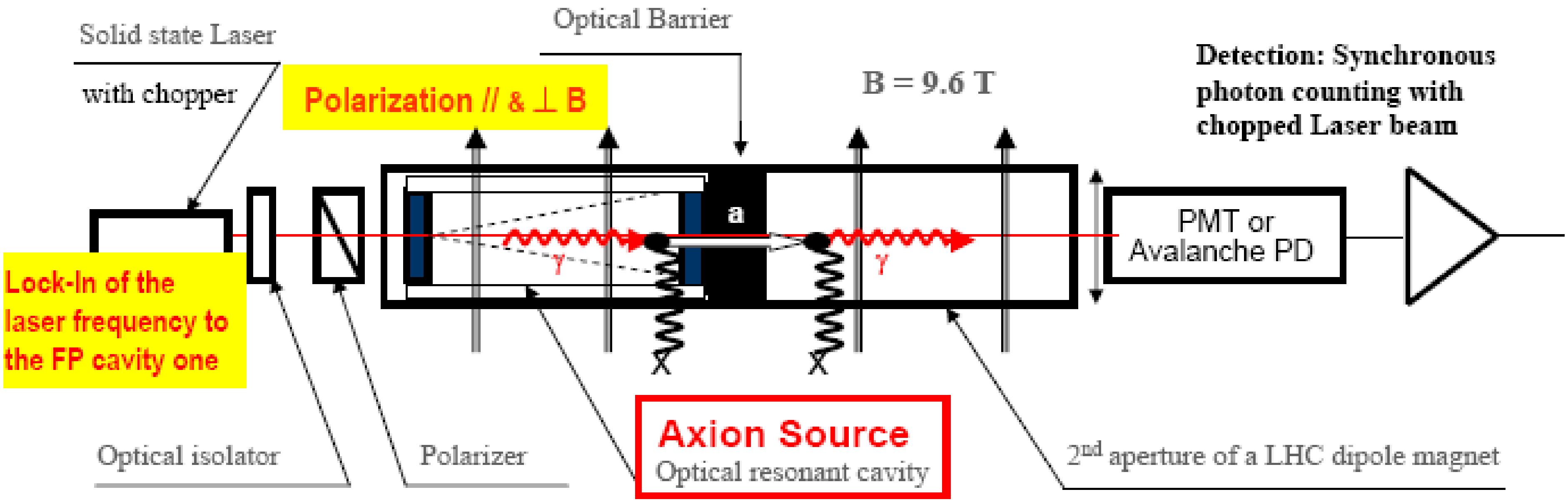


K. van Bibber et al. PRL 59 (1987) 759

In the limit $qL<<1$

$$P(a\to\gamma)=P(\gamma\to a)\approx\frac{B^2L^2}{4M^2}$$

$$R\approx\frac{\eta\ P}{h\nu}\ \frac{N}{2}\left(\frac{B^2l^2}{4M^2}\right)\cdot\left(\frac{B^2L^2}{4M^2}\right)$$



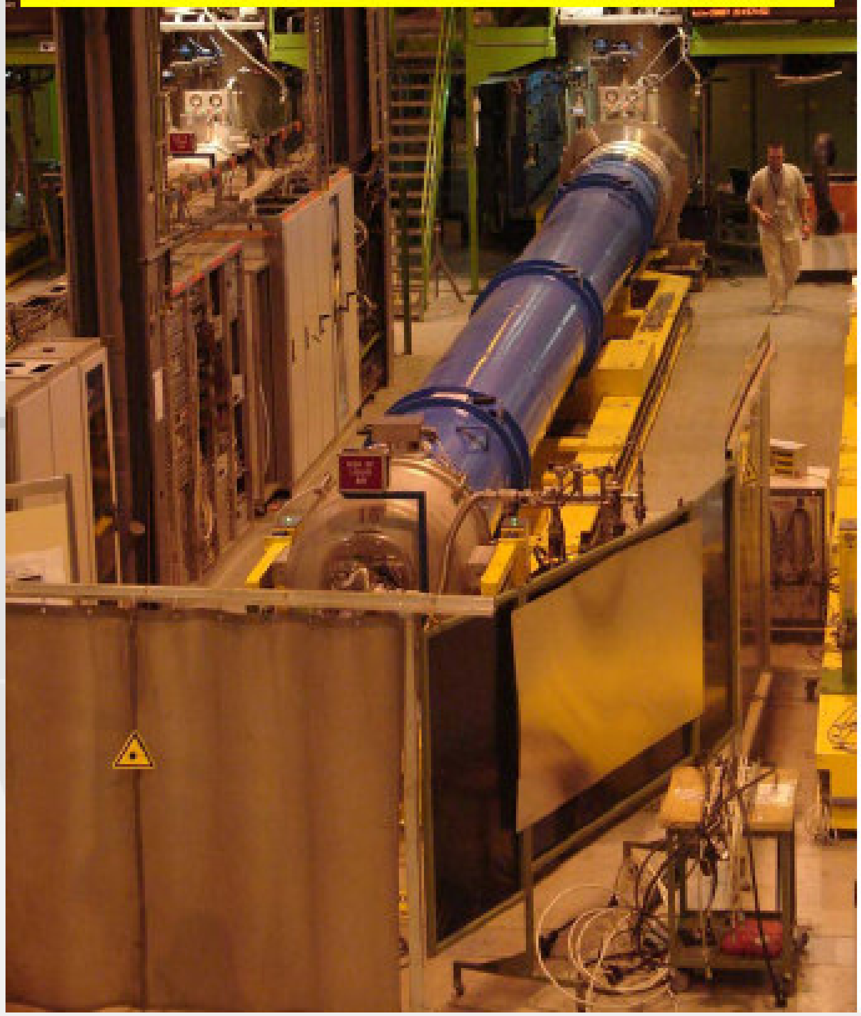
Nd-YAG laser: Power P = 0.1 – 10 kW
λ = 1064 nm
Optical cavity: F = 10^4-10^5, l = 7 m
Detection part: L = 7 m

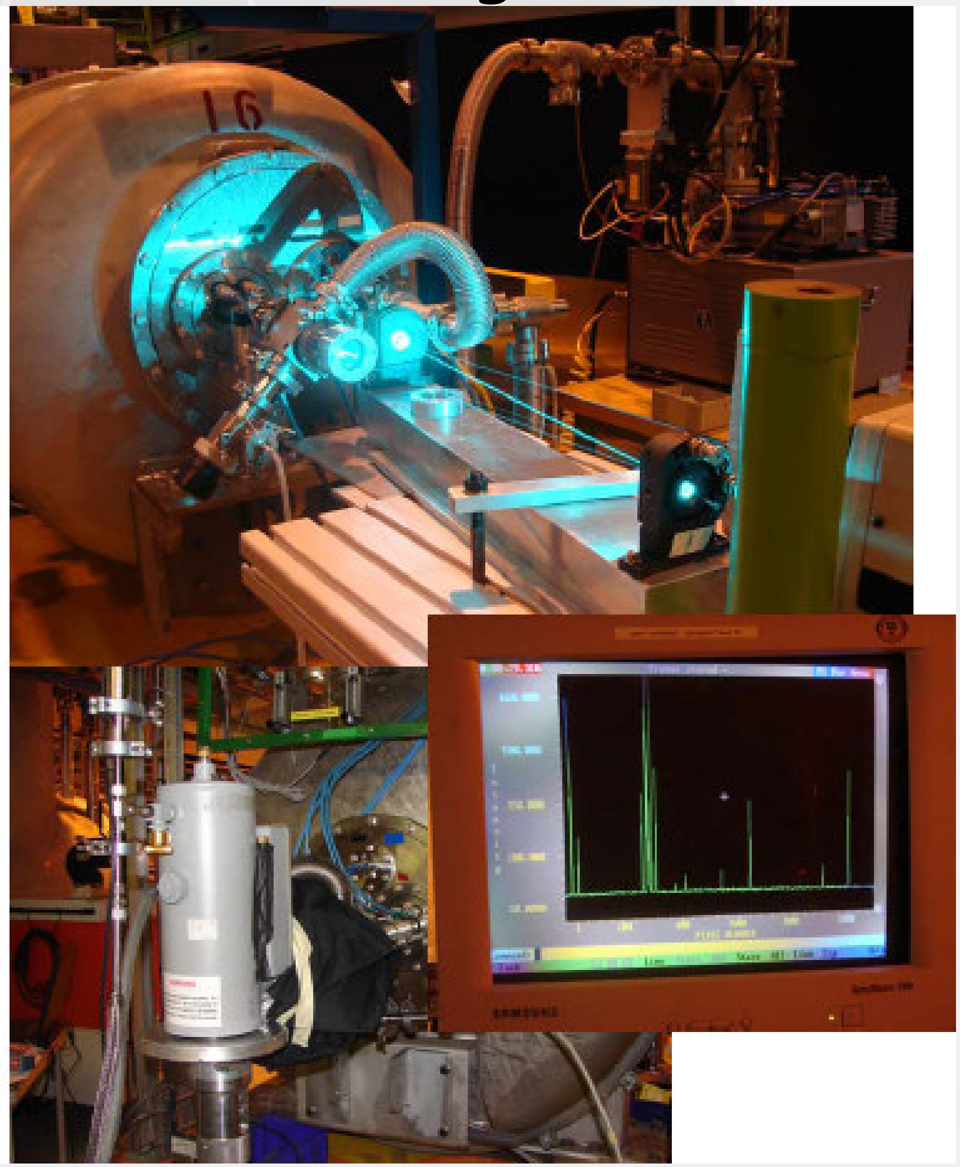
Expectations: Improvement / the present reference result of Cameron et al. Phys. Rev. D47 (1993) 3707 ~ R x 10^7 with 1 magnet & 100 W

Axion ?

- photon regeneration: laser + LHC magnet

Weekend & night activities
to solve Resources & Safety Issues





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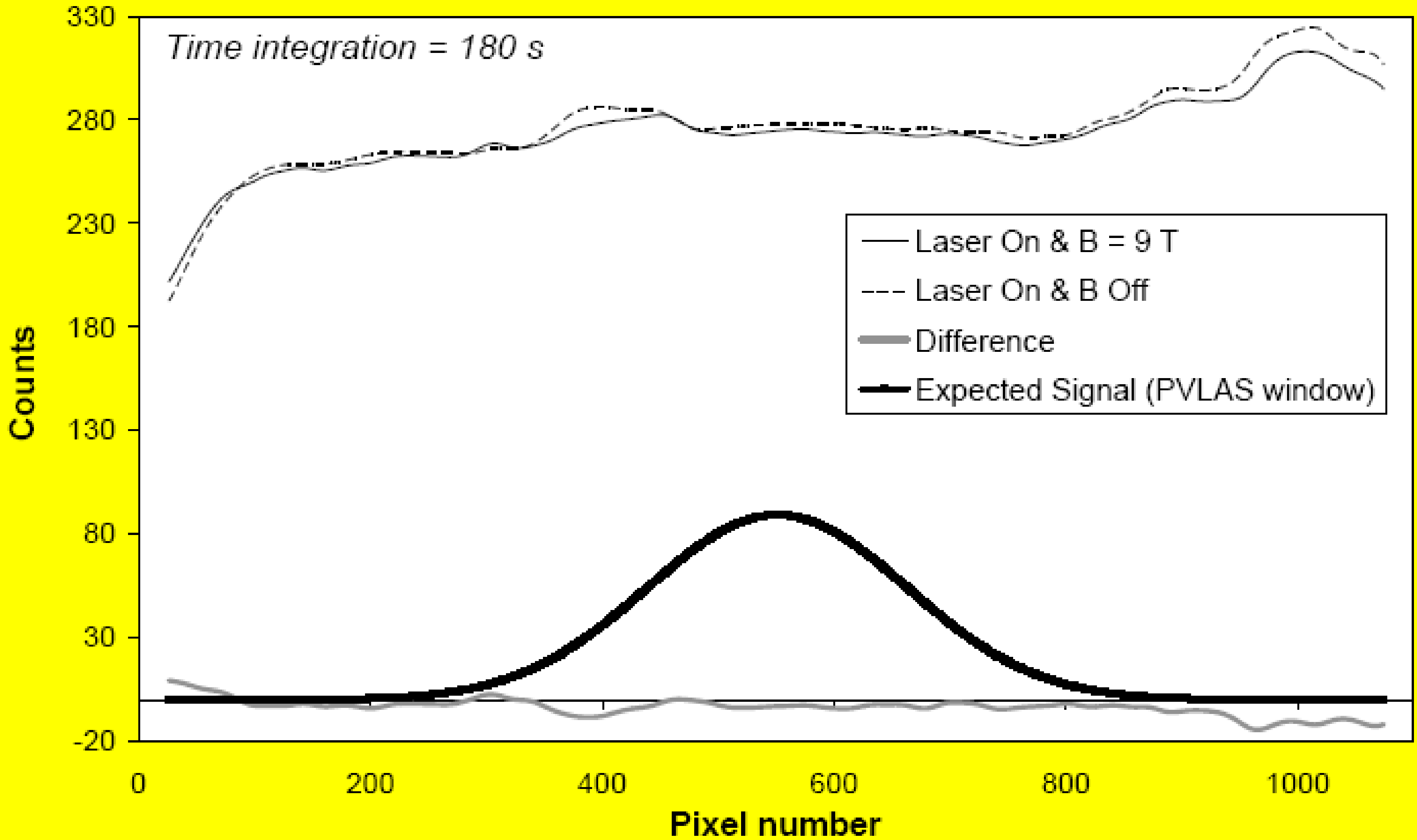
Axion ?

- photon regeneration: laser + LHC magnet



Axion ?

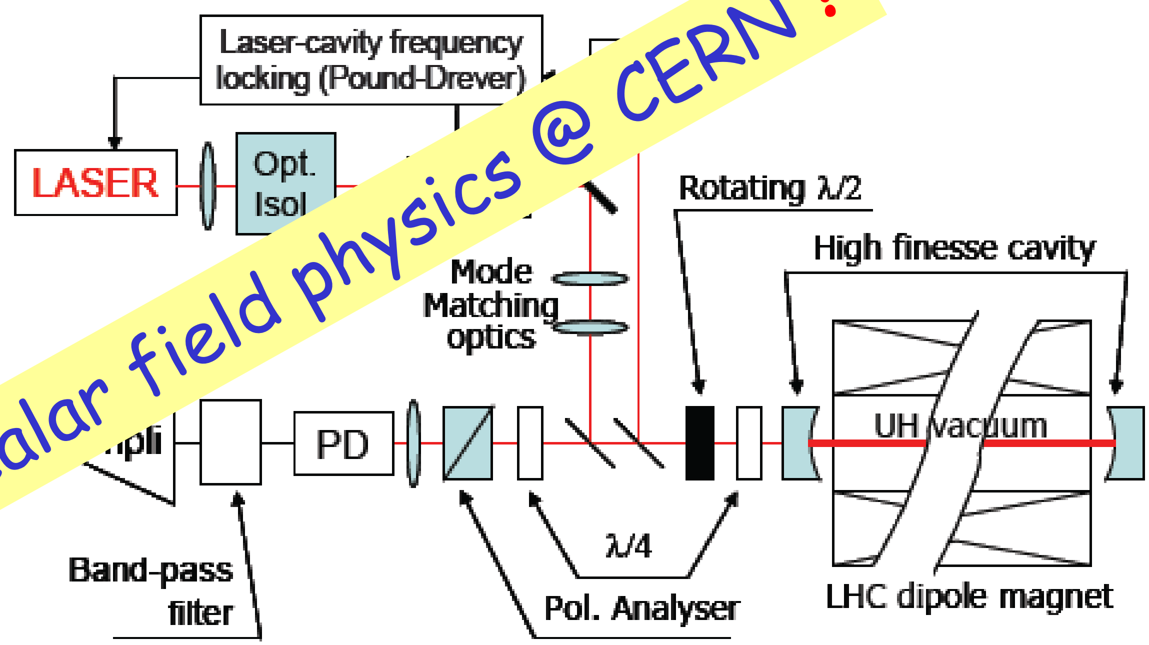
VMB & Linear Dichroism measurements for Axion Search: *Principle & Proposed Optical Scheme*

- Axions ⇒ Change of the linear polarisation of a laser beam after propagation in the vacuum with B transverse:
  - Elliptical
  - “Pseudo”-rotation
- Background for the ellipticity coming from the QED VMB

  ⇒ Physics is guaranteed
- Very small eff... ~10^{-14} ra...

  ⇒ ...vity to incr... the path in B

P. Pugnat, L. Duvillaret, M. Finger, M. Kral , A. Siemko, J. Zicha, Czechoslovak Journal of Physics, Vol.55 (2005), A389; Optical scheme with inputs from D. Roma...



future for scalar field physics @ CERN ?

Field Modulation at 1-10 mHz & dedicated filtering techniques

L. Maiani, R. Petronzio, and E. Zavattini, Phys. Lett. 175B (1986) 359

8. Neutrino Physics @ CERN

- neutrino (ν) flavour eigenstates ≠ mass eigenstates
  - oscillation in probability for given flavour

oscillation phase $\frac{\Delta m^2 c^3 L}{4\hbar E} \approx 1.267 \times \frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{\mathrm{km}} \frac{\mathrm{GeV}}{E}$,

- $\sin^2(2\theta_{13}) < 0.19$ at 90% confidence level ($\theta_{13} < 13°$) [3]
- $\tan^2(\theta_{12}) = 0.45^{+0.09}_{-0.07}$. This corresponds to $\theta_{12} = \theta_{sol} = 33.9°{}^{+2.4°}_{-2.2°}$
- $\sin^2(2\theta_{23}) = 1^{+0}_{-0.1}$, corresponding to $\theta_{23} = \theta_{atm} = 45 \pm 7°$ ("atm"
- $\Delta m^2_{21} = \Delta m^2_{sol} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5} \mathrm{eV}^2$ [4]
- $\Delta m^2_{31} \approx \Delta m^2_{32} = \Delta m^2_{atm} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3} \mathrm{eV}^2$ [5]
- δ, α_1, and α_2 are unknown

↳ τ appearance ?

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CNGS

Complementary with NUMI

- Provide an unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for ν_τ appearance in a pure ν_μ beam
- Search for the subleading $\nu_\mu \rightarrow \nu_e$ oscillations (measurement of Θ_{13})

- Beam: CNGS (approved 1999)
- ν_τ appearance experiments

NO near detector

OPERA — CNGS1 (approved 2000)

ICARUS — CNGS2 (approved 2002)
Limited to 600 tons in 2005

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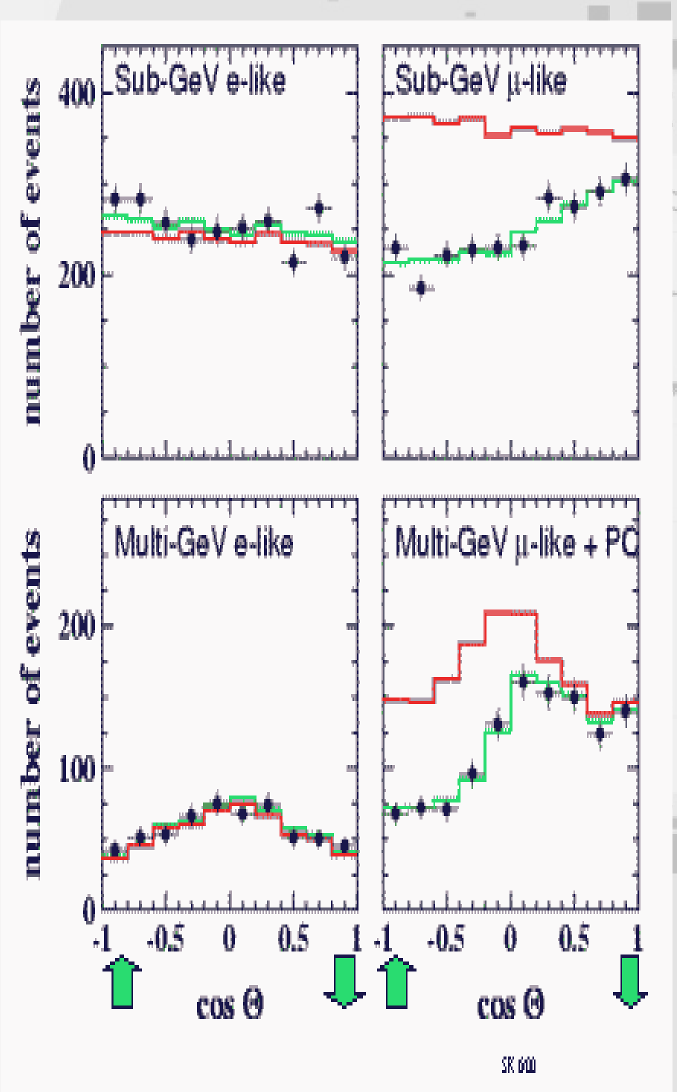
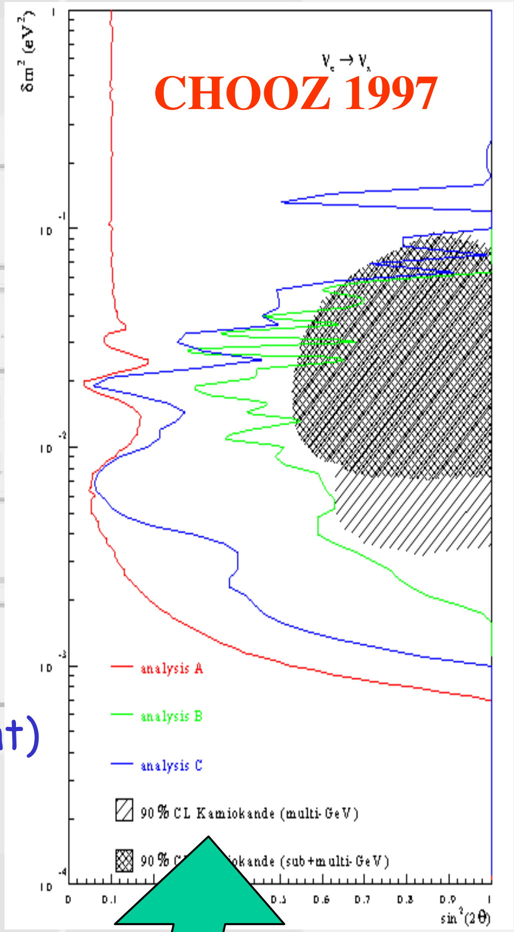


SuperK 1998

From Kamiokande to SuperK:
Atmospheric neutrinos anomaly intepretable in terms of $\nu_\mu \rightarrow \nu_\tau$ oscillations

CHOOZ (reactor experiment)
no $\nu_e \rightarrow \nu_x$ oscillations
$\Rightarrow \Theta_{13} < 11°$



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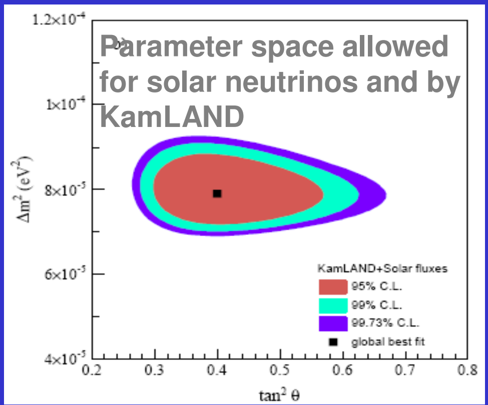
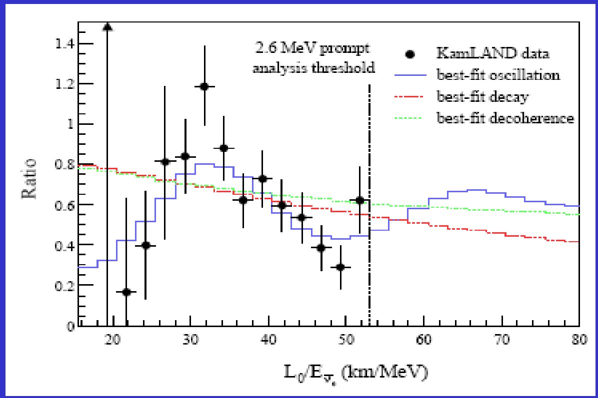
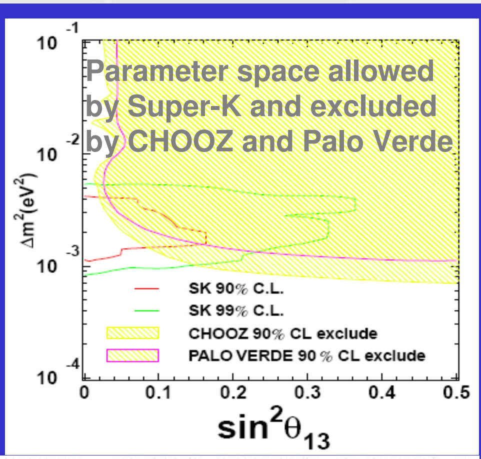
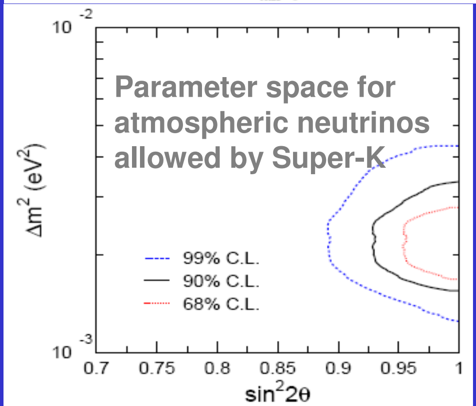
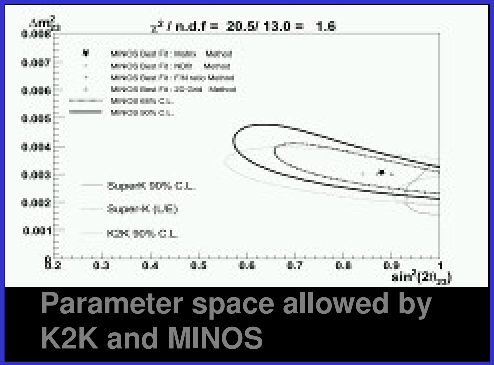
Despite compelling evidences of neutrinos oscillation at all available sources: Sun, atmosphere, LBL reactors & accelerators

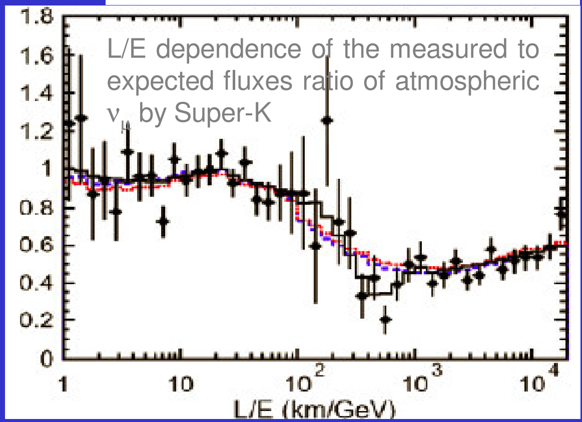












No *direct* evidence yet of flavour APPEARANCE tagged by identification of l^- emitted in CC interaction

(only *indirect* evidence from NC measurement in SNO, and soon in MINOS)

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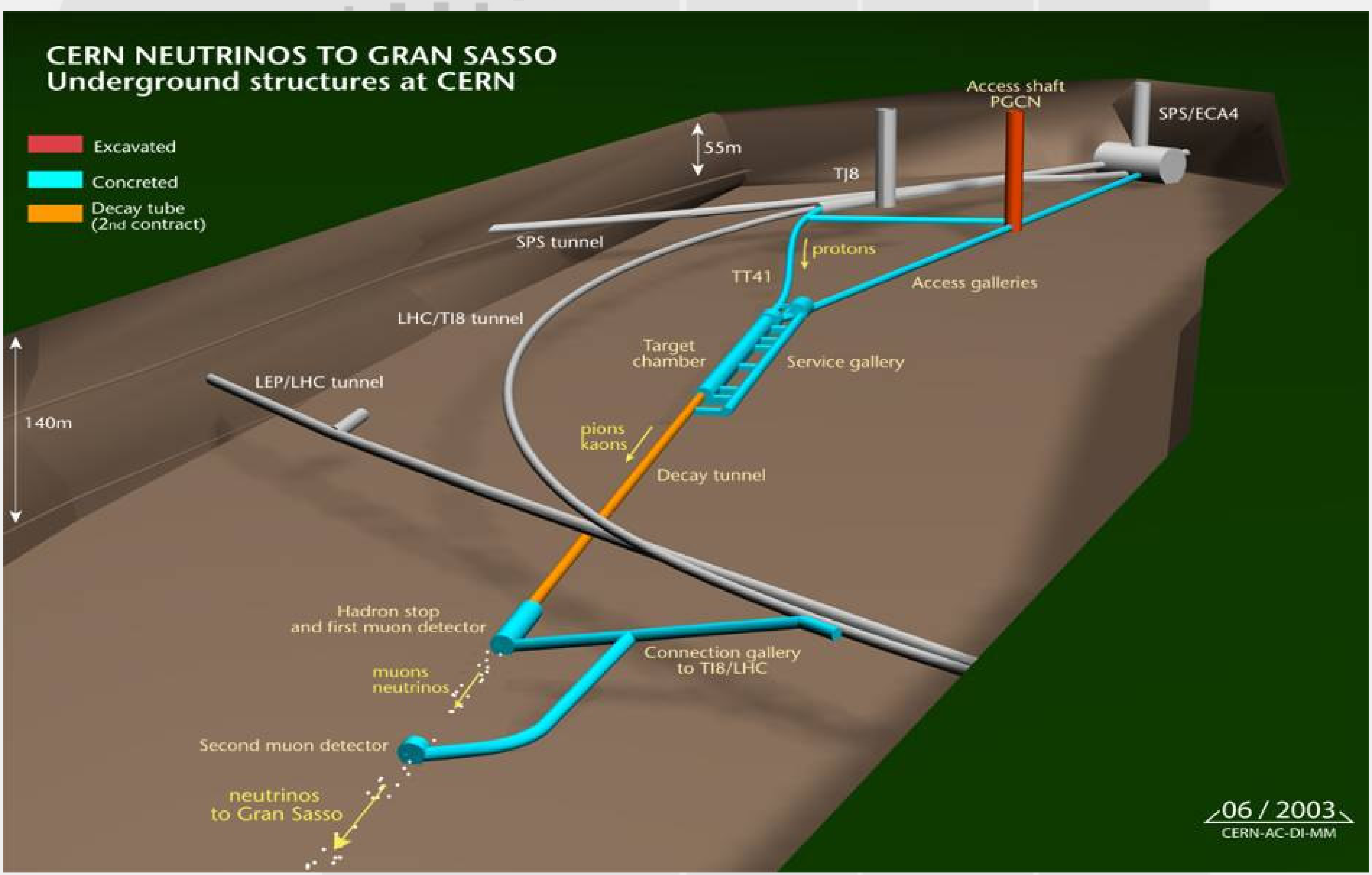

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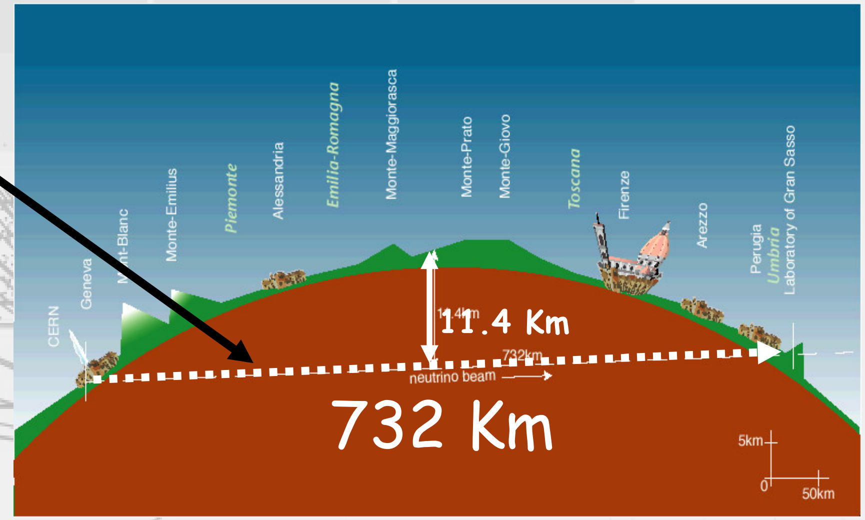
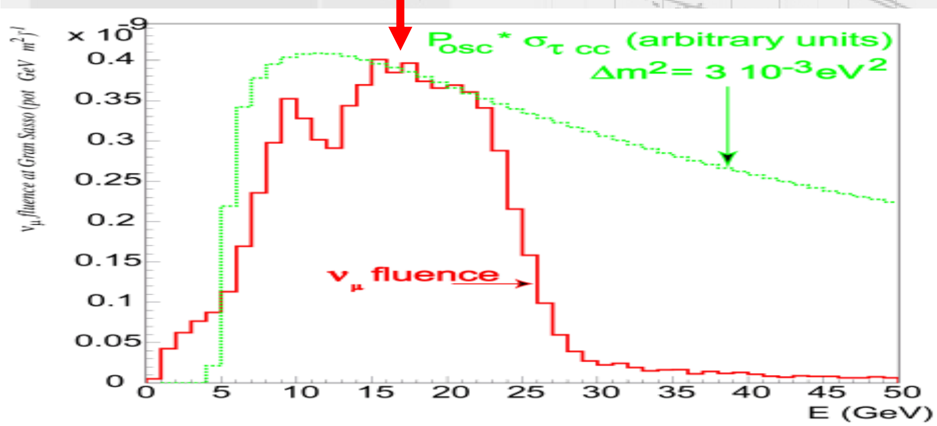
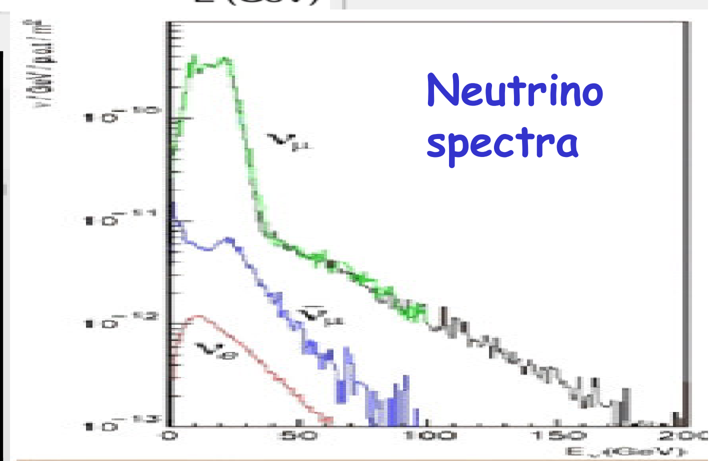
Given the distance CERN-LNGS:

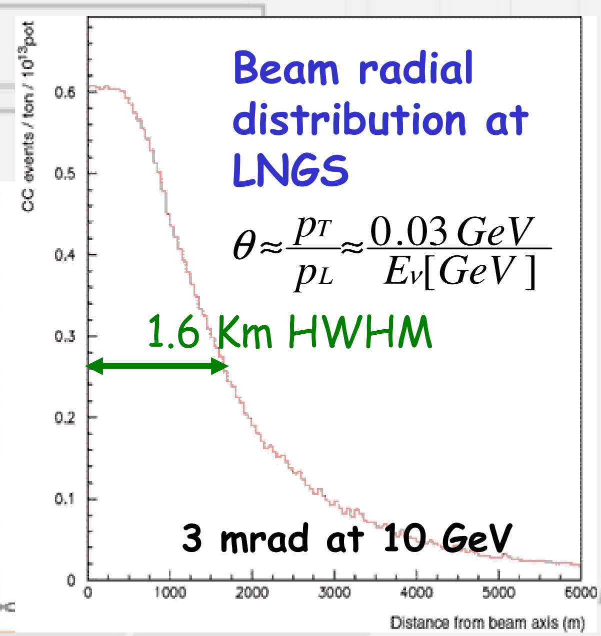


ν_μ flux optimized for the maximal number of ν_τ charged current interactions



$<E\nu_\mu>$	17 GeV
$(\bar{\nu}_e+\nu_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu$ / ν_μ	2.1%
ν_τ prompt	negligible





$$\theta \approx \frac{p_T}{p_L} \approx \frac{0.03\,GeV}{E_\nu[GeV]}$$

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OPERA

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Veto plane
(RPC)

High precision tracker
- 6 4-fold layers of drift tubes

Instrumented dipole magnet
- 1.53 *T*
- 22 XY planes of RPC in both arms

Muon spectrometer (8×10 m^2)

Target and Target Tracker (6x7m)^2

- Target : 77500 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT for
  - Brick selection
  - Calorimetry

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OPERA

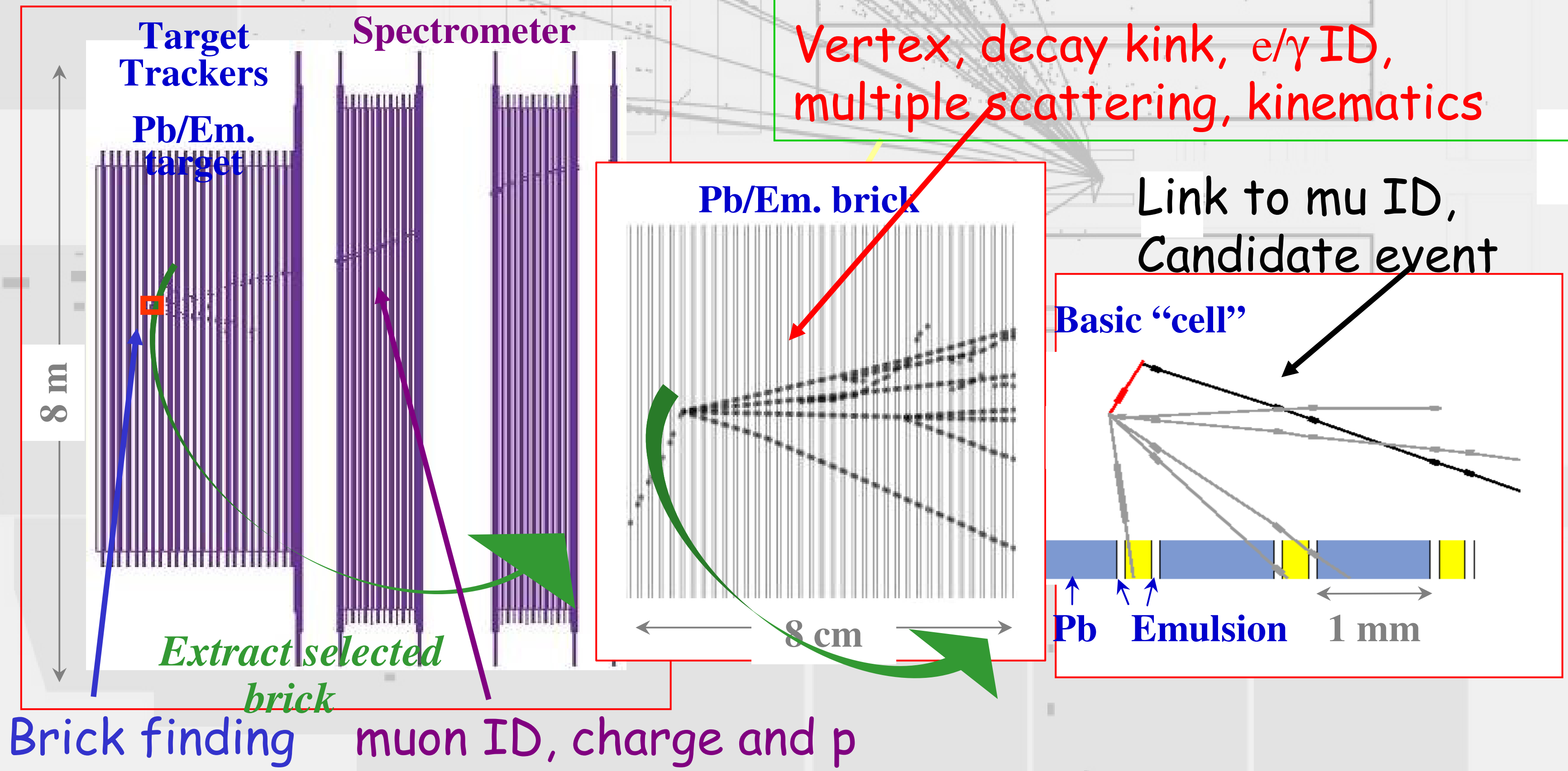
What the brick cannot do:

- trigger for a neutrino interaction
- muon identification and momentum/charge measurement → need for an hybrid detector

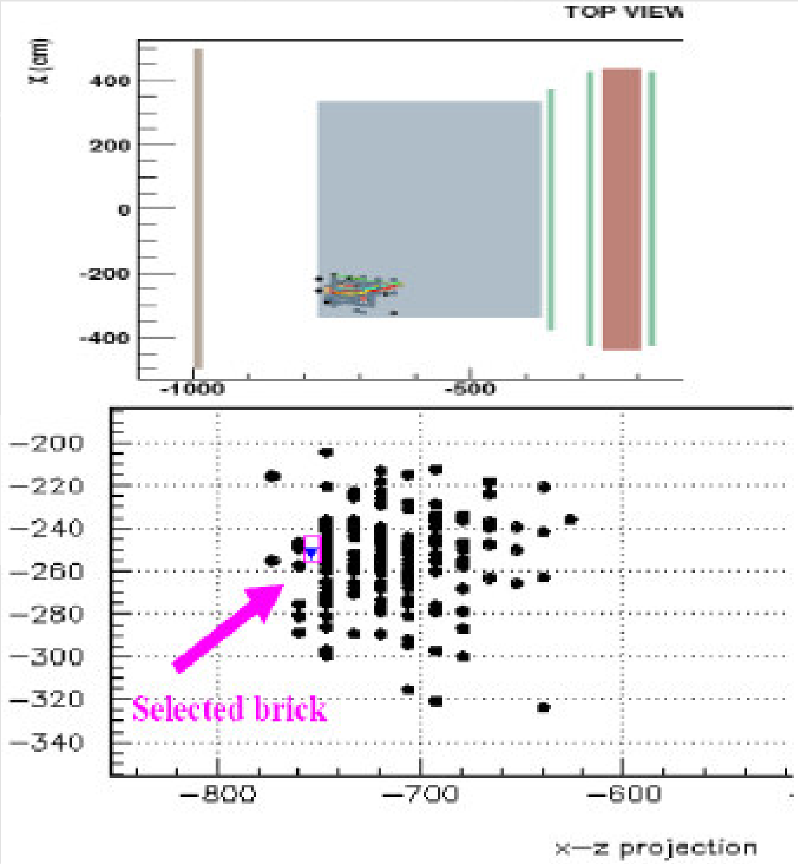
Electronic detectors:

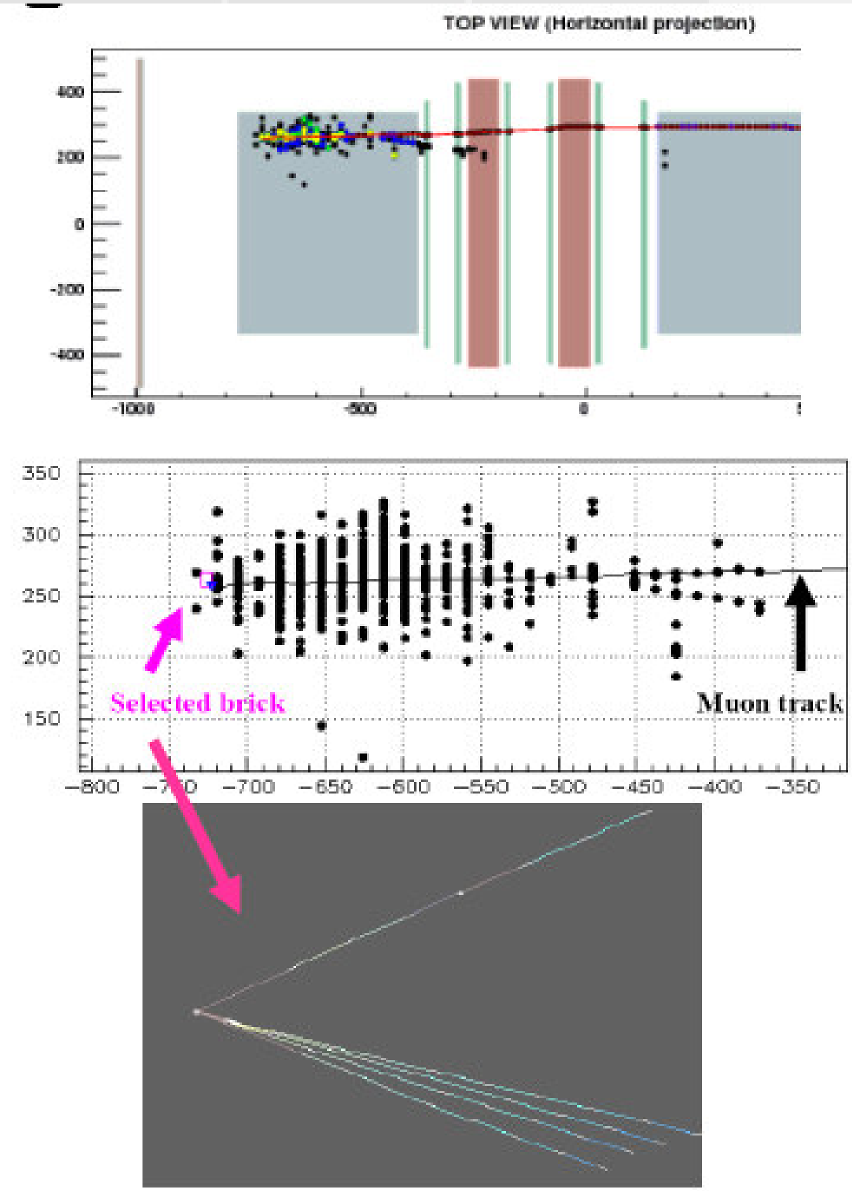
Emulsion analysis:

Vertex, decay kink, e/γ ID, multiple scattering, kinematics



OPERA Events





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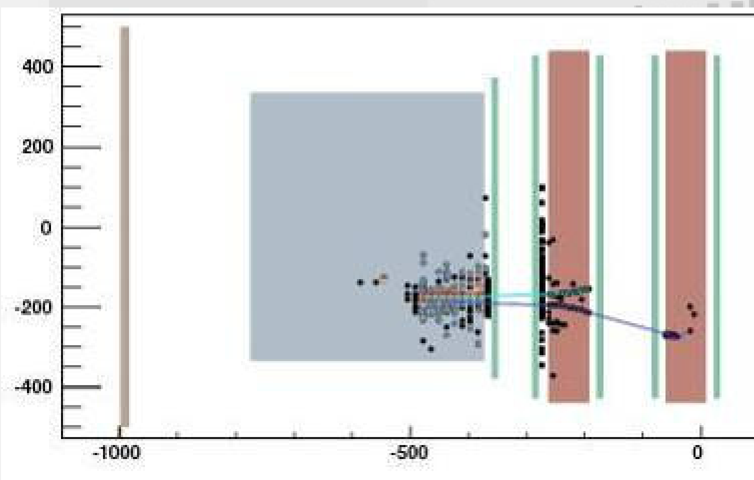
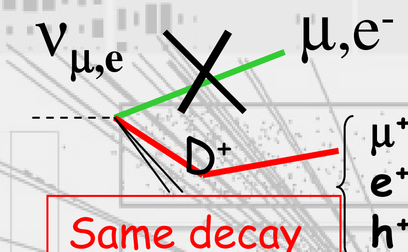
OPERA Events





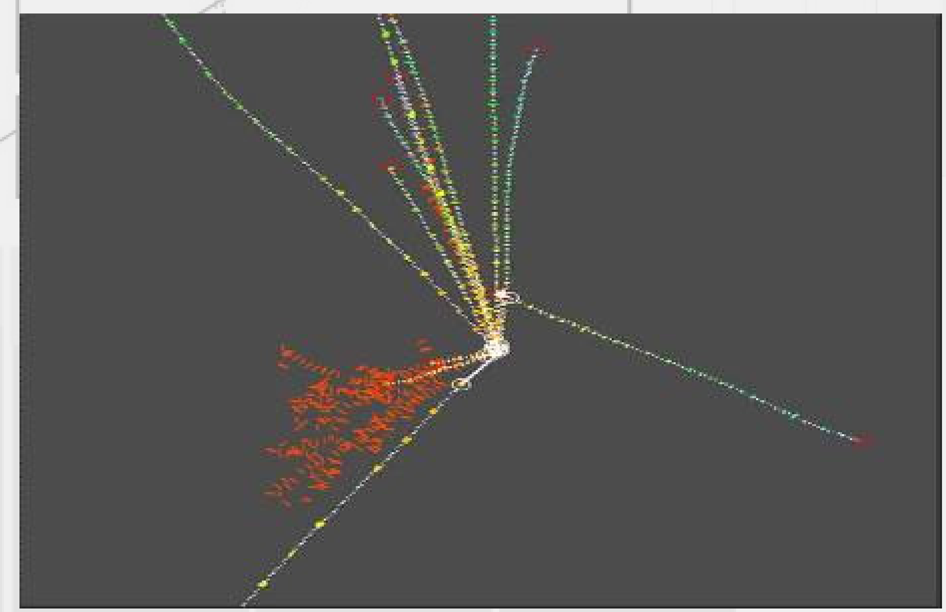
Primary lepton not identified

Same decay topology as τ

Charm production in CC, common to the 3 channels

Good muon identification is fundamental

During the run in 2007 we have observed, out of 38 events, one CC interaction containing a Charm decay as expected. The 2 muons can be identified inside the spectrometer as stopping tracks.



OPERA

For 1 year of CNGS operation (200 days), we expect:
4.5×10^{19} protons on target in shared mode
(Ongoing studies at CERN to increase the intensity x 1.5)

Event rates in 5 years
for $4.5\ 10^{19}$ pot /year
S/B ~ $3\ 10^{-3}$

	OPERA 1.35 kton
ν_μCC	19572
ν_μNC	5880
$\bar{\nu}_\mu$CC	411
ν_eCC	156
$\bar{\nu}_e$CC	13
Total	26032

ν_τCC interactions

Δm^2	OPERA
1×10^{-3} eV^2	20
2×10^{-3} eV^2	80
3×10^{-3} eV^2	180

Additional 10K events in the OPERA magnets

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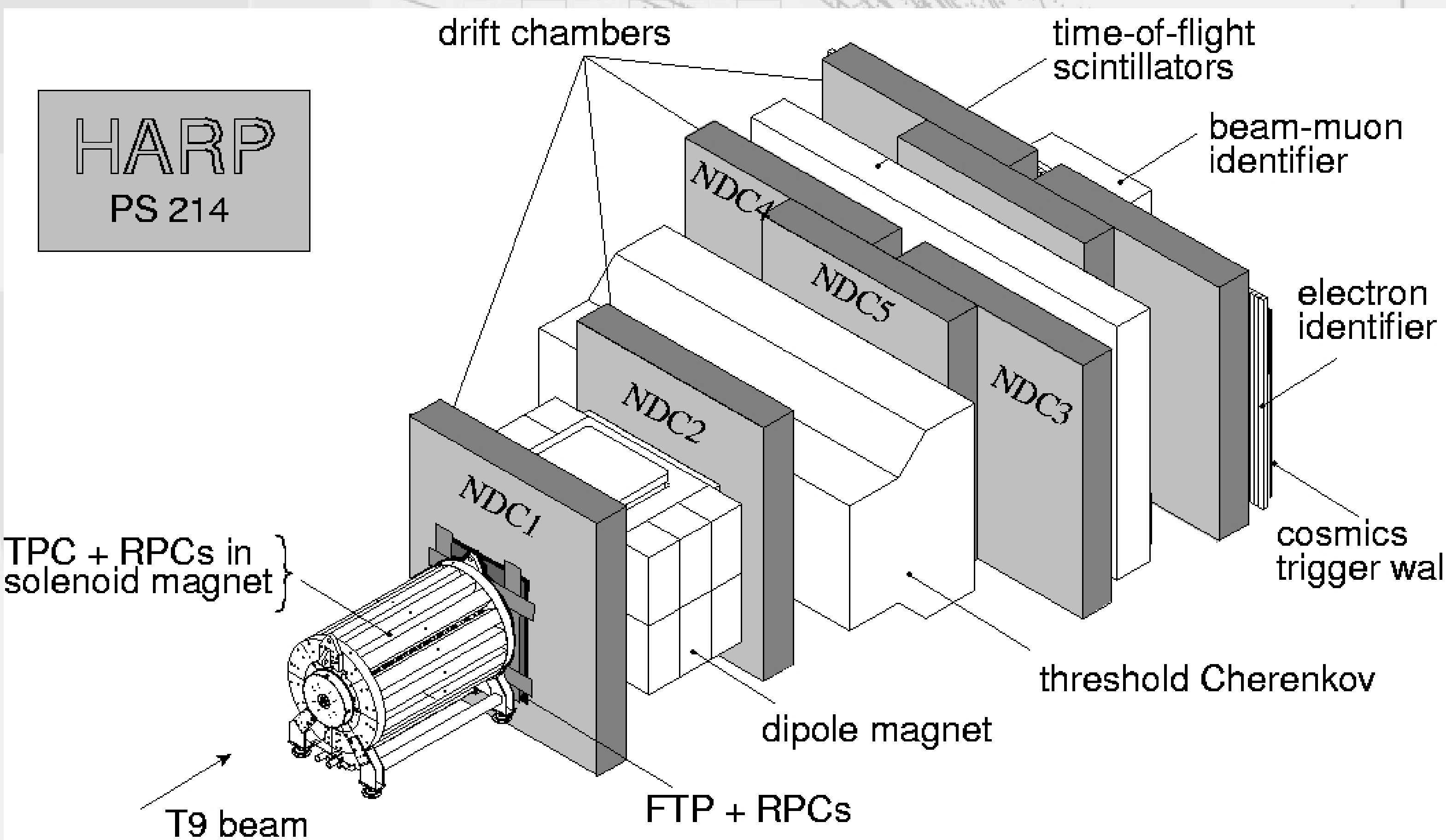
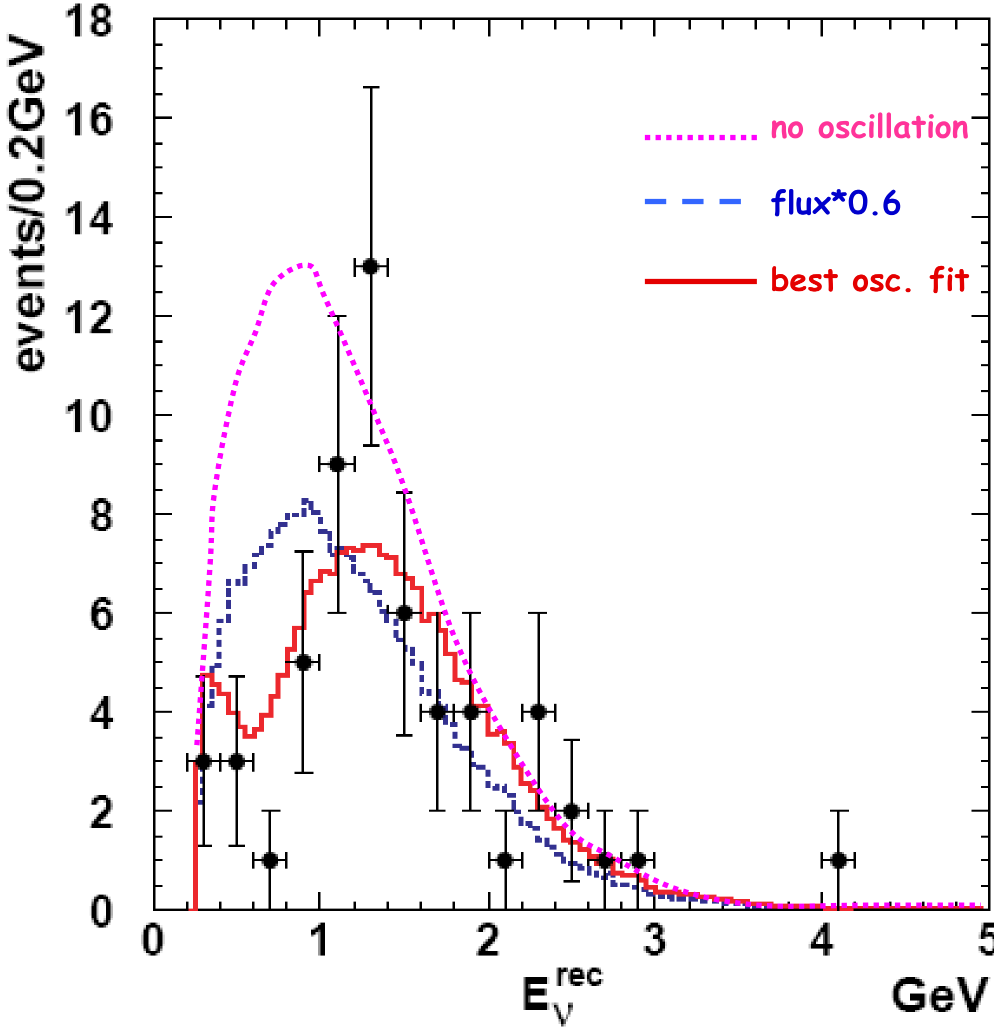
ν Systematics: HARP

- HARP – impacting on ν systematics
  challenging measurement – small angle on nuclei





Reconstructed « single ring »
Quasi-elastics in SuperKamiokande

==> spectral shape + normalization
show oscillation

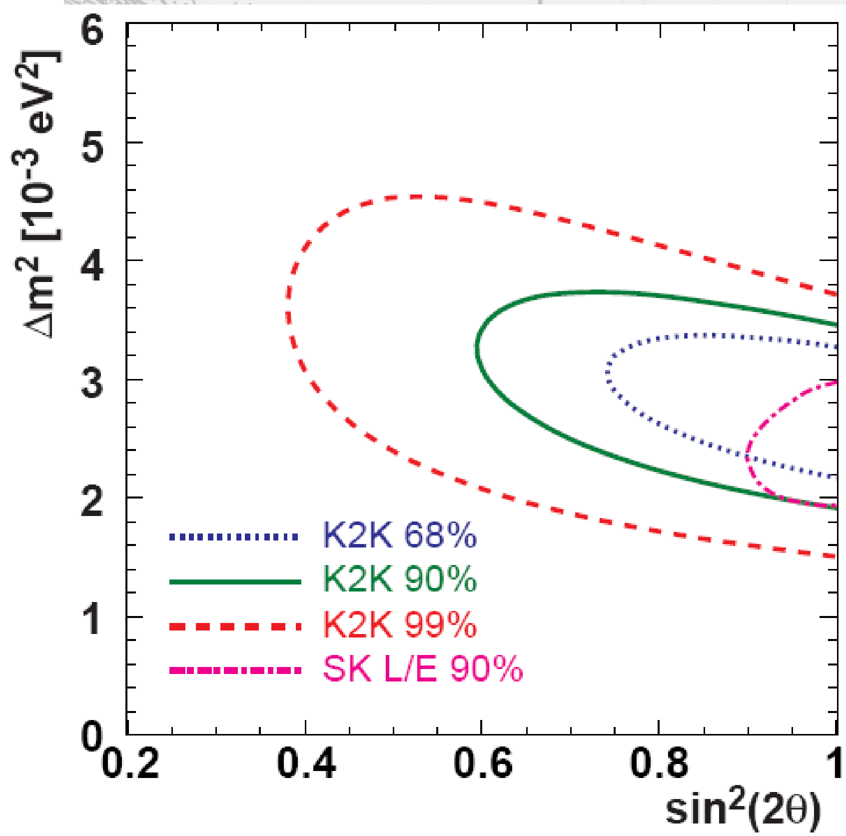
HARP

The Cockcroft Institute of Accelerator Science and Technology

UNIVERSITY OF LIVERPOOL

K2K results

M. H. Ahn et al.,
K2K Collaboration, Phys. Rev. **D74** (2006) 072003



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9. Onwards

- AD programme on-going to ~~CPT~~ ?
- PS: DIRAC + CLOUD
- SPS: COMPASS
  - completed muon programme
  - preparing hadron programme

  CNGS → OPERA

  new *K*-physics: NA62

  P136 R&D for $K\to\pi\nu\bar{\nu}$

  NA61 *pA* for HI ν and cosmic showers
- astro-particle physics CAST

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Onwards

- horizon ?
  - AD programme on-going → ~~CPT~~ tests
  - PS: DIRAC (until GSI FAIR)
  - SPS: COMPASS - hadron programme
    CNGS - OPERA (ICARUS) (until T2K)
    $K \to \pi\nu\nu$ physics from 2010 ?
    NA61: heavy ion 4th generation ?
  - "photon science"
    scalar fields and VMB (OSQAR) ?
- high quality results still from "old" experiments
  far-sighted investment pays off

↳ **FT programme is unique: only possible at CERN**