Future Nuclear and Hadronic Physics at CERN AD: ideas and brainstorming

SPICE Workshop

Strange Hadron as a **P**recision Tool for Strongly **I**ntera**c**ting Syst**e**ms

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Outline

- Introductory remarks
- Physics with low energy antinucleons
  - Overview and open problems: a few selected topics
- The onset of strangeness in $\bar{N}N$ annihilation
  - Strangeness in nucleons
  - Hyperon physics and related topics
- State-of-art of $\bar{p}$ infrastructure at CERN and timeline
- Conclusions

Introduction: why antinucleons again?

- Ideas for new measurements to be performed with low energy $\bar{p}$'s at a (possible) forthcoming future facility were discussed in a kickstart meeting at SMI, Vienna
  - FuPhy2024 meeting, April 8-10, 2024: https://indico.cern.ch/event/1374378/

- Lively interplay among physicists (mostly originating from past experiments at LEAR) and AD/ELENA machine staff
  - Lot of interest from machine staff in the ideas of a new hadron physics program to extend AD's life
  - A rich hadron physics program can be easily worked out, based on the outcomes of old LEAR experiments
    - New experimental techniques
    - Big progresses on the theoretical side for the interpretation of observations
  - Far time horizon but it needs to be laid out now!

Some ideas for new measurements with low energy antiprotons

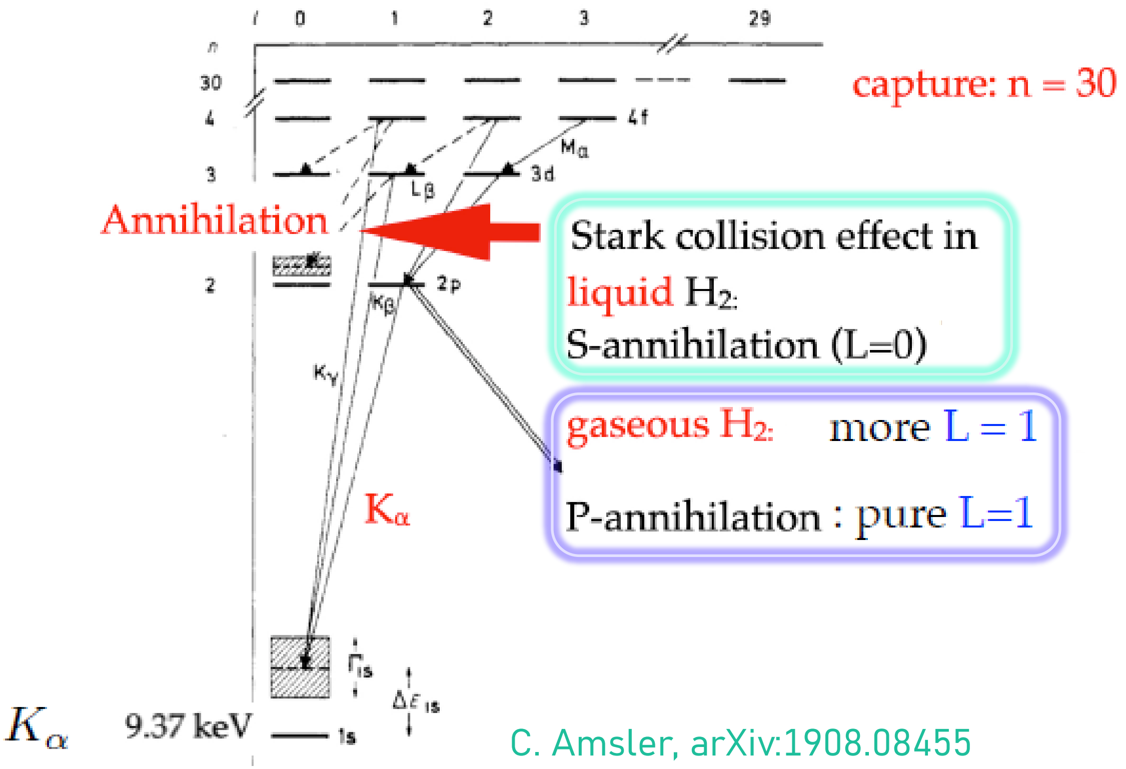
Physics with low energy antiprotons: open issues

- Several issues left open since LEAR times and new research topics
  - **Annihilation dynamics studies**
    - $\bar{p}$ annihilation: at rest vs in flight processes
    - Pontecorvo reactions
    - Physics with antineutrons
    - Antideuterons/antideuterium production
  - **Meson and baryon spectroscopy**
    - Glueballs/exotic searches
    - S-dibaryons searches
    - Baryonium searches
  - **Onset of strangeness in annihilation processes**
    - Strangeness in the nucleons
    - Hyperon physics
    - Strange mesonic excitations/hybrids
    - Neutron skin measurements
  - **Other topics**
    - $\bar{n}$-n oscillations, …

Antinucleons ($\bar{p}, \bar{n}$) annihilation dynamics

$\bar{N}N$ annihilation at rest

- Annihilation at rest occurs from protonium states: atomic $p\bar{p}$ states following $\bar{p}$ capture in the n=30 orbital
- Cascade down to P and S states, density dependent
  - strongly suppressed by collisions with neighboring atoms through Stark effect



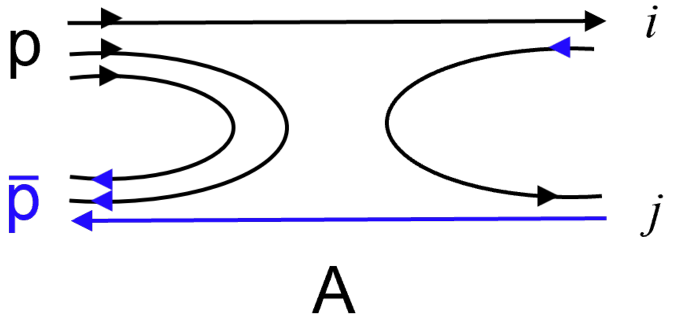
C. Amsler, arXiv:1908.08455

- Which mechanism underlying the production of particles in annihilation?
  - Gluon rich environment
  - Hot evaporating fireball gas
    - Pion final multiplicity distributed statistically (roughly ok with experiment)
    - But: keep into account the excitation of intermediate resonances
  - Quark and antiquark interactions
    - Clear evidences, but the exact mechanism is still unclear
    - Annihilation vs rearrangement interplay

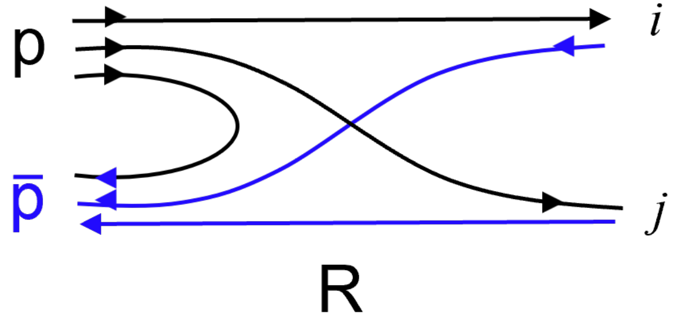
Dynamic selection rules in $\bar{N}N$ annihilations

- Experimental observation of peculiar behaviors in two-body processes
- More comprehensive theoretical interpretation needed
- More precise data could be useful…
  1. Suppression of K^+K^- production from P waves
     - Missing contribution from the quark annihilation graph A?
  2. Suppression of the $\rho\pi$ channel from ${}^1S_0$
  3. Dominance of $\omega\omega$ vs $\rho\rho$ channel
     - Can be explained through rearrangement diagrams R?
  4. Suppression of φ production from P wave
  5. Suppression of $f_2'(1525)$ production from S wave
     - Both leading to sizeable excess compared to OZI-rule predictions

i, j: u ($\bar{u}$) and d ($\bar{d}$)



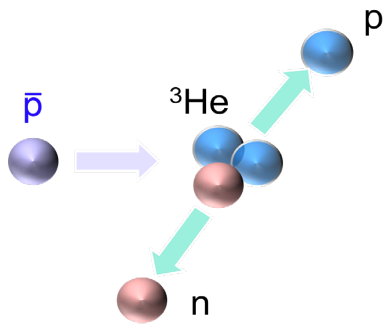
Annihilation: no $(u\bar{u} + d\bar{d})$



Rearrangement: no $(d\bar{d} + d\bar{d})$

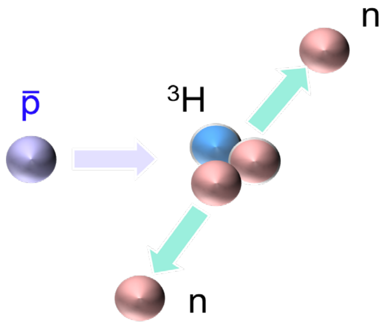
Pontecorvo reactions on three nucleons

- Class of (rare) annihilation reactions occurring on nuclei, forbidden on free nucleons: **B.R. < 10^{-5}**
- Sensitive to small internuclear distances and to the dynamics in nucleon pairs in nuclei
- The two main approaches to explain the process expect large differences in branching ratios



$\bar{p}\,{}^{3}He \rightarrow np$

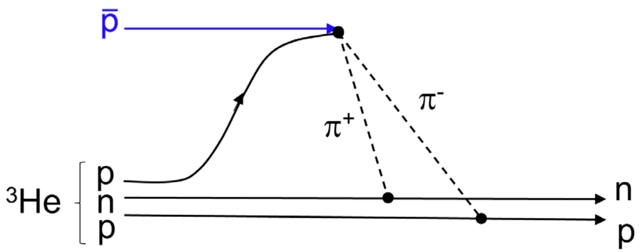
$\bar{p}\,{}^{3}H \rightarrow nn$

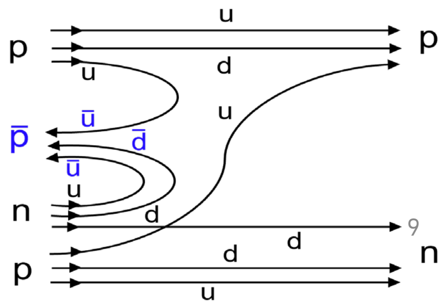


- Systematic studies of $\bar{p}d$ @LEAR
  - Experimental measurements mutually agree
  - Disagreement with model expectations

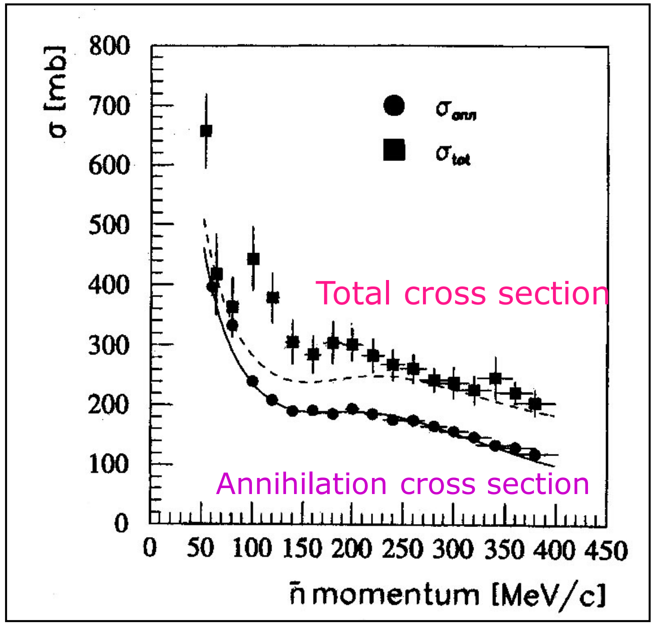
Predicted rates differ by 1-2 orders of magnitude
- **Fireball: 10^{-6}**
- **Rescattering: 10^{-7}-10^{-8}**

- Large differences expected from the models for reactions on ^{3}He, never measured so far
  - Possibility @ASACUSA or with a slowly extracted beam facility



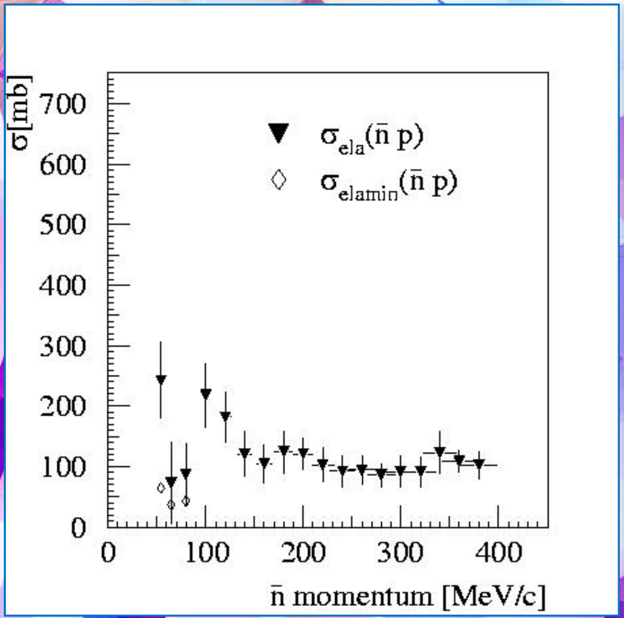


Physics with $\bar{n}$'s: motivations



- $(\bar{n}\,p)$ is a fixed isospin system: $I=1$
- $(\bar{p}\,p)$ contains both the $I=0$ and $I=1$ sources
  - $\bar{n}$'s offer a powerful selection rule excluding several initial states and constraining the combination of quantum numbers of intermediate objects/resonances
- The same quantum numbers are featured by the $(\bar{p}\,n)$ system formed in deuterium targets
  - PRO's:
    - higher statistics/cross section
    - $\bar{p}$ annihilation can occur at rest, $\bar{n}$ annihilation always in flight (more initial partial waves involved)
  - CON's
    - The hit neutron in deuteron has a Fermi momentum: the kinematics are not "exactly" closed
    - The recoiling nucleon has a momentum which should be measured
    - The recoiling nucleon can re-scatter against the particles produced in the annihilation
    - Additional complication: does the annihilation occur on a proton or a neutron in deuteron?

Physics with $\bar{n}$'s: four puzzles

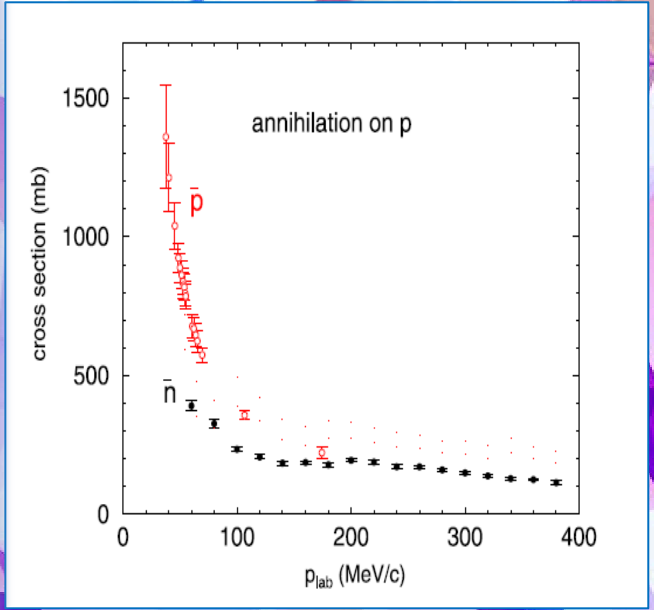


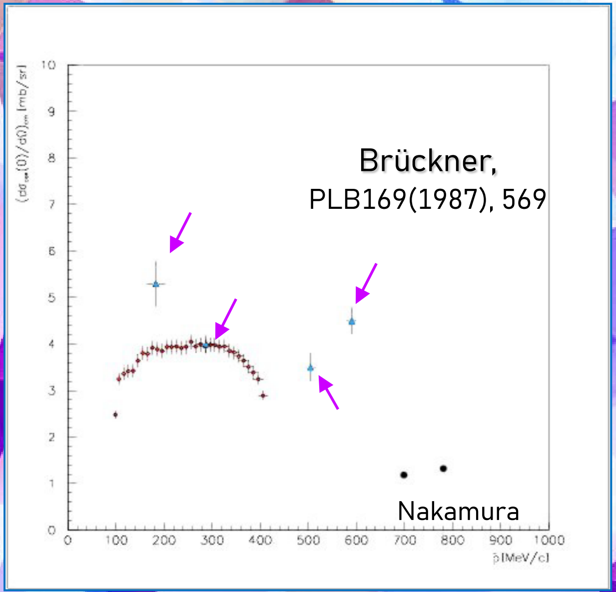
Anomaly in the elastic $\bar{n}p$ channel

- Can it be due to a quasi-nuclear bound state close to threshold?
- Can it be explained by a (sort-of) Ramsauer-Townsend nuclear effect?
  - The points at 64.5 and 80 MeV/c are close to the lower bound for σ_{el} imposed by S-wave unitarity

$I=0$ vs $I=1$ sources interplay

- From the ratio between the total $\sigma_T(\bar{n}p)$ and $\sigma_T(\bar{p}p)$
- $\sigma_{ann}(\bar{n}p) < \sigma_{ann}(\bar{p}p)$
- Strong dominance of the $I=0$ source both in σ_T and σ_{ann}
- But the trend is not monotonical for the annihilation:
  - R(0,1) = 2.4 @ 70 MeV/c vs 1.5 @ 700 MeV/c





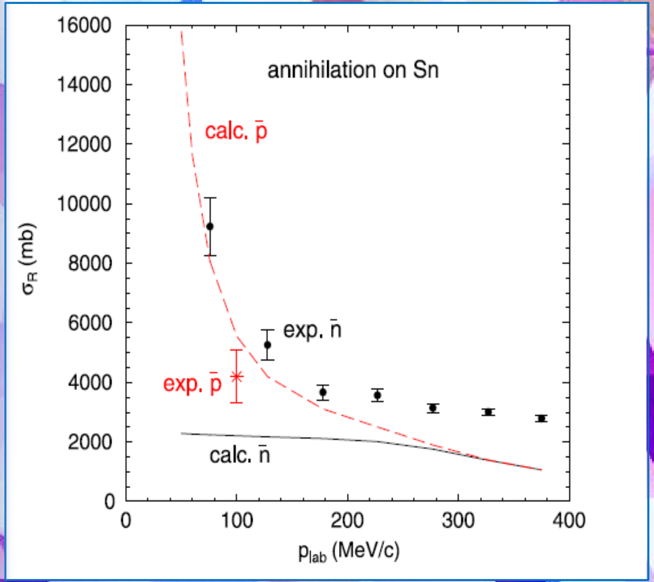
Charge-Exchange total and differential cross section

- Few measurements exist and mostly at high momenta
- *Full angular range*: excess at backward angles
- *0°* : disagreement among several measurements, call for new data

Annihilation cross section on nuclei at low momenta

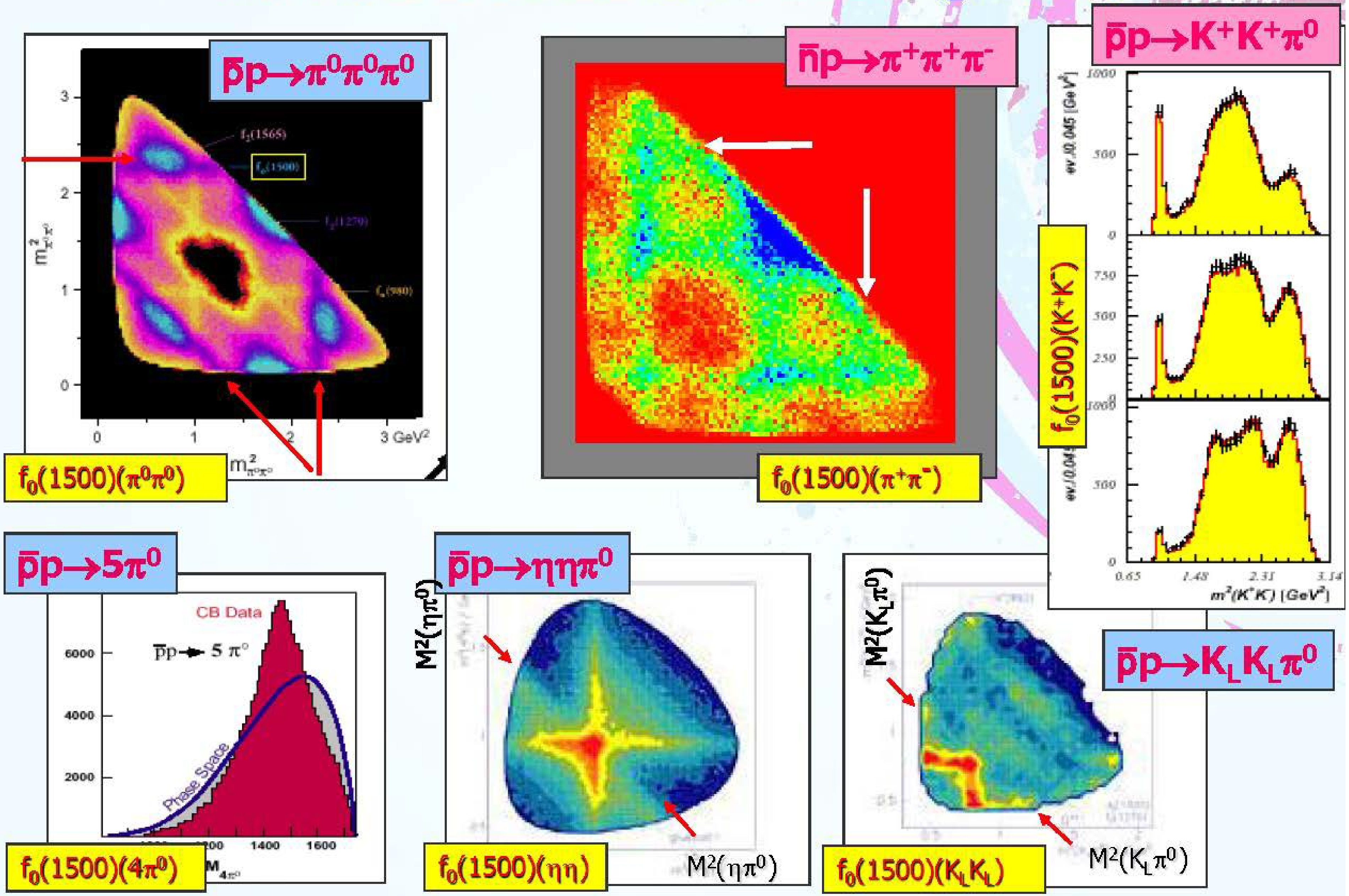
- Friedman (2014): the $\bar{n}$A annihilation cross section cannot be described by an optical potential fitting well also the $\bar{p}$A interactions
- Too few data on $\bar{p}$A for a thorough comparison
  - One single data from ASACUSA on Sn

Friedman, NPA925 (2014), 141



Meson spectroscopy: open problems

Lightest glueball candidate: $f_0(1500)$ seen by CRYSTAL BARREL and OBELIX @ LEAR



Glueballs signatures in $\bar{N}N$ annihilations

$\bar{N}N$ annihilation is a glue-rich environment suitable for glueball production

Several observation performed @LEAR in different final states by OBELIX and Crystal Barrel

Meson spectroscopy with kaons

A larger statistics and more precise detecting methods could help improving our knowledge on a few still open issues

E/ι puzzle: $K\bar{K}\pi$ excitations

- **($K\bar{K}\pi$): J^P = (even)$^+$ or (odd)$^-$**
- **Pseudoscalar states 0^{-+}:** all of them decay in $K\bar{K}\pi$ **(direct), K^*K, $a_0(980)\pi$**
  - $\eta\,(1275)$
  - $\eta\,(1440)$: $\eta\,(1405)$ **(gluonium) +** $\eta(1475)$ **?**
- **Axial states 1^{++}:**
  - $f_1(1285)$ – does not decay in KK*
  - $f_1(1420)$ – hybrid? 4-q? K*$\bar{\text{K}}$ molecule?
  - $f_1(1510)$
  - Isovector $a_1(1420)$ (COMPASS)

Search for strangeonium & radial excitations

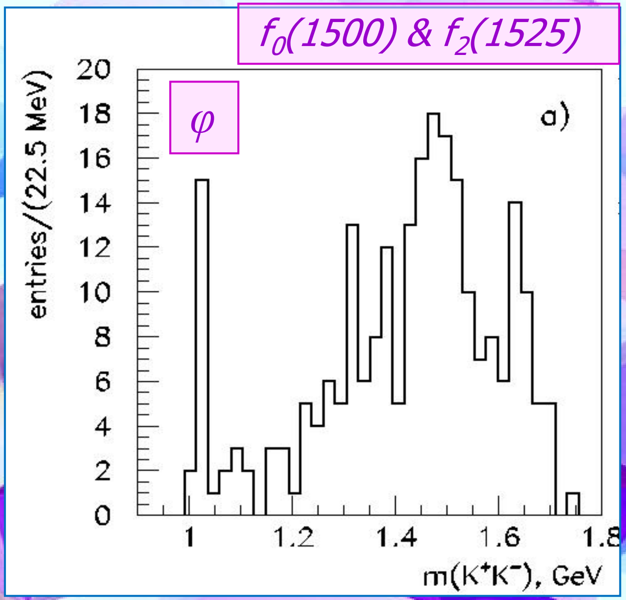
- The strangeonium spectrum does not simply replicate the light meson spectrum ~250 MeV higher in mass
- several channel dependent couplings
- To-date, only a few confirmed $s\bar{s}$ resonances:
  - η-η' (1 $^1S_0$ 0^{-+})
  - $\varphi(1020)$ (1 $^3S_1$ 1^{--})
  - $f_1(1420)$ (1 $^3P_1$ 1^{++})
  - $f_2(1525)$ (1 $^3P_2$ 2^{++})
  - φ (1680) (2 $^3S_1$ 1^{--})
  - $\varphi_3(1854)$ (1 $^3D_3$ 3^{--})
- Several observations still controversial

Open/hidden strangeness spectroscopy with $\bar{n}$'s

- Antineutrons as probes offer stringent quantum numbers selection rules
- Basic problem: lack of statistics!

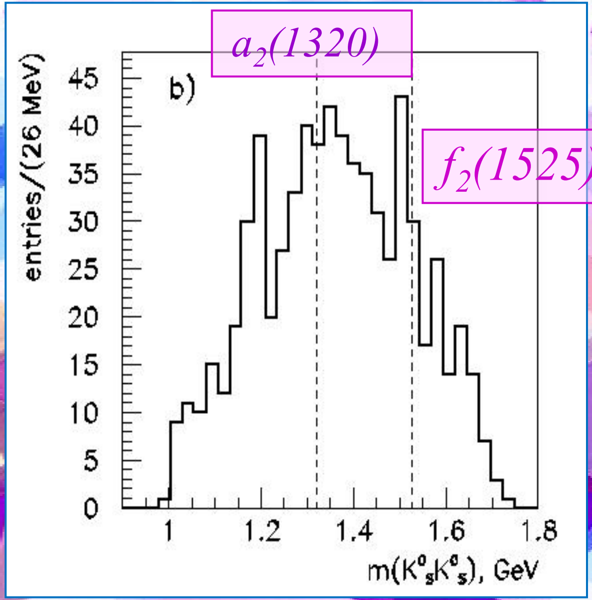
$\bar{n}p \rightarrow K^+K^-\pi^+$

- Hidden strangeness resonances decaying in K^+K^-
  - $J^{PC} = (even)^{++}$ or $(odd)^{--}$
    - f_0, f_2, a_0, φ and radial excitations
- open strangeness radial excitations: $K^*, \kappa, K_1, K_2, \ldots$



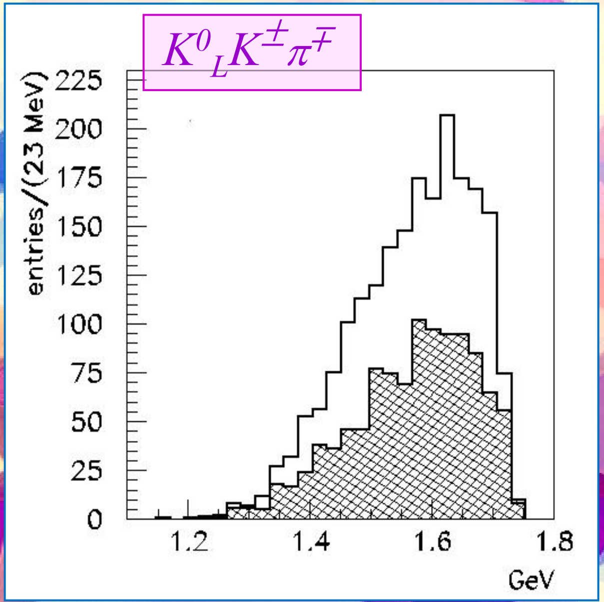
$\bar{n}p \rightarrow K^0_S K^0_S \pi^+$

- $K^0_S K^0_S$: $J^{PC} = (even)^{++}$
- Possible resonant states:
  - No φ nor 1^{--} strangeonium states
  - f_0, f_2 : only from $G = -1$ ($^1S_0$, $^3P_1$, $^3P_2$)
  - a : only from $G = +1$ ($^3S_1$, $^1P_1$)



$\bar{n}p \rightarrow K^0_L K^\pm \pi^\mp \pi^+$

- Search for intermediate states decaying in $\bar{K}K\pi$
- Channel produced only by P-waves for G-parity conservation
  - Axial states production potentially favored
  - $K^0K^\pm$ systems: $I^G = 1^+$: a_0, a_2, ρ



The S-dibaryon

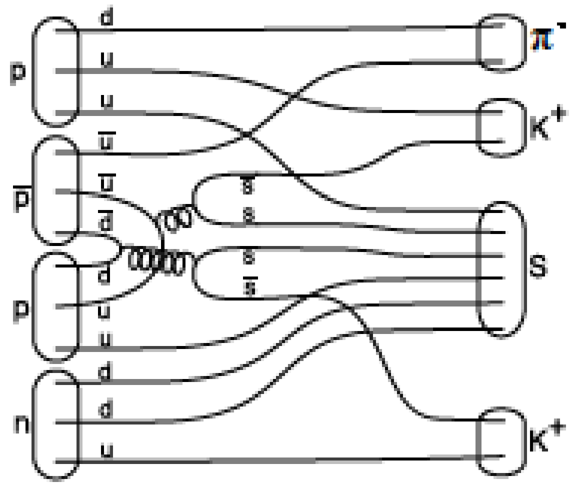
M. Doser et al., arXiv:2302.00759

Features: S ~ |uuddss >

- G. Farrar, 2017: possible Dark Matter candidate (arXiv: 1708.08951)
- **Tightly bound** six-quark combination, doubly strange
  - Q = 0, B = 2, S = -2
  - Flavor singlet: very small coupling to γ, π, ρ, …
  - **Very compact object: r ~ 0.1-0.4 fm (< r_N/4)**
  - **Large binding energy, smaller mass: m_S < 2.05 GeV**
    - new stable hadron, $\Lambda\Lambda$ bound state
    - If $m_S < m_\Lambda + m_p + m_e$ = 2.05 GeV: only doubly-weak decays allowed, cosmologically stable
- $S\,N$ interaction suppressed by tiny wavefunction overlap ($\sigma \sim 10^{-30}$ cm^2)
  - It does not bind to nuclei (no exotic isotopes)
- Not excluded so far by experiments: upper limit by *BaBar* < 10^{-7}

Detection: $\bar{p}\ ^3\mathrm{He} \rightarrow S(uuddss) + K^+ K^+ \pi^-$

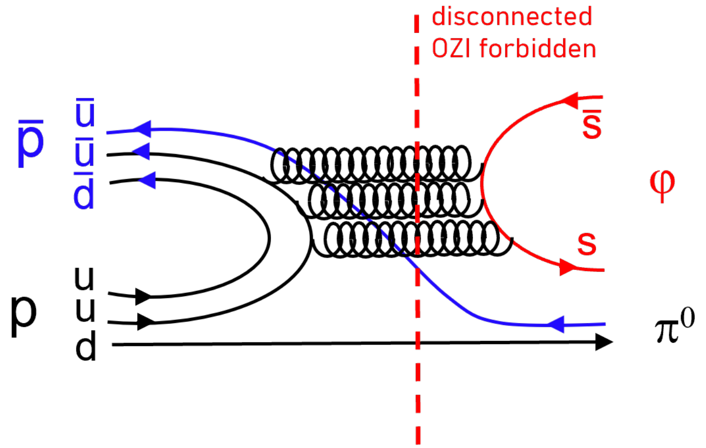
- Requires a multinucleon annihilation
- An antiprotonic ^{3}He can be formed by eV-KeV antiprotons
  - in a trap (requires a cryogenic environment)
    - Experimental equipment: Solid Ar TPC
  - using a jet target (problems with vacuum, low rate…)
    - Experimental equipment: gaseous TPC + Si strips/pixels + TOF
    - It could exploit the AeGIS setup post LS3

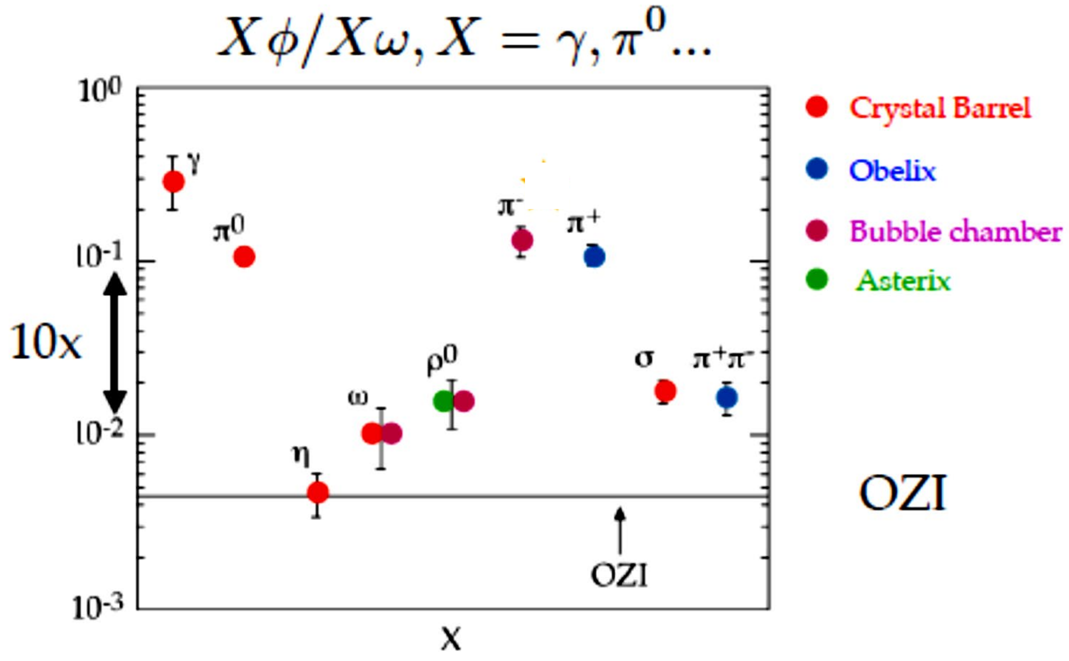


Strangeness physics with antiprotons

Strangeness in the nucleon

- Annihilation at rest/low energy: good environment for the study in a non-perturbative regime of the sea-quark content in the nucleon
  - no strange valence quarks in nucleons
  - Almost ideal mixing in the vector meson nonet
- Signature of strangeness in the nucleon: sizeable OZI rule violation
  - Comparison of the production of hidden strangeness vs non-strange mesons
  - Different mechanisms can be advocated:
    - Quark-lines rearrangement
    - $(\bar{s}s)$ quark content of the nucleon, possibly polarized since the behavior changes with the initial state
    - Existence of a tetraquark $sq\bar{s}\bar{q}$ states?





C. Amsler, arXiv:1908.08455

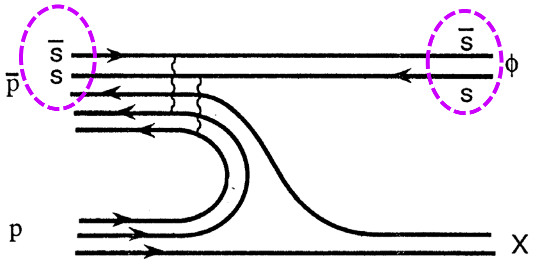
Polarized strange sea at low energy?

- Dynamical selection rule: $\bar{p}p \rightarrow K^+K^-$ reaction suppressed from P wave

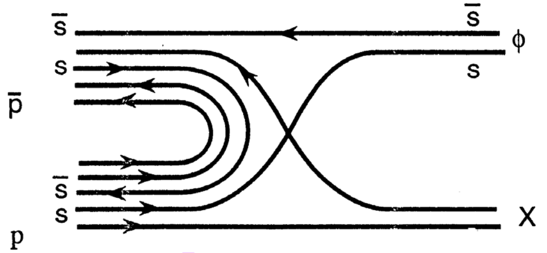
- Selected final states in $\bar{n}p$ annihilations: trend of the meson production and OZI ratio compatible with the hypothesis of an energy-dependent polarized strange content of the nucleon
  - $\bar{s}s$ spins are parallel and opposite to the $\bar{n}p$ $^3S_1$ initial state
  - Muon induced DIS at high energies (*color transparency* effect): $\bar{s}s$ have spins parallel and opposite to the nucleon spin

- Increasing production of $f_2'(1525)$ with P wave and large OZI violation also in the meson tensor nonet

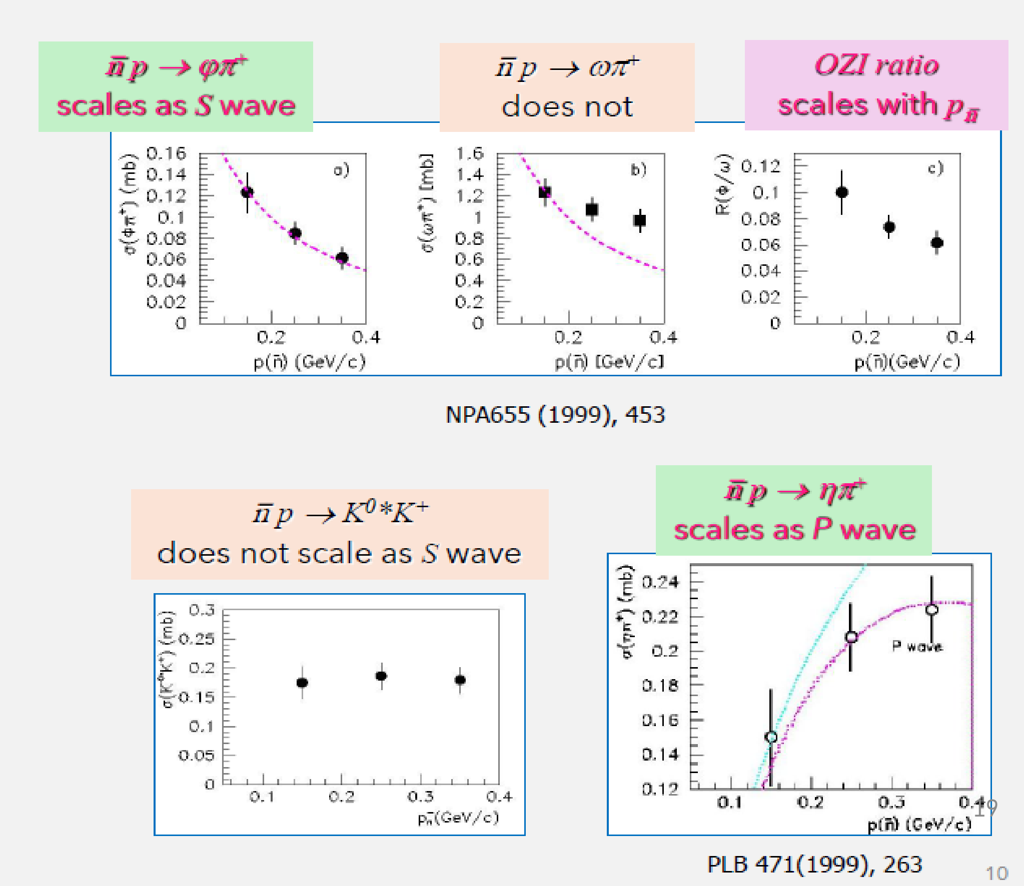
J. Ellis et al., PL**B353** (1995), 319



Shake-out

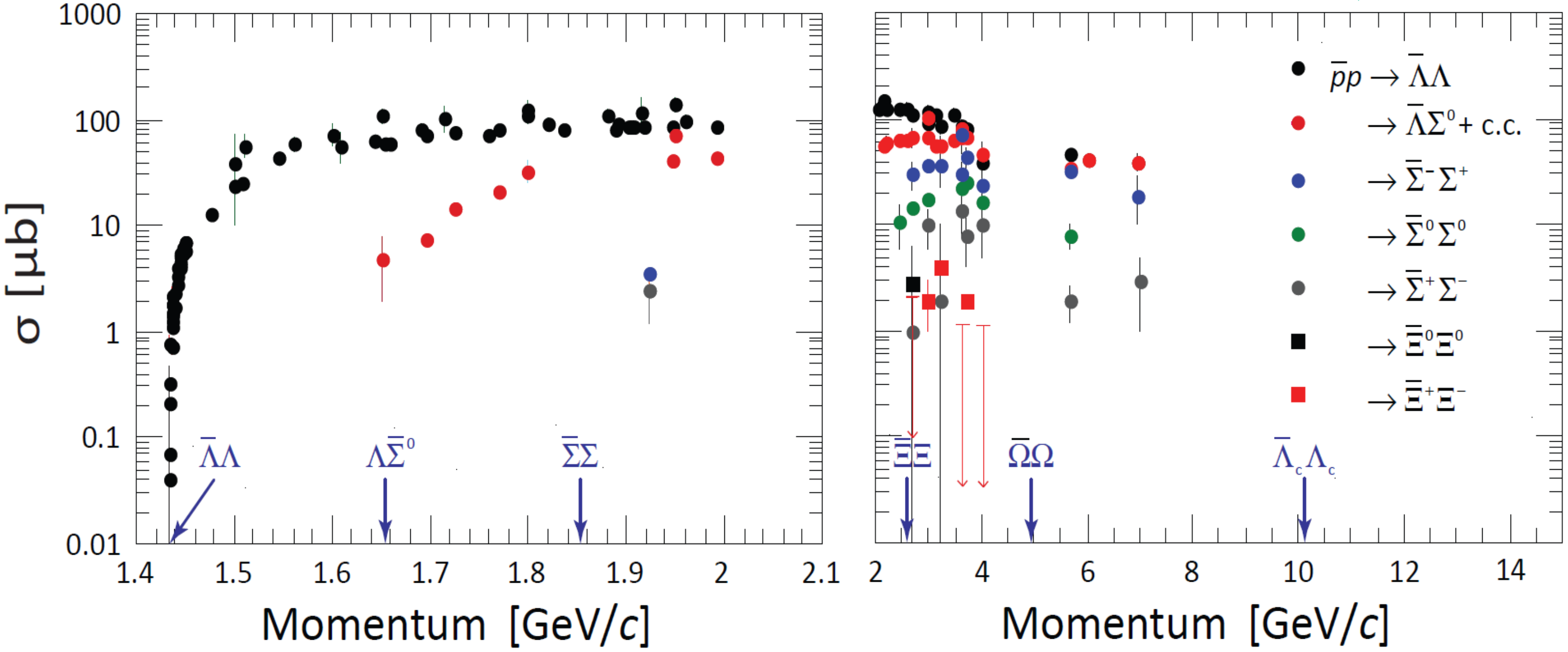


Rearrangement



Hyperon production with $\bar{p}$'s

T. Johansson, LEAP 2003



$\bar{p}p \to Y\bar{Y}$ reaction	p_{beam} thr. (GeV/c)
$\bar{p}p \to \Lambda\bar{\Lambda}$	1.44
$\bar{p}p \to \Sigma^0\bar{\Lambda}$	1.65
$\bar{p}p \to \Sigma^+\bar{\Sigma}^-$	1.85
$\bar{p}p \to \Sigma^*(1385)\bar{\Lambda}$	2.20
$\bar{p}p \to \Xi^0\bar{\Xi}^0$	2.58
$\bar{p}p \to \Lambda(1520)\bar{\Lambda}$	2.60
$\bar{p}p \to \Xi^-\bar{\Xi}^+$	2.61
$\bar{p}p \to \Xi^*(1620)\bar{\Lambda}$	3.55
$\bar{p}p \to \Xi^*(1690)\bar{\Lambda}$	3.78
$\bar{p}p \to \Xi^*(1820)\bar{\Lambda}$	4.22
$\bar{p}p \to \Omega^-\bar{\Omega}^+$	4.93
$\bar{p}p \to \Omega^*(2100)\bar{\Lambda}$	6.58

- Exclusive $Y\bar{Y}$ production: cleanest environment to constrain models of non-perturbative QCD
  - Quark-gluon interaction vs meson exchange
  - Discriminating observables (spin dependent): polarization and spin correlations
- PS185: most complete data-set of $\bar{p}p \to \bar{Y}Y$ cross sections
  - "large" production rates for both ground and (expected) radial excitations: 1-100 μb – high energy threshold (esp. for multi-strange production)

Spin observables

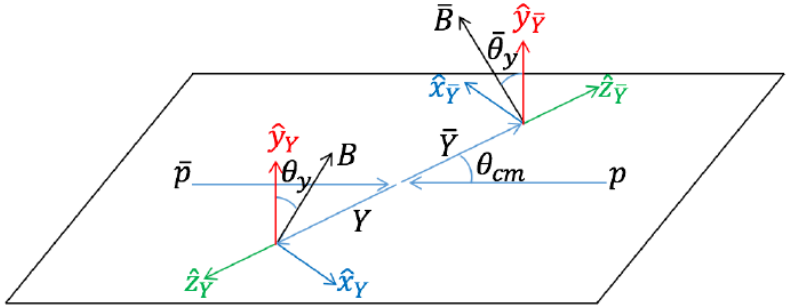
- Hyperons’ unique feature: self-analyzing decay
  - The hyperon decay products are emitted along the spin direction of the parent hadron
  - The angular distribution of the daughter baryon is related to the hyperon polarization by:

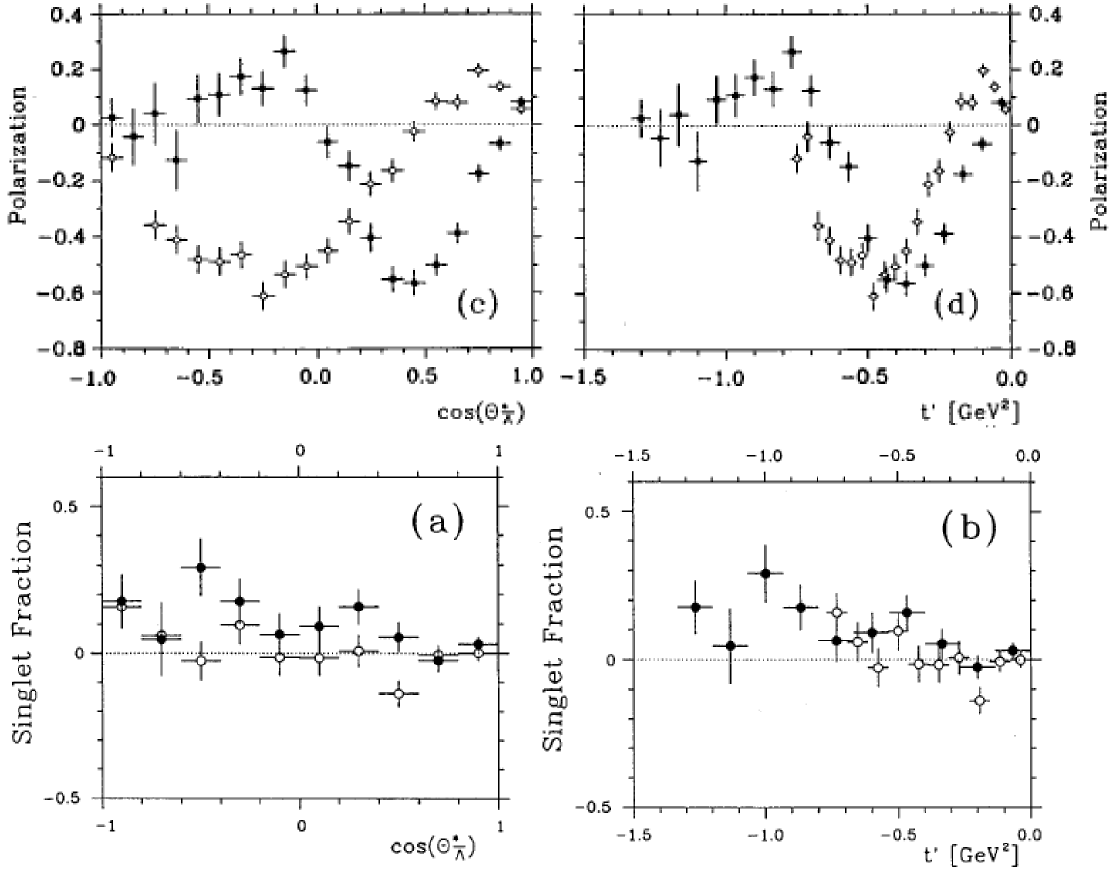
$$I(\cos\theta_B) = (1 + \alpha_Y P_y \cos\theta_B)$$

- In $\bar{p}p \to Y\bar{Y}$ the hyperon decay products are correlated
  - the polarization vector P is related to the production dynamics

- The differential cross-sections can be expressed in terms of
  - Angles
  - Decay asymmetries
  - Spin observables: polarizations and correlations

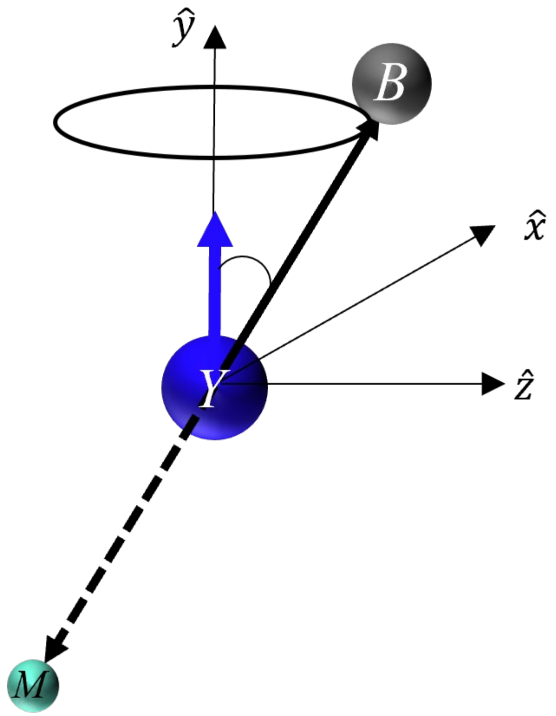
- The spin correlations are sensitive to the singlet fraction in the $\bar{p}p \to Y\bar{Y}$ reaction
  - PS185: dominance of spin triplet in $\bar{p}p \to \Lambda\bar{\Lambda}$





Barnes et al., PR **C54** (1996), 1877

CP-violation measurements



- Related to the baryogenesis mechanisms and matter-antimatter asymmetry in the Universe

- Deduced from weak phases in direct decays
  - Due to interference between strong and weak amplitudes
  - A non-zero difference between hyperon/antihyperon decay asymmetries can hint to CP-violation:

$$I(\cos\theta_B) = (1 + \alpha_Y P_y \cos\theta_B)$$

If CP is conserved: $\alpha = -\bar{\alpha}$

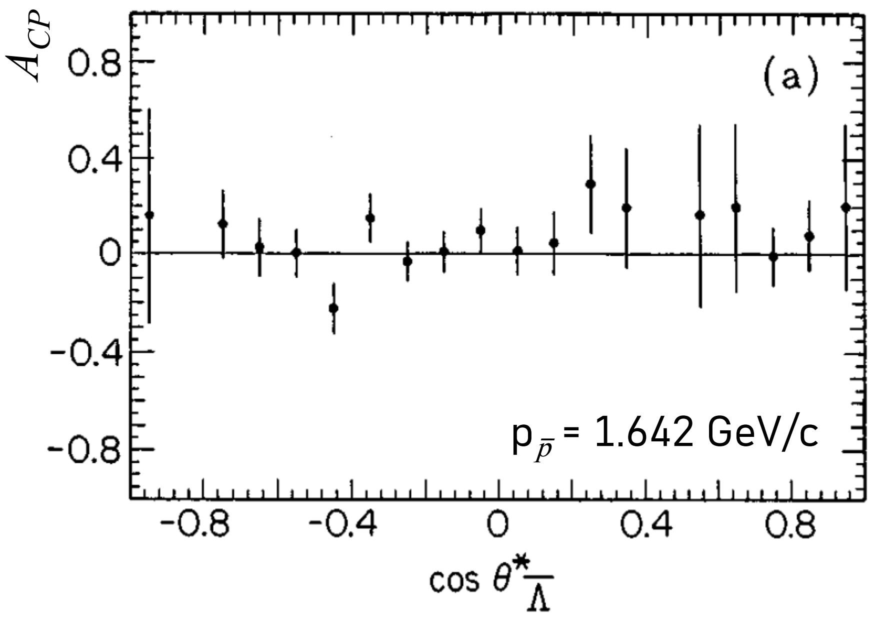
$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \sim -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S)$$

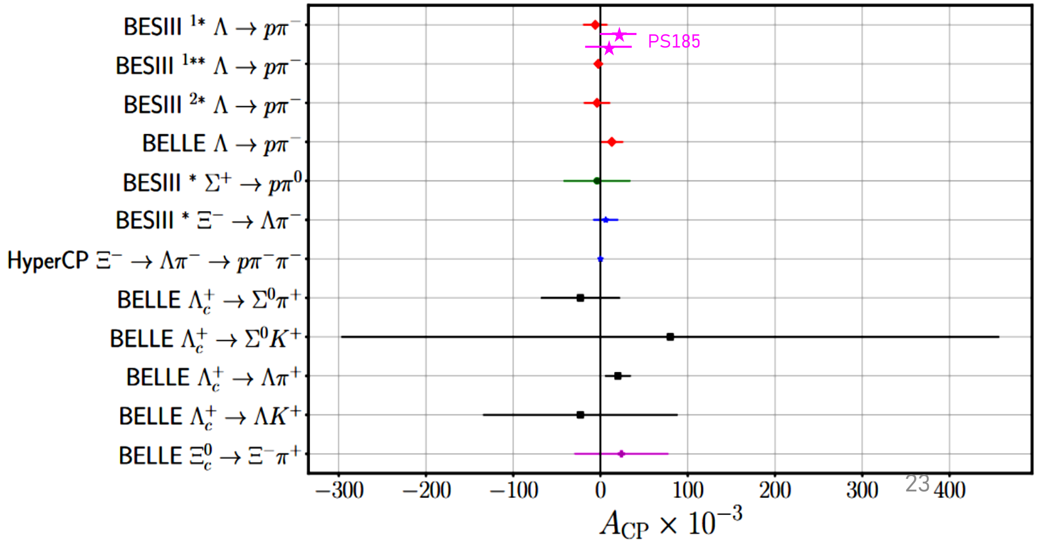
strong, non-~~CP~~ weak, possibly-~~CP~~

CP-tests in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

- Measurement by PS185 in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$
- Clean test since the initial state is a CP-eigenstate and no mixing occurs between hyperons
- Based on a sample of 96000 reconstructed events
- Reached a sensitivity of 10^{-2}: consistent with zero at two $\bar{p}$ momenta:
    - $p_{\bar{p}}$ = 1.642 GeV/c: A_{CP} = (0.026 ± 0.030)
    - $p_{\bar{p}}$ = 1.918 GeV/c: A_{CP} = (0.010 ± 0.037)
    - World average: 0.01
- With heavier hyperons: subsequent decay chains ⇒ more weak phases

Barnes et al., PR **C54** (1996), 1877



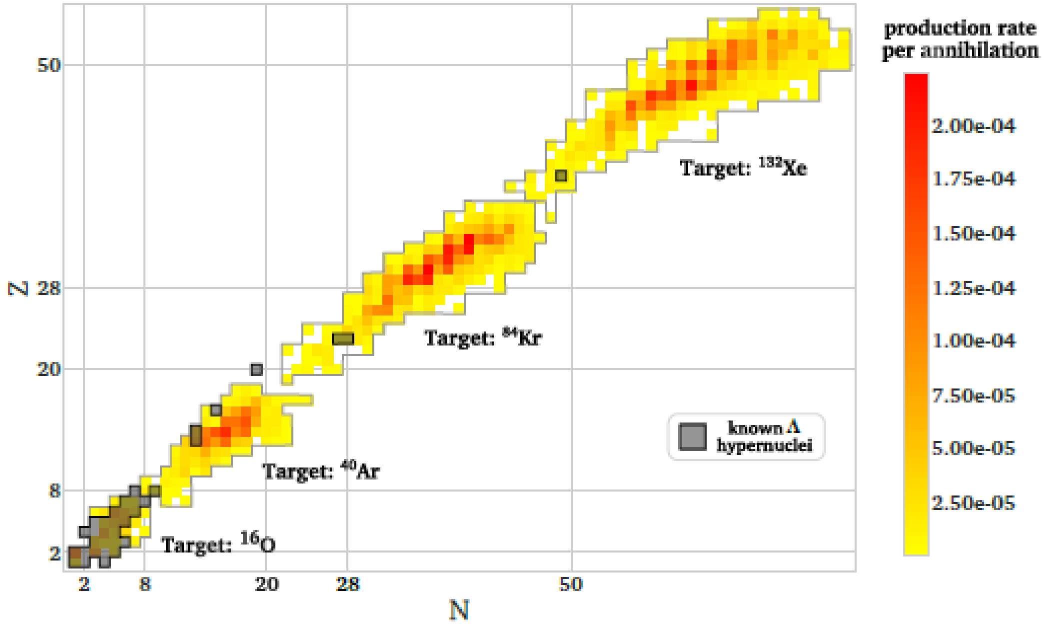


Λ-Hypernuclei production with low-energy $\bar{p}$'s

- Coherent production of hypernuclei can occur in $\bar{p}$ induced reactions on nuclei
  - Formation of protonium in the nuclear density tail
  - Annihilation of $\bar{p}$ at rest
    - 5% in kaons
      - Strangeness exchange reaction $N(K^-, \Lambda)\pi$ (80%)
      - Strangeness pair production induced by pions (20%)
    - Total expected rate:
      - 0.3% (^{16}O) → 1.2% (^{132}Xe)

- First measurements at LEAR: PS177, Bi and U targets
  - (0.3-0.7)% /annihilation

A. Schmidt et al., EPJ A60, 55 (2024)



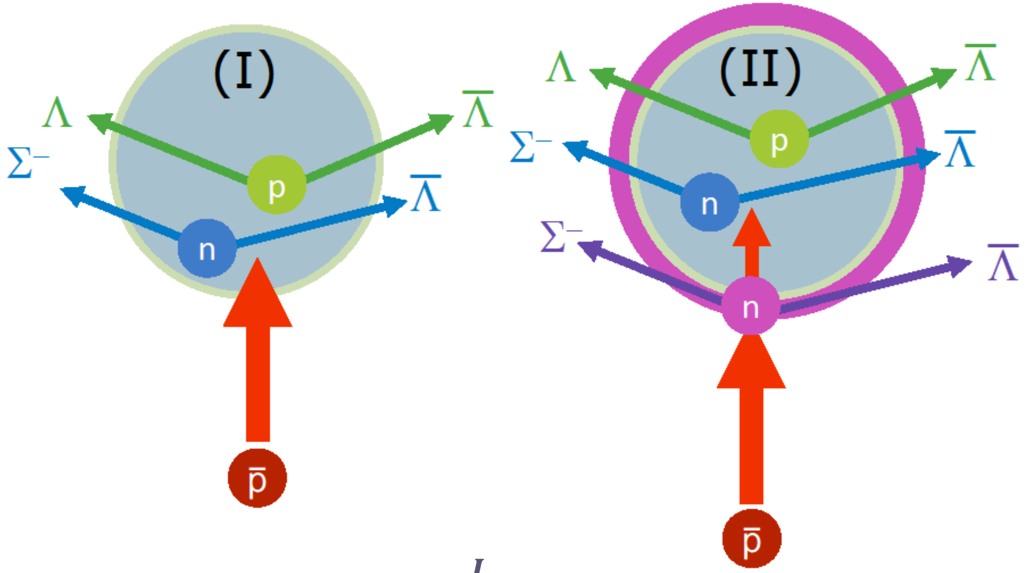
- Yields on the order of **10^{-4} hyp/annih.** can be achieved for many hypernuclear species, never observed before

- Challenge: how to detect the production of a hyperfragment
  - Mesonic vs non mesonic decay

Measurements of neutron skin with $\bar{p}$'s

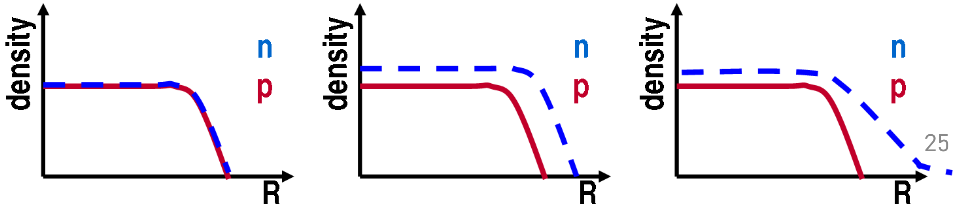
- Production of $Y\bar{Y}$ pairs on the nuclear surface/halo can provide a measurement of the extension/features of the neutron skin
  - Measurement of the ratio of $Y\bar{Y}$ production in two isotopes with different neutron content (^{40}Ca, ^{48}Ca, ^{208}Pb)
    - $\Sigma^-\bar{\Lambda}$ pairs only produced in $\bar{p}n$ interactions

- Important input for the nuclear EoS, basic ingredient to define the hydrostatic equilibrium of stellar matter
  - The EoS is defined through the nuclear density
  - The isospin dependence of the EoS is correlated to the distribution of neutrons



$$DR = \frac{\frac{p^{I}_{\Sigma\bar{\Lambda}}}{p^{I}_{\Lambda\bar{\Lambda}}}}{\frac{p^{II}_{\Sigma\bar{\Lambda}}}{p^{II}_{\Lambda\bar{\Lambda}}}} \sim \frac{1+p_{abs}}{1-p_{abs}}$$

$$p_{abs} = 1 - e^{-(\sigma_{\bar{p}n} \int_{\Delta_n} \rho_n dr_n)}$$



M. Christiansen et al., arXiv:2209.03875

The CERN facility for $\bar{p}$ production: status, plans and time schedule

AD/ELENA: a Unique pbar Facility!

Courtesy of D. Gamba, CERN

- **The only place in the world with low energy pbars in a synchrotron!**
  - It seems unlikely to have similar capabilities elsewhere for the next 10-20 years
- **Serving 60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations**

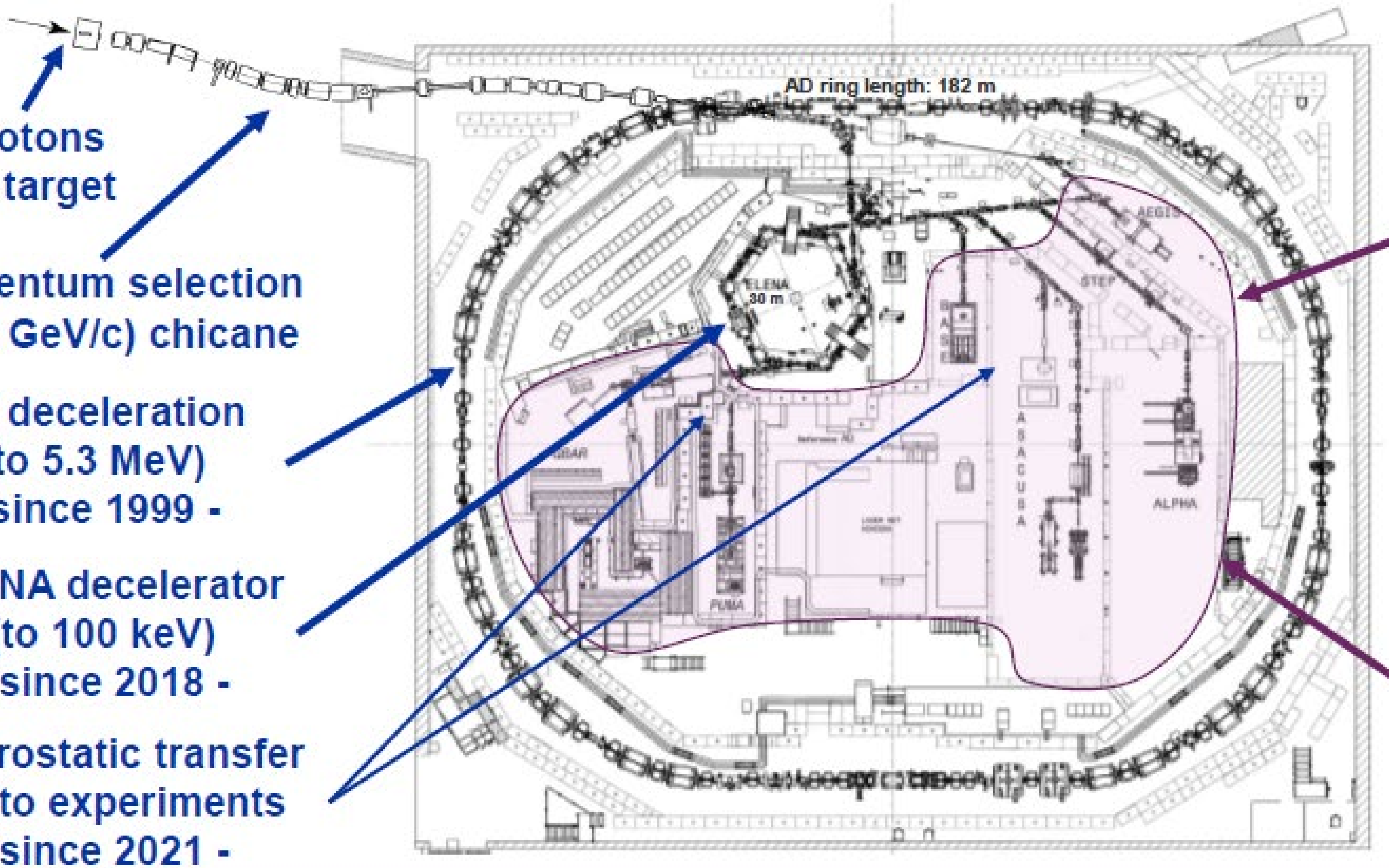
26 GeV protons on iridium target

Momentum selection (3.57 GeV/c) chicane

AD deceleration (to 5.3 MeV) - since 1999 -

ELENA decelerator (to 100 keV) - since 2018 -

Electrostatic transfer line to experiments - since 2021 -



antiprotons

ASACUSA
Antiprotonic helium spectroscopy

BASE, BASE-STEP
Fundamental properties of the proton/antiproton, tests of clock WEP / tests of exotic physics / antimatter-dark matter interaction, etc...

PUMA
Antiproton/nuclei scattering to study neutron skins

antihydrogen

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

Some AD technical aspects – current situation

- PS: spill frequency of 4.8 s, only one spill/115 s used for AD
- AD delivers approximately 4×10^7 p̄/2 min
  - AD needs 90 s to cool p̄ to 5.3 MeV
- So far, no slow extraction
  - Never required, it would be a major change - but possible: 4×10^5 p̄, similar to LEAR intensity

- All existing caves are occupied
- Some digging will be done – one could profit of these operations
- New building? Not much space available…
- The life of PS is guaranteed until 2042 – end of LHC-HiLumi
- Extension possible but depending on several factors…
  - Interest of the community
  - Program after LHC-HL: FCC?
  - New PS needed?
  - 2042 is really a far future horizon

Summary

- A new facility producing low energy antinucleons would be highly desirable to explore new physics topics and to solve some puzzles left open since LEAR times

- Antiproton annihilation at rest:
  - The details of the annihilation mechanisms at microscopic level are not understood yet
  - More accurate data on branching ratios would be desirable to understand dynamical selection rules, the onset of strangeness, …
  - A more accurate assessment of all systematic uncertainties would be appropriate, with more advanced detectors and analysis tools
  - New items of nuclear physics at rest: Pontecorvo reactions, sexaquarks, hyperon physics, meson and baryon spectroscopy, neutron skin…

- Antinucleon annihilation in flight:
  - Investigation of long-sought baryonium below the $\bar{N}N$ threshold
  - Study of the peculiar behavior of the annihilation cross-section close to threshold/study of the elastic channel
  - Understand the *I=0* vs *I=1* puzzle from the comparison of $\bar{p}p$ vs $\bar{n}p$ annihilation cross-sections
  - Closer look to CEX cross sections
  - More precise measurements of annihilation cross sections on nuclei

- ***THIS IS THE MOMENT TO PROPOSE NEW IDEAS!***

Backup slides

Antideuterons/antideuterium production?

R.Caravita, arXiv:2404.08000

Antideuterons

- Precise measurements of elementary observables
  - $\bar{d}$ mass
  - Magnetic momentum
  - Binding energy
- $\bar{d}$ can be produced via proton scattering on fixed solid targets (like $\bar{p}$'s at CERN, from 26 GeV PS protons on Iridium)

Antideuterium

- CPT-violation tests through antideuterium spectroscopy
- Weak Equivalence Principle tests through free falling antideuterium
- Tests of B - L interactions
- $\bar{D}$ could possibly be produced via a Penning Trap (similar to $\bar{H}$ – AeGIS) once $\bar{d}$ are available

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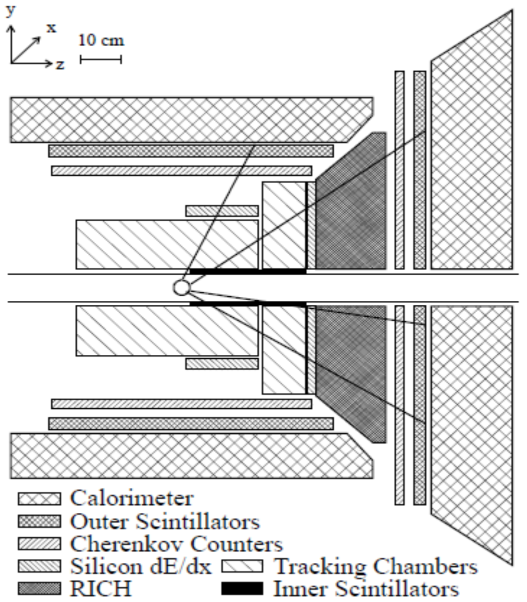
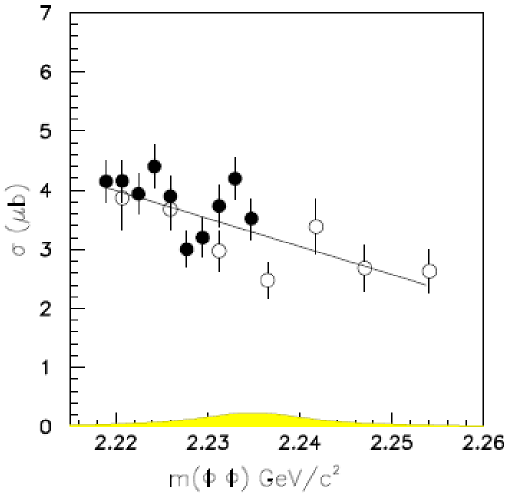
- Estimated cross-section @30 GeV: 10 nb/(sr MeV/c)
  - 3 order of magnitudes larger @200 GeV/c
- $\bar{d}$ are formed at rest in the c.m. by $\bar{n}$ and $\bar{p}$ coalescence
  - Production mechanism for E < 30 GeV: cascade model (+ coalescence, + nuclear scatterings, …)
- Better use targets with low Z: Al and Be (better than Ir)
  - On Be, at 26 GeV/c: $\frac{R_{\bar{d}}}{R_{\bar{p}}} \sim 4.6 \cdot 10^{-6}$
- @PS with an Ir target: 40×10^6 $\bar{p}$/shot $\Rightarrow \sim 120$ $\bar{d}$/shot expected, p_{max} 1.7 GeV/c

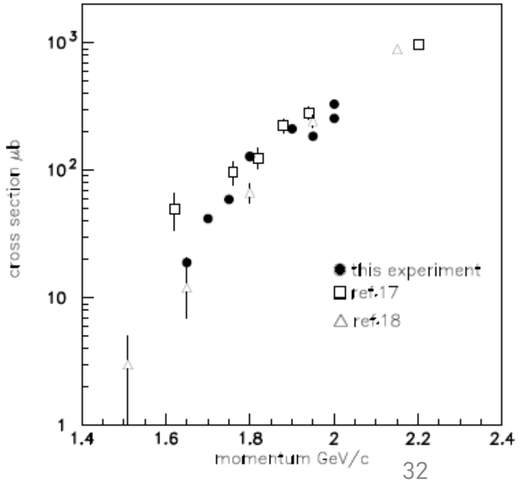
Spectroscopy of mesons with open/hidden strangeness

- JETSET (PS202) revival: compact detector around a hydrogen cluster jet target
  - **Hadron spectroscopy** in the (1.96-2.43) GeV mass range
    - $\bar{p}p \to \varphi\varphi$: **abundant production**
      - Signal compatible with a 2^{++} structure: first signature for a tensor glueball?
      - ***ξ(2230):*** **m = 2.225 GeV, Γ = 30 MeV**
    - $\bar{p}p \to p\bar{p}\pi^+\pi^-$
      - Centrality cut for baryonium searches
      - No signal observed





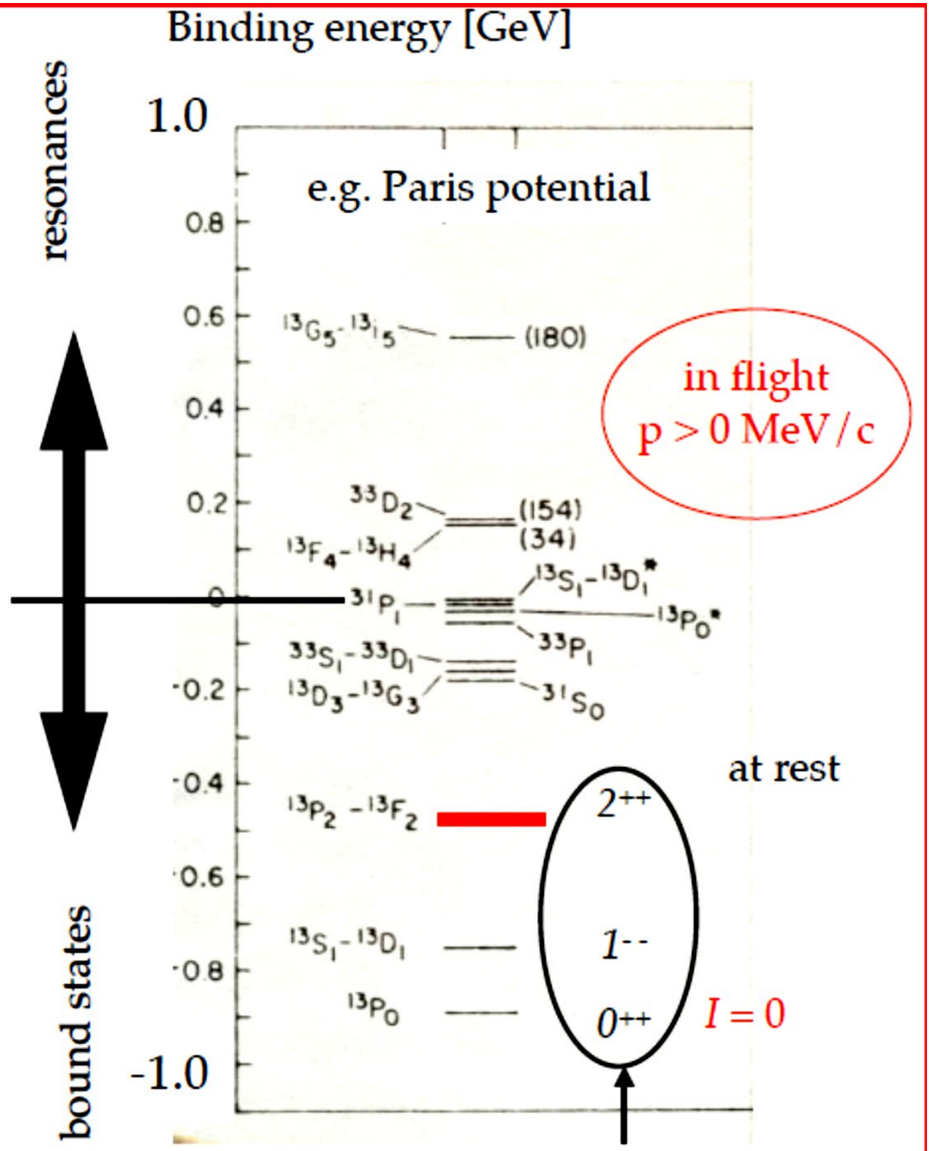
PRD**57**, 5370 (1998)



ZPC**76**, 475 (1997)

Searches for baryonium

- Bound states predicted in the $\bar{N}N$ system due to the attractive short-range force
- Expected as a charged neutral state in the $I=0$ channel
  - $I=0$: the ω and σ-exchange provide an attractive central contribution to the $\bar{N}N$ potential
  - $I=1$: ρ-exchange $\Rightarrow$ repulsive contribution
- Many attempts to search for baryonium signatures at LEAR, none reliable enough
- Better understanding of the $\bar{N}N$ potential structure would be needed

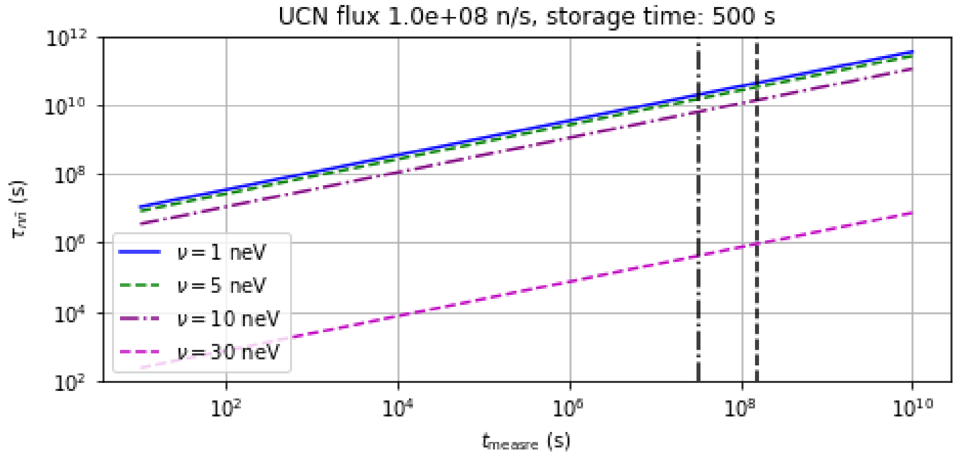


W. Buck et al., Ann. Phys. 121 (1979) 47

Additional items $\bar{n}\,n$: oscillation studies

$$P_{n\bar{n}} \approx (\cos \nu t_W)^{2N} \left(\frac{t_s}{\tau_{n\bar{n}}} \right)^2$$

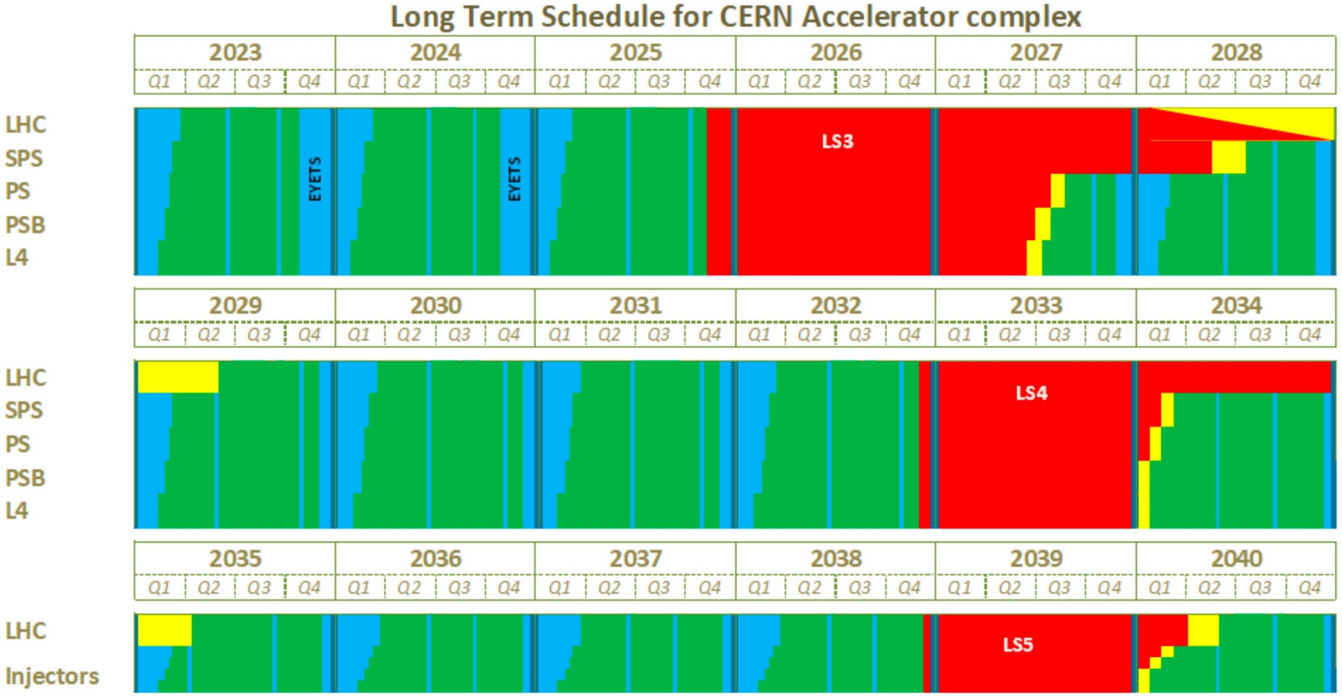
- Motivation: search for a violation of the baryon number |ΔB|=2
  - Could help to distinguish between GUT models, which predict different oscillation periods
- Experimental status
  - ILL(1994) on free neutrons:
    - $\tau(\bar{n}\,n) > 8.6 \times 10^7$ s, 90% CL
  - Super-Kamiokande on nuclei:
    - $\tau(\bar{n}\,n) > 4.7 \times 10^8$ s, 90% CL
  - New proposals with new techniques:
    - $\bar{n}$ mirrors could extend x10^4 the observation time
      - $\bar{n}$A scattering length needed as input
    - Usage of ultra-cold neutrons (neutron optics)
    - Neutron-gas interactions to compensate the magnetic field interaction
- Key issue: wall interaction of n's and $\bar{n}$'s



- The oscillation frequency depends on the scattering length of $\bar{n}$ in nuclei
  - extracted through $\bar{n}$A optical potential models (Friedman, Gal, PRD**78** (2008), 016002)
  - Lack of experimental verification

AD/ELENA @CERN timeline

- CERN calendar structured adapted to the long shutdowns (LS) periods
  - LS3: fall 2025-mid 2027
    - No new installations can be possible, too early – really exceptionally good reasons to operate during this LS
  - LS4: fall 2032
    - New installations possible at this point if proposed NOW



- Groundwork, building construction and installations could be possible between shutdowns
- AD program could be over between LS3-LS4 (around 2030?)