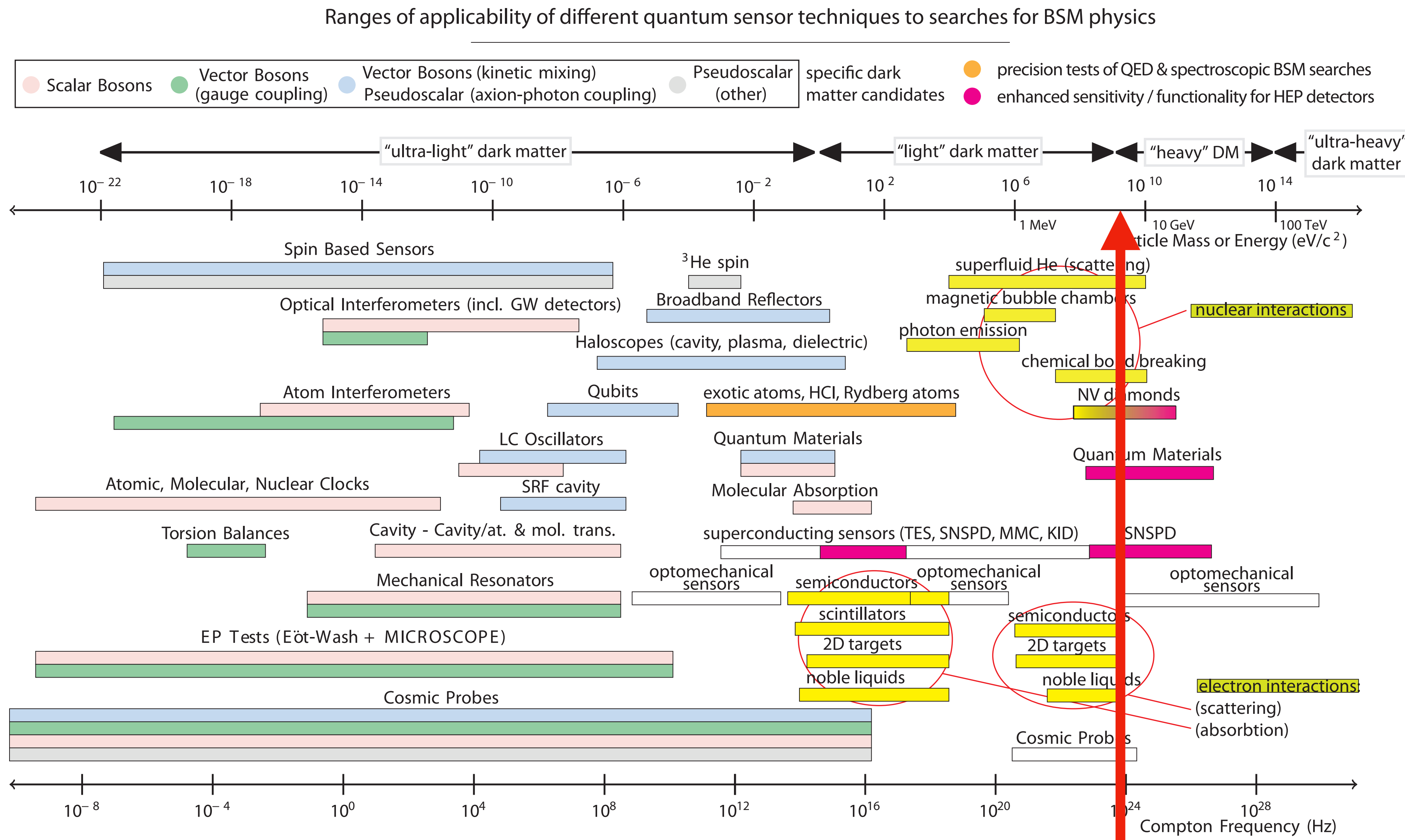
Searching for a DM candidate via antiprotonic ^{3}He

Doser, M., Farrar, G. & Kornakov, G. Searching for a dark matter particle with anti-protonic atoms.
Eur. Phys. J. C **83**, 1149 (2023). https://doi.org/10.1140/epjc/s10052-023-12319-8

Michael Doser / CERN

focus on a rather well-investigated area around 2GeV:



a novel dark matter search via antiprotonic atoms

sexaquark: uuddss bound state (m ~ 2m$_p$) [Glennys Farrar `https://arxiv.org/abs/1708.08951`]

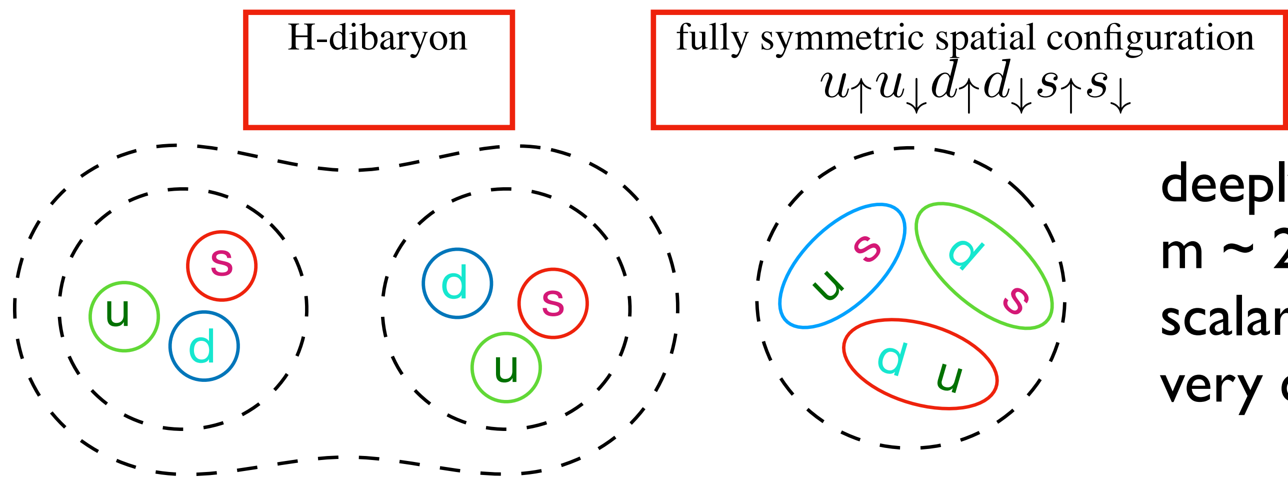
neutral, very compact (no pion cloud), stable against weak decay if mass < 2 m$_\Lambda$ (2230 MeV)

not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds have been carefully studied by G.F. & co-workers, can be evaded
standard model compatible (uuddss bound state)

similar to H-dibaryon proposed in 1970's, but searched for via (weak) decays into ΛΛ

S(uuddss):

The S(uuddss) [1] is an electrically neutral spin-less boson with baryon number $B_S = 2$ and strangeness $S_S = -2$ in a flavor-singlet state.



deeply bound,
m ~ 2 m_n (1879 MeV),
scalar: no pion cloud,
very compact (O(0.2 fm))

FIG. 1. Comparison of two realisations of a color singlet hadron with the quark content (uuddss). Left: hadronic molecule of two Λ(uds) hyperons, corresponding to the H-dibaryon. Right: compact bound state of three diquarks, bound by color forces, which corresponds to a possible structure of the sexaquark.

S(uuddss) is not H-dibaryon: the later would decay weakly into ΛΛ with τ~ 10^{-8} s. $m_S \overset{!}{<} 2m_{\Lambda\Lambda}$ (=2230 MeV)

S(uuddss): if ~ stable, good candidate for DM, survives hadronization epoch

Ref. [13] studied the formation of S at the QCD phase transition in the early Universe using statistical mechanics and found that the abundance of S is comparable to that of ordinary baryons, and that with a sufficiently small breakup cross section the sexaquark component of the baryon asymmetry could survive the hot hadronic phase.

The ratio of densities of S dark matter (SDM) and baryons in the Universe can be estimated from statistical equilibrium in the quark-gluon plasma using known parameters from QCD [13] and is consistent with observation. Primordial nucleosynthesis limits on unseen baryons are satisfied as long as ambient S's do not participate actively in nucleosynthesis, i.e., S does not form bound states with light nuclei D, T or He.

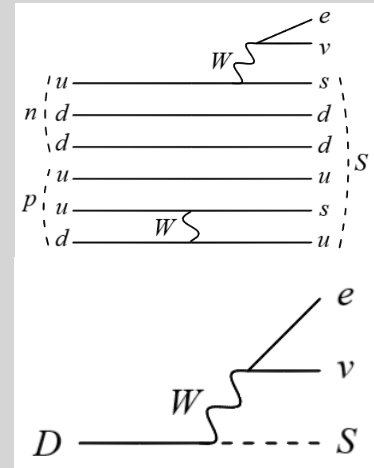
[1] G. R. Farrar, (2017), arXiv:1708.08951v2 [hep-ph]

[13] G. R. Farrar, (2018), arXiv:1805.03723 , A precision test of the nature of dark matter and a probe of the QCD phase transition

S(uuddss): decay considerations

stability of nuclei

stability of neutron stars excludes light baryonic states below 1.2 GeV

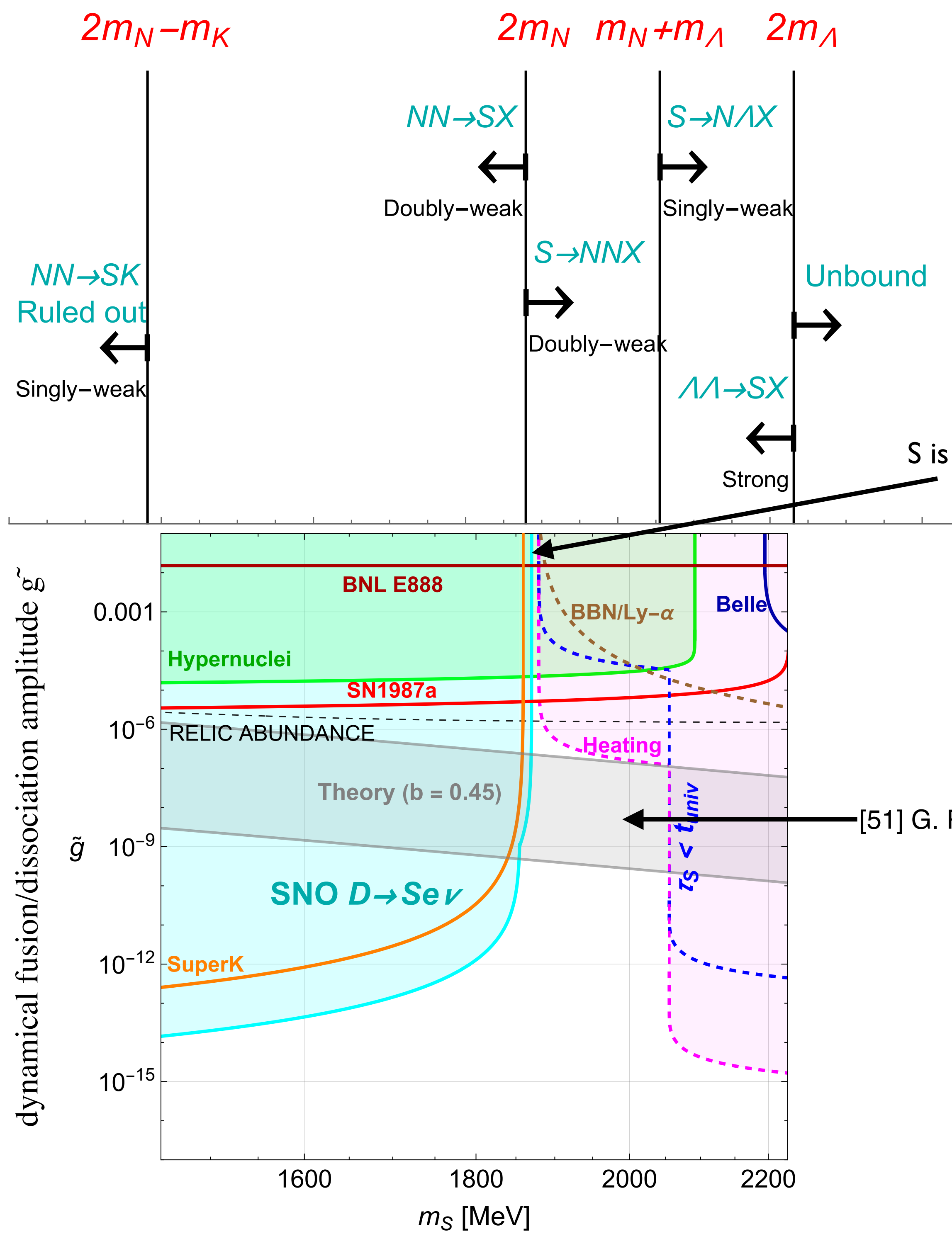


S decays to 2-nucleon FS (Λn),

resulting in e-

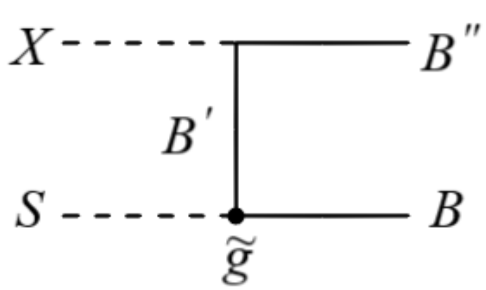
Strong interact. ΛΛ → SX allowed

2306.03123v2.pdf



S is too light to decay to a deuteron & is heavy enough that nuclear stability is ensured

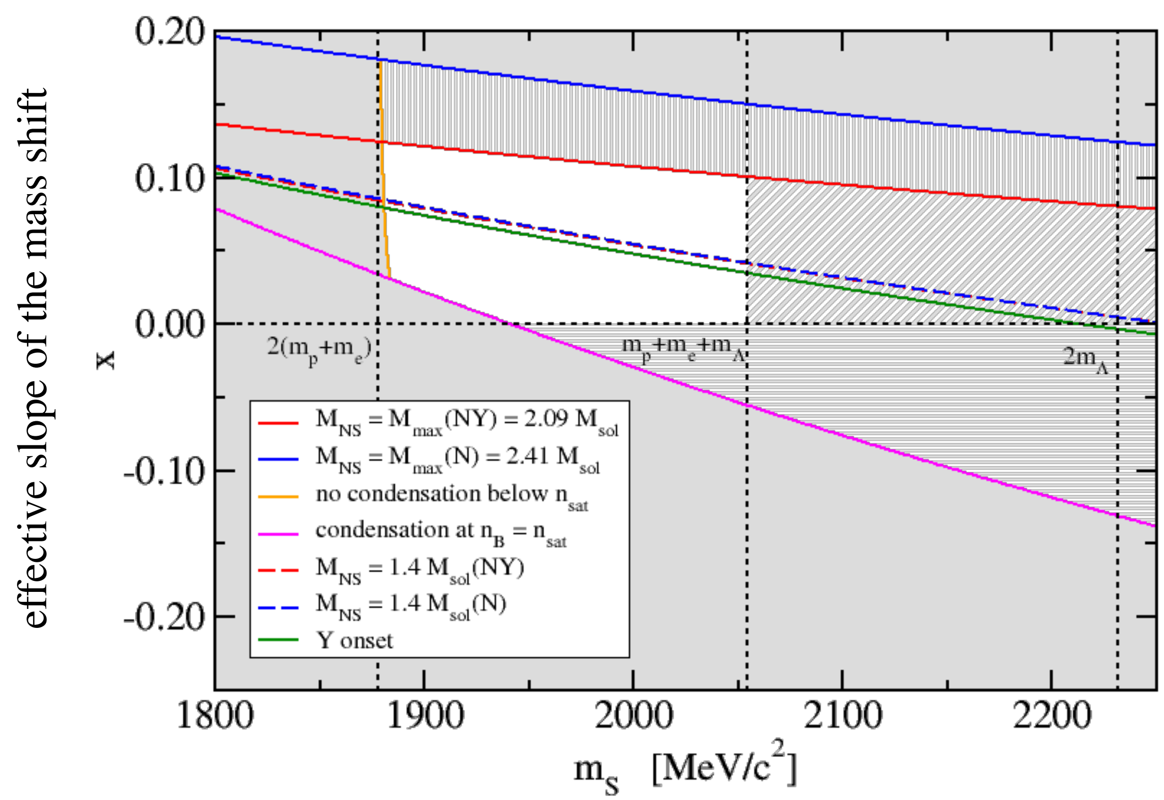
[51] G. R. Farrar and Z. Wang, (2023), arXiv:2306.03123



$KS \leftrightarrow p\Lambda$, $\pi S \leftrightarrow \Sigma\Lambda$, $\gamma S \leftrightarrow \Lambda\Lambda$ and $\pi\pi S \leftrightarrow \Lambda\Lambda$

region of interest: 1850-2050 MeV

S(uuddss): constraints from neutron star mergers and EOS



2202.00652v2.pdf

"We find that the existence of a stable sexaquark is well-compatible with both the maximum mass and the highly constraining tidal deformability of GW170817, given present knowledge of the properties of hadronic and quark matter."

"Whether or not a sexaquark exists, within our framework the most massive stars must have a quark matter core with stiff EoS to support their high mass. Among the successful hybrid star solutions which we develop, we find two general types: those in which the quark matter core is surrounded by nucleons, and others in which the core and interpolated region is surrounded by a layer with a substantial sexaquark (but negligible hyperon) fraction. This potentially may lead to an observable signature of sexaquarks in the cooling curve or kilonova properties.

At low density the EoS must be quite soft to produce compact $\approx 1.4\,M_\odot$ neutron stars, while at high density it must be stiff to support high mass stars. Intriguingly, the sexaquark neatly solves this problem by naturally producing the needed softening."

(1) a deconfined (quark matter) core is essential to support the most massive neutron stars ($m \approx 2\,M_\odot$); (2) a significant contribution of hyperons must be excluded in any density regime, as that excessively softens the equation of state; (3) present observational constraints are compatible either with early deconfinement such that sexaquarks also never play a role, or with a sexaquark-dominated phase. This raises the interesting possibility of low mass neutron stars with a sexaquark core, or a more massive neutron star with a sexaquark layer, potentially giving a means to probe and constrain sexaquark properties

S(uuddss): proposed formation channels

- The S is neutral and a flavor singlet, so it does not couple to photons, pions and most other mesons, nor does it leave a track in a detector.
- The S has no pion cloud and may be more compact than ordinary baryons; the amplitude for interconversion between S and baryons is small.
- The mass of the S makes it difficult to distinguish from the much more copious neutron.

The sexaquark production rate in hadronic interactions can be expected to vary strongly with the experimental conditions.

low energy: $\tilde{g}^2$ suppression: Kp → $S\Lambda$ is suppressed by $O(10^{-10})$ wrt other QCD states

higher energy: Υ(1S, 2S, 3S) decays → (>6) gluons → $S\Lambda\Lambda$ + *pions.*

Exclusive channels: rare; Semi-Inclusive analyses: still require >10^9 Υ decays, hermetic detector (Belle-II)

high energy: pp collisions @ LHC: 10^{16} collisions, $O(10^{-1})$ per quark: 10^{-3}~10^{-5} S / neutron. Detection!

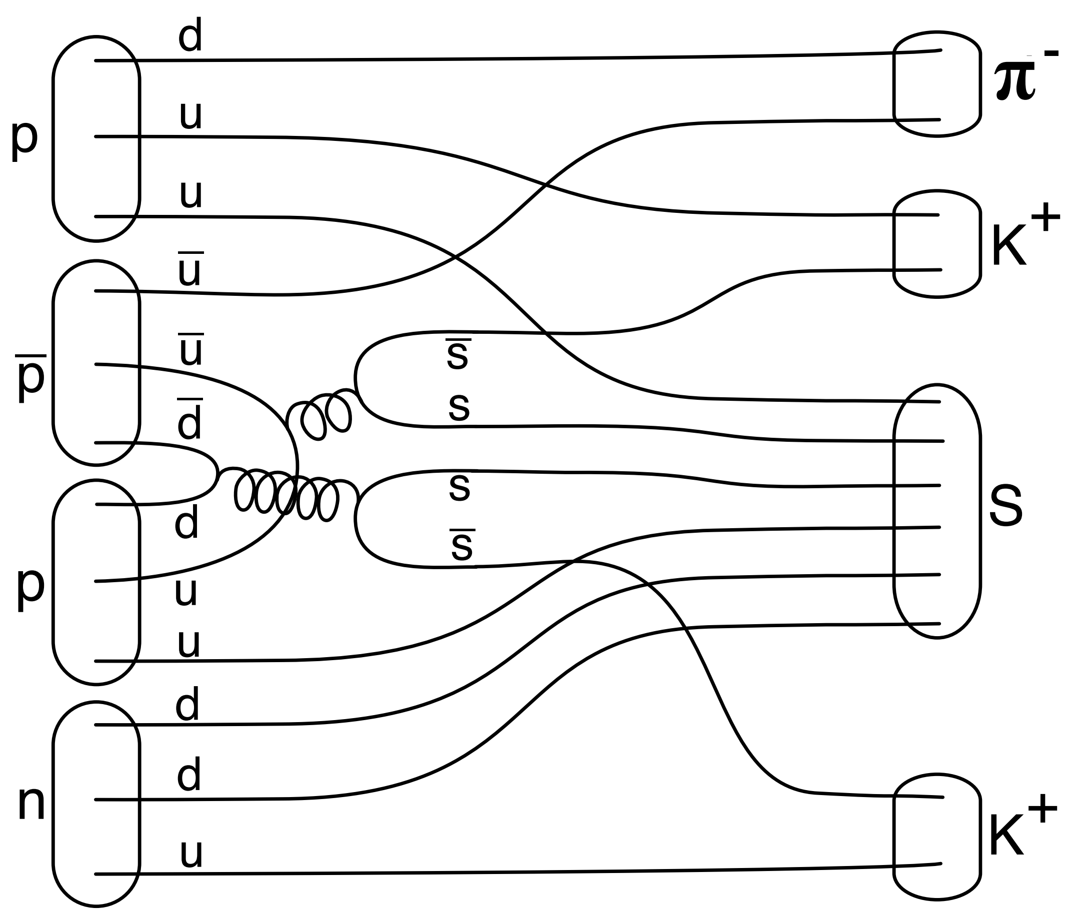
high energy: PbPb collisions @ LHC: 10^{10} collisions, O(1) S / deuteron. Detection!

high energy: long interaction-length neutral hadrons (beyond n): not comparable to cosmic DM energies

S(uuddss): a novel formation mechanism (at rest!)

Doser, M., Farrar, G. & Kornakov, G. Searching for a dark matter particle with anti-protonic atoms. *Eur. Phys. J. C* **83**, 1149 (2023). https://doi.org/10.1140/epjc/s10052-023-12319-8

antiproton annihilation on ^{3}He nucleus at rest:



formation reaction:

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

$S= +2, Q= -1$

requires multi-nucleon annihilation !

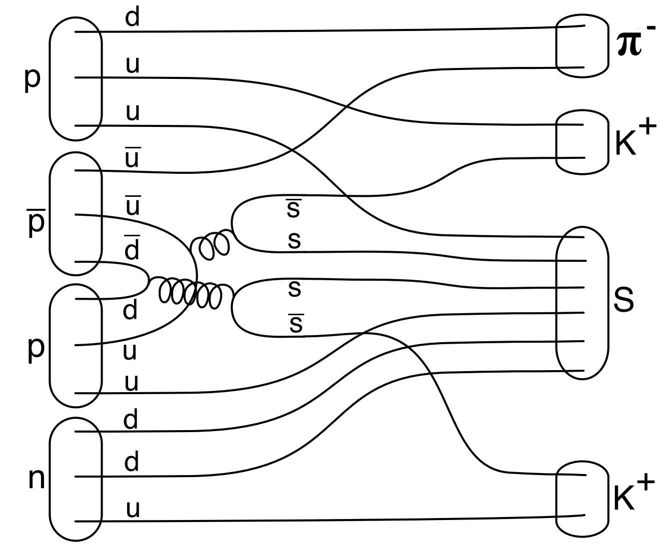
other multi-nucleon annihilations seen at $O(10^{-5})$ - ASTERIX, OBELIX

no SM process produces such a signature

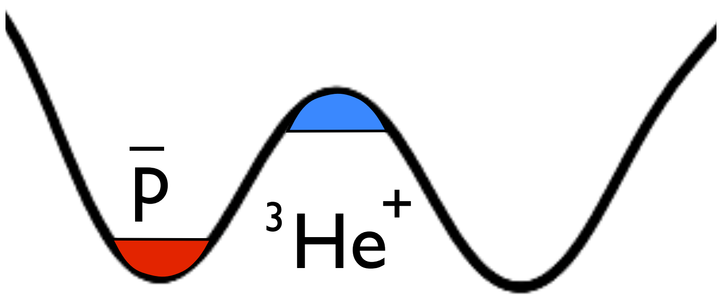
production at rest allows full kinematic reconstruction of all particles (except S)

S(uuddss): two formation pathways

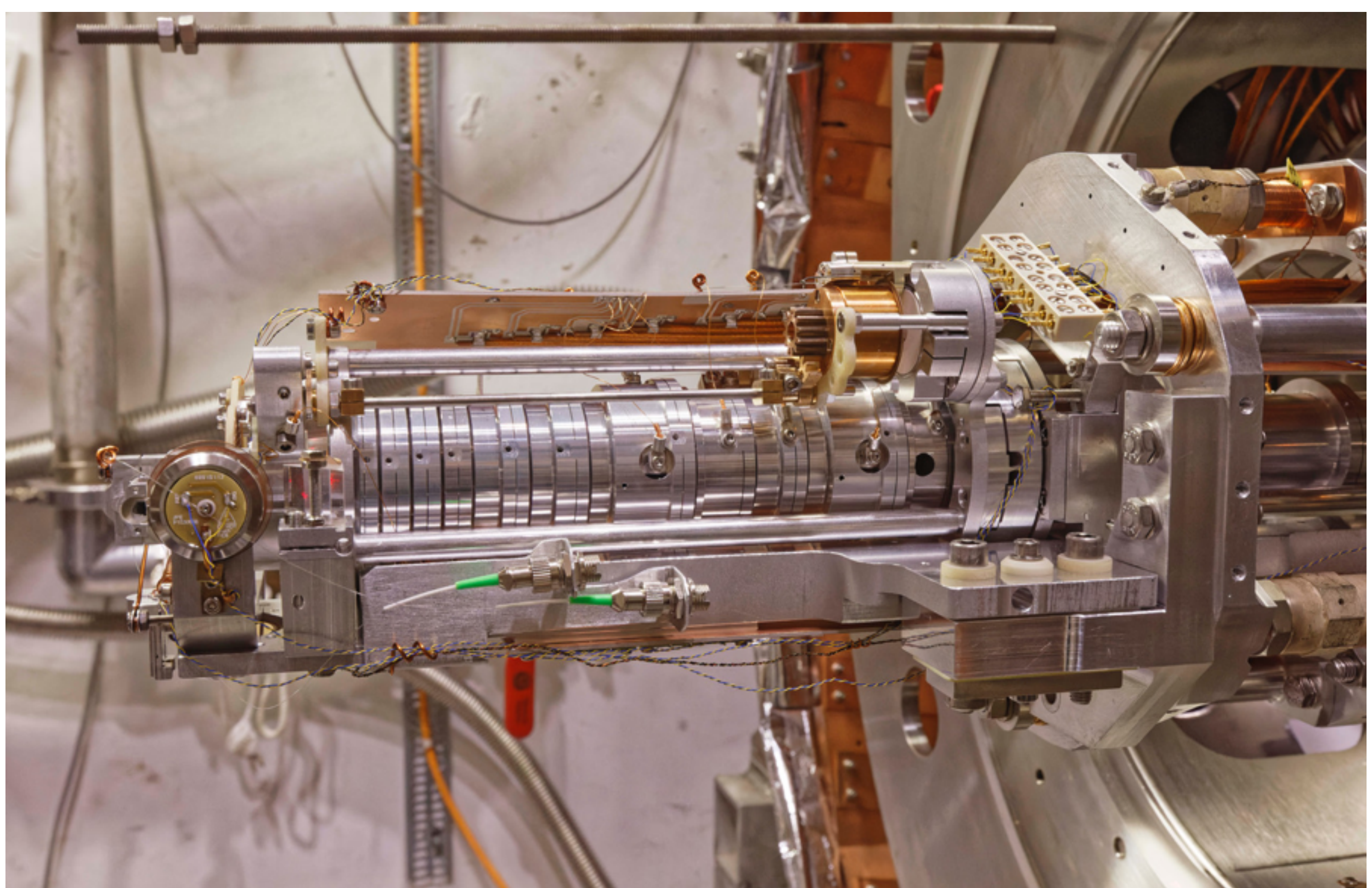
formation reaction:
$(\bar{p}\ ^3He) \rightarrow S(uuddss) + K^+K^+\pi^-$



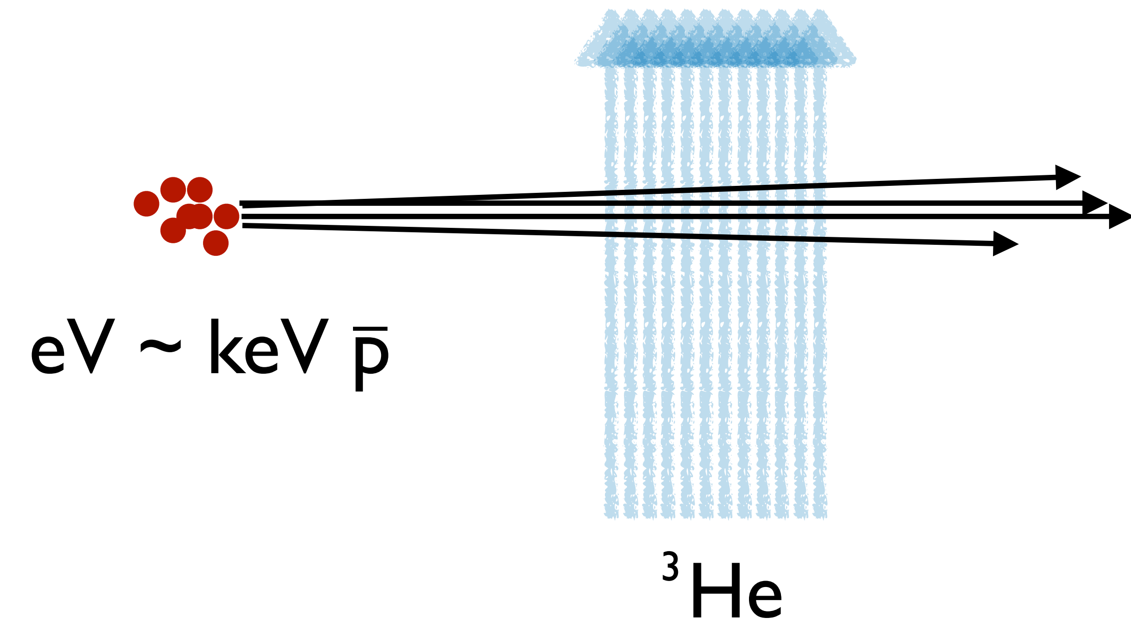
→ *in-trap formation of antiprotonic atoms*



small numbers of ^{3}He ions needed



→ *formation in gas jet target*



low rate, vacuum?, ^{3}He recuperation required

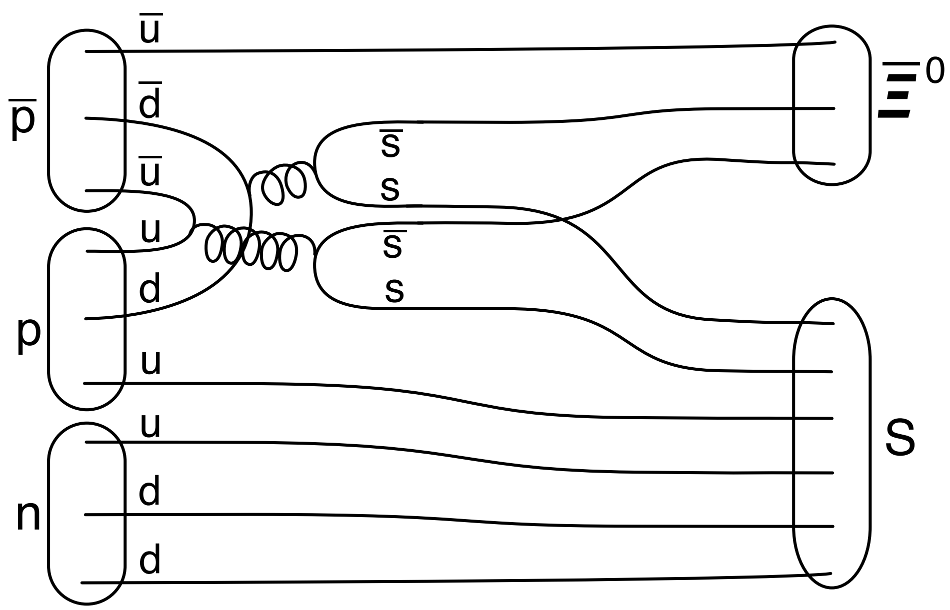
S(uuddss): backgrounds

formation reaction:
$(\bar{p}\,^3He) \rightarrow S(uuddss) + K^+K^+\pi^-$

1) $\bar{p}p(d) \rightarrow K^+\bar{K}^0\pi^+\pi^-(d),$

spectator d, mis-identification, mm²

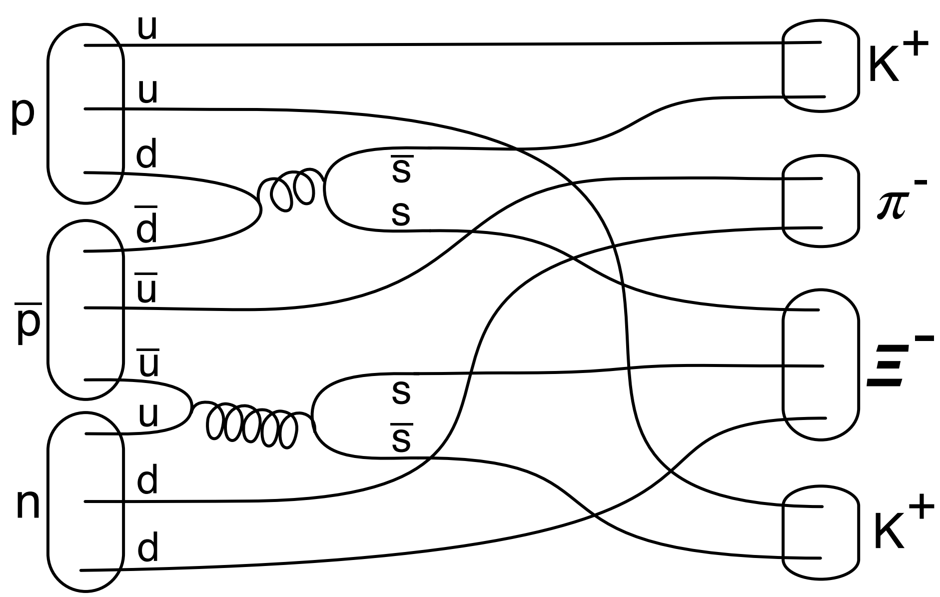
2)



$\rightarrow \Lambda\pi^0 \rightarrow K\pi\pi^0$

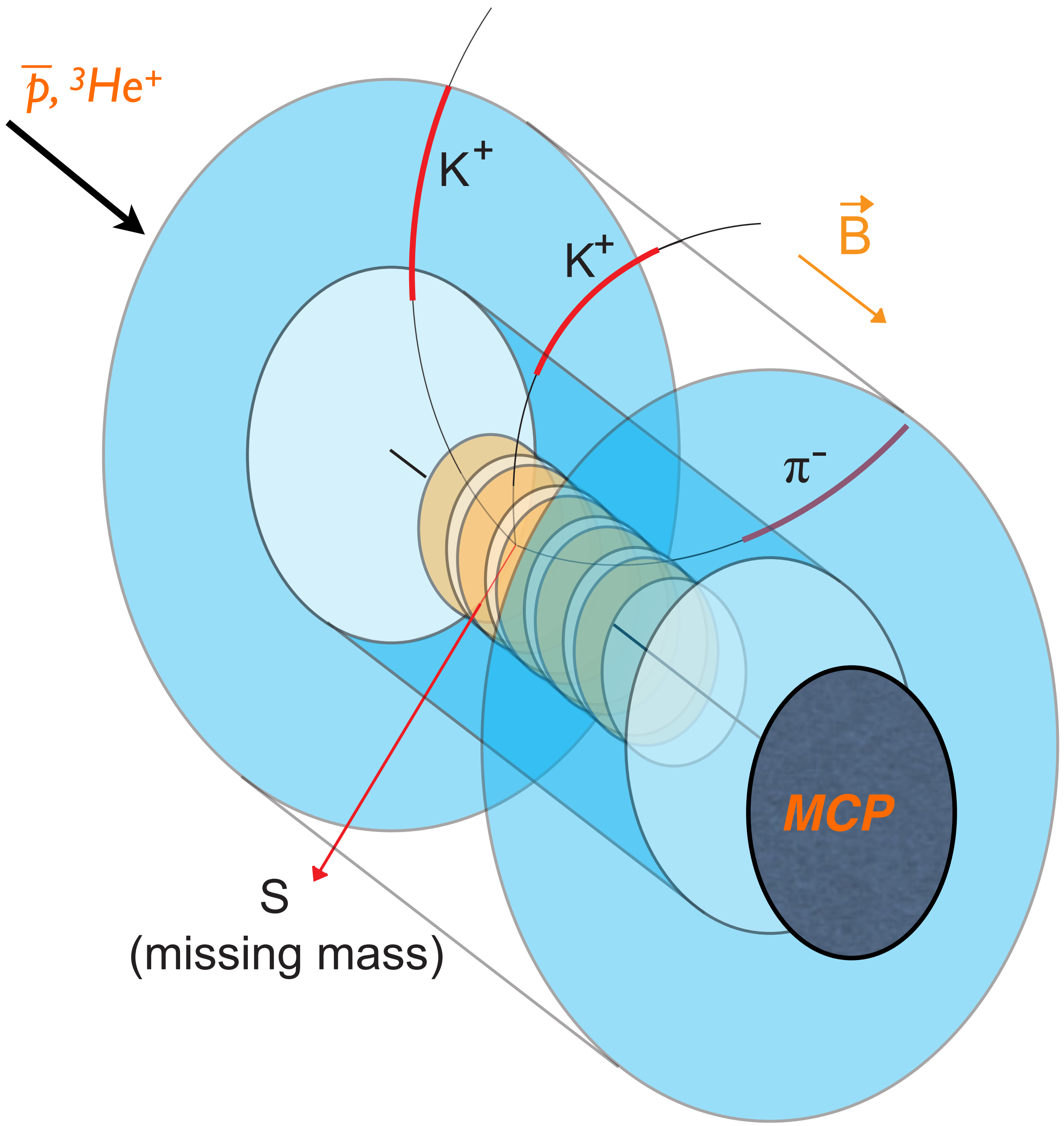
spectator p, topology, mm²

3)



spectator p

S(uuddss): detector designs



particle ID !!! (1:10⁴!)
momentum !
magnetic field !
solid angle !
spectator detection !

Penning traps = cryogenic environment:

solid Ar TPC ?
silicon strip/pixel ?

+ TOF
+ MCP

Gas jet target = warm bore possible:

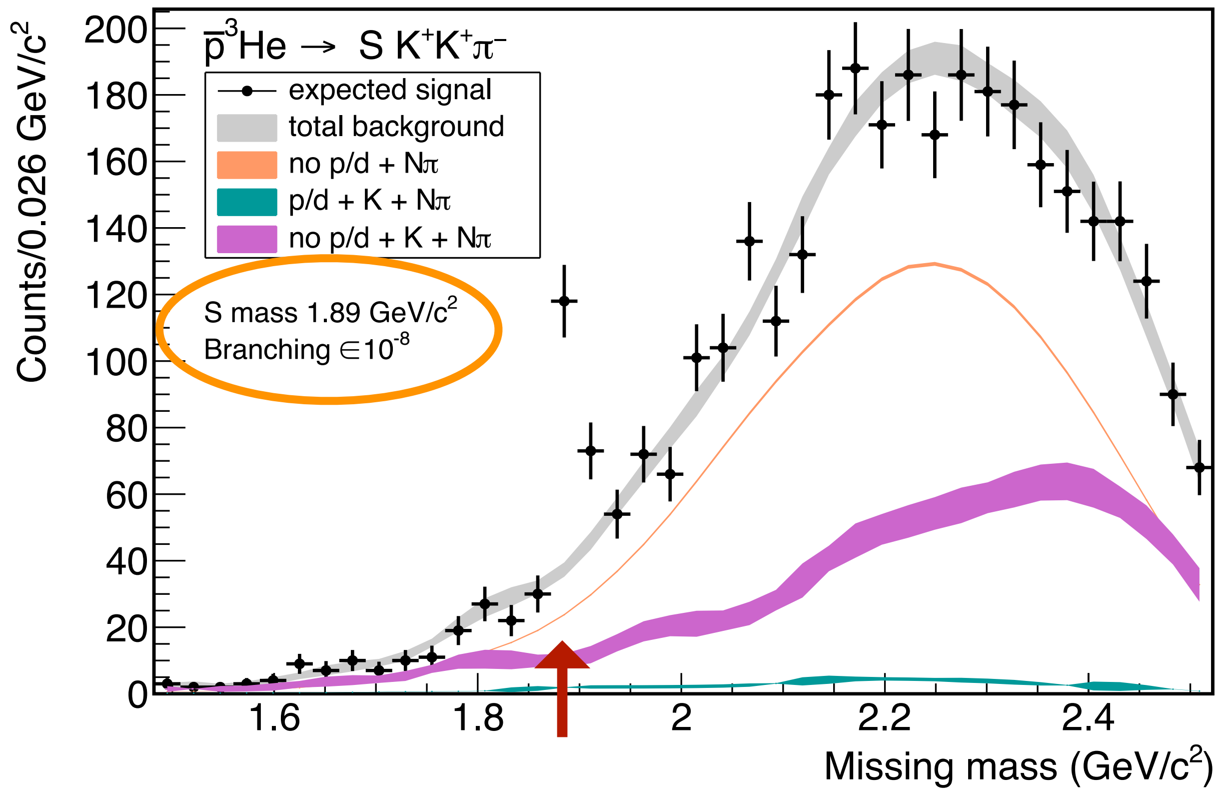
TPC ?
silicon strip/pixel ?
drift tubes ?

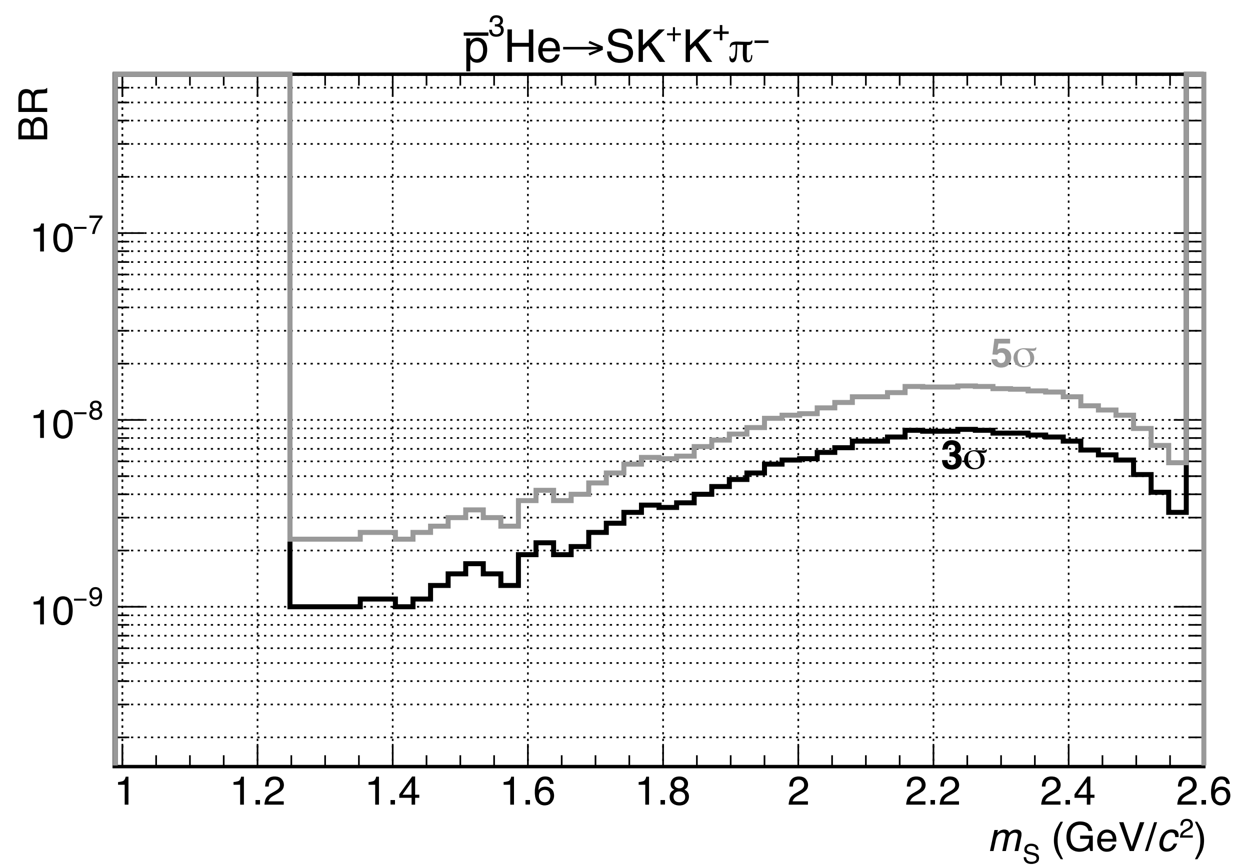
+ TOF

PUMA setup = warm bore possible:

S(uuddss): simulation

Geant-4 simulation





→ *sensitivity down to 10^{-9}*

S(uuddss) formation and detection via p^3He: summary

Penning traps = cryogenic environment:

solid Ar TPC ? ← *requires R&D, discussions started w/ potential partner*

silicon strip/pixel ? ← *requires significant funding, some R&D ($T_{operation}$ ~ 4K)*

+ TOF ← *experience with scintillating fiber tracker (FACT)*

+ MCP ← *one of two workhorse technologies in AEgIS*

ion source ← *being installed in AEgIS in 2024*

in line with the longer term physics program with thrust on antiprotonic atoms but could also constitute a (longer term, more costly) dedicated experiment

(other physics opportunities provided by such a set-up, in particular the investigation of multi-nucleon annihilations)

realistic time line: post LS3, ~ 2030 (some development work and some R&D is going to be needed...)

thank you for your attention!

references:

Glennys R. Farrar, (2017), arXiv:1708.08951v2 [hep-ph] , Stable Sexaquark

Glennys R. Farrar, (2018), arXiv:1805.03723 , A precision test of the nature of dark matter and a probe of the QCD phase transition

Glennys R. Farrar and Zihui Wang (2023), arXiv:2306.03123v2 , Constraints on long-lived di-baryons and di-baryonic dark matter

M. Shahrbaf, D. Blaschke, S. Typel, G. R. Farrar, D. E. Alvarez-Castillo (2022), arXiv:2202.00652v2 ,
Sexaquark dilemma in neutron stars and its solution by quark deconfinement

Glennys R. Farrar (2022), arXiv:2201.01334v2 , A Stable Sexaquark: Overview and Discovery Strategies

Doser, M., Farrar, G. & Kornakov, G. Searching for a dark matter particle with anti-protonic atoms.
Eur. Phys. J. C **83**, 1149 (2023). https://doi.org/10.1140/epjc/s10052-023-12319-8

S(uuddss): observability in recoil detectors

• The S is neutral and a flavor singlet, so it does not couple to photons, pions and most other mesons, nor does it leave a track in a detector.
• The S has no pion cloud and may be more compact than ordinary baryons; the amplitude for interconversion between S and baryons is small.
• The mass of the S makes it difficult to distinguish from the much more copious neutron.

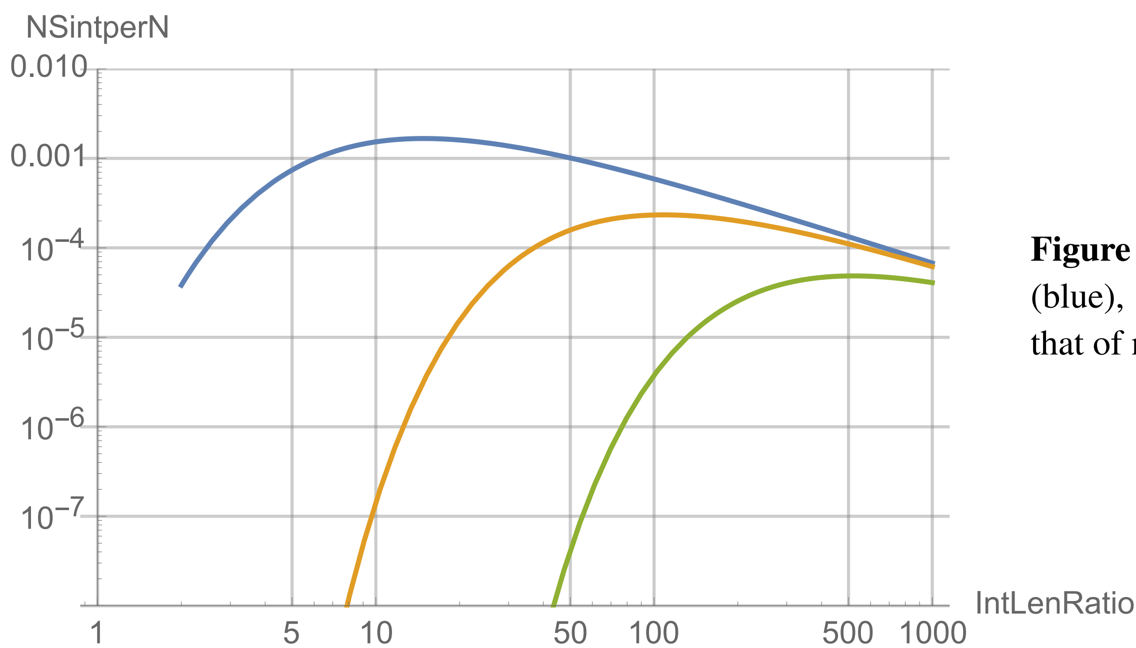


Figure 5. Number of S and $\bar{S}$ interactions in 1m of Fe, per produced neutron in the central region, after 1m (blue), 10m (gold) and 50m (green) of Fe absorber, as a function of the ratio of interaction length of S to that of n, taking $\sigma_{\rm prod,S} = 1/300\,\sigma_{\rm prod,n}$.

S(uuddss) as keV DM (300 km/s)

[12]Direct DM detection experiments are at much lower energy than encountered in accelerator experiment contexts, with Galactic DM having a typical 300 km/s velocity implying keV-range kinetic energies for SDM. Furthermore, direct detection experiments with significant material overburden lose sensitivity when the DM particles reaching the detector have lost enough energy via scattering in the overburden that they are no longer capable of triggering the detector. This effect is particularly important for DM in the GeV range; as a consequence, the ultra-sensitive deep underground WIMP detectors are not sensitive to sexaquark DM. Near-surface experiments to date suffer from the problem that SDM deposits little energy in detectors and the detector responses have not been calibrated in the relevant regime. Note that SENSEI which is sensitive to GeV-and-below masses, relies on a DM-electron coupling which is not present for the electrically neutral S.

S(uuddss): can it account for the ratio of baryonic to DM?

1805.03723v3.pdf