Search for a stable six-quark state in Υ decays

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on behalf of the *BABAR* collaboration

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PRISMA

Six-quark configurations

In recent years, have found good candidates for

- tetraquarks / molecules: $q\bar{q}q\bar{q}$, *e.g.* $Z_c(4430)^+, Z_c(3900)^+$, …
- pentaquarks: $qqqq\bar{q}$: $P_c(4380)^+, P_c(4450)^+$

Di-Baryon: quark configuration $|qqqqqq\rangle$

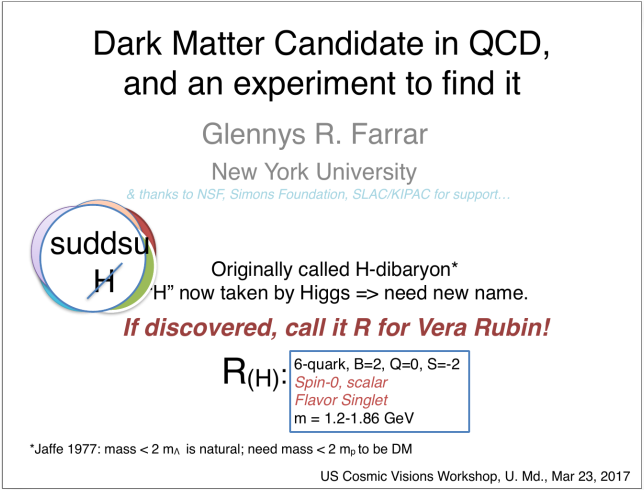
Jaffe (1977): H-dibaryon, flavour-singlet, S-wave $|udsuds\rangle$.
$\sim$ loosely bound $\Lambda\Lambda$.
Bag model prediction $m_H \approx 2150\,\mathrm{MeV}$ R. Jaffe, Phys. Rev. Lett. **38**, 195 (1977)

If $m_H < 2m_\Lambda = 2230\,\mathrm{MeV}$, stable against strong decays.
Expected to decay weakly: lifetime $\sim 10^{-10}\mathrm{s}$

Numerous searches failed to find H-dibaryon

A new beginning ...

G. Farrar (2017): new dark matter candidate from QCD $|uuddss\rangle$



A new beginning ...

Tightly bound six-quark combination $S \sim |uuddss\rangle$

- $B = 2$, $Q = 0$, $S = -2$
- spin 0 (scalar: $J^P = 0^+$)
- flavour singlet with very small coupling to $\pi, \rho, \ldots$
- mass $M < 2.05\,\mathrm{GeV}$
- very compact, $r \sim 0.1\,\mathrm{fm}$ to $0.4\,\mathrm{fm}$

Dubbed the "‘sexaquark”’, to distinguish from H-dibaryon (loosely bound, weak-decay lifetime)

Motivation:

QCD new stable hadron.
Recent LQCD calculations indicate tightly bound $\Lambda\Lambda$ state

Dark Matter candidate for dark matter

QCD aspects

- $|uuddss\rangle$ spatial wave function completely symmetric.
  Generic arguments imply S should be most tightly bound state of its class
- Sexaquark S tightly bound state.
  if $m_S < m_\Lambda + m_p + m_e = 2.05\,\text{GeV}$: only doubly-weak decays allowed
  cosmological lifetime

  if $m_S < 2m_p$: absolutely stable
- S–N interaction suppressed by tiny wavefunction overlap.
  Neutron stars do not decay to S.

  Non-observation of $nn \to S\pi^0$ in nuclei may imply lower bound
  $$m_S \gtrsim 2m_N - m_\pi \approx 1.7\,\text{GeV}$$
- Not excluded by current constraints on H-dibaryon
  does not bind to nuclei (no constraints from exotic isotopes)
  not excluded by accelerator experiments below 2 GeV
  not excluded by hypernuclear experiments

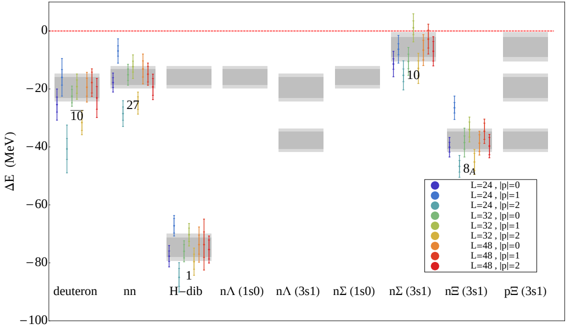
  stable hexaquark with $m < 2.05\,\text{GeV}$ still allowed

See G. Farrar, arXiv:1708.08951 for QCD phenomenology

Lattice QCD?

Lattice calculation in the limit of $SU(3)$ flavour symmetry, with $m_\pi = m_K \approx 800\,\text{MeV}$.

Binding energy for various baryon–baryon systems:



S. Beane *et al.*, Phys. Rev. D 87, 034506 (2013)

Singlet state most tightly bound.
More work needed to get to physical pion mass.

Candidate for Dark Matter?

If DM consists of nearly equal amount of u, d, s quarks:
formation rate driven by QGP transition to hadronic phase.

Sexaquark DM with mass $\sim$ 1860–1880 MeV can reproduce ratio of DM to ordinary matter densities, $\Omega_{\mathrm{DM}}/\Omega_{\mathrm{B}}$ within 15%; fairly insensitive to details of DM.

Not excluded by current direct searches.

See G. Farrar, arXiv:1805.03723 for detailed explanation of DM phenomenology.

Ongoing discussion — see *e.g.* E. Kolb & M. Turner, arXiv:1809.06003

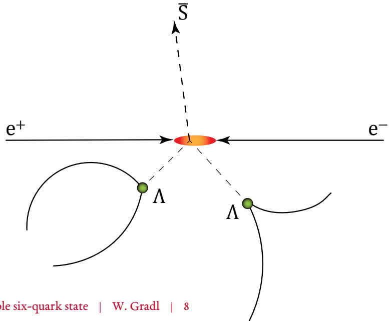
Searching for S

Proposed search channels:

- $K^- p \to \overline{\Lambda} S$ (*e.g.* NA61, but rates may be negligibly small)
- $\overline{S}$ production at LHC, followed by annihilation in beam pipe or detector material
- Υ decays, below open-bottom threshold:

$$\Upsilon(2S, 3S)\ [\to \text{gluons}] \to S\overline{\Lambda}\overline{\Lambda} \text{ or } \overline{S}\Lambda\Lambda$$

Inclusive branching fraction, from heuristic arguments based on statistical model: 10^{-7}, with large uncertainties

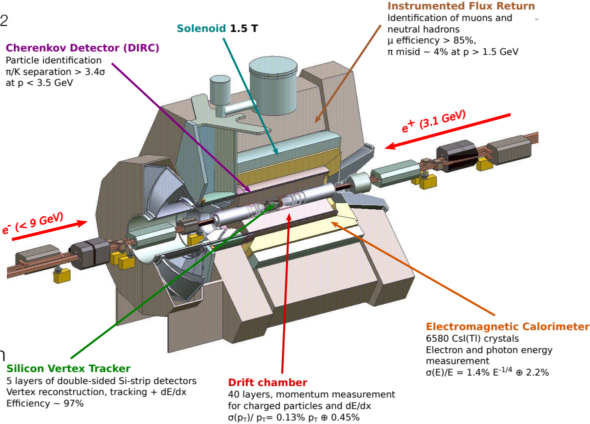


Identify S in the recoil against $\Lambda\Lambda$:

$$m^2_{\text{rec}} = \left(p^\mu_\Upsilon - p^\mu_{\Lambda_1} - p^\mu_{\Lambda_2}\right)^2$$

The *BABAR* experiment

- PEP-II: e^+e^- collider, $3.1 \times 9\ \text{GeV}^2$
  $\sqrt{s} = 10.58\,\text{GeV}\ [\Upsilon(4S)]$
- Asymmetric beam energies
  c.m. lab boost $\beta\gamma = 0.56$
- Asymmetric detector
  - acceptance in c.m.
    $-0.9 \lesssim \cos\theta^* \lesssim 0.85$
- excellent performance
  - Good tracking, mass resolution
  - Good γ, π^0 reco.
  - Full PID for e, μ, π, K, p
- in operation 1999 – 2008;
  collaboration still active

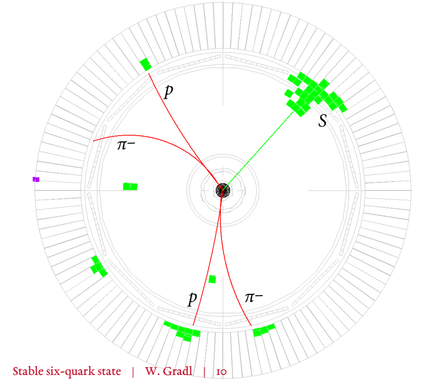


- High luminosity
  - $\mathcal{L}_{\text{peak}} = 12 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$
  - $426\,\text{fb}^{-1}$ on $\Upsilon(4S)$
    90 million $\Upsilon(2S)$
    110 million $\Upsilon(3S)$

Analysis overview

Search for $\Upsilon(nS) \to \bar{\Lambda}\bar{\Lambda}S + c.c.$,
Fully reconstruct $\Lambda \to p\pi^-$, $\mathcal{B} \approx 0.64$; aim for zero background in signal region.

- Require four charged tracks + at most one additional track not from IP
- Apply loose PID criteria to select (anti-)protons
- $\Lambda\Lambda$ or $\bar{\Lambda}\bar{\Lambda}$ with $\Lambda \to p\pi^-$
- Flight significance of each Λ: $|\vec{r}|/\sigma_r > 5$
- Λ points back to IP: $\cos\sphericalangle(\vec{r},\vec{p}) > 0.9$



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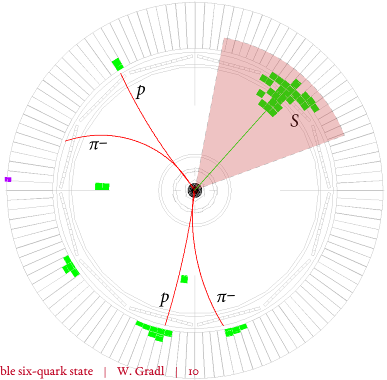
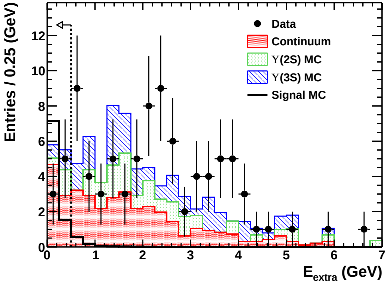
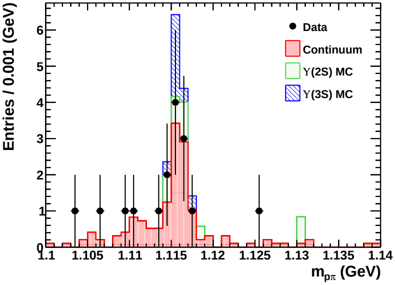


- Sum energy in EMC outside of cone around inferred S direction: $E_{\text{extra}} < 0.5\,\text{GeV}$
- Apply blind analysis: design and tune analysis on MC simulated data and on validation sample with $E_{\text{extra}} > 0.5\,\text{GeV}$

After preselection

BABAR preliminary, arXiv:1810.04724





Use E_{extra} sideband to assess backgrounds and to normalize $\Upsilon(2S)$, $\Upsilon(3S)$ MC.
Continuum background estimated using $\Upsilon(4S)$ data sample.

Signal region $E_{\text{extra}} < 0.5\,\text{GeV}$:
2 entries per event, peak at Λ mass.

Finally, apply kinematic fit constrainig Λ masses and requiring common origin;
select events with $\chi^2 < 25$.
4 signal candidates remain.

Efficiency

Efficiency obtained from dedicated signal MC:

- decay amplitude given by G. Farrar (default)
- alternatively, generate flat in phase space

- model S like a neutron (default)
- alternatively, like neutrino (no interaction with detector material)

Use differences to assess systematic uncertainties.

Efficiency, not including $\mathcal{B}(\Lambda \to p\pi^-)^2$:
from 17% at threshold to 20% near 2 GeV
mainly driven by geometrical acceptance.

Mass resolution (using recoil mass technique) about 100 MeV.

$$m^2_{\text{rec}} = \left(p^\mu_\Upsilon - p^\mu_{\Lambda_1} - p^\mu_{\Lambda_2}\right)^2$$

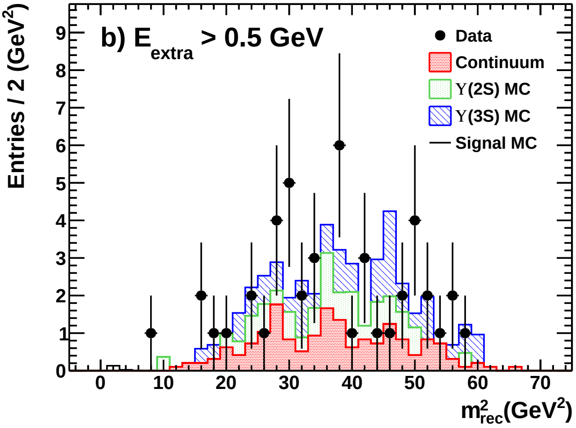
Systematic uncertainties on efficiencies

Mainly from the following sources:

- Signal modelling
  - production amplitude, influencing angular distribution
  - interactions in detector
- Data/MC differences in reconstruction

S angular distribution	5 – 8%
S particle type	8 – 11%
Λ reconstruction	4% per Λ
MC statistics	2%
$\mathcal{B}(\Lambda \to p\pi^-)$	1.6%
proton PID	1% per proton
Number of Υ	0.6%

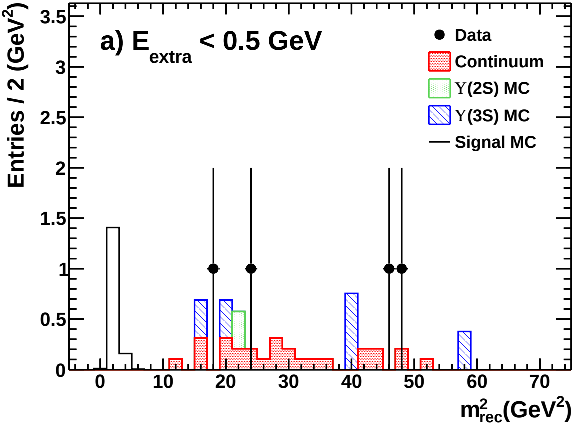
E_{extra} Sideband data



E_{extra} sideband: zero observed background events in signal region.

Final results, signal region $E_{\mathrm{extra}} < 0.5$ GeV

BABAR preliminary, arXiv:1810.04724



Signal MC: S with mass 1.6 GeV and $\mathcal{B}(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda}) = 10^{-7}$

No signal event observed, no background event expected!

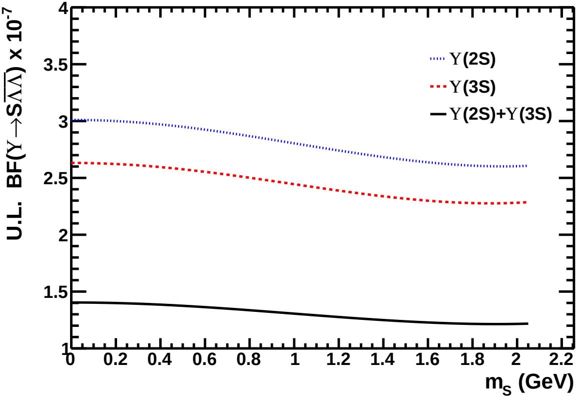
Upper limit on $\mathcal{B}(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda})$

BABAR preliminary, arXiv:1810.04724

Scanning S masses $0 \leq m_S \leq 2.05$ GeV in steps of 50 MeV.

Use profile likelihood method to set upper limit at the 90% C.L. including systematic uncertainties.

$$\mathcal{B}(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda}) < 1.2 \cdots 1.4 \times 10^{-7}$$



Summary

- Tightly bound $S \sim |uussdd\rangle$ may be more stable than previously thought.
  Stable even on cosmological time scales if $m_S < m_p + m_\Lambda + m_e = 2054.5\,\text{MeV}$
- If it exists, candidate for dark matter
- Surprisingly, not yet excluded by dozens of searches for H-dibaryon
- Clean search channel: $\Upsilon(2S, 3S)$ decays, in recoil against $\Lambda\Lambda$ or $\bar{\Lambda}\bar{\Lambda}$

- Use BABAR's data sample of 200 million $\Upsilon(2S, 3S)$
- No signal found, no background left: Stringent limits on existence of S
  $\mathcal{B}(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda}) < 1.2 \cdots 1.4 \times 10^{-7}$

- However, *exclusive* BF may be much smaller than BABAR's sensitivity; need to look into semi-inclusive channels like $S\bar{\Lambda}\bar{\Lambda}X$

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