Stable Sexaquark as Dark Matter

S

Glennys R. Farrar
New York University

Stable Sexaquark and other uds Dark Matter

How could we have missed a stable particle made of quarks?

[Hints from Astrophysics]

[Primordial Nucleosynthesis]

Dark-Matter to Ordinary-Matter ratio

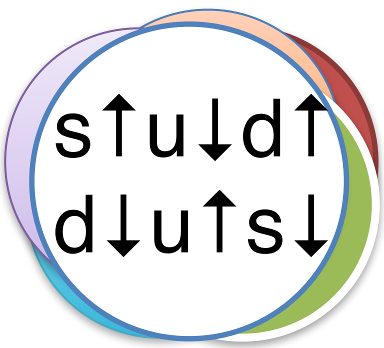
[Detecting S dark matter]

Discovering a stable sexaquark in the lab

Unique among multi-quark states:

Fermi statistics is compatible with a
totally symmetric spatial wave function AND

antisymmetric (singlet) in:
color
flavor
spin
totally symmetric in space



S

(Most-Attractive Channel)^3 :

6-quark, Q=0, B=2
Spin-0, scalar
Flavor singlet
$m_S < 2$ GeV???

Same quark content as H-dibaryon* (Jaffe 1977), but different physics: **not a loosely bound di-Λ!**

*mass ~ 2150 MeV in bag model — decays in 10^{-10} s

Why consider $m_S \sim 2\ m_p{}^*$?
(*1.876 GeV)

- Light quarks almost massless, i.e. relativistic
  - $m_{u,d} \approx 0$, $m_s = 91$ MeV
- S has same QNs as ground state glueball
  - why not $m_S \approx m_{glueball}$ +180 MeV = (1.5-1.7)+ 0.18 GeV $\lesssim 2\ m_p$
- 3 x di-quark mass = 1.2 - 2 GeV

- $m_S < 2\ (m_p + m_e)$: S is absolutely stable
- $m_S > 2\ (m_p$ - 8 MeV) : nuclei are stable

Interesting DM candidate

- triple-singlet (color,flavor,spin): MAC, lattice, almost all models => $m_S < 2\ m_\Lambda$
- *extensive experimental searches **exclude** weak-lifetime & m > 2 GeV*

➜ bound state exists and mass < 2 GeV ($\tau > \tau_{Univ}$ or stable)

Stable Sexaquark Hypothesis

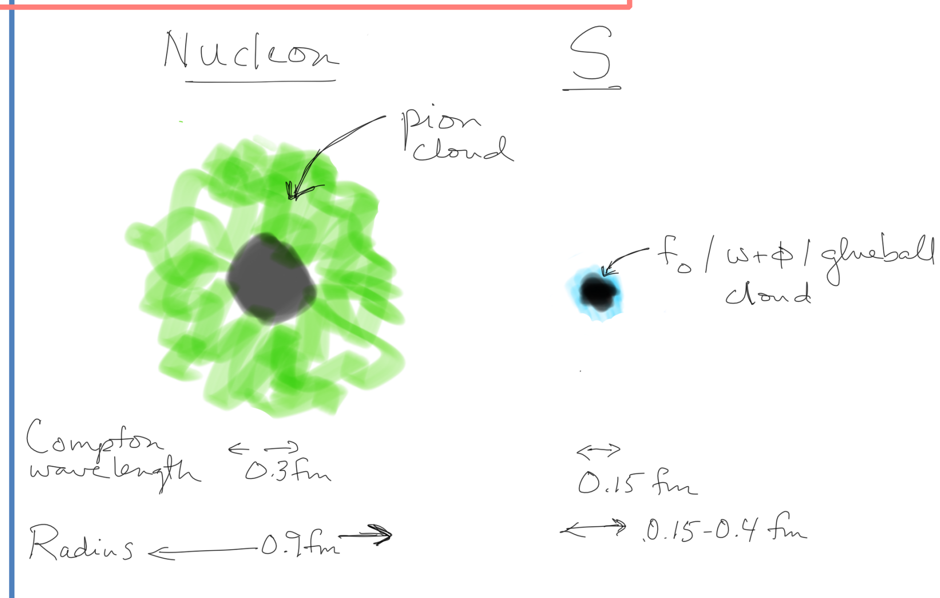
6	sexa-[19]	–	sen-[20]	sext-[21]	hex-[22]	hexakis- hexaplo- hexad- e.g. hexahedron	hect-[23] hectaio-	shat-

a b Sometimes Greek *hexa-* is used in Latin compounds, such as *hexadecimal*, due to taboo avoidance with the English word *sex*.

https://en.wikipedia.org/wiki/Numeral_prefix

Crucial fact:

S does not couple to pions => much smaller than usual hadrons => hard to produce with hadrons



6-quark, Q=0, B=2

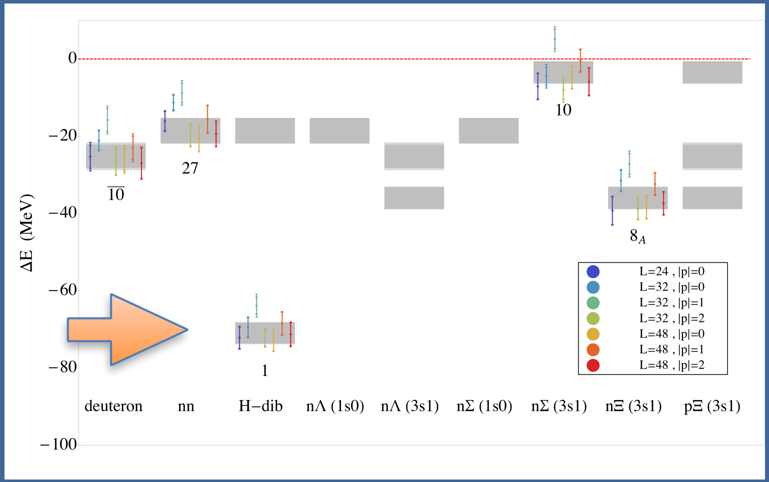
Spin-0, scalar

Flavor singlet

m ~ 1.7-2 GeV

Stable S?

- $\tau > \tau_{Univ}$
  - **$M_S < 2\, m_p + 2\, m_e$ = 1877.6 MeV ➜ absolutely stable**
  - **$M_S > 2\, m_p + 2$ BE** = 1860 MeV **➜ nuclei absolutely stable**
  - higher and lower mass may also work $\Gamma \sim G_F^4$ x (wave function overlap)^2
- **Lattice predicts binding (Beane+13)**
  - (m_q = 850 MeV so not realistic)
  - 80 MeV binding



- **Experiments exclude decaying S**

=> it must be STABLE ! ;-)

Conditions on QCD Dark Matter

- ✓ $\tau_{DM} > \tau_{Univ}$, cold, neutral
- ✓ primordial nucleosynthesis
- ✓ Particle must not be already excluded
  - accelerator searches
  - exotic isotopes
  - DM searches
  - indirect impacts (heating planets, helioseismology,…)
  - stability of nuclei
  - equation of state of neutron stars (and their stability)
- ✓ Correct relic density (for natural m_{DM} & $\sigma_{f.o.}$)

Relic Abundance of *uds* Dark Matter

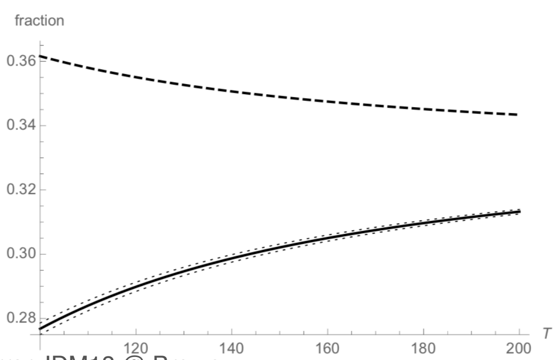
Quark-Gluon Plasma ➜ Hadrons @~150 MeV

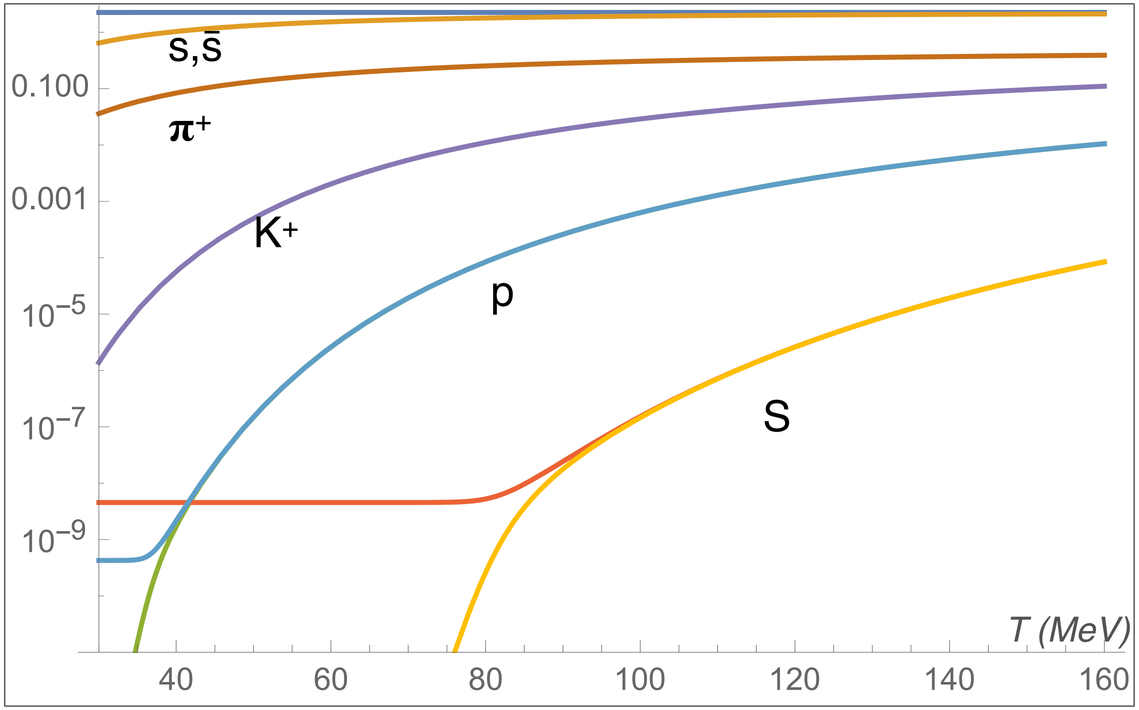
- Lattice QCD: crossover transition 160-140 MeV
  - T > 160 MeV: u,ū,d,d̄,s,s̄,gluons; NO vacuum condensates
  - T < 140 MeV: pions, kaons, p,p̄, …; <qq̄> & <GG> condensates
  - Abundance relative to photons (for species in equilibrium):
- Baryogenesis ⇒

$$\eta_{\rm tot} = \eta(1 + \Omega_{DM}/(y_b \Omega_b)) \approx 4.1 \times 10^{-9}$$

- u,d,s ratio from q masses

  m_u = 2.118(38) MeV
  m_d = 4.690(54) MeV
  m_s = 92.52(69) MeV

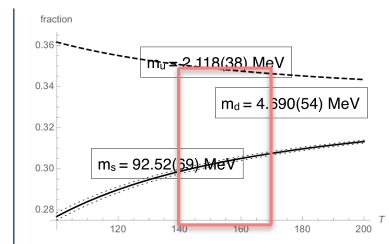


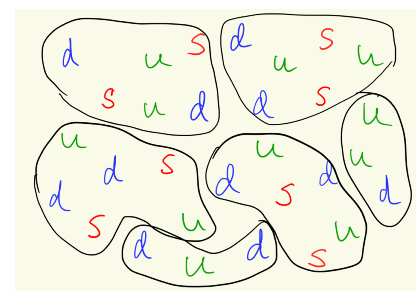


DM to (left-over) baryon ratio

- Hypothesis: DM has u,d,s in equal numbers
  - *sexaquark DM, strange quark nuggets (Witten,1984)*

$$\frac{\Omega_{DM}}{\Omega_b} = \frac{y_b\, \kappa_s\, 3 f_s}{1 - \kappa_s\, 3 f_s}$$





- *y_b = DM mass/m_p (mass per unit baryon number)*
- *f_s = fraction of quarks that are s*
- *3 f_s is number uds per unit baryon # — ranges from 0.964 to 0.948 as T decreases from 160 MeV to 140 MeV.*
- *κ_s is efficiency of uds ➜ DM (Boltzmann, from hyperon and S masses)*

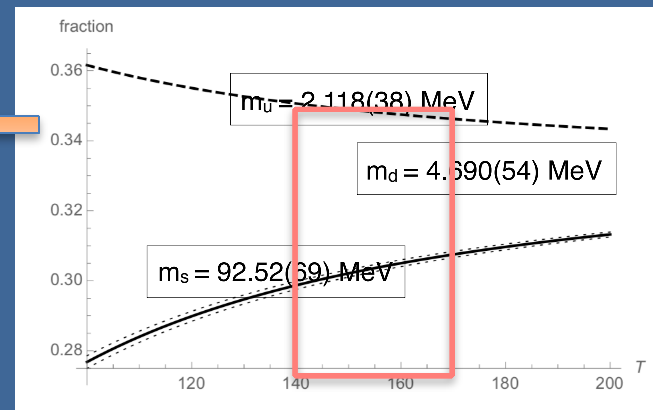
$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda,\Lambda} + r_{\Lambda,\Sigma} + 2r_{\Sigma,\Sigma} + 2r_{N,\Xi})} \qquad \boxed{r_{1,2} \equiv \exp[-(m_1 + m_2 - m_S)/T]}$$

Ω_{DM} / Ω_b

follows from **stat mech , quark masses** & temperature of **QGP-hadronization** transition

$m_S/(2m_p)$

$$\frac{\Omega_{DM}}{\Omega_b} = \frac{y_b\, \kappa_s\, 3 f_s}{1 - \kappa_s\, 3 f_s}$$



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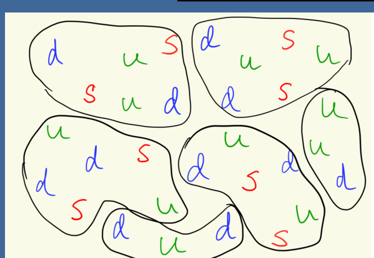
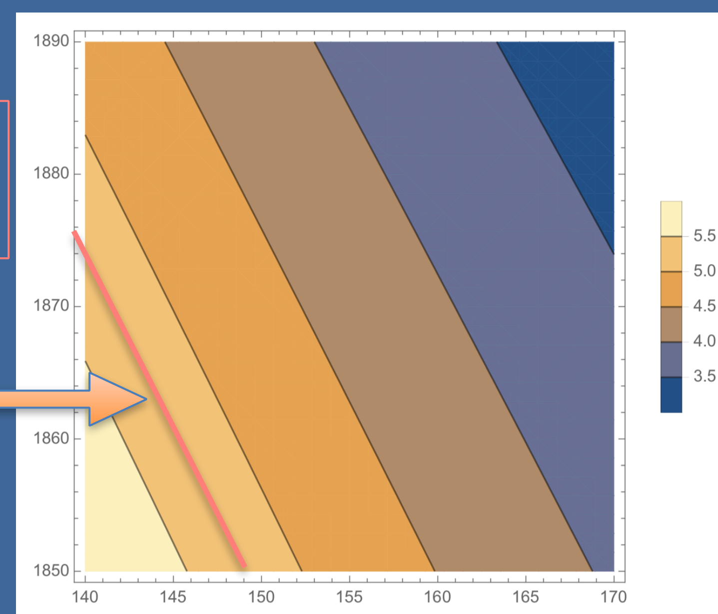


Prediction is both correct AND accurate to ~20% for entire range (uncertainties cancel)

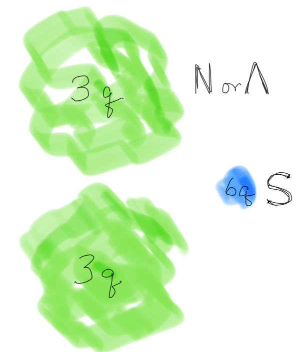


Ω_{DM} / Ω_b = 5.3 ± 0.1

Prediction also applies to strange quark nuggets…

S has not been discovered at accelerators because it is <u>elusive</u>

- **Many negative searches, but all are inapplicable.** They either:
  - looked for H-dibaryon through decays (but S is stable)
  - restricted to mass > 2 GeV (but $m_S < 2$ GeV)
  - required fast production in S=-2 hypernuclei (but small overlap with baryons)



- **Wavefunction overlap with baryons is very small.** Extremely rare fluctuation required for S ⇔ ΛΛ; S⇔NN is G_F^4 smaller =>
  - nuclei can be stable ($\tau > 10^{29}$ yr) even for $m_S > 2\, m_p$
  - hard to produce in fixed target experiments

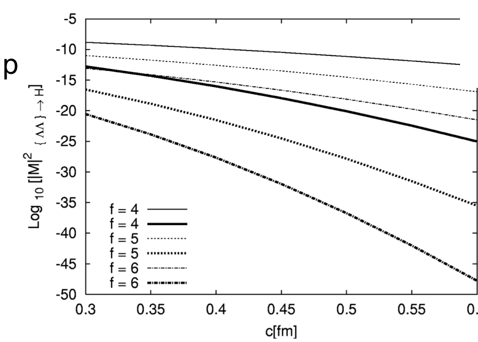


FIG. 1. Log_{10} of $|\mathcal{M}|^2_{\Lambda\Lambda\to H}$ versus hard core radius in femtometers, for ratio $f = R_N/R_H$ and two values of the Isgur-Karl oscillator parameter: $\alpha_B = 0.406$ GeV (thick lines) and $\alpha_B = 0.221$ GeV (thin lines).

GRF+G.Zaharijas 2004

- **S is similar to** (much more copious) **neutrons**

- **Promising accelerator detection strategies**
  - **Apparent lack of baryon number and strangeness conservation:**
    - $\Delta B = \pm 2$ with $\Delta S = \mp 2$
  - **Reconstruct missing mass, e.g.:**
    - $\Upsilon \to \Lambda\,\Lambda\,\bar{S}$ (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$

Experimental searches so far

Looking for Jaffe's H-dibaryon (same QN but assumed to be unstable and r~1 fm)

- Require M > 2 GeV:
  - Gufstafson+ FNAL1976 : Beam-dump + tof *Limit on production of neutral stable strongly interacting particle with mass > 2 GeV.*
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  - Ahn+ BNL 2001
  - Takahashi+ KEK 2001

Search for Six-Quark States

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and
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[1]*Brookhaven National Laboratory, Upton, New York 11973*
[2]*University of California, Irvine, California 92717*
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[4]*Princeton University, Princeton, New Jersey 08544*
[5]*Stanford University, Stanford, California 94309*
[6]*Temple University, Philadelphia, Pennsylvania 19122*
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[3]*Department of Physics, University of Freiburg, D-79104 Freiburg, Germany*
[4]*Department of Physics, Hampton University, Hampton, Virginia 23668*
[5]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*
[6]*Institute for Nuclear Research (INR), Moscow 117312, Russia*
[7]*Department of Physics, Kyoto University, Sakyo-Ku, Kyoto 606-8502, Japan*
[8]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB, Canada R3T 2N2*
[9]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131*
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[12]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[13]*Department of Physics, Pusan National University, Pusan 609-735, Korea*
[14]*TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3*
[15]*Laboratory of Physics, Osaka Electro-Communication University, Neyagawa, Osaka 572-8530, Japan*
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NOT APPLICABLE to S!

Cosmology & structure formation

- DM-baryon interaction: momentum transfer => *slight drag on DM during structure formation*
  - Dvorkin, Blum, Kamionkowski (2014), Gluscevic+Boddy (2017), Xu+18
    - **Ly-alpha forest: $\sigma <\sim 10$ mb if v-indept — no problem for S**
  - Buen-Abad, Marques-Tavares, Schmaltz (2015):
    - **momentum transfer helps reconcile H_o & σ_8**
  - Boring or an opportunity? To be determined…
- S-S self interactions + S-baryon interactions:
  - could have similar benefits as Self Interacting DM
    - core-cusp, "too-big-to-fail" & missing sub-halos problems.

Galaxies & Clusters

DM-gas scattering provides a source of heating, useful for

- Milky Way's extended hot gas halo — 2 x10^6 K
- Quenching star formation
- Avoiding "cooling flow catastrophe" in X-ray clusters

Key points to take home

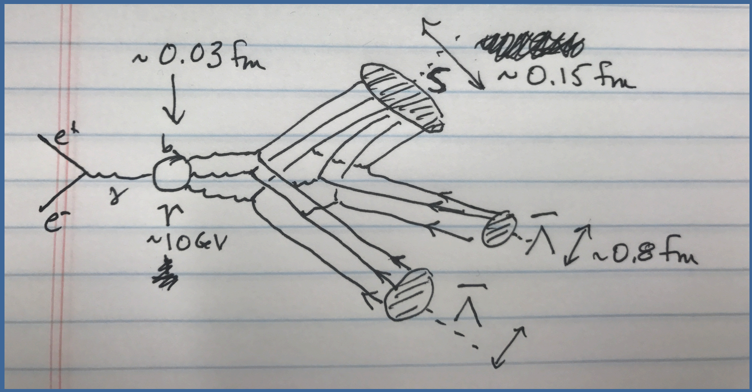
- ***There may a tightly bound 6-quark state*** **S= uuddss**
  - **Unique, symmetric structure ⇒ other hadrons don't provide guidance**
    - mass is not driven by chiral symmetry breaking (unlike baryons)
    - constituent quark model probably completely misleading
  - ***If*** $M_S < 2\, m_p + 2\, m_e$ ***, S is absolutely stable***
- ***If S is stable, its an excellent Dark Matter candidate***
  - Relic abundance is natural. **EXPLAINS 7Li Discrepancy in BBN and Dark Matter to baryon ratio**
  - Usual WIMP detection strategy isn't applicable.
  - May reconcile tension in H_0 & σ_8 and explain astrophysics puzzles ("quenching", core-cusp, DM rotation curves…)
- ***S may be waiting to be discovered in existing*** Υ***-decays or LHC experiments… mass can be accurately measured in*** Υ***-decay exclusive final states.***
- ***SDM will be challenging to detect, but not impossible. Astrophysical and cosmological effects may allow it to be constrained, excluded or confirmed.***

Backup Slides

Sexaquark Discovery Strategy

- Apparent lack of B and S conservation:
  - **$\Delta B = \pm 2 \quad + \quad \Delta S = \mp 2$**
- Reconstruct missing mass, e.g.:
  - **$\Upsilon \to \Lambda\, \Lambda\, \bar{S}$** (+ pions) $\quad M_S^2 = (p_Y - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$
  - LHC: $\bar{S} + N \to \bar{\Lambda}\ K^+ \qquad M_S^2 = (p_{\bar{\Lambda}} + p_K - p_N)^2$
- Snolab nuclei: $pn \to S\, e^+ \nu \qquad G_F^4 \qquad \tau > 10^{+29}$ yr

$\Upsilon \to \Lambda \Lambda \bar{S}$ & $\bar{\Lambda} \bar{\Lambda} S$ (+ pions)



- **Υ is *localized* source of ggg**

  ⇒ *production of S is (relatively) enhanced*

- Many x 10^8 events collected (CLEO, Babar, Belle)
  - detectors pretty hermetic, have good mass resolution, O(10 MeV)
  - Λ decays quickly to $p\pi^-$ so easy to ID. $c\tau$ = 8 cm
- **Can MEASURE m_S via missing mass**
- ***Very clean***
  - Main bkg is $K_S K_S K_L K_L$ (+ pions)
    - K_S's mis-ID'd as Λ's and K_L's escaping before decay : *negligible for Belle*
      - rare and can model accurately
      - $K_S K_S K_L K_L$ (+ pions) ***is measurable***, from $K^+ K^+ K^- K^-$ (+ pions)
  - "Conspiracy" of missed particles producing $\Delta B = \pm 2$, $\Delta S = \mp 2$ very hard

Background does not have narrow peak in missing mass!

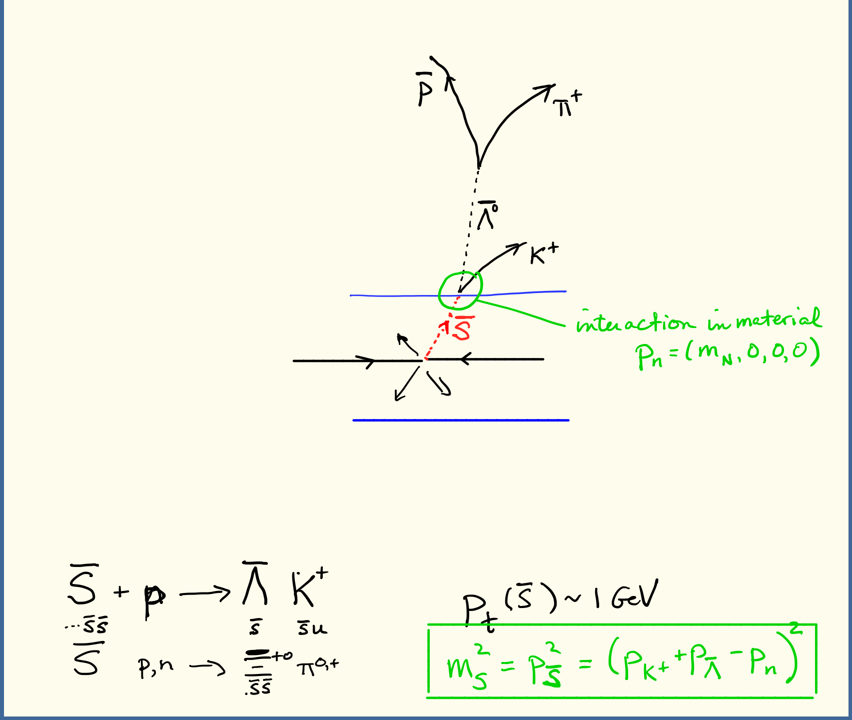
LHC

- Hadronic collisions: low production rate due to small wfn overlap
- Find a needle in a haystack (10^{11} recorded events; potential for trigger >>> more
- Statistical examination of correlation between

  $\Delta B = \pm 2$, $\Delta S = \mp 2$
- **$\bar{S}$ annihilation in tracker, tag by**

  $\bar{\Xi}^{+,o} \rightarrow \bar{\Lambda}\ \pi^{+,o}$ ($c\tau = 5\gamma$ cm) $\bar{\Lambda} \rightarrow \bar{p}\ \pi^{+}$

  or $\bar{\Lambda}\ K^{+}$



- 2nd exponential in scattering-length distribution of n-like interactions, due to S