Search for Dark Matter in Υ Decays at BABAR

Representing the *BABAR* Collaboration

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Introduction

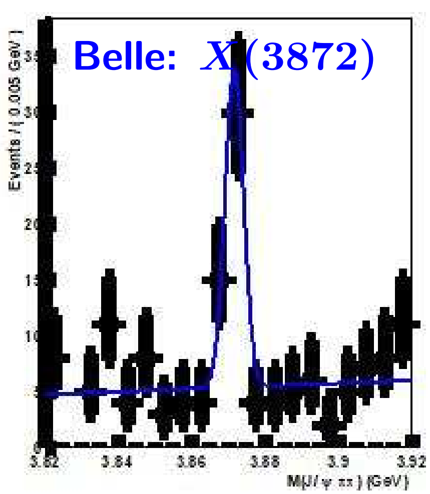
□ **Quark Model classification scheme:** Hadrons

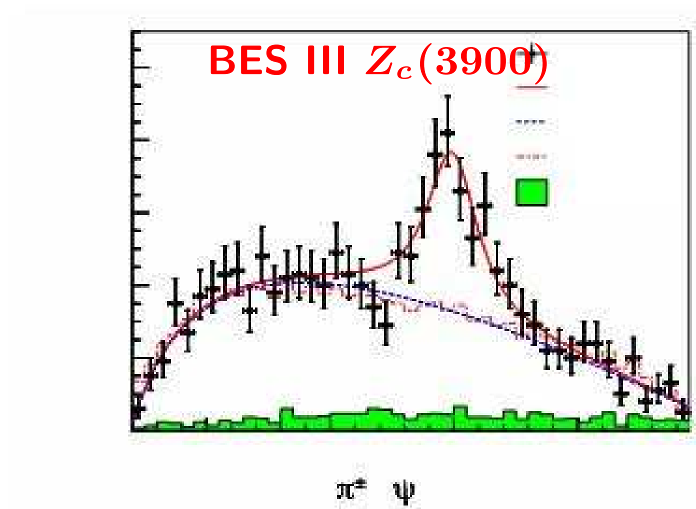
- Only Mesons $(q\bar{q})$ and Baryons (qqq) are predicted
- Other multiquark states: $(q\bar{q}q\bar{q})$, $(q\bar{q}qqq)$, $(qqqqqq)$ are forbidden,

  → however, these states are allowed by Quantum Chromodynamics

□ In recent years some experiments found tetraquarks states $(q\bar{q}q\bar{q})$:

- Belle: $X(3872)$ PRL 91, 262001, 2003
- BES III: $Z_c(3900)$ and $Z_c(4430)$ PRL 110, 252001, 2013

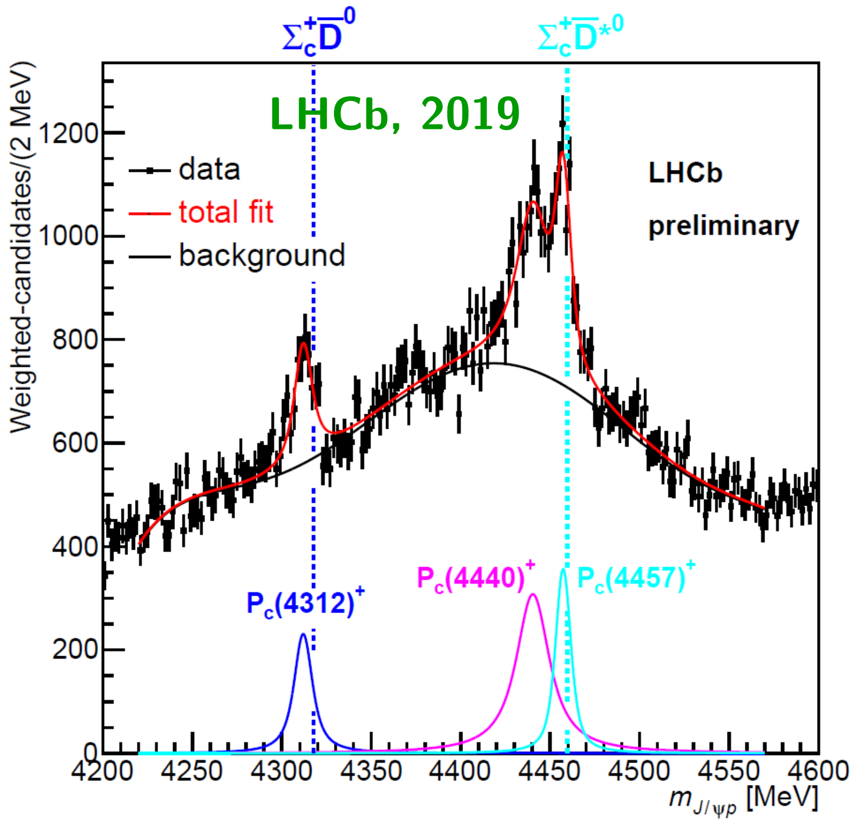




Introduction

☐ **LHCb found Pentaquarks: PRL 122, 072002, 2019**

$P_c(4312)$, $P_c(4440)$, $P_c(4457)$



☐ **Can we find six-quark state?**

New Beginning...

- New proposal: G. Farrar, arXiv: 1708.08951, 2017
  - Six-quark state S: $|uuddss>$ tightly bound to $\Lambda\Lambda$ state
  - Scalar: $\Upsilon \rightarrow gluons \rightarrow S\bar{\Lambda}\bar{\Lambda}$, charge 0, baryon number 2

$$m_S = m_\Lambda + m_p + m_e < 2.05 \text{ GeV}$$

  - Flavor singlet, allowed couplings to mesons, does not bind to atoms
  - If $m_S < 1.878$ GeV (below $2m_p$) $\rightarrow$ absolutely stable state
- Neutron stars do not decay to Six-quark state S:

$nn \rightarrow S\pi^0$ is not observed

- Six-quark state S is not excluded by present experiments

New Beginning...

- Six-quark S could be the astronomical dark matter candidate

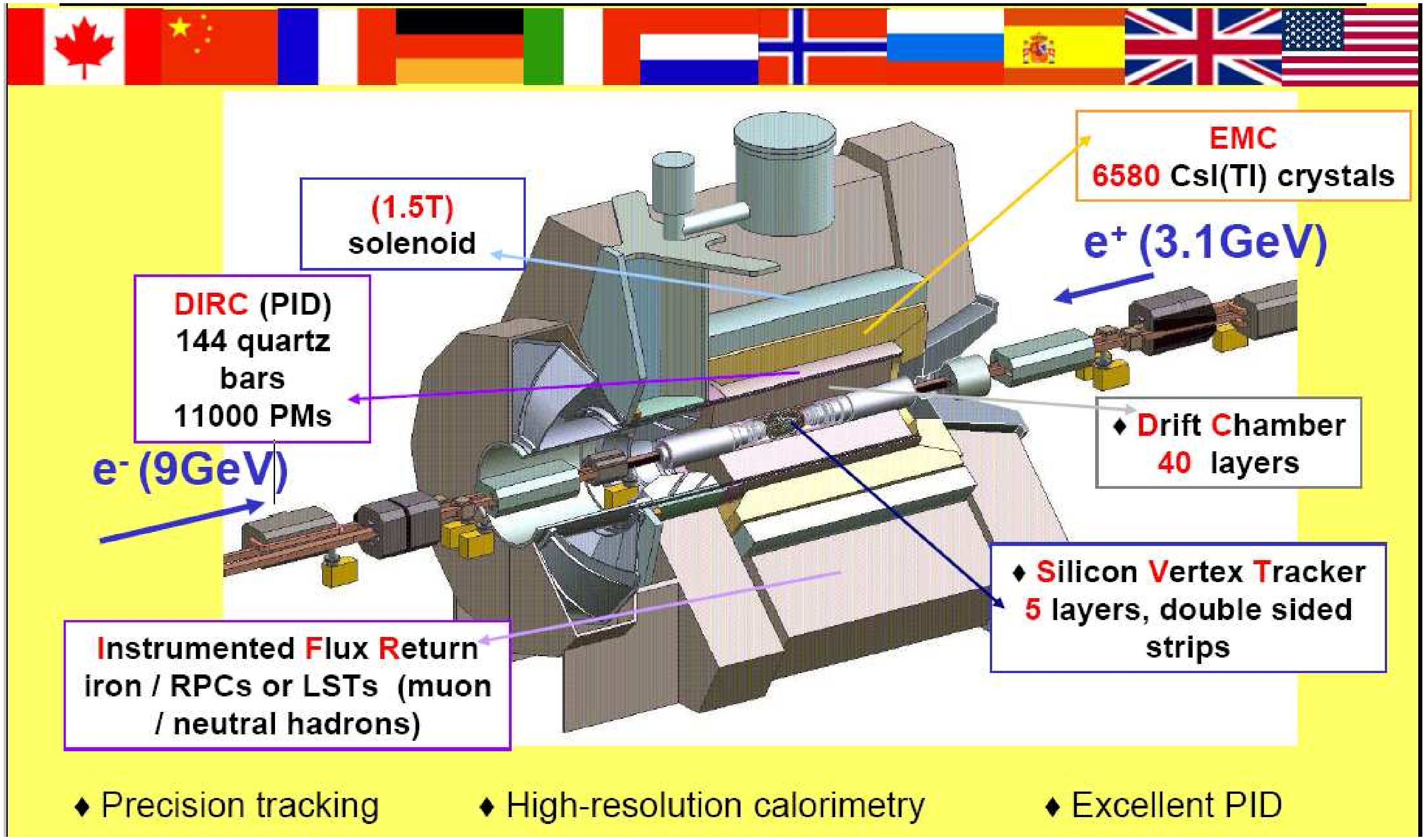
  - If Dark Matter (DM) consists of nearly equal amount of u, d, s quarks, the formation rate is driven by Quark-Gluon-Plasma transition to hadronics phase including Hexaquarks

G. Farrar, arXiv: 1805.03723, 2018

  - Hexaquarks DM with mass $\sim$ 1.86-1.88 GeV can reproduce the ratio of DM to the ordinary matter densities:

$$\frac{\Omega_{DM}}{\Omega_b} = 5.3 \text{ within } 15\%$$

BABAR Detector



- ☐ **Collides (9 GeV)** $e^- \bowtie e^+$ **(3.1 GeV)** $\hookrightarrow \Upsilon(2S), \Upsilon(3S), \Upsilon(4S)$
- ☐ **Peak luminosity :** $\sim 1.21 \times 10^{34}\ cm^{-2}s^{-1}$, $B^0\overline{B}^0$ **production** $\sim$ **12 Hz**

Search for Six-Quark State

- Search for six-quark state S in $\Upsilon(2S,3S) \rightarrow$ gluons $\rightarrow S\bar{\Lambda}\bar{\Lambda}$ or $\bar{S}\Lambda\Lambda$

  - Blind analysis on data sets:

    $\Upsilon(2S) : 90 \times 10^6 (14 fb^{-1}) + \Upsilon(3S) : 110 \times 10^6 (28 fb^{-1})$

    $\Upsilon(4S) : 450 \times 10^6 (428 fb^{-1})$ for continuum backgrounds

  - Fully reconstruct $\Lambda\Lambda \rightarrow p\pi^- p\pi^-$

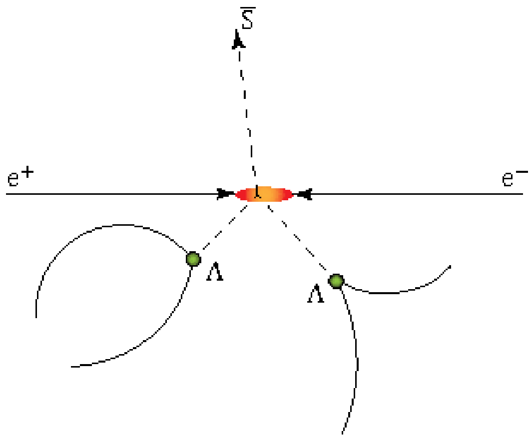
  - Required 4 charged tracks + one track not associated with Λ

    and a distance of closest approach (DOCA) from interaction point

    $\rightarrow$ DOCA > 5 cm

  - Observable Recoil Mass Squared

$$m^2_{rec} = (p_T - p_\Lambda - p_\Lambda)^2$$



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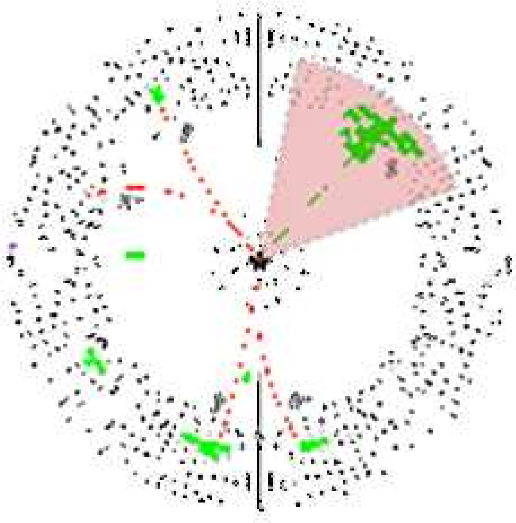
Search for Six-Quark State

- Require flight significance of each Λ: $\frac{|\vec{r}|}{\sigma_r} > 5$
- Λ points back to IP: $cos(\vec{r}, \vec{p}) > 0.9$
- Apply PID (Particle Identification) criteria to select proton
- Examine extra neutral energy (E_{extra}) in EM calorimeter

  $\longrightarrow$ $E_{extra} < 0.5$ GeV (not associate with charged particles)

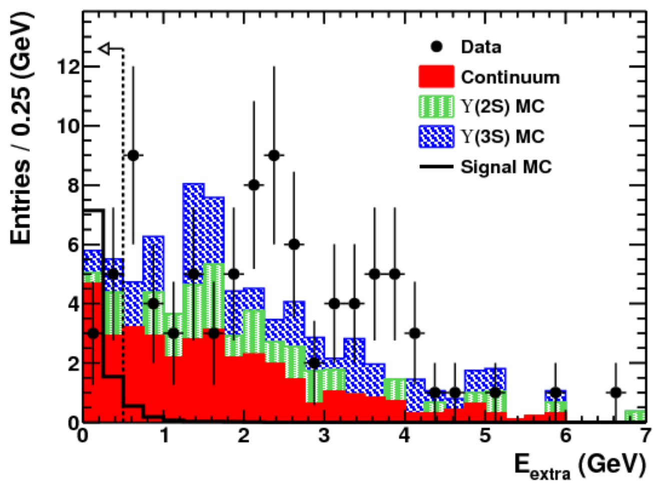
  $\longrightarrow$ outside of signal cone



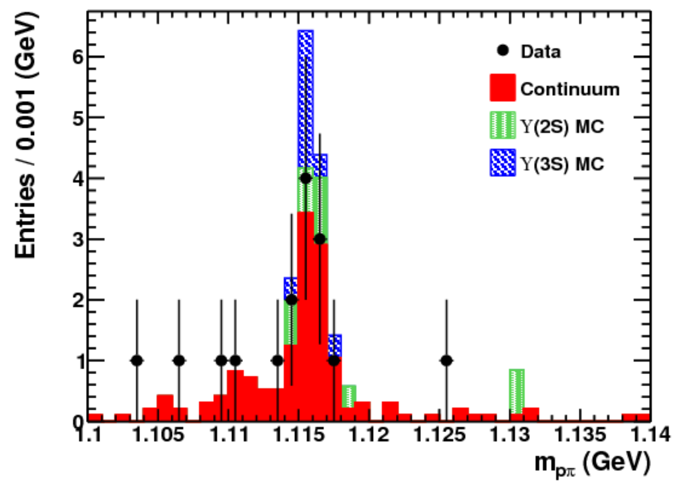
- Sample of $E_{extra} > 0.5$ GeV is used to validate the background

Sample after Preselection

- E_{extra} distribution after preselection: 92 events of which 8 events satisfy with $E_{extra} < 0.5$ GeV
- $p\pi$ invariant mass $(m_{p\pi})$ shows true Λ signal



E_{extra} Distribution



$m_{p\pi}$ Distribution

- Apply kinematic fit constraining Λ mass and common production point and select events with $\chi^2 < 25$

  $\rightarrow$ 4 signal candidates remain

Efficiency and Backgrounds

Signal MC efficiency

- Signal events are generated with decay amplitude provided by Farrar
- Model the S interaction as neutron or neutrino with reduced cross section

Backgrounds contributions

- For $q\bar{q}$ continuum background we use $\Upsilon(4S)$ data

  $\longrightarrow$ negligible background

- The $\Upsilon(2S,3S)$ background component is estimated using MC sample

  normalized to $E_{extra} > 0.5$ GeV sideband

- Remaining background: $e^+e^- \rightarrow \Lambda\Lambda\bar{\Lambda}\bar{\Lambda}(X)$, where the two $\Lambda \rightarrow n\pi^0$

Systematic Uncertainties

Summary of systematic uncertainties for six-quark S particle

Source	Systematic Uncertainty
S angular distribution	$(4-15)\%$
Modeling S particle	$(8-10)\%$
Λ reconstruction	4% per Λ
Λ branching fraction	1.6%
Finite MC statistics	1.5%
Proton PID	1.0% per proton
Number of $\Upsilon(2S,3S)$	0.6%

- **Dominant systematic uncertainties:**

  Modeling S production & angular distribution

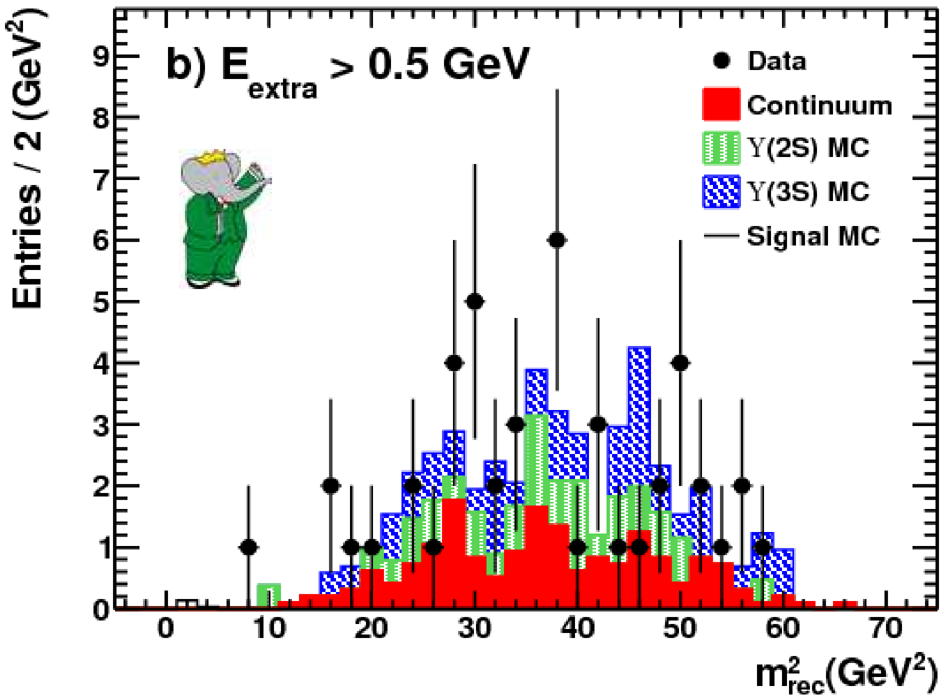
- **Total systematic uncertainty:**

Total systematic uncertainty = (12.8-16.1)%

Validation: $E_{extra} > 0.5$ GeV

- E_{extra} sideband distribution: $E_{extra} > 0.5$ GeV

  We observed zero background event in m^2_{rec} signal region

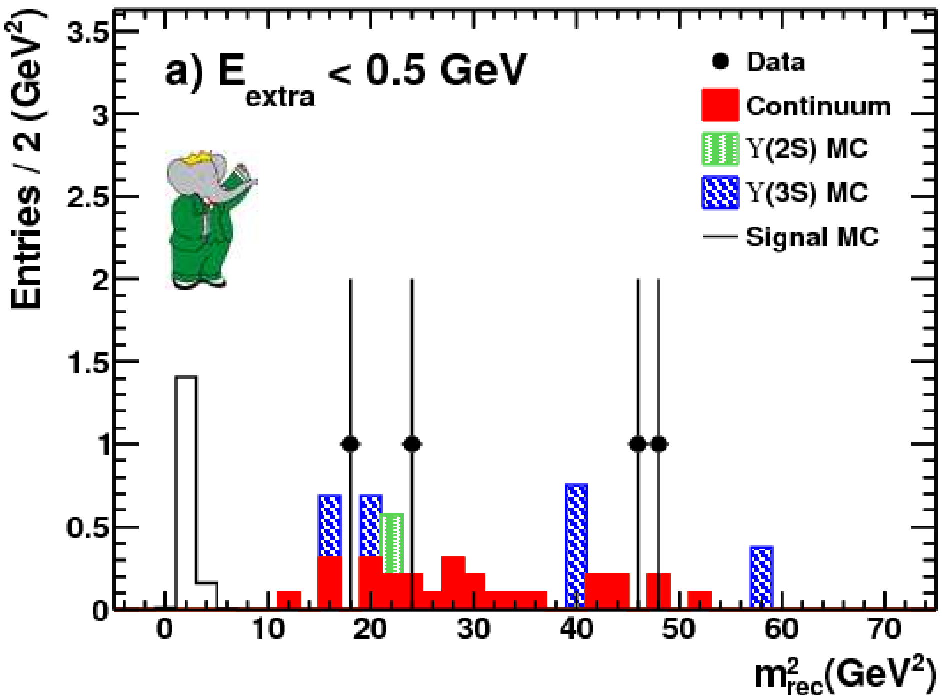


- E_{extra} sideband distribution with various backgrounds

Signal Region: $E_{extra} < 0.5$ GeV

☐ **Final result in signal region: $E_{extra} < 0.5$ GeV**

We observed no signal event for zero expected background in m^2_{rec}



☐ **Signal MC (solid line):**

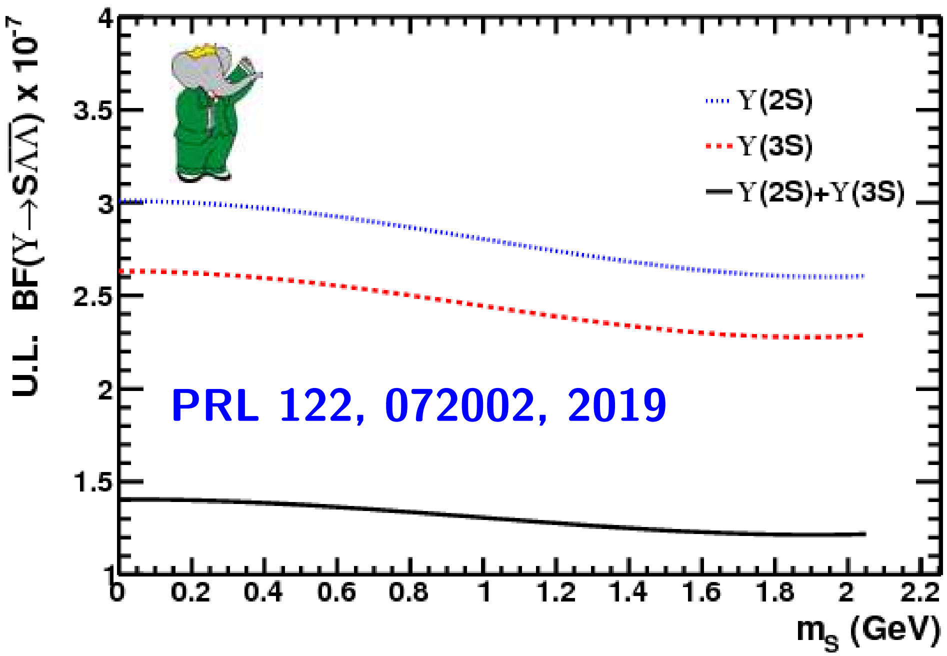
Six-quark state S with mass of 1.6 GeV $\rightarrow \mathcal{B}(\Upsilon(nS) \rightarrow S\bar{\Lambda}\bar{\Lambda}) = 10^{-7}$

Conclusions

- ☐ No signal is observed for $\Upsilon(2S, 3S) \to S\bar{\Lambda}\bar{\Lambda}$
- ☐ Scanning S masses $0 < m_S < 2.05$ GeV in steps of 50 MeV

  Set upper limit on branching fraction at 90% C.L.

$$\mathcal{B}(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda}) < (1.2 - 1.4) \times 10^{-7} \text{ @}90\% \; C.L.$$



- ☐ Set stringent bounds on the existence of six-quark state S