Search for a Stable Six-quark State in Upsilon Decays at BABAR

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On behalf of the BABAR collaboration

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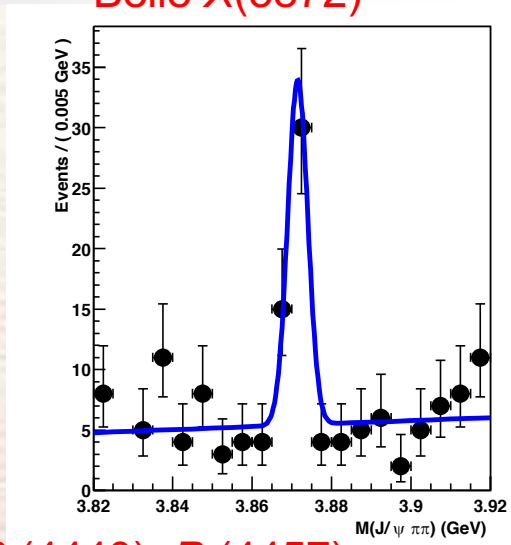
Introduction

- In the quark model, only mesons ($q\bar{q}$) and baryons (qqq) are predicted
  - ➔ other states such as ($q\bar{q}\,q\bar{q}$), ($q\bar{q}\,qqq$) ($qq'q''qq'q''$) are forbidden
- In recent years, however, several experiments found states consistent with tetraquarks ($q\bar{q}\,q\bar{q}$)
  - Belle: $X(3872)$
  - BES III: $Z_c(3900)^+$
  - BES III: $Z_c(4430)^+$

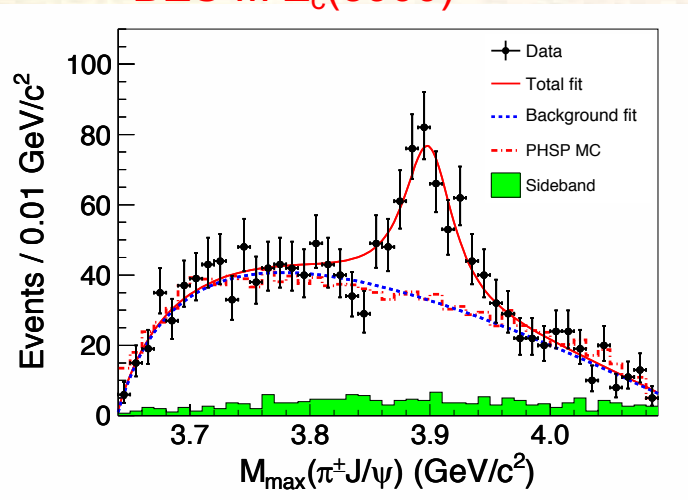
  …
- LHCb found pentaquarks:
  - $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$

Belle $X(3872)$



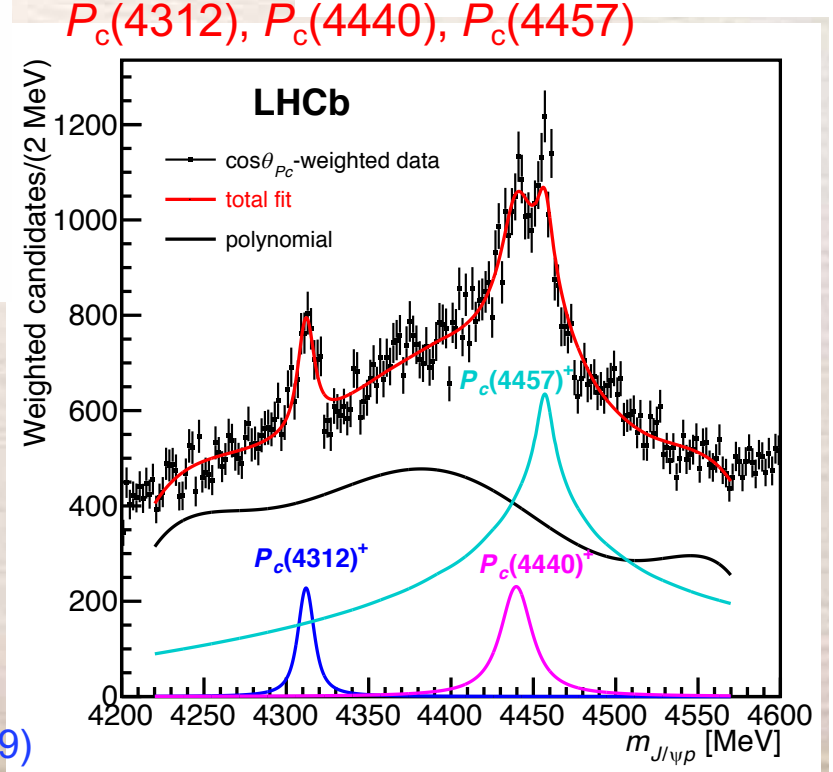
PRL 91, 262001 (2003)

BES III $Z_c(3900)$



PRL 110, 252001 (2013)

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



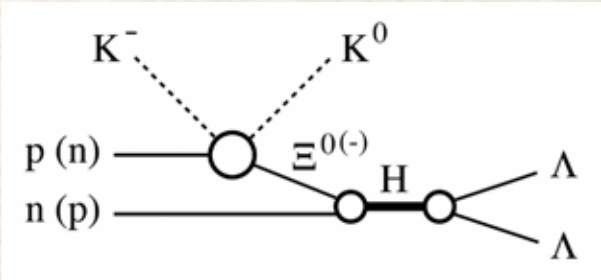
PRL 122, 072002 (2019)

Introduction

- So why not six-quark states?

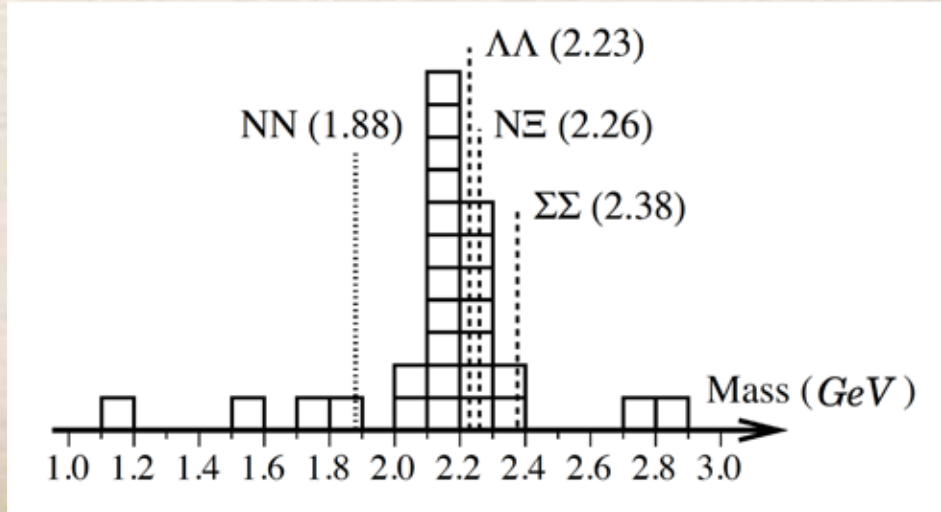
- 1977 Jaffe proposed *H*-dibaryon: *S*-wave, flavor singlet state: |*udsuds*⟩
  - a loosely bound $\Lambda\Lambda$ state
  - Bag model prediction: mass m_H = 2150 MeV

Jaffe PRL 38, 195 (1977)



- If $m_H < 2m_\Lambda$, state is stable wrt strong decays
  ➔ *H* is expected to decay weakly, lifetime ~ 10^{-10} s

- Numerous searches for H-dibaryon did not find any state



Jaffe, Nucl.Phys. A625, 167 (1997)

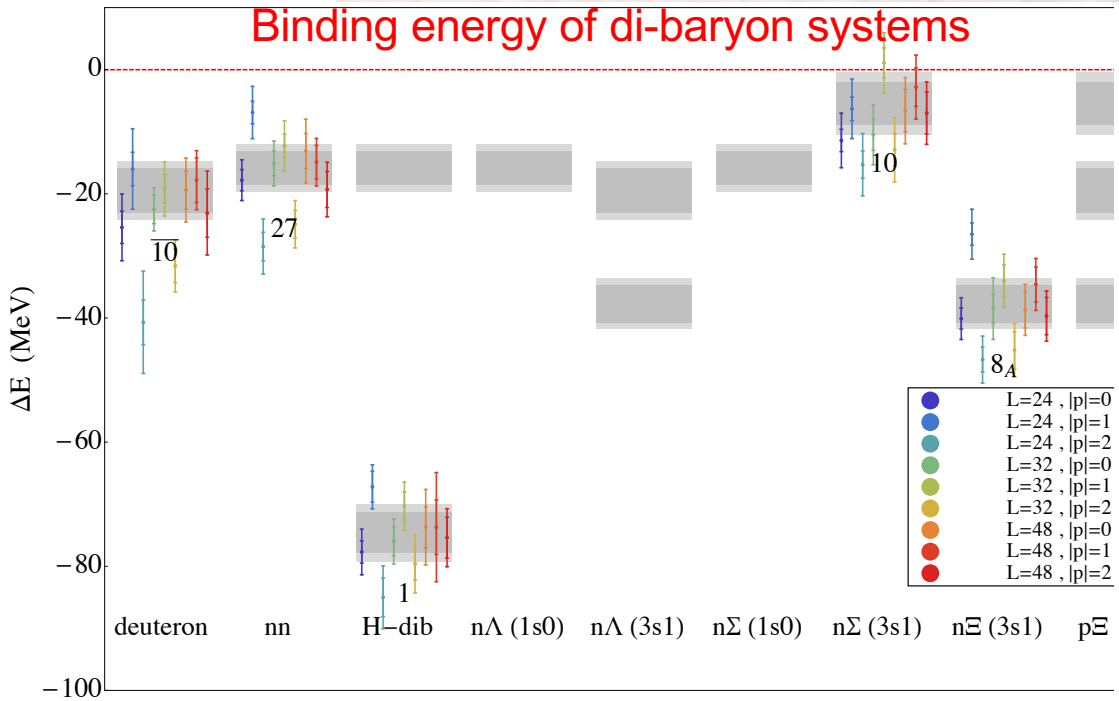
New Proposal

- In 2017, G. Farrar proposed a |*uuddss*⟩ 6-quark state *S* that is different from the loosely bound H-dibaryon state at 2150 MeV predicted by Jaffe
  - Charge: 0 , baryon number: 2, strangeness: -2, scalar, $\Upsilon \rightarrow \text{gluons} \rightarrow S\bar{\Lambda}\bar{\Lambda}$
  - Very compact state: *r*~0.1-0.4 fm ➔ recent Lattice QCD calculations indicate tightly bound $\Lambda\Lambda$ state arXiv:1708.08951 [hep-ph]
  - Mass: $m_S < 2.0545$ GeV$=m_\Lambda+m_p+m_e$ ➔ if $m_S < 1.878$ GeV, *S* is absolutely stable
  - flavor singlet ➔ allowed by QCD with small couplings to mesons

- *S*-nucleon interactions are suppressed due to tiny wavefunction overlap
➔ neutron stars do not decay to *S*

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

- *S* is not excluded by present experiments



Beanne et al, PRD 87, 034506 (2013)

Dark Matter Candidate

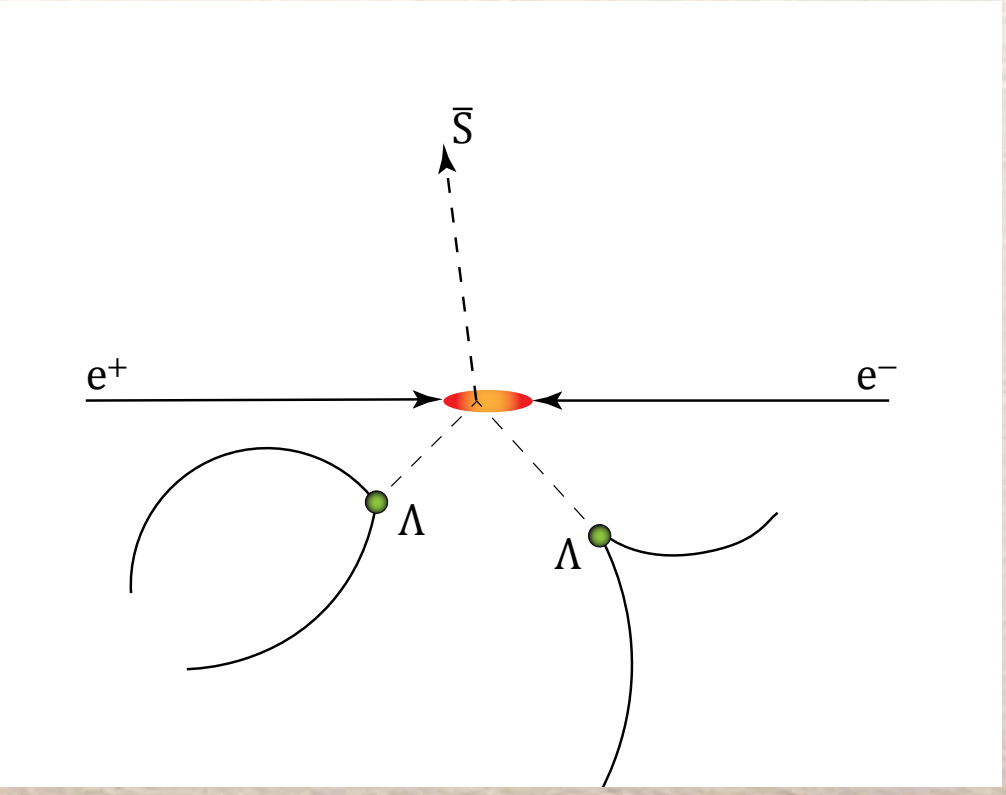
- The six-quark *S* state could be the astronomical dark matter
- If dark matter (DM) consists of a nearly equal number of *u*, *d*, *s* quarks, the formation rate is driven by a quark-gluon plasma transition to the hadronic phase ➔ DM models in this category include hexaquarks
- Hexaquark DM with a mass ~1860-1880 MeV can reproduce the ratio of DM to ordinary matter densities Ω_{DM}/Ω_b within 15%
- In this scenario, the total baryon asymmetry in universe would be at a level close to the observed value after including the dark-matter contribution
- Note, that a low-mass hexaquark is hard to distinguish kinematically from a *n*

Search Strategy

- Look for *S or hexaquark* in the process $\Upsilon(2S,3S) \rightarrow$ gluons $\rightarrow S\bar{\Lambda}\bar{\Lambda}$ or $\bar{S}\Lambda\Lambda$
- Perform blind analysis of $\Upsilon(2S,3S)$ data sets: 90×10^6 $\Upsilon(2S)$ decays and 110×10^6 $\Upsilon(3S)$ decays
- Use $\Upsilon(4S)$ data sets of 424.2 fb^{-1} to evaluate off-peak background
- Fully reconstruct $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ in $p\pi$ decay ($\mathcal{B}$=0.64) and calculate recoil mass

$$m_{rec}^2 = \left(p_T - p_{\bar{\Lambda}} - p_{\bar{\Lambda}}\right)^2$$

- Distance of closest approach for Λ is > 5 cm

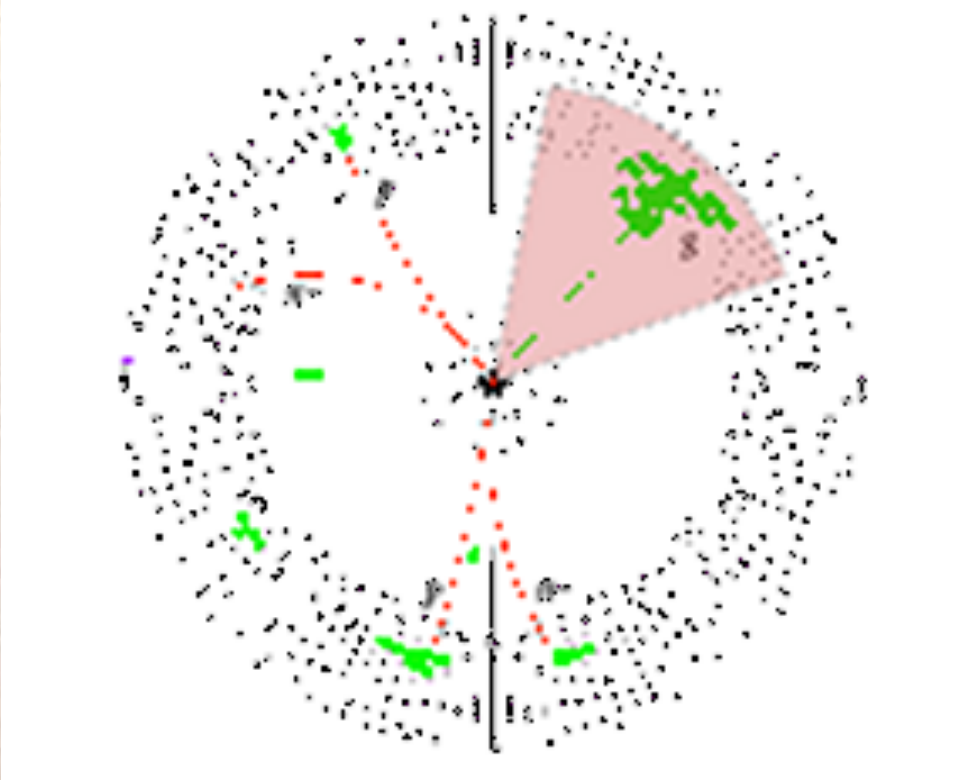


Search Strategy

- Event selection
  - Require 4 charged tracks +1 additional track not from IR with DOCA>5 cm
  - Apply loose PID criteria to select p or $\bar{p}$
  - Reconstruct $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ with $\Lambda \to p\pi^-$
  - Require flight significance of each Λ: $|\vec{r}|/\sigma_r>5$
  - Require Λ to point back to IR $\frac{\vec{r}_\Lambda \bullet \vec{p}_\Lambda}{|\vec{r}_\Lambda||\vec{p}_\Lambda|} > 0.9$

- Signal: Examine extra neutral energy, E_{extra} in region outside signal cone, i.e. the energy of all neutral clusters in EM calorimeter and require E_{extra}<500 MeV

- Use sample of E_{extra} >500 MeV as validation sample



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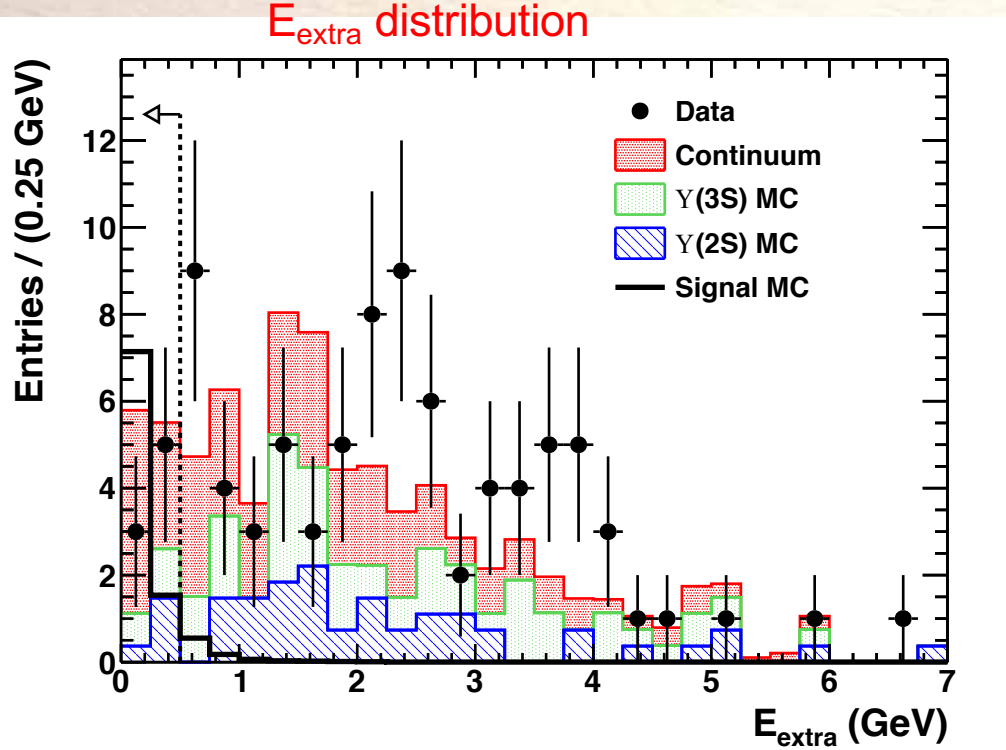
Sample after Preselection

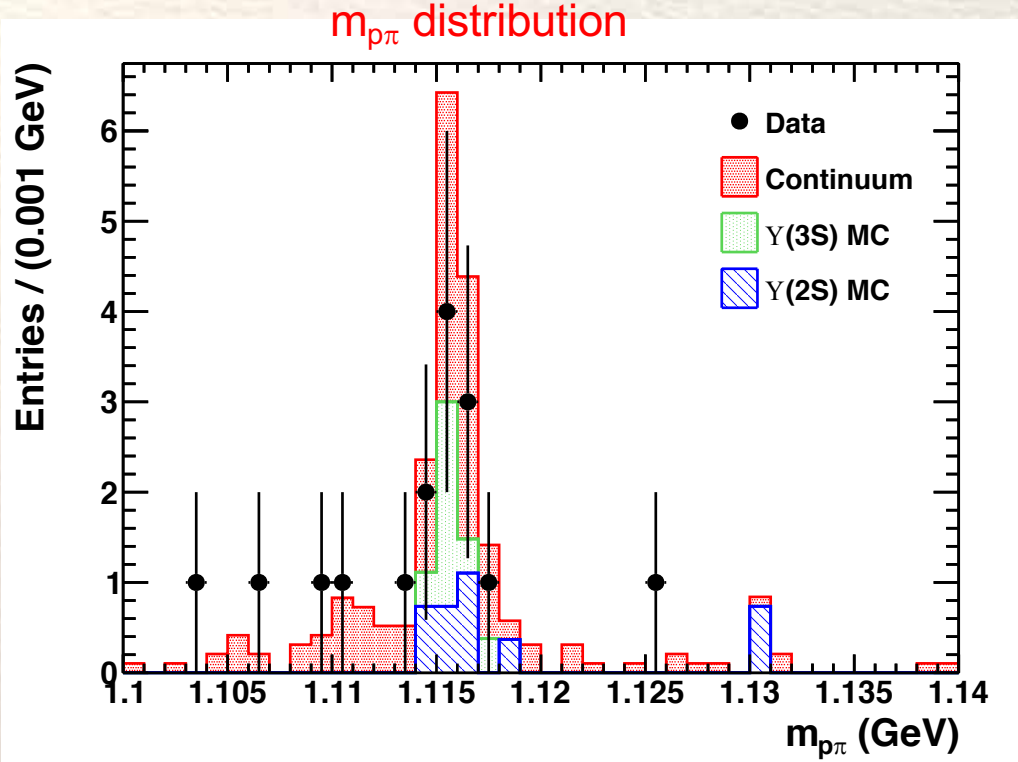
- E_{extra} distribution after preselection shows 92 events of which 8 events satisfy E_{extra} < 500 MeV

- $p\pi$ invariant mass shows true Λ signal

E_{extra} distribution



$m_{p\pi}$ distribution



- Kinematic fit of each Λ to PDG mass and common production point in beam spot leaves 4 events

Efficiency and Backgrounds

- Use dedicated signal MC
  - Generated with decay amplitude provided by Farrar
  - Generated with phase space (uniform)
  - Model S as a neutron or as neutrino (no interaction with detector material)

- Assess systematic errors from the different assumptions: σ_{tot}=12.8% -16.1%

- Efficiency including $\mathcal{B}(\Lambda \to p\pi^-)^2$ varies from 7.2% at threshold to 8.2% near 2 GeV mainly driven by the geometric acceptance

- Resolution of the recoil mass is 100 MeV

- Background originates from $q\bar{q}$ continuum or $\Upsilon(2S, 3S)$ decays
  - Use $\Upsilon(4S)$ decays for $q\bar{q}$ continuum (signal is negligible)
  - Scale $\Upsilon(2S, 3S)$ MC so that MC+ $q\bar{q}$ continuum matches E_{extra} sideband
  - Remaining background ~ $\Lambda\Lambda$ $\bar{\Lambda}\bar{\Lambda}$ (X)

$n\pi^0$
$n\pi^0$ } may pass or fail E_{extra} selection

Hexaquarks: Systematic Uncertainties

- Largest effects come from modeling production amplitude including angular distribution

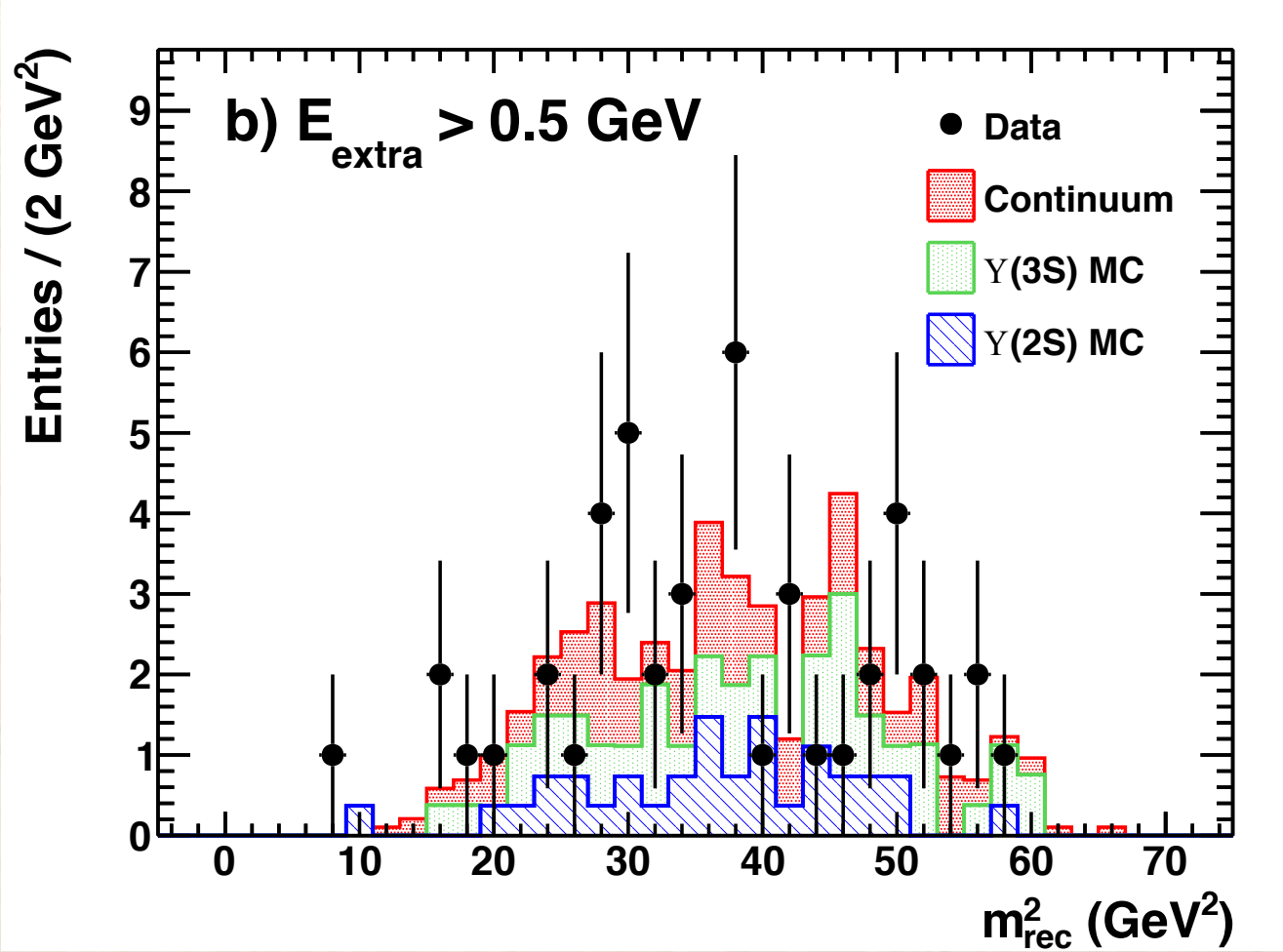
- Assumption on *S* particle type

Source	Systematic error
S angular distribution modeling	5-8%
S particle type modeling	8-11%
Λ reconstruction	4% per Λ
MC statistics	2%
Λ branching fraction	1.6%
Proton PID	1% per *p*
Number of Υ(2S, 3S)	0.6%

- Total systematic error: 12.8-16.1%

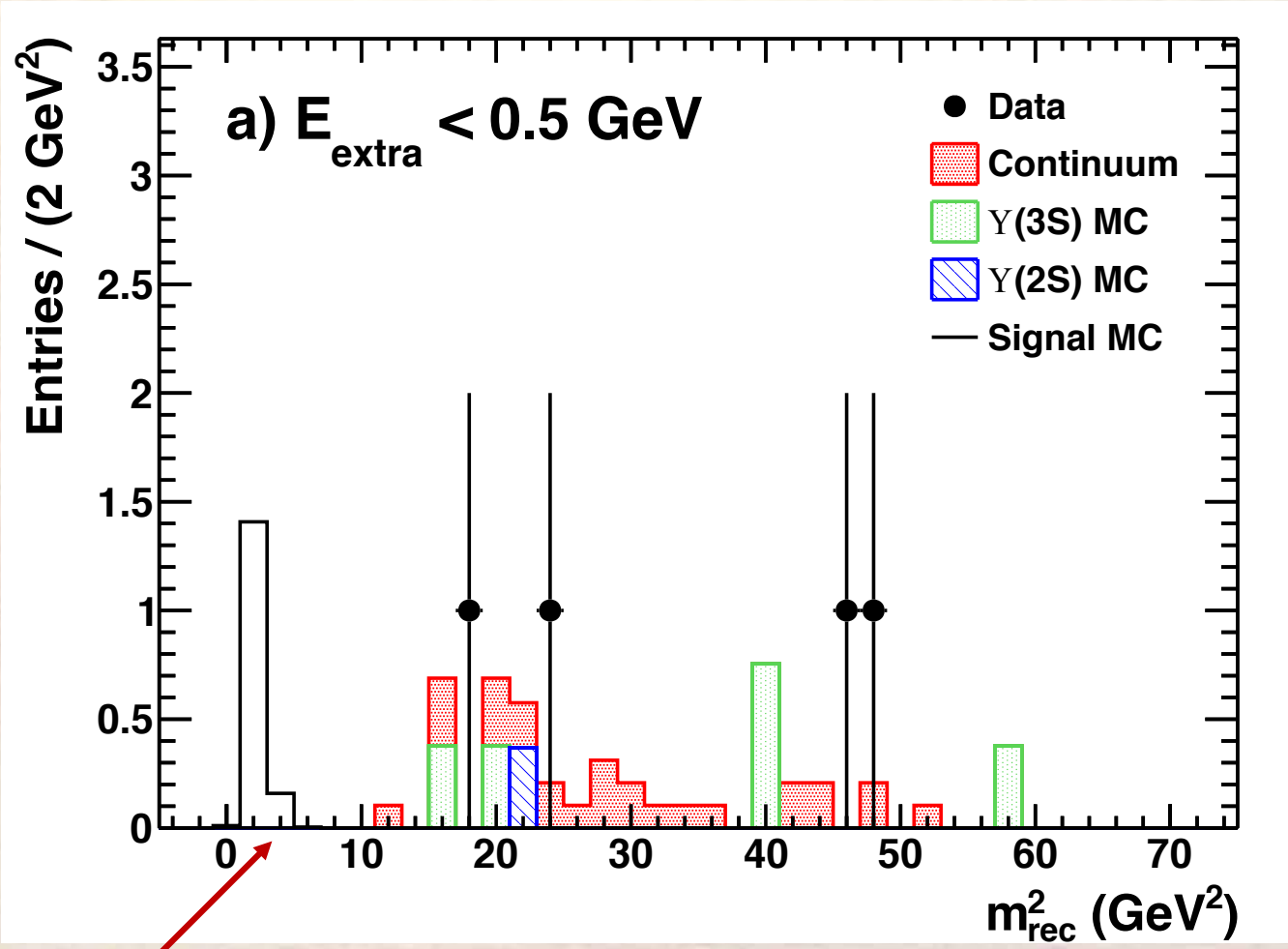
Validation: E_{extra}>0.5 GeV

- In the E_{extra} sideband we observe zero background events in the m^2_{rec} signal region



Signal Region

- Final results in the E_{extra}< 500 MeV region show no signal events for zero expected background



signal MC for S with mass of 1.6 GeV and $\mathcal{B}(\Upsilon(\mathrm{n}S)\to S\bar{\Lambda}\bar{\Lambda})=10^{-7}$

Results

- We see no evidence for hexaquarks in the decay $\Upsilon(2S,3S) \to S\bar{\Lambda}\bar{\Lambda}$
- We use the profile likelihood method to set branching fraction upper limits @ 90% confidence level in the mass range 0.0-2.05 GeV including systematic errors
- **$\mathcal{B}(\Upsilon \to S\bar{\Lambda}\bar{\Lambda})$ < (1.2-1.4)×10^{-7} @90% CL**
- We could further look for $\Upsilon \to S\bar{\Lambda}\bar{\Lambda}X$
  ➔ much harder analysis but may have branching fraction reachable with the BABAR sensitivity

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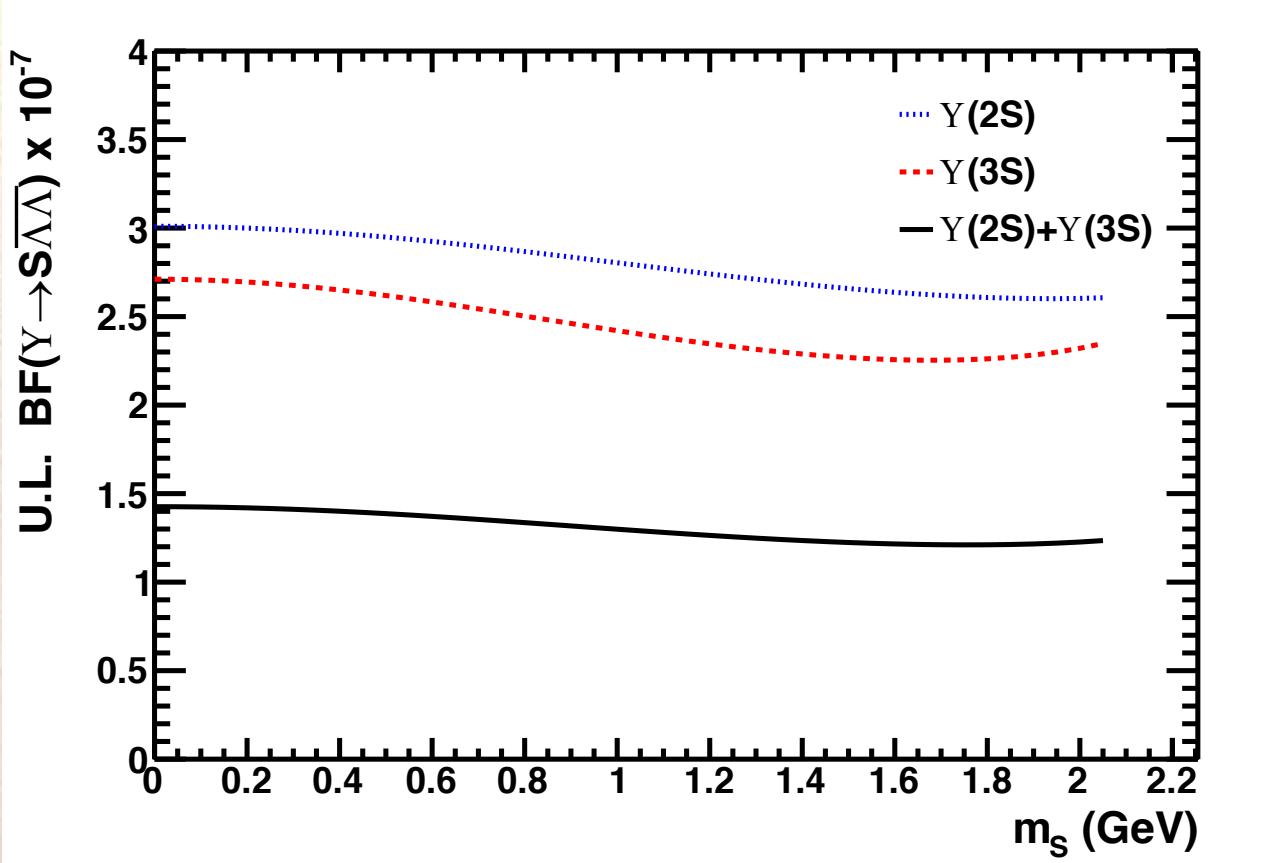

Conclusions

- A tightly bound S=|uuddss ⟩ state may be more stable than previously predicted,
  - ➔ if $m_S < m_\Lambda + m_p + m_e$ = 2.0545 GeV, it may be stable even on cosmological time scales
  - ➔ if it exists, it is a good candidate for dark matter
  - ➔ It is not excluded by searches for the H-dibaryon
- BABAR has searched for the S in $\Upsilon(2S)$ and $\Upsilon(3S)$ decays in the recoil against $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ using a data sample of 200 million events
- No evidence for a stable hexaquark state is found in Υ(nS) decays and no background remains in signal region ➔set stringent branching fraction upper limit:
  - **$\mathcal{B}(\Upsilon \to S\bar{\Lambda}\bar{\Lambda}) < (1.2\text{-}1.4)\times 10^{-7}$ @ 90% CL for m<2.05 GeV**
- Need to extend searches to more inclusive channels like $S\bar{\Lambda}\bar{\Lambda}$X since BABAR's sensitivity for the exclusive channel $S\bar{\Lambda}\bar{\Lambda}$ may not be sufficient

Hexaquarks: Distance of Closest Approach

- Expected background distribution of DOCA of tracks not associated with a Λ after application of all other selection criteria plus predicted signal distribution from MC
- The continuum background is evaluated from on-peak $\Upsilon(4S)$ data, signal MC is for $\Upsilon(2S, 3S)$
- Signal MC simulates hexaquark as n or ν
- # tracks not associated with a Λ for DOCA > 5 cm and DOCA < 5 cm