Search for a stable six-quark state in Υ decays at *BABAR*

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BABAR

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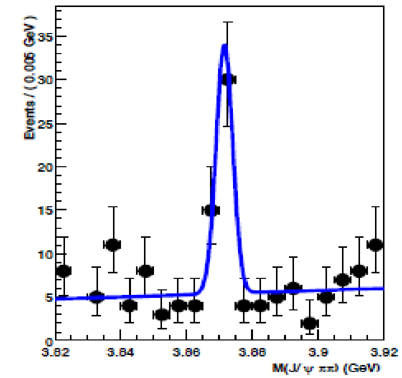
Outline

- Introduction and motivations
  - Multi-quark configurations
  - Six-quark configurations and lattice QCD expectations
  - Dark matter candidates and implications
- Analysis approach in *BABAR*
  - Pre-selections
  - Efficiencies and systematic uncertainties
- Results
  - Signal region and sidebands
  - Upper limits
- Conclusions

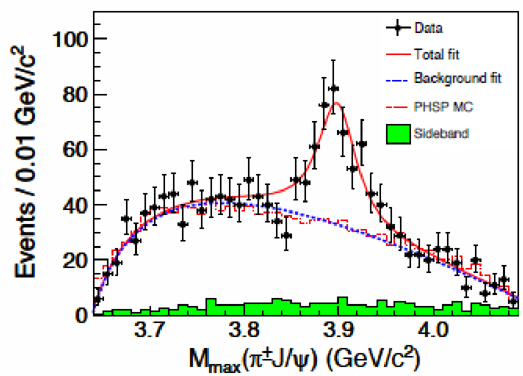
Multiquark configurations

- Multiquark states allowed by QCD
- Recent observations of many-quark systems :

Belle Coll., PRL**91**, 262001 (2003)

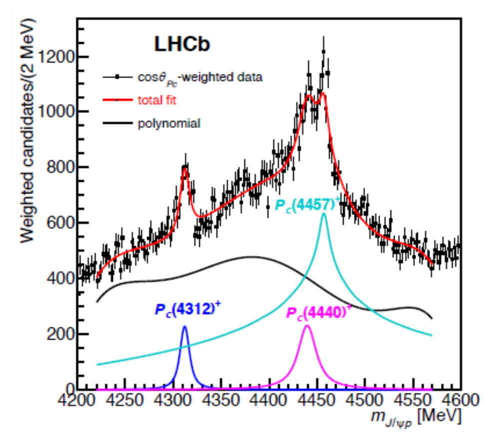


  – **Tetraquarks**
    - Belle:
      – *X(3872)*, $J^{PC} = 1^{++}$, observed in $B \rightarrow K\,\pi^+\pi^- J/\psi$
      – $Z_c(4430)^+$
    - BESIII: $Z_c(3900)^{\pm}$, observed in $\pi^{\pm} J/\psi$



BESIII Coll., PRL**110**, 252100 (2013)

  – **Pentaquarks:**
    - LHCb: $P_c(4312)$, $P_c(4440)$, $P_c(4457)$, observed in $J/\psi\ p$

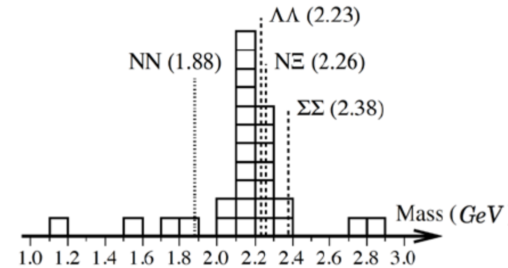


LHCb Coll., PRL**122**, 072002 (2019)

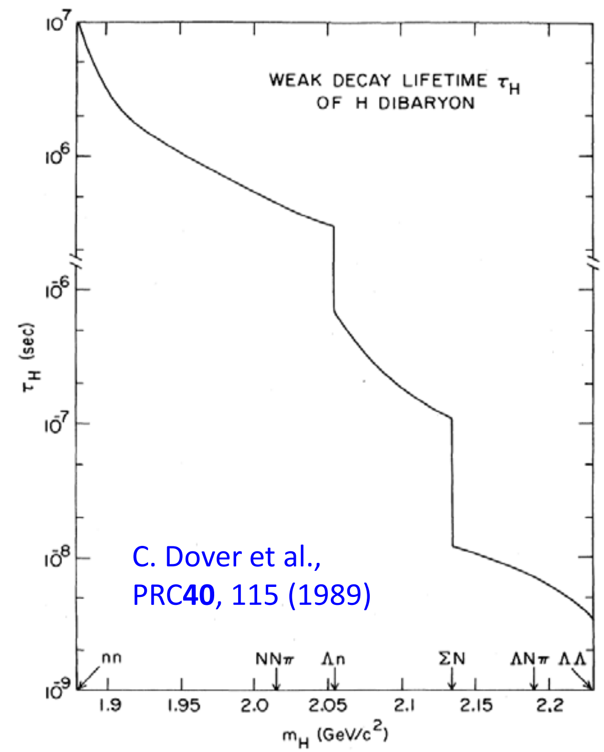
  – **What about 6-quark states?**

Six-quark states

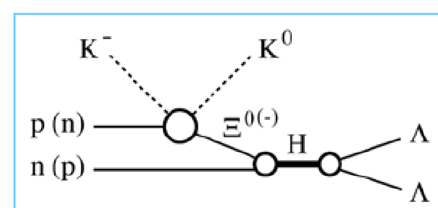
- First proposed by R. Jaffe in 1977: **H dibaryon**
  - Flavor singlet state $|udsuds>$
  - **Loosely bound $\Lambda\Lambda$ state**
  - Bag model prediction: $m_H \sim 2150$ MeV
  - Decay modes: if $m_H < 2m_\Lambda$ (2230 MeV)
    - Strong decay forbidden
    - Weak decay allowed, lifetime ~10^{-10} s
    - Wide expected range depending on the binding energy:
      - $B.E. \sim 180$ MeV: days/months
      - $B.E. > 350$ MeV: stable object
  - Many searches over the years in several channels, all unsuccessful
    - Main channel: one-nucleon absorption of kaons on deuterons + Ξ absorption
    - Double Λ hypernuclei observations set limits to mass/$B.E.$ ($_{\Lambda\Lambda}^{6}He$)



R. Jaffe et al., PRL**38**, 195 (1977)
S. Bashinsky et al., NPA**625**, 167 (1997)



C. Dover et al., PRC**40**, 115 (1989)



A light H dibaryon: the S six-quark state

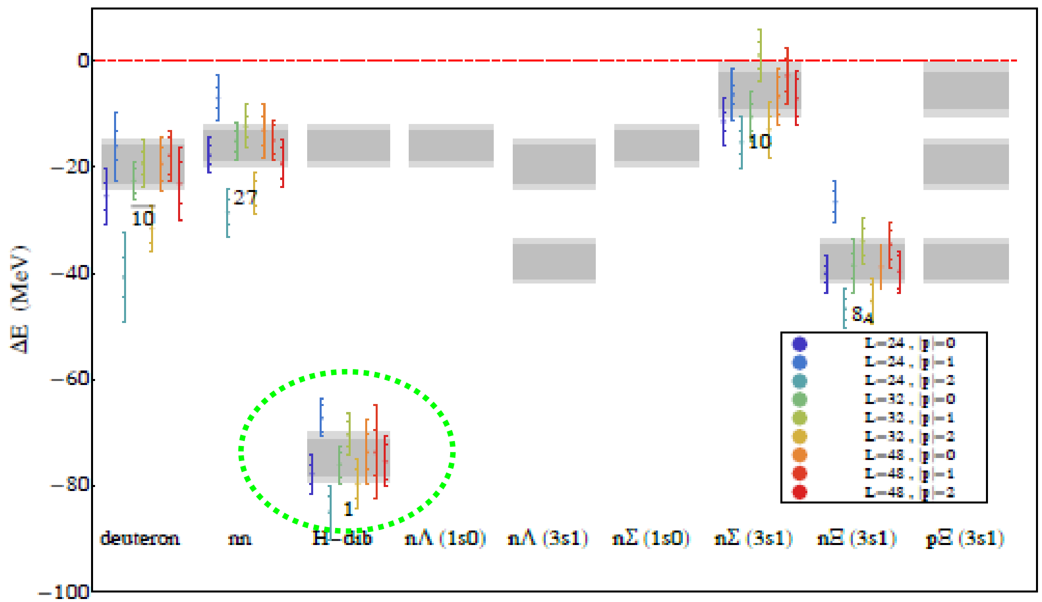
- Proposed by G. Farrar in 2017 as possible Dark Matter candidate (arXiv: 1708.08951)

- **Tightly bound** six-quark combination, doubly strange
  - $S \sim |uuddss>$, $Q = 0$, $B = 2$, $S = -2$
  - Completely symmetric spatial wave function
  - Flavor singlet: very small coupling to $\gamma, \pi, \rho, \ldots$
  - **Very compact object: $r \sim$ 0.1-0.4 fm (< $r_N/4$)**
  - **Large binding energy, smaller mass: m_S < 2.05 GeV**
    - new stable hadron, $\Lambda\Lambda$ bound state
    - If $m_S < m_\Lambda + m_p + m_e$ = 2.05 GeV: only doubly-weak decays allowed, cosmologically stable
    - Lower bound on mass can be fixed by non-observation of $nn \rightarrow S\pi^0$ in nuclei:
      - $m_S \geq 2m_n - m_\pi \sim$ 1.7 GeV

- SN interaction suppressed by tiny wavefunction overlap ($\sigma \sim 10^{-30}$ cm^2)
  - It does not bind to nuclei (no exotic isotopes)

- Not excluded so far by experiments

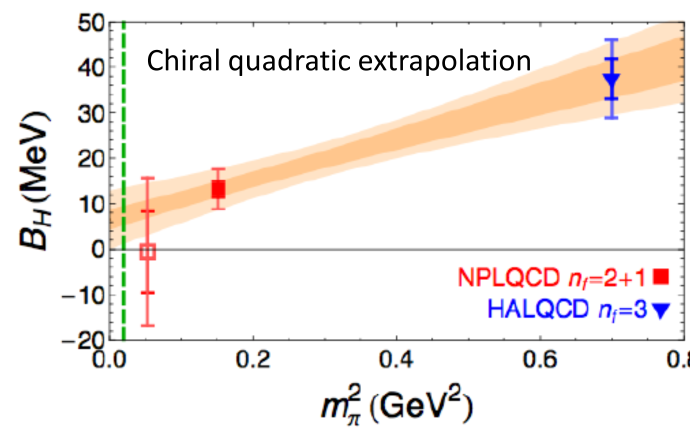
Dibaryons on the lattice



NPLQCD Coll.,
S. Beane et al., PRD**87**, 034506 (2013)

- LQCD calculations in the limit of SU(3) flavor symmetry, with $m_\pi = m_K \approx 800$ MeV
  - Pion mass still (too) unphysical
  - Quarks are non-relativistic at this mass scale (not realistic)
  - Several bound baryon-baryon systems foreseen
  - Most tightly bound: singlet state
    - H: *B.E.* ~ 90 MeV
  - Lower binding energies expected in earlier calculations, with lower m_π mass

HALQCD, Prog. Theor. Phys. **124**, 591 (2010)
NPLQCD, PRL**106**, 162001 (2011)

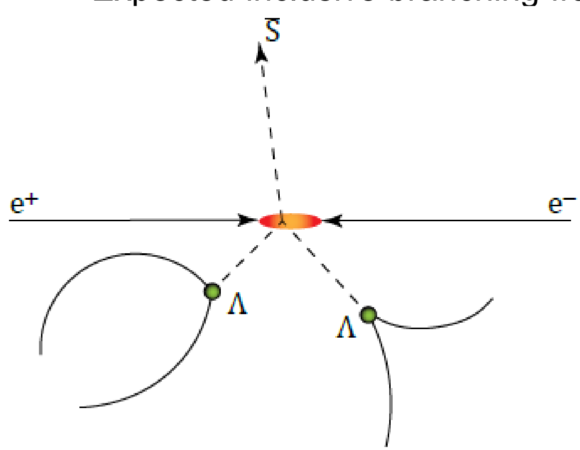


Hexa-quarks as Dark Matter candidates

- Hypothesis (G. Farrar, arXiv:1805.03723): DM formed by an equal amount of *u, d, s* quarks
  - Formation rate driven by QGP transition to the hadronic phase
  - DM models include hexa-quarks/quark nuggets/many-quark aggregates
    - negligible coupling to photons
- Hexa-quarks with mass 1860-1880 MeV can reproduce the ratio of densities within 15%: $\Omega_{DM}/\Omega_{B} \sim 5$
  - The total baryon asymmetry in the Universe, including Dark Matter, would be close to the observed value: asymmetric DM models
- Not excluded by current direct searches yet
- Ongoing discussion about the validity of this hypothesis (Kolb & Turner, PRD99, 063519 (2019))
  - Hexa-quarks better candidates as relics, rather than DM constituents

Search for S

- Viable search channels:
  - Fixed target experiments with intense beams (small rates expected)
    - $K^- p \rightarrow \bar{\Lambda} S$
  - S production in hadronic collisions: $\bar{S}$ annihilation along the beampipe/detector, detection of decay products $B = -1$, $S = +2$
    - $\bar{S} N \rightarrow \Xi^{+,0} X$, $\bar{S} N \rightarrow \bar{\Lambda} K^{+,0} X$
    - $\bar{S} n \rightarrow \bar{\Lambda} K^0_S$, $\bar{S} p \rightarrow \bar{\Lambda} K^+$
  - Υ decays below open-bottom threshold:
    - $\Upsilon(2S, 3S) \rightarrow$ **gluons** $\rightarrow S \bar{\Lambda}\bar{\Lambda}$ **+ pions /** γ **(+ c.c.)**
      - High Λ reconstruction efficiency ($c\tau \sim 8$ cm)
    - Other discovery avenues: $\Xi^- p$, or Λ replaced by $K^- p$
    - Short distance nature of the gluonic force
    - Expected inclusive branching fractions (based on statistical models): **O(10^{-7})**



Missing-mass analysis for exclusive decays: S recoils against a $\bar{\Lambda}\bar{\Lambda}$ $(\Lambda\,\Lambda)$ system in the Υ center of mass

$$m_{rec}^2 = (p_{\Upsilon} - p_{\bar{\Lambda}} - p_{\bar{\Lambda}})^2$$

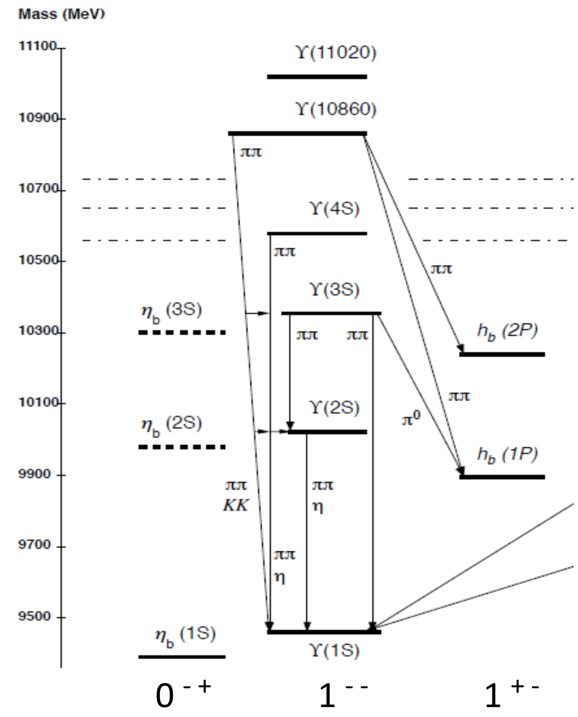
Low-lying Υ states (below open b)

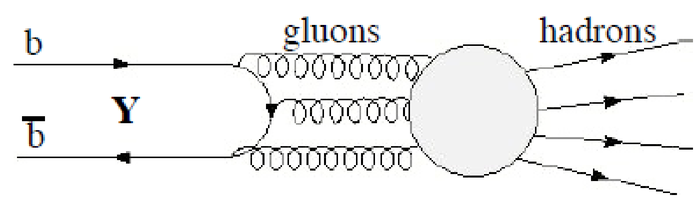
- Nearly non-relativistic
- Low lying bottomonia are the mesons with the highest energy density
  - R = 0.25 – 0.5 fm
  - $E/(4\pi R^3/3)$ = 20 – 200 GeV/fm^3
- $J^{PC} = 1^{--}$

- Υ(1S,2S,3S) annihilate to light hadrons *(u, d, s, c)* via:
  - *3 gluons*
  - *2 gluons +* γ
    - Channels with access to gluon fragmentation
  - γ*

- Strong decay suppressed (OZI rule)

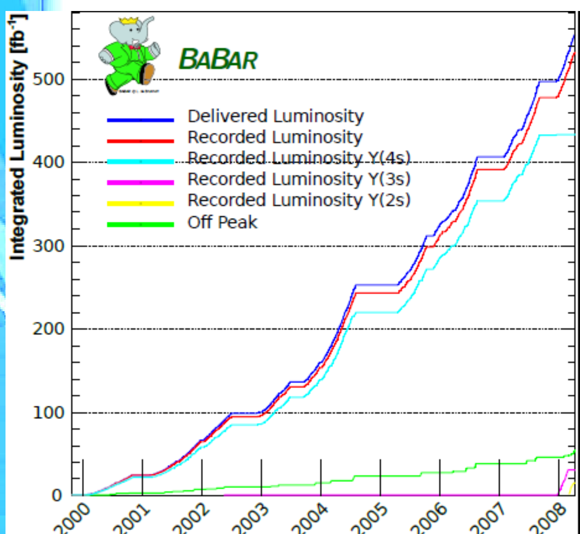
- Main background from QED processes: $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$ + radiative corrections

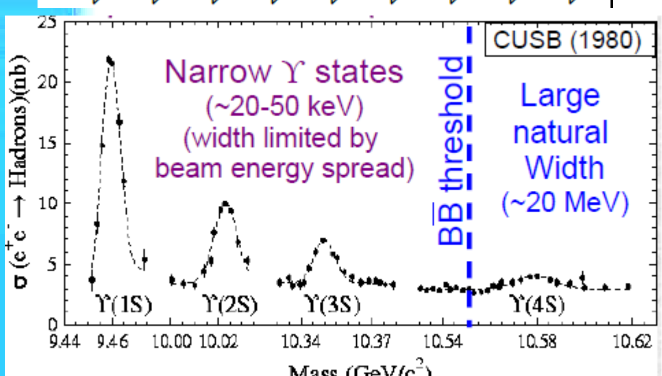


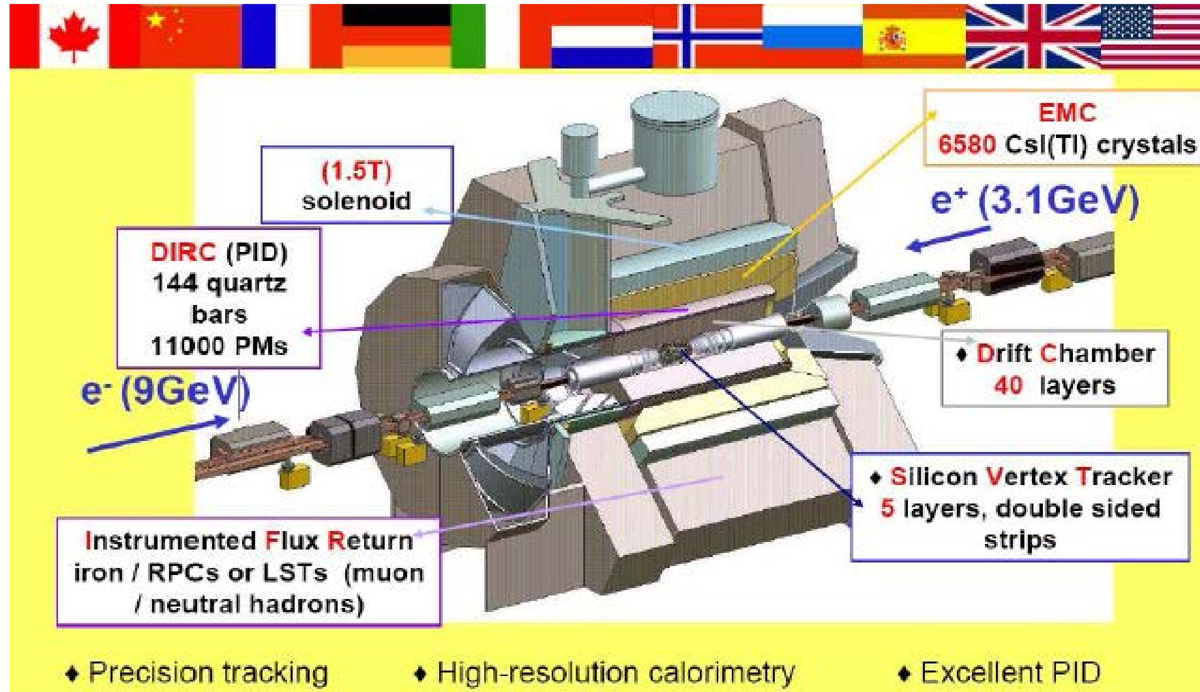


- Annihilation to gluons happens at a scale $R \sim 1/m_b \sim$ 0.04 fm
- Initial gluon density: 40 TeV/fm^3

The *BABAR* experiment at PEP-II, SLAC







NIM **A479**, 1 (2002); NIM **A729**, 615 (2013)

PEP-II and *BABAR* operated from Oct 1999 to Apr 2008

~ 460 fb^{-1} integrated luminosity

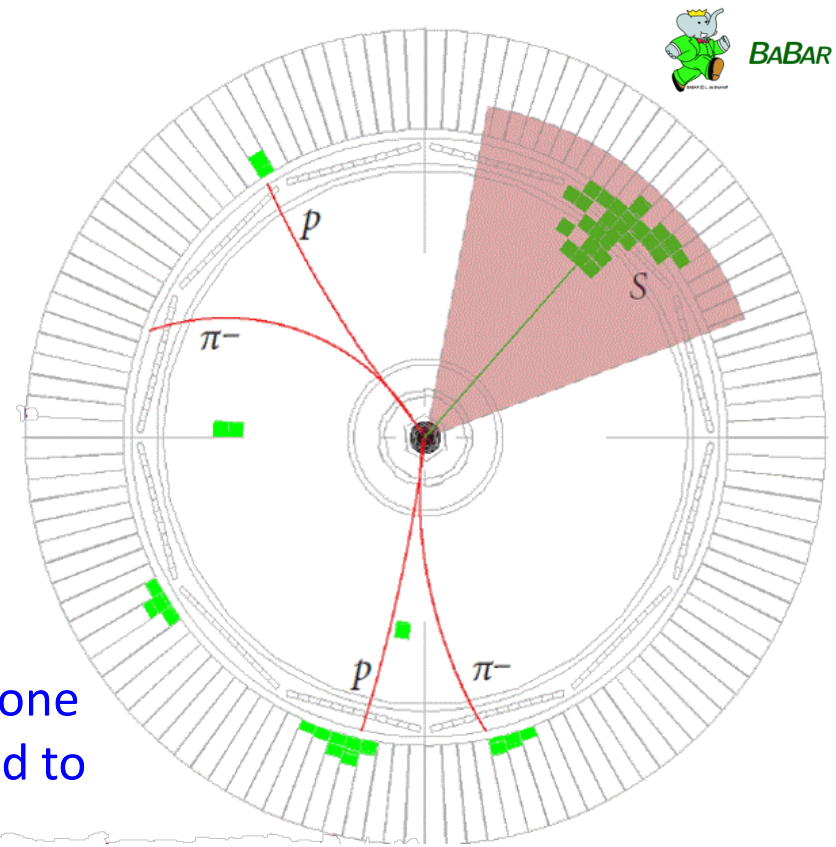
- ~470 ×10^6 Υ(4S)
- ~120 ×10^6 Υ(3S) (10x BELLE)
- ~100 ×10^6 Υ(2S) (10x CLEO)
- ~18 ×10^6 Υ(1S) from Υ(2S) → $\pi^+\pi^-$ Υ(1S)

For this analysis: 90M Υ(2S) + 110M Υ(3S)

Search for $\Upsilon(2S, 3S) \to S\bar{\Lambda}\bar{\Lambda}$ (+ c.c.) in BABAR

- Full reconstruction of 2x$\bar{\Lambda}$ (2Λ) decays: $\bar{\Lambda} \to \bar{p}\pi^+$
- Target: zero background in the signal region

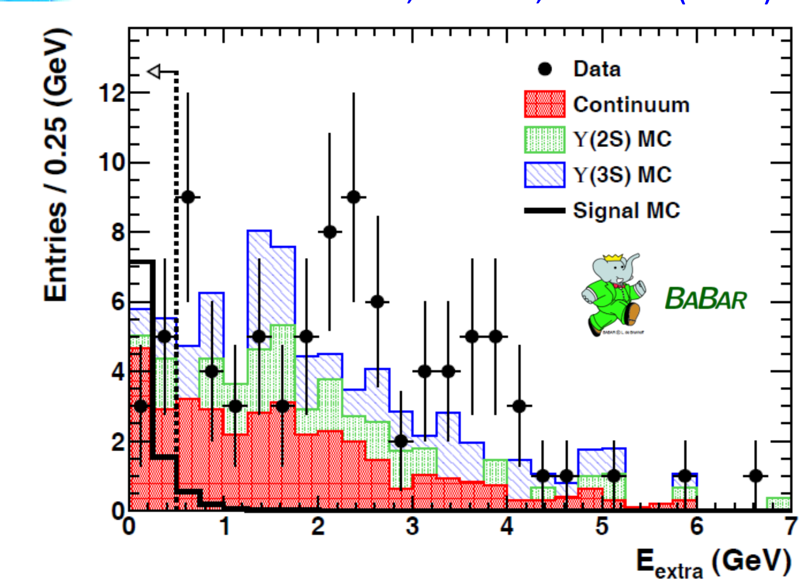
- Selection criteria:
  - Four charged tracks + at most one additional track not from IP
  - Loose PID criteria to select $\bar{p}$
  - Selection of events with 2Λ or 2$\bar{\Lambda}$
    - flight significance for each Λ:
      $$|\vec{r}_\Lambda| / \sigma_r > 5$$
    - Λ pointing back to IP:
      $$\cos(\vec{r}_\Lambda, \vec{p}_\Lambda) > 0.9$$
  - Minimal contribution from out of cone events + hits on ECAL not connected to tracks: E_{extra} < 0.5 GeV
  - Blind analysis (MC tuning)



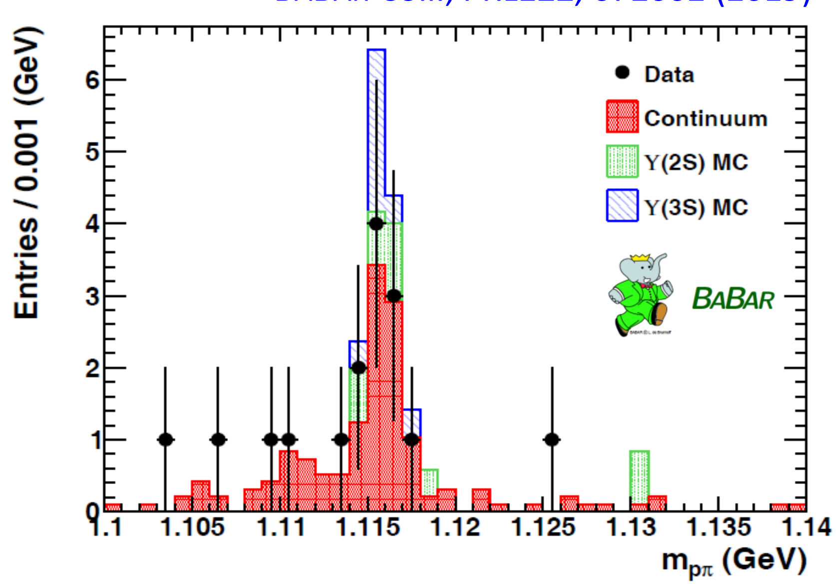
Event preselection

- 2xΛ candidates, 5 tracks/event at most: 92 events
- E_{extra} distribution of ECAL hits
  - Signal: E_{extra} < 500 MeV: 8 events (2 entries/event)
    - True signal in $(p\pi)$ invariant mass
- Backgrounds: dominated by hadronic events with several strange baryons (typically 2Λ) and additional charged and neutral particles escaping detection

BABAR Coll., PRL**122**, 072002 (2019)



BABAR Coll., PRL**122**, 072002 (2019)



- Last step: kinematic fit imposing mass constraint to each Λ candidate, requiring common origin from beamspot (χ^2<25): 4 events

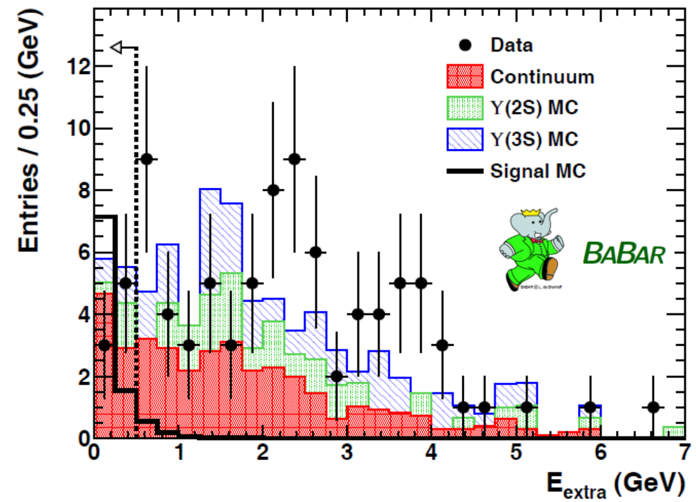
Background studies

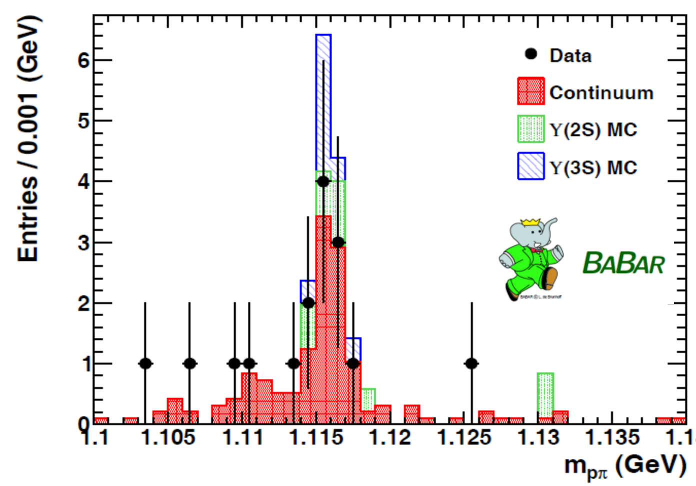
- MC generation of $\Upsilon(2S, 3S)$ decays with EVTGEN generator

- Continuum $e^+e^- \rightarrow q\bar{q}$ from $\Upsilon(4S)$ data ($q = u, d, s, c$)

- Background sample normalization chosen to match the sideband $E_{extra} > 500$ MeV distribution

- Remaining background (may filter through the E_{extra} selection):
  - $e^+e^- \rightarrow \Lambda\Lambda\bar{\Lambda}\bar{\Lambda}\,(X)$ with the two Λ's decaying in the neutral channel $\Lambda \rightarrow n\pi^0$





Efficiencies evaluation

- Necessary for the determination of branching fractions

- The efficiencies have been obtained by simulations of the signal MC based on:
  - different models for decay amplitudes
    1. G. Farrar: effective Lagrangian with constant matrix elements combined in different arrangements according to the relative angular momentum
    2. phase-space flat decays
  - Different interaction patterns of *S* with the detector materials
    1. As a neutron
    2. Non interacting (as a neutrino)

- Differences used as systematic uncertainties

- The efficiency is mainly determined by the geometrical acceptance
  - 7.2% at threshold, 8.2% @ 2 GeV

- *Mass resolution* (on recoiling mass) in *BABAR*: ~ 100 MeV

Systematic uncertainties

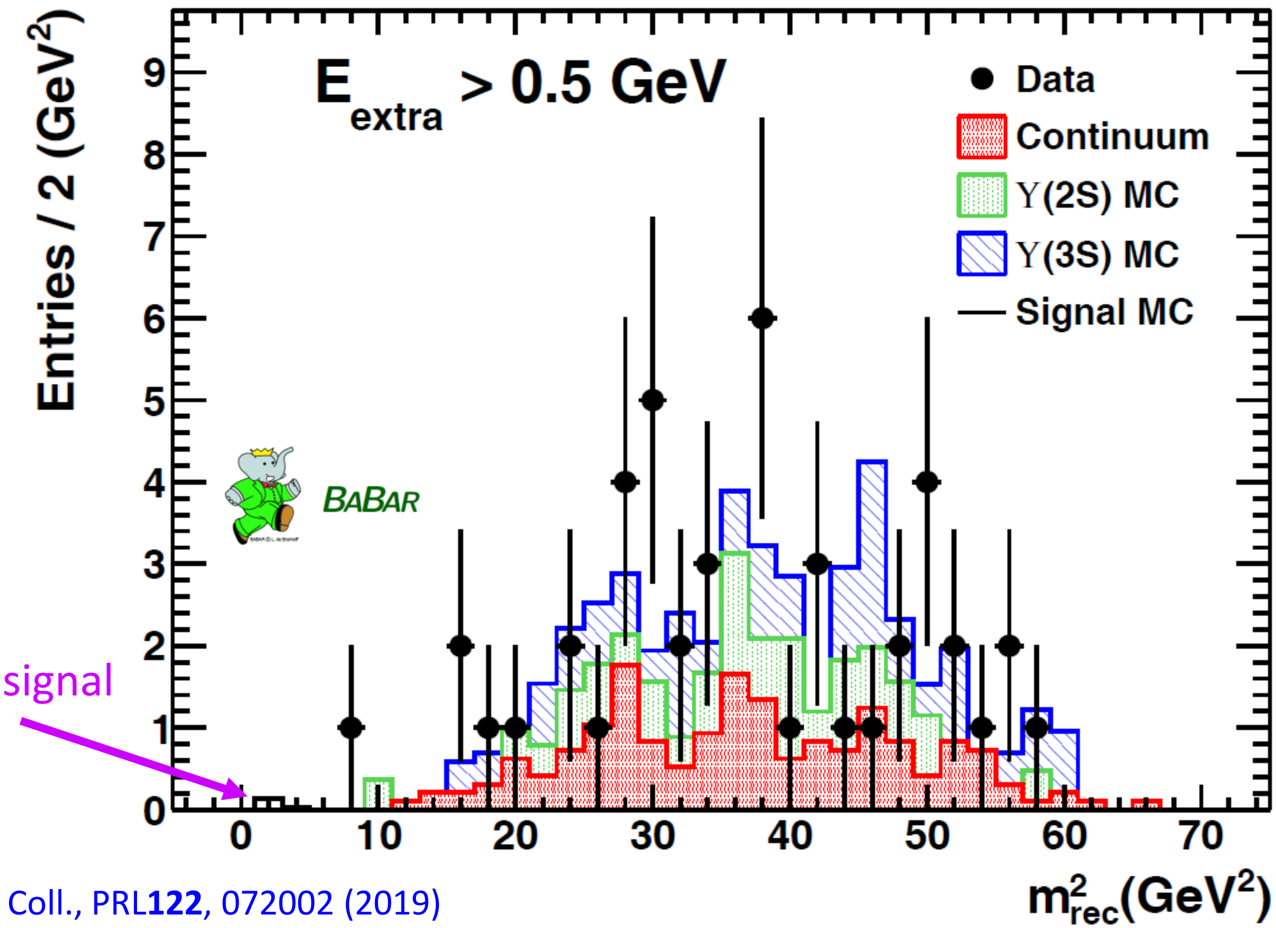
- Main sources:
  - MC signal modelling
    - Production amplitude ⇒ different angular distributions
    - *S* interactions in the detector (neutron? neutrino?)
  - Data/MC differences in the reconstruction, PID

Source	Systematic error
S angular distribution modelling	(4-15)%
S interactions modelling	(8-10)%
Λ reconstruction	4%/Λ
proton/antiproton PID	1%/p
MC sample size	1.5%
Λ branching fraction	1.6%
Υ(2*S*, 3*S*) counts	0.6%

Total systematic uncertainty: (12.8-16.1)%

Validation on sideband: E_{extra} > 0.5 GeV

- Study of m^2_{rec} distribution for events in the sideband (combined $\Upsilon(2S)$ and $\Upsilon(3S)$ datasets)
  - Zero background event in the **expected signal region (0 - 5 GeV²)**
    - Signal region expected to be background free



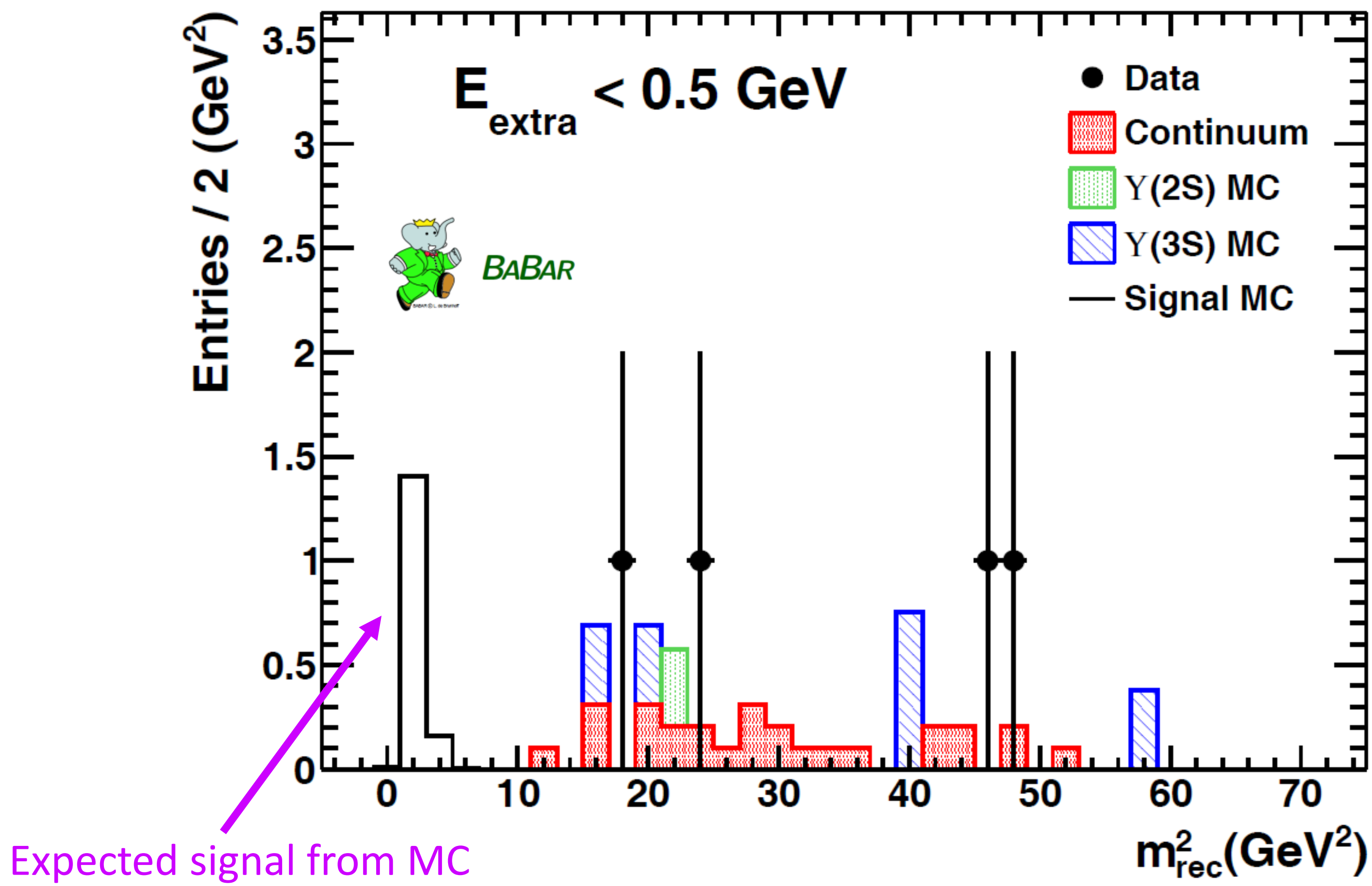
Expected signal from MC

BABAR Coll., PRL**122**, 072002 (2019)

Signal region: E_{extra} < 500 MeV

- No event observed in the expected signal region
- MC signal simulated in the hypotheses:
  - m_S = 1.6 GeV
  - $B(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda})$ = 10^{-7}

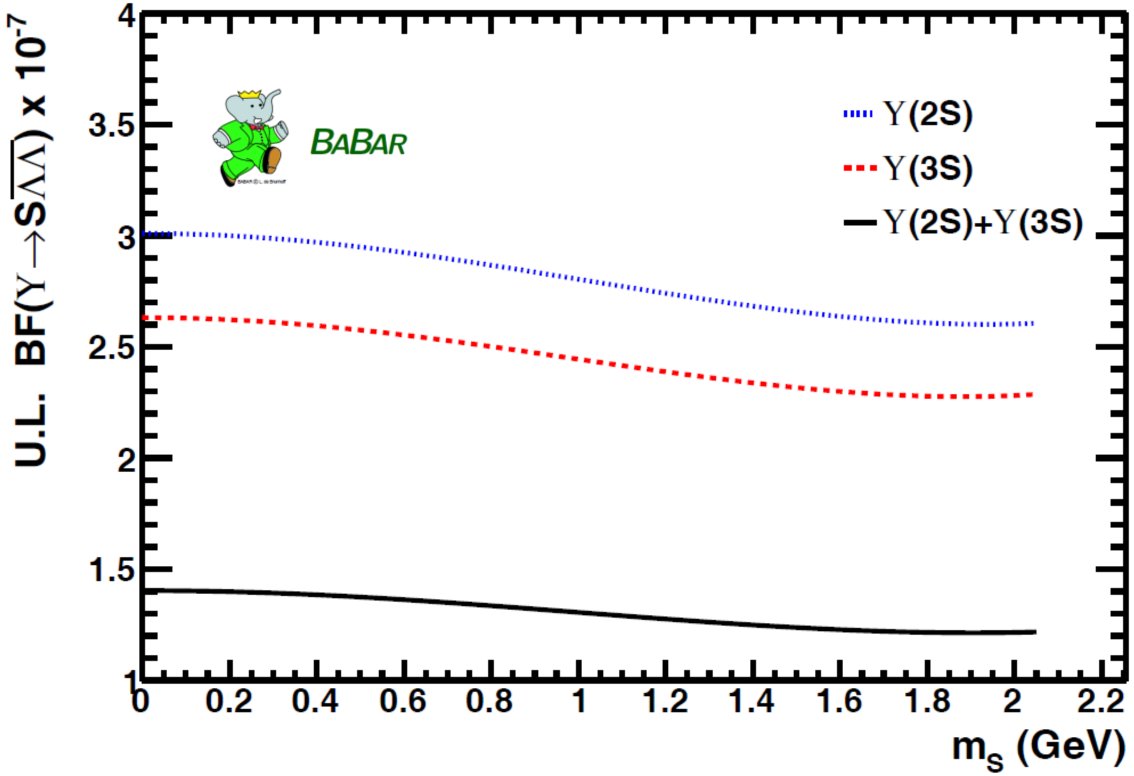
BABAR Coll., PRL**122**, 072002 (2019)



Upper limits: $B(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda})$

- Scan on *S* masses in the (0 - 2.05) GeV range in 50 MeV steps
- No signal event observed
- Set upper limit at 90% C.L. using profile likelihood method (single event sensitivity: one event, zero bck) including systematic uncertainties

BABAR Coll., PRL**122**, 072002 (2019)



$B(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda}) < (1.2 - 1.4)\times10^{-7}$ @ 90% C.L.

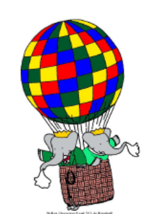
Conclusions

- Some interest recently revived in the search for stable six-quark states as possible baryonic Dark Matter candidates

- 200 millions Υ *(2S,3S)* decay events analysed by *BABAR* to search for signatures of S = |*uuddss* > six-quark state recoiling against $\bar{\Lambda}\bar{\Lambda}$ *($\Lambda\Lambda$)* pairs
- No signal found, no background
- Stringent limit set, at 90% C.L.:
  - **B (Υ(2S, 3S) $\rightarrow S\bar{\Lambda}\bar{\Lambda}$) < (1.2 – 1.4)×10^{-7}** — *BABAR* Coll., PRL**122**, 072002 (2019)

- This limits add up to a former measurement by Belle for S production in Υ*(1S,2S)* decays, with S recoiling against $\Lambda p \pi^-$ or $\Lambda\Lambda$: (0.8 – 33) $\times 10^{-7}$
  Belle Coll., PRL**110**, 222002 (2013)

- The exclusive branching fraction could be too small than *BABAR*'s sensitivity
  - Need to look for semi-inclusive decays: Υ *(nS)* $\rightarrow S\bar{\Lambda}\bar{\Lambda}X$
  - Analysis ongoing, but probably the available *BABAR* statistics won't be enough

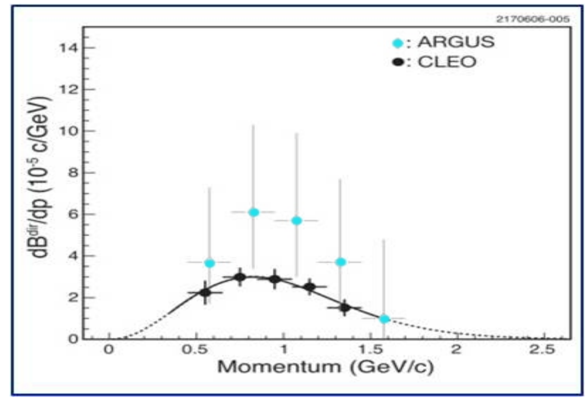


Backup slides

(Anti-)deuteron formation models: fireball and coalescence

- **Fireball spectrum** for C.M. $d\ (\bar{d})$ energy: thermal production

$$P(E) = \alpha v^2(E)\exp(-\beta E) =$$
$$= \alpha \frac{E^2 - m_d^2}{E^2}\exp(-\beta E)$$



maxwellian temperature β = 160 MeV (CLEO)

PLB98 (1981) 153 - PR131 (1986), 223

- **Coalescence**: production of the bound state expected when $(pn)(\bar{p}\bar{n})$ are emitted nearby in phase-space
  - The relative p^* momentum is ~ deuteron binding energy (or smaller)
  - The $d\ (\bar{d})$ production is related to the **square** of the nucleon σ_{prod}
  - Coalescence volume $4\pi p_0^3/3$: related to the spatial size of $\bar{d}$ wave function and the size of the fragmentation region (CLEO: 130 MeV/c)
  - No correlation between the momenta of nucleons produced in the same fragmentation

Inclusive antideuteron production in Υ decays at *BABAR*

Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ $[\sqrt{s} \approx 10.58$ GeV$]$	$(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb
$\frac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \text{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$

BABAR Coll., PRD**89**, 111102(R) (2014)

- Agreement with CLEO Υ(1,2S) results: fits of the $\bar{d}$ yields to a fireball spectrum
- Results: integral of the fireball spectrum
- Production of $\bar{d}$ measured from $q\bar{q}$ continuum @10.58 GeV and Υ(1,2,3S) decays
  - First measurements from continuum and Υ(3S)
  - Most precise measurement from Υ(2S)
- Orders of magnitude smaller than ordinary branching fractions
- Decreasing *BF* with c.m. energy
- Suppressed production in $q\bar{q}$ vs gluons
  - Slightly harder spectrum from continuum