Recent results from Υ decays at BABAR

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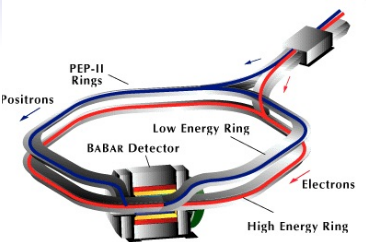
13th International Workshop on Heavy Quarkonium

Searches for

- gluonium in radiative $\Upsilon(1S)$ decays
- stable six-quark states in $\Upsilon(2S)$ and $\Upsilon(3S)$ decays

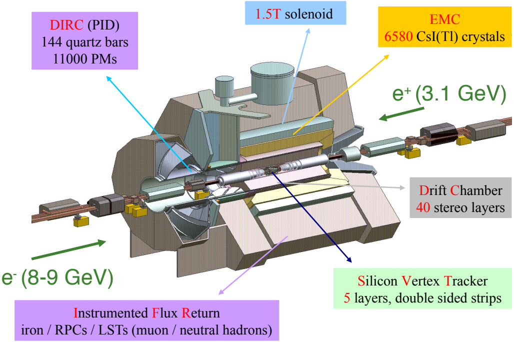
The *BABAR* experiment



PEP-II asymmetric e^+e^- collider operating at center of mass energies near the $\Upsilon(4S)$ (for most of the time)

$$\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$$

General-purpose detector



Asymmetric:

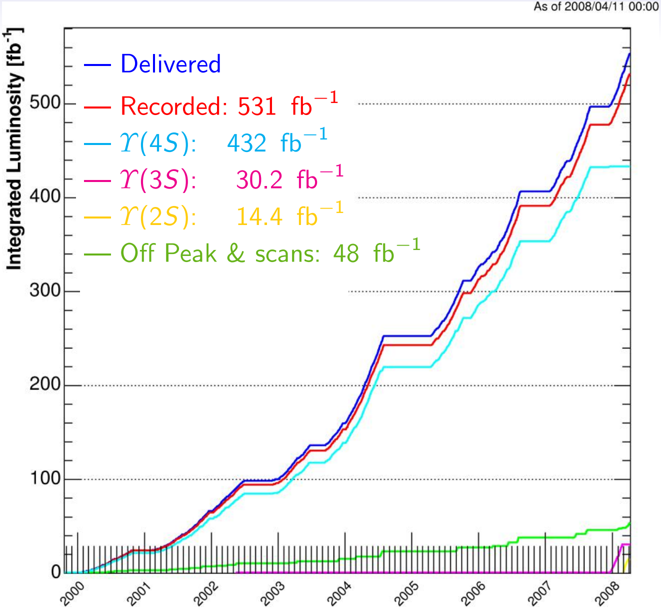
$$-0.9 < \cos\theta^* < 0.85$$

wrt electron beam

excellent performance:

- vertexing
- tracking
- PID
- calorimeter

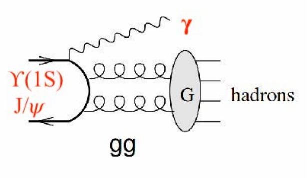
Data samples

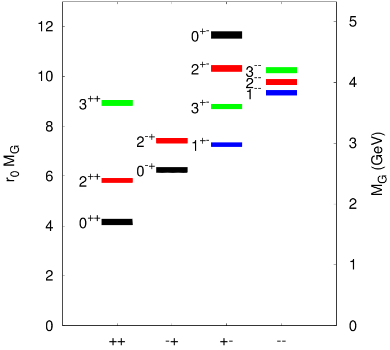


Search for gluonium in quarkonia radiative decays

$J^{PC} = 0^{++}$ glueball expected in the region $M \approx 1.5 \div 2$ GeV

Searched extensively in J/ψ radiative decays





in radiative $\Upsilon(1S)$ decays ≈25 reduction
(quark mass and width differences)

see e.g. Ochs, J. Phys. G 40, 043001 (2013)

Y. Chen et al., PRD 73 (2006) 014516

First study of $\Upsilon(1S)$ radiative decays from CLEO PRD 73, (2006) 032001

large backgrounds from $e^+e^- \to \gamma$ *Vector*

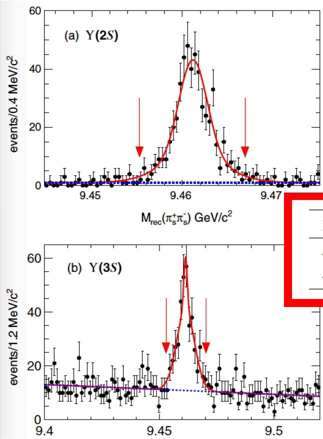
$\Upsilon(1S) \to \gamma\, h^+ h^-$ from $\Upsilon(2S), \Upsilon(3S)$

PRD 97 (2018) 112006

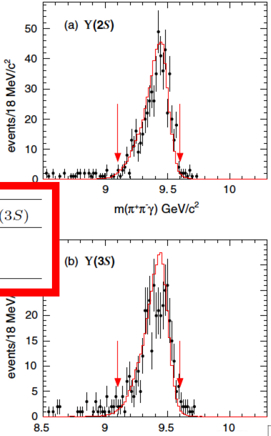
Exploit $\Upsilon(2S)$ and $\Upsilon(3S)$ tagging: fully reconstruct

$$\Upsilon(3S), \Upsilon(2S) \to \pi_s^+ \pi_s^- \, \Upsilon(1S) \to \pi_s^+ \pi_s^- \quad (\gamma\, h^+ h^-)$$

mass recoiling against slow pions



Reconstructed $\pi^+\pi^-\gamma$ for tagged $\Upsilon(1S)$



Final state	Yield $\Upsilon(2S)$	Yield $\Upsilon(3S)$
$\gamma\pi^+\pi^-$	507	277
γK^+K^-	164	63

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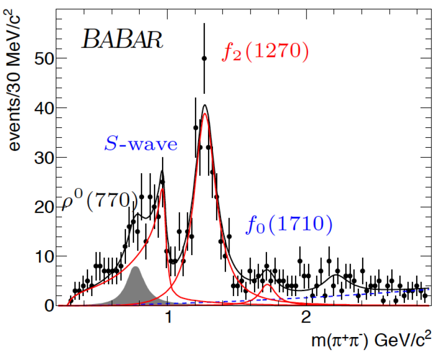
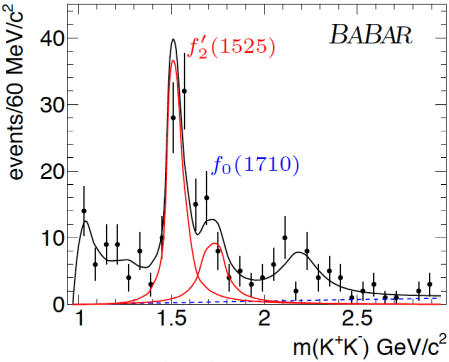
$\Upsilon(1S) \to \gamma\, h^+ h^-$: hadronic spectrum

A rich $\pi^+\pi^-$ and K^+K^- spectrum





"simple" fit with S-wave plus interfering BW (+ $\rho^0(770)$ background)

some of the resonances clearly visible!

$$S\text{-wave} = \left| BW_{f_0(500)}(m) + cBW_{f_0(980)}(m)e^{i\phi} \right|^2$$

The fraction of S-wave associated with the $f_0(500)$ is $(27.7 \pm 3.1)\%$

$\Upsilon(1S) \to \gamma h^+ h^-$: Legendre moments

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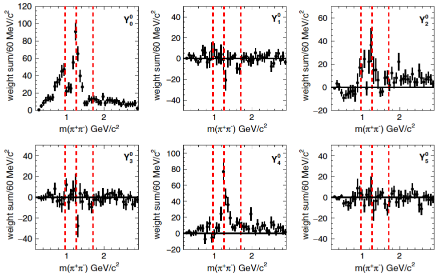
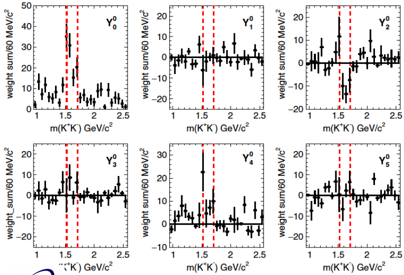
$\pi^+\pi^-$



K^+K^-



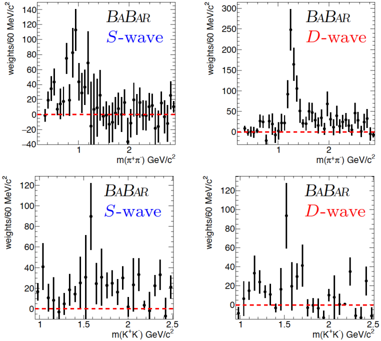
Assuming only S and D wave

$$\sqrt{4\pi}\langle Y^0_0\rangle = S^2 + D^2,$$

$$\sqrt{4\pi}\langle Y^0_2\rangle = 2SD\cos\phi_{SD} + 0.639D^2,$$

$$\sqrt{4\pi}\langle Y^0_4\rangle = 0.857D^2,$$

extract amplitudes as a function of mass (model independent!)

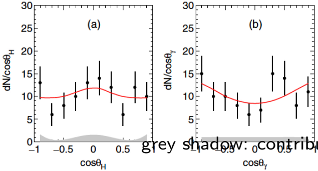


$\Upsilon(nS) \to \pi_s^+\pi_s^-\Upsilon(1S) \to \pi_s^+\pi_s^- \ \gamma h^+h^-$ angular analysis

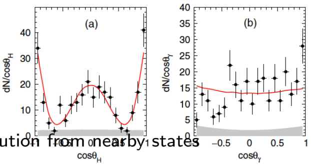
PRD 97 (2018) 112006

Full angular analysis of the decay chain in the helicity formalism (see backup) in three different mass ranges

$\pi^+\pi^-$ S-wave

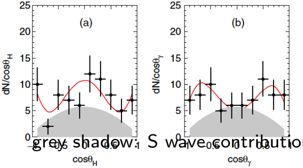


$f_2(1270) \to \pi^+\pi^-$



grey shadow: contribution from nearby states

$f_J(1500) \to K^+K^-$



grey shadow: S wave contribution

Fit results for the yields and helicities

Resonance	Mass range (GeV/c^2)	Events	Spin	$\lvert A_{00}\rvert^2/\lvert A_{01}\rvert^2$		
$\pi\pi$ S-wave	0.6–1.0	104	0	0.09 ± 0.33		
				$\lvert A_{01}\rvert^2/\lvert A_{00}\rvert^2$	$\lvert C_{11}\rvert^2/\lvert C_{10}\rvert^2$	$\lvert C_{12}\rvert^2/\lvert C_{10}\rvert^2$
$f_2(1270) \to \pi^+\pi^-$	1.092–1.460	280	2	1.07 ± 0.31	0.00 ± 0.03	0.29 ± 0.08
$f_2'(1525) \to K^+K^-$	1.424–1.620	36	2	47.9 ± 10.8	0.42 ± 0.36	1.43 ± 0.35
$f_0(1500) \to K^+K^-$		40	0	0.04 ± 0.07		

Reweight yields by efficiency to obtain $\mathcal{B}$'s:

$$w_R = \frac{\sum_{i=1}^{N_R} 1/\epsilon_i(\cos\theta_H, \cos\theta_\gamma)}{N_R}$$

$\mathcal{B}(\Upsilon(1S) \to \gamma\ R)$

PRD 97 (2018) 112006

Normalize to known $\Upsilon(3S)$ and $\Upsilon(2S)$ $\mathcal{B}$'s

$$\mathcal{B}(R) = \frac{N_R(\Upsilon(nS)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to R\gamma))}{N(\Upsilon(nS)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to\mu^+\mu^-))} \times \mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)$$

based on observed yields for the normalization modes

$$N(\Upsilon(2S)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to\mu^+\mu^-)) = (4.35 \pm 0.12_{\rm sys}) \times 10^5$$
$$N(\Upsilon(3S)\to\pi_s^+\pi_s^-\Upsilon(1S)(\to\mu^+\mu^-)) = (1.32 \pm 0.04_{\rm sys}) \times 10^5$$

Good agreement BaBar/CLEO for $f_J(1500)$ and $f_2(1270)$

Resonance	$\mathcal{B}(10^{-5})$ (BaBar)	CLEO
$\pi\pi$ S-wave	$4.63 \pm 0.56 \pm 0.48$	($f_0(980)$) $1.8^{+0.8}_{-0.7} \pm 0.1$
$f_2(1270)$	$10.15 \pm 0.59\ ^{+0.54}_{-0.43}$	$10.2 \pm 0.8 \pm 0.7$
$f_0(1710)\to\pi\pi$	$0.79 \pm 0.26 \pm 0.17$	
$f_J(1500)\to K\bar{K}$	$3.97 \pm 0.52 \pm 0.55$	$3.7^{+0.9}_{-0.7} \pm 0.8$
$f_2'(1525)$	$2.13 \pm 0.28 \pm 0.72$	
$f_0(1500)\to K\bar{K}$	$2.08 \pm 0.27 \pm 0.65$	
$f_0(1710)\to K\bar{K}$	$2.02 \pm 0.51 \pm 0.35$	$0.76 \pm 0.32 \pm 0.08$

First observation ($5.7\,\sigma$) of $\Upsilon(1S)$ radiative decays to $f_0(1710)$:

$$\boxed{\frac{\mathcal{B}(f_0(1710)\to\pi\pi)}{\mathcal{B}(f_0(1710)\to K\bar{K})} = 0.64 \pm 0.27_{\rm stat} \pm 0.18_{\rm sys}}$$

Radiative decays $\Upsilon(1S) \to \gamma h^+ h^-$

PRD 97 (2018) 112006

In the $\Upsilon(1S)$ radiative decays to $\pi^+\pi^-$ and K^+K^- final state we observe

- broad S-wave component
  in J/ψ decays impossible to study due to irreducible $\pi^+\pi^-\pi^0$ background
- $f_0(980)$, $f_2(1270)$, $f_0(1500)$, $f_2'(1525)$ and $f_0(1710)$ resonances

the scalars include many of the "gluonium" candidates considered by theorists and the $\mathcal{B}$'s we measure will be useful to shed some more light:

- $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710))$ predicted $\mathcal{O}(10^{-4})$ R. Zhu, JHEP 1509, 166 (2015)
  - we have observed it for the first time at a rate that is consistent either with expectations for gluonium or with $s\bar{s}$ dominance
- $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500)) \approx 2 \div 4 \times 10^{-5}$ He et al., PRD 66, 074015 (2002)
  - consistent with our measurement
- $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1370)) \approx 3 \times 10^{-5}$ Zhu, JHEP 1509, 166 (2015)
  - evidence for $f_0(1370)$) is controversial, but prediction in the range for our measurement of $\pi^+\pi^-$-S-wave

Stable six-quark state?

- LQCD calculations suggest tightly bound *uuddss* state could be stable or nearly stable Beane et al, PRD 87, 034506 (2013)

  $$Q = 0; \ B = 2; \ S = -2$$

  $\mathcal{S}$: scalar, flavour singlet, very compact: r=0.1÷0.4 fm

  $$\text{m} \approx 1.2 \div 1.86 \ \text{GeV}$$

  - if $m < M_\Lambda + M_p + m_e$ only doubly weak decays allowed
    lifetime on the cosmological scale
  - if $m < 2\,M_p$ is stable
- Experimentally not excluded by earlier searches
- NOT the same as the loosely bound H-dibaryon proposed by Jaffe PRL 38 (1977) 195, PRL 38 (1977) 617 with M≈2150 MeV and typical weak lifetime – excluded by many searches
  - even suggested as possible dark matter candidate (G. Farrar, arXiv:1708.08951,arXiv:1805.03723) but not everybody agrees (eg. Kolb, Turner, PRD 99, 063519 (2019) , Gross et al. PRD 98, 063005 (2018) , McDermott et al PRD 99, 035013 (2019))

Could be produced in $\Upsilon \to \bar{\Lambda}\bar{\Lambda}\mathcal{S}$

Search for $\Upsilon \to \bar{\Lambda}\bar{\Lambda}\mathcal{S}$ in BABAR

PRL 122 (2019) 072002

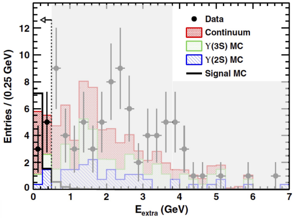
If $\mathcal{S}$ is stable it might interact hadronically in the detector, but signature not easy – better to just reconstruct the two Λ's

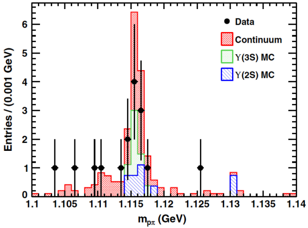
$\Longrightarrow$ Search for peak in missing mass distribution recoiling against the two Λ's

Blind analysis based on 90×10^6 $\Upsilon(2S)$ and 110×10^6 $\Upsilon(3S)$ reconstructing $\Lambda \to p\pi^-$ ($\mathcal{B} \approx 0.64$)

$\Longrightarrow$ Select events with two Λ's of same strangeness and nothing else

- p and π from both Λ's must be positively identified
- Λ's must have a significant flight length and point back to the interaction vertex
- at most one additional track candidate and little extra energy outside a cone around $\mathcal{S}$ direction ($E_{extra} < 0.5$ GeV)





Background in $\Upsilon \to \bar{\Lambda}\bar{\Lambda}S$

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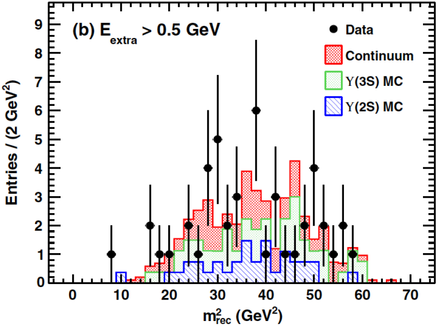
Dominant source from $e^+e^- \to \Lambda\Lambda\bar{\Lambda}\bar{\Lambda}(X)$ where the two other Λ's of same strangeness decay to $n\pi^0$ ... Cross section not known

B decays do not contribute to background: $\Upsilon(4S)$ data can be used to model background in continuum

Loose χ^2 cut ($<$25) on kinematic fit constraining the two Λ's to the same vertex and to their known mass

scale $\Upsilon(2S)$ and $\Upsilon(3S)$ MC background to match what observed in "sideband" region with $E_{extra} > 0.5\ \mathrm{GeV}$



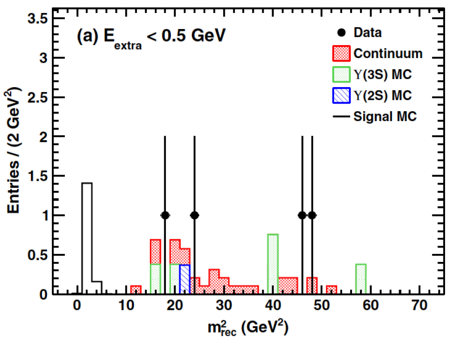
Upper limit on $\mathcal{B}(\Upsilon \to \bar{\Lambda}\bar{\Lambda}\mathcal{S})$

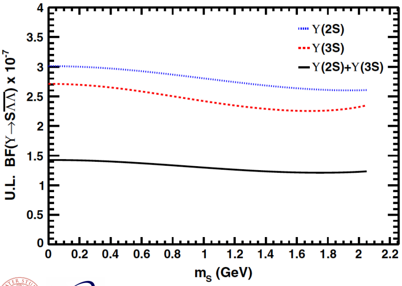
PRL 122 (2019) 072002

Only 4 events with $E_{extra} < 0.5$ GeV

– None in the $\mathcal{S}$ mass region

Upper limit from profile likelihood including systematic ($\approx 10 - 15\%$) as a function of mass separately for $\Upsilon(2S)$ and $\Upsilon(3S)$ and combined assuming same partial width





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

Conclusions

PRD 97 (2018) 112006

- Radiative decays $\Upsilon(1S) \to \gamma h^+ h^-$ measured in tagged $\Upsilon(1S)$ from $\Upsilon(3S)$ and $\Upsilon(2S)$ dipion transitions
  - Clean samples, not affected by $e^+e^- \to \gamma$ *Vector* background
  - historically a good place to search for gluonium
  - numerous resonances observed in $\pi^+\pi^-$ and K^+K^- final states
  - $f_0(1710)$ observed for the first time

PRL 122 (2019) 072002

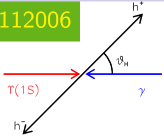
- Search for stable exa-quark $\mathcal{S}$, *uuddss*, in $\Upsilon(2S)$ and $\Upsilon(3S)$ decays
  - LQCD suggest $\mathcal{S}$ can be a tightly bound state
  - extremely long lifetime if $m < M_\Lambda + M_p + M_e$, stable if $m < 2\,N_p$
  - not excluded by earlier searches

    whether it's dark matter candidate or not, search for it!
  - Upper limit on $\mathcal{B}(\Upsilon \to \bar{\Lambda}\bar{\Lambda}\mathcal{S}) < (1.2 \div 1.4) \cdot 10^{-7}$
    stringent limit, but other modes are possible ...

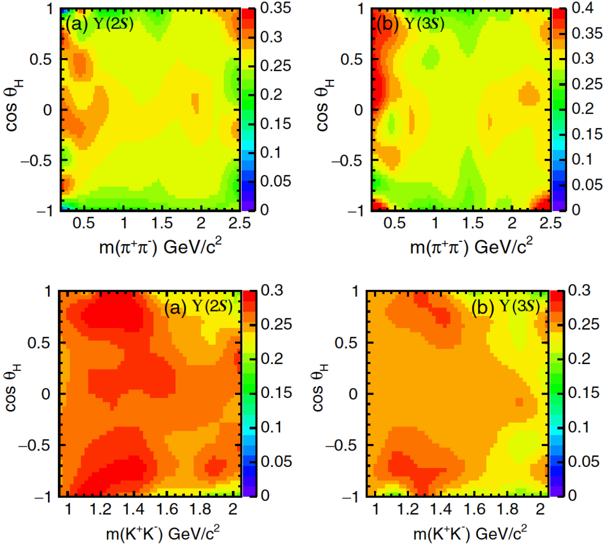
Backup

$\Upsilon(1S) \to \gamma h^+ h^-$:Efficiency correction

PRD 97 (2018) 112006



Efficiency correction as a function of m_{hh} and $\cos\theta_H$, the h^+ helicity angle in the $h^+h^-\gamma$ rest frame

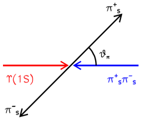


$\Upsilon(nS) \to \pi_s^+\pi_s^-\Upsilon(1S) \to \pi_s^+\pi_s^- \;\gamma h^+h^-$ angular analysis

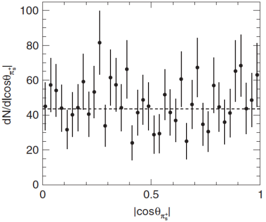
PRD 97 (2018) 112006

The slow pions in

$$\Upsilon(nS) \to \pi_s^+\pi_s^- \,\Upsilon(1S)$$



compatible with S-wave (as expected)



In each reasonance region maximum likelihoood fit to signal+ background (from tail of nearby resonances)

$$\mathcal{L} = \prod_{n=1}^{N}\left[f_{\text{sig}} \frac{\epsilon(\cos\theta_H,\cos\theta_\gamma)W_s(\theta_H,\theta_\gamma)}{\int W_s(\theta_H,\theta_\gamma)\epsilon(\cos\theta_H,\cos\theta_\gamma)d\cos\theta_H d\cos\theta_\gamma} + (1-f_{\text{sig}})\frac{\epsilon(\cos\theta_H,\cos\theta_\gamma)W_b(\theta_H,\theta_\gamma)}{\int W_b(\theta_H,\theta_\gamma)\epsilon(\cos\theta_H,\cos\theta_\gamma)d\cos\theta_H d\cos\theta_\gamma}\right],$$

with angular distribution for J=0 or J=2 from

arXiv:1804.04044

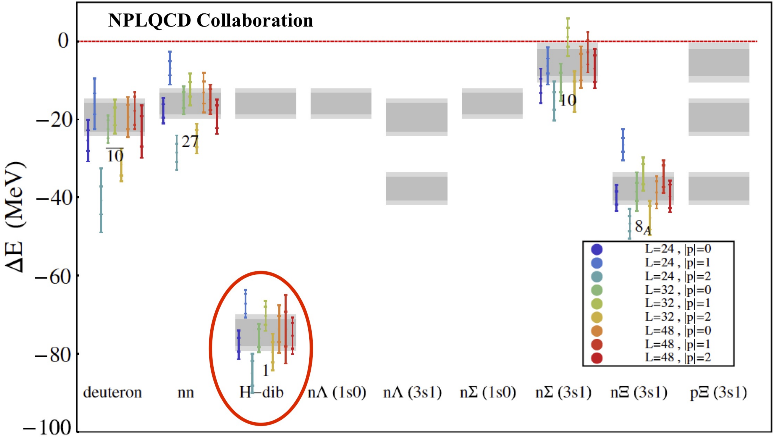
$$W_0(\theta_\gamma) = \frac{dU(\theta_\gamma)}{d\cos\theta_\gamma} = \frac{3}{8}|C_{10}|^2|E_{00}|^2(|A_{00}|^2 + 3|A_{01}|^2 - (|A_{00}|^2 - |A_{01}|^2)\cos 2\theta_\gamma).$$

$$\begin{aligned} W_2(\theta_\gamma,\theta_H) = \frac{dU(\theta_\gamma,\theta_H)}{d\cos\theta_\gamma\, d\cos\theta_H} = \frac{15}{1024}|E_{00}|^2[&6|A_{01}|^2(22|C_{10}|^2 + 8|C_{11}|^2 + 9|C_{12}|^2) \\ &+ 2|A_{00}|^2(22|C_{10}|^2 + 24|C_{11}|^2 + 9|C_{12}|^2) + 24(|A_{00}|^2 + 3|A_{01}|^2)(2|C_{10}|^2 - |C_{12}|^2)\cos 2\theta_H \\ &+ 6(|A_{00}|^2(6|C_{10}|^2 - 8|C_{11}|^2 + |C_{12}|^2) + |A_{01}|^2(18|C_{10}|^2 - 8|C_{11}|^2 + 3|C_{12}|^2))\cos 4\theta_H \\ &- 2(|A_{00}|^2 - |A_{01}|^2)\cos 2\theta_\gamma(22|C_{10}|^2 - 24|C_{11}|^2 + 9|C_{12}|^2 + 12(2|C_{10}|^2 - |C_{12}|^2)\cos 2\theta_H \\ &+ 3(6|C_{10}|^2 + 8|C_{11}|^2 + |C_{12}|^2)\cos 4\theta_H)]. \end{aligned}$$

Can be expressed in terms of longl/trans polarization of $\Upsilon(1S)$ and γ (1 or 3 free parameters for S/D)

Tightly bound six-quark state?

LQCD calculations for binding energies for various six-quark systems in the limit of SU(3)-flavour, $m_\pi = m_K \approx 800\ \mathrm{MeV}$



Beane et al, PRD 87, 034506 (2013)

Systematic uncertainties on $\Upsilon \to \bar{\Lambda}\bar{\Lambda}\mathcal{S}$

PRL 122 (2019) 072002

Main sources from

- signal modelling: production amplitudes – angular distribution; interaction with 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%