And now, a word or two on the *other* heavy onia …

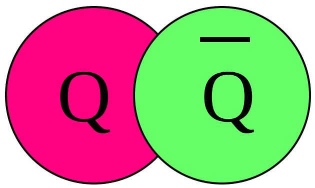
Recent Results in Bottomonium
Ties to Charmonium

*Richard S. Galik and **David Kreinick***

Cornell **L**aboratory for **A**ccelerator-based **S**cience**S** and **E**ducation

Bottom compared to Charm

Heavy quark symmetry



Q = b or c

$m_b / m_c = 5\text{ GeV}/1.7\text{ GeV} \approx 3$

$|q_b / q_c| = e/3 \;/\; 2e/3 = 1/2$

$r_b / r_c \approx 0.3\text{ fm} / 0.5\text{ fm} = 0.6$

$\beta_b^2 / \beta_c^2 \approx m_c / m_b \approx 1/3$

$\alpha_{S,b} / \alpha_{S,c} \approx 0.2/0.3 = 2/3$

Cornell potential ~ (a/r) + br

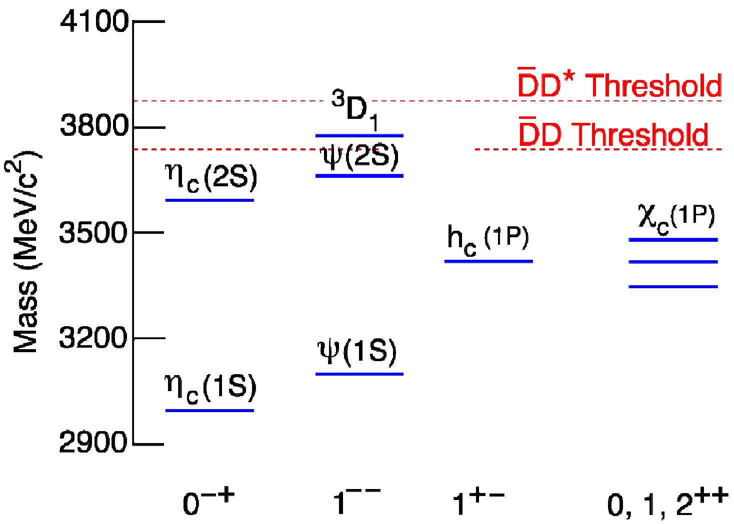
Some implications … b-bbar will differ in a calculable way …

More Coulomb-like, less able to probe confinement region, more asymptotically free, more states below threshold, more non-relativistic, smaller M1 rates, higher decay multiplicities, less copiously produced in e^+e^-

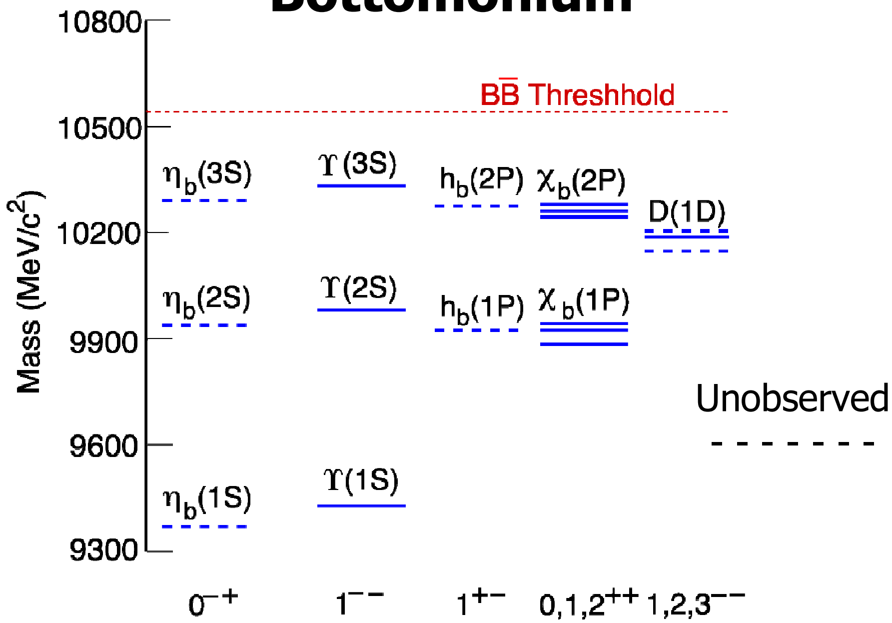
Bottomonium a different laboratory to study the same physics

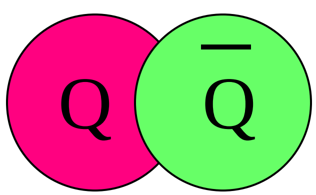
Charmonium and Bottomonium

Charmonium



Bottomonium

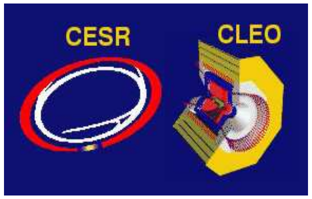




Q = b or c

Rich spectroscopy, various production schemes, interesting decay scenarios, many important states not yet observed

Players of Note



- **Direct production in e^+e^-:**
  - CLEO: 6M **Υ(3S)**, 9M **Υ(2S)**, 21M **Υ(1S)**
  - Belle: 11M **Υ(3S)** (in a ***few*** days' run!)
  - Belle and BaBar: 100's of M **Υ(4S)**

- **ISR Production:**
  - Belle and BaBar: 10's of M **Υ(1S)**, **Υ(2S)**, **Υ(3S)**
  - Harder to know how to use effectively
- **Hadro-production**:
  - CDF
  - D0

  } { Production Ratios / Polarizations

Polarization in Production

$p\bar{p}$ production of onia can be modeled with NRQCD

- Uses "universal" matrix elements with color-octet pieces, which describe production cross sections adequately
- Polarization parametrized by $\alpha = (\sigma_T - 2\,\sigma_L)/\,(\sigma_T + 2\,\sigma_L)$
- Measured by angular distribution in di-lepton (dimuon) decays:

$$dN/d\cos\theta^* \sim (1 + \alpha \cos^2\theta^*)$$

NRQCD predicts a large transverse polarization at high p_T

- gluon fragmentation becomes dominant mechanism
- α should approach unity at high p_T

k_T-factorization ("semi-hard") makes opposite prediction

- large longitudinal polarizations at high p_T
- α becomes negative at large p_T

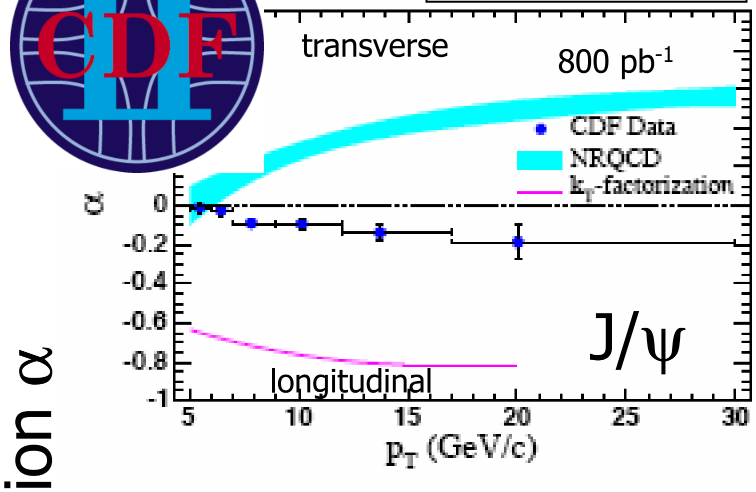
Neither formulation works well in charmonium

New results in bottomonium from D0 with 1.3/fb, ~420K Υs

Polarization in Production

arXiv:0704.0638

Neither phenomenology describes $c\bar{c}$ well

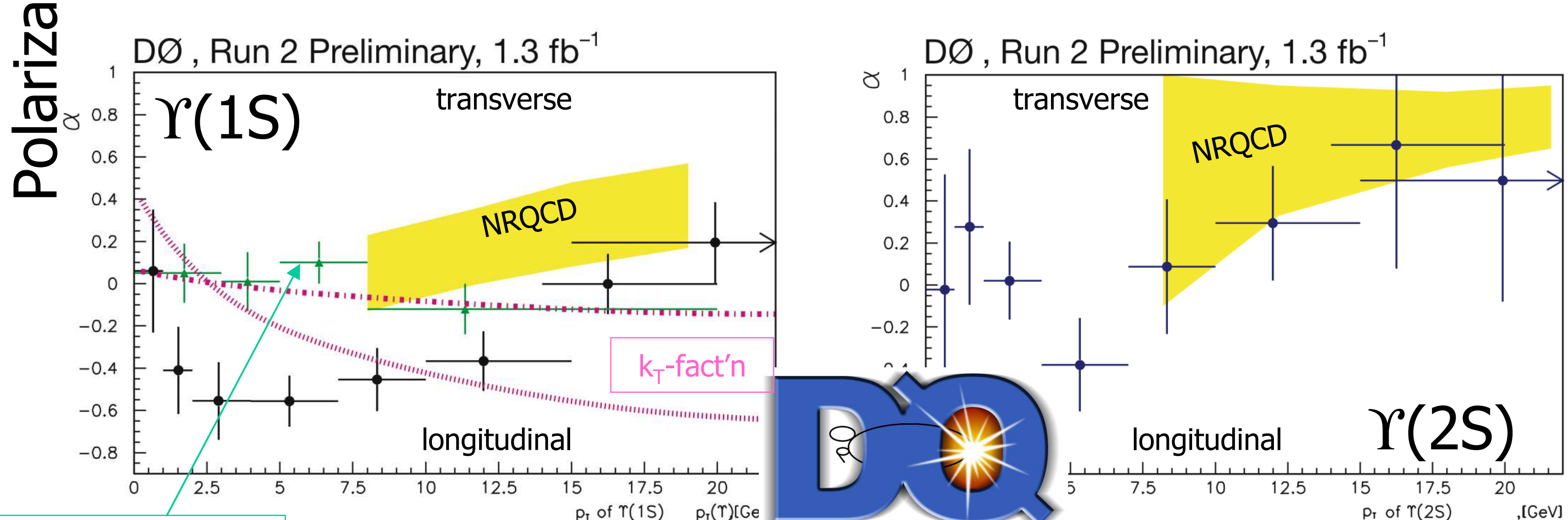


D0 observes significant polarization in ϒ(1S) production, inconsistent with NRQCD

ϒ(2S) is "not inconsistent" with NRQCD

Bottomonium only deepens the puzzle for polarization in onium production

Polarization α

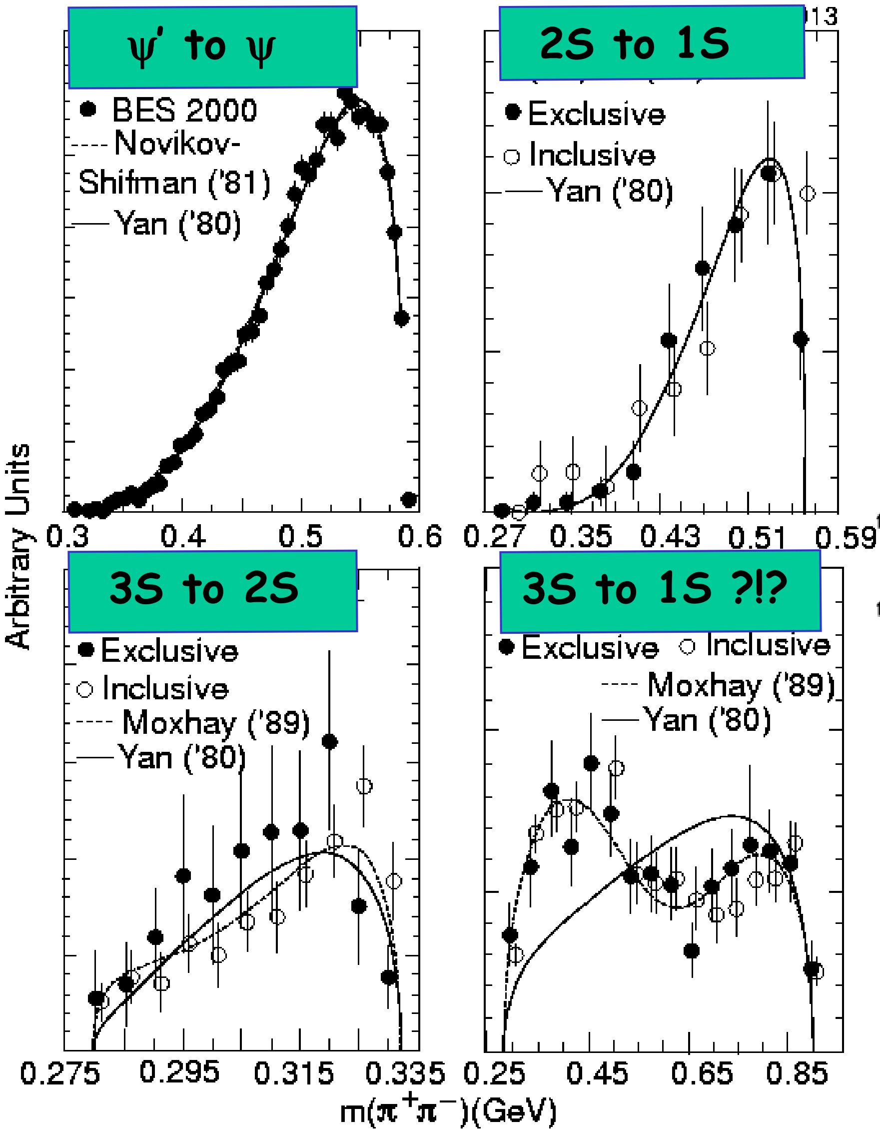


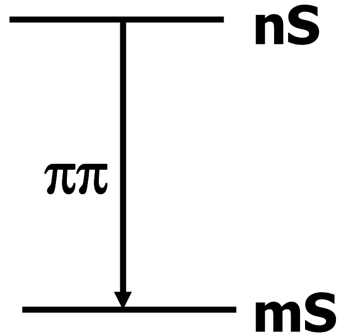
CDF PRL88,161802(2002)

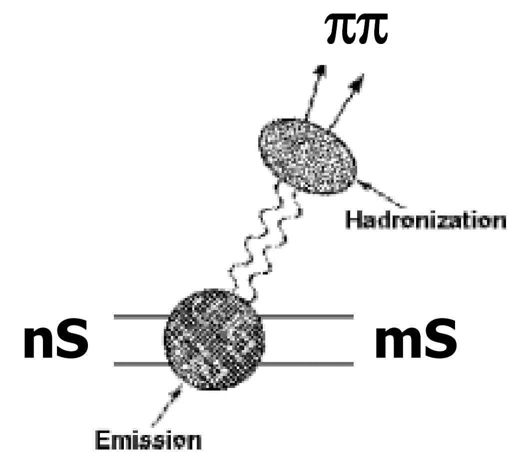
EPS07: D0 note 5089

Dipion Transition Matrix Element

Older studies

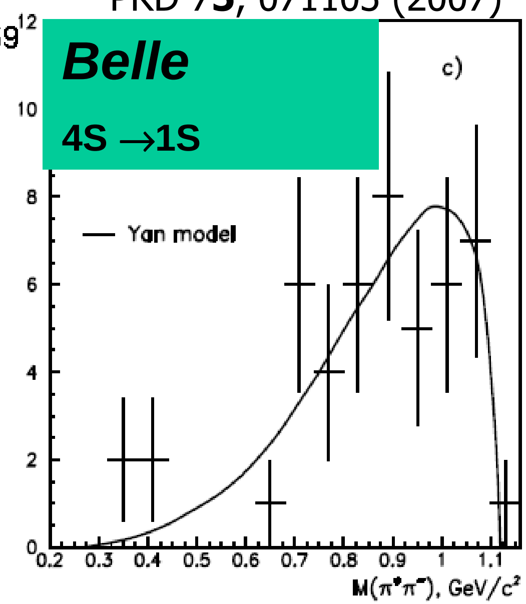




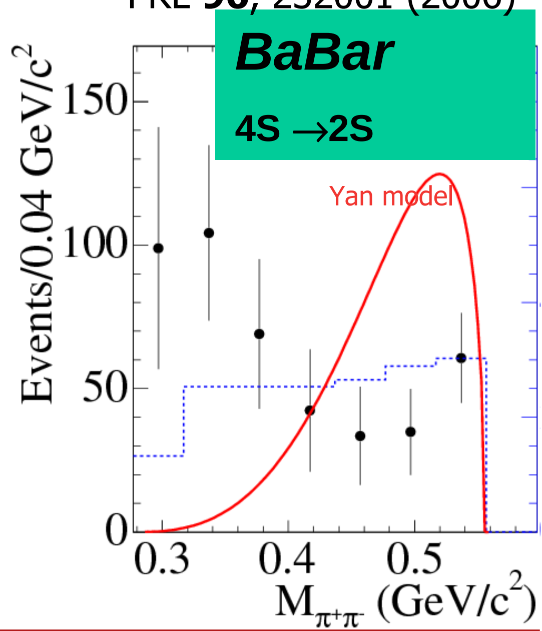


New inputs to old puzzle

PRD 7**5**, 071103 (2007)



PRL **96**, 232001 (2006)



Dipion Transition Matrix Element

Brown and Cahn [PRL **35**, 1 (1975)] use PCAC and current algebra:

$$M = A\,(\varepsilon'\cdot\varepsilon)(q^2 - 2m_\pi^2) + B\,(\varepsilon'\cdot\varepsilon)\mathbf{E_1E_2} + C\,[(\varepsilon'\cdot q_1)(\varepsilon\cdot q_2) + (\varepsilon'\cdot q_2)(\varepsilon\cdot q_1)]$$

- CLEO fits 2-D "Dalitz" plot ($q^2=M_{\pi\pi}^2$ & $M_{\Upsilon\pi}^2$), for the three di-pion transitions among the Υ(nS) states [hep-ex/0706.2317]
- Only the two terms, with complex, constant form factor coefficients A and B, are needed to give good fits to the data

Initial Υ	Final Υ	Re (B/A)	Im (B/A)
3S	1S	-2.52 ± 0.04	±1.19 ± 0.06
2S	1S	-0.75 ± 0.15	0.00 ± 0.11
3S	2S	-0.40 ± 0.32	0.00 ± 1.10
Includes system. uncert's		$\lvert C/A\rvert_{3to1} < 1.09$ @ 90% CL	

CLEO hep-ex/0706.2317

Dubynskiy/Voloshin [hep-ph/0707.1272] argue that CLEO parametrization is too naïve, B cannot be constant over the Dalitz plot

Good to revisit with Belle (Q = b) and CLEOc/BES (Q = c) data!

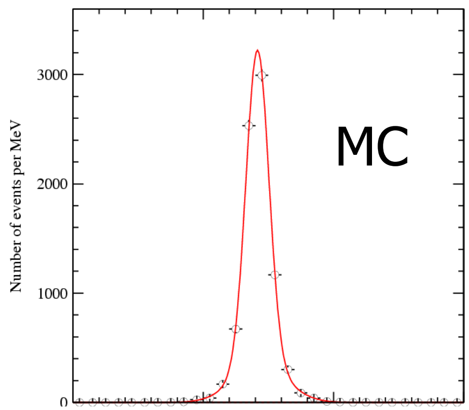
Pseudo-scalar Transitions

In charmonium $\psi(2S)\rightarrow\eta J/\psi$ is (surprisingly) large ~3%

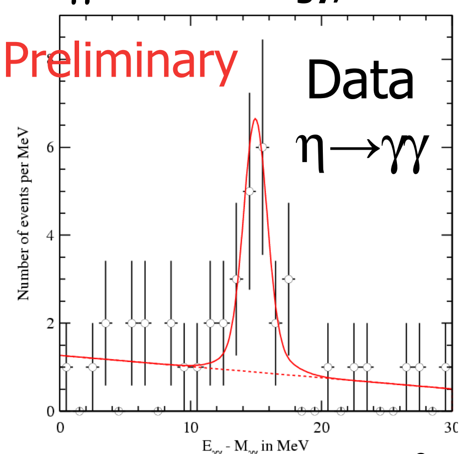
Kuang [hep-ph10601044 v2] scales $\Gamma \sim (p^*)^3/m_Q^4$ to predict

$B(\Upsilon(2S)\rightarrow\eta\Upsilon(1S)) = (8.1 \pm 0.8) \times 10^{-4}$

$B(\Upsilon(3S)\rightarrow\eta\Upsilon(1S)) = (6.7 \pm 0.7) \times 10^{-4}$



$\gamma\gamma$ **Kinetic energy, MeV** →



Also 3 events in $\eta\rightarrow\pi^+\pi^-\pi^0$ mode

CLEO seeks $\Upsilon(2S)\rightarrow\eta\Upsilon(1S)$ with
$\Upsilon(1S) \rightarrow \mu\mu$ or ee, and $\eta\rightarrow\gamma\gamma$ or $\pi^+\pi^-\pi^0$

Sees preliminary ~5σ evidence

$B(\Upsilon(2S)\rightarrow\eta\Upsilon(1S)) = (2.5 \pm 0.7 \pm 0.5) \times 10^{-4}$

Also seek π^0, find no excess over background

$B(\Upsilon(2S)\rightarrow \pi^0\Upsilon(1S)) < 2.1 \times 10^{-4}$
consistent with expected ratio to η (.16)

Υ Decays to Invisible Particles

Onia decays to undetectable particles are a window on physics beyond the Standard Model (BSM):

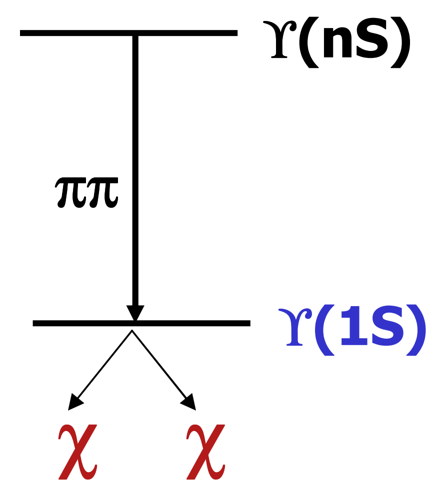
- **Dark matter candidate, χ?**
  $B(\Upsilon(1S) \rightarrow \chi\,\chi)$ = 0.41% McElrath [PRD**72**, 103508 (2005)]
- **New gauge bosons*?* Light gravitino**? Fayet [PRD**74**, 054034 (2006)]
- **$\nu\nu$ via Z^0 a very small potential background**

But how does one "see" such invisible decays?

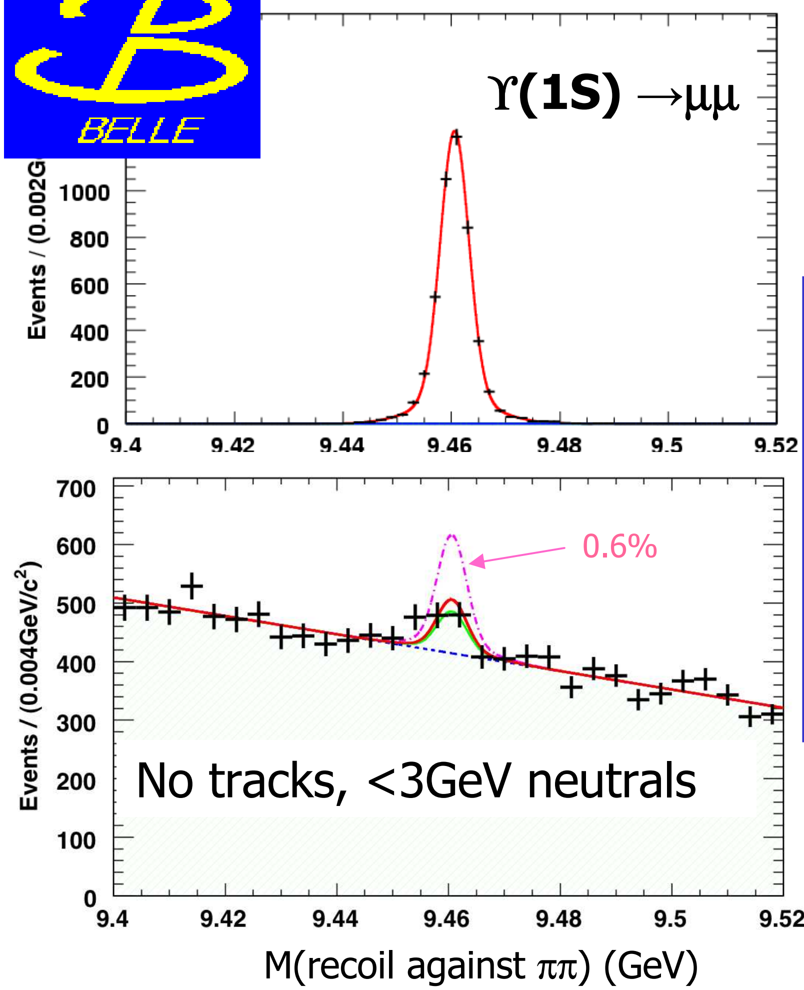
Tag presence of Υ via $\pi\pi$ transition from higher state!

Require recoil against $\pi\pi$ be Υ

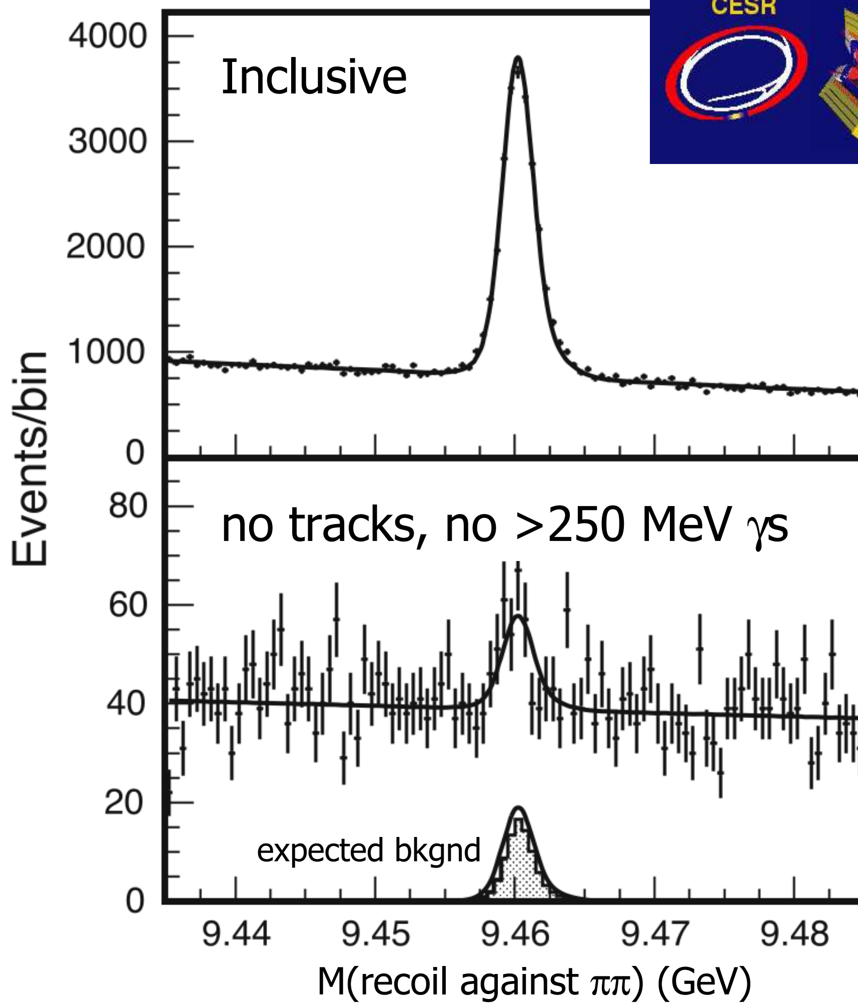
Require detector otherwise empty



ϒ Decays to Invisible Particles



PRL **98**, 132001 (2007)



PRD **75**, 031104 (2007)

11M ϒ(3S) events
Poor trig/accep efficiency

9M ϒ(2S) events
2 track trigger prescaled by 20

Υ Decays to Invisible Particles

90%CL limits:

$B(\Upsilon \rightarrow$ "invisible"$)_{Belle} < 0.25\%$

$B(\Upsilon \rightarrow$ "invisible"$)_{CLEO} < 0.39\%$

Each limit is an order of magnitude better than previous best

Combined limit about half $\chi\chi$ prediction of 0.41%

Betters gravitino mass limit by ×4 to $m_{3/2} > 1.2 \times 10^{-7}$ eV

Such BSM decays also accessible in charmonium!

- More limited mass range
- Smaller predicted branching fraction

See R. McElrath's talk next in this session!

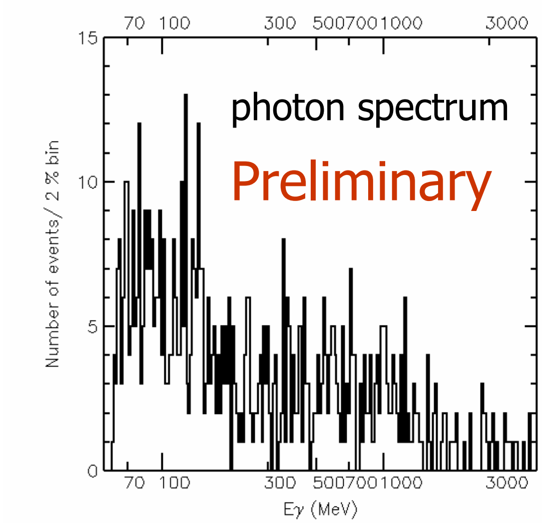
Radiative Decays to Higgs?

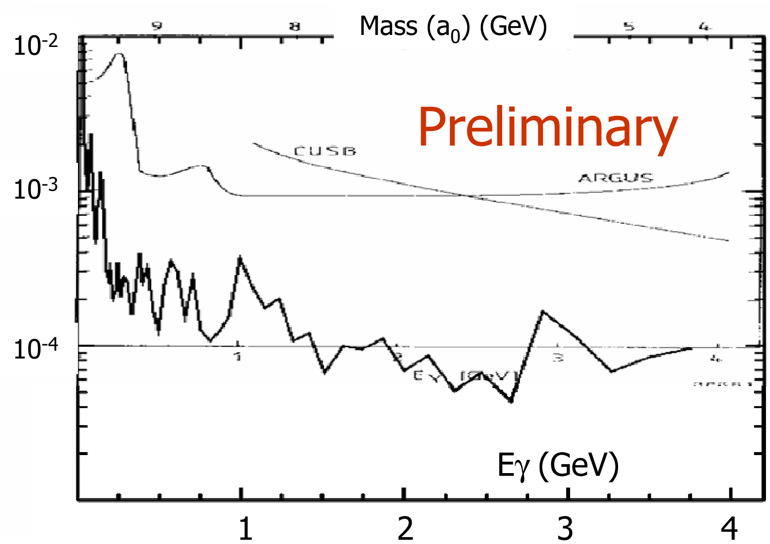
Dermisek, Gunion, McElrath propose adding to the MSSM a non-SM-like pseudoscalar higgs a_0 with $m_{a0} < 2m_b$ [hep-ph/0612031] "NMSSM"

- "natural," avoids fine tuning
- evades the LEP limit M_h>100 GeV since $h \to a_0 a_0$, but $a_0 \not\to bb$ and LEP sought b jets
- $a_0 \to \tau^+\tau^-$ should predominate if $m_{a0} > 2m_\tau$
- Should be visible in $\Upsilon \to \gamma\, a_0$

Experimentally, CLEO seeks monochromatic γ

- Use $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$ tag to eliminate $e^+e^- \to \tau\tau\gamma$ background
- Flag presence of τ pair with two 1-prong τ decays (one lepton), missing energy

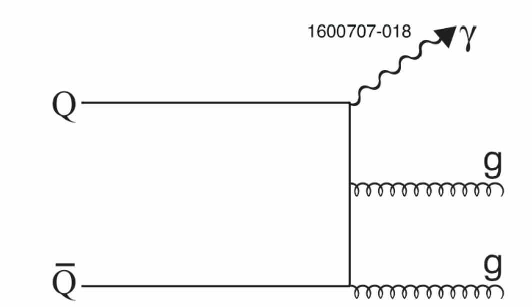




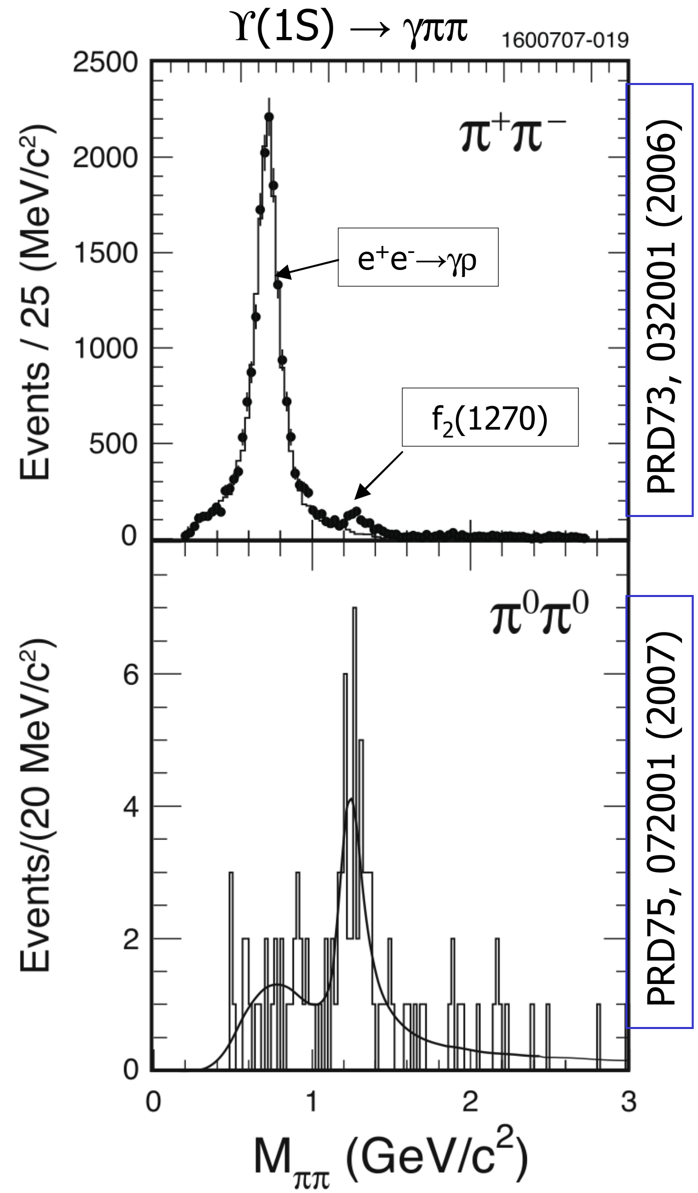
ULs improved an order of magnitude or more

Rules out many, but not all NMSSM models

Other Radiative Decays



$\Rightarrow$ hadron



Among the most common radiative decays in J/ψ is $\gamma f_2(1270)$.

Unlike in the J/ψ system, few exclusive radiative decays of the Υ are known, but CLEO has now found this decay for Υ in two modes.

Radiative Decays to f's

For $\Upsilon \to \gamma f_2(1270)$ simple scaling from charmonium works:

Expect $B(\psi \to \gamma f_2) / B(\Upsilon \to \gamma f_2) = (q_c / q_b)^2 (m_b / m_c)^2 (\Gamma_{bb} / \Gamma_{cc}) \approx 20$

Observe

$B(\Upsilon \to \gamma f_2(1270)) = (10.2 \pm 0.8 \pm 0.7) \times 10^{-5}$ $(\pi^+ \pi^-)$ PRD73, 032001 (2006)

$B(\Upsilon \to \gamma f_2(1270)) = (10.5 \pm 1.6 \pm 1.9) \times 10^{-5}$ $(\pi^0 \pi^0)$ PRD75, 072001 (2007)

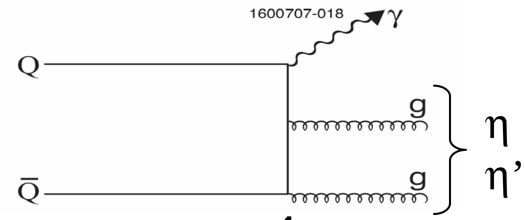
$B(\Upsilon \to \gamma f_2(1270)) = (10.23 \pm 0.97) \times 10^{-5}$ (combined)

$B(\psi \to \gamma f_2) / B(\Upsilon \to \gamma f_2) = 14.0 \pm 1.7$

Dominant helicity = 0, as expected from theory

Radiative Decays to η, η′

Another prominent radiative decay is $J/\psi \to \gamma\eta'$:



$B(J/\psi \to \gamma\eta') = (4.7 \pm 0.3) \times 10^{-3}$

$B(J/\psi \to \gamma\eta') / B(J/\psi \to \gamma f_2) = 3.4 \pm 0.4$

$B(J/\psi \to \gamma\eta') [B(\Upsilon \to \gamma f_2)/B(J/\psi \to \gamma f_2)] = (3.5 \pm 0.5) \times 10^{-4}$

naïve scaling

$B(J/\psi \to \gamma\eta) [B(\Upsilon \to \gamma f_2)/B(J/\psi \to \gamma f_2)] = (0.7 \pm 0.1) \times 10^{-4}$

But we know the η′ to be rather unconventional

- **Anomalous 5x larger branching ratio compared to η**
- **14% gluonic content? - KLOE [PLB648 267 (2007)]**
- **Possible charmonium content?**

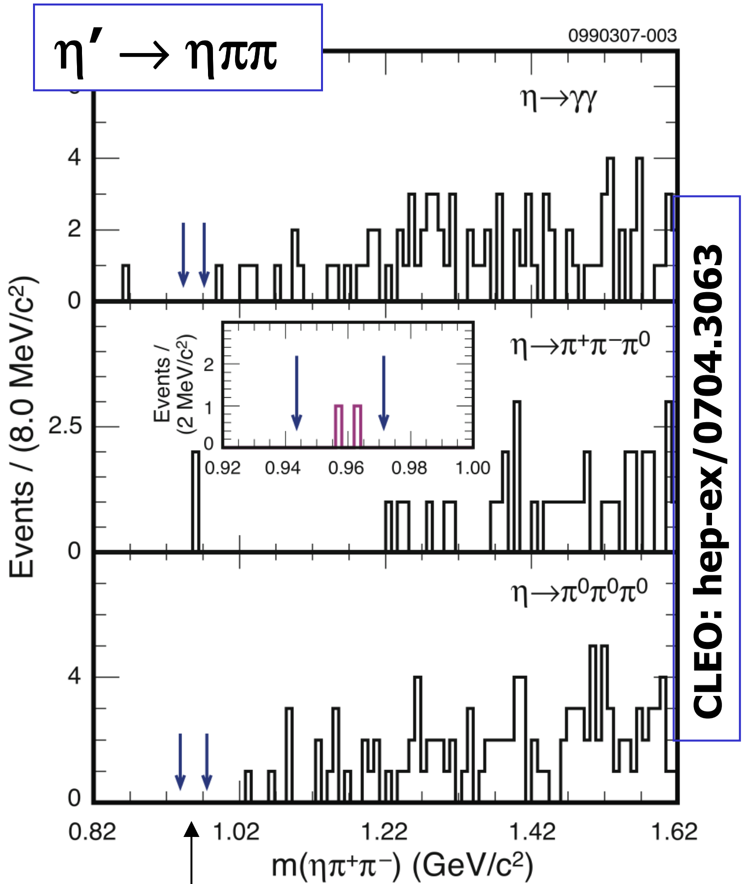
Theoretical approaches include:

- **VDM - Intemann [PRD 27 2755 (1983)]**
- **Mixing with η_b - Chao [Nucl Phys B335 101 (1990)]**
- **Higher twist contribution - Ma [PRD65 097506 (2002)]**

Radiative Decays to η, η′

New 90% CL limits from **CLEO**

$\eta' \to \eta\pi\pi$



$m_{\eta'}$

Use 21 M ϒ decays to get: — Naïve scaling

$B(\Upsilon \to \gamma\eta') < 1.9 \times 10^{-6}$ — 350×10^{-6}

$B(\Upsilon \to \gamma\eta) < 1.0 \times 10^{-6}$ — 70×10^{-6}

Significant improvement in limits

Naïve scaling fails by 2 orders of magnitude

Chao's mixing approach not supported for η′ (factor of 30)

Intemann's VDM predictions ~ 10^{-7}

Ma's predictions a bit below these limits

Summary

Bottomonium is a useful complement to charmonium in studying QCD in production, spectroscopy and decay

New results in polarization of Υ in $p\bar{p}$ production are not well described by NRQCD or k_T-factorization

A 2D fitting technique for $\Upsilon(nS) \rightarrow \pi\pi(mS)$ transitions may help clarify a longstanding puzzle

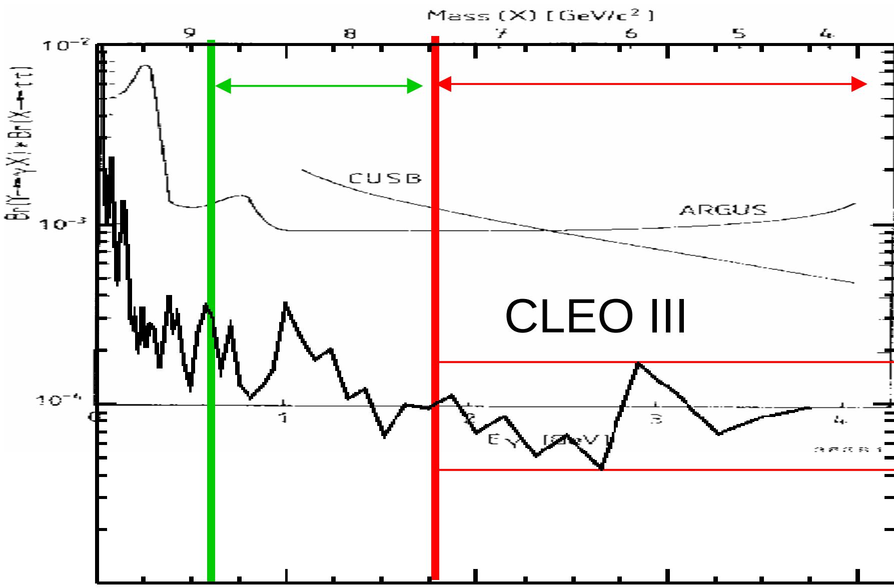
The pseudoscalar hadronic transition $\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$ has finally been seen, about 1/3 as large as scaling from charm predicts

Searches for decays of $\Upsilon(1S)$ to invisibles have upper limits smaller than the predictions of $\chi\chi$ or gravitino

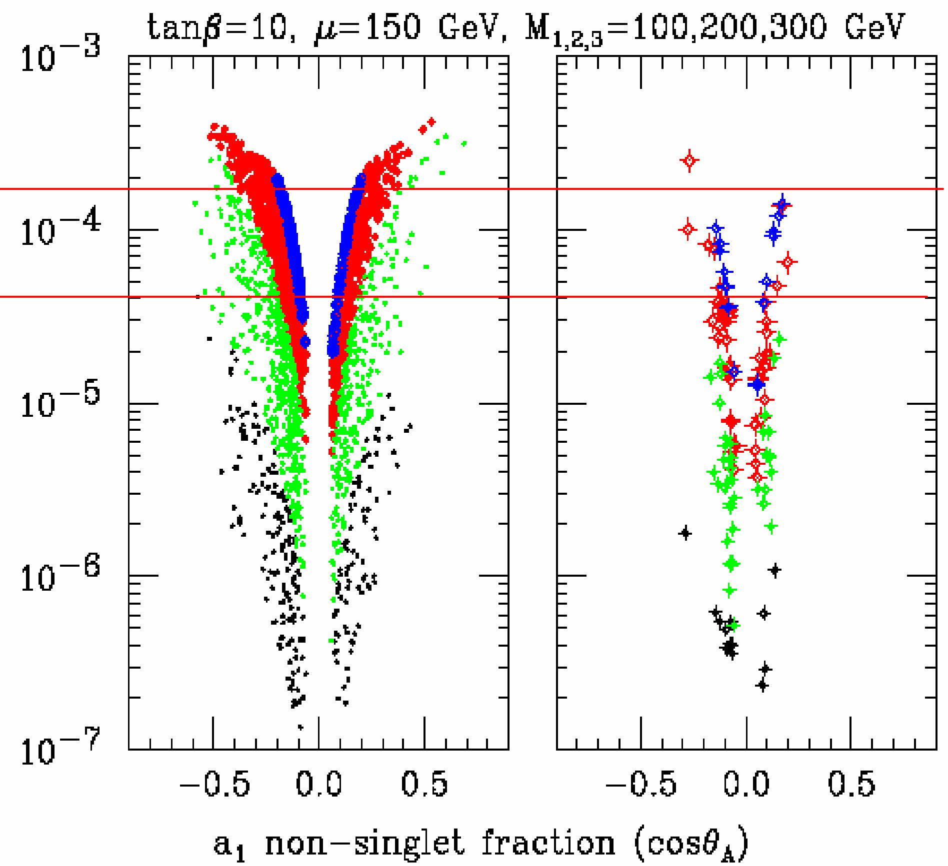
A search for low mass pseudoscalar higgs a_0 sees none

The radiative decay $\Upsilon(1S) \rightarrow \gamma f_2(1270)$ has been seen at about the strength predicted from charmonium, but $\Upsilon(1S) \rightarrow \gamma\eta'$ upper limit is two orders of magnitude smaller than naïve scaling from J/ψ decay

Backup Slides



From
Dermisek, Gunion, McElrath: hep-ph/0612031
NMSSM consistent with all previous results



We have improved ULs by about an order of magnitude or more.

We are constraining NMSSM models.

Many models with $2m_\tau<m_a<7.5$ GeV (represented by red points) ruled out by our results.