Bottomonium Results from CLEO

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on behalf of the CLEO Collaboration

Outline

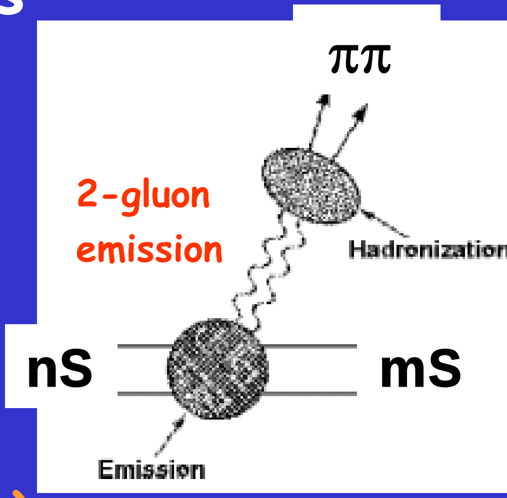
- Common decays
  - Dipion matrix elements in $\Upsilon(mS)\to\pi\pi\Upsilon(nS)$
  - $\chi_{bJ} \to$ Open charm
- Rare decays
  - $\Upsilon(mS) \to \eta/\pi^0\ \Upsilon(nS)$
  - Deuteron production in *ggg+γgg* vs $\gamma^*\to q\underline{q}$
- Beyond the Standard Model decays
  - $\Upsilon(1S) \to$ Invisible
  - $\Upsilon(1S) \to \gamma$ + light pseudoscalar Higgs($\to \tau^+\tau^-$)

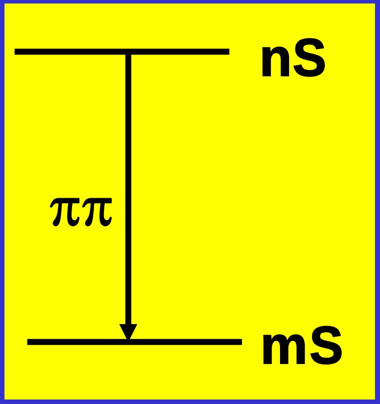
Common Decays of Bottomonium

ππ Transitions in Onia

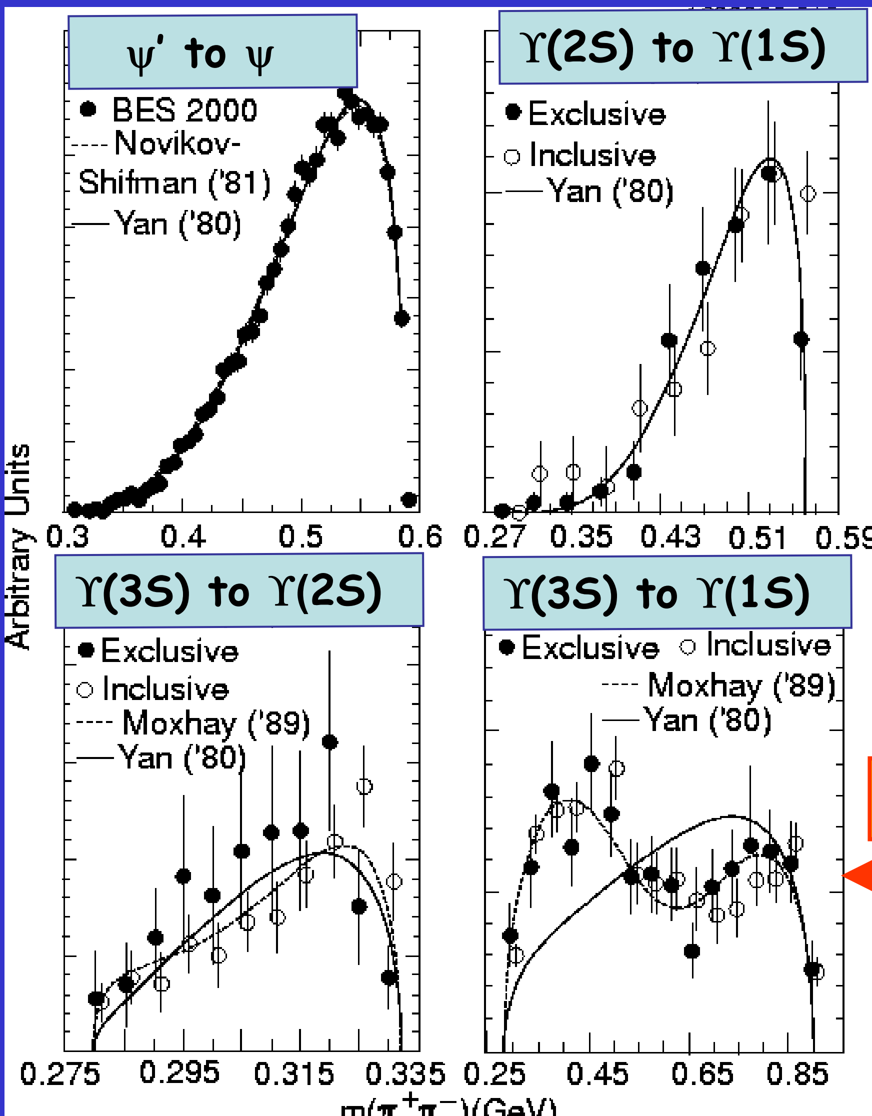
- Provide insight into the multipole moments of chromo-dynamic field
- Theoretical interest in factoring out dipion excitation
- PCAC provides guidance for the form of matrix element
  - Phase space alone not enough
  - Simplest term gives enhancement at high M(ππ)
  - Yan model [PRD 22, 1652 (1980)] fits explain
    - ❑ ψ(2S) → ππ J/ψ
    - ❑ Υ(2S) → ππ Υ(1S)
    - ❑ Υ(3S) → ππ Υ(2S)

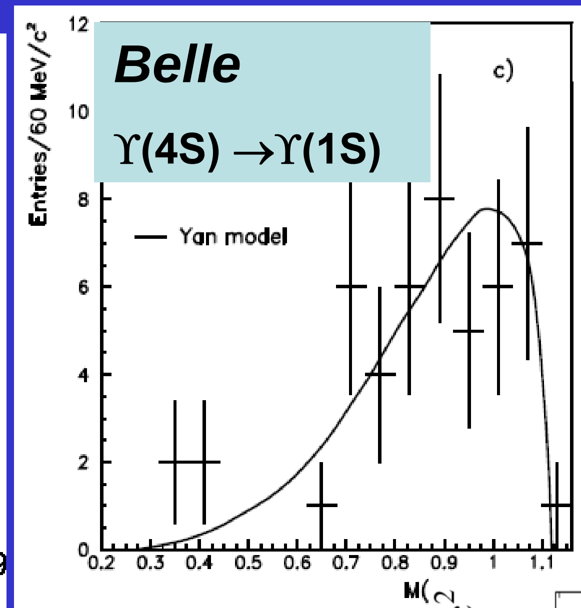
  Yan model does NOT explain:
    - ❑ Υ(3S) → ππ Υ(1S)
    - ❑ Υ(4S) → ππ Υ(2S)





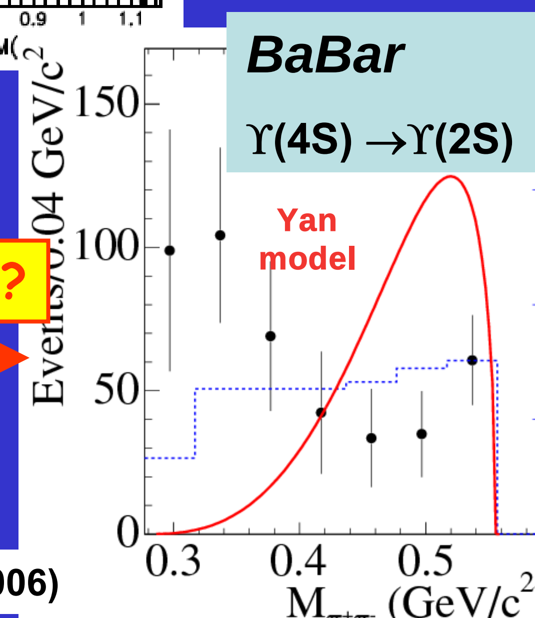
The M(ππ) Territory





PRD 75, 071103 (2007)

What is going on?

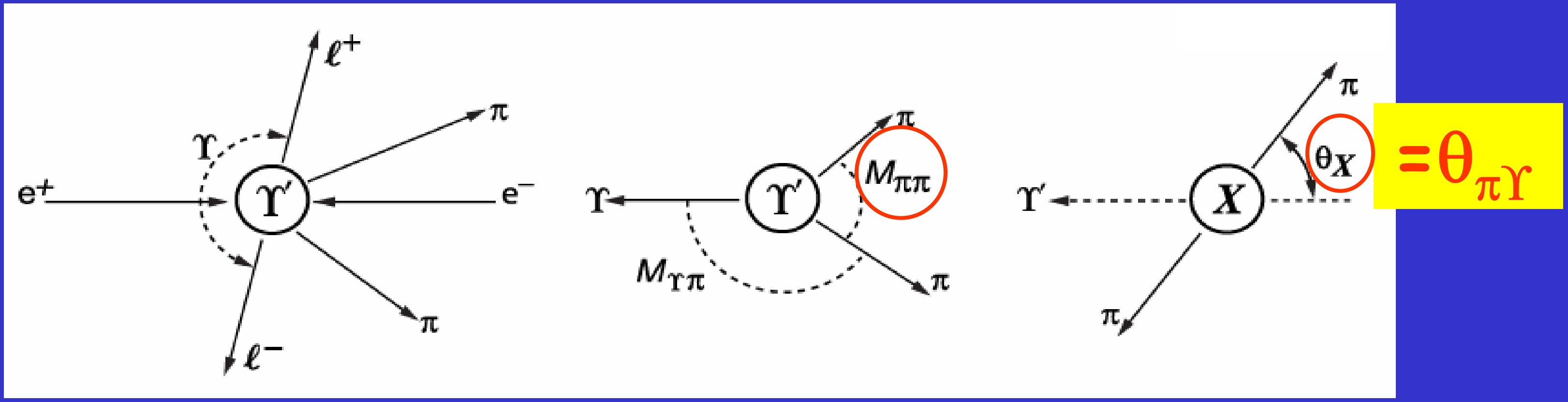


PRL 96, 232001 (2006)

How to understand it?

- $M(\pi\pi)$ structure has been long considered an anomaly worth addressing- many ideas
  - Final state interactions?
  - σ [$f_0(600)$] resonance in the $\pi\pi$ system
  - Exotic $\Upsilon\pi$ resonances
  - *ad hoc* constant term in matrix element
  - coupled channel effects
  - S-D mixing
  - Relativistic corrections
- How can CLEO III bottomonium data help?
  - Υ system is non-relativistic
    - theoretically simpler than ψ
  - Dataset allows a 2D Dalitz analysis
  - CLEO III's ability to reconstruct $\pi^+\pi^-$ & $\pi^0\pi^0$
    - Statistics & sensitivity to make the 2D fit

2D Approach



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

$$M = A\,(\varepsilon' \bullet \varepsilon)\,(M_{\pi\pi}^2 - 2m_\pi^2) \;+$$
$$B\,(\varepsilon' \bullet \varepsilon)\,E_{\pi 1} E_{\pi 2} \;+$$
$$C\,[\,(\varepsilon' \bullet q_{\pi 1})(\varepsilon \bullet q_{\pi 2}) + (\varepsilon' \bullet q_{\pi 2})(\varepsilon \bullet q_{\pi 1})\,]$$

Gives usual high mass peak

$\propto$ **cos** $\theta_{\pi\Upsilon}$ in $\pi\pi$ rest frame

Requires spin flip

where

A, B, C = **form factors** (assumed constant over phase space)

$\varepsilon', \varepsilon$ = polarization vectors of parent Υ, child Υ

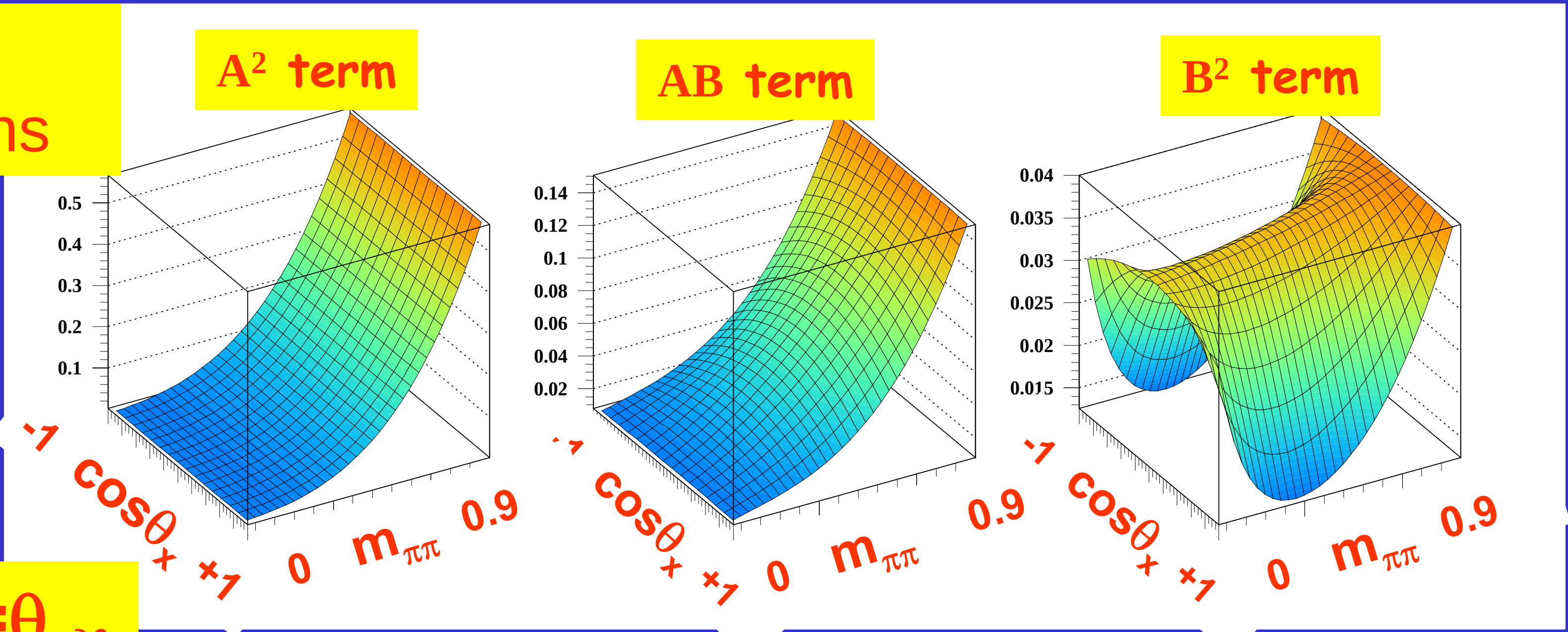
$q_{\pi i}$ = pion 4-vectors

$E_{\pi i}$ = energies in parent Υ rest frame

- C term: large m_b strongly suppresses spin flip: expect it to be small
- B term has traditionally been neglected: NOT THIS ANALYSIS !
- 2 degrees of freedom – take as $M_{\pi\pi}$ & $\cos\theta_X$

2-D distributions (all MC)

Cross Sections



$\theta_X = \theta_{\pi\Upsilon}$

B term gives low mass peak but also has distinctive behavior in $\cos\theta_X$

Results

PRD 76, 072001 (2007)

Set C=0. Errors include systematics

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

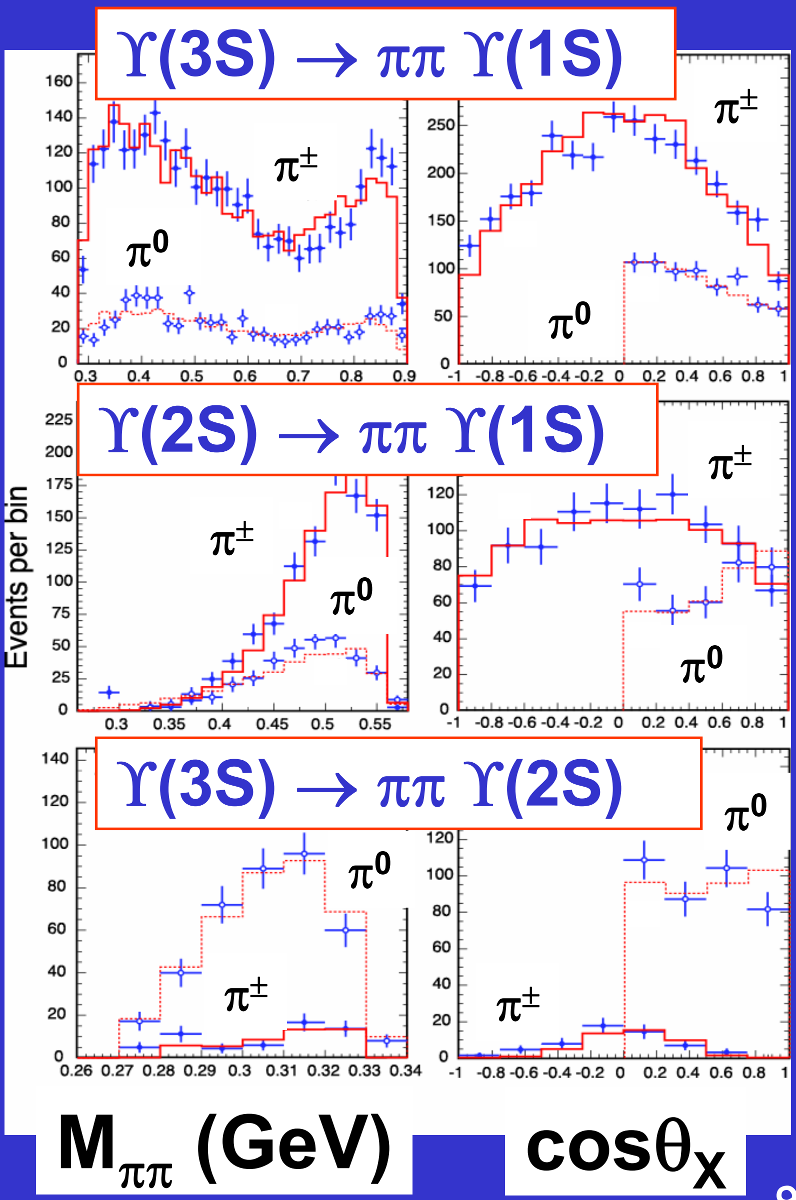
- B term essential to describe the data
- $\pi^+\pi^-$ results consistent w/$\pi^0\pi^0$
- If C allowed to float in 3S→1S:

  |B/A|=2.79±0.05   C=0

  =2.89±0.25   C floats

  |C/A|=0.45±0.40   (<1.09 @ 90% CL)

  [Consistent w/ zero]



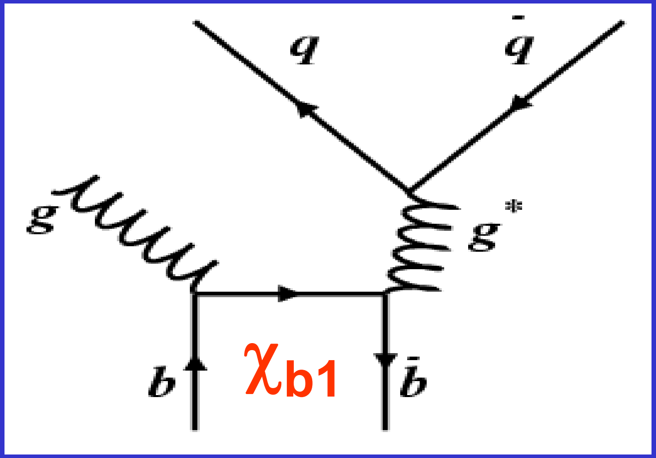
Dipion Transition Conclusions

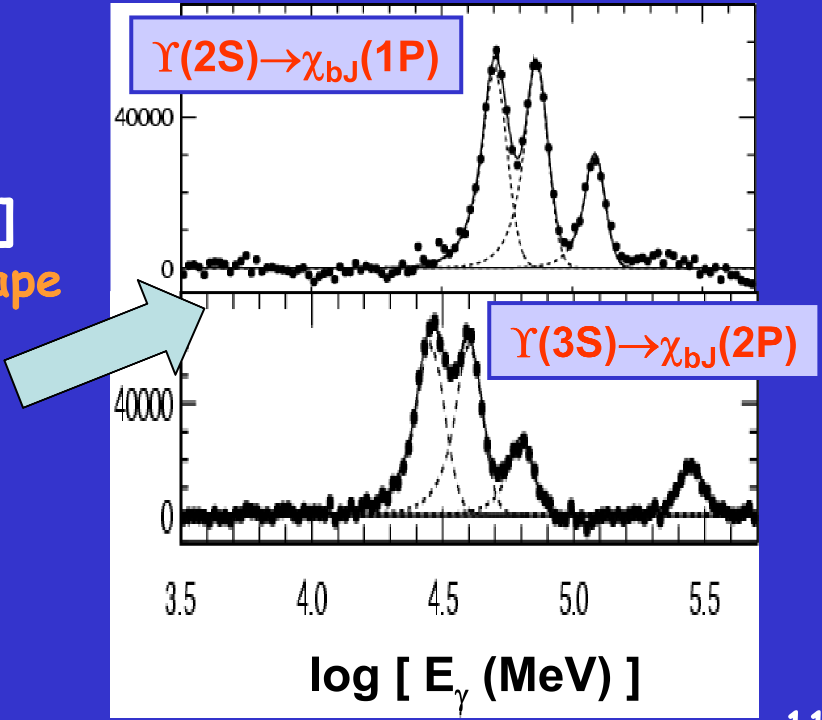
PRD 76, 072001 (2007)

- A different approach: use $M_{\pi\pi}$ & $\cos\theta_X$
- Challenging systematics (soft tracks in some important parts of phase space): use both $\pi^0\pi^0$ & $\pi^+\pi^-$
- CLEO-c $\Upsilon(nS) \rightarrow \pi\pi\ \Upsilon(mS)$ data are well described by a simple 2D fit to expected dependences
  - Double-peaked $M_{\pi\pi}$ distributions might not be so "anomalous" after all !
  - $\cos\theta_X$ distributions support underlying formalism
- However…
  - Dubynskiy & Voloshin [hep-ph/0707.1272] argue that **B/A** cannot be constant over the Dalitz plot, & in this case Im(**B/A**) = 0, in conflict with the CLEO $\Upsilon(3S) \rightarrow \pi\pi\ \Upsilon(1S)$ result.
    - They propose using Υ polarization information in the fit
- B-factory analyses of $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(5S)$ $\pi\pi$ transitions could help shed more light on the matter

$\chi_{bJ} \to$ Open Charm

- Unlike χ_{b0} & χ_{b2}, χ_{b1} cannot decay to 2-gluons on-shell
  - $\chi_{b1} \to g^* g \to q\bar{q}\ g$
- χ_{b1} expected to yield more open charm than χ_{b0}, χ_{b2}
- Investigate w/CLEO III
  - Select inclusive γ, find # χ_{bJ}
  - Select inclusive $D^0 \to K\pi$, $K\pi\pi$, $K\pi\pi\pi$
    - Require $p(D^0)$>2.5 GeV/c
    - Find # χ_{bJ} in such events
- First step is reproducing previous CLEO III results on B[$\Upsilon(nS) \to \gamma\chi_{bJ}$]
  - Suppress fake photons w/shower shape
  - Suppress π^0 decays by pairing with other γ's
  - Fit background, subtract, fit signal
  - Obtained same result: we have denominator for branching fraction
- Exploit RICH & dE/dx for K & π identification

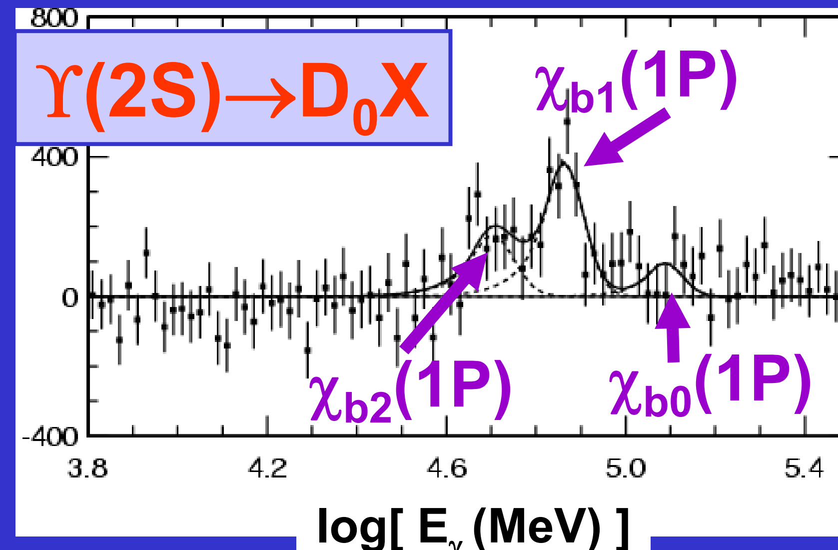


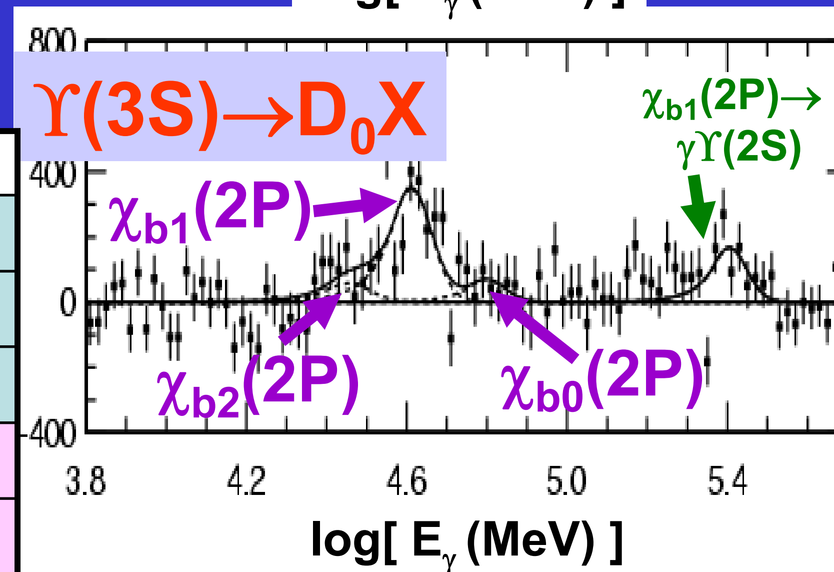


1^{st} Observation of $\chi_{bJ} \to$ Open Charm

- Plot E_γ for tagged D_0 near M_D
  - D-sideband subtraction
  - Smooth bgd subtraction
  - Fit using lineshapes from inclusive γ's
- $>7\sigma$ signals for $\chi_{b1}(1P)$, $\chi_{b1}(2P$
- Correct for efficiency
  - Assume $\rho_8 = 0.1$ (non-perturbative model parameter) for p>2.5 GeV/c cut
- Subtract secondary sources of χ_{bJ}
- Correct for $\chi_{bJ} \to \Upsilon X$: quote B^*

$B^*(\chi_{bJ}(nP) \to c\bar{c}\, X)(\%)$	Theory (Barbieri, et al., PLB 83, 345 (1979))	$\rho_8=0.1$ (Bodwin, et al., arXiv:0704.2599v1)
$\chi_{b0}(1P)$: $13 \pm 7 \pm 2$	6	5
$\chi_{b1}(1P)$: $31 \pm 5 \pm 5$	25	23
$\chi_{b2}(1P)$: $13 \pm 4 \pm 2$	12	8
$\chi_{b0}(2P)$: $8 \pm 6 \pm 1$	6	5
$\chi_{b1}(2P)$: $19 \pm 3 \pm 2$	25	23
$\chi_{b2}(2P)$: $1 \pm 3 \pm 1$	12	8



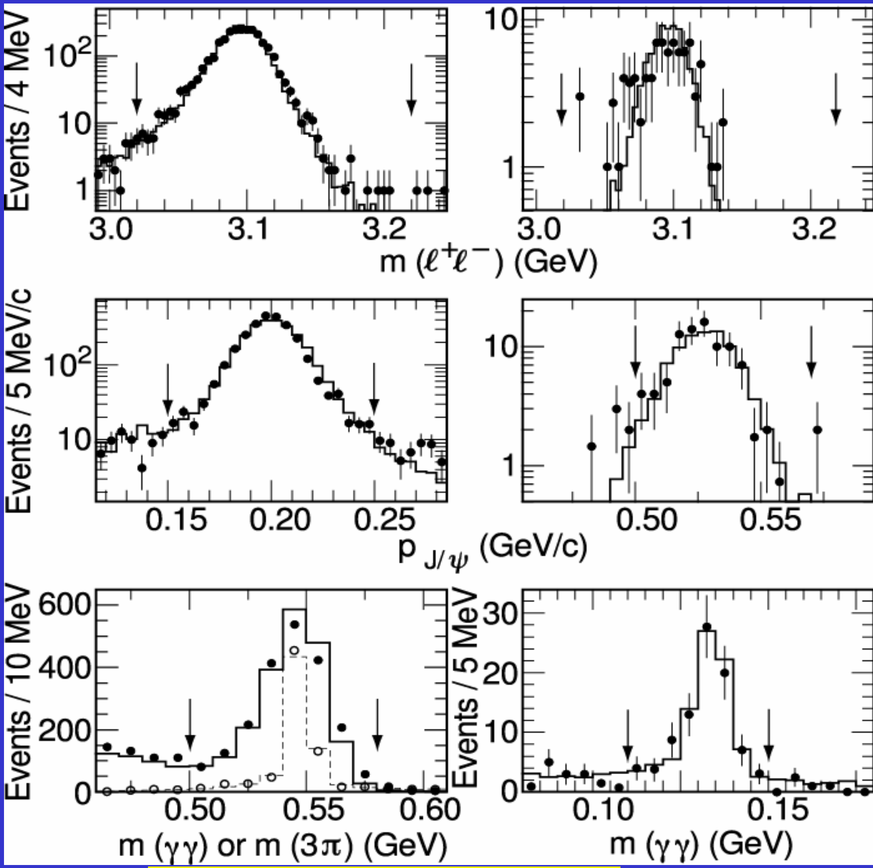


CLEO Preliminary

Rare Decays of Bottomonium

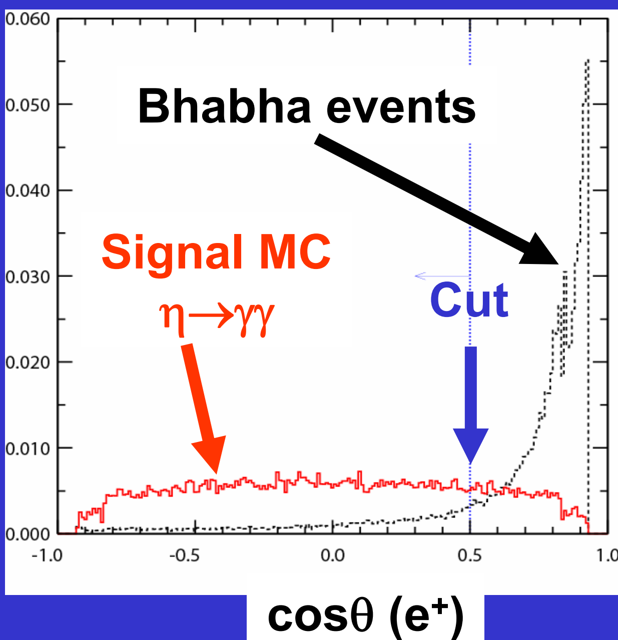
1^{st} Observation of $\Upsilon(2S)\to\eta\Upsilon(1S)$

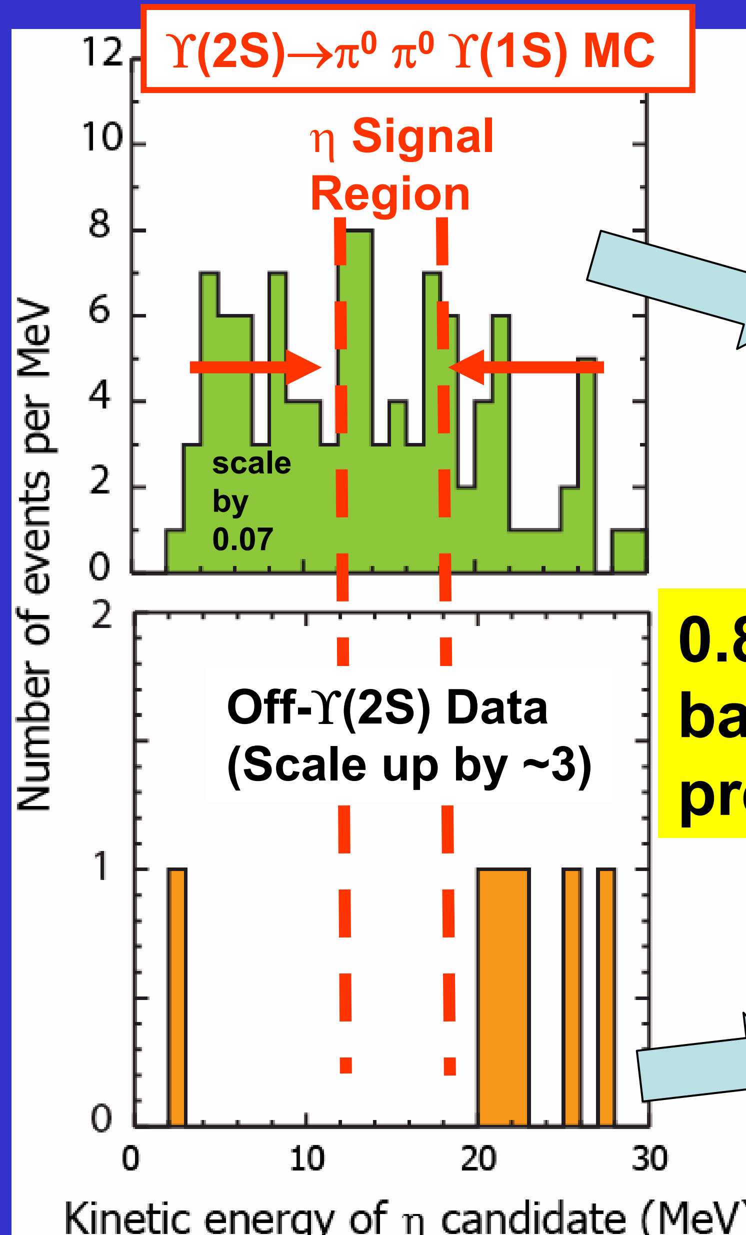
- Υ transitions via a single η or π^0 NOT yet observed
- By scaling from $\psi(2S) \to \eta\, J/\psi$ using QCDME (multipole expansion), **Kuang [hep-ph/060144v2]** predicts
  - **B[$\Upsilon(2S)\to\eta\Upsilon(1S)$] ≈ 7 × 10^{-4}**
    PDG: <20 × 10^{-4}
  - **B[$\Upsilon(3S)\to\eta\Upsilon(1S)$] ≈ 5 × 10^{-4}**
    PDG: <22 × 10^{-4}
  - **~same as Yan [PRD 22, 1652 (1980)]**
- In 2005 CLEO-c reported the most precise determinations of $\psi(2S) \to \eta\, J/\psi$ & $\psi(2S) \to \pi^0\, J/\psi$ using $J/\psi\to l^+l^-$ & $\eta,\pi^0\to\gamma\gamma$ & $\eta\to\pi^+\pi^-\pi^0$: **B_η~3.3%, $B_{\pi0}$~0.13%**
- What about Υ's in CLEO III ?
  - **9.32×10^6 $\Upsilon(2S)$**
  - **Use $\Upsilon(1S)\to ee$ & $\mu\mu$**
  - **Need kinematic fitting for bgd suppression: χ^2/dof < 10**



CLEO-c $\psi(2S)\to\eta\, J/\psi$
PRL 94 232002 (2005)

Bgd for $\eta\to\gamma\gamma$





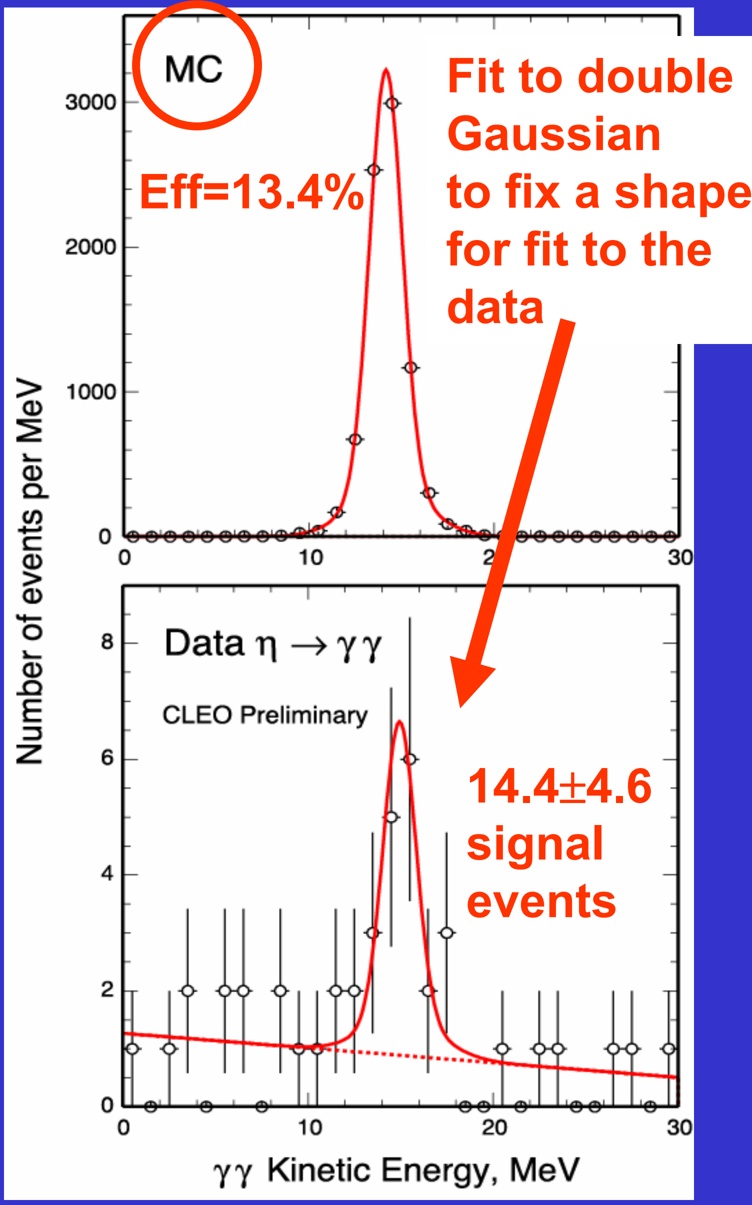
0.25±0.03 evt/MeV

0.59±0.24 evt/MeV

0.84±0.24 evt/MeV background predicted for $\eta\to\gamma\gamma$

$\eta \to \gamma\gamma$ Result

- Signal shown is ~4.6σ
- B[$\Upsilon(2S) \to \eta \Upsilon(1S)$] $_{\gamma\gamma}$ =
  (2.32±0.74) × 10^{-4}
- $\Upsilon(1S) \to ee$ (7.3 events)
  $\to \mu\mu$ (7.2 events)
  - give consistent B's
- B & significance are robust w.r.t. M(l^+l^-) limits, cosθ_+ cut, floating or fixed peak position
- ~20% relative systematic error, mostly from Bhabha suppression uncertainty
- Background level is 0.9±0.2 evt/MeV, consistent w/estimate



$\Upsilon(2S)\to\eta/\pi^0\ \Upsilon(1S)$ Conclusion

- $\eta\to\pi^+\pi^-\pi^0$ gives 3 events, no background expected

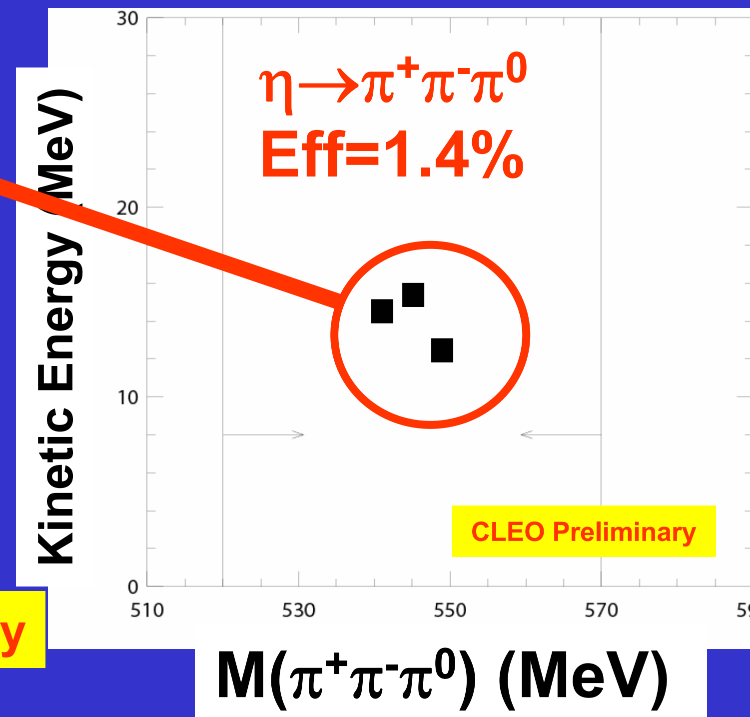
  $B[\ \Upsilon(2S)\to\eta\Upsilon(1S)\ ]_{+-0} = (4.8^{+4.7}_{-2.6}) \times 10^{-4}$

- Combined , significance $\sim 5\sigma$

  $B[\ \Upsilon(2S)\to\eta\Upsilon(1S)\ ]_{\gamma\gamma + (+-0)} = (2.51 \pm 0.71 \pm 0.50) \times 10^{-4}$

- ~Half of prediction
- First observation

CLEO Preliminary



- $\Upsilon(2S)\to\pi^0\ \Upsilon(1S)$
  - 4 evts (3 ee, 1 $\mu\mu$)
  - 6 bgd expected

$B[\ \Upsilon(2S)\to\pi^0\ \Upsilon(1S)\ ] < 1.6 \times 10^{-4}$

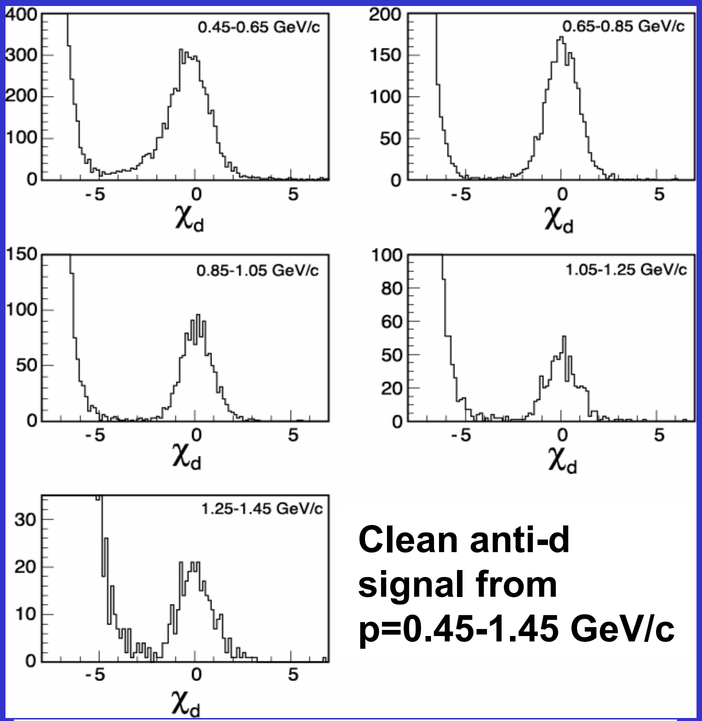
CLEO Preliminary

Next Steps:

- $\Upsilon(3S)$ analysis
- Add $\eta\to 3\pi^0$, $\eta\to\pi^+\pi^-\gamma$

Deuteron production in $ggg+\gamma gg$ vs $\gamma^* \to qq$

- d=bound (pn)
- "Coalescence models" attempt to describe appearance in fragmentation
  - How often do p & n appear "close enough" in phase space to combine into d ?
- Studies from ARGUS [PLB 236, 102 (1990)] in $\Upsilon \to d+X$ & ALEPH [PLB 639, 192 (2006)] in $Z \to d+X$
  - Accommodated by string model of Gustafson & Hakkinen [Zeit. Phys. C61, 683 (1994)]
  - Appearance in Υ ($ggg+\gamma gg$) vs γ^* or $Z \to qq$
  - Statistics-limited
- Experimental challenge is that d's can easily be produced in beam-gas and beam-material collisions
  - Look only for anti-d's
    - dE/dx in drift chamber
- Will present CLEO III data for inclusive anti-d's
  - Separate results for Υ vs continuum
  - For $\Upsilon(1S)$, rescale branching fraction to reflect DIRECT production from $ggg+\gamma gg$: B^*



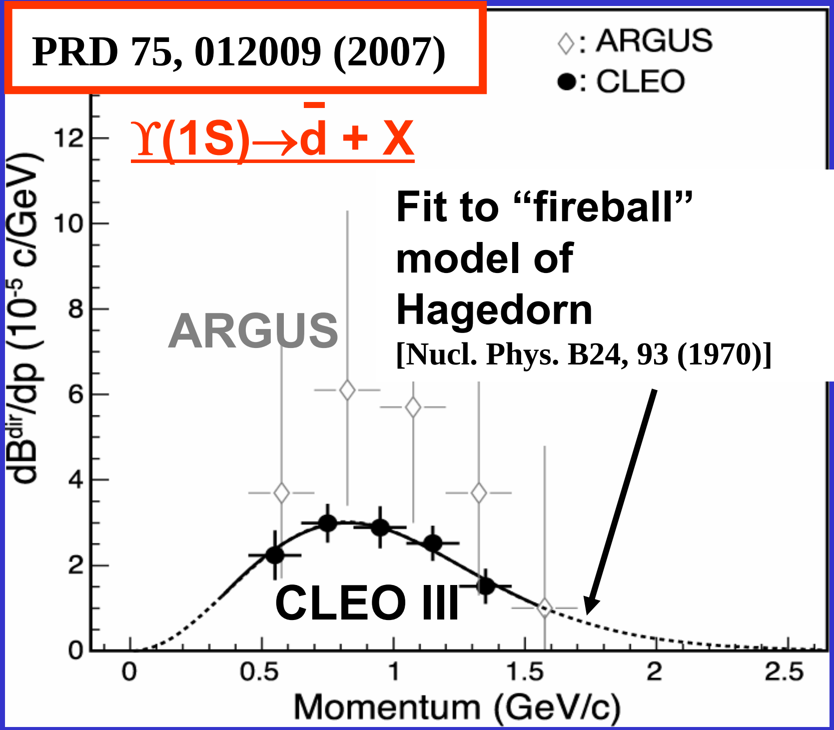
Normalized dE/dx for anti-d

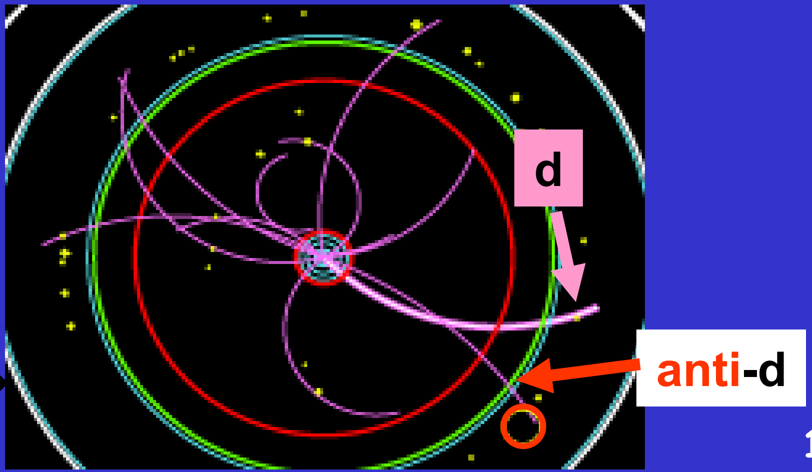
Anti-d Production Result

- $B^{*}(\Upsilon(1S)\to\bar{d}X) =$
  $(3.36 \pm 0.23 \pm 0.25) \times 10^{-5}$
  - based on 338 events
- $B(\Upsilon(2S)\to\bar{d}X) =$
  $(3.37 \pm 0.50 \pm 0.25) \times 10^{-5}$
  - based on 58 events
- $B(\Upsilon(4S)\to\bar{d}X) < 1.3 \times 10^{-5}$
  - based on 3 events
- $B(\gamma^{*}\to q\bar{q}\to\bar{d}X) < 1 \times 10^{-5}$
  - based on 4.5 events

- Hence $(ggg + \gamma gg)$ is about 3 times more likely than $\gamma^{*}\to q\bar{q}$ to produce deuterons

- How often is an anti-d compensated by a d as compared to (n, p) combinations?
  - We see roughly equal compensation by nn, np, pp relative to each other
  - ~1% of the time a d compensates
  - 3 d anti-d events observed





BSM Decays of Bottomonium

Υ Decays to Invisible Particles

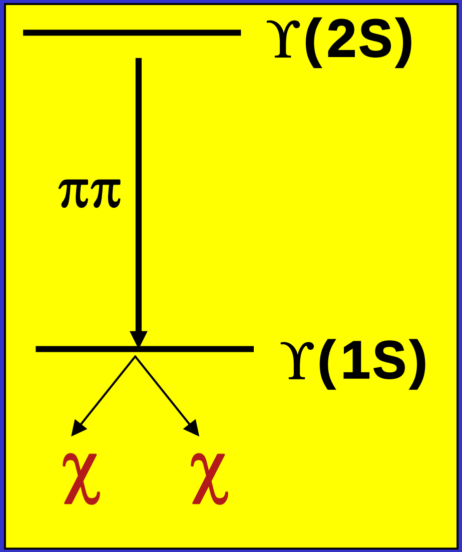
- **Onia decays to undetectable particles are a window on physics Beyond the Standard Model:**
- Dark matter candidate, χ?
  - $B(\Upsilon(1S) \to \chi\chi) = 0.41\%$ **McElrath [PRD72, 103508 (2005)]**
- New gauge bosons? Light gravitino? **Fayet [PRD74, 054034 (2006)]**
- $\nu\nu$ via Z^0 a very small potential background

But how does one "see" such invisible decays?

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

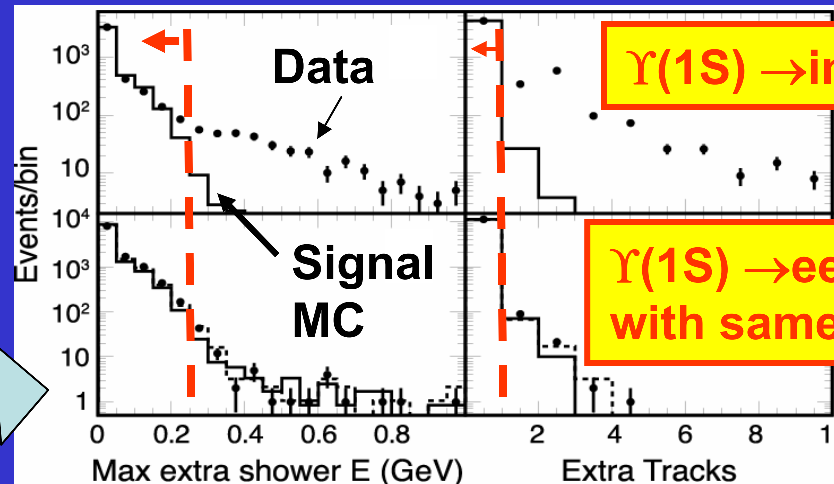
Require recoil against $\pi\pi$ be Υ

Require detector otherwise empty

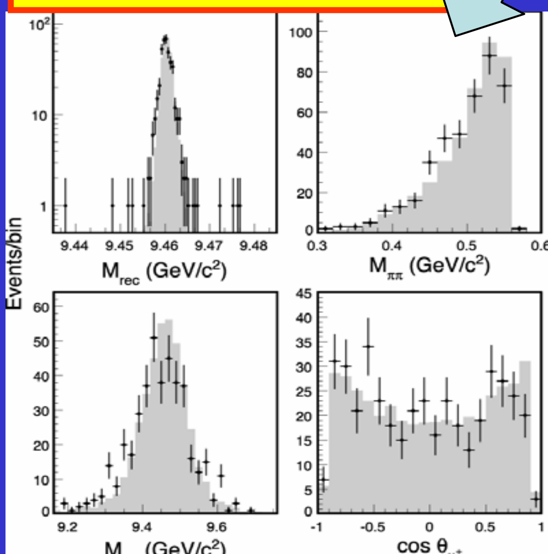


Result for ϒ(1S)→Invisible

- Require low calorimeter energy & zero tracks
- "2-track" trigger that will fire for signal events was (unfortunately) prescaled by a factor of 20 for CLEO III
- Use $\Upsilon(2S) \rightarrow \pi\pi\ \Upsilon(1S)$, $\Upsilon(1S) \rightarrow ee\ \&\ \mu\mu$ as the standard candle to make sure we understand our efficiency



ϒ(1S) →ee & μμ with same trigger

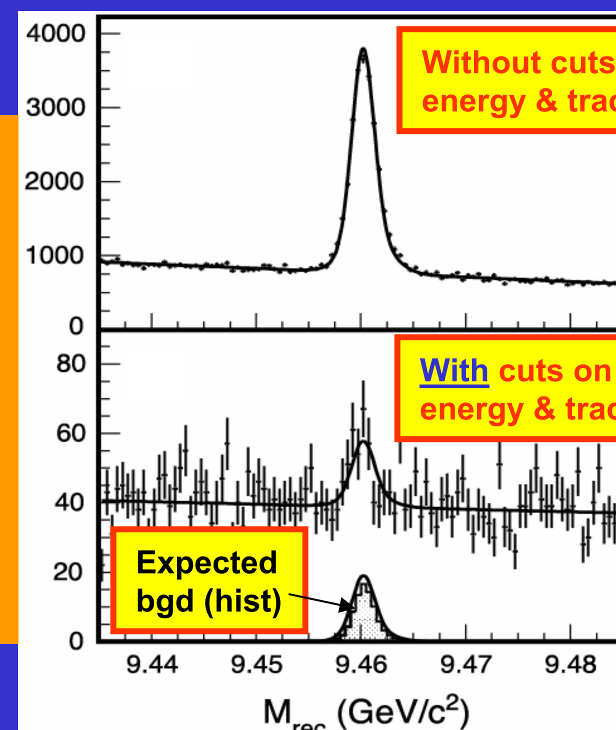


Sys error set in part by level of agreement observed

$N_{evt} = 31 \pm 24 \pm 10$

B[ϒ(1S)→Invis] <0.39% @90%CL

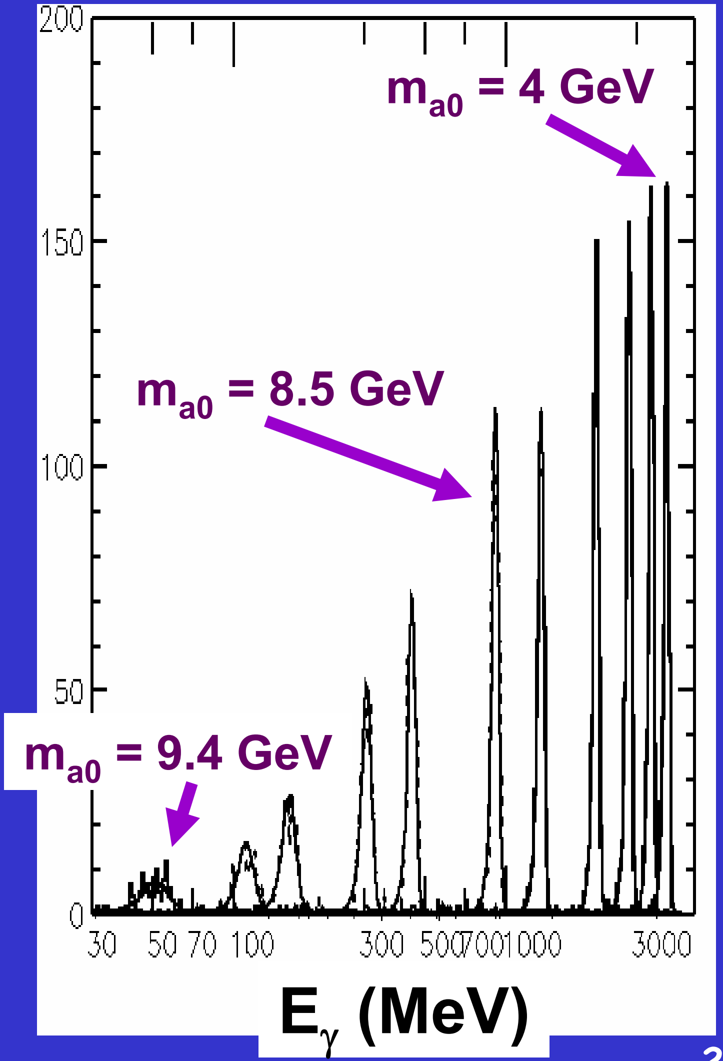
PRD 75, 031104 (2007)



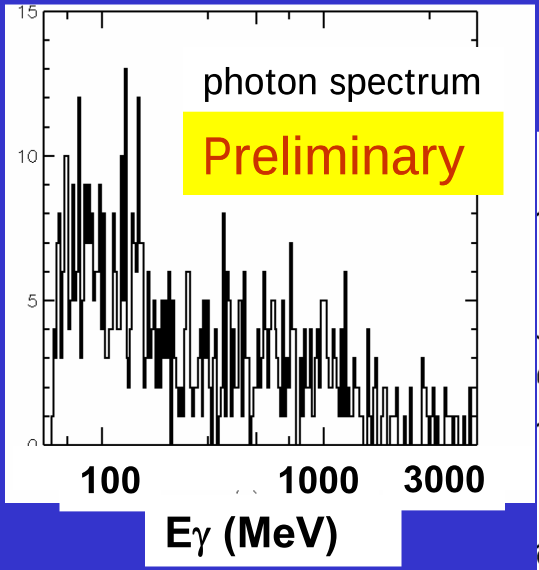
$\Upsilon(1S) \to \gamma$ + light Higgs

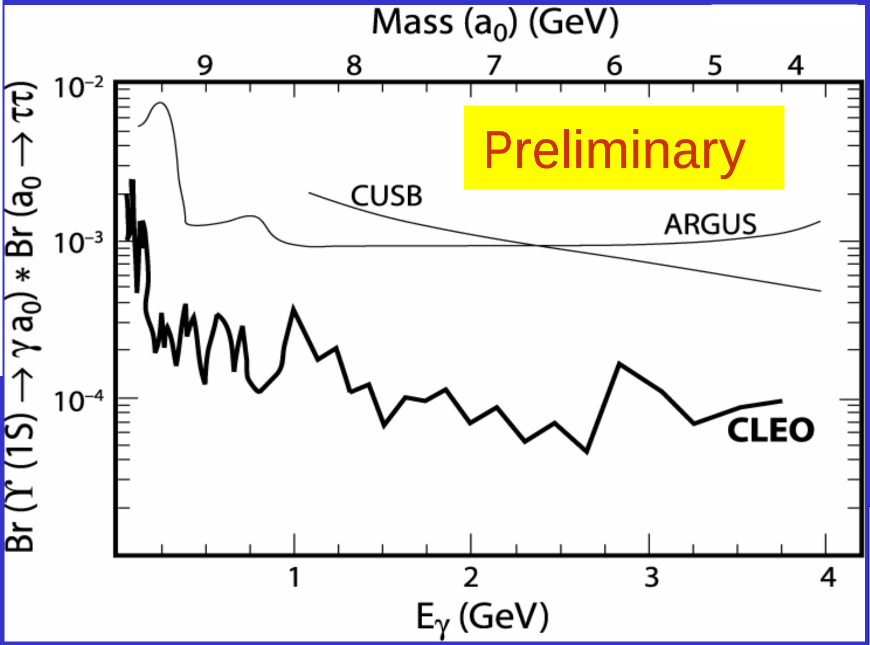
- **Dermisek, Gunion, McElrath**

  [hep-ph/0612031] **add to the MSSM a non-SM-like pseudoscalar Higgs a_0 with $m_{a0} < 2m_b$ "NMSSM"**
  - "natural", avoids fine tuning
  - evades the LEP limit $M_h > 100$ GeV since $h \to a_0 a_0$, but $a_0 \to bb$ and LEP sought b jets
  - $a_0 \to \tau^+\tau^-$ should dominate 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



NMSSM Light Higgs Result





ULs improved an order of magnitude or more

Rules out many, but not all NMSSM models for $2m_\tau < m(a_0) < 9$ GeV

Assumes a "narrow" a_0, where "narrow" is w.r.t. shower energy resolution, which is $\sim 2\% \times E_\gamma$ above 1 GeV

Conclusions

- $M(\pi\pi)$ distributions in $\Upsilon(3S)\to\pi\pi\Upsilon(1S)$, $\Upsilon(3S)\to\pi\pi\Upsilon(2S)$, $\Upsilon(2S)\to\pi\pi\Upsilon(1S)$ can all be explained via 2D fits using angular information without any "anomalies"
- 1st Observation of $\chi_{bJ}\to$Open Charm
  - B(χ_{b1}(nP) $\to$ open charm) ~ 25%, consistent w/NRQCD (Preliminary)
- 1st Observation of $\Upsilon(2S)\to\eta\Upsilon(1S)$ (Preliminary)
  - B[$\Upsilon(2S)\to\eta\Upsilon(1S)$] = ($2.51\pm0.71\pm0.50$) $\times 10^{-4}$
- *(ggg + γ gg)* is about 3 times more likely than $\gamma^*\to q\bar{q}$ to fragment into deuterons (Preliminary)
- B[$\Upsilon(1S)\to$Invis] <0.39% @90%CL
- B[$\Upsilon(1S)\to\gamma\, a_0$]$\times$B($a_0\to\tau^+\tau^-$) < ~10^{-4}
  for narrow a_0 with $M(a_0)$=4-9 GeV (Preliminary)
- **New CLEO III bottomonium results continue to flow for common, rare, & BSM decays**

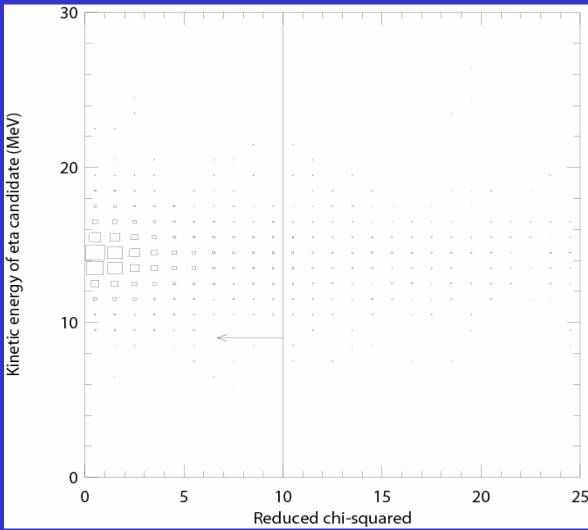
Backup Slides

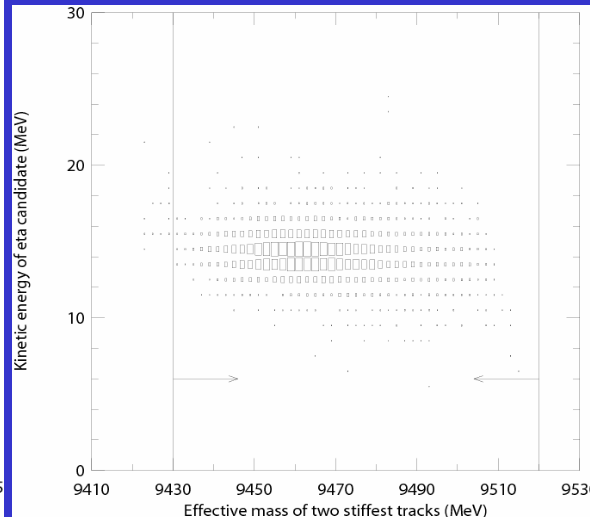
Basics of $\Upsilon(2S) \to \eta/\pi^0\ \Upsilon(1S)$

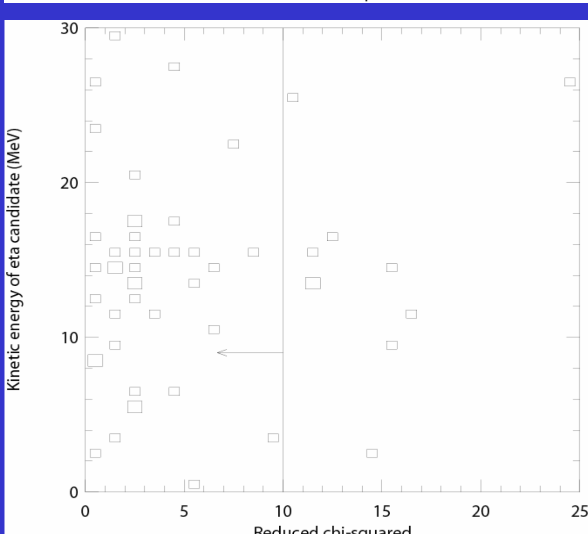
- 9.32×10^6 $\Upsilon(2S)$ produced in CLEO III dataset
- Use $\Upsilon(1S) \to ee$ & $\mu\mu$.
  - B~5% total (for J/ψ, was ~12%)
- Use $\eta, \pi^0 \to \gamma\gamma$ & $\eta \to \pi^+\pi^-\pi^0$
- Unlike the $\psi(2S)$ incarnation, here we need to exploit the improved resolution obtained from kinematic fitting:
  - constrain final state particles to the known center-of-mass 4-momentum: χ^2/dof < 10
- Require M($l^+ l^-$) = [-20,+30] MeV around M[$\Upsilon(1S)$]
- Extract signal by looking for a peak in the
  - Mass of the $\pi^0 \to \gamma\gamma$ or $\eta \to \pi^+\pi^-\pi^0$ candidate
  - Kinetic energy (KE) of the $\eta \to \gamma\gamma$: KE = $E_{\gamma 1} + E_{\gamma 2} - m(\gamma\gamma)$
    - Peak expected at ~15 MeV
    - Slightly better resolution than using the η-candidate mass
      - due to an accident of the kinematics
      - partly compensates for calorimeter resolution effects

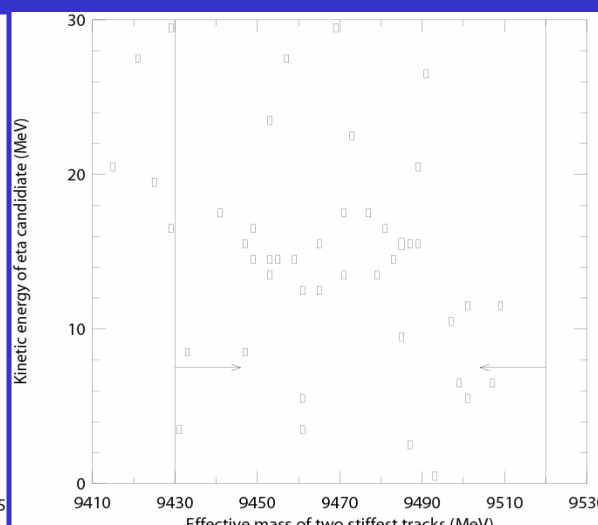
Backgrounds

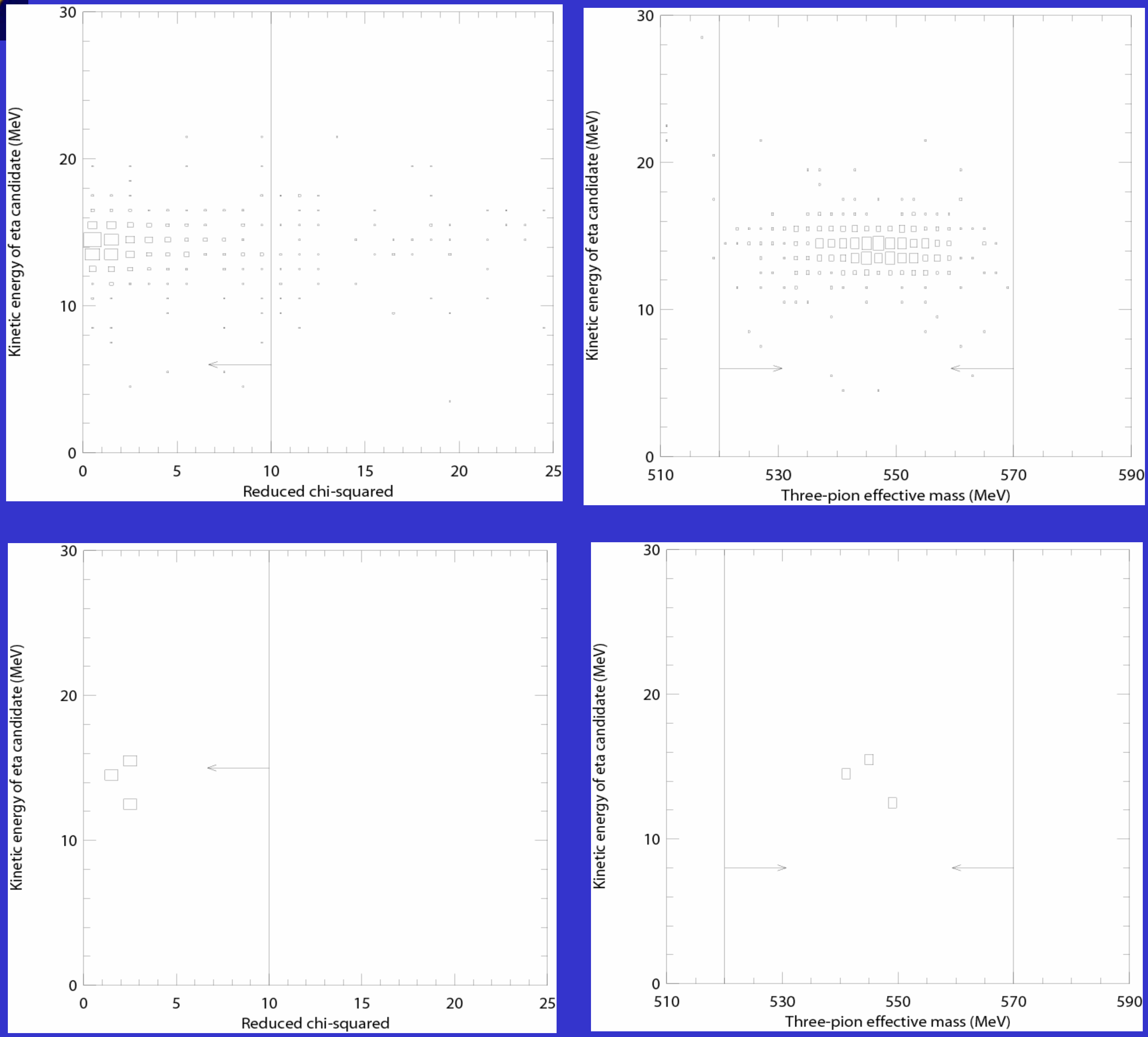
- For η, $\pi^0 \to \gamma\gamma$:
  - $e^+e^- \to l^+ l^- \gamma \gamma$ (mostly Bhabhas w/2 extra showers)
    - MC estimate not practical nor reliable: large σ_{Bhabha}
      - Suppress with $\cos\theta_+ < 0.5$ (Bhabhas have e^+ forward)
    - $\Upsilon(2S) \to \pi^0 \pi^0 \Upsilon(1S)$ with 2 asymmetric $\pi^0 \to \gamma\gamma$ decays
    - Dangerous due to large branching fraction (~9%)
- For $\eta \to \pi^+\pi^-\pi^0$, we can't yet find any backgrounds
- Estimate the backgrounds in several ways
  - KE or mass <u>sidebands</u> in <u>on-resonance</u> data
  - For continuum backgrounds, use <u>below-Υ(2S) data</u> where we have about a third of the on-Υ(2S) luminosity
    - Here we have to define a "pretend" M[Υ(1S)] mass window which reproduces the correct KE of the η
  - MC for $\Upsilon(2S) \to \pi^0 \pi^0 \Upsilon(1S)$ normalized to data
    - Scale MC prediction for leakage into the η signal by the observed number of fully reconstructed $\pi^0 \pi^0 \Upsilon(1S)$


Kinetic energy of eta candidate (MeV)
Reduced chi-squared
0 5 10 15 20 25
0 10 20 30


Kinetic energy of eta candidate (MeV)
Effective mass of two stiffest tracks (MeV)
9410 9430 9450 9470 9490 9510 9530
0 10 20 30

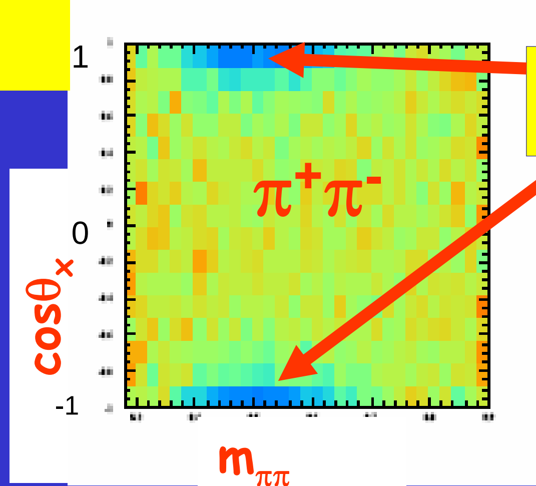

Kinetic energy of eta candidate (MeV)
Reduced chi-squared
0 5 10 15 20 25
0 10 20 30

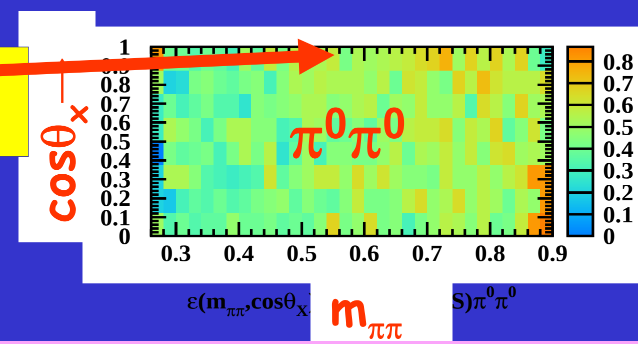

Kinetic energy of eta candidate (MeV)
Effective mass of two stiffest tracks (MeV)
9410 9430 9450 9470 9490 9510 9530
0 10 20 30



Kinetic energy of eta candidate (MeV)
Reduced chi-squared
Kinetic energy of eta candidate (MeV)
Three-pion effective mass (MeV)
Kinetic energy of eta candidate (MeV)
Reduced chi-squared
Kinetic energy of eta candidate (MeV)
Three-pion effective mass (MeV)

Efficiency





Sensitivity to B term comes precisely where efficiency in $\pi^+\pi^-$ falls steeply. This made $\pi^0\pi^0$ essential for verifying the presence of this term.