Searches for Invisible Decays of Charmonium

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Elba SuperB Meeting
Elba, Italy
June 1st, 2008

Motivation

Current work inspired by a conversation with Bob McElrath at Valencia SuperB meeting:

"...too bad BABAR can't set a limit on invisible decays of the J/ψ..."

References:

- B. McElrath, Light Higgses and Dark matter at Bottom and Charm Factories, arXiv:0712.00116v2 [hep-ph]
- J. Gunion, D. Hooper and B. McElrath, Light Neutralino Dark Matter in the NMSSM, hep-ph/0509024.

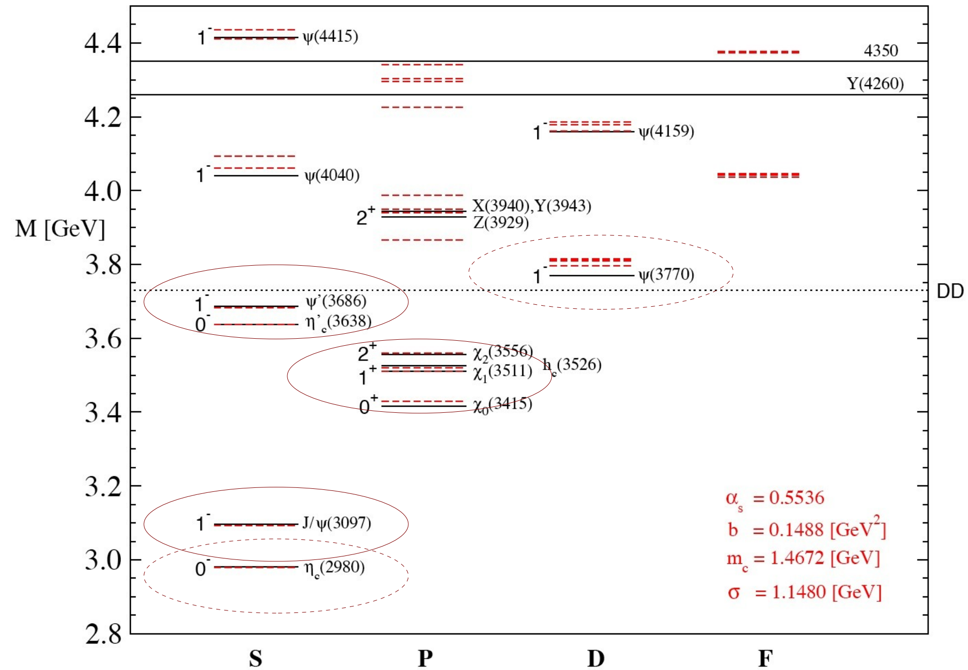
Introduction

Searches for invisible decays of quarkonium resonances motivated by need for dark matter candidate

- Light (pseudoscalar) Higgs/light gauge boson can act as a mediator of quarkonium decay in well-motivated New Physics models e.g. NMSSM.

Neither light Higgs/gauge boson nor light dark matter candidates are ruled out by *direct* experimental constraints

- Same models that were used to motivate the BABAR Bottomonium runs at the beginning of 2008
- Naïve model anticipates that narrow quarkonia states are best candidates (annihilate into flavor-conserving mediator)



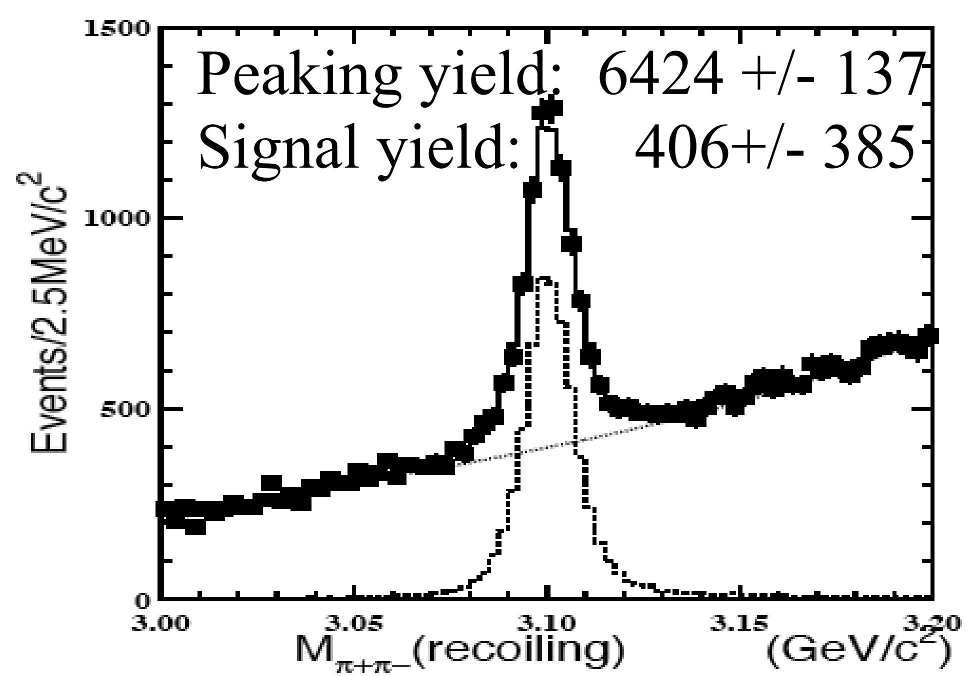
Other J/ψ→invisible searches

Problem: how do you identify an invisible final state?

- Upsilon search exploits cascade to Υ(1S) to tag the bottomonium state (i.e. identify the transition photon)
- BES reported a limit on $J/\psi \rightarrow$ invisible by searching for $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$
  - $B(J/\psi \rightarrow \text{invisible}) / B(J/\psi \rightarrow \mu^+ \mu^-) < 1\times10^{-2}$ based on a sample of 14M $\psi(2S)$ decays

    (arXiv:710.0039 [hep-ex])

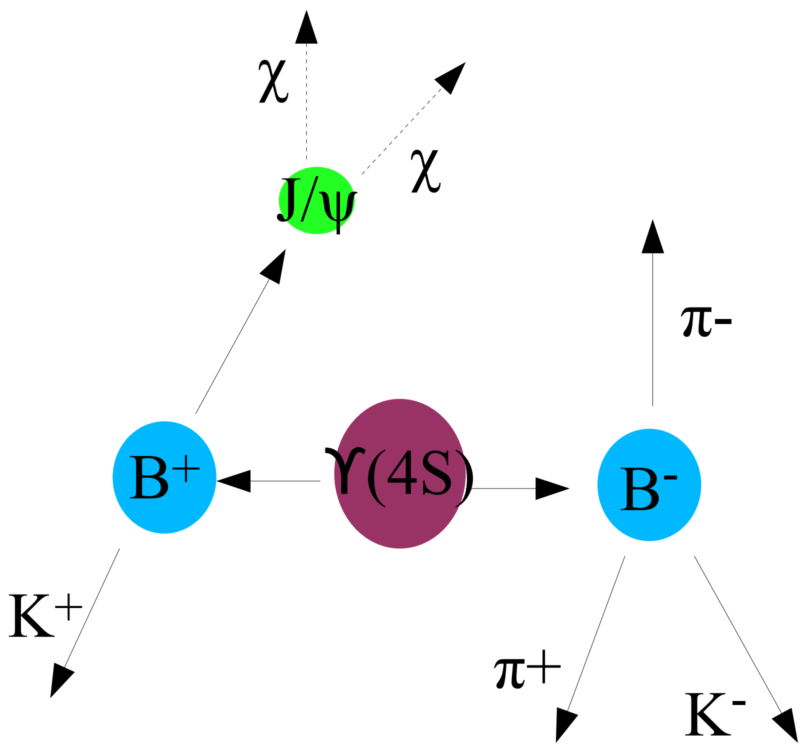
⇒ Limit driven by (irreducible) peaking background contribution



SuperB Method

Can use a similar trick using B's to tag the charmonium decay:

- Kinematic advantage over BES that J/ψ daughters are not back-to-back in lab frame – unlikely that all daughters will be outside of fiducial acceptance



- Need B^+ 4-vector to obtain J/ψ recoil mass, hence hadronic tag reconstruction
- As usual, disadvantage is the low tag efficiency, compounded by low signal B→charmonium branching fractions :
  - $B^{+/0} \rightarrow J/\psi K^{+/0}$
  - $B^{+/0} \rightarrow \psi(2S) K^{+/0}$
  - $B^{+/0} \rightarrow \eta_c K^{+/0}$
  - $B^{+/0} \rightarrow \chi_{c1} K^{+/0}$
  - $B^{+/0} \rightarrow \psi(3770) K^{+/0}$

Br ~(5-10) $\times 10^{-4}$

K* and Kππ can be used as well...

Hadronic tag reconstruction

Use tag reconstruction (aka “recoil method”) for decays which otherwise lack sufficient constraints to identify the signal

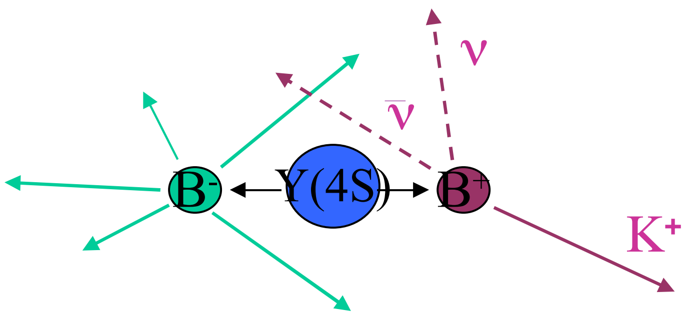
- BABAR uses a method based on a $D^{(*)}$ seed, to which individual charged and neutral pions and kaons are added until a B candidate is identified

Advantages:

- clean separation of signal and tag decay products
- strong suppression of (and precise determination of) continuum backgrounds
- knowledge of tag (and hence signal B) 4-vector
- improved determination of missing energy

Disadvantage:

- efficiency



$B^- \rightarrow D^{(*)0} X^-$
- $\rightarrow K^- \pi^+$
- $\rightarrow K^- \pi^+ \pi^0$
- $\rightarrow K^- \pi^+ \pi^- \pi^+$
- $\rightarrow K^0_s \pi^+ \pi^-$

$B^{+/-}$ tag reconstruction

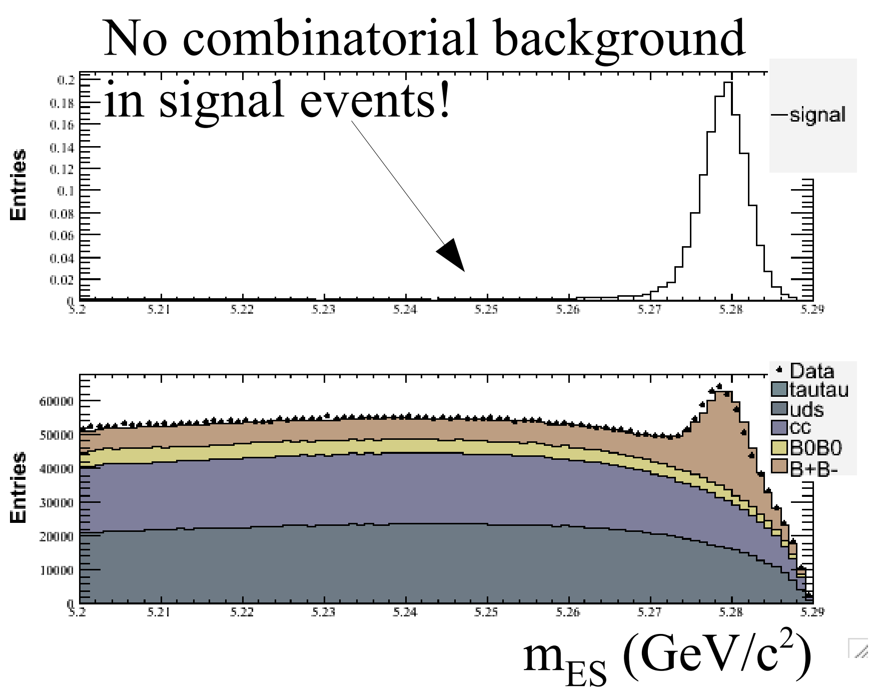
Realistic tagging efficiency (per $B^{+/-}$) of ~0.24% in events containing a low-multiplicity "signal" event

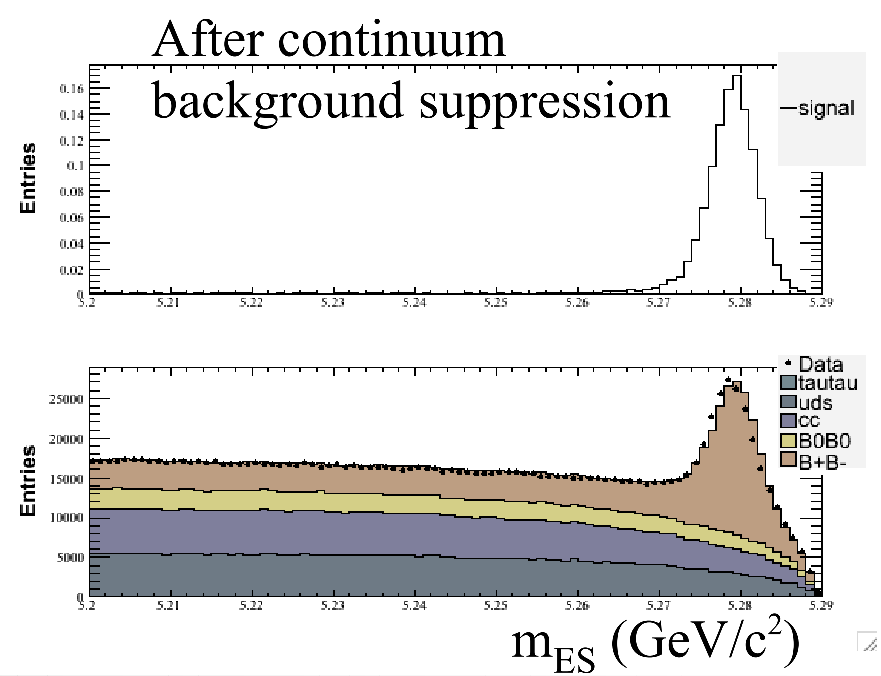
- typically "signal-side" selection is fairly efficient (~10% - 70%)

Assuming 30% gives "single-event sensitivity" at:

$Br(B \rightarrow \text{rare}) \sim 3 \times 10^{-6}$ with 500 fb^{-1}

$Br(B \rightarrow \text{rare}) \sim 5 \times 10^{-8}$ with 75 ab^{-1}





Neutral B tags

- Realistic tagging efficiency (per B^0) of ~0.16% in events containing a low-multiplicity "signal" event
- Assuming 30% gives "single-event sensitivity" at

  $Br(B \rightarrow \text{rare})$ ~4.5×10^{-6} with 500 fb^{-1}

  $Br(B \rightarrow \text{rare})$ ~7×10^{-8} with 75 ab^{-1}

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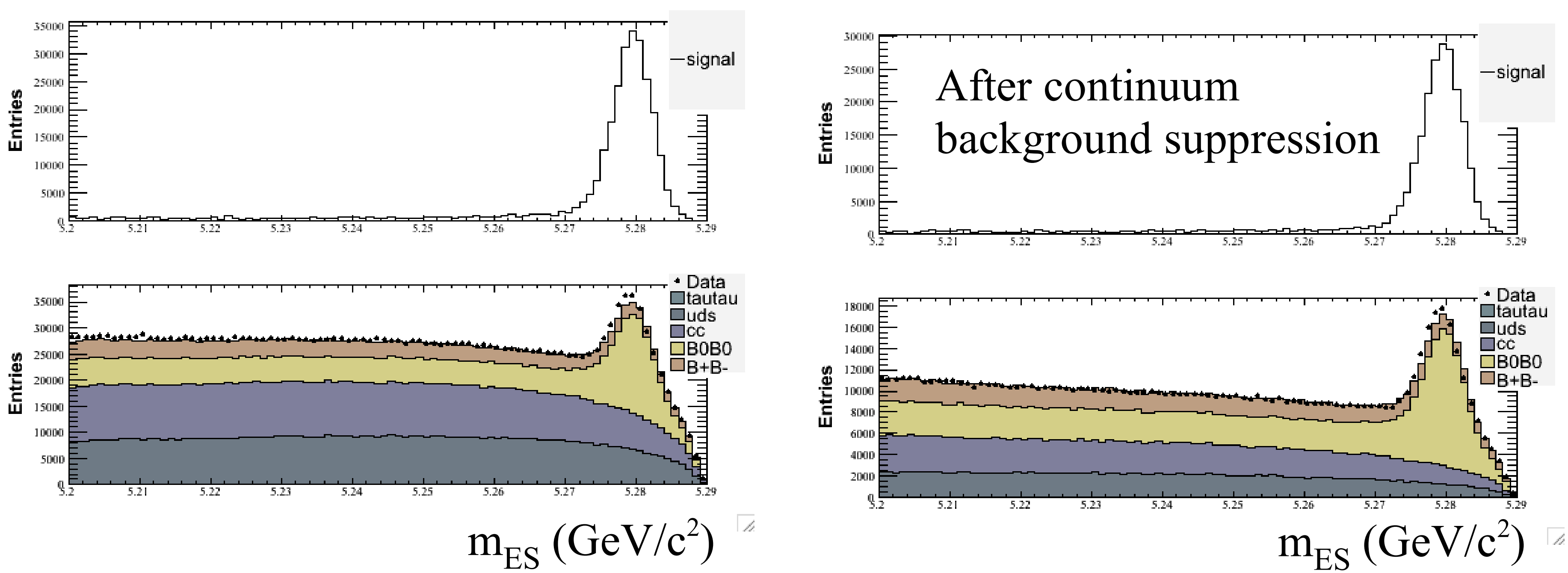
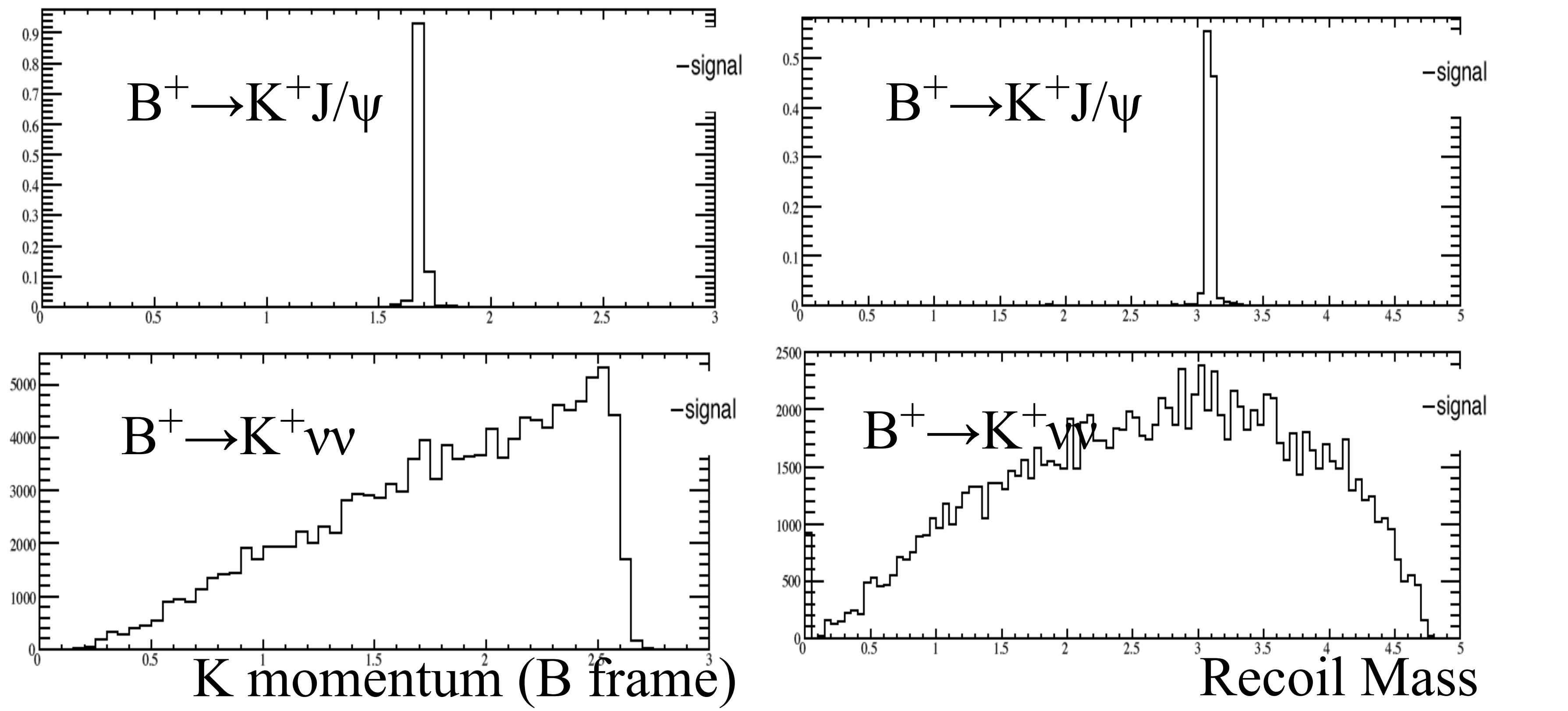


B→ $K^{(*)}\nu\nu$ Selection

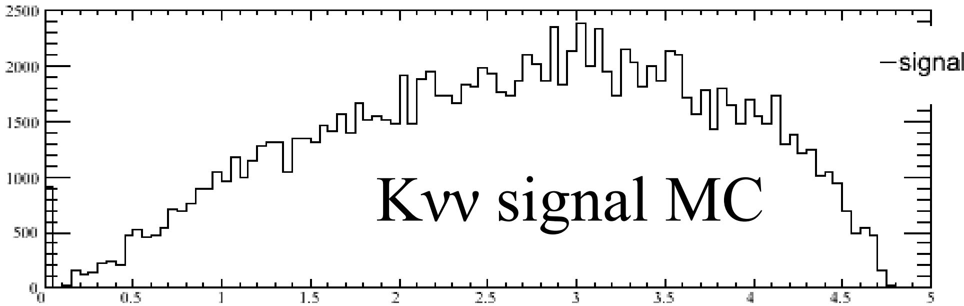
Charmonium selection is identical to $B^+ \to K^+\nu\nu$ analysis

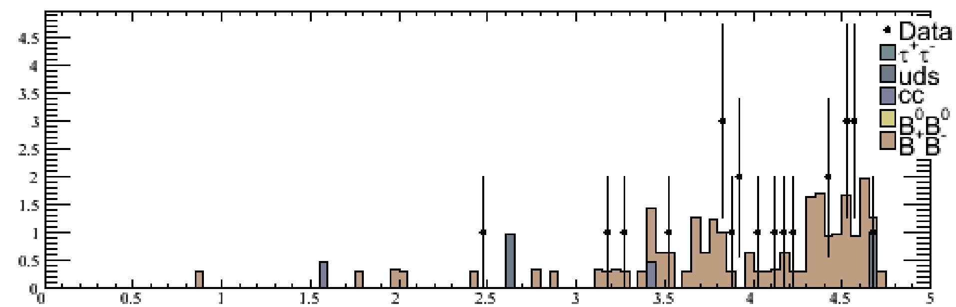
- Only difference is that charmonium events populate limited kinematic region of kaon momentum:



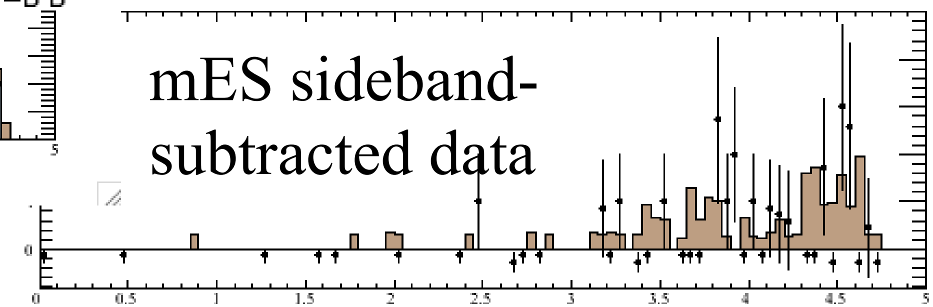
- Signal selection requires identifying a single charged kaon (and no other tracks) then restricting residual activity in the calorimeter

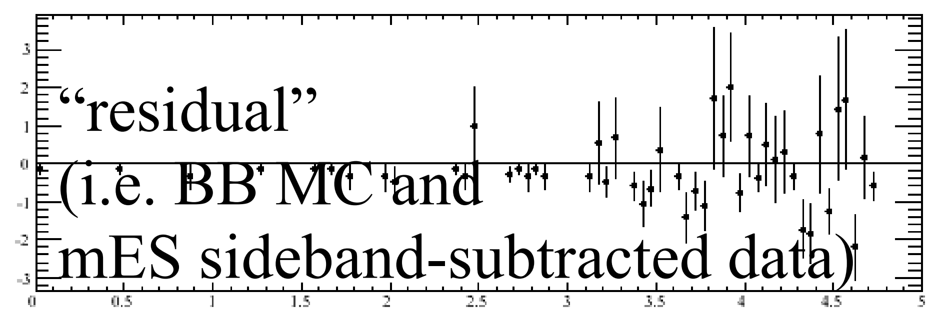
BABAR Result (almost...)





- Some naïve suggestion of an excess in data, but consistent with continuum (i.e. observed also in m_{ES} sideband)
  - perform explicit sideband subtraction to remove dependence on non-BB MC:





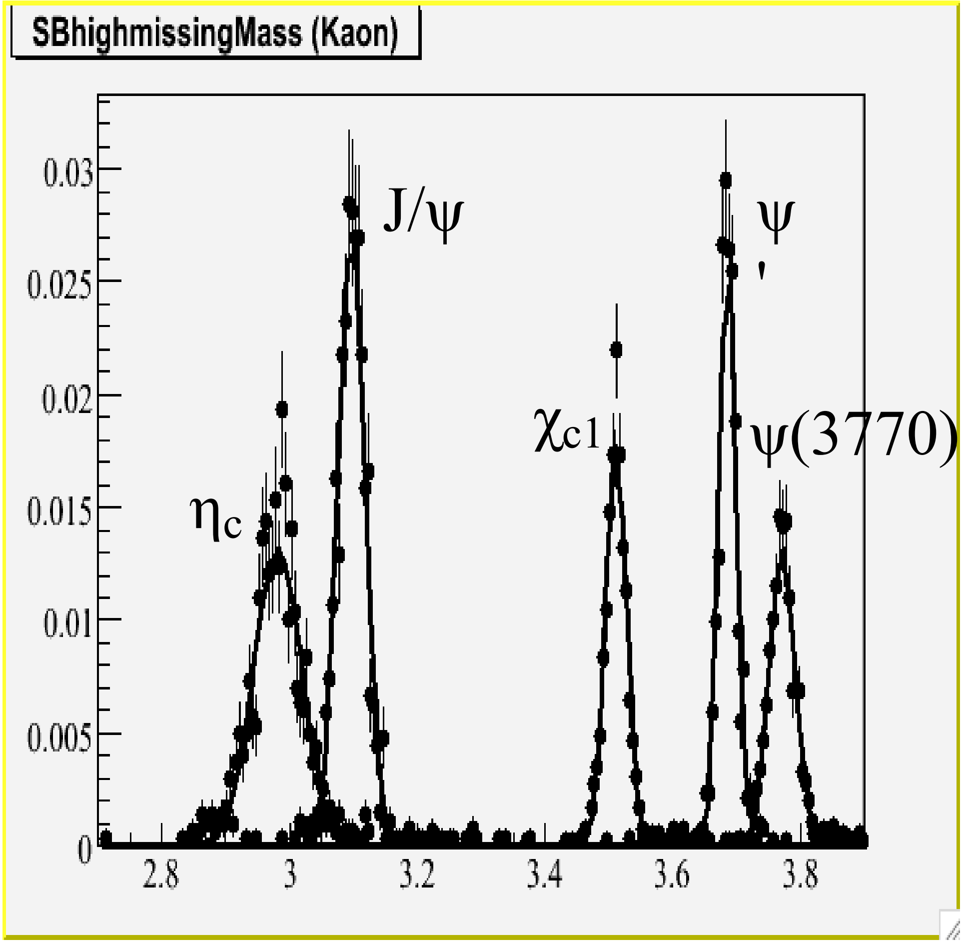
- Plots correspond to luminosity of ~100 fb^{-1}
  - "Easiest" invisible signal extraction method would be a simple 1-d fit of a "peaking" function on above a ~flat background

Other charmonium states

Obviously, the same method can be used with similar effectiveness for various other charmonium final states...

- Only difference is the specific branching fractions to the K+charmonium final state, and the (effective) width of the charmonium resonance
- For narrow states, the measured width is dominated by detector resolution (MC widths appear to be ~15-20 MeV for BABAR); only η_c seems to be significantly broadened by natural width

  ⇒ limit sensitivity just proportional to B decay branching fraction to charmonium final state (in the absence of pathological backgrounds)



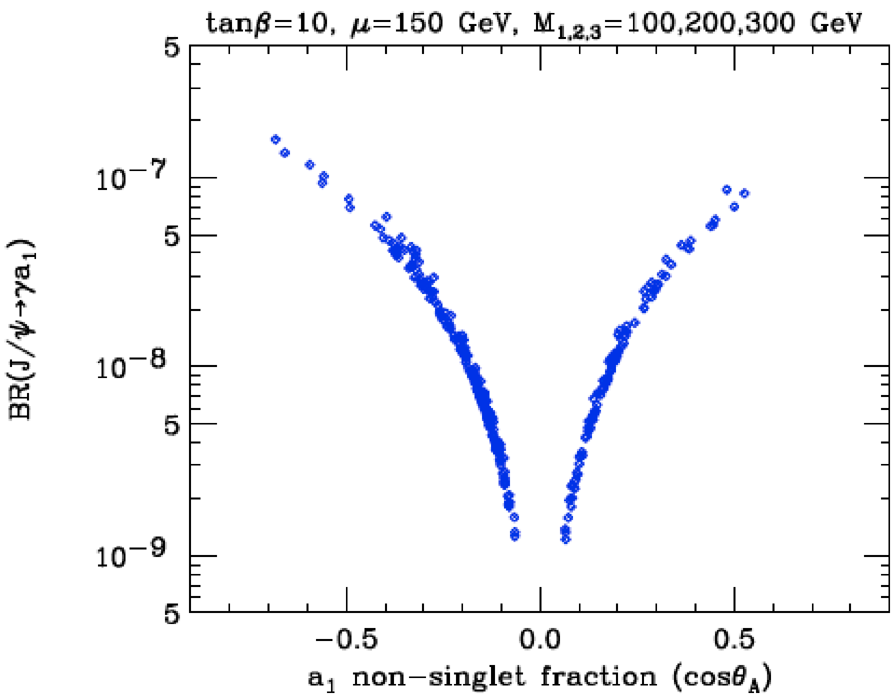
Radiative modes

Can also search for lightest pseudo-scalar Higgs in radiative decays of $J/\psi \to a_1 \gamma$ etc, where the a_1 decays invisibly

- Constraints obtained in charmonium are not redundant with bottomonium limits:

$$BR(\Upsilon \to \gamma a_1) \propto \cos\theta_A \tan\beta$$
$$BR(J/\Psi \to \gamma a_1) \propto \cos\theta_A \cot\beta,$$

- tests flavour-conserving decays, in contrast to $b \to s\chi\chi$ (i.e. $B \to K^{(*)}\nu\nu$) which is flavour-changing



Currently no published limits (that I know of...)

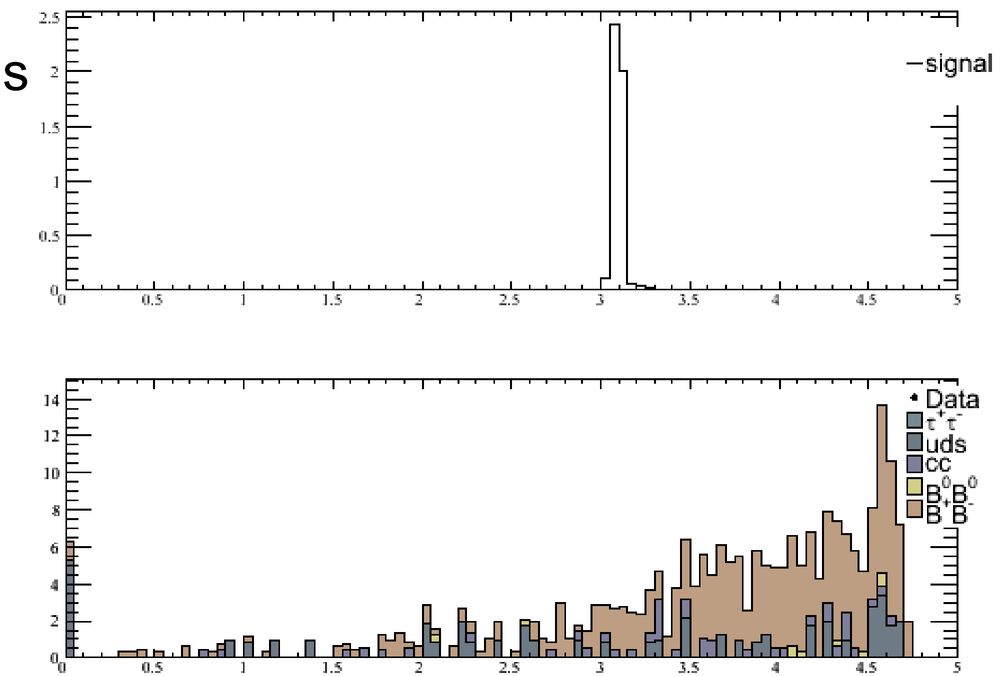
Plot from

arXiv:0712.00116v2 [hep-ph]

Radiative modes (cont)

Selection is essentially the same as invisible modes, except that the highest energy photon (excluding “tag” B photons) is retained

- Can't show full selection, but no evidence of peaking backgrounds in full BABAR MC
- 2-body kinematics of $J/\psi \to a_1 \gamma$ means that signal will produce a peak in the photon energy spectrum as well as the recoil mass
    - ⇒ potentially even lower backgrounds than invisible modes!
- Need to think about possible peaking background sources, but naïve SuperB sensitivity at level of $Br(J/\psi \to a_1 \gamma) \sim (few) \times 10^{-5}$ with $75 ab^{-1}$ using only $B^+ \to K^+ J/\psi$



Recoil mass (GeV)

Scaled to $425 fb^{-1}$
No restriction on calorimeter energy or multiplicity

Peaking backgrounds?

Serious problem for BES measurement, but in BABAR/SuperB charmonium state is boosted such that it is unlikely that all decay products simultaneously are outside of fiducial acceptance

- No evidence of peaking backgrounds from real $B \to J/\psi K$ in generic MC
  - Have also checked directly using $B \to J/\psi K$ exclusive modes (also $\psi(2S)$, η_C χ_{C1} and $\psi(3770)$ exclusive modes) but total equivalent luminosity only ~$5 ab^{-1}$
  - BES also claims a (smaller) peaking contribution from almost-invisible processes which may or may not be included in our MC e.g. $nn\gamma$ - need to understand this to claim an observation, but not to quote a limit.
- Analysis performance relies on detector hermeticity, calorimeter "junk" occupancy etc etc..

Conclusion

Light dark matter candidates, Higgses and/or gauge bosons can occur in reasonably well motivated extensions of the MSSM and are not ruled out by direct experimental evidence

B recoil technique provides a means to search for invisible/radiative decays of charmonium states, although with quite low efficiency

- Limits/discovery sensitivities to level of Br ~10^{-5} with $75ab^{-1}$ in each of several possible B decay modes (and depending on possible peaking backgrounds)
    - interesting reach, but does not exhaust full discovery potential
- Technique is probably extendable to other similar processes...