“Search for a light CP-odd Higgs boson in radiative decays of J/$\psi$”
Background (Motivation)

\[ \frac{\Gamma(V \to H\gamma)}{\Gamma(V \to \mu\mu)} = \frac{G_F m_q^2}{\sqrt{2} \pi \alpha} \left( 1 - \frac{m_H^2}{m_V^2} \right)^{1/2} \]


\[ B(V \to \gamma A^0) = \frac{G_F m_q^2 g_q^2 C_{QCD}}{\sqrt{2} \pi \alpha} \left( 1 - \frac{m_{A^0}^2}{m_V^2} \right), \quad (1) \]

- NMSSM expects very light mass Higgs boson which might be less than twice the mass of the charmed quark.

- Depending on \( \tan(\beta) \) and another mixing term \( \cos(\theta_A) \) (=between the newly added singlet & the rest)
SM Higgs

\[ \mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \]

\[ V = -\mu^2 \Phi^\dagger \Phi + \lambda^2 \left( \Phi^\dagger \Phi \right)^2 \]

\[ \langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v \end{pmatrix} \]

\[ m_H = \sqrt{2\lambda} v \]
Minimal Super Symmetric Model (MSSM)

\[ V_{\text{MSSM}} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \]

\[ + \frac{1}{8} \left( g^2 + g'^2 \right) \left[ |\Phi_1|^2 - |\Phi_2|^2 \right]^2 \]

\[ + \frac{1}{2} g^2 |\Phi_1^\dagger \Phi_2|^2 \]

Sometimes written as “\( \mu \)”, and it is free parameter

\[ \Phi_1 = \left( \begin{array}{c} H_1^+ \\ \frac{1}{\sqrt{2}} (v_1 + \eta_1 + i\zeta_1) \end{array} \right) \]

\[ \Phi_2 = \left( \begin{array}{c} H_2^+ \\ \frac{1}{\sqrt{2}} (v_2 + \eta_2 + i\zeta_2) \end{array} \right) \]

\[ m_A^2 = m_1^2 + m_2^2 \]

\[ m_{h,H}^2 = \frac{1}{2} \left[ m_A^2 + m_Z^2 \pm \sqrt{\left( m_A^2 - m_Z^2 \right)^2 + 4 m_A^2 m_Z^2 \sin^2 2\beta} \right] \]

\[ m_{H^\pm}^2 = m_A^2 + m_W^2 \]

\[ m_A, \tan \beta = v_1/v_2 \]
Next-to-Minimal Super Symmetric Model (NMSSM)

\[ V_{NMSSM} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 + m_N^2 |N|^2 \]
\[ - \left[ \lambda A_\lambda N \Phi_1 \Phi_2 + \frac{kA_k}{3} N^3 + h.c. \right] \]
\[ + |\lambda \Phi_1 \Phi_2 - kN|^2 + \lambda^2 \left( |\Phi_1|^2 + |\Phi_2|^2 \right)|N|^2 \]
\[ + \frac{1}{8} \left( g^2 + g'^2 \right) \left( |\Phi_1|^2 - |\Phi_2|^2 \right)^2 \]

expect more “Higgs” than MSSM
Why going to the NMSSM?

- **MSSM**

  \[
  m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[ \ln \frac{m_t^2}{m_H^2} + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12 m_t^2} \right) \right]
  \]

  \[X_t = m_t (A_t - \mu \cot \beta)\]

- **NMSSM: Mixing with singlet**

  \[
  m_h^2 \approx \lambda v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\text{rad}} + \Delta_{\text{mix}}
  \]

  Ellwanger, arXiv 1108.0157

  Increases Higgs mass for large values of \(\lambda\)

**Getting \(m_h = 126\) GeV for TeV instead of multi-TeV stops**
1. Introduction: The SM Higgs Sector

The SM → The Hierarchy Problem → The MSSM

One SM Higgs boson → The MSSM

The Hierarchy Problem → The μ-problem

The MSSM → The Peccei-Quinn Symmetric NMSSM → The Axion

5 Higgs bosons + 2 charged Higgsinos + 2 neutral Higgsinos

As NMSSM + extra $Z'$ → A local PQ symmetry

Domain Walls → The NMSSM → The mnSSM

6 Higgs bosons + 2 charged Higgsinos + 3 neutral Higgsinos
Background (Motivation)

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- NMSSM expects very light mass Higgs boson which might be less than twice the mass of the charmed quark.

- Depending on tan(\(\beta\)) and another mixing term \(\cos(\theta_A)\) (=between the newly added singlet & the rest)

\[ \frac{B(V \rightarrow \gamma A^0)}{B(V \rightarrow l^+ l^-)} = \frac{G_F m_q^2 g_q^2 C_{QCD}}{\sqrt{2} \pi \alpha} \left( 1 - \frac{m_{A^0}^2}{m_V^2} \right) \]
Data Set & Event Selection

Data: 225M $J/\psi$, collected in 2009

Channel: $J/\psi \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+ \mu^-$ (final state: 1 gamma+di-muon)

Event Selection:

-- charged track ( $|Vz| < 10.0$ cm, $|Vxy| < 1.0$ cm, $|\cos(\theta)| < 0.93$ )

-- gamma candidate ( $E > 25$ MeV (barrel), $E > 50$ MeV (endcap), $0 < t < 14$ )

-- angle separation between tracks$\&$gamma: 20 deg.

-- Muon identification

$E^\mu_{\text{cal}}/p < 0.9$, $0.1 < E^\mu_{\text{cal}} < 0.3$

$\Delta t^{\text{TOF}}$ (diff of TOF and expected time) $< 0.26$ ns

Require MUC depth: $(-40.0 + 70*p/(\text{GeV/c}))$ cm for $0.5 < p < 1.1$, or 40.0 ($p > 1.1$)

four-constraint (4C) kinematic fitting

$|\cos(\theta)^{\text{hel}}_\mu| < 0.92$ (angle between direction of muon $\&$ direction of $J/\psi$, in $A^0$ rest frame)
“Reduced mass” distribution and background components

“non-peaking background”

\[ e^+e^- \rightarrow \gamma \mu^+\mu^- \]

“peaking background”

\[ J/\psi \rightarrow \gamma f_2(1270); \ f_2(1270) \rightarrow \pi^+\pi^- \]

\[ J/\psi \rightarrow \gamma f_0(1710); \ f_0(1710) \rightarrow \pi^+\pi^- \]

\[ J/\psi \rightarrow \rho^-\pi^+, \ \rho^- \rightarrow \pi^-\pi^0 \]

\[ J/\psi \rightarrow \pi^-\rho^+, \ \rho^+ \rightarrow \pi^0\pi^+ \]

\[ m_{\text{red}} \] is equal to twice the muon momentum in the A0 rest frame and is easier to model near threshold than the dimuon invariant mass. “ (from the paper)
Ref: Reduced Mass?

Invariant Mass

\[ M^2 = (E_1 + E_2)^2 - | \vec{p}_1 + \vec{p}_2 |^2 \]
\[ = m_1^2 + m_2^2 + 2(E_1E_2 - \vec{p}_1 \cdot \vec{p}_2) \]

if both particles are muons,

\[ M_{\mu\mu}^2 = 2m_\mu^2 + 2(E_\mu - \vec{p}_\mu \cdot (-1)\vec{p}_\mu) = 4m_\mu^2 + 4|\vec{p}_\mu|^2 \]

Reduced Mass

\[ m_{\text{red}} = \sqrt{M_{\mu\mu}^2 - 4m_\mu^2} = 2|\vec{p}_\mu| \]
### PDF & Fitting

I(RK) am not familiar with those functions . . .

**Signal PDF**: sum of two Crystal Ball functions

**Background PDF (non-peaking)**: polynomial functions

**Background PDF (peaking)** \( \rho \): “Cruijff” function

\[
f_{L,R}(m_{\text{red}}) = \exp\left[-(m_{\text{red}} - \mu)^2/(2\sigma_{L,R}^2) + \alpha_{L,R}(m_{\text{red}} - \mu)^2\right].
\] (2)

**Background PDF (peaking)** \( f_2(1270)/f_0(1710) \): sum of two Crystal Ball functions

\[
f(x|\mu,\sigma,\alpha,n) = C \begin{cases} 
\exp(-\frac{(x-\mu)^2}{2\sigma^2}), & \frac{x-\mu}{\sigma} > -\alpha \\
\left(\frac{n}{|\alpha|}\right)^n \exp\left(-\frac{\alpha^2}{2}\right) \cdot \left(\frac{n}{|\alpha|} - |\alpha| + \frac{x-\mu}{\sigma}\right)^{-n}, & \frac{x-\mu}{\sigma} \leq -\alpha
\end{cases}
\]

Fig 2. Plot of the fit to the \( m_{\text{red}} \) distribution
The distribution of $S$ (significant) is expected to follow the normal distribution under the null hypothesis, consistent with the distribution in Fig. 4.

(from the paper)
The 90% C.L. upper limits (UL) on the product branching fractions $\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$ as a function of $m_{A^0}$ including all the uncertainties (solid line), together with expected limits computed using a large number of pseudoexperiments. The inner and outer bands include statistical uncertainties only and contain 68% and 95% of the expected limit values. The average dashed line in the center of the inner band is the expected average upper limit of 1600 pseudoexperiments. A better sensitivity in the mass region of $0.212 \leq m_{A^0} \leq 0.22 \text{ GeV}/c^2$ is achieved due to almost negligible backgrounds as seen in Fig. 2 (top).

The 90% C.L. upper limits on $g_b = g_c \tan^2 \beta \times \sqrt{\mathcal{B}(A^0 \to \mu^+\mu^-)}$ for the BABAR [16] and BESIII measurements and $\cos \theta_A = \frac{|g_b g_c|}{\sqrt{\mathcal{B}(A^0 \to \mu^+\mu^-)}}$ as a function of $m_{A^0}$. We compute $g_c \tan^2 \beta \times \sqrt{\mathcal{B}(A^0 \to \mu^+\mu^-)}$ for different values of $\tan \beta$ to compare our results with the BABAR measurement [16].
Summary

- Search was conducted for a light Higgs boson in the radiative decays of $J/\psi$, using large data sample taken in 2009.

- No significant signal and set 90% C.L. upper limit on $B(J/\psi\rightarrow\gamma A^0)xB(A^0\rightarrow\mu^+\mu^-)$ for $0.212 < M_{A^0} < 3.0$ GeV/c$^2$

- The combined limits on $\cos(\theta_A)\times\sqrt{B(A^0\rightarrow\mu^+\mu^-)}$ for BESIII & BABAR favor that the $A^0$ is to be mostly singlet.