Search for exotic scalars in the two-photon channel at *BABAR*

The 13th International Workshop on Tau Physics
Aachen (Germany) 15 - 19 September 2014

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University of Victoria

Outline

Introducing the *BaBar* Experiment

The pion-photon transition form-factor results

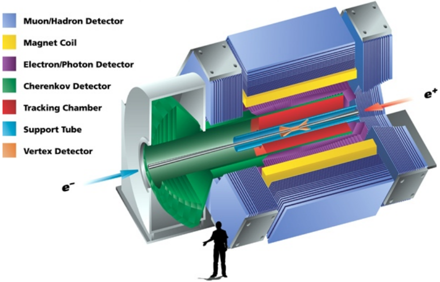
The new states hypothesis

Methodology for the search

Results

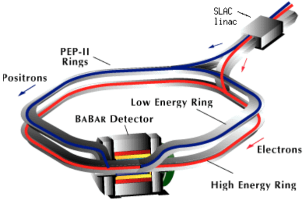
Conclusions

The *BABAR* experiment



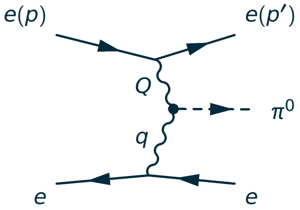
- Located at PEP-II asymmetric e^+e^- collider at the SLAC National Accelerator Laboratory
- Operated from 1999 to 2008
- Centre-of-mass energy $\sqrt{s} = 10.58\,\text{GeV}$, just above the $B\bar{B}$ threshold
- B-factory: optimized for B physics but excellent for τ and c studies
- $\Upsilon(4S)$ sample: $\mathcal{L} = 468\,\text{fb}^{-1}$

  $\approx 430 \times 10^6$ τ pairs



Measurement of the pion-photon transition form-factor at *BaBar*

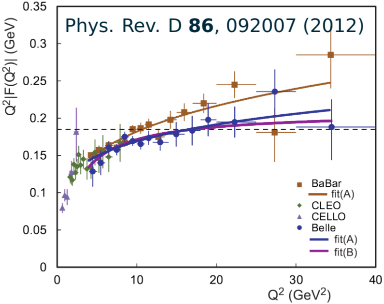
- Based on the two-photon — or "photon-fusion" — process:



+ charge conjugation

- Measurement becomes simpler when $q^2 \to 0$:
  - one photon is real or quasi-real
  - $F_{\pi^0}\left(q^2, Q^2\right) \to F_{\pi^0}\left(Q^2\right)$.
  - One $e^{\pm}$ reconstructed: "single-tag" measurement

Current results for $Q^2|F_{\pi^0}(Q^2)|$ from different experiments



Comparison $F_{\pi^0}\left(Q^2\right)$ measurements and models

- The pion form factor at sufficiently large Q^2 should approach the Brodsky-Lepage limit of

$$\sqrt{2} f_\pi / Q^2 \simeq 185\,\mathrm{MeV}/Q^2.$$

- At $Q^2 > 15\,\mathrm{GeV}^2$, this is a highly reliable prediction well beyond the non-perturbative QCD regime.

"No sign of convergence towards perturbative QCD asymptotics is seen in the *BaBar* data for the π^0"[1]

[1] D. McKeen, M. Pospelov and J.M. Roney, Phys. Rev. D **85**, 053002 (2012)

Potential for new states or particles

- Could observed excess come from an undiscovered process?[1]
- New theory allows objects coupling to the τ lepton (other couplings constrained by theory or other experiments).
- Candidates could be scalar (ϕ_S), pseudo-scalar (ϕ_P), or hardcore-pion (π^0_{HC}, a $\phi_P - \pi^0$ mixing).
- "pion impostors": $m_\phi \sim m_{\pi^0} \pm 10\,\mathrm{MeV}/c^2$, decay to $\gamma\gamma$

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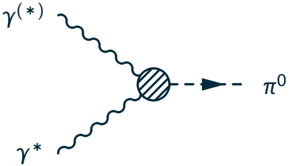

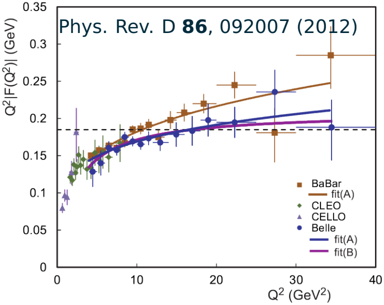

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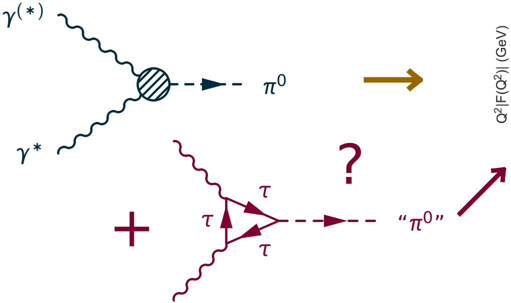

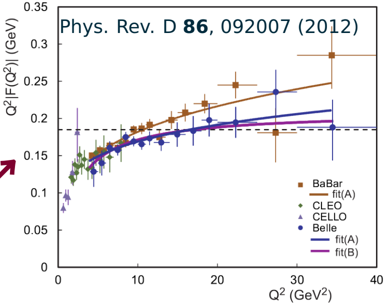

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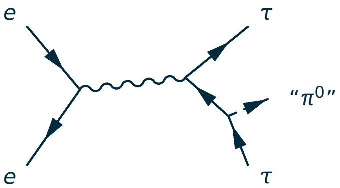
Production in e^+e^- collisions



+ charge conjugation

- Lowest cross section values[1] (at 95% CL) for $Q^2 > 8\,\text{GeV}^2$:

$$\sigma_{HCP} = 0.25\,\text{pb},\ \sigma_P = 2.5\,\text{pb},\ \text{and}\ \sigma_S = 68\,\text{pb}.$$

- This theory predicts at least 120×10^3, 1.2×10^6, or 32×10^6 of these events *produced* in the $\Upsilon(4S)$ BABAR dataset!

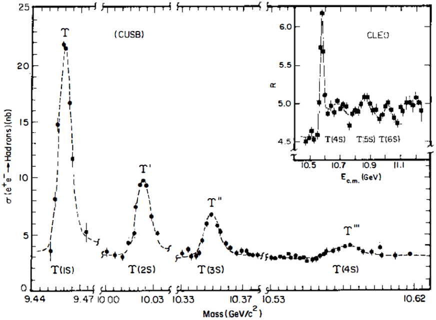
The goal of this project is to search for π^0-like particles in the BABAR data through their production in association with τ pairs

- Challenge is to suppress backgrounds to negligible levels

[1] D. McKeen, M. Pospelov and J.M. Roney, Phys. Rev. D **85**, 053002 (2012)

Data samples

- Use $\Upsilon(4S)$ sample: $\mathcal{L}_{\text{int}} = 468\,\text{fb}^{-1}$ ($\approx 430 \times 10^6$ τ pairs)
- $\tau^+\tau^-$ production simulated with KK2F, decays with `Tauola` and detector interaction from `GEANT4`
- Other simulated backgrounds: $\mu^+\mu^-$, $B\bar{B}$, $q\bar{q}$ ($q = u, d, s, c$), Bhabha.
- Retrieve and pre-select events on *BABAR*'s Long Term Data Access



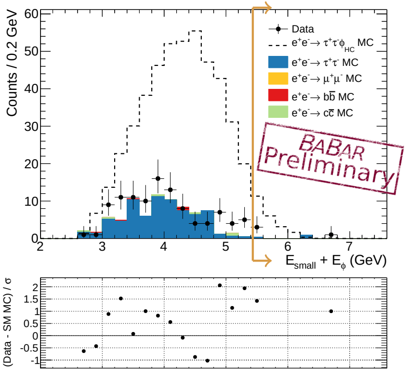
Event Selection

Signal: $e^+e^- \to \tau^+\tau^-$ "π^0" where "π^0" is not from τ decay

- Select $\tau^+\tau^- \to e^\pm\mu^\mp\nu_e\nu_\mu$
- Require $p_\perp > 0.3\,\mathrm{GeV}/c$
- Require one π^0: $\gamma\gamma$
  - $\sum E_\gamma(\text{non-}\pi^0) < 300\,\mathrm{MeV}$
- Require π^0 energy
  - $E_{\pi^0} \in [2.2,\ 4.7]$ GeV
- Reduce radiative γ
  - $E_\gamma \geq 250\,\mathrm{MeV}$
  - $30° \leq \theta(e,\gamma) \leq 150°$
- Reduce background from $\tau^+\tau^- \to 2\nu_\ell\ell^\pm + \pi^\mp\pi^0\nu_\tau$
  - $E_{small} + E_{\pi^0} > E_{CM}/2$
  - $m_{\pi^0\pi^\pm} > m_\tau$ for $\pi^\pm$ mis-ID'd as $\mu^\pm$

E_{small}: smaller of track energies

$E_{small} + E_{\pi^0}$ when this cut is lifted, events with $m_{\gamma\gamma} \in [100,\ 160]$ MeV/c^2



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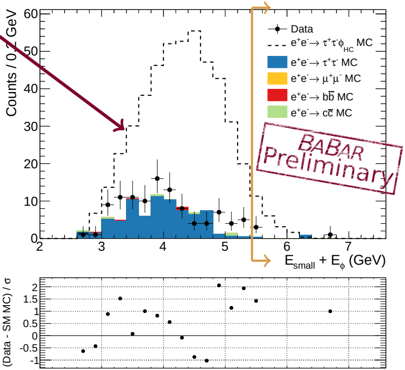

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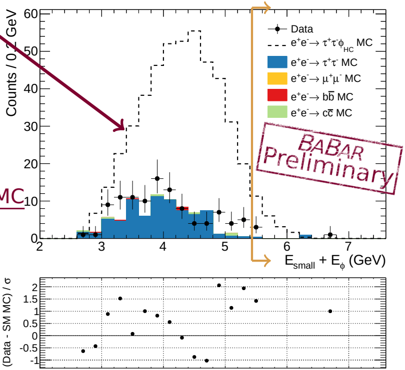
Minimal signal

$\frac{\text{Data} - \text{Standard Model MC}}{\text{Error}}$

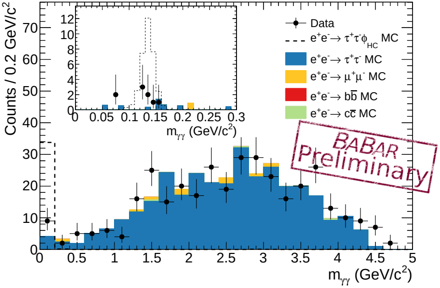


Using $m_{\gamma\gamma}$ to extract the yield

- Fit $m_{\gamma\gamma}$ with linear background model + Gaussian peak

$$n(m_{\gamma\gamma}) = N_{lin}\left(1 + a_1 m_{\gamma\gamma}\right) + N_p G\left(\mu_p, \sigma_p\right) \text{ for } m_{\gamma\gamma} \in [50, 300]\,\text{MeV}/c^2$$

$m_{\gamma\gamma}$ spectrum near signal region



- Extended unbinned max $\log(L)$ fit
- Fit for a_1, N_p and N_{lin}
- Get σ_p from control sample studies
- Scan mass hypotheses μ_p between 110 and 160 MeV/c^2
- Report highest yield in range

- Correct for peaking background and fit bias

Backgrounds and pseudo-experiments

Study of background:

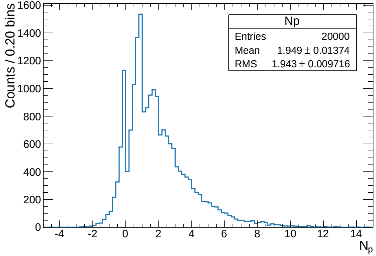
- Combinatorial background from fit
- Peaking background evaluation
  - From *BABAR* $e^+e^- \to \tau^+\tau^-$ simulation: 0.38 ± 0.09
  - But $\gamma\gamma$ physics not simulated: data-driven estimate for $e^+e^- \to e^+e^- \, \pi^+\pi^- \, \pi^0$: 0.86 ± 0.36
  - Peaking events total:

$$N_p^{\text{bkg}} = 1.24 \pm 0.37$$

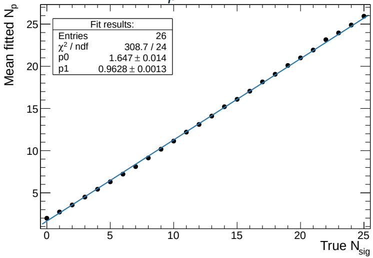
Study fit bias:

- Repeat study adding 0 – 25 events
- Correct for the average fit error (bias): -0.06 ± 0.02 events

Background-only distribution



Fitted N_p vs true value



These results will give the p-value of background hypothesis (p_0)

Signal efficiency calculations

- Generate $e^+e^- \to \tau^+\tau^-\ \pi^0$; 3-body decay phase space model
- Re-weight according to matrix element of actual process
- Fit using signal + linear background model

$$\varepsilon_P = (0.455 \pm 0.019)\% \qquad \varepsilon_S = (0.0896 \pm 0.004)\%$$

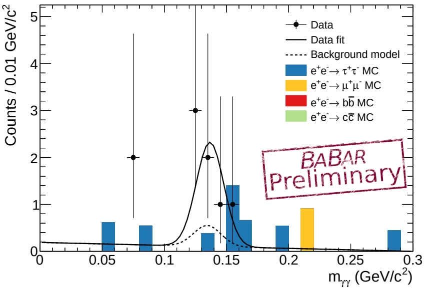
Tab.: Summary of the contributions to $\sigma(\varepsilon_x)$.

	$\varepsilon_{\phi_P,\pi^0_{\mathrm{HC}}}$	ε_{ϕ_S}
Nominal value	0.455%	0.0896%
Relative uncertainties		
MC statistics	3.5%	3.7%
π^0 efficiency	1.0%	1.1%
Particle identification	0.5%	0.5%
Momentum scale	0.2%	0.2%
Momentum resolution	0.1%	$<$0.1%
Energy scale	2.0%	2.0%
Energy resolution	0.6%	0.6%
Combined uncertainty	4.2%	4.4%

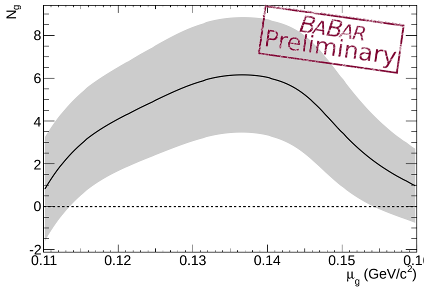
Final result

Extended likelihood fits and mass scan

Data $m_{\gamma\gamma}$ spectrum and fit



Number of peaking events vs mass



$$N_p = 6.2 \pm 2.7 \pm 0.06 \text{ @ } 137\,\text{MeV}/c^2$$

$$N_{sig} = N_p - N_p^{\text{bkg}} = 5.0 \pm 2.7 \pm 0.4$$

$$\sigma = \begin{cases} 37.7 \pm 20.5(\text{stat}) \pm 3.2(\text{syst})\,\text{fb} & \text{for } \phi_P \text{ and } \pi^0_{HC} \\ 191 \pm 104(\text{stat}) \pm 17(\text{syst})\,\text{fb} & \text{for } \phi_S \end{cases}$$

Limits on cross sections and compatibility with theory

- p-value of the background-only hypothesis

$$p_0 = 3.71 \times 10^{-2}$$

BABAR Preliminary

- Use the CL_s method to get limit on N_{sig}

$$N_{sig} \leq 9.6 \text{ events at the 90\% CL}$$

- Corresponding limit on cross sections [theory 95% C.I.]:

$$\sigma \leq \begin{cases} 73\,\text{fb} & \text{for } \phi_P \text{ and } \pi^0_{\text{HC}} \quad [250\,\text{fb} - 820\,\text{fb}] \\ 370\,\text{fb} & \text{for } \phi_S \quad [68\,\text{nb} - 1850\,\text{nb}] \end{cases}$$

Compatibility with theory

- Fit $F_{\pi^0}\left(Q^2\right)$ data including a contribution from this measurement in the χ^2. Increase in $\chi^2 \rightarrow p$-value
- p-value = 5.9×10^{-4}, 8.8×10^{-10}, 2.2×10^{-9} for π^0_{HC}, ϕ_P, ϕ_S.

Conclusions (Preliminary)

- Searching for the proposed “pion impostors” was conducted in *BABAR* data.
- $5.0 \pm 2.7 \pm 0.4$ signal candidates found in data at $137\,\mathrm{MeV}/c^2$

$$\sigma \le \begin{cases} 73\,\mathrm{fb} & \text{for the } P \text{ models} \\ 370\,\mathrm{fb} & \text{for the } S \text{ model} \end{cases}$$

- Minimal cross sections to explain $F_{\pi^0}\left(Q^2\right)$ excess are 250 fb, 2,600 fb or 68,000 fb (depending on the model)
- Probability of measuring these cross sections, assuming the impostor theory is correct, corresponds to $> 3.4\sigma$ discrepancy

Questions / Comments?

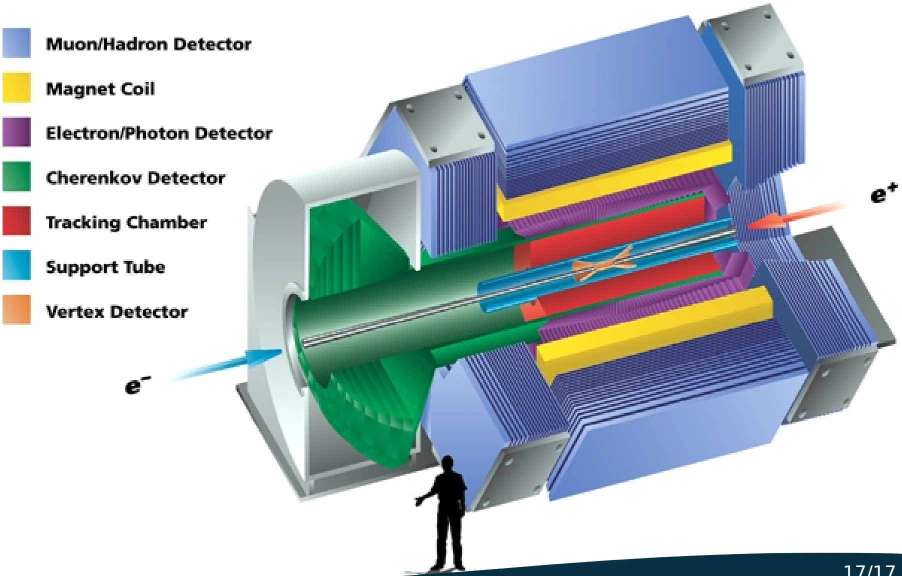
Thank you for listening.

Also: many thanks to Dr. M. Pospelov, Dr. D. McKeen at UVic for the constructive discussions.

This work is funded by

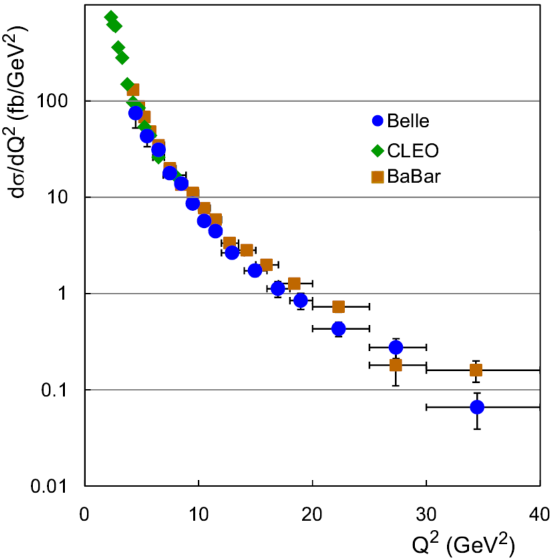
Additional Material

The *BABAR* Detector



Cross section for $e^+e^- \to (e)e\pi^0$

Taken from Phys. Rev. D **86**, 092007 (2012)



Why τ?[2]

- Has to be SM (otherwise $m > 100\,\mathrm{GeV}/c^2$ to escape collider pair production bounds; unrealistically large coupling)
- Coupling to light q: would have to be greater that $\pi^0 - u, d, s$ couplings $\rightarrow$ unrealistic
- Coupling to c: constrained by $\mathcal{B}(\psi' \rightarrow \gamma\pi^0) \sim 1.6 \times 10^{-6}$
- Coupling to b: constrained by $\mathcal{B}(\Upsilon(2S) \rightarrow Y1S\pi^0) < 1.8 \times 10^{-4}$
- Coupling to e: constrained by $\mathcal{B}(\pi^0 \rightarrow \gamma\gamma) \sim 0.99$
- Coupling to μ: constrained $(g-2)_\mu$ to $\sim 10^{-3} - 10^{-4}$

Coupling to the τ is the most likely scenario!

[2] See D. McKeen, M. Pospelov and J.M. Roney, Phys. Rev. D **85**, 053002 (2012)

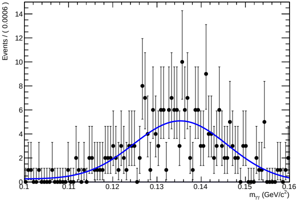
Control sample studies

for peak shape parameters

Data $m_{\gamma\gamma}$ spectrum

$\mu_m = 135.36 \pm 0.93\,\mathrm{MeV}/c^2$

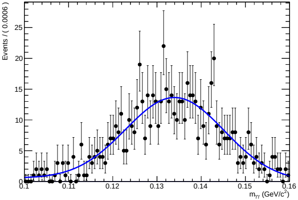
$\sigma_m = 10.6 \pm 1.8\,\mathrm{MeV}/c^2$



$e^+e^- \rightarrow \tau^+\tau^-$ SP

$\mu_m = 134.05 \pm 0.62\,\mathrm{MeV}/c^2$

$\sigma_m = 11.15 \pm 0.80\,\mathrm{MeV}/c^2$



- Allow π^0 from τ decays
  - Remove $E_{small} + E_{\pi^0}$ requirement
  - Reverse mass requirement: $m_{\pi^0\pi^\pm} \leq m_\tau$
- Require $E_{\pi^0} > 3\,\mathrm{GeV}$ in the CM frame
- Fit peak + linear background model
- Average shape parameters

$$\mu_m = 134.5\,\mathrm{MeV}/c^2$$
$$\sigma_m = 11.1\,\mathrm{MeV}/c^2$$