Searches for new low-mass states at *BABAR*

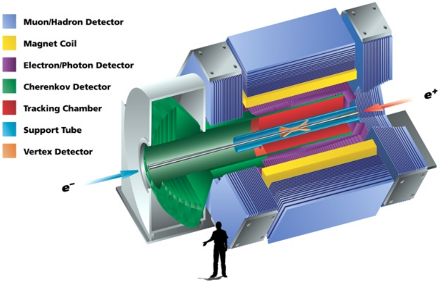
$\Upsilon(1S) \to \gamma A^0, A^0 \to c\bar{c}$ (To be submitted to PRD-RC)
$e^+e^- \to \tau^+\tau^- \pi^0$ (Phys. Rev. D 90, 112011)

2015 Lake Louise Winter Institute
Lake Louise, February 15 – 21 2015

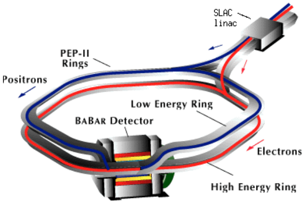
Alexandre Beaulieu for the *BABAR* Collaboration

University of Victoria

The *BABAR* experiment



- Located at PEP-II asymmetric e^+e^- collider at the SLAC National Accelerator Laboratory
- Collected data from 1999 to 2008
- *B*-factory: optimized for *B* physics
- General-purpose detector is also excellent to study τ and *c* physics, and dark sector searches



Context and motivation

Light Higgs produced in $\Upsilon(nS)$ ($n = 1, 2, 3$) radiative decays

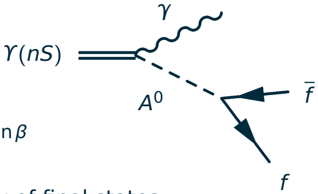
- A light CP-odd Higgs boson A^0 is expected in a number of extensions of the Standard Model, such as non-minimal supersymmetry Phys. Rep. **496**:1 (2010):

$$A^0 = \cos\theta_A A_{\text{MSSM}} + \sin\theta_A A_S$$

- Couplings of A^0 to fermions are a function of $\cos\theta_A$ and parameter $\tan\beta$
  - To up-type fermion pair: $\sim m_f \cos\theta_A / \tan\beta$
  - To down-type fermion pair: $\sim m_f \cos\theta_A \tan\beta$

$\tan\beta = \nu_u/\nu_d$
$\nu_{(u,d)}$: v.e.v. of Higgs field coupling to (u,d)-type fermions

- Searches for an A^0 lighter than two bottom quarks are possible at B Factories from processes:



- Couplings are proportional to mass:
  - $\tau^+\tau^-$ decays dominate for large (~ 20) $\tan\beta$
  - $c\bar{c}$ decays dominate for small (~ 1) $\tan\beta$
- *BABAR* already provided limits on a variety of final states:
  - $\mu^+\mu^-$ Phys. Rev. Lett. **103**, 081803, Phys. Rev. D **87**, 031102(R)
  - $\tau^+\tau^-$ Phys. Rev. Lett. **103**, 181801, Phys. Rev. D **88**, 071102(R)
  - invisible Phys. Rev. Lett. **107**, 021804 (2011)
  - inclusive hadronic Phys. Rev. Lett. **107**, 221803 (2011)
  - gg and $s\bar{s}$ Phys. Rev. D **88**, 031701(R)

Overview of the analysis

- Today we present a new result for

$$\mathcal{B}\left(\Upsilon(1S) \to \gamma A^0\right) \cdot \mathcal{B}\left(A^0 \to c\bar{c}\right)$$

- Study of the decay

$$\Upsilon(2S) \to \pi^+\pi^- \; \Upsilon(1S), \quad \Upsilon(1S) \to \gamma A^0, \quad A^0 \to c\bar{c}$$

- Search for events with a $\pi^+\pi^-$ pair, a γ, and a D meson
- Reconstruct D meson in five final states:

$D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$, $D^0 \to K^- \pi^+ \pi^+\pi^-$, $D^0 \to K^0_S \pi^+\pi^-$, $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+ \pi^0$

- Select signal using boosted decision trees (BDT)
- Search for A^0 in

$$m_X^2 = \left(P_{e^+e^-} - P_{\pi^+\pi^-} - P_\gamma\right)^2, \quad m_X \in [4.00, 9.25]\,\mathrm{GeV}/c^2$$

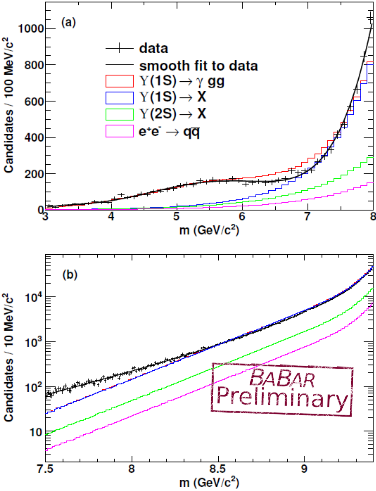
Data sample and event selection

Data sample:

- 13.6 fb^{-1} on $\Upsilon(2S)$ resonance:
  - $(98.3 \pm 0.9) \times 10^{6}$ $\Upsilon(2S)$ mesons
  - $(17.5 \pm 0.3) \times 10^{6}$ $\hookrightarrow \pi^{+}\pi^{-}$ $\Upsilon(1S)$ decays
- 1.4 fb^{-1} sample 30 MeV below $\Upsilon(2S)$ to study backgrounds
- Signal MC for different A^{0} masses

Event selection:

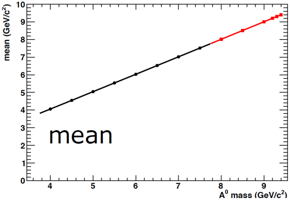
- Split mass spectrum in two regions:
  - Dominating background is different
  - Low mass $m_{A^0} \in [4.00,\ 8.00]\,\mathrm{GeV}/c^{2}$
  - High mass $m_{A^0} \in [7.50,\ 9.25]\,\mathrm{GeV}/c^{2}$

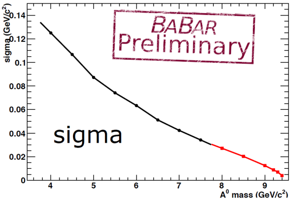


- Train 10 BDTs (2 regions, 5 D channels) using 24 variables
- 9.8×10^{3} (low-mass) and 7.4×10^{6} (high-mass) candidates pass all selection.

Signal yield extraction

- Extended binned maximum likelihood fits (float N_{sig} and N_{bkg})
- Signal m PDF modeled as Crystal Ball Function
  - Shape parameters (function of m_{A^0}) given by signal MC:





- Background m PDF: 2nd order polynomial
- Fitting domain: A^0 mass hypothesis ± 10 Gaussian σ
- Scan in 10 (2) MeV/c^2 steps in the low (high) region
  - Keep the highest significance
- Calculate 90% Bayesian upper limits (UL) assuming uniform prior
  - Combine 2 mass regions where their upper limits meet

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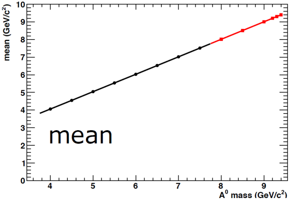

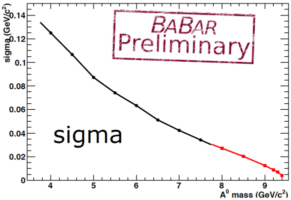

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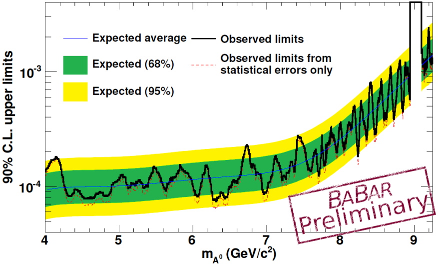
$$\frac{\int_0^{UL} \exp\left(-\frac{(x-n_{sig})^2}{2\Delta n_{sig}^2}\right) dx}{\int_0^{\infty} \exp\left(-\frac{(x-n_{sig})^2}{2\Delta n_{sig}^2}\right) dx} = 0.9$$

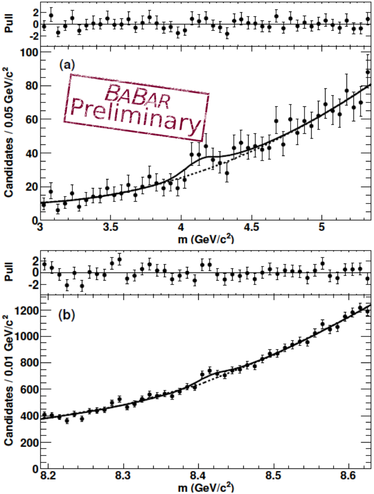
Results

To be published in PRD-RC

No significant signal observed

- Upper limits on $\mathcal{B}\left(\Upsilon(nS) \rightarrow \gamma A^0\right) \cdot \mathcal{B}\left(A^0 \rightarrow c\bar{c}\right)$:
  - 7.4×10^{-5} to 2.4×10^{-3}



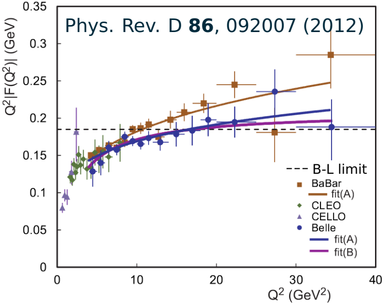


- Highest local significances:
  - 2.3σ @ $4.145\,\mathrm{GeV}/c^2$
  - 2.0σ @ $8.411\,\mathrm{GeV}/c^2$

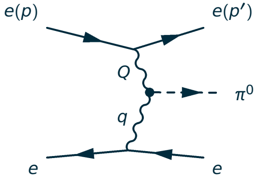
for $m_{A^0} \in [4.00,\ 9.25]\,\mathrm{GeV}/c^2$. This excludes $[8.95,\ 9.10]\,\mathrm{GeV}/c^2$ due to peaking background from $\chi_{bJ}(1P)$ transitions.

Search for new scalars near m_{π^0}

Motivation: *BABAR* pion-photon transition form-factor data



- Single-tag measurement of photon-fusion process:



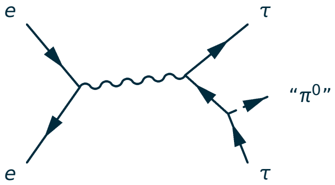
- $Q^2 > 15\,\text{GeV}^2$ is well beyond the non-perturbative QCD regime → should approach the Brodsky-Lepage limit: $\sqrt{2}f_\pi/Q^2 \simeq 185\,\text{MeV}/Q^2$.

"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

- Possibility of exotic scalars[1] 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 $\gamma\gamma$
- Production in e^+e^- annihilations:



+ charge conjugation

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

$$\sigma_{\pi^0_{\mathrm{HC}}} = 0.25\,\mathrm{pb},\ \sigma_{\phi_P} = 2.5\,\mathrm{pb},\ \text{and}\ \sigma_{\phi_S} = 68\,\mathrm{pb}.$$

- Assuming these σ, 120×10^3, 1.2×10^6, or 32×10^6 were *produced* in the $\Upsilon(4S)$ data set!

[1] Phys. Rev. D **85**, 053002 (2012)

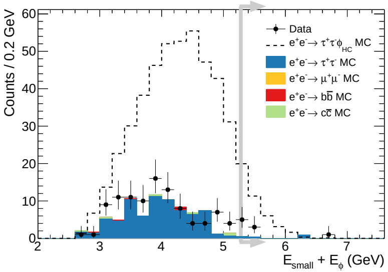
Data sample and signal selection

- Use $\Upsilon(4S)$ sample: $\mathcal{L}_{\text{int}} = 468\,\text{fb}^{-1}$ ($\approx 430 \times 10^6$ τ pairs)
- Simulation of signal and generic backgrounds (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $B\bar{B}$, $q\bar{q}$ ($q = u, d, s, c$)).

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

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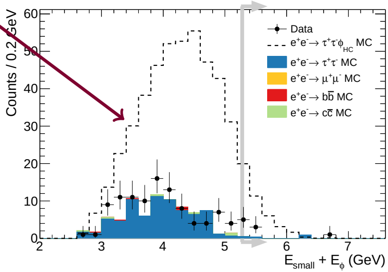
Minimal signal



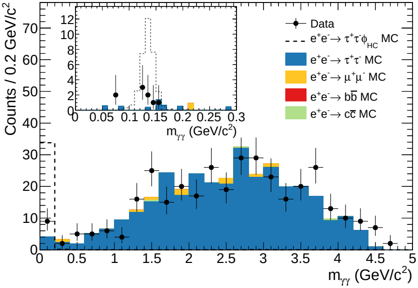
$E_{small} + E_{\pi^0}$ when this cut is lifted, events with $m_{\gamma\gamma} \in [100,\ 160]$ MeV/c^2

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

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

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

$m_{\gamma\gamma}$ 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: $N_p^{\mathrm{bkg}} = 1.24 \pm 0.37$
- Correct for fit bias -0.06 ± 0.02 events

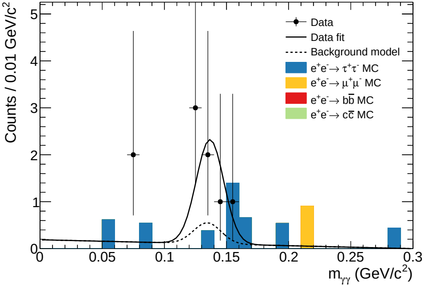
- Signal MC is used to get efficiency: $\varepsilon_{\phi_P} = \varepsilon_{\pi^0_{\mathrm{HC}}} = (0.455 \pm 0.019)\%$; $\varepsilon_{\phi_S} = (0.0896 \pm 0.004)\%$

Phys. Rev. D **90**, 112011

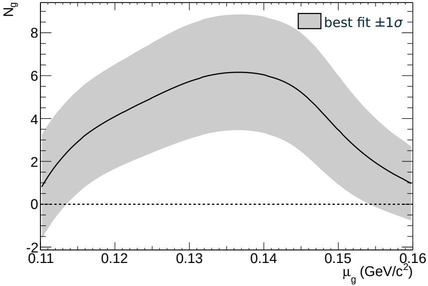
Final result

Extended likelihood fits and mass scan

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



Number of peaking events vs mass



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

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

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

$$\sigma \leq \begin{cases} 73\,\text{fb} \;\text{ for } \pi^0_{HC} & \left[250\,\text{fb} - 840\,\text{fb}\right] \text{ and } \phi_P \left[2.5\,\text{pb} - 6.9\,\text{pb}\right] \\ 370\,\text{fb} \;\text{ for } \phi_S & \left[68\,\text{pb} - 185\,\text{pb}\right] \end{cases}$$

Summary

Light Higgs decays to $c\bar{c}$:

- Highest local significances 2.3σ (2.0σ) for the low (high) mass region
- p-values of 54% and 80% respectively (with trial factors)
- Upper limits on $\mathcal{B}\left(\Upsilon(1S) \to \gamma A^0\right) \cdot \mathcal{B}\left(A^0 \to c\bar{c}\right)$:
  - 7.4×10^{-5} to 2.4×10^{-3}

Exotic scalars near π^0 mass:

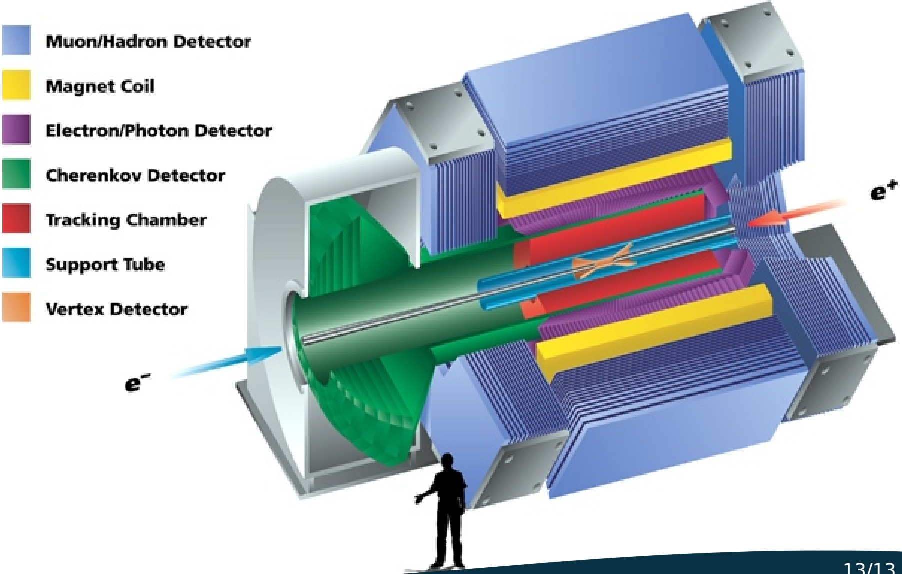
- $5.0 \pm 2.7 \pm 0.4$ candidates found in data at $137\,\mathrm{MeV}/c^2$

$$\sigma_{e^+e^- \to \tau^+\tau^-\phi} \leq \begin{cases} 73\,\mathrm{fb} & \text{for the } P \text{ models} \\ 370\,\mathrm{fb} & \text{for the } S \text{ model} \end{cases}$$

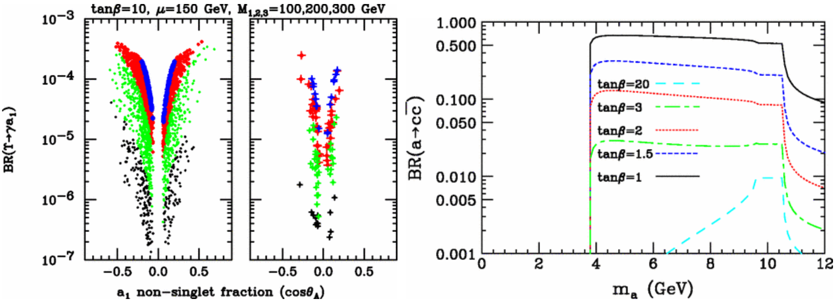
- Minimal cross sections to explain $F_{\pi^0}\left(Q^2\right)$ excess are 250 fb, 2,500 fb or 68,000 fb ($> 3.4\sigma$ discrepancy)

Additional Material

The *BABAR* Detector



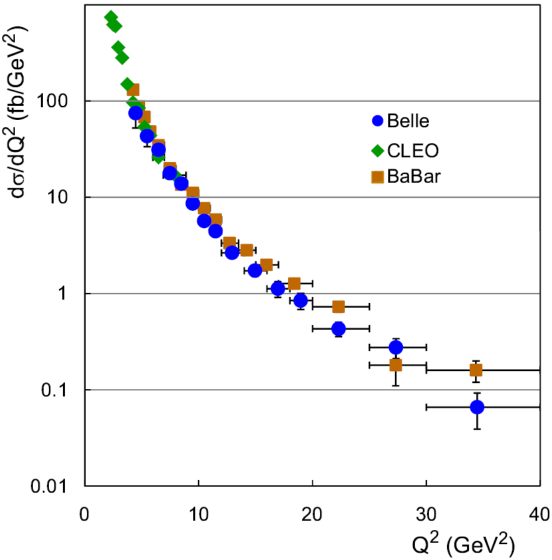
Branching fractions for different NMSSM parameters:



Dermíšek, Gunion & McElrath, Phys. Rev. D **76**, 051105(R)

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)

Backgrounds and pseudo-experiments

Study of background:

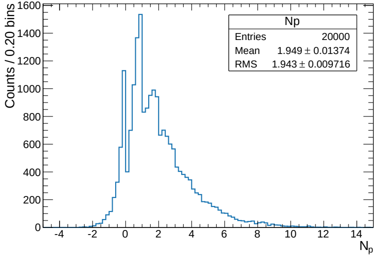
- Combinatorial background from fit
- Peaking background evaluation
  - From *BABAR* $e^+e^- \to \tau^+\tau^-$ simulation: 0.38 ± 0.09
  - But $\gamma\gamma$ physics not simulated: data-driven estimate for $e^+e^- \to e^+e^- \pi^+\pi^- \pi^0$: 0.86 ± 0.36
  - Peaking events total:

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

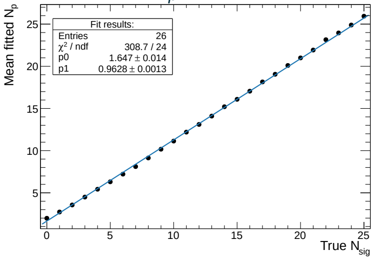
Study fit bias:

- 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

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

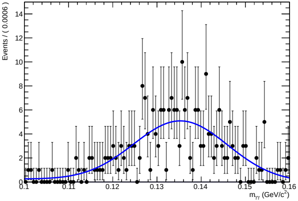
Tab.: Summary of the contributions to $\sigma(\varepsilon_x)$.

	$\boldsymbol{\varepsilon_{\phi_P,\pi^0_{\mathrm{HC}}}}$	$\boldsymbol{\varepsilon_{\phi_S}}$
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%

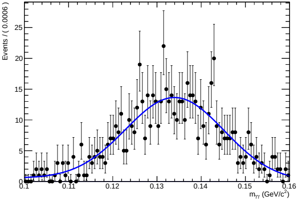
Control sample studies

for peak shape parameters

Data $m_{\gamma\gamma}$ spectrum
$\mu_m = 135.36 \pm 0.93\,\mathrm{MeV}/c^2$
$\sigma_m = 10.6 \pm 1.8\,\mathrm{MeV}/c^2$



$e^+e^- \to \tau^+\tau^-$ MC
$\mu_m = 134.05 \pm 0.62\,\mathrm{MeV}/c^2$
$\sigma_m = 11.15 \pm 0.80\,\mathrm{MeV}/c^2$



- 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

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