Beyond the Standard Model in bottomonia decays at the *BABAR* experiment

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Introduction

Two recent analyzes based on the *BABAR* data are reviewed in this talk.

$\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$

A precision test of lepton-flavor universality in leptonic $\Upsilon(3S)$ decays.

Result is published [Phys.Rev.Lett. **125** (2020) 241801] and a preprint is available [arXiv:2005.01230].

$\Upsilon(3S) \to \mu^\pm e^\mp$

A direct search for lepton-flavor violation in $\Upsilon(3S)$ decays with light leptons.

Preliminary result is ready. Paper is in preparation.

Introduction $\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$

Vector $q\bar{q}$ resonance decay width into $\ell\ell$

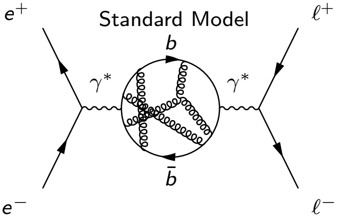
$$\Gamma_{\ell\ell} = 4\alpha^2 e_q^2 \frac{|\Psi(0)|^2}{M^2} \left(1 + 2\frac{m_\ell^2}{M^2}\right) \sqrt{1 - 4\frac{m_\ell^2}{M^2}}$$

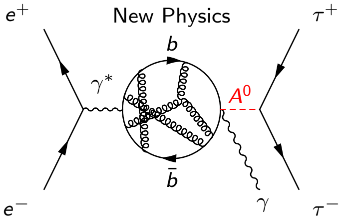
$R_{\ell\ell'} = \dfrac{\Gamma_{\ell\ell}}{\Gamma_{\ell'\ell'}}$ – free of hadronic uncertainties, good probe of the SM.

New Physics Contribution to $R_{\ell\ell'}$

In [Phys. Lett. B**653**, 67, 2007] a light CP-odd Higgs boson A^0 is proposed. In 2HDM(II) with large $\tan\beta$ the A^0 boson exclusively decays into $\tau\tau$ pair and thus New Physics effects might modify visible $R_{\tau\ell}$ in $\Upsilon(nS)$ decays.

In [J. High Energ. Phys. **06**, 019 (2017)] a new physics contribution to $b \to c\tau\nu$ which explains a tension in $R(D^{(*)})$ also necessarily modifies the $R_{\tau\ell}$ observable.



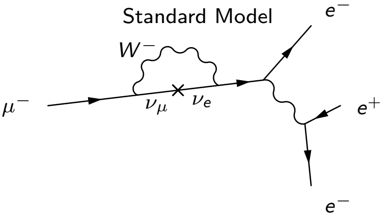


Introduction $\Upsilon(3S) \to \mu^{\pm} e^{\mp}$

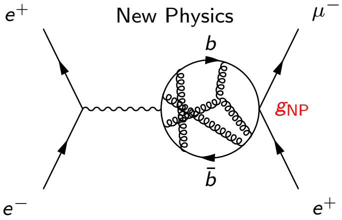
This decay has a very clean and distinct experimental signature of the two body decay.

Vector $q\bar{q}$ resonance into $e^{\pm}\mu^{\mp}$

One can relate $e^+e^- \to \Upsilon(3S) \to e^{\pm}\mu^{\mp}$ and the LFV process $\mu^+ \to e^+e^-e^+$ via the cross-symmetry.



In [Phys.Rev.D**63**,016003] based on the current upper limit $\mathcal{B}(\mu^+ \to e^+e^-e^+) < 10^{-12}$ an upper limit $\mathcal{B}(\Upsilon(3S) \to e^{\pm}\mu^{\mp}) < 2.5 \times 10^{-8}$ is derived. However the contribution from $\Upsilon(3S)$ might be kinematically suppressed in the decay $\mu^+ \to e^+e^-e^+$ by $\sim m_\mu^2/M_\Upsilon^2$ which translates into a much weaker upper limit $\mathcal{B}(\Upsilon(3S) \to e^{\pm}\mu^{\mp}) < 10^{-3}$.

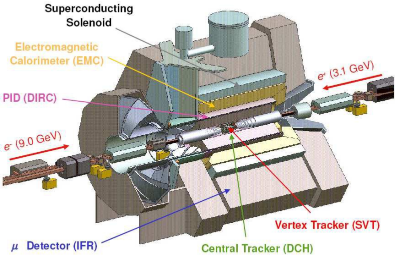


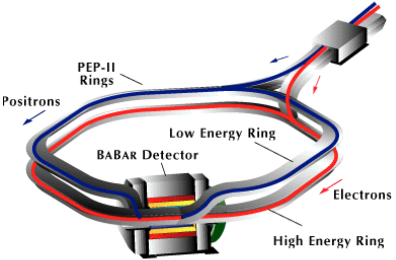
Other LFV vector resonance decays $V \to e^{\pm}\mu^{\mp}$

V	Upper Limit	Ref
Z^0	7.5×10^{-7}	Phys.Rev.D**90**, 072010
ϕ	2.0×10^{-6}	Phys.Rev.D**81**, 057102
J/ψ	1.6×10^{-7}	Phys.Rev.D**87**, 112007

BABAR and analyzed data

BABAR and PEP-II operated in 1999 – 2008 at SLAC.





Total data (Run 1-7)

On resonances:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 28 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off reson./scan: 54 fb^{-1}
Total: 529 fb^{-1}

Data sample	On resonance fb^{-1}	Off resonance fb^{-1}
Run 7 $\Upsilon(3S)$	27.96	2.62
Run 6 $\Upsilon(4S)$	78.3	7.75

- Blind analysis technique – only 2.41 fb^{-1} of $\Upsilon(3S)$ on resonance and $\Upsilon(3S)$ and $\Upsilon(4S)$ off resonance data are used to tune selections in $R_{\tau\mu}$ and 0.93 fb^{-1} of $\Upsilon(3S)$ on resonance in the $\Upsilon(3S) \to \mu^{\pm} e^{\mp}$ search.
- $\Upsilon(3S)$ off-resonance statistic is low $\Rightarrow$ Run 6 $\Upsilon(4S)$ on-resonance data with the same detector configuration is used to estimate backgrounds.

Measurement of

$$\frac{\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)}{\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)}$$

Signal selections

$\mu^+\mu^-$ selections

1. Two and only two charged particles with opposite charges
2. $P^{cm}_{high} > 4\,\mathrm{GeV}/c$ and $P^{cm}_{low} > 2\,\mathrm{GeV}/c$
3. $2.8\,\mathrm{rad} < \theta^{cm}_{-} + \theta^{cm}_{+} < 3.5\,\mathrm{rad}$
4. $E^{EMC}_{+} + E^{EMC}_{-} < 2\,\mathrm{GeV}$
5. $0.65\,\mathrm{rad} < \theta^{cm}_{-} < 2.5\,\mathrm{rad}$ and $0.58\,\mathrm{rad} < \theta^{cm}_{+} < 2.56\,\mathrm{rad}$
6. $\psi^{cm} = \arccos \dfrac{\vec{P}^{cm}_{+} \cdot \vec{P}^{cm}_{-}}{|\vec{P}^{cm}_{+}| \cdot |\vec{P}^{cm}_{-}|} > 160°$
7. $0.8 < M_{\mu\mu}/\sqrt{s} < 1.1$
8. At least one particle having IFR response

0.1% non-$\mu\mu$ contamination

$\tau^+\tau^-$ selections

1. Two and only two charged particles with opposite charges
2. $41° < \theta^{cm}_{\pm} < 148°$.
3. $\psi^{cm} > 110°$
4. $E^{EMC}_{tot} < 0.7 \times E_{\text{PEP-II}}$
5. One of the particles must be an electron and the other not [$e\not{e}$]
6. $||\phi_+ - \phi_-| - 180°| > 3°$
7. $|M^2_{miss}| > 0.01 \times s$
8. $|\cos\theta_{miss}| < 0.85$
9. $P^{\perp}_{\pm} \notin \gamma^*\gamma^*$ region
10. $|\Delta\phi| = ||\phi_{e\gamma} - \phi_{\not{e}}| - 180°| > 2°$ and $|\Delta\theta| = |\theta_{e\gamma} + \theta_{\not{e}} - 180°| > 2°$

1% non-$\tau\tau$ contamination

All selections are designed to be beam-energy insensitive.

MC selection efficiency correction

Precision measurement ⇒ data driven efficiency correction is needed!
The $\Upsilon(3S)$ and $\Upsilon(4S)$ off-resonance date samples are used derive and test the correction to the efficiency ratio.

Sample	$\varepsilon_{\mu\mu}$	$\varepsilon_{\tau\tau}$	$\varepsilon_{\tau\tau}/\varepsilon_{\mu\mu}$
MC $\Upsilon(3S)$	69.951 ± 0.018	7.723 ± 0.010	0.11041 ± 0.00015
MC $\Upsilon(3S)$ off peak	49.250 ± 0.017	7.018 ± 0.010	0.14249 ± 0.00021
MC $\Upsilon(4S)$ off peak	48.997 ± 0.016	6.979 ± 0.007	0.14245 ± 0.00015

DATA/MC efficiency correction $\tilde{R}_{\tau\mu} = N_{\tau\tau}/N_{\mu\mu}$

Sample	$N_{\mu\mu}^{\text{data}}$	$N_{\mu\mu}^{\text{MC}}$	$N_{\tau\tau}^{\text{data}}$	$N_{\tau\tau}^{\text{MC}}$	$\tilde{R}_{\tau\mu}^{\text{data}}/\tilde{R}_{\tau\mu}^{\text{MC}}$
$\Upsilon(3S)$ off peak	1,538,569	1,554,208	179,466	178,569	1.0152 ± 0.0030
$\Upsilon(4S)$ off peak	4,422,407	4,398,983	515,067	505,133	1.0143 ± 0.0020
Efficiency correction C_{MC}					1.0146 ± 0.0016

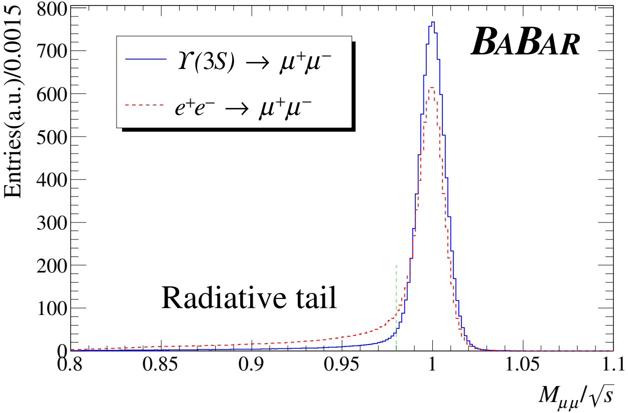
Off-peak DATA

$\tilde{R}_{\tau\mu}(3S) = 0.11665 \pm 0.00029 (0.25\%)$
$\tilde{R}_{\tau\mu}(4S) = 0.11647 \pm 0.00017 (0.15\%)$
$\tilde{R}_{\tau\mu}(4S)/\tilde{R}_{\tau\mu}(3S) - 1 = -0.0015 \pm 0.0029$

Off-peak MC

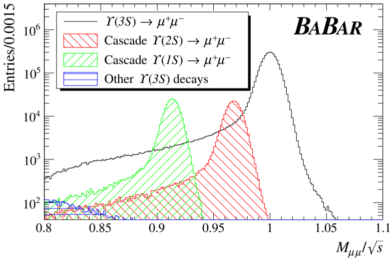
$\tilde{R}_{\tau\mu}(3S) = 0.11489 \pm 0.00018 (0.16\%)$
$\tilde{R}_{\tau\mu}(4S) = 0.11483 \pm 0.00014 (0.13\%)$
$\tilde{R}_{\tau\mu}(4S)/\tilde{R}_{\tau\mu}(3S) - 1 = -0.0006 \pm 0.0020$

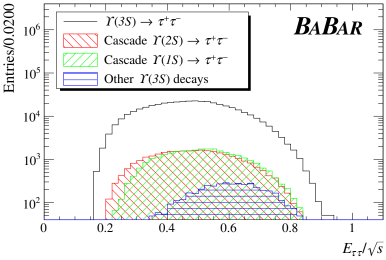
The ratio of τ-μ candidates does not depend on energy in data and MC!



Only about 7% of the selected dimuon events from $\Upsilon(3S)$ decays have invariant mass $M_{\mu\mu}$ less than 98% of interaction energy due to final state radiation whereas in the continuum selected events this fraction is 23% because of initial state radiation.

Exploit this difference in shape to distinguish resonance decays from continuum one.





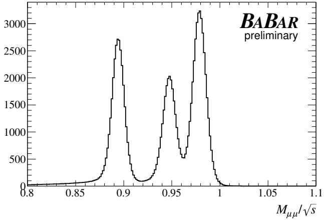
- "Cascade" decays or leptonic decays of $\Upsilon(1S)$ or $\Upsilon(2S)$ are also there.
- Only in the $M_{\mu\mu}$ variable can cascade decays be separated from $\Upsilon(3S)$ decays. In all $\tau\tau$ distributions they are indistinguishable so use information from the $\mu\mu$ channel to fix them in $\tau\tau$.
- Use off-resonance data to describe the shape of the continuum background in on-resonance data in $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$ variables.
- Combine available $M_{\mu\mu}$ shape information in a template-based fit to extract the number of $\Upsilon(3S)$ decayed into $\mu\mu$ and $\tau\tau$ pairs.
- To overcome low statistic of the $\Upsilon(3S)$ off-resonance data sample use high statistic Run 6 experimental data where about 44×10^6 $\mu^+\mu^-$ and 5×10^6 $\tau^+\tau^-$ pairs are selected.
- MC based cascade decay templates.

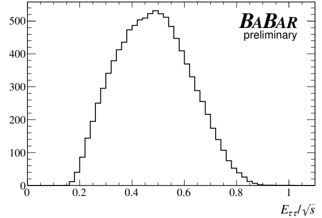
ISR produced $\Upsilon(nS)$

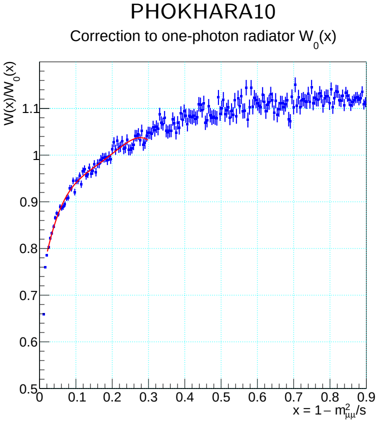
The Run 6 continuum template is corrected to take into account $\Upsilon(nS)$ produced by the radiative return process. Total ISR cross section for a narrow resonance is

$$\sigma(s) = \frac{12\pi^2\Gamma_{ee}\Gamma_{\mu\mu}}{sM\Gamma}W(s,x_0),\ x_0 = 1-\frac{M^2}{s},\ W_0(s,x) = \frac{\alpha}{\pi x}\left(\ln\frac{s}{m_e^2}-1\right)(2-2x+x^2),$$

where W_0 is one photon radiator function, since all $\Upsilon(nS)$ resonances are close to each other – photon emission is soft and corrections have to be evaluated.

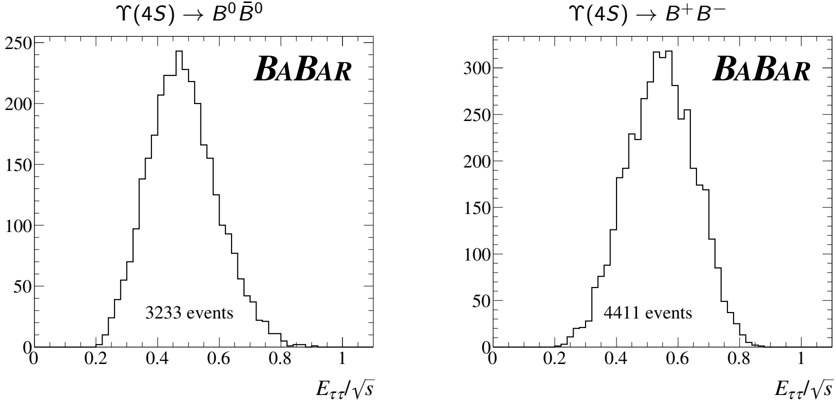




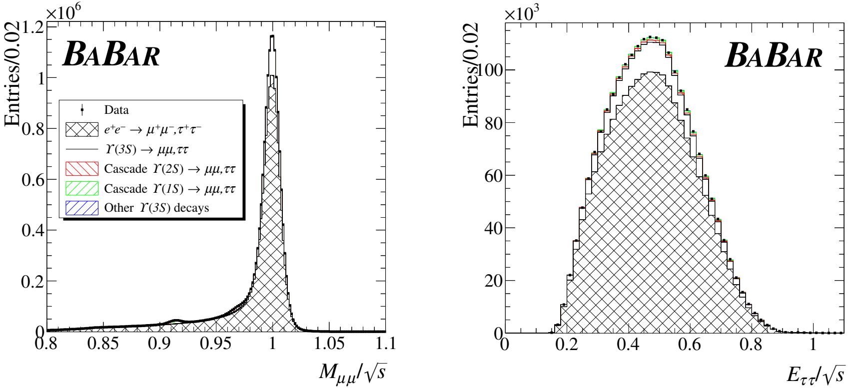


MC based $B\bar{B}$ correction

Since the continuum template is taken @ $\Upsilon(4S)$ – there are plenty of $B\bar{B}$ events and some of the low multiplicity B decays (e.g. charmless semileptonic) might mimic τ decays and modify the template. From more than 265 million of generated $B\bar{B}$ ($\times 3$ data) events only 15 were selected as dimuon candidates whereas 7644 were selected as $\tau\tau$.



Amount of $B\bar{B}$ misidentified as $\tau\tau$ translates to $\delta_{B\bar{B}} = 0.4\%$ of $\Upsilon(3S) \to \tau\tau$ events. This contribution is taken into account as a correction in the final result.

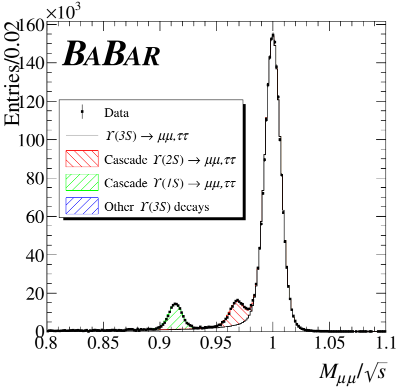


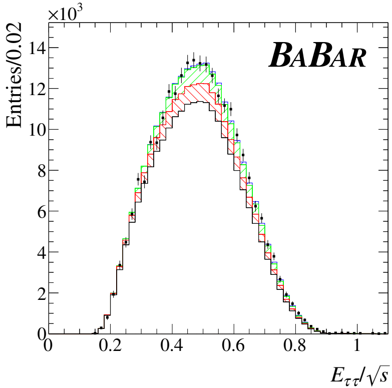
Dominant continuum $e^+e^- \to \ell^+\ell^-$ background is clearly visible.

The raw result of the fit $\tilde{R}_{\tau\mu} = N_{\tau\tau}/N_{\mu\mu} = 0.1079 \pm 0.0009$

$$R_{\tau\mu} = \tilde{R}_{\tau\mu} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}} \frac{1}{C_{\mathrm{MC}}} \cdot (1 + \delta_{B\bar{B}}) = 0.966 \pm 0.008_{\mathrm{stat}} \pm 0.014_{\mathrm{syst}} = 0.966 \pm 0.016_{\mathrm{tot}}$$

Fit result – continuum subtracted

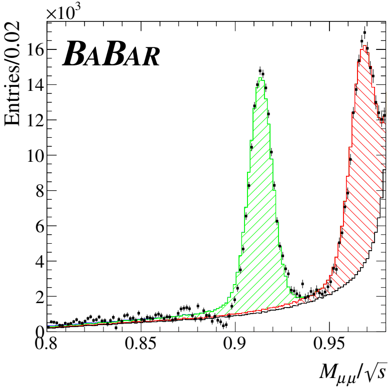




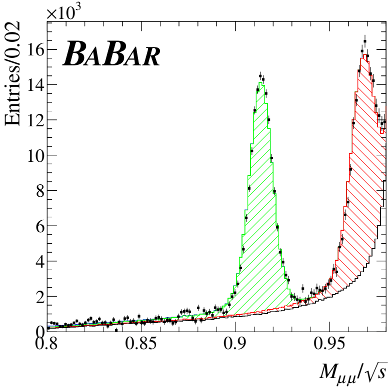
When the continuum background is subtracted the "cascade" backgrounds are clearly visible in dimuon invariant mass distribution.

Fit result – effect of ISR produced $\Upsilon(nS)$

If the continuum template were NOT corrected for ISR produced $\Upsilon(nS)$



The continuum template IS corrected for ISR produced $\Upsilon(nS)$



Note that ISR produced $\Upsilon(nS)$ are clearly visible in the continuum subtracted distribution especially $\Upsilon(1S)$ as a statistically significant dip. Radiative tail well matches to MC prediction.

Systematic uncertainty estimation

Source	Uncertainty (%)
Particle identification	0.9
Cascade decays	0.6
Two-photon production	0.5
$\Upsilon(3S) \to$ hadrons	0.4
MC shape	0.4
$B\bar{B}$ contribution	0.2
ISR subtraction	0.2
Total	1.4

- Various other particle identification criteria were applied to estimate the PID uncertainty e.g. explicit muon ID.
- In cascade decays the ratios for lower Υ resonances were varied within experimental uncertainties around the SM value.
- Various other $P_{\perp}$ selections are tested up to 2 times loss in efficiency.
- In order to estimate possible effect of MC shapes to the ratio radiative effects are modelled by PHOTOS and KKMC generators. Invariant mass resolution varied up to 10% off.
- $\Upsilon(nS)$ cross sections are varied according uncertainties as well as overall uncertainty of 10% applied.
- Remaining small background from $\Upsilon(3S)$ decays fixed to MC prediction as well as $B\bar{B}$ contribution varied as much as 50% to conservatively estimate their contribution to the systematic uncertainty.

Search for

$$\Upsilon(3S) \to \mu^{\pm} e^{\mp}$$

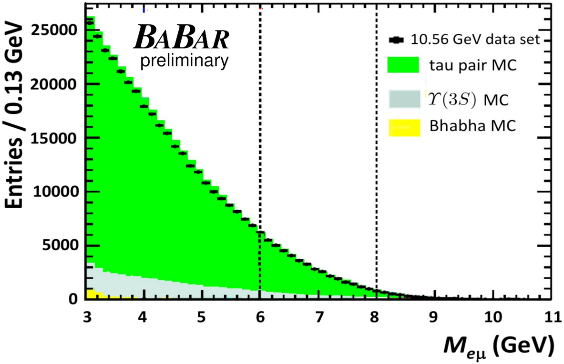
Selection criteria

$\mu^{\pm} e^{\mp}$ selections

1. Two and only two charged particles with opposite charges
2. One of the particles must be identified as an electron and the other as a muon by the *BABAR* identification procedure.
3. $(p_e/E_B - 1)^2 + (p_\mu/E_B - 1)^2 < 0.01$ (reversed for bkg study)
4. $\psi^{\text{cm}} > 179°$ (reversed for bkg study)
5. $24° < \theta_{\pm}^{\text{Lab}} < 130°$.
6. At least 50 MeV energy deposition is associated in the calorimeter with each track to suppress the misidentified Bhabha events.

23.4% selection efficiency

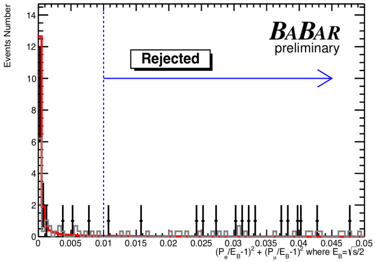
Data/MC efficiency correction

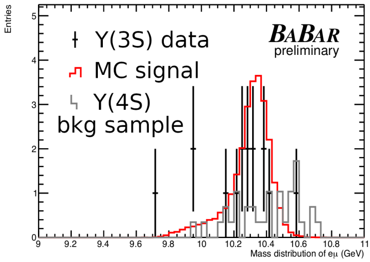


The efficiency correction is evaluated on the $e^+e^- \to \tau^+\tau^- \to e^\pm\mu^\mp\nu\nu$ enriched sample with the reversed kinematic selections in the signal sideband region $6 < M_{e\mu}/(\mathrm{GeV}/c^2) < 8$.

$$\frac{N^{\mathrm{Data}} - N^{\mathrm{MC}}_{\mathrm{BG}}}{M^{\mathrm{MC}}_{\tau^+\tau^-}} = 1.007 \pm 0.010$$

The evaluated correction shows good agreement between data and MC in the *BABAR* experiment.





15 candidates selected with expected background 12.2 ± 2.3 based on 27/fb of data.

The first preliminary experimental limit in the $\Upsilon(nS)$ decays

$$\mathcal{B}(\Upsilon(3S) \to e^\pm\mu^\mp) = (1.0 \pm 1.4_{\rm stat} \pm 0.8_{\rm syst}) \times 10^{-7},$$

based on [Eur.Phys.J.C**71**,1554] the modified frequentist approach the limit is

$$\mathcal{B}(\Upsilon(3S) \to e^\pm\mu^\mp) < 3.6 \times 10^{-7} \text{@ 90\% CL}$$

$$\frac{(g_{\rm NP}^2/\Lambda_{\rm NP})^2}{(4\pi\alpha q_b/M_{\Upsilon(3S)})^2} = \frac{\mathcal{B}(\Upsilon(3S) \to e^\pm\mu^\mp)}{\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)} \Rightarrow \Lambda_{\rm NP}/g_{\rm NP}^2 > 80\,\text{TeV}$$

Conclusion

The unique *BABAR* data set of $\Upsilon(nS)$ decays is still a valuable source of new physics results!

$\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)$

Based on Run 7 27.96 fb^{-1} collected at $\Upsilon(3S)$ energy as well as 78.3 fb^{-1} of Run 6 $\Upsilon(4S)$ on-peak data the inclusive of radiation effects ratio

$$R_{\tau\mu} = \frac{\mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)}{\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-)} = 0.966 \pm 0.008_{\mathrm{stat}} \pm 0.014_{\mathrm{syst}}$$

is precisely measured. This result is published in [Phys.Rev.Lett. **125** (2020) 241801] and a preprint is available [arXiv:2005.01230]. It can be compared with $R_{\tau\mu} = 0.9948$ in the Standard Model (radiation effects are included) as well as the only previous measurement reported by the CLEO collaboration [Phys.Rev.Lett.**98** (2007) 052002]: $R_{\tau\mu} = 1.05 \pm 0.08 \pm 0.05$.

$\Upsilon(3S) \to e^\pm\mu^\mp$

First LFV result with bottomonia decaying into light leptons

$$\mathcal{B}(\Upsilon(3S) \to e^\pm\mu^\mp) < 3.6 \times 10^{-7} \text{@ } 90\% \text{ CL}$$

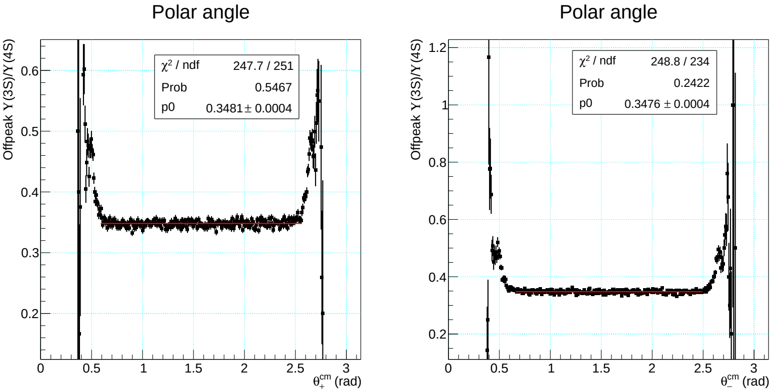
which can be interpreted as an effective limit $\Lambda_{\mathrm{NP}}/g^2_{\mathrm{NP}} > 80\,\mathrm{TeV}$. Paper is in preparation.

BACKUP SLIDES

$\mu^+\mu^-$ selection – polar angle selection

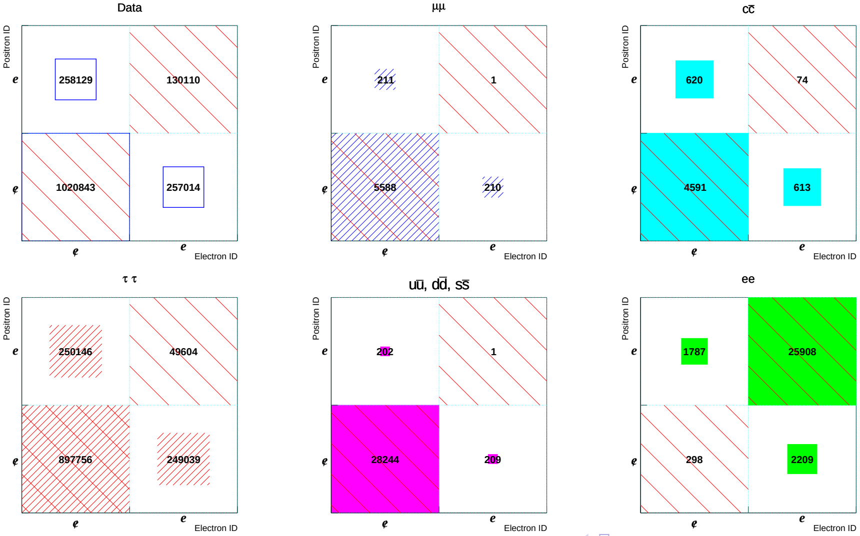
In order to maintain equal efficiency between $\Upsilon(3S)$ and $\Upsilon(4S)$ data samples just narrow angle selections are needed because different boost leads to different efficiency drop at the fiducial volume borders.

Selection criteria are derived from ratios of polar angle distributions for $\Upsilon(3S)$ and $\Upsilon(4S)$ off peak data.



$\tau^+\tau^-$ selection – $[e\not{e}]$

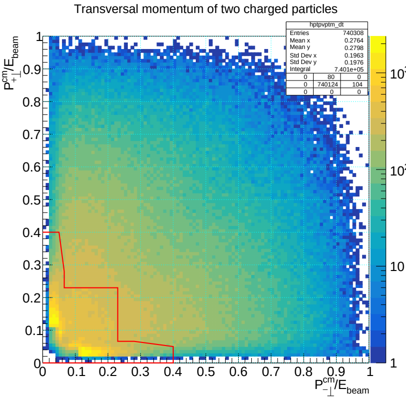
Electron identification is based on dE/dx measurements in the drift chamber and energy deposition in EMC. Among other tested PID selections it gives the best performance.



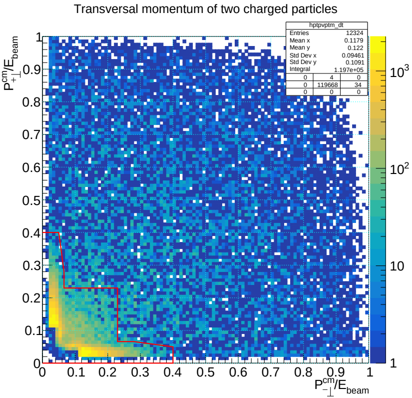
$\tau^+\tau^-$ selection – $P^{\perp}_{\pm} \notin \gamma^*\gamma^*$ region

Since momenta of particles of two-photon production are correlated, a two-dimensional selection is applied to maintain good efficiency for signal and reject two-photon background.

Data



Data

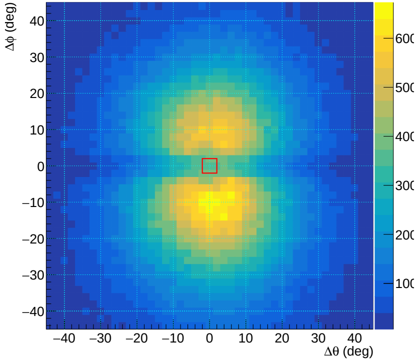


Known MC backgrounds are subtracted.

$\tau^+\tau^-$ selection #10

To further suppress radiative Bhabha events when a hard photon is emitted at large angle the direction of the electron is corrected using the most energetic photon found in the calorimeter $\vec{P}_{e\gamma} = \vec{P}_e + \vec{P}_\gamma$ to restore collinearity and then reject collinear events: $|\Delta\phi| < 2^\circ$ and $|\Delta\theta| < 2^\circ$ with $\Delta\phi = |\phi(\vec{P}_{e\gamma}) - \phi(\vec{P}_{\not e})| - 180^\circ$ and
$\Delta\theta = \theta(\vec{P}_{e\gamma}) + \theta(\vec{P}_{\not e}) - 180^\circ$

MC $ee \to \tau\tau$
Track open angle corrected



Data
Track open angle corrected