30 years of Tau Lepton International Workshops
The 16th International Workshop on Tau Lepton Physics (TAU2021) (Virtual Edition)
September 27, 2021 to October 1, 2021
Indiana University

Search for Lepton Flavor Violation in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ at BABAR

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On behalf of the BaBar Collaboration

Sept 27- Oct 01, 2021.

BABAR
St. Francis Xavier University
University of Victoria

A Snapshot from the Particle Data Group (PDG) Upsilon Decays

— LEPTON FAMILY NUMBER (*LF*) VIOLATING MODES —

$\Gamma(e^{\pm}\tau^{\mp})/\Gamma_{total}$ Γ_{31}/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<4.2	90	LEES	10B	BABR	$e^{+}e^{-} \rightarrow e^{\pm}\tau^{\mp}$

$\Gamma(\mu^{\pm}\tau^{\mp})/\Gamma_{total}$ Γ_{32}/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3.1	90	LEES	10B	BABR	$e^{+}e^{-} \rightarrow \mu^{\pm}\tau^{\mp}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<20.3	95	LOVE	08A	CLEO	$e^{+}e^{-} \rightarrow \mu^{\pm}\tau^{\mp}$

Branching Fraction

$$\Gamma(e^{\pm}\mu^{\pm})/\Gamma_{total}$$

A journal paper has submitted in the PRL
arXiv link: http://arxiv.org/abs/2109.03364

No published experimental measurement of the decay on $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ yet!

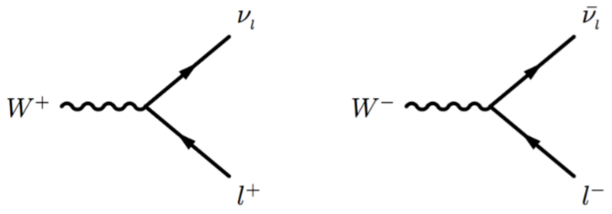
Outline of the Talk

- Motivation: Charged Lepton Flavour Violation
- Theoretical Expectations and Experimental Limit
- Data and MC Samples
- Analysis Strategy
- Results
- Conclusion

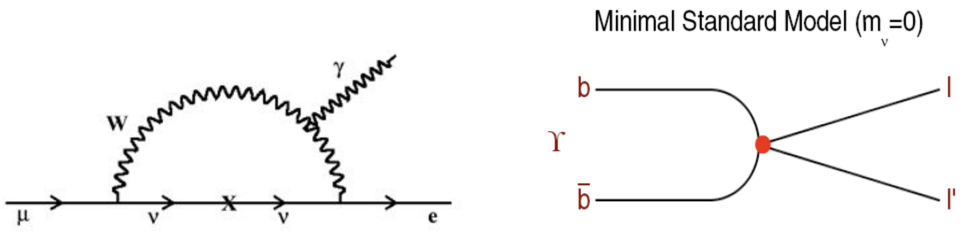
Charged Lepton Flavour Violation

- Charged Lepton Flavour Violation is a transition among e, μ, τ that doesn't conserve lepton family number.
- In Standard Model, Lepton Flavour is conserved for zero degenerate **ν** masses and now we have clear indication that $\boldsymbol{\nu}$'s have finite mass.

- Example of **lepton flavour conservation** is a muon decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



- Example of **charged lepton flavour violation** is a neutrinoless muon decay: $\mu^- \to e^- \gamma$



Opportunity to search for the New Physics!!!

- In the charged lepton sector, **Lepton Flavor Violation** is **heavy suppressed** in the Standard Model

$$l_\alpha \to l_\beta \approx \boldsymbol{O}\left(\mathbf{10^{-54}}\right)$$

$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-decay} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-vertex} \underbrace{sin^2 2\theta sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\vartheta-oscillation}$$

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left(\frac{3\alpha}{32\pi}\right) \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

with $\Delta \sim 10^{-3} eV^2, M_W \sim O(10^{11}) eV \approx \boldsymbol{O}\left(\mathbf{10^{-54}}\right)$

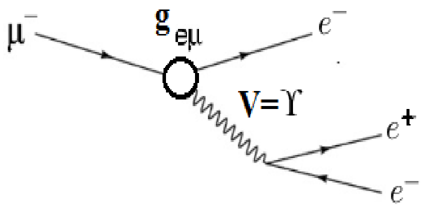
Experimentally not measurable!!

- Various BSM models such as Supersymmetry, Compositeness, Heavy Neutrino, Leptoquarks, Heavy Z', Anomalous boson Coupling, Higgs/top loops etc. predict CLFV.
- A clear experimental signature = **"New Physics"**

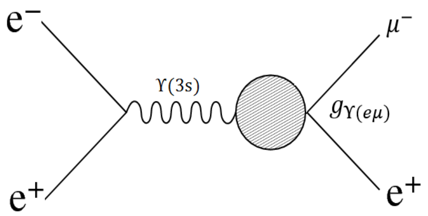
Theoretical Expectations and Experimental Limit

- S.Nussinov, et. al. estimated that the contribution of the virtual Υ (3S) $\rightarrow e^{\pm}\mu^{\mp}$ to the $\mu \rightarrow eee$ rate would be reduced by approximately $M^2_{\mu}/ (2 M^2_{\Upsilon})$ leading to a recalculated indirect bound:

BF(Υ (3S) $\rightarrow e^{\pm}\mu^{\mp}$) < 1×10^{-3}



Re-ordering of incoming/outgoing particles



$$[BR(\mu \rightarrow 3e)]_{V-exch} \approx \frac{[\Gamma(V \rightarrow e^+e^-)][\Gamma(V \rightarrow e^{\pm}\mu^{\mp})]}{[\Gamma^2(W \rightarrow e\nu)]}\left(\frac{M_W}{M_V}\right)^6 \quad [1]$$

BF($\mu \rightarrow eee$) $<1.0 \times 10^{-12}$ [2]

BF($\Upsilon \rightarrow ee$) $=2.18 \times 10^{-2}$ [3]

Existing Measurements	Results	CL (%)	Collaboration
BF($\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp}$)	$< 4.2 \times 10^{-6}$	90	J.P. Lees et al. PR D89 111102 [BaBar Collaboration]
BF($\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp}$)	$< 3.1 \times 10^{-6}$	90	
BF($\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp}$)	$< 20.3 \times 10^{-6}$	95	Love et al. PRL 101, 201601 [CLEO Collaboration]

[1] S.Nussinov, et. al. PRD 63 (2001)

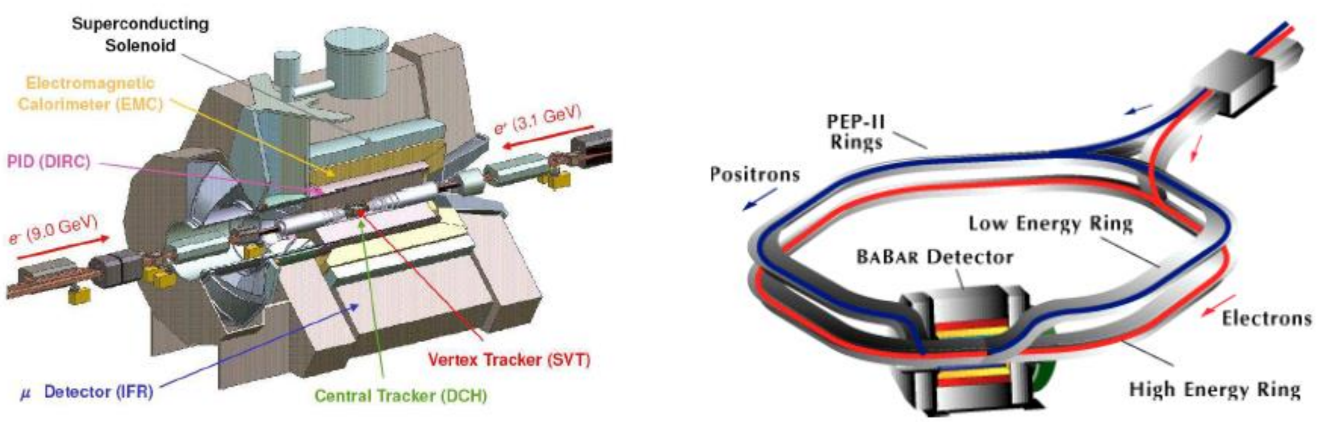
[2] Bellgardt, et al., Nucl.Phys. B299 (1988)

[3] P.A. Zyla et al. (Particle Data Group)

- **We report a limit several orders of magnitude more sensitive than this indirect limit.**
- **No published experimental measurement of the decay on $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ yet!**

Data, MC Sample

BABAR and PEP-II operated from 1999-2008 at SLAC

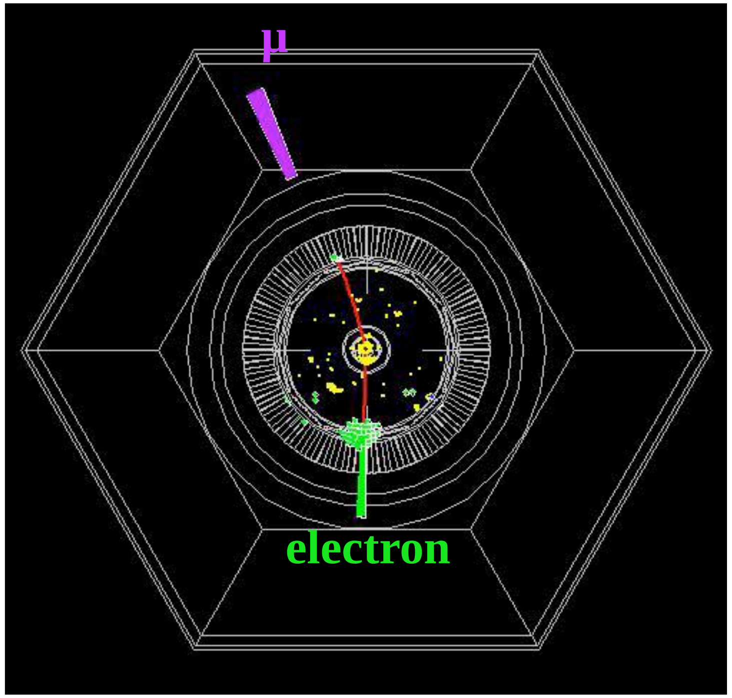


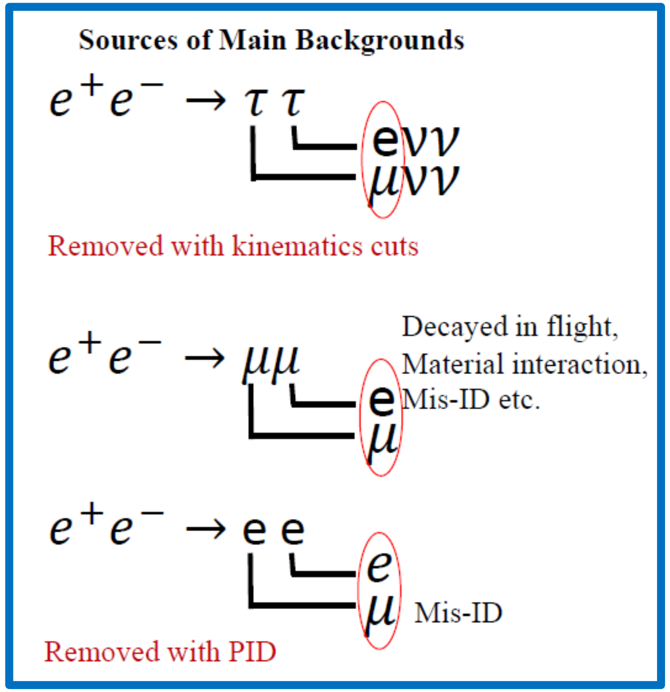
Data Sample	**On resonance (fb^{-1})**	**Off resonance (fb^{-1})**
Run 7 $\boldsymbol{\Upsilon(3S)}$ **(Data)**	27.9 = 27.0 + 0.93	2.62 To validate the systematic study
Run 6 $\boldsymbol{\Upsilon(4S)}$ **Data driven continuum background**	78.31 Systematic study pre-selected as $e^{\pm}\mu^{\mp}$and $\mu^{\pm}\mu^{\mp}$	7.75 To validate the systematic study
MC signal: $e^+e^- \to \Upsilon(3S) \to e^{\pm}\mu^{\mp}$: 103000 events		

Signal and Background Characteristics

- $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$: Required two primary track signal of $e^{\pm}$ ***and*** $\mu^{\mp}$
- CM Momentum: $p_{e^{\pm}} \sim \frac{\sqrt{s}}{2} \sim E_B$ and $p_{\mu^{\pm}} \sim \frac{\sqrt{s}}{2} \sim E_B$ where E_B=Beam Energy in Centre of Mass System
- Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^{\circ}$ to emerged as back to back.
- Energy deposit by $\mu^{\mp}$ track on the Electromagnetic Calorimeter > 50 MeV
- EMC acceptance $24^{\circ} < \theta_{Lab} < 130^{\circ}$ etc.

Sample Background event
$e^- e^+ \rightarrow \tau^{\pm}\tau^{\mp} \rightarrow e^{\pm}\mu^{\mp} + 4\nu$

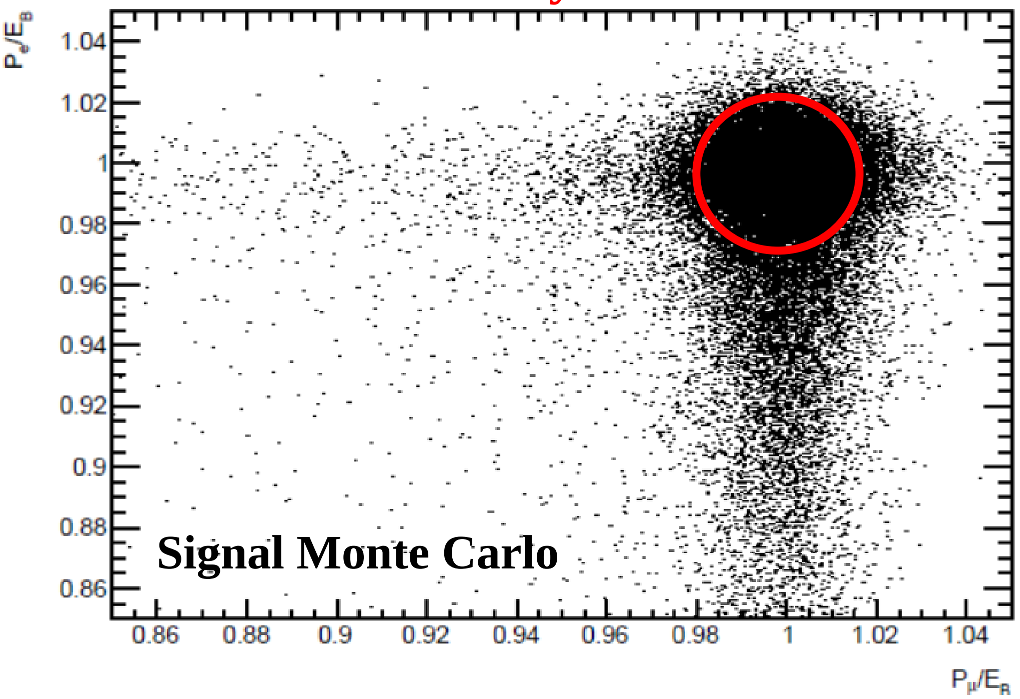




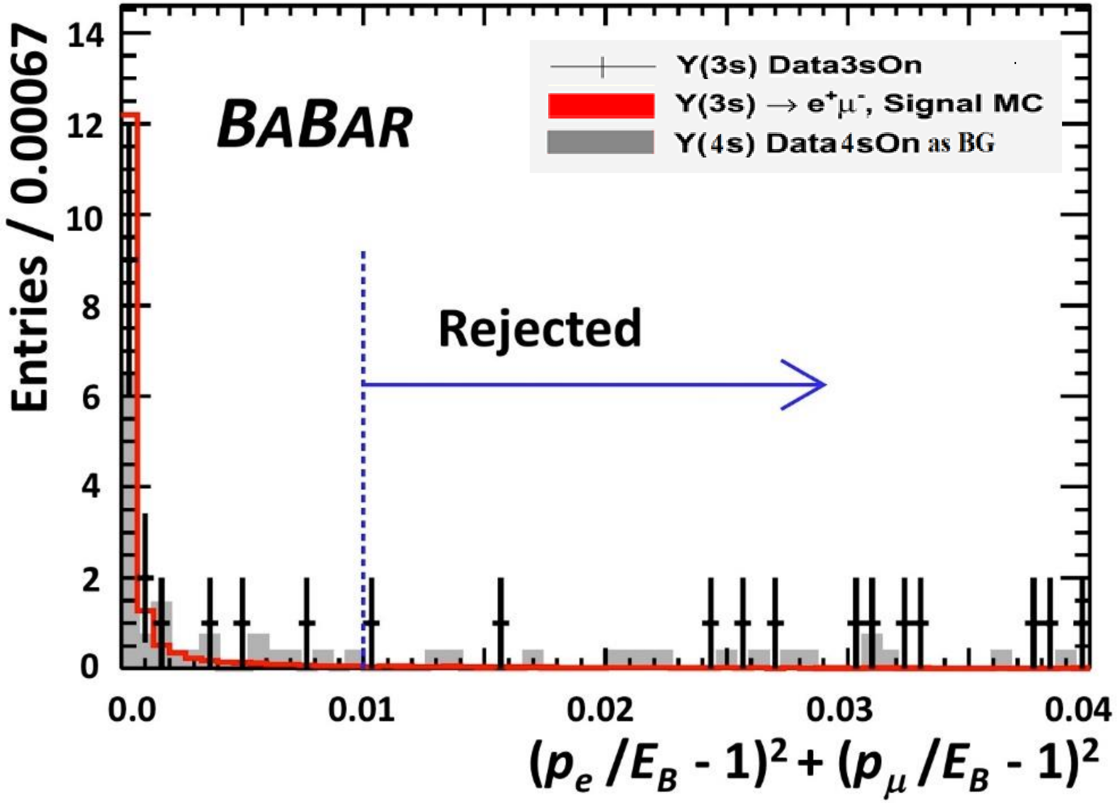
Different Sources of Background

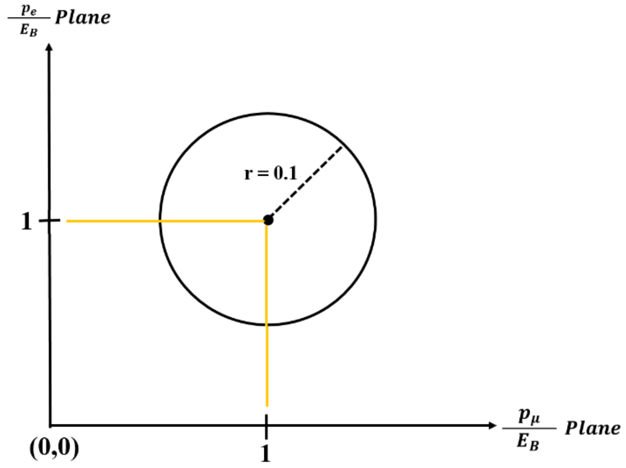
Final Selection Criterion

BABAR **Preliminary**



BABAR **Preliminary**





Selection Criteria: The lepton momenta must satisfy the condition which is defining a circle of radius $\left(\frac{p_e}{E_B} - 1\right)^2 + \left(\frac{p_\mu}{E_B} - 1\right)^2 = (0.1)^2 = 0.01$

Where, $p_{e^\pm, \mu^\pm} \sim \frac{\sqrt{s}}{2} \sim E_B$

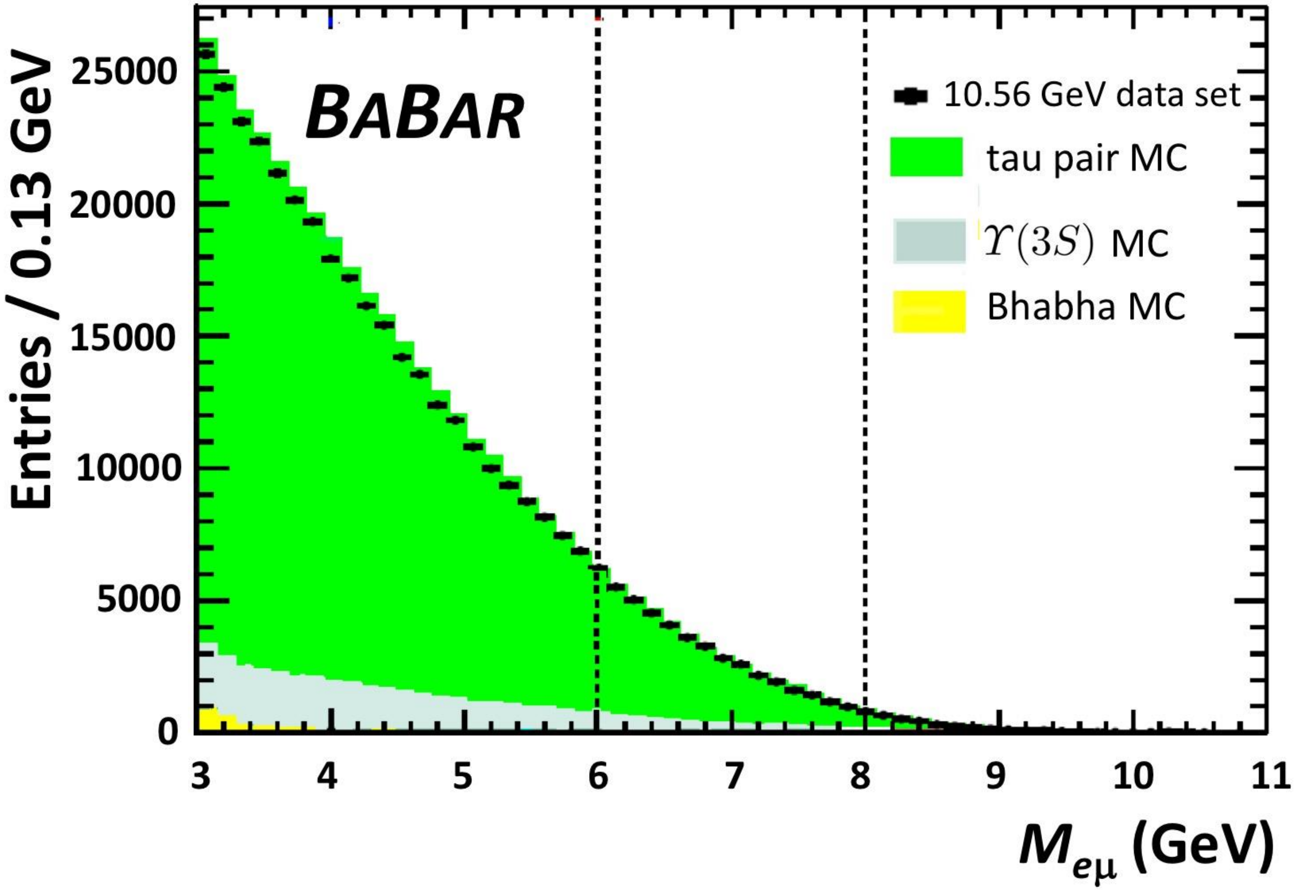
Impact of each component of the selection on the signal efficiency, background and data.

- The first row provides information on the pre-selection.
- The last row provides information after applying all selection criteria.
- Rows 2-7 provides information when all requirements are applied except the criterion associated with the particular row. The luminosity-normalized expected number of events in the third and forth columns are for the background events from the $e^+e^- \to \Upsilon(3S)$ EvtGen MC and the data-driven continuum background events estimated from the $e^+e^- \to \Upsilon(4S)$ sample, respectively.
- The last column represented the number of events in the 27.02 fb^{-1} data sample after unblinding.

Selection Criterion	Efficiency $\varepsilon_{e\mu}$	$\Upsilon(3S)$ BG	Continuum BG	Events in Data
Pre-Selec.	0.8020 $\pm$ 0.0012	75516 $\pm$ 180	725003 $\pm$ 500	945480
Optimized PID	0.5074 $\pm$ 0.0015	5178 $\pm$ 49	320911 $\pm$ 333	358322
2 tracks in final state	0.2354 $\pm$ 0.0013	0	14.1 $\pm$ 2.2	18
Lep. Mom.	0.2684 $\pm$ 0.0012	86.5 $\pm$ 6.3	253.3 $\pm$ 9.4	302
Back-to-back	0.2402 $\pm$ 0.0013	0.46 $\pm$ 0.46	36.2 $\pm$ 6.0	39
EMC Accept.	0.2495 $\pm$ 0.0013	0	13.5 $\pm$ 2.2	17
Energy on EMC	0.2452 $\pm$ 0.0013	0	16.9 $\pm$ 2.4	19
All Criteria	0.2342 $\pm$ 0.0013	0	12.2 $\pm$ 2.1	15

Systematic Uncertainty on Signal Efficiency

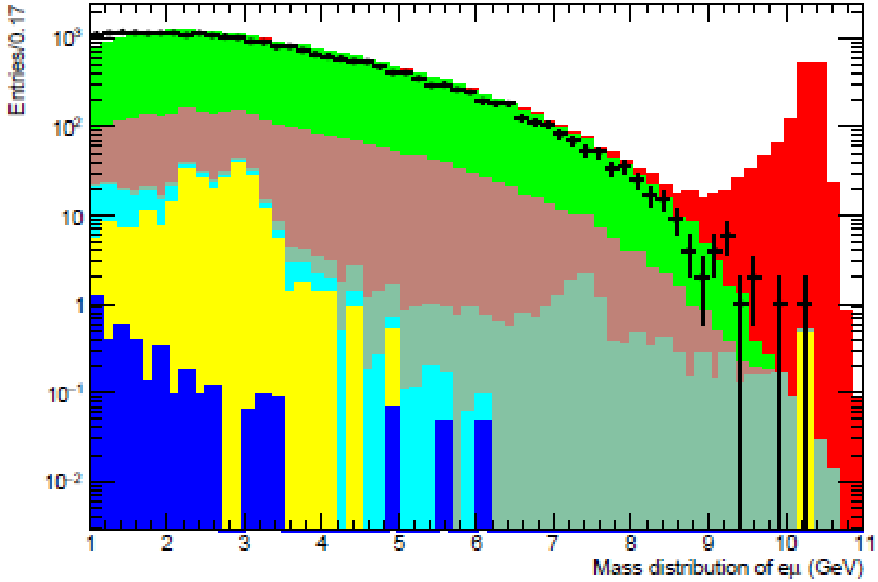
***BABAR* Preliminary**



- Controlled Sample: A data set where two major cuts were reversed to check the data/MC agreement.
- Disagreement arises due to uncertainties in PID, Tracking, kinematics, trigger etc.
- Uncertainty in "Side Bands": 1.2%

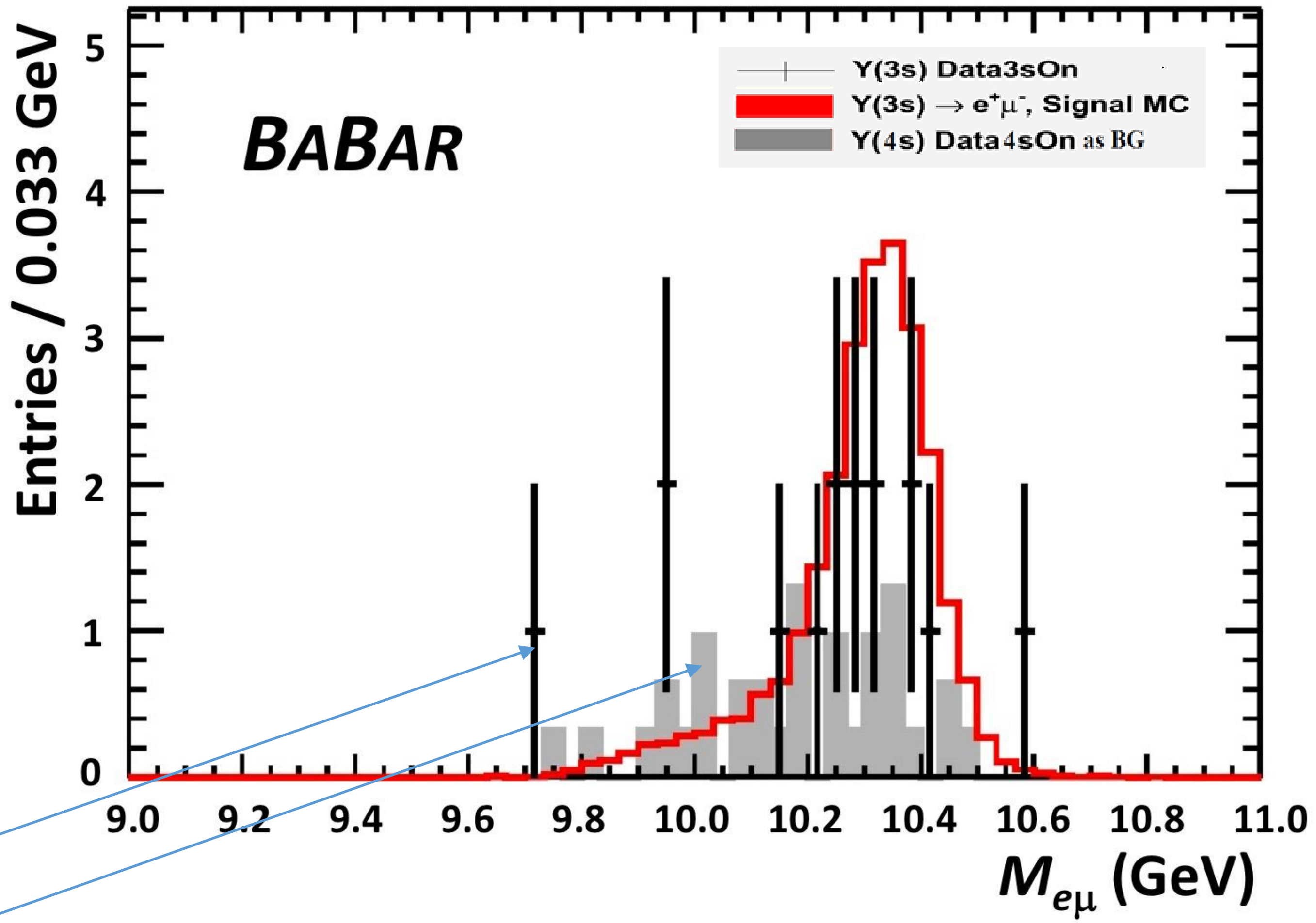
Invariant Mass distribution of $e^{\pm}\mu^{\mp}$

***BABAR* Preliminary**



Before final selection criteria were applied (3% unblinded preselected data)

***BABAR* Preliminary**



After all selection criteria are applied

Candidate Events:15 (black)
Data Driven Estimated
Background : 12.2 (grey)

Summary: Background, Uncertainty, Candidate

Source of Background	**Data Driven Continuum Background $\Upsilon(4S)$**	**Peaking Background from Generic $\Upsilon(3S)$ MC**
Tight PID selection	12.2 ± 2.1	0
Loose PID selection	N/A	1.80 ± 0.9

Values	**Uncertainties** ***BABAR*** **Preliminary**
ε_{SIG} (systematics) • In the "Lepton Momentum" cut • In the "Back to back" cut • In all other cuts on the "Side bands"	 0.029 (2.9%) 0.011 (1.1%) 0.012 (1.2%)
ε_{SIG} (total)	$0.2342 \pm (0.0077_{SYST} \pm 0.0013_{STAT})$ $0.2342 \pm 0.0078_{TOTAL}$ (3.3%)
N_{Υ} (27.0 fb^{-1})	$(117.7 \pm 1.18) \times 10^{6}$ (1.02%) [Phys. Rev. Lett. 104, 151802.(2010).]
Total Background (equivalent to 27.0 fb^{-1})	**12.2 ± 2.3** (18.9%)
Candidate Seen in Data Sample	**15**

Results on Lepton Flavour Violating Decays

BABAR **Preliminary**

- **Data:** $\left(27.0\ fb^{-1}\right)$

- **Branching Fraction:**

$$\frac{N_{\text{Candidate}} - N_{BG}}{\varepsilon_{sig} \times N_{\Upsilon}}$$

$$\left(1.0\ \pm 1.4_{stat(N_{Candidate})} \pm 0.8_{syst}\right) \times 10^{-7}$$

- **Upper Limits with Confidence Level of 90%:** $< 3.6 \times 10^{-7}$ **CLs Method**

[J.Phys.G 28 (2002) 2693-2704]

Implication For New Physics

- A measurement of BF($\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$) can be used to place constraints on $\frac{g^2_{NP}}{\Lambda_{NP}}$ of new physics processes that include lepton flavour violation.

$$where, \frac{g^2_{NP}}{\Lambda_{NP}} = \frac{\text{effective coupling of the new physics}}{\text{energy scale of the NP, given by the mass of the NP propagator.}}$$

- Place constraints on $\frac{g^2_{NP}}{\Lambda_{NP}}$ of new physics processes that include lepton flavor violation using

BF($\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$) < 3.6 × 10^{-7} @ 90%CL ***BABAR*** **Preliminary**

$$\left(\frac{g^2_{NP}}{\Lambda_{NP}}\right)^2 / \left(\frac{4\pi\alpha_{QED}Q_b}{M_{\Upsilon(3S)}}\right)^2 = \frac{BF(\Upsilon(3S)\rightarrow e\mu)}{BF(\Upsilon(3S)\rightarrow \mu\mu)}$$

$$\Lambda_{NP}/g^2_{NP} \geq 80 \text{ TeV @90\% CL}$$

Conclusion

- **This is the first reported experimental upper limits on $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$**

$$\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp} < 3.6 \times 10^{-7} \text{ @ } 90\% \text{ C.L.}$$

***BABAR* Preliminary**

- Our reported limit is several orders of magnitude tighter than the indirected limit according to the ref [S.Nussinov, et. al. PRD 63, 016003 (2001)].

$$\Lambda_{NP}/g_{NP}^2 \geq 80 \text{ TeV}$$

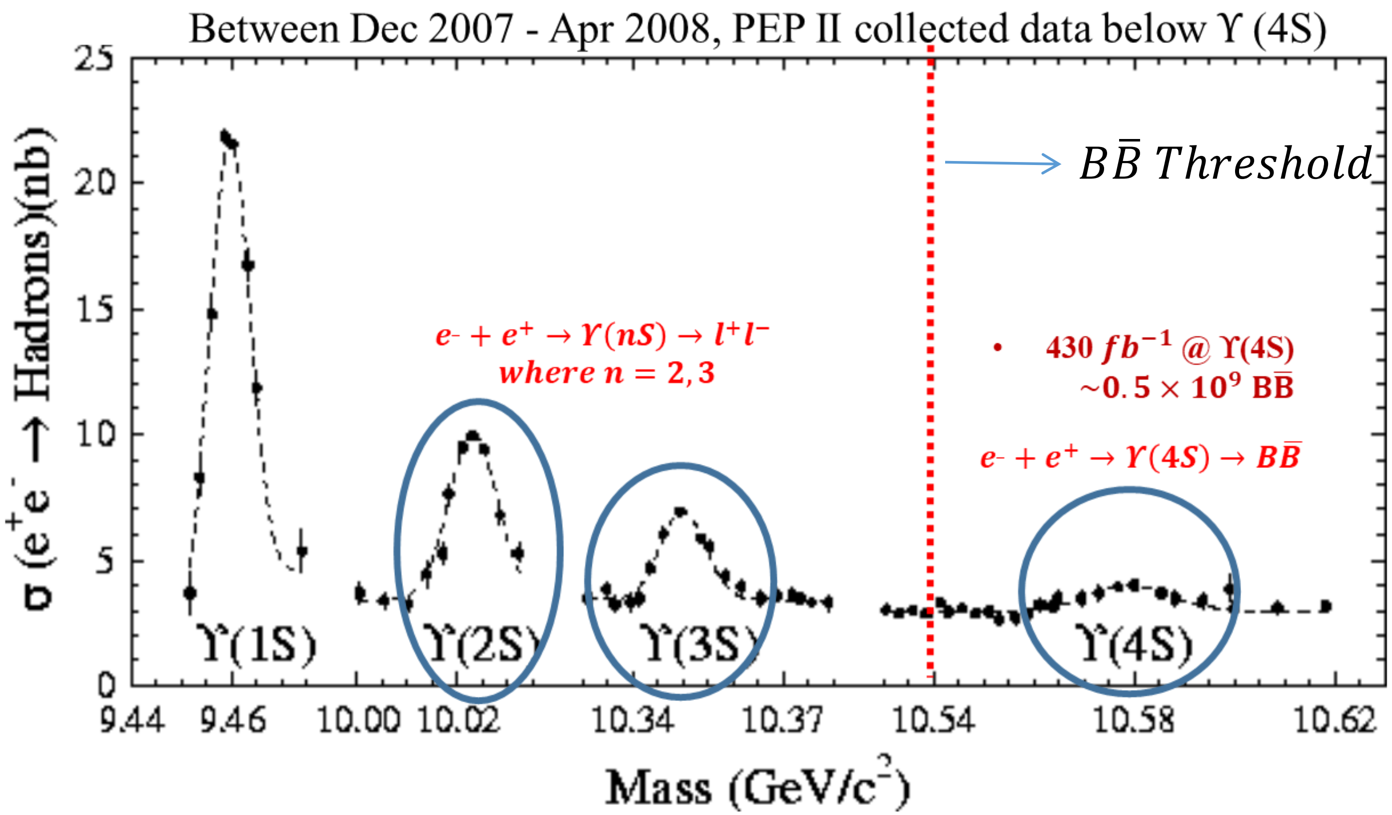
***BABAR* Preliminary**

- This result can be interpreted as a limit on NP:

- A PRL journal paper has already submitted for the publication.

Thanks and Questions

Back up: Charged Lepton Flavour Violation in Upsilon Decays



- **30 fb^{-1}@ Υ(3S) 122 M Υ decays**
  ~ 10 × Belle
  ~ 20 × CLEO

- **15 fb^{-1}@ Υ(2S) 100 M Υ decays**
  ~ 12 × CLEO

Dramatic Increase in sensitivity to rare decays: $\Gamma_{\Upsilon(4S)}/\Gamma_{\Upsilon(nS)} \approx 10^3$

Upsilon System: **CUSB detector, CLEO Collaboration**
T. Bohringer et al., Phys. Rev. Lett. 44, 1111 (1980) and P. Finocchiaro et al., Phys. Rev. Lett. 45, 222 (1980)

Back up: Theoretical Upper limit (Indirect)

Nussinov, Peccei, Zhang [1]

- Assume coupling of Υ to eμ looks like: $L_{eff} = gV_{e\mu}\bar{\mu}\gamma_\alpha e V^\alpha$
- Through Fig 1. this coupling contributes to $A\ (\mu \to 3e)$

$$A(\mu \to 3e) = (\bar{u}_\mu(p)\gamma^\alpha u_e(k_3))(\bar{v}_e(k_1)\gamma_\alpha u_e(k_2))\frac{g_{V_{e\mu}} g_{V_{ee}}}{M_V^2 - S} \quad \text{----(1)}$$

$$\frac{[\Gamma(\mu \to 3e)]_{V-exch}}{[\Gamma(\mu \to e\nu\bar{\nu})]} \approx \frac{g^2 V_{e\mu} g^2 V_{ee}}{M_V^4} / \frac{g_W^4}{M_W^4} \quad \text{----(2)}$$

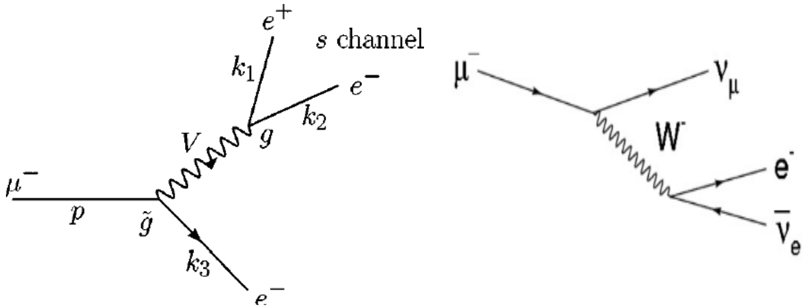
Since $[\Gamma(\mathrm{V} \to \mathrm{e}^+\mathrm{e}^-)] \sim \mathrm{g}^2\ \mathrm{V}_{ee}\ \mathrm{M}_V$ and

$[\Gamma(\mathrm{V} \to \mathrm{e}^\pm\mu^\mp)] \sim \mathrm{g}^2\ \mathrm{V}_{e\mu}\ \mathrm{M}_V$, while $[\Gamma(\mathrm{W} \to \mathrm{e}\nu)] \sim \mathrm{g}_W^2\ \mathrm{M}_W$

$$[BR(\mu \to 3e)]_{V-exch} \approx \frac{[\Gamma(V \to e^+e^-)][\Gamma(V \to e^\pm\mu^\mp)]}{[\Gamma^2(W \to e\nu)]}(\frac{M_W}{M_V})^6 \quad \text{----(3)}$$

$$BR(\Upsilon \to e\mu) = BR(\mu \to eee)\frac{\Gamma(W \to e\nu)^2}{\Gamma(\Upsilon)\Gamma \to ee}(\frac{M_\Upsilon}{M_W})^6 \quad \text{----(4)}$$

$$\mathrm{BR}(\Upsilon(3S) \to e^\pm\mu^\mp \leq 2.5 \times 10^{-8}.$$



(Left) A vector exchange diagram contributing to $\mu \to 3e$
(Right) Ordinary muon decay, $\mu \to e\nu\bar{\nu}$, which proceeds via W exchange.

- $\mathrm{BF}(\mu \to \mathrm{eee}) \leq 1.0 \times 10^{-12}$
- $\mathrm{BF}(\mu \to e\nu\bar{\nu}) \simeq 100\ \%$
- $\mathrm{BF}(\mathrm{W} \to \mathrm{e}^+\nu) \simeq (10.71 \pm 0.09)\ \%$
- $\mathrm{BF}(\Upsilon(3S) \to \mathrm{l}^+\mathrm{l}^-) \simeq (2.18 \pm 0.21)\ \%$
- $\Gamma(\Upsilon(3S)) = (20.32 \pm 1.85)\ keV$
- $\Gamma(\mathrm{W}) = (2.046 \pm 0.049)\ GeV$

S.Nussinov, et. al. estimate that the contribution of the virtual $\Upsilon\ (3S) \to e^\pm\mu^\mp$ to the μ →*eee* rate would be reduced by approximately $M^2_\mu / (2\ M^2_\Upsilon)$ leading to a re-calculated indirect bound:
$\mathrm{BF}(\Upsilon\ (3S) \to e^\pm\mu^\mp) < 1\times 10^{-3}$

[1] Nussinov, et. al. PRD 63, 016003 (2001)

Back up: Analysis Scheme

- **Blind Analysis:** To eliminate experimenter's bias.
- **Pre-Selection:** Needs a special background filter to collect $e^{\pm}\mu^{\mp}$ events efficiently.
- **Final Selection by the analyst:** Applied on the pre-selected events
- **PID Selection:** Multivariate Technique applied, tested 16 different PID selectors.
- **Optimized Electron and Muon selectors:** $\varepsilon_{e\mu}/\sqrt{(1+N_{BG})}$ where

  $\varepsilon_{e\mu}$ is the final efficiency as determined by signal MC and

  N_{BG} is the number of expected background events

Final Selection:
2 tracks (1 electron and 1 muon in the final state), one in each hemisphere;
$24^{\circ} < \theta_{Lab} < 130^{\circ}$ EMC acceptance for both tracks.
The lepton momenta must satisfy the following condition $\left(\frac{p_e}{E_{Beam}} - 1\right)^2 + \left(\frac{p_\mu}{E_{Beam}} - 1\right)^2 < 0.01$ where $E_{Beam} = \sqrt{s}/2$
Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^{\circ}$ to ensure they emerged as back to back.
Energy deposit by Muon track on the Electromagnetic Calorimeter should be greater than 50 MeV.