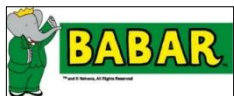




Search for the Lepton Flavor Violating decays in $\Upsilon(nS) \rightarrow e^\pm \mu^\mp$ (n=3 and 2) at BaBar

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On behalf of the BaBar Collaboration
July 30 – August 05, 2026.



Outline of the Talk

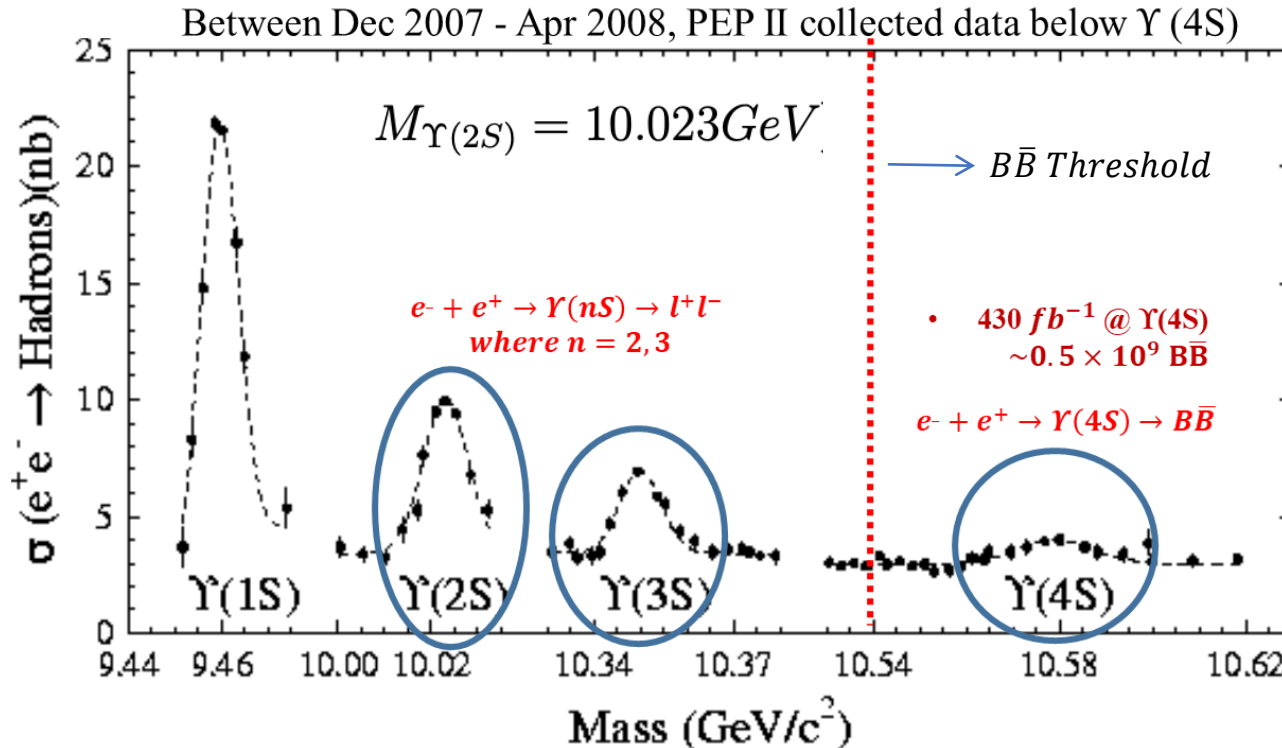
- Charged Lepton Flavor Violation in $\Upsilon(nS) \rightarrow e^\pm \mu^\mp$ (n=2,3)
- Theoretical Expectations and Experimental Limits
- Asymmetric PEP-II Collider and BaBar Detector
- Data, MC and Data Driven Background
- Analysis Strategy
 - Signal and Background Characteristic
 - Selection Criterion
 - Validation of Using the Data Driven Background
- $\Upsilon(nS) \rightarrow e^\pm \mu^\mp$ (n=2,3) Results and Indication for New Physics
- Conclusion

Motivation

- Lepton Flavor Violation (LFV) in the neutral lepton sector has already indicated by the observation of neutrino oscillations by the Super-Kamiokande Observatory and the Canadian Sudbury Neutrino Observatories (SNO).
- Such an oscillation mechanism cannot induce observable LFV in the charged lepton sector.
- Charged Lepton flavor violating (CLFV) processes are strongly suppressed in the standard model by powers of (small) neutrino masses, e.g. $\left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 \leq 10^{-48}$
[1]
- Observation of CLFV is, therefore, a clear sign of new physics (NP) beyond the SM.

[1] Phys. Rev. Lett. 104, 151802

Charged Lepton Flavor Violation in Upsilon Decays



- $30 \text{ fb}^{-1} @ \Upsilon(3S)$ 122 M Υ decays
~ $10 \times \text{Belle}$
~ $20 \times \text{CLEO}$

- $15 \text{ fb}^{-1} @ \Upsilon(2S)$ 100 M Υ decays
~ $12 \times \text{CLEO}$

**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)

Motivation

Table: CLEO, BELLE, and BABAR results on different decay modes of Υ

Experiments	Measurements	Upper limits	Confidence level (%)
BABAR	$\mathcal{B}[\Upsilon(3S) \rightarrow e^\pm \tau^\mp]$	$< 5 \times 10^{-6}$	90
BABAR	$\mathcal{B}[\Upsilon(3S) \rightarrow \mu^\pm \tau^\mp]$	$< 4.1 \times 10^{-6}$	90
BABAR	$\mathcal{B}[\Upsilon(3S) \rightarrow e^\pm \mu^\mp]$	$< 3.7 \times 10^{-7}$	90
BABAR	$\mathcal{B}[\Upsilon(2S) \rightarrow e^\pm \mu^\mp]$	NEW!	NEW!
BELLE	$\mathcal{B}[\Upsilon(2S) \rightarrow \mu^\pm \tau^\mp]$	$< 0.23 \times 10^{-6}$	90
BELLE	$\mathcal{B}[\Upsilon(2S) \rightarrow e^\pm \tau^\mp]$	$< 1.12 \times 10^{-6}$	90
CLEO	$\mathcal{B}[\Upsilon(1S) \rightarrow \mu^\pm \tau^\mp]$	$< 6 \times 10^{-6}$	95
CLEO	$\mathcal{B}[\Upsilon(2S) \rightarrow \mu^\pm \tau^\mp]$	$< 14.4 \times 10^{-6}$	95
CLEO	$\mathcal{B}[\Upsilon(3S) \rightarrow \mu^\pm \tau^\mp]$	$< 20.3 \times 10^{-6}$	95

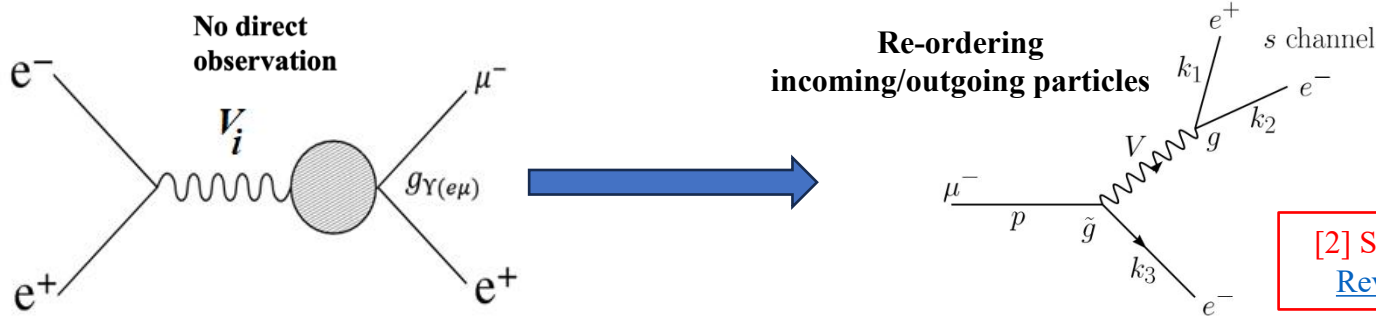
- In this talk, we will focus on two analysis:

➤ $\mathcal{B}[\Upsilon(2S) \rightarrow e^\pm \mu^\mp]$ New analysis – to be published in a next few months

➤ $\mathcal{B}[\Upsilon(3S) \rightarrow e^\pm \mu^\mp]$ BaBar Collaboration, [Phys. Rev. Lett. 128, 091804 \(2022\)](#)

Theoretical Background

- Let us assume that a vector boson V_i (here V_i could be either a fundamental state, such as the Z^0 , or a quark-antiquark bound state such as the ϕ , J/ψ , or Υ) couples to $e^\pm \mu^\mp$. The effective coupling between the vector boson V_i and $e^\pm \mu^\mp$ can be written as [2]



[2] S. Nussinov, et al., [Phys. Rev. D63 \(2001\) 016003](#)

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

$$[BR(\Upsilon(2S) \rightarrow e\mu)] \cong BR(\mu \rightarrow eee) \frac{[BR(W \rightarrow e\nu) * \Gamma_W]^2}{[BR(\Upsilon(2S) \rightarrow e^+e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}} \left(\frac{M_{\Upsilon(2S)}}{M_W} \right)^6$$

Using $\mathcal{B}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ [3] and other data pertaining to the e^+e^- -widths of the various vector mesons V_i , we find

$$\mathcal{B}(\Upsilon(3S) \rightarrow e^\pm \mu^\mp) \leq 2.5 \times 10^{-8}$$

$$\mathcal{B}(\Upsilon(2S) \rightarrow e^\pm \mu^\mp) \leq 9.58 \times 10^{-9}$$

[3] SINDRUM collaboration, [Nucl. Phys. B299, 1 \(1988\)](#)

Theoretical Background

- The size of the vector boson exchange contribution to the $\mu \rightarrow eee$ decay amplitude can be significantly reduced if there are kinematical suppressions.
- Such suppressions are possible when the effective vector boson couplings involve derivatives (momentum factors).
- The contribution of the virtual $\Upsilon(2S) \rightarrow e^\mp \mu^\pm$ to the $\mu \rightarrow eee$ the rate would be reduced by approximately:

$$\frac{M_\mu^2}{2M_{\Upsilon(2S)}^2}$$

S. Nussinov, et al., [Phys. Rev. D63 \(2001\) 016003](#)

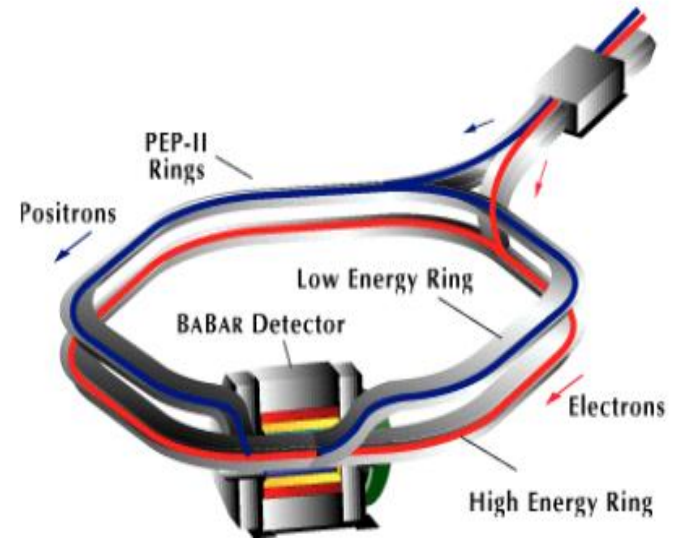
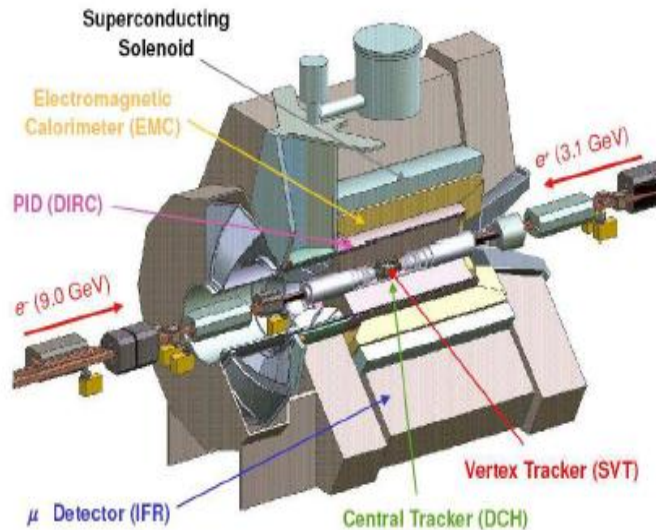
- Leading to a modified bound on

$\mathcal{B}(\Upsilon(3S) \rightarrow e^\pm \mu^\mp)$ reduced by $\leq 1 \times 10^{-3}$

$\mathcal{B}(\Upsilon(2S) \rightarrow e^\pm \mu^\mp)$ reduced by $\leq 1.7 \times 10^{-4}$

BaBar Detector and PEP-II

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



[B. Aubert et al., The BABAR detector, Nucl. Instrum. Meth., A 479:1116, 2002.]

Data and SP samples

Samples	$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})[4]
$\Upsilon(2S)$ $\Upsilon(2S)$ off – peak (~ 40 MeV below $\sqrt{s}$) MC – continuum QED, $\Upsilon(2S)$ generic $\Upsilon(2S)$ signal MC $\Upsilon(4S)$ data driven continuum background	10.023 10.579	$13.60 \pm 0.02 \pm 0.09$ $1.419 \pm 0.006 \pm 0.011$ 145,000 events [EvtGen] $78.31 \pm 0.02 \pm 0.35$
$\Upsilon(3S)$ $\Upsilon(3S)$ off – peak (~ 40 MeV below $\sqrt{s}$) MC – continuum QED, $\Upsilon(3S)$ generic $\Upsilon(3S)$ signal MC $\Upsilon(4S)$ data driven continuum background	10.355 10.579	$27.96 \pm 0.03 \pm 0.16$ $2.623 \pm 0.008 \pm 0.017$ 103,000 events [EvtGen] $78.31 \pm 0.02 \pm 0.35$

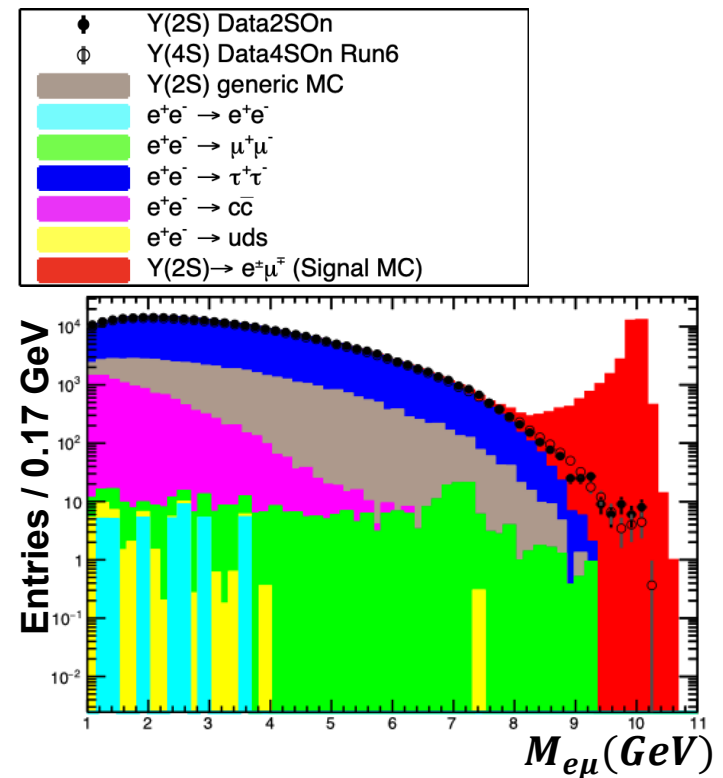
- We used about 7% of data as blinded analysis to optimize our selection criteria and signal efficiency; we then discarded these from the total data luminosity

[4] BaBar collaboration, [NIMA 726 \(2013\) 203-213](#)

Signal and Background

$$\Upsilon(nS)[n = 2, 3] \rightarrow e^\pm \mu^\mp (e^+ \mu^- \text{ or } e^- \mu^+)$$

- Event selection proceeds in two stages:
 - **Pre-selection and**
 - **Final selection**
- Events consists of exactly two oppositely charged primary particles
- Two charge tracks with total charge = 0
- Sum of momentum of two tracks $> 9 \text{ GeV}/c$
- A dedicated $e\mu$ filter is used to preselect events with only an electron candidate and a muon candidate in the detector
- The preselection has an 80% (in $\Upsilon(3S)$) and 82% (in $\Upsilon(2S)$) efficiency for signal events
- Main sources of background:
 - a) $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ and
 - b) $e^+e^- \rightarrow e^+e^-(\gamma)$
- Background from $e^+e^- \rightarrow \tau^+\tau^- \rightarrow e^\pm \mu^\mp 2\nu 2\bar{\nu}$ is efficiently removed with the kinematic requirements



Signal and Background

$$\Upsilon(nS)[n = 2, 3] \rightarrow e^\pm \mu^\mp (e^+ \mu^- \text{ or } e^- \mu^+)$$

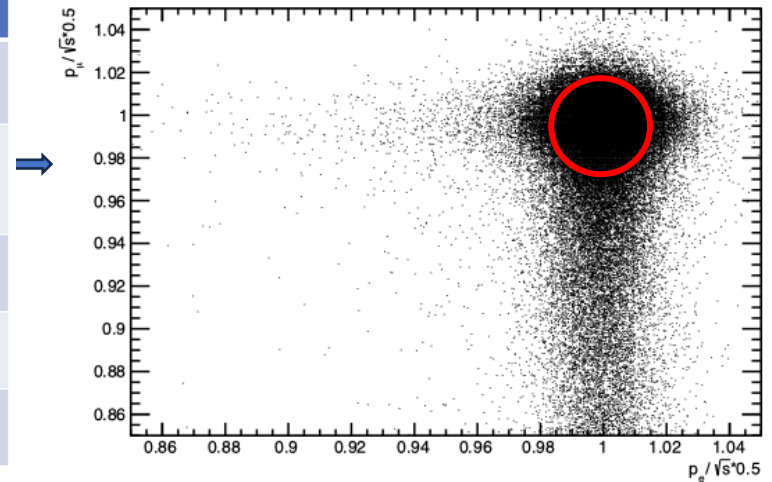
Event selection proceeds in two stages:

- 1) Pre-selection and
- 2) **Final selection**

Definition	Selection
Two tracks (one in each hemisphere)	one electron and one muon in the final state
Lepton momentum plane	$\left(\frac{p_e}{\sqrt{s} * 0.5} - 1\right)^2 + \left(\frac{p_\mu}{\sqrt{s} * 0.5} - 1\right)^2 < 0.01$
Back-to-back	$\theta_{12}^{\text{CM}} > 179^\circ$
EMC acceptance	$24^\circ < \theta_{\text{lab}} < 130^\circ$
Muon energy deposited in EMC	$> 50 \text{ MeV}$

- Optimized PID selection for $e^\pm \mu^\mp$ track

Signal MC
($\Upsilon(nS)$) $n=2,3$

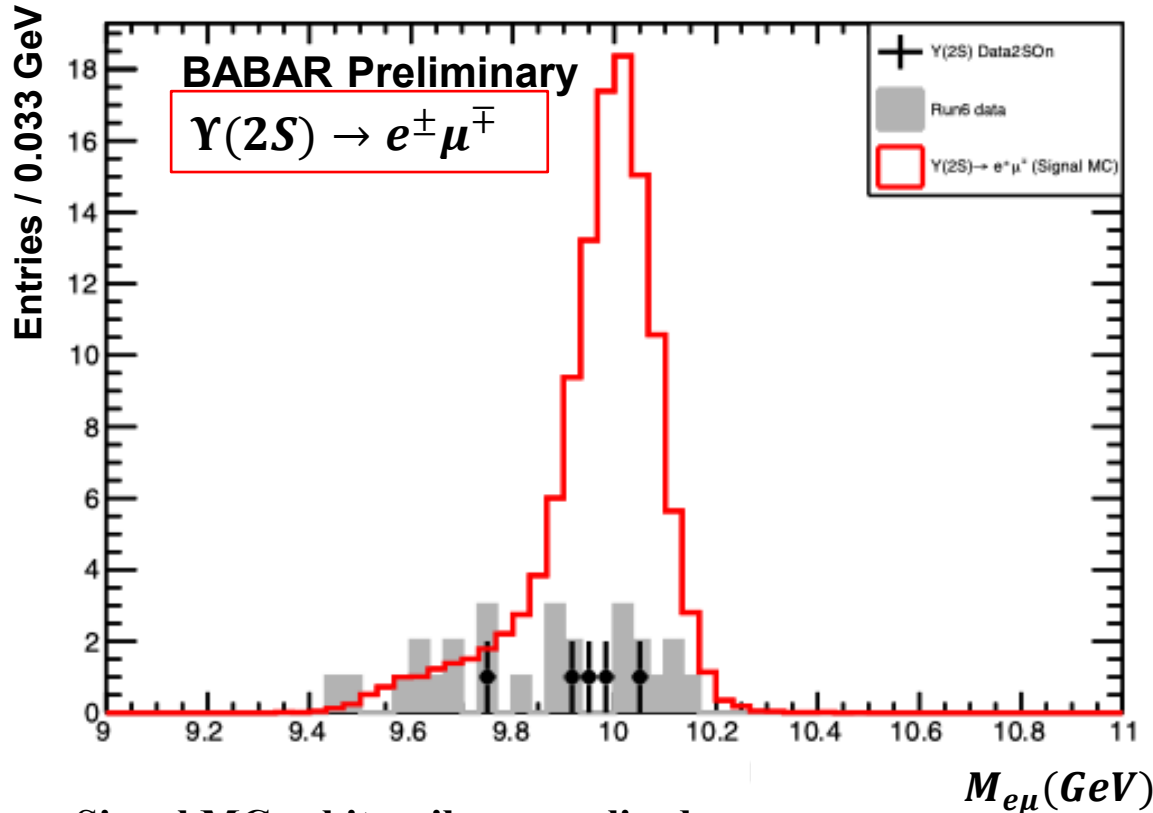


Distribution of the squared distance from the point (1,1) in the plane of the scaled electron vs muon momenta for events satisfying all other selection criteria in the data.

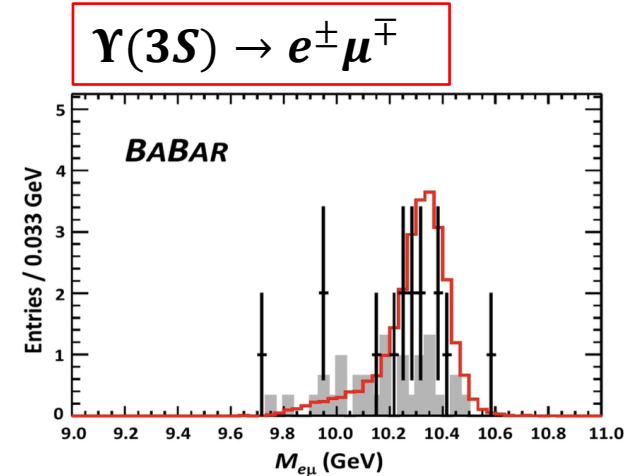
Final Mass distribution of

$$\Upsilon(2S, 3S) \rightarrow e^{\pm} \mu^{\mp}$$

(after all selection and optimized PID criteria are applied)



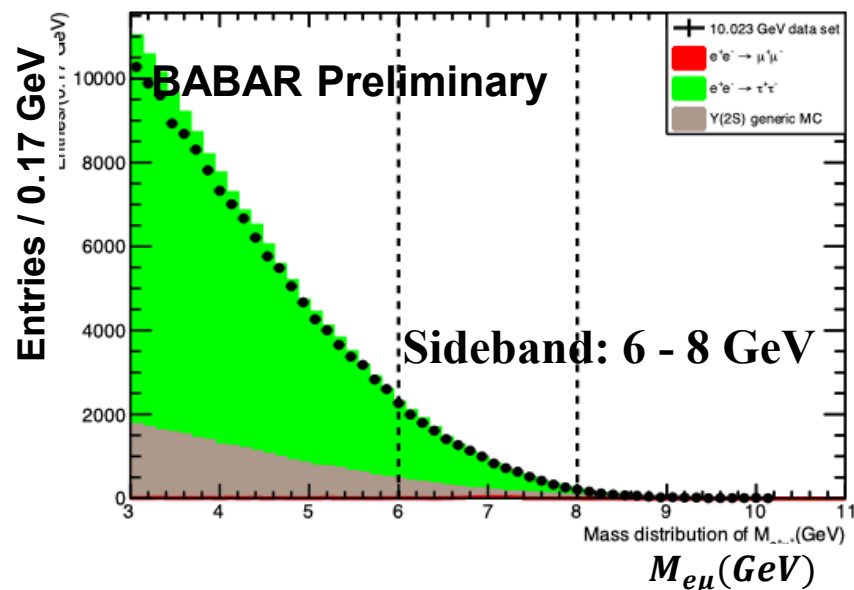
- Signal MC arbitrarily normalized
- Run 6 data is scaled to $\Upsilon(2S)$
- $N_{\text{Cand}} = 5$
- Expected background = 4.19 ± 0.83



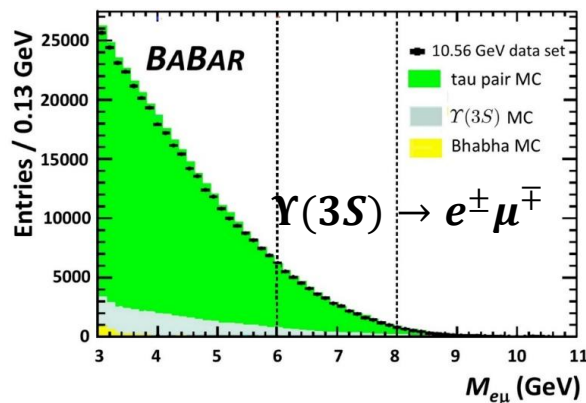
- $N_{\text{Cand}} = 15$
- Expected background = 12.2 ± 2.3

BaBar Collaboration, [Phys. Rev. Lett. 128, 091804 \(2022\)](#)

Systematic Studies



$$\frac{N_{Data} - N_{BG}}{N_{\tau\text{-pairs}}} \approx 0.012 \text{ or } 1.2\%$$



$$\mathcal{BF} = \frac{N_{Cand} - N_{BG_{\Upsilon(4S)RUN6}}}{\mathcal{E}_{SIG} \times N_{\Upsilon(2S)}}$$

We assess the systematic uncertainties in the signal efficiency by the data-driven approach. Data to MC yields for a control sample of $e^+e^- \rightarrow \tau^+\tau^- \rightarrow e^\pm\mu^\mp 2\nu 2\bar{\nu}$ events in an $e\mu$ mass sideband.

The Control sample is produced by reversing two major kinematic requirements: the E_B (beam energy) normalized lepton momentum cut and the requirement on the angle between the two tracks.

- This τ control sample study measures the systematic uncertainty associated with particle identification, tracking, kinematics, trigger selection criteria, and all other effects except those associated with the two major kinematic requirements used to select the control sample.

Summary of systematic uncertainties ($\Upsilon(2S)$)

Table: Summary of systematic uncertainties. The values of the efficiency, background, and number of $\Upsilon(2S)$ decays are presented in the first column and their uncertainties in the second column. The different contributions to the efficiency systematic uncertainties are also presented.

Component Value	Uncertainties by Source
Signal Efficiency: 0.1837	Lep. Mom. cut: 0.0039 (2.1 %)
	Back-to-back cut: 0.0014 (0.8 %)
	All other cuts: 0.0022 (1.2 %)
	MC statistics: 0.0002 (0.1 %)
	± 0.0047 (2.6 %)
$N_\Upsilon: 91.6 \times 10^6$	$\pm 0.9 \times 10^6$ (1.0 %)
BG: 4.19	± 0.83 (20 %)

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

Component value	Uncertainties by source
Signal efficiency: 0.2342	Lepton momentum cut: 0.0068 (2.9%)
	Back-to-back cut: 0.0026 (1.1%)
	All other cuts: 0.0028 (1.2%)
	MC statistics: 0.0003 (0.13%)
	Total ± 0.0078 (3.3%)
	$N_\Upsilon: 117.7 \times 10^6 \pm 1.2 \times 10^6$ (1.0%)
	BG: 12.2 ± 2.3 (19%)
Candidate events:	15 (27.0 fb⁻¹)

Summary and results ($\Upsilon(2S)$ and $\Upsilon(3S)$)

$$\mathcal{B} = (N_{cand} - N_{BG\Upsilon(4S)}) / (\epsilon_{SIG} \times N_{\Upsilon(2S)})$$

$$(\sigma_{BF})^2 = \underbrace{\left(\frac{\delta_{BF}}{\delta_{N_{data}}}\right)^2 (\sigma_{N_{data}})^2}_{\text{Statistical error}} + \underbrace{\left(\frac{\delta_{BF}}{\delta_{N_{BG}}}\right)^2 (\sigma_{N_{BG}})^2 + \left(\frac{\delta_{BF}}{\delta_{N_{\epsilon}}}\right)^2 (\sigma_{\epsilon})^2 + \left(\frac{\delta_{BF}}{\delta_{N_{\Upsilon}}}\right)^2 (\sigma_{N_{\Upsilon}})^2}_{\text{Systematic error}}$$

Statistical error

Systematic error

$$\mathcal{B} [\Upsilon(2S) \rightarrow e^{\pm} \mu^{\mp}] = [0.5 \pm 1.3 \text{ (stat)} \pm 0.5 \text{ (syst)}] \times 10^{-7}$$

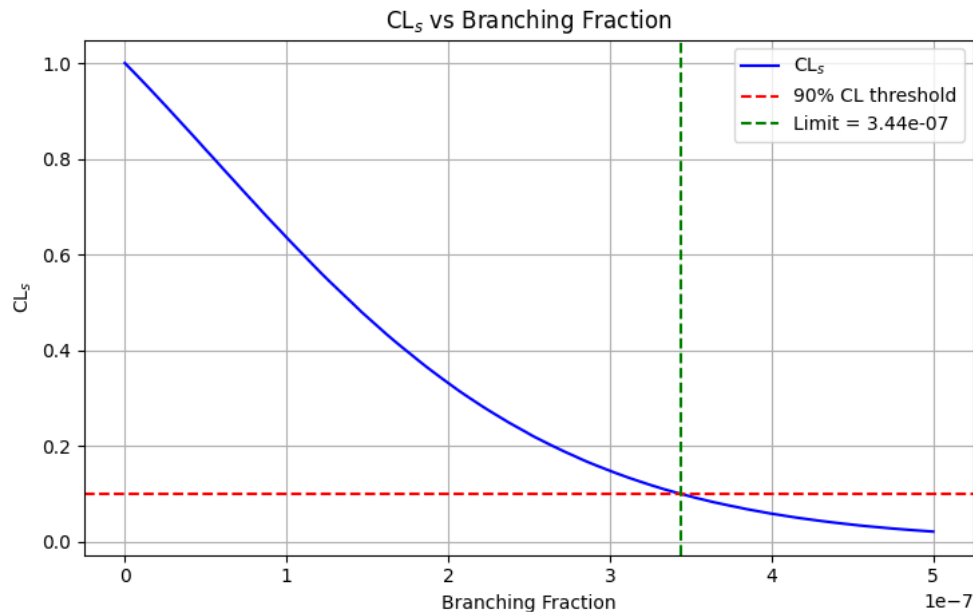
BABAR preliminary

$$\mathcal{B}[\Upsilon(3S) \rightarrow e^{\pm} \mu^{\mp}] = [1.0 \pm 1.4 \text{ (stat)} \pm 0.8 \text{ (syst)}] \times 10^{-7}$$

BaBar Collaboration, [Phys. Rev. Lett. 128, 091804 \(2022\)](#)

Results and upper limits ($\Upsilon(2S)$ and $\Upsilon(3S)$)

- As this result is consistent with no signal, we set an upper limit at 90% confidence level (C.L.) on the branching fraction by using CLs method including the systematic uncertainties.



A. L. Read, J. Phys. G **28**, 2693 (2002); G. Cowan, K. Cranmer, E. Gross, O. Vitells, Eur. Phys. J. C **71**, 1554 (2011), Erratum: Eur. Phys. J. C **73**, 2501 (2013).

$$\mathcal{B}[\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}] < 3.4 \times 10^{-7} \text{ @ 90\% CL}$$

BABAR preliminary

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

BaBar Collaboration, [Phys. Rev. Lett. 128, 091804 \(2022\)](#)

Upper limits vs constraints on NP

- Since this result reports the first search for electron-muon LFV in the $\Upsilon(2S)$ decays, we use this result to place constraints on $\frac{\Lambda_{NP}}{g_{NP}^2}$ @ 90% C.L. of New Physics processes that include LFV

$$\boxed{\Upsilon(2S)} \quad \frac{\left(\frac{g_{NP}^2}{\Lambda_{NP}}\right)^2}{\left(\frac{4\pi\alpha_{2S}Q_b}{M_{\Upsilon(2S)}}\right)^2} = \frac{\mathcal{B}[\Upsilon(2S) \rightarrow e\mu]}{\mathcal{B}[\Upsilon(2S) \rightarrow \mu\mu]} \rightarrow \frac{\Lambda_{NP}}{g_{NP}^2} > 75 \text{ TeV}$$

BABAR preliminary

$$\boxed{\Upsilon(3S)} \quad \frac{\left(\frac{g_{NP}^2}{\Lambda_{NP}}\right)^2}{\left(\frac{4\pi\alpha_{3S}Q_b}{M_{\Upsilon(3S)}}\right)^2} = \frac{\mathcal{B}[\Upsilon(3S) \rightarrow e\mu]}{\mathcal{B}[\Upsilon(3S) \rightarrow \mu\mu]} \rightarrow \frac{\Lambda_{NP}}{g_{NP}^2} > 80 \text{ TeV}$$

BaBar Collaboration, [Phys. Rev. Lett. 128, 091804 \(2022\)](#)

- g_{NP}^2 is the coupling of the new physics, Λ_{NP} is the energy scale of the new physics, α_{nS} (n=2,3) is the fine structure constant at $M_{\Upsilon(nS)}$ scale, and Q_b is the charge of the bottom quark respectively.
- $\mathcal{B}[\Upsilon(2S) \rightarrow \mu\mu] = 1.93 \pm 0.17$, and $\mathcal{B}[\Upsilon(3S) \rightarrow \mu\mu] = 2.18 \pm 0.21$

P. A. Zyla et al., [Phys. 2020, 083C01 \(2020\)](#)

Conclusions

- ❑ BABAR has made a significant contribution to CLFV searches in $\Upsilon(nS) \rightarrow e^\pm \mu^\mp$ [$n = 2, 3$] decays
 - no significant evidence for CLFV has been observed
 - an upper limit at 90% CL has been set
- ❑ These are the leading experimental limits on the branching fraction of $\Upsilon(nS) \rightarrow e^\pm \mu^\mp$ [$n = 2, 3$]
- ❑ The measurement we report here is several orders of magnitude more sensitive than the indirect limit
- ❑ These results translated into the constraints on NP processes that include LFV

Thanks!

Back up: Theoretical Upper limit (Indirect)

Nussinov, Peccei, Zhang [1]

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

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

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

Since $[\Gamma(V \rightarrow e^+e^-)] \sim g^2 V_{ee} M_V$ and

$[\Gamma(V \rightarrow e^\pm\mu^\mp)] \sim g^2 V_{e\mu} M_V$, while $[\Gamma(W \rightarrow e\nu)] \sim g_W^2 M_W$

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

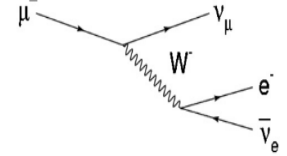
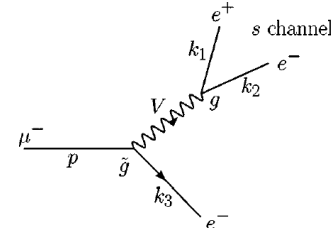
$$BR(\Upsilon \rightarrow e\mu) = BR(\mu \rightarrow eee) \frac{\Gamma(W \rightarrow e\nu)^2}{\Gamma(\Upsilon)\Gamma \rightarrow ee} \left(\frac{M_\Upsilon}{M_W}\right)^6 \quad \text{---(4)}$$

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

S.Nussinov, et. al. estimate that the contribution of the virtual $\Upsilon(3S) \rightarrow e^\pm\mu^\mp$ to the $\mu \rightarrow eee$ rate would be reduced by approximately $M_\mu^2 / (2 M_\Upsilon^2)$ leading to a re-calculated indirect bound:

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

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



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

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

$$\frac{m_\mu^2}{2M_V^2} = \left\{ \begin{array}{ll} 3 \times 10^{-3} & V = \phi \\ 3 \times 10^{-4} & V = J/\psi \\ \boxed{3 \times 10^{-5}} & V = \Upsilon \\ 3 \times 10^{-7} & V = Z^0 \end{array} \right\}.$$

Back up: Analysis Scheme

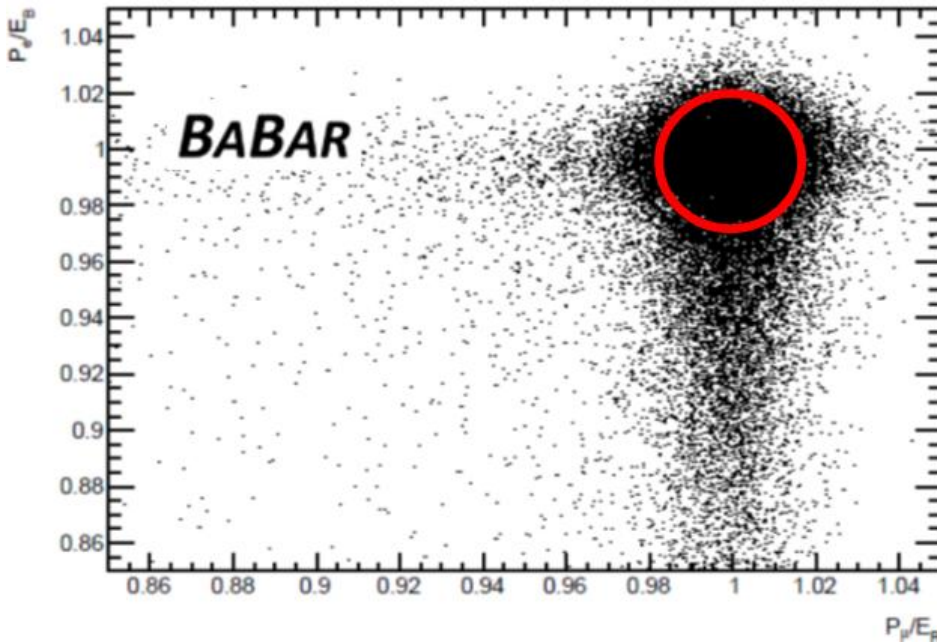
- **Blind Analysis:** To eliminate experimenter's bias.
- **Pre-Selection:** Needs a special background filter to collect $e^{\pm}\mu^{\mp}$ events efficiently.
- **Final Selection by the analyst:** Applied on the pre-selected events
- **PID Selection:** Multivariate Technique applied, tested 16 different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

Peaking Background

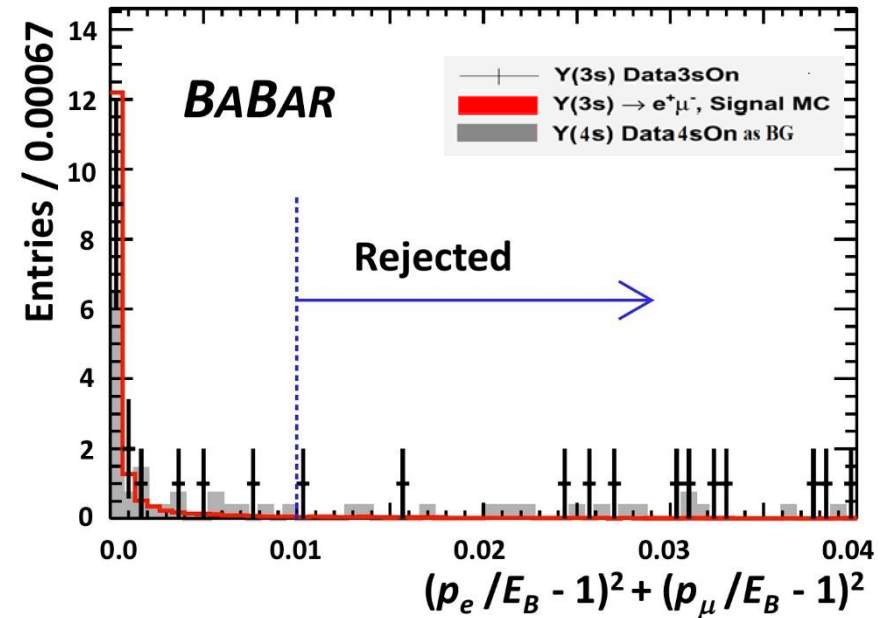
Source of Background	Data Driven Continuum Background $\Upsilon(4S)$	Peaking Background from Generic $\Upsilon(3S)$ MC
Tight PID selection	12.2 ± 2.1	0
Loose PID selection	N/A	1.80 ± 0.9

Selection criteria on the lepton momentum plane

Signal Monte Carlo



Distribution of the squared distance from the point (1,1) in the plane of the scaled electron vs muon momenta for events satisfying all other selection criteria in the data.



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