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Search for charged lepton flavor violation in $\Upsilon(2S, 3S) \rightarrow e^\pm \mu^\mp$ decays

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On behalf of the BaBar Collaboration



Motivation

- The observation of neutrino oscillations by the Super-Kamiokande Observatory and the Canadian Sudbury Neutrino Observatories (SNO) indicates Lepton Flavor Violation (LFV) in the neutral lepton sector.
- Such an oscillation mechanism cannot induce observable LFV in the charged lepton sector.
- In the Standard Model (SM), Charged Lepton Flavour Violation (CLFV) is highly suppressed due to the 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.
- With the results of $\mathcal{B}[Y(2S, 3S) \rightarrow e^\pm \mu^\mp]$ we placed constraints on NP processes that include LFV.

[1] Benjamin W. Lee and Robert E. Shrock [Phys. Rev. D 16, 1444, 1977](#)

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	$\mathcal{B}[\Upsilon(2S) \rightarrow e^\pm \mu^\mp]$	To be presented (TBP)	TBP
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

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

Theoretical Background

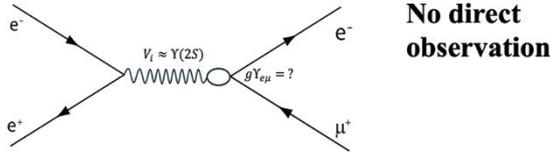
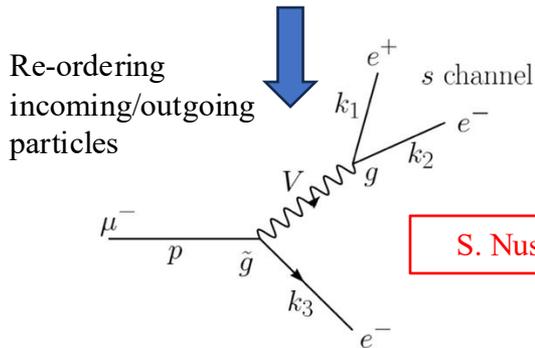
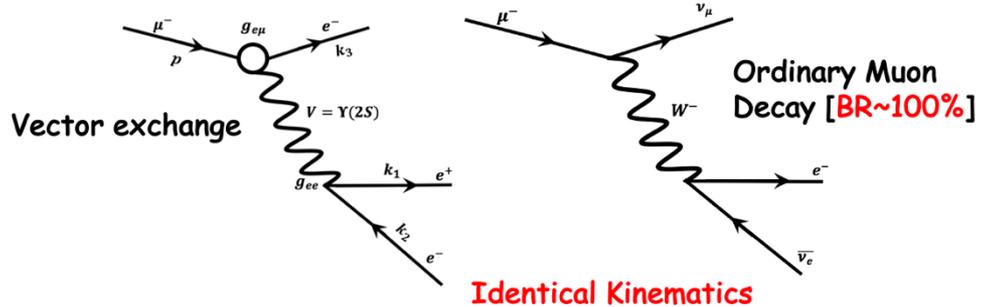


Figure : Forbidden Standard Model process. V_i is a vector boson that could be a fundamental states, such as γ , Z^0 or a quark-antiquark bound state such as ϕ , J/ψ , or Υ . V_i couples to $e^\mp\mu^\pm$



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

$$[BR(\Upsilon(2S) \rightarrow e\mu)] \cong BR(\mu \rightarrow eee) \frac{[BR(W \rightarrow e\nu) * \Gamma_W]^2}{[BR(\Upsilon(2S) \rightarrow e^+e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}} \left(\frac{M_{\Upsilon(2S)}}{M_W}\right)^6 \dots\dots\dots (1)$$

$\mathcal{B}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ [SINDRUM collaboration, Nucl. Phys. B299, 1 \(1988\)](#)

$M_{\Upsilon(2S)} = 10.023 GeV$

and other data from PDG $\longrightarrow \mathcal{B}[\Upsilon(2S) \rightarrow e^\mp\mu^\pm] \leq 9.58 \times 10^{-9}$

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 (or 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:

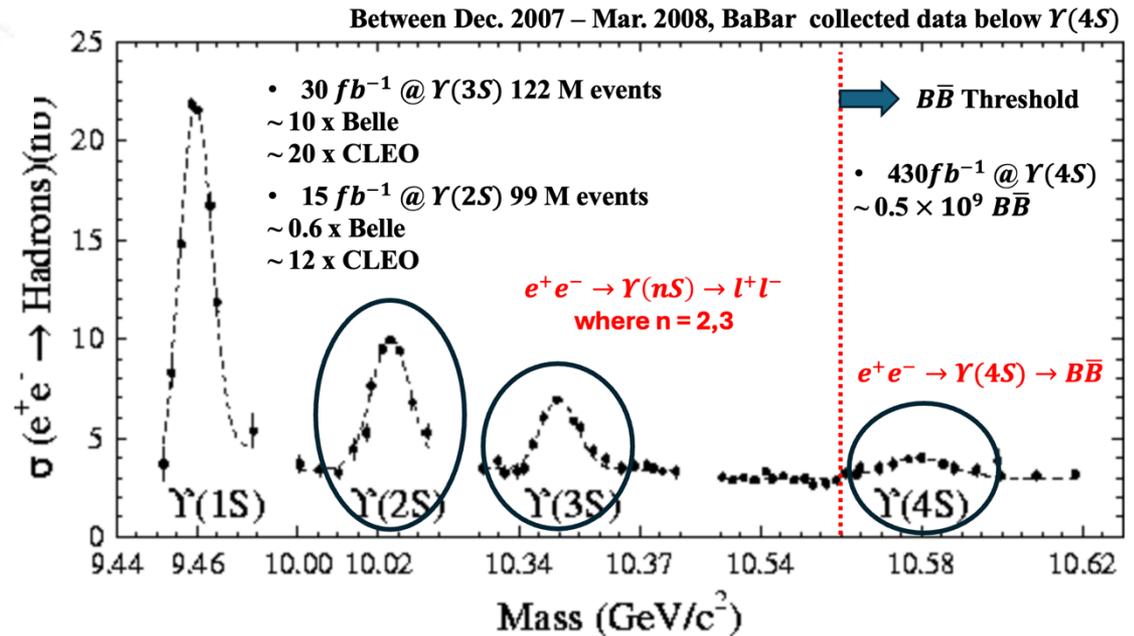
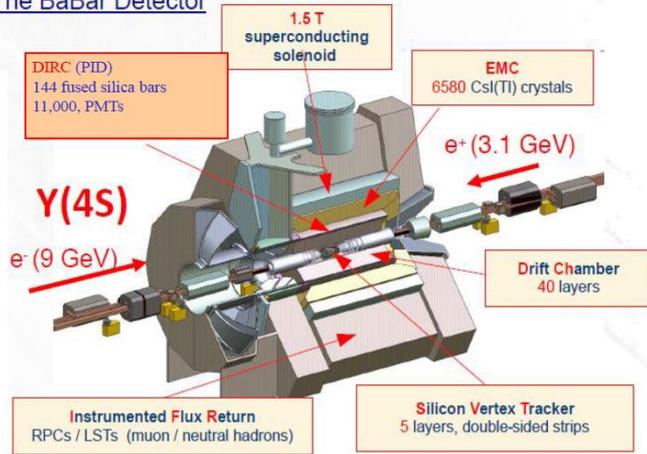
$$\frac{M_\mu^2}{2M_{\Upsilon(2S)}^2}$$

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

- Leading to a modified bound on $\mathcal{B}[\Upsilon(2S) \rightarrow e^\mp \mu^\pm] \leq 1.7 \times 10^{-4}$

BaBar Detector

The BaBar Detector



Upsilon system: CLEO collaboration
 D. Andrews et al., [Phys. Rev. Lett. 44, 1108 \(1980\)](#)

Data and SP samples

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

- 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

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

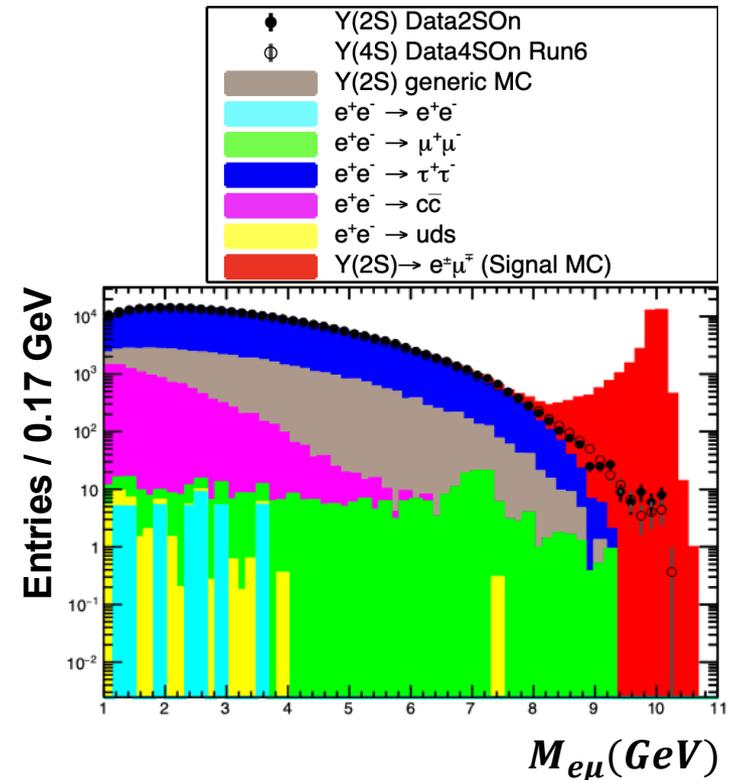
Signal and Background

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

Event selection proceeds in two stages:

- 1) Pre-selection and
- 2) 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



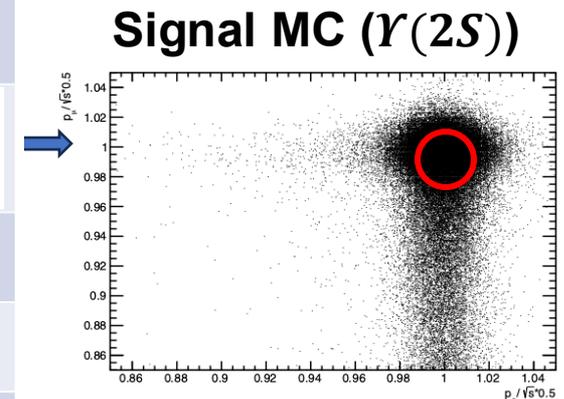
Signal and Background

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

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	$\theta_{12}^{CM} > 179^\circ$
EMC acceptance	$24^\circ < \theta_{lab} < 130^\circ$
Muon energy deposited in EMC	$> 50 \text{ MeV}$



Signal efficiencies after N-1 cuts ($\Upsilon(2S)$)

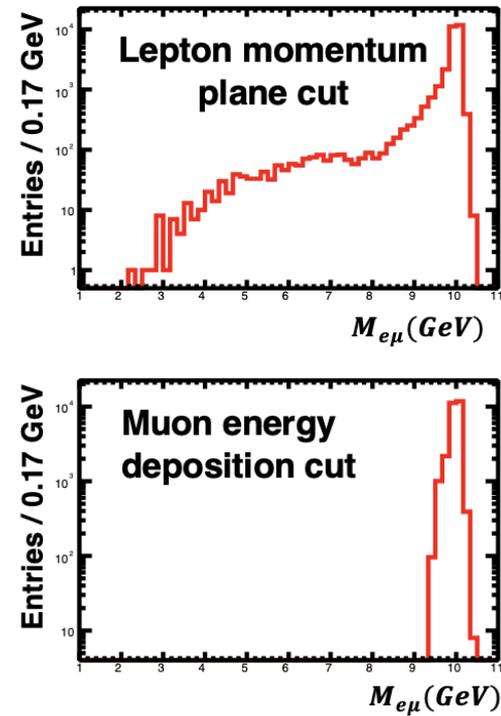
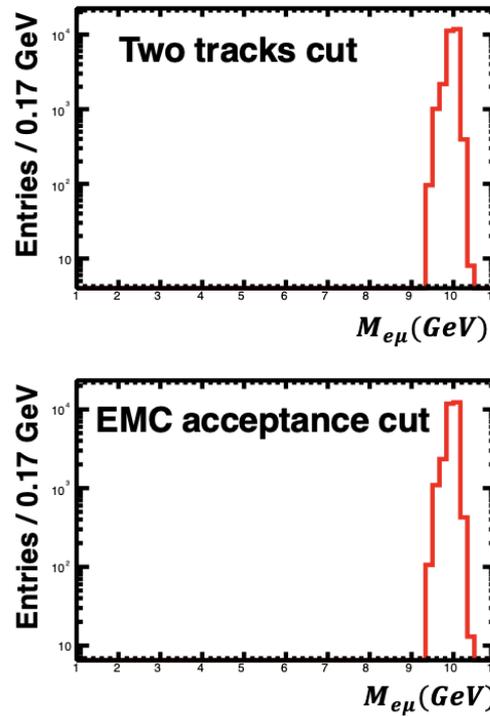
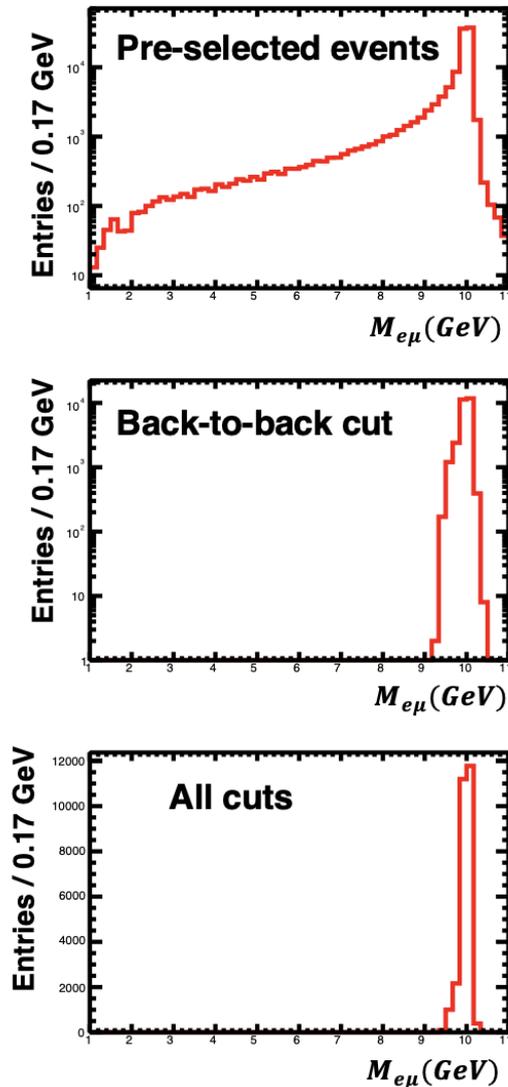
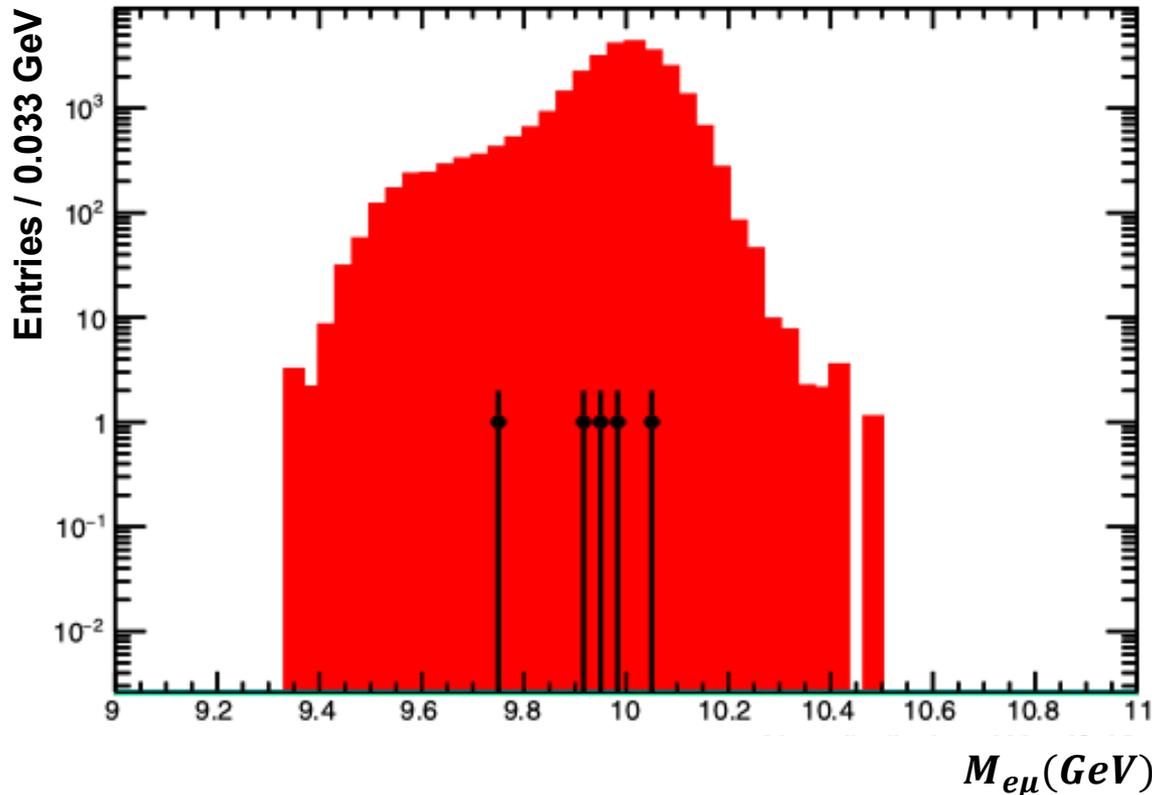


Table : Signal efficiency is calculated for each user-defined selection criterion, and the last row displays the signal efficiency after all selections have been implemented. The first row represents the signal efficiency when no user-defined selections are applied.

Selection criterion	Signal efficiency (%)
Preselection	81.80 ± 0.32
Two tracks in final state	18.44 ± 0.12
Lepton momentum	21.02 ± 0.13
Back-to-back	18.82 ± 0.12
EMC acceptance	19.38 ± 0.13
Muon energy on EMC	18.41 ± 0.12
All cuts	18.37 ± 0.11

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

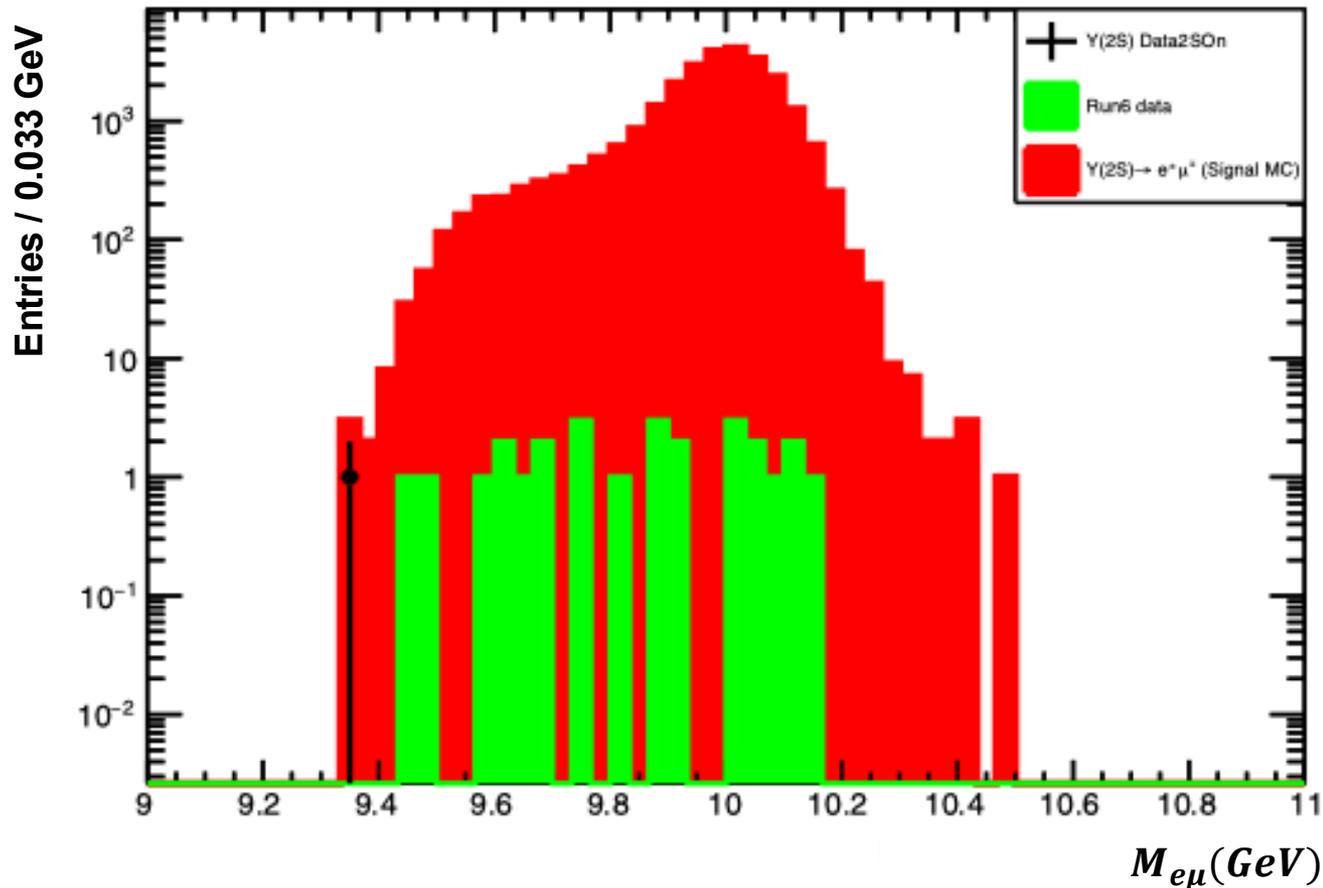
(after all selection and optimized PID criteria are applied ($\Upsilon(2S)$))



Survived events in data2son = 5
Survived events in MC signal = 26636
Survived events in mumu = 0
Survived events in tautau = 0
Survived events in uds = 0
Survived events in cc = 0
Survived events in bhabha = 0
Survived events in generic = 0

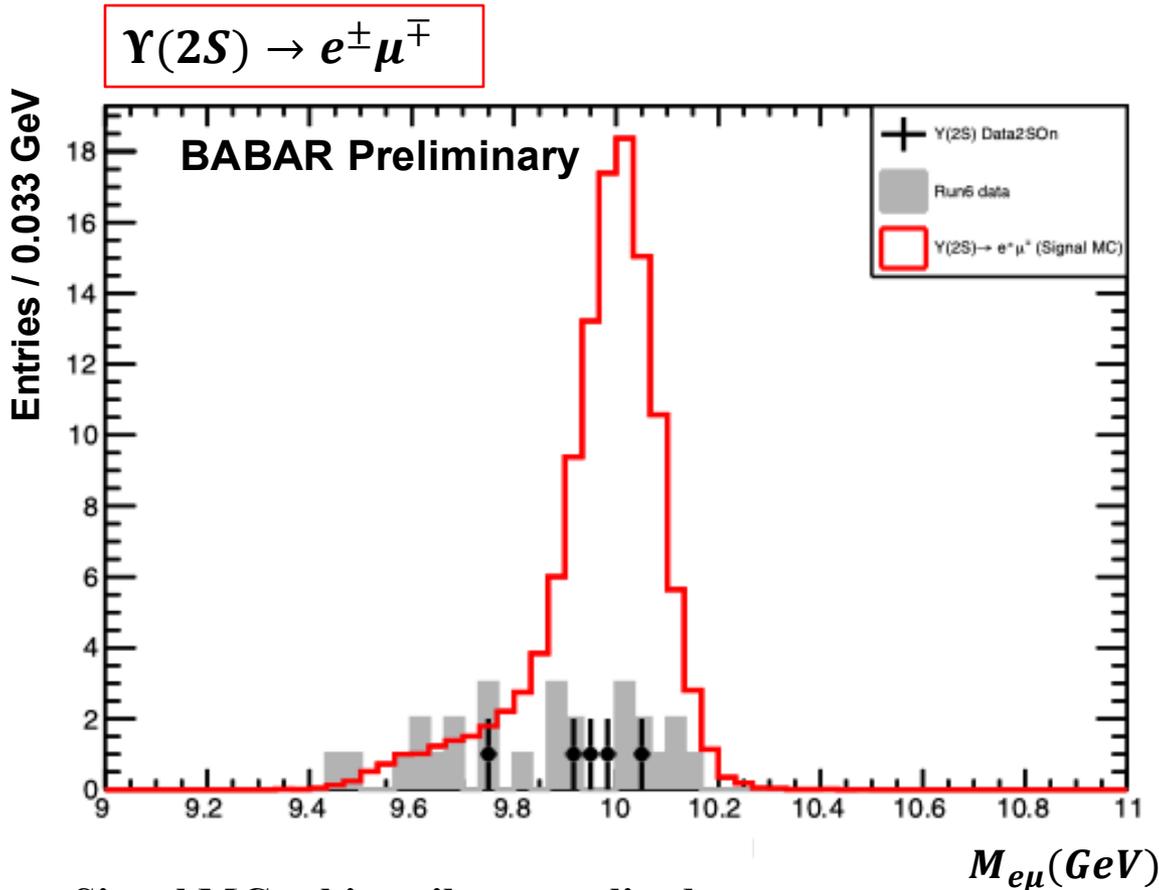
- The $\Upsilon(4S)$ Run 6 data, which is at a centre of mass (CM) energy above the $\Upsilon(2S)$ mass, is used as a high statistics control sample to estimate the continuum

Background estimation in blinded luminosity($\Upsilon(2S)$)

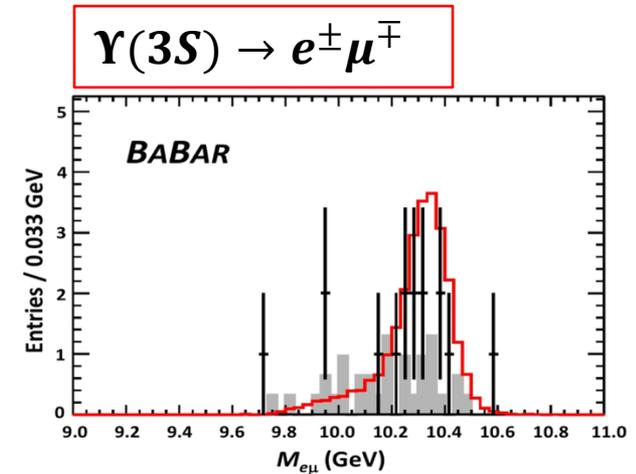


Final Mass distribution of $\Upsilon(2S, 3S) \rightarrow e^\pm \mu^\mp$

(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

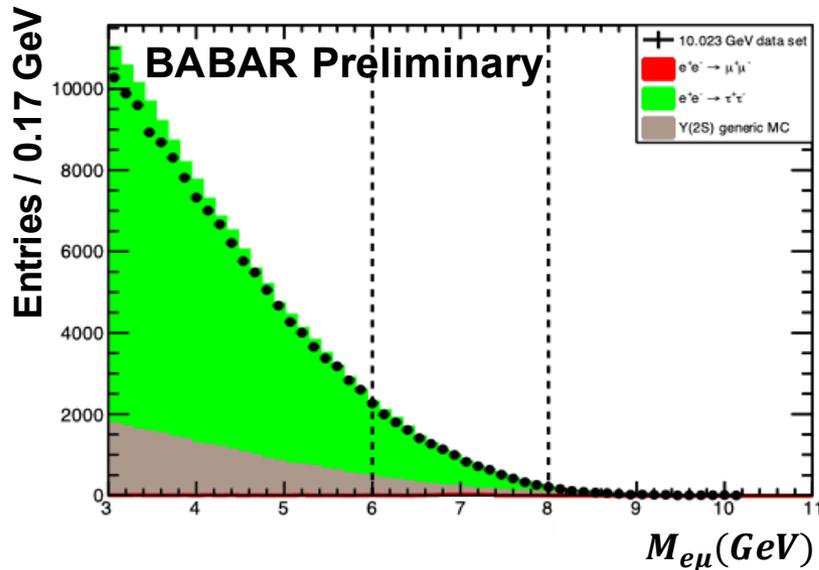


- $N_{\text{Cand}} = 15$
- Expected background = 12.2 ± 2.3

BaBar Collaboration, [Phys. Rev. Lett. 128, 091804 \(2022\)](https://arxiv.org/abs/2201.09180)

Systematic Studies

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



Sideband: 6 - 8 GeV

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

- We assess the systematic uncertainties in the signal efficiency by the data 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 EB 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 %)

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

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

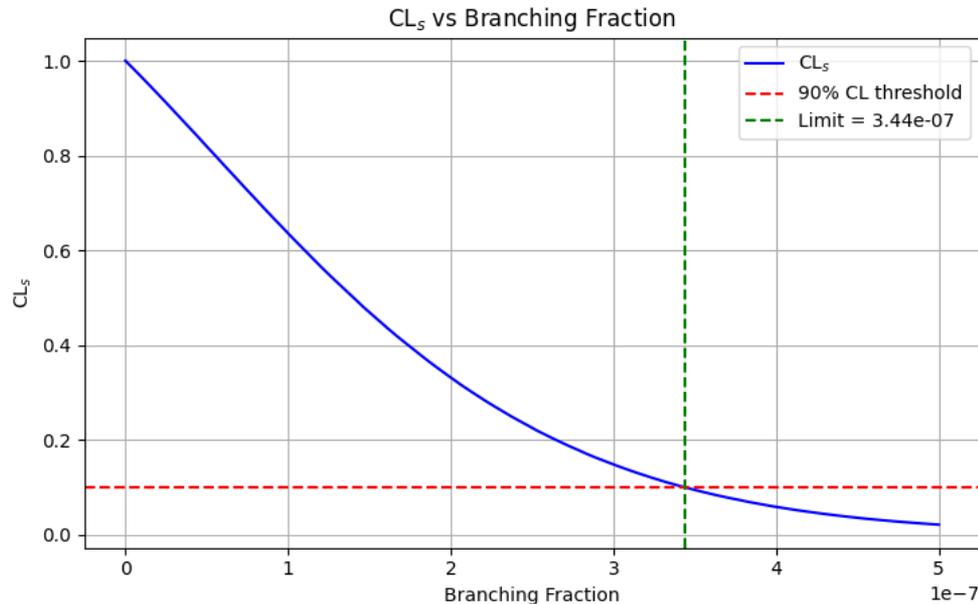
BABAR preliminary

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

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).

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

BABAR preliminary

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

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 \(2020\)](#)

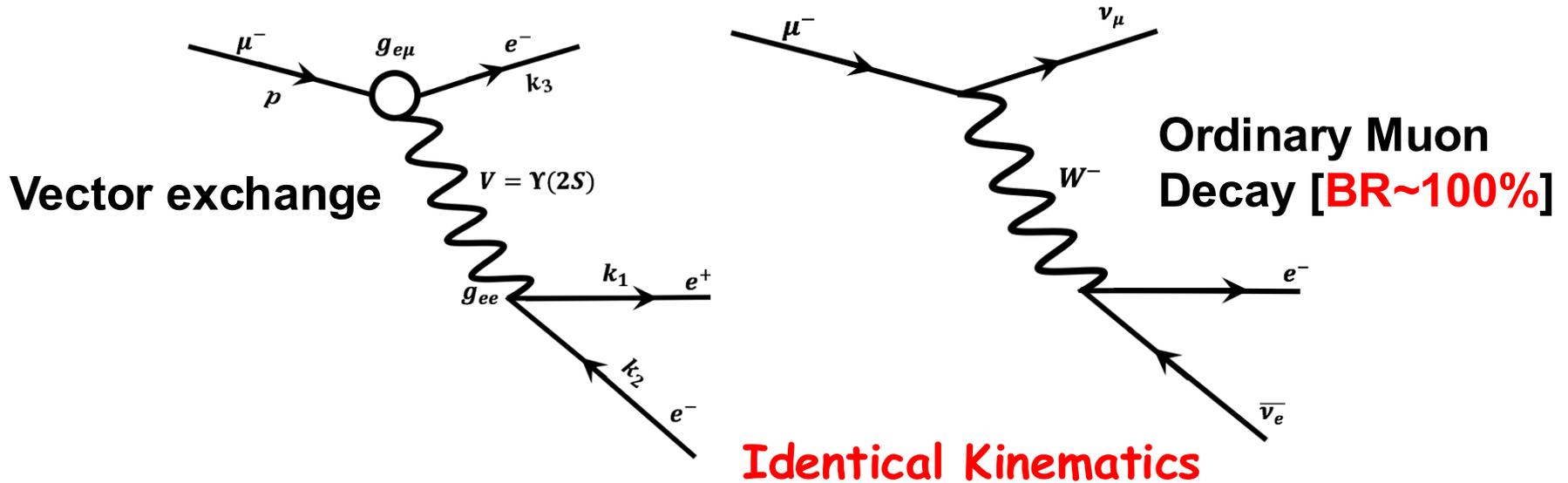
Conclusions

- ❑ 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!

Backup slides

Theoretical Background



$$\frac{\Gamma(\mu \rightarrow 3e)_{V\text{-exchange}}}{\Gamma(\mu \rightarrow e\nu\bar{\nu})} \approx [\text{BR}(\mu \rightarrow 3e)]_{V\text{-exch.}}$$

$$\approx \frac{\Gamma(V \rightarrow e^+e^-)\Gamma(V \rightarrow e^\pm\mu^\mp)}{\Gamma^2(W \rightarrow e\nu)} \left(\frac{M_W}{M_V}\right)^6$$

$$\begin{aligned} \Gamma(W \rightarrow e\nu) &\sim g_W^2 M_W \\ \Gamma(V \rightarrow e^+e^-) &\sim g_{Vee}^2 M_V \\ \Gamma(V \rightarrow e\mu) &\sim g_{V_{e\mu}}^2 M_V \end{aligned}$$

Theoretical Background

Using:

$$BR \approx \frac{\Gamma_i}{\Gamma_{tot}} \quad \text{----- (1)}$$

$$\frac{\Gamma(V \rightarrow e^+ e^-) \Gamma(V \rightarrow e^\pm \mu^\mp)}{\Gamma^2(W \rightarrow e\nu)} \quad \text{----- (2)}$$

$$\approx \frac{[BR(V \rightarrow e^+ e^-) * \Gamma_V] [BR(V \rightarrow e^\pm \mu^\mp) * \Gamma_V]}{[BR(W \rightarrow e\nu) * \Gamma_W]^2} \quad \text{----- (3)}$$

$$V \cong \Upsilon(2S) \quad \text{----- (4)}$$

$$BR(\Upsilon(2S) \rightarrow e\mu) = BR(\mu \rightarrow eee) \frac{[BR(W \rightarrow e\nu) * \Gamma_W]^2}{[BR(\Upsilon(2S) \rightarrow e^+ e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}} \left(\frac{M_{\Upsilon(2S)}}{M_W} \right)^6 \quad \text{----- (5)}$$

From: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Theoretical Background

$$\text{BR}(\Upsilon(2S) \rightarrow e\mu) = \text{BR}(\mu \rightarrow eee) < 1.0 \times 10^{-12} \frac{[\text{BR}(W \rightarrow ev) * \Gamma_W]^2}{[\text{BR}(\Upsilon(2S) \rightarrow e^+e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}} \left(\frac{M_{\Upsilon(2S)}}{M_W} \right)^6$$

Annotations for the equation above:

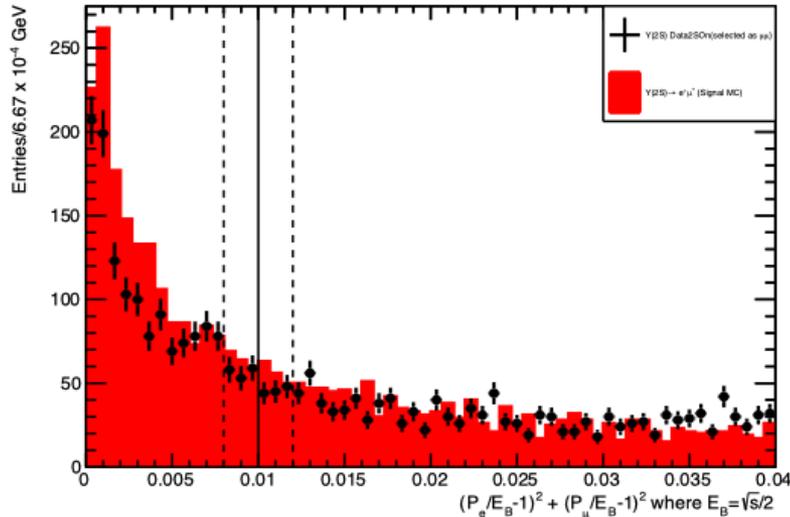
- $< 1.0 \times 10^{-12}$ points to the overall branching ratio.
- $\approx 10.71\%$ points to $\text{BR}(W \rightarrow ev)$.
- $\approx 2.085 \text{ GeV}$ points to Γ_W .
- $\approx 10.023 \text{ GeV}$ points to $M_{\Upsilon(2S)}$.
- $\approx 1.98\%$ points to $\text{BR}(\Upsilon(2S) \rightarrow e^+e^-)$.
- $\approx 31.98 \text{ keV}$ points to $\Gamma_{\Upsilon(2S)}$.
- $\approx 80.4 \text{ GeV}$ points to M_W .

$$\text{BR}(\Upsilon(2S) \rightarrow e\mu) \leq 9.58 \times 10^{-9}$$

- Number of generated events and Cross-sections for the corresponding decay modes. The reference article for cross-sections provides the corresponding values, measured at $\Upsilon(4S)$ resonance, thus we have used cross-sections with a correction factor equal to $(10.58)^2/(10.023)^2 = 1.11$ that corresponds to $\Upsilon(2S)$ resonance energy.

Mode	Number of events (N_{gen})	Cross-section (nb)
$e^+e^- \rightarrow \mu^+\mu^-$	52,555,000	$1.147 * 1.11 = 1.27$
$e^+e^- \rightarrow e^+e^-$	72,496,000	$25 * 1.11 = 27.75$
$e^+e^- \rightarrow \tau^+\tau^-$	40,005,000	$0.919 * 1.11 = 1.02$
$e^+e^- \rightarrow uds$	95,001,000	$2.179 * 1.11 = 2.41$
$e^+e^- \rightarrow c\bar{c}$	192,924,000	1.356
$e^+e^- \rightarrow \Upsilon(2S)generic$	115,248,000	7.25
$e^+e^- \rightarrow \Upsilon(4S) run 6$	82,200,000	$1.08*1.11 = 1.2$

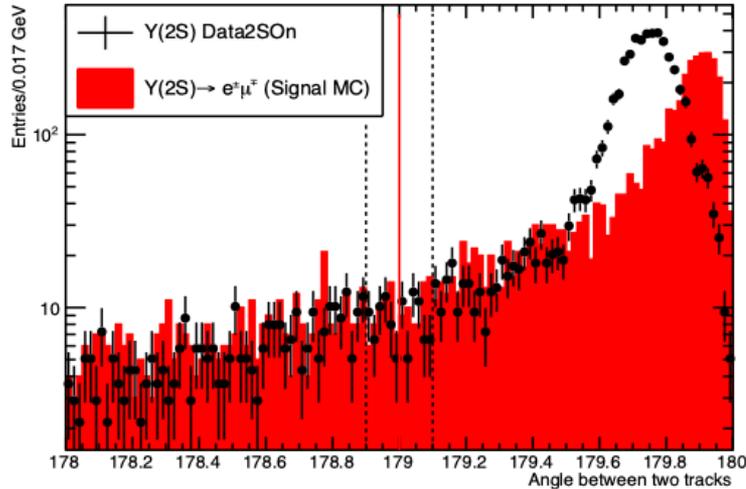
5.0.2 Systematic uncertainties in the reversed cuts



➤ $\sqrt{(0.018)^2 + (0.010)^2} \approx 0.021$ or 2.1%

Cut values	Data events	ϵ_{Data}	Signal MC ($e\mu$)	$\epsilon_{Signal MC}$	$\frac{\epsilon_{Data}}{\epsilon_{Signal MC}}$
0.01 (bin 15)	54	0.0016	58	0.120	
0.01 + 0.002 = 0.012 (bin 18)	47	0.0021	50	0.115	0.018
0.01 - 0.002 = 0.008 (bin 12)	72	0.0013	78	0.126	0.010

5.0.2 Systematic uncertainties in the reversed cuts



$$\triangleright \sqrt{(0.005)^2 + (0.006)^2} \approx 0.008 \text{ or } 0.8\%$$

Cut values	Data events	ϵ_{Data}	Signal MC ($e\mu$)	$\epsilon_{Signal MC}$	$\frac{\epsilon_{Data}}{\epsilon_{Signal MC}}$
179 ⁰ (bin 60)	7	0.0008	7	0.19	
179.1 ⁰ (bin 66)	9	0.001	8	0.22	0.005
178.9 ⁰ (bin 54)	16	0.002	13	0.35	0.006

3.1.3 Statistical Uncertainty in Signal Efficiency

Due to the finite statistics, there is a statistical uncertainty in the signal efficiency too. The uncertainty in ϵ_{SIG} is given by $\sqrt{\frac{\epsilon(1-\epsilon)}{n}}$. This procedure gives a statistical uncertainty of 0.0010 which is approximately 0.10%.