ICHEP 2020 | PRAGUE

28 July 2020 to 6 August 2020
virtual conference
Europe/Prague timezone

Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$

Nafisa Tasneem
ntasneem@uvic.ca
On behalf of the BaBar Collaboration

July 31, 2020.

BABAR ™ and © Nelvana, All Rights Reserved
St. Francis Xavier University
University of Victoria

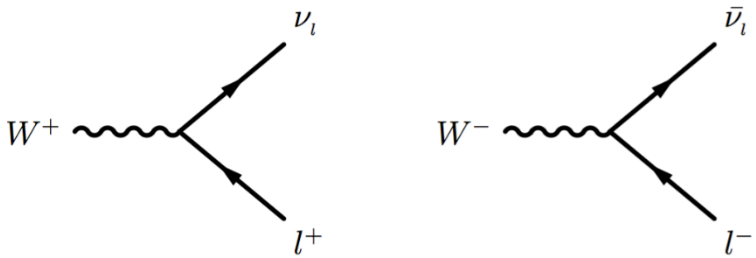
Outline of the Talk

- Charged Lepton Flavour Violation
- Data and MC Samples
- Analysis Strategy
- Results
- Conclusion

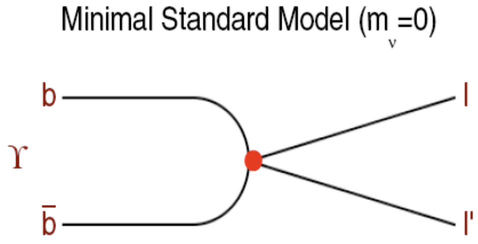
ntasneem@uvic.ca; ntasneem@stfx.ca

Charged Lepton Flavour Violation

- In Standard Model (SM) , Lepton Flavour is conserved for zero degenerate **ν** masses
- Now we have clear indication that **ν**’s have finite mass
- All interactions must conserve energy, charge, lepton number & type, baryon number
- Lepton Flavour is violated in nature: but by **HOW MUCH**?

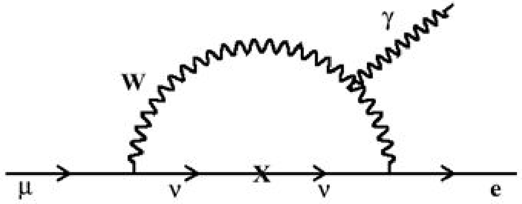


Lepton Flavour Conserving Process



Forbidden

- SM extended to include finite **ν** mass and mixing predicts Lepton Flavour Violation (LFV).



How Much Violation?

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

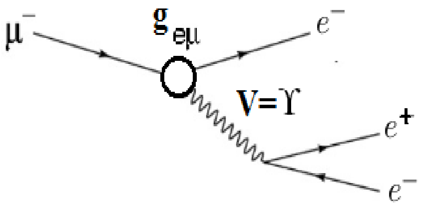
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \quad \left(\frac{3\alpha}{32\pi}\right) \quad \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

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

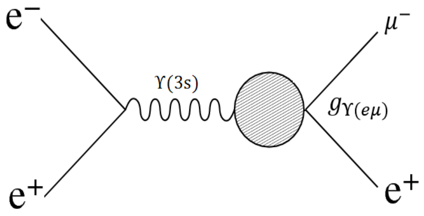
Experimentally not measurable!!

Indirect Limit on Upsilon Decays

- No direct observation, but μ → *eee* observable (?)
- Calculated theoretical constraints on the limit (indirect):



Re-ordering of incoming/outgoing particles



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

S.Nussinov, et. al. PRD 63, 016003 (2001)

$\mathrm{BF}(\mu \to eee) < 1.0 \times 10^{-12}$

$\mathrm{BF}(\Upsilon \to ee) = 2.18 \times 10^{-2}$

Bellgardt, et al., Nucl.Phys. B299 (1988)

PDG

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

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

- **We report a limit several orders of magnitude more sensitive than this indirect limit.**

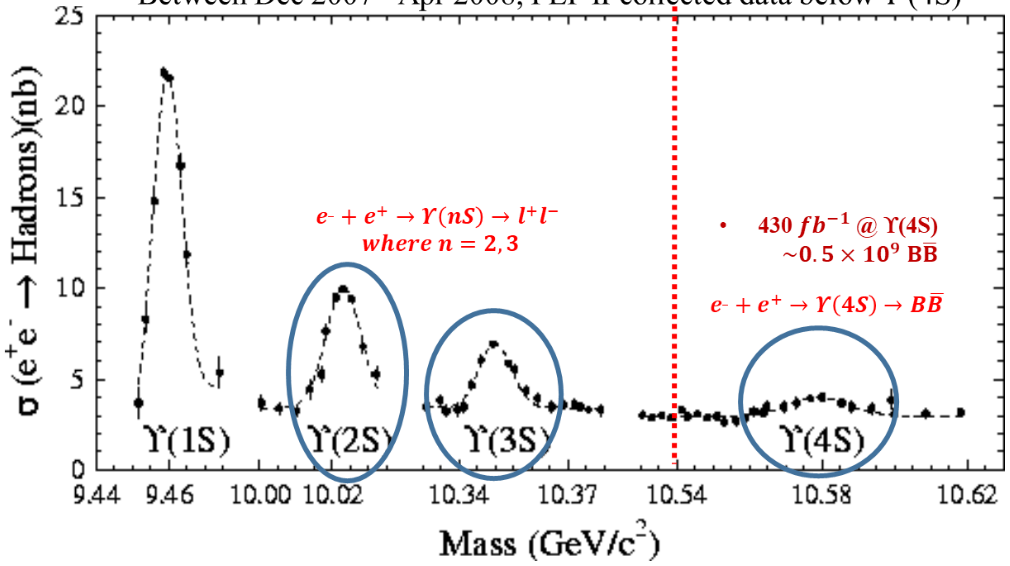
ntasneem@uvic.ca; ntasneem@stfx.ca

Existing Experimental Searches and BaBar Measure Rates

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]

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

Between Dec 2007 - Apr 2008, PEP II collected data below Υ (4S)



$e^- + e^+ \rightarrow \Upsilon(nS) \rightarrow l^+l^-$ where $n = 2,3$

- $430\ fb^{-1}$ @ Υ(4S) $\sim 0.5 \times 10^9$ $B\bar{B}$

$e^- + e^+ \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

- **$30\ fb^{-1}$ @ 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)

ntasneem@uvic.ca; ntasneem@stfx.ca

Data, MC Sample and Blind Analysis Technique

- Blind analysis was performed to eliminate experimenter's bias.
- All selection criteria and uncertainty studies performed without looking at the result of data sample.
- Results were unblinded by the approval of Review Committee.

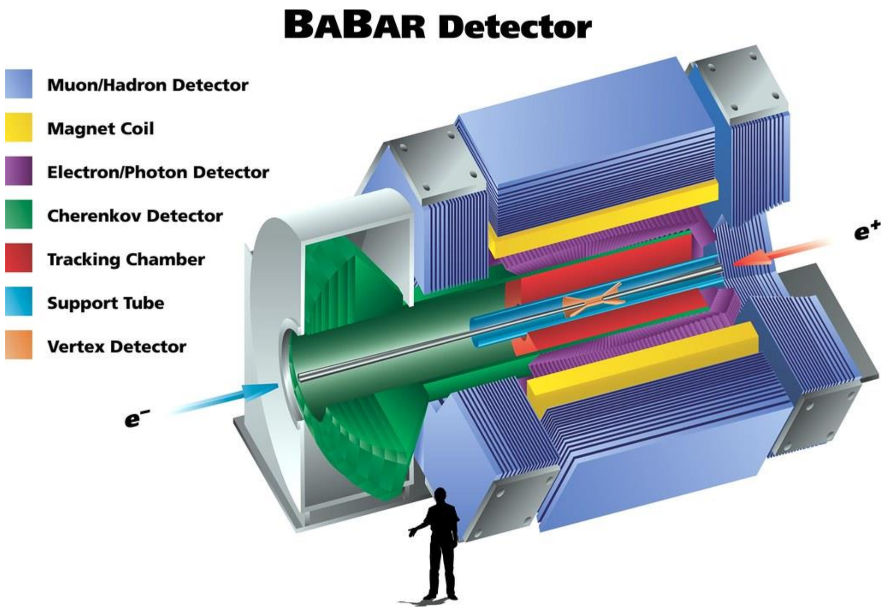
Data $\Upsilon(3S)$, $\sqrt{s} = 10.36$ GeV	**Luminosity (fb^{-1})**	**Upsilon Numbers**
Pre-unblinded Sample (3%)	0.93	$(4.06 \pm 0.04) \times 10^6$
Data Sample	27.0	$(117.7 \pm 1.2) \times 10^6$
Total	27.9	$(121.7 \pm 1.2) \times 10^6$

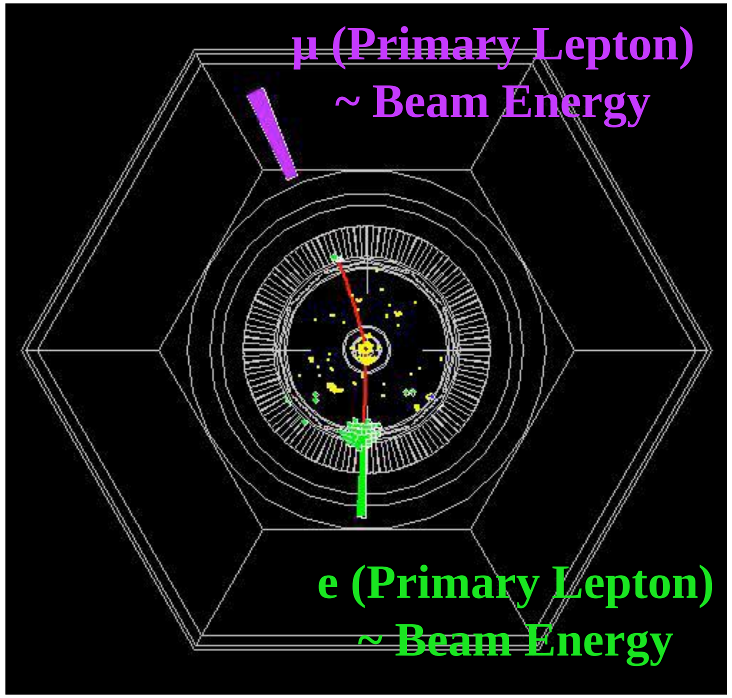
MC signal: $e^+e^- \to \Upsilon(3S) \to e^\pm\mu^\mp$: 103000 events

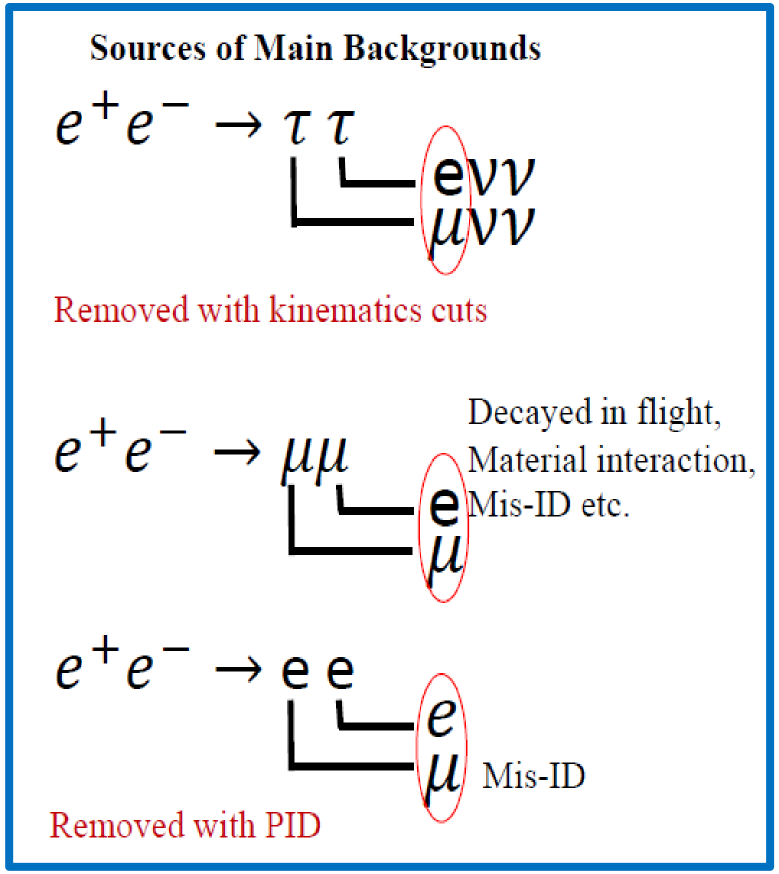
Data and MC	**Luminosity (fb^{-1})**	**Purpose**
Data $\Upsilon(4S)$ *On Resonance* , $\sqrt{s} = 10.58$ GeV Preselected as $e^\pm\mu^\mp$ events	**78.31 ± 0.35**	**Data driven continuum background estimate** **and** Systematics
Data $\Upsilon(4S)$ *On Resonance* , $\sqrt{s} = 10.58$ GeV Preselected as $\mu^\pm\mu^\mp$ events	78.31 ± 0.35	Systematics
Data $\Upsilon(3S)$On Resonace, $\sqrt{s} = 10.36$ GeV Preselected as $\mu^\pm\mu^\mp$ events	27.96 ± 0.16	Systematics

ntasneem@uvic.ca; ntasneem@stfx.ca

Signal and Background Characteristics







Sources of Main Backgrounds

$e^+e^- \to \tau\,\tau$

$e\nu\nu$

$\mu\nu\nu$

Removed with kinematics cuts

$e^+e^- \to \mu\mu$

e

μ

Decayed in flight,
Material interaction,
Mis-ID etc.

$e^+e^- \to e\,e$

e

μ

Mis-ID

Removed with PID

- $\boldsymbol{\Upsilon(3S) \to e^{\pm}\mu^{\mp}}$: Required two primary track signal of $\boldsymbol{e^{\pm}}$ ***and*** $\boldsymbol{\mu^{\mp}}$.
- CM Momentum: $\boldsymbol{P_{e^{\pm}} \sim \frac{\sqrt{s}}{2}}$ and $\boldsymbol{P_{\mu^{\pm}} \sim \frac{\sqrt{s}}{2}}$

ntasneem@uvic.ca; ntasneem@stfx.ca

Analysis Strategy

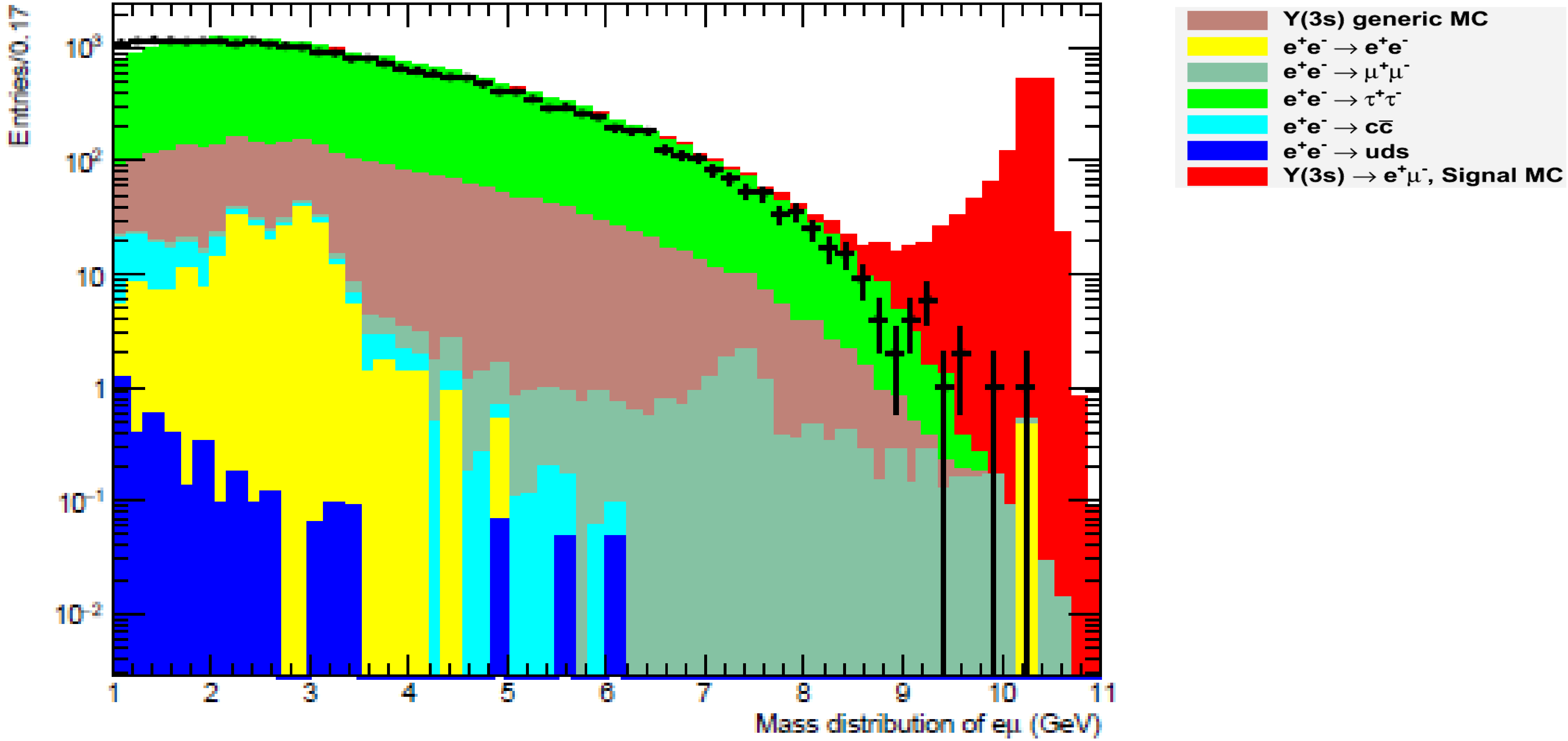
- **Pre-Selection:** Needs a special background filter to collect $e^{\pm}\mu^{\mp}$ events efficiently.
- **Final Selection:** Applied on the pre-selected events
- **PID Selection:** Multivariate Technique applied, 16 different PID selectors. We optimized the choice of the electron and muon selectors to maximize using ${}^{\varepsilon_{e\mu}}\!/\!{}_{\sqrt{(1+N_{BG})}}$ where $\varepsilon_{e\mu}$ is the final efficiency as determined by signal MC and N_{BG} is the number of expected background events as predicted by data control samples and generic (3S) MC 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.

ntasneem@uvic.ca; ntasneem@stfx.ca

Data/MC Comparison

BABAR **Preliminary**

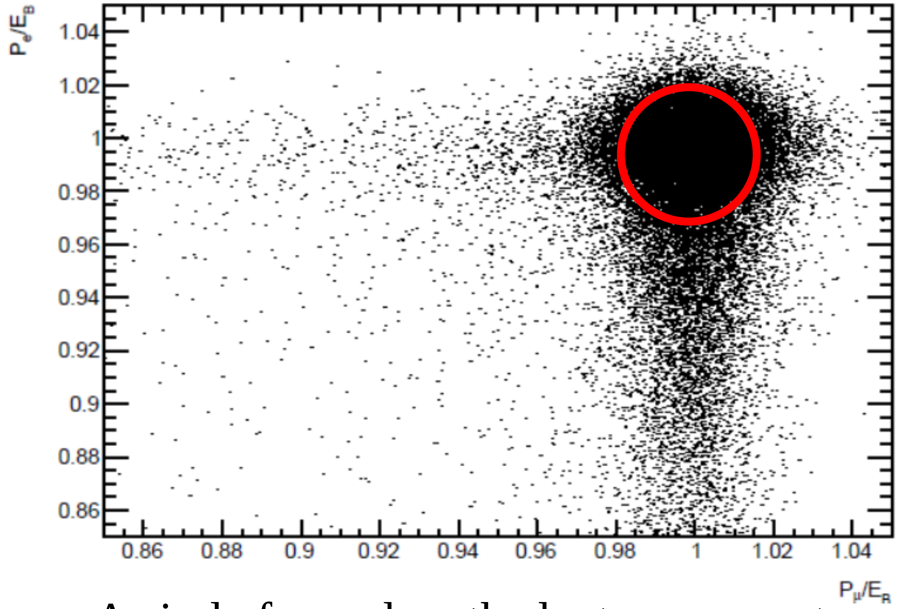


Distribution of $e^{\pm}\mu^{\mp}$ mass before applying any user defined selection criteria, only preselection criteria has been applied on the 3% pre-unblinded data.

ntasneem@uvic.ca; ntasneem@stfx.ca

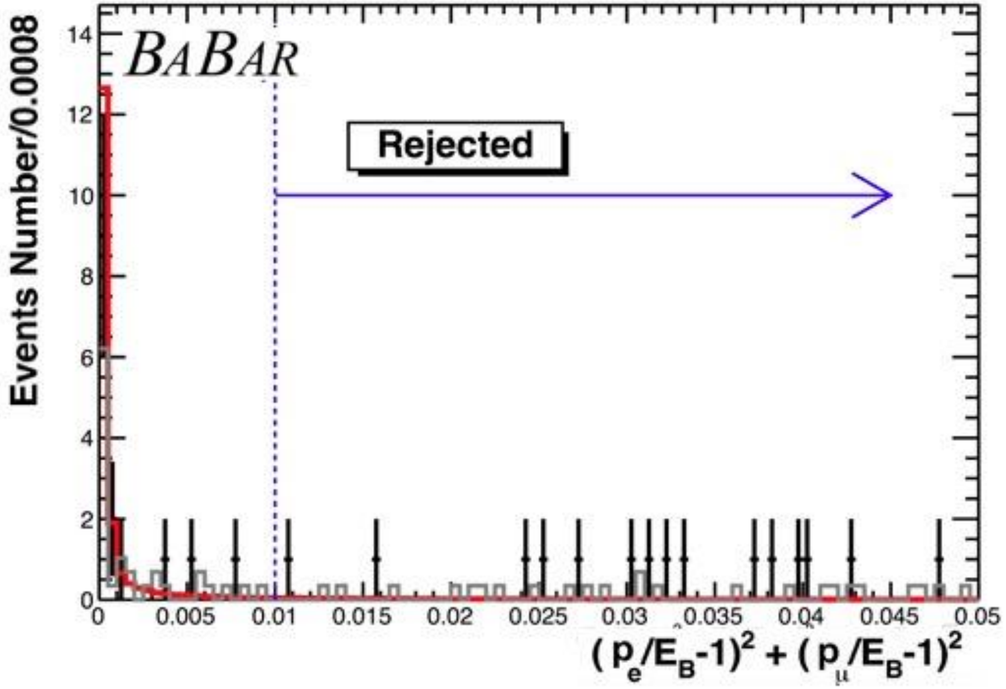
Selection Criteria in (N-1) plots

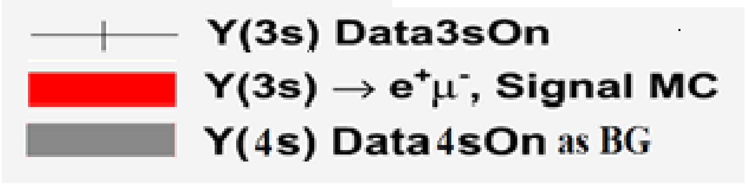
***BABAR* Preliminary**



A circle formed on the lepton momentum plane in Signal Monte Carlo

***BABAR* Preliminary**



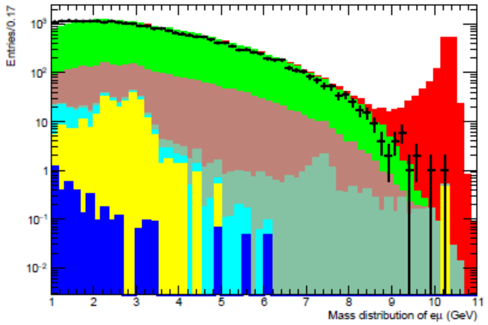


The lepton momenta must satisfy the following condition which is defining a circle of radius

$$\left(\frac{p_e}{E_B} - 1\right)^2 + \left(\frac{p_\mu}{E_B} - 1\right)^2 < 0.01 \quad \text{where } E_B = \sqrt{s}/_2$$

ntasneem@uvic.ca; ntasneem@stfx.ca

Mass Distribution

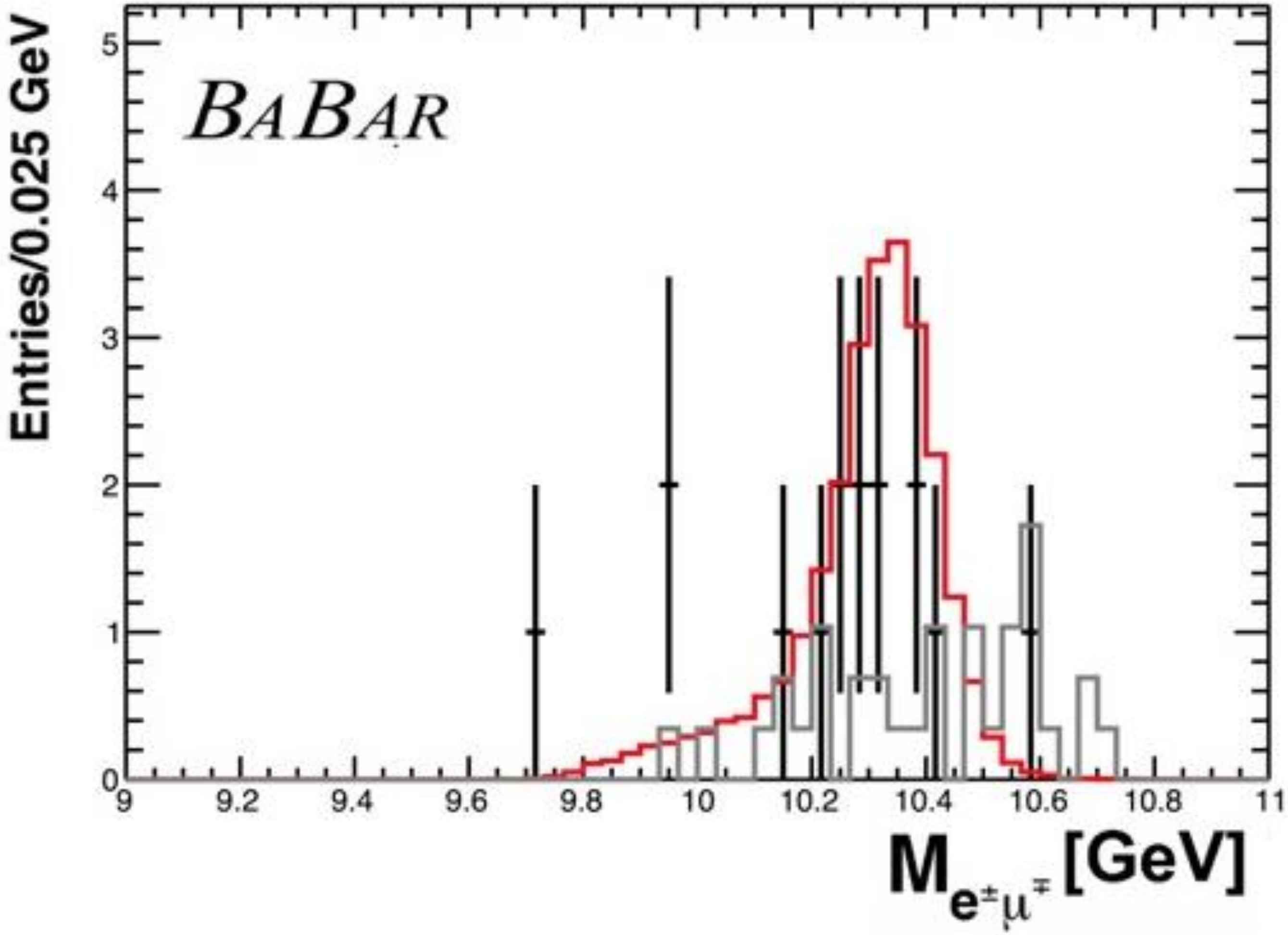


— Υ(3s) Data3sOn

🟥 Υ(3s) → $e^+\mu^-$, Signal MC

▨ Υ(4s) Data4sOn as BG

***BABAR* Preliminary**

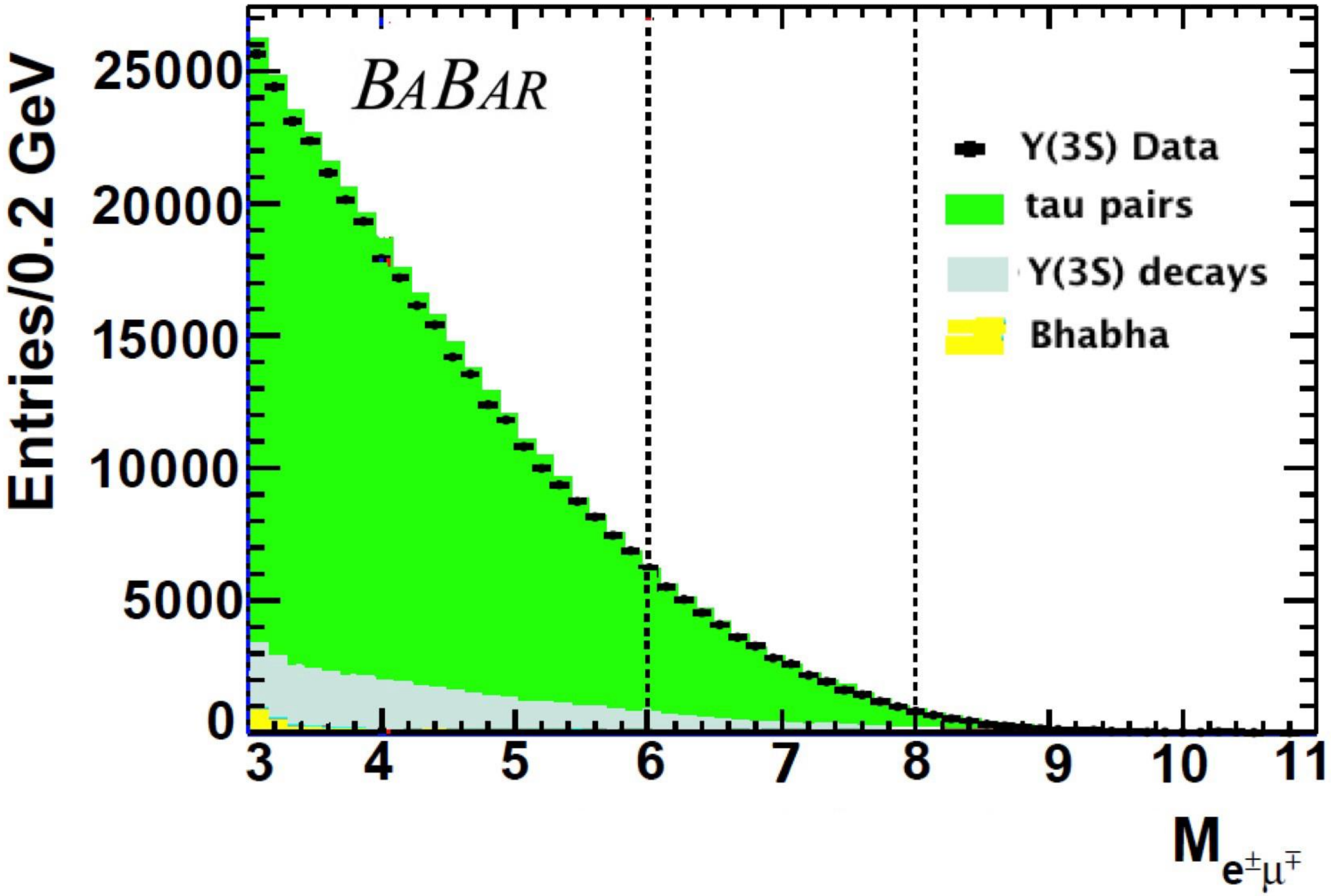


Mass distribution of $e^{\pm}\mu^{\mp}$ after all selection criteria are applied

ntasneem@uvic.ca; ntasneem@stfx.ca

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%

ntasneem@uvic.ca; ntasneem@stfx.ca

Summary: Background, Uncertainty, Candidate

Source	**Data Driven Continuum Background ($78\ fb^{-1}$) (events seen 34)**	**Peaking Background from Generic $\Upsilon(3S)$ MC ($61.44\ fb^{-1}$) (events seen 4)**
Tight PID selection	12.2 ± 2.1	0
Loosen PID selection	N/A	1.80 ± 0.9

Values	**Uncertainties**
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%) [PRL104, 151802]
Total Background (equivalent to $27.0\ fb^{-1}$)	**12.2 ± 2.3** (18.9%)
Candidate Seen in Data Sample	**15**

BABAR **Preliminary**

ntasneem@uvic.ca; ntasneem@stfx.ca

Results

BABAR **Preliminary**

- **Data:** $(27.0\ fb^{-1})$
- **Branching Fraction:**

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

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

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

CLs Method: [A. L. Read, J. Phys. G28 (2002) 2693- 278 2704]

ntasneem@uvic.ca; ntasneem@stfx.ca

New Physics

BABAR **Preliminary**

- Lepton flavour violating decays are predicted by many beyond SM processes. Thus a clear experimental signature = "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($\boldsymbol{\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}}$) < 3.6 × $\mathbf{10^{-7}}$ @90%CL

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

$$\Lambda_{NP}/g^2_{NP} \geq 83\ \text{TeV} \quad @90\%\ \text{CL}$$

Conclusion

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

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

- Our reported result is several orders of magnitude stronger that this limit according to the ref [S.Nussinov, et. al. PRD 63, 016003 (2001)].

- This result can be interpreted as a limit on NP: $\Lambda_{NP}/g^2_{NP} \geq 83$ TeV ***BABAR* Preliminary**

- A PRL draft is ready to publish within a month.

- Thanks to my BaBar and PEPII Colleagues for providing support for this analysis.

Thanks!
Any Question!!

ntasneem@uvic.ca; ntasneem@stfx.ca

Back up: Theoretical Upper limit (Indirect)

Nussinov, Peccei, Zhang [1]

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

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

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

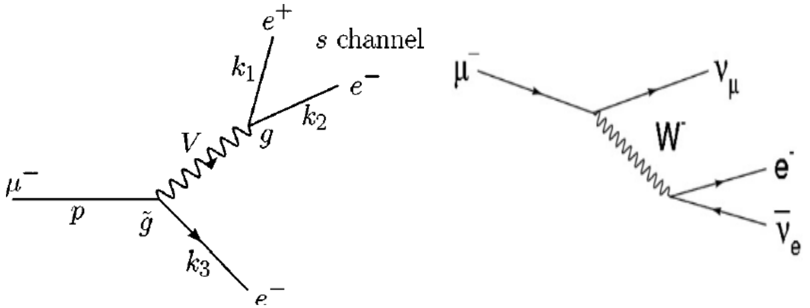
Since $[\Gamma(\mathrm{V} \to \mathrm{e^+e^-})] \sim \mathrm{g}^2\ \mathrm{V}_{ee}\ \mathrm{M}_V$ and

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

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

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

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



(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.

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

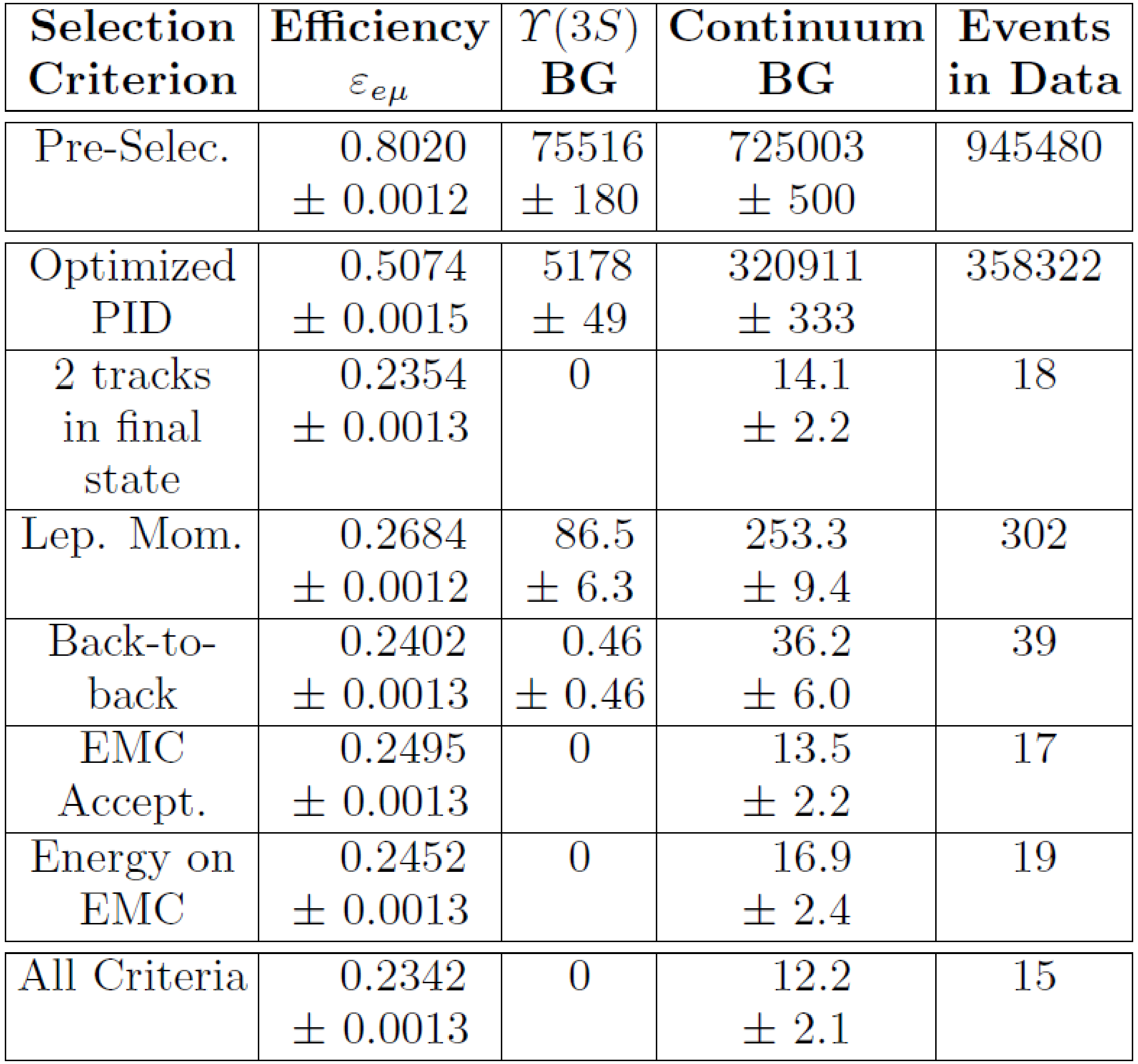
S.Nussinov, et. al. estimate that the contribution of the virtual ϒ $(3S) \to e^\pm\mu^\mp$ to the μ →*eee* rate would be reduced by approximately $\mathrm{M}^2_\mu / (2\ \mathrm{M}^2_\Upsilon)$ leading to a re-calculated indirect bound:
$\mathrm{BF}(\Upsilon\ (3S) \to e^\pm\mu^\mp) < 1\times 10^{-3}$

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

ntasneem@uvic.ca; ntasneem@stfx.ca

Back Up: 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 ± 0.0012	75516 ± 180	725003 ± 500	945480
Optimized PID	0.5074 ± 0.0015	5178 ± 49	320911 ± 333	358322
2 tracks in final state	0.2354 ± 0.0013	0	14.1 ± 2.2	18
Lep. Mom.	0.2684 ± 0.0012	86.5 ± 6.3	253.3 ± 9.4	302
Back-to-back	0.2402 ± 0.0013	0.46 ± 0.46	36.2 ± 6.0	39
EMC Accept.	0.2495 ± 0.0013	0	13.5 ± 2.2	17
Energy on EMC	0.2452 ± 0.0013	0	16.9 ± 2.4	19
All Criteria	0.2342 ± 0.0013	0	12.2 ± 2.1	15

ntasneem@uvic.ca; ntasneem@stfx.ca