Tests of the Standard Model by means of $\Upsilon(3S)$ meson decays with the BABAR detector

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On behalf of the BaBar Collaboration

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Outline of the Talk

- Analysis-1: Charged Lepton Flavour Violation

A journal paper will be submitted in the near future.

- Analysis-2: Testing Lepton Universality

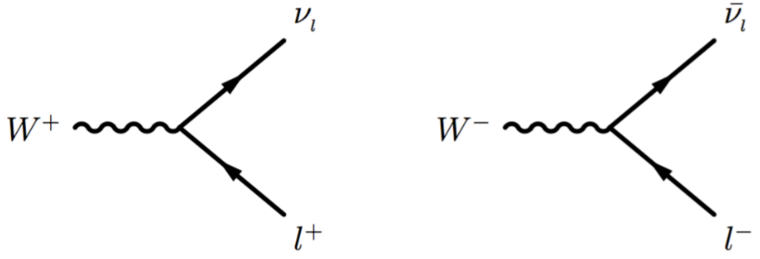
Phys. Rev. Lett. 125, 241801 (2020) by BABAR Collaboration.

- Data and MC Samples
- Analysis Strategy
- Results
- Conclusion

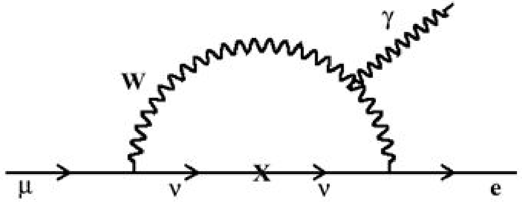
Charged Lepton Flavour Violation

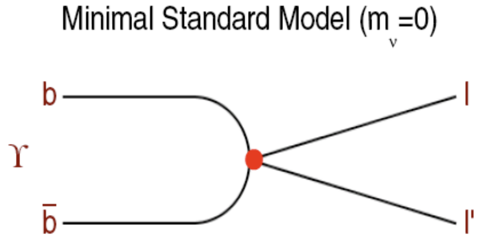
- Charged Lepton Flavour Violation is a transition among e, μ, τ that doesn't conserve lepton family number.
- In Standard Model, Lepton Flavour is conserved for zero degenerate ν masses and now we have clear indication that $\boldsymbol{\nu}$'s have finite mass.

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



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



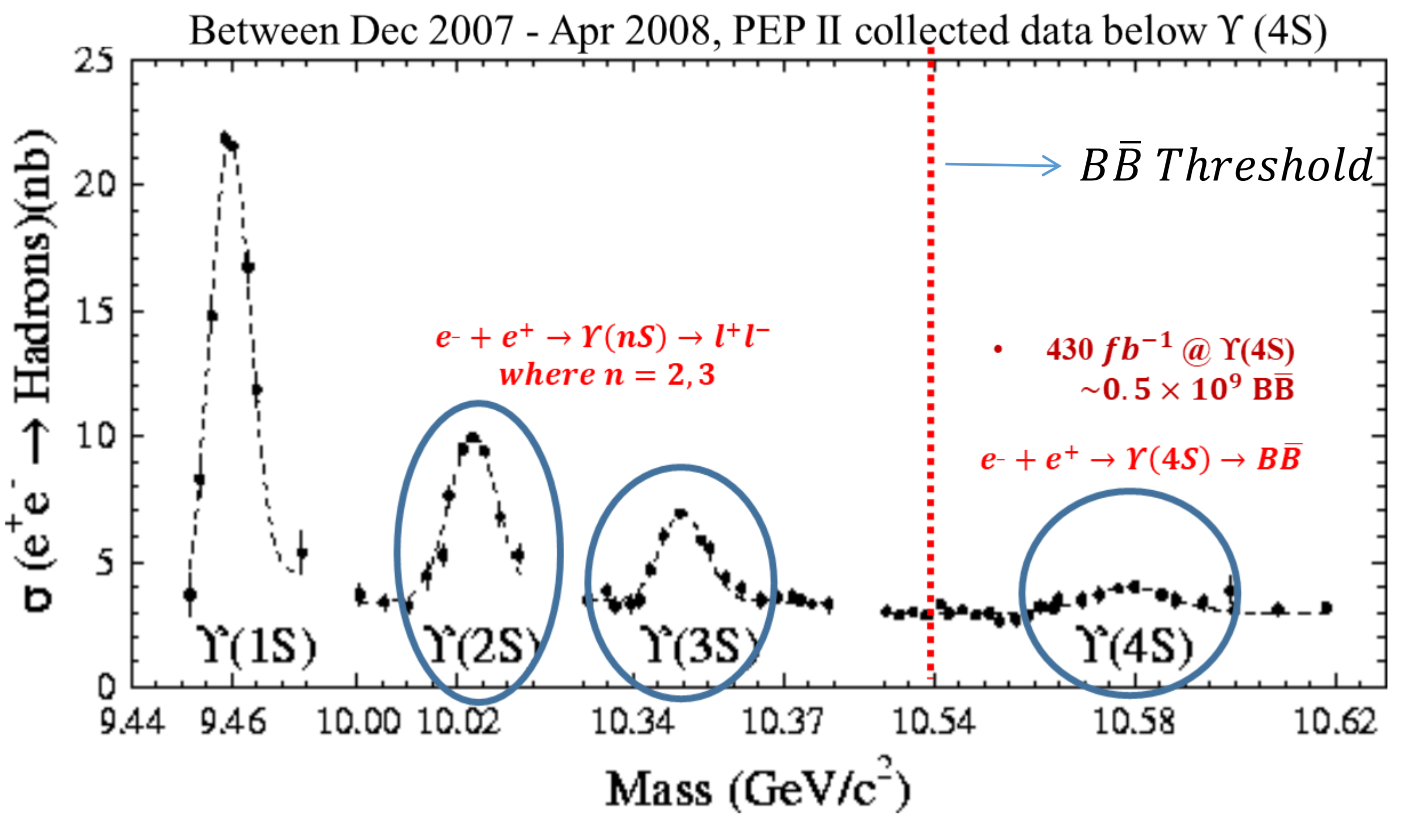


Opportunity to search for the New Physics!!!

- In the charged lepton sector, **Lepton Flavor Violation** is **heavy suppressed** in the Standard Model $l_\alpha \rightarrow l_\beta \approx \boldsymbol{O(10^{-54})}$

- 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"**

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

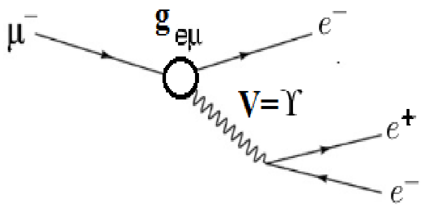
Dramatic Increase in sensitivity to rare decays: $\Gamma_{\Upsilon(4S)}/\Gamma_{\Upsilon(nS)} \approx 10^3$

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)

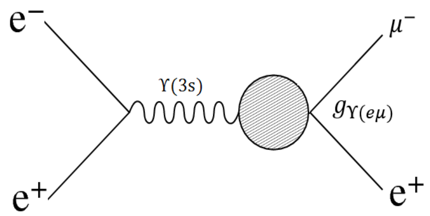
Theoretical Expectations and Experimental Limit

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

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



Re-ordering of incoming/outgoing particles



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

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

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

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

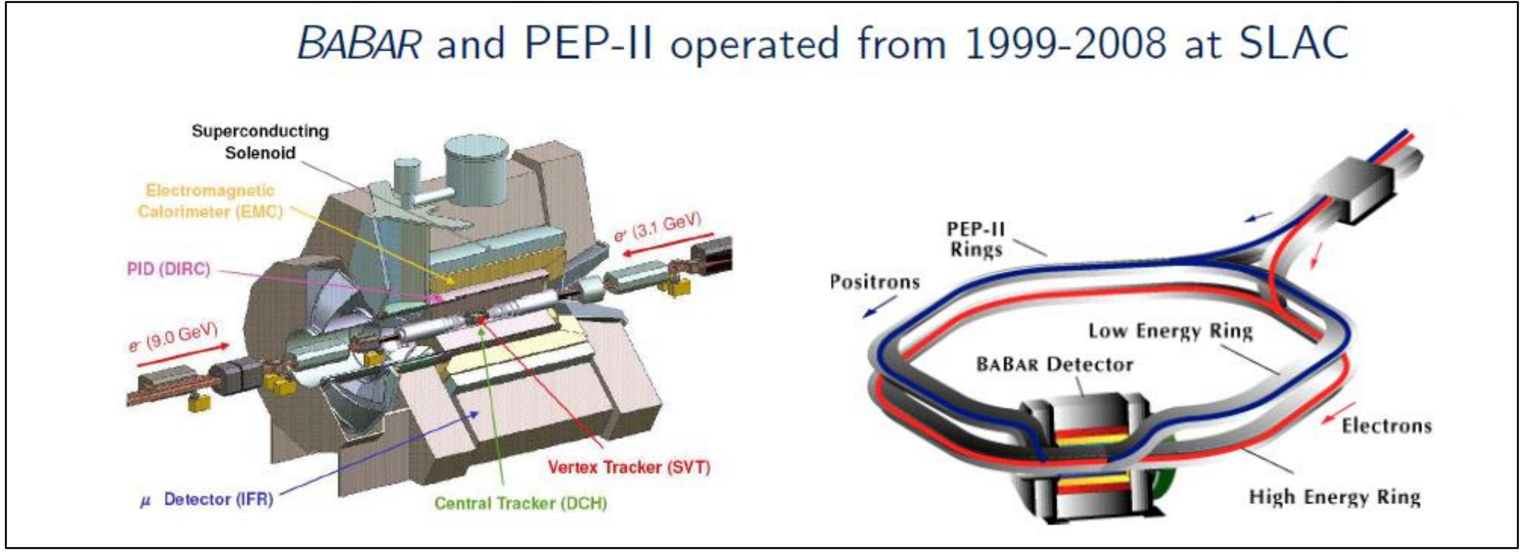
[1] S.Nussinov, et. al. PRD 63 (2001)

[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 $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ yet!**

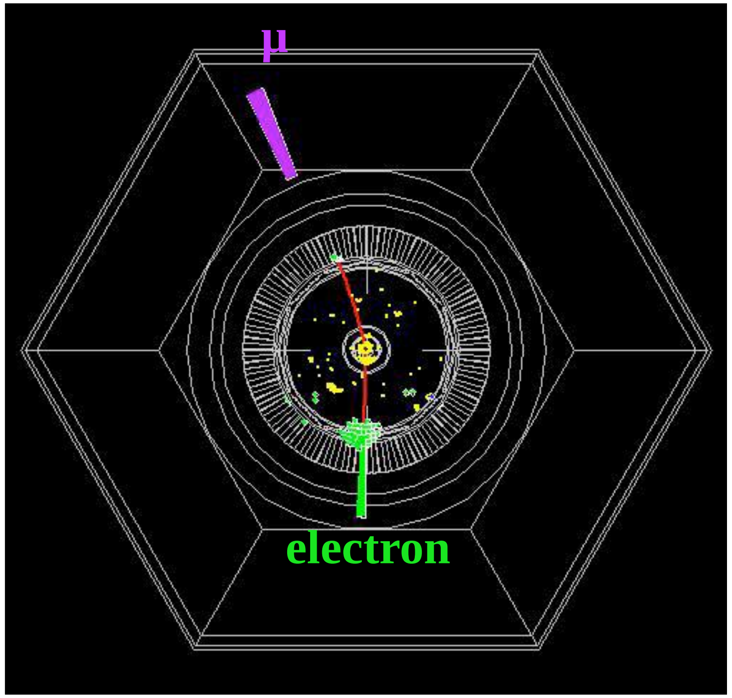
Data, MC Sample



Data Sample	On resonance (fb^{-1})	Off resonance (fb^{-1})
Run 7 $\Upsilon(3S)$ **(Data)**	27.9 = 27.0 + 0.93	2.62 To validate the systematic study
Run 6 $\Upsilon(4S)$ **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		

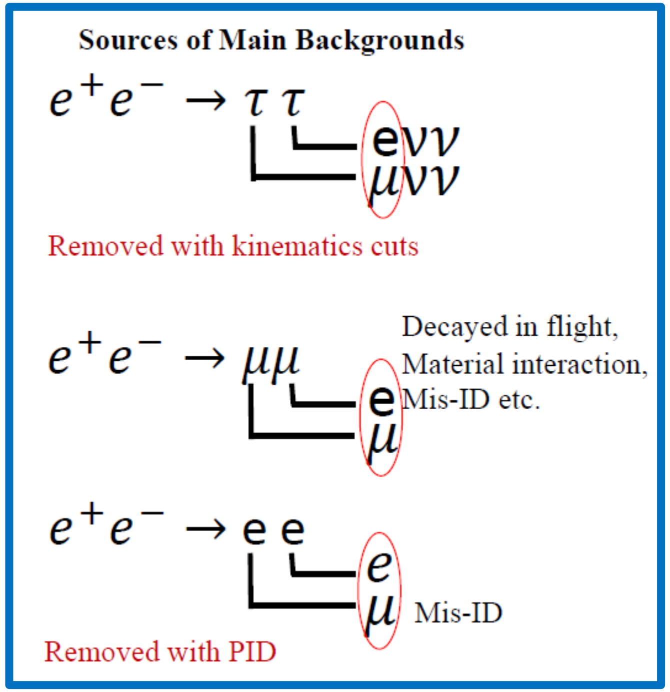
Signal and Background Characteristics

- $\boldsymbol{\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}}$: Required two primary track signal of $\boldsymbol{e^{\pm}}$ ***and*** $\boldsymbol{\mu^{\mp}}$
- CM Momentum: $\boldsymbol{p_{e^{\pm}} \sim \frac{\sqrt{s}}{2} \sim E_B}$ and $\boldsymbol{p_{\mu^{\pm}} \sim \frac{\sqrt{s}}{2} \sim E_B}$ where $\boldsymbol{E_B}$=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 $\boldsymbol{\mu^{\mp}}$ track on the Electromagnetic Calorimeter > 50 MeV
- EMC acceptance $24^{\circ} < \theta_{Lab} < 130^{\circ}$ etc.



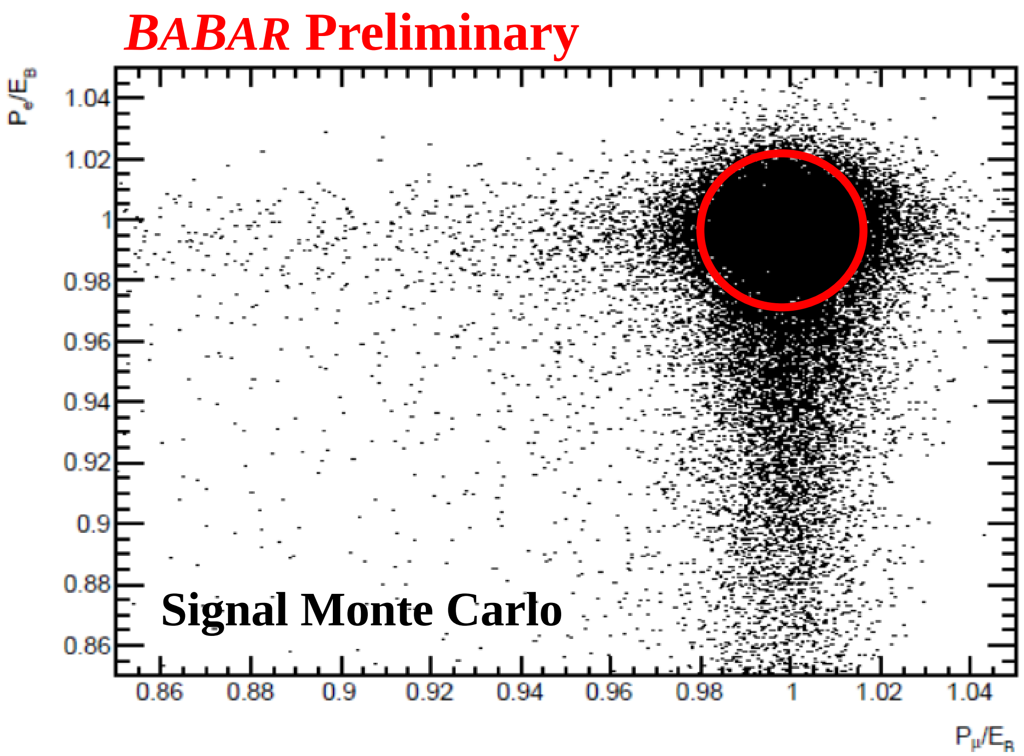
Sample Background event

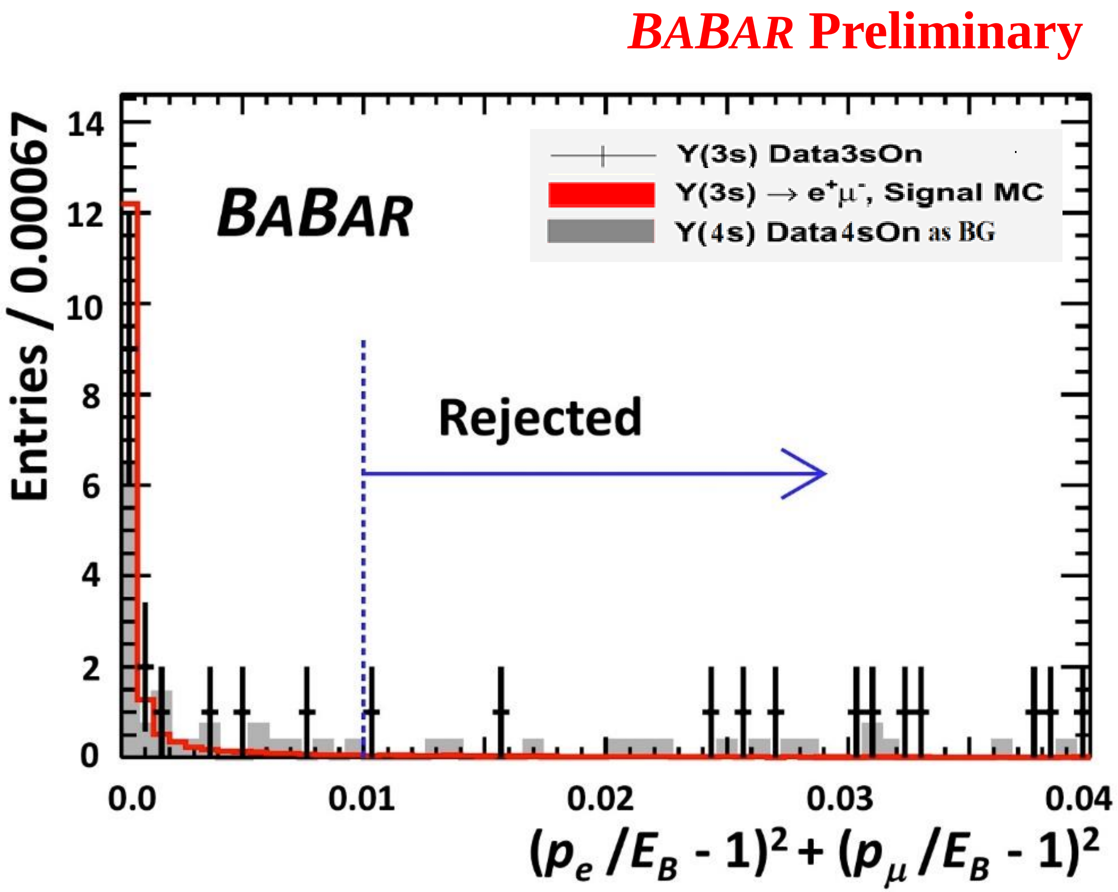
$\boldsymbol{e^{-}e^{+} \rightarrow \tau^{\pm}\tau^{\mp} \rightarrow e^{\pm}\mu^{\mp} + 4\nu}$

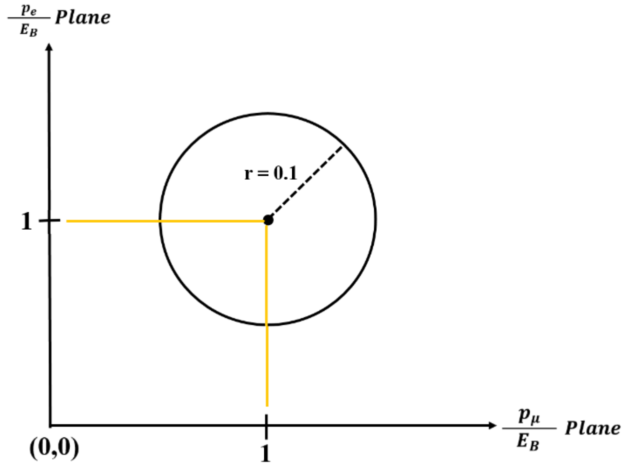


Different Sources of Background

Final Selection Criterion



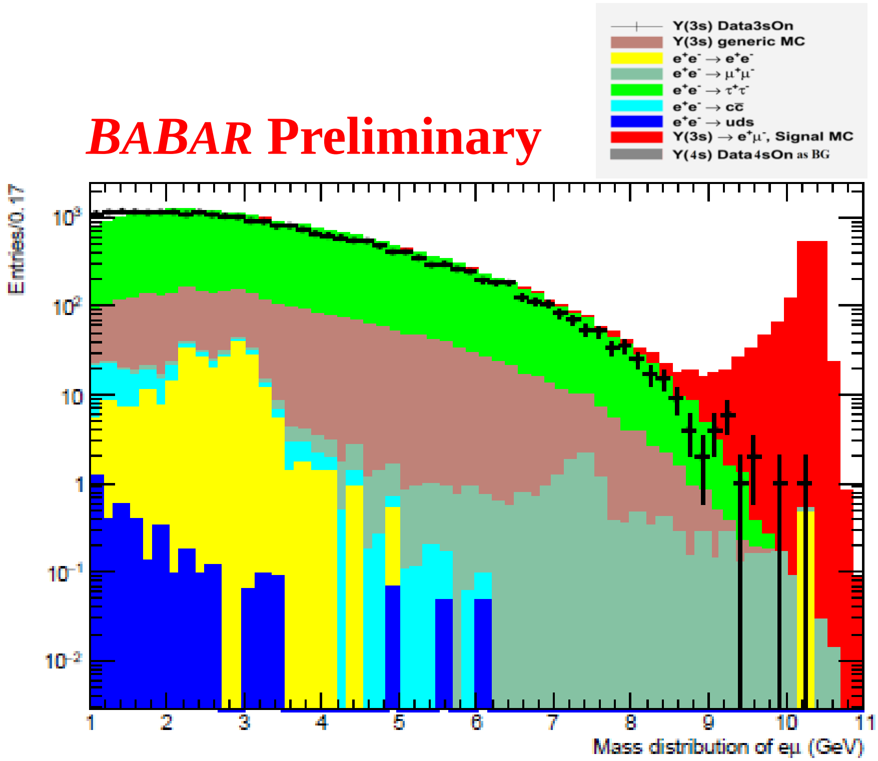




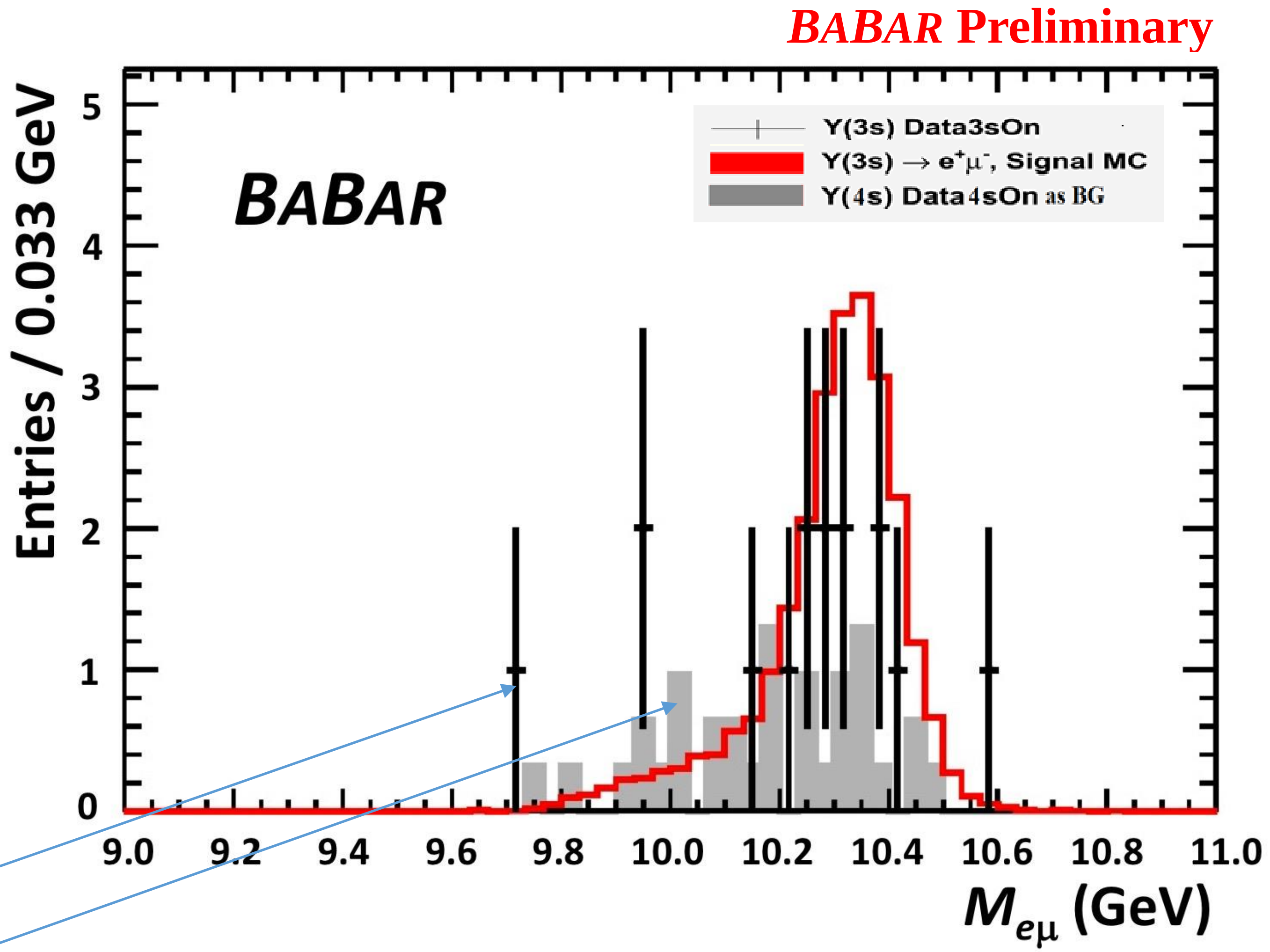
Selection Criteria: The lepton momenta must satisfy the condition which is defining a circle of radius $\left(\frac{p_e}{E_B} - 1\right)^2 + \left(\frac{p_\mu}{E_B} - 1\right)^2 = (0.1)^2 = 0.01$

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

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



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



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:**

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

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

- **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

***BABAR* Preliminary**

- 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

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

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

Motivation for the Testing Lepton Universality

Phys. Rev. Lett. 125, 241801 (2020)
BABAR Collaboration

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

$$R_{\tau\mu} = \frac{\Gamma_{\Upsilon\to\tau\tau}}{\Gamma_{\Upsilon\to\mu\mu}} = \frac{(1 + 2m_\tau^2/M^2)\sqrt{1 - 4m_\tau^2/M^2}}{(1 + 2m_\mu^2/M^2)\sqrt{1 - 4m_\mu^2/M^2}} \quad (2)$$

- A CP-odd Higgs boson A^0 would couple more strongly to τ's and thus have leave a new physics signal in the measurement[1]
- A new physics contribution in $b \to c\tau\nu$ decays to resolve the existing tension in R(D(*)) measurements will also have a signature in this ratio[2]
- There is one prior measurement from CLEO[3] at $R_{\tau\mu} = 1.05 \pm 0.08_{stat} \pm 0.05_{sys}$
- Standard model predicts, after radiative corrections, $R_{\tau\mu} = 0.9948 \pm \mathcal{O}(10^{-5})$

[1] M. A. Sanchis-Lozano, Int. J. Mod. Phys. A 19, 2183(2004)
[2] D. Aloni *et al.* , J. High Energ. Phys. 06, 019 (2017)
[3] D. Besson *et al.* (CLEO), Phys. Rev. Lett.98, 052002 (2007).

Data sample	On resonance fb^{-1}	Off resonance fb^{-1}
Run 7 $\Upsilon(3S)$	27.96 = 25.55 +2.41	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 selection
- $\Upsilon(3S)$ off resonance statistic is small, Run 6 $\Upsilon(4S)$ on resonance data with same detector configuration used to get the final result

Ratio and Systematics

- The full ratio $R_{\tau\mu}$ is calculated from the fit results

$$R_{\tau\mu} = \tilde{R}_{\tau\mu} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}} \frac{1}{C_{MC}} (1 + \delta_{BB}) = 0.966 \pm 0.008_{\text{stat}} \pm 0.014_{\text{sys}} \qquad (3)$$

- $\frac{\varepsilon_{\mu\mu}}{\varepsilon_{\tau\tau}}$ accounts for the different event selection efficiencies, $\sim$0.11
- C_{MC} is the data-driven data/MC correction, $\mathcal{O}(1\%)$
- $\delta_{B\bar{B}}$ corrects for a small amount of $B\bar{B}$ in the final selection, $\mathcal{O}(0.4\%)$

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

Results

- Using 27.96 fb^{-1} $\Upsilon(3S)$ data sample with $\Upsilon(4S)$ and off resonance data controls to describe continuum, BaBar measures:

$$R_{\tau\mu} = 0.966 \pm 0.008_{\text{stat}} \pm 0.014_{\text{sys}}$$

- The methodology described resulted in a measurement 6x more precise than the CLEO measurement
- The final ratio is with 2σ of the SM value of 0.9948

Phys. Rev. Lett. 125, 241801 (2020)
BABAR Collaboration

Conclusion

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

  $\Upsilon(3S) \to e^{\pm}\mu^{\mp} < 3.6 \times 10^{-7}$ @ 90% 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)].
- This result can be interpreted as a limit on NP: $\Lambda_{NP}/g^2_{NP} \geq 80\ \mathrm{TeV}$ ***BABAR* Preliminary**
- A journal paper will be submitted in the near future.
- **We also reported the most precise measurement by a factor of 6 the branching ratio of**

$$R_{\tau\mu} = \frac{\mathrm{BF}\,(\Upsilon\,(3S) \to \tau^{\pm}\tau^{\mp})}{\mathrm{BF}\,(\Upsilon\,(3S) \to \mu^{\pm}\mu^{\mp})} = 0.966 \pm 0.008_{stat} \pm 0.014_{sys}$$

(Lepton Universality)

(Phys. Rev. Lett. 125, 241801 (2020))

Thanks and Questions

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 $A\ (\mu \to 3e)$

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

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

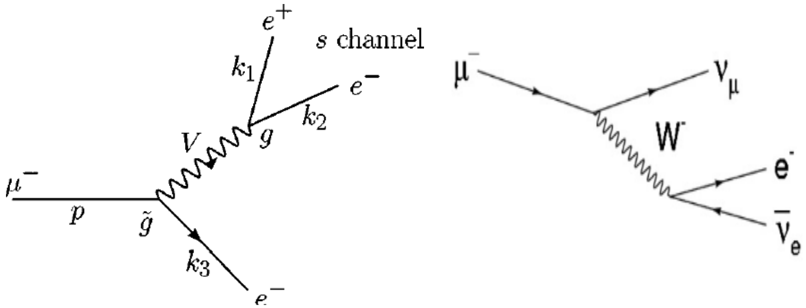
Since $[\Gamma(\mathrm{V} \to \mathrm{e}^+\mathrm{e}^-)] \sim \mathrm{g}^2\ \mathrm{V}_{ee}\ \mathrm{M}_V$ and

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

Analysis Scheme (Backup slide)

- **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.

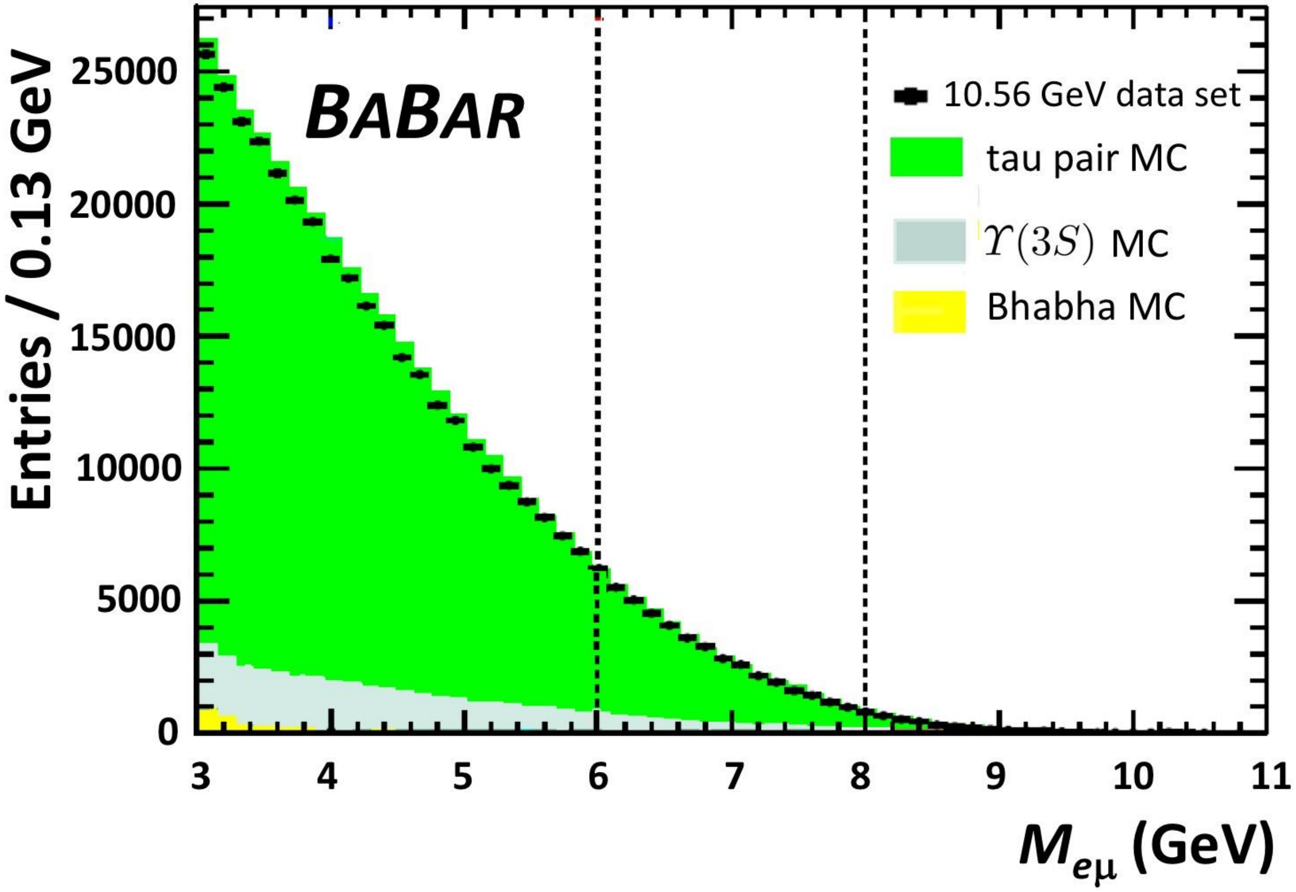
Back Up: Impact of each component of the selection on the signal efficiency, background and data.

- 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 $\pm$ 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

Back Up: Systematic Uncertainty on Signal Efficiency

BABAR **Preliminary**

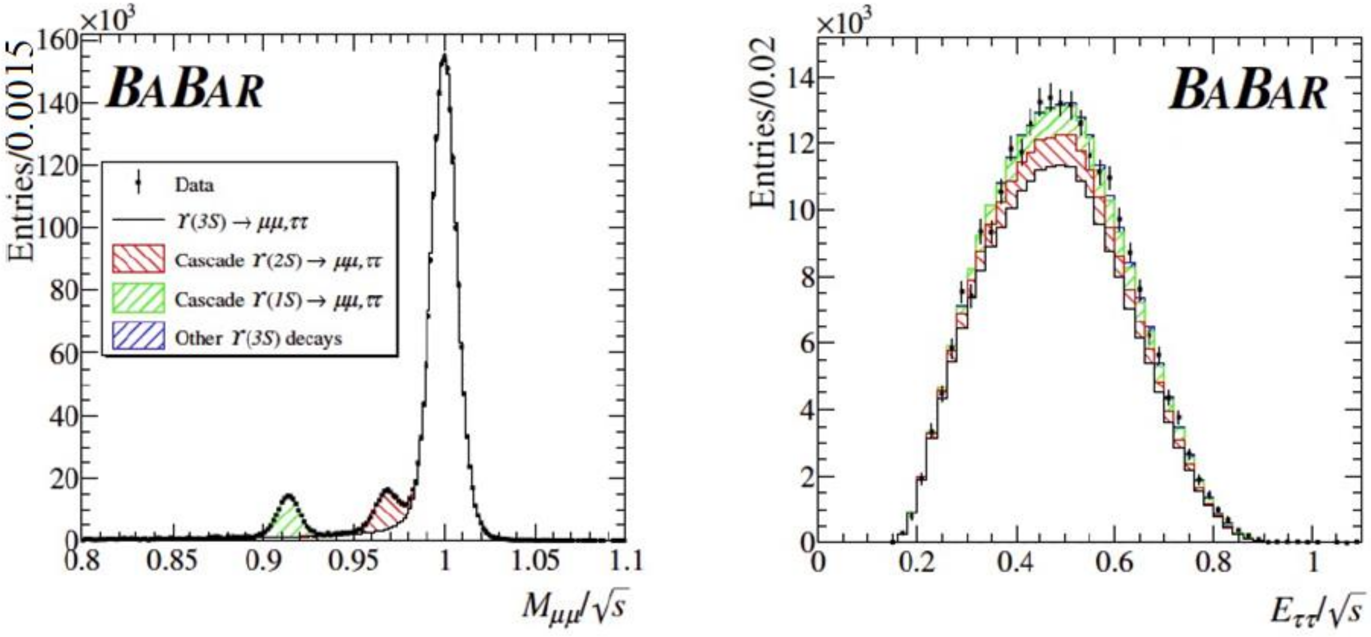


- Controlled Sample: A data set where two major cuts were reversed to check the data/MC agreement.
- Disagreement arises due to uncertainties in PID, Tracking, kinematics, trigger etc.
- Uncertainty in "Side Bands": 1.2%

Backup: Results on Lepton Universality

Fit Results, Continuum Fit Subtracted

- $M_{\mu\mu}/\sqrt{s}$ and $E_{\tau\tau}/\sqrt{s}$ are simultaneously fit using MC and data derived templates
- The free parameters of the fit are the number of $\Upsilon \to \mu^+\mu^-$ events ($N_{\mu\mu}$), and the ratio $\tilde{R}_{\tau\mu} = N_{\tau\tau}/N_{\mu\mu}$



$\tilde{R}_{\tau\mu}$=0.10778±0.00091, $N_{\mu\mu}$=(2.02±0.015)×10^6