University of Victoria

APS DIVISION OF PARTICLES & FIELDS
DPF 2017
MEETING OF THE AMERICAN PHYSICAL SOCIETY DIVISION OF PARTICLES AND FIELDS

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

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On Behalf of BaBar Collaboration

All Results Are Preliminary

The 2017 Division of Particles and Fields meeting

July 31 – August 4, 2017

Fermilab, Batavia, IL

Charged Lepton Flavor Violation

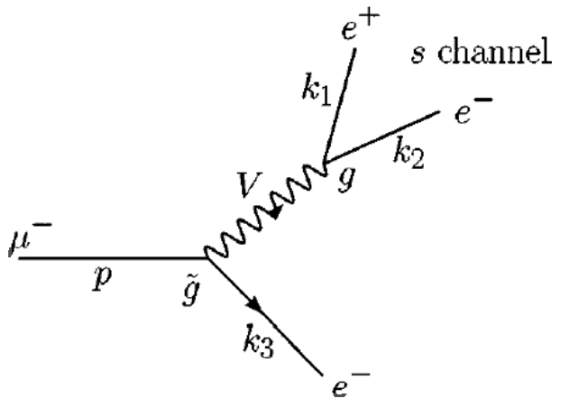
- CLFV highly suppressed in SM, allowed in many BSM models + clear exp. signature = "NP"
- Theoretical constraints on the limit (indirect): BF$(\Upsilon(3S) \to e^{\pm}\mu^{\mp}) < 2.0 \times 10^{-8}$ (2000) [1]
- **No experimental measurement of the decay $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ yet!**

Some $e^{\pm}\tau^{\mp}$ and $\mu^{\pm}\tau^{\mp}$ Limits

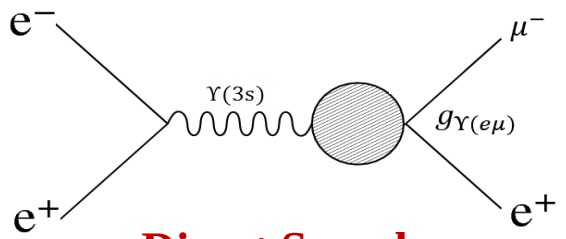
Measurements	Results	CL (%)	Collaboration
BF$(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	$< 5.0 \times 10^{-6}$	90	BaBar Collaboration (2010) [2]
BF$(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$< 4.1 \times 10^{-6}$	90	BaBar Collaboration (2010) [2]
BF$(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$< 20.3 \times 10^{-6}$	95	CLEO Collaboration (2008) [3]

Some of the direct experimental bounds from vector particles decay

Measurements	Results	CL (%)	Collaboration
BF$(\Phi \to e^{\pm}\mu^{\mp})$	$< 2.0 \times 10^{-6}$	90	SND Collaboration (2010) [4]
BF$(J/\Psi \to e^{\pm}\mu^{\mp})$	$< 1.6 \times 10^{-7}$	90	BES III Collaboration (2013) [5]
BF$(Z^0 \to e^{\pm}\mu^{\mp})$	$< 7.5 \times 10^{-7}$	95	ATLAS Collaboration (2014) [6]

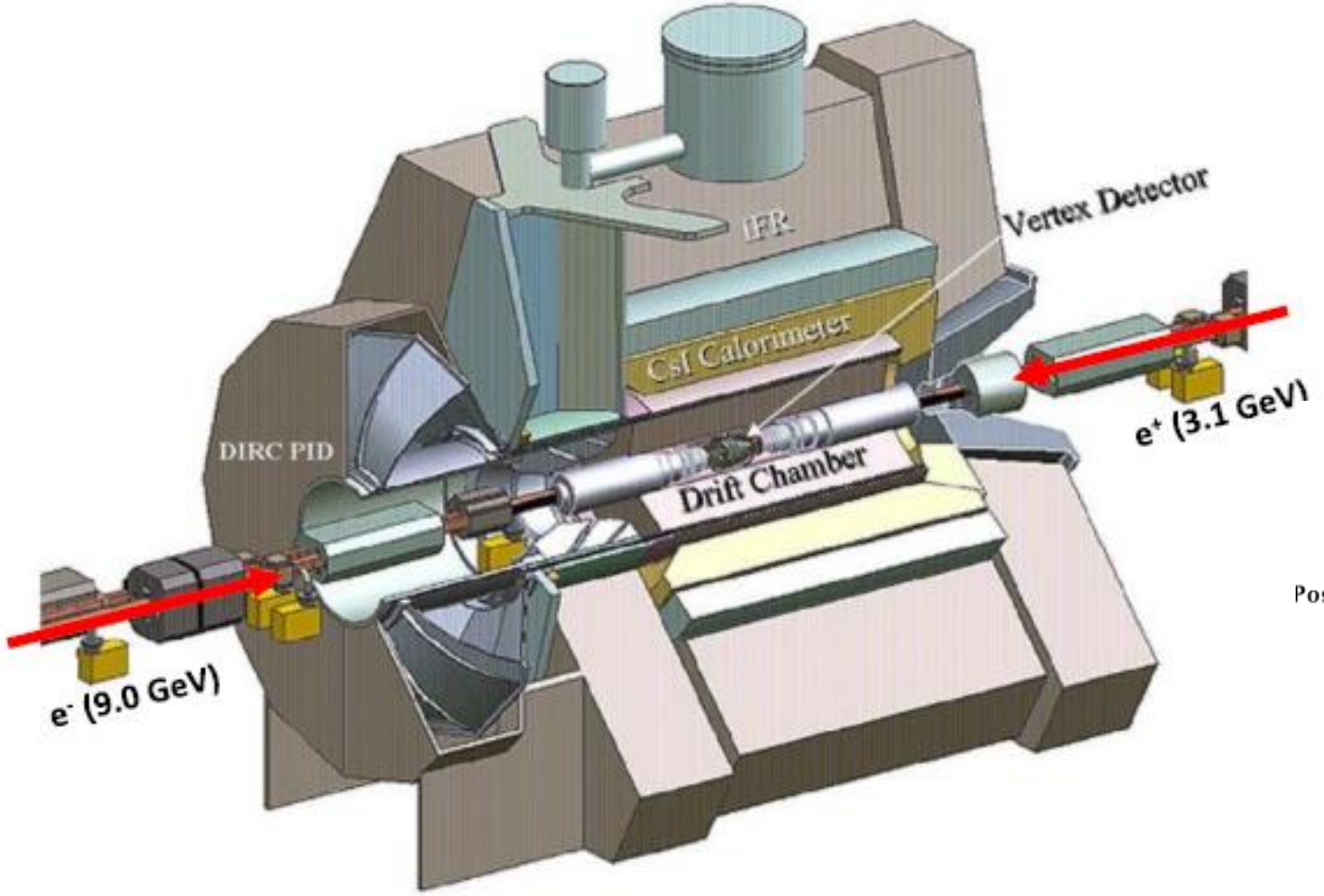


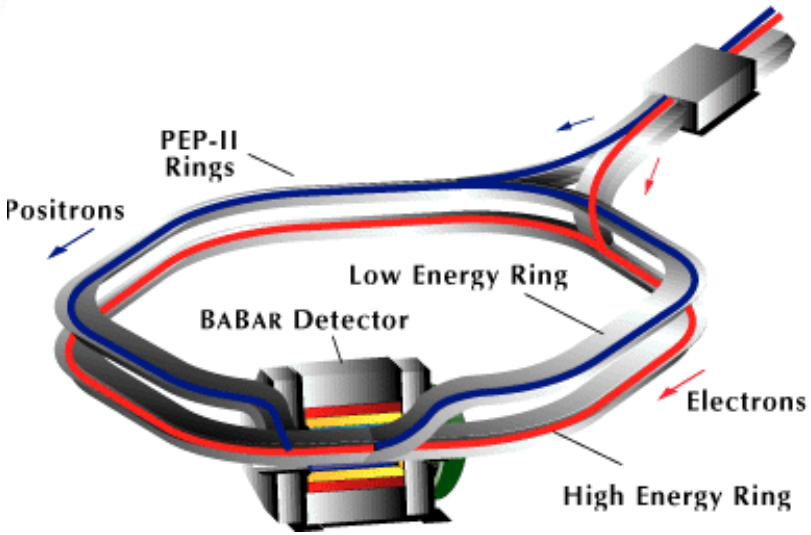
Indirect Search
Provides limit assuming Unitarity



Direct Search

The BaBar Detector at PEP-II





Data Sample, Signal and Backgrounds

Data $\Upsilon(3S)$, $\sqrt{s} = 10.355$	Luminosity (fb^{-1})	Upsilon Numbers
(3%) Pre-blinded Sample	0.93 ± 0.01	$(4.06 \pm 0.04) \times 10^6$
Unblinded Sample	27.02 ± 0.16	$(117.7 \pm 1.2) \times 10^6$
Total	27.96 ± 0.16	$(121.7 \pm 1.2) \times 10^6$

MC Signal (for Background)	Generators
$e^+e^- \to \mu^+\mu^-$	KK2F
$e^+e^- \to e^+e^-$	BHWIDE
$e^+e^- \to \tau^+\tau^-$	KK2F
$e^+e^- \to uds$	EvtGen
$e^+e^- \to c\bar{c}$	EvtGen
Generic $\Upsilon(3S)$ MC	EvtGen

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

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

Control Data Sample

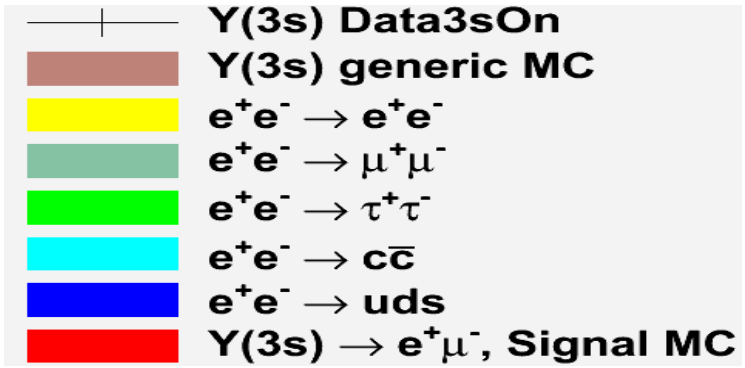
Data	Luminosity (fb^{-1})	Purpose
$Data\ \Upsilon(4S) On\ Resonance$, $\sqrt{s} = 10.58$ Preselected as $e^{\pm}\mu^{\mp}$ events	78.31 ± 0.35	**Estimate Continuum Background** Systematics
$Data\ \Upsilon(4S) On\ Resonance$, $\sqrt{s} = 10.58$ Preselected as $\mu^{\pm}\mu^{\mp}$ events	78.31 ± 0.35	Systematics
$Data\ \Upsilon(4S)$Off Resonance	7.752 ± 0.04	BG Control Sample
$Data\ \Upsilon(3S)$On Resonance , $\sqrt{s} = 10.355$ Preselected as $\mu^{\pm}\mu^{\mp}$ events	27.96 ± 0.16	Systematics
$Data\ \Upsilon(3S)$Off Resonance	2.62 ± 0.02	BG Control Sample

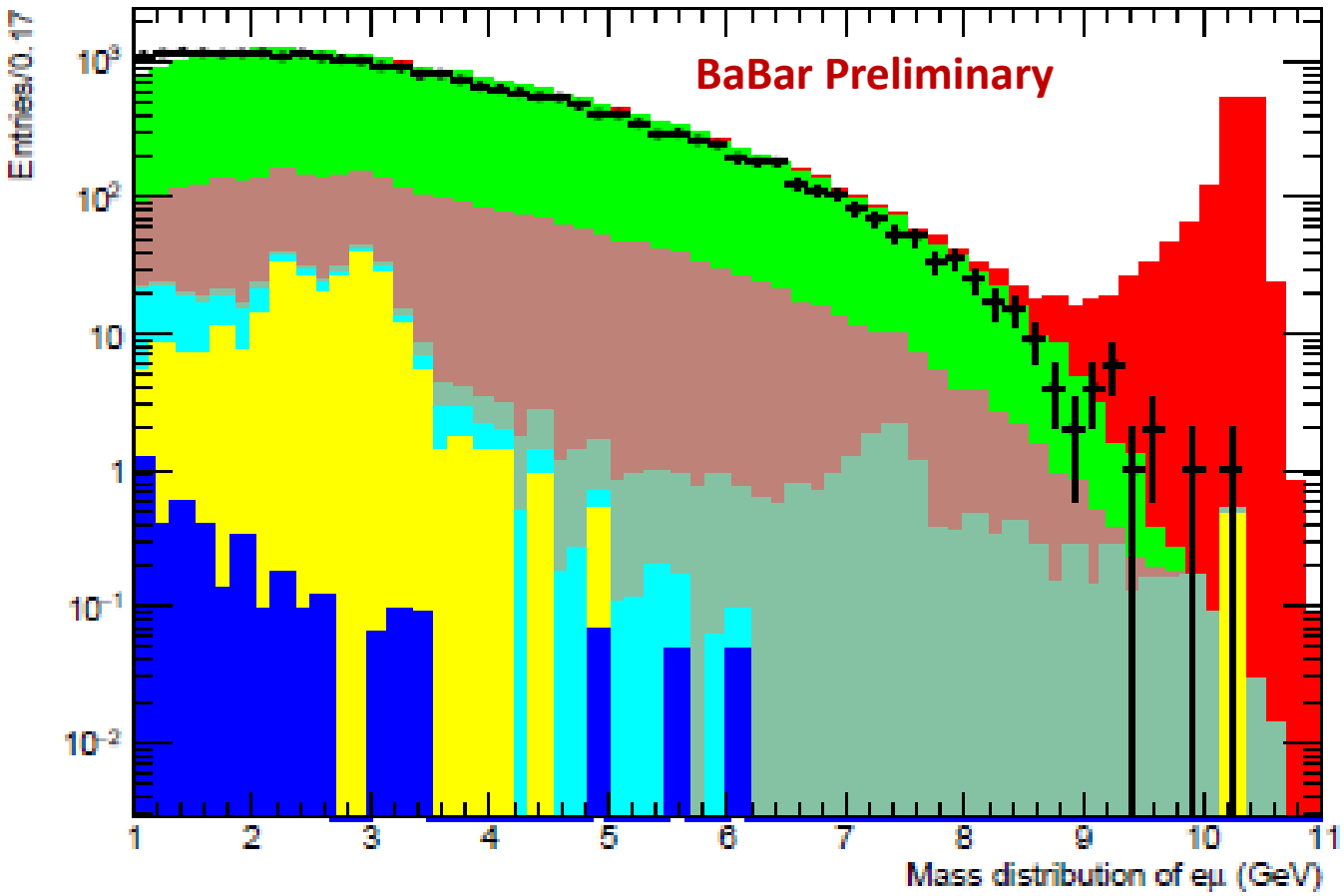
Analysis Methodology

- **Pre-Selection:** A Background filter to select $e^{\pm}\mu^{\mp}$ events
- **User defined Selection:** Applied on the pre-selected events
- **PID Selection:** Multivariate Technique applied, 16 different PID selector used in optimization ($S/\sqrt{B}$)

Pre-Selection:	**User defined Selection:**
Distance of closest approach of any track vertex w.r.t. the beam spot in Drift Chamber • in x - y plane < 1 cm and in z < 4 cm.	2 tracks (1 electron and 1 muon in the final state), one in each hemisphere,
Number of hits in the Drift Chamber > 0. Transverse Momentum p_T > 100 MeV.	$24^\circ < \theta_{Lab} < 130^\circ$ EMC acceptance for both tracks.
Exactly 2 oppositely charged tracks ;	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 $E_{Beam} = \sqrt{s}/2$
Polar angle of the two tracks: $2.8 < (\theta_1 + \theta_2) < 3.5$	
Sum of momentum of the two tracks $\lvert P_1\rvert + \lvert P_2\rvert$ > 9 GeV.	
One and only one electron of two tracks defined by E/P > 0.8	Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^\circ$ to ensure they are emerged as back to back.
Acolinearity angle associated with the two tracks < 0.1 radians in CM.	Energy deposit by Muon track on the Electromagnetic Calorimeter should be greater than 50 MeV.

Data/MC Comparison

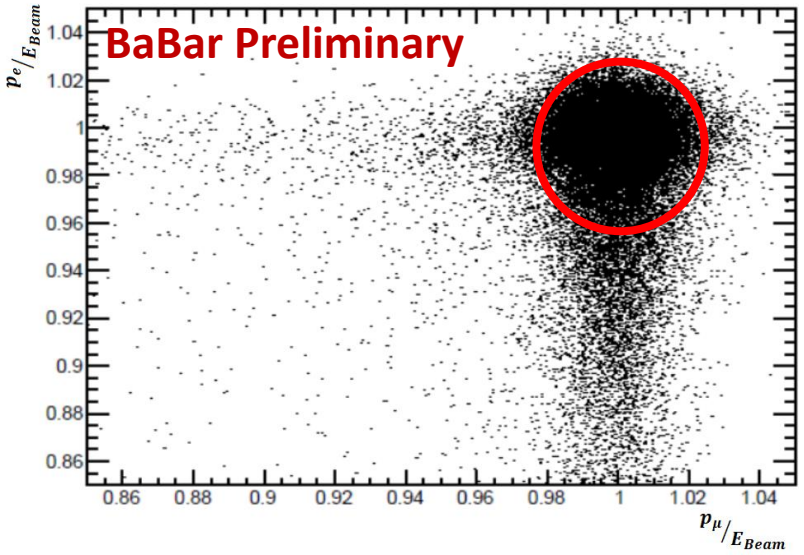




Distribution of $e^{\pm}\mu^{\mp}$ mass before applying any user defined selection criteria, only preselection criteria has applied for 3% pre-unblinded sample.

Selection Criteria in (N-1) plots

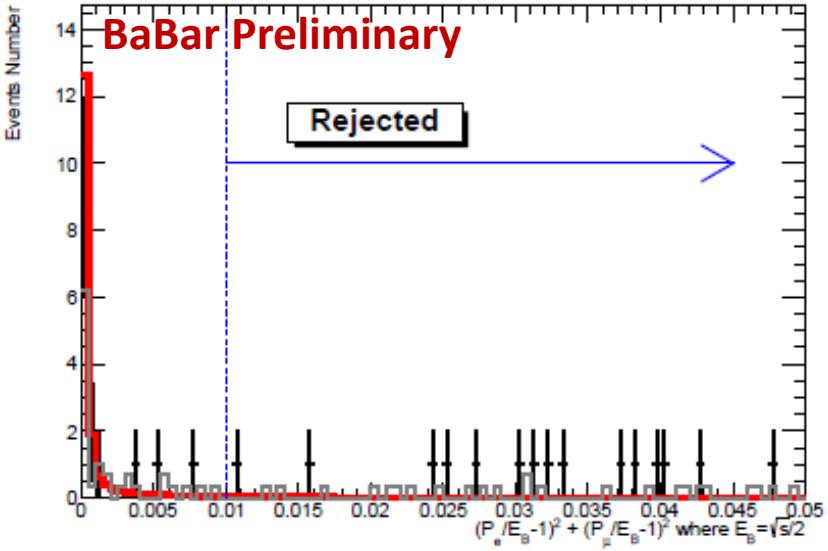
(N-1) plots→ all cuts applied except that on the variable plotted

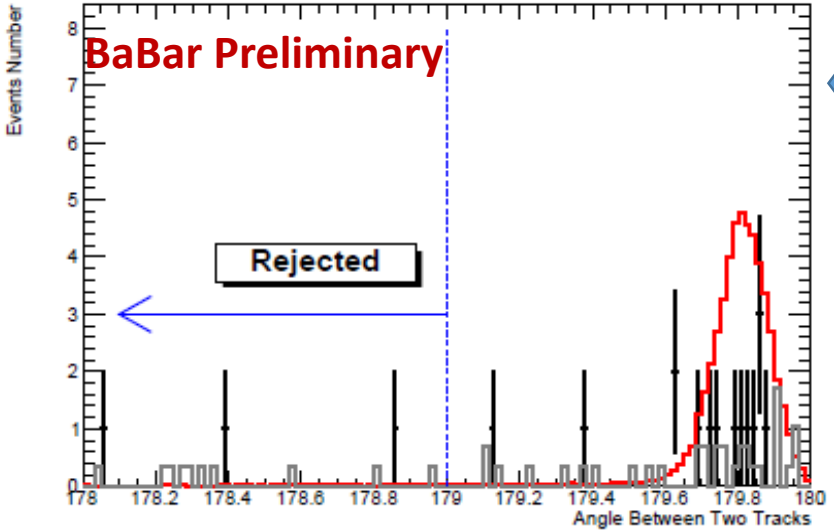


Y(3s) Data 27.02 fb^{-1}
Y(4s) Data as BG
Signal MC

$$\left(\frac{p_e}{E_{Beam}} - 1\right)^2 + \left(\frac{p_\mu}{E_{Beam}} - 1\right)^2 < 0.01$$

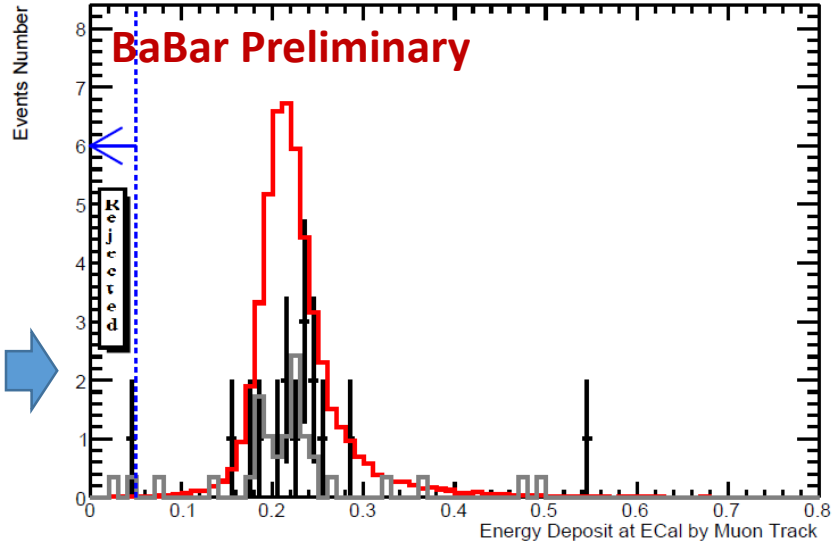
where $E_{Beam} = \sqrt{s}/2$



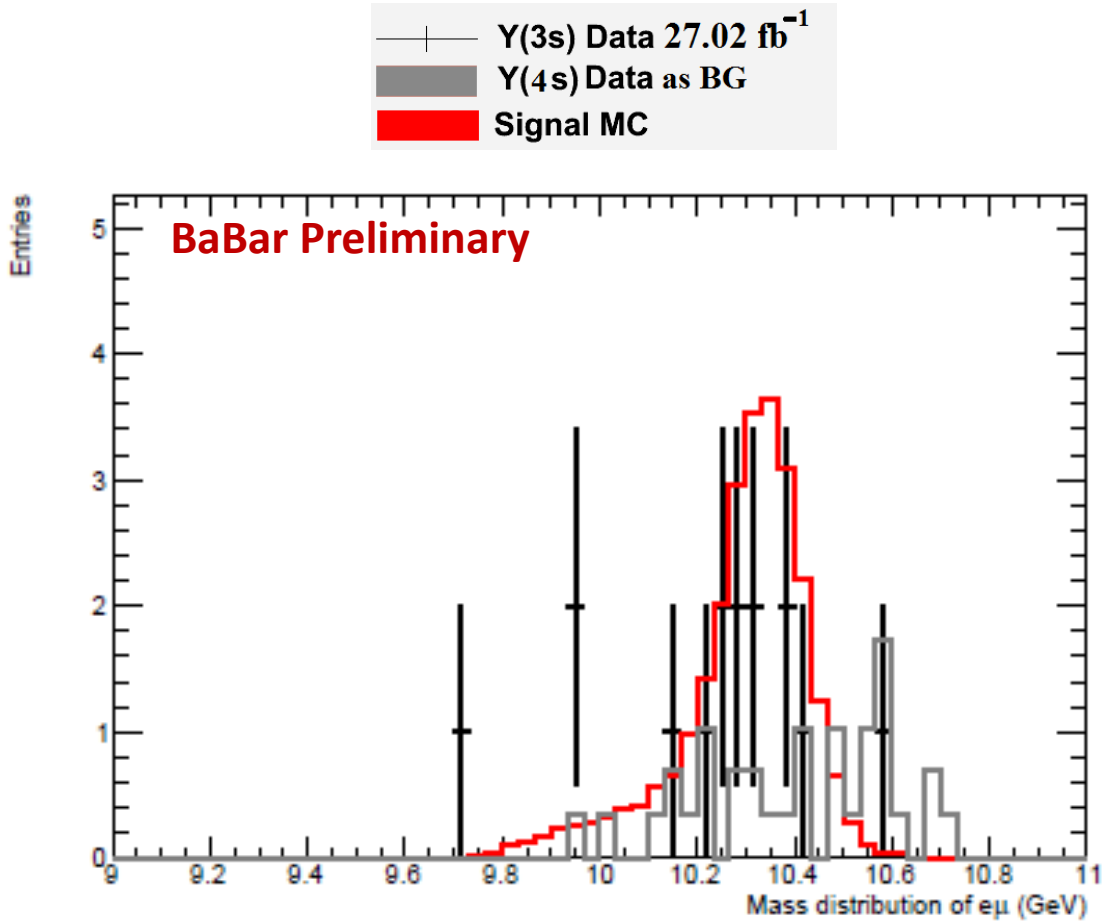


The angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^\circ$ to emerged as back to back.

Energy deposit by Muon track on EMC should be greater than 50 MeV.



All Selection Criteria Applied



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

Data, BG Selection Summary & Signal Efficiency in (N-1) Cuts

(N-1) Selection	Signal Efficiency $\varepsilon_{e\mu}$	*BG Events* $\Upsilon(3S)$ MC	*BG Events* $\Upsilon(4S)On$	*Candidate* $\Upsilon(3S)On$ (27.02 fb^{-1})
Pre-selection	82612	7134301	152445188	
PID selection	0.2355 ± 0.0013	0	14.7 ± 2.3	18
Lepton Momentum	0.2684 ± 0.0012	82.7 ± 6.03	263.4 ± 9.7	302
Back to back	0.2402 ± 0.0013	0.44 ± 0.44	37.7 ± 3.7	39
EMC acceptance	0.2495 ± 0.0013	0	13.9 ± 2.2	17
EMC Energy	0.2452 ± 0.0013	0	17.6 ± 2.5	19
All Cuts	**0.2342 ± 0.0013$_{STAT}$**	**0**	**12.2 ± 2.1$_{STAT}$**	**15**

- BG events are the equivalent events on 27.0 fb^{-1}
- Uncertainties are statistical

Note: For the 3% Pre-blinded sample (0.93 fb^{-1}): N_{Data}=1, agrees with BG estimate: 0.43 ± 0.07 events

Systematic Uncertainty and Background

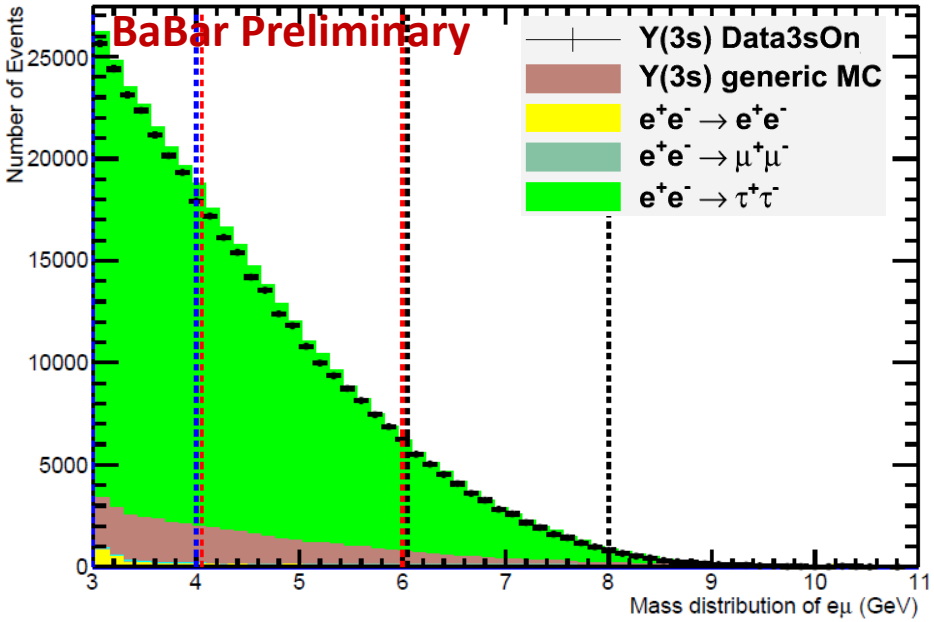
Systematic Uncertainty on Efficiency:

- Tracking, PID, kinematics, trigger determined using controlled sample of tau's in the "**Side Bands**" where "lepton momentum" and "back to back" cuts are reversed: **1.2%**
- Systematic uncertainty on "**lepton momentum**" cut: **2.9%**
- Systematic uncertainty on "**back to back**" cut: **1.1%**

Systematic Uncertainty on $N_{\Upsilon(3S)}$: [8]

- Total Uncertainty on $N_{\Upsilon(3S)}$ at Run 7 Dataset: **1%**

Source of BG	No. of events after all selection criteria
Continuum	ϒ(4S)On Data: 12.2 ± 2.3
Peaking	ϒ(3S) MC: 0 ± 0.9



Mass distributions for ϒ(3S)On data and MC control samples (τ-pair)

Summary on Efficiency, Background and Candidate

Values	Sources	Uncertainties
ε_{SIG} (SYST)	• In the "Lepton. Momentum" cut • In the "Back to back" cut • In all other cuts on the Side bands	0.029 0.011 0.012
ε_{SIG} (SYST $\oplus$ STAT)		$0.2342 \pm 0.0077_{SYST} \pm 0.0013_{STAT}$ 0.2342 ± 0.0078
N_{Υ} (0.93 fb^{-1}) N_{Υ} (27.02 fb^{-1})		$(4.06 \pm 0.04) \times 10^6$ $(117.7 \pm 1.2) \times 10^6$
Background (0.93 fb^{-1}) Background (27.0 fb^{-1})		0.42 ± 0.7 12.2 ± 2.3

Candidate seen (0.93 fb^{-1}) Candidate seen (27.0 fb^{-1})	1 15

Results: Branching Fraction and Upper limit

$$\mathbf{BF} = \frac{N_{\mathrm{Data}} - N_{BG}}{\varepsilon_{sig} \times N_{\Upsilon}} = (1.0 \pm 1.4_{STAT\ (N_{DATA})} \pm 0.8_{SYST}) \times 10^{-7}$$

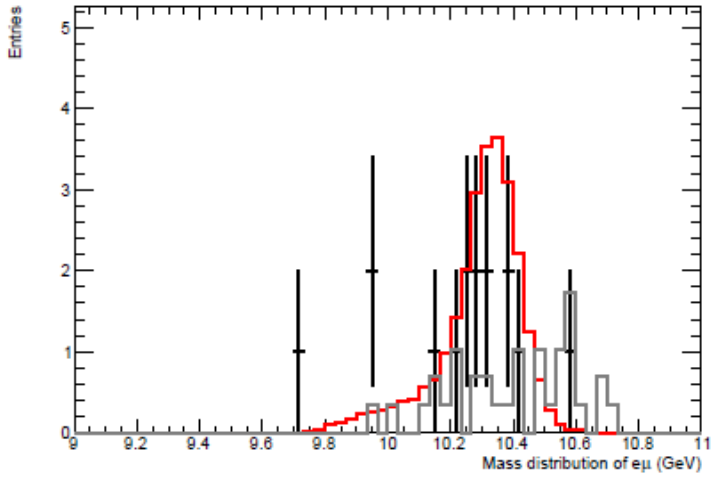
Measurements $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$	**Upper Limit with Confidence Level of 90%**			
	Observed Upper limit		Expected Upper limit	
	Barlow Method [9]	CLs Method [10]	Barlow Method	CLs Method
Unblinded Data Sample (27.0 fb^{-1})	$< 3.6 \times 10^{-7}$	$< 3.6 \times 10^{-7}$	$< 2.3 \times 10^{-7}$	$< 2.8 \times 10^{-7}$

Conclusion

- On behalf of the BaBar Collaboration we presented the preliminary result on experimental upper limits of a data sample (27.02 fb^{-1})

$$\boldsymbol{BF(\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}) < 3.6 \times 10^{-7}}\ \textbf{with Confidence Level of 90\%}$$

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



Reference

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2. B. Aubert et al. Search for the Lepton-Flavor Violating Decays, BABAR-CONF-08/020,2008. (BABAR Collaboration)
3. 5. W. Love et al., Search for Lepton Flavor Violation in Upsilon Decays, Phys. Rev. Lett. 101, 201601, 2008. (CLEO Collaboration)
4. M. N. Achasov, K. I. Beloborodov, A.V. Bergyugin et al., Phys. Rev. D 81, 057102 (2010).
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10. A. L. Read, \Presentation of search results: The CL(s) technique", J.Phys. G28 (2002) 2693-
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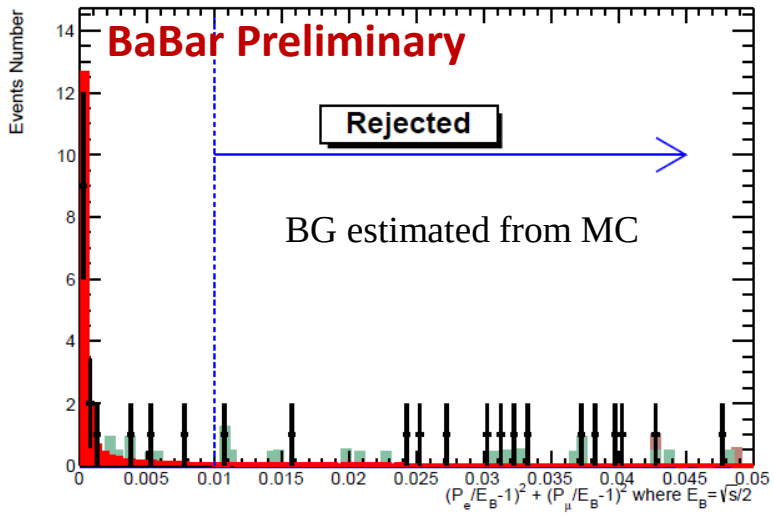
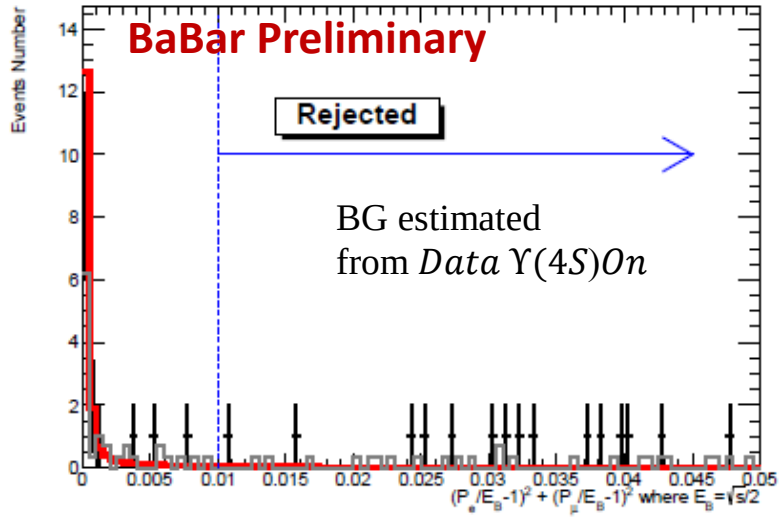
280 C73 (2013) 2501.

Back up:1 Selection Criteria

Y(3s) Data3sOn
Y(3s) generic MC
$e^+e^- \rightarrow e^+e^-$
$e^+e^- \rightarrow \mu^+\mu^-$
$e^+e^- \rightarrow \tau^+\tau^-$
$e^+e^- \rightarrow c\bar{c}$
$e^+e^- \rightarrow uds$
$\Upsilon(3s) \rightarrow e^+\mu^-$, Signal MC
$\Upsilon(4s)$ Data as BG

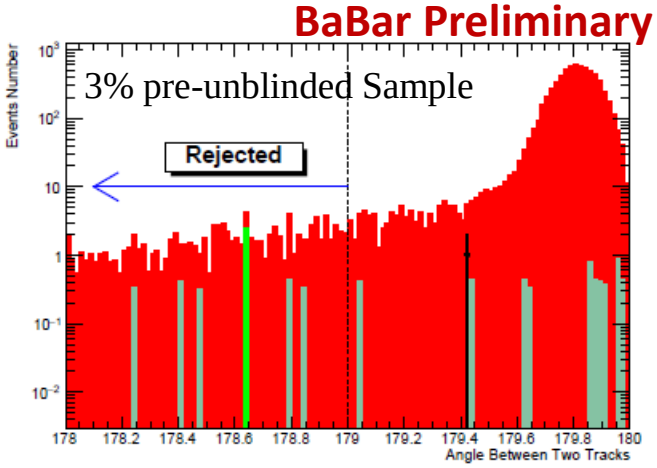


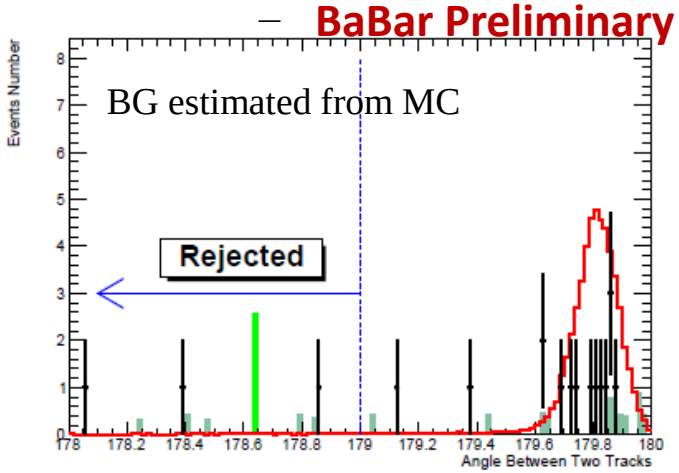


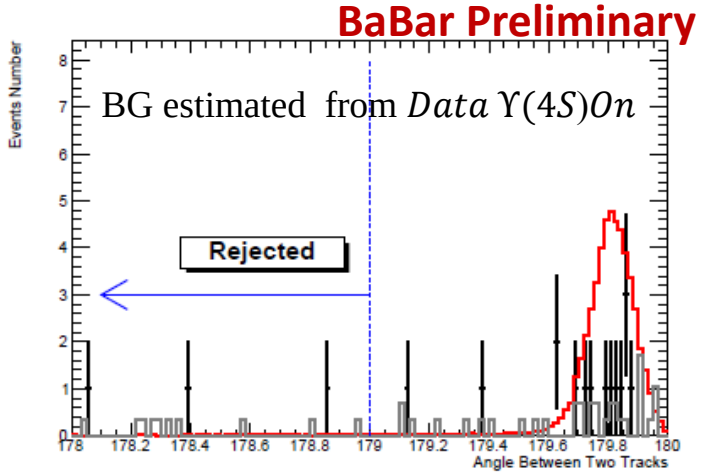
The lepton momenta must satisfy the following condition which is defining a circle of radius 0.1 centered at (1,1) in the $\frac{p_e}{E_{Beam}}$ vs $\frac{p_\mu}{E_{Beam}}$ plane.

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

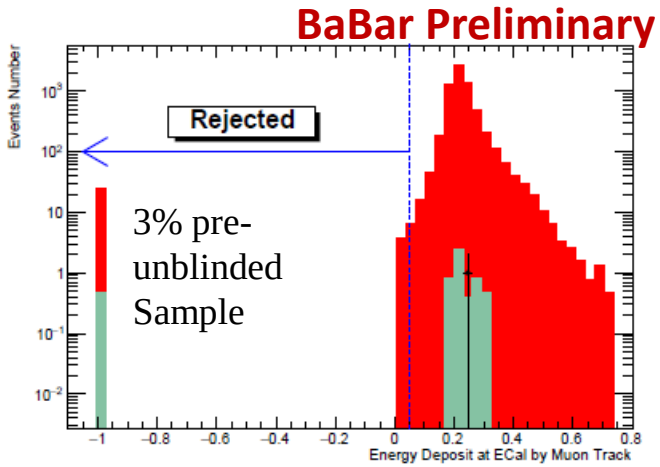
Backup: 2 Selection Criteria in (N-1)

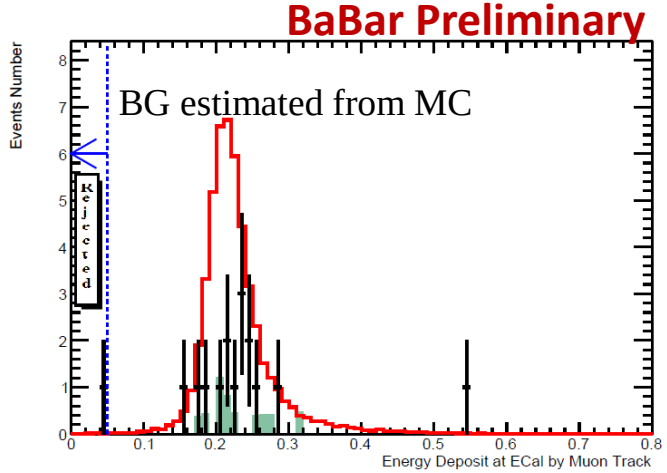


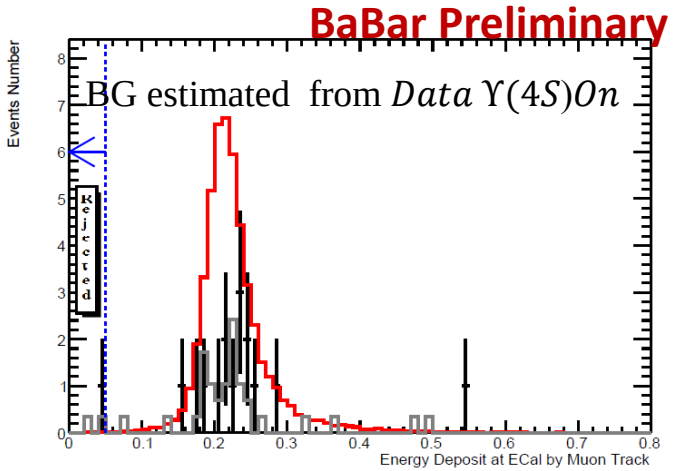




The angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^{\circ}$ to ensure they are emerged as back to back.

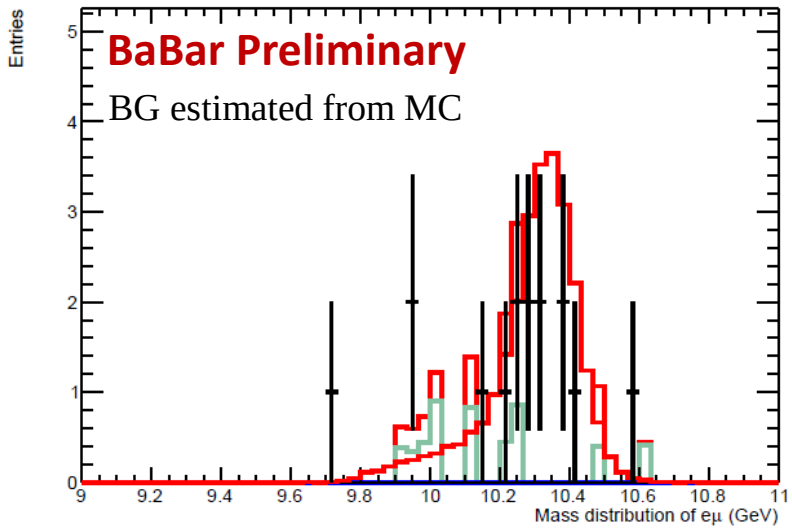


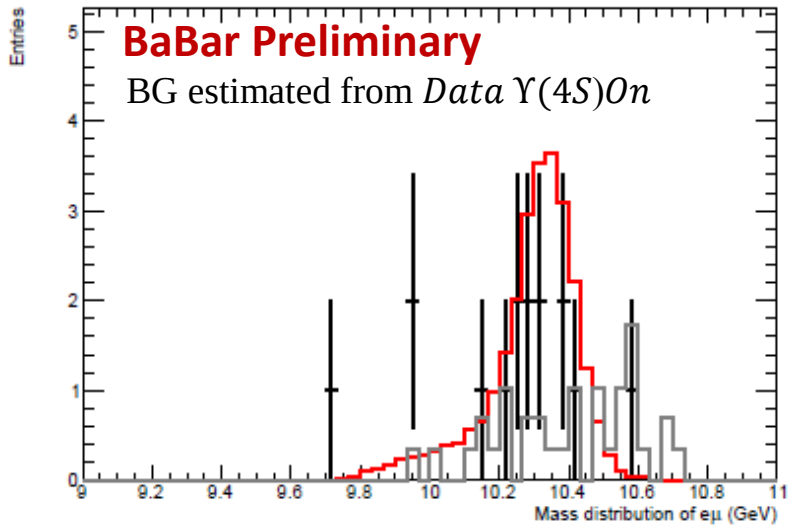




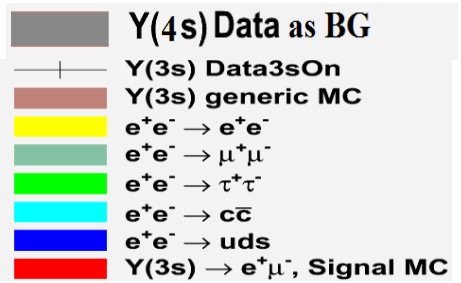
Energy deposit by Muon track on the Electromagnetic Calorimeter should be greater than 50 MeV.

Back up: 3 All Selection Criteria Applied





Mass distribution of $e^{\pm}\mu^{\mp}$ after all selection criteria are applied in the Υ(3S) data (within 27.02 /fb).

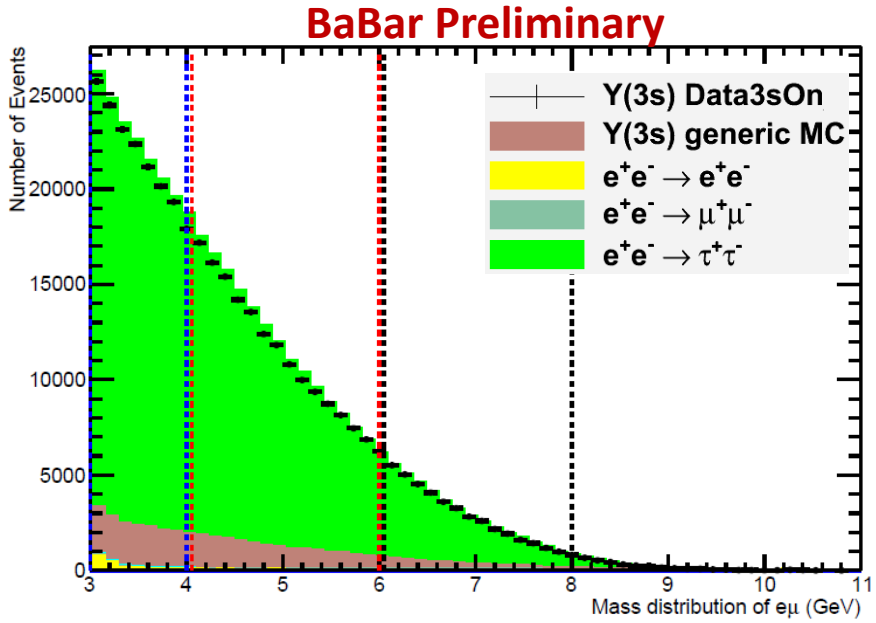


Back up: 4 Data, BG Selection Summary & Signal Efficiency in (N-1) Cuts

Selection (27.02 fb^{-1})	$\varepsilon_{e\mu}$	Survived BG Events on MCs			*BG Events* $\Upsilon(3S)$ MC	$\Upsilon(4S)Off$	$\Upsilon(4S)On$	$\Upsilon(3S)Off$	$\Upsilon(3S)On$
		μμ	ττ	Bhabha					
Pre-selection	82612	22649650	13333831	599556063	7134301	148286975	152445188	257079590	
PID selection	0.2355 ± 0.0013	4.7 ± 1.4	0	0	0	3.6 ± 3.6	14.7 ± 2.3	0	18
Lepton Momentum	0.2684 ± 0.0012	54.0 ± 4.61	91.4 ± 6.3	24.9 ± 14.4	82.7 ± 6.03	210.2 ± 26.9	263.4± 9.7	288.4 ± 54.5	302
Back to back	0.2402 ± 0.0013	9.07 ± 1.9	43.3 ± 43.3	0	0.44 ± 0.44	68.8 ± 15.8	37.7 ± 3.7	51.50 ± 23.03	39
EMC accpt	0.2495 ± 0.0013	5.1 ± 1.4	0	0	0	7.2 ± 5.1	13.9 ± 2.2	0	17
EMC Energy	0.2452 ± 0.0013	5.1 ± 1.4	0	0	0	3.6 ± 3.6	17.7 ± 2.5	0	19
All Cuts	0.2342 ± 0.0013	4.7 ± 1.4	0	0	0	3.6 ± 3.6	12.20 ± 2.09	0	15

Survived events are the equivalent events on 27.0 fb^{-1}

Back up: 5
Systematic Uncertainty in the Sidebands

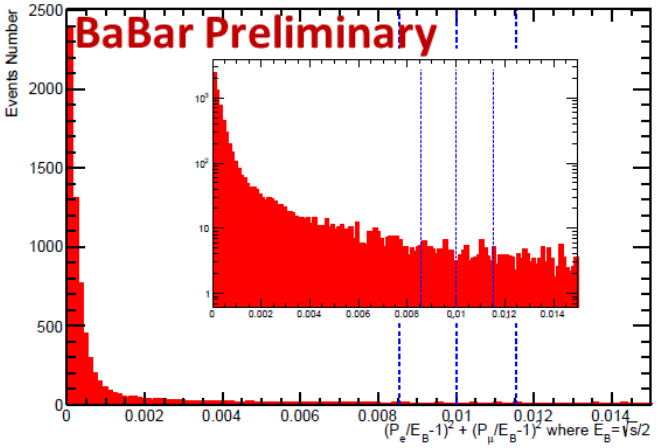


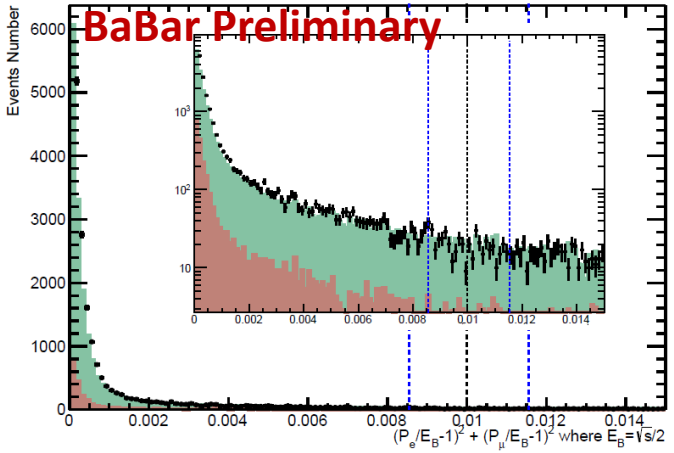
Mass distributions for ϒ(3S)On data and MC control samples (τ-pair)

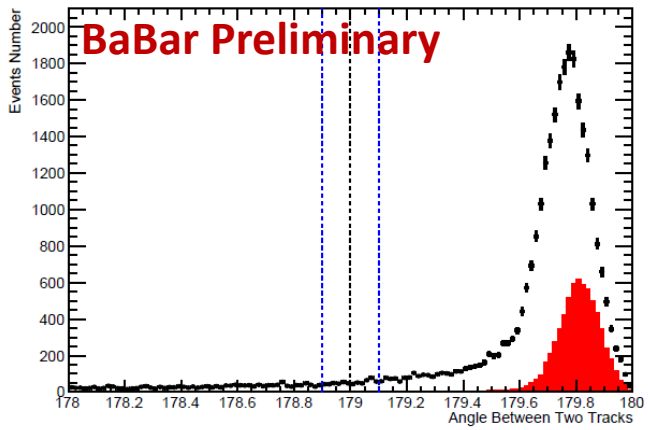
R± σ_R	0.9825 ± 0.0029	0.9795 ± 0.0032	1.0072 ± **0.010**

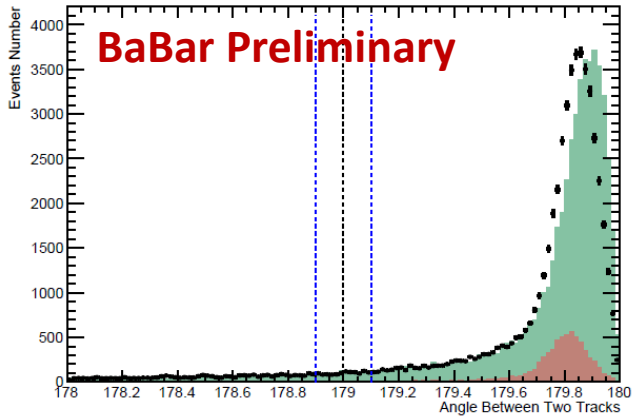
Non tau BGs Generic $\Upsilon(3S)$, $\mu^+\mu^-$, Bhabha, uds, $c\bar{c}$

Back up 6: Systematic Uncertainty in the “lepton mom plane” cut in the “back to back” cut









Signal MC	Data $\Upsilon(4S)On$	Background MC (μμ)
0.0065	0.0360	0.0217

Uncertainty between data and MC signal:
0.0360-0.0065= **0.029**
Uncertainty between data and MC (μμ):
0.0360-0.0217= 0.014 (for cross check)

Signal MC	Data $\Upsilon(4S)On$
0.002	0.013

Uncertainty between data and MC signal:
0.013-0.002 = **0.011**

Back Up:
Results: Branching Fraction and Upper limit

$$\mathbf{BF} = \frac{N_{\mathrm{Data}} - N_{BG}}{\varepsilon_{sig} \times N_{\Upsilon}} = (1.0 \pm 1.4_{STAT\,(N_{DATA})} \pm 0.8_{SYST}) \times 10^{-7}$$

Measurements $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$	**Upper Limit with Confidence Level of 90%**			
	Observed Upper limit		Expected Upper limit	
	Barlow Method [9]	CLs method [10]	Barlow Method	CLs method
3% Pre-blinded sample (0.93 fb^{-1})	$< 3.7 \times 10^{-6}$	$< 3.0 \times 10^{-6}$	$< 2.7 \times 10^{-7}$	$< 2.2 \times 10^{-6}$
Blinded Sample (27.0 fb^{-1})	$< 3.6 \times 10^{-7}$	$< 3.6 \times 10^{-7}$	$< 2.3 \times 10^{-7}$	$< 2.8 \times 10^{-7}$