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

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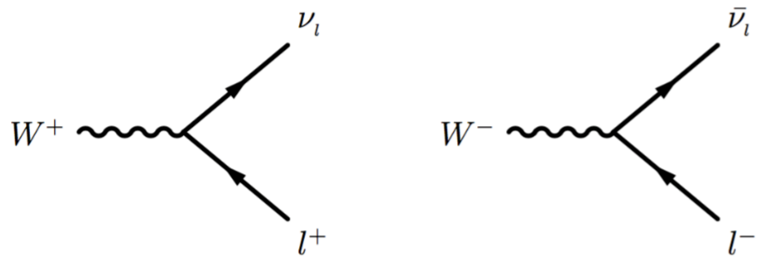
Outline of the Talk

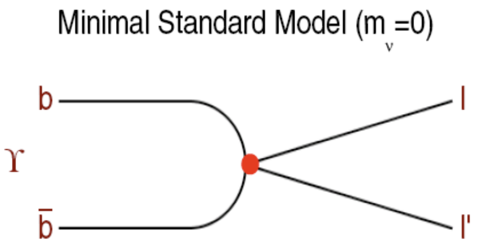
- Charged Lepton Flavour Violation
- Asymmetric PEP-II Collider and BaBar Detector
- Data and Experiment
- Analysis Strategy
- Results
- Conclusion

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**?

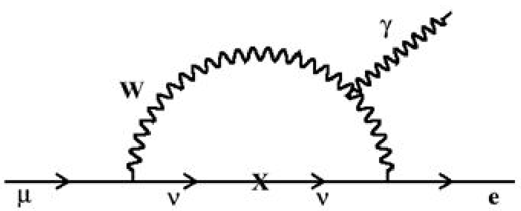


Lepton Flavour Conserving Process



Forbidden

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



How Much Violation?

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

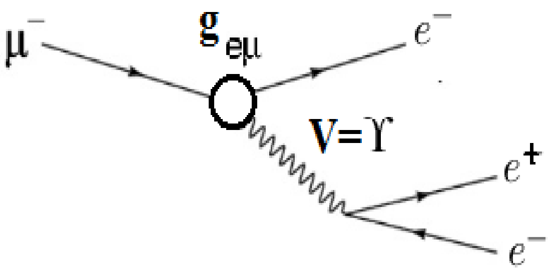
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left(\frac{3\alpha}{32\pi}\right) \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

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

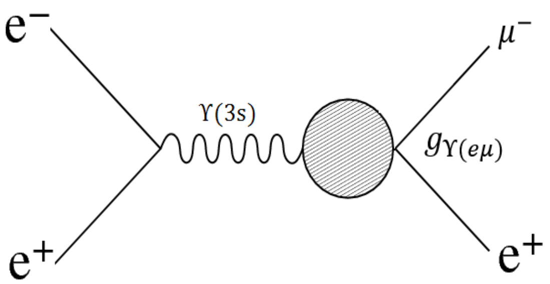
Experimentally not measurable!!

Indirect Limit on Upsilon Decays

- No direct observation, but $\mu \rightarrow eee$ observable (?)
- Calculated theoretical constraints on the limit (indirect):



Re-ordering of incoming/outgoing particles



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

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

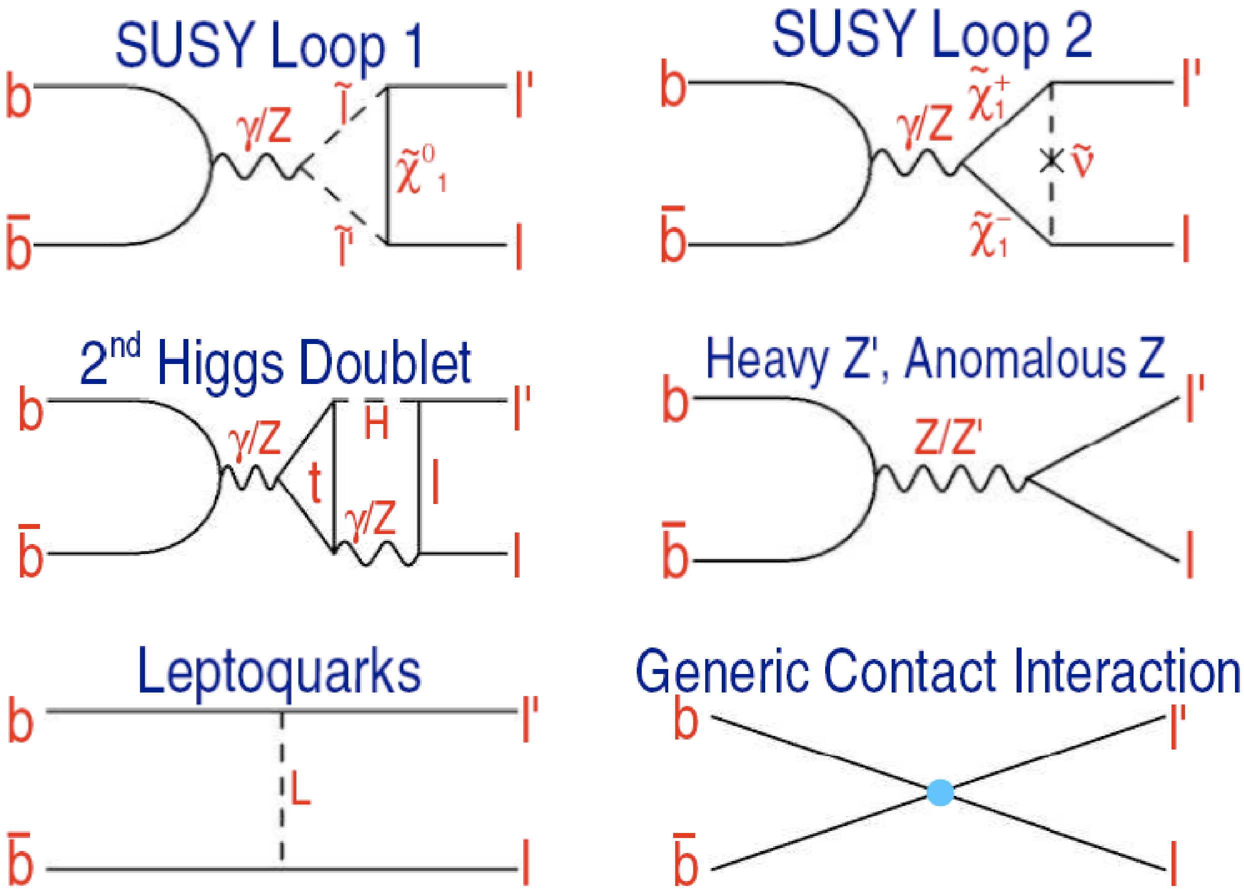
$BF(\mu \rightarrow eee) < 2\text{-}4 \times 10^{-8}$ — Bellgardt, et al., Nucl.Phys. B299 (1988)

$BF(\Upsilon \rightarrow ee) < 3\text{-}6 \times 10^{-3}$ — Belle PLB 660,154 (2008)

$BF(\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}) < \mathbf{2.5 \times 10^{-8}}$ — Calculated according to Nussinov

New Physics

- Lepton flavour violating decays are predicted by many beyond SM processes
- Clear experimental signature = "New Physics"



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Existing Experimental Searches

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

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]

LEPTON FAMILY NUMBER (*LF*) VIOLATING MODES

$\Gamma(e^{\pm}\tau^{\mp})/\Gamma_{total}$ — **Γ_{31}/Γ**

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<4.2	90	LEES	10B	BABR	$e^+e^- \rightarrow e^{\pm}\tau^{\mp}$

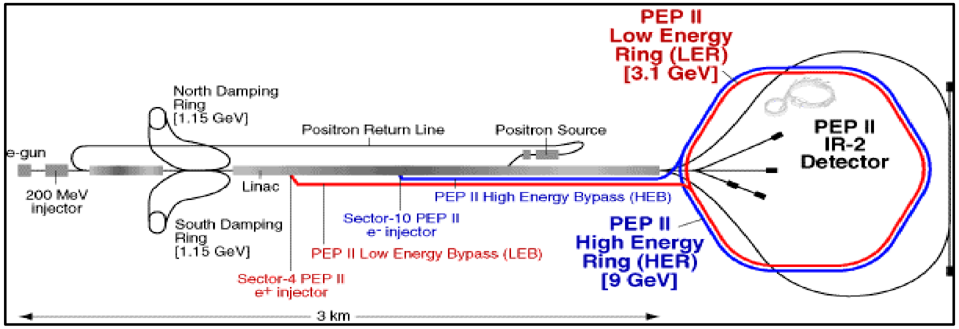
$\Gamma(\mu^{\pm}\tau^{\mp})/\Gamma_{total}$ — **Γ_{32}/Γ**

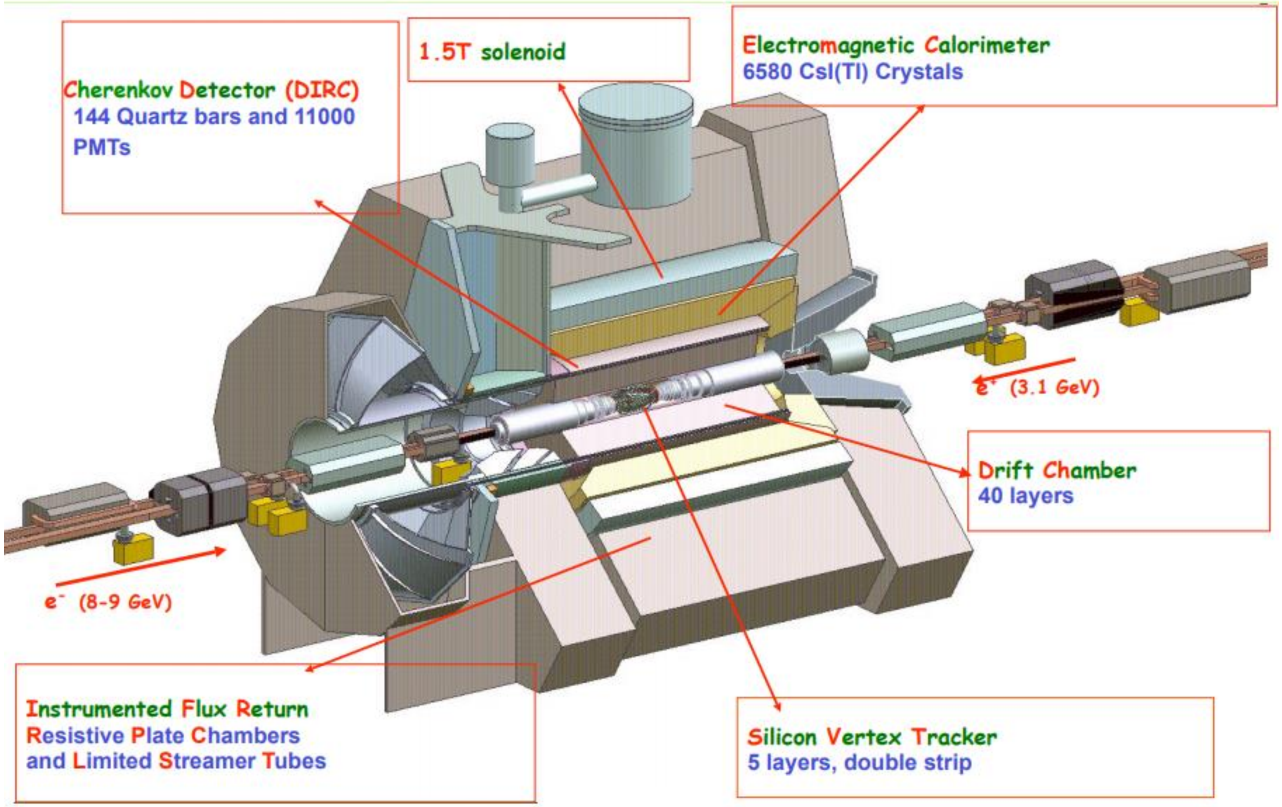
VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3.1	90	LEES	10B	BABR	$e^+e^- \rightarrow \mu^{\pm}\tau^{\mp}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<20.3	95	LOVE	08A	CLEO	$e^+e^- \rightarrow \mu^{\pm}\tau^{\mp}$

Branching Fraction

$$\Gamma(e^{\pm}\mu^{\pm})/\Gamma_{total}$$

Asymmetric PEP-II Collider & BaBar Detector





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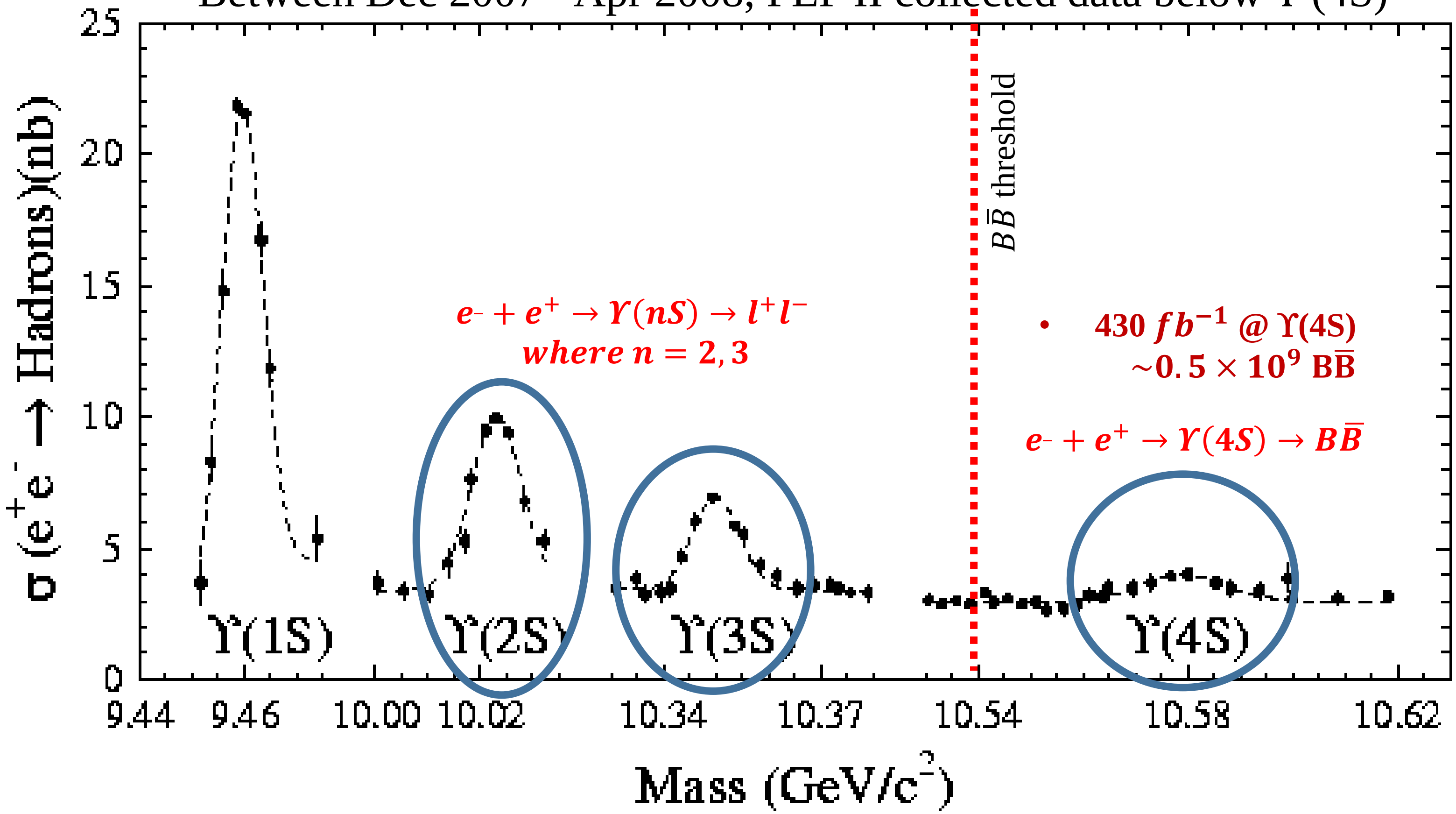
How small a rate can BaBar measure?

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



- **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 Ref: **CUSB detector, CLEO Collaboration**

Data, MC Sample and Blind Analysis Technique

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 (for Background)	**Luminosity (fb^{-1})**	**Generators**
$e^+e^- \to \mu^+\mu^-$	68.55	KK2F
$e^+e^- \to e^+e^-$	3.26	BHWIDE
$e^+e^- \to \tau^+\tau^-$	62.37	KK2F
$e^+e^- \to uds$	19.15	EvtGen
$e^+e^- \to c\bar{c}$	41.23	EvtGen
Generic $\Upsilon(3S)$ MC	61.44	EvtGen

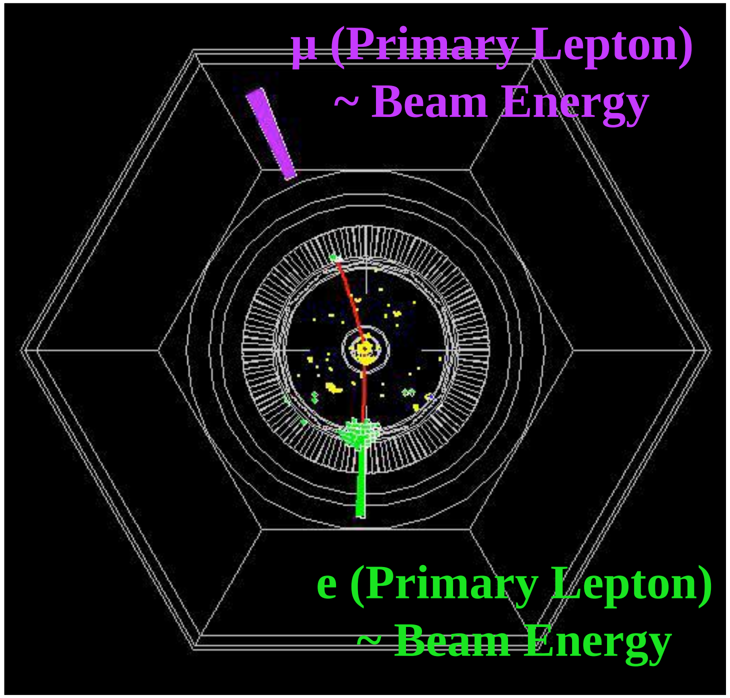
MC signal: $e^+e^- \to \Upsilon(3S) \to e^\pm\mu^\mp$: 103000 events

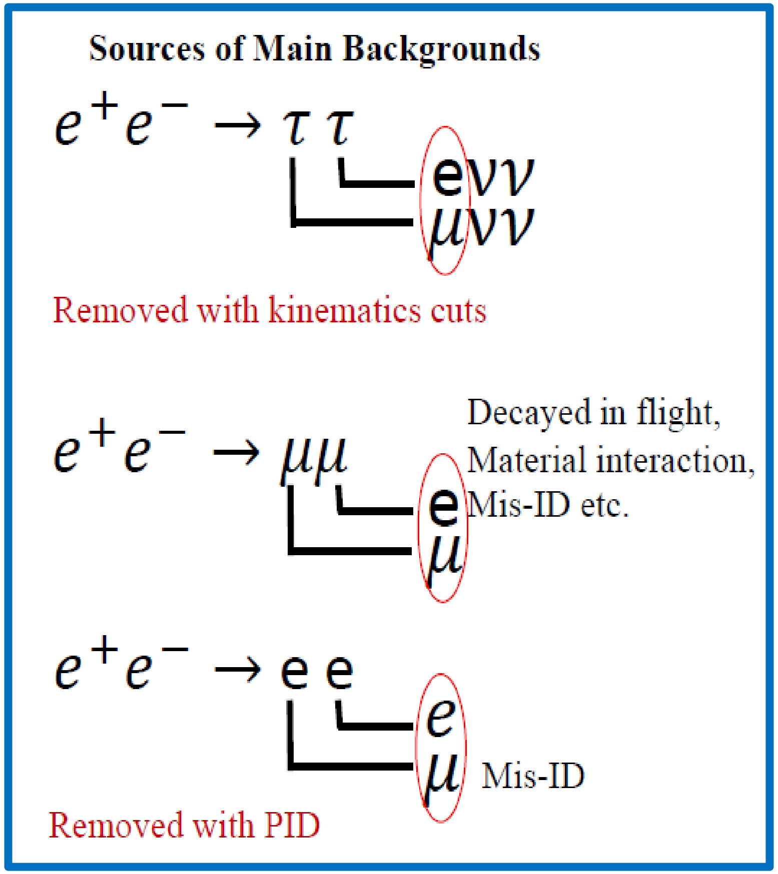
- Blind analysis was performed to eliminate experimenter's bias.
- All selection criteria and uncertainty studies performed without looking at the result of data sample.
- Results were unblinded by the approval of Review Committee and presented to American Physical Society Conference at FermiLab on Aug 3, 2017.

Control Data Sample

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** Systematics
$Data\ \Upsilon(4S) On\ Resonance\ ,\ \sqrt{s} =$ 10.58 GeV Preselected as $\mu^{\pm}\mu^{\mp}$ events	78.31 ± 0.35	Systematics
$Data\ \Upsilon(4S)$Off Resonace	7.75 ± 0.04	BG Control Sample
$Data\ \Upsilon(3S)$On Resonace, $\sqrt{s} = 10.36$ GeV Preselected as $\mu^{\pm}\mu^{\mp}$ events	27.96 ± 0.16	Systematics
$Data\ \Upsilon(3S)$Off Resonace	2.62 ± 0.02	BG Control Sample

Signal and Background Characteristics





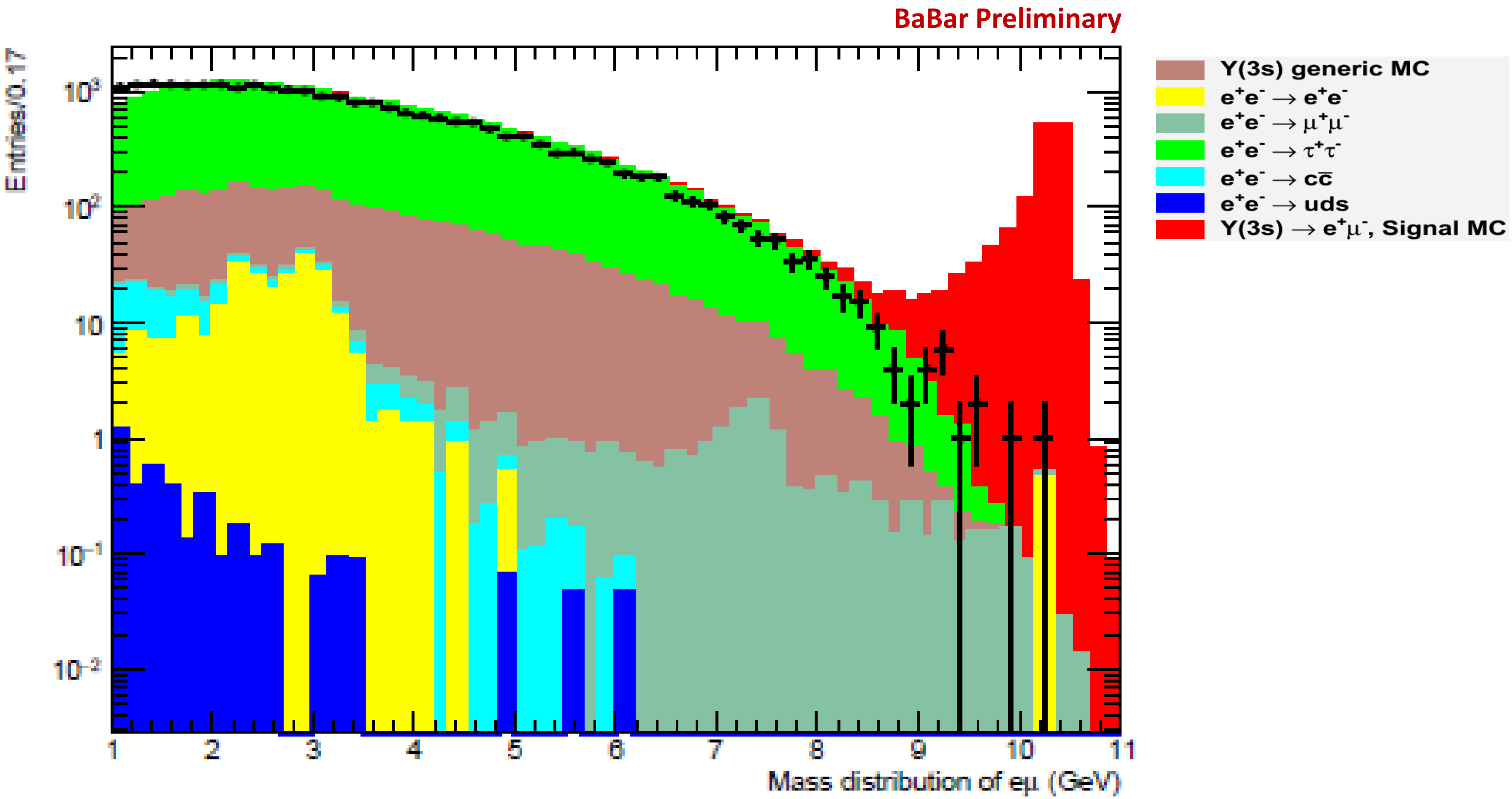
- $\boldsymbol{\Upsilon(3S) \to e^{\pm}\mu^{\mp}}$: Required two primary track signal of $\boldsymbol{e^{\pm}}$ ***and*** $\boldsymbol{\mu^{\mp}}$.
- CM Momentum: $\boldsymbol{P_{e^{\pm}} \sim \frac{\sqrt{s}}{2}}$ and $\boldsymbol{P_{\mu^{\pm}} \sim \frac{\sqrt{s}}{2}}$

Analysis Strategy

- **Pre-Selection:** Needs a special A background filter to collect $e^{\pm}\mu^{\mp}$ events efficiently.
- **User defined Selection:** Applied on the pre-selected events
- **PID Selection:** Multivariate Technique applied, 16 different PID selector used in optimization ($^{s}/_{\sqrt{BG}}$)

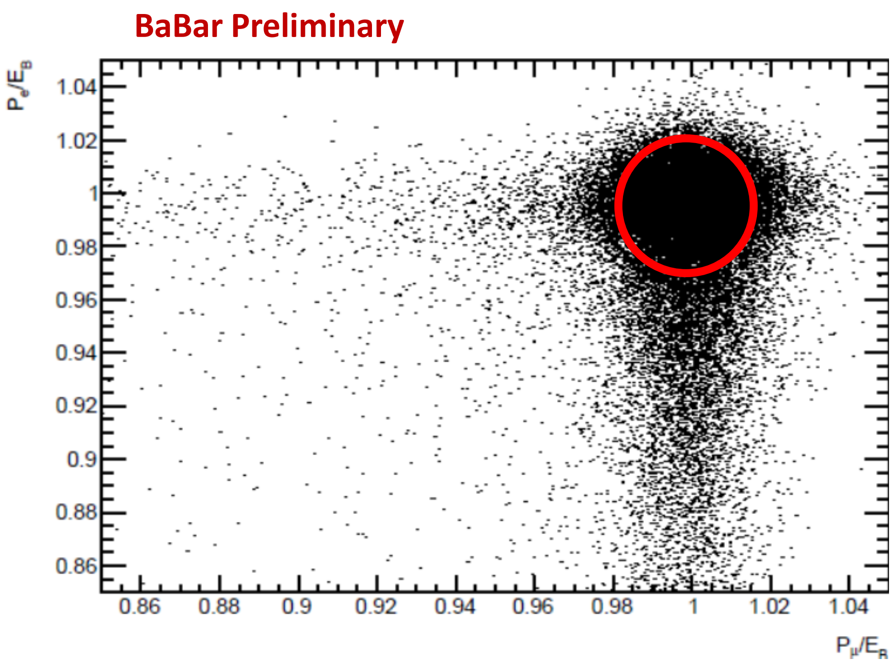
Pre-Selection:	**User defined Selection:**
Distance of closest approach of any track vertex w.r.t. the beam spot in Drift Chamber • in the x - y plane < 1 cm and in the z plane < 4 cm;	2 tracks (1 electron and 1 muon in the final state), one in each hemisphere;
Number of hits in the Drift Chamber > 0. Transverse Momentum p_T > 100 MeV;	$24° < \theta_{Lab} < 130°$ EMC acceptance for both tracks.
Exactly 2 oppositely charged tracks ; Polar angle of the two tracks: 2.8 < $(\theta_1 + \theta_2)$ < 3.5; Sum of momentum of the two tracks $\|P_1\| + \|P_2\|$ > 9 GeV	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 $E_{Beam} = {}^{\sqrt{s}}/_{2}$
One and only one electron of the two tracks uses E/P > 0.8	Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179°$ to ensure they 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

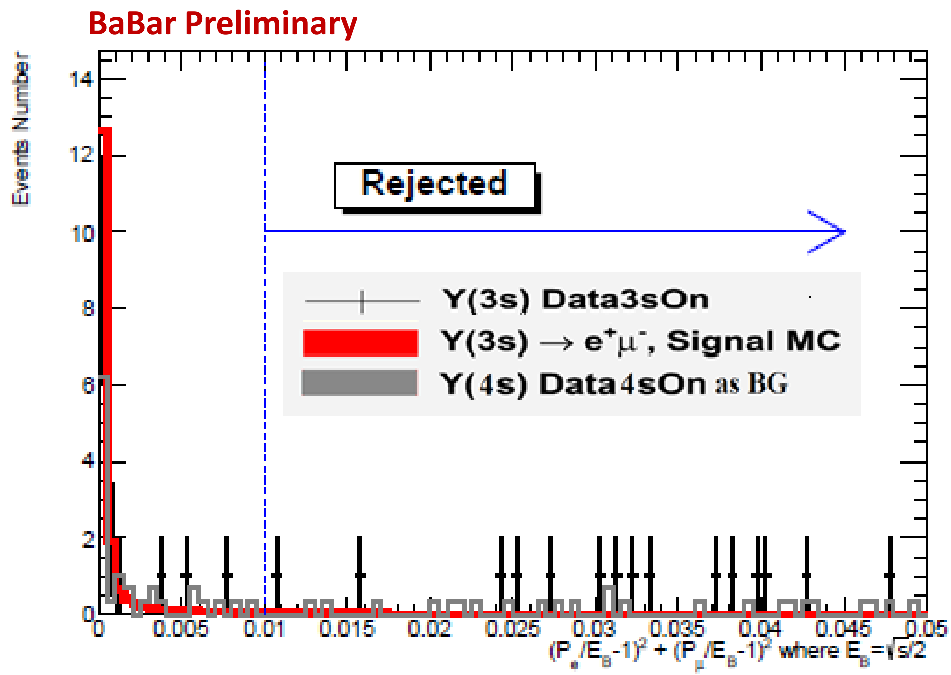


Distribution of $e^{\pm}\mu^{\mp}$ mass before applying any user defined selection criteria, only preselection criteria has been applied on the 3% pre-unblinded data.

Selection Criteria in (N-1) plots



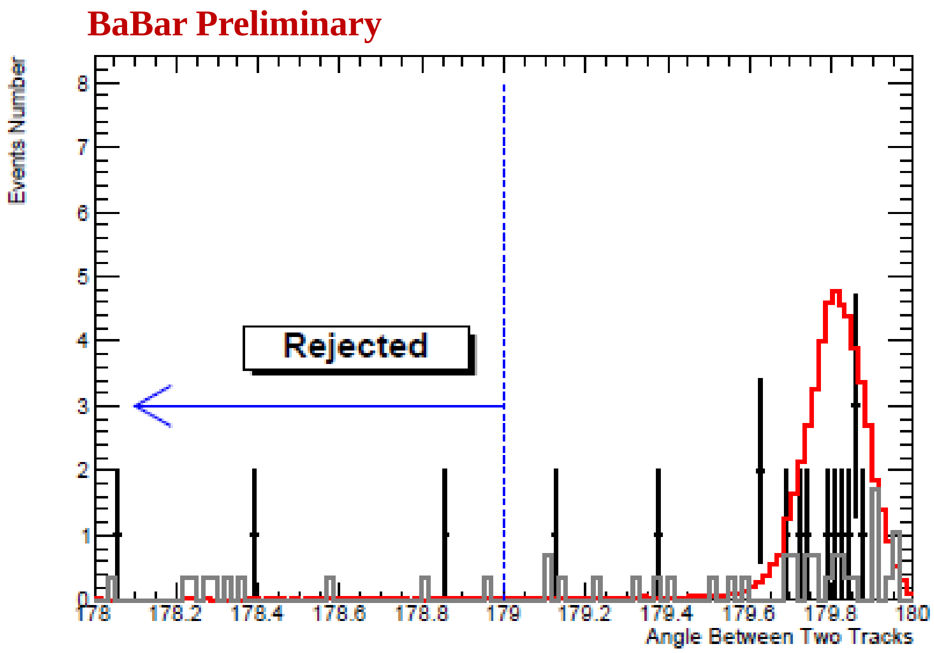
A circle formed on the lepton momentum plane in Signal Monte Carlo



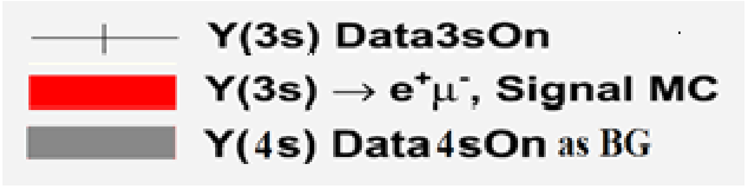
Radius of the Circle in Data sample With Data driven background $\Upsilon(4S)On$

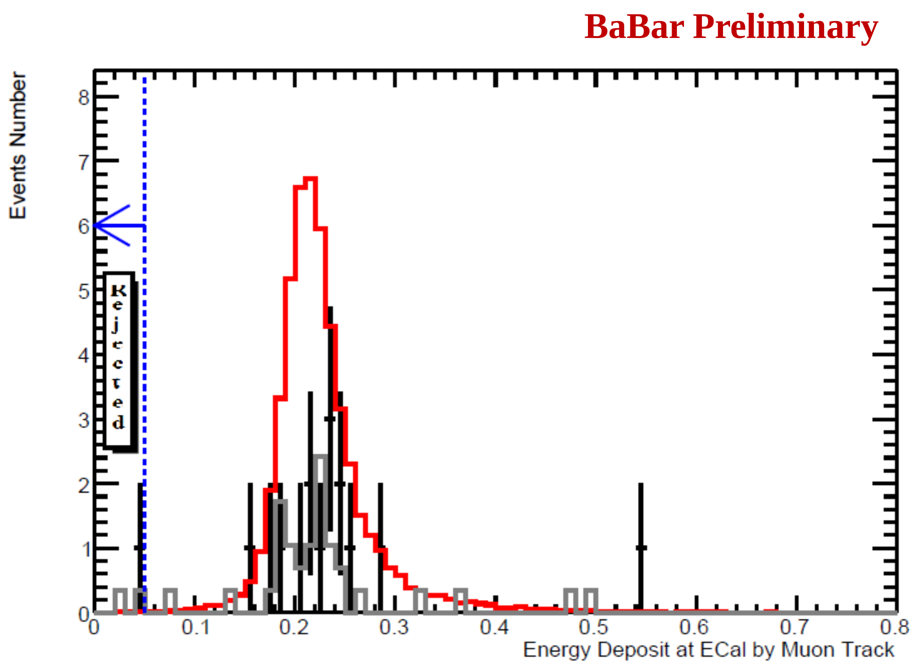
The lepton momenta must satisfy the following condition which is defining a circle of radius $\left(\frac{p_e}{E_{Beam}} - 1\right)^2 + \left(\frac{p_\mu}{E_{Beam}} - 1\right)^2 < 0.01$ where $E_{Beam} = \sqrt{s}/2$

Selection Criteria in (N-1) plots



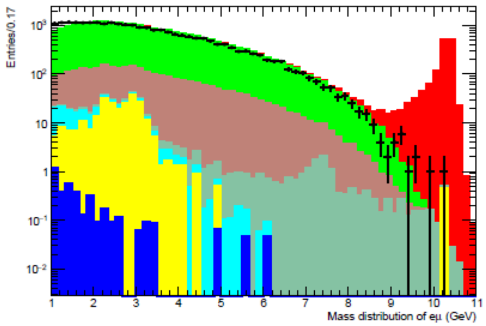
The angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179^{\circ}$ to emerge as back to back.

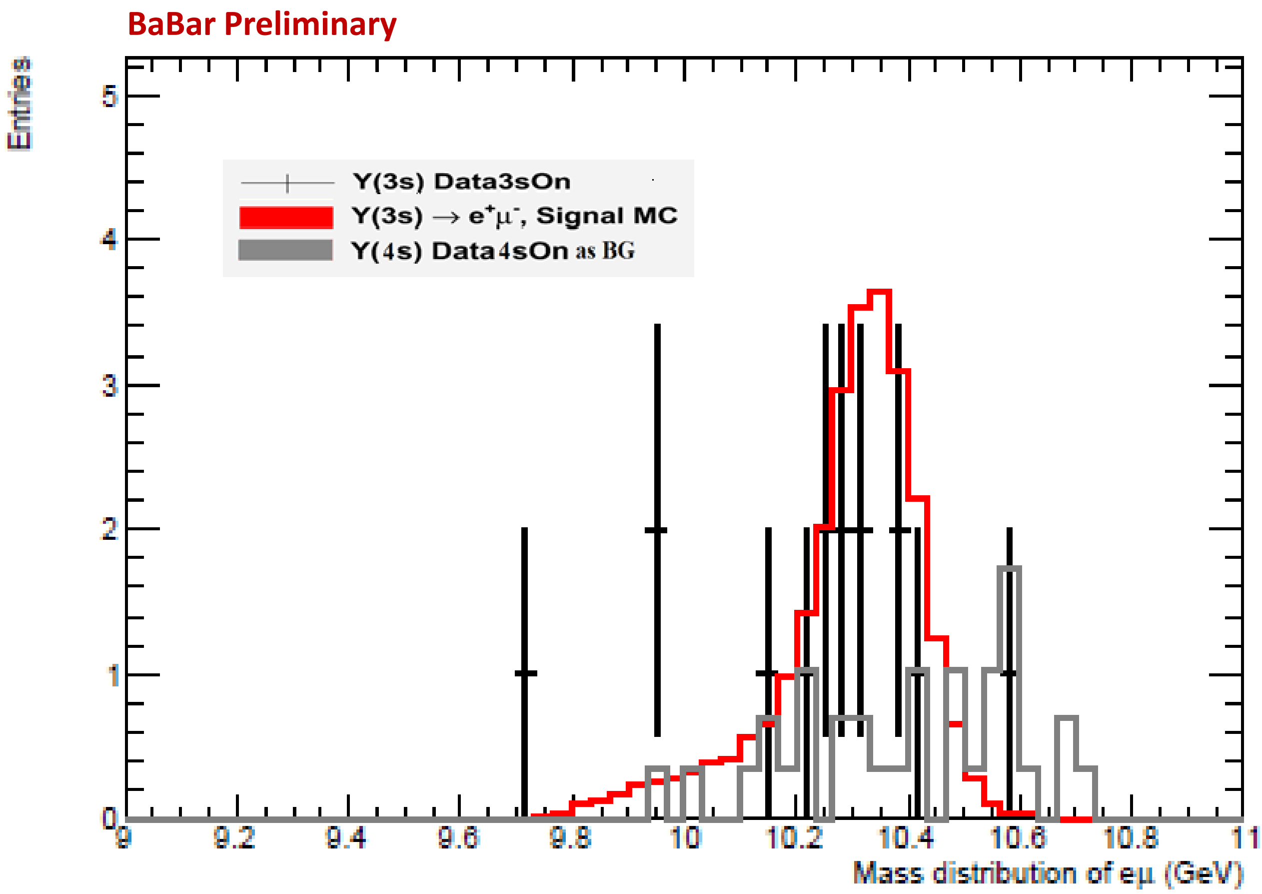




Energy deposit by Muon track on the EMC should be greater than 50 MeV.

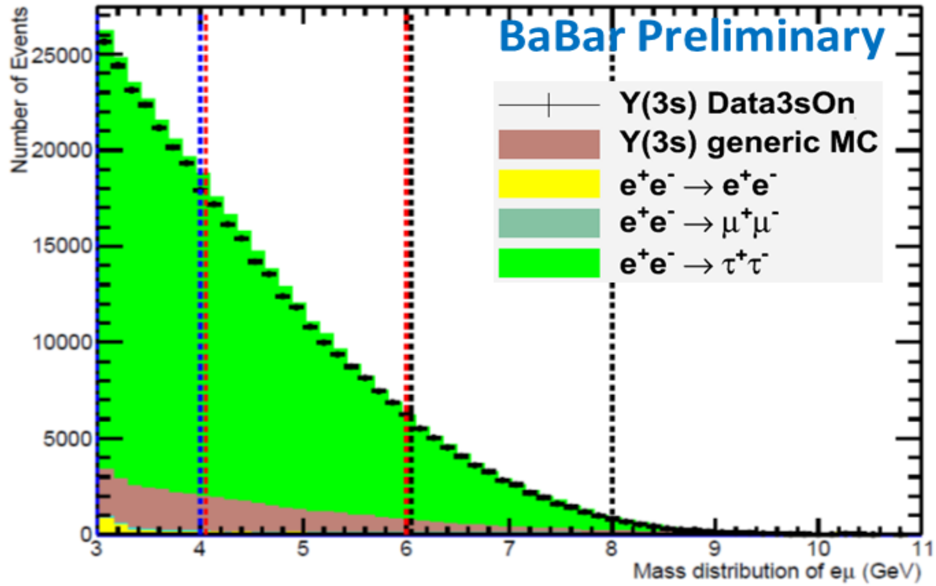
Mass Distribution





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

Systematic Uncertainty on Signal Efficiency



Side Bands

- 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.
- Uncertainty in "Side Bands": 1.2%

Summary: Background, Uncertainty, Candidate

BaBar Preliminary

Source	Data Driven Continuum Background (events seen 34)	Peaking Background from Generic $\Upsilon(3S)$ MC (events seen 4)
Tight PID selection	12.2 ± 2.1	0
Loosen PID selection	N/A	1.80 ± 0.9

BaBar Preliminary

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**

Results

[BaBar Preliminary]

$$\textbf{Data Sample}\ (27.0\ fb^{-1})$$

Branching Fraction:

$$\frac{N_{\text{Candidate}} - N_{BG}}{\varepsilon_{sig} \times N_{\Upsilon}} \qquad (1.0 \pm 1.4_{stat(N_{Candidate})} \pm 0.8_{syst}) \times 10^{-7}$$

Upper Limits with Confidence Level of 90%:

$< 3.6 \times 10^{-7}$ **Barlow Method**

$< 3.6 \times 10^{-7}$ **CLs Method**

Barlow Method: [R. Barlow, ScienceDirect 149, 2 (2002), pp 97-102.]
CLs Method: [A. L. Read, J. Phys. G28 (2002) 2693- 278 2704**]**

Conclusion

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

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

- Our reported result is several orders of magnitude stronger that this limit according to the ref [S.Nussinov, et. al. PRD 63, 016003 (2001), Gutsche et. al. PRD 83, 115015 (2011)] in case LFV vertex involves to some kinematical suppression such as anomalous magnetic moment coupling which can yield a limit ~ up to $< 5 \times 10^{-4}$.

- Searches for LFV and rare ϒ decays can be improved with Super B-Factory as BELLE II and other future high luminosity experiments.

- Thanks to my BaBar Colleagues for providing all kinds of support for this analysis.

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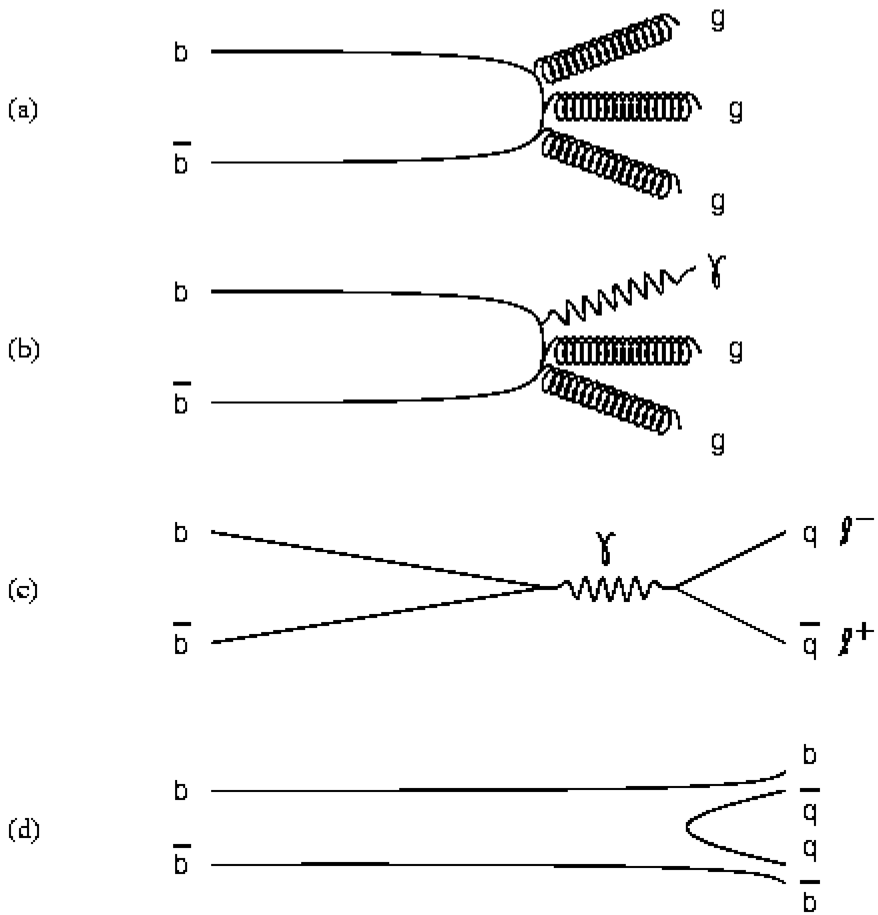
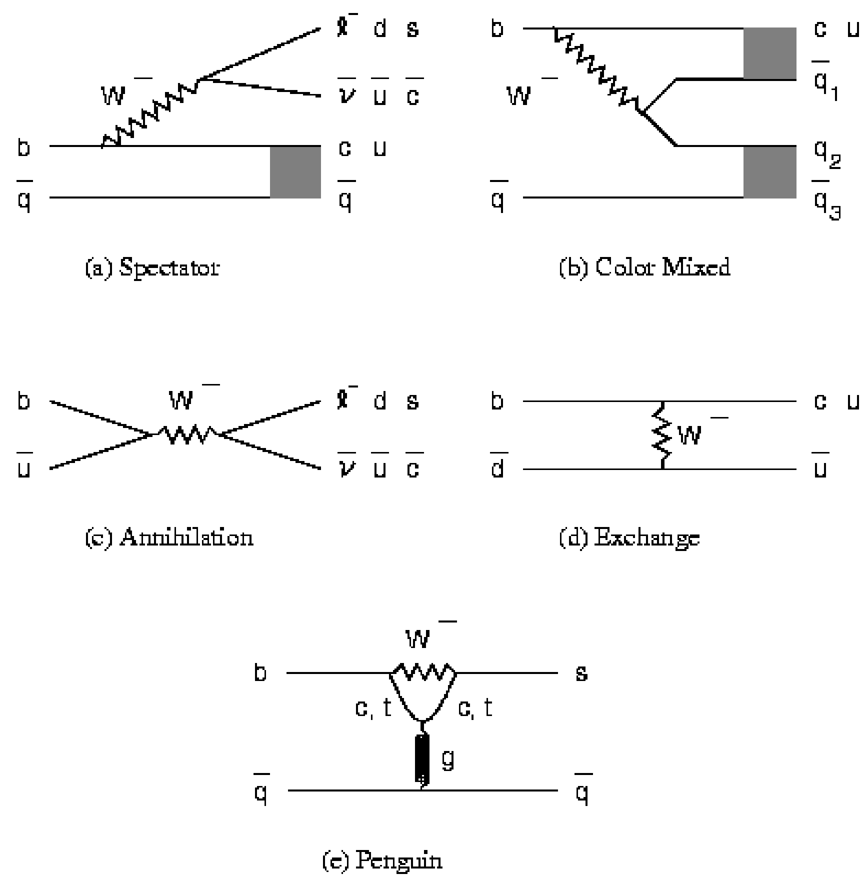
Backup: Upsilon System

At the first three resonances, the Upsilon system can only decay by the *b* quark and anti *b* quark annihilating, as shown in the decay diagrams (a)-(c):



At the fourth resonance, called the Upsilon(4S), there is enough energy in the excited stated to create a light quark/anti-quark pair, producing a pair of B mesons, as shown in diagram (d) above. Once produced, B mesons can decay via any one of the processes illustrated here



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

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

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

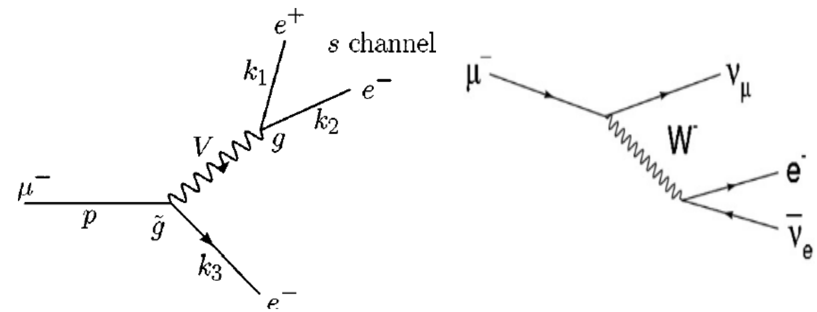
Since $[\Gamma(\mathrm{V} \rightarrow \mathrm{e}^+\mathrm{e}^-)] \sim \mathrm{g}^2\ \mathrm{V}_{ee}\ \mathrm{M}_V$ and

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

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

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

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



(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.

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

Back Up: Signal Efficiency and Selection Summary

BaBar Preliminary

Pre-selected Events	**MC Signal: 82612**	***BG*** **$\Upsilon(3S)$ MC 7134301**	***BG*** **$\Upsilon(4S)$ MC 152445188**	**Candidate $\Upsilon(3S)$ 254122200**
(N-1) Selection	**Signal Efficiency ($\varepsilon_{e\mu}$)**	***BG Events*** **$\Upsilon(3S)$ MC**	**Data Driven Continuum BG $\Upsilon(4S)On$**	**Candidate seen in Data**
PID selection	0.2355 ± 0.0013	0	14.7 ± 2.3	18
Lepton Momentum	0.2684 ± 0.0012	82.67 ± 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**	**0**	**12.2 ± 2.1**	**15**

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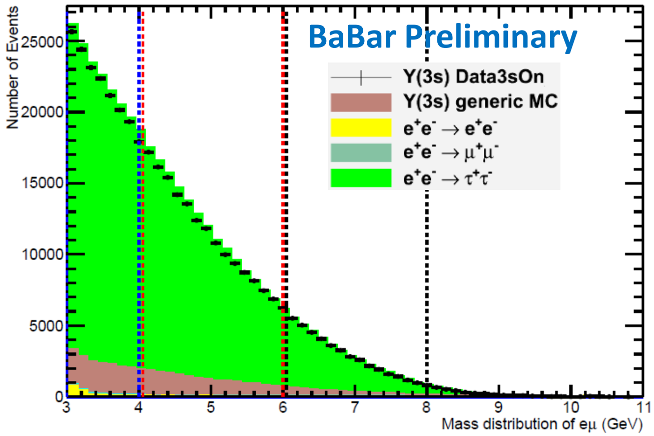
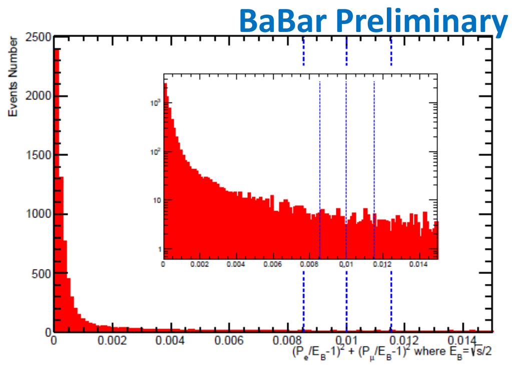
Backup: Systematic Uncertainty in the Sidebands

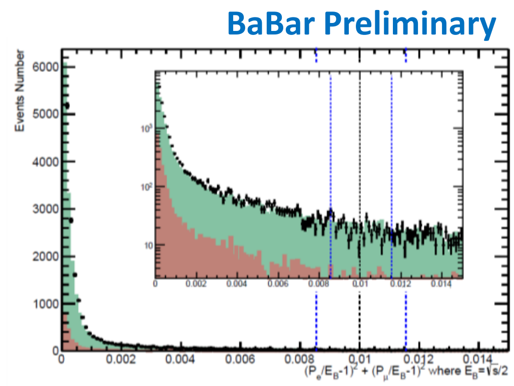


Mass distributions for ϒ(3S)On data and MC control samples (τ-pair) N_{BG}: $\Upsilon(3S)$, $\mu^+\mu^-$, Bhabha, uds, $c\bar{c}$

	Blue Side band (3-4) GeV	Red Side band (4-6) GeV	Black Side band (6-8) GeV
R± σ_R	0.9825 ± 0.0029	0.9795 ± 0.0032	1.0072 ± **0.010**

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



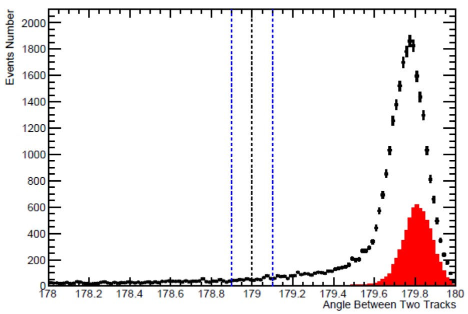


	Signal MC	Data $\Upsilon(4S)On$	Background MC (μμ)
$\frac{\varepsilon^{0.0115-0.010}_{0.010-0.0085}}{\varepsilon_{e\mu}}$	$\frac{0.001526}{0.234243} = 0.0065$	$\frac{0.0000010}{0.000028} = 0.0360$	$\frac{0.00001}{0.00046} = 0.0217$

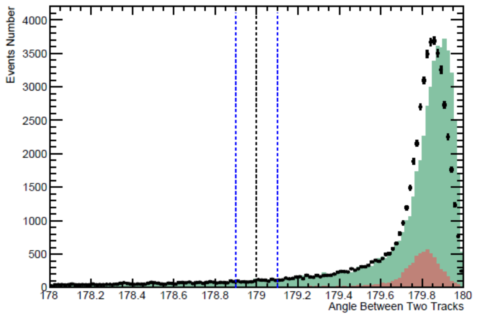
- Uncertainty between data and MC signal: 0.0360-0.0065= **0.029**
- Uncertainty between data and MC (μμ): 0.0360-0.0217= 0.014 (for cross check)

Back up: Systematic Uncertainty in "back to back" cut

BaBar Preliminary



BaBar Preliminary



	Signal MC	Data $\Upsilon(4S)On$
$\frac{\varepsilon_{179^0-178.9^0}^{179.1^0-179^0}}{\varepsilon_{e\mu}}$	$\frac{0.000538}{0.234243} = 0.002$	$\frac{0.00000035}{0.000028} = 0.013$

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