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Search for Lepton Flavor Violation in $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$ at BABAR

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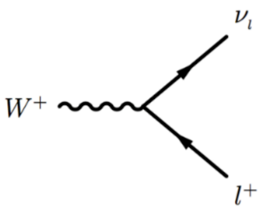
Outline of the Talk

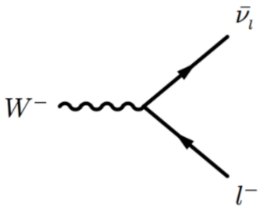
- Charged Lepton Flavor Violation
- Theoretical Expectations and Experimental Limit
- Asymmetric PEP-II Collider and BaBar Detector
- Data, MC and Data Driven Background
- Analysis Strategy
    - ➢ Signal and Background Characteristic
    - ➢ A Selection Criterion
    - ➢ Validation of Using the Data Driven Background
- Results and Indication for New Physics
- Conclusion

Charged Lepton Flavour Violation

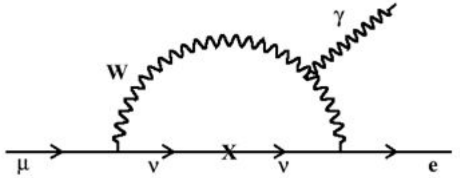
- Charged Lepton Flavour Violation is a transition among e, μ, τ that doesn't conserve lepton family number.
- In Standard Model, Lepton Flavour is conserved for zero degenerate **ν** masses and now we have clear indication that $\boldsymbol{\nu}$'s have finite mass.

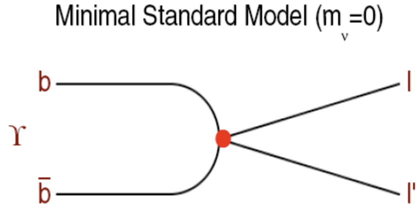
- Example of **lepton flavour conservation** is a muon decay: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$





- 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

$$l_\alpha \rightarrow l_\beta \approx \boldsymbol{O}\left(\mathbf{10^{-54}}\right)$$

- 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"**

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

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

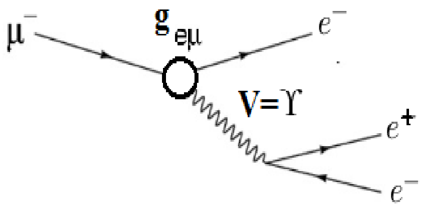
with $\Delta \sim 10^{-3} eV^2, M_W \sim O(10^{11}) eV \approx \boldsymbol{O}\left(\mathbf{10^{-54}}\right)$

Experimentally not measurable!!

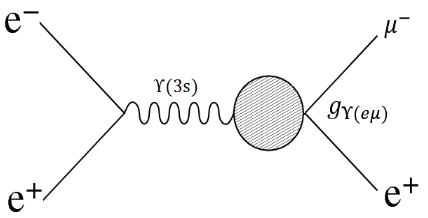
Theoretical Expectations and Experimental Limit

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

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



Re-ordering of incoming/outgoing particles



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

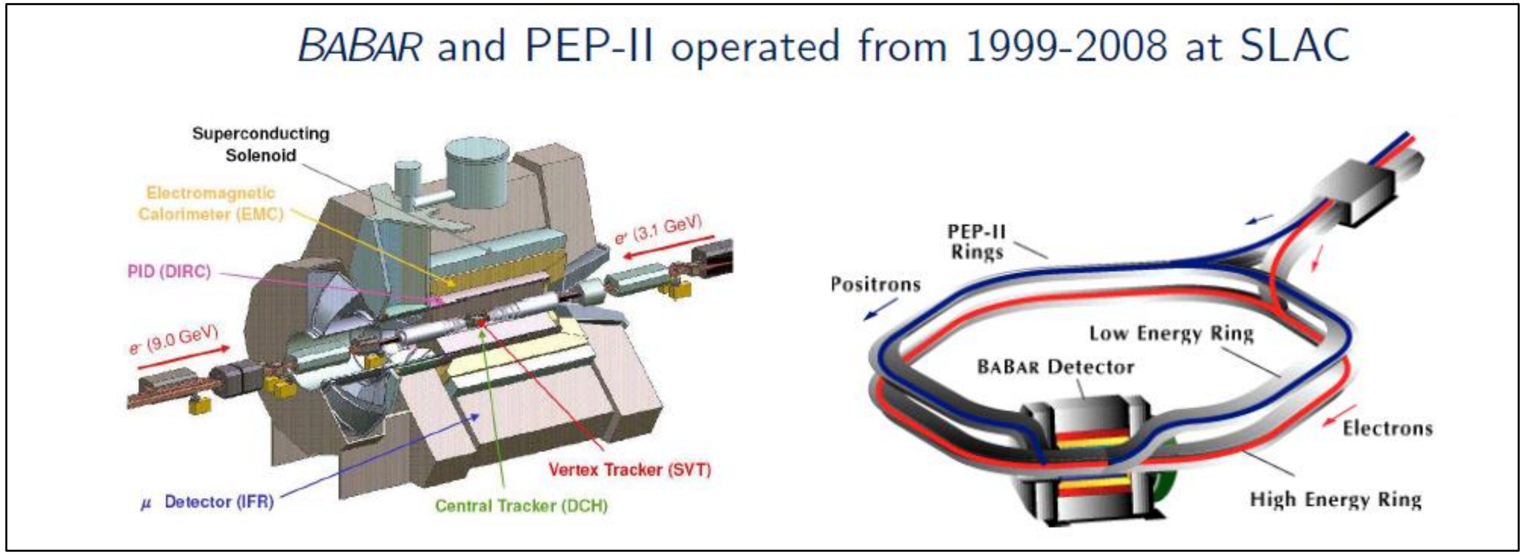
$\mathrm{BF}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ [2]

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

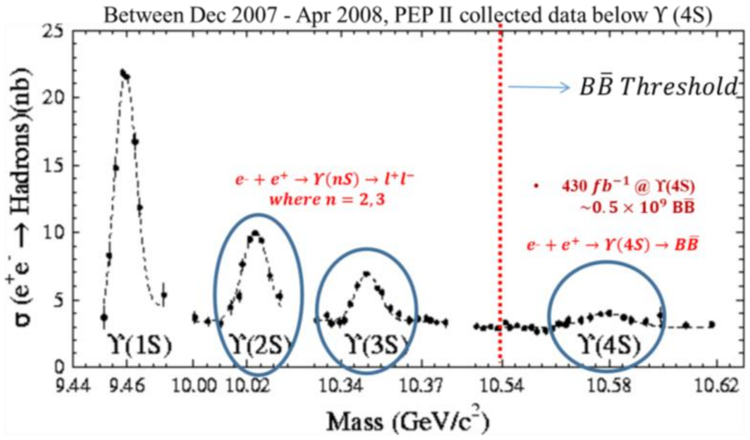
[1] S.Nussinov, et. al. PRD 63 (2001)
[2] Bellgardt, et al., Nucl.Phys. B299 (1988)
[3] P.A. Zyla et al. (Particle Data Group)

Existing Measurements	Results	CL (%)	Collaboration
$\mathrm{BF}(\Upsilon(3S) \rightarrow e^{\pm}\tau^{\mp})$	$< 4.2 \times 10^{-6}$	90	J.P. Lees et al. PR D89 111102 [BaBar Collaboration]
$\mathrm{BF}(\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp})$	$< 3.1 \times 10^{-6}$	90	
$\mathrm{BF}(\Upsilon(3S) \rightarrow \mu^{\pm}\tau^{\mp})$	$< 20.3 \times 10^{-6}$	95	Love et al. PRL 101, 201601 [CLEO Collaboration]
$\mathrm{BF}(\Upsilon(3S) \rightarrow e^{\mp}\mu^{\pm})$	**Reported**		J. P. Lees et al. PR 128, 091804 (2022) [BaBar Collaboration] **Published March 3, 2022.**

Data, MC Sample


BABAR and PEP-II operated from 1999-2008 at SLAC

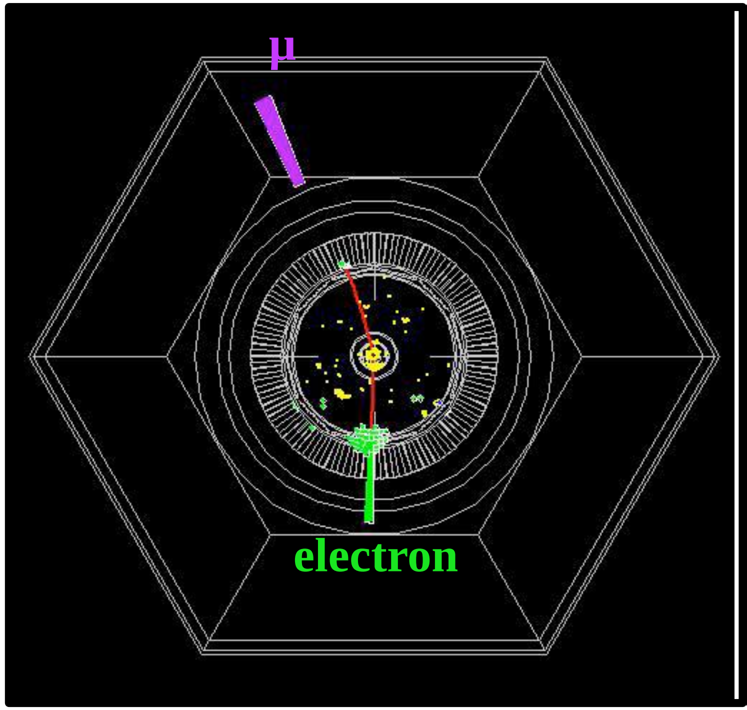
Data Sample	On resonance (fb^{-1})	Off resonance (fb^{-1})
Run 7 $\Upsilon(3S)$ **(Data)**	27.9 = 27.0 + (0.9 **Blinded Analysis**)	2.62 To validate the systematic study
Run 6 $\Upsilon(4S)$ **Data driven continuum background**	78.31 **Systematic study** pre-selected as $e^{\pm}\mu^{\mp}$and $\mu^{\pm}\mu^{\mp}$	7.75 To validate the systematic study
MC signal: $e^+e^- \to \Upsilon(3S) \to e^{\pm}\mu^{\mp}$: 103000 events		



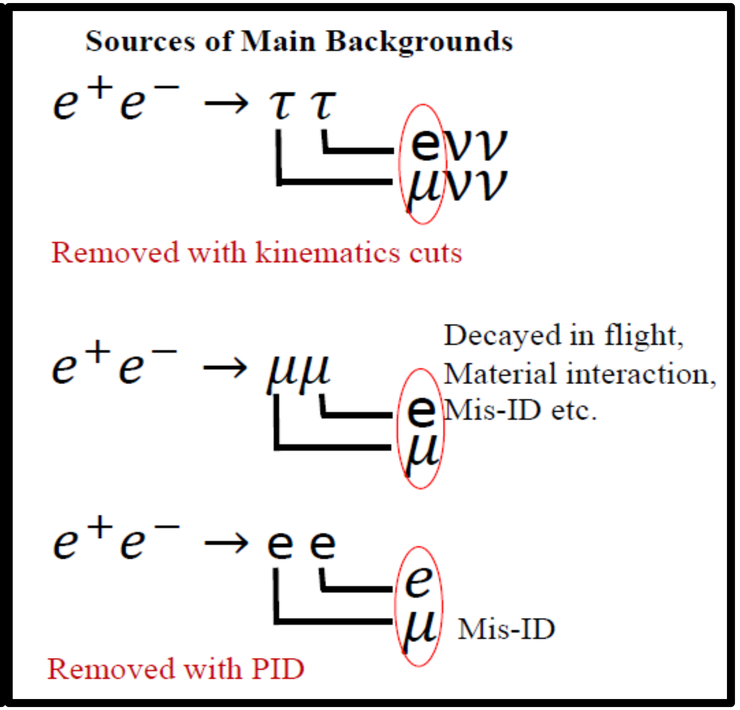
Upsilon System: **CUSB detector, CLEO Collaboration**
T. Bohringer et al., Phys. Rev. Lett. 44, 1111 (1980) and P. Finocchiaro et al., Phys. Rev. Lett. 45, 222 (1980)

Signal and Background Characteristics

- Optimized PID selection for $\boldsymbol{e^{\pm}}$ $\boldsymbol{\mu^{\mp}}$ track
- $\boldsymbol{\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}}$: Required two primary track signal of $\boldsymbol{e^{\pm}}$ $\boldsymbol{and}$ $\boldsymbol{\mu^{\mp}}$
- CM Momentum: $\boldsymbol{p_{e^{\pm}}} \sim \frac{\sqrt{s}}{2} \sim \boldsymbol{E_B}$ and $\boldsymbol{p_{\mu^{\pm}}} \sim \frac{\sqrt{s}}{2} \sim \boldsymbol{E_B}$ 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 (EMC) > 50 MeV
- EMC acceptance $24° < \theta_{Lab} < 130^{\circ}$ etc.



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



Sources of Main Backgrounds

$e^{+}e^{-} \rightarrow \tau\,\tau$ — $e\nu\nu$, $\mu\nu\nu$

Removed with kinematics cuts

$e^{+}e^{-} \rightarrow \mu\mu$ — e, μ

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

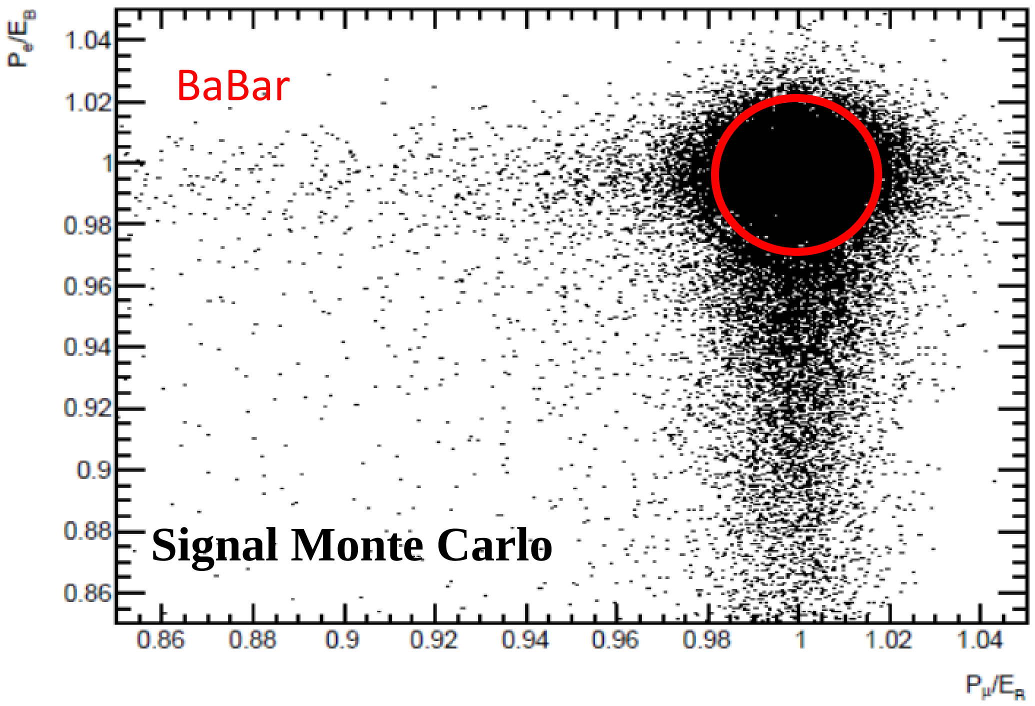
$e^{+}e^{-} \rightarrow$ e e — e, μ

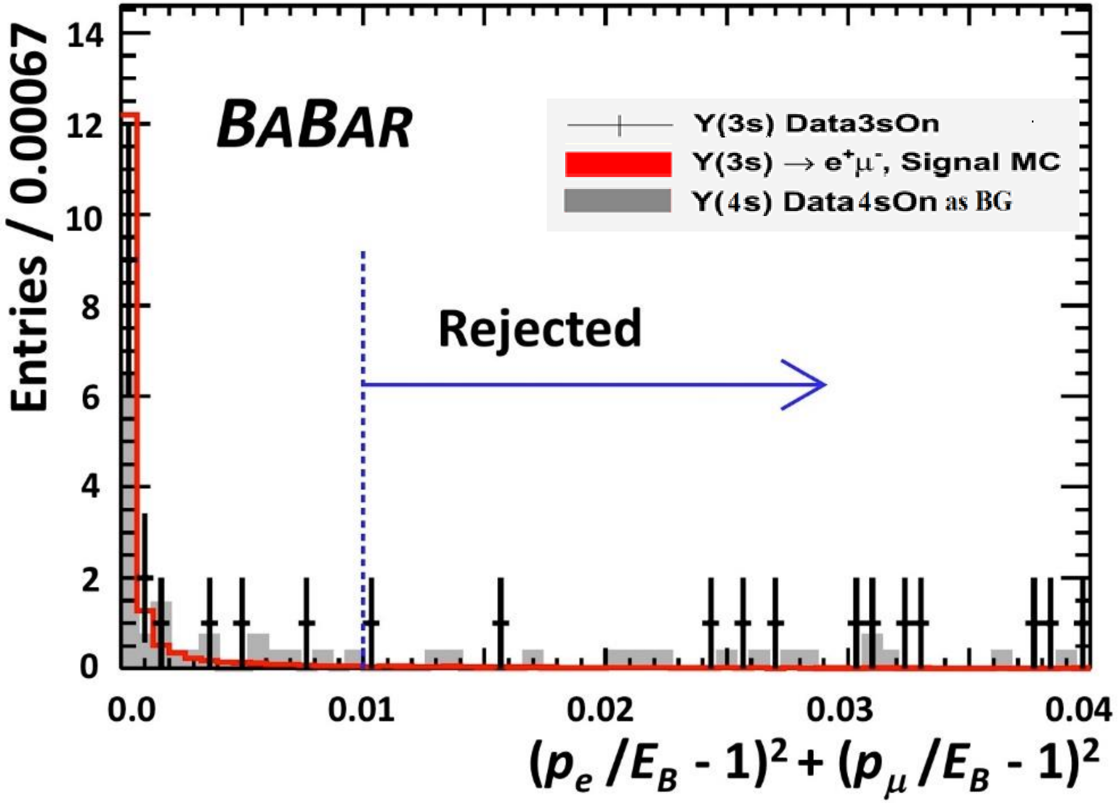
Mis-ID

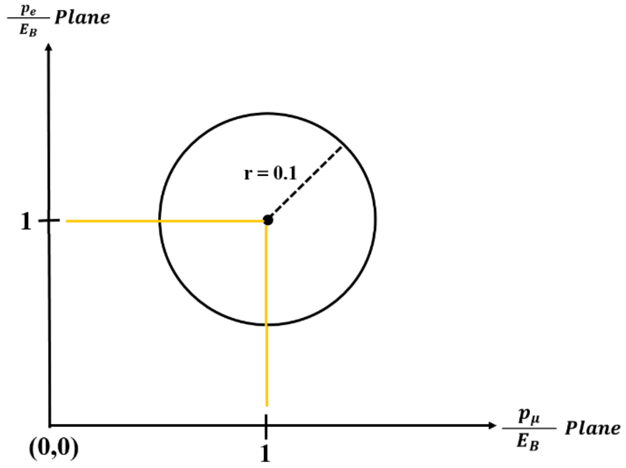
Removed with PID

Different Sources of Background

Final Selection Criterion



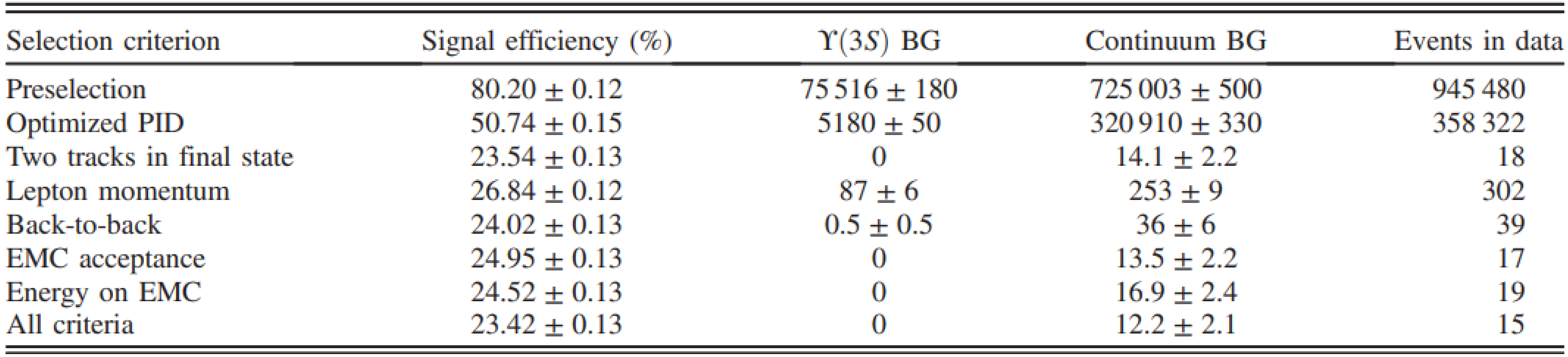




Selection Criteria: The lepton momenta must satisfy the condition which is defining a circle of radius $\left(\frac{p_e}{E_B} - 1\right)^2 + \left(\frac{p_\mu}{E_B} - 1\right)^2 = (0.1)^2 = 0.01$

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

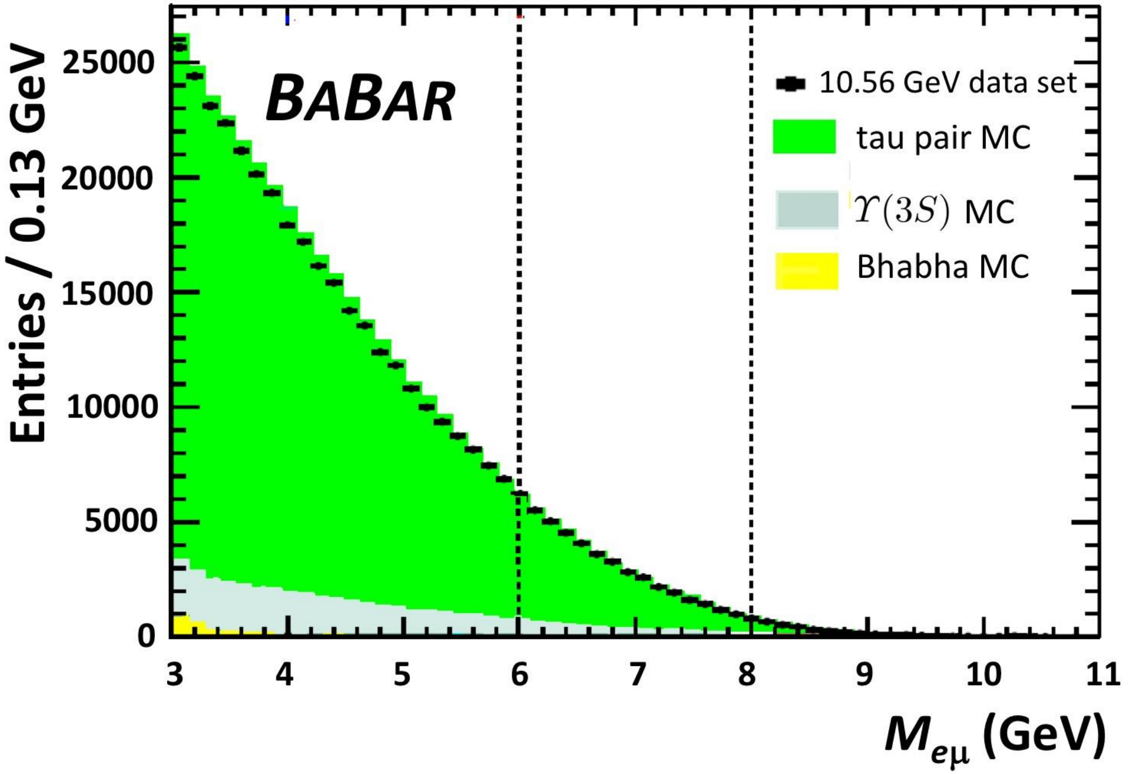
Impact of each component of the selection on the signal efficiency, background and data



Selection criterion	Signal efficiency (%)	$\Upsilon(3S)$ BG	Continuum BG	Events in data
Preselection	80.20 ± 0.12	$75\,516 \pm 180$	$725\,003 \pm 500$	945 480
Optimized PID	50.74 ± 0.15	5180 ± 50	$320\,910 \pm 330$	358 322
Two tracks in final state	23.54 ± 0.13	0	14.1 ± 2.2	18
Lepton momentum	26.84 ± 0.12	87 ± 6	253 ± 9	302
Back-to-back	24.02 ± 0.13	0.5 ± 0.5	36 ± 6	39
EMC acceptance	24.95 ± 0.13	0	13.5 ± 2.2	17
Energy on EMC	24.52 ± 0.13	0	16.9 ± 2.4	19
All criteria	23.42 ± 0.13	0	12.2 ± 2.1	15

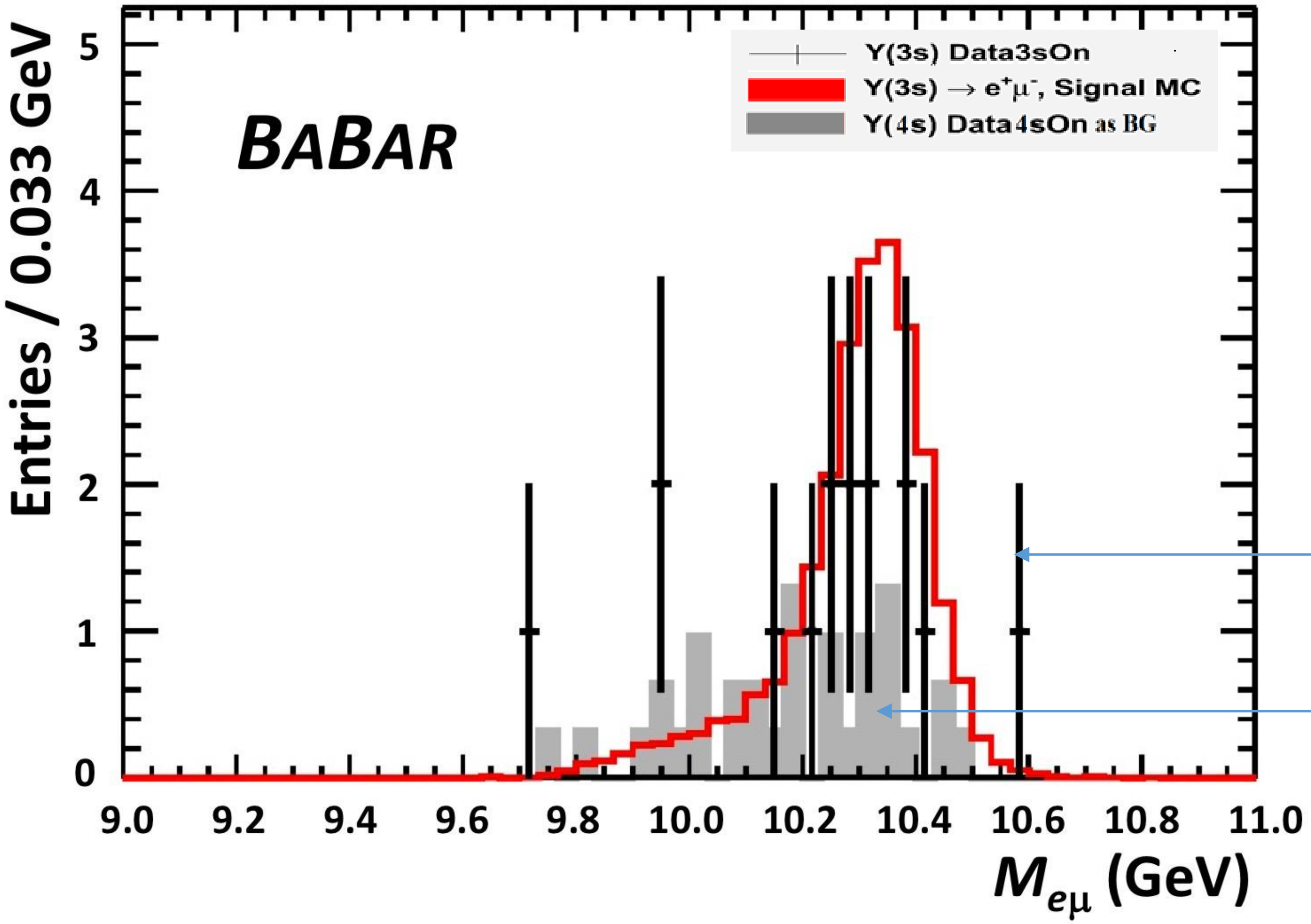
- The first row provides information on the pre-selection of the events as Υ **(3*S*)** $\rightarrow \boldsymbol{e}^{\pm}\boldsymbol{\mu}^{\mp}$.
- The last row provides information after applying all selection criteria.
- Rows 2-7 provides information when all requirements are applied except the criterion associated with the particular row.
- Third column represents the background events from $e^{+}e^{-} \rightarrow \boldsymbol{\Upsilon(3S)}$ **known as generic MC Background**.
- Fourth column represents the background events from $e^{+}e^{-} \rightarrow \boldsymbol{\Upsilon(4S)}$ **known as data-driven Continuum Background.**
- Event numbers in the third and forth columns are the luminosity-normalized.
- The last column gives the number of events in the 27 fb^{-1} data sample after unblinding.
- We have added an additional uncertainty of ± 0.9 any potential peaking background from the $\Upsilon(3S)$ decays which estimate the background events 12.2 ± 2.3

Data Driven Continuum Background and MC Background



- For the systematic study we have used the data driven continuum background $e^+e^- \rightarrow \Upsilon(4S)$ of 78.31/fb pre-selected as $e^\pm\mu^\mp$and $\mu^\pm\mu^\mp$
- Two major cuts (CM momentum cut and angle between two lepton tracks cut) were reversed to check the data/MC agreement.
- Disagreement arises due to uncertainties in PID, Tracking, kinematics, trigger etc.
- The difference in continuum background and MC background (in the energy band 6-8 GeV) was 1.2%

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

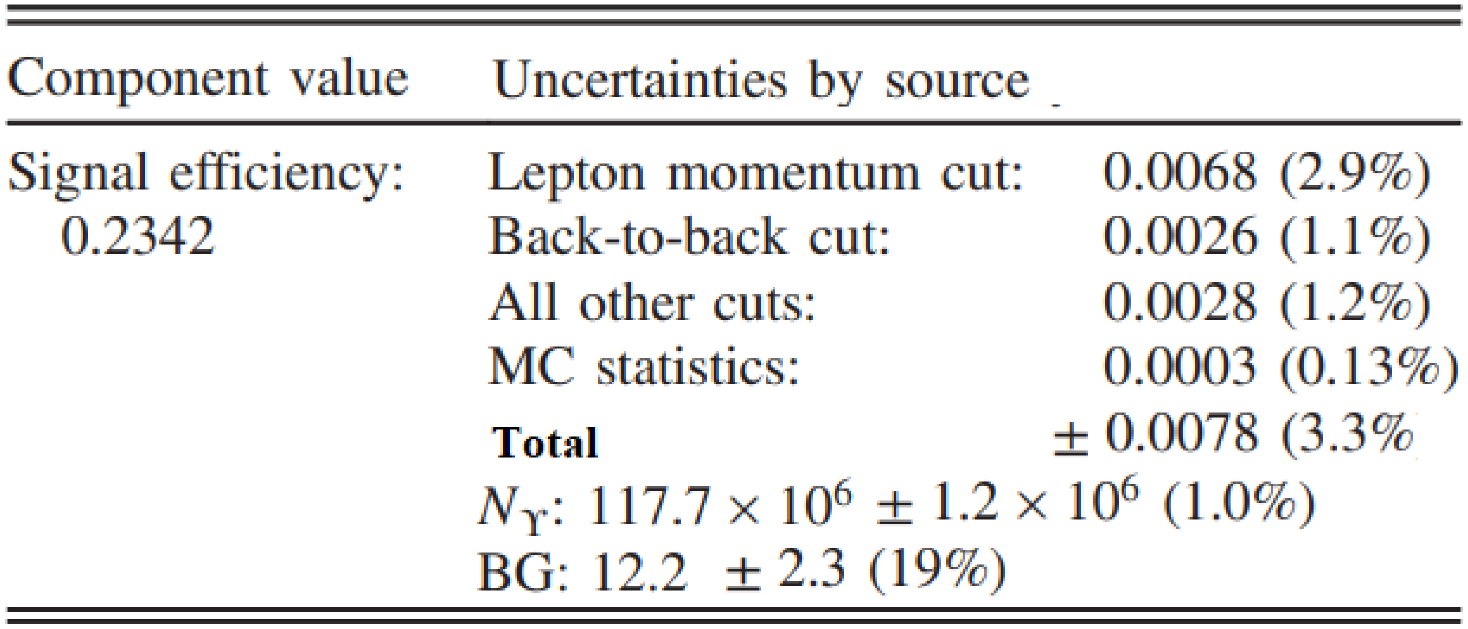


Candidate Events:15 (black)

Data Driven Estimated Background from $\Upsilon(4S)$: 12.2 (grey)

After all selection criteria are applied

Summary: Background, Uncertainty, Candidate



Component value	Uncertainties by source	
Signal efficiency: 0.2342	Lepton momentum cut:	0.0068 (2.9%)
	Back-to-back cut:	0.0026 (1.1%)
	All other cuts:	0.0028 (1.2%)
	MC statistics:	0.0003 (0.13%)
	Total	± 0.0078 (3.3%
	N_{Υ}: $117.7 \times 10^6 \pm 1.2 \times 10^6$ (1.0%)	
	BG: 12.2 ± 2.3 (19%)	

TABLE II. Summary of systematic uncertainties. The values of the efficiency, background, and number of $\Upsilon(3S)$ 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.

Results on $\Upsilon(3S) \rightarrow e^{\pm}\mu^{\mp}$

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

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

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

[J.Phys.G 28 (2002) 2693-2704]

- **First reported experimental Branching Fraction and We report a limit several orders of magnitude more sensitive than this indirect limit.**

Implication For New Physics

- A measurement of BF(Υ (3S) →$e^{\pm}\mu^{\mp}$) can be used to place constraints on $\frac{\mathrm{g}^2_{\mathrm{NP}}}{\Lambda_{NP}}$ of new physics processes that include lepton flavour violation.

$$where, \frac{\mathrm{g}^2_{\mathrm{NP}}}{\Lambda_{NP}} = \frac{\text{effective coupling of the new physics}}{\text{energy scale of the NP, given by the mass of the NP propagator.}}$$

- Place constraints on $\frac{\mathrm{g}^2_{\mathrm{NP}}}{\Lambda_{NP}}$ of new physics processes that include lepton flavor violation using

BF(Υ (3S) →$e^{\pm}\mu^{\mp}$) < 3.6 × 10^{-7} @ 90%CL

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

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

Conclusion

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

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

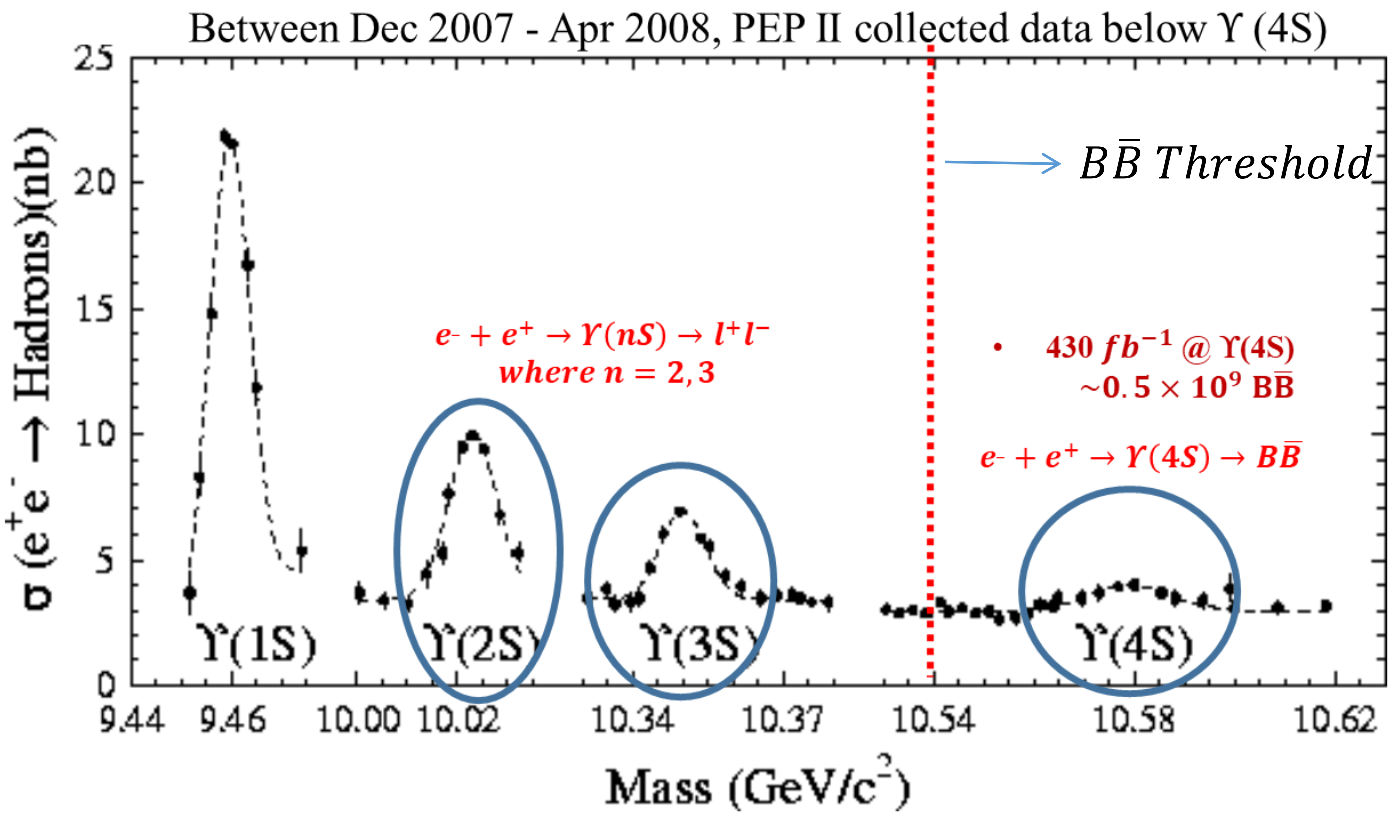
Phys.Rev.Lett. 128 (2022) 9, 091804

- 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: $\Lambda_{NP}/g^2_{NP} \geq 80\,\mathrm{TeV}$

Thanks, and Any Questions

Back up: Charged Lepton Flavour Violation in Upsilon Decays



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

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

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

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

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

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

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

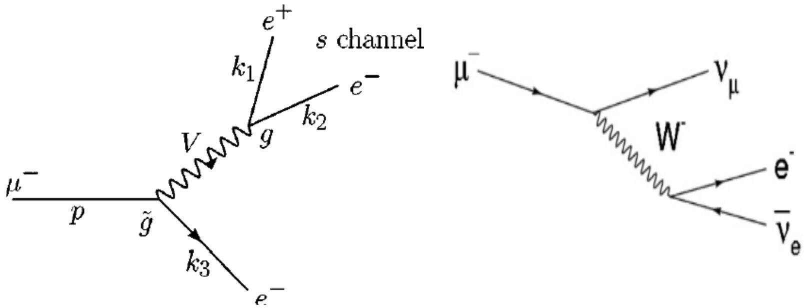
Since $[\Gamma(\mathrm{V} \to \mathrm{e}^+\mathrm{e}^-)] \sim \mathrm{g}^2\ \mathrm{V}_{ee}\ \mathrm{M}_V$ and

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

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

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

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



(Left) A vector exchange diagram contributing to $\mu \rightarrow 3e$
(Right) Ordinary muon decay, $\mu \rightarrow e\nu\bar{\nu}$, 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 $\Upsilon\ (3S) \rightarrow e^\pm\mu^\mp$ 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:
$\mathrm{BF}(\Upsilon\ (3S) \rightarrow e^\pm\mu^\mp) < 1\times 10^{-3}$

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

Back up: Analysis Scheme

- **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:** ${}^{\varepsilon_{e\mu}}\big/_{\sqrt{(1+N_{BG})}}$ 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;
$24° < \theta_{Lab} < 130°$ 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 $E_{Beam} = {}^{\sqrt{s}}\big/_{2}$
Angle between the two lepton tracks must satisfy $\theta_{12}^{CM} > 179°$ to ensure they emerged as back to back.
Energy deposit by Muon track on the Electromagnetic Calorimeter should be greater than 50 MeV.

Peaking Background

Source of Background	**Data Driven Continuum Background Υ(4S)**	**Peaking Background from Generic Υ(3S) MC**
Tight PID selection	12.2 ± 2.1	0
Loose PID selection	N/A	1.80 ± 0.9