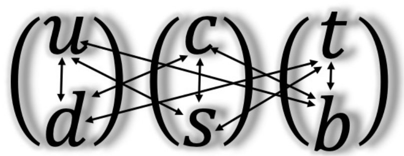
Search for charged lepton flavour violation in $\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}$ decay

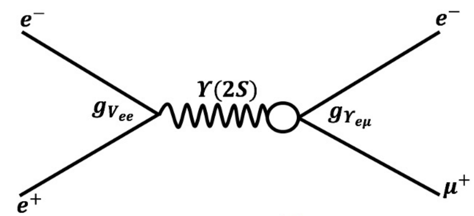
H. Ahmed, and N. Tasneem
St. Francis Xavier University
&
M. Roney
University of Victoria

Recall…..

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



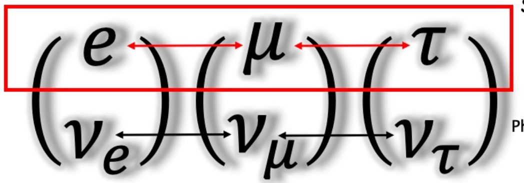
Quark Mixing Observed



No direct observation

Re-ordering incoming/outgoing particles

Charged lepton Mixing not Observed yet!



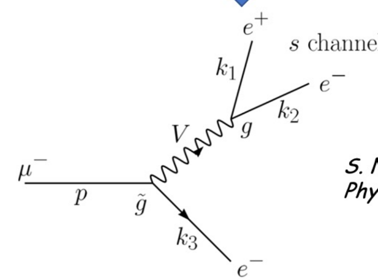
Suppressed by the quantity

$$\left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 \lesssim 10^{-48}$$

Phys.Rev.Lett.104:151802

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

Neutral lepton Mixing Observed



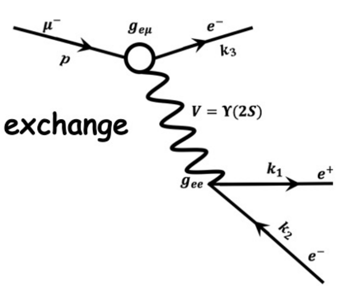
S. Nussinov, et. al. Phys.Rev. D63 (2001) 016003

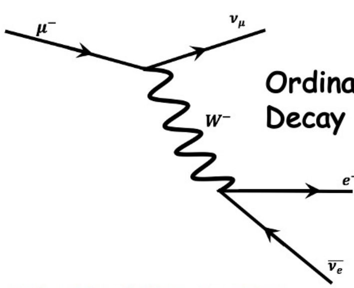
$$\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}$$

$$\mathrm{BR}(\Upsilon(2S) \rightarrow e\mu) = \mathrm{BR}(\mu \rightarrow eee) \frac{[\mathrm{BR}(W \rightarrow e\nu) * \Gamma_W]^2}{[\mathrm{BR}(\Upsilon(2S) \rightarrow e^+e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}} \left(\frac{M_{\Upsilon(2S)}}{M_W}\right)^6$$

$< 1.0\times10^{-12}$; ≈ 10.71% ; ≈ 2.085 GeV ; ≈ 10.023 GeV ; ≈ 1.98% ; ≈ 31.98 keV ; ≈ 80.4 GeV

Vector exchange

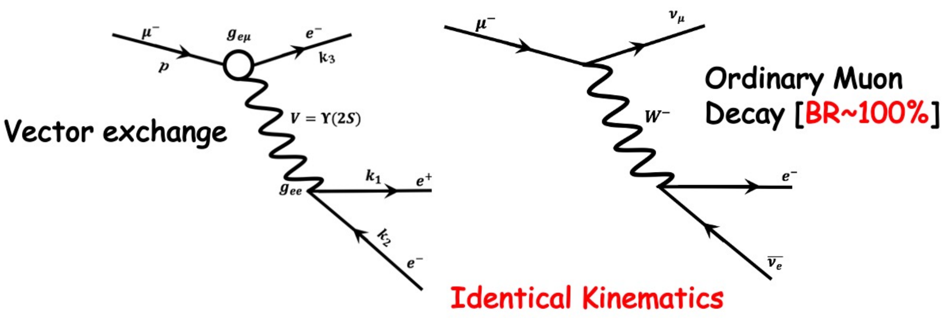




Ordinary Muon Decay [BR~100%]

Identical Kinematics

$$\mathrm{BR}(\Upsilon(2S) \rightarrow e\mu) \leq 9.58 \times 10^{-9}$$



$\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}$

$$BR(\Upsilon(2S) \rightarrow e\mu) = BR(\mu \rightarrow eee) \frac{[BR(W \rightarrow e\nu) * \Gamma_W]^2}{[BR(\Upsilon(2S) \rightarrow e^+e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}} \left(\frac{M_{\Upsilon(2S)}}{M_W}\right)^6$$

$< 1.0\times10^{-12}$
$\approx$ 10.71%
$\approx$ 2.085 GeV
$\approx$ 10.023 GeV
$\approx$ 1.98%
$\approx$ 31.98 keV
$\approx$ 80.4 GeV

$BR(\Upsilon(2S) \rightarrow e\mu) \leq 9.58 \times 10^{-9}$

- PHYSICAL REVIEW D 83, 115015 (2011), "New bounds on lepton flavor violating decays of vector mesons and the Z^0 boson" set an upper bounds Br $(\Upsilon \rightarrow e\mu) \leq 3.9\times10^{-6}$
- S. Nussinov, et. al. PRD 63, 016003 (2001) estimate the contribution of the virtual vector boson ($\Upsilon(2S)$ in our case) to $\mu \rightarrow 3e$ is reduced by a factor of $\frac{{m_\mu}^2}{2{M_{\Upsilon(2S)}}^2}$, which leads the bound $BR(\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}) \leq 9.58\times10^{-9}$ reduced to $BR(\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}) \approx 1.7\times10^{-4}$

Data and SP samples

- Data: NIMA 726 (2013) 203-213
  - ➢ $\Upsilon(2S)$ OnPeak – 13.60 fb^{-1}
  - ➢ $\Upsilon(2S)$ OffPeak – 1.419 fb^{-1}
- MC: Continuum

$$e^+e^- \to \mu^+\mu^-$$
$$e^+e^- \to \tau^+\tau^-$$
$$e^+e^- \to e^+e^-$$
$$e^+e^- \to uds$$
$$e^+e^- \to c\bar{c}$$

- MC: Generic $\Upsilon(2S)$ decays

➢ We use 0.995 fb^{-1} data for this blinded analysis

- MC: Signal events

```
#####################################################################
#                                                                   #
# Upsilon(2S)->e mu                                                 #
#      (for lepton flavor violation studies)                        #
# Author:   Ben Hooberman  bhoob Mar 11 2008                        #
# Modified: Hossain Ahmed May 2018                                  #
#####################################################################

Decay Upsilon(2S)
0.500 e- mu+      PHOTOS VLL;
0.500 e+ mu-      PHOTOS VLL;
Enddecay

End
#####################################################################
```

➢ SP-11974-Run7-Y2S_OnPeak-R24
➢ 145,000 events are generated!

Pre-Selections

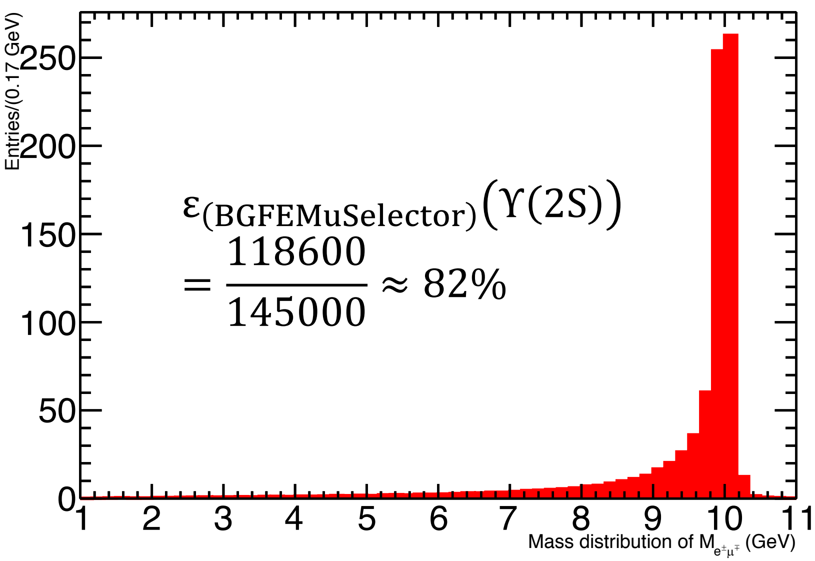
- BGF →Background filter
  - BGFMuMu → Events in the dimuon sample required to pass
  - Events in the tau-pair are required to pass BGFTau or BGFTwoProng
  - BGFEMuSelector → specific filter for emu search
  - TauMiniUser package reads the input collections and process events that pass BGFEMuSelector
  - BGFEMuSelector efficiency ~ 82%

- Pre-conditions:
  - 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;
  - two tracks in GoodTracksLoose (one in each hemisphere)
  - DigiFL1Open and DigiFL3Open
  - Two charge tracks with total charge = 0
  - Sum of momentum of two tracks > 9 GeV/c

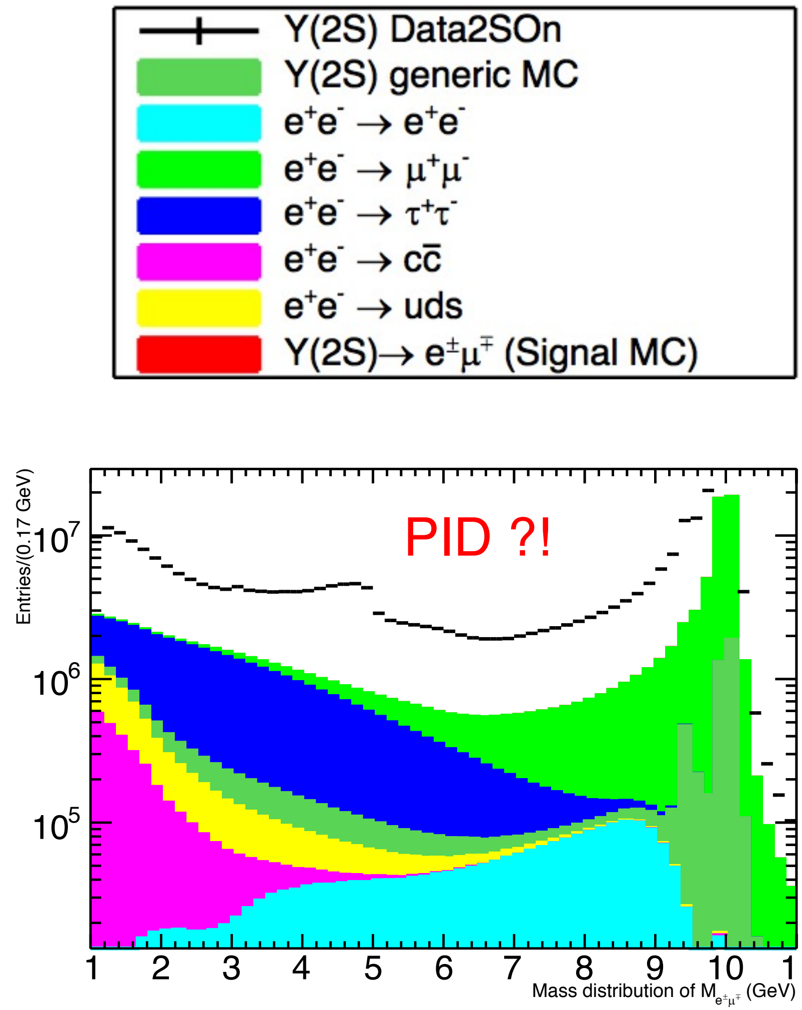
Pre-Selections

Data/MC (signal)/SP	Before pre-selection	After pre-selection
$\Upsilon_{DATA}(2S)$	519183811	6691951
$\Upsilon_{MC}(2S)$	145000	118600
$\Upsilon_{generic}(2S)$	115248000	3821026
$e^+e^- \to \mu^+\mu^-$	52555000	36172190
$e^+e^- \to \tau^+\tau^-$	40005000	16774419
$e^+e^- \to e^+e^-$	72496000	1158500
$e^+e^- \to uds$	95001000	4419715
$e^+e^- \to c\bar{c}$	192924000	3419842

- MCs are nomalized to 0.995 fb^{-1} of total data



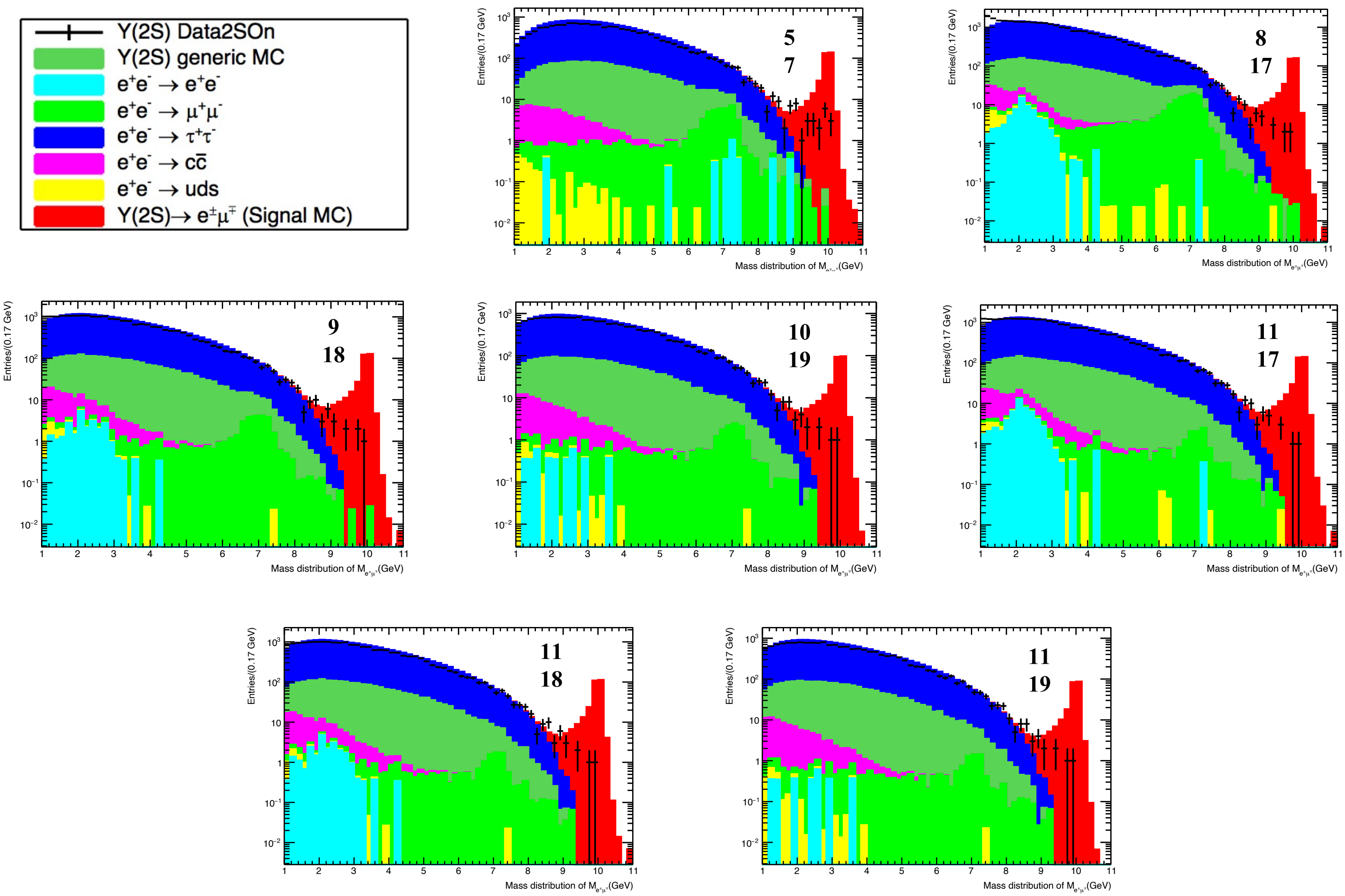
$$\varepsilon_{(\mathrm{BGFEMuSelector})}(\Upsilon(2S)) = \frac{118600}{145000} \approx 82\%$$



PID Selections

PID Selectors	Survived Events							
	Data	MC Signal	$\mu\mu$	$\tau\tau$	$c\bar{c}$	uds	Bhabha	Generic
PidLHElectrons(tight) (bit 5) NNTightMuonSelection (bit 7)	15607	55384	2796	713641	11666	282	10	48319
LooseKMElectronMicroSelection (bit 8) BDTLooseMuonSelection(17)	42974	69526	8487	1192364	36823	2912	213	79689
TightKMElectronMicroSelection (bit 9) BDTTightMuonSelection(18)	27361	54543	2310	990079	26266	931	83	65622
VeryTightKMElectronMicroSelection (bit 10) BDTVeryTightMuonSelection (bit 19)	18966	40758	1376	799807	17746	284	13	53204
SuperTightKMElectronMicroSelection (bit 11) BDTLooseMuonSelection(17)	32997	57816	1639	1088661	29878	884	171	72200
SuperTightKMElectronMicroSelection (bit 11) BDTTightMuonSelection(18)	24420	46377	1314	932872	23725	522	73	61745
SuperTightKMElectronMicroSelection (bit 11) BDTVeryTightMuonSelection (bit 19)	18102	35730	1042	769806	16928	251	10	51204

PID Selections



PID Selections (optimization)

$$\frac{\varepsilon_{e\mu}}{\sqrt{1 + N_{BG}}}$$

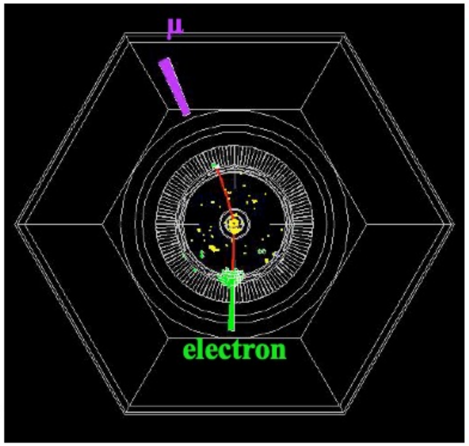
- $\varepsilon_{e\mu}$ is the final efficiency as determined from signal MC and
- N_{BG} is the number of expected background events as prdicted by data control samples in Run 6 and generic $\Upsilon(2S)$ MC events

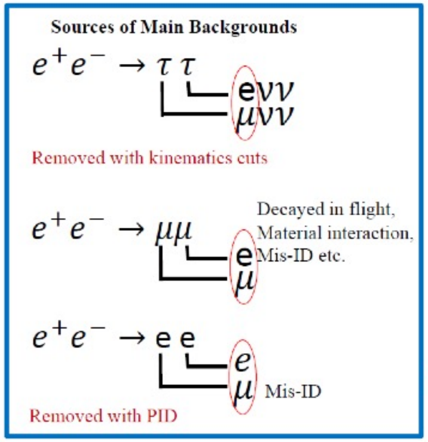
User Selections (N-1 cuts)

Definition	Selection
Two tracks (one in each hemisphere)	one electron and one muon in the final state
Lepton momentum plane	$\left(\frac{p_e}{\sqrt{s}*0.5}-1\right)^2+\left(\frac{p_\mu}{\sqrt{s}*0.5}-1\right)^2<0.01$
Back-to-back	$\theta_{12}^{CM} > 179^0$
EMC acceptance	$24^0 < \theta_{lab} < 130^0$
Muon track energy	> 50 MeV

N. Tasneem: EPS talk

Sample Background event
$e^-e^+ \to \tau^\pm\tau^\mp \to e^\pm\mu^\mp + 4\nu$



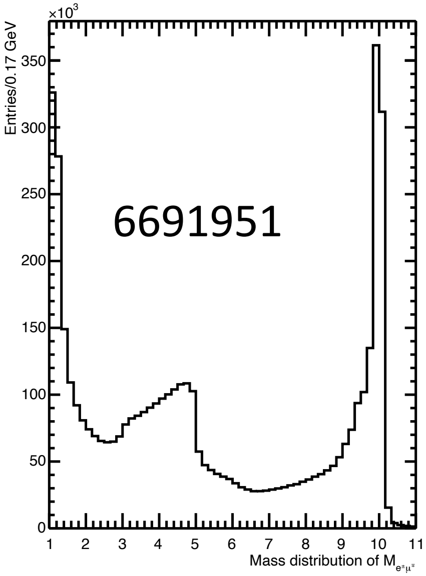


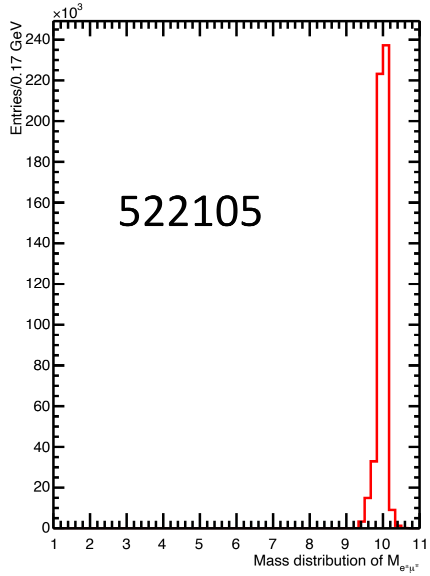
Different Sources of Background

User Selections (Two Tracks)

(Trk_userpid[0]==0 && Trk_userpid[1]==1) || (Trk_userpid[0]==1 && Trk_userpid[1]==0);

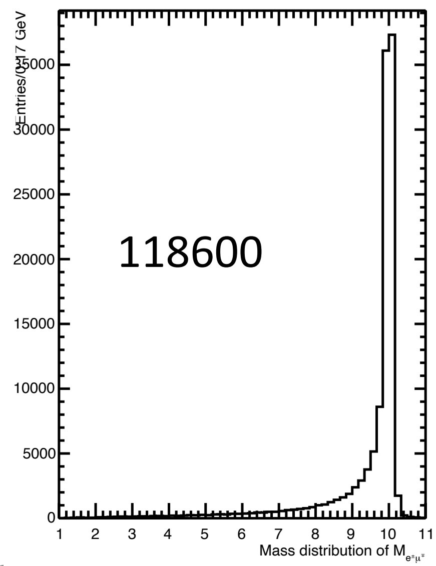
- Applied on events survived after pre-selection

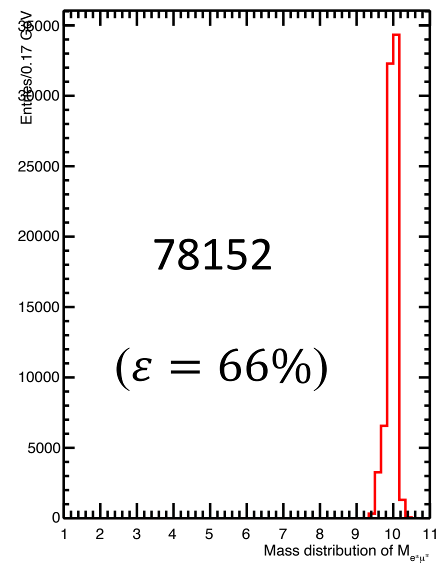




Data
(PID is not included)

MC
(PID is not included)

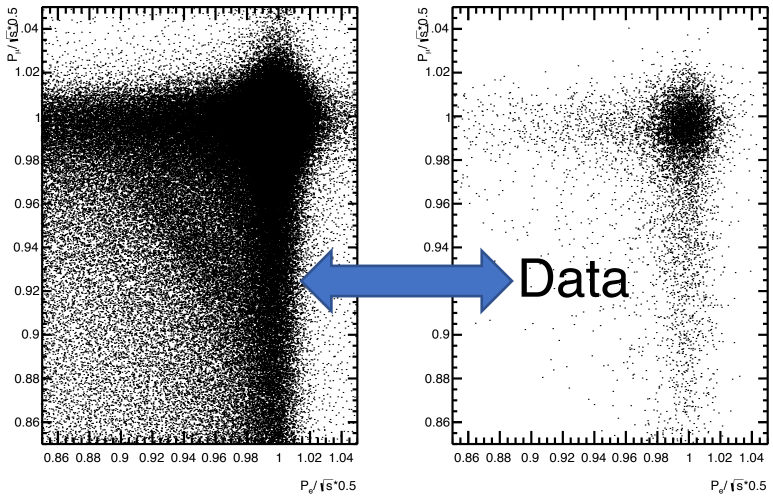




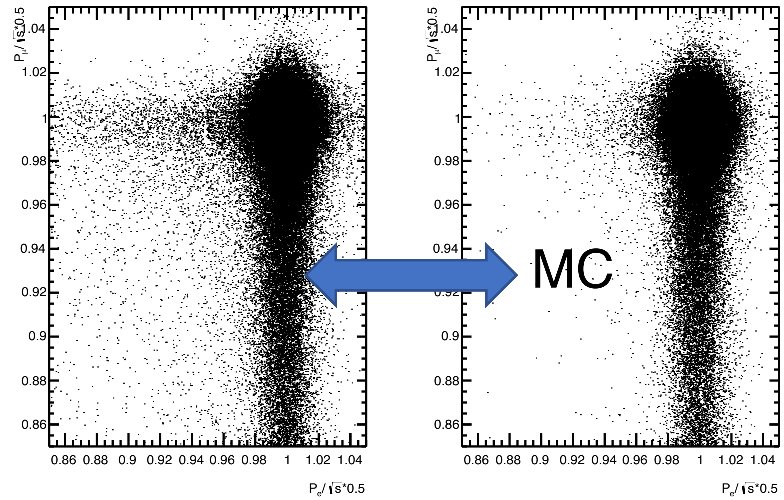
User Selections (Lepton momentum plane)

$$\left(\frac{p_e}{\sqrt{s}*0.5}-1\right)^2+\left(\frac{p_\mu}{\sqrt{s}*0.5}-1\right)^2<0.01$$

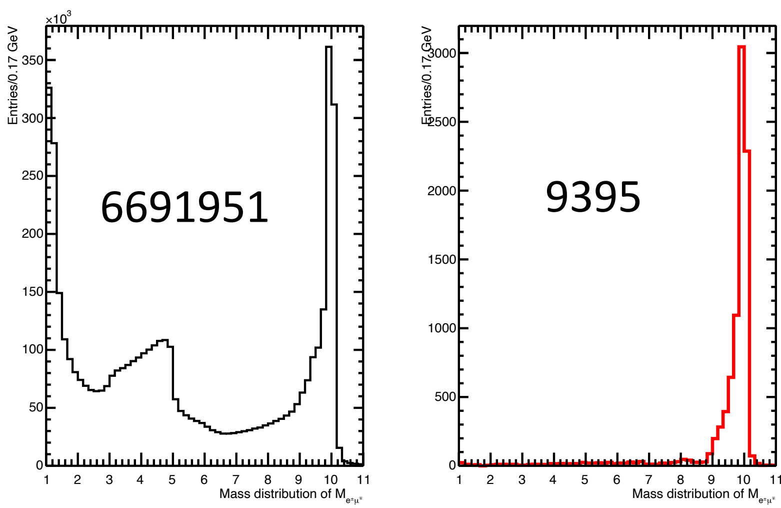
- Applied on events survived after pre-selection

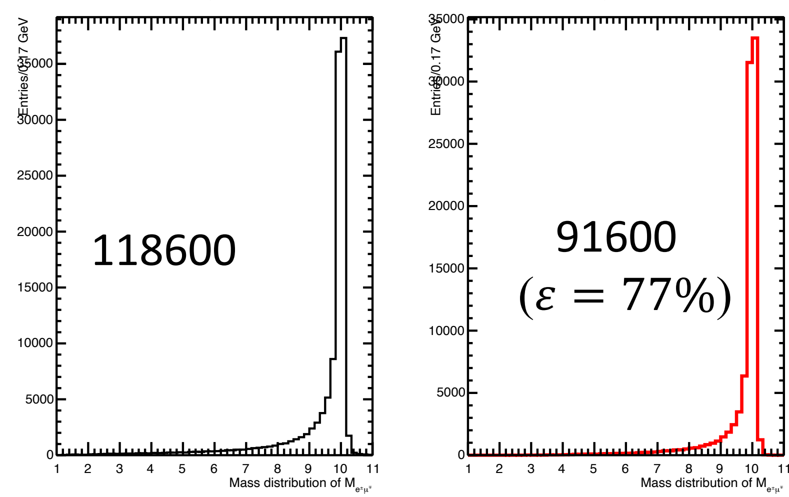


(PID is not included)



(PID is not included)

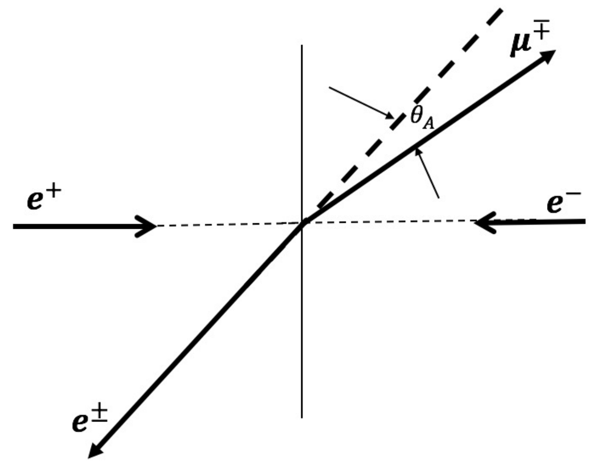


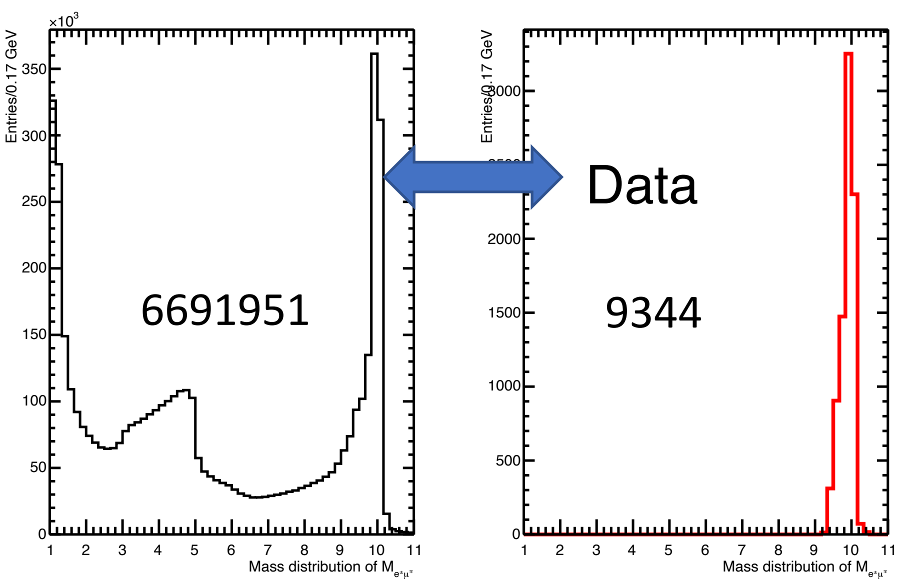


User Selections (Back-to-back)

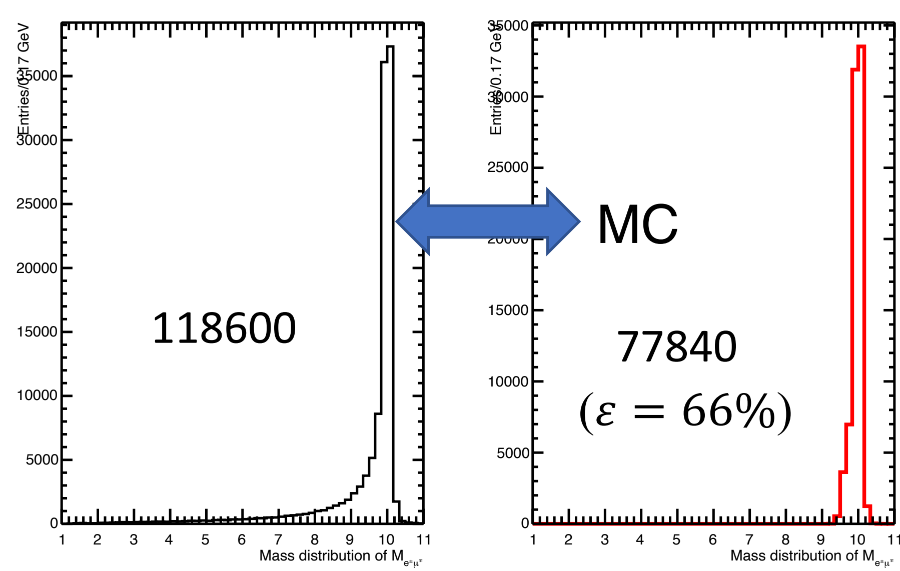
$$\theta_{12}^{CM} > 179^0$$

- Applied on events survived after pre-selection





(PID is not included)

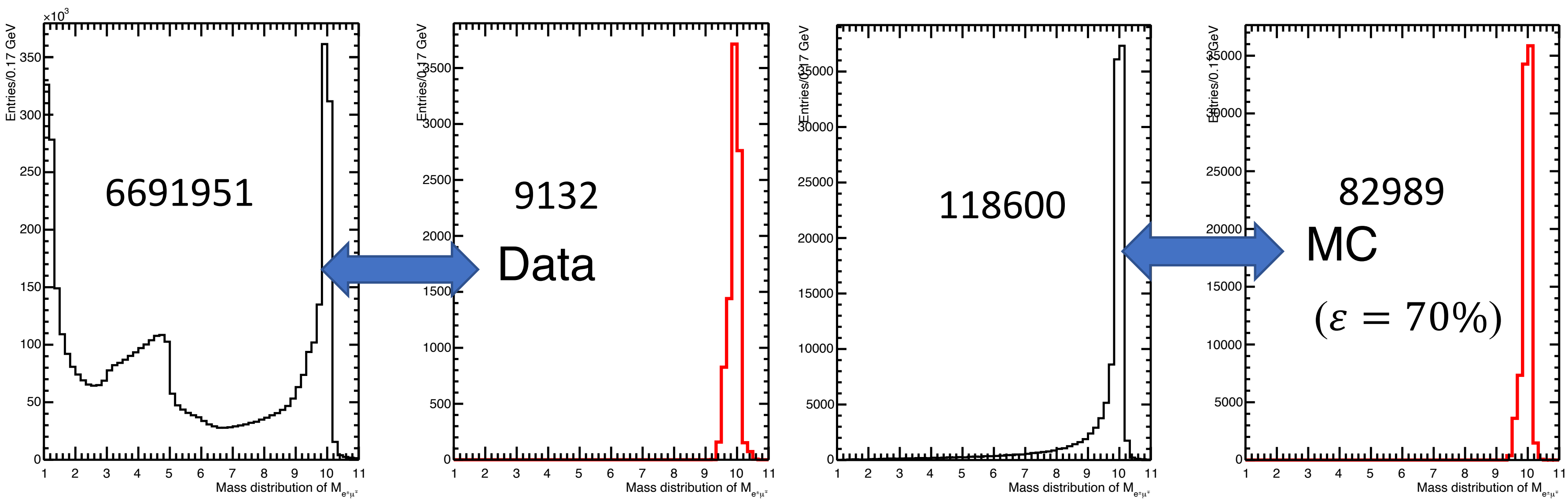


(PID is not included)

User Selections (EMC acceptance region)

Trk_Eltheta>0.41 && Trk_Eltheta<2.268 && Trk_Mutheta>0.41 && Trk_Mutheta<2.268;

➢ Applied on events survived after pre-selection



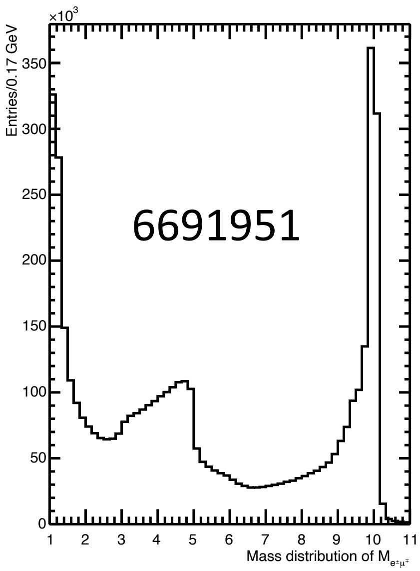
(PID is not included)

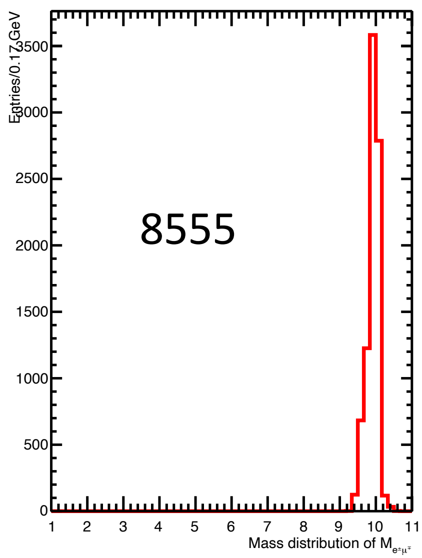
(PID is not included)

User Selections (Muon Energy in ECal)

Trk_Muecal >0.05 GeV

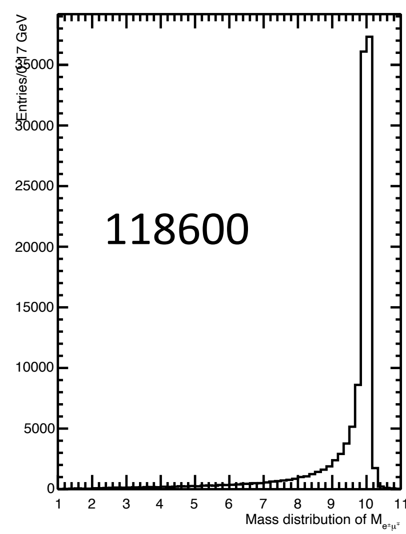
- ➢ Applied on events survived after pre-selection

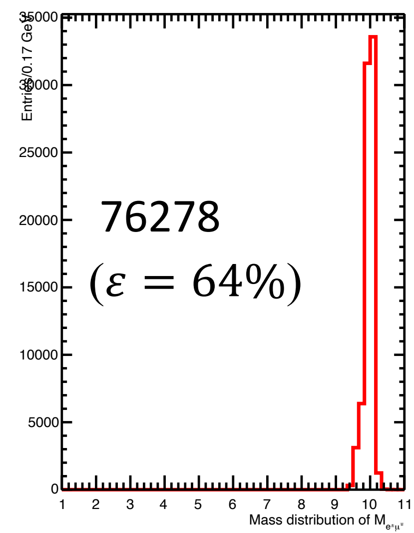




Data
(PID is not included)

MC
(PID is not included)





User Selections plus PID

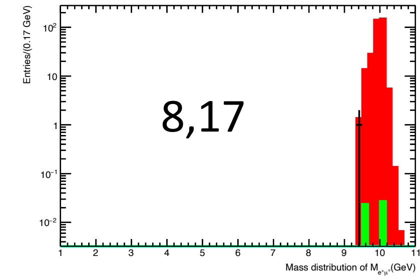
Definition	Selection
Two tracks (one in each hemisphere)	one electron and one muon in the final state
Lepton momentum plane	$\left(\frac{p_e}{\sqrt{s} * 0.5} - 1\right)^2 + \left(\frac{p_\mu}{\sqrt{s} * 0.5} - 1\right)^2 < 0.01$
Back-to-back	$\theta_{12}^{CM} > 179^0$
EMC acceptance	$24^0 < \theta_{lab} < 130^0$
Muon track energy	> 50 MeV

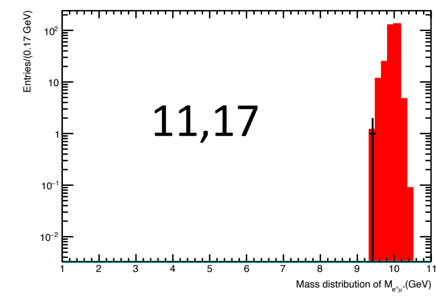
User selections on:

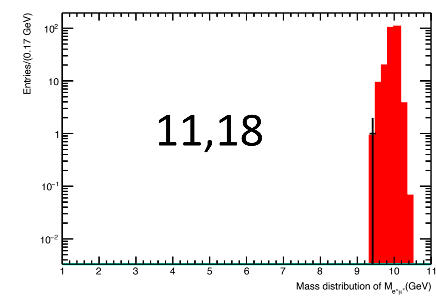
8, 17	Loose electron, loose muon
11, 17	SuperTight electron, loose muon
11, 19	SuperTight electron, VeryTight muon

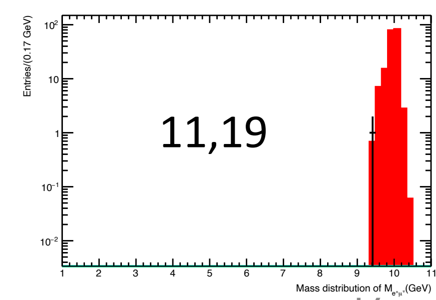
All Criteria (N-1 cuts) with PID

PID	Number of sig events (MC)	Number of sig events ($\Upsilon(2S)$)	Number of bkg events ($\Upsilon(2S)$)
8 &17: Loose electron, loose muon	49039	1	2
11 & 17: SuperTight KMElectron, BDTLooseMuon	42662	1	0
11 & 18:SuperTight KMElectron, BDTTightMuon	34445	1	0
11 & 19: SuperTight KMElectron, BDTVeryTightMuon	26636	1	0







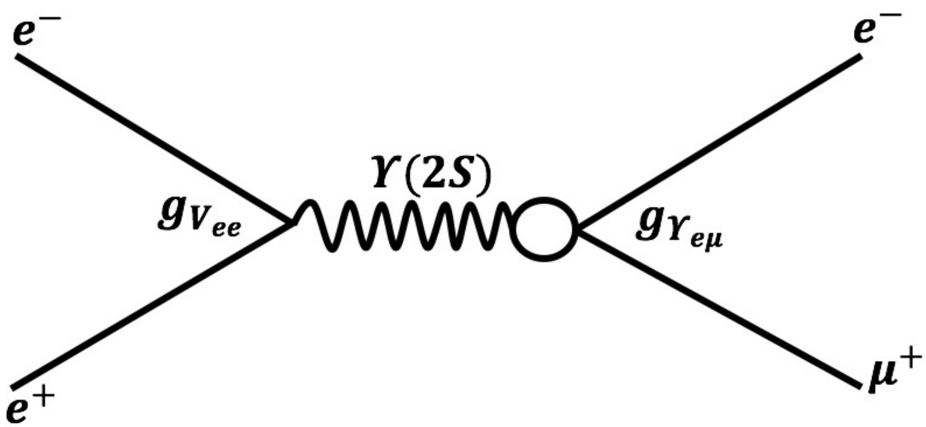


Future works

- Use Run6 data as background (ntuples from Nafisa)
- Systematics
- Unblinding the analysis

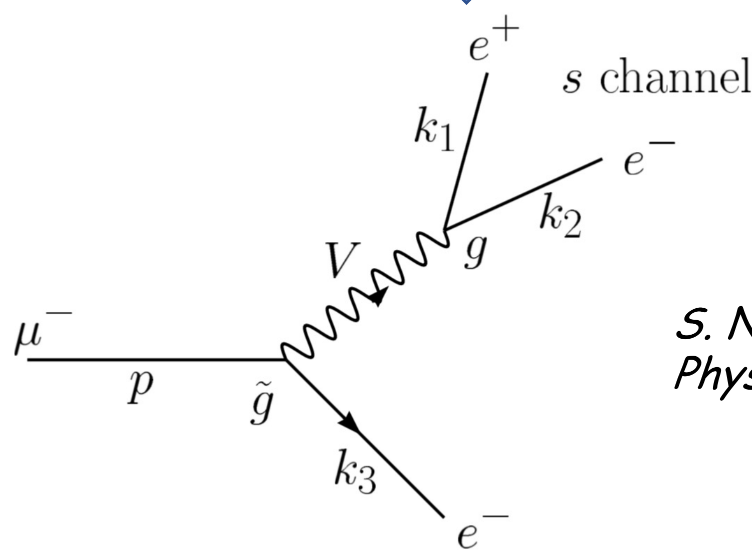
Backup slides

We are aiming to analyze: $\Upsilon(2S) \to e^{\pm}\mu^{\mp}$



No direct observation

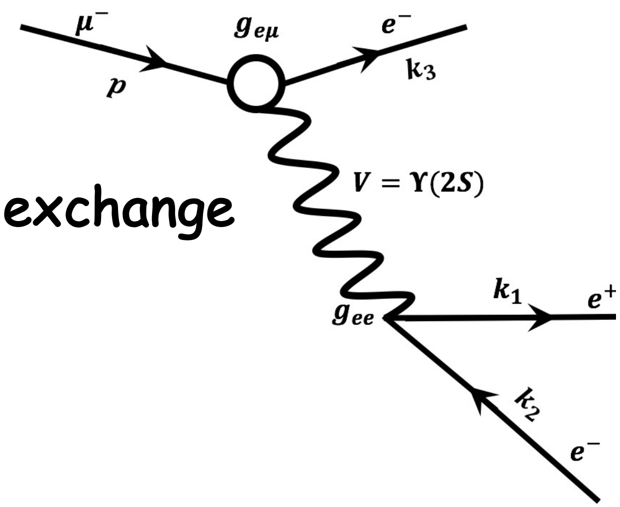
Re-ordering incoming/outgoing particles

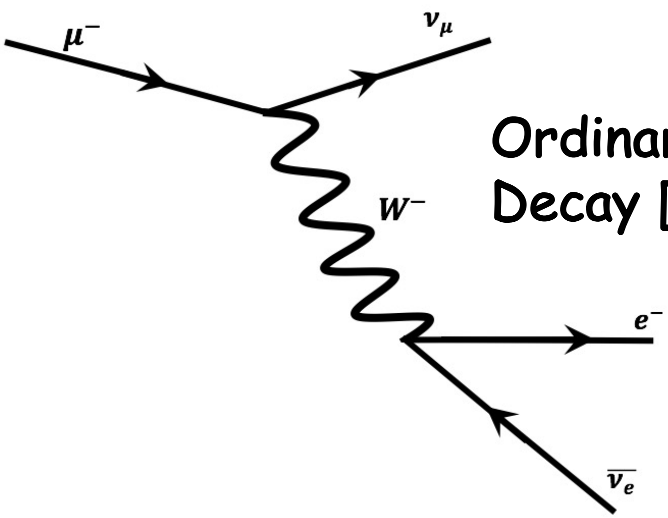


S. Nussinov, et. al.
Phys.Rev. D63 (2001) 016003

$\Upsilon(2S) \to e^{\pm}\mu^{\mp}$

Vector exchange





Ordinary Muon Decay [BR~100%]

Identical Kinematics

$$\frac{\Gamma(\mu \to 3e)_{V-exchange}}{\Gamma(\mu \to e\nu\bar{\nu})} \approx [BR(\mu \to 3e)]_{V-exch.}$$

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

$$\Gamma(W \to e\nu) \sim g_W^2 M_W$$
$$\Gamma(V \to e^+e^-) \sim g_{V_{ee}}^2 M_V$$
$$\Gamma(V \to e\mu) \sim g_{V_{e\mu}}^2 M_V$$

$\Upsilon(2S) \rightarrow e^{\pm}\mu^{\mp}$

Using: $$BR \approx \frac{\Gamma_i}{\Gamma_{tot}} \quad \text{------------ (1)}$$

$$\frac{\Gamma(V\to e^+e^-)\Gamma(V\to e^{\pm}\mu^{\mp})}{\Gamma^2(W\to e\nu)} \quad \text{------------------ (2)}$$

$$\approx \frac{[BR(V\to e^+e^-)*\Gamma_V][BR(V\to e^{\pm}\mu^{\mp})*\Gamma_V]}{[BR(W\to e\nu)*\Gamma_W]^2} \quad \text{---------- (3)}$$

$$V \cong \Upsilon(2S) \quad \text{-------------- (4)}$$

$$BR(\Upsilon(2S) \rightarrow e\mu) = BR(\mu \rightarrow eee)\frac{[BR(W \rightarrow e\nu) * \Gamma_W]^2}{[BR(\Upsilon(2S) \rightarrow e^+e^-) * \Gamma_{\Upsilon(2S)}] * \Gamma_{\Upsilon(2S)}}\left(\frac{M_{\Upsilon(2S)}}{M_W}\right)^6$$

------------ (5)

From: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)