Lepton Universality
in
$\Upsilon(nS)$ Decays at CLEO

Hajime Muramatsu

University of Rochester
For the CLEO Collaboration

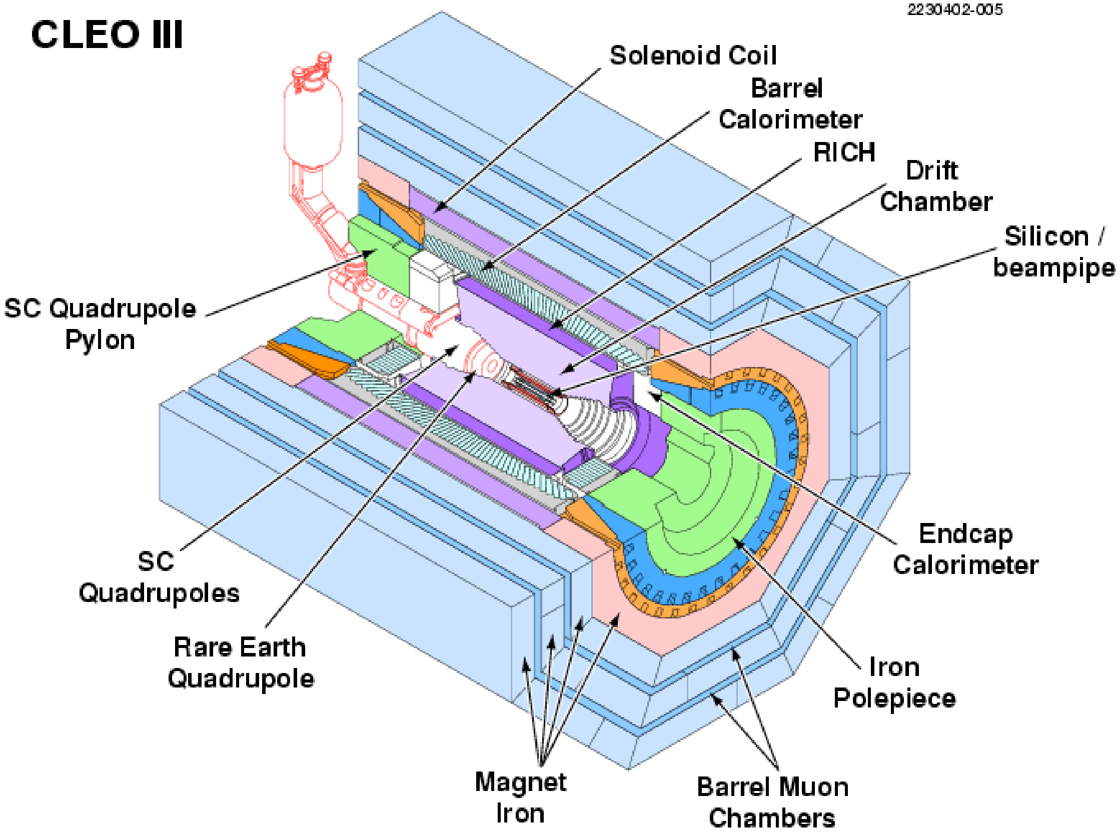
Topics

(“n” on this page means 1, 2, and 3, but NOT 4)

- **Testing lepton universality in**
  $\Upsilon(nS) \rightarrow \tau^+\tau^-$ vs $\Upsilon(nS) \rightarrow \mu^+\mu^-$
  PRL98, 052002 (2007)
- **Search for lepton flavor violating decay**
  via $\Upsilon(nS) \rightarrow \tau\mu$ ***(preliminary)***

CLEO-III detector

- **Located at Cornell Electron Storage Ring**
- **e^+e^- collisions at $\sqrt{s}$ ~ 10GeV (2001~2002)**



- **EM calorimeter - Essential for photon spectroscopy**
  - **~8000 CsI(Tl) crystals + photo-diodes**
  - **First crystal calorimeter in magnetic field (1.5T)**
  - **2.2 (5)% at E_γ=1(0.1)GeV**

Excellent charged particle detection

Excellent particle identification

- **dE/dx**
- **Ring Imaging Cherenkov (RICH)**

Data sets taken with CLEO-III detector

Reso-nance	CLEO-III Integrated Luminosity (fb^{-1})	Number of resonance decays (10^6)				
		CLEO III	CLEO II	Crystal Ball *(CUSB)*	Belle	BaBar
Υ(3S)	1.2 (0.1)	6	0.46	*(1.3)*	11	???
Υ(2S)	1.2 (0.4)	9	0.49	0.19		
Υ(1S)	1.0 (0.2)	21	1.9	0.48		

taken right below Υ(nS)

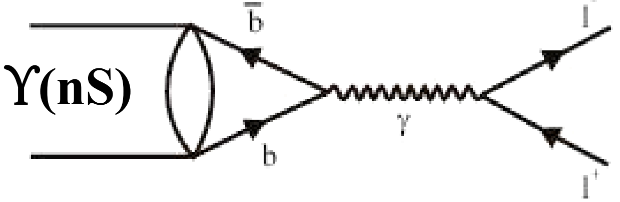
~30/fb by March

Still the largest samples in the world!!

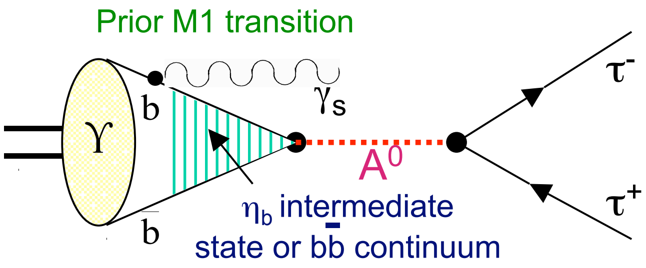
Belle and BaBar can tag (e.g.) $\pi^+\pi^-$ to reach Υ(1,2S) states → can avoid continuum ($B_{\pi+\pi-} \cdot \varepsilon_{\pi+\pi-} \sim$ a few %).

One way to test Lepton universality

- **Naively we expect;**
  $B(\Upsilon(nS) \to e^+e^-) = B(\Upsilon(nS) \to \mu^+\mu^-) = B(\Upsilon(nS) \to \tau^+\tau^-)$



- **Obtain $R(nS) = B(\Upsilon(nS) \to \tau^+\tau^-)/B(\Upsilon(nS) \to \mu^+\mu^-)$**
  See if it is consistent with 1.
- **One way to deviate from 1;**
  $\Upsilon(nS) \to \gamma\eta_b(mS)$, $(\eta_b(mS) \to A^0)$, $A^0 \to \tau^+\tau$, $n \geq m$.
  if the photon is undetected (E_γ~60MeV for 1S→1S) . Here, A^0 is a non-Standard CP-odd Higgs boson whose mass is ~10GeV → possible mixing between η_b and A^0.
  (i.e. see Miguel-Angel Sanchis-Lozano hep-ph/0610046, contributed paper to BNM2006)



Procedure to obtain $R(nS) = \mathcal{B}(\Upsilon(nS) \rightarrow \tau^+\tau^-)/\mathcal{B}(\Upsilon(nS) \rightarrow \mu^+\mu^-)$

1. **Select $\mu\mu$ and $\tau\tau$ signals at and below $\Upsilon(nS)$, n=1,2,3, and 4.**
2. **Subtract scaled continuum.**
   a) **Check with $\Upsilon(4S)$ data first to make sure this subtraction is working. Since $\mathcal{B}(\Upsilon(4S) \rightarrow e^+e^-) \sim 10^{-5}$, no measurabale tau-pair and mu-pair is expcted here.**
   b) **Compare $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ with $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ in off-resonance data by measuring their luminosities respectively.**
   c) **Apply the above continuum subtraction to $\Upsilon(nS)$-on-resonance data (n=1, 2, 3) for $\mu^+\mu^-$ and $\tau^+\tau^-$ candidates.**
3. **Extract R(nS)**

Bonus: Can obtain $\mathcal{B}(\Upsilon(nS) \rightarrow \tau^+\tau^-)$ using the published $\mathcal{B}(\Upsilon(nS) \rightarrow \mu^+\mu^-)$ with R(nS).

Step 1: Selecting muon pairs

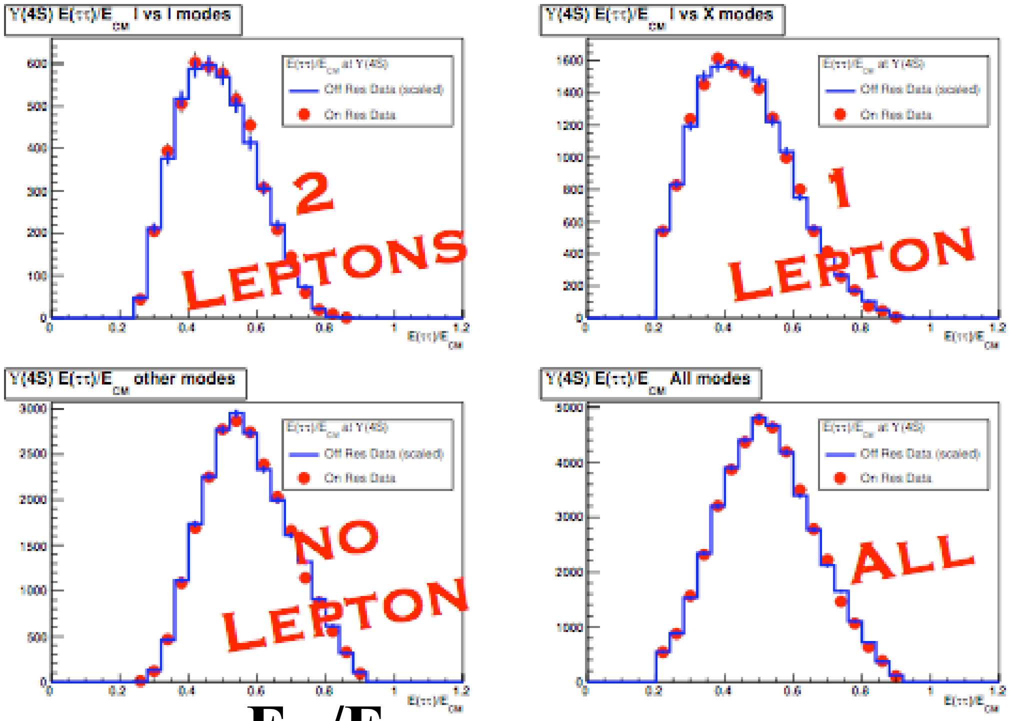
Similar to study of *B*(Υ(nS) → $\mu^+\mu^-$) : PRL94,012001 (2005)

- 2 energetic (P_{tk}/E_{beam}~1), well separated (>170^0 of their opening ang.) tracks with opposite sign
- EM CC energy and Muon-chamber signal consistent with muons.

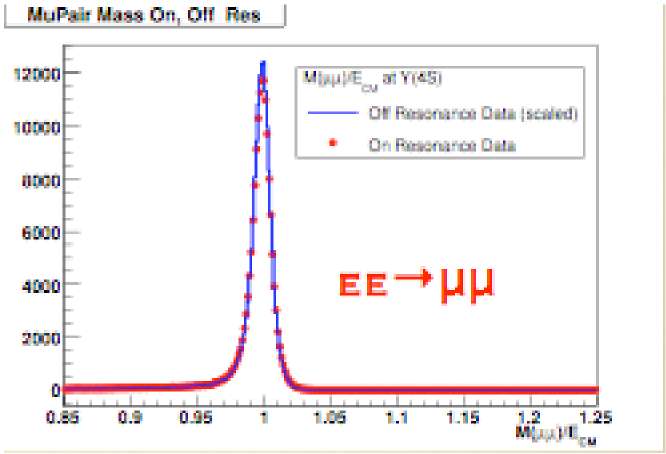
Selecting tau pairs.

- Look for one-prong tau decays:*B*(τ→ 1 prong)~75%
  - 2 track events, cuts on generic ττ missing momentum and energy.
- Classify tracks as e (dEdx, E/p), μ (muon-chamber, E_{cc}), and X (= not e nor μ. Mixture of misidentified leptons and hadrons).

Step 2-a: Subtracting scaled continuum at Υ(4S).



$E_{\tau\tau}/E_{cm}$



$M_{\mu\mu}/E_{cm}$

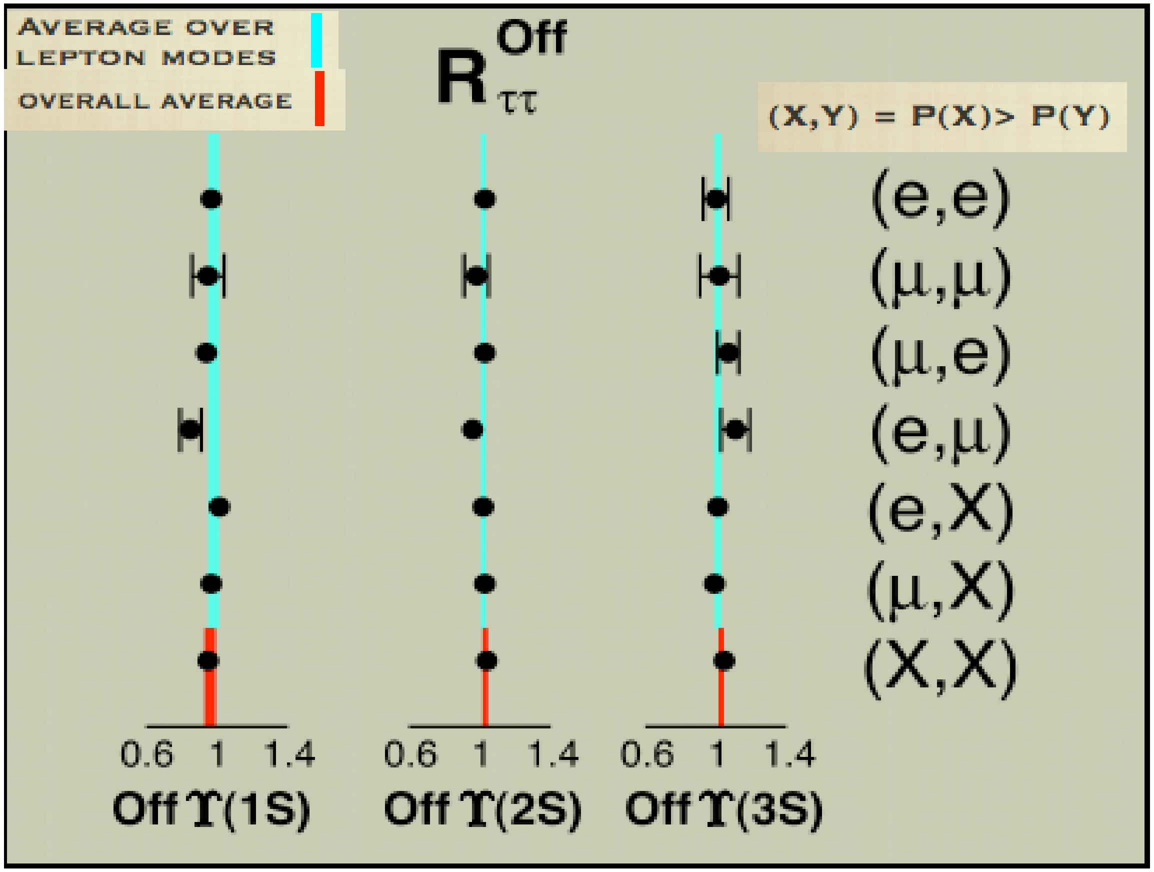
- Scaled continuum data (solid histograms)
- On-resonance data (points)

- **ON - S·OFF, $S \propto 1/s$ works.**
- **No evidence for background that does not scale as 1/s.**

Step 2-b: $\sigma(ee\rightarrow\tau\tau)/\sigma(ee\rightarrow\mu\mu)$ in off-resonance data

$\sigma(ee\rightarrow\tau\tau)/\sigma(ee\rightarrow\mu\mu)$ theoretically expected to be 0.83.

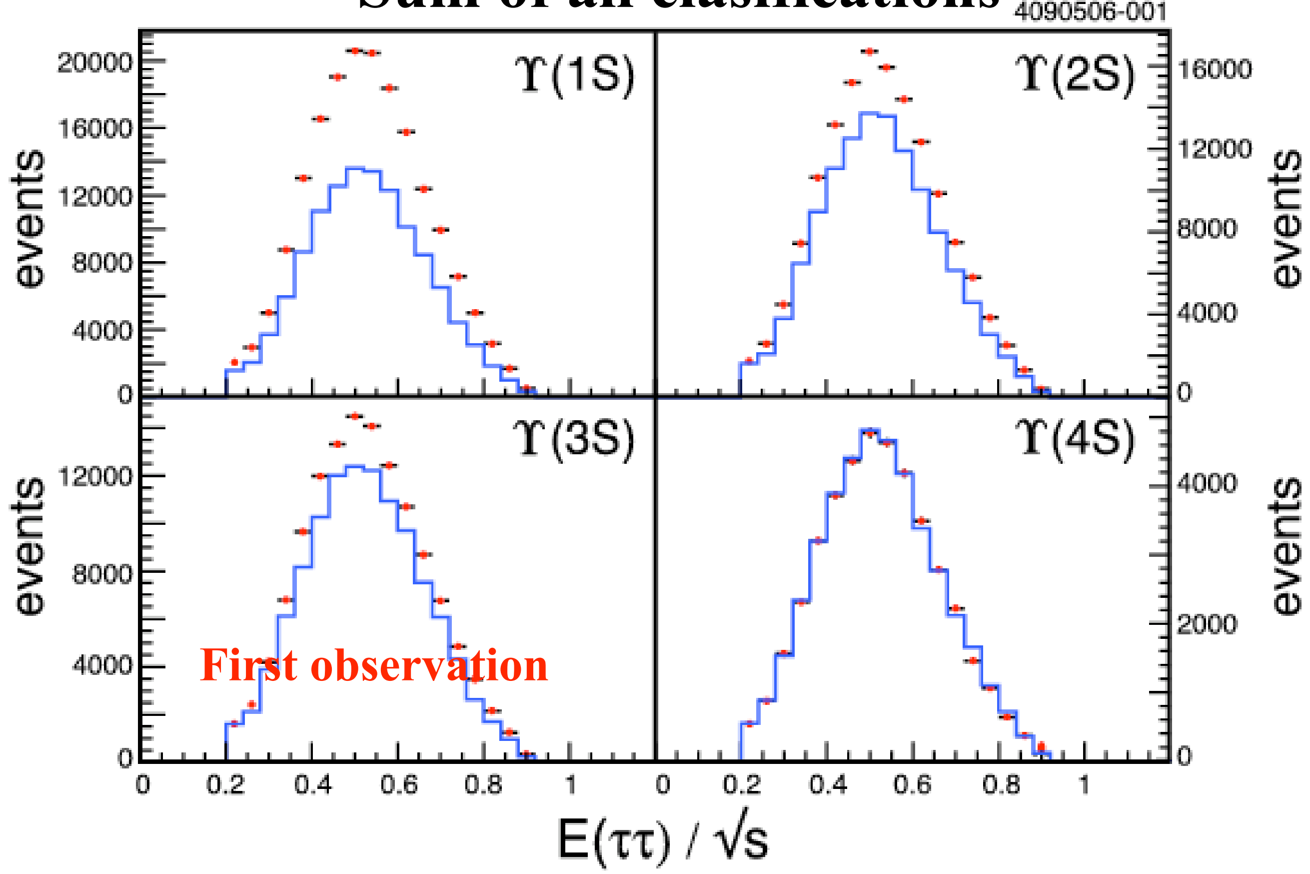
$$R^{Off}_{\tau\tau} = \sigma(ee\rightarrow\tau\tau)/\sigma(ee\rightarrow\mu\mu)/0.83$$



- All decay channels agree.
- Confidence that we can reconstruct ee→ττ, μμ

Step 2-c: Subtracting scaled continuum at Υ(nS) for n=1, 2, and 3.

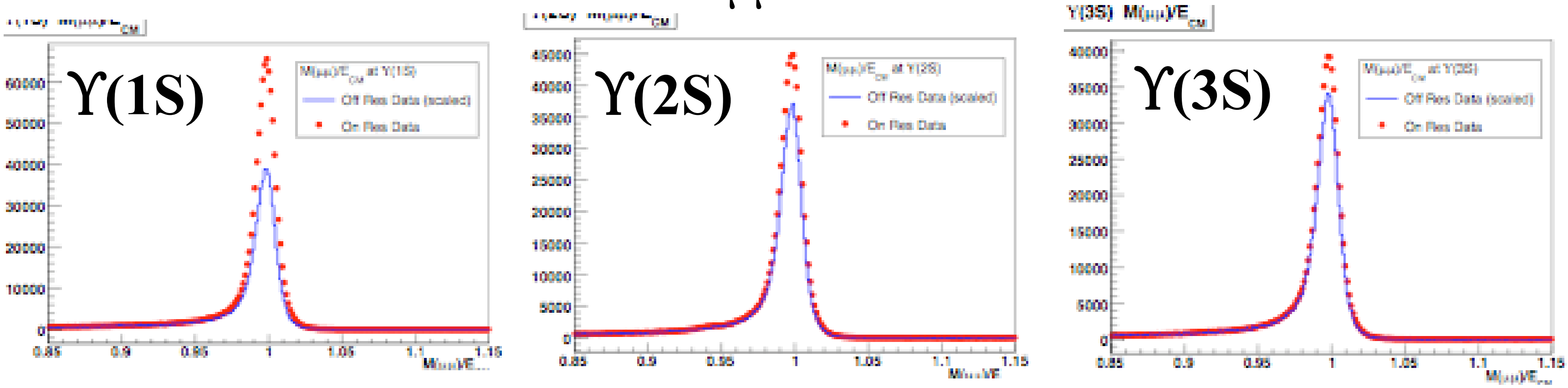
Sum of all clasifications



- Scaled continuum data (solid histograms)
- On-resonance data (points)

Step 2-c: Subtracting scaled continuum at Υ(nS) for n=1, 2, and 3.

$M_{\mu\mu}/E_{cm}$



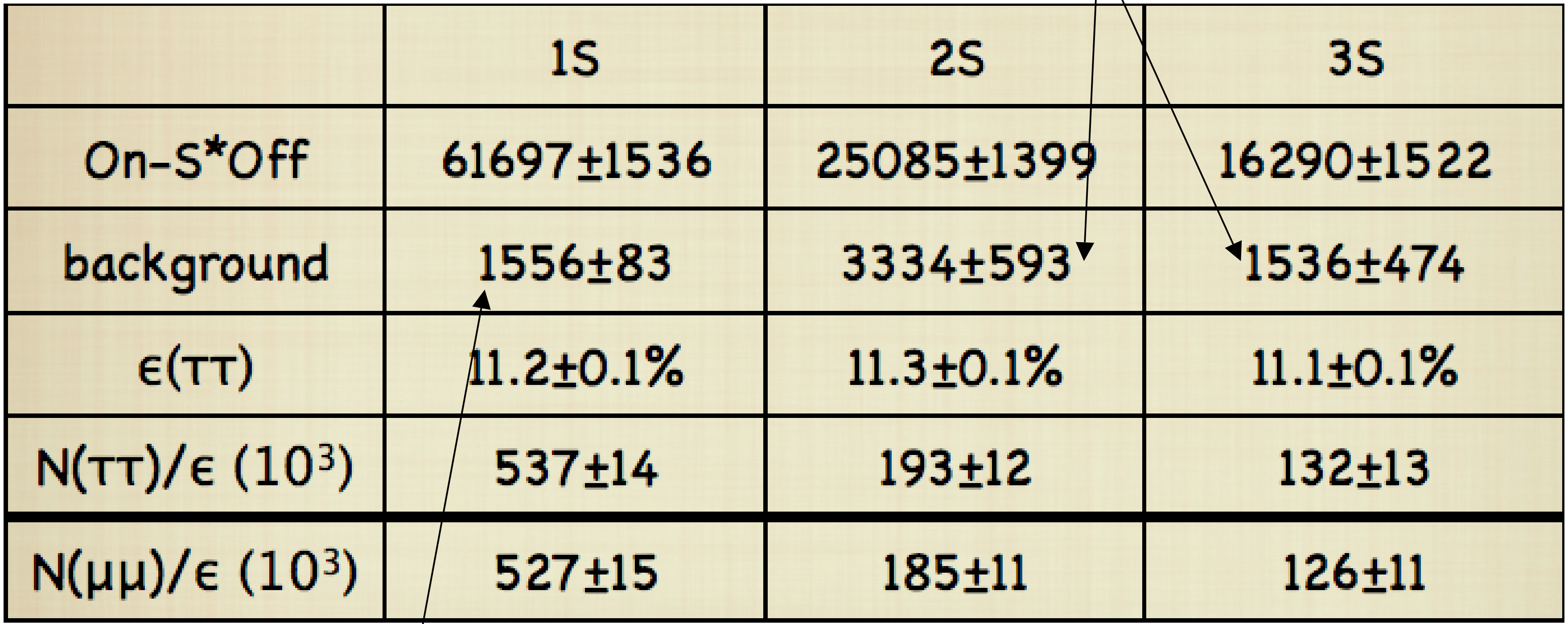
- Scaled continuum data (solid histograms)
- On-resonance data (points)

Similarly, clear excesses are seen in mu-pairs

Step 3: obtaining R(nS)

Sum of all clasifications

- The remaining backgrounds are due to cascade decays (e.g. $\Upsilon(2S) \to \Upsilon(1S)\, X$, $\Upsilon(1S) \to \tau\tau$).

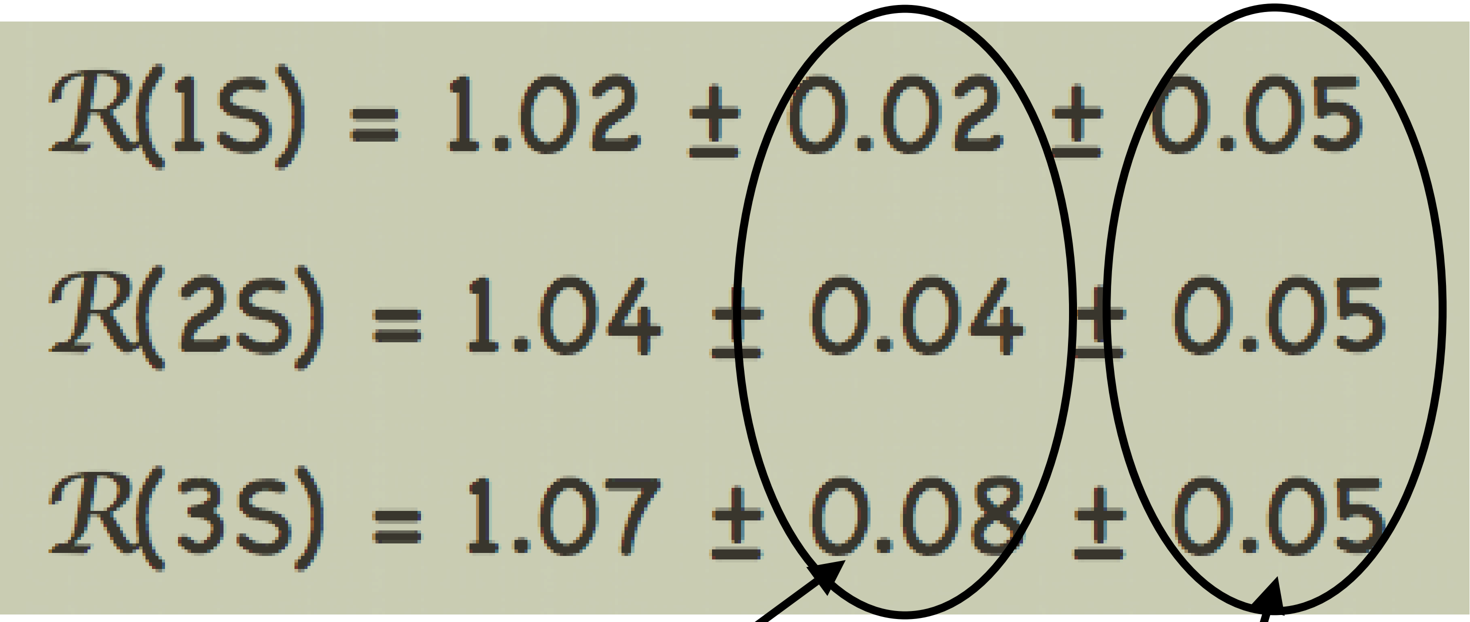


	1S	2S	3S
On-S*Off	61697±1536	25085±1399	16290±1522
background	1556±83	3334±593	1536±474
$\epsilon(\tau\tau)$	11.2±0.1%	11.3±0.1%	11.1±0.1%
$N(\tau\tau)/\epsilon\ (10^3)$	537±14	193±12	132±13
$N(\mu\mu)/\epsilon\ (10^3)$	527±15	185±11	126±11

- From non l^+l^-

- Backgrounds were estimated based on MC simulation.

Final R(nS)
$= \mathcal{B}(\Upsilon(nS) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$



$$\mathcal{R}(1S) = 1.02 \pm 0.02 \pm 0.05$$

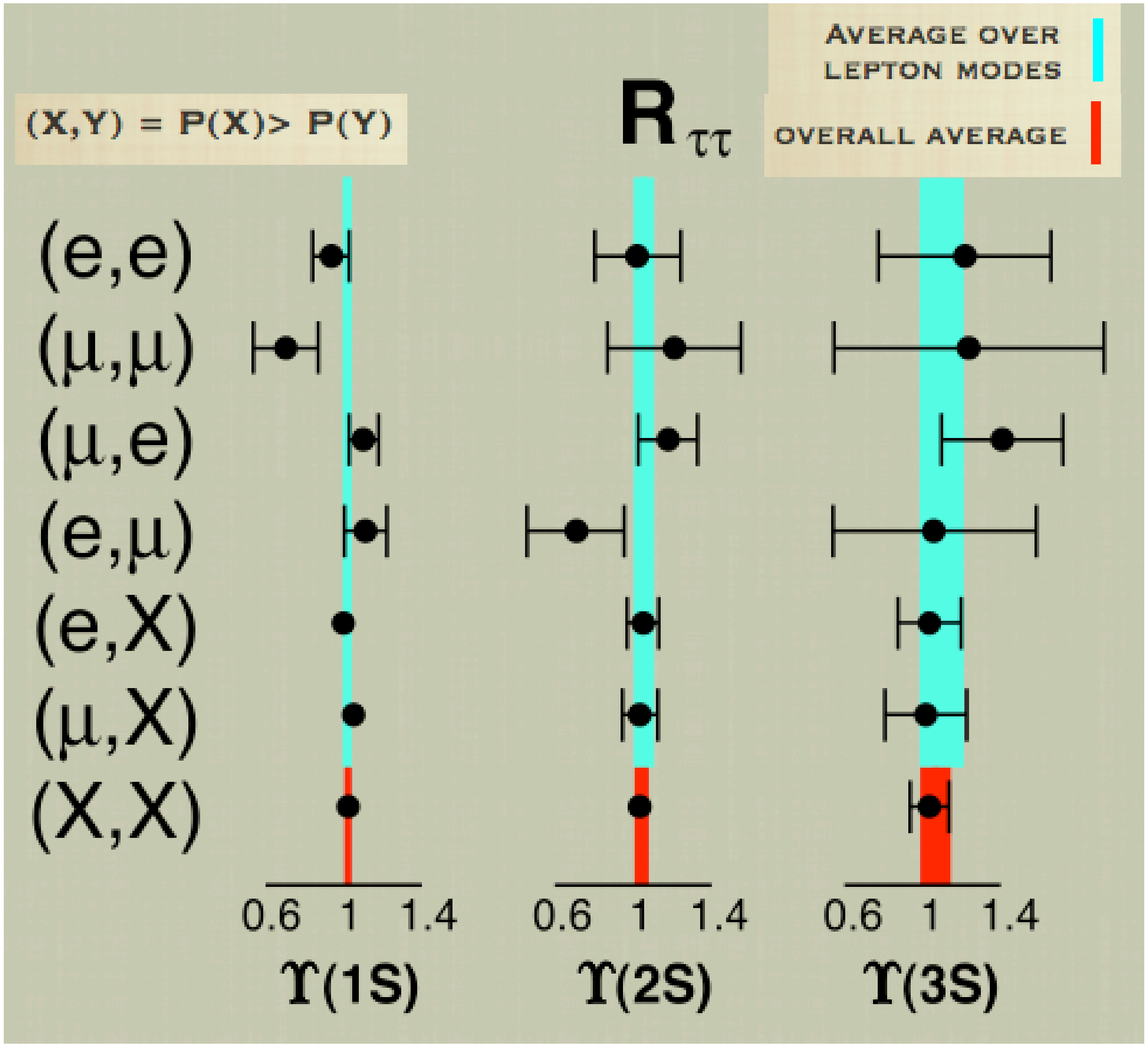
$$\mathcal{R}(2S) = 1.04 \pm 0.04 \pm 0.05$$

$$\mathcal{R}(3S) = 1.07 \pm 0.08 \pm 0.05$$

Statistical: Mostly due to scaled continuum subtractions

Systematics: Domnated by τ selection criteria (2.9%) and trigger (1.6%)

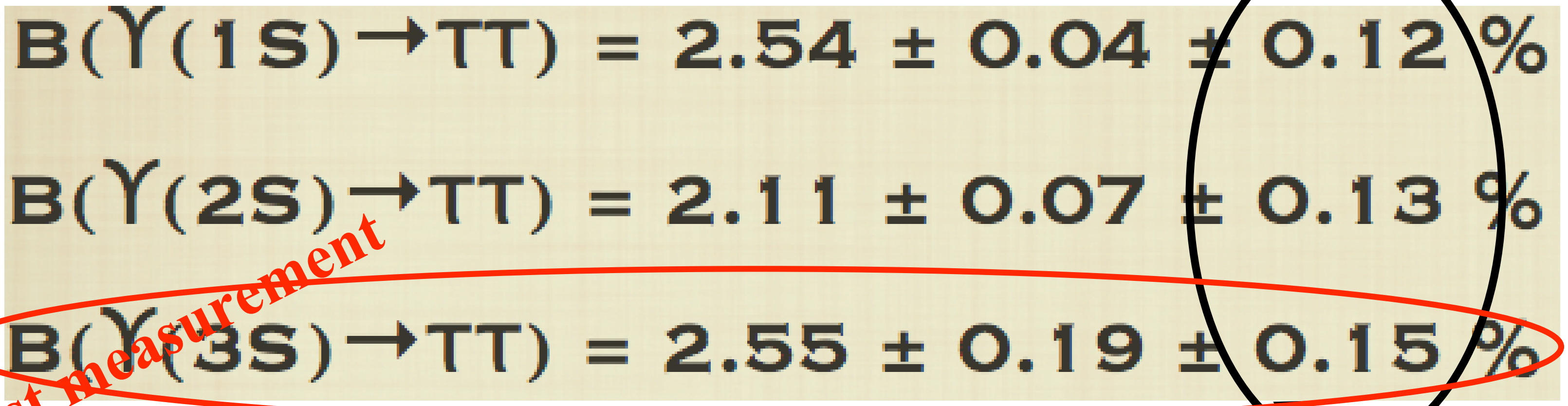
R(nS) for each decay modes



Good consistency for all modes

Step4: extracting $B(\Upsilon(nS) \to \tau\tau)$

With R(nS) and CLEO's published $B(\Upsilon(nS) \to \mu\mu)$ (PRL94,012001(2005)), we have:



$$B(\Upsilon(1S) \to \tau\tau) = 2.54 \pm 0.04 \pm 0.12\ \%$$

$$B(\Upsilon(2S) \to \tau\tau) = 2.11 \pm 0.07 \pm 0.13\ \%$$

$$B(\Upsilon(3S) \to \tau\tau) = 2.55 \pm 0.19 \pm 0.15\ \%$$

First measurement

Systematics + statistical uncertainty from $B(\Upsilon(nS) \to \mu\mu)$

Published in PRL98, 052002 (2007)

Upper limit on the Higgs contribution

"R-1" can be used to set an upper limit on:

$$B_H = B(\Upsilon(1S) \rightarrow \gamma A^0) \cdot B(A^0 \rightarrow \tau^+\tau^-)$$
$$= (R(1S)-1) \cdot B(\Upsilon(1S) \rightarrow \mu^+\mu^-) \cdot (\varepsilon_{\tau\tau}/\varepsilon_H)$$

$\varepsilon_{\tau\tau}$ is the selection efficiency for $\Upsilon(1S) \rightarrow \tau^+\tau^-$

ε_H is the selection efficiency for Higgs mediated decay assuming $M(\Upsilon(1S)) - M(A^0) \sim 100$MeV and $\Gamma(A^0) \sim 5$MeV:

$$B_H < 0.27\% \text{ at } 95\% \text{ C.L.}$$

No obvious peaks were seen in photon spectra of $\Upsilon(2S)$ and $\Upsilon(3S)$ data.

Search for Lepton Flavor Violation
in
$\Upsilon(nS) \rightarrow \mu\, \tau$

Lepton Flavor Violation (LFV)

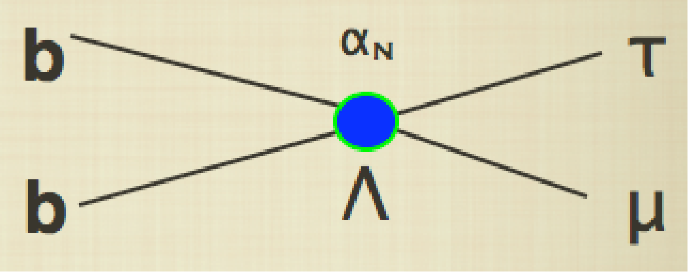
- **LFV is forbidden in the standard model.**
- **After discovering neutrinos have mass, hence oscillations, it MAY BE natural to think or look for LFV beyond the SM (or BSM).**

Lepton Flavor Violation (LFV)

- **W/ Effective Field Theory, Z.K. Silagadze (Phys.Scripta 64,128 (2001)) relates LFV BF of ϒ decays to the scale Λ of LFV BSM physics via:**

$$\frac{B(\Upsilon \to \mu\tau)}{B(\Upsilon \to \mu\mu)} \propto (\alpha_N/\alpha)^2 (M_\Upsilon/\Lambda)^4$$

α is fine structure constant and
α_N is the effective LFV coupling



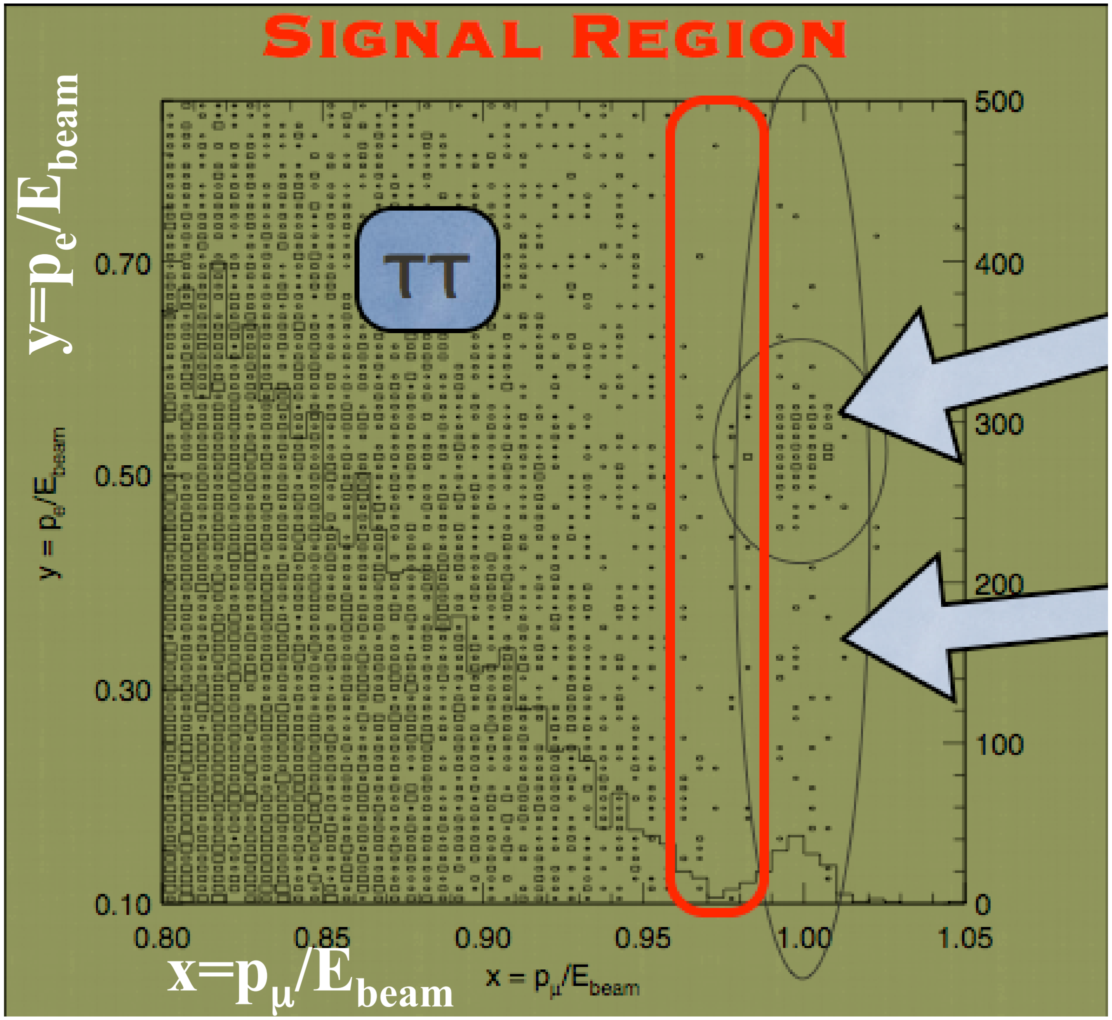
$\Upsilon(nS) \rightarrow \mu\tau$

- **Look for $\Upsilon(nS) \rightarrow \mu\tau$, $\tau \rightarrow e\nu_e\nu_\tau$**
- **Demand two tracks**
  - **One needs to be IDed as a μ (muon-chamber) $p_\mu/E_{beam} \sim 1$**
  - **For electrons, use information from E/p and dE/dx**
- **To select signal candidate events, maximize the likelihood function:**

$$\mathcal{L} = e^{-N_{evnt}} \Pi_{evnt} \left(\Sigma N_i \mathcal{P}_i (X|S) \right)$$

  - **Use product PDF:** $\mathcal{P}(p_\mu) \times \mathcal{P}(p_e) \times \mathcal{P}(dE/dx(e)) \times \mathcal{P}(E/p(e))$
  - **Sum over signal events plus 3 classes of bkg events: ττ, μμ + hard γ, and μ→e (see the next slide).**

Υ(4S) data (control sample)

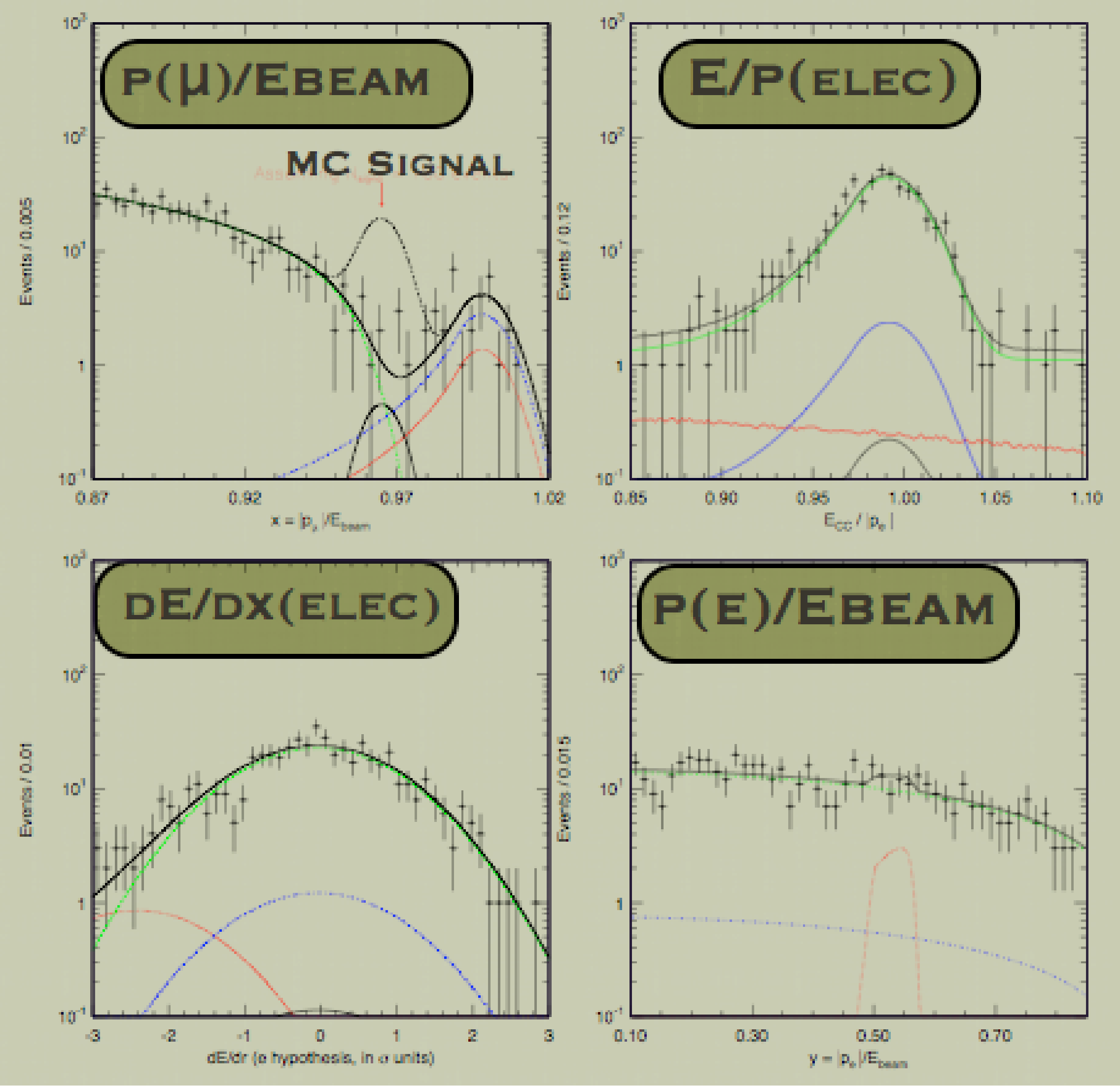


Muon pairs with hard bremsstrahlung. The photon his CC → peaks in E/p.

Muon pairs with decay to e in flight.

PDF shapes were extracted from Υ(4S) and continuum data.

Fitting to Υ(1S) data



🟩 TT

🟥 μμ hard γ

🟦 μμ, decay in flight

PRELIMINARY LFV results

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
$B(\Upsilon(nS)\to\mu\tau)$ @ 95% CL ($\times10^{-6}$)	<6.0	<24.2	<23.4
$B(\Upsilon(nS)\to\mu\tau)/ B(\Upsilon(nS)\to\mu\mu)$	<0.00025	<0.0018	<0.0015
Λ @ 95% CL Lower Limits in TeV with $\alpha_N=1$	>1.29	>0.84	>0.93

- **Largest source of syst: PDF shape (up to 15%)**
- **Assuming $\alpha_N=1$, these BRs set lower limit on $\Lambda\sim1$TeV.**

Summary

- **Measured $B(\Upsilon(\mathrm{nS}) \rightarrow \tau\tau)/B(\Upsilon(\mathrm{nS}) \rightarrow \mu\mu)$ to be consistent with 1**
  - **The measured $B(\Upsilon(2\mathrm{S}) \rightarrow \tau\tau)$ is the most precise to date.**
  - **$B(\Upsilon(3\mathrm{S}) \rightarrow \tau\tau)$ was measured for the first time.**
- **Set limit on CP-odd Higgs in $\Upsilon(1\mathrm{S})$ region.**
- **Searched for LFV. Preliminary results are; $B(\Upsilon(\mathrm{nS}) \rightarrow \mu\tau) \sim< 10^{-5}$ at 95% CL UL.**