# A Search for Lepton Flavor Violation in Upsilon Decays with the CLEO Detector

(reporting preliminary results, analysis approved by the collaboration, to be submitted to PRL)

$$\Upsilon \to \mu\,\tau, \quad \tau \to \nu_\tau \bar{\nu}_e\, e$$

Vladimir Savinov

University of Pittsburgh

on behalf of CLEO collaboration

# Noeter's Theorem, the Language of Quantum Field Theory, Conservation Laws and the Breaking of Global Symmetries

QED example shows how the invariance under local, i.e. space-dependent rotation introduces new (gauge) field!

Global symmetries of the Lagrangian do NOT correspond to new gauge fields, however, they still have conservation laws associated with them. What if they are broken?

$$\Upsilon(\mathbf{nS}) \to \tau^- \mu^+$$

$$\tau^- \to \mathbf{e}^- \gamma \quad \tau^- \to \mathbf{e}^+ \mathbf{e}^- \mathbf{e}^- \quad \tau^- \to \mu^+ \mu^- \mathbf{e}^-$$

$$\tau^- \to \mu^- \gamma \quad \tau^- \to \mu^+ \mu^- \mu^- \quad \tau^- \to \mathbf{e}^+ \mu^- \mu^-$$

neutrinoless double beta decay

proton decay

Lepton number, lepton flavor numbers and baryon numbers are conserved at low energies, these are accidental SM symmetries

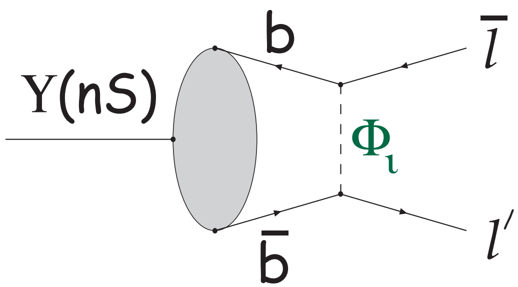
Standard Model: B and L (but not B-L) are violated non-perturbatively

Lepton flavor is violated at very high energies - neutrino oscillations are living proof - so what do we search for in our analysis? What kind of New Physics? Any model?

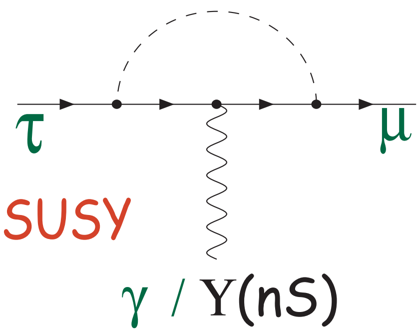
We search for LFV processes that would occur at "intermediate" energies, between 1 TeV and below GUT scale... LFV at such energies is possible (anything is), e.g. in SUSY (even with conserved R-parity)

(LSP interpretation of Dark Matter is OK if L and B are conserved)

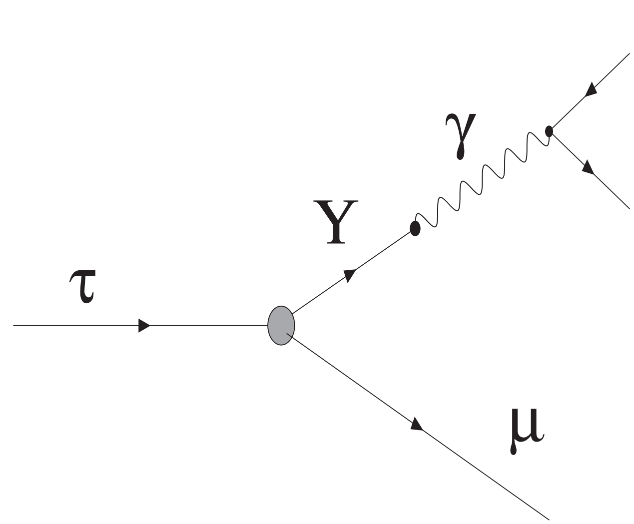
## LFV Decays of $\tau$ lepton and Upsilon Mesons

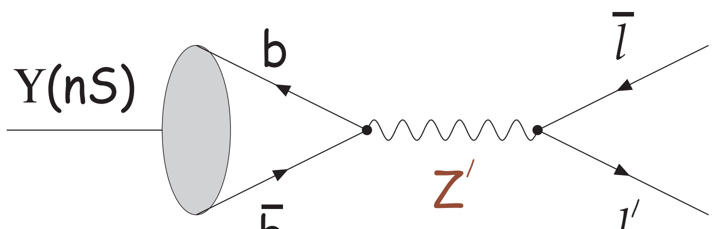



Leptoquarks or some (other) scalars




Unitarity arguments




Additional vector bosons and CP-odd Higgs(es)

# Effective Field Theory Approach

D.Black, T.Han, H.-J. He and M.Sher: PRD 66, 053002 (2002)

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \Delta\mathcal{L}$$

$$\Delta\mathcal{L} = \Delta\mathcal{L}^{(6)}_{\tau\mu} = \sum_{j,\alpha,\beta} \frac{\mathcal{C}^{j}_{\alpha\beta}}{\Lambda^2} (\overline{\mu}\Gamma_j \tau)(\overline{q}^{\alpha}\Gamma_j q^{\beta})$$

$$\Gamma_j \in (1, \gamma_5, \gamma_\sigma, \gamma_\sigma\gamma_5)$$

$$\Delta\mathcal{L}^{\mathrm{linear}}_{\tau\mu(6)} = \sum^{j}_{\alpha,\beta,\chi,\zeta} \frac{\mathcal{C}^{j\chi\zeta}_{\alpha\beta}}{\Lambda^2} (\overline{\mu_\chi \Gamma_j \tau_\chi})(\overline{q_\zeta}^{\alpha}\Gamma_j q^{\beta}_{\zeta})$$

$$\mathcal{G}_{\mathrm{SM}} = SU(2)_L \otimes U(1)_Y \qquad \chi, \zeta = L, R$$

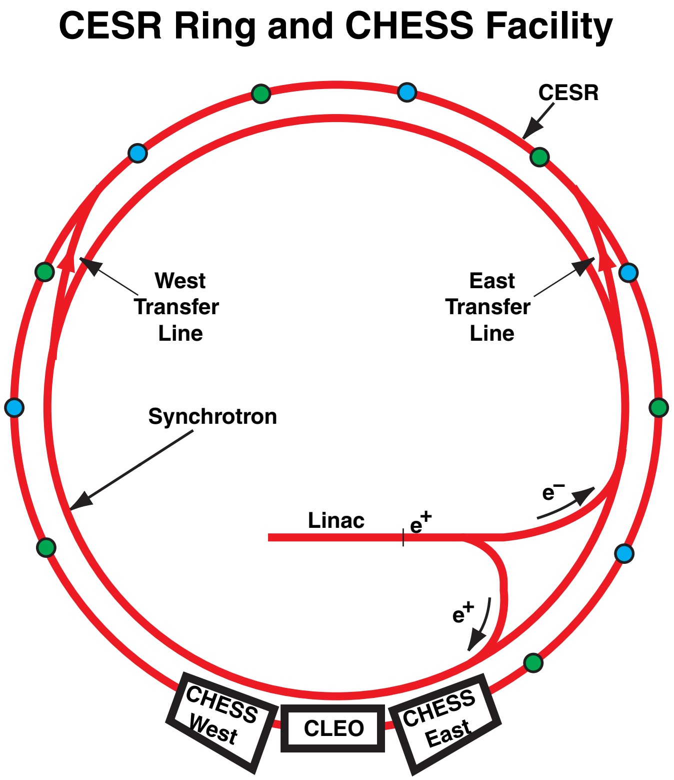
# D.Black, T.Han, H.-J. He and M.Sher: PRD 66, 053002 (2002)

| Bound | 1 | $\gamma_5$ | $\gamma_\sigma$ | $\gamma_\sigma\gamma_5$ |
|---|---|---|---|---|
| $\bar{u}u$ | 2.6 TeV ($\tau\to\mu\pi^+\pi^-$) | 12 TeV ($\tau\to\mu\pi^0$) | 12 TeV ($\tau\to\mu\rho$) | 11 TeV ($\tau\to\mu\pi^0$) |
| $\bar{d}d$ | 2.6 TeV ($\tau\to\mu\pi^+\pi^-$) | 12 TeV ($\tau\to\mu\pi^0$) | 12 TeV ($\tau\to\mu\rho$) | 11 TeV ($\tau\to\mu\pi^0$) |
| $\bar{s}s$ | 1.5 TeV ($\tau\to\mu K^+K-$) | 9.9 TeV ($\tau\to\mu\eta$) | 14 TeV ($\tau\to\mu\phi$) | 9.5 TeV ($\tau\to\mu\eta$) |
| $\bar{s}d$ | 2.3 TeV ($\tau\to\mu K^+\pi^-$) | 3.7 TeV ($\tau\to\mu K^0$) | 13 TeV ($\tau\to\mu K^\star$) | 3.6 TeV ($\tau\to\mu K^0$) |
| $\bar{b}d$ | 2.2 TeV ($B\to\pi\mu\tau$) | 9.3 TeV ($B\to\mu\tau$) | 2.2 TeV ($B\to\pi\mu\tau$) | 8.2 TeV ($B\to\mu\tau$) |
| $\bar{b}s$ | 2.6 TeV ($B\to K\mu\tau$) | 2.8 TeV ($B_s\to\mu\tau$) | 2.6 TeV ($B\to K\mu\tau$) | 2.5 TeV ($B_s\to\mu\tau$) |

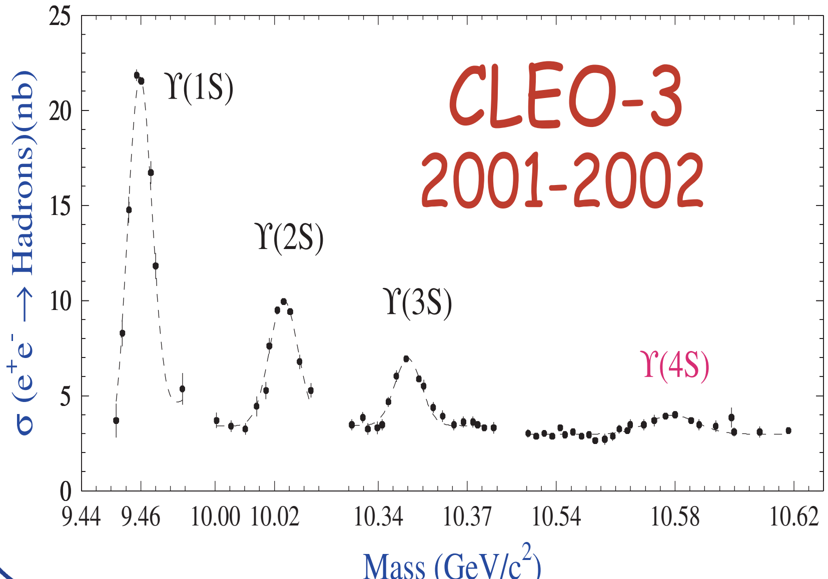
| Bound | 1 | $\gamma_5$ | $\gamma_\sigma$ | $\gamma_\sigma\gamma_5$ |
|---|---|---|---|---|
| $\bar{t}c$ | 190 GeV ($t\to c\mu\tau$) | 190 GeV ($t\to c\mu\tau$) | 310 GeV ($B\to\mu\tau$) | 310 GeV ($B\to\mu\tau$) |
| $\bar{t}u$ | 190 GeV ($t\to u\mu\tau$) | 190 GeV ($t\to u\mu\tau$) | 650 GeV ($B\to\mu\tau$) | 650 GeV ($B\to\mu\tau$) |
| $\bar{c}u$ | ⋆ | ⋆ | 550 GeV ($\tau\to\mu\phi$) | 550 GeV ($\tau\to\mu\phi$) |
| $\bar{c}c$ | ⋆ | ⋆ | 1.1 TeV ($\tau\to\mu\phi$) | 1.1 TeV ($\tau\to\mu\phi$) |
| $\bar{b}b$ | ⋆ | ⋆ | 180 GeV ($\Upsilon\to\mu\tau$) | ⋆ |
| $\bar{t}t$ | ⋆ | ⋆ | 75 GeV ($B\to\mu\tau$) | 120 GeV ($B\to\mu\tau$) |

Before CLEO analysis no experimental information was available that could be used to estimate this BSM contribution directly

# Cornell Electron Storage Ring (CESR)
# Past: Upsilons, now: τ-charm factory

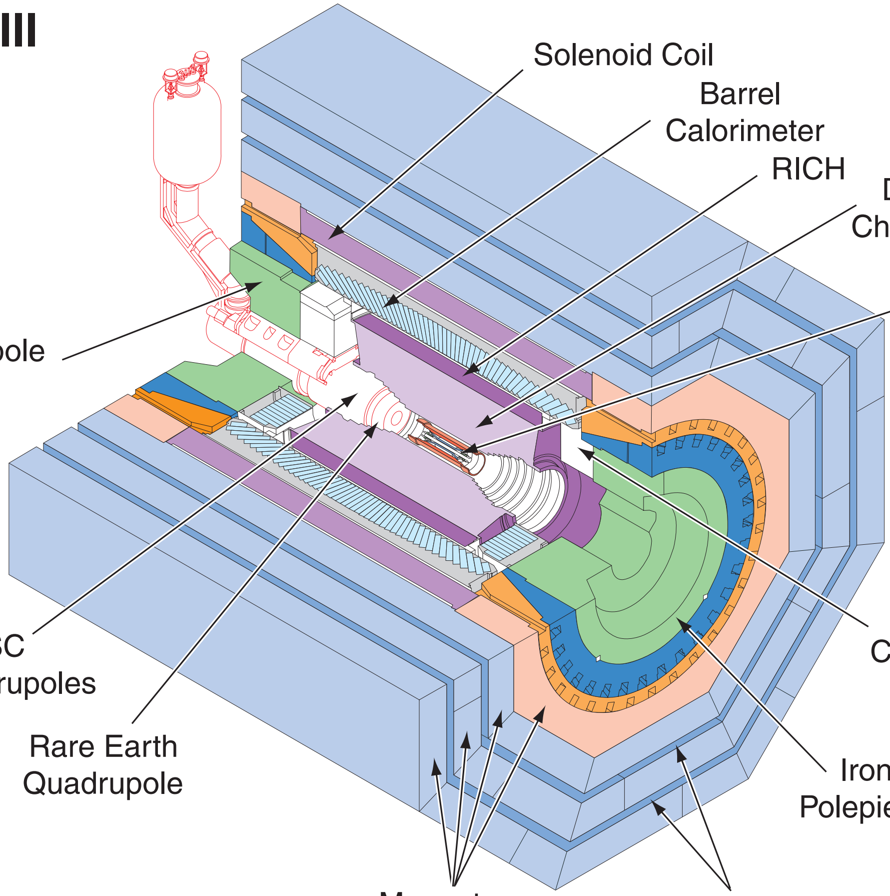



$$\Upsilon \to \mu\,\tau,\quad \tau \to \nu_\tau \bar{\nu}_e\, e$$




# The Detector, Data Sample and CLEOns

CLEO III




CsI EM calorimetry,
muon identification, dE/dx
$\delta p/p$(@5GeV) ~0.8% tracking

21 million Υ(1S)
5.4 million Υ(2S)
5.0 million Υ(3S)

# Analysis Algorithm and Selection Criteria

Exactly two charged tracks

Only one muon candidate (muon ID)

Only one electron candidate (E/|p|, dE/dx)

$$\mathcal{L} = e^{-(N_1+N_2+..+N_M)} \prod_{i=1}^{N_{\mathrm{ev.}}} \sum_{j=1}^{N_M} N_j \mathcal{P}_j(\{x_i\},\{s_j\})$$

Muon momentum normalized to beam energy: $x = \frac{E_\mu}{E_{\mathrm{beam}}}$

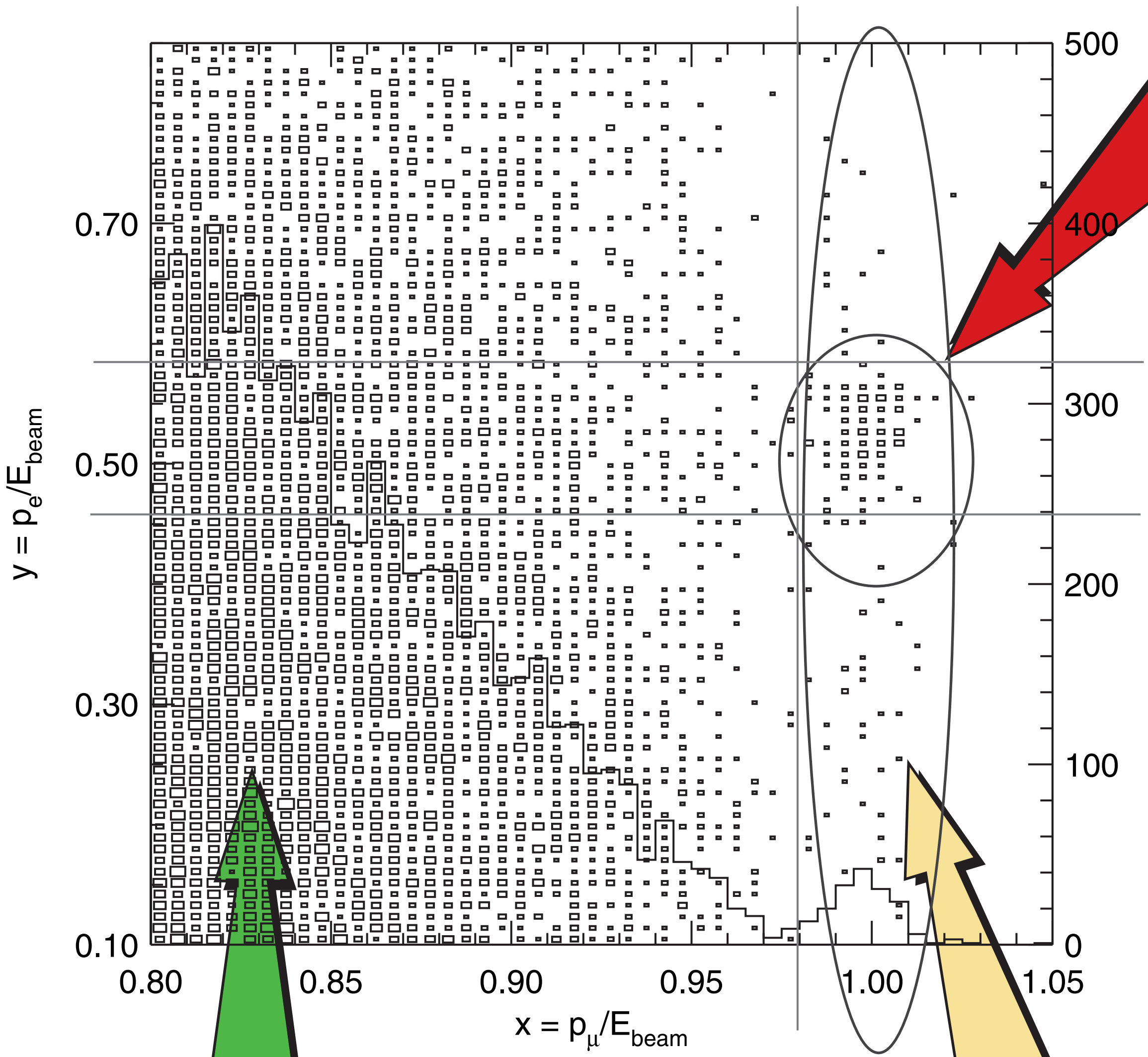
Electron momentum normalized to beam energy: $y = \frac{E_e}{E_{\mathrm{beam}}}$

dEdx measurement for electron candidate

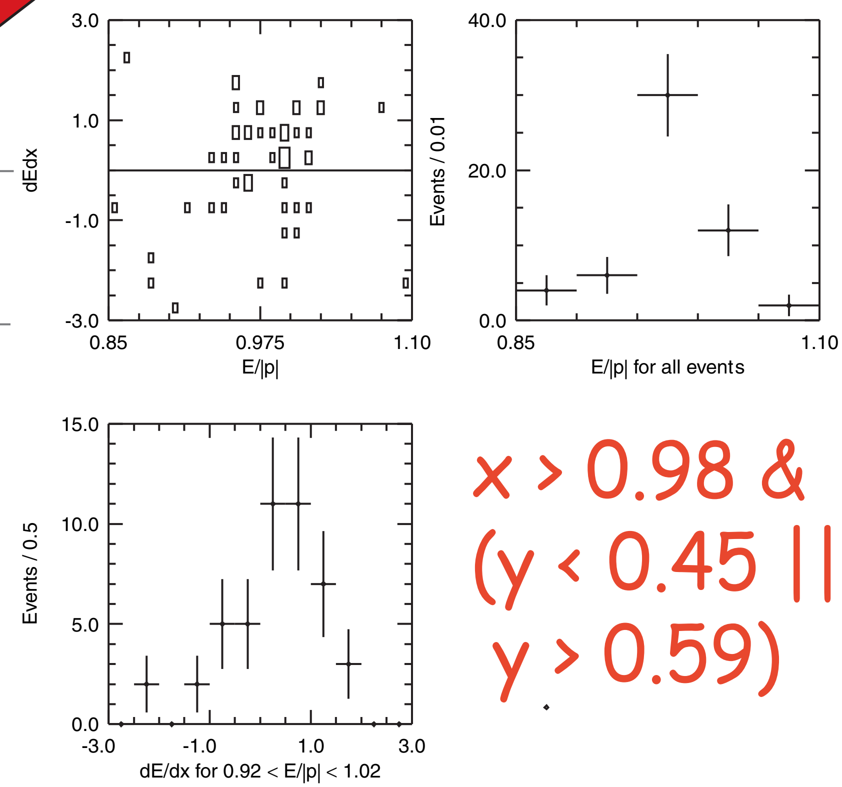
$E/|p|$ for electron candidate

Using Υ(4S) data for efficiency calibration

# Backgrounds arise from tau and muon pairs




Muon pairs with hard bremsstrahlung




on-Υ(4S) data

Tau pairs (irreducible)

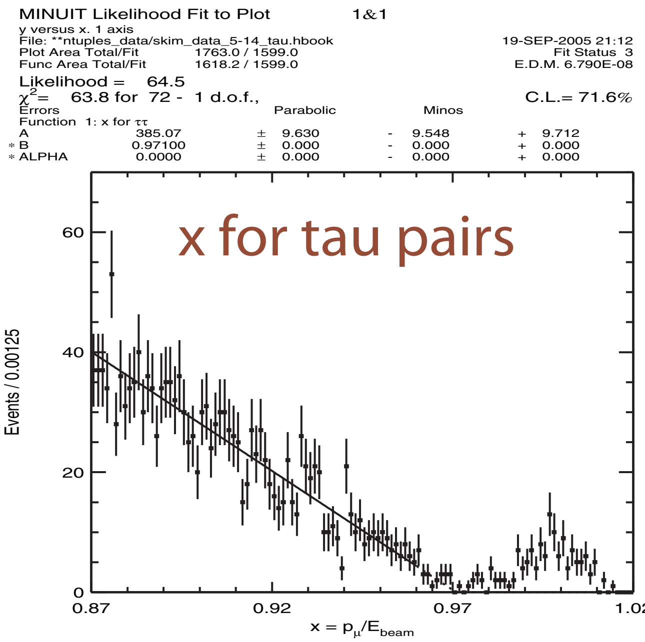
Muon pairs with decay to e in flight

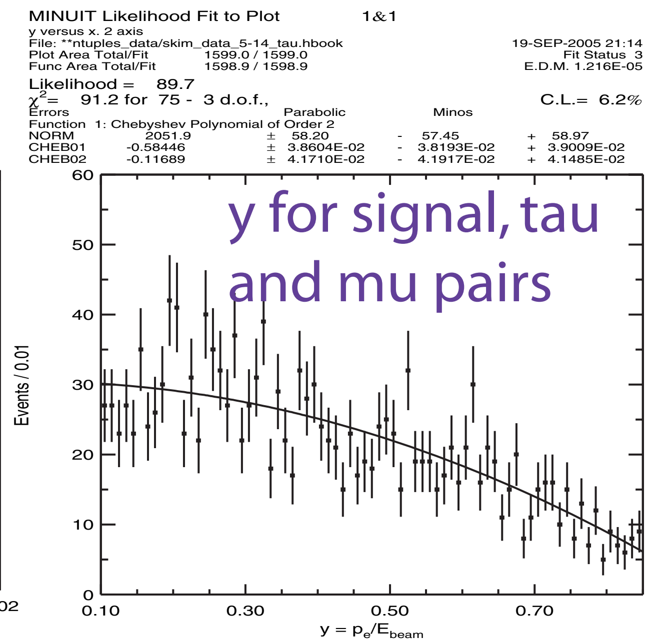
$x > 0.98$ & ($y < 0.45$ || $y > 0.59$)

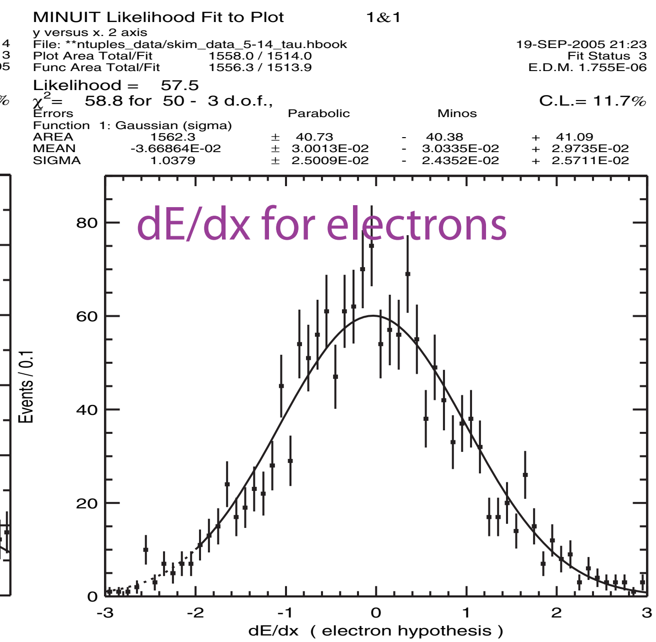
$\beta c\tau$ = 33km -> the fraction of $\mu$ decaying at R < 1m = 3 x E-5

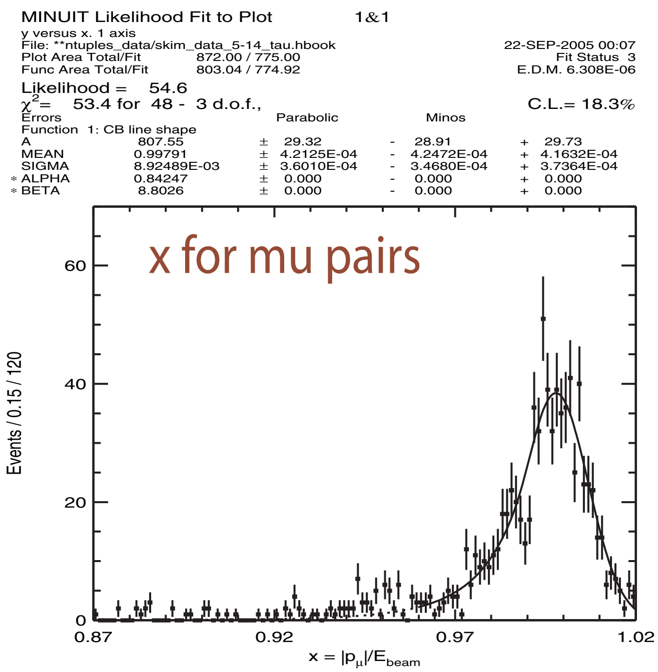
on-Υ(4S): 380 decays!

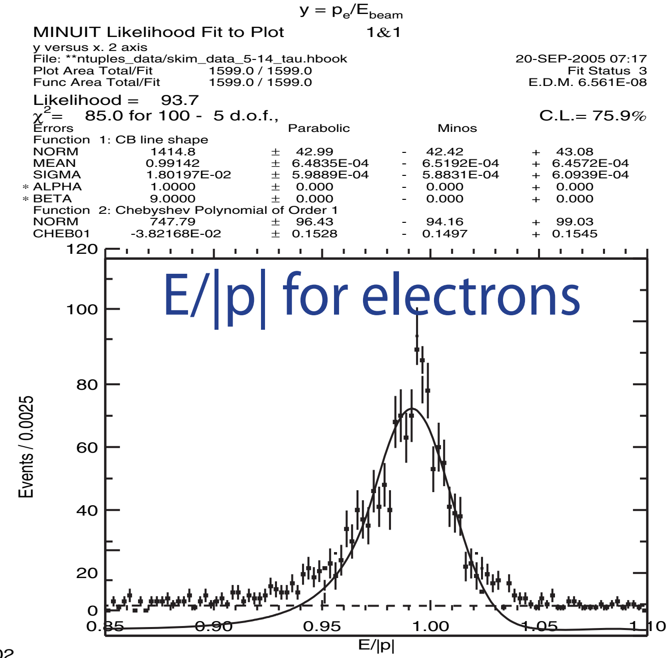
# Most PDFs were measured from Y(4S) data

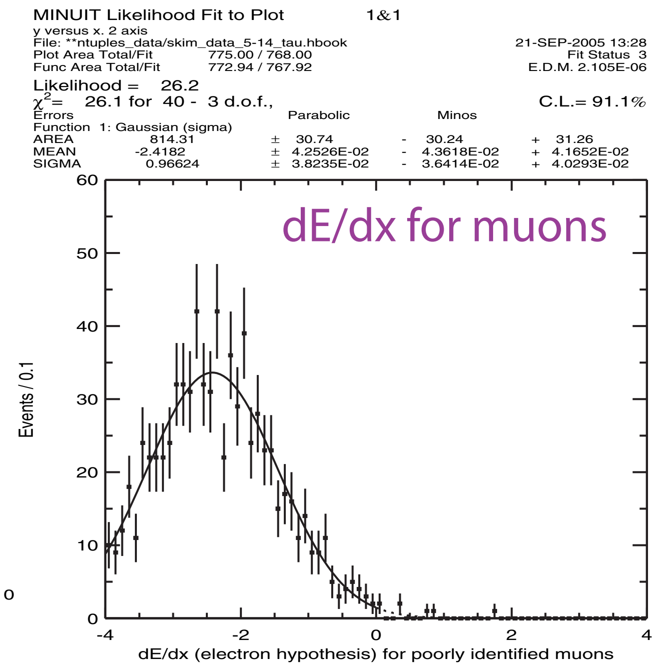


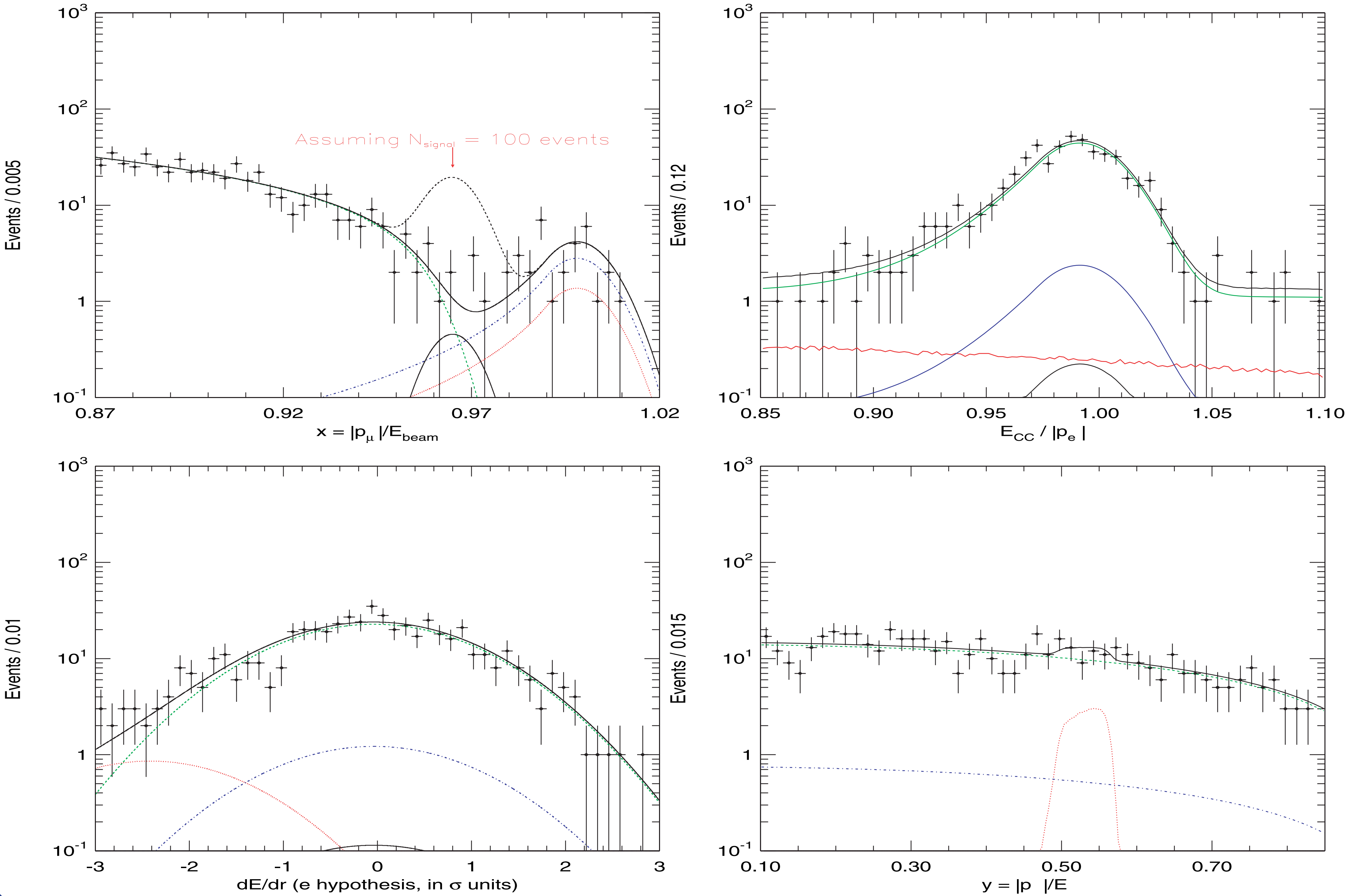



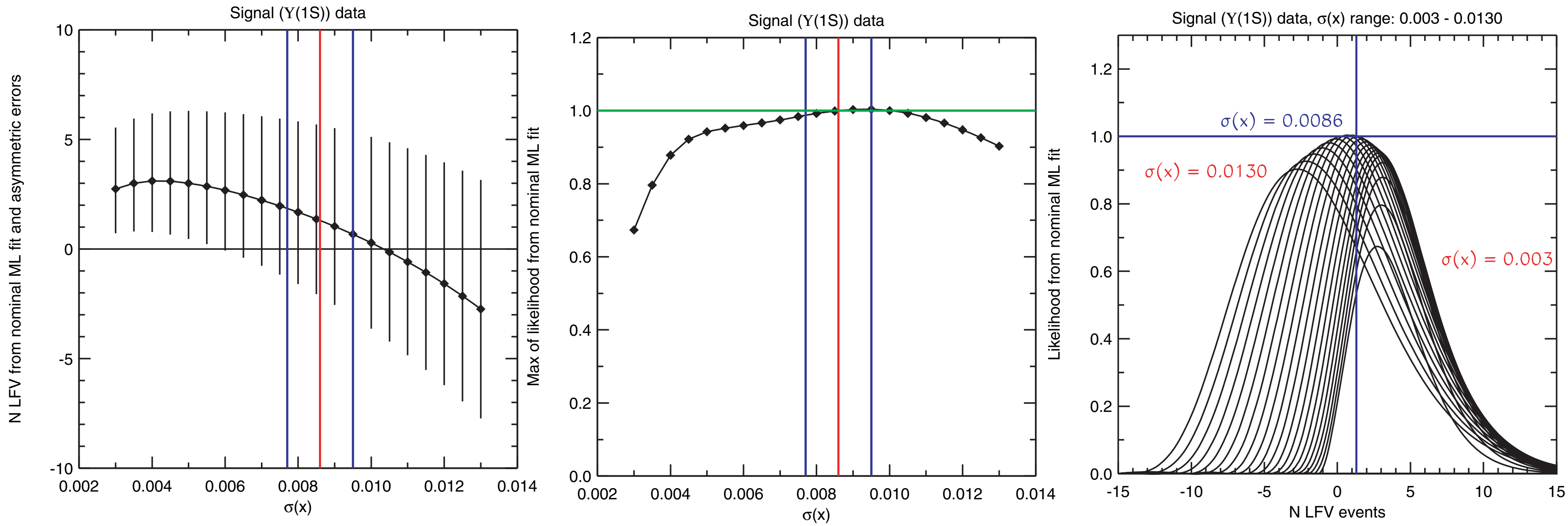



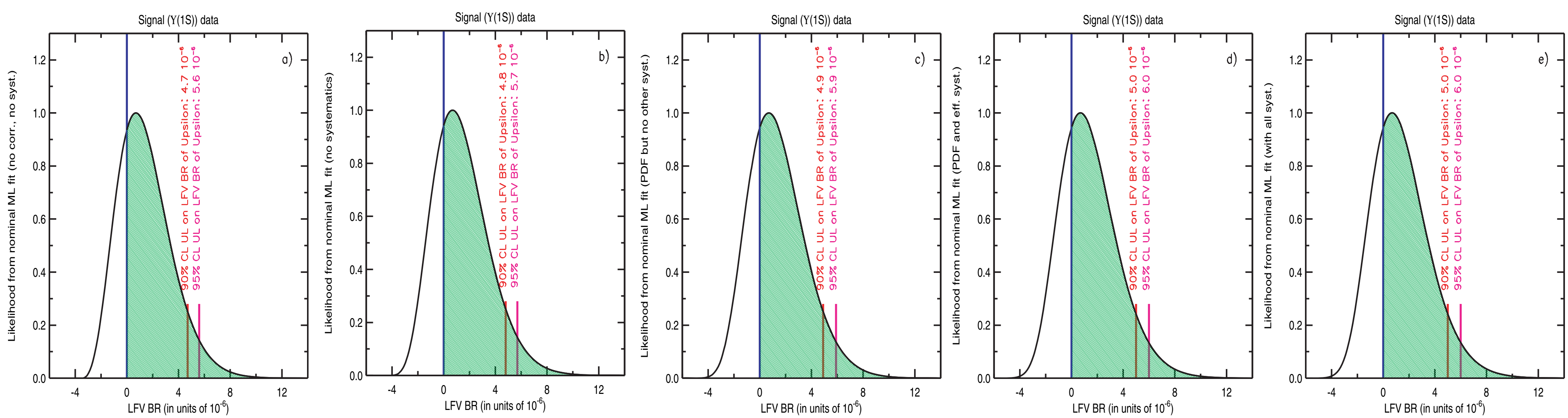
# 4D Four-Components Fits to Υ(1S) Data



# Important (but sooo boring!) details of ML fitting

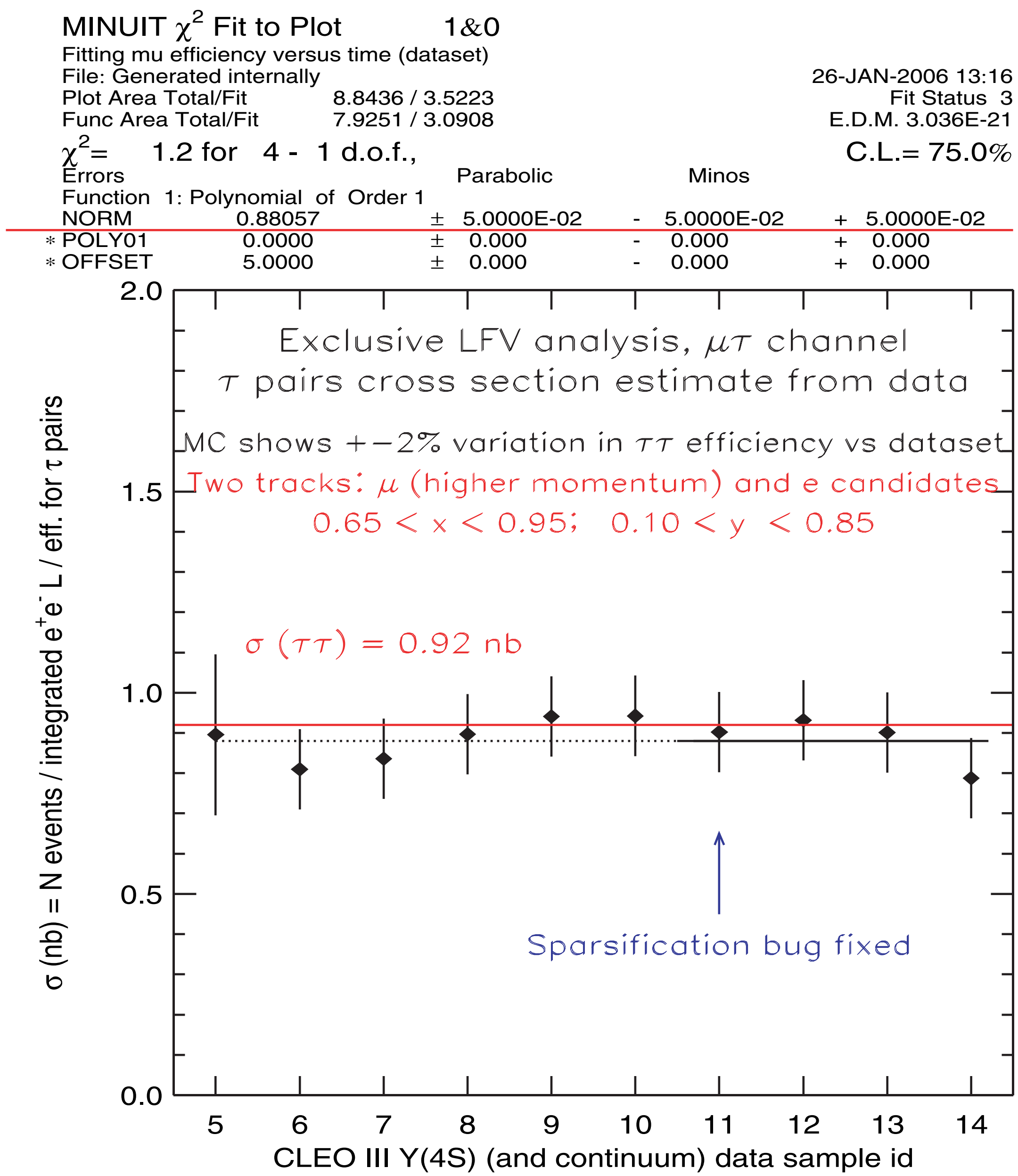



Relative resolution on beam energy-scaled momentum of signal muon candidate




"Evolution" of the likelihood function as more effects are taken into account

# Using the data to calibrate the efficiency



# Preliminary Results

| Resonance | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ |
|---|---|---|---|
| Signal in data (events, 90% CL) | 10.0 | 10.7 | 8.5 |
| Overall efficiency (%, central value) | 8.9 | 8.9 | 8.9 |
| Systematics in efficiency (%, $\sigma$) | 8.5 | 8.5 | 8.5 |
| Overall efficiency (%, -1$\sigma$) | 8.1 | 8.1 | 8.1 |
| Statistics (number of $\Upsilon$'s) | $21 \pm 1$ | $5.4 \pm 0.2$ | $5.0 \pm 0.3$ |
| $\mathcal{B}(\Upsilon \to \mu\tau)$ (90% CL UL, $\times 10^{-6}$) | 5.9 | 24 | 21 |
| With $\Upsilon$ statistics included | 6.2 | 25 | 22 |

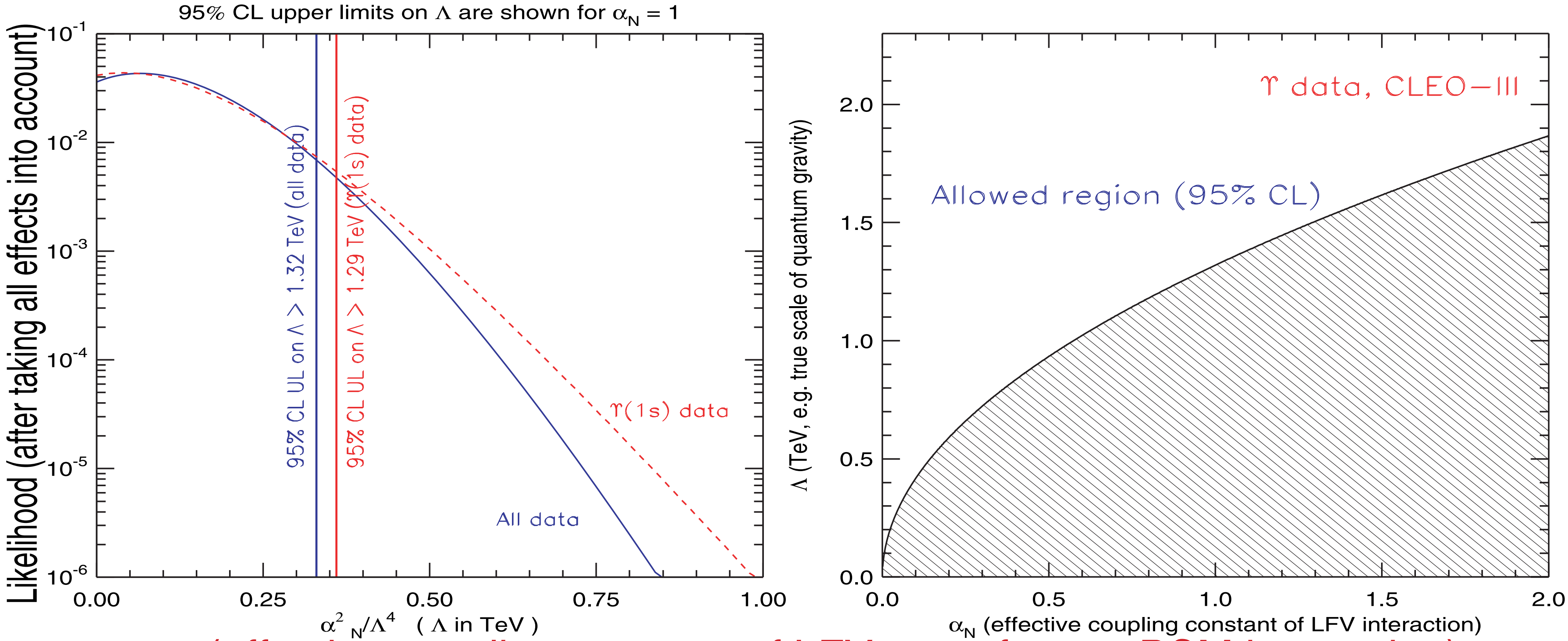
| Resonance | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ |
|---|---|---|---|
| Resonance mass (GeV/c$^2$) | 9.46 | 10.02 | 10.36 |
| $\Gamma(\Upsilon \to \mu\mu)$ (keV, central value) | 1.336 | 0.616 | 0.425 |
| $\Gamma(\Upsilon)$ (keV, central value) | 53.0 | 43.0 | 26.3 |
| $\mathcal{B}(\Upsilon \to \mu\mu)$ ($\times 10^{-3}$) | 25.2 | 14.3 | 16.2 |
| $\mathcal{B}(\Upsilon \to \mu\tau)$ (90% CL UL, $\times 10^{-6}$) | 5.9 | 24 | 21 |
| $\mathcal{B}(\Upsilon \to \mu\tau)/\mathcal{B}(\Upsilon \to \mu\mu)$ | 0.00023 | 0.0017 | 0.0013 |
| $\Lambda$ from Equation 2 assuming $\alpha_N = 1.0$ (90% CL *lower* limit, TeV) | 1.3 | 0.84 | 0.93 |

# No LFV discovered in decays of Upsilon Mesons

$$\frac{\Gamma(\Upsilon \to \mu^{\pm}\tau^{\mp})}{\Gamma(\Upsilon \to \mu^{+}\mu^{-})} = \frac{1}{2e_b^2}\left(\frac{\alpha_N}{\alpha}\right)^2\left(\frac{M_\Upsilon}{\Lambda}\right)^4$$

Leading-order estimate, e.g. from Z.Silagadze (*Phys. Scripta* 64 (2001), 128)

# Exclusion Plots for Generic LFV BSM Physics




$\alpha_N$ (effective coupling constant of LFV part of some BSM interaction)

# Back to M.Sher's et al. effective theory approach

| Bound | 1 | $\gamma_5$ | $\gamma_\sigma$ | $\gamma_\sigma\gamma_5$ |
|---|---|---|---|---|
| $\bar{t}c$ | 190 GeV ($t\to c\mu\tau$) | 190 GeV ($t\to c\mu\tau$) | 310 GeV ($B\to\mu\tau$) | 310 GeV ($B\to\mu\tau$) |
| $\bar{t}u$ | 190 GeV ($t\to u\mu\tau$) | 190 GeV ($t\to u\mu\tau$) | 650 GeV ($B\to\mu\tau$) | 650 GeV ($B\to\mu\tau$) |
| $\bar{c}u$ | ⋆ | ⋆ | 550 GeV ($\tau\to\mu\phi$) | 550 GeV ($\tau\to\mu\phi$) |
| $\bar{c}c$ | ⋆ | ⋆ | 1.1 TeV ($\tau\to\mu\phi$) | 1.1 TeV ($\tau\to\mu\phi$) |
| $\bar{b}b$ | ⋆ | ⋆ | 180 GeV ($\Upsilon\to\mu\tau$) | ⋆ |
| $\bar{t}t$ | ⋆ | ⋆ | 75 GeV ($B\to\mu\tau$) | 120 GeV ($B\to\mu\tau$) |

BES($J/\psi$) PLB 598(2004)172-177:
$\Lambda >$ 0.5 TeV

Notice that BES and CLEO results are probing different operators, so the direct comparison between the results would be unfair

CLEO $\Upsilon$ results: $\Lambda >$ 1.3 TeV

# More Results, Some Musings and the Summary

No Lepton Flavour Violation discovered in Upsilon Decays…
Though obtained another limit on the scale of BSM physics…

No trip to Stockholm for anybody. The question is if we came any closer to understanding if Dark Matter is due to SUSY's LSPs

We actually searched for Dark Matter particles pair production:

PHYSICAL REVIEW D **75,** 031104(R) (2007)

**Search for invisible decays of the $\Upsilon(1S)$ resonance**

We present a measurement of the branching fraction of invisible $\Upsilon(1S)$ decays, using 1.2 $\mathrm{fb}^{-1}$ of data collected at the $\Upsilon(2S)$ resonance with the CLEO III detector at CESR. After subtracting expected backgrounds from events that pass selection criteria for invisible $\Upsilon(1S)$ decay in $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, we deduce a 90% C.L. upper limit of $\mathcal{B}[\Upsilon(1S) \to \text{invisible}] < 0.39\%$.

Using only WMAP result on the relic density of the universe

B. McElrath, Phys. Rev. D **72**, 103508 (2005)

estimated $\mathcal{B}[\Upsilon(1S) \to \chi\chi] \approx 0.41\%$

insignificant SM rate: $\mathcal{B}[\Upsilon(1S) \to \nu\bar{\nu}]$ is of order $10^{-5}$

Didn't find LFV, didn't find Dark Matter, (probably) have to look elsewhere…