

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)

$$Y \rightarrow \mu \tau, \tau \rightarrow \nu_\tau \bar{\nu}_e e$$



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on behalf of CLEO collaboration



Noether'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?

$$\Upsilon(\text{nS}) \rightarrow \tau^- \mu^+$$

$$\begin{array}{lll} \tau^- \rightarrow e^- \gamma & \tau^- \rightarrow e^+ e^- e^- & \tau^- \rightarrow \mu^+ \mu^- e^- \\ \tau^- \rightarrow \mu^- \gamma & \tau^- \rightarrow \mu^+ \mu^- \mu^- & \tau^- \rightarrow e^+ \mu^- \mu^- \end{array}$$

neutrinoless double beta decay

proton decay

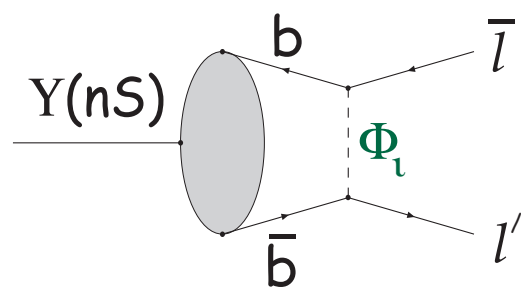
Lepton number, lepton flavor numbers and baryon numbers are conserved at low energies, these are accidental SM symmetries

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

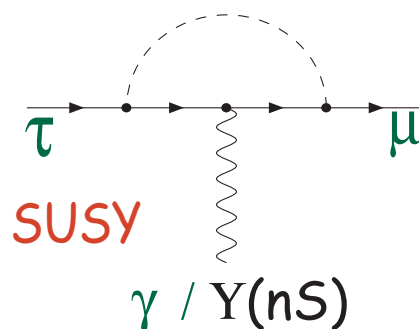
Lepton flavor **is** violated at very high energies - neutrino oscillations are living proof - so what do we search for in our analysis? What kind of New Physics? Any model?

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)

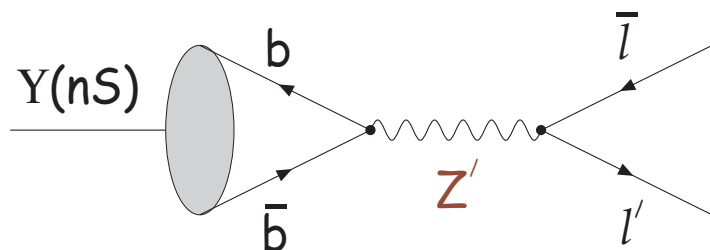
LFV Decays of τ lepton and Upsilon Mesons



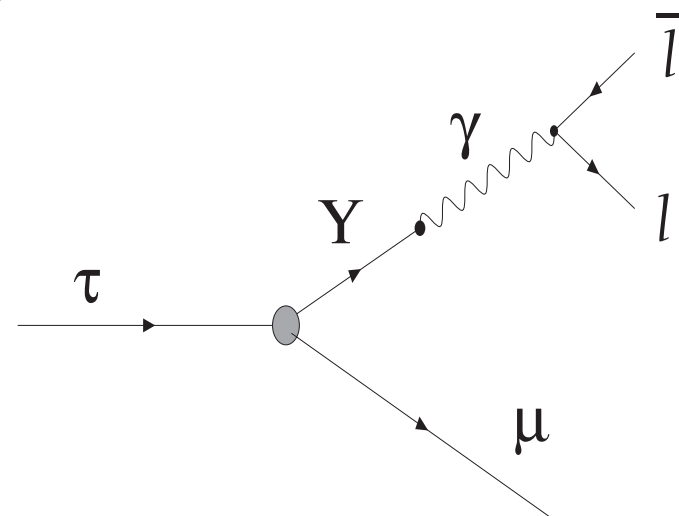
Leptoquarks or some (other) scalars



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)

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

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

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

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

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

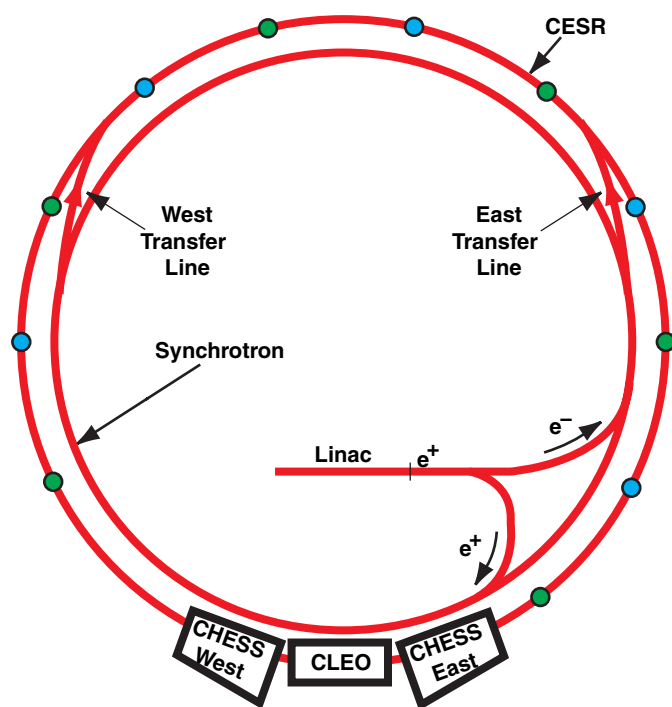


D.Black, T.Han, H.-J. He and M.Sher: PRD 66, 053002 (2002)

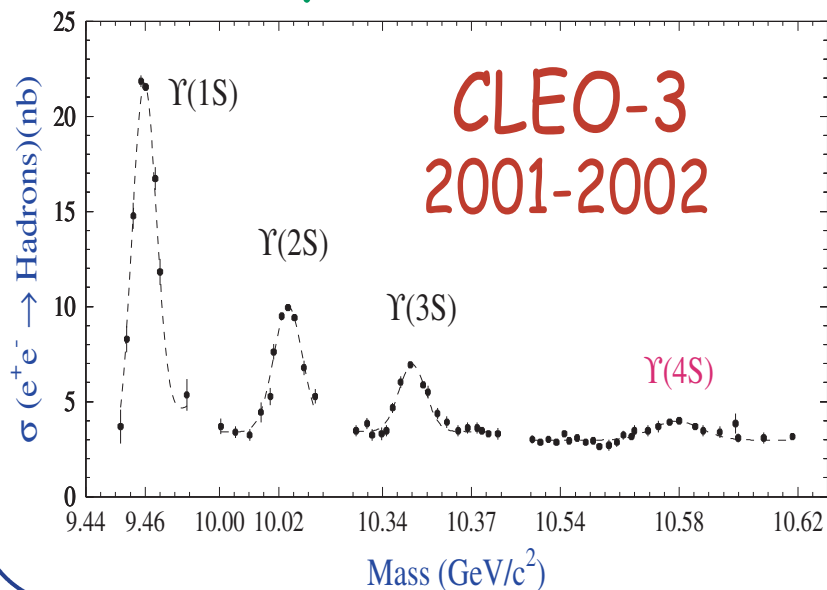
Bound	1	γ_5	γ_σ	$\gamma_\sigma\gamma_5$	Bound	1	γ_5	γ_σ	$\gamma_\sigma\gamma_5$
$\overline{uu}$	2.6 TeV ($\tau \rightarrow \mu \pi^+ \pi^-$)	12 TeV ($\tau \rightarrow \mu \pi^0$)	12 TeV ($\tau \rightarrow \mu \rho$)	11 TeV ($\tau \rightarrow \mu \pi^0$)	$\overline{tc}$	190 GeV ($t \rightarrow c \mu \tau$)	190 GeV ($t \rightarrow c \mu \tau$)	310 GeV ($B \rightarrow \mu \tau$)	310 GeV ($B \rightarrow \mu \tau$)
$\overline{dd}$	2.6 TeV ($\tau \rightarrow \mu \pi^+ \pi^-$)	12 TeV ($\tau \rightarrow \mu \pi^0$)	12 TeV ($\tau \rightarrow \mu \rho$)	11 TeV ($\tau \rightarrow \mu \pi^0$)	$\overline{tu}$	190 GeV ($t \rightarrow u \mu \tau$)	190 GeV ($t \rightarrow u \mu \tau$)	650 GeV ($B \rightarrow \mu \tau$)	650 GeV ($B \rightarrow \mu \tau$)
$\overline{ss}$	1.5 TeV ($\tau \rightarrow \mu K^+ K^-$)	9.9 TeV ($\tau \rightarrow \mu \eta$)	14 TeV ($\tau \rightarrow \mu \phi$)	9.5 TeV ($\tau \rightarrow \mu \eta$)	$\overline{cu}$	★	★	550 GeV ($\tau \rightarrow \mu \phi$)	550 GeV ($\tau \rightarrow \mu \phi$)
$\overline{sd}$	2.3 TeV ($\tau \rightarrow \mu K^+ \pi^-$)	3.7 TeV ($\tau \rightarrow \mu K^0$)	13 TeV ($\tau \rightarrow \mu K^*$)	3.6 TeV ($\tau \rightarrow \mu K^0$)	$\overline{cc}$	★	★	1.1 TeV ($\tau \rightarrow \mu \phi$)	1.1 TeV ($\tau \rightarrow \mu \phi$)
$\overline{bd}$	2.2 TeV ($B \rightarrow \pi \mu \tau$)	9.3 TeV ($B \rightarrow \mu \tau$)	2.2 TeV ($B \rightarrow \pi \mu \tau$)	8.2 TeV ($B \rightarrow \mu \tau$)	$\overline{bb}$	★	★	180 GeV ($Y \rightarrow \mu \tau$)	★
$\overline{bs}$	2.6 TeV ($B \rightarrow K \mu \tau$)	2.8 TeV ($B_s \rightarrow \mu \tau$)	2.6 TeV ($B \rightarrow K \mu \tau$)	2.5 TeV ($B_s \rightarrow \mu \tau$)	$\overline{tt}$	★	★	75 GeV ($B \rightarrow \mu \tau$)	120 GeV ($B \rightarrow \mu \tau$)

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

CESR Ring and CHESS Facility



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



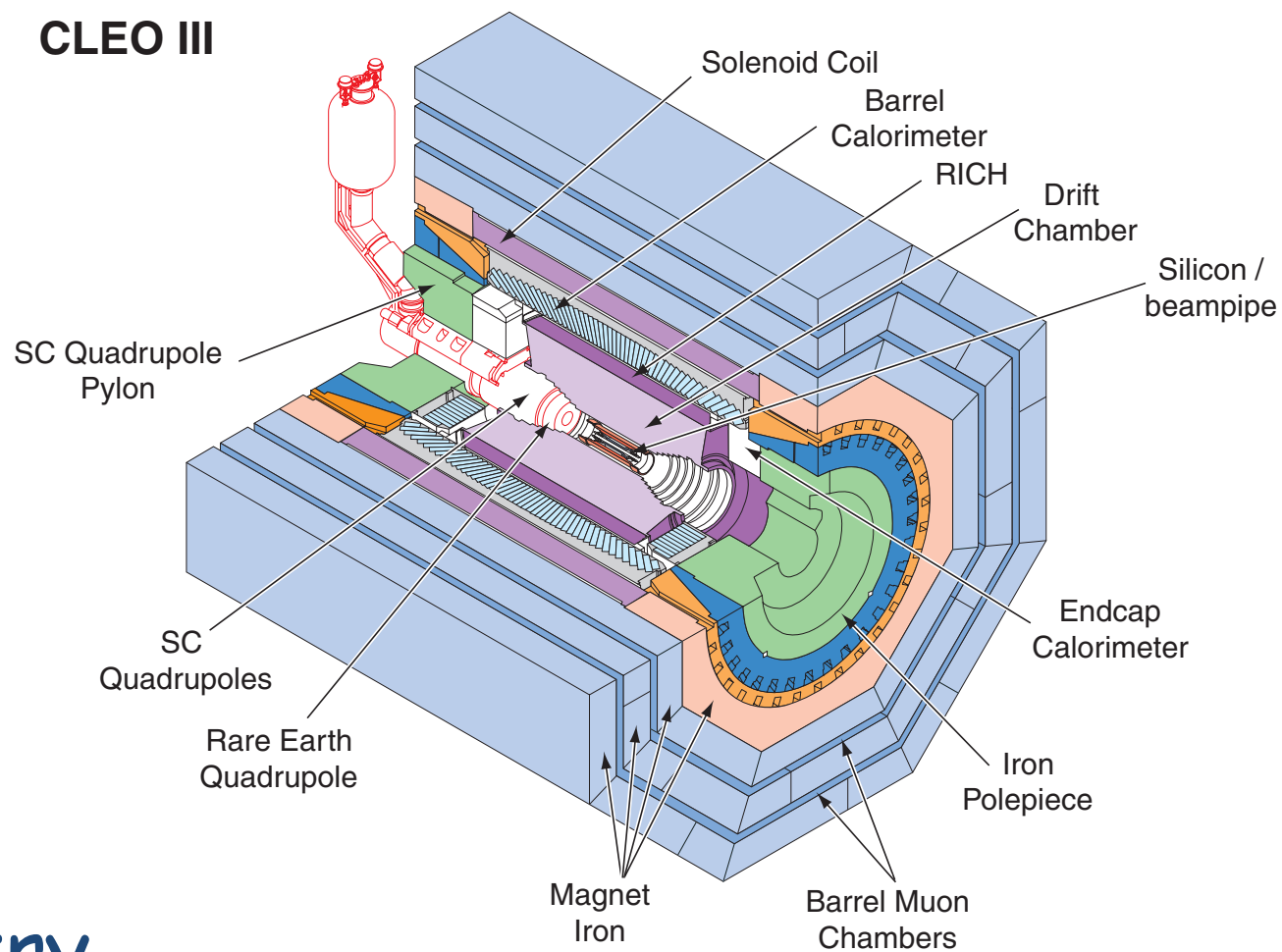
Cornell Electron Storage Ring (CESR)
Past: Upsilons, now: τ -charm factory



The Detector, Data Sample and CLEOns



CLEO III



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

21 million $Y(1S)$
5.4 million $Y(2S)$
5.0 million $Y(3S)$

Analysis Algorithm and Selection Criteria

Exactly two charged tracks

Only one muon candidate (muon ID)

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

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

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

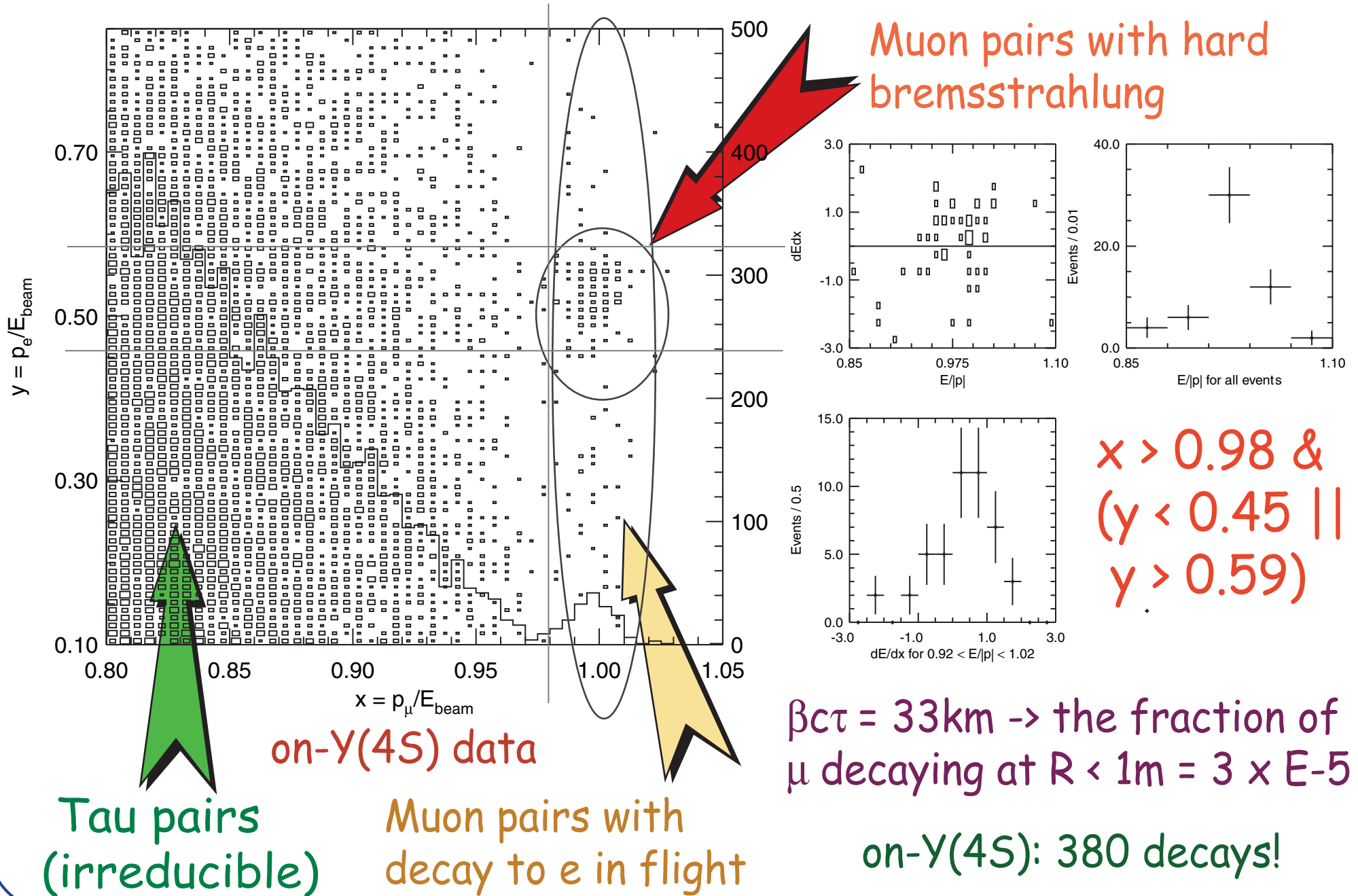
Electron momentum normalized to beam energy: $y = \frac{E_e}{E_{\text{beam}}}$

dE/dx measurement for electron candidate

$E/|p|$ for electron candidate

Using $\Upsilon(4S)$ data for efficiency calibration

Backgrounds arise from tau and muon pairs





Most PDFs were measured from $\Upsilon(4S)$ data

MINUIT Likelihood Fit to Plot

1&1

y versus x, 1 axis
File: **ntuples_data/skim_data_5-14_tau.hbook
Plot Area Total/Fit 1763.0 / 1599.0
Func Area Total/Fit 1618.2 / 1599.0

19-SEP-2005 21:12
Fit Status 3
E.D.M. 6.790E-08

Likelihood = 64.5

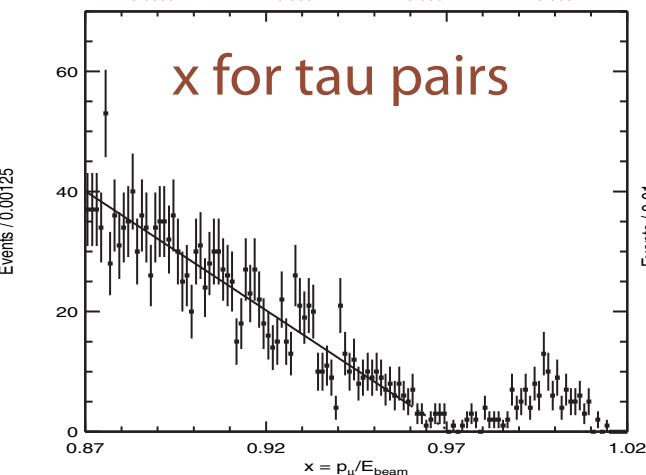
 $\chi^2 = 63.8$ for 72 - 1 d.o.f.,

C.L. = 71.6%

Errors

Function 1: x for $\tau\tau$

	Parabolic	Minos
A	385.07 ± 9.630	- 9.548 + 9.712
* B	0.97100 ± 0.000	- 0.000 + 0.000
* ALPHA	0.0000 ± 0.000	- 0.000 + 0.000



MINUIT Likelihood Fit to Plot

1&1

y versus x, 2 axis
File: **ntuples_data/skim_data_5-14_tau.hbook
Plot Area Total/Fit 1599.0 / 1599.0
Func Area Total/Fit 1598.9 / 1598.9

19-SEP-2005 21:14
Fit Status 3
E.D.M. 1.216E-05

Likelihood = 89.7

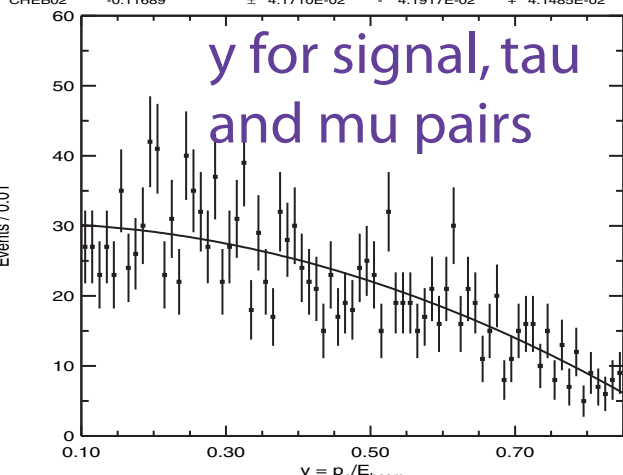
 $\chi^2 = 91.2$ for 75 - 3 d.o.f.,

C.L. = 6.2%

Errors

Function 1: Chebyshev Polynomial of Order 2

	Parabolic	Minos
NORM	2051.9 ± 58.20	- 57.45 + 58.97
CHEB01	-0.58446 ± 3.8604E-02	- 3.8193E-02 + 3.9009E-02
CHEB02	-0.11689 ± 4.1710E-02	- 4.1917E-02 + 4.1485E-02



MINUIT Likelihood Fit to Plot

1&1

y versus x, 2 axis
File: **ntuples_data/skim_data_5-14_tau.hbook
Plot Area Total/Fit 1558.0 / 1514.0
Func Area Total/Fit 1556.3 / 1513.9

19-SEP-2005 21:23
Fit Status 3
E.D.M. 1.755E-06

Likelihood = 57.5

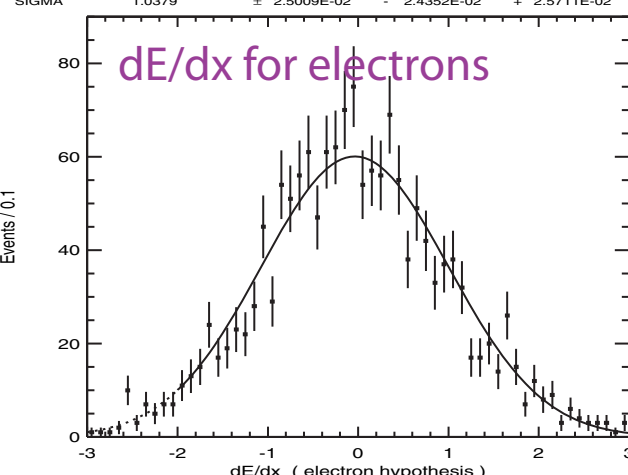
 $\chi^2 = 58.8$ for 50 - 3 d.o.f.,

C.L. = 11.7%

Errors

Function 1: Gaussian (sigma)

	Parabolic	Minos
AREA	1562.3 ± 40.73	- 40.38 + 41.09
MEAN	-3.66864E-02 ± 3.0013E-02	- 3.0335E-02 + 2.9735E-02
SIGMA	1.0379 ± 2.5009E-02	- 2.4352E-02 + 2.5711E-02



MINUIT Likelihood Fit to Plot

1&1

y versus x, 1 axis
File: **ntuples_data/skim_data_5-14_tau.hbook
Plot Area Total/Fit 872.00 / 775.00
Func Area Total/Fit 803.04 / 774.92

22-SEP-2005 00:07
Fit Status 3
E.D.M. 6.308E-06

Likelihood = 54.6

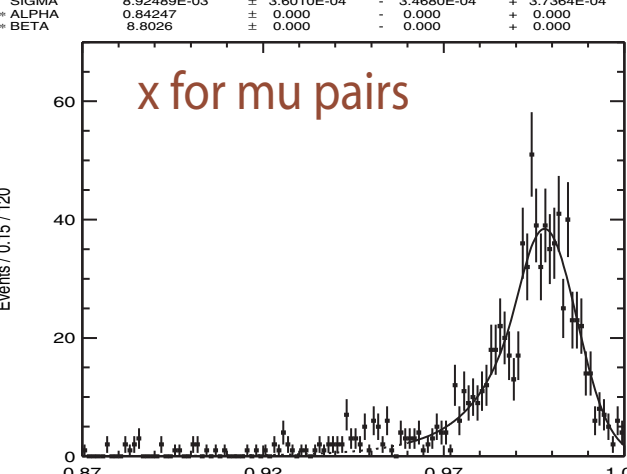
 $\chi^2 = 53.4$ for 48 - 3 d.o.f.,

C.L. = 18.3%

Errors

Function 1: CB line shape

	Parabolic	Minos
A	807.55 ± 29.32	- 28.91 + 29.73
MEAN	0.99791 ± 4.2125E-04	- 4.2472E-04 + 4.1632E-04
SIGMA	8.92489E-03 ± 3.6010E-04	- 3.4680E-04 + 3.7364E-04
* ALPHA	0.84247 ± 0.000	- 0.000 + 0.000
* BETA	8.8026 ± 0.000	- 0.000 + 0.000



MINUIT Likelihood Fit to Plot

1&1

y versus x, 2 axis
File: **ntuples_data/skim_data_5-14_tau.hbook
Plot Area Total/Fit 1599.0 / 1599.0
Func Area Total/Fit 1599.0 / 1599.0

20-SEP-2005 07:17
Fit Status 3
E.D.M. 6.561E-08

Likelihood = 93.7

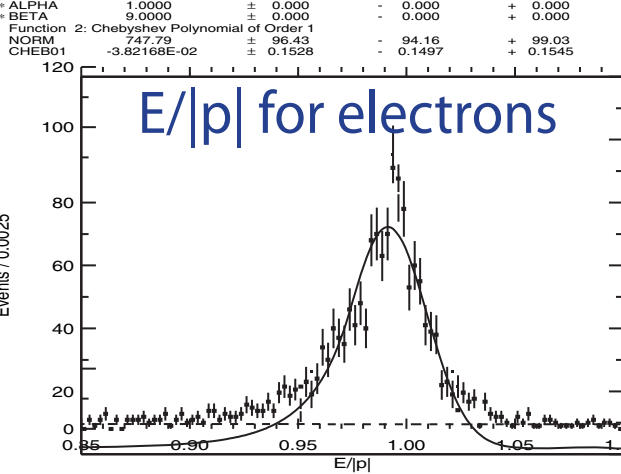
 $\chi^2 = 85.0$ for 100 - 5 d.o.f.,

C.L. = 75.9%

Errors

Function 1: CB line shape

	Parabolic	Minos
NORM	1414.8 ± 42.99	- 42.42 + 43.08
MEAN	0.99142 ± 6.4835E-04	- 6.5192E-04 + 6.4572E-04
SIGMA	1.80197E-02 ± 5.9889E-04	- 5.8831E-04 + 6.0939E-04
* ALPHA	1.0000 ± 0.000	- 0.000 + 0.000
* BETA	9.0000 ± 0.000	- 0.000 + 0.000



MINUIT Likelihood Fit to Plot

1&1

y versus x, 2 axis
File: **ntuples_data/skim_data_5-14_tau.hbook
Plot Area Total/Fit 775.00 / 768.00
Func Area Total/Fit 772.94 / 767.92

21-SEP-2005 13:28
Fit Status 3
E.D.M. 2.105E-06

Likelihood = 26.2

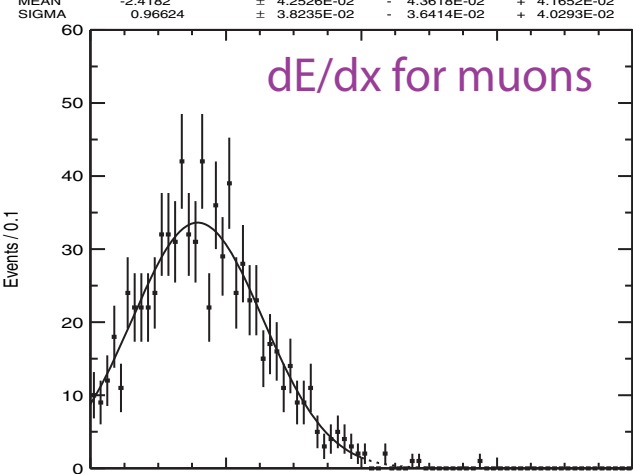
 $\chi^2 = 26.1$ for 40 - 3 d.o.f.,

C.L. = 91.1%

Errors

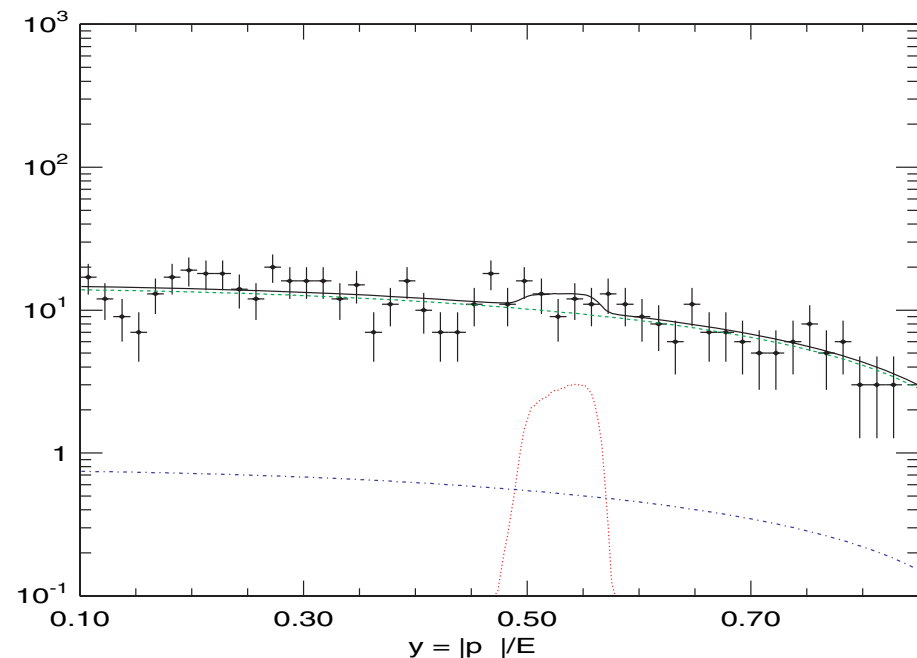
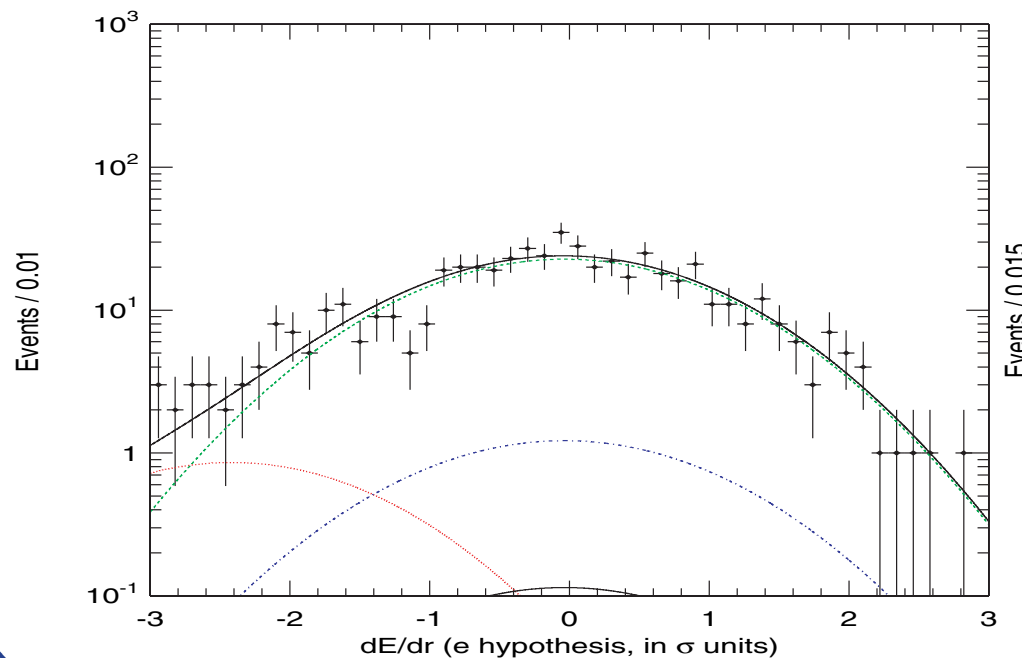
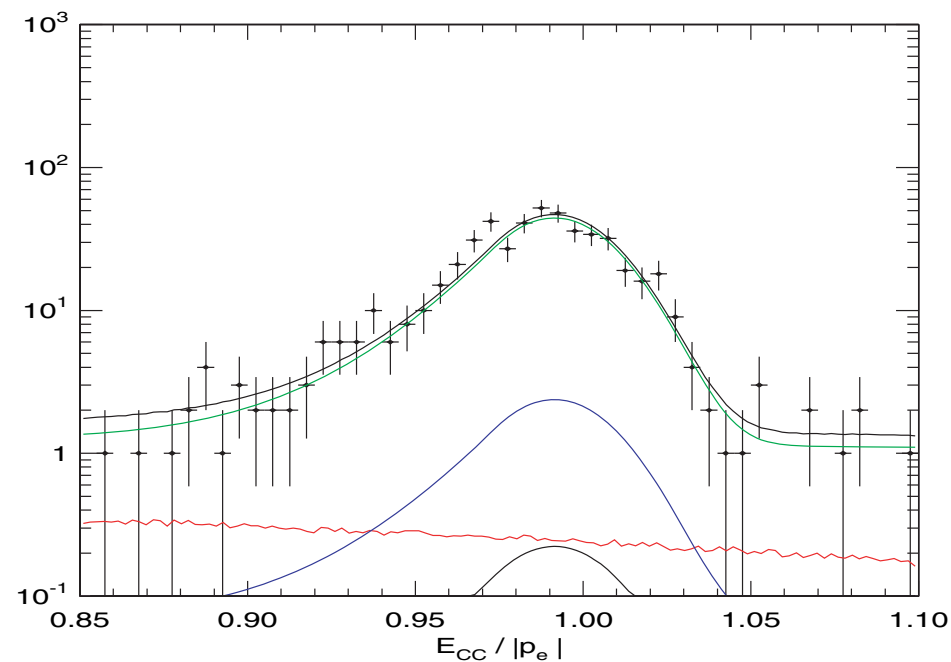
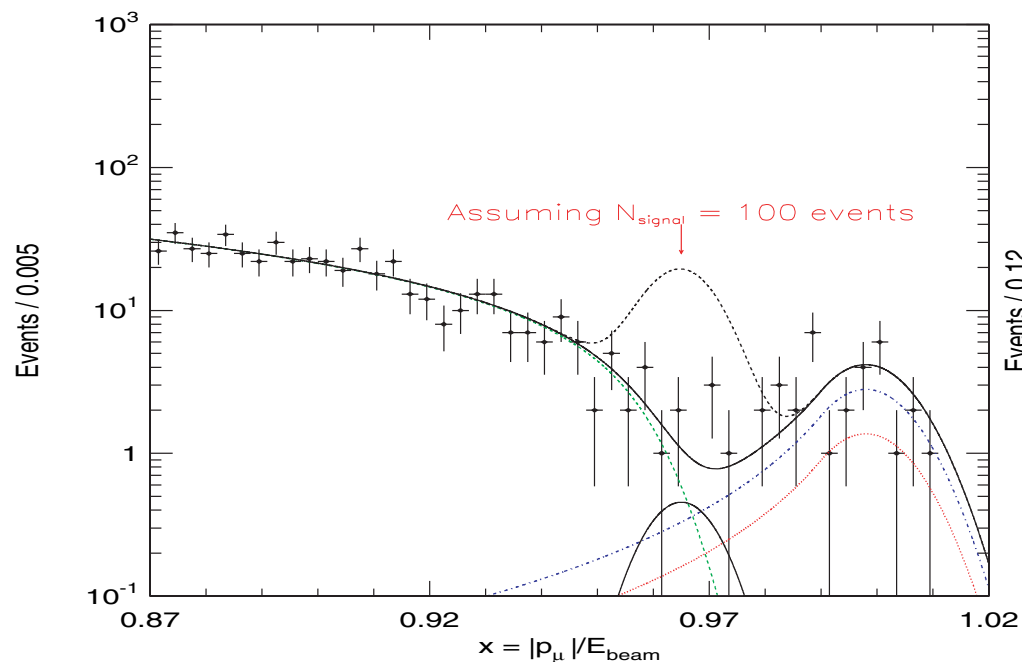
Function 1: Gaussian (sigma)

	Parabolic	Minos
AREA	814.31 ± 30.74	- 30.24 + 31.26
MEAN	-2.4182 ± 4.2526E-02	- 4.3618E-02 + 4.1652E-02
SIGMA	0.96624 ± 3.8235E-02	- 3.6414E-02 + 4.0293E-02

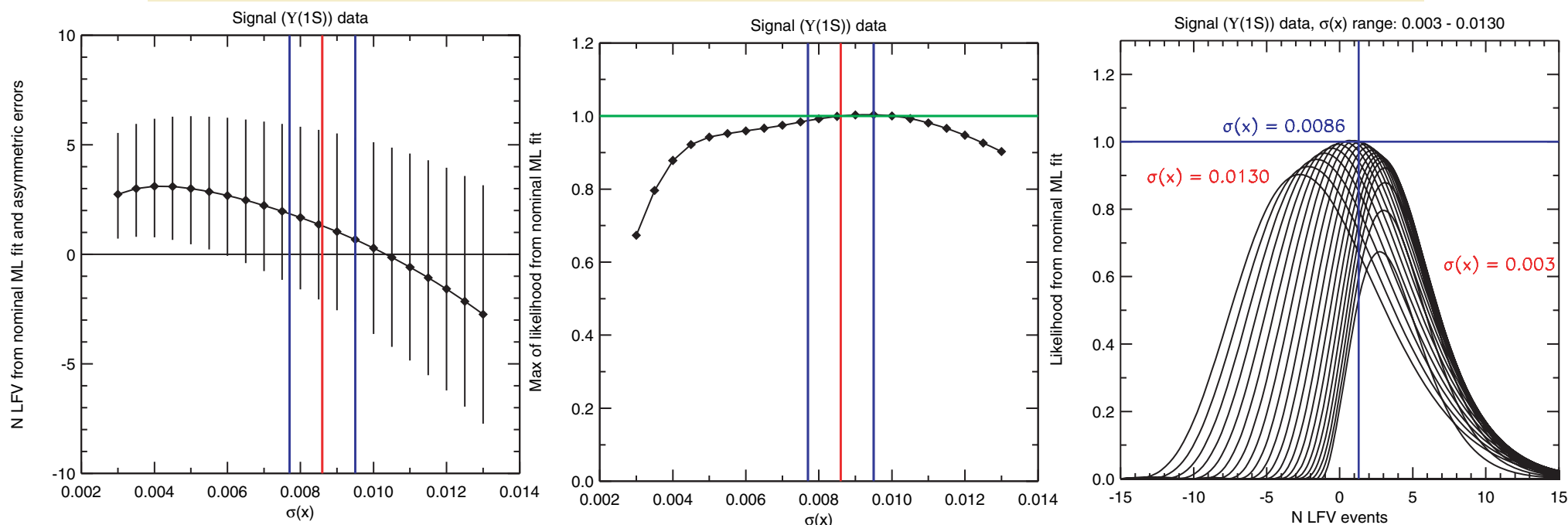




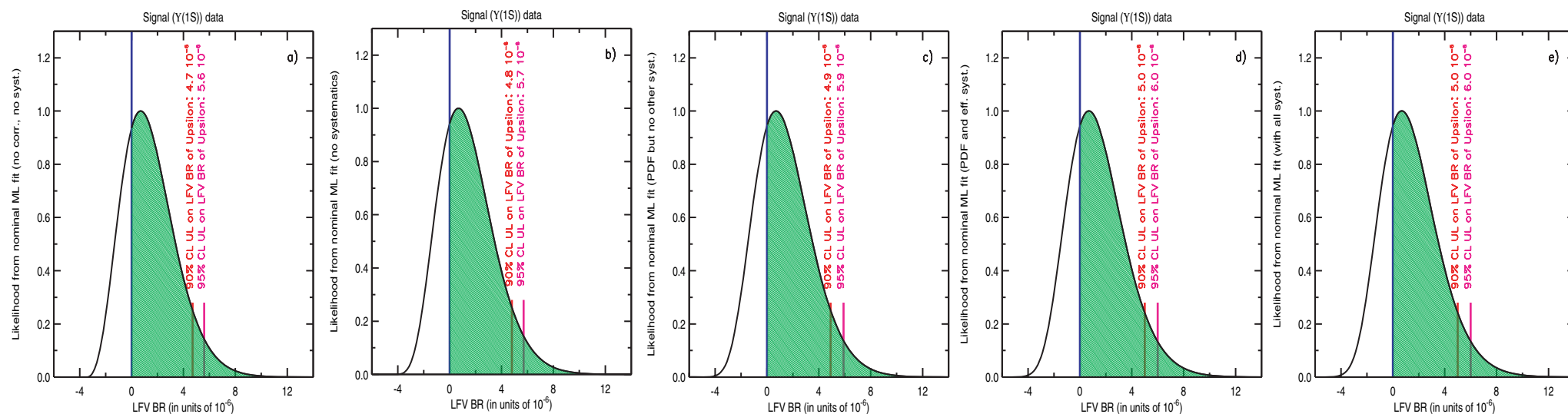
4D Four-Components Fits to $\Upsilon(1S)$ Data



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

MINUIT χ^2 Fit to Plot 1&0

Fitting mu efficiency versus time (dataset)

File: Generated internally

Plot Area Total/Fit 8.8436 / 3.5223

Func Area Total/Fit 7.9251 / 3.0908

26-JAN-2006 13:16

Fit Status 3

E.D.M. 3.036E-21

$\chi^2 = 1.2$ for 4 - 1 d.o.f.,

C.L. = 75.0%

Errors

Parabolic

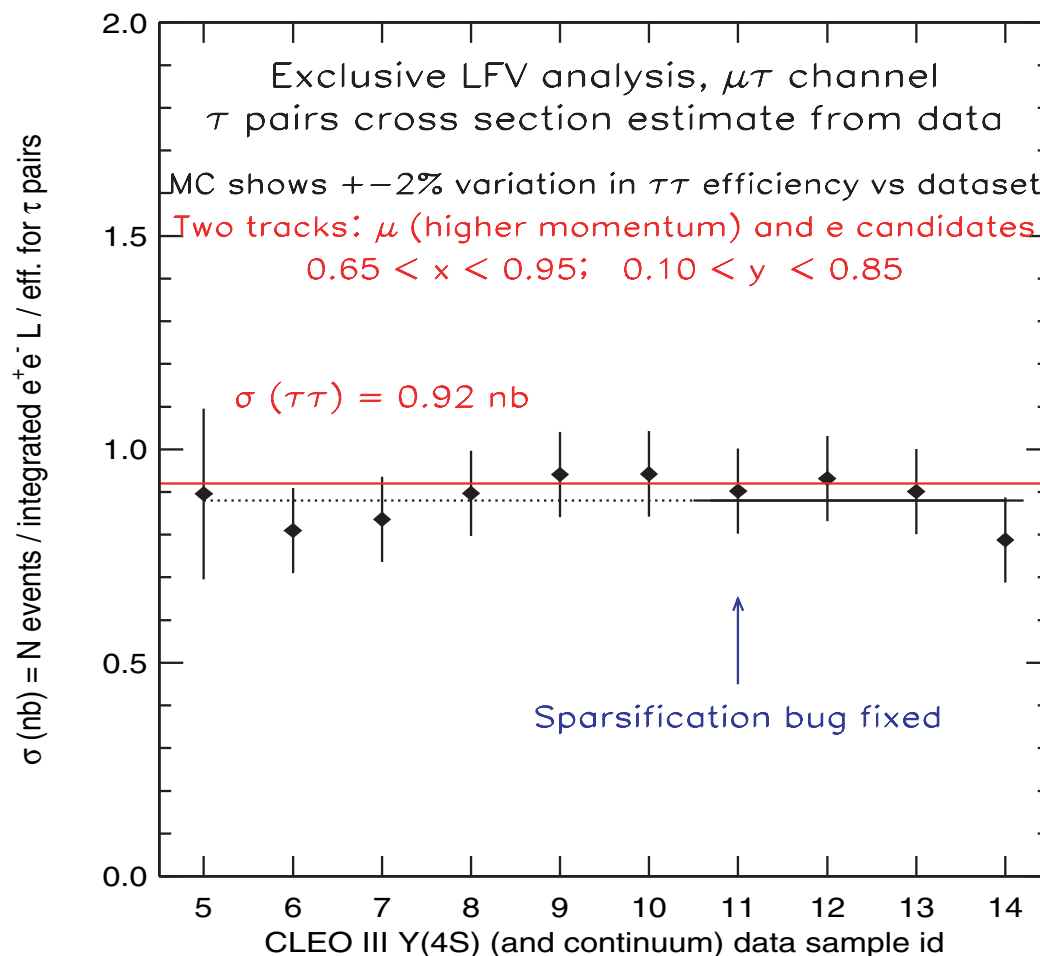
Minos

Function 1: Polynomial of Order 1

NORM 0.88057 $\pm$ 5.0000E-02 - 5.0000E-02 + 5.0000E-02

* POLY01 0.0000 $\pm$ 0.000 - 0.000 + 0.000

* OFFSET 5.0000 $\pm$ 0.000 - 0.000 + 0.000



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 (% , σ)	8.5	8.5	8.5
Overall efficiency (% , -1σ)	8.1	8.1	8.1
Statistics (number of Υ 's)	21 ± 1	5.4 ± 0.2	5.0 ± 0.3
$\mathcal{B}(\Upsilon \rightarrow \mu\tau)$ (90% CL UL, $\times 10^{-6}$)	5.9	24	21
With Υ statistics included	6.2	25	22

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

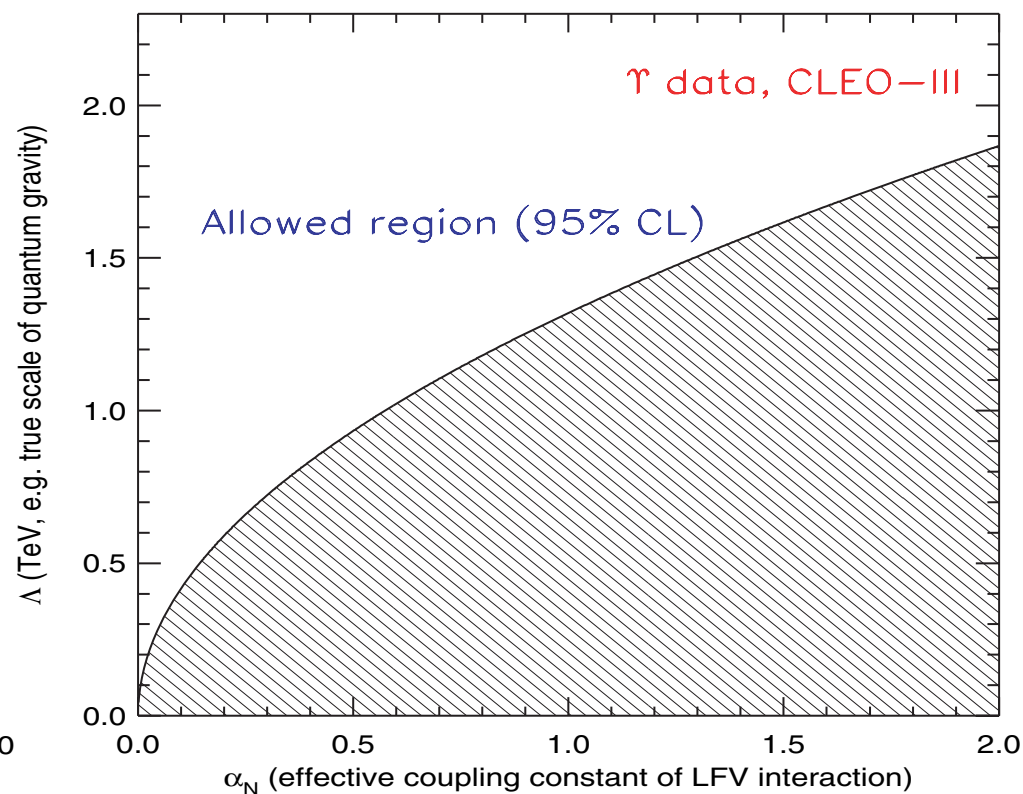
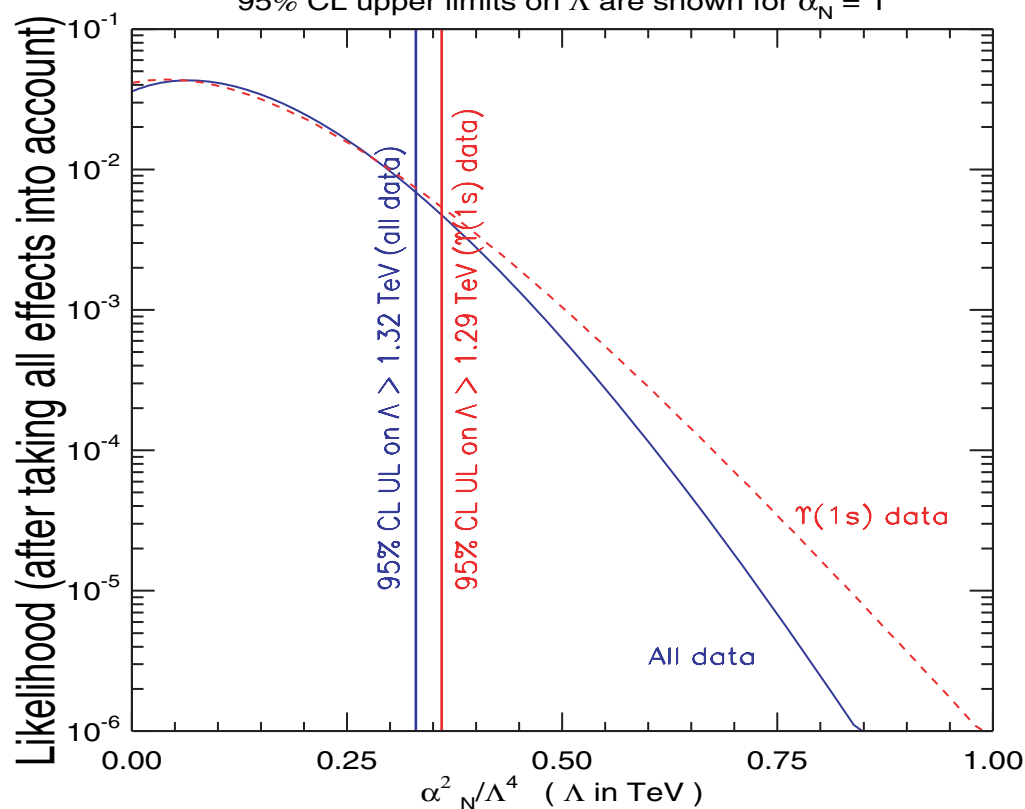
No LFV discovered in decays of Upsilon Mesons

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

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

Exclusion Plots for Generic LFV BSM Physics

95% CL upper limits on Λ are shown for $\alpha_N = 1$



α_N (effective coupling constant of LFV part of some BSM interaction)

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

Bound	1	γ_5	γ_σ	$\gamma_\sigma\gamma_5$
$\bar{t}c$	190 GeV ($t \rightarrow c \mu \tau$)	190 GeV ($t \rightarrow c \mu \tau$)	310 GeV ($B \rightarrow \mu \tau$)	310 GeV ($B \rightarrow \mu \tau$)
$\bar{t}u$	190 GeV ($t \rightarrow u \mu \tau$)	190 GeV ($t \rightarrow u \mu \tau$)	650 GeV ($B \rightarrow \mu \tau$)	650 GeV ($B \rightarrow \mu \tau$)
$\bar{c}u$	★	★	550 GeV ($\tau \rightarrow \mu \phi$)	550 GeV ($\tau \rightarrow \mu \phi$)
$\bar{c}c$	★	★	1.1 TeV ($\tau \rightarrow \mu \phi$)	1.1 TeV ($\tau \rightarrow \mu \phi$)
$\bar{b}b$	★	★	180 GeV ($\Upsilon \rightarrow \mu \tau$)	★
$\bar{t}t$	★	★	75 GeV ($B \rightarrow \mu \tau$)	120 GeV ($B \rightarrow \mu \tau$)

BES (J/ ψ) 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 Υ 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 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 $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, we deduce a 90% C.L. upper limit of $\mathcal{B}[\Upsilon(1S) \rightarrow \text{invisible}] < 0.39\%$.

Using only WMAP result on the relic density of the universe

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

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

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

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