andries van der schaaf, Zürich

1 Why do it? [1]

- Flavor puzzle: what is the origin of the patterns of quark and lepton masses and mixings?
- Most models predict observable rates for LFV decays involving charged leptons which may even be required to solve the flavor puzzle.
- Rare μ decays give best constraints in most scenarios and their relative strengths would help in the interpretation.
- Experimental prospects differ considerably between the three modes of interest:
- Previous talk: searches for $\mu - e$ conversion are limited by the available beam intensities and large improvements in sensitivity may still be achieved.
- Next talk: searches for $\mu^+ \to e^+\gamma$ are limited by accidental $e^+\gamma$ coincidences and muon beam intensities have to be reduced now already.
- This talk: what about $\mu \to 3e$ [2] (20 year old upper limit 10^{-12}) ?

[1] "Flavor physics of leptons and dipole moments", report of Working Group 3, CERN Workshop "Flavor in the era of the LHC", November 2005 - March 2007. http://www.springerlink.com/content/784n166817gp2gj8/

[2] Discussed at a PSI workshop four months ago

1.1 $\mu \to 3e$ has many more diagrams than $\mu \to e\gamma$

Testing Supersymmetry with Lepton Flavor Violating
τ and μ decays
Ernesto Arganda and Maria J. Herrero

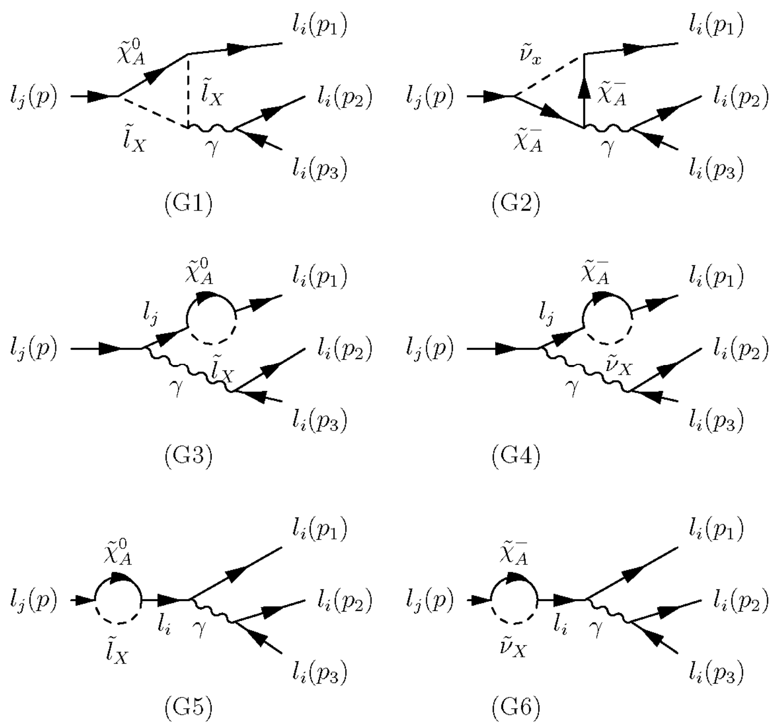

FIG. 1: γ-penguin diagrams contributing to the $l_j^- \to l_i^- l_i^- l_i^+$ decay

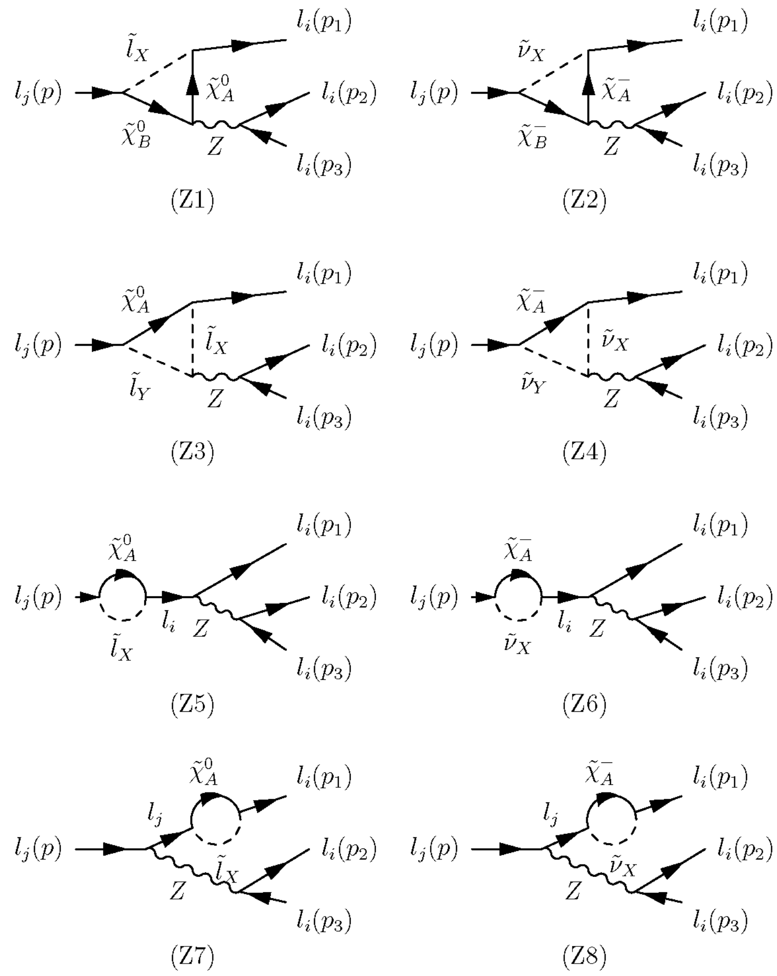

FIG. 2: Z-penguin diagrams contributing to the $l_j^- \to l_i^- l_i^- l_i^+$ decay

a $\mu \to 3e$ search at 10^{-16} ?

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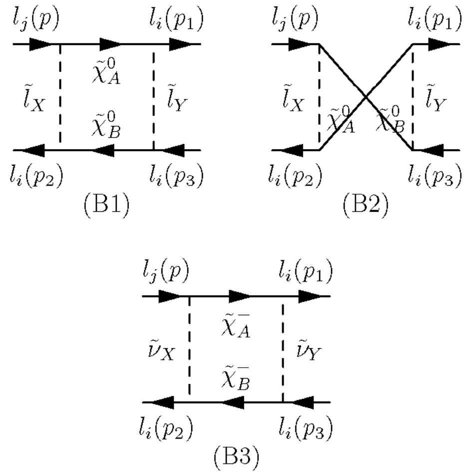


FIG. 3: Box-type diagrams contributing to the $l_j^- \to l_i^- l_i^- l_i^+$ decay

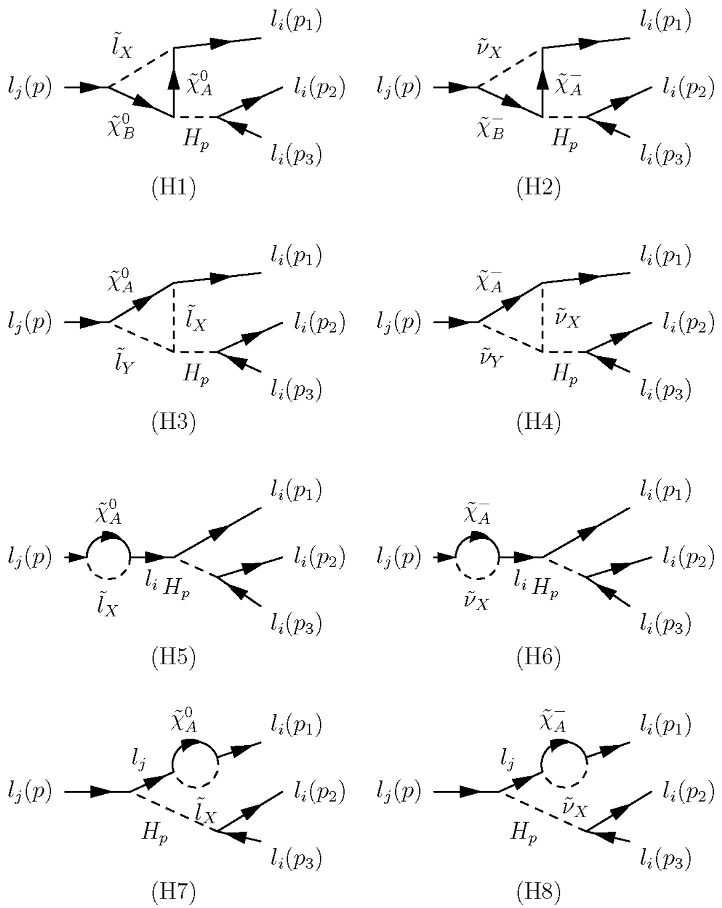
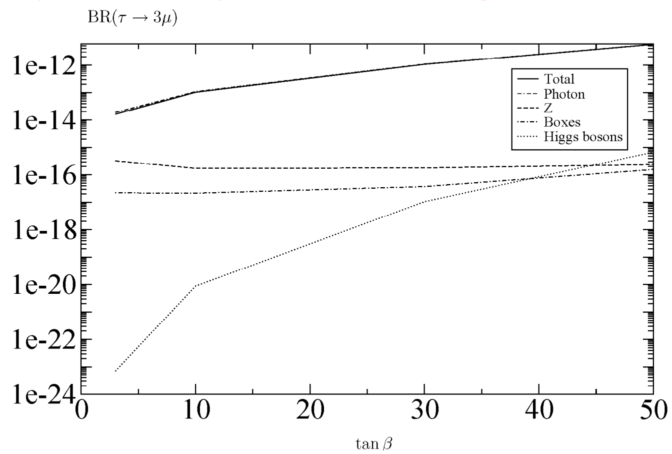


FIG. 4: Higgs-penguin diagrams contributing to the $l_j^- \to l_i^- l_i^- l_i^+$ decay. Here

unfortunately, the photonic graphs dominate



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1.2 A recent example: the Littlest Higgs Model

An alternative to SUSY recently developped by Arkani-Hamed et al.

A (The ?) minimal extension of the SM "weakly coupled to new physics" at the TeV scale:

- **below 1 TeV nothing changes and around 1 TeV a handful of additional particles are predicted.**

Buras et al., 2007

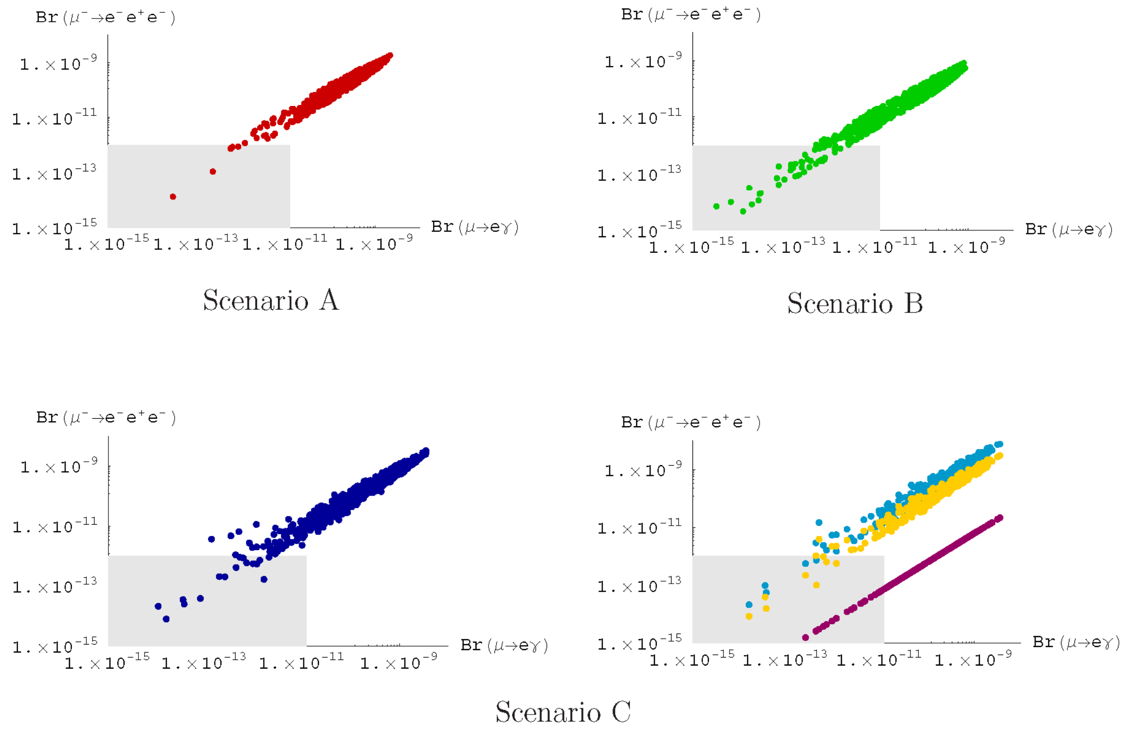

Figure 9: *Correlation between $\mu \to e\gamma$ and $\mu^- \to e^- e^+ e^-$ in the scenarios of Section 12.2. In the right plot of Scenario C we show the contributions to $\mu^- \to e^- e^+ e^-$ from $\bar{D}'^{\mu e}_{odd}$ (purple, lowermost), $\bar{Z}^{\mu e}_{odd}$ (orange, middle) and $\bar{Y}^{\mu e}_{e,odd}$ (light-blue, uppermost) separately. The shaded area represents the experimental constraints.*

a $\mu \to 3e$ search at 10^{-16} ?

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decay	$f = 1000\,\text{GeV}$	$f = 500\,\text{GeV}$	exp. upper bound
$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$ $(1 \cdot 10^{-11})$	$1.2 \cdot 10^{-11}$ $(1 \cdot 10^{-11})$	$1.2 \cdot 10^{-11}$ [17]
$\mu^- \to e^-e^+e^-$	$1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$	$1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$	$1.0 \cdot 10^{-12}$ [42]
$\mu\text{Ti} \to e\text{Ti}$	$2 \cdot 10^{-10}$ $(5 \cdot 10^{-12})$	$4 \cdot 10^{-11}$ $(5 \cdot 10^{-12})$	$4.3 \cdot 10^{-12}$ [29]
$\tau \to e\gamma$	$8 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$1 \cdot 10^{-8}$ $(1 \cdot 10^{-8})$	$9.4 \cdot 10^{-8}$ [33]
$\tau \to \mu\gamma$	$8 \cdot 10^{-10}$ $(8 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(1 \cdot 10^{-8})$	$1.6 \cdot 10^{-8}$ [33]
$\tau^- \to e^-e^+e^-$	$7 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$2.0 \cdot 10^{-7}$ [71]
$\tau^- \to \mu^-\mu^+\mu^-$	$7 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$3 \cdot 10^{-8}$ $(3 \cdot 10^{-8})$	$1.9 \cdot 10^{-7}$ [71]
$\tau^- \to e^-\mu^+\mu^-$	$5 \cdot 10^{-10}$ $(5 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$2.0 \cdot 10^{-7}$ [72]
$\tau^- \to \mu^-e^+e^-$	$5 \cdot 10^{-10}$ $(5 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$1.9 \cdot 10^{-7}$ [72]
$\tau^- \to \mu^-e^+\mu^-$	$5 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$2 \cdot 10^{-14}$ $(2 \cdot 10^{-14})$	$1.3 \cdot 10^{-7}$ [71]
$\tau^- \to e^-\mu^+e^-$	$5 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$2 \cdot 10^{-14}$ $(2 \cdot 10^{-14})$	$1.1 \cdot 10^{-7}$ [71]
$\tau \to \mu\pi$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	$5.8 \cdot 10^{-8}$ $(5.8 \cdot 10^{-8})$	$5.8 \cdot 10^{-8}$ [33]
$\tau \to e\pi$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	$4.4 \cdot 10^{-8}$ $(4.4 \cdot 10^{-8})$	$4.4 \cdot 10^{-8}$ [33]
$\tau \to \mu\eta$	$6 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$5.1 \cdot 10^{-8}$ [33]
$\tau \to e\eta$	$6 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$4.5 \cdot 10^{-8}$ [33]
$\tau \to \mu\eta'$	$7 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$3 \cdot 10^{-8}$ $(3 \cdot 10^{-8})$	$5.3 \cdot 10^{-8}$ [33]
$\tau \to e\eta'$	$7 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$3 \cdot 10^{-8}$ $(3 \cdot 10^{-8})$	$9.0 \cdot 10^{-8}$ [33]
$K_L \to \mu e$	$4 \cdot 10^{-13}$ $(2 \cdot 10^{-13})$	$3 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$4.7 \cdot 10^{-12}$ [50]
$K_L \to \pi^0\mu e$	$4 \cdot 10^{-15}$ $(2 \cdot 10^{-15})$	$5 \cdot 10^{-16}$ $(5 \cdot 10^{-16})$	$6.2 \cdot 10^{-9}$ [73]
$B_d \to \mu e$	$5 \cdot 10^{-16}$ $(2 \cdot 10^{-16})$	$9 \cdot 10^{-17}$ $(9 \cdot 10^{-17})$	$1.7 \cdot 10^{-7}$ [74]
$B_s \to \mu e$	$5 \cdot 10^{-15}$ $(2 \cdot 10^{-15})$	$9 \cdot 10^{-16}$ $(9 \cdot 10^{-16})$	$6.1 \cdot 10^{-6}$ [75]
$B_d \to \tau e$	$3 \cdot 10^{-11}$ $(2 \cdot 10^{-11})$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$1.1 \cdot 10^{-4}$ [76]
$B_s \to \tau e$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	—
$B_d \to \tau\mu$	$3 \cdot 10^{-11}$ $(3 \cdot 10^{-11})$	$3 \cdot 10^{-10}$ $(3 \cdot 10^{-10})$	$3.8 \cdot 10^{-5}$ [76]
$B_s \to \tau\mu$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$3 \cdot 10^{-9}$ $(3 \cdot 10^{-9})$	—

Table 2: *Upper bounds on LFV decay branching ratios in the LHT model, for two different values of the scale f, after imposing the constraints on $\mu \to e\gamma$ and $\mu^- \to e^-e^+e^-$. The numbers given in brackets are obtained after imposing the additional constraint $R(\mu Ti \to e Ti) < 5 \cdot 10^{-12}$. For $f = 500\,\text{GeV}$, also the bounds on $\tau \to \mu\pi, e\pi$ have been included. The current experimental upper bounds are also given.*

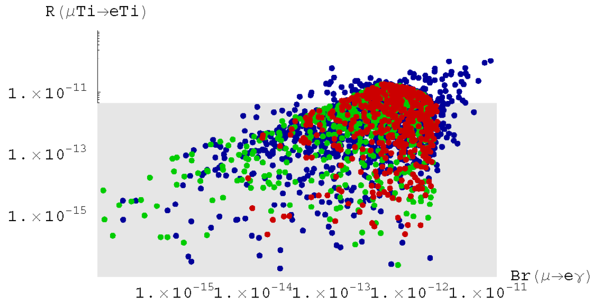


Figure 10: *$\mu - e$ conversion rate in $^{48}_{22}Ti$ as a function of $Br(\mu \to e\gamma)$, after imposing the existing constraints on $\mu \to e\gamma$ and $\mu^- \to e^-e^+e^-$. The shaded area represents the current experimental upper bound on $R(\mu Ti \to e Ti)$.*

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^-e^+e^-)}{Br(\mu \to e\gamma)}$	$0.4 \ldots 2.5$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^-e^+e^-)}{Br(\tau \to e\gamma)}$	$0.4 \ldots 2.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^-\mu^+\mu^-)}{Br(\tau \to \mu\gamma)}$	$0.4 \ldots 2.3$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^-\mu^+\mu^-)}{Br(\tau \to e\gamma)}$	$0.3 \ldots 1.6$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^-e^+e^-)}{Br(\tau \to \mu\gamma)}$	$0.3 \ldots 1.6$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^-e^+e^-)}{Br(\tau^- \to e^-\mu^+\mu^-)}$	$1.3 \ldots 1.7$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^-\mu^+\mu^-)}{Br(\tau^- \to \mu^-e^+e^-)}$	$1.2 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\text{Ti} \to e\text{Ti})}{Br(\mu \to e\gamma)}$	$10^{-2} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

Table 3: *Comparison of various ratios of branching ratios in the LHT model and in the MSSM without and with significant Higgs contributions.*

Programm $\mu \to 3e$ Workshop (https://midas.psi.ch/elogs/MEEE/)

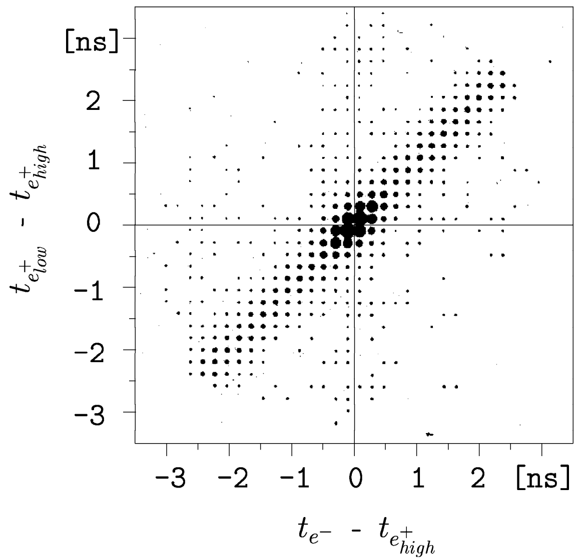
Welcome	**Stefan Ritt**	**PSI**
purpose of the exercise		
Motivation	**Andries van der Schaaf**	**UZH**
$\mu \to 3e$ ***v.s.*** $\mu \to e\gamma$ ***v.s.*** $\mu - e$ ***conversion***		
SINDRUM I	**Willi Bertl**	**PSI**
the best result since 20 years		
Design criteria for a new $\mu \to 3e$ experiment	**Andries van der Schaaf**	**UZH**
limitations to the sensitivity		
Ideas for a new $\mu \to e^+e^+e^-$ experiment	**Roland Horisberger**	**PSI**
a large radial TPC with fine-grained readout		
ΠE5 beam line	**Peter-Raymond Kettle**	**PSI**
the MEG experience		
Active targets IKAR & MAYA	**Oleg Kiselev**	**PSI**
alternatives mainly for heavy fragments		
MuCAP TPC	**Malte Hildebrandt**	**PSI**
a TPC based on hydrogen		
Geiger mode APDs	**Dieter Renker**	**PSI**
from strips to pads for the plastic scintillator		

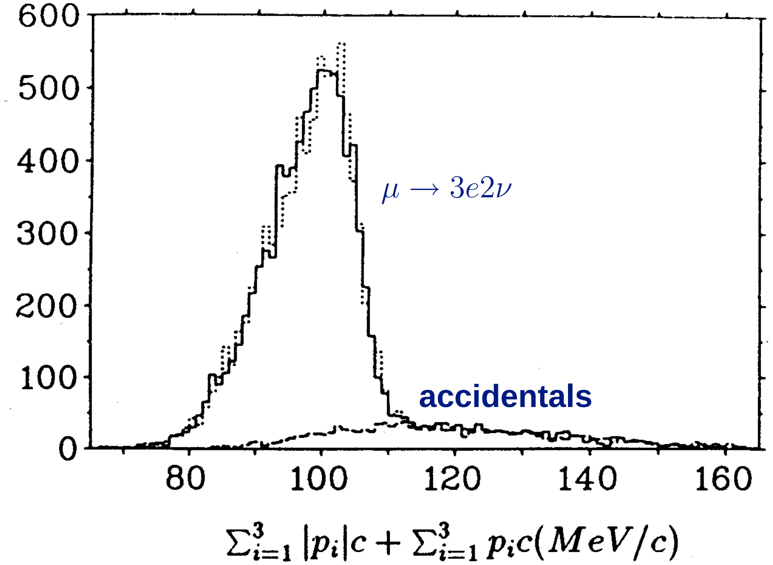
2 signature $\mu \to 3e$ at rest

- total energy, total momentum ($\to$ coplanarity).
- Phase space distribution gives additional information if observed.
- In a constant B field the acceptance is defined by the p_t threshold.

3 background

SINDRUM I

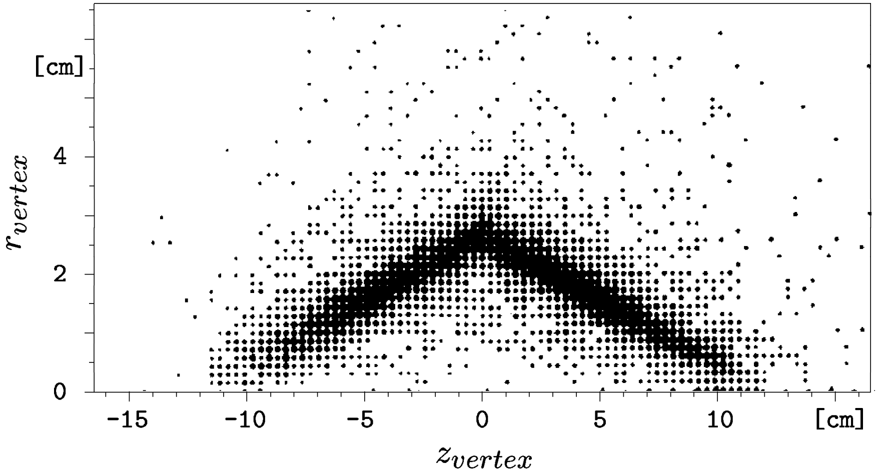




Accidental background
involves low invariant mass e^+e^- pairs produced by photons or by Bhabha scattering.

Suppressing accidental background:

- **The three trajectories meet in a common vertex.**
- **The common vertex has to be in a muon-stop region. For this reason SINDRUM I used a relatively large surface target.**



- **An active target could lead to a dramatic supression since one would know the interaction point of γ conversions and Bhabha scatterings.** [3]

[3] Peter Kammel is gratefully acknowledged for bringing this up

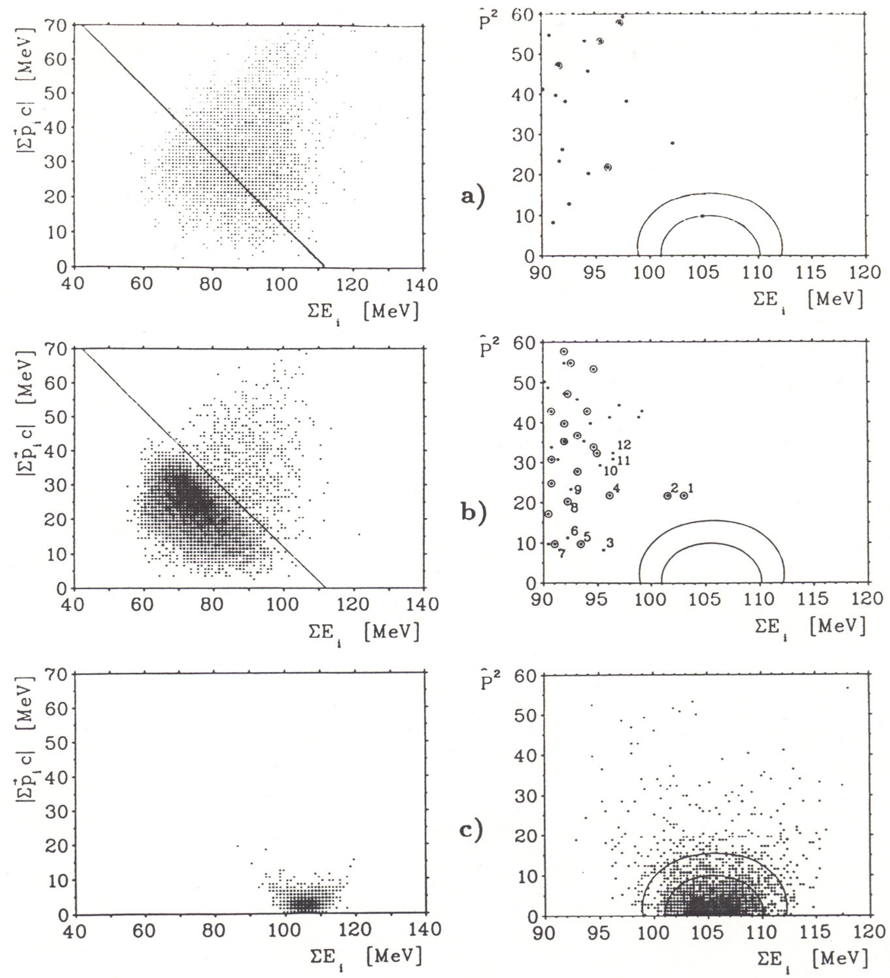
3.1 How to reach a single-event sensitivity of $O(10^{-16})$?

- **Measure 100 instead of 10 weeks.**
- **Raise stop rate from 5×10^6 to 10^9/s.**
- **Lower threshold on p_t to gain in acceptance.**

χ^2 is a test of the $e^+e^+e^-$ correlation based on time and vertex variables

$$\hat{P}^2 \equiv \left(\frac{P\|}{\sigma_{P\|}}\right)^2 + \left(\frac{P\perp}{\sigma_{P\perp}}\right)^2$$

$\|$ and $\perp$ are defined w.r.t. the decay plane.



χ^2 >2

χ^2 <1.3

$\mu \to 3e$ simulation

3.2 What about background ?

reducing accidental background by improving detector resolutions

assumption [a]	gain factor	background
SINDRUM I	1	40000
$\Delta t \times$ 0.25	4	10000
vertex $\times$ 0.5	4	2500
energy $\times$ 0.5	2	1250
momentum $\times$ 0.5	4	300
target size $\times$ 2	2	150
target mass/area $\times$ 0.5	2	75

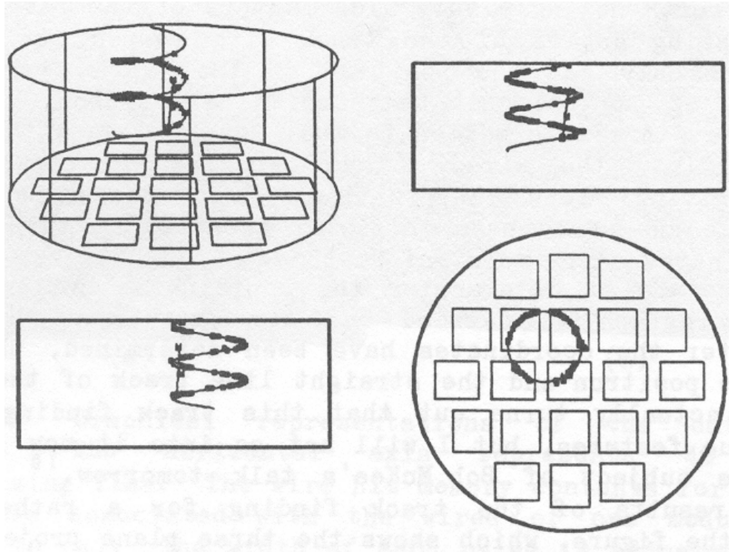
[a] for example by linear scaling the detector by factor 2

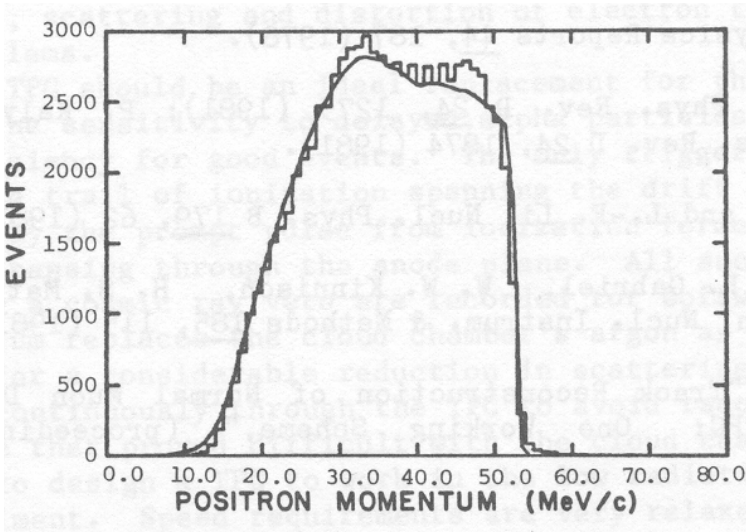
So one would need an additional factor 100.

A vertex detector would do the job if it would stand the rate.

3.3 1985: LAMPF TPC

The Time Projection Chamber
AIP Conference Proceedings 108, ed. J.A. Macdonald
contributions by W.W. Kinnison and R.J. McKee

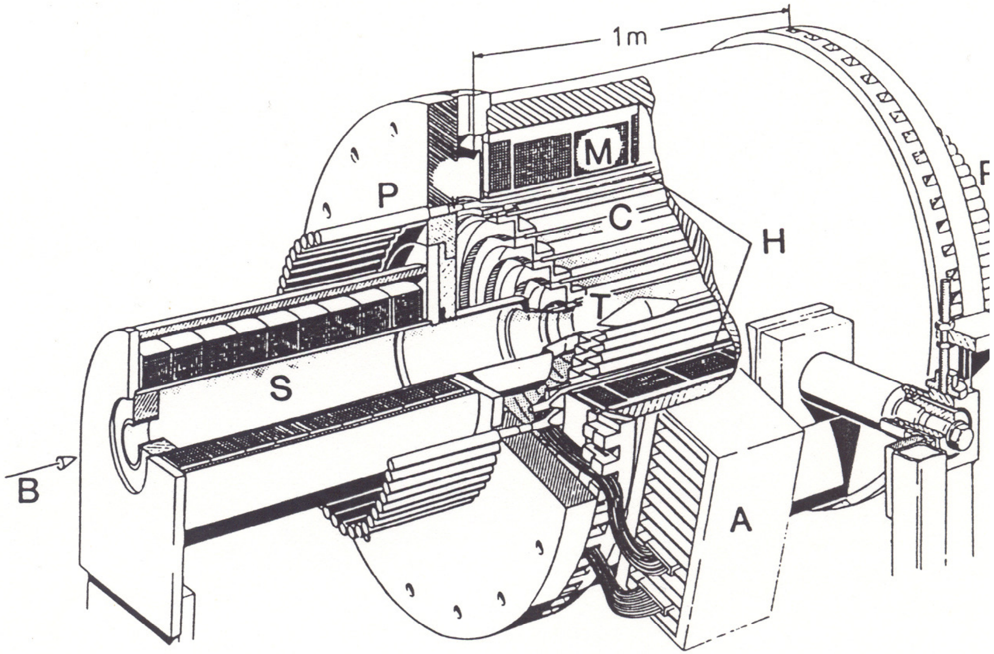




- **six authors!**
- **diameter 122 cm, length 55 cm**
- **Both the incoming surface muon and its decay positron are observed.**
- **momentum resolution 1$\%$**

3.4 Detector issues

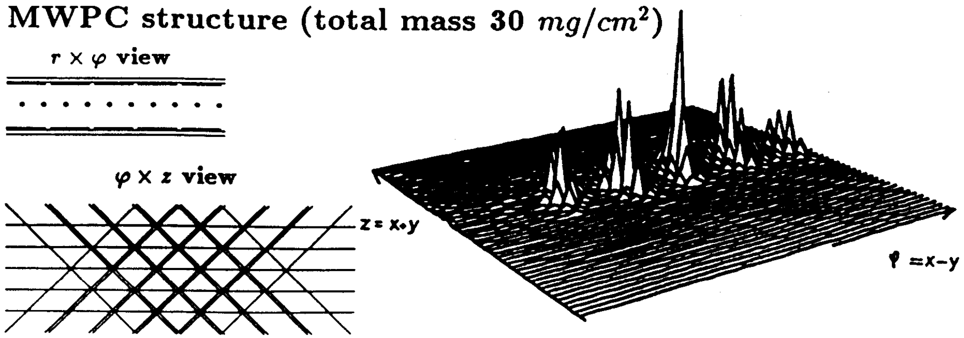
SINDRUM I



B beam
S focussing solenoid
T hollow target
C MWPC tracking
H plastic hodoscope

Events triggered with an ultra-thin scintillator.

- *Cathodes image the avalanches at the anodes.*
- *Phi resolution given by number of anode wires.*
- *z resolution 0.2 mm.*



Could one stand the rate?

- extra tracks, combinatorial background
  SINDRUM I saw about 0.1 extra track per event at the 50 - 70 ns gating time. If the detector would twice faster there would be 10 random tracks. No problem with sufficient granularity (at least 500 anode wires and cathode strips per plane).

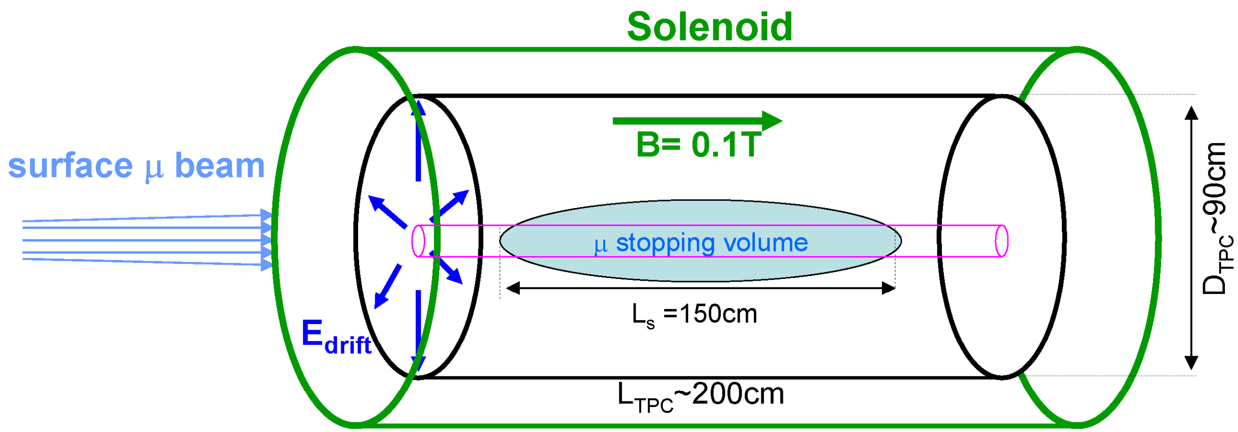
SINDRUM I v.s. MEGA

	SINDRUM I	MEGA	
self-supporting	yes	no	
thickness	10^{-3}	0.3×10^{-3}	rad. length
wire spacing	2	1.3	mm
gas	Ar-C_2H_6 (50-50)	CF_4-C_4H_{10} (80-20)	
gate width	60	30	ns
turns/helix	≈ 1	≈ 5	
peak stop rate	5×10^6	2.5×10^8	1/s
rate per anode	10^5	10^7	1/s
max. fluence	3×10^2	4×10^4	1/mm$^2\cdot$s

Conclusion: it could work

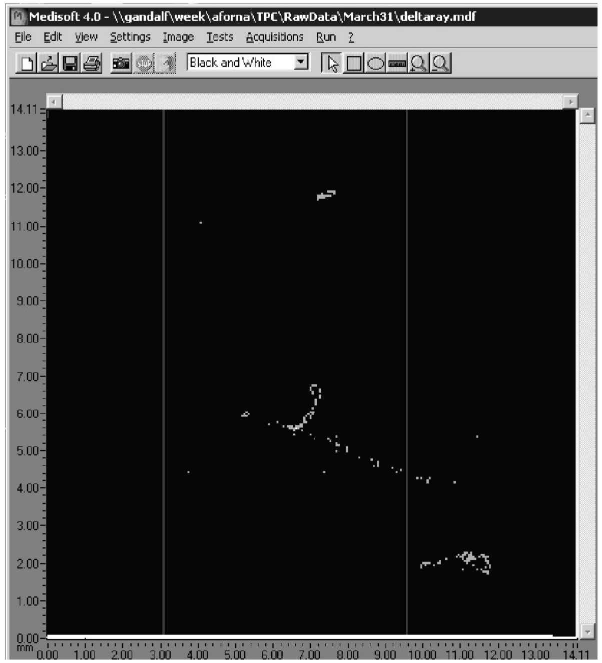
4 A radial TPC ?

(Roland Horisberger)



Micro-pattern readout schemes as studied by LCTPC and CERN RD51 (5 years starting now, Geneva is in) would:

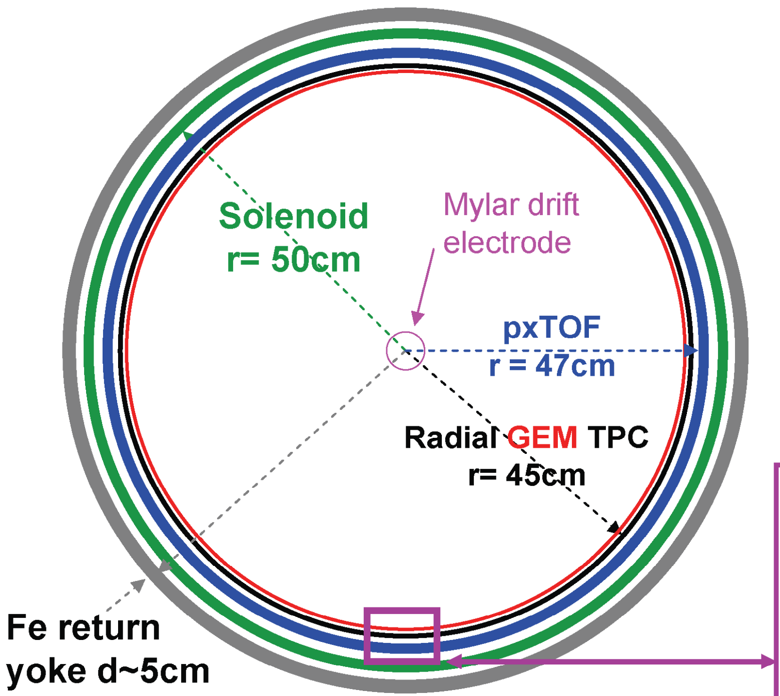
- **match the intrinsic precission offered by TPC's,**
- **stand high particle fluxes by suppression of ion back-flow,**
- **allow curved structures for radial drift field.**



delta electron imaged by LCTPC prototype
14×14 mm^2

PAUL SCHERRER INSTITUT PSI

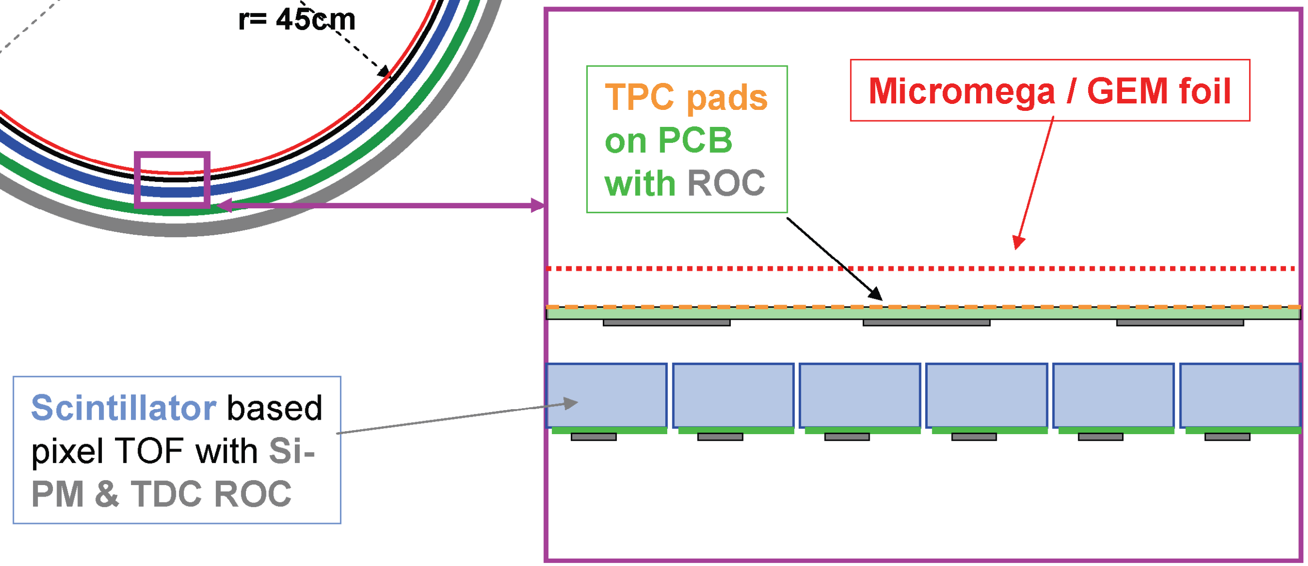
Cross-section of μ→ 3e Experiment



Inner surface of solenoid (~6m²) is equipped:

1) **GEM or Micromega TPC Pad readout**
   0.75mm x 0,75mm pad size, gain ~ 3-4K
   resolution ~ 200μ in x,y & t (ILC exp.)
   few mm double track resolution

2) **Scint. Pixel TOF system**
   1cm x 1cm time resolution ~ 50psec



4.1 Open issues

- What is the highest beam intensity that PSI can deliver in 5 years?
  Proton current 2→3 mA, optimized target geometry.
- How harmful is loss of central region? One would like to see the $e^+e^+e^-$ vertex.
- A TPC is a slow device. Can events with 10^4 additional muon tracks and decay positrons be analyzed?
- Can triggering be solved? Would a second plastic layer help to trigger fast on charge?
- Would a hybrid scheme (much smaller and faster gated TPC for vertex only combined with 25 ns tracker) solve some of the above?
- Budget? Comparable to MEG?
- Sufficient interest to form an international collaboration?
  No problem if MEG finds a signal!