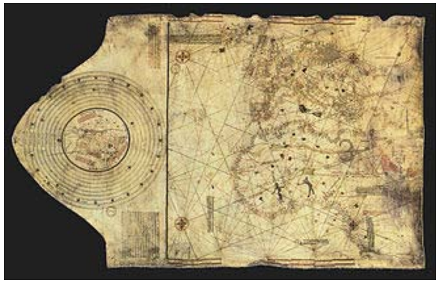
Observations on Lepton Flavor Violation Experiments

Doug Bryman

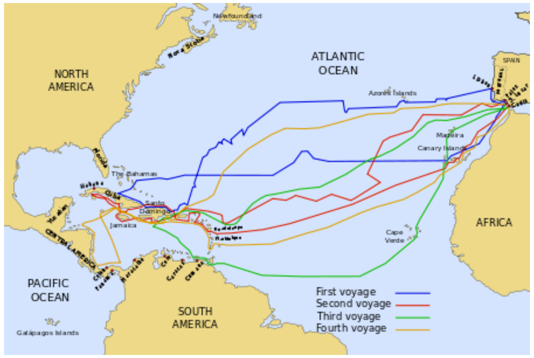
1st Conference on Charged Lepton Flavor Violation
Lecce 2013

15-16th Century Explorations into Unknown Waters

Christoforo Colombo– 1492 search for East Indies…



Discovered



Amerigo Vespucci– 1499 search for Asia …

Discovered

Ponce de Leon – 1513 search for the Fountain of Youth …

Discovered

Disney World

21^{st}Century Explorations Into Unknown Waters

- High energy
- Dark matter
- Dark energy
- Charged lepton flavor violation, EDMs, and CP violation

Vague but well motivated ideas of what to look for --- really searching in the dark….

Here be dragons.

The 1265 Psalter world map.

1st Conference on Charged Lepton Flavor Violation Conference Summary

Day 1+ Theory:

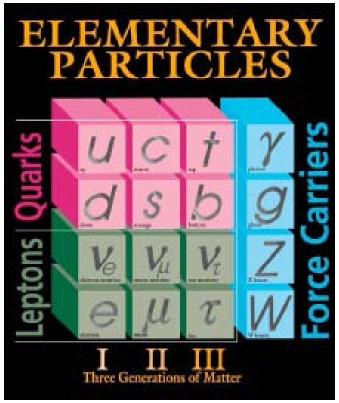
Grossman, Theory of charged leptons
Lavignac, CLFV Model Constraints from MEG, BELLE/BaBar and LHCb
Redi, Lepton Violation in non-SUSY
Mannel, Possibilities with Angular Distribution and Polarization
Shadmi, Model Constraints from CLFV at Muons and Taus
Paradisi, Interrelationships among g-2, EDMs and CLFV
Hambye, Lepton flavor violation in low-energy see-saw models
Czarnecki, Calculations of Radiative Backgrounds
Vicente, Charged Lepton Flavor Violation beyond minimal SUSY

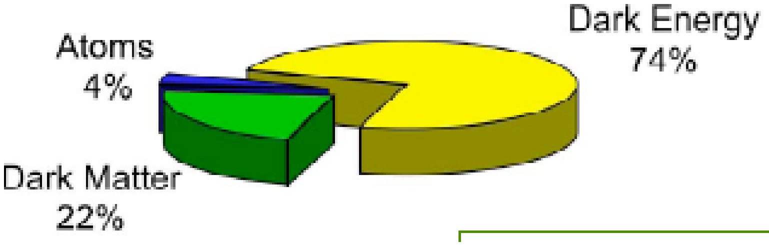
Conclusion:

No tail, no definite theory,
but if you find it,
we'll make one!

Standard Model : *A great story …* *but* definitely *not the whole story…*

+ Higgs (√)





- ***Cosmological issues***: inflation, dark matter, dark energy, ***matter anti-matter asymmetry…***
- ***Theoretical issues***: gravity (CC), neutrino mass, ***flavor***, hierarchy problem, strong CP, ….

The Flavor Puzzle

Experiments ahead of theory

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

- **Weak states ℑ mass states**
- **Quark, lepton flavors not conserved**

Unexplained observations (no theory of flavor):

- Three (“identical”) generations
- Huge mass differences between and within the generations
- Universality of interactions
- CP violation
- Symmetry between lepton and quark sectors (GUT, scale?)

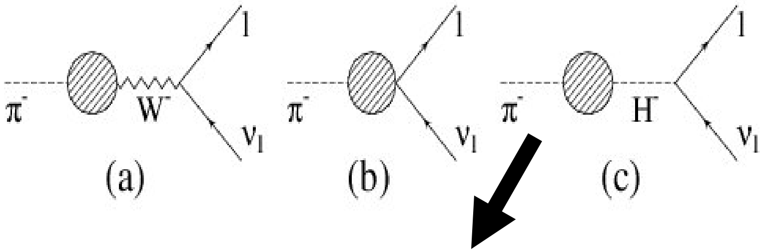
Experiments Seeking Insight into the Flavor Puzzle

- **Sensitivity to New Physics at High Mass Scales**
- **Unknown Couplings**

Exotic Searches ***New physics if seen.*** ***Experiments limit how far we can go***	$\mu \to e\gamma, 3e$ Lepton Flavor Violation $\tau \to e\gamma, \mu\gamma ...$ $\mu^- N \to e^- N$ $K_L^0 \to \mu e$ $\beta\beta_{0\nu}$ Lepton Number Violation
BSM Physics ***New physics if deviations from well-calculated SM predictions occur. Theory limits how far we can go***	$e, \mu, n ... \ edm$ CP / T Violation $(g-2)_\mu$ $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}, \frac{\tau^+ \to e^+\nu\nu}{\tau^+ \to \mu^+\nu\nu}$ Universality $K^+ \to \pi^+ \nu\bar{\nu}, K_L^0 \to \pi^0 \nu\bar{\nu}$ $B \to \mu\mu, b \to s\gamma, ...$

Example: Universality Tests Sensitive to high mass scales

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$$



Non-standard Higgs couplings

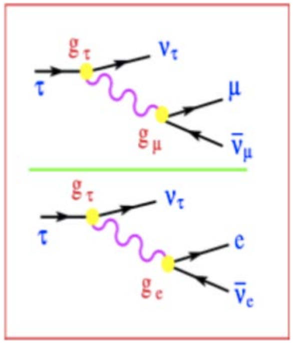
$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d + m_u)} \sim \left(\frac{1TeV}{\Lambda_{eP}}\right)^2 \times 10^3$$

0.05 % Measurement $R_{e/\mu}$ → Λ_{eP} >1000 TeV

Charged Higgs mass $m_{H^\pm}$ ~200 TeV probed.

Sensitivity to new physics $\sim \frac{1}{M_H^2}$

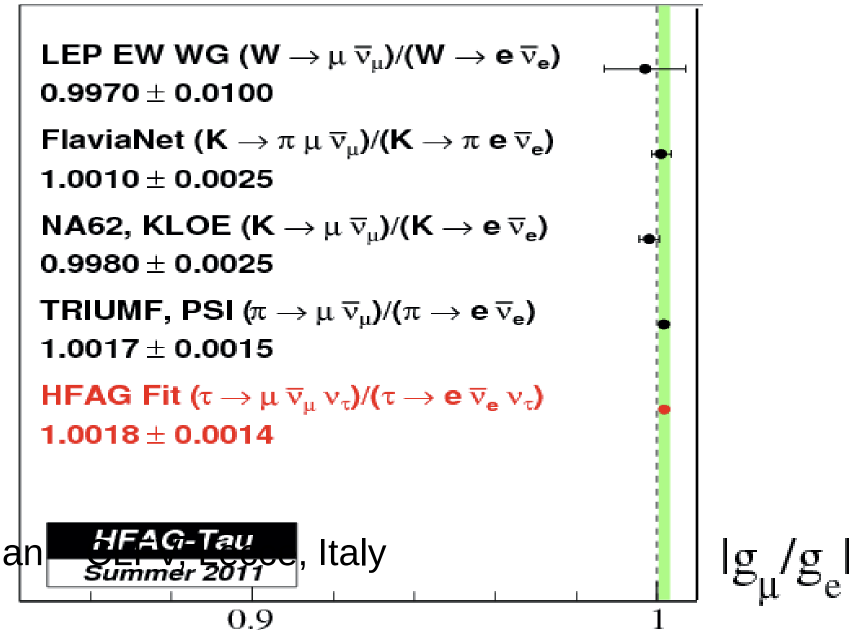
$$\frac{\tau \to e\nu\bar{\nu}}{\tau \to \mu\nu\bar{\nu}}$$



$e - \mu$

Universality

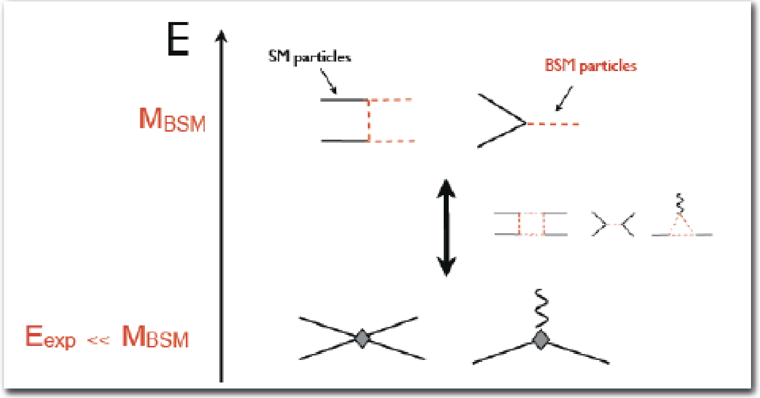
Tests



CPV and LFV

Cirigliano
IF Workshop 2013

Effective theory framework



At low energy, BSM physics is described by local operators; LFV and dipole moments probe strengths of different operators and their flavor structures

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

$\Lambda \leftrightarrow M_{\rm BSM}$ $C_i\ [g_{\rm BSM},\ M_a/M_b]$

Effective Operators for CP-violating EDMs and LFV processes:

Lavinac Paradisi

$$\bar{l}_i\sigma^{\mu\nu}\gamma_5 l_i F^{em}_{\mu\nu} \quad l_i\sigma^{\mu\nu} l_j F^{em}_{\mu\nu} \quad \bar{l}_i\Gamma^a l_j \bar{q}_k \Gamma^a q_l \quad \bar{l}_i\Gamma^a l_j \bar{l}_k \Gamma^a l_l$$

with dimensionless coefficients $\varepsilon \sim \frac{M_W^2}{M_{NP}^2}\frac{g_{NP}^2}{g_W^2}\delta_{CPV}\delta_{mix}$

Observable	Operator	Limit on ϵ
eEDM	$\overline{e_L}\sigma^{\mu\nu}\gamma_5 e_R F_{\mu\nu}$	$\leq 1.1 \times 10^{-3}$
B($\mu \to e\gamma$)	$\overline{\mu}\sigma^{\mu\nu} e F_{\mu\nu}$	$\leq 1.4 \times 10^{-4}$
B($\tau \to \mu\gamma$)	$\overline{\tau}\sigma^{\mu\nu} \mu F_{\mu\nu}$	$\leq 2.2 \times 10^{-2}$
B($K_L^0 \to \mu^\pm e^\mp$)	$(\overline{\mu}\gamma^\mu P_L e)(\overline{s}\gamma^\mu P_L d)$	$\leq 2.9 \times 10^{-7}$

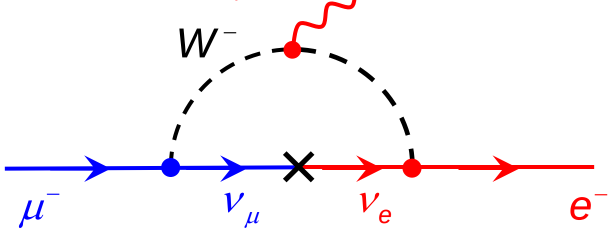
Flavour physics of leptons and dipole moments Eur.Phys.J.C57:13-182,2008

Lepton Flavor Violation

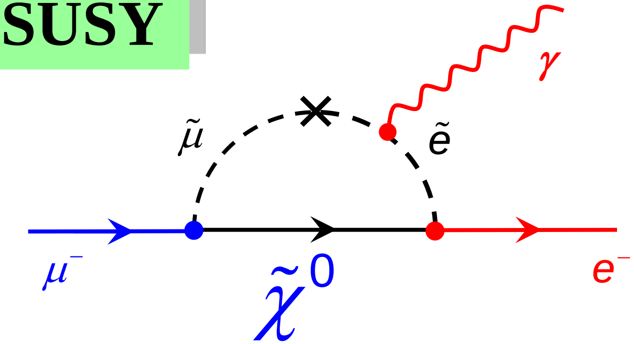
Neutrino oscillations→ lepton family numbers not conserved

SM

$\mu \to e\gamma$



SUSY



$$\mathrm{BR}(\mu^- \to e^-\gamma)\Big|_{\mathrm{SM}} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-54}$$

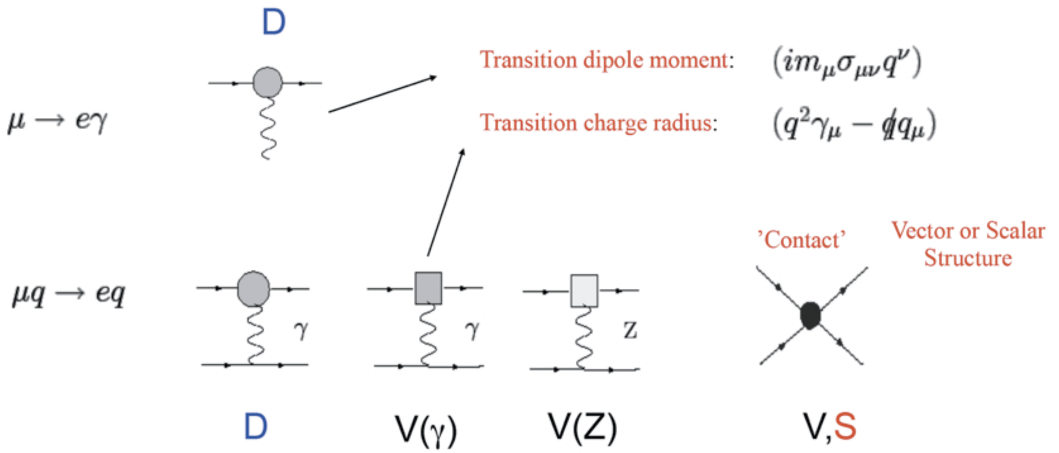
Petcov '77, Marciano-Sanda '77

$$\mathrm{BR}(\mu^- \to e^-\gamma)\Big|_{\mathrm{SUSY}} \approx 10^{-5}\,\frac{\Delta m^2_{\tilde e\tilde\mu}}{\bar m^2_{\tilde\ell}}\left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^4 \tan^2\beta \approx 10^{-13}$$

- Observation means new physics.
- Some SUSY models predict BR(μ → eγ) near the experimental limit (always!). CLFV may also be observable at the LHC (Shadmi).

$$\text{Sensitivity to new physics} \sim \frac{1}{\mathrm{M}_\mathrm{H}^4} \ \text{ with } \mathrm{M}_\mathrm{H} \sim 1\text{–}100\ \text{TeV}$$

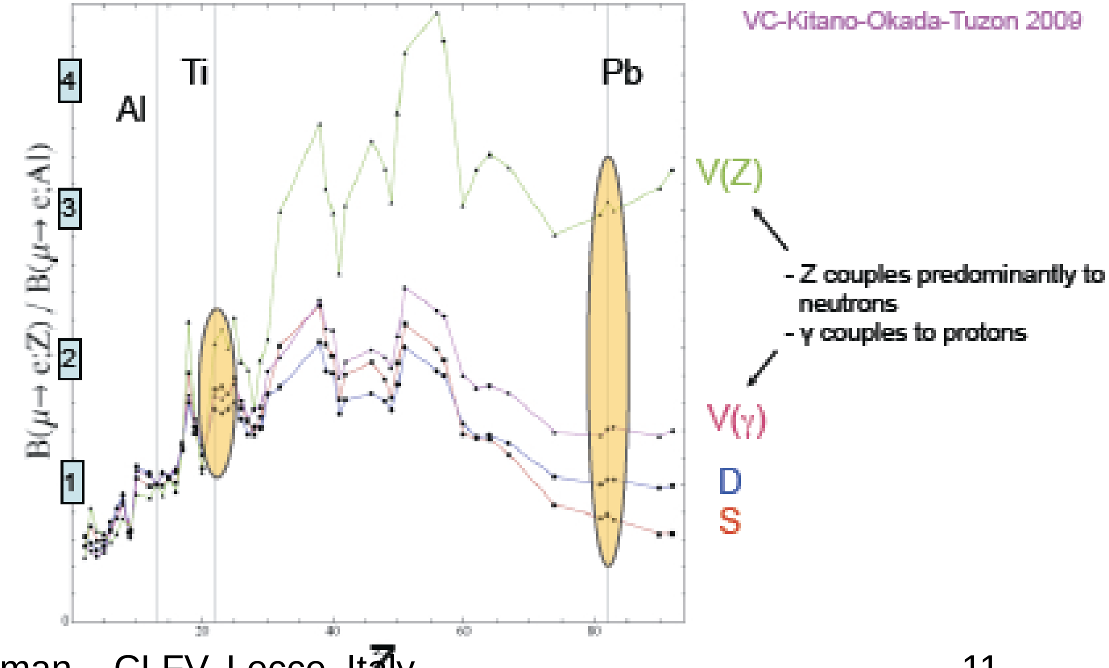
$\mu \to e\gamma$ and $\mu \to$ e Conversion Test Different Operators



Cirigliano
IF Workshop
2013

Target-dependence of μ→e rate

Theory uncertainties
cancel in ratios



VC-Kitano-Okada-Tuzon 2009

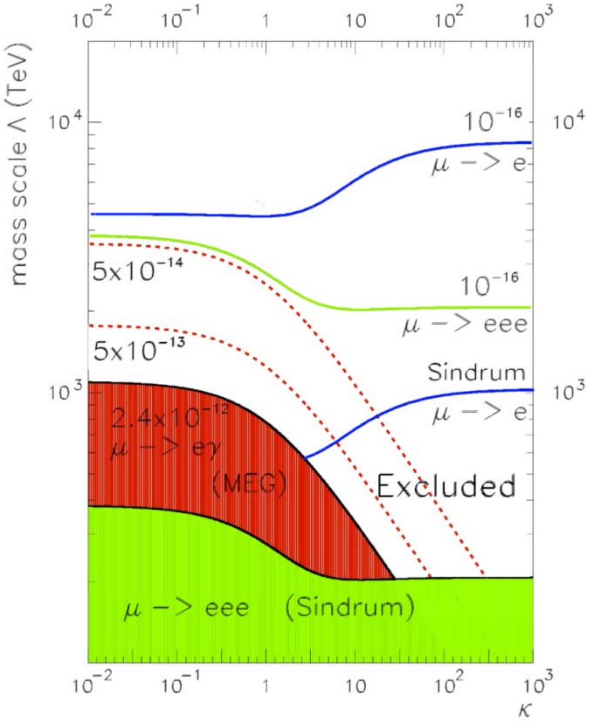
- Z couples predominantly to neutrons
- γ couples to protons

Model discriminating power by
Measuring different processes.

Two operators:

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa + 1)\,\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa + 1)\,\Lambda^2}\bar{\mu}_R\gamma_\mu e_L \bar{f}\gamma^\mu f$$

κ controls relative strength of
dipole vs vector operator



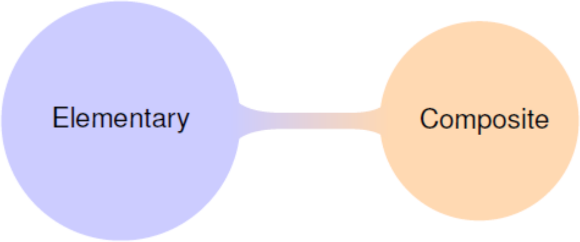
De Gouvea, Vogel

There may also be important connections between models for CLFV, g-2, and neutrino mass generation e.g. via Seesaw types I, II, III..

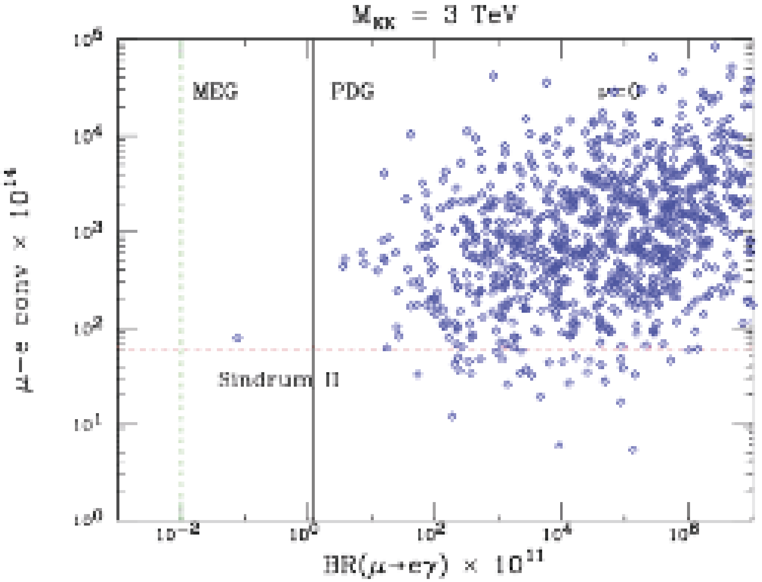
Paradisi, Hambye

Flavor Physics Testing COMPOSITE HIGGS MODELS

Bauer
Redi



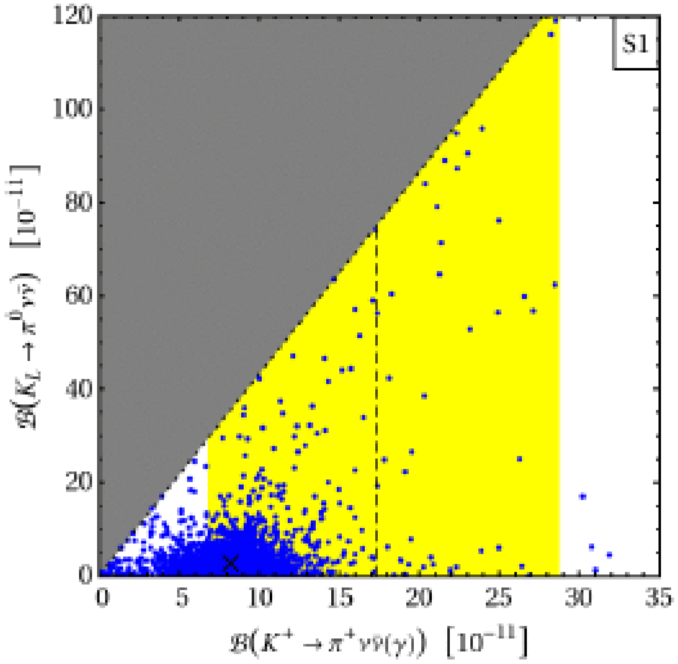
μe Conversion vs $\mu \to e\gamma$



Some parameters are not viable anymore.

Randall Sundrum Model
Warped extra dimensions

$K_L^0 \to \pi^0 \nu\bar{\nu}$ vs $K^+ \to \pi^+ \nu\bar{\nu}$



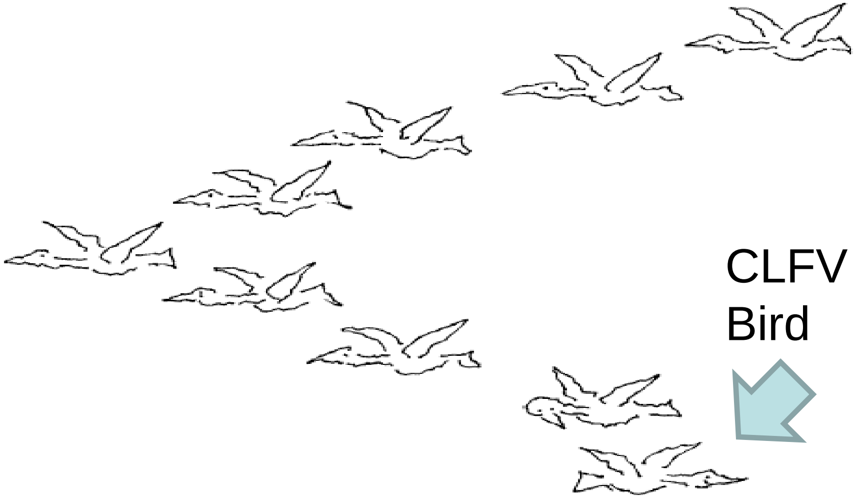
Large parameter space open.

1st Conference on Charged Lepton Flavor Violation Conference Summary

Day 2-3 Experiments

Sawada, MEG:Status and Upgrades
Berger, Mu->3e
Brown, Mu2e
Edmonds, COMET Stage 1 and 2
Natori, DeeMe
Goudzovski, Kaon System: Rare Decay Experiments
Hitlin, CLFV at BaBar
Schawanda, CLFV at BELLE and BELLE-II
Liu, CLFV at ATLAS
Lusito, CLFV at CMS
Khanji, Charged Lepton Flavor Violation at LHCb
Tschirhart, Future Facilities

Summary:



"Hope springs eternal"
but
"Wishing does not make a poor man rich."
(*Arabian Proverb*)

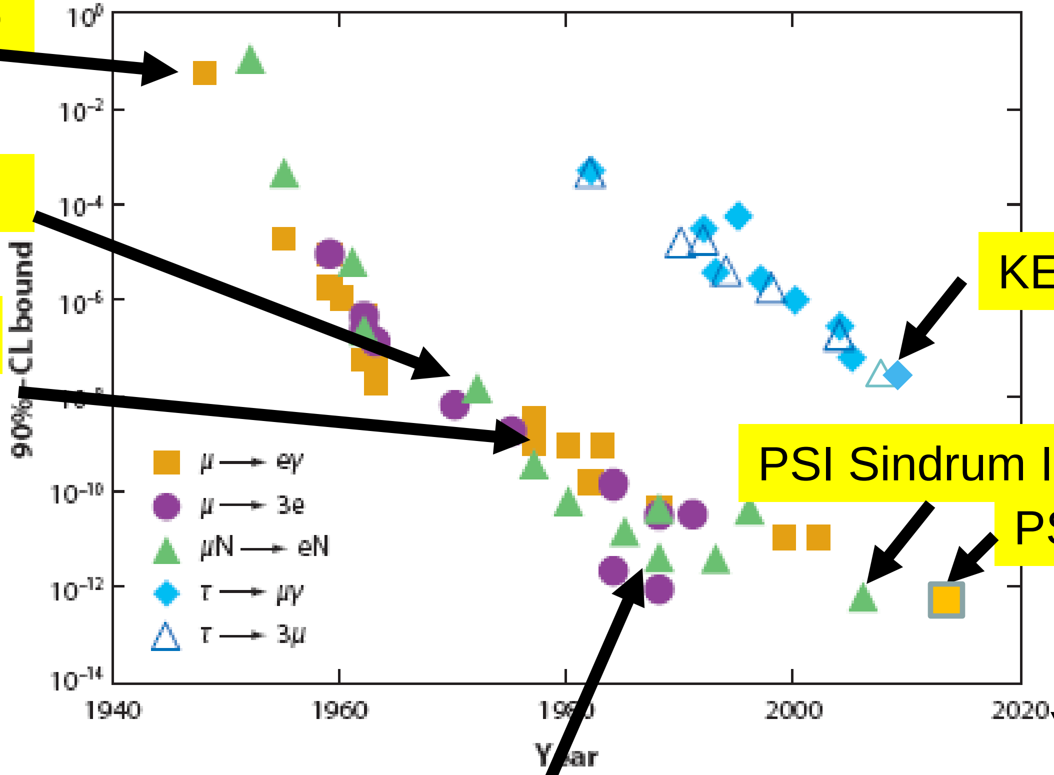
History of Some Rare Decay Experiments

Lepton Flavor Violation

Hincks, Pontecorvo

D.B. Thesis

μ->eγ 1977



KEK Belle

PSI Sindrum II (2006)

PSI MEG (2013)

TRIUMF TPC (1987)

Future: Many new experiments coming.

From Marciano, Mori, Roney 2010

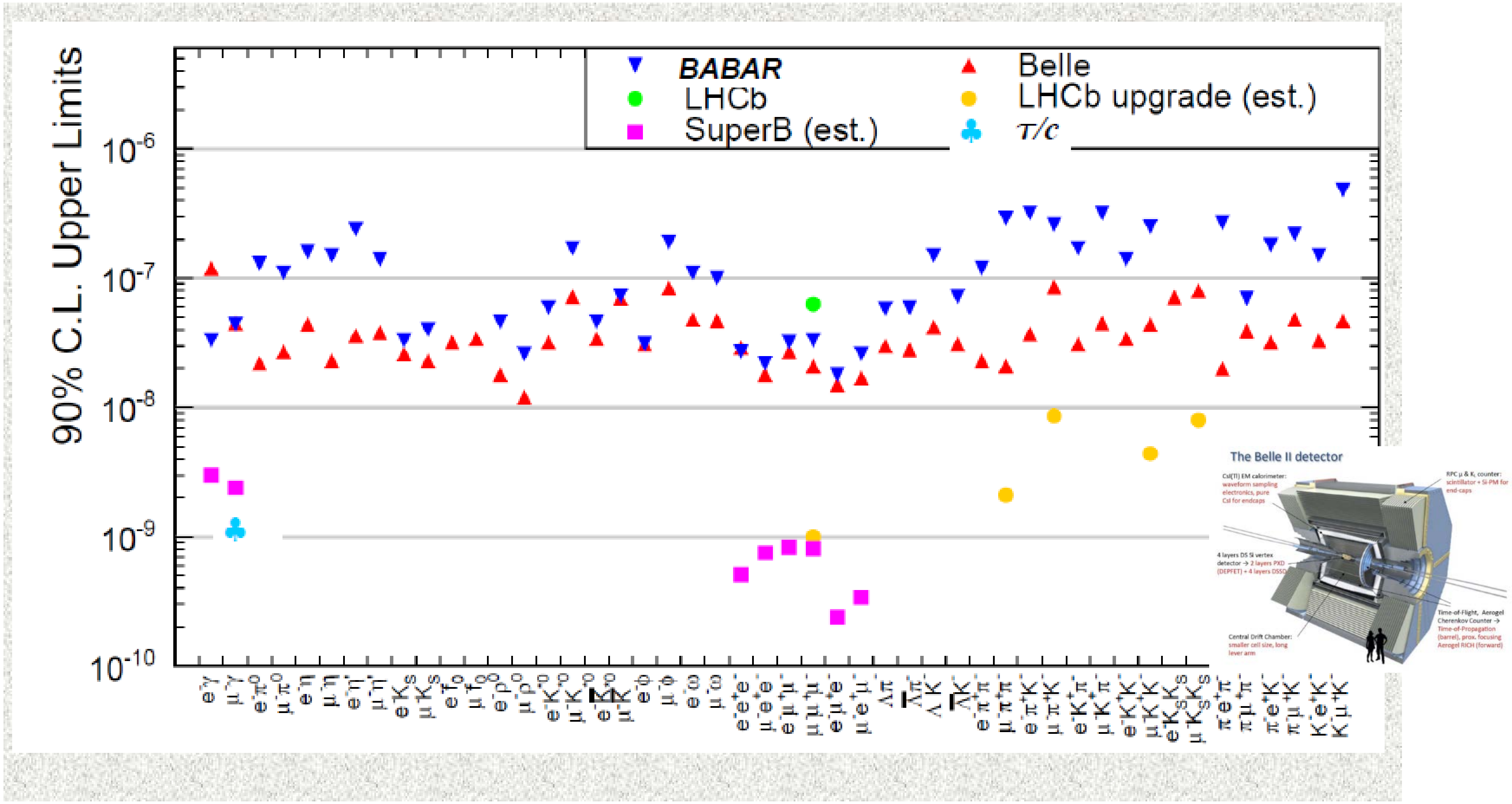
90% CL

Some LFV Limits and Prospects

Reaction	**Present limit**	**Future Possibilities**
μ+ → e+γ	*< 5.7 × 10−13*	*6x10-14 (PSI)*
μ+ → e+e+e−	*< 1.0 × 10−12*	*10-16 (PSI)*
μ−Ti → e−Ti	*< 4.6 × 10−12*	*10-14->10-16*
μ−Au → e−Au	*< 7 × 10−13*	*(Fermilab, JPARC)*
μ+e− → μ−e+	*< 8.3 × 10−11*	
τ → eγ	*< 1.1 × 10−7*	*<10-9 (KEK Belle II)*
τ → μγ	*< 4.4 × 10−8*	
τ → μμμ	*< 2.1 × 10−8*	*~10-9 LHCb*
τ → eee	*< 3.6 × 10−8*	
π0 → μe	*< 8.6 × 10−9*	*10-11 NA62*
K0L→ μe	*< 4.7 × 10−12*	*Project X (?)*
K+ → π+μ+e−	*< 2.1 × 10−10*	*10-12 NA62*
K0L→ π0μ+e−	*< 3.1 × 10−9*	
Z0 → μe	*< 1.7 × 10−6*	
Z0 → τe	*< 9.8 × 10−6*	
Z0 → τμ	*< 1.2 × 10−5*	

David Hitlin
Christoph Schwanda

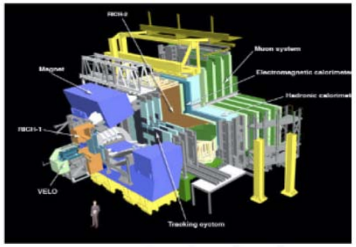
LFV τ Decays



B. Khanji, LHCb (Milano-Bicocca, INFN)

LHCb

Joining the LFV Club



$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) \quad < \quad 8.3(10.2) \times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL}$$

Becoming
Competitive.

$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) \quad < \quad 4.6(5.9) \times 10^{-7} \text{ at } 90\% \ (95\%)\text{CL}$$

$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) \quad < \quad 5.4(6.9) \times 10^{-7} \text{ at } 90\% \ (95\%)\text{CL}$$

New

$$\mathcal{B}(\mathrm{D}^+ \to \pi^-\mu^+\mu^+) \quad < \quad 2.2(2.5) \times 10^{-8} \text{ at } 90\% \ (95\%) \text{ CL}$$

$$\mathcal{B}(\mathrm{D_s} \to \pi^-\mu^+\mu^+) \quad < \quad 1.2(1.4) \times 10^{-7} \text{ at } 90\% \ (95\%) \text{ CL}$$

Best
So far.

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}^+\mu^-\mu^-) \quad < \quad 6.9 \times 10^{-7} \text{ at } 95\% \text{ CL}$$

Best

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}^*\mu^-\mu^-) \quad < \quad 2.4 \times 10^{-6} \text{ at } 95\% \text{ CL}$$

New

$$\mathcal{B}(\mathrm{B}^- \to \pi^+\mu^-\mu^-) \quad < \quad 1.3 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}_s^+\mu^-\mu^-) \quad < \quad 5.8 \times 10^{-7} \text{ at } 95\% \text{ CL}$$

Best
So far.

$$\mathcal{B}(\mathrm{B}^- \to \mathrm{D}^0\pi^+\mu^-\mu^-) \quad < \quad 1.5 \times 10^{-6} \text{ at } 95\% \text{ CL}$$

Cautionary Tales

LFV Experiments	Limit Reached	Goal; (Result/Goal)	“Comments”
Badertscher et al. 1982 μ->e	7x10^{-11}		
TRIUMF TPC Ahmad et al. 1987 μ->e	4.6x10^{-12}	2x10^{-12} (2)	Data collection took 5x as long as originally guessed (1 month!)
SINDRUM II Bertl et al. 2006 μ->e	7x10^{-13} Au	“10^{-14}”$^{(1987)}$-> 3x$10^{-14(1993)}$ “engineering” Ti (>60)	Flux lower by 10; pion suppression device didn’t work; unanticipated high electron bkg.; shorter running.
MEGA Ahmed et al. 2002 μ->eγ	1.2x10^{-11}	0.9->4x10^{-13} “engineering” (133-35)	Death by a thousand blows to acceptance

Case Study I: MEGA at LAMPF

$$\mathcal{B} = \left(\frac{R_\mu}{d}\Delta t\right)\left(\frac{\Delta E_e}{m_\mu/2}\right)\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta}{2}\right)^2 f(\theta_\gamma)\eta_{\rm IBV}.$$

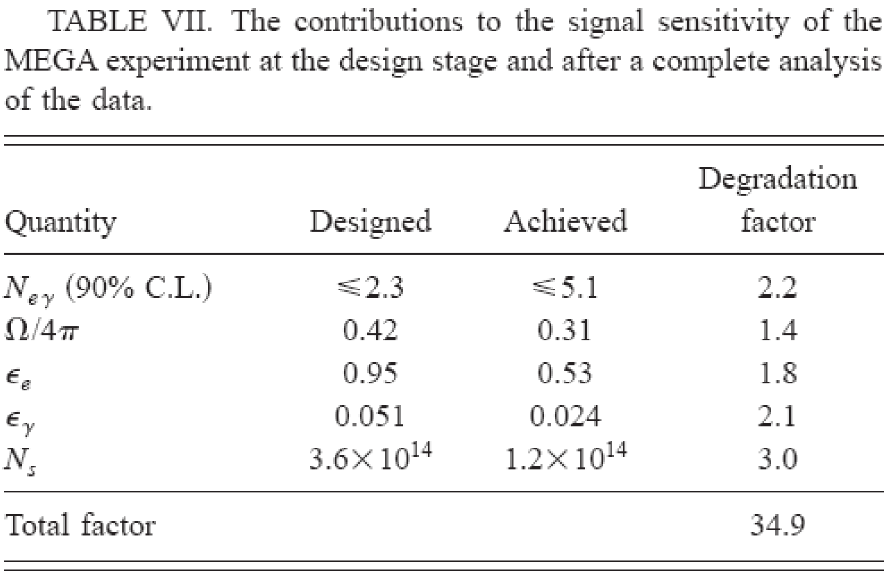


TABLE VII. The contributions to the signal sensitivity of the MEGA experiment at the design stage and after a complete analysis of the data.

Quantity	Designed	Achieved	Degradation factor
$N_{e\gamma}$ (90% C.L.)	$\leqslant 2.3$	$\leqslant 5.1$	2.2
$\Omega/4\pi$	0.42	0.31	1.4
ϵ_e	0.95	0.53	1.8
ϵ_γ	0.051	0.024	2.1
N_s	3.6×10^{14}	1.2×10^{14}	3.0
Total factor			34.9

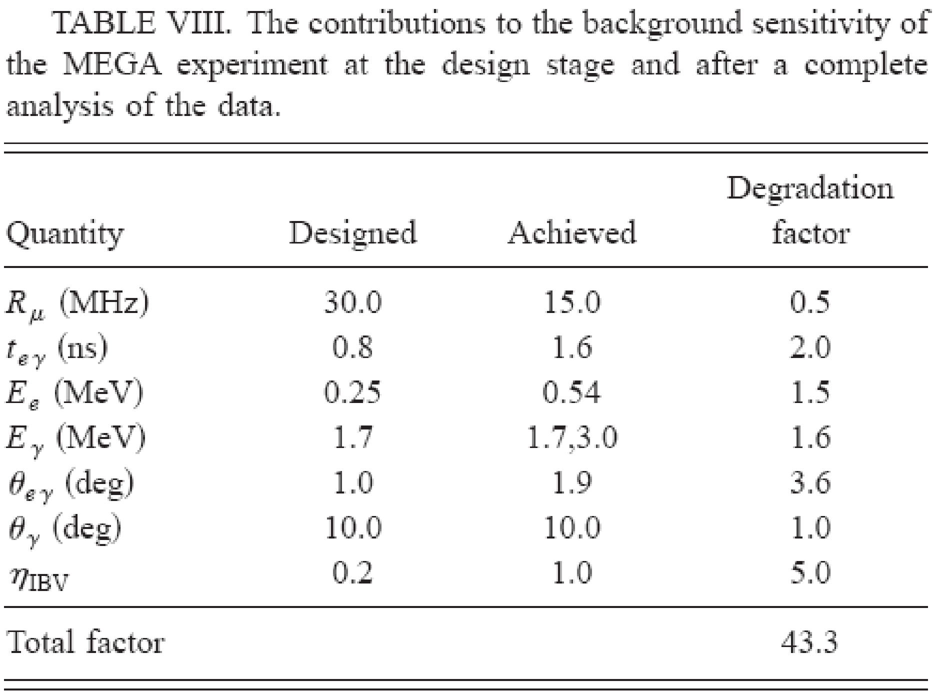
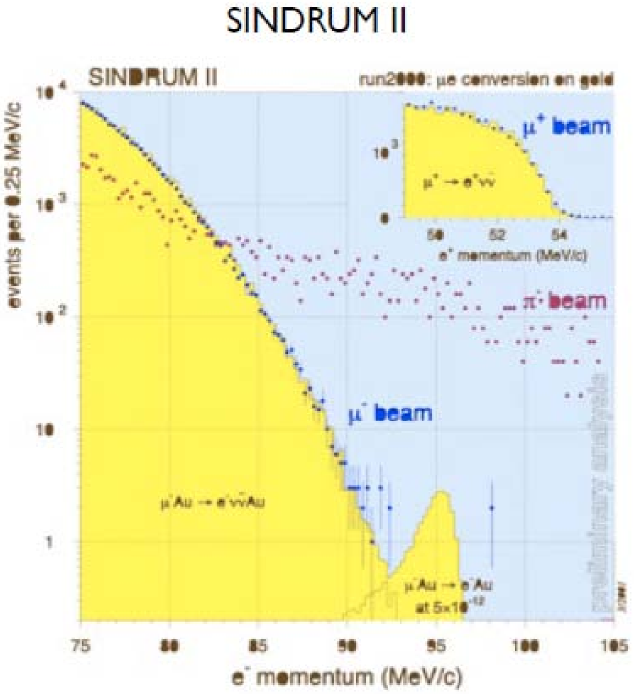


TABLE VIII. The contributions to the background sensitivity of the MEGA experiment at the design stage and after a complete analysis of the data.

Quantity	Designed	Achieved	Degradation factor
R_μ (MHz)	30.0	15.0	0.5
$t_{e\gamma}$ (ns)	0.8	1.6	2.0
E_e (MeV)	0.25	0.54	1.5
E_γ (MeV)	1.7	1.7,3.0	1.6
$\theta_{e\gamma}$ (deg)	1.0	1.9	3.6
θ_γ (deg)	10.0	10.0	1.0
$\eta_{\rm IBV}$	0.2	1.0	5.0
Total factor			43.3

Phys.Rev. D65 (2002) 112002

Case study II: SINDRUM II PSI



- Proposed 10^8 stops; (muE1) beam was only 10^7
- Designed "PMC" to kill pions; simulated; swamped unexpectedly by electrons; solenoid took years longer to obtain.
- Eventually went to very low momentum (50 MeV/c) killing pions by range; pion background persisted.
- Final result obtained in a couple of months; group had dispersed…." could have done better"….

Remarks: How to lose a factor 10 (100…) in a LFV experiment?

Tension between needing high rates and high sensitivities.

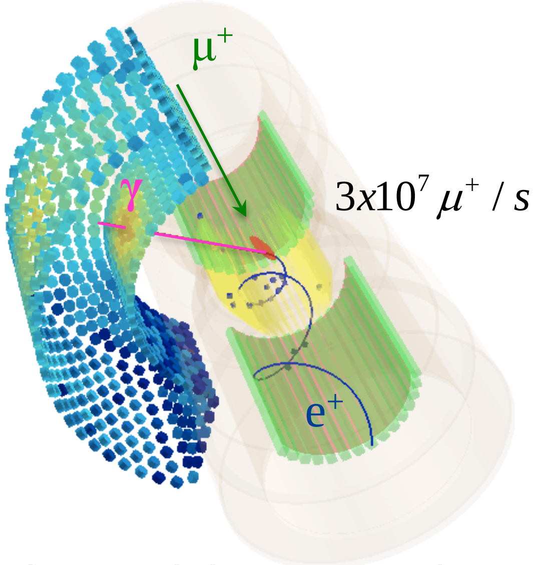
- Optimistic resolutions – excessive rates or beam contamination?
- Optimistic acceptances – extra losses due to cuts?
- Missing background sources e.g. due to high energy production or multiple low probability events …
- Cosmic rays and other effects?
- Fill in your own….

Ryu Sawada

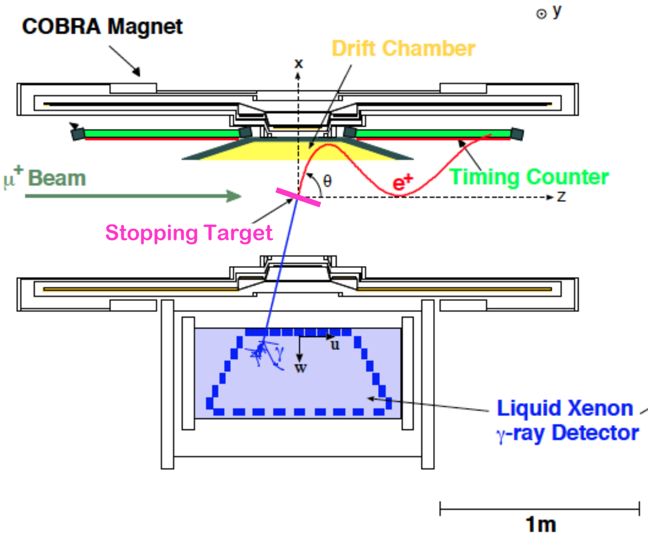
Eur. Phys. J. C 73 (2013) 2365

MEG

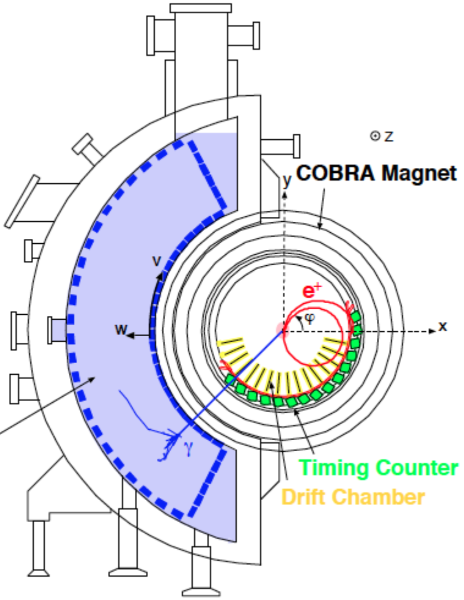
3D view:



Top view:



Front view:



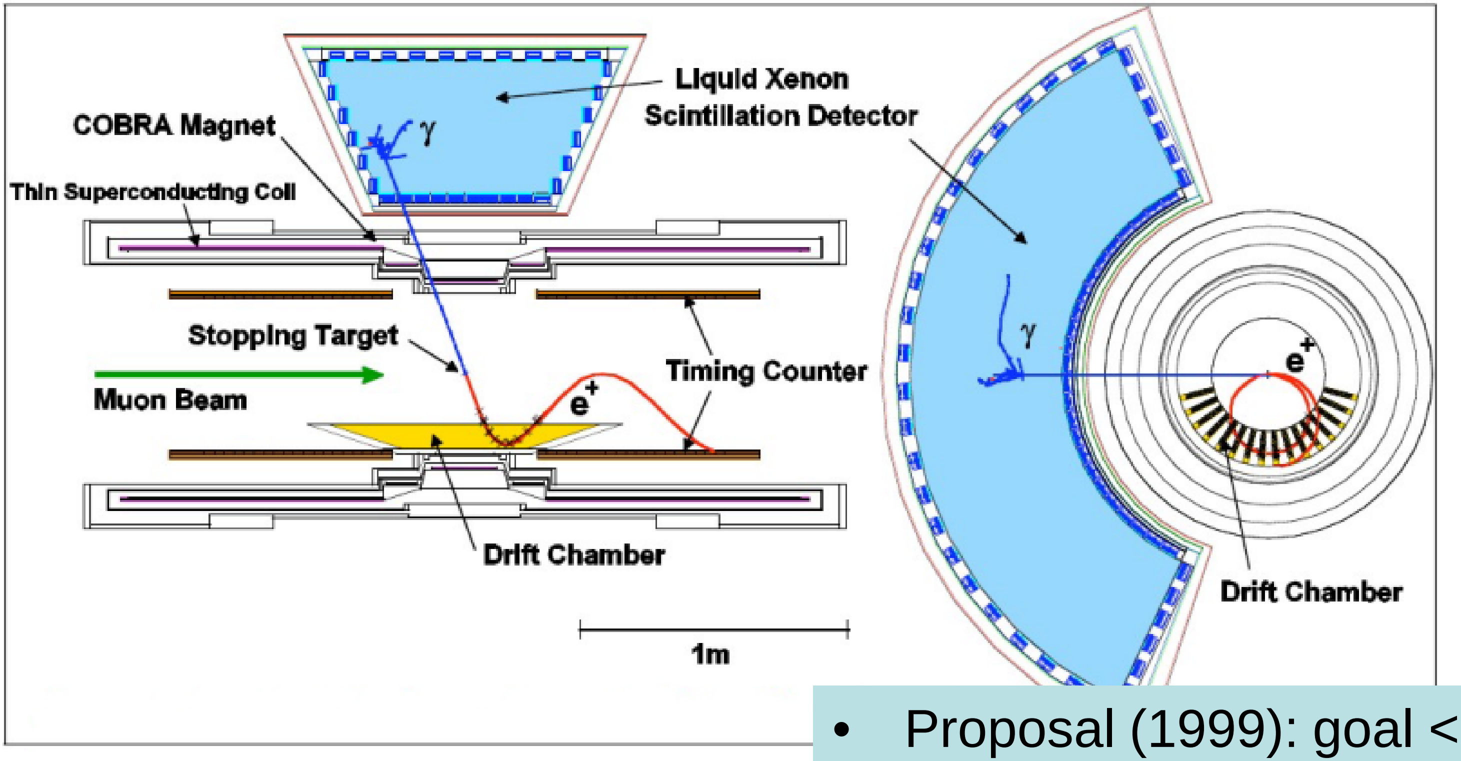
G. Lim IF Workshop Argonne 4/2013

Dedicated detector with asymmetric coverage ($\Omega_{MEG}/4\pi = 11\%$):

1. Liquid Xenon photon calorimeter with excellent position, time and energy resolutions
2. Low-mass positron spectrometer with gradient B-field for fast positron sweep out
3. Stable, well monitored & calibrated detector (arsenal of calibration & monitoring tools)
4. High performance DAQ system (multi-GHz waveform digitization of nearly all 3k channels)

MEG Experiment at PSI

$\mu \rightarrow e\ \gamma$



- 3×10^7 μ/sec, 100% duty factor
- LXe for efficient γ detection
- Solenoidal magnetic spectrometer

- Proposal (1999): goal $<2 \times 10^{-14}$ (2.2×10^7 s)
- 2013 Result: $<5.7 \times 10^{-13}$
- New goal (~2020): $<6 \times 10^{-14}$

S. Ritt

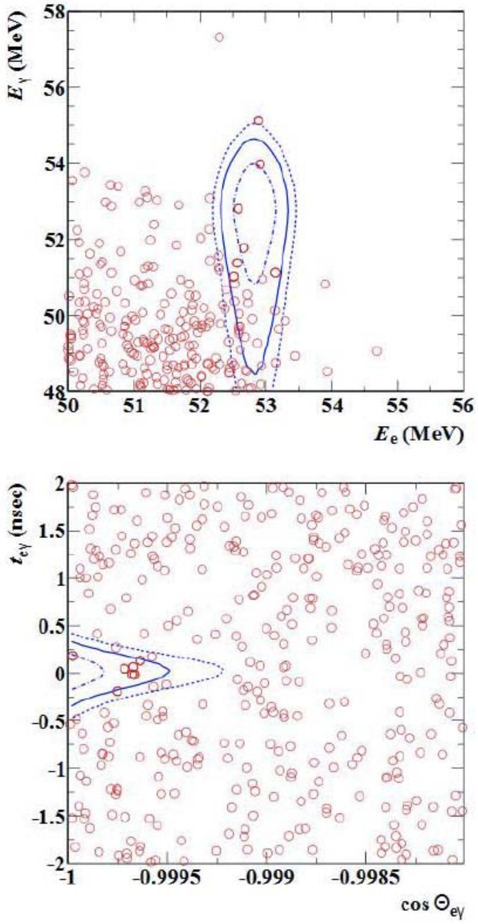
arXiv:1303.0754

MEG Current result (2013)

B <5.7 x 10^{-13} (90% c.l.)

(Additional data to be analyzed)

MEG 2013 Upgrade Plan → 6x10^{-14}



signal PDF contours at 1, 1.64 and 2 sigma

Data 2009-2011

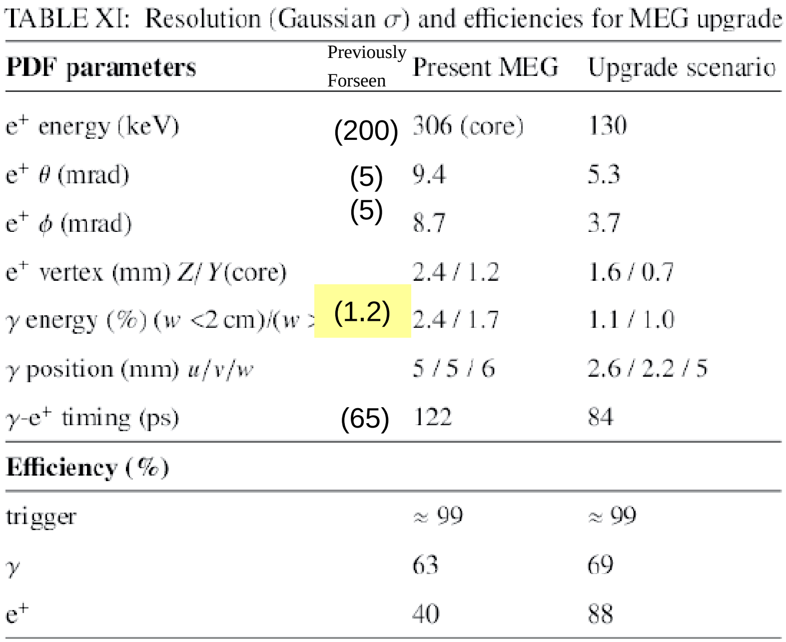
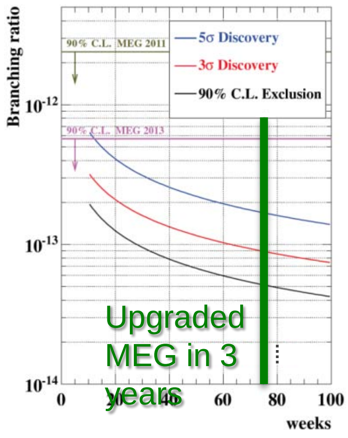


TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Previously Forseen	Present MEG	Upgrade scenario
e^+ energy (keV)	(200)	306 (core)	130
e^+ θ (mrad)	(5)	9.4	5.3
e^+ ϕ (mrad)	(5)	8.7	3.7
e^+ vertex (mm) Z/Y(core)		2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >	(1.2)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$		5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	(65)	122	84
Efficiency (%)			
trigger		≈ 99	≈ 99
γ		63	69
e^+		40	88



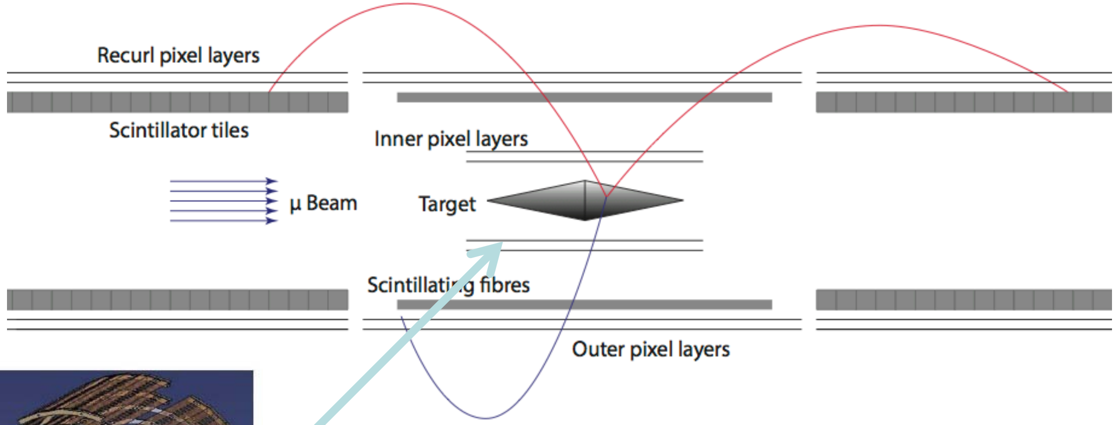
Upgraded MEG in 3 years

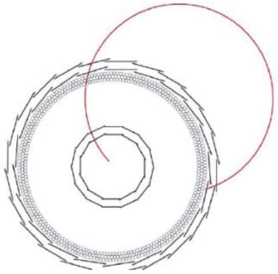
Niklaus Berger

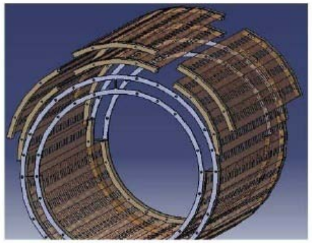
$\mu \to 3e$ at PSI: Goal $<10^{-16}$

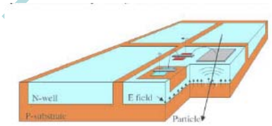
Mu3e proposal

- Phase I uses MEG beamline to provide ~ 10^8 μ^+/s to get to 10^{-15}
- Phase II assumes construction of new high intensity beam at PSI spallation neutron source to reach 10^{-16}









50μm Monolithic active pixel (MAP) detectors

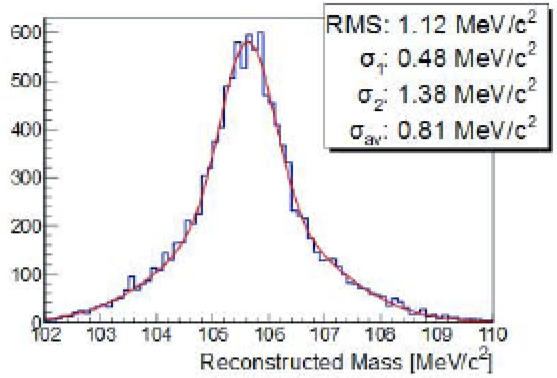


Figure 17.2: Reconstructed mass resolution for signal events in the phase IA configuration.

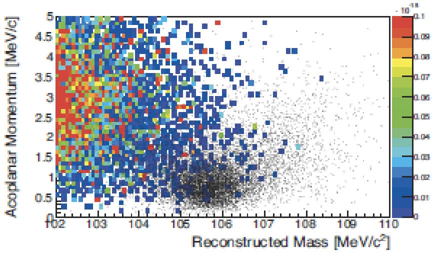
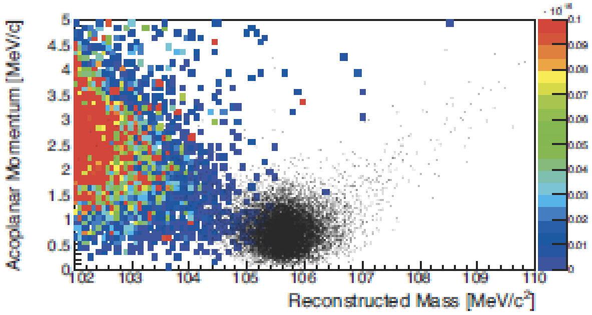
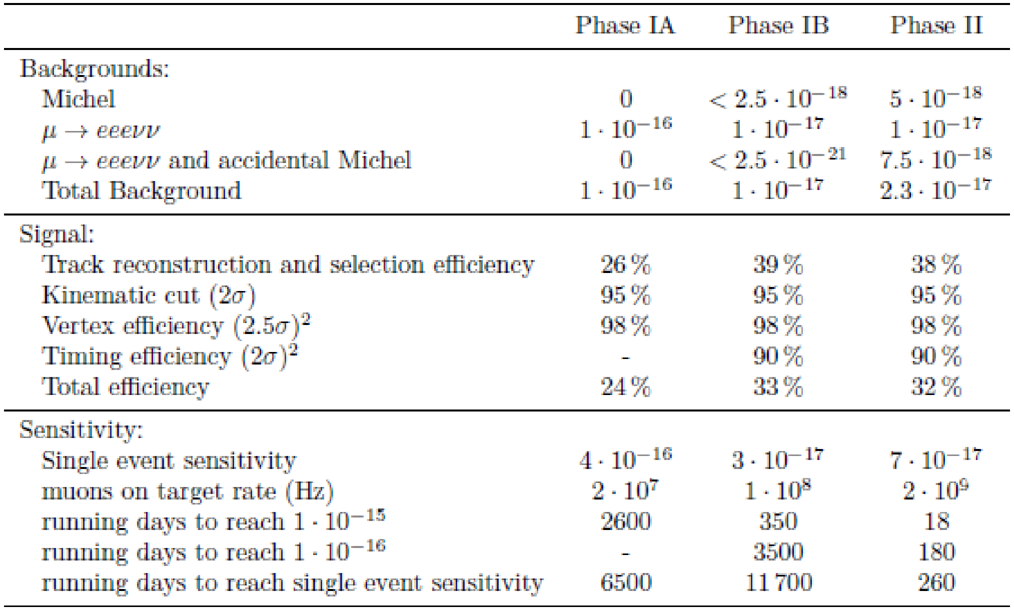
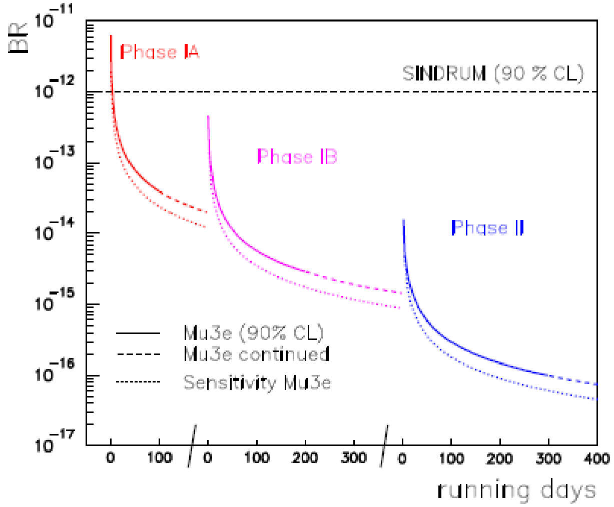


Figure 17.9: Internal conversion background (colours) and signal (black dots) in the acoplanar momentum - reconstructed mass plane for the phase IA detector configuration.





	Phase IA	Phase IB	Phase II
Backgrounds:			
Michel	0	$< 2.5 \cdot 10^{-18}$	$5 \cdot 10^{-18}$
$\mu \to ee e \nu\nu$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$1 \cdot 10^{-17}$
$\mu \to ee e \nu\nu$ and accidental Michel	0	$< 2.5 \cdot 10^{-21}$	$7.5 \cdot 10^{-18}$
Total Background	$1 \cdot 10^{-16}$	$1 \cdot 10^{-17}$	$2.3 \cdot 10^{-17}$
Signal:			
Track reconstruction and selection efficiency	26 %	39 %	38 %
Kinematic cut (2σ)	95 %	95 %	95 %
Vertex efficiency $(2.5\sigma)^2$	98 %	98 %	98 %
Timing efficiency $(2\sigma)^2$	-	90 %	90 %
Total efficiency	24 %	33 %	32 %
Sensitivity:			
Single event sensitivity	$4 \cdot 10^{-16}$	$3 \cdot 10^{-17}$	$7 \cdot 10^{-17}$
muons on target rate (Hz)	$2 \cdot 10^{7}$	$1 \cdot 10^{8}$	$2 \cdot 10^{9}$
running days to reach $1 \cdot 10^{-15}$	2600	350	18
running days to reach $1 \cdot 10^{-16}$	-	3500	180
running days to reach single event sensitivity	6500	11 700	260



$\mu^- N \to e^- N$ Experiments

- **Singles experiment allows ultra-high beam rates.**
- **Intrinsic background (decay-in-orbit) known and calculable.**

Czarnecki et al.

$$N(E_e)\,dE_e \simeq 0.4\cdot 10^{-21}\left(1-\frac{E_e}{E_{\max}}\right)^5 dE_e$$

PRD84,013006,2011

Radiative corrections under study.

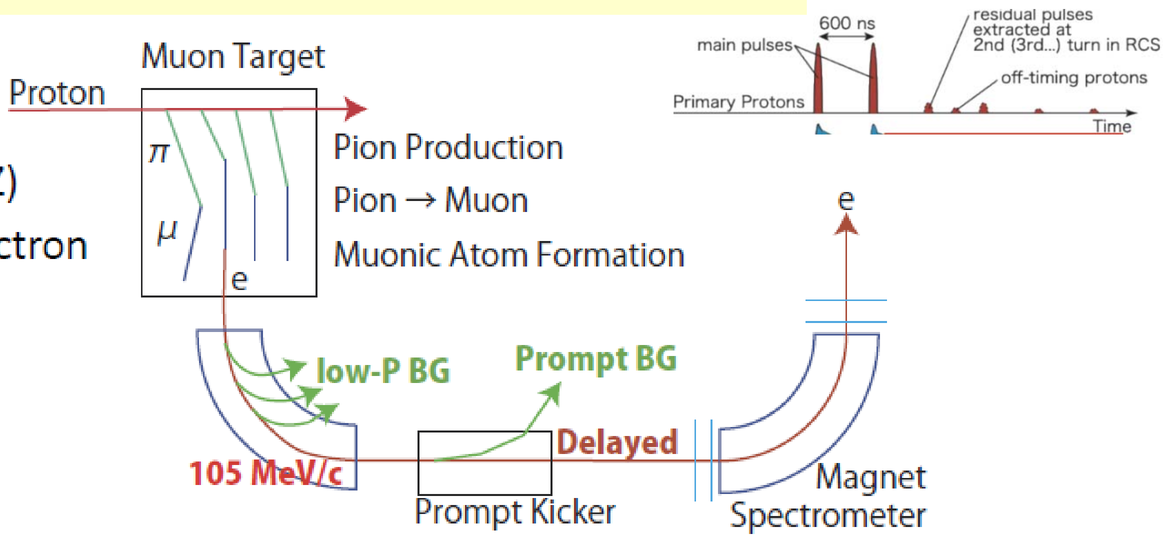
- **High resolution detector feasible.**
- **Proposed improvements > 10^4**

JPARC: DeeMe

$\mu^- N \to e^- N$ at $<10^{-14}$

Hiroaki Natori

DeeMe(P41)



- Process : μ^- +(A,Z) → e^- +(A,Z)
- A single mono-energetic electron
  - 105 MeV
  - Delayed : ~1μS
- No accidental backgrounds
- Physics backgrounds
- Muon Decay in Orbit (DIO)
  - E_e > 102.5 MeV (BR:10^{-14})
  - E_e > 103.5 MeV (BR:10^{-16})
- Beam Pion Capture
  - π^-+(A,Z) → (A,Z-1)* → γ+(A,Z-1)
    γ → $e^+ e^-$
  - Prompt timing

- Low Energy main part: suppressed by the beamline.
- High Energy tail: Magnet Spectrometer (Δp < 0.3%)

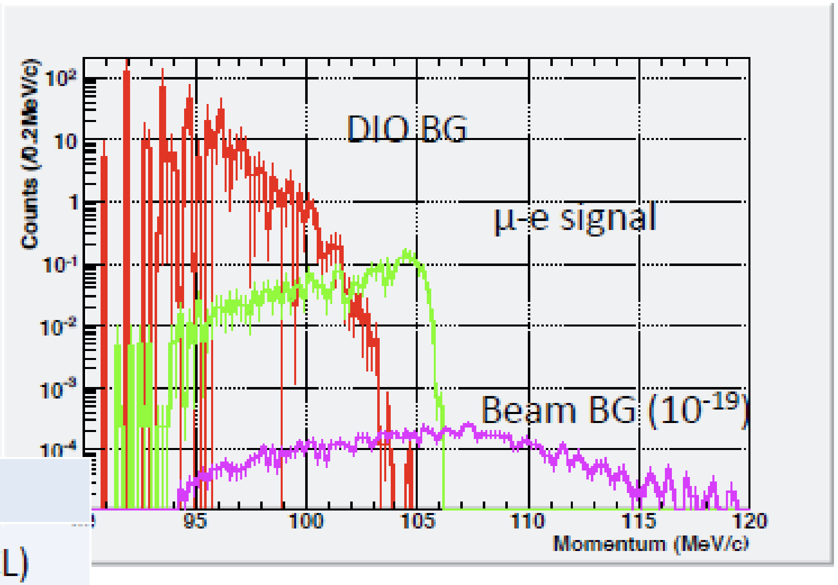
- Main pulse: Kicker to reduce the detector rate.
- after-protons: Suppressed owing to the extremely small after-protons from RCS -- $R_{AP}<10^{-17}$.

JPARC: DeeMe

Sensitivity and Backgrounds

- Signal Sensitivity
  - S.E.S.: 2×10^{-14} (1 MW, 2×10^{7}sec)
- Backgrounds
  - $R_{AP} < 9 \times 10^{-18}$
  - Detector live-time Duty = 1/20000

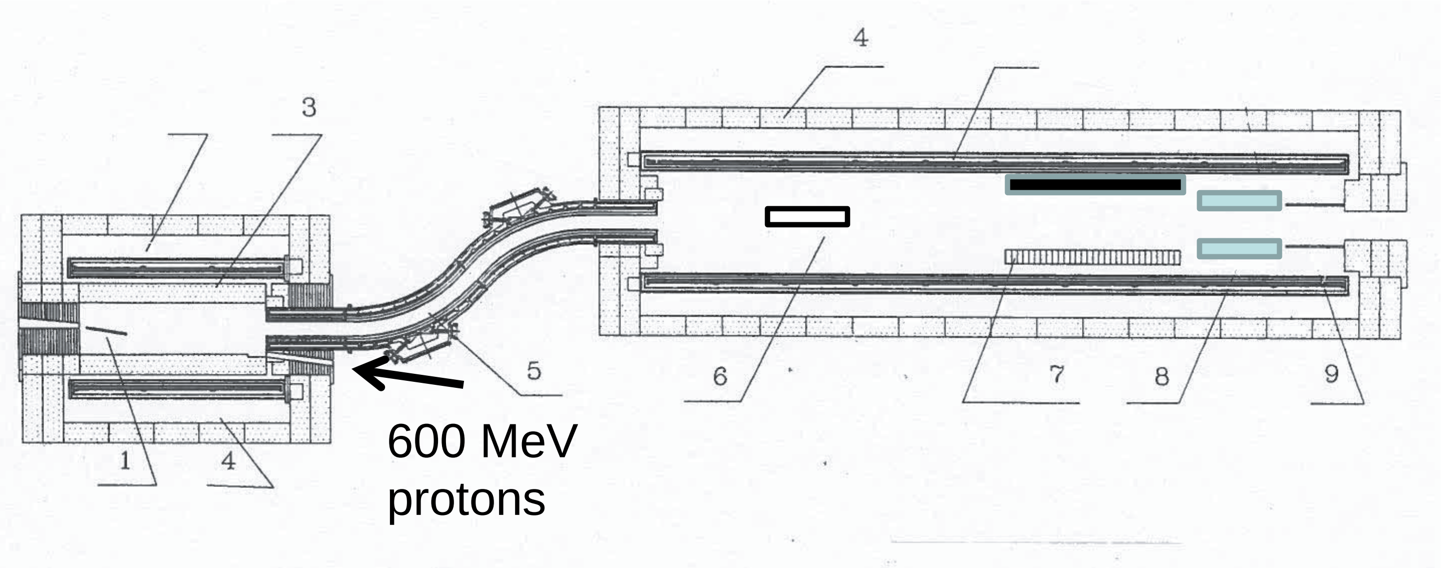
DIO Background	0.09
After-Proton Background	< 0.027 (<0.05 90%CL)
Cosmic-Muon Induced Electron BG	<0.018 (MC stat. limited)
Cosmic-Muon Induced Muon BG	<0.001
Radiative Muon Capture BG	<0.0009



Signal Region: 102.0 -- 105.6 MeV/*c*

$\mu^- N \rightarrow e^- N$ at 10^{-16}

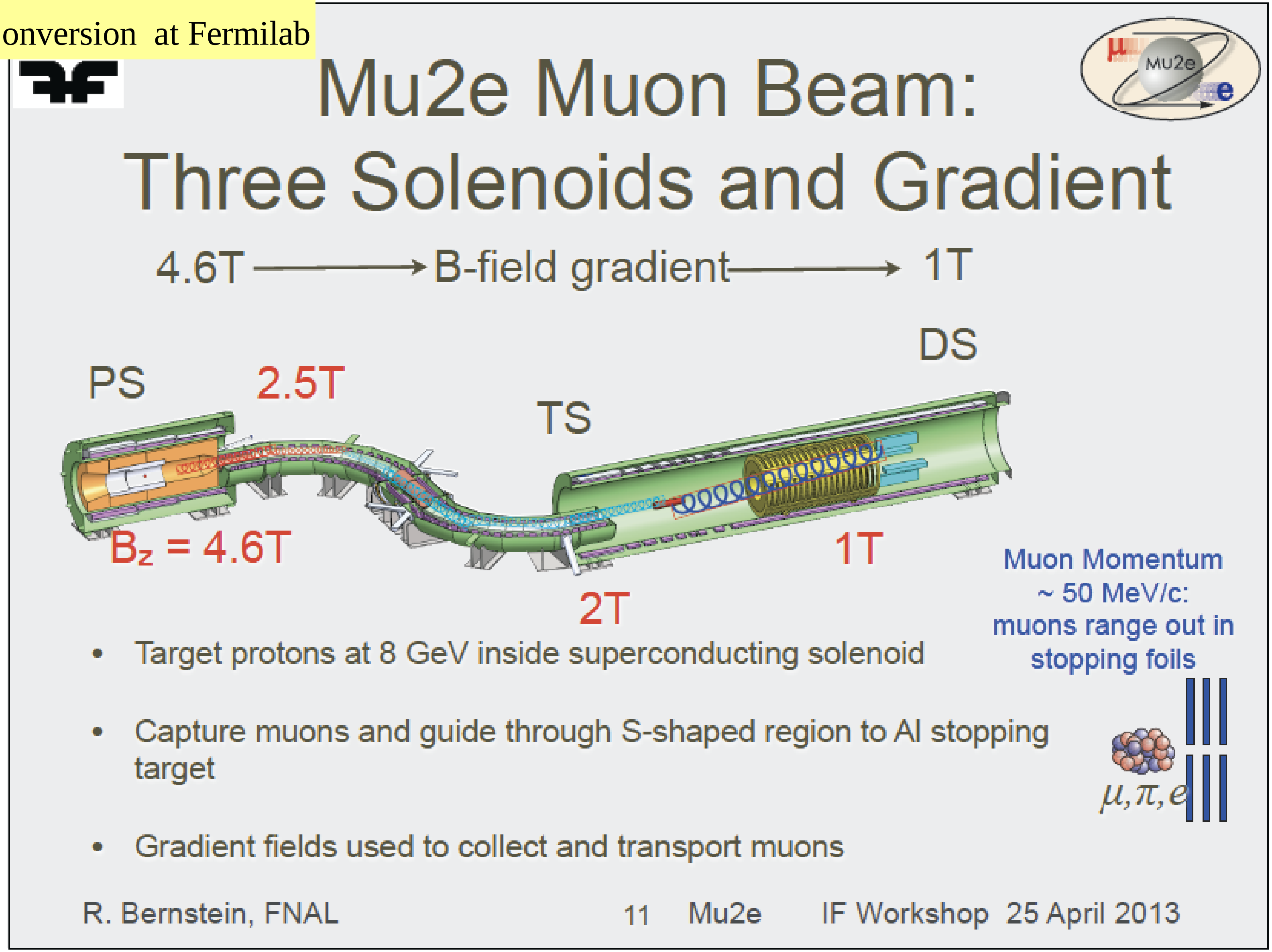
Lobashov, Djilkibaev (1980→1989):
Solenoid Pion Collector; flux x 1000.



Moscow Meson Factory***

David Brown

BNL MECO $\rightarrow$ *Mu2E*
$\mu \rightarrow$ e Conversion at Fermilab

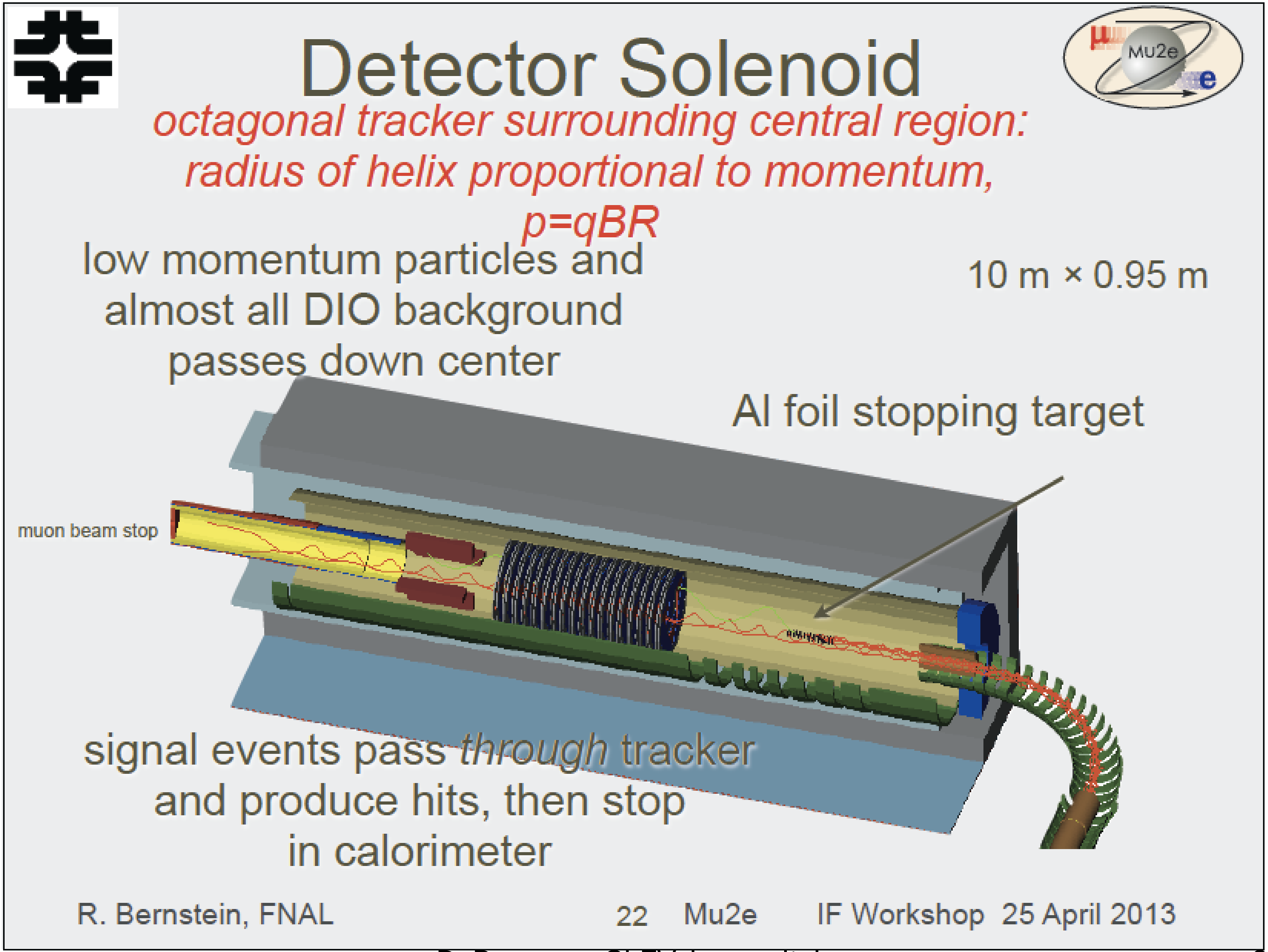


Mu2e Muon Beam: Three Solenoids and Gradient

Muon Momentum ~ 50 MeV/c: muons range out in stopping foils

- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

R. Bernstein, FNAL 11 Mu2e IF Workshop 25 April 2013



Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center

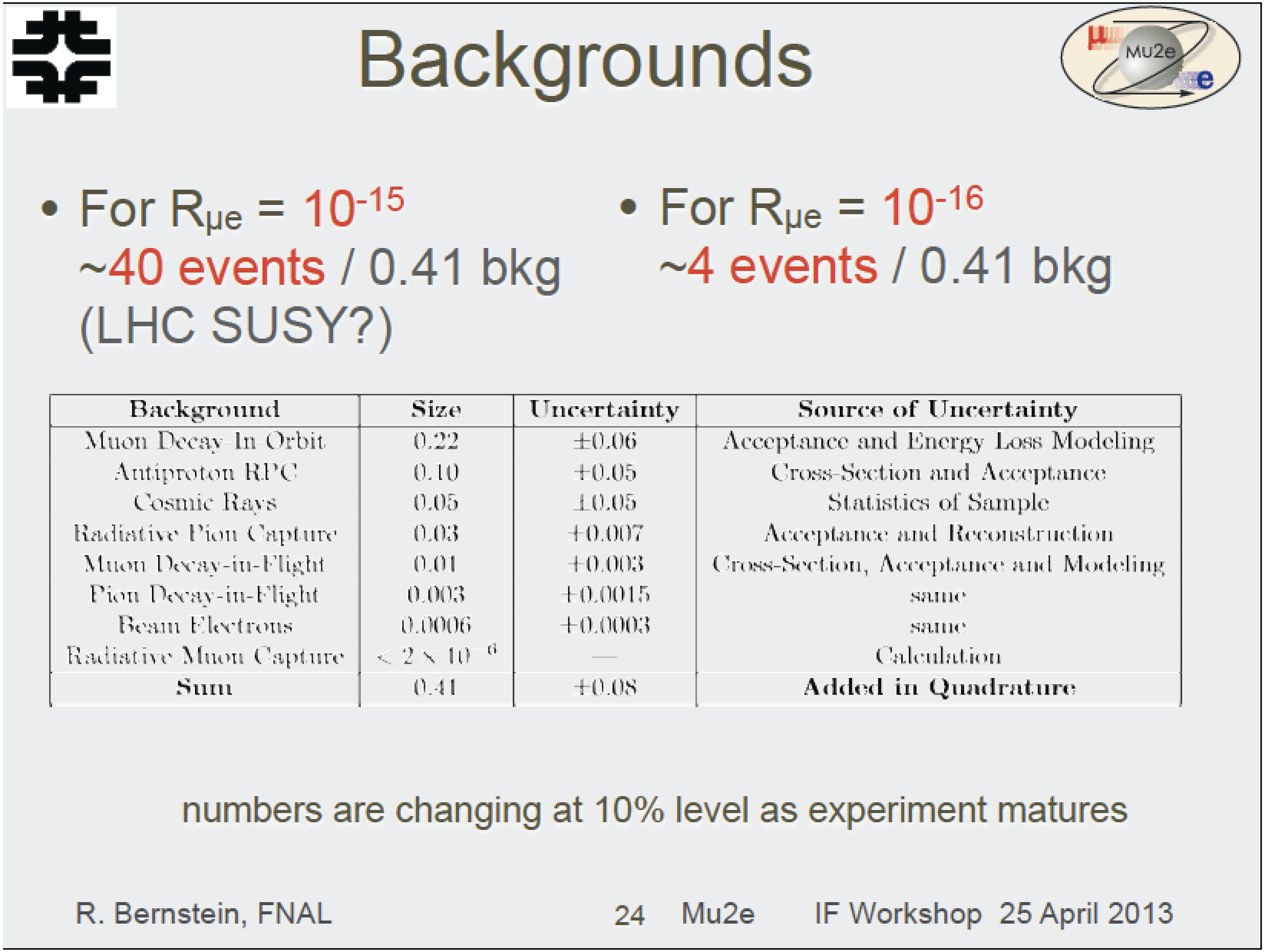
10 m × 0.95 m

Al foil stopping target

muon beam stop

signal events pass *through* tracker and produce hits, then stop in calorimeter

R. Bernstein, FNAL 22 Mu2e IF Workshop 25 April 2013



Backgrounds

- For $R_{\mu e} = 10^{-15}$
  ~40 events / 0.41 bkg
  (LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
  ~4 events / 0.41 bkg

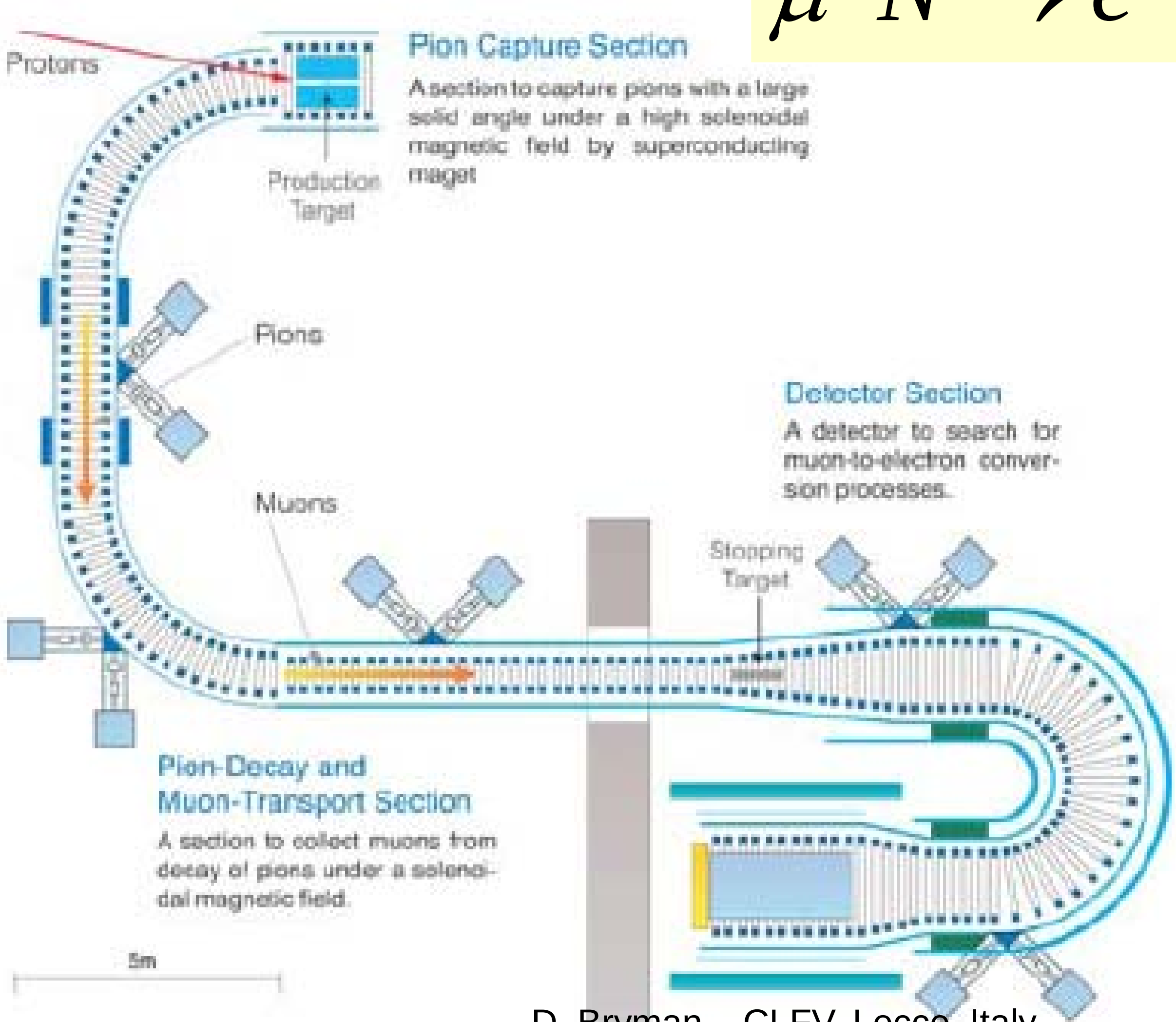
Background	Size	Uncertainty	Source of Uncertainty
Muon Decay-In-Orbit	0.22	±0.06	Acceptance and Energy Loss Modeling
Antiproton RPC	0.10	±0.05	Cross-Section and Acceptance
Cosmic Rays	0.05	±0.05	Statistics of Sample
Radiative Pion Capture	0.03	±0.007	Acceptance and Reconstruction
Muon Decay-in-Flight	0.01	±0.003	Cross-Section, Acceptance and Modeling
Pion Decay-in-Flight	0.003	±0.0015	same
Beam Electrons	0.0006	±0.0003	same
Radiative Muon Capture	$< 2 \times 10^{-6}$	—	Calculation
Sum	0.41	±0.08	**Added in Quadrature**

numbers are changing at 10% level as experiment matures

R. Bernstein, FNAL 24 Mu2e IF Workshop 25 April 2013

COMET at JPARC

$\mu^- N \to e^- N$ at 10^{-16}



Pion Capture Section

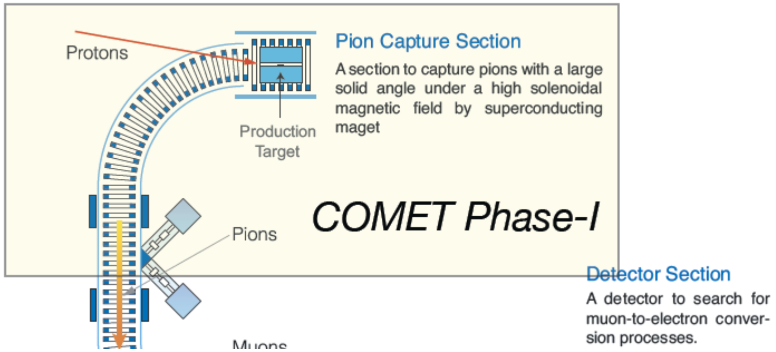
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

Detector Section

A detector to search for muon-to-electron conversion processes.

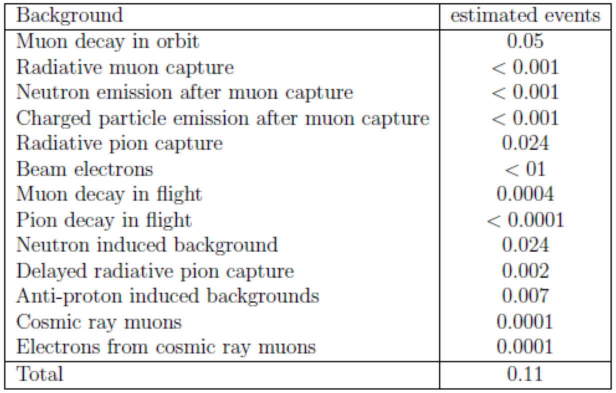
Pion-Decay and Muon-Transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

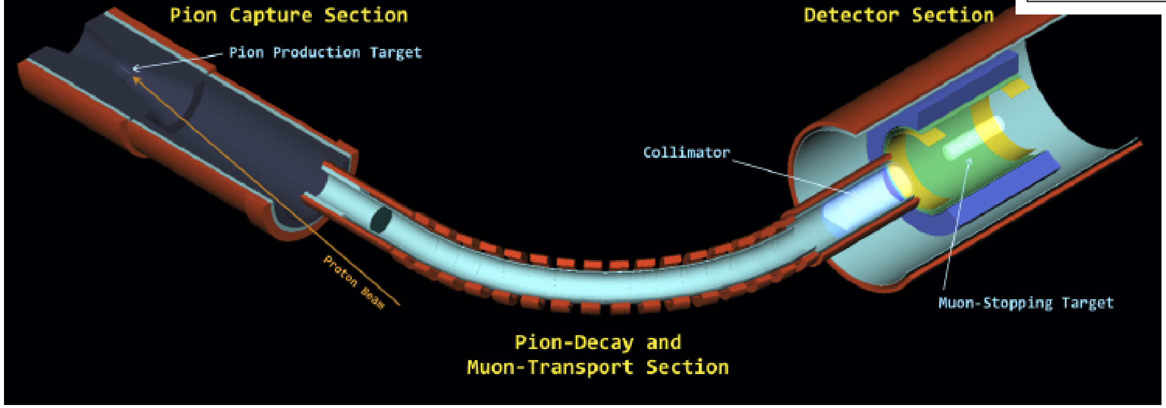


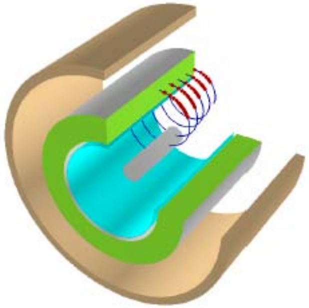
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

A detector to search for muon-to-electron conversion processes.

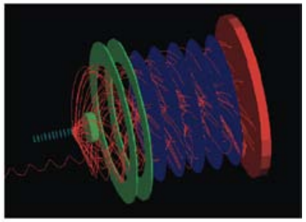


Background	estimated events
Muon decay in orbit	0.05
Radiative muon capture	< 0.001
Neutron emission after muon capture	< 0.001
Charged particle emission after muon capture	< 0.001
Radiative pion capture	0.024
Beam electrons	< 01
Muon decay in flight	0.0004
Pion decay in flight	< 0.0001
Neutron induced background	0.024
Delayed radiative pion capture	0.002
Anti-proton induced backgrounds	0.007
Cosmic ray muons	0.0001
Electrons from cosmic ray muons	0.0001
Total	0.11



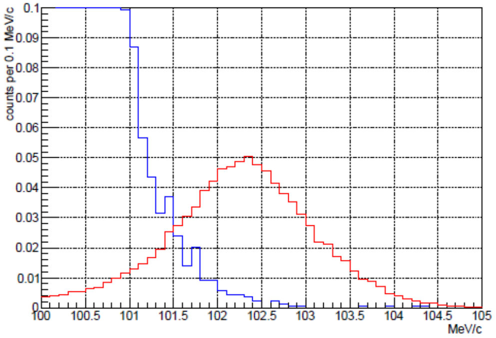


Tracker options



Comet Phase I Goal

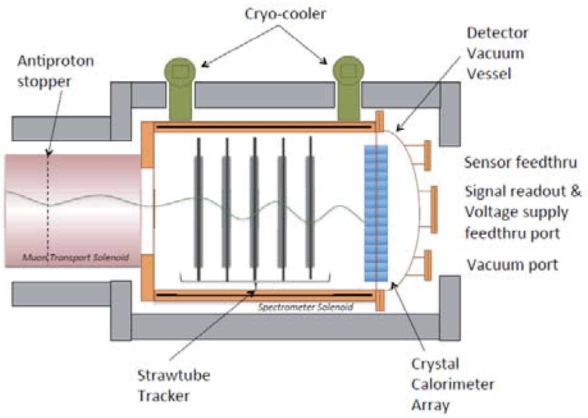
s.e.s. $3\text{x}10^{-15}$



Engineering runs >2016

COMET Phase I: Background Studies

COMET Detector for
Background measurements



- Proton Extinction
- Particle content, rates, especially pbars
- Others?

Useful Advanced Measurements for μ-e Conversion Experiments

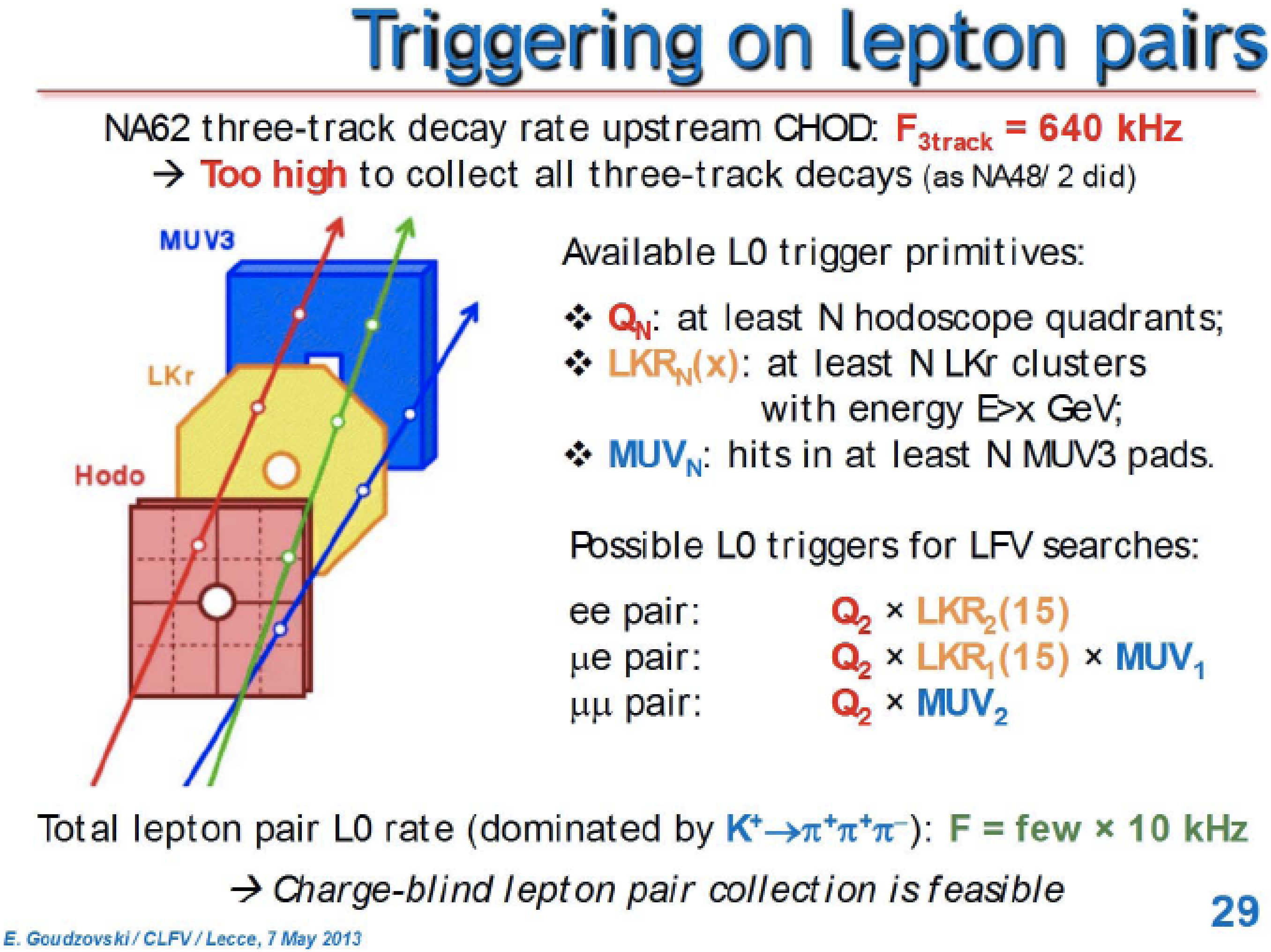
- Extinction rate
- Particle fluxes (e,μ,π,K,$\overline{\mathrm{p}}$...)at detector (Comet phase I)
- p and n rates from μ Capture (in the works at PSI)
- Cosmic rays – could be done in a test setup?
- Radiative pion capture -> 100MeV electrons?
- Pbar background rate -> 100MeV electrons?
- …

General questions for high sensitivity μ-e Conversion Experiments

- What are the uncertainties and risk factors in the background, acceptance estimates?
- How are the backgrounds to be measured during the experiment?
- How is a blind analysis to be done?
- What would make a believable signal?

E. Goudzoski

LFV in Kaon Decays: NA62



Triggering on lepton pairs

NA62 three-track decay rate upstream CHOD: F_{3track} = 640 kHz
→ Too high to collect all three-track decays (as NA48/2 did)

Available L0 trigger primitives:

- Q_N: at least N hodoscope quadrants;
- $LKR_N(x)$: at least N LKr clusters with energy E>x GeV;
- MUV_N: hits in at least N MUV3 pads.

Possible L0 triggers for LFV searches:

ee pair:	$Q_2 \times LKR_2(15)$
μe pair:	$Q_2 \times LKR_1(15) \times MUV_1$
μμ pair:	$Q_2 \times MUV_2$

Total lepton pair L0 rate (dominated by $K^+ \to \pi^+\pi^+\pi^-$): F = few × 10 kHz

→ *Charge-blind lepton pair collection is feasible*

29

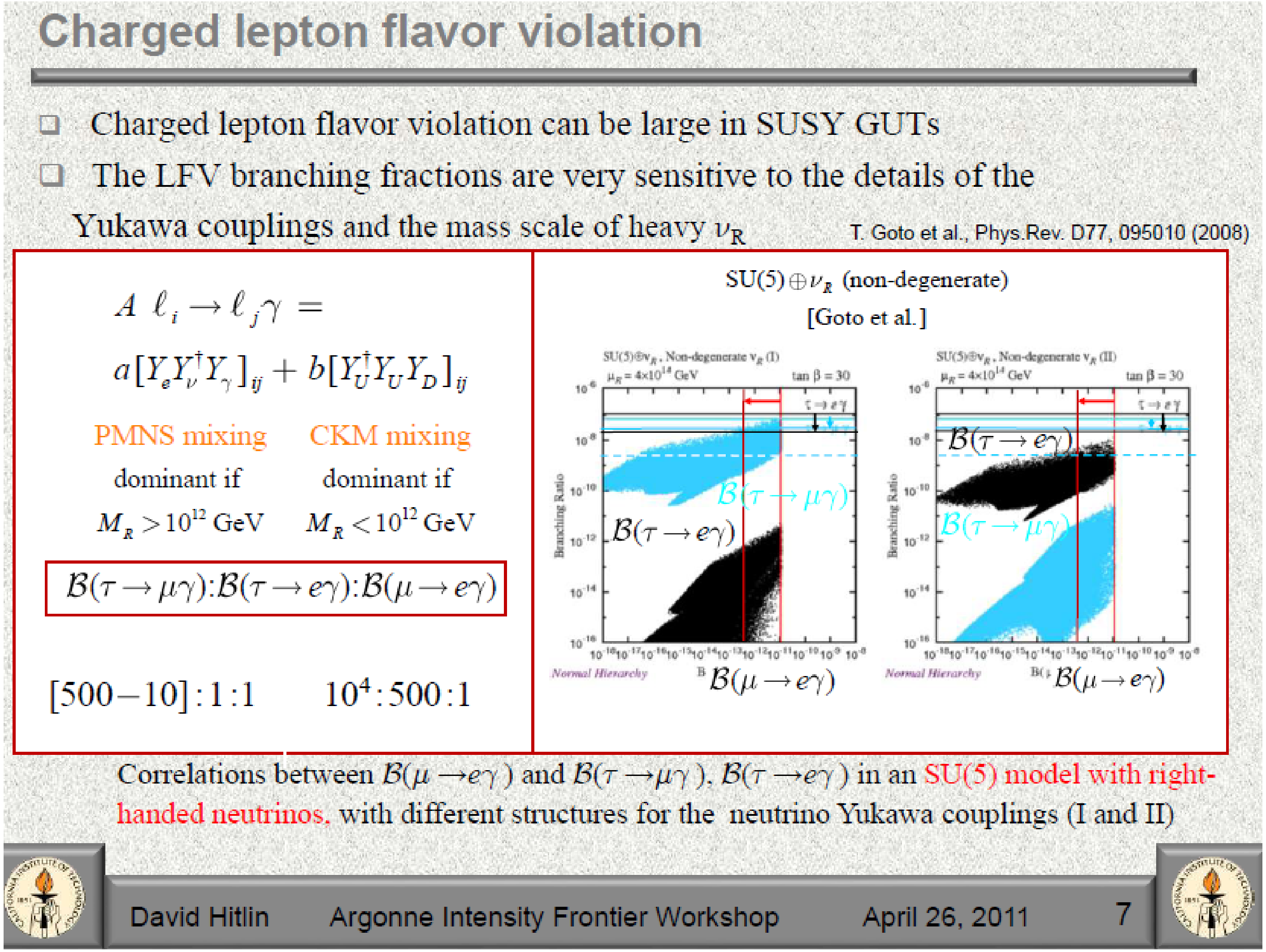
E. Goudzovski / CLFV / Lecce, 7 May 2013

S.E.S

10^{-12}

$\tau \to \mu, \tau \to e, \mu \to e$ Rates are Model Dependent!

Third generation effects could dominate.



Charged lepton flavor violation

- ❑ Charged lepton flavor violation can be large in SUSY GUTs
- ❑ The LFV branching fractions are very sensitive to the details of the Yukawa couplings and the mass scale of heavy ν_R

T. Goto et al., Phys.Rev. D77, 095010 (2008)

$$A\ \ell_i \to \ell_j \gamma =$$

$$a[Y_e Y_\nu^\dagger Y_\gamma]_{ij} + b[Y_U^\dagger Y_U Y_D]_{ij}$$

PMNS mixing	CKM mixing
dominant if	dominant if
$M_R > 10^{12}$ GeV	$M_R < 10^{12}$ GeV

$$\mathcal{B}(\tau \to \mu\gamma):\mathcal{B}(\tau \to e\gamma):\mathcal{B}(\mu \to e\gamma)$$

$[500-10]:1:1$ $\qquad 10^4:500:1$

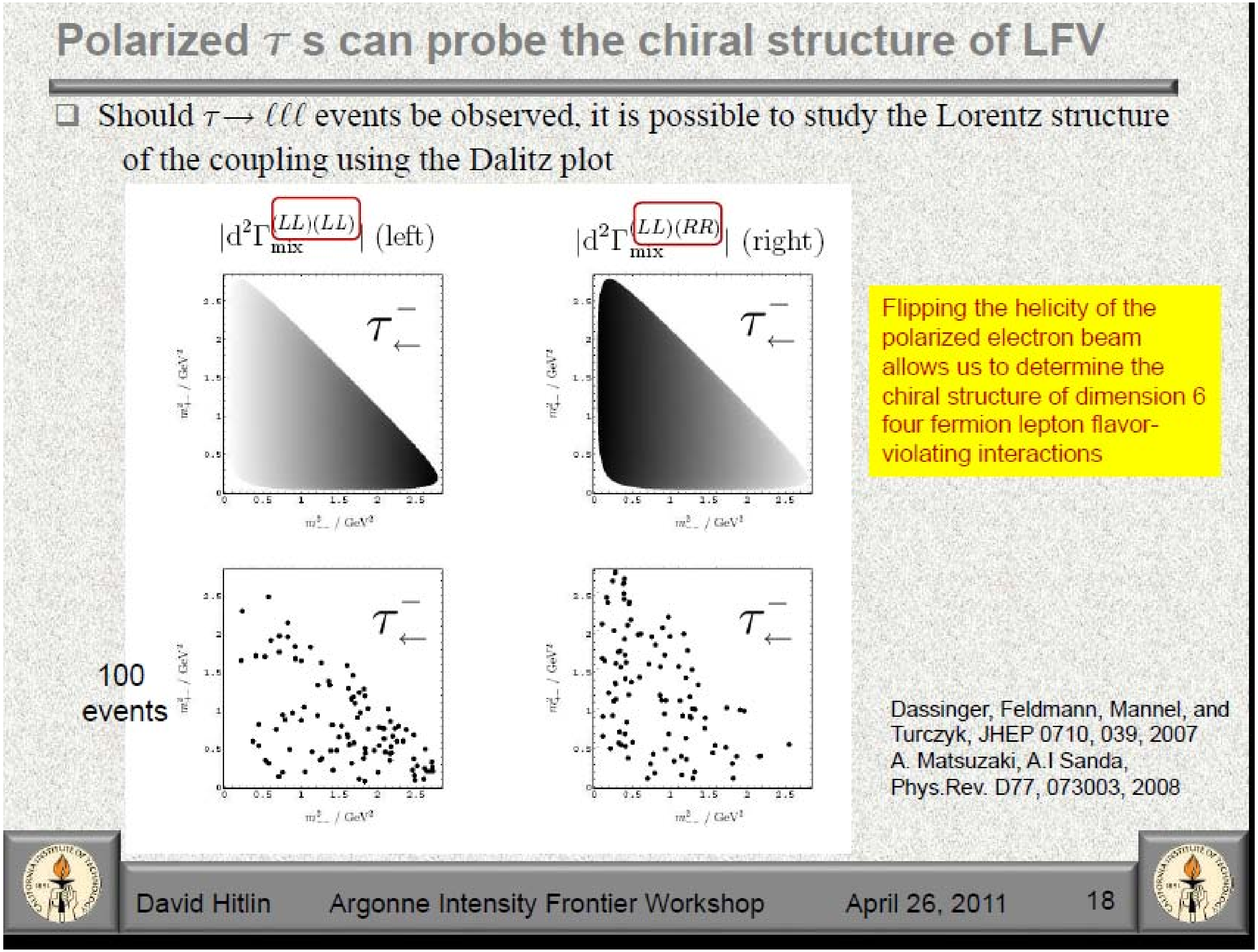
$\mathrm{SU}(5) \oplus \nu_R$ (non-degenerate)

[Goto et al.]

Correlations between $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$, $\mathcal{B}(\tau \to e\gamma)$ in an SU(5) model with right-handed neutrinos, with different structures for the neutrino Yukawa couplings (I and II)

David Hitlin Argonne Intensity Frontier Workshop April 26, 2011 7

Mannel



Polarized τ s can probe the chiral structure of LFV

- Should $\tau \rightarrow \ell\ell\ell$ events be observed, it is possible to study the Lorentz structure of the coupling using the Dalitz plot

$|d^2\Gamma^{(LL)(LL)}_{\rm mix}|$ (left)

$|d^2\Gamma^{(LL)(RR)}_{\rm mix}|$ (right)

100 events

Flipping the helicity of the polarized electron beam allows us to determine the chiral structure of dimension 6 four fermion lepton flavor-violating interactions

Dassinger, Feldmann, Mannel, and Turczyk, JHEP 0710, 039, 2007
A. Matsuzaki, A.I Sanda, Phys.Rev. D77, 073003, 2008

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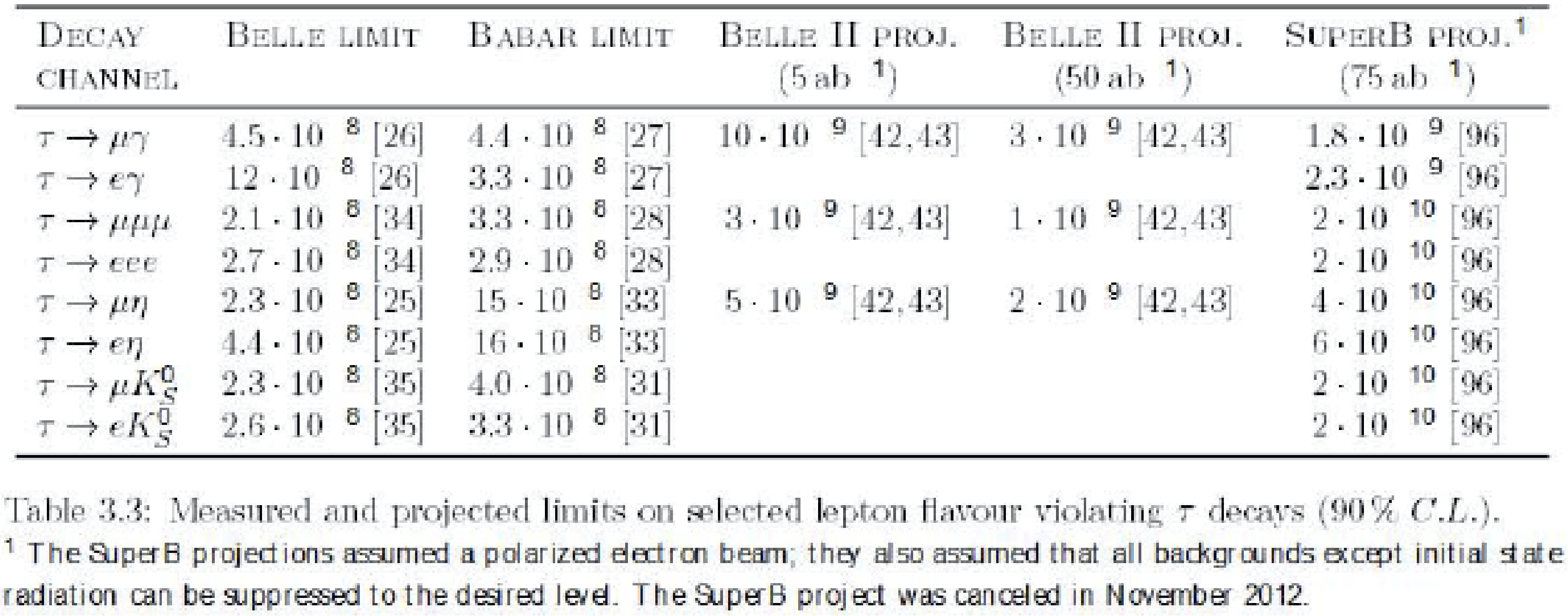
Belle II Sensitivity to LFV



Decay channel	Belle limit	Babar limit	Belle II proj. (5 ab ^{1})	Belle II proj. (50 ab ^{1})	SuperB proj.[1] (75 ab ^{1})
$\tau \to \mu\gamma$	$4.5 \cdot 10^{8}$ [26]	$4.4 \cdot 10^{8}$ [27]	$10 \cdot 10^{9}$ [42,43]	$3 \cdot 10^{9}$ [42,43]	$1.8 \cdot 10^{9}$ [96]
$\tau \to e\gamma$	$12 \cdot 10^{8}$ [26]	$3.3 \cdot 10^{8}$ [27]			$2.3 \cdot 10^{9}$ [96]
$\tau \to \mu\mu\mu$	$2.1 \cdot 10^{8}$ [34]	$3.3 \cdot 10^{8}$ [28]	$3 \cdot 10^{9}$ [42,43]	$1 \cdot 10^{9}$ [42,43]	$2 \cdot 10^{10}$ [96]
$\tau \to eee$	$2.7 \cdot 10^{8}$ [34]	$2.9 \cdot 10^{8}$ [28]			$2 \cdot 10^{10}$ [96]
$\tau \to \mu\eta$	$2.3 \cdot 10^{8}$ [25]	$15 \cdot 10^{8}$ [33]	$5 \cdot 10^{9}$ [42,43]	$2 \cdot 10^{9}$ [42,43]	$4 \cdot 10^{10}$ [96]
$\tau \to e\eta$	$4.4 \cdot 10^{8}$ [25]	$16 \cdot 10^{8}$ [33]			$6 \cdot 10^{10}$ [96]
$\tau \to \mu K_S^0$	$2.3 \cdot 10^{8}$ [35]	$4.0 \cdot 10^{8}$ [31]			$2 \cdot 10^{10}$ [96]
$\tau \to e K_S^0$	$2.6 \cdot 10^{8}$ [35]	$3.3 \cdot 10^{8}$ [31]			$2 \cdot 10^{10}$ [96]

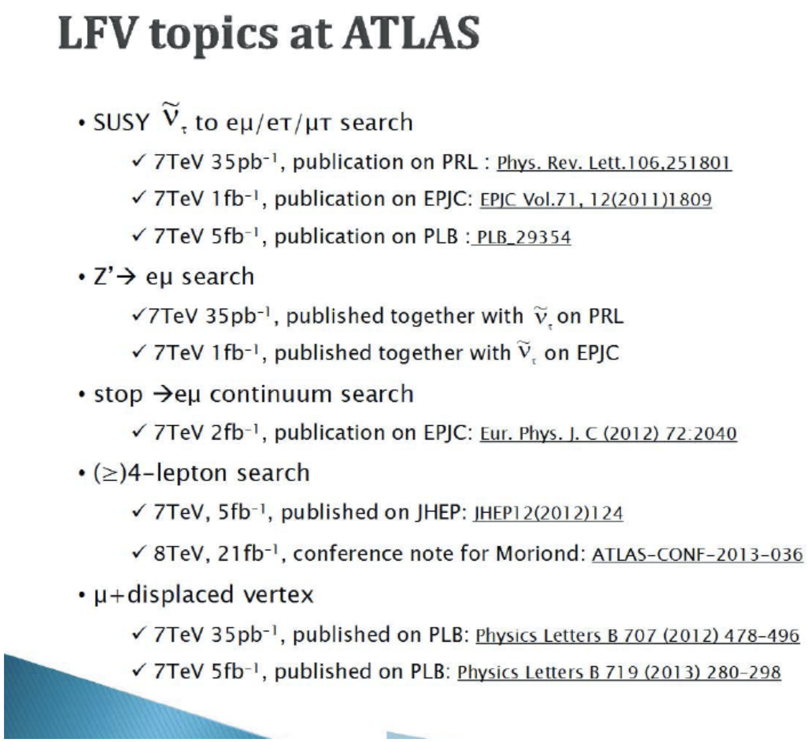
Table 3.3: Measured and projected limits on selected lepton flavour violating τ decays (90 % $C.L.$).

[1] The SuperB projections assumed a polarized electron beam; they also assumed that all backgrounds except initial state radiation can be suppressed to the desired level. The SuperB project was canceled in November 2012.

LHCb is now also a player.

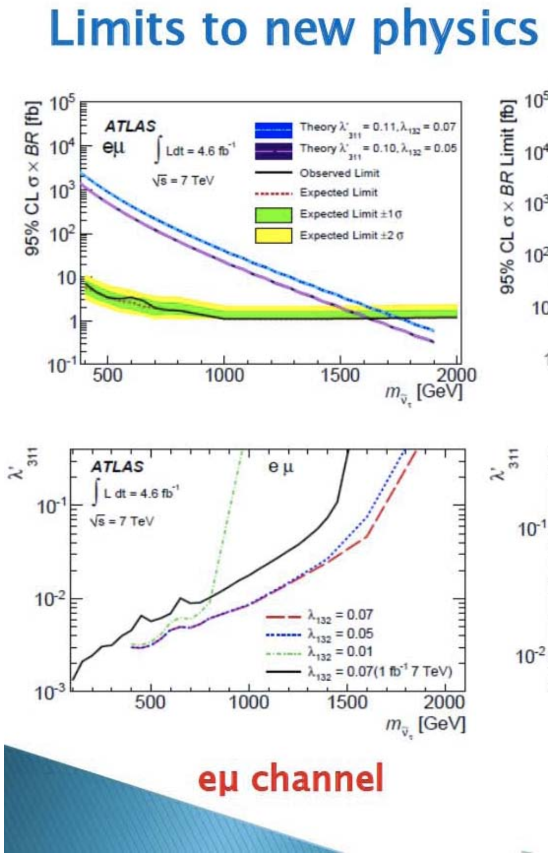
LFV at the LHC

Minghui Liu



LFV topics at ATLAS

- SUSY $\tilde{\nu}_\tau$ to eμ/eτ/μτ search
  - ✓ 7TeV 35pb^{-1}, publication on PRL : Phys. Rev. Lett.106,251801
  - ✓ 7TeV 1fb^{-1}, publication on EPJC: EPJC Vol.71, 12(2011)1809
  - ✓ 7TeV 5fb^{-1}, publication on PLB : PLB_29354
- Z'→ eμ search
  - ✓7TeV 35pb^{-1}, published together with $\tilde{\nu}_\tau$ on PRL
  - ✓ 7TeV 1fb^{-1}, published together with $\tilde{\nu}_\tau$ on EPJC
- stop →eμ continuum search
  - ✓ 7TeV 2fb^{-1}, publication on EPJC: Eur. Phys. J. C (2012) 72:2040
- (≥)4-lepton search
  - ✓ 7TeV, 5fb^{-1}, published on JHEP: JHEP12(2012)124
  - ✓ 8TeV, 21fb^{-1}, conference note for Moriond: ATLAS-CONF-2013-036
- μ+displaced vertex
  - ✓ 7TeV 35pb^{-1}, published on PLB: Physics Letters B 707 (2012) 478-496
  - ✓ 7TeV 5fb^{-1}, published on PLB: Physics Letters B 719 (2013) 280-298



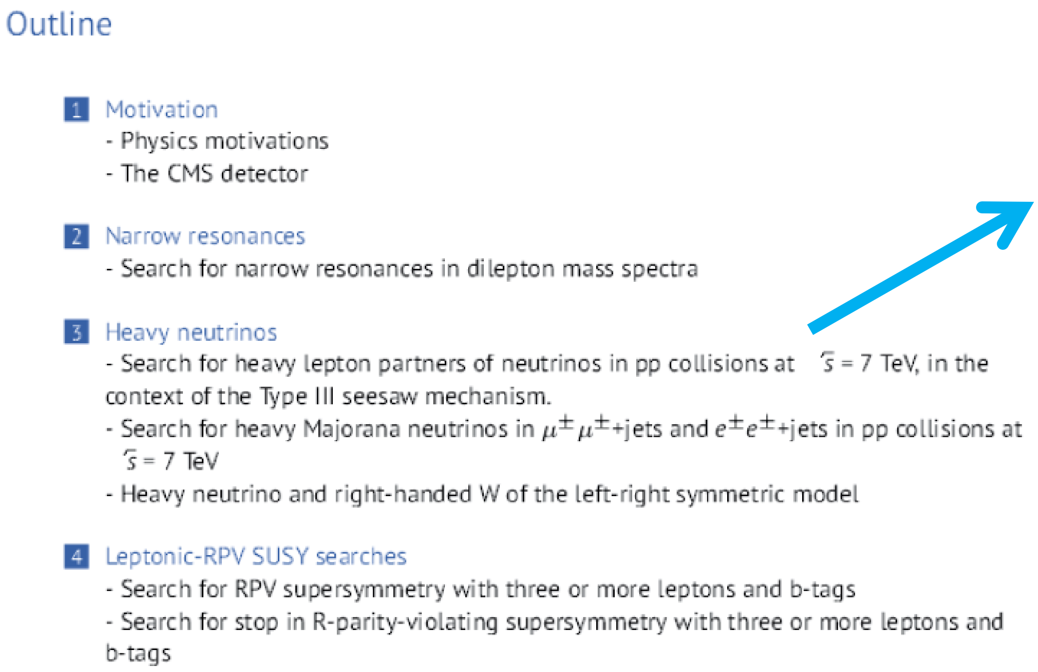
Limits to new physics

eμ channel

$$\tilde{\nu}_\tau \rightarrow e\mu$$

CMS Searches

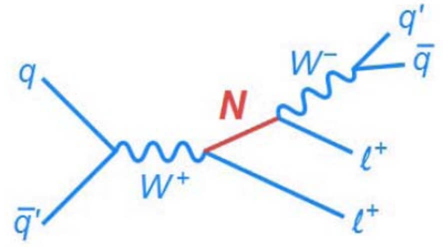
Letizia Lusito



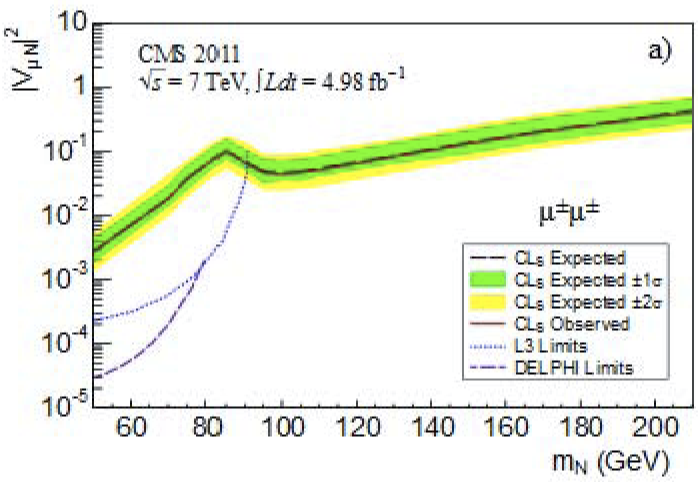
Outline

1. Motivation
   - Physics motivations
   - The CMS detector
2. Narrow resonances
   - Search for narrow resonances in dilepton mass spectra
3. Heavy neutrinos
   - Search for heavy lepton partners of neutrinos in pp collisions at $\sqrt{s}$ = 7 TeV, in the context of the Type III seesaw mechanism.
   - Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$+jets and $e^{\pm}e^{\pm}$+jets in pp collisions at $\sqrt{s}$ = 7 TeV
   - Heavy neutrino and right-handed W of the left-right symmetric model
4. Leptonic-RPV SUSY searches
   - Search for RPV supersymmetry with three or more leptons and b-tags
   - Search for stop in R-parity-violating supersymmetry with three or more leptons and b-tags

Experimental strategy



Heavy Majorana Neutrino

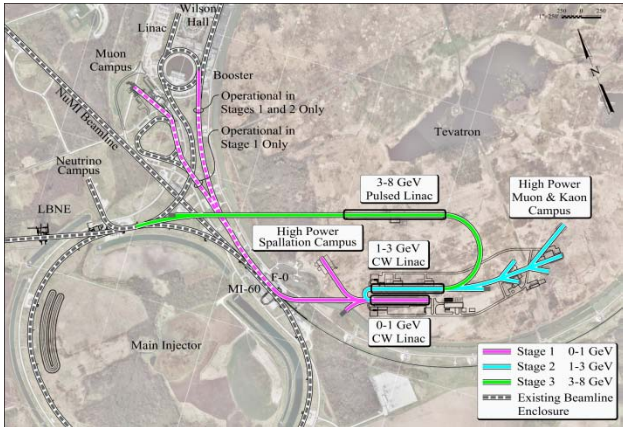


Tschirhart

Project X Staging Plan

	Present complex with PIP*	**Stage 1 Project X 1 GeV CW Linac**	**Stage 2 Project X 3 GeV CW Linac**
8 GeV Muon	20 kW	0 – 20 kW	0 – 20 kW
1 GeV Muon	None	80 kW	none
3 GeV Muon	None	None	1000 kW
Kaon Program	0 – 30 kW	0 – 75 kW	1100 kW

* PIP = Proton Improvement Plan



Example of an Experimental Program at Fermilab Project X

	Present complex with PIP*	**Stage 1 Project X 1 GeV CW Linac**	**Stage 2 Project X 3 Gev CW Linac**
Mu2e	X	X	X
g-2	X	X (1 GeV into Booster)	
$\mu \rightarrow e\gamma$			X
$\mu \rightarrow 3e$			X
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	X	X	X
$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$			X
EDM		X	X

* PIP = Proton Improvement Plan

Concluding Observations

- Charged lepton flavor violation experiments are powerful searches for new physics at high mass scales
- CLFV remains popular in most BSM theories but target sensitivities are obscure and gains in mass scale ($Br \sim 1/M^4$) are slow
- Big gains in experimental sensitivity are in the works
- Worthwhile to keep at it until BSM physics becomes clearer or experimental capabilities wane (or experiments become too expensive)