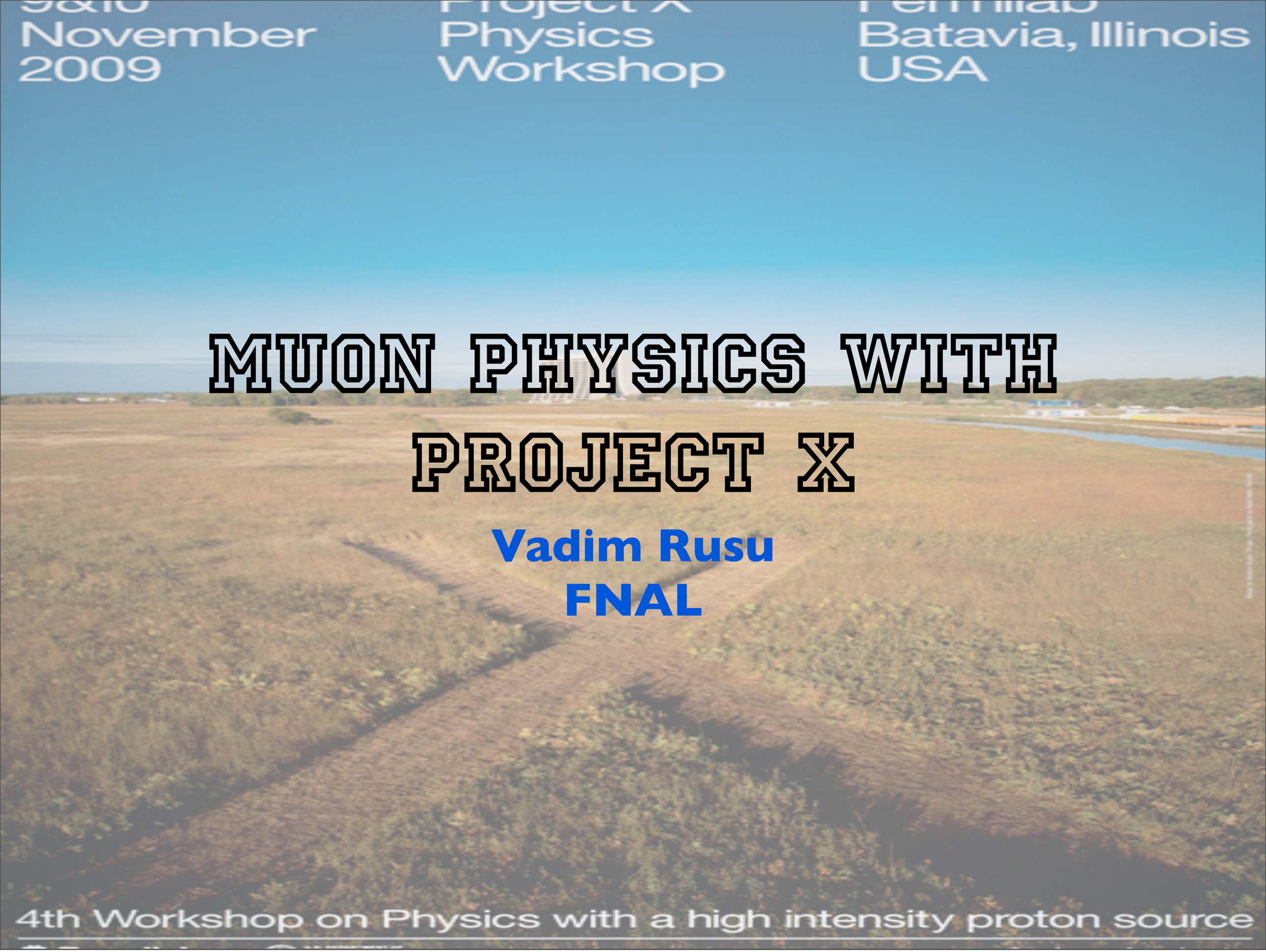
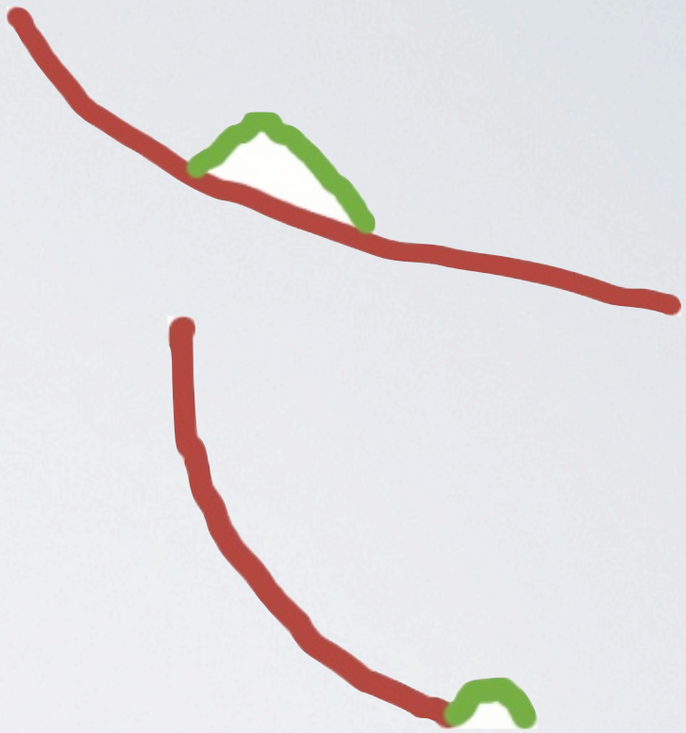


MUON PHYSICS WITH PROJECT X

Vadim Rusu
FNAL

TOWARDS THE "NEW PHYSICS"

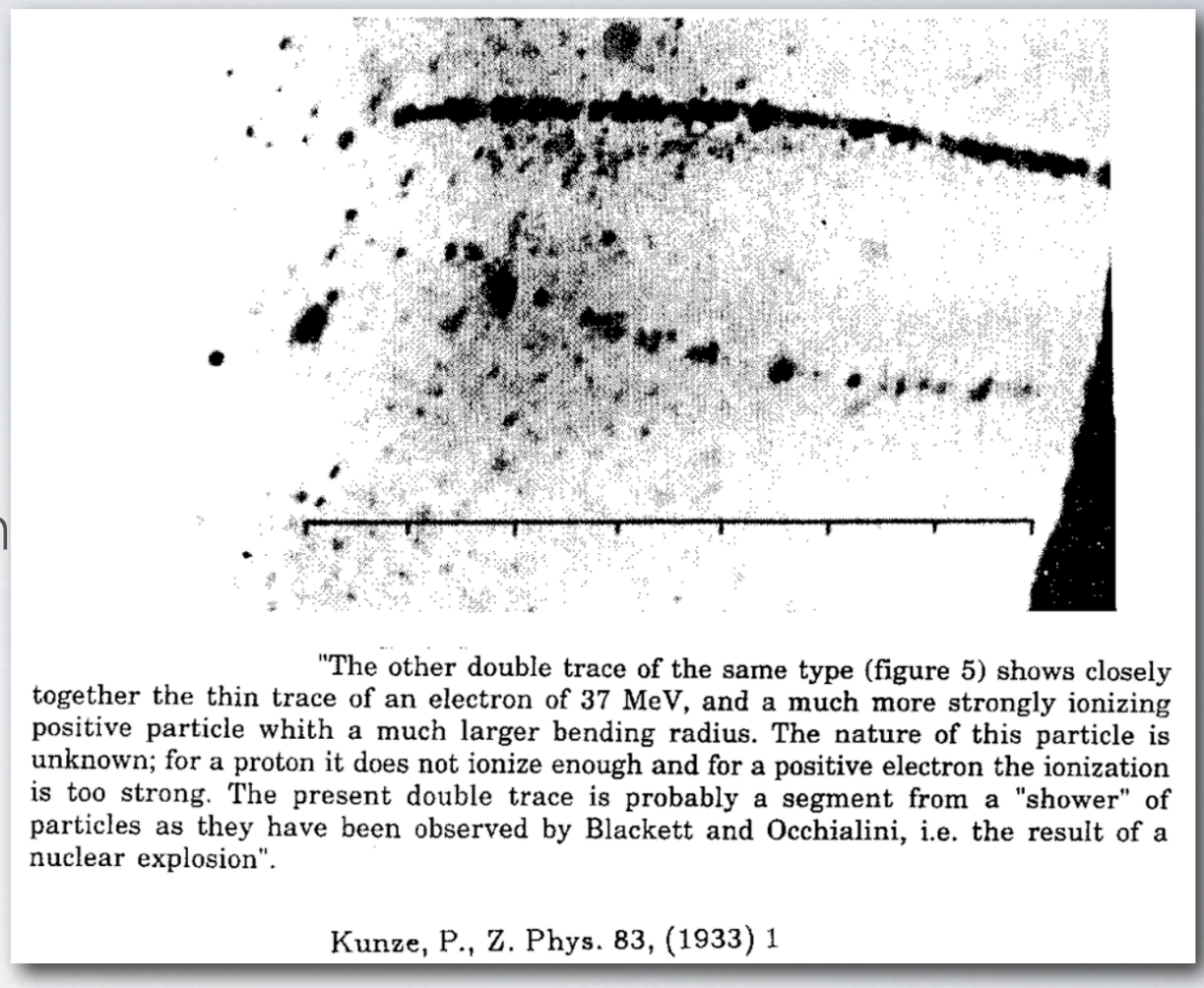
- How new physics can show up:
  - ➡ The "Einstein way" - High energy - $E=mc^2$
    - No need to throw dice
  - ➡ The "Heisenberg way" - High intensity - $\Delta p \times \Delta x \geq h$
    - Need to throw lots of dice



- Something BSM found in the next decade
  - ➡ An excess in a distribution does not make a new theory
    - Unless is a wrong calibration constant
  - ➡ You need more than one measurement to understand what we have
    - SM was not built on one measurement
    - **Muon is a good candidate for the "lots of dice" game**

MUONS

- I will concentrate on the muon
  - ➡ Most experiments require stop muons
    - Low energy (KE<50MeV) to medium energy (~3GeV)
    - Lots of them - intensity frontier



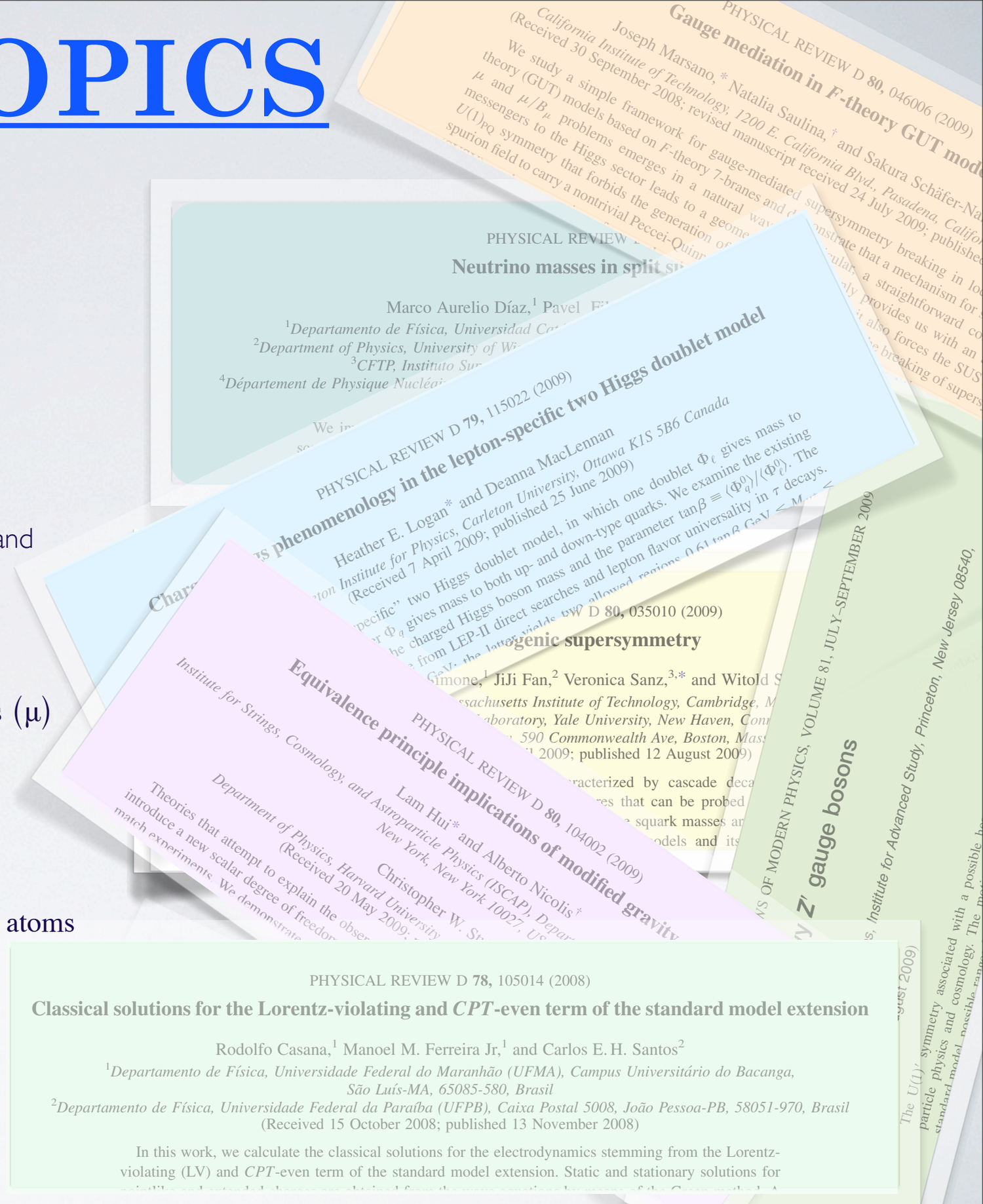
"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

- Aside from lots of theoretical arguments, study of the second generation of charged leptons
- Ultimately answer the question:

PHYSICS TOPICS

- search for rare and forbidden processes
  - ➡ $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$
  - ➡ M-Mbar
  - ➡ μ edm
- precise determination of the muon properties
  - ➡ mass, magnetic moment, magnetic anomaly, charge and lifetime
- CPT tests - compare μ^+ and μ^- properties
- Equivalence principle tests with fundamental particles (μ)
  - ➡ free fall of the muons
- muon decay parameters (Michel)
- precise determination of nuclear properties in muonic atoms
- μCF
- applications in condensed matter, life sciences, etc.

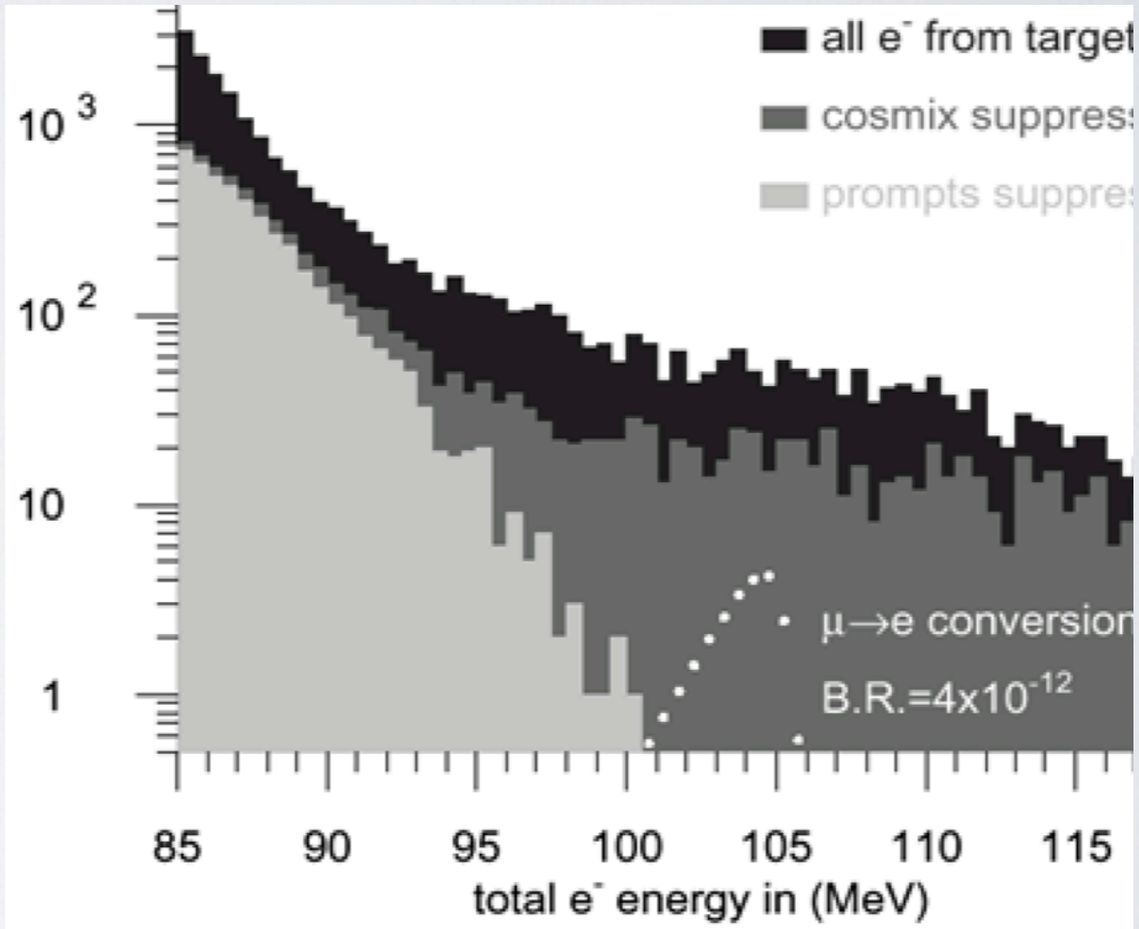


EXPERIMENTS

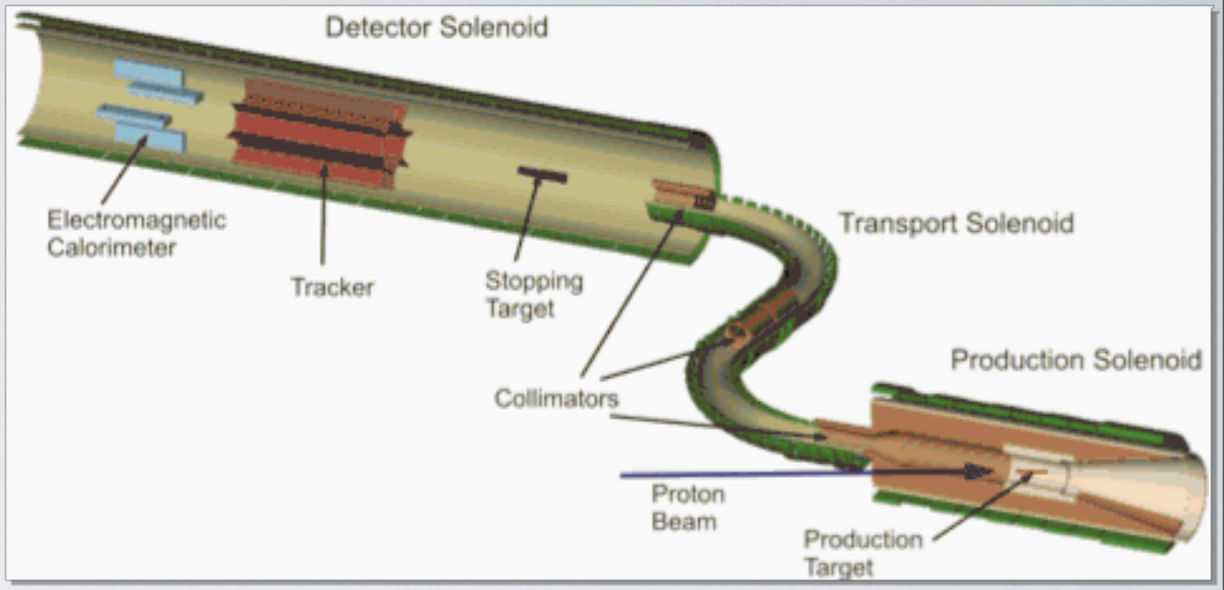
Type of Experiment	Physics Issues	Possible Experiments	previously established accuracy	present activities (proposed accuracy)
"Classical" Rare & Forbidden Decays	Lepton Number Violation; Searches for New Physics: SUSY, L-R Symmetry, R-parity violation,.....	$\mu^- N \to e^- N$ $\mu \to e\gamma$ $\mu \to eee$ $\mu^+ e^- \to \mu^- e^+$	$6.1 \cdot 10^{-13}$ $1.2 \cdot 10^{-11}$ $1.0 \cdot 10^{-12}$ $8.1 \cdot 10^{-11}$	PSI, proposed FNAL ($6 \cdot 10^{-17}$) running PSI ($1 \cdot 10^{-14}$) completed 1985 PSI completed 1999 PSI
Muon Decays	G_F; Searches for New Physics; Michel Parameters	τ_μ $non(V-A)$	$18 \cdot 10^{-6}$ $typ.\ few\ 10^{-3}$	PSI (2x), RAL ($1 \cdot 10^{-6}$) PSI, TRIUMF ($1 \cdot 10^{-3}$)
Muon Moments	Standard Model Tests; New Physics; CPT Tests T- resp. CP-Violation in 2nd lepton generation	$g_\mu - 2$ edm_μ	$0.7 \cdot 10^{-6}$ $3.4 \cdot 10^{-19} e\,cm$	proposed FNAL ($1.4 \cdot 10^{-7}$) proposed BNL ($10^{-24} e\,cm$)
Muonium Spectroscopy	Fundamental Constants, μ_μ,m_μ,α; Weak Interactions; Muon Charge	M_{HFS} M_{1s2s}	$12 \cdot 10^{-9}$ $1 \cdot 10^{-9}$	completed 1999 LAMPF completed 2000 RAL
Muonic Atoms	Nuclear Charge Radii; Weak Interactions	$\mu^- atoms$	*depends*	PSI, possible CERN ($< r_p >$to 10^{-3})
Condensed Matter	surfaces, catalysis bio sciences ...	surface μSR	n/a	PSI, RAL (n/a)

MUON TO E CONVERSION

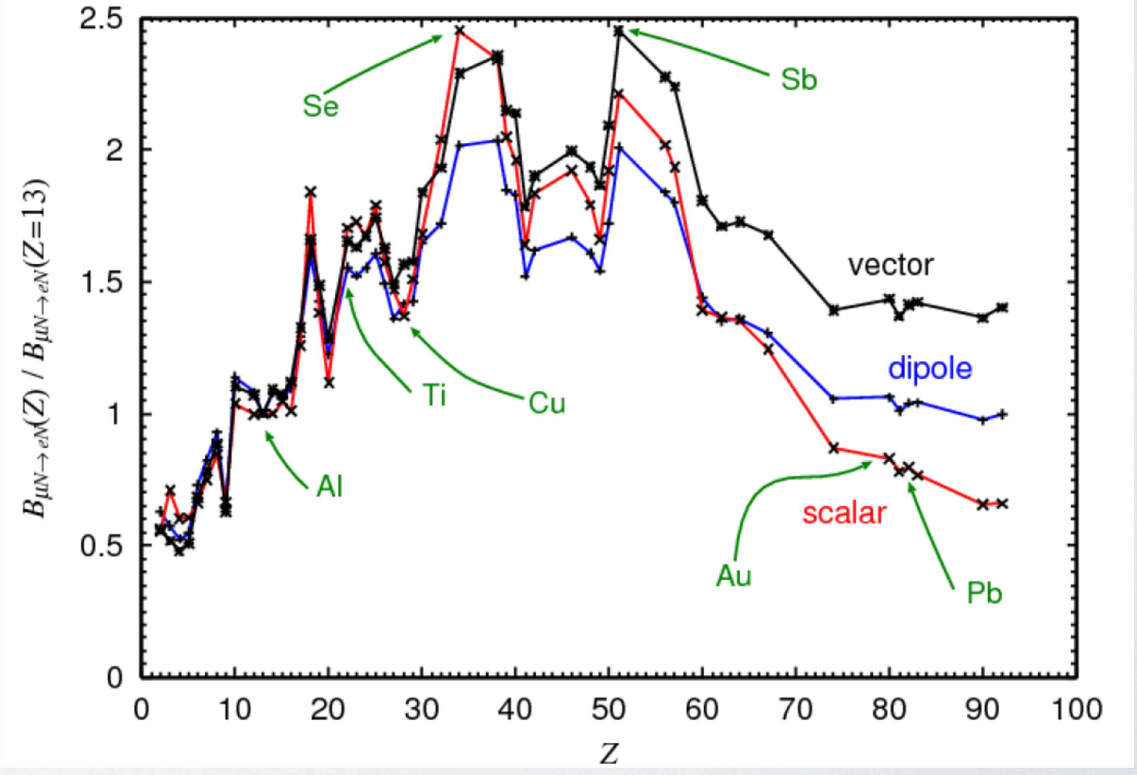
- Charged lepton flavor changing currents
  - ➡ $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - ➡ Strongly suppressed in SM
  - ➡ New physics can contribute
- Everything else oscillates!
- Current best SINDRUMII:
  - ➡ $R<4.3\times10^{-12}$(Ti) $R<7\times10^{-13}$(Au)
  - ➡ Background limited (?)
- mu2e Phase I goal of $R<6\times10^{-17}$(Al)



MU2E

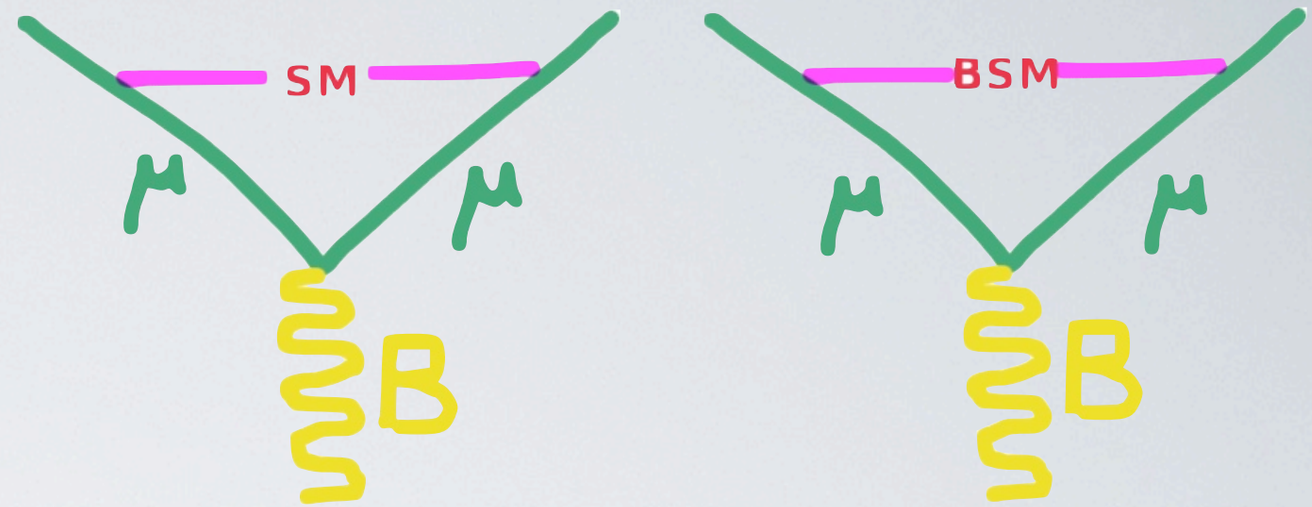


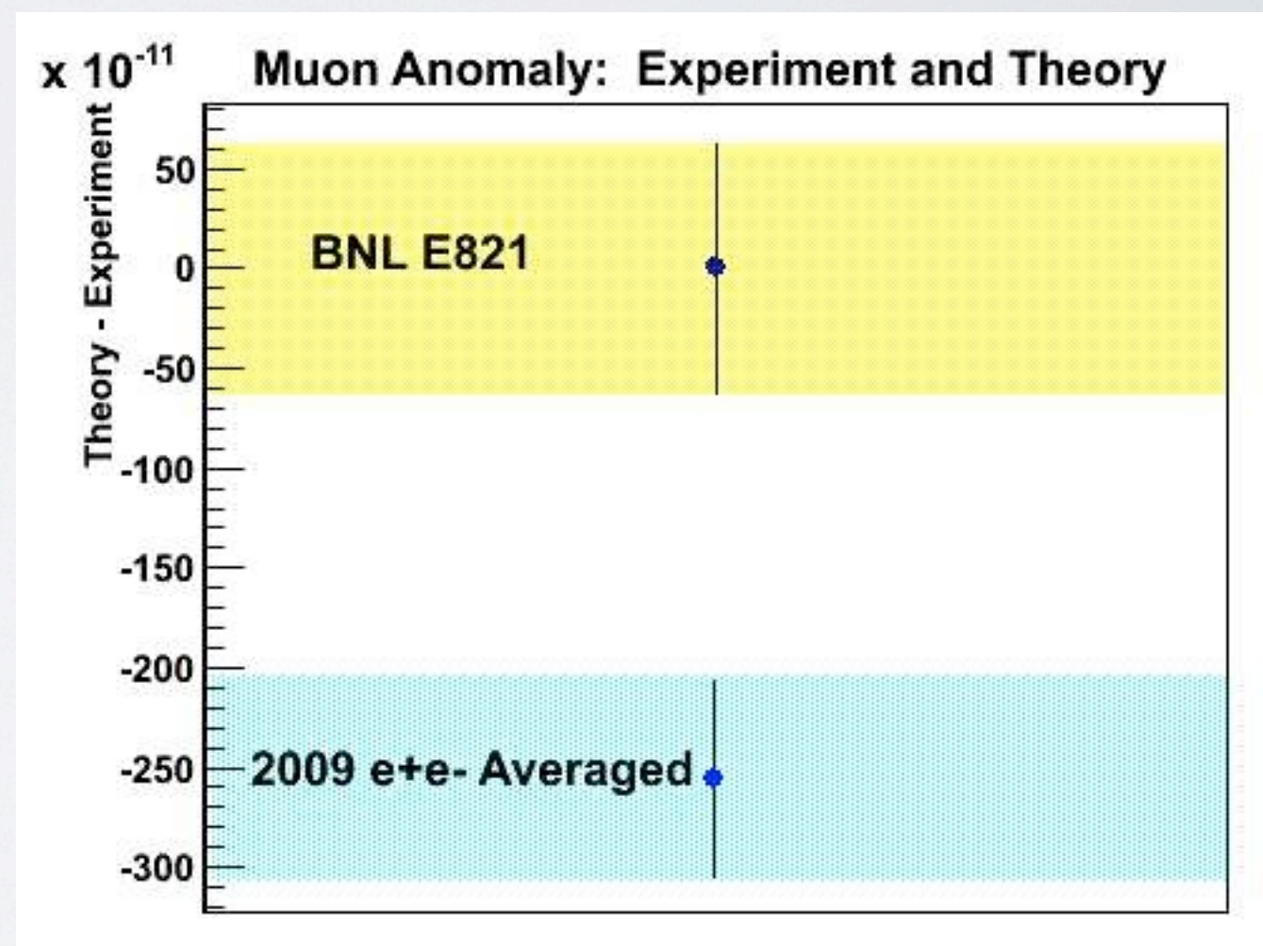
- Experimental principle
  - ➡ Pulsed beam start measurement after initial burst
- mu2e Phase II
  - ➡ **depends on what Phase I finds**
    - positive - check with more stats and different target
    - negative - push to two more order of magnitude
- Issues to be investigated:
  - ➡ extinction
  - ➡ backgrounds
- Other efforts: PRIME at PRISM
  - ➡ 10^{-20} pion survival rate
  - ➡ 3% momentum spread - reduce DIO



g-2

- compare with theoretical calculations
  - ➡ any deviation - new physics through loops
- precision measurement of a_μ constrains tanβ and determine sign(μ)
- BNL '04 0.54ppm
  - ➡ theory 0.42 ppm
  - ➡ Δa_μ(exp.-theory) = $(255\pm80)\times10^{-11}$ (3.2σ)
- **current proposal down to 0.14ppm**

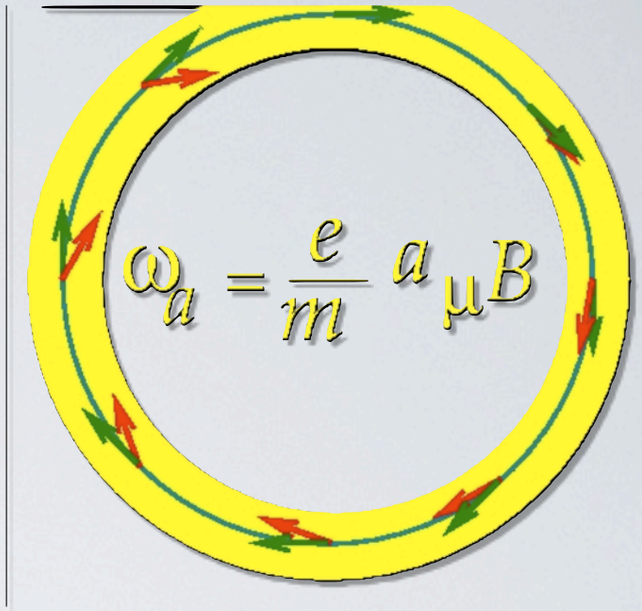




g-2

- Experimental principle:

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{1}{\gamma^2 - 1}\right)\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \rightarrow 0$$

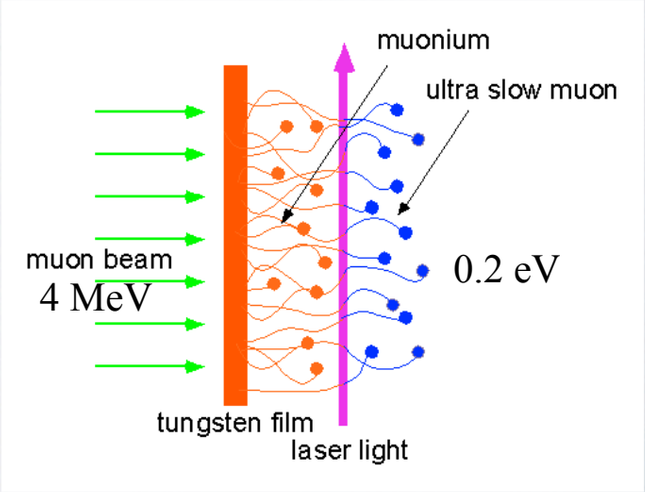


  - ➡ 3.1 GeV "magic momentum"

- repeat the experiment with μ^-
  - ➡ π^- xsection reduced by a factor of 3 (@ 8GeV proton beam)

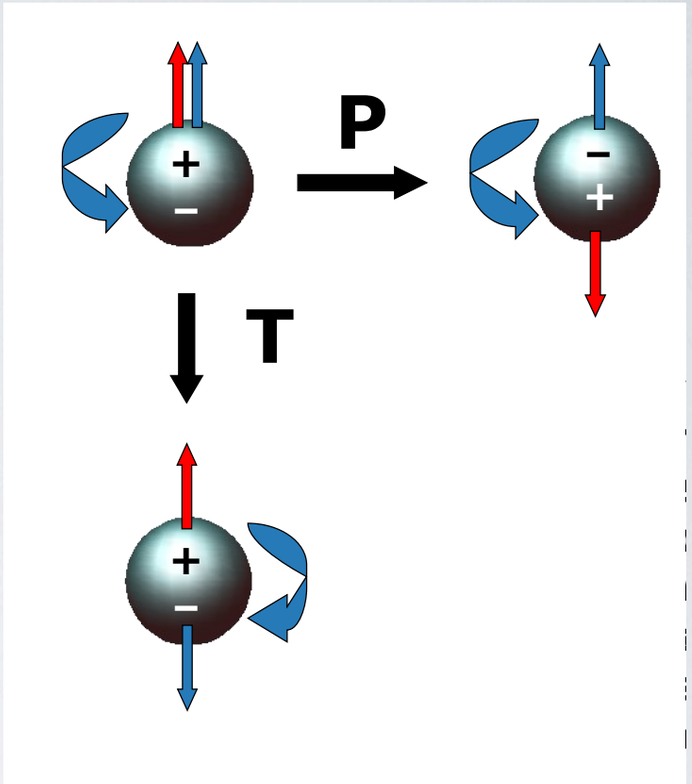
- narrow select μ^+ beam - reduced exp. uncert.

- other techniques based on muonium source
  - ➡ laser ionize muonium ➠ $\Delta p/p < 10^{-5}$
  - ➡ low energy pulsed muon beam required



MUON EDM

- Violates both P and T symmetries
  - ➡ assume CPT holds -> CP violation
  - ➡ Help understand the baryon asymmetry of the Universe
- **EDM explores the CP violating phases of the lepton mixing matrix (CKM, MNS, XYZ)**
- Usually done with neutral probes (neutrons and atoms)
- Searches with charged particles possible with storage rings utilizing the relativistic vxB electric field

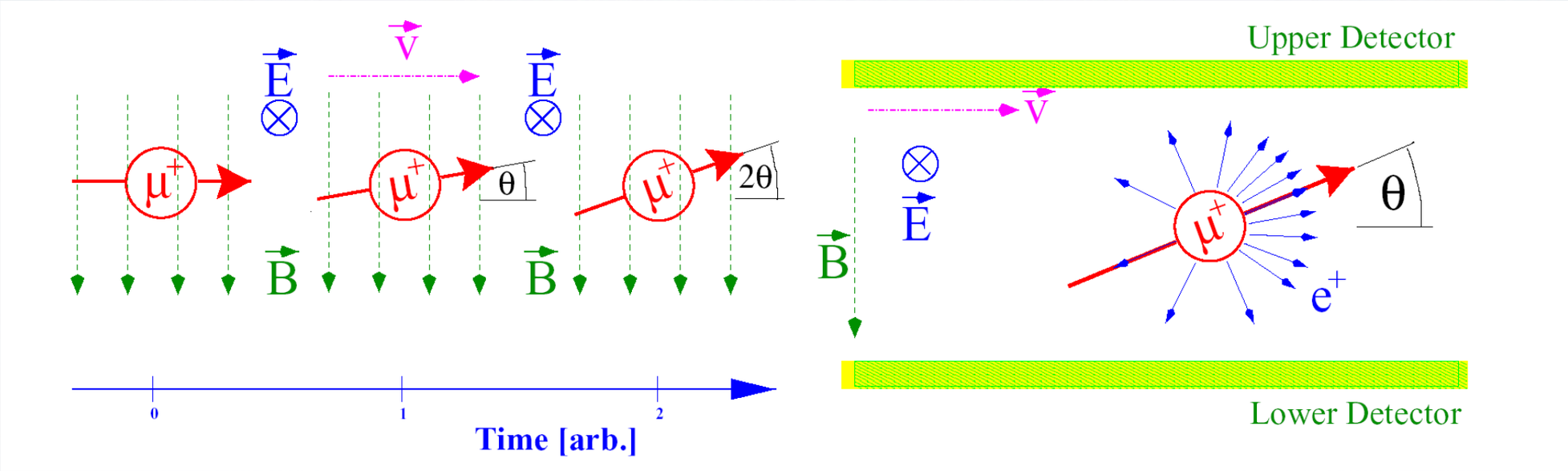


eEDM probed to 10^{-27}e-cm for electrons

MUON EDM

Proposal at JPARC
Aoki et al [2003]

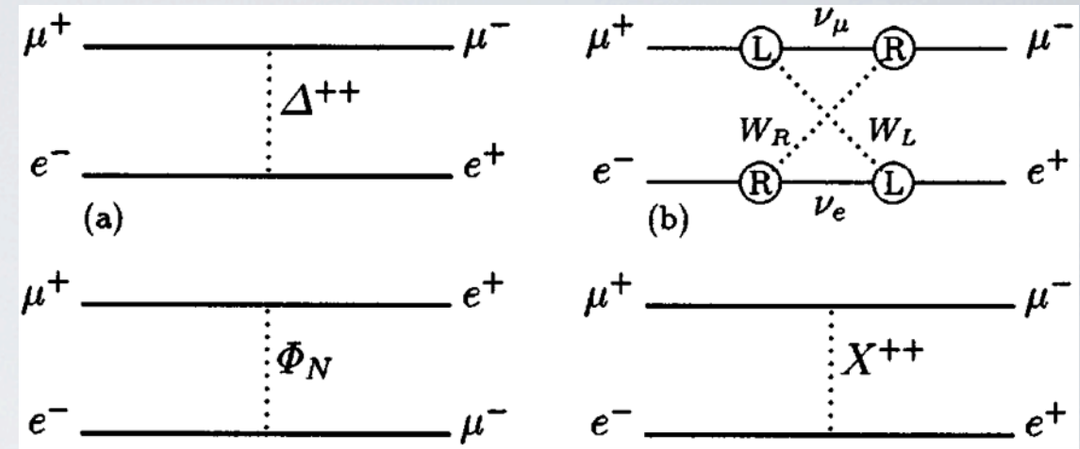
- Experimental principle:
  - ➡ Longitudinally polarized muons in storage rings - g-2 precession
  - ➡ The (g-2) precession can be cancelled by applying a radial electric field to freeze the spin
    - Lower momentum than for g-2
  - ➡ An EDM would cause a precession around the strong vxB electric field
    - Up-down asymmetry growing with time



M-MBAR OSCILLATIONS

- $M=\mu^+e^-$

  ➡ **ΔL=2 process**



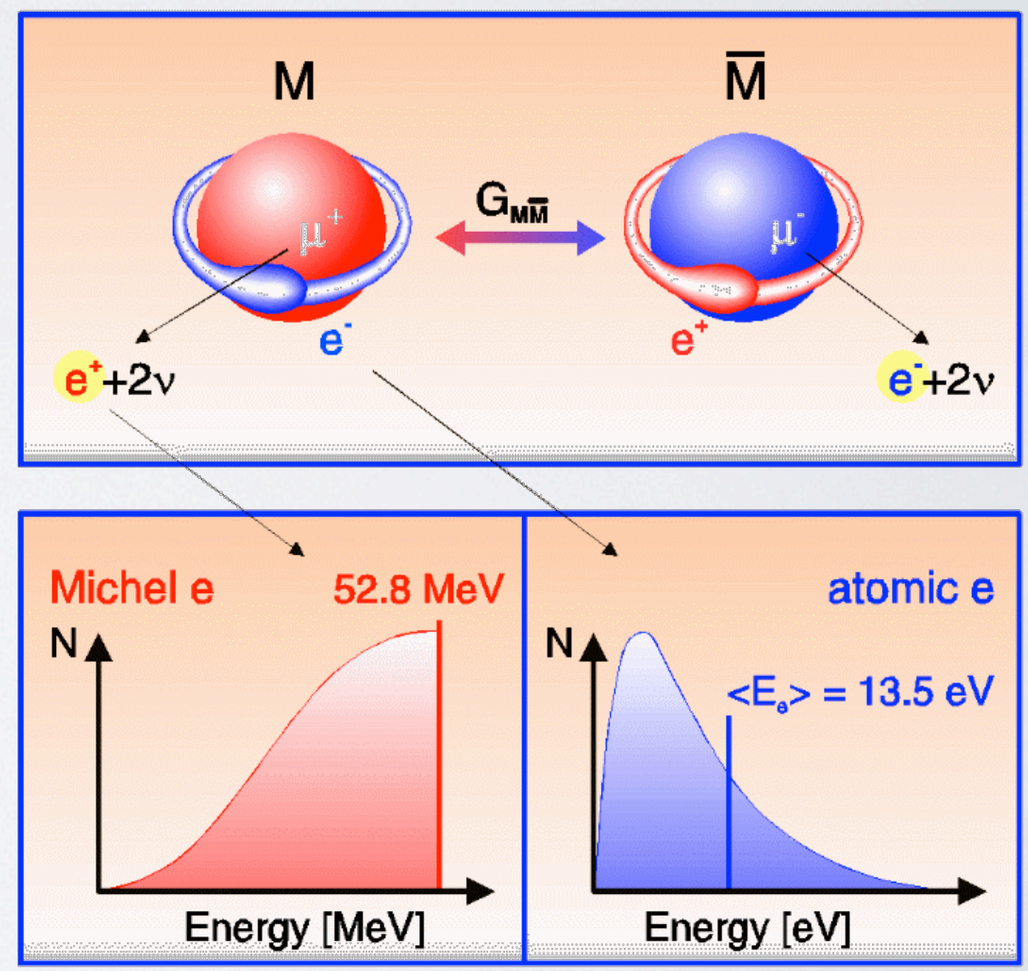
- Analogous in lepton sector to the K_0-$\overline{K}_0$ and B_0-$\overline{B}_0$ oscillations

- MACS experiment at PSI

  ➡ 26 MeV/c μ^+ at 8×10^6 μ^+/s

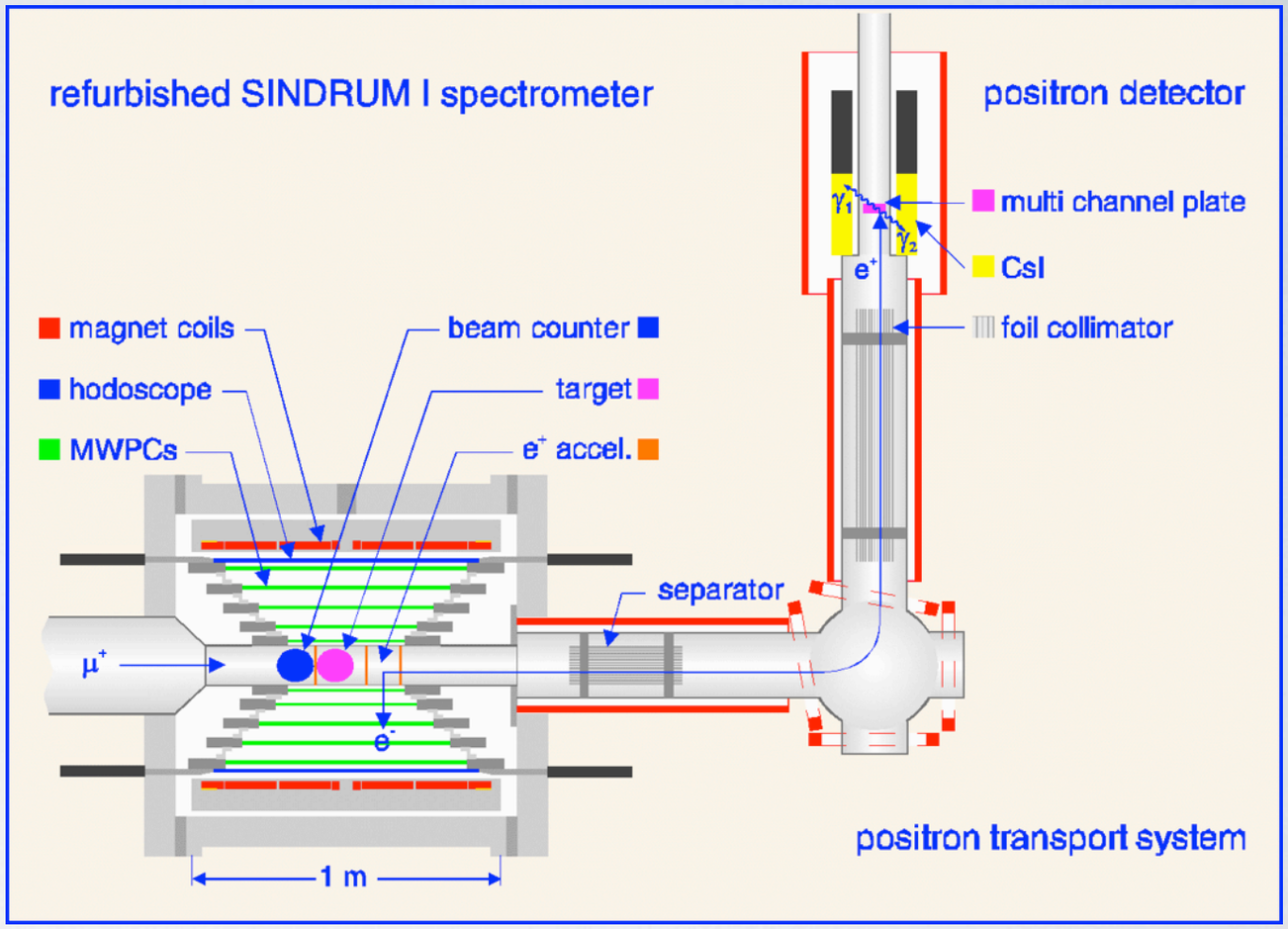
  ➡ 5.6×10^{10} M in 6 mo.

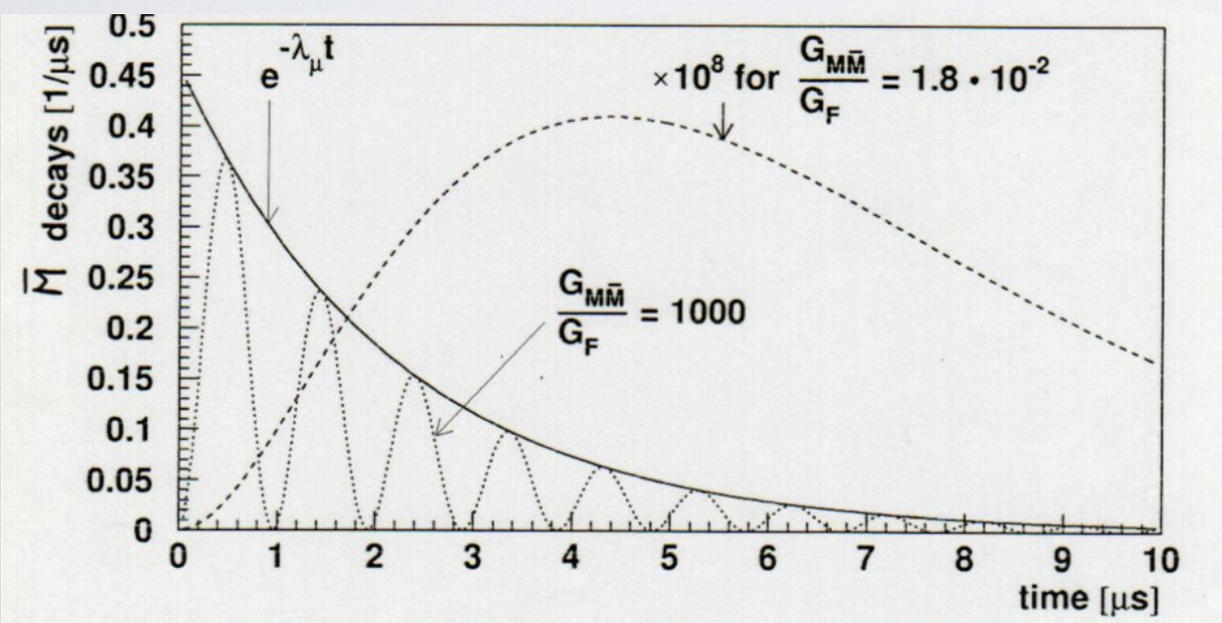
  ➡ $G_{M\text{-}Mbar} < 3.0\times10^{-3}\ G_F$ (90%CL)



M-MBAR OSCILLATIONS

- Experimental principle
  - ➡ Muonium formation in silicate powder (ε=60%)
  - ➡ 5% thermally emerge into surrounding vacuum
  - ➡ Conversion signature
    - Michel electron from $\mu^- \rightarrow e^- \nu\nu$
    - atomic e^+ (13.5MeV)
  - ➡ Backgrounds - μ^+ decays
    - Bhabha scattering of e^+
    - $\mu^+ \rightarrow e^+ e^+ e^- \nu\nu$





$P(M)=\sin^2[\text{const} \times (G_{MM}/G_F)\times t]\times\exp[-\lambda\times t]$

Background$\approx\exp(-n\,\lambda\times t)$; n-fold coincidence detection

For $G_{MM} << G_F$ M gains over Background

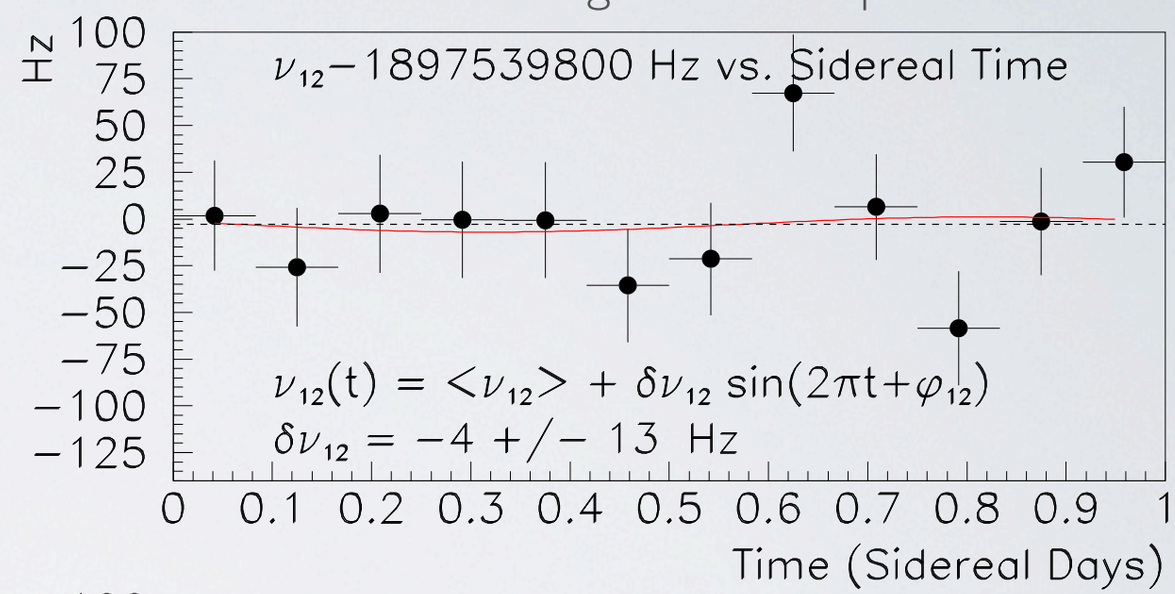
$P(M)/\text{Background} = t^2 \times \exp[+(n-1)\times\lambda\times t]$

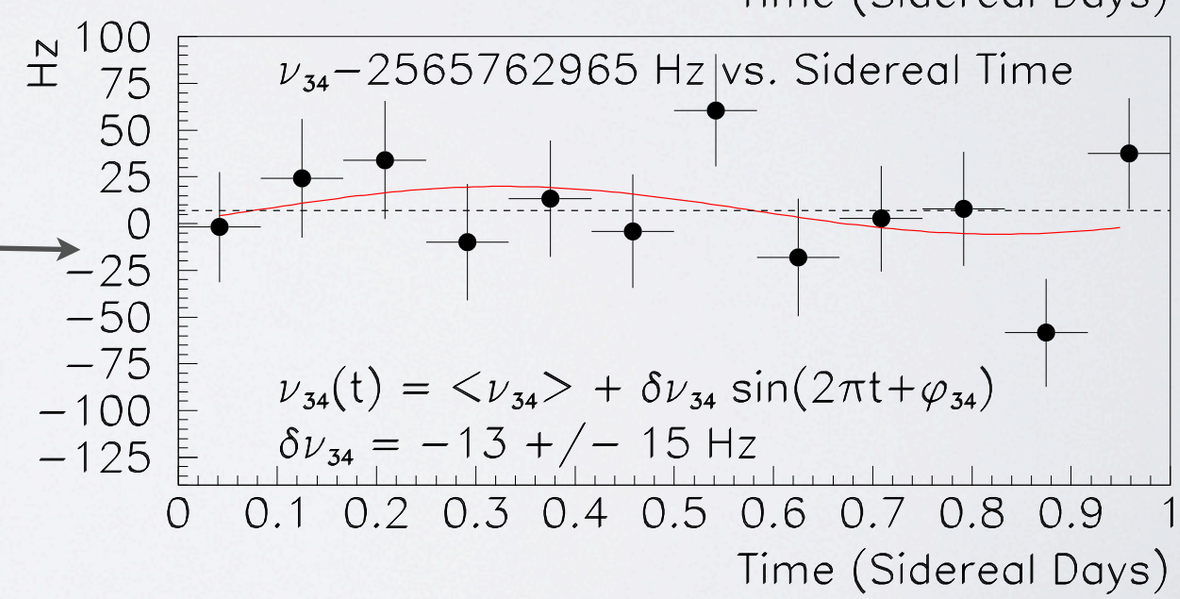
Pulsed beam

MUONIUM PHYSICS

- $M=\mu^+e^-$ both particles structureless object
- muonium spectroscopy
- calculation at higher order than for hydrogen isotopes
  - ➡ $\Delta\nu_{HFS}$ as a precise measurement of α
  - ➡ CPT tests with ν_{12}, ν_{34}
- **All these limited by statistics…**

Hughes *et al* hep-ex0106103



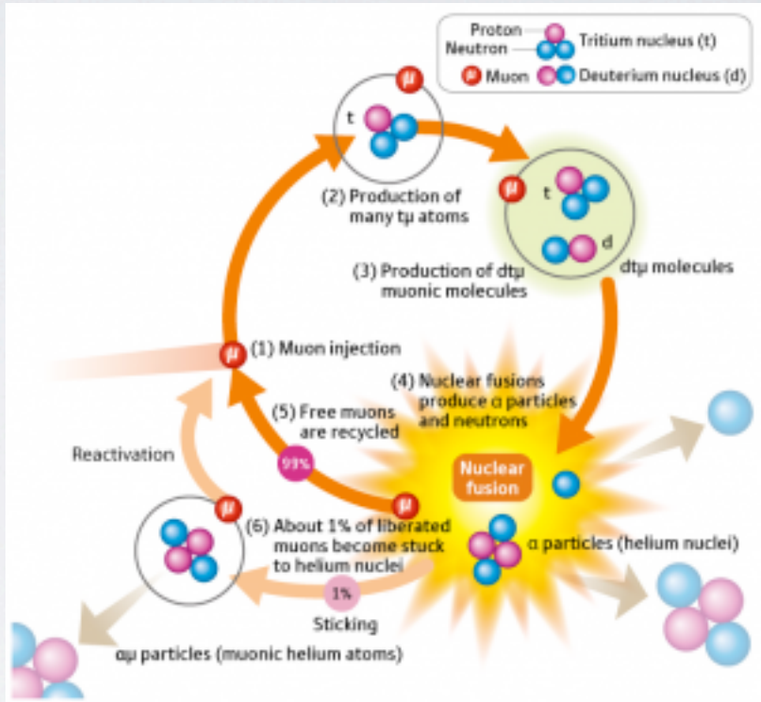


CRAZY UNCLE IN THE TREE

- Free fall of the muon
  - ➡study the gravitational pull on fundamental particles
  - ➡50Å for 20 out of 10^{10} muons
  - ➡1 μK to win over thermal motion
- $\mu^+\mu^-$ atom
  - ➡substantially higher weak effects than in other system
  - ➡how to make it (low xsection)
    - $\mu^- + (\mu^+ e^-) \rightarrow (\mu^+ \mu^-) + e^-$

... AND THE REST

- muon catalyzed fusion
- muonic atoms
- radioactive muonic atoms
- muon spin rotation and muon spin resonance



CONCLUSIONS

- Next(++) generation of muon experiments require a large statistics muon sample
- There is a plethora of physics topics that can be addressed using low energy and stopped muons
- Project X can be the place to do the next large set of muon experiments and continue a long tradition in muon physics
- **We still don't know who ordered that**