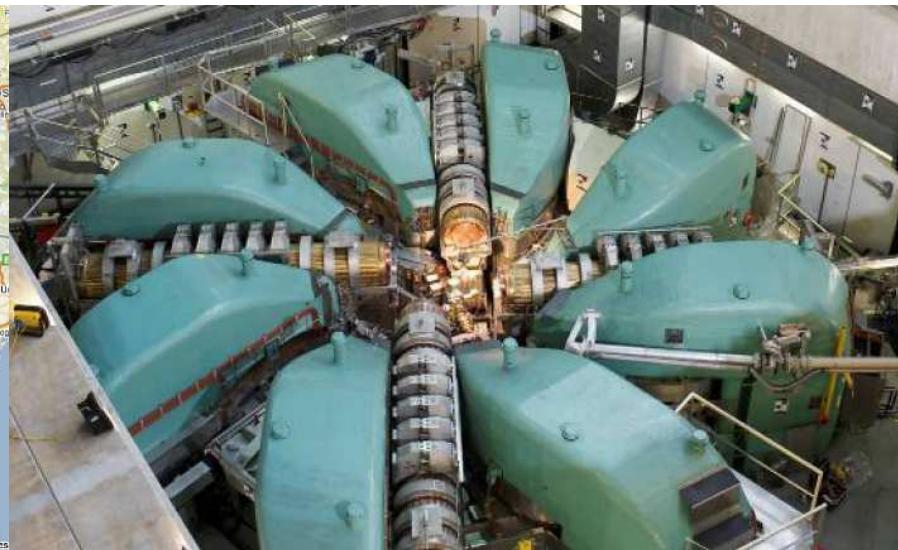


Teilchenphysik mit langsamen Myonen

Klaus Kirch

ETH Zürich & PSI Villigen

KET Perspektivworkshop 25./26.10.2010



Contents and conclusions

- **Precision physics with high intensity slow muon beams**
offers a unique window to new physics. It is complementary to other low energy precision physics and in particular also to running and future collider experiments
- World-wide activities and renewed interest:
Major muon programs ongoing or planned at
PSI, FNAL, J-PARC, RCNP [TRIUMF, RAL, LANL]
- Today's highest intensity low momentum
pion and muon beams at PSI
- In the future: high intensity, pulsed beam facilities
FNAL, J-PARC [ESS has been discussed, but ..]
- Also in the future: PSI will remain the best DC beam facility
and aims at improved intensity and beam quality



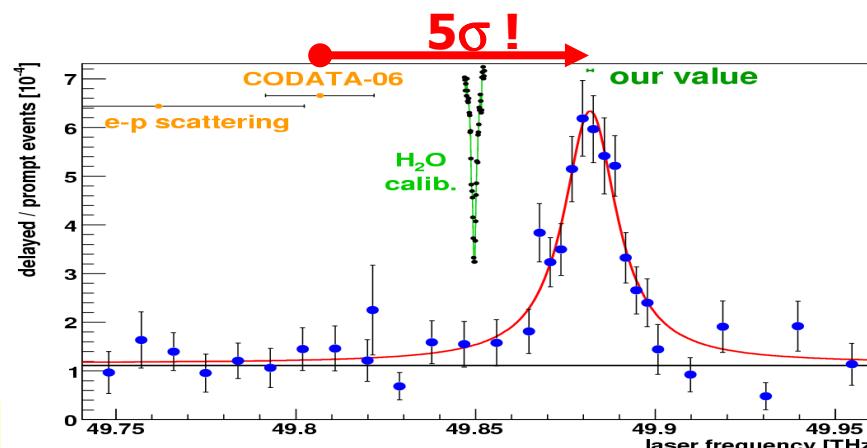
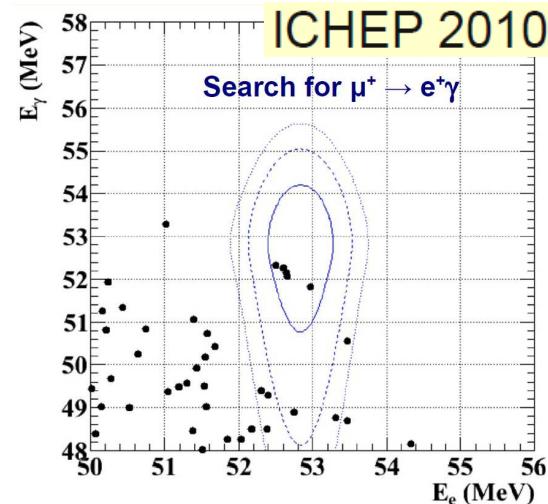
major opportunity in Europe

Puzzling and exciting muon physics

■ BNL g-2 $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (296 \pm 81) \times 10^{-11}$
 $\rightarrow 3.6\sigma$ Davier, Hoecker, Malaescu, Zhang (DHMZ)

■ μ Lambshift

■ MEG

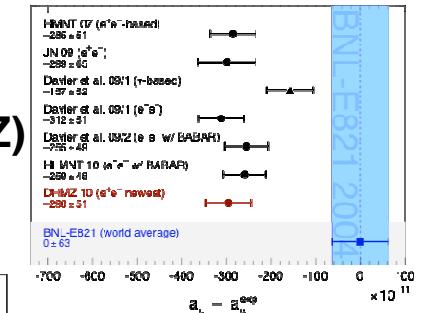


R. Pohl et al., Nature **466** (2010) 213

■ MuLAN

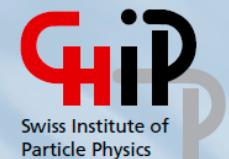
Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

arXiv:1010.0991v1 [hep-ex] 5 Oct 2010



Physics of fundamental Symmetries & Interactions

PSI 2010



October 11–14, 2010
Paul Scherrer Institut, Switzerland

psi2010.web.psi.ch

2nd International Workshop on the
Physics of fundamental Symmetries and Interactions
at low energies and the precision frontier.

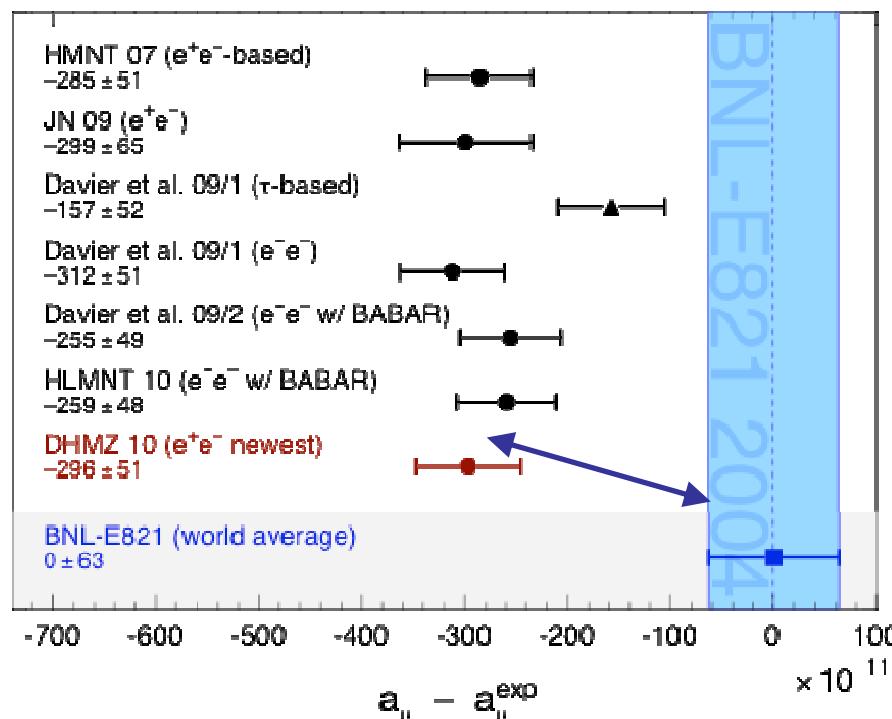
We just got a comprehensive overview at this meeting. I will be partially using transparencies shown by various colleagues 2 weeks ago.

HVP evaluations by 2 groups, updated Tau'10

■ Hagiwara, Liao, Martin, Nomura, Teubner (HLMNT)

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (259 \pm 81) \times 10^{-11} \rightarrow 3.2 \sigma$$

■ M. Davier, A. Hoecker, B. Malaescu, Z. Zhang (DHMZ) ■ (BaBar team with access to preliminary data)



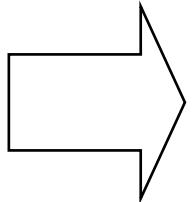
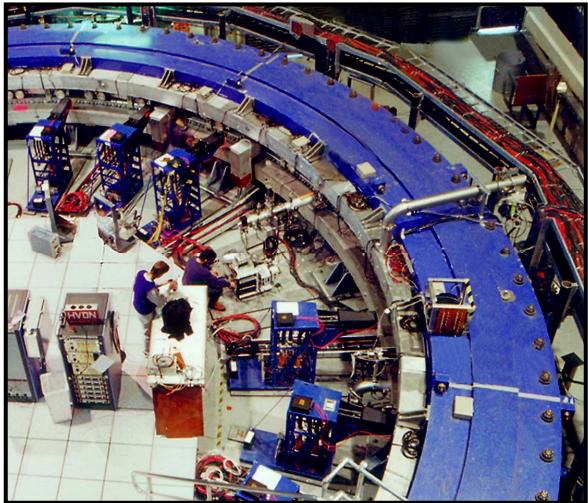
Biggest difference is from high multiplicity states now measured at BaBar; > 1 GeV region
→ Reduces cross sections

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (296 \pm 81) \times 10^{-11} \rightarrow 3.6 \sigma$$

courtesy: D. Herzog

The New Muon g-2 (and μ EDM) Experiment at Fermilab

David Hertzog
University of Washington



- Why mount a new experiment?
 - Especially in “the LHC era?”
- What makes it different compared to BNL E821?
- Status

The values & the new experimental goal

BNL E821

Theory uncertainty = 51×10^{-11} (0.44 ppm)

Experimental uncertainty = 63×10^{-11} (0.54 ppm)

- 0.46 ppm statistical ← limit was counts
- 0.21 ppm precession systematic
- 0.17 ppm field systematic

$$a_{\mu}^{Expt} = (116\ 592\ 089 \pm 63) \times 10^{-11}$$

$$a_{\mu}^{Thy} = (116\ 591\ 793 \pm 51) \times 10^{-11}$$

Leads to $\Delta a_{\mu}(\text{Expt} - \text{Thy}) = 296 \pm 81 \times 10^{-11}$ 3.6

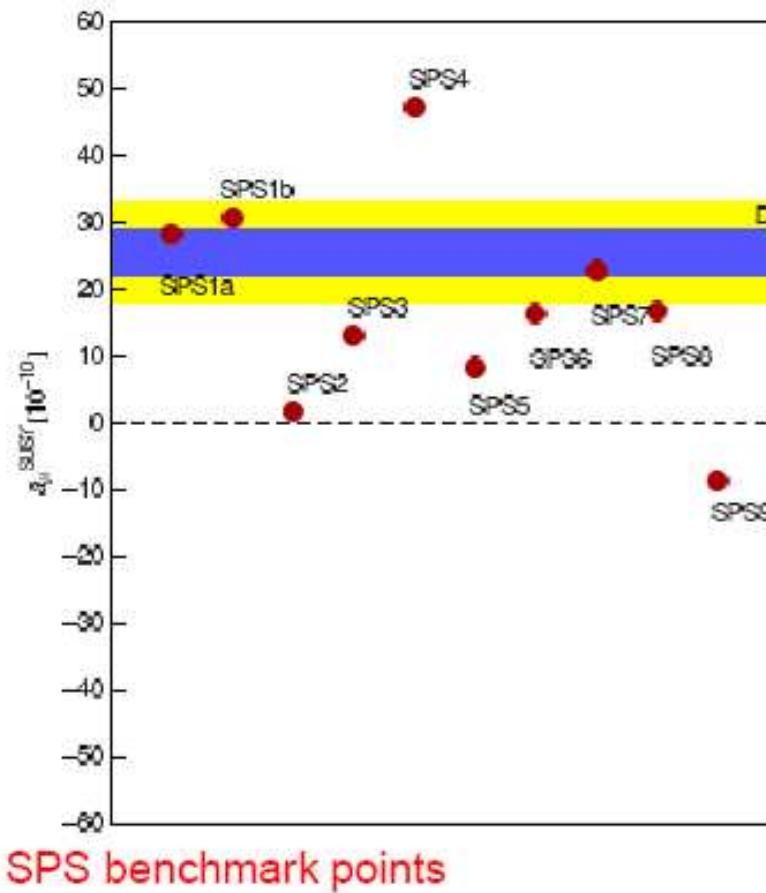
Experimental goal: $63 \rightarrow 16 \times 10^{-11}$

Theory uncertainty expect: $51 \rightarrow 30 \times 10^{-11}$

Leads to $\Delta a_{\mu}(\text{Expt} - \text{Thy}) = XXX \pm 34 \times 10^{-11}$

If central value remained, Δa_{μ} would exceed 8σ

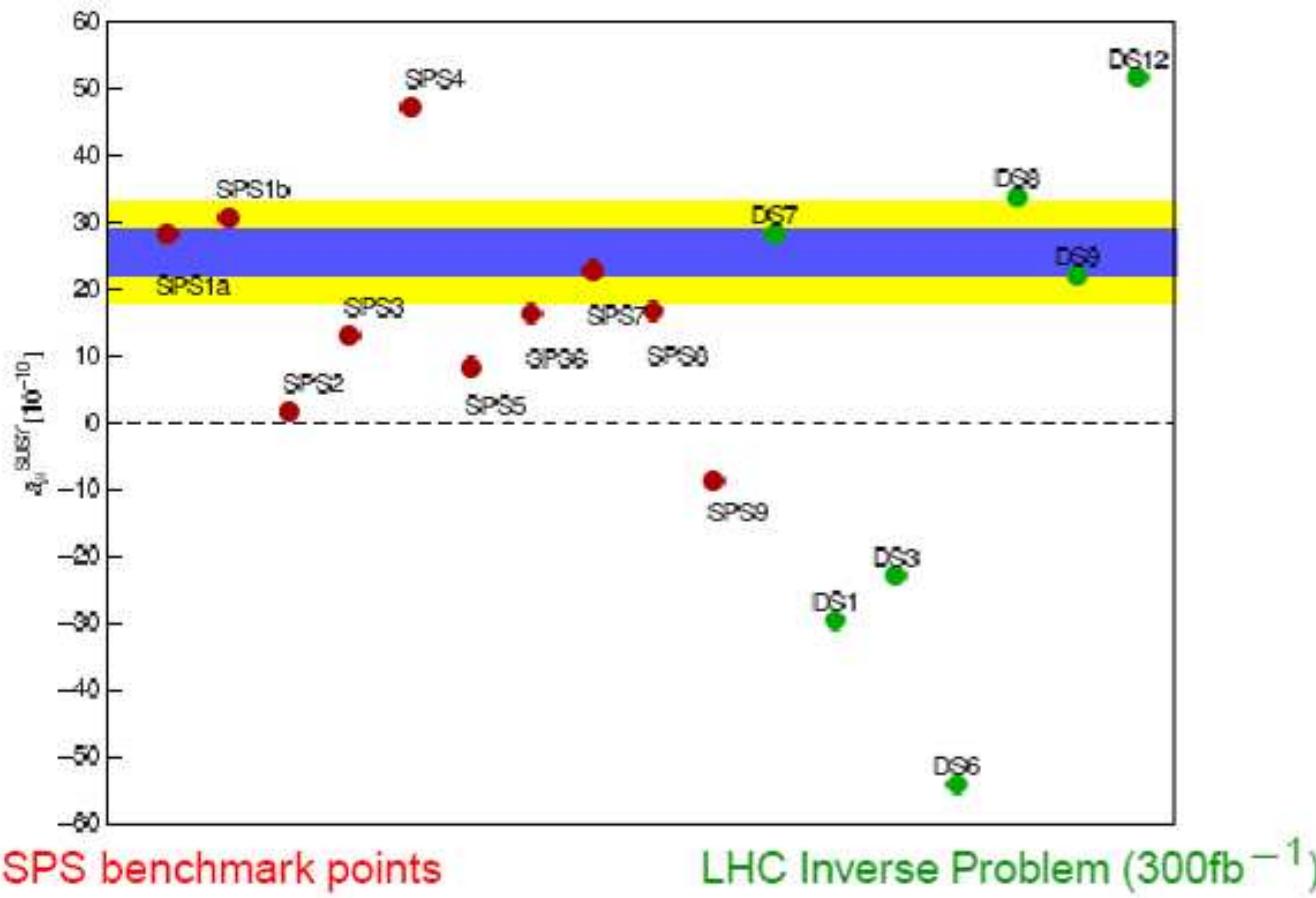
SUSY and g-2: The power to resolve among models and break LHC degeneracies



Note: Δa_μ centered at 255 here

courtesy: D. Herzog; discussions: D. Stöckinger

SUSY and g-2: The power to resolve among models and break LHC degeneracies



SPS benchmark points

LHC Inverse Problem (300fb^{-1})

can't be distinguished at LHC
[Sfitter: Adam, Kneur, Lafaye,
Plehn, Rauch, Zerwas '10]

Note: Δa_μ centered at 255 here

courtesy: D. Hertzog; discussions: D. Stöckinger

The proton radius puzzle

8 July 2010 | www.nature.com/nature | \$10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

OIL SPILLS
There's more
to come

PLAGIARISM
It's worse than
you think

CHIMPANZEES
The battle for
survival

SHRINKING THE PROTON

New value from exotic atom
trims radius by four per cent

NATURE JOBS
Researchers for hire

ETH



Measure the μp Lamb shift



determine the proton rms radius r_p

But large discrepancy observed:

- 5σ from H spectroscopy value
- 3σ from e-proton scattering value

A. Antognini

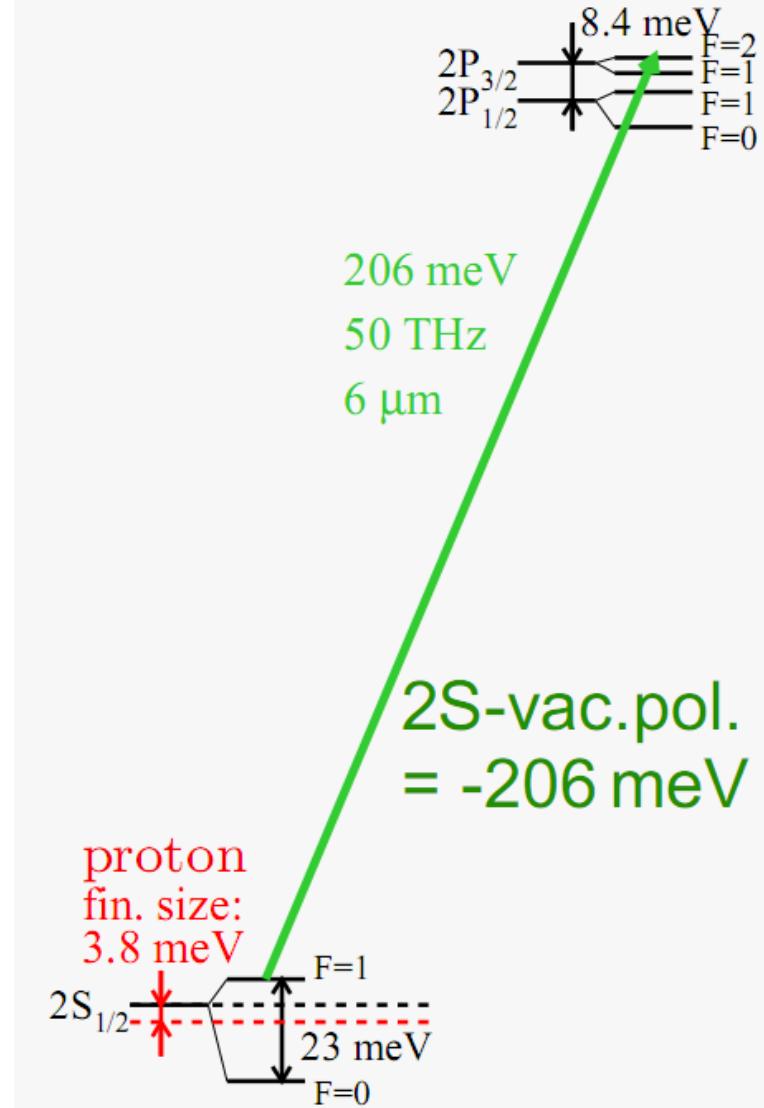
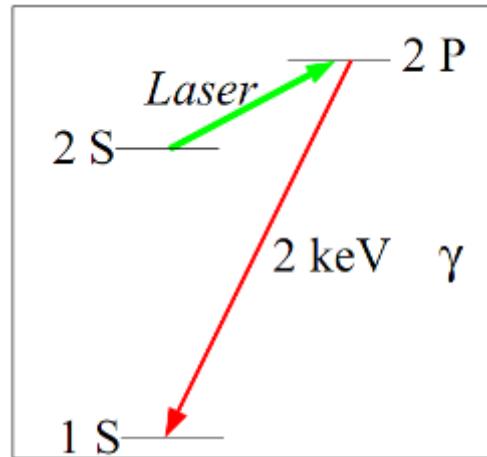
ETH, Zurich, Switzerland

A. Antognini, PSI, Villigen

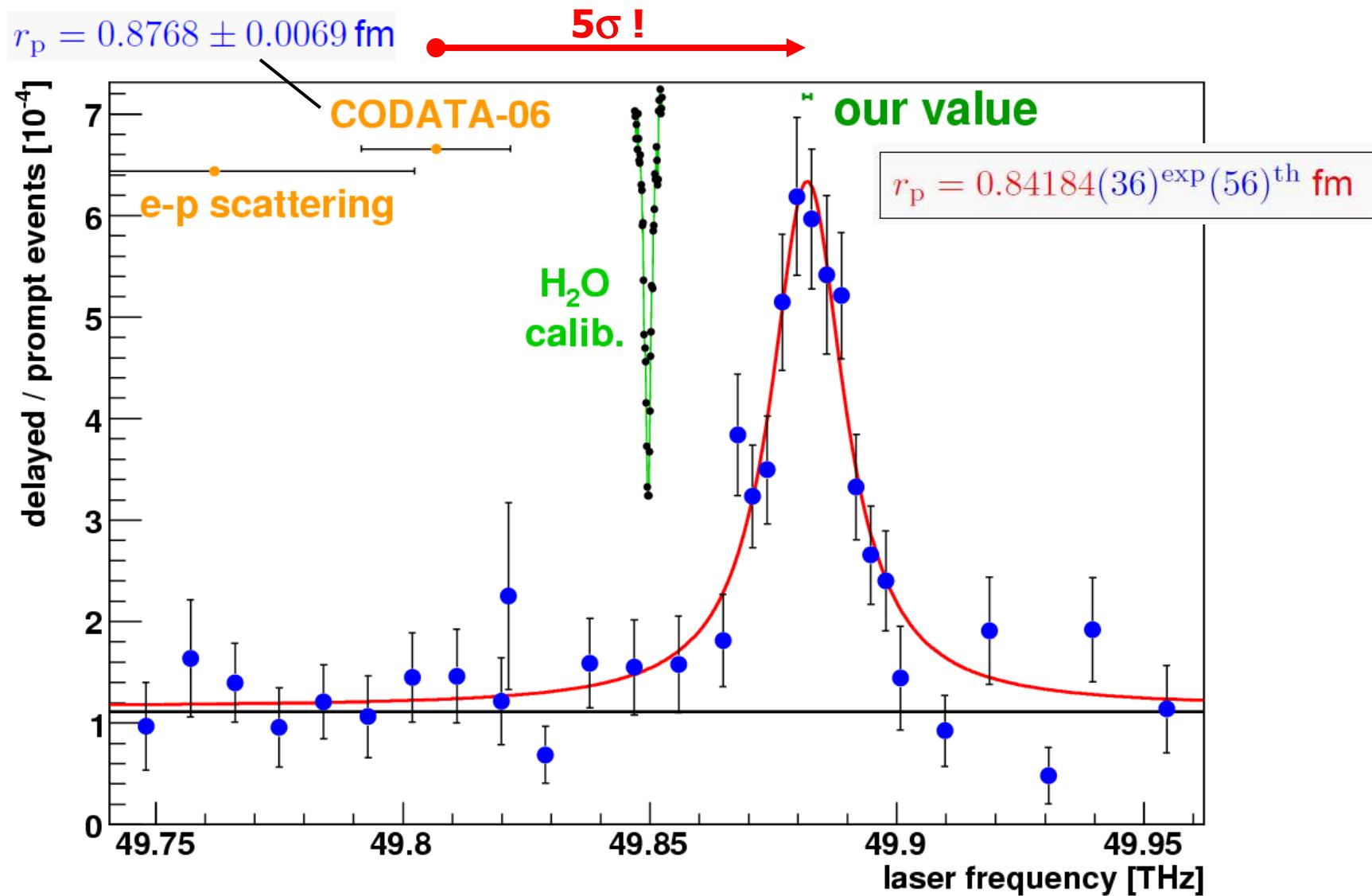
13.10.2010 – p.1

Muonic Hydrogen Lamb Shift Experiment

- μ^- DC muon beam
- μ^- detected in flight to trigger laser system
- $\mu^- p$ atom forms in 1 mbar H_2 gas
- ~1% of muons go to 2S state
- Laser pulse excites 2S – 2P state ($\lambda \approx 6\mu m$)
- 2P – 1S 2 keV γ detected
- By fine-tuning the laser, the $2S_{1/2} - 2P_{3/2}$ level is measured with high precision
→ determination of proton radius



Muonic Hydrogen Lamb Shift Experiment

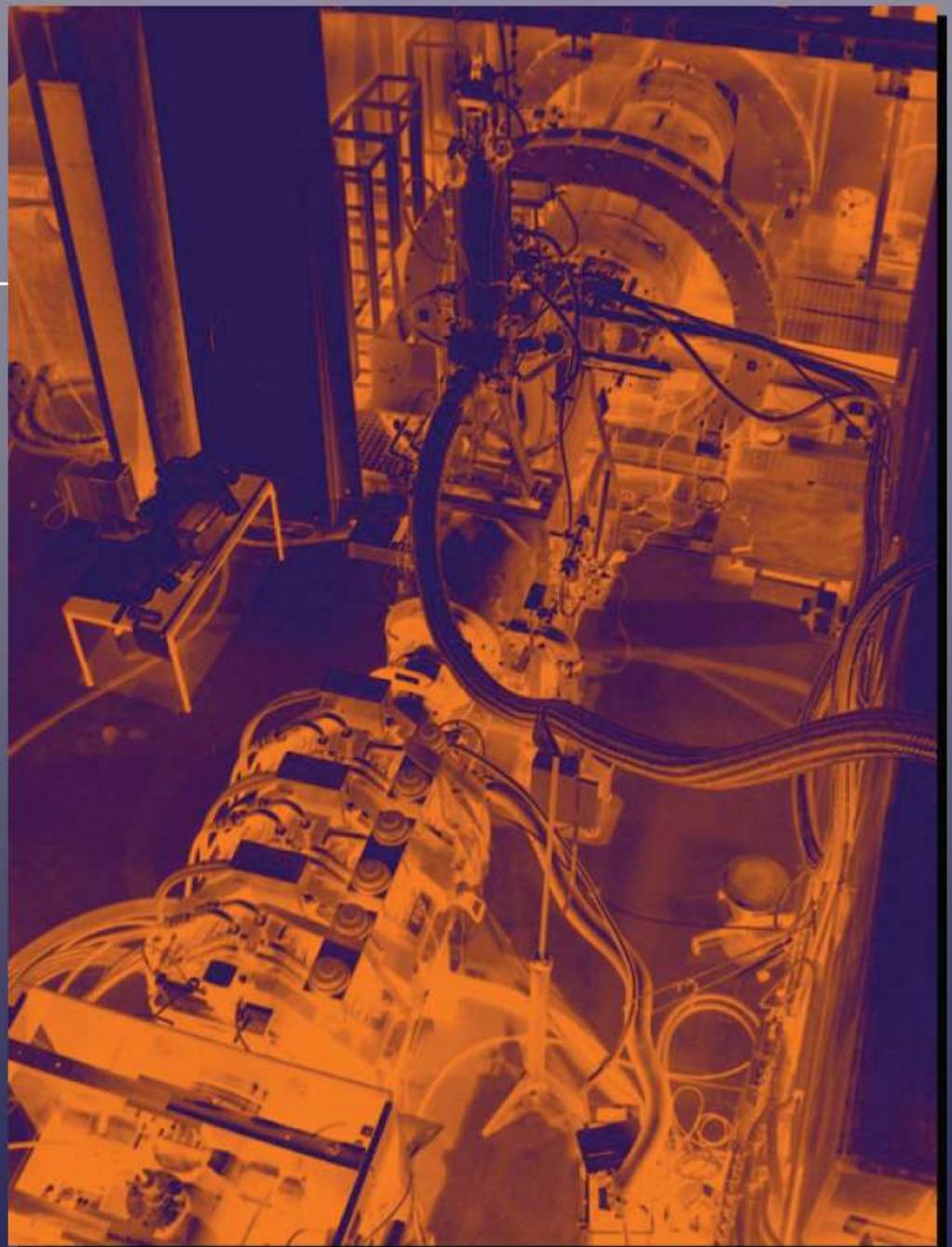


R. Pohl, A. Antognini, F. Nez, D. Taqqu, et al., Nature **466** (2010) 213

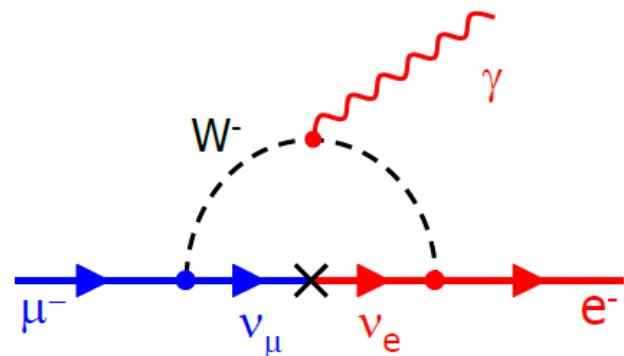
In Search of $\mu \rightarrow e\gamma$ The MEG Experiment - Status & Latest Results

*Peter-Raymond Kettle
Paul Scherrer Institut PSI*

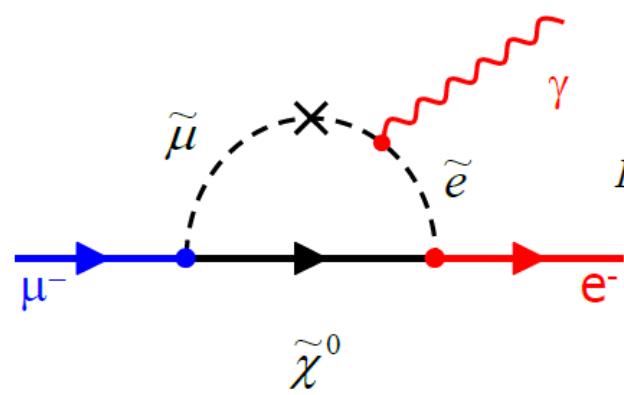
On behalf of the MEG Collaboration



- Search for Lepton Flavor Violation in the $\mu^+ \rightarrow e^+ \gamma$ decay
- While LFV is “forbidden” in SM, it is possible through virtual loops in new physics (SUSY, ...)



$$BR(\mu^+ \rightarrow e^+ \gamma) \Big|_{SM} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-50} \dots 10^{-60}$$

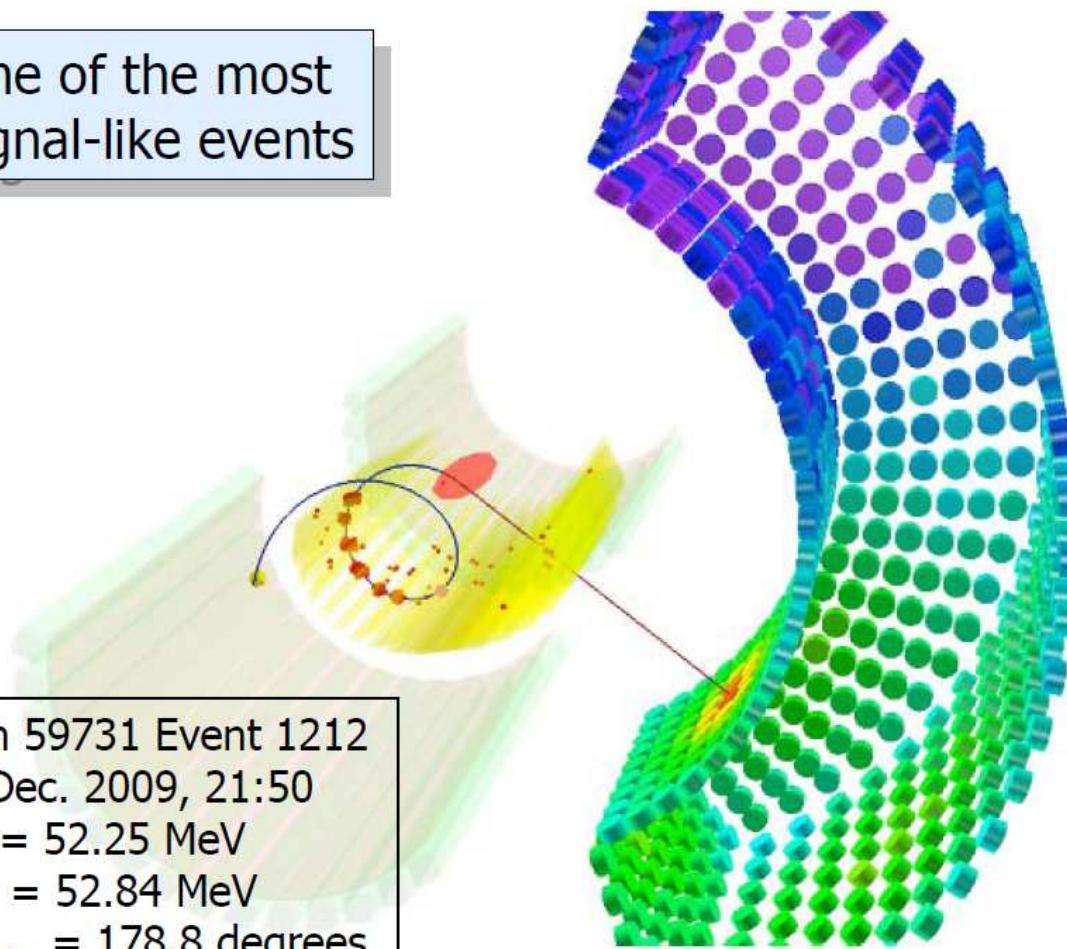


$$BR(\mu^+ \rightarrow e^+ \gamma) \Big|_{SUSY} \approx 10^{-5} \frac{\Delta m_{\tilde{e}\tilde{\mu}}^2}{\bar{m}_{\tilde{l}}^2} \left(\frac{100 \text{ GeV}}{m_{SUSY}} \right)^4 \tan^2 \beta \approx 10^{-12} \dots 10^{-14}$$

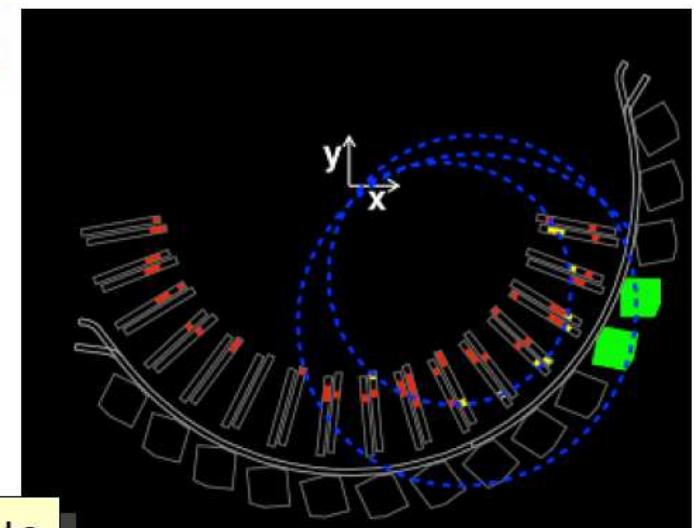
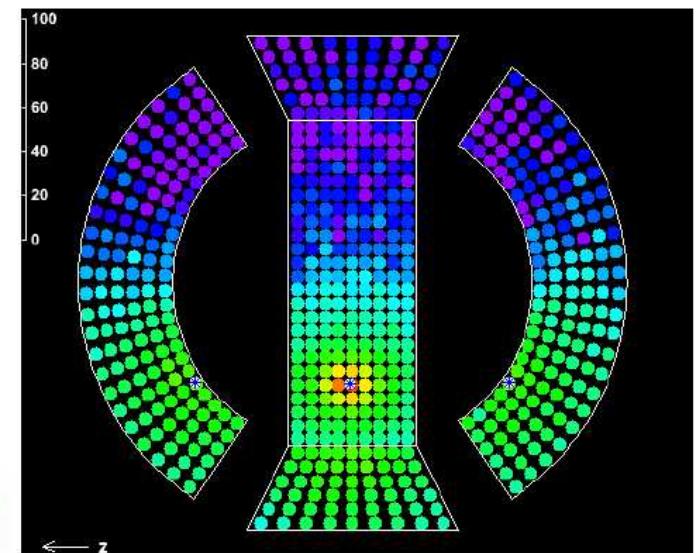
“Beauty of MEG”

Current experimental limit: $BR(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$
Aim of MEG experiment: $BR(\mu^+ \rightarrow e^+ \gamma) < \text{few} \times 10^{-13}$

One of the most signal-like events



Run 59731 Event 1212
4. Dec. 2009, 21:50
 $E_{\gamma} = 52.25 \text{ MeV}$
 $E_{e+} = 52.84 \text{ MeV}$
 $\Delta\theta_{e+g} = 178.8 \text{ degrees}$
 $\Delta T_{e\gamma} = 26.8 \text{ ps}$



2009: Expected 1-2 background events, found 5 events
2010: Triple statistics

Summary

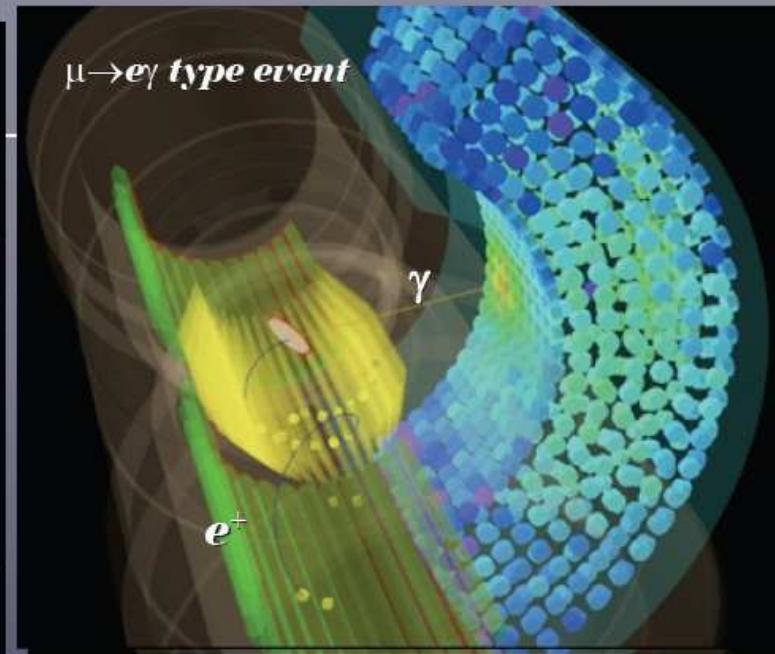


- **1st Engineering Run - end 2007**
- **1st Physics Run - end 2008 (3 Months)**
Published - Nucl. Phys. B 834 1-12 (2010)

• **Physics Run in 2009:**
Sensitivity $6.1 \cdot 10^{-12}$
 $BR(\mu \rightarrow e\gamma) \leq 1.5 \cdot 10^{-11}$ (90% C.L.)
 $N_{sig} = 0$ still contained in 90% C.L. region
but prob. of best-fit $N_{sig} = 3$ approx. 2-3% (null hypothesis)

Preliminary

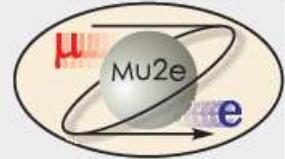
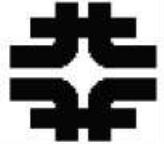
- **2010 Long Run 19 weeks (Physics Data)**
further trigger & electronics improvements being implemented
- **then data-taking through → end 2012**
to reach our planned sensitivity of $O(10^{-13})$



Current PDG-value: Set by MEGA Experiment in 1999 $BR(\mu \rightarrow e\gamma) \leq 1.2 \cdot 10^{-11}$ (90% C.L.)
Expected MEG Sensitivity for 2010 Data $\sim 2.0 - 2.2 \cdot 10^{-12}$

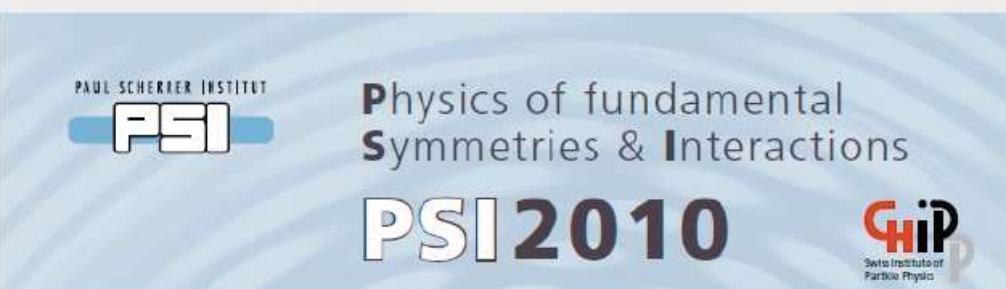
Then towards $\Rightarrow 10^{-13}$

What else is going on?



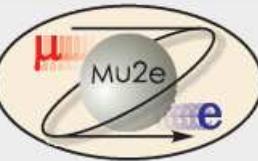
A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

R. Bernstein
Fermilab
for the Mu2e Collaboration





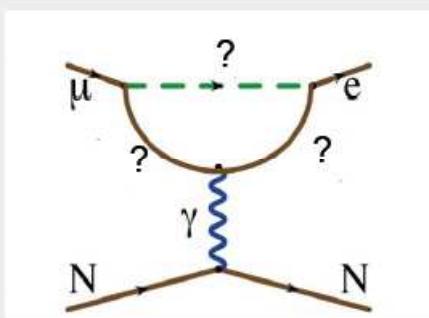
“Model-Independent” Form



$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

“Loops”

$\kappa=0$

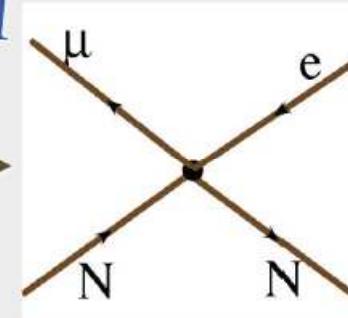


mass scale Λ

κ

“Contact Terms”

$\kappa=1$



Supersymmetry and Heavy
Neutrinos

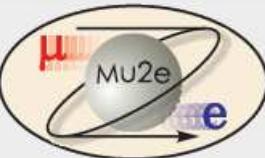
Contributes to $\mu \rightarrow e\gamma$ (γ real)

Does not produce $\mu \rightarrow e\gamma$

Quantitative Comparison?



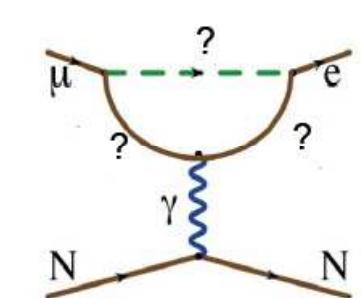
“Model-Independent” Form



$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

“Loops”

$\kappa=0$

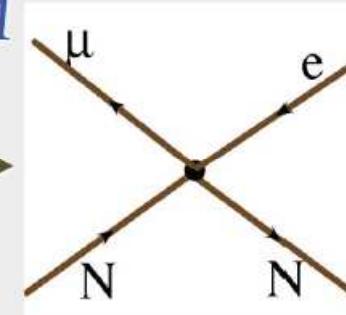


mass scale Λ

κ

“Contact Terms”

$\kappa=1$



Supersymmetry and Heavy
Neutrinos

Contributes to $\mu \rightarrow e\gamma$ (γ real)

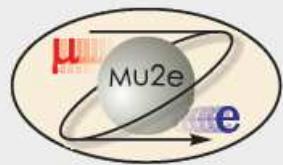
see also $\mu \rightarrow eee$
complementarity

Does not produce $\mu \rightarrow e\gamma$

Quantitative Comparison?

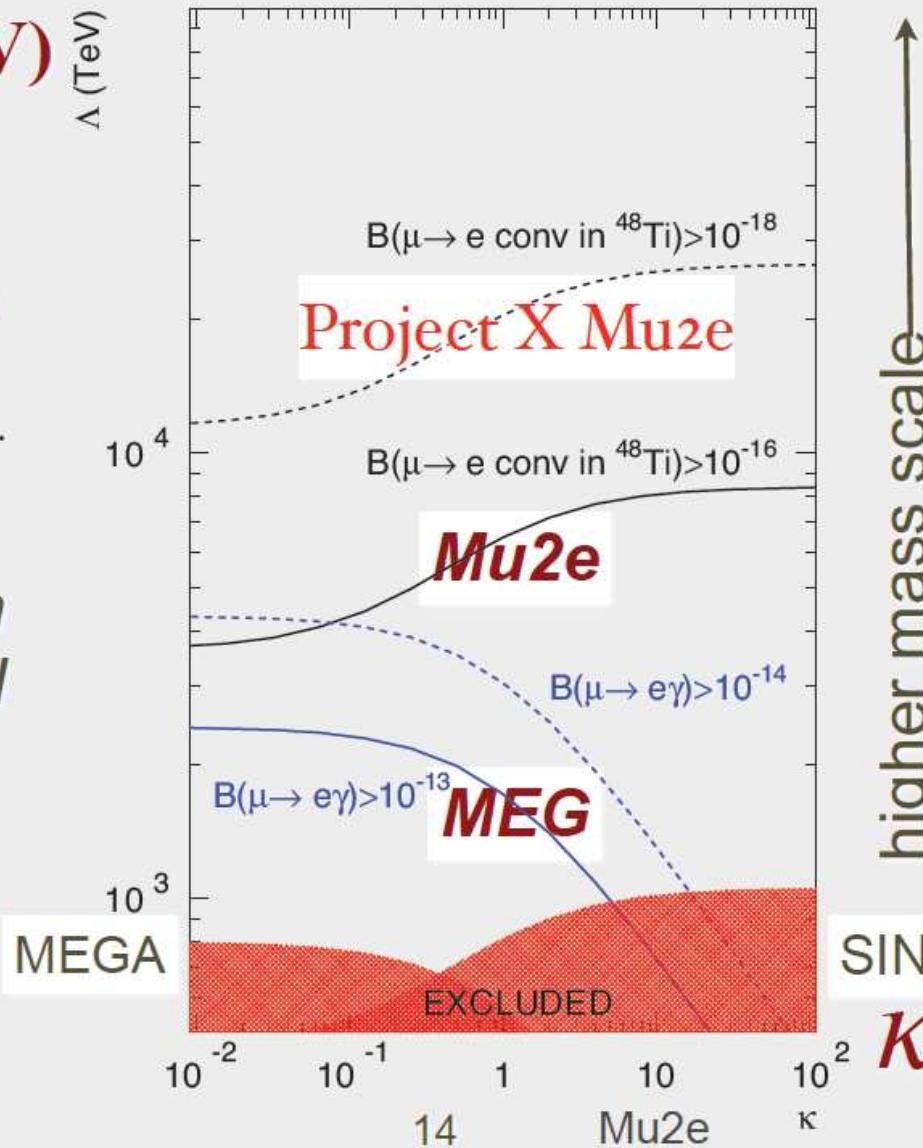


μe Conversion and $\mu \rightarrow e\gamma$



1) Mass Reach
to $\sim 10^4$ TeV

2) about x2
beyond MEG in
loop-dominated
physics

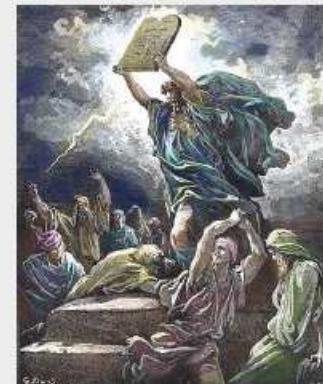
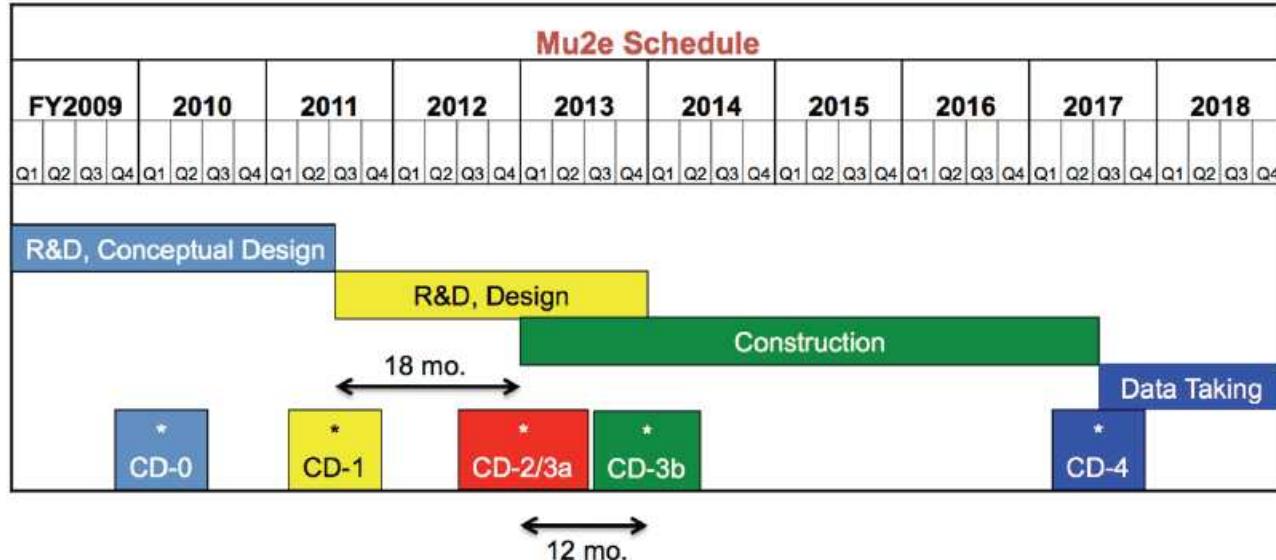




Cost and Schedule



- *This is a technically limited schedule*
- Critical Path is Superconducting Solenoids
- \$200M “fully-loaded” Total Cost





Conclusions



- Mu2e will either:
 - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude* ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)
 - *Discover unambiguous proof of Beyond Standard Model physics and*
 - *Provide important information either complementing LHC results or probing up to 10^4 TeV mass scales*
- With upgrades, we could extend the limit by up to two orders of magnitude or study the details of new physics

Muon Physics Program at J-PARC

Satoshi MIHARA
KEK, Japan

Muon physics program at J-PARC

- mu-e conversion search experiments
- muon g-2/EDM measurement

J-PARC Particle Physics Program

- Neutrino oscillation measurement
 - T2K
- Mu-e conversion search experiments
 - COMET
 - DeeMe
- Muon g-2/EDM measurement
- T-violating Muon P_T Measurement in $K^+ \rightarrow \pi^0 \mu^+ \nu$ Decays
 - TREK
- Study on $K_L \rightarrow \pi^0 \bar{\nu} \nu$
 - KOTO
- Neutron EDM

MuSIC

- A new DC muon beamline at RCNP -

Akira SATO

Department of Physics, Osaka University

2010/10/12, PSI201

Muon Science in Japan

DC muon

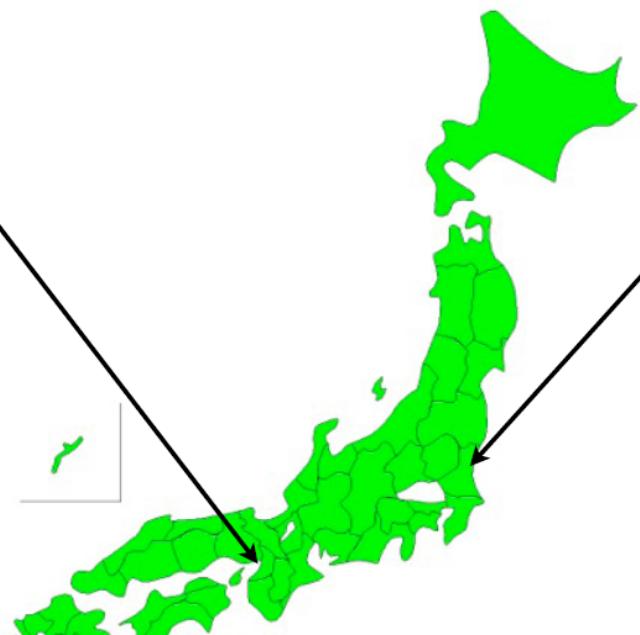
Pulsed muon

Muon Facility
MuSIC
(Osaka)

400W
CW
 10^8 /sec
single channel

Muon Facility
MUSE
(J-PARC)

1000kW
pulsed (25 Hz)
 10^8 /sec
many channels



Japan will be the only country which has both
DC and pulsed muon beam facilities.

A Large Muon EDM from Flavor?

arXiv:1008.5091[hep-ph]

G. Hiller*, K. Huitu[†], J. Laamanen[†] and T. Rüppell[‡]

* Institute für Physik, Technische Universität Dortmund

† Theoretical High Energy Physics, Radbound University, Nijmegen

‡ University of Helsinki and Helsinki Institute of Physics, Helsinki

Physics of fundamental Symmetries and Interactions
Paul Scherrer Institut
14.10.2010

Conclusions

A Large Muon EDM from Flavor?

- CP violation from flavor can bypass the constraint from d_e^{exp} .
- Mass Insertion Approximation
 - Large $d_\mu \sim 10^{-23}$ ecm possible within the approximation.
 - Improvements on $\text{Br}^{\text{exp}}(\tau \rightarrow \mu\gamma)$ show a significant effect.
- Exact Low Scale MSSM
 - Conventional SUSY spectrum can reach $d_\mu > 10^{-22}$ ecm.
 - Potential for indirect SUSY discovery since an LHC eluding spectrum can have $d_\mu > 10^{-22}$ ecm.
 - Heavy spectrum is not favored; 2% vs. 35% random walk success rate, fine tuning of the complex phases.
- Hybrid Gauge-Gravity SUSY breaking
 - Realistic example has $d_\mu \lesssim 10^{-24}$ ecm.
 - Discovery of such a d_μ would be very indicative for the SUSY breaking mechanism and flavor structure.

Thank You!

Muon EDM

BNL g-2: PHYSICAL REVIEW D **80**, 052008 (2009)

Improved limit on the muon electric dipole moment

$$d_\mu < 1.8 \times 10^{-19} \text{ ecm}$$

FNAL g-2 improved sensitivity:

$$d_\mu \sim \text{few} \times 10^{-21} \text{ ecm}$$

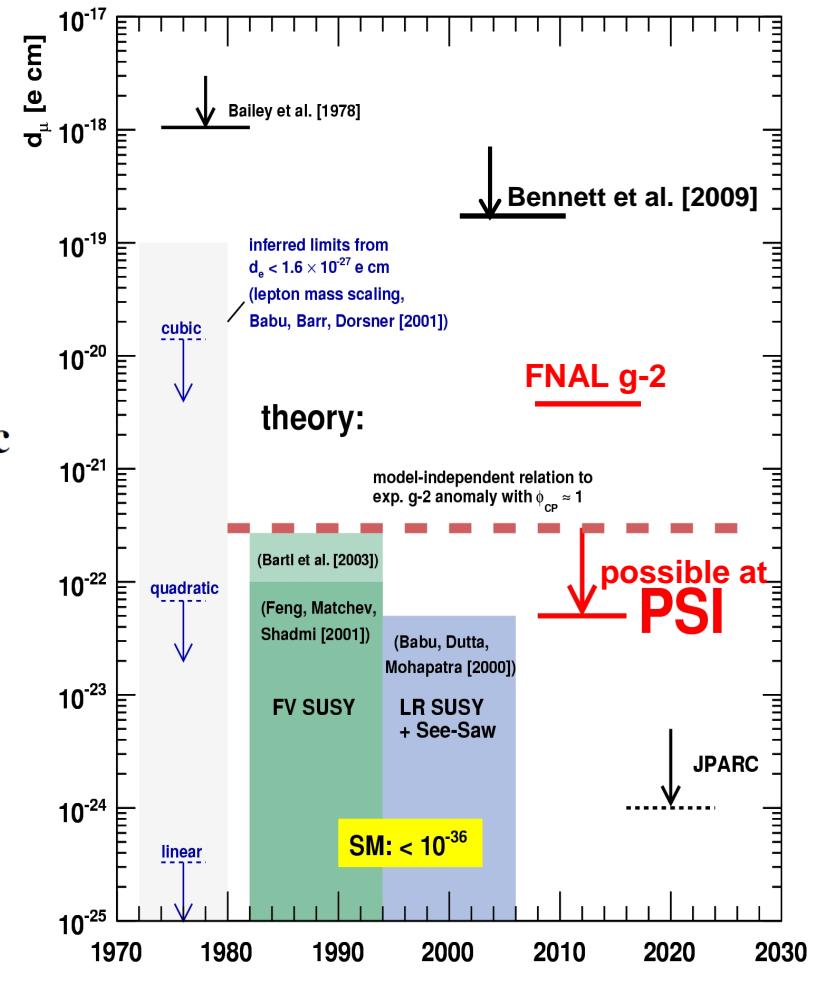
J. Phys. G: Nucl. Part. Phys. **37** (2010) 085001

Compact storage ring to search for the muon electric dipole moment

$$d_\mu \sim \text{few} \times 10^{-23} \text{ ecm}$$

→ Storage ring EDM talk to come

frozen spin: Farley et al., PRL 93 (2004) 052001



A Novel $\mu \rightarrow \text{eee}$ Experiment



Sebastian Bachmann, Rohin Narayan,
André Schöning

Physikalisches Institut
Universität Heidelberg



The poster features the PSI logo (Paul Scherrer Institut) and the text "Physics of fundamental Symmetries & Interactions". Below this, the year "PSI 2010" is prominently displayed. A small logo for CERN is visible on the right. At the bottom, a dark banner contains the text "October 11–14, 2010" and "Paul Scherrer Institut, Switzerland".

PAUL SCHERRER INSTITUT
PSI

Physics of fundamental
Symmetries & Interactions

PSI 2010

CERN
Swiss Institute of
Particle Physics

October 11–14, 2010
Paul Scherrer Institut, Switzerland

Motivation for $\mu^+ \rightarrow e^+e^+e^-$ Search

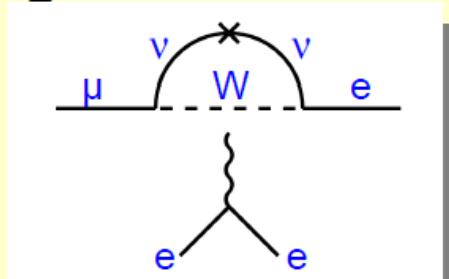
- New Particles at the “Terascale” naturally induce LFV
- Search $\mu^+ \rightarrow e^+e^+e^-$ is complementary to other LFV searches
(e.g. $\mu^+ \rightarrow e^+\gamma$)
- Advances in detector technologies allow for high rate / high precision experiments
- Plans to improve PSI beamlines and targets:
 - > 10^9 muon stops/s seem possible
 - would allow to test muon decay branching ratios at $10^{-15} - 10^{-16}$
 - current exp. limit $B(\mu^+ \rightarrow e^+e^+e^-) = 10^{-12}$ (Bellgard 1988)
- A search for $B(\mu^+ \rightarrow e^+e^+e^-) > 10^{-16}$ has a large potential to find LFV signal or to set very stringent bounds on new physics

Lepton Flavor Violation

- SM process LFV muon decay has tiny branching ratio:

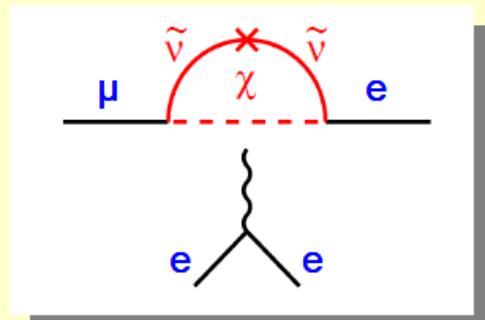
$$\text{BR}(\mu^+ \rightarrow e^+ e^+ e^-) \ll 10^{-50}$$

- high sensitivity to beyond SM particles!
(e.g. SUSY, Higgs triplets)

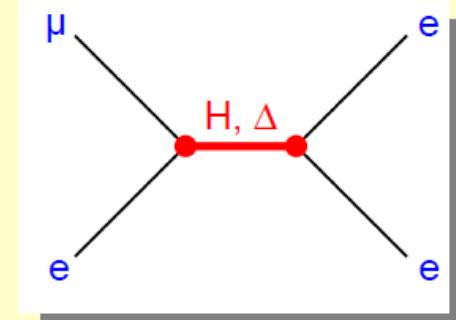


Standard Model

- $\mu^+ \rightarrow e^+ e^+ e^-$ sensitive to loop (penguin) and four-fermion diagrams



Supersymmetry



Higgs, Doubly Charged Higgs

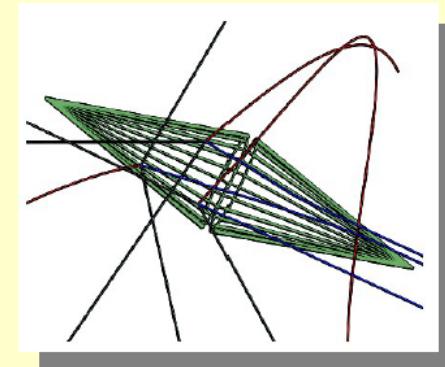
Summary

- Novel detector concept for muon decay experiment proposed
- Technologies: Silicon Pixel and Sintillating Fibers Trackers
- sensitivity $\text{BR}(\mu \rightarrow \text{eee}) < 10^{-16}$ seems feasible but more detailed simulation are required
- first prototype detector could be produced within 1-2 years
- detector could replace completed MEG experiment (in 3 years)
- later go to an upgraded high intensity beamline

Conclusion

After more than 20 years time has come to repeat a search for
 $\mu \rightarrow eee$ and to repeat very a successful experiment (Sindrum)

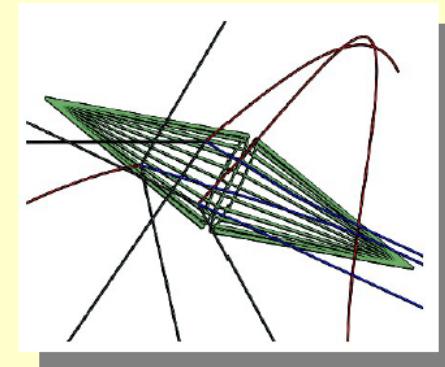
new collaborators are highly welcome!



Conclusion

After more than 20 years time has come to repeat a search for
 $\mu \rightarrow eee$ and to repeat very a successful experiment (Sindrum)

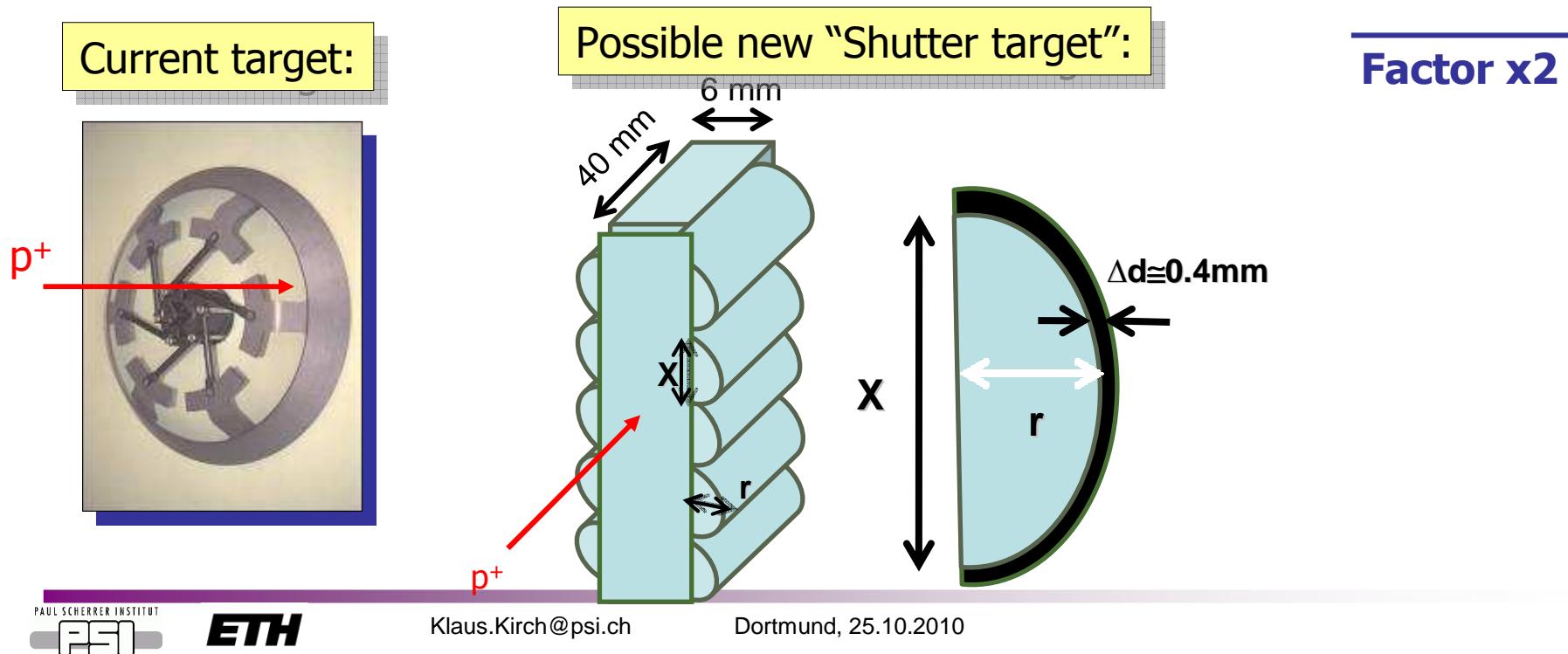
new collaborators are highly welcome!



Also various CH-groups interested in $\mu \rightarrow eee$

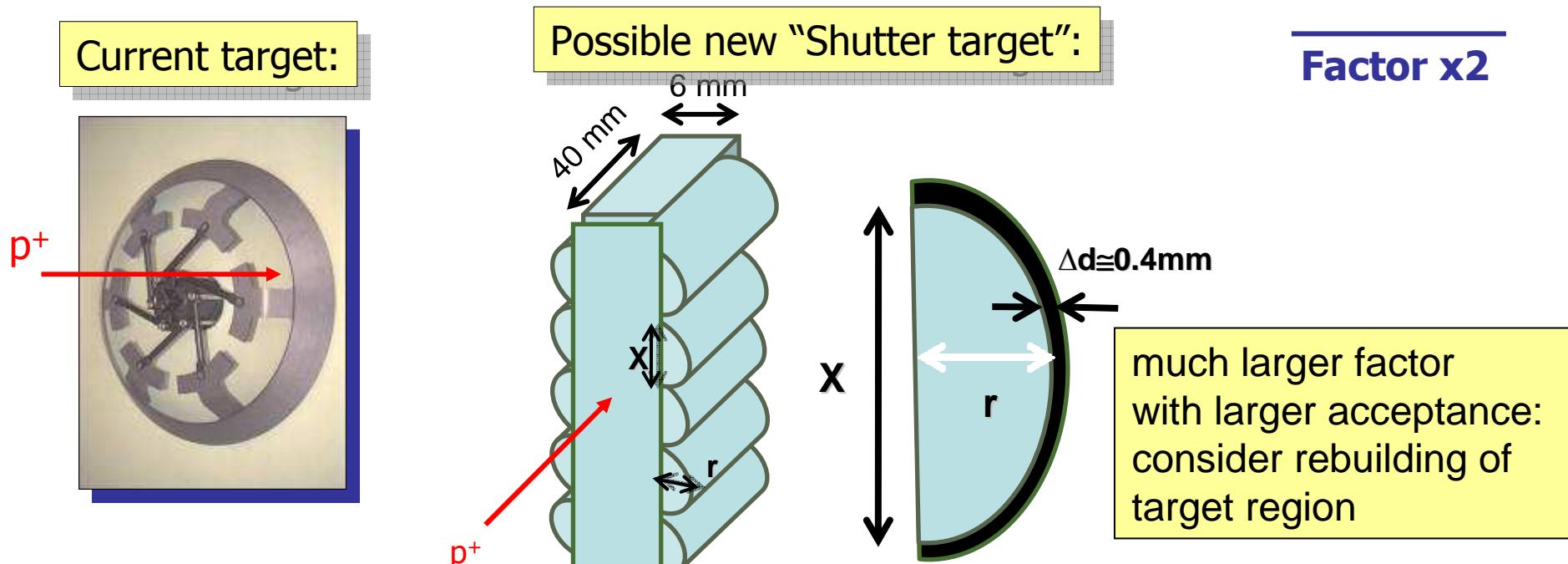
Higher Intensity Muon Beams

- Currently $\sim 10^8 \mu^+/\text{s}$ (DC “surface” μ^+ 28 MeV/c) at several beam lines at PSI
- Next generation of μ -beam experiments need **GHz Muon Beams**
 - Accelerator plans: $2.2 \text{ mA} \rightarrow 3 \text{ mA}$ (1.8 MW) **+36%**
Limit: 3~3.5 mA heat load on production target (vaporization)
 - Use of 6 cm thick target instead 4 cm **+30-50%**
 - New shutter target **+50%**
 - New extraction coupling to muon channel **(+30%)**



Higher Intensity Muon Beams

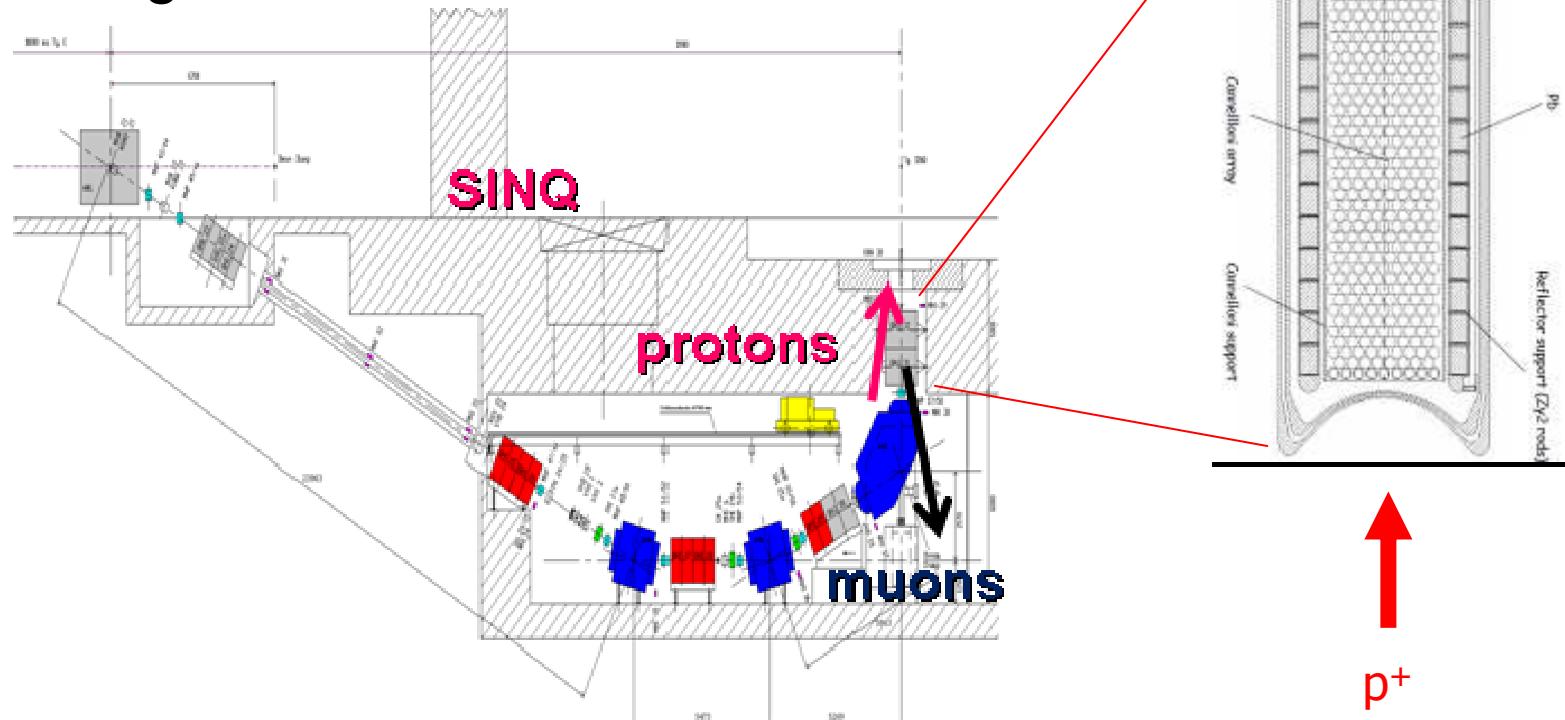
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Spallation source as muon target?

■ Spallation target is also a muon source

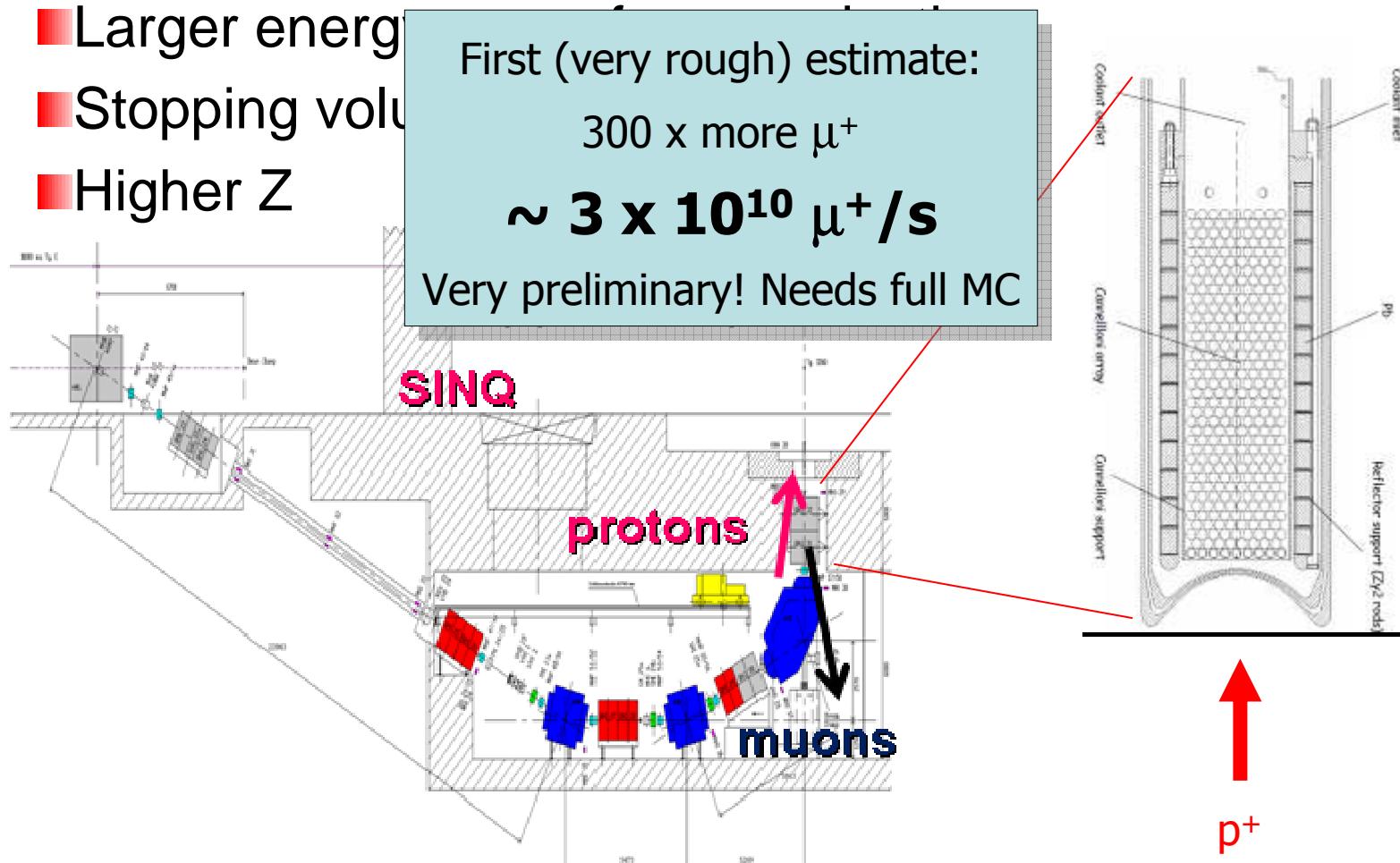
- Larger energy range for π production
- Stopping volume 9000x larger
- Higher Z



Spallation source as muon target?

■ Spallation target is also a muon source

- Larger energy
- Stopping volume
- Higher Z



Coming to an end ...

- Sorry, I had to skip important things
PEN, MuCap, MuSUN, FAST, TWIST,
Muonium physics, ...
- Thanks to many colleagues for their various active inputs and “passive help”
- I would be excited to continue discussions about future CH-D, European muon projects --
I am sure these are timely, would have major impact, and we already have much of the infrastructure that others wish to build!

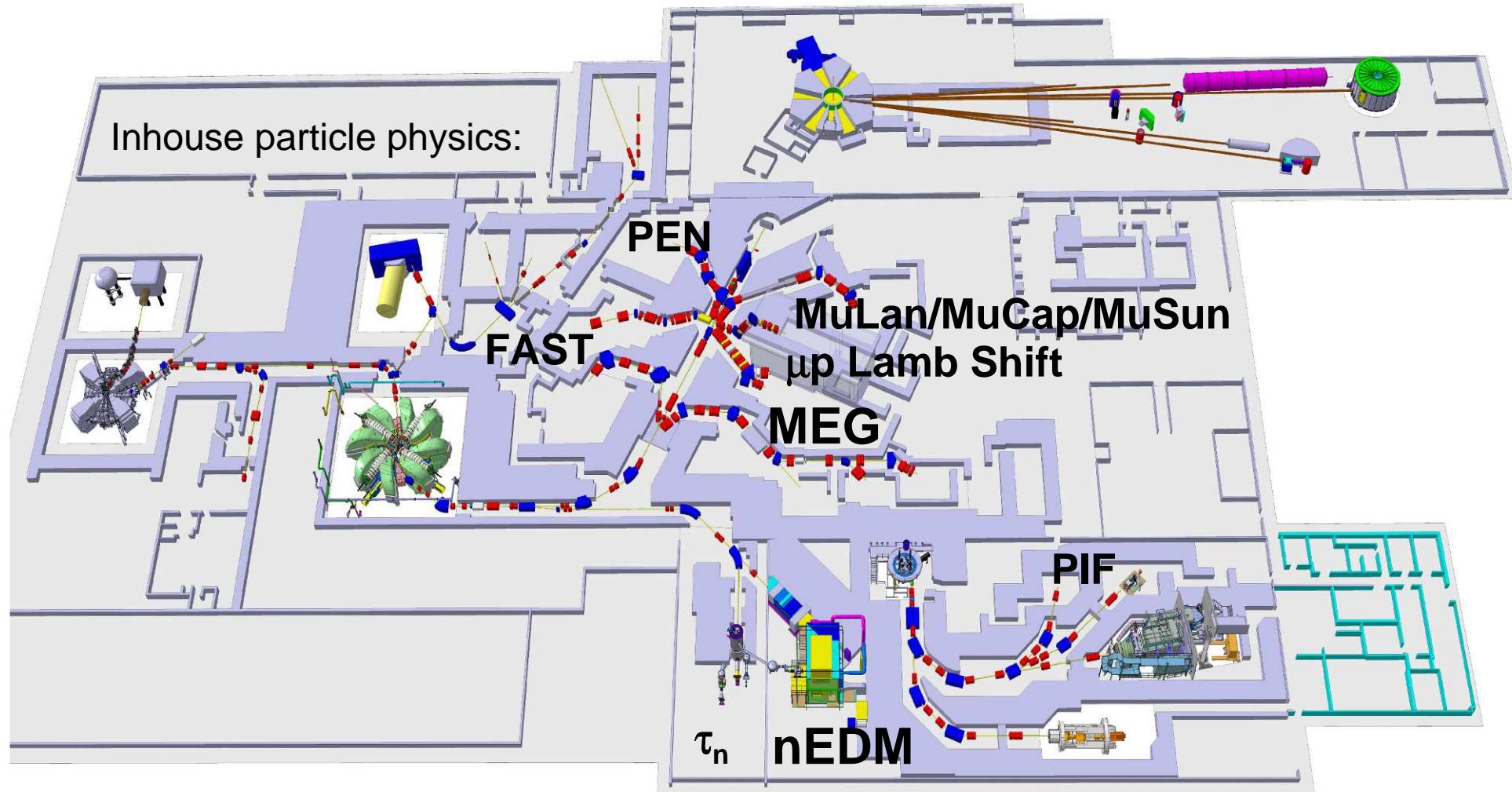
Conclusions

- **Precision physics with high intensity slow muon beams** offers a unique window to new physics. It is complementary to other low energy precision physics and in particular also to running and future collider experiments
- World-wide activities and renewed interest:
Major muon programs ongoing or planned at
PSI, FNAL, J-PARC, RCNP [TRIUMF, RAL, LANL]
- Today's highest intensity low momentum
pion and muon beams at PSI
- In the future: high intensity, pulsed beam facilities
FNAL, J-PARC [ESS has been discussed, but ..]
- Also in the future: PSI will remain the best DC beam facility
and aims at improved intensity and beam quality



major opportunity in Europe

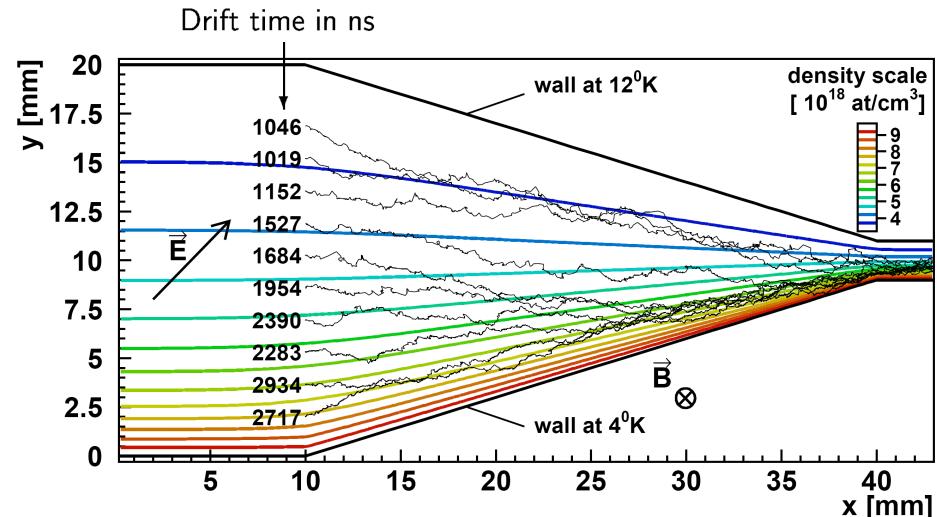
Proton Accelerator Facility



Cold Muon Beam “MuCatcher”

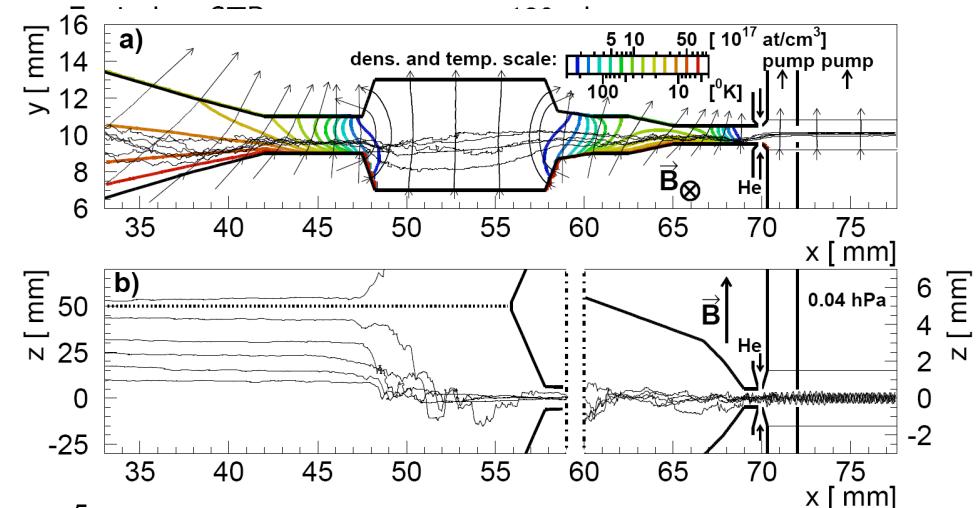
- D. Taqqu proposed a new technique for the production of a high-quality low energy μ^+ beam
PRL 97 (2006) 194801.
- This μ^+ beam could be used for surface μ SR. Phase space density increases by 10^8 - 10^{10} .
- Post-acceleration possible, could e.g. be used for a **$g-2$ measurement**
- The μ^+ beam could be converted into high quality **Muonium (μ^+e^-)** beam for testing **gravity with anti-matter** and **Muonium spectroscopy**
- Estimates: 10^{-3} efficiency gives 10^5 – $10^6 \mu^+/s$
- MC ongoing, project looks feasible, first beam tests planned for next year

Gas: Helium



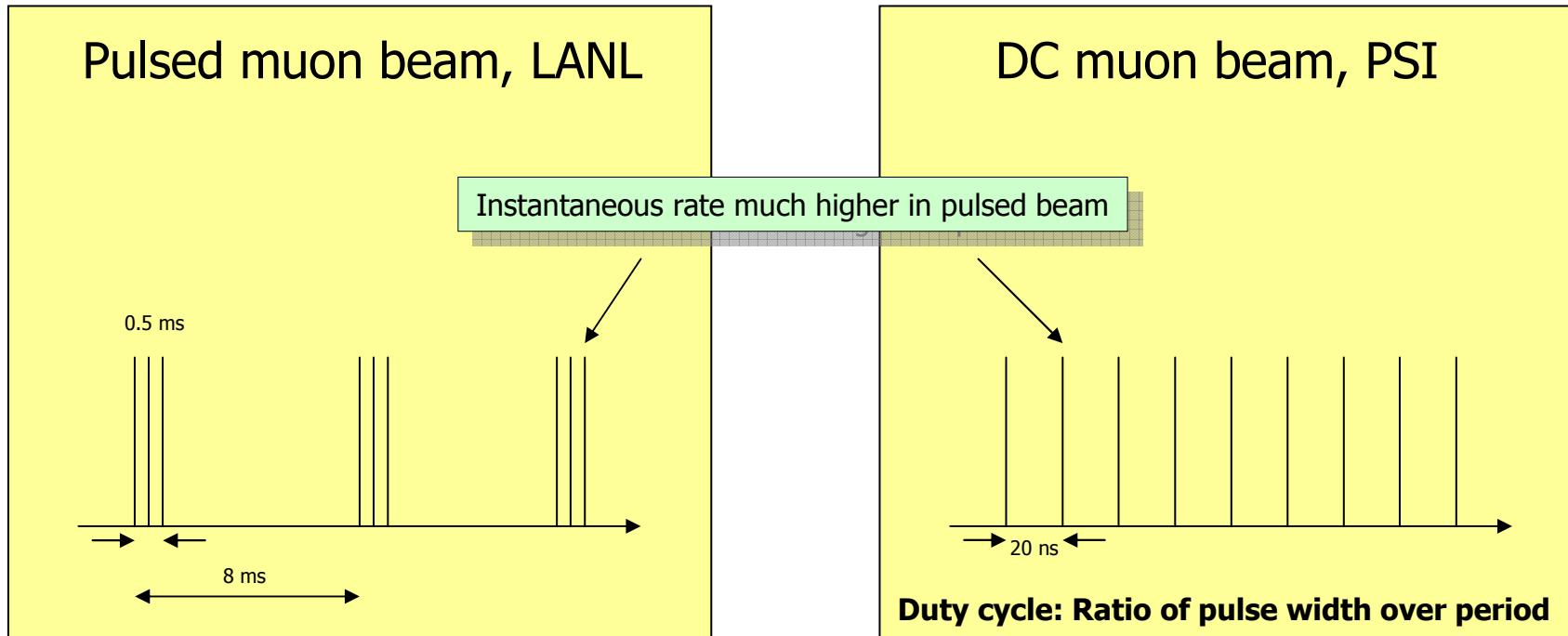
Average energy at throat: 3 eV

Swarm width FWHM after compression: 0.4 mm



Pion/Muon Beam Structure

- Beam structure differs for different accelerators



Duty cycle: 6 %
Good for low pion contamin.
 $\rightarrow \mu - e$ conversion

Duty cycle: 100 %
Good for coincidence expts.
 \rightarrow Low pile-up

What can we do with pions?

π^\pm Mass

VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
139.57018±0.00035 OUR FIT	Error includes scale factor of 1.2.			
139.57018±0.00035 OUR AVERAGE	Error includes scale factor of 1.2.			
139.57071±0.00053	¹ LENZ 98	CNTR	—	pionic N2-atoms gas target
139.56995±0.00035	² JECKELMANN 94	CNTR	—	π^- atom, Soln. B
• • • We do not use the following data for averages, fits, limits, etc. • • •				
139.57022±0.00014	³ ASSAMAGAN 96	SPEC	+	$\pi^+ \rightarrow \mu^+ \nu_\mu$
139.56782±0.00037	⁴ JECKELMANN 94	CNTR	—	π^- atom, Soln. A
139.56996±0.00067	⁵ DAUM 91	SPEC	+	$\pi^+ \rightarrow \mu^+ \nu$
139.56752±0.00037	⁶ JECKELMANN 86B	CNTR	—	Mesonic atoms
139.5704 ±0.0011	⁵ ABELA 84	SPEC	+	See DAUM 91
139.5664 ±0.0009	⁷ LU 80	CNTR	—	Mesonic atoms
139.5686 ±0.0020	CARTER 76	CNTR	—	Mesonic atoms
139.5660 ±0.0024	^{7,8} MARUSHEN... 76	CNTR	—	Mesonic atoms



π^+ Branching Ratios

Mode	Fraction (Γ_i/Γ)	Confidence level
$\Gamma_1 \mu^+ \nu_\mu$	[a] $(99.98770 \pm 0.00004) \%$	
$\Gamma_2 \mu^+ \nu_\mu \gamma$	[b] $(2.00 \pm 0.25) \times 10^{-4}$	
$\Gamma_3 e^+ \nu_e$	[a] $(1.230 \pm 0.004) \times 10^{-4}$	
$\Gamma_4 e^+ \nu_e \gamma$	[b] $(7.39 \pm 0.05) \times 10^{-7}$	
$\Gamma_5 e^+ \nu_e \pi^0$	$(1.036 \pm 0.006) \times 10^{-8}$	
$\Gamma_6 e^+ \nu_e e^+ e^-$	$(3.2 \pm 0.5) \times 10^{-9}$	
$\Gamma_7 e^+ \nu_e \nu \bar{\nu}$	$< 5 \times 10^{-6}$	90%



π^0 Branching Ratios, π^+ Form Factors...

What can we do with muons?

μ^- Branching Ratios

Mode	Fraction (Γ_i/Γ)	Confidence level	
$\Gamma_1 e^- \bar{\nu}_e \nu_\mu$	$\approx 100\%$		
$\Gamma_2 e^- \bar{\nu}_e \nu_\mu \gamma$	[a] $(1.4 \pm 0.4) \%$		
$\Gamma_3 e^- \bar{\nu}_e \nu_\mu e^+ e^-$	[b] $(3.4 \pm 0.4) \times 10^{-5}$		
Lepton Family number (<i>LF</i>) violating modes			
$\Gamma_4 e^- \nu_e \bar{\nu}_\mu$	<i>LF</i> [c] $< 1.2 \%$	90%	
$\Gamma_5 e^- \gamma$	<i>LF</i> $< 1.2 \times 10^{-11}$	90%	
$\Gamma_6 e^- e^+ e^-$	<i>LF</i> $< 1.0 \times 10^{-12}$	90%	
$\Gamma_7 e^- 2\gamma$	<i>LF</i> $< 7.2 \times 10^{-11}$	90%	
			BERTL
			BELLGARDT
			MEG
			MEEE

$\mu^- \rightarrow e^-$ Conversion (LFV)

^{32}S **BADERTSCHER**

Cu

Ti **DOHMEN**

Pb **HONECKER**

Au **BERTL**

$\mu^+ \rightarrow e^+$ Conversion (LFV)

^{32}S **BADERTSCHER**

I **ABELA**

Cu

Ti **KAULARD**

μ Life Time

FAST **MuLAN**

PEN Experiment

- Lepton universality (flavour independence of lepton – gauge boson coupling) is a cornerstone of the SM and most precisely measured in the $\pi^+ \rightarrow e^+ \nu$ branching ratio.
- Deviations from universality could indicate new physics:
 - Extra Higgs $> 6.9 \text{ TeV}$
 - Leptoquarks $> 3.8 \text{ TeV}$
 - Vector leptoquarks $> 630 \text{ TeV}$
 - ...
- Current uncertainties:

$$\frac{\Gamma(\pi \rightarrow e \bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu \bar{\nu}(\gamma))}_{\text{CALC}} = (1.2352 \pm 0.0005) \times 10^{-4}$$

4×10^{-4}

Marciano and Sirlin, PRL 71 (1993) 3629

$$\frac{\Gamma(\pi \rightarrow e \bar{\nu}(\gamma))}{\Gamma(\pi \rightarrow \mu \bar{\nu}(\gamma))}_{\text{EXP}} = (1.230 \pm 0.004) \times 10^{-4}$$

3.3×10^{-3}

PDG 2008

- Goal of PEN Experiment: 5×10^{-4}

Spectroscopy of hydrogenlike exotic atoms

r_p, R_∞, r_Z

2S-2P in μp

benchmark for lattice QCD
bound-state QED test in H
discrepancy: new physics??

$r_d (r_p, R_\infty)$

2S-2P in μd

benchmark for few-nucleon theories
check nuclear polarizability

$r_{^3He}$ and $r_{^4He}$ radii

2S-2P in $\mu^{3,4}He^+$

benchmark for few-nucleon theories
solving the discrepancy
enhanced bound-state QED test

$m_e/m_\mu, \alpha, R_\infty, r_Z$

1S-2S and HFS in $\mu^+ e^-$

best test of electron g-2
bound-state QED test
antigravity, q_{e^-}/q_{μ^+}
 μ -mass important in muonic g-2, G_F

SPS points and slopes

- SPS 1a: ``Typical " mSUGRA point with intermediate value of tan_beta.
- SPS 1b: ``Typical " mSUGRA point with relatively high tan_beta; tau-rich neutralino and chargino decays.
- SPS 2: ``Focus point " scenario in mSUGRA; relatively heavy squarks and sleptons, charginos and neutralinos are fairly light; the gluino is lighter than the squarks
- SPS 3: mSUGRA scenario with model line into ``co-annihilation region"; very small slepton-neutralino mass difference
- SPS 4: mSUGRA scenario with large tan_beta; the couplings of A, H to b quarks and taus as well as the coupling of the charged Higgs to top and bottom are significantly enhanced in this scenario, resulting in particular in large associated production cross sections for the heavy Higgs bosons
- SPS 5: mSUGRA scenario with relatively light scalar top quark; relatively low tan_beta
- SPS 6: mSUGRA-like scenario with non-unified gaugino masses
- SPS 7: GMSB scenario with stau NLSP
- SPS 8: GMSB scenario with neutralino NLSP
- SPS 9: AMSB scenario

Standard model lepton EDMs

Fourth order electroweak,

F. Hoogeveen:

The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322

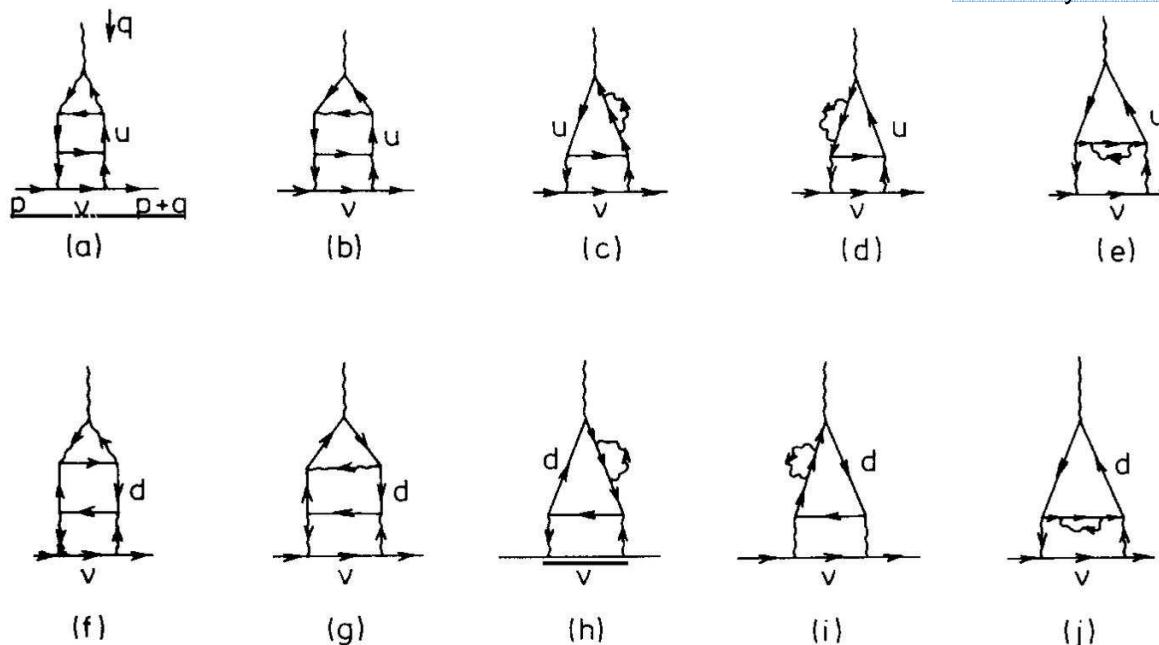


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

... + new physics?

Standard model lepton EDMs

Fourth order electroweak,

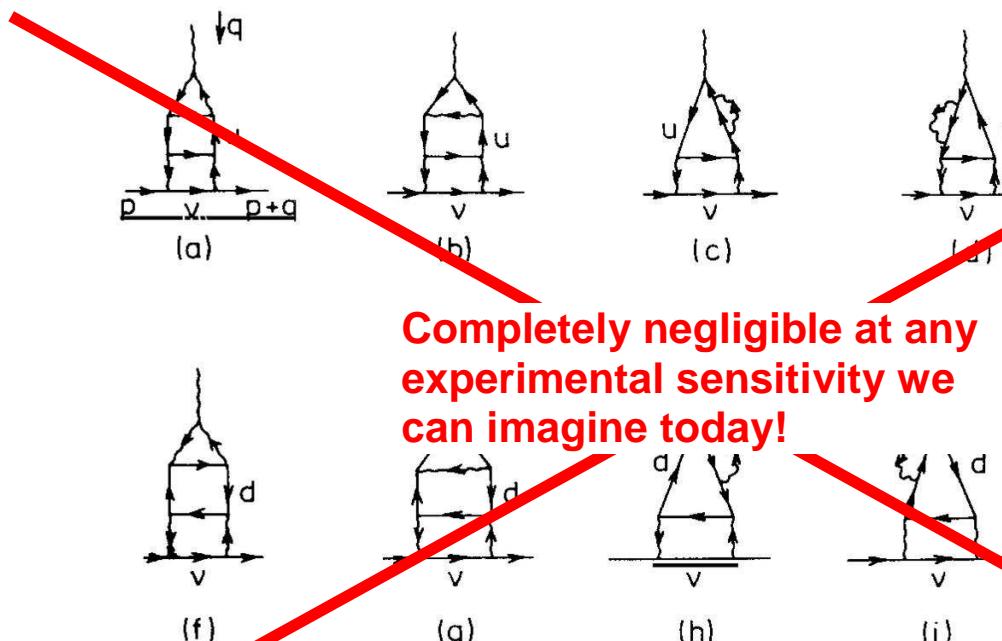


Fig. 1. The ten diagrams which contribute to the edm of the electron. The W-propagators.

F. Hoogeveen:

The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322

Expect from SM,
approximately:

$$d_e \leq 10^{-38} \text{ e}\cdot\text{cm}$$

$$d_\mu \leq 10^{-36} \text{ e}\cdot\text{cm}$$

$$d_\tau \leq 10^{-35} \text{ e}\cdot\text{cm}$$

Experimentally so far:

$$d_e < 2 \times 10^{-27} \text{ e}\cdot\text{cm}$$

$$d_\mu < 2 \times 10^{-19} \text{ e}\cdot\text{cm}$$

$$d_\tau < 3 \times 10^{-17} \text{ e}\cdot\text{cm}$$

... + new physics?

Much greater sensitivity to
new, CP-violating physics!

Muon spin precession in B and E field

$$\vec{\omega} = -\frac{e}{m} \left\{ a \vec{B} + \left(\frac{1}{1 - \gamma^2} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\}$$

The equation is shown with red lines crossing through the terms involving \vec{B} and \vec{E} . Below the equation, a green bracket underlines the term $a \vec{B}$, which is then labeled $\vec{\omega}_a$. A blue bracket underlines the term $\frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right)$, which is then labeled $\vec{\omega}_e$.

New method for EDM measurement: the “frozen spin” technique!

- Go to lower momentum, install a “**magic E field**” (radially), such that $\vec{\omega}_a$ vanishes completely:

$$E \approx a B c \beta \gamma^2$$

- The spin remains parallel to the momentum along the orbit (“frozen spin”)
- In the presence of an EDM ($\eta \neq 0$) the spin is slowly rotated out of the orbital plane.
- Much superior sensitivity** than with parasitic approach!

$$\vec{\omega} = -\frac{e}{m} \frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right)$$

F. Farley et al.:
New Method of Measuring Electric Dipole Moments in Storage Rings,
 Phys. Rev. Lett. 93 (2004) 052001