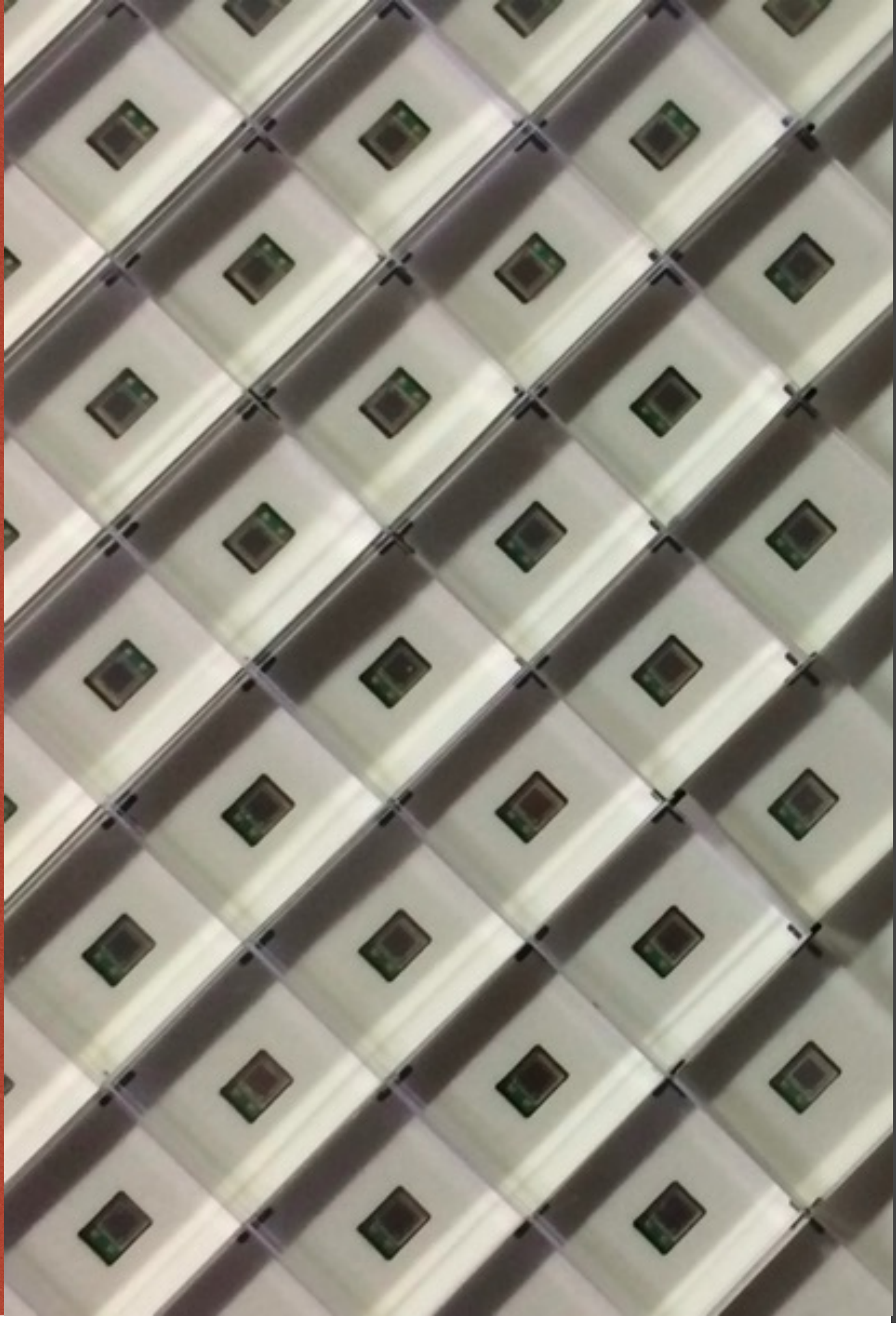
Precision physics with muon and muonic systems



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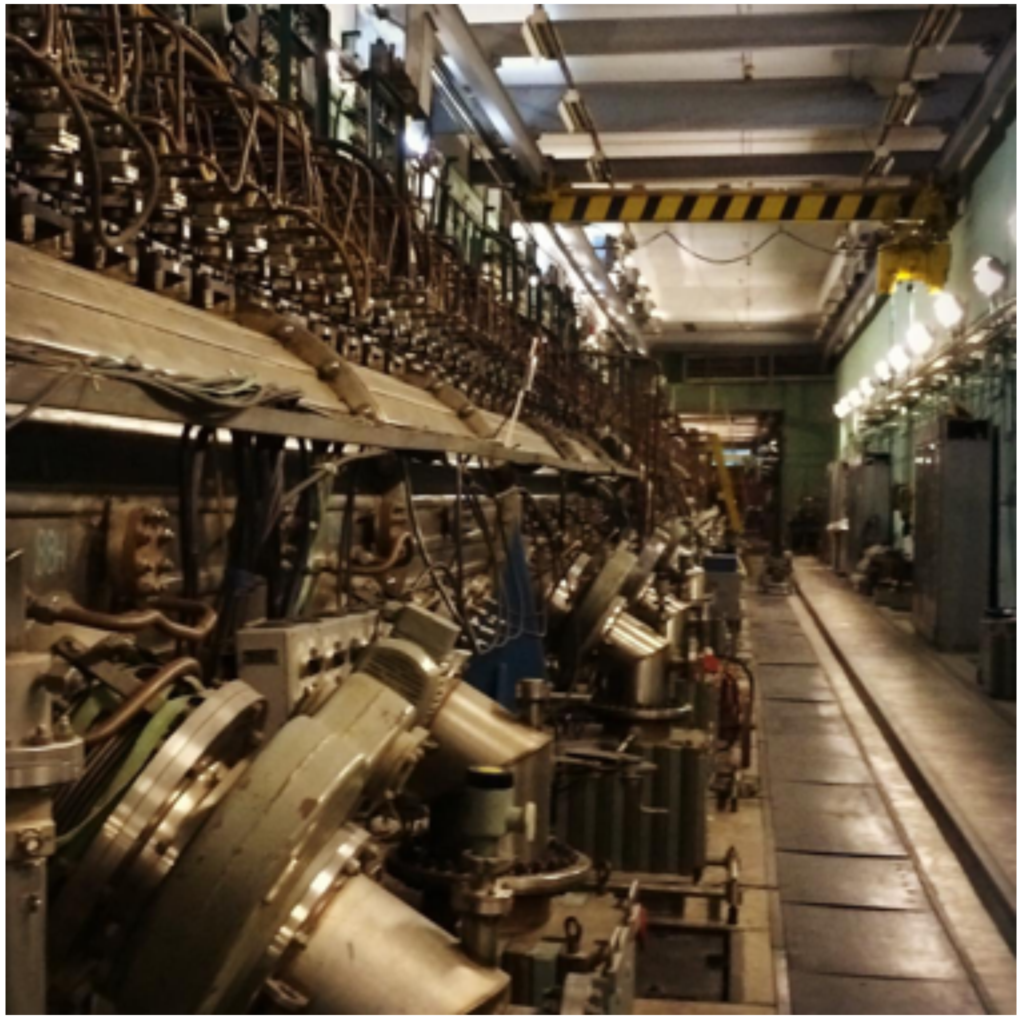
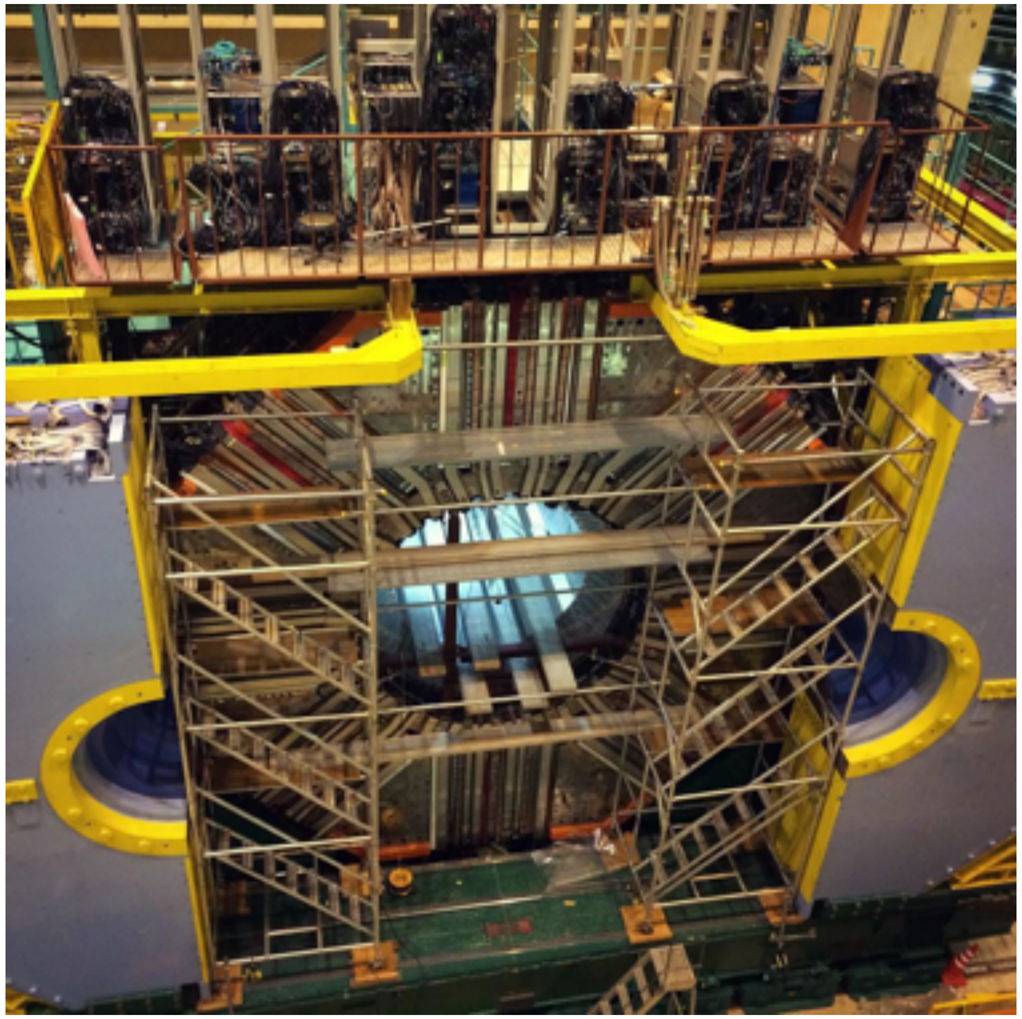
2017/05/18

High Energy Physics

- 高エネルギー物理学とは
  - 粒子を高いエネルギーに加速して
  - 物質との相互作用を調べること
    - 誰も見たことがないものを調べたい



LINAC at Troitsk, Moscow



Belle detector at KEK, Tsukuba

Frontiers of the Physics

- 誰も見たことのないものとは
  - 未知の物質・相互作用・現象・構造
- 前人未到の領域に到達するためには極端な環境が必要
  - キーワードは強いビーム

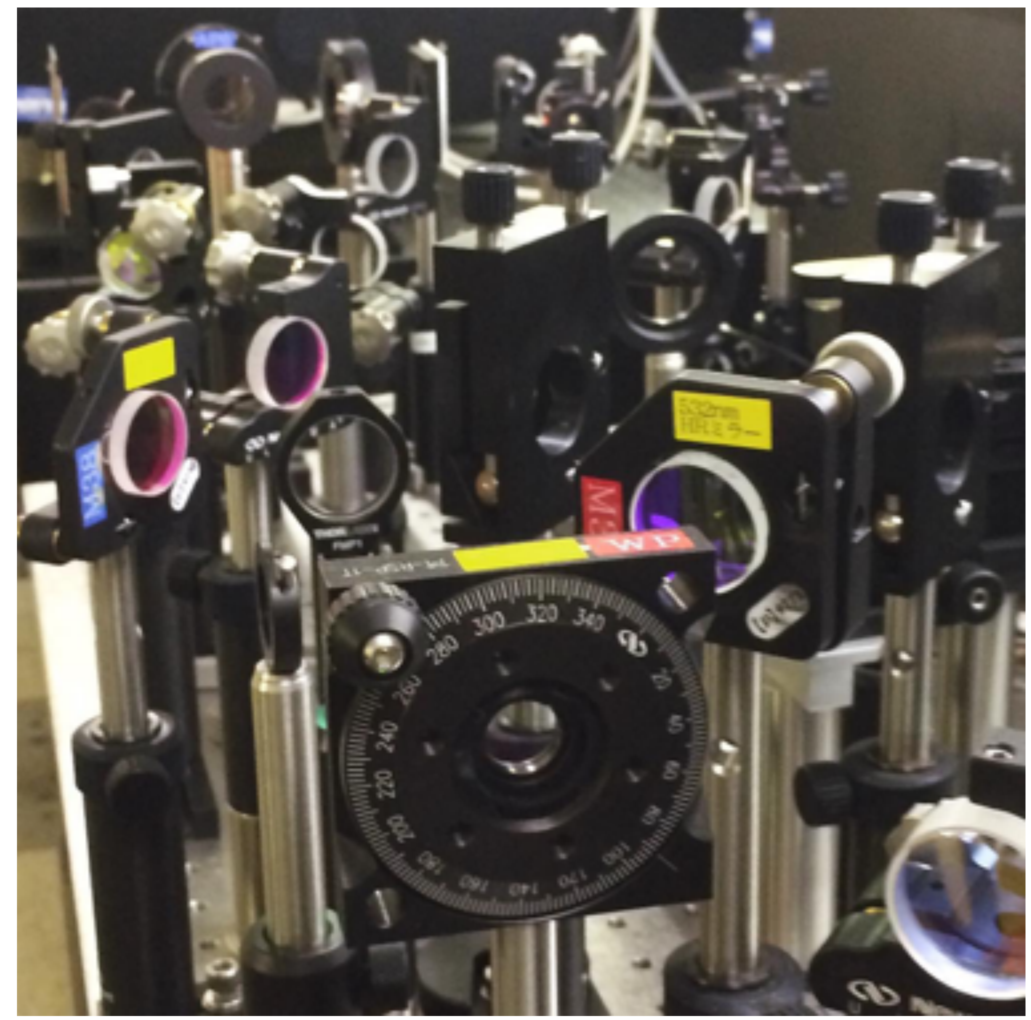
PHENIX at BNL, New York
高いエネルギーでの粒子衝突

Super KEKB, Tsukuba
高い頻度での粒子衝突

Tools for Extreme Experiments

- 粒子ビーム以外の重要な構成要素
  - 強い磁場 (超伝導電磁石)
  - 強い光 (レーザー)

Superconducting magnet
at J-PARC, Tokai



Laser optics
at RAL, Oxford

Particle Beams for Physics

- 目的に応じて様々な粒子ビームがある
  - 電子・陽電子
  - 陽子・反陽子
  - π中間子・K中間子
  - ミューオン・中性子
  - 各種イオン
- ビームの性質
  - エネルギー
  - 強度
  - 時間構造
  - スピン
  - 電荷

Superconducting Ring Cyclotron at RIBF, RIKEN, Wako

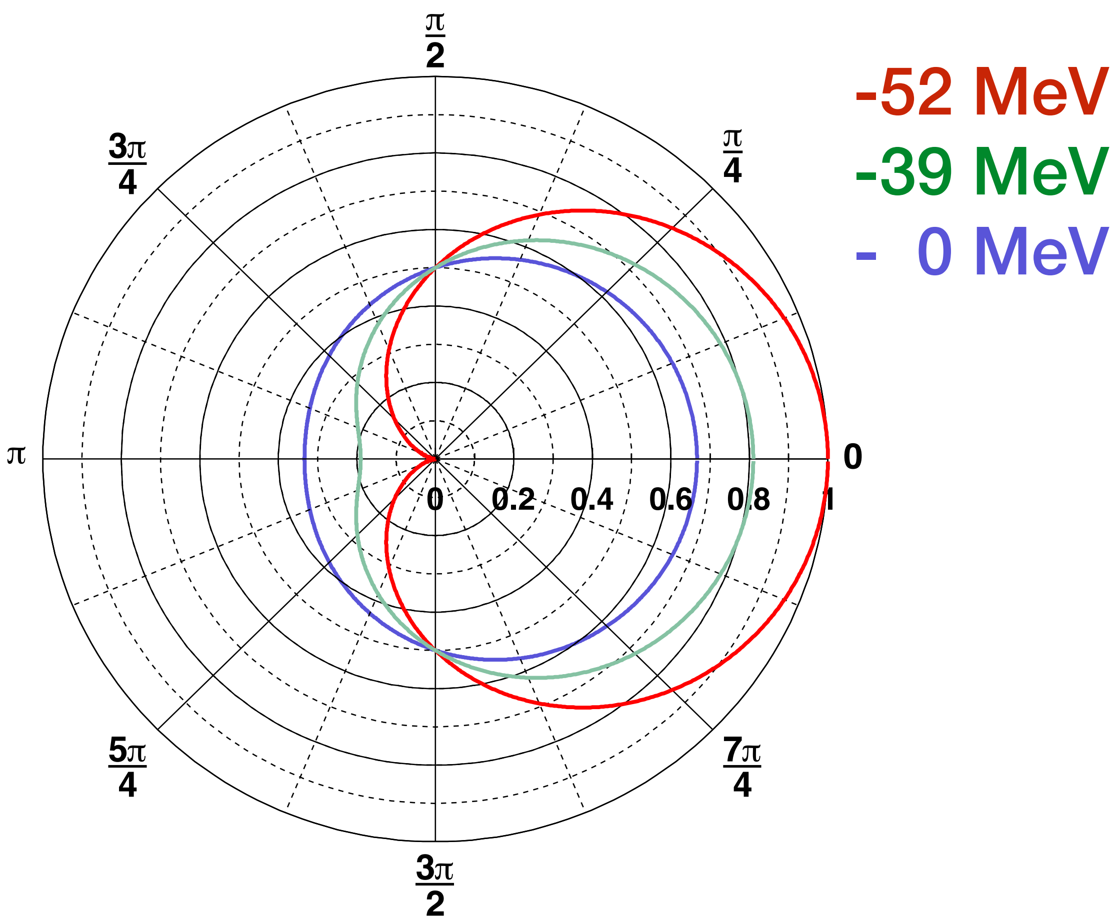
Particle Beams for Physics

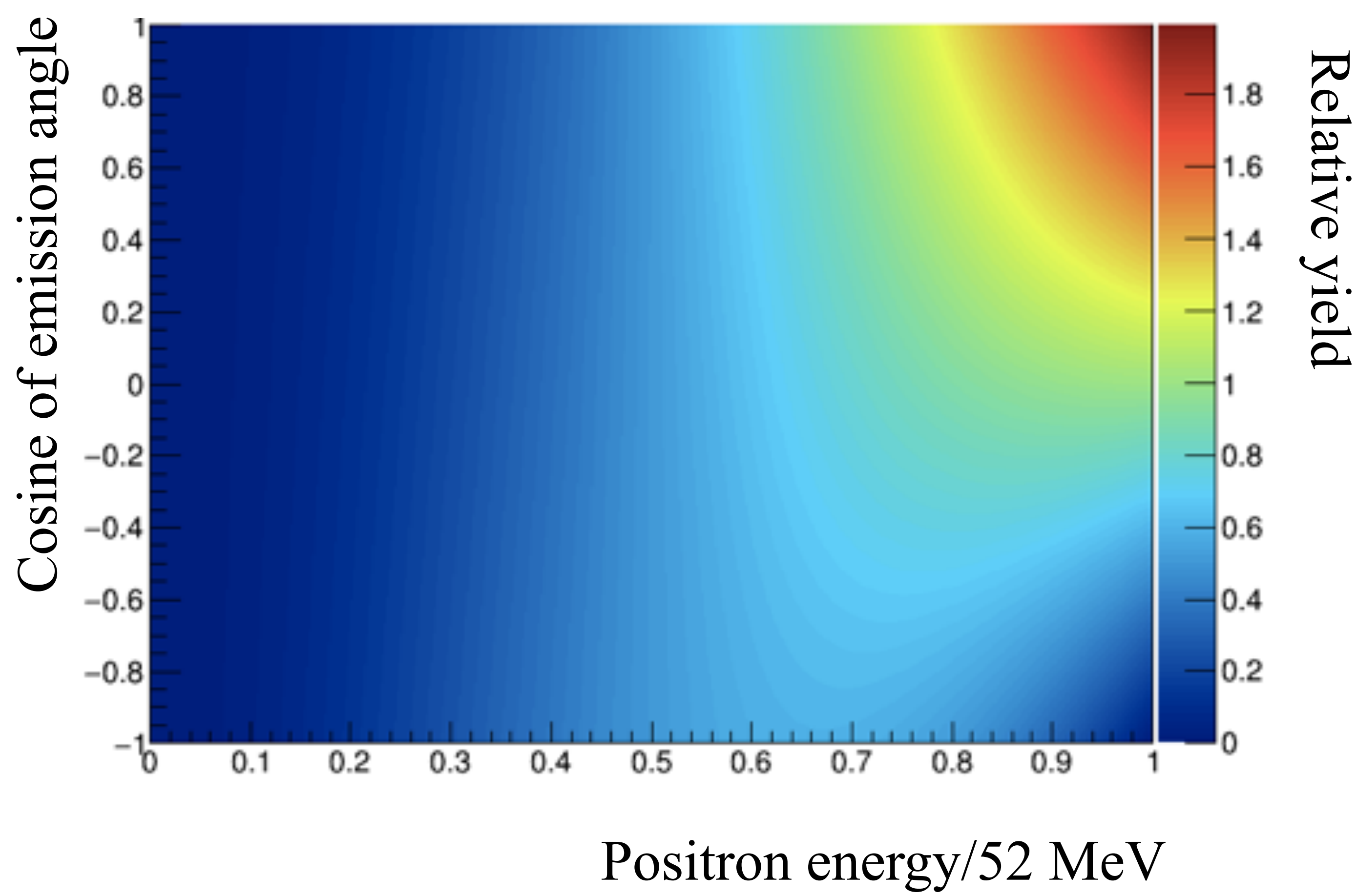
- 粒子ビームは多彩な用途で使われている

ビーム	物性	素核
放射光	物質の結晶, 磁気, 電子構造	真空の構造 ハドロン光生成
陽電子	物質の表面構造 多孔質の構造	ポジトロニウム分光 反水素原子生成
中性子	材料中の原子位置 物質中のスピン, 原子, 分子の運動	中性子寿命 中性子EDM
ミュオン	物質中の局所磁場 材料中の元素組成	ミュオン寿命, 磁気能率 ミュオニウム分光

Muon

- 第二世代の荷電レプトン (正負の電荷を持つ, 構造を持たない)
- 質量106 MeV (電子の200倍, 陽子の1/9), 寿命2.2 μs
- 弱い相互作用で(陽)電子とニュートリノに崩壊
- 崩壊(陽)電子はミュオンの磁気モーメントと並行に出やすい





ミューオン崩壊で生じる陽電子の角度異方性

Discovery of Muon

Note on the Nature of Cosmic-Ray Particles

Seth H. Neddermeyer and Carl D. Anderson
Phys. Rev. **51**, 884 – Published 15 May 1937

New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron

J. C. Street and E. C. Stevenson
Phys. Rev. **52**, 1003 – Published 1 November 1937

Particle tracks (energy and energy deposit) were measured by using a cloud chamber

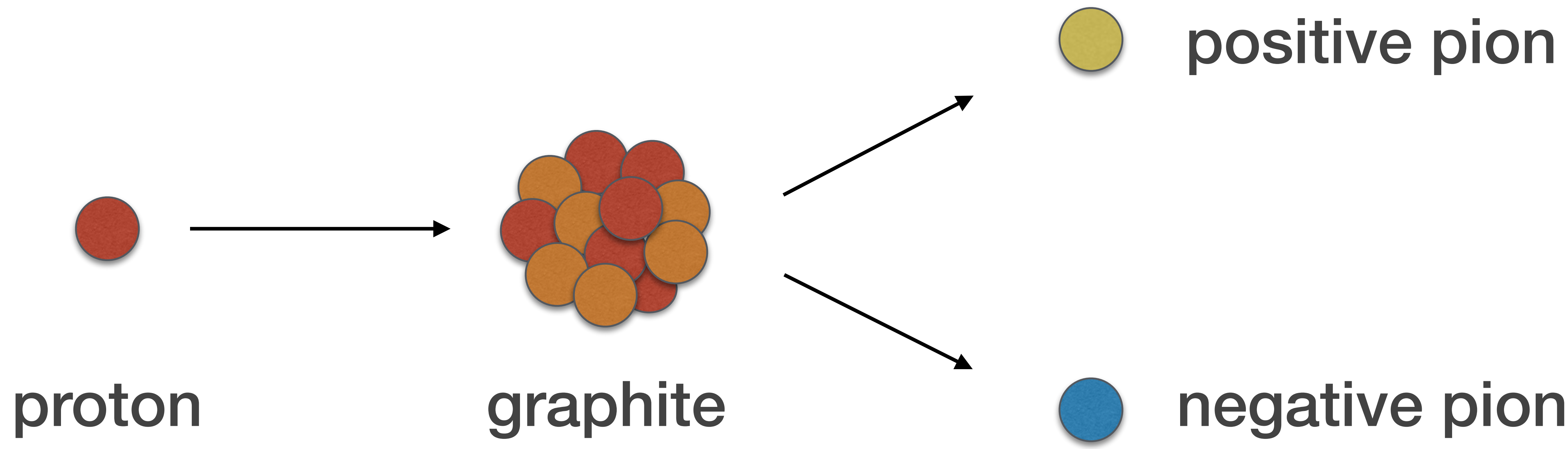
Incident particles trigger an ionization in supersaturated water

Anderson with a cloud chamber

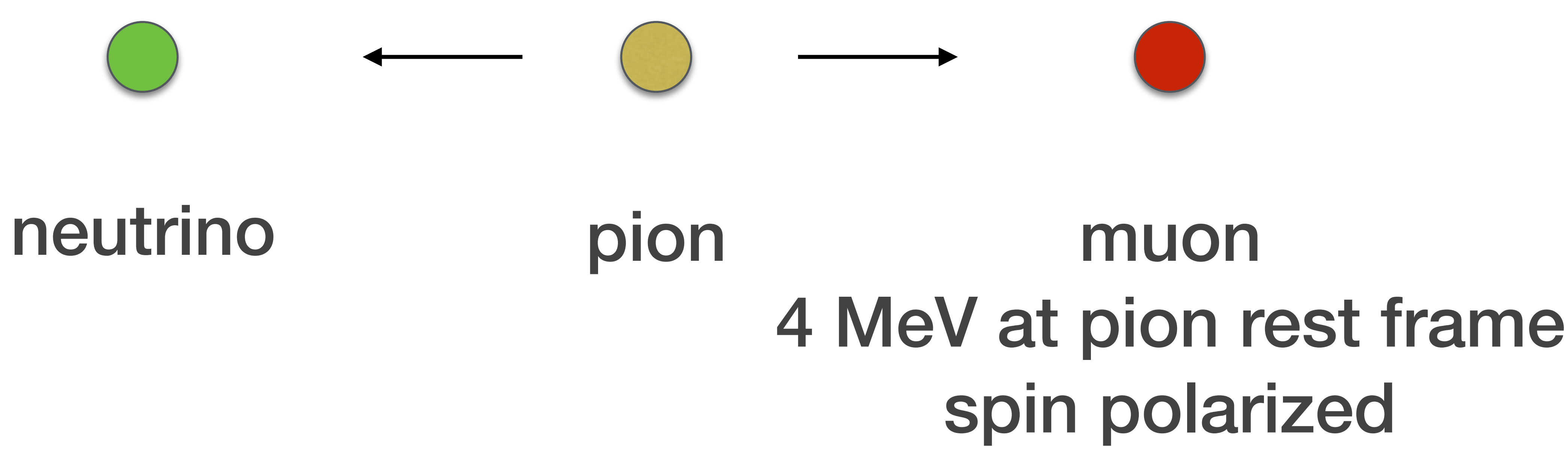
Muon track measured by Street and Stevenson

Muon Production

- **Proton driver**

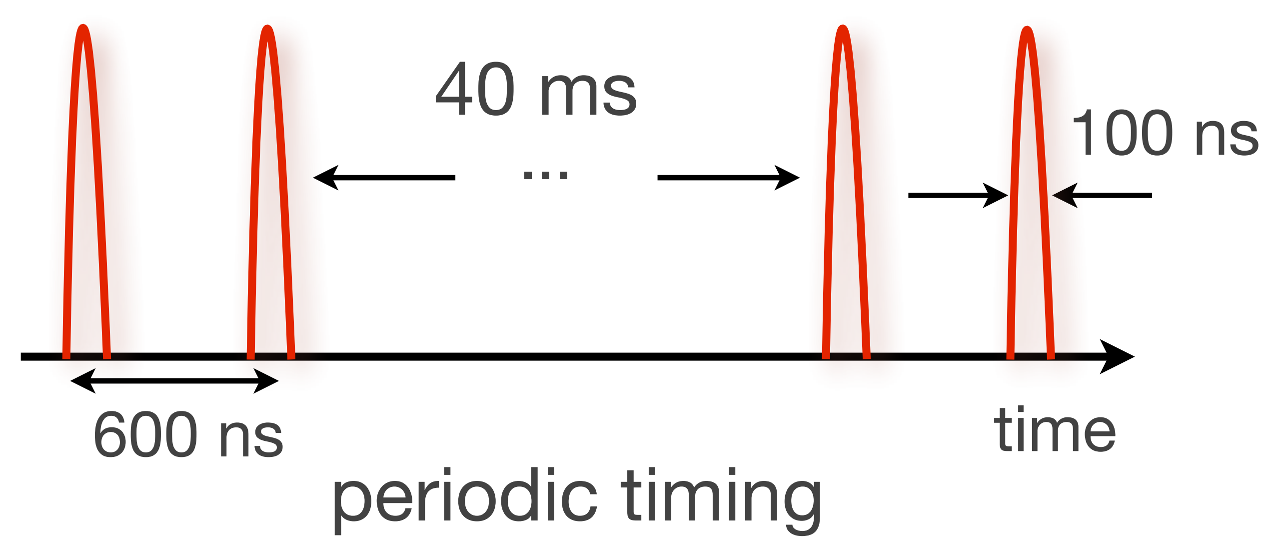


- **Parity violating pion decay**

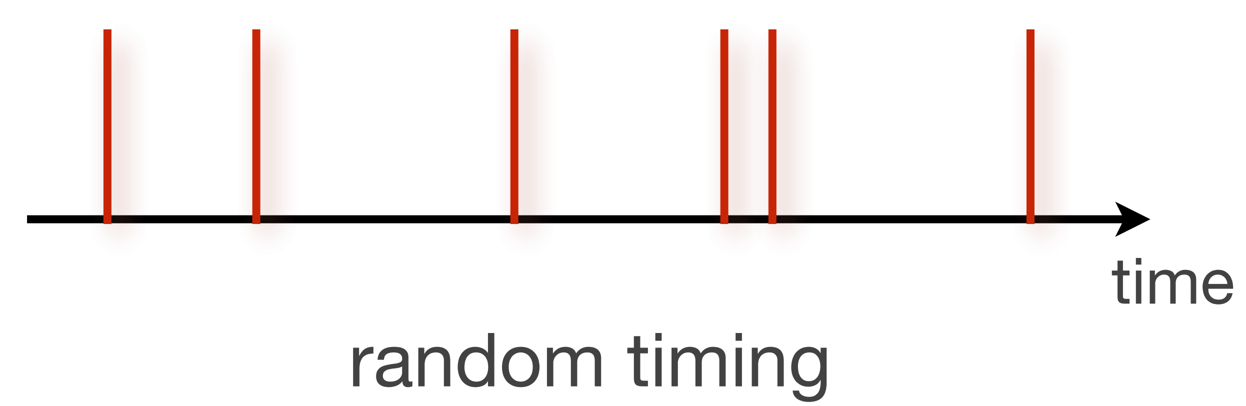


Muon Beam Timing Structure

- **Pulsed beam : J-PARC, RAL**
  - Higher event rate
  - Higher S/N
  - Limited timing resolution
  - Pulse synchronized trigger
  - Ensemble average

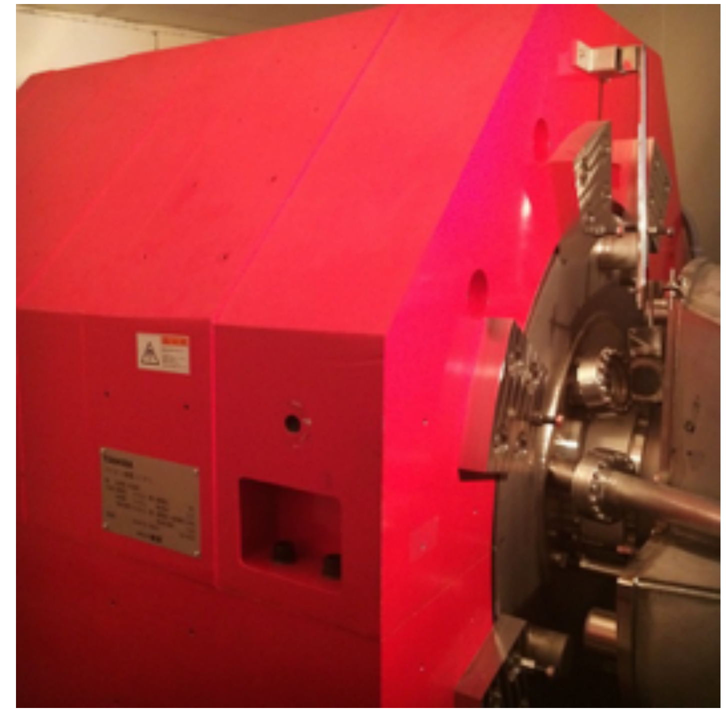


- **Continuous (DC) beam : PSI, TRIUMF, MuSIC**
  - Less event rate
  - Less S/N
  - High timing resolution
  - Necessity of trigger counter
  - Event-by-event analysis



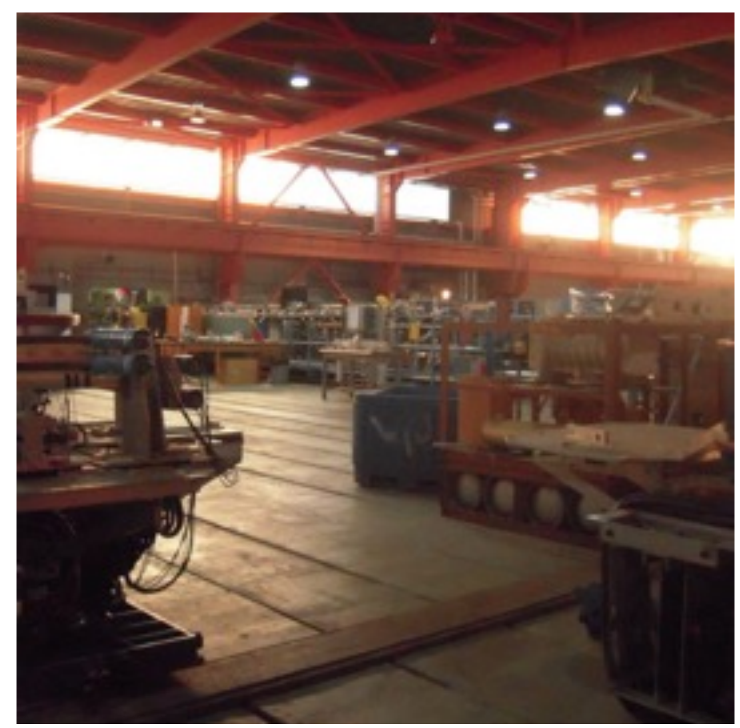
Muon Beam Faciities

J-PARC MLF
MUSE
Pulse
最高強度



RCNP
MuSIC
DC
最高効率

RAL
Pulse
理研



TRIUMF
DC
歴史と伝統

他にもPSI, FNAL, SPSなどがある

Muon Physics

- **Measured muon properties**

	Method	Beam	Precision	Stat.	Syst.	Ref.
Mass	Muonium HFS spectroscopy	DC (Chopped)	120 ppb	117 ppb	38 ppb	Liu 1999
Mean lifetime	Decay positron counting	DC (Accumulated)	1 ppm	0.96 ppm	0.32 ppm	Tishchenko 2013
g-2	Decay positron tracking in storage ring	Pulse	540 ppb	463 ppb	283 ppb	Bennet 2007

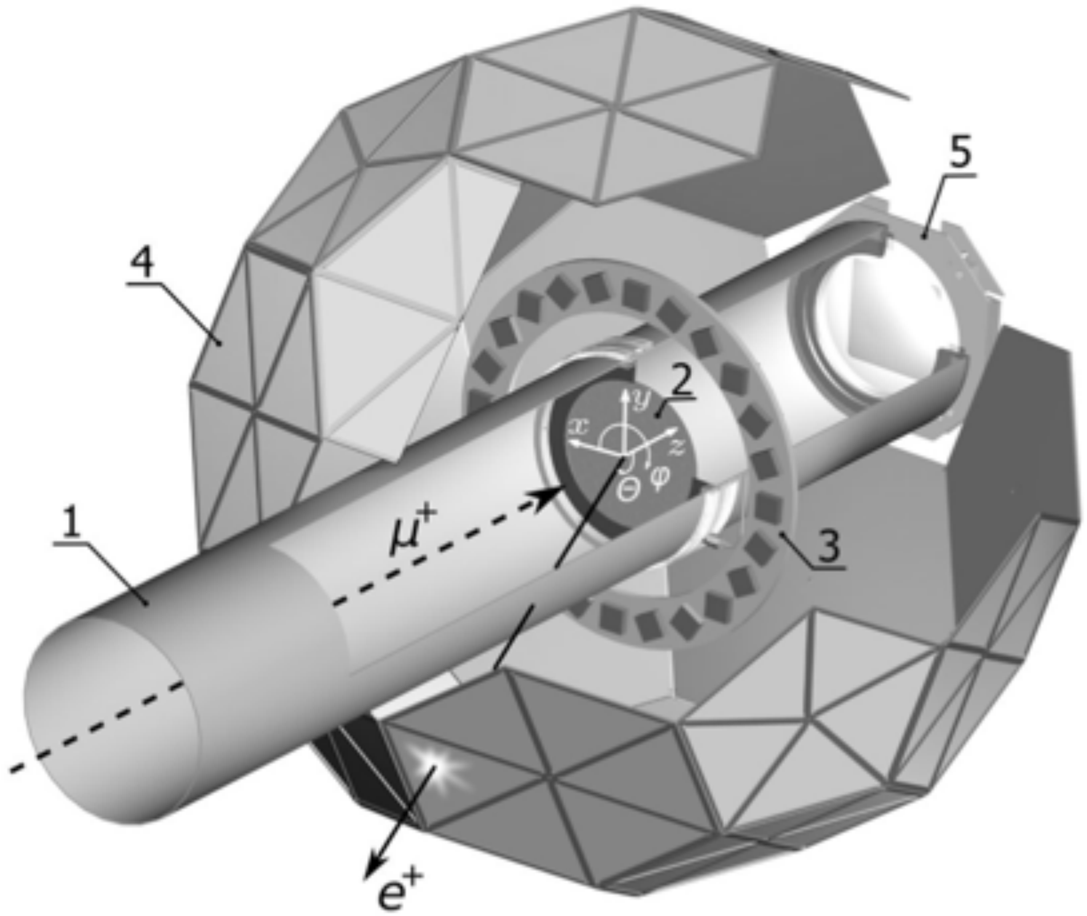
Muon Physics

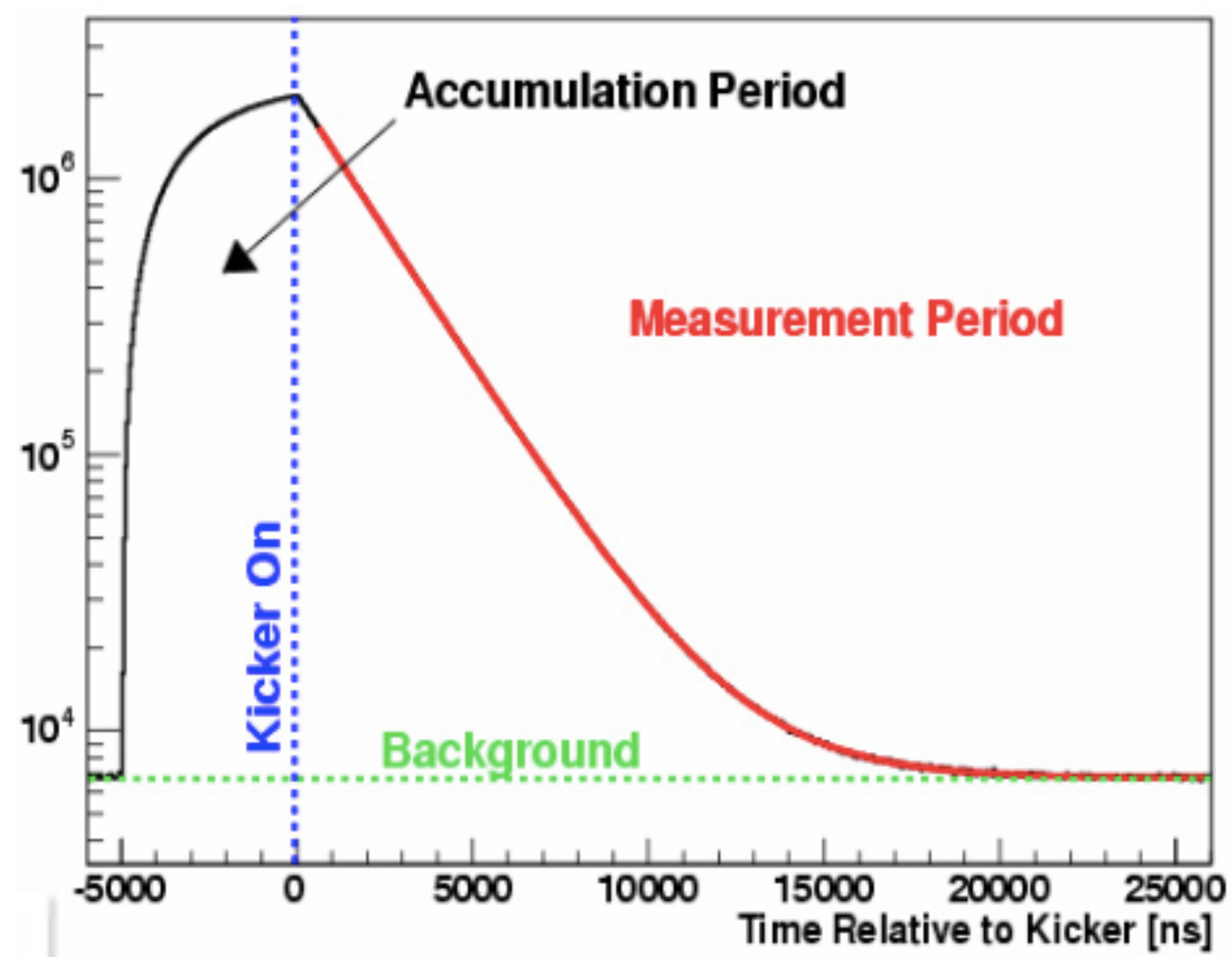
- **Muon as a probe for new physics search**

	Method	Beam	Limit	Exp.
$\mu^+ \to e^+ \gamma$	52.8 MeV e^+ and γ back to back	DC	$Br<4.2\times10^{-13}$	PSI MEG 2016
$\mu^- N \to e^- N$	105 MeV e^-	DC	$Br<7\times10^{-13}$	PSI SINDRUM-II
$\mu \to eee$	e^- tracking	DC	$Br<1.0\times10^{-12}$	PSI SINDRUM-I
g-2	μ^+ in storage ring	Pulse	Δa_μ(Exp.-Th.)=289(80)$\times10^{-11}$	BNL E821 2006
EDM	μ^+ in storage ring	Pulse	$d_\mu<1.9\times10^{-19}$ e cm	BNL E821 2009
Lorentz Violation	$\mu^+ e^-$ spectroscopy	DC	2×10^{-23} GeV	LAMPF 1999
$\mu^+ e^-$ - $\mu^- e^+$ conversion	$e^+ e^-$ annihilation	DC	$P<8.3\times10^{-11}$	PSI 1999

Muon Lifetime

- MuLAN Experiment at PSI
- V. Tishchenko et al., PRD87, 052003 (2013).

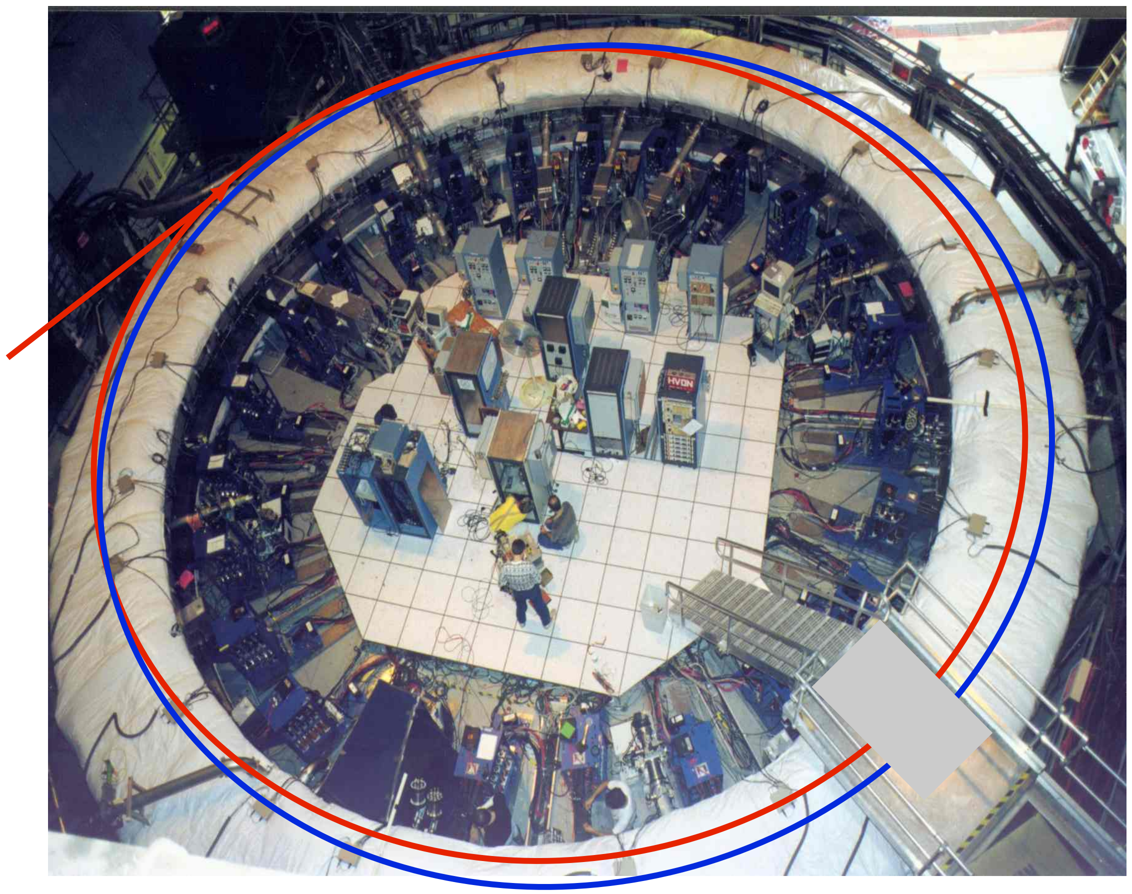


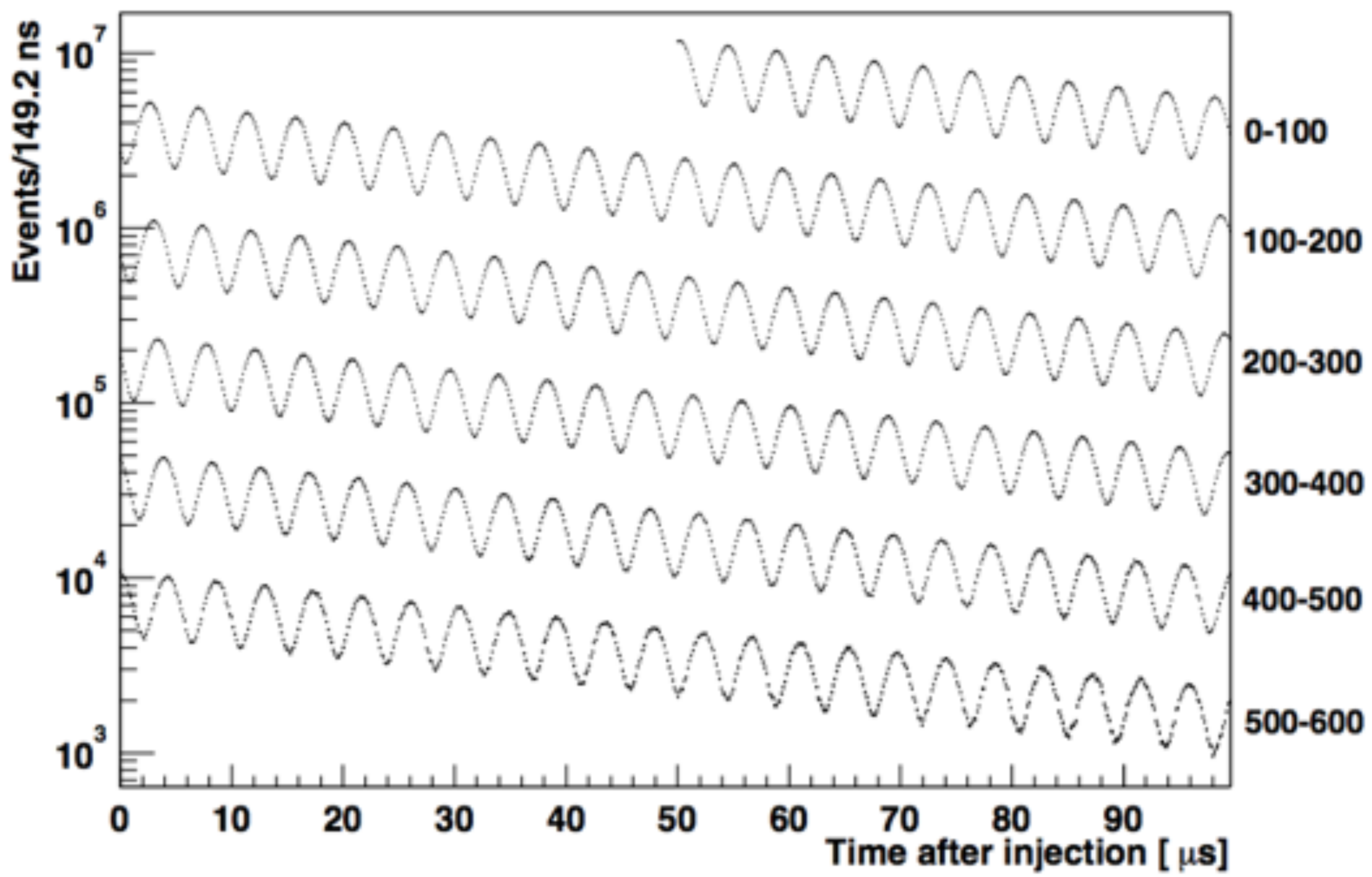


- 連続ビームを5 μsの間，標的に当て続ける
- ミューオンを標的に溜めてからビームを遮断
- 崩壊陽電子の時間分布を測定してミューオンの寿命を決定する

Muon magnetic moment

- E821 Experiment at BNL
- G.W. Bennet et al., PRD 80, 052008 (2009).

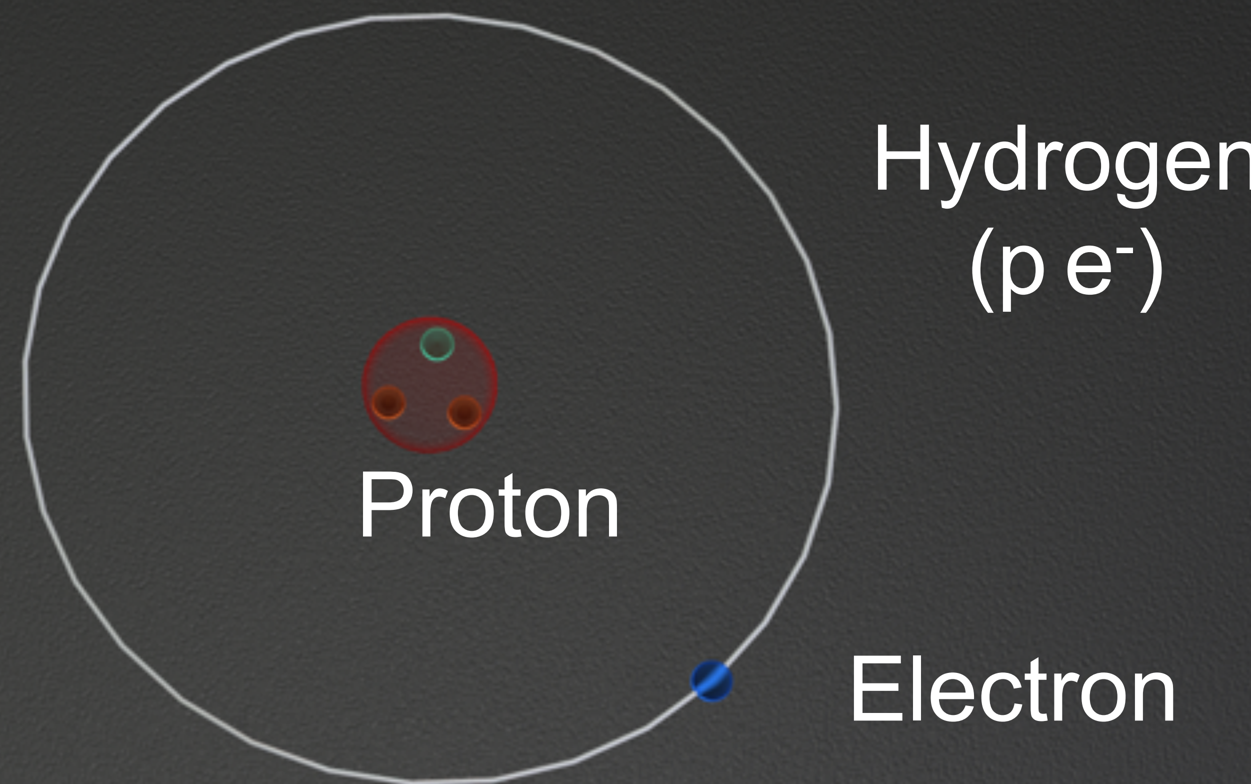


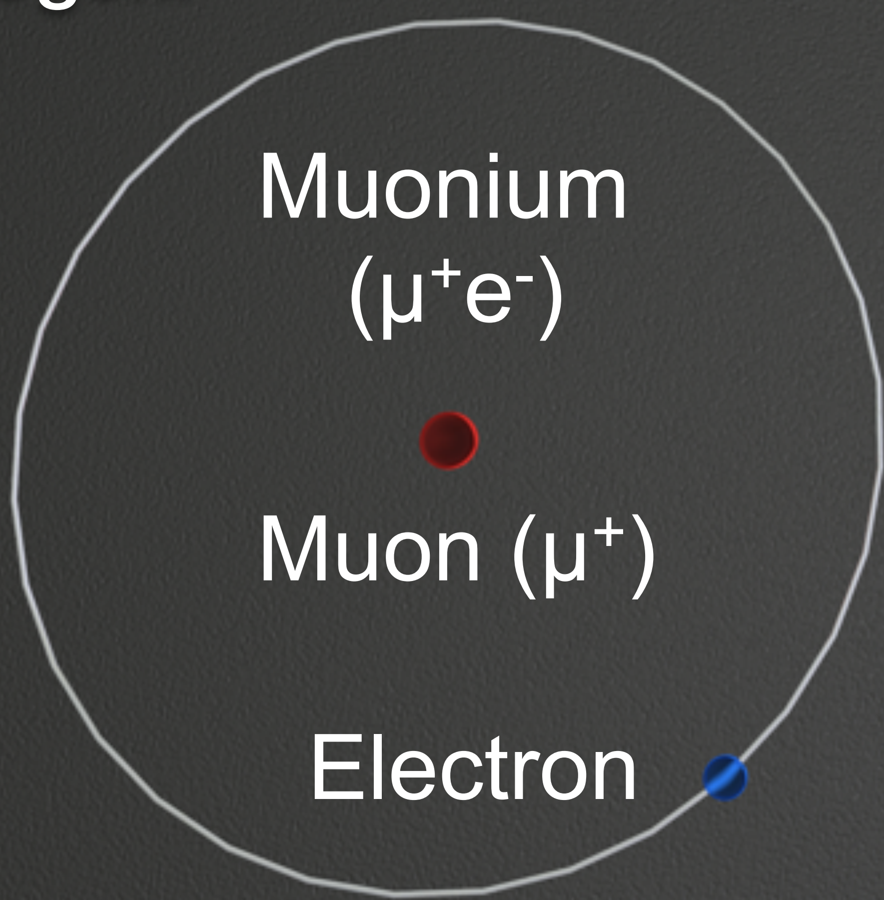


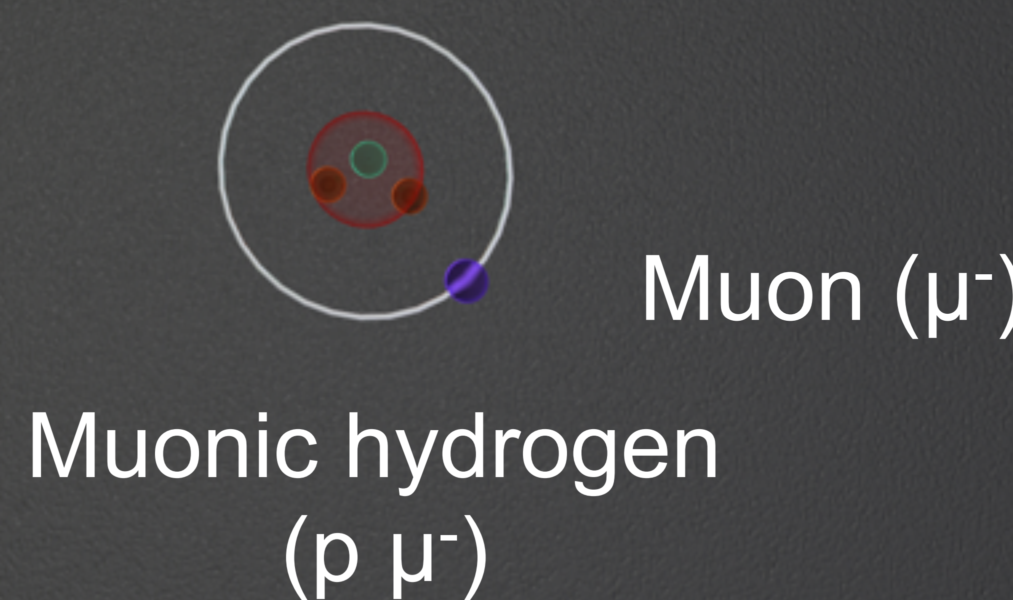
- パルスビームを直径14 mのリング中に入射して周回させる
- リング内の磁場を受けてミューオンのスピンが回転する
- スピンの回転周期を求めてミューオンの異常磁気能率を決定する

Muonic Systems

Muon is the 2nd generation particle of charged leptons. It is 200 times heavier than electron and decays in 2.2 μs of the mean lifetime. Muon forms a bound-state as well as hydrogen.

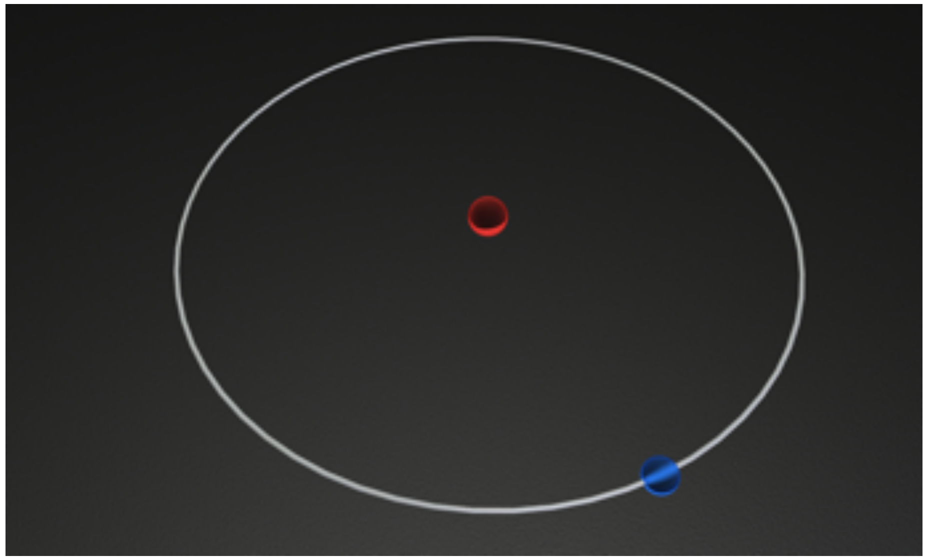






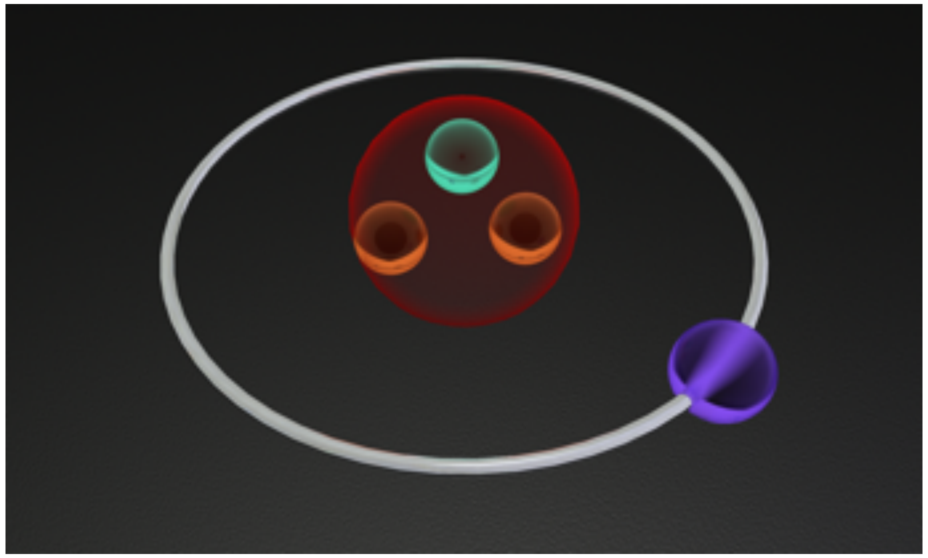
Muonium and Muonic Hydrogen

- **Muonium: consisting a positive muon and an electron**



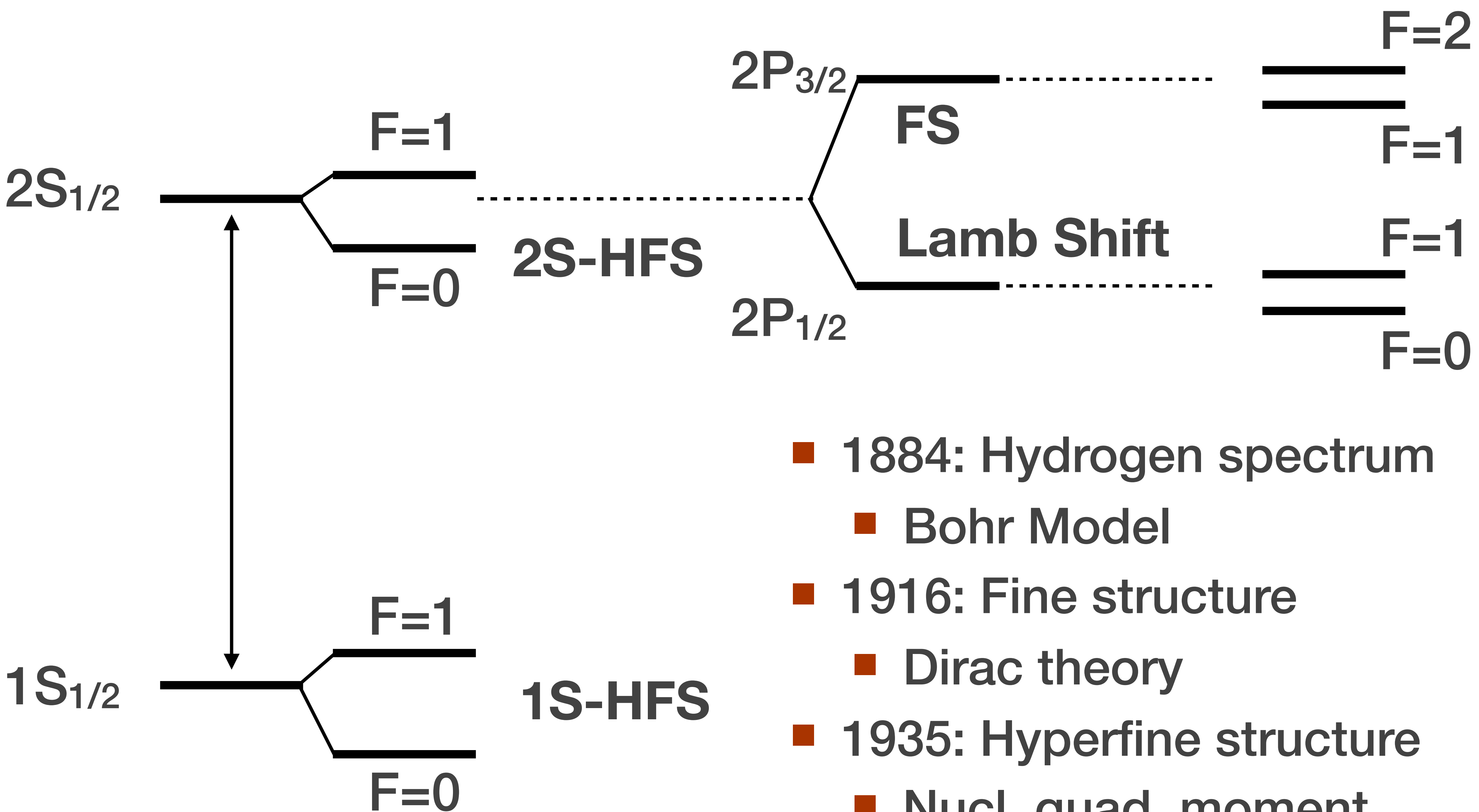
- Leptonic two-body system
- Bound state QED validation
- Muon mass measurement
- Lorentz violation search
- J-PARCで実験中

- **Muonic hydrogen: consisting a negative muon and a proton**



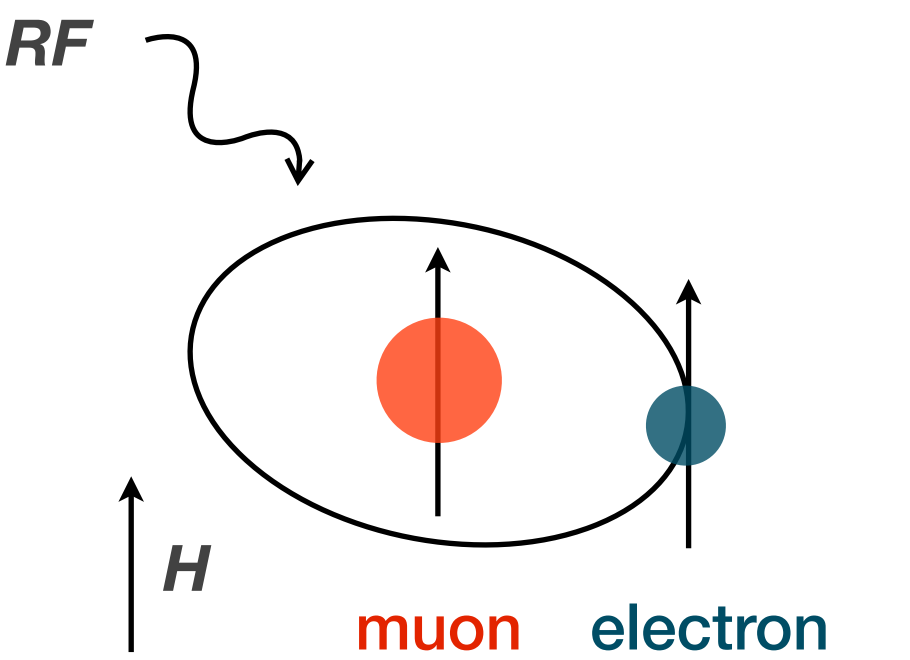
- Small Bohr radius (1/200 of H)
- Sensitive to the proton structure
- Proton radius measurement
  - “Proton radius puzzle”
- 理研RALで実験準備中

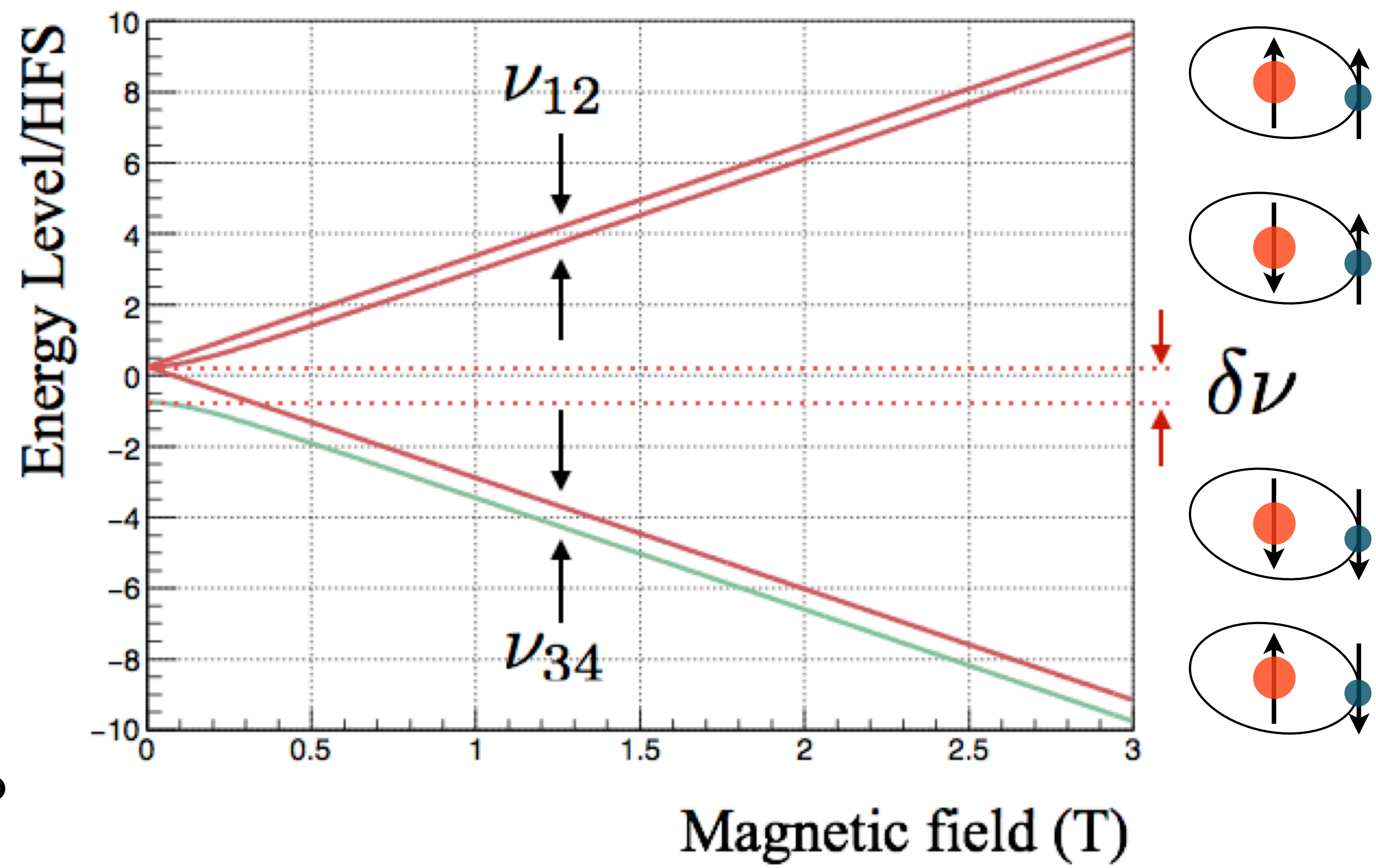
Hydrogen Atom Spectroscopy



- 1884: Hydrogen spectrum
  - Bohr Model
- 1916: Fine structure
  - Dirac theory
- 1935: Hyperfine structure
  - Nucl. quad. moment
- 1947: Lamb shift
  - QED

Muonium Energy Levels





$$\nu_{12} + \nu_{34} = \delta_\nu$$

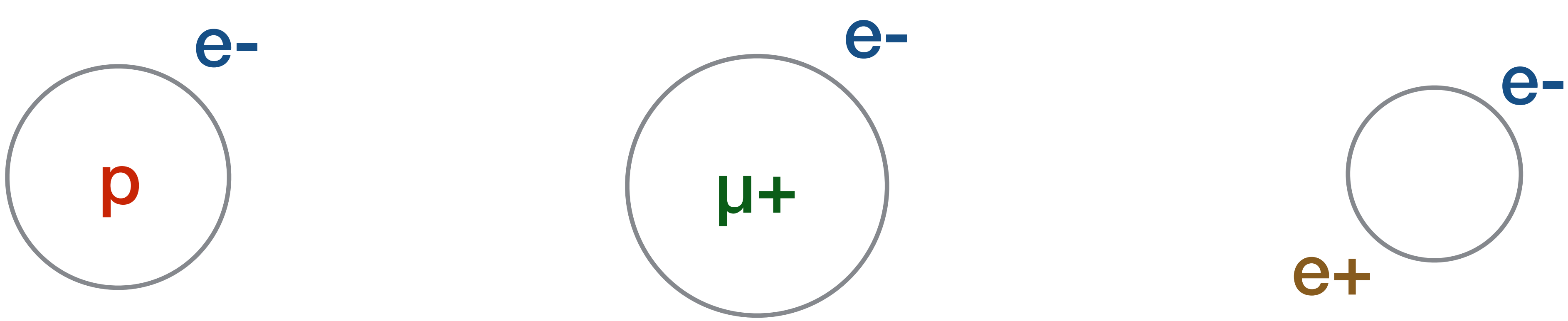
$$\nu_{12} - \nu_{34} \propto \mu_\mu / \mu_\mathrm{p}$$

or $\delta_\nu = (\frac{16}{3}\alpha^2 R_\infty c g_e g'_\mu)(1 + m_e/m_\mu)^{-3}(1 + \delta_\mathrm{QED})$

- ゼロ磁場における直接測定と高磁場における間接測定が可能
- ゼロ磁場では4463.3 MHzの三重項⇄一重項の遷移を直接測定

Hydrogen-like atoms HFS

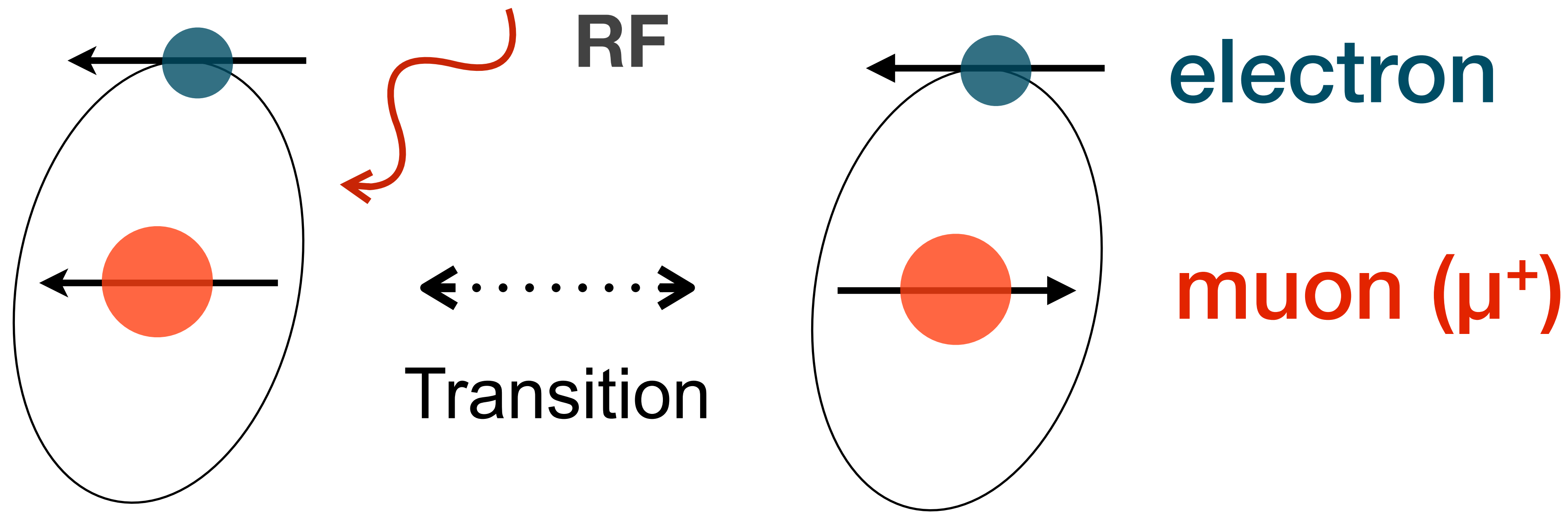
水素原子 (H)　ミュオニウム (Mu)　ポジトロニウム (Ps)



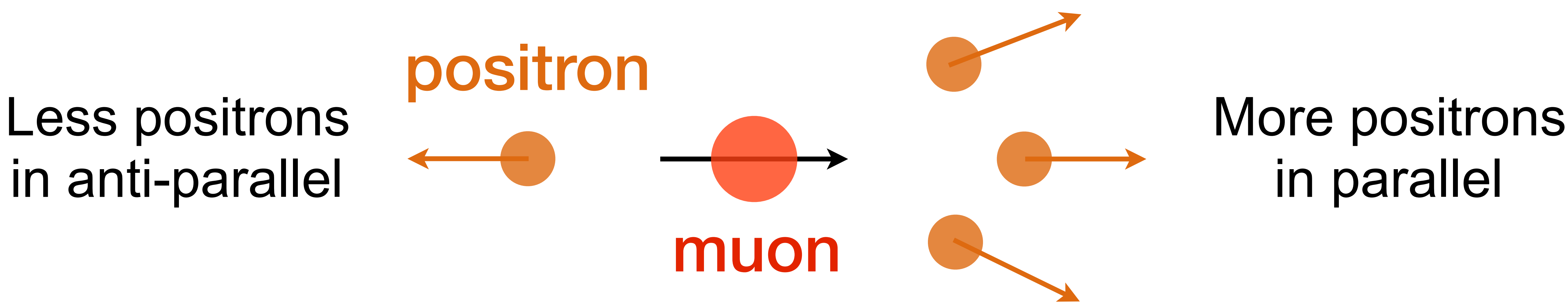
原子	HFS測定精度	HFS理論計算精度
H	0.2 ppt	1.2 ppm
Mu	**300 ppb (直接測定)** **12 ppb (間接測定)**	**63 ppb**
Ps	10 ppm	1.2 ppm

Principle of Spectroscopy

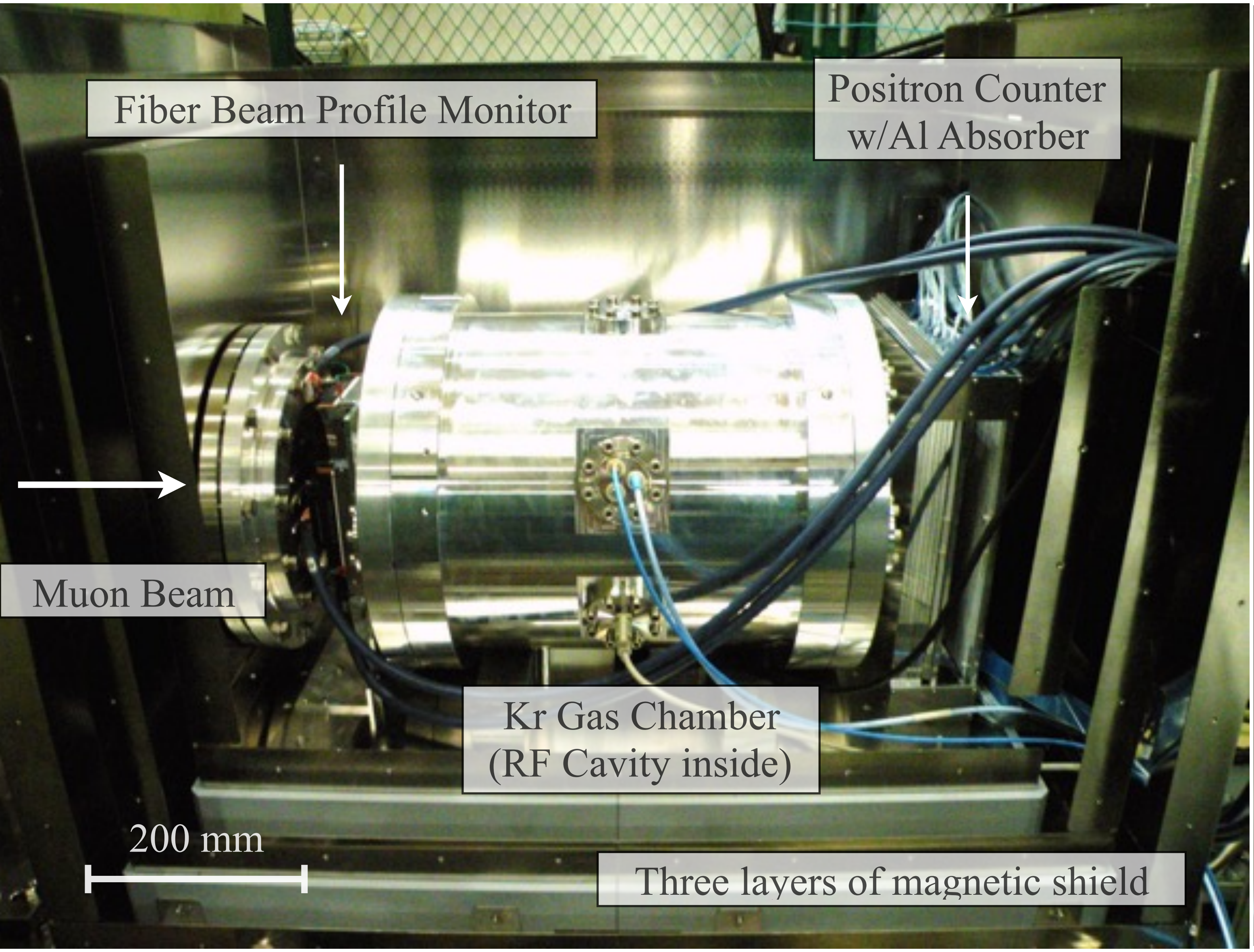
- Muonium HFS transition is induced by a microwave magnetic field

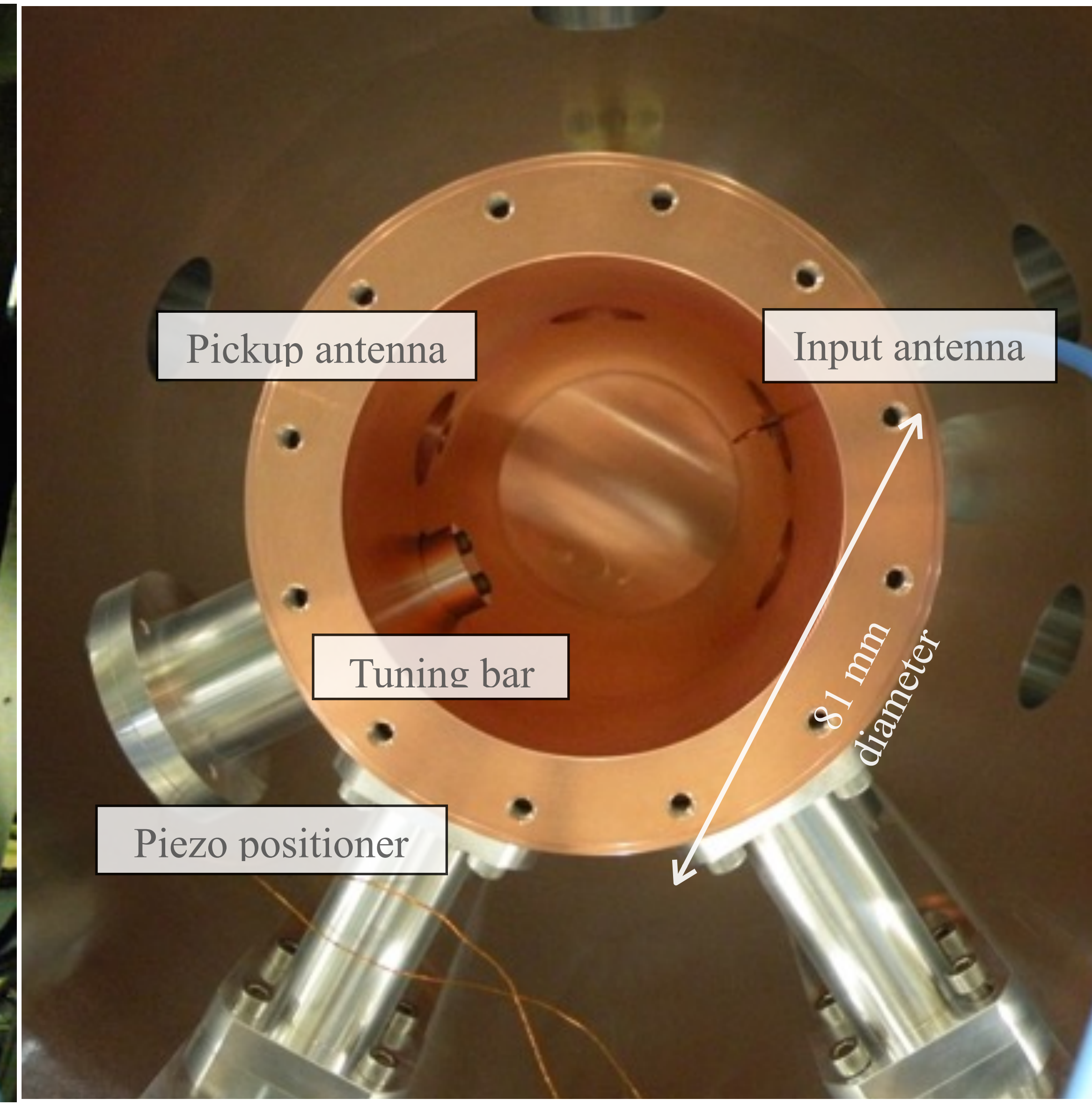


- The emission angle of decay positron is correlated to the muon spin



Muonium Spectroscopy

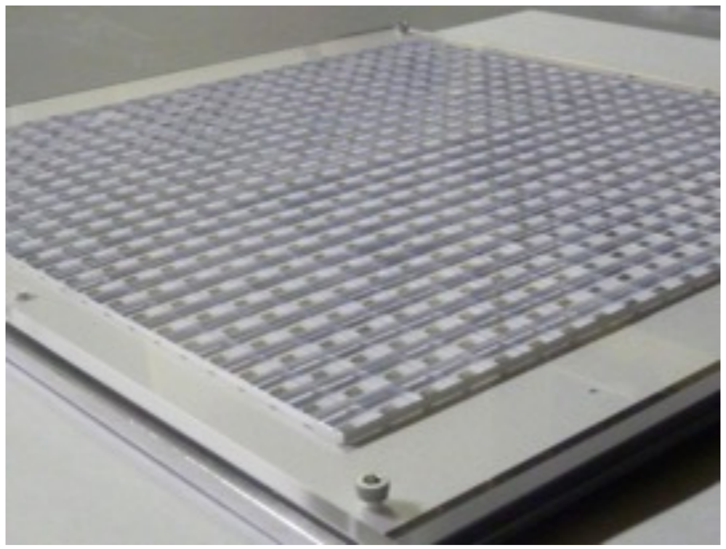




The fiber beam profile monitor and the positron detector were placed at front and behind of the gas chamber, respectively. The gas chamber was filled with Kr gas at 1.0 atm of the pressure. The entire setup was enclosed by the three-layers of permalloy magnetic shield.

Key technologies

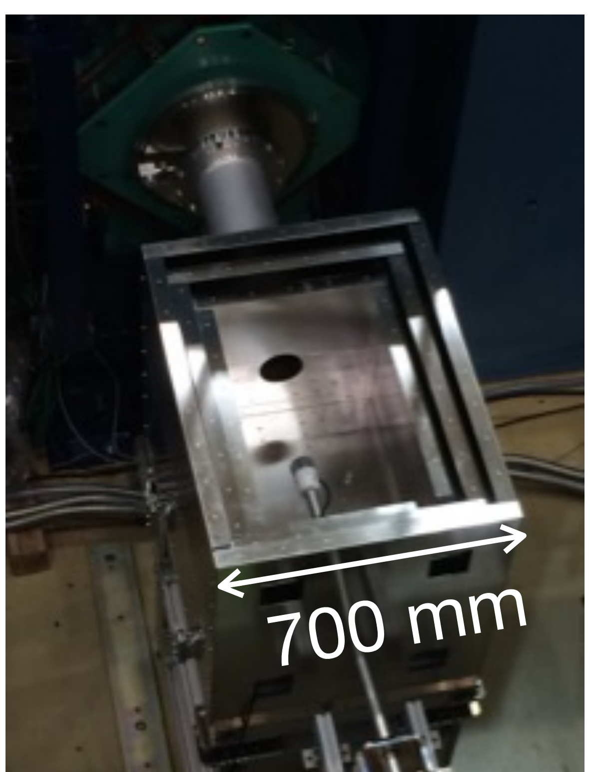
- **High-rate capable positron detector**

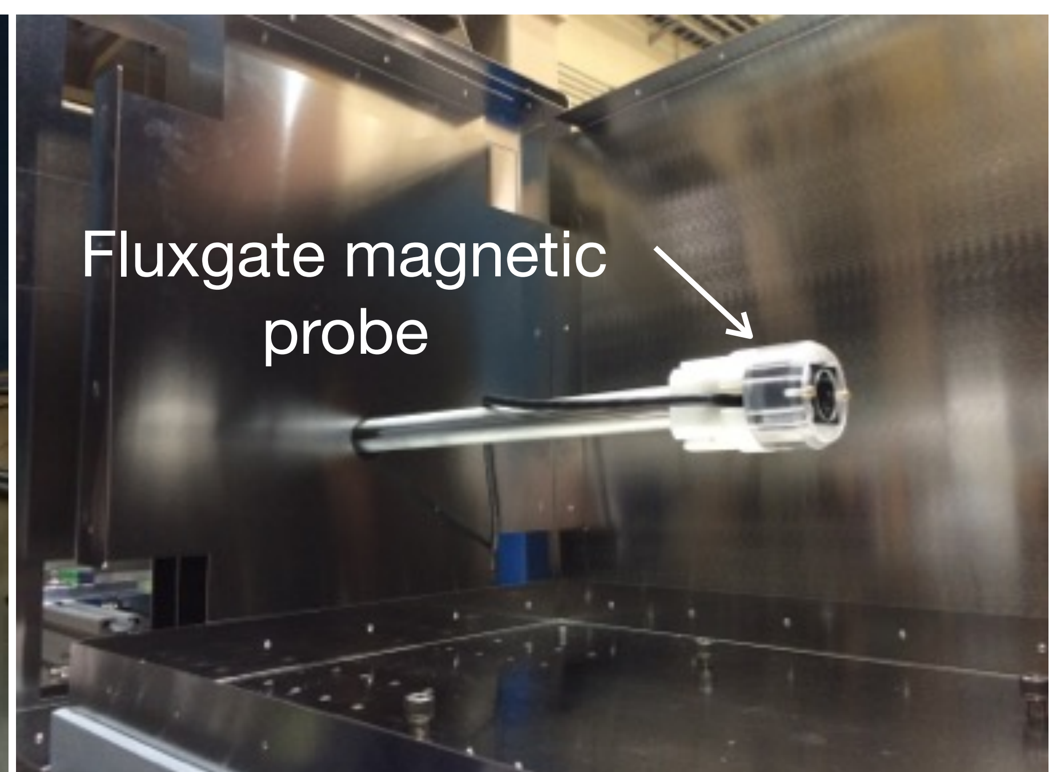


Fast front-end electronics with ASIC and FPGA

Segmented scintillation counter with SiPM readout ($1cm^2$ x576_{ch} x2_{layer})

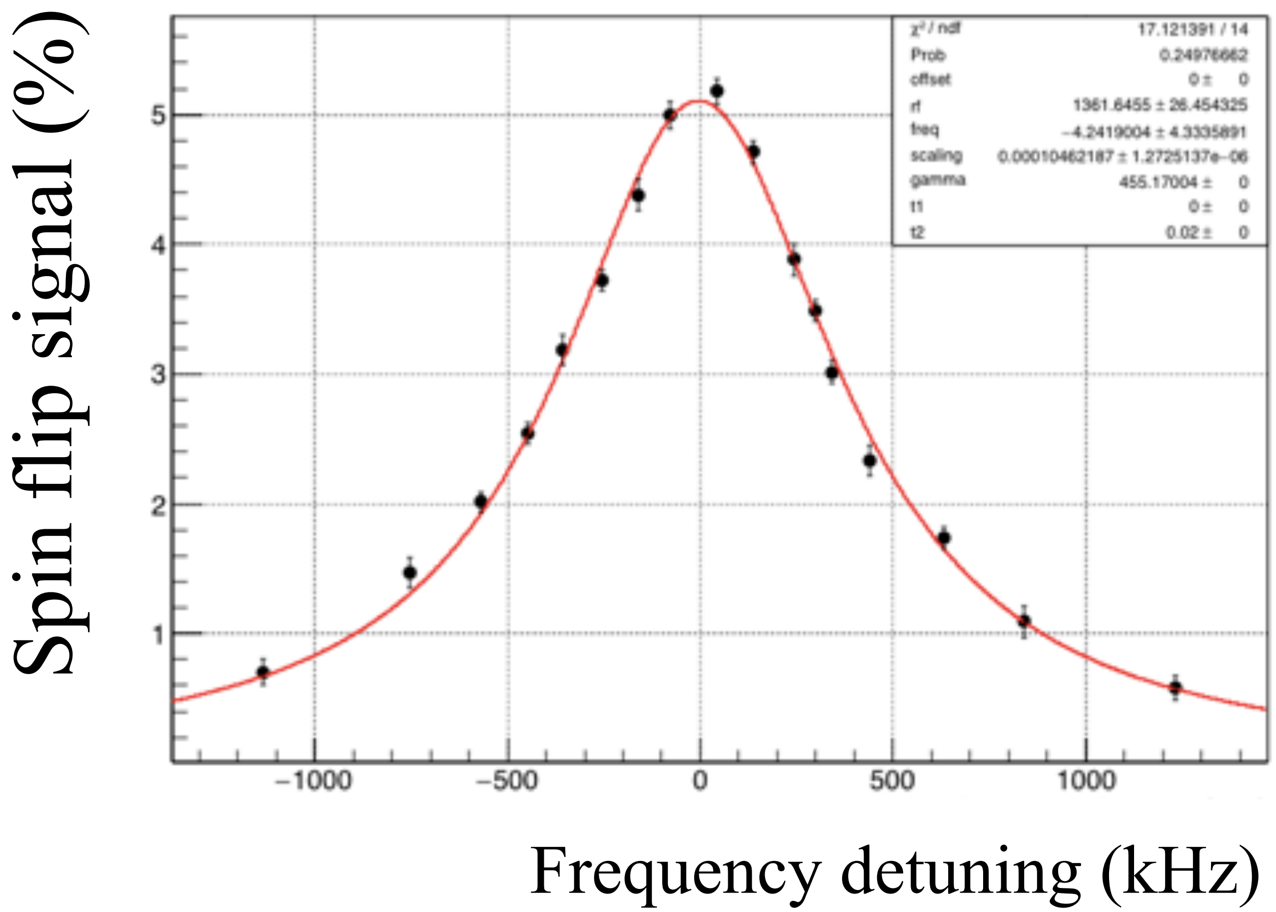
- **Three-layers of permalloy magnetic shield**





Magnetic field is suppressed to 1/1000, less than 100 nT

Result of Muonium Spectroscopy

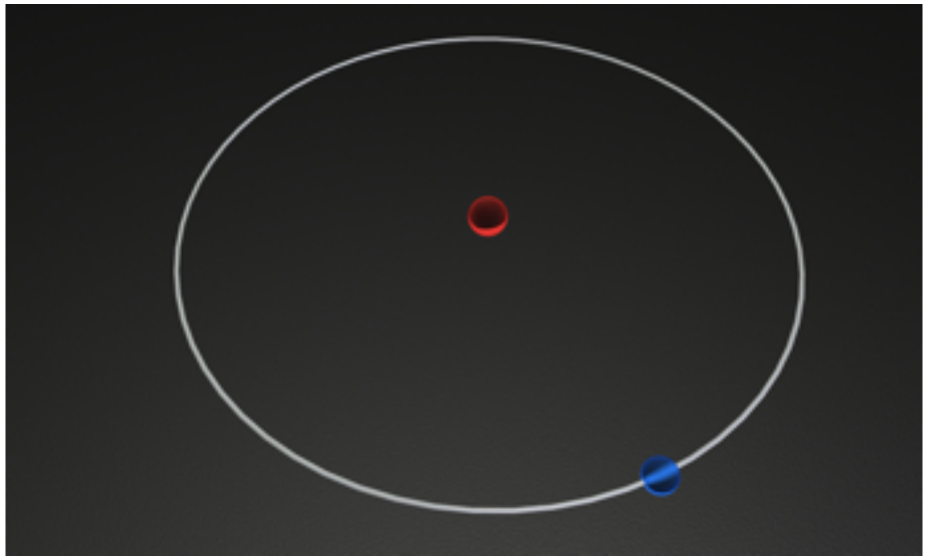


Muonium hyperfine structure was observed with the high-intensity pulsed muon beam. Measurement precision was mostly limited by statistical uncertainty. Significant improvement of statistics is expected at new muon beam line which is under construction.

	Uncertainty
Statistics	4 kHz
Atomic collisional shift	66 Hz
RF power drift	26 Hz
Gas impurity	12 Hz
Beam profile	9.8 Hz
Gas pressure fluctuation	6 Hz
Detector pileup	2 Hz
Beam intensity	0 Hz
Magnetic field	0 Hz

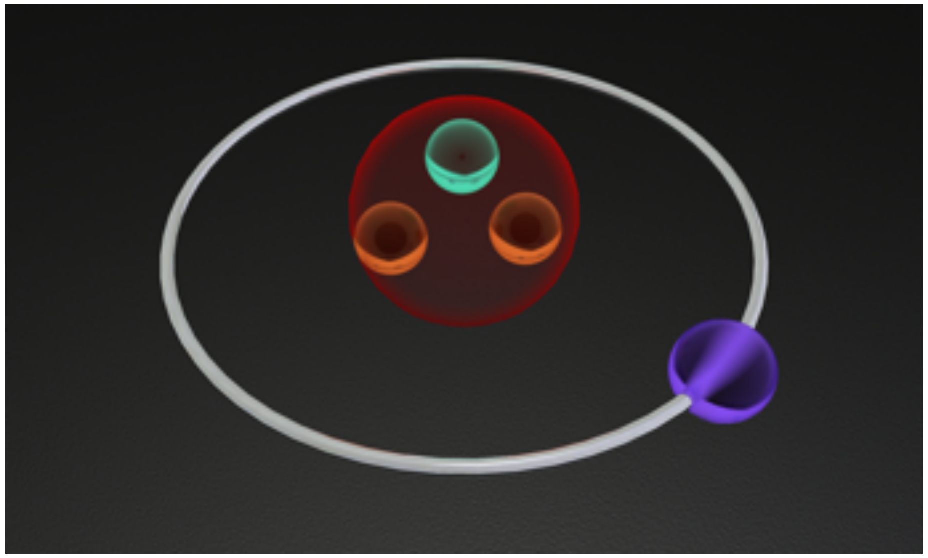
Muonium and Muonic Hydrogen

- Muonium: consisting a positive muon and an electron



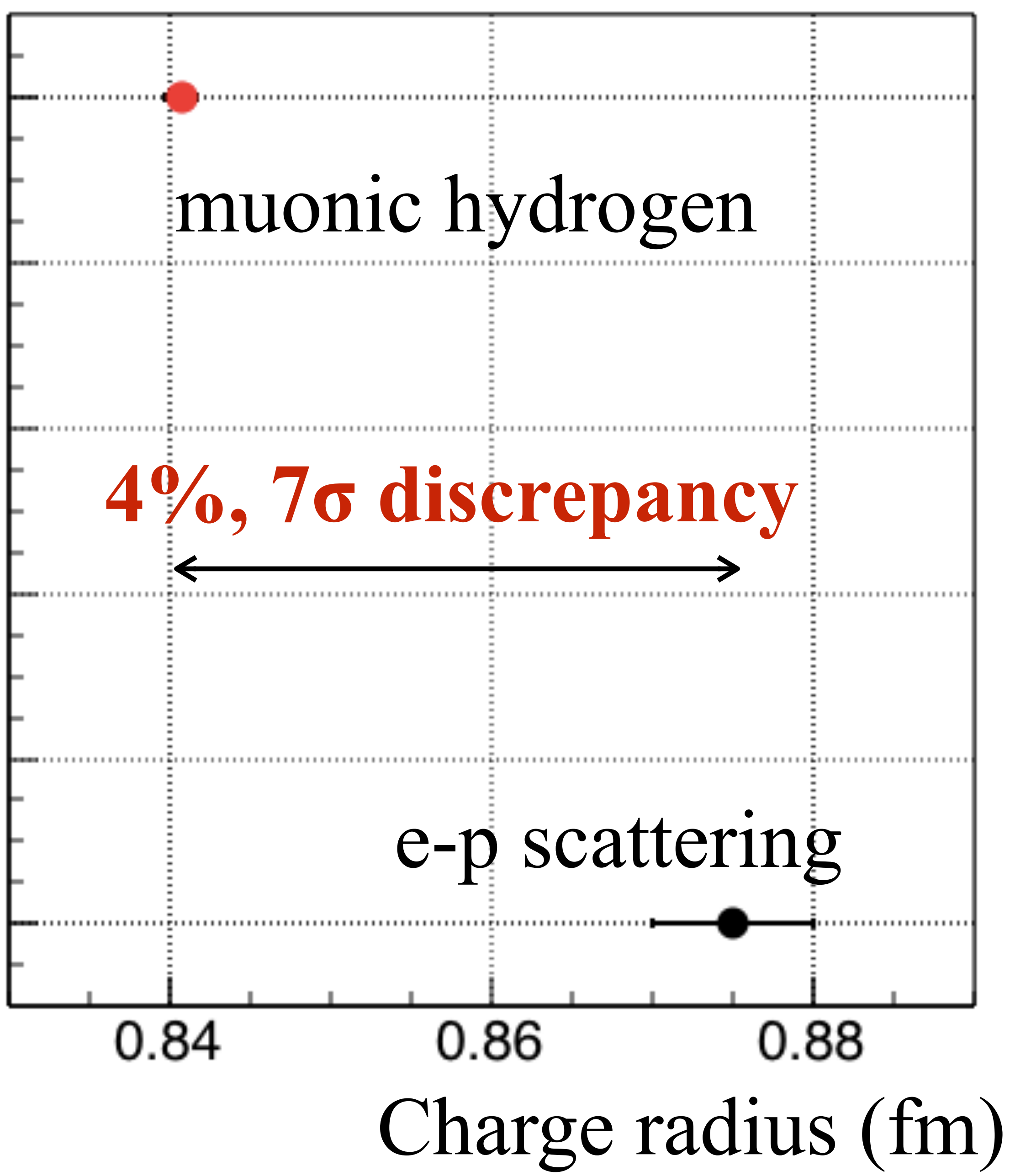
  - Leptonic two-body system
  - Bound state QED validation
  - Muon mass measurement
  - Lorentz violation search
  - J-PARCで実験中

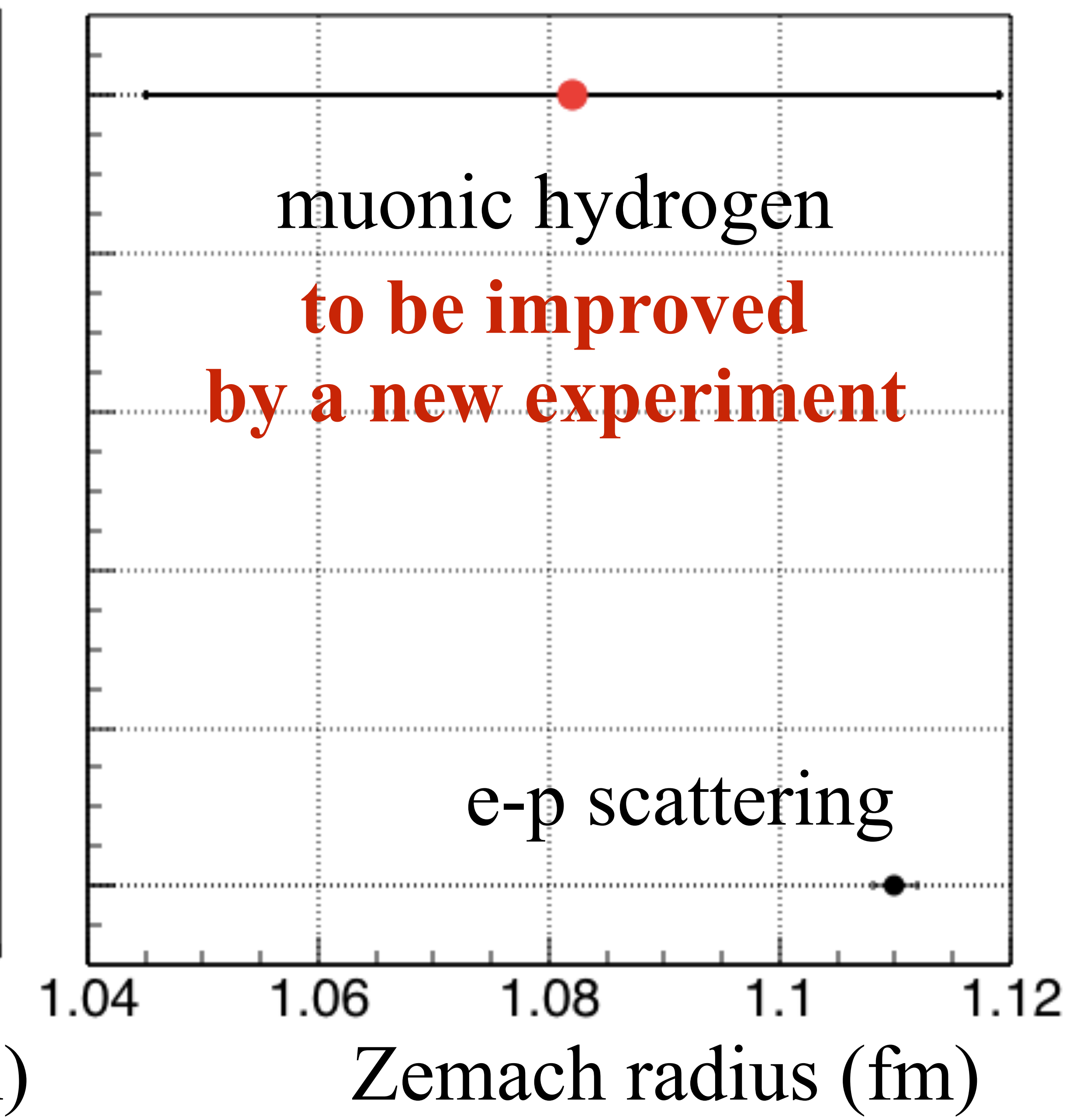
- Muonic hydrogen: consisting a negative muon and a proton



  - Small Bohr radius (1/200 of H)
  - Sensitive to the proton structure
  - Proton radius measurement
    - “Proton radius puzzle”
  - 理研RALで実験準備中

Proton Radius Puzzle





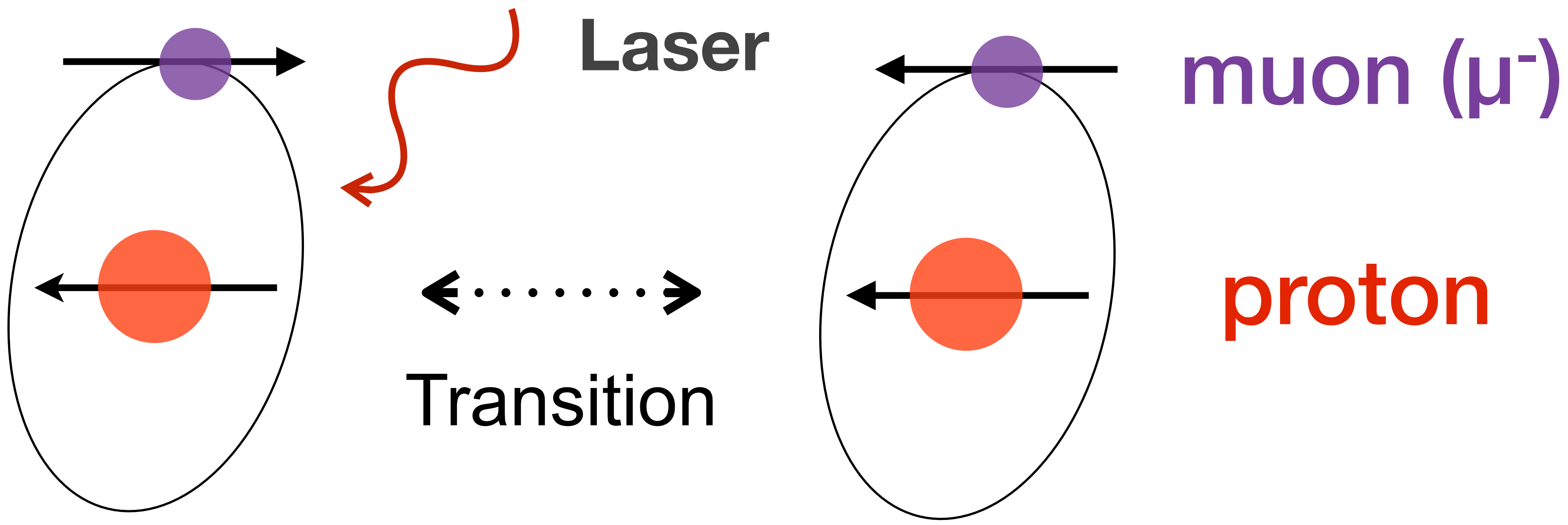
電荷半径では有意にずれている

Zemach半径では

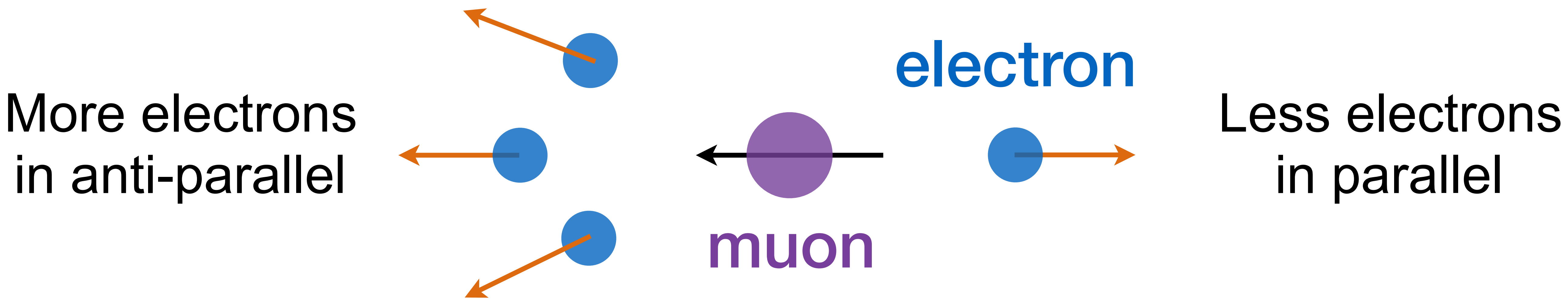
μpによる測定の精度が不足

Principle of Spectroscopy

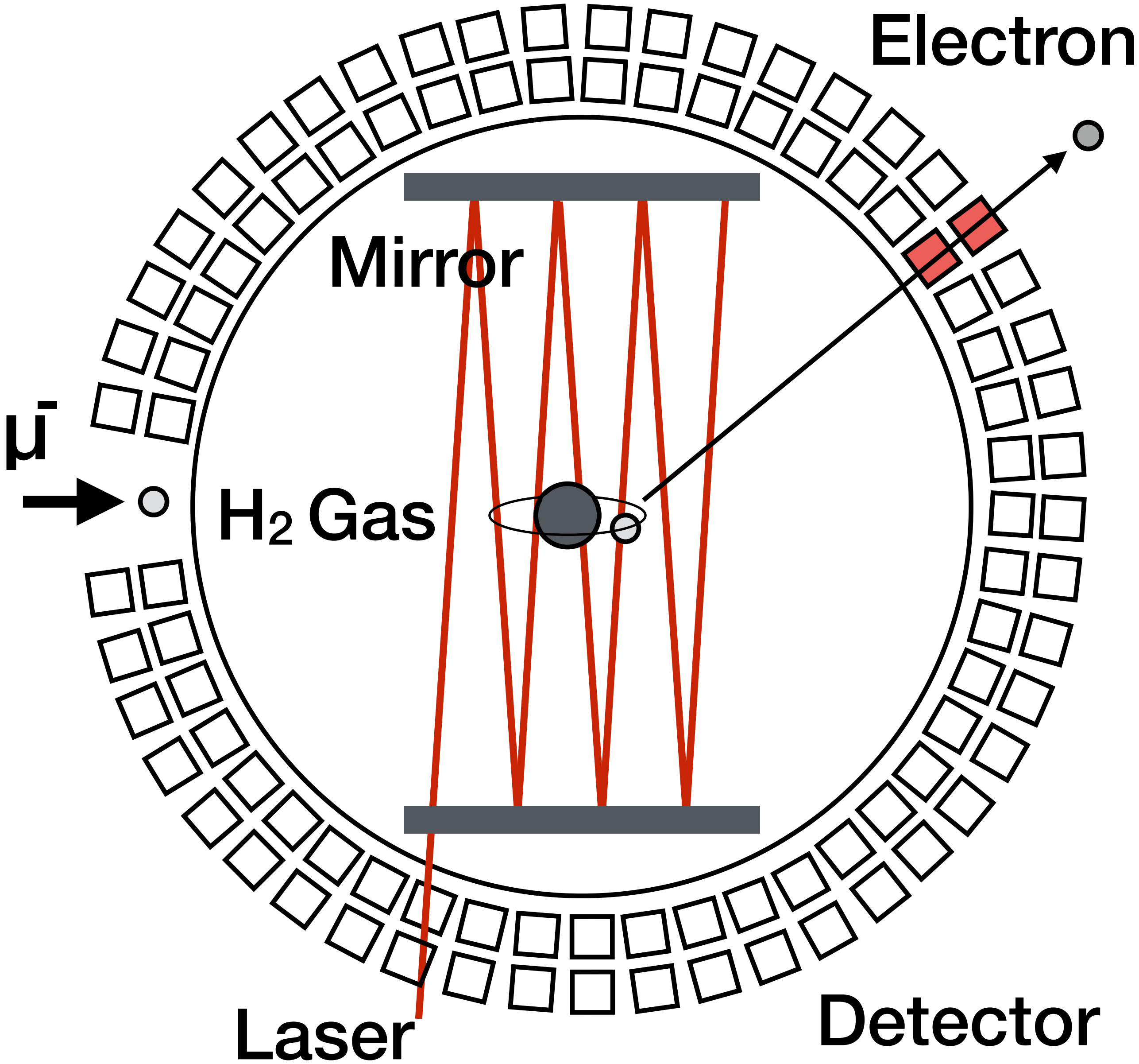
- MuP HFS transition is induced by a circular polarized laser light

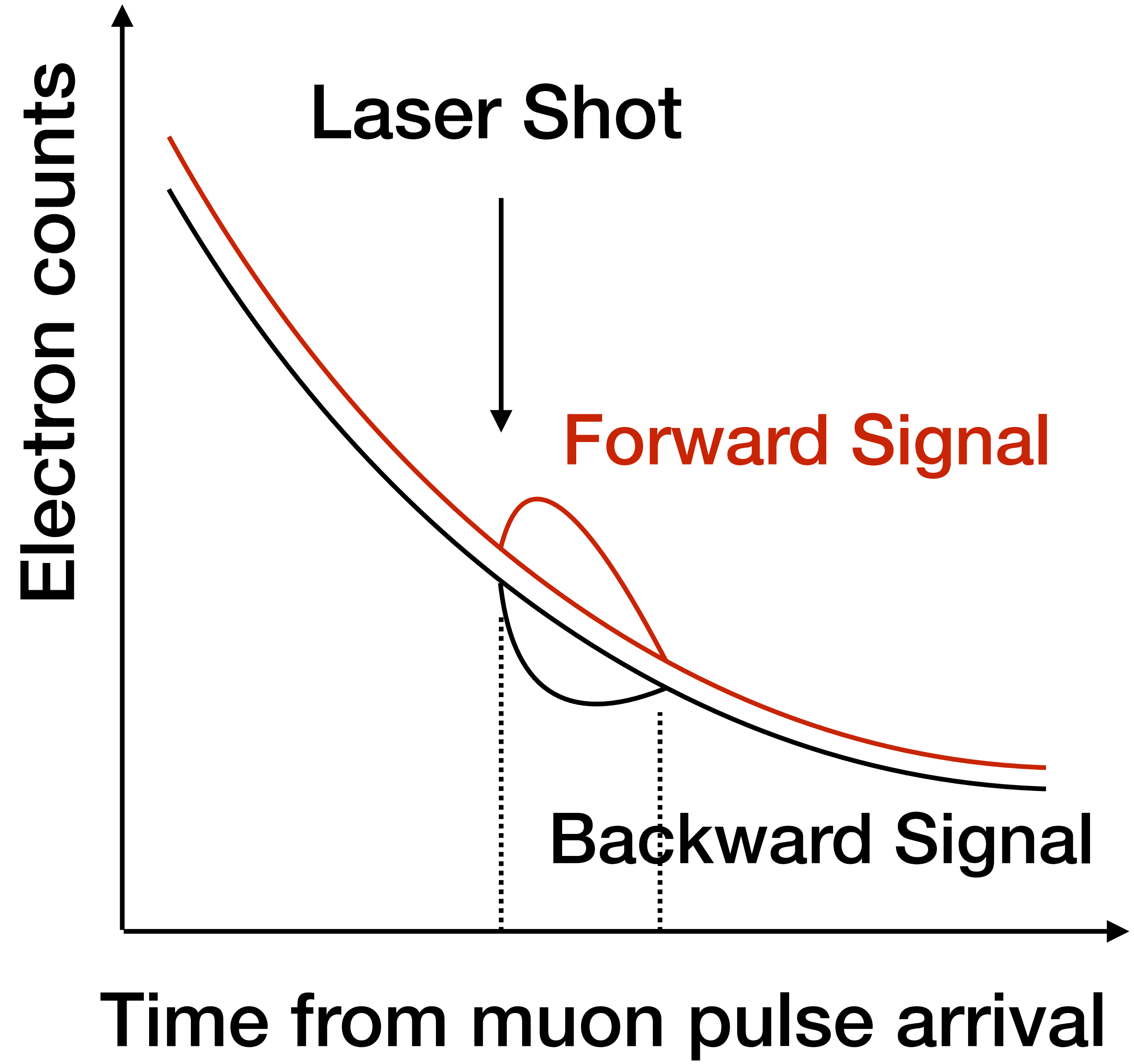


- The emission angle of decay electron is correlated to the muon spin



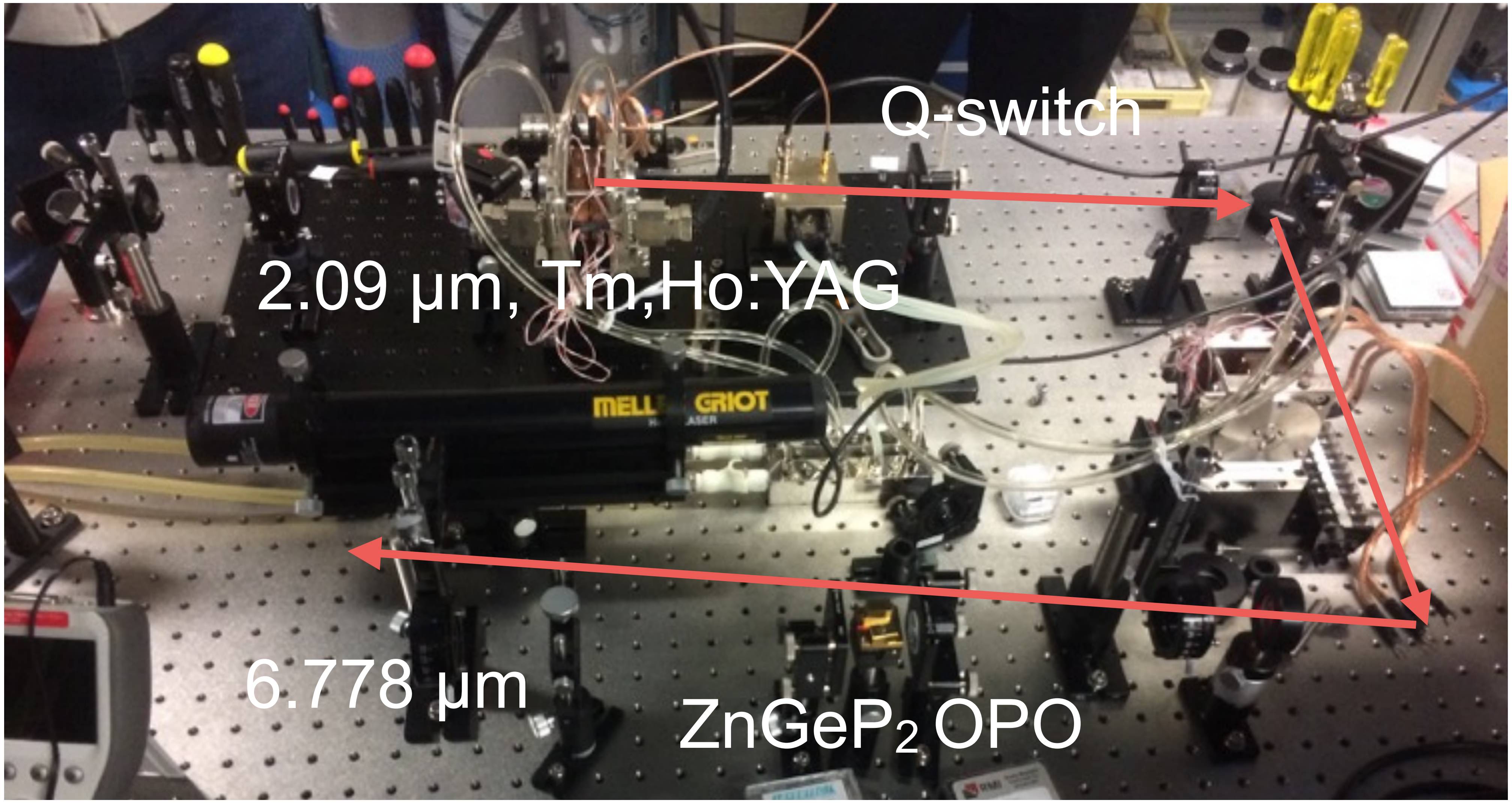
Muonic Hydrogen Spectroscopy





Key technologies:
High-intensity pulsed mid-infrared laser (6.778 μm, 50 MHz width, 10 mJ)
Non-resonant laser cavity (99.95% reflection)
Nuclear spin polarized proton target (Static, DNP, Optical pumping…)

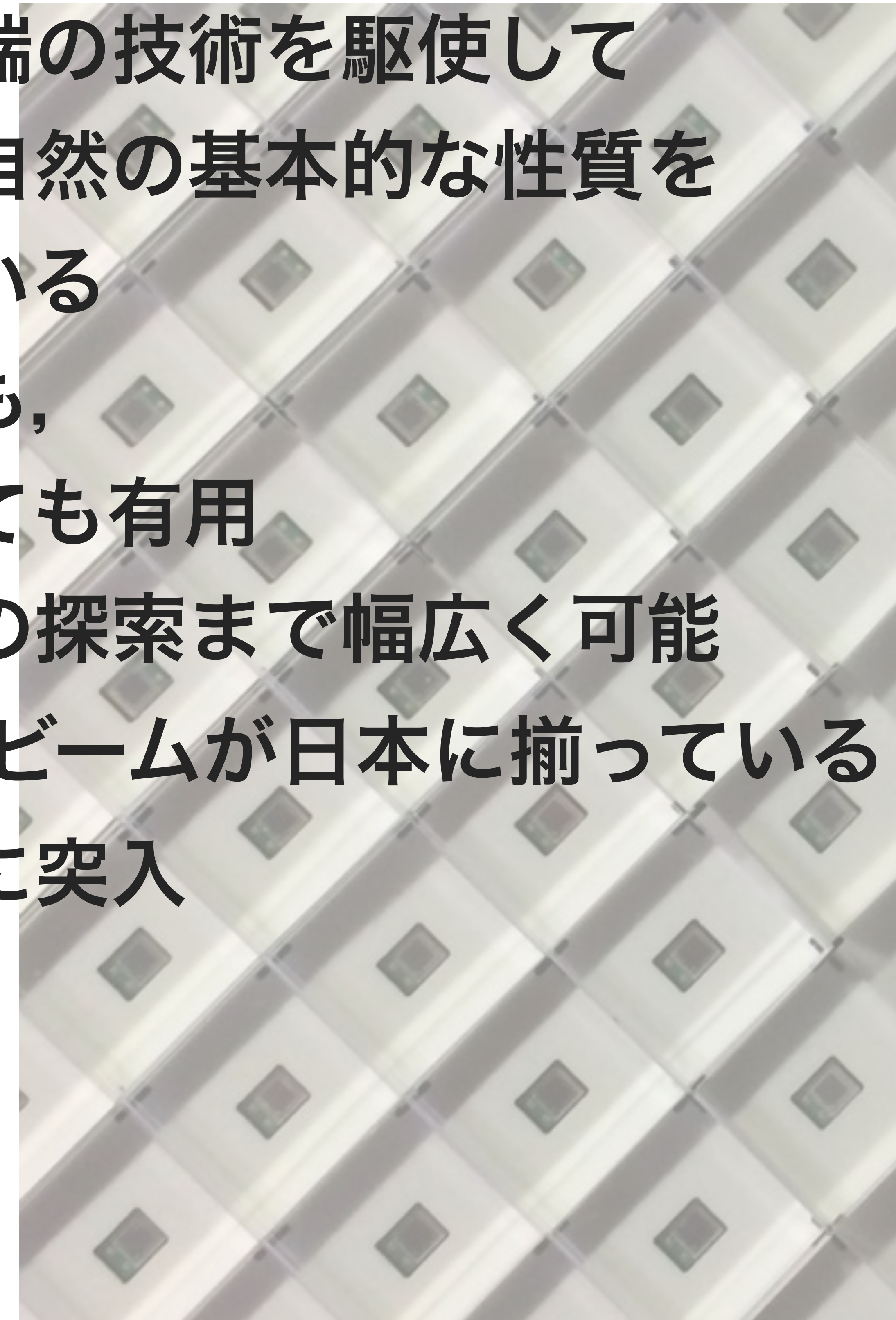
Development of Laser System



- Development of high-intensity pulsed mid-infrared laser
- Designing of a laser cavity
- Basic study about the polarized proton target
- Two years for development, one year for physics measurement

Summary and Outlook

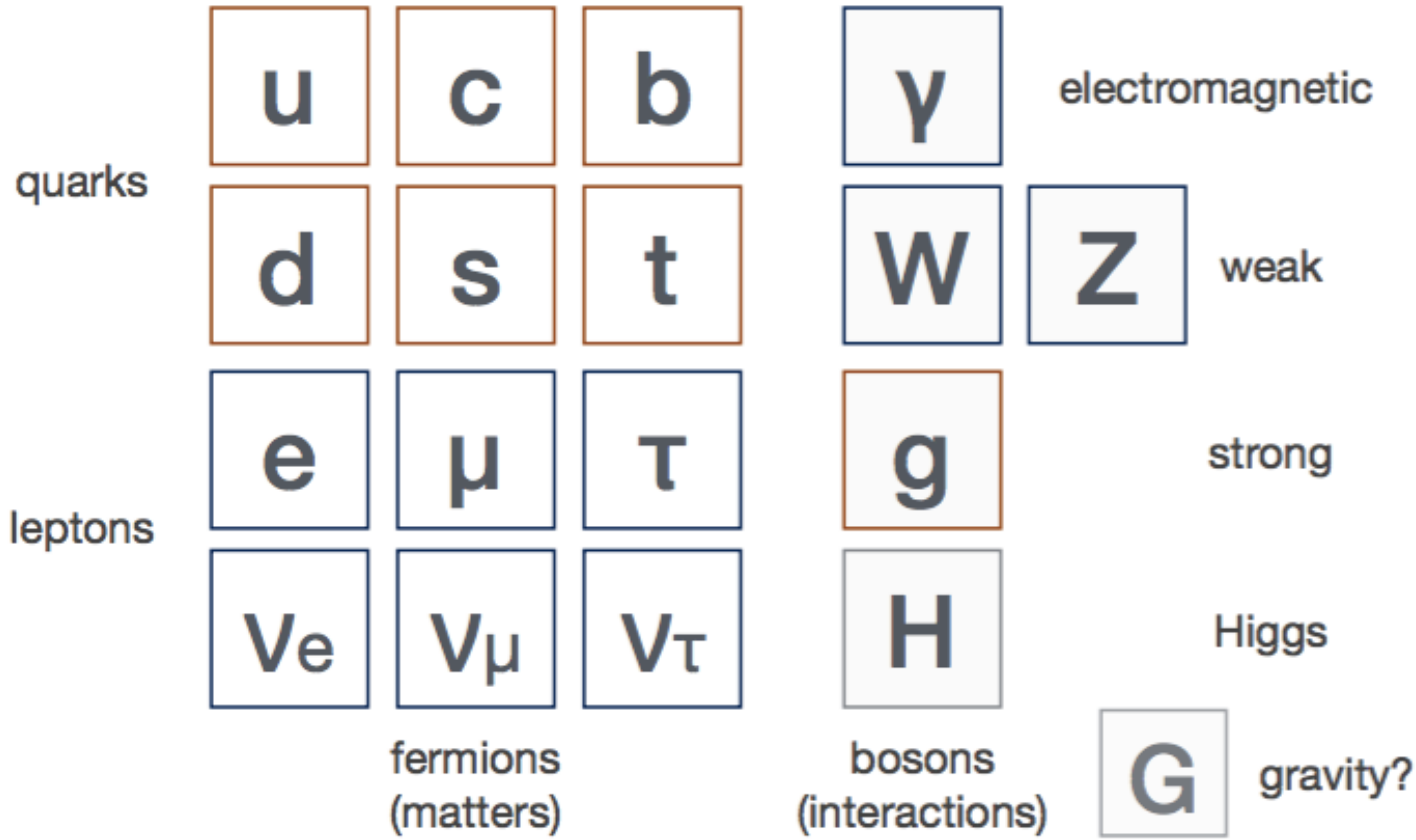
- 高エネルギー物理学は，最先端の技術を駆使して前人未踏の領域に踏み込み，自然の基本的な性質を明らかにすることを目指している
- ミューオンは粒子単独としても，他の粒子と束縛した原子としても有用
- 厳密な理論の検証から新物理の探索まで幅広く可能
- 強力なパルス/連続ミューオンビームが日本に揃っている
- ミューオン精密物理は新時代に突入
- これからが熱い



Supplements

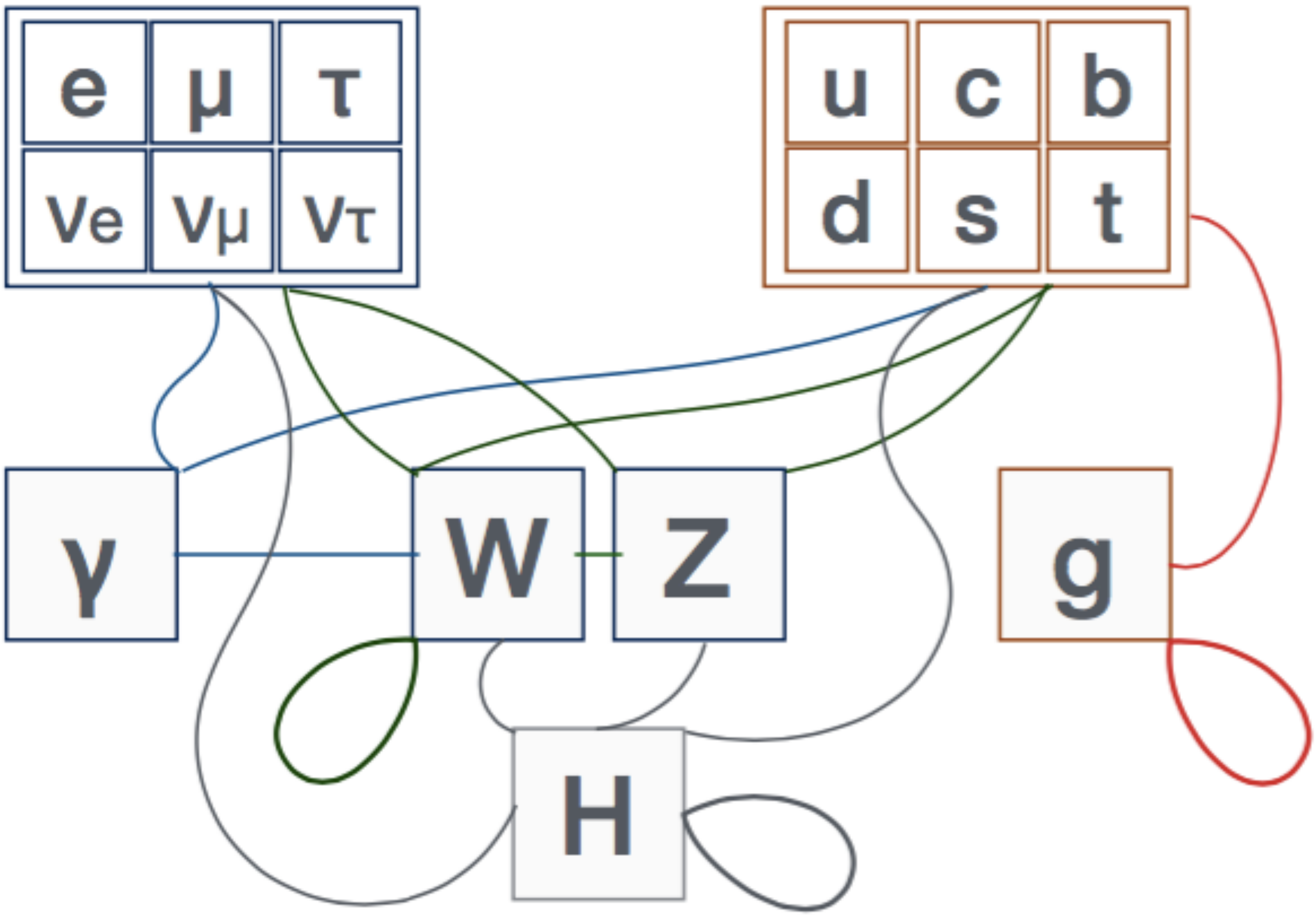
Standard Model of Particle Physics

- 素粒子物理学の標準模型
- 17の素粒子，4つの相互作用



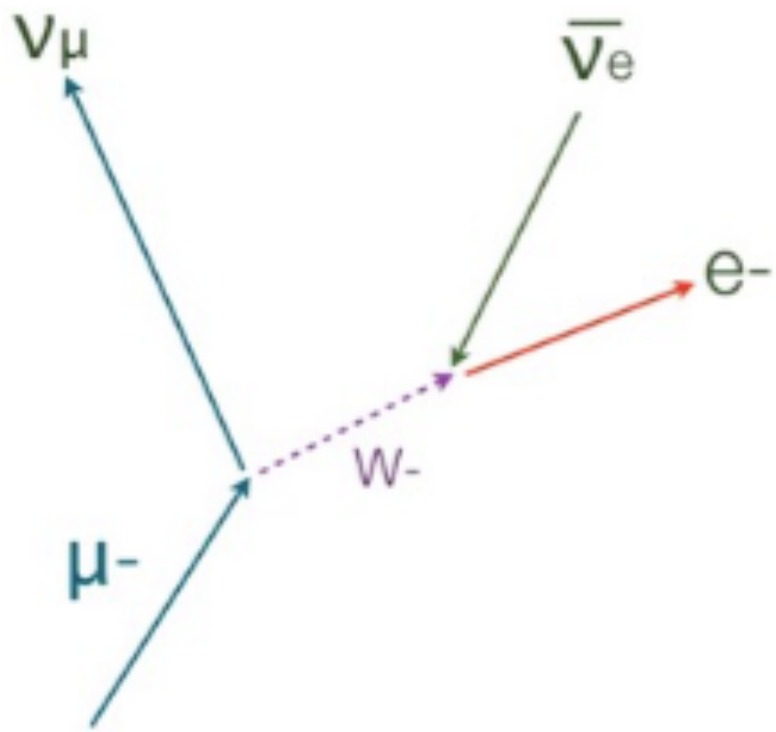
Standard Model of Particle Physics

- 素粒子物理学の標準模型
- 17の素粒子，4つの相互作用



Particle Interaction

- 相互作用は粒子間でゲージ粒子が交換されることで起こる



Muon weak decay

Fermi's Golden Rule

$$T_{i\rightarrow f} = \frac{2\pi}{\hbar}|\langle f|H'|i\rangle|^2$$

f : final state, i : initial state
H' : Hamiltonian perturbation
ρ : density of final state

Diagram represents calculation of transition amplitude

1. Consider Lagrangian or action
2. Write an equation of motion by least action principle
3. Solve an equation of motion

Discovery of Muon

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Note on the Nature of Cosmic-Ray Particles

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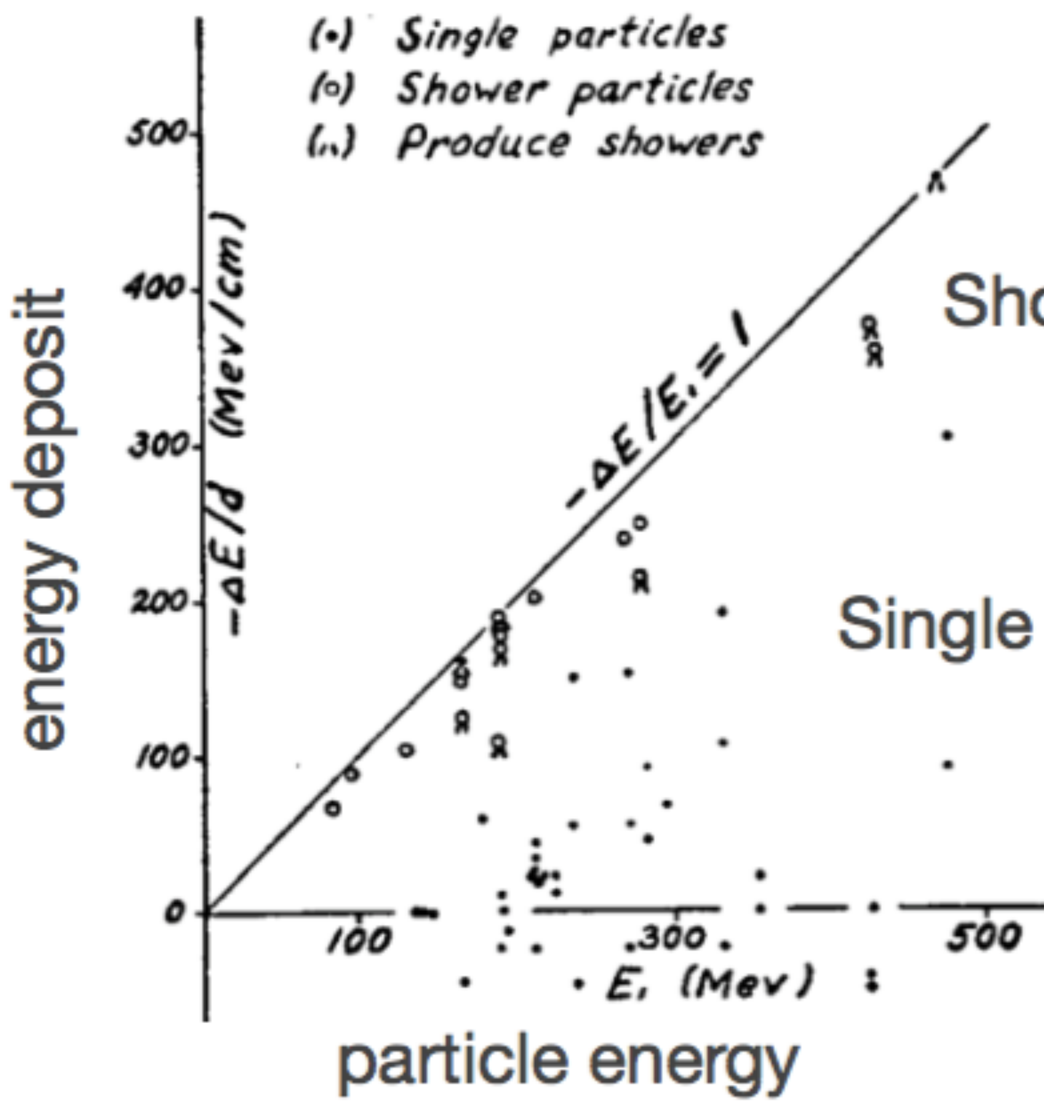

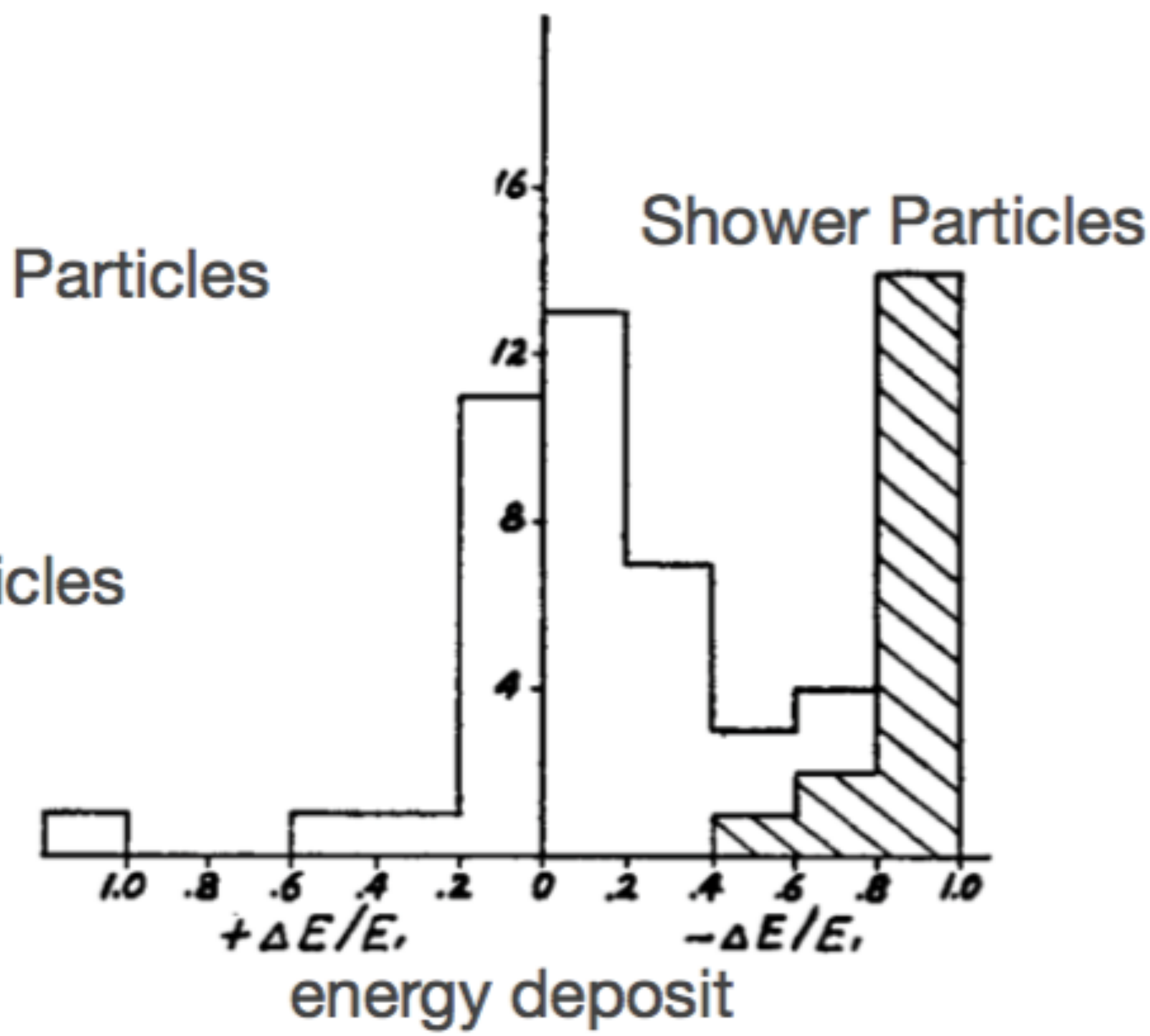

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