Towards the realization of a dream muon source

Meng Lv

SYSU-PKU Collider Physics Forum
for Young Scientists

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李政道研究所
TSUNG-DAO LEE INSTITUTE

Outline

- Introduction to muon and muon source
  - Muon and its applications
  - Current muon sources worldwide
- Muon source driven by electron-on-target
  - POT vs. EOT
  - GEANT4 Simulation
  - A muon source based on SHINE
- Potential Applications of SHINE muon source
- Summary

Muon in fundamental physics

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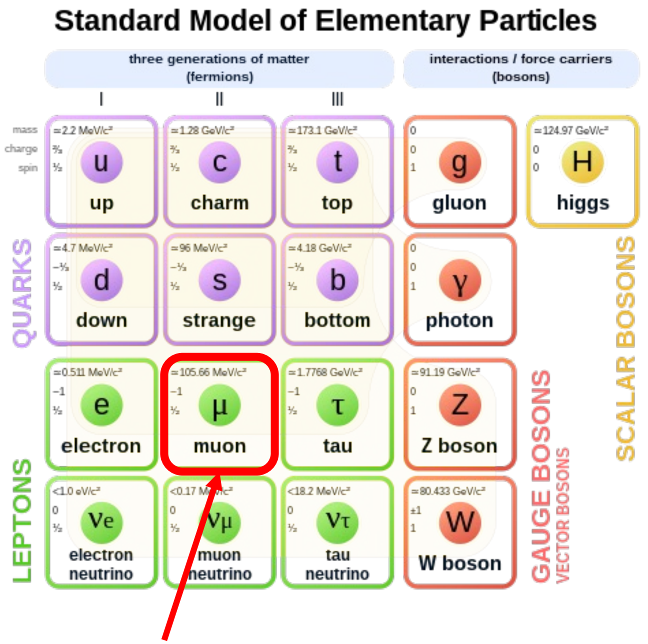
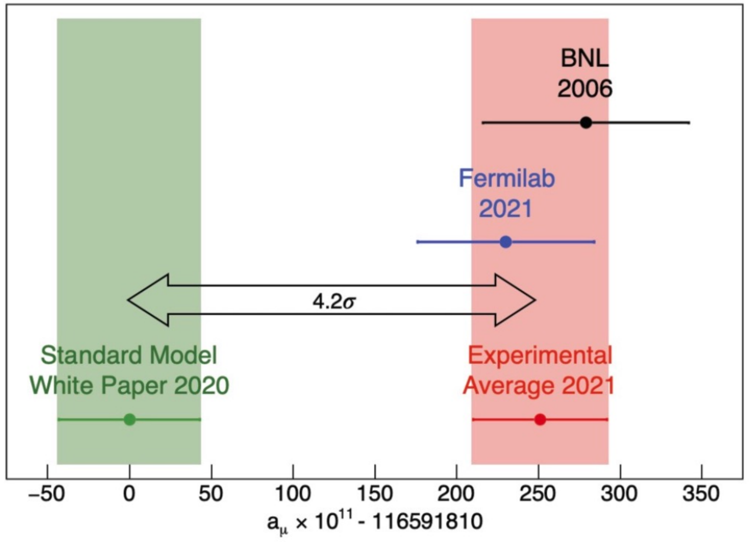
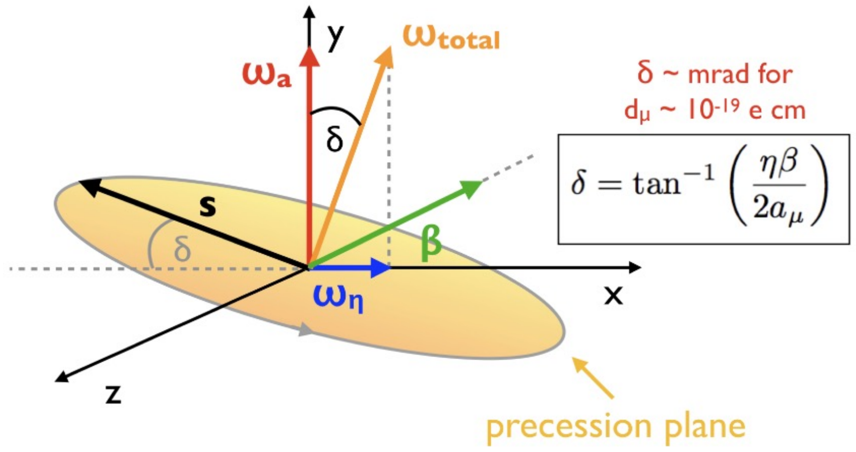






$$\frac{d^2\Gamma}{dx\, d(\cos\theta)} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \times$$
$$\times \left[F_{IS}(x) + P_{\mu^+} \cos\theta\, F_{AS}(x)\right] \left[1 + \vec{P}_{e^+}(x,\theta) \cdot \hat{\zeta}\right]$$

Isotropic part:

$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta\, x_0(1-x)$$

Anisotropic part:

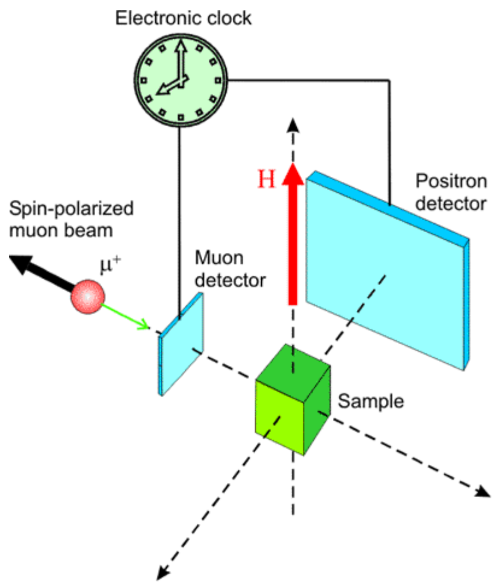
$$F_{AS}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left(1 - x + \frac{2}{3}\delta\left[4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right]\right)$$

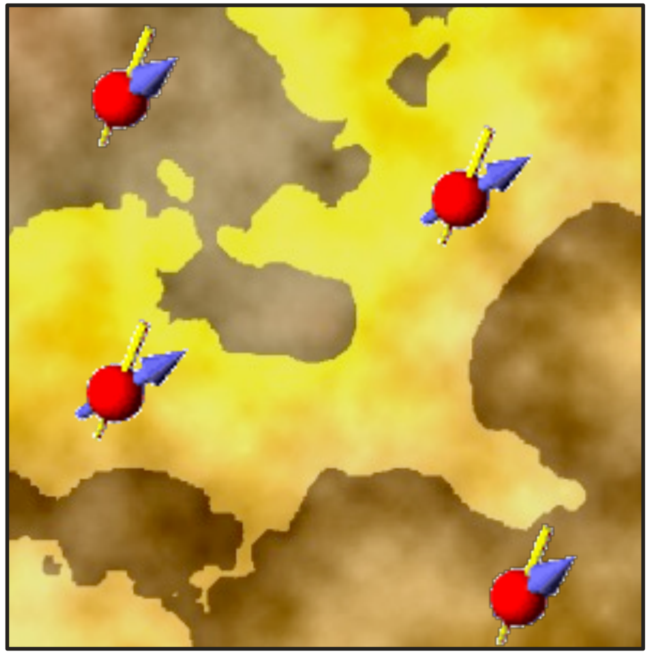
where $x = \frac{E_e}{E_{max}}$, $x_0 = \frac{m_e}{E_{max}}$, and $E_{max} \simeq \frac{m_\mu}{2}$, .

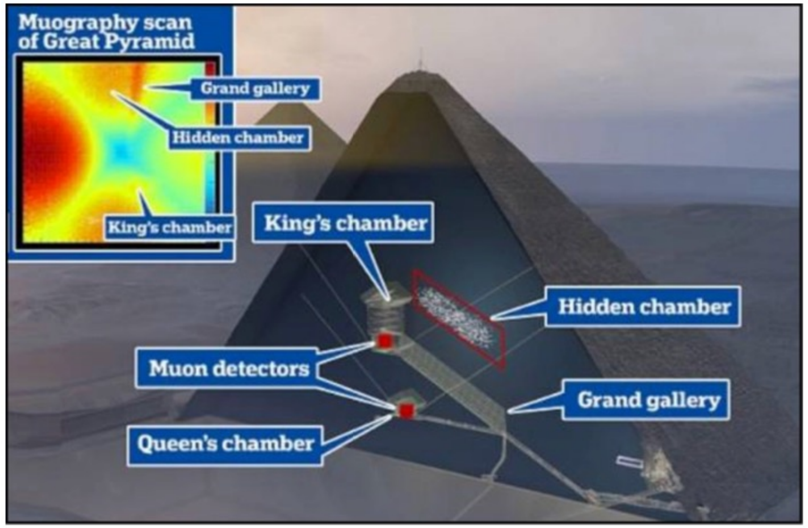
- Muon: one of the elementary particles in SM
- A sensitive probe in fundamental physics:
  - Muon g-2/EDM experiment
  - Muon lifetime(G_F) & Michel parameter

Muon in applied physics & engineering

- Muon spin rotation (μSR): a sensitive magnetic field probe
  - Measure muon precession frequency in material $\mu_\mu = 3.18\,\mu_p$
- Muon tomography: detect inner structure of ancient remains







Central idea: self-analyzing muon decay

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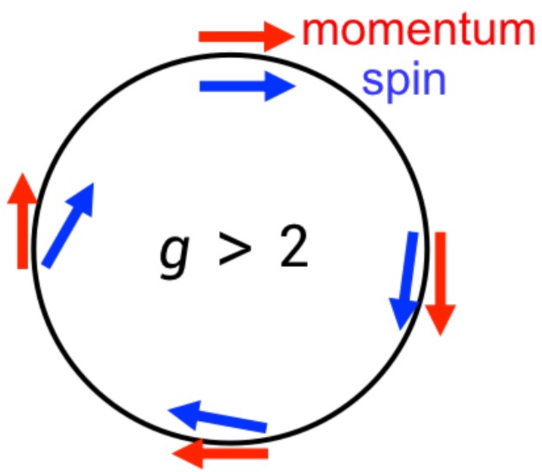
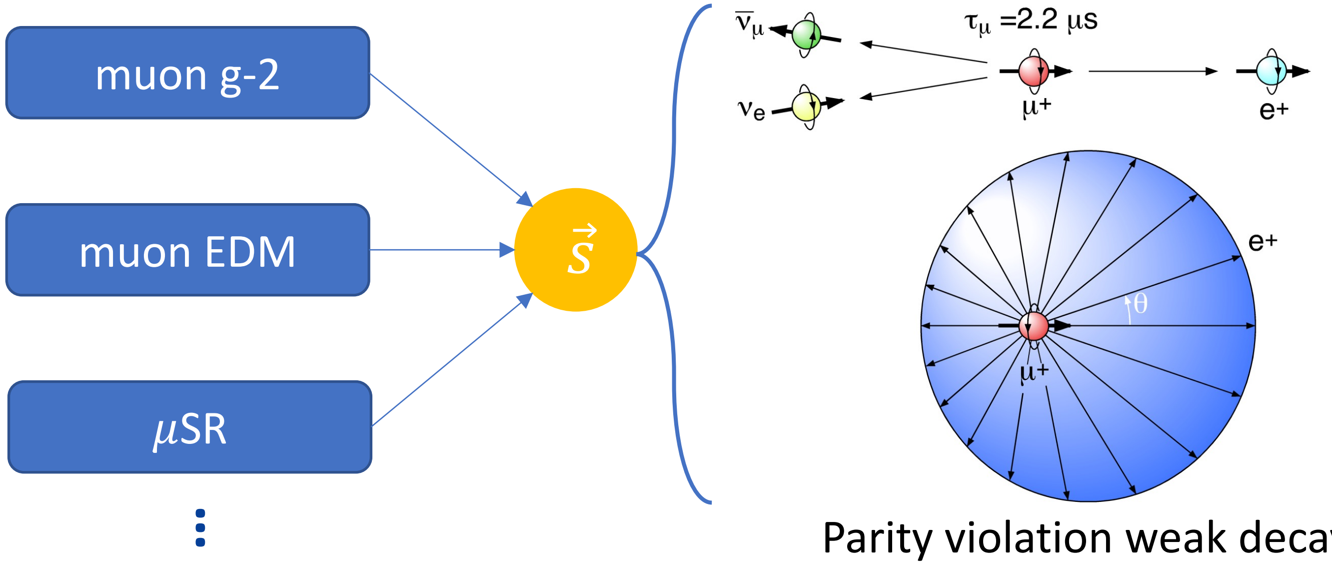
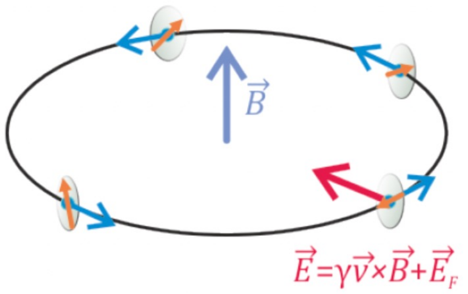


ω_a measuremet
in muon g-2
experiment

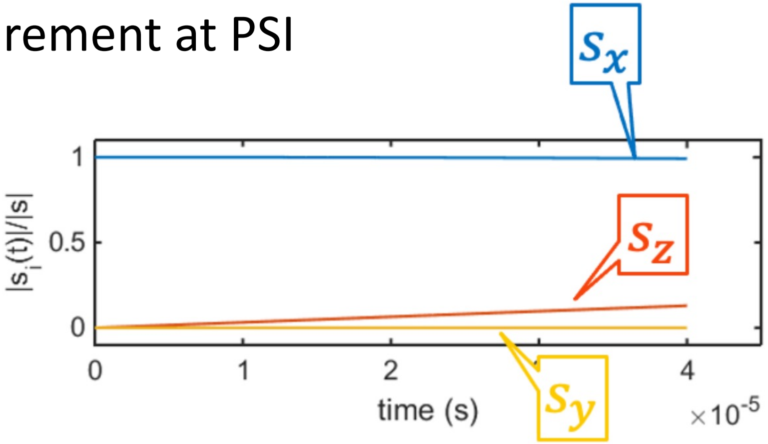


Parity violation weak decay

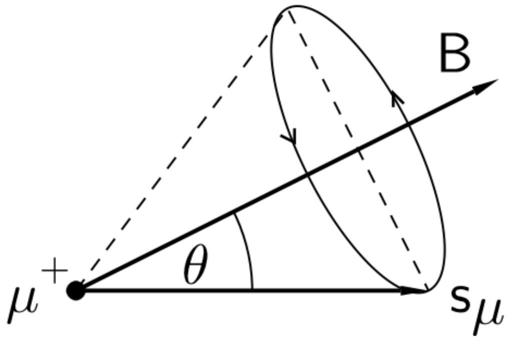
‘Frozen Spin’ muon EDM
measurement at PSI



frozen & EDM

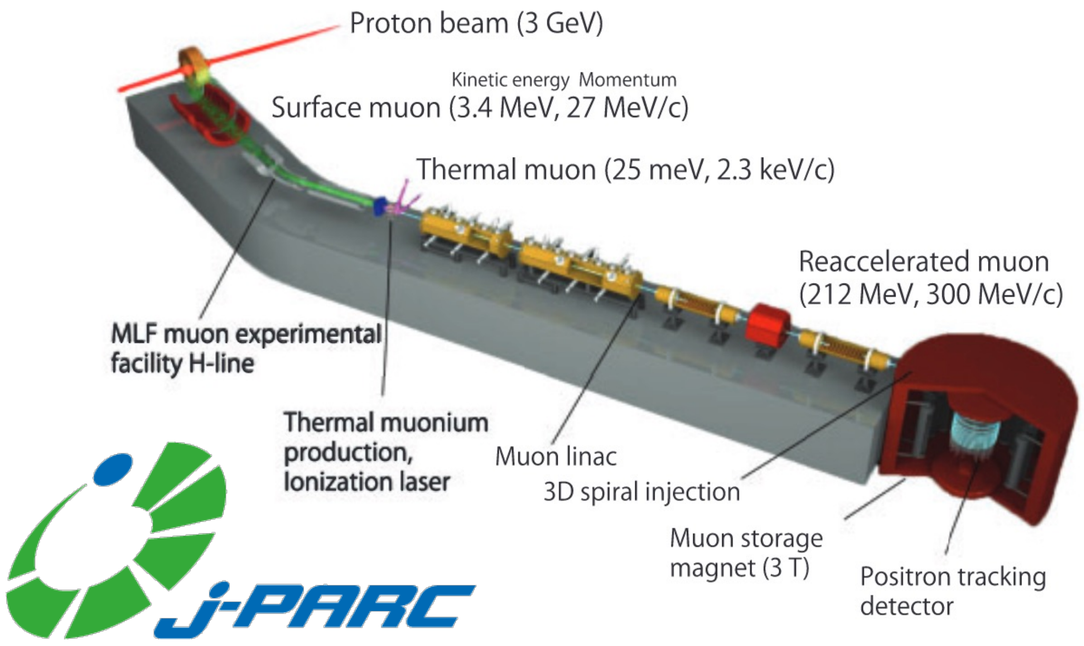


Lamor Precession in μSR

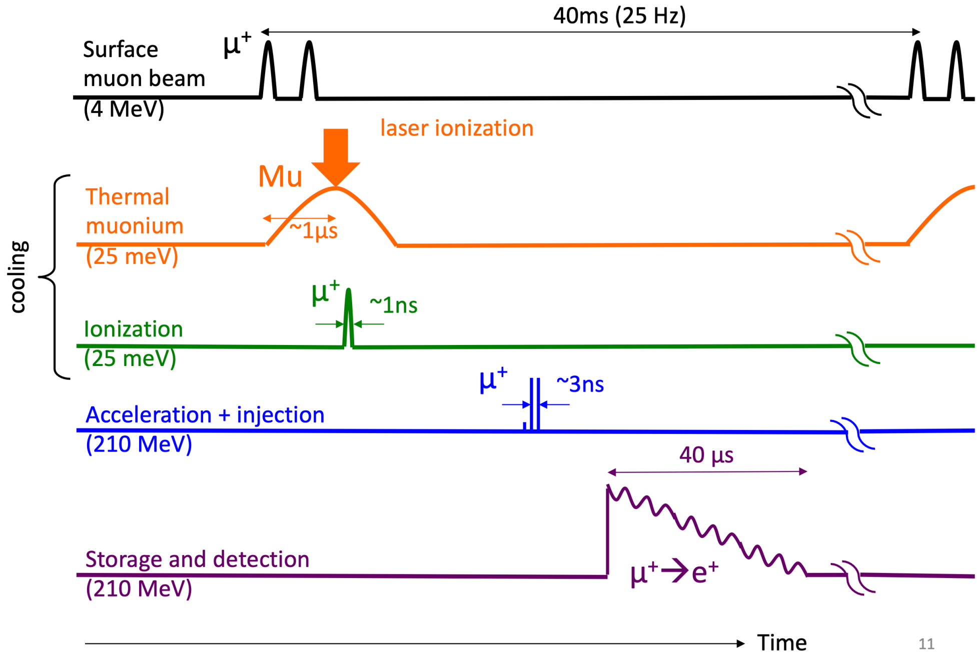


Low-repetition-rate pulsed muon source

- Example: J-PARC in Japan
- Bunch frequency: 25 Hz (double bunch)
- Experiments: muon g-2/EDM, μSR, COMET($\mu^- + N \rightarrow e^- + N$)...



Experimental sequence



Continuous wave muon source

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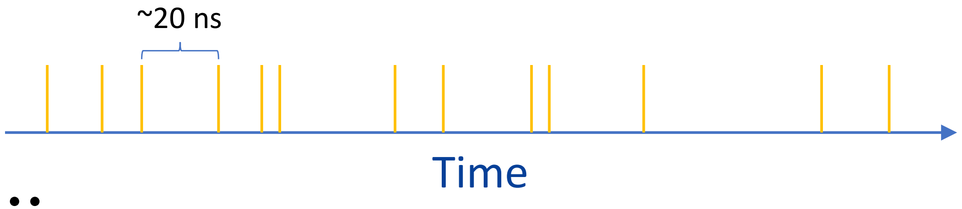
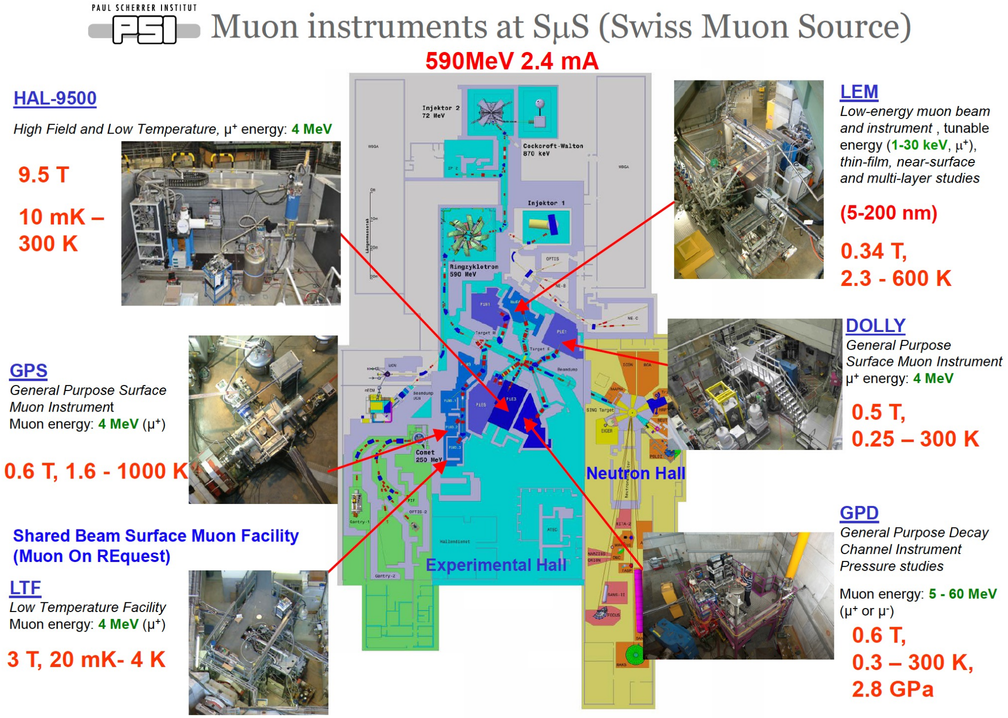
- Example: PSI in Switzerland
- Beam frequency: 50 MHz
- Experiments: muon EDM, μSR, Mu3e...

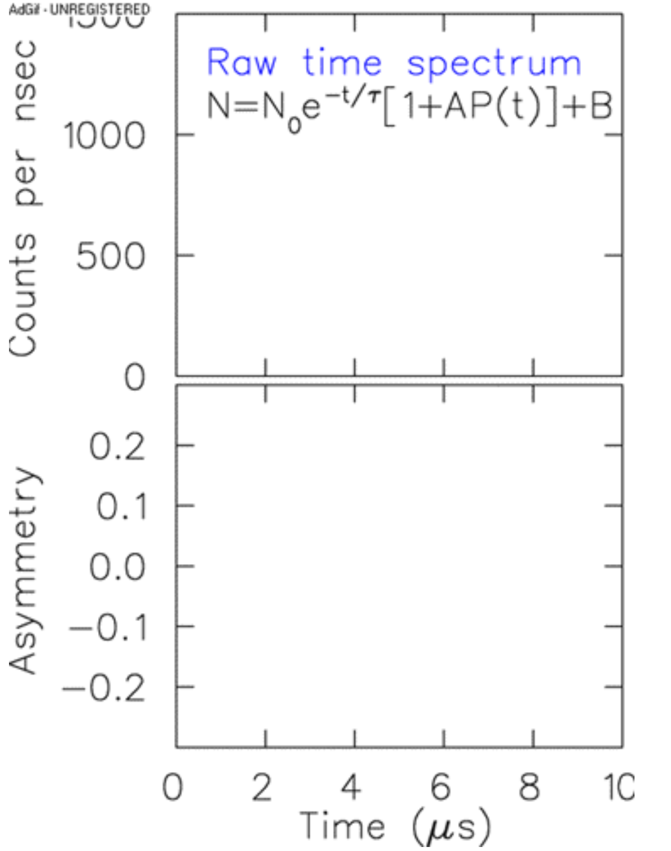
Single muon beam





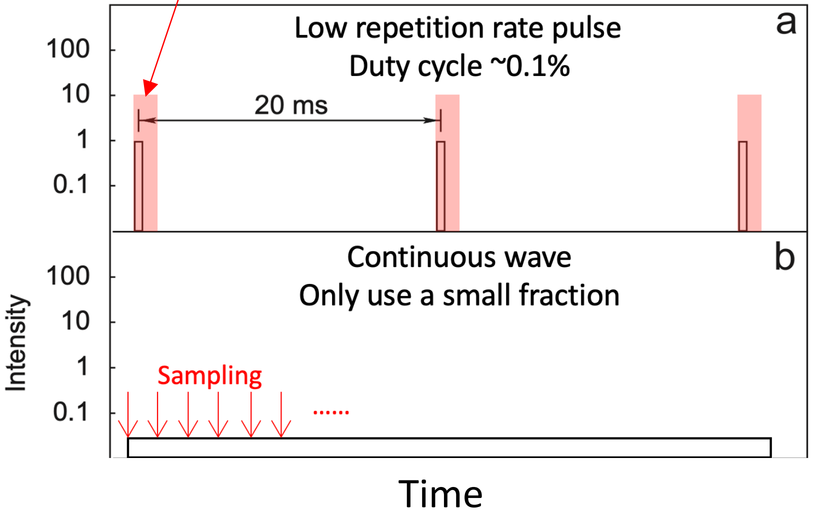
Limitation of current muon sources

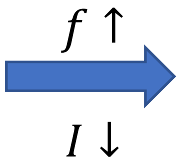
μSR



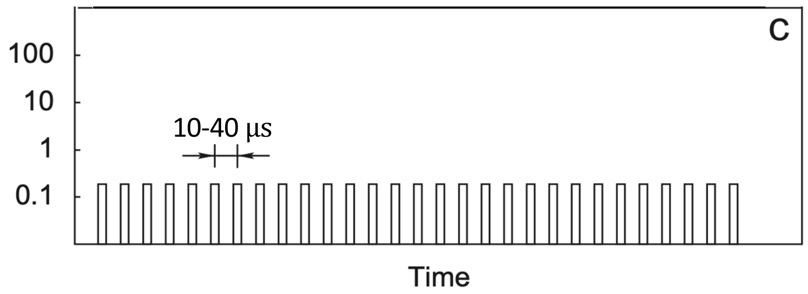
Measurement Duration ~10 µs

Duty cycle





An ideal muon source



- Pulsed muon source
  - Dead time limitation
  - Low duty cycle
- Continuous wave muon source
  - Sample 1 muon per 10 µs
  - Only use 0.1% of total muon

- Less muon per bunch
  less pileup ($\sim 10^3\ \mu^+/s$)
- Higher bunch repetition rate:
  Higher duty cycle (>50%)

Where to find such a muon source?

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POT vs. EOT

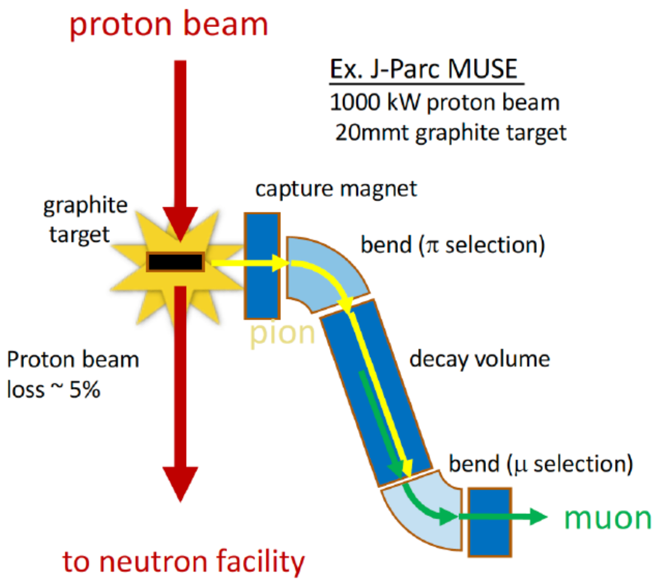
There is no high repetition rate proton accelerator in China

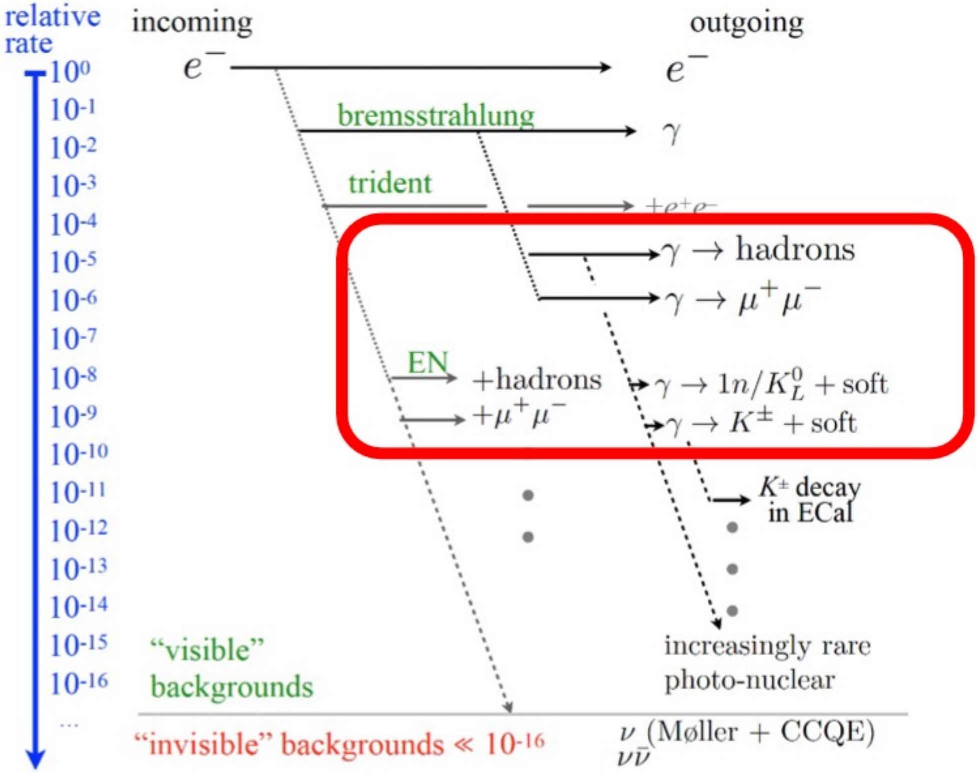
We got inspiration from dark photon search experiments like NA64, LDMX and DarkSHINE

Proton on target

pp Collision

$$p + p \rightarrow p + n + \pi^+$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$





Branches of electron on target

Electron on target

Photo-nuclear process

$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \pi^\pm + Z_3$$

Electro-nuclear process

$$e^- + Z_1 \rightarrow$$
$$(e^-)' + Z_1 + \pi^\pm + Z_2$$

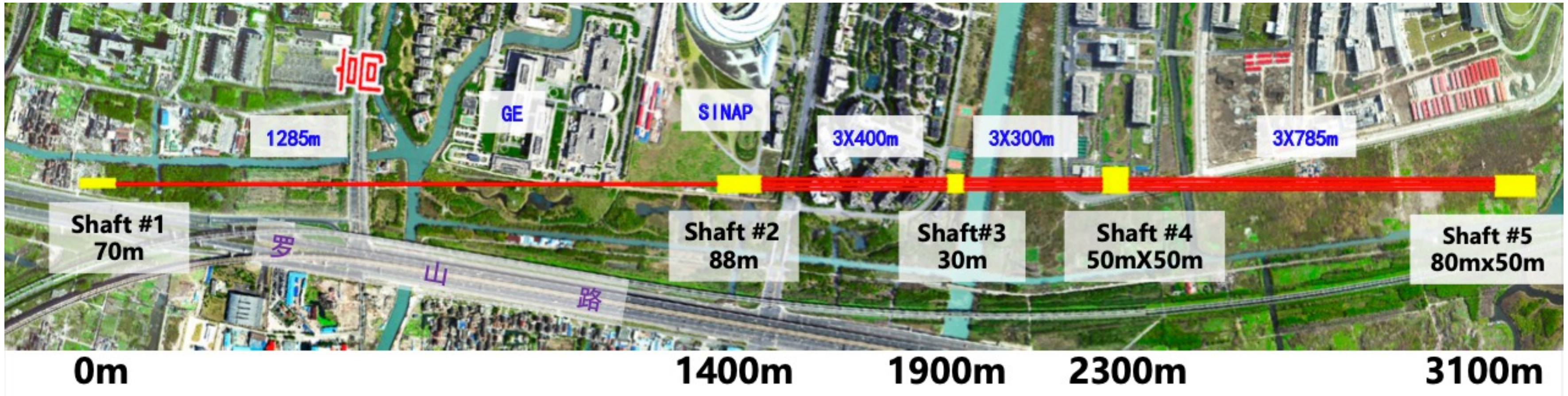
Bethe-Heitler process

$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \mu^+ + \mu^- + Z_2$$

SHINE introduction

- Located in Zhangjiang, Shanghai
- Expect to complete in 2026
- Electron beam:
  - 8 GeV energy
  - 1 MHz bunch frequency
  - 100 pC charge (6.25×10^8 electrons) per bunch

Only 3 km from TDLI!



Muon from two processes

- Simulation setup: 8 GeV, 100 pC, 10 mm tungsten target
- $\gamma \rightarrow \mu^+\mu^-$ process: High energy, low emittance, low cross-section
- Photo-nuclear process: Low energy, high emittance, high cross-section

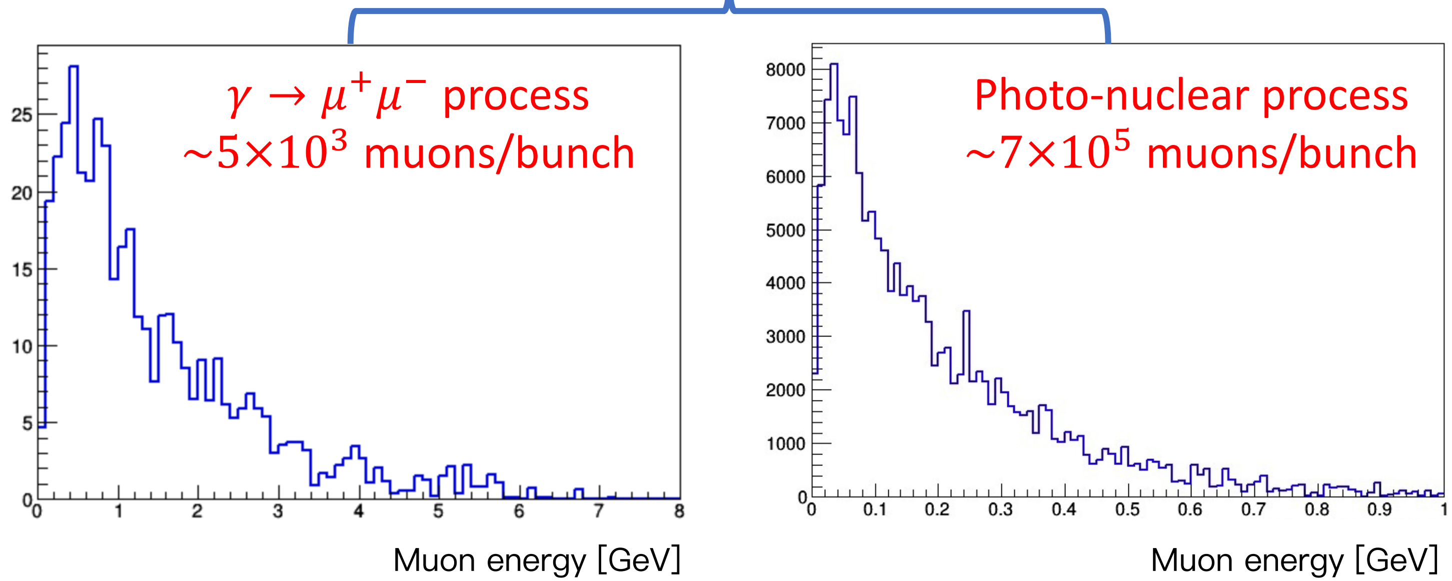
Bethe-Heitler process

$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \mu^+ + \mu^- + Z_2$$

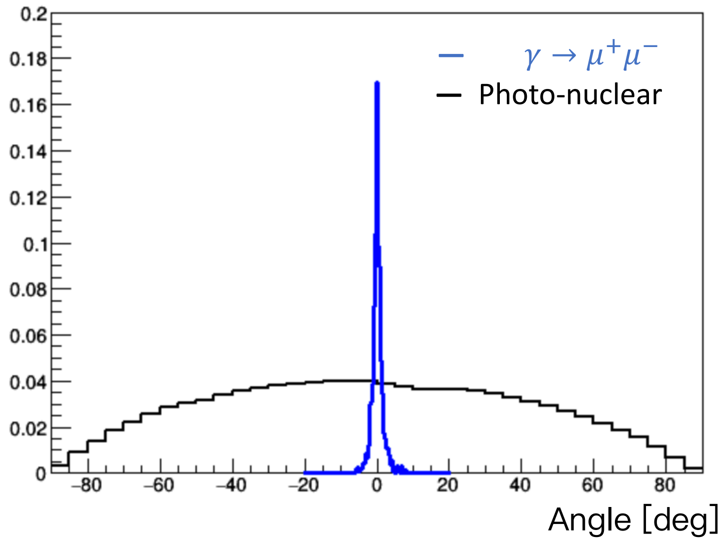
Photo-nuclear process

$$e^- + Z_1 \rightarrow Z_1 + \gamma$$
$$\gamma + Z_2 \rightarrow \pi^\pm + Z_3$$

Energy distribution

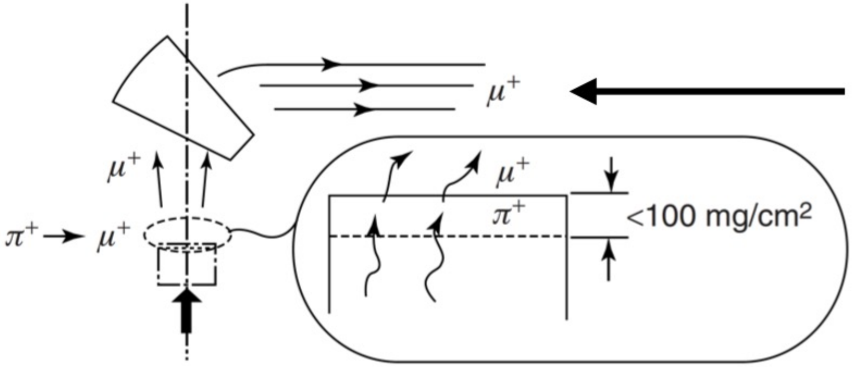


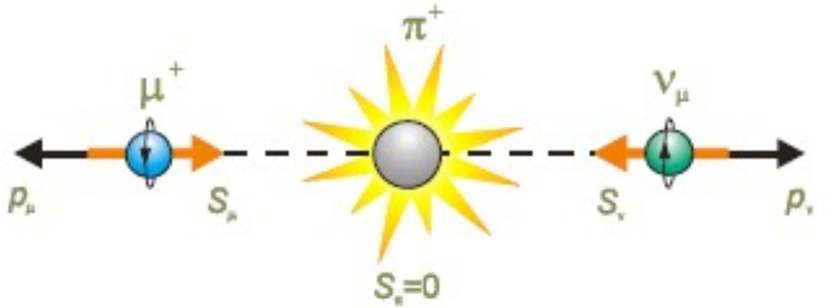
Angular distribution



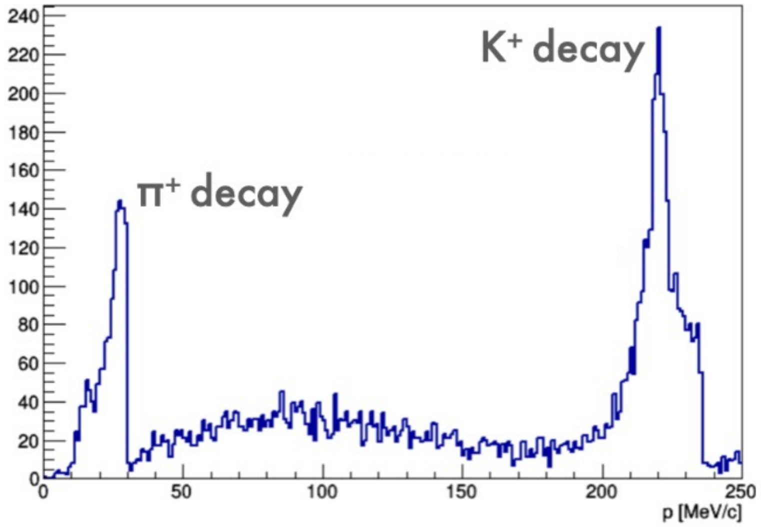
Surface muon production

- Surface muon: $\pi^{\pm}/K^{\pm}$ decay near target surface
- Nearly 100% polarization
- Monoenergetic:
  - 28 MeV/c for $\pi^{\pm}$ decay
  - 220 MeV/c for $K^{\pm}$ decay
  - Expected to reach $8 \times 10^{8}\ \mu^{+}/s$ in SHINE

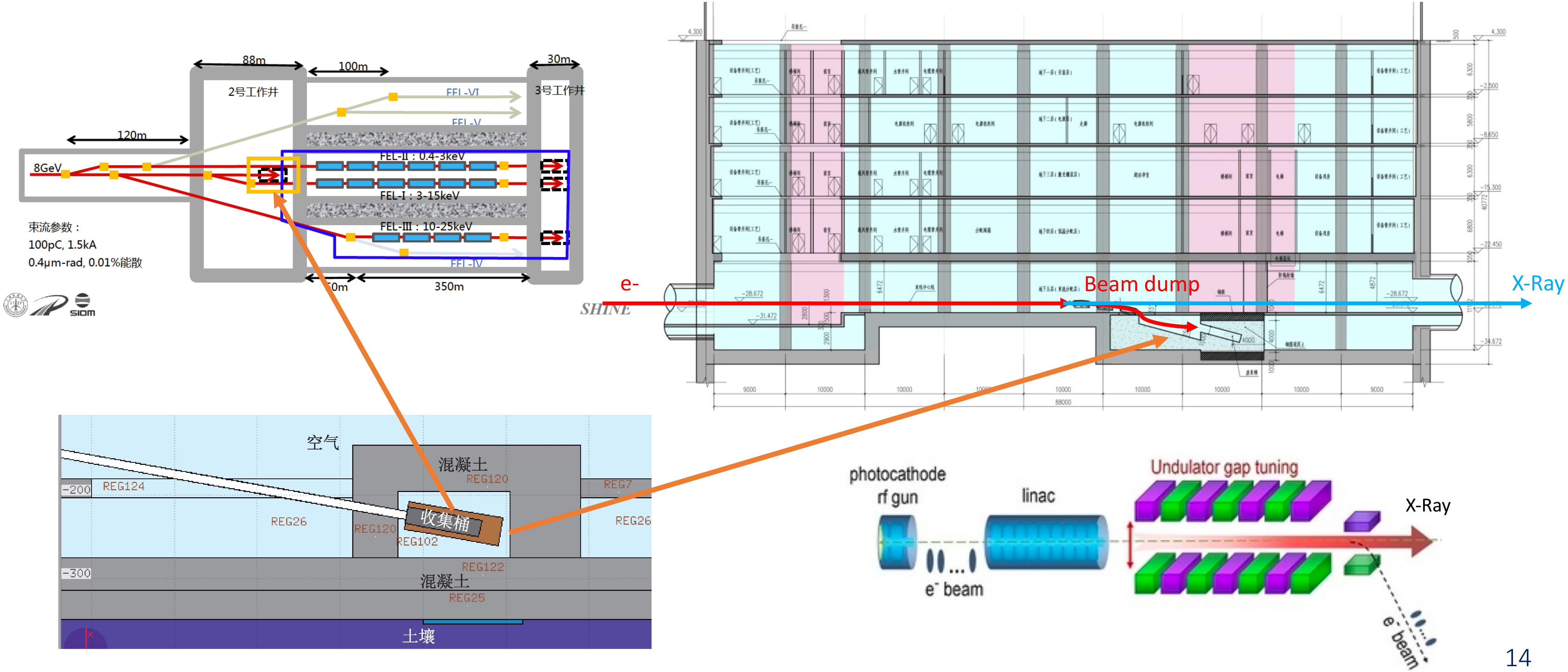




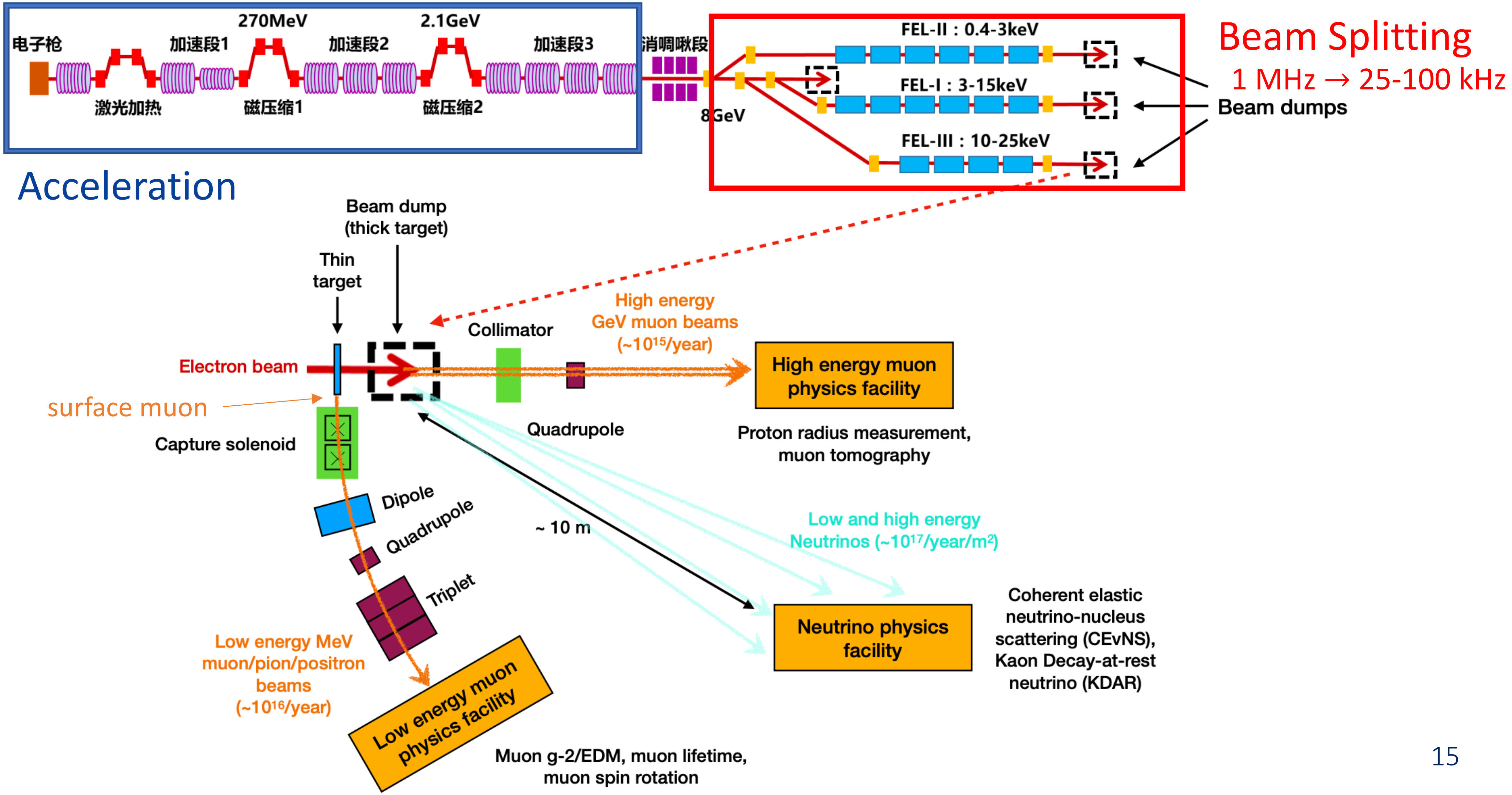
Parity violation weak decay



Schematic of SHINE Beam Dump



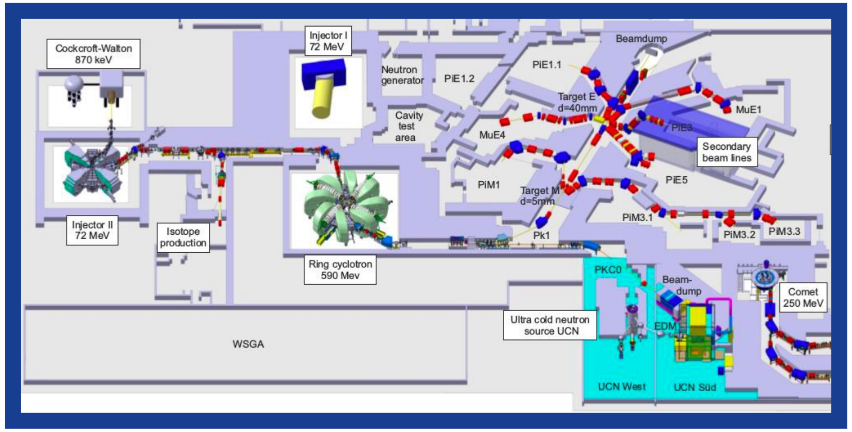
Build a muon source based on SHINE



Advantages of this muon source

- Using to-be-dumped electron beam
- No need to build a new accelerator
  (SHINE costs 10 billion RMB!!!)
- Can be driven by a LWFA electron accelerator
  - Accelerate to ~GeV electron within 20m

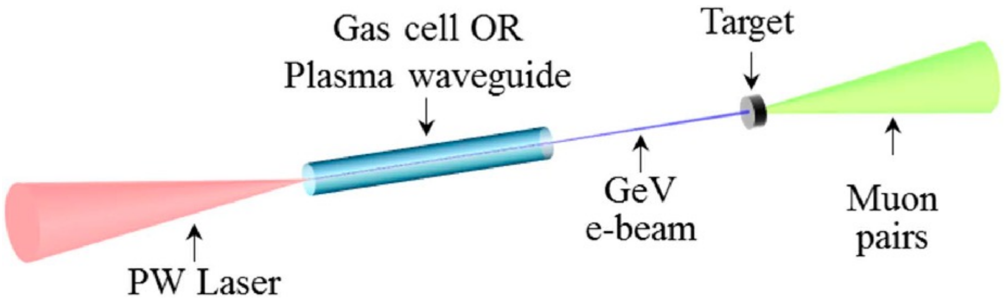
A moving muon source built in a truck?!



120 m

POT muon source in PSI

Laser Wakefield Acceleration (LWFA)



<20 m

Compact muon source

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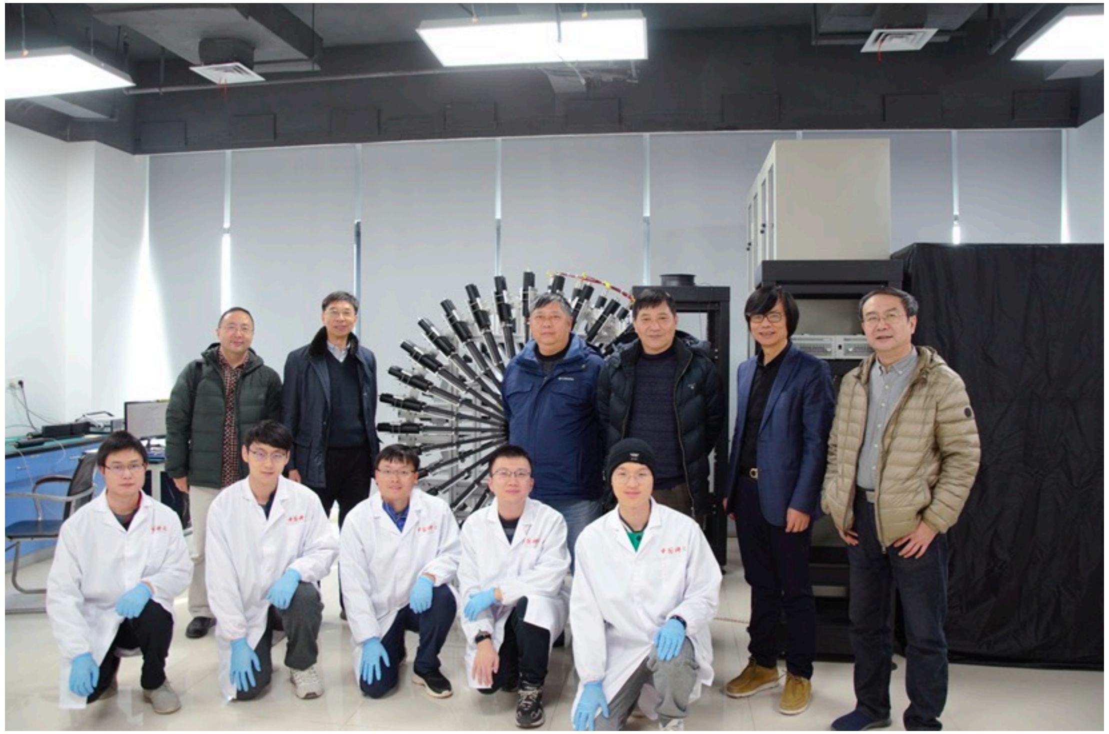
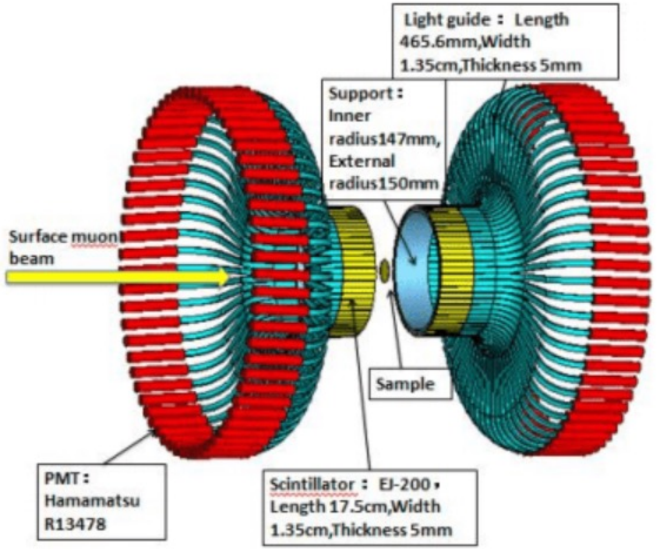
Muon Spin Rotation (μSR)

- Each measurement lasts more than $5\tau_\mu$
- Optimal frequency: $\sim 100\ \mathrm{kHz}$
- China's first MuSR prototype has been built in USTC

中国首台MuSR谱仪样机部分探测器在英国完成初步测试



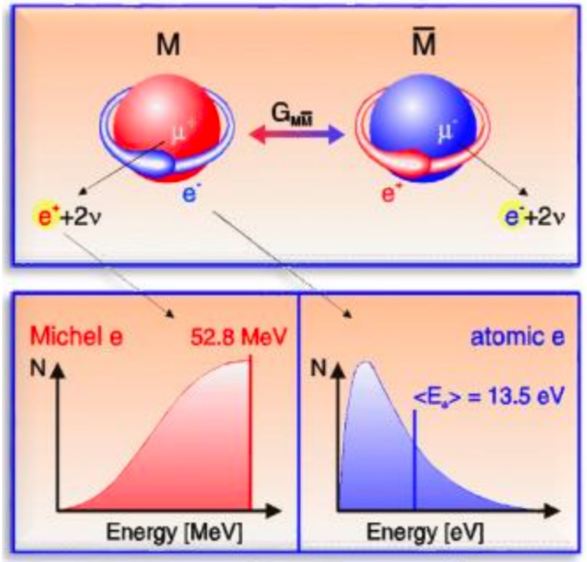
https://pba.ustc.edu.cn/2022/0914/c31828a568272/page.htm



128路μSR谱仪整体设计图

Mu-$\overline{\text{Mu}}$ conversion

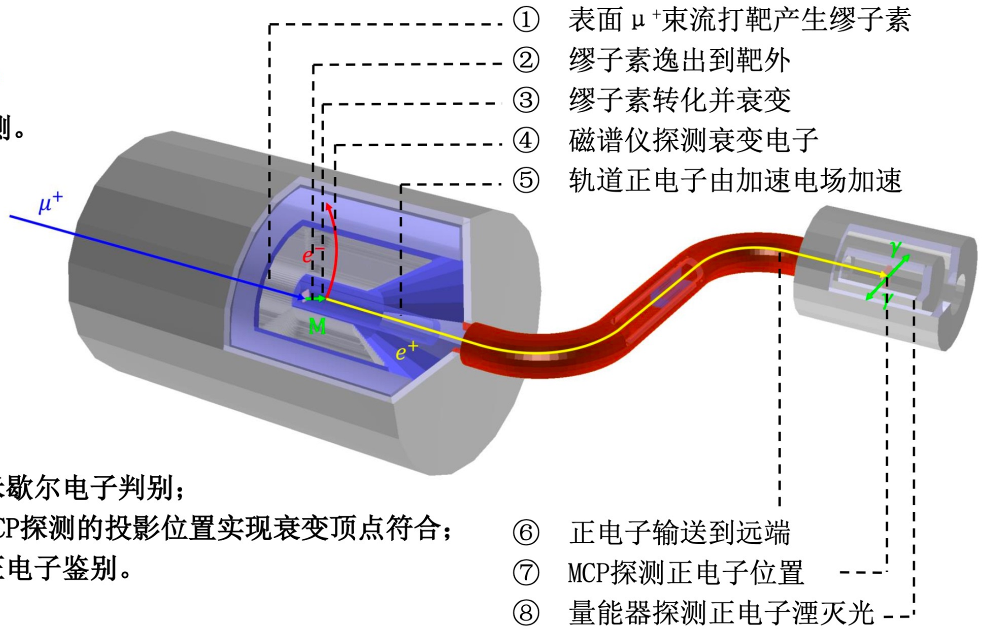
- Mu- $\overline{\text{Mu}}$ conversion is a double lepton flavor violating process
- $\overline{\text{Mu}}$ is detected through atomic e^+ (low energy) and decayed e^- (high energy)
- Measurement duration: $10 - 20\ \mu s$
- Prof. Jian Tang (SYSU) is leading the R&D of this experiment (MACE)



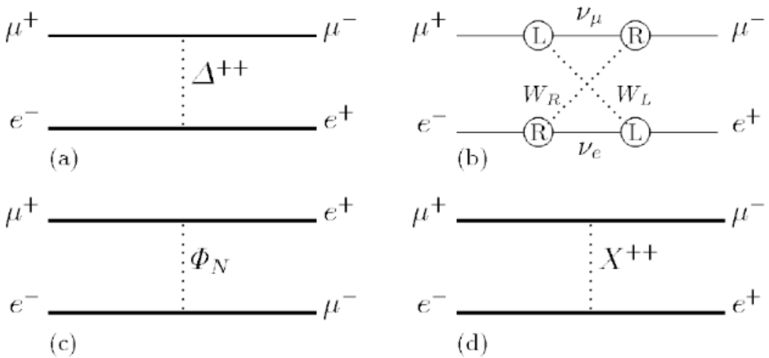
基本方法：

磁谱仪、MCP、量能器

三个探测器的符合探测。



- 通过磁谱仪实现米歇尔电子判别；
- 通过谱仪径迹和MCP探测的投影位置实现衰变顶点符合；
- 通过量能器实现正电子鉴别。



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Summary

- Current proton-driven muon sources are either low-repetition-rate pulsed sources or continuous wave sources, which is not optimal for muon decay experiments
- An ideal high-repetition pulsed muon can be built based on a to-be-dumped electron beam in the SHINE facility
  - Bunch rate: 25-100 kHz
  - 10^3 muons per bunch
- Our simulation predicts SHINE muon source will produce both surface muon and high-energy muon for different experiments
- Any new ideas for muon-related physics are very welcome!

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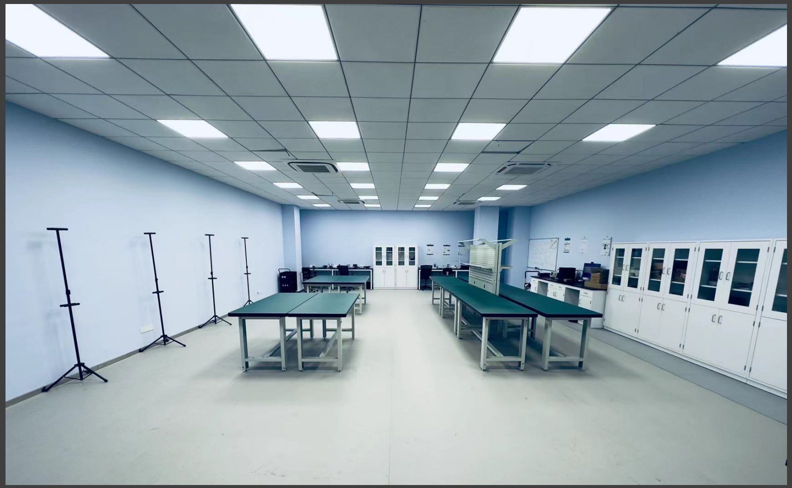
Group dinner in Zhangjiang

Group dinner in Minhang



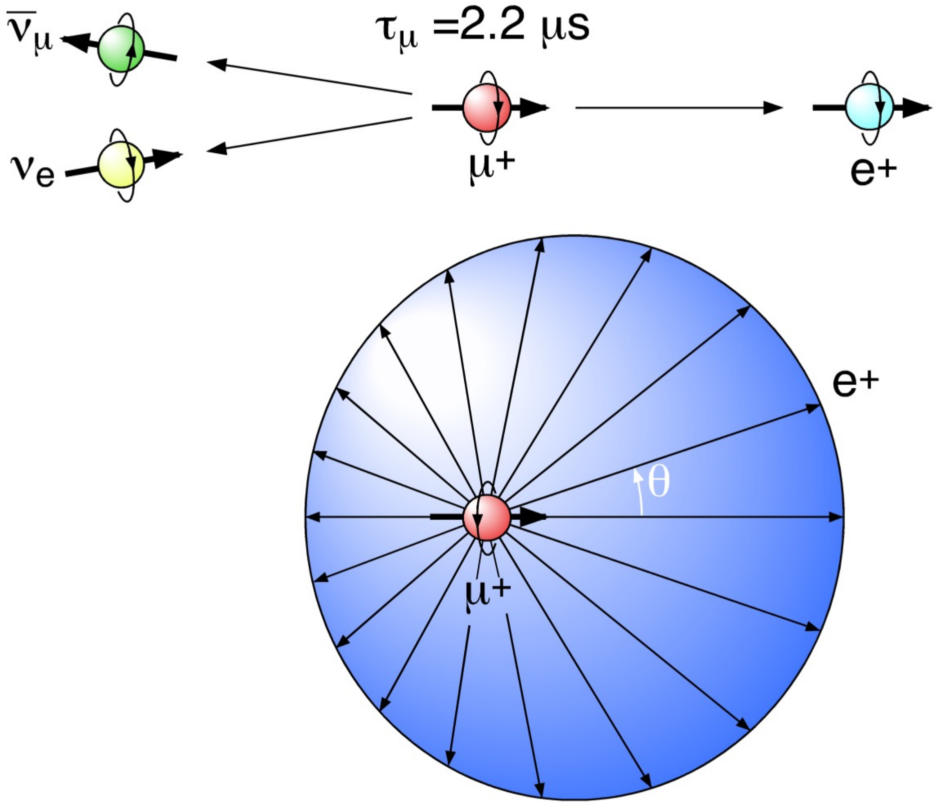
我们项目获得上海市《基础研究特区计划》与李所的支持

团队欢迎热爱缪子物理的伙伴加入！

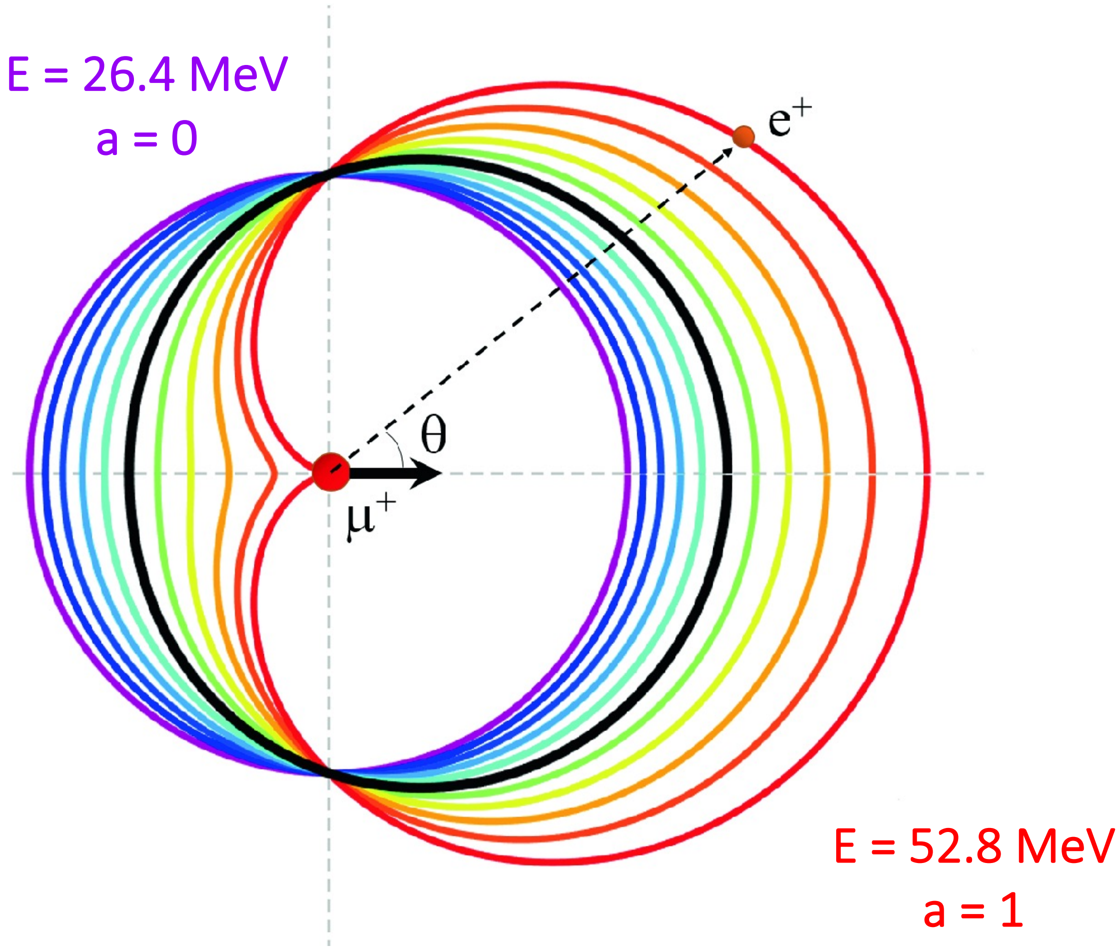
Thanks for listening!

Backup

Muon weak decay



$$\frac{dN_{e^+}}{d\Omega} \propto (1 + AP\cos\theta) = (1 + A\vec{P}(t)\cdot\vec{n})$$



$$a(\epsilon) = (2\epsilon - 1)/(3 - 2\epsilon)$$