基于SHINE的高重频脉冲型缪子源

许金祥，上海交通大学李政道研究所

第二届惠州大科学装置高精度物理研讨会

2024.08.24 @ 中山大学

合作者：上海交大李所--Yusuke Takeuchi、Siew Yan Hoh、吕濛、王江涛、刘方超、黄俊凯、Vadim Grinenko等，上海高研院--王东、万维实、许文贞等

致谢：中山大学--唐健，PSI--Thomas Prokscha、Henning Klauss、Luetkens Hubertus，高能所--鲍煜、USTC--潘子文、苏州实验室--陈建辉、上海市科委基础研究特区计划

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缪子科学简介

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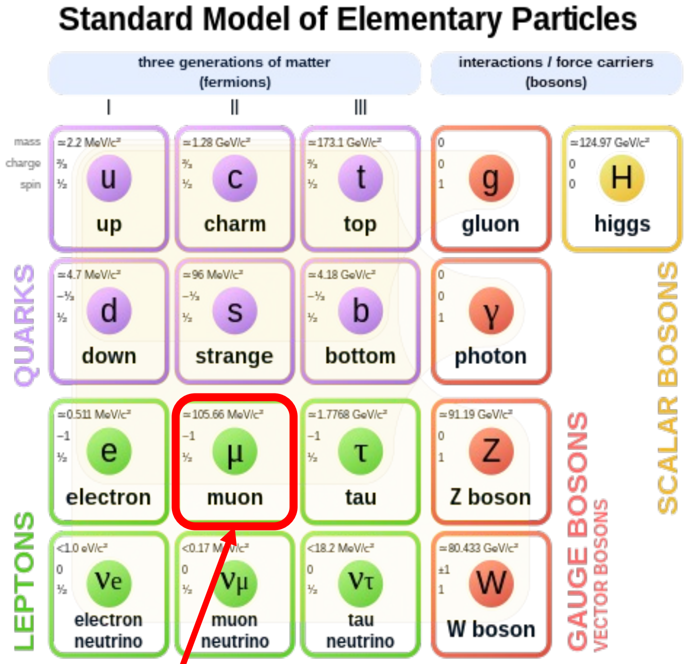
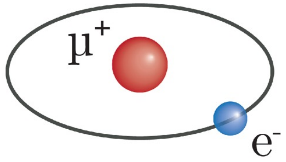


- 标准模型中的第二代费米子
- 正负电荷、自旋1/2、寿命2.2微秒
- $m_\mu \sim 206\ m_e$, $m_\mu \sim 1/9\ m_p$
- 在1936被发现, 物理学诺奖得主 Isidor Rabi：“Who ordered that?!”

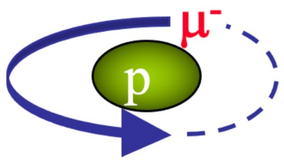
缪子可以以各种形态出现

负缪子

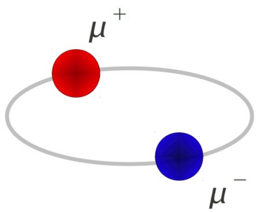
正缪子



缪子偶素



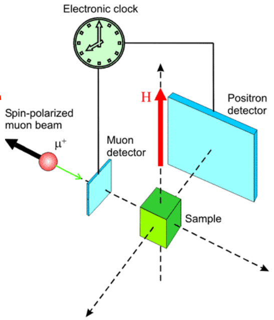
缪原子

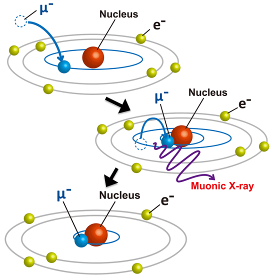


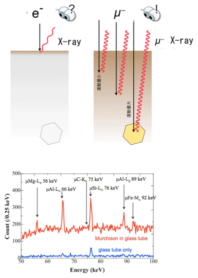
“真”缪子偶素

- 缪子成像
  - 大气层缪子有很强的穿透能力
    - 金字塔、火山、金矿、西安城墙、秦始皇陵

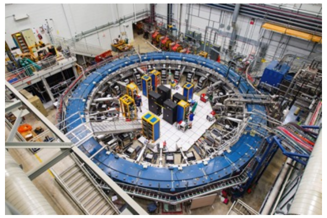
- 凝聚态物理和化学
  - 缪子作为非常灵敏的磁性探针
    - 利用缪子自旋旋转技术研究超导和磁性材料
  - 利用缪原子的X射线进行元素分析
    - 在考古学中研究文物的元素构成



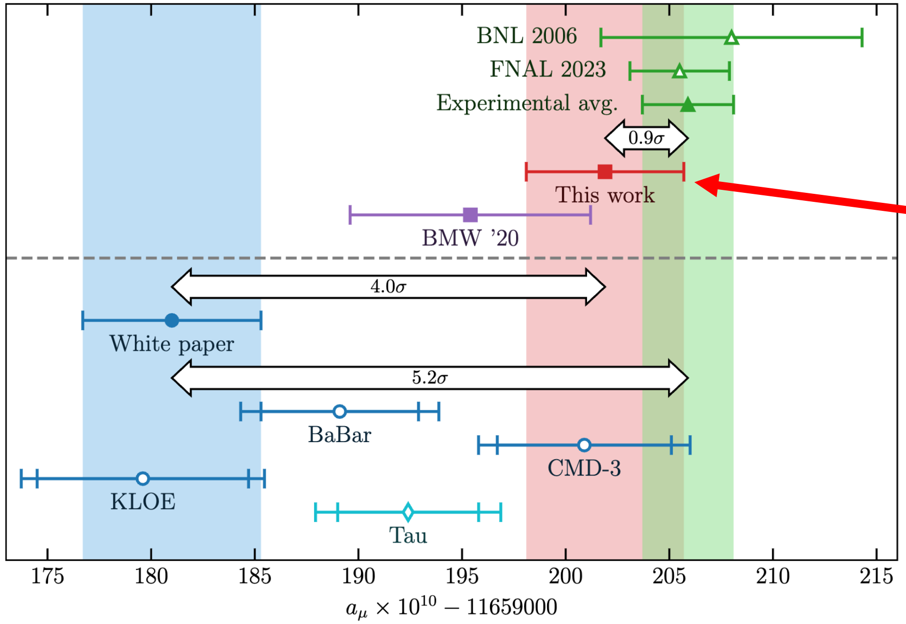




- 粒子物理学
  - 粒子物理标准模型的高精度检验
    - 缪子反常磁矩、弱相互作用的理论结构等等
  - 以缪子为探针寻找超越标准模型的新物理现象
    - 缪子电偶极矩、轻子数破坏过程、超越标准模型新粒子等等



缪子反常磁矩之谜?



High Energy Physics – Lattice

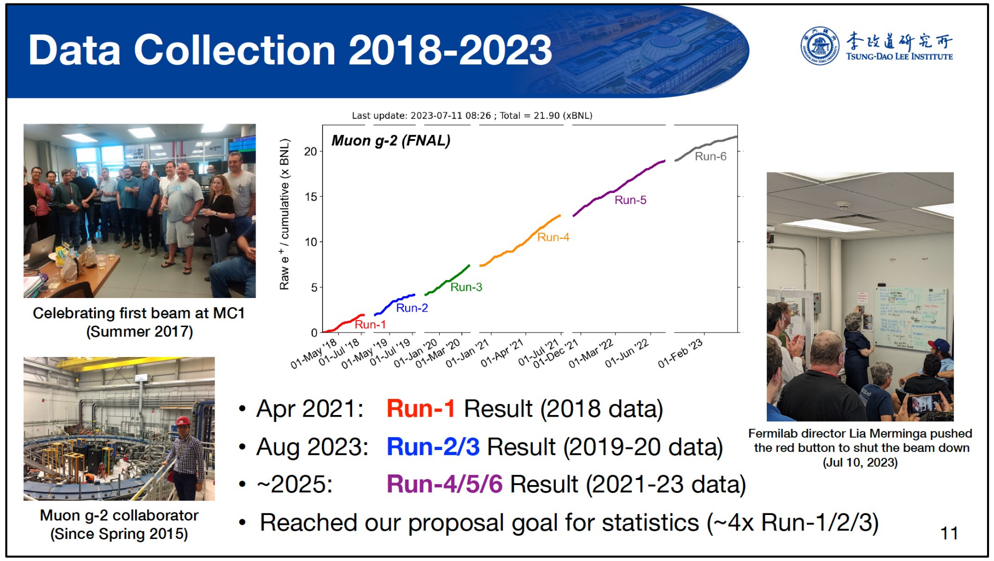
[Submitted on 15 Jul 2024]

High precision calculation of the hadronic vacuum polarisation contribution to the muon anomaly

A.Boccaletti, Sz.Borsanyi, M.Davier, Z.Fodor, F.Frech, A.Gerardin, D.Giusti, A.Yu.Kotov, L.Lellouch, Th.Lippert, A.Lupo, B.Malaescu, S.Mutzel, A.Portelli, A.Risch, M.Sjo, F.Stokes, K.K.Szabo, B.C.Toth, G.Wang, Z.Zhang

We present a new lattice QCD calculation of the leading order hadronic vacuum polarization contribution to the muon anomalous magnetic moment a_μ. We reduce uncertainties compared to our earlier computation by 40%, arXiv:2002.12347. We perform simulations on finer lattices allowing for an even more accurate continuum extrapolation. We also include a small, long-distance contribution obtained using input from experiments in a low-energy regime where they all agree. Combined with other standard model contributions our result leads to a prediction that differs from the measurement of a_μ by only 0.9 standard deviations. This provides a remarkable validation of the standard model to 0.37ppm.

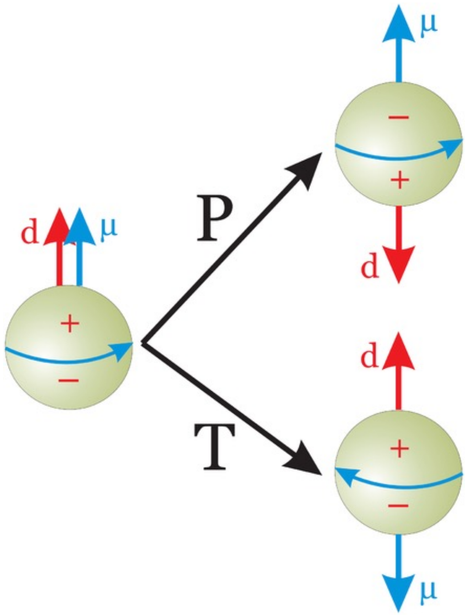
Comments: 55 pages, 31 figures
Subjects: **High Energy Physics – Lattice (hep-lat)**; High Energy Physics – Phenomenology (hep-ph); High Energy Physics – Theory (hep-th)
Cite as: arXiv:2407.10913 **[hep-lat]**
(or arXiv:2407.10913v1 **[hep-lat]** for this version)
https://doi.org/10.48550/arXiv.2407.10913



***Phys. Rev. Lett.* 126, 141801 (2021) , *Phys. Rev. Lett.* 131, 161802 (2023)**

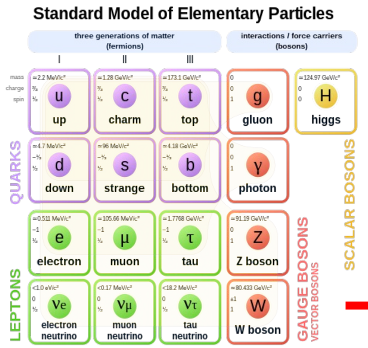
缪子电偶极矩和CP破坏

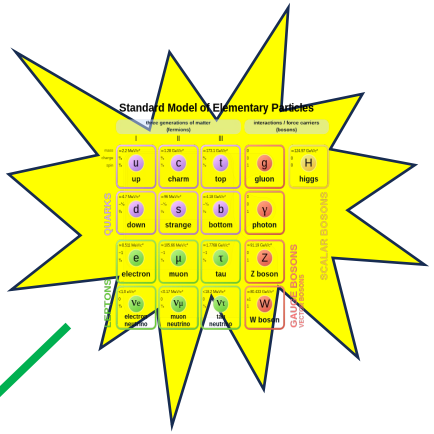
- 除了磁矩（自旋）以外，缪子也可以拥有电偶极矩！
  - 电偶极矩破坏时间反演对称性（T->CP), 对新CP破坏非常灵敏的探针！



$$\vec{\mu} = \frac{ge}{2m}\vec{s}$$

$$\vec{d} = \frac{\eta e}{2mc}\vec{s}$$



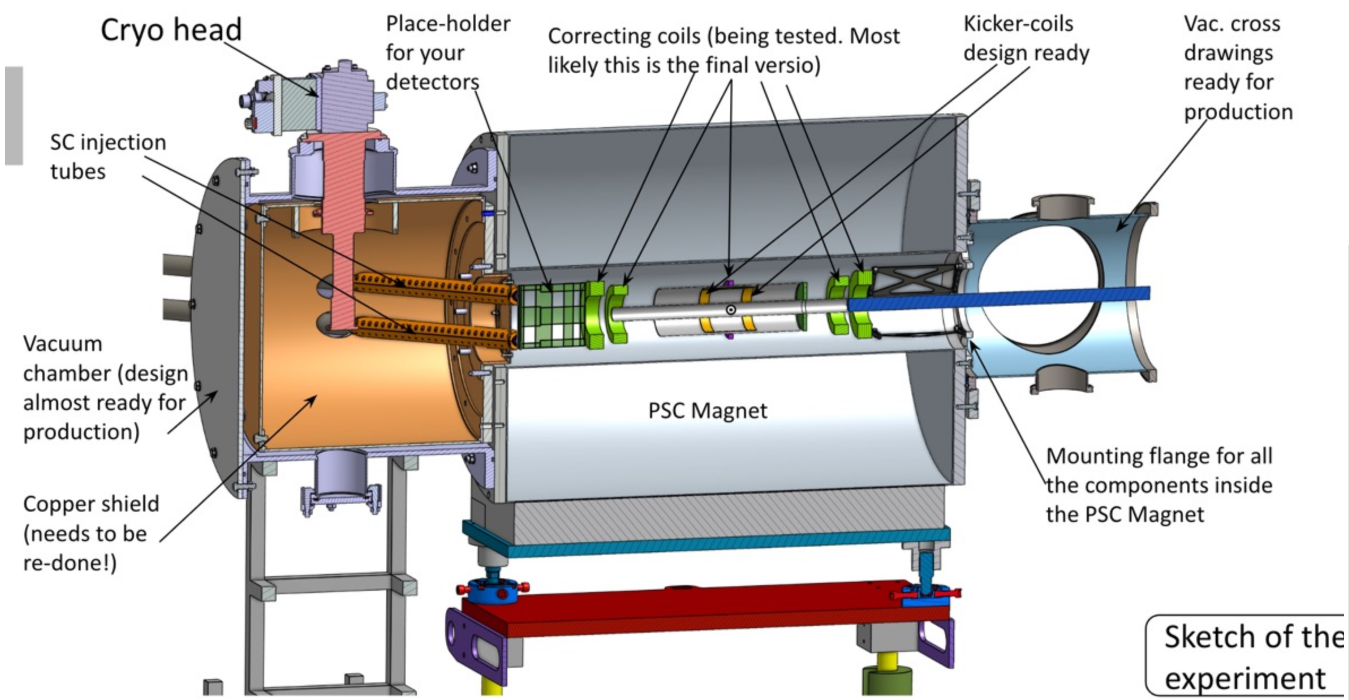


实验值（上限）	~ 0.0000000000 000000001
新物理	~ 0.0000000000 0000000000 XXXXXXXXXX XXXXXXXX
标准模型	~ 0.0000000000 0000000000 0000000000 00000001

Phys. Rev. D 80 (2009) 052008, *Phys. Rev. Lett.* 125 (2020), 241802, *Phys. Lett. B* 831 (2022) 137194

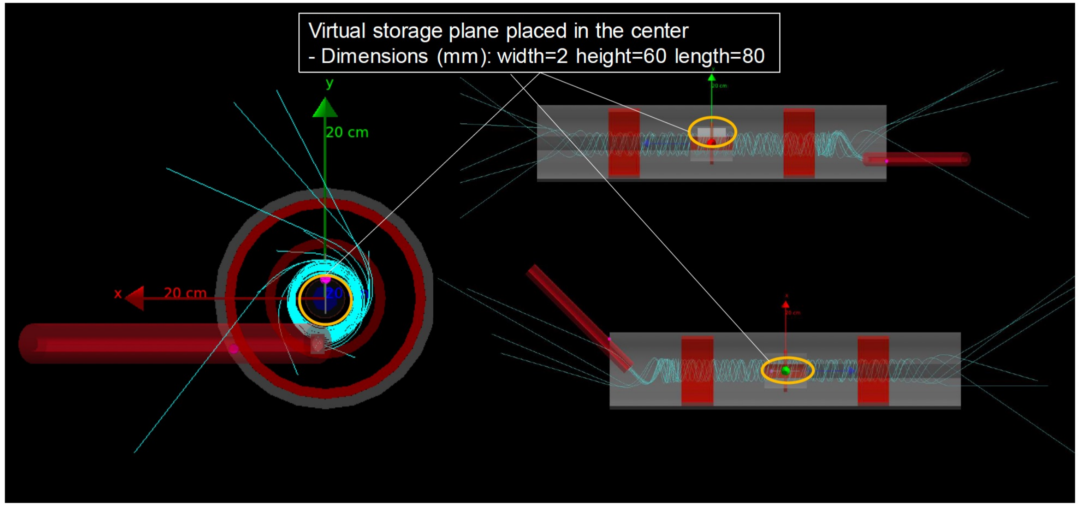
缪子电偶极矩实验 muEDM@PSI

目标 6 x 10^{-23} e cm

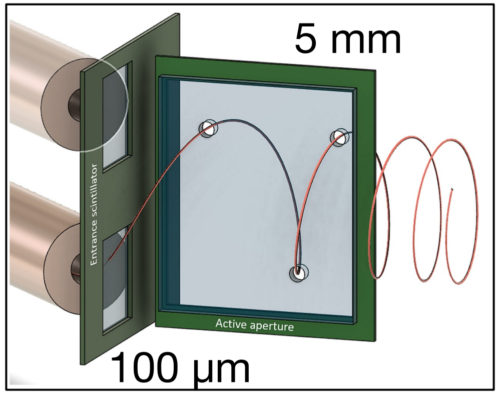


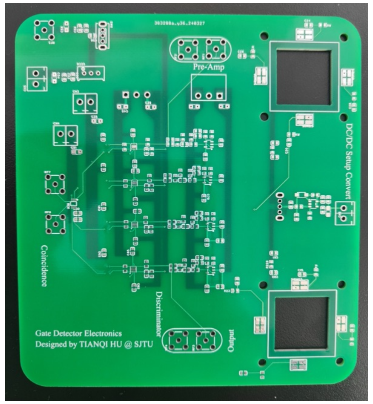
Sketch of the experiment

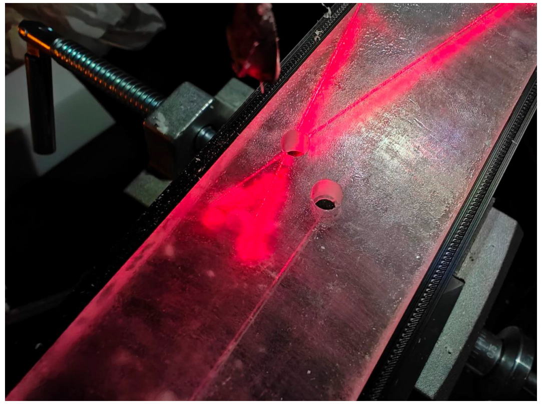
基于G4Beamline的束流注入和储存研究
(利用Bayesian Optimization方法优化)

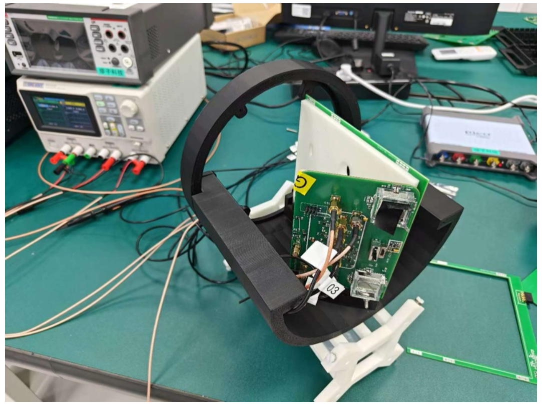


缪子入射触发系统研发（~10 ns）









今年10月份到PSI
进行为期2个星期
的Beam Test

国际上的缪子源装置

李政道研究所
TSUNG-DAO LEE INSTITUTE

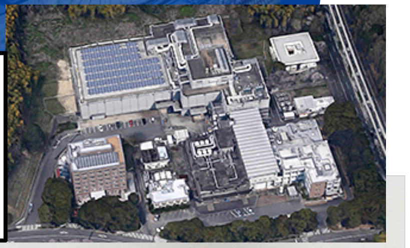
★ **TRIUMF**
TWIST, Mu studies

Fermilab
Muon g-2, Mu2e

★ **Paul Scherrer Institut (PSI)**
muEDM, MEG II, Mu3e, MUSE, CREMA, etc

★ **ISIS**
muSR, elemental analysis

★ **RCNP**
muSR, elemental analysis



RAON
muSR

★ **J-PARC**
Muon g-2/EDM, COMET, DeeMe, Mu HFS/1S-2S, etc

SHINE
muSR, EDM, tomography, etc

ORNL
muSR

★ in operation (for users)

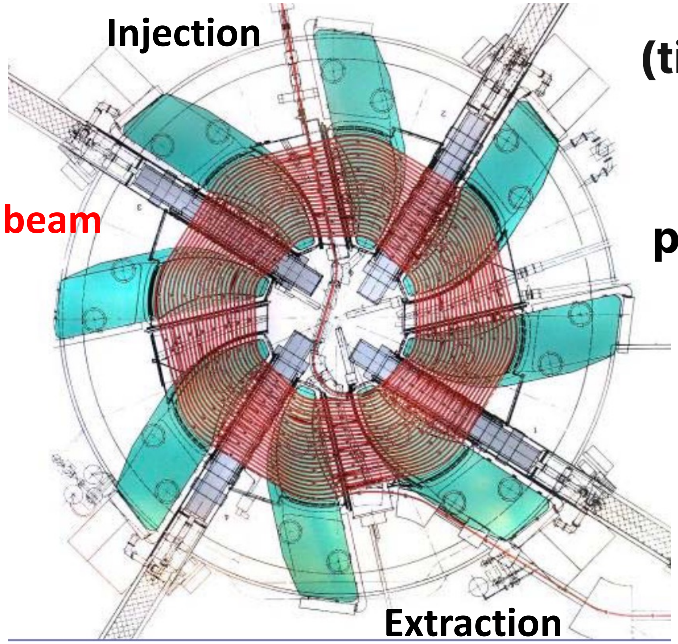
HIAF/CiADS
Muon Science, MACE

CSNS
Muon Science

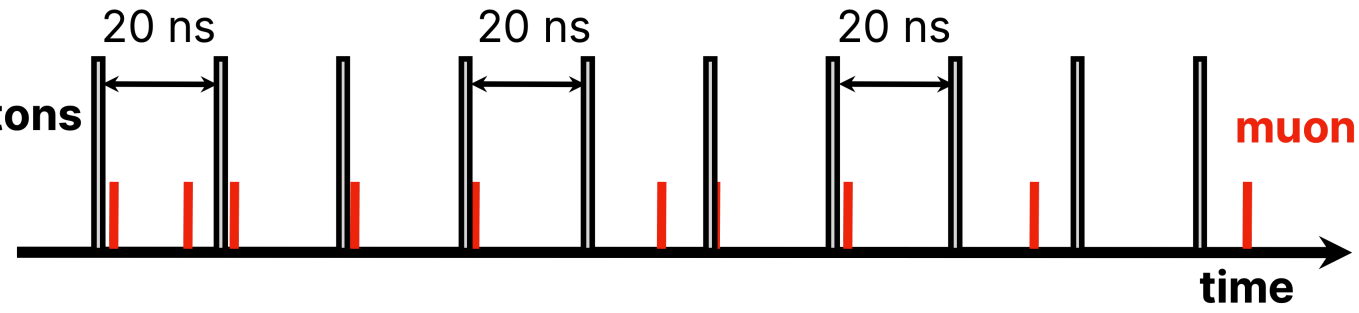
连续式缪子源（回旋加速器）

李政道研究所 Tsung-Dao Lee Institute

590 MeV Ring Cyclotron @ PSI



PSI Ring Cyclotron, 50 MHz continuous beam: muons arrive randomly (time structure smeared out by pion life time of 26 ns ~ order of rep-rate)



- Muon counter required to measure arrival time
- Less muon (positron) at a once
  ⇨ Only few positron detectors needed

A large number of bunches can be accelerated simultaneously (continuous beam)

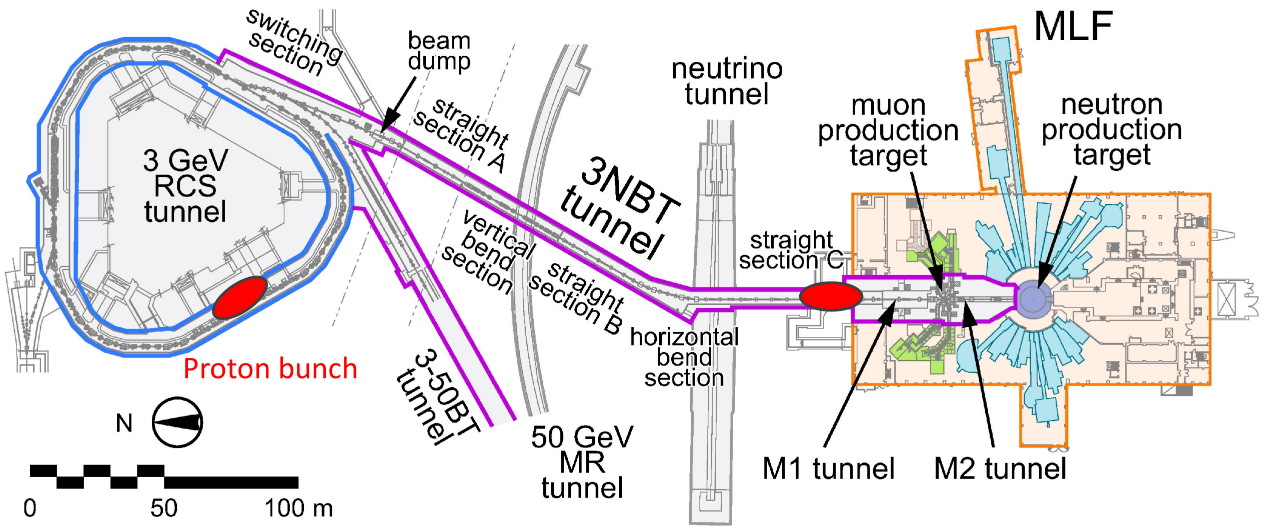
Typical characteristics taken from "Introduction to Muon Spin Spectroscopy"

- Muon event rate: To avoid pile-up events, limited ~ 20 M events/h with 10 μs time window
- Time resolution: Limited only by detector and electronics ~ 60 ps
- Beam size: Can be reduced to a few mm^2

Courtesy Yusuke Takeuchi

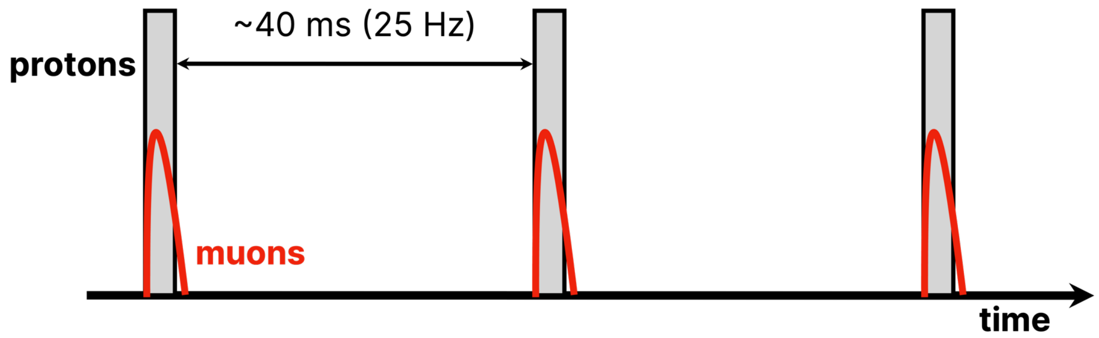
脉冲式缪子源（同步加速器）

3 GeV Rapid-cycling Synchrotron @ J-PARC



Quantum Beam Sci. **2017**, 1(1), 11

J-PARC RCS, 25 Hz pulsed beam: all protons/muons in one bunch



- Can be synchronized with accelerator
  ⇨ No muon counter required
- Long interval helps us to reduce background
- Large number of muons (positron) at a once
  ⇨ Large number of positron detector needed

Only one (two) bunches can be accelerated at the same time (pulsed beam)

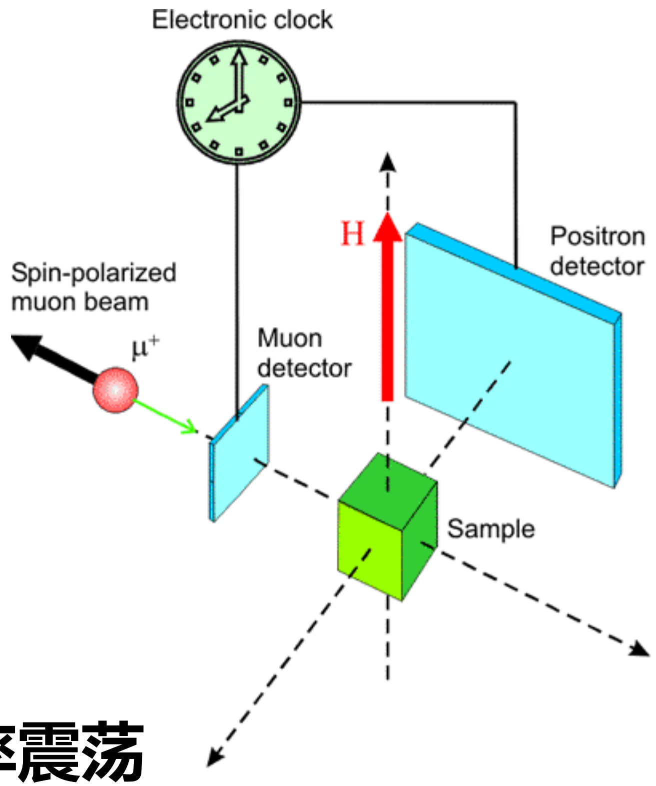
Typical characteristics taken from “Introduction to Muon Spin Spectroscopy”

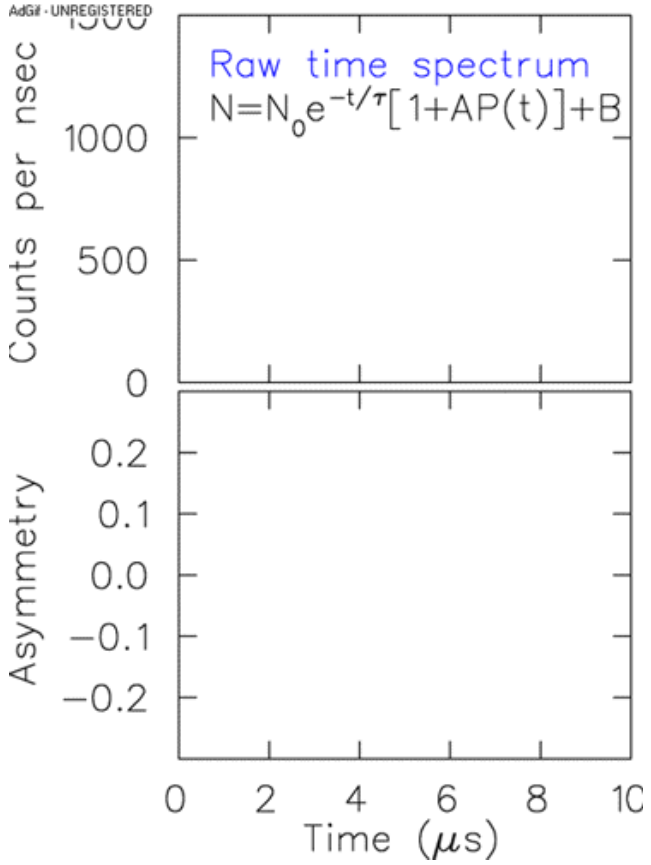
- Muon event rate: Limited by detector granularity ~ 150 M events/h
- Time resolution: Limited only by muon pulse width ~ 40 ns
- Beam size: Basically a few cm^2

Courtesy Yusuke Takeuchi

缪子自旋谱仪 μSR 原理

- 缪子最重要的应用
  - 超导材料和磁性材料
- 缪子的平均寿命2.2微秒
  - 衰变成电子和两个中微子
- 由于宇称不守恒
  - 电子的平均方向=缪子的自旋方向
- 所探测到的电子数量以进动频率震荡
  - 从拟合可得到频率

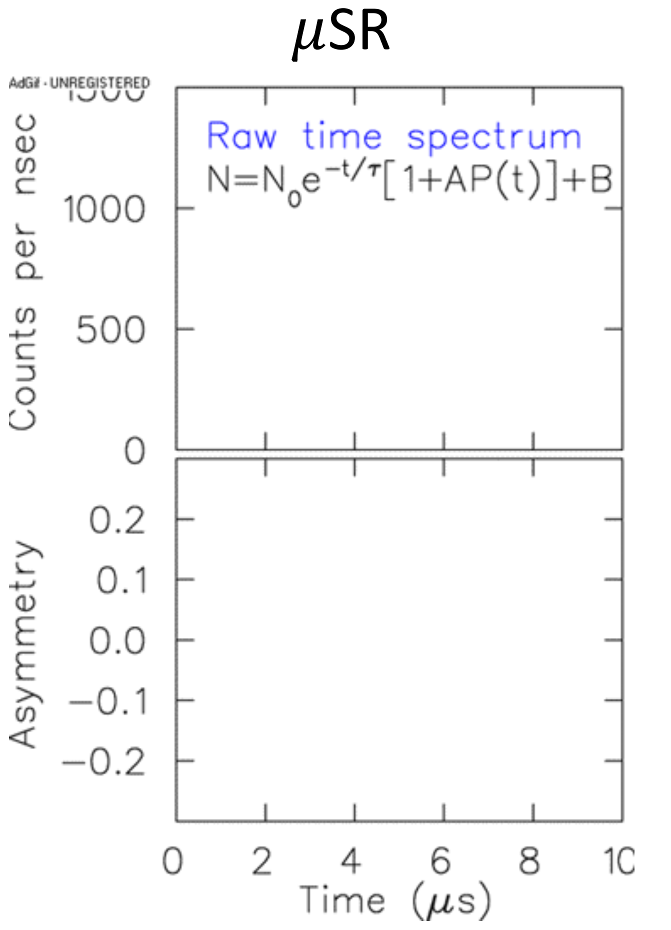




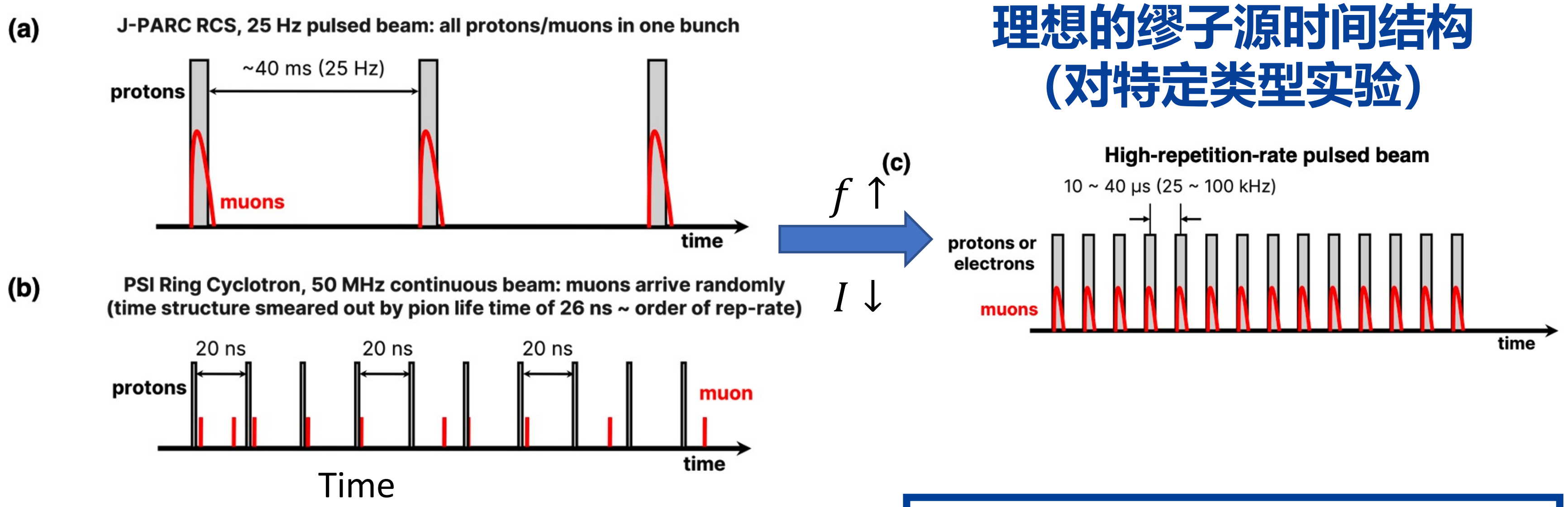
$$\frac{N_F(t)-N_B(t)}{N_F(t)+N_B(t)} = A_0 \cdot P(t) = A(t)$$

TRIUMF http://neutron.magnet.fsu.edu/muon_relax.html

传统缪子源的局限：重复频率



Typical measurement period: a few muon lifetimes ~ 10 μs



理想的缪子源时间结构（对特定类型实验）

Pulsed muon source

- Long waiting time until the next pulse
- Detector dead time limitation
- Low duty cycle

DC muon source

- Allows only 1 muon every 10 μs
- Most of the muons are kicked away

Ideal Muon Source

- Higher repetition rate: tuned to 5-10x the muon lifetime in the experiment
- Less muon per bunch, less pileup ($\sim 10^2 - 10^3\ \mu^+/\text{pulse}$)

JACoW IPAC2023 (2023) TUPA087

高重频缪子源在不同实验中的需求

李政道研究所 TSUNG-DAO LEE INSTITUTE

Muon EDM

IOP PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. 37 (2010) 085001 (7pp) doi:10.1088/0954-3899/37/8/085001

Compact storage ring to search for the muon electric dipole moment

A Adelmann[1], K Kirch[1,2], C J G Onderwater[3] and T Schietinger[1]

[1] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
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[3] Kernfysisch Versneller Instituut and University of Groningen, NL-9747AA Groningen, The Netherlands

of the difference between the measured anomalous magnetic moment and its SM prediction. It would furthermore test various SM extensions, in particular those that do not respect lepton universality.

In view of the possible advent of new, more powerful pulsed muon sources, the same experimental scheme can be realized but with considerably more muons per bunch being injected into the ring. It appears realistic to expect accelerators with on the order of 100 kHz repetition rates and more than 10^4 muons stored per bunch. The statistical sensitivity of the described approach would then reach down to a few times 10^{-25} e cm. Although systematic issues at this level of precision have been discussed in some detail in [19], more detailed studies would be needed.

MuMuBar

SciPost — SciPost Phys. Proc. 5, 009 (2021)

Muonium-antimuonium conversion

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PAUL SCHERRER INSTITUT PSI
Review of Particle Physics at PSI
doi:10.21468/SciPostPhysProc.5

$\overline{\mathrm{M}}$ grows in time to a maximum at $2\tau_\mu$ (see Figure 9.5). Thus the ratio of M to $\overline{\mathrm{M}}$ decays grows with t^2. In case of a multiple coincidence, as in MACS, this implies that the potential $\overline{\mathrm{M}}$ signal/background increased. Therefore a new experiment should be considered, e.g., in connection with the muon source of a muon collider, provided high muon beam quality, i.e. a narrow μ^+ momentum band at subsurface μ^+ momentum. We note that for such an improved experiment beam repetition rates of up to several 10 kHz with μ^+ bunches of up to $\approx$ μs length would be ideal.

With a new experiment, from the viewpoint of signal to background ratio, an improved value for $G_{M\overline{M}}$ by at least 2 orders of magnitude should be possible, i.e., 4 orders of magnitude in the conversion probability. At such sensitivity there would be strong constraints for the development of models beyond standard theory [5–8].

muSR

Physica B 404 (2009) 1024–1027
Contents lists available at ScienceDirect
Physica B
journal homepage: www.elsevier.com/locate/physb
ELSEVIER

Towards a dedicated high-intensity muon facility

R. Cywinski[a,*], A.E. Bungau[a], M.W. Poole[b], S. Smith[b], P. Dalmas de Reotier[c], R. Barlow[d], R. Edgecock[e], P.J.C. King[e], J.S. Lord[e], F.L. Pratt[e], K.N. Clausen[f], T. Shiroka[f]

[a] School of Applied Sciences, University of Huddersfield, Huddersfield HD1 3DH, UK
[b] ASTeC, STFC Daresbury Laboratory, Warrington, Cheshire WA4 4AD, UK
[c] CEA/INAC, 17, rue des Martyrs, 38054 Grenoble cedex 9, France
[d] School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[e] ISIS Facility, STFC Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK
[f] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

that the threshold for double pion production is ~600 MeV, the second alternative affords higher muon production rates and, therefore, represents the preferred choice.

Proton driver frequency: The 50 Hz pulsed operation of ISIS is sub-optimal for μSR studies. Typically, time resolved spectra are collected over no more than 32 μs (i.e. ~15 muon lifetimes), giving an effective duty cycle of only 0.16%. While advantageous for some types of experiments (e.g. those involving pulsed sample environments), the 50 Hz operation is generally inefficient: ideally a muon-source proton driver should operate at ~25 kHz.

It is important to note that operation at this frequency, with an associated gain in intensity of 100 over ISIS (see above), would actually alleviate detector dead time problems by a factor of 5 with respect to those presently encountered at ISIS. This is illustrated in Fig. 1, where it can be seen that the available muons will be distributed over 500 (i.e. 25 kHz/50 Hz) as many

Muon Lifetime

Toward a high-precision measurement of the muon lifetime with an intense pulsed muon beam at J-PARC

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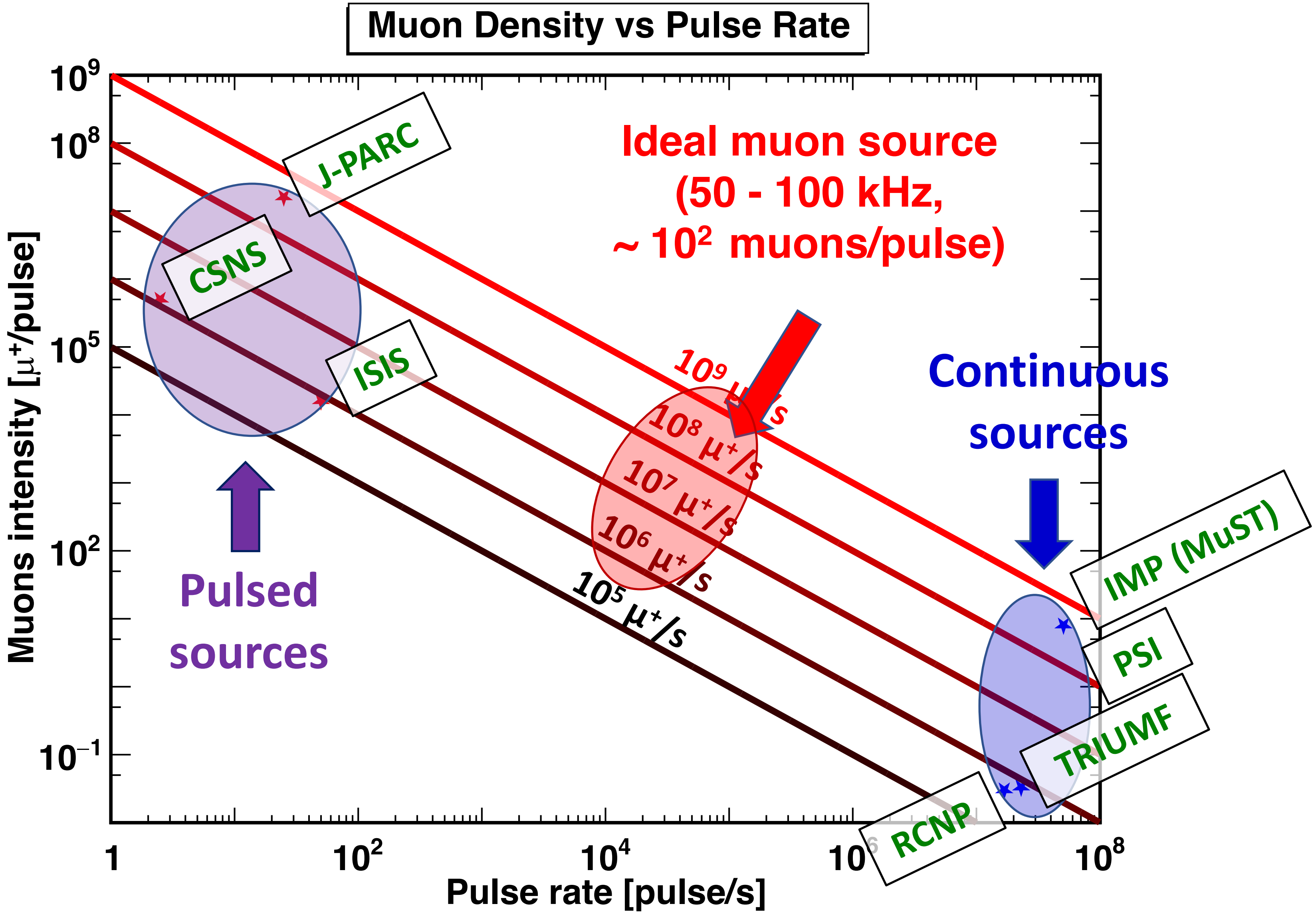
In the MuLan experiment, a continuous muon beam was pulsed with an electrostatic kicker to achieve high statistical precision. In general, an experiment using a pulsed beam is statistically efficient because no trigger pileup occurs. On the other hand, the higher the beam intensity, the higher the requirement on the high-rate tolerance of the detector. The MuLan's positron detector covered 70% of 4π steradians with 170 segments. The contribution of the statistical uncertainty to the precision of 1.0 ppm was 0.95 ppm, and the main systematics was 0.2 ppm each for muon spin rotation (μSR) and detector's gain variations.

A O(100) kHz pulsed muon beam is needed!

理想缪子源所在区域

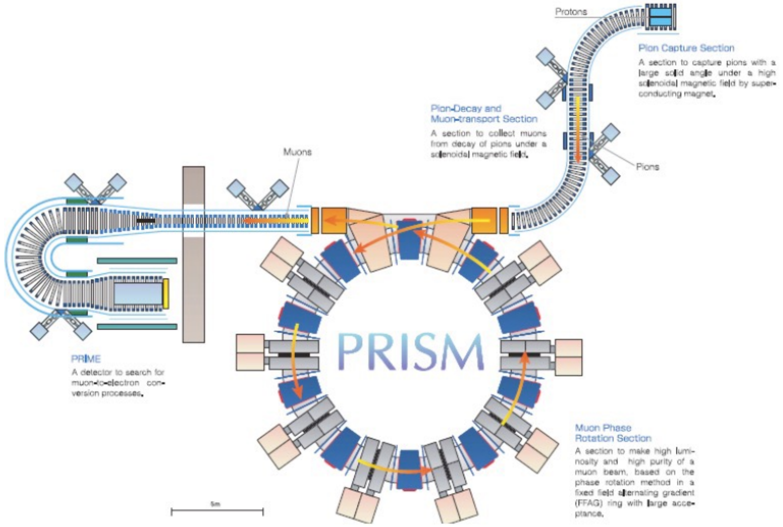


Muon Density vs Pulse Rate
Ideal muon source
(50 - 100 kHz,
~ 10² muons/pulse)
Continuous
sources
Pulsed
sources
J-PARC
CSNS
ISIS
IMP (MuST)
PSI
TRIUMF
RCNP
10⁹ μ⁺/s
10⁸ μ⁺/s
10⁷ μ⁺/s
10⁶ μ⁺/s
10⁵ μ⁺/s
Muons intensity [μ⁺/pulse]
Pulse rate [pulse/s]

高重频质子束流方案

李政道研究所 TSUNG-DAO LEE INSTITUTE

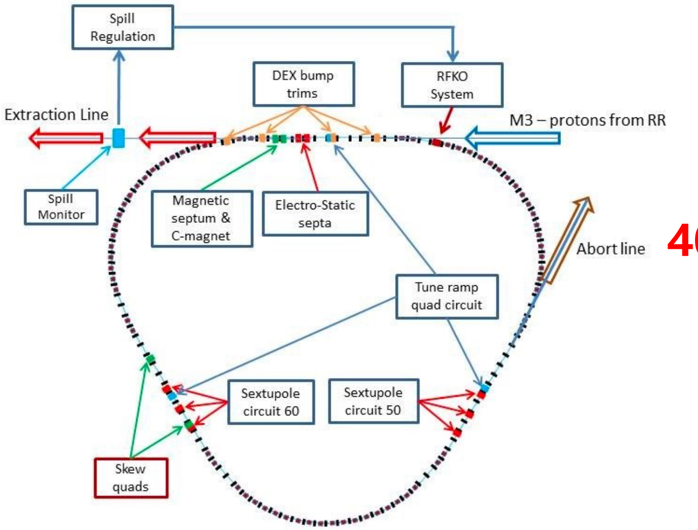
Fixed Field Alternating Gradient （FFAG）Synchrotron @ J-PARC



- **Intensity**：10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy**：20±0.5 MeV (=68 MeV/c)
- **Purity**：π contamination < 10^{-20}

Research in progress

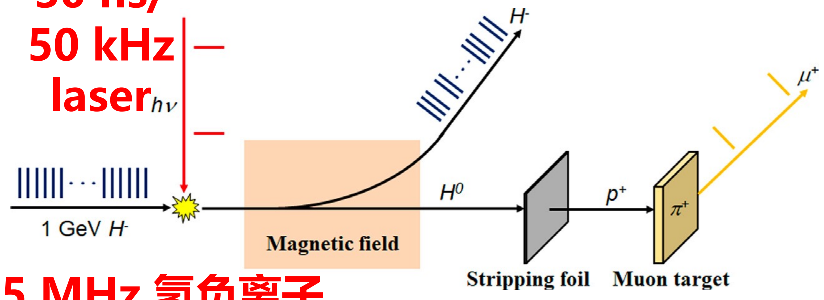
Resonant extraction Mu2e@FNAL



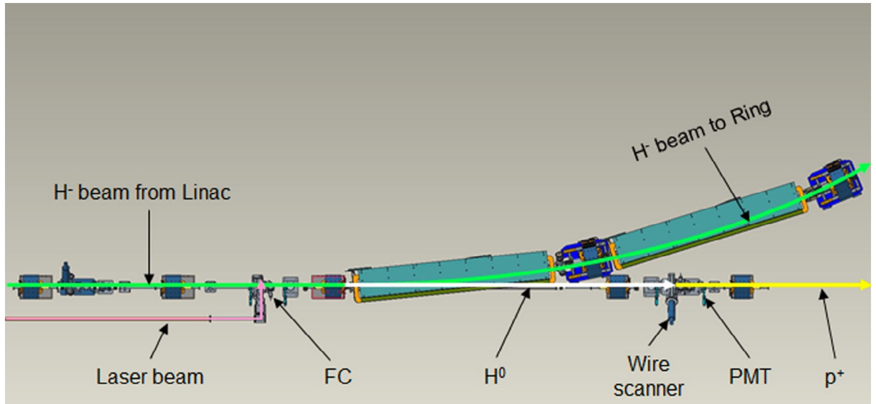
Effectively achieve 0.59 MHz!
(same idea for COMET@J-PARC)

Laser neutralization @ ORNL

30 ns/ 50 kHz laser



402.5 MHz 氢负离子



Successfully demonstrated 30 ns/50 kHz proton pulses in 2019

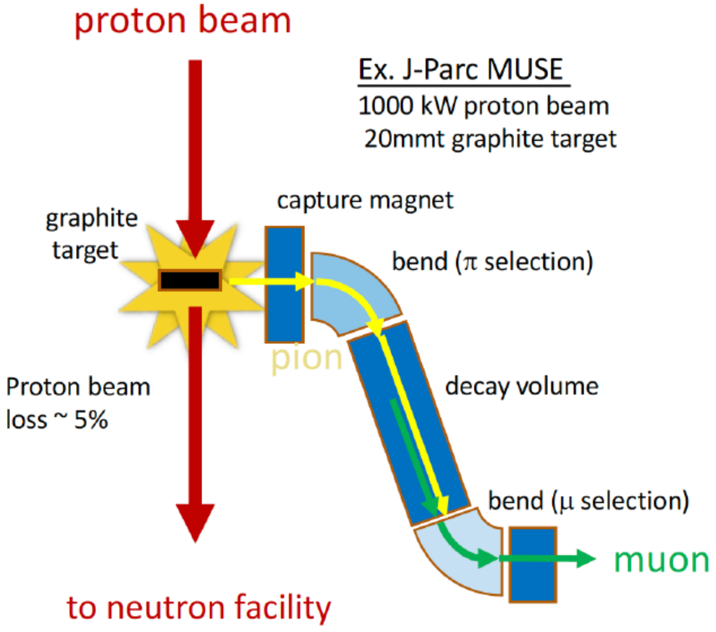
NIM A 962 (2020) 163706

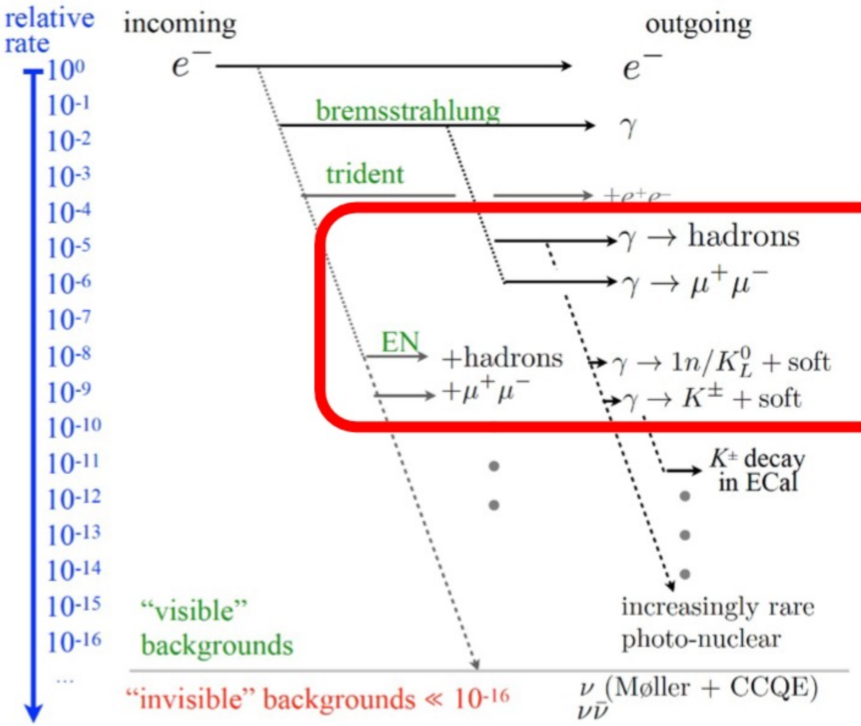
质子打靶与电子打靶的对比

质子打靶

pp Collision

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





Motivated by the LDMX/DarkSHINE project
Can I turn background into signal?

电子打靶

Photo-nuclear process

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

Bethe-Heitler process
(Dimuon production)

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

without pion production!

基于加速器电子的缪子源方案（1960s-)

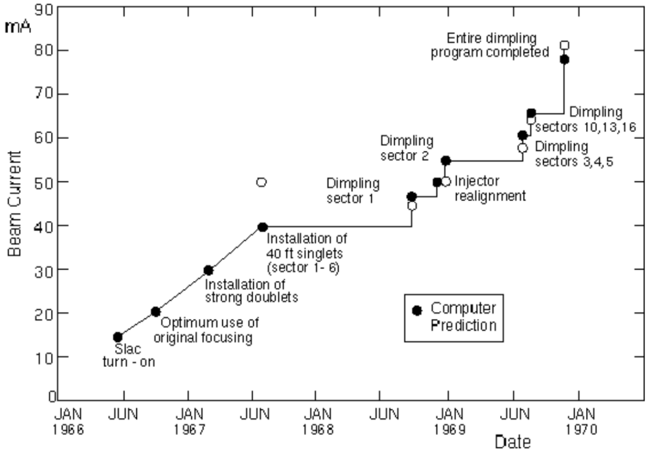
李政道研究所 TSUNG-DAO LEE INSTITUTE

SLAC: The Program

At the Stanford Linear Accelerator Center attention is shifting from construction and testing of the two-mile machine to the actual experimental program. Large spectrometers, bubble chambers, spark chambers and special beams are being prepared for a variety of experiments that will utilize the unusually high resolution, intensity and energy of the accelerator.

WITH TRIAL RUNS NEARING completion, the Stanford Linear Accelerator Center is getting ready to carry out its initial experimental program. This program has been planned to expoit fully the special properties of the two-mile-long electron beam—its 20-GeV energy, very good optical properties and great intensity. These features will permit the production of useful beams of electrons, positrons, photons, muons and even strongly interacting particles such as pions, kaons and antiprotons. The electron, positron and photon beams will have the highest energy presently available (except for very weak beams produced by the decay of neutral pions at the CERN

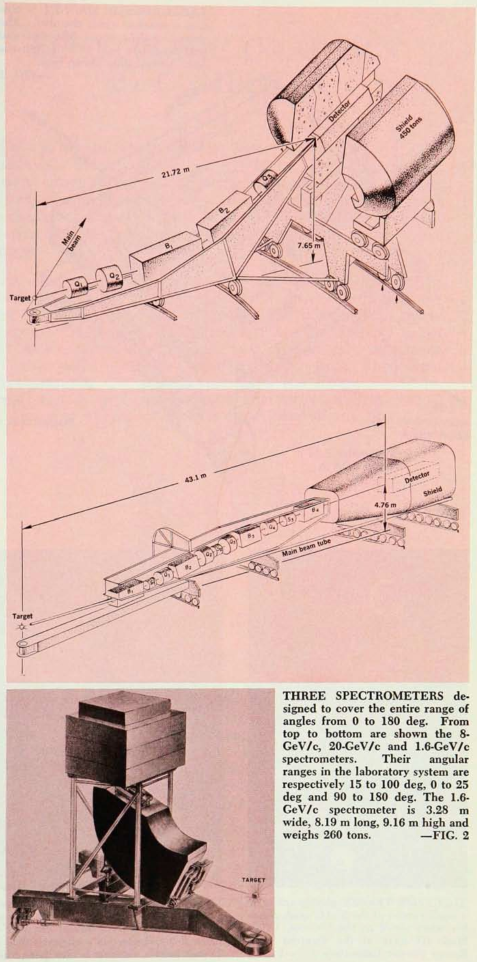
A muon-beam transport system capable of momentum analyzing and transporting up to 14-GeV muons is being assembled. The SLAC muon beam has several advantages. The main one is that the muons are created in pairs, as in electron-positron pair production, whereas at proton accelerators muon beams are derived from the decay in flight of mesons produced in the primary proton interaction. Consequently the SLAC muon beams originate from a highly localized source



that, just as in optical beams, allows improved resolution at the detector. Furthermore, the pion contamination in the beam can easily be held to 1 in 10^7 muons—a very important feature because the pions are strongly interacting. The muon beam at SLAC originates from electrons hitting a copper target followed by a filter containing 16 attenuation lengths of beryllium. The muons will degrade in energy by 15% and multiple scatter (this somewhat increases the effective source size but not seriously) while the pions are reduced in intensity by a factor of 3×10^{-7}. By adding more filter material this number can be made almost arbitrarily small.

A high-energy secondary-particle beam which can produce charged pions, kaons or protons by means of a beam transport system coupled with a radiofrequency particle separator is being constructed at SLAC. Such beams have already been established both at CERN and Brookhaven, but require two such separators—one for bunching in time and the other for mass separation. At SLAC the linear accelerator provides inherent internal bunching and only one separator is required. Thus the beam transport systems are simpler and, more important, shorter so that attrition from decay is less damaging. This system will separate kaons from pions and protons at any energy between 10 and 15 GeV.

It is interesting to compare the properties of the SLAC beams of strongly interacting particles and the beams at the large proton accelerators especially since there exists some misunderstanding as to the nature of the linear accelerator. It has a high repetition rate (360 cycles/sec) of short bursts (no longer than 1.7 microsec), and for some measurements, especially coincidence counting, this is a poor duty cycle compared with circular machines. For example, the Brookhaven AGS pulses for 300 millisec once every three seconds, and is "on" about 10 percent of the total time. At SLAC the corresponding number is 0.06%, a factor of 160 less. This must be partially compensated by determining the interaction kinematics from precise measurements of displacement and angle alone, using the large, complicated apparatus described above. Nev-



THREE SPECTROMETERS designed to cover the entire range of angles from 0 to 180 deg. From top to bottom are shown the 8-GeV/c, 20-GeV/c and 1.6-GeV/c spectrometers. Their angular ranges in the laboratory system are respectively 15 to 100 deg, 0 to 25 deg and 90 to 180 deg. The 1.6-GeV/c spectrometer is 3.28 m wide, 8.19 m long, 9.16 m high and weighs 260 tons. —FIG. 2

Physics Today **20** (4), 43–52 (1967)

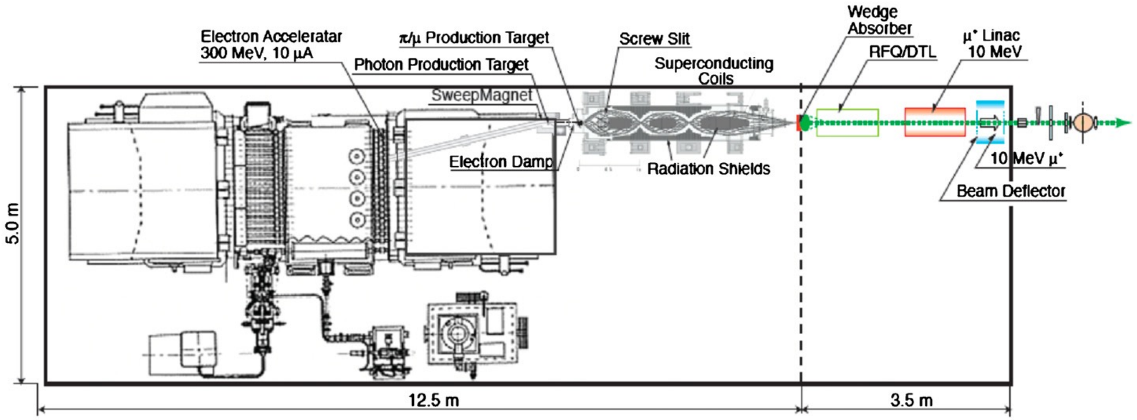
基于加速器电子的缪子源方案（2009-）

李政道研究所 TSUNG-DAO LEE INSTITUTE

Physica B 404 (2009) 1020–1023
Contents lists available at ScienceDirect
Physica B
journal homepage: www.elsevier.com/locate/physb

Compact muon source with electron accelerator for a mobile μSR facility

K. Nagamine[a,b,c,*], H. Miyadera[d], A. Jason[d], R. Seki[e]

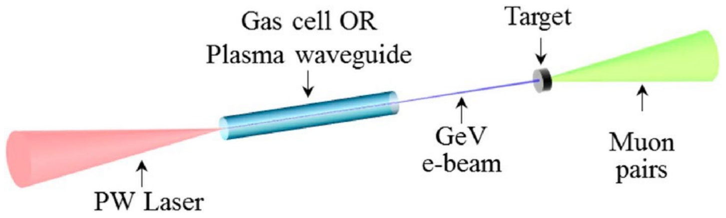


300 MeV and 10 μA electron microtron → 8 x 10³ μ⁺/s

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 111301 (2009)

Dimuon production by laser-wakefield accelerated electrons

A. I. Titov,[1,2,3] B. Kämpfer,[1,4] and H. Takabe[3]



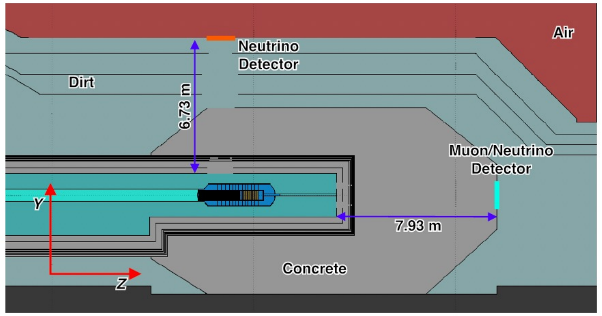
100 pC, 10 GeV electron → 8 x 10³ μ±/s

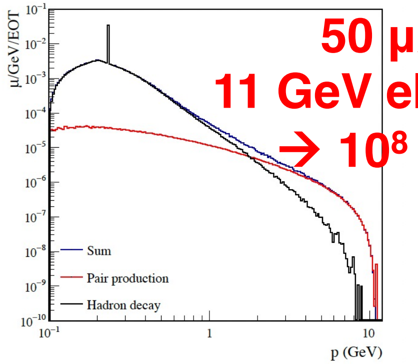
instruments
MDPI
Article

JLab CEBAF

Secondary Beams at High-Intensity Electron Accelerator Facilities

Marco Battaglieri[1], Andrea Bianconi[2,3], Mariangela Bondí[4], Raffaella De Vita[1], Antonino Fulci[4,5,*], Giulia Gosta[2], Stefano Grazzi[1,5], Hyon-Suk Jo[6], Changhui Lee[6], Giuseppe Mandaglio[4,5], Valerio Mascagna[2,3], Tetiana Nagorna[1], Alessandro Pilloni[4,5], Marco Spreafico[1,7], Luca J. Tagliapietra[8], Luca Venturelli[2,3] and Tommaso Vittorini[1,7]





50 μA, 11 GeV electron → 10⁸ μ±/s

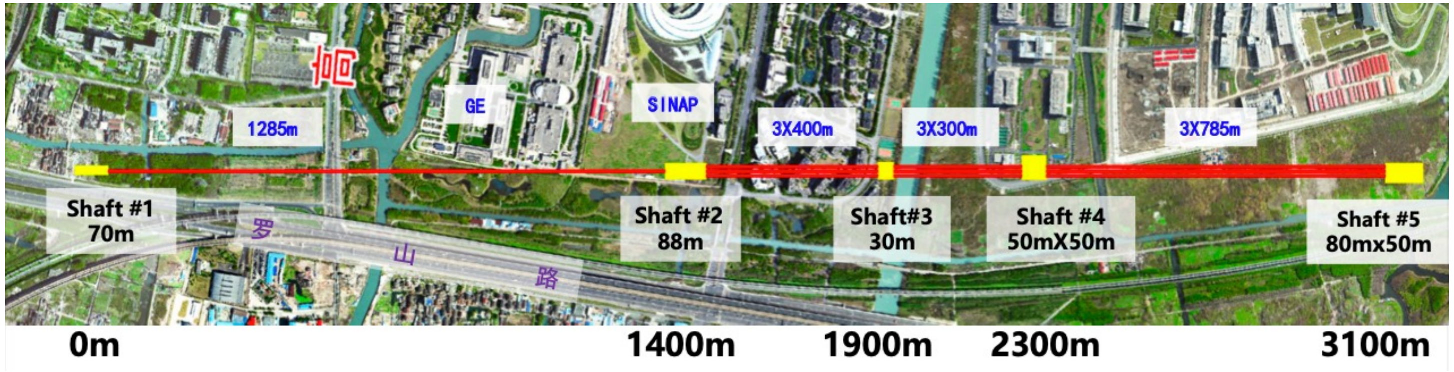
SHINE作为缪子源驱动装置

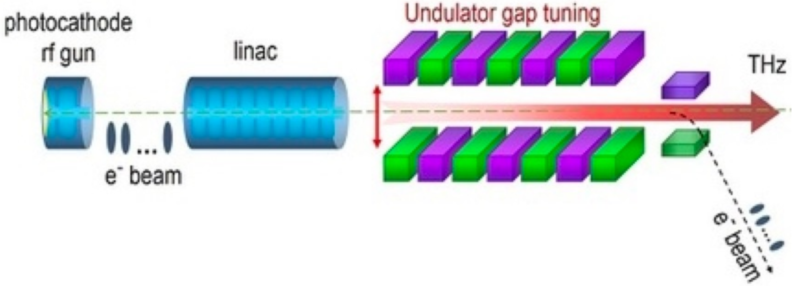
李政道研究所
TSUNG-DAO LEE INSTITUTE

Only 4 km from TDLI!

- 位于上海张江
- 预计于2025年底竣工
- 超导电子直线加速器
  - 8 GeV 能量
  - 1 MHz 重复频率
  - 100 pC 电荷量

SHINE
SHANGHAI HIGH REPETITION RATE XFEL AND EXTREME LIGHT FACILITY
硬X射线自由电子激光装置

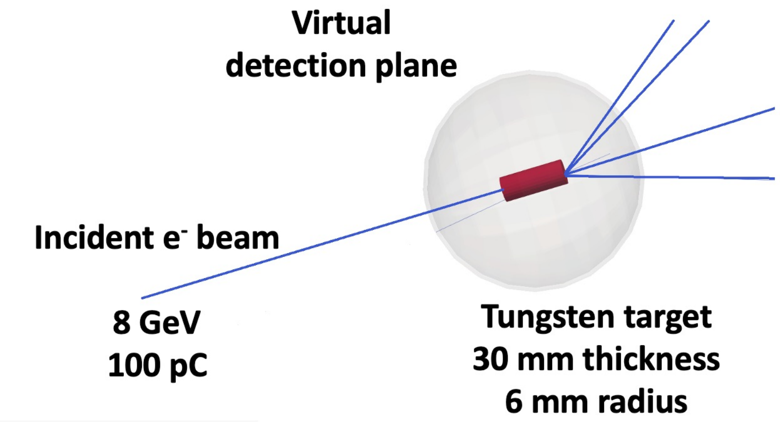




初步模拟结果：缪子产额

Work by Jiangtao

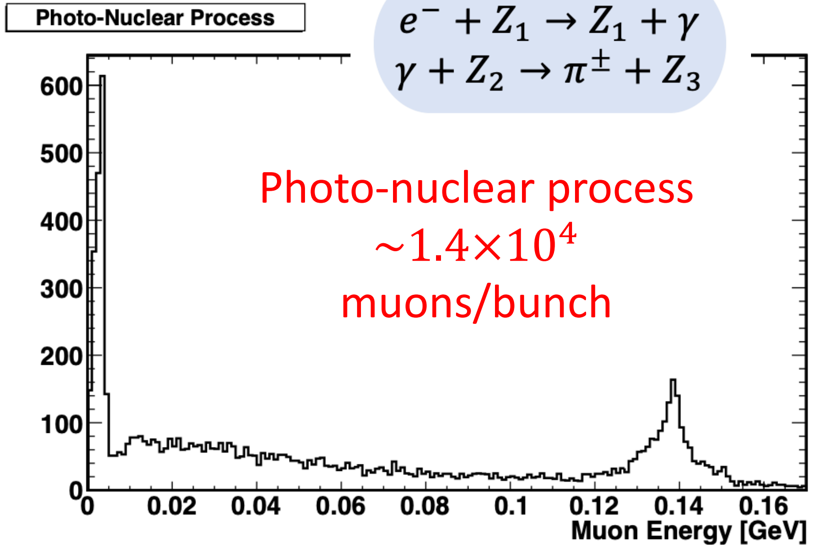
- 蒙特卡洛模拟：SHINE电子+钨靶/铜靶
- Photo-nuclear过程：低能量，高反应截面
- $\gamma \to \mu^+\mu^-$ 过程: 高能量，底反应截面，方向性好



JACoW IPAC2023 (2023) TUPA087

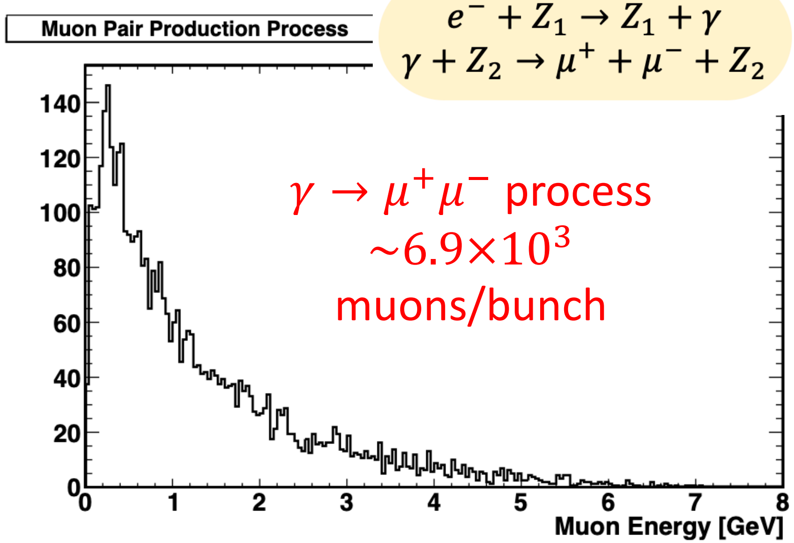
Photo-nuclear process

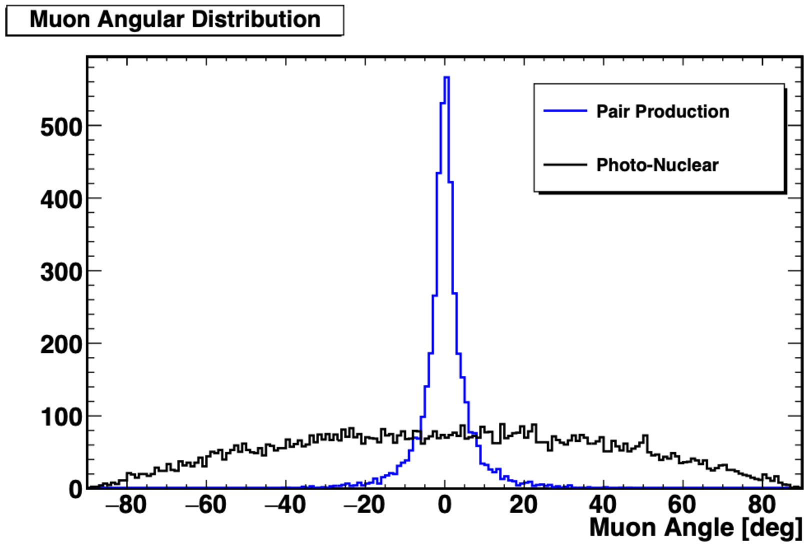
$$e^- + Z_1 \to Z_1 + \gamma$$
$$\gamma + Z_2 \to \pi^\pm + Z_3$$



Bethe-Heitler process

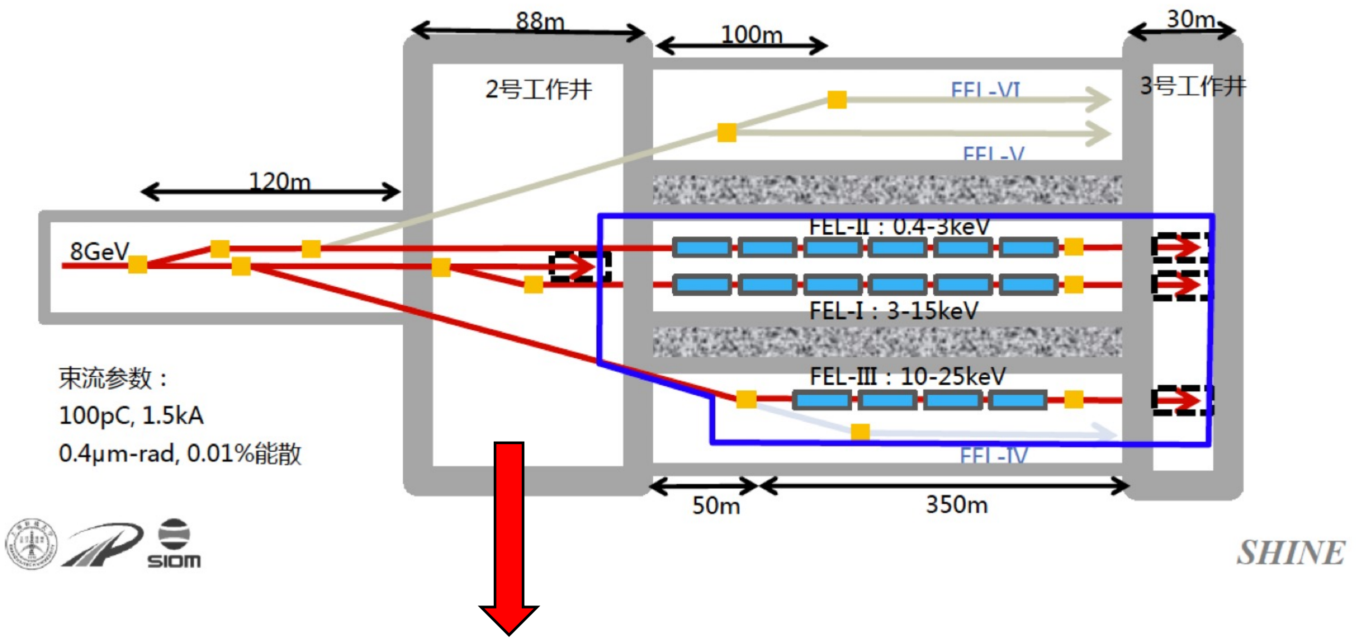
$$e^- + Z_1 \to Z_1 + \gamma$$
$$\gamma + Z_2 \to \mu^+ + \mu^- + Z_2$$

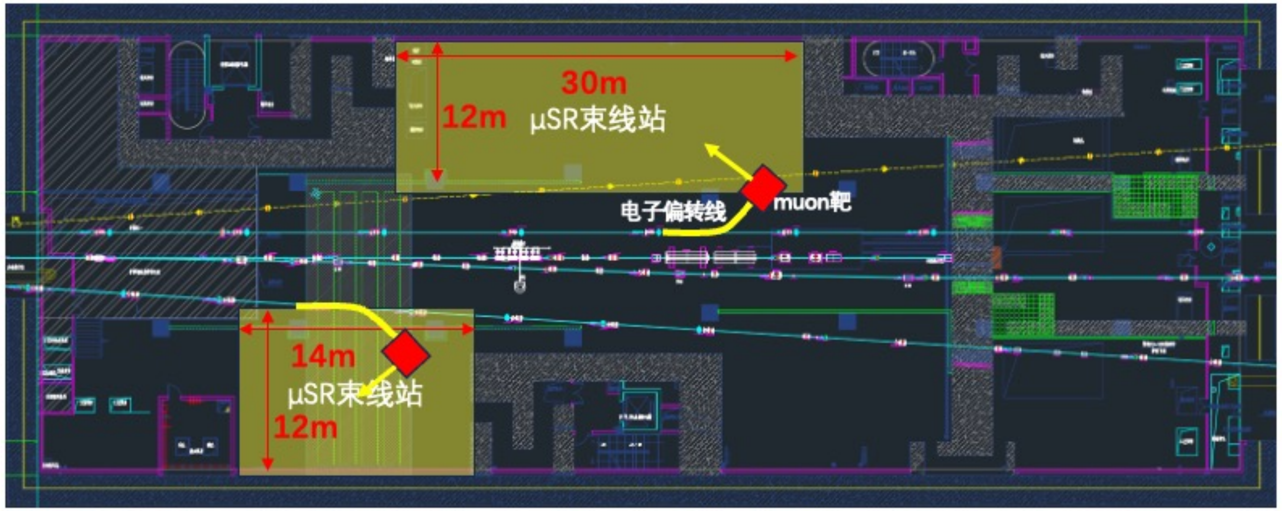




SHINE可用于建设缪子源的区域

李政道研究所 TSUNG-DAO LEE INSTITUTE





二号井用于μSR线站建设的设想

- 有比较充足的空间
- 电子输运线是在规划内，可以快速衔接起来
- 在已有较厚屏蔽隧道内，既省略大量的屏蔽设施，不用考虑靶站和实验区尽量远离的情况，可以缩短束线总长

许文贞（上海高研院）提供

电子束流击中位置和靶材优化

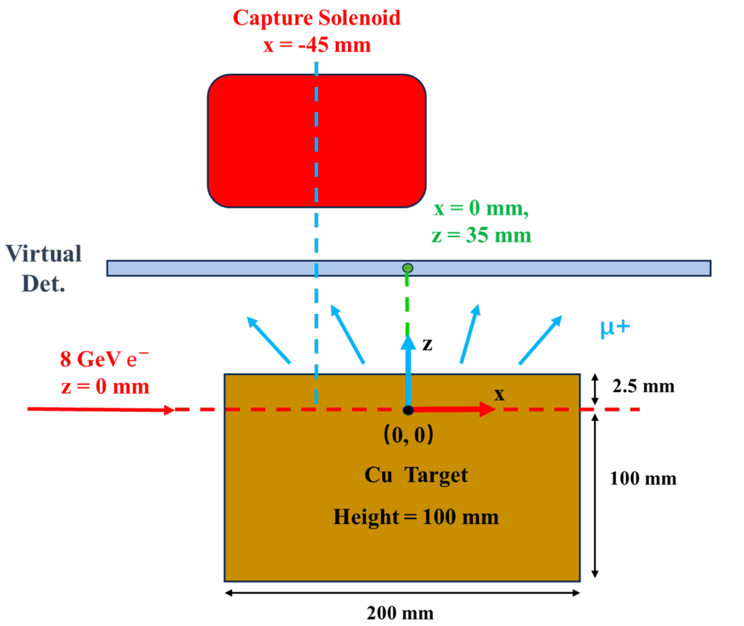
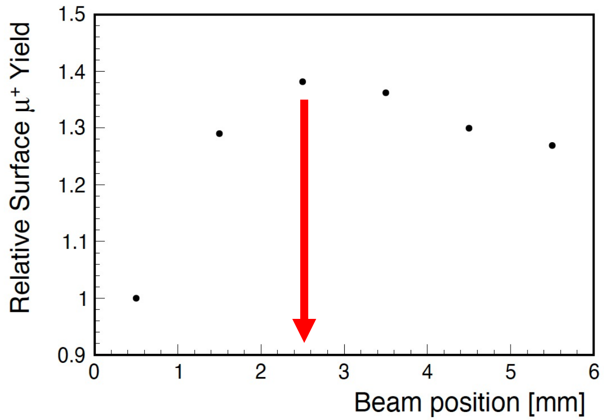


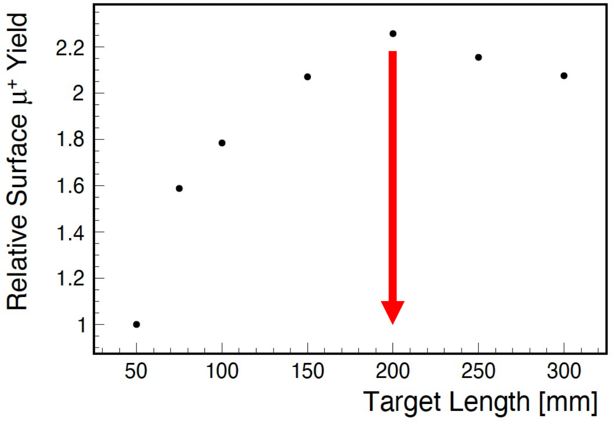
TABLE I. The electromagnetic shower characteristics for 8 GeV × 100 μA beam and material properties.

Materials	Graphite	Cu	W
Z	6	29	74
A	12	64	184
ρ [g/cm^3]	1.82	8.94	19.25
X_{max} [mm]	839	73.9	20.7
dE/dz [kW/cm]	0.24	3.26	13.2
L_{99} [mm]	3090	281	798

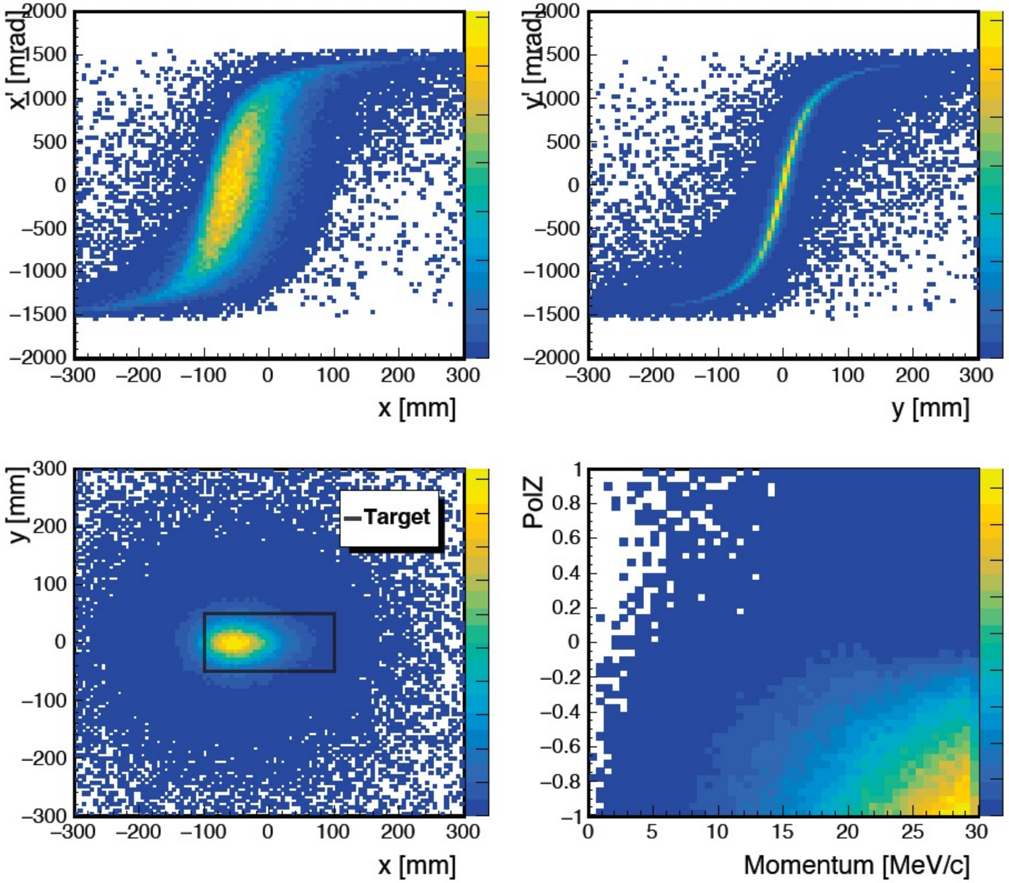
束流位置扫描



靶长度扫描



缪子在靶表面的Phase Space

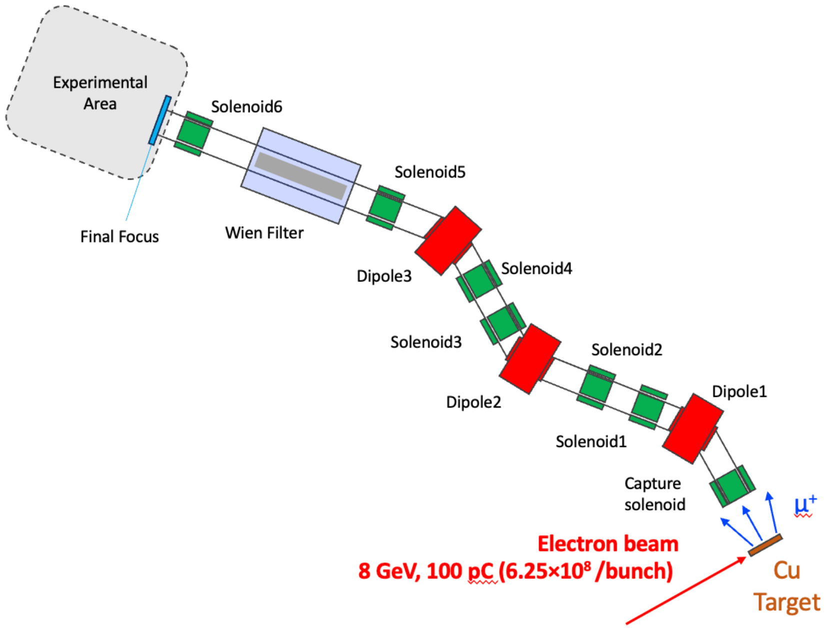


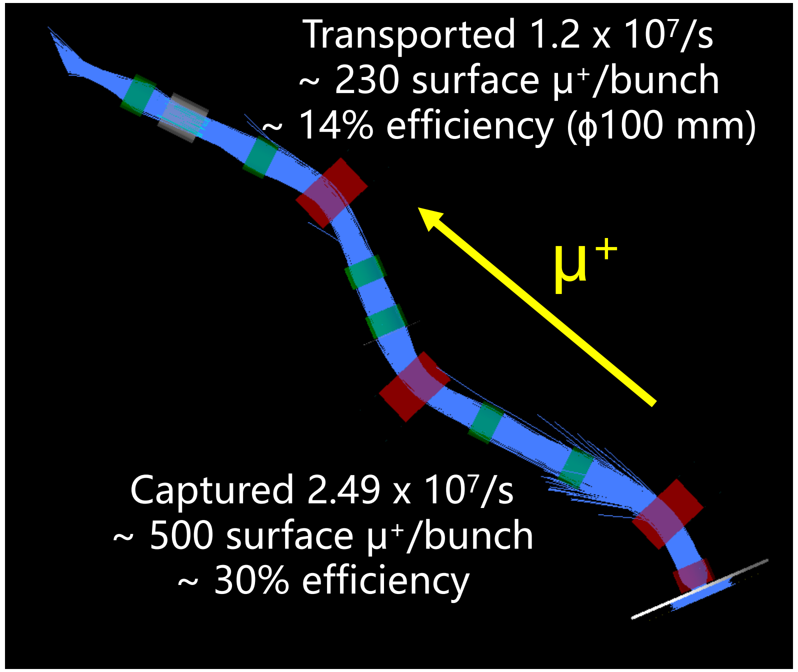
近期准备投稿

束流引出方案 (基于G4beamline)

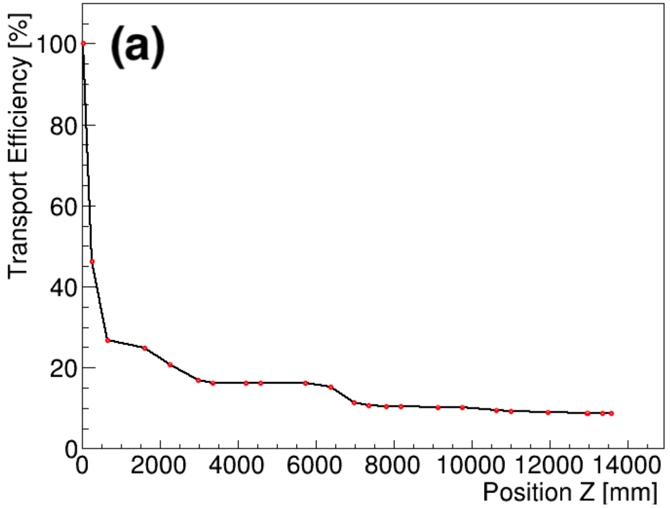
李政道研究所 Tsung-Dao Lee Institute

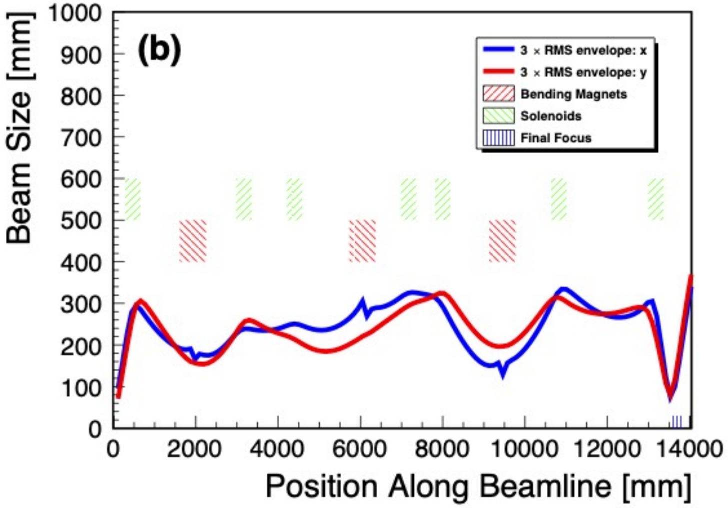
Work by Fangchao Liu





Source 8.24 x 10^7/s
~ 1,650 surface μ^+/bunch





. The optics parameters applied in the extraction beam line to transport surface muon beam.

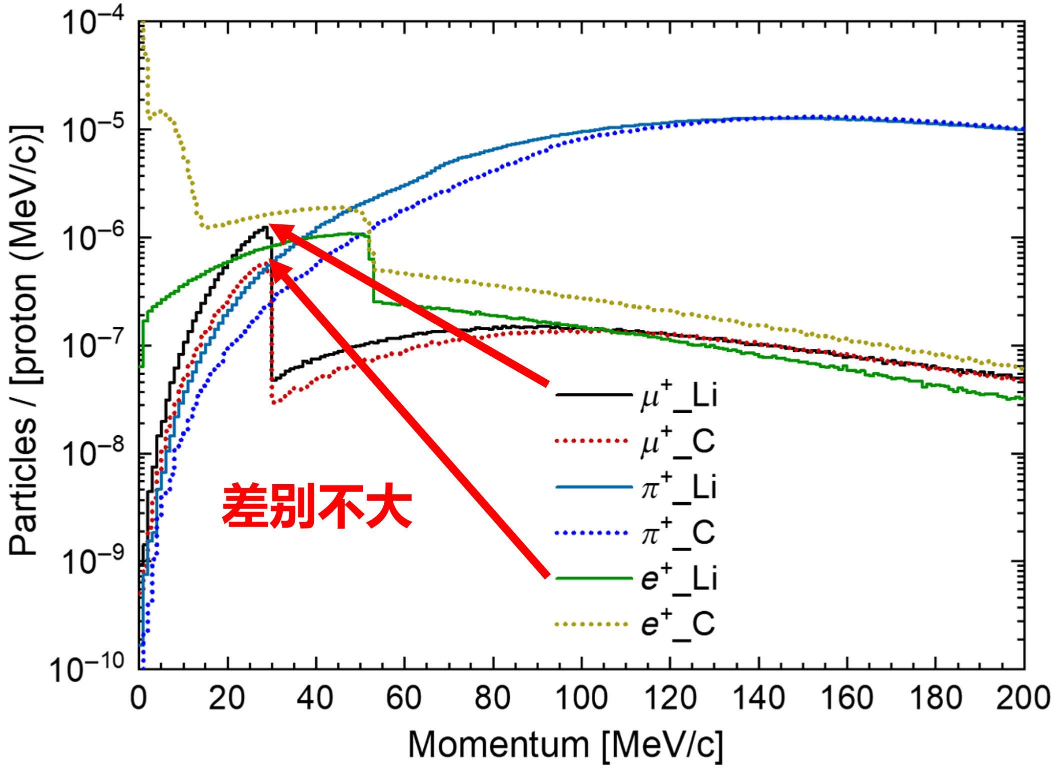
Components	Position (m)	Length (mm)	Aperture (mm)	Field (T)
Capture solenoid	0.47	373	500	0.432
Dipole1	1.93	640	400	-0.100
Solenoid1	3.17	373	500	0.241
Solenoid2	4.40	373	500	0.173
Dipole2	6.05	640	400	0.100
Solenoid3	7.17	373	500	0.136
Solenoid4	8.00	373	500	0.199
Dipole3	9.45	640	400	-0.104
Solenoid5	10.82	373	500	0.226
Wien Filter	12.45	800	200	
Solenoid6	13.18	373	500	0.440
Exit	13.58			

TABLE IV. Parameters of the surface muon beam spot at the experimental area (ϕ30 mm), assuming a 50 kHz operation for the pulsed electron beam.

Parameters	Value
x/x' (FWHM)	20 mm / 600 mrad
y/y' (FWHM)	24 mm / 400 mrad
$\Delta p/p$	9.2%
PolZ	92%
μ^+ rate	$2.8 \times 10^6 \mu^+$/s

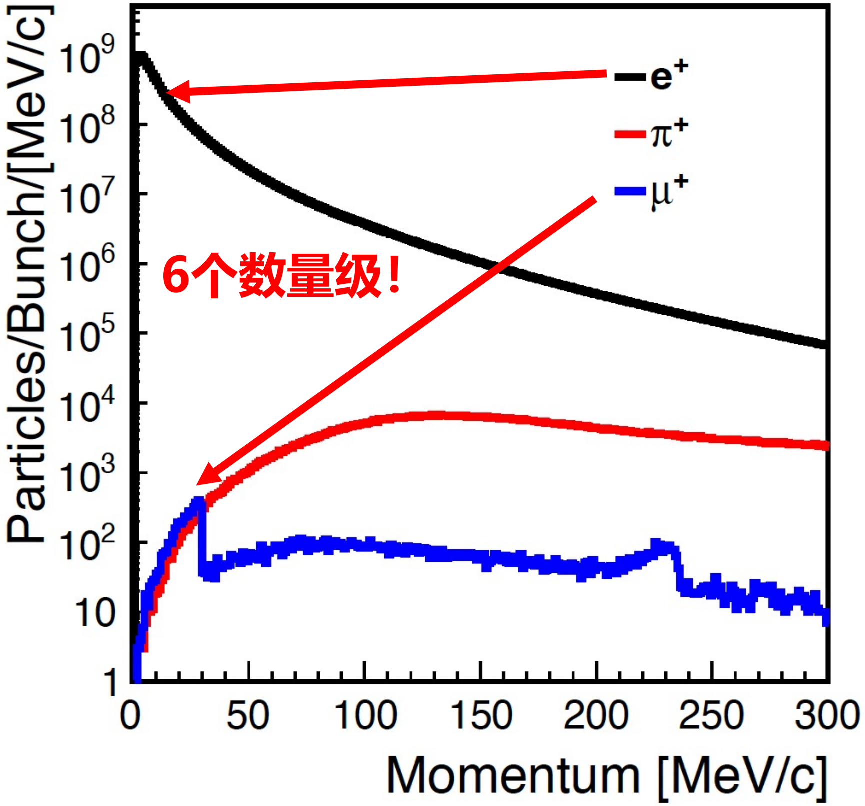
近期准备投稿

缪子 vs 正电子



CiADS (质子打靶)

PHYS. REV. ACCEL. BEAMS 27, 023403 (2024)



OUR STUDY （电子打靶）

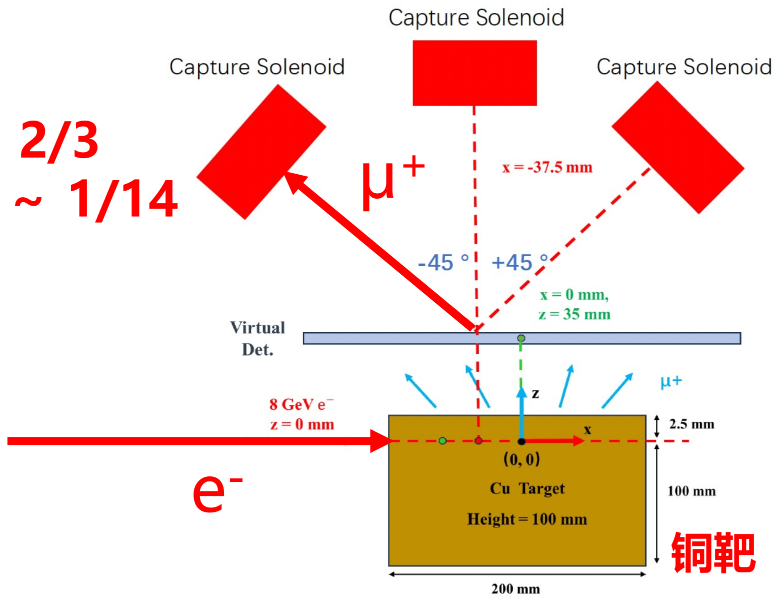
挑战：如何进一步降低本底粒子？

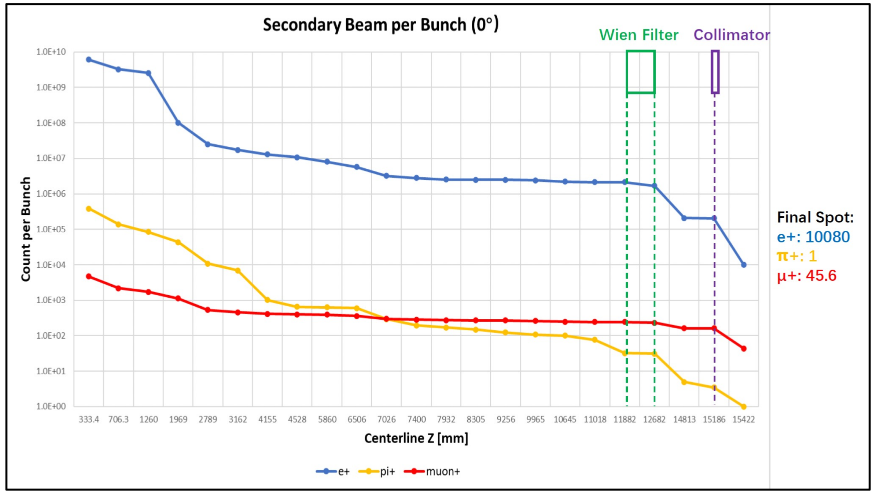
机遇：强流MeV正电子源？ （每秒>10⁸@50 kHz）

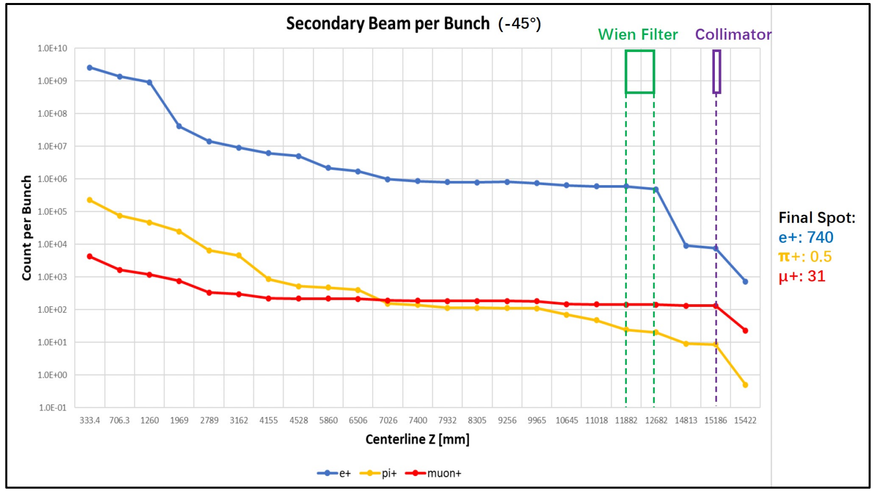
俘获螺线管角度+准直器

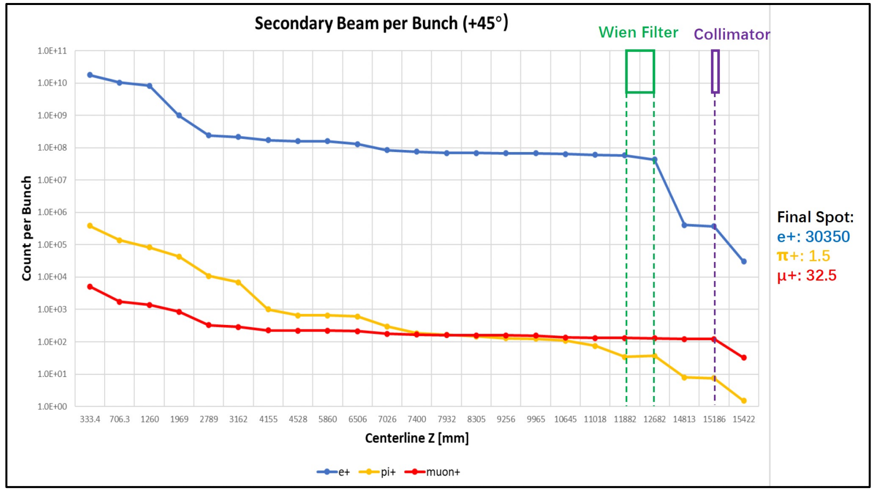
李政道研究所 TSUNG-DAO LEE INSTITUTE

缪子 ~ 2/3
正电子 ~ 1/14





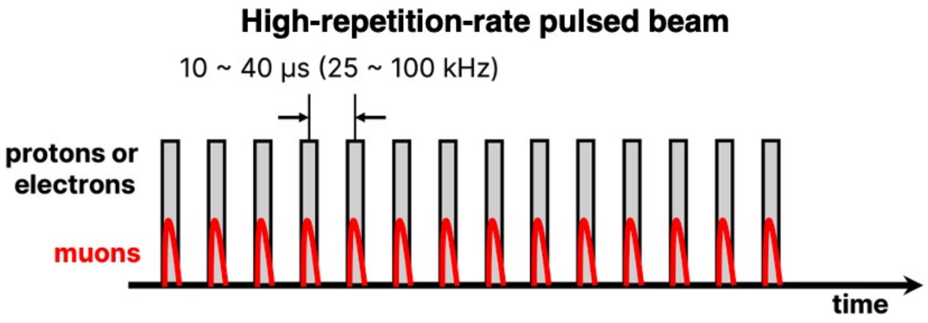




还需要进一步降低正电子数量！

总结

- 利用SHINE高重频加速器电子可以驱动时间结构理想的缪子源
  - 重复频率：~50 kHz（可调控）
  - 每个100 pC电子束团可产生 ~ 50-250个缪子
  - 可应用到粒子物理、凝聚态物理、化学等领域



- 目前计划通过几个步骤进行
  - 缪子源已被纳入SHINE Science Plus 白皮书
  - 利用SXFEL装置的1.6 GeV电子进行模拟产额验证（2024-2025）
  - 利用SHINE装置的6-8 GeV电子打靶，搭建引出表面缪子源的束流线（2030？）
  - 将来拓展到负缪子、高能量缪子等等