Testing entanglement between free-traveling electron-positron or electron-muon pairs

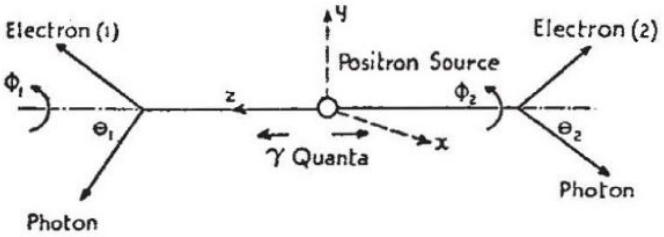
Qiang Li (Peking University) 2025/7

JPG52 (2025) 075002, MPLA (2025) 2530008, PRD111 (2025) 11, 116018
and Phys.Rev.Accel.Beams 28 (2025) 5, 053401

Quantum entanglement measurements — history and today

- C. N. Yang (IJMPA 2015): the first experiment on quantum entanglement is the **Wu-Shaknov** Experiment (PR1950) which measures **the angular correlation of two Compton-scattered photons arising from $e+e-$ annihilation**

- The violation of **Bell inequality (**PPF1964**)** was demonstrated in 1970s and afterwards using entangled photons, confirming the non-locality of our universe.
- Alain Aspect, John Clauser and Anton Zeilinger won the Nobel Prize in Physics in 2022 for demonstrating the potential to investigate and control particles (photons) that are in entangled states.



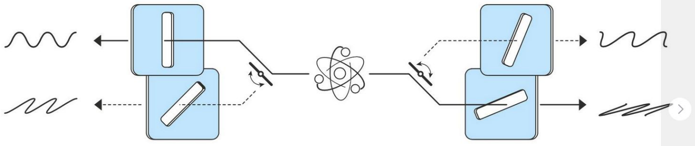
The Angular Correlation of Scattered Annihilation Radiation*

C. S. Wu and I. Shaknov

Pupin Physics Laboratories, Columbia University, New York, New York

November 21, 1949

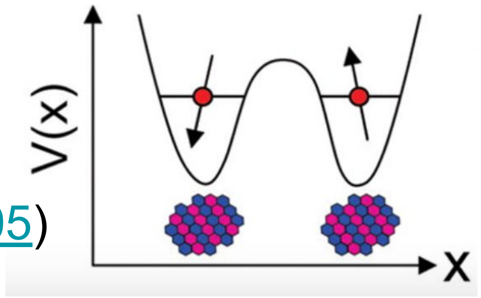
As early as 1946, J. A. Wheeler[1] proposed an experiment to verify a prediction of pair theory, that the two quanta emitted in the annihilation of a positron-electron pair, with zero relative angular momentum, are polarized at right angles to

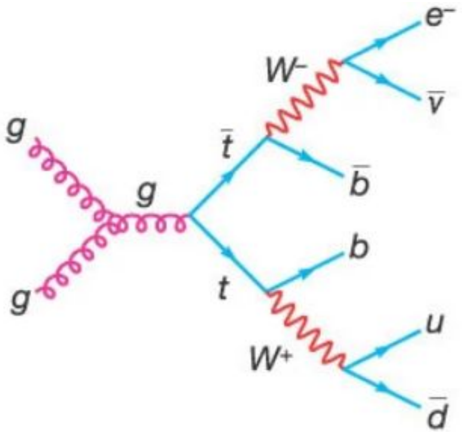


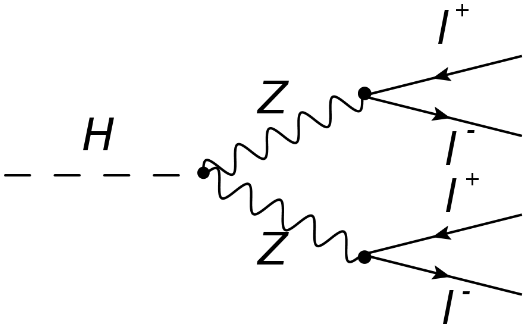
Alain Aspect developed this experiment, using a new way of exciting the atoms so they emitted entangled photons at a higher rate. He could also switch between different settings, so the system would not contain any advance information that could affect the results.

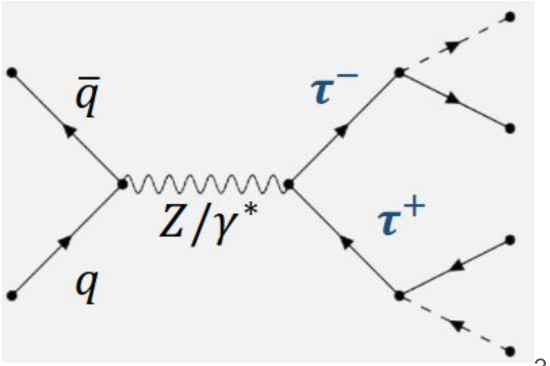
QE between top quarks, tau leptons and …

- The ATLAS and CMS Collaborations recently observed quantum entanglement involving top quarks at a center-of-mass energy of 13 TeV
  - marking the highest energy measurements of QE
- Recent proposals on vector bosons, and tau leptons
- Less attention has been given to **electrons and muons**
  - **Confined electron pairs** (Science309(5744)1116955,2005)
    - confined in semiconductor quantum dots
    - entangled states were prepared, coherently manipulated









QE between free electrons and muons

- None similar experiment has been done with free-traveling electrons as **measuring the spin of a single traveling electron poses a significant challenge** due to interference from its orbital motion

Original Articles

Does a flying electron spin?

B. M. Garraway & S. Stenholm

Pages 147-160 | Published online: 08 Nov 2010

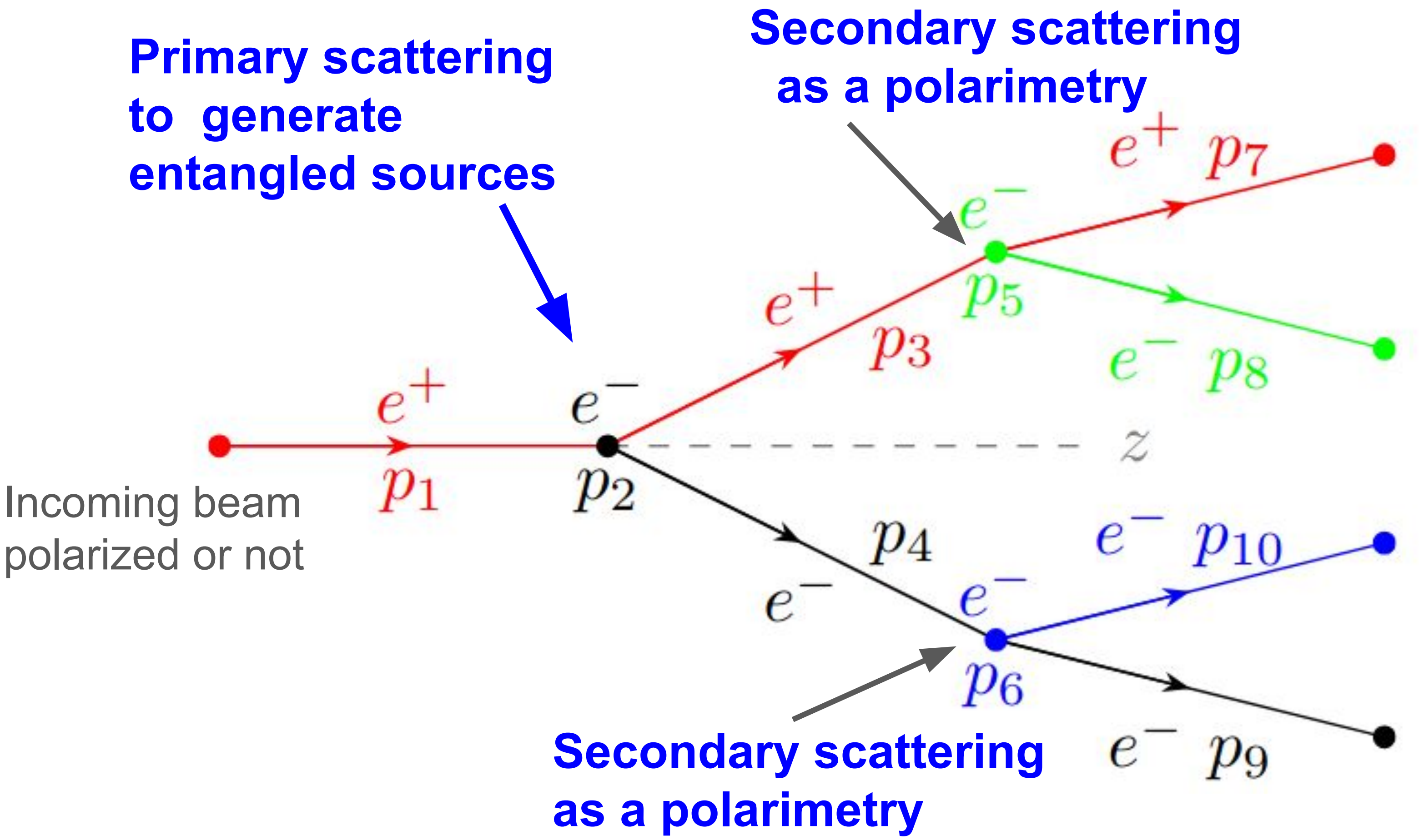
Cite this article https://doi.org/10.1080/00107510110102119

bobbi_john jfcbat.com <bobbi_john@jfcbat.com>
To: Qiang Li <qliphy@gmail.com>

Dear Qiang Li
Please be aware that Stern Gerlach magnets, because they also have a finite magnetic field, cannot separate a charged g=2 electron beam into 2 spin states. This fact was first noted (and proven for g=2) by Nils Bohr. It is obscurely reported (only) in Mott and Massey's book, Theory of Atomic scattering.
John Clauser

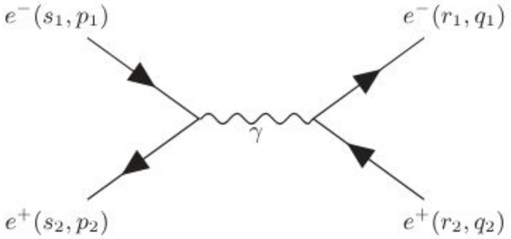
- **Our proposal:**
  - a first measurement on **polarization correlations**
    - **between charged lepton beams**
  - through **joint measurements** of their individual polarization-sensitive scatterings off two separate targets.

Lepton scattering experiment proposal

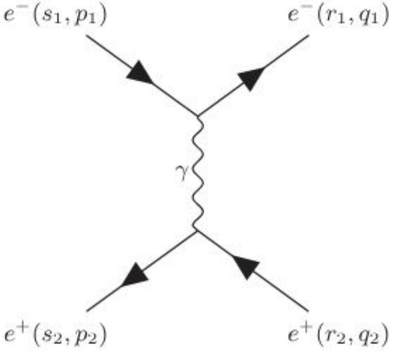


Tree-level entanglement in quantum electrodynamics

Bhabha scattering

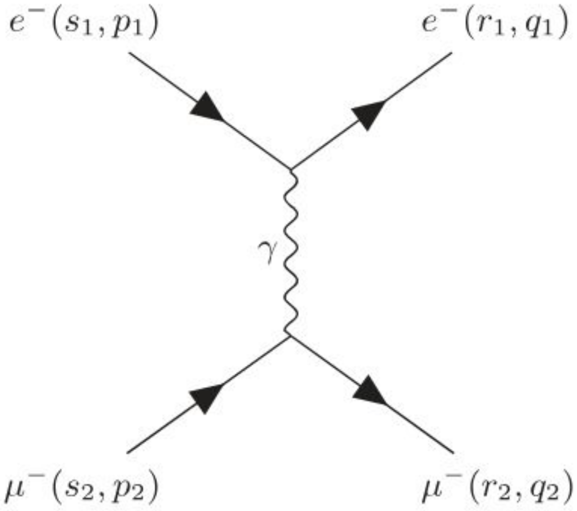


(a) s-channel

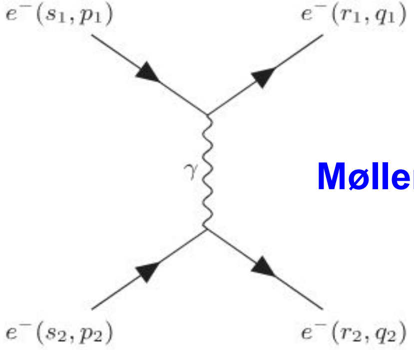


(b) t-channel

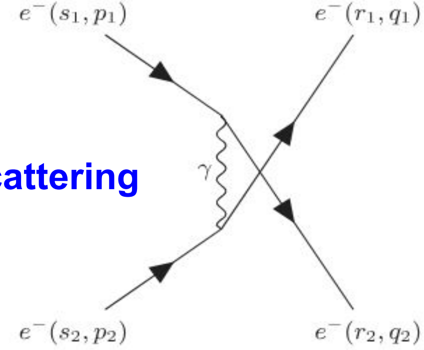
electron-muon scattering (Mott scattering)



Møller scattering

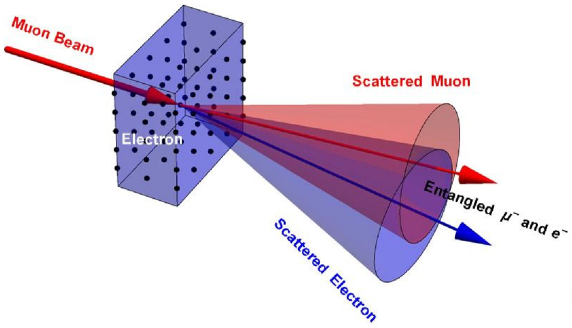


(a) t-channel



(b) u-channel

Controllable Source: muon on-target experiments

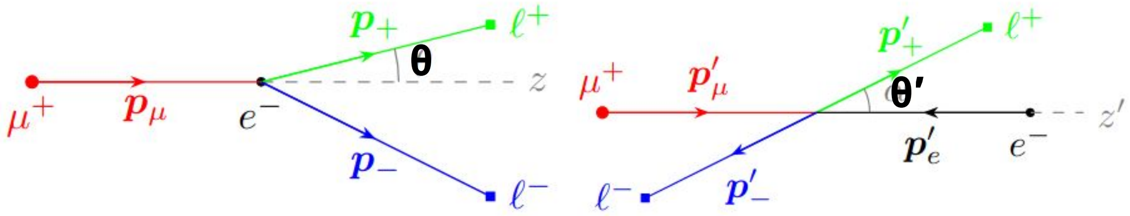


$$\rho_{s_3's_4's_3s_4} = \langle s_3's_4'|\rho_f|s_3s_4\rangle = \frac{1}{4}\sum_{s_1s_2}\left(\frac{\mathcal{M}_{s_3's_4's_1s_2}\mathcal{M}^*_{s_3s_4s_1s_2}}{\sum_{s_3''s_4''}\left|\mathcal{M}_{s_3''s_4''s_1s_2}\right|^2}\right). \tag{1}$$

where s_1 and s_2 are the helicities of the muon and electron before scattering, and $s_3^{(')}$ and $s_4^{(')}$ are those after scattering. The polarized scattering amplitude $\mathcal{M}$ is calculated using the helicity spinors of each particle with momentum p_i as

Let **$\theta_e(\theta'_e)$** and **$\theta_\mu(\theta'_\mu)$** denote the polar angles of the final state electron and muon momenta in the lab (center of mass) frame

$$i\mathcal{M}_{s_3s_4s_1s_2} = \bar{u}(p_3,s_3)(-ie\gamma^\mu)u(p_1,s_1)\frac{(-ig_{\mu\nu})}{(p_1-p_3)^2}\bar{u}(p_4,s_4)(-ie\gamma^\nu)u(p_2,s_2), \tag{2}$$



(a) lab frame (b) COM frame

Controllable Source: Concurrence, CHSH inequality

PRL 80 (1998) 2245
PRL 23 (1969) 880

- Entanglement can be quantified by *concurrence*

$$\mathcal{C}(\rho_f) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\} \in [0, 1]$$

for a two-qubit system, where λ_i $(\lambda_i \geq \lambda_j, \ \forall i < j)$ are the square roots of the eigenvalues of the matrix $\rho_f(\sigma_2 \otimes \sigma_2)\rho_f^*(\sigma_2 \otimes \sigma_2)$. If $\mathcal{C} > 0$, the two-qubit system is entangled.

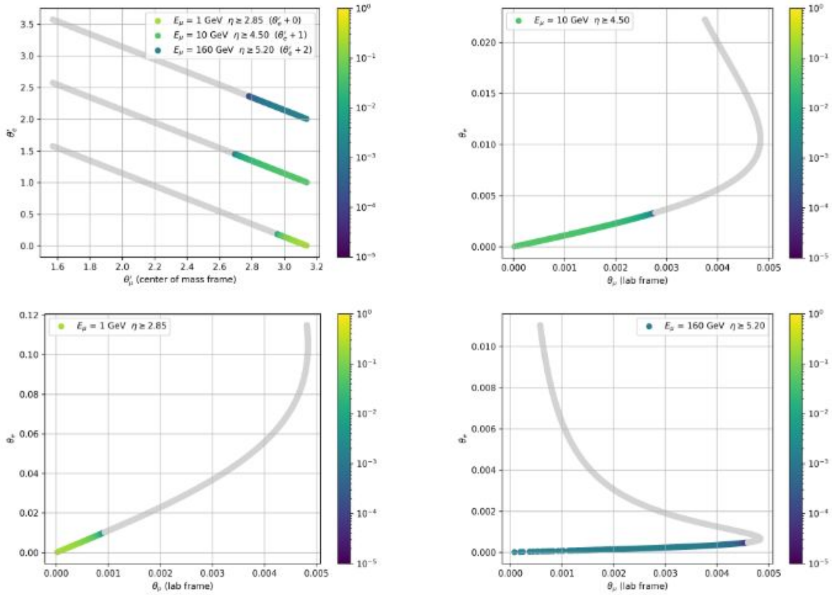
- The *CHSH inequality*, $I_2 \leq 2$, is the Bell inequality for a two-qubit system. The optimal (maximal) I_2

$$I_2 = 2\sqrt{\lambda_1 + \lambda_2},$$

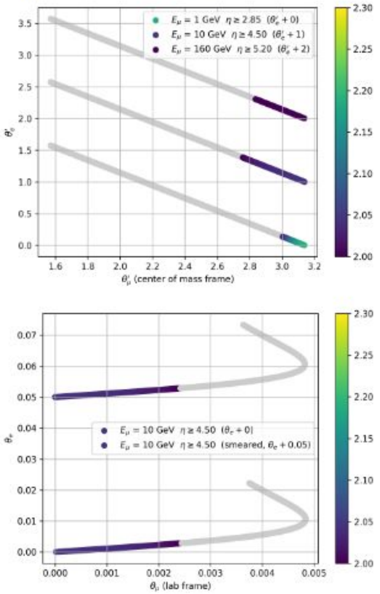
where λ_1 and λ_2 are the two largest eigenvalues of the matrix $C^{\mathrm{T}}C$, and C is the correlation matrix calculated by $C_{ij} = \mathrm{Tr}\left(\rho_f\left(\sigma_i \otimes \sigma_j\right)\right)$. $I_2 = 2\sqrt{2}$ is the upper limit of the quantum mechanics.

Controllable Source: muon on-target experiments

Concurrence $\mathcal{C}(\rho_f)$:



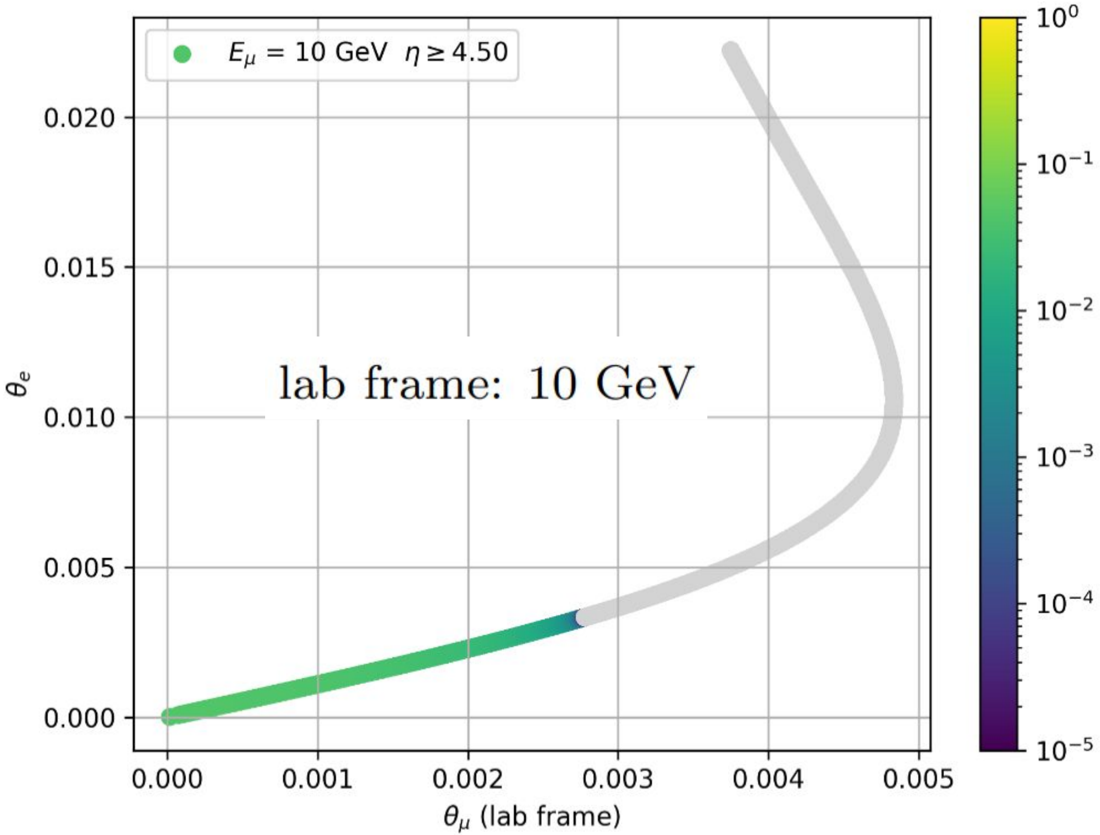
Optimal I_2:



- Simulated by MG5_aMC@NLO 3.5.5 [32] in tree-level QED with non-zero lepton masses
- The light gray regions depict $\mathcal{C}(\rho_f) = 0$ or $I_2 \leq 2$
- Assuming a **1-day** run with a **10 GeV** muon beam of flux $\mathbf{10^5}$/s on 10 cm Al targets, the expected number of events with $\mathcal{C}(\rho_f) > 0$ is $\mathbf{2.6 \times 10^4}$

$E_{\rm beam}$/GeV	$E_{\rm COM}$/GeV	$\mathcal{C}(\rho_f)_{\max}$	$\theta_{\mu,\max}$/mrad	$\theta_{e,\max}$/mrad	$E_{\mu,\min}$/GeV	$E_{e,\min}$/GeV	$\sigma_{\rm E}$/μb	$\sigma_{\rm E,\,\theta\geq 0.5\,mrad}$/μb
1	0.111	**0.22**	0.9	10.2	0.92	0.08	0.56	0.56
10	0.146	**0.044**	**2.8**	**3.3**	**5.2**	**4.5**	**0.39**	**0.39**
160	0.418	0.0014	4.6	0.5	10	145	0.027	0.022

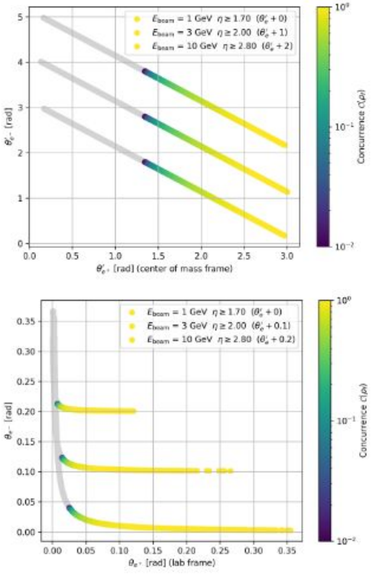
Controllable Source: muon on-target experiments



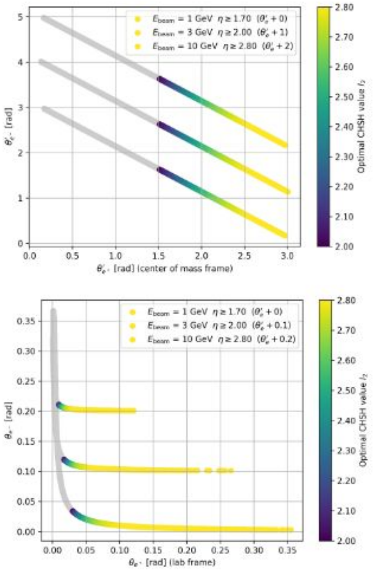
concurrence $\mathcal{C}(\rho_f)$

Controllable Source: positron on-target experiments

Concurrence $\mathcal{C}(\rho_f)$:



Optimal I_2:



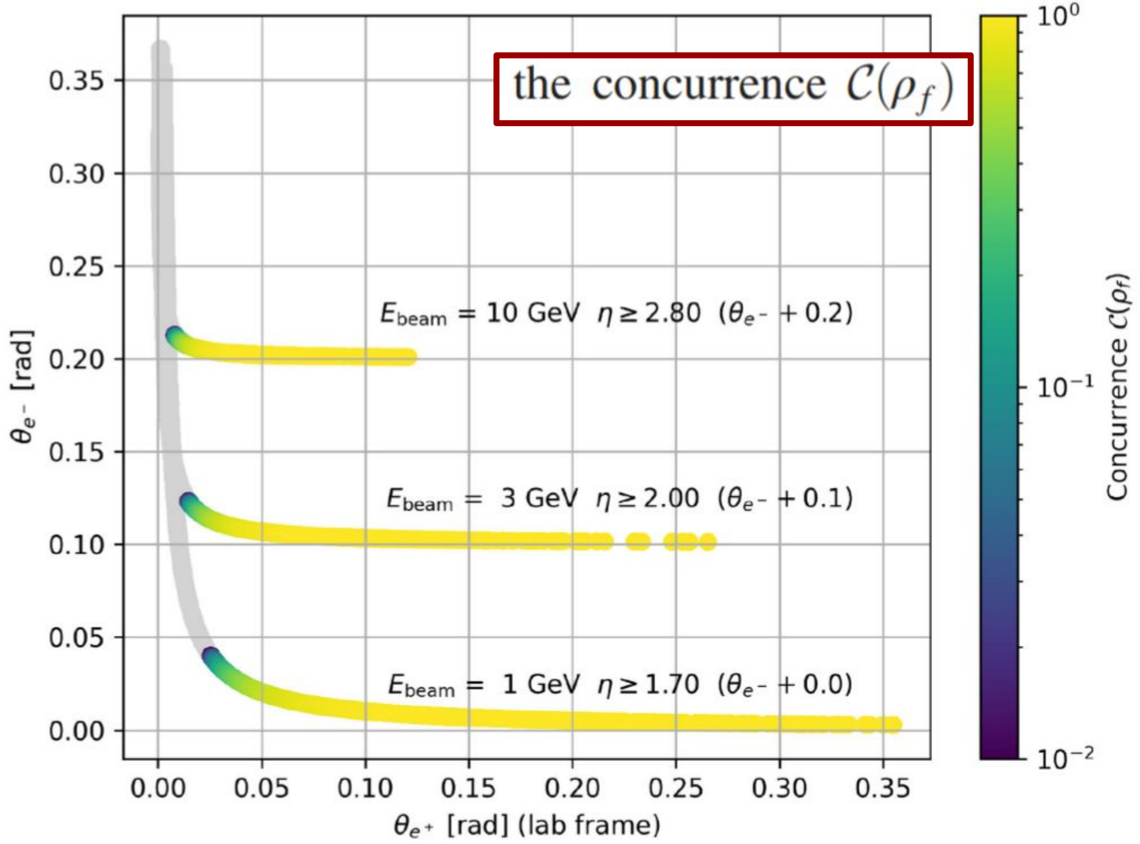
- The angular ranges exhibiting $\mathcal{C}(\rho_f) > 0$ in the center-of-mass frame are significantly broader
- The theoretical upper limits for both $\mathcal{C}(\rho_f)$ and I_2 in quantum mechanics are nearly reached as θ'_{e^+} approaches 3

STCF

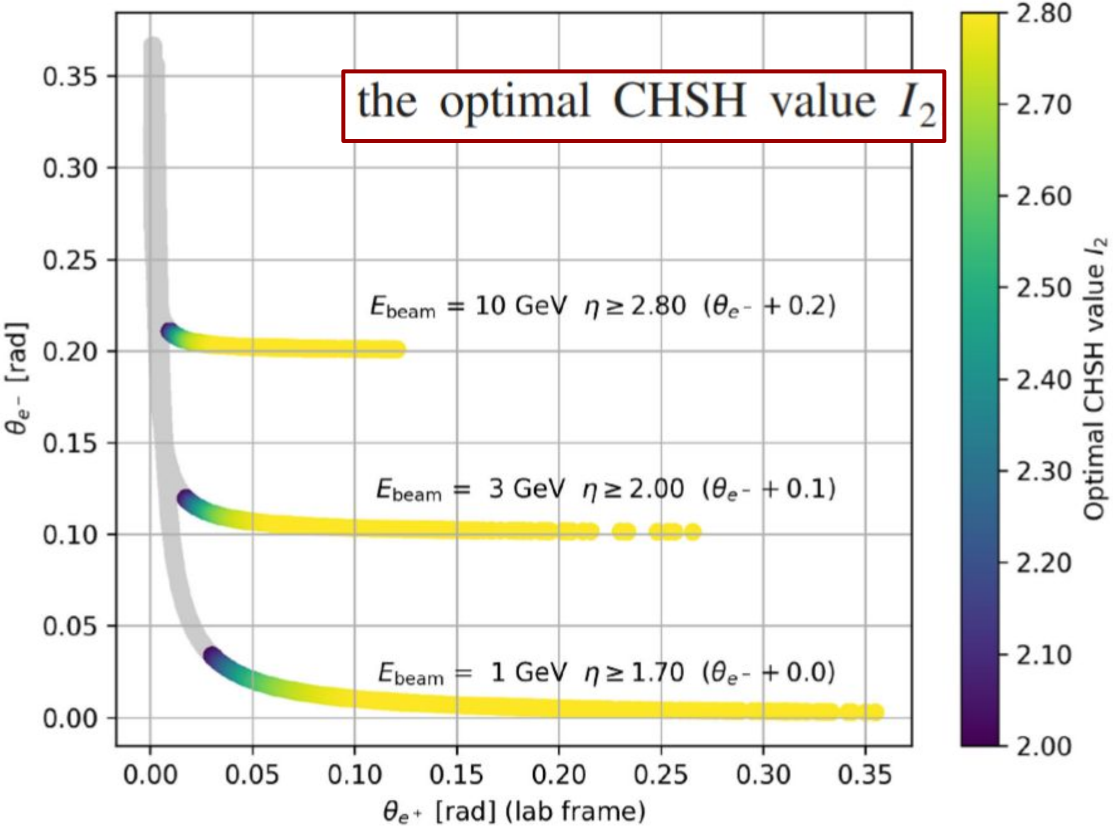
- Assuming a **1 GeV** positron beam with a flux of $\mathbf{10^{12}/s}$ directed at a 10 cm thick Al target, the expected entangled event rate is $\mathbf{1.9 \times 10^9/s}$
- A golden region for measurements:
  - $E_{\text{beam}} = \mathbf{1\ GeV}$, $0.05\ \text{rad} \le \theta_{e^+} \le 0.1\ \text{rad}$
  - 23.4% of all events with $\mathcal{C}(\rho_f) > 0$
  - $E \ge \mathbf{0.094\ GeV}$, $\theta \ge \mathbf{0.0103\ rad}$
  - $\mathcal{C}(\rho_f)$ reaching up to $\mathbf{0.953}$ and I_2 up to $\mathbf{2.8281}$

E_{beam}/GeV	E_{COM}/GeV	$\mathcal{C}^{\max}(\rho_f)$	$I_2^{\max}$	$E_{e^+}^{\min}$/GeV	$E_{e^-}^{\min}$/GeV	$\theta_{e^+}^{\min}$/rad	$\theta_{e^-}^{\min}$/rad	σ_{E}/μb
1	0.032	0.9996	2.8281	0.008	0.389	0.0255	0.0028	243.6
3	0.055	0.9997	2.8282	0.023	1.166	0.0147	0.0016	82.1
10	0.101	0.9997	2.8282	0.074	3.890	0.0081	0.0009	26.5

Controllable Source: positron on-target experiments



Controllable Source: positron on-target experiments



A new kind of Wu experiment

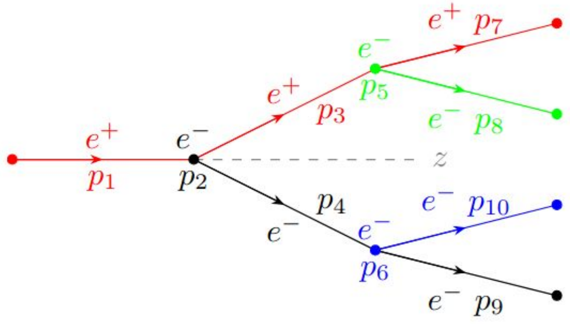


FIG. Proposed cascade experiment for measuring polarization correlations of the primary products

Simulation setup:

- $0.05\ \mathrm{rad} \leq \theta_3 \leq 0.1\ \mathrm{rad}$ in a 1 GeV positron on-target experiment
- The spins of target electrons 5 and 6 are aligned with the beam direction
- Consider the main component of the primary state, $(LL + RR)/\sqrt{2}$

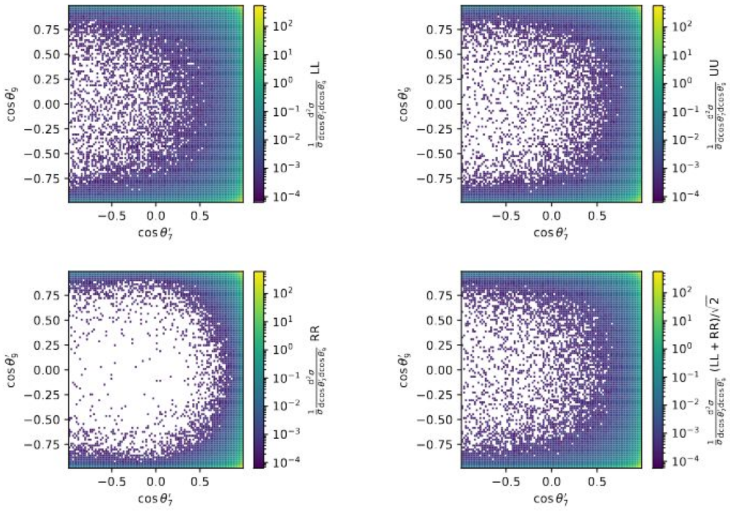


FIG. Joint angular distribution densities of the two secondary scattering processes

Assuming the two secondary targets are $10\ \mathrm{cm}$ thick iron, the event rate in $\cos\theta'_7 \leq 0.5 \wedge -0.75 \leq \theta'_9 \leq 0.75$ is $\mathbf{1.4 \times 10^2}$/s for the state $(LL + RR)/\sqrt{2}$.

A new kind of Wu experiment

Take $0.05 \text{ rad} \leq \theta_3 \leq 0.1 \text{ rad}$ in a 1 GeV positron on-target experiment as an example:

- The state of the primary products is approximately 1% $(RL + LR)/\sqrt{2}$, 1% $(RL - LR)/\sqrt{2}$, 7% $(RR - LL)/\sqrt{2}$, and 90% $(RR + LL)/\sqrt{2}$ in the lab frame
- The optimized ratio of the yields of $(LL + RR)/\sqrt{2}$ to UU is $1.29 \pm 0.03(\text{MC})$, corresponding to 4.4×10^3 post-optimization efficient signal event counts and an expected signal yield over a **27-second** run; the result for $(LR + RL)/\sqrt{2}$ is $0.78 \pm 0.02(\text{MC})$ in comparison
- Other uncertainties, such as those from process modeling and background suppression, may dominate the real experimental analysis
- For the 20% polarized targets, the ratios are 1.010 ± 0.009 and 0.986 ± 0.009 generated from 25 times the number of Monte Carlo events, corresponding to 2.5×10^4 efficient event counts accumulated in **680 seconds**

A new kind of Wu experiment

- The **high event rate** can help mitigate the decline in resolving power associated with low target polarization purities in real-world applications

- **A simplified state tomography** can be performed assuming **prior knowledge** from the primary scattering

- Further studies with **polarized muon beam** in underway
  - 70% polarized beam at HIAF is possible with 10^5/s
  - muon decay can act as a polarimetry

Proposal Summary

- GeV-scale muon and positron on-target experiments are examined as **controllable entangled lepton pair sources** through the kinematic approach
- Quantum entanglement and the CHSH inequality violation are present in the primary scattering products
- A **first measurement of the correlation between entangled free-traveling lepton pairs** is proposed to verify the entanglement
- The electron-positron beam polarization correlation measurement can be conducted with **a high event rate at many domestic positron beam facilities**

Process	Incident flux	Primary event rate	Secondary coincidence rate
$\mu^- e^- \to \mu^- e^-$	$10^5/\mathrm{s}$	$2.6 \times 10^4/\mathrm{d}$	(not estimated)
$e^+ e^- \to e^+ e^-$	$10^5/\mathrm{s}$	$1.9 \times 10^2/\mathrm{s}$	$4.4 \times 10^2/\mathrm{y}$
$e^+ e^- \to e^+ e^-$	$10^{12}/\mathrm{s}^*$	$\mathbf{1.9 \times 10^9/s}$	$\mathbf{1.4 \times 10^2/s}$

*Possibly from the beam dump of the STCF.

PKMu (R&D) & MUonE (ongoing)

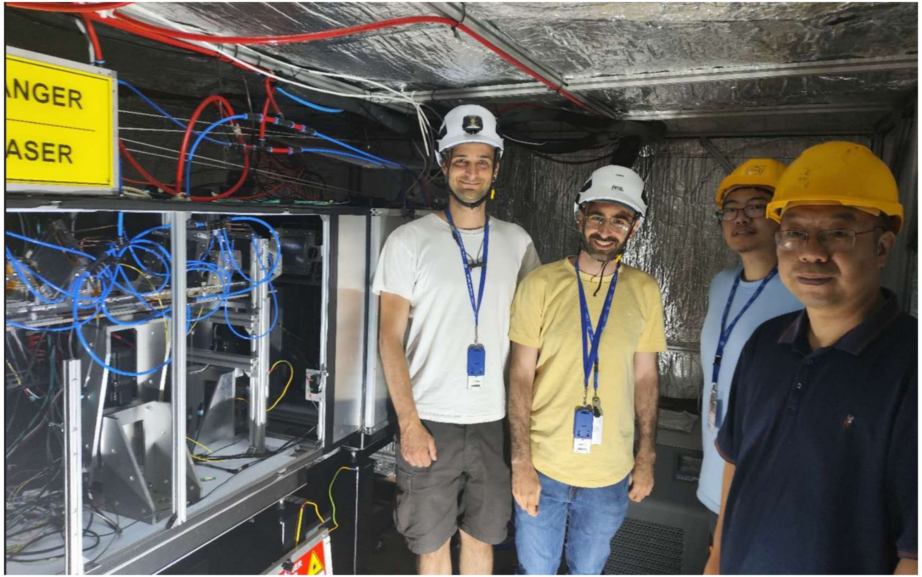
PKMu: Muon on target experiment proposed by PKU for multi-purpose including cosmic ray, dark boson, and **quantum entanglement**.

HIRIBL: 1-10GeV 10^6-10^7/s muon beam line from the HIAF facility from the imp, cas, China.

MUonE: a Muon Electron scattering experiment at CERN exploiting 150-160 GeV Muon beam, aims at an independent and precise determination of the leading hadronic contribution to the muon g-2.

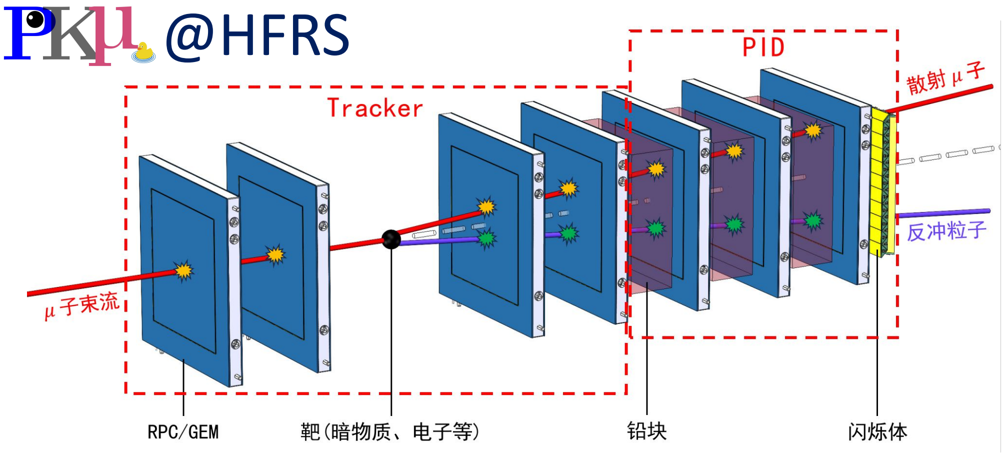
HIAF, Hui Zhou

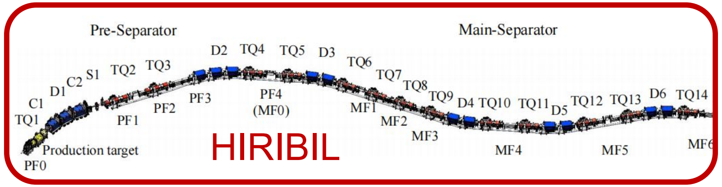
MUonE CERN



Muon Scattering Experiment at HIAF-HIRIBL

PKMu(Probing and Knocking with Muons) Proposed by Peking University together with HIAF-HFRS from Institute of Modern Physics, Chinese Academy of Sciences, China: **using 1-10 GeV Muon to probe new physics beyond the Standard Model**



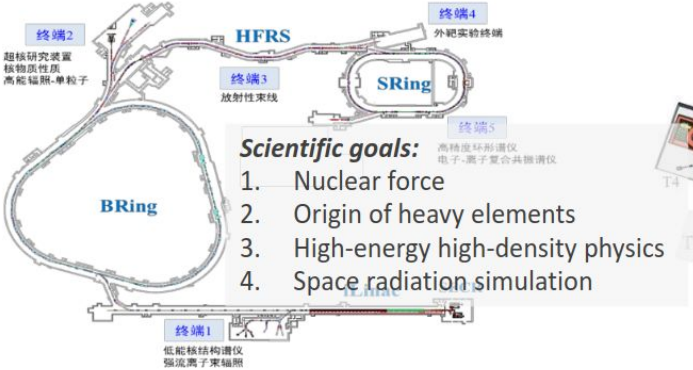


References: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

The under-construction HIAF and CiADS accelerator complex

Location: Huizhou city, Guangdong province

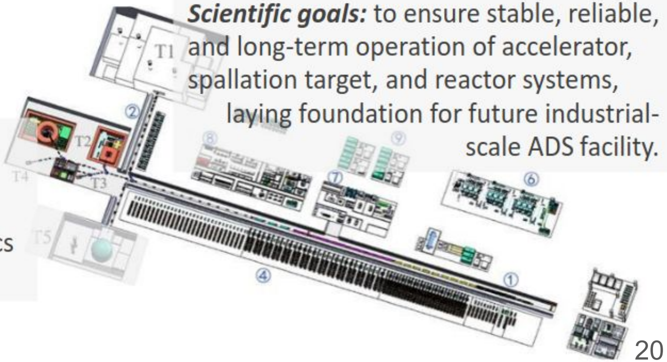
High-Intensity heavy-ion Accelerator Facility (HIAF): the world's most advanced heavy-ion accelerator with the highest pulsed beam intensity



Scientific goals:

1. Nuclear force
2. Origin of heavy elements
3. High-energy high-density physics
4. Space radiation simulation

China-initiative Accelerator-Driven Subcritical system (CiADS): the world's first megawatt-level ADS research facility



Scientific goals: to ensure stable, reliable, and long-term operation of accelerator, spallation target, and reactor systems, laying foundation for future industrial-scale ADS facility.

Two Major National Science and Technology Infrastructure Projects, approved by central government in December 2015.

Total investment: ~ 6.8 billion CNY

Construction periods:

HIAF: Dec. 2018 – Dec. 2025

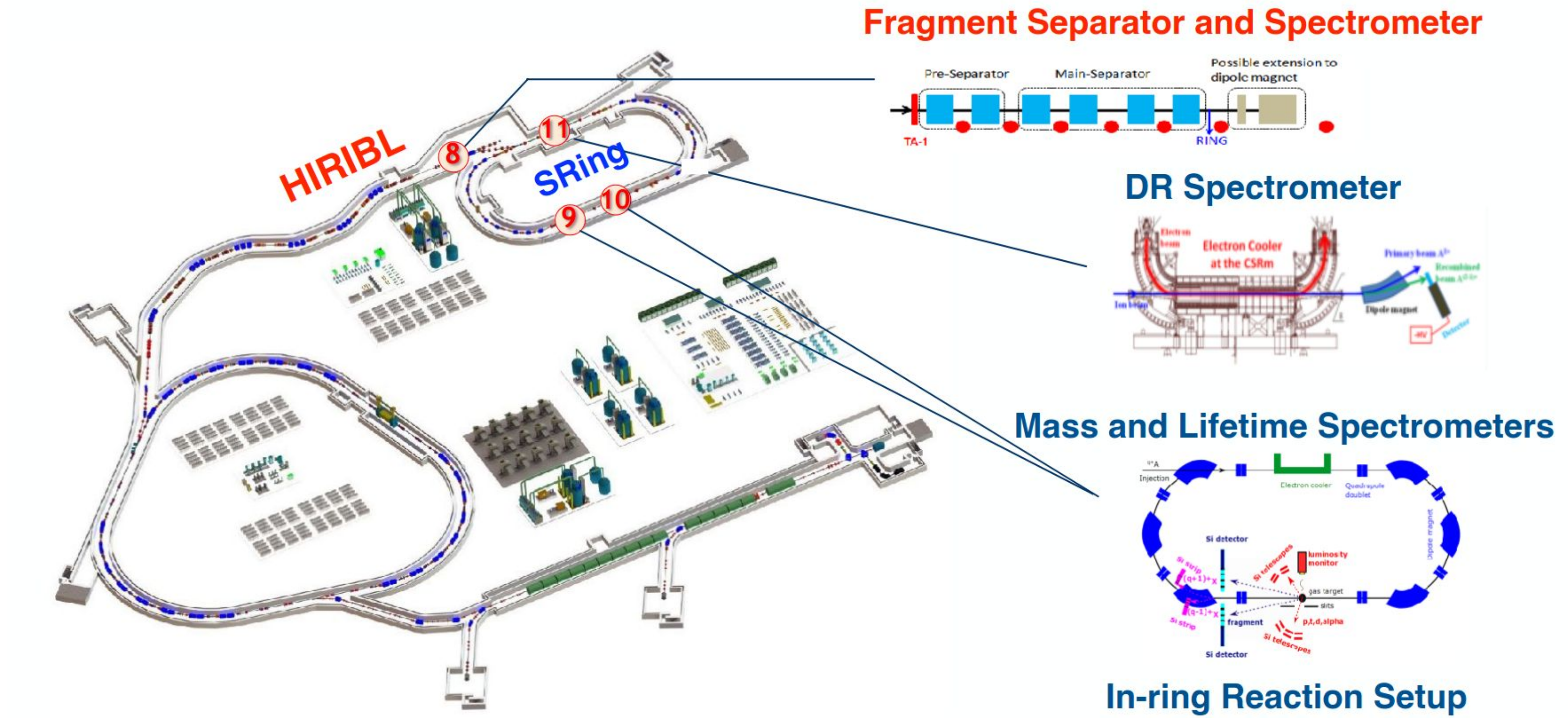
CiADS: July 2021 – July 2027

The under-construction HIAF and CiADS accelerator complex

https://indico3.cns.s.u-tokyo.ac.jp/event/320/contributions/3046/attachments/1010/1757/PCM2025_Ong2.pdf

HIAF Facility

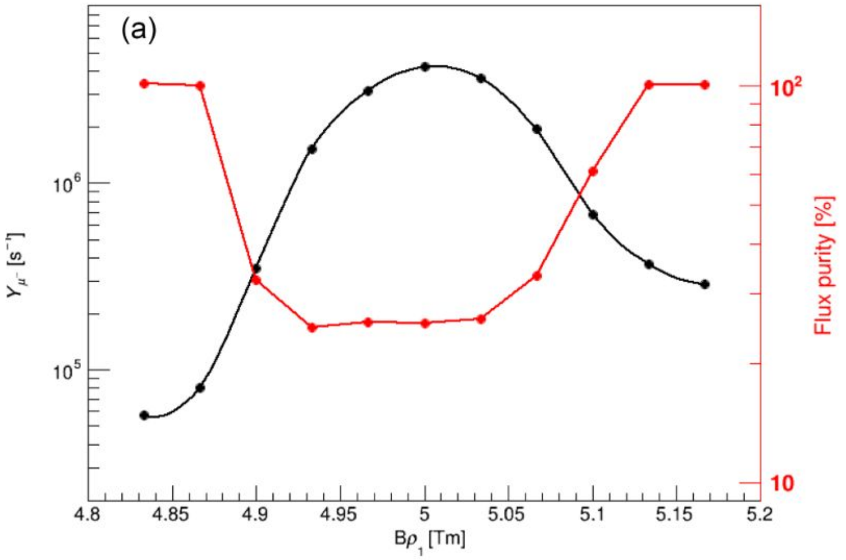
HIAF: A National Major Fundamental Research Facility under the 12th Five Year Plan



HIAF Muon beam

TABLE IV. The maximum muon flux intensities with proton, $^{18}O^{6+}$, and $^{78}Kr^{19+}$ projectiles, and the corresponding muon beam momenta and purities.

	Proton	$^{18}O^{6+}$	$^{78}Kr^{19+}$
μ^+ beam			
Momentum (GeV/c)	3.5	1.5	1.0
Flux intensity (μ^+/s)	8.2×10^6	3.5×10^6	1.8×10^6
Muon purity	2.0%	0.80%	0.60%
μ^- beam			
Momentum (GeV/c)	2.3	1.5	1.0
Flux intensity (μ^-/s)	3.8×10^6	4.2×10^6	1.6×10^6
Muon purity	13%	20%	23%

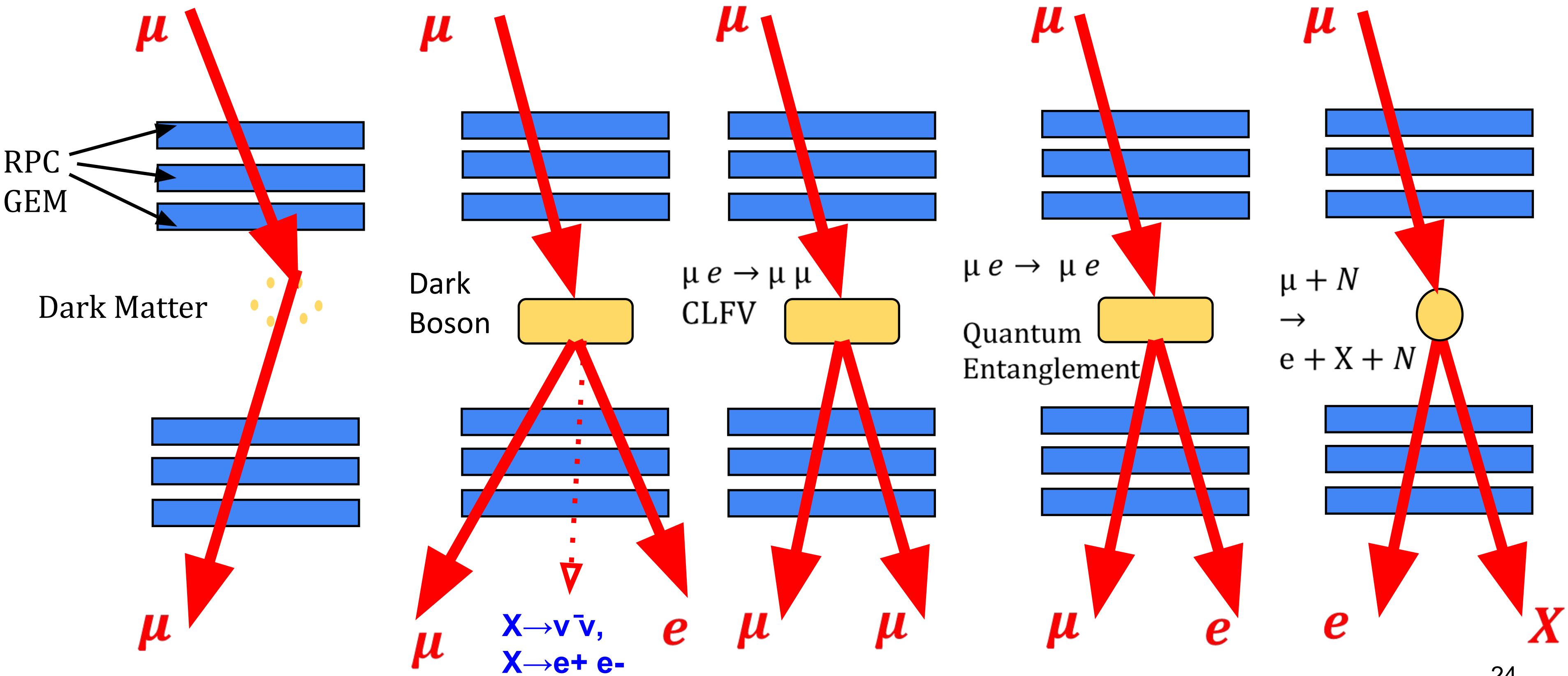


Phys.Rev.Accel.Beams 28 (2025) 5, 053401

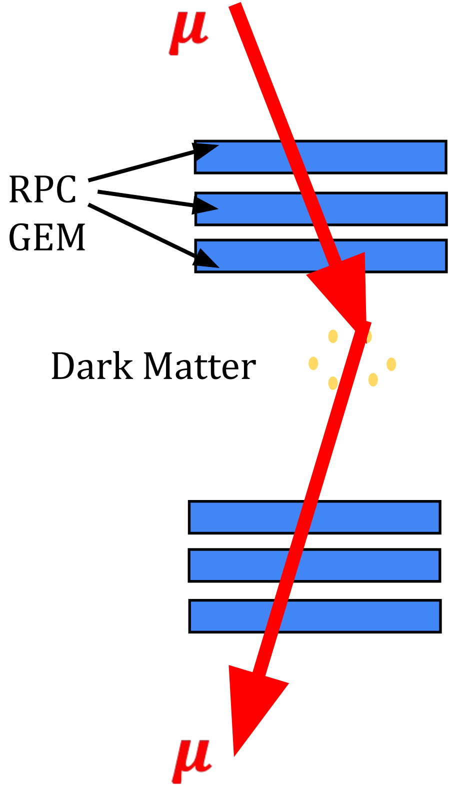
Multi-purpose platform

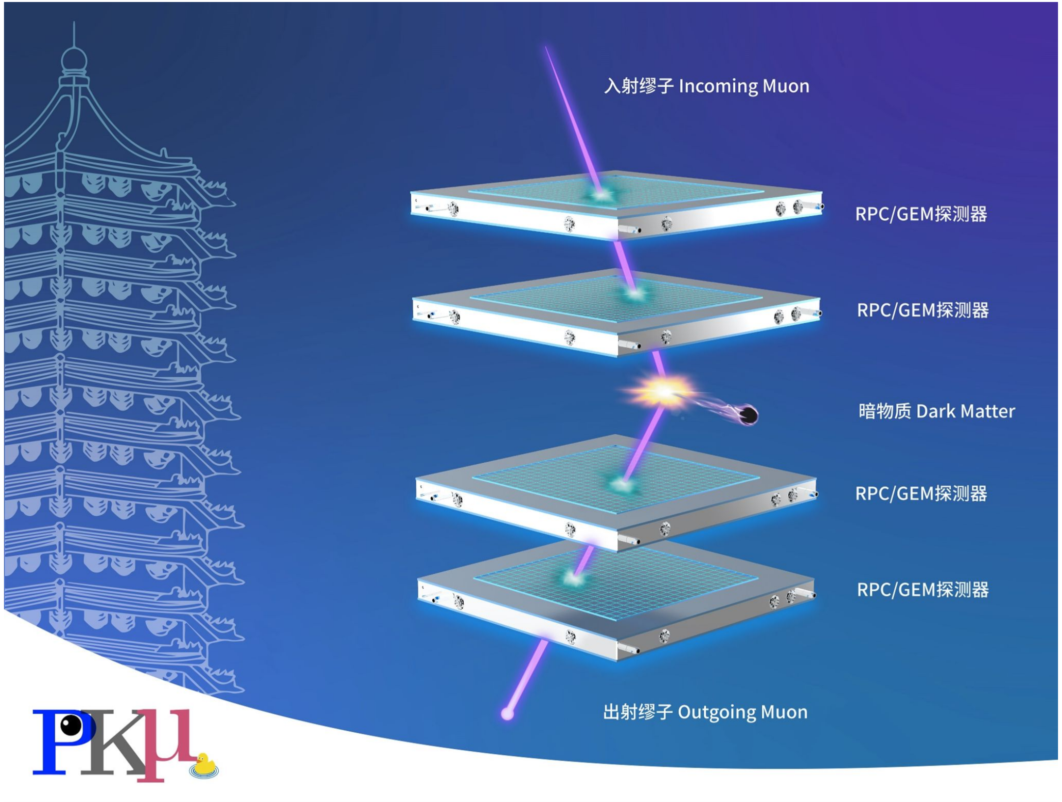
→Cosmic μ or μ beam

[Modern Physics Letters A (2025) 2530008]



1) Direct searches for DM

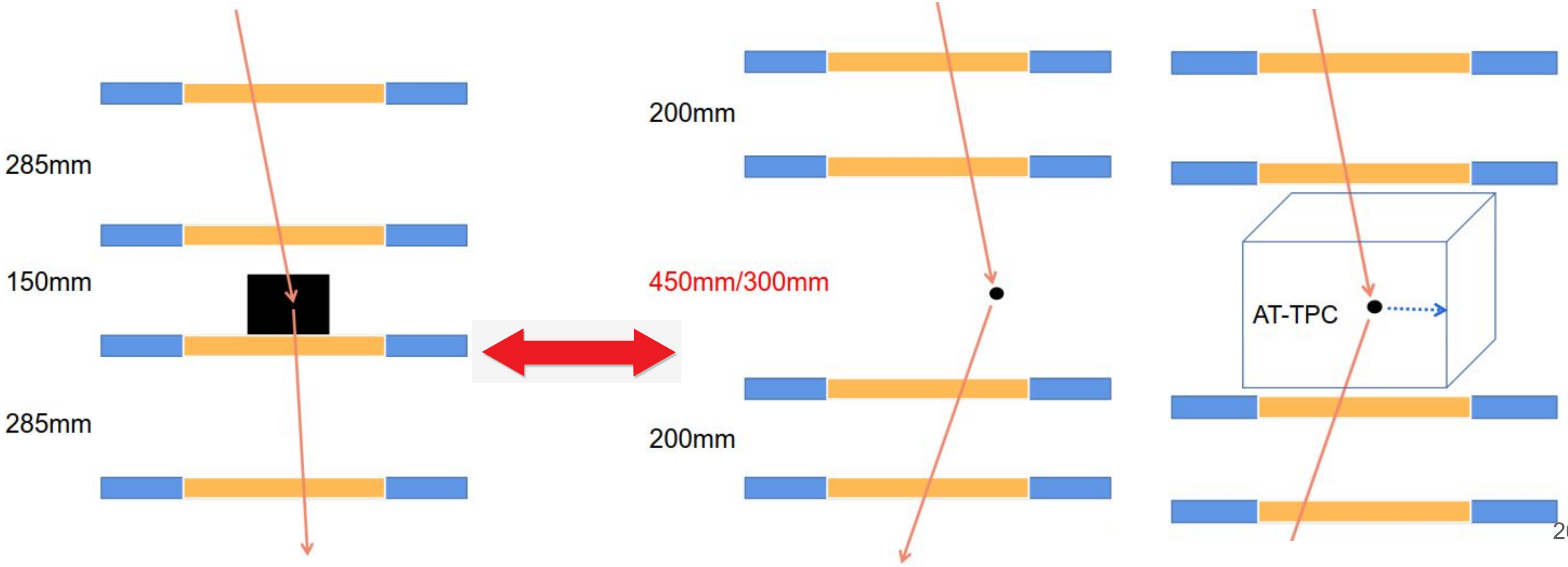




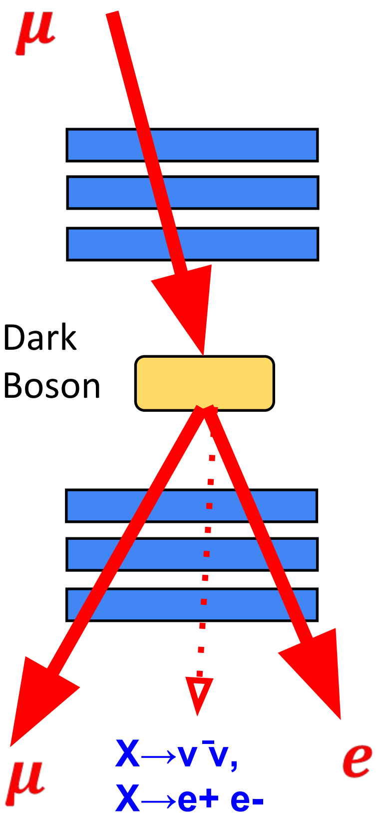
Muon Tomography and Muon-DM scattering

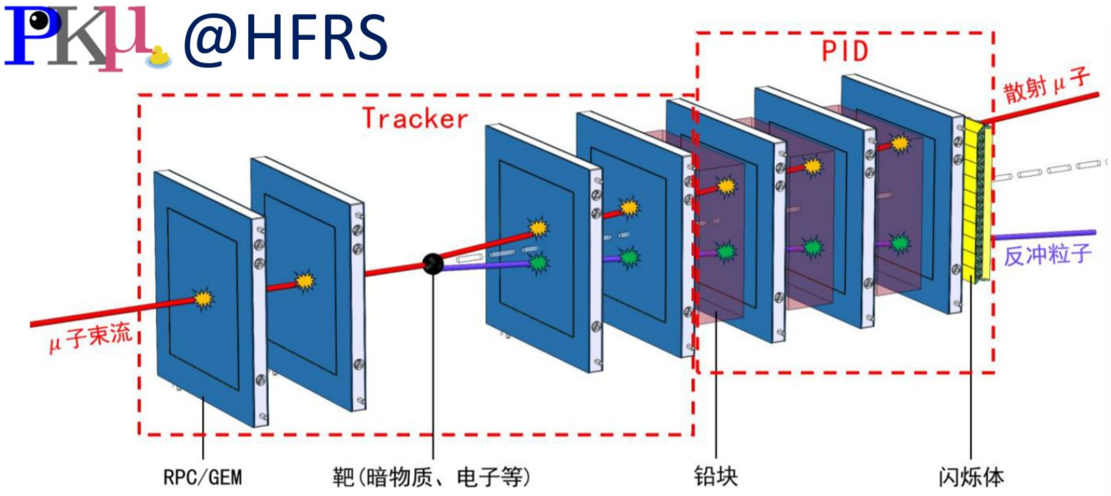
Muon Tomography 缪子成像 ⟷ Dark Matter Search 暗物质寻找

Phys.Rev.D 110 (2024) 1, 016017



2) On target experiments for Dark Boson



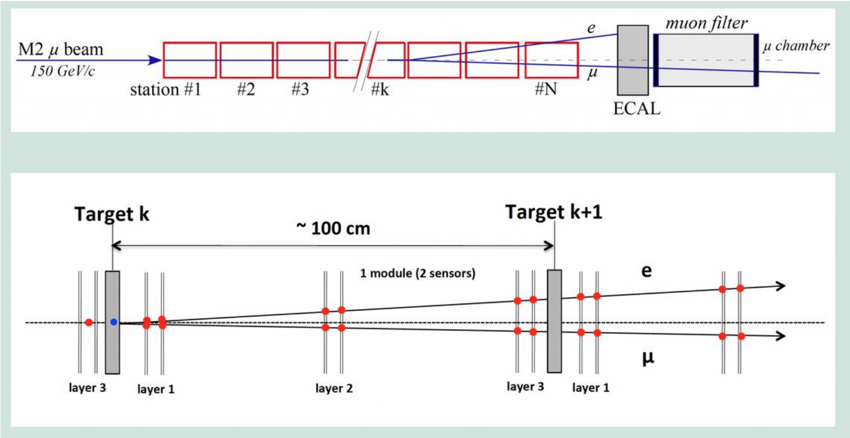


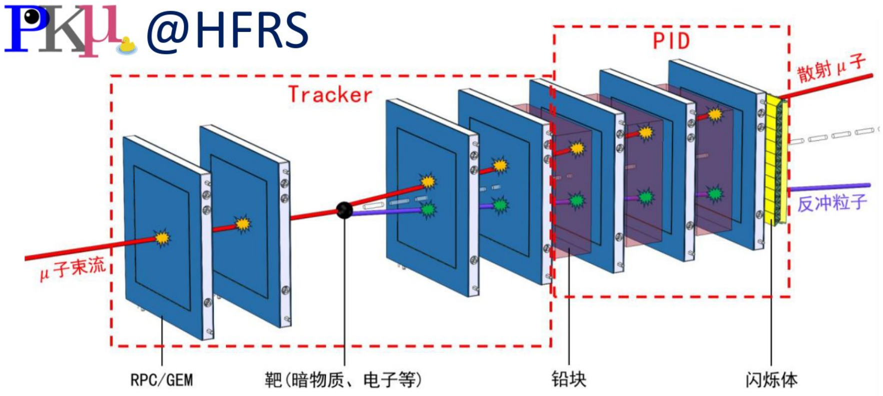
参考文献： [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

PKMu@HIAF vs. MUonE

- Muon Beam energy: 150-160 GeV vs. 1-10 GeV
- C.O.M energy for PKMu@HFRS is around 10 MeV
  - suitable for low mass searches
- Detector Can be more compact

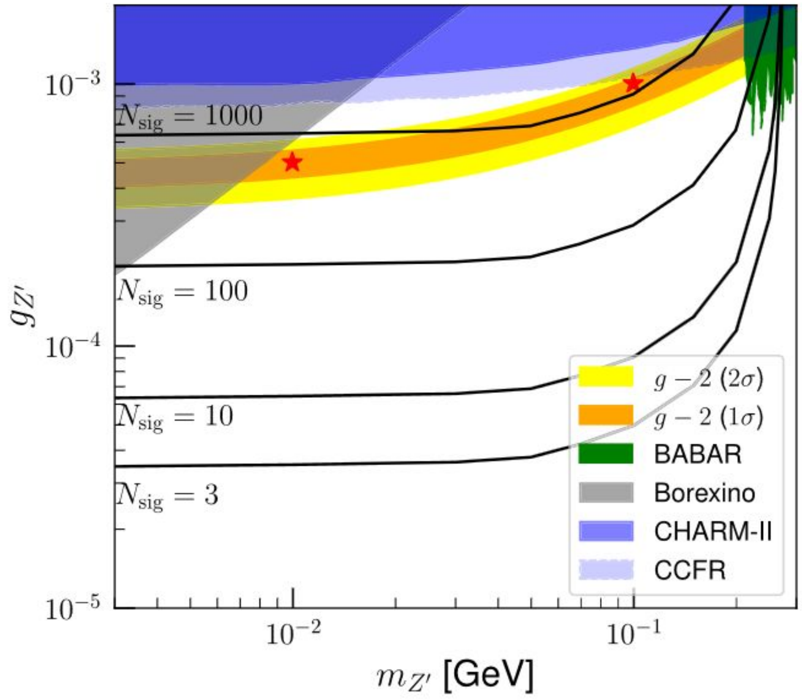
PKU joined MUonE recently, and will also perform BSM searches there



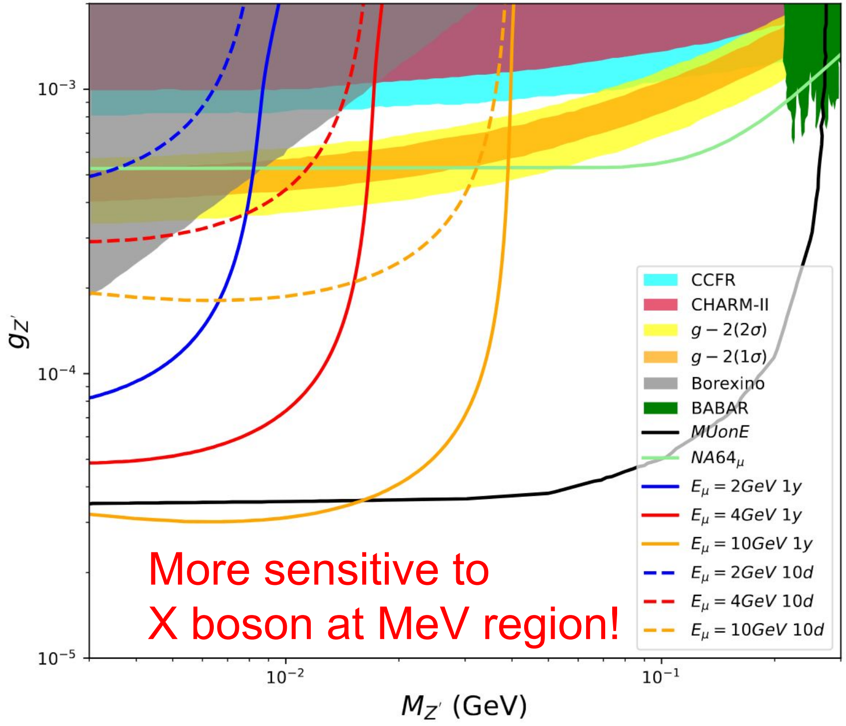


参考文献: [1] Phys. Rev. D 110, 016017 [2] arxiv:2410.20323 [3] arXiv:2411.12518 [4] Nucl. Instrum. Methods. Phys. Res. A 663 (2012) 22-25

PKMu@HIAF vs. MuonE on Dark Boson



Phys.Rev.D 106 (2022) 5, L051702



Preliminary results

Current Software and Simulation Status

PKMuon Collaboration

PKMuon Collaboration

3 followers · China · https://lyazj.github.io/pkmuon-site/ · seeson@pku.edu.cn

Overview · Repositories 10 · Projects · Packages · People 2

Pinned

PKMUON_G4sim Public
Forked from yuxdPKU/PKMUON_G4sim
Geant4-based simulation of PKMUON
C++

geomu Public
Forked from lyazj/geomu
Geographic Muon Simulation
C++

pkmuon-site-src Public
Forked from lyazj/pkmuon-site-src
source code of PKMUON site
Stylus

root-easy-debug Public
Forked from lyazj/root-easy-debug
Debug CERN ROOT macros in an extremely easy way
C

PHYSICAL REVIEW D **110,** 016017 (2024)

Proposed Peking University muon experiment for muon tomography and dark matter search

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(Received 23 March 2024; accepted 24 June 2024; published 19 July 2024)

A set of new methods are proposed here to directly detect light mass dark matter through its scattering with abundant atmospheric muons or accelerator beams. A first plan is to use the free cosmic-ray muons interacting with dark matter in a volume surrounded by tracking detectors, to trace the possible interaction between dark matter and muons. Secondly, the same device can be interfaced with domestic or international muon beams. Due to the much larger muon intensity and focused beam, it is anticipated that the detector can be made further compact, and the resulting sensitivity on dark matter searches will be improved. Furthermore, it may also be possible to measure precisely directional distributions of cosmic-ray muons, either at mountain or sea level, and the differences may reveal possible information about dark matter distributed near the Earth. Specifically, methods described here can have advantages over "exotic" dark matters that are either muonphilic or slowed down due to some mechanism, and the sensitivity on dark matter and muon scattering cross section can reach as low as microbarn level.

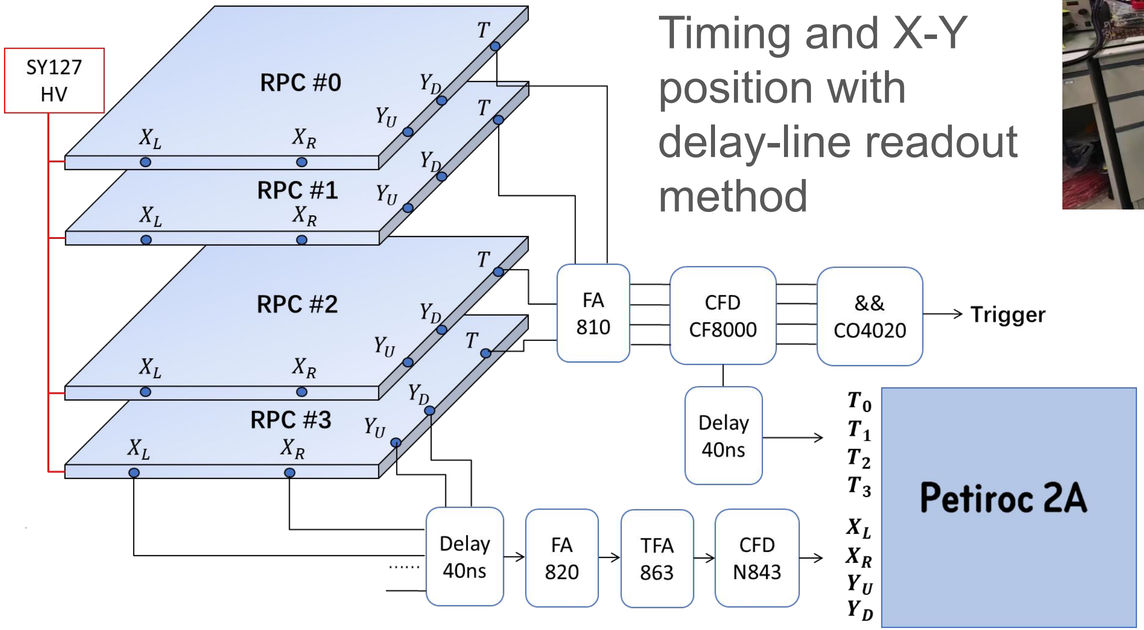
DOI: 10.1103/PhysRevD.110.016017

Current Box Exp. Status

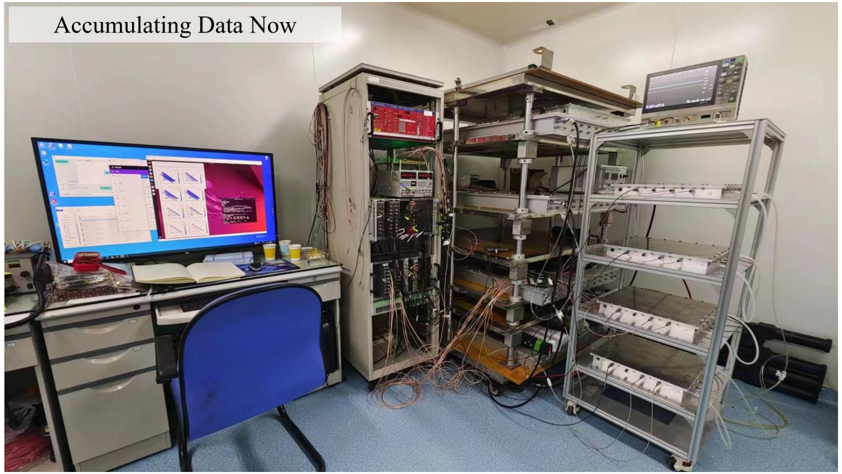
recent report from Cheng-en Liu and Qite Li

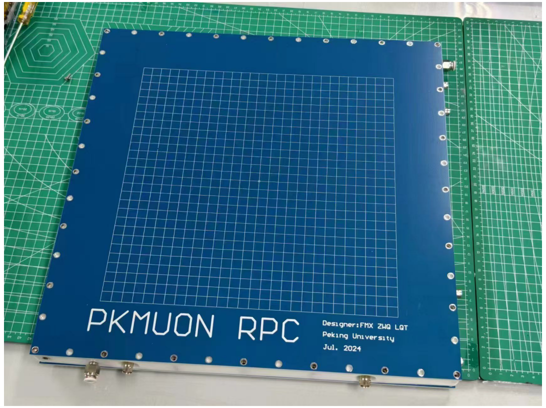
4-station 20cm*20cm RPC for the moment

Petiroc 2A is a 32-channel front-end ASIC



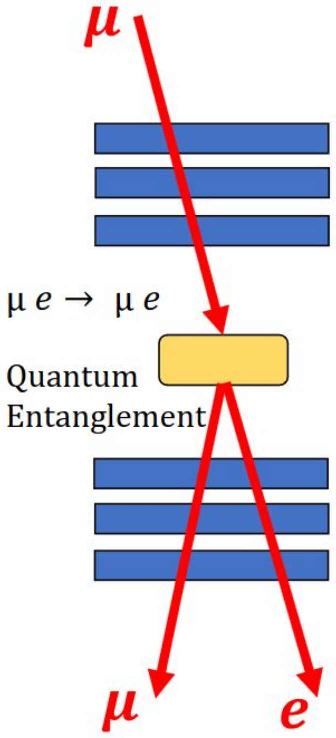
Timing and X-Y position with delay-line readout method

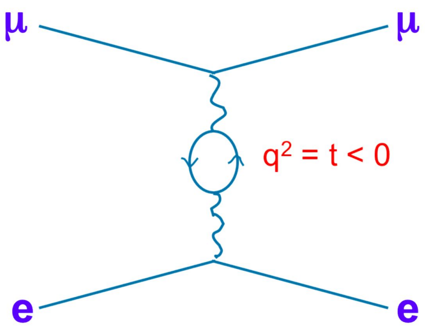




Muon Electron Scattering

- MuonE exploits 160 GeV Muon beam to measure muon electron scattering, and a precise determination of the leading hadronic contribution to the muon g-2.
- **Muon electron scattering at lower energy (~GeV)** may be interesting to SM test itself, and Quantum entanglement probe PRD 107, 116007 (2023):





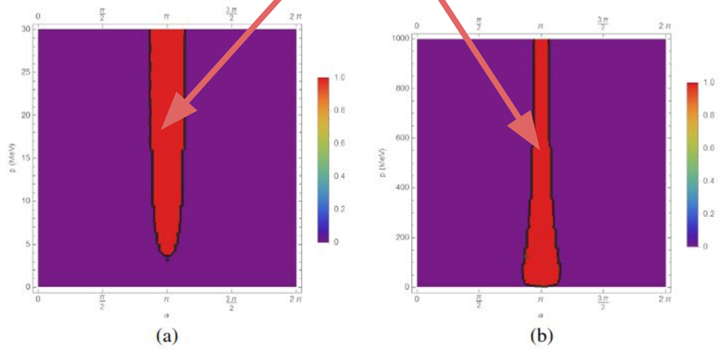


FIG. 15. The red regions correspond to the values of p and θ for which the final state is entangled at low—< 30 MeV—(a) and high—< 1 GeV—(b) energies.

arXiv:2502.07597 arXiv:2411.12518

Thanks for your attention!

solid-state system. However, in high energy experiments, measuring the spin of a single traveling electron poses a significant challenge due to interference from its orbital motion [32]. Instead, it is feasible to measure the average polarization of a beam of electrons or positrons by analyzing the distributions of the beam's scattering products following polarization-sensitive processes such as Mott scattering, Møller scattering, and Compton scattering [33]. Utilizing these strategies, the spin correlation of electron-positron pairs generated by positron targeting can be measured through two individual polarized secondary scattering processes: Bhabha scattering for positrons and Møller scattering for electrons. Simulation results and feasibility

particularly at the GeV scale, the polarization of keV- to GeV-scale electron beams can be measured with a precision of 2–3% through collective scattering behaviors of beam electrons using various methods [53].

field. However, measuring the spin of a single traveling electron presents significant challenges. For many years following the Stern-Gerlach experiment, it was deemed impossible to spatially separate traveling electrons with different spins due to the comparable effects of the Lorentz force and the uncertainty principle on spin-induced motion [44]. It wasn't until 1997 that Stern-Gerlach-like apparatuses, similar to those proposed by Brillouin in 1928 [45], were first analytically and numerically demonstrated to achieve this separation using strong magnetic fields [44,46–48]. Since then, various proposals have emerged to tackle this challenge, primarily focusing on minimizing the Lorentz force in novel Stern-Gerlach-like setups [49–52]. Most of these proposals target low-energy electrons and may not be effective for relativistic electrons. To date, measuring the spin of flying electrons remains a significant and fundamental research area. Despite the considerable challenges asso-

Despite the representability of the $\theta'_7 - \theta'_9$ correlation to the $s_3 - s_4$ correlation and the promising potential event rates for the cascade scattering experiment, reconstructing the density matrix $\rho_{s'_3 s'_4 s_3 s_4}$ from the secondary scattering products presents a significant challenge. A 4×4 density matrix is typically defined by 15 independent real parameters, which is considerably more than the four pure states we have examined. For arbitrary mixed states, we find significant degeneracy among them which complicates the quantitative reconstruction of the density matrix. However, the correlation effects can still be investigated, and a simplified state tomography can be performed assuming prior knowledge from the primary scattering, which indicates that approximately only a few linear combinations of the bases RR, RL, LR, and LL exist. We encourage the