Muon Beamline Optimization based on AI

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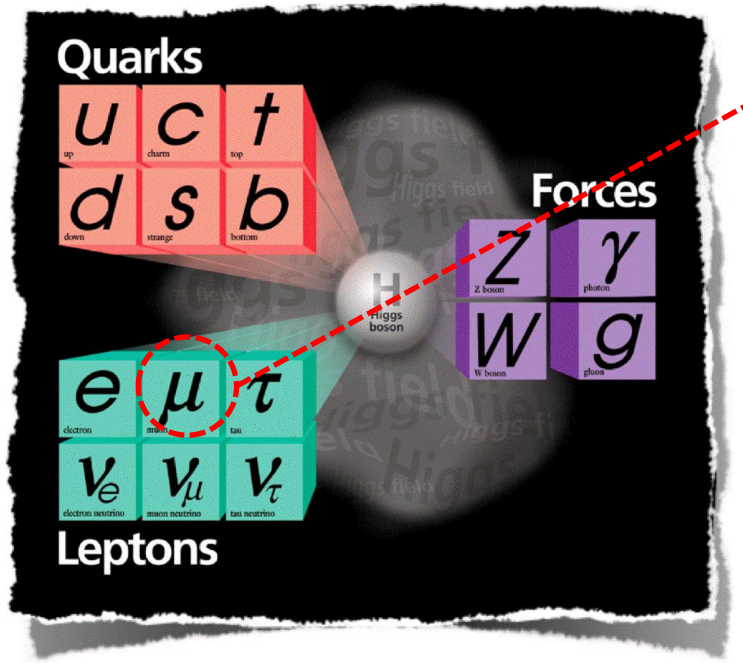
MIP2026 | Huizhou

26 Apr. 2026

Muon Applications and Muon Beam

China Spallation Neutron Source

Basic Properties and Applications of Muons



particles	charge	spin	Mass [MeV]	magnetic moment	gyromagnetic ratio γ/2π [kHzG^{-1}]	life [μs]
e	±e	1/2	0.511	$658\mu_p$	2800	∞
μ	±e	1/2	105.7	$3.18\mu_p$	13.5	2.197
π	±e, 0	0	139.6	0	0	26×10^{-3}, 8.4×10^{-11}
p	±e	1/2	938	μ_p	4.26	∞

Muon Physics

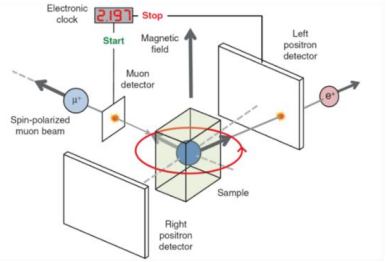
- Precision measurements
  - g-2
  - EDM
- cLFV

$\mu^+ \to e^+\gamma$	3.1×10^{-13} (MEG-II)
$\mu^+ \to e^+e^+e^-$	$< 10^{-12}$ (SINDRUM)
$\mu^-N \to e^-N$	7×10^{-13} (SINDRUM-II)
$Mu-\overline{Mu}$	8.3×10^{-11} (MACSI)[19]

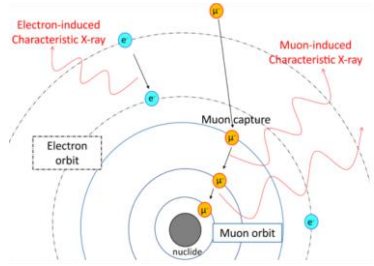
- Muon collider
- Neutrino facility

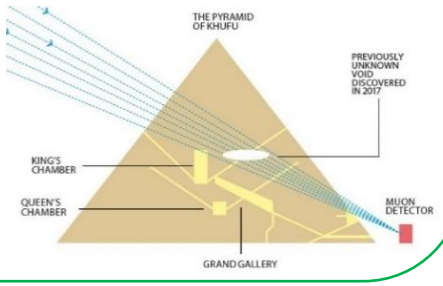
Muon Applications

- μSR



- MIXE/MuX
- Muon tomography

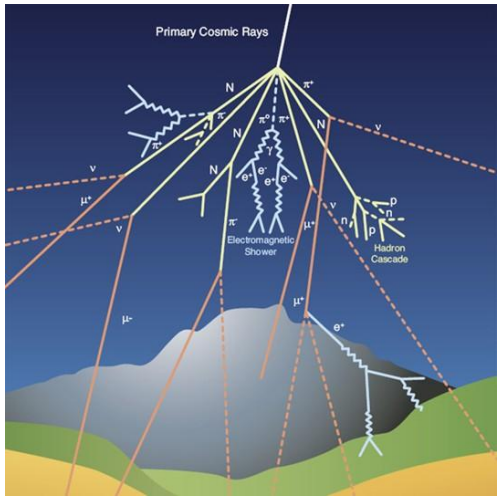


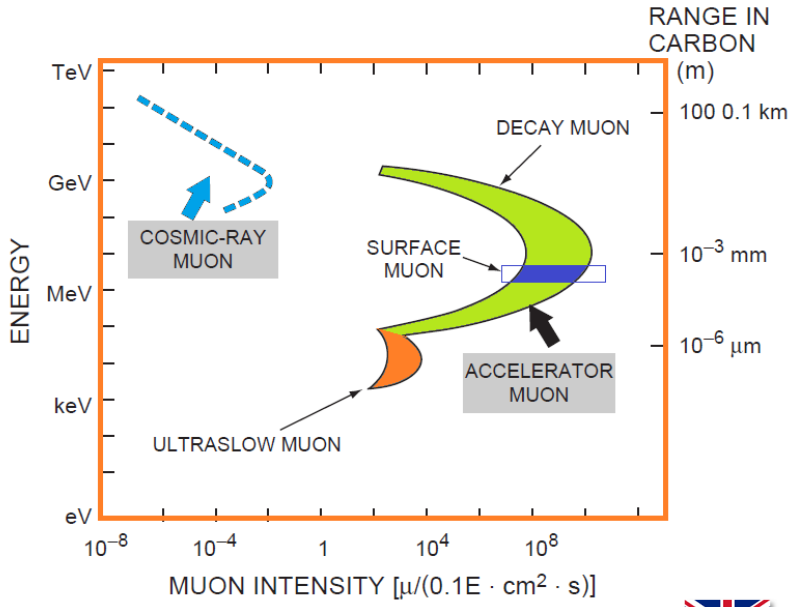


Muon Applications and Muon Beam

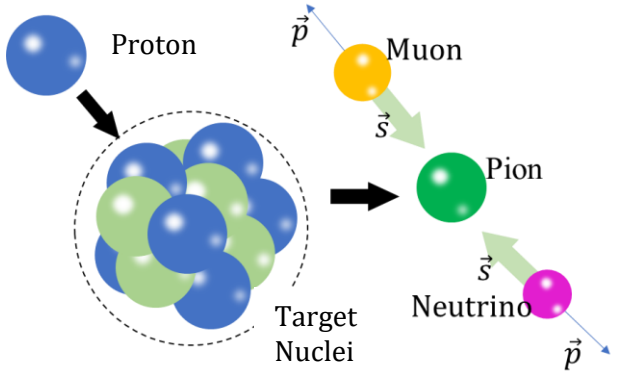
Muon Sources

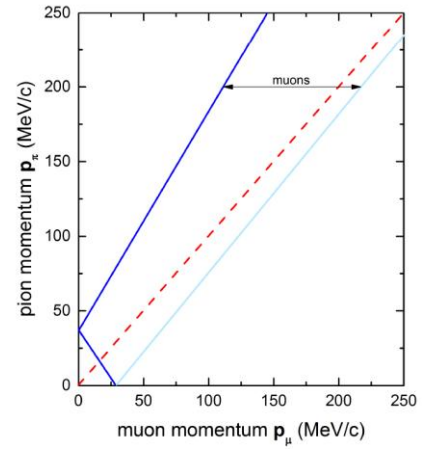
Cosmic-ray Muon





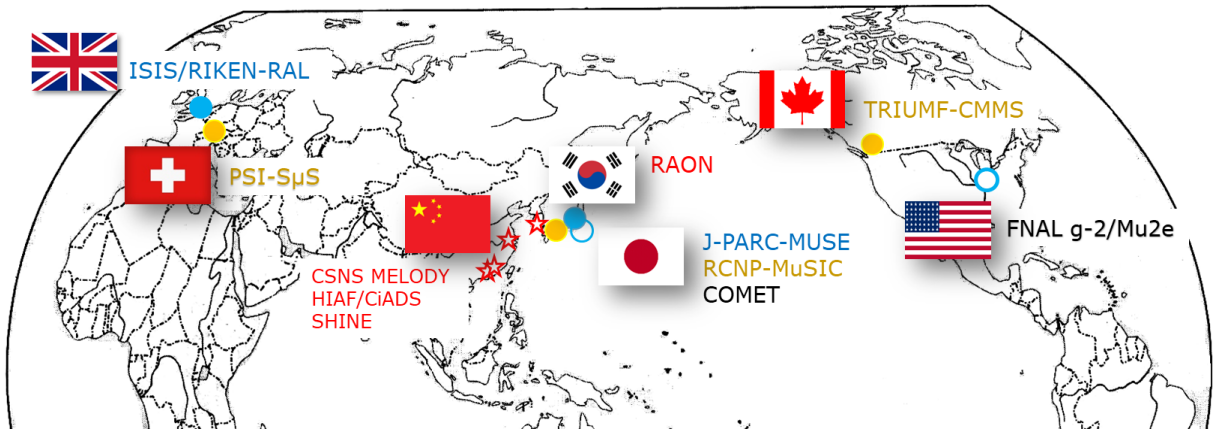
Proton-Driven Muon Source





Expansion of Muon Applications: Increasing Demand for **Higher Intensity** and **Better Beam Quality**

- *In Operation*: construct new or reconstruct existing muon beamlines to enhance beam quality
- ***Construction/Planned***
  - CSNS-MELODY , HIAF/CiADS, SHINE (e-Driven)
  - RAON (Korea), SNS (USA)

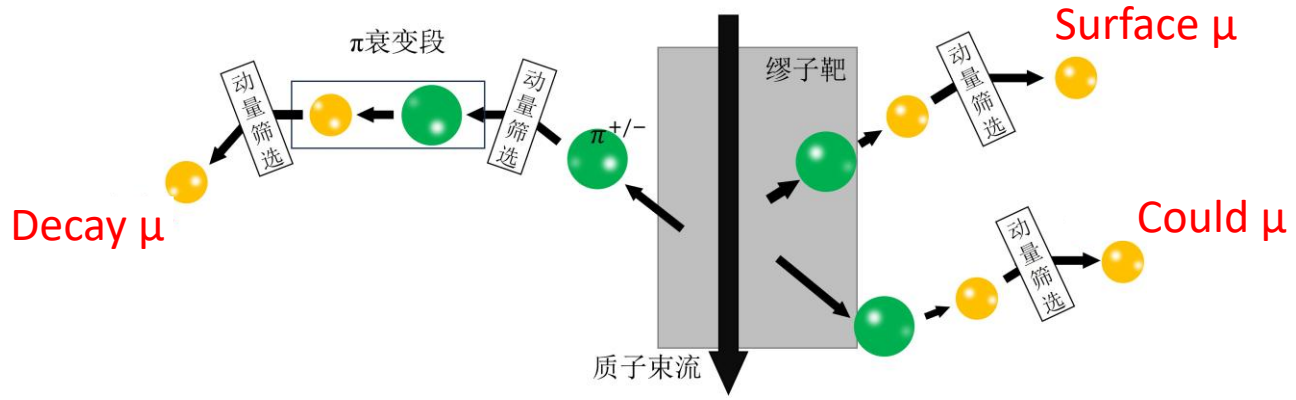


CW muon Pulsed muon For particle physics experiments

Muon Applications and Muon Beam

Muon Beamlines and Design Methods

- Muon Beamlines： Extracting muons from the target and transporting them to the terminal,
  A critical step that determines the quality of the muon beam



Improving Beam Quality
- Intensity
- Spot size
- Momentum rang
- Polarization
- Pulse width & frequency

- Design and Optimization: Enhance beamline performance and improve design efficiency

➢ Beam Optics Design
beam envelope,
dispersion function, etc.,
to provide initial parameters

+

➢ Particle Tracking Simulation
more accurate particle distribution and
magnet modules,
beam spot, background, polarization, etc.

+

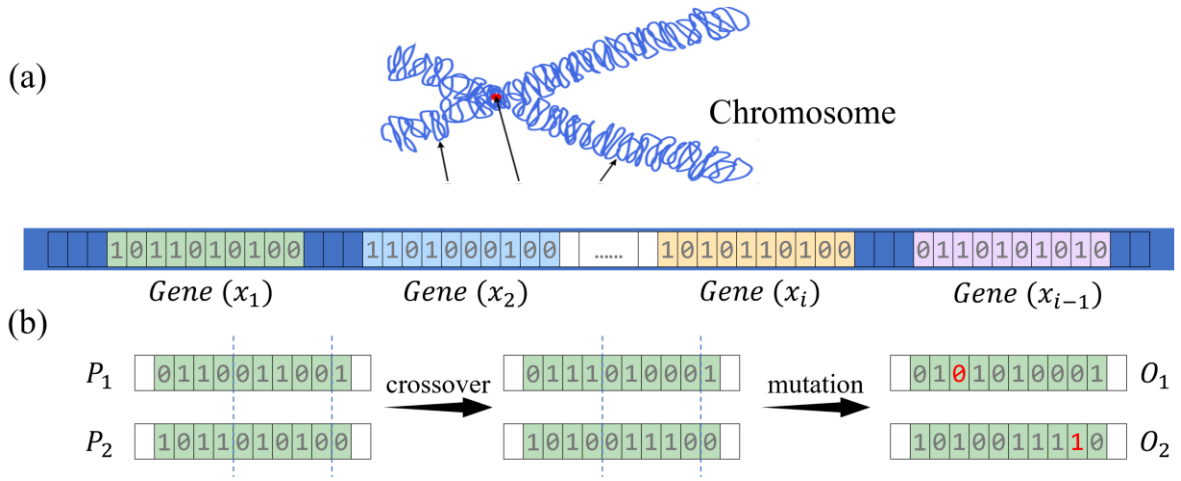
➢ Intelligent Optimization Methods
- Genetic Algorithms
- Center-Evolving Algorithm

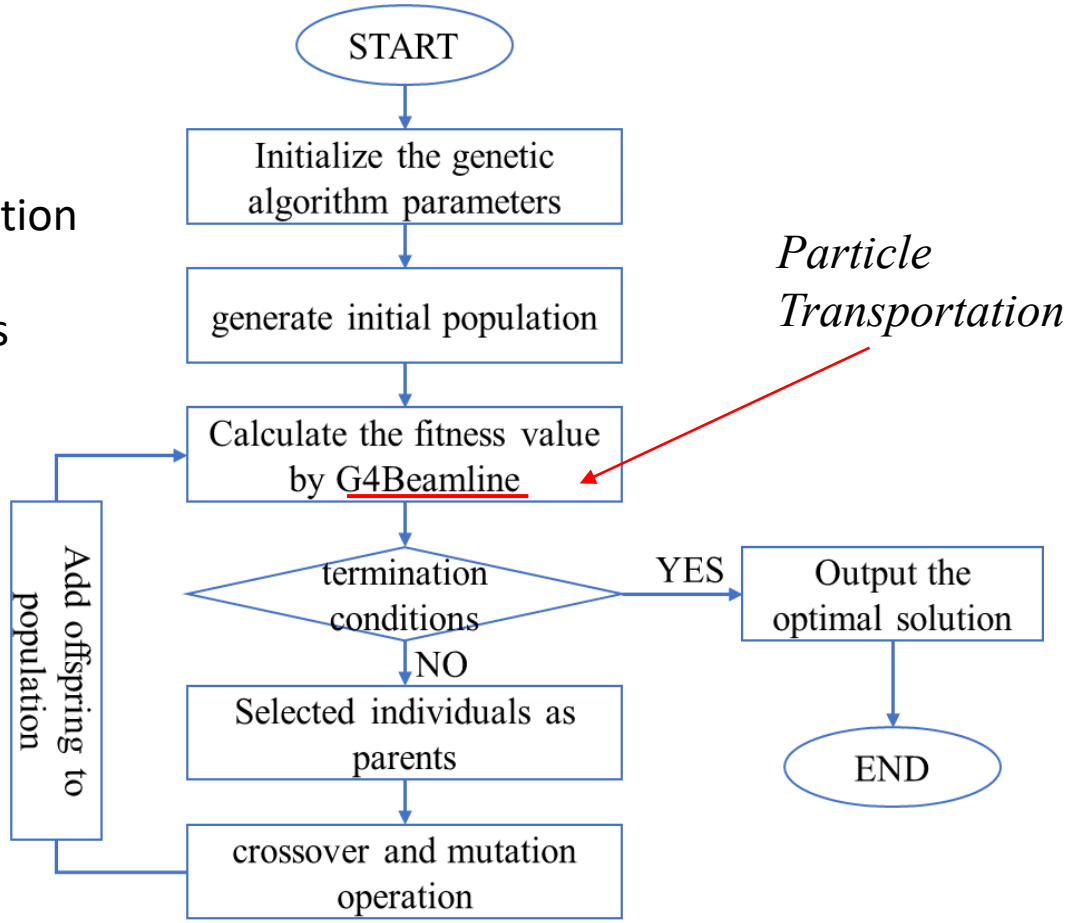
Tradition methods

Muon Beamline Optimization based on GAs

Methodology

- **Algorithm Principle:** A population-based evolutionary algorithm
- Inspired by the natural selection process in biological evolution
  - Operations: Encoding, Evaluation, Selection, Crossover, Mutation
  - Strong global exploration capability
  - Effective for solving complex nonlinear optimization problems





- Fitness function: $F = \sum_{i}^{n} w_i \cdot N_i + N_c^{w_c}$
- Mutation property:

$$P_m^j = P_m \cdot \left(-c_1 \cdot \arctan\left(c_4 \cdot \left(j - c_3\right)\right) + c_2\right), \text{ bit } j = 1, 2, 3 \cdots, 15$$

Tailored to the muon beamline design

Muon Beamline Optimization based on GAs

China Spallation Neutron Source

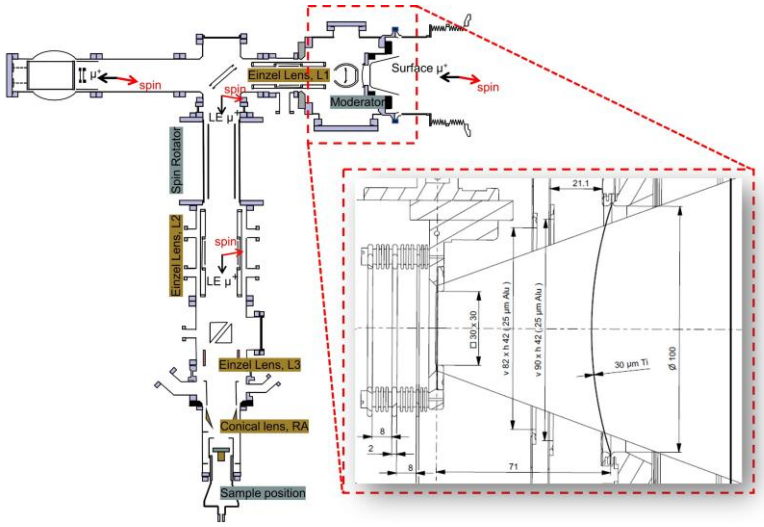
μE4 beamline and optimization objectives

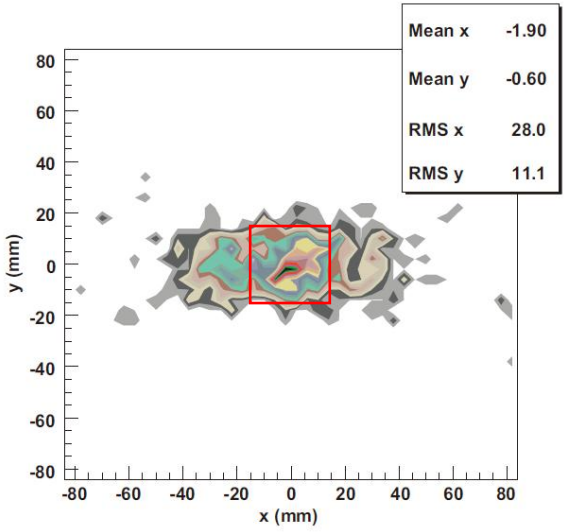
μE4: delivers the world's highest-intensity continuous surface muon beam

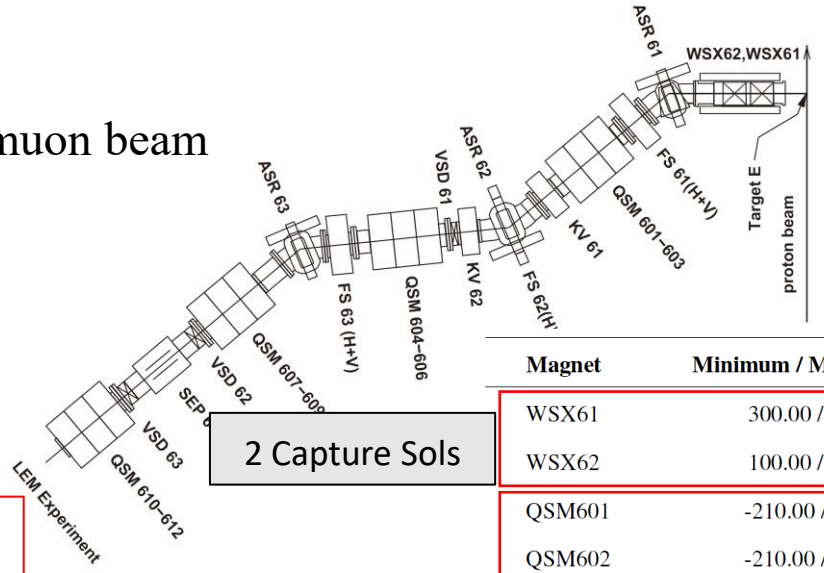
- Large-aperture magnets: Solenoids + Quadrupoles
- Beam emittance: 5500 / 10000 π mm·mrad
- 2.2 ×10^8 μ/mAs
- Serves as the injector for LEM setup

Optimization Objective:

maximize the surface muon intensity focused onto the moderator







2 Capture Sols

12 Quadrupoles

3 Dipoles

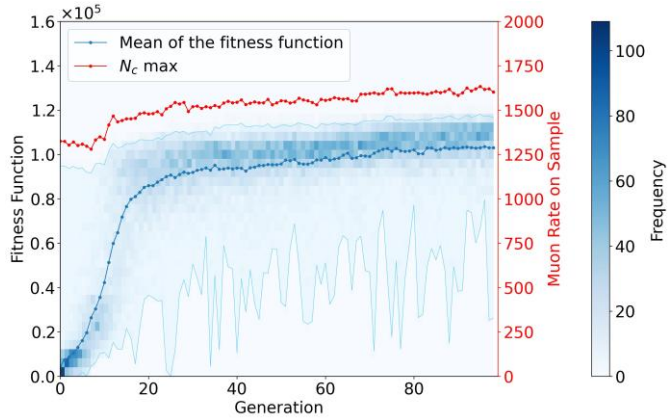
Magnet	Minimum / Maximum (A)	Optics design
WSX61	300.00 / 320.00	288.10
WSX62	100.00 / 150.00	143.80
QSM601	-210.00 / 210.00	44.81
QSM602	-210.00 / 210.00	-136.75
QSM603	-210.00 / 210.00	73.43
QSM604	-210.00 / 210.00	41.13
QSM605	-210.00 / 210.00	-131.85
QSM606	-210.00 / 210.00	77.78
QSM607	-210.00 / 210.00	67.51
QSM608	-210.00 / 210.00	-133.14
QSM609	-210.00 / 210.00	66.73
QSM610	-210.00 / 210.00	-94.87
QSM611	-210.00 / 210.00	190.11
QSM612	-210.00 / 210.00	-186.69
ASR61	290.00 / 330.00	311.10
ASR62	260.00 / 300.00	278.60
ASR63	260.00 / 300.00	267.80

Muon Beamline Optimization based on GAs

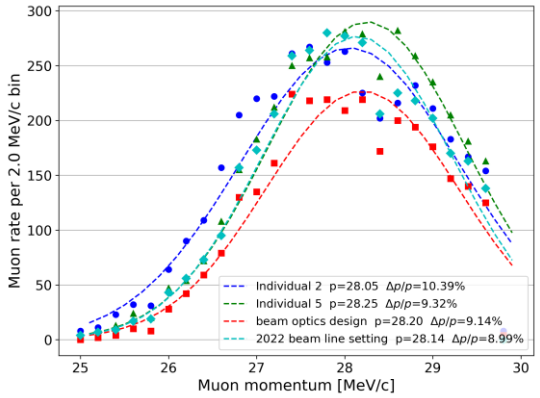
China Spallation Neutron Source

Optimization Results

- Number of muons: 1×10^5
- 100 generations require ~8 hours



- Central Beam momentum variation < 1%



Magnet	index 1	index 2	index 3	index 4	index 5	index 6	index 7	index 8	Optics design
WSX61	305.266	304.615	307.877	304.082	308.26	308.221	302.559	304.395	287
WSX62	123.888	123.843	126.369	126.221	125.943	125.226	125.635	128.223	143
QSM601	47.646	47.695	49.988	47.988	51.193	48.732	46.758	45.9375	44.814
QSM602	-136.076	-136.094	-134.249	-139.863	-133.788	-132.198	-132.48	-136.172	-136.752
QSM603	73.437	73.418	72.303	78.75	72.252	72.47	73.418	76.6992	73.437
QSM604	45.434	44.81	50.898	36.914	51.103	50.885	42.246	52.0898	41.139
QSM605	-111.264	-111.534	-131.417	-115.254	-131.442	-132.147	-125.508	-118.125	-131.859
QSM606	61.655	61.926	78.942	71.367	79.904	78.776	79.57	65.2148	77.784
QSM607	72.595	72.43	67.381	66.035	69.804	68.009	72.188	76.2891	67.515
QSM608	-136.992	-136.996	-133.16	-132.48	-132.198	-133.749	-132.07	-132.48	-133.140
QSM609	66.035	65.207	71.098	65.625	65.843	70.239	66.035	60.293	66.738
QSM610	-98.532	-98.453	-89.004	-91.875	-90.324	-90.568	-89.414	-88.5938	-94.878
QSM611	186.982	186.999	185.468	189.082	186.019	186.185	185.391	184.98	190.113
QSM612	-173.518	-173.43	-188.582	-190.723	-189.338	-187.39	-188.262	-186.211	-186.690
ASR61	309.763	309.763	310.842	306.914	311.014	310.923	309.023	309.805	309.0
ASR62	274.375	274.375	275.574	271.406	275.36	275.378	273.164	275.742	275.5
ASR62	265.586	265.586	267.98	265	268.024	268.105	267.891	268.672	268.01
μ⁺ by G4bl	**1597**	**1590** (+21%)	**1725**	**1690**	**1759** (+33%)	**1745**	**1715**	**1635**	**1318**

Muon beam intensity is at least 20% higher than the original Optics Design

Muon Beamline Optimization based on GAs

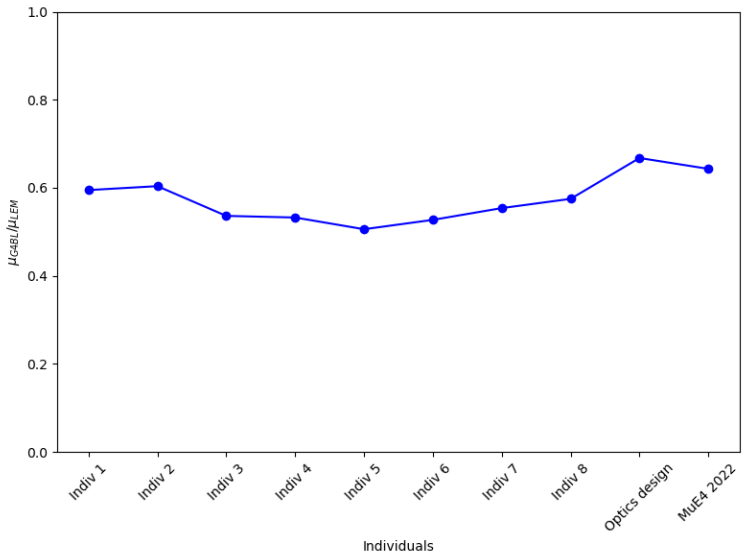
Online Beam Tuning Results

- Optimized muon beam intensity is 10% higher than the Optics Design

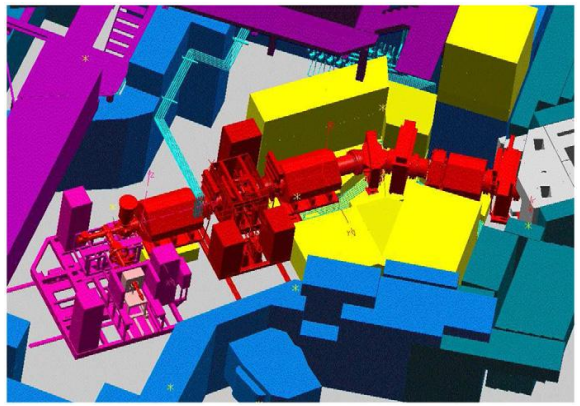
Magnet	index 1	index 2	index 3	index 4	index 5	index 6	index 7	index 8	Optics design
μ^+ by G4bl	1597	1590	1725	1690	1759	1745	1715	1635	1318
μ^+/mAs on LEM	950	960	925	900	890	920	950	940	880

The optimization method enables **rapid optimization** of beamline settings, and significantly **increases the surface muon intensity** focused onto the moderator

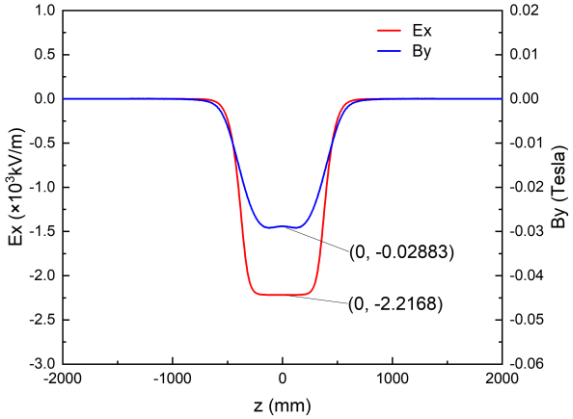
- Beam Tuning vs. Simulation Expected



- Main Reasons



- ASR61 and ASR62: The cast iron shielding affects the effective length and fringe fields



- SEP61: The electric field and magnetic field differ from those of the actual components

Muon Beamline Optimization based on GAs

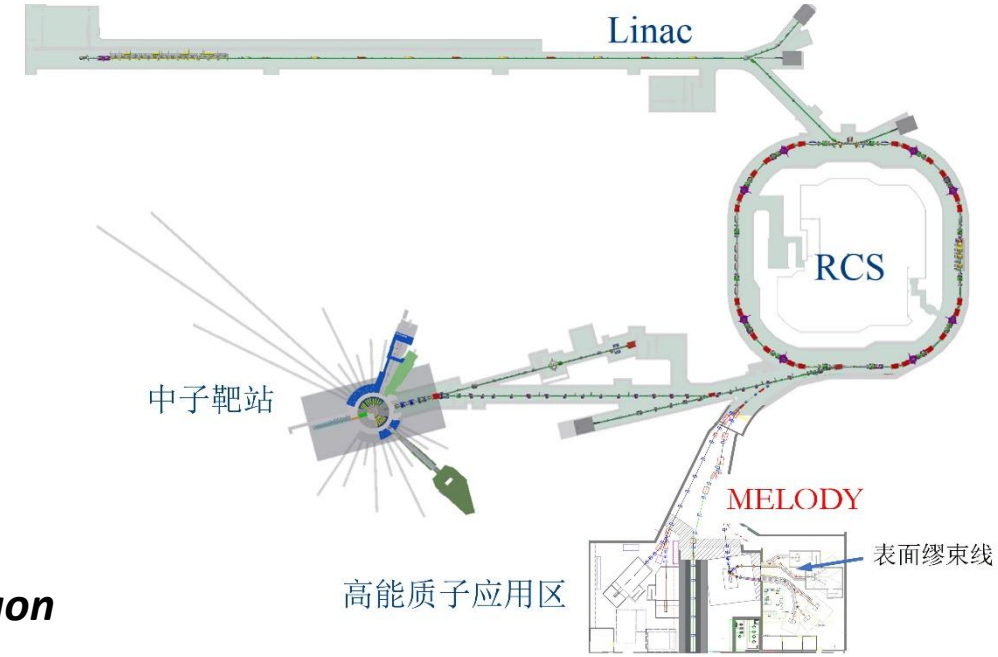
Muon Beamline for the CSNS-II

CSNS-II

- RCS：1.6 GeV、500 kW、25 Hz

MELODY

- A muon platform primarily focused on multidisciplinary muon applications
- Target station: Independent (10 cm Cu, 1 Hz, 20 kW)
- Beamlines***: Surface muon, Decay muon and Negative muon***

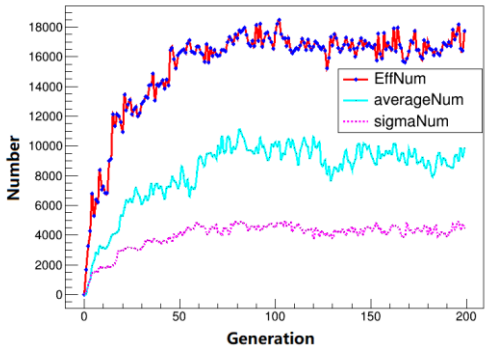


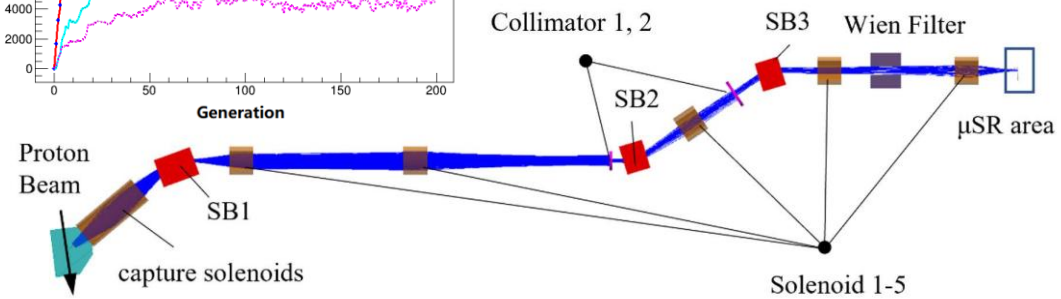
Muon Beamline Optimization based on GAs

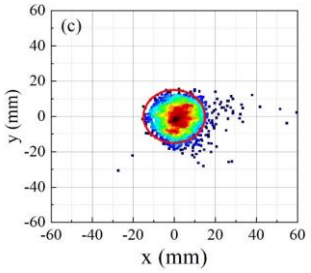
China Spallation Neutron Source

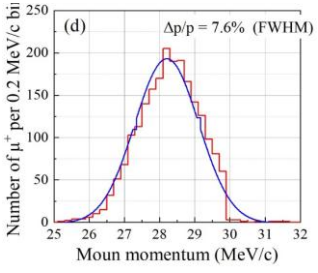
Surface Muon beamline (Feasibility Design)

- Solenoid focusing
- 15 variables: Positions and strengths of all magnets
- Optimization objective: Beam intensity for μSR





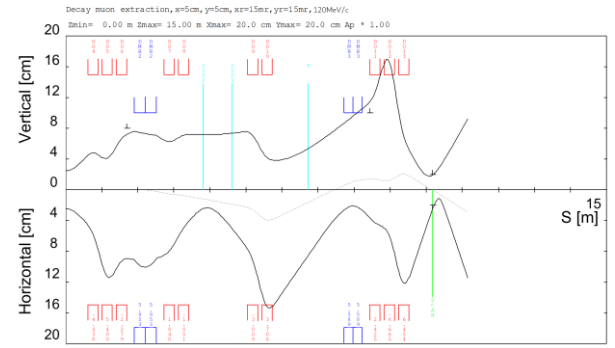


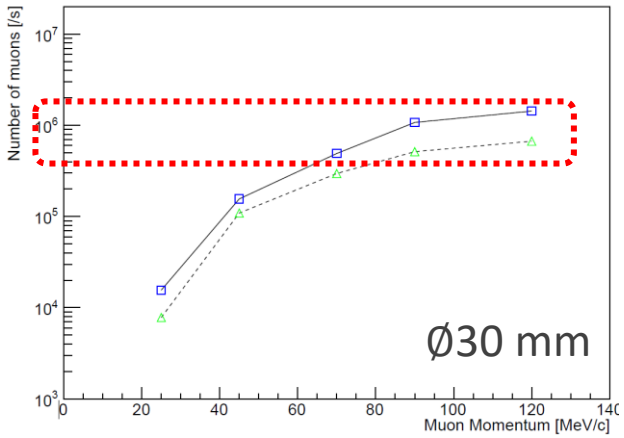


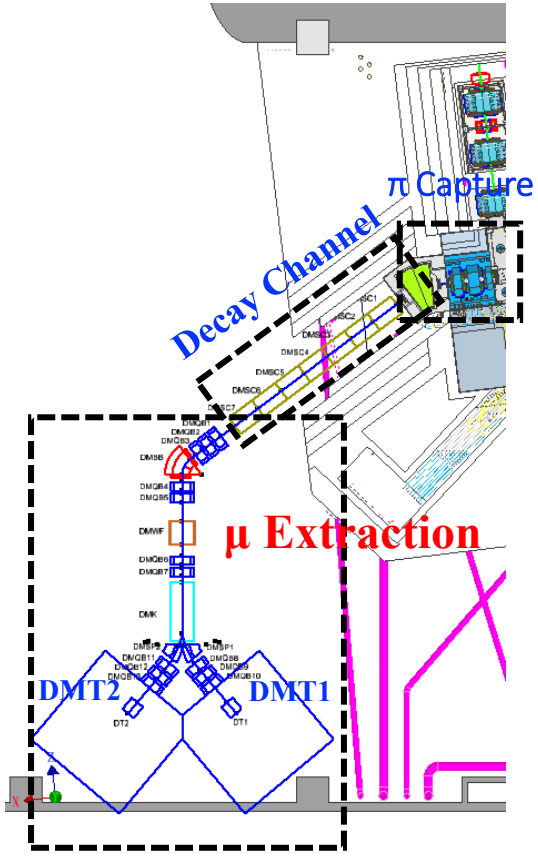
Parameters	Value
$\Delta p/p$ (FWHM)	~ 7.6%
μ^+ rate	1.68×10^6 μ^+/s
μ^+ rate on Ø30 mm	1.53×10^6 μ^+/s
Core ratio	~ 90%
Polarization	~ 95%
e^+/μ^+	<1%

Decay Muon Beamline

- Muon Extraction Part
- Quadrupole focusing: Higher Momentum
- Different momenta with the same layout





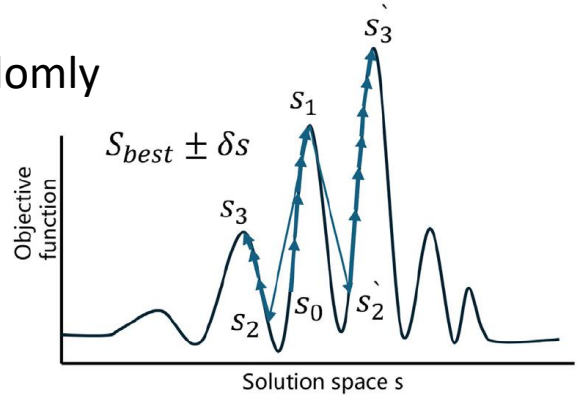


Standard GAs: **Weak Convergence Precision**, Particularly Insufficient for **Small Beam Spot Optimization**

Muon Beamline Optimization based on CE

Methodology

- **Algorithm Principle**
  1. A queen: releases flying ants randomly
  2. the flying ants climb upward
  3. they report their altitude
  4. the highest ants become the new queen

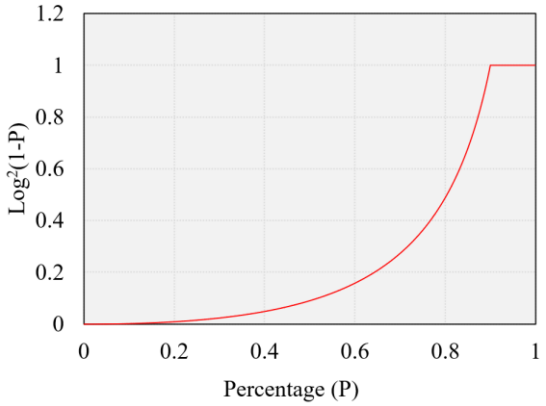


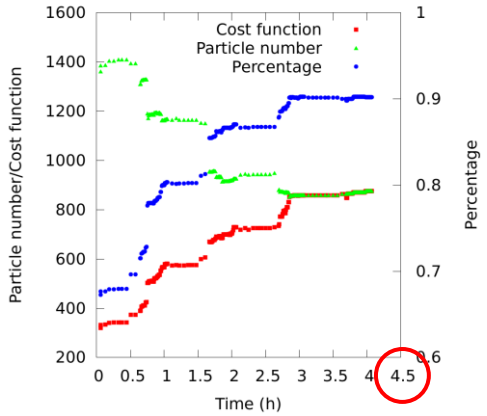
- **Parallel Simulation**: Rapid exploration
- **Penalty Function**: Multi-objective Optimization

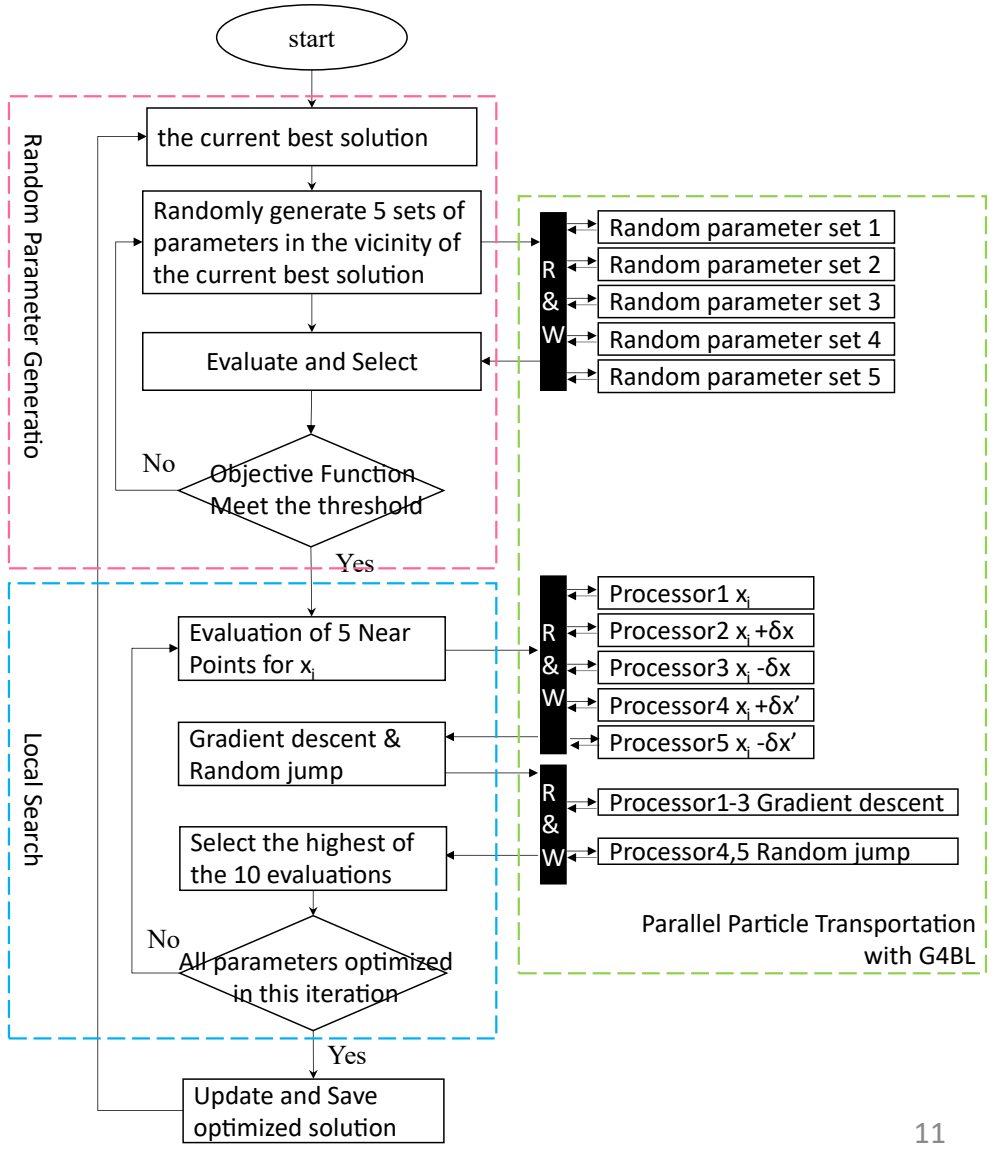
$$N \times \log^2(1-P)$$

N: the total number,
P: the fraction of muons

- **Gradient descent:** Local Search via Parabolic Fitting
- **Random Jump:** escape local optima

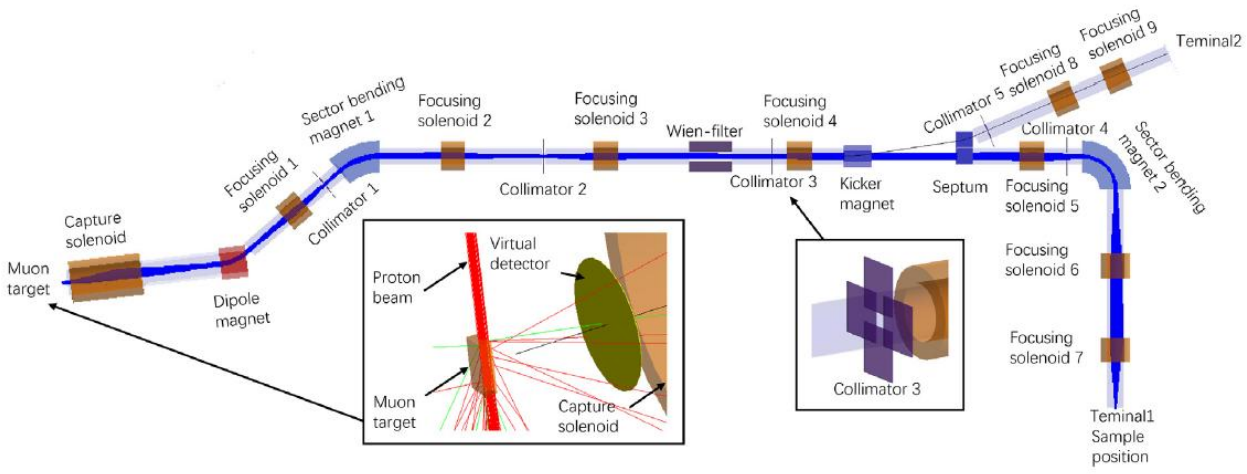




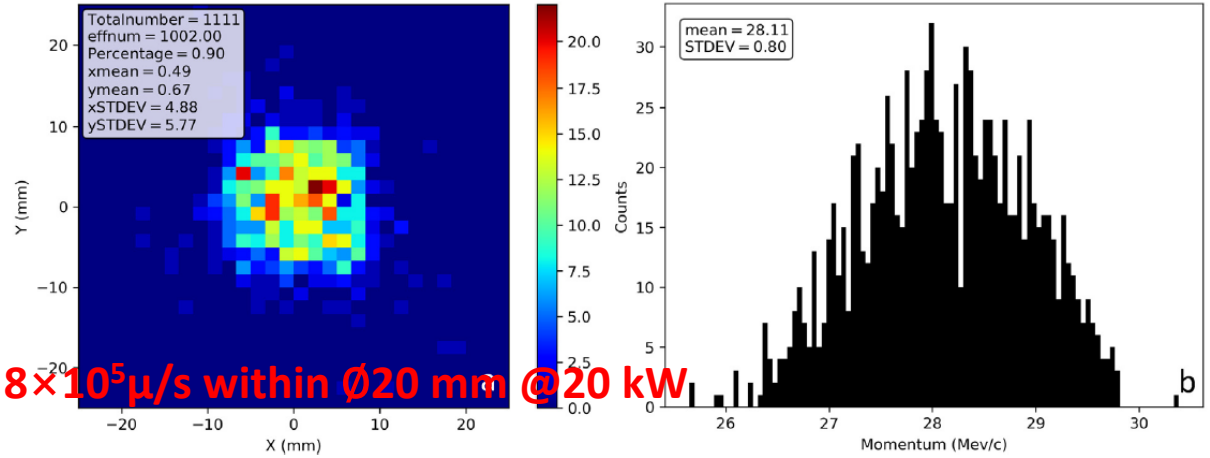


Muon Beamline Optimization based on CE

Surface Muon beamline



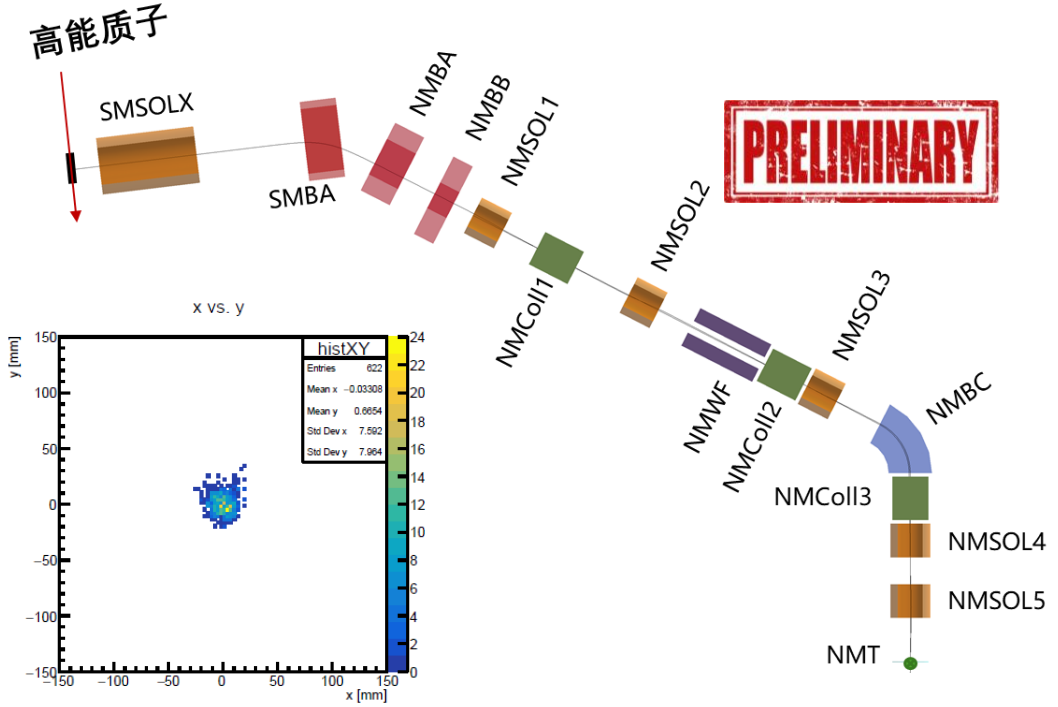
- Schematic illustration of the MELODY surface muon beamline



7.8×10⁵μ/s within Ø20 mm @20 kW

- Optimized beam profile and the momentum distribution

Negative Muon Beamline



	30 MeV/c	60 MeV/c
Ø100 mm	1.2×10^6 μ/s	1.07×10^6 μ/s
Ø60 mm	7.4×10^5 μ/s	7.3×10^5 μ/s
Ø30 mm	5.3×10^4 μ/s	1×10^5 μ/s

Muon Beamline Optimization based on AI

Summary

1）Muon Beamline Optimization based on GAs：

- Verified the feasibility of the optimization program by maximizing the muon intensity on the μE4 beamline
- Enabled the feasibility design of the MELODY surface muon beamline and decay muon beamline, achieving full optimization of beam intensity.

2）Muon Beamline Optimization based on CE：

- Efficiently accomplished the small beam spot design for the MELODY surface muon.

- MELODY Beamlines Team：You Lv、Cong Chen、Guangdong Liu 、Changdong Deng、Yuwen Wu、Junhao Wei、Xin Qi、Wenqing Zhang、Pengcheng Wang、Yuliang Zhang、Yongcheng He

Thank you for your attention