LUNE

-- Muon-nucleon fixed target experiment at HIAF

Many thanks to 章学恒、刘栋、王亚平、陈凯、张宇、聂茂武、熊伟志, for their valuable contributions to this talk!

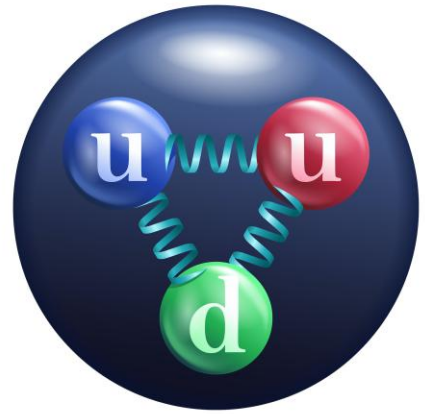
Hang Yin (尹航)

Central China Normal University

MIP2026

April 27th, 2026

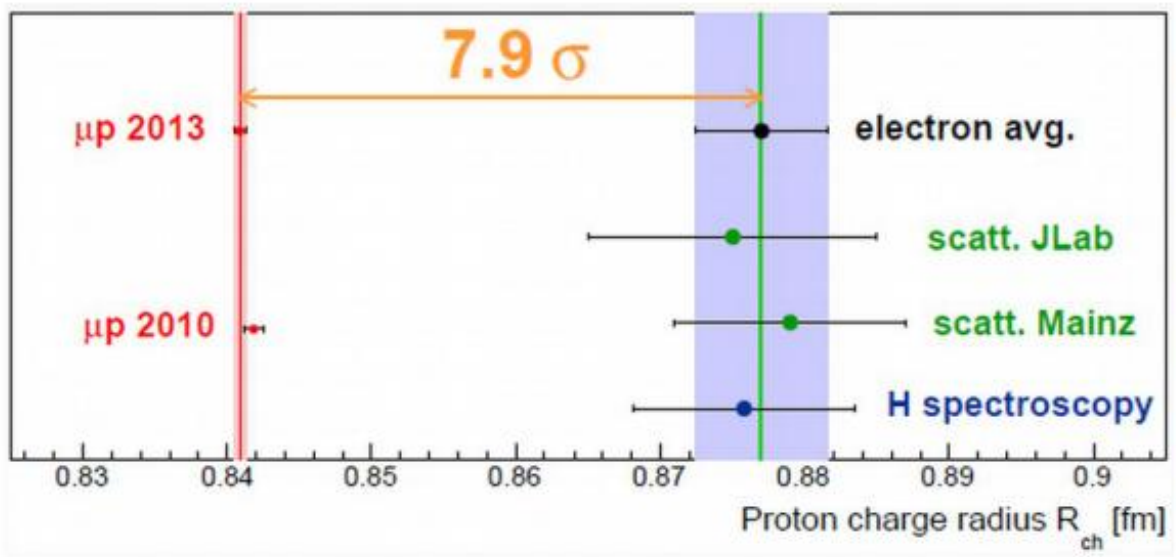
Proton: basic questions



- The origin of its mass?
  - Make up nearly 90% of the normal matter in the universe
  - Elementary valence quarks: 1% level contribution
- The origin of confinement?
  - Quarks hadronized and form protons as the universe cooled below Hagedorn temperature
- Distribution of strong force?
  - Keep quarks confined
  - Make protons stable particles

Proton charge radius

- Back to 2010/2013, a lot of interest on the proton charge radius
- The Proton Radius Puzzle
  - Test theoretical understanding of proton
  - Related to the QCD



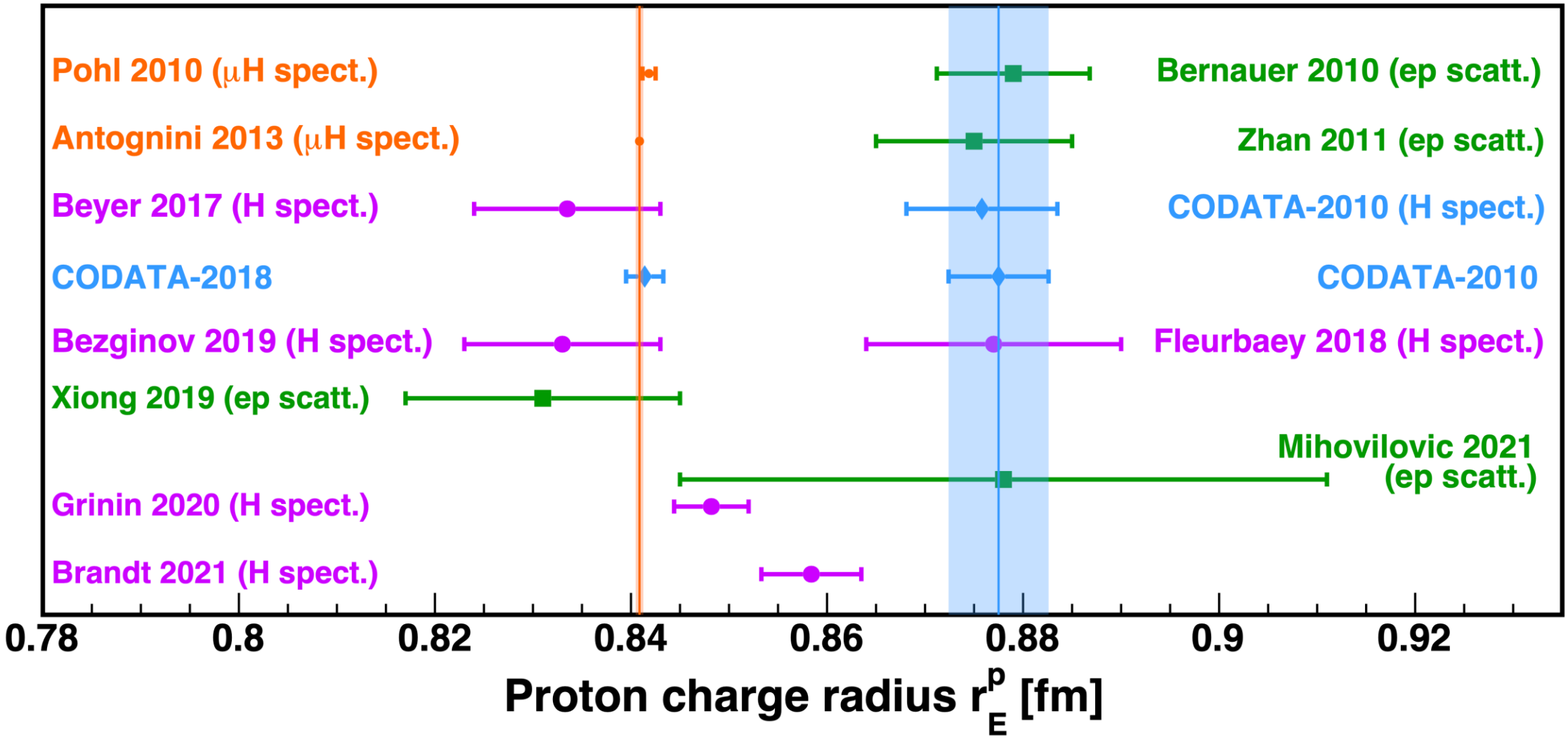
μp 2013: Antognini *et al.*, Science **339,** 417 (2013)

JLab: Zhan *et al.*, PLB **705,** 59-64 (2011)

Mainz: Bernauer *et al.*, PRL **105**, 242001 (2010)

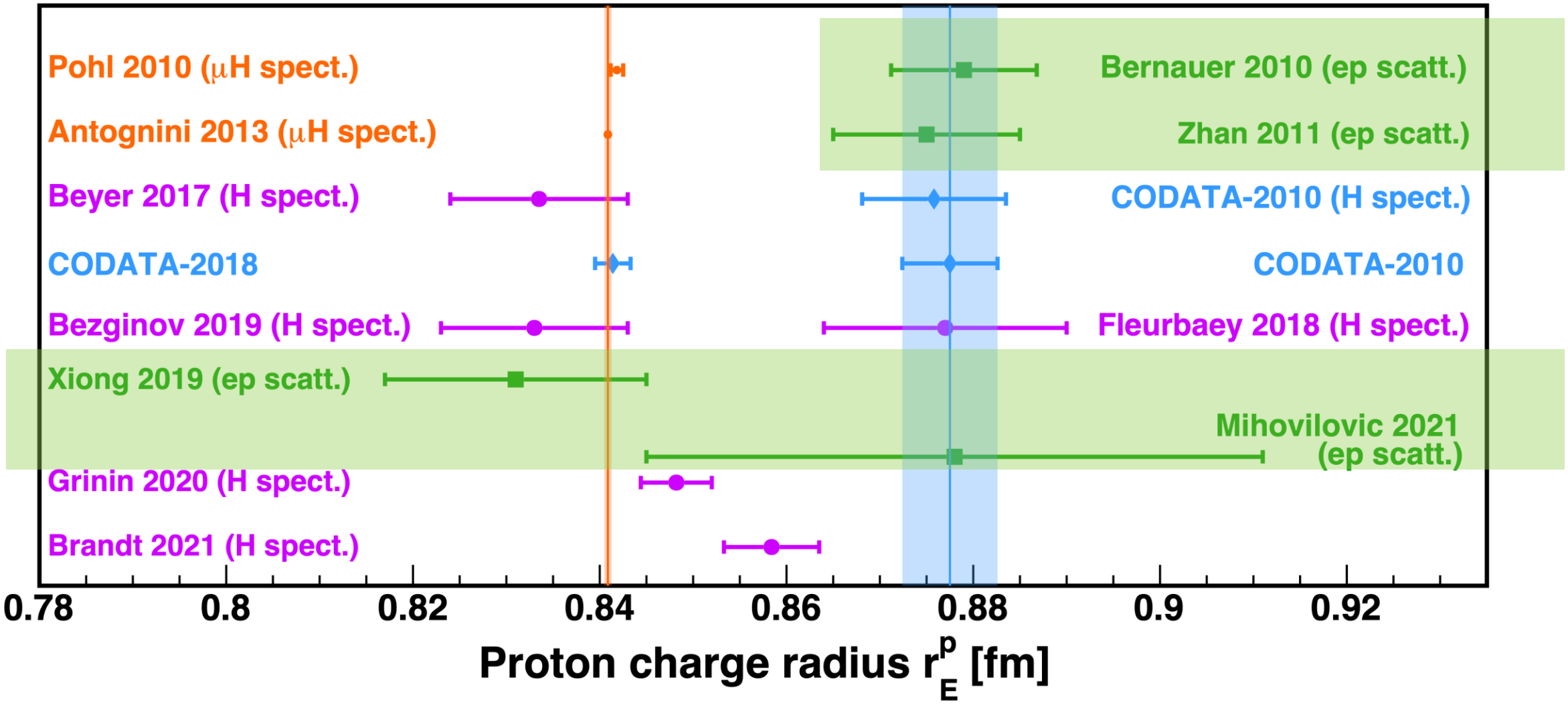
μp 2010: Pohl *et al.*, Nature **466**, 213 (2010)

Proton charge radius

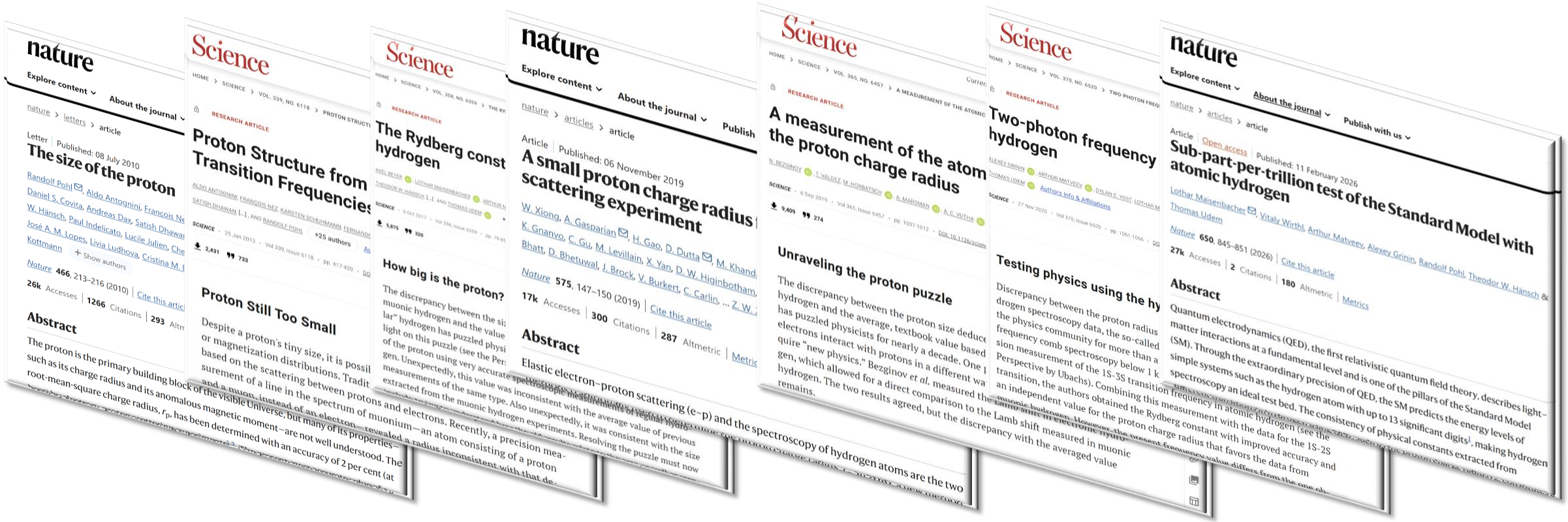


Proton charge radius

Results from electron-scattering experiments



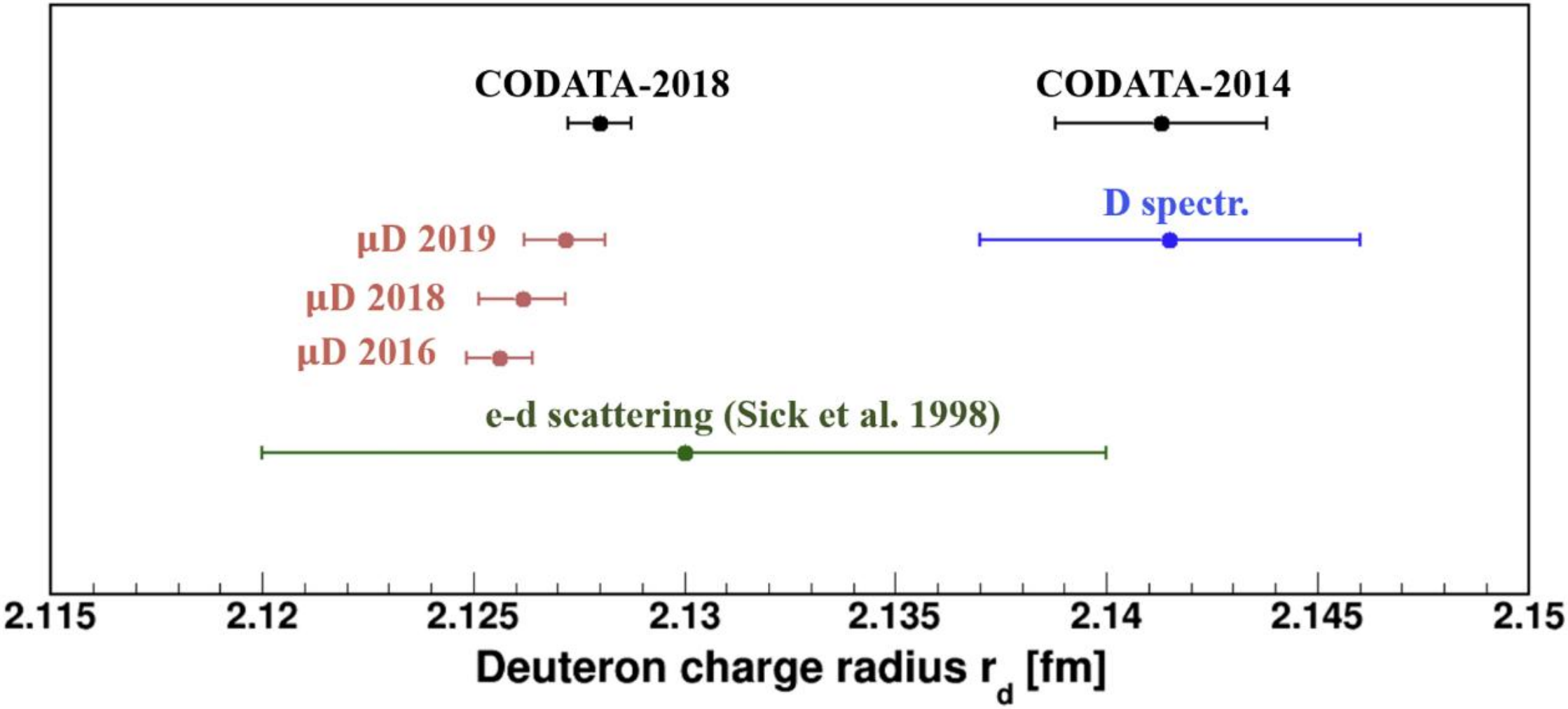
A Fundamental Mystery



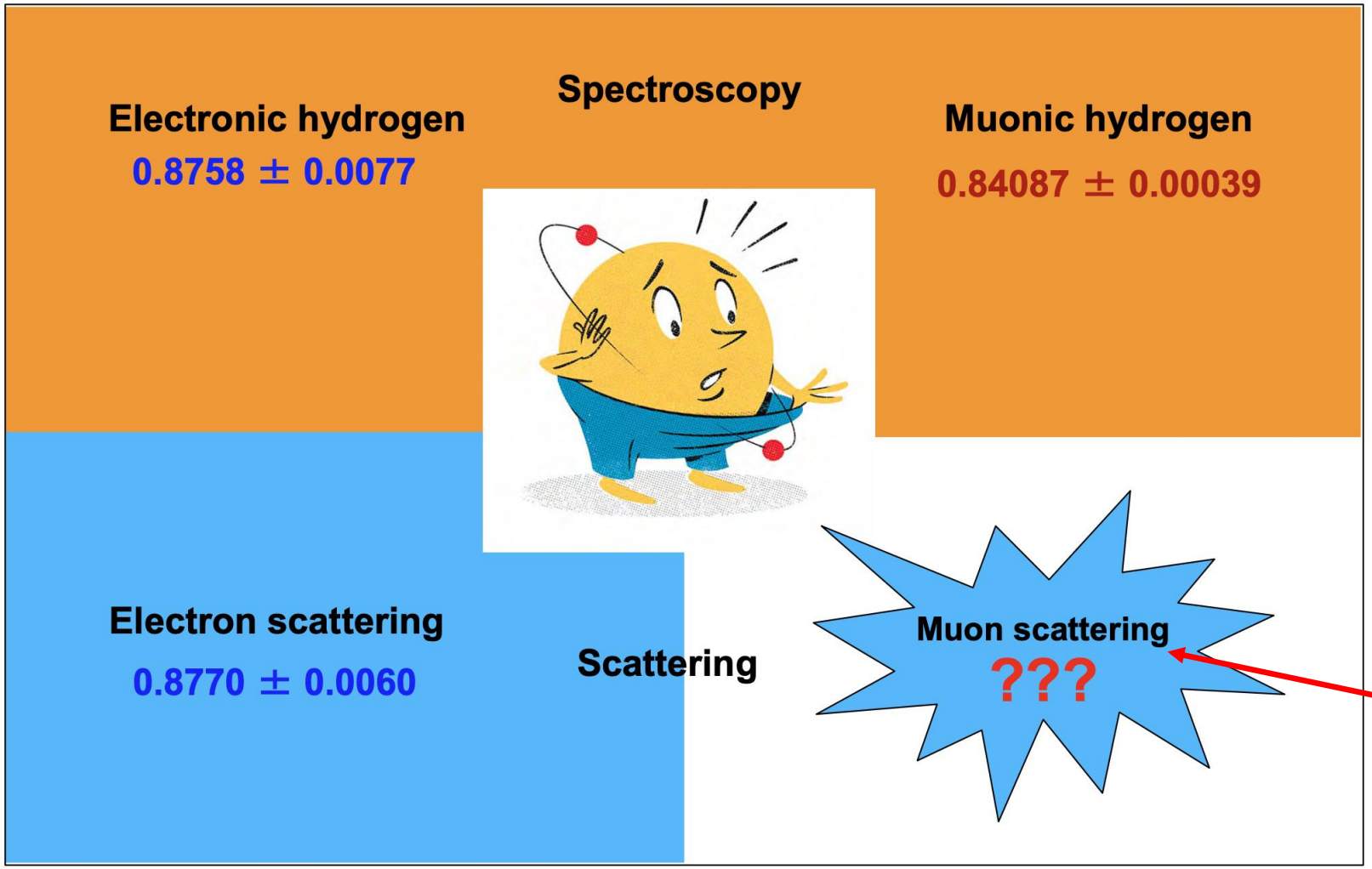
2010 2012 2014 2017 2019 2022 2026

Since 2010: 3 *Nature* papers, 4 *Science* papers!

Same story for deuteron

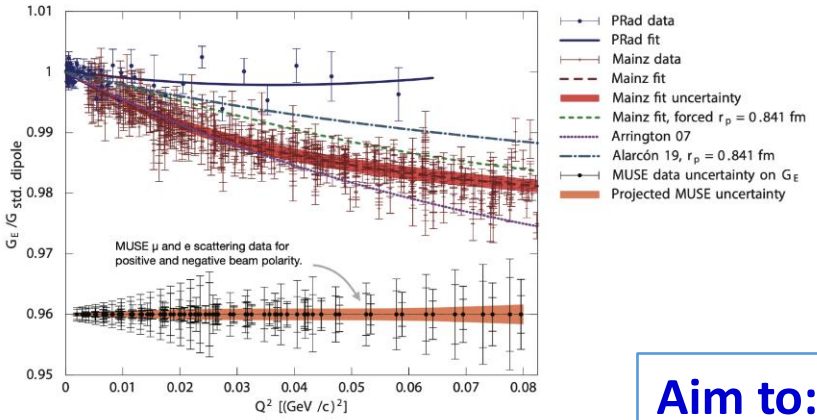


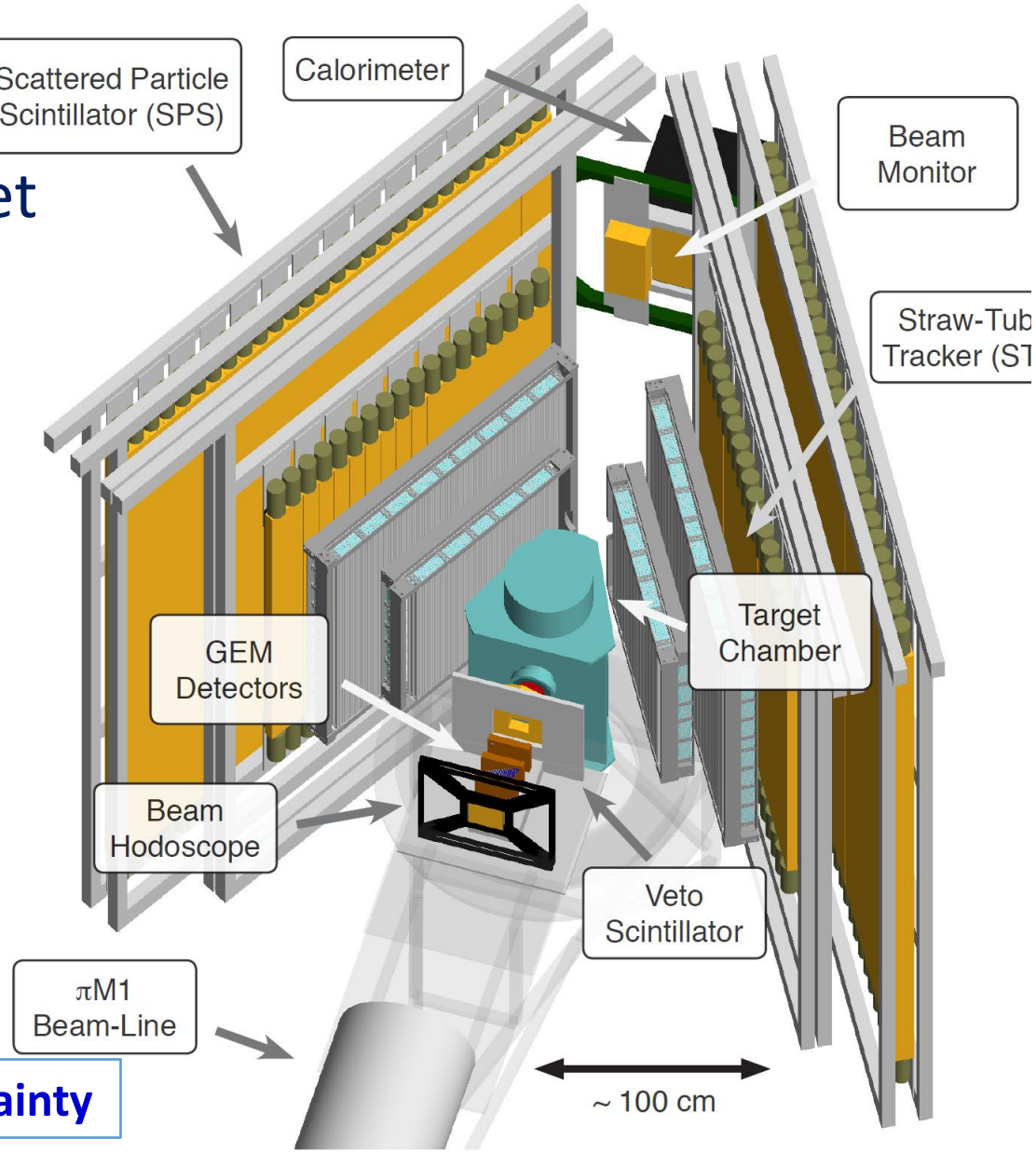
μp scattering



MUSE @ PSI

- Beams of $e^{\pm}, \pi^{\pm}, \mu^{\pm}$ on liquid H_2 target
  - Separate particles by TOF
  - End of data taking: 2025
- Muon beam:
  - $115 - 210\ MeV/c$
  - θ: $20^o - 100^o$

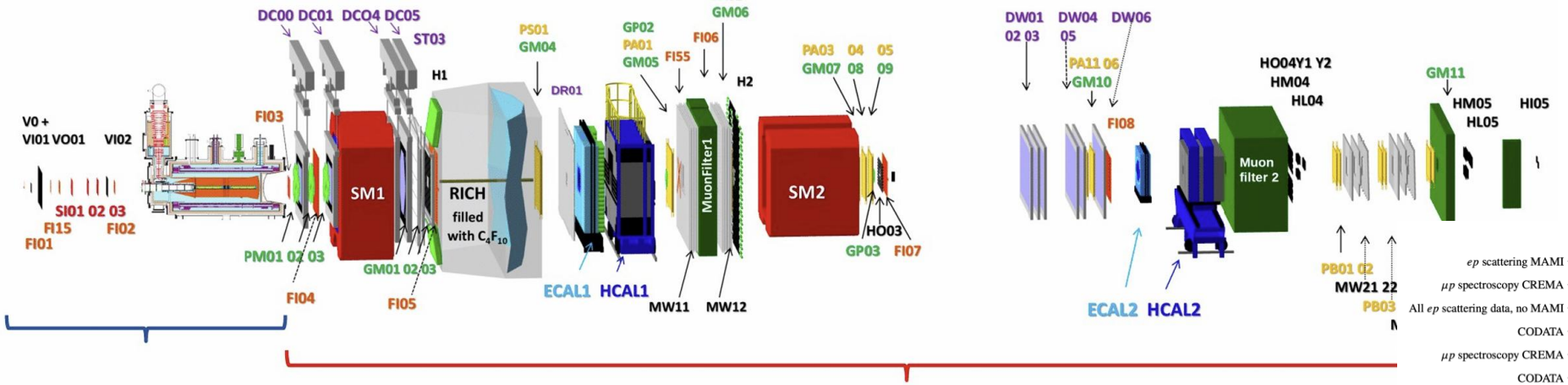




Aim to: 0.5-1% uncertainty

Amber @ CERN

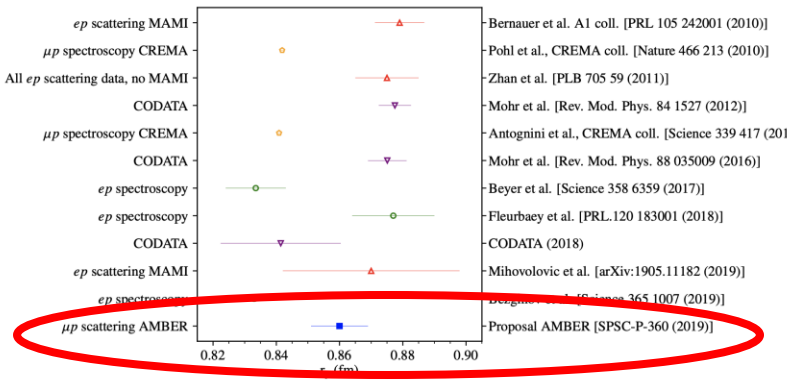
- Compass -> Amber (NA66): Apparatus for Meson and Baryon Experimental Research
  - A fixed target experiment at M2 beam line
  - Beam: muon, proton, pion, kaon from 50 GeV to 280 GeV



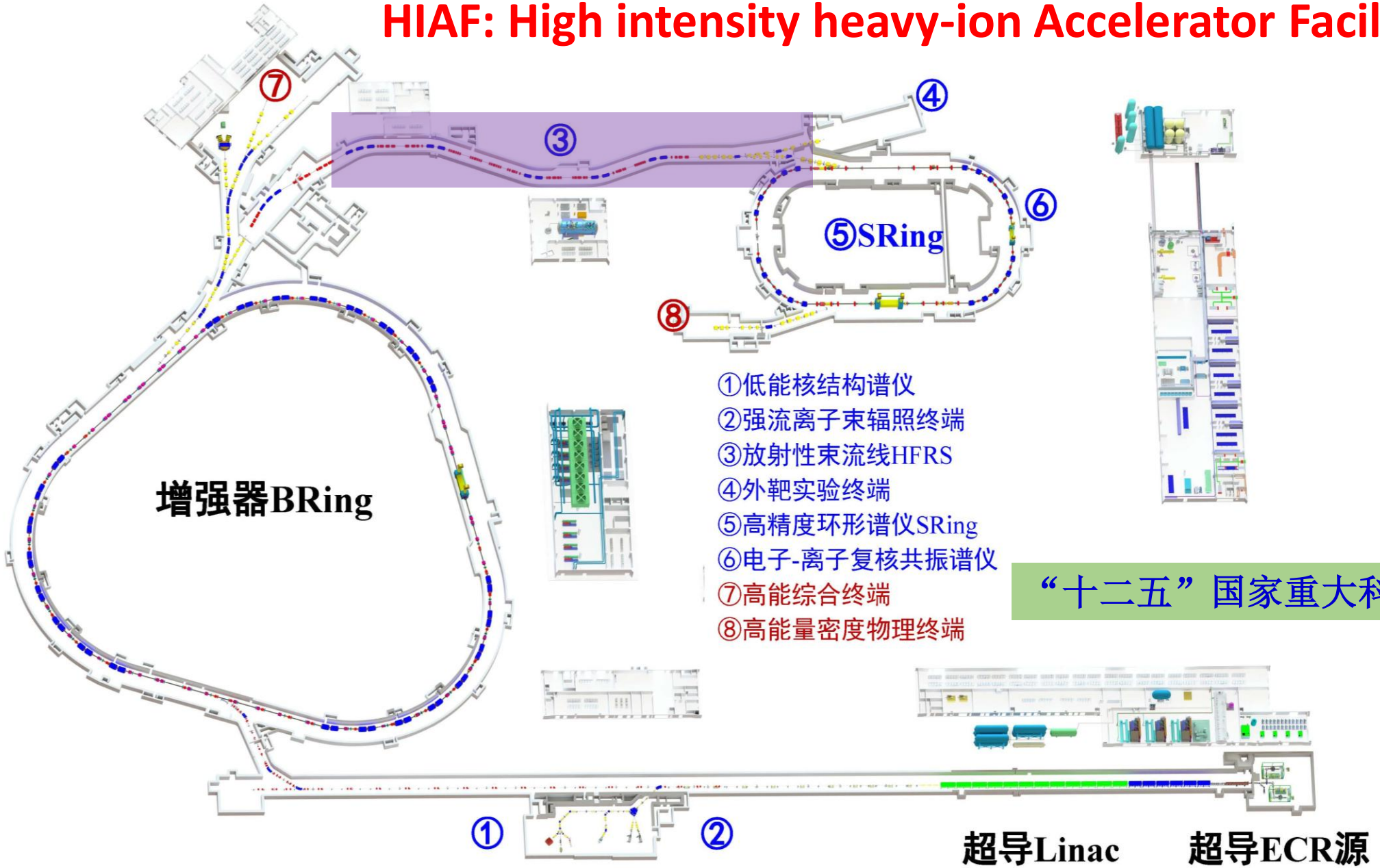
Target region: program-specific

Spectrometer: common for all measurements

Aim to: 1% uncertainty



HIAF: High intensity heavy-ion Accelerator Facility

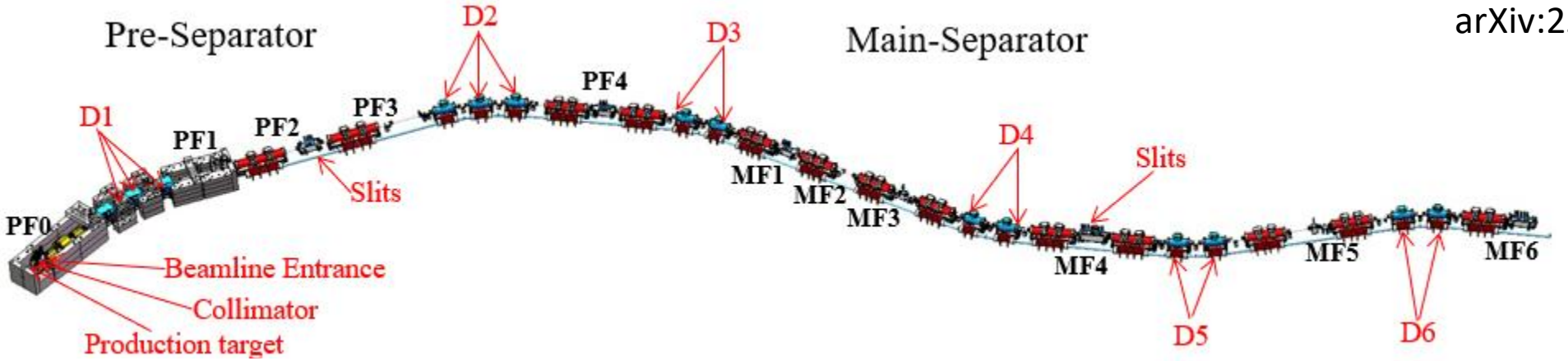


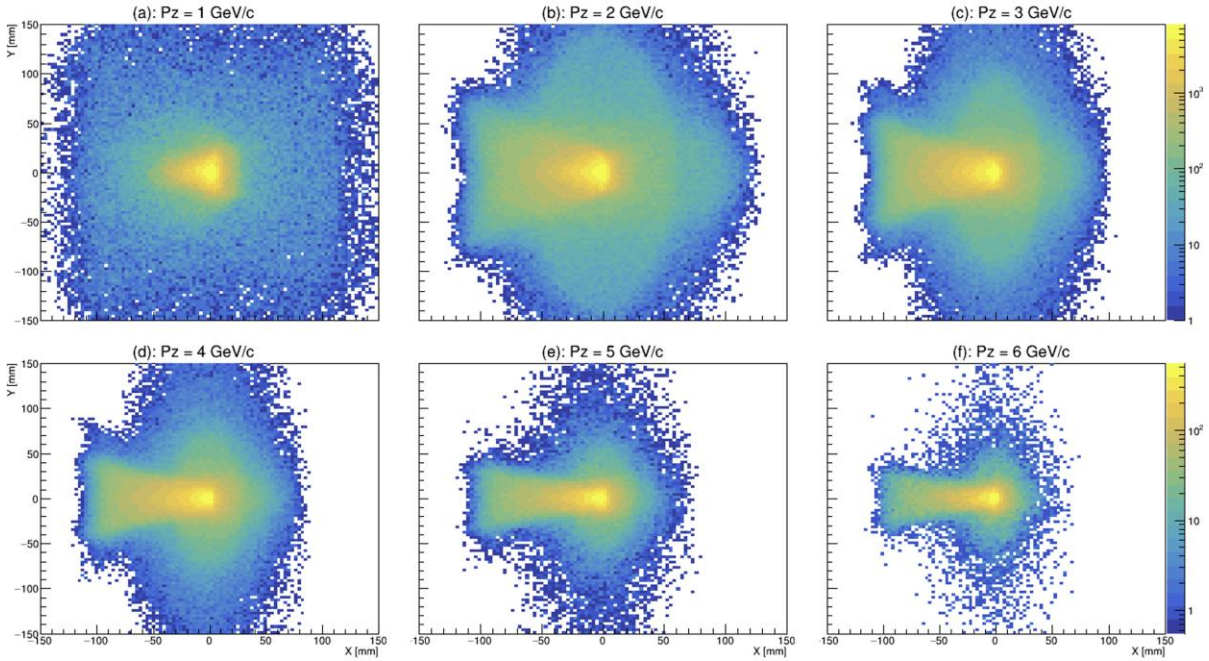
①低能核结构谱仪
②强流离子束辐照终端
③放射性束流线HFRS
④外靶实验终端
⑤高精度环形谱仪SRing
⑥电子-离子复核共振谱仪
⑦高能综合终端
⑧高能量密度物理终端

“十二五”国家重大科技基础设施

HIAF muon source

arXiv:2502.20915

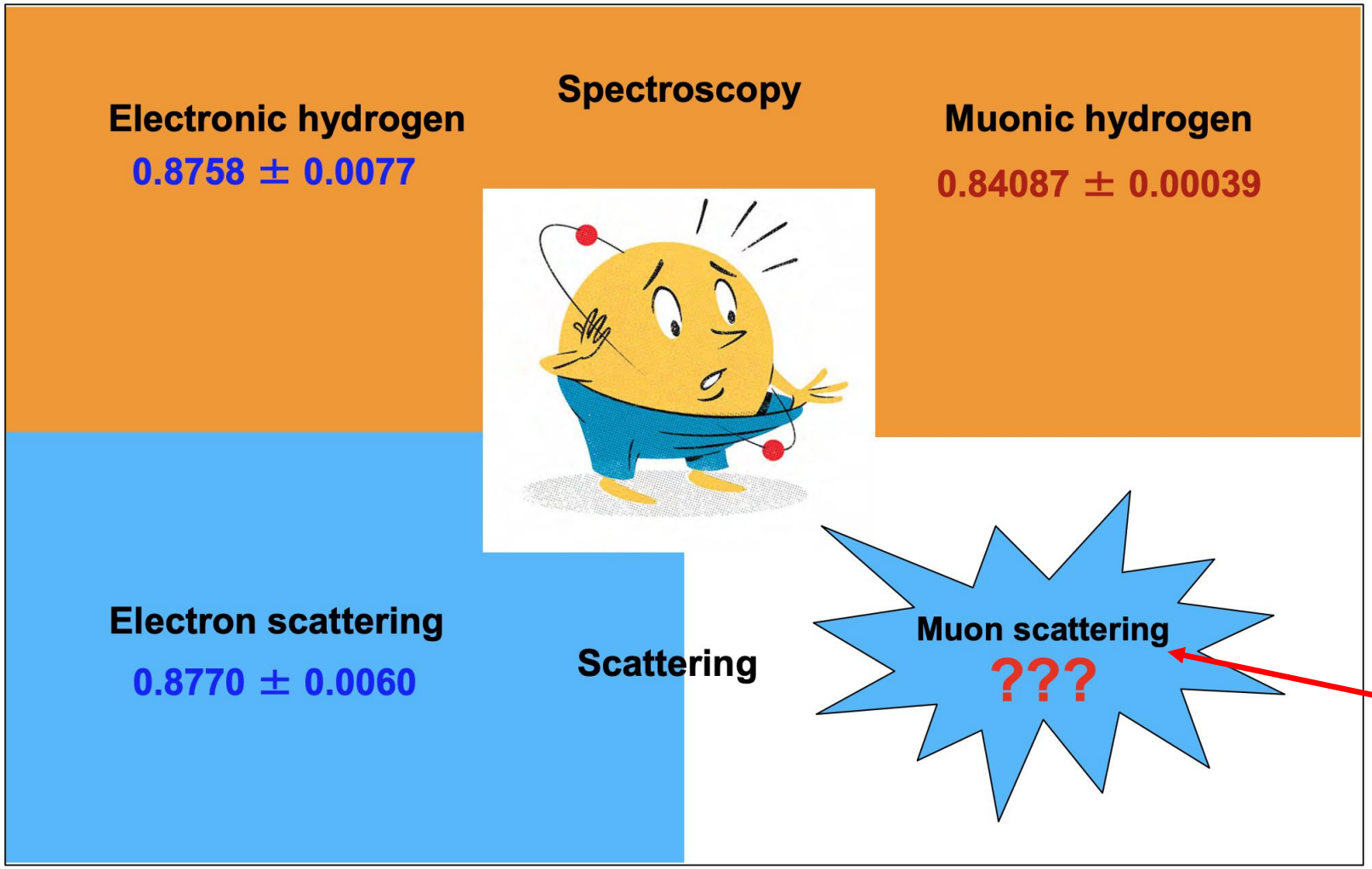




P_μ	20 mm	40 mm	60 mm	80 mm	100 mm
1 GeV/c	63.1%	79.0%	82.9%	85.2%	86.8%
2 GeV/c	72.2%	85.4%	88.0%	89.9%	91.7%
3 GeV/c	76.9%	89.4%	91.5%	93.2%	94.5%
4 GeV/c	80.5%	91.9%	93.6%	94.9%	95.9%
5 GeV/c	82.4%	93.6%	95.0%	96.0%	96.7%
6 GeV/c	83.8%	94.8%	95.9%	96.7%	97.3%

μp scattering

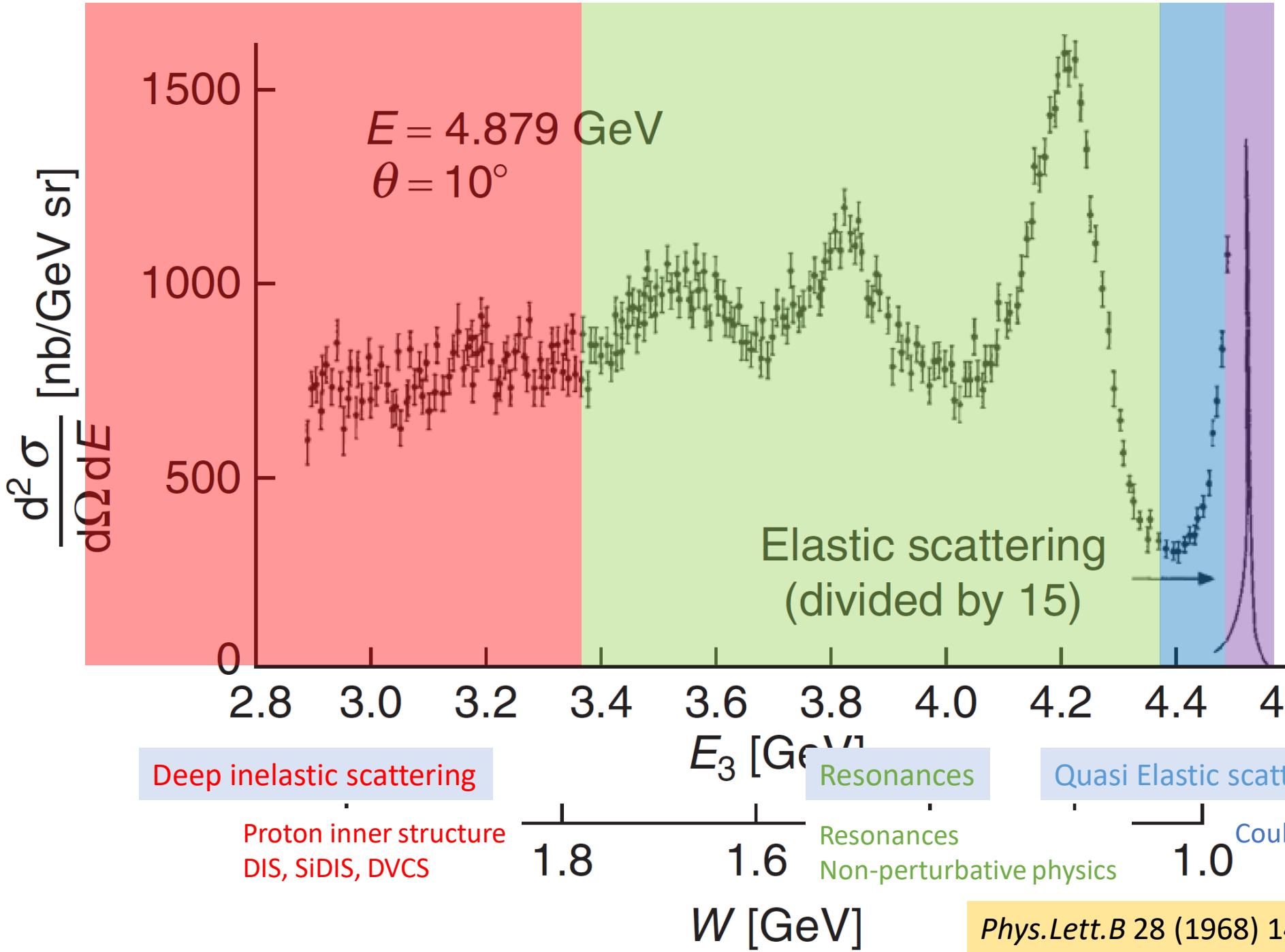
Scientific opportunities with a few-GeV muon beam at HIAF?



PSI: MUSE experiment
CERN: Amber experiment
HIAF: LUNE experiment

LUNE Collaboration

- Low-energy mUon-Nucleon scattering Experiment
- 目前参与单位及成员:
  - 华中师范大学: 陈凯、龚畅、胡辉港、李新强、计晨、宋晓程、孙向明、汪虎林、王翔鹏、王亚平、魏焰冰、谢跃红、尹航、袁兴博、张冬亮、周晓康等
  - 山东大学:李远、刘栋、聂茂武、熊伟志
  - 近代物理所:陈良文、窦彦昕、徐宇、张瑞田、章学恒等
  - 中国科学技术大学:韩良、潘子文、王宇、杨思奇、赵梓含
  - 合肥工业大学：王泽人、张宇
  - 上海交通大学:陈翔、李亮、卢泽嘉
  - 北京大学：李奇特
  - 河海大学：柏栋
  - 武汉大学：王纪科
  - 深圳技术大学：李迪开
  - 汕头大学：刘浪天
  - 郑州大学：宋勤涛
  - 帕多瓦大学：韩群东



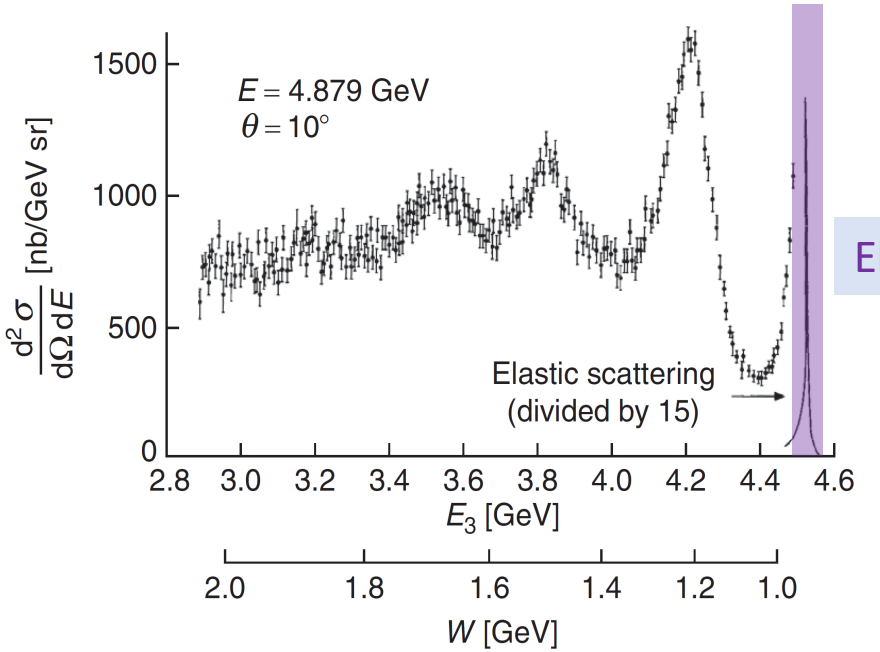
Elastic scattering

Proton charge radius

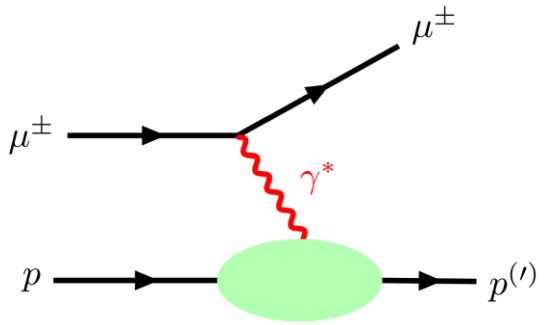
Phys.Lett.B 28 (1968) 148-151

Physics Motivation (liquid hydrogen)

- **Elastic scattering:**
  - **Proton charge radius**
  - Two photon exchange: μ^+ and μ^-
  - Proton charge form factors: (LFU)
- Advantages:
  - Large cross-section: mb
  - small scattering angle (1-10^o)
  - momentum measurement of incoming/scattered muon
- Detector requirements:
  - Dipole magnetic field: a few GeV muons
  - Precision measurement of particle direction



Elastic scattering



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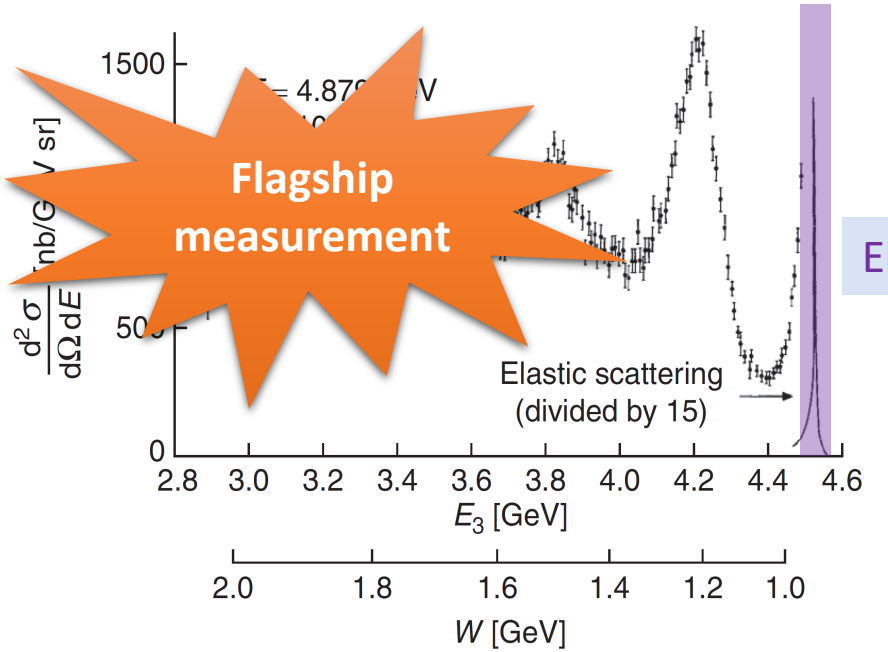
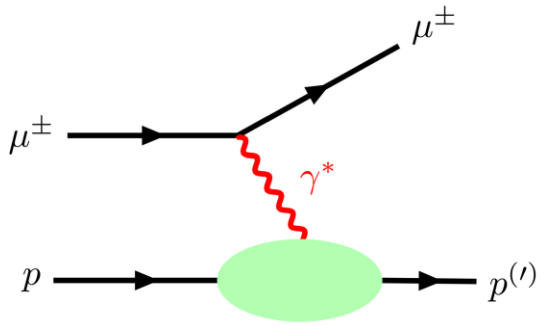


Elastic scattering



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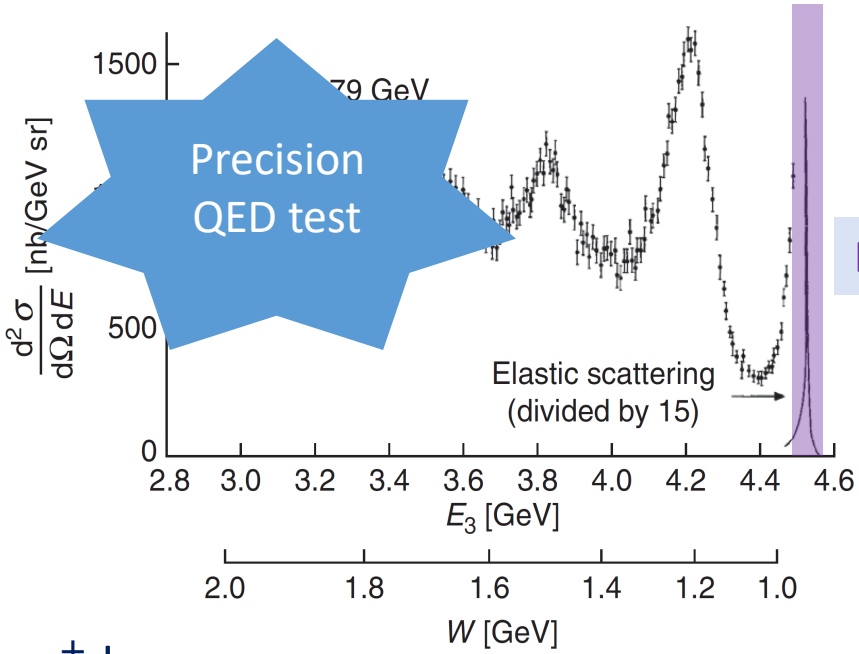
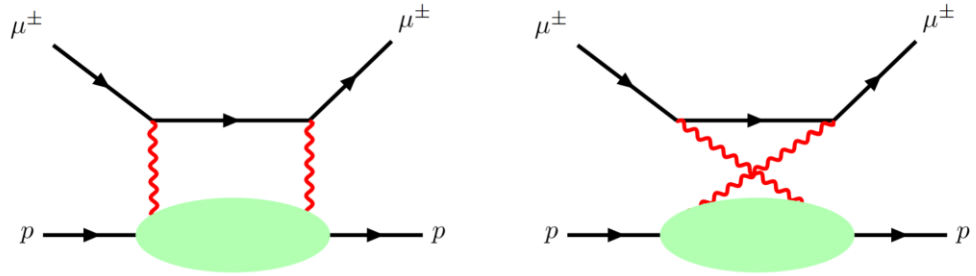
  - Proton charge radius
  - **Two photon exchange: μ^+ and μ^-**
  - Proton charge form factors: (LFU)
- Advantages:
  - Large cross-section: mb
  - Electron-scattering experiments:
    - the difficulty of producing high-intensity e^+ beams
- Detector requirements:
  - Dipole magnetic field: a few GeV muons
  - Precision measurement of particle angle

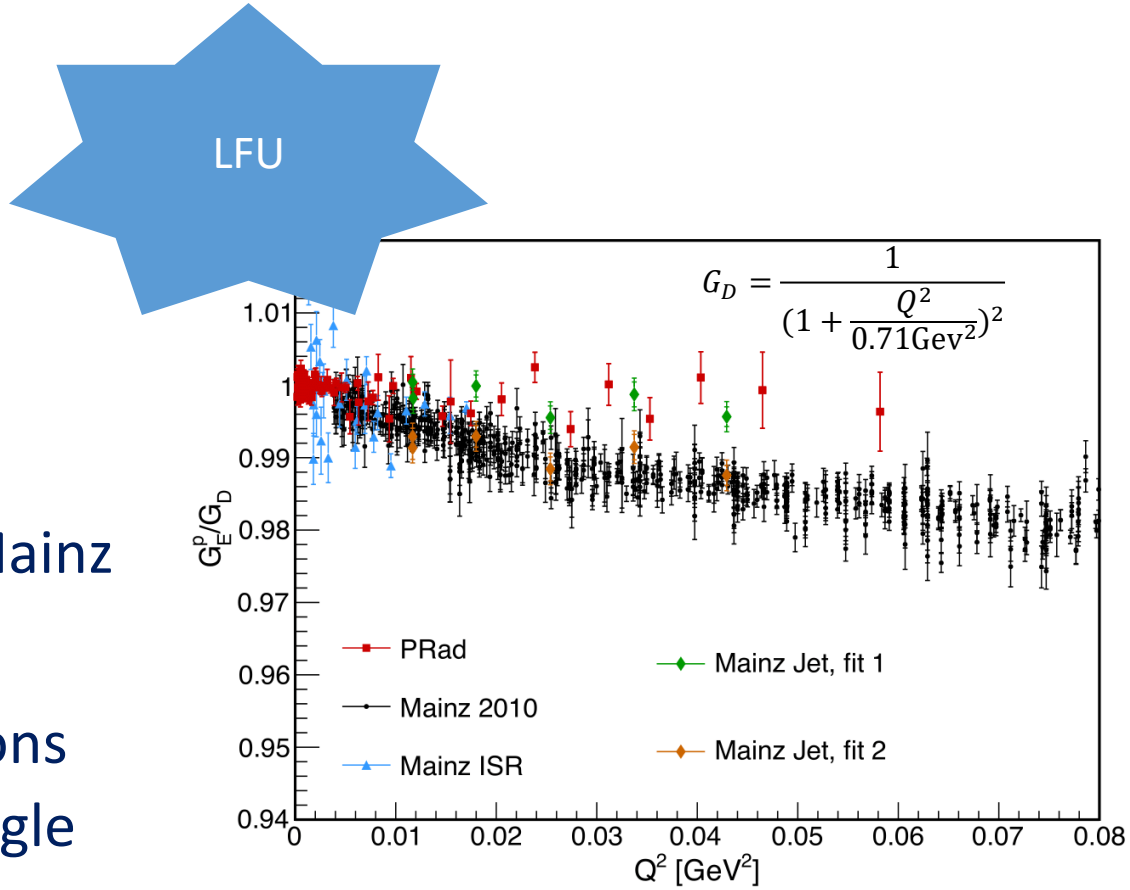


Elastic scattering



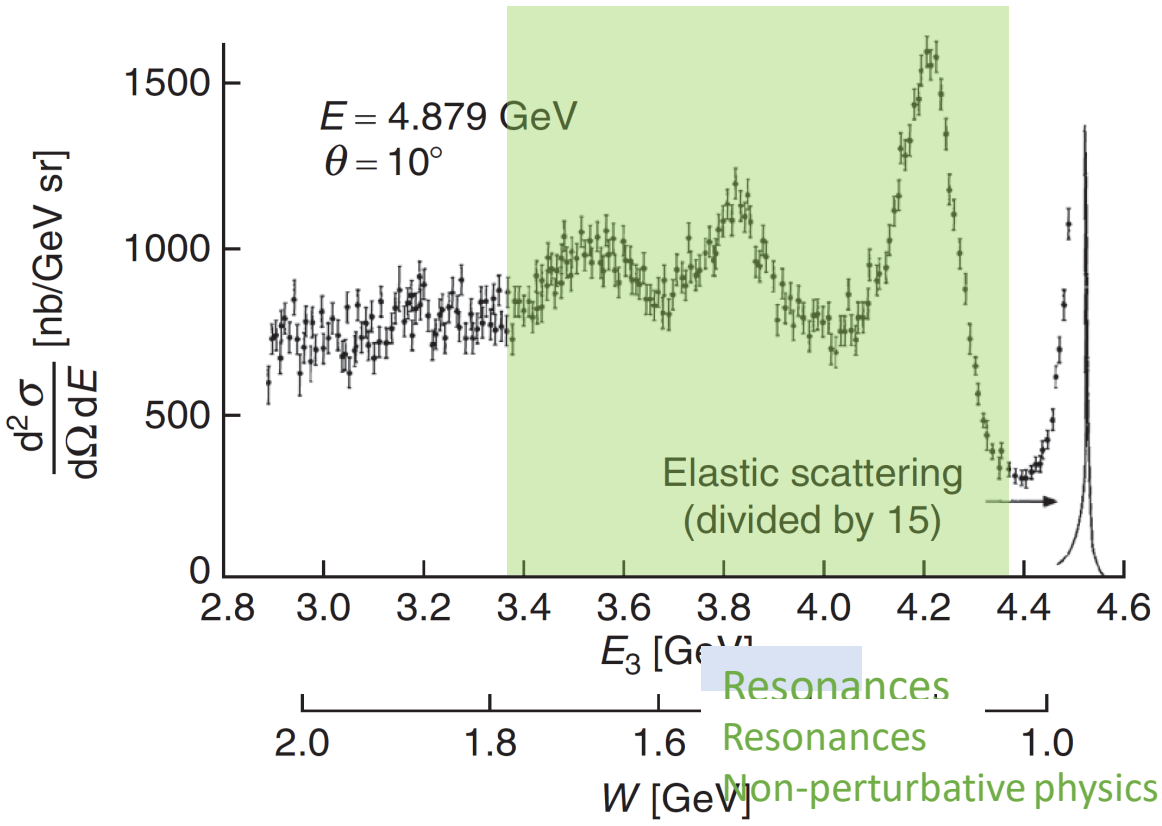
Physics Motivation (liquid hydrogen)

- **Elastic scattering:**
  - Proton charge radius
  - Two photon exchange: μ^+ and μ^-
  - **Proton charge form factors: (LFU)**
- Advantages:
  - Large cross-section: mb
  - Resolve tension between PRad and Mainz
- Detector requirements:
  - Dipole magnetic field: a few GeV muons
  - Precision measurement of particle angle



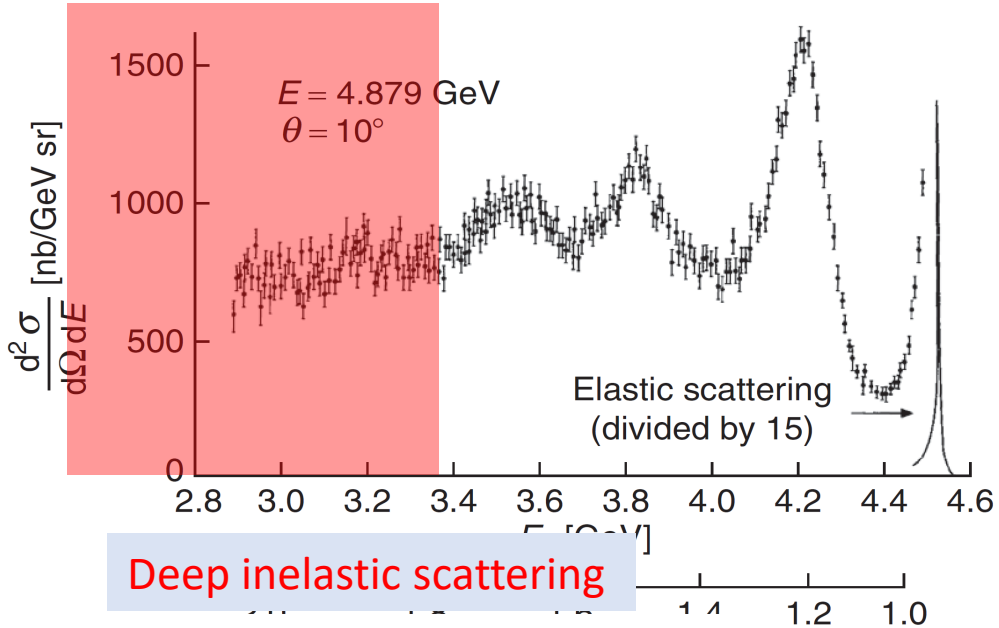
Physics Motivation (inelastic)

- **Inelastic scattering (resonances):**
  - Resonance studies
  - A clean probe of non-perturbative QCD
- Reasonable cross-section:
  - μb
  - momentum measurement of incoming/scattered muon



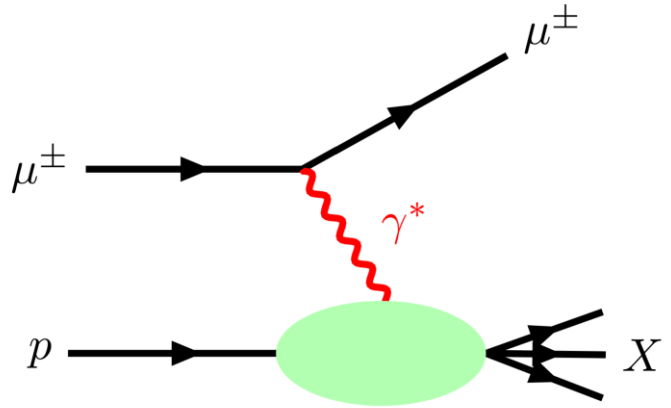
Physics Motivation (DIS)

- **Deep-Inelastic scattering (DIS):**
  - Proton structure
  - New physics
- Reasonable cross-section:
  - μb - nb
  - momentum measurement of scattered muon
  - Multiple final states: $\pi^0, \pi^\pm, \gamma, K$
- Detector requirements:
  - Particle-ID: PID



Deep inelastic scattering

Proton inner structure
DIS, SiDIS, DVCS



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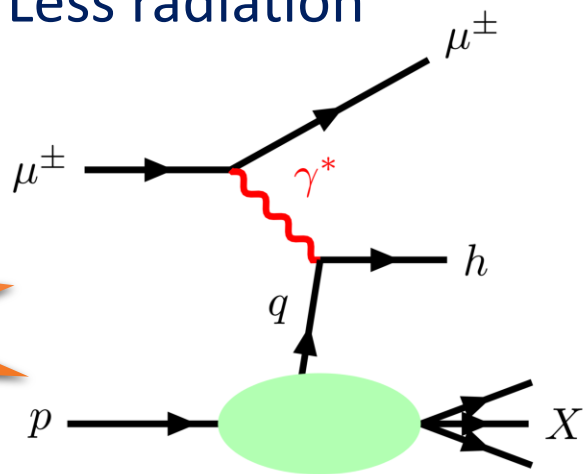
- Detector requirements:
  - Particle-ID: PID

Flagship measurement

- Semi-inclusive Deep-Inelastic scattering (SIDIS):
  - TMD
- Small cross-section:
  - 100-900 nb
  - Clean environment
  - Less radiation



Physics Motivation (DIS)

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- Reasonable cross-section:
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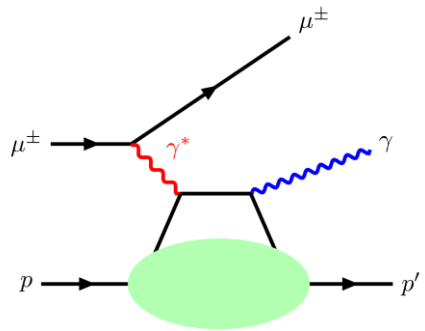
  - momentum measurement of scattered muon
  - Multiple final states: $\pi^0, \pi^{\pm}, \gamma, K$
- Detector requirements:
  - Particle-ID: PID

- Deeply Virtual Compton Scattering (DVCS):
  - Proton inner structure
  - Gravitational form factor
- Small cross-section:
  - nb
  - polarized muon beam
  - motivation for upgrade of HIAF muon source

High impact measurement, but with limited statistics



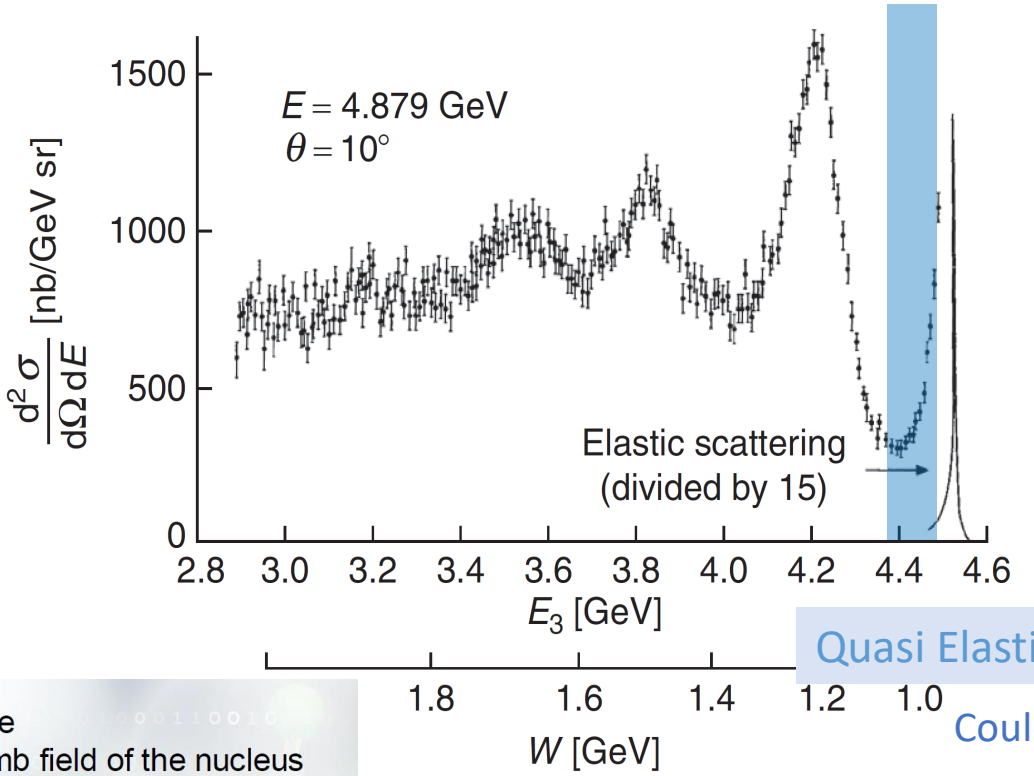
Physics Motivation (DIS)

- **Deep-Inelastic scattering (DIS):**
  - Proton structure
  - **New physics**
- Reasonable cross-section:
  - μb - nb
  - momentum measurement of scattered muon
  - Multiple final states: $\pi^0, \pi^{\pm}, \gamma, K$
- Detector requirements:
  - Particle-ID: PID

- New physics:
- With Pb as target
  - $\mu N \rightarrow \mu N + MET$
  - $\mu N \rightarrow \mu\mu\mu N$
  - $\mu N \rightarrow \gamma\gamma\mu N$
  - $\mu N \rightarrow \mu N' + MET$

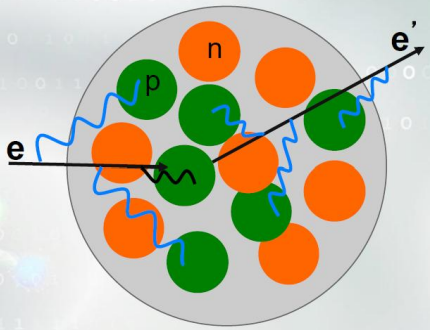
Physics Motivation (Quasi-elastic)

- **Quasi-Elastic scattering:**
  - Coulomb Distortion
- Target: Copper/Carbon
  - Study this from QE to DIS
  - Muon has less radiations



Quasi Elastic scattering

Coulomb Distortion



Electrons scattering from nuclei can be accelerated/decelerated in the Coulomb field of the nucleus

→ This effect is in general **NOT** included in most radiative corrections procedures

→ *Coulomb Corrections are perhaps more appropriately described in terms of multi-photon exchange, but Coulomb Corrections provide convenient shorthand*

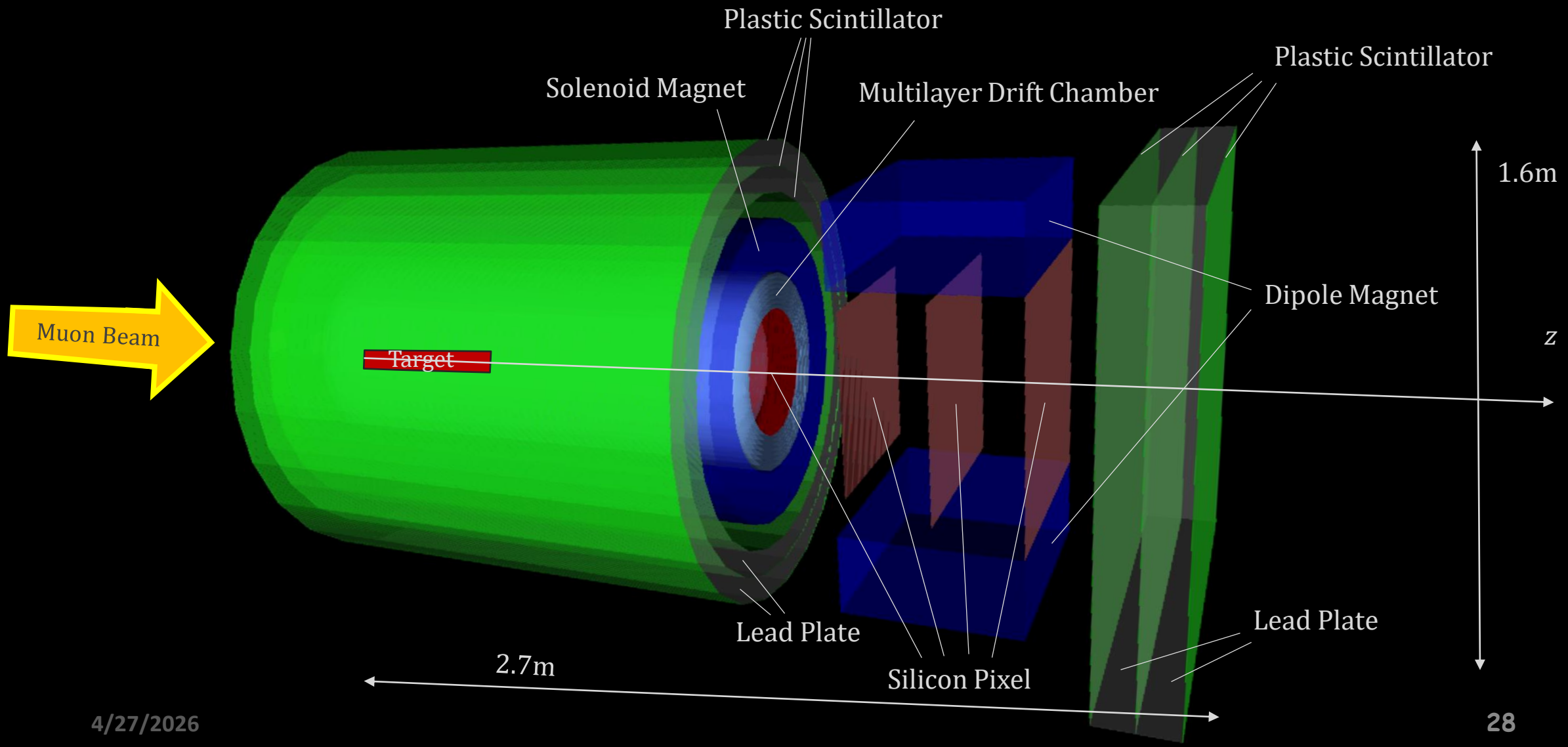
Physics Motivation (Other targets)

- Liquid Deuterium (LD_2)
- Helium (^3He)
- Motivations:
  - Neutron charge distribution
  - EMC
  - SRC: Short range correlation
  - Form factors

Physics @ LUNE

Analyses	Impacts	Target	Comments
Proton charge radius	★★★★★	Liquid hydrogen	With low momentum muon beam
Two photon exchange	★★★★	Liquid hydrogen	Measured in both elastic/DIS regions
Proton Form factors	★★★★	Liquid hydrogen	Probe LFU
Resonances	★★★	Liquid hydrogen	Limited statistics compared with JLab experiments
DIS	★★★★★	Liquid hydrogen	Probe proton inner structure: TMD
Semi inclusive DIS	★★★★★	Liquid hydrogen	Probe proton inner structure: TMD, 3D
DVCS	★★★★	Liquid hydrogen	Need polarized beam, higher flux (HIAF upgrade)
NP (Dark matter)	★★★★	Pb	Need find more physics channels
Neutron charge distri.	★★★★★	LD_2 / ^3He (gas)	Polarized beam, polarized target
Short range corr./EMC	★★★★★	LD_2, ^3He,C,Fe,Pb	Better have Neutron detector
Coulomb Distortion	★★★★★	C, Cu	Important for precision prediction

First version of Lune Detector



Phase-I and Phase-II

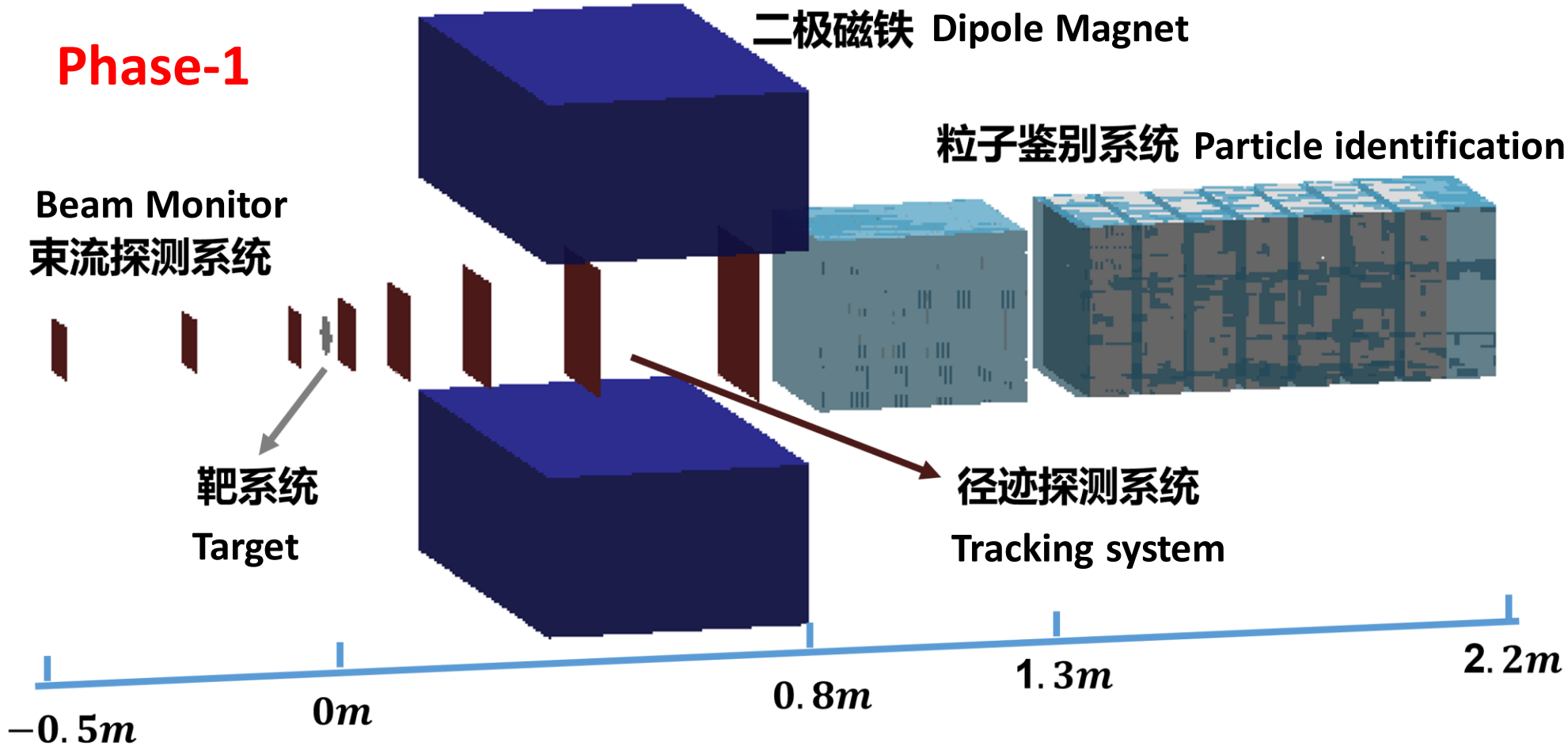
- Given the detector cost exceeds 50 M CNY level, we adopt two-Phase approach
- Stage-I: demonstration phase **(< 10 M CNY)**
  - Muon beam energies: 1 GeV, 1.5 GeV and 2.0 GeV
  - Physics: proton (deuteron) charge radius measurement
  - Detector coverage: Forward region only
  - Operation: 1-2 years, with 1-2 months of running per year
- Stage-II: full operation phase
  - Muon beam energies: > 3 GeV
  - Physics: Proton structure studies (DIS, SIDIS, DVCS)
  - Detector upgrade: addition of barrel region
  - Operation: More than 2 years

The following slides will focus on the Phase-I

Phase-I vs. Phase-II

	Phase-I	Phase-II
Beam energies	1.0, 1.5, 2.0 GeV	> 3 GeV
Detector	Forward region	+ Barrel region
Target	Solid (CH_2, CD_2)	Liquid hydrogen
Physics	Proton (deuteron) charge radius	Proton structure etc
Costs	< 10 M CNY	> 50 M CNY

低能缪子-核子散射实验装置（LUNE）

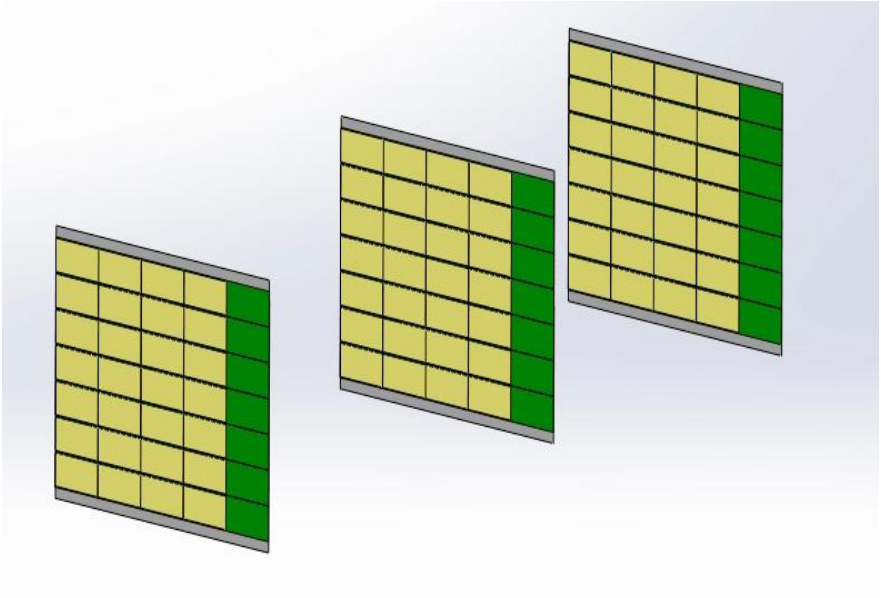


Adopts mature and well-proven technologies developed in China

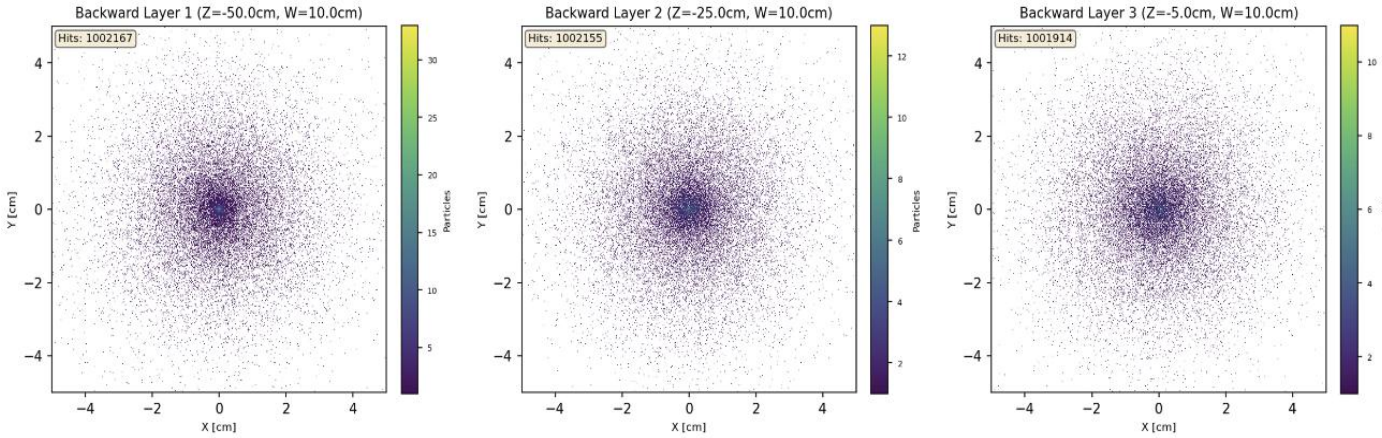
Key components are reusable

Beam monitor

- Three modules: $10 \times 10\ cm^2$ pixel pads
- MPAS (MIC6): designed for HNS, ultra-thin
  - Chip thickness: 100 μm (down to 50 μm)
  - Position resolution: $< 5\ \mu m$
- No Pile-up with high muon flux
  - Maximum occupancy per pixel: $< 10^2/s$
  - Pixel readout speed: $10^{-4}\ s$

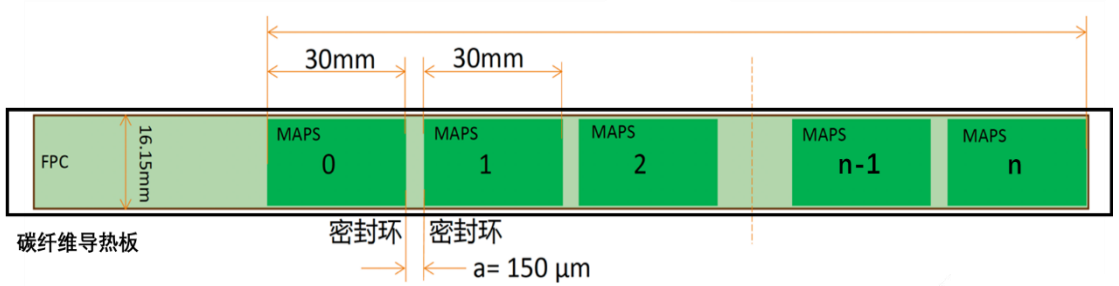


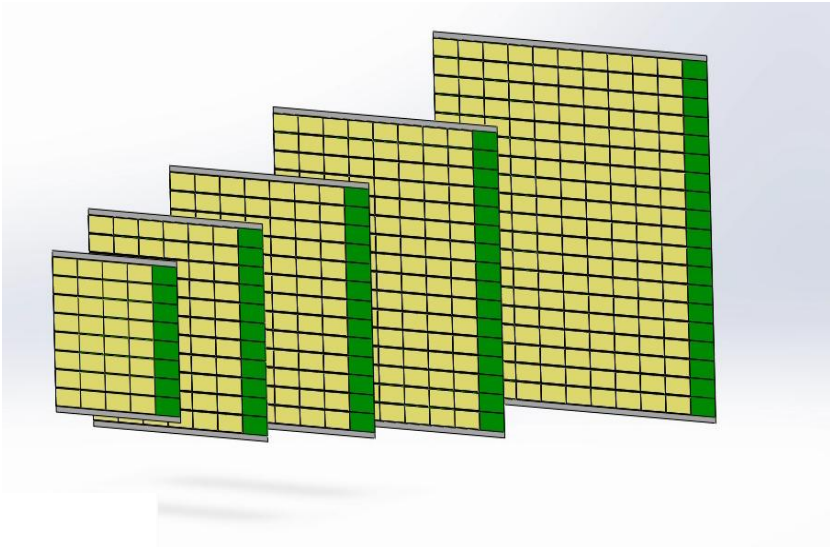
Works well even after the HIAF upgrade: the muon flux increased by a factor of 100

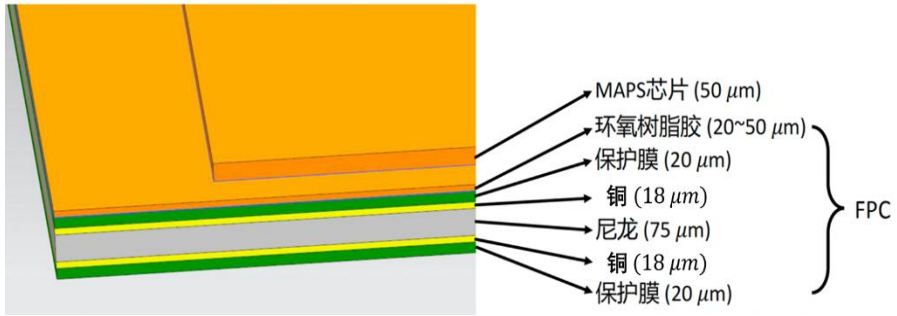


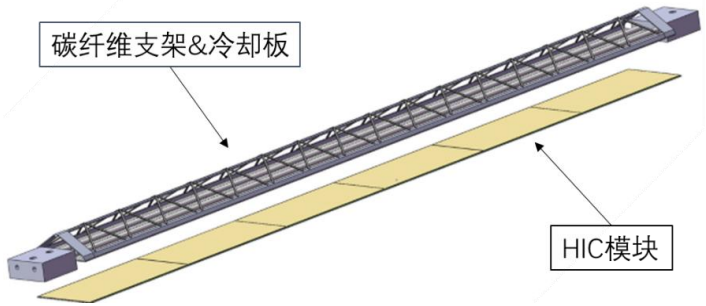
Tracking detector

- Pixel detector: same as beam monitor, pixel MIC6
  - Together with magnetic field to measure momentum
- Material budget: within 0.5% X_0
- Coverage: $< 5^o$



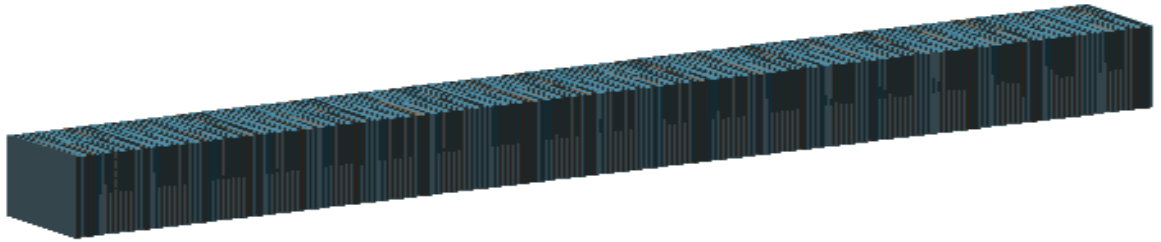


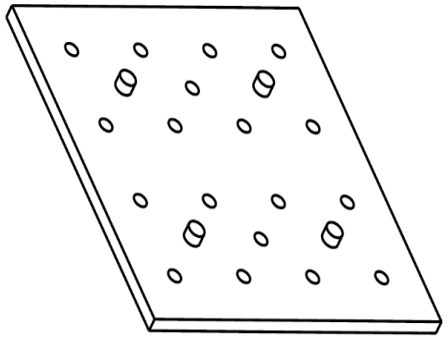


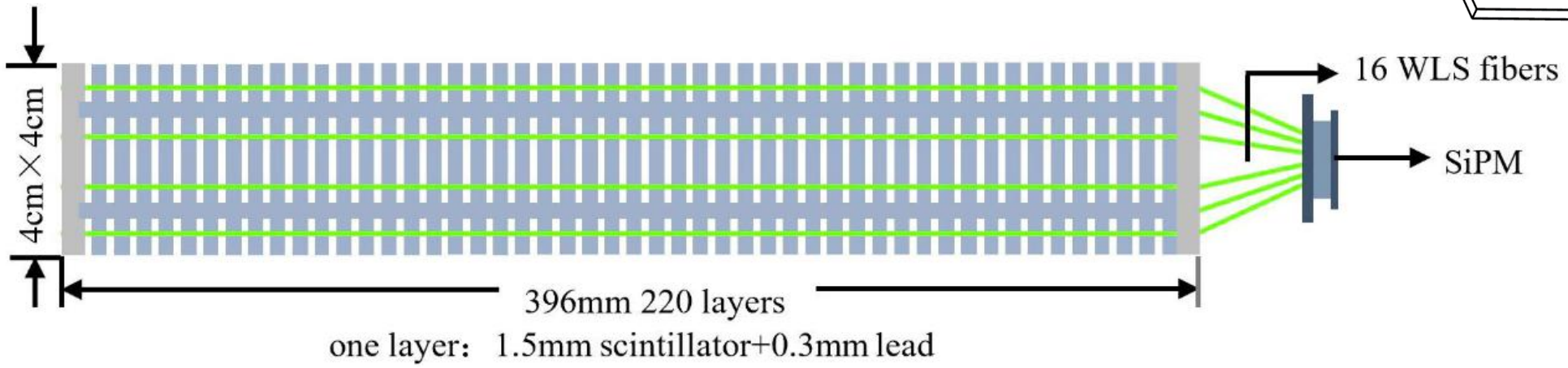


EM Calorimeters

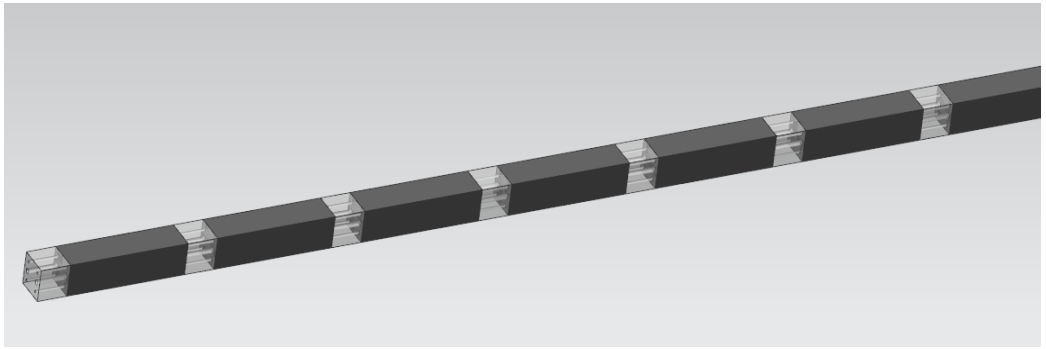
- Shashlyk (NICA/MPD):
  - 8×8 towers
  - Tower size: : $4\ cm \times 4\ cm$, 39.6 cm
  - 220 layers: $1.5\ mm$ scintillator + $0.3\ mm$ absorb (Pb)
  - Material budget : $11.8\ X_0$
  - Resolution: 5% @ 1 GeV



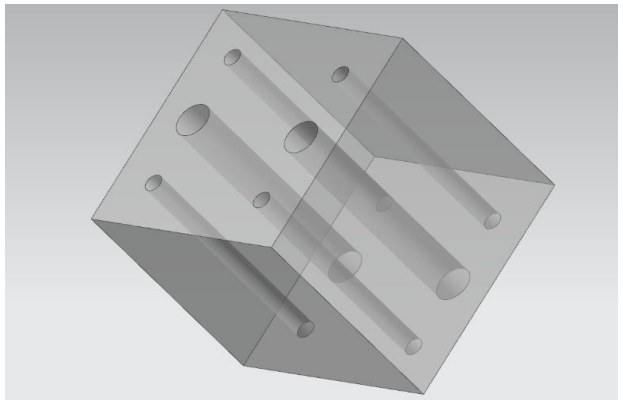


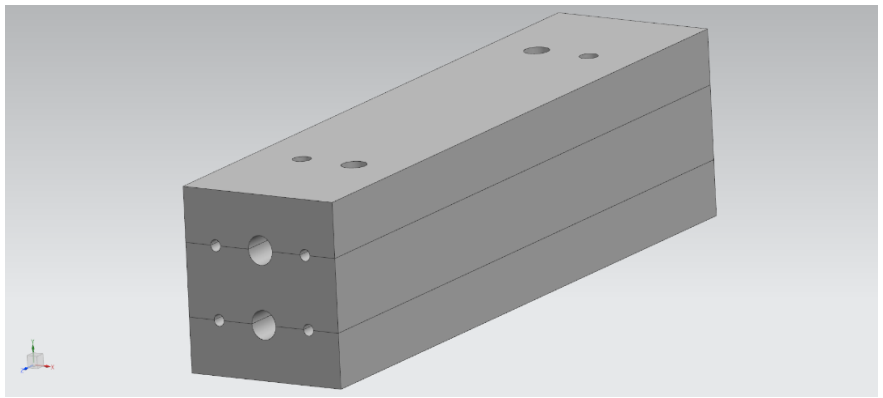


Hadronic Calorimeters



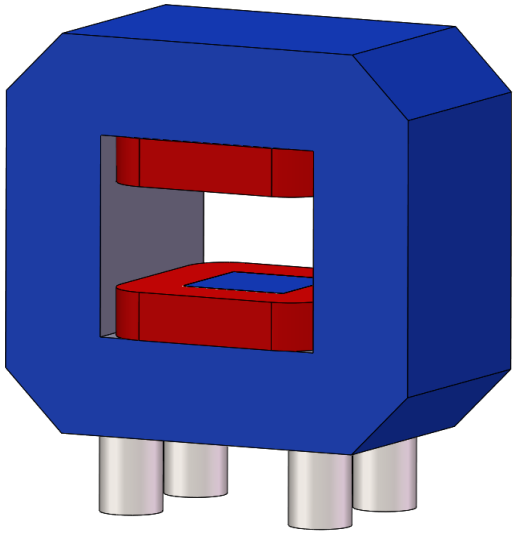
- Shashlyk
  - 16×16 towers
  - Tower size: : $2\ cm \times 2\ cm$, 80 cm
  - 8 layers: $2.0\ cm$ scintillator + $8\ cm$ absorb (Fe)
  - Material budget : $4.1\ \lambda_I$
  - Used for PID: muon and pion separation

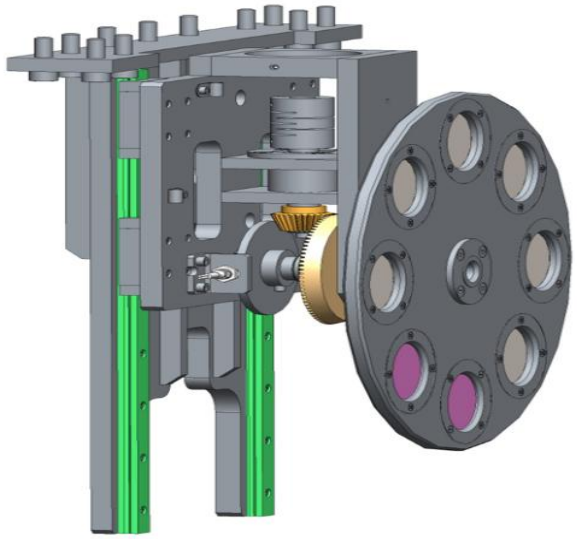


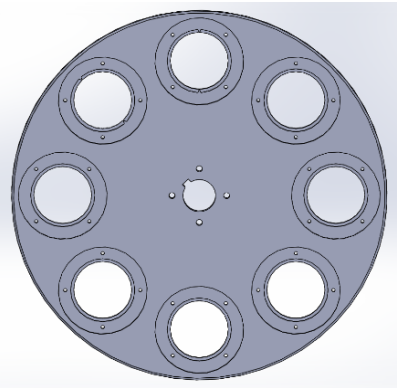


Magnetic field and target station

- Dipole magnetic field: room-temperature magnet technology
  - 0.5 T, $0.5\ m \times 0.4\ m \times 0.5\ m$
  - Uniformity of the field: $\pm 5 \times 10^{-3}$
- Target station: (solid targets, $\boldsymbol{CH_2, CD_2, C}$)
  - Repeatability of positioning after switching is better than $\pm 0.1\ mm$

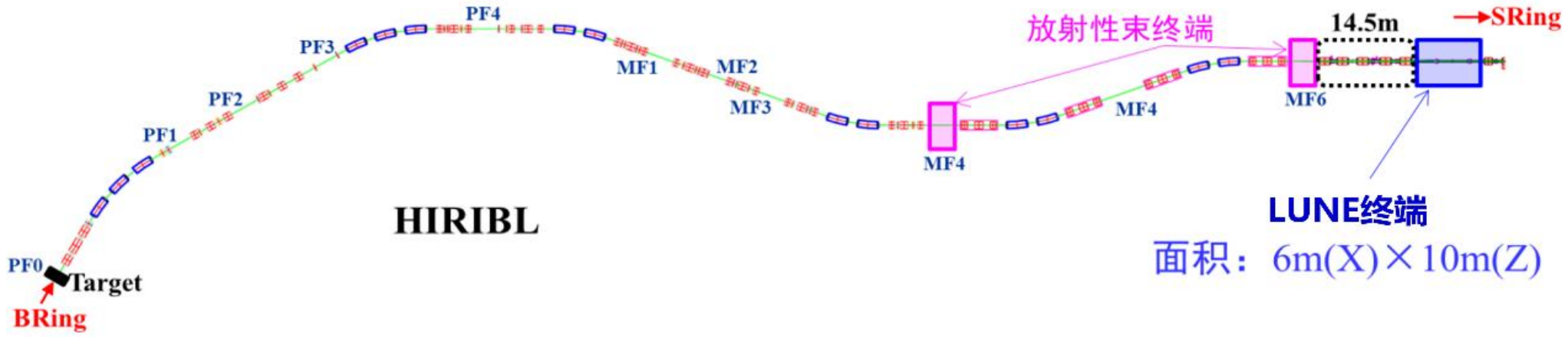






Upgrading of the HIRIBL beamline

- Upgrade HIRIBL beamline for muon beam
  - Maximum magnetic rigidity of $15\ T \cdot m$
  - Horizontal and vertical acceptances of $30\ \pi\ mm \cdot mrad$ and $37.5\ \pi\ mm \cdot mrad$
  - Momentum acceptance of $\pm 2\%$



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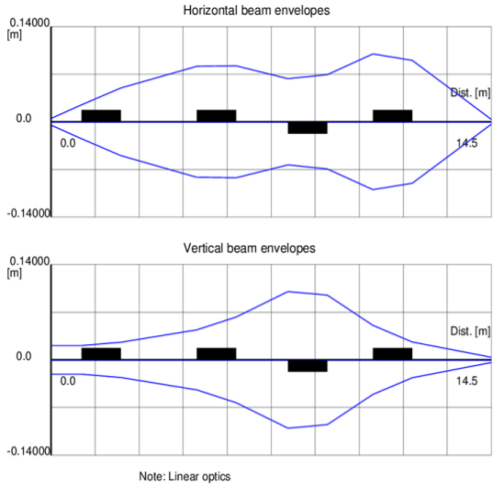
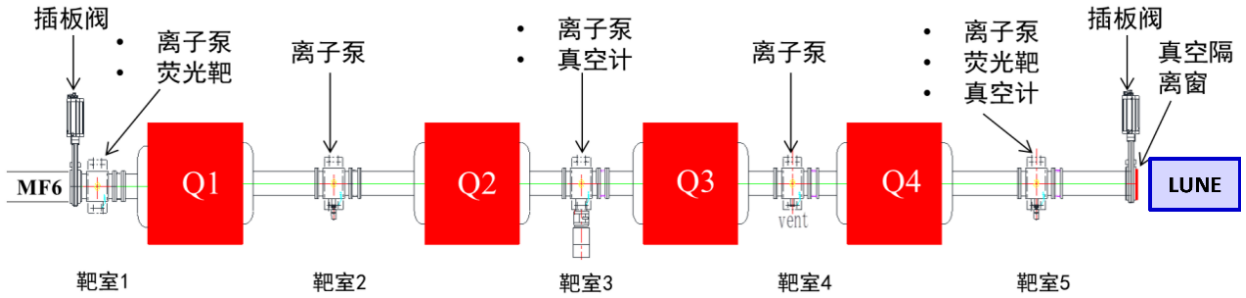
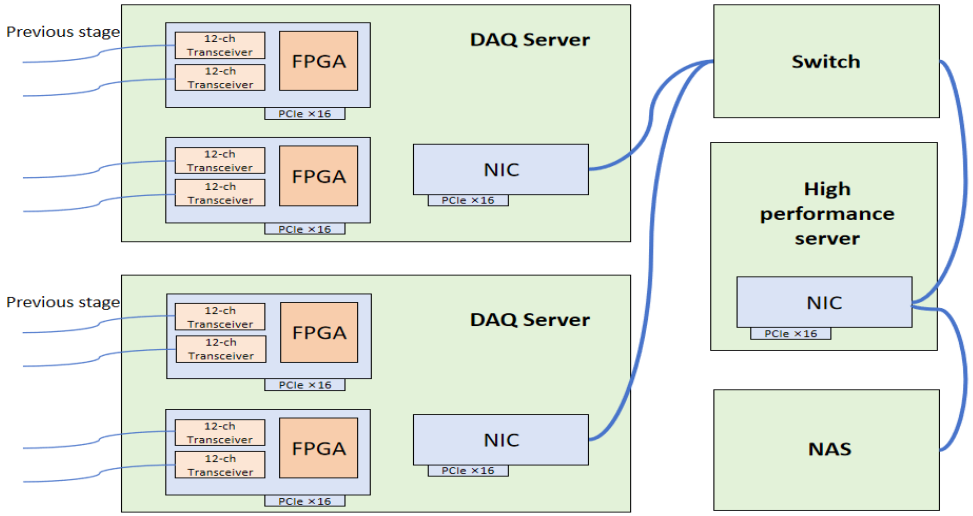


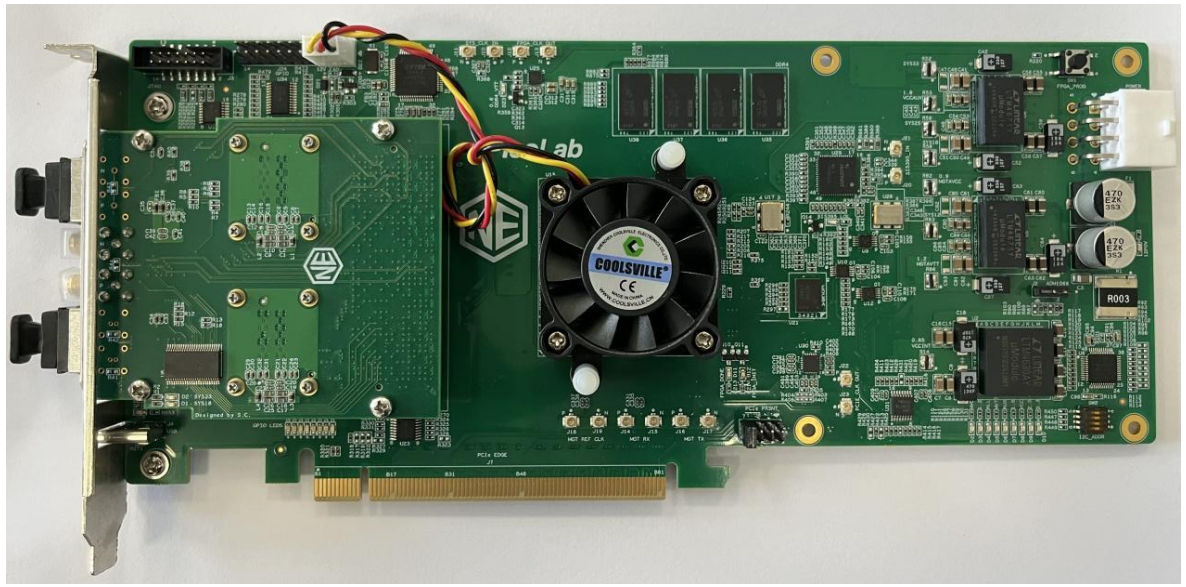
参数	数值
磁铁规格	四极磁铁
台数	3
有效长度	1.3 m
梯度场范围	1.1~6.4T/m
气隙R	140 mm
好场区范围	±134mm×±134mm
好场区范围均匀度	$\pm 1\times 10^{-3}$



DAQ system

- Triggerless readout architecture
  - A PCIe + NIC co-design architecture
  - 200G-class PCIe DMA with zero-copy transfer
  - Integrated precision clock distribution and synchronization system: < 10 ps timing alignment





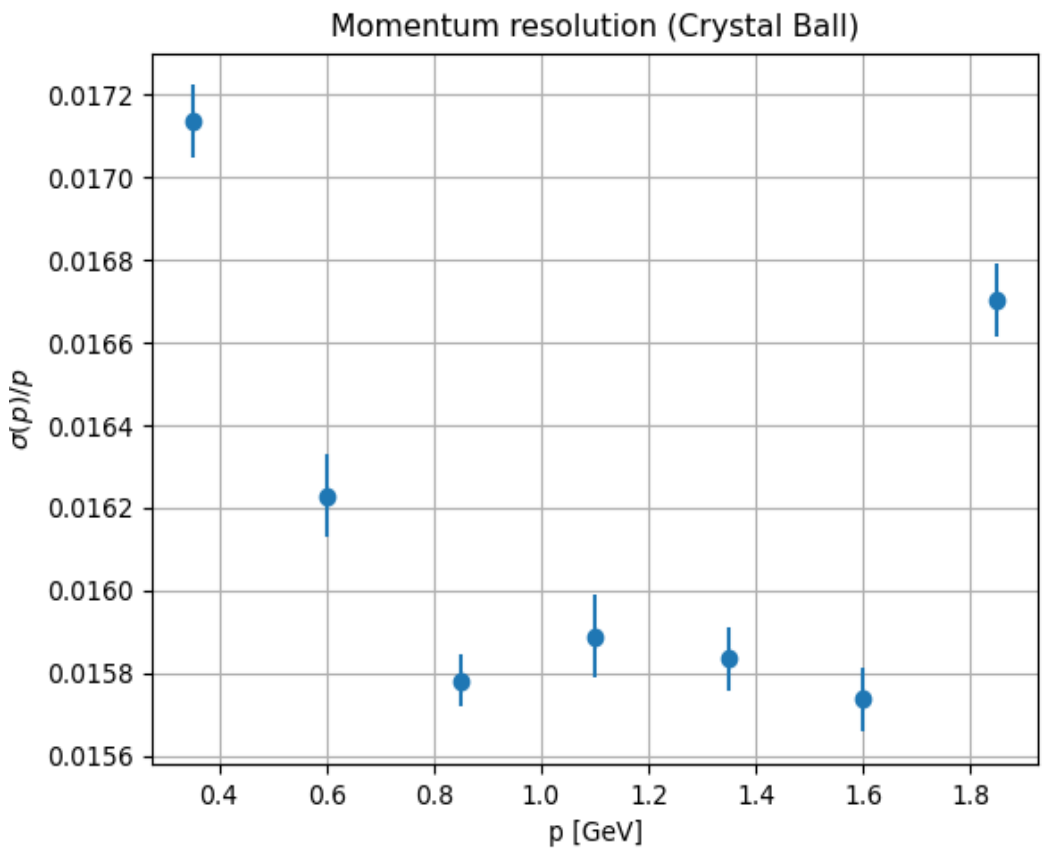
PDQ127 for STCF

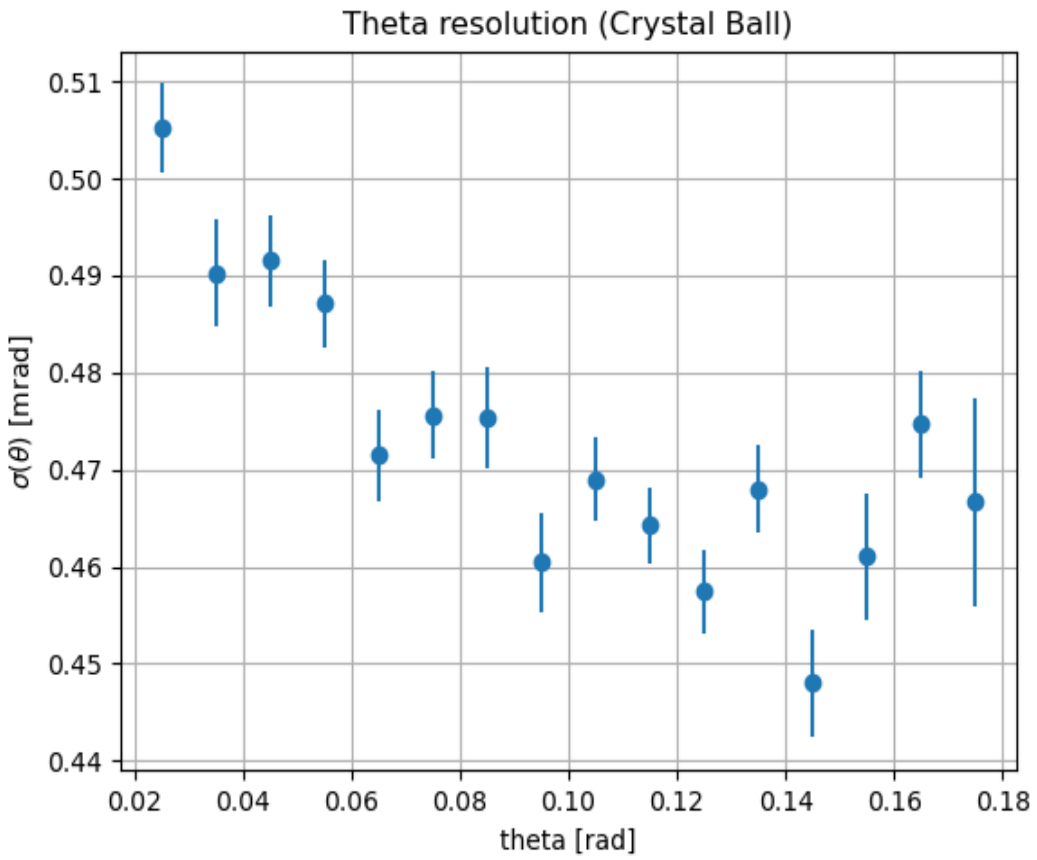
Detector costs

Detectors	Costs (CNY)
Silicon pixel detector	2.45 M
Calorimeter	1.45 M
DAQ	2.33 M
Magnet and Target station	1.95 M
Total	**8.18 M**

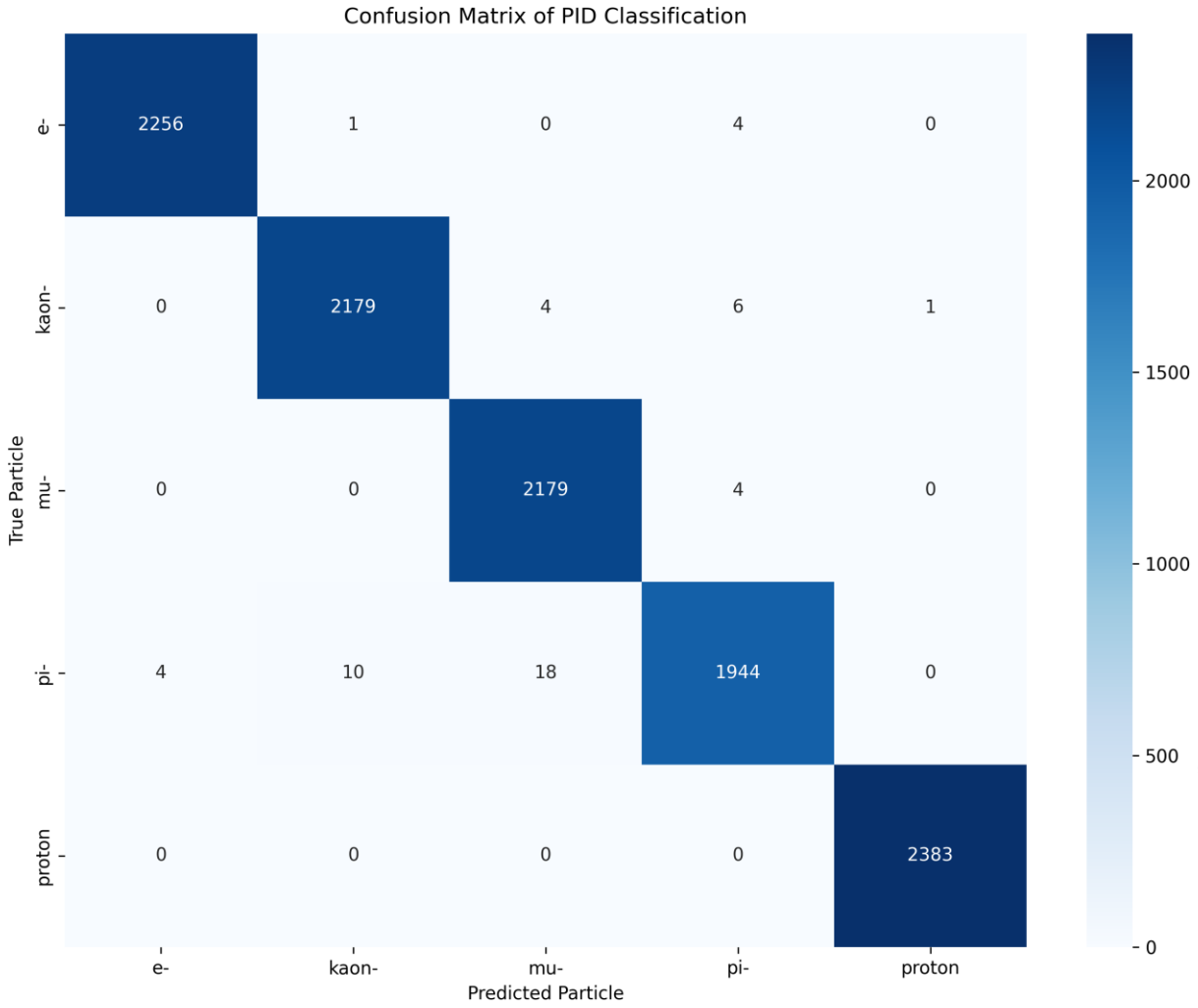
In Phase I, with funding below 10 million CNY, we can build a detector with strong potential for high-impact results in the scientific community.

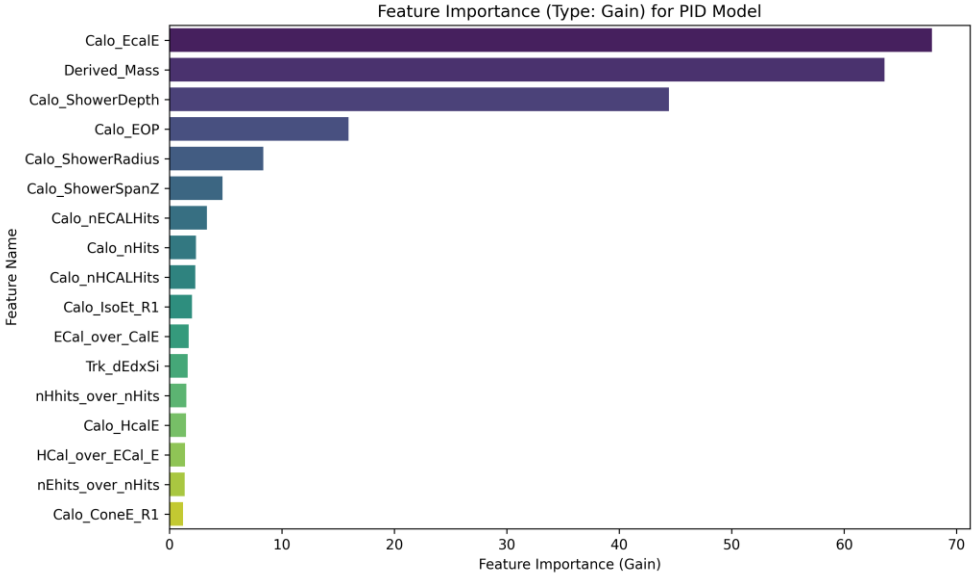
Detector performance





PID performance





- Could achieve better than 90% pion and muon separation

Conclusion

- The HIAF muon source offers a unique opportunity to explore new frontiers in nuclear and particle physics
  - **Proton charge radius**: critical cross-check from muon scattering
  - **Proton inner structure**: DIS, SIDIS, DVCS
  - **Neutron charge distribution**
  - **Nuclear effects**: SRC/EMC, Coulomb Distortion
  - **New physics**: Dark matter searches
- An unexplored research domain @ HIAF muon facility
  - LUNE collaboration would like to contribute to it
- Phase-I and Phase-II: **$< 10\ M$ CNY for phase-I detector!!!**

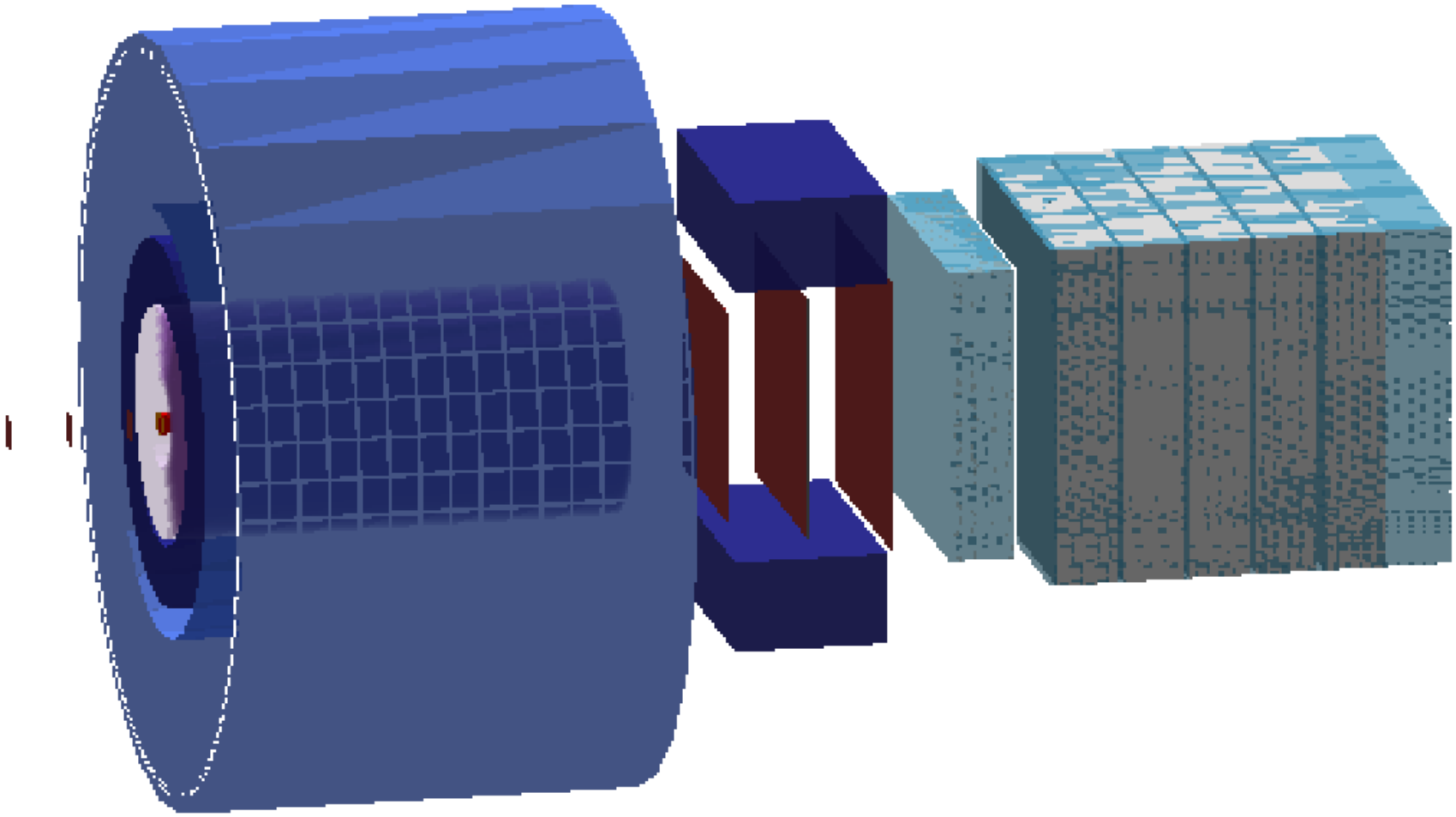
Conclusion

- The HIAF muon source offers a unique opportunity to explore new frontiers in nuclear and particle physics
  - **Proton charge radius**: critical cross-check from muon scattering
  - **Proton inner structure**: PDF, GPDs, DVCS
  - **Neutron charge distribution**
  - **Nuclear effects**: SRC/EMC, Coulomb Distortion
  - **New physics**: Dark matter searches
- An unexplored research domain @ HIAF muon facility

欢迎加入我们！！！

Backup

New detector

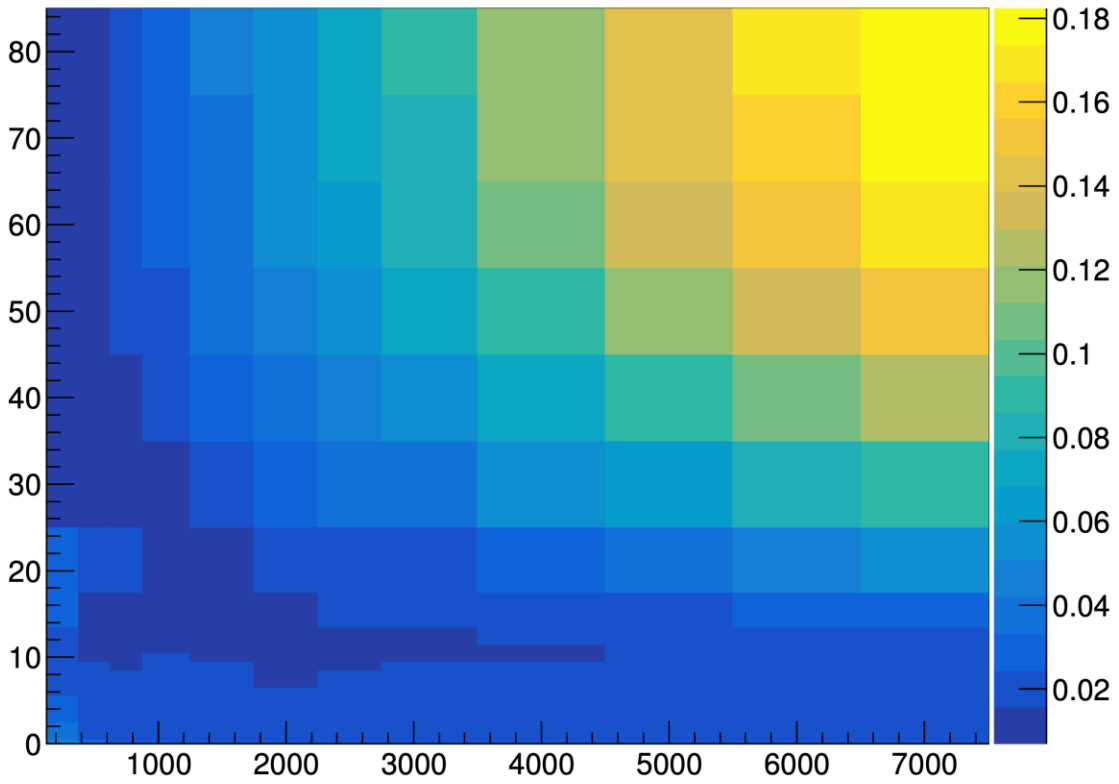


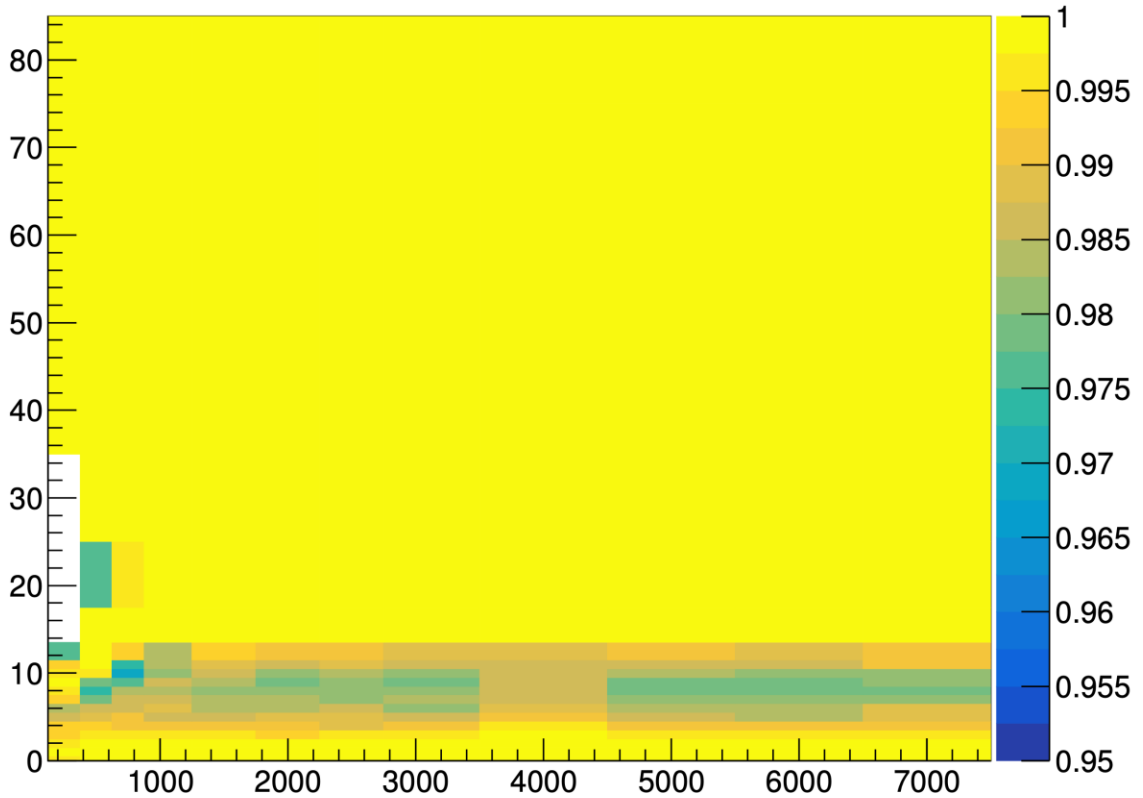
Fundamental global properties of proton

- The structure of strongly interacting particles can be probed using other fundamental forces
  - Electromagnetic, weak, gravity (in principle)

em:	$\partial_\mu J^\mu_{\rm em} = 0$	$\langle N' \vert J^\mu_{\bf em} \vert N \rangle$	$\longrightarrow$	$Q_{\rm prot}$	$=$	$1.602176487(40) \times 10^{-19}$C
Vector				$\mu_{\rm prot}$	$=$	$2.792847356(23)\mu_N$
weak:	PCAC	$\langle N' \vert J^\mu_{\bf weak} \vert N \rangle$	$\longrightarrow$	g_A	$=$	$1.2694(28)$
Axial				g_p	$=$	$8.06(0.55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\bf grav} = 0$	$\langle N' \vert T^{\mu\nu}_{\bf grav} \vert N \rangle$	$\longrightarrow$	$M_{\rm prot}$	$=$	$938.272013(23)\,{\rm MeV}/c^2$
				J	$=$	$\frac{1}{2}$
Tensor				D	$=$	**?**

Track resolution and reco efficiency



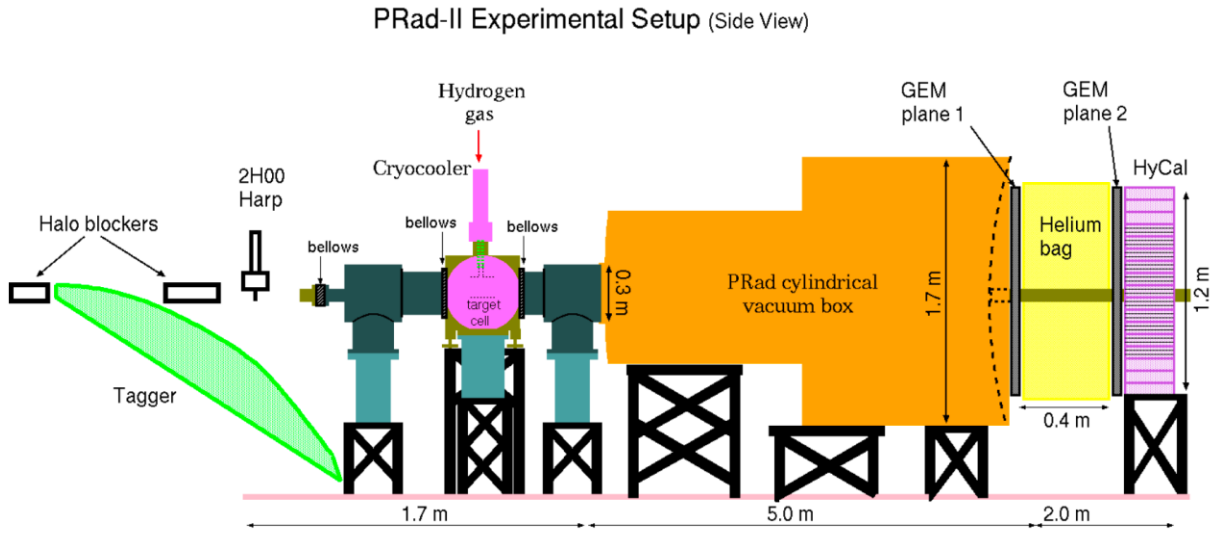


Reconstruction/Generators

- GenFit: for track reconstruction
  - Experiment independent framework for track reconstruction
  - Also used in PANDA @FAIR, Belle II
- Rave: vertex finding and reconstruction
  - A toolkit for vertex reconstruction
  - Developed from CMS
- K4reco: cluster reconstruction + PID
  - Marlin algorithms ported to Gaudi, included in Key4hep
- Generators:
  - esepp (elastic), djangoh (DIS), epic (DVCS), HEPGen++ (DVCS)

PRad-II @ JLab

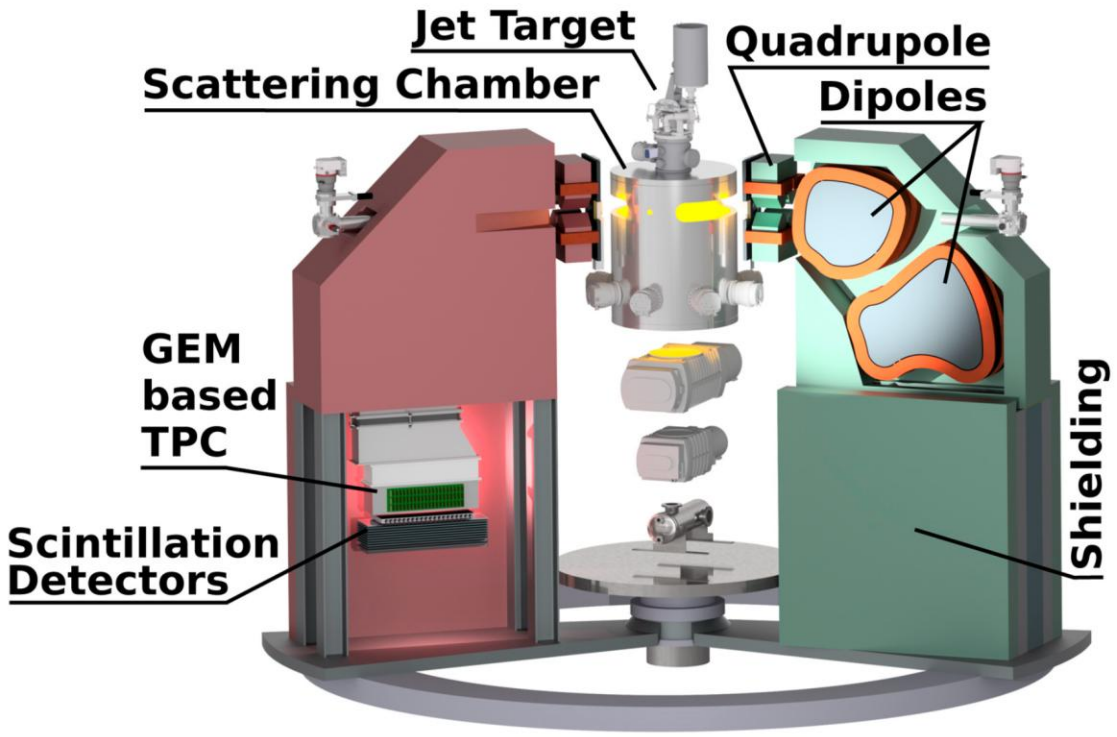
- Forward acceptance, high resolution EM calorimetry and coordinate detector for tracking
  - Data taking: 2026
- Large angular acceptance:
  - θ_e: $0.5^o - 7^o$
  - Q^2: 2×10^{-5} to 6×10^{-2} GeV/c²



Source	PRad Δr_p (fm)	PRad-II Δr_p (fm)
Stat. uncertainty	0.0075	0.0015
Event selection	0.0070	0.0030
Radiative correction	0.0069	0.0004
Detector efficiency	0.0042	0.0025
Beam background	0.0039	0.0014
HyCal response	0.0029	0.0001
Acceptance	0.0026	0.0001
Beam energy	0.0022	0.0001
Inelastic ep	0.0009	0.0001
G_M^p model	0.0006	0.0005
Total syst.	0.0115	0.0043
Total uncertainty	0.0137	0.0046

MAGIX @ Mainz

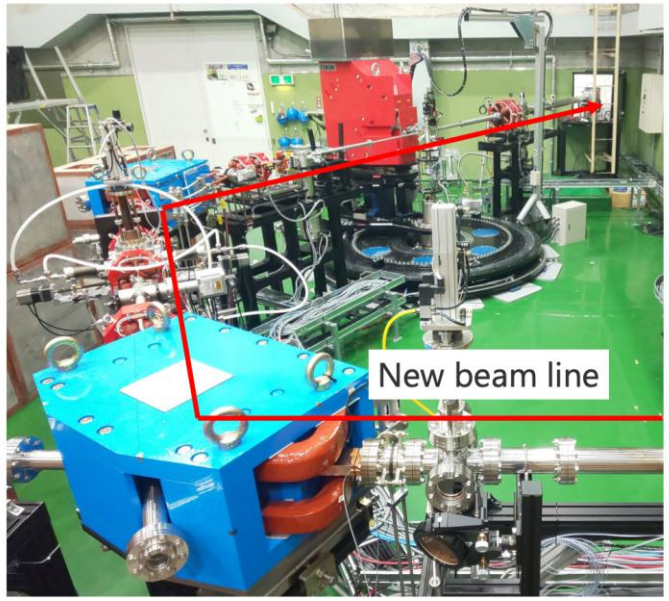
- Accelerator: 1 mA electron beam, energy up to 105 MeV
- Target: cryogenic supersonic gas jet
  - Effectively point-like target
- Expected precision: < 0.1%

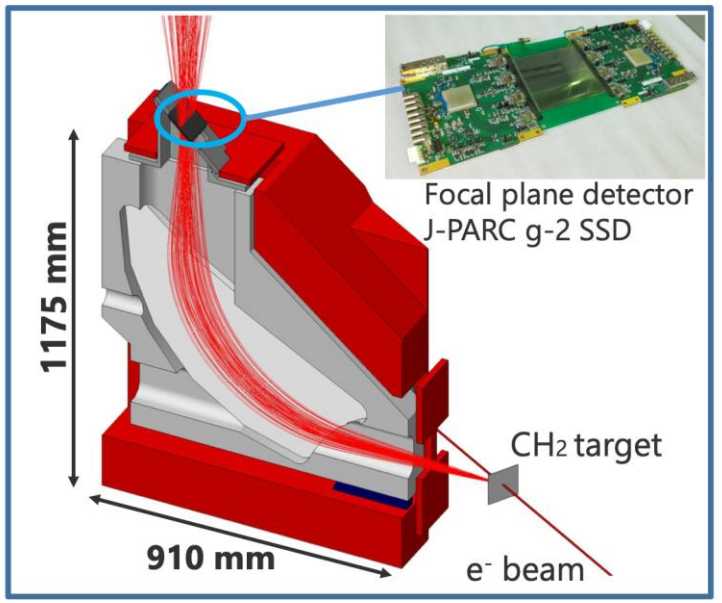


ULQ2 experiment

- Tohoku University: ELPH (Electron photon Science)
- Electron beam energy: from 20 to 60 MeV
- Q^2: 3×10^{-4} to 8×10^{-3} GeV/c²
- Target: CH2
- Precision: 0.1%

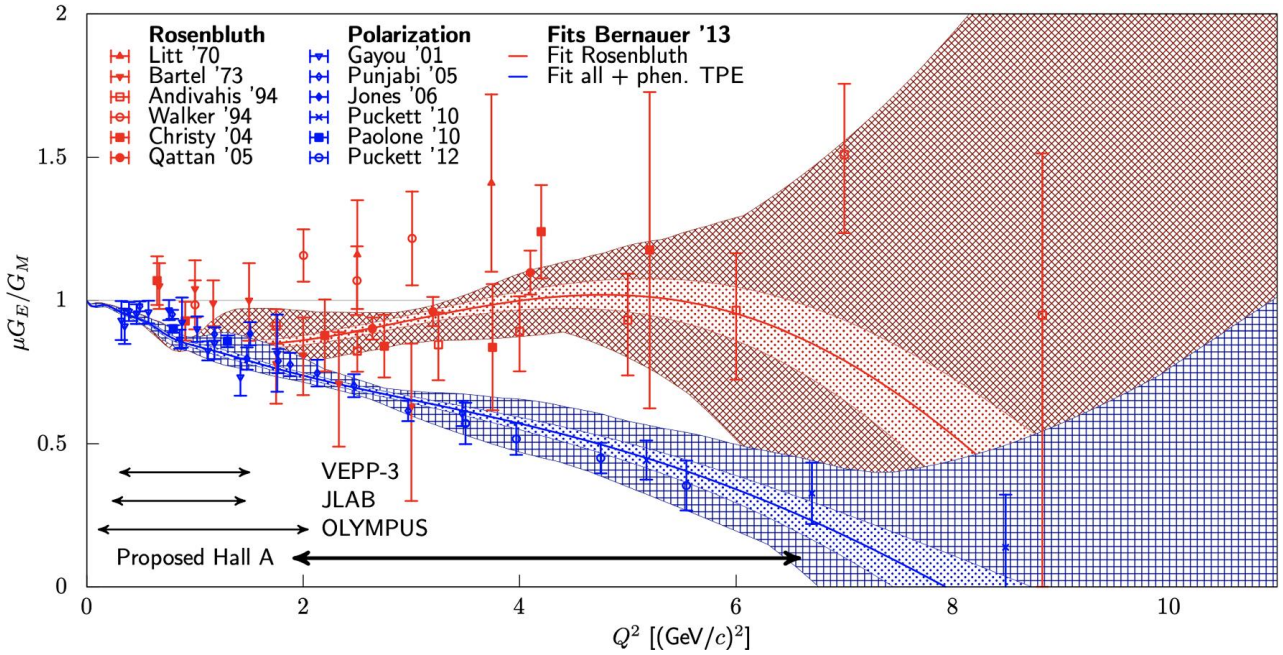
First beam	Sep. 11, 2020
Commissioning	Sep., Oct., Nov. 2020, May, June, July 2021

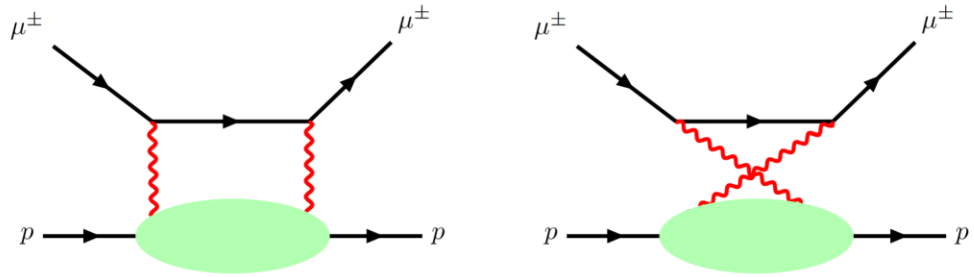




Two photon exchange (TPE)

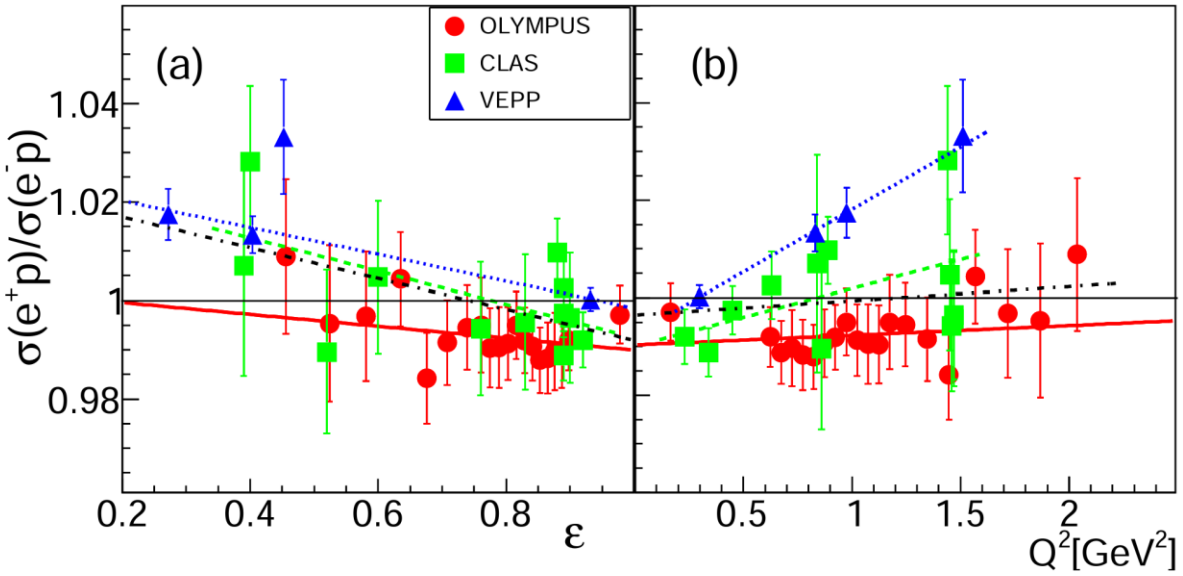
- Interference between one photon and two photon diagrams: $\ell^{\pm}$
- Key to resolving the proton form factor discrepancy
  - Rosenbluth vs. polarization transfer methods
- Muon-proton scattering: unique test of lepton universality





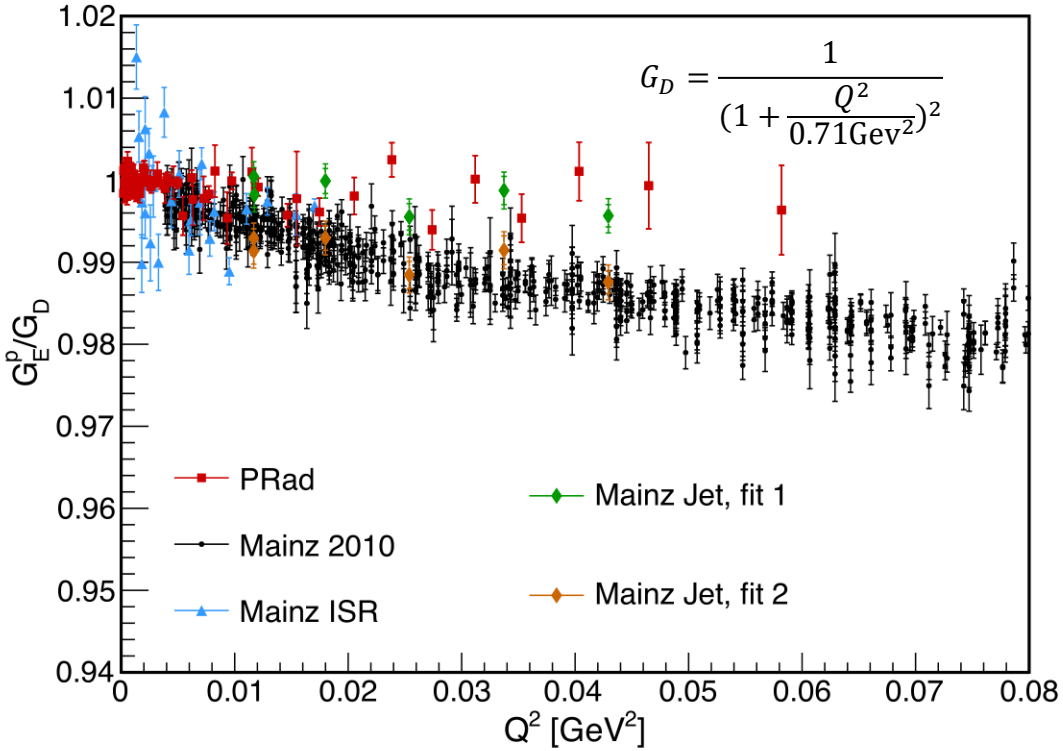
Two photon exchange (TPE)

- Electron scattering:
  - JLab, OLYMPUS@DESY, VEPP-3@Novosibirsk
  - Compared e^+p with e^-p elastic scattering
  - TPE at few-% level: explain part of form factor discrepancy
- Muon scattering:
  - Heavier mass: sensitivity to TPE at low Q^2
  - Direct test of TPE universality
- Essential correction for proton charge radius measurement

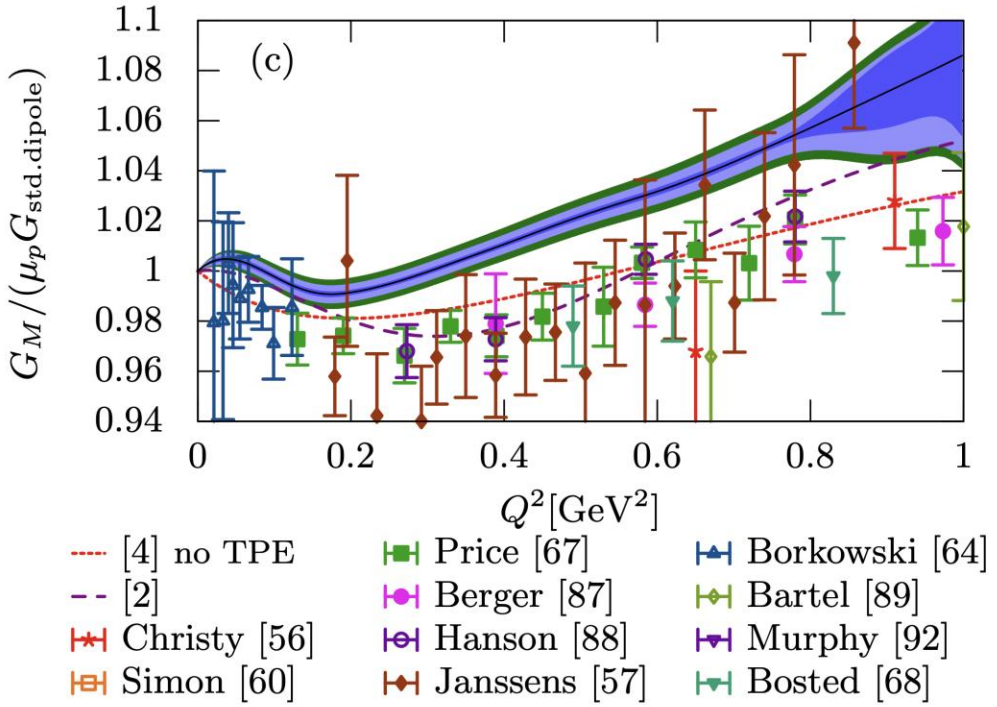


Proton form factor puzzle

- Over 1% difference for G_E between the PRad data and the Mainz data
  - Possible reasons: radiative correction? Unknown systematics? Fitting procedure?...
- Large discrepancy also exist for magnetic radius and G_M
  - 0.776(38) fm for Mainz data , 0.914 (35) fm for world data excluding Mainz (G. Lee et al. PRD 92 013013)



WX and Chao Peng (彭潮) *Universe* 9 (2023) 4, 182



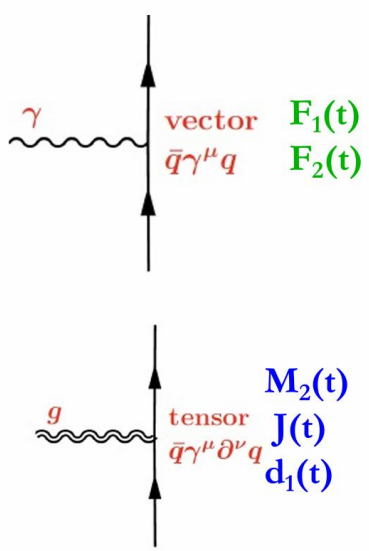
J. Bernauer et al. *PRC* 90 (2014) 1, 015206

Proton properties

The structure of strongly interacting particles can be probed by means of the other fundamental forces: *electromagnetic*, *weak*, and (in principle) *gravity*.

em:	$\partial_\mu J^\mu_{\rm em} = 0$	$\langle N'\|J^\mu_{\rm em}\|N\rangle$	$\longrightarrow$	$Q_{\rm prot}$	$=$	$1.602176487(40)\times 10^{-19}$C
	vector			$\mu_{\rm prot}$	$=$	$2.792847356(23)\mu_N$
weak:	PCAC	$\langle N'\|J^\mu_{\rm weak}\|N\rangle$	$\longrightarrow$	g_A	$=$	$1.2694(28)$
	axial			g_p	$=$	$8.06(0.55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\rm grav} = 0$	$\langle N'\|T^{\mu\nu}_{\rm grav}\|N\rangle$	$\longrightarrow$	$M_{\rm prot}$	$=$	$938.272013(23)\,{\rm MeV}/c^2$
				J	$=$	$\frac{1}{2}$
	tensor			D	$=$	**?**

P. Schweitzer et al., arXiv:1612.0672, 2016.



extreme weakness of the gravitational interaction

The D-term is the "last unknown global property" of the nucleon

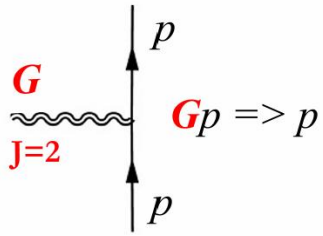
Gravitational form factor (GFFs)

- Nucleon matrix element of Energy-Momentum Tensor (EMT) has three scalar form factors

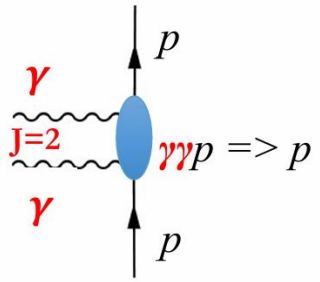
$$\left\langle p_2 \left| \hat{T}^q_{\mu\nu} \right| p_1 \right\rangle = \bar{U}(p_2) \left[M_2^q(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{\iota\left(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho}\right)\Delta^\rho}{2M} + d_1^q(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\Delta^2}{5M} \right] U(p_1)$$

- $M_2^q(t)$: Mass/energy distribution inside the nucleon
- $J^q(t)$: Angular momentum distribution
- $d_1^q(t)$: Forces and pressure distribution

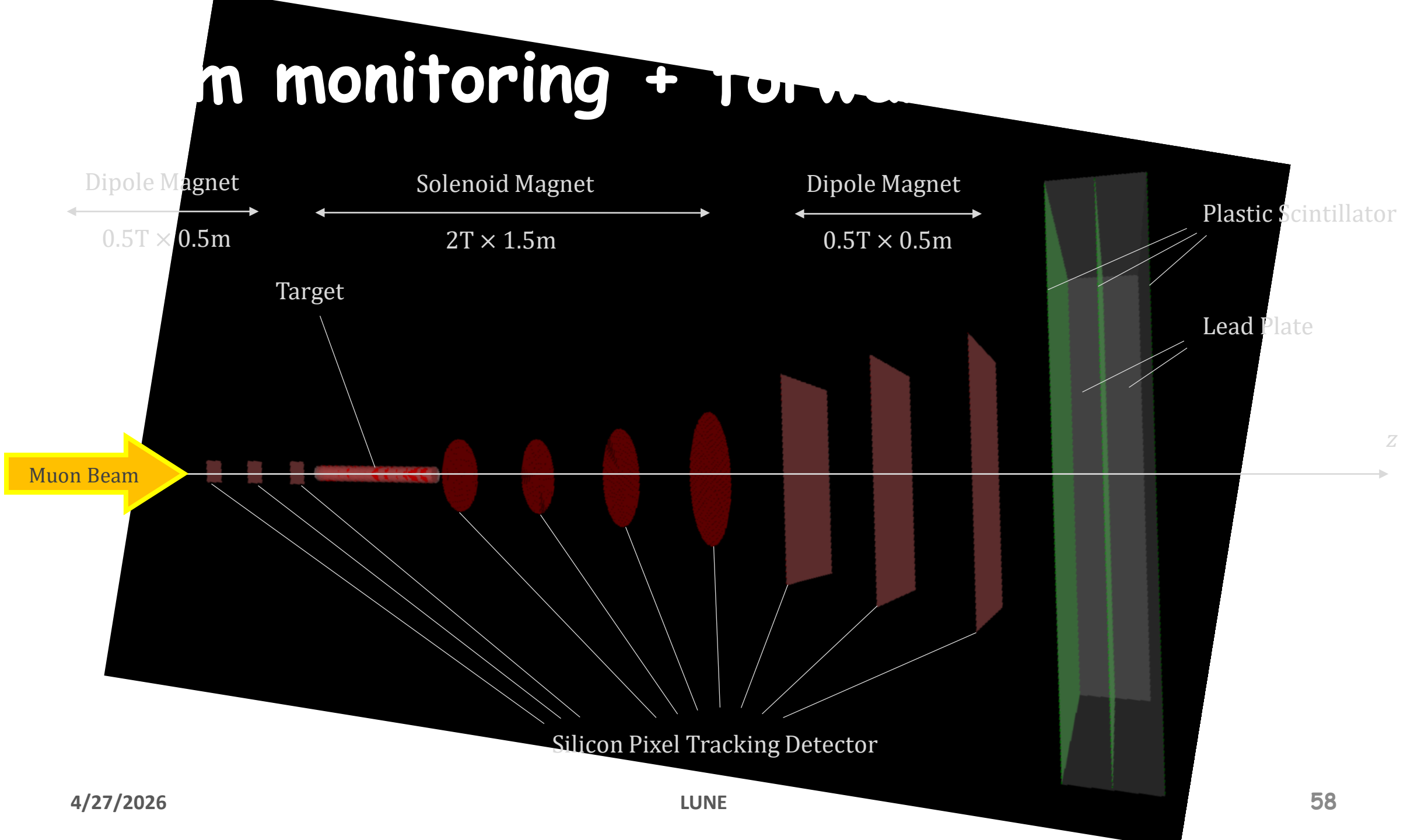
GPDs ←→ GFFs



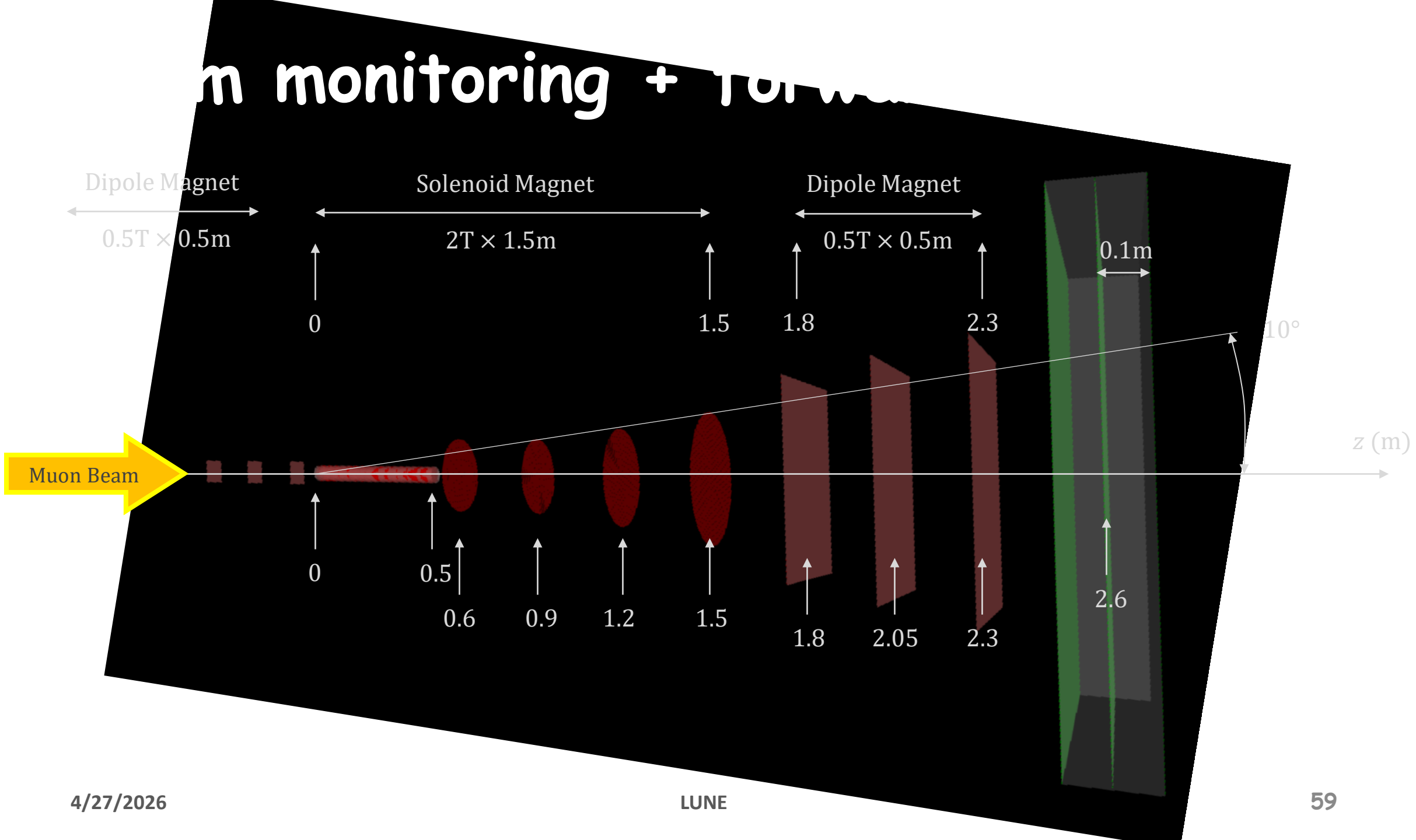
DVCS

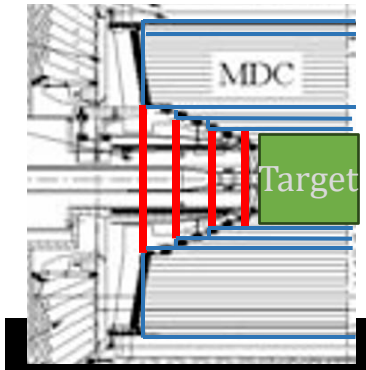


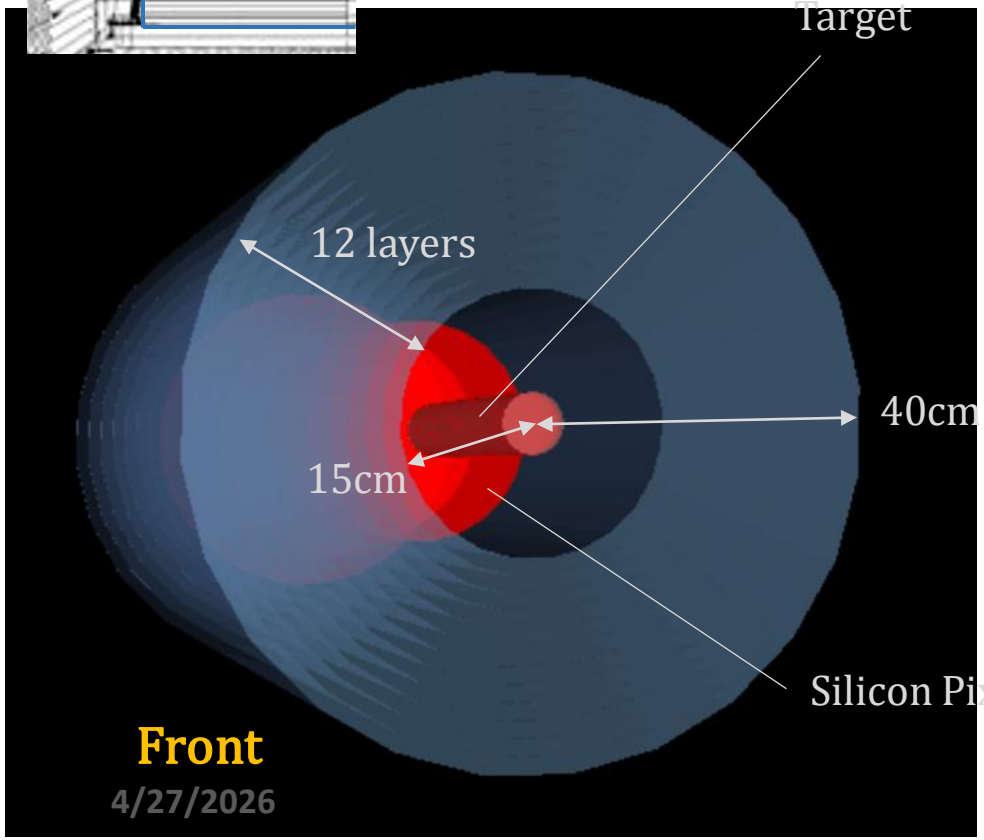
m monitoring + forwa



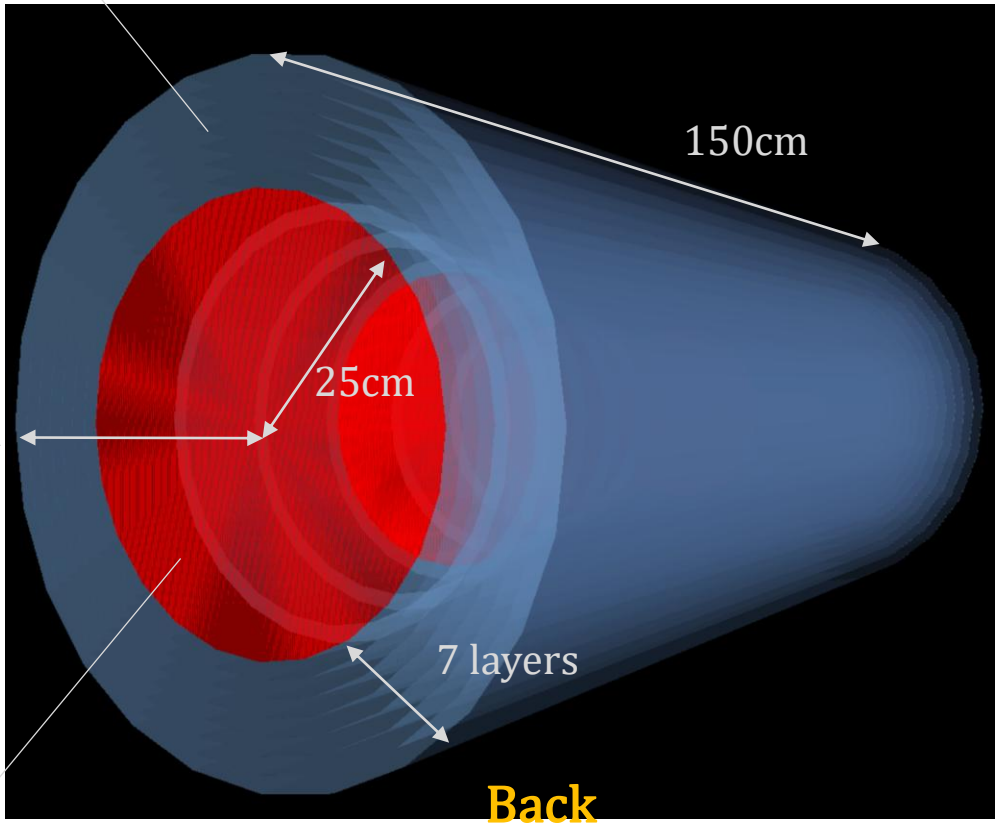
m monitoring + for



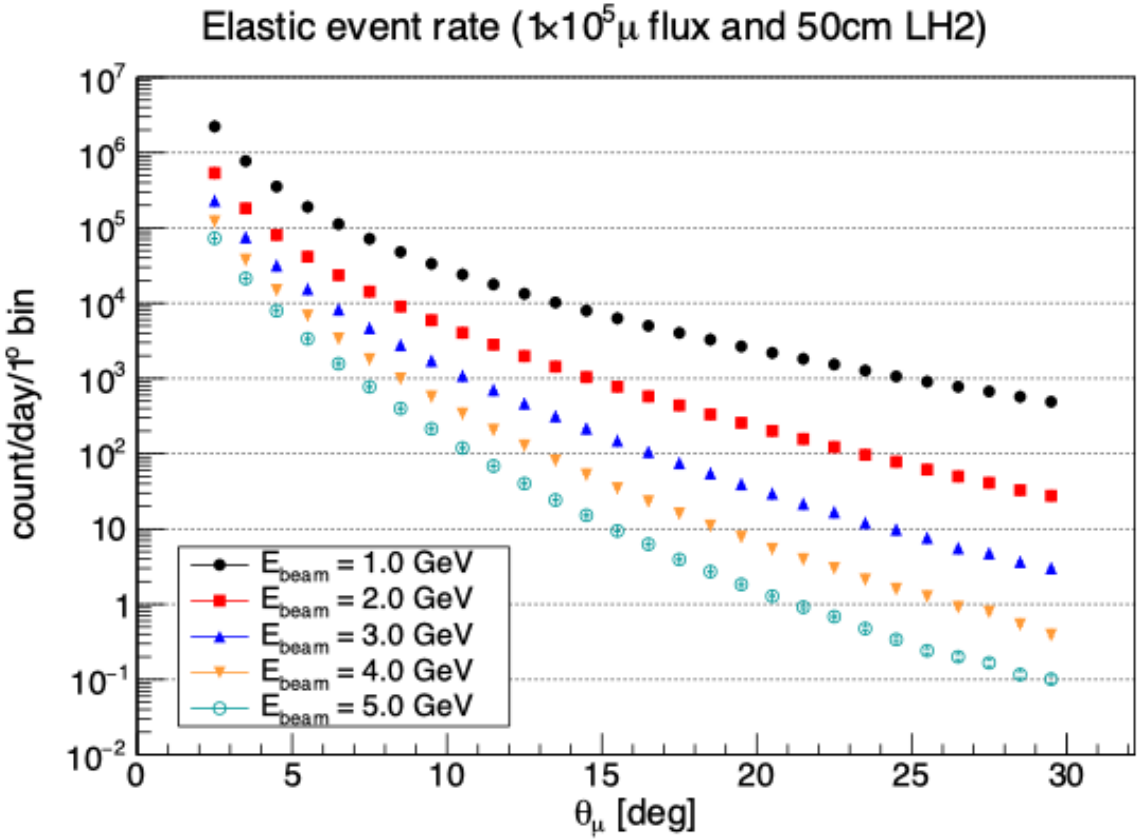


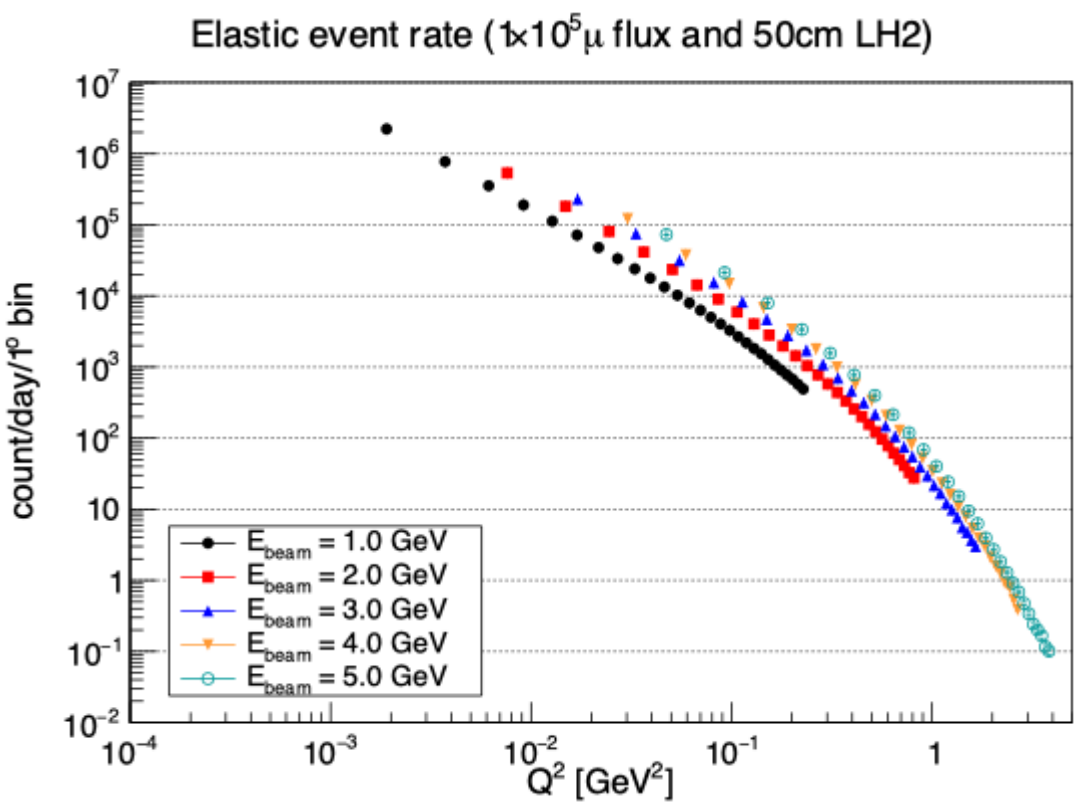


Multilayer Drift Chamber



Elastic scattering: event rate





Projection

- Proton radius measurement needs low momentum muon beam

- Assuming 20 cm LH2 target
  - 15 days @ 1.0 GeV
  - 30 days @ 1.5 GeV
  - 60 days @ 2.0 GeV

- Stat. uncertainty on proton radius:
  - ~ 0.0022 fm (~0.3%)
  - Compared to 1% (Amber), 0.5% (MUSE)