Low-energy muon beams for experiments

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Overview

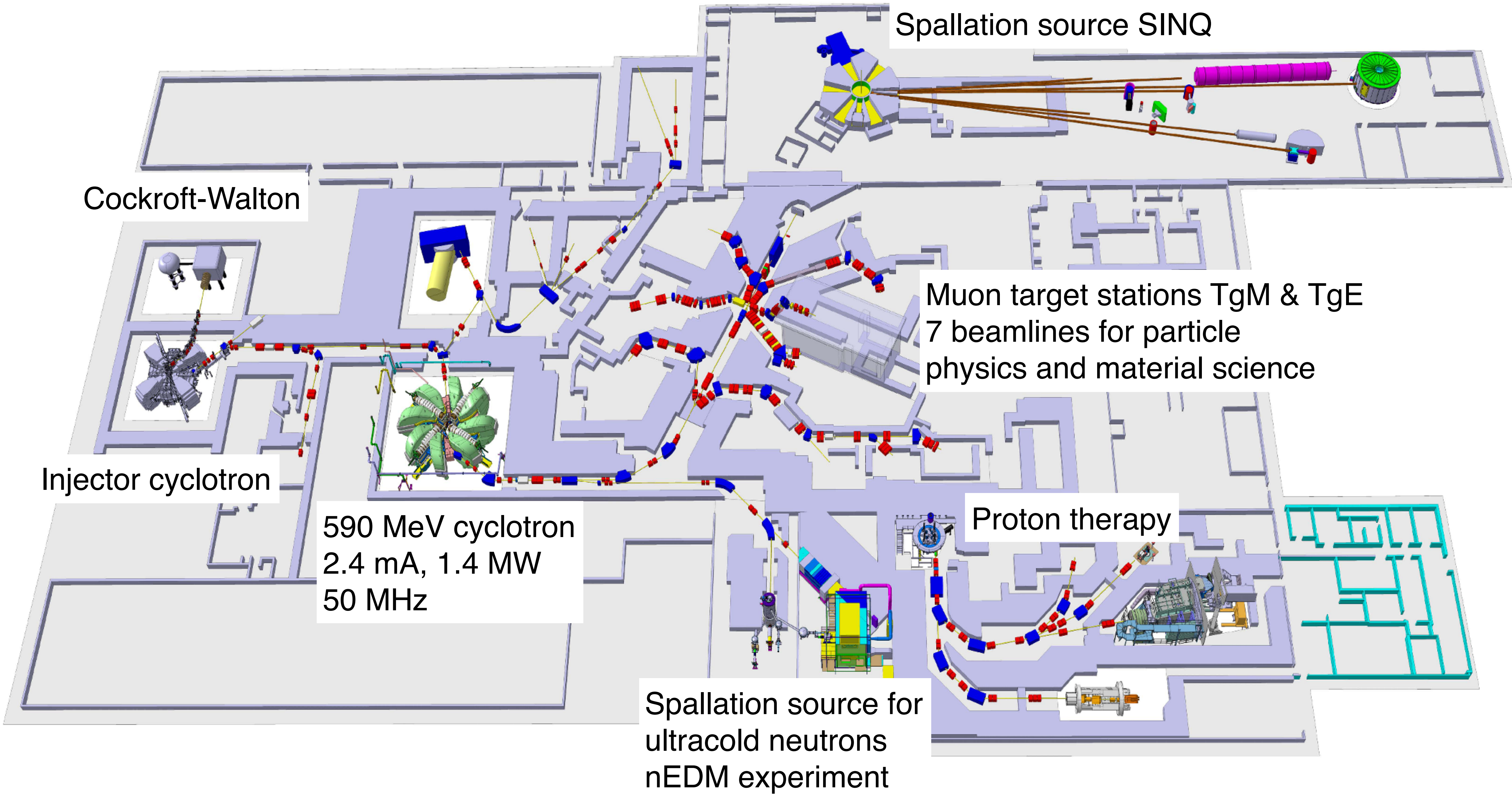
- Low-energy muon beams
- cLFV experiments
- Ultralow-energy muons
- Future high-brightness and high-intensity beam lines:
  muCool and HiMB projects

(Low Energy) Muon Sources in the World

Existing

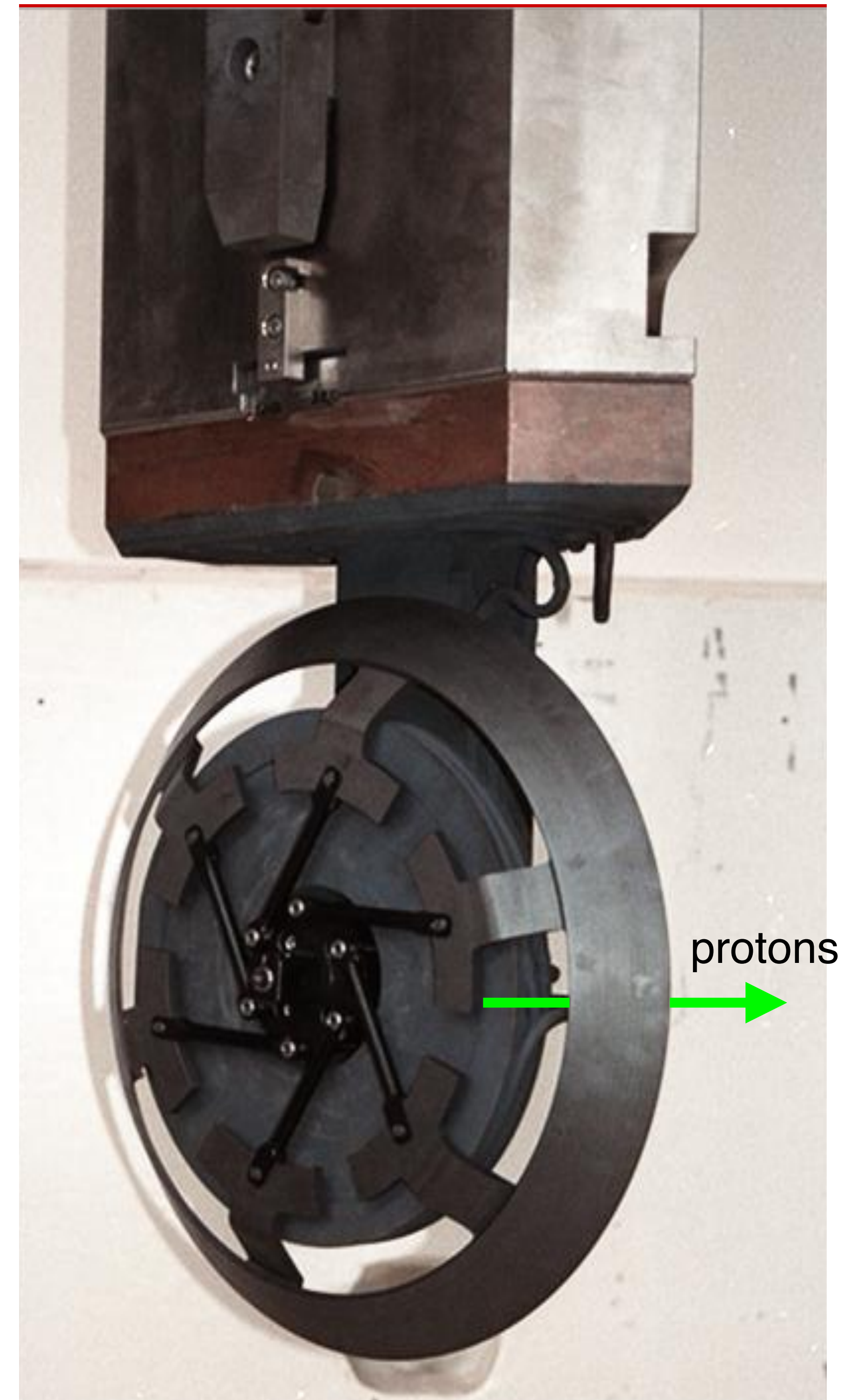
Future

PSI Proton Accelerator HIPA



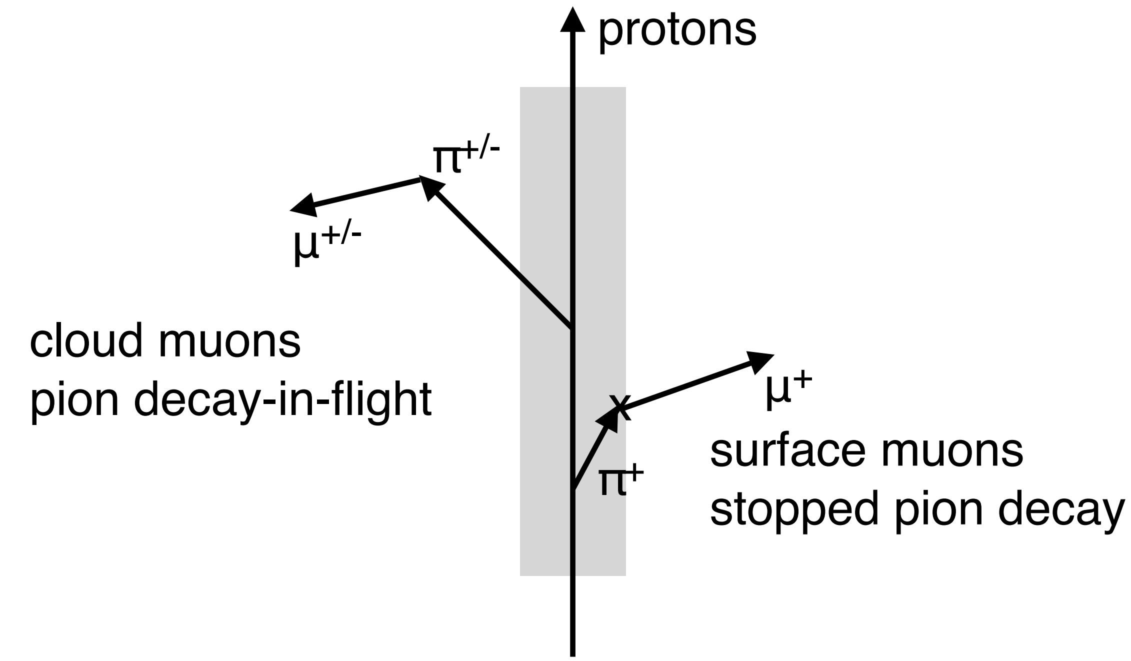
Muon Production Target TgE

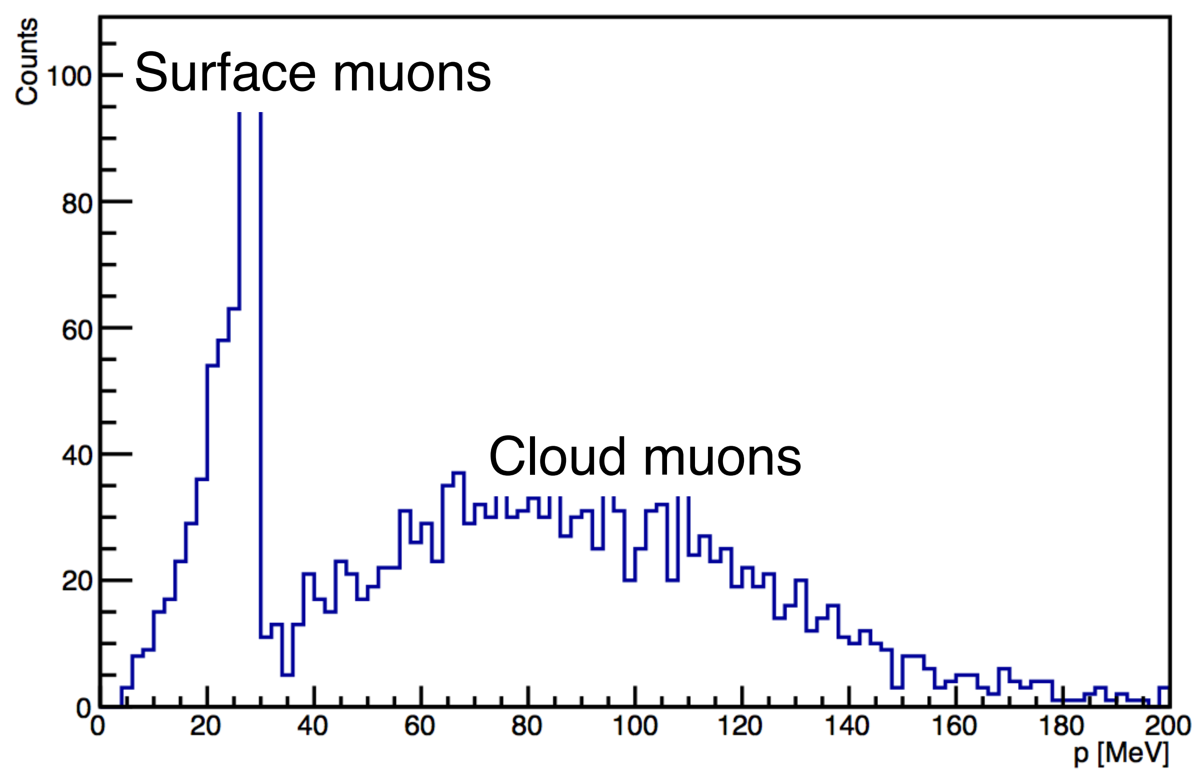
- 40 mm polycrystalline graphite
- ~40 kW power deposition
- Temperature 1700 K
- Radiation cooled @ 1 turn/s
- Beam loss 12% (+18% from scattering)



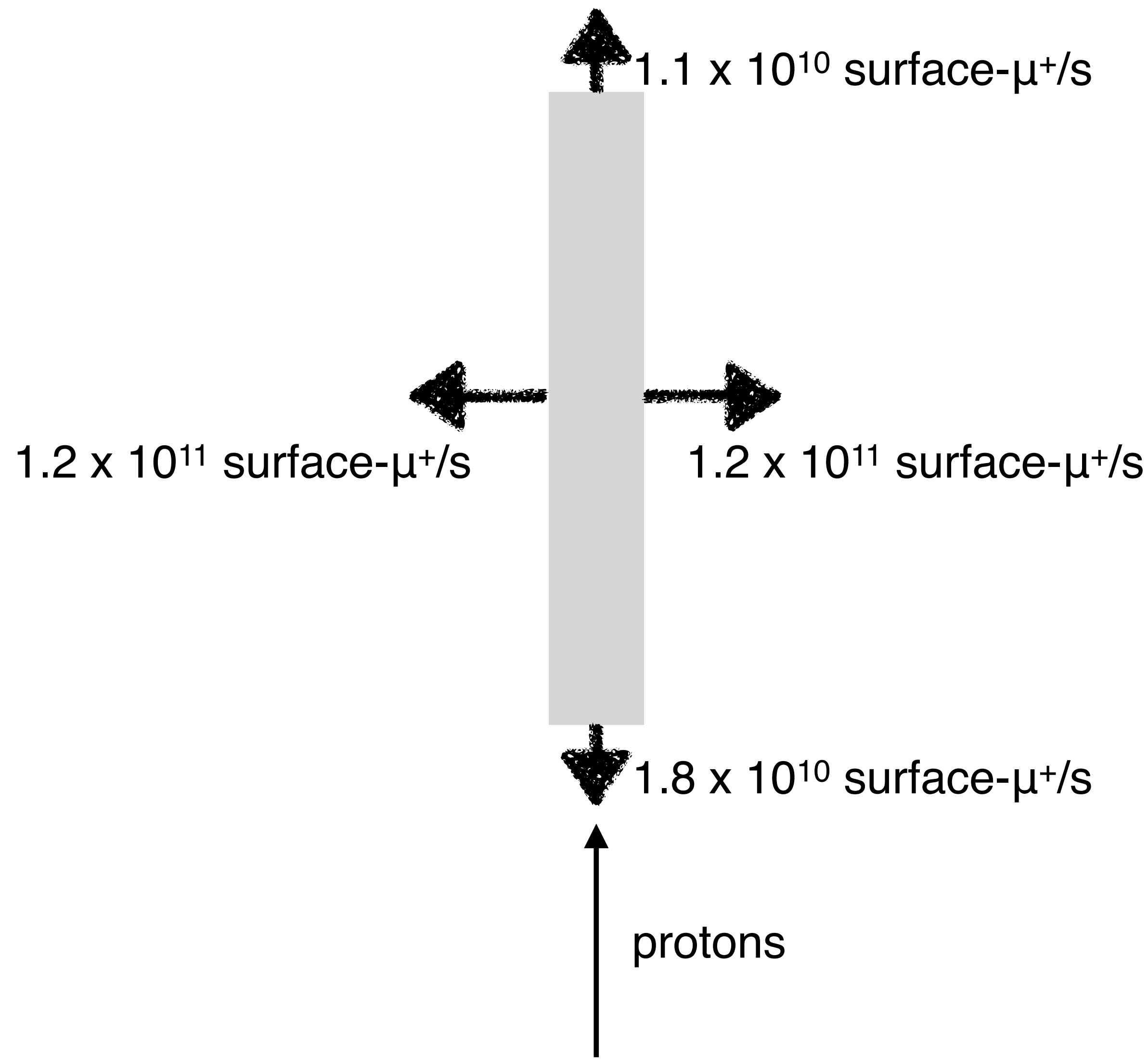
Surface muons

- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons
- Time structure of cyclotron smeared out by pion lifetime → DC muon beams





Surface Muon Rates: TgE



- Graphite: 40 mm length, 6 mm width
- 2.4 mA protons at 590 MeV
- Conventional muon targets are highly efficient in generating surface muons!

Surface Muon Rates: Beam Lines

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μE4 beamline
5.5 x 10^8 μ^+/s
material science

πE5 beamline
1.3 x 10^8 μ^+/s
particle physics

- Five beam beam lines around TgE, two with high-intensity
- Only small fraction of initial surface muons are transported (< 0.5%)

Experiments at Low Energy Beam Lines

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Material science:
Muon Spin Rotation (µSR)

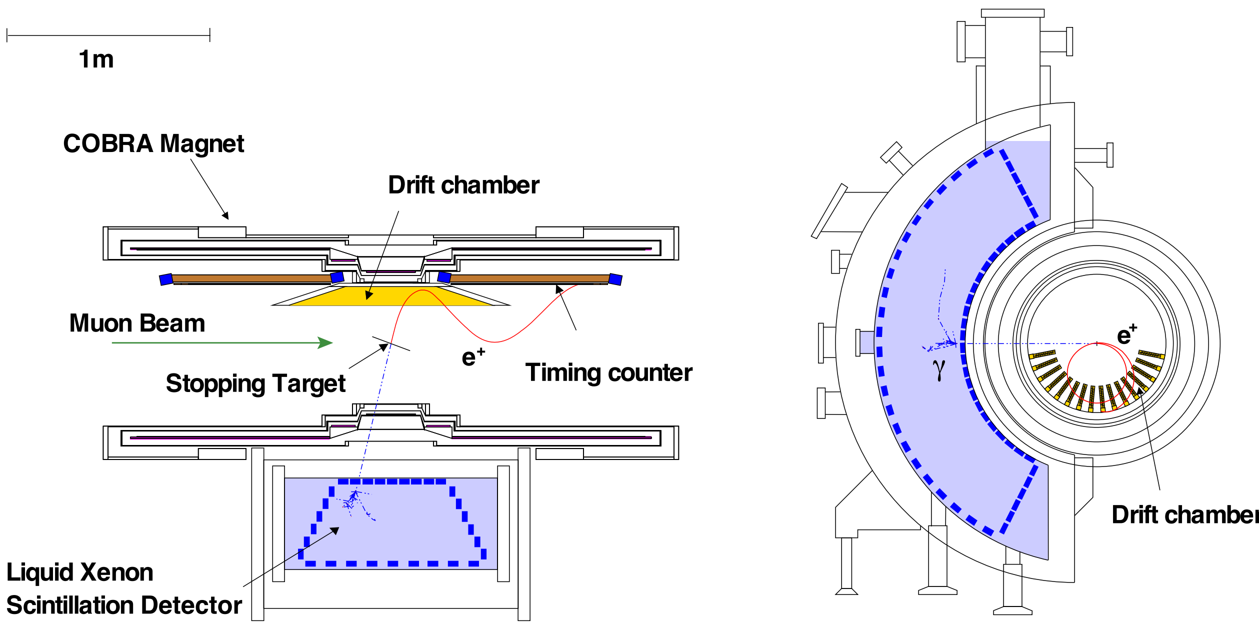
- Bulk properties
- Surface effects

Particle physics

- Muon lifetime
- cLFV: µ→eγ, µ→eee, µ+N→e+N
- Light muonic atoms: proton radius
- Muon capture
- …

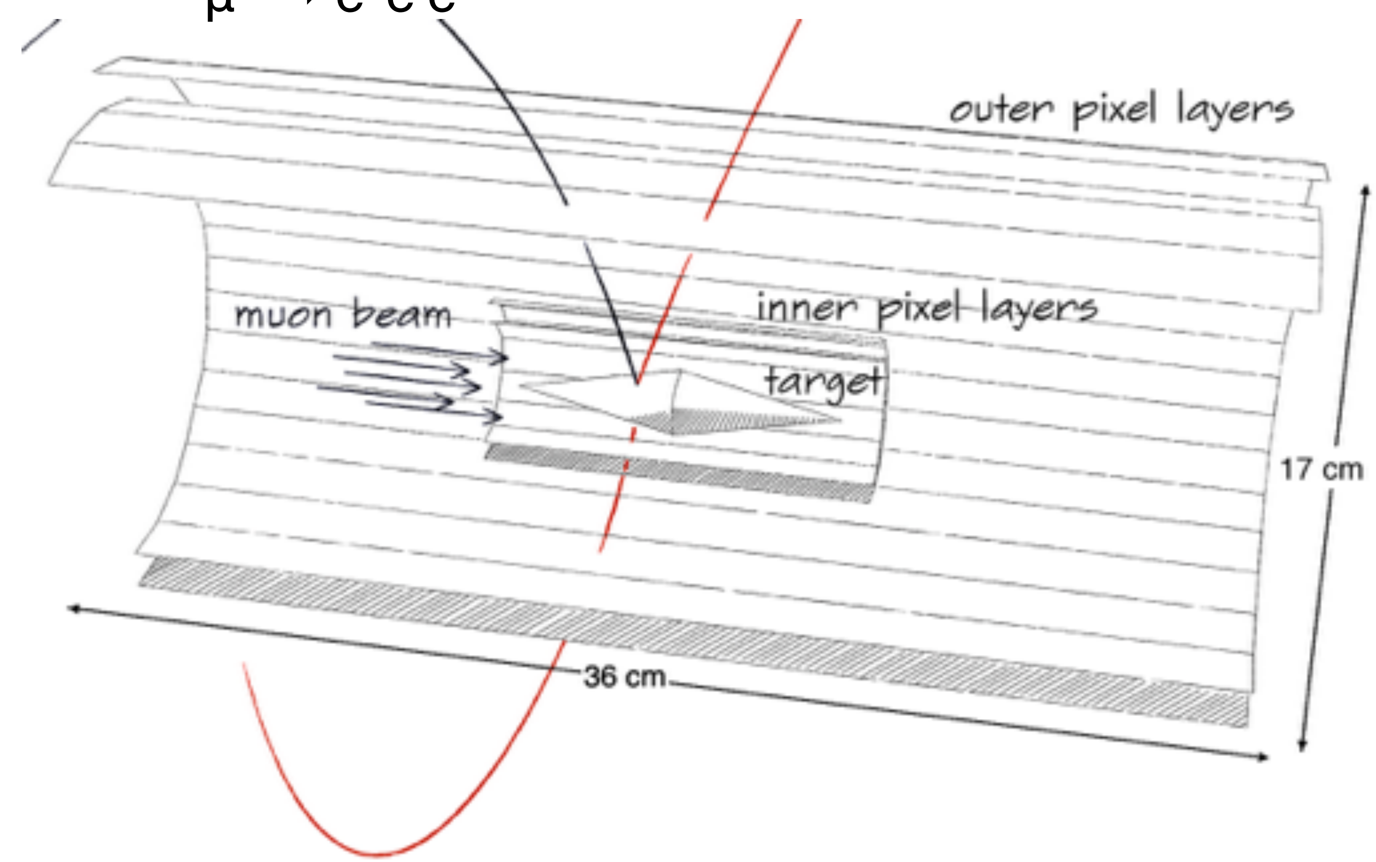
Needs high intensity

cLFV Experiments



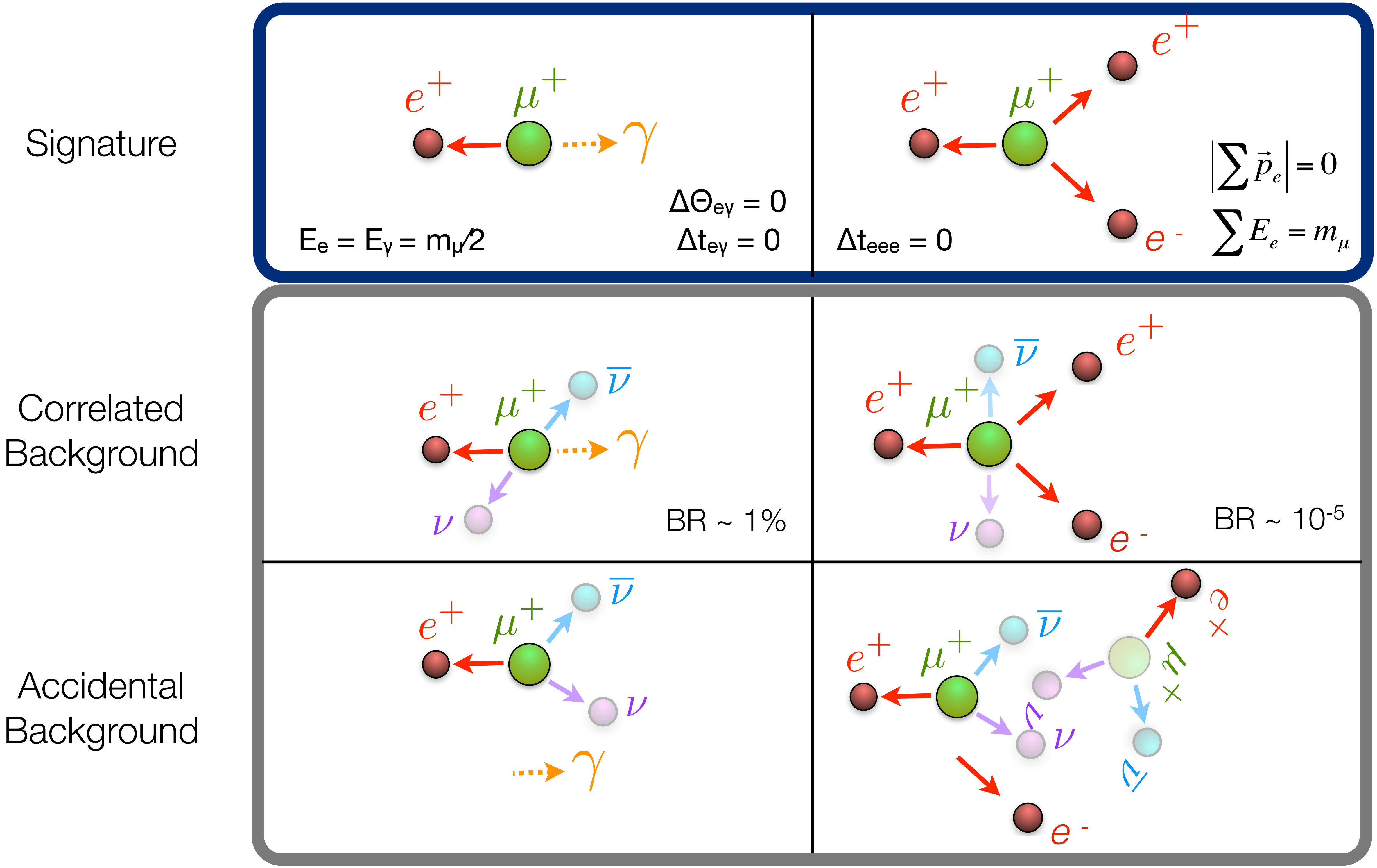
MEG experiment at PSI
$\mu^+ \rightarrow e^+\gamma$

Mu3e experiment at PSI
$\mu^+ \rightarrow e^+e^-e^+$



- Physics of cLFV experiments: see talk by Y. Kuno

cLFV Coincidence Experiments



- Need low instantaneous rate → DC muon beams at PSI

cLFV Results & Prospects

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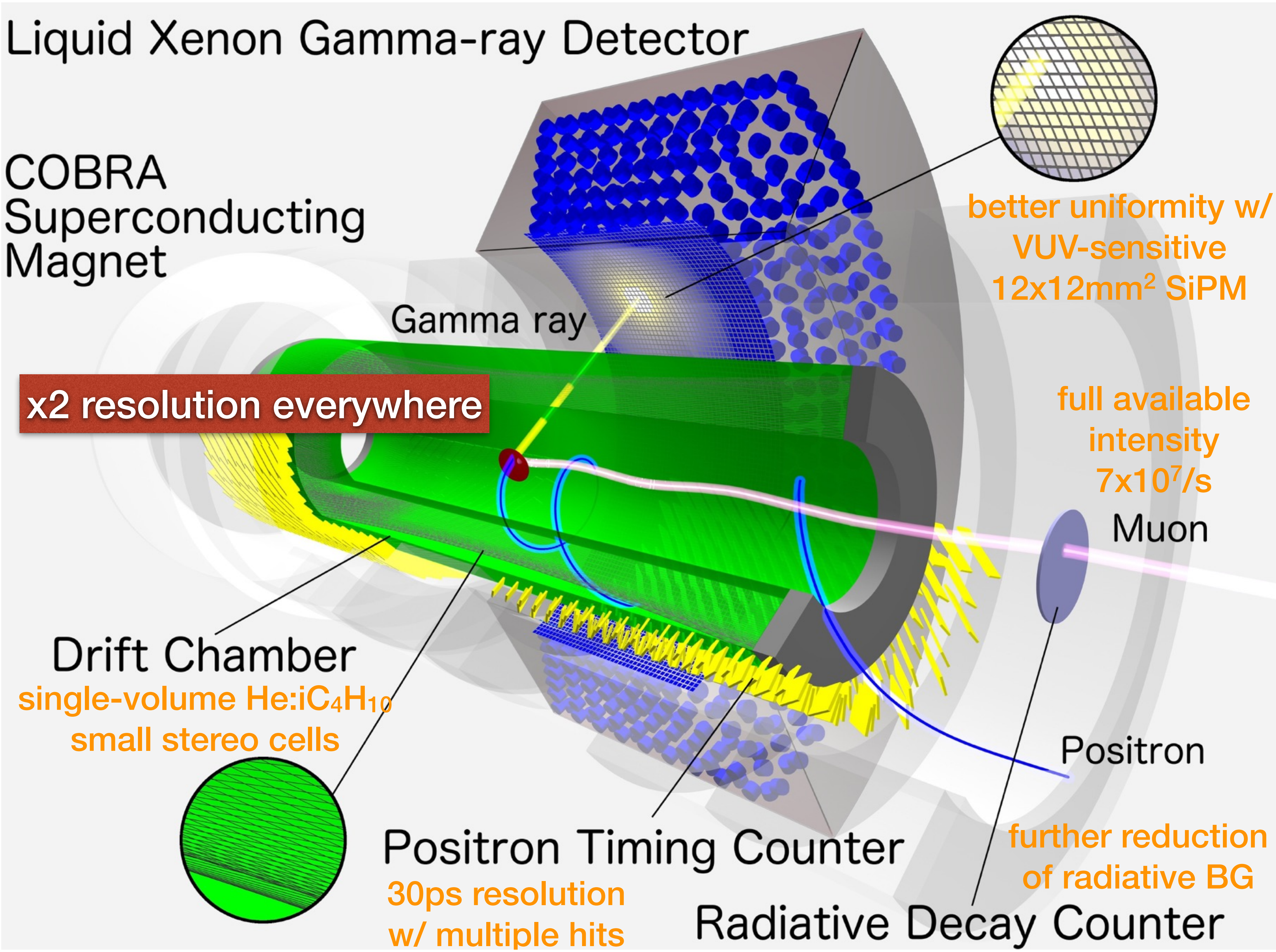
Current upper limit	Future sensitivity
BR ($\mu^+ \rightarrow e^+ \gamma$) < 5.7×10^{-13} (MEG)	SES ($\mu^+ \rightarrow e^+ \gamma$) ~ 5×10^{-14} (MEGII)
BR ($\mu^+ \rightarrow e^+ e^+ e^-$) < 1.0×10^{-12} (SINDRUM)	SES ($\mu^+ \rightarrow e^+ e^+ e^-$) ~ 10^{-15} (Mu3e Phase I) SES ($\mu^+ \rightarrow e^+ e^+ e^-$) ~ 10^{-16} (Mu3e Phase II)

- Potential of probing mass scales of new physics of 1000 TeV

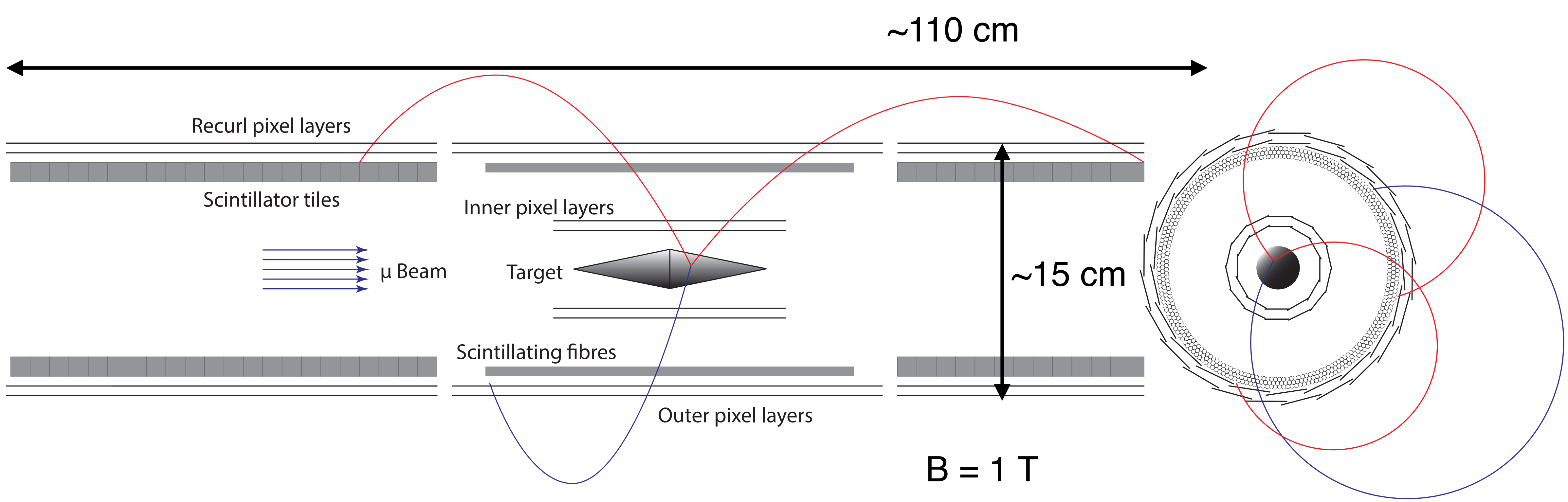
- Future sensitivity needs high intensity
- For Mu3e Phase II need 10^9 μ^+/s → currently not available!

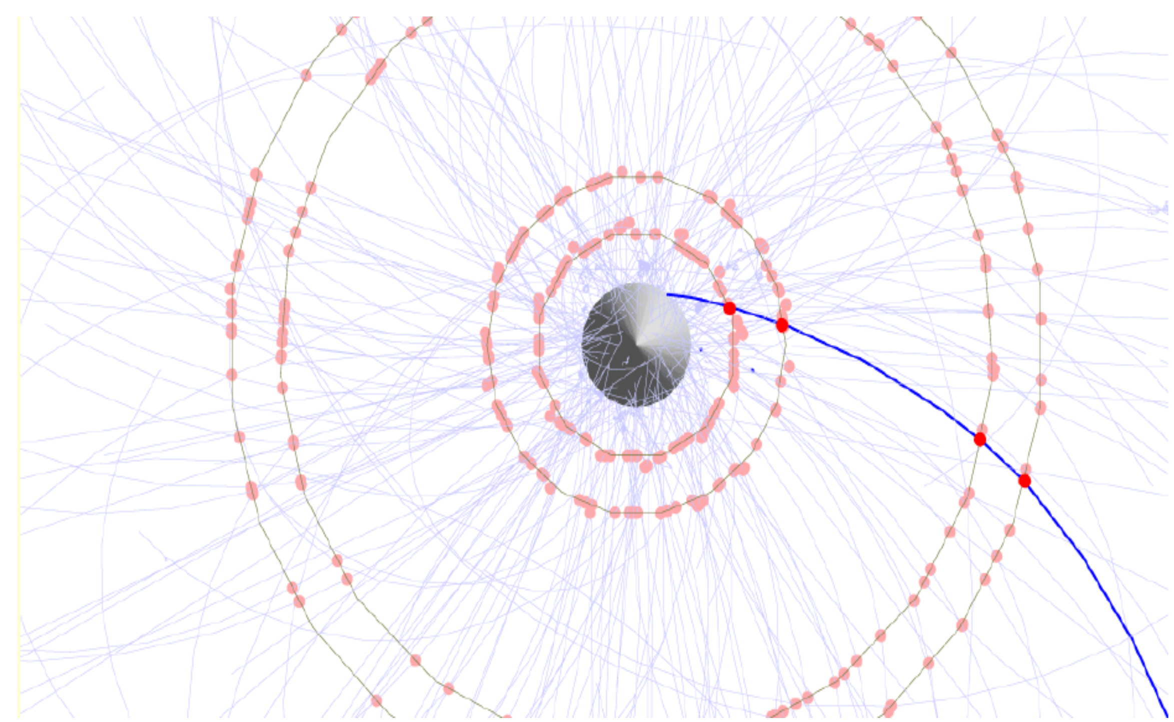
Adam et al., PRL **110**, 201801 (2013)
Bellgardt et al., Nucl. Phys. **B299**, 1 (1988)

MEG II Detector



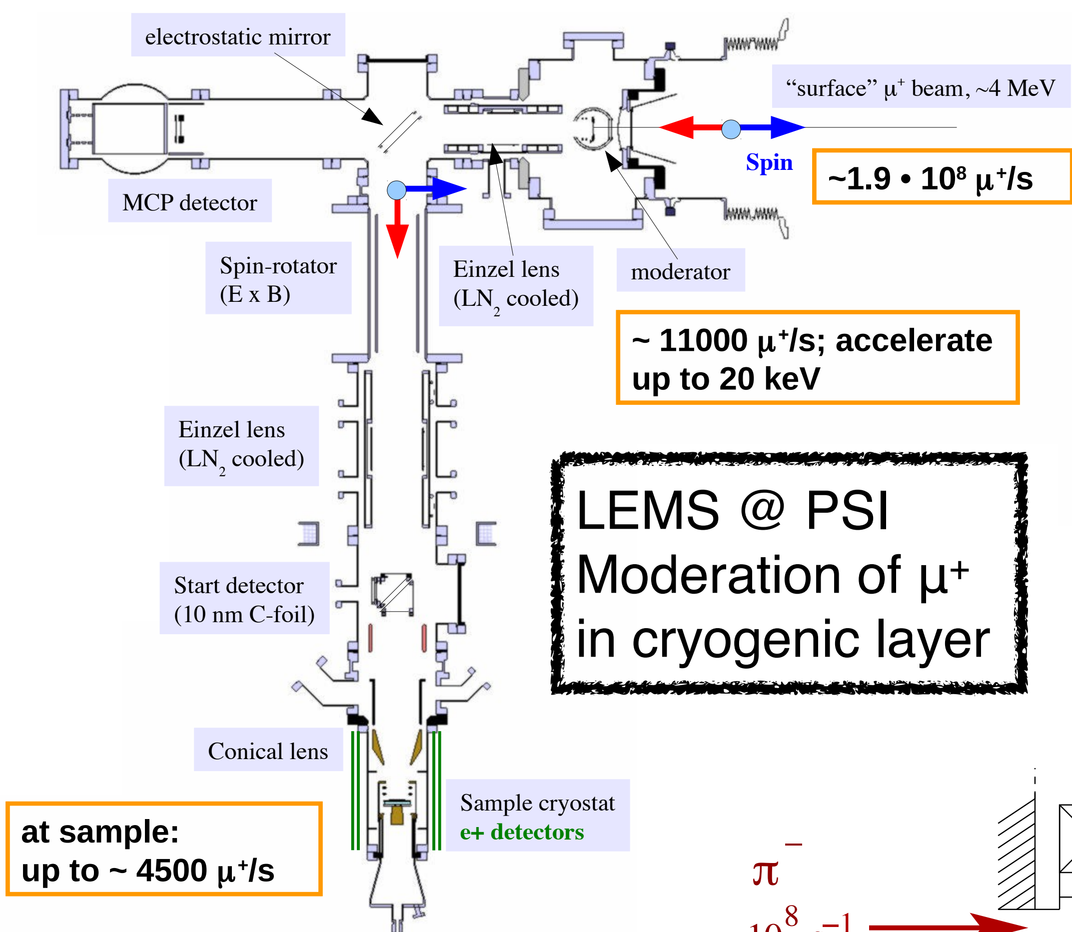
Mu3e Detector





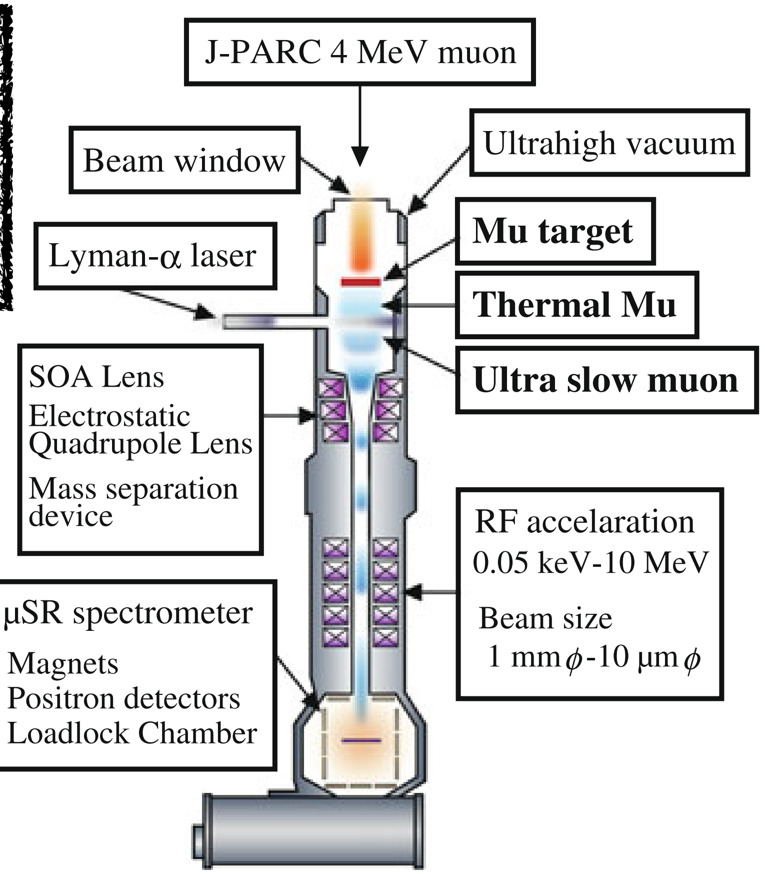
- Timing is key at ~10^9 μ^+/s
- Challenge to bring 10^9 μ^+/s on 20 mm target for Phase II

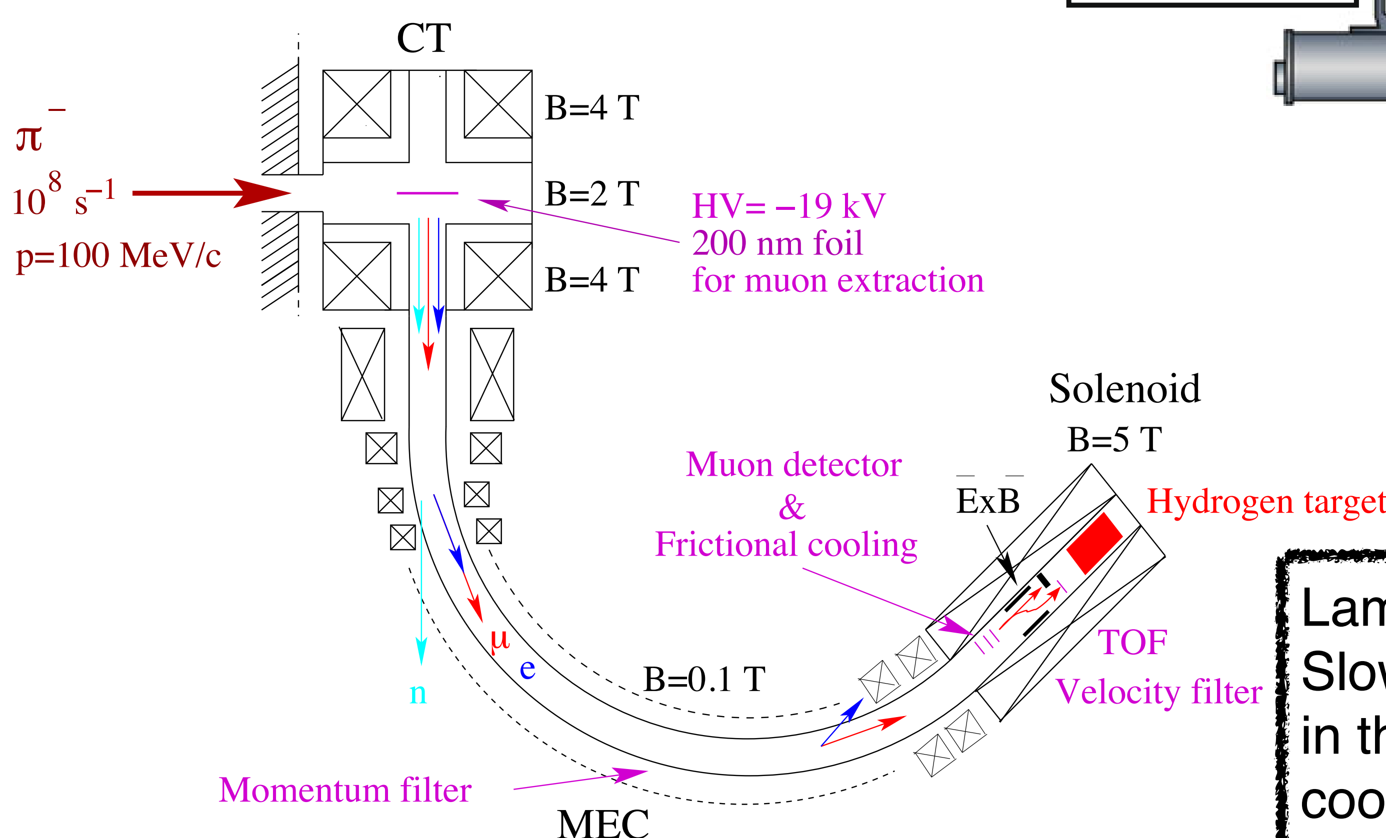
Ultralow-Energy Muons: Beam Lines



LEMS @ PSI
Moderation of μ⁺ in cryogenic layer

Ultraslow muons @ J-Parc
Laser ionization of muonium

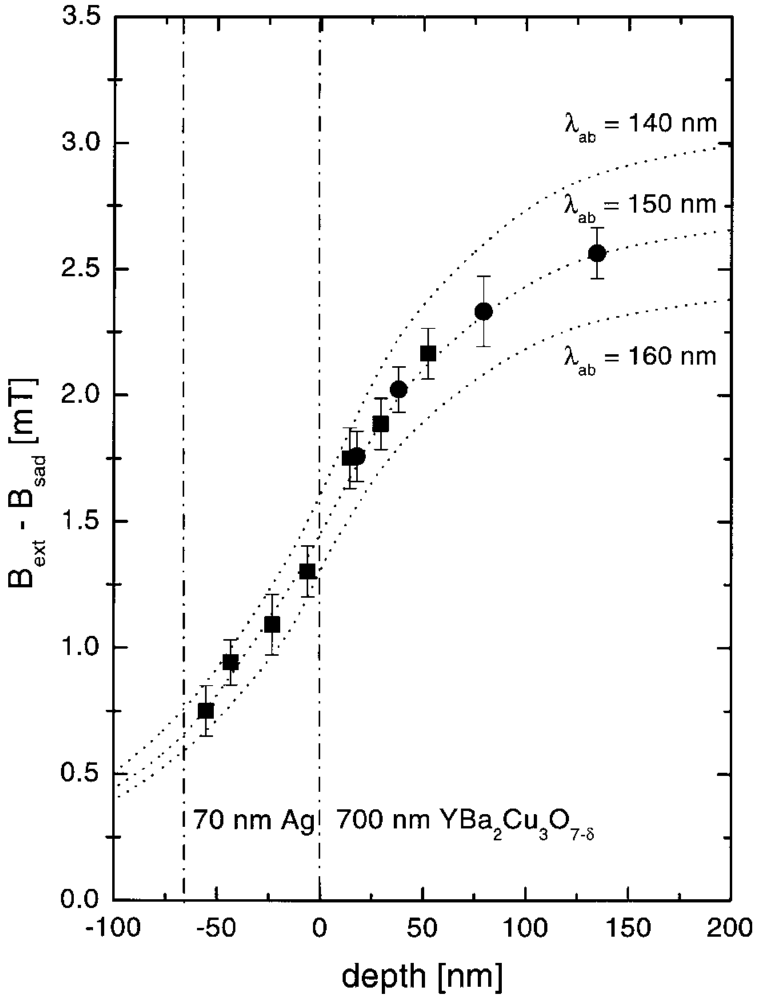




Lambshift @ PSI
Slowing down of π/μ⁻ in thin foil + frictional cooling

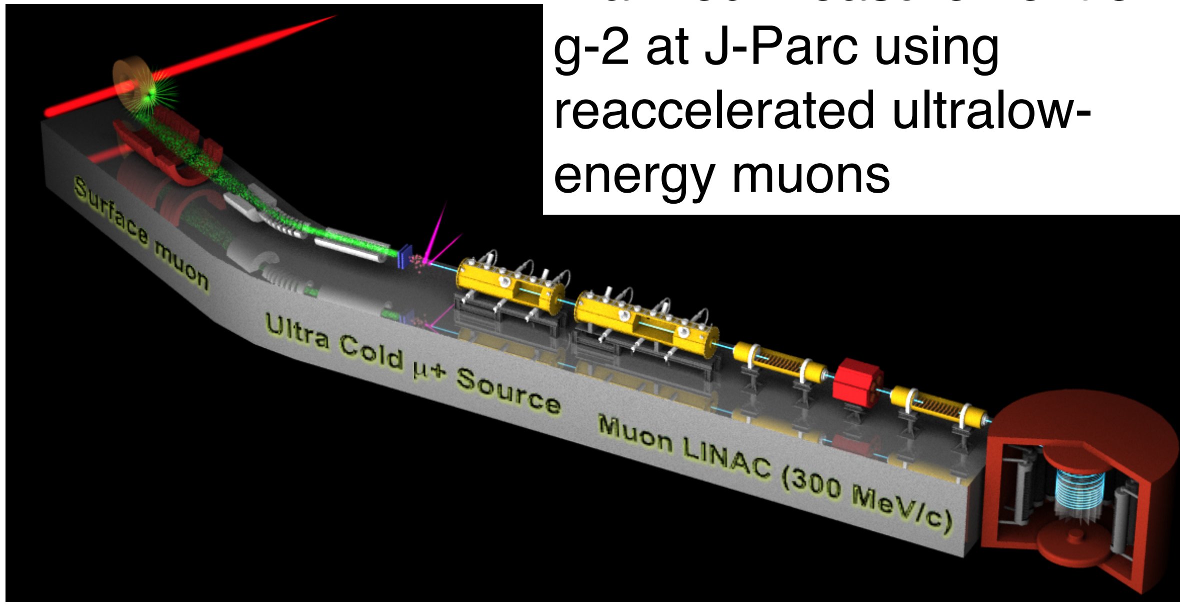
- All ultralow-energy muon beam lines extremely limited by intensity of incoming particles

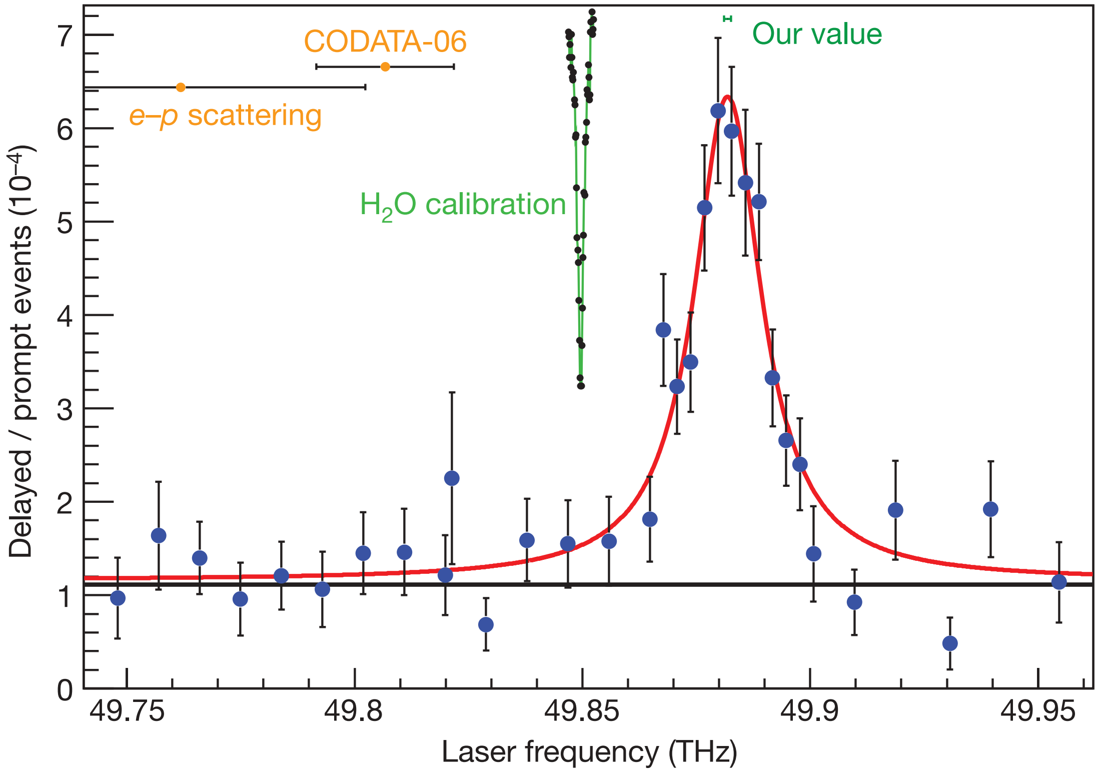
Ultralow-Energy Muons: Applications



Study of the penetration of magnetic fields into high-Tc superconductor

Planned measurement of g-2 at J-Parc using reaccelerated ultralow-energy muons

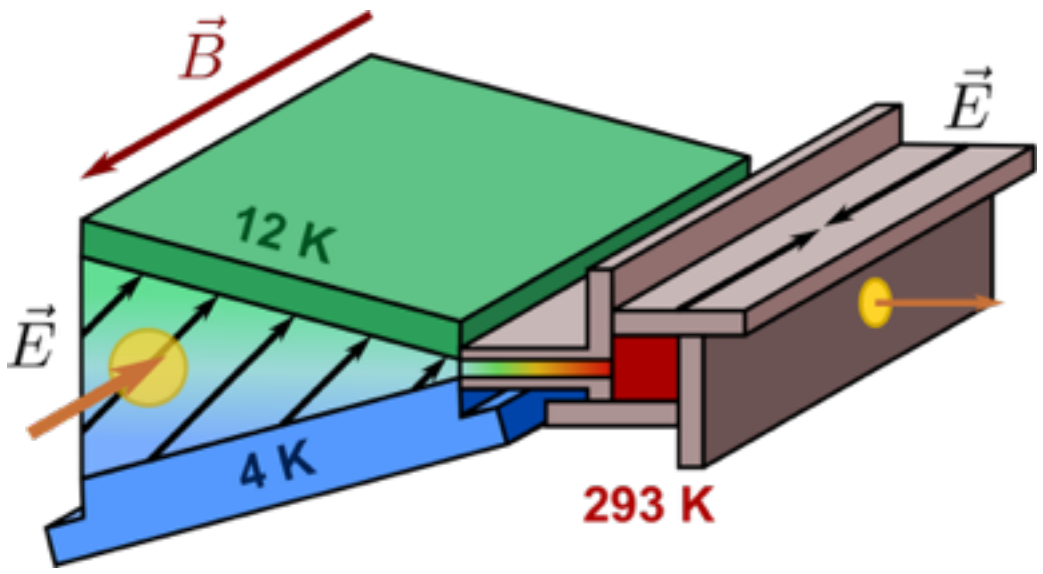




Spectroscopy of muonic hydrogen to determine proton radius
→ proton radius puzzle

Niedermayer et al., PRL **83**, 3932 (1999)
Pohl et al., Nature **466**, 213 (2010)

R&D Projects: muCool and HiMB



muCool:

- Development of high-brightness ultralow-energy beam by stopping and compression of surface muon beam
- Reduction of phase space by factor 10^{10}

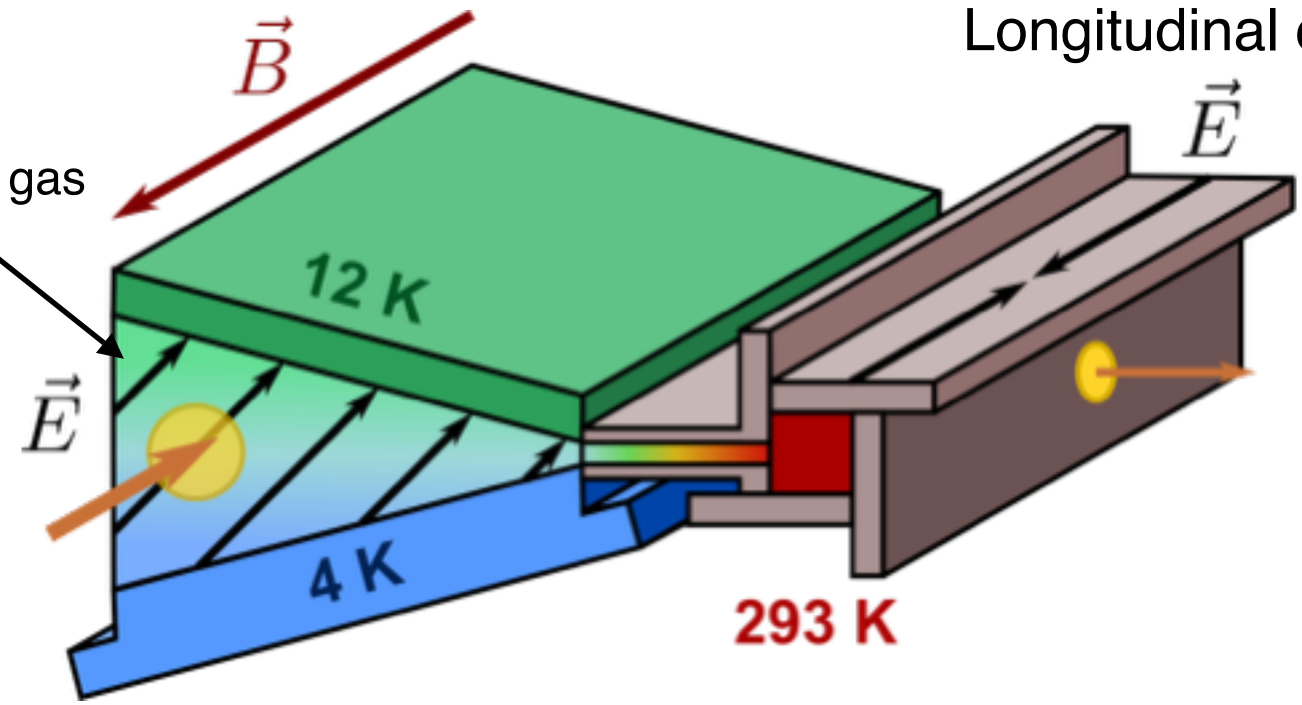
HiMB:

- Development of high-intensity beam by modification of existing target (TgM) and beam lines
- Goal of 10^{10} surface-μ^+/s

muCool Project

Transverse compression

Longitudinal compression



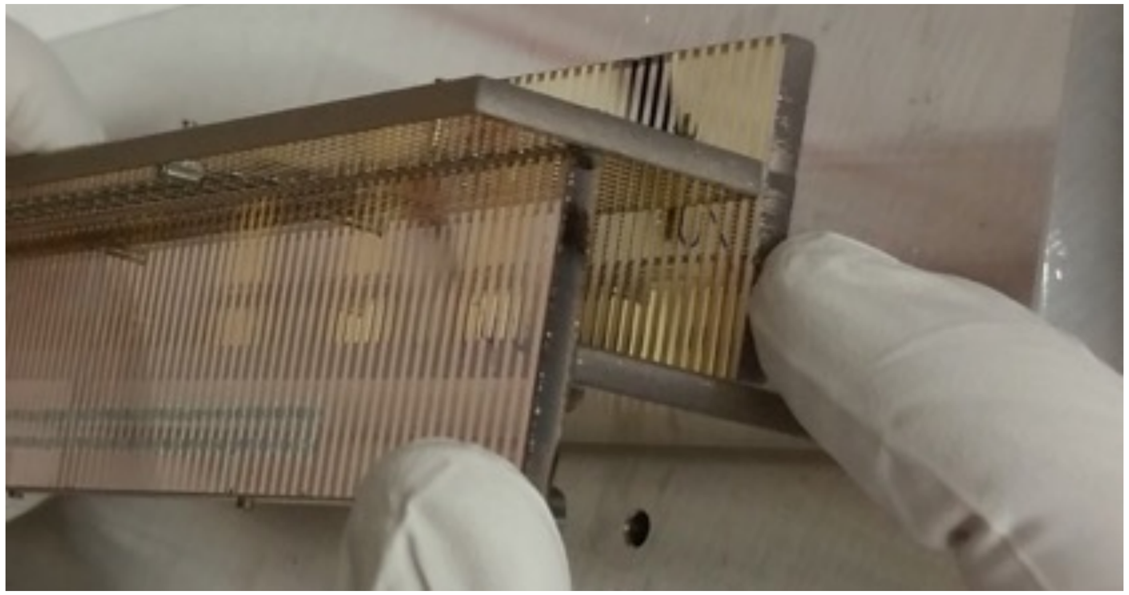
Secondary μ⁺ beam
D ≈ 10 mm
E ≈ 4 MeV
continuous
polarized

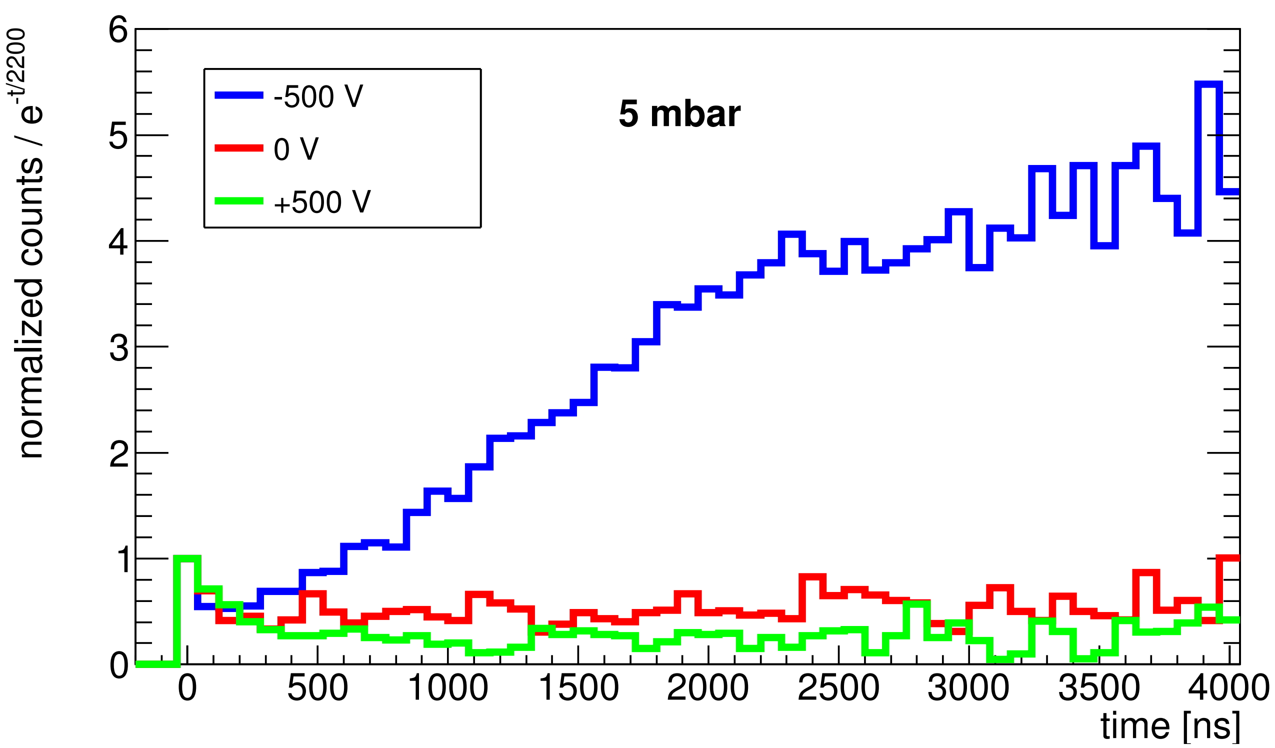
Tertiary μ⁺ beam
D < 1 mm
E < 1 eV
pulsed, tagged
polarized

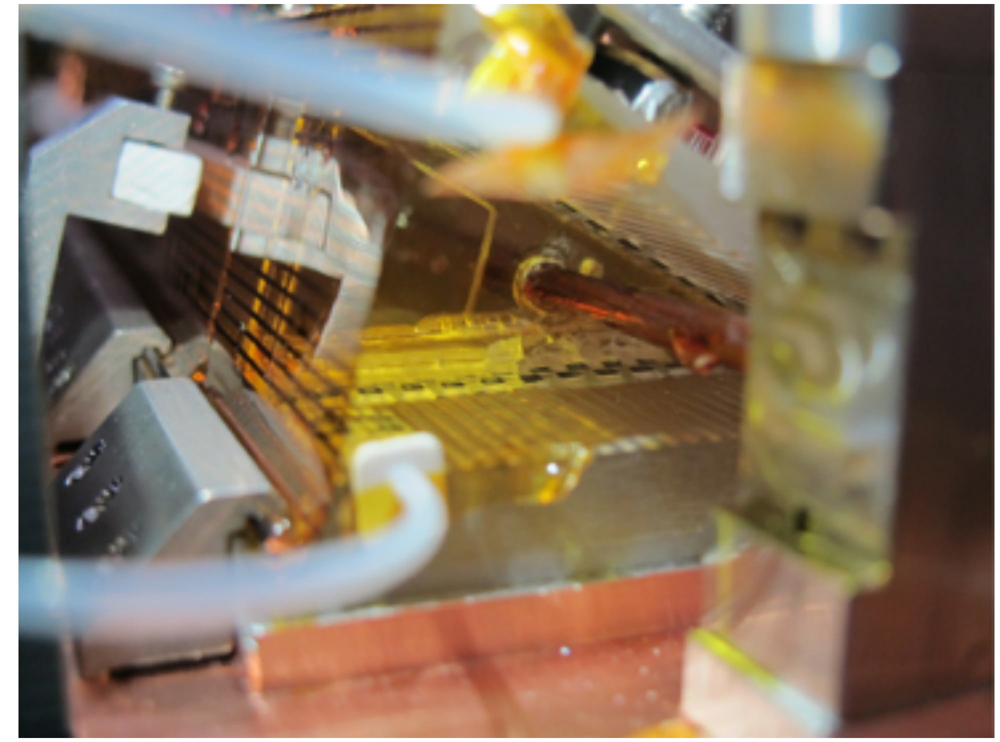
Muon swarm compression inside a helium gas target employing position-dependent muon drift velocity followed by extraction into vacuum.

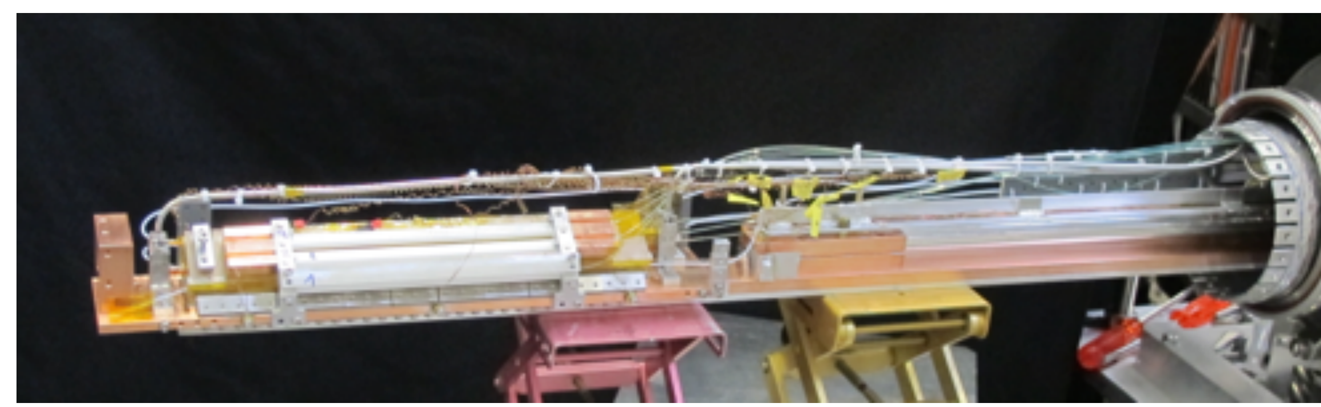
D. Taqqu, Phys. Rev. Lett. **97**, 194801 (2006)

muCool Results









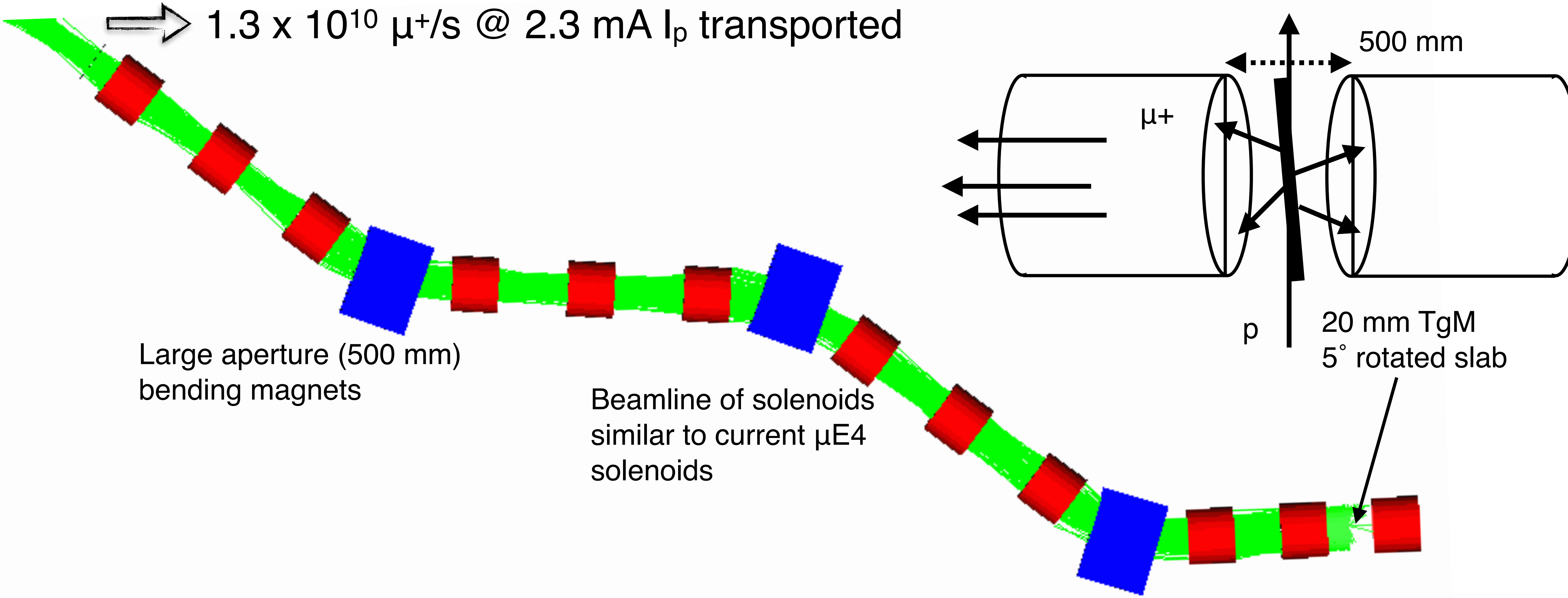
- Longitudinal compression demonstrated experimentally

Bao et al., Phys. Rev. Lett. **112**, 224801 (2014)

- First results from transverse compression expected this year

HiMB Project

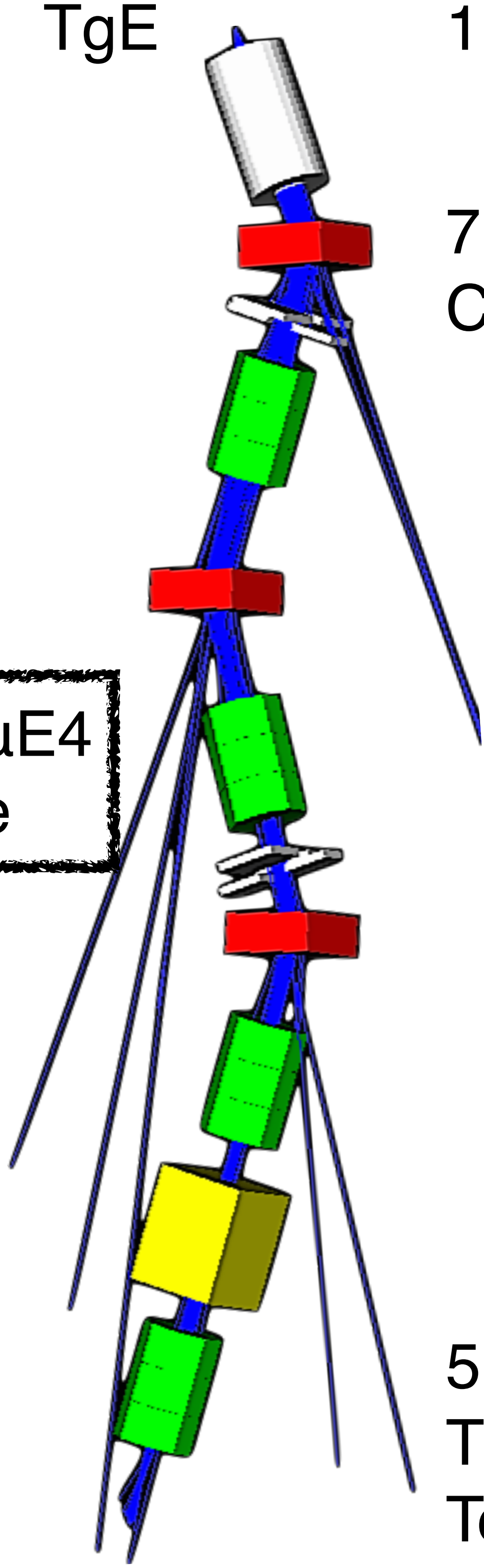
$\Rightarrow$ 1.3 x 10^{10} μ^+/s @ 2.3 mA I_p transported



- First version of beam optics showing that large number of muons can be captured and transported.
- Almost parallel beam, no focus, no separator, …
- Final beam optics under development

HiMB Project

TgE

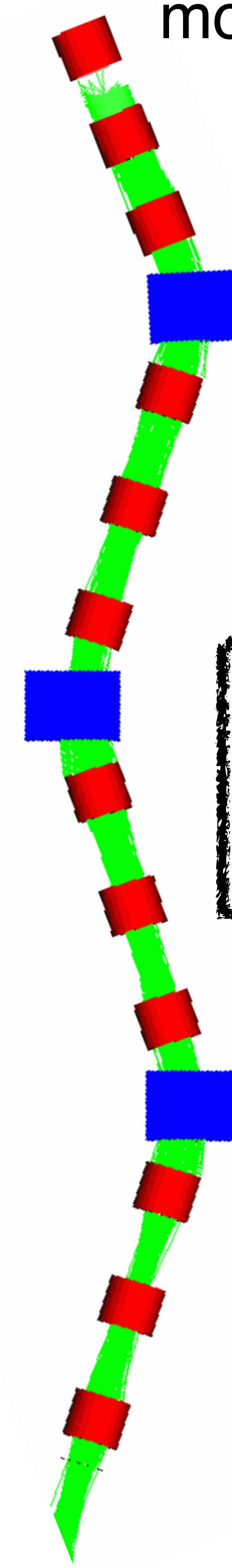


Existing μE4 beam line

TgE		modified TgM
1.2×10^{11} μ+/s	Source	1.3×10^{11} μ+/s
7.2×10^{9} μ+/s C ~ 6%	Capture	3.4×10^{10} μ+/s C ~ 26%
5×10^{8} μ+/s T ~ 7% Total ~ 0.4%	Transmission	1.3×10^{10} μ+/s T ~ 40% Total ~ 10%

⇨ Gain due to high capture and transmission efficiency

modified TgM



Proposed solenoid beam line

Conclusions

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- Large variety of experiments at existing low-energy muon beam lines from material science to particle physics
- cLFV experiments and ultralow-energy muon beams in need of higher beam intensities
- Synergies between low-energy and muon collider concepts:
  - High-power accelerators
  - Targets for muon generation
  - Capture solenoid technology
  - Muon cooling R&D
  - Concept for muon collider based on low-energy muon cooling developed 20 years ago → worth revisiting D. Taqqu, AIP Conf. Proc. **372,** 301 (1996)