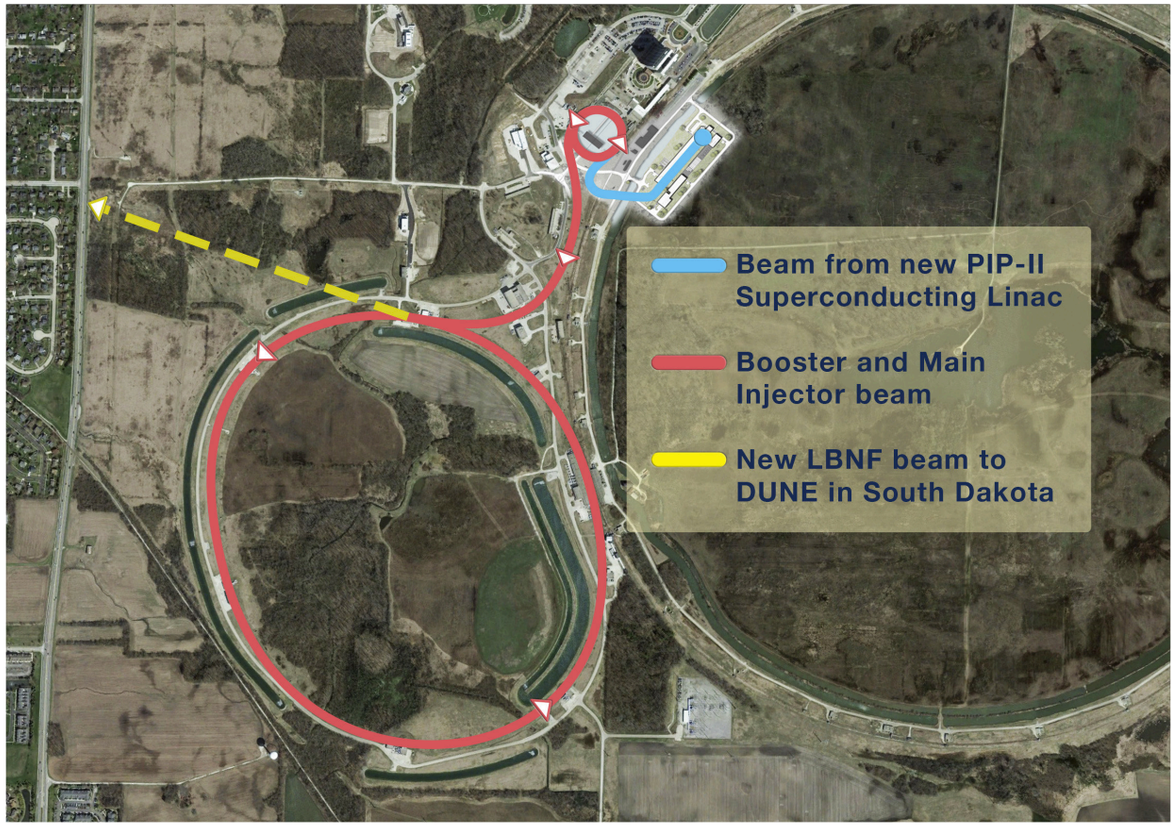


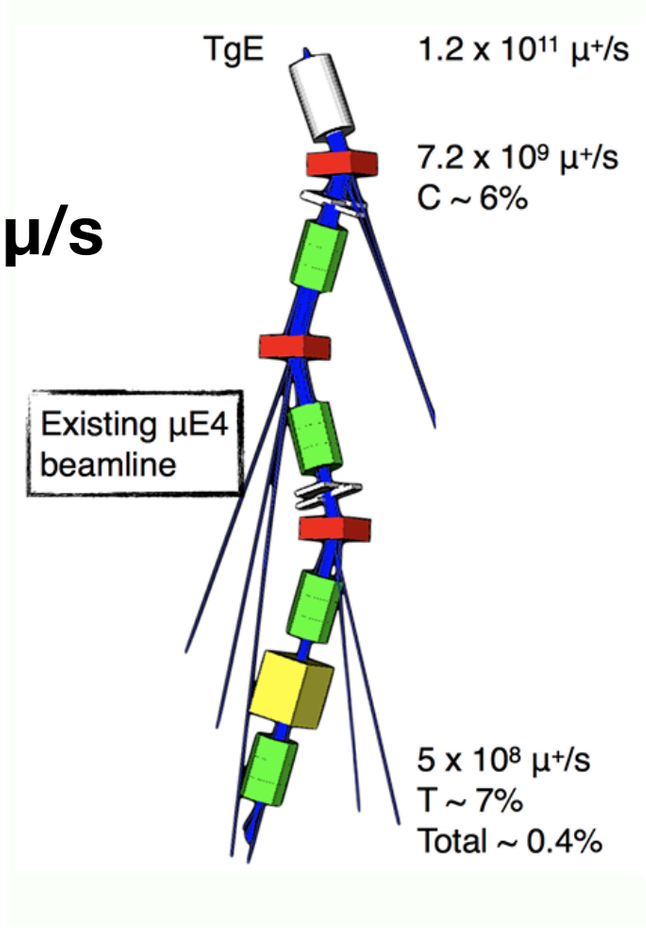
Perspective on cLFV with high-intensity muon beams at PSI and FNAL

Francesco Renga
INFN Roma

The most intense DC muon beam in the world

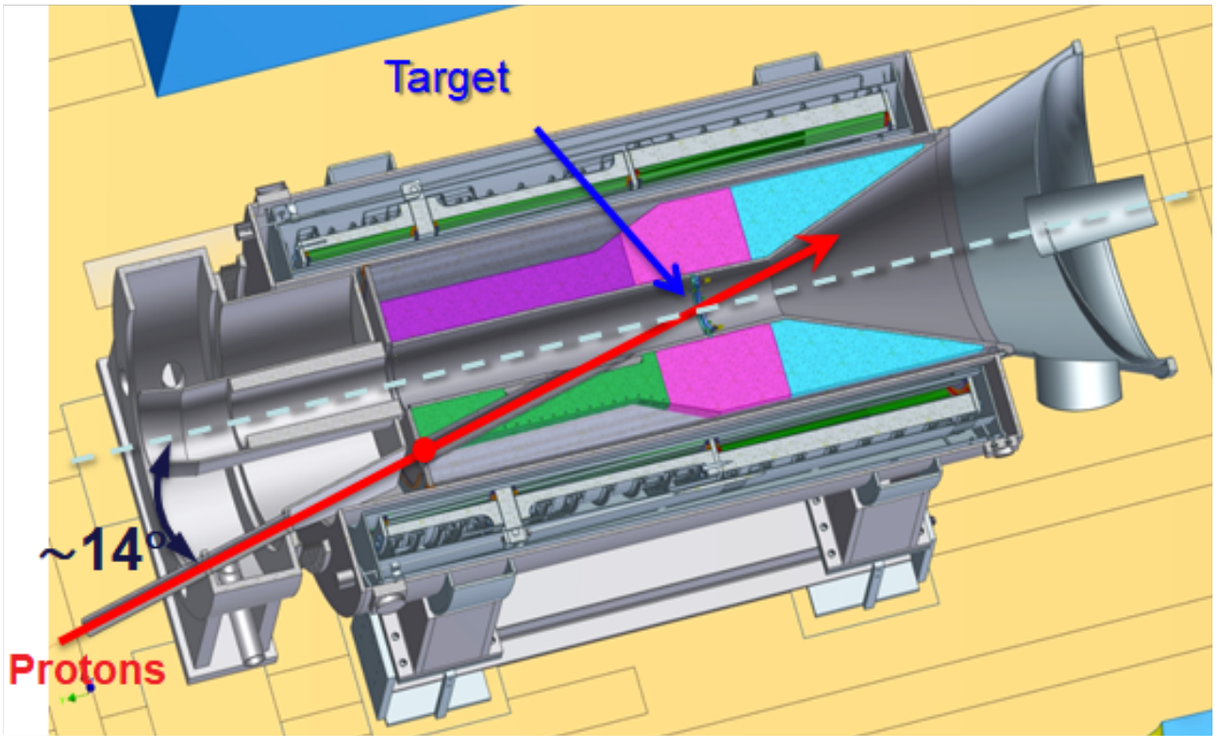
- The ring cyclotron at PSI (Villigen, CH) serves the most intense DC muon beam lines in the world

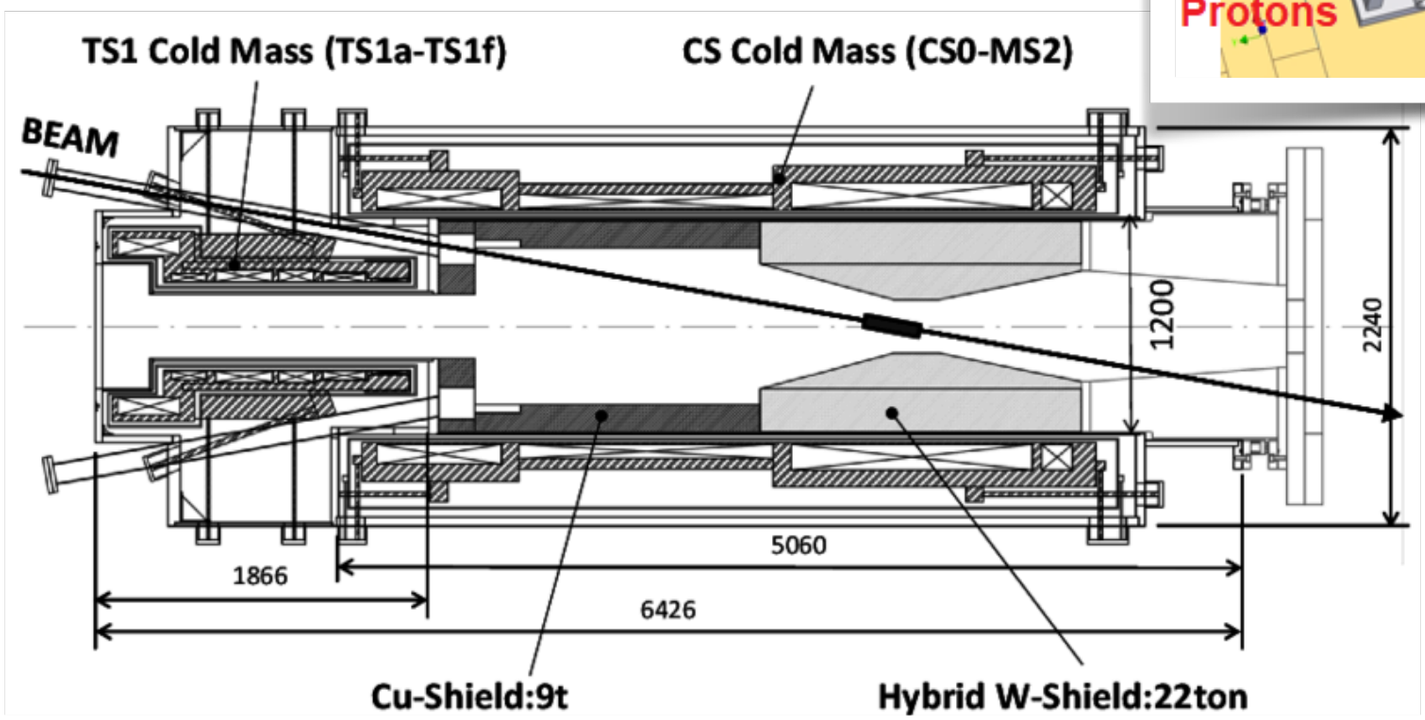
μE4
up to 5 x 10^8 μ/s



FNAL and J-PARC beams for μ-e conversion

- Dedicated target stations + capture solenoids for μ-e conversion experiments (mu2e & COMET)





~8 kW at the target

The HiMB Project @ PSI

- PSI is designing a high intensity muon beam line (HiMB) with a goal of ~ 10^{10} μ/sec (x200 the MEG-II beam, x25 the highest PSI intensity)

- Optimization of the beam optics:

  - improved muon capture efficiency at the production target

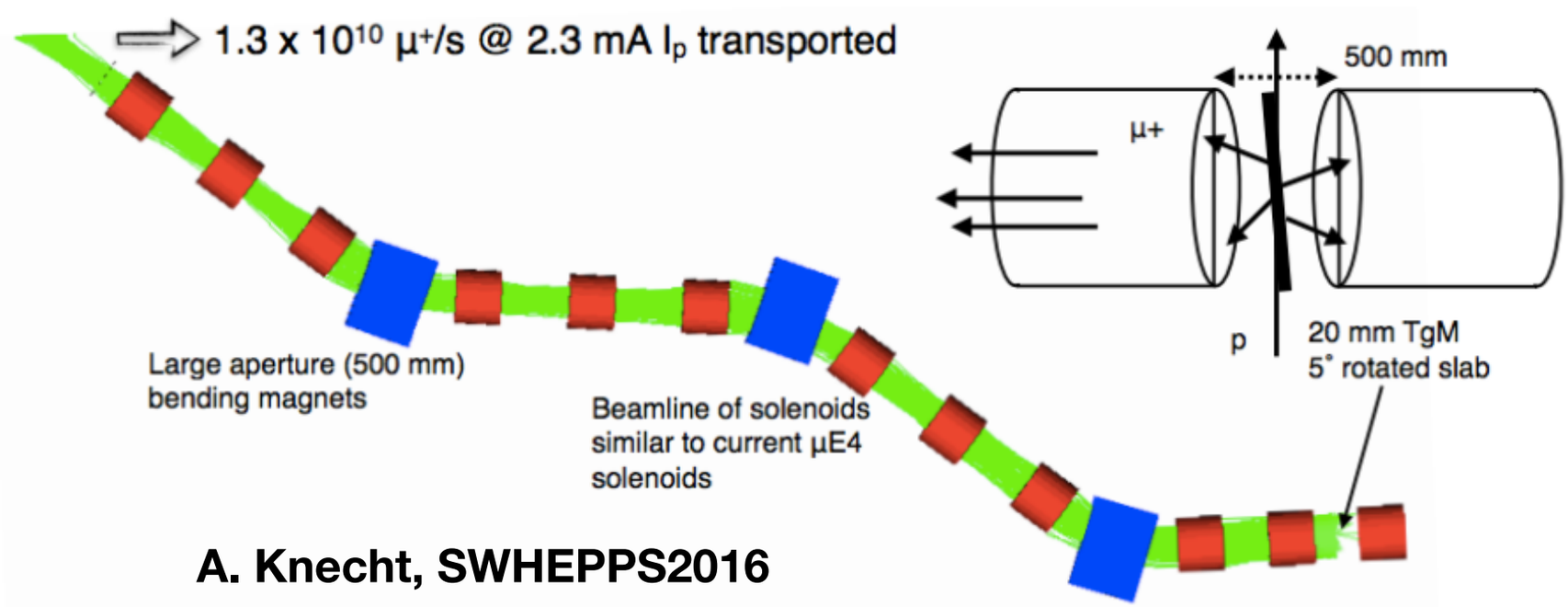
  - improved transport efficiency to the experimental area

x4 μ capture eff.

x6 μ transport eff.

1.3 x 10^{10} μ/s

in the experimental area with 1400 kW beam power



A. Knecht, SWHEPPS2016

The HiMB Project @ PSI

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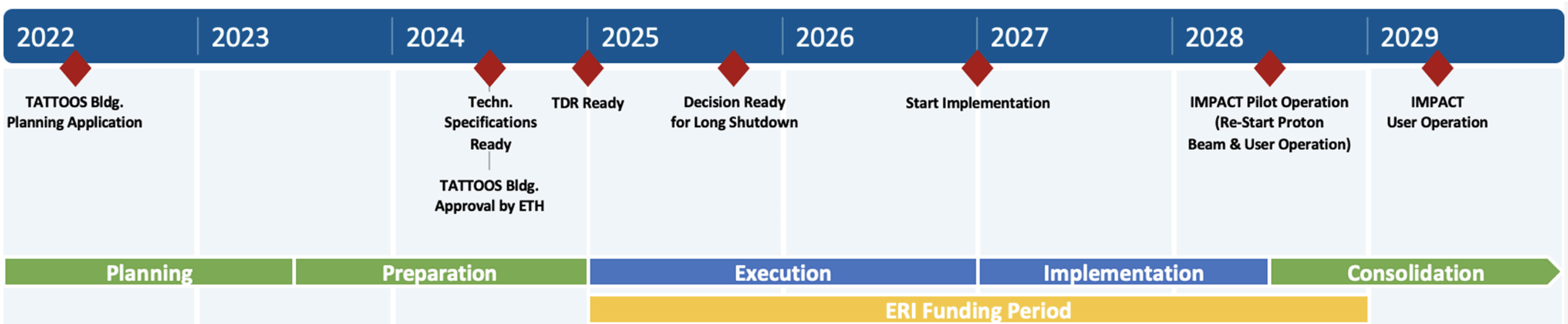
- Optimization of the beam optics:

  - improved muon capture efficiency at the production target

  - improved transport efficiency to the experimental area

Part of a larger project including also tumor therapy with alpha's (TATTOOS)

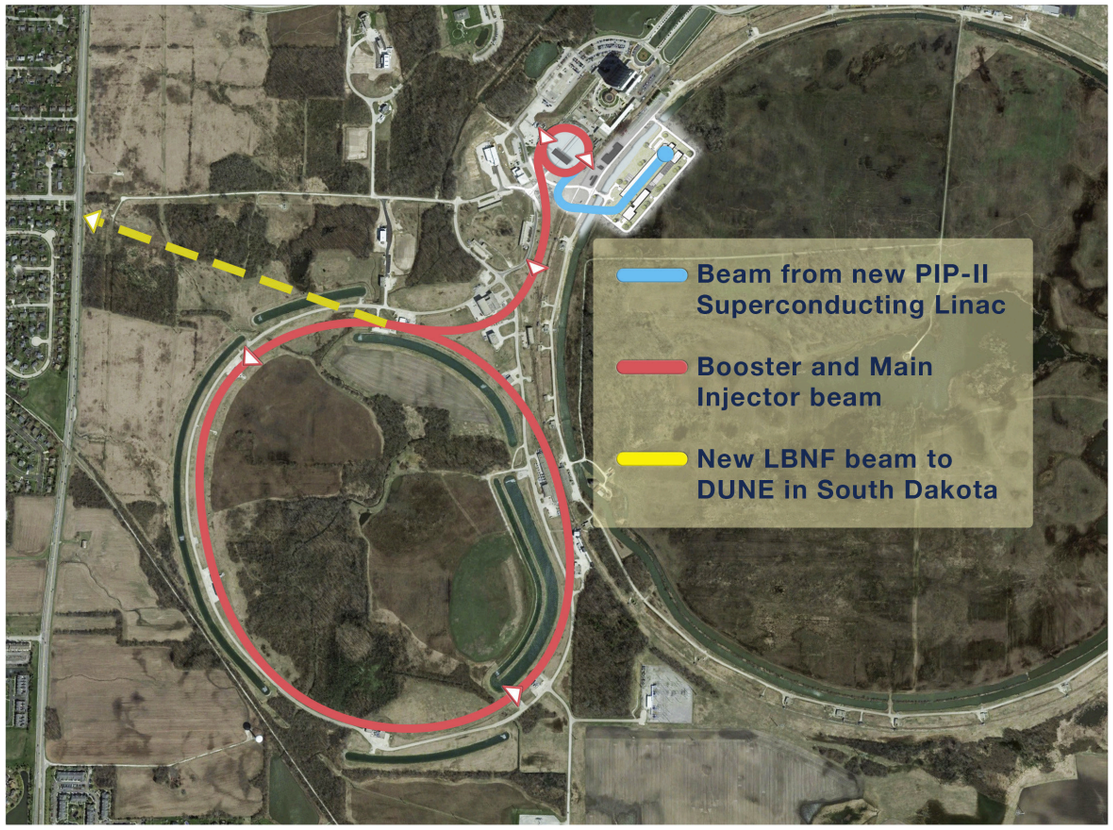


Muons @ FNAL with PIP-II

- The PIP-II complex will serve the Long Baseline Neutrino Factory (LBNF), but it will take only 1% of the power

- ~1.6 MW of beam power available for other physics projects

  - what about muons?



HiMB Physics Case

Science Case for the new High-Intensity Muon Beams HIMB at PSI

Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

M. Aiba[1], A. Amato[1], A. Antognini[1,2], S. Ban[3], N. Berger[4], L. Caminada[1,5], R. Chislett[6], P. Crivelli[2], A. Crivellin[1,5], G. Dal Maso[1,2], S. Davidson[7], M. Hoferichter[8], R. Iwai[2], T. Iwamoto[3], K. Kirch[1,2], A. Knecht[1], U. Langenegger[1], A. M. Lombardi[9], H. Luetkens[1], F. Meier Aeschbacher[1], T. Mori[3], J. Nuber[1,2], W. Ootani[3], A. Papa[1,10], T. Prokscha[1], F. Renga[11], S. Ritt[1], M. Sakurai[2], Z. Salman[1], P. Schmidt-Wellenburg[1], A. Schöning[12], A. Signer[1,5,*], A. Soter[2], L. Stingelin[1], Y. Uchiyama[3], and F. Wauters[4]

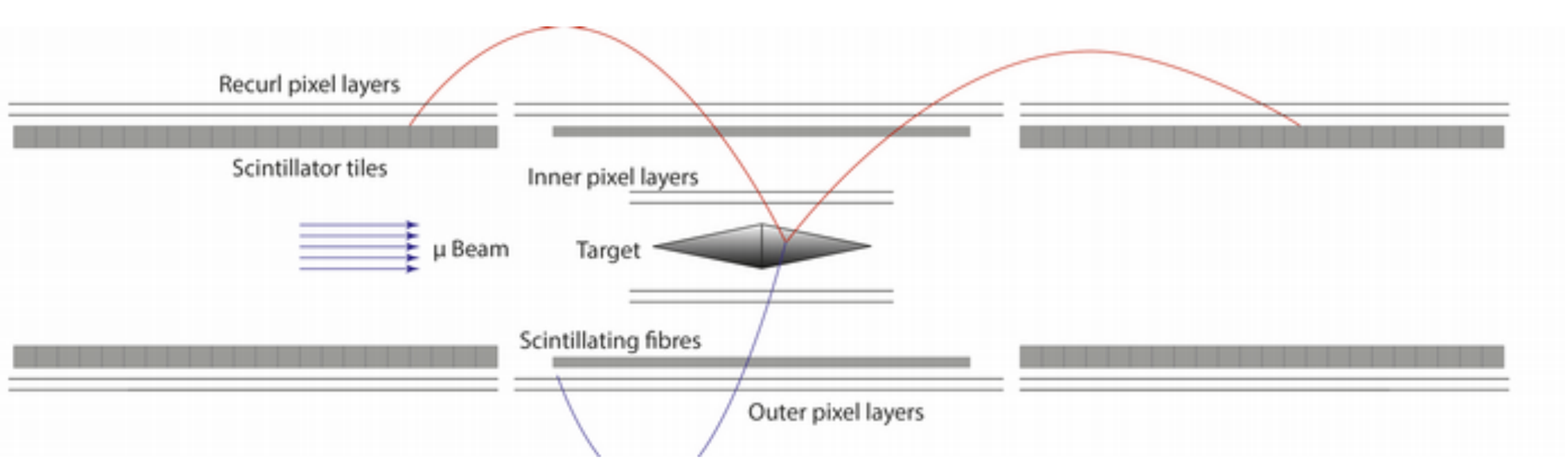
A report about physics perspectives for high-intensity muon beam lines at PSI

arXiv:2111.05788

Particle physics (cLFV, μEDM, muonium…) and material science (μSR)

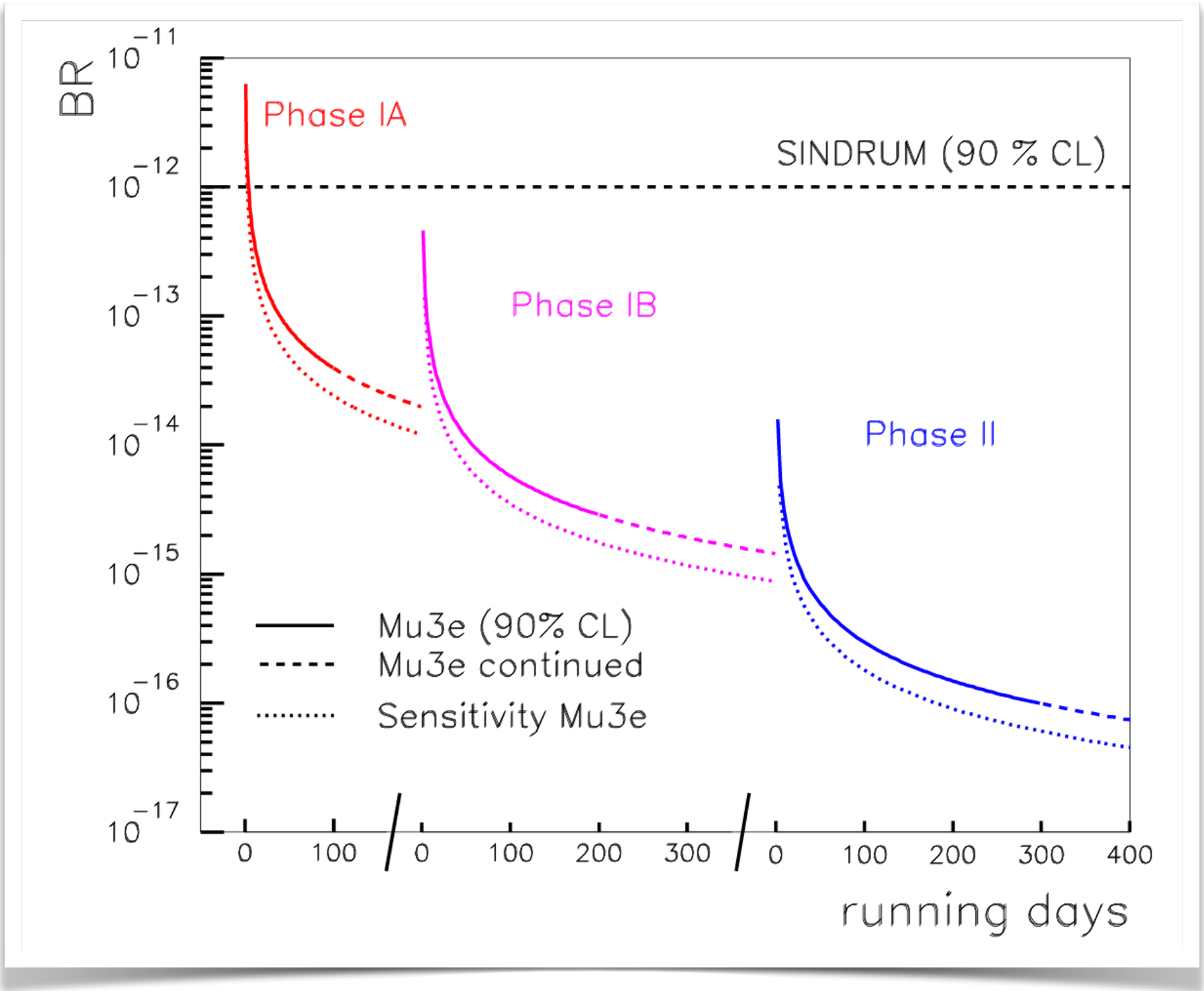
Mu3e @ PSI

- $\mu^+ \rightarrow e^+ e^+ e^-$ with a detector based on silicon pixels (50 μm thick HV-MAPS) and scintillators for timing
- Phase-I Mu3e experiment expected to run before the PSI shutdown, foreseen in 2026-2028



- Detector already designed to cope with intensities up to 10^{10} μ/s
  - Phase-II (with additional detector stations for improved performances) expected to be the first particle-physics experiment at HiMB

Mu3e @ PSI


BR
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Phase IA
SINDRUM (90 % CL)
Phase IB
Phase II
Mu3e (90% CL)
Mu3e continued
Sensitivity Mu3e
0
100
0
100
200
300
0
100
200
300
400
running days

Snowmass contributions

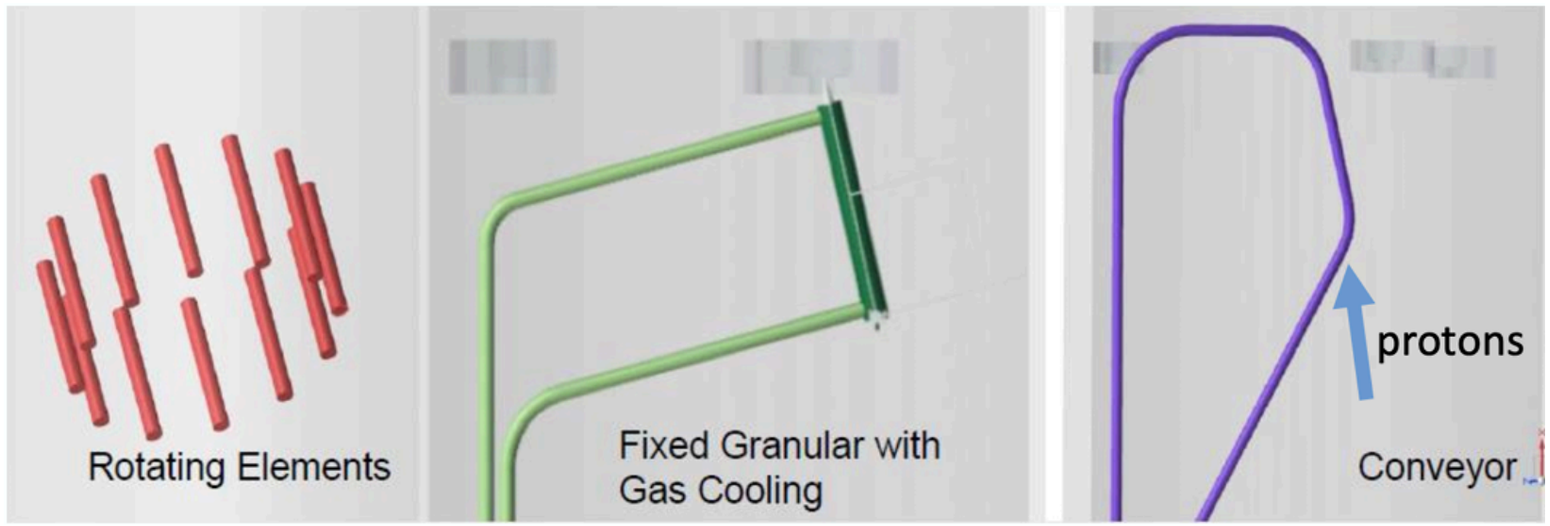
Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass

K. Byrum,[1] S. Corrodi,[1] Y. Oksuzian,[1] P. Winter,[1] L. Xia,[1] A. W. J. Edmonds,[2] J. P. Miller,[2] J. Mott,[3] W. J. Marciano,[4] R. Szafron,[4] R. Bonventre[b],[5] D. N. Brown[b],[5] Yu. G. Kolomensky[ab],[5] O. Ning[a],[5] V. Singh[a],[5] E. Prebys,[6] L. Borrel,[7] B. Echenard,[7] D. G. Hitlin,[7] C. Hu,[7] D. X. Lin,[7] S. Middleton,[7] F. C. Porter,[7] L. Zhang,[7] R.-Y. Zhu,[7] D. Ambrose,[8] K. Badgley,[8] R. H. Bernstein,[8] S. Boi,[8] B. C. K. Casey,[8] R. Culbertson,[8] A. Gaponenko,[8] H. D. Glass,[8] D. Glenzinski,[8] L. Goodenough,[8] A. Hocker,[8] M. Kargiantoulakis,[8] V. Kashikhin,[8] B. Kiburg,[8] R. K. Kutschke,[8] P. A. Murat,[8] D. Neuffer,[8] V. S. Pronskikh,[8] D. Pushka,[8] G. Rakness,[8] T. Strauss,[8] M. Yucel,[8] C. Bloise,[9] E. Diociaiuti,[9] S. Giovannella,[9] F. Happacher,[9] S. Miscetti,[9] I. Sarra,[9] M. Martini,[10] A. Ferrari,[11] S. E. Müller,[11] R. Rachamin,[11] E. Barlas-Yucel,[12] A. Artikov,[13] N. Atanov,[13] Yu. I. Davydov,[13] v. Glagolev,[13] I. I. Vasilyev,[13] D. N. Brown,[14] Y. Uesaka,[15] S. P. Denisov,[16] V. Evdokimov,[16] A. V. Kozelov,[16] A. V. Popov,[16] I. A. Vasilyev,[16] G. Tassielli,[17] T. Teubner,[18] R. T. Chislett,[19] G. G. Hesketh,[19] M. Lancaster,[20] M. Campbell,[21] K. Ciampa,[22] K. Heller,[22] B. Messerly,[22] M. A. C. Cummings,[23] L. Calibbi,[24] G. C. Blazey,[25] M. J. Syphers,[25] V. Zutshi,[25] C. Kampa,[26] M. MacKenzie,[26] S. Di Falco,[27] S. Donati,[27] A. Gioiosa,[27] V. Giusti,[27] L. Morescalchi,[27] D. Pasciuto,[27] E. Pedreschi,[27] F. Spinella,[27] M. T. Hedges,[28] M. Jones,[28] Z. Y. You,[29] A. M. Zanetti,[30] E. V. Valetov,[31] E. C. Dukes,[32] R. Ehrlich,[32] R. C. Group,[32] J. Heeck,[32] P. Q. Hung,[32] S. M. Demers,[33] G. Pezzullo,[33] K. R. Lynch,[34] and J. L. Popp[34]

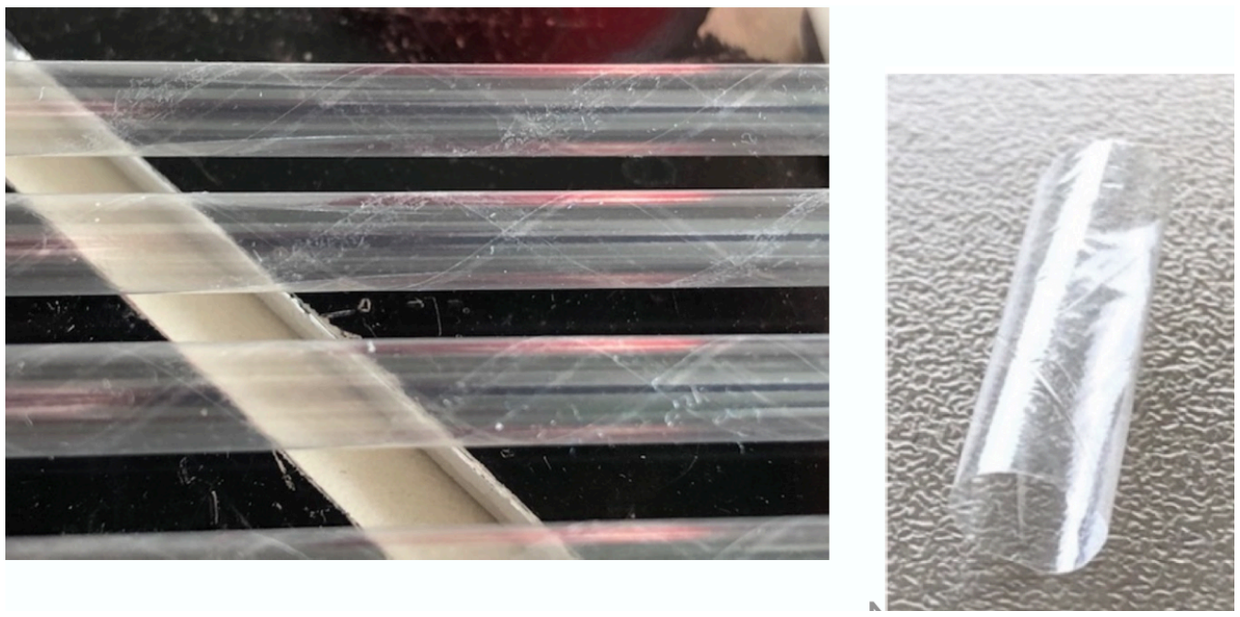
An upgrade of Mu2e, to cope with higher beam rates

The Mu2e-II project

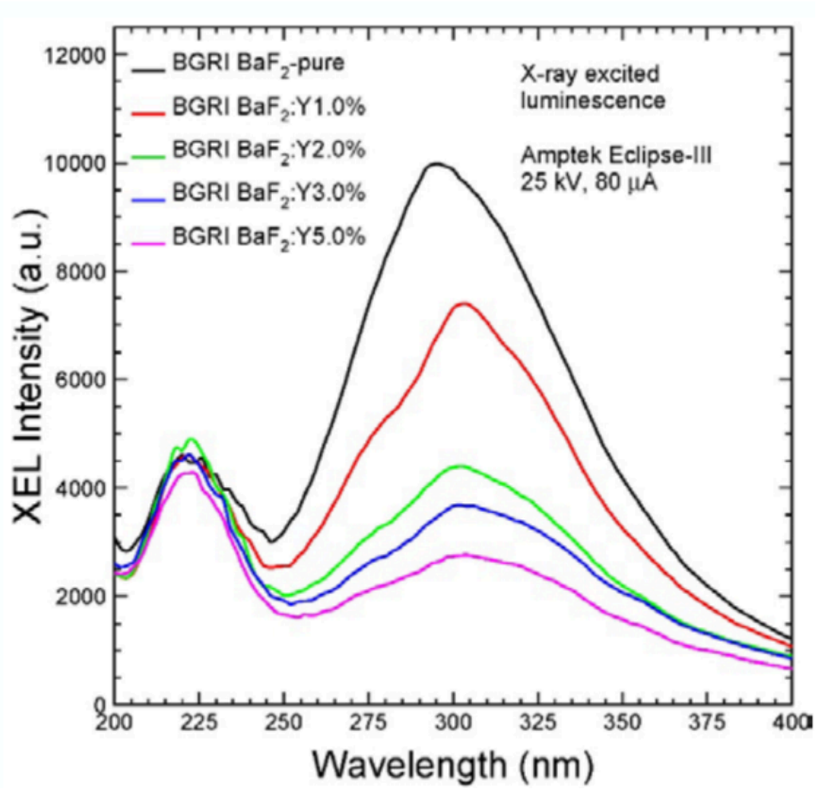
100 kW on target



A further step in thinning down straw tubes (3-8 μm)



New crystals for calorimetry



Snowmass contributions

Mu2e-II: Muon to electron conversion with PIP-II
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K. Byrum,[1] S. Corrodi,[1] Y. Oksuzian,[1] P. Winter,[1] L. Xia,[1] A. W. J. Edmonds,[2] J. P. Miller,[2] J. Mott,[3] W. J. Marciano,[4] R. Szafron,[4] R. Bonventre[b],[5] D. N. Brown[b],[5] Yu. G. Kolomensky[ab],[5] O. Ning[a],[5] V. Singh[a],[5] E. Prebys,[6] L. Borrel,[7] B. Echenard,[7] D. G. Hitlin,[7] C. Hu,[7] D. X. Lin,[7] S. Middleton,[7] F. C. Porter,[7] L. Zhang,[7] R.-Y. Zhu,[7] D. Ambrose,[8] K. Badgley,[8] R. H. Bernstein,[8] S. Boi,[8] B. C. K. Casey,[8] R. Culbertson,[8] A. Gaponenko,[8] L. Goodenough,[8] A. Hocker,[8] M. Kargiantoulakis,[8] V. Kashikh P. A. Murat,[8] D. Neuffer,[8] V. S. Pronskikh,[8] D. Pushka,[8] G. C. Bloise,[9] E. Diociaiuti,[9] S. Giovannella,[9] F. Happacher,[9] S. A. Ferrari,[11] S. E. Müller,[11] R. Rachamin,[11] E. Barlas-Yucel,[12] Davydov,[13] v. Glagolev,[13] I. I. Vasilyev,[13] D. N. Brown,[14] Y. Uesaka,[15] S. P. Denisov,[16] V. Evdokimov,[16] A. V. Kozelov R. T. Chislett,[19] G. G. Hesketl B. Messerly,[22] M. A. C. Cu Zutshi,[25] C. Kampa,[26] M. Mac L. Morescalchi,[27] D. Pasciuto Z. Y. You,[29] A. M. Zanetti,[30] J. Heeck,[32] P. Q. Hung,[32] S.

A new concept to boost the potential of cLFV searches

A New Charged Lepton Flavor Violation Program at Fermilab

M. Aoki,[1] R. B. Appleby,[2,3] M. Aslaninejad,[4] R. Barlow,[5] R.H. Bernstein,[6] C. Bloise,[7] L. Calibbi,[8] F. Cervelli,[9] R. Culbertson,[6] André Luiz de Gouvêa,[10] S. Di Falco,[9] E. Diociaiuti,[7] S. Donati,[9] R. Donghia,[7] B. Echenard,[11] A. Gaponenko,[6] S. Giovannella,[7] C. Group,[12] F. Happacher,[7] M. T. Hedges,[13] D.G. Hitlin,[11] E. Hungerford,[14] C. Johnstone,[6] D. M. Kaplan,[15] M. Kargiantoulakis,[6] D. J. Kelliher,[16] K. Kirch,[17] A. Knecht,[18] Y. Kuno,[1,19] A. Kurup,[20] J.-B. Lagrange,[16] M. Lancaster,[21] K. Long,[20] A. Luca,[6] K. Lynch,[22] S. Machida,[16] M. Martini,[23,*] S. Middleton,[11] S. Mihara,[24] J. Miller,[25] S. Miscetti,[7] L. Morescalchi,[9] Y. Mori,[26] P. Murat,[6] B. Muratori,[27,3] D. Neuffer,[6] A. Papa,[9] J. Pasternak,[20] E. Pedreschi,[9] G. Pezzullo,[28] T. Planche,[29] F. Porter,[11] E. Prebys,[30] C. R. Prior,[16] V. Pronskikh,[6] R. Ray,[6] F. Renga,[31] C. Rogers,[16] I. Sarra,[7] A. Sato,[1] S. L. Smith,[27,3] F. Spinella,[9] D. Stratakis,[6] M. Syphers,[32] N.M. Truong,[30] S. Tygier,[2,3] Y. Uchida,[20] and M. Yucel[6]

The Advanced Muon Facility (AMF)

- A new concept to
  - **maximally exploit the PIP-II power**
  - **permit a Mu2e run with high-Z nuclei**
  - **make possible rare muon decay searches at FNAL**

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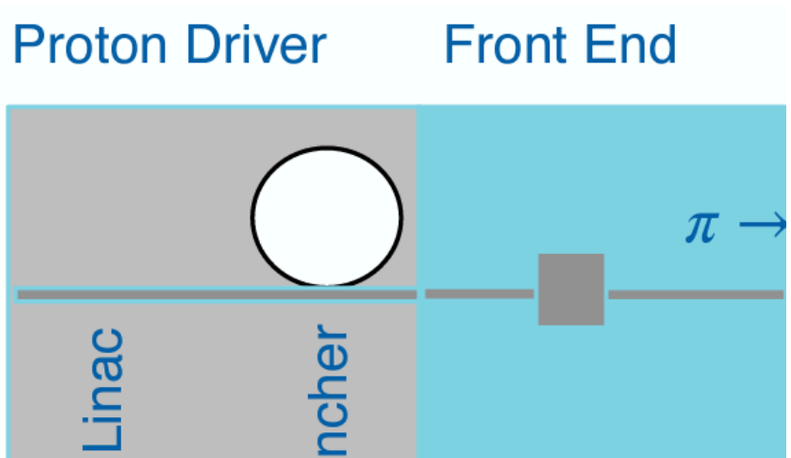
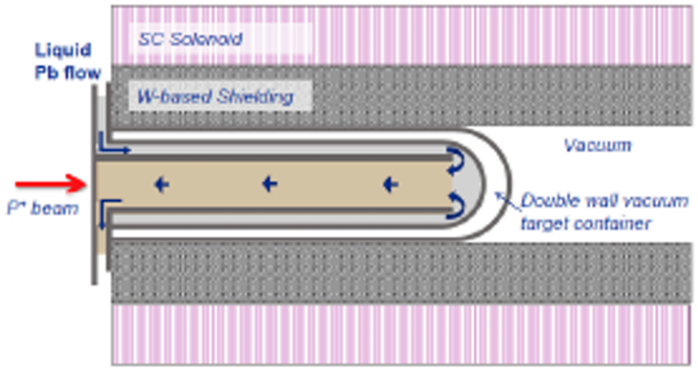
Proton Driver Front End



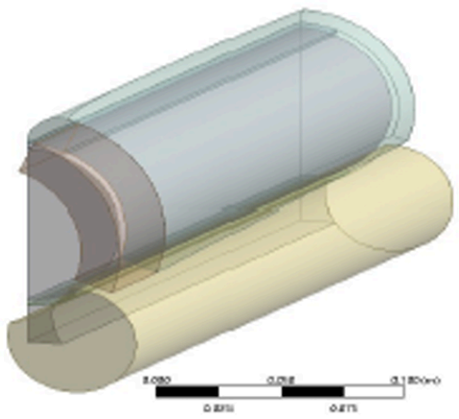
100kW-1MW target in a Capture Solenoid

100 kW - 1 MW target in a solenoid

Liquid Lead Flow



Lead Curtain



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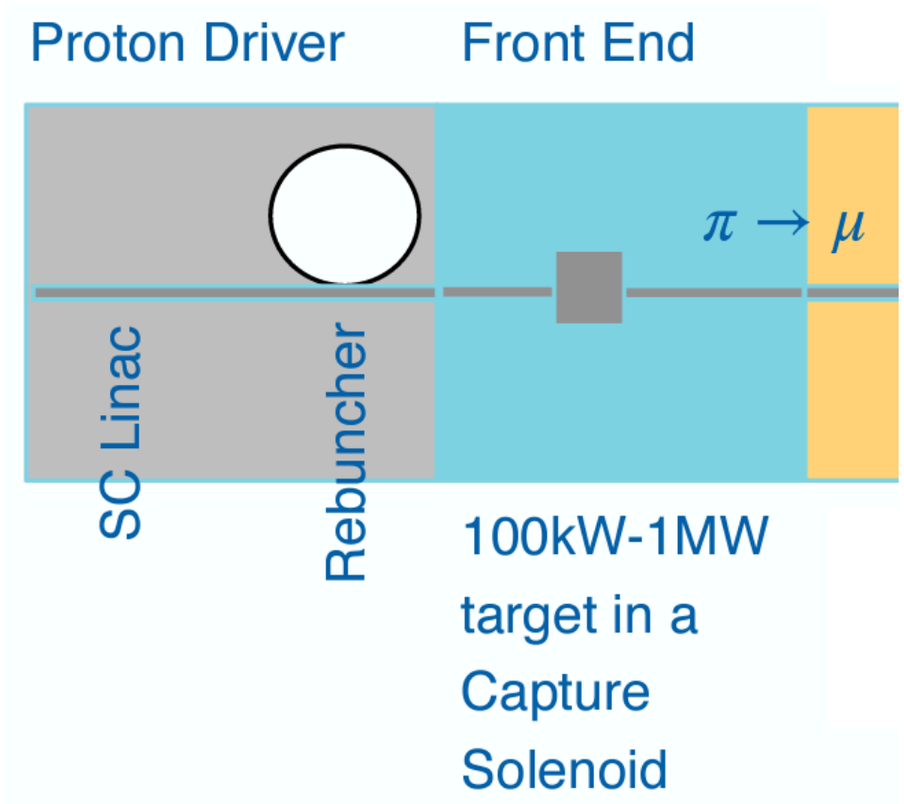
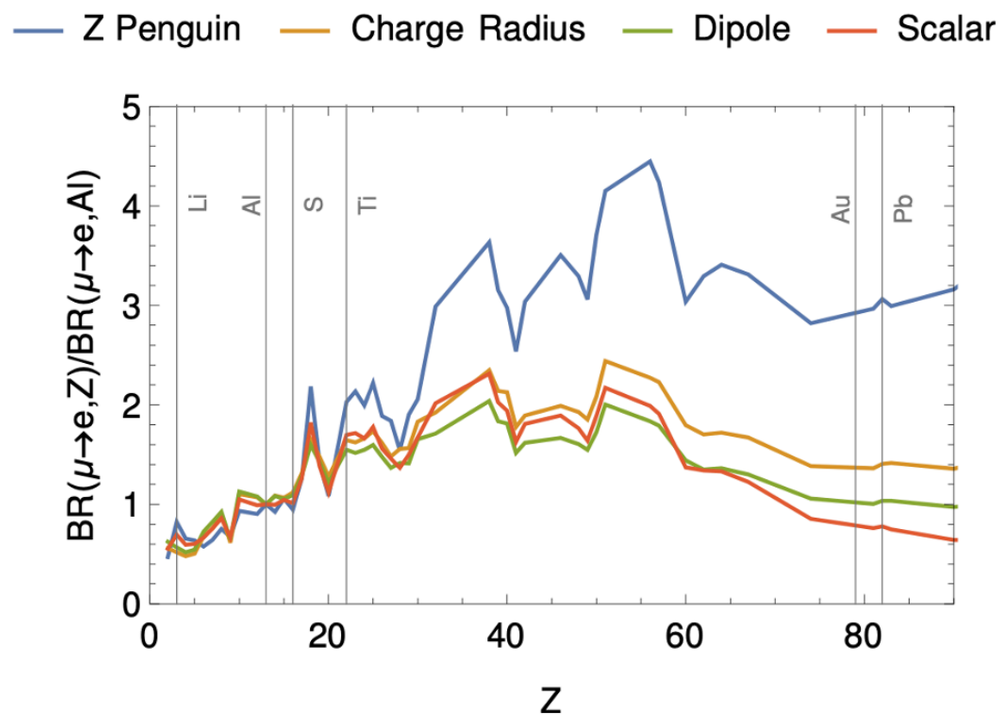


High-Z vs. low-Z nuclei allows to differentiate NP contributions



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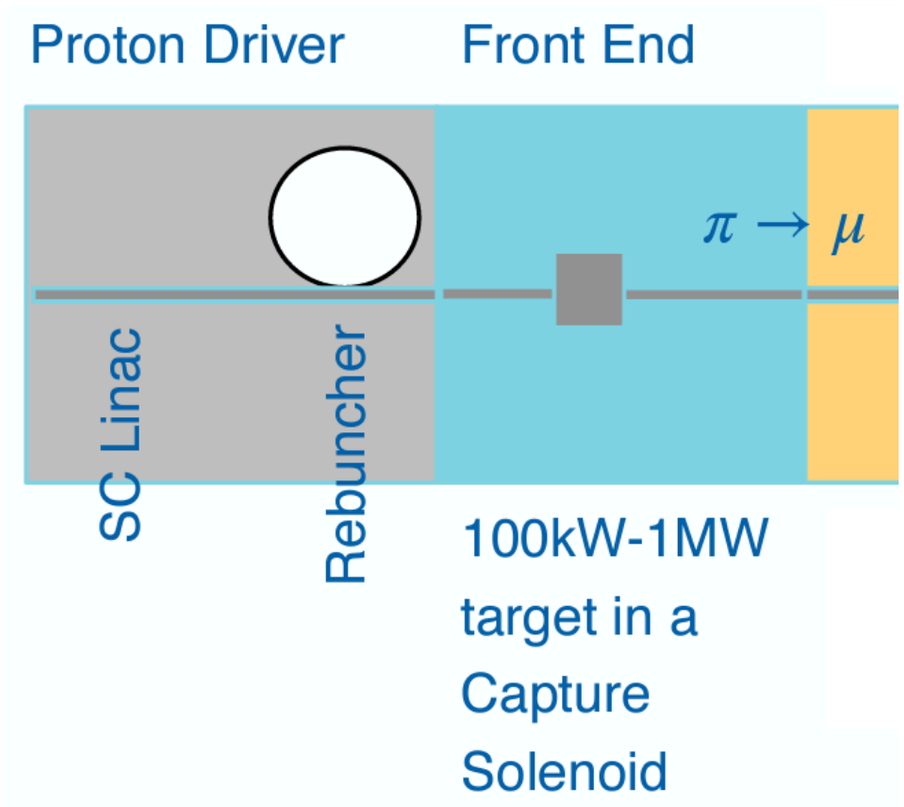
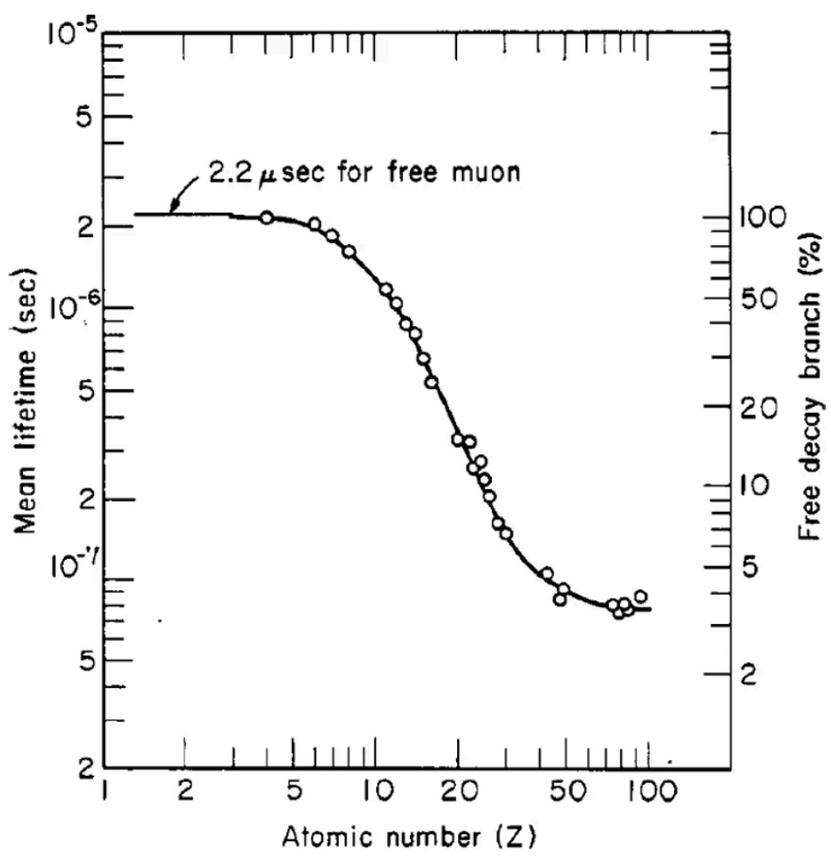


High-Z muonic atoms have short lifetime -> beam estinction à la Mu2e doesn't work



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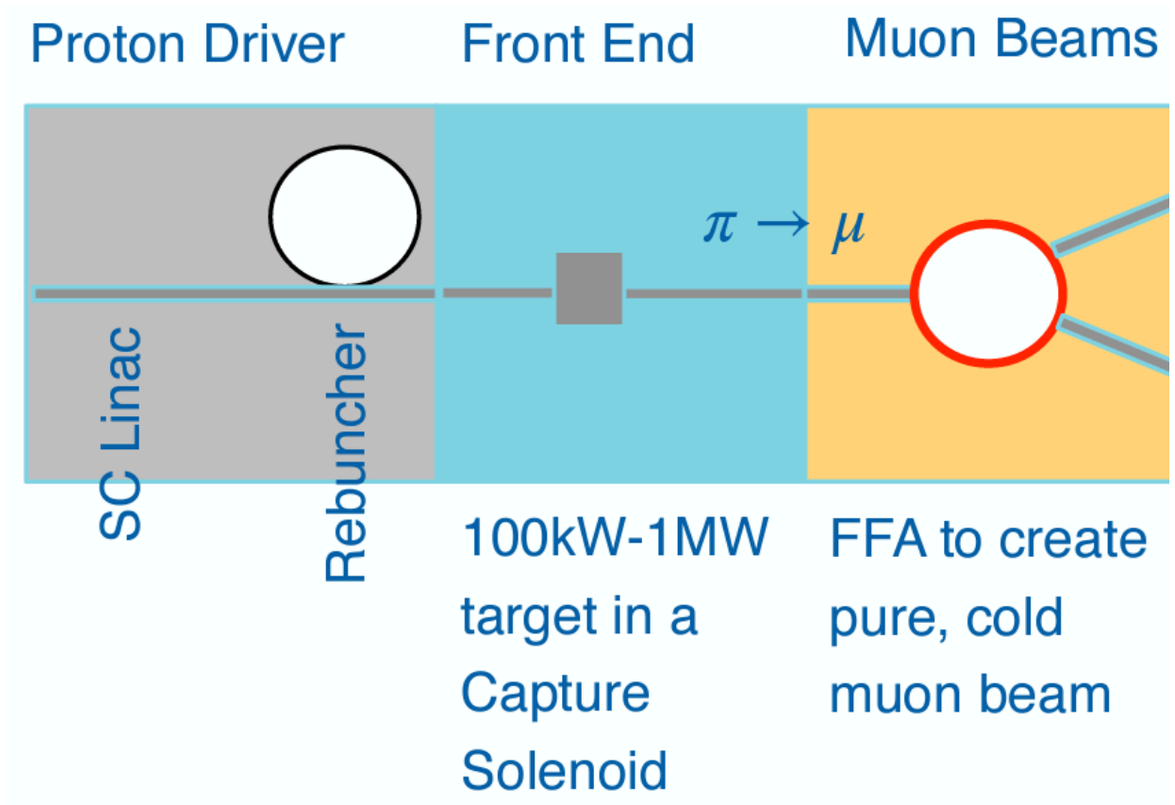
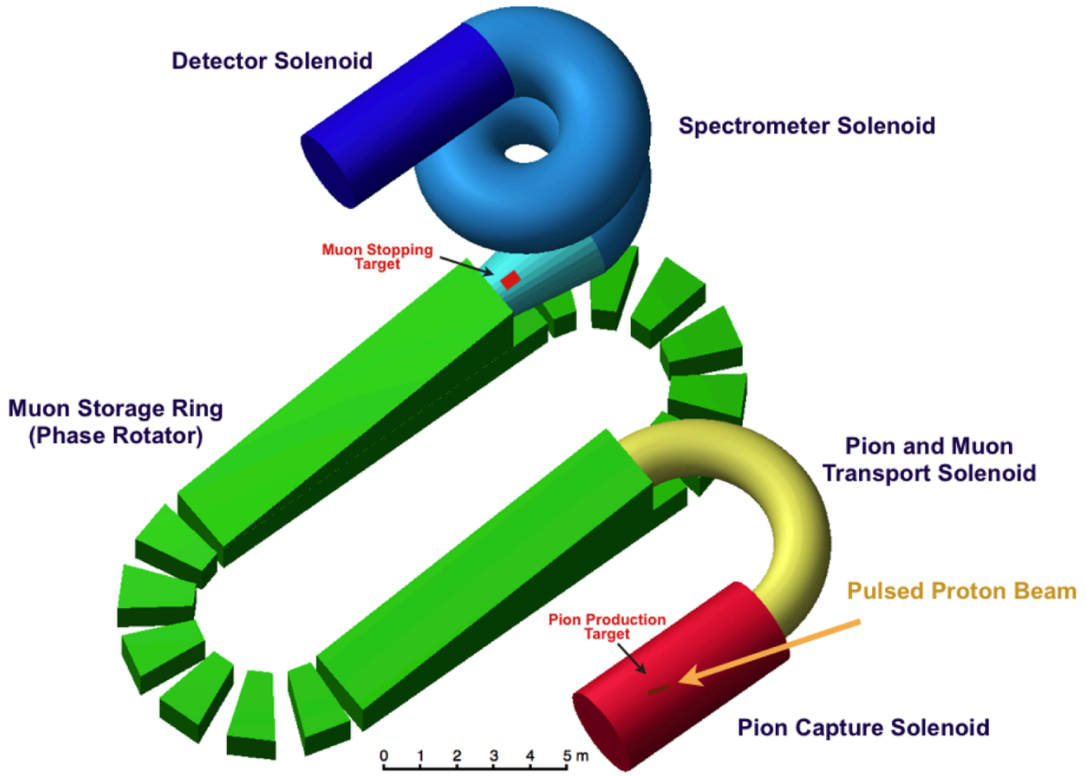
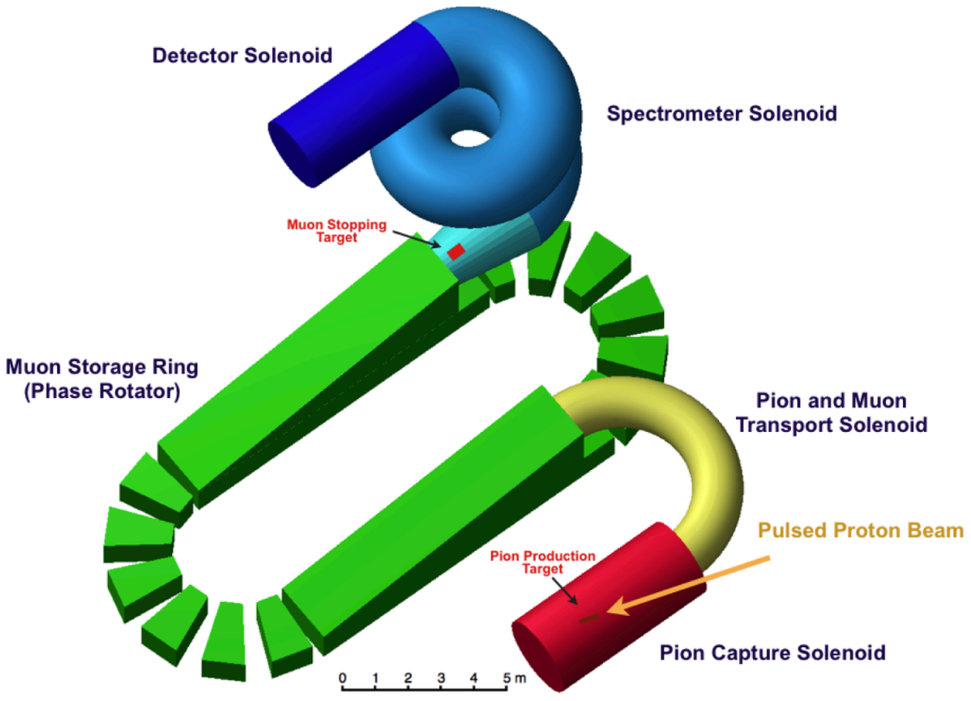


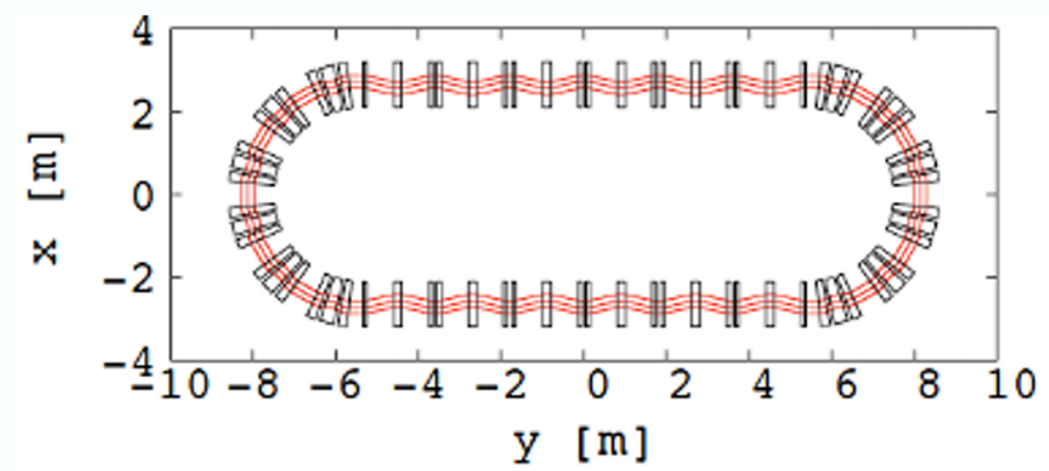
New idea: store muons in a ring until pions decay



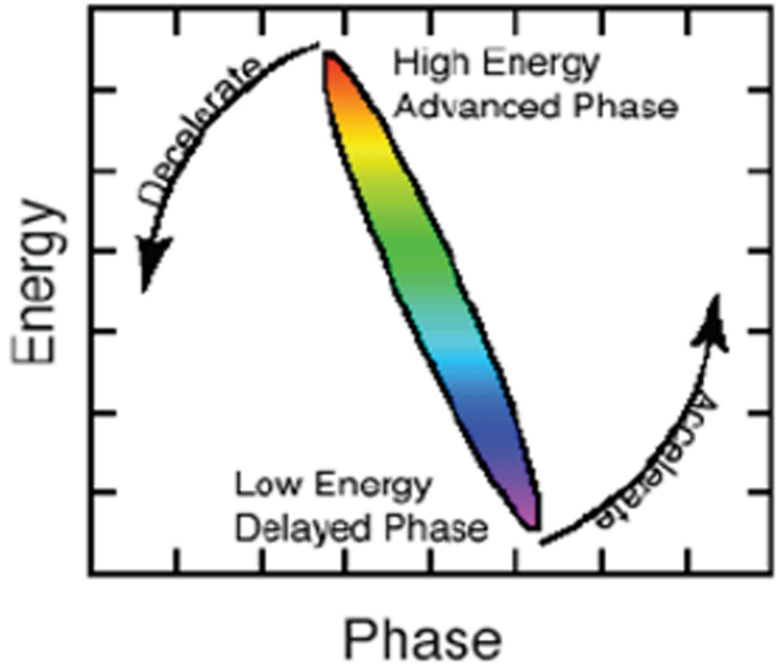
Fixed Field Alternating Gradient Ring (FFA)

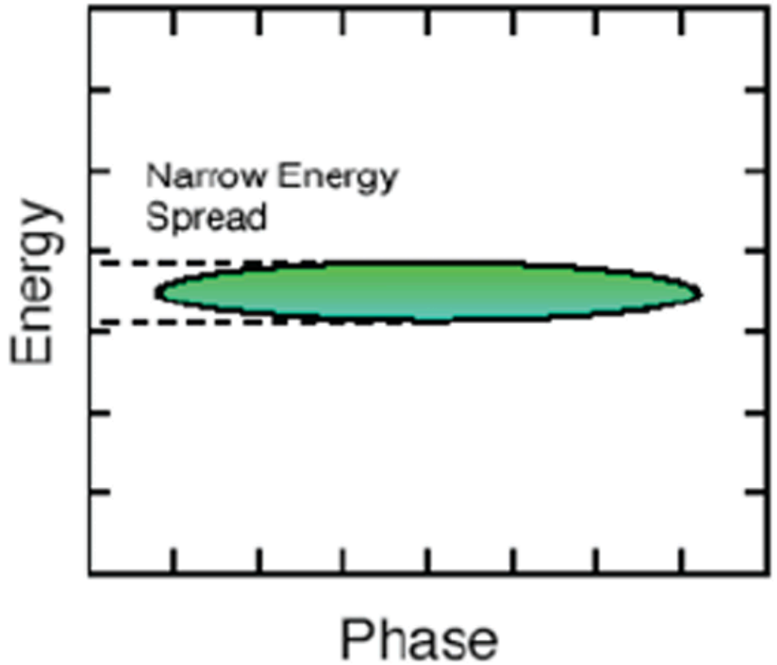


See PRISM [arXiv:1310.0804]



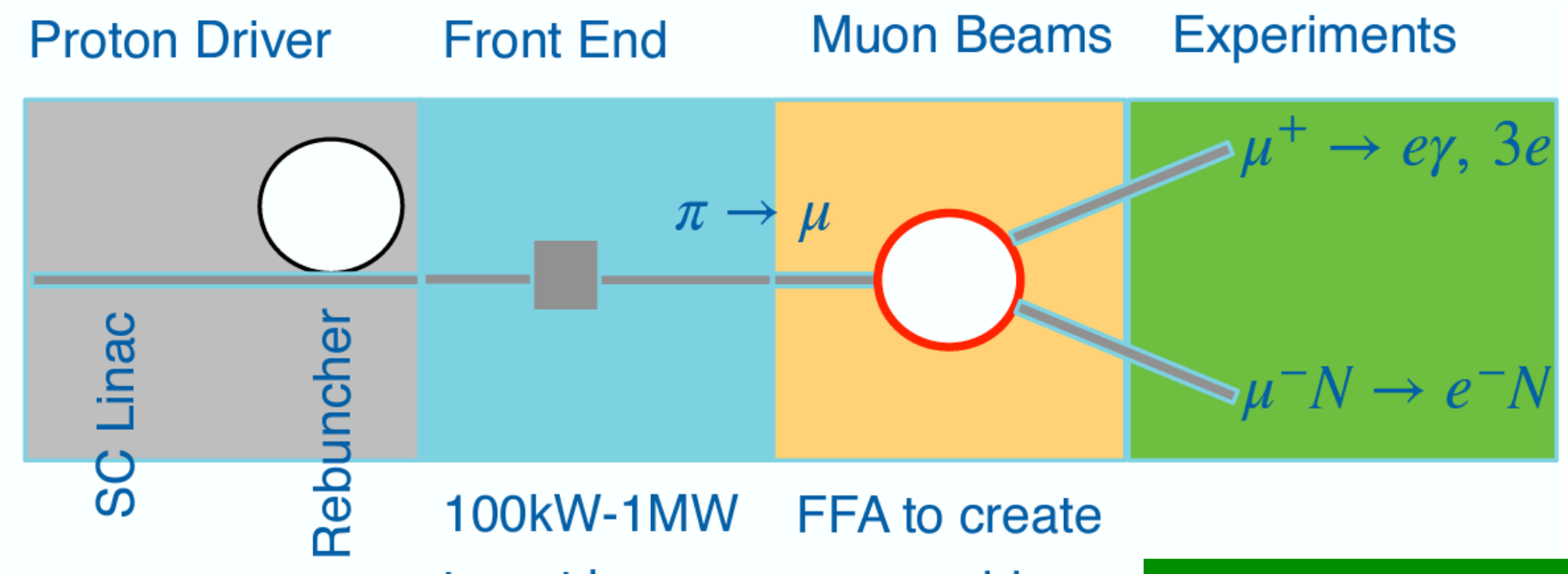
Storage ring with strong focusing
+ RF phase space rotation
—> narrow energy spread, ideal for muon stopping





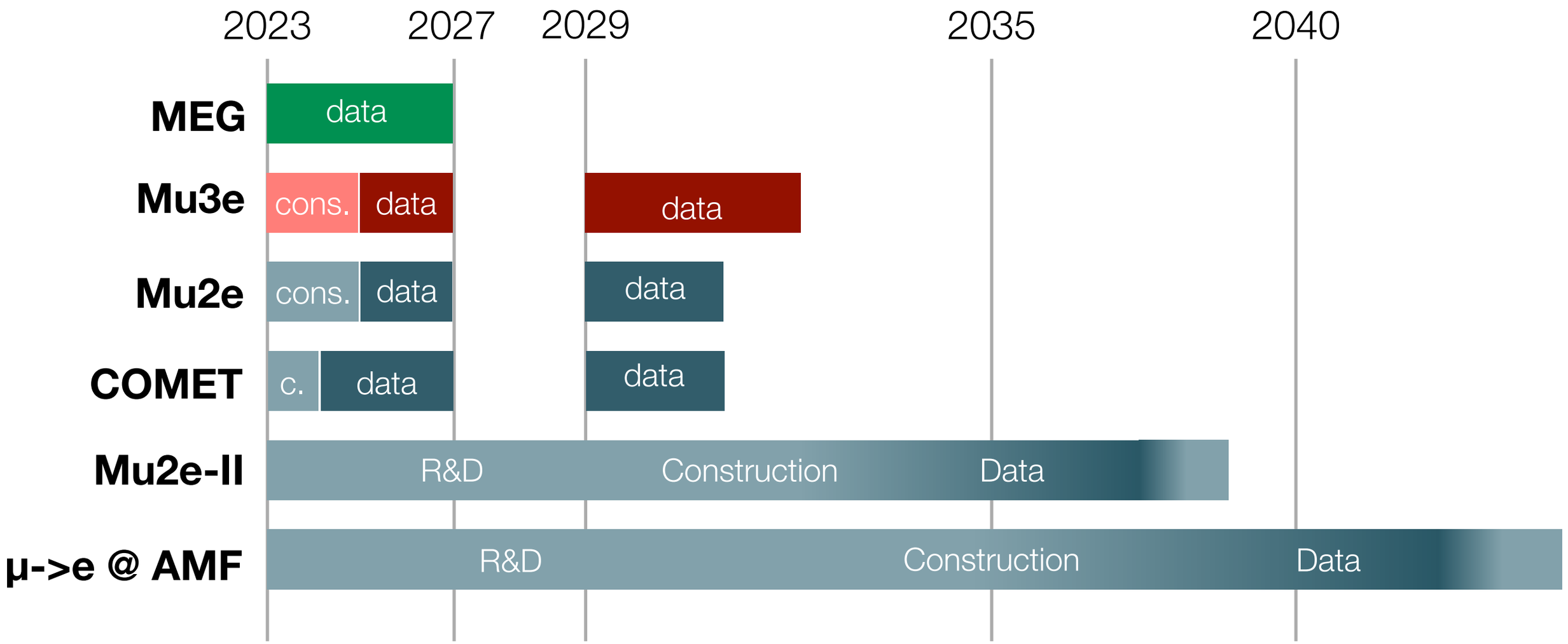
The Advanced Muon Facility (AMF)

- A new concept to
  - **make possible rare muon decay searches at FNAL**

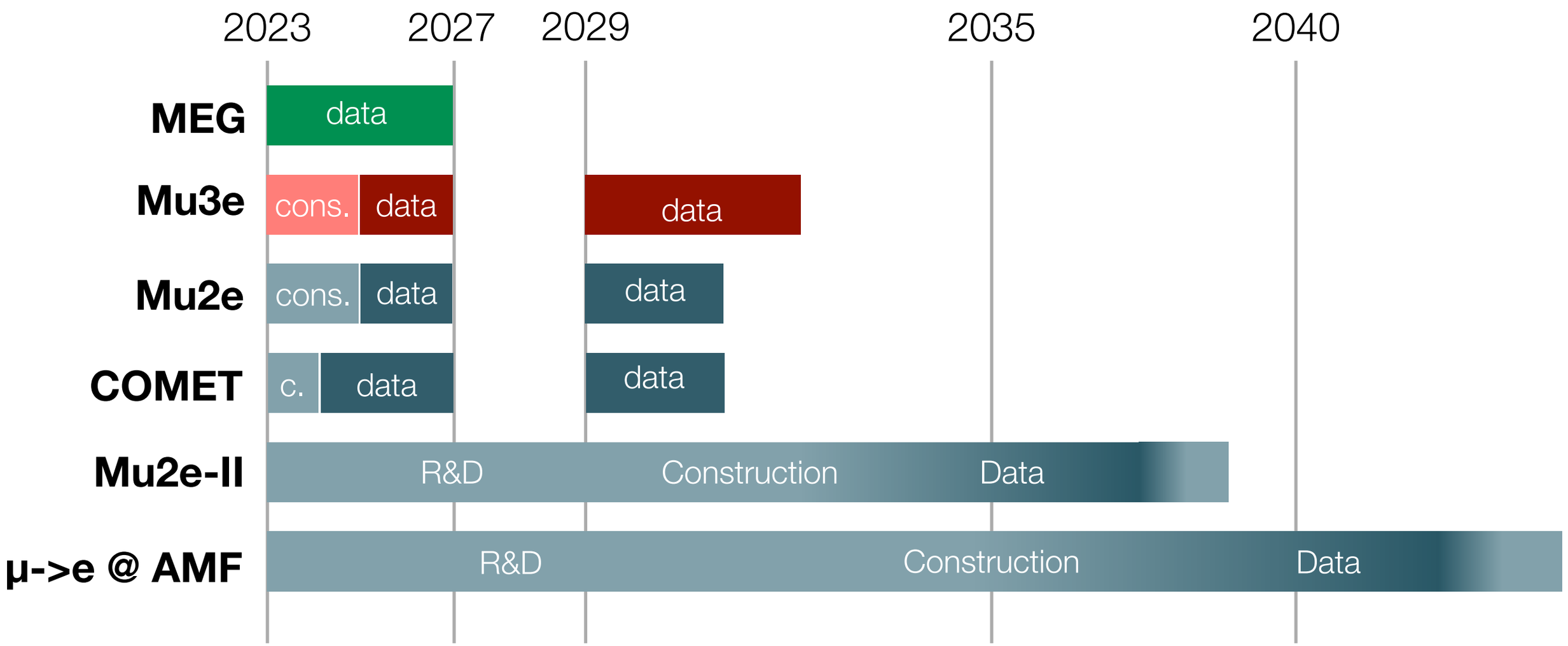


Possibility of getting ~continuous beams of negative muons, needed by muon decay experiments

A possible schedule



A possible schedule



What about the future of μ -> e γ ?

μ -> e γ searches and beam rate

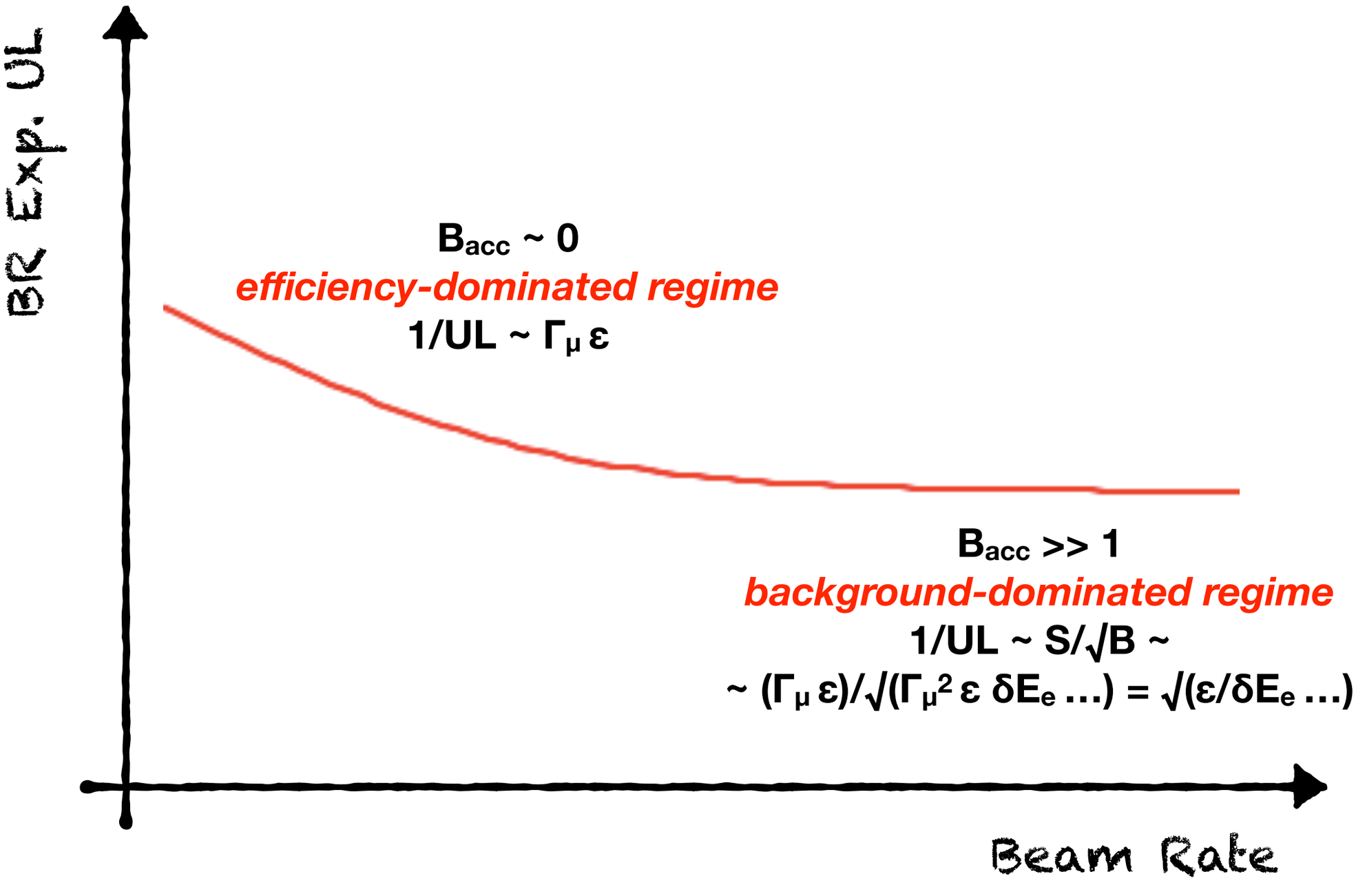
- μ -> e γ searches are dominated by **accidental background**, $B \propto \Gamma_{\mu}^{2}$

  ➡ Increasing the beam rate increases signal linearly, background quadratically

➡ Sensitivity improves only if B ~ 0

➡ Increasing the beam rate helps only if the resolutions are good enough to keep B ~ 0

μ -> e γ searches and beam rate

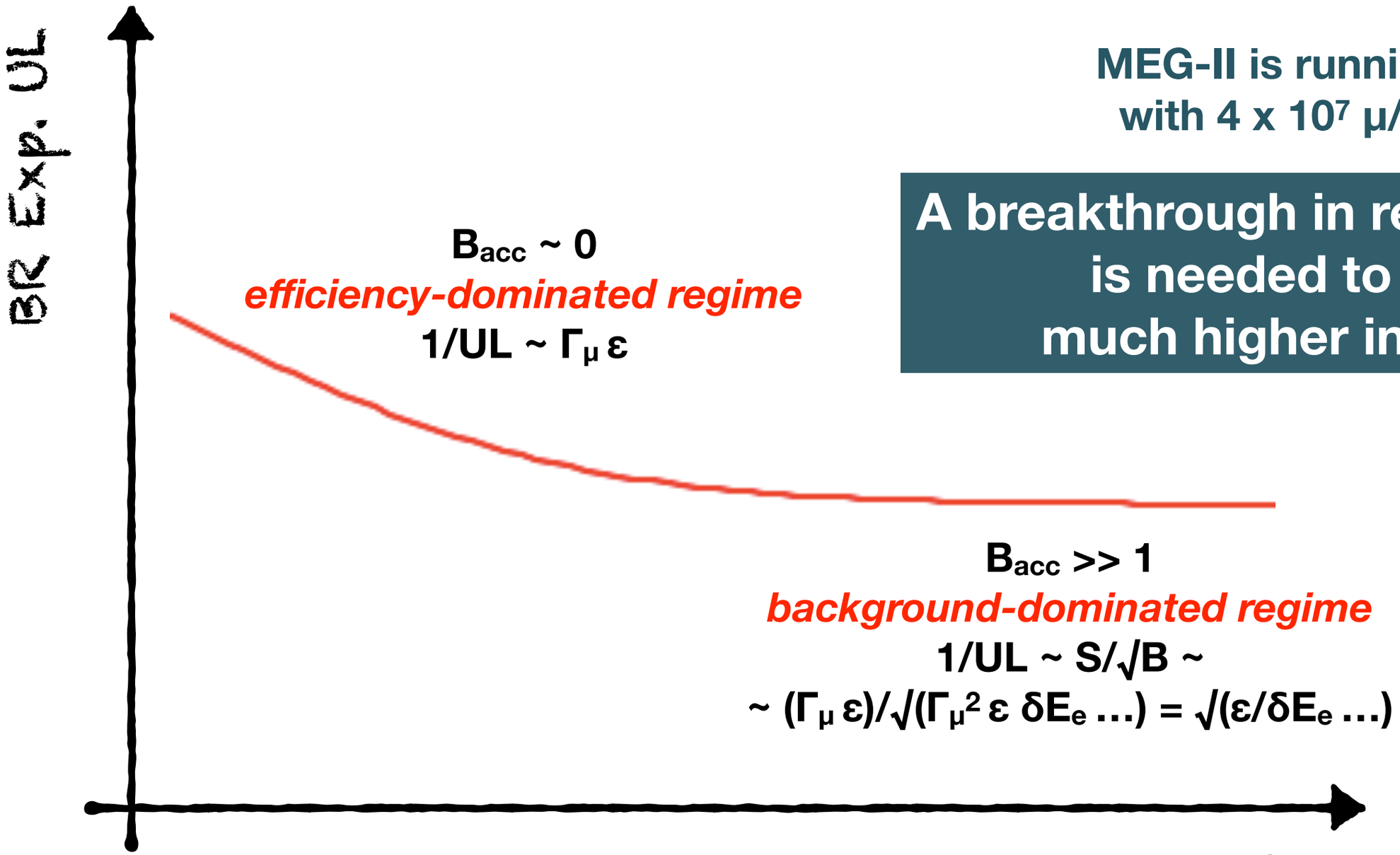


μ -> e γ searches and beam rate

MEG was operated with 3.3 x 10^7 μ/s

MEG-II is running with 4 x 10^7 μ/s

A breakthrough in resolutions is needed to go much higher in rate



Toward the next generation of μ -> e γ searches

- An **informal study group** with collaborators from MEG and Mu3e has been setup to develop new concepts and start R&Ds for the next generation of μ -> e γ searches

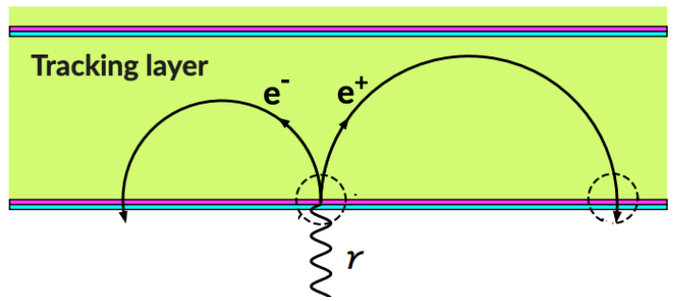
- Going toward a concept based on:

  - Positron tracking with pixels (*à la Mu3e*, R&D needed for 25 μm thickness)

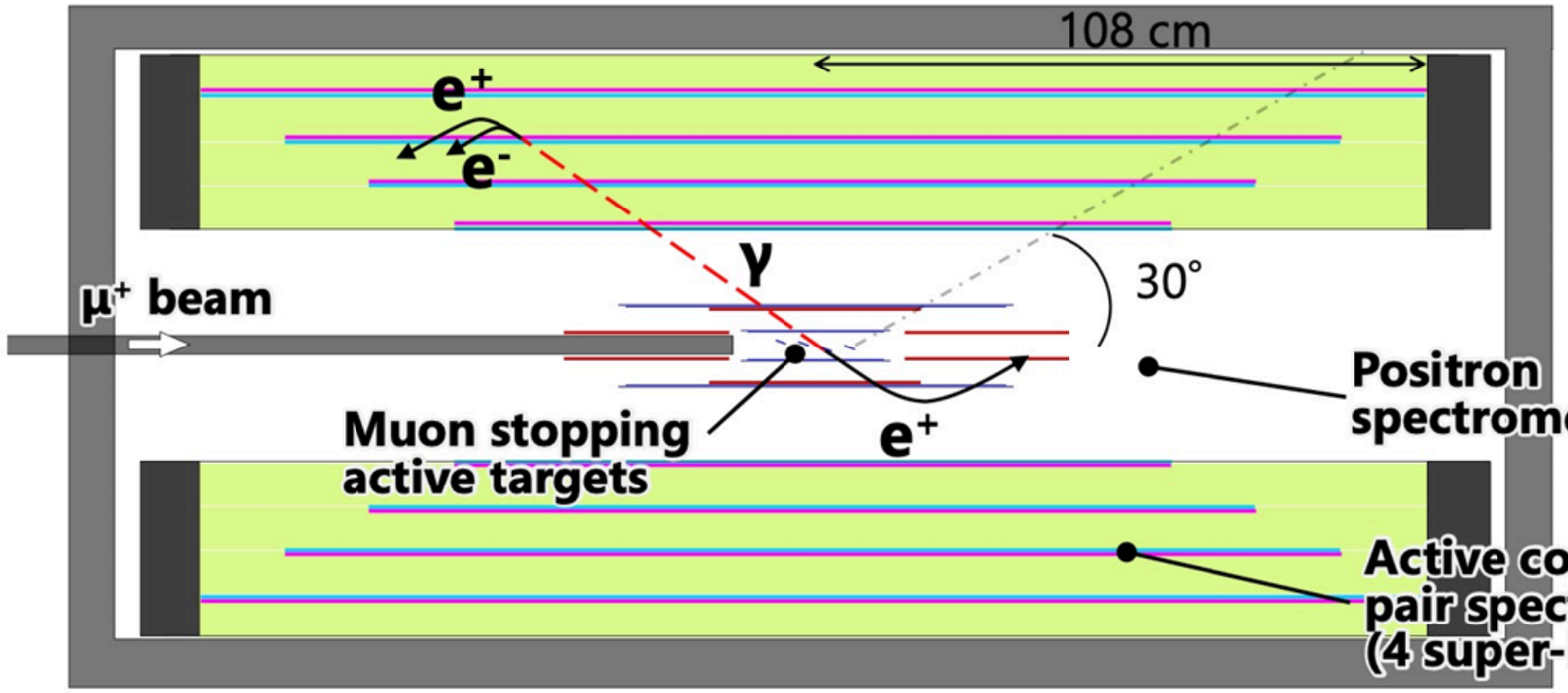
    ➡ Good resolution (limited by multiple scattering), high-rate capabilities

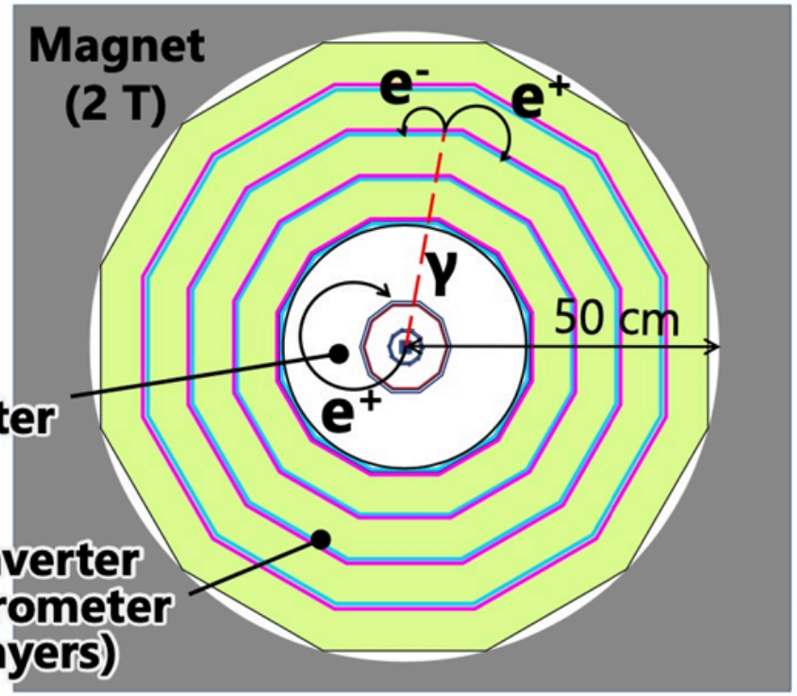
    - Tracking with gaseous detectors also considered (*synergy with Mu2e-II*), but extremely challenging

  - Photon reconstruction with **pair conversion**



    ➡ low efficiency (compensated by high beam rate), excellent resolutions



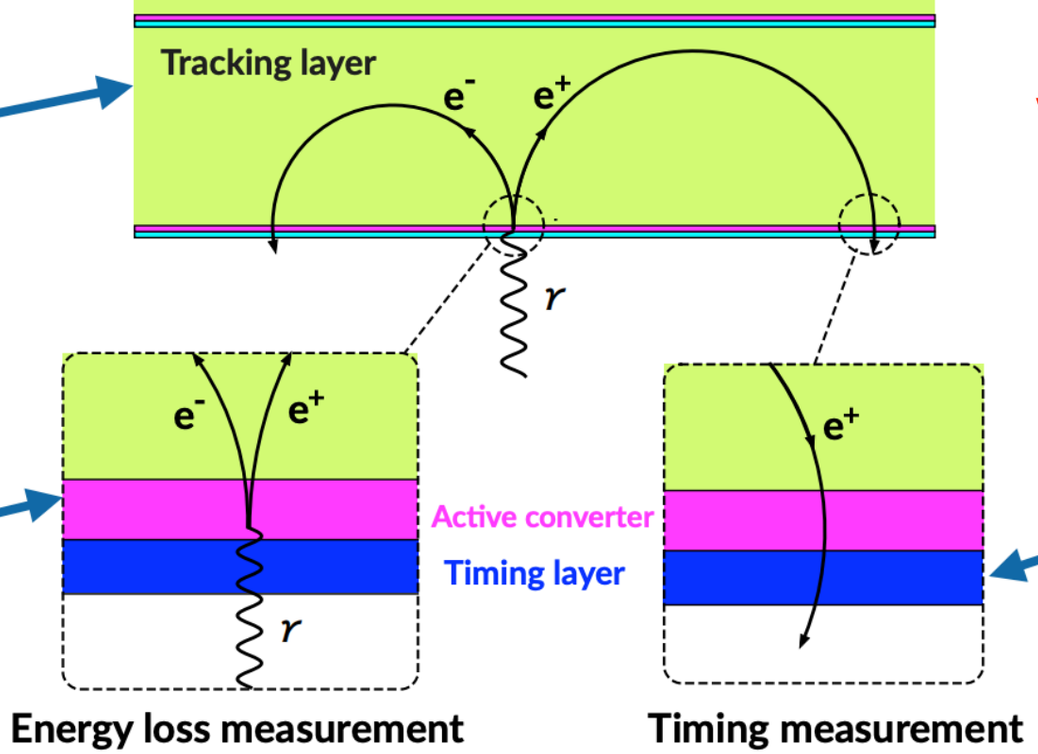


Tracking layer

- Measure momentum of conversion pair
- Possible technologies
  - Drift chamber (a la MEG II CDCH)
  - Radial-TPC
  - Silicon detector

Active conversion layer

- Thin active material to measure energy loss of conversion pair
- Possible technologies
  - Scintillator + photo-detector
  - Silicon detector



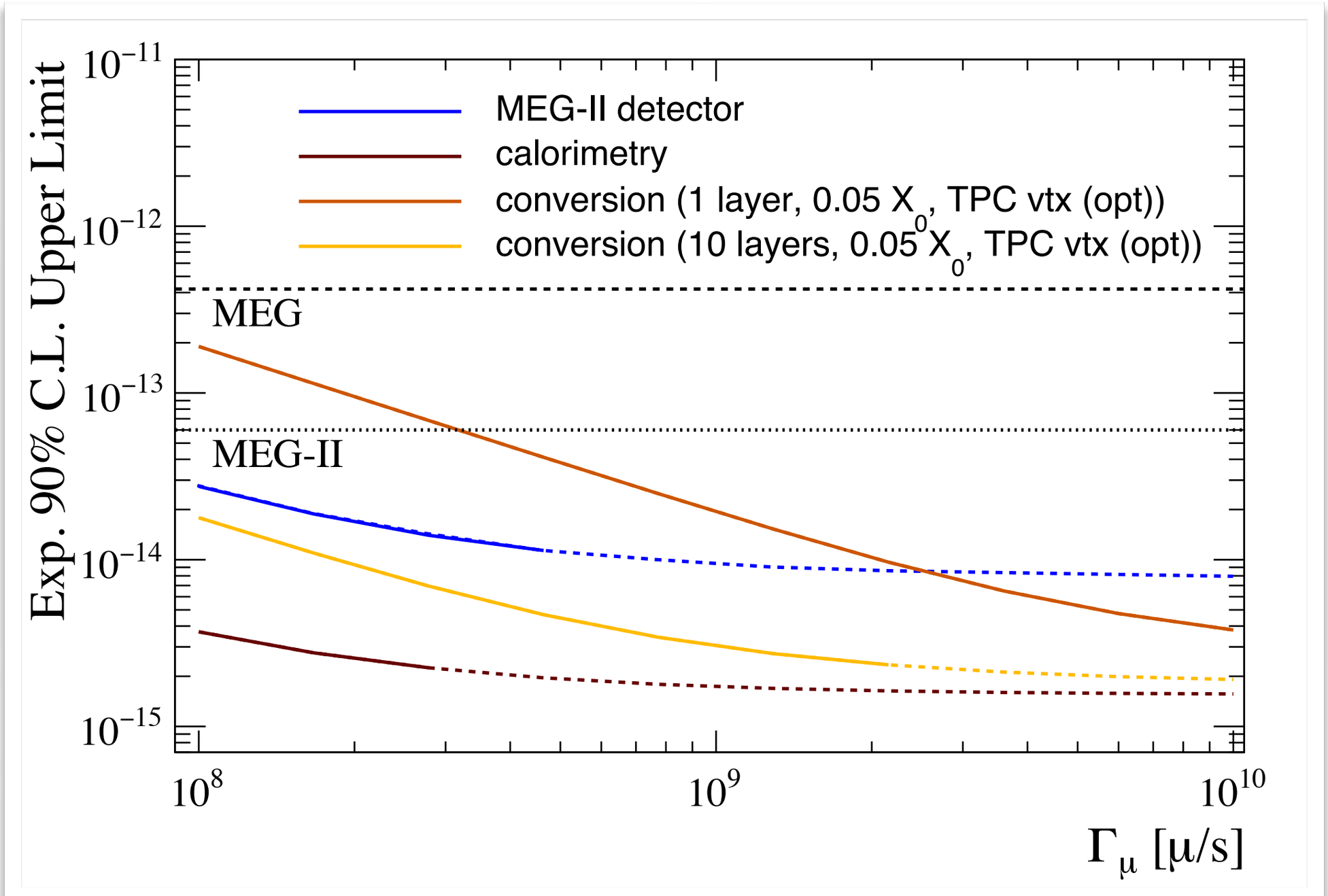
Timing layer

- Measure timing of returning conversion pair
- in front of active converter
- Possible technologies
  - Multi-layer RPC (mRPC)
  - Active converter = timing detector

Photon conversion with active converter

Detector R&D already started for crystals and pair tracker

Sensitivity



Conclusions

- Upgrade programs at PSI and FNAL open new opportunities in muon cLFV searches
- **HiMB at PSI** will deliver ~ 10^{10} μ/s
  - Mu3e phase-II already designed for such a high rate
- PIP-II at FNAL
  - **Mu2e-II**
  - An **Advanced Muon Facility** is under study —> a unique possibility of adapting the beam to the experiments' needs and exploit synergies having all cLFV experiments in a single place
- Detector R&Ds are well advanced for Mu2e-II, and just started for μ -> e γ, with synergic programs
- Interesting synergies with the muon collider program