DC Muon Physics

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Virginia Tech, Blacksburg, USA
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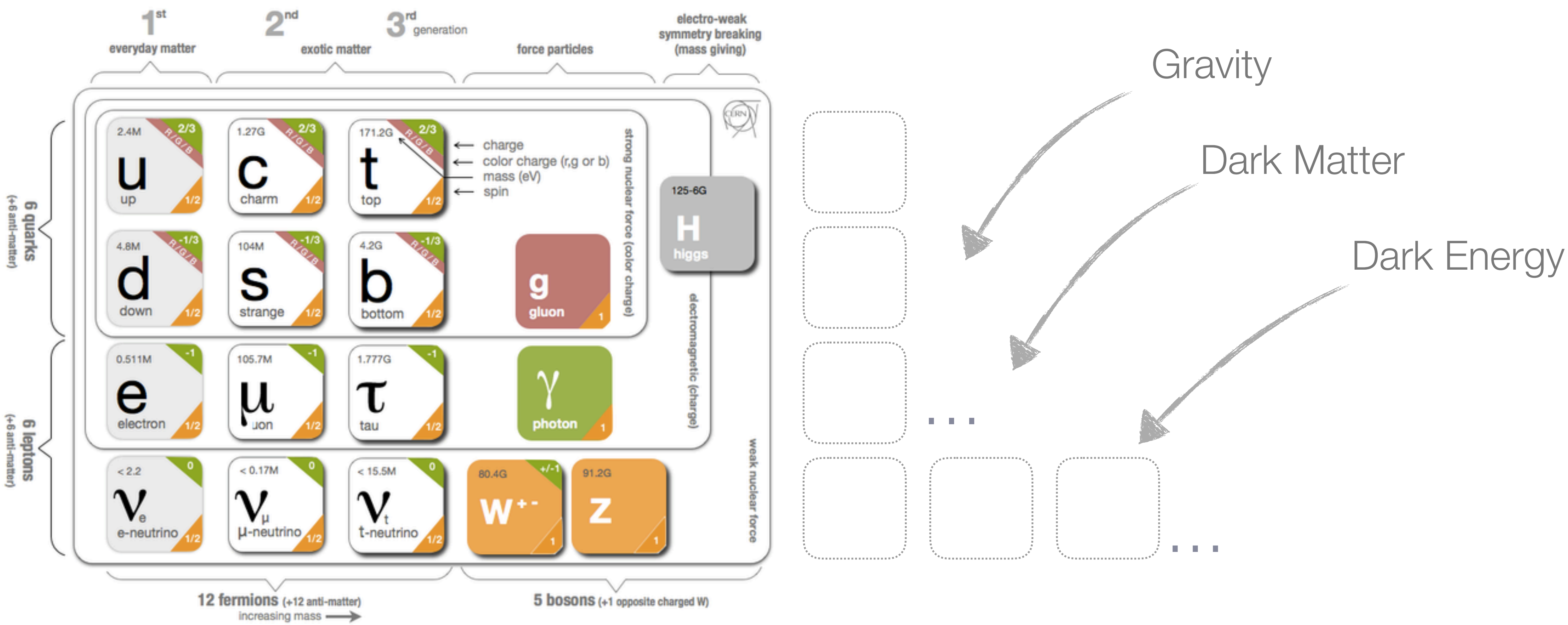
Content

- Introduction: The physics cases with DC muon beams
- The Most Intense DC Muon Beams in the World:
  Present and future prospects
- Overview of current experimental activities based on DC muon beams

The role of the low energy precision physics

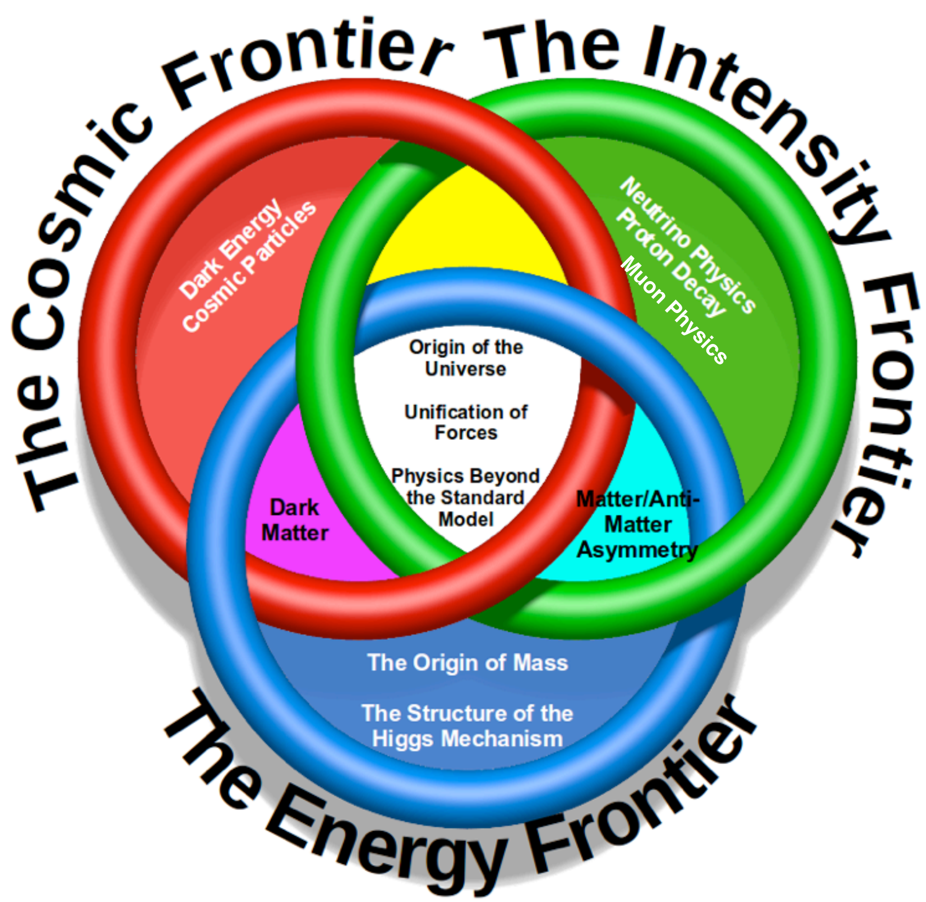
- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory

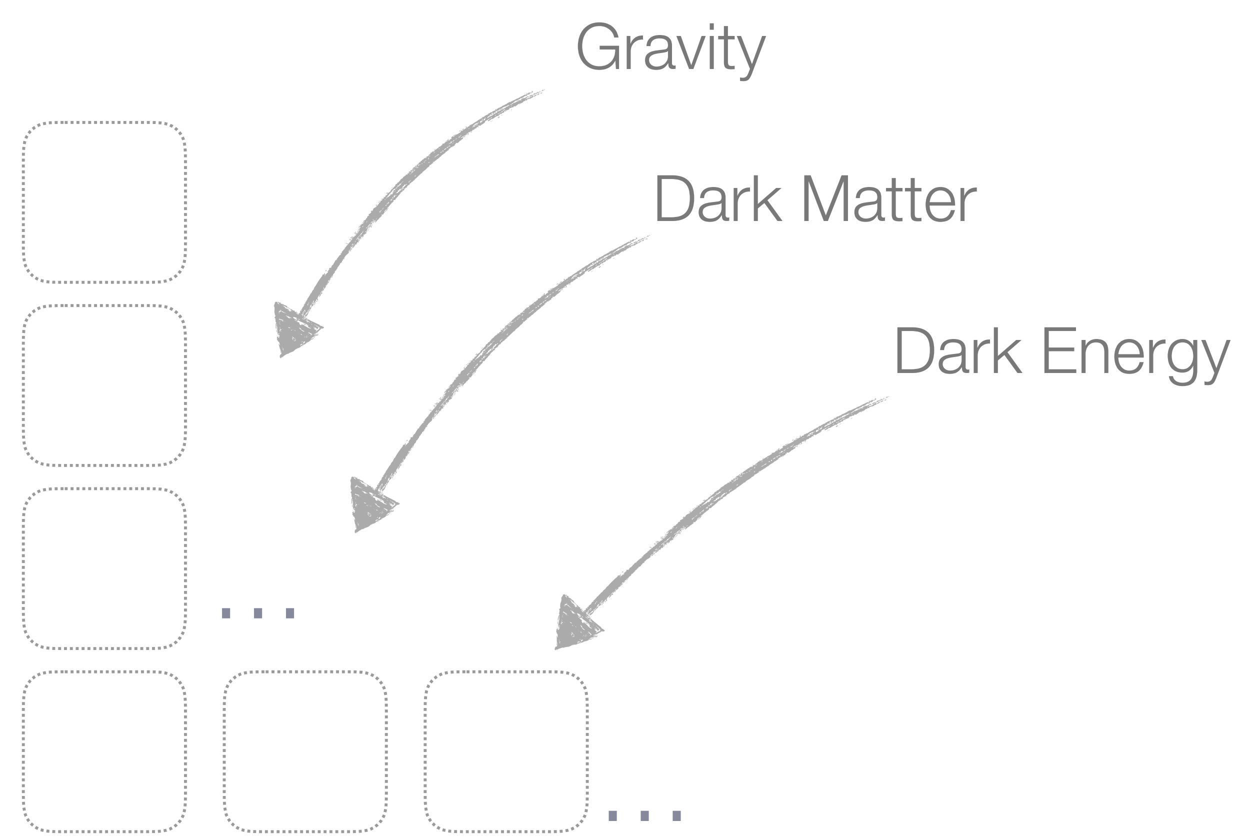


- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory





- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

The role of the low energy precision physics

- Two main strategies to unveil new physics
  - Indirect searches
  - Precision tests

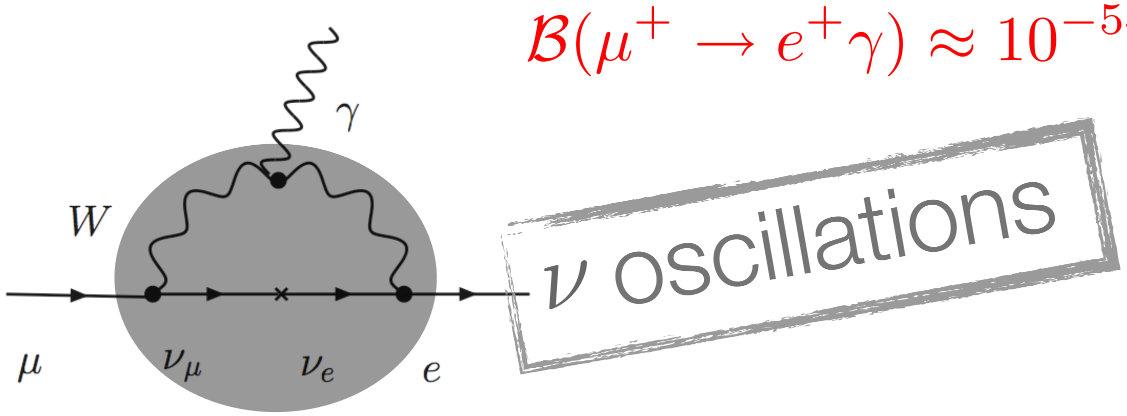
The role of the low energy precision physics

- Two main strategies to unveil new physics
    - **Indirect searches**
    - Precision tests

Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

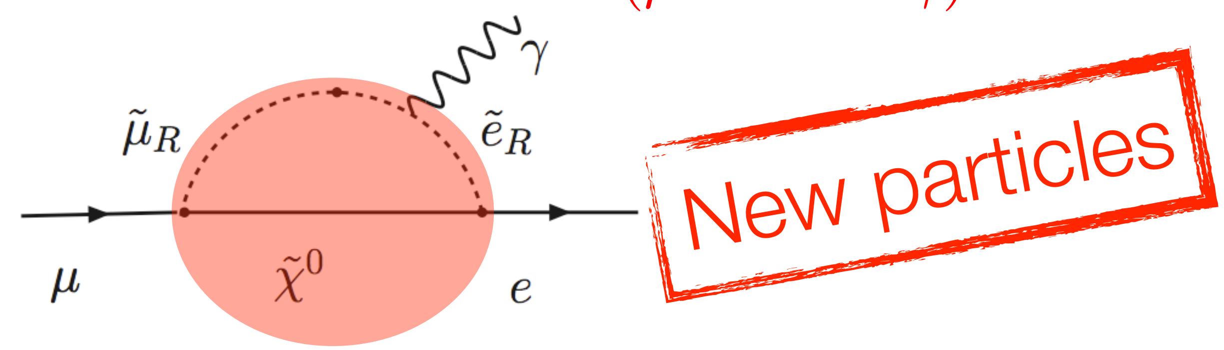
$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$



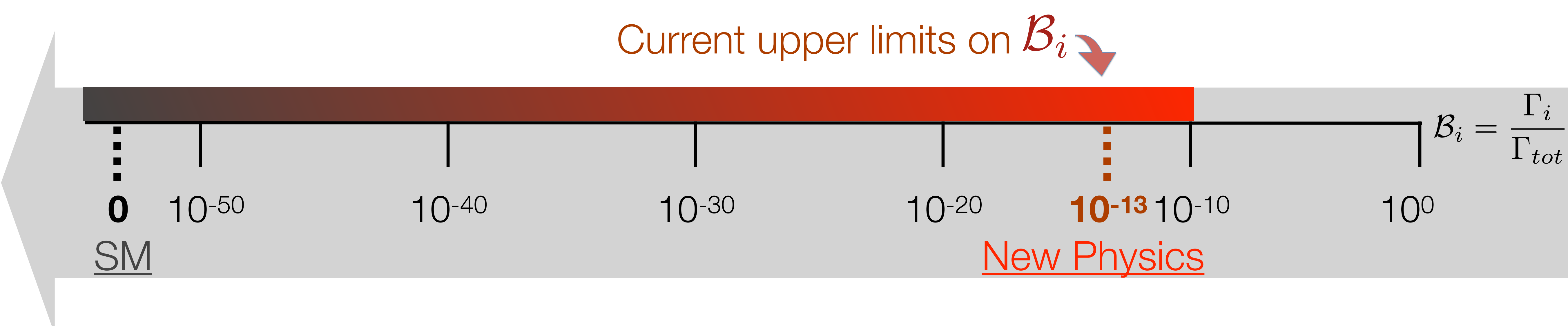
too small to access experimentally

BSM

$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$

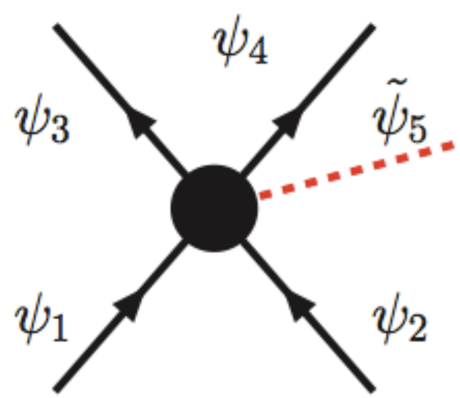


an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)



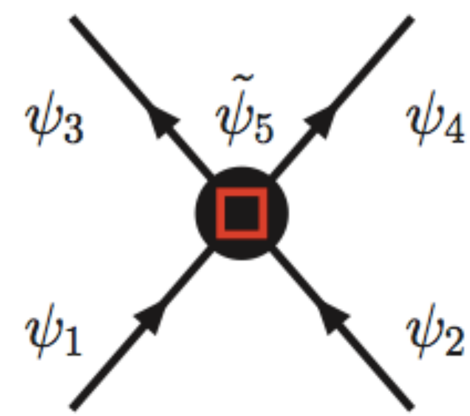
Complementary to "Energy Frontier"

Energy frontier



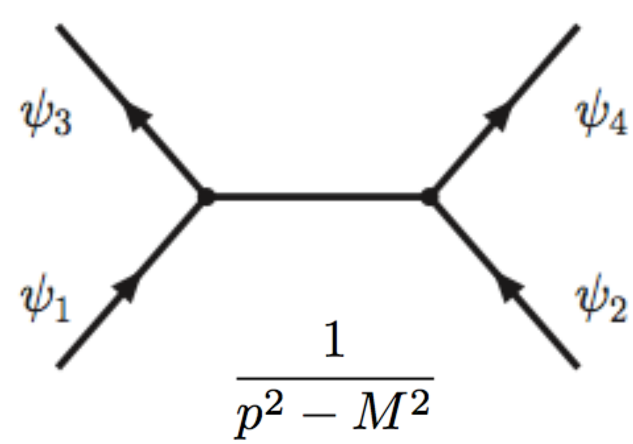
Real BSM particles

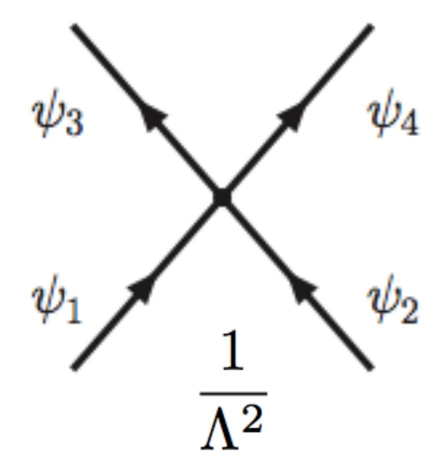
Precision and intensity frontier



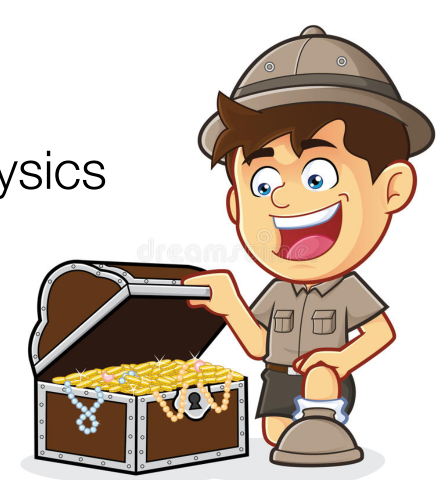
Virtual BSM particles

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$





Unveil new physics



Probe energy scale otherwise unreachable

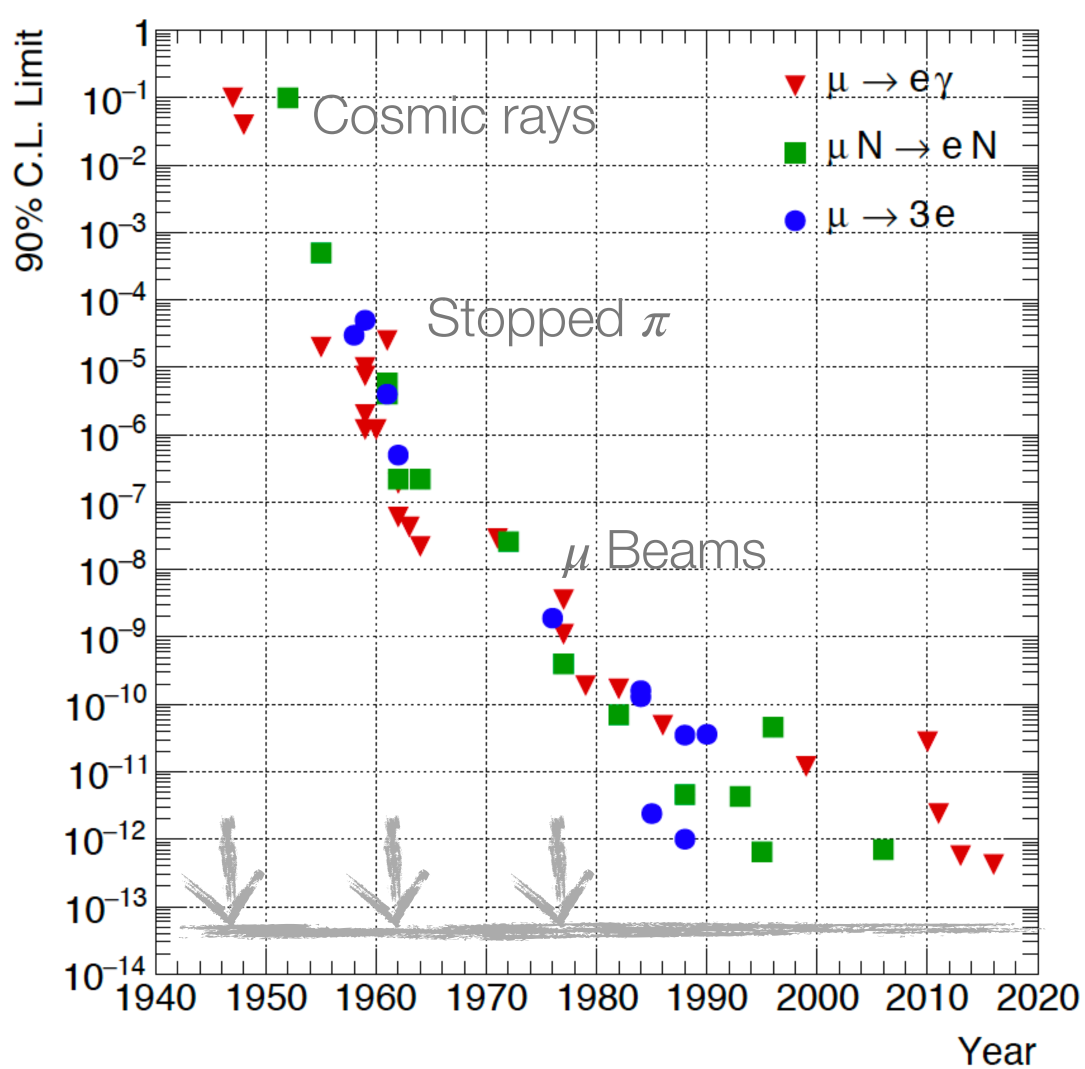
E > 1000 TeV

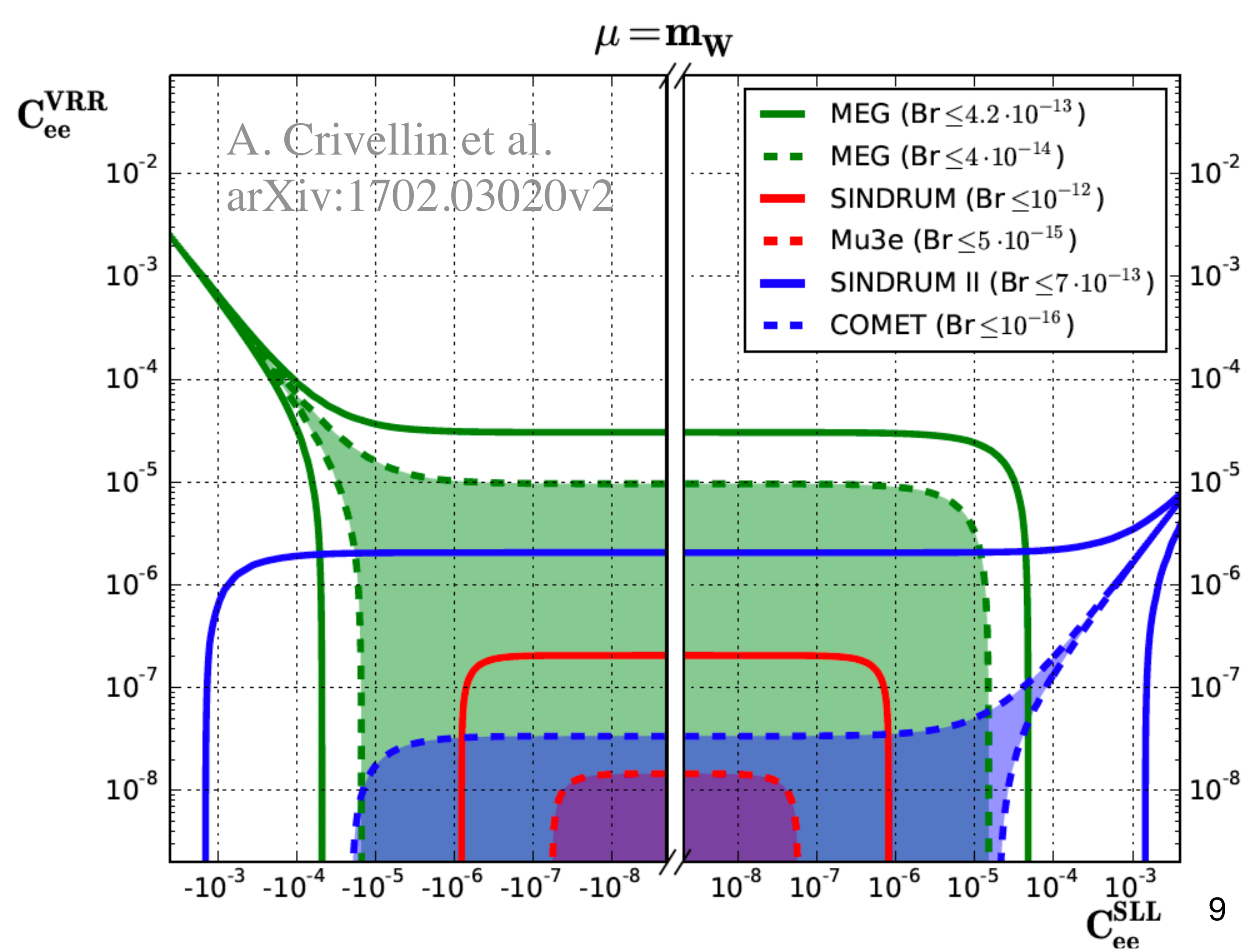
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 4 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	< 10^{-16}

- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV





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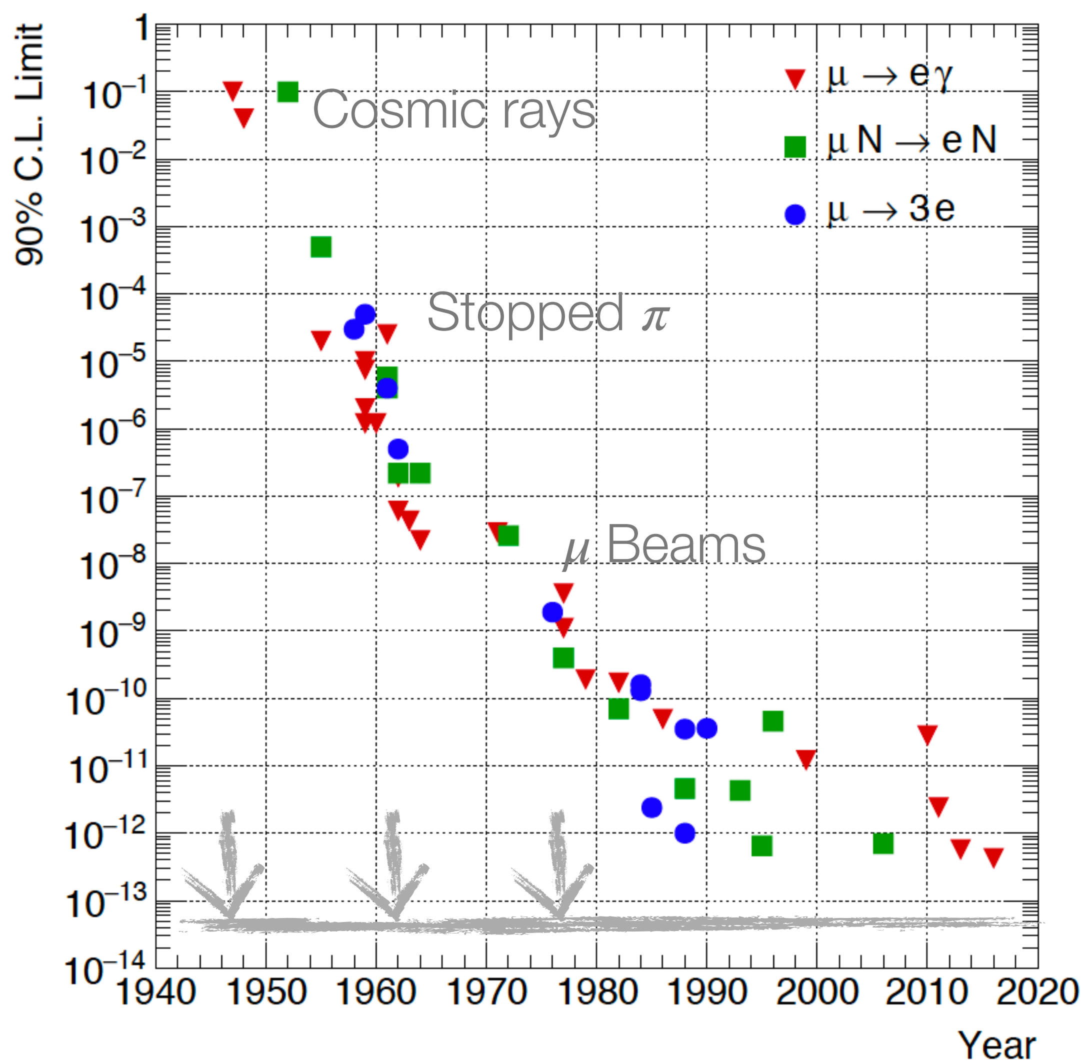
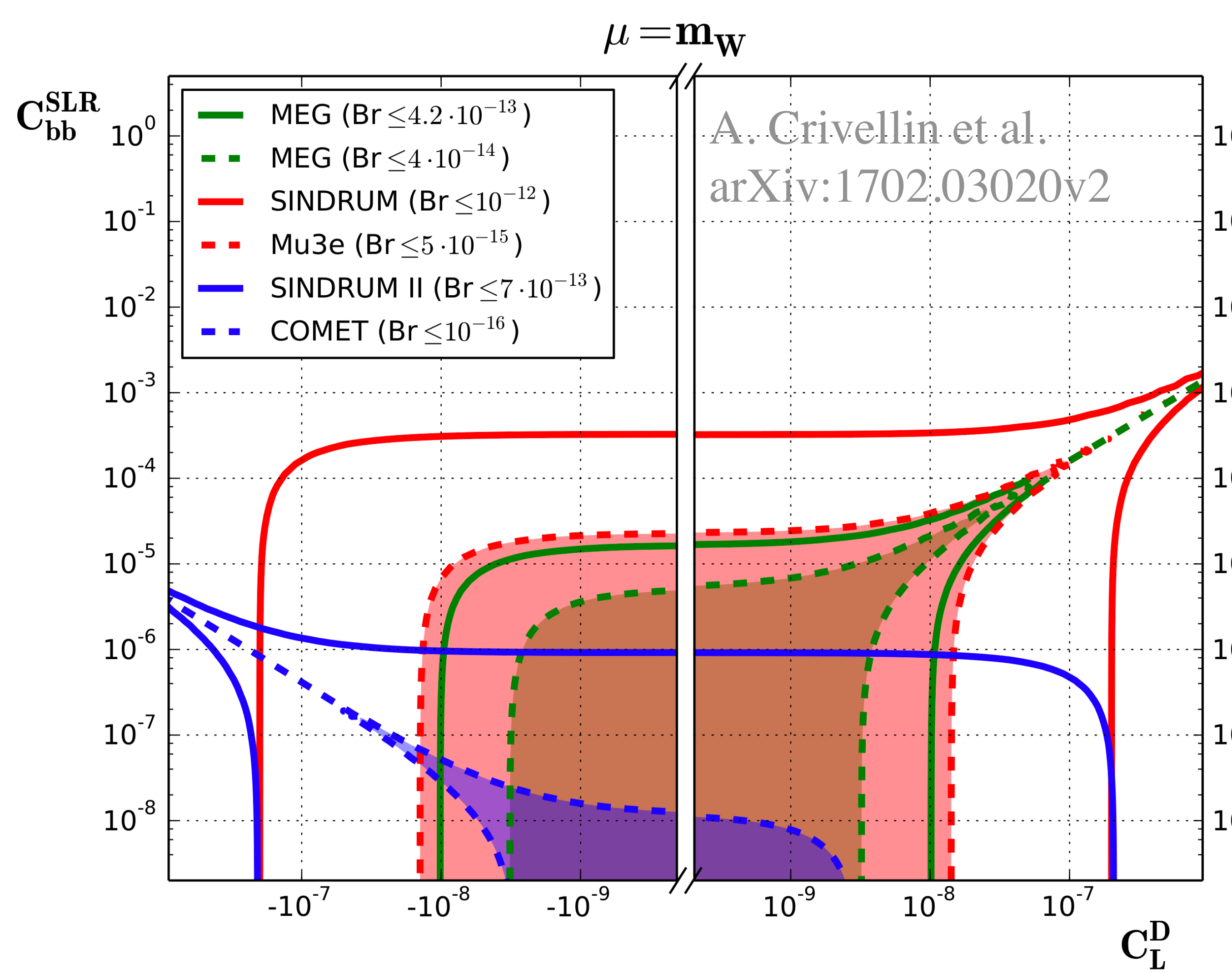
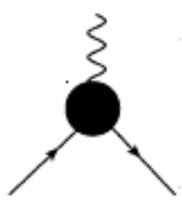
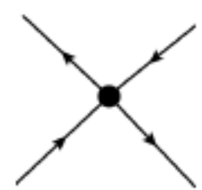


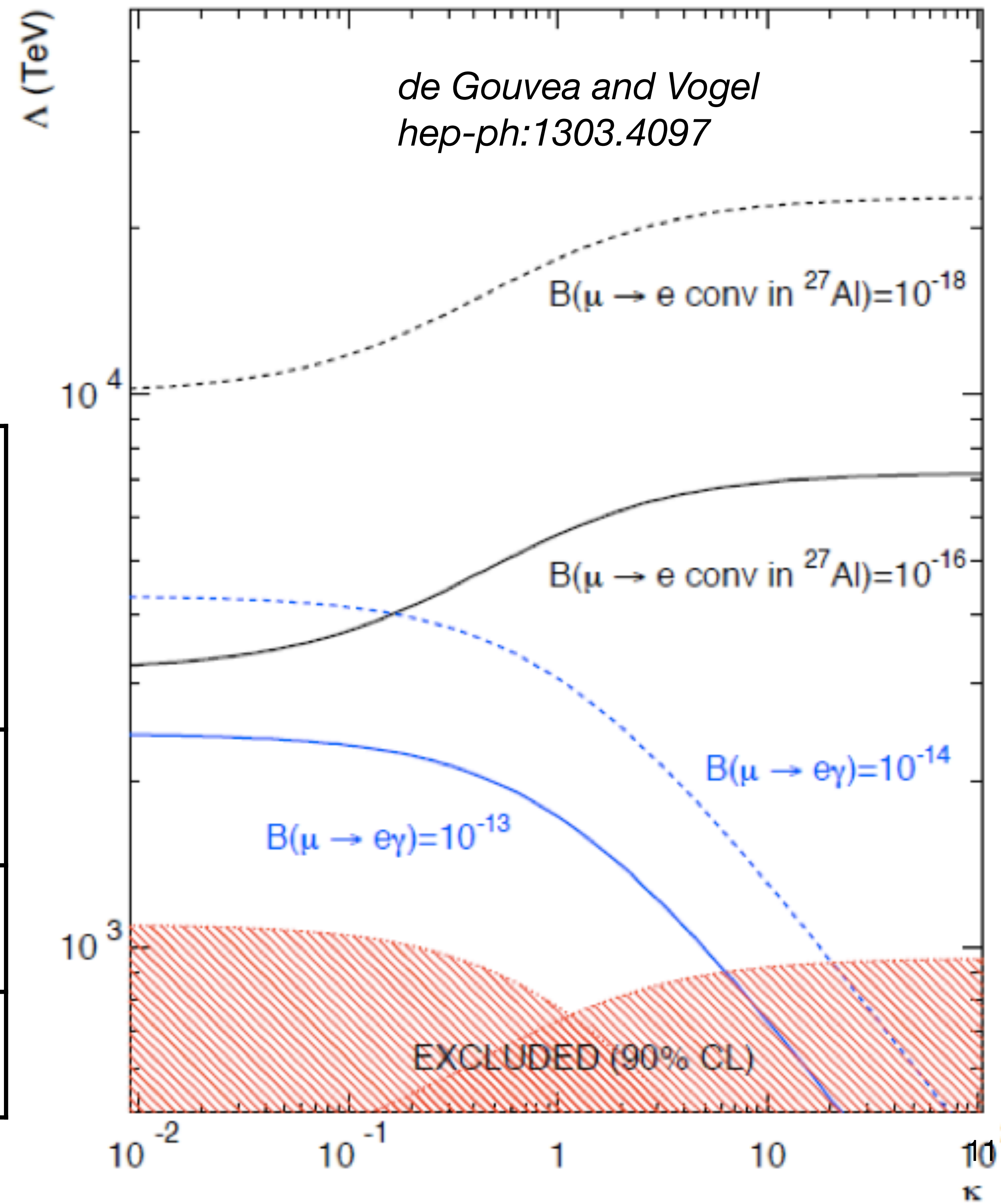


cLFV: “Effective” lagrangian with the k-parameter

- Due to the **extremely-low** accessible **branching ratios**, muon cLFV can strongly **constrain** new physics models and scales

Model independent lagrangian

$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$  +	$\frac{\kappa}{(\kappa+1)\Lambda^2} \times$ 
dipole term	contact term
$\mu \rightarrow e\gamma$	
$\mu \rightarrow eee$	
$\mu N \rightarrow eN$	



cLFV searches with muons: Status and prospects

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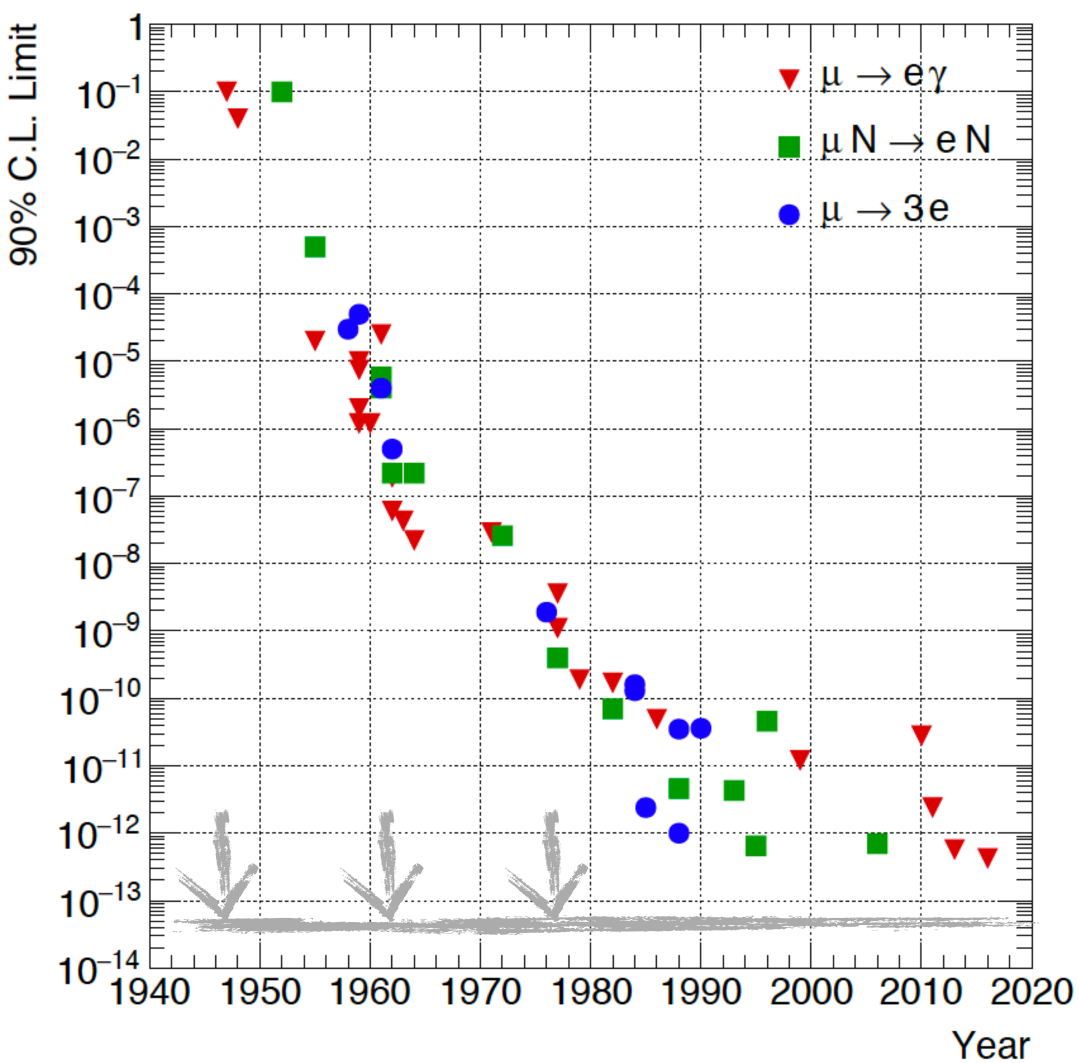
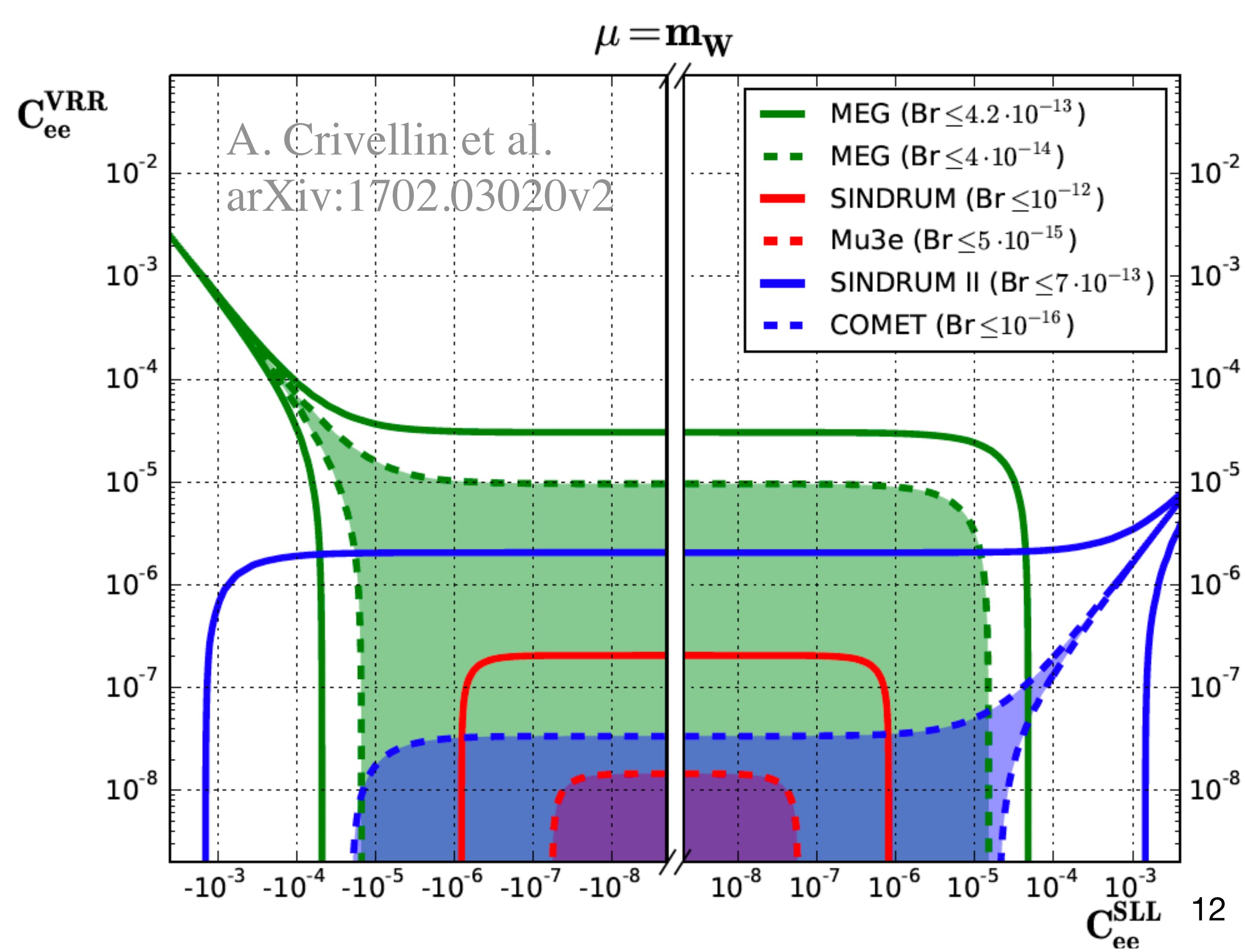




Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

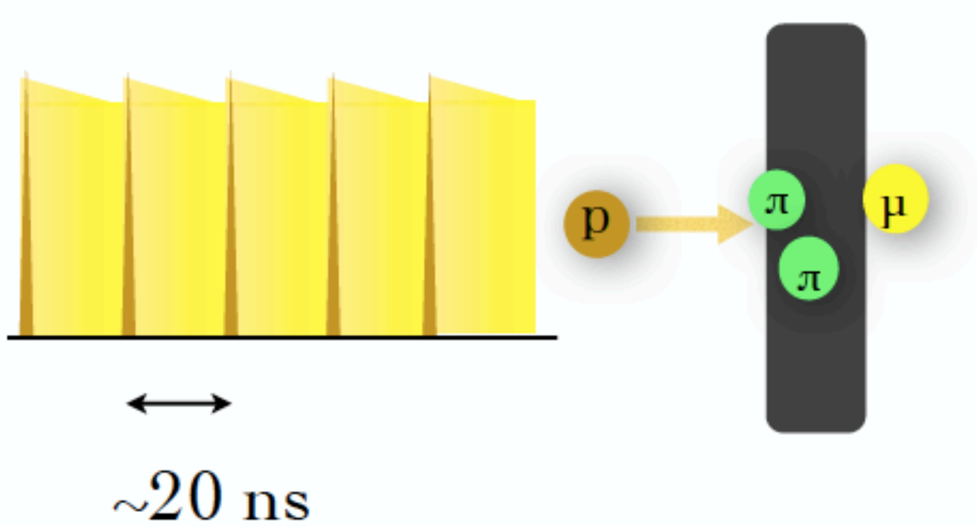
$I_{beam} \sim 10^8 - 10^{10}$ μ/s

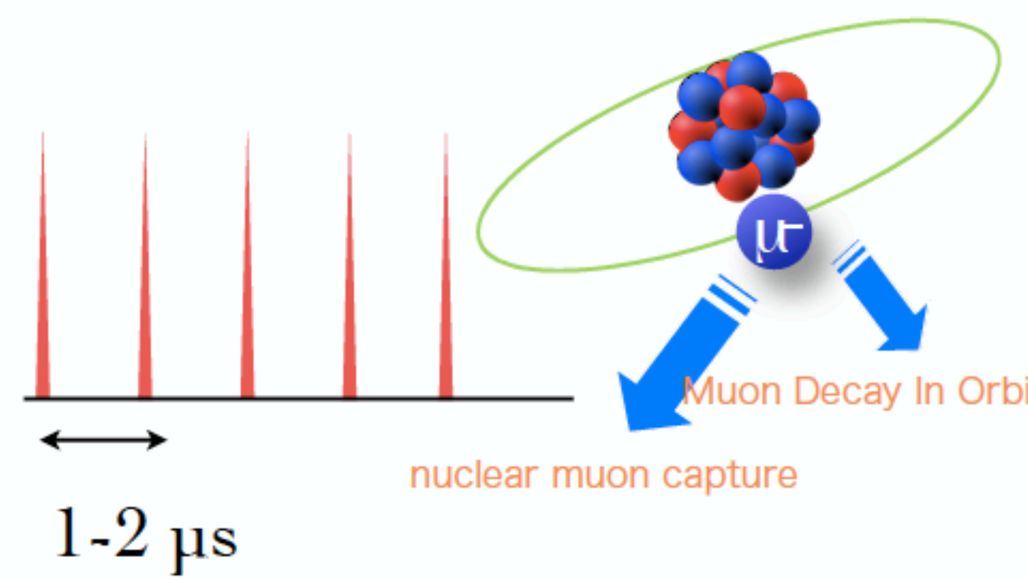
DC or Pulsed?

$I_{beam} \sim 10^{11}$ μ/s

- DC beam for coincidence experiments
  - $\mu \rightarrow e \gamma$, $\mu \rightarrow e\ e\ e$
- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI





@ JPARC, FERMILAB

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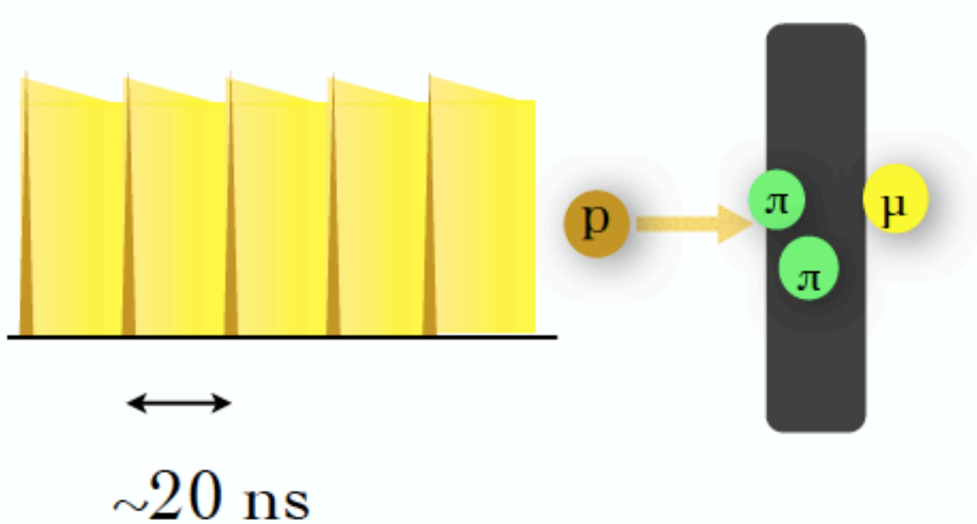
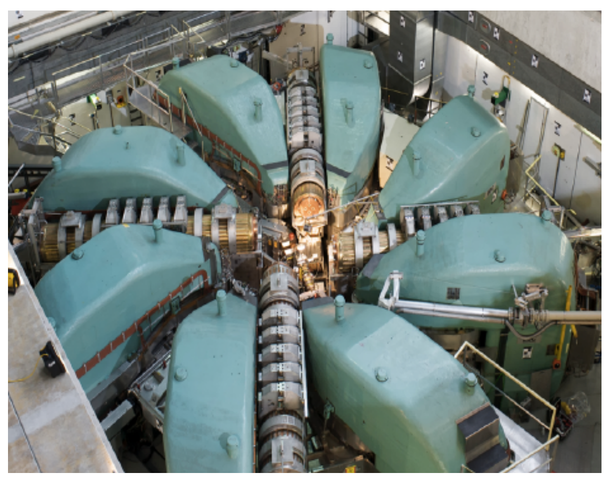


@ JPARC, FERMILAB

The world’s most intense continuous muon beam

- τ ideal probe for NP w. r. t. μ
    - Smaller GIM suppression
    - Stronger coupling
    - Many decays
- μ most sensitive probe
    - Huge statistics

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
- MEG/MEG II/Mu3e beam requirements:
    - Intensity O(10^8 muon/s), low momentum p = 29 MeV/c
    - Small straggling and good identification of the decay

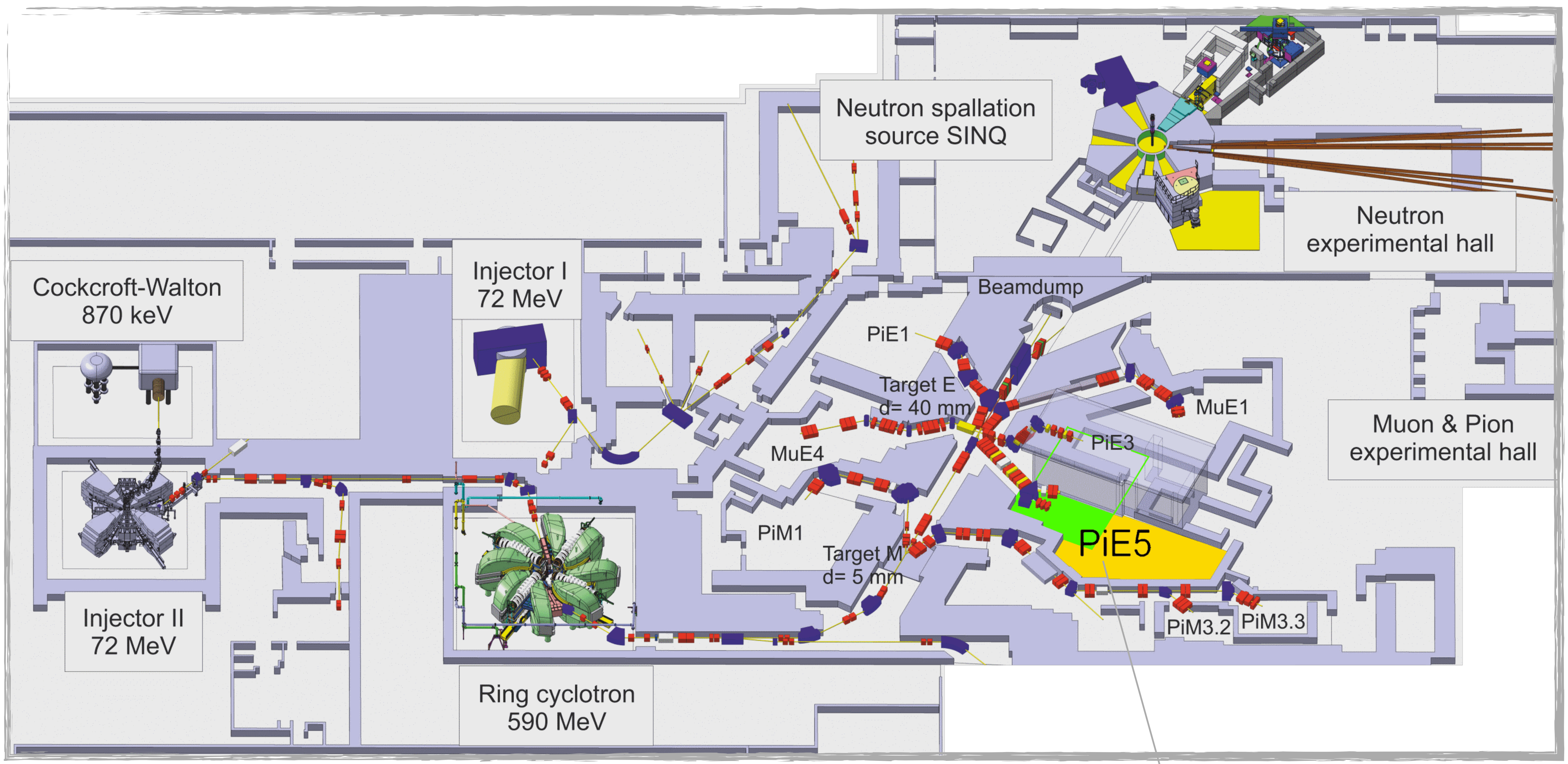


590 MeV proton
ring cyclotron
1.4 MW

PSI landscape

The world’s most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas

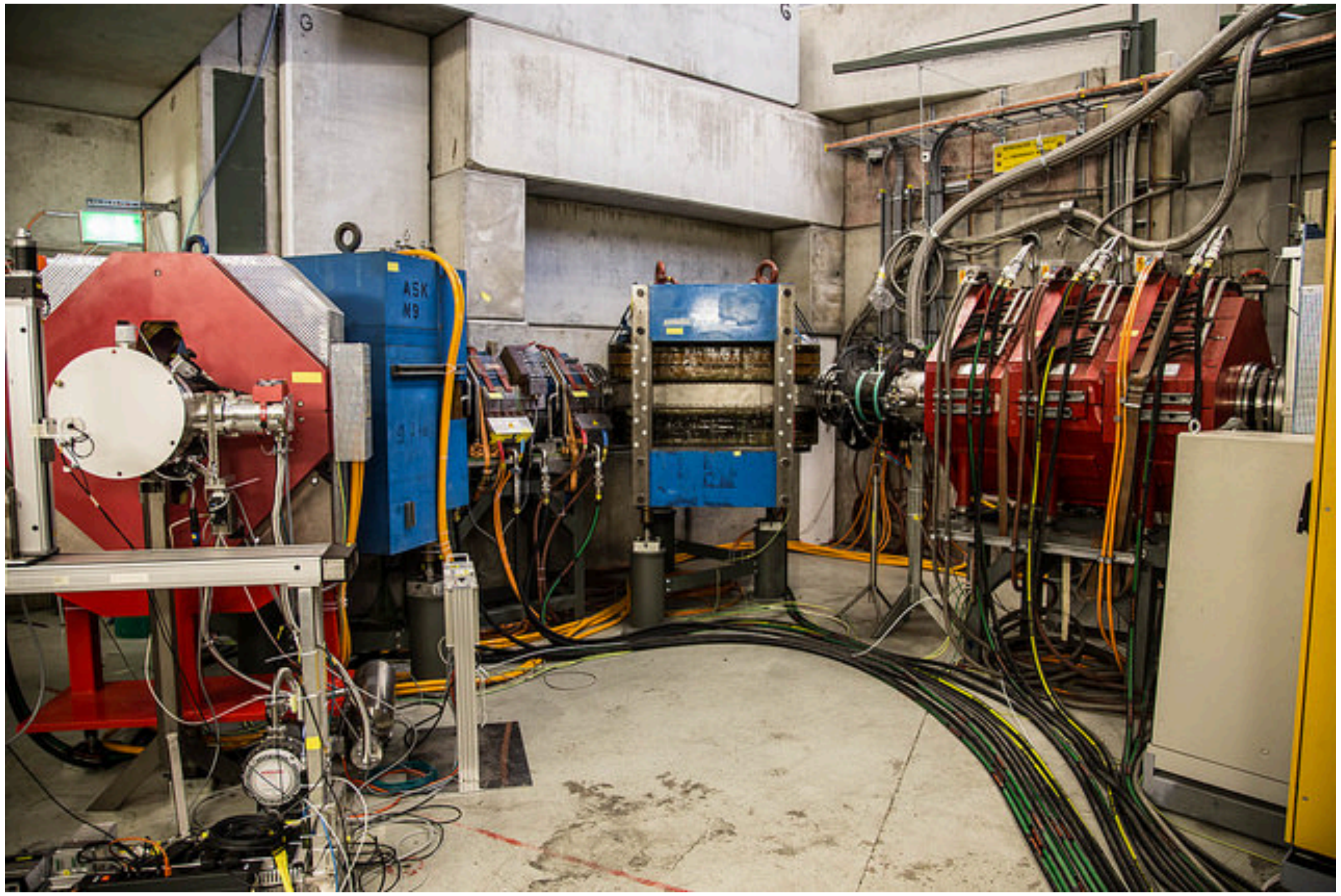


MEGII / Mu3e Experimental area

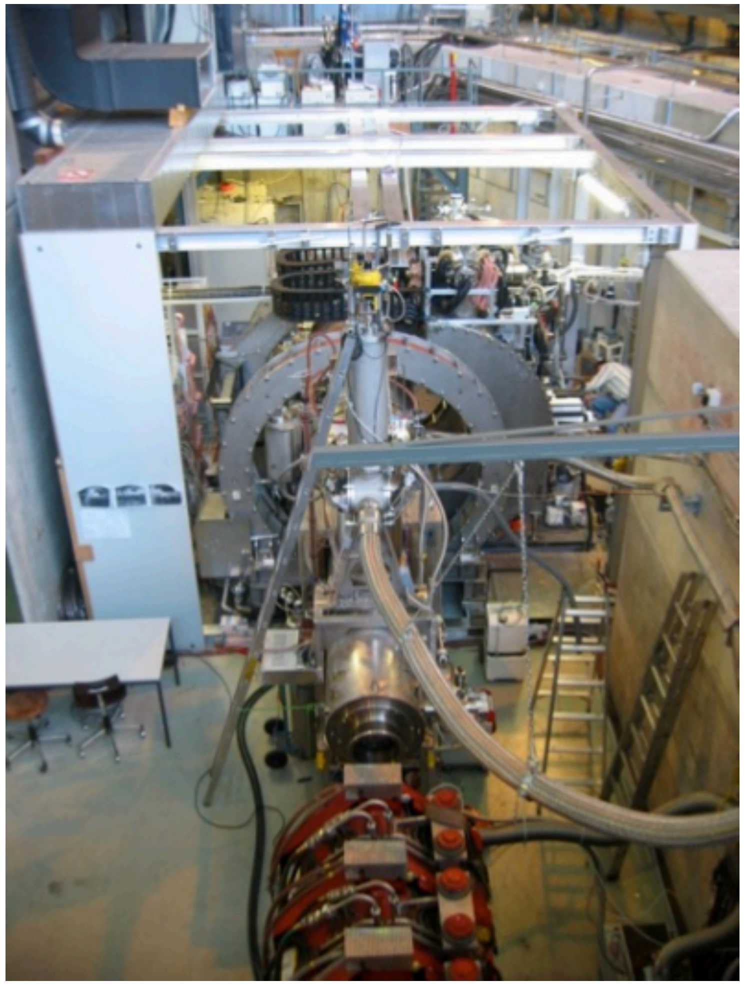
The MEGII (and Mu3e) beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered 8 x 10^7 muon/s during 2016 test beam

The Mu3e CMBL



The MEGII BL



The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Strategy:
  - Target optimization
  - Beam line optimization
- Time schedule: **O(2025)**

A. Knecht et al.,

The High intensity Muon Beam (HiMB) project at PSI

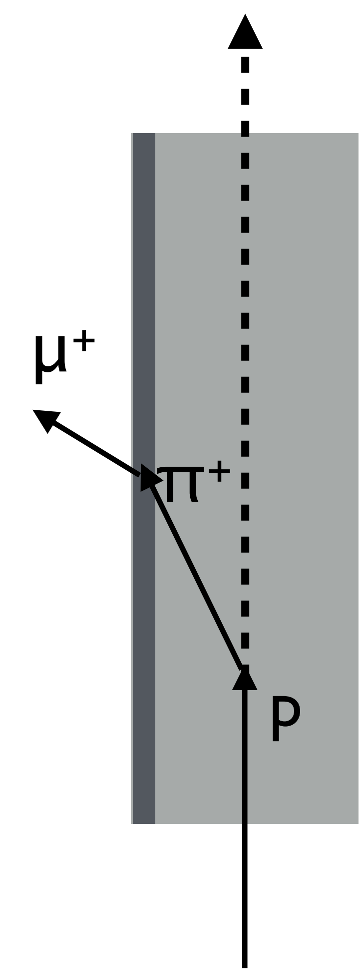
- Back to standard target to exploit possible improvements towards high intensity beams:
  - **Target geometry and alternate materials**
    - Search for high pion yield materials -> higher muon yield

$$\text{relative } \mu^+ \text{yield} \propto \pi^+ \text{stop density} \cdot \mu^+ \text{Range} \cdot \text{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_X (Z/A)_X}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

$$\propto \frac{1}{Z^{2/3}}$$



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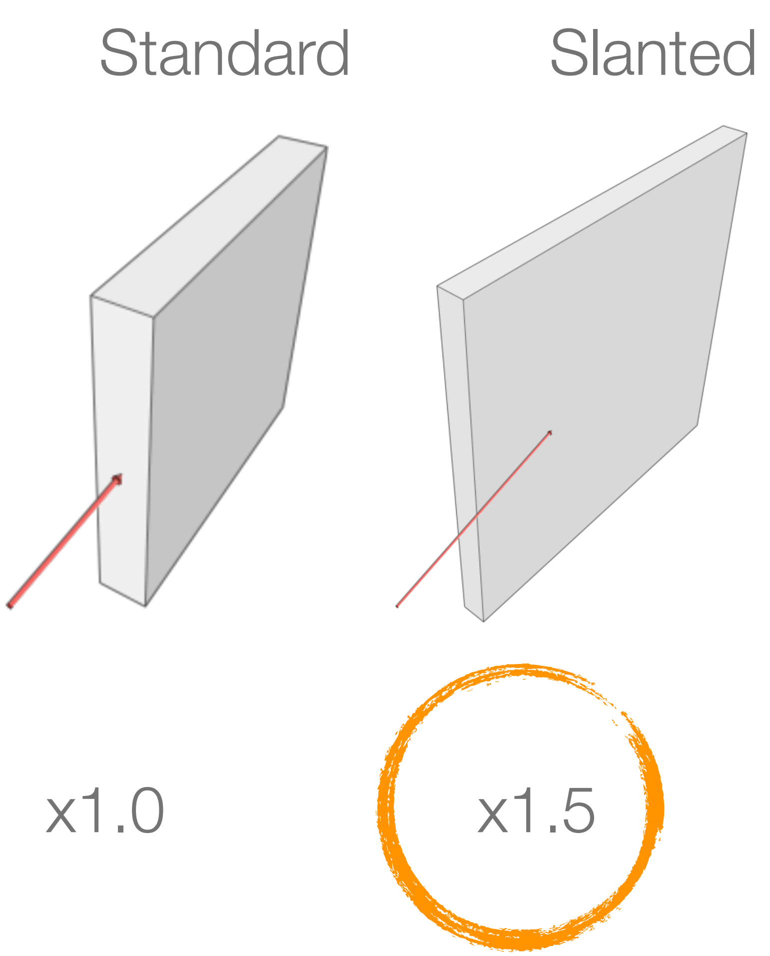
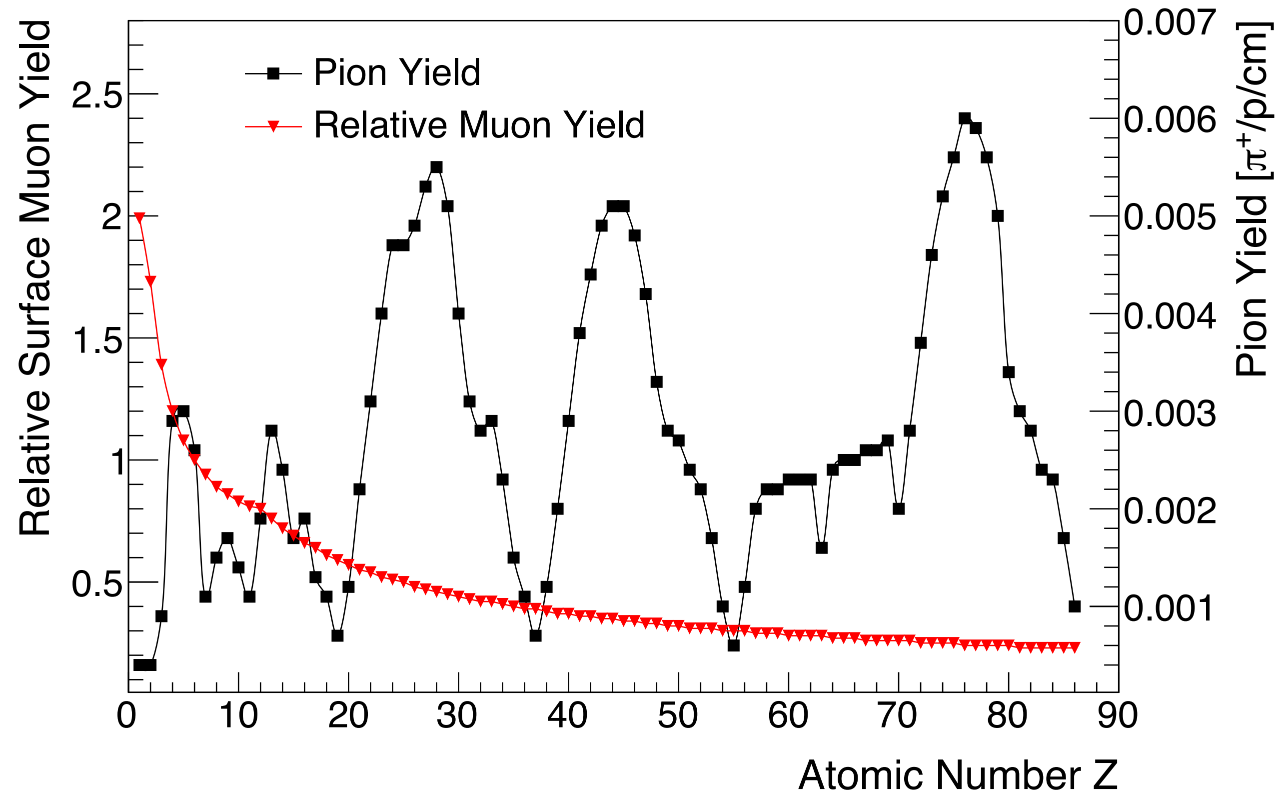
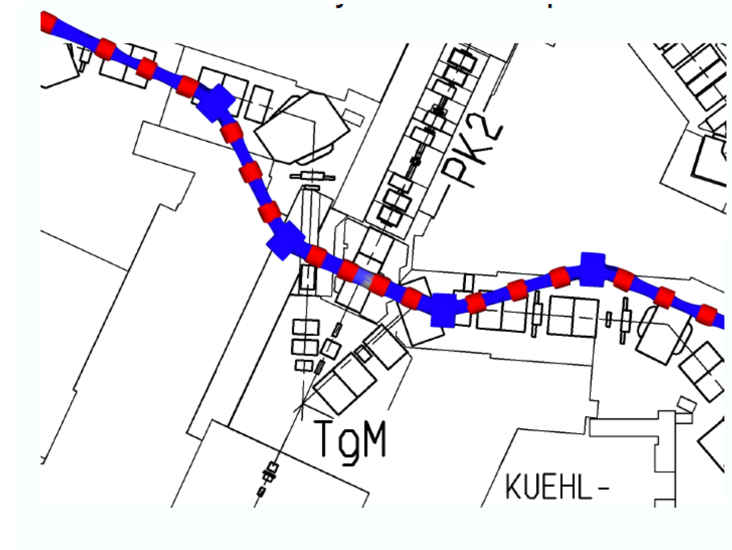




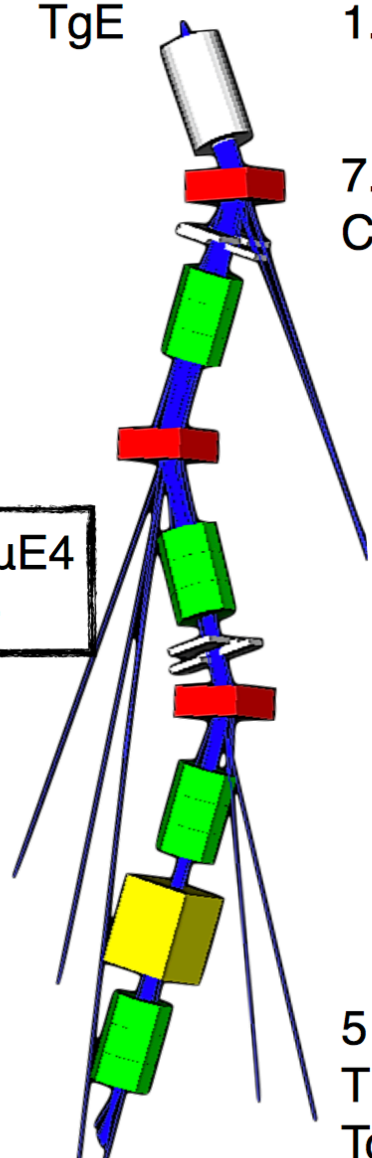
New

The High intensity Muon Beam (HiMB) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Slanted E target test (“towards the new M-target”): planned for **next year**
- Time schedule: **O(2025)**

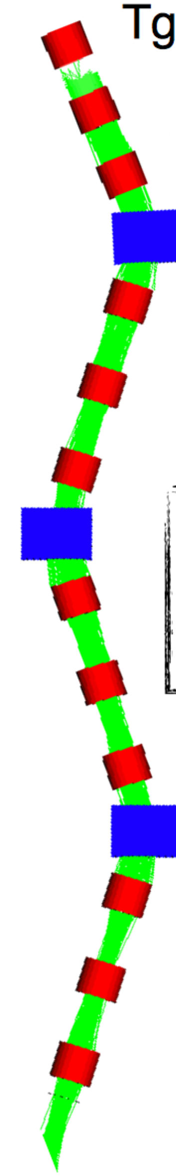


TgE



Existing μE4 beamline

TgM*



Proposed solenoid beamline

TgE		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%

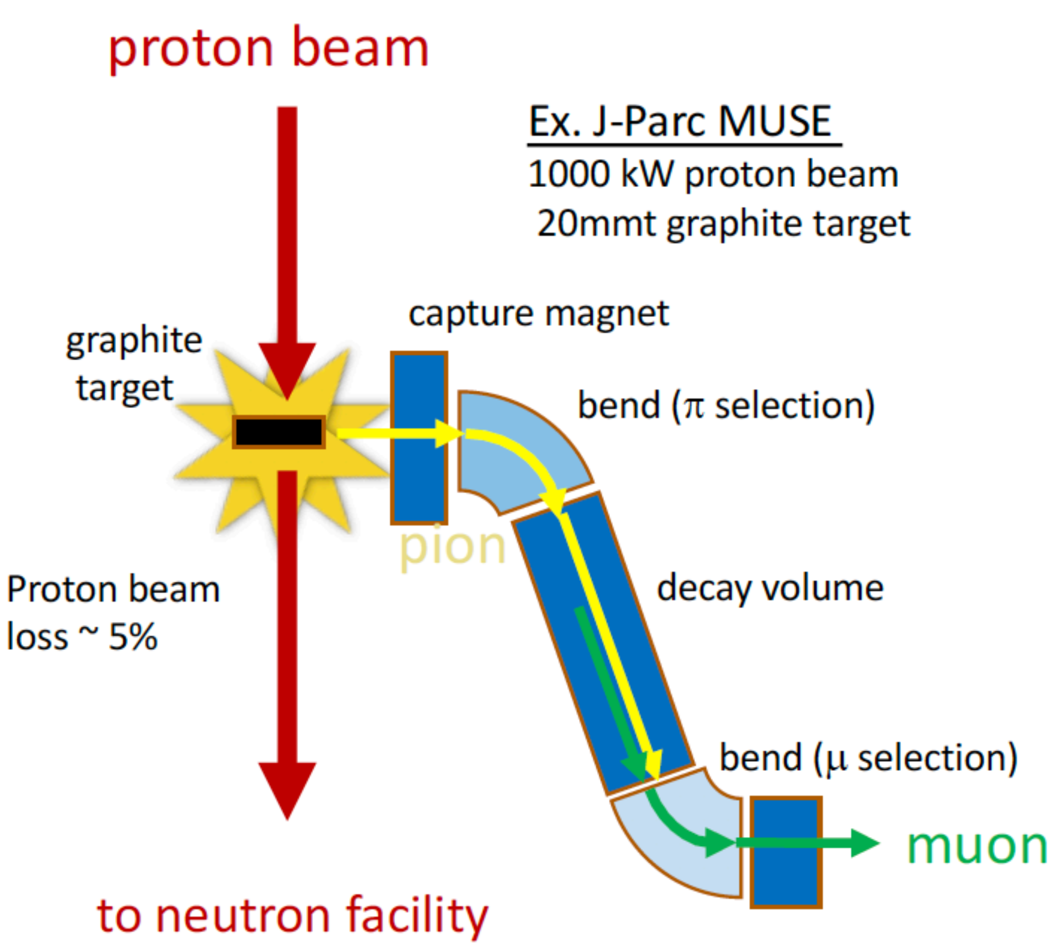
⇒ Gain due to high capture and transmission efficiency

A. Papa’s talk: This afternoon WG4 group

MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Aim: O($\mathbf{10^8}$ muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam

Conventional muon beamline



- Thin target (~ 20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

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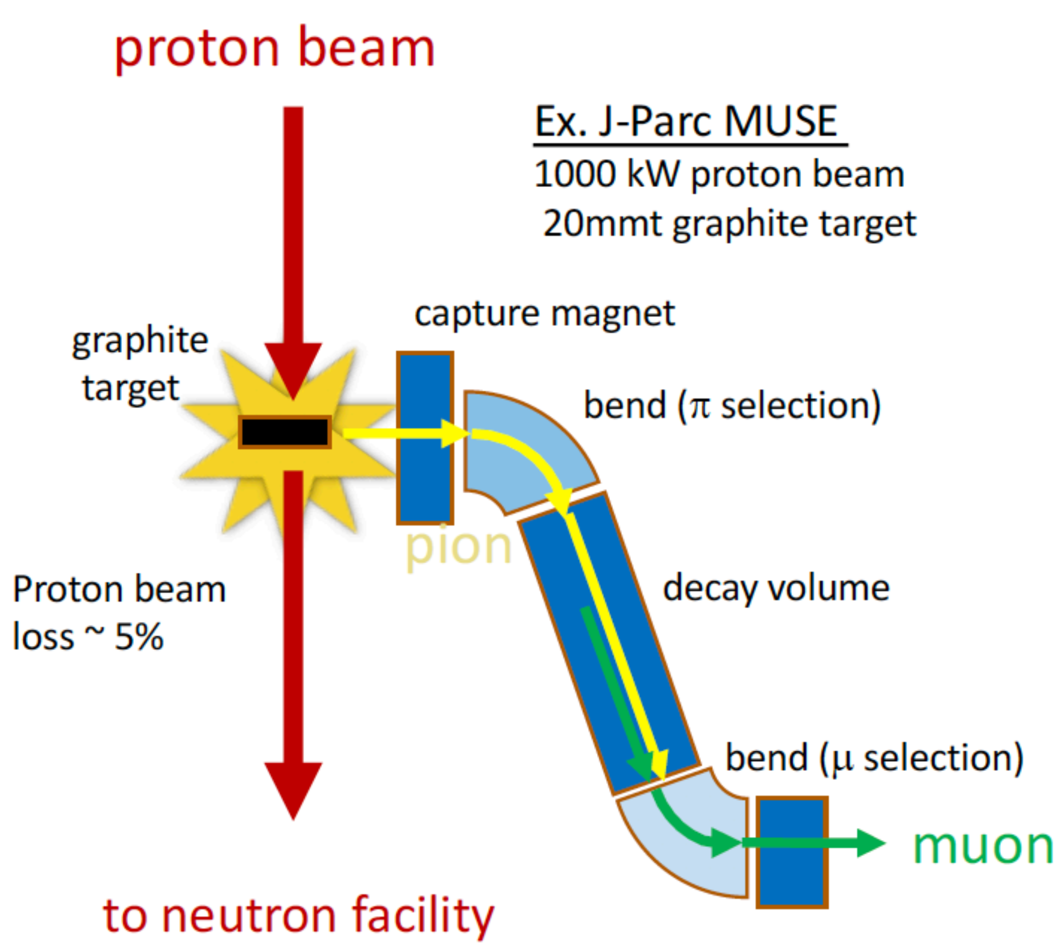

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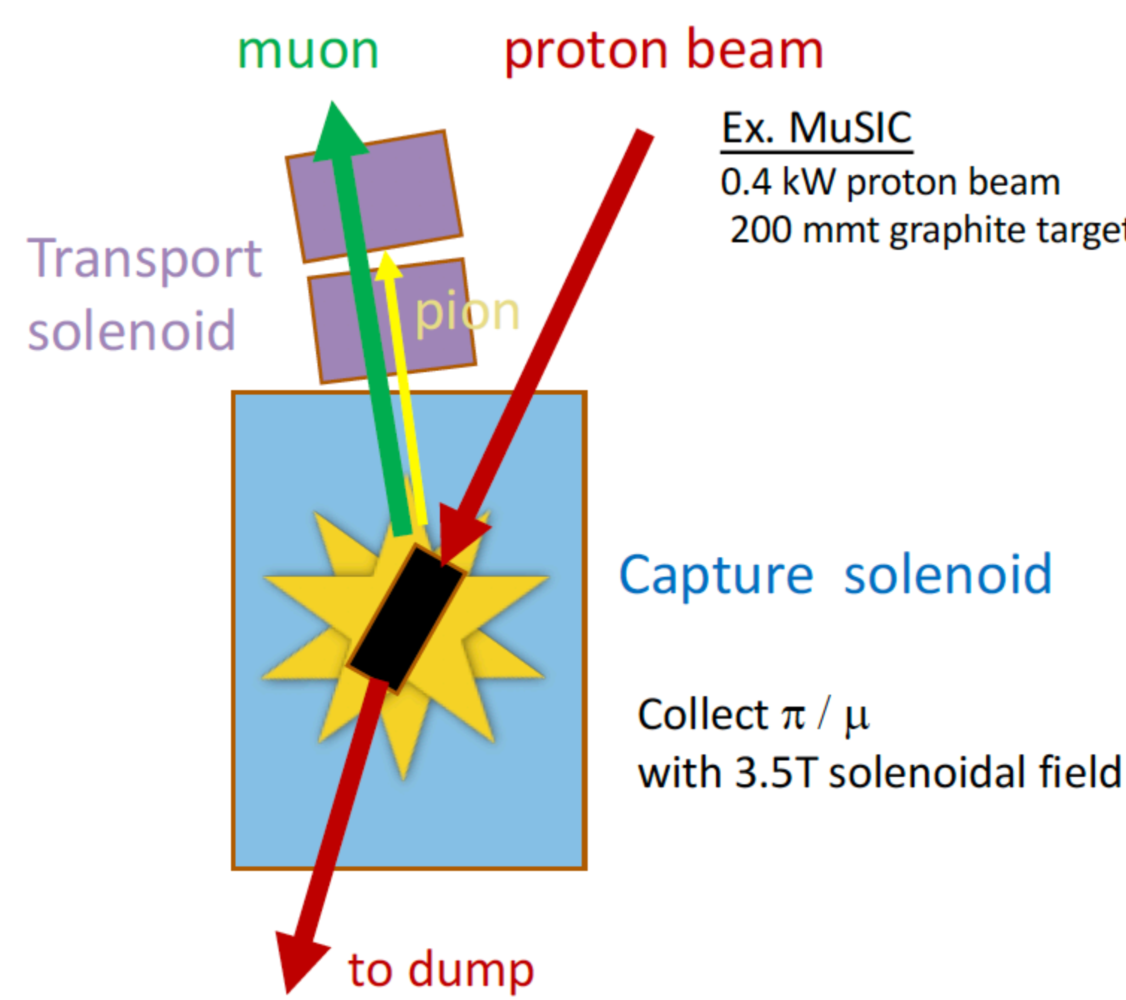
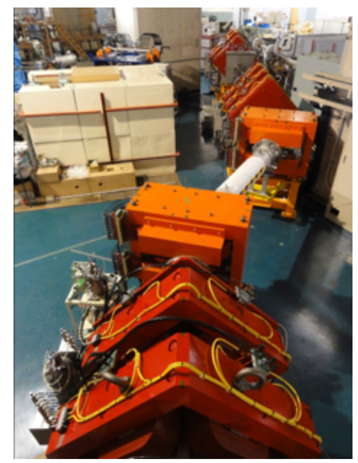
MuSIC beamline



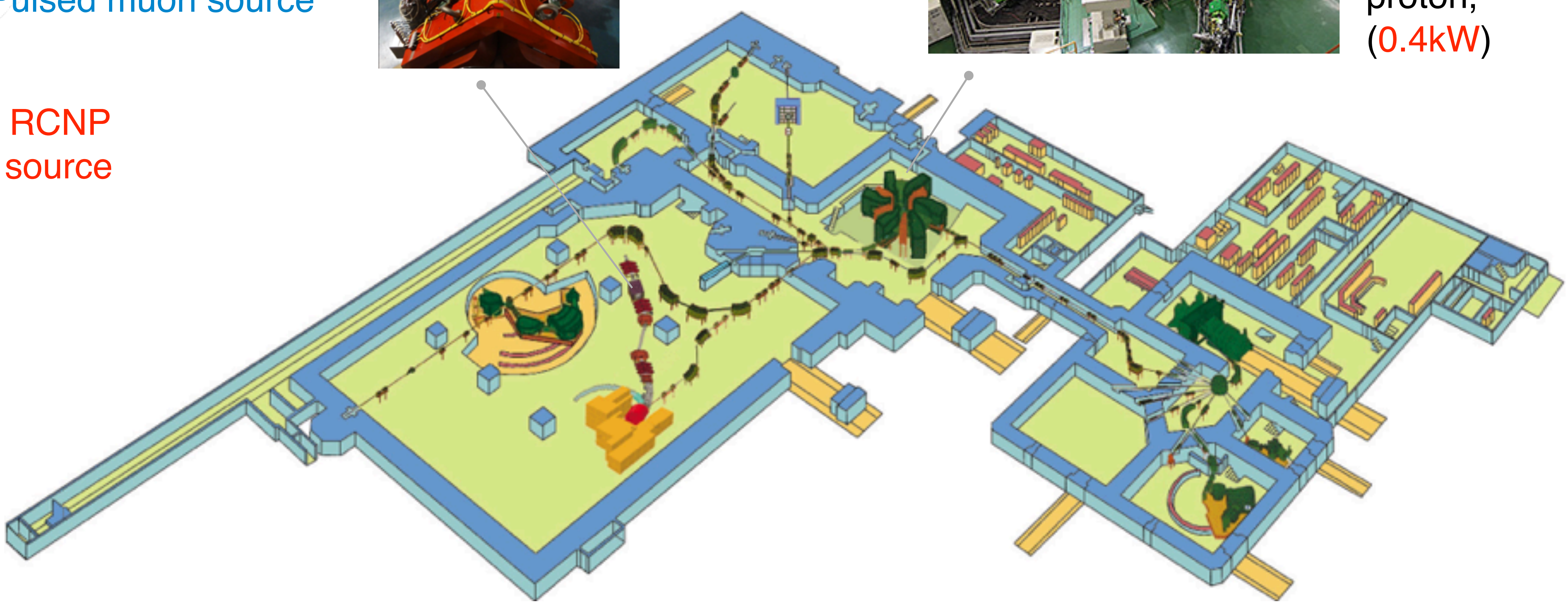
- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University



MuSIC
M1 Beam line

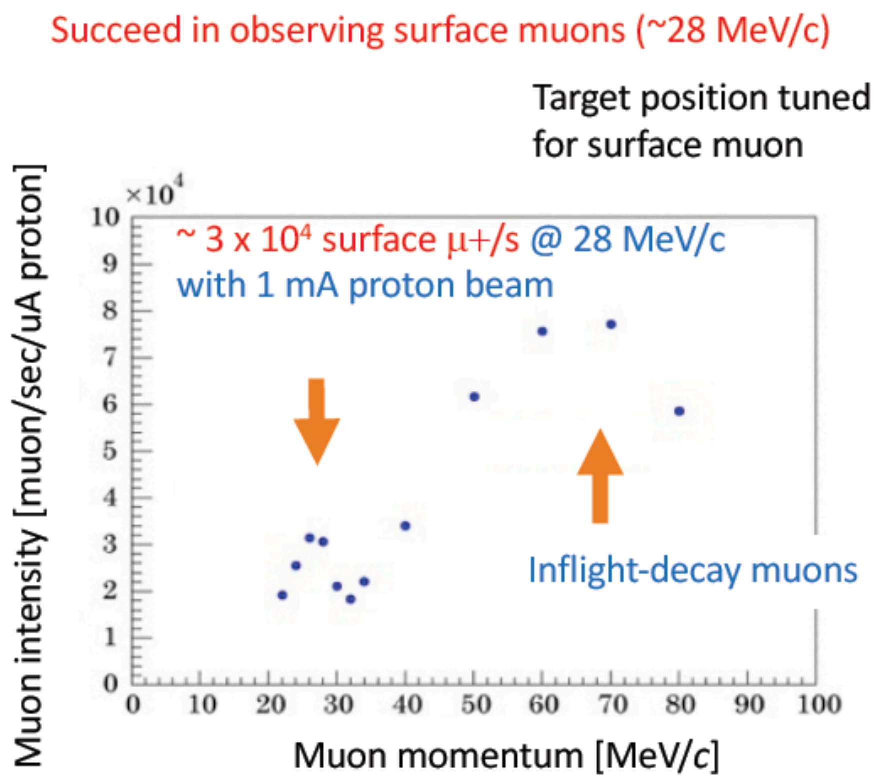
Ring
Cyclotron
~392MeV
(variable)
1.1uA
proton,
(0.4kW)

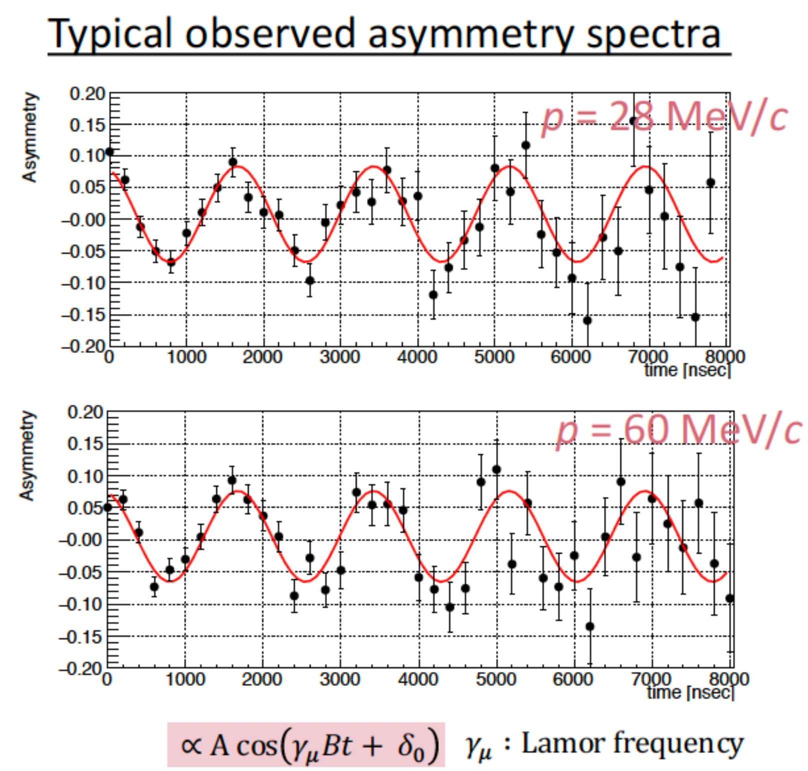


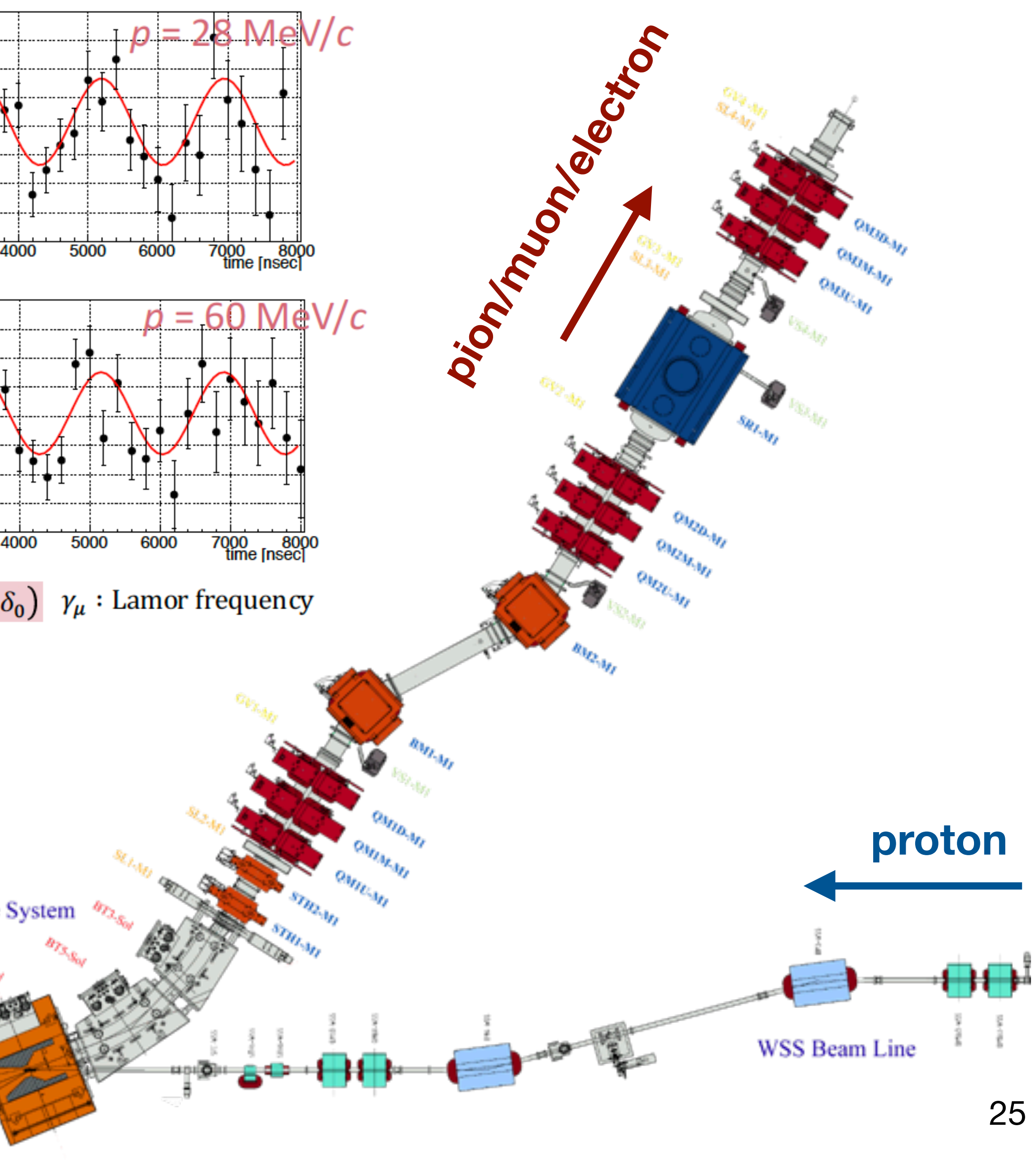
- proton beam energy is only 100 MeV above pion production threshold (～$2m_\pi$)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)

MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Multi-purpose facility. Beam line commissioning







Status:

- Start experiments with negative and positive muons
- Muon capture and X-ray elemental analysis are in progress
- DC μSR study (still in commissioning for user experiments)

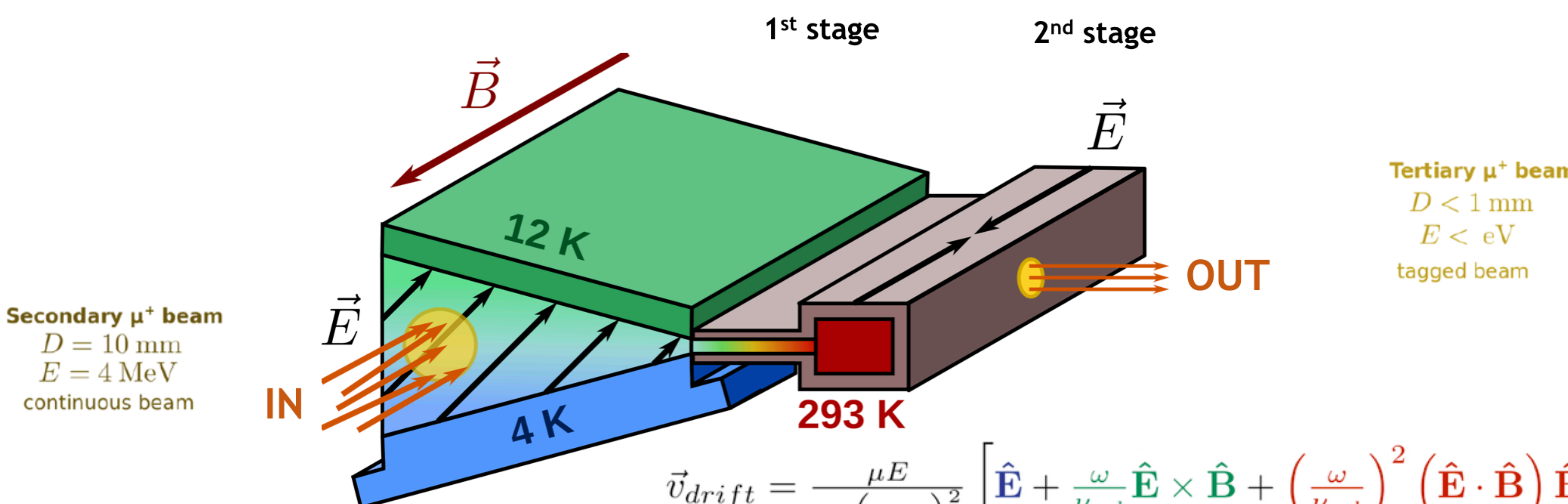
D. Taqqu, PRL 97 (2006) 194801
Y. Bao, A.P. et al., PRL 112 (2014) 224801

The muCool project at PSI

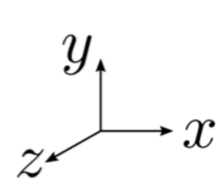
New

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-3}**

for:
μSR (solid state physics)
muonium (spectroscopy, gravitational interaction...)
muon experiments (μEDM, g-2…)



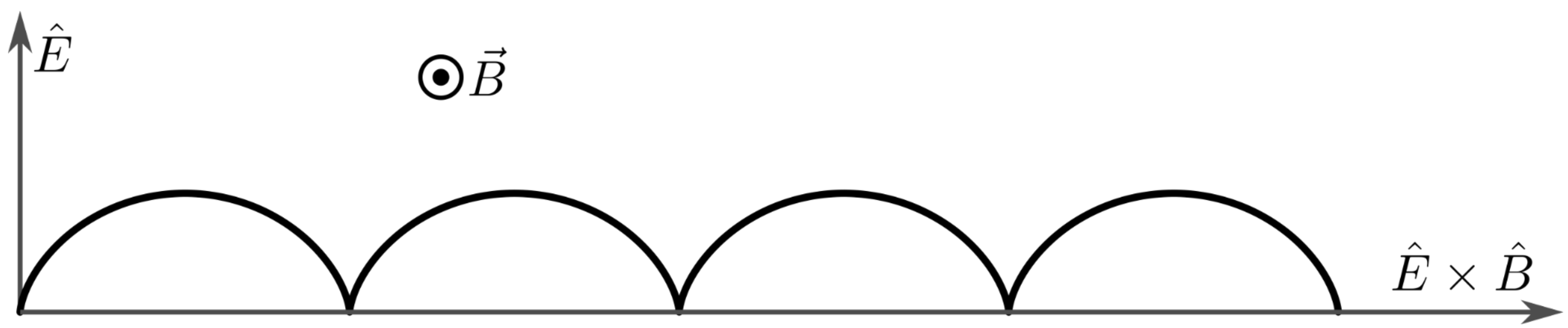
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$



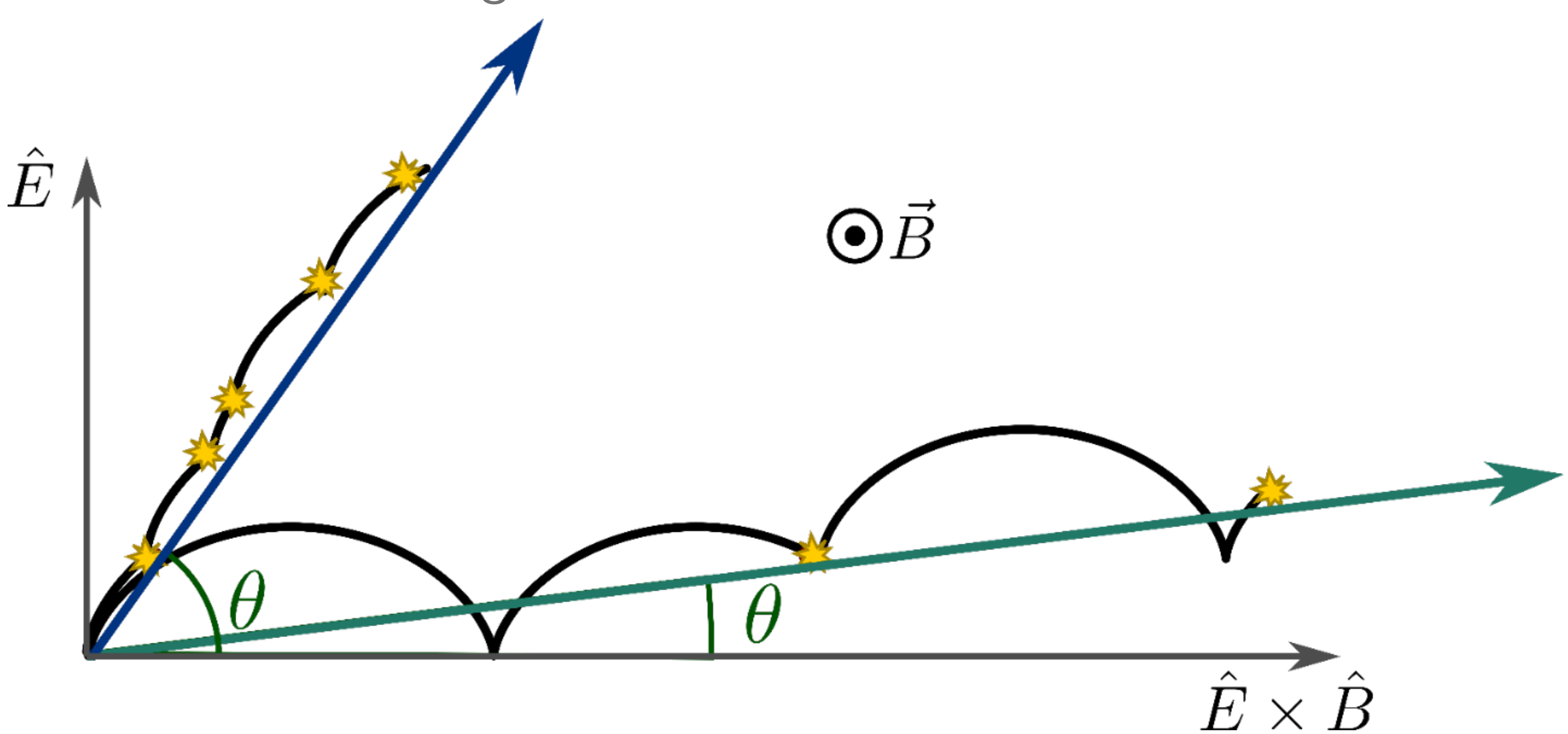
→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

Trajectories in E and B field + gas

- E and B field

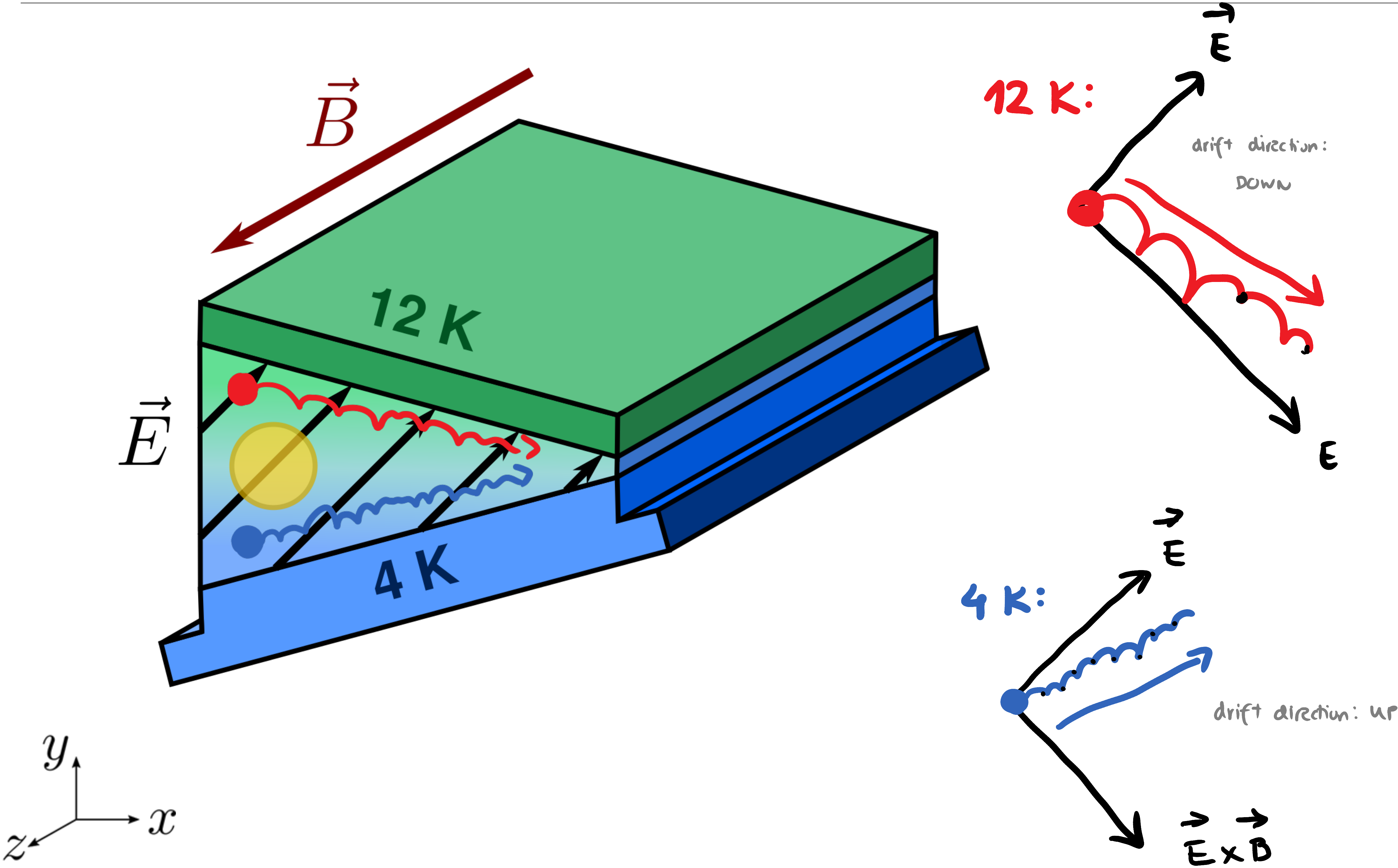


- E and B field + gas



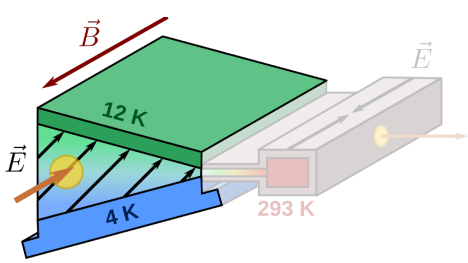
$$\tan\theta \propto f_{col}$$

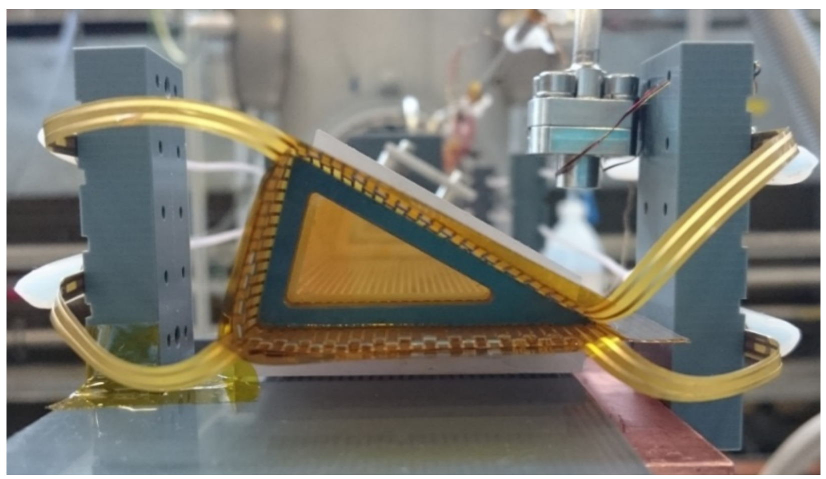
Working principle: 1st Stage

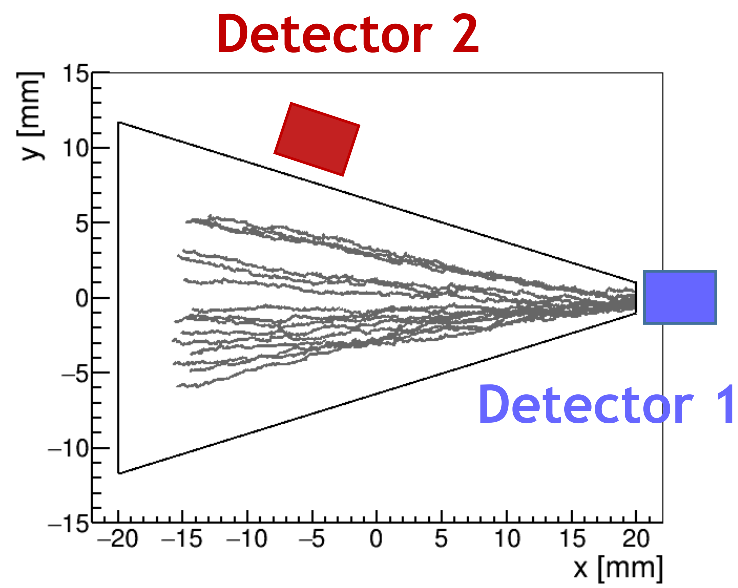


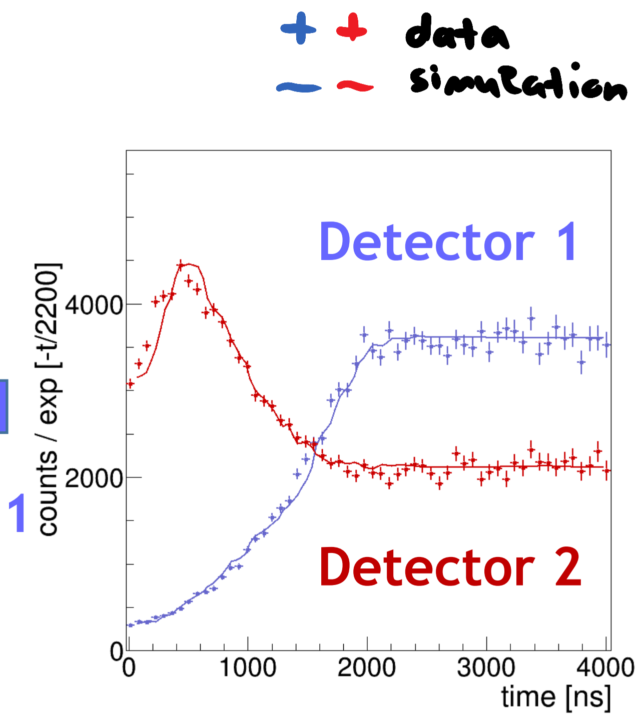
The muCool project at PSI: Status

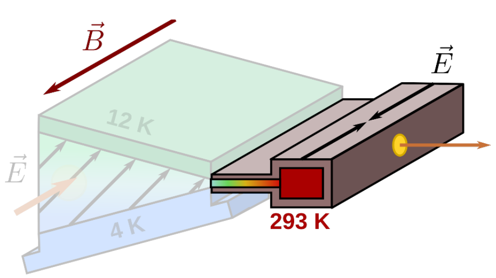
- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**

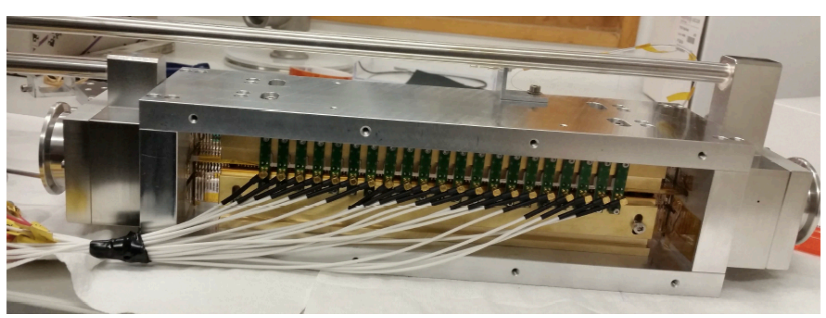


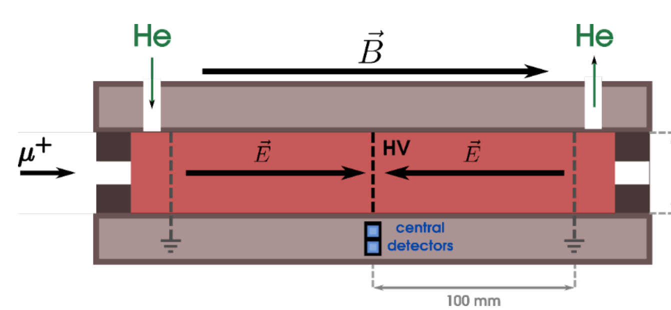


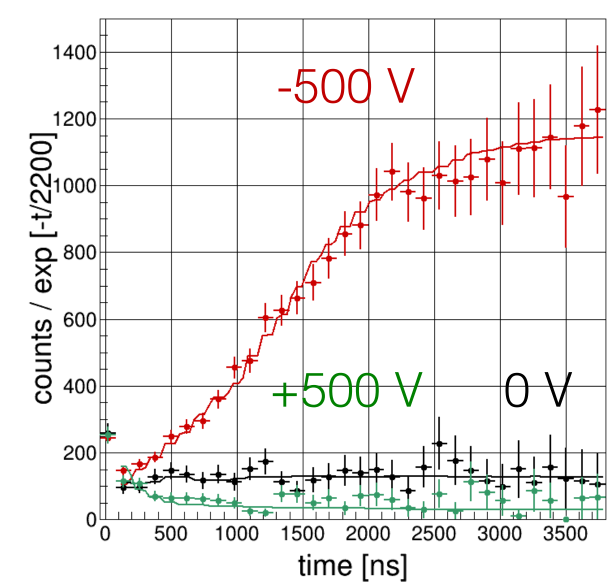






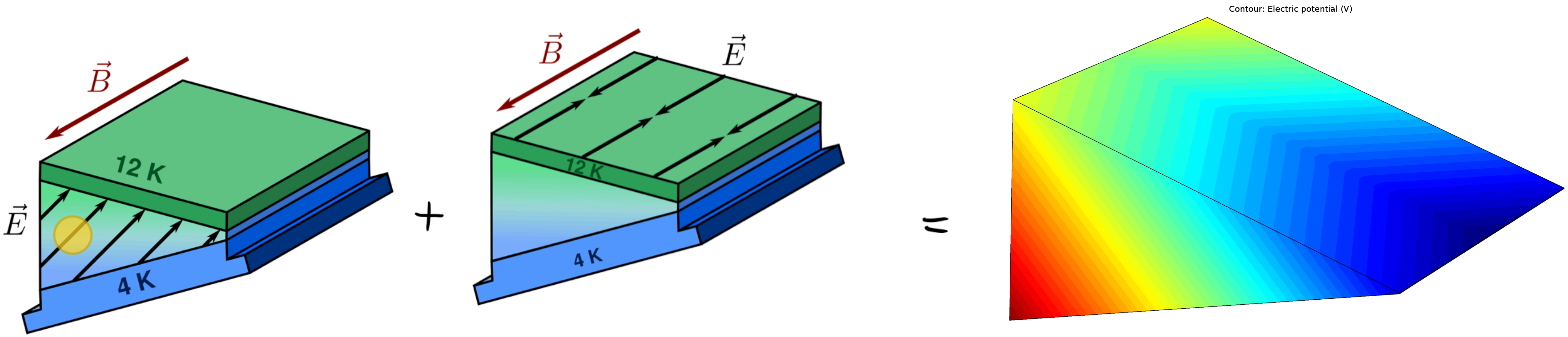


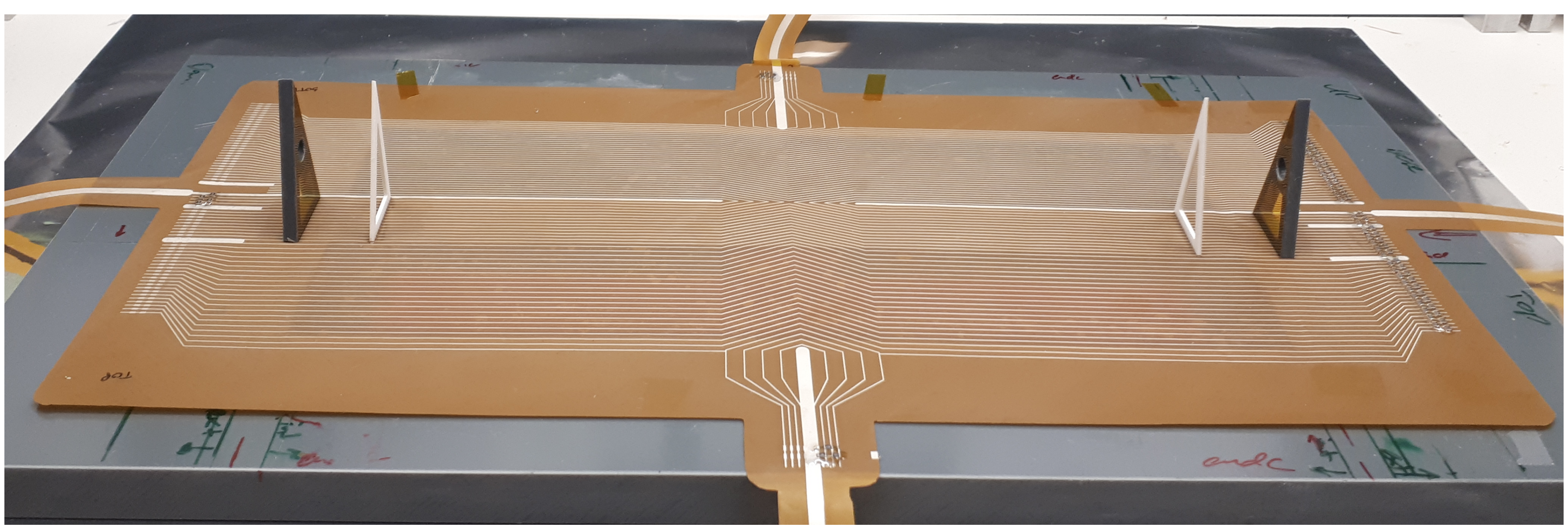




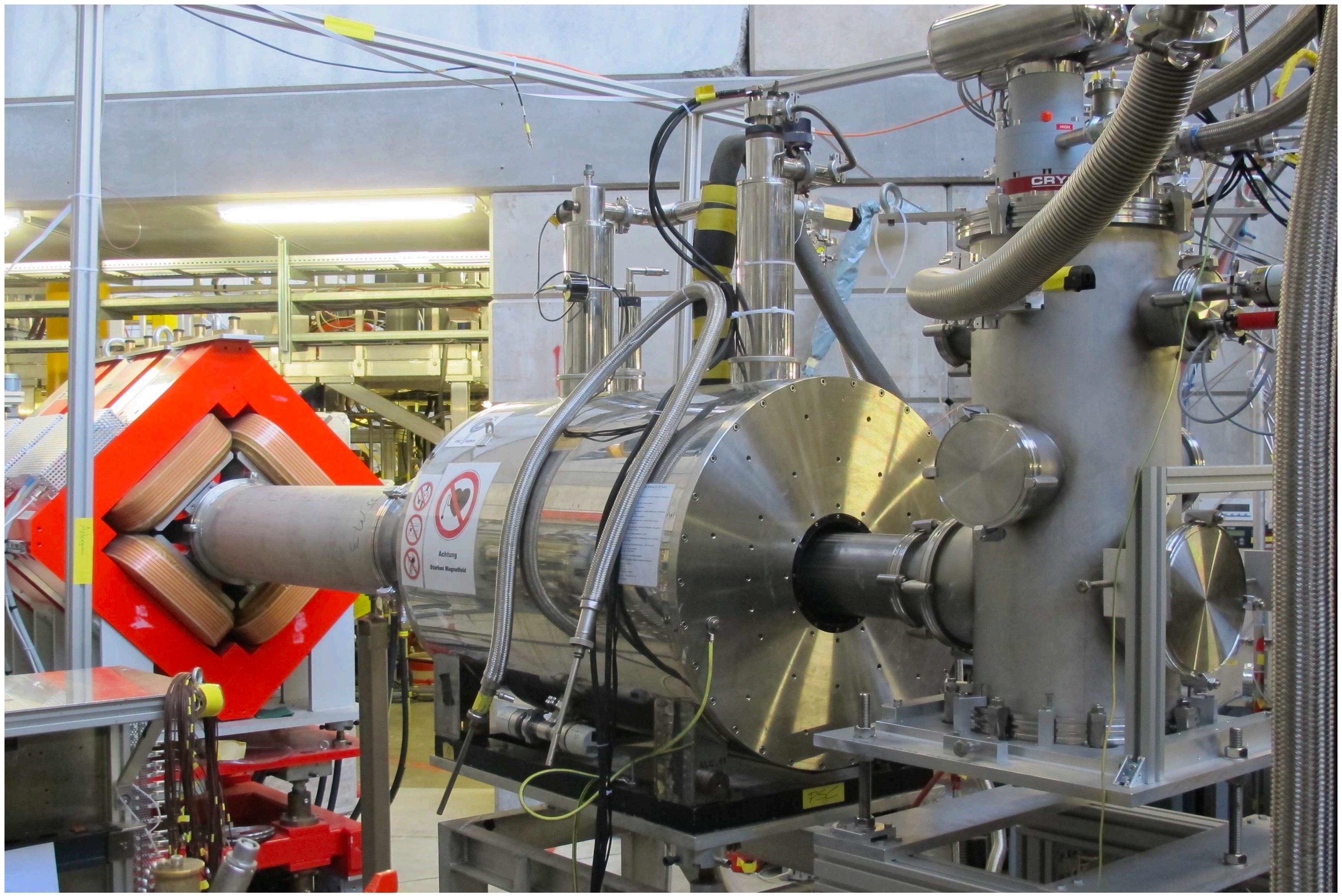
The muCool project at PSI: Status

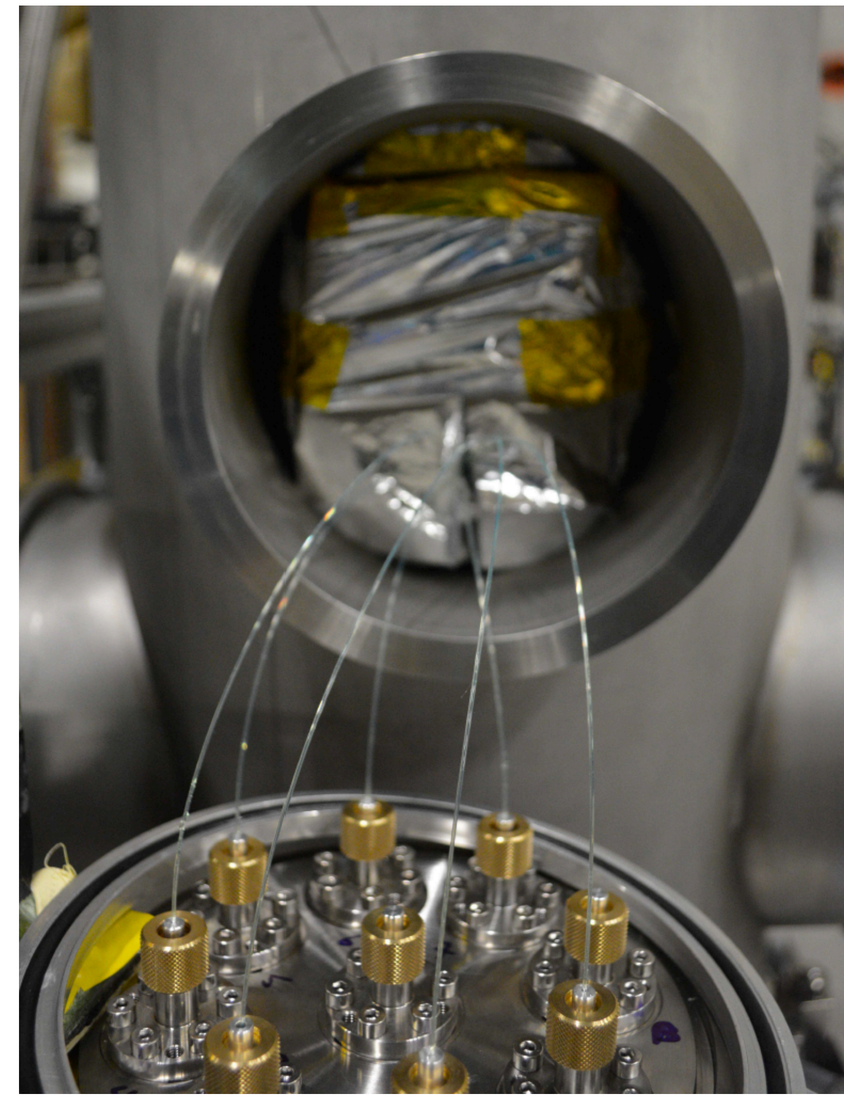
- 1st stage + 2nd stage
- **Next Step**: Extraction into vacuum



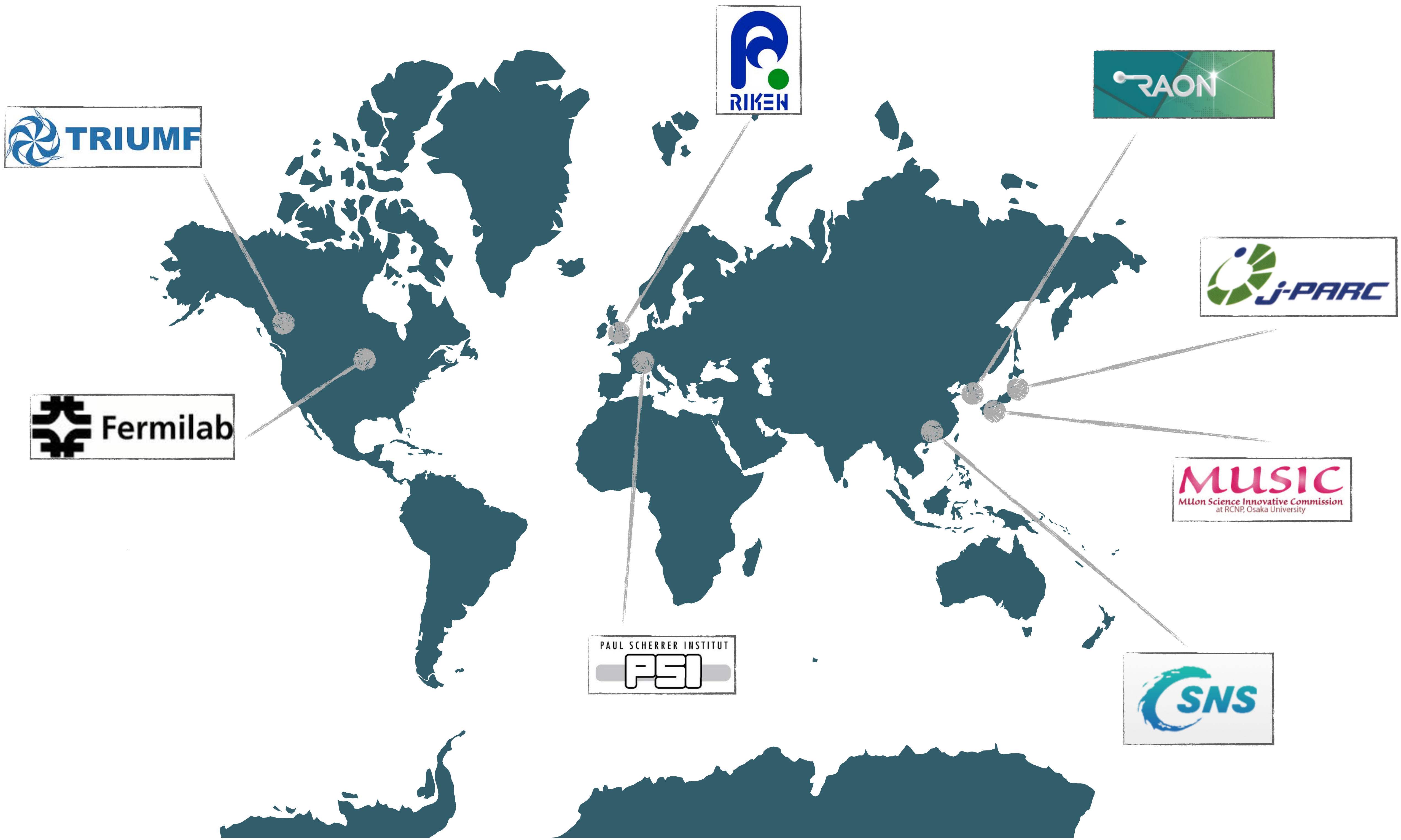


The muCool project at PSI: Status





DC and Pulsed muon beams - present and future



L. Calibbi and G. Signorelli, il Nuovo Cimento **41** (2018) 71

DC and Pulsed muon beams - present and future

Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7 (\mu^+)$ $6.4 \times 10^7 (\mu^+)$ $1 \times 10^{11} (\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10} (\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6 (\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4 (\mu^-)$ $6 \times 10^5 (\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5 (\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4 (\mu^-) \div 10^5 (\mu^+)$ $10^7 (\mu^-) \div 10^8 (\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5 (\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8 (\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8 (\mu^+)$(>2020)	

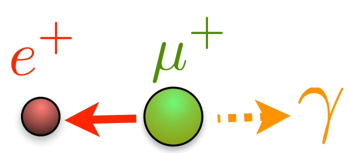
MEG: Signature, experimental setup and result

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

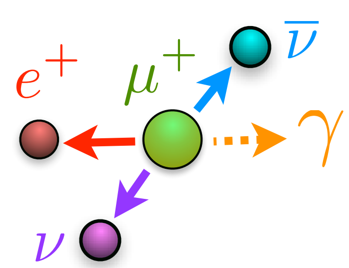
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

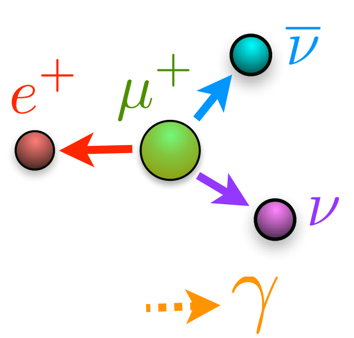
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events

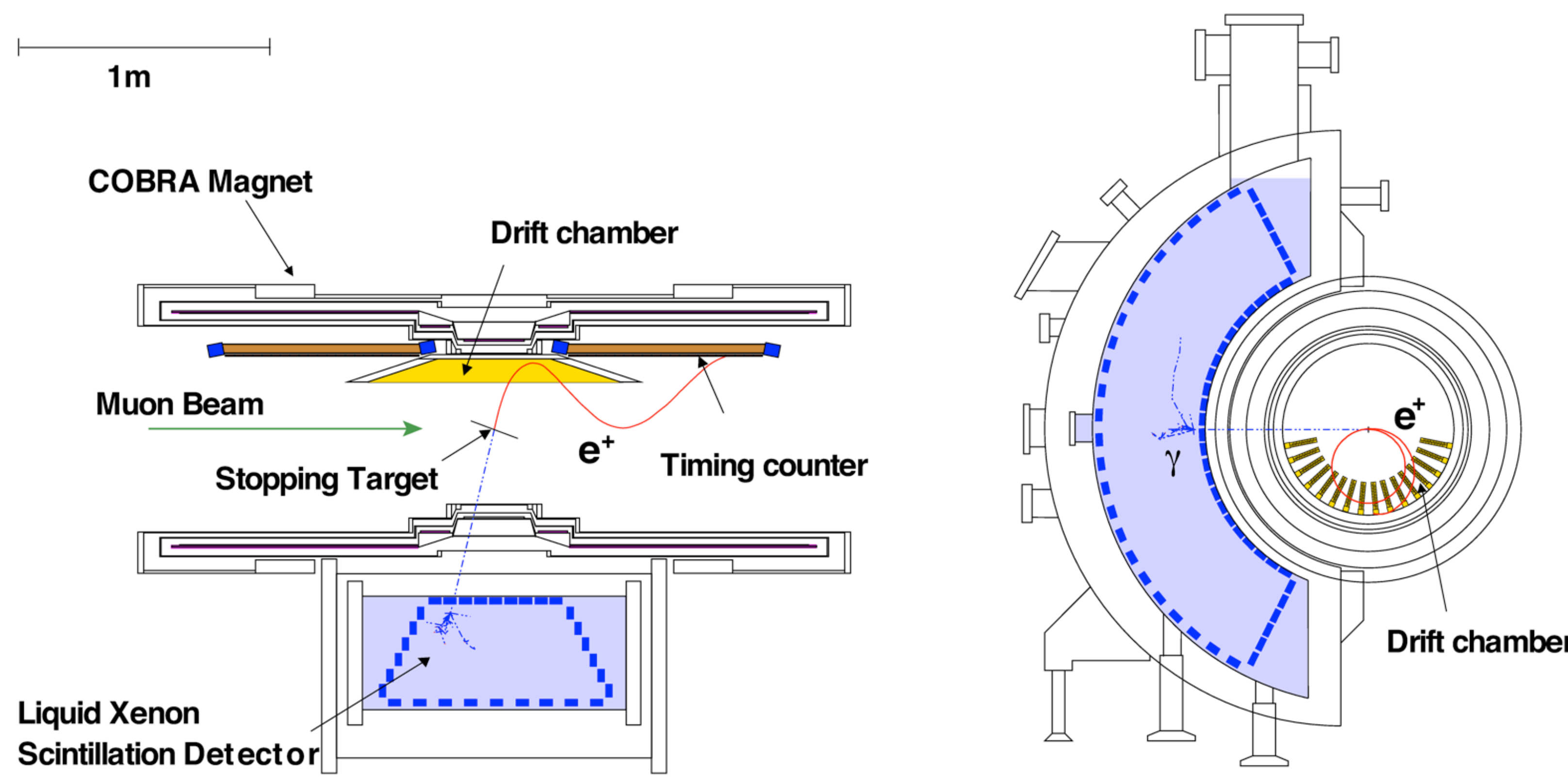
Signature



Backgrounds







Full data sample: 2009-2013
Best fitted branching ratio at 90% C.L.:

$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$$

A.M. Baldini et al. (MEGII collab.)
Eur. Phys. J. 78 (2018) 380

The MEGII experiment

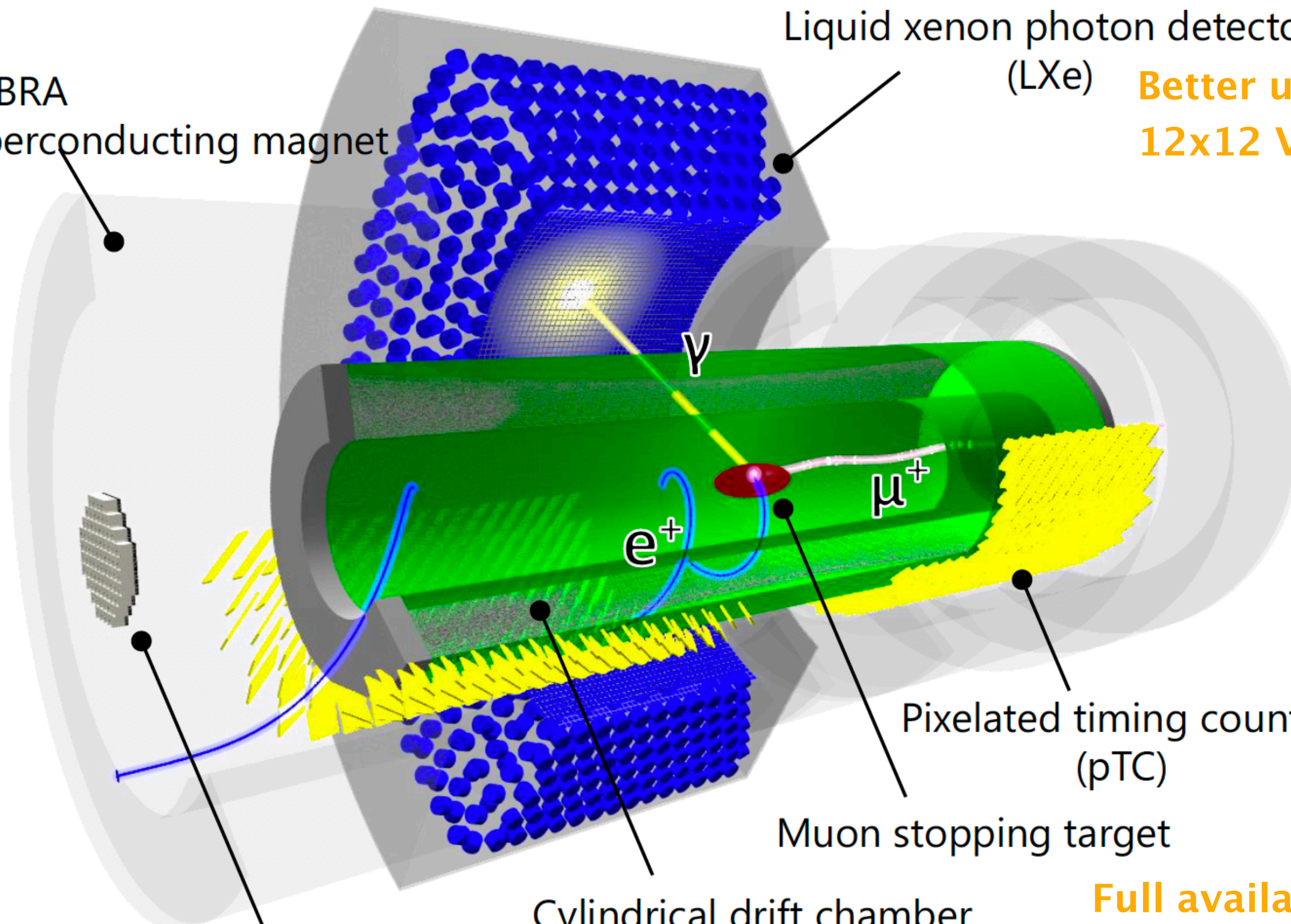
New electronics:
Wavedream

~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

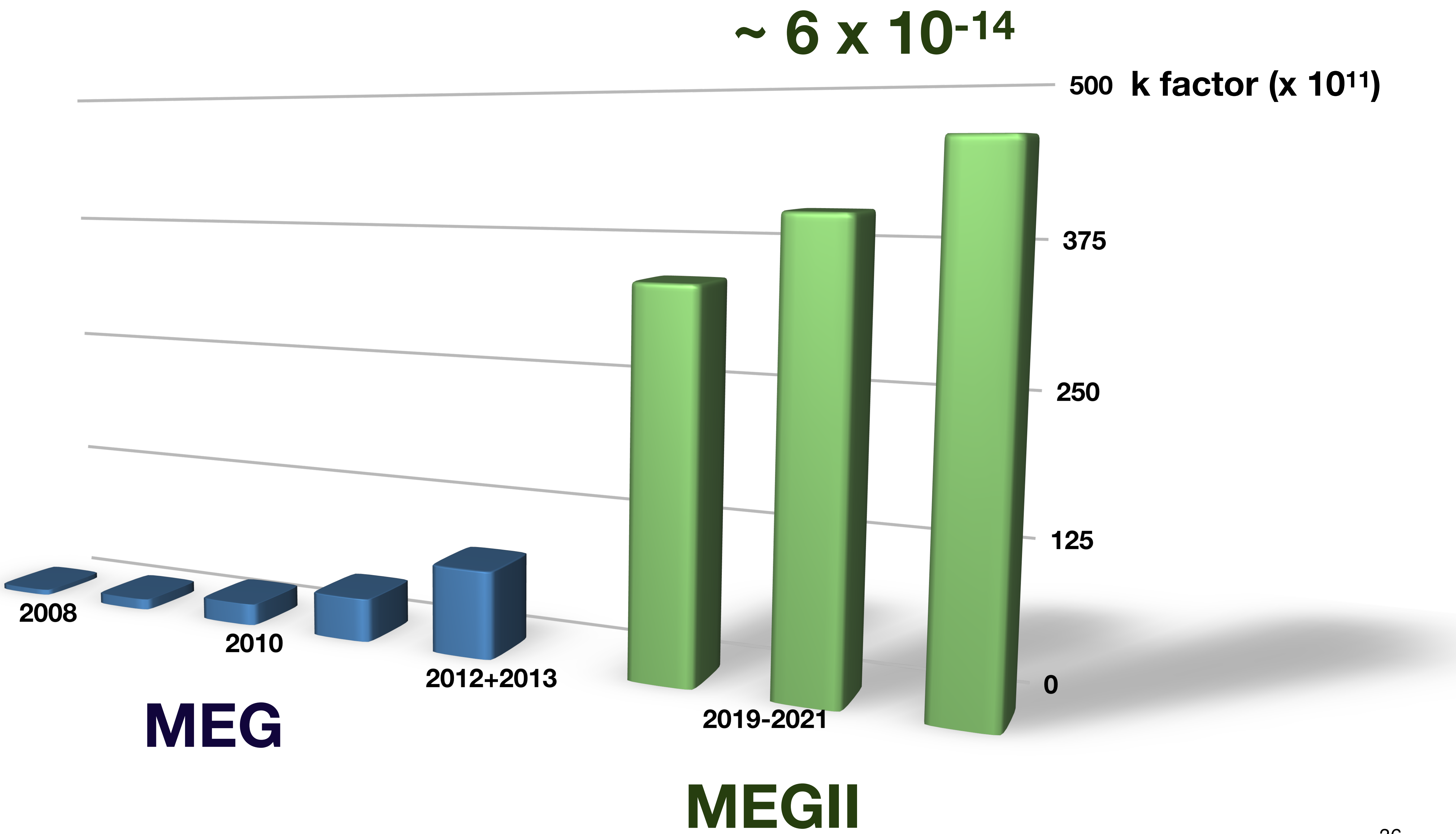
35 ps resolution w/ multiple hits

Background rejection

Single volume $He:iC_4H_{10}$

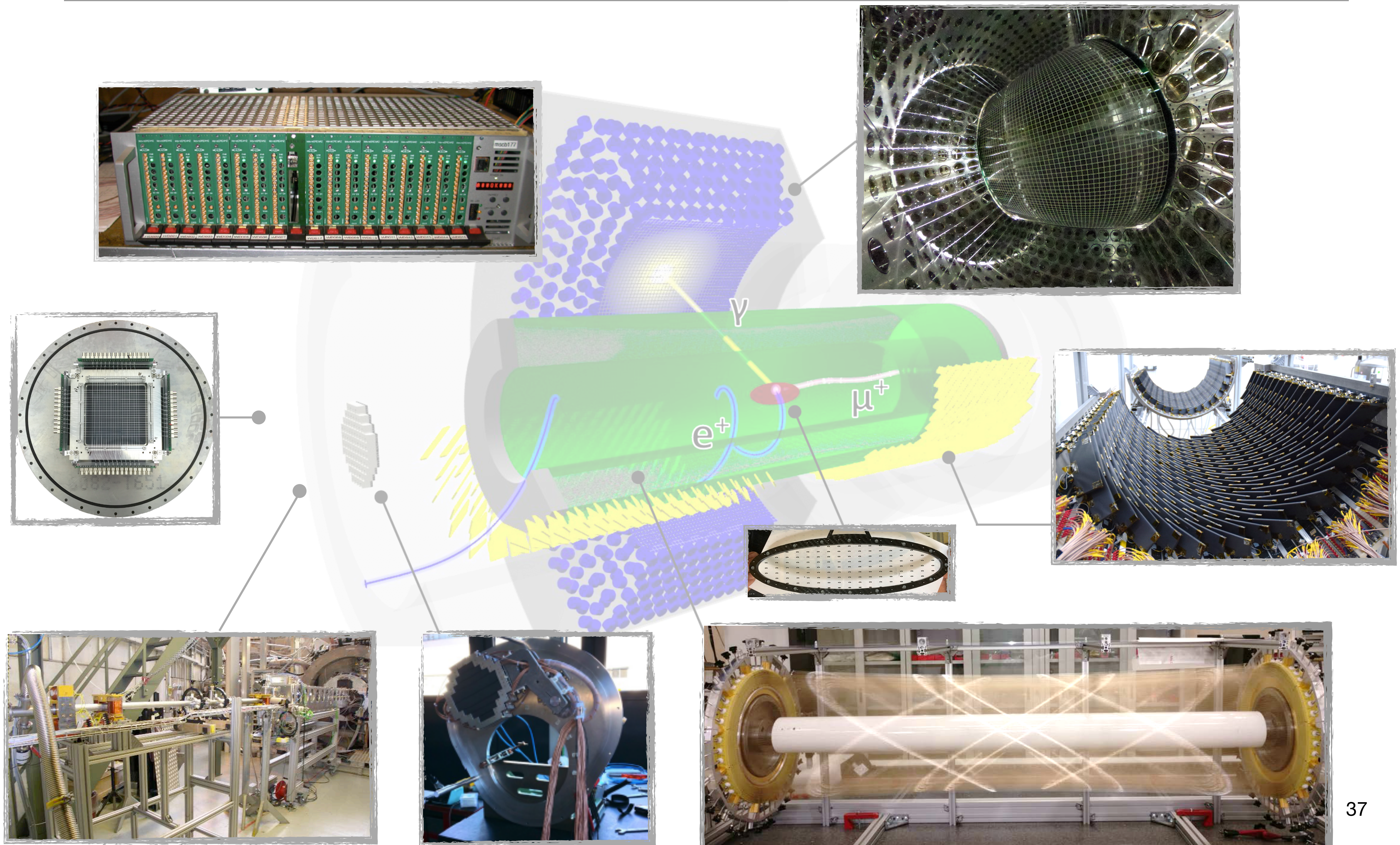
Full available stopped beam intensity
7×10^7

Where we will be



A. Papa’s talk:
Mon. WG4 group

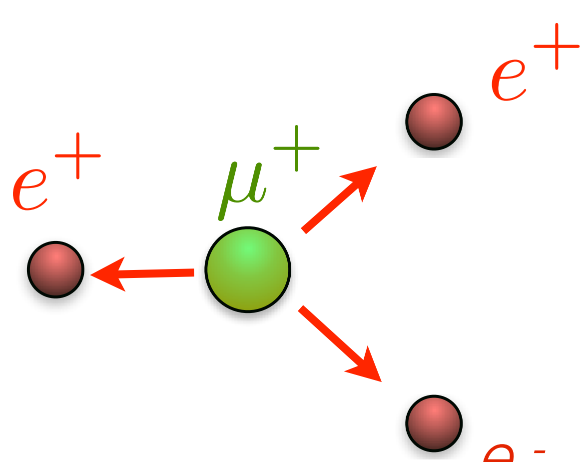
Where we are: Full engineering run in preparation



Mu3e: The $\mu^+ \to e^+ e^+ e^-$ search

- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit $BR(\mu^+ \to e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to eee$ events

Signature

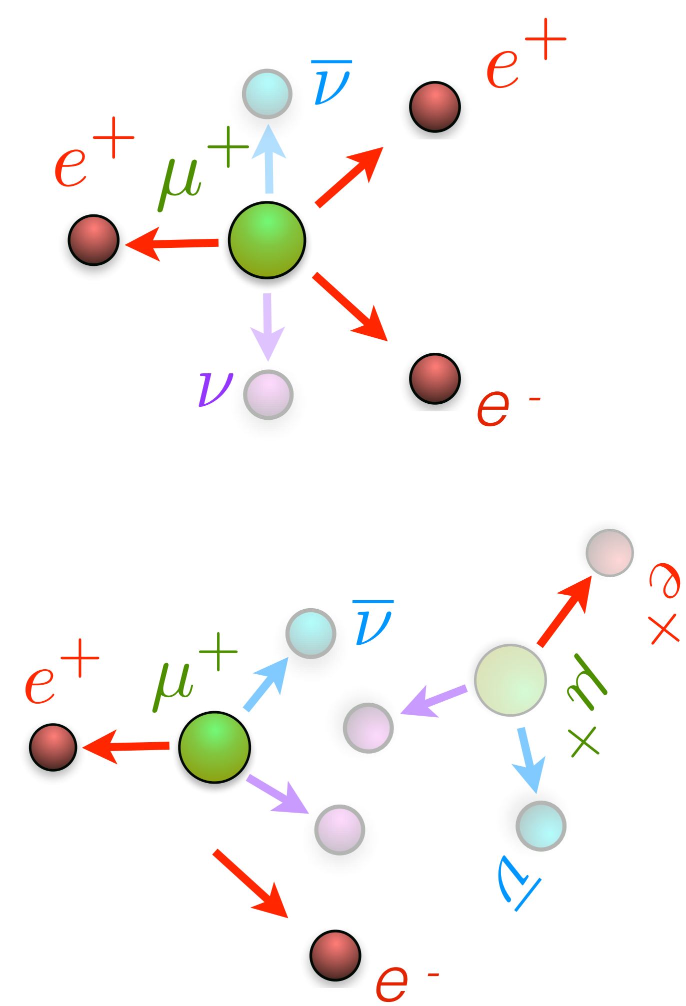


$$\Delta t_{eee} = 0$$

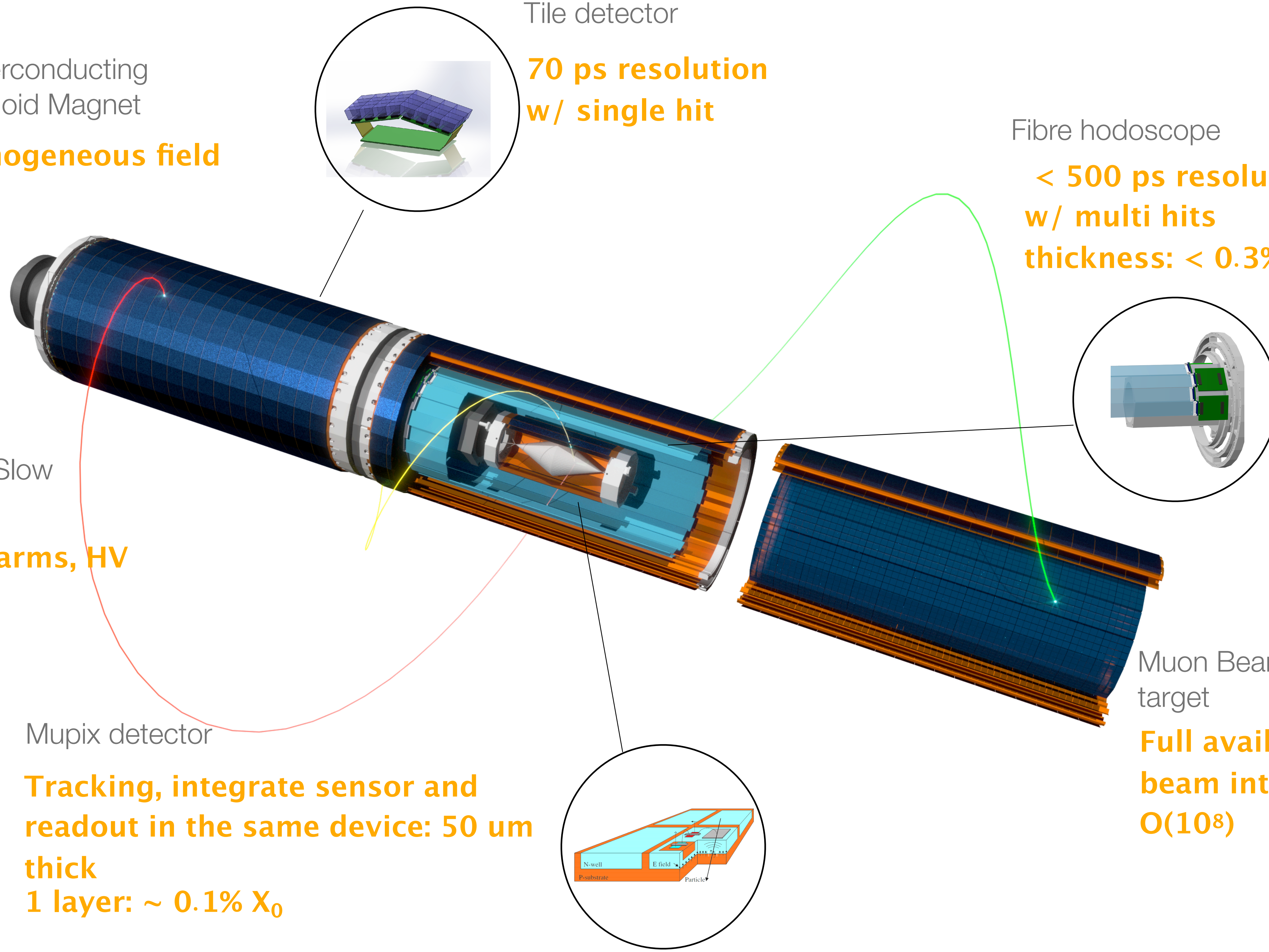
$$\Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

Background



The Mu3e experiment: Schematic 3D



Superconducting solenoid Magnet

Homogeneous field 1T

Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

< 500 ps resolution w/ multi hits thickness: < 0.3% X_0

MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Muon Beam and target

Full available beam intensity O(10^8)

Mupix detector

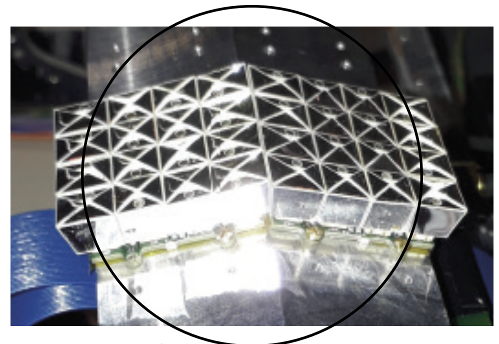
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0

F. Wauters's talk:
Mon. WG4 group

The Mu3e experiment: R&D completed. Prototyping phase

Superconducting solenoid Magnet

Homogeneous field 1T



Tile detector

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Fibre hodoscope

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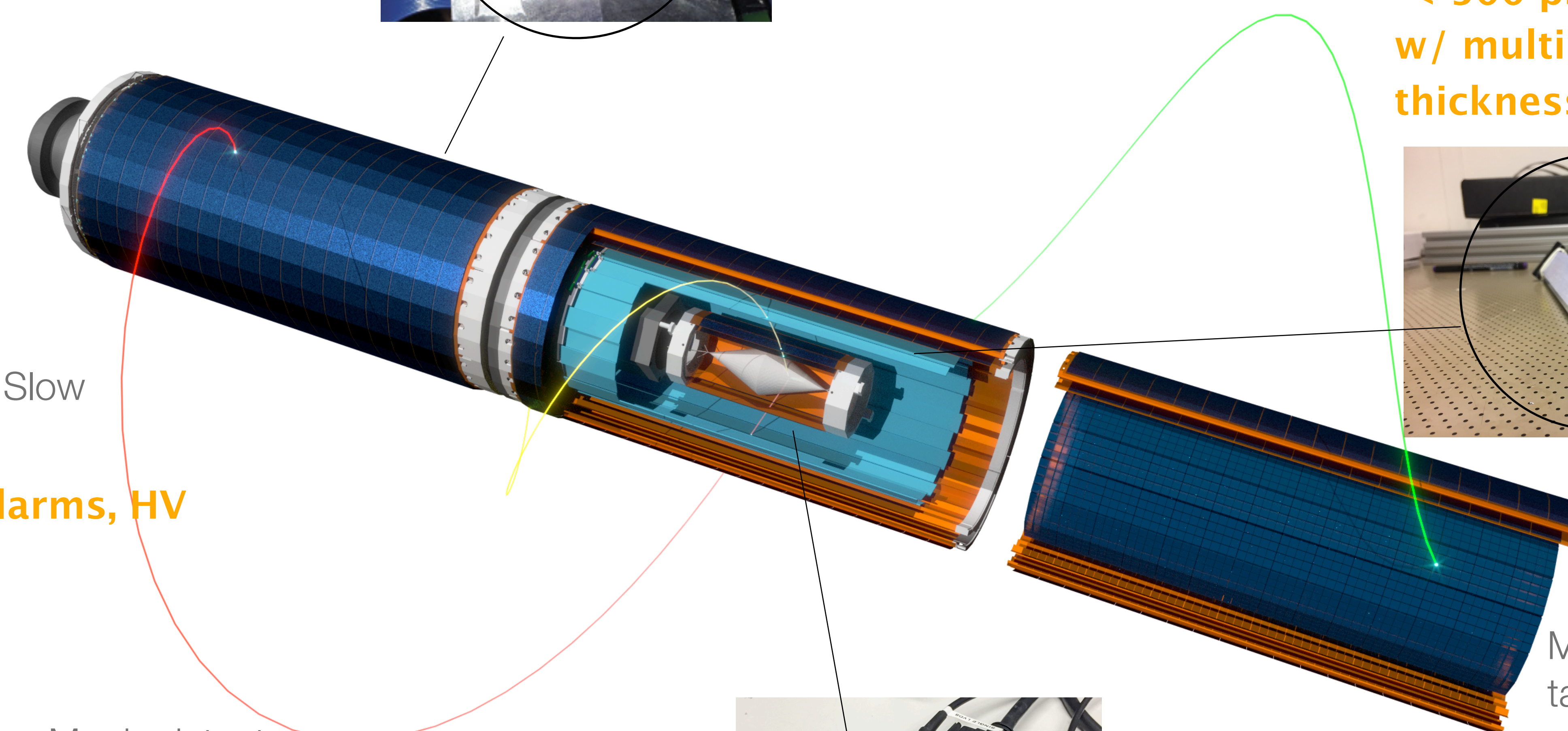

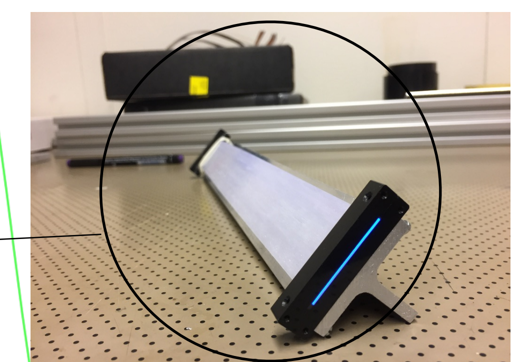

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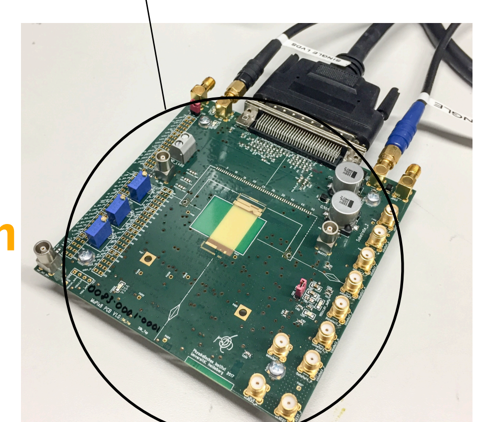


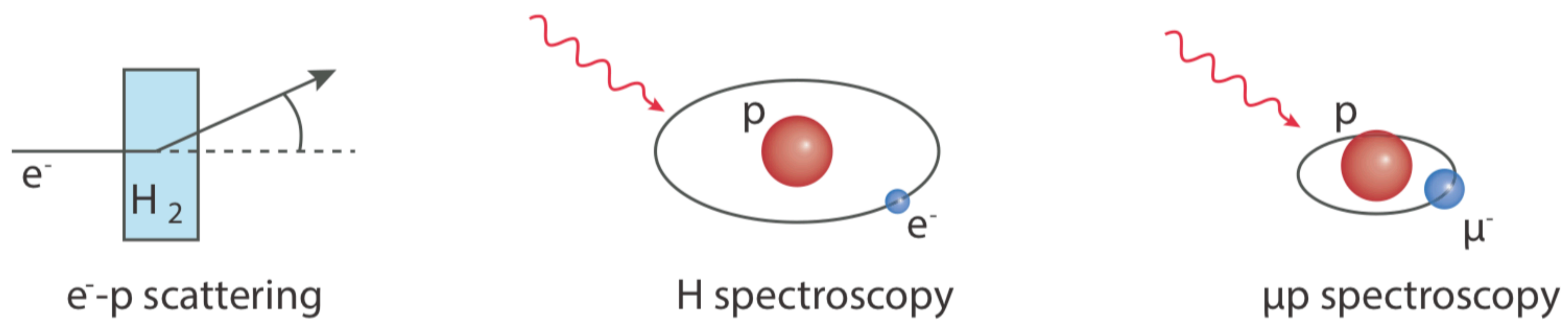
The role of the low energy precision physics

- Two main strategies to unveil new physics
  - Indirect searches
  - **Precision tests**

R. Pohl at al., Nature 466 (2010) 213
A. Antognini et al., Science 339 (2013) 417
R. Pohl et al., Science 353 (2016) 669

Spectroscopy of muonic atoms

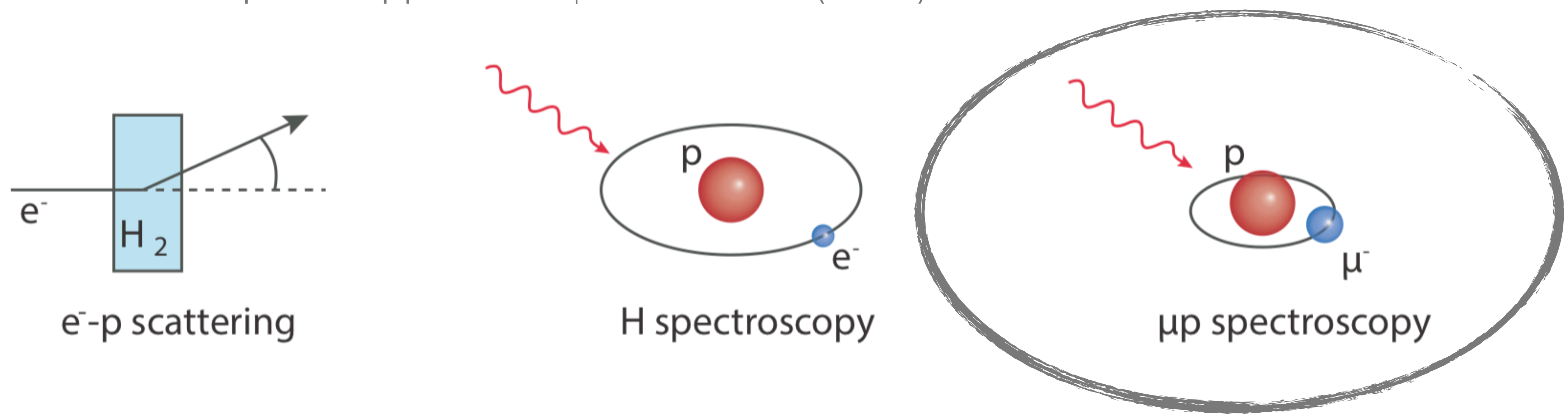
- Strong interplay between atomic physics and particle/nuclear physics
- Enhanced sensitivity for μp due to strong overlap of muon wave-function with the nucleus ($m_\mu \sim 200\ m_e$)

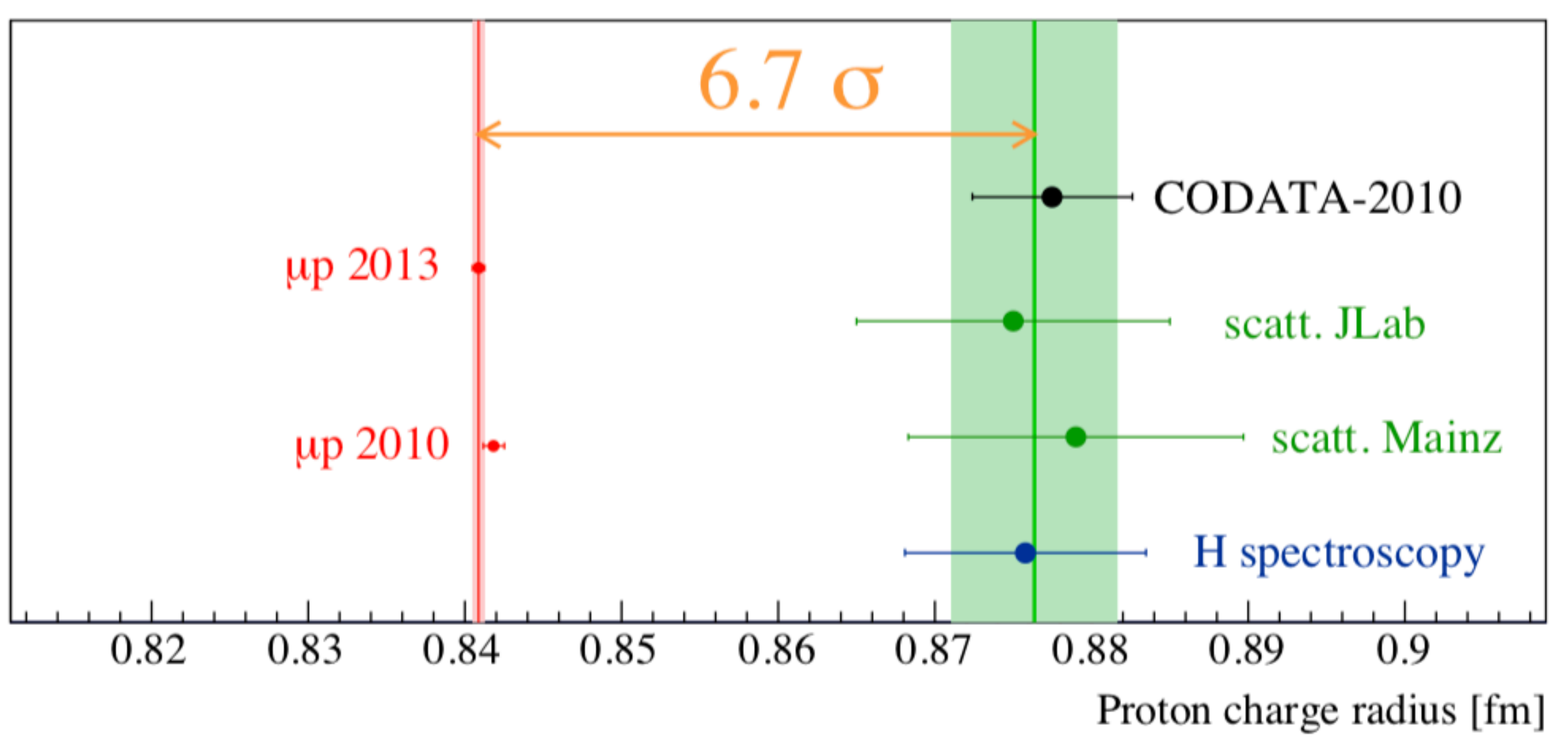


R. Pohl at al., Nature 466 (2010) 213
A. Antognini et al., Science 339 (2013) 417
R. Pohl et al., Science 353 (2016) 669

Spectroscopy of muonic atoms

- Strong interplay between atomic physics and particle/nuclear physics
- Enhanced sensitivity for μp due to strong overlap of muon wave-function with the nucleus ($m_\mu \sim 200\ m_e$)
- The proton radius puzzle: μp result: r_p 4% smaller (6.7 σ) and 10 times more accurate





Principle of the μp 2S-2P experiment

Measure 2S-2P splitting (20 ppm)
and compare with theory
→ proton radius

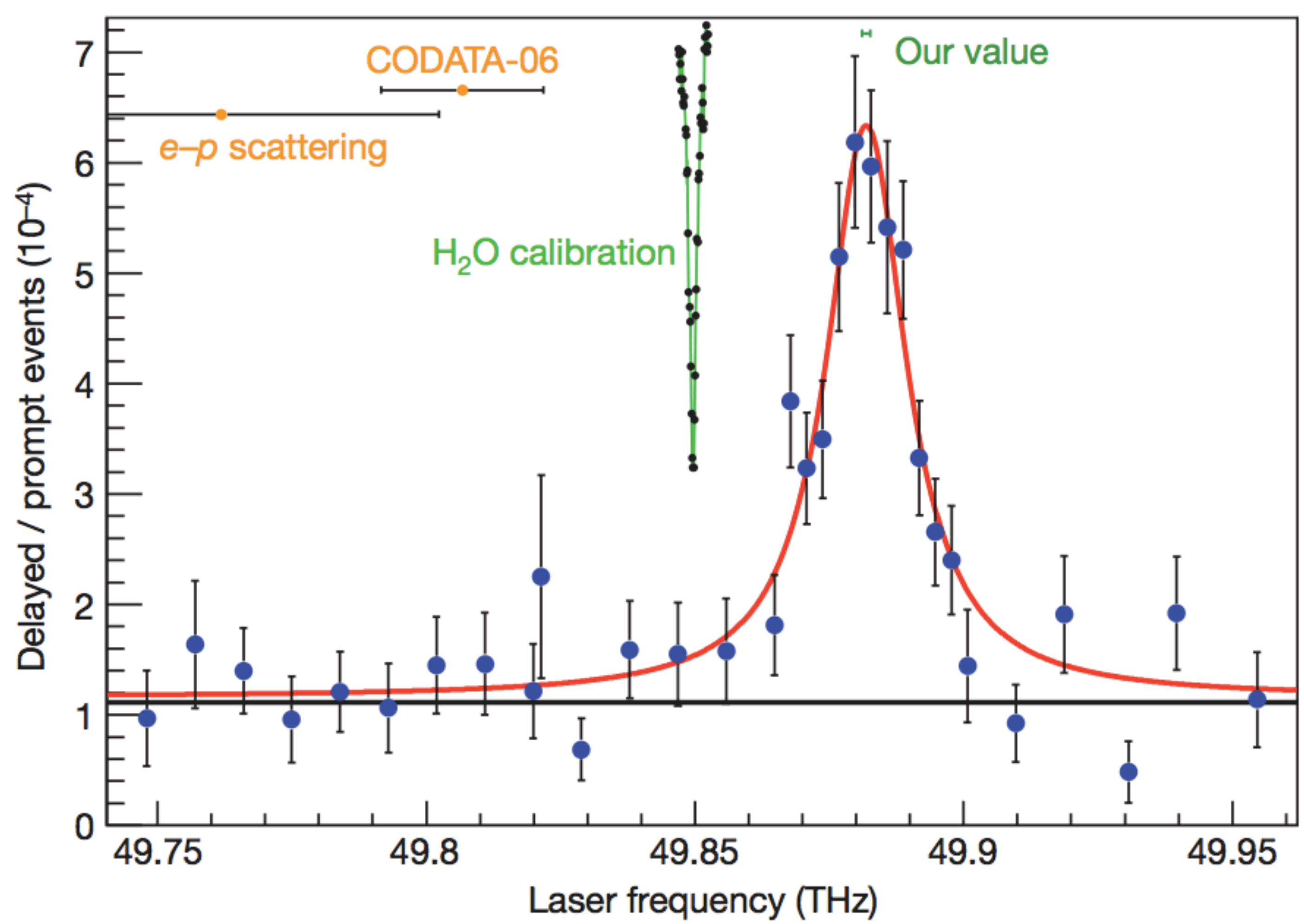
Produce many μ^- at keV energy

Form μp by stopping μ^- in 1 mbar H_2 gas

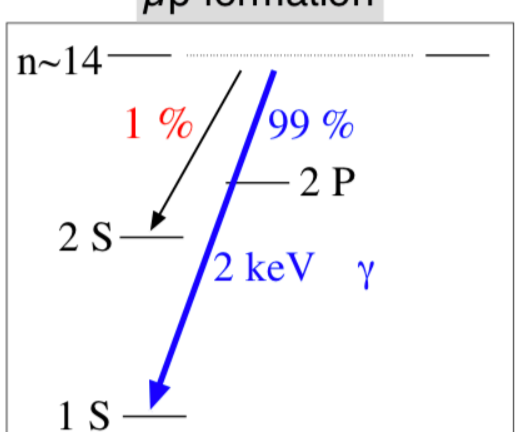
Fire laser to induce the 2S-2P transition

Measure the 2 keV X-rays from 2P-1S decay

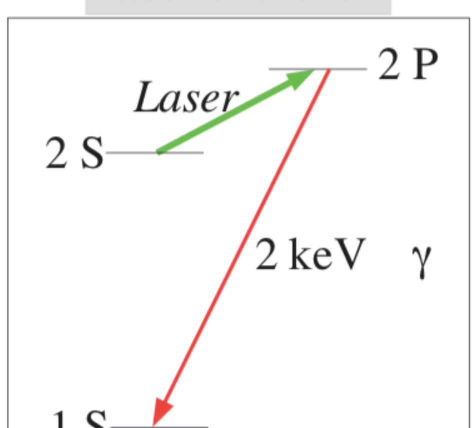
$$\Delta E^{\mathrm{th}}_{2P-2S} = 206.0336(15) - 5.2275(10)\, r_{\mathrm{p}}^2 + 0.0332(20) \quad [\mathrm{meV}]$$



μp formation

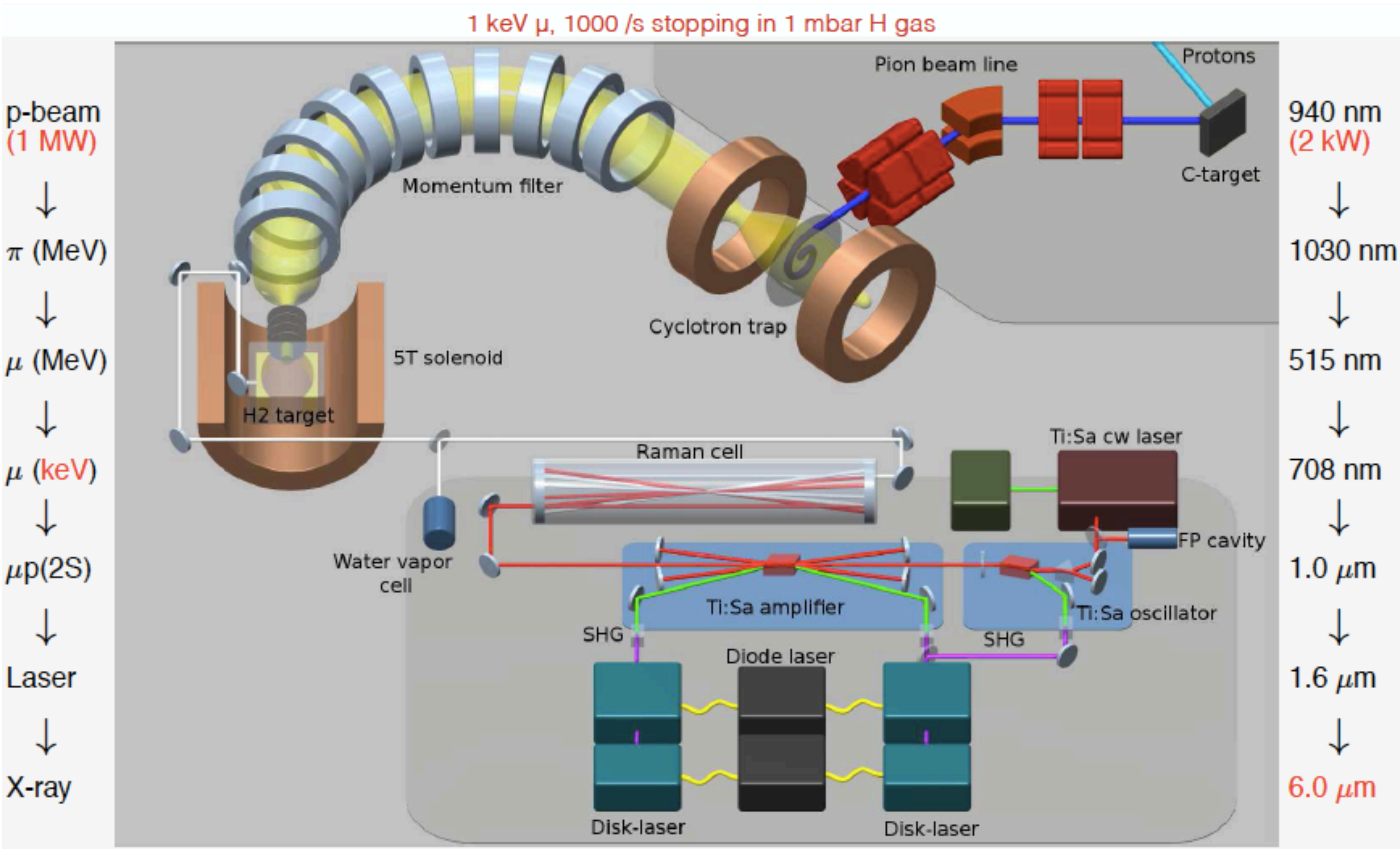


Laser excitation



The experimental setup

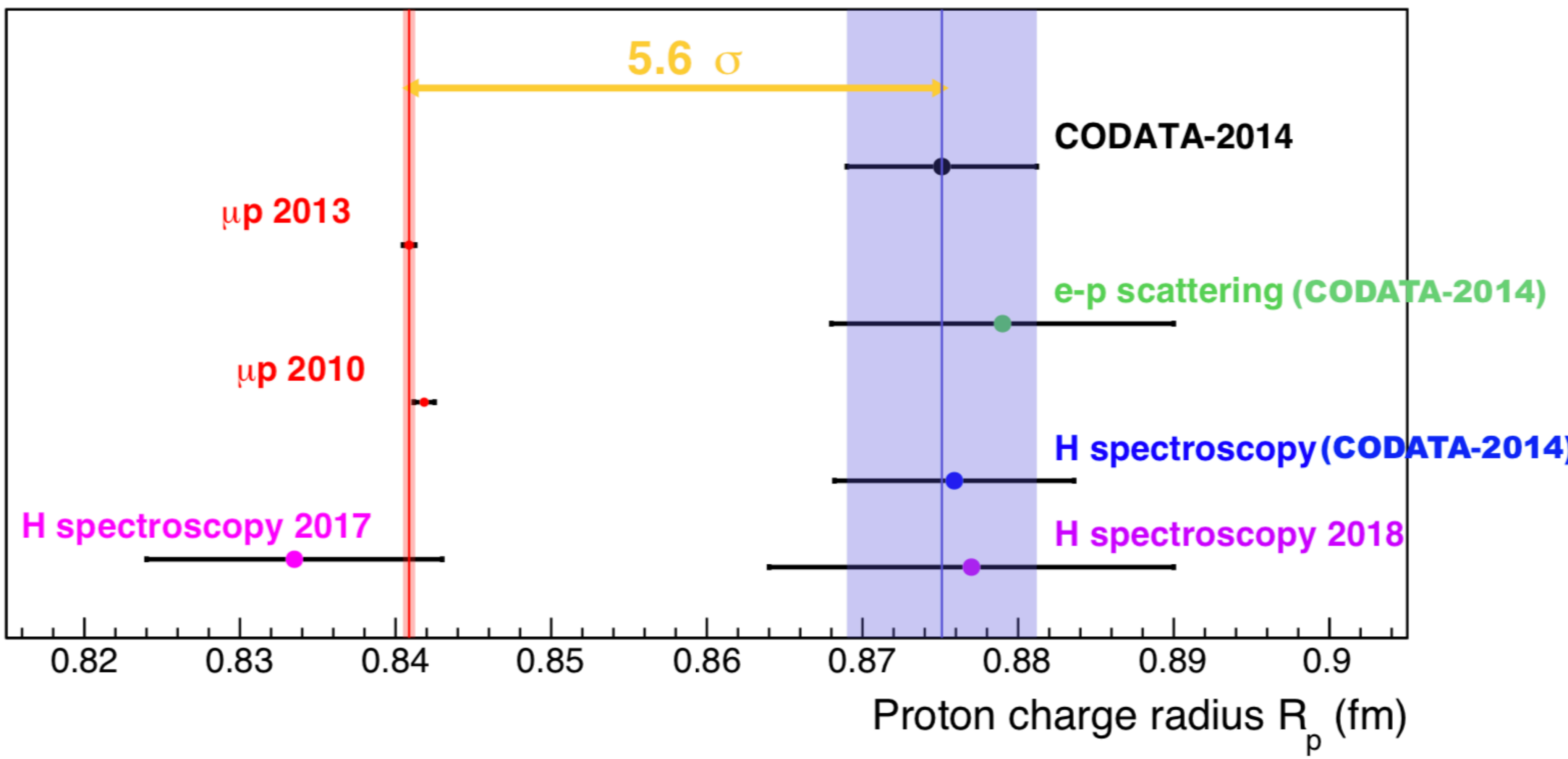
- A low energy muon beam line / laser system / target and detectors



A. Beyer et al. Science 358 (6359), 79-85
W. Vassen, Science 358 (6359), 39-40
H. Fleurbaey et al., Phys. Rev. Lett. 120, 183001 (2018)

Proton radius revisited

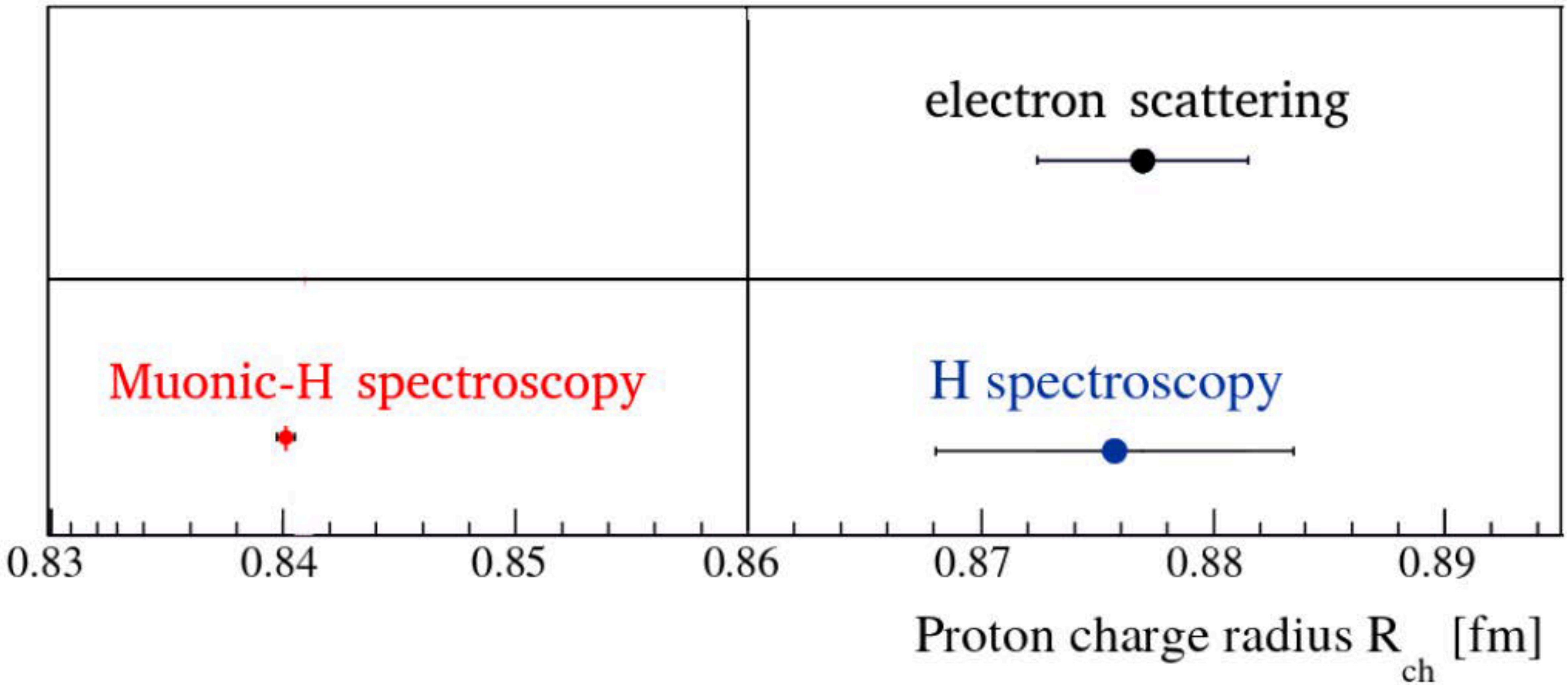
- Hydrogen spectroscopy brings a surprise in the search for a solution to a long-standing puzzle



C. Gu's talk: Thur.
WG4 group

The MUSE experiment: Motivations

- Can we attack the proton-size puzzle from a different side?



The MUSE experiment: Motivations

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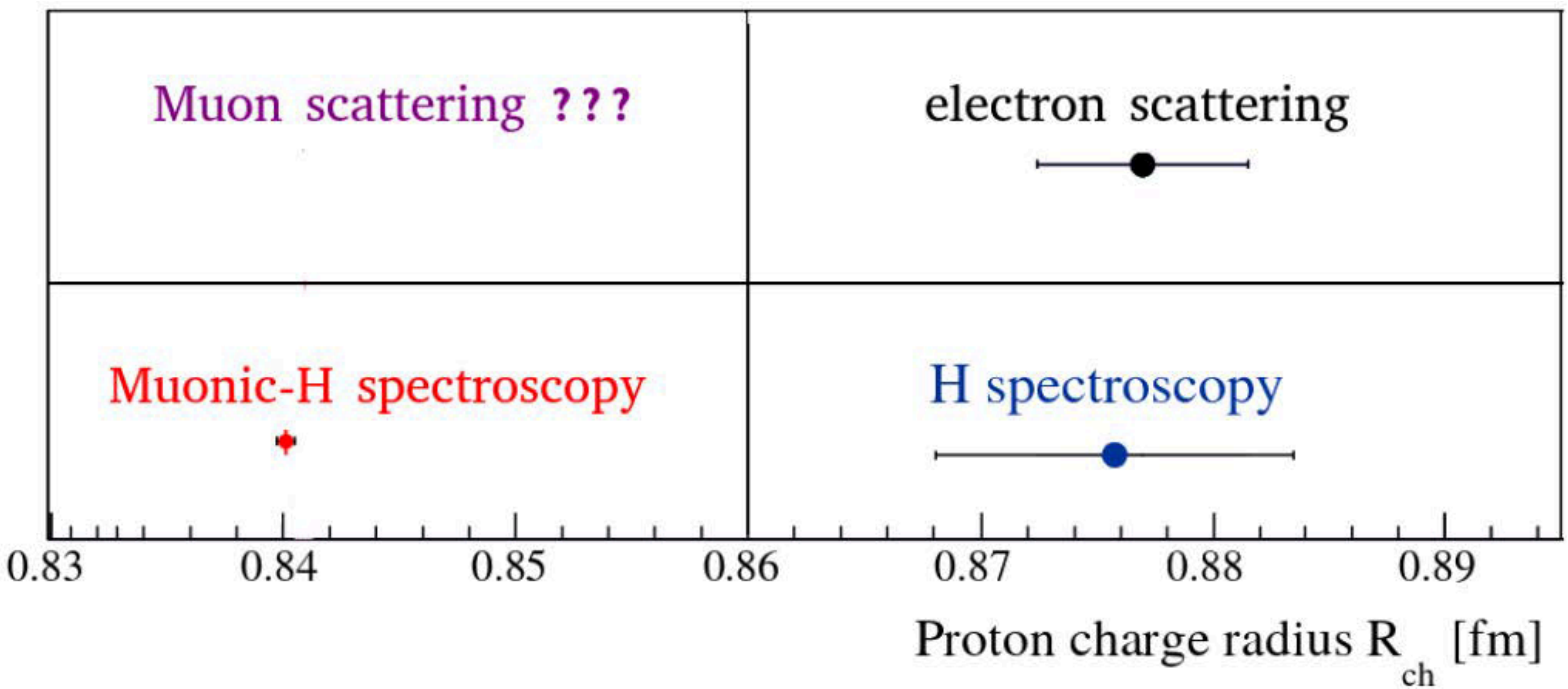


The MUSE experiment: Ready for the physics run

- Beam line: piM1@PSI

with μp and ep to have direct **μ/e comparison**

$\theta \approx 20^\circ - 100^\circ$

$Q^2 \approx 0.002 - 0.07$ GeV^2

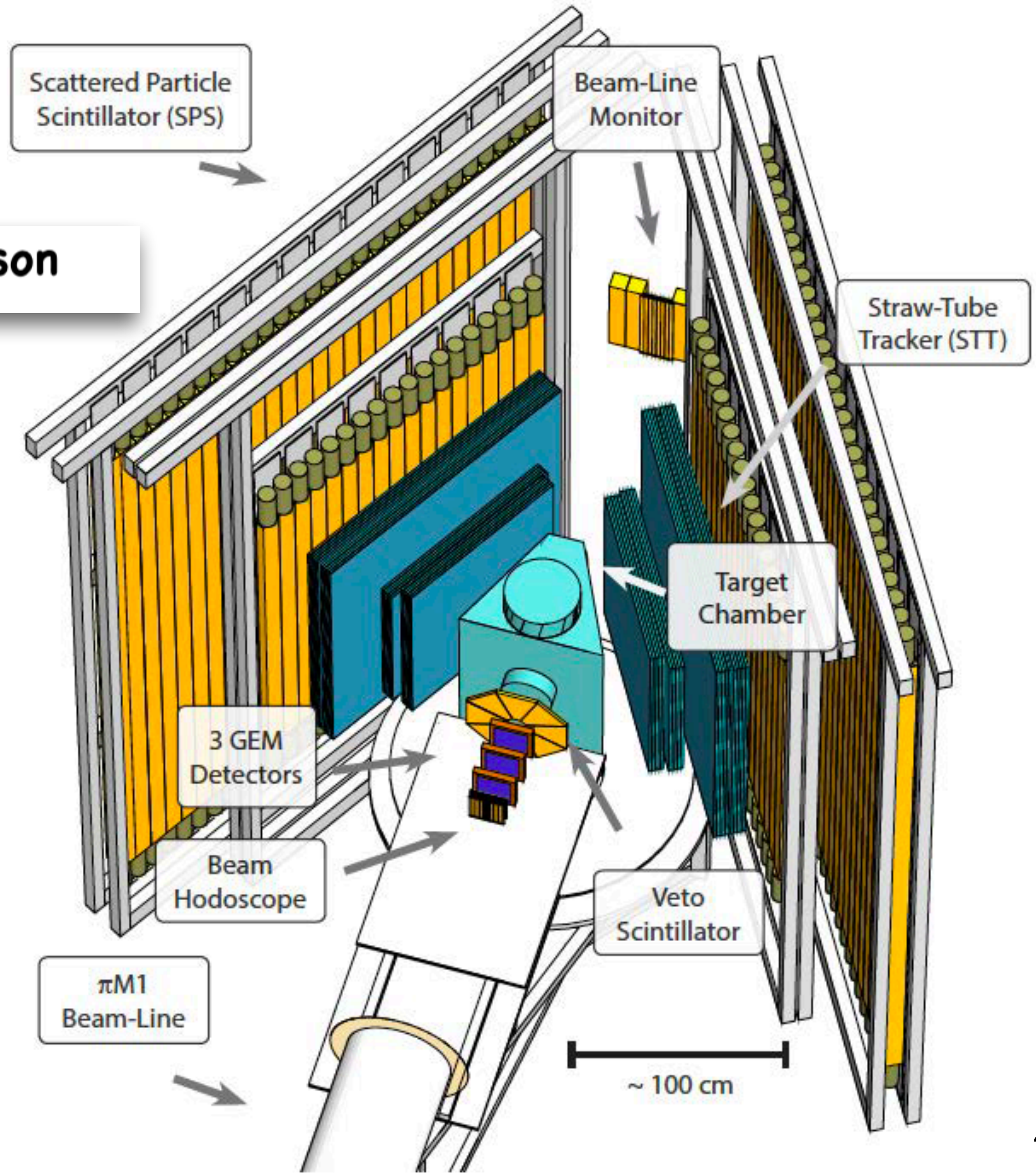
3.3 MHz total beam flux

$\approx 2 - 15\%$ μ's

$\approx 10 - 98\%$ e's

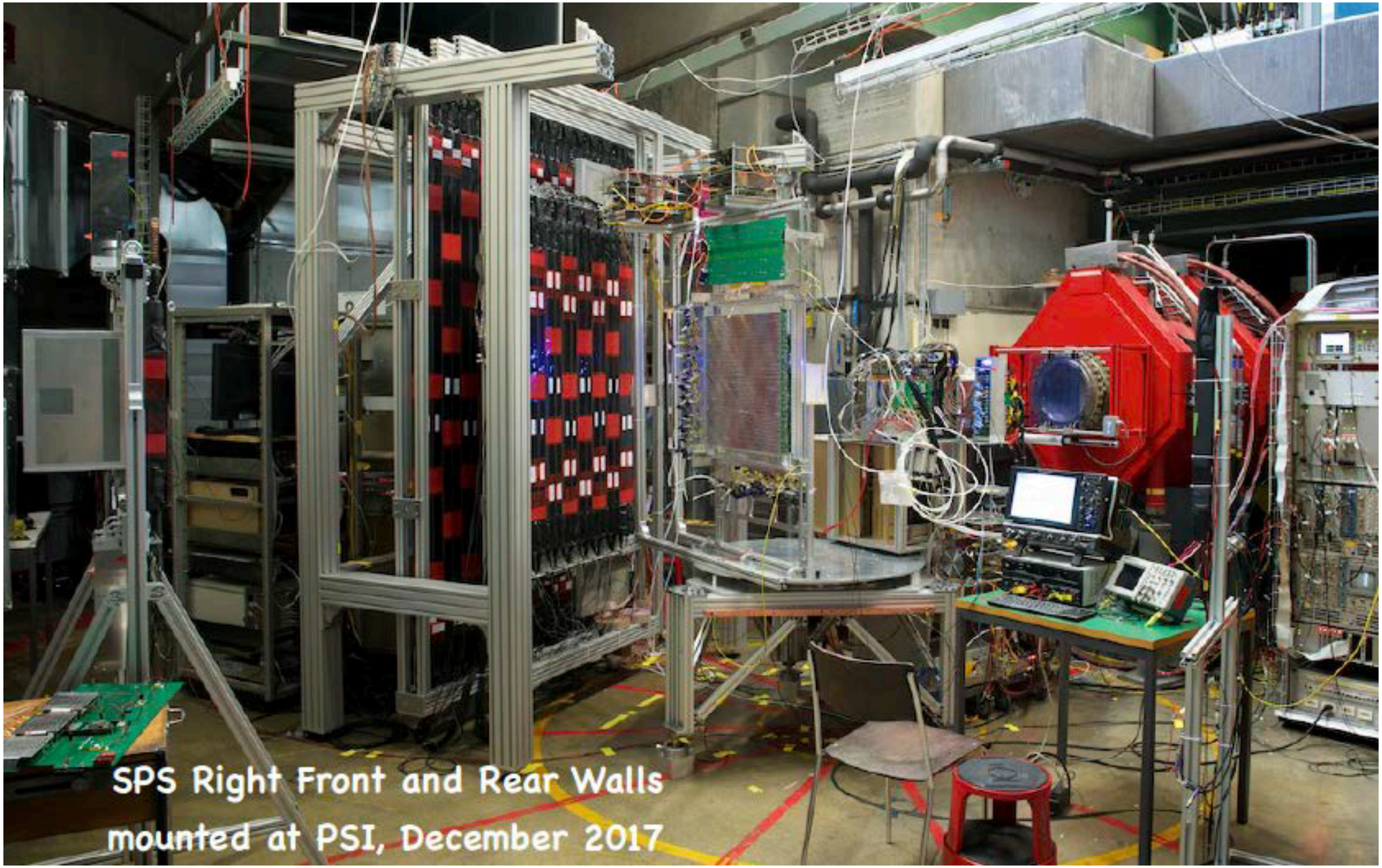
$\approx 0 - 80\%$ π's

S. Strauch's talk: Thur. WG4 group

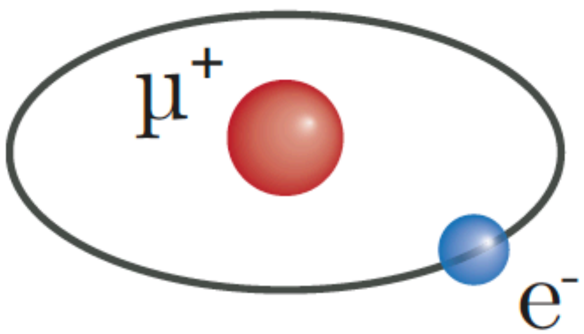


The MUSE experiment: Towards the physics run

- Beam line: piM1@PSI



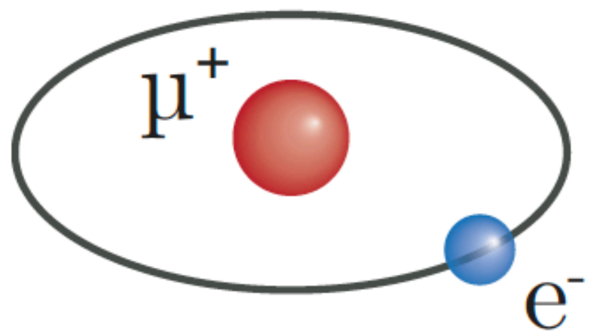
Muonium: A precision tool in atomic and particle physics



Muonium (Mu)

- hydrogen-like exotic atom
- pure leptonic system (1st and 2nd gen.)
- no finite size / nuclear effects

Muonium: A precision tool in atomic and particle physics



Muonium (Mu)

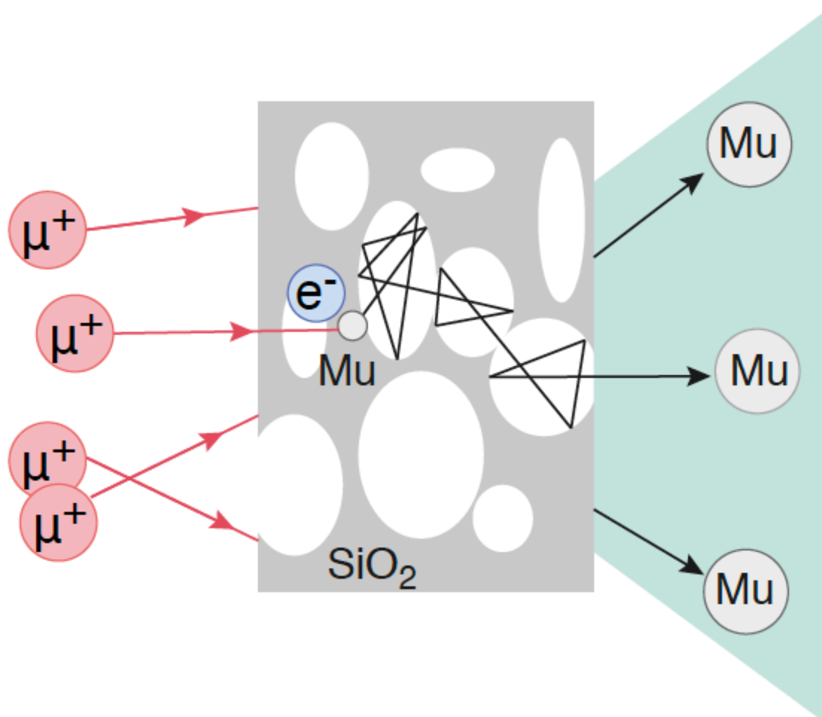
- hydrogen-like exotic atom
- pure leptonic system (1st and 2nd gen.)
- no finite size / nuclear effects

- Precision spectroscopy: test of bound-state QED, fundamental constants: m_μ, R_∞, m_μ/m_p, q_μ/q_e ...

- Mu - antiMu
  - Charged lepton number violation

- Mu gravity experiment?
  - test of weak equivalence principle on μ^+ :
    - elementary antiparticle
    - second generation lepton

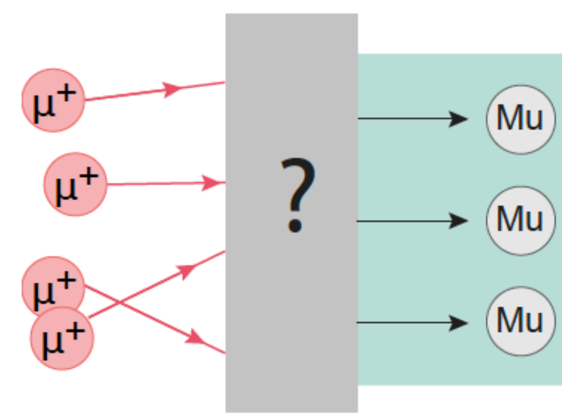
Needed: A ‘cold’ Mu source



- Large (thermal) energy spread
- Broad angular distribution (~cosθ)
- 3-30 % conversion efficiency at T=296 K

Needed: a ˋcold’ Mu source

- Low emittance, narrow energy distribution, large Mu number



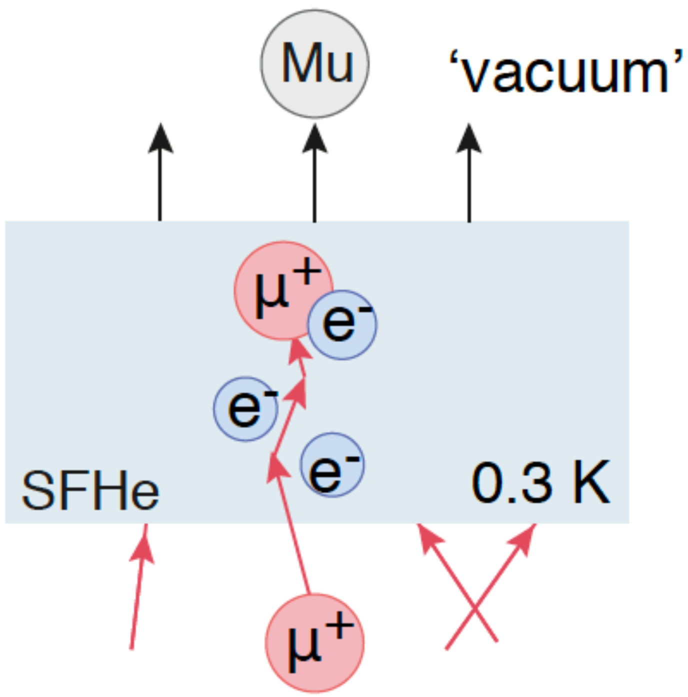
- cooling conventional samples: almost no Mu emission below 100 K (decreased velocities, and atoms sticking to the pore walls)

A. Soter et al.

Cold Mu production

New

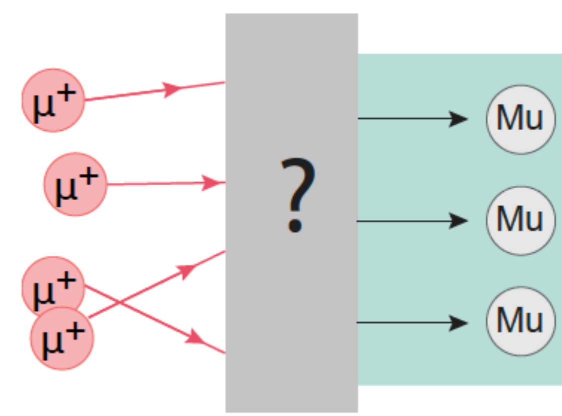
- Proposal: Mu production in superfluid helium (SFHe)



A. Soter's talk: This afternoon WG4 group

Needed: a `cold' Mu source

- Low emittance, narrow energy distribution, large Mu number



- cooling conventional samples: almost no Mu emission below 100 K (decreased velocities, and atoms sticking to the pore walls)

Outlooks

- Continuous and intense low energy muon beams (**I~ 10^8 muon/s, 1.4 MW**) plays a crucial role for particle, nuclear and atomic physics
  - via indirect searches and precision measurements

- While experiments hunger after even more muons the developments of next generation proton drivers with beam powers in excess of **few MW** still requires significant research and development
  - The attention has turned to the optimization of existing target stations and beam lines and the exploration of novel target ideas
    - i.e. HiMB at PSI aiming at (**I~ 10^{10} muon/s**)
    - i.e. MuSIC at RCNP aiming at (**I~ 10^8 muon/s - 400W**)

- New ideas about
  - High brightness low energy beam line (tertiary beam line): MuCool at PSI (**D< 1mm, E < eV**, phase space improvement: **10^{10}**, efficiency: **10^{-3}**)
  - Cold muonium production

Acknowledgments

- Thanks a lot for your attentions
- Credits: A. Antognini, I. Belosevic, F. Berger, E. J. Downie, P.-R. Kettle, A. Knecht, Y. Kuno, S. Mihara, D. Tomono, A. Soter, F. Wauters

Questions from conveners

Color code: ⚪ 🔵 🟣

Focus questions for WG4:

Q1: Neutrino/Muon Physics: (Overlaps with WG1 and WG5)
- What overlaps exist to non-standard model neutrino interactions?
- How would these manifest in both the near term muon/precision measurements sector & in the neutrino sector?

Q2: Beam/Machine/Detector Design: (Overlaps with WG3)
- Are the ultimate sensitivities really exploited with current facilities?
- How can we improve experiments without increasing the beam power?
- What will be the ultimate sensitivity that we can reach even by increasing beam power, and what are its implications?
- Cooled muon beams w/ phase rotations? New methods?

Q3: Program Planning: (Overlaps with WG3)
- How do you support the physics needs for both DC and pulsed (high sculpted) beam structures in the planning (and cost) of new facilities?
- How can muon physics benefit from future neutrino facilities?
- Could new ideas from muon physics developments turn out to be useful for future neutrino facilities?

Questions from conveners

Q2: Beam/Machine/Detector Design: (Overlaps with WG3)

- Are the ultimate sensitivities really exploited with current facilities?
- How can we improve experiments without increasing the beam power?
- What will be the ultimate sensitivity that we can reach even by increasing beam power, and what are its implications?
- Cooled muon beams w/ phase rotations? New methods?

Back-up

How the sensitivity can be pushed down?

high statistics

- More sensitive to the signal...

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(gamma) \times \varepsilon(TRG) \times \varepsilon(sel)}$$

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

high resolutions

- More effective on rejecting the background...

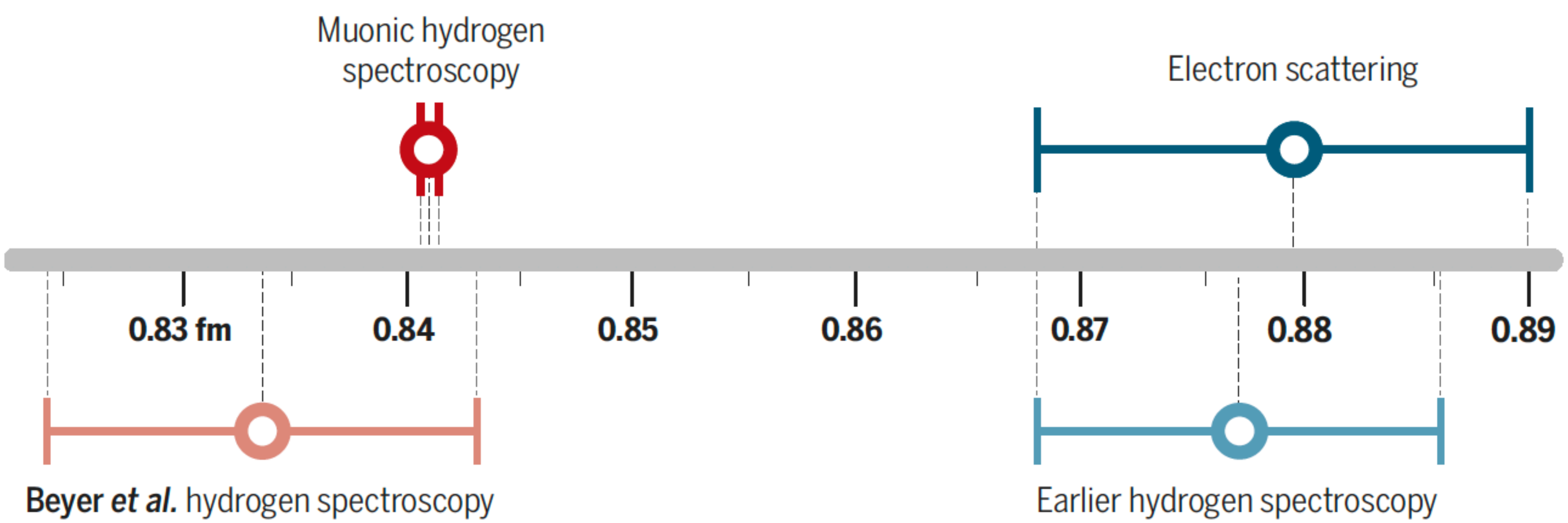
$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta\Theta_{egamma})^2$$

Positron Energy resolution
Gamma Energy resolution
Relative timing resolution
Relative angular resolution

A. Beyer et al. Science 358 (6359), 79-85
W. Vassen, Science 358 (6359), 39-40

Proton radius revisited

- Hydrogen spectroscopy brings a surprise in the search for a solution to a long-standing puzzle



H. Fleurbaey et al., Phys. Rev. Lett. 120, 183001 (2018)

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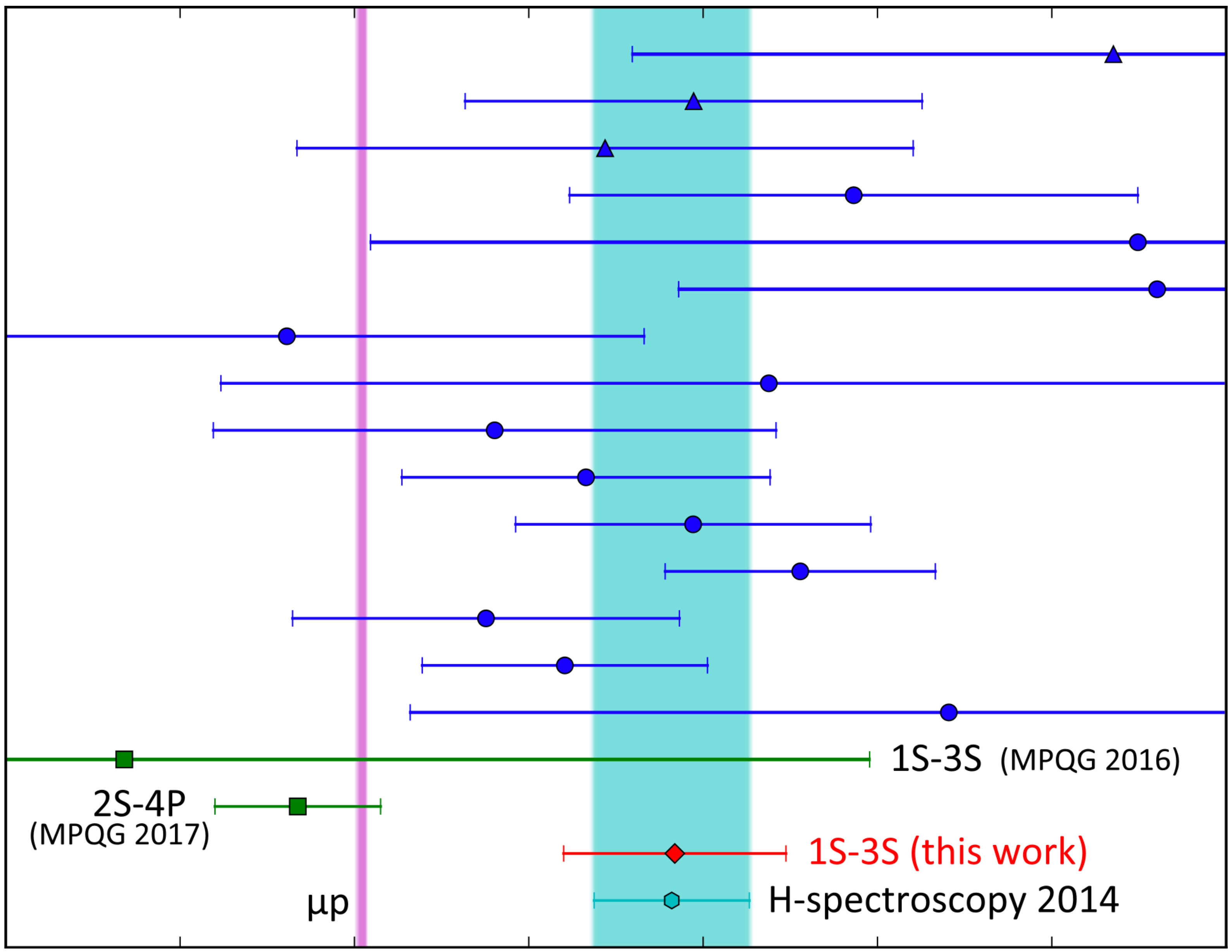
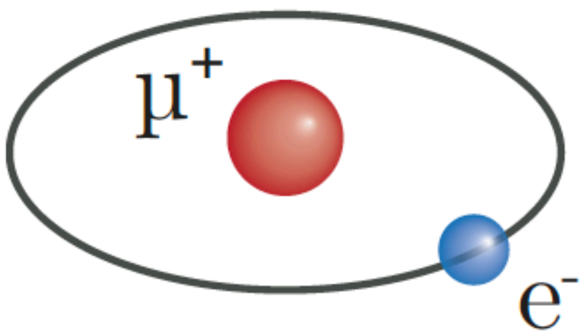


Muonium: A precision tool in atomic and particle physics



Muonium (Mu)

- hydrogen-like exotic atom
- pure leptonic system (1st and 2nd gen.)
- no finite size / nuclear effects

Mu 1s-2s and HFS spectroscopy

- test of bound-state QED
- fundamental constants: m_μ, R_∞, m_μ/m_p, q_μ/q_e ...
- fundamental symmetries

Muonium - antimuonium

- put limits on the charged lepton number violation

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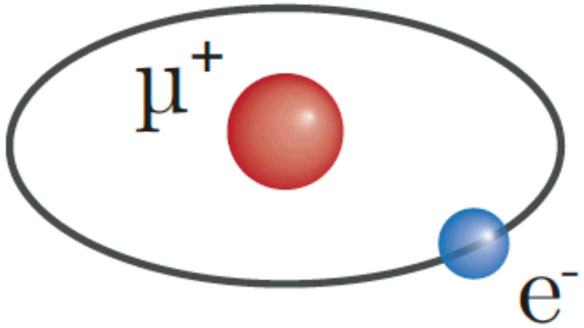

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Muonium - antimuonium

- put limits on the charged lepton number violation

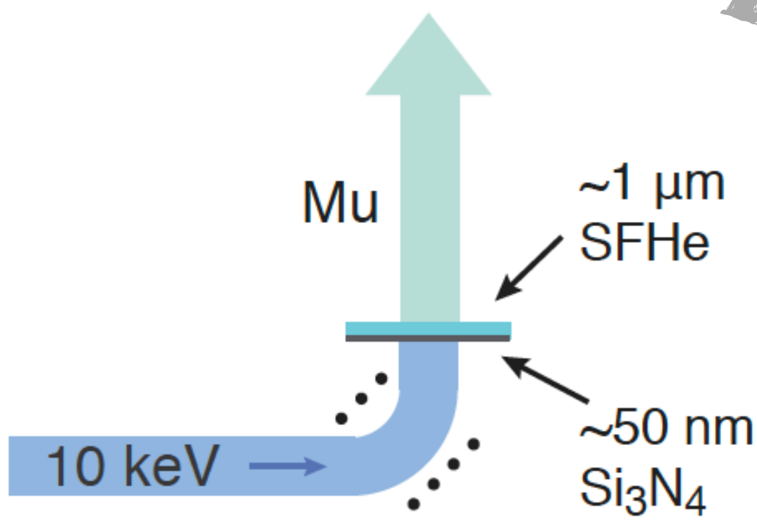
Mu gravity experiment?

μ^+ : elementary antiparticle from the second generation

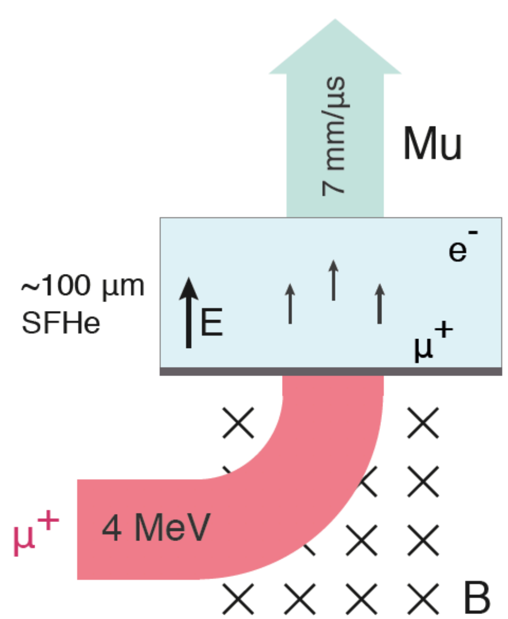
- complementary to the composite antimatter (antihydrogen) gravity experiments @ CERN
- unique possibility to compare gravity (test weak eq.princ.) in lepton generations

Cold Mu production

- MuCool beam

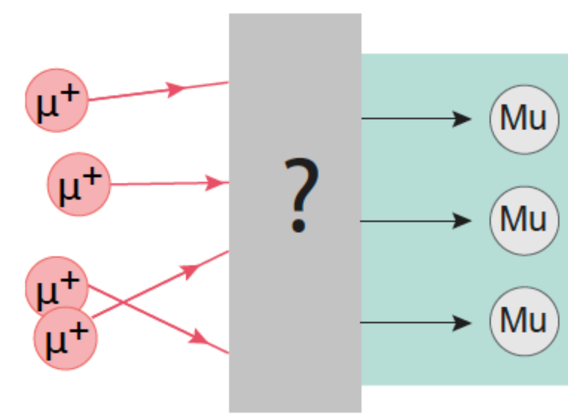


- Standard beam



Needed: a `cold' Mu source

- Low emittance, narrow energy distribution, large Mu number

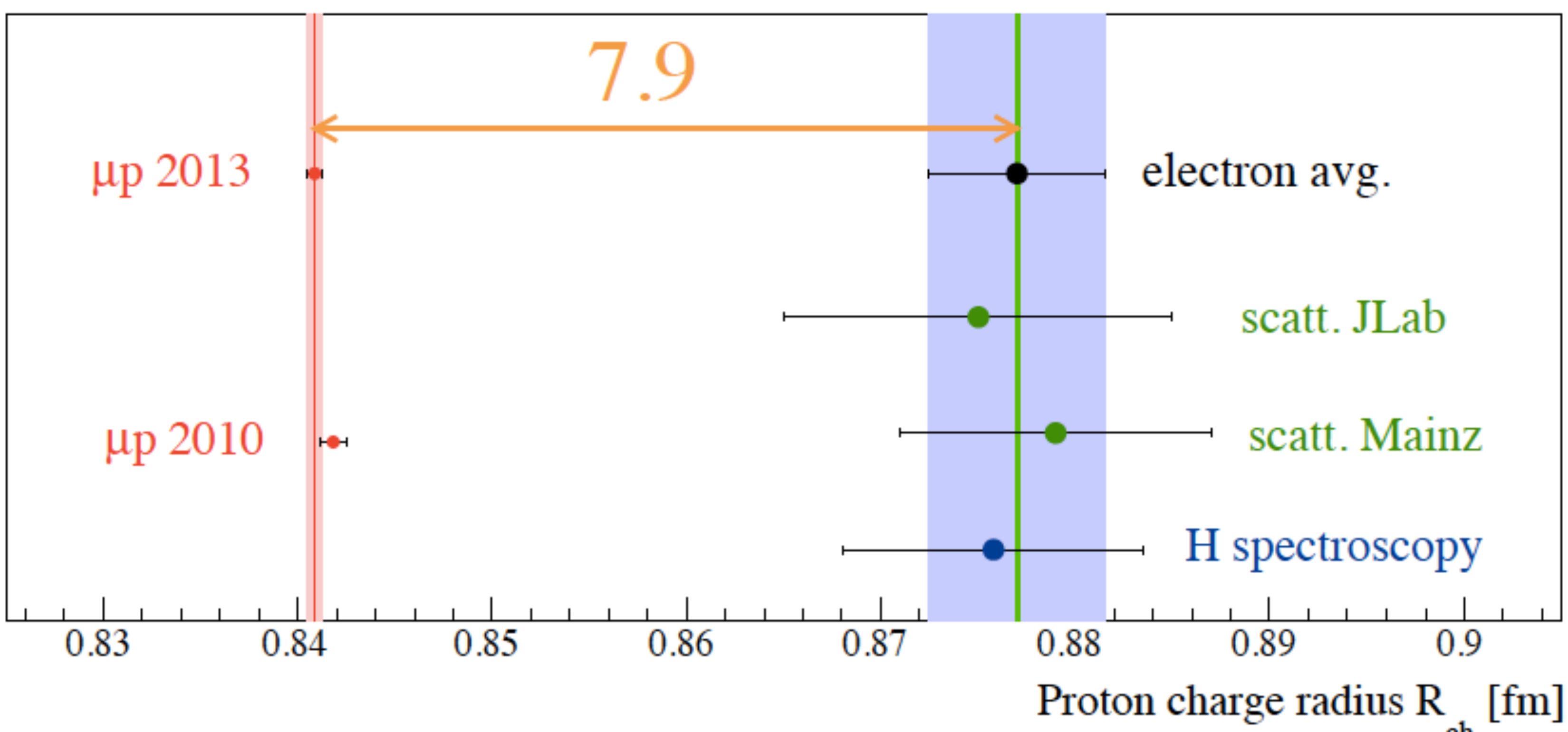


- cooling conventional samples: almost no Mu emission below 100 K (decreased velocities, and atoms sticking to the pore walls)

Spectroscopy of muonic atoms

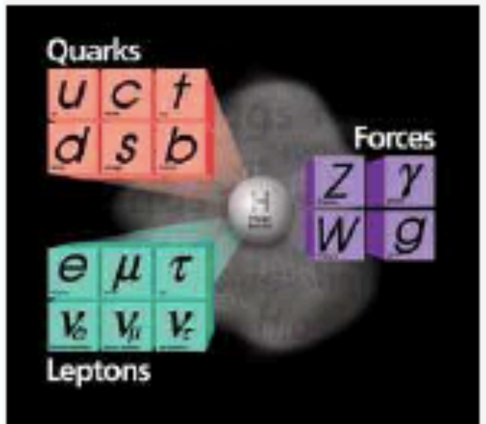
- Strong interplay between atomic physics and particle/nuclear physics
- Three ways to measure the proton charge radius: electron proton scattering, laser spectroscopy of hydrogen, laser spectroscopy of muonic hydrogen (μp)
- enhanced sensitivity for μp due to strong overlap of muon wave-function with the nucleus ($m_\mu \sim 200\ m_e$)
- The proton radius puzzle
  - μp result: r_p 4% smaller (7.9 σ) and 10 times more accurate

r_p = 0.84087 $(26)_{exp}$ $(29)_{th}$ = 0.84087 (39) fm



ref.: R. Pohl at al. Nature ***466*** (2010) 213
A. Antognini et al. Science ***339*** (2013) 417

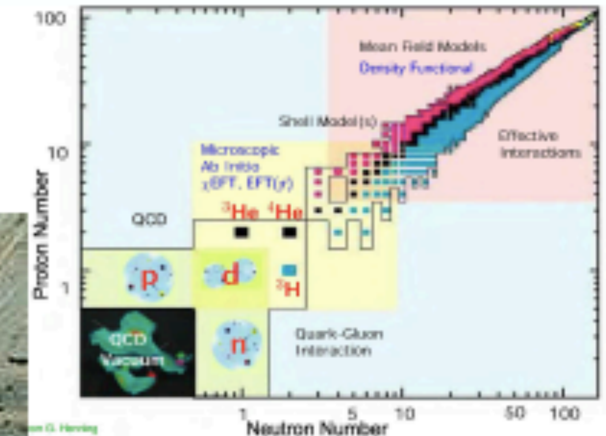
Impact of the muonic atoms



New physics?
Parity violation?

Test of H energy levels
Bound-state QED

Mu= $\mu^+ e^-$
Ps= $e^+ e^-$



Scattering

$e + p \rightarrow e + p$

$e + d \rightarrow e + d$

$\mu + p \rightarrow \mu + p$

$\gamma + p \rightarrow \gamma + p$

$e + Z \rightarrow e + Z$

...

r_p, r_d, r_{He}

EFT, χpt, lattice

few-nucleon th.

high-Z radii

quadrupole mom.

mean-field nucl. th.

magnetic radii

H, He spectroscopy

μp, μd, $\mu\,\mathrm{He}^+$ (2S-2P)

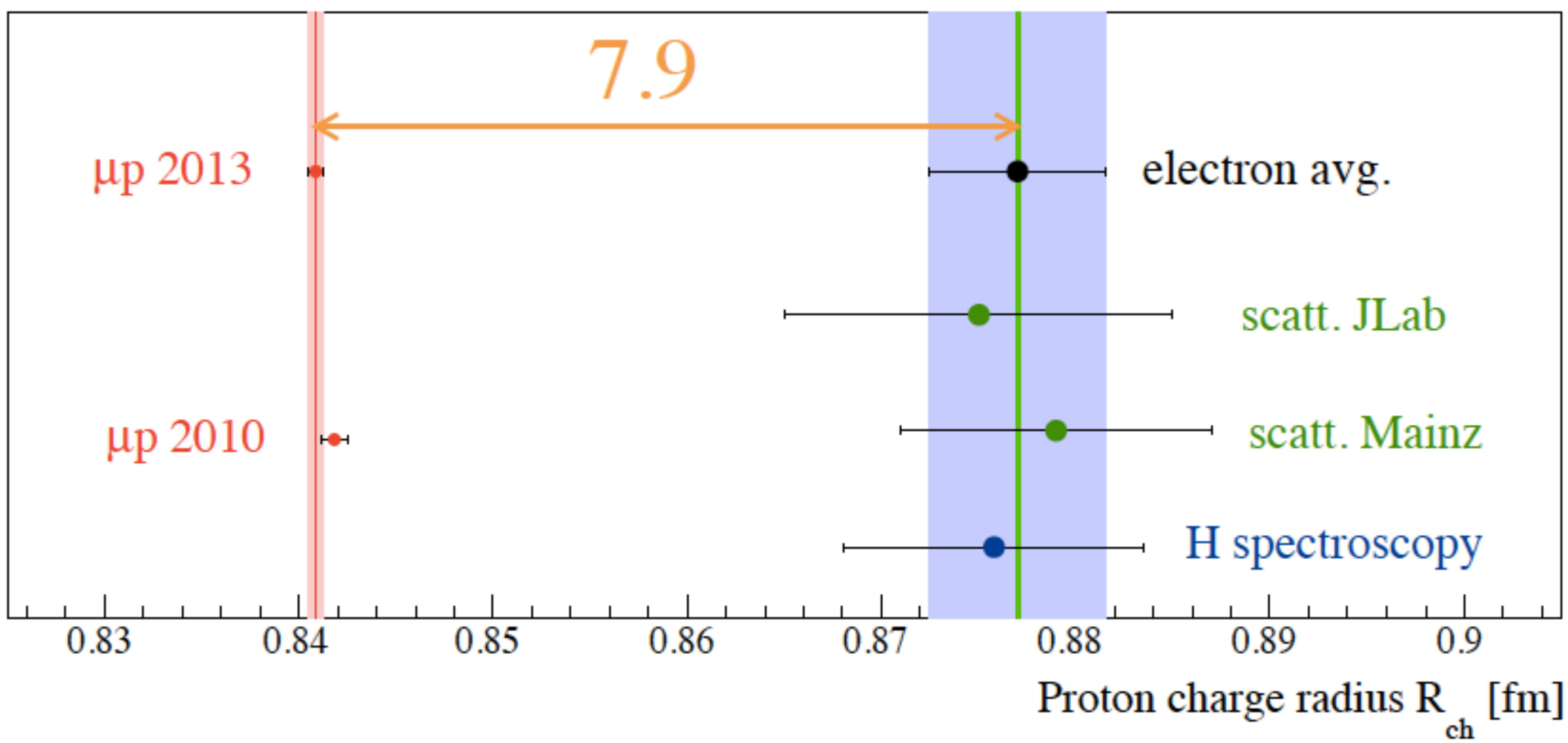
high-Z muonic atoms (radioactive)

HFS in μp and $\mu\,\mathrm{He}^+$

Fundamental constants

Proton radius until 2013

- Hydrogen spectroscopy and scattering, muonic atom spectroscopy



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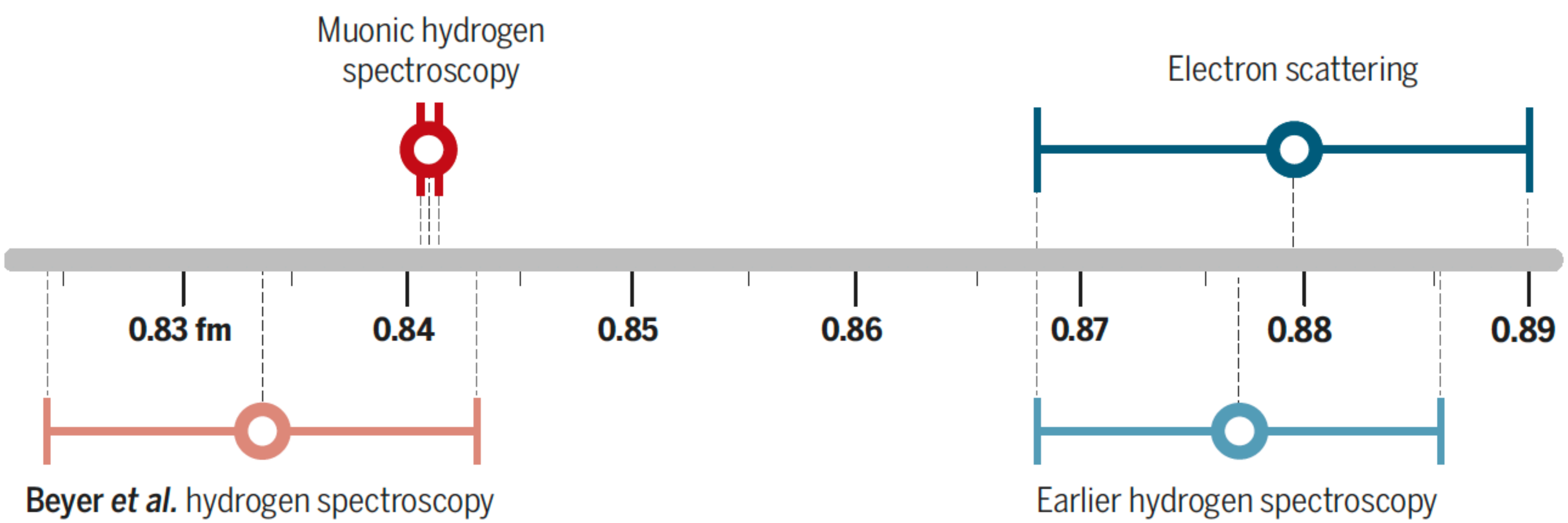
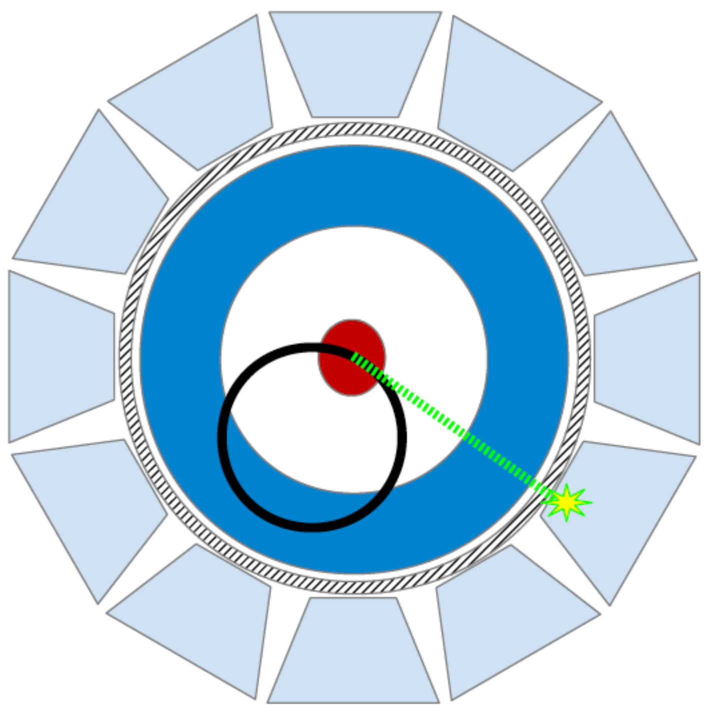


G. Cavoto, A. Papa, F. Renga, E. Ripiccini, C. Voena, Eur. Phys. J. C**78** (2018) 37

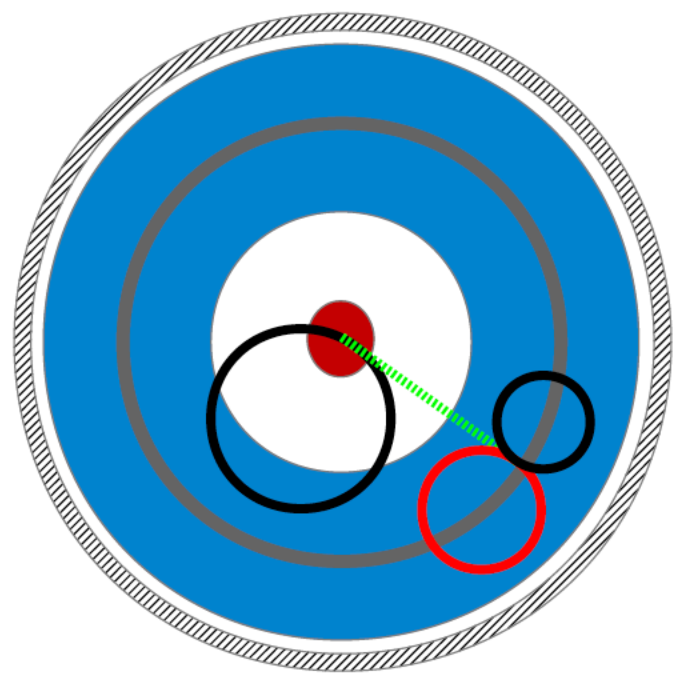
Future prospects: A first thought

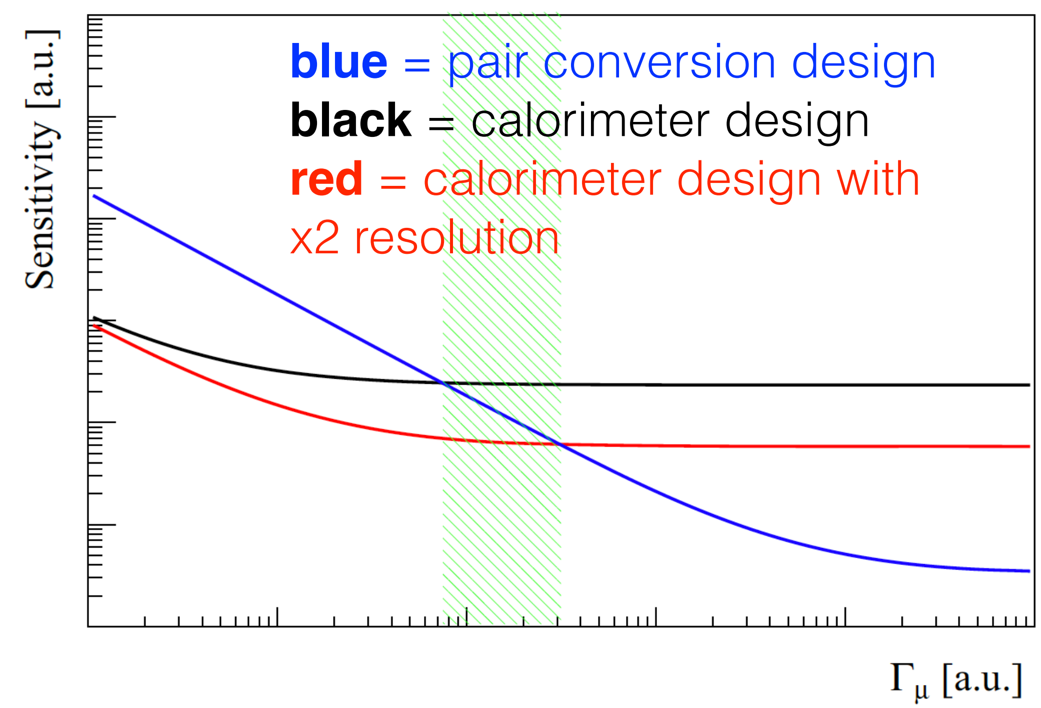
- **$\mu^+ \to e^+ \gamma$** at the highest muon beam intensities: Calorimetry vs gamma conversion + tracking

Calorimetry



Conversion + tracking

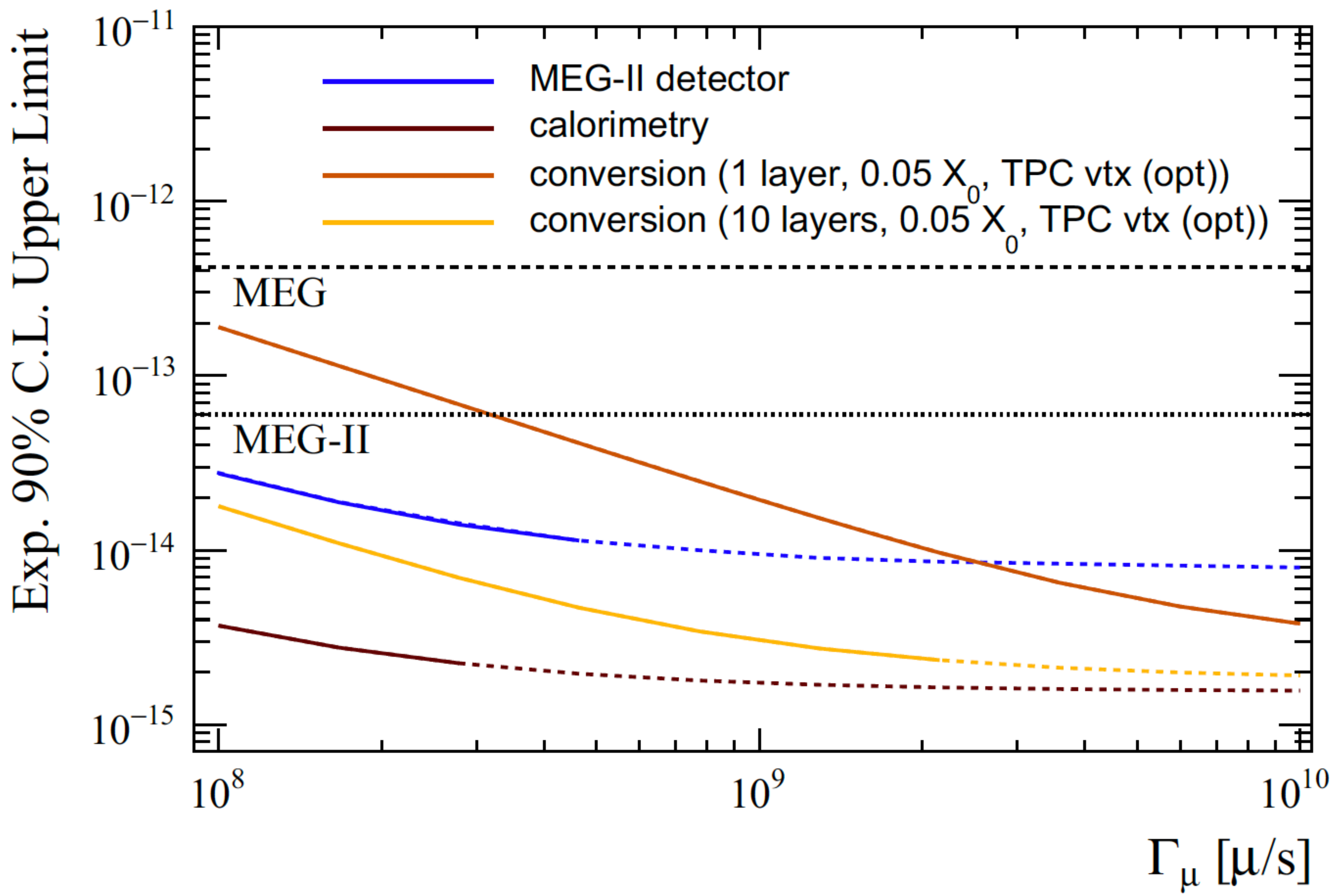




- High detection efficiency (calorimetry) vs better energy resolution (conversion+tracking)
- For a given detector the optimum R is that corresponding to negligible (no more than few) background events over the running time
- At very high rate the low efficiency of the conversion can be compensated keeping the background under control thanks to the better resolutions

Future prospects: A first thought

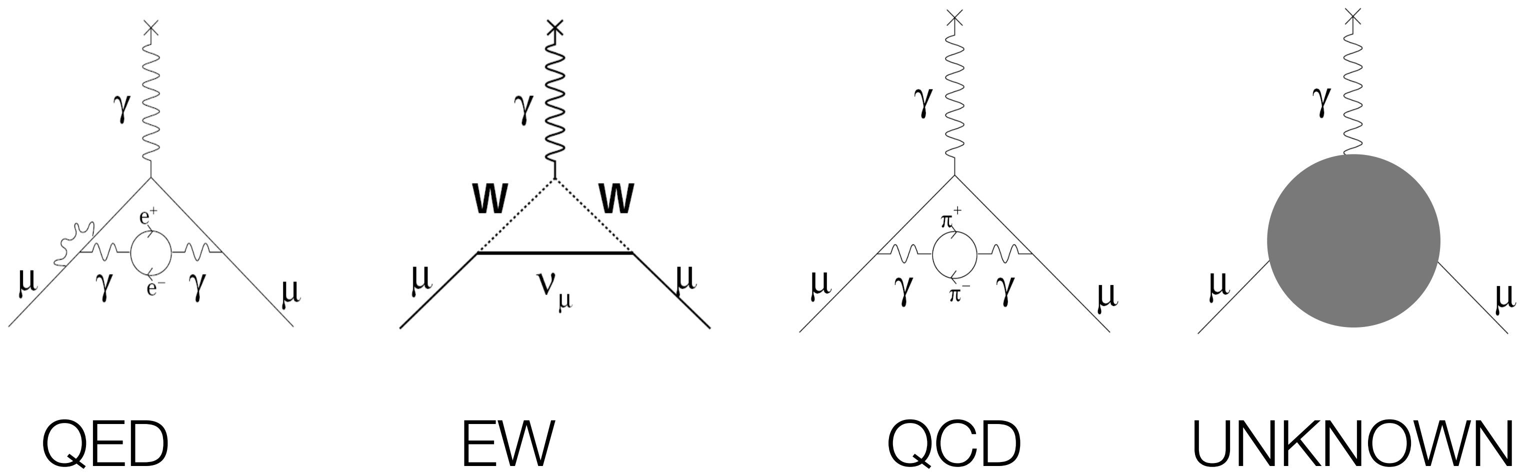
Observable	One photon conversion layer	Photon calorimeter
$T_{e\gamma}$ (ps)	60	50
E_e (keV)	100	100
E_γ (keV)	320	850
Efficiency (%)	1.2	42

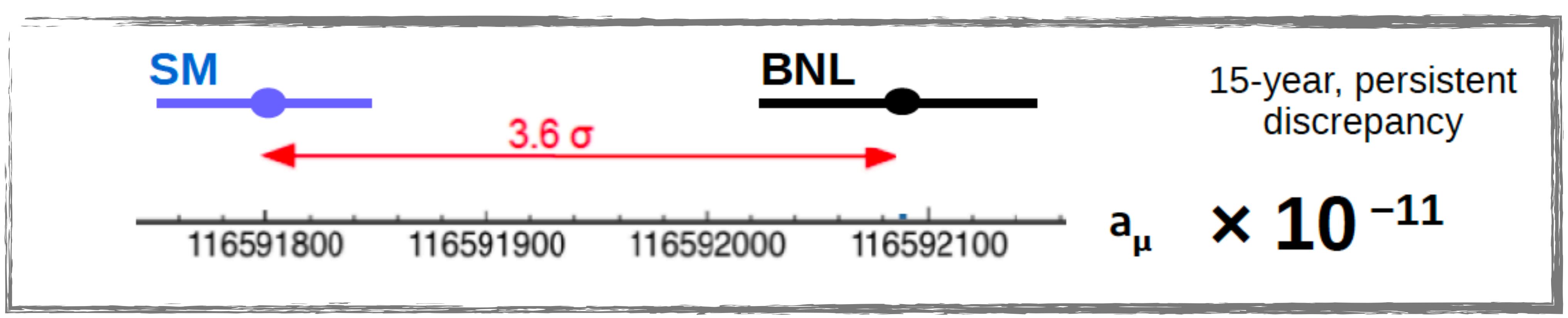


g_μ-2: Motivation

- Dirac's relativistic theory predicted muon magnetic moment “g” = 2
- Experiment suggested that g-factor differs from the expected value of 2
- Standard Model prediction: a(SM) = a(QED) + a(Had) + a (Weak) + **a (NP)**
- BNL E821 result: 3.3σ deviation from SM prediction

$$\mu = (1 + a_\mu)\frac{e\hbar}{2m} \qquad a_\mu = \frac{g_\mu - 2}{2}$$





g_μ-2 in numbers and experimental approaches

Anomalous magnetic moment (g-2)

a_μ = (g-2)/2 = 11 659 208.9 (6.3) x 10^{-10} (BNL E821 exp) **0.5 ppm**

11 659 182.8 (4.9) x 10^{-10} (standard model)

Δa_μ = Exp - SM = 26.1 (8.0) x 10^{-10} **3σ anomaly**

In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 = 0

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

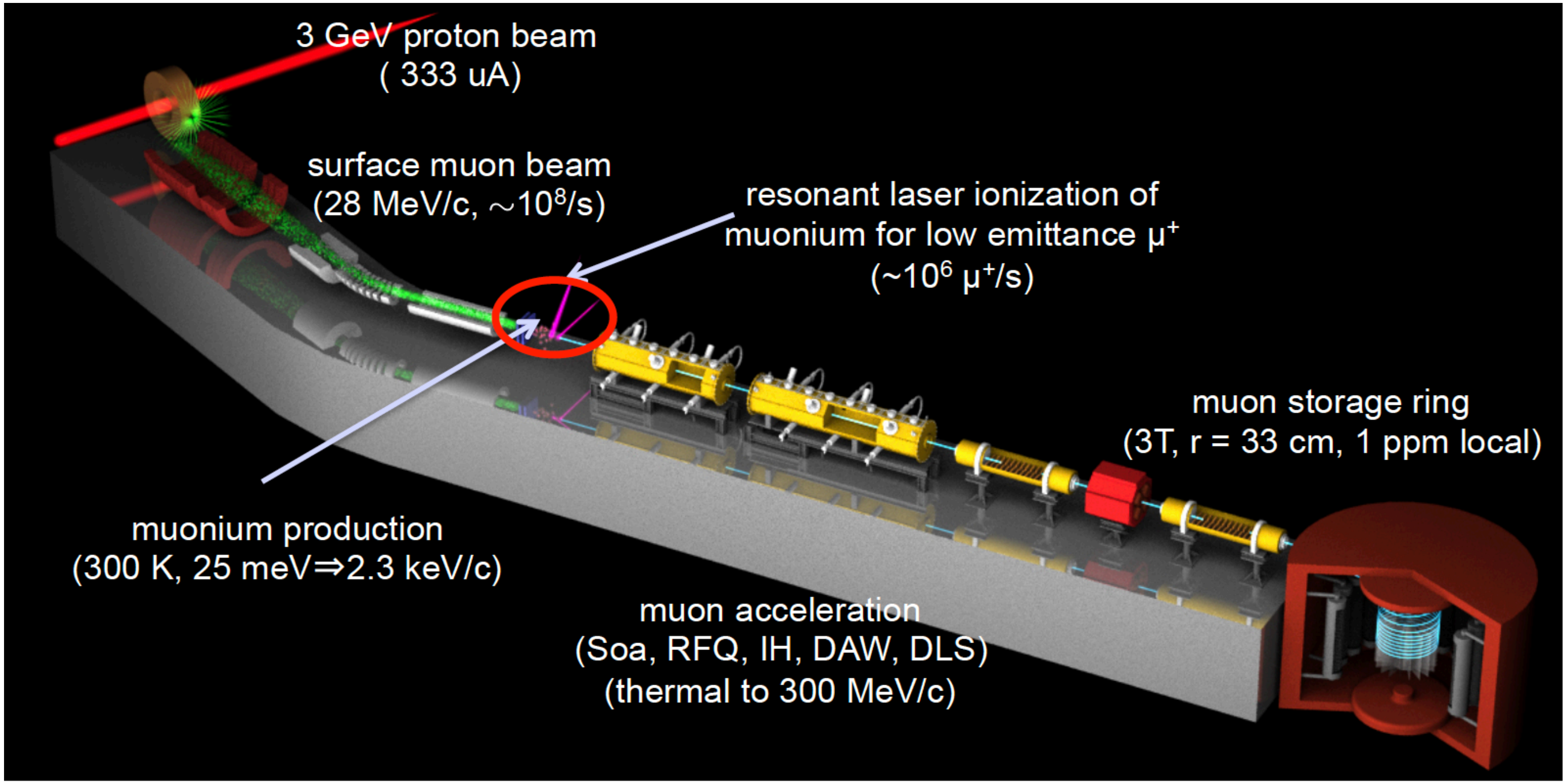
Continuation at **FNAL** with **0.1ppm** precision

Proposed at **J-PARC** with **0.1ppm** precision

g_μ-2/EDM at J-PARC

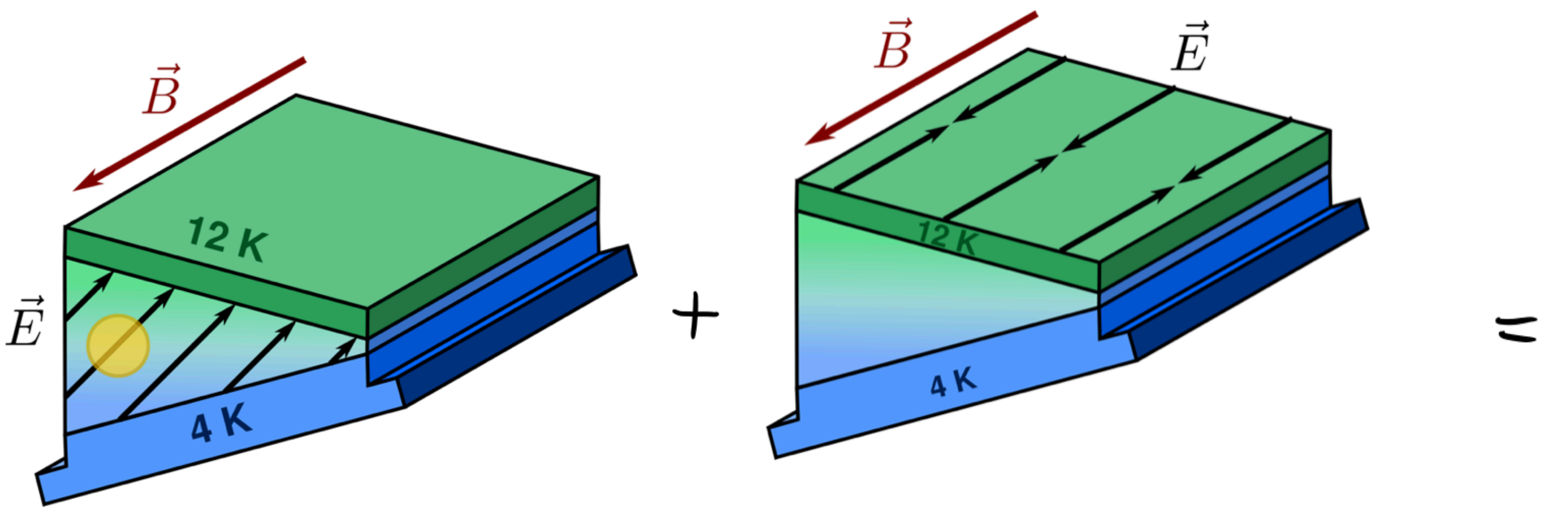
- Put E = 0;
- Weak B field focusing: Need low emittance cold muon
- Uniform tracker detector throughout stored orbit

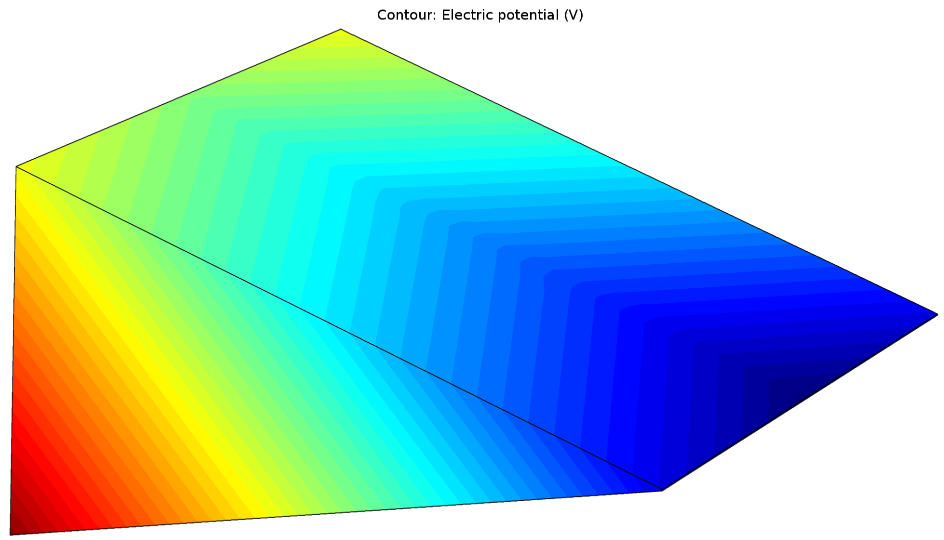
$$-\frac{q}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

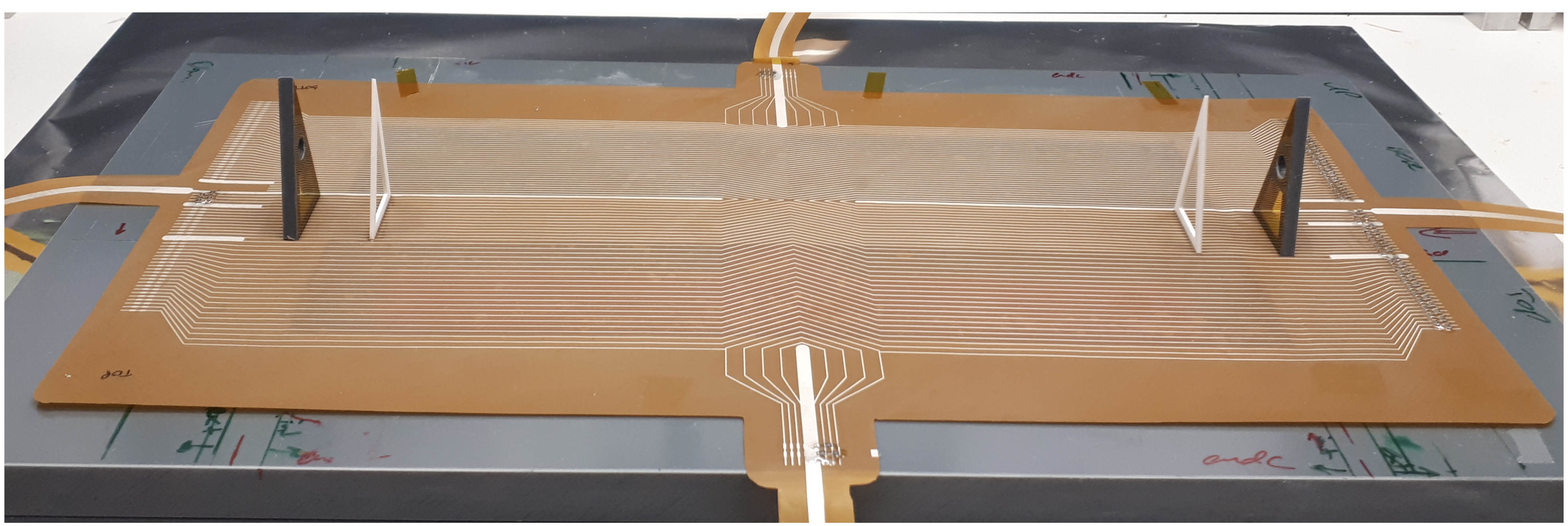


The muCool project at PSI: Status

- 1st stage + 2nd stage
- Next Step: Extraction into vacuum

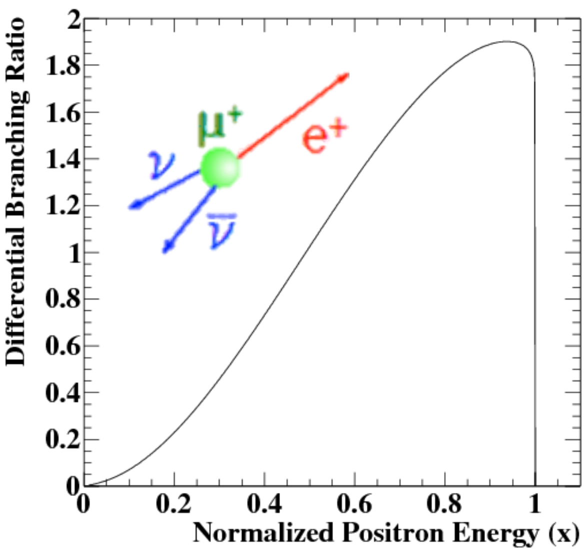


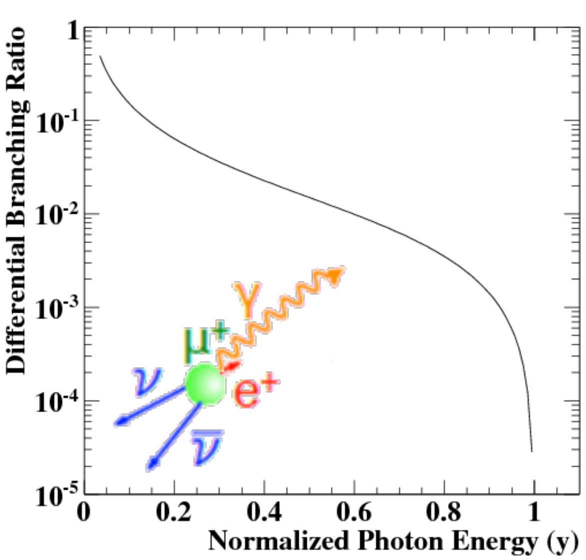


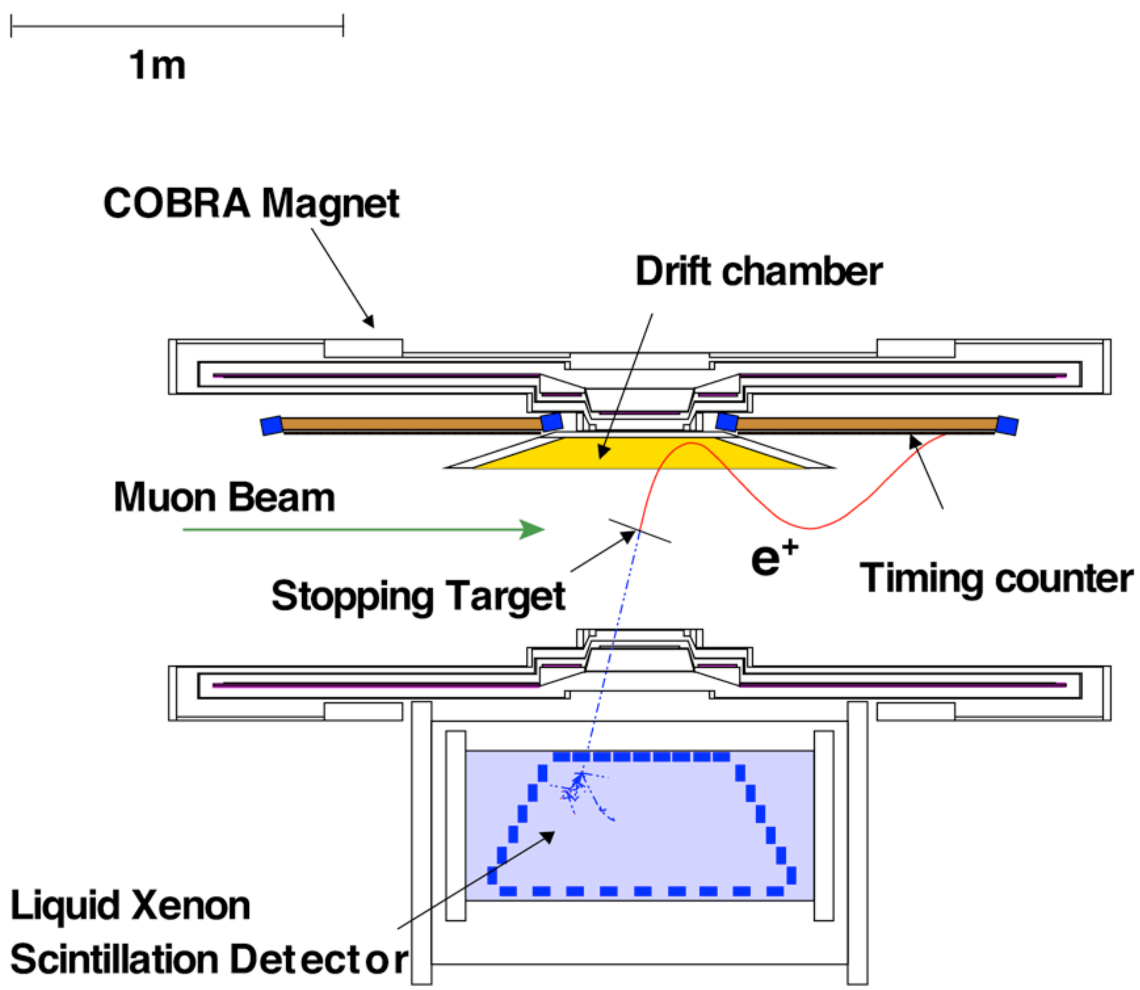


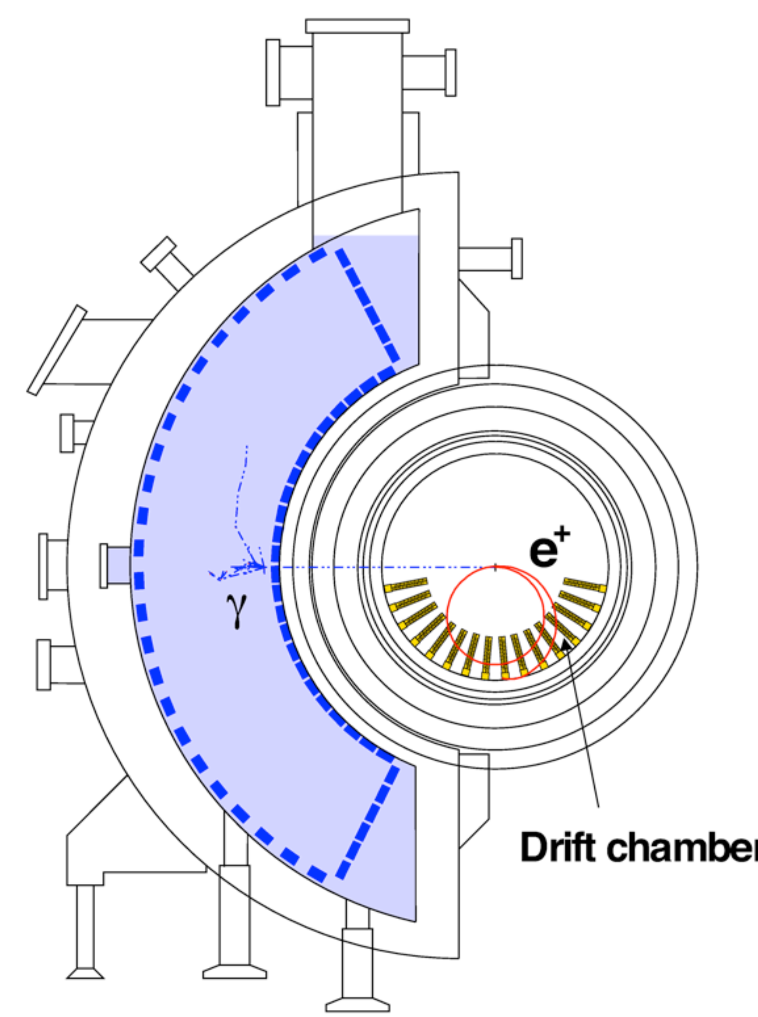
MEG: The key elements

1. The world's intense low momentum muon beam stopped in a thin and slanted target
2. The gradient field e+-spectrometer
3. The innovative Liquid Xenon calorimeter
4. The full waveform based DAQ (digitization up to 1.6 GSample/s)
5. Complementary calibration and monitoring methods









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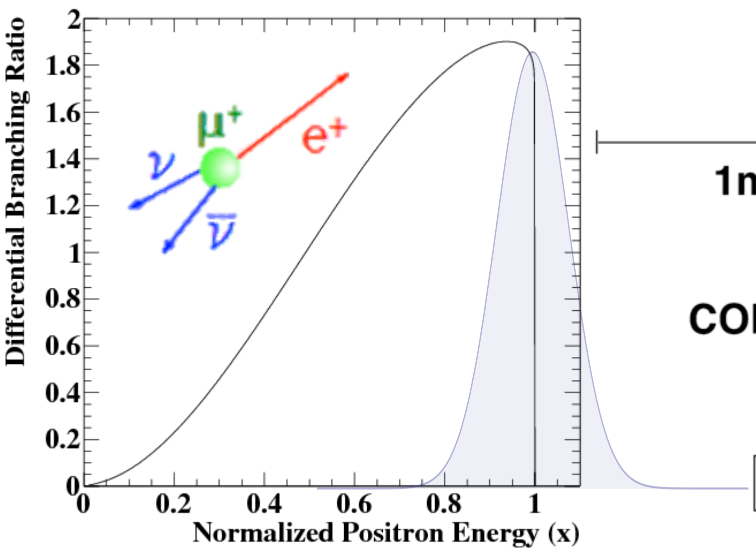
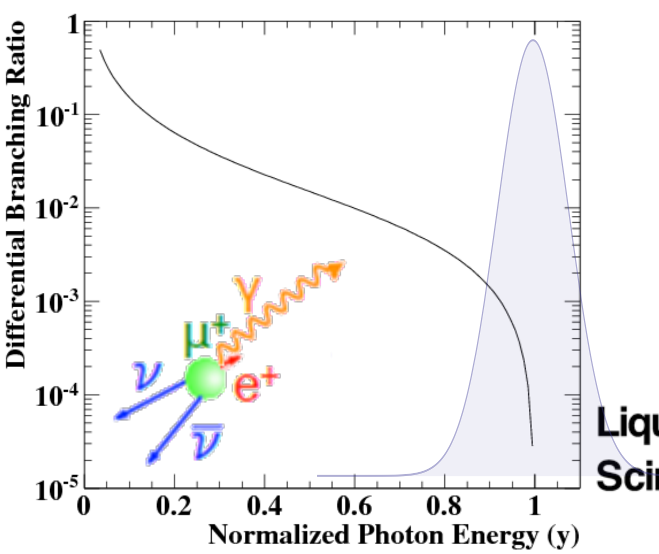
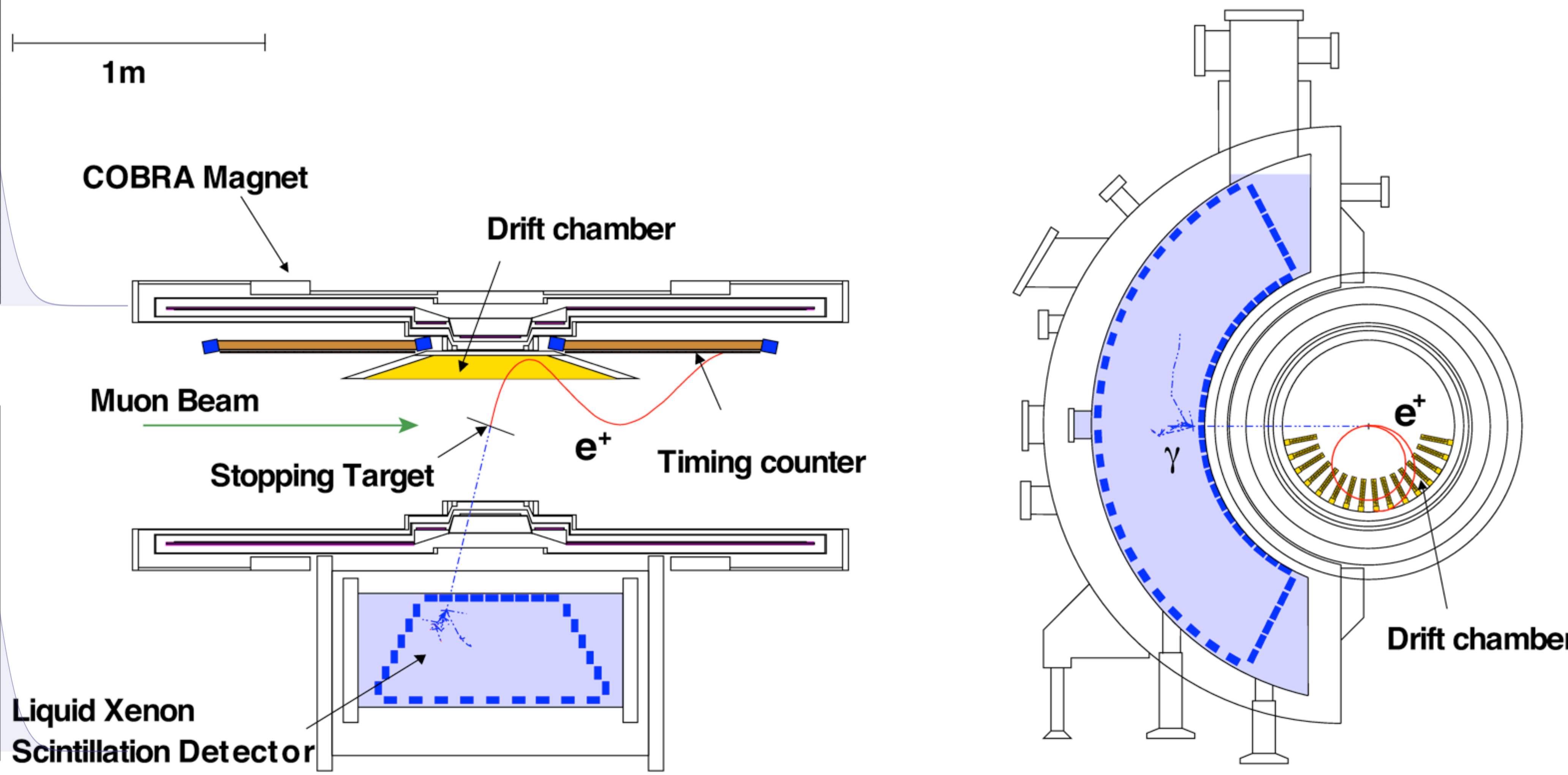
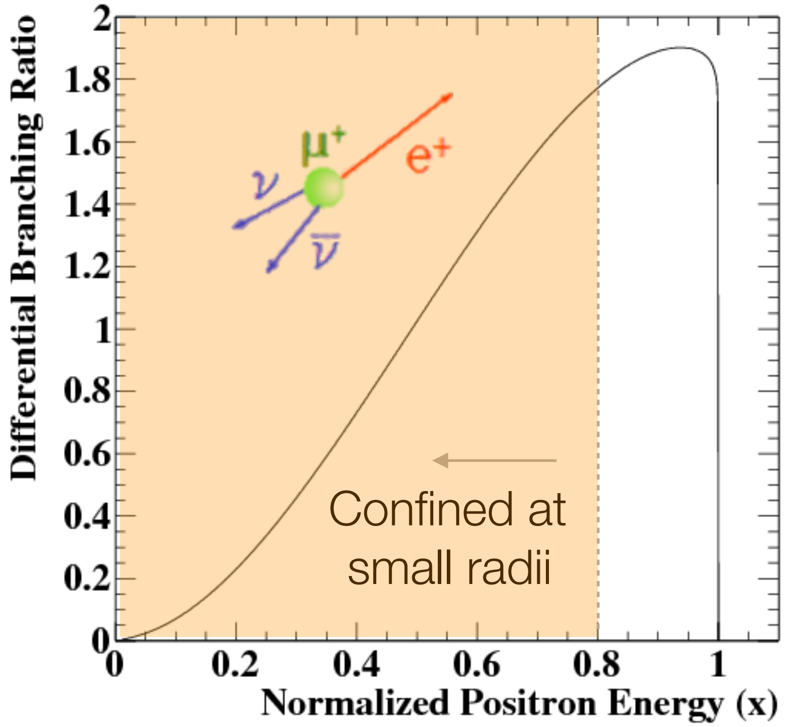


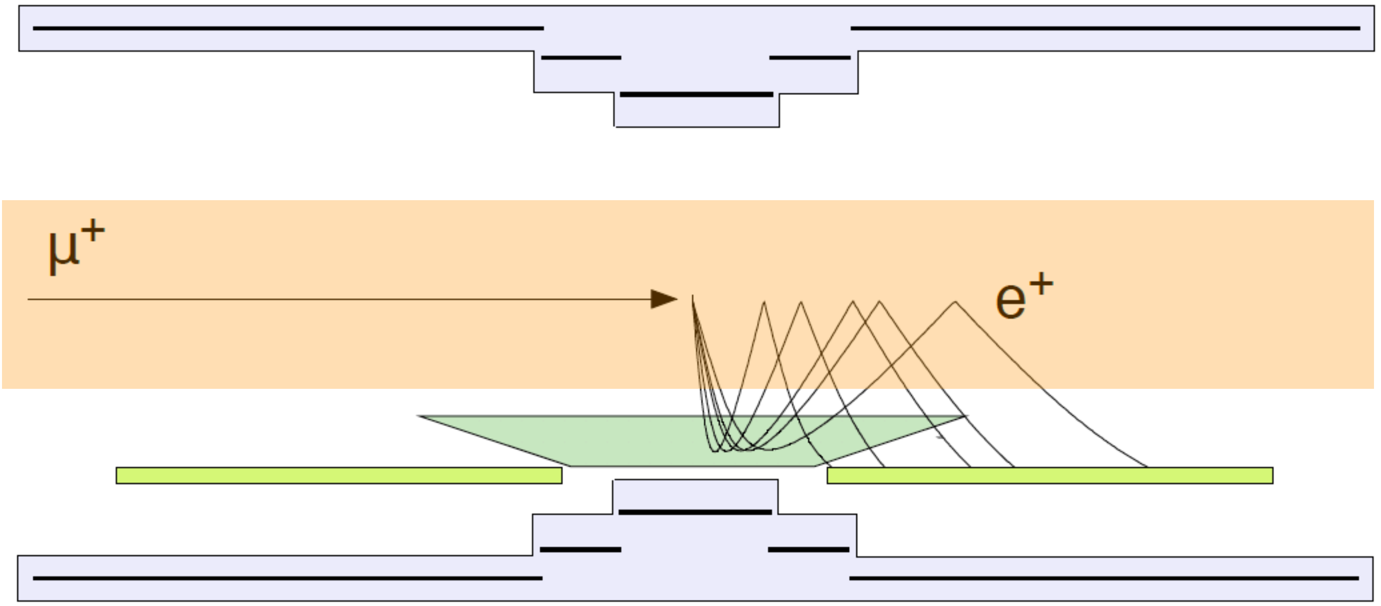




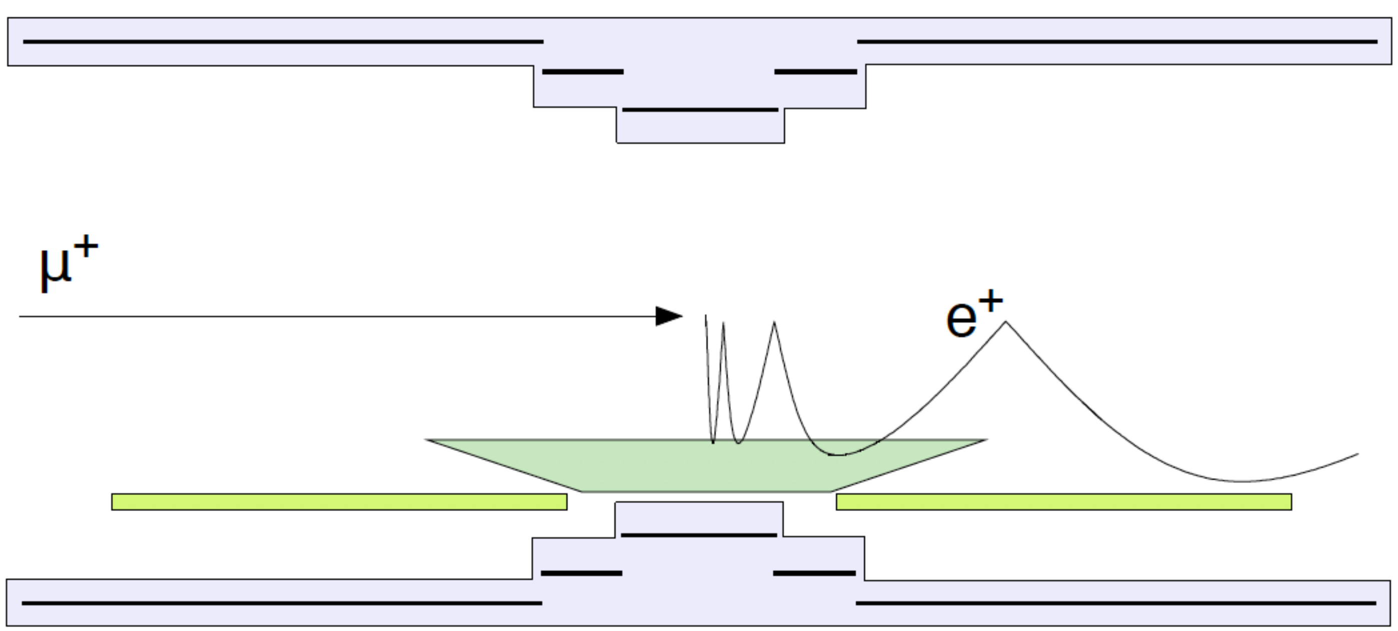
MEG: The spectrometer



- Low momentum positrons swept away without hitting the chambers
- Projected radius independent of the emission angle
- Very low material budget (~ 2 10^{-3} X_0)
- High momentum resolution (σ_p ~ 315 keV/c), angular resolutions (σ_ϕ ~ 7.5 mrad , σ_θ ~ 10.6 mrad) and timing resolution (σ_t ~ 100 ps) never reached up to now with a single detector at 52.8 MeV!



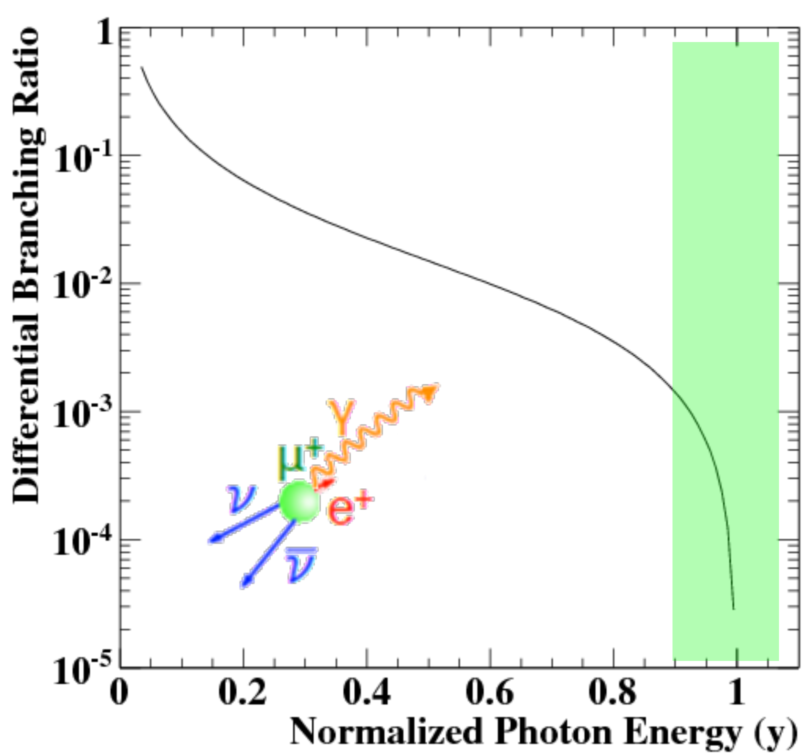
a) Constant projected bending radius for positrons with equal momentum.

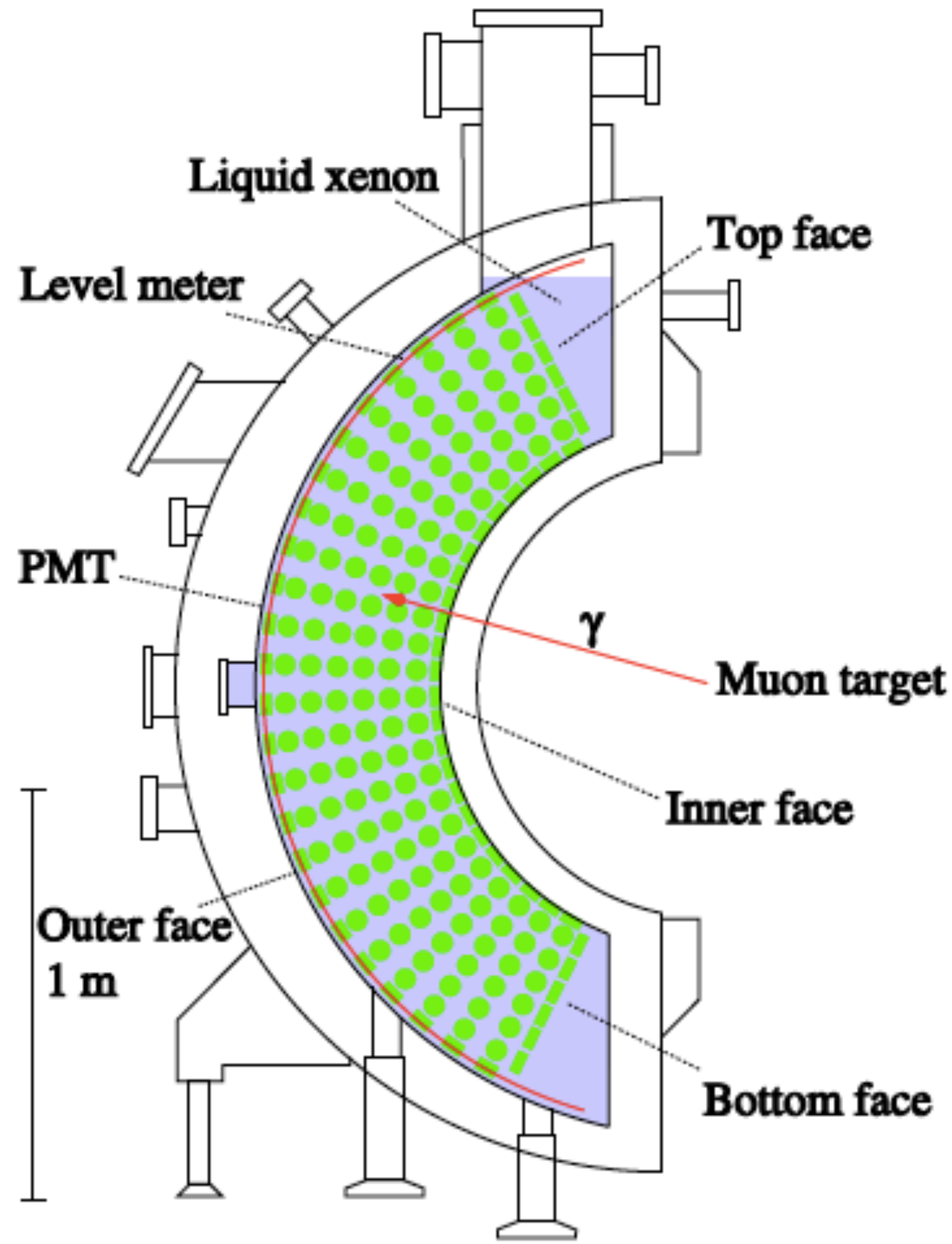


b) Quick sweep-out of particles with $\cos\theta_{e^+} \approx 0$.

MEG: The LXe calorimeter

- High detection efficiency (High Z/ Low X_0)
- High energy, timing and position resolutions (High LY, Fast time constants, High density, High photosensor coverage)
- Purity < 1 ppm and stable conditions over the time
- Particle ID
- Energy (σ_E /E <2.5%) and timing resolutions(σ_t < 70 ps) never reached up to now with a single detector at 52.8 MeV!

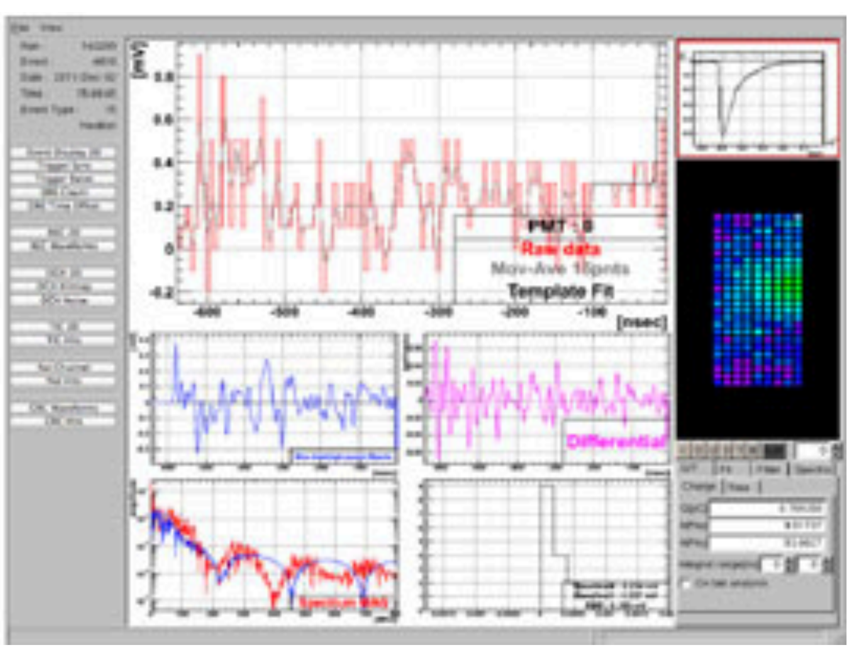


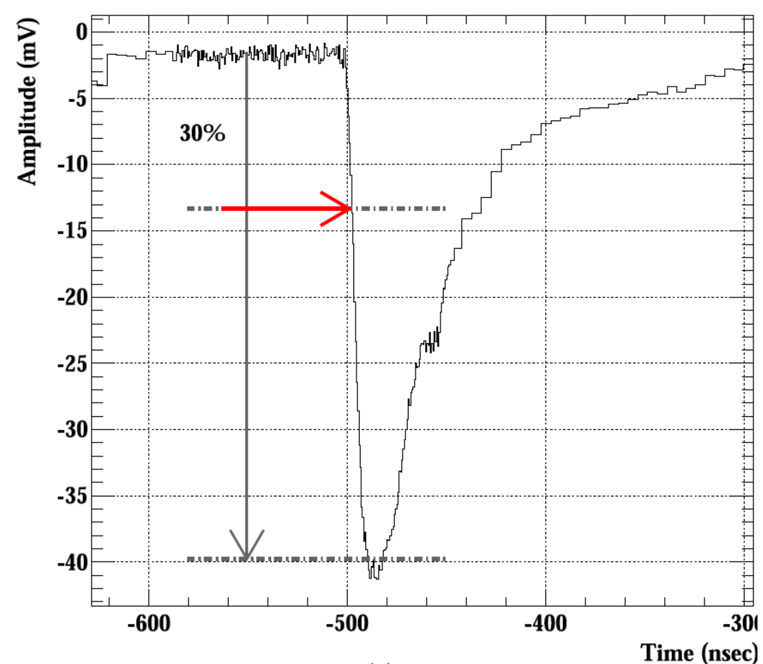


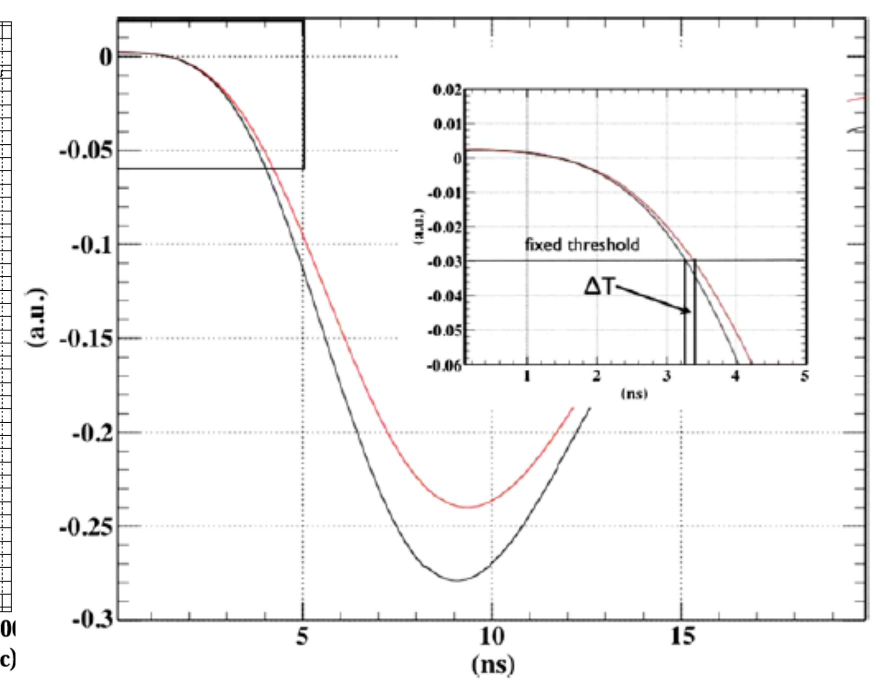
- Volume: 0.9 m^3 LXe
- 846 PMTs immersed in LXe
- thin entrance wall (honeycombe structure)
- Photocathodic coverage 40%
- Solid angle coverage 10%of 4π
- X_0 = 2.77 cm
- density = 2.95 g/cm^3
- n = 1.65
- Z = 54
- R_M = 4.1 cm
- LY = 40000 ph/MeV
- Time constants = 4, 22 and 45 ns
- Particle Identification

MEG: The Data Acquisition (DAQ)

- Flexible and efficient trigger system, to select the candidate events, using fast detectors only
  - FADC digitization at 100 MHz
  - online selection algorithms implemented into FPGAs
- Domino Ring Sampler (DRS) chip for excellent pile-up rejection and timing resolutions with a full waveform digitization (> 100 MHz)
  - all 1000 PMTs signals (LXe and TC) digitize at 1.6 GSample/s
  - all 3000 DC channels (anodes and cathodes) digitize at 800 MSample/s



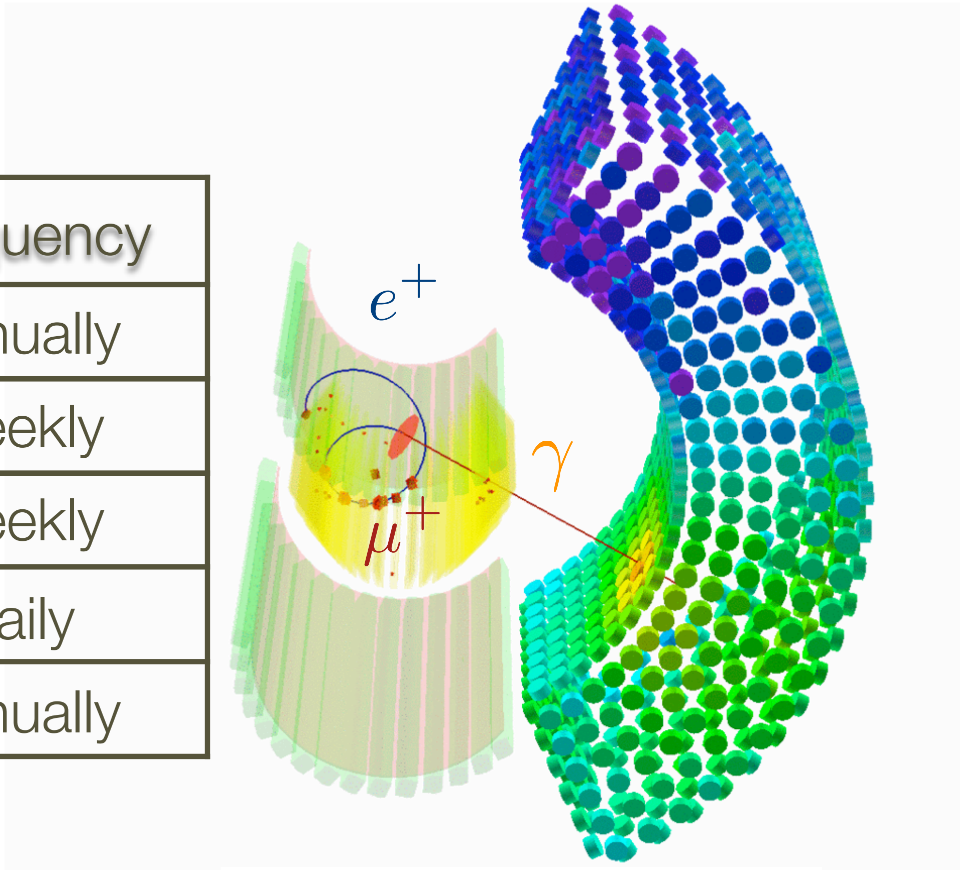


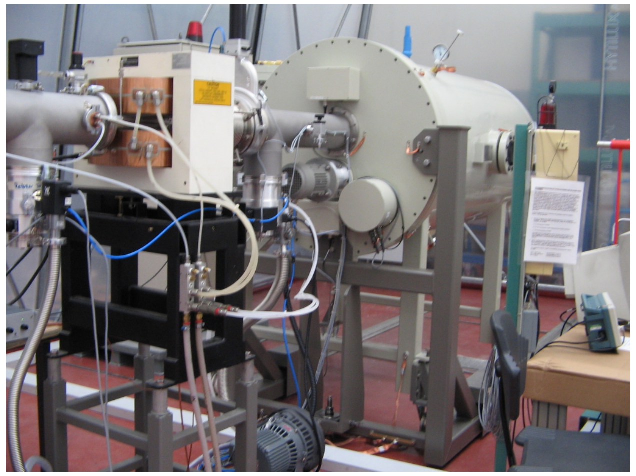


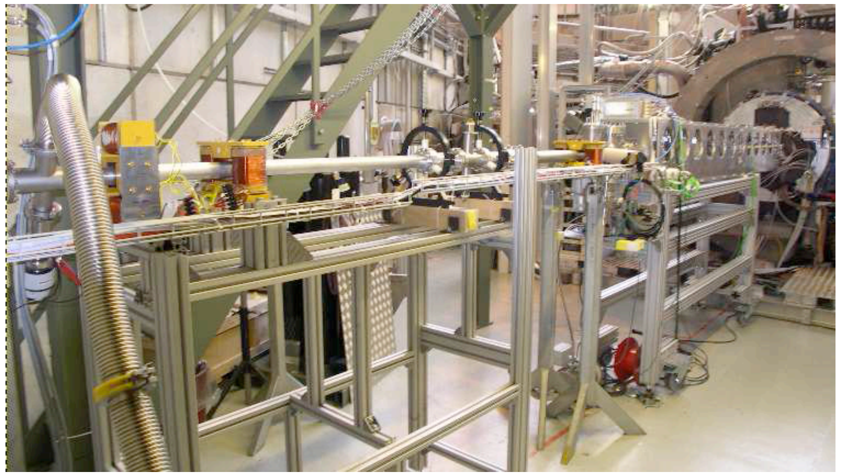
MEG: The calibration methods

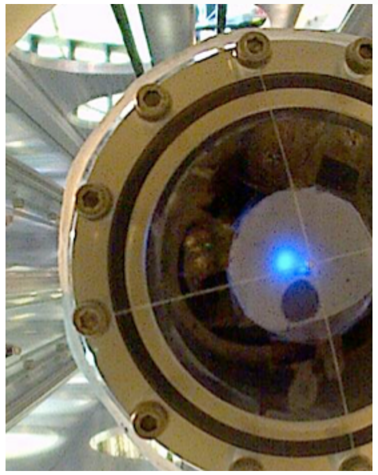
- Multiple calibration and monitoring methods: detector resolution and stability are the key points in the search for rare events over the background

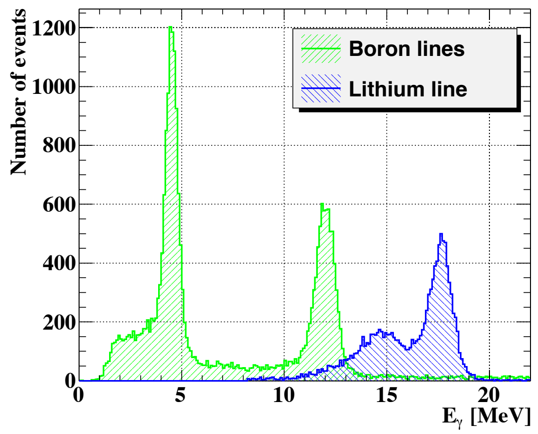
Process		Energy (MeV)	Frequency
CEX reaction	$p(\pi^-, \pi^0)n, \pi^0 \rightarrow \gamma\gamma$	55, 83	annually
C-W accelerator	${}^{7}Li(p, \gamma_{17.6}){}^{8}Be$	17.6	weekly
	${}^{11}B(p, \gamma_{11.6}){}^{12}C$	4.4&11.6	weekly
Neutron Generator	${}^{58}Ni(n, \gamma_{9}){}^{59}Ni$	9	daily
Mott Positrons	$p(e^+, e^+)p$	53	annually











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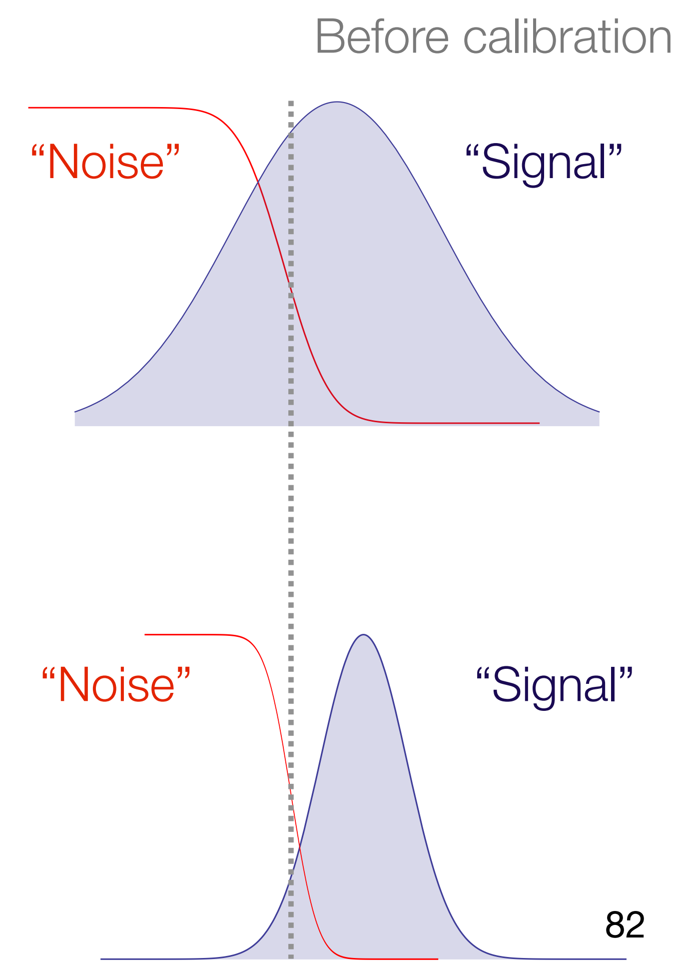
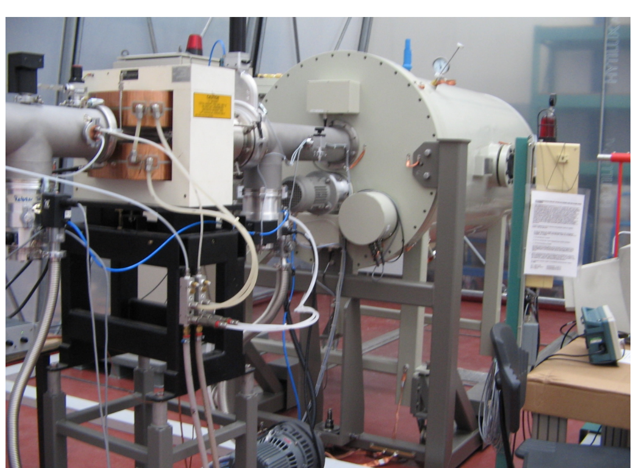
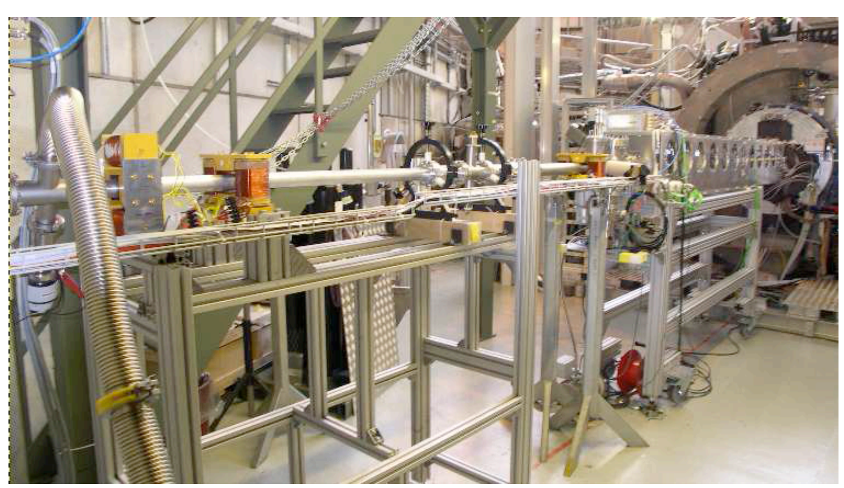
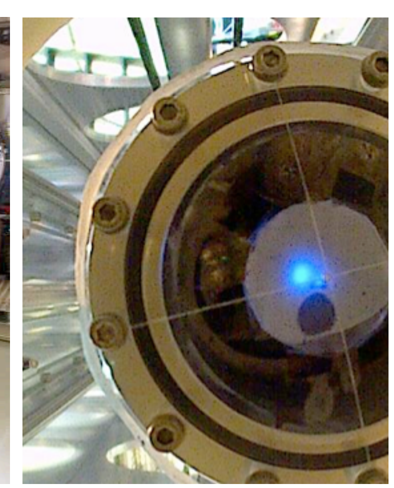








cLFV search landscape

Rough estimate of numbers of researchers, in total ~ 850 (with some overlap)

Muons ~ 250
- MEG, PSI
- MEGII, PSI
- Mu3e, PSI
- DeeMee, J-PARC
- MuSiC, Osaka
- Mu2e, FNAL
- COMET, J-PARC
- PROJECT X, FNAL
- PRIME, J-PARC

Kaons ~ 100
- NA48,CERN
- NA62,CERN
- KOTO, J-PARC

cLFV @ LHC ~ 250
- ATLAS,CERN
- CMS,CERN
- LHCb, CERN

Taus ~ 250
- BABAR, PEPII
- BELLE/BELLE II, KEKB/SuperKEKB

J/ψ @ BEPCII ~ 100
- BESIII, Beijing

cLFV best upper limits

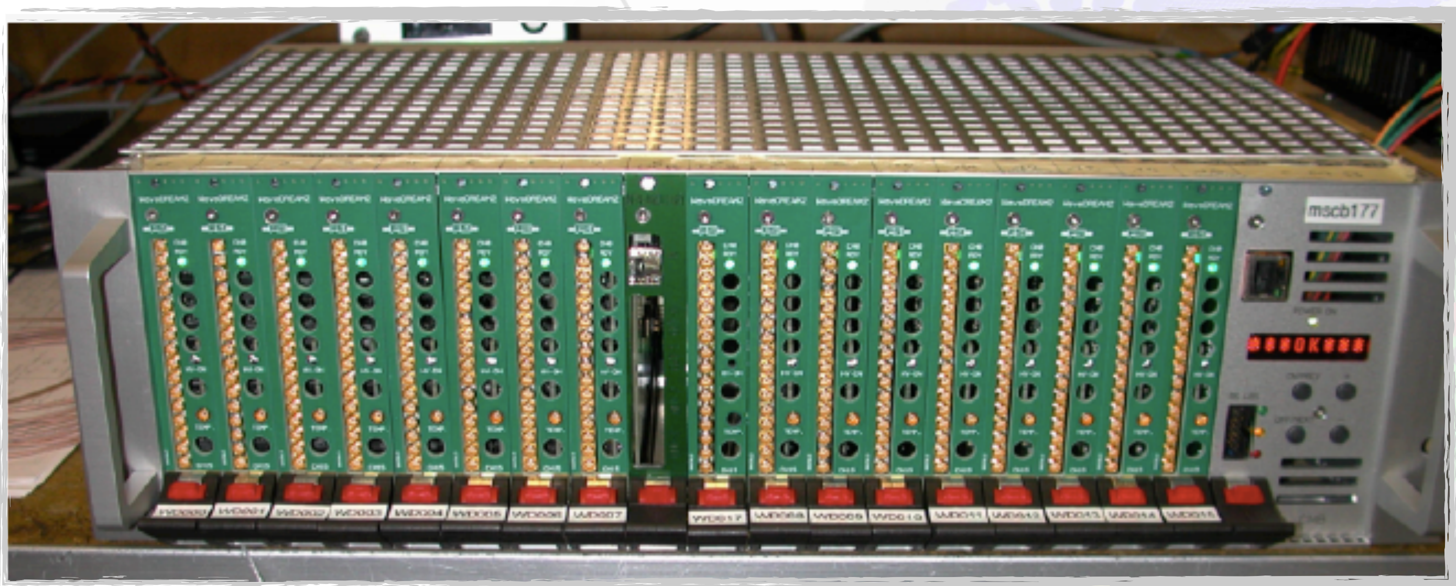
Process	Upper limit	Reference	Comment
$\mu^+ \to e^+ \gamma$	4.2×10^{-13}	arXiV:1605.05081	MEG
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	Nucl. Phy. B299 (1988) 1	SINDRUM
$\mu^- N \to e^- N$	7.0×10^{-13}	Eur. Phy. J. c 47 (2006) 337	SINDRUM II
$\tau \to e \gamma$	3.3×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau \to \mu \gamma$	4.4×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau^- \to e^- e^+ e^-$	2.7×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^- \mu^+ \mu^-$	2.1×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$Z \to \mu e$	7.5×10^{-7}	Phy. Rev. D 90 (2014) 072010	Atlas
$Z \to \mu e$	7.3×10^{-7}	CMS PAS EXO-13-005	CMS
$H \to \tau \mu$	1.85×10^{-2}	JHEP 11 (2015) 211	Atlas (*)
$H \to \tau \mu$	1.51×10^{-2}	Phy. Let. B 749 (2015) 337	CMS
$K_L \to \mu e$	4.7×10^{-12}	PRL 81 (1998) 5734	BNL

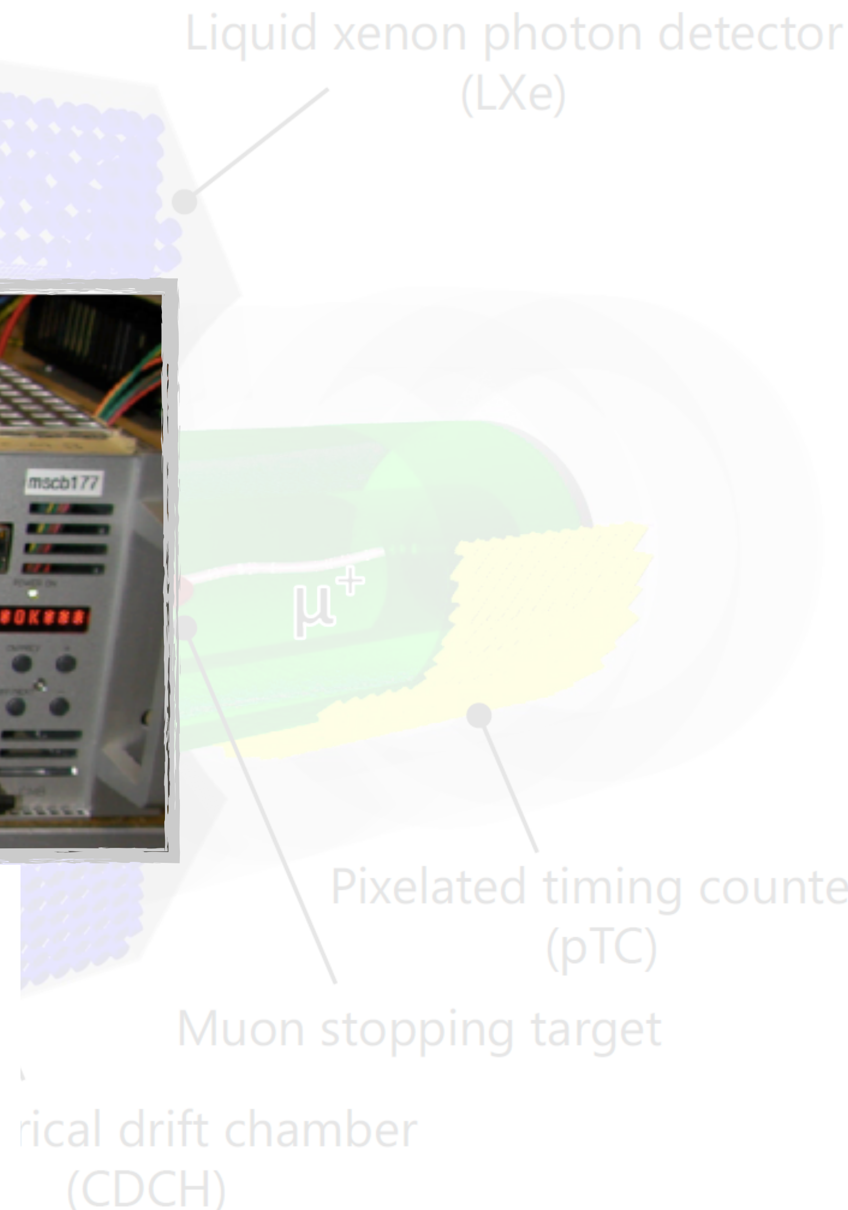
* $B(H \to \mu e) < O(10^{-8})$ from $\mu \to e \gamma$

The MEGII experiment: Status

New electronics:
Wavedream

~9000 channels at 5GSPS

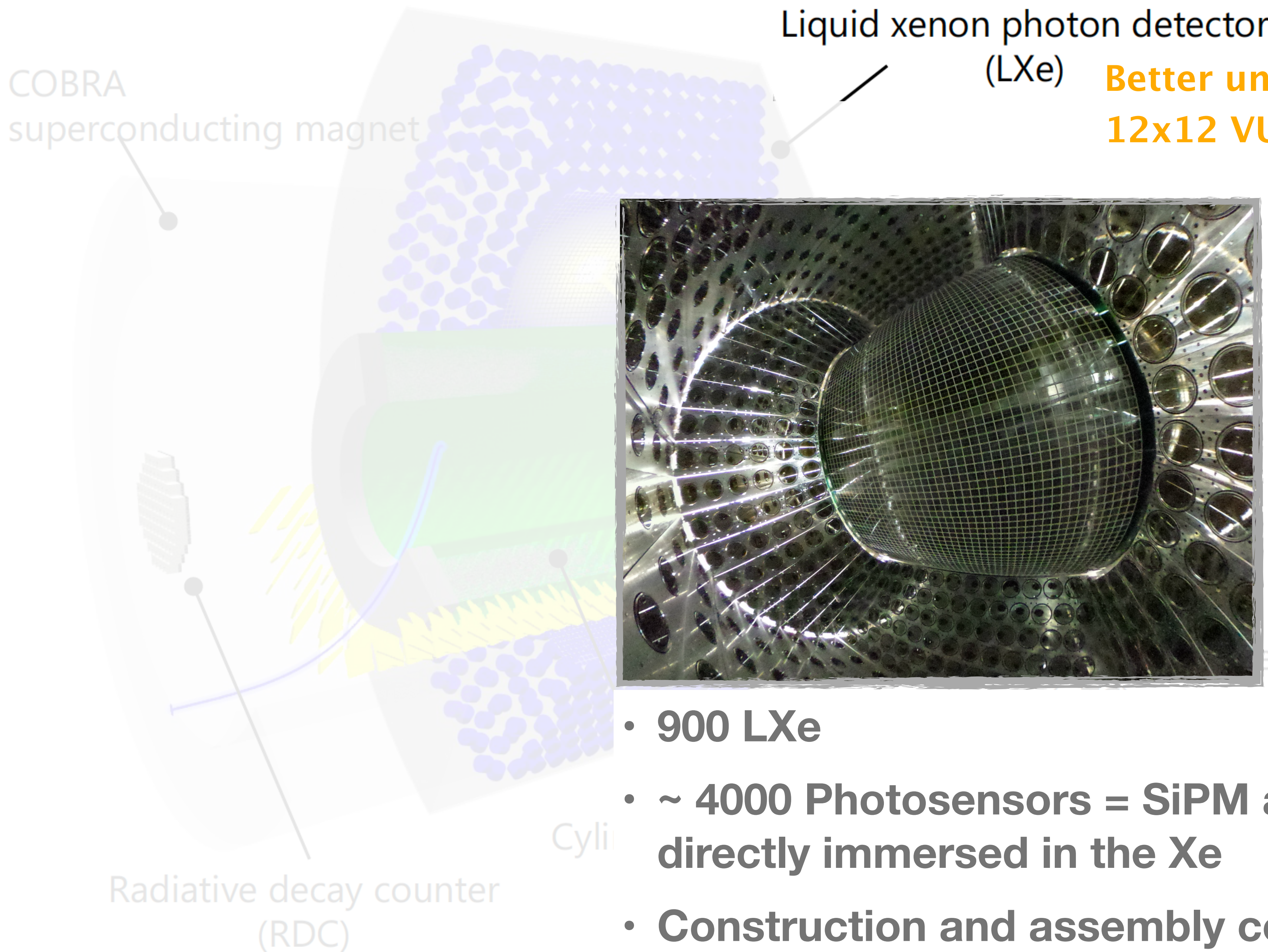




- **>1000 channels available for the incoming 2017 pre-engineering run**
- **For SiPM: bias voltage, pre-amp and shaping included**

A. Baldini et al. arXiv:1301.7225v2

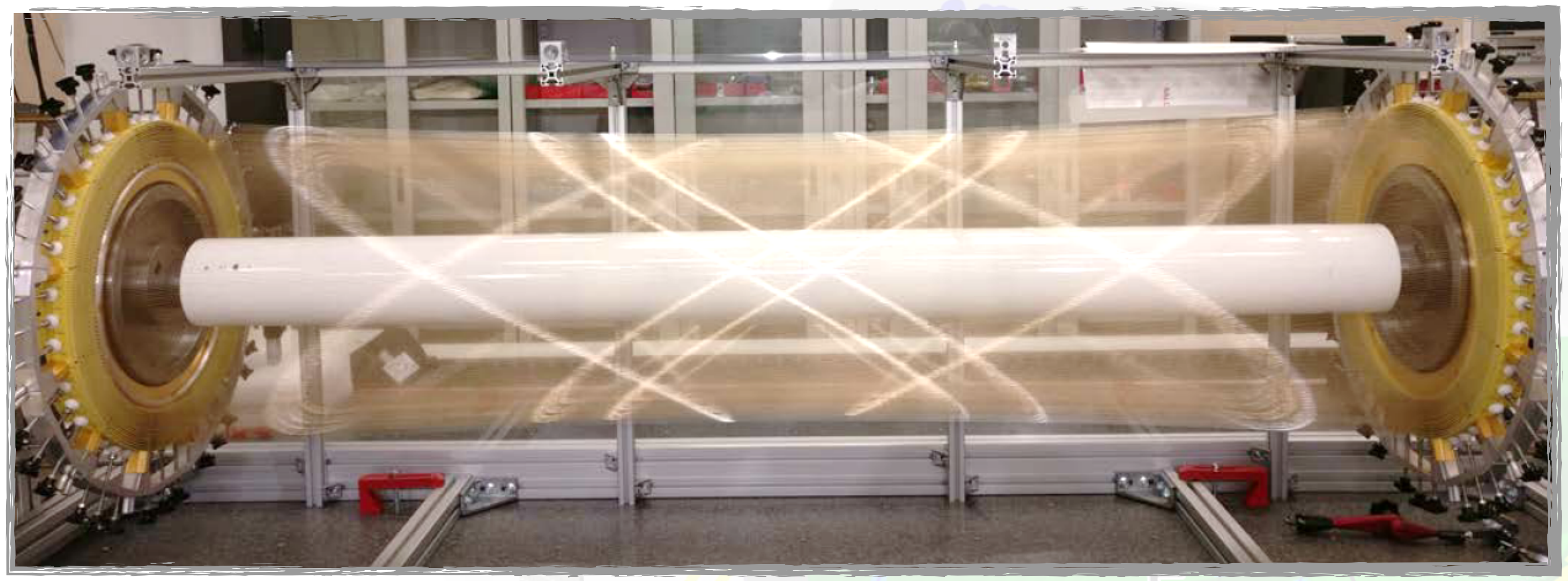
The MEGII experiment: Status



Better uniformity w/ 12x12 VUV SiPM

- **900 LXe**
- **~ 4000 Photosensors = SiPM and PMT directly immersed in the Xe**
- **Construction and assembly completed**
- **Commissioning phase started (with reduced number of electronics channels)**

The MEGII experiment: Status



- **Low material budget detector: < 0.0016 X_0**
- **In construction (Assembly: 70%, wiring: 80%)**
- **Mock-up installed in Cobra**
- **Gas system: commissioning phase**

Liquid xenon photon detector
(LXe)

Pixelated timing counter
(pTC)

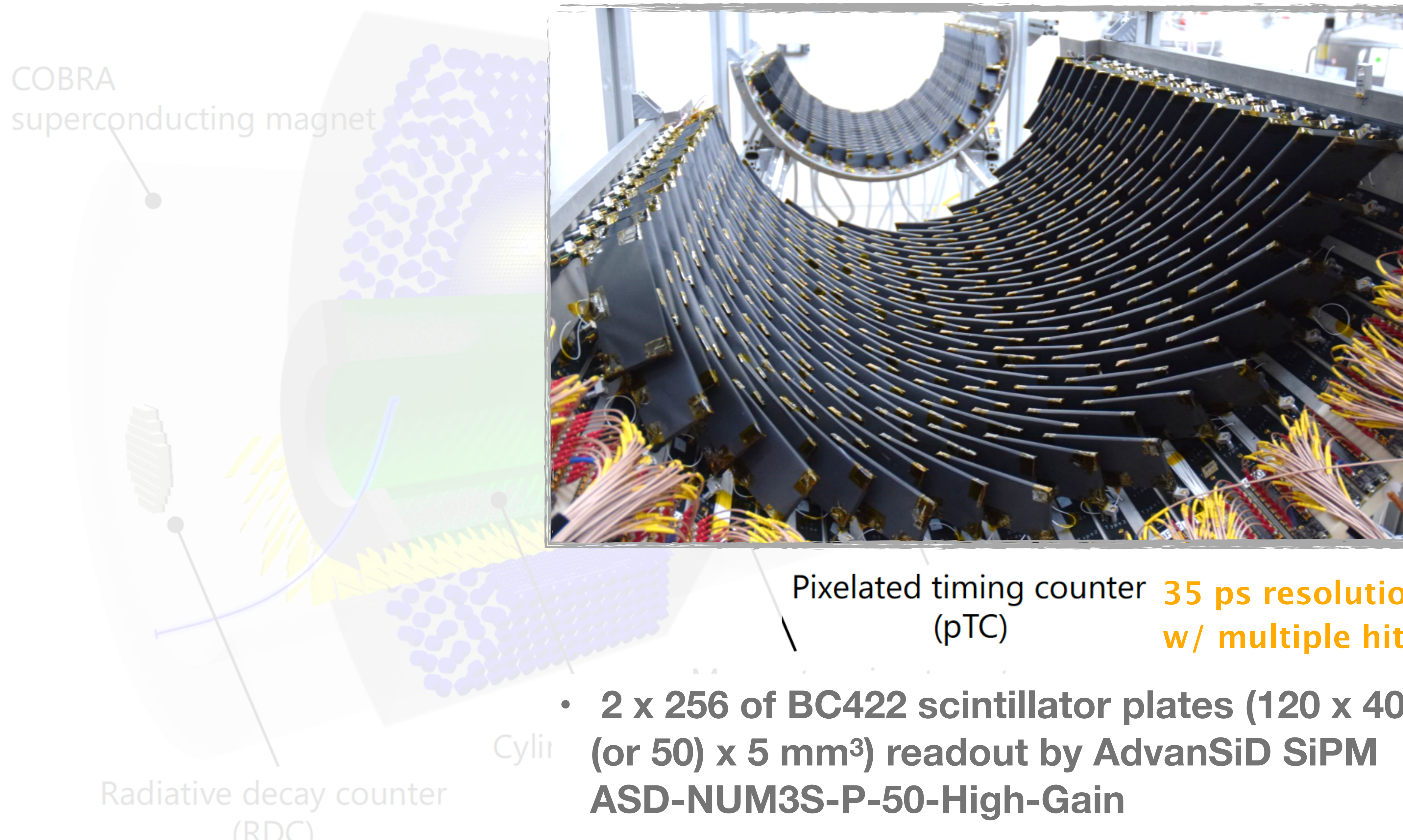
Muon stopping target

Radiative decay counter
(RDC)

Cylindrical drift chamber
(CDCH)

Single volume $He:iC_4H_{10}$

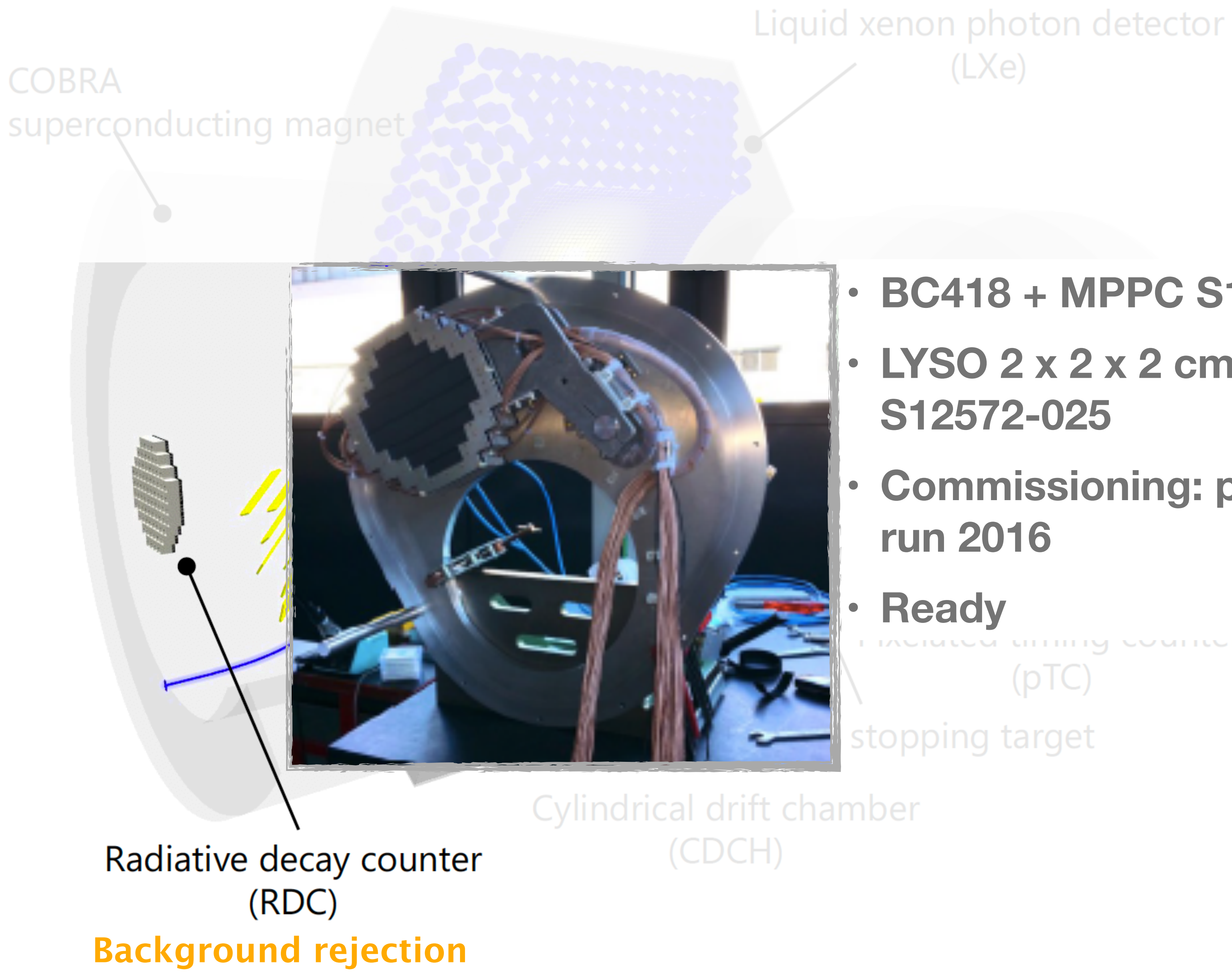
The MEGII experiment: Status



35 ps resolution w/ multiple hits

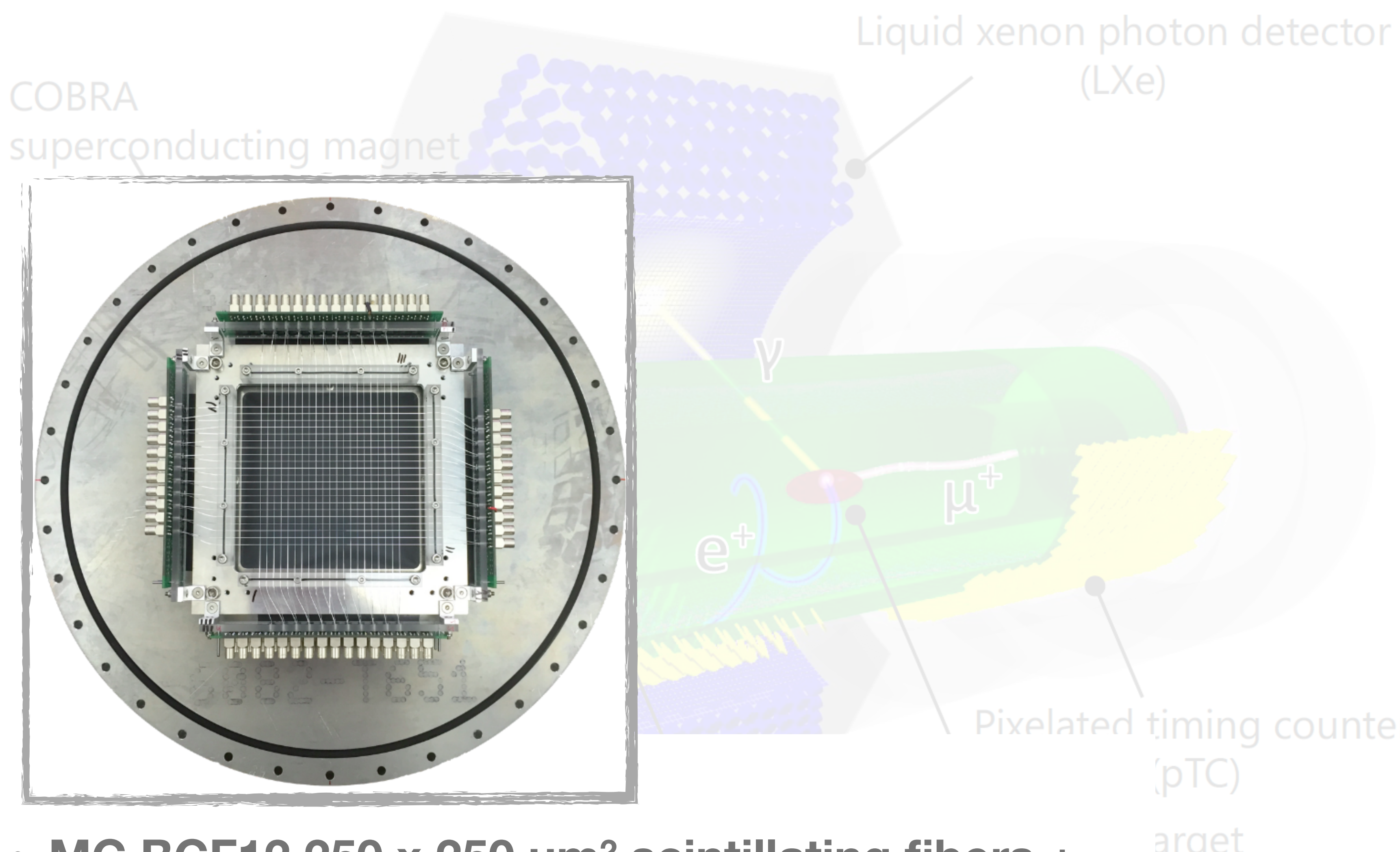
- 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm^3) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain
- Full detector: Commissioning phase

The MEGII experiment: Status



- **BC418 + MPPC S13360-3050PE**
- **LYSO 2 x 2 x 2 cm^3 + MPPC S12572-025**
- **Commissioning: pre-engineering run 2016**
- **Ready**

The MEGII experiment: Status



Updated and new Calibration methods

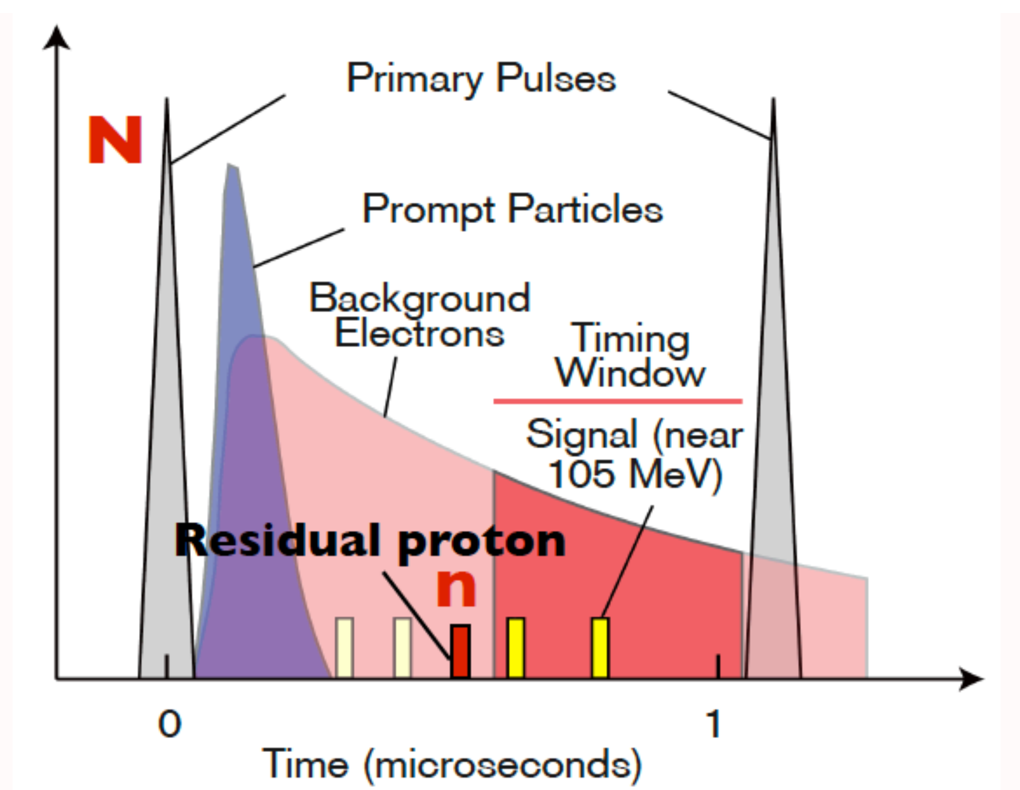
Quasi mono-chromatic positron beam

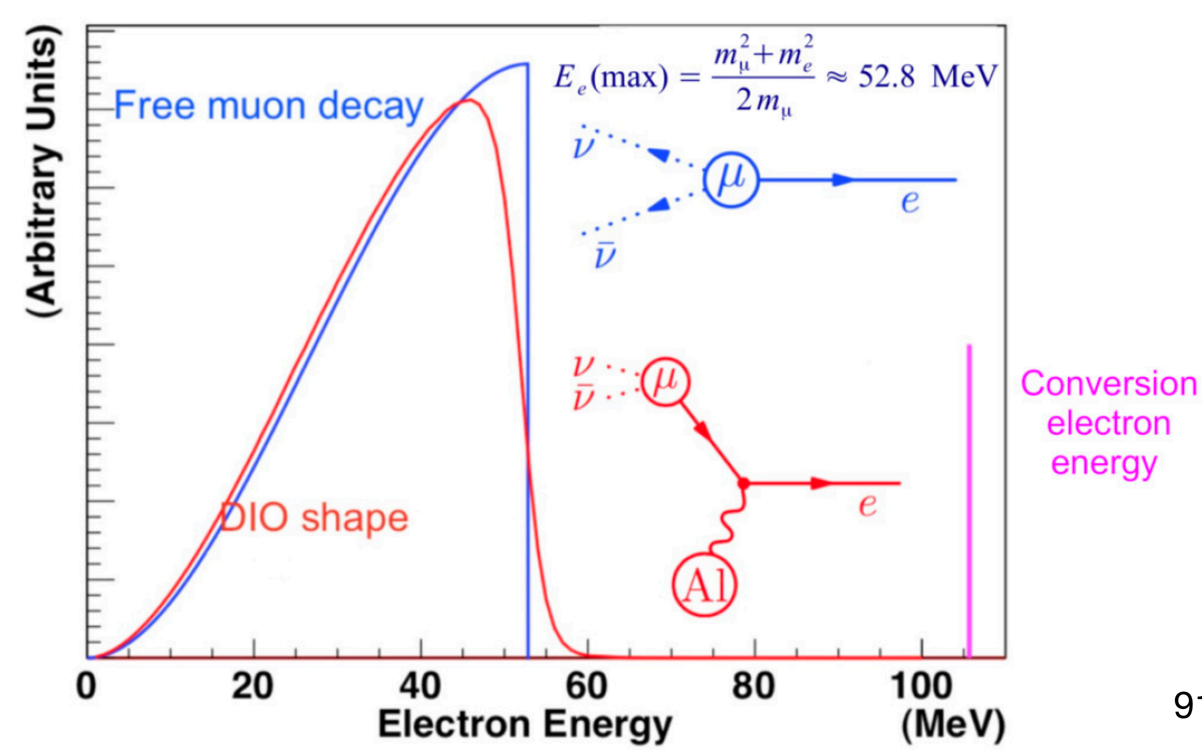
- **MC BCF12 250 x 250 um^2 scintillating fibers + MPPC S13360-3050C**
- **Commissioning: pre-engineering run 2016**
- **Movable configuration: in preparation**

μ⁻ N → e⁻ N experiments

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}$$

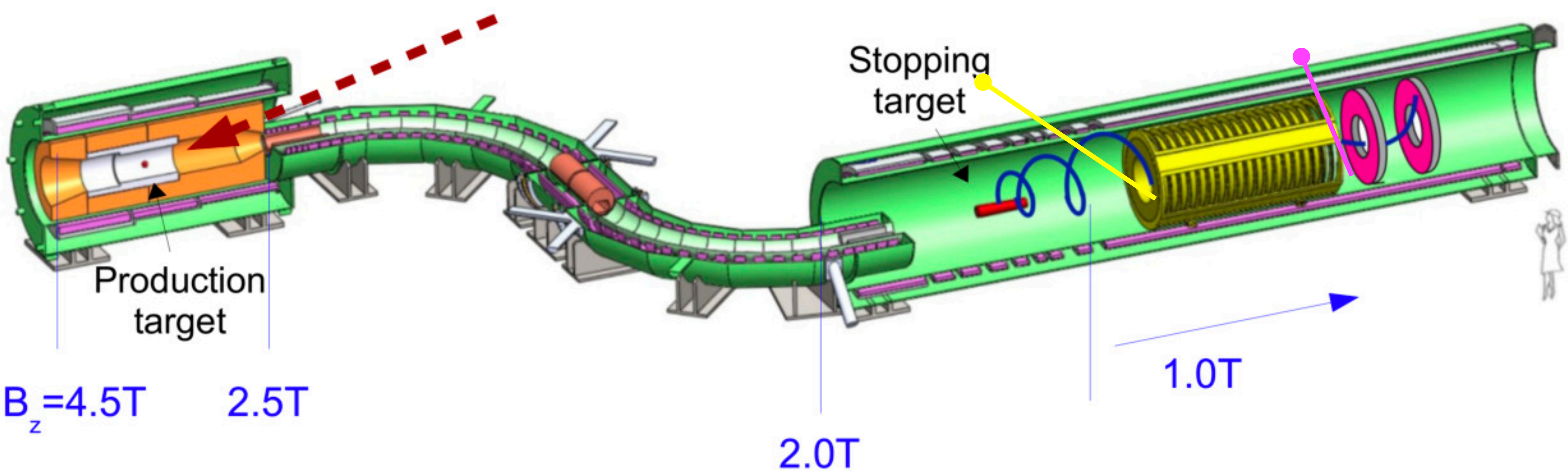
- Signal of mu-e conversion is single mono-energetic electron
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Stop a lot of muons! $O(10^{18})$
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays





The Mu2e experiment

- Three superconducting solenoids: Production, Transport and Detector solenoids
- Muons stop in thin aluminum foils
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID
- Scintillators for the Veto



The COMET experiment

- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]