



DC Muon Physics

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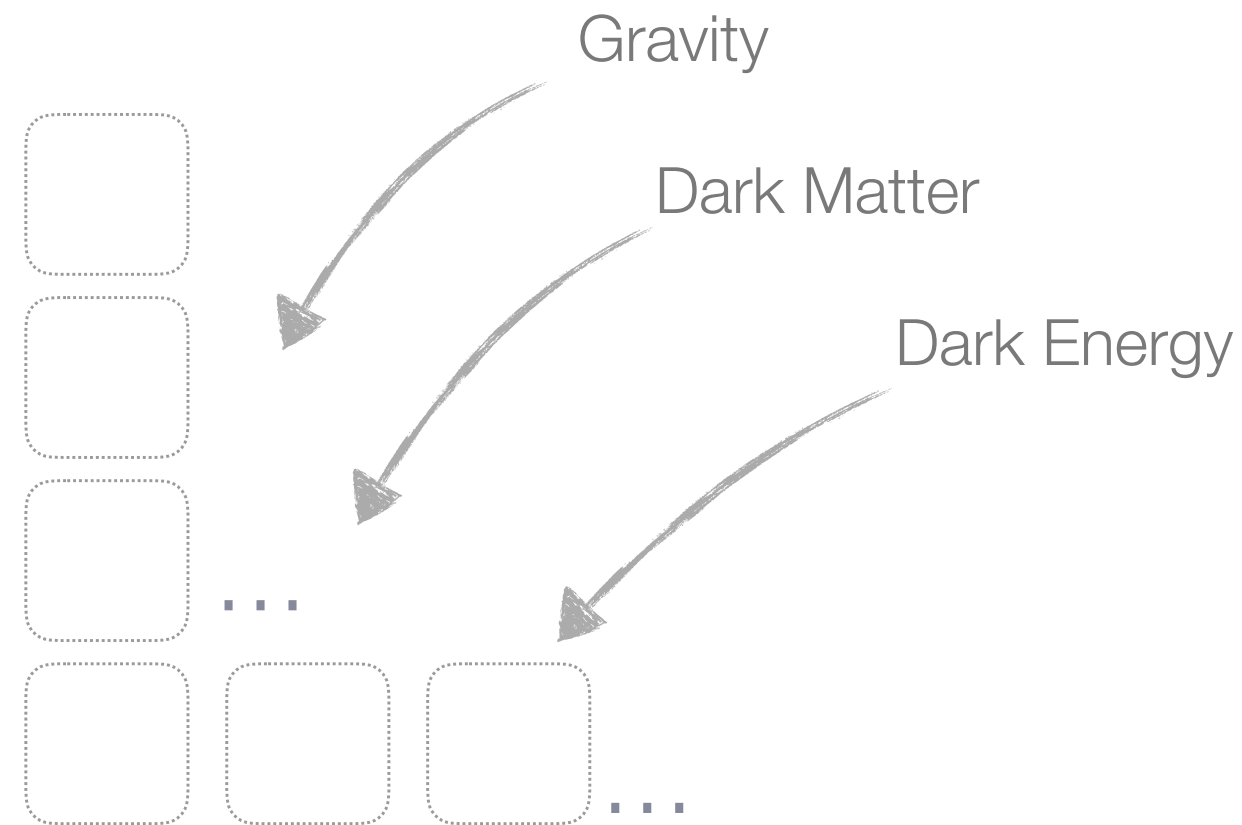
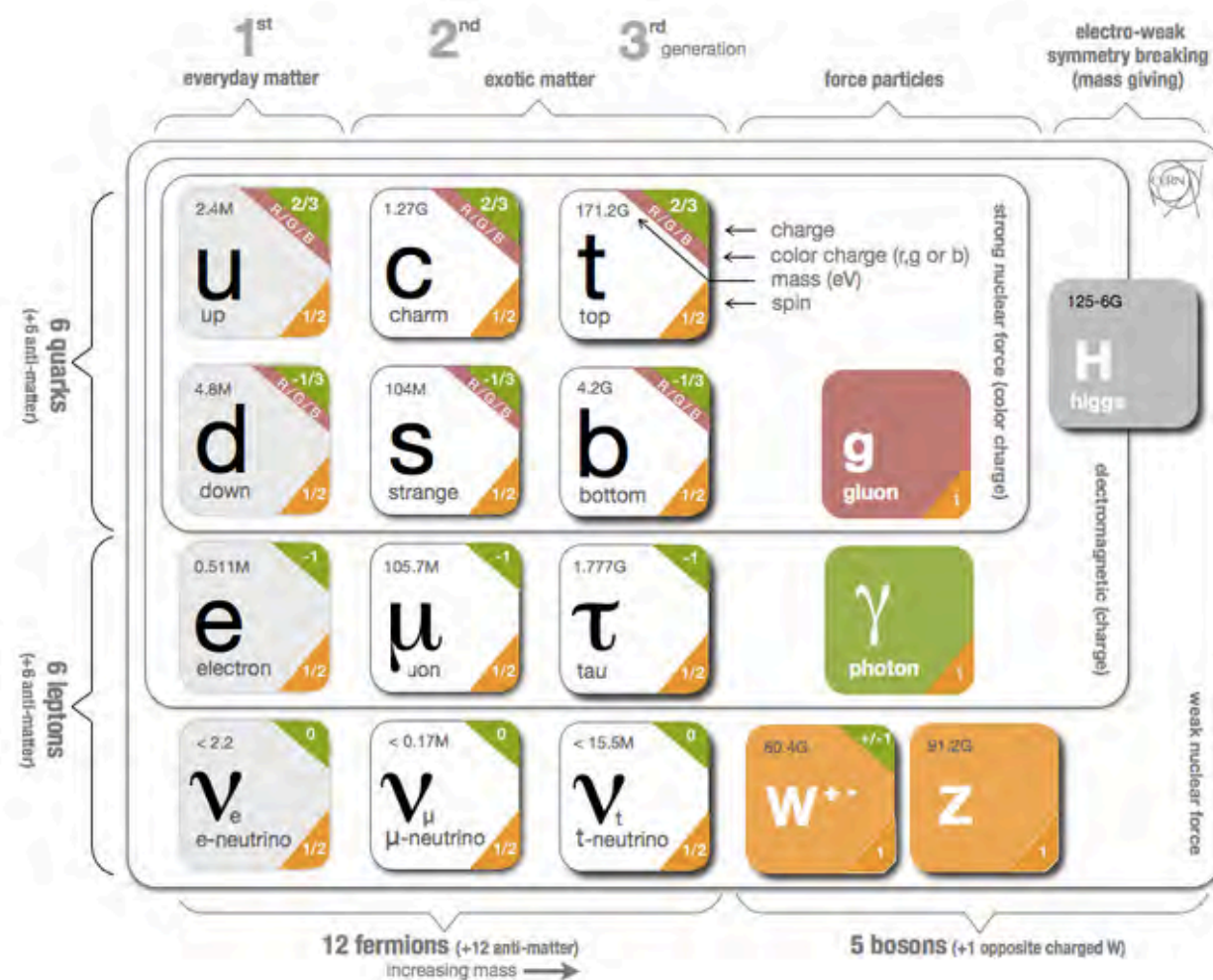


Content

- 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

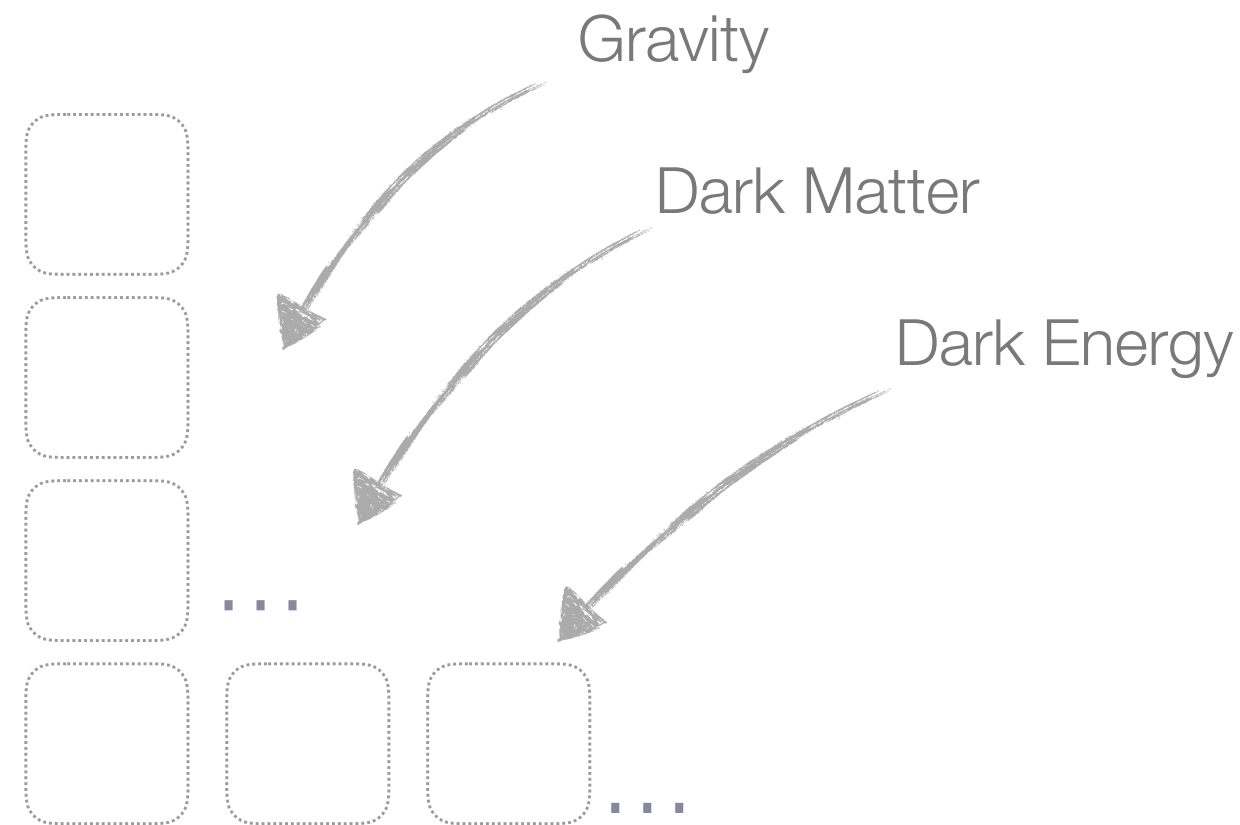
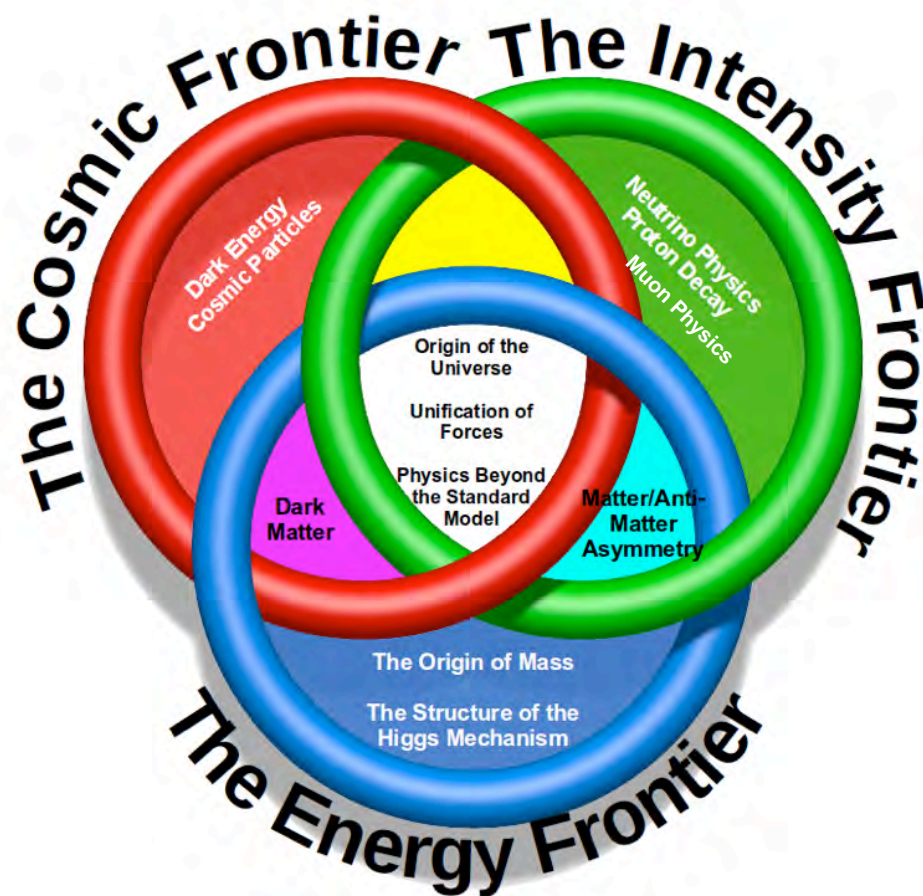
- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



- 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

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The role of the low energy precision physics

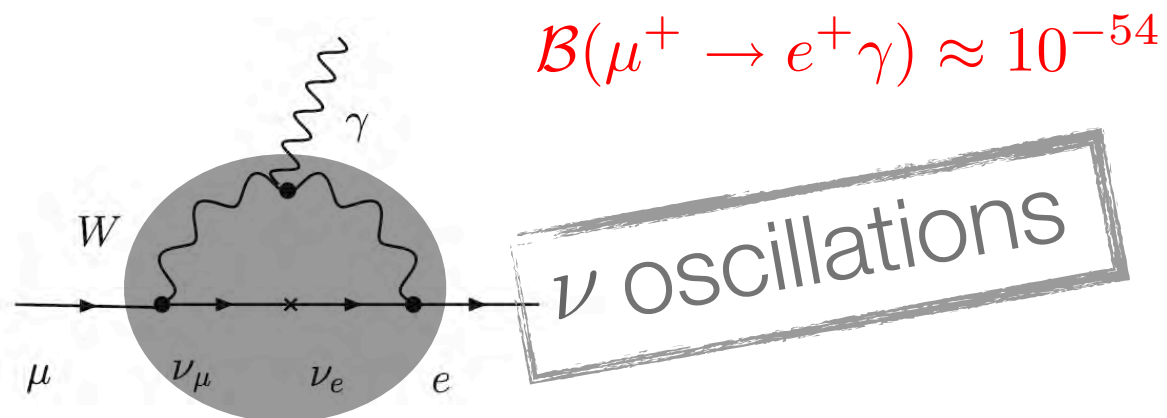
- Two main strategies to unveil new physics
 - Indirect searches
 - Precision tests

The role of the low energy precision physics

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

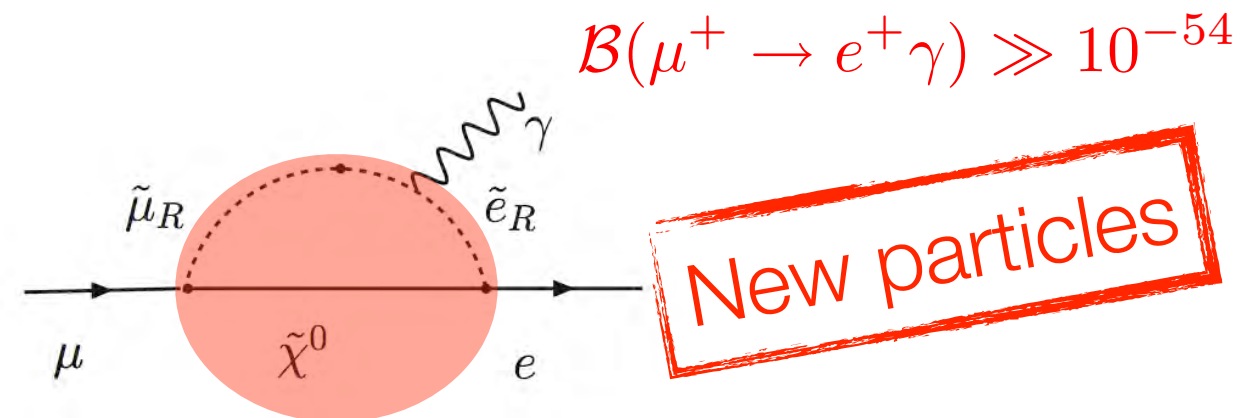
Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)



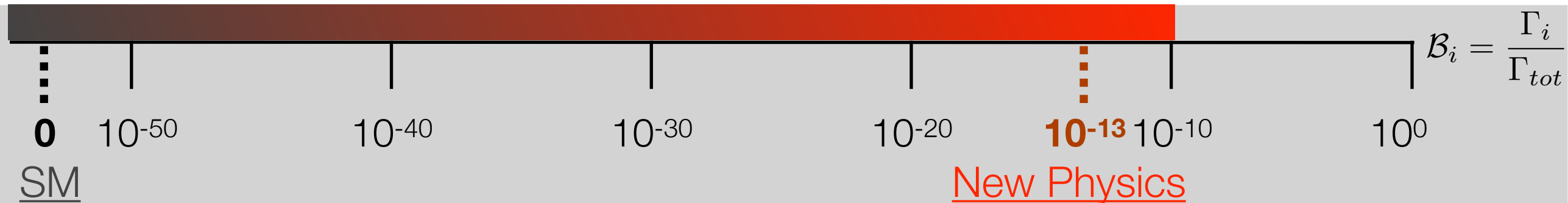
too small to access experimentally

BSM



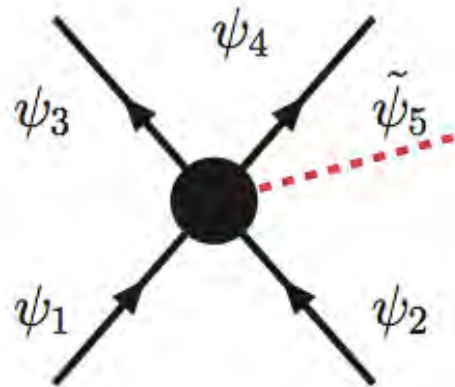
**an experimental evidence:
a clear signature of New Physics NP**
(SM background FREE)

Current upper limits on \mathcal{B}_i



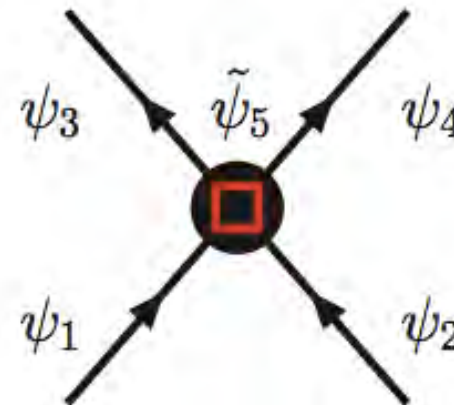
Complementary to “Energy Frontier”

Energy frontier



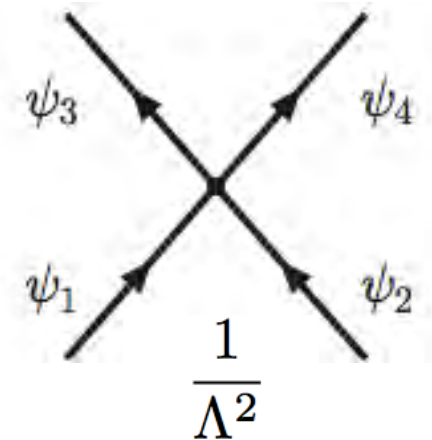
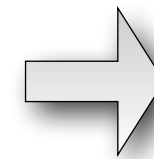
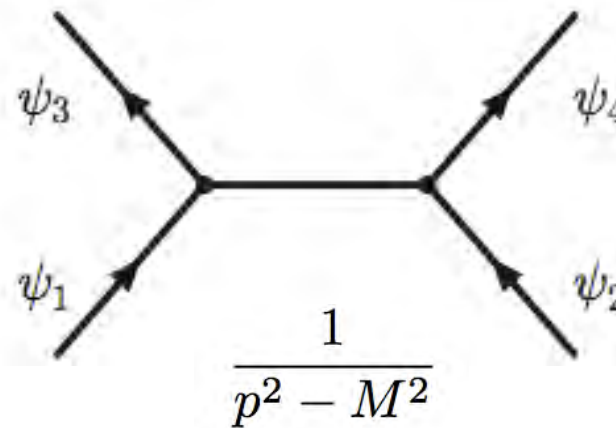
Real BSM particles

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



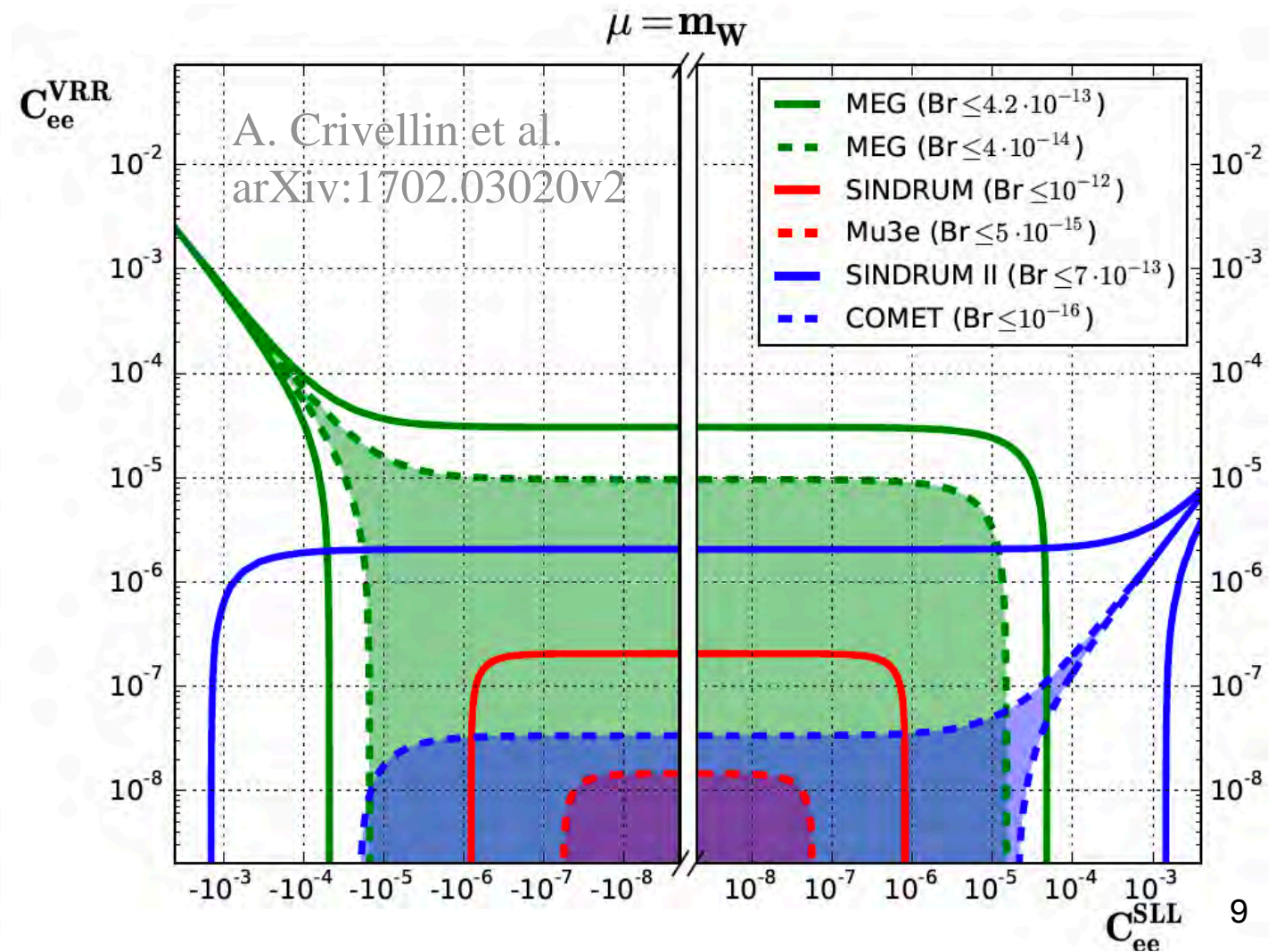
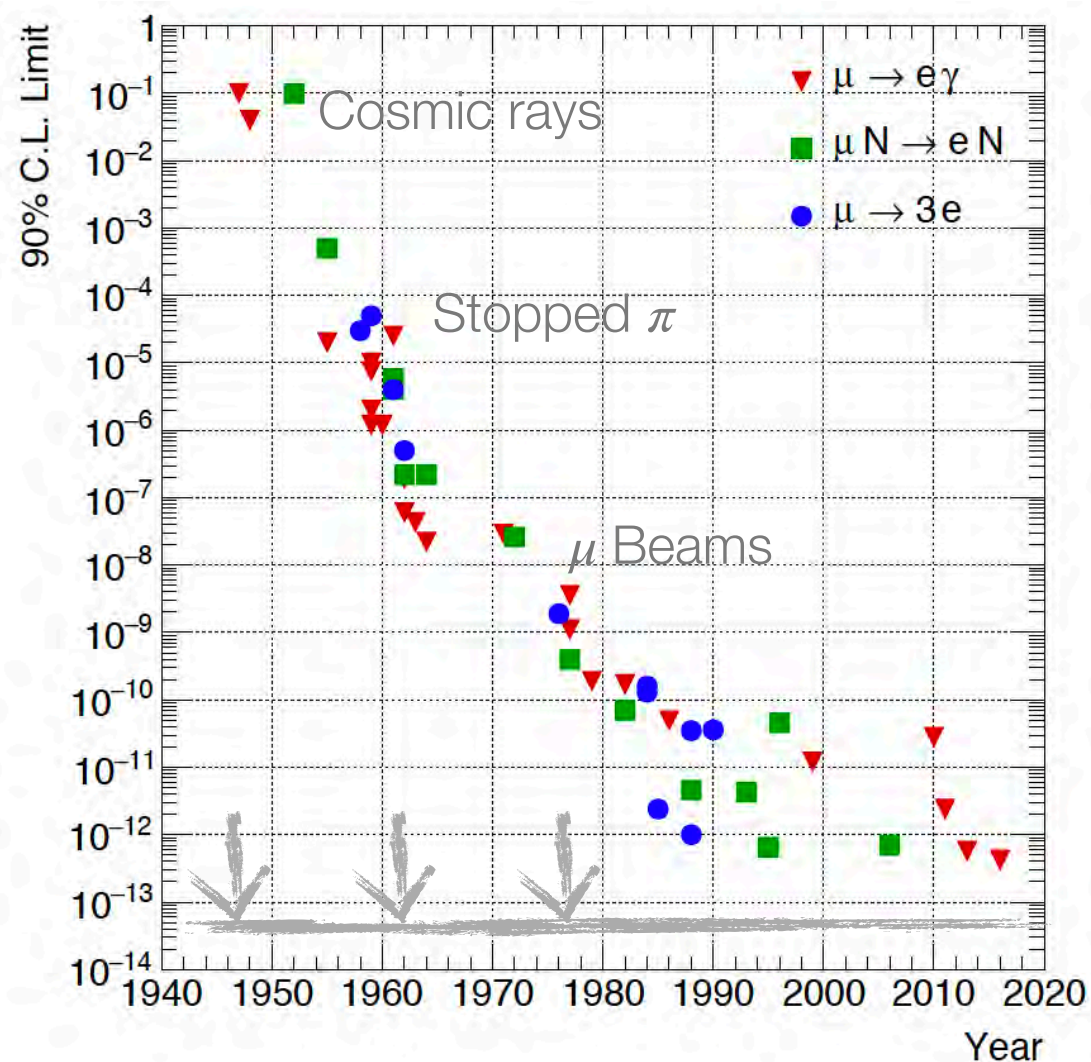
E > 1000 TeV

cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

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

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

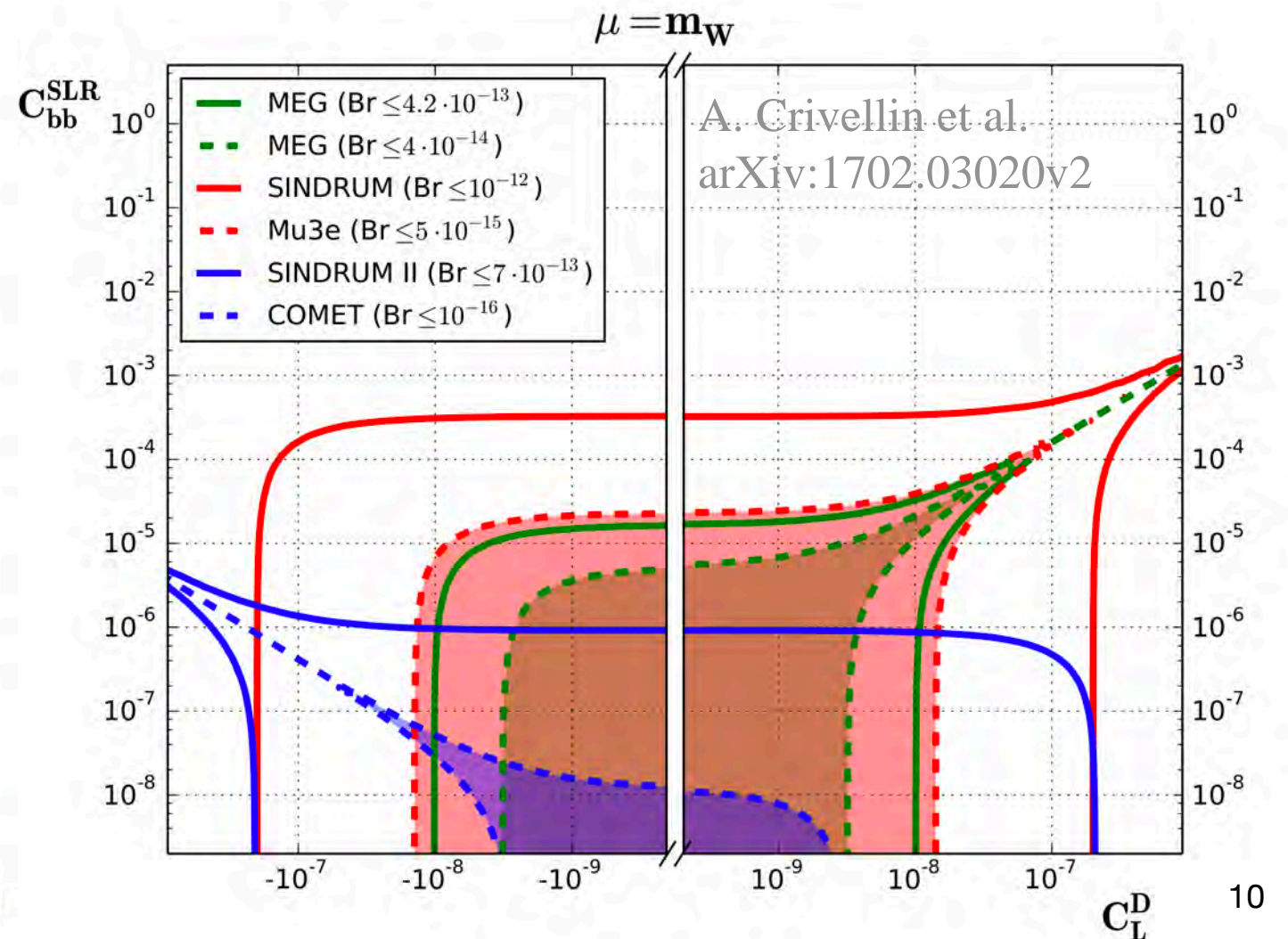
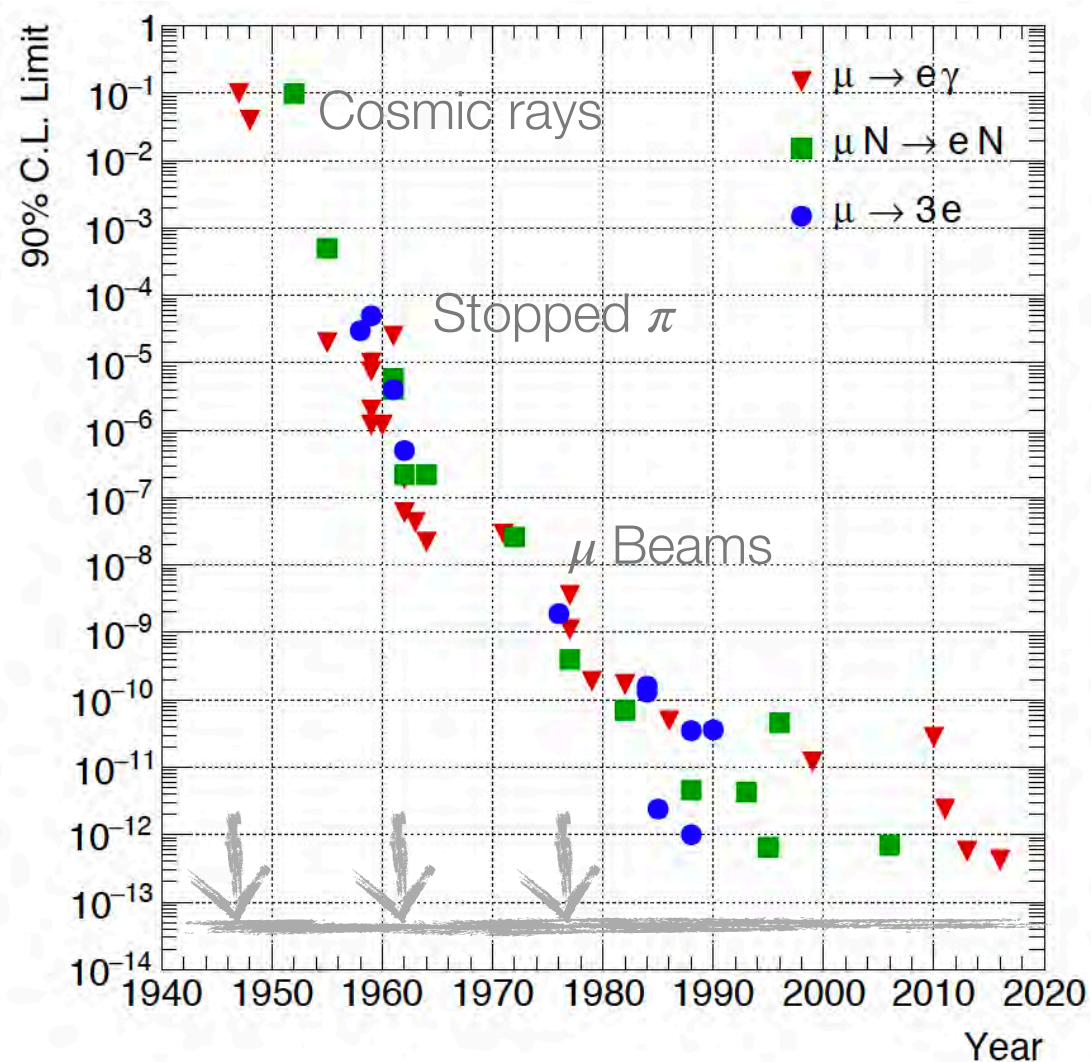


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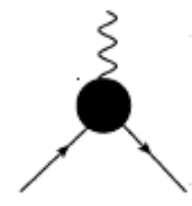
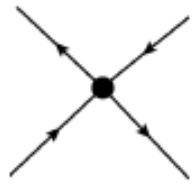
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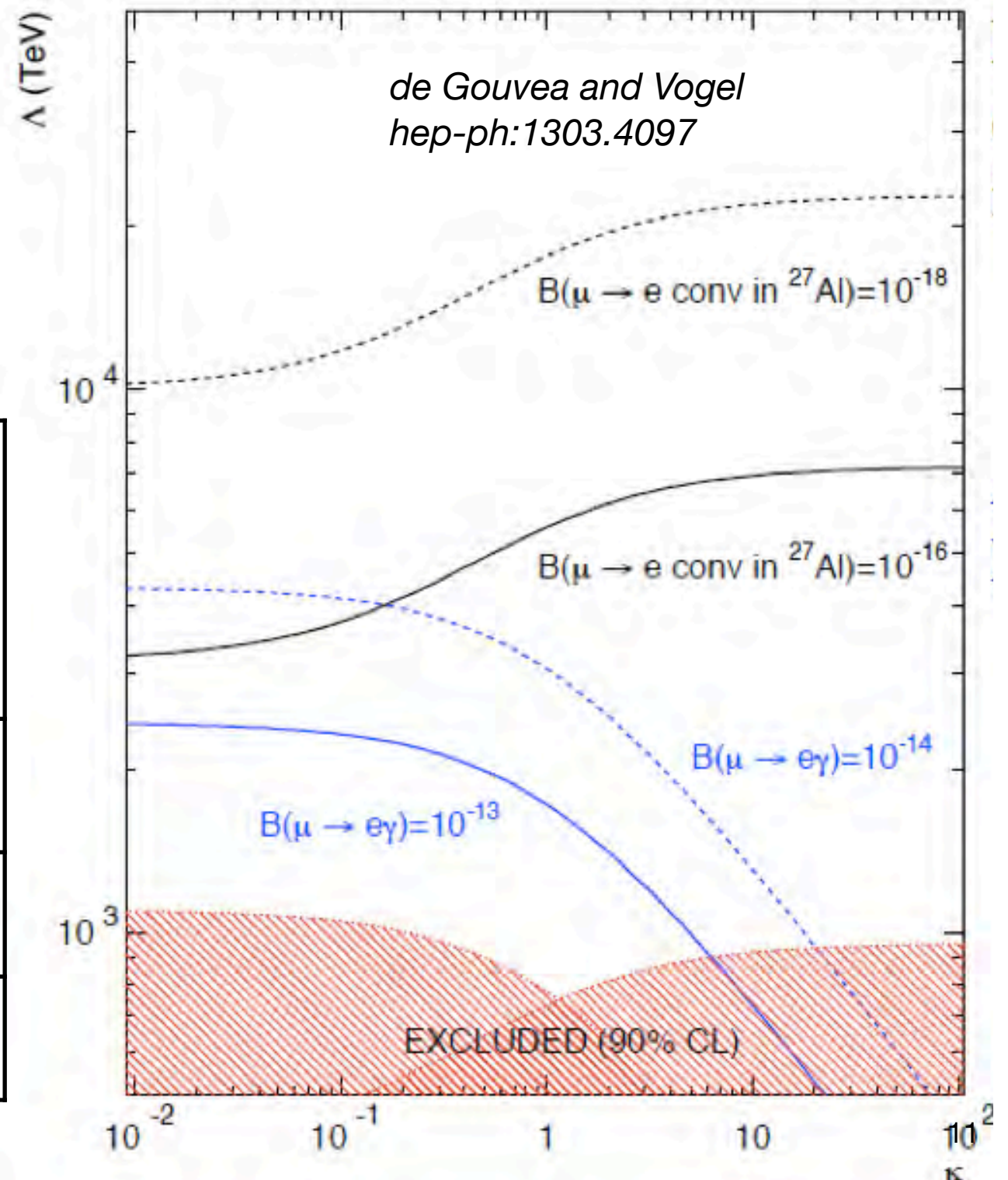


cLFV: “Effective” lagrangian with the k-parameter

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

Model independent lagrangian

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

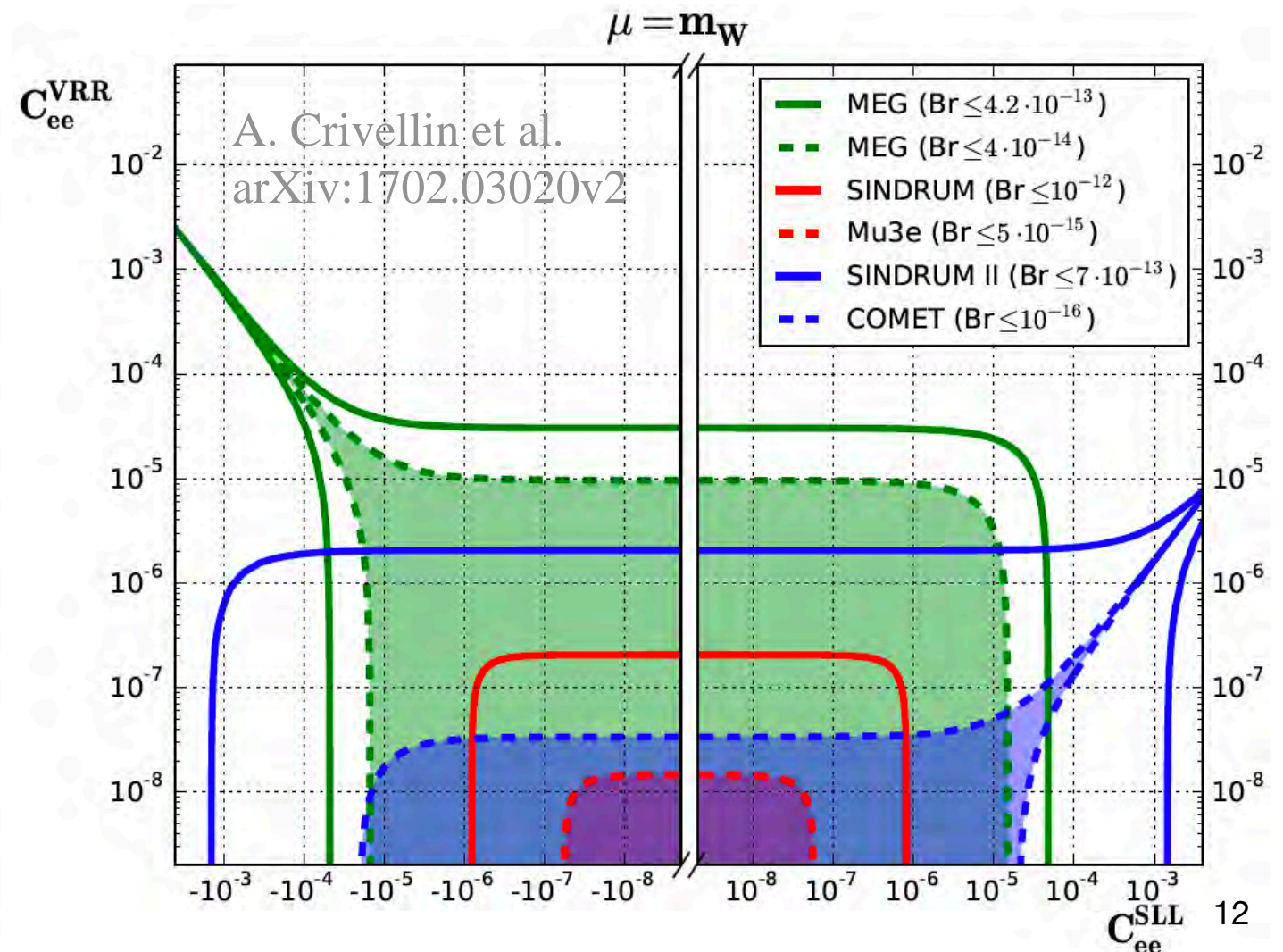
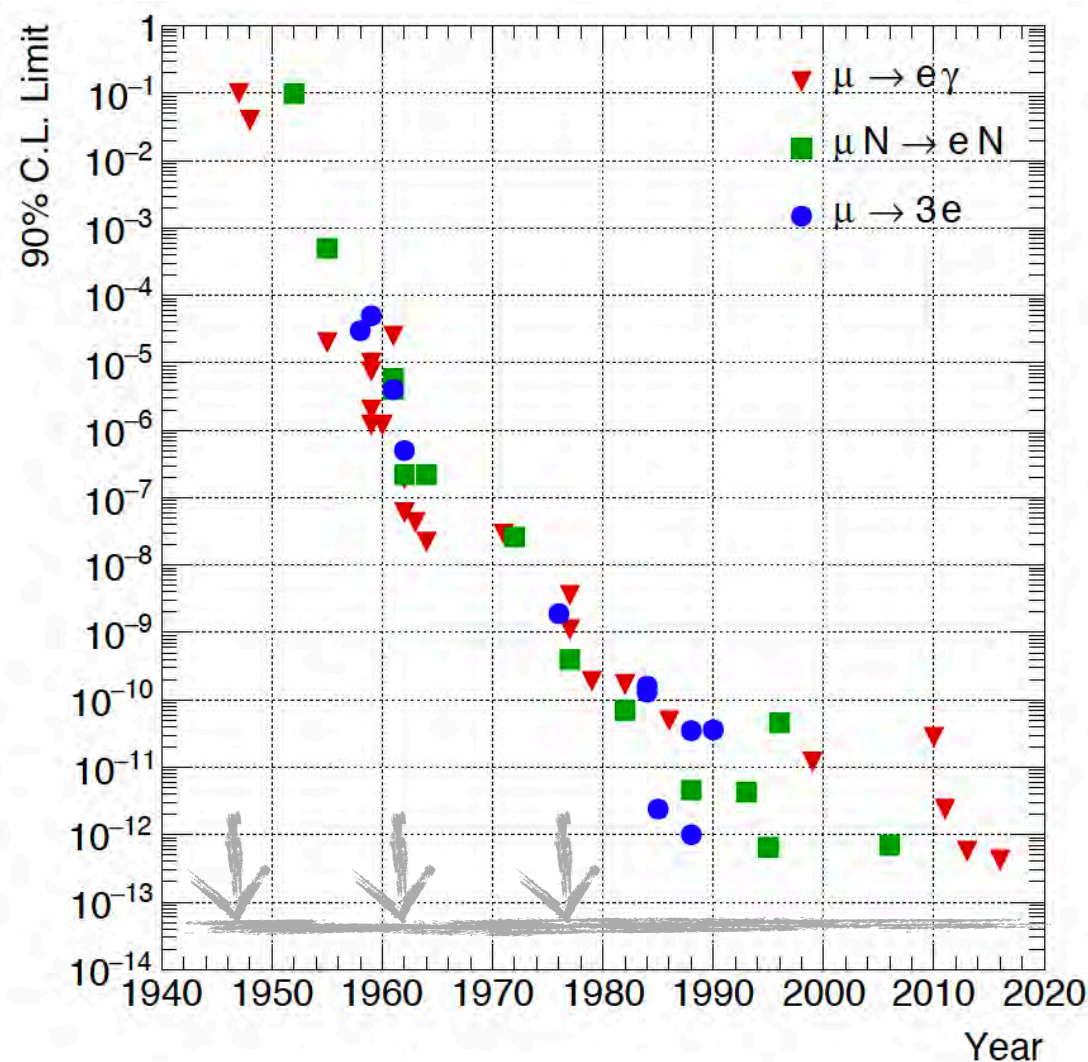


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Beam features vs experiment requirements

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

DC or Pulsed?

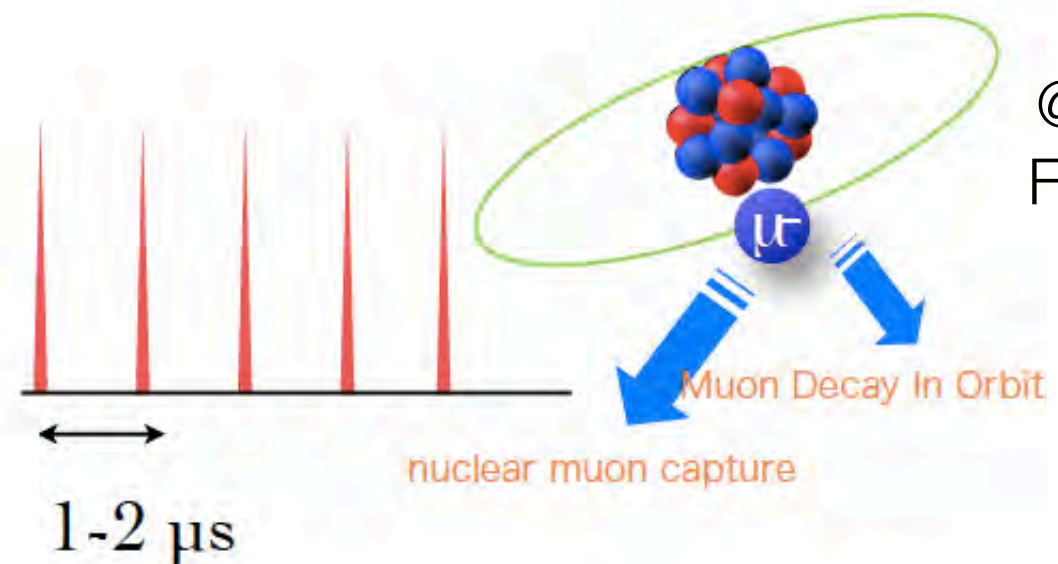
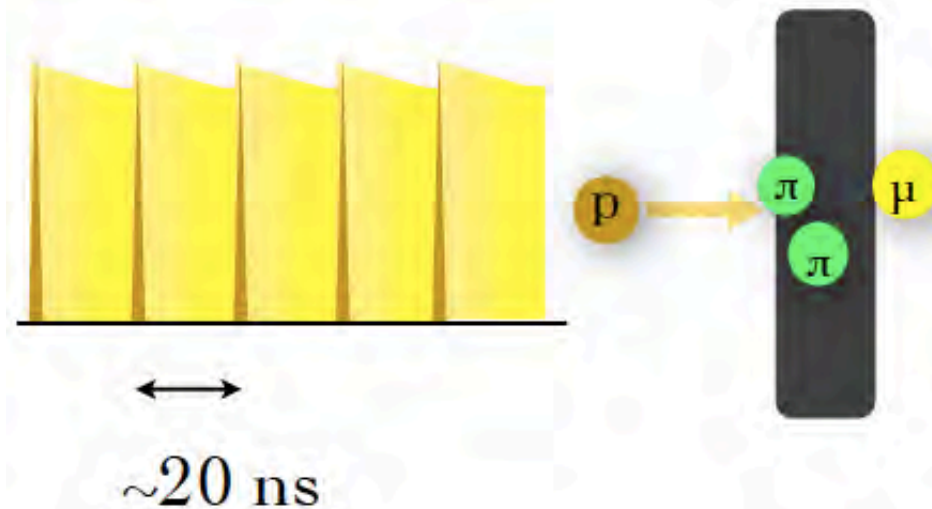
$I_{\text{beam}} \sim 10^8 - 10^{10} \mu/s$

- DC beam for coincidence experiments
- $\mu \rightarrow e \gamma, \mu \rightarrow e e e$

$I_{\text{beam}} \sim 10^{11} \mu/s$

- Pulse beam for non-coincidence experiments
- μ -e conversion

@ PSI



@ JPARC,
FERMILAB

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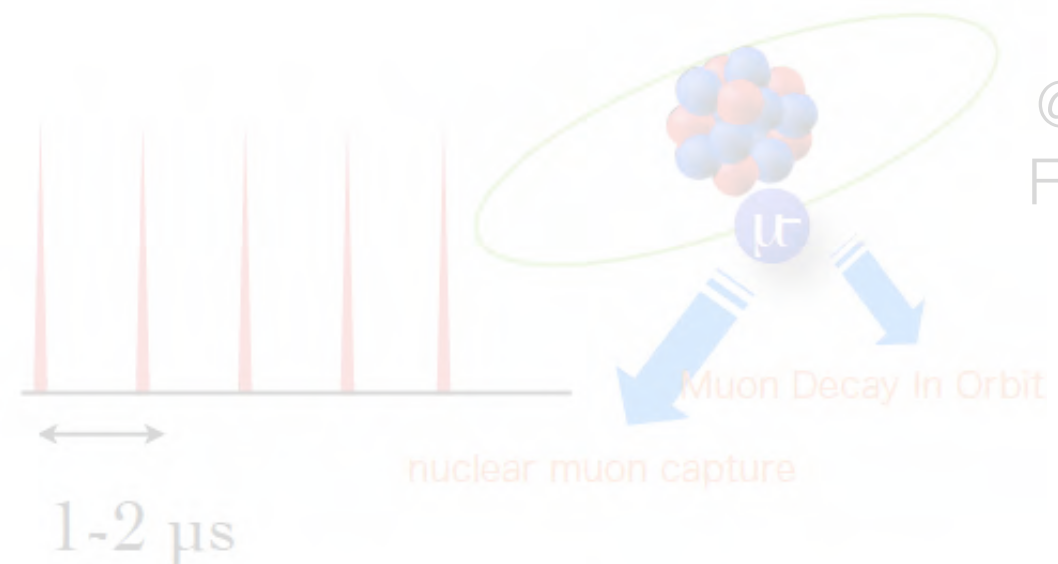
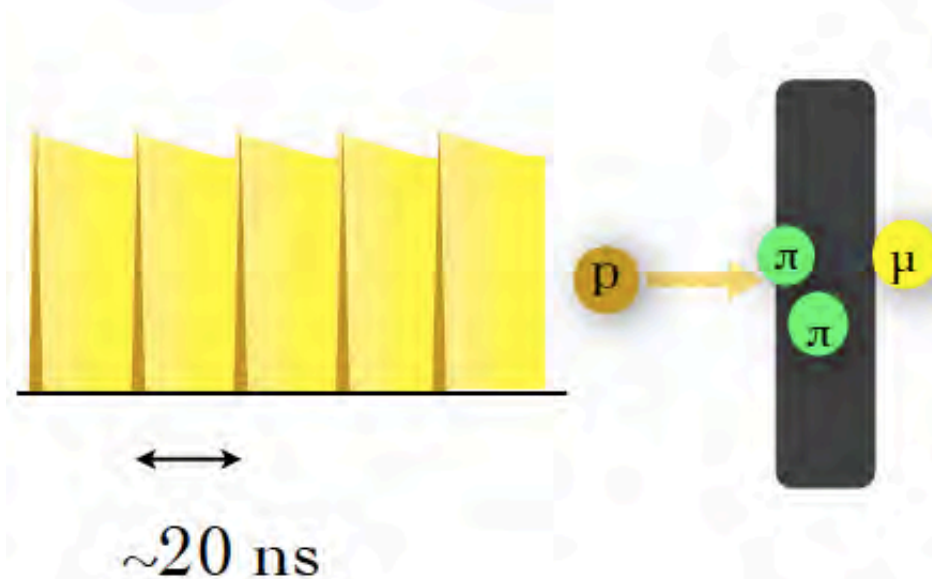
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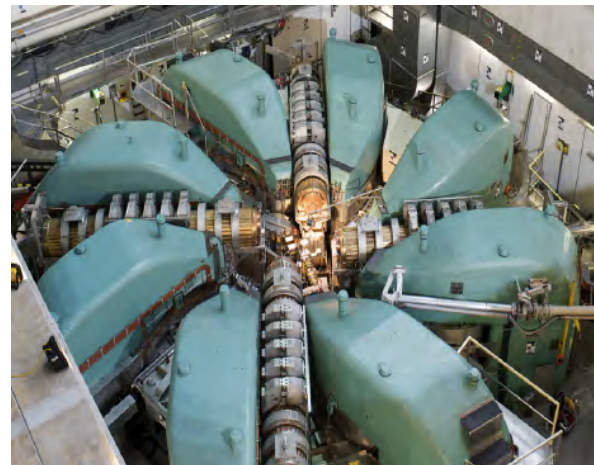
@ PSI



@ JPARC,
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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 $O(10^8 \text{ muon/s})$, low momentum $p = 29 \text{ MeV}/c$
 - Small straggling and good identification of the decay



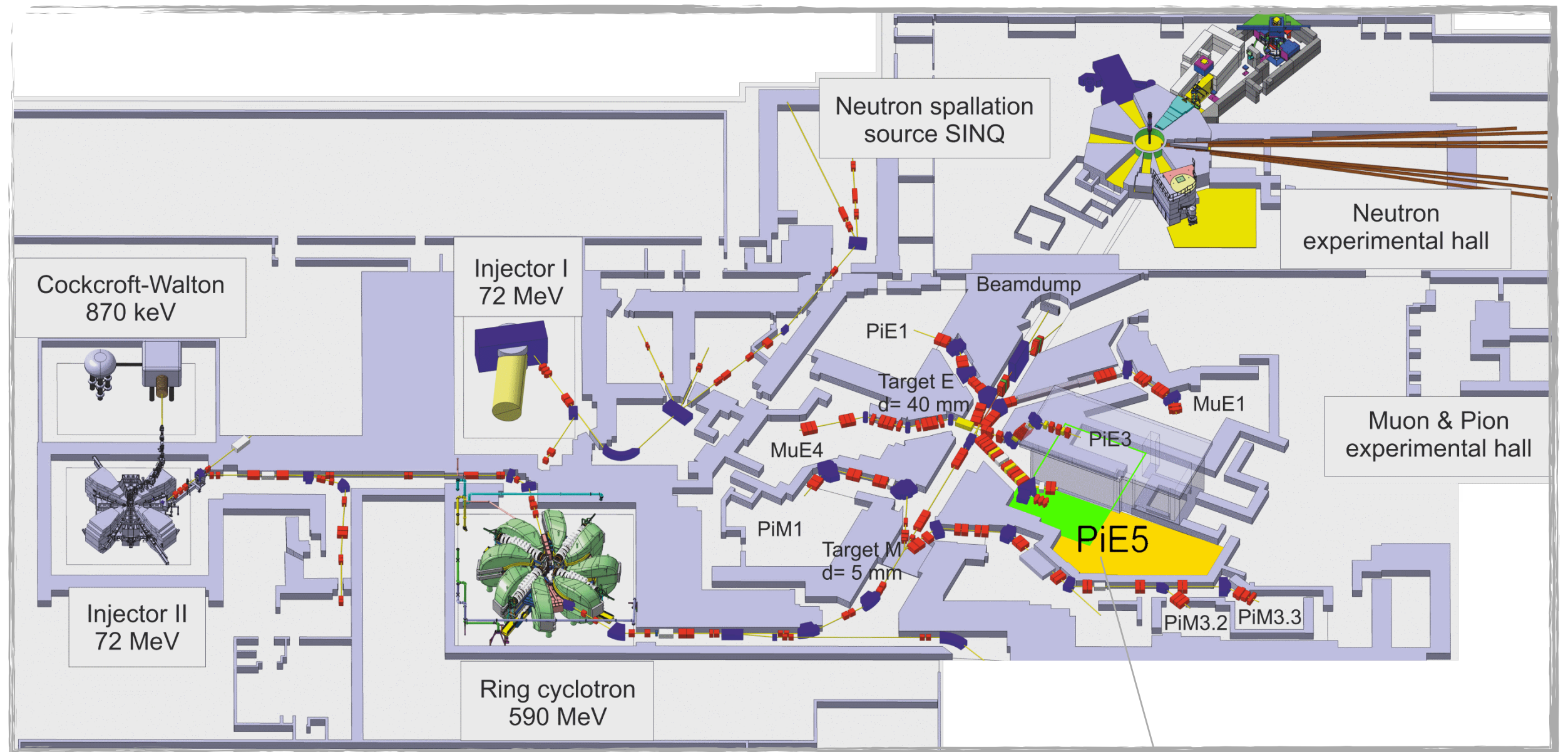
590 MeV proton
ring cyclotron
1.4 MW

PSI landscape



The world's most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas

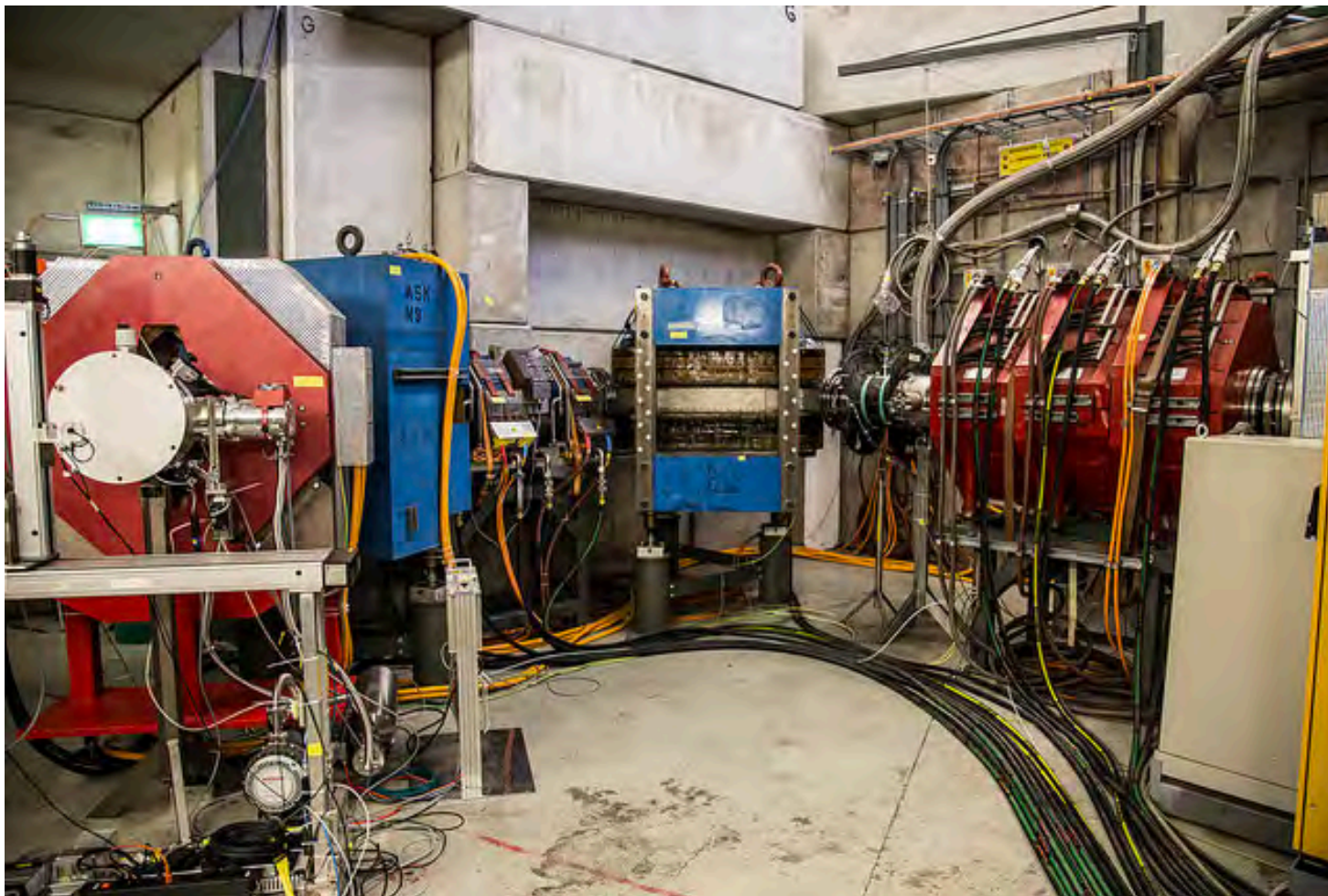


MEGII / Mu3e Experimental area

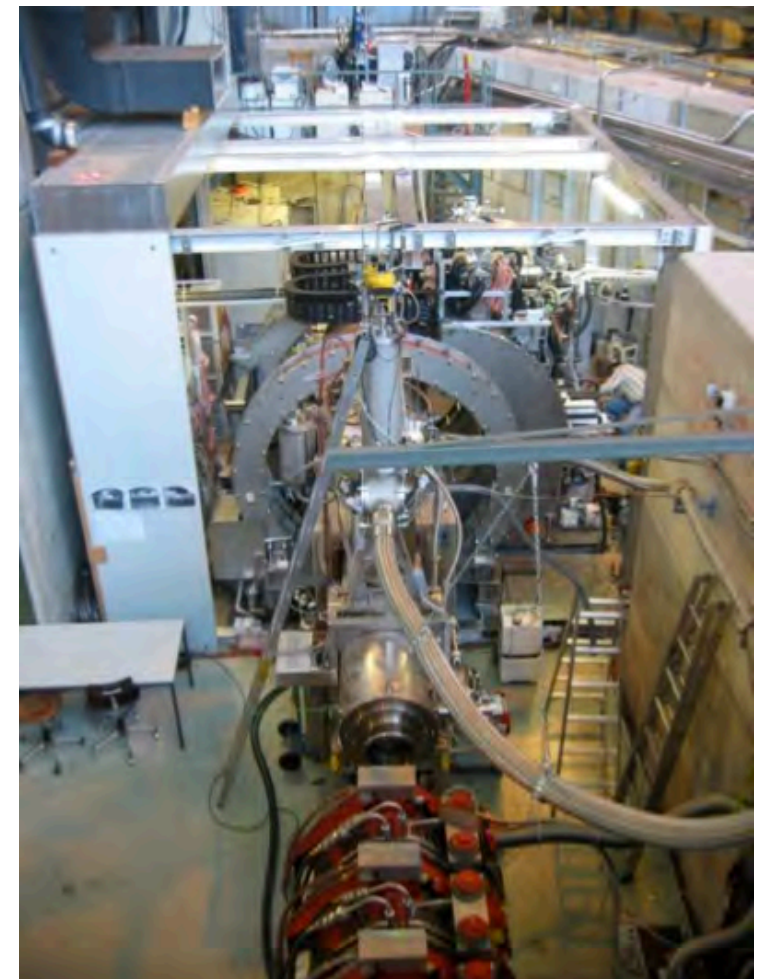
The MEGII (and Mu3e) beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
 - **Intensity $O(10^8 \text{ muon/s})$, low momentum $p = 28 \text{ MeV/c}$**
 - **Small straggling and good identification of the decay region**
- A dedicated compact muon beam line (CMBL) will serve Mu3e
- Proof-of-Principle: Delivered $8 \times 10^7 \text{ muon/s}$ 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 ($p = 28 \text{ MeV/c}$); **DC** beam
- Strategy:
 - Target optimization
 - Beam line optimization
- Time schedule: **O(2025)**

The High intensity Muon Beam (HiMB) project at PSI

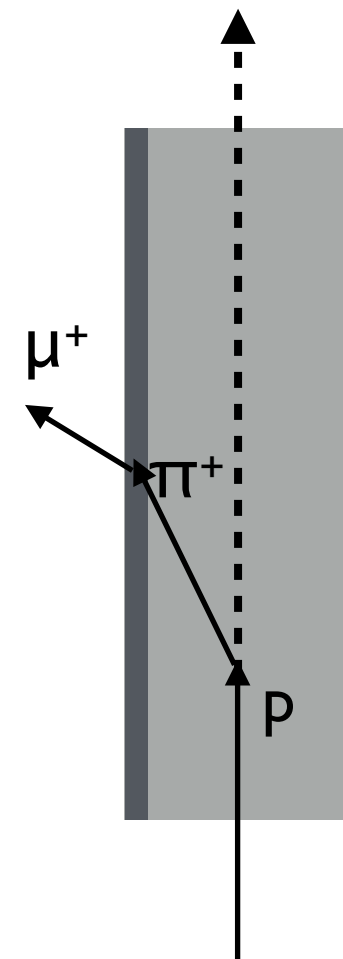
- Back to standard target to exploit possible improvements towards high intensity beams:
- **Target geometry and alternate materials**
 - Search for high pion yield materials -> higher muon yield

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

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_c (6/12)_c}{\rho_x (Z/A)_x}$$

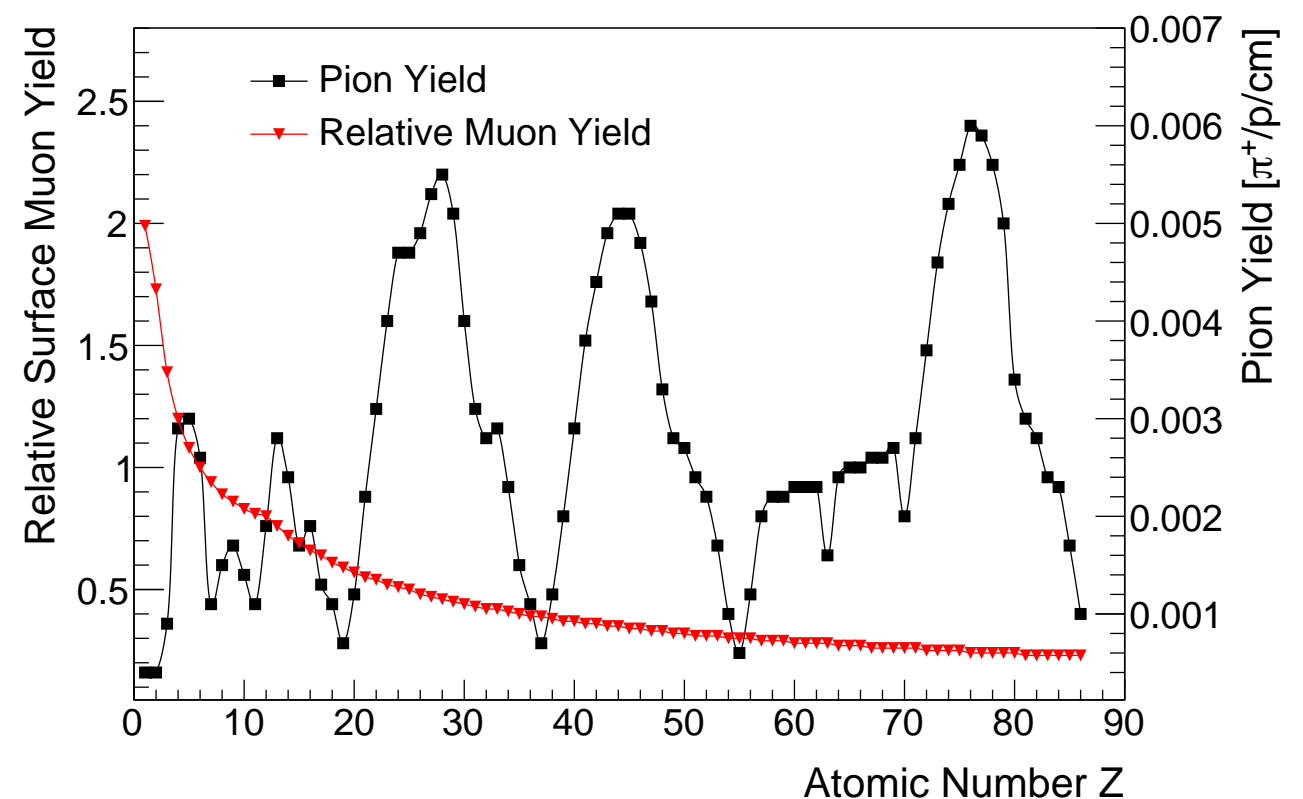
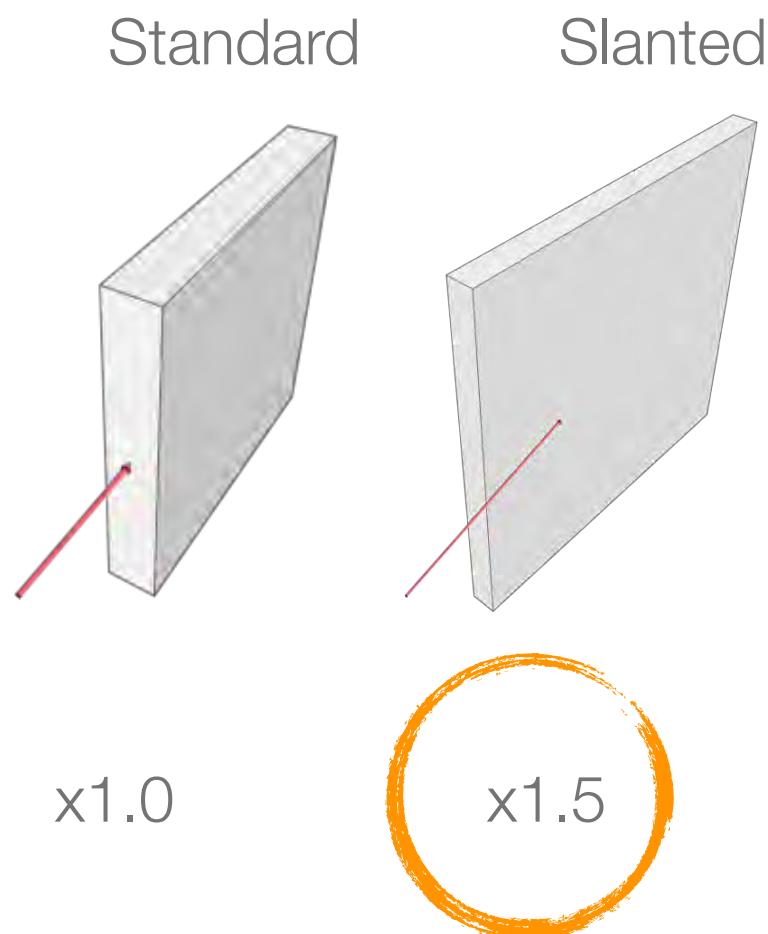
$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

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



The High intensity Muon Beam (HiMB) project at PSI

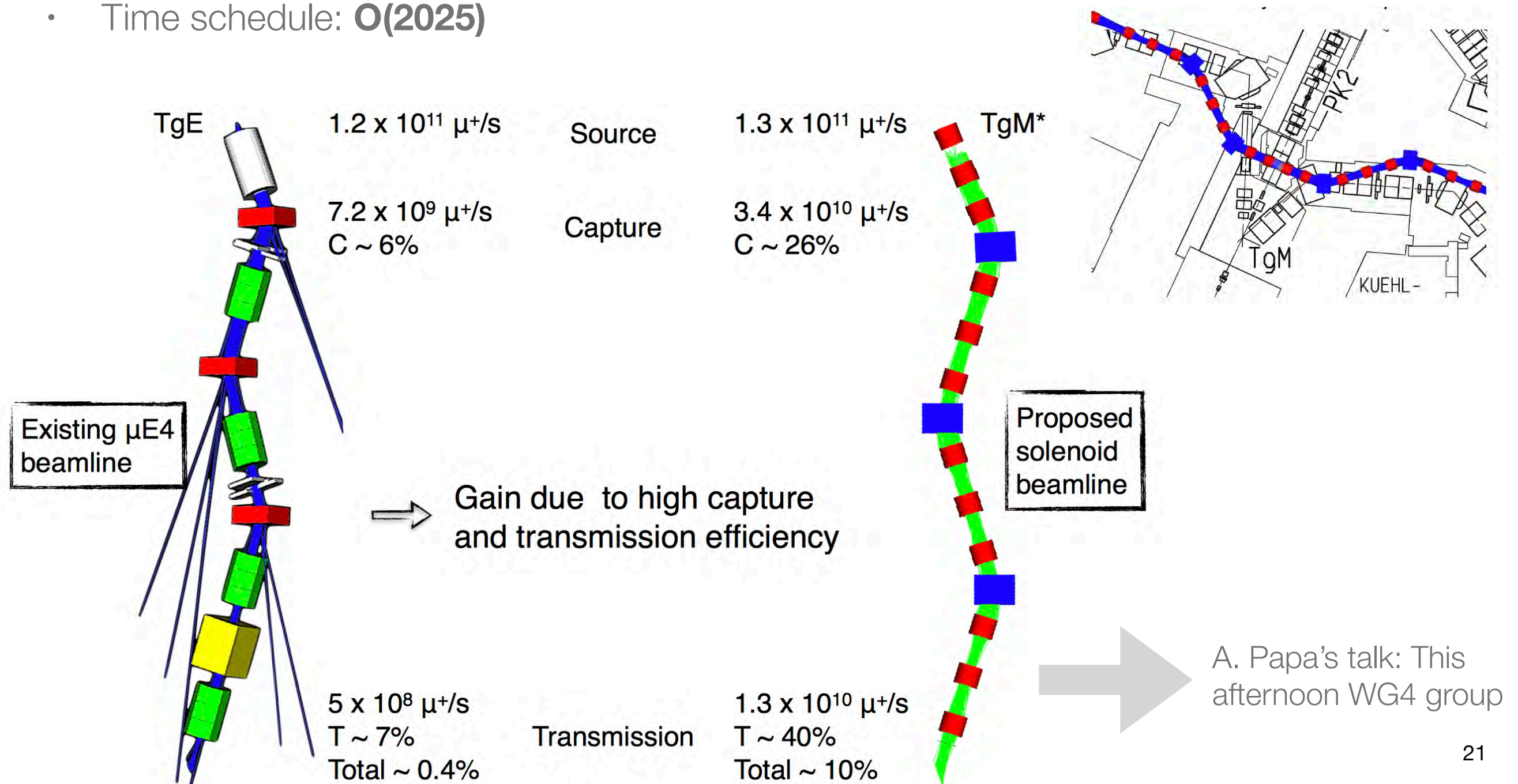
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New

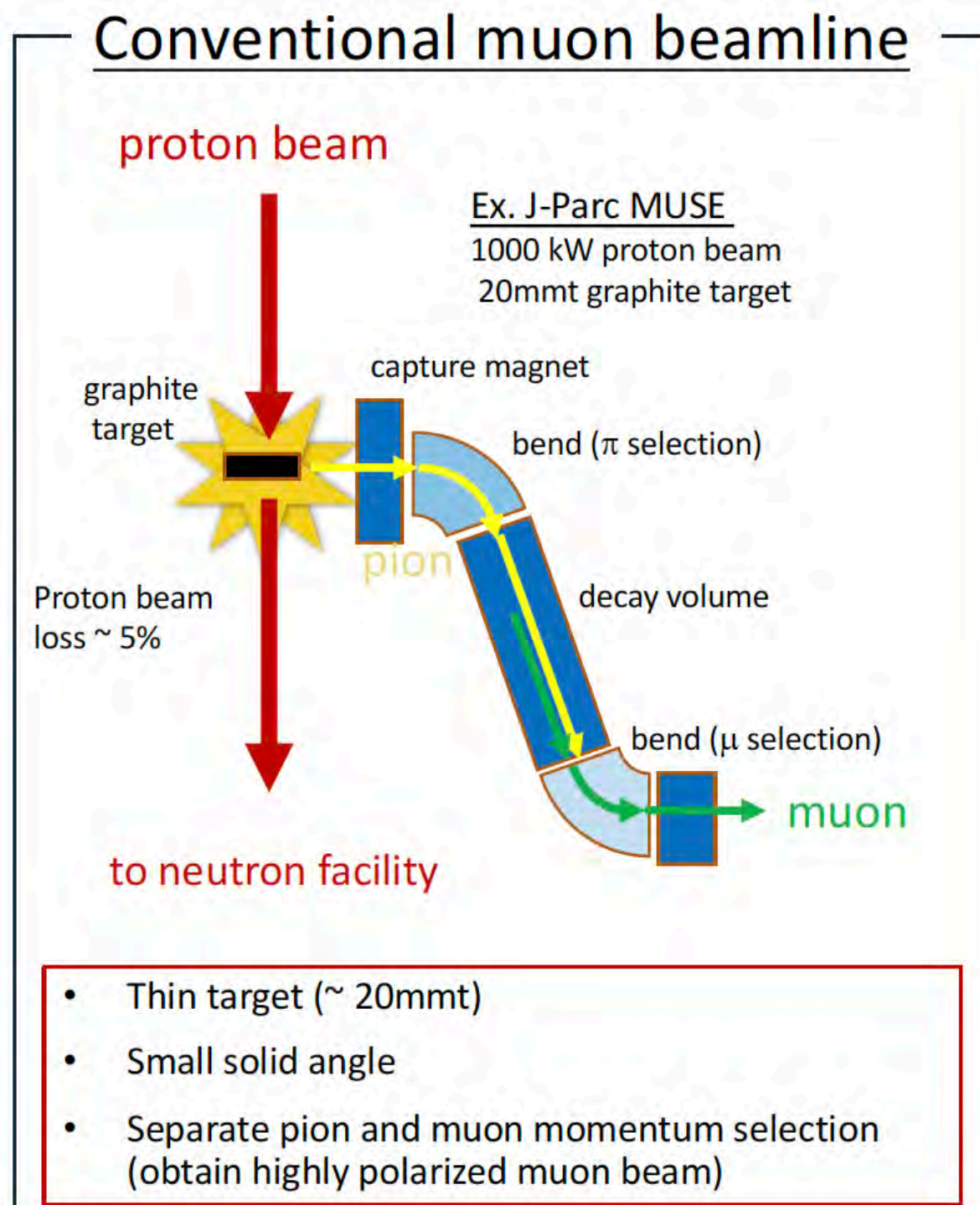
The High intensity Muon Beam (HiMB) project at PSI

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



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

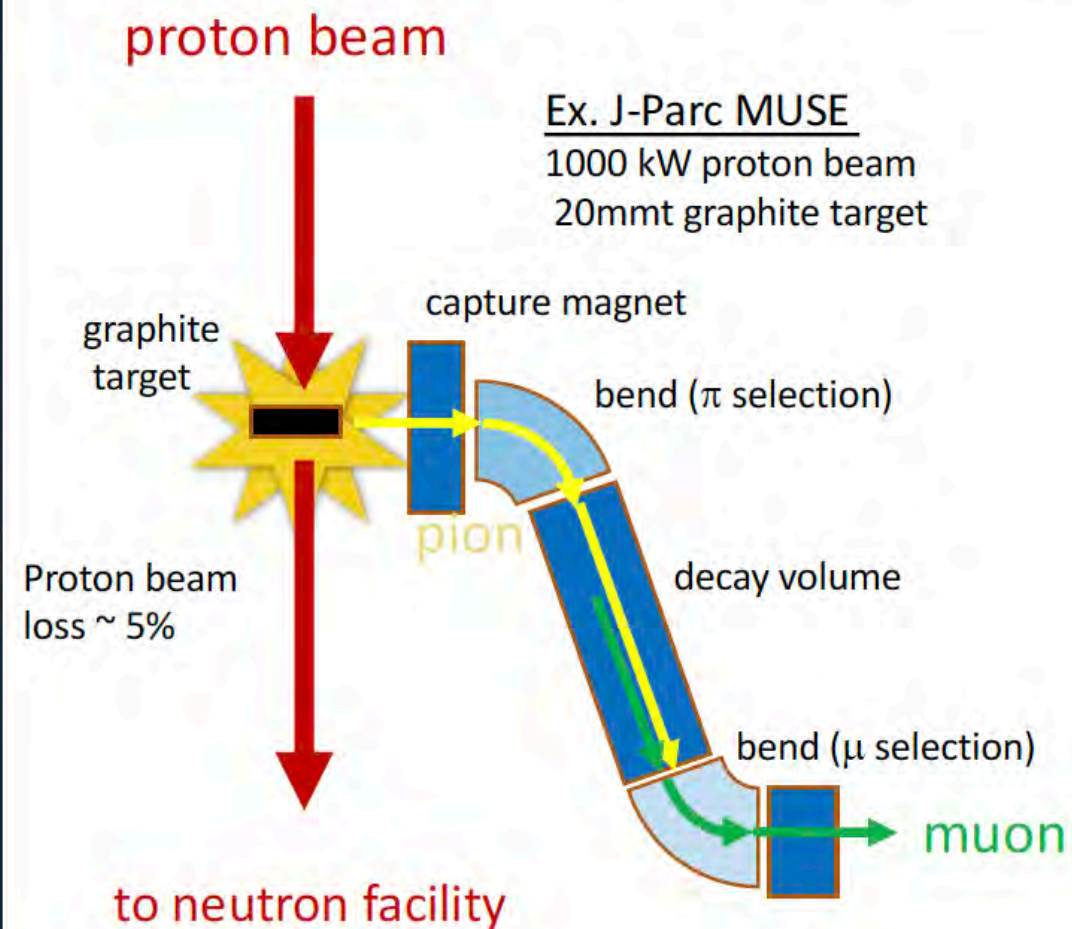
- Aim: $O(10^8)$ muon/s; Surface (positive) muon beam ($p = 28 \text{ MeV}/c$); **DC** beam



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

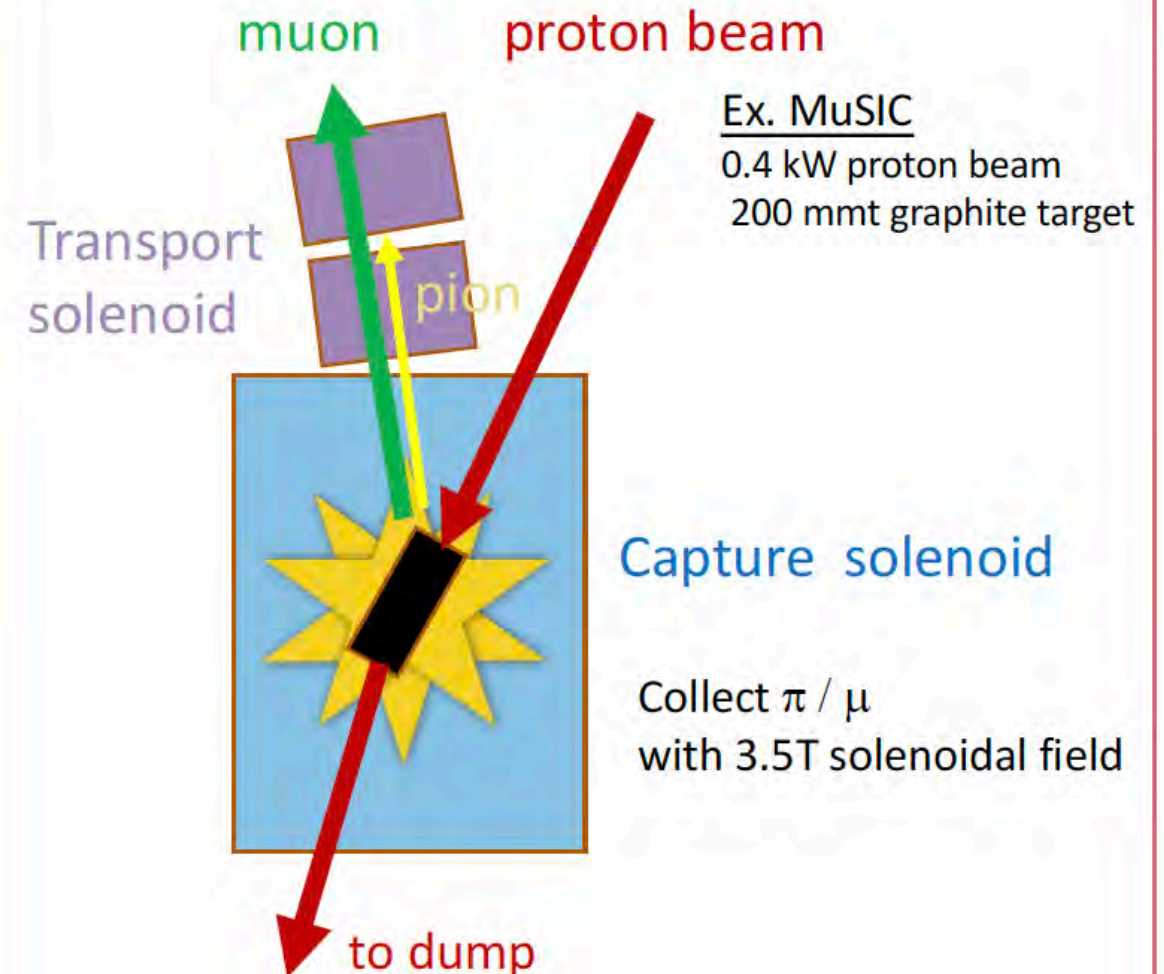
- Aim: $O(10^8)$ muon/s; Surface (positive) muon beam ($p = 28 \text{ MeV/c}$); **DC** beam

Conventional muon beamline



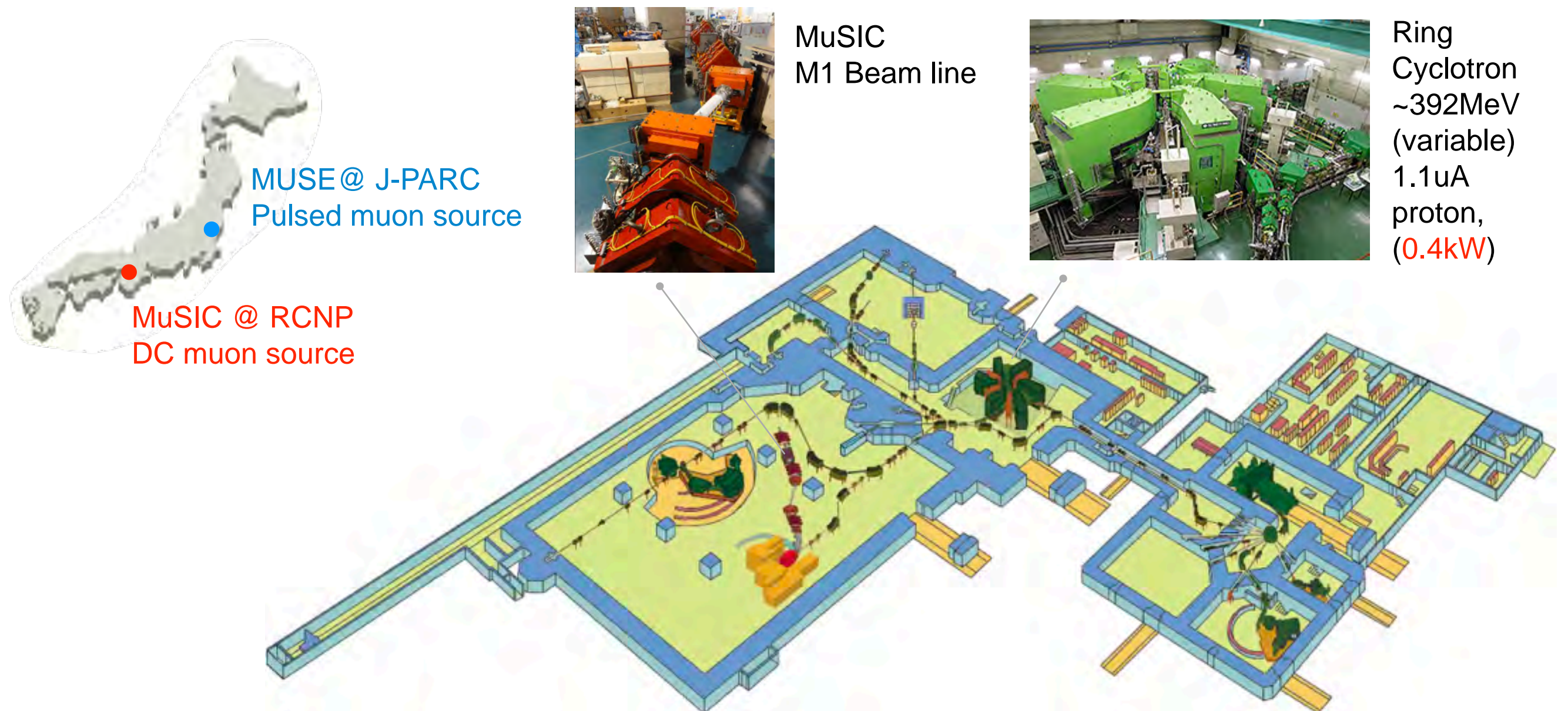
- Thin target ($\sim 20\text{mmt}$)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

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

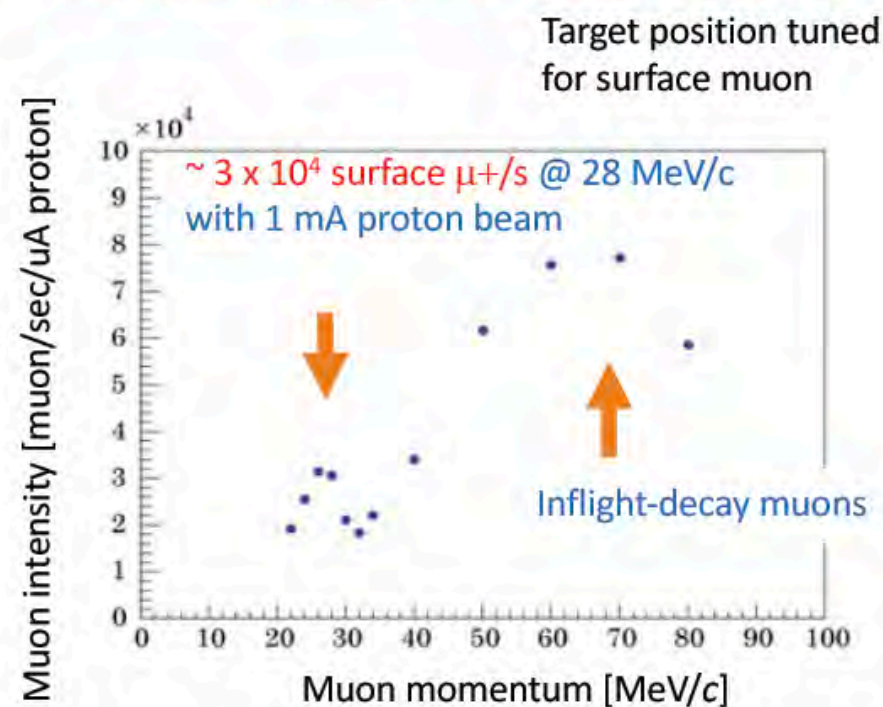


- proton beam energy is only 100 MeV above pion production threshold ($\sim 2m_\pi$)
- muon source with low proton power (1.1 uA ~ 0.4 kW, 5 uA in future)

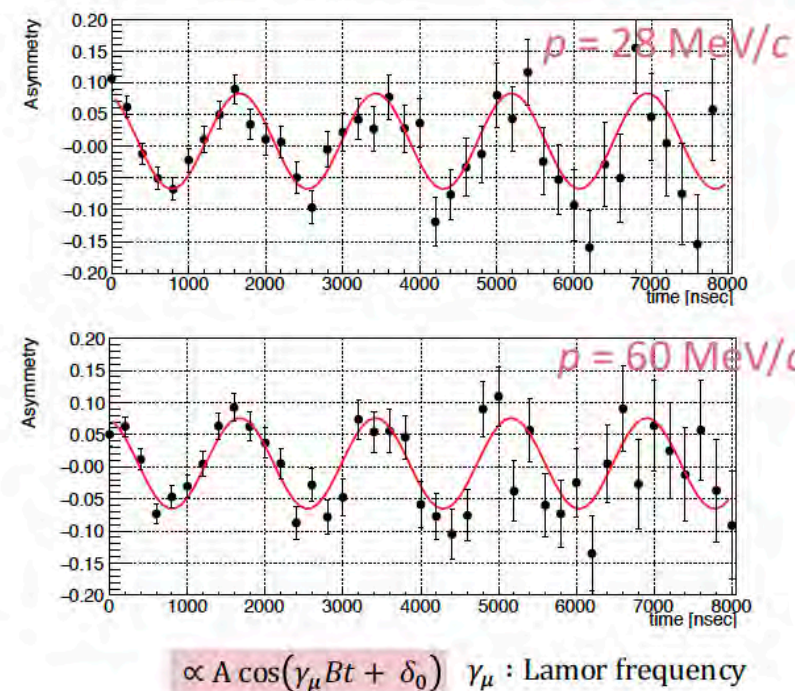
MuSIC at Research Center for Nuclear Physics (RCNP), Osaka University

- Multi-purpose facility. Beam line commissioning

Succeed in observing surface muons (~ 28 MeV/c)

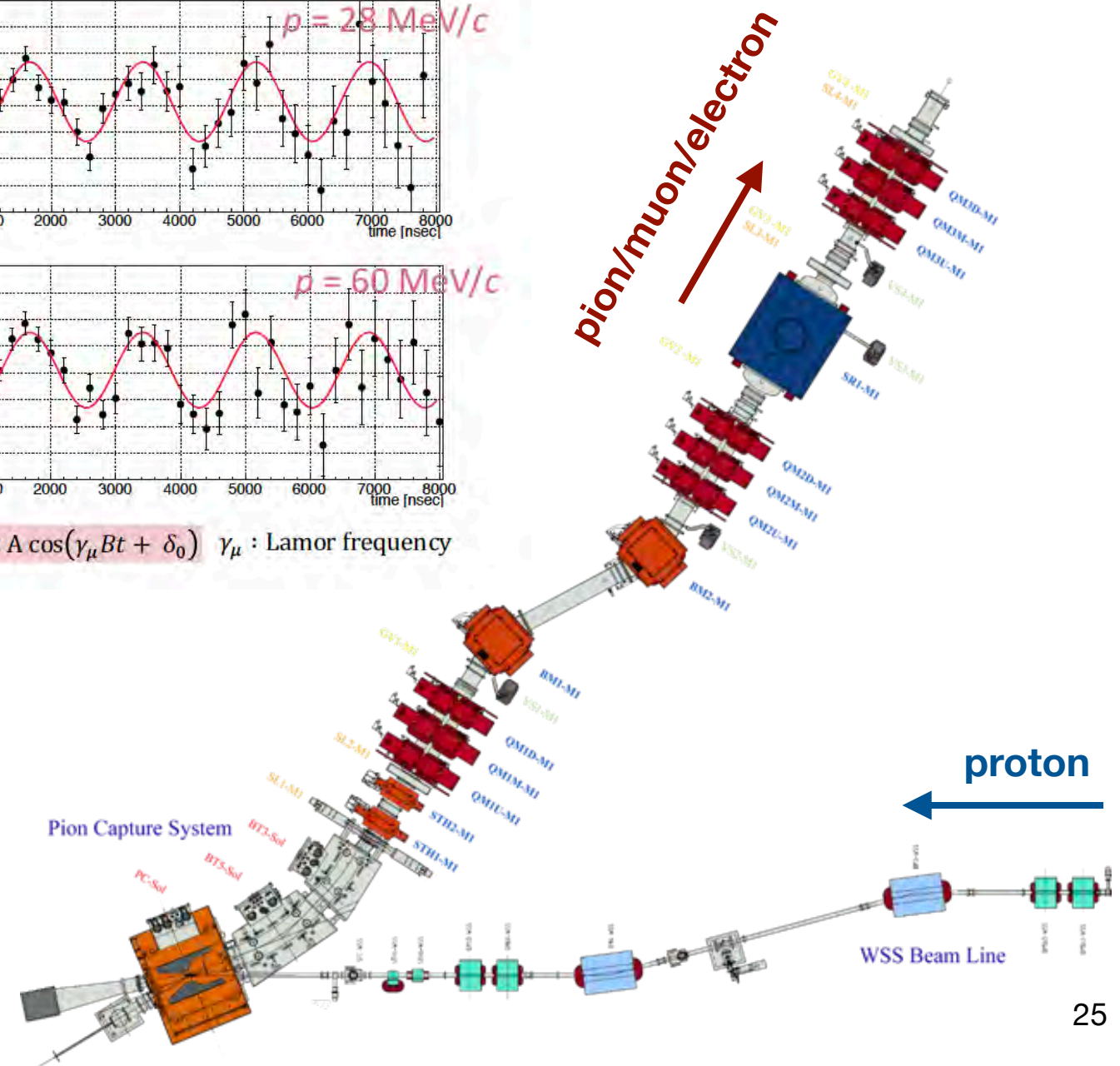


Typical observed asymmetry spectra



Status:

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



The muCool project at PSI

New

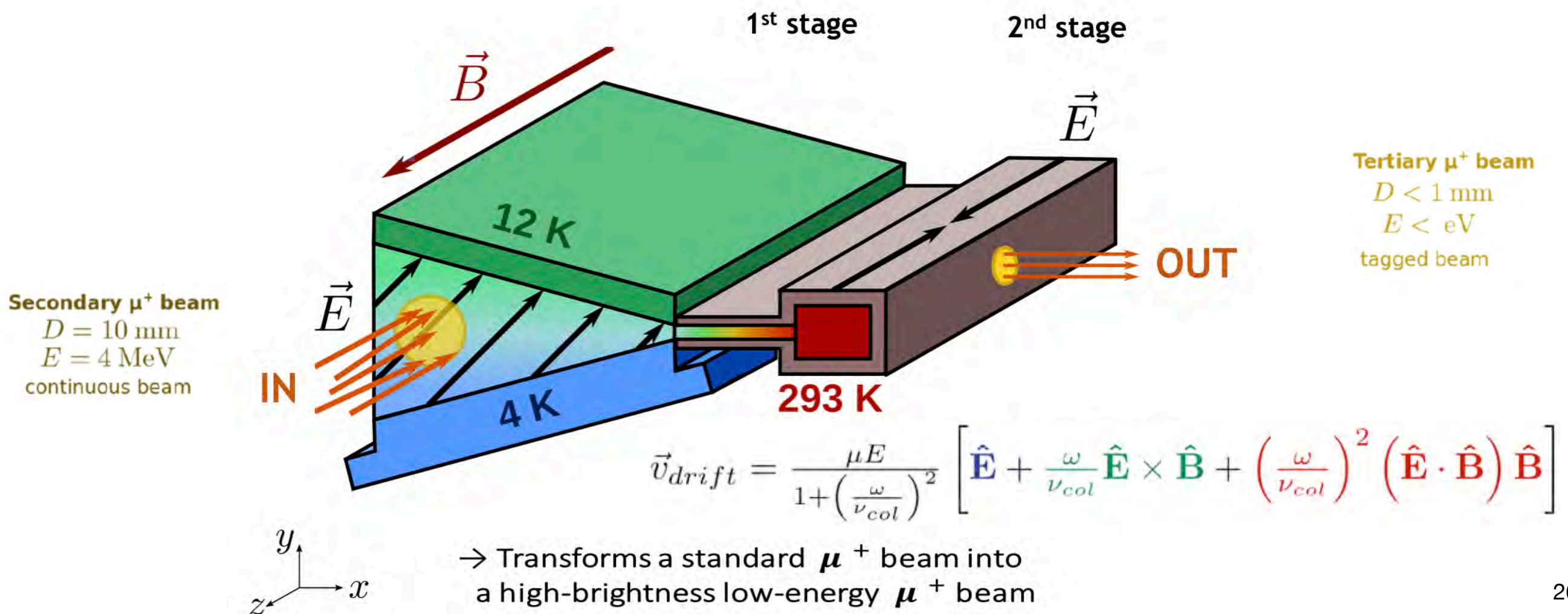
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor 10^{10} with an efficiency of 10^{-3}

for:

μ SR (solid state physics)

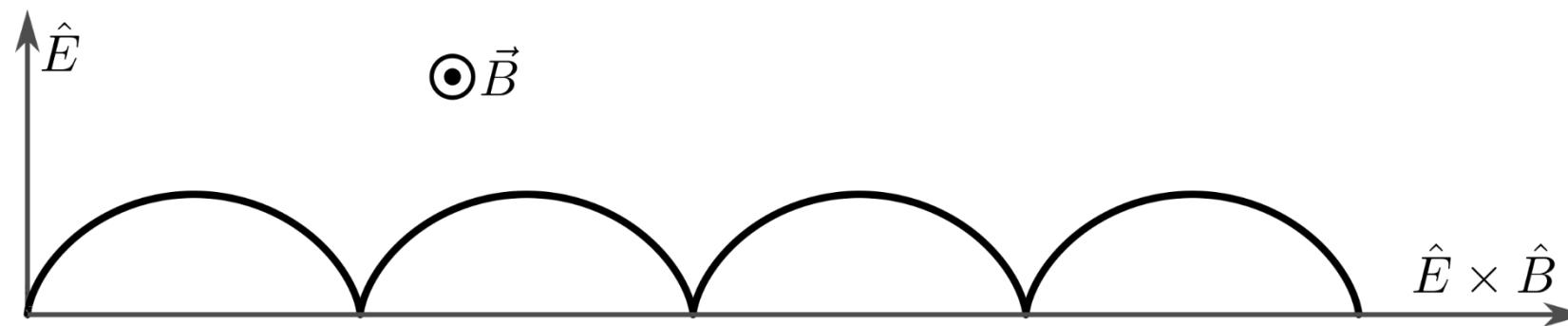
muonium (spectroscopy, gravitational interaction...)

muon experiments (μ EDM, g-2...)

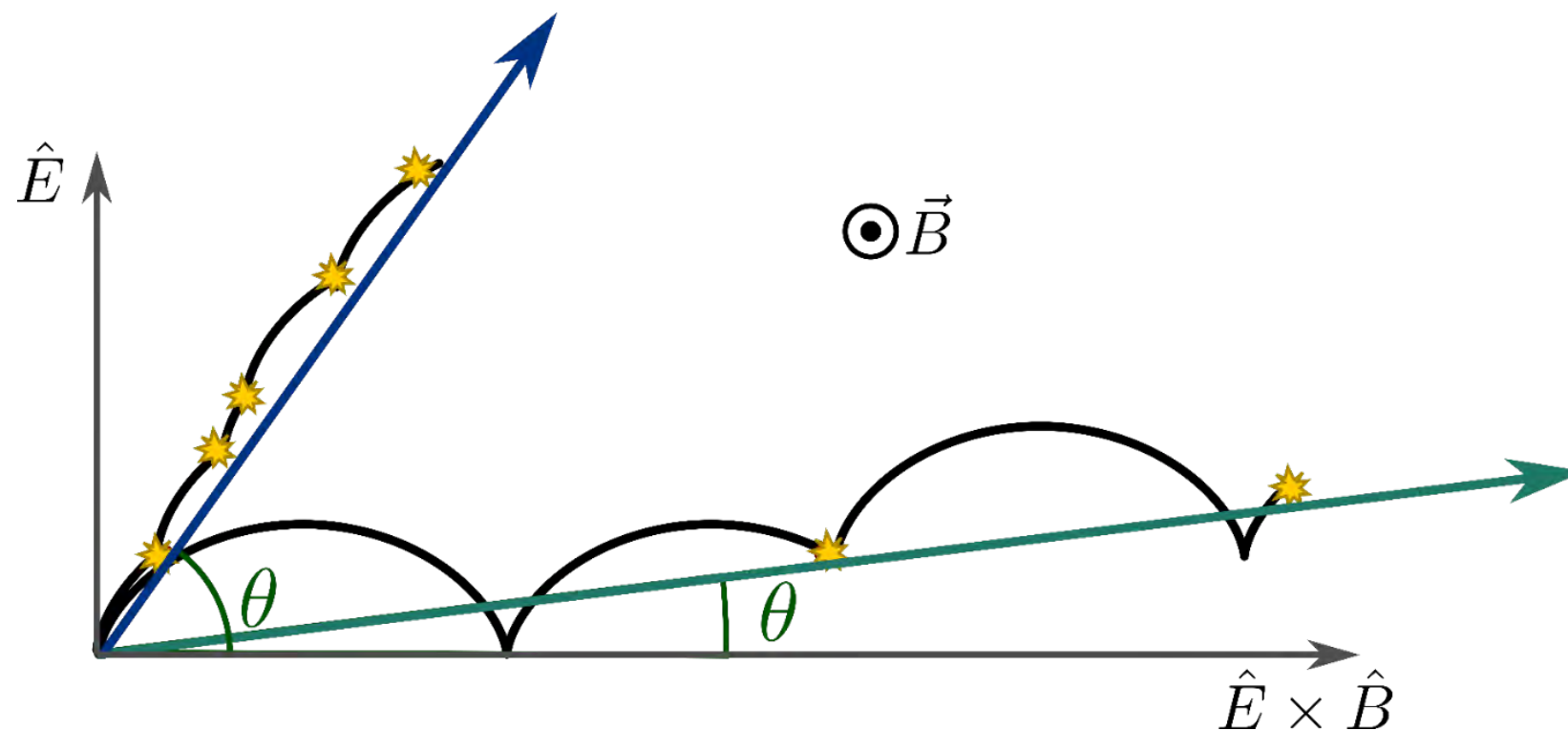


Trajectories in E and B field + gas

- E and B field

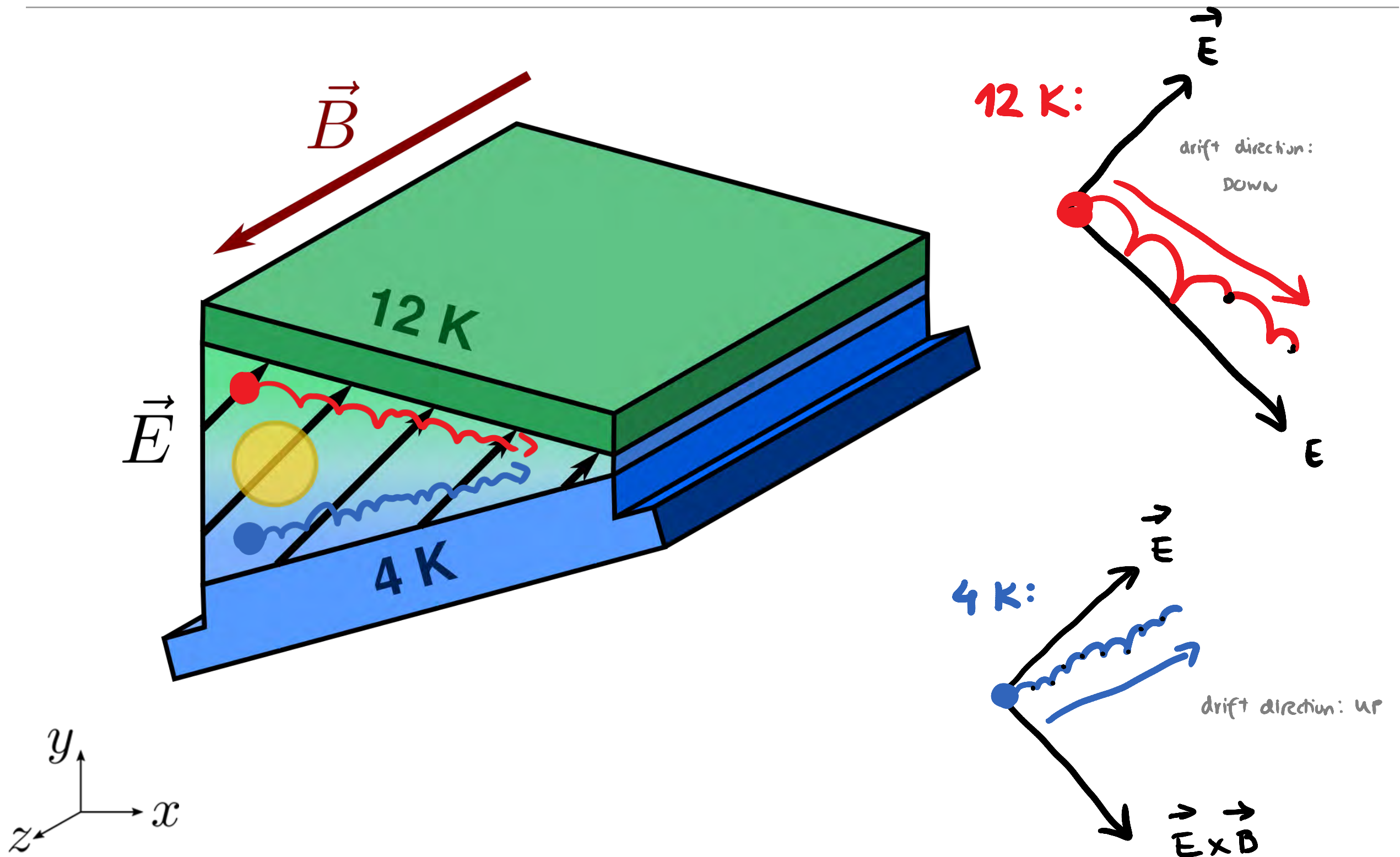


- E and B field + gas



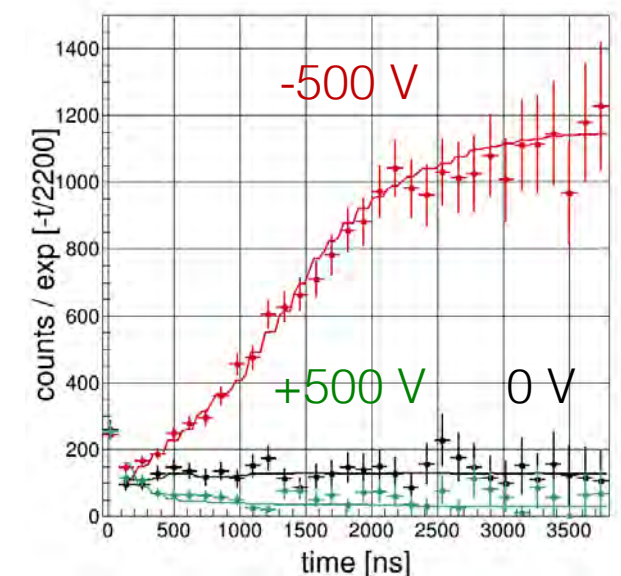
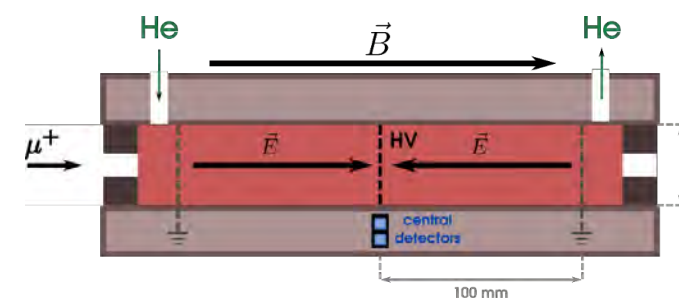
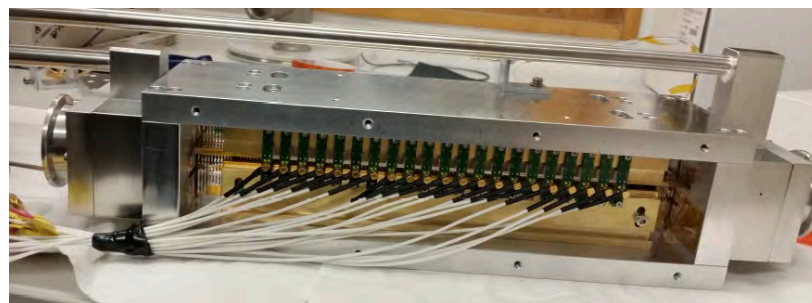
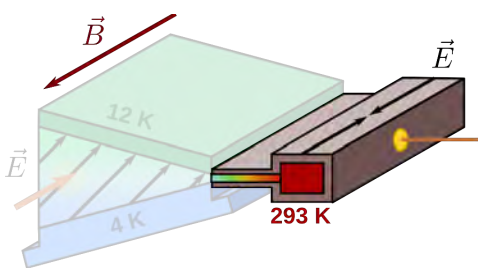
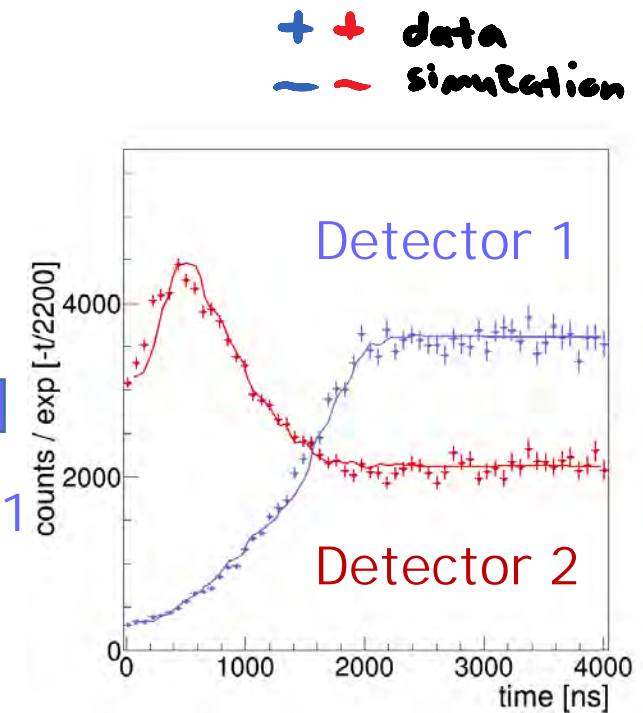
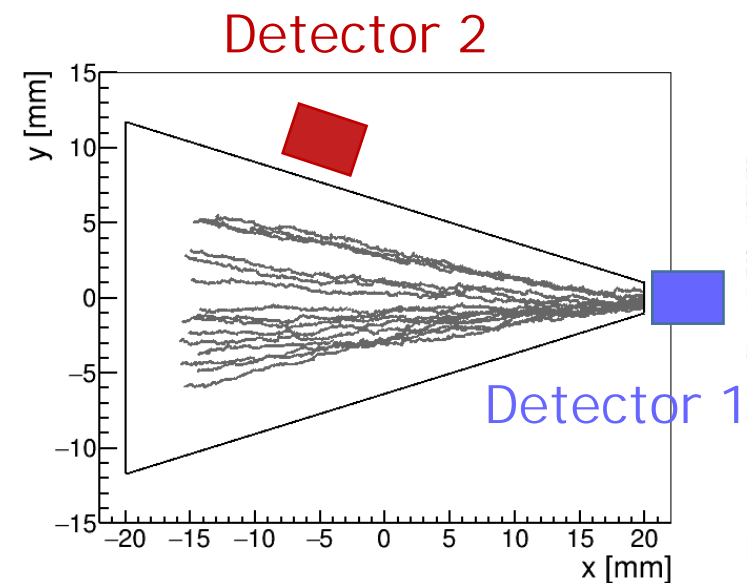
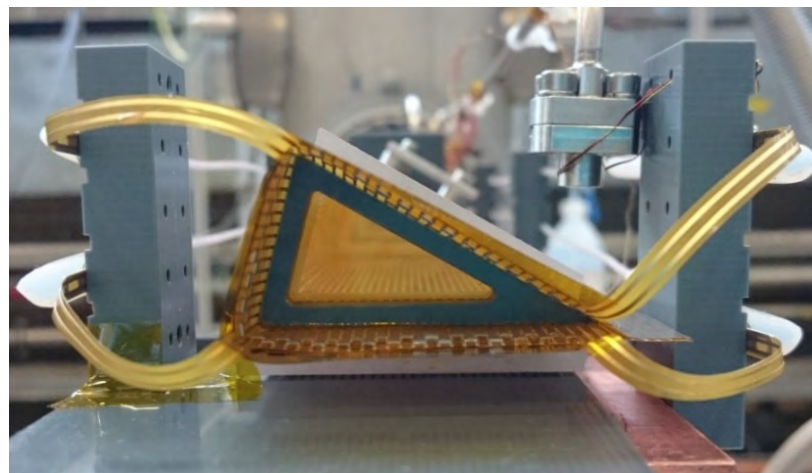
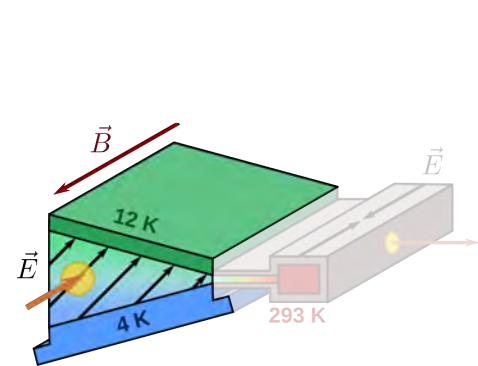
$$\tan \theta \propto f_{col}$$

Working principle: 1st Stage



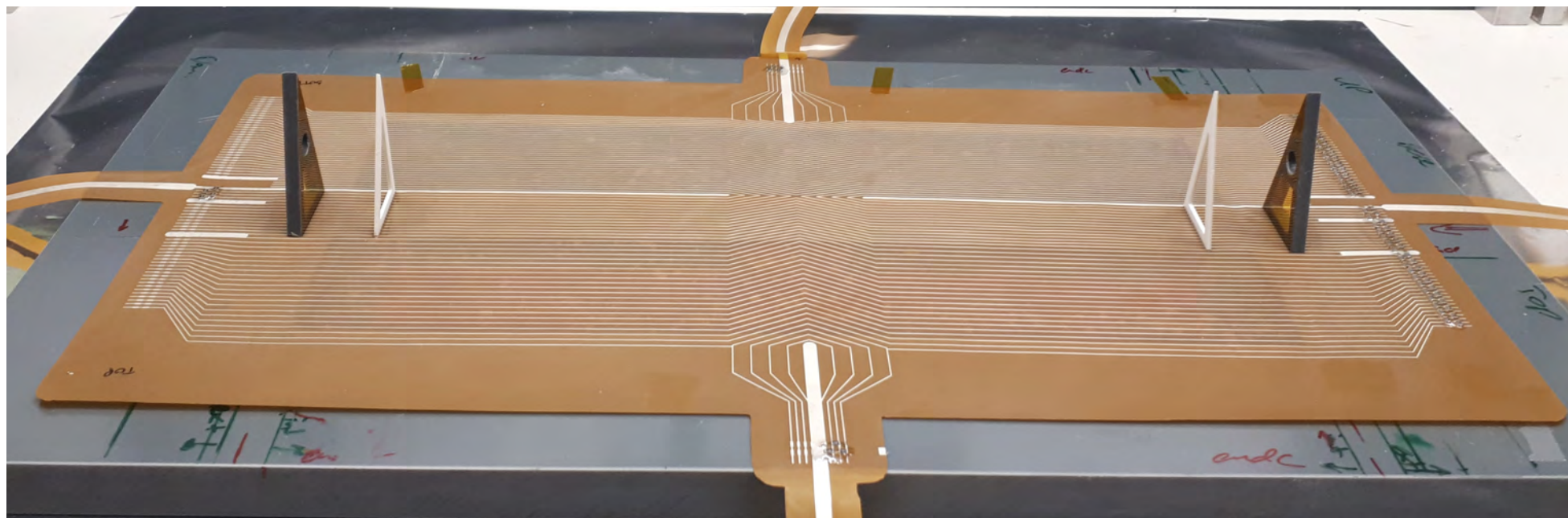
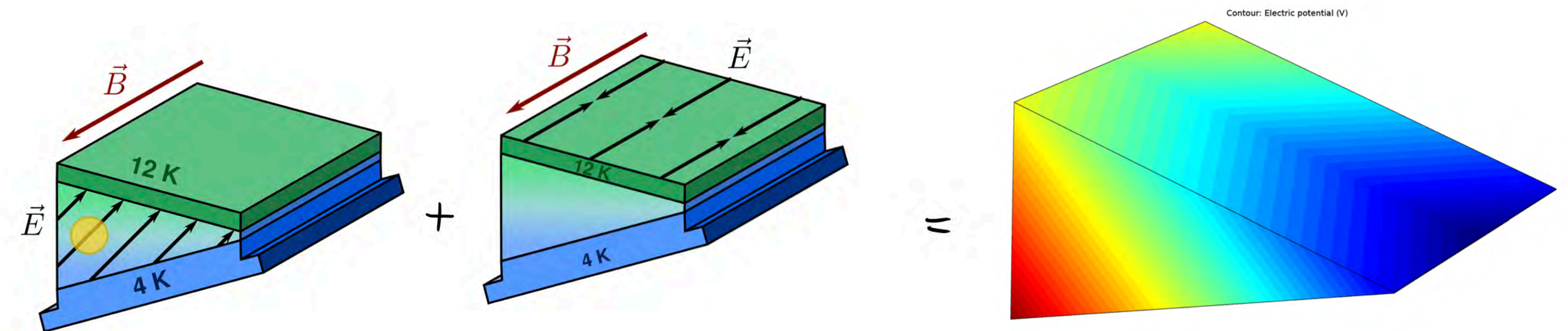
The muCool project at PSI: Status

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

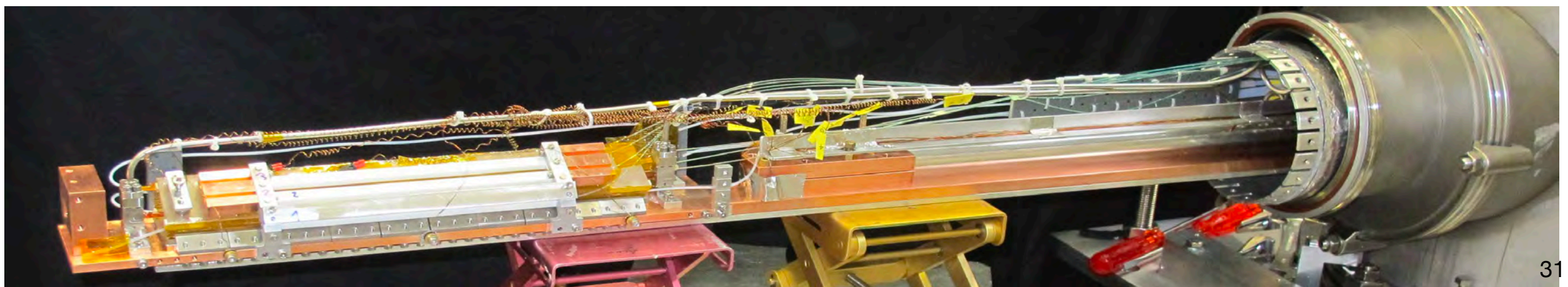
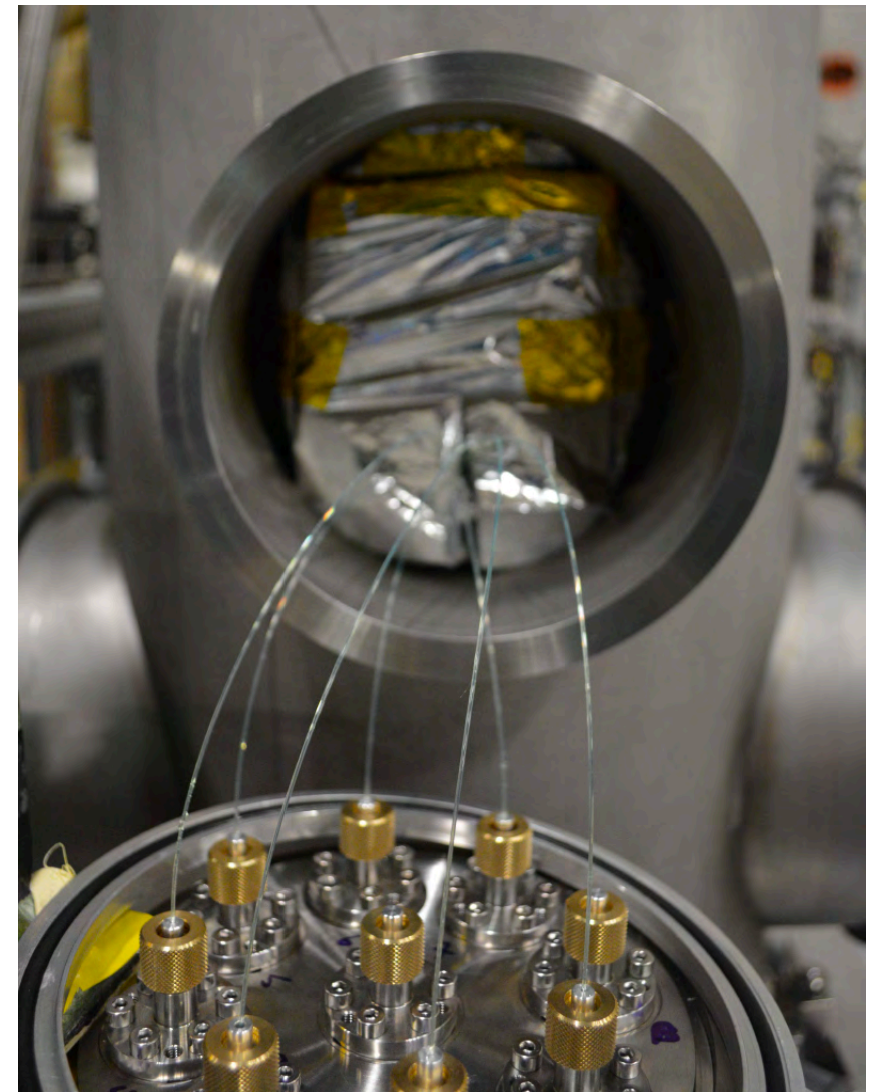
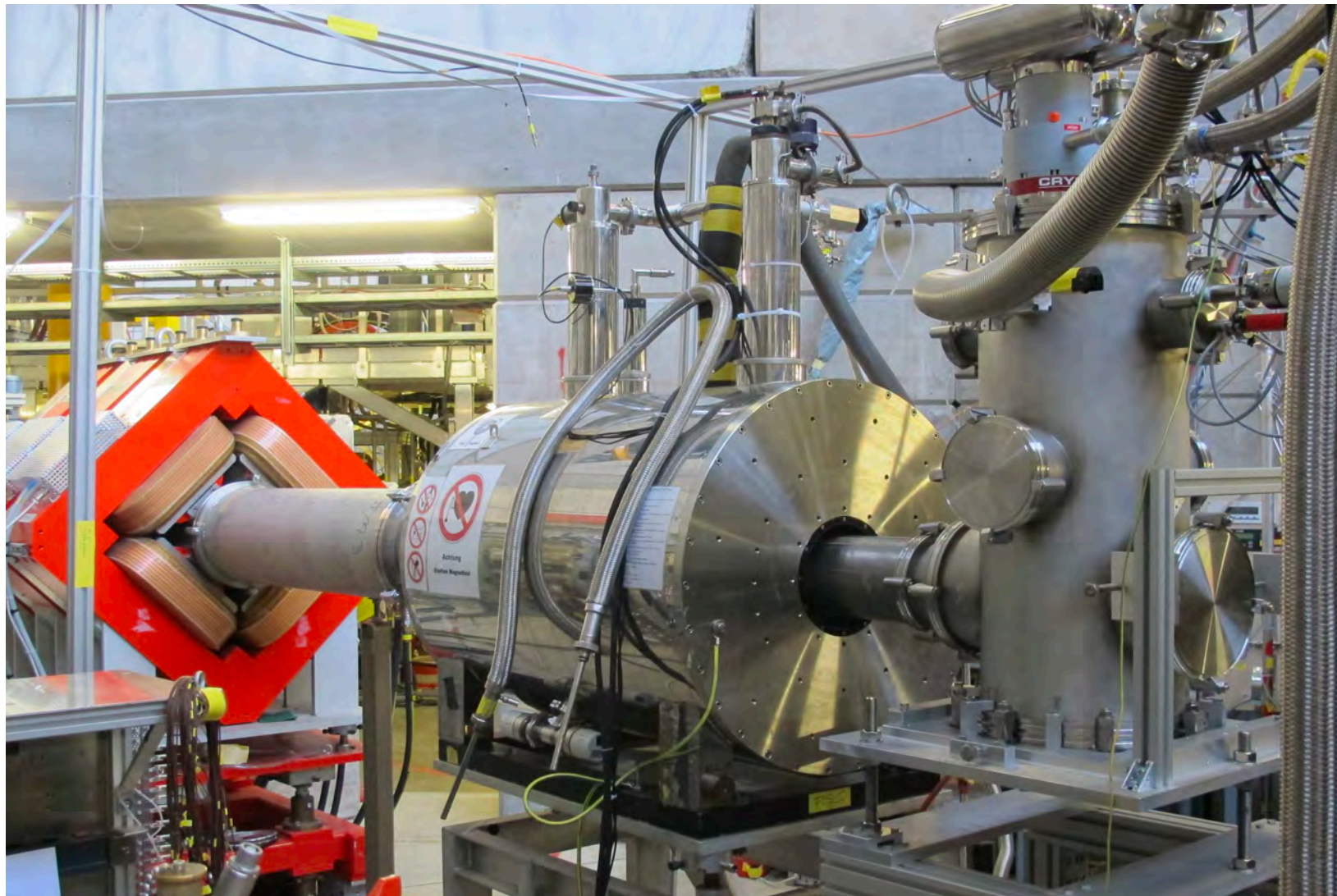


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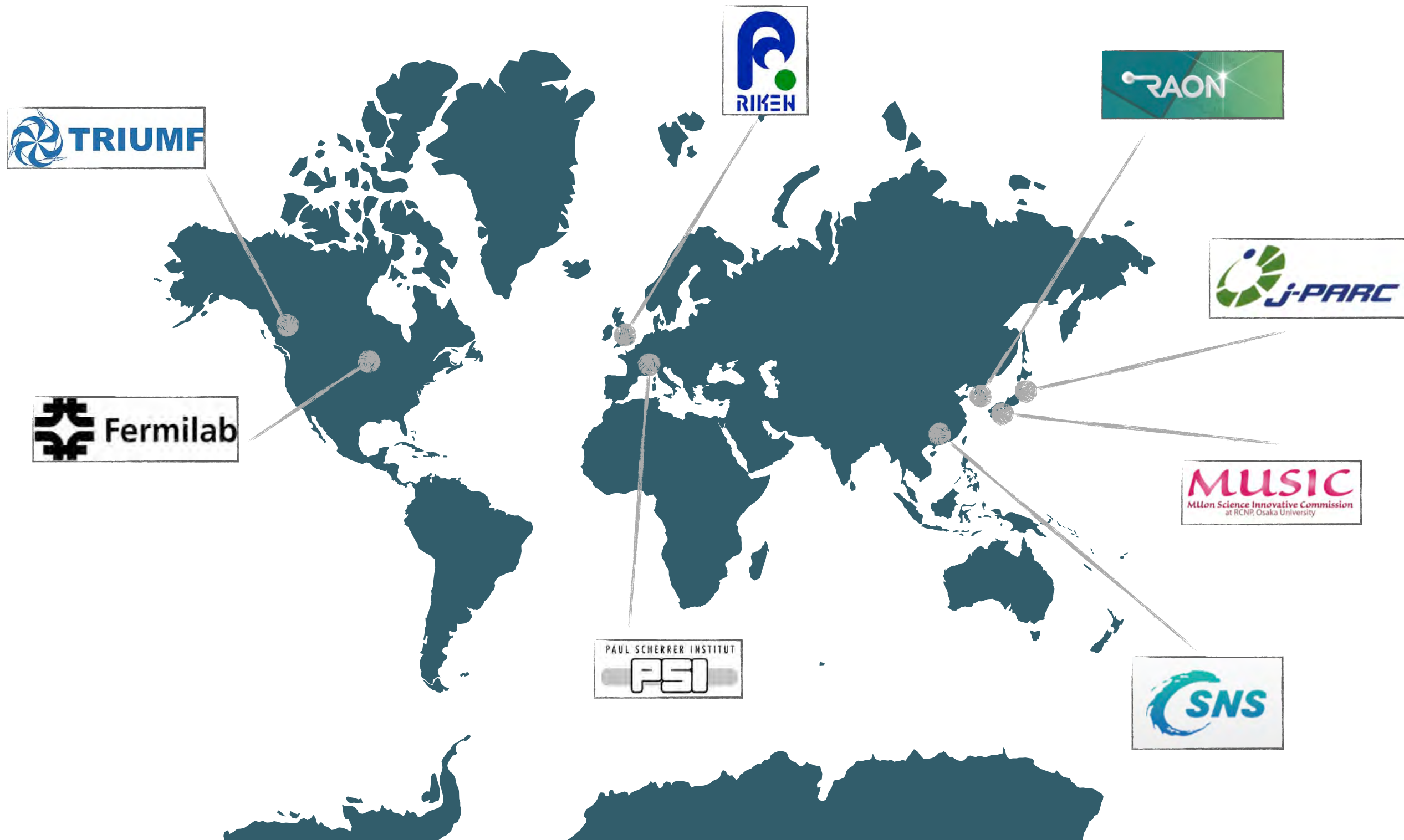
- 1st stage + 2nd stage
- **Next Step:** Extraction into vacuum



The muCool project at PSI: Status



DC and Pulsed muon beams - present and future



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	$2 \div 4 \times 10^8 (\mu^+)$ $\mathcal{O}(10^{10}) (\mu^+) (>2018)$	
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 GeV, 4 kW)	HEPEA	$1 \times 10^8 (\mu^+) (>2020)$	

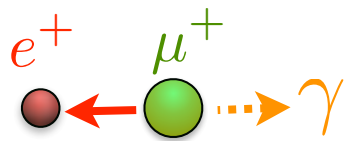
MEG: Signature, experimental setup and result

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

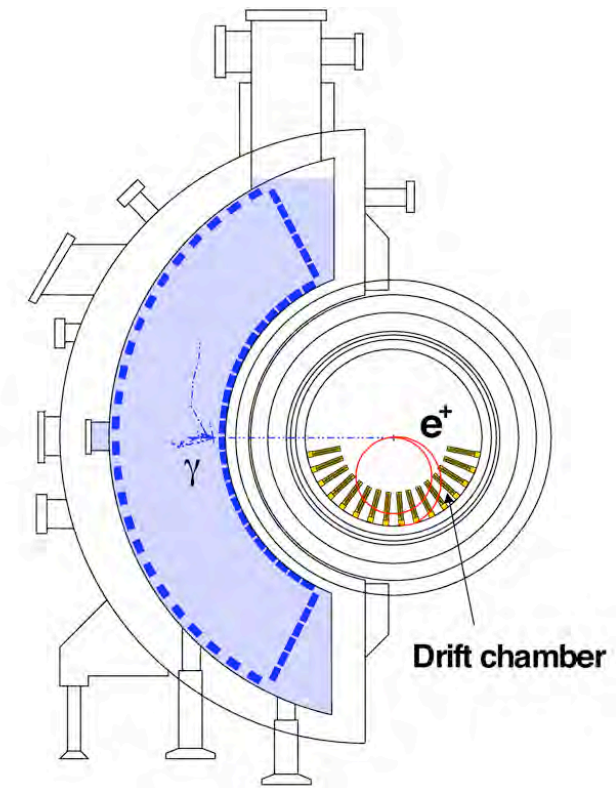
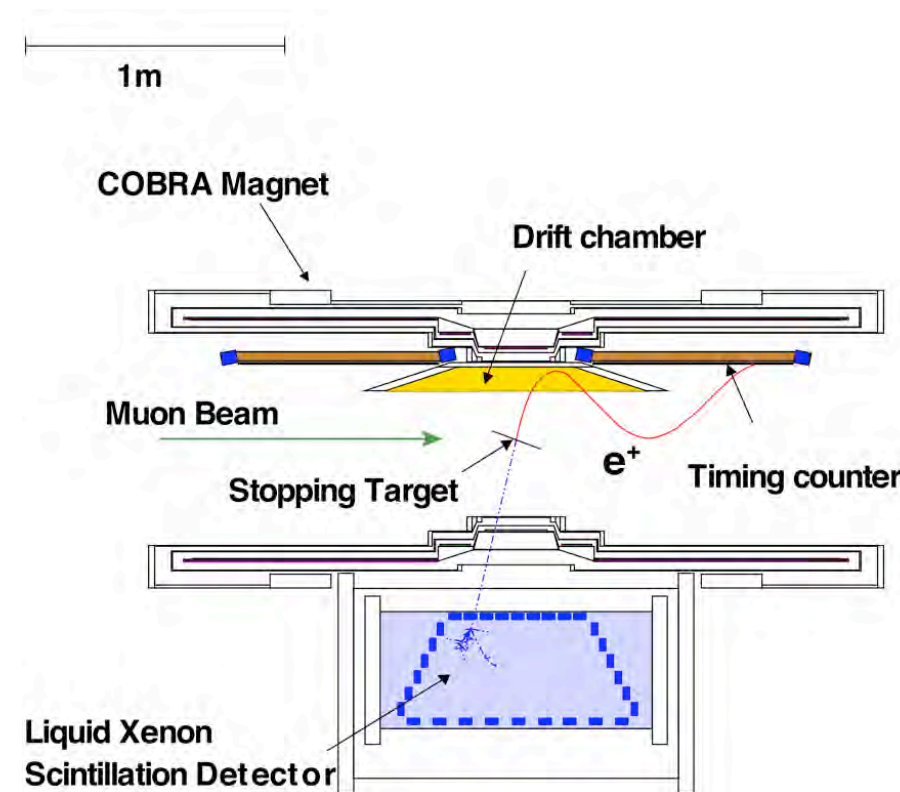
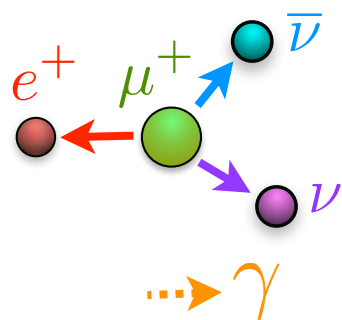
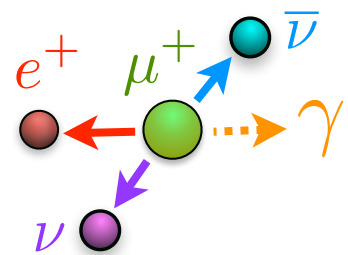
A. Baldini et al. (MEG Collaboration),
Eur. Phys. J. C76 (2016) no. 8, 434

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_γ , 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.:

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

The MEGII experiment

New electronics:
Wavedream

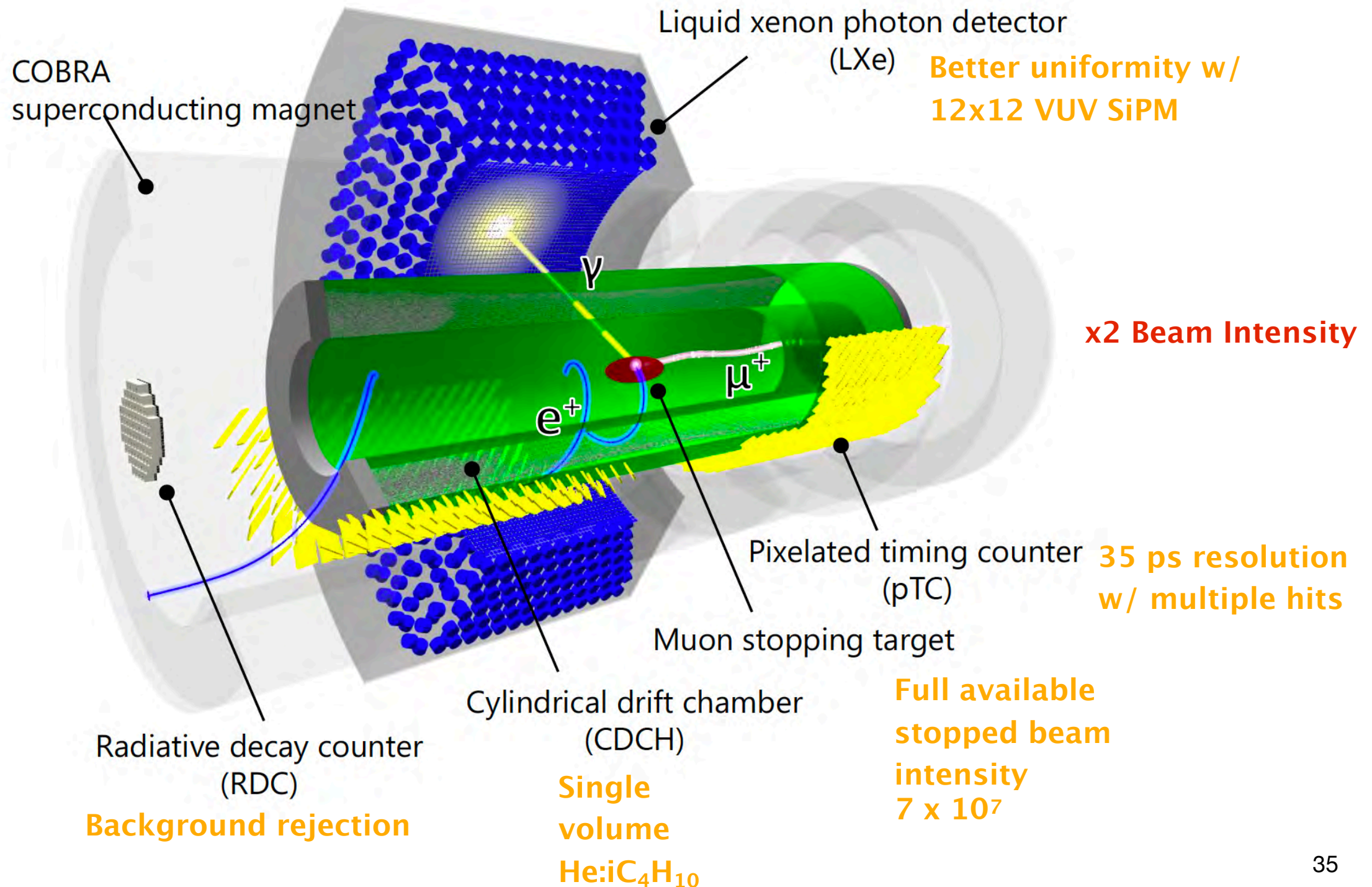
~9000
channels
at 5GSPS

x2 Resolution
everywhere

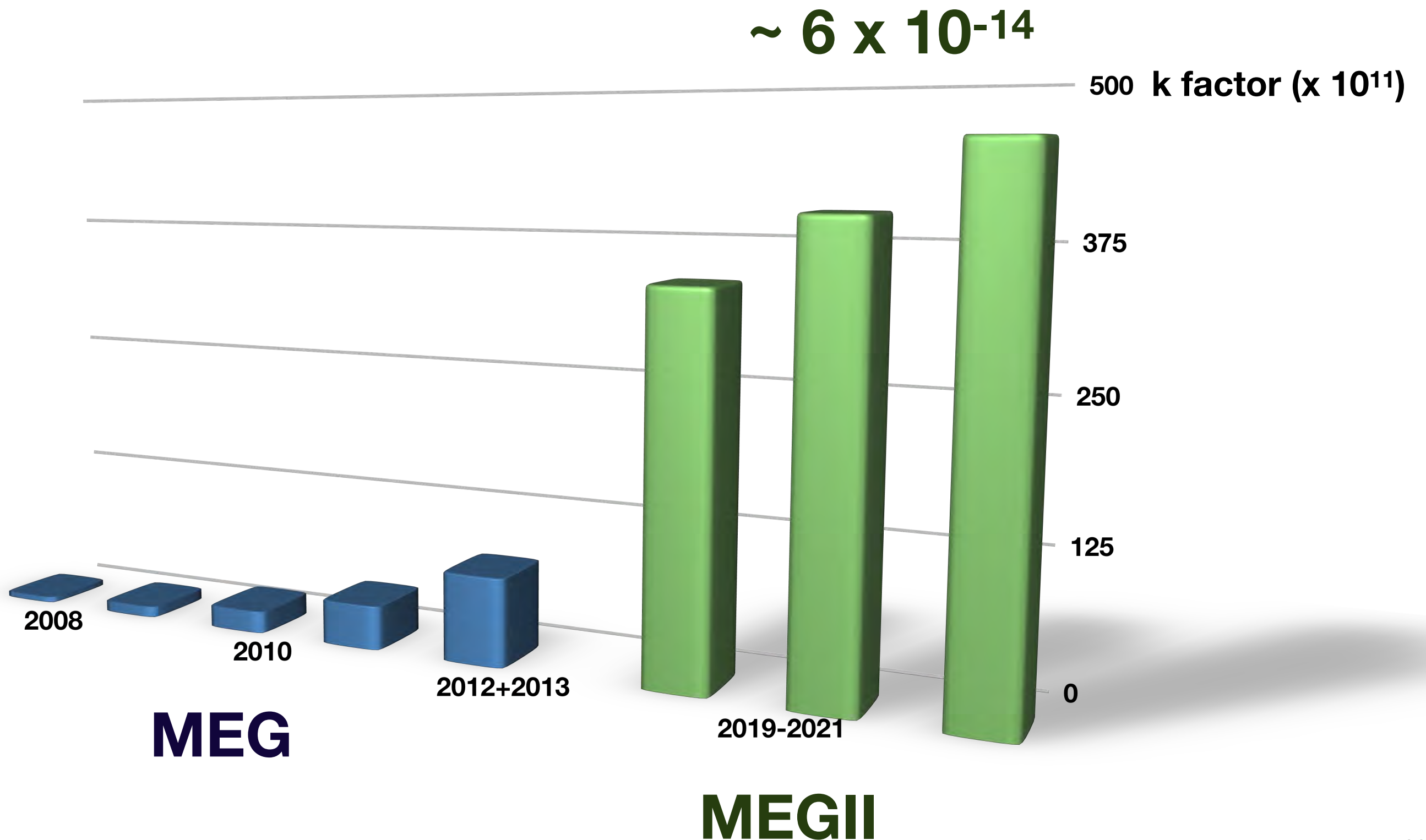
Updated and
new Calibration
methods

Quasi mono-
chromatic
positron beam

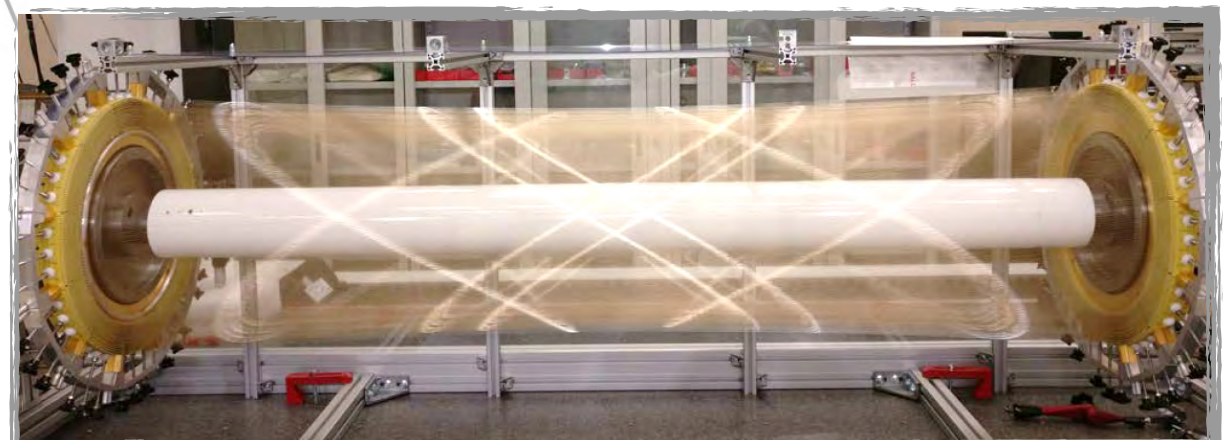
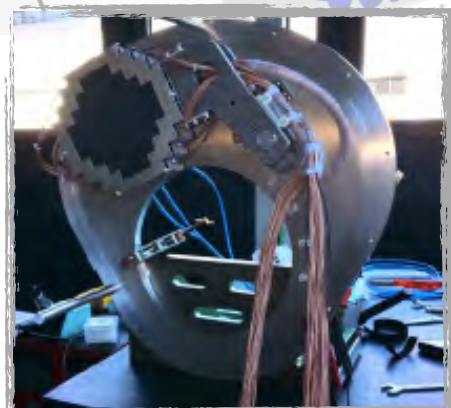
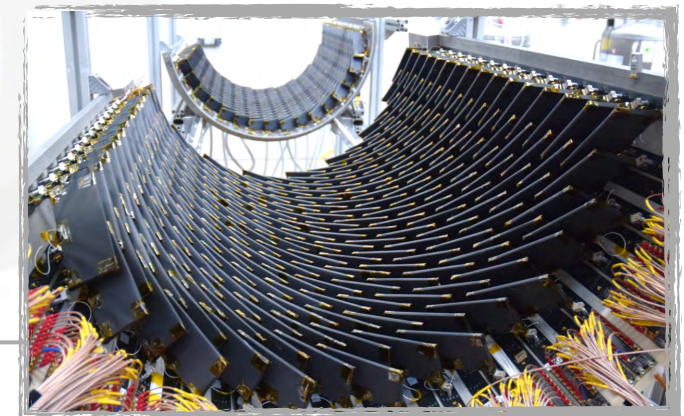
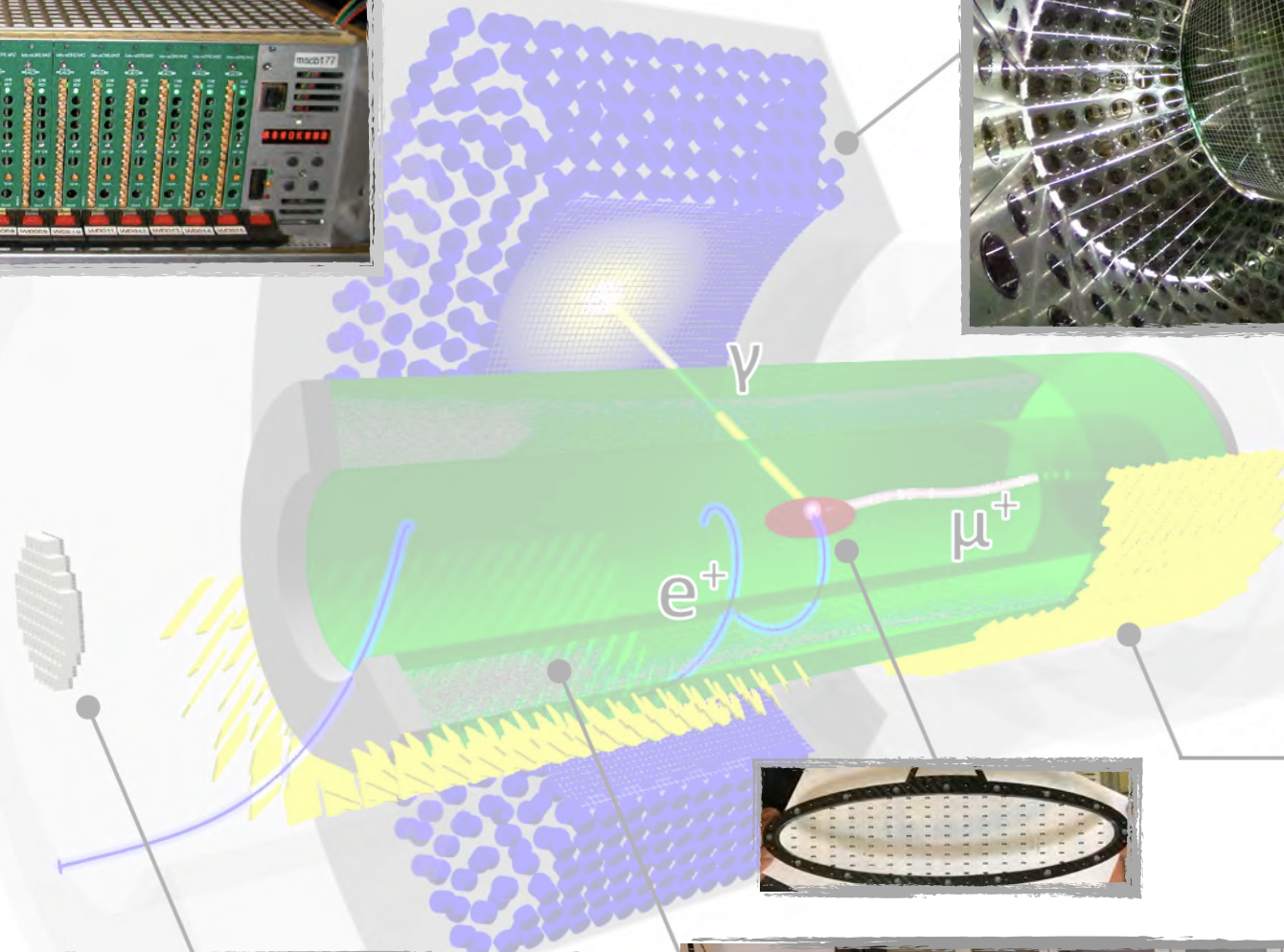
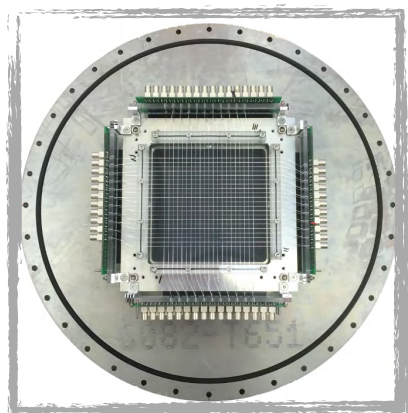
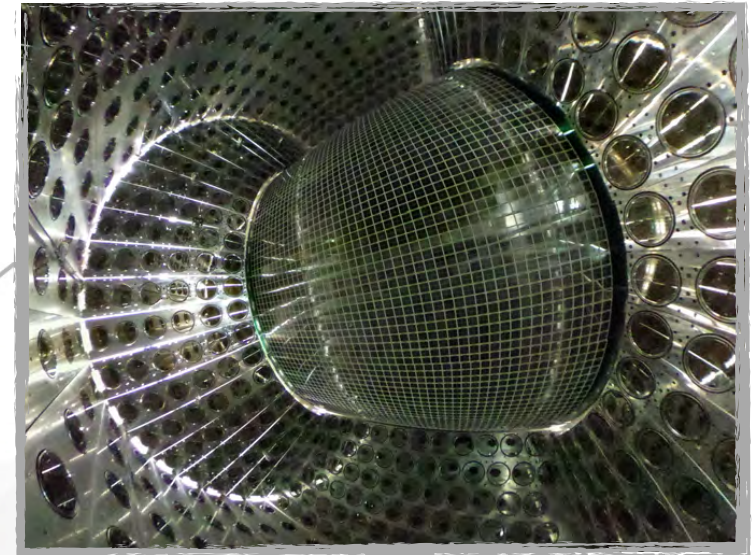
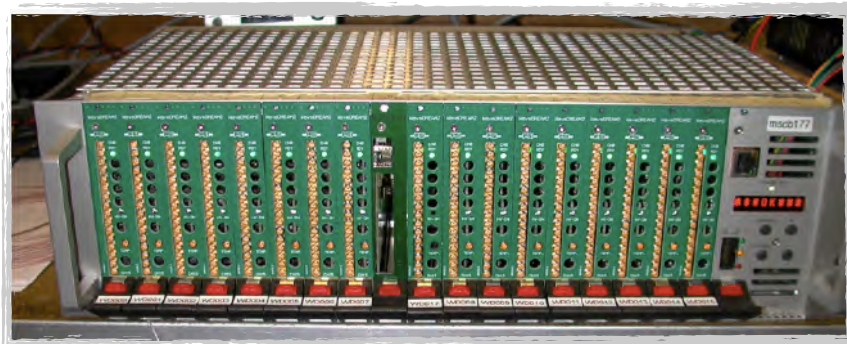
Background rejection



Where we will be



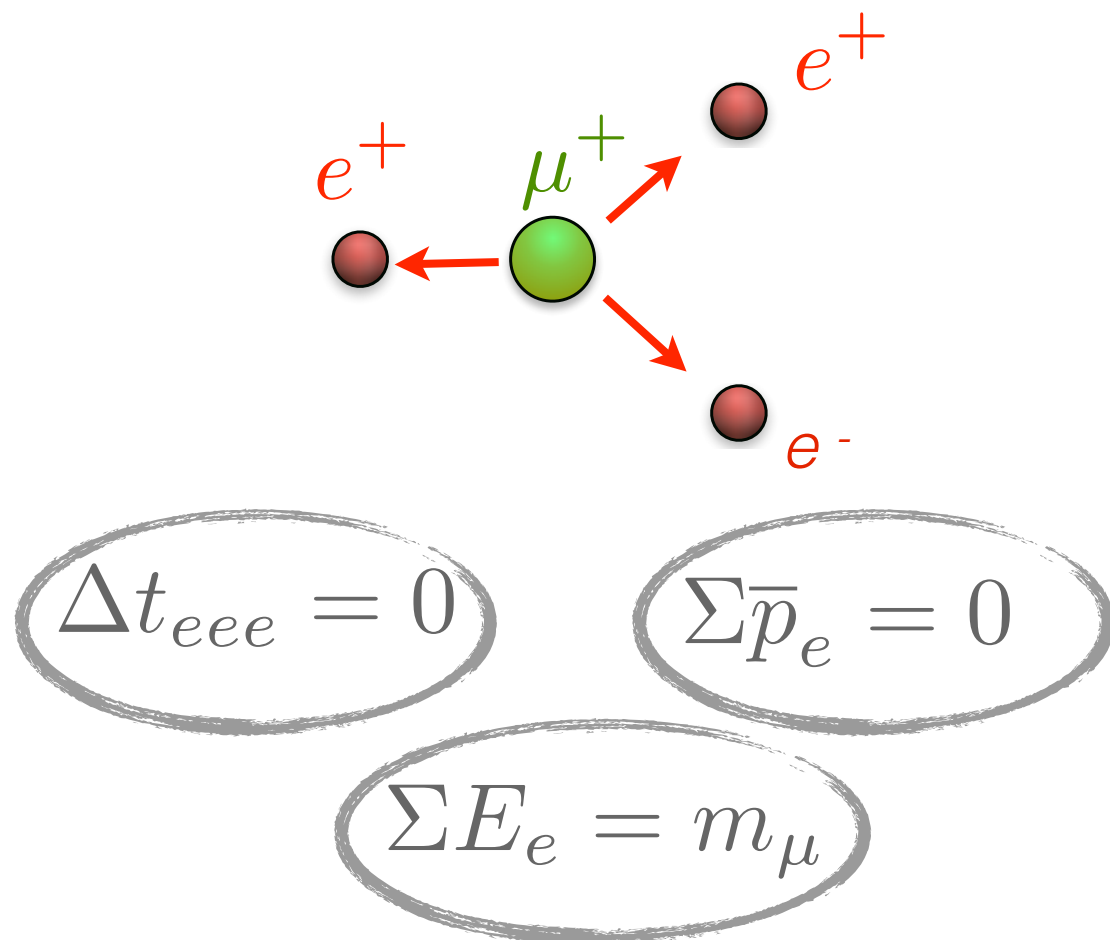
Where we are: Full engineering run in preparation



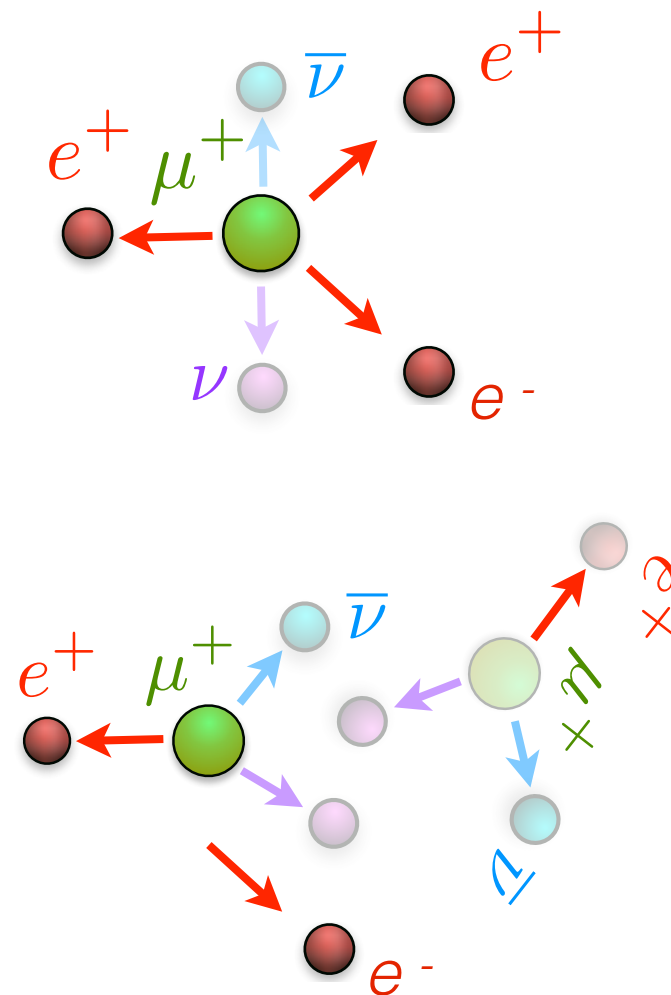
Mu3e: The $\mu^+ \rightarrow e^+ e^+ e^-$ search

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

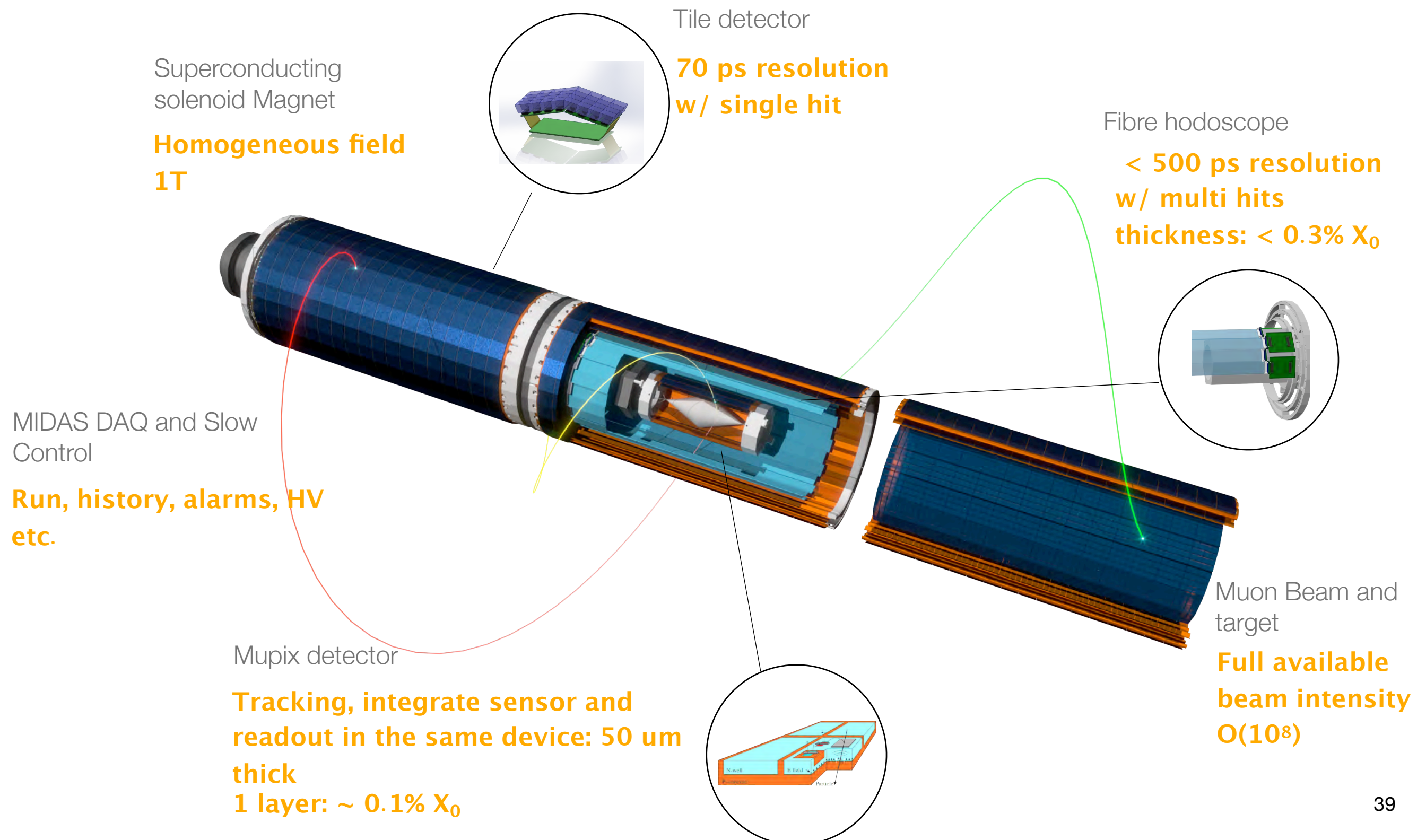
Signature

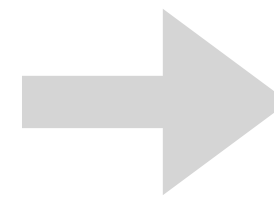


Background



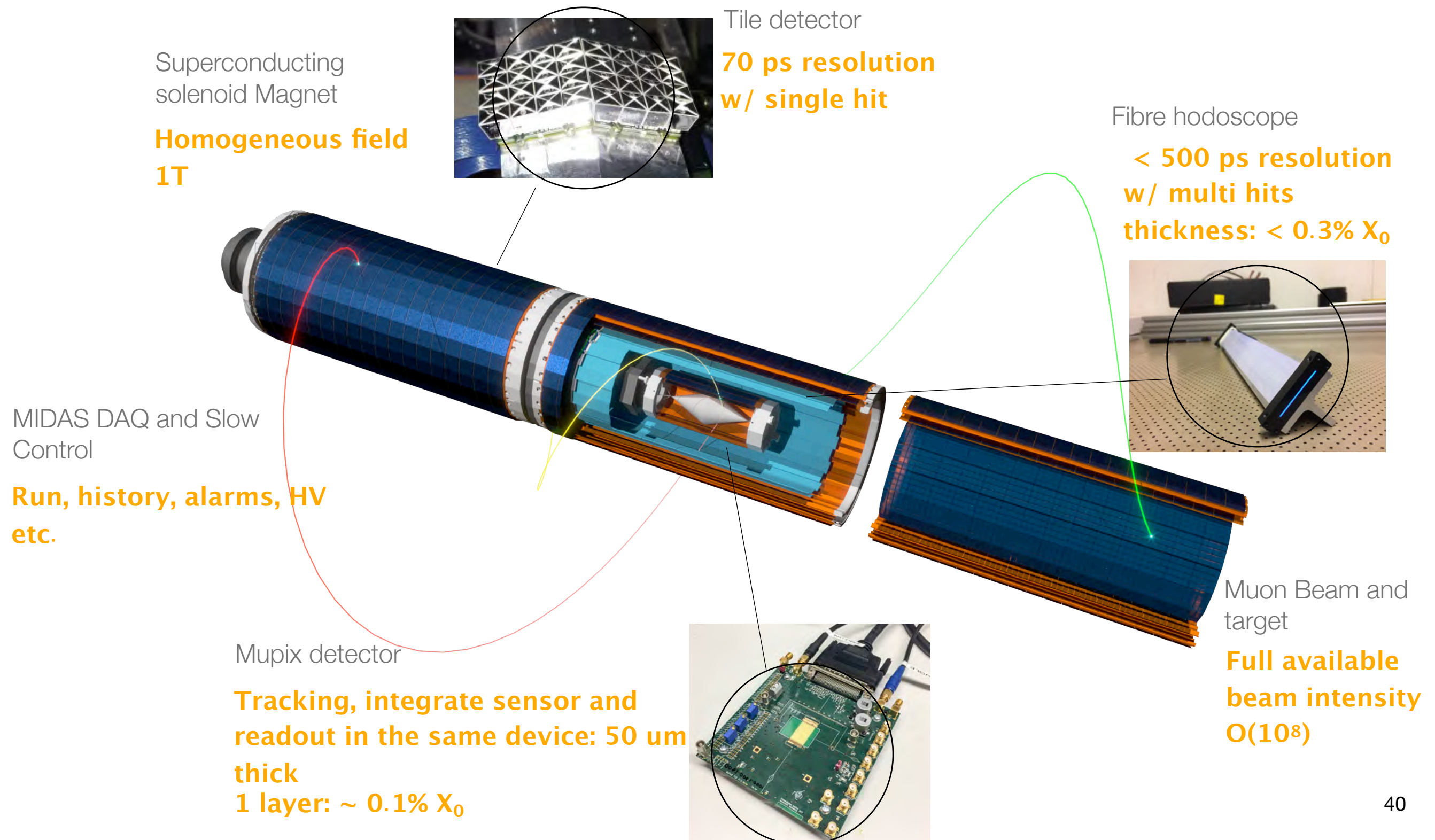
The Mu3e experiment: Schematic 3D





F. Wauters's talk:
Mon. WG4 group

The Mu3e experiment: R&D completed. Prototyping phase

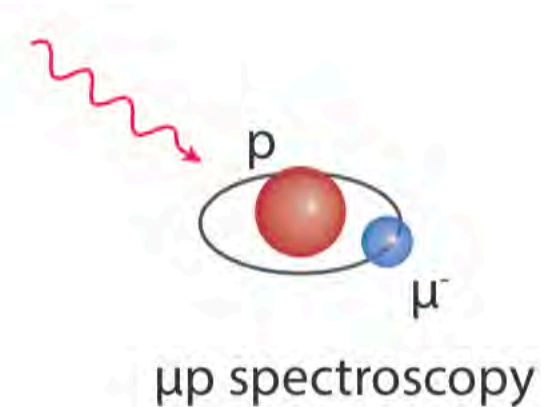
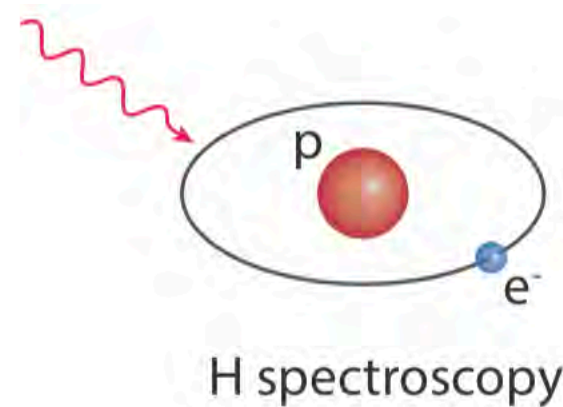
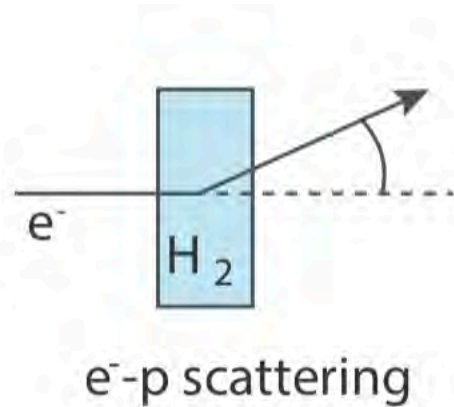


The role of the low energy precision physics

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

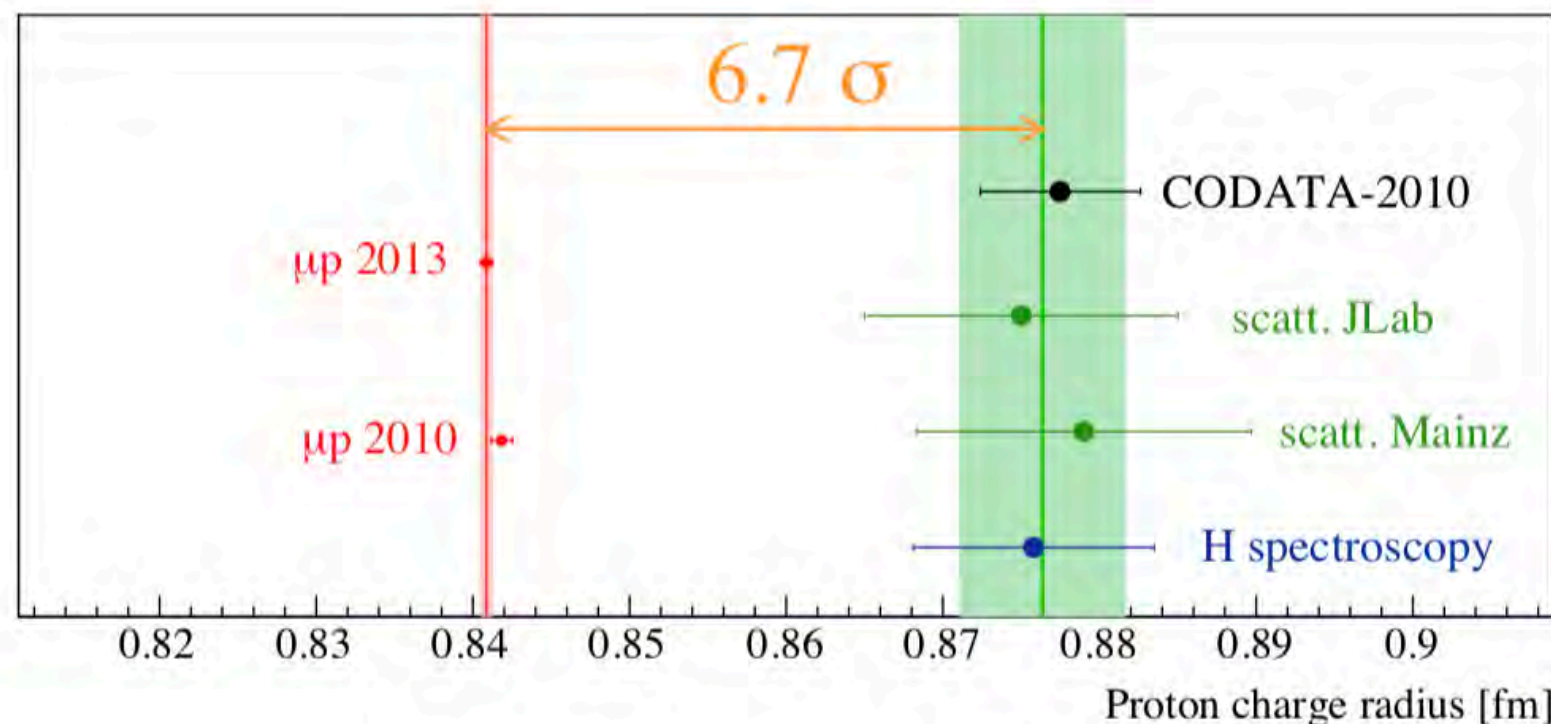
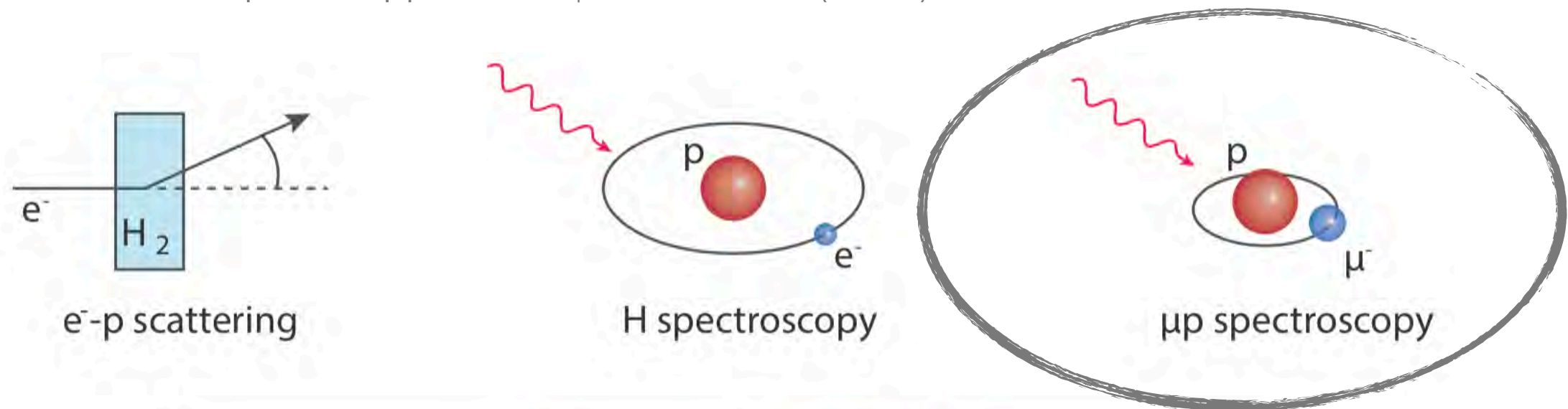
Spectroscopy of muonic atoms

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



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 (6.7σ) and 10 times more accurate



Principle of the μp 2S-2P experiment

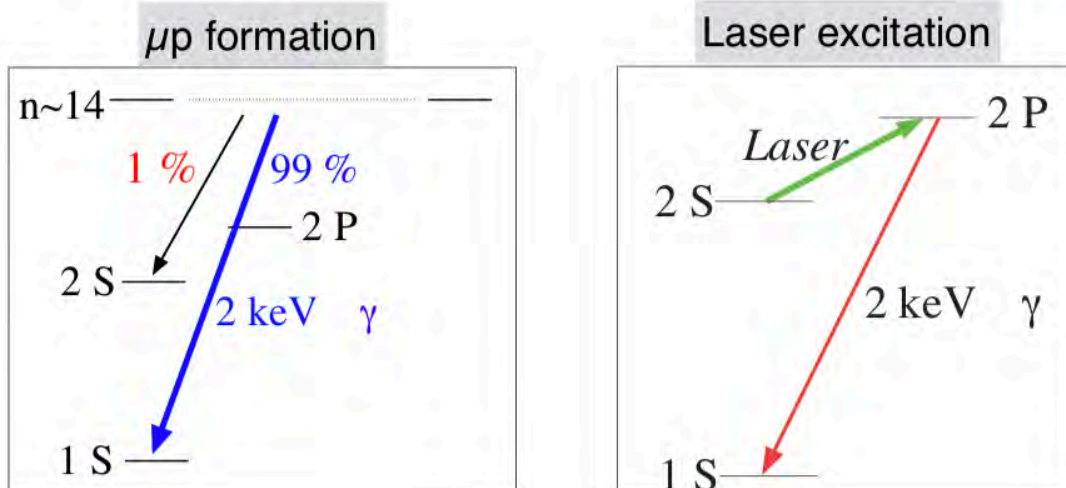
Measure 2S-2P splitting (20 ppm)
and compare with theory
→ proton radius

Produce many μ^- at keV energy

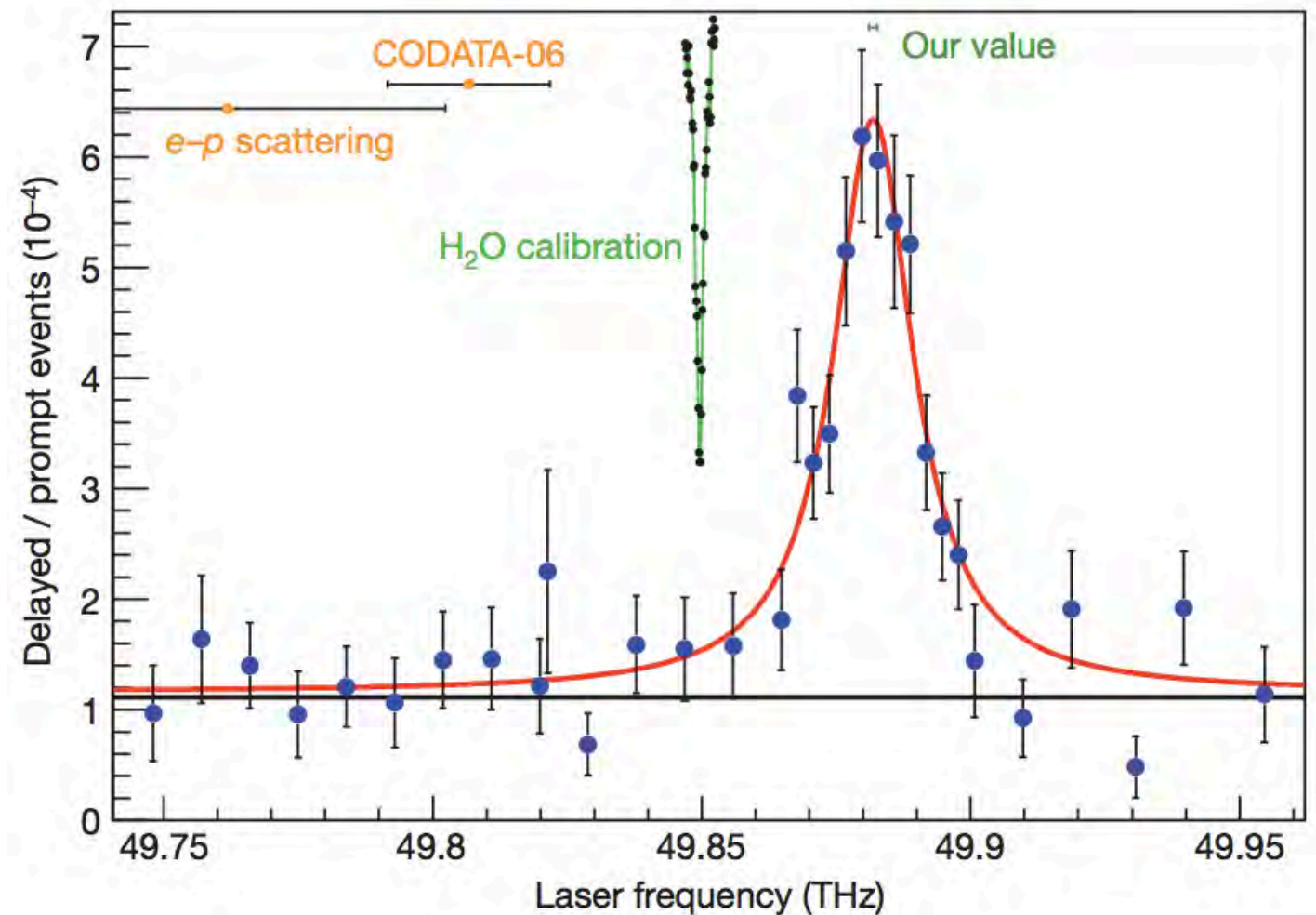
Form μp by stopping μ^- in 1 mbar H_2 gas

Fire laser to induce the 2S-2P transition

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

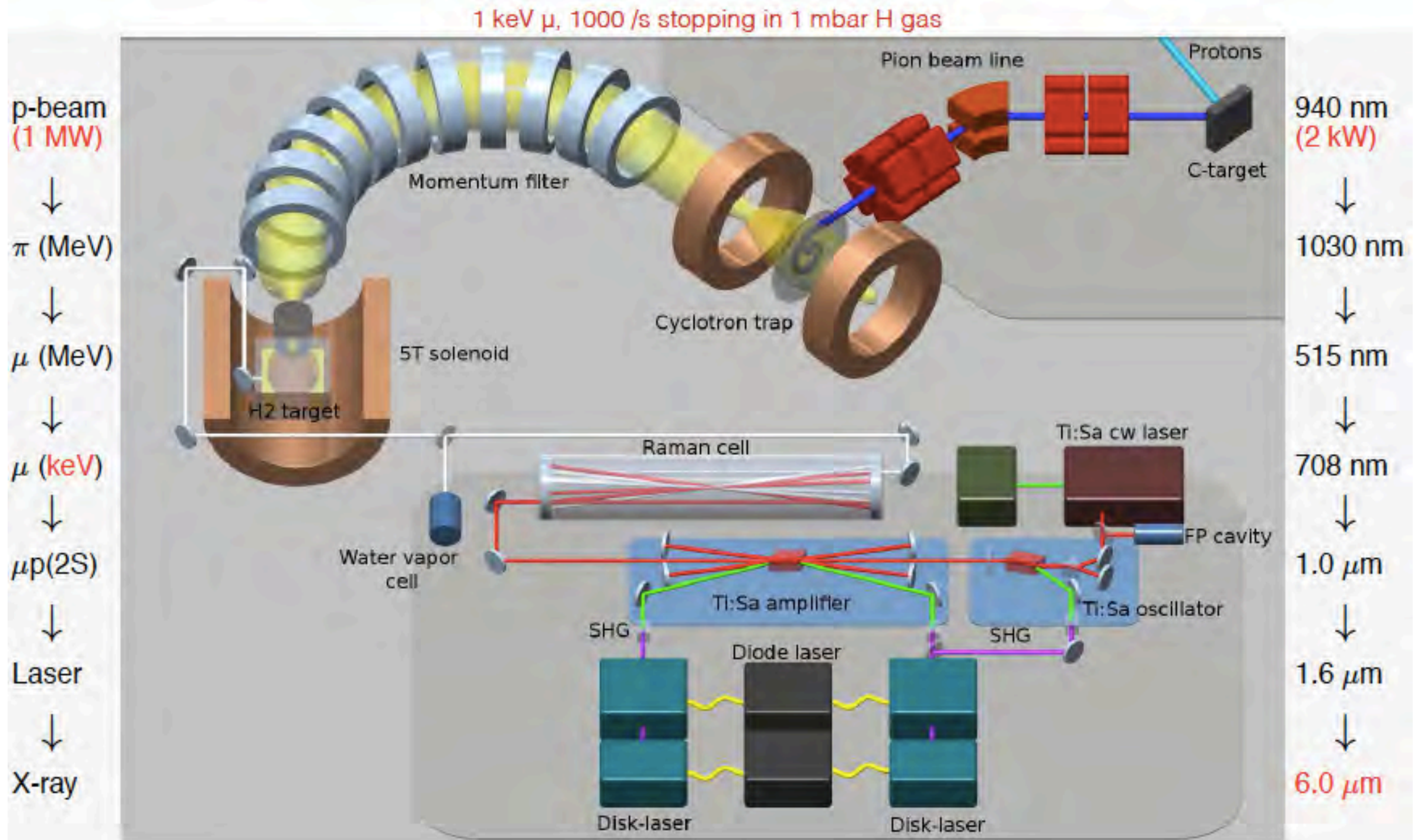


$$\Delta E_{2P-2S}^{\text{th}} = 206.0336(15) - 5.2275(10) r_p^2 + 0.0332(20) \text{ [meV]}$$



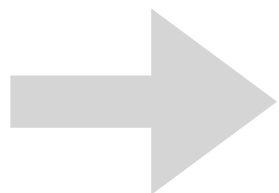
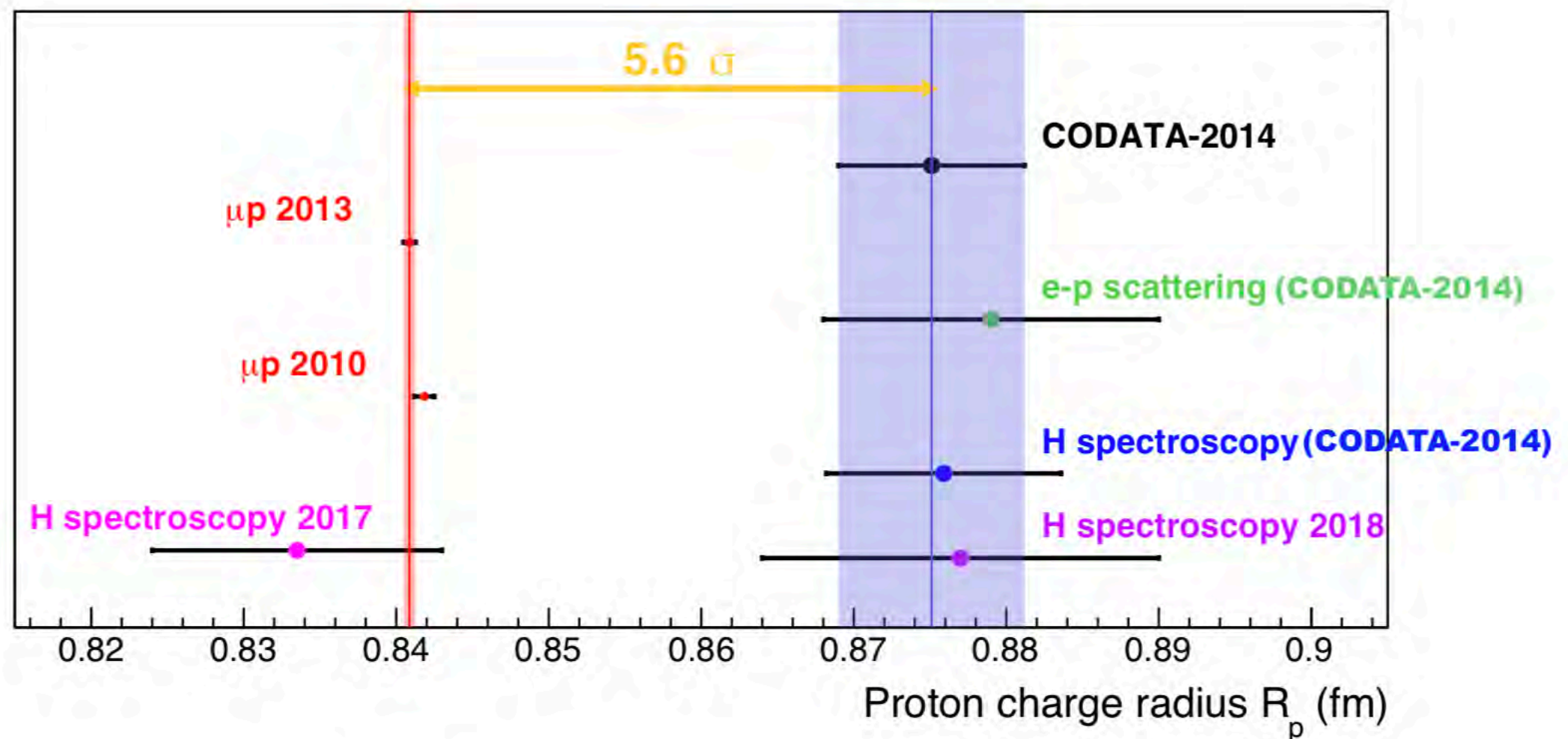
The experimental setup

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



Proton radius revisited

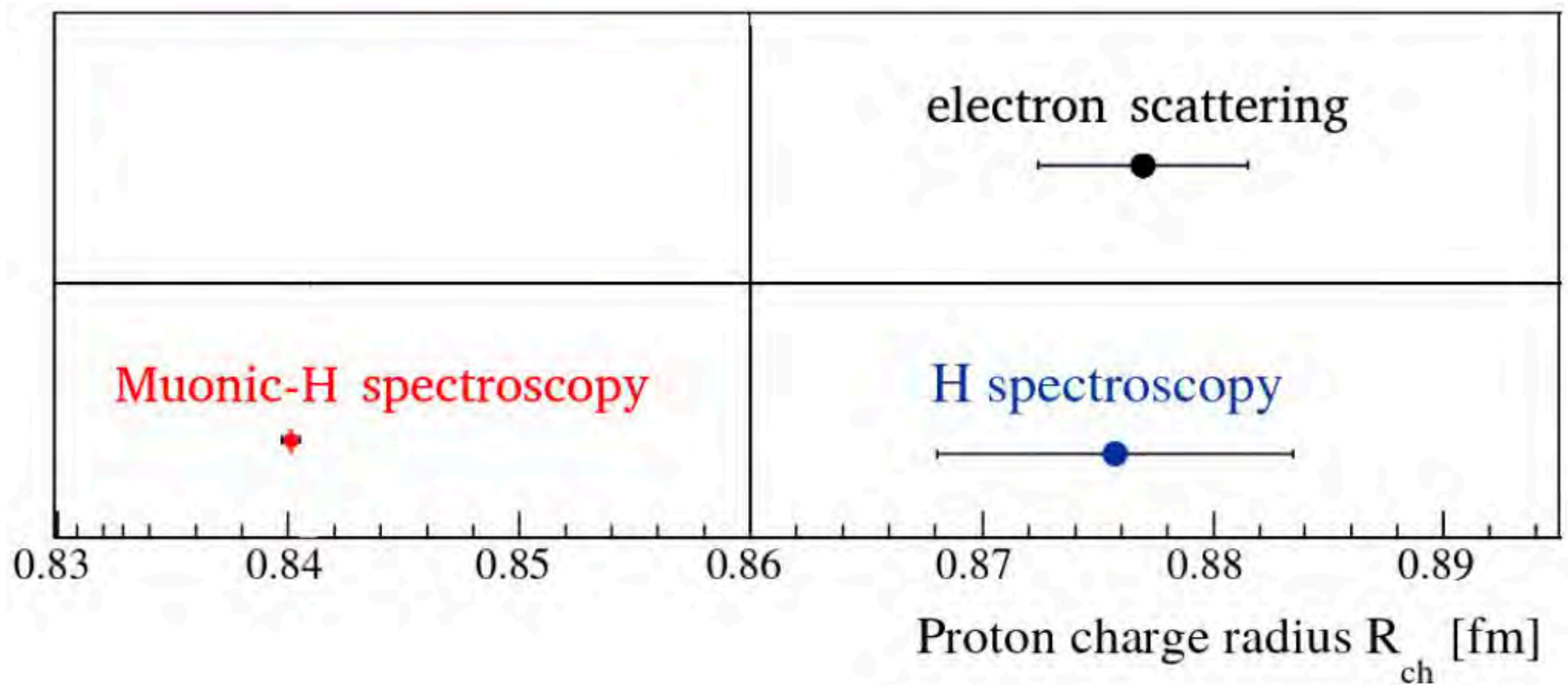
- Hydrogen spectroscopy brings a surprise in the search for a solution to a long-standing puzzle



C. Gu's talk: Thur.
WG4 group

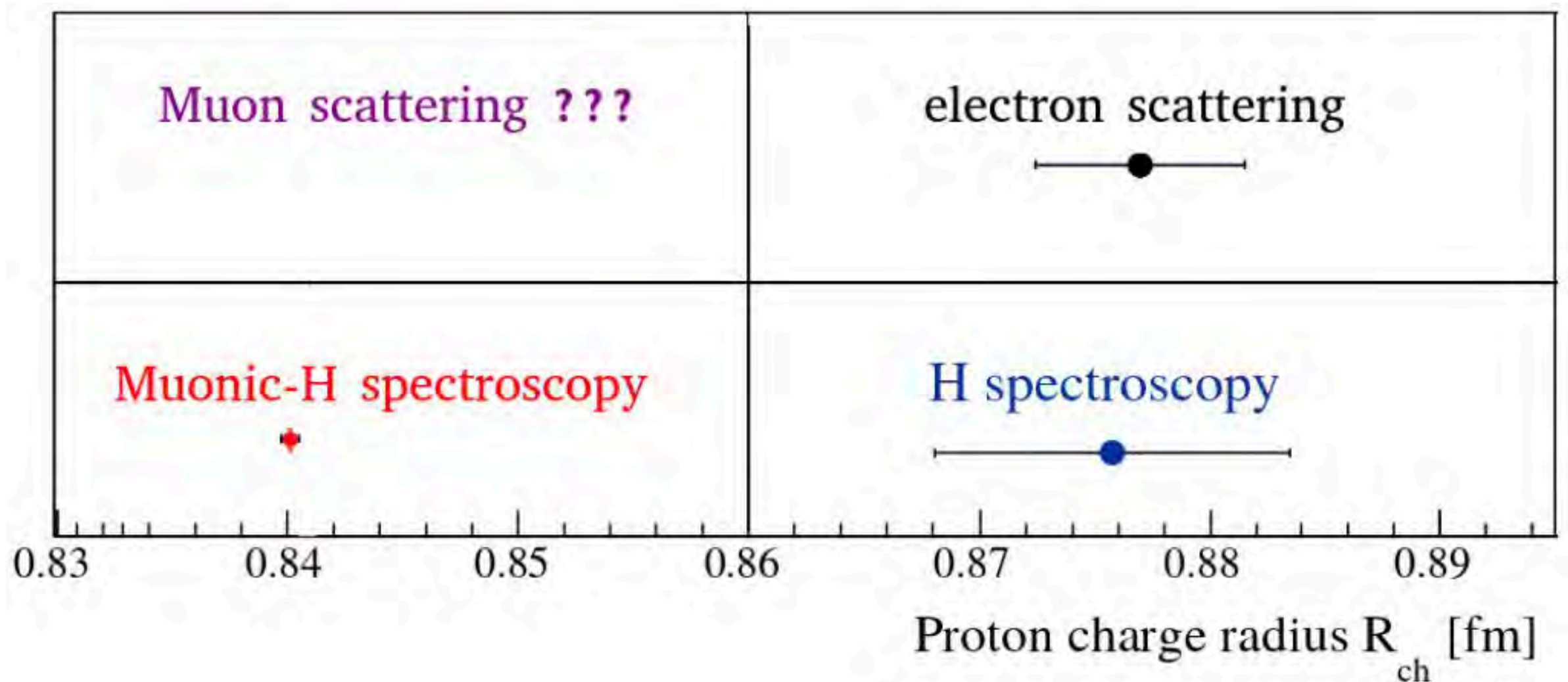
The MUSE experiment: Motivations

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



The MUSE experiment: Motivations

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



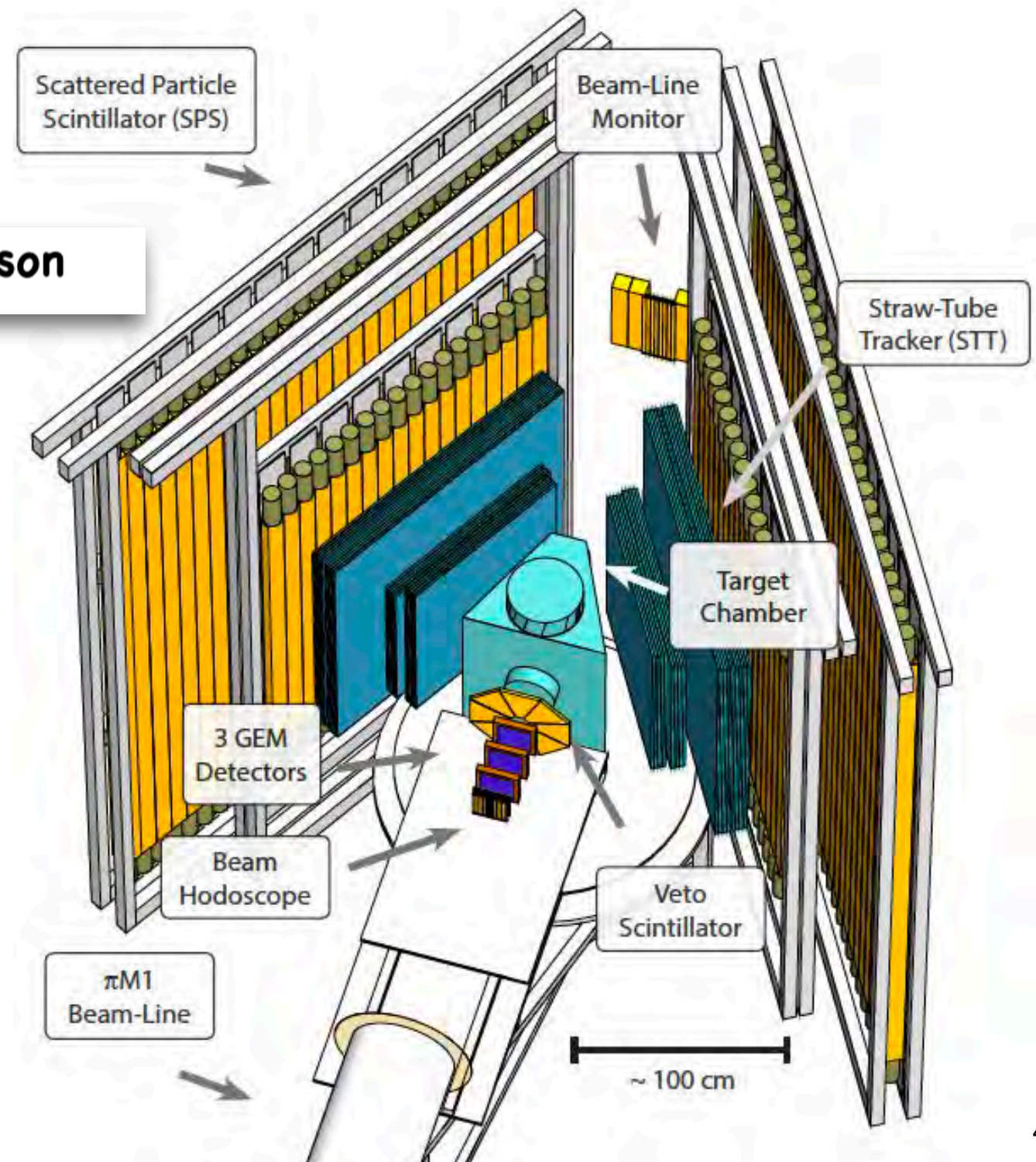
The MUSE experiment: Ready for the physics run

- Beam line: $\pi M1$ @PSI

with μp and $e p$ to have direct μ/e comparison

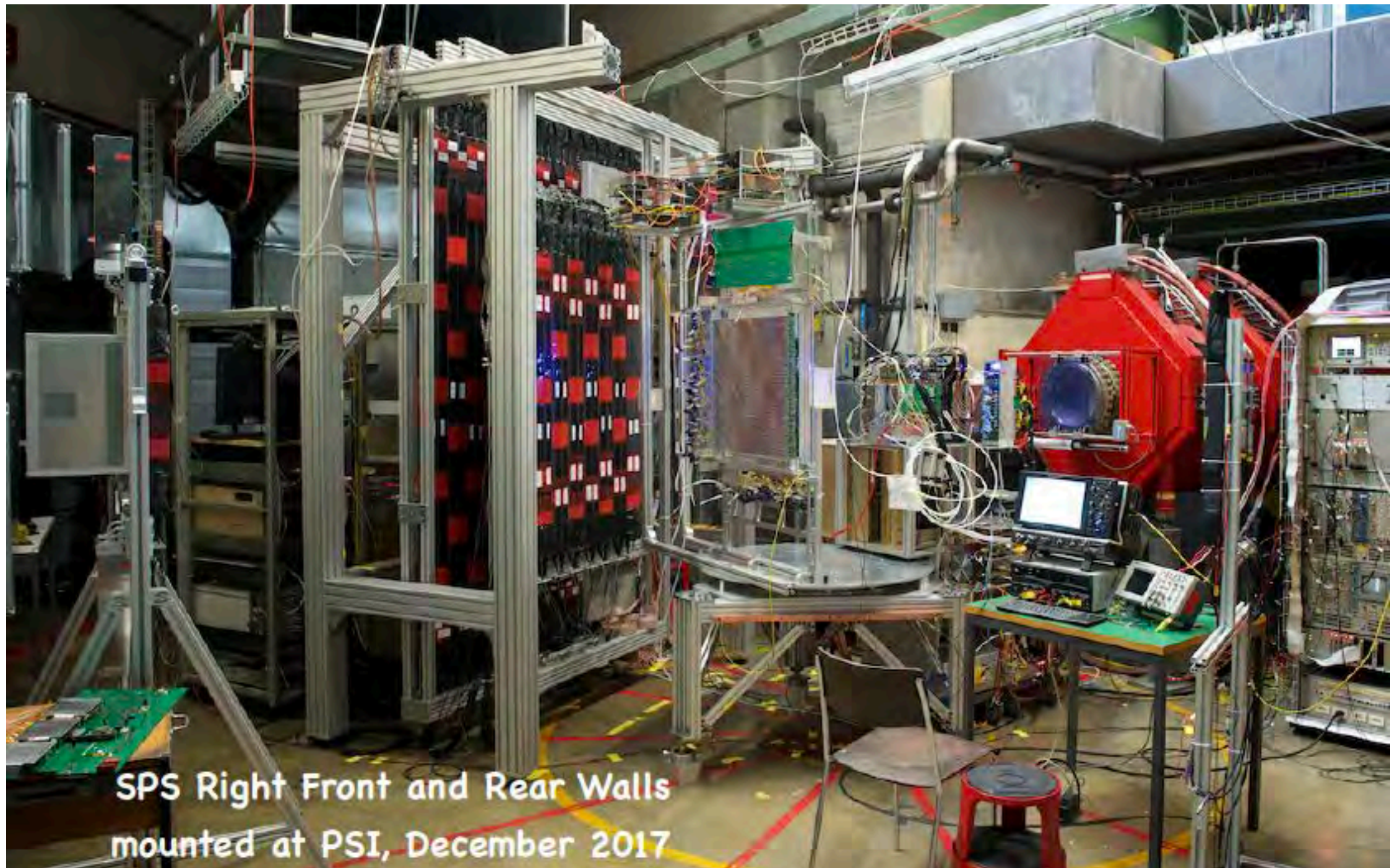
$\theta \approx 20^\circ - 100^\circ$
 $Q^2 \approx 0.002 - 0.07 \text{ GeV}^2$
3.3 MHz total beam flux
 $\approx 2 - 15\% \mu$'s
 $\approx 10 - 98\% e$'s
 $\approx 0 - 80\% \pi$'s

➔ S. Strauch's talk:
Thur. WG4 group



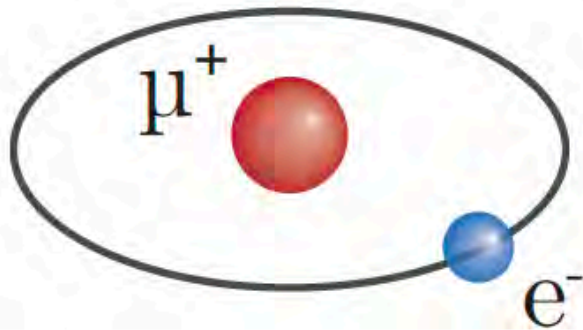
The MUSE experiment: Towards the physics run

- Beam line: piM1@PSI



SPS Right Front and Rear Walls
mounted at PSI, December 2017

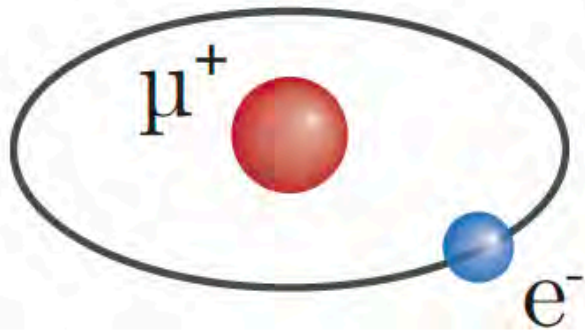
Muonium: A precision tool in atomic and particle physics



Muonium (Mu)

- ▶ hydrogen-like exotic atom
- ▶ pure leptonic system (1st and 2nd gen.)
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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

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

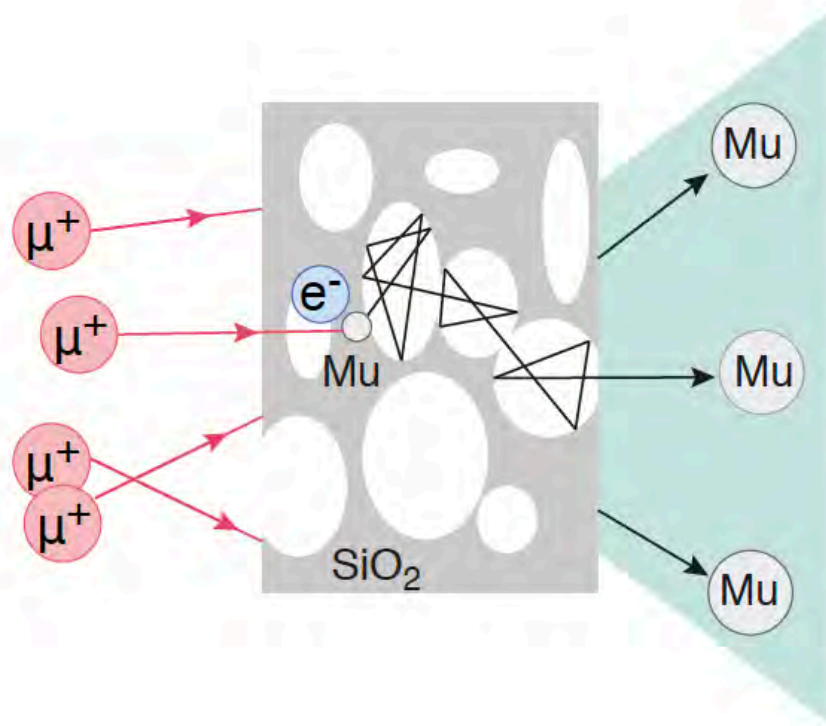
▶ Mu - antiMu

- ▶ Charged lepton number violation

▶ Mu gravity experiment?

- ▶ test of weak equivalence principle on μ^+ :
 - ▶ elementary antiparticle
 - ▶ second generation lepton

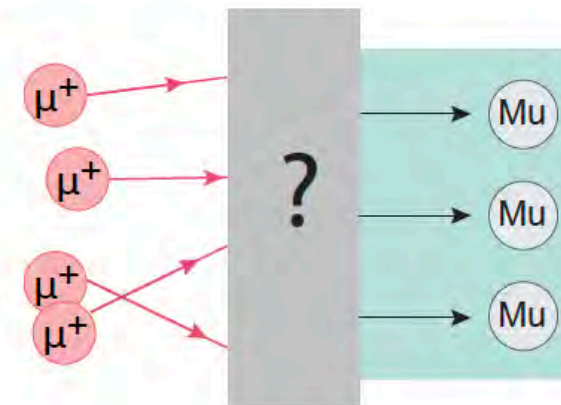
Needed: A 'cold' Mu source



- Large (thermal) energy spread
- Broad angular distribution ($\sim \cos\theta$)
- 3-30 % conversion efficiency at $T=296\text{ K}$

Needed: a 'cold' Mu source

- Low emittance, narrow energy distribution, large Mu number

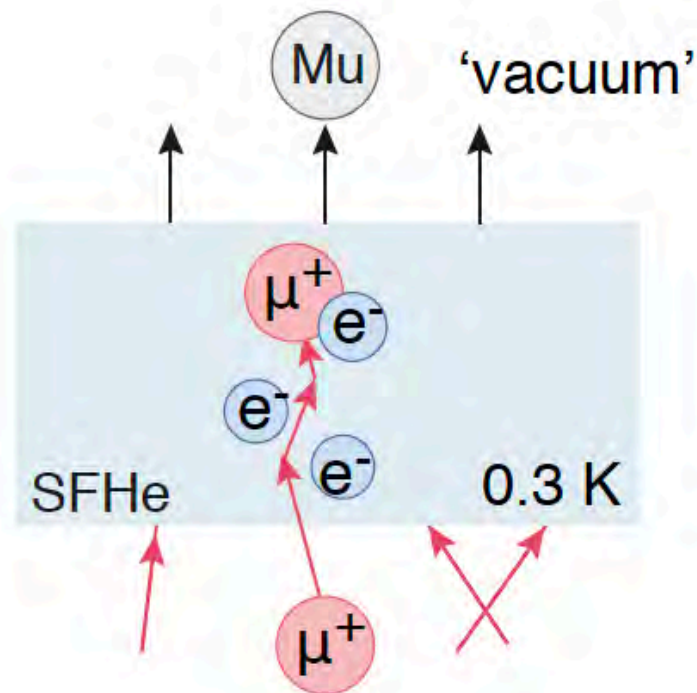


- cooling conventional samples: almost no Mu emission below 100 K (decreased velocities, and atoms sticking to the pore walls)

New

Cold Mu production

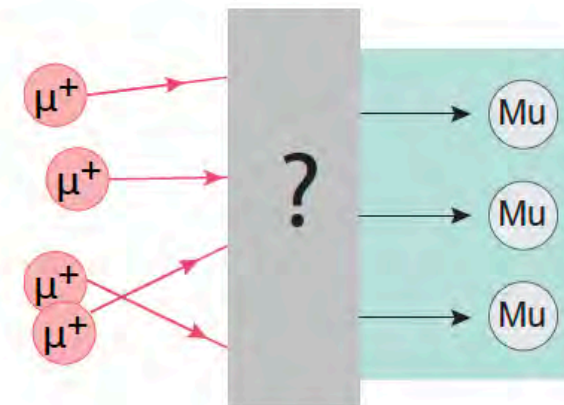
- Proposal: Mu production in superfluid helium (SFHe)



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 (**$I \sim 10^8$ 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 (**$I \sim 10^{10}$ muon/s**)
 - i.e. MuSIC at RCNP aiming at (**$I \sim 10^8$ muon/s - 400W**)
- New ideas about
 - High brightness low energy beam line (tertiary beam line): MuCool at PSI (**$D < 1\text{mm}$, $E < \text{eV}$** , 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?
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- Cooled muon beams w/ phase rotations? New methods?

Back-up

How the sensitivity can be pushed down?

- More sensitive to the **signal**...

high statistics

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

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

- More effective on rejecting the **background**...

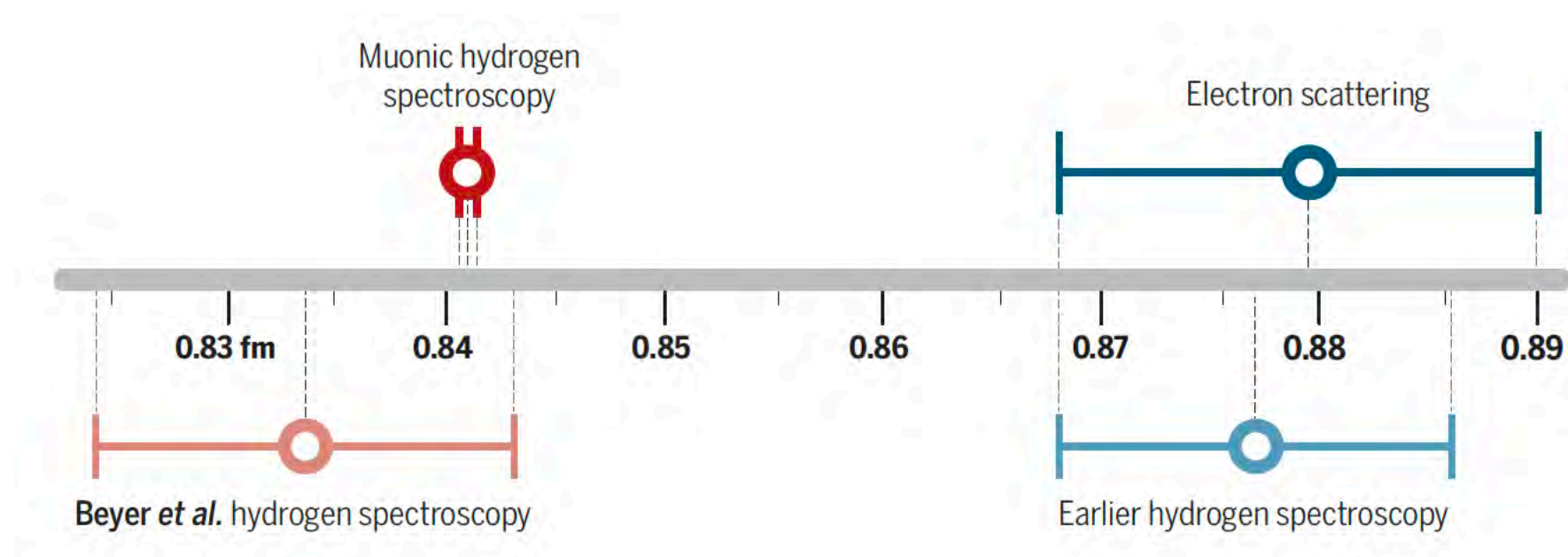
high resolutions

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

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

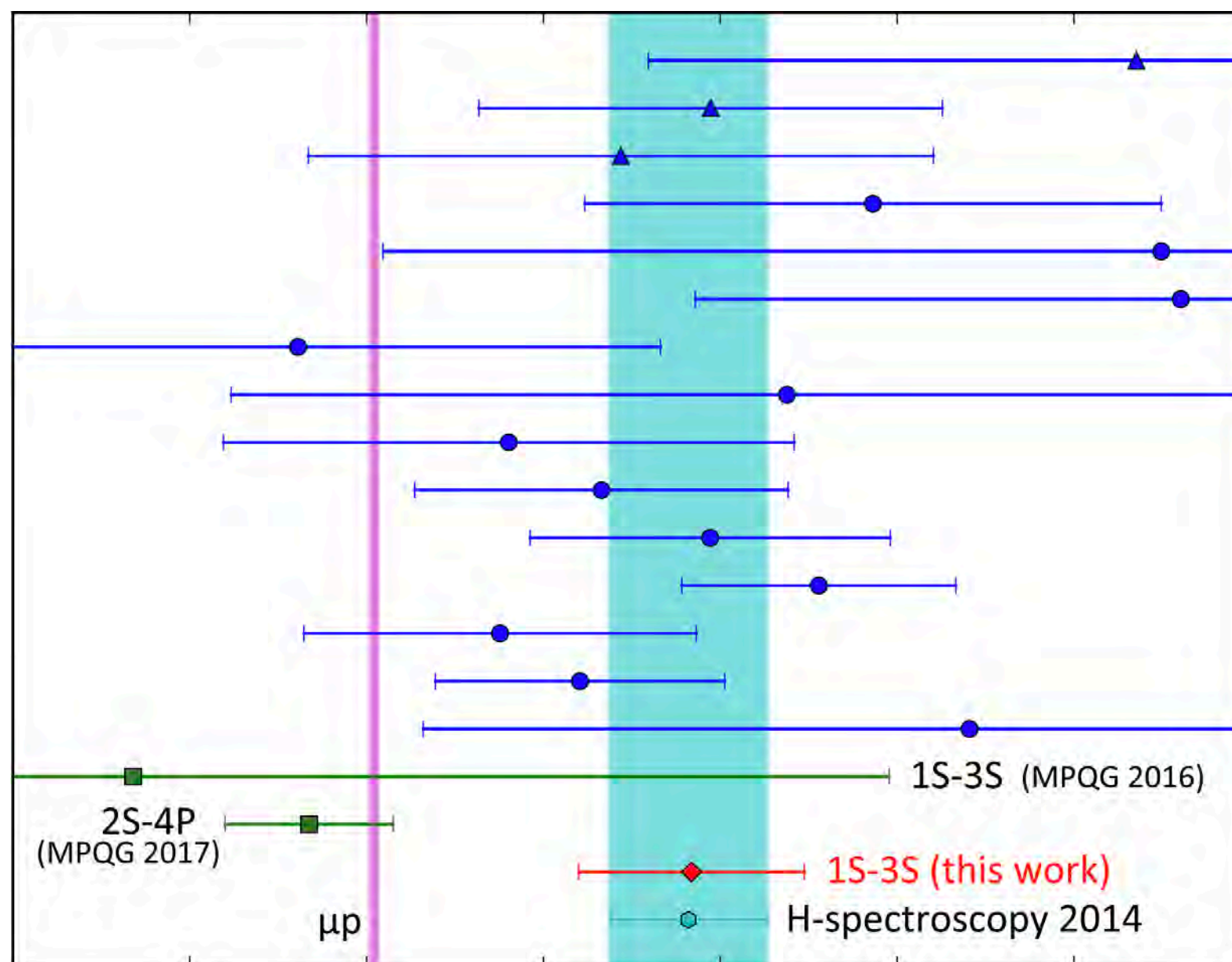
Proton radius revisited

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

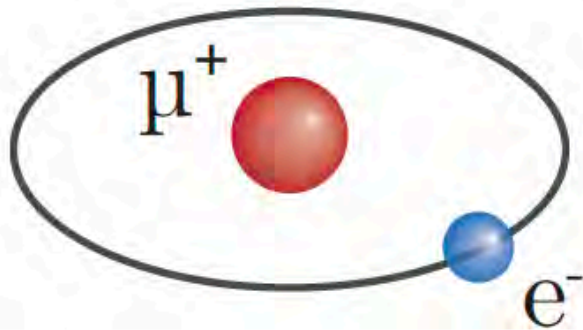


Proton radius revisited

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Muonium: A precision tool in atomic and particle physics



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

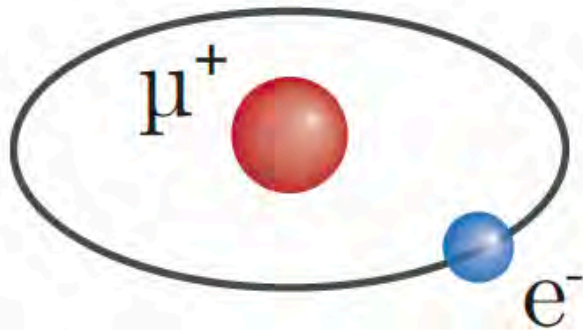
Mu 1s-2s and HFS spectroscopy

- ▶ test of bound-state QED
- ▶ fundamental constants:
 $m_\mu, R_\infty, m_\mu/m_p, q_\mu/q_e \dots$
- ▶ fundamental symmetries

Muonium - antimuonium

- ▶ put limits on the charged lepton number violation

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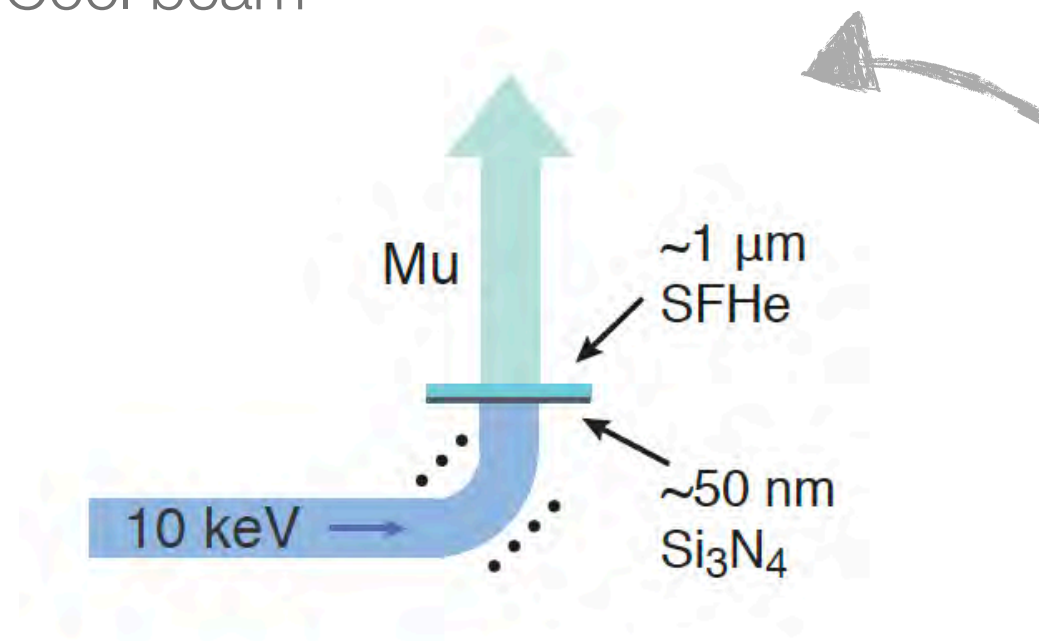
Mu gravity experiment?

μ^+ : elementary antiparticle from the second generation

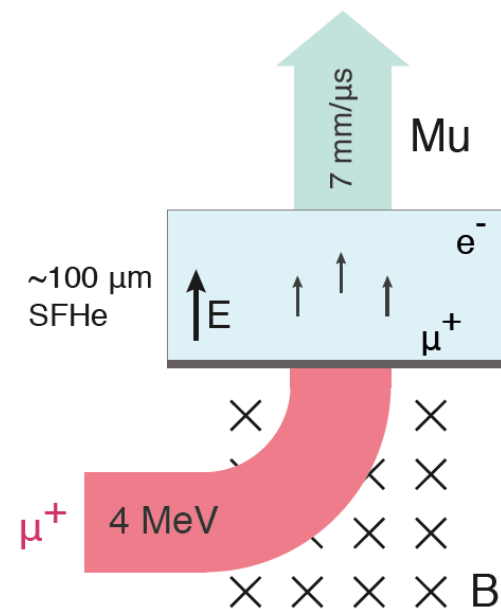
- ▶ complementary to the composite antimatter (antihydrogen) gravity experiments @ CERN
- ▶ unique possibility to compare gravity (test weak eq.princ.) in lepton generations

Cold Mu production

- MuCool beam

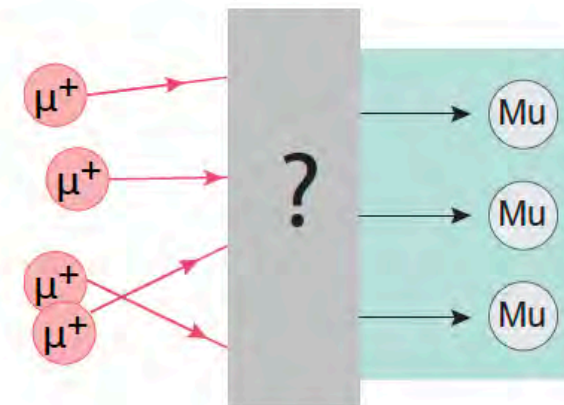


- Standard beam



Needed: a 'cold' Mu source

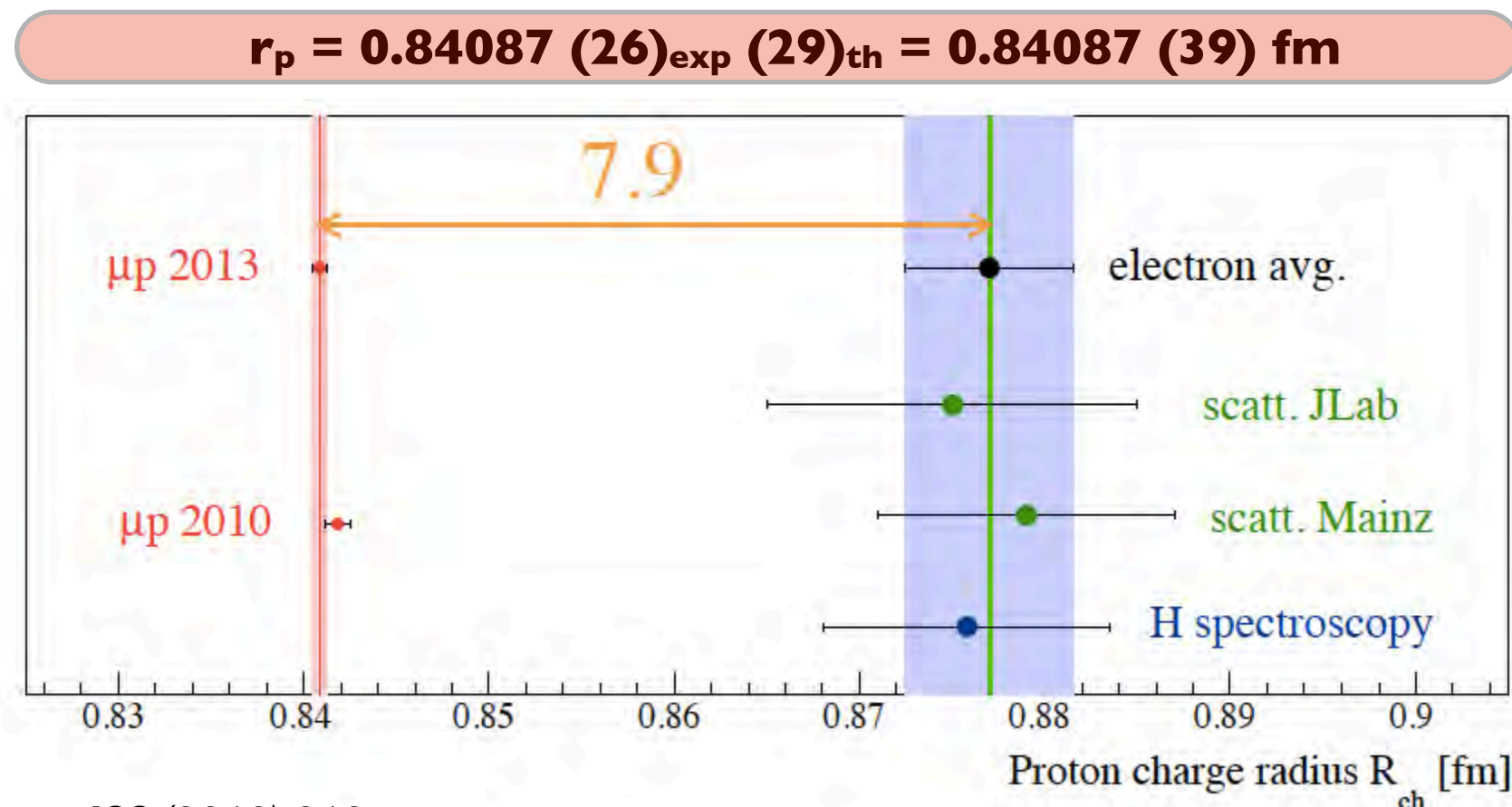
- Low emittance, narrow energy distribution, large Mu number



- 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 (7.9σ) and 10 times more accurate



ref.: R. Pohl et al. *Nature* **466** (2010) 213

A. Antognini et al. *Science* **339** (2013) 417

Impact of the muonic atoms



New physics?
 Parity violation?

Scattering

$e + p \rightarrow e + p$
 $e + d \rightarrow e + d$
 $\mu + p \rightarrow \mu + p$
 $\gamma + p \rightarrow \gamma + p$
 $e + Z \rightarrow e + Z$
 ...

Test of H energy levels
 Bound-state QED

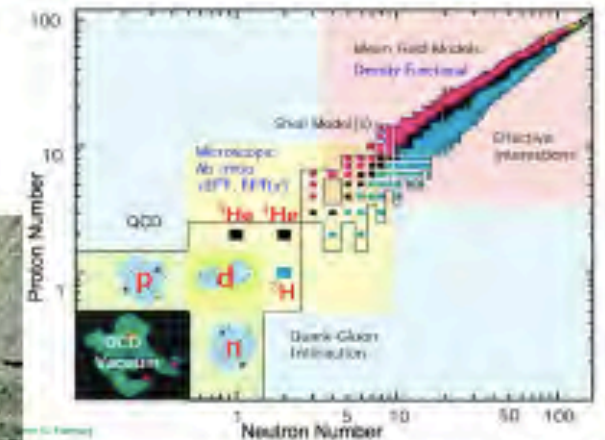
$\text{Mu} = \mu^+ e^-$

$\text{Ps} = e^+ e^-$



H, He spectroscopy

Fundamental constants

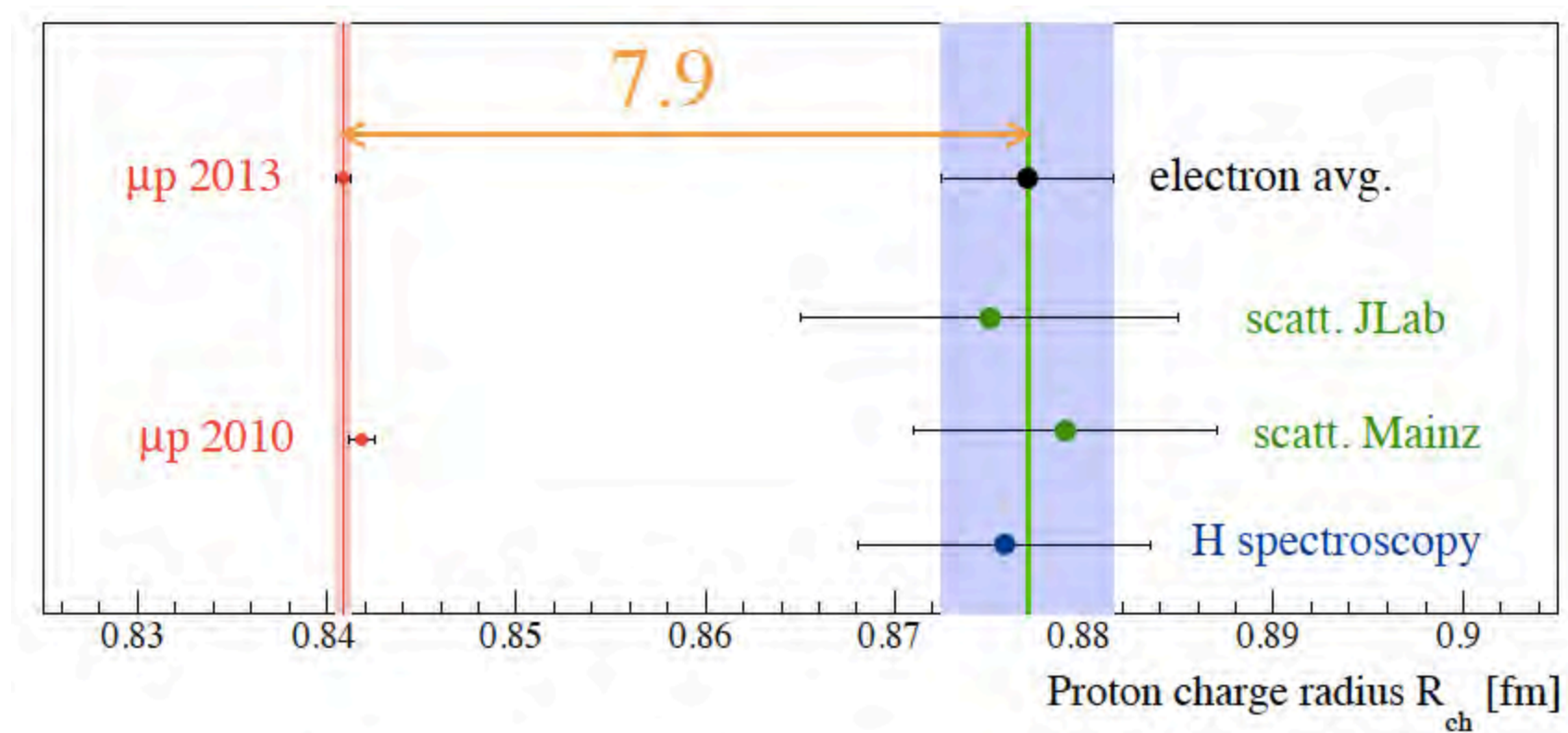


r_p, r_d, r_{He}
 EFT, χ_{pt} , lattice
 few-nucleon th.
 high-Z radii
 quadrupole mom.
 mean-field nucl. th.
 magnetic radii

$\mu p, \mu d, \mu \text{He}^+ (2S-2P)$
 high-Z muonic atoms (radioactive)
 HFS in μp and μHe^+

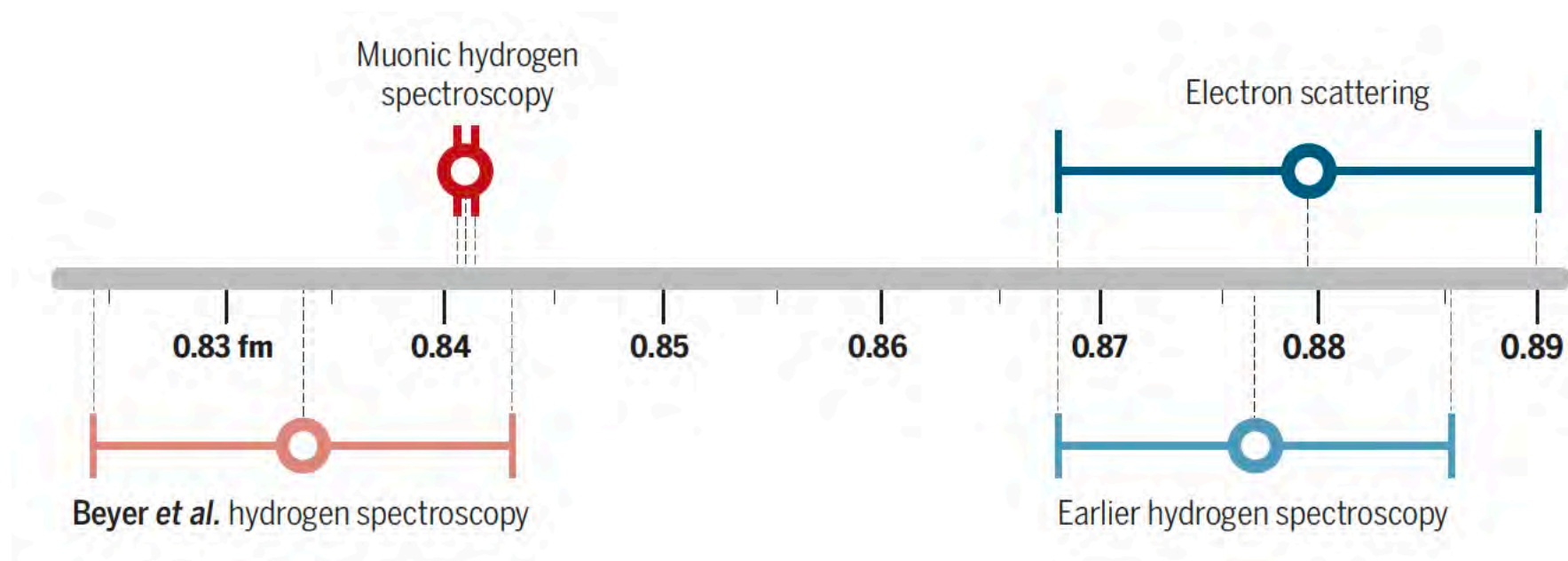
Proton radius until 2013

- Hydrogen spectroscopy and scattering, muonic atom spectroscopy



Proton radius revisited

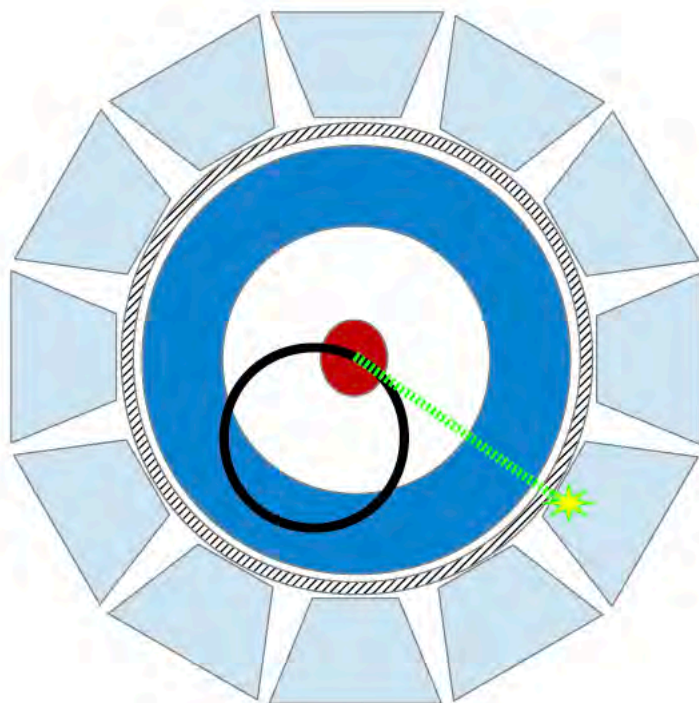
- Hydrogen spectroscopy brings a surprise in the search for a solution to a long-standing puzzle



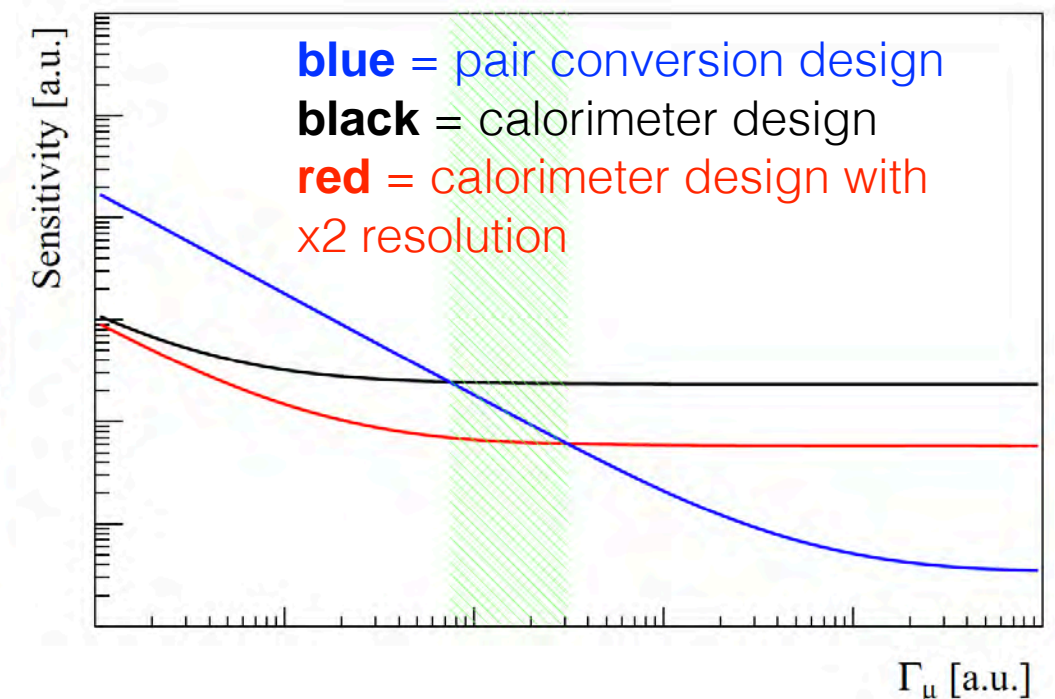
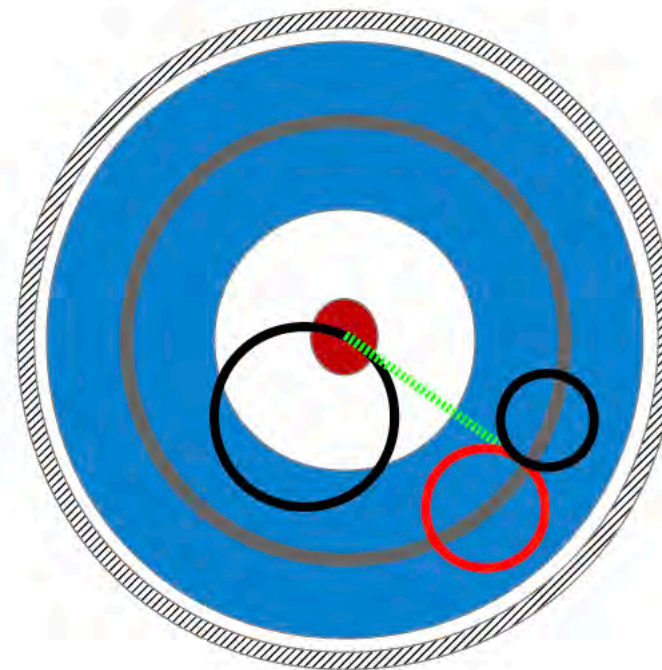
Future prospects: A first thought

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

Calorimetry



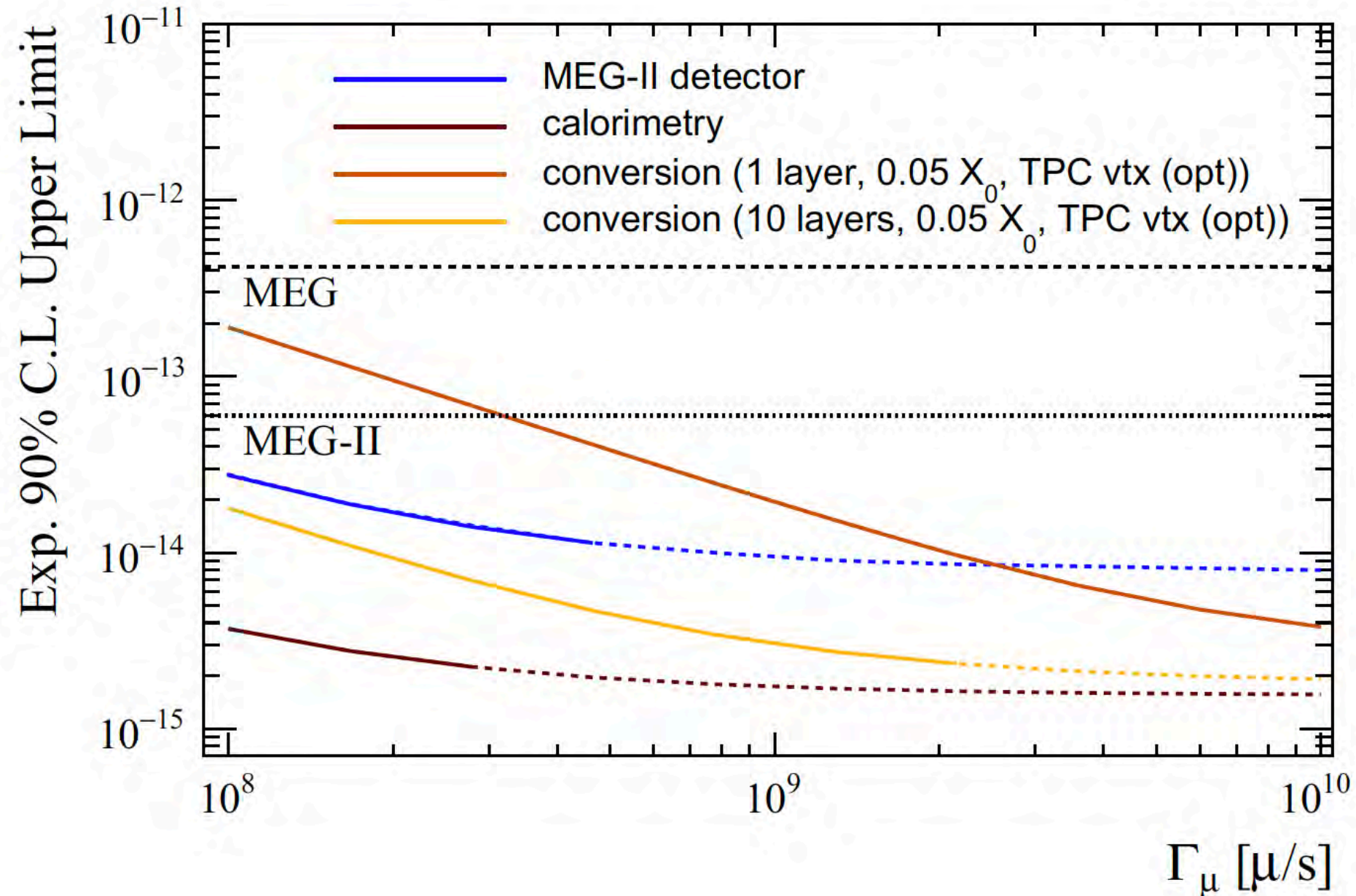
Conversion + tracking



- 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

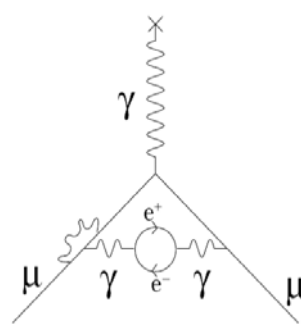
Observable	One photon conversion layer	Photon calorimeter
$T_{e\gamma}$ (ps)	60	50
E_e (keV)	100	100
E_γ (keV)	320	850
Efficiency (%)	1.2	42



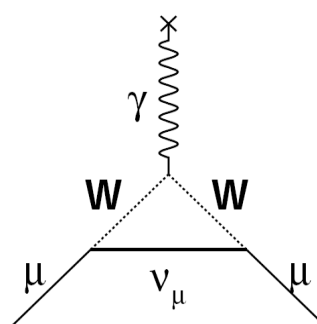
$g_\mu - 2$: Motivation

- 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: $a(\text{SM}) = a(\text{QED}) + a(\text{Had}) + a(\text{Weak}) + \mathbf{a(\text{NP})}$
- BNL E821 result: 3.3σ deviation from SM prediction

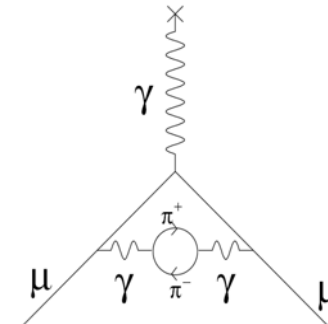
$$\mu = (1 + a_\mu) \frac{e\hbar}{2m} \quad a_\mu = \frac{g_\mu - 2}{2}$$



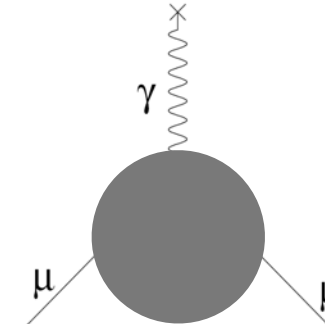
QED



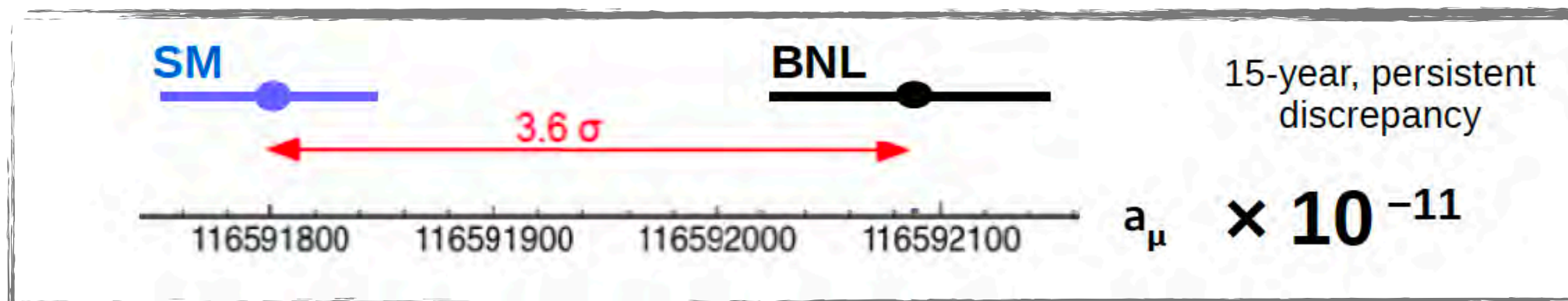
EW



QCD



UNKNOWN



$g_\mu-2$ in numbers and experimental approaches

Anomalous magnetic moment ($g-2$)

$$a_\mu = (g-2)/2 = 11\,659\,208.9\,(6.3) \times 10^{-10} \text{ (BNL E821 exp)} \quad \mathbf{0.5\,ppm}$$

$$11\,659\,182.8\,(4.9) \times 10^{-10} \text{ (standard model)}$$

$$\Delta a_\mu = \text{Exp} - \text{SM} = 26.1\,(8.0) \times 10^{-10} \quad \mathbf{3\sigma\,anomaly}$$

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

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

BNL E821 approach
 $\gamma=30$ ($P=3\text{ GeV}/c$)

J-PARC approach
 $E = 0$ at any γ

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

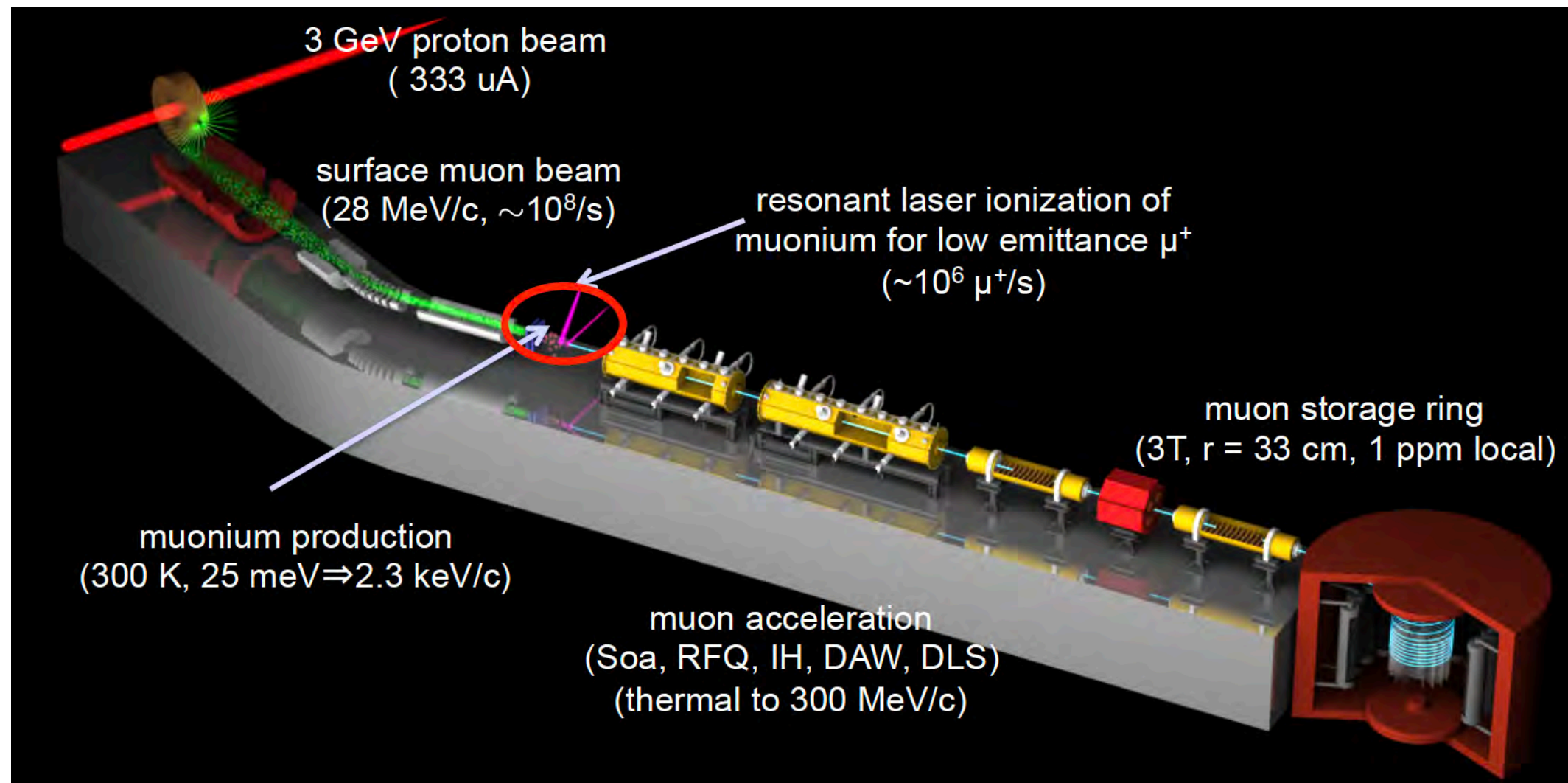
$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} (\vec{\beta} \times \vec{B}) \right]$$

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

$g_\mu - 2/EDM$ at J-PARC

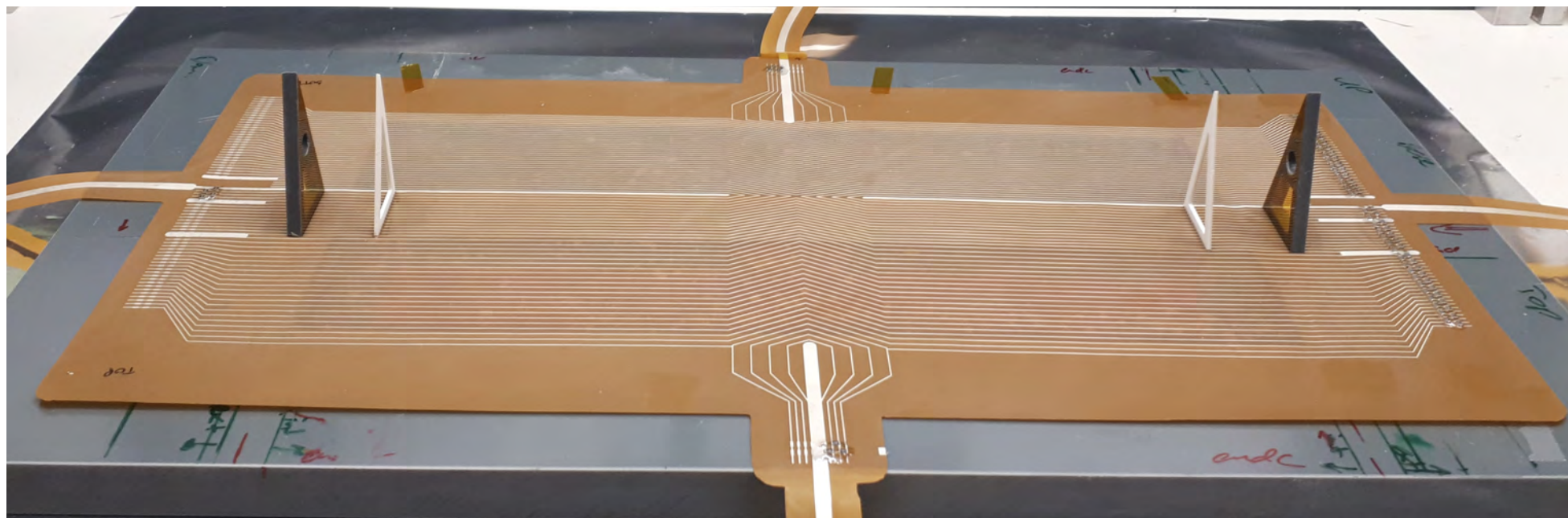
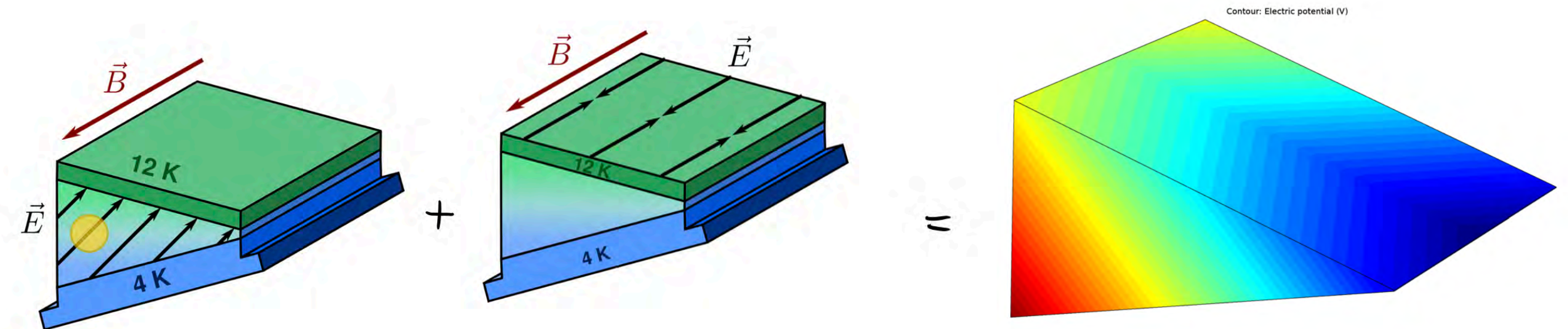
- Put $E = 0$;
- Weak B field focusing: Need low emittance cold muon
- Uniform tracker detector throughout stored orbit

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



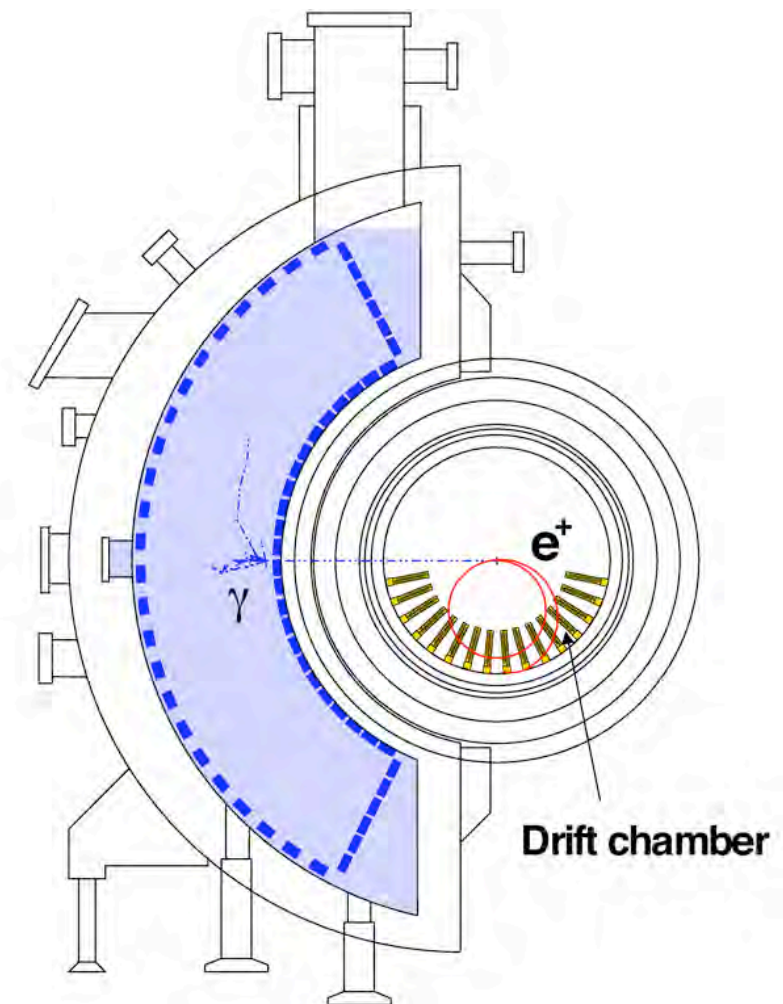
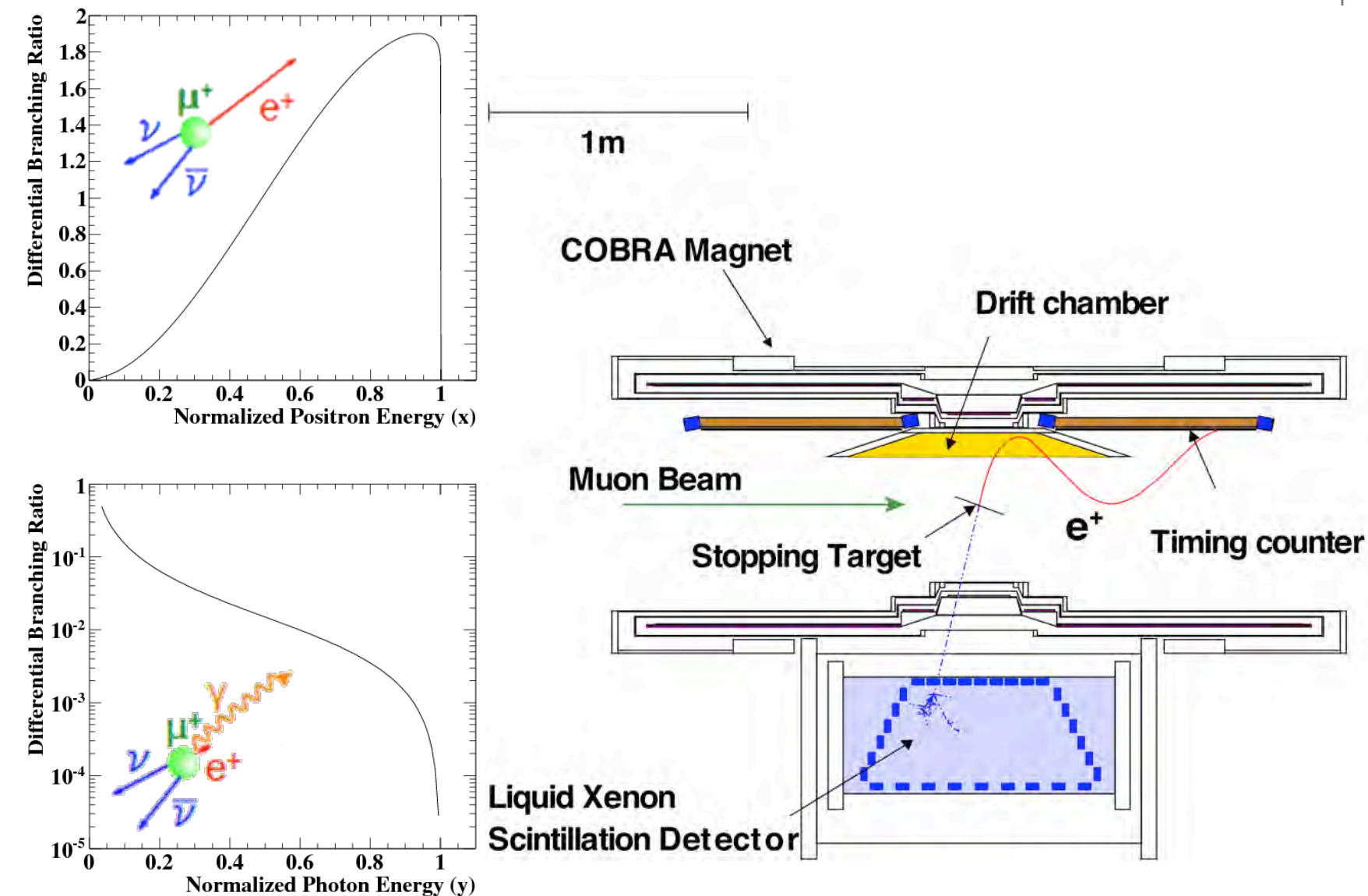
The muCool project at PSI: Status

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



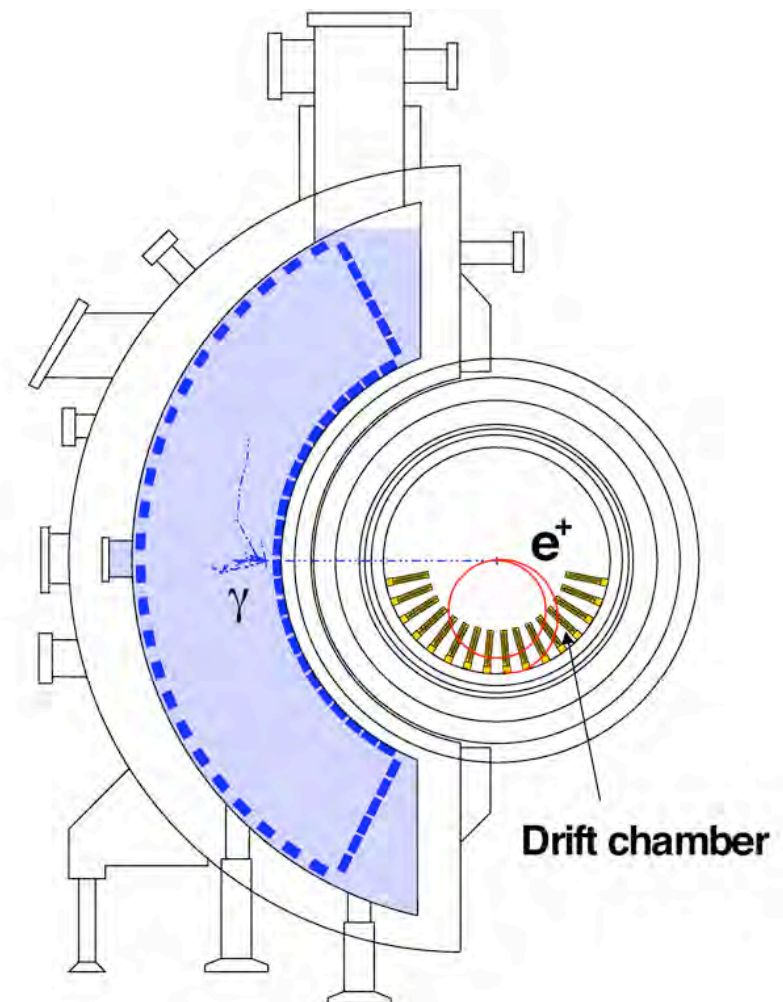
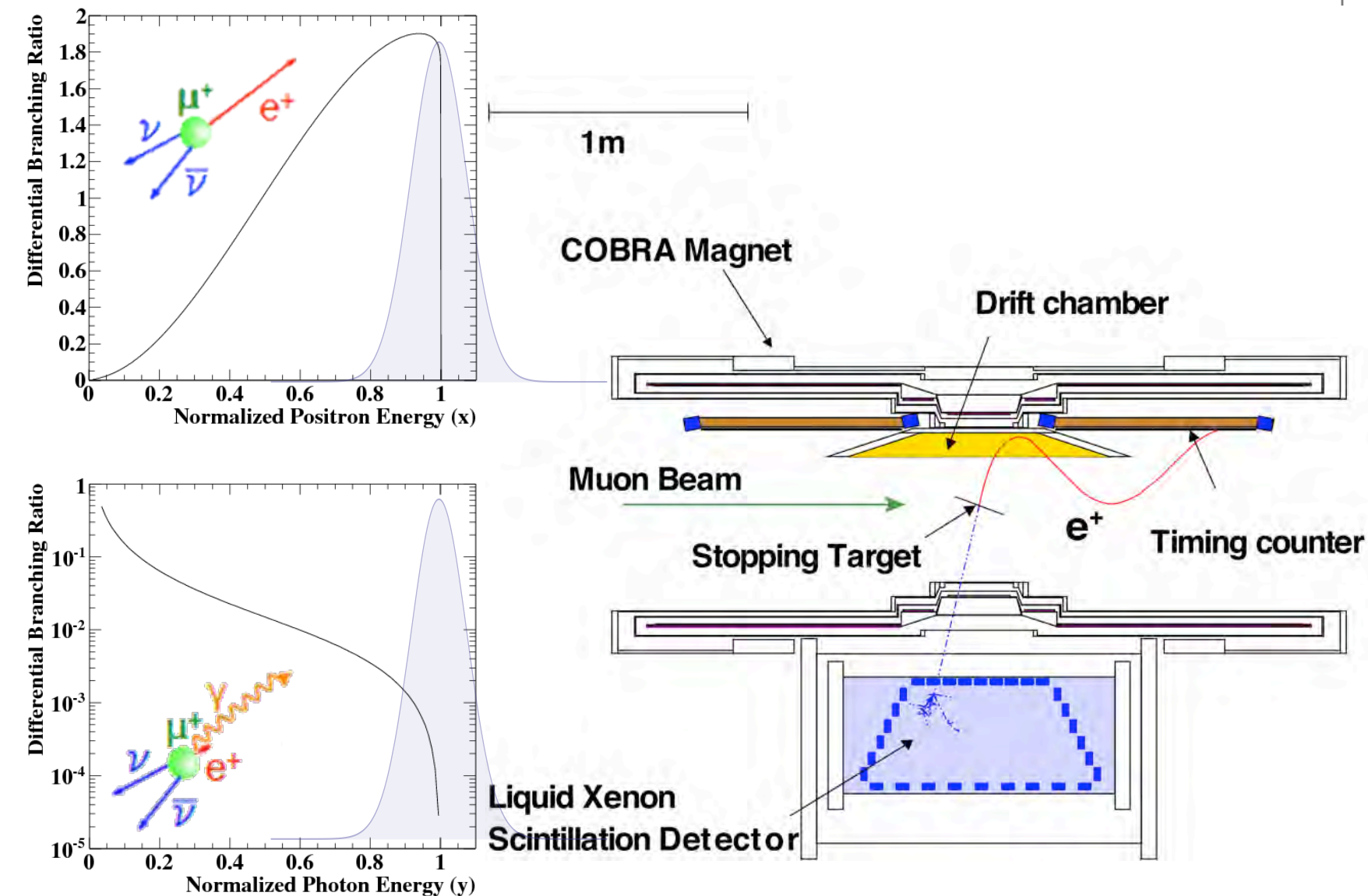
MEG: The key elements

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

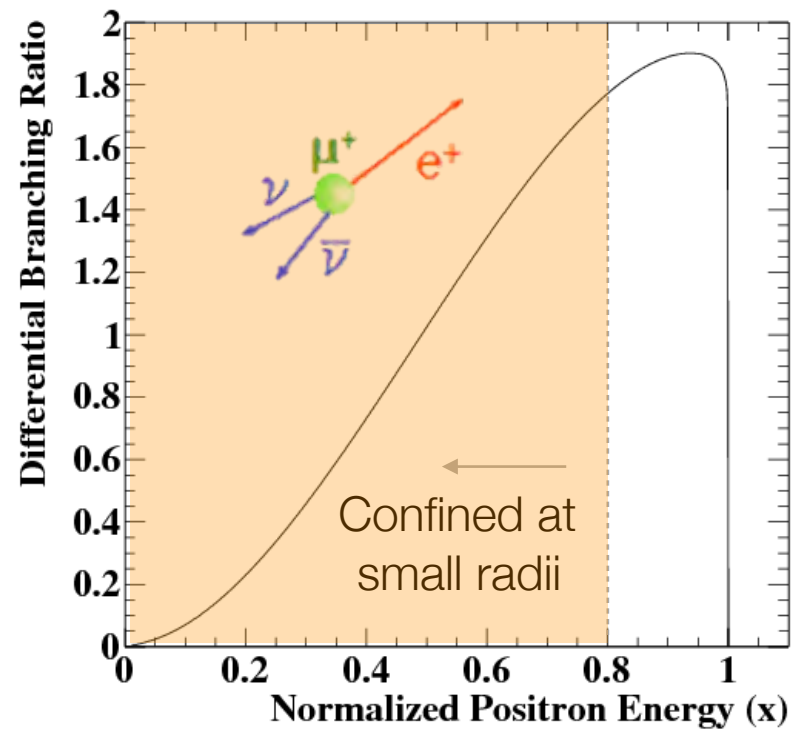


MEG: The key elements

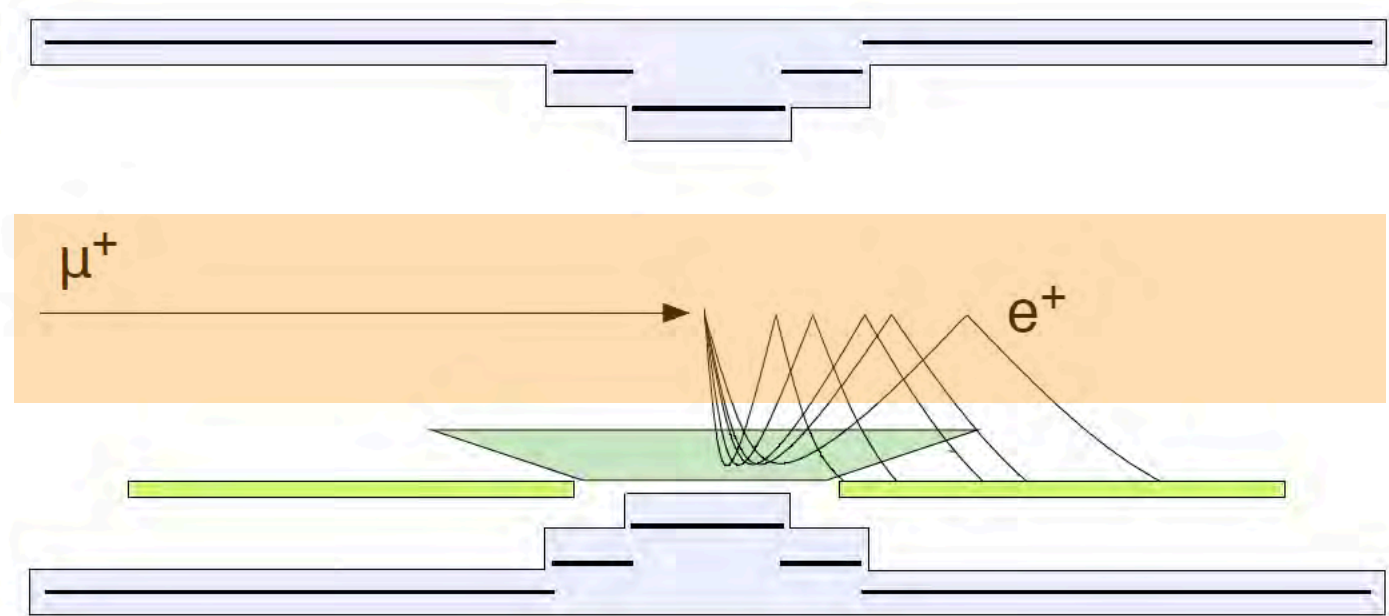
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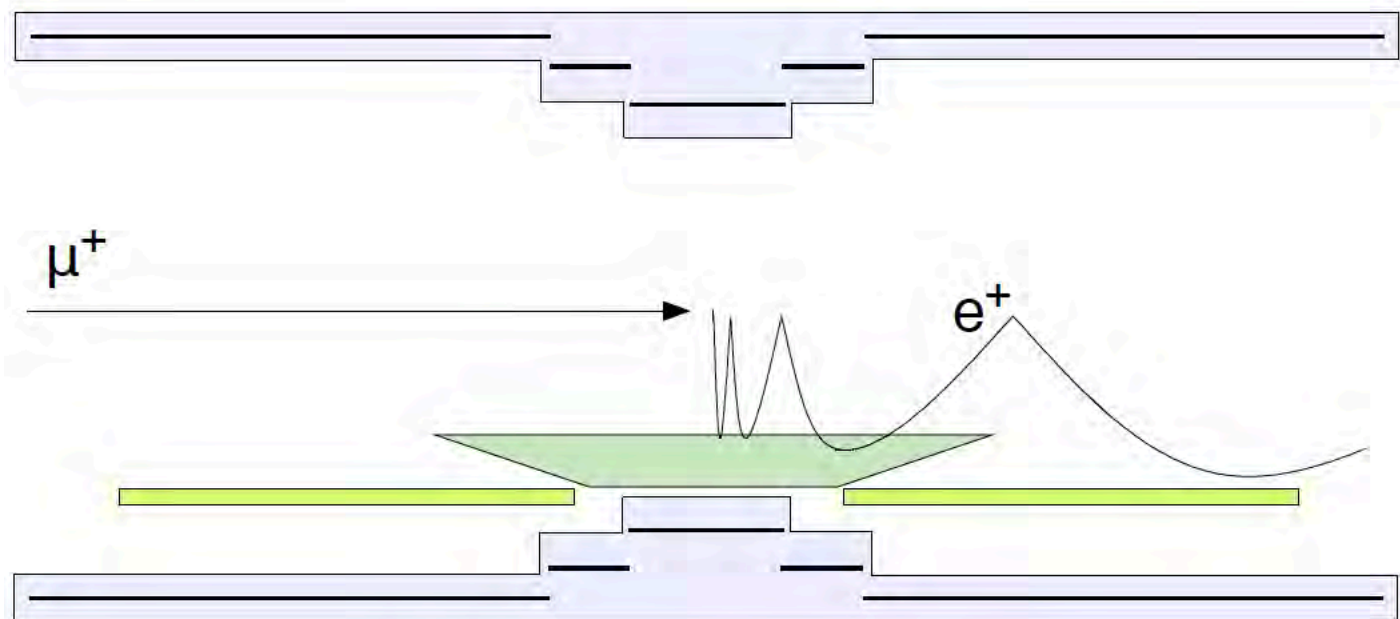
MEG: The spectrometer



- Low momentum positrons swept away without hitting the chambers
- Projected radius independent of the emission angle
- Very low material budget ($\sim 2 \cdot 10^{-3} X_0$)
- High momentum resolution ($\sigma_p \sim 315 \text{ keV}/c$), angular resolutions ($\sigma_\phi \sim 7.5 \text{ mrad}$, $\sigma_\theta \sim 10.6 \text{ mrad}$) and timing resolution ($\sigma_t \sim 100 \text{ ps}$) never reached up to now with a single detector at 52.8 MeV!



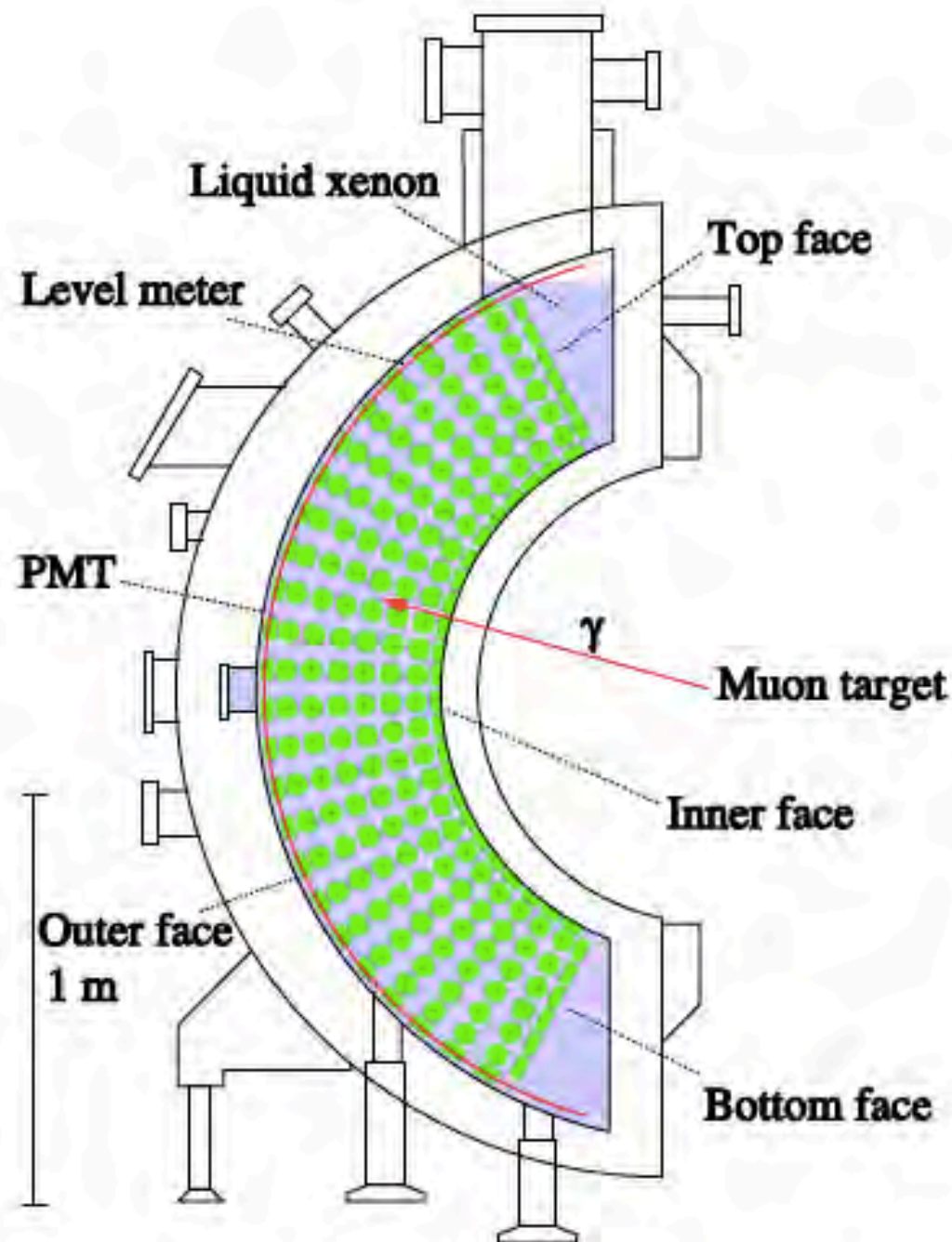
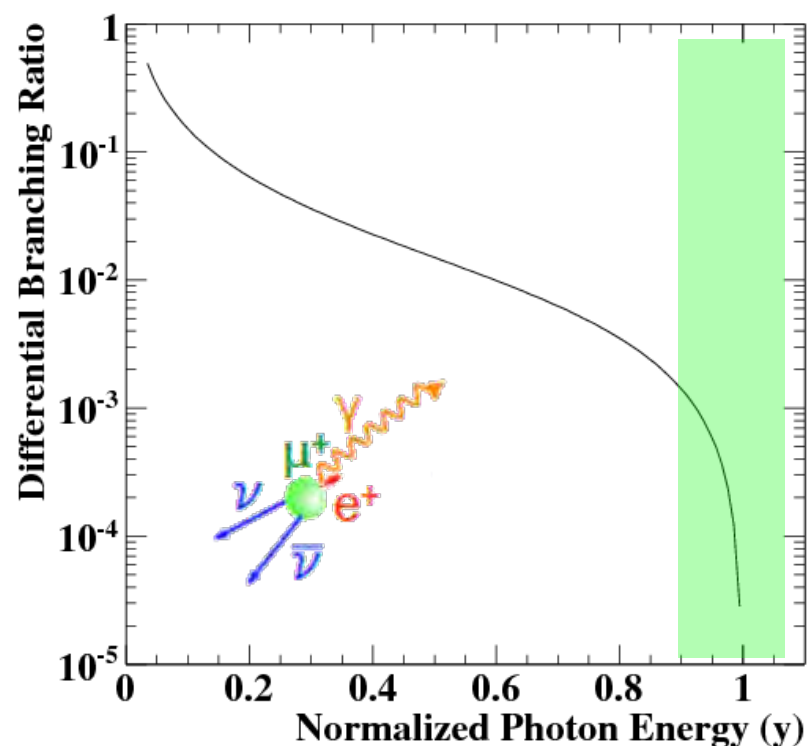
a) Constant projected bending radius for positrons with equal momentum.



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

MEG: The LXe calorimeter

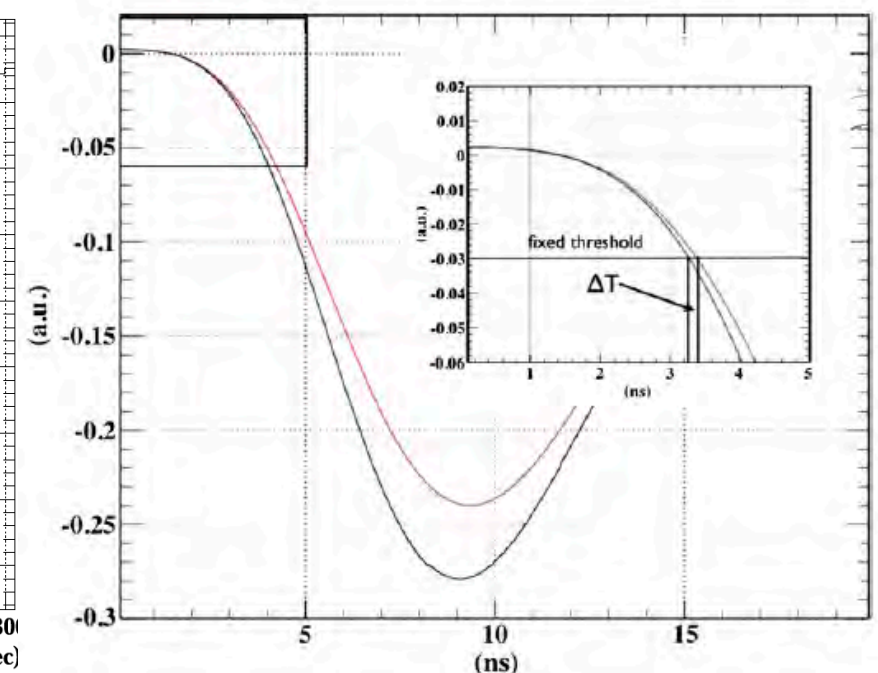
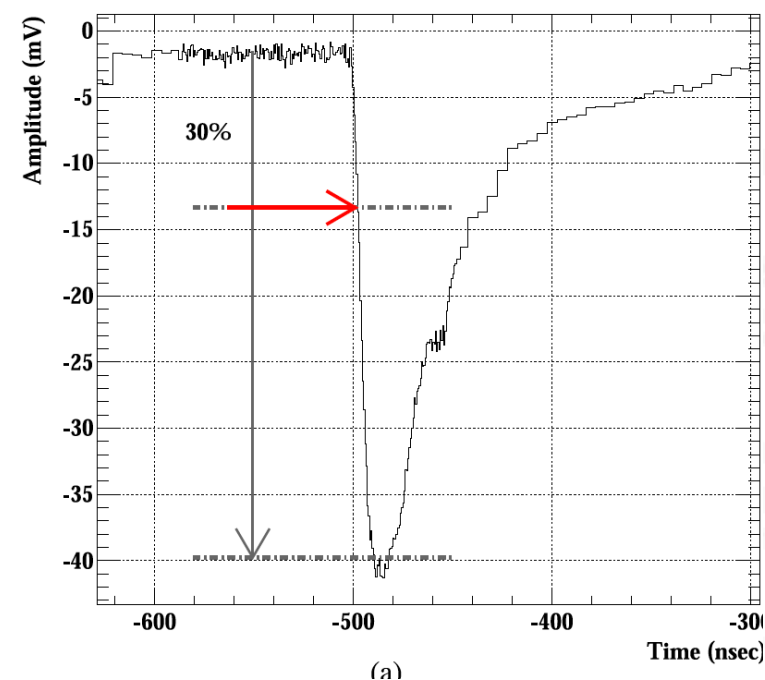
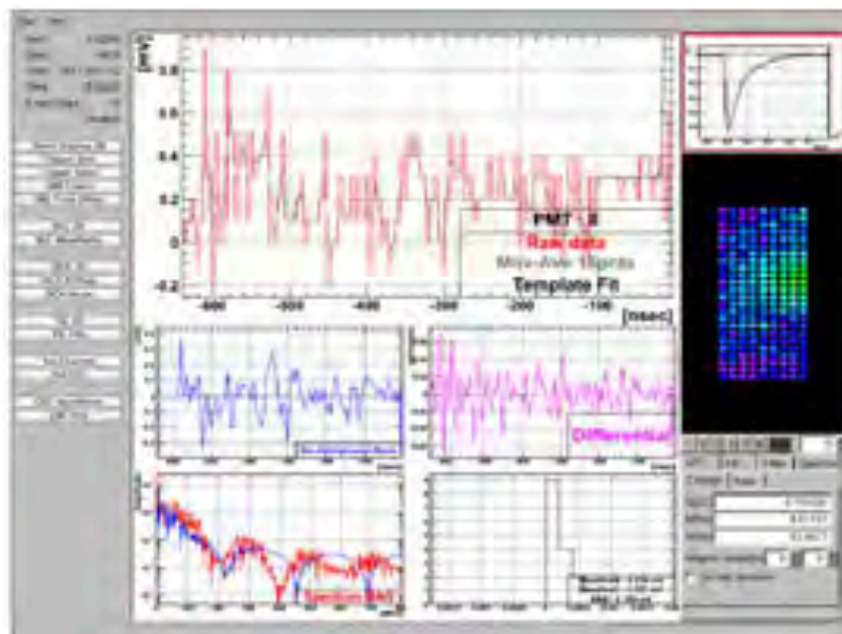
- High detection efficiency (High Z / Low X_0)
- High energy, timing and position resolutions (High LY, Fast time constants, High density, High photosensor coverage)
- Purity < 1 ppm and stable conditions over the time
- Particle ID
- Energy ($\sigma_E / E < 2.5\%$) and timing resolutions ($\sigma_t < 70$ 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
- $X_0 = 2.77 \text{ cm}$
- density = 2.95 g/cm^3
- $n = 1.65$
- $Z = 54$
- $R_M = 4.1 \text{ cm}$
- LY = 40000 ph/MeV
- Time constants = 4, 22 and 45 ns
- Particle Identification

MEG: The Data Acquisition (DAQ)

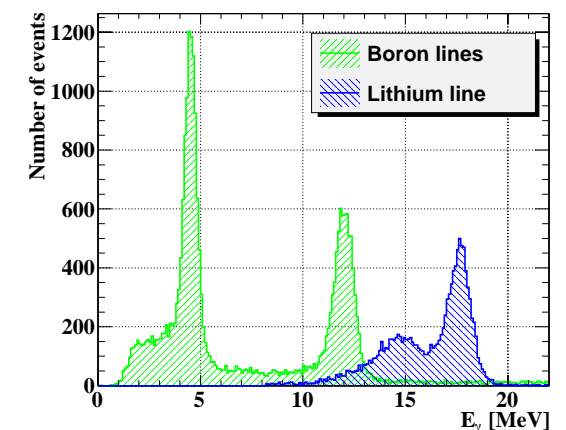
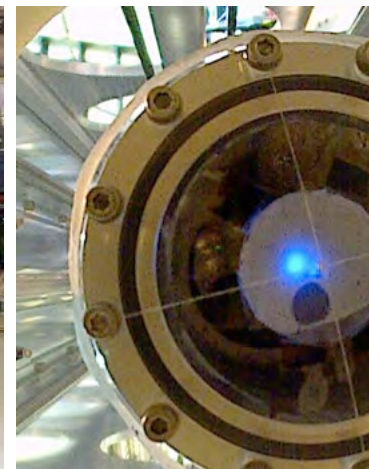
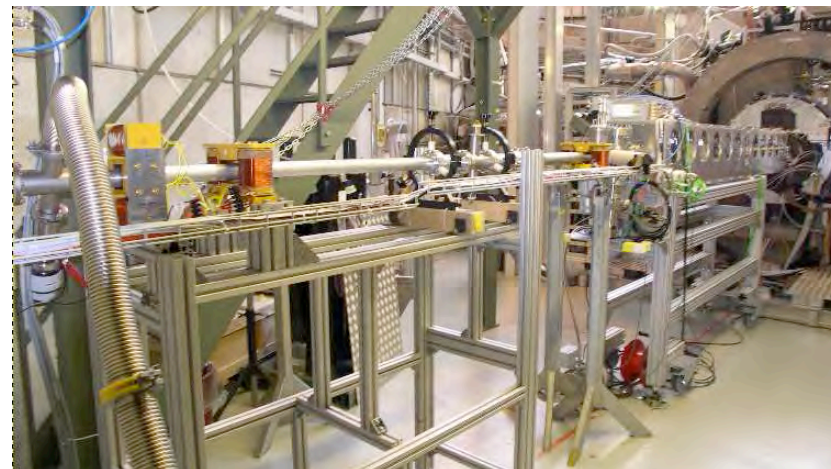
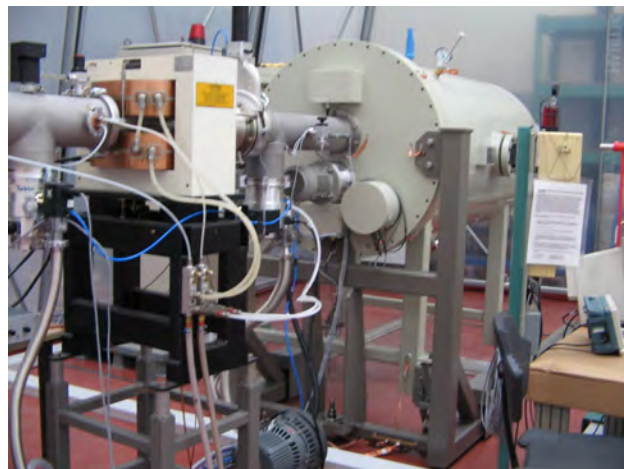
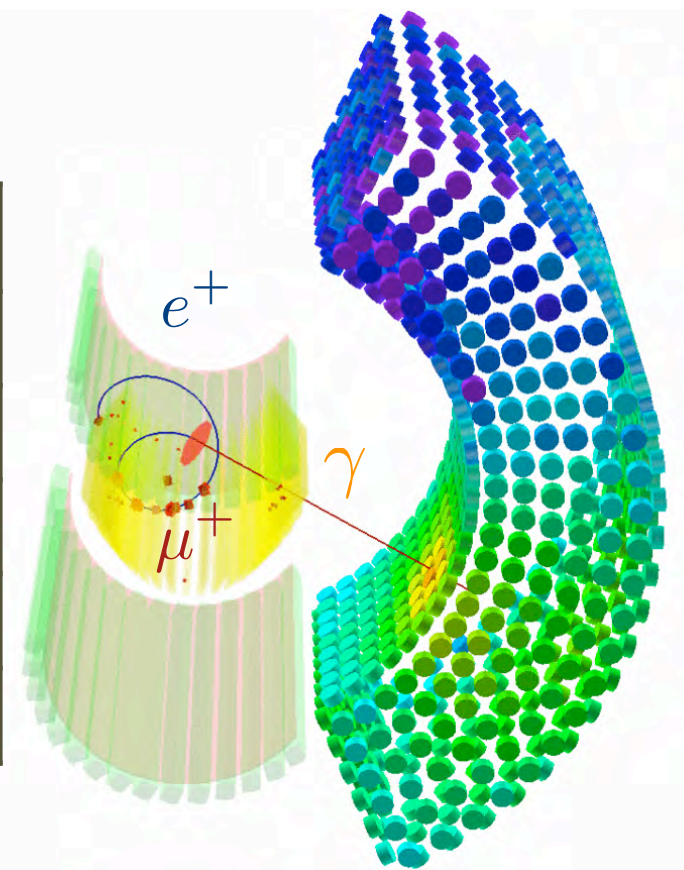
- Flexible and efficient trigger system, to select the candidate events, using fast detectors only
 - FADC digitization at 100 MHz
 - online selection algorithms implemented into FPGAs
- Domino Ring Sampler (DRS) chip for excellent pile-up rejection and timing resolutions with a full waveform digitization (> 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

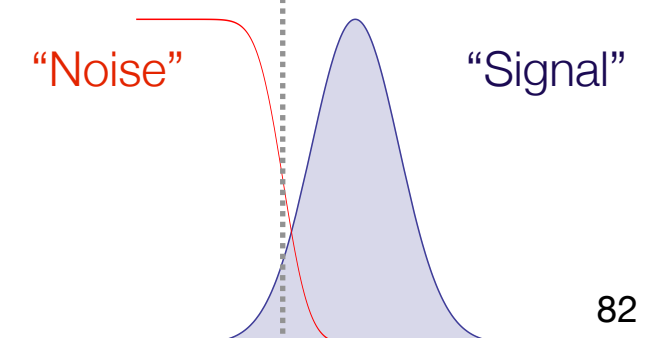
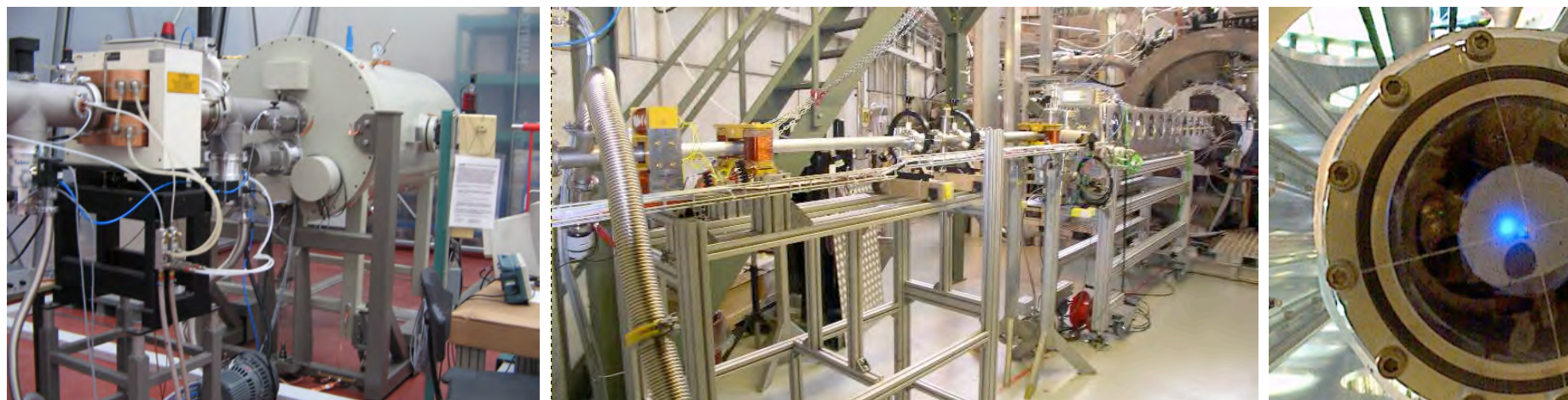
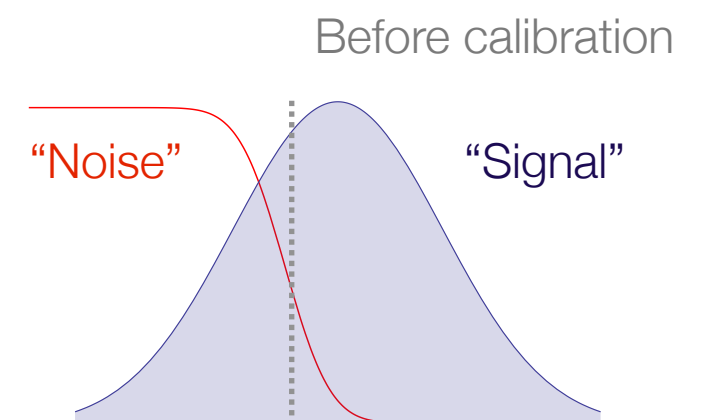
Process		Energy (MeV)	Frequency
CEX reaction	$p(\pi^-, \pi^0)n, \pi^0 \rightarrow \gamma\gamma$	55, 83	annually
C-W accelerator	${}^7\text{Li}(p, \gamma_{17.6}){}^8\text{Be}$	17.6	weekly
	${}^{11}\text{B}(p, \gamma_{11.6}){}^{12}\text{C}$	4.4&11.6	weekly
Neutron Generator	${}^{58}\text{Ni}(n, \gamma_9){}^{59}\text{Ni}$	9	daily
Mott Positrons	$p(e^+, e^+)p$	53	annually



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cLFV search landscape

● Muons ~ 250

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

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



● Taus ~ 250

- BABAR, PEP-II
- BELLE/BELLE II, KEKB/SuperKEKB

● Kaons ~ 100

- NA48, CERN
- NA62, CERN
- KOTO, J-PARC

● cLFV @ LHC ~ 250

- ATLAS, CERN
- CMS, CERN
- LHCb, CERN

● J/ψ @ BEPCII ~ 100

- BESIII, Beijing

cLFV best upper limits

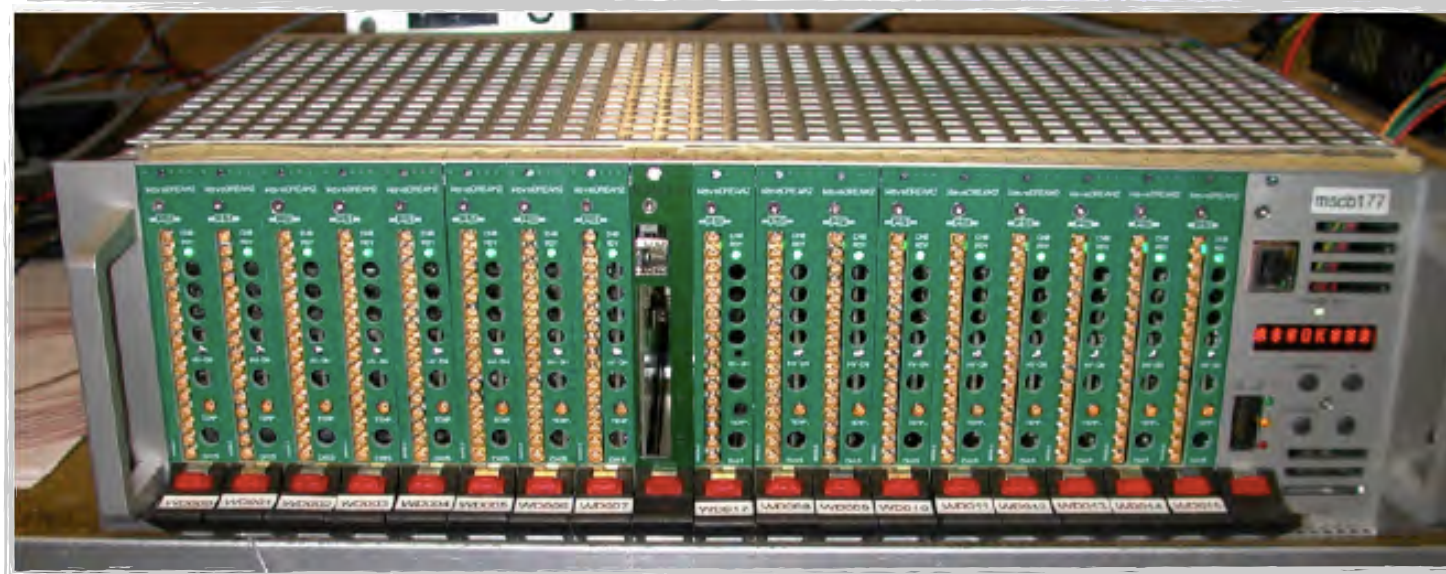
Process	Upper limit	Reference	Comment
$\mu^+ \rightarrow e^+ \gamma$	4.2×10^{-13}	arXiv:1605.05081	MEG
$\mu^+ \rightarrow e^+ e^+ e^-$	1.0×10^{-12}	Nucl. Phys. B299 (1988) 1	SINDRUM
$\mu^- N \rightarrow e^- N$	7.0×10^{-13}	Eur. Phys. J. C 47 (2006) 337	SINDRUM II
$\tau \rightarrow e \gamma$	3.3×10^{-8}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

* $B(H \rightarrow \mu e) < O(10^{-8})$ from $\mu \rightarrow e \gamma$ 84

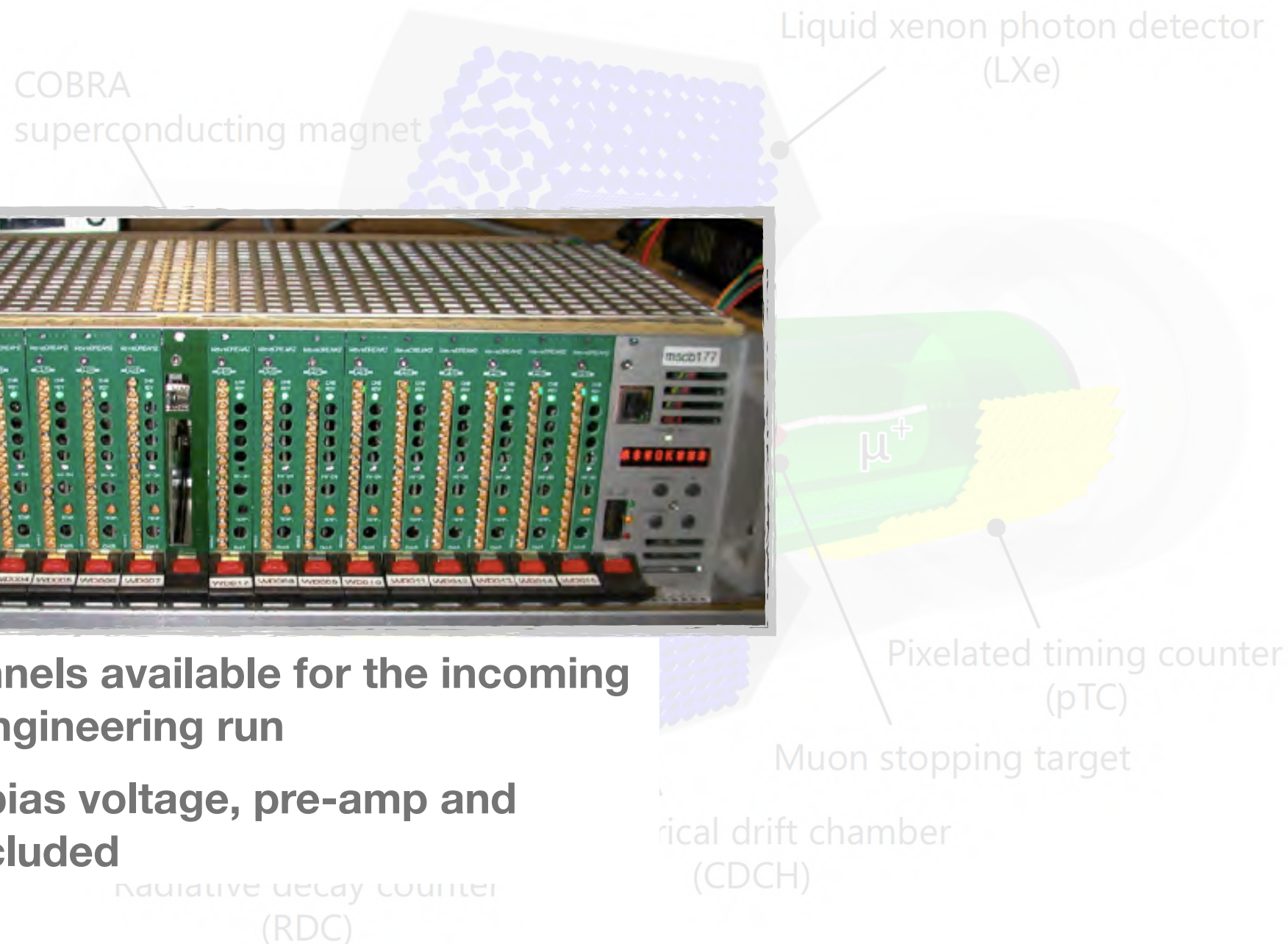
The MEGII experiment: Status

New electronics:
Wavedream

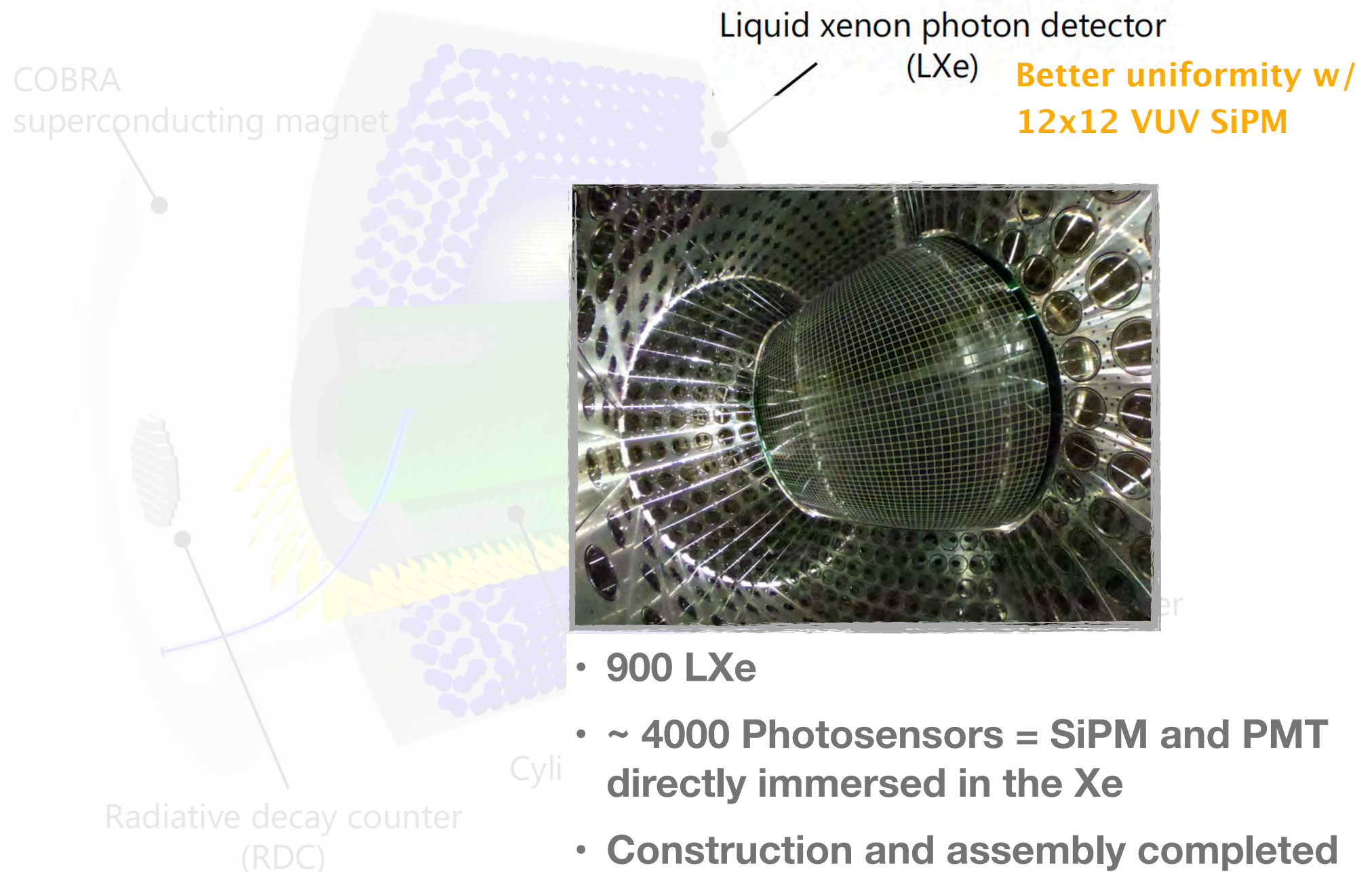
~9000
channels
at 5GSPS



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

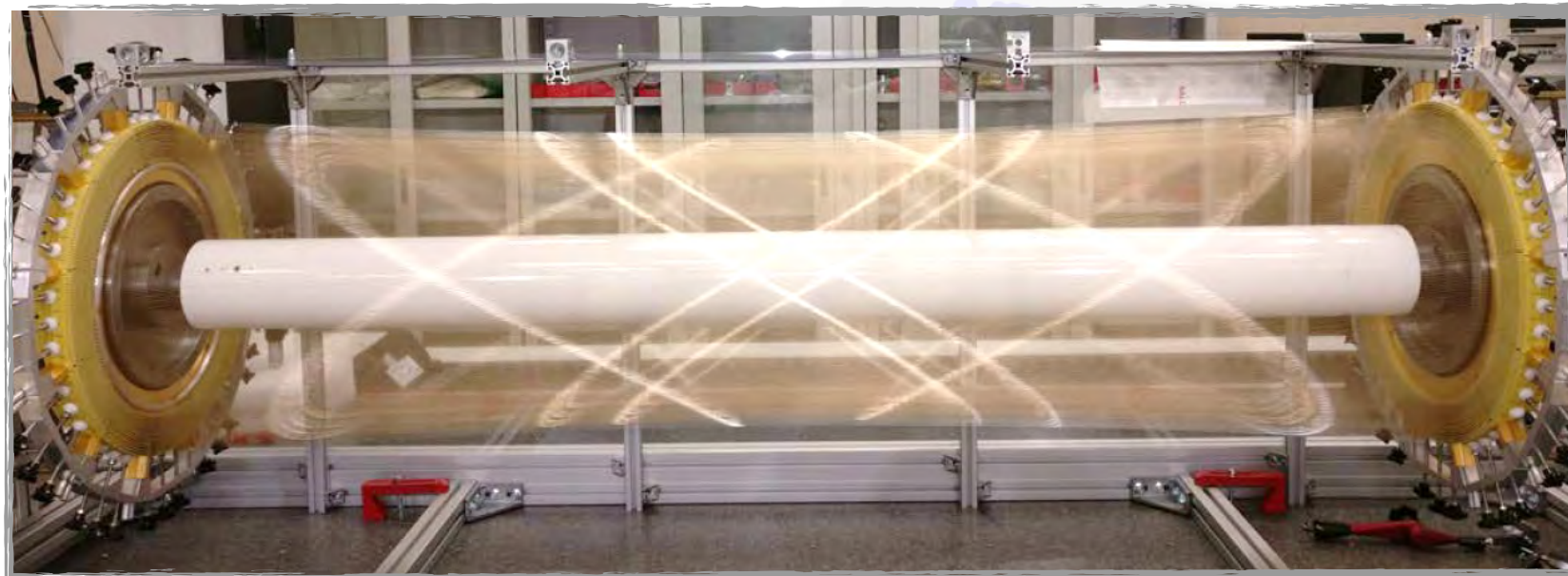


The MEGII experiment: Status



- 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

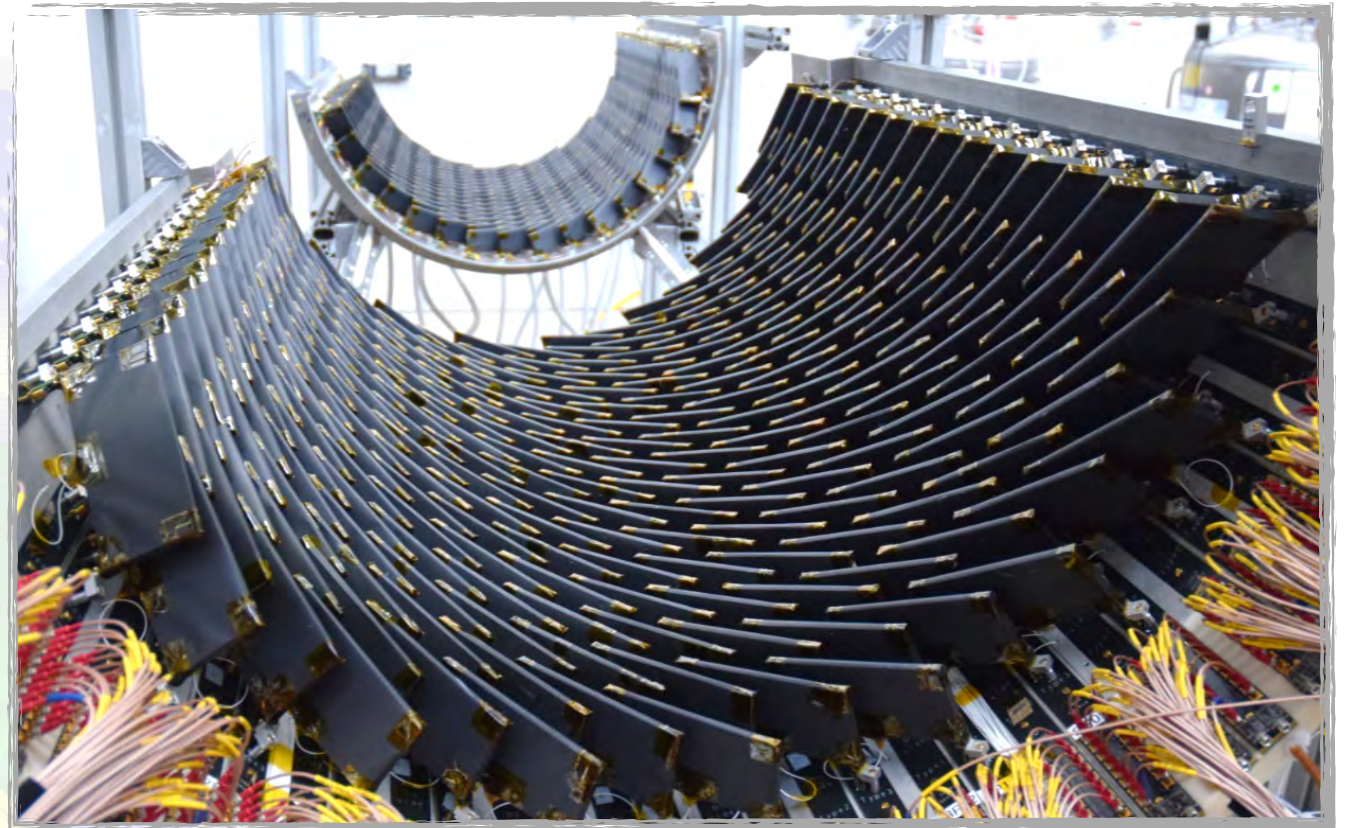
Radiative decay counter
(RDC)

Cylindrical drift chamber
(CDCH)

Single
volume
He:iC₄H₁₀

The MEGII experiment: Status

COBRA
superconducting magnet



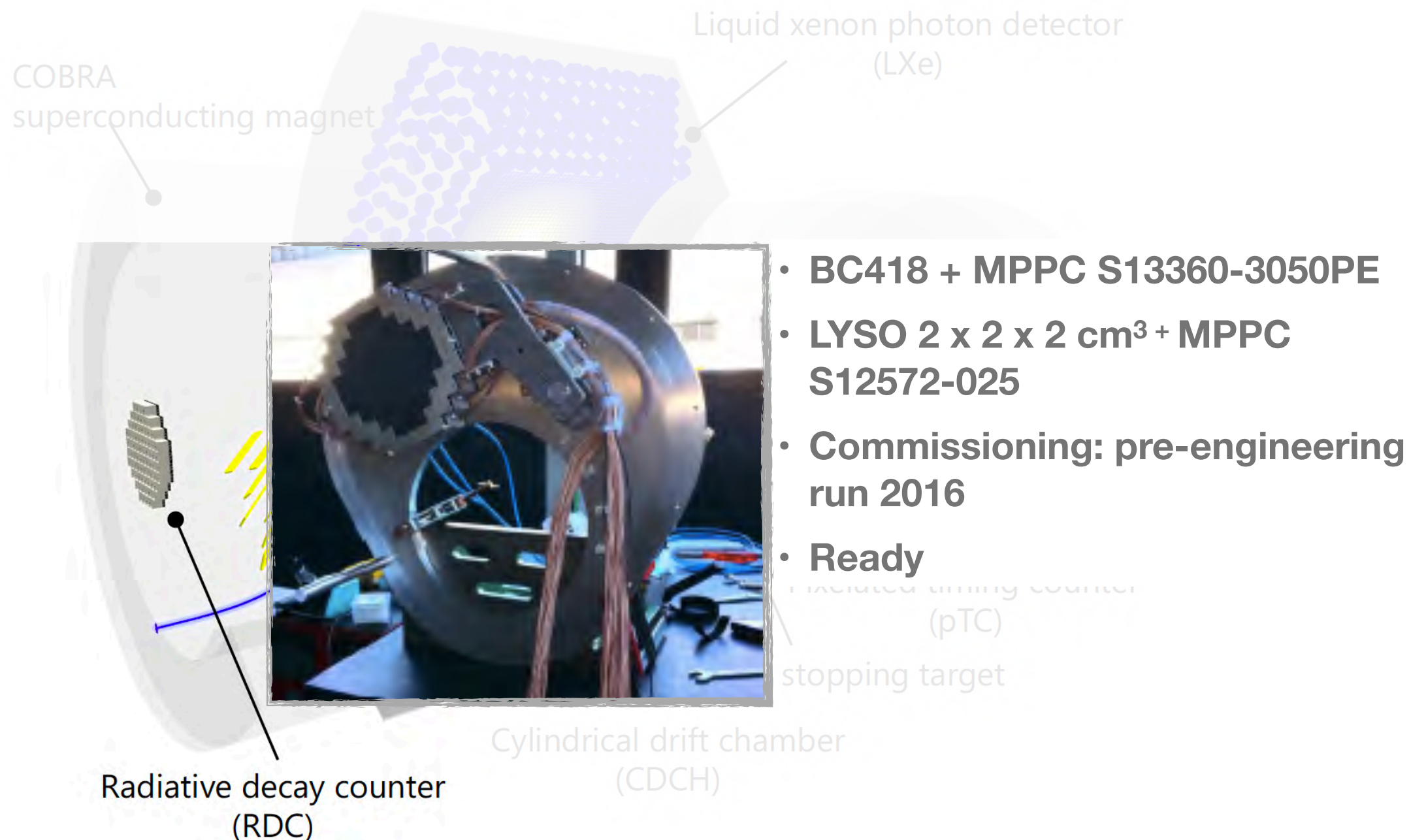
Pixelated timing counter (pTC) **35 ps resolution
w/ multiple hits**

Radiative decay counter
(RDC)

Cylir

- 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm³) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain
- Full detector: Commissioning phase

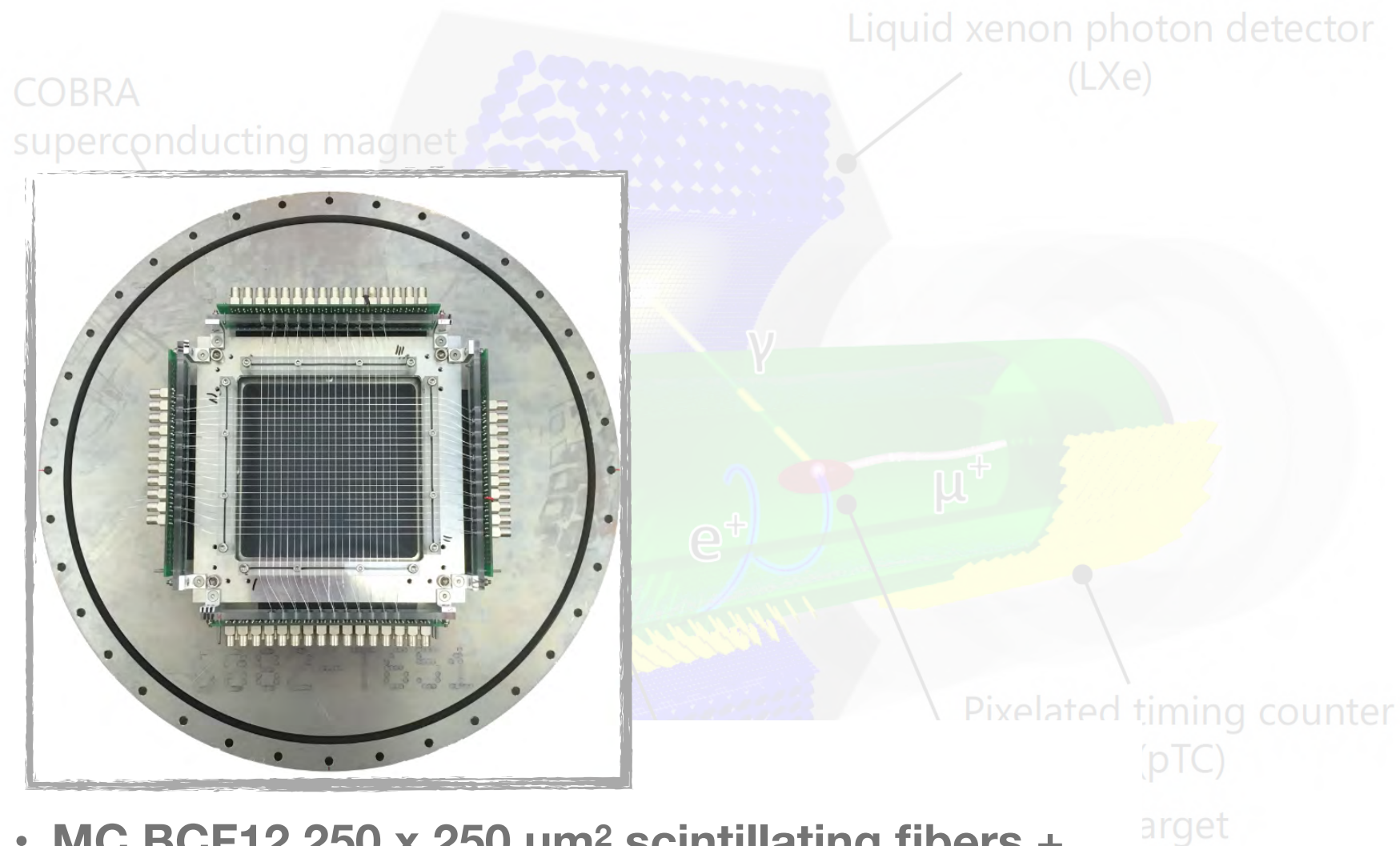
The MEGII experiment: Status



- **BC418 + MPPC S13360-3050PE**
- **LYSO 2 x 2 x 2 cm³ + MPPC S12572-025**
- **Commissioning: pre-engineering run 2016**
- **Ready**

Background rejection

The MEGII experiment: Status



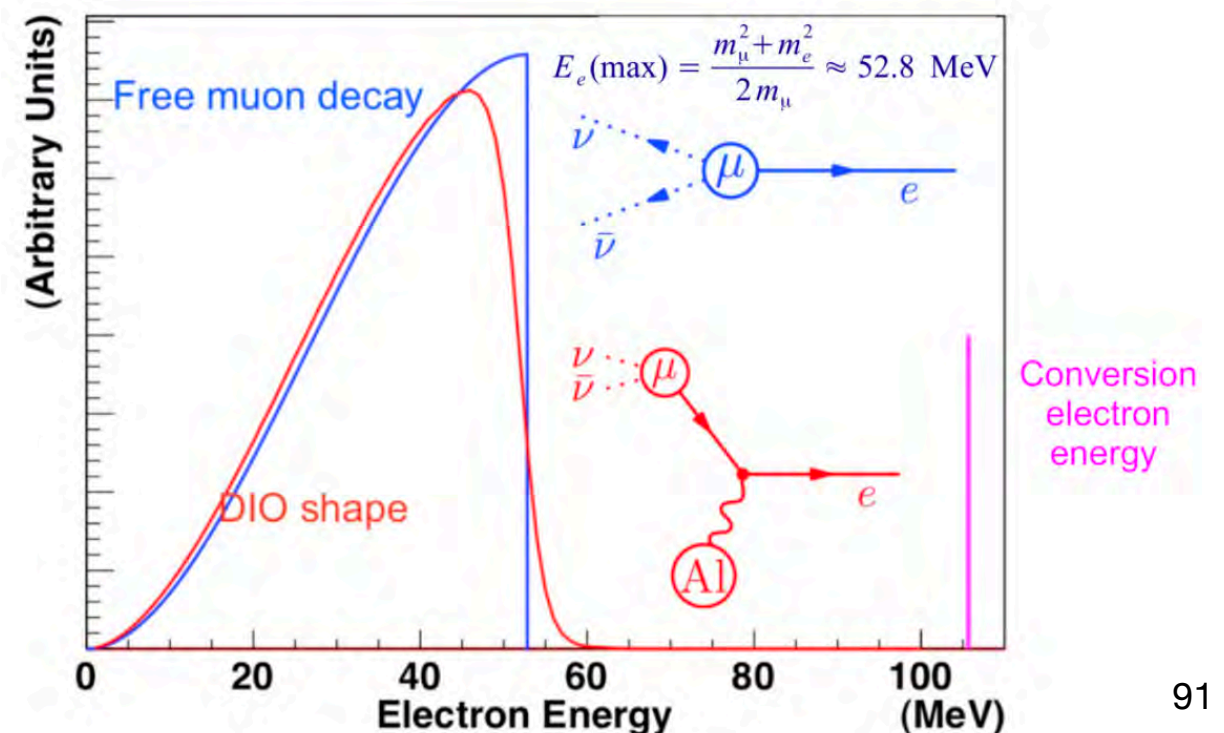
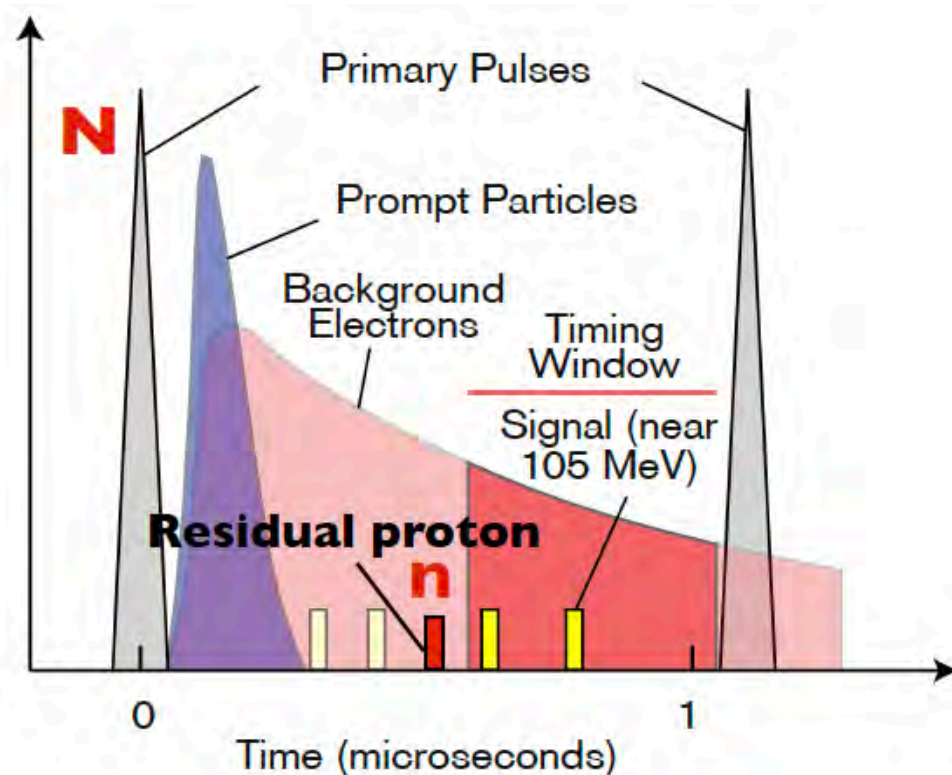
Updated and
new Calibration
methods
**Quasi mono-
chromatic
positron beam**

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

$\mu^- N \rightarrow e^- N$ experiments

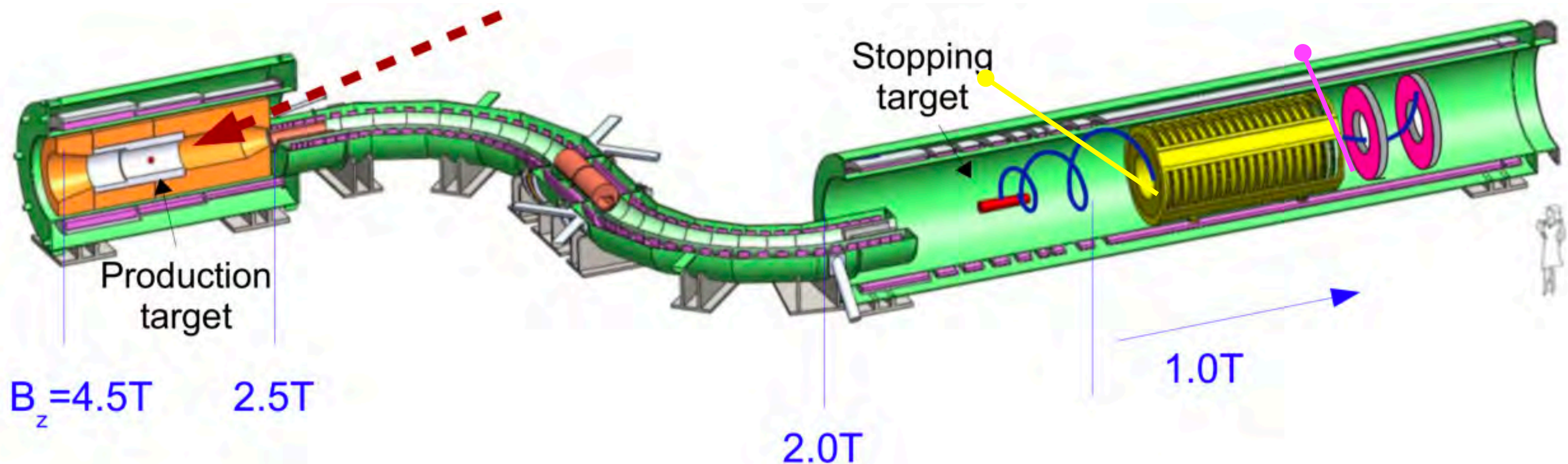
$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)}$$

- 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]

