Searching for New Physics at the intensity frontier

(at low energies with lots of particles)

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Heidelberg Graduate Days
Heidelberg, April 2018

JG|U

Emmy
Noether-
Programm

Deutsche
Forschungsgemeinschaft
DFG

Overview

Why and where to search for new physics:

- Triumph and tragedy of the Standard Model

Proton decay:

- Watching lots of water

Proton radius, neutron lifetime:

- Puzzling discrepancies

Muon magnetic moment:

- Measuring and calculating at the precision limit

The electric dipole moment of the neutron:

- Particles in a bottle

The weak mixing angle:

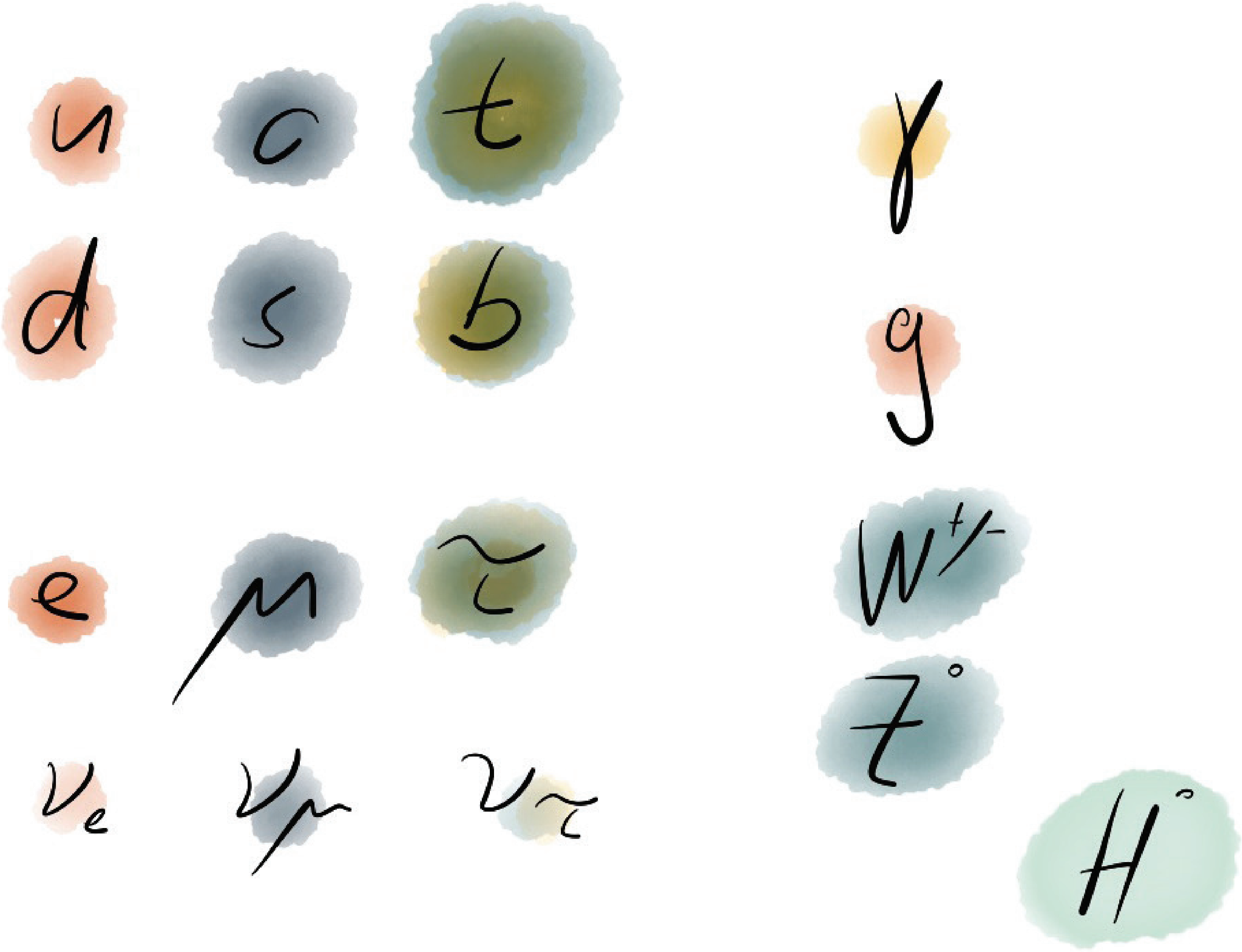
- New Physics in tiny differences between left- and right-handed

Important warnings

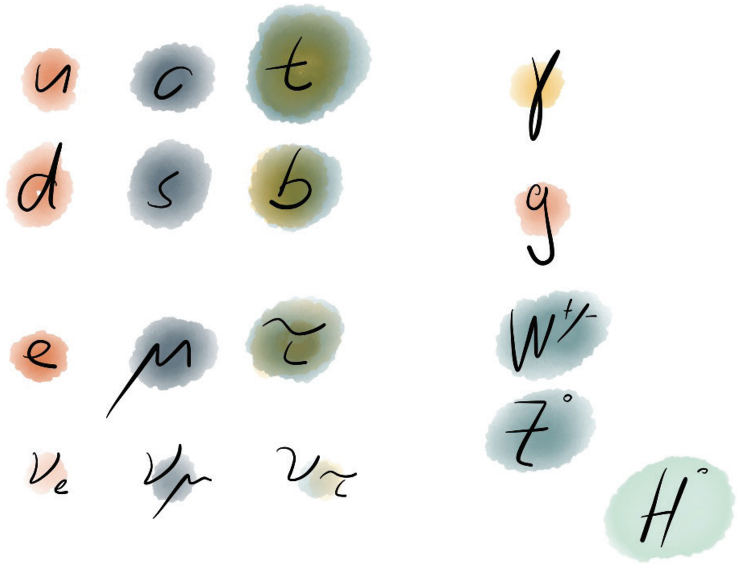
- This is a very vibrant field, I will talk about a lot, but there is much more I will not talk about…
- The selection is very biased: Experiments I like, experiments I am part of, experiments I understand (hopefully with some overlap)
- I am a member of the Mu3e, P2 and BESIII collaborations
- For most other experiments, I "borrowed" material from many colleagues hopefully mostly indicated - if forgotten, sincere apologies, anyway thanks to all of them
- If you want to read a book, get Roberts/Marciano: Lepton Moments (only 400 something Euros - ask your library)

Particle Physics:
What are the fundamental constituents of matter and how do they interact?

The Standard Model of Elementary Particles



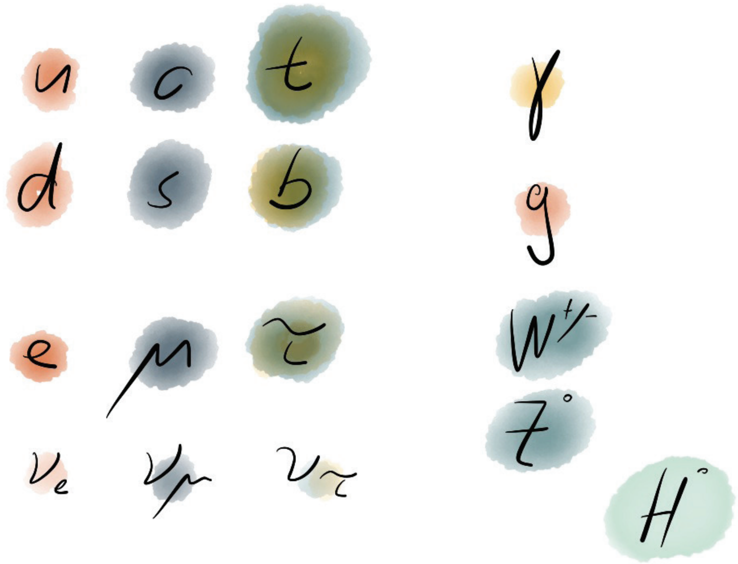
The Standard Model of Elementary Particles



Quantum field theory

- 12 fermion fields constitute matter
- SU(3) x SU(2) x U(1) gauge group providing interactions
- Broken to SU(3) x U(1) by the Higgs mechanism
- All degrees of freedom have been observed and behave mostly as expected

Hugely successful



Magnetic moment of the electron:

- Theory:

  g_e = -2.002 319 304 363 56 (154)

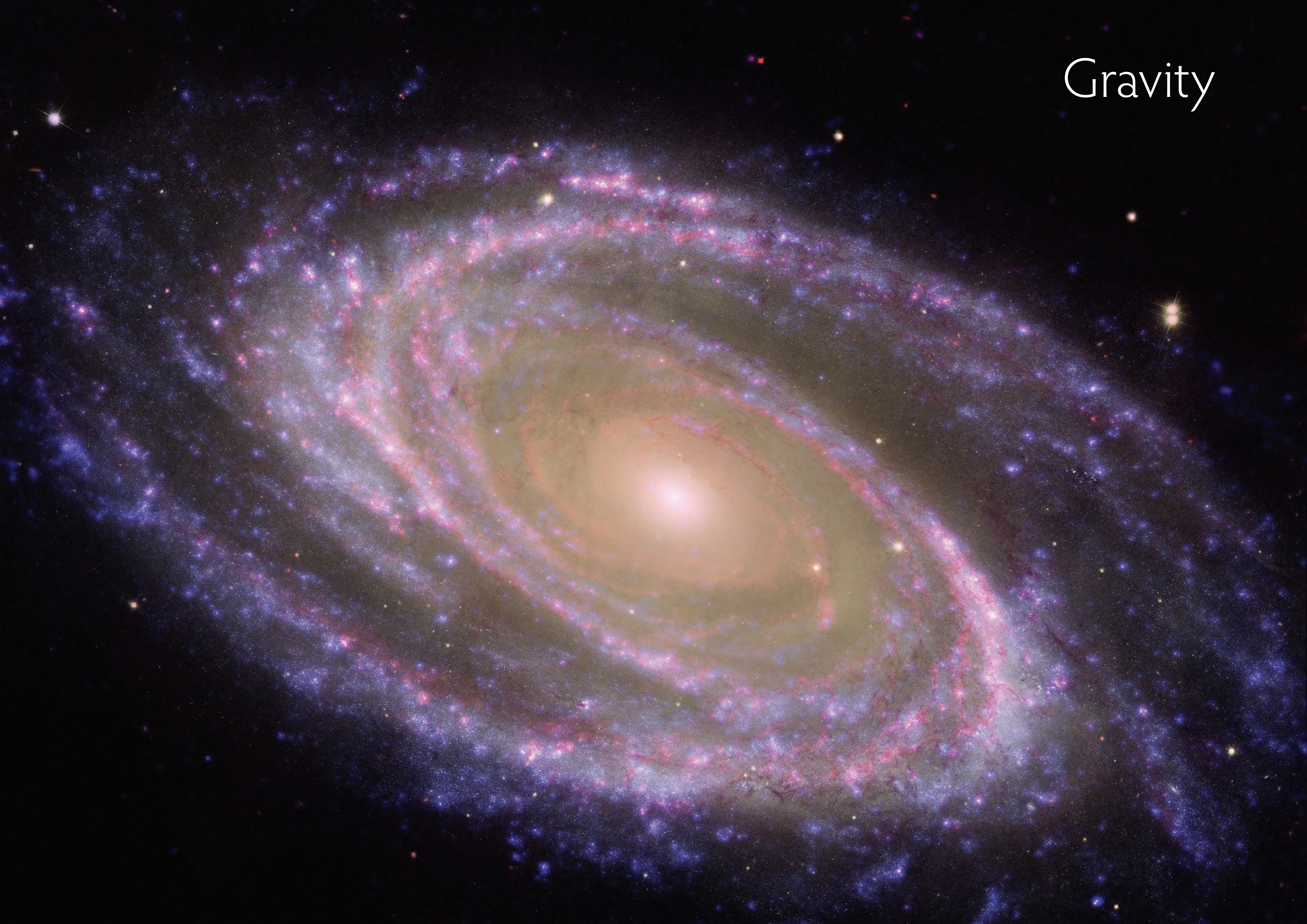
  (Aoyama et al., PRL 109, 111807 (2012))

- Experiment:

  g_e = - 2.002 319 304 361 53 (53)

  (Hanneke et al. PRL 100, 120801 (2008))

Open Questions?

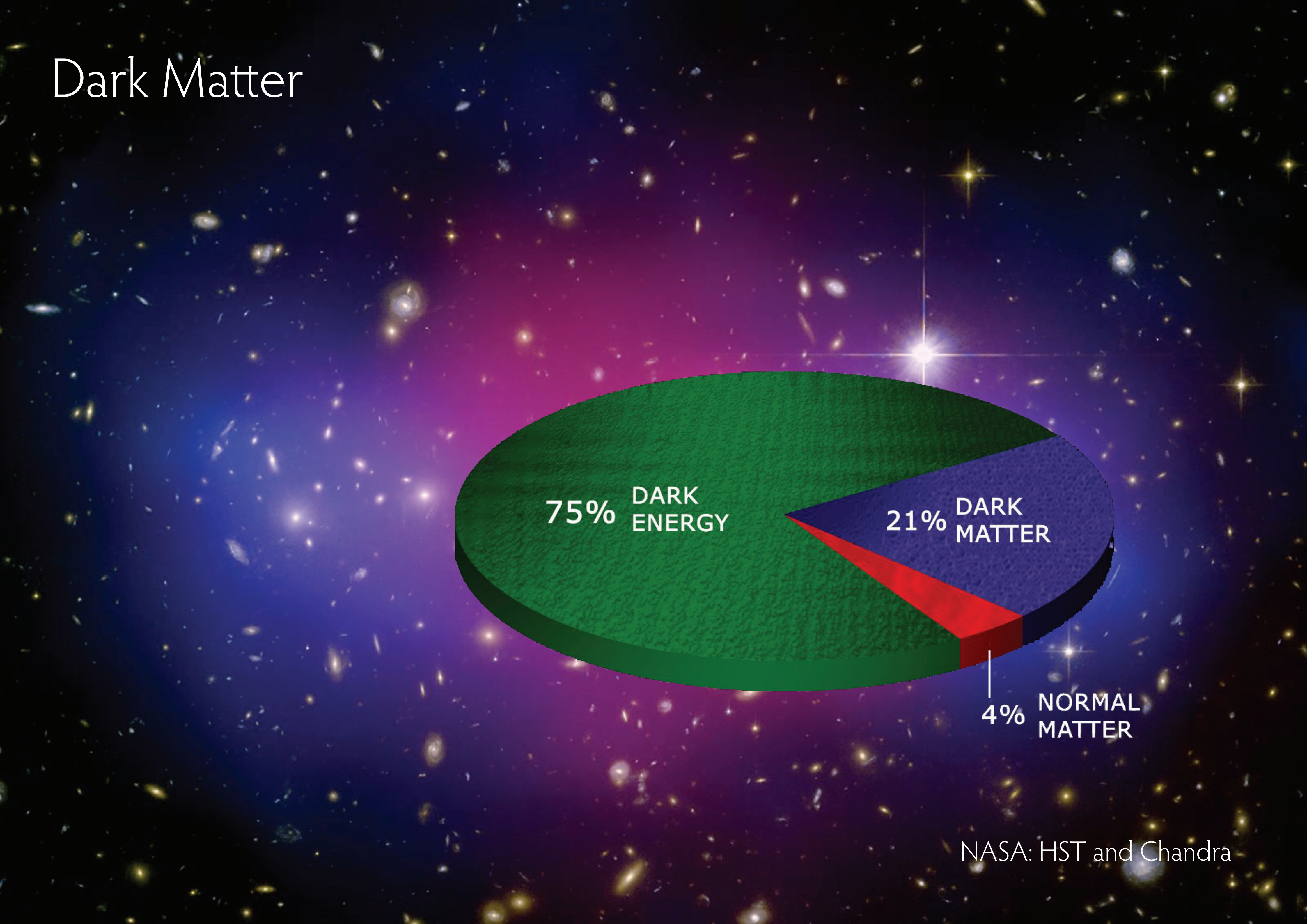


Gravity

Dark Matter

NASA: HST and Chandra

Dark Matter



NASA: HST and Chandra

Matter-Antimatter Asymmetry

10’000’000’000

Antimatter

10’000’000’001

Matter

Matter-Antimatter Asymmetry

Radiation

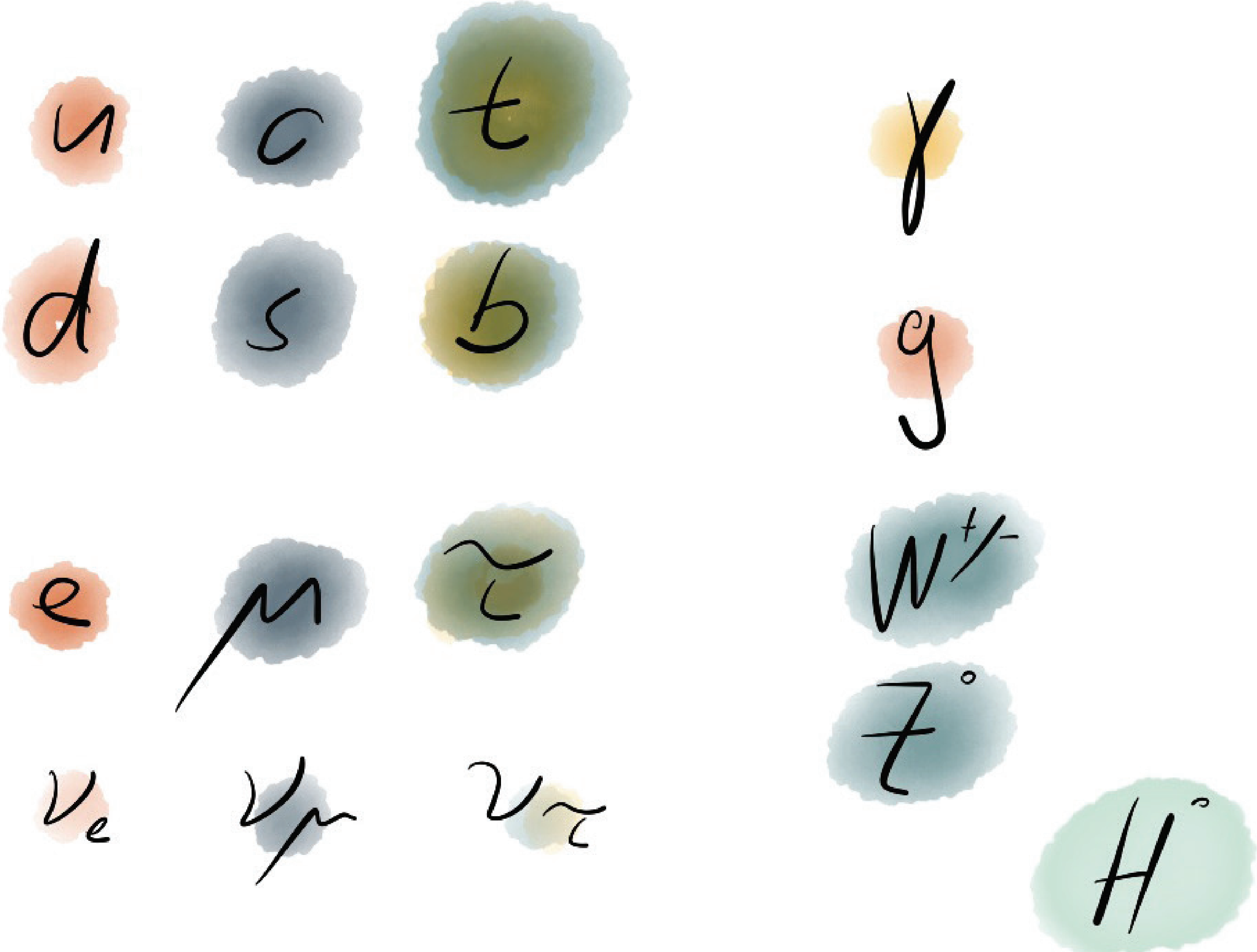
■

1

Us

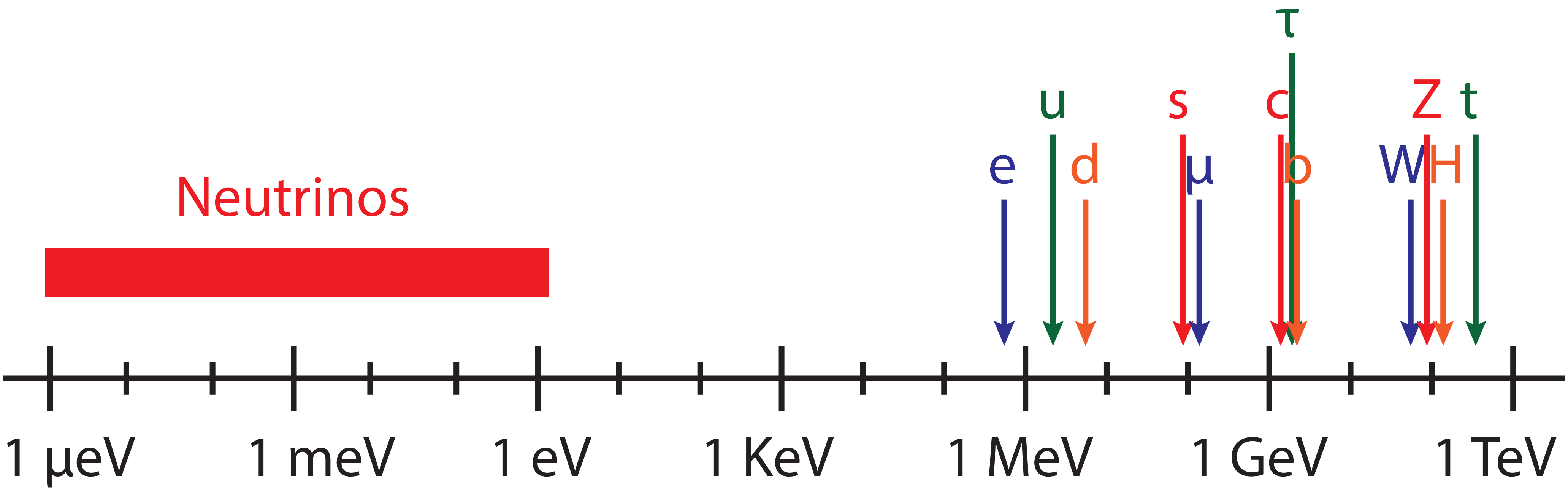
Sakharov-Criteria

The Structure of the Standard Model

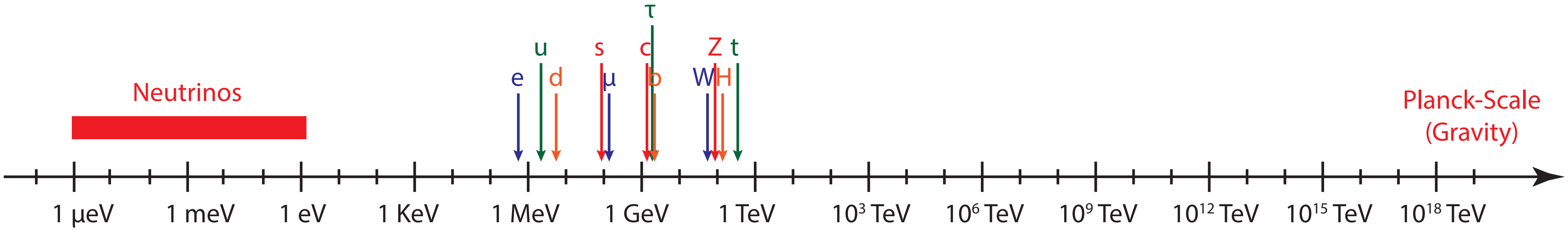


26 free parameters

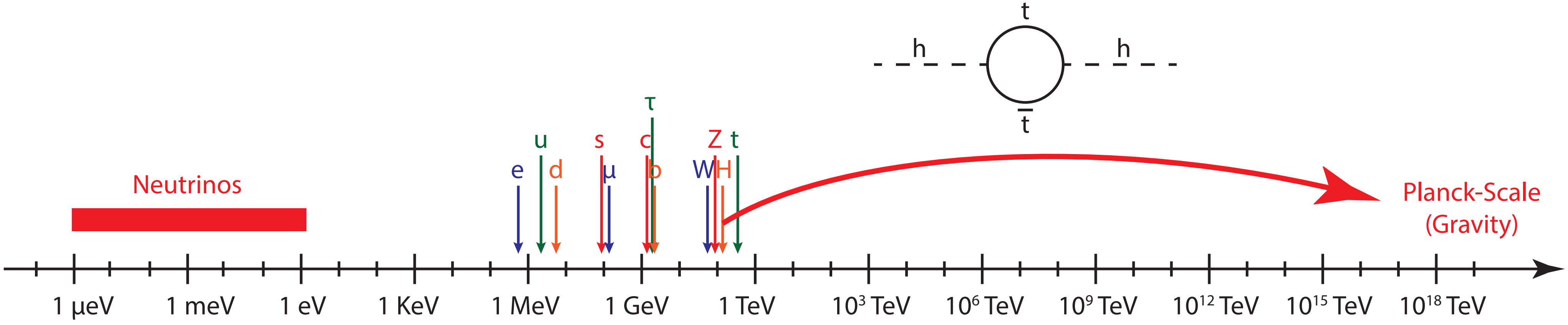
The Structure of the Standard Model



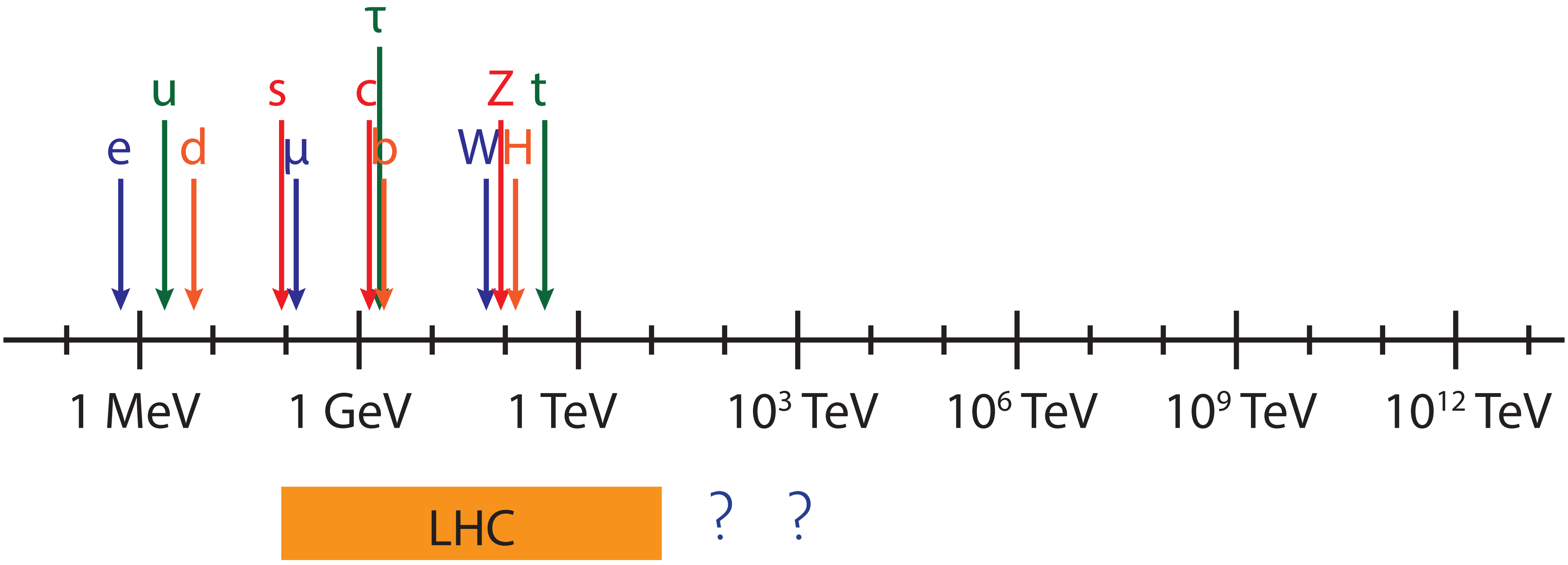
The Structure of the Standard Model



The Structure of the Standard Model



The Structure of the Standard Model

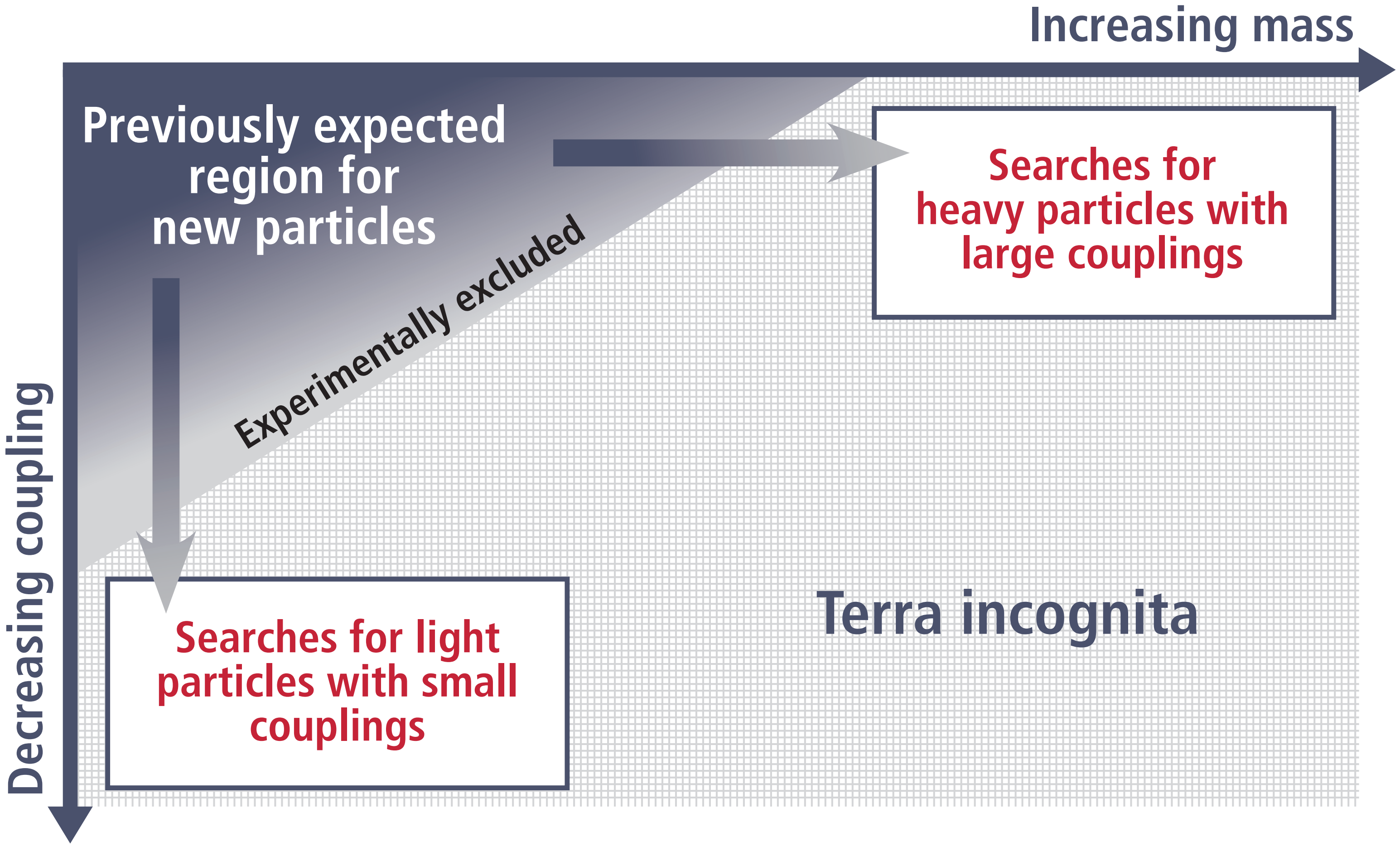


Where is the new physics?

- Not where we already looked...

Where is the new physics?

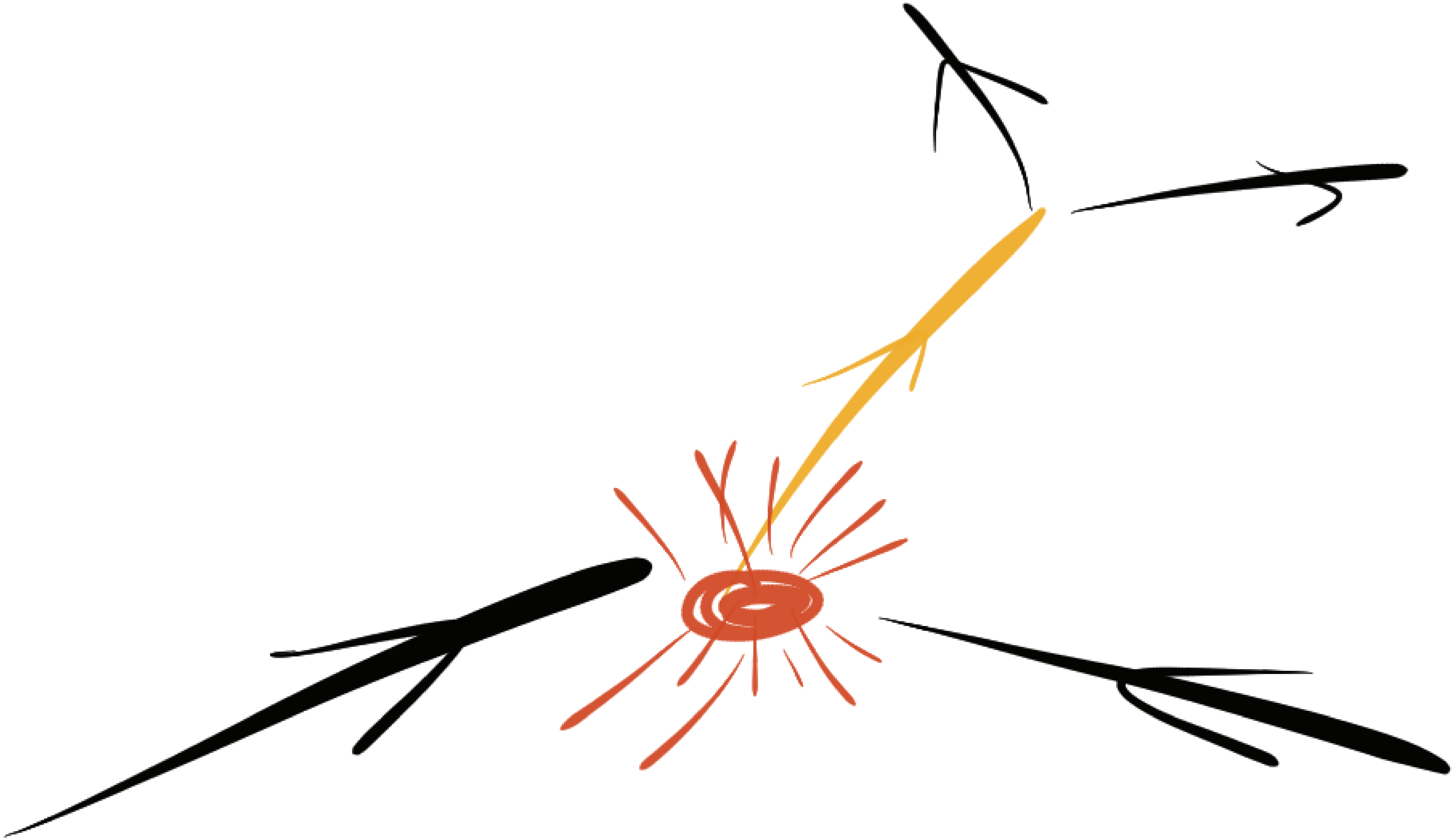
- Not where we already looked…
- Could be at very high energies
- or at very weak couplings

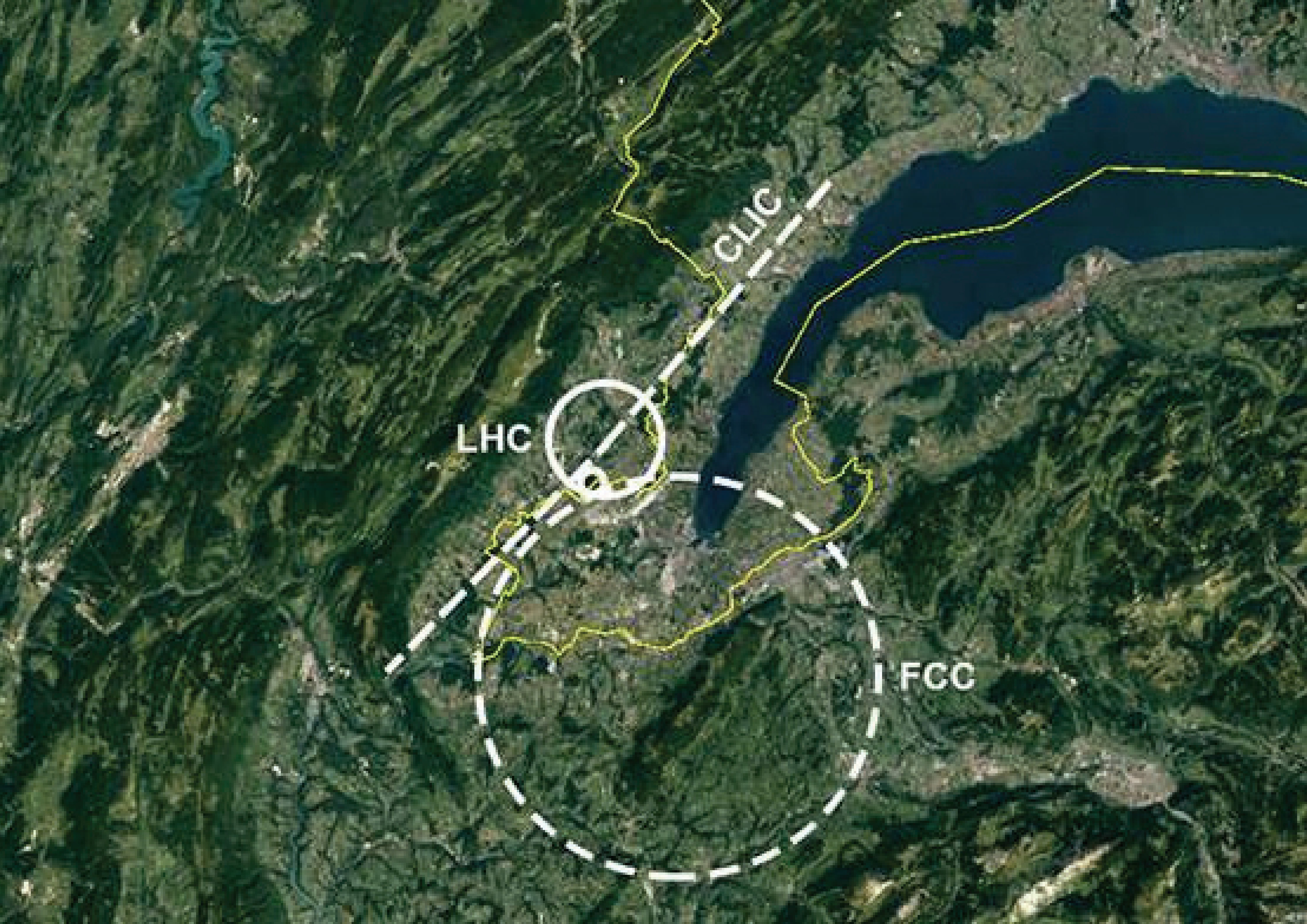


Searches for heavy particles with large couplings

Searches for light particles with small couplings

Direct production




CLIC
LHC
FCC


S363
S269
S251
S266
S048
G1
高能所
秦皇岛市
G102
抚宁县
S267
G205
S265
15.1 公里
S261
S36
Image © 2013 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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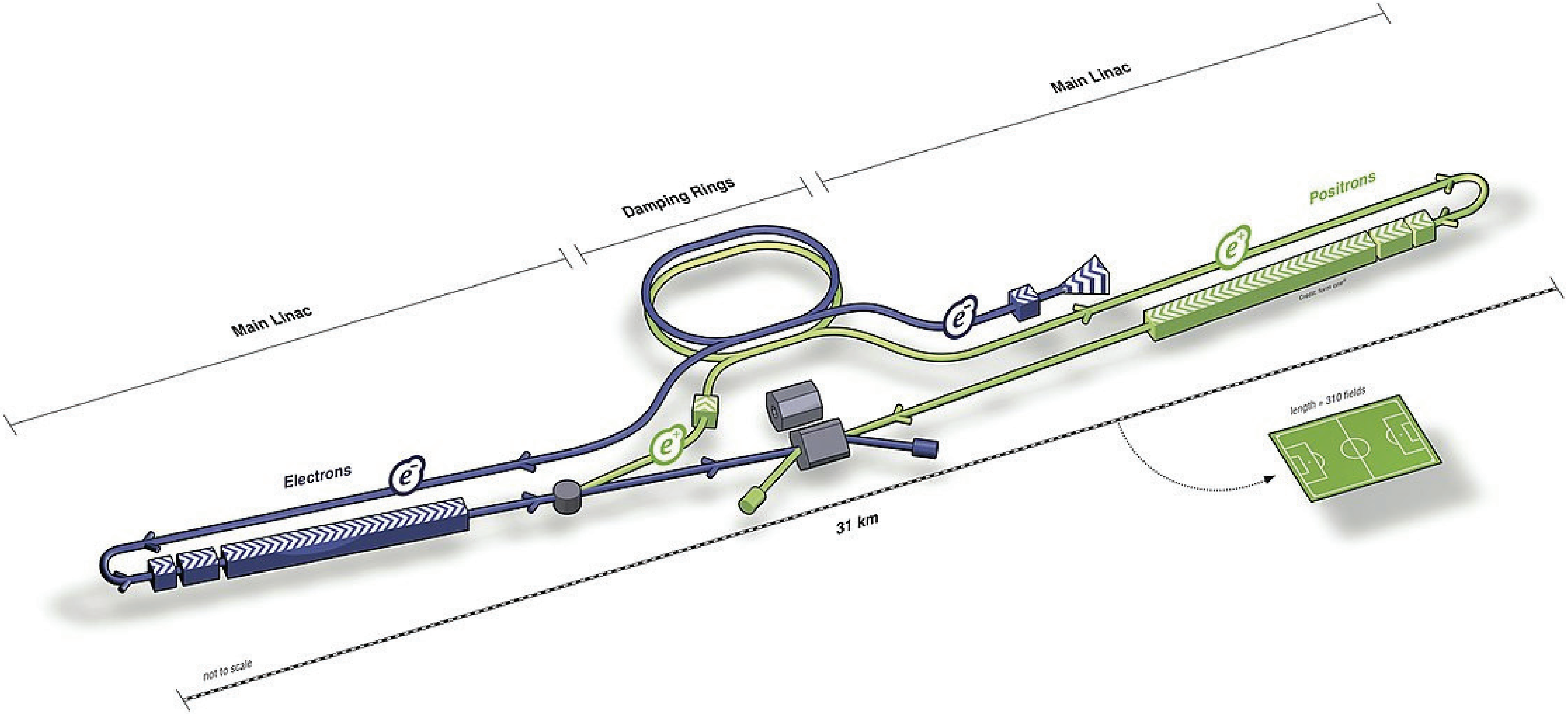
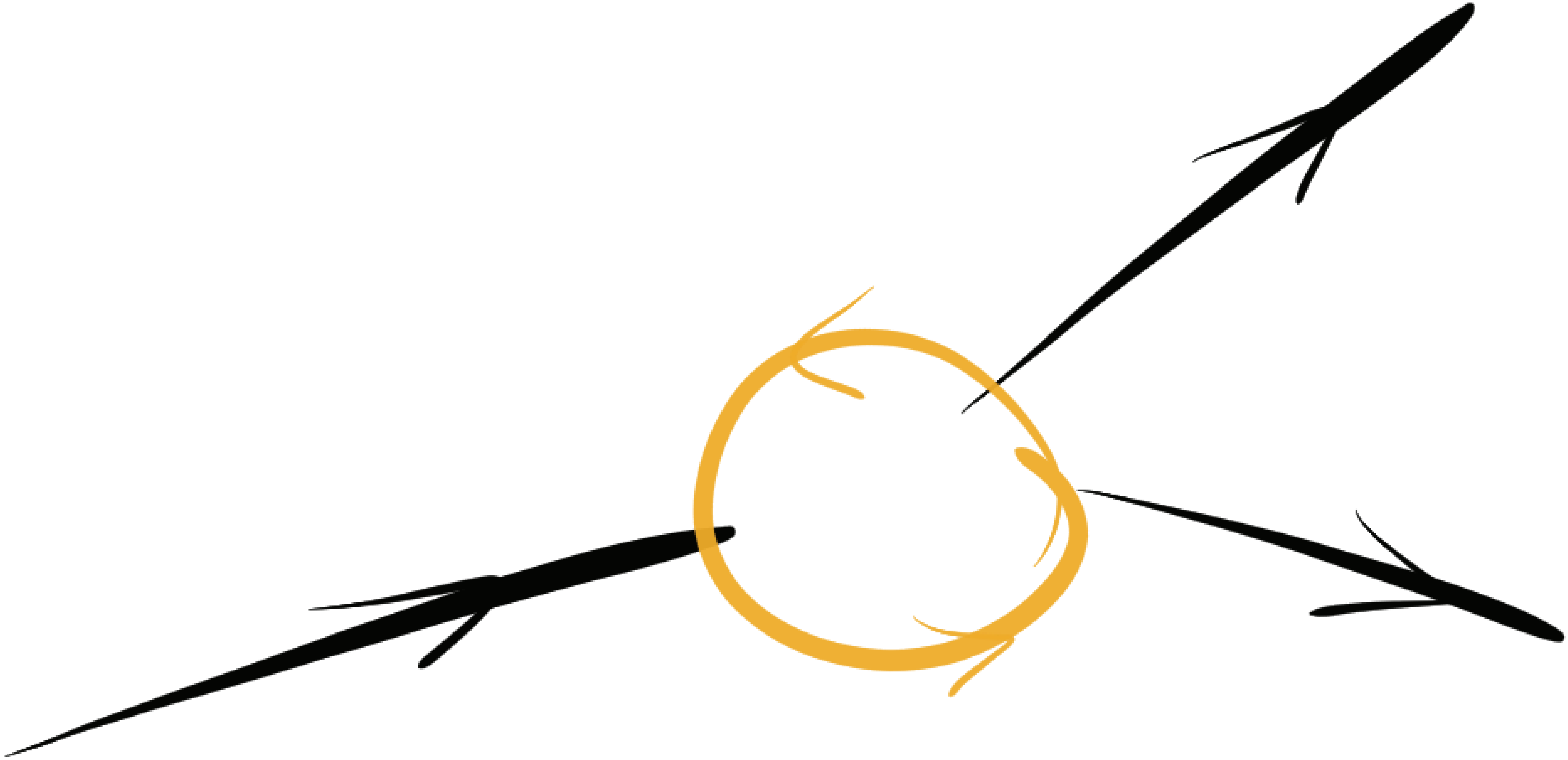
Google


Main Linac
Damping Rings
Main Linac
Positrons
e^+
e^-
e^+
Electrons
e^-
length = 310 fields
31 km
not to scale

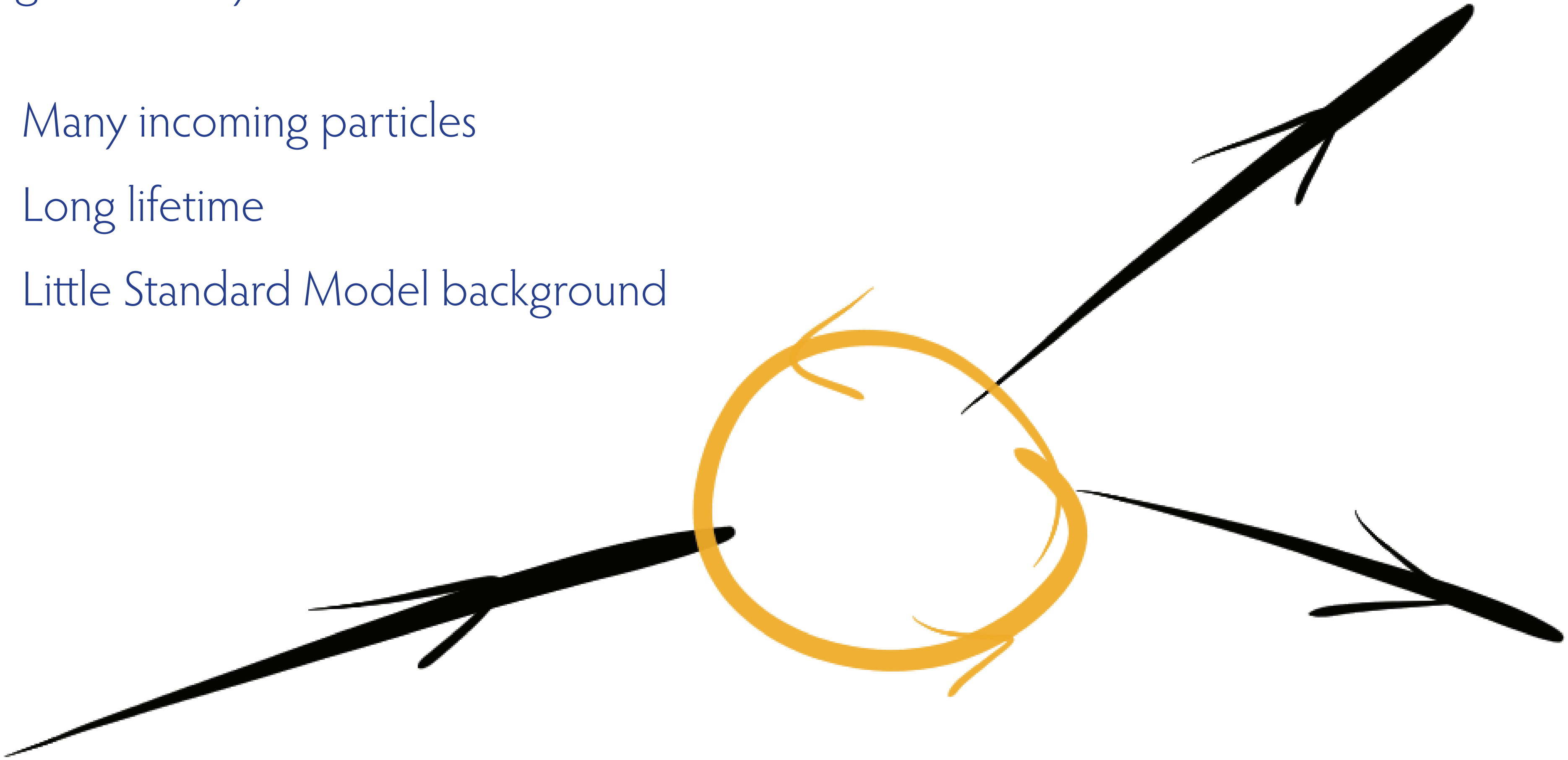
Indirect effects in quantum loops



Indirect effects in quantum loops

Large discovery reach if:

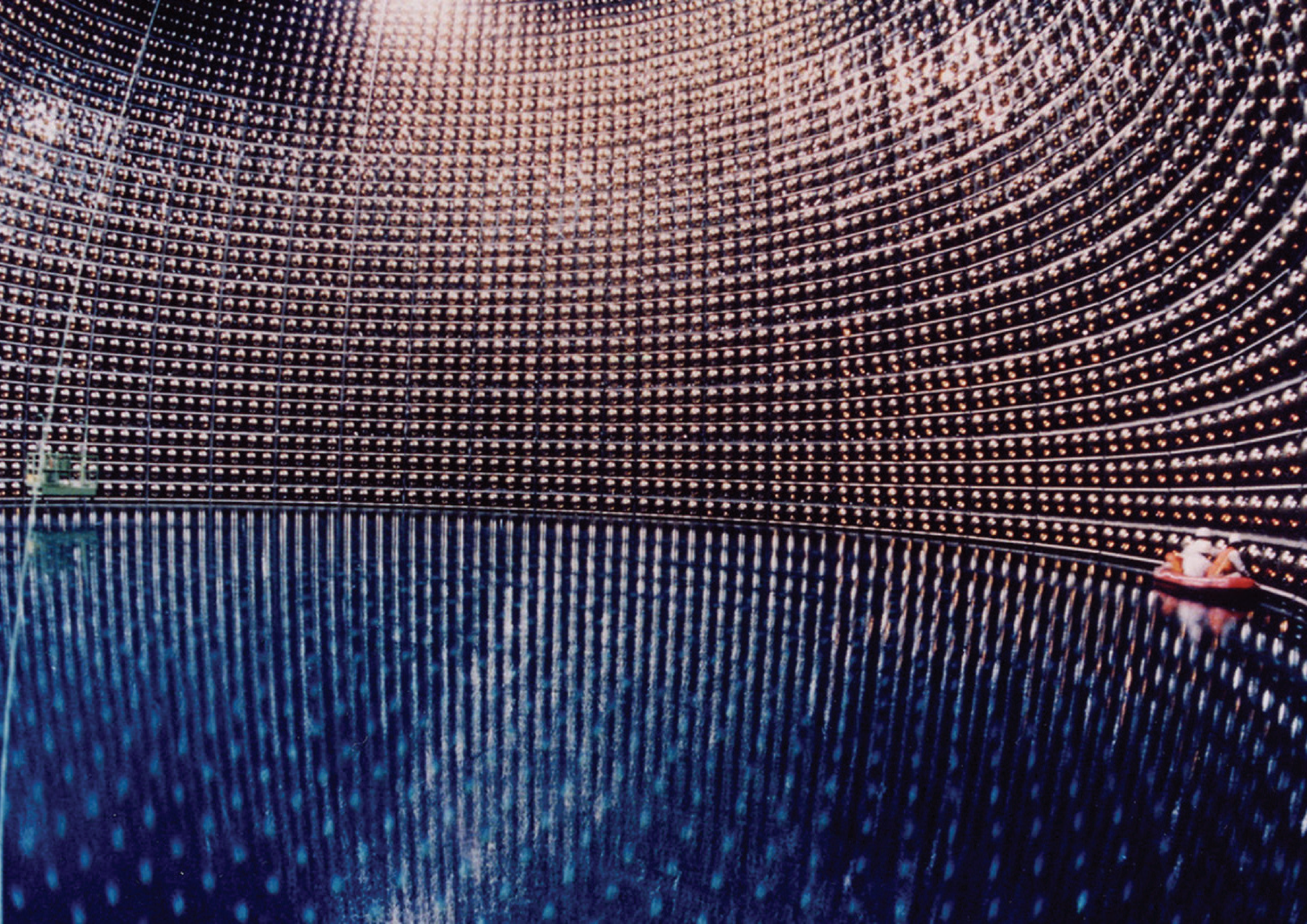
- Many incoming particles
- Long lifetime
- Little Standard Model background

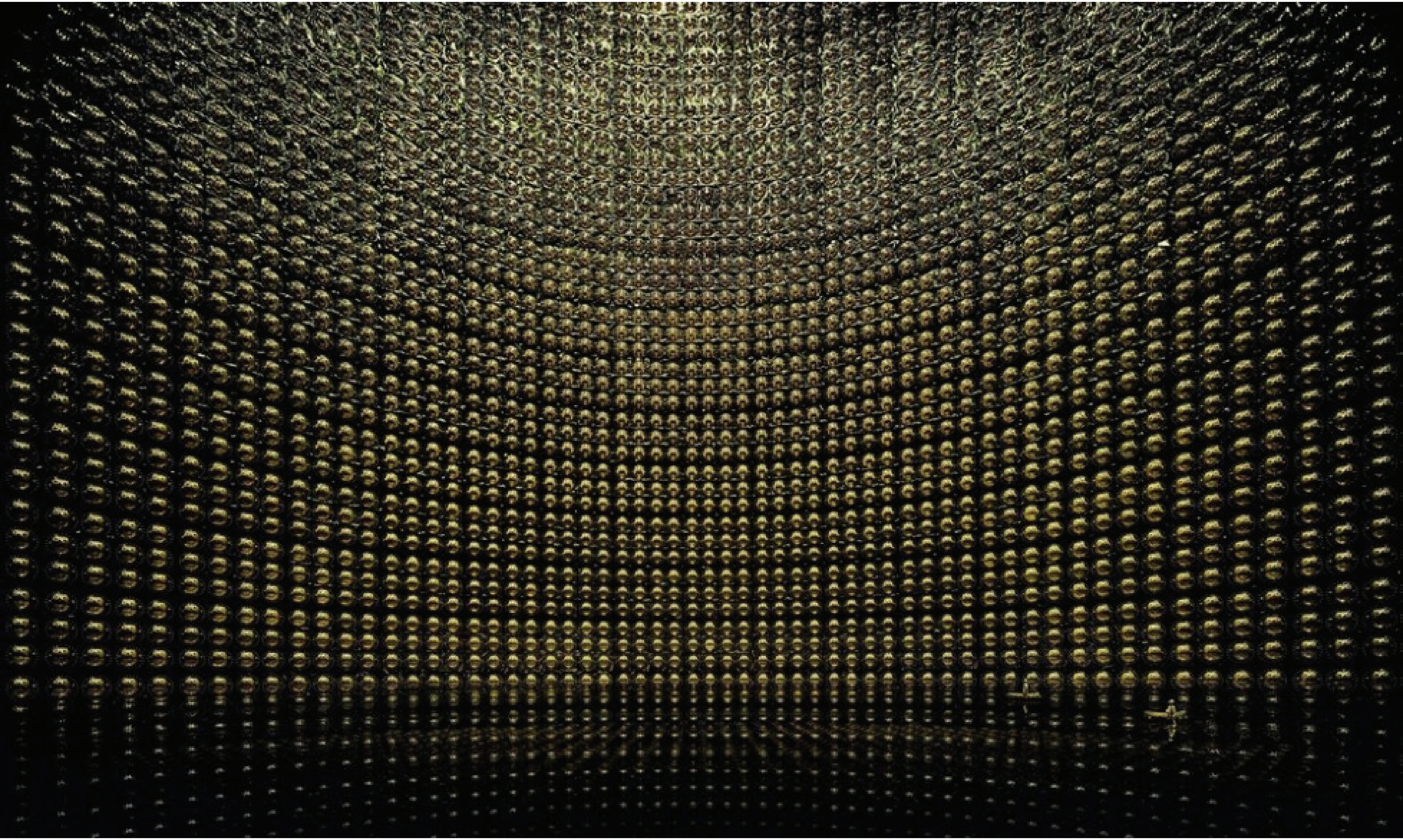


The best channel: Proton decay

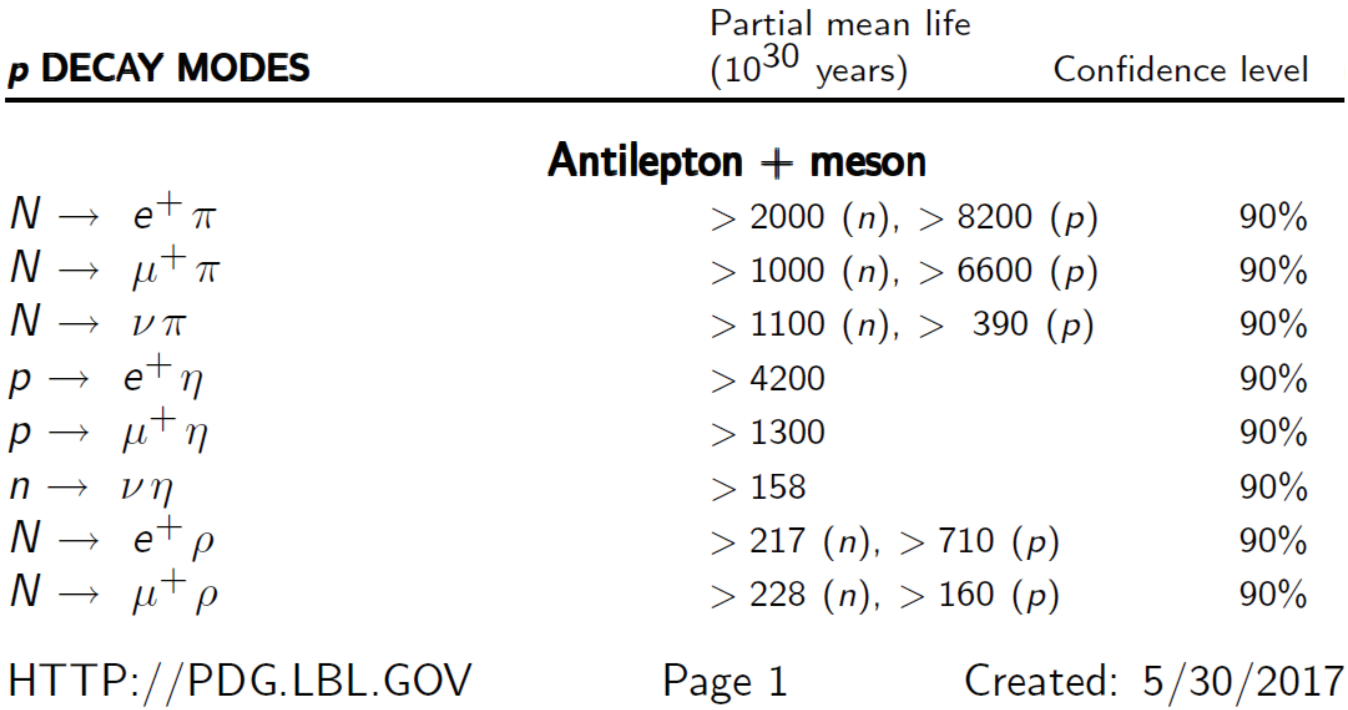
- The proton is stable in the SM
- You can buy a lot of protons cheaply (talk to your local water works)
- You can watch them for a long time
- You can kill beautiful models with not observing proton decay

- Proton decay detectors are also very useful for neutrino physics (that is where you know them from)





Super-Kamiokande



p DECAY MODES	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson	
$N \rightarrow e^+\pi$	> 2000 (n), > 8200 (p)	90%
$N \rightarrow \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
$N \rightarrow \nu\pi$	> 1100 (n), > 390 (p)	90%
$p \rightarrow e^+\eta$	> 4200	90%
$p \rightarrow \mu^+\eta$	> 1300	90%
$n \rightarrow \nu\eta$	> 158	90%
$N \rightarrow e^+\rho$	> 217 (n), > 710 (p)	90%
$N \rightarrow \mu^+\rho$	> 228 (n), > 160 (p)	90%

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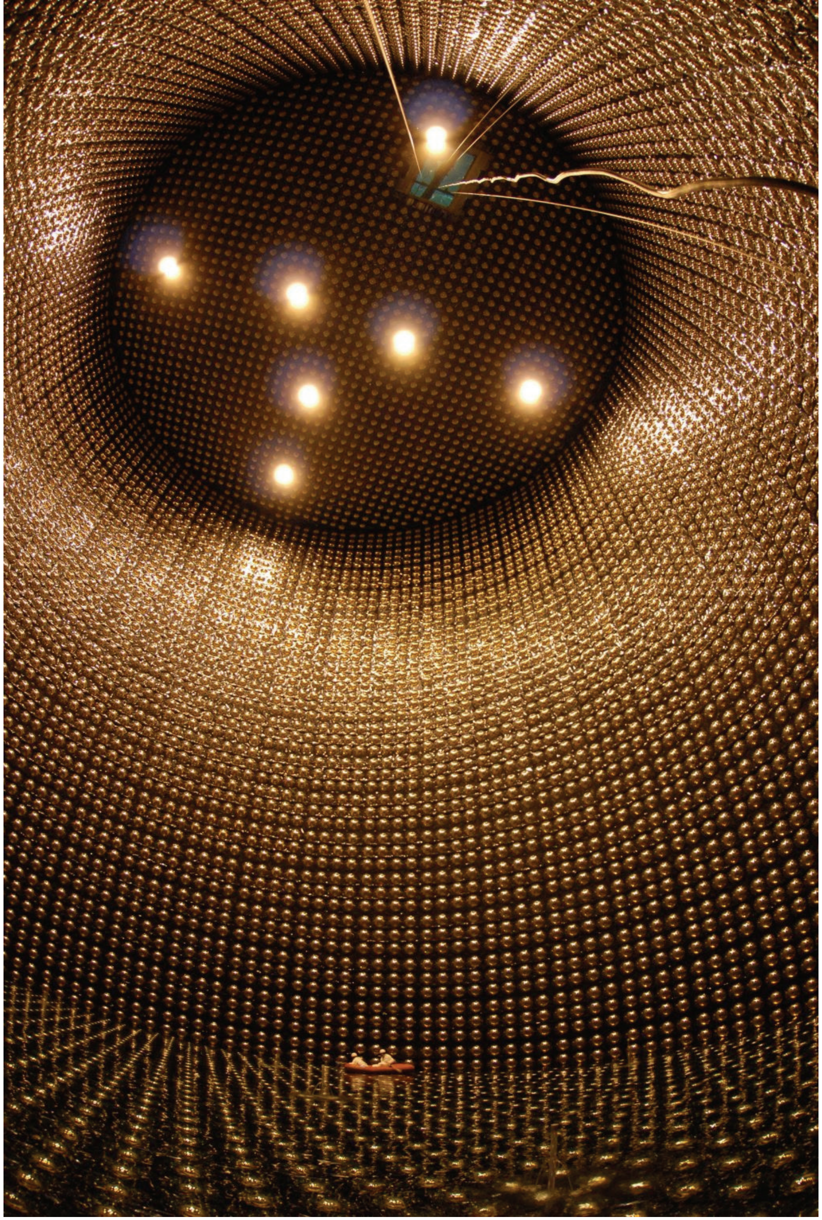
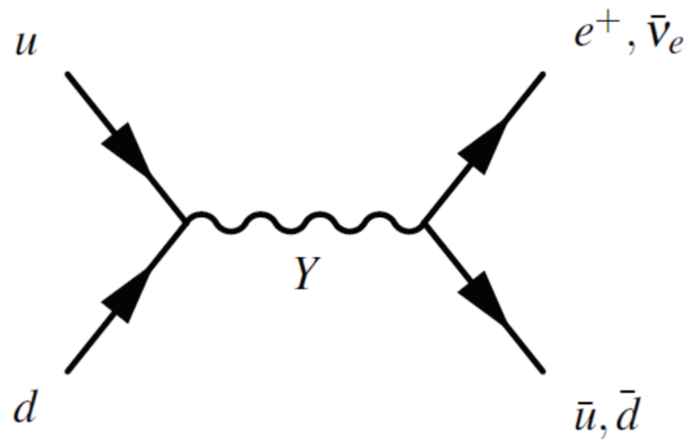
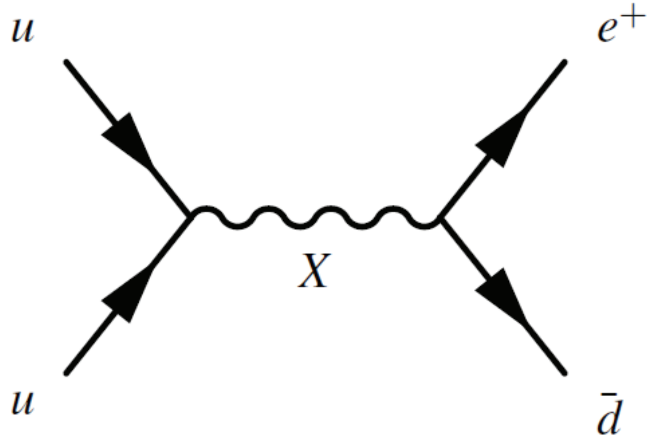


This killed SU(5) GUT...

The dream of unification

- SM SU(3) x SU(2) x U(1) gauge group from braking a larger symmetry
- Smallest group to accommodate SM: SU(5)
- SU(5) gives 24 massless gauge bosons
- SM gauge bosons just right
- Predicts (!) quark charges and weak mixing angle and...
- ... proton decay





$$V_\mu = \begin{pmatrix} G^1_1 - \frac{2}{\sqrt{30}}B & G^1_2 & G^1_3 & \bar{X}^1 & \bar{Y}^1 \\ G^2_1 & G^2_2 - \frac{2}{\sqrt{30}}B & G^2_3 & \bar{X}^2 & \bar{Y}^2 \\ G^3_1 & G^3_2 & G^3_3 - \frac{2}{\sqrt{30}}B & \bar{X}^3 & \bar{Y}^3 \\ X^1 & X^2 & X^3 & \frac{1}{\sqrt{2}}W^3 + \frac{3}{\sqrt{30}}B & W^+ \\ Y^1 & Y^2 & Y^3 & W^- & -\frac{1}{\sqrt{2}}W^3 + \frac{3}{\sqrt{30}}B \end{pmatrix}$$

No SU(5) GUT...

After some [thirty] years, we are still waiting. No protons have decayed. We have been waiting long enough to know that SU(5) grand unification is wrong. It's a beautiful idea, but one that nature seems not to have adopted.
(Page 64)

Indeed, it would be hard to underestimate the implications of this negative result. SU(5) is the most elegant way imaginable of unifying quarks with leptons, and it leads to a codification of the properties of the standard model in simple terms. Even after [thirty] years, I still find it stunning that SU(5) doesn't work.
(Page 65)

Smolin, Lee (2007). The Trouble with Physics.

If not protons, then what?

- Neutrons?
  Very long lived, might tell us something about the strong CP problem
  Neutron electric dipole moment searches

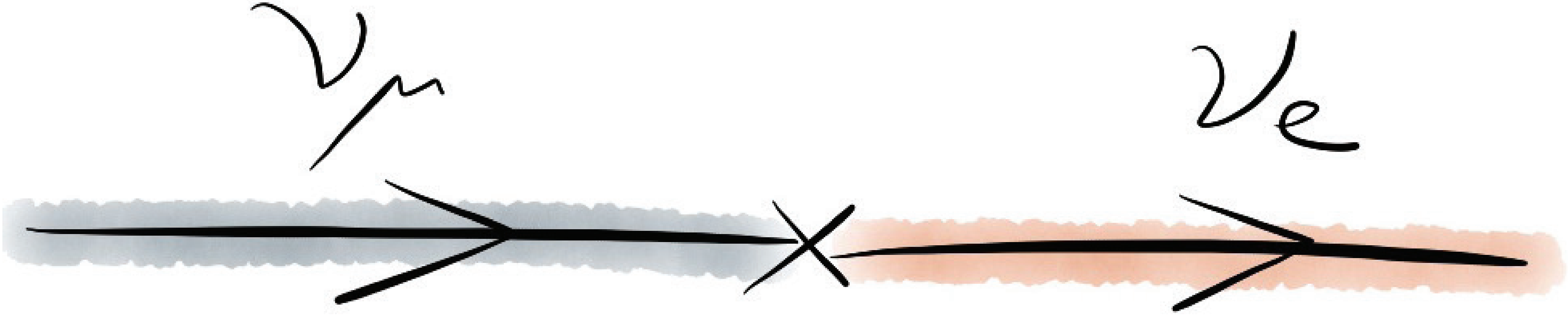
- Muons?
  Very long lived, might tell us something about flavour
  Lepton flavour violation experiments

  Allow for extremely precise calculations and measurements
  Muon magnetic dipole moment

- If we are at precise: Ways to cleverly over-constrain the SM
  Weak mixing angle in parity violating e-p scattering

Hints for physics beyond the Standard Model in particle physics?

Neutrinos have mass!



- In the original SM, neutrinos are massless
- Oscillations show that they have mass
- There are probably (heavy) right-handed neutrinos out there

Discrepancies and anomalies

(could all also be experimental or theory problems)

(will not talk about the B-physics anomalies)

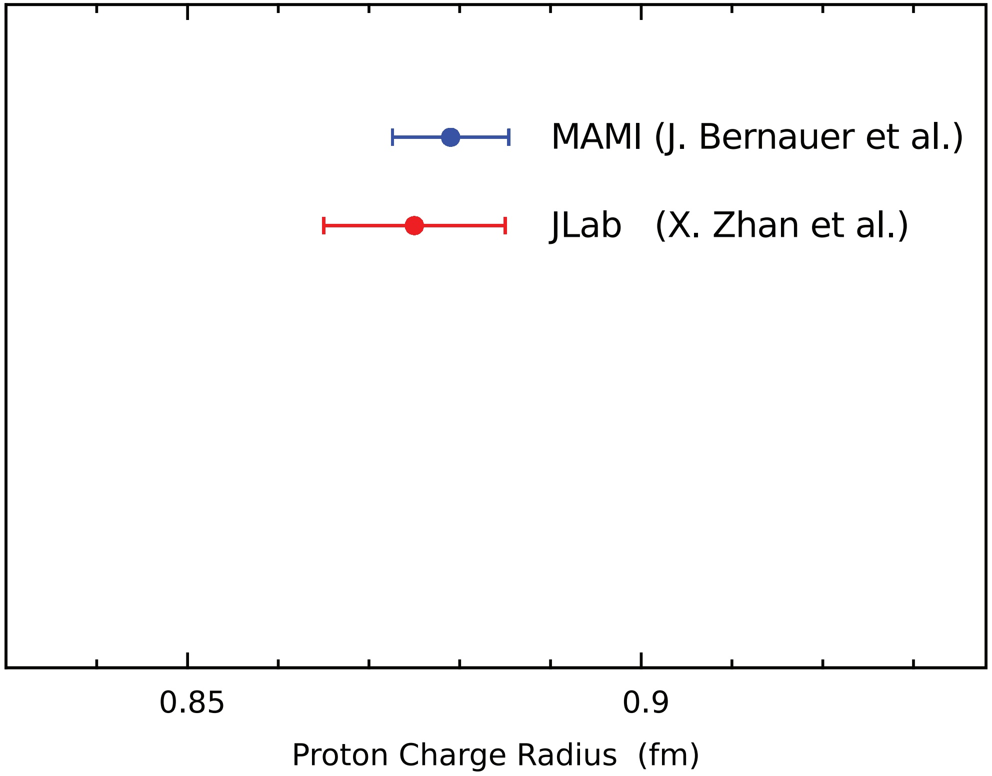
Muon magnetic moment
(later)

The Proton Radius Puzzle

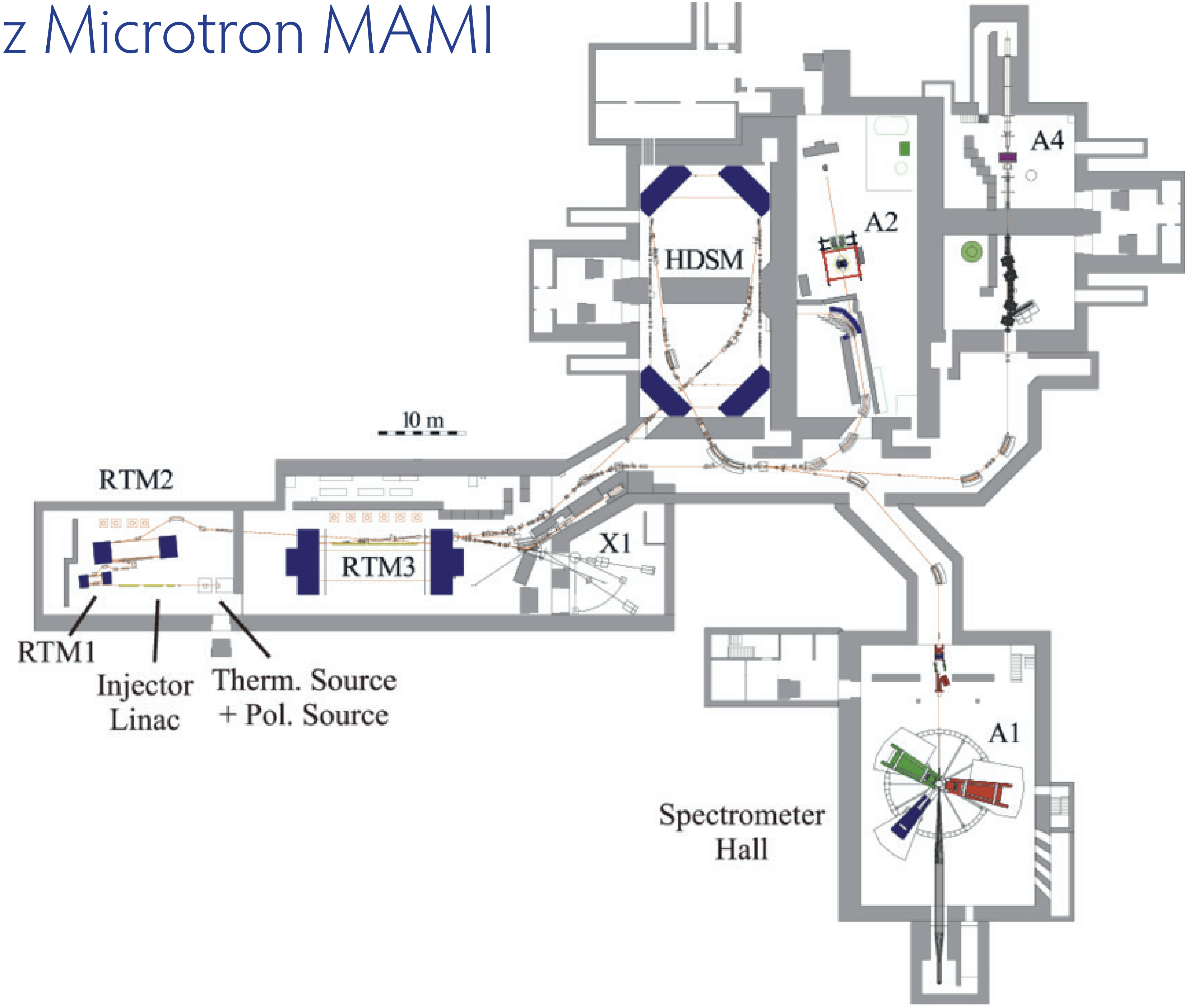
Proton Radius Puzzle

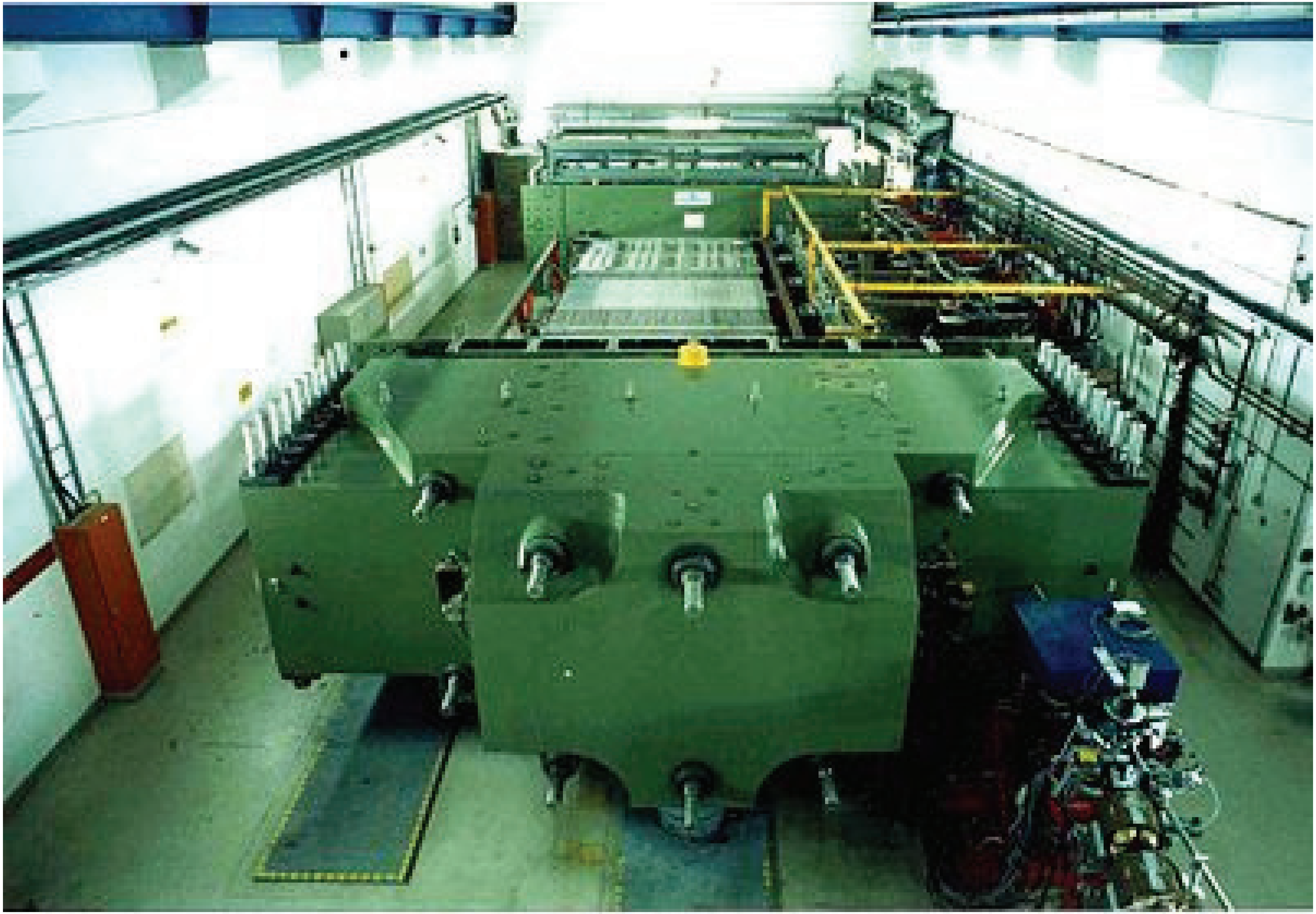
How big is a proton?
(electromagnetic charge radius)

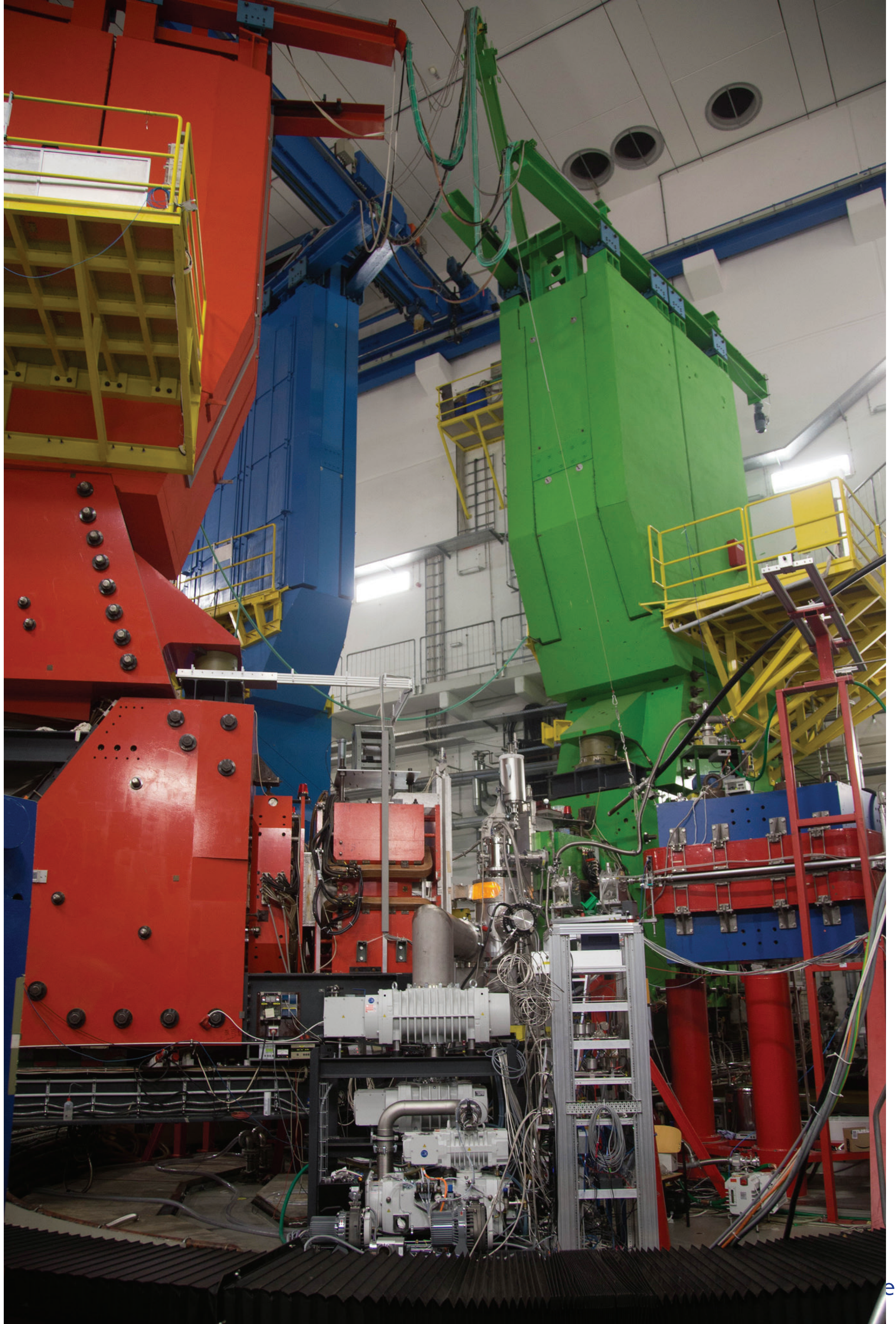
- Measure in scattering experiments (Mainz)



The Mainz Microtron MAMI



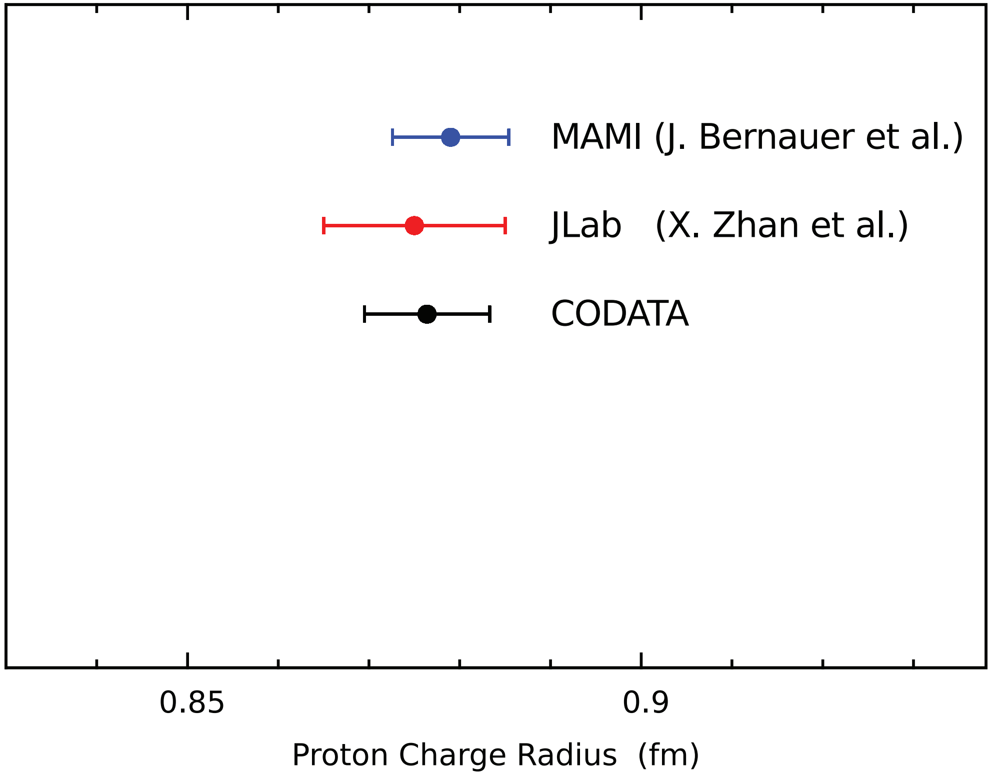




Proton Radius Puzzle

How big is a proton?
(electromagnetic charge radius)

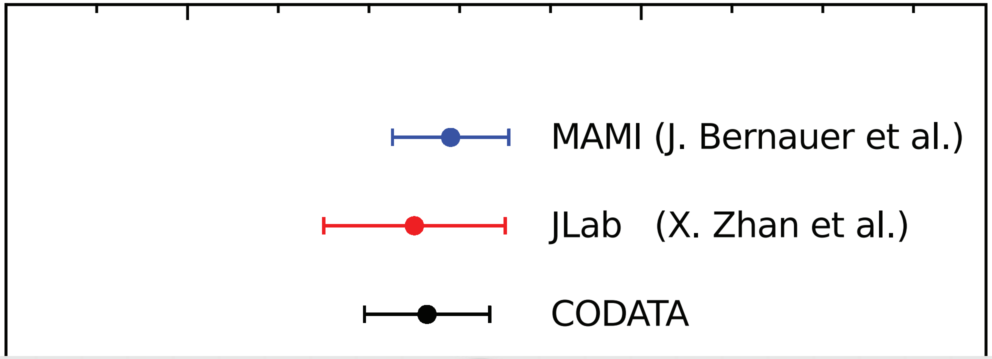
- Measure in scattering experiments (Mainz!)
- Measure in spectroscopy (Lamb-shift)

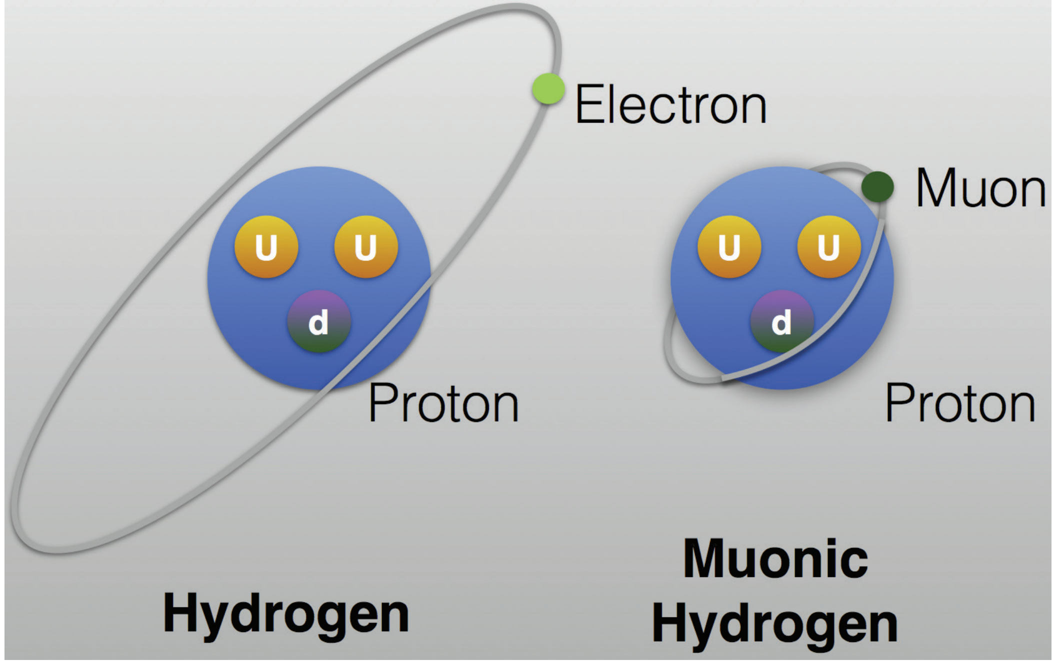


Proton Radius Puzzle

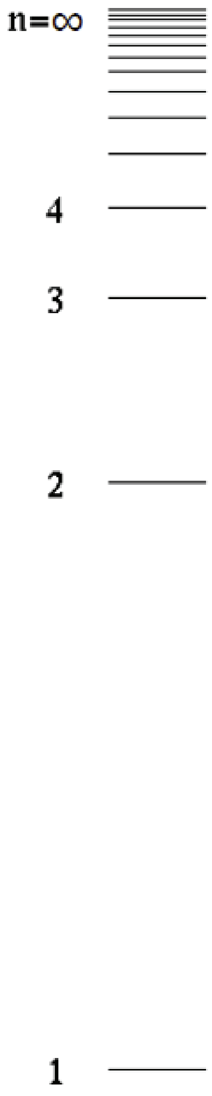
How big is a proton?
(electromagnetic charge radius)

- Measure in scattering experiments (Mainz)
- Measure in spectroscopy (Lamb-shift)
- Lamb shift is tiny - except in muonic hydrogen





Energy levels of hydrogen

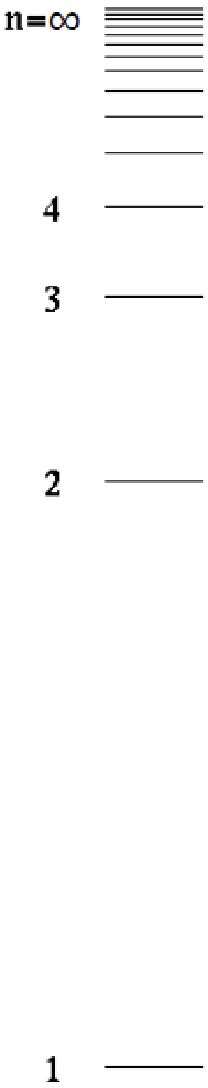


$$E_n \approx -\frac{R_\infty}{n^2}$$

Bohr formula

R. Pohl

Energy levels of hydrogen

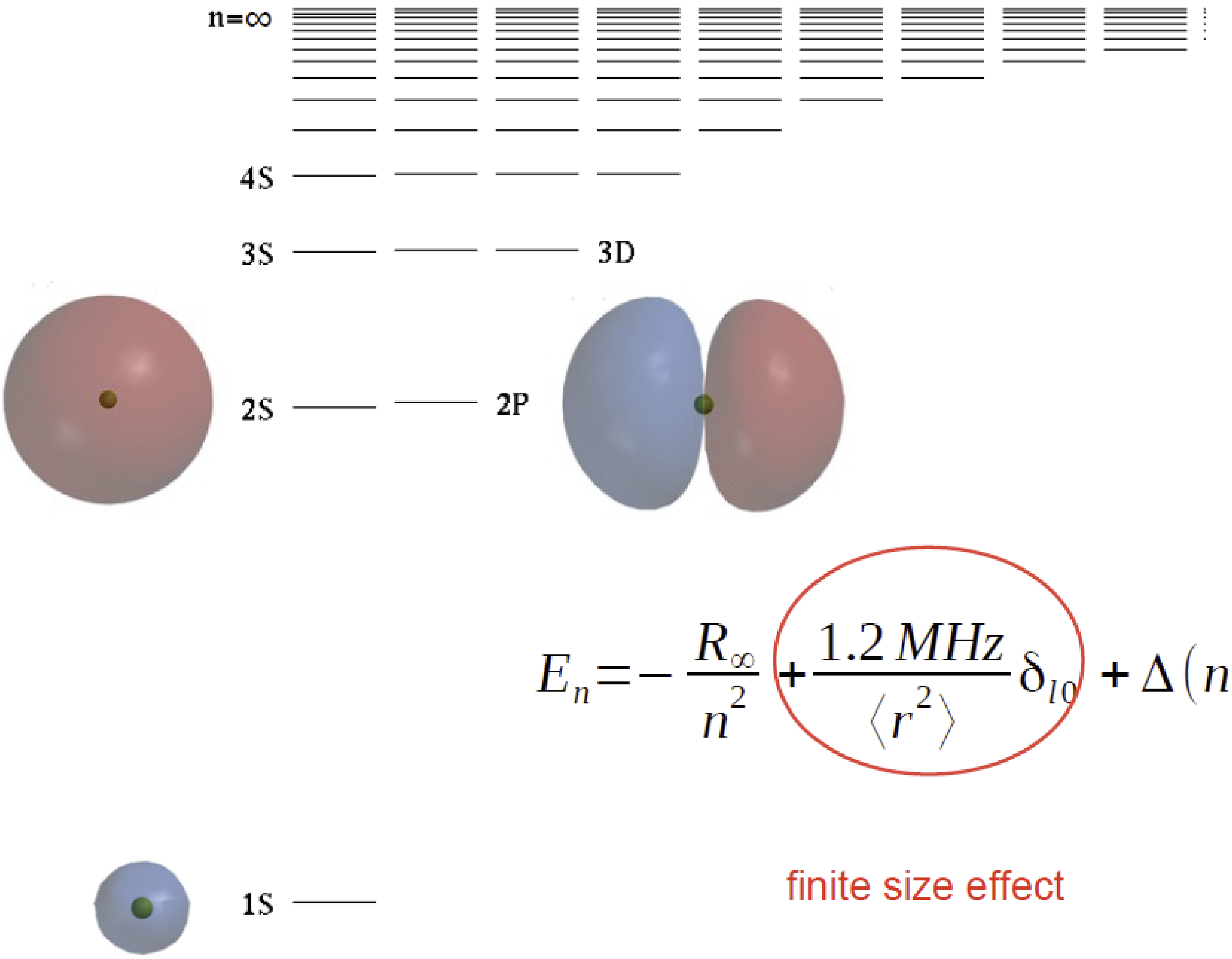


Rydberg constant

$$E_n \approx -\frac{\boxed{R_\infty}}{n^2}$$

Bohr formula

Energy levels of hydrogen

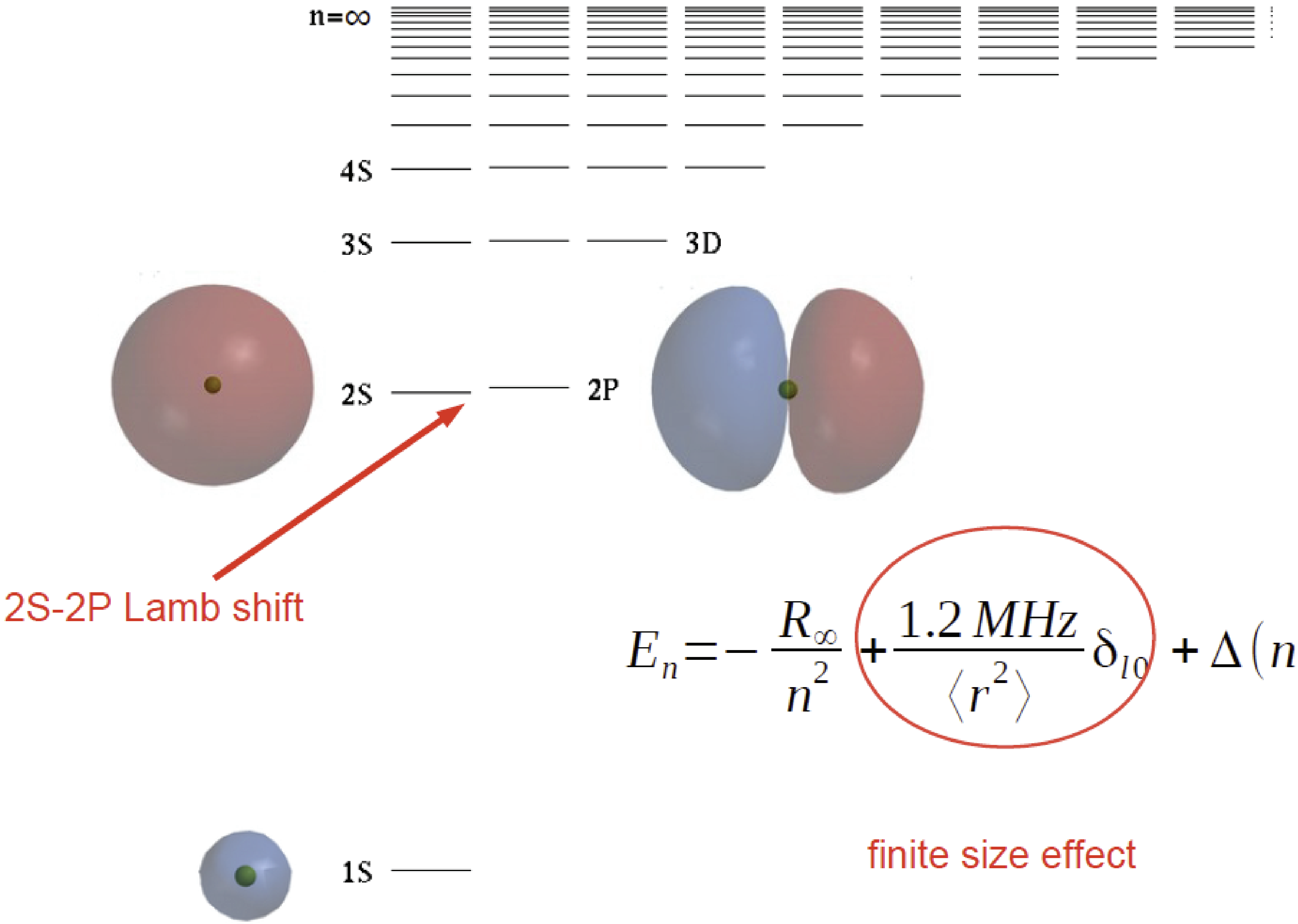


$$E_n = -\frac{R_\infty}{n^2} + \boxed{\frac{1.2\,MHz}{\langle r^2 \rangle}\delta_{l0}} + \Delta(n, l, j)$$

finite size effect

R. Pohl

Energy levels of hydrogen



2S-2P Lamb shift

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{\langle r^2 \rangle}\delta_{l0} + \Delta(n,l,j)$$

finite size effect

R. Pohl

Muonic atoms

A nucleus, orbited by one negative muon

Muon mass = 200 x electron mass

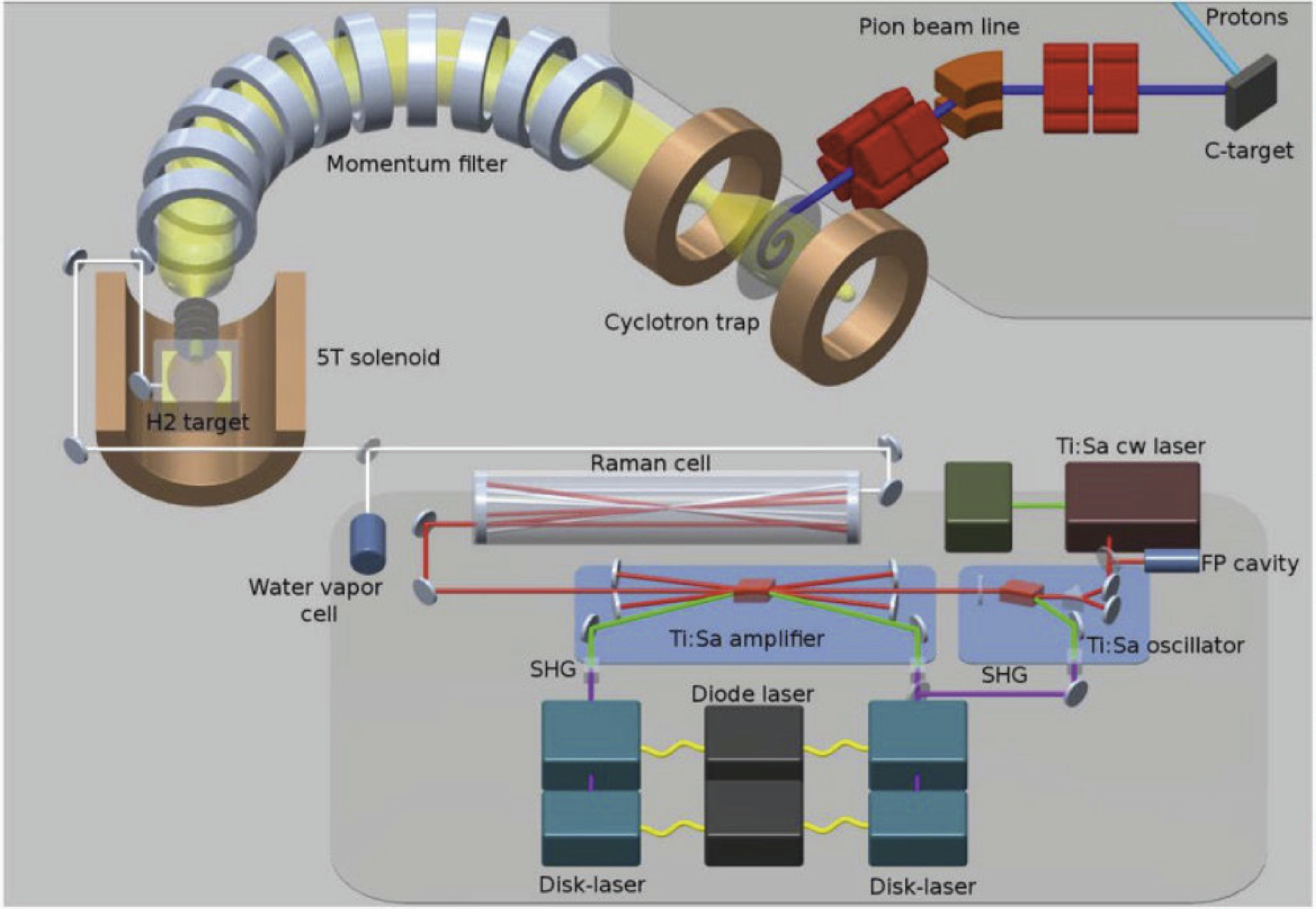
muonic Bohr radius = 1/200 electronic Bohr radius

wave function overlap = 200^3 = **10 million times larger**

muon = very sensitive probe of nuclear properties

R. Pohl

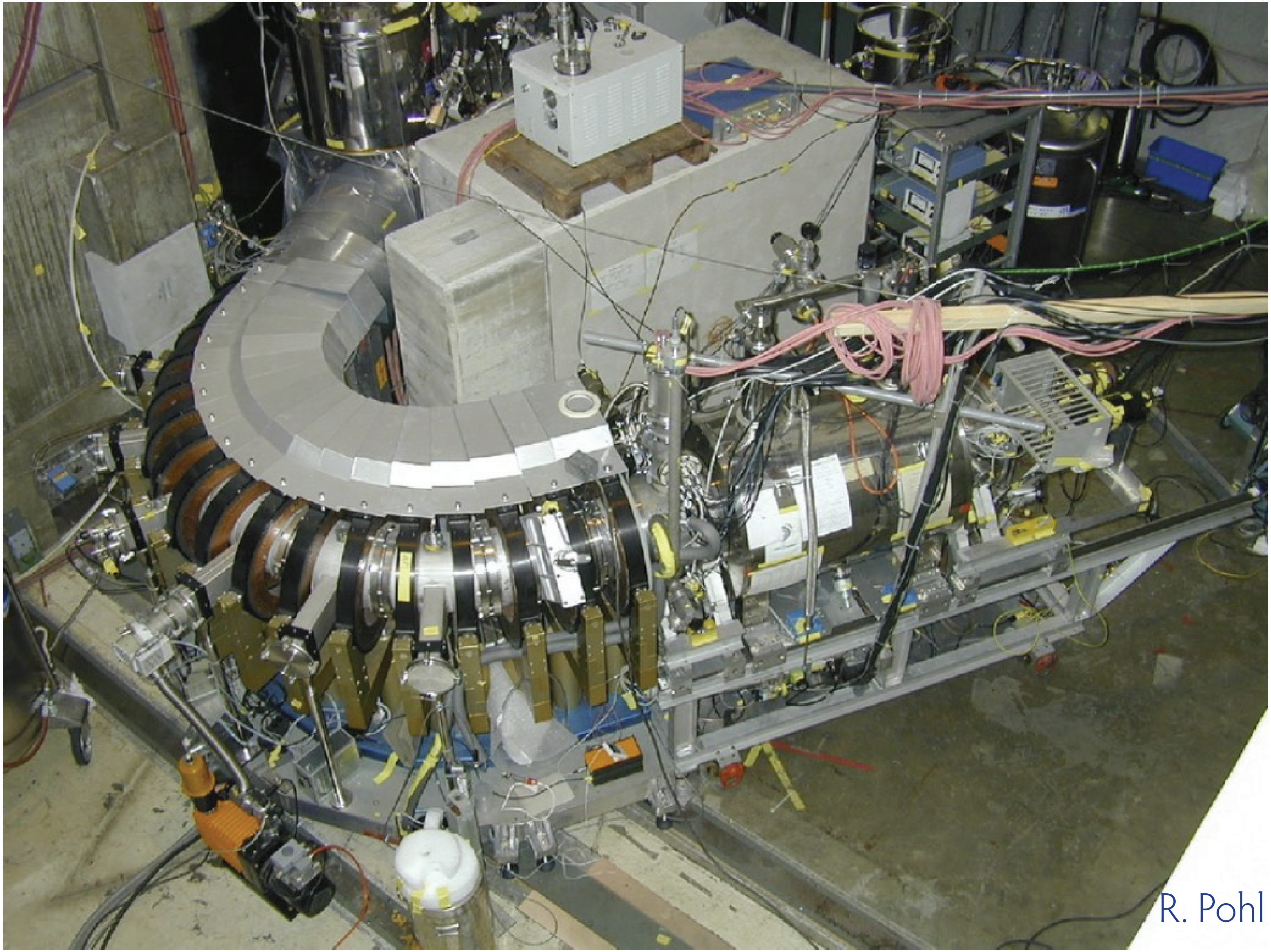
p-beam
(1 MW)
↓
π (MeV)
↓
μ (MeV)
↓
μ (keV)
↓
μp(2S)
↓
Laser
↓
X-ray



940 nm
(2 kW)
↓
1030 nm
↓
515 nm
↓
708 nm
↓
1.0 μm
↓
1.6 μm
↓
6.0 μm

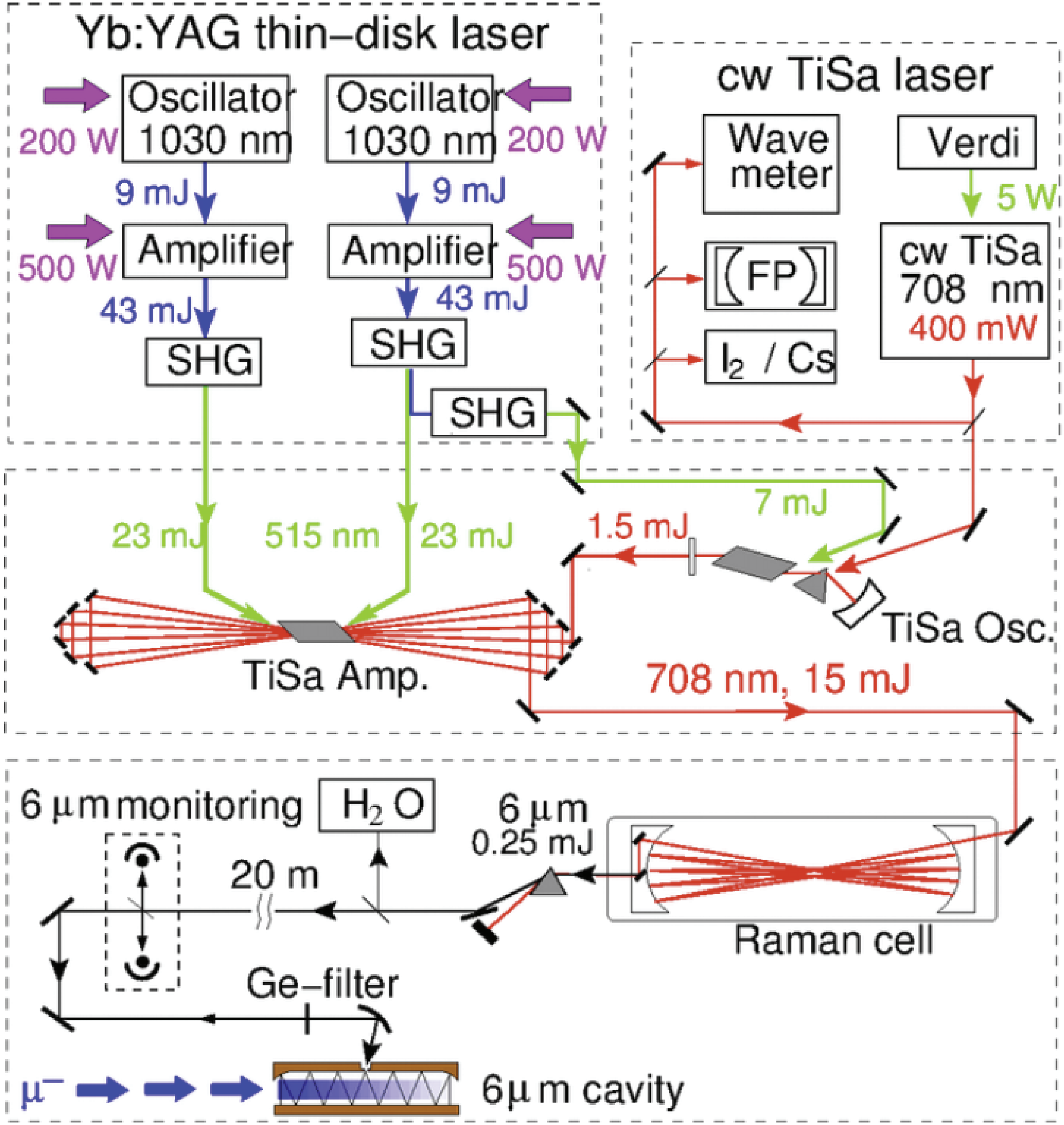
A. Antognini

The muon beam line in πE5



R. Pohl

The laser system



Yb:YAG Disk laser
→ fast response on µ

Frequency doubling (SHG)
→ green light to pump
Ti:sapphire laser

Ti:sapphire cw laser
→ determines laser frequency

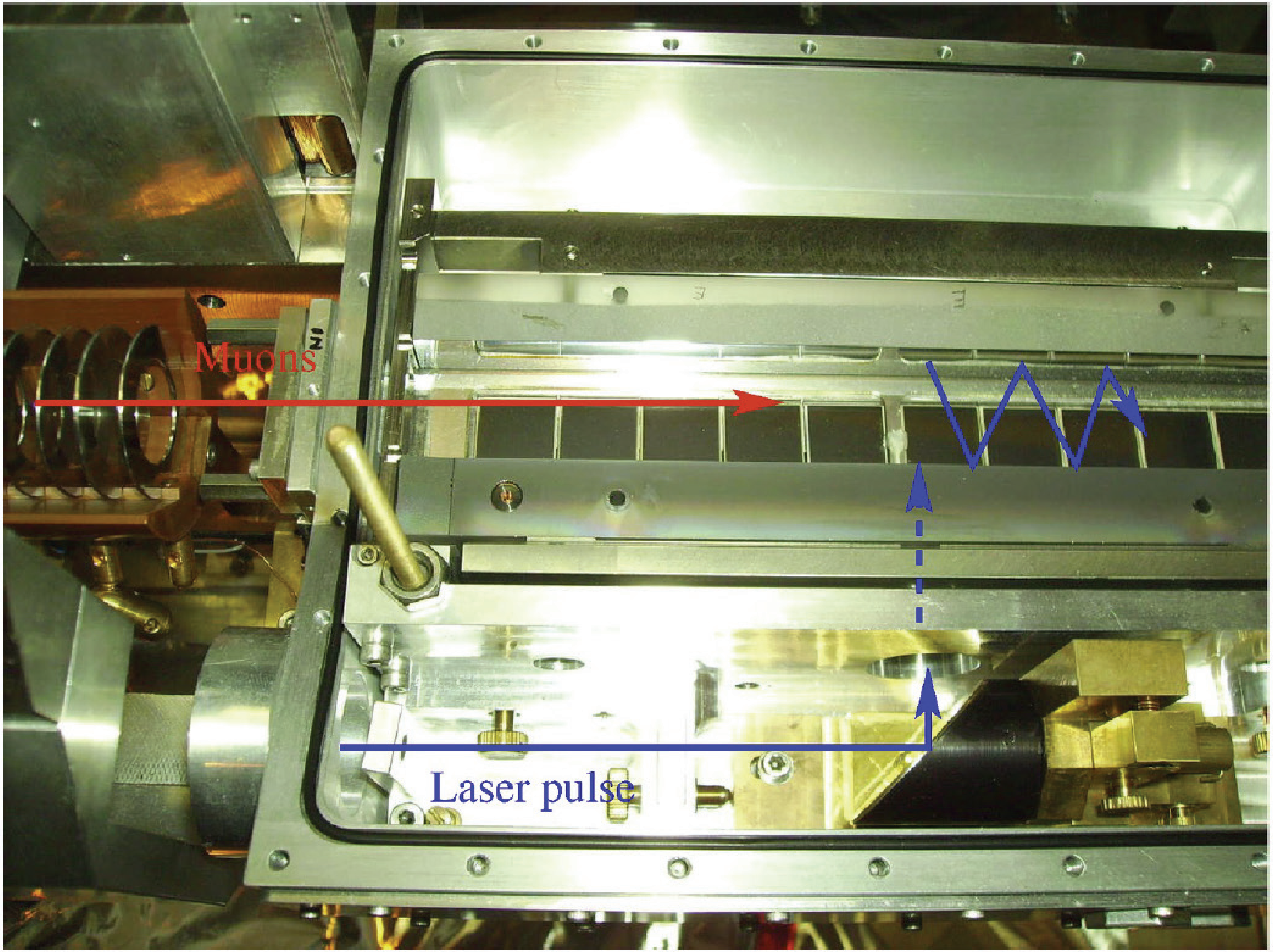
Ti:sapphire MOPA
→ high pulse energy (15 mJ)

Raman cell
→ 3 sequential stimulated
Raman Stokes shifts
Laser wave length → 6 µm

Target Cavity
→ Mirror system to fill the
muon stop volume (H_2)

R. Pohl

The hydrogen target



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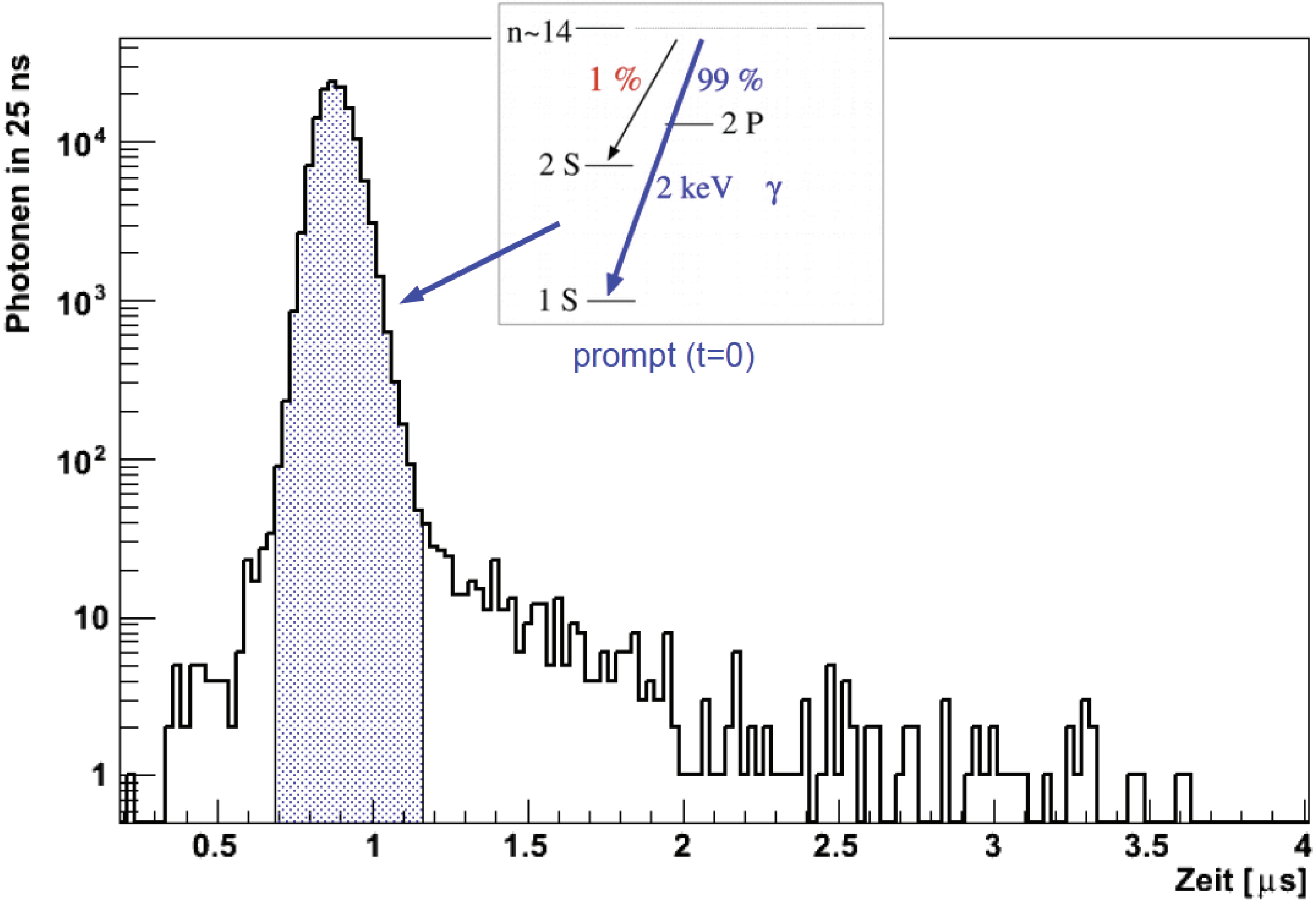
Time Spectra

13 hours of data



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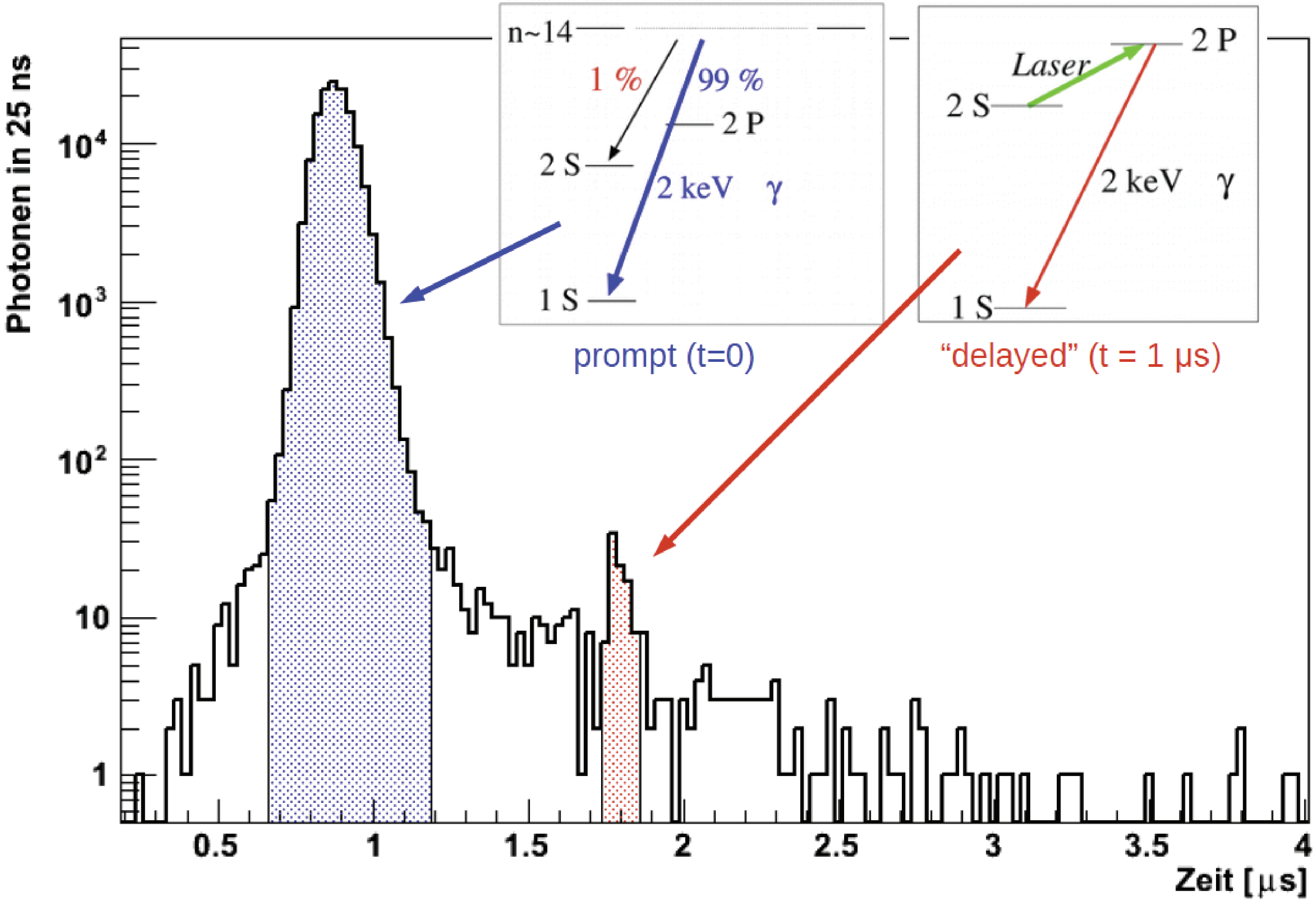
Time Spectra



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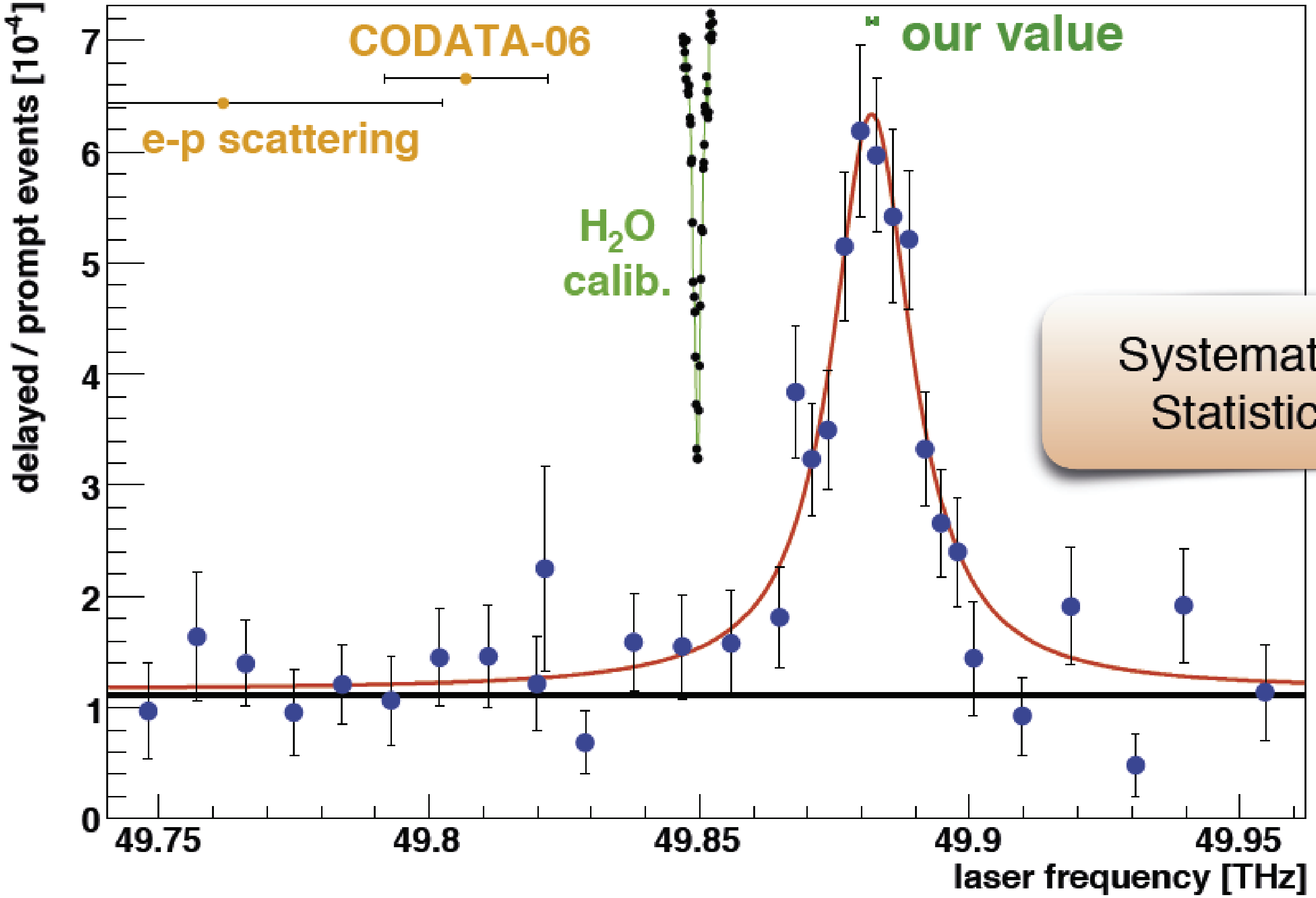


Systematics: 300 MHz
Statistics: 700 MHz

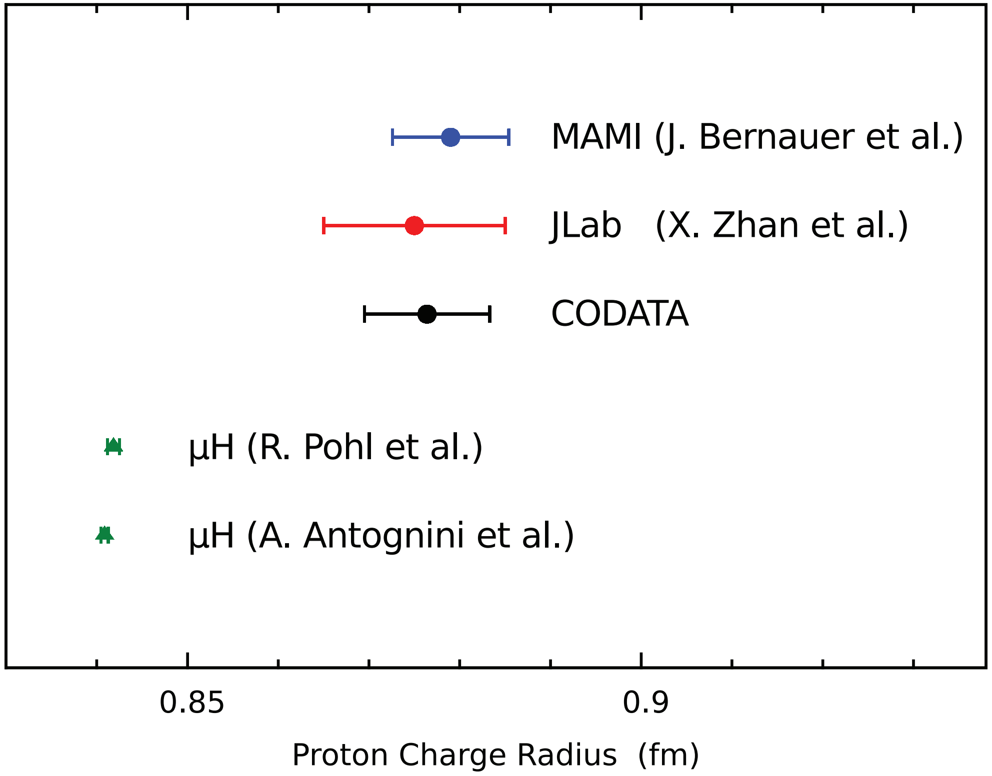
Pohl et al., Nature 466, 213 (2010)

A. Antognini

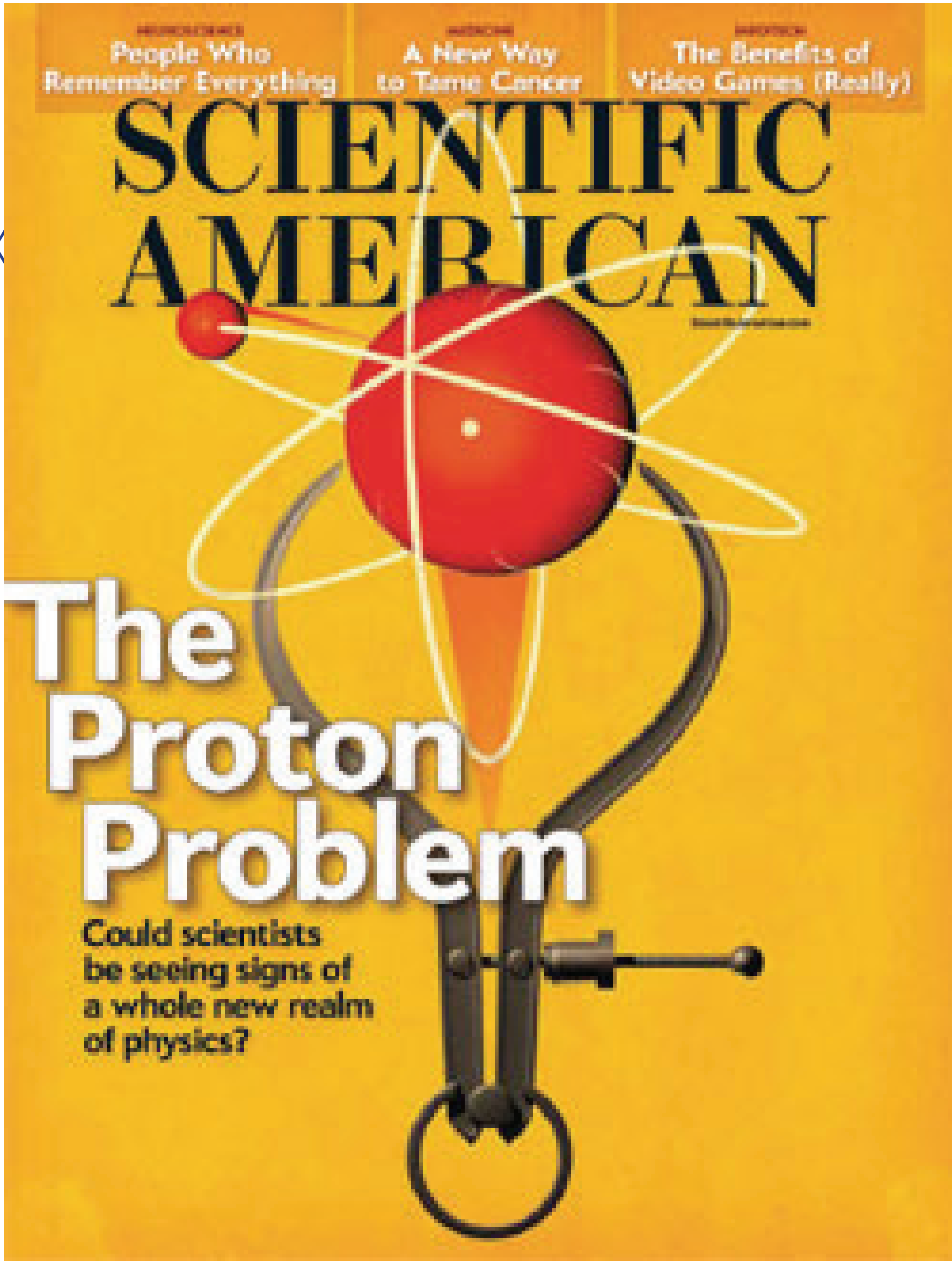
Proton Radius Puzzle

How big is a proton?
(electromagnetic charge radius)

- Measure in scattering experiments (Mainz)
- Measure in spectroscopy (Lamb-shift)
- Lamb shift is tiny - except in muonic hydrogen
- Big surprise!
  4 - 7 σ discrepancy - why?

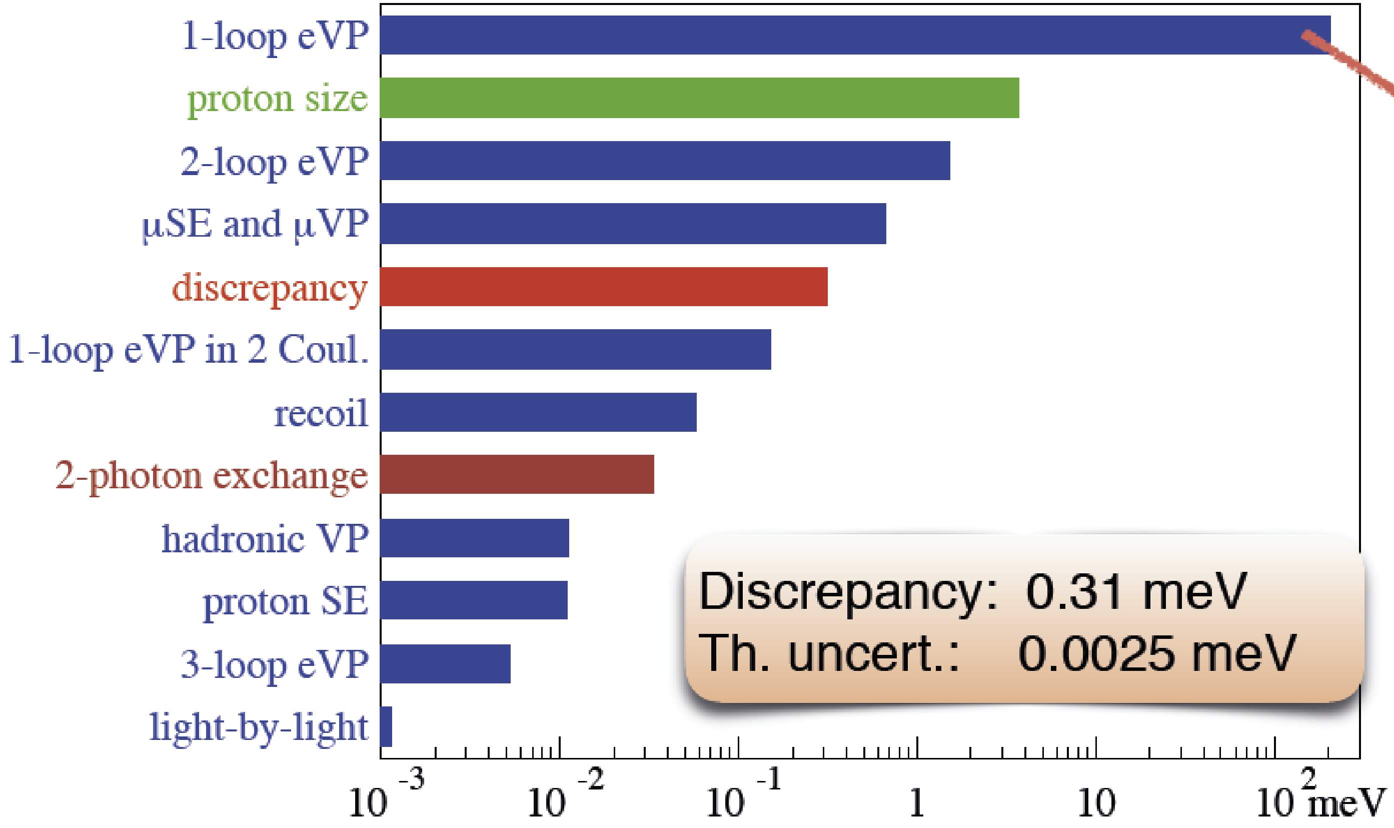



8 July 2010 | www.nature.com/nature | £10
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
nature
OIL SPILLS
There's more to come
PLAGIARISM
It's worse than you think
CHIMPANZEES
The battle for survival
SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent
NATUREJOBS
Reseachers for hire

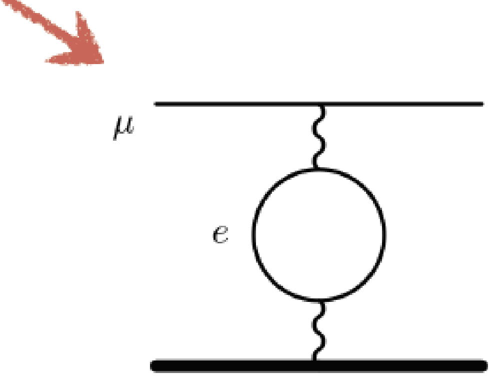

People Who Remember Everything
A New Way to Tame Cancer
The Benefits of Video Games (Really)
SCIENTIFIC AMERICAN
The Proton Problem
Could scientists be seeing signs of a whole new realm of physics?

Is the theory reliable?

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



Discrepancy: 0.31 meV
Th. uncert.: 0.0025 meV



A. Antognini

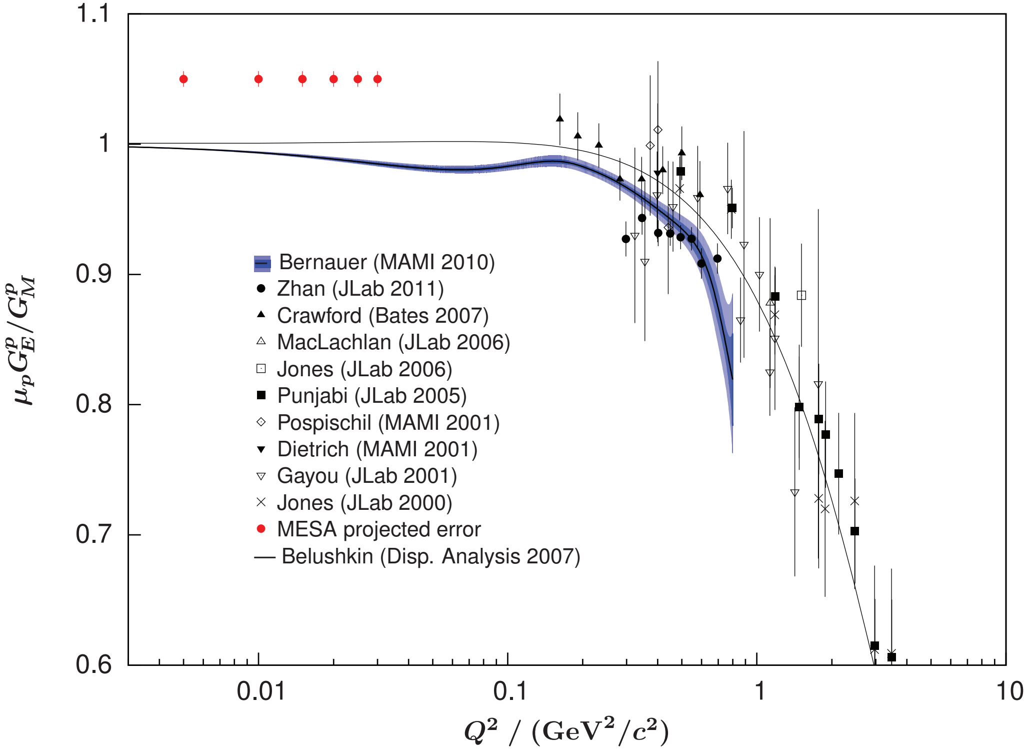
If muonic hydrogen is right…

- then there is an issue with both electron scattering and electron spectroscopy

- or there is New Physics

- consider first option first…

Scattering, Q^2 and substructure

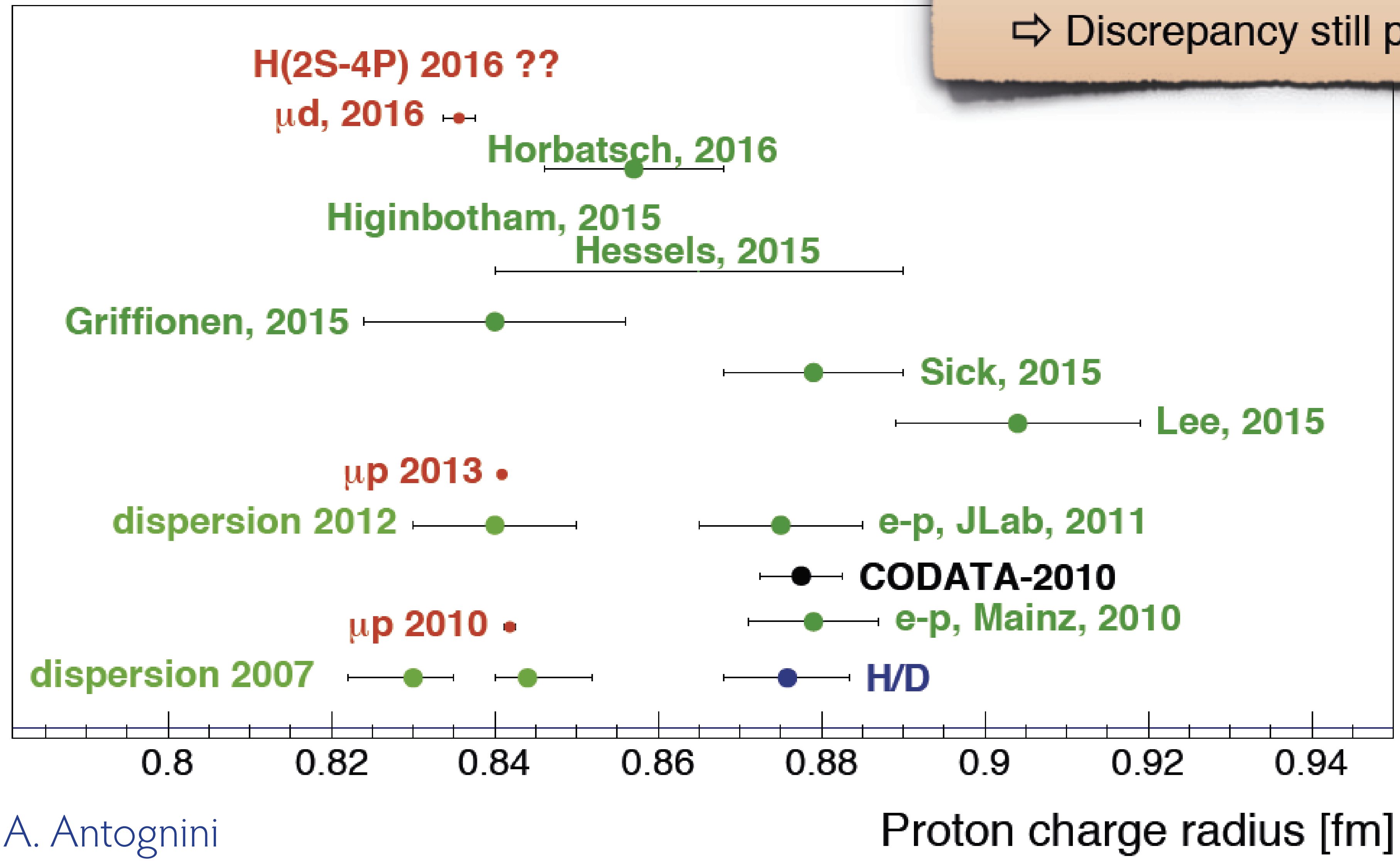


- Scattering experiments happen at finite momentum transfer Q^2
- They will see some of the proton substructure
- Charge radius is defined as the slope of the form factor at $Q^2 = 0$
- Need to extrapolate: Potentially large error: Choice of data points, fit function...

Bernauer, Distler, arXiv:1606.02159
Sick, Trautmann, arXiv:1701.01809
Horbatsch, Hessels, Pineda, arXiv:1610.09760
Lee, Arrington, Hill, arXiv:1505.01489

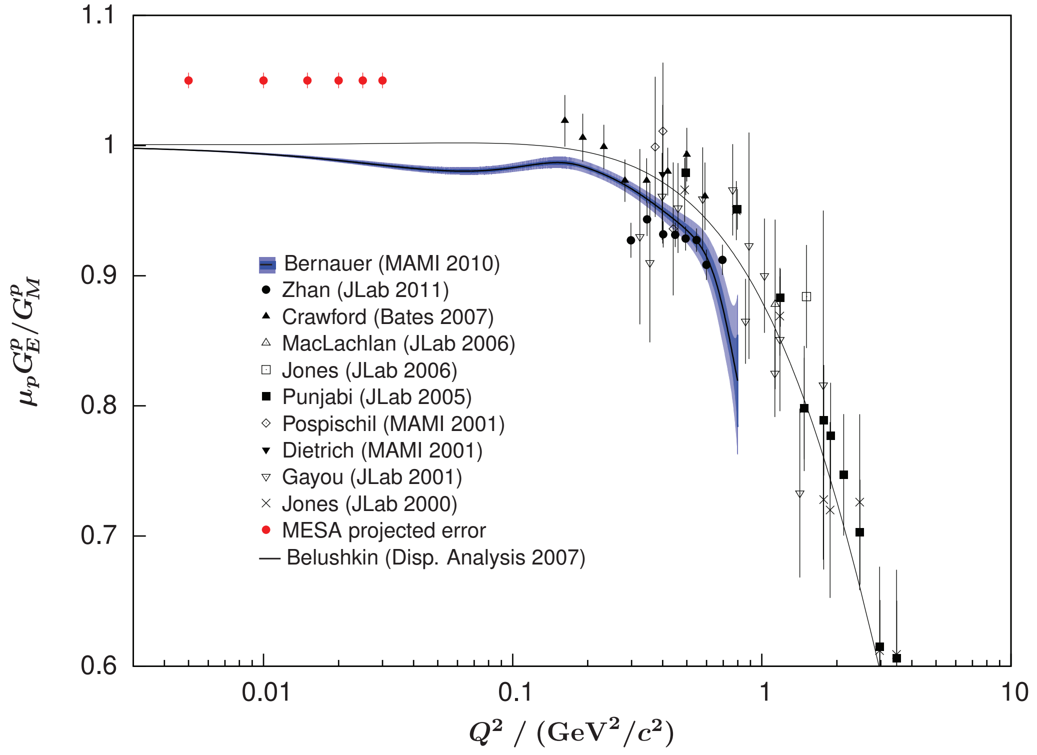
Various e-p scattering analysis in agreement with muonic results **BUT** these analysis are opposed by the experts of the field.

⇨ Discrepancy still persists



A. Antognini

Scattering, Q^2 and substructure



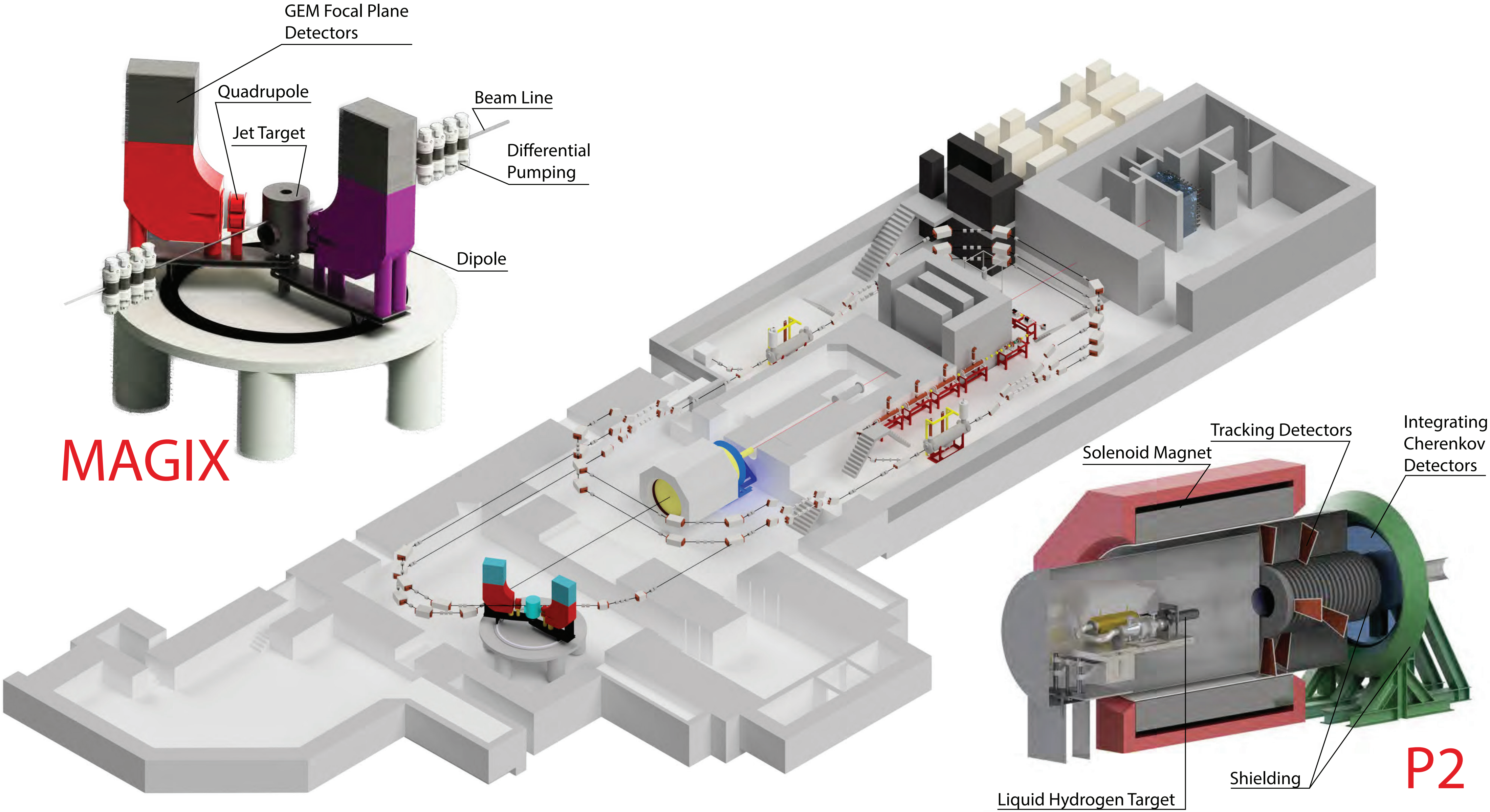
- Scattering experiments happen at finite momentum transfer Q^2
- They will see some of the proton substructure
- Charge radius is defined as the slope of the form factor at $Q^2 = 0$
- Need to extrapolate: Potentially large error
- Want to measure at as small Q^2 as possible and with large lever arm

Our project in Mainz:

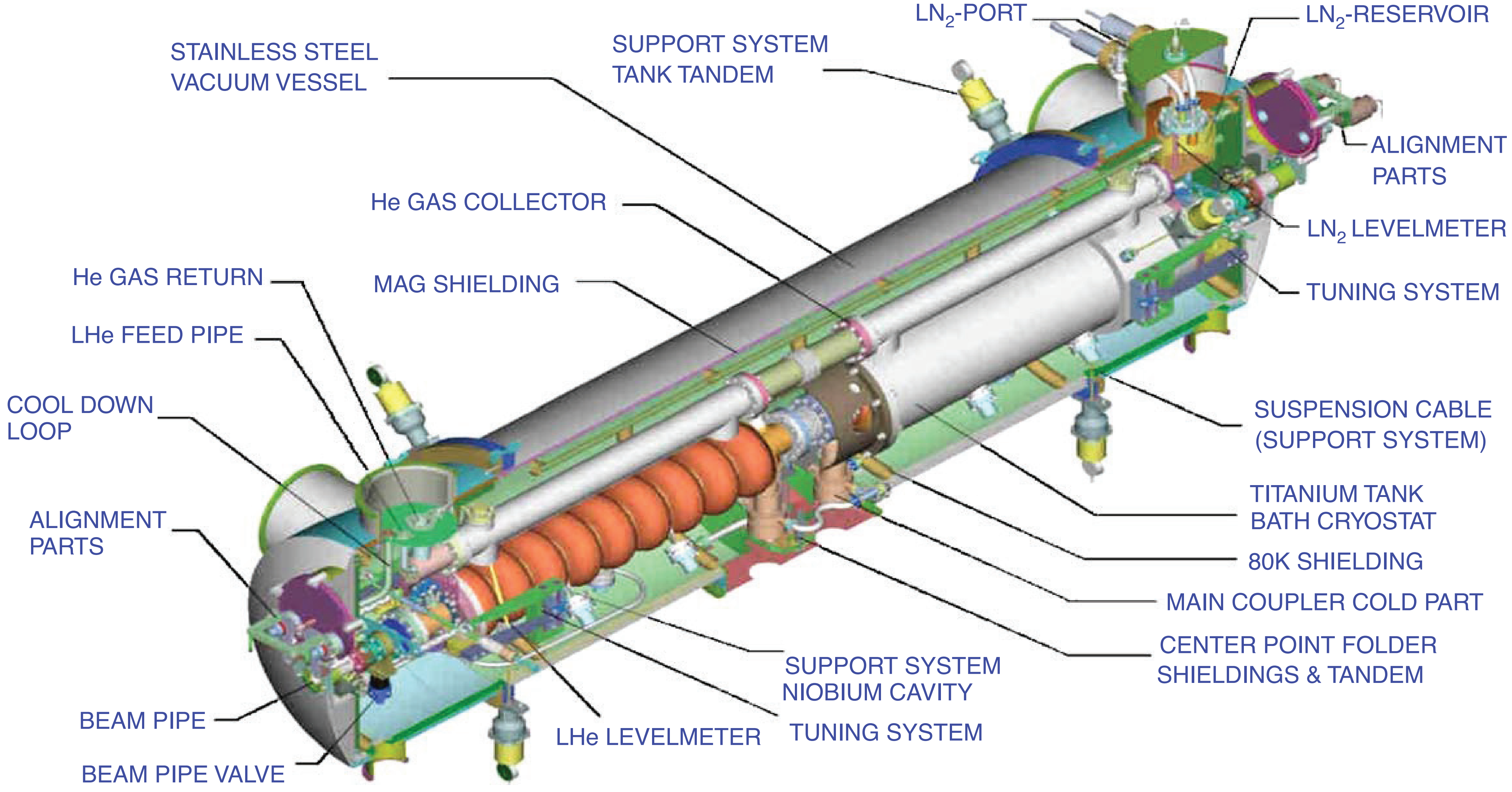
MAGIX

Mesa Gas Internal Target Experiment

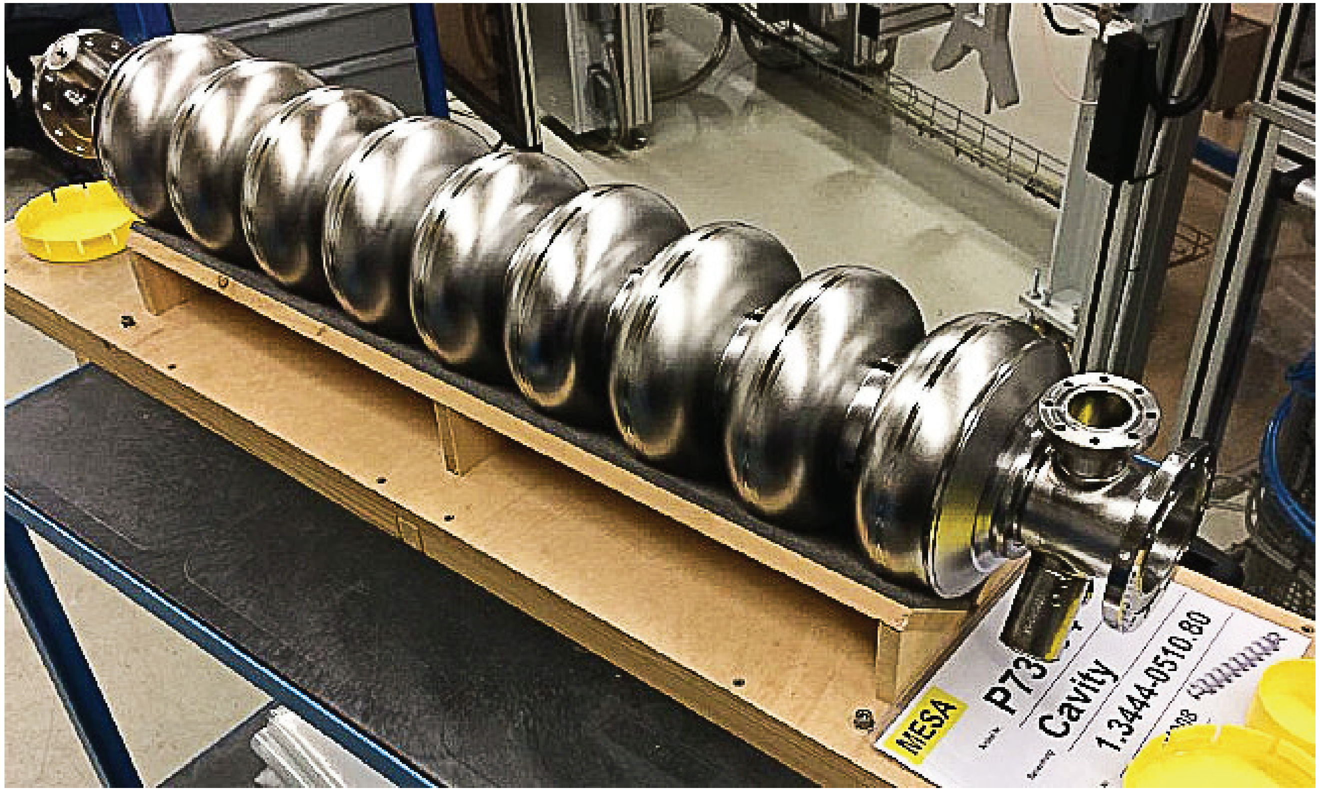
Mainz Energy-Recovery Superconducting Accelerator



Superconducting Cryomodules



Teichert et al. NIM A 557 (2006) 239


MESA
P73
Cavity
1.3444-0510.80

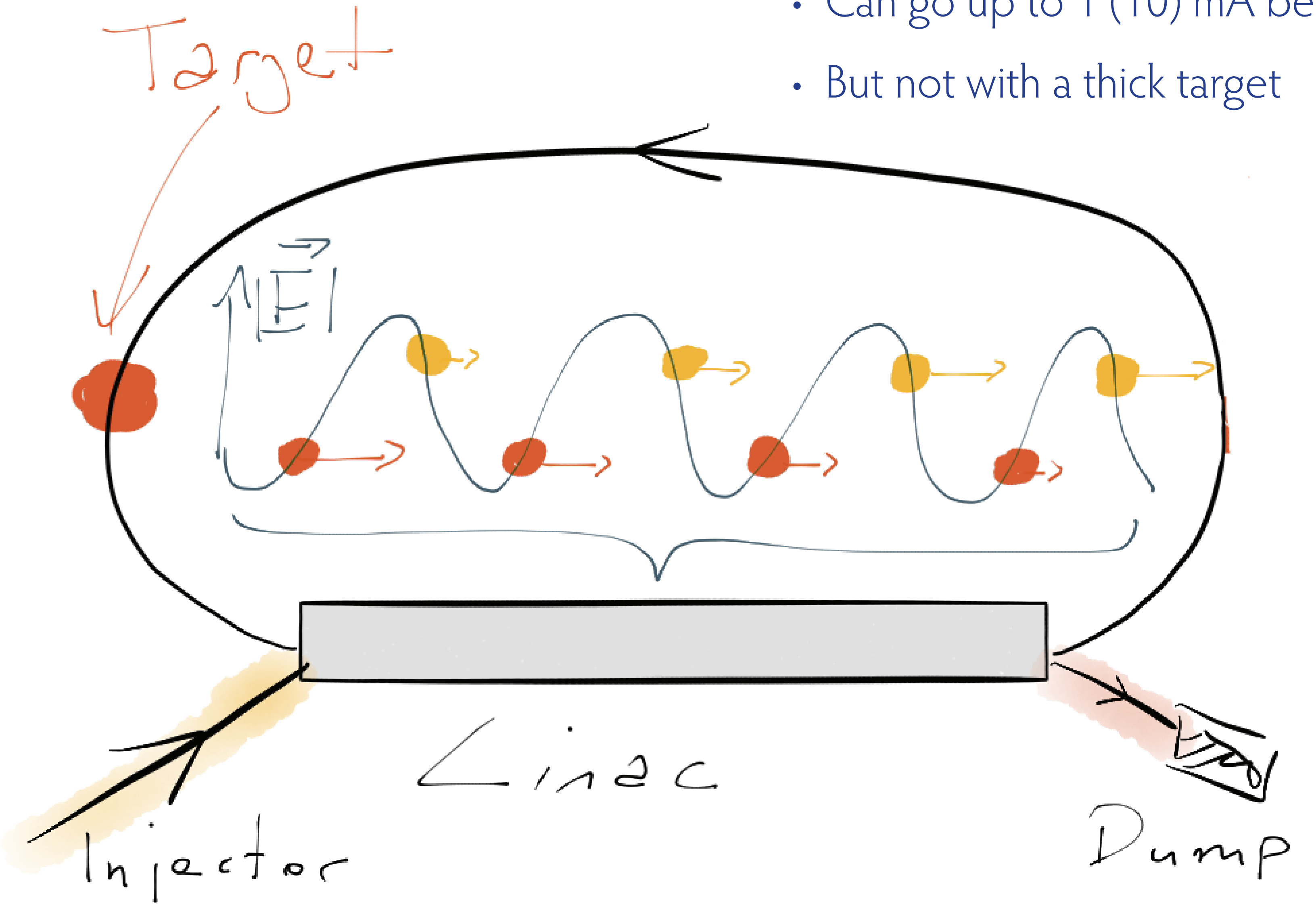

research
instruments

Energy recovery

Can we go to higher beam currents?

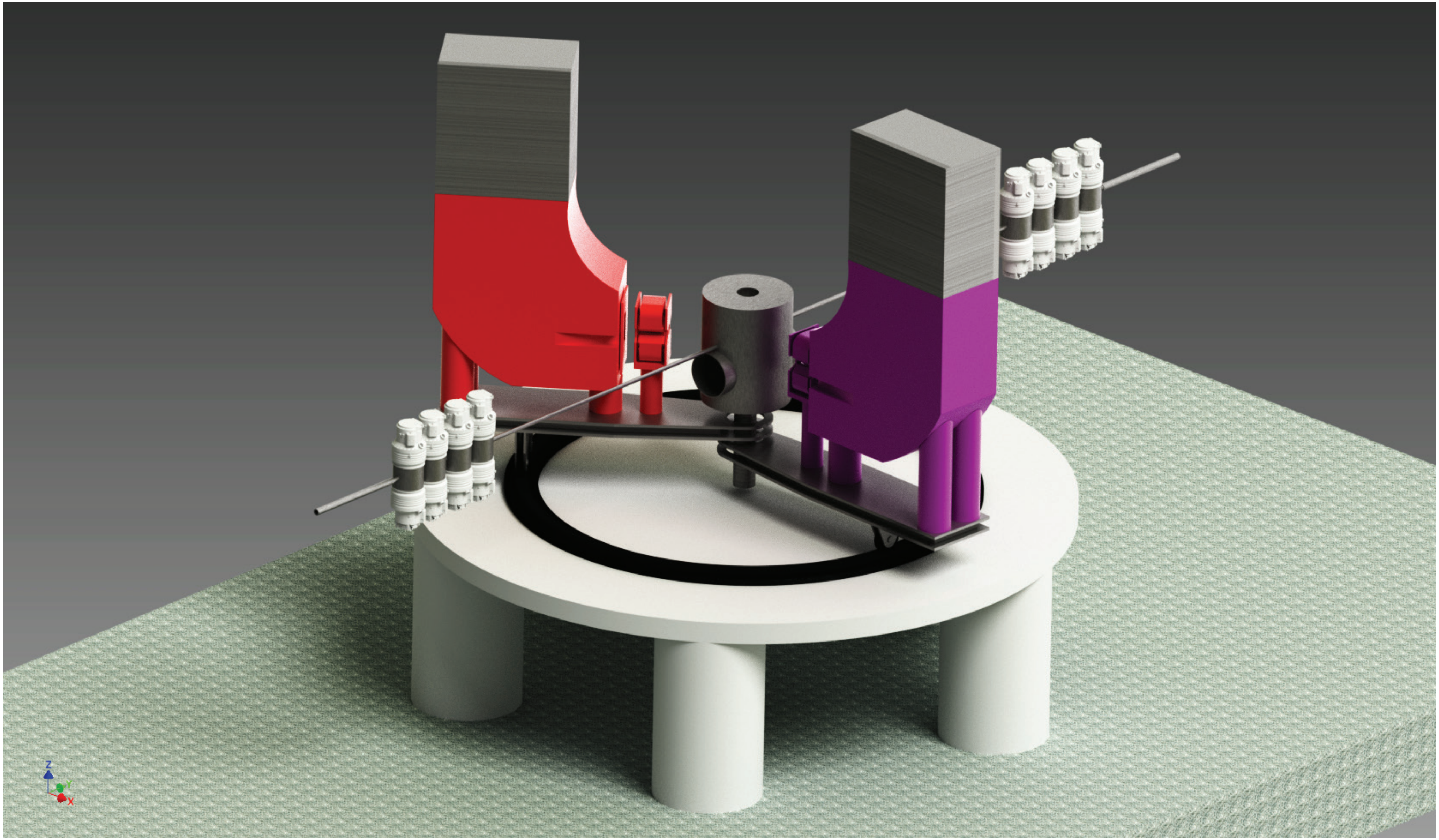
- In principle yes...
- But power is expensive
- Why dump electrons?

Energy recovery



- Put energy back into field!
- Can go up to 1 (10) mA beam current
- But not with a thick target

MAGIX Spectrometer



Requirements for the detector

Energy recovery: We want the beam back

- Energy loss less than 10^{-3}
- As little scattering as possible

No target window

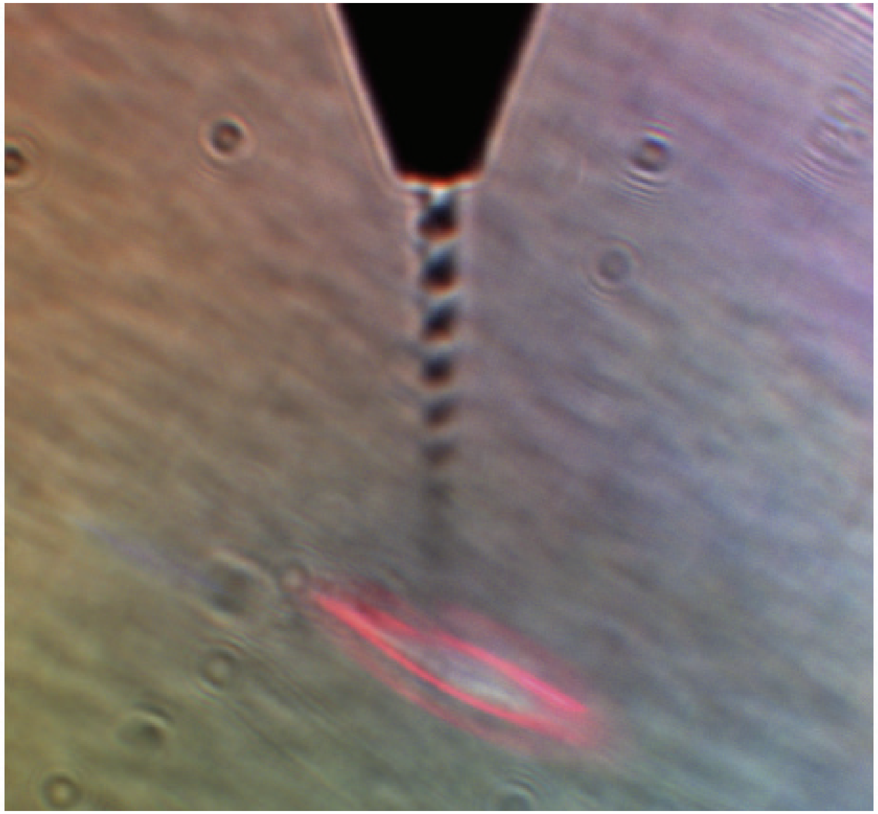
High resolution spectrometer

- No beam interactions in target window
- As little scattering as possible

Thin walls, thin detectors

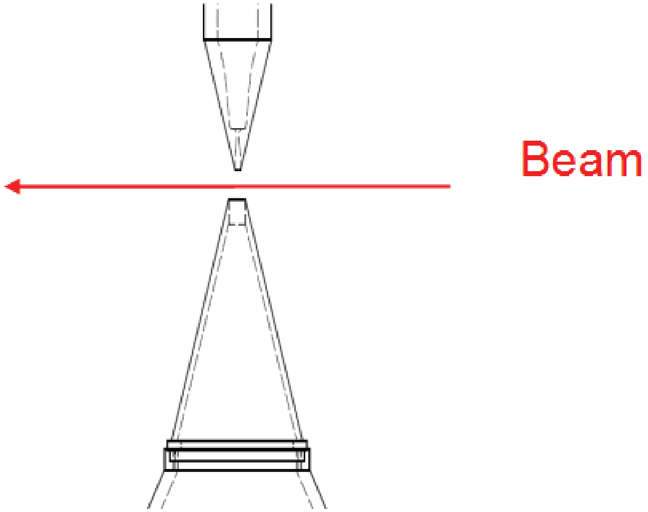
Extremely intense beam: Do not need very high acceptance

Internal gas target

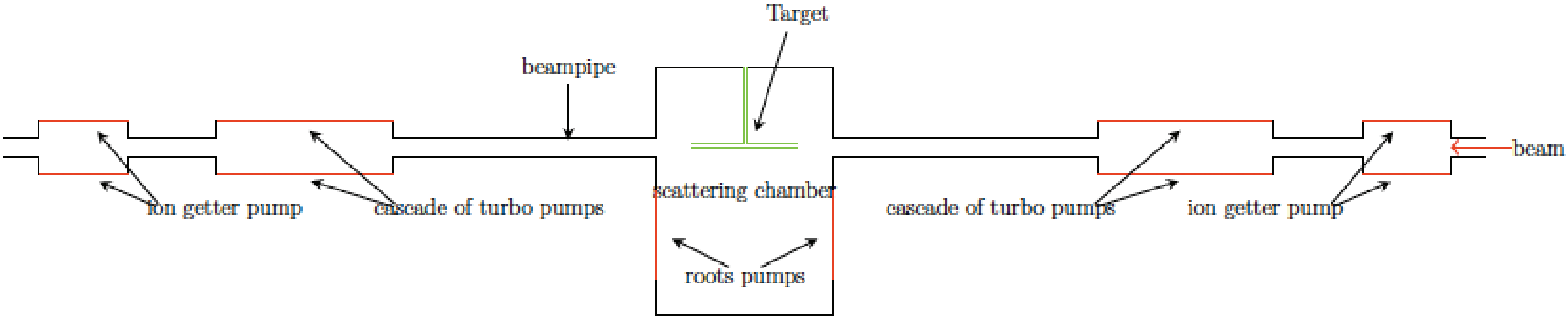


University of Münster (Group of A. Khoukaz)

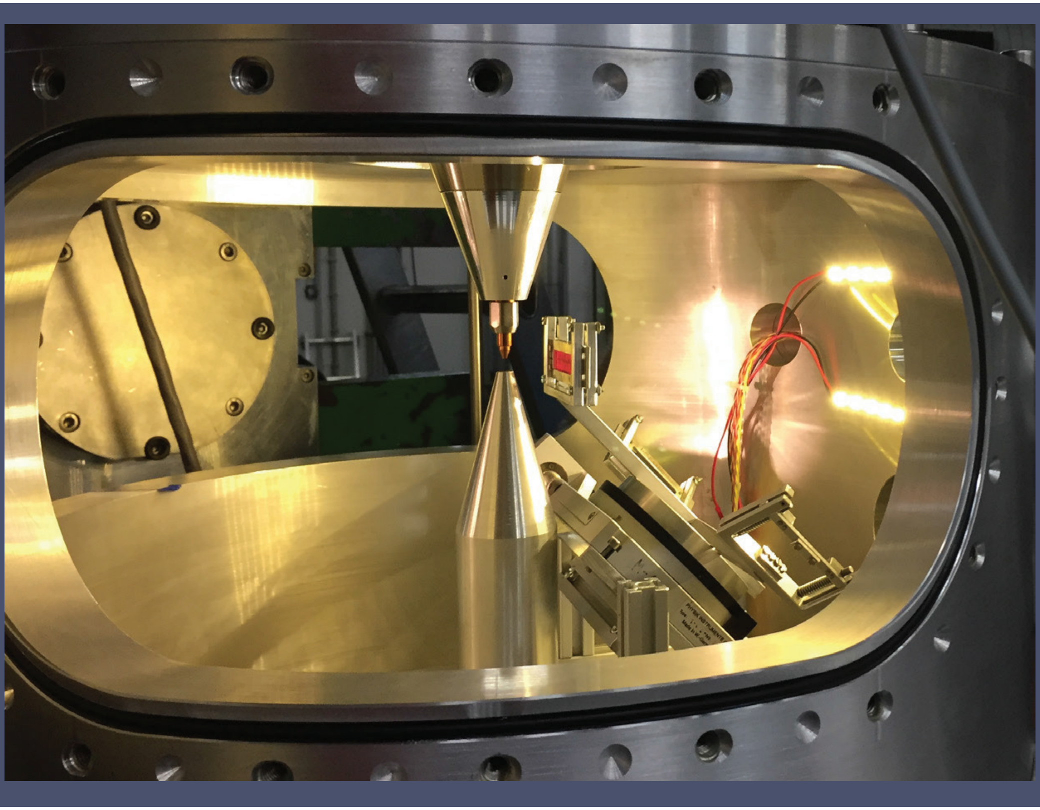
- Inject gas directly into the beam pipe

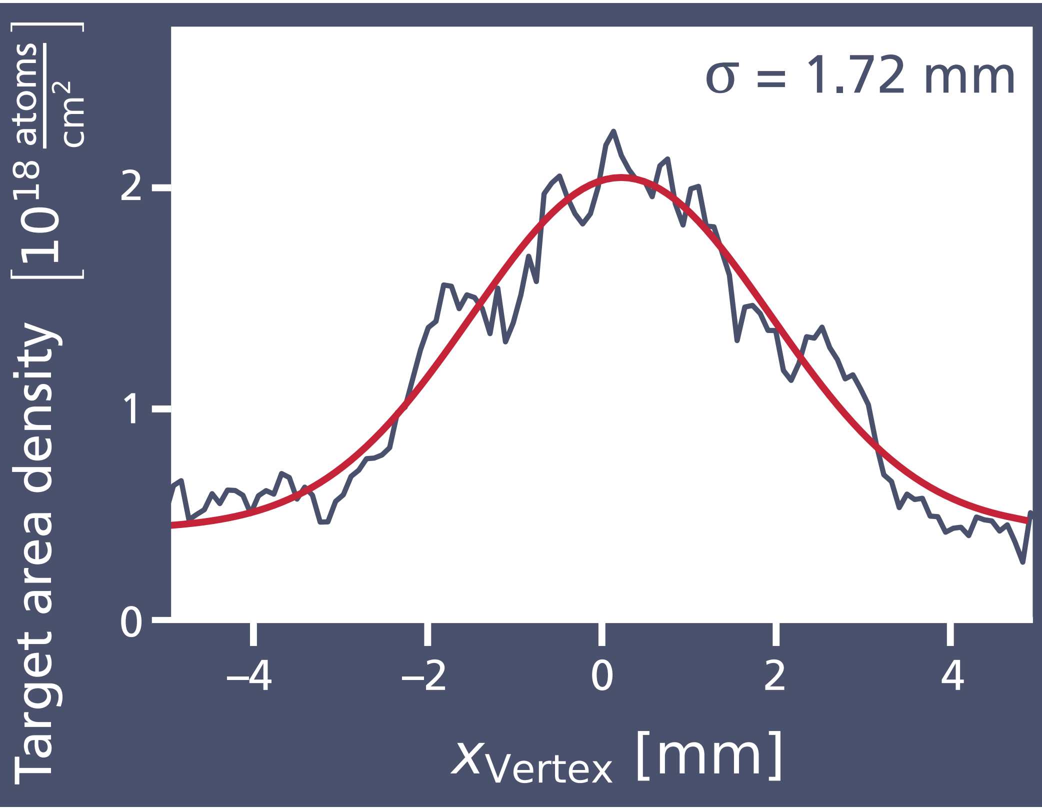


- Differential pumping to keep beam vacuum



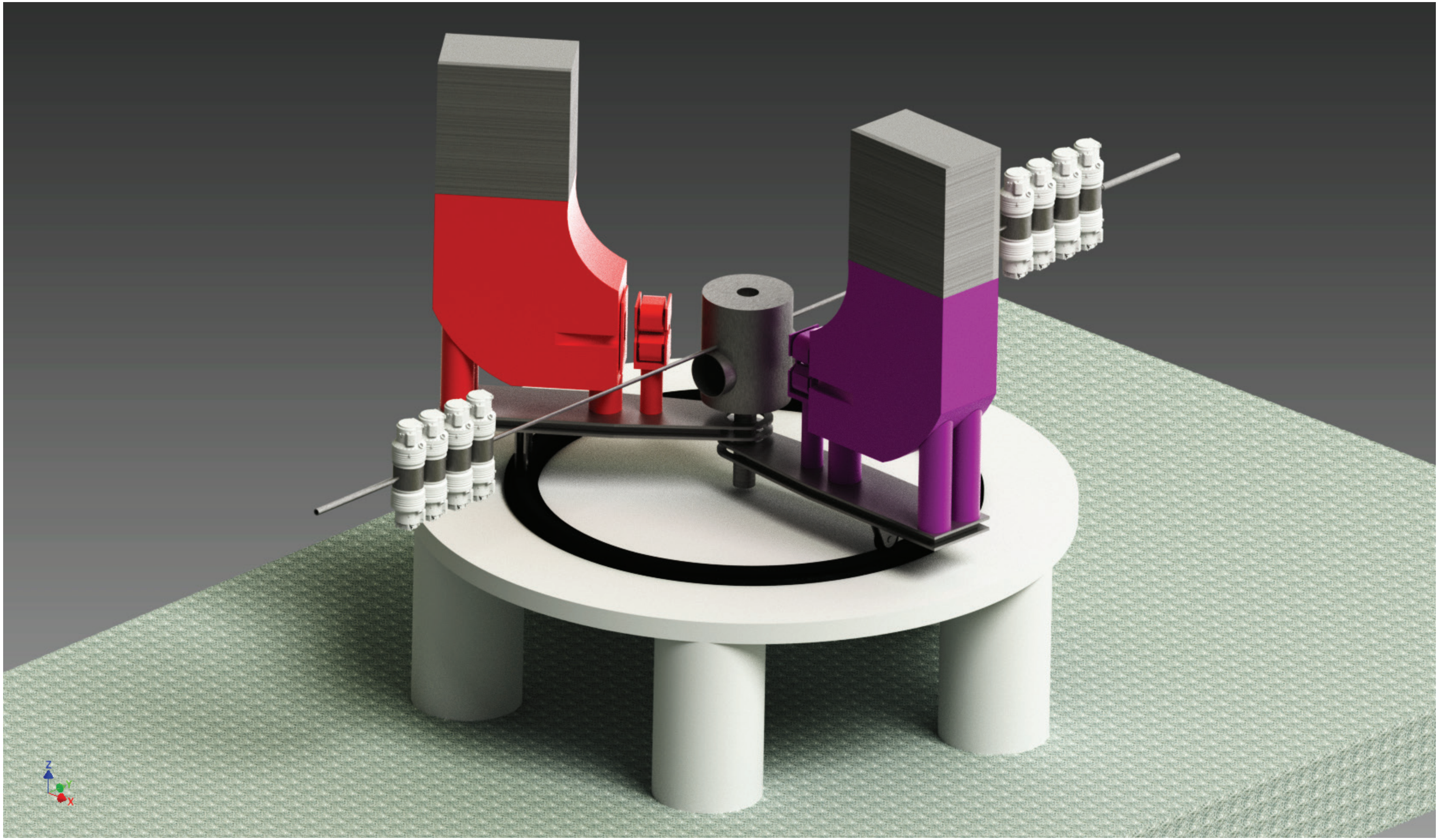
Tested in A1




σ = 1.72 mm
Target area density $[10^{18}\,\frac{\text{atoms}}{\text{cm}^2}]$
0
1
2
−4
−2
0
2
4
x_{Vertex} [mm]

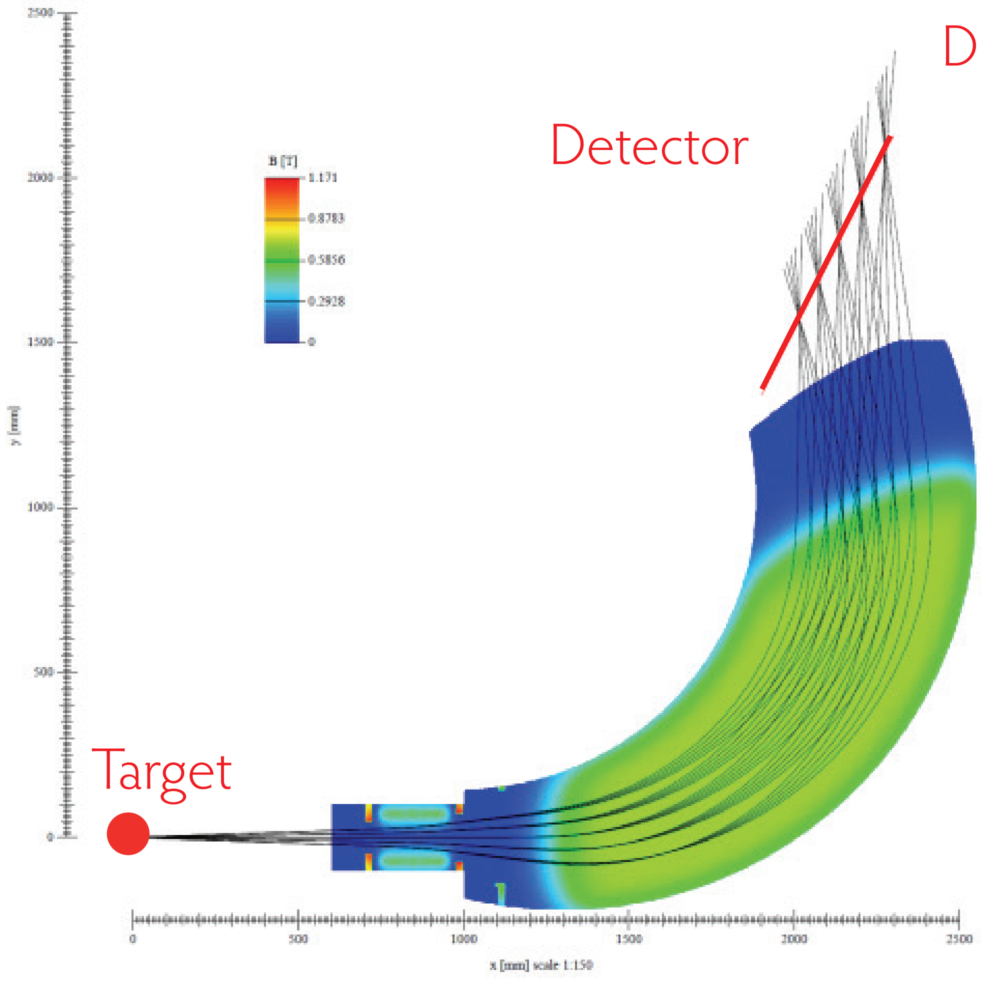
TARDIS

Twin-arm dipole spectrometer

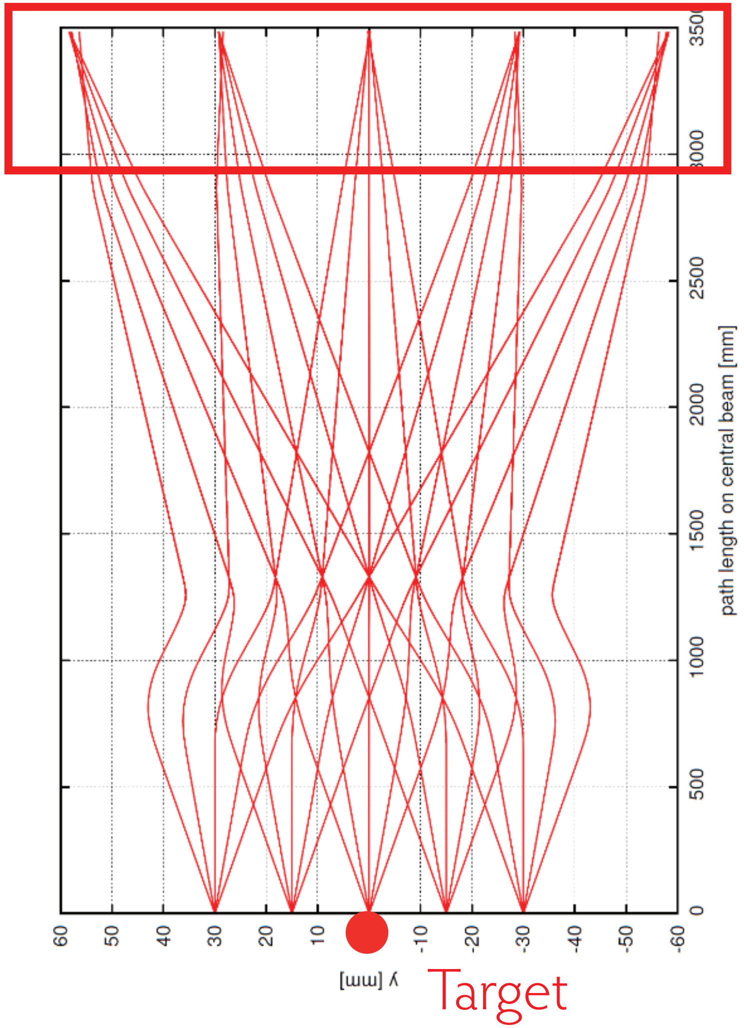


TARDIS

- Image momentum to position
- 10^{-4} momentum resolution for 50 µm position resolution



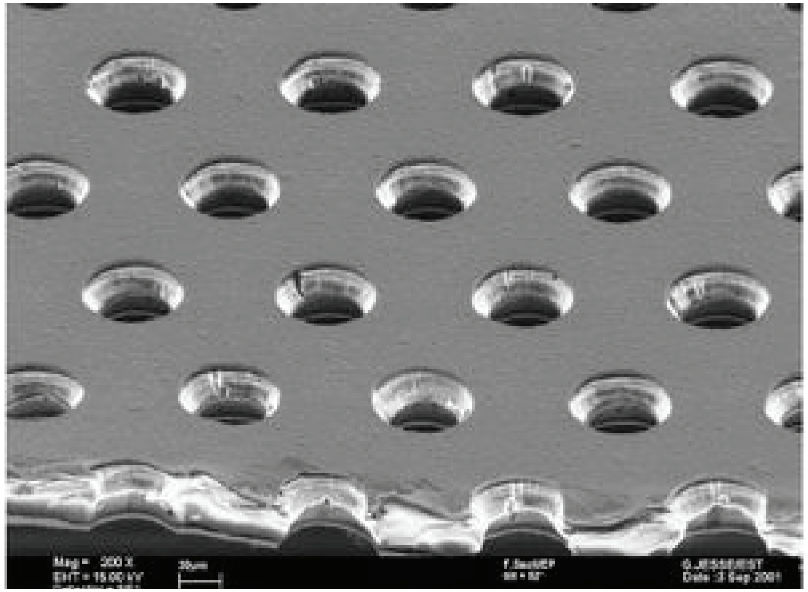
- Image angle to position

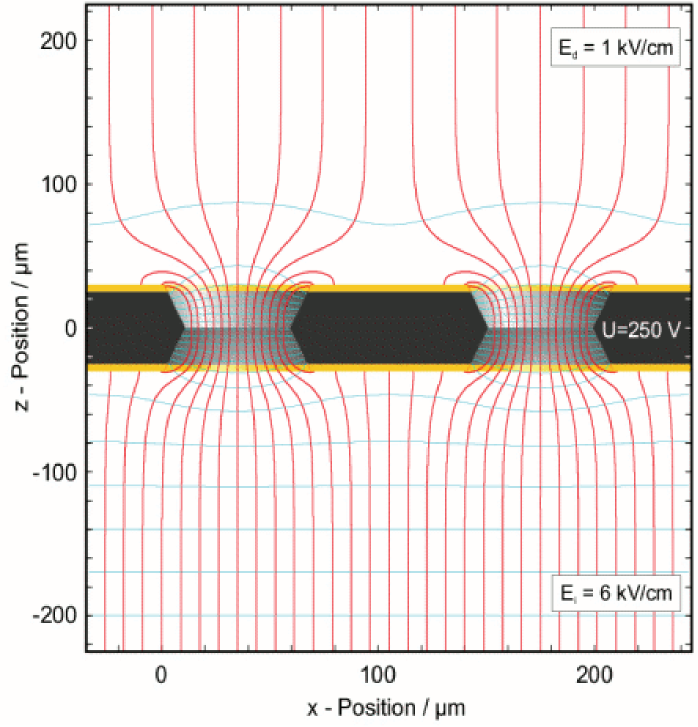


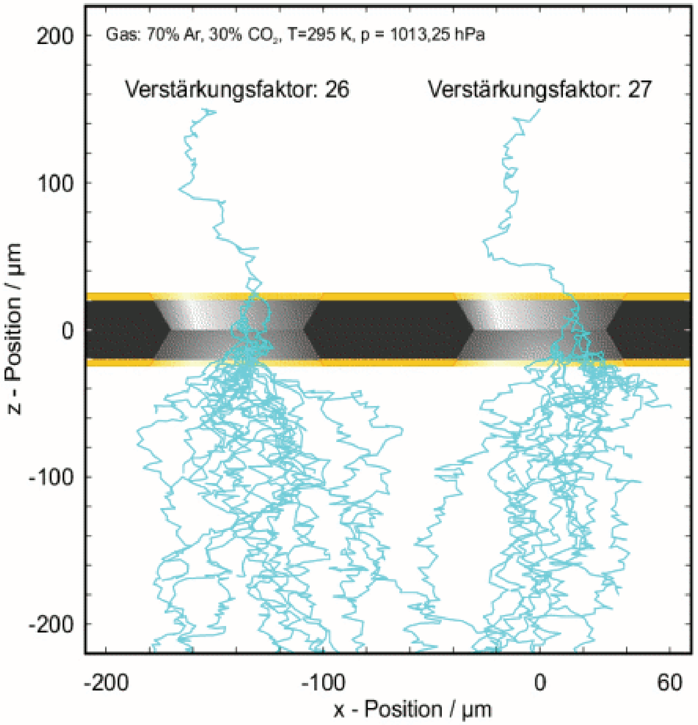
Focal plane detectors

Gas Electron Multipliers (GEMs)

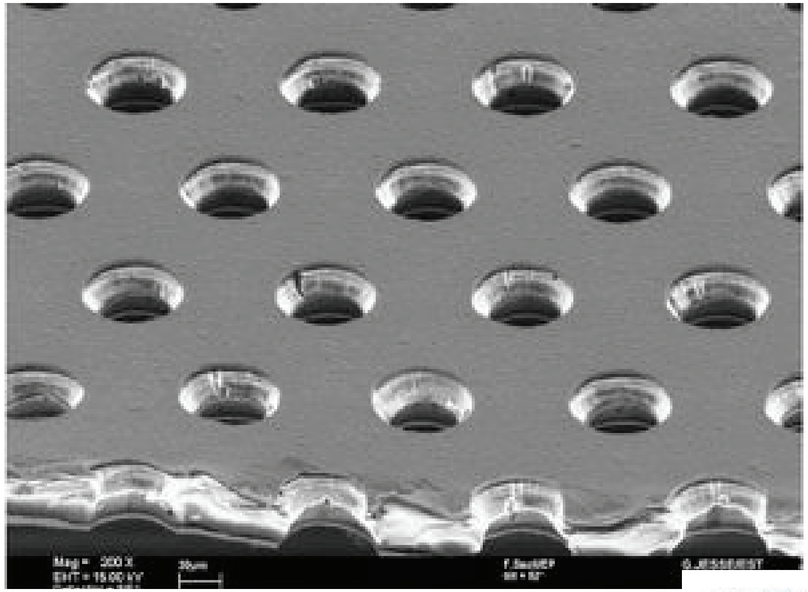
- Metalized Kapton foil with tiny holes
- Apply electric field





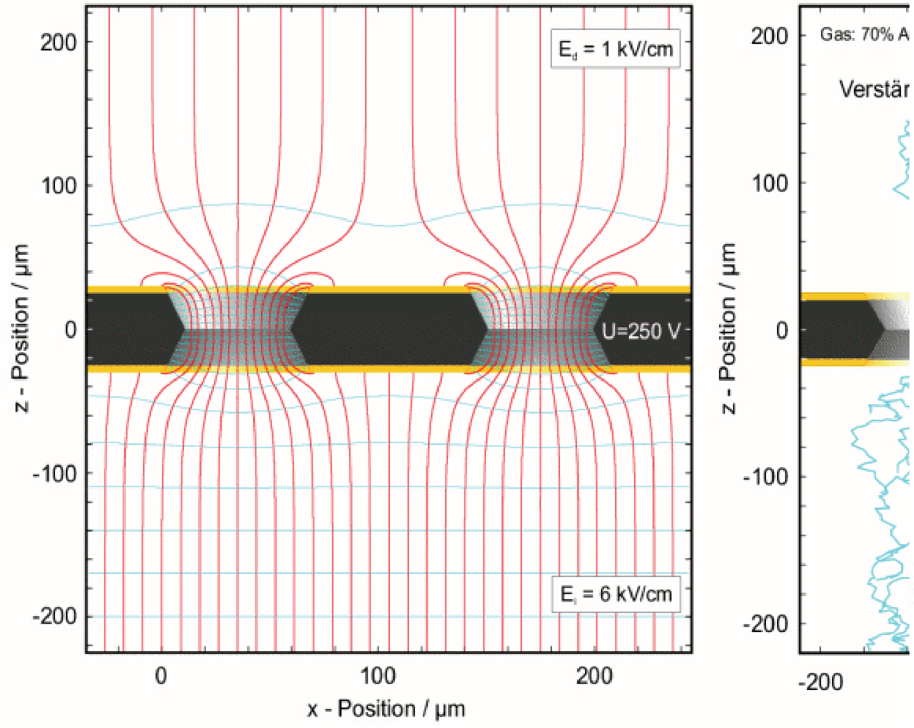


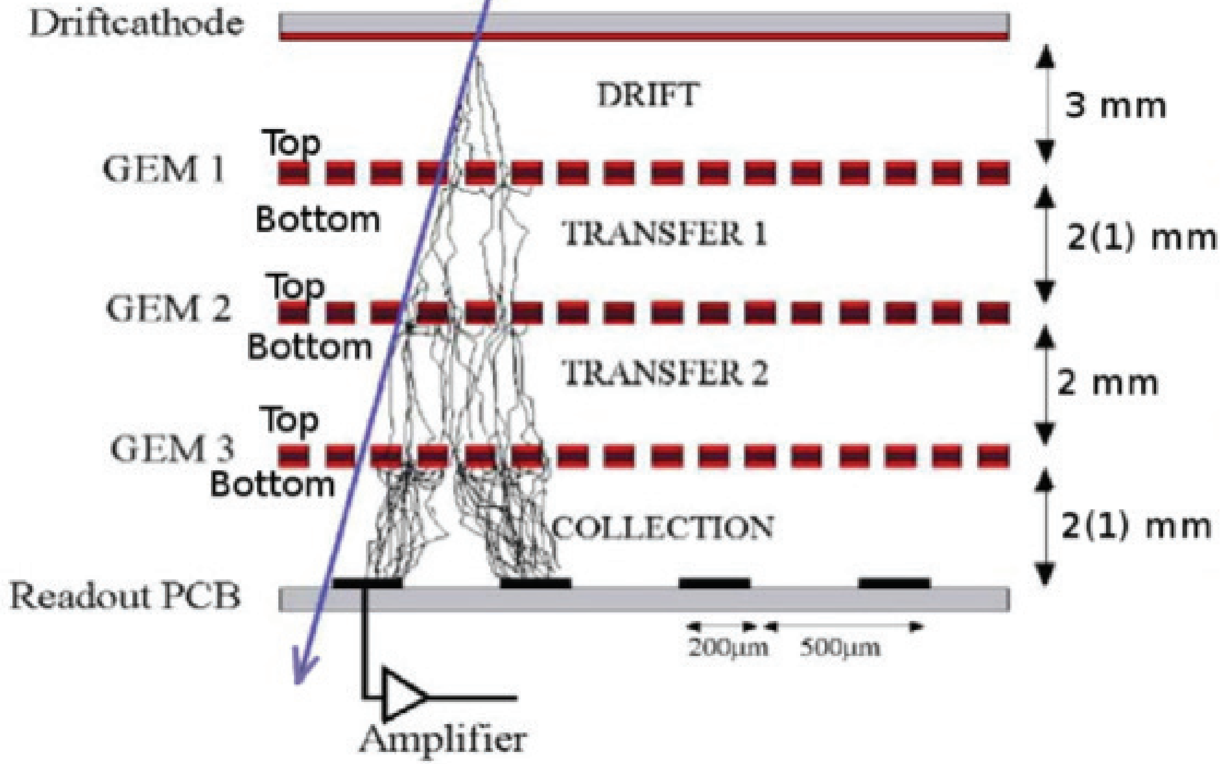
Focal plane detectors



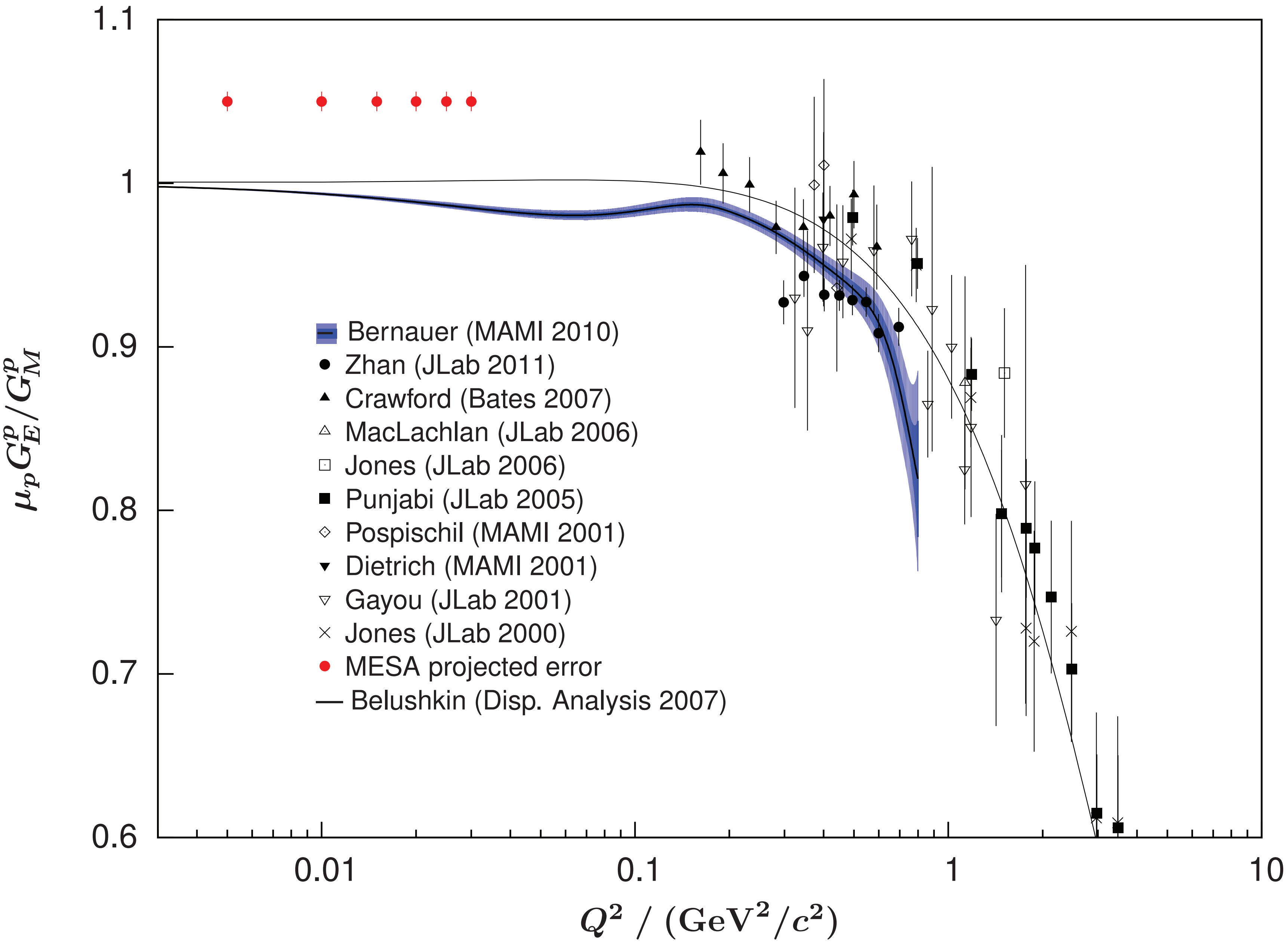
Gas Electron Multipliers (GEMs)

- Metalized Kapton foil with tiny holes
- Apply electric field
- Stack GEMs to reduce ion back drift
- PRISMA detector lab



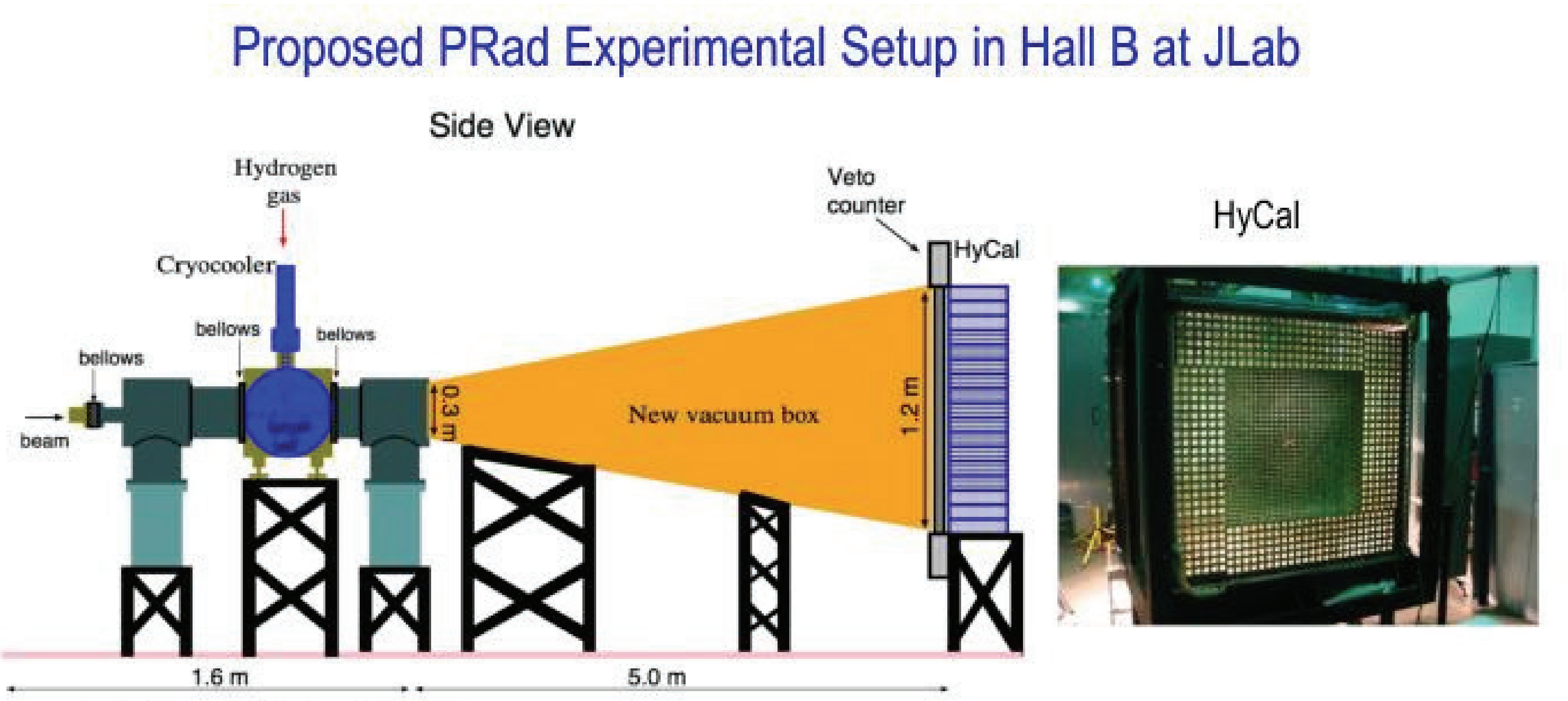


Where this could get us



Many other ongoing projects…

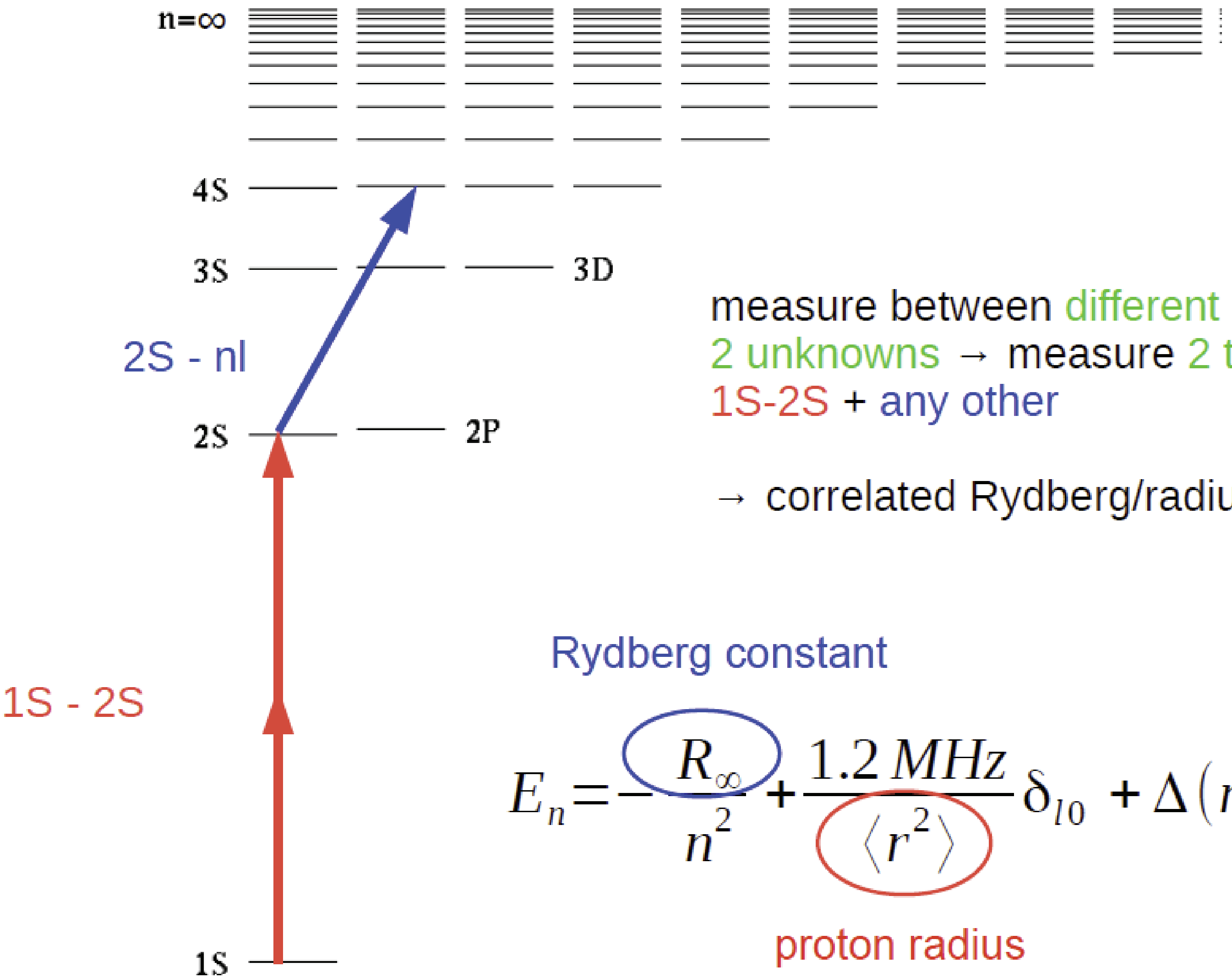
- PRad at Jefferson Lab
- PRAE at Orsay
- …



Proposed PRad Experimental Setup in Hall B at JLab

And the conventional spectroscopy?

Energy levels of hydrogen



measure between different n
2 unknowns → measure 2 transitions:
1S-2S + any other

→ correlated Rydberg/radius pairs

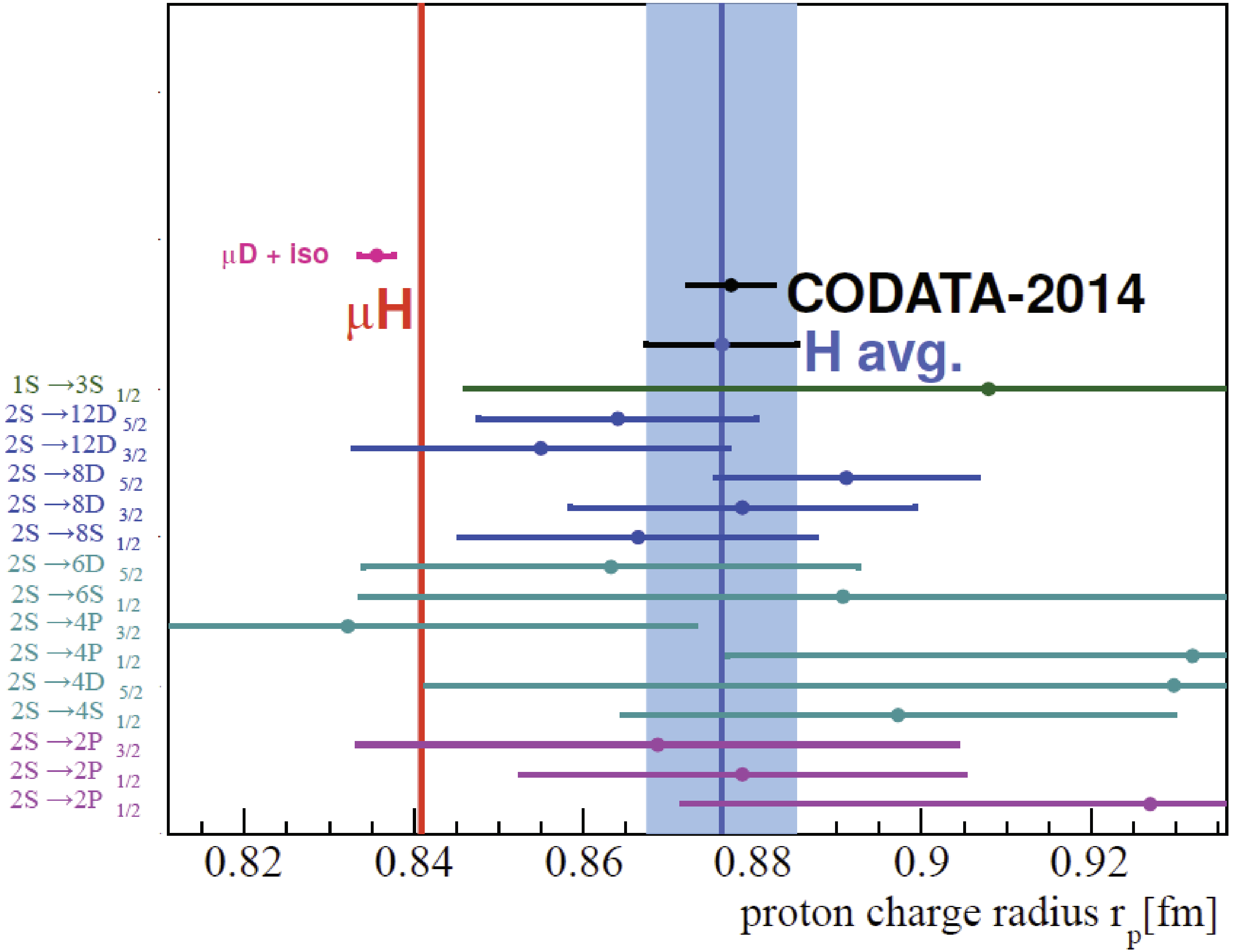
Rydberg constant

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{\langle r^2 \rangle}\delta_{l0} + \Delta(n,l,j)$$

proton radius

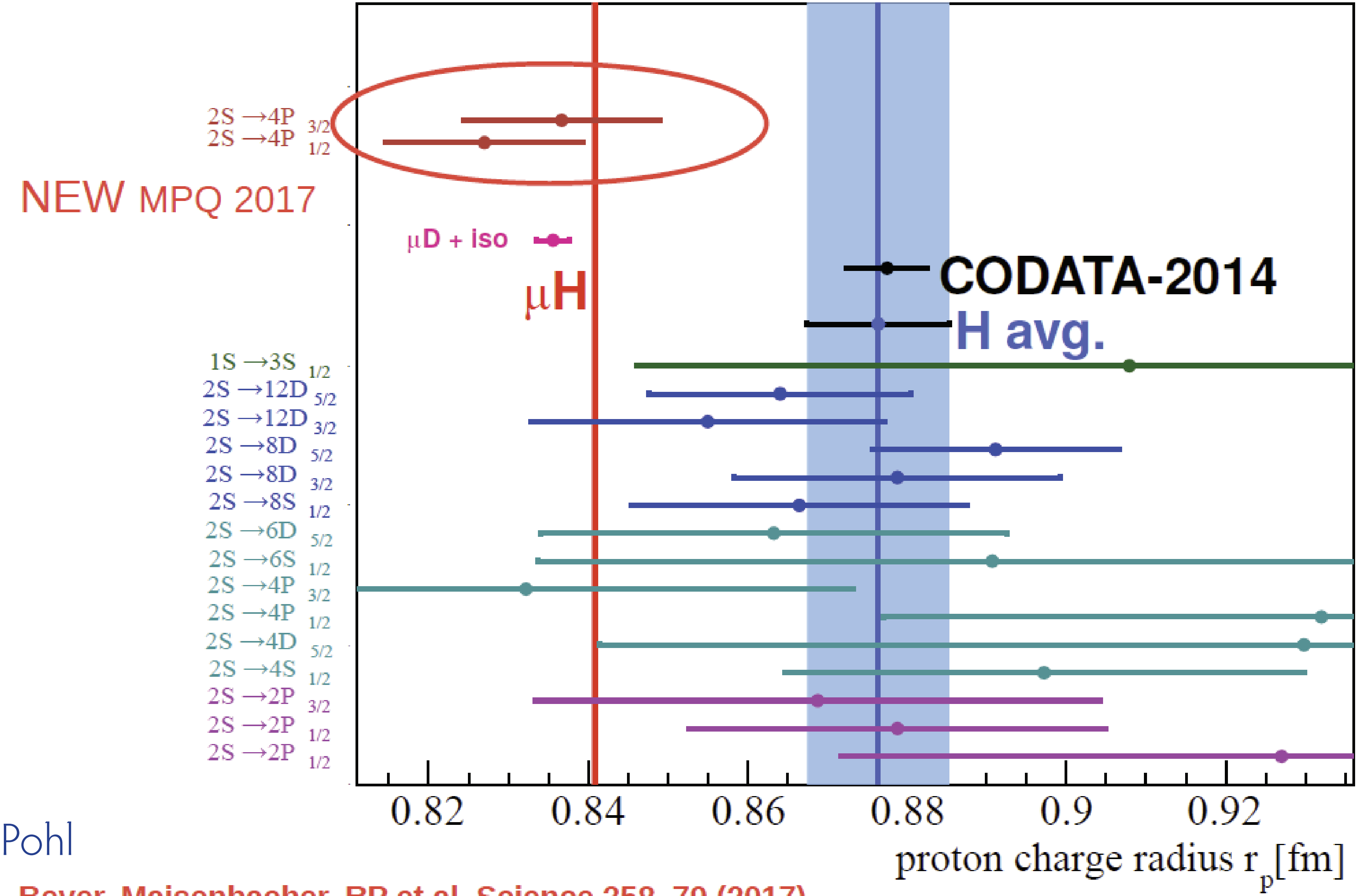
R. Pohl

Rp from H spectroscopy



R. Pohl

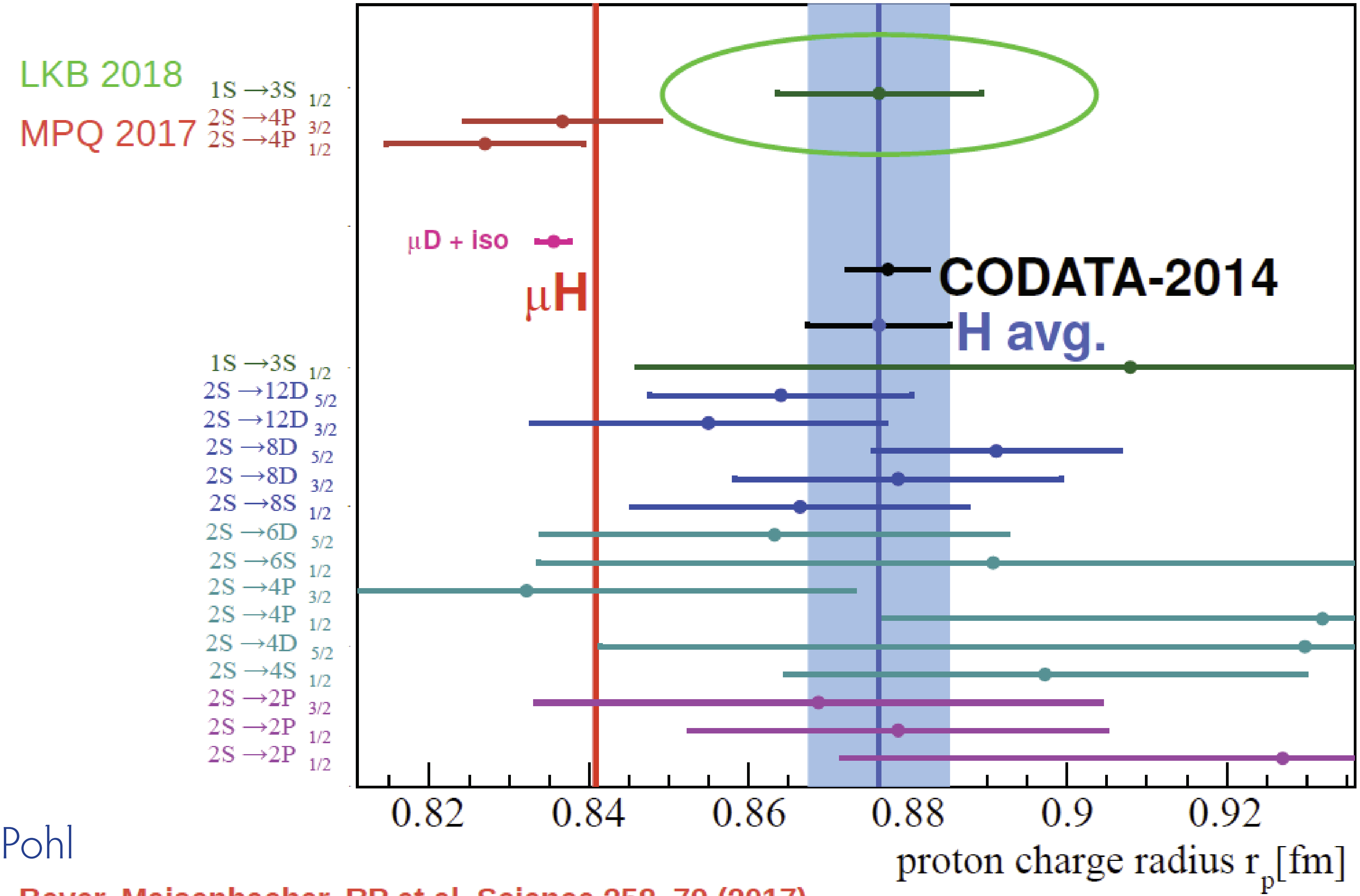
Rp from H spectroscopy



R. Pohl

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

Rp from H spectroscopy

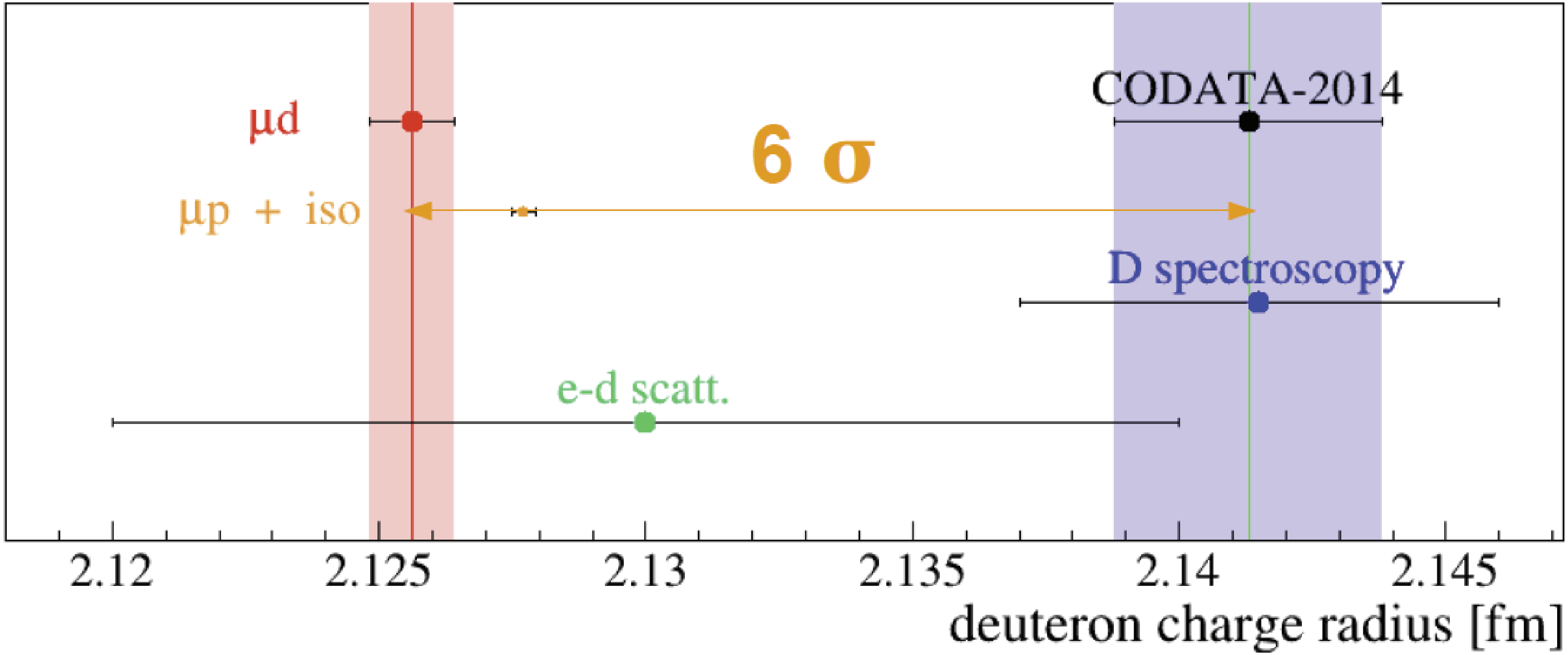


R. Pohl

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

Fleurbaey , PhD thesis (2017)

Muonic Deuterium



μD: 2.12562 (13)$_{\text{exp}}$ (77)$_{\text{theo}}$ fm (nucl. polarizability)

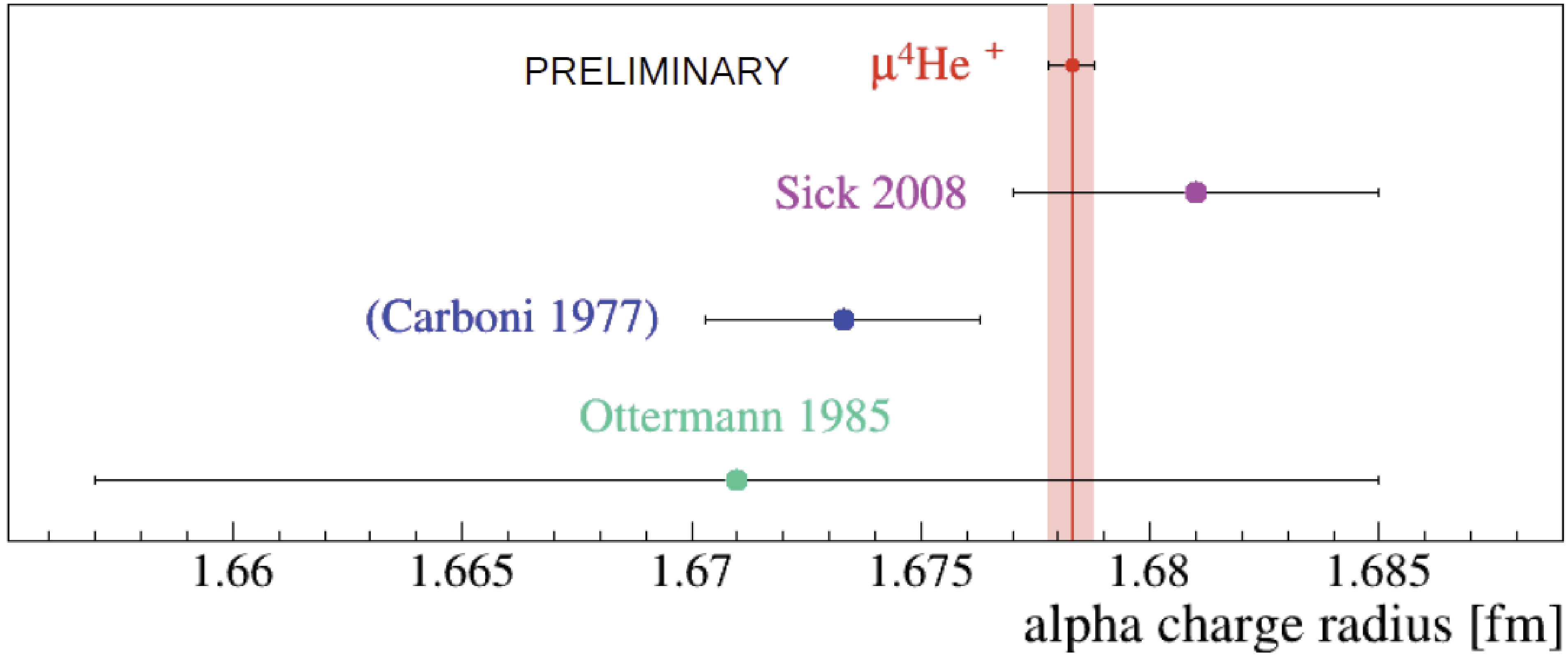
μH + H/D(1S-2S): 2.12771 (22) fm

CODATA-2014: 2.1**4**130 (250) fm

R. Pohl

RP et al. (CREMA Coll.), Science 353, 559 (2016)

Muonic Helium-4

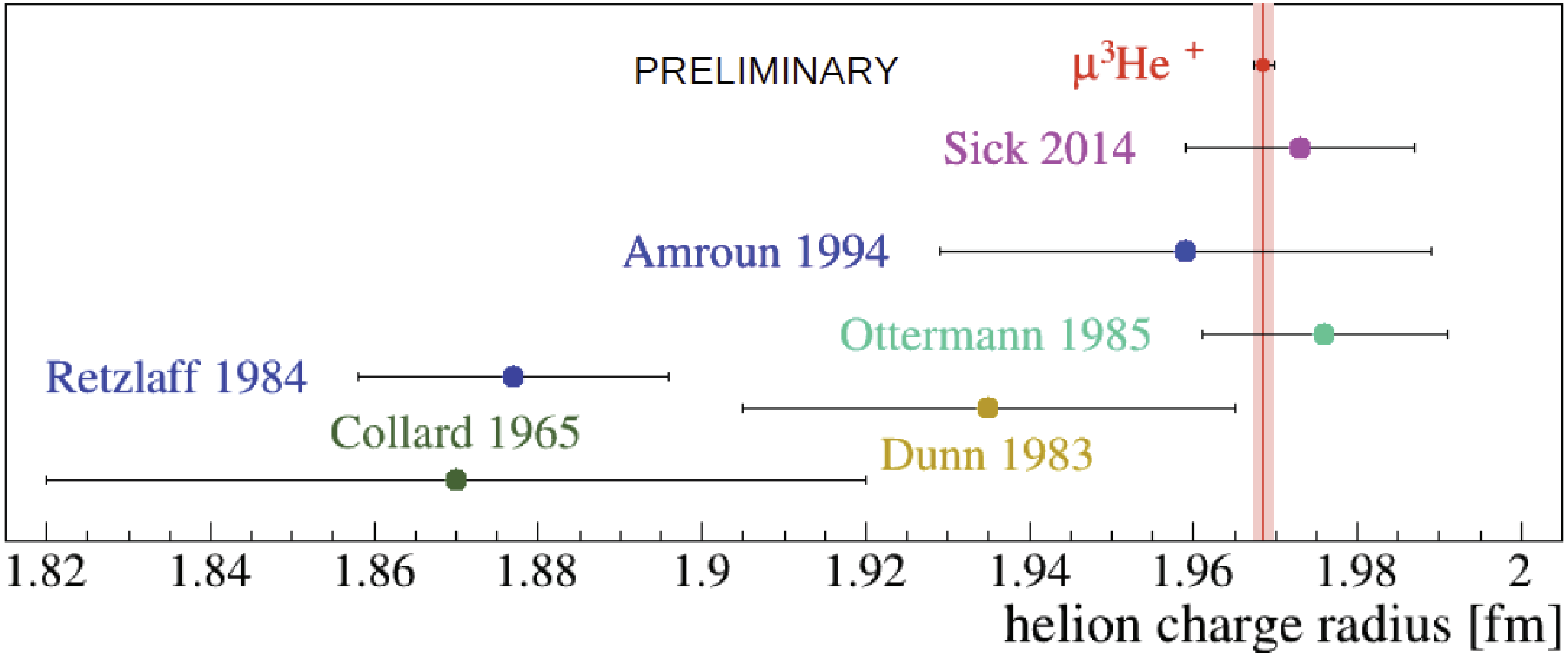


prel. accuracy: exp +- 0.00019 fm, theo +- 0.00058 fm (nucl. polarizability)

Theory: see Diepold et al. arxiv 1606.05231

R. Pohl

Muonic Helium-3



prel. accuracy: exp +- 0.00012 fm, theo +- 0.00128 fm (nucl. polarizability)

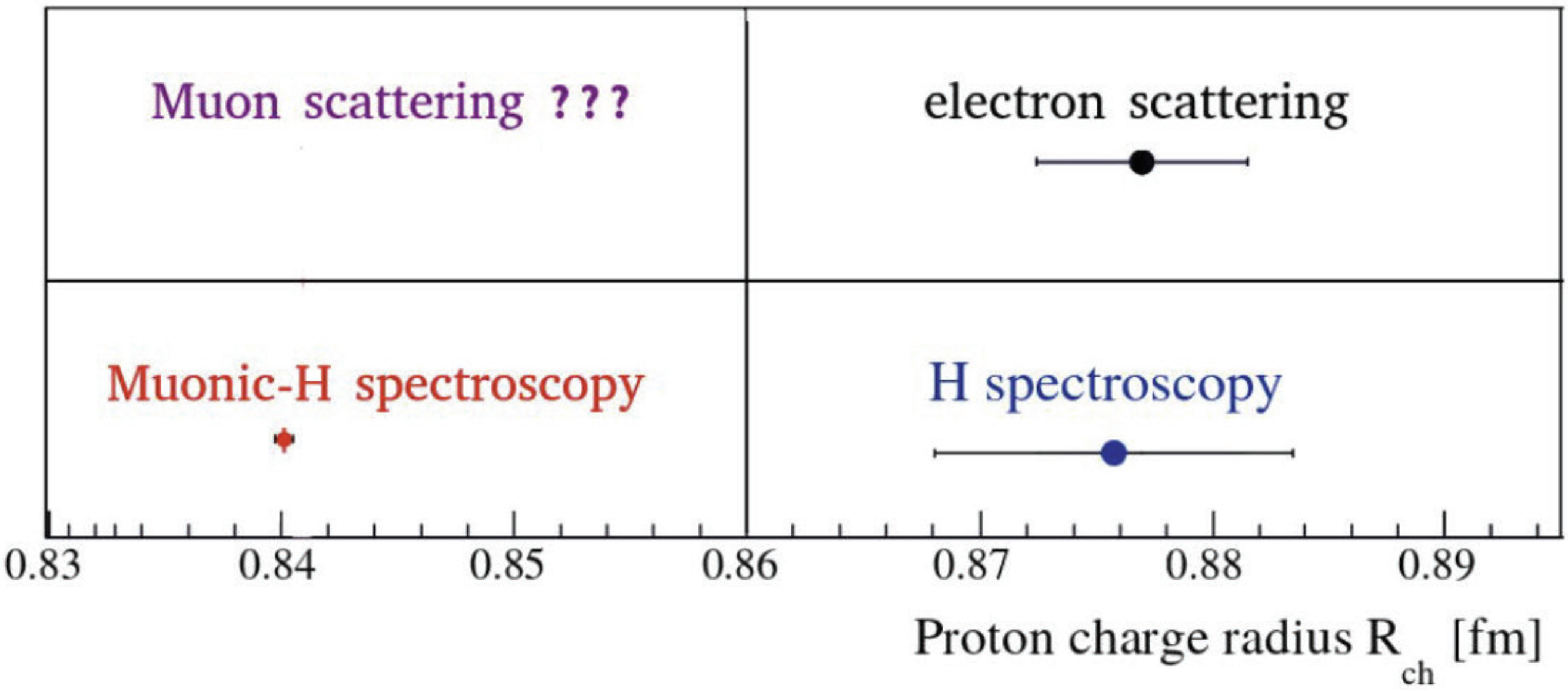
Theory: see Franke et al. EPJ D 71, 341 (2017) [1705.00352]

R. Pohl

Proton radius situation remains interesting...

could there be a difference between
muons and electrons interacting with the proton?

MUSE experiment at PSI


Muon scattering ???
electron scattering
Muonic-H spectroscopy
H spectroscopy
0.83
0.84
0.85
0.86
0.87
0.88
0.89
Proton charge radius R_{ch} [fm]

E. Downie

MUSE

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

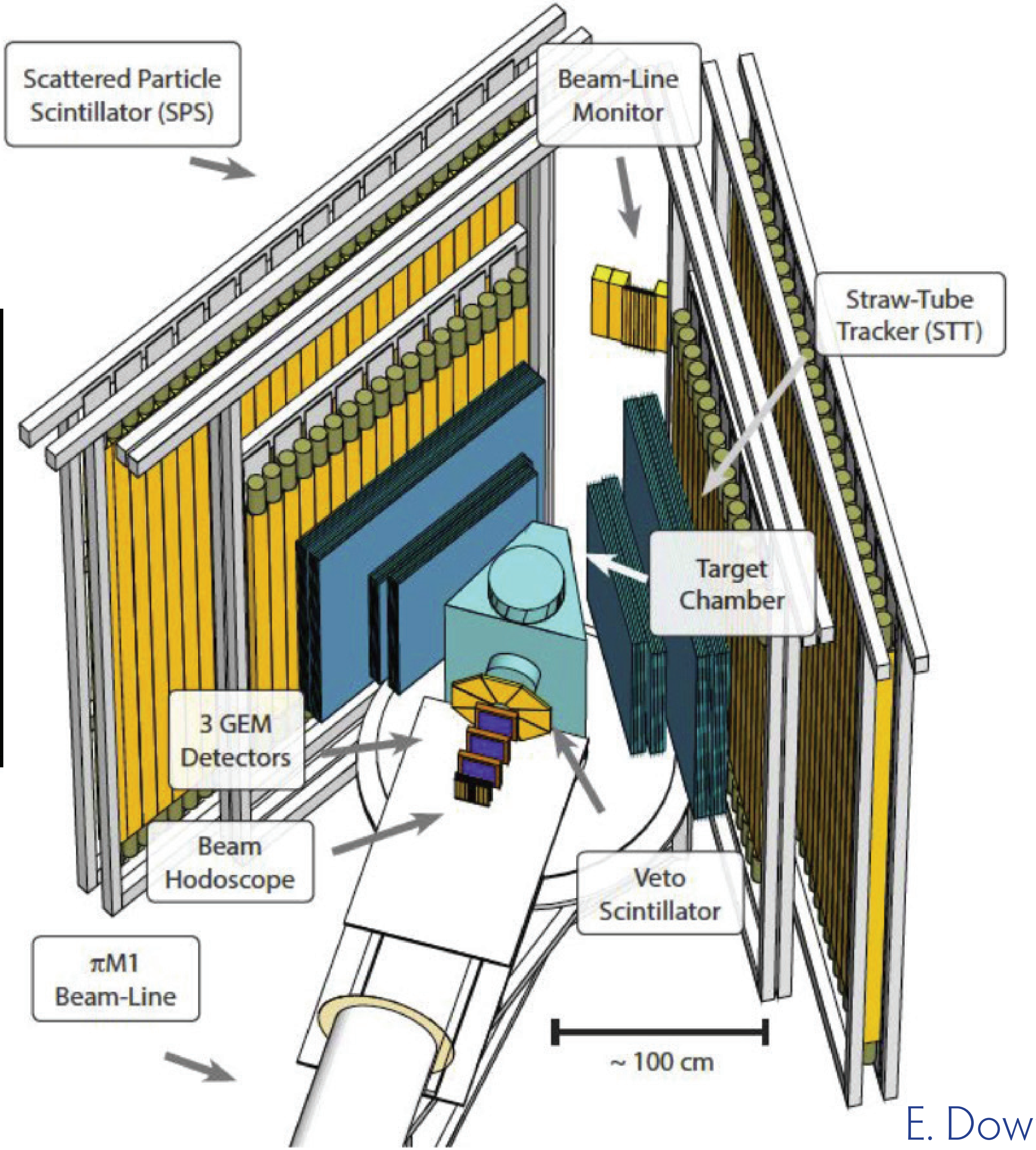
$Q^2 \approx 0.002 - 0.07\ \mathrm{GeV}^2$

3.3 MHz total beam flux

$\approx 2 - 15\%$ μ's

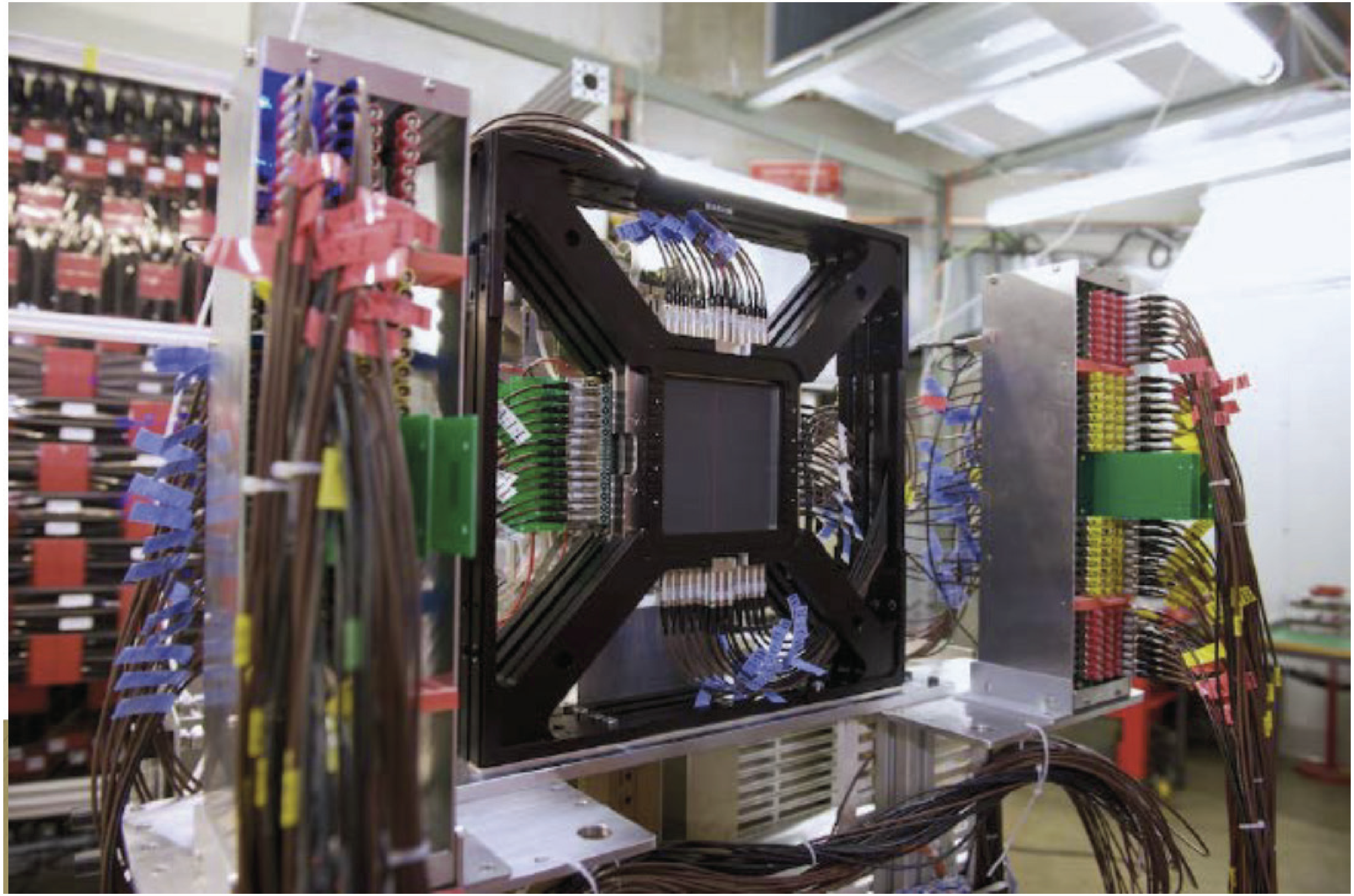
$\approx 10 - 98\%$ e's

$\approx 0 - 80\%$ π's

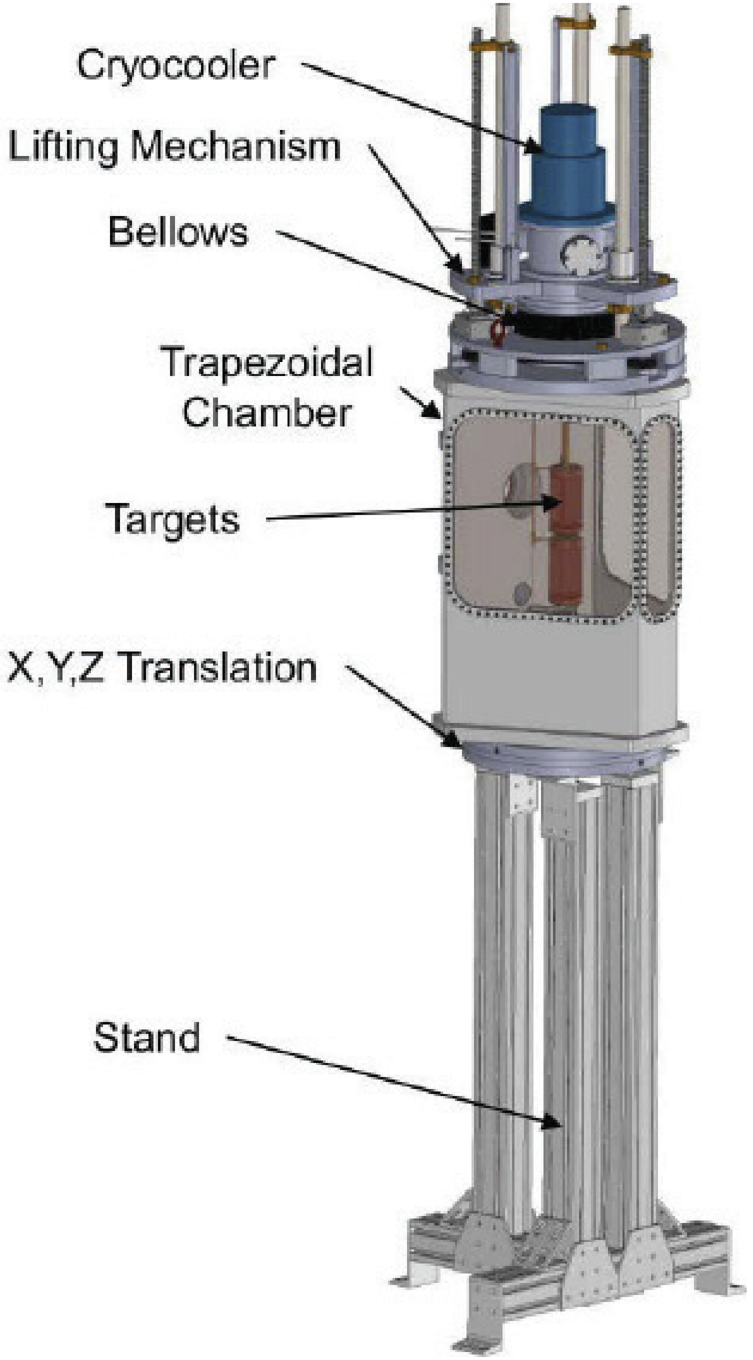


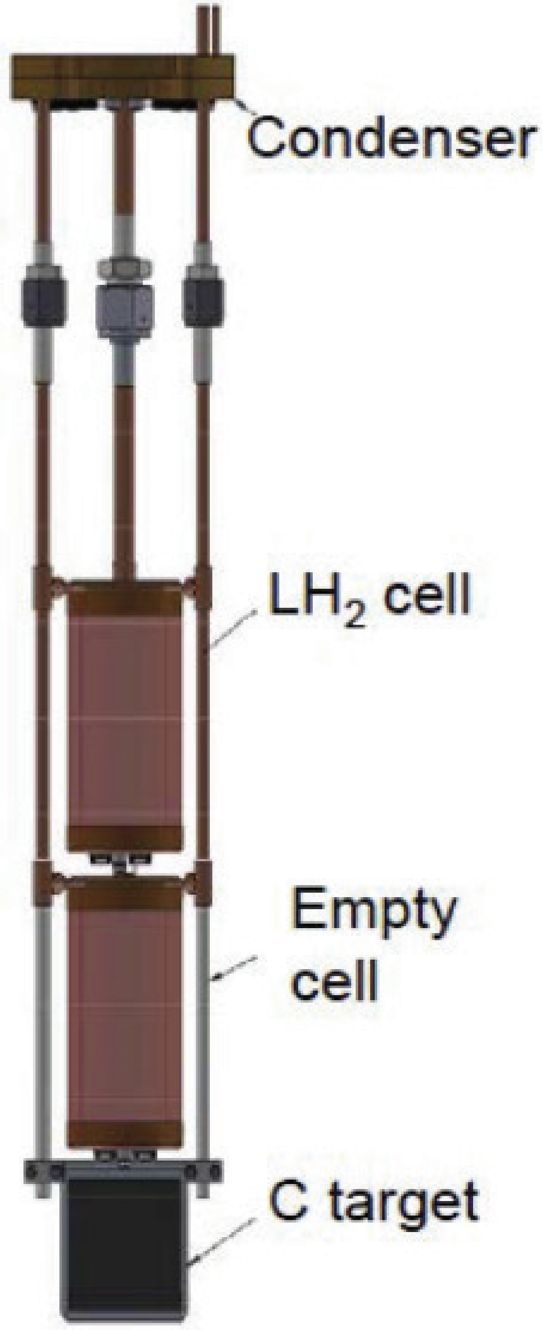
E. Downie

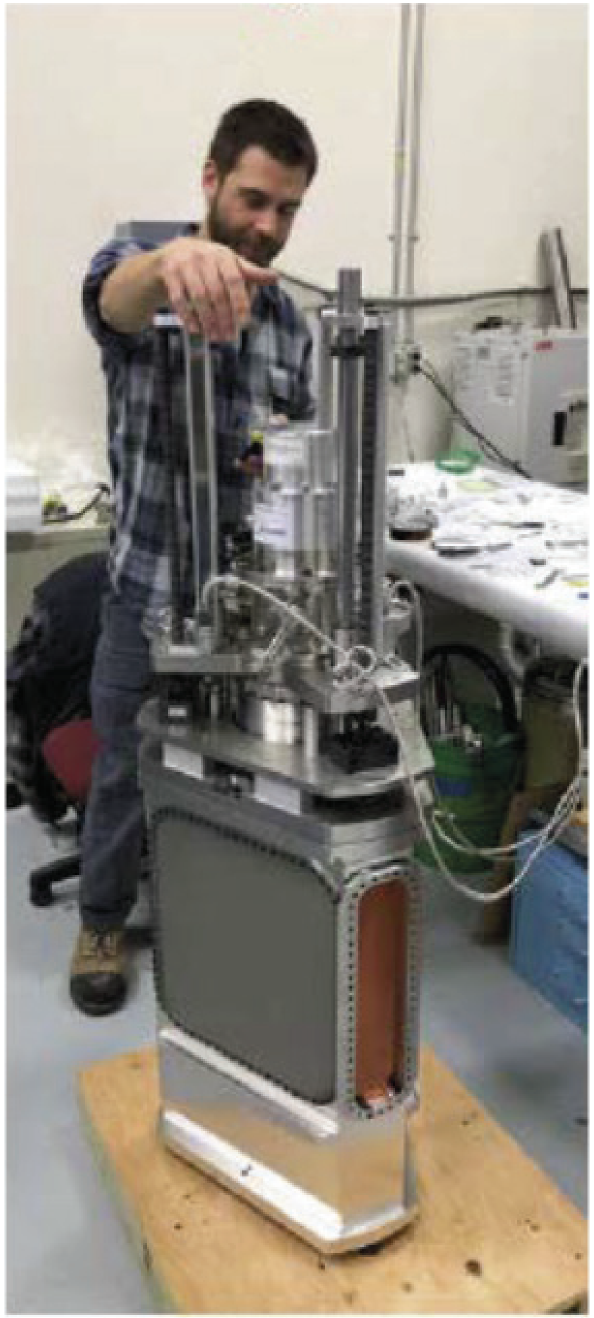
Beam Hodoscope – November 2017



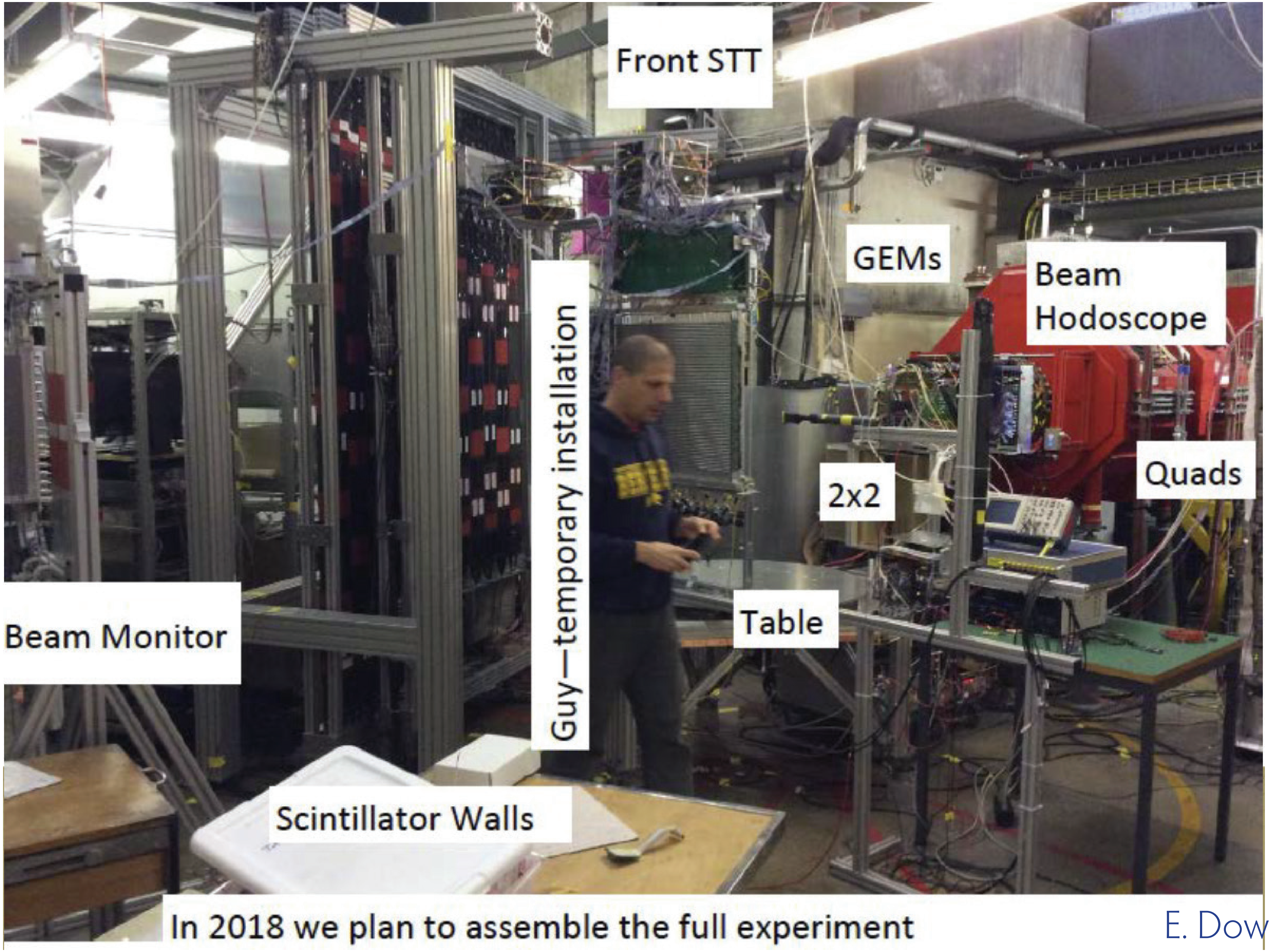
E. Downie


Cryocooler
Lifting Mechanism
Bellows
Trapezoidal Chamber
Targets
X,Y,Z Translation
Stand


Condenser
LH_2 cell
Empty cell
C target



E. Downie



In 2018 we plan to assemble the full experiment

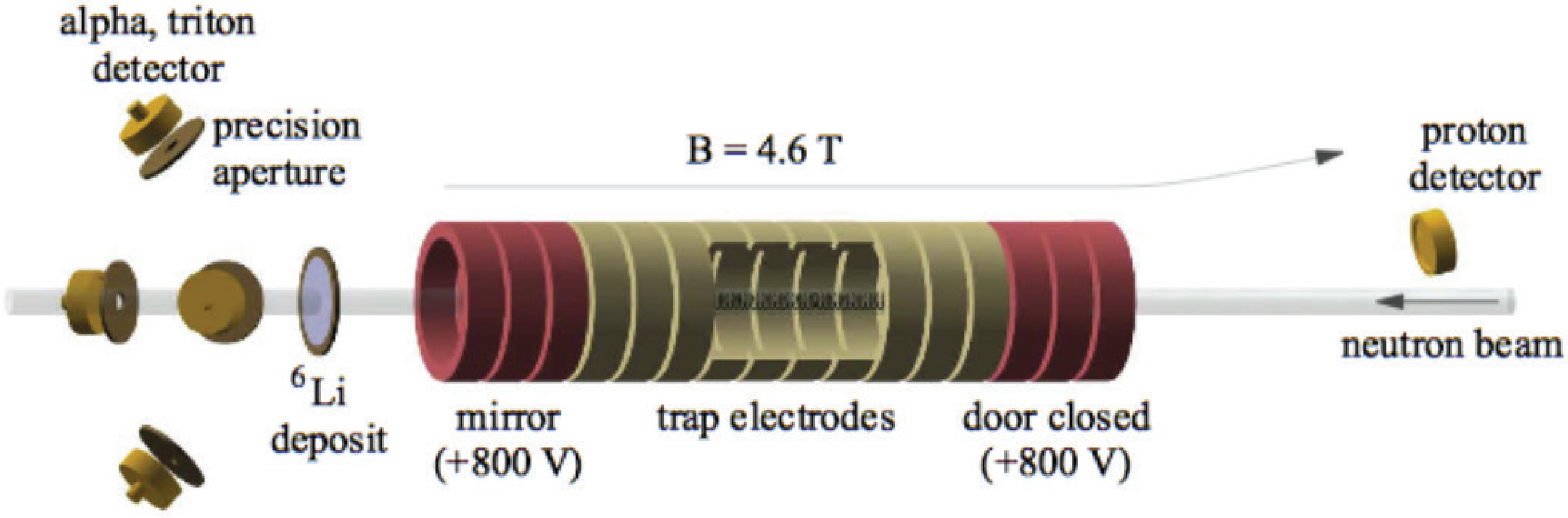
E. Downie

Another Puzzle:

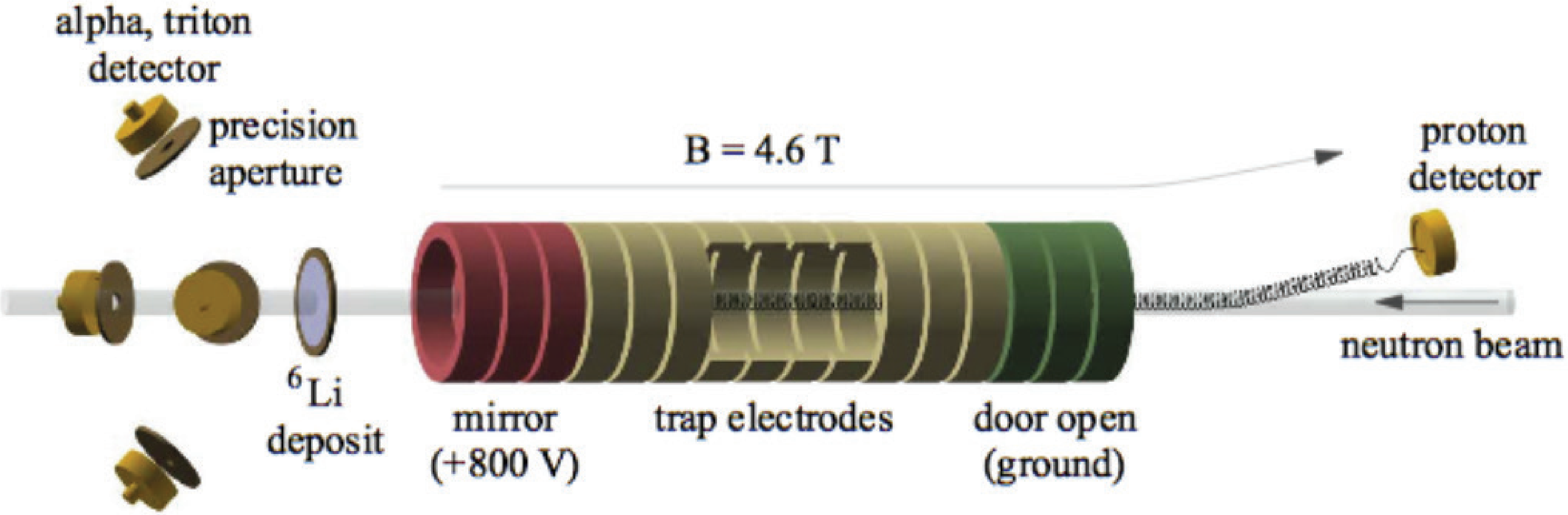
The neutron lifetime

Neutron lifetime

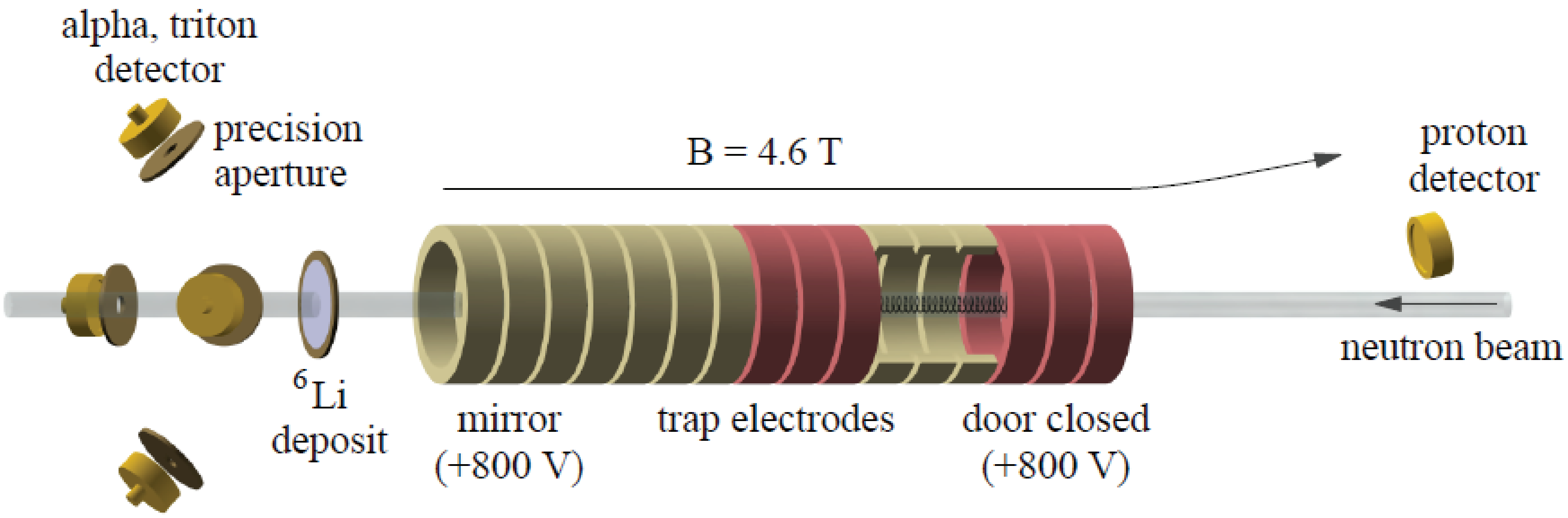
Spallation Neutron Source Beam Lifetime Experiment



F. E. Wietfeldt

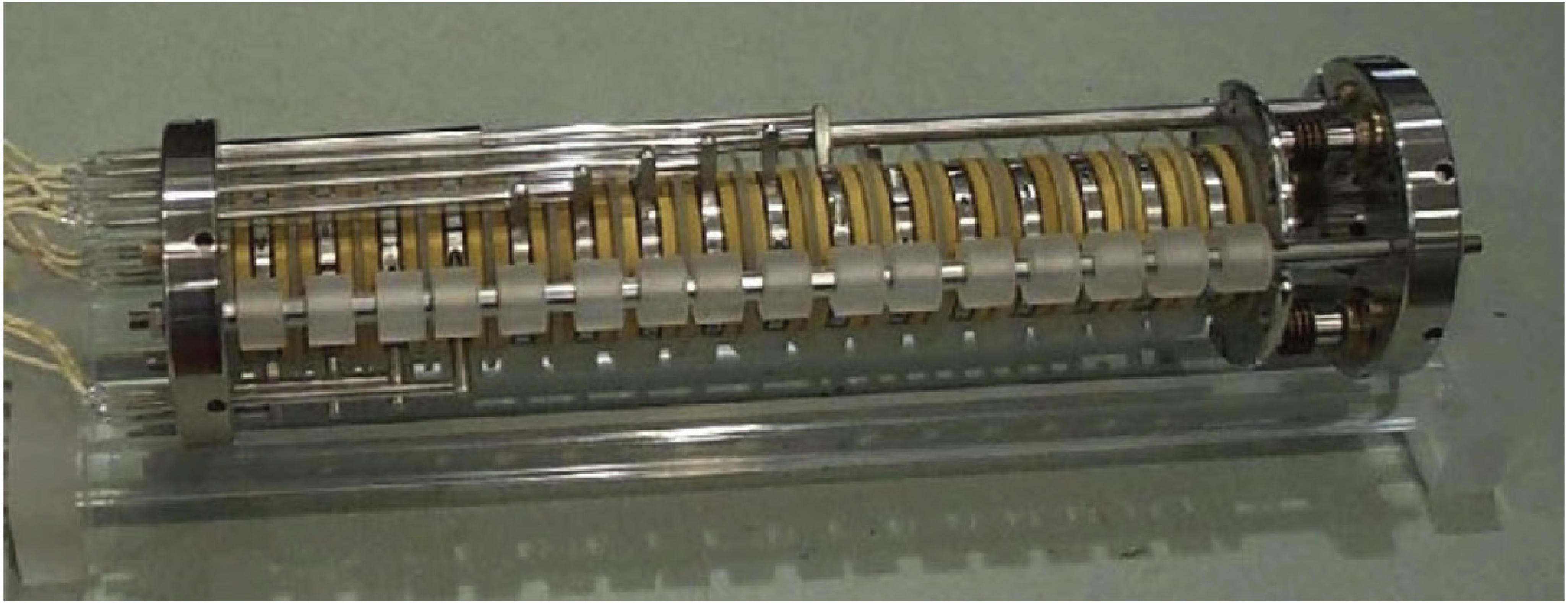


F. E. Wietfeldt



F. E. Wietfeldt

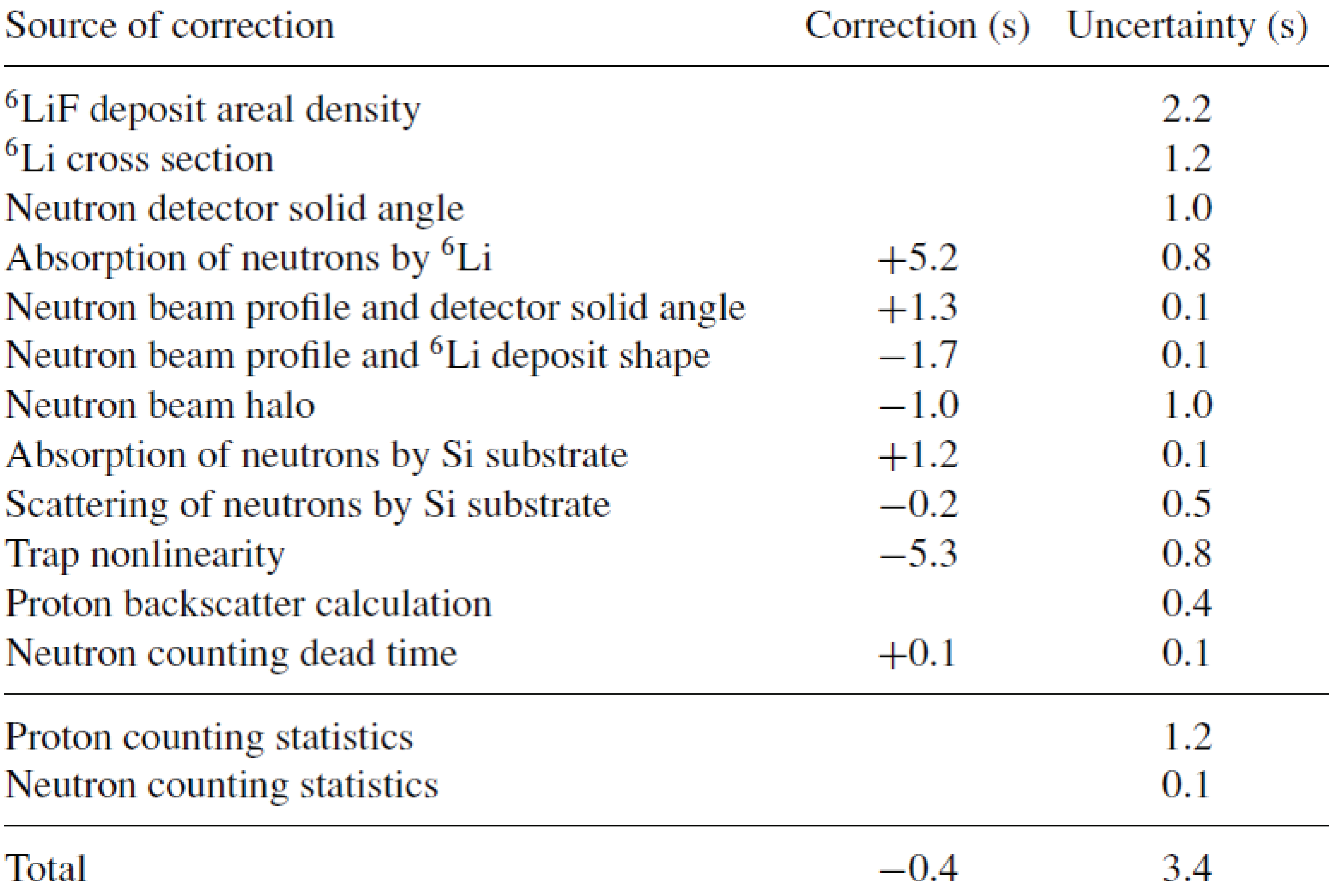
F. E. Wietfeldt



F. E. Wietfeldt

J. S. NICO *et al.* PHYSICAL REVIEW C **71**, 055502 (2005)

Error Budget



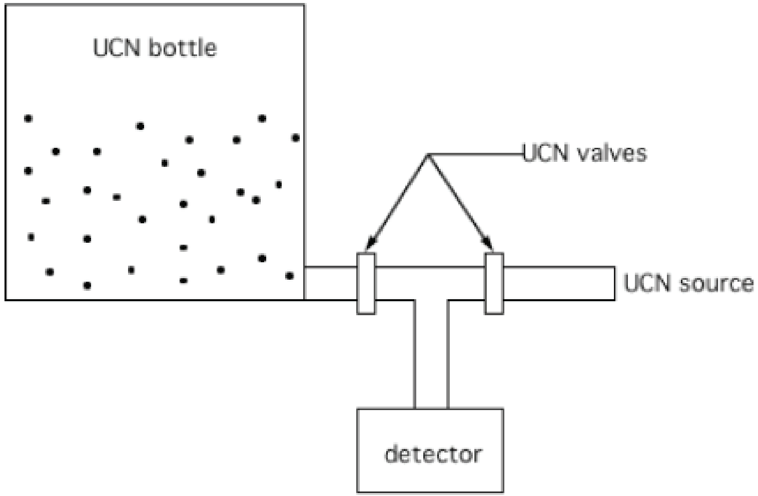
Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

2005: $\tau_n = 886.3 \pm 3.4$ s

F. E. Wietfeldt

Ultra-Cold Neutrons

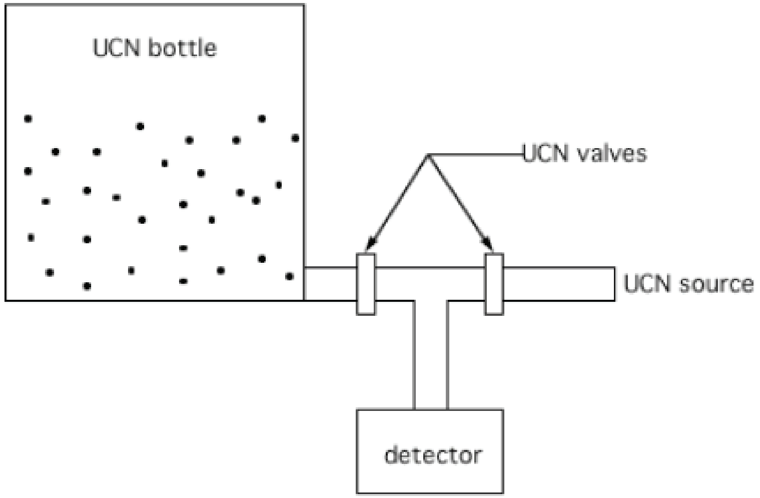
Ultracold neutron bottle method



1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.

F. E. Wietfeldt

Ultracold neutron bottle method

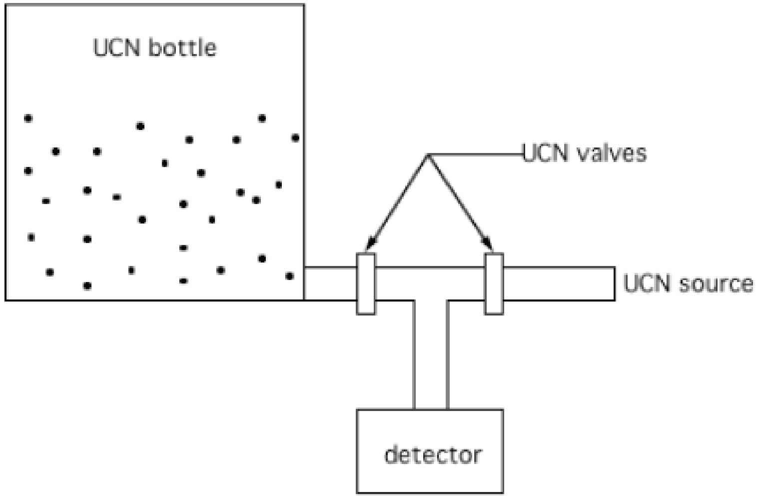


1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.

2. Store UCN for a variable storage time interval Δt.

F. E. Wietfeldt

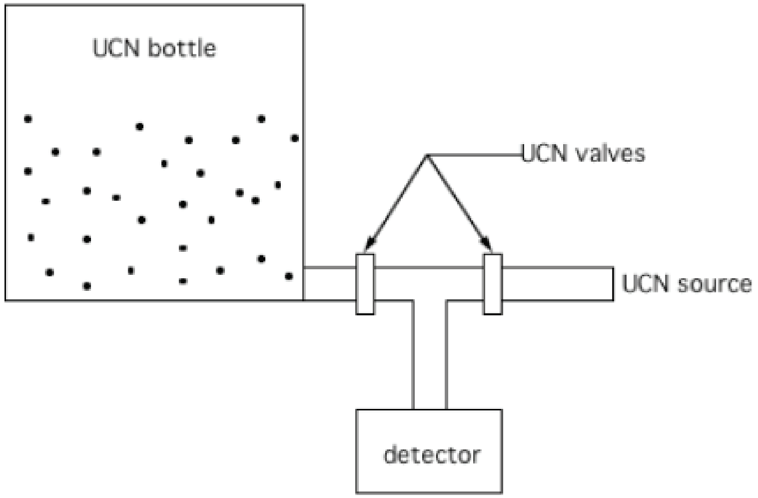
Ultracold neutron bottle method



1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.
2. Store UCN for a variable storage time interval Δt.
3. Empty the bottle and count the remaining UCN in a detector.

F. E. Wietfeldt

Ultracold neutron bottle method



1. Fill bottle with ultracold neutrons (UCN) in a reproducible way.

2. Store UCN for a variable storage time interval Δt.

3. Empty the bottle and count the remaining UCN in a detector.

4. Repeat steps 1-3 using different wall collision rates to account for wall losses (upscattering, absorption).

F. E. Wietfeldt

UCN storage time

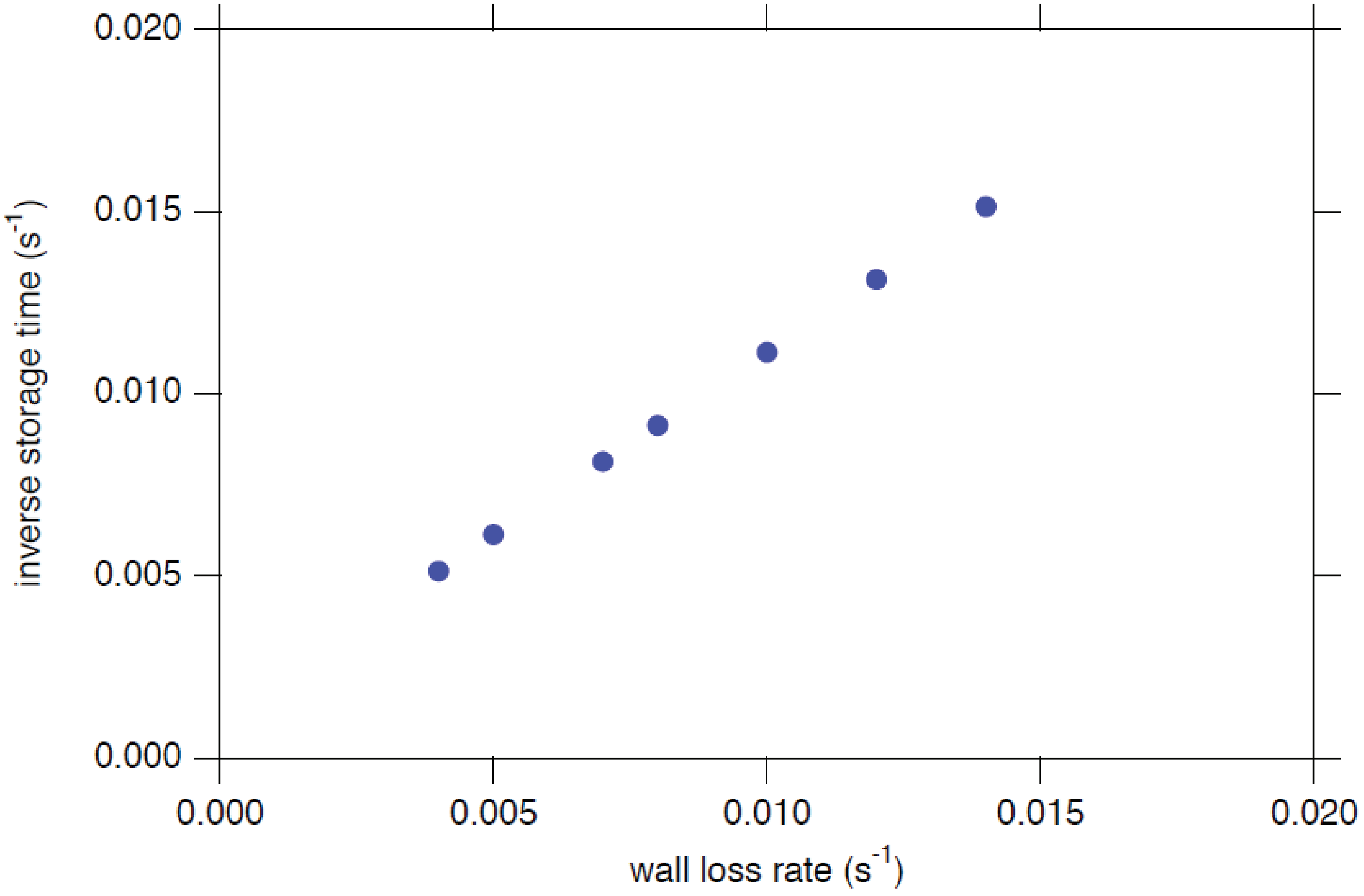
radioactive decay law: $N(\Delta t) = N_0 e^{-\Delta t/\tau_{\text{stor}}}$

$$\tau_{\text{stor}} = \frac{\Delta t}{\ln\left(\frac{N_0}{N(\Delta t)}\right)}$$

$$\frac{1}{\tau_{\text{stor}}} = \frac{1}{\tau_n} + \frac{1}{\tau_{\text{wall}}}$$

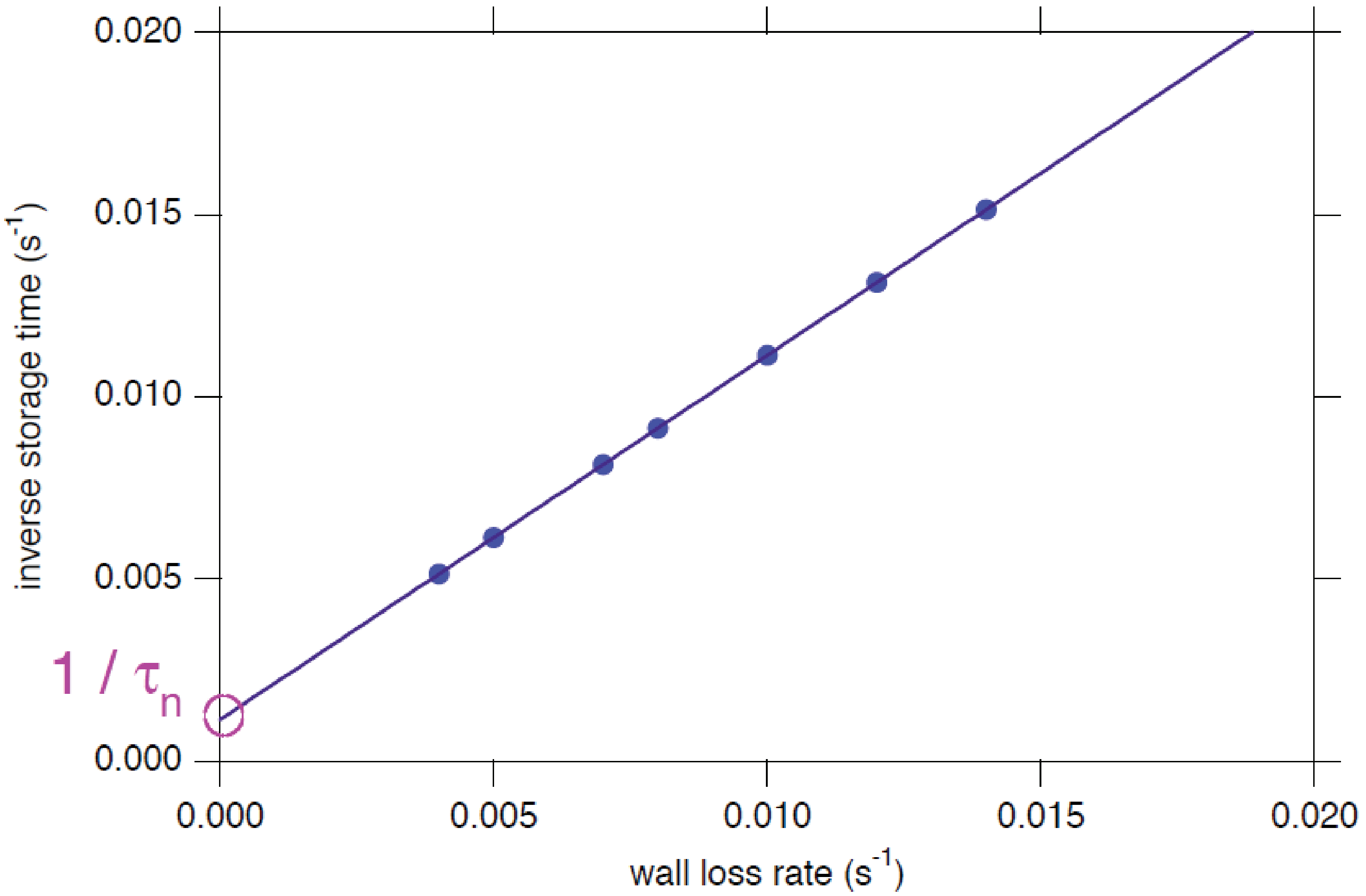
F. E. Wietfeldt

UCN bottle neutron lifetime



F. E. Wietfeldt

UCN bottle neutron lifetime

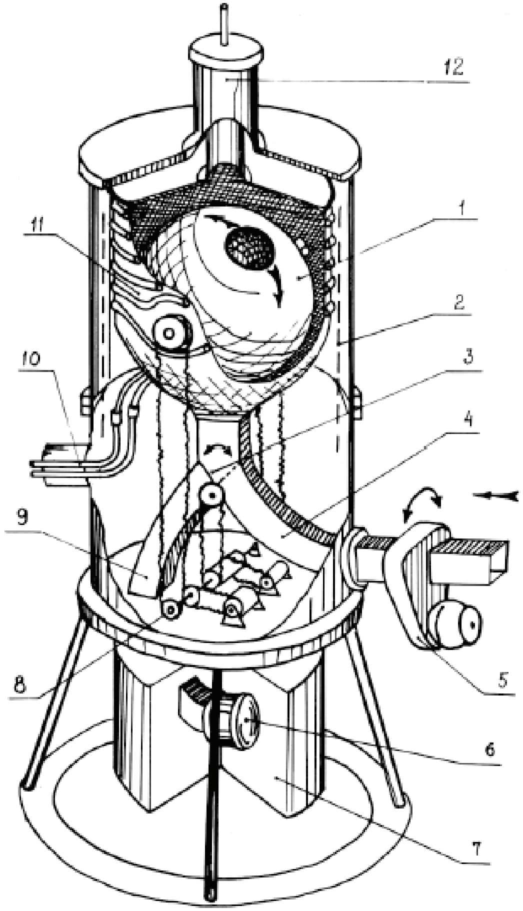


F. E. Wietfeldt

PHYSICAL REVIEW C **78**, 035505 (2008)

Neutron lifetime measurements using gravitationally trapped ultracold neutrons

A. P. Serebrov,[1,*] V. E. Varlamov,[1] A. G. Kharitonov,[1] A. K. Fomin,[1] Yu. N. Pokotilovski,[2] P. Geltenbort,[3]
I. A. Krasnoschekova,[1] M. S. Lasakov,[1] R. R. Taldaev,[1] A. V. Vassiljev,[1] and O. M. Zherebtsov[1]
[1]*Petersburg Nuclear Physics Institute, Russian Academy of Sciences, RU-188300 Gatchina, Leningrad District, Russia*
[2]*Joint Institute for Nuclear Research, RU-141980 Dubna, Moscow Region, Russia*
[3]*Institut Max von Laue Paul Langevin, Boîte Postal 156, F-38042 Grenoble Cedex 9, France*
(Received 11 February 2008; published 23 September 2008)



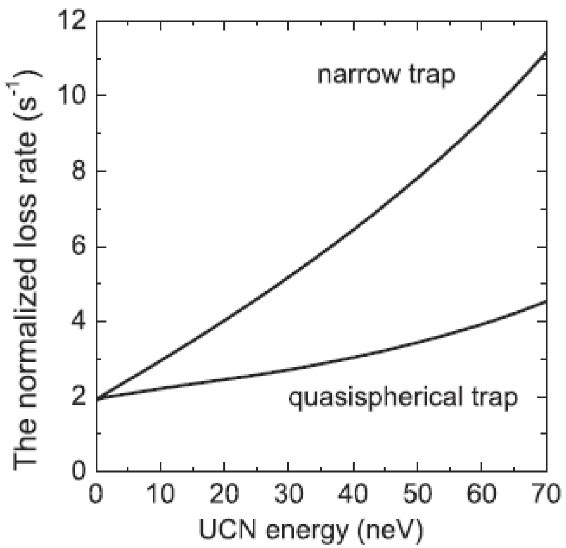
cryogenic liquid fluoropolymer oil wall coating to minimize wall losses

rotate bottle to allow high energy UCN to escape, to vary neutron velocity spectrum

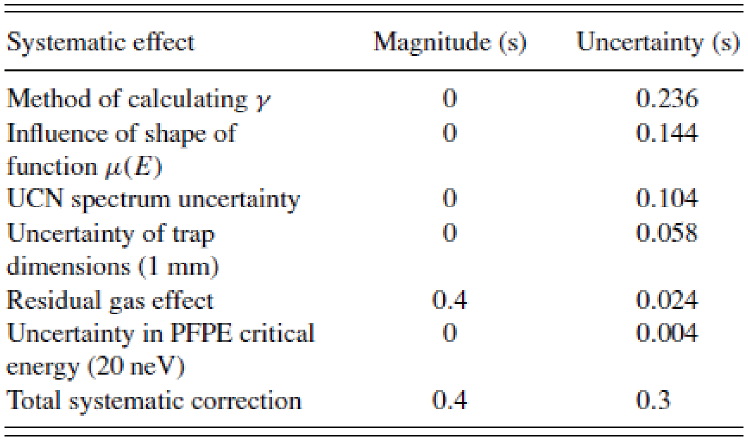
two storage bottles, spherical (large) and cylindrical (small) to vary S/V ratio

F. E. Wietfeldt

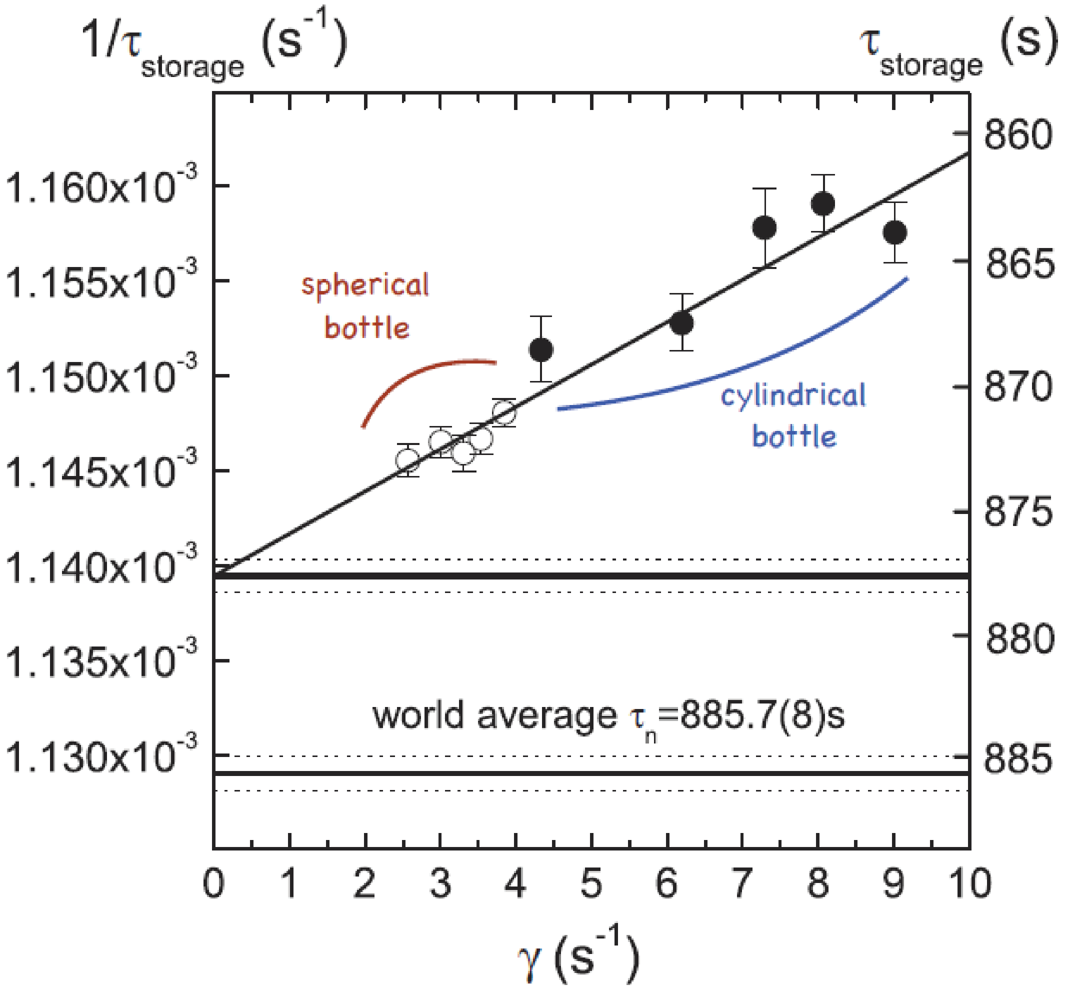
calculated loss rates



error budget

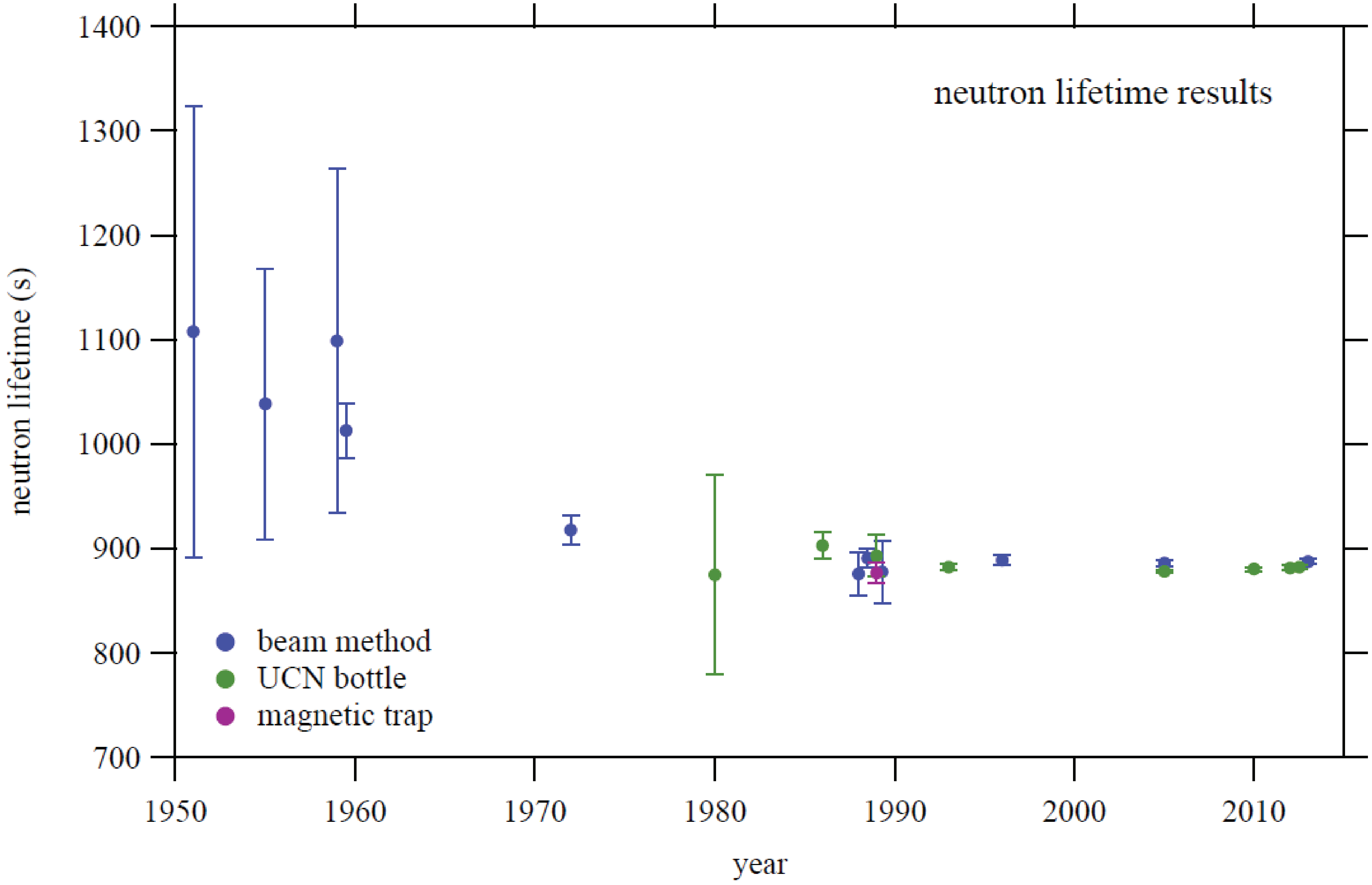


Systematic effect	Magnitude (s)	Uncertainty (s)
Method of calculating γ	0	0.236
Influence of shape of function $\mu(E)$	0	0.144
UCN spectrum uncertainty	0	0.104
Uncertainty of trap dimensions (1 mm)	0	0.058
Residual gas effect	0.4	0.024
Uncertainty in PFPE critical energy (20 neV)	0	0.004
Total systematic correction	0.4	0.3

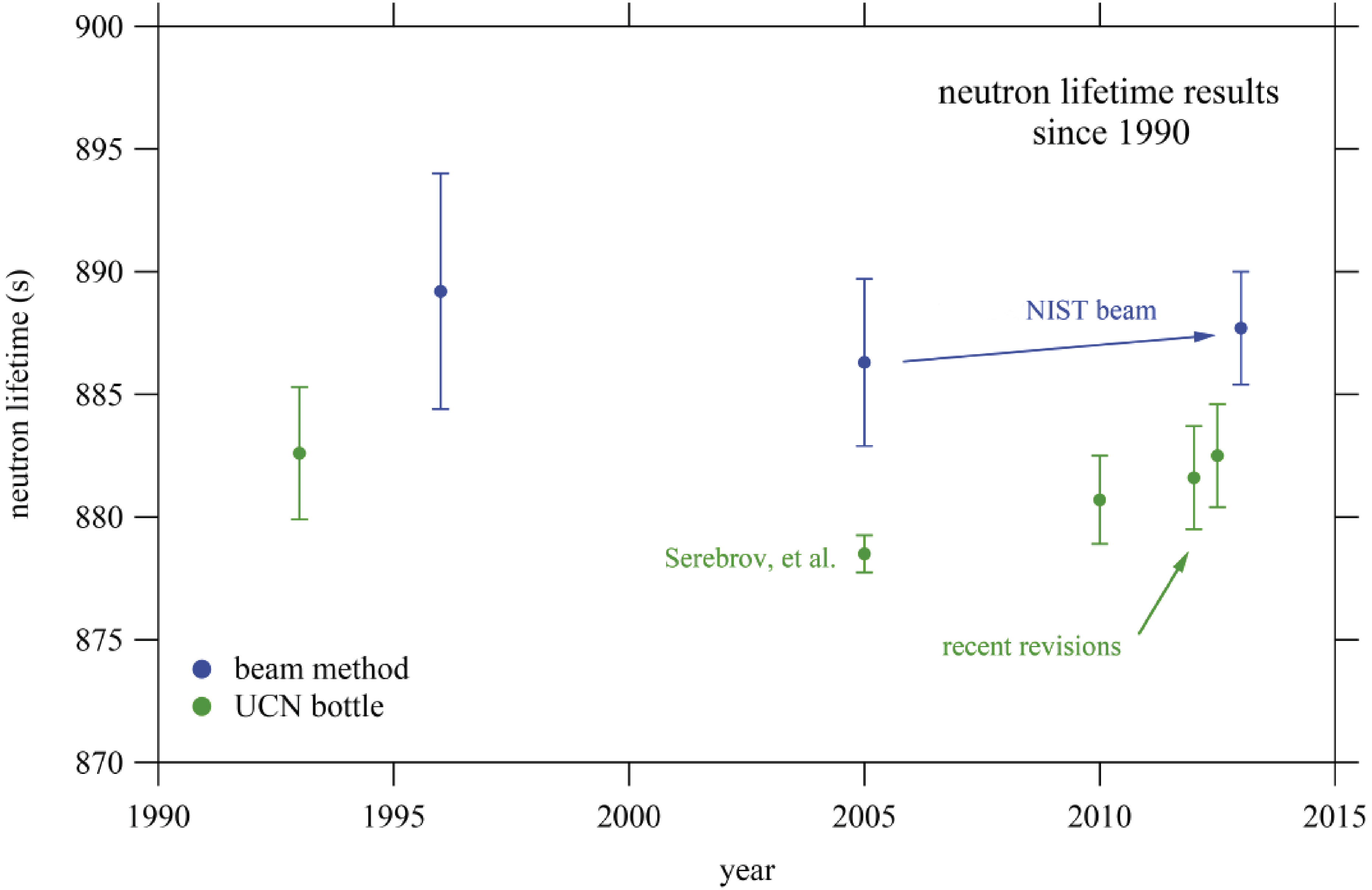


result: τ_n = 878.5 ± 0.8 s

F. E. Wietfeldt



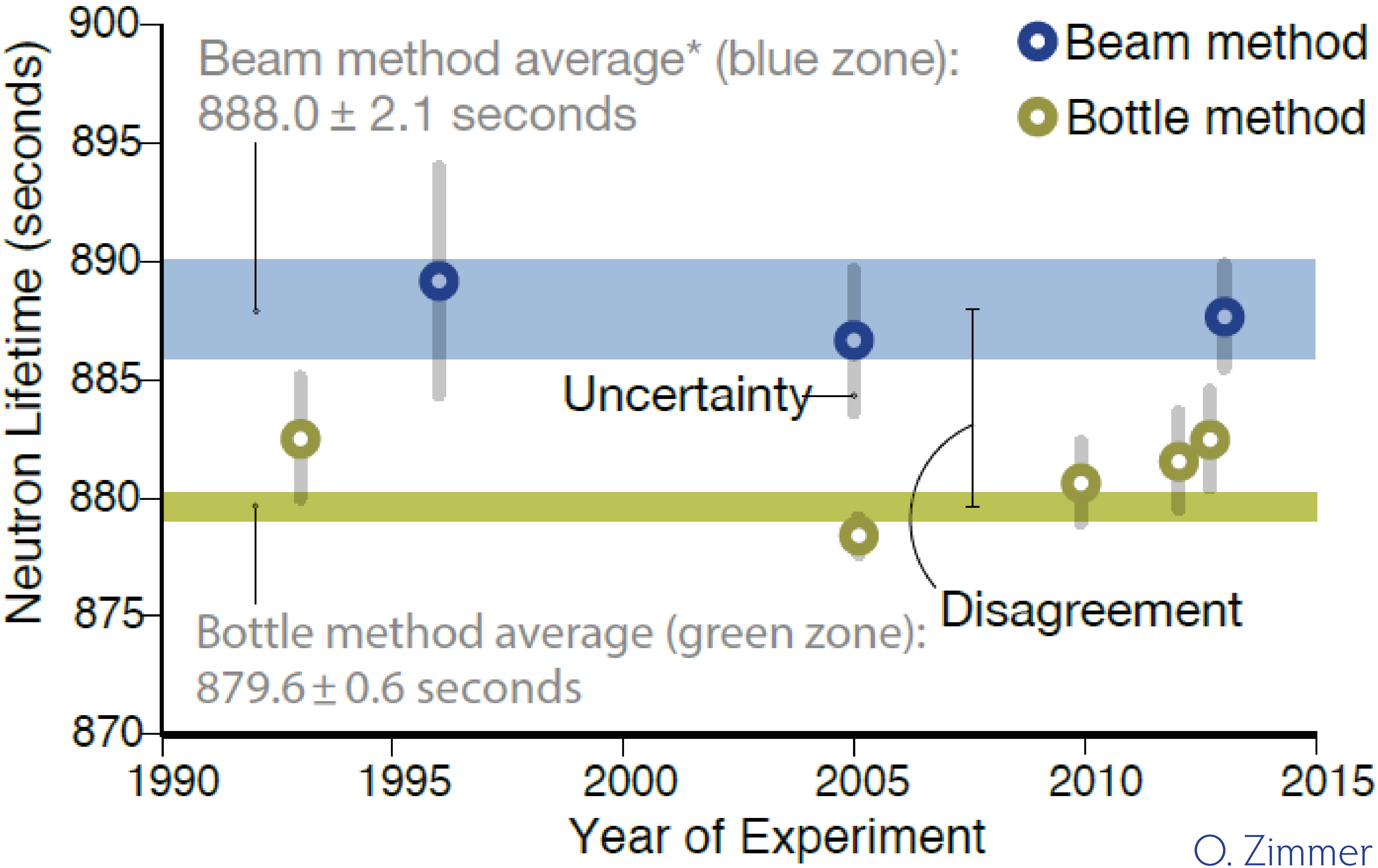
F. E. Wietfeldt



F. E. Wietfeldt

Experimental situation in 2016

G. Greene and P. Geltenbort, Sci. Am. **314** (2016) 36



Beam method average* (blue zone):
888.0 ± 2.1 seconds

Bottle method average (green zone):
879.6 ± 0.6 seconds

O. Zimmer

What is going on?

- Are the beam fluxes wrong?
- Are the bottle losses not understood?
- Is there another decay channel?

- Many new approaches in the making:

  Gravitational storage
  Magnetic storage
  Counting both the dead and the survivors
  Better beam experiments

Successor experiment „Big GraviTrap“ (PNPI)

(during installation in 2014 at ILL)

O. Zimmer

Job (installation) done...

Work on trap preparation

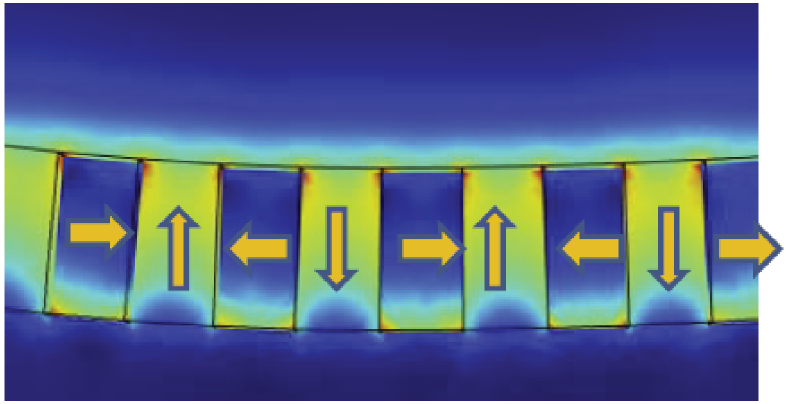
O. Zimmer

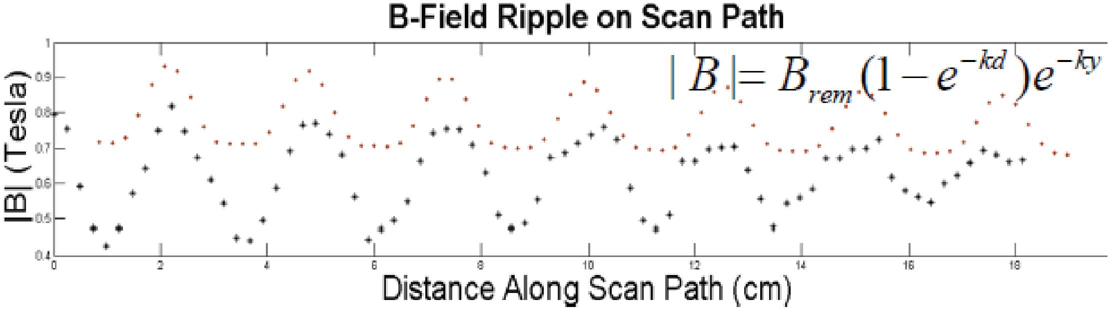
First result (measurements to be continued with colder trap):

Serebrov et al., arXiv:1712.05663:

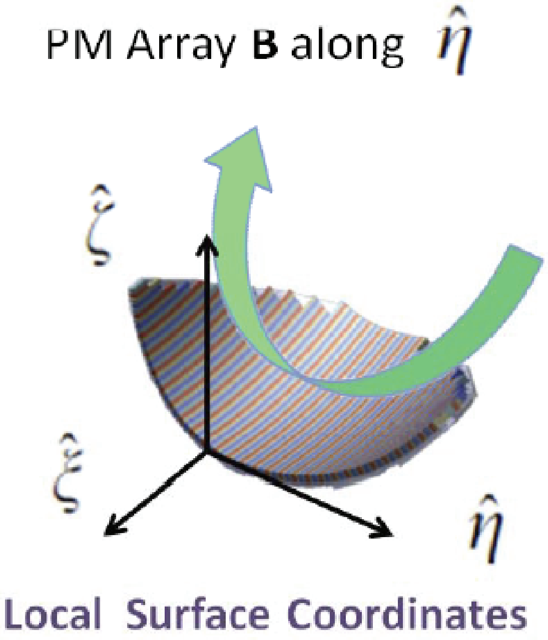
$\tau_n = (881.5 \pm 0.7 \pm 0.6)$ s

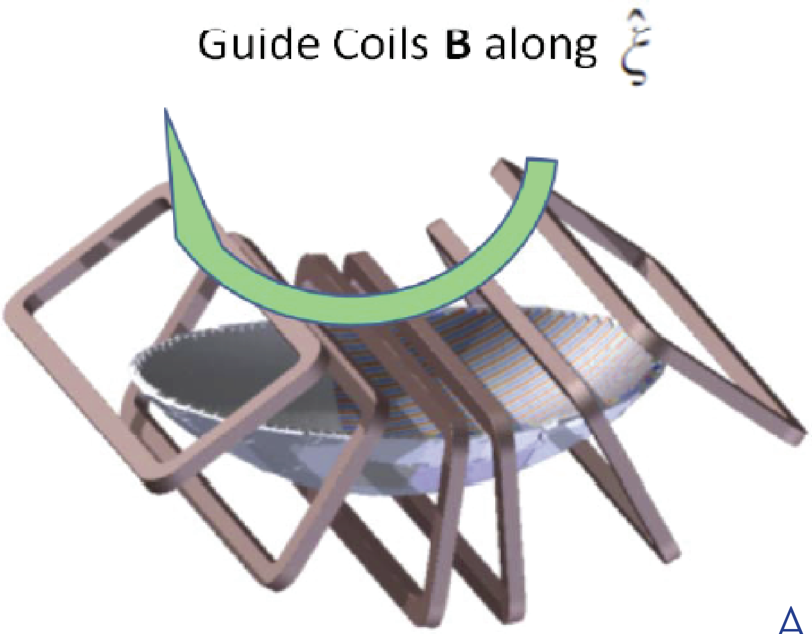
Magneto-Gravitational Trap





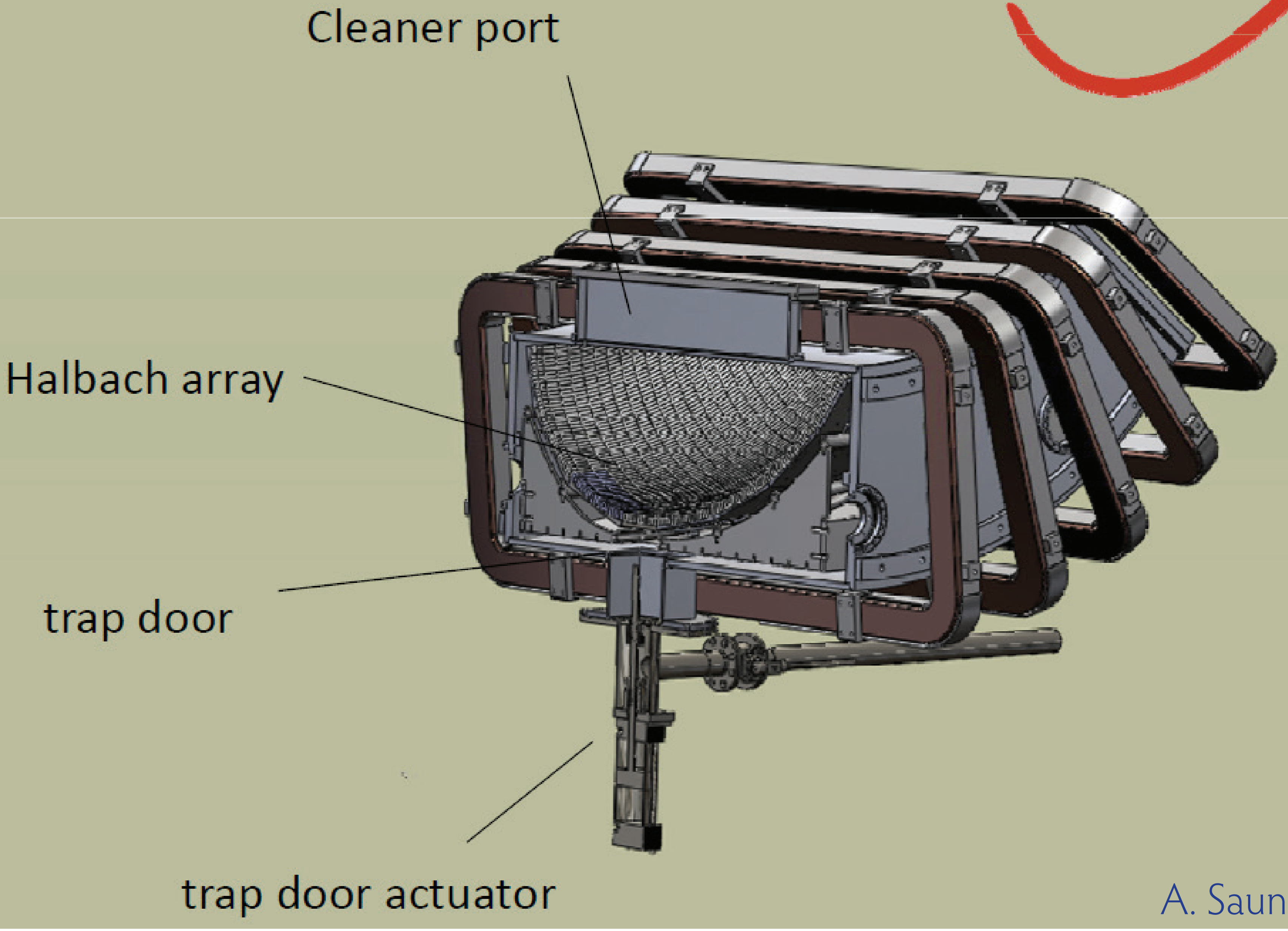
- **Halbach array** provides field (along η) gradient for magnetic levitation.
- **Window-frame electromagnet** provides spin holding field (β guiding field) along ξ.
- **Gravity** bounds UCN from the top.





A. Saunders

UCNτ

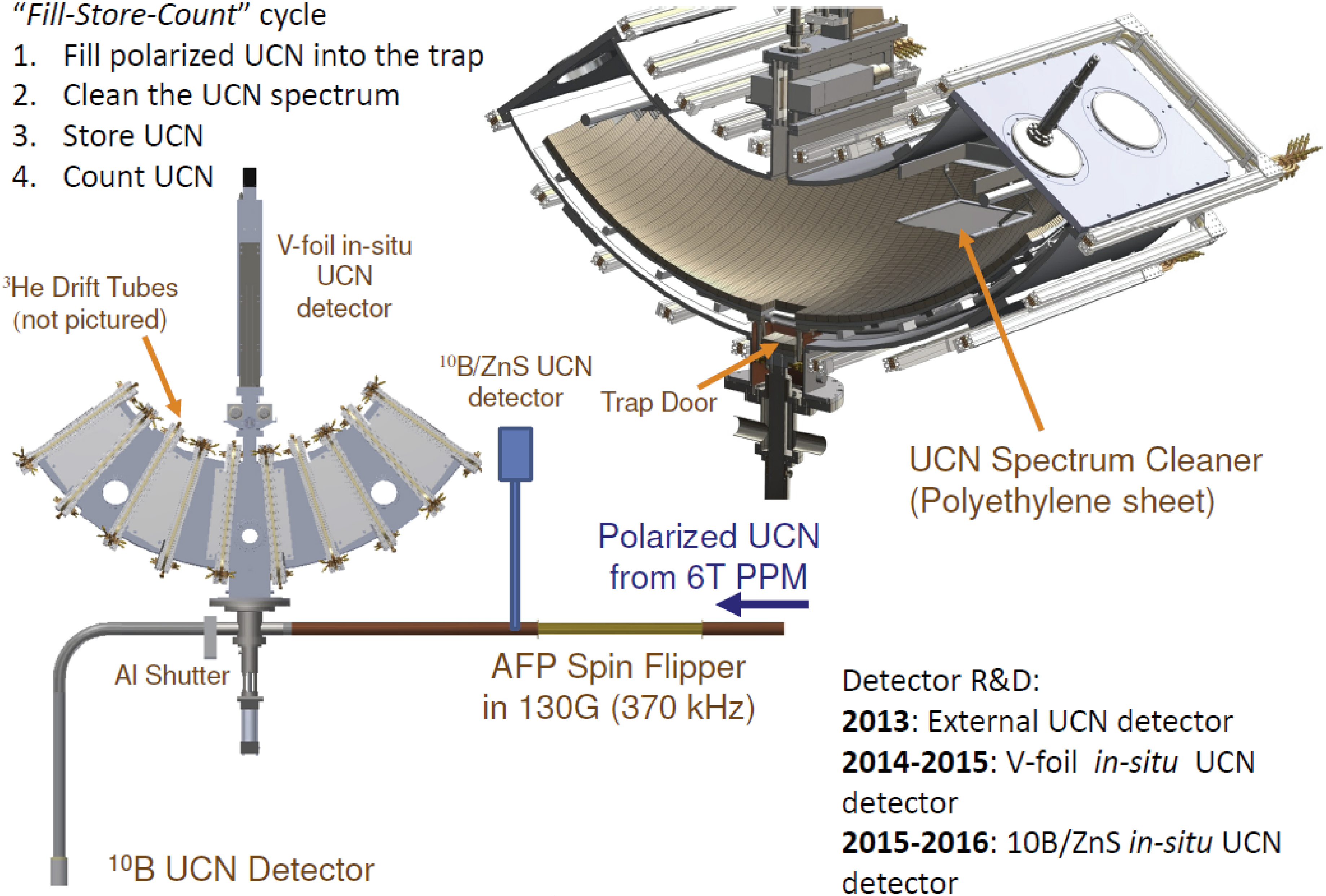


A. Saunders

Operation of the UCNτ Experiment

"Fill-Store-Count" cycle

1. Fill polarized UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Count UCN



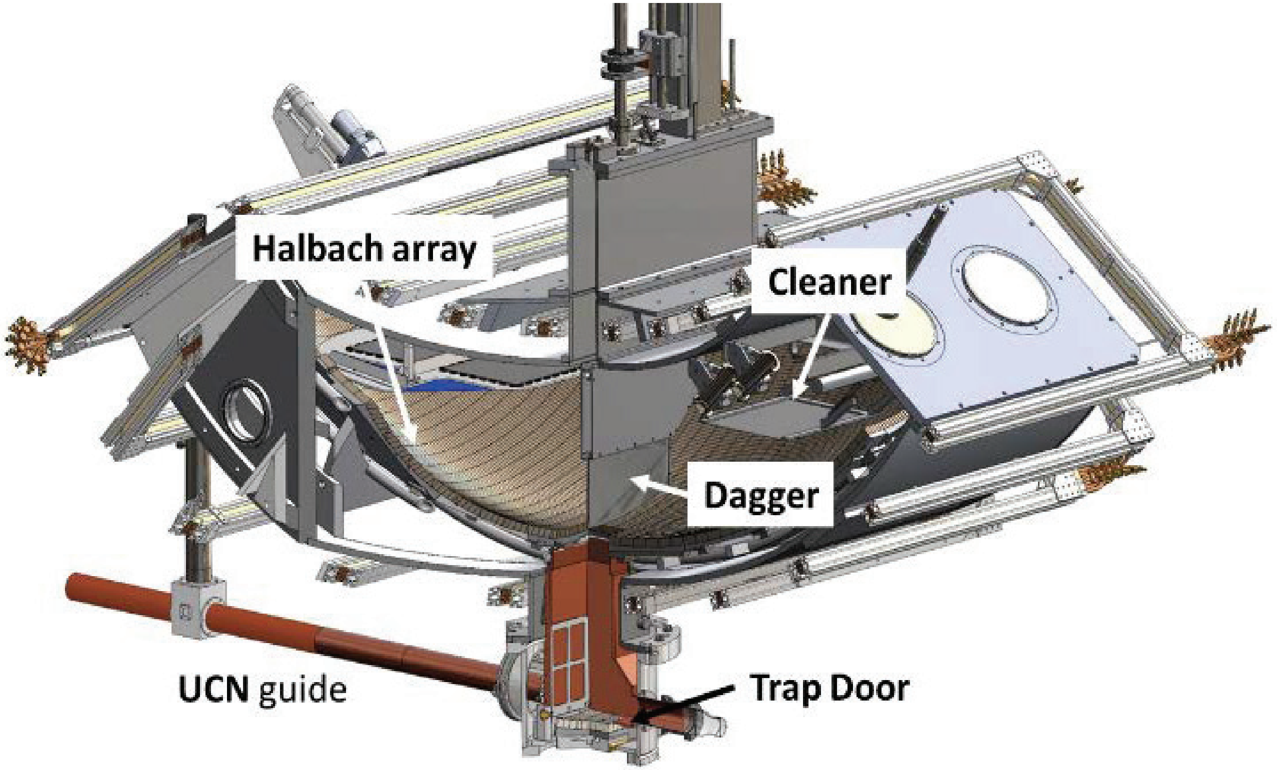
Detector R&D:
2013: External UCN detector
2014-2015: V-foil *in-situ* UCN detector
2015-2016: 10B/ZnS *in-situ* UCN detector

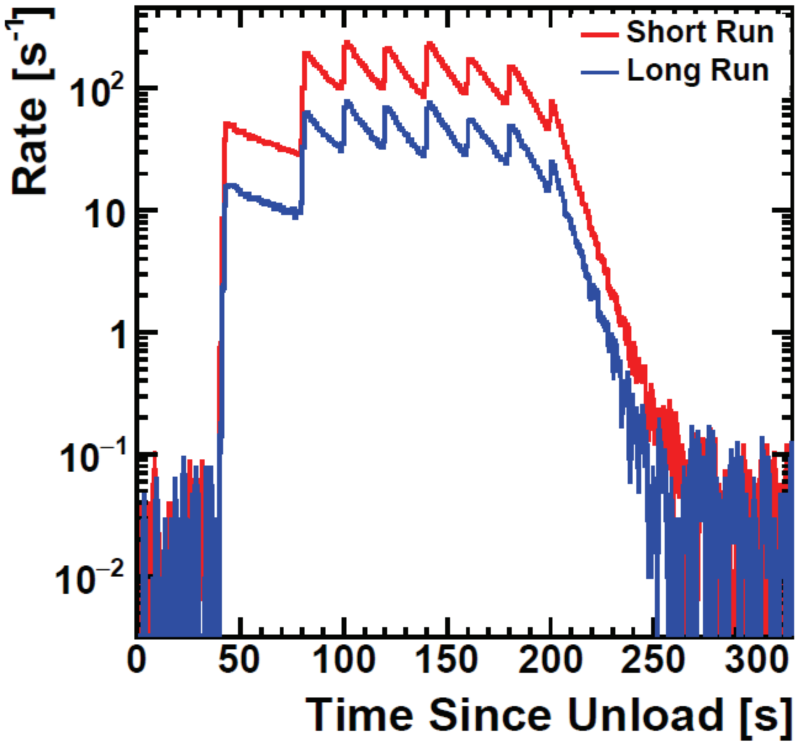
C.-Y. Liu

UCNτ ("fill and kill")

Done at the solid-deuterium UCN source at Los Alamos

+ triple blind analysis
– no monitoring of depolarised UCNs





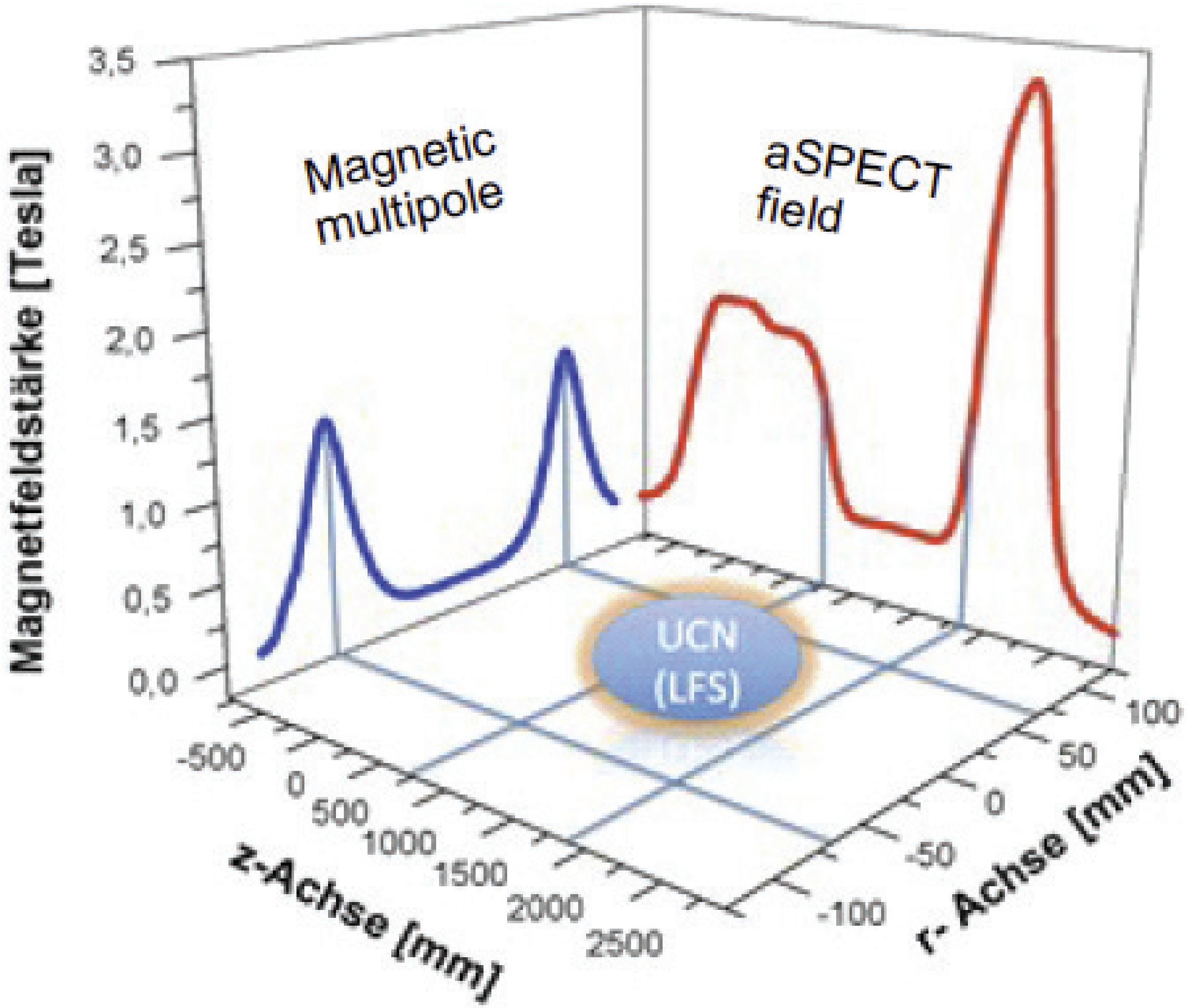
O. Zimmer

Morris et al., arXiv:1610.04560:

τ_n = (878.8 ± 2.6 ± 0.6) s

Pattie et al., arXiv:1707.01817:

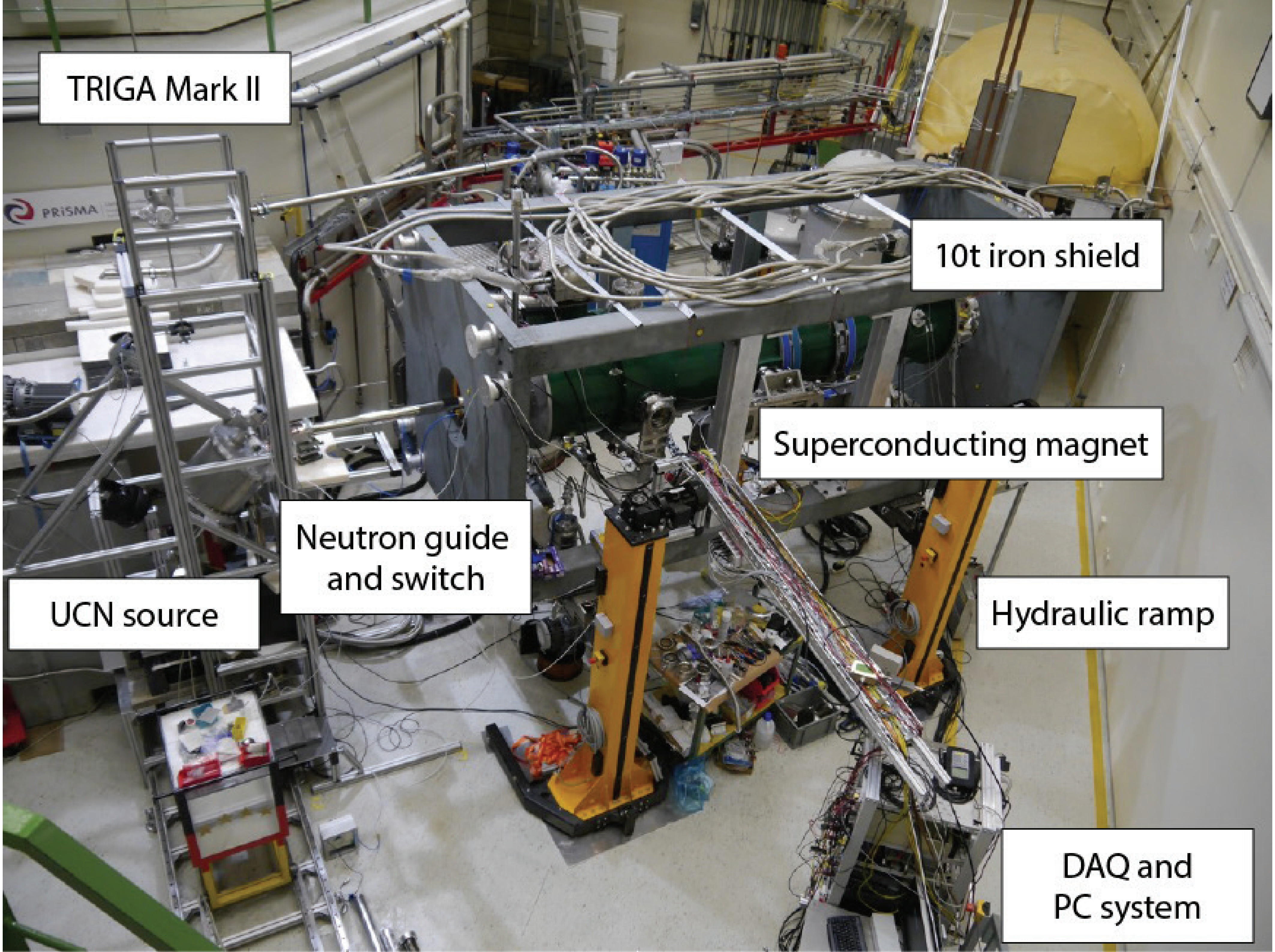
τ_n = (877.7 ± 0.7 + 0.3/-0.1) s



Stern-Gerlach-force:

$F = -(\mu \cdot \nabla)\ \mathbf{B}$

M. Beck


TRIGA Mark II
PRISMA
10t iron shield
Superconducting magnet
Neutron guide and switch
UCN source
Hydraulic ramp
DAQ and PC system

Neutron lifetime stays interesting,
should be clarified before 2025

Summary of “anomalies”

(Experiments involving particles)

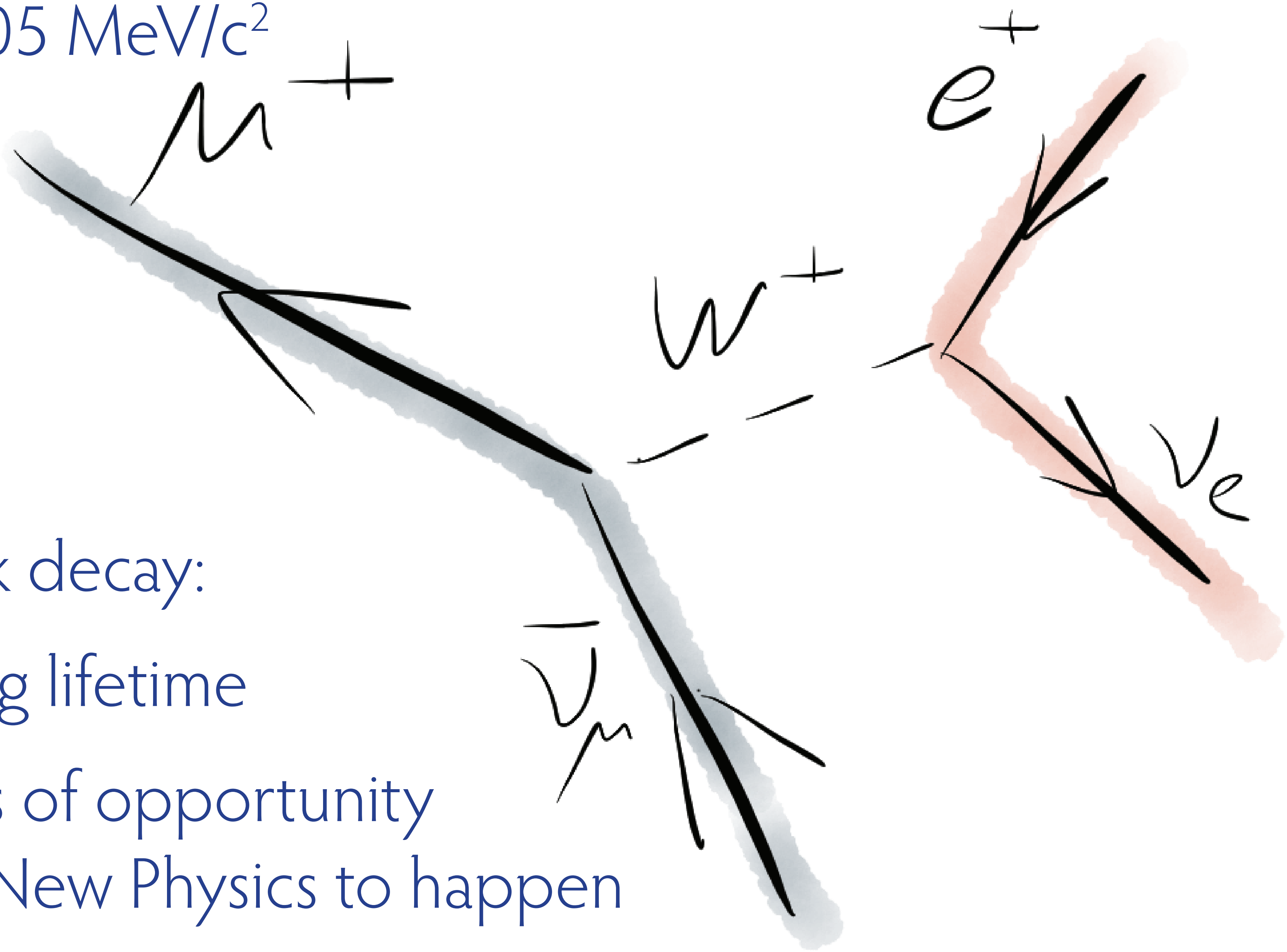
- B-physics (mostly LHCb)
- Proton radius
- Neutron lifetime
- Muon magnetic moment

Dipole Moments and Symmetries

Dipoles and Symmetries

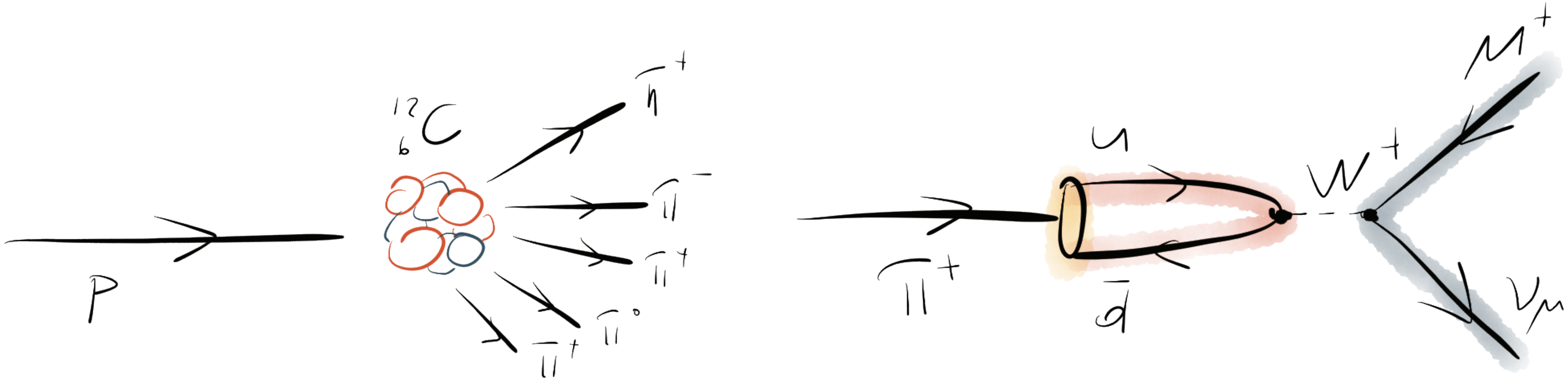
Muon Magnetic Dipole Moment

$m_\mu = 105\ \mathrm{MeV}/c^2$



Weak decay:

- Long lifetime
- Lots of opportunity for New Physics to happen
- Theory well under control



Easy to produce with intense proton beams:

10^8 μ/s available

> 10^{10} μ/s planned

Polarized

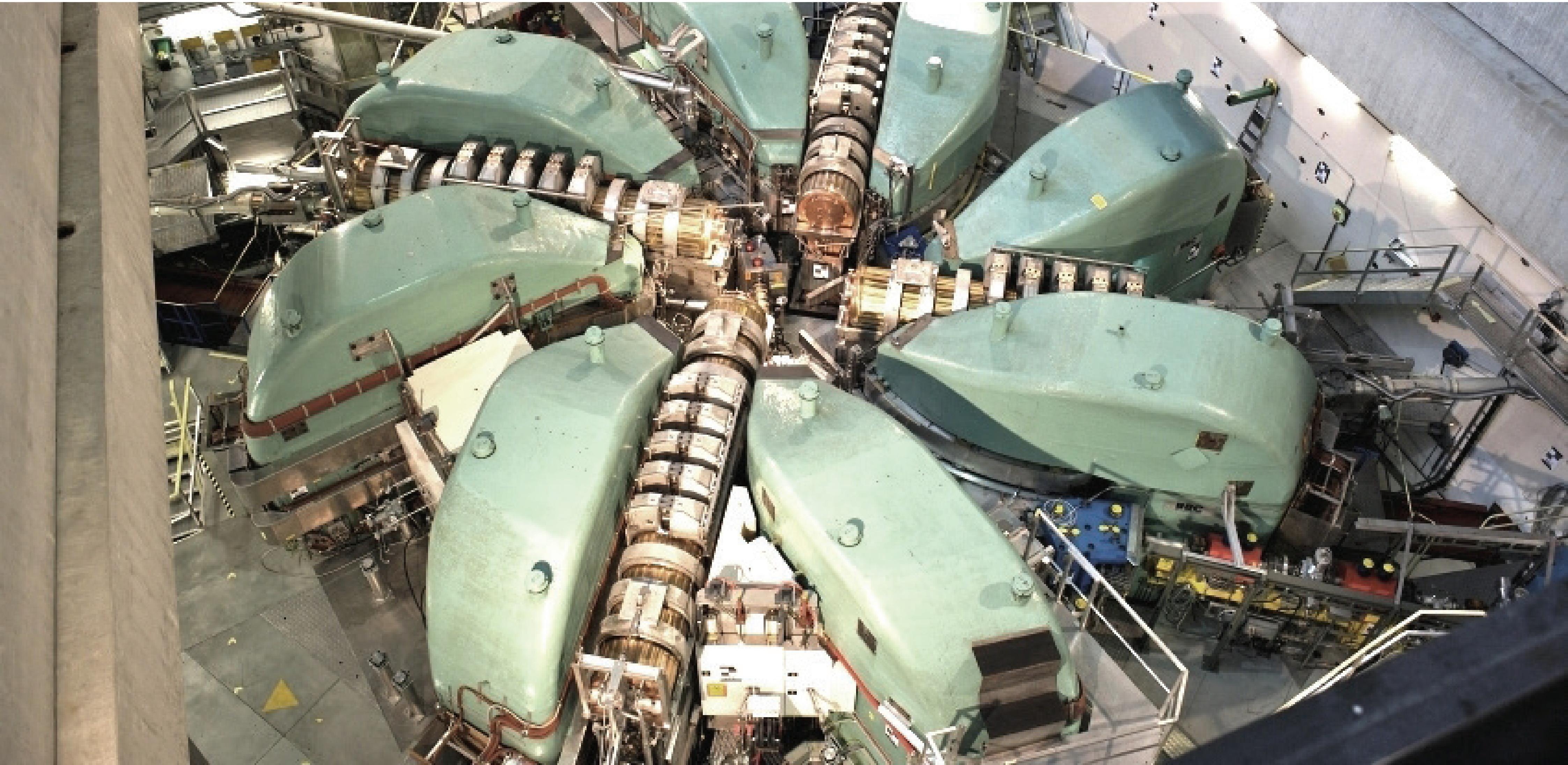
Muons from PSI

Paul Scherrer Institute in Villigen, Switzerland

World's most intensive proton beam
2.2 mA at 590 MeV: 1.3 MW of beam power

Continuous beam

10^8 μ/s available
options for 10^{10} μ/s under study



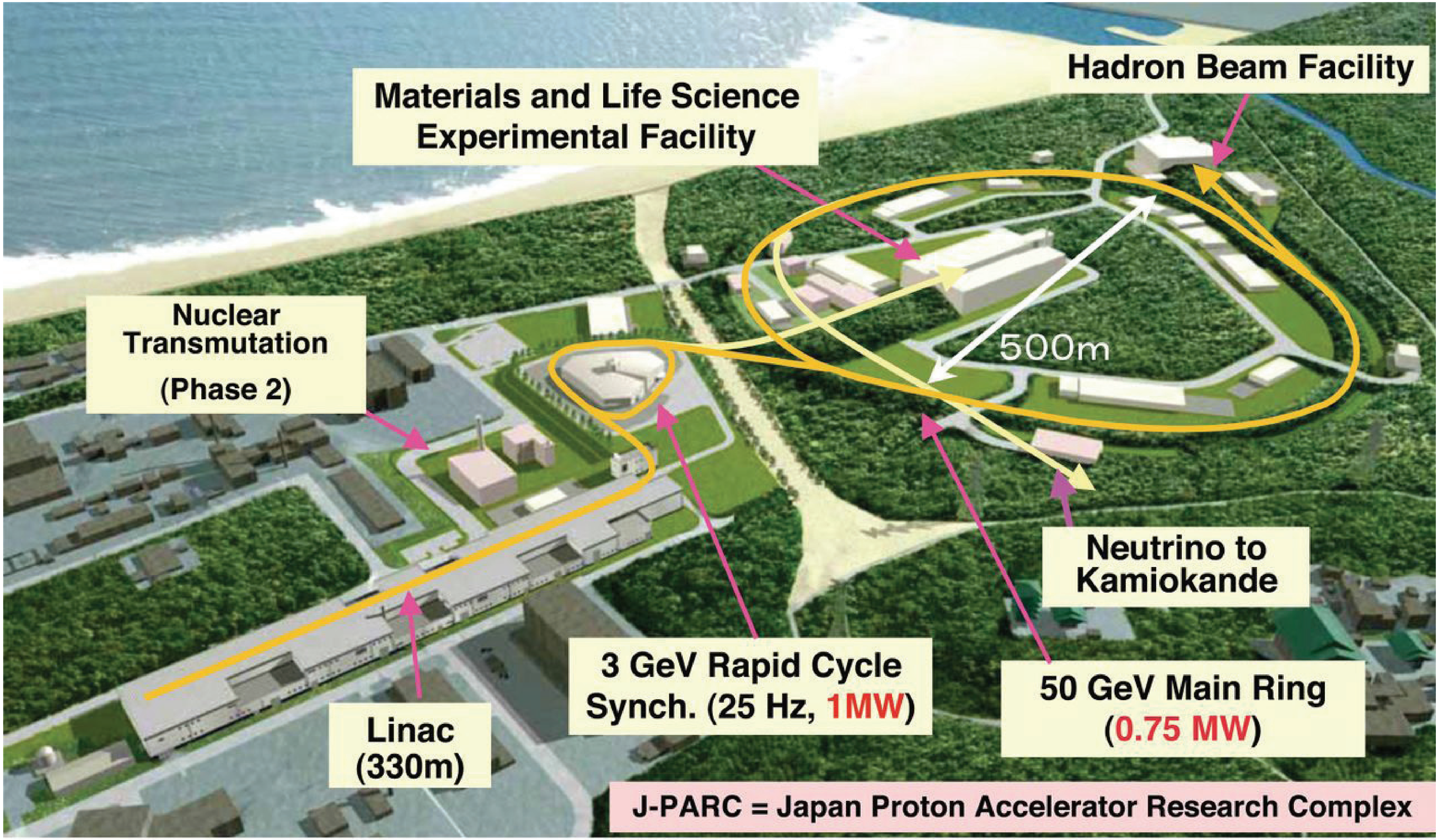
Muons from Fermilab …

fnal.gov

- Re-use part of the Tevatron infrastructure
- Proton pulses every 1700 ns
- > 10^{10} μ/s

- Project X (now Proton Improvement Plan-II) would give another 2 orders of magnitude with a new powerful proton linac

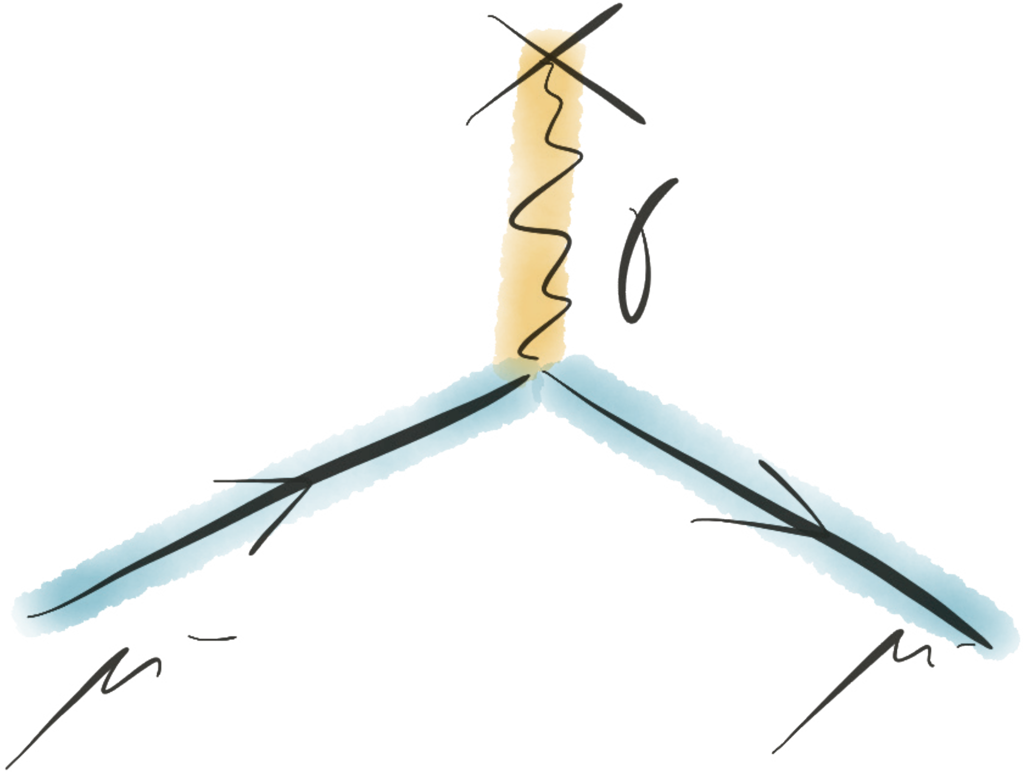
… and J-PARC



10^{11} μ/s from 8 GeV/c protons, pulsed

S. Nagamiya, Prog. Theor. Exp. Phys. (2012) 02B001

The magnetic moment of the muon



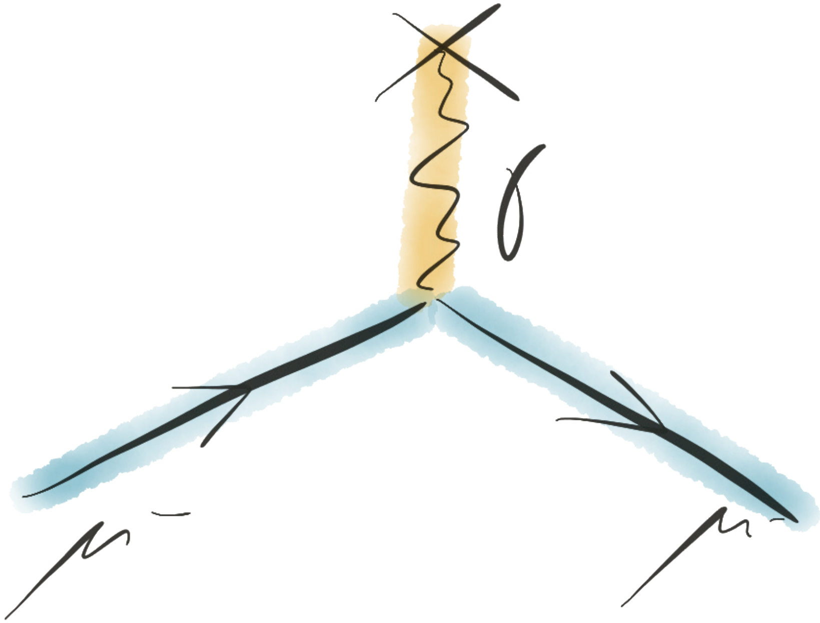
Magnetic moment of the muon

Spin precession in magnetic field:

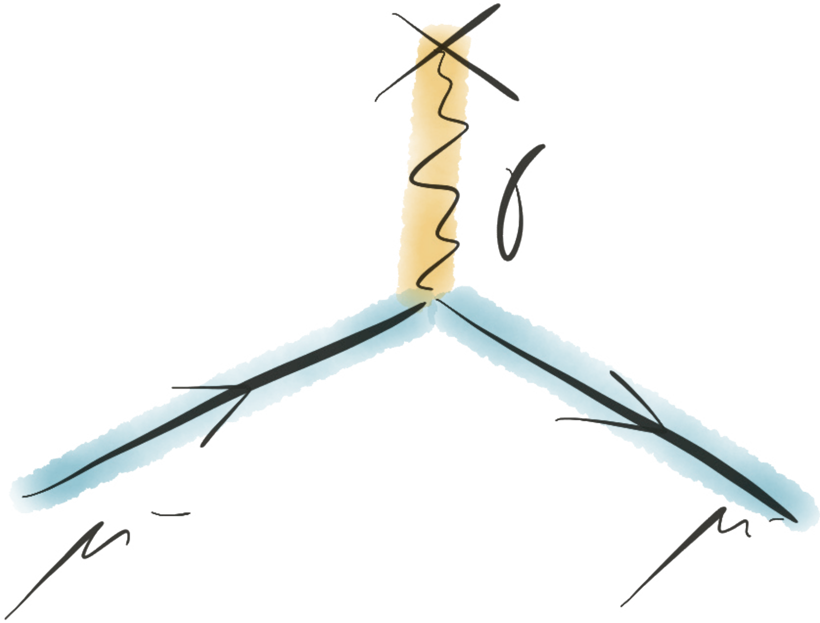
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\mu} \times \vec{B}$$

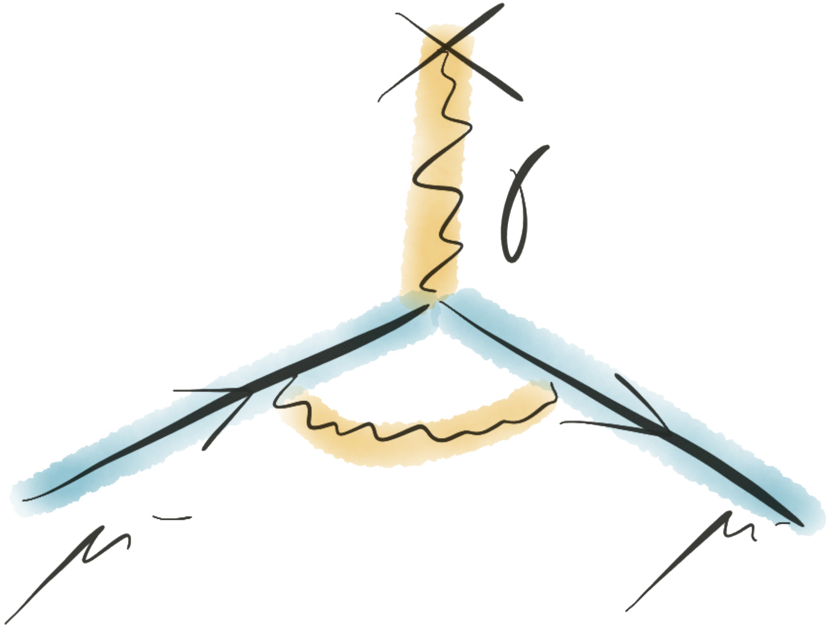
$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

Dirac: $g = 2$



Magnetic moment of the muon





Dirac:

$$g = 2$$

Schwinger:

$$a = \frac{g-2}{2} = \frac{\alpha}{2\pi}$$

J. S. Schwinger, Phys. Rev. 73, 416 (1948)

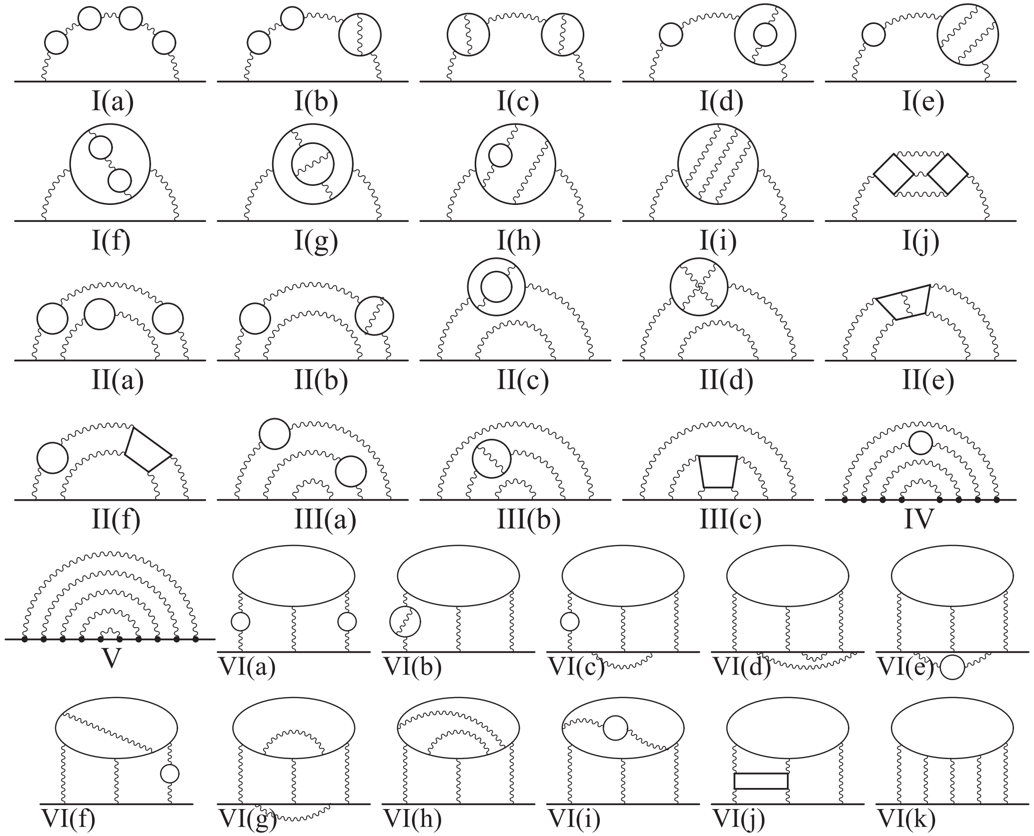
$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

Known analytically to 3 loops

numerically to 5 loops

12672 diagrams



A. Petermann, Helv. Phys. Acta 30, 407 (1957)

C. M. Sommerfield, Ann. Phys. (N.Y.) 5, 26 (1958)

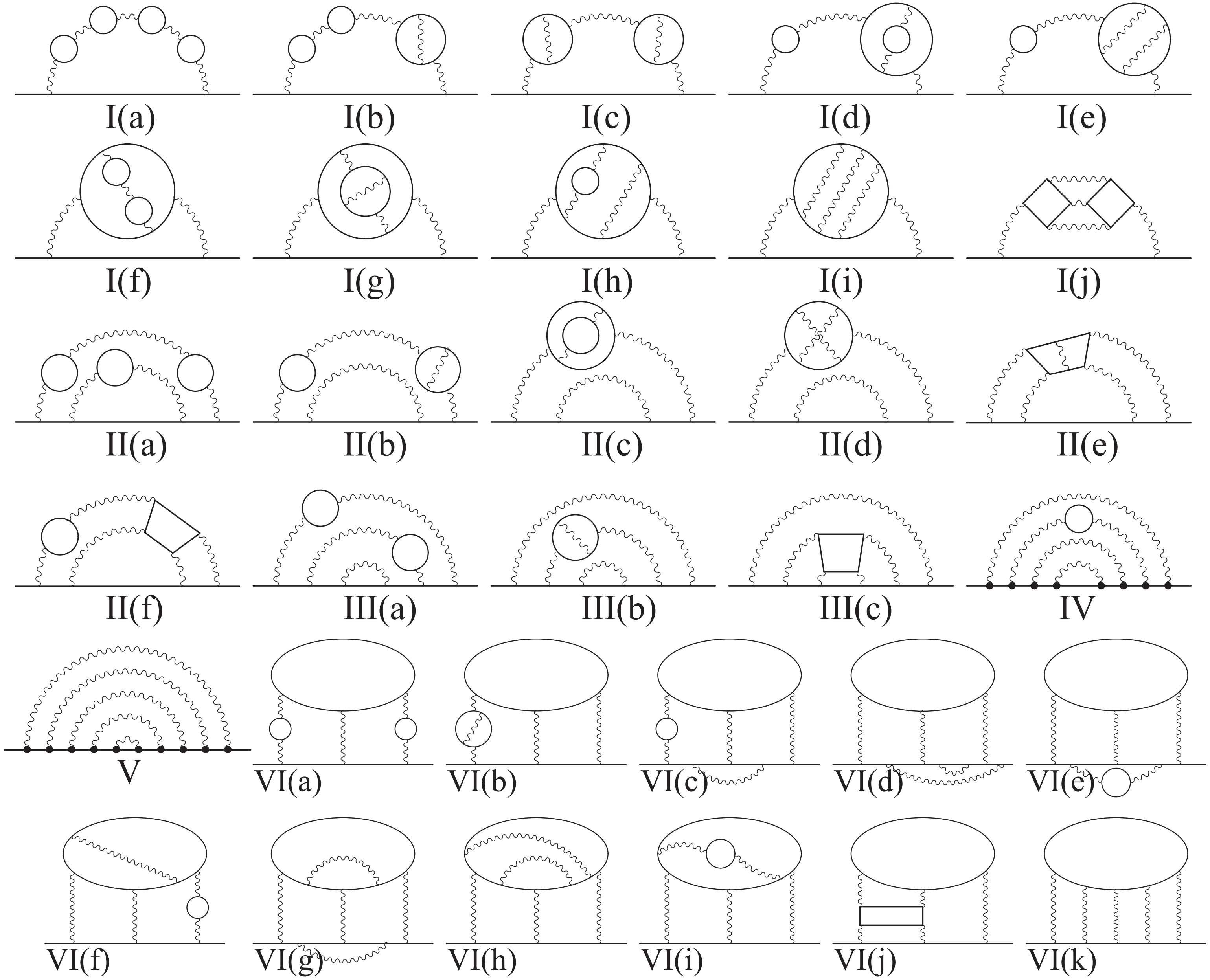
S. Laporta and E. Remiddi, Phys. Lett. B379, 283 (1996)

S. Laporta, Phys. Lett. B312, 495 (1993).

T. Kinoshita and M. Nio, Phys. Rev. D73, 013003 (2006).

T. Aoyama et al., Phys. Rev. Lett. 99, 110406 (2007);
Phys. Rev. D77, 053012 (2008)

T. Aoyama et al., Phys.Rev.Lett. 109, 111808 (2012)


I(a)
I(b)
I(c)
I(d)
I(e)
I(f)
I(g)
I(h)
I(i)
I(j)
II(a)
II(b)
II(c)
II(d)
II(e)
II(f)
III(a)
III(b)
III(c)
IV
V
VI(a)
VI(b)
VI(c)
VI(d)
VI(e)
VI(f)
VI(g)
VI(h)
VI(i)
VI(j)
VI(k)

g-2 in QED

- Probably the best hint that perturbation theory makes sense
  (series seems to converge)

$$a_\mu(\mathrm{QED}) = A_1 + A_2(m_\mu/m_e) + A_2(m_\mu/m_\tau) + A_3(m_\mu/m_e, m_\mu/m_\tau)$$

$$A_i = A_i^{(2)}\left(\frac{\alpha}{\pi}\right) + A_i^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_i^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + \ldots, \quad i = 1, 2, 3,$$

$a_\mu(\mathrm{QED})$ including mass-dependent terms, is known up to $n = 10$.

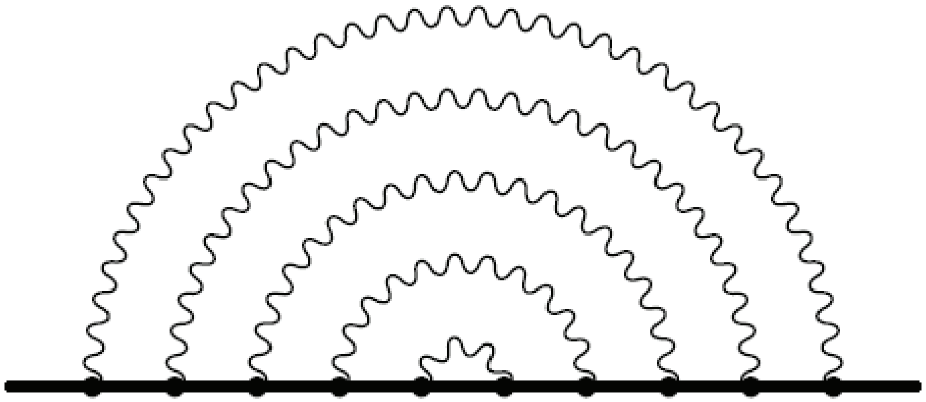
$$a_\mu^{(2)}(QED) = 0.5$$
$$a_\mu^{(4)}(QED) = 0.765\,857\,425\,(17)$$
$$a_\mu^{(6)}(QED) = 24.050\,509\,96\,(32)$$
$$a_\mu^{(8)}(QED) = 130.877\,4\,(61)$$
$$a_\mu^{(10)}(QED) = 751.77\,(93)$$

T. Kinoshita, Lepton Moments 2014

Contribution to $A_1^{(10)}$ comes mainly from diagrams of Set 5, which consists of 6354 proper vertices with no closed lepton loop.

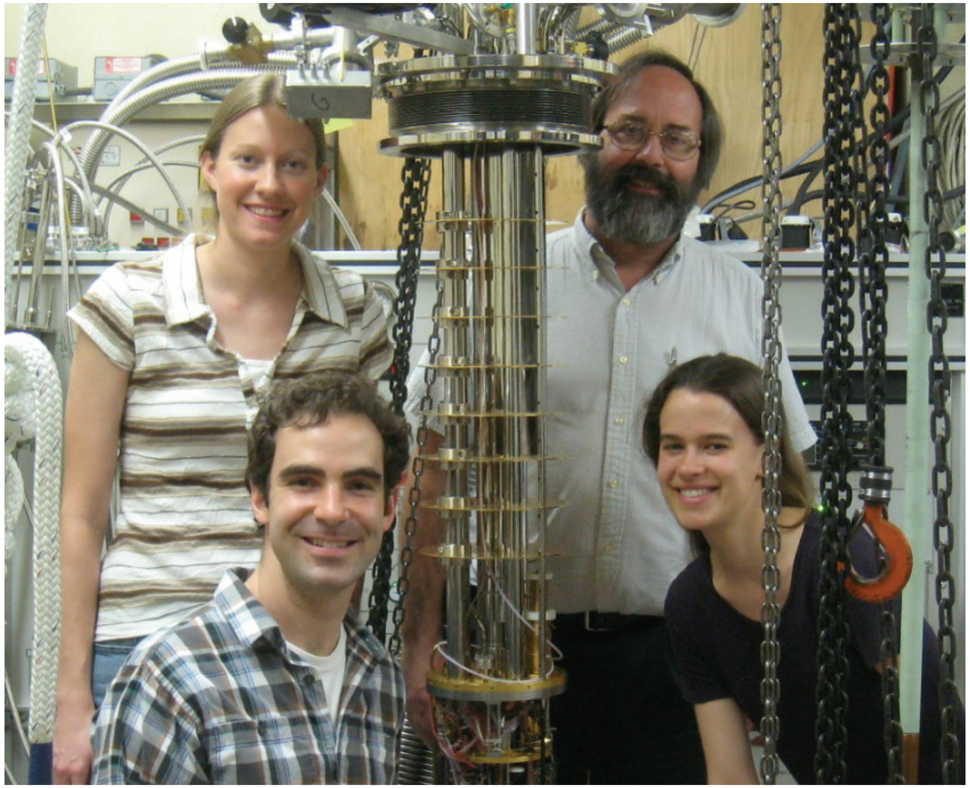
They are compressed with the help of Ward-Takahashi identity and time-reversal symmetry into 389 self-energy-like diagrams.

Each integral occupies more than 10^5 lines of FORTRAN code.

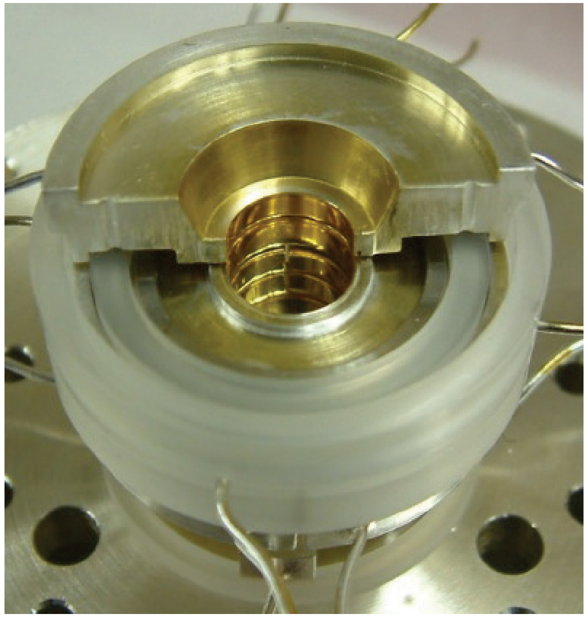


T. Kinoshita, Lepton Moments 2014

Inputs to the QED calculation

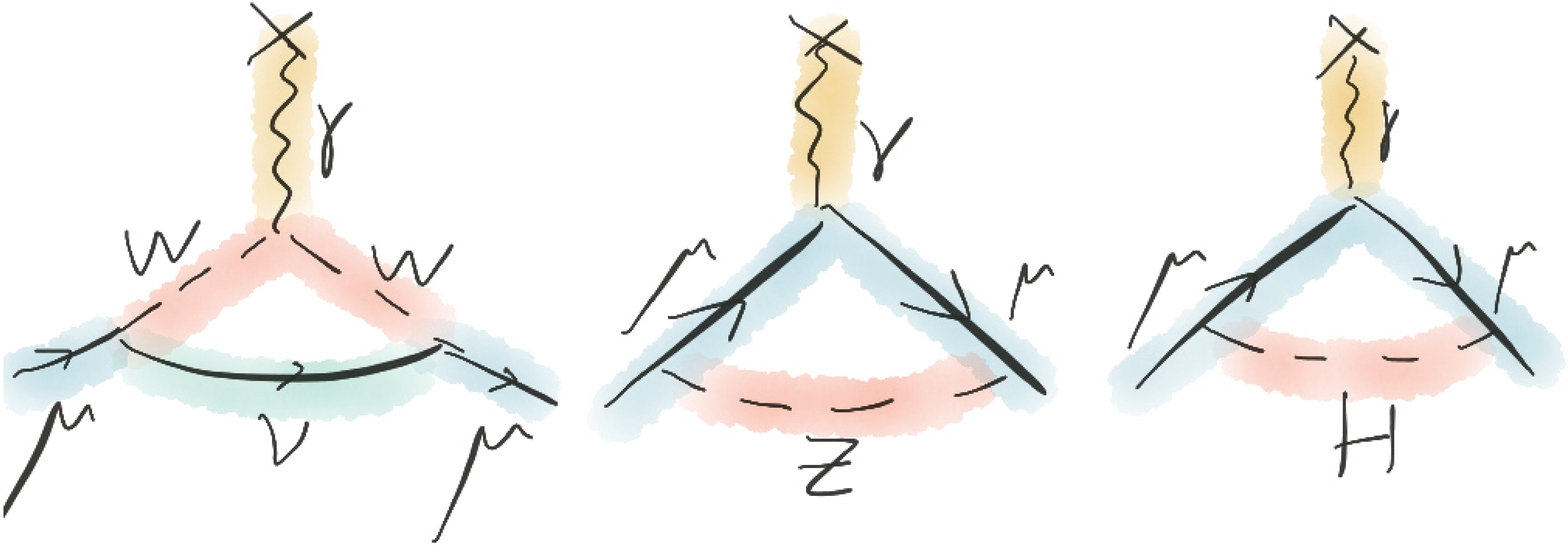


- Ratios of the lepton masses:
  Very well known
- α_{EM} : Best determination from electron g-2
- Essentially the same calculation
- Extremely precise measurement
  (Gabrielse group, Harvard)
  Hanneke et al. PRL 100, 120801 (2008)
- Single electron in a penning trap



$$a_{SM} = a_{QED} + \boxed{a_{EW}} + a_{had}$$

Known analytically to 2 loops



K. Fujikawa, B. Lee, and A. Sanda, Phys. Rev. D 6, 2923 (1972)

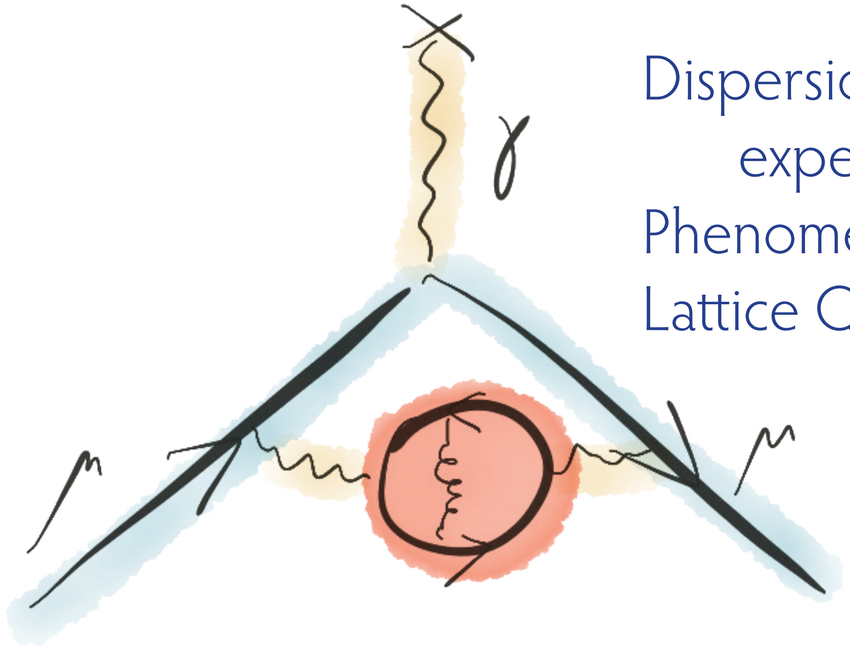
A. Czarnecki, B. Krause, and W. J. Marciano, Phys. Rev. Lett. 76, 3267 (1996)

M. Knecht, S. Peris, M. Perrottet, and E. De Rafael, J.High Energy Phys. 11, 003 (2002)

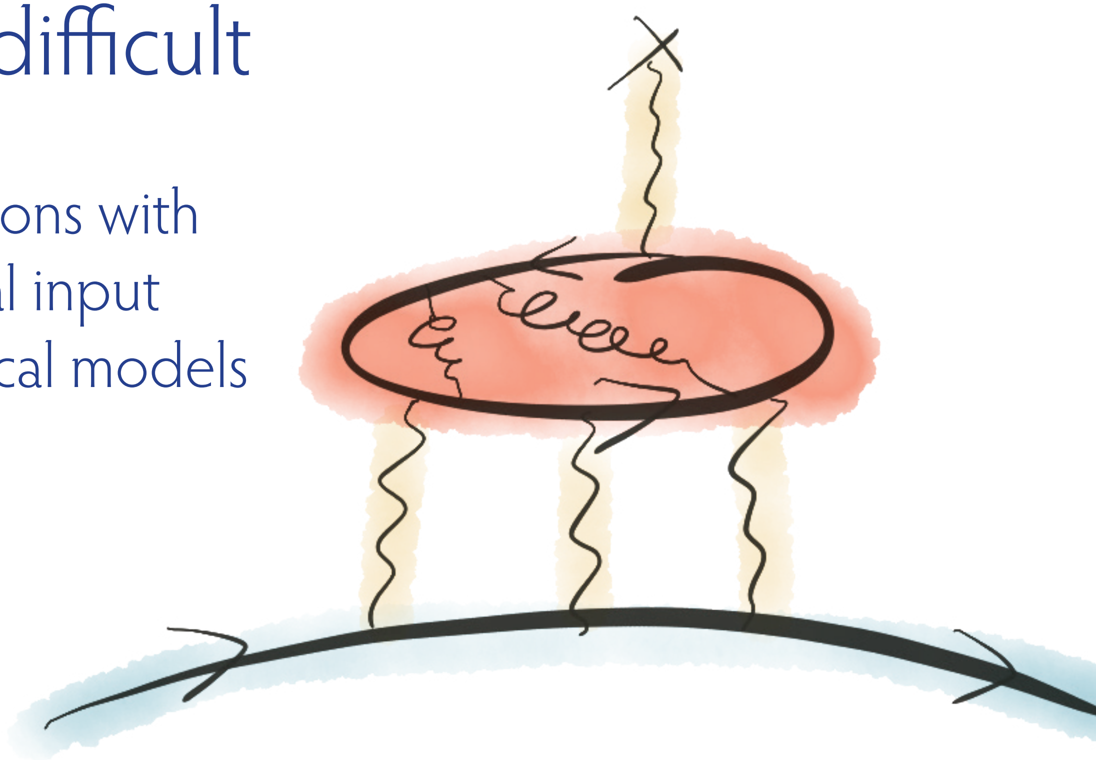
A. Czarnecki, W. J. Marciano, and A. Vainshtein, Phys. Rev. D 67, 073006 (2003)

$$a_{SM} = a_{QED} + a_{EW} + a_{had}$$

Hadronic contribution most difficult

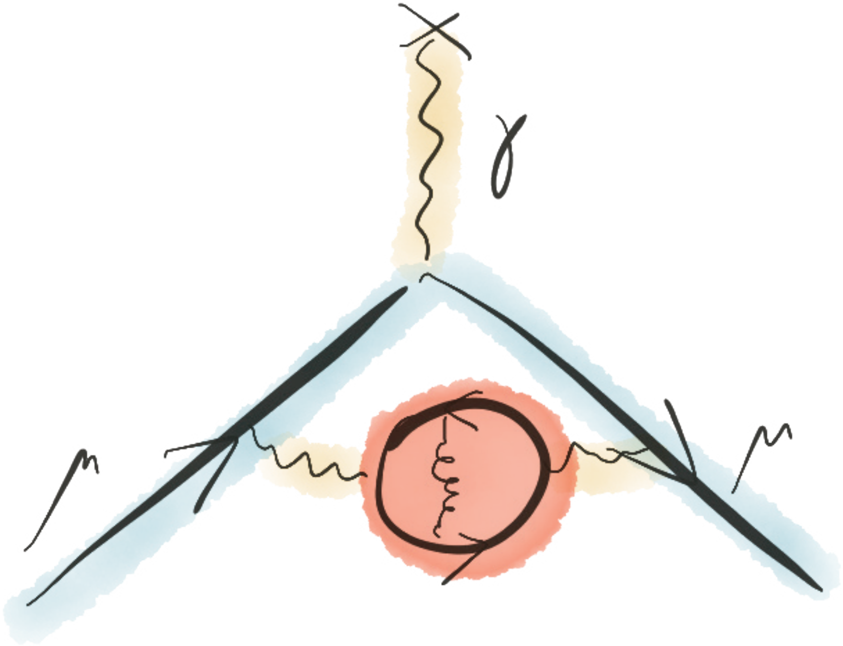


Dispersion relations with
experimental input
Phenomenological models
Lattice QCD



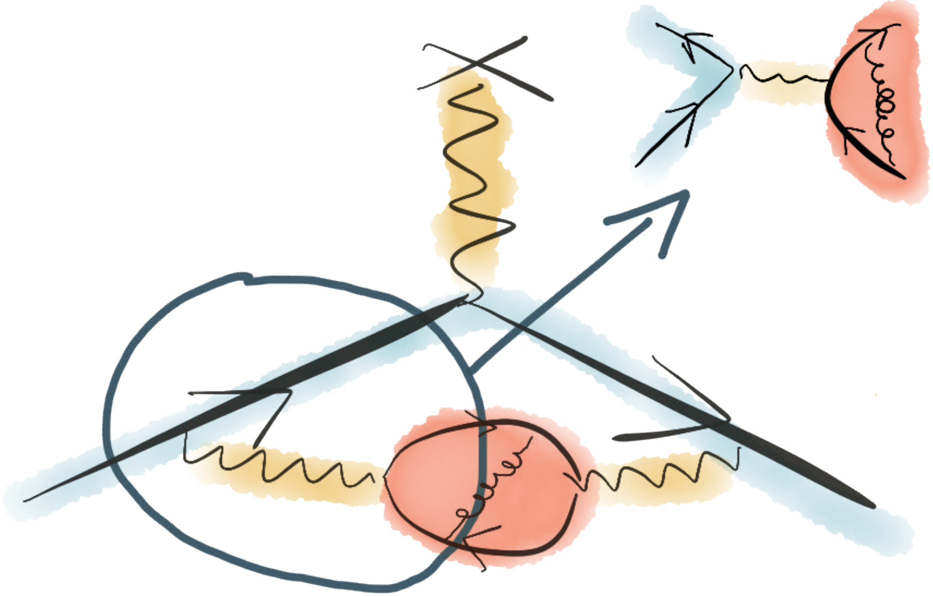
M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C71, 1515 (2011).
F. Jegerlehner and R. Szafron, Eur. Phys. J. C71, 1632 (2011).
K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, and T. Teubner, J. Phys. G38, 085003 (2011).
K. Melnikov and A. Vainshtein, Phys. Rev. D70, 113006 (2004).
J. Bijnens and J. Prades, Mod. Phys. Lett. A22, 767 (2007).
J. Prades, E. de Rafael, and A. Vainshtein, in Lepton Dipole Moments pp. 303–319 (2009).
A. Nyffeler, Phys. Rev. D79, 073012 (2009)
...

Hadronic Vacuum Polarization



- Largest hadronic contribution
- Low scale, strong coupling very large: Perturbative expansion does not work

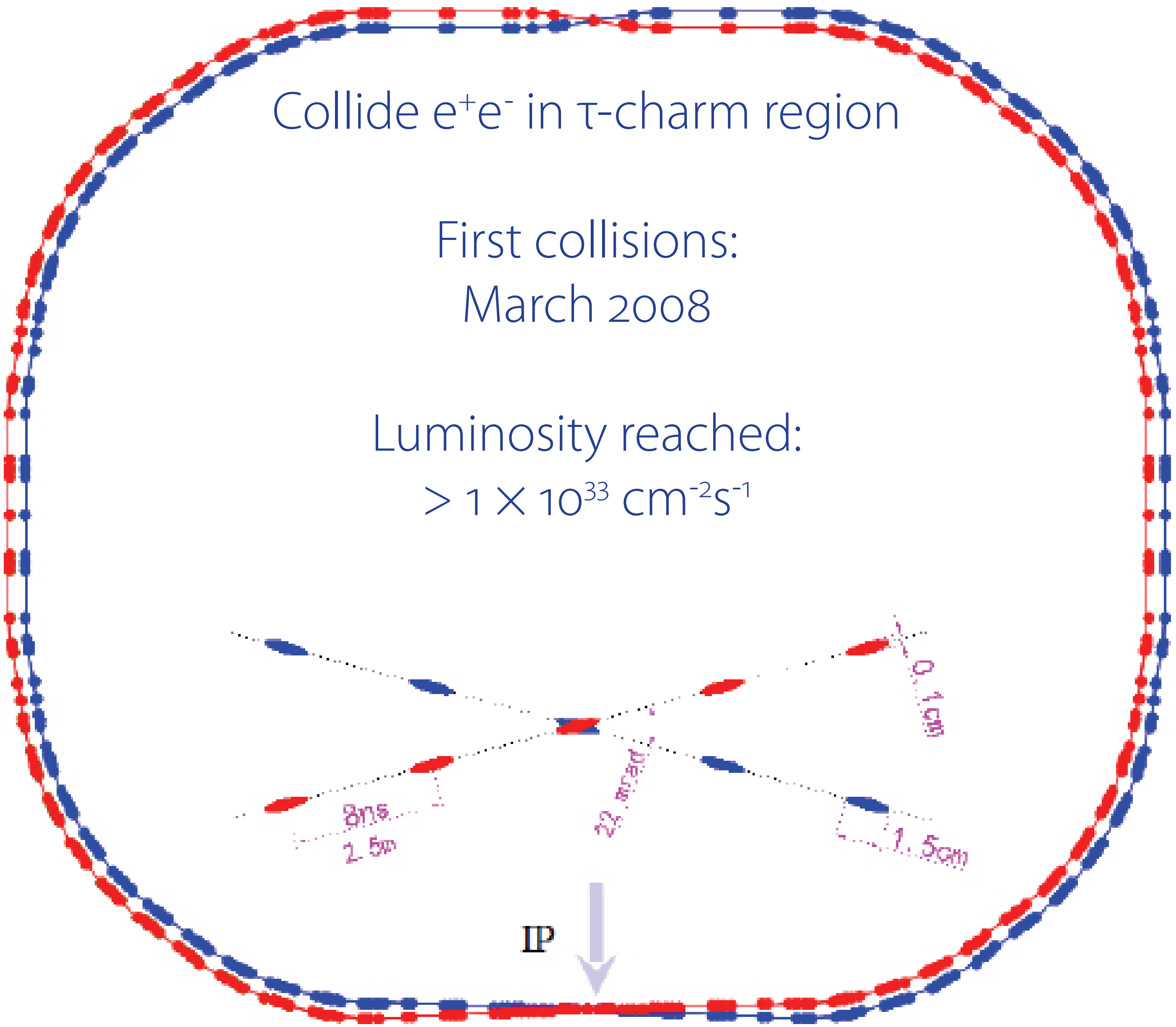
Hadronic Vacuum Polarization



- Largest hadronic contribution
- Low scale, strong coupling very large: Perturbative expansion does not work
- Optical theorem to the rescue: Can link HVP to $e^+e^- \rightarrow$ hadrons using a dispersion integral
- Dispersion integral dominated by low centre-of-mass energies s

- Large program of measurements at e^+e^- colliders

BEPC II

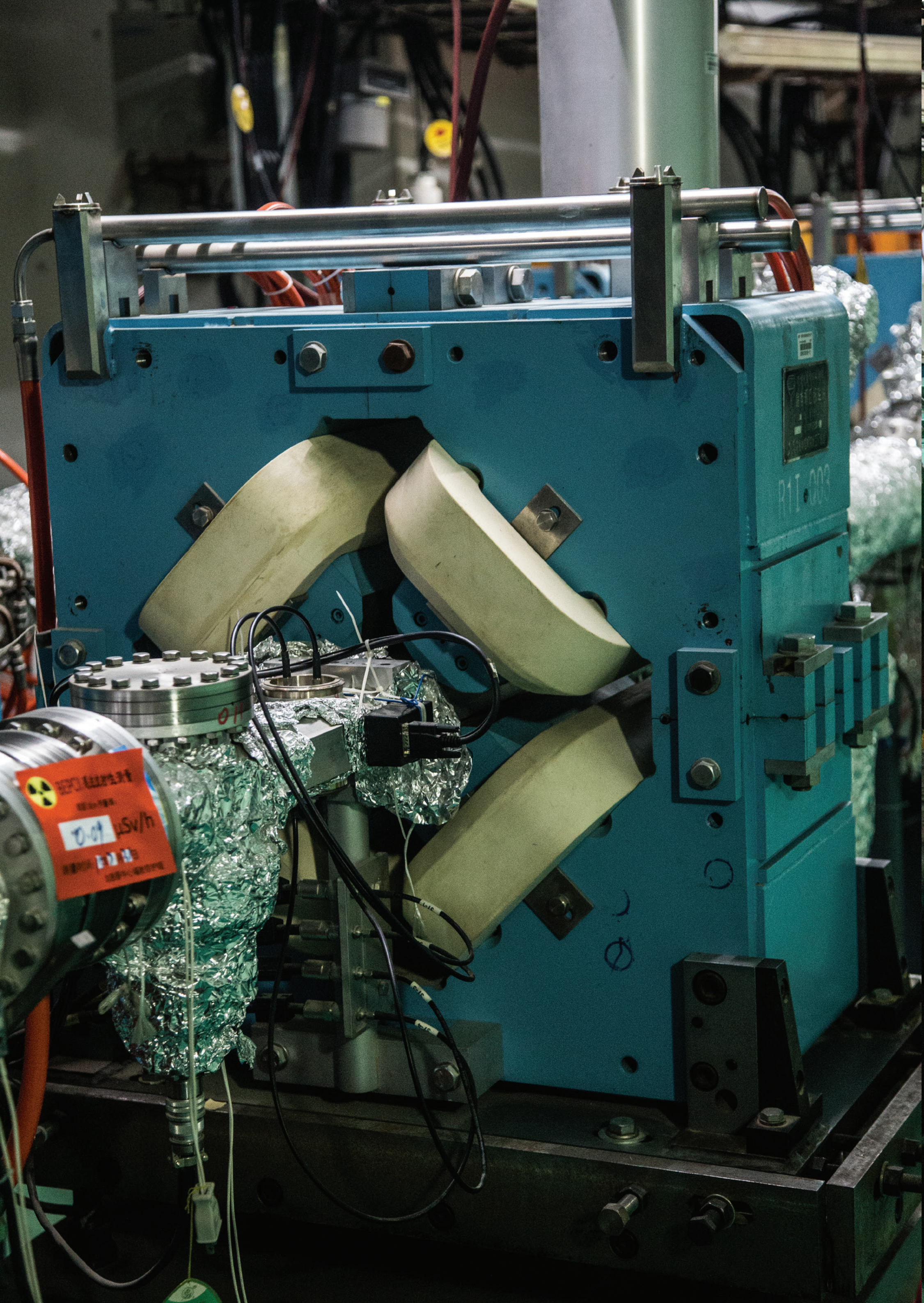


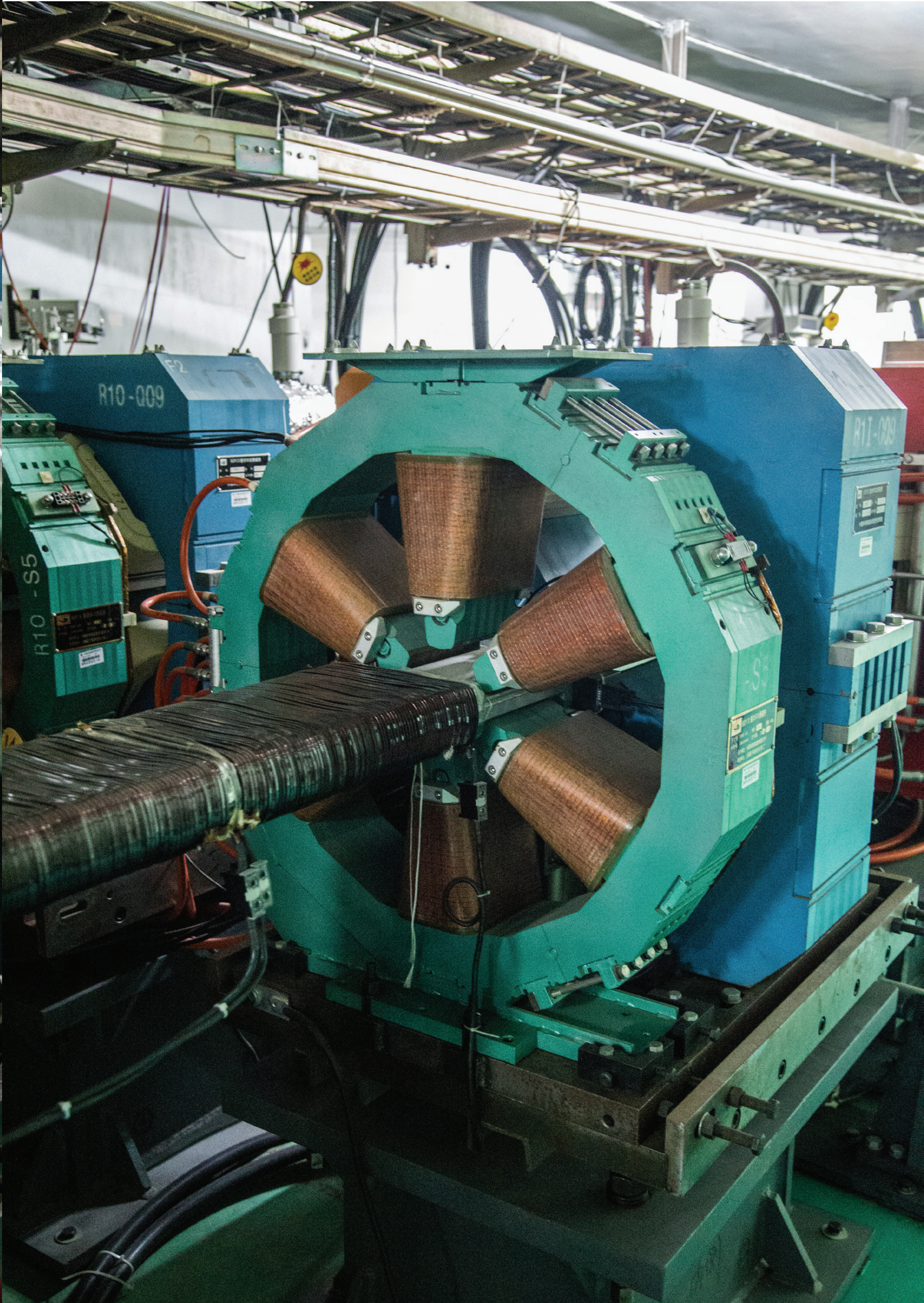
Collide e^+e^- in τ-charm region

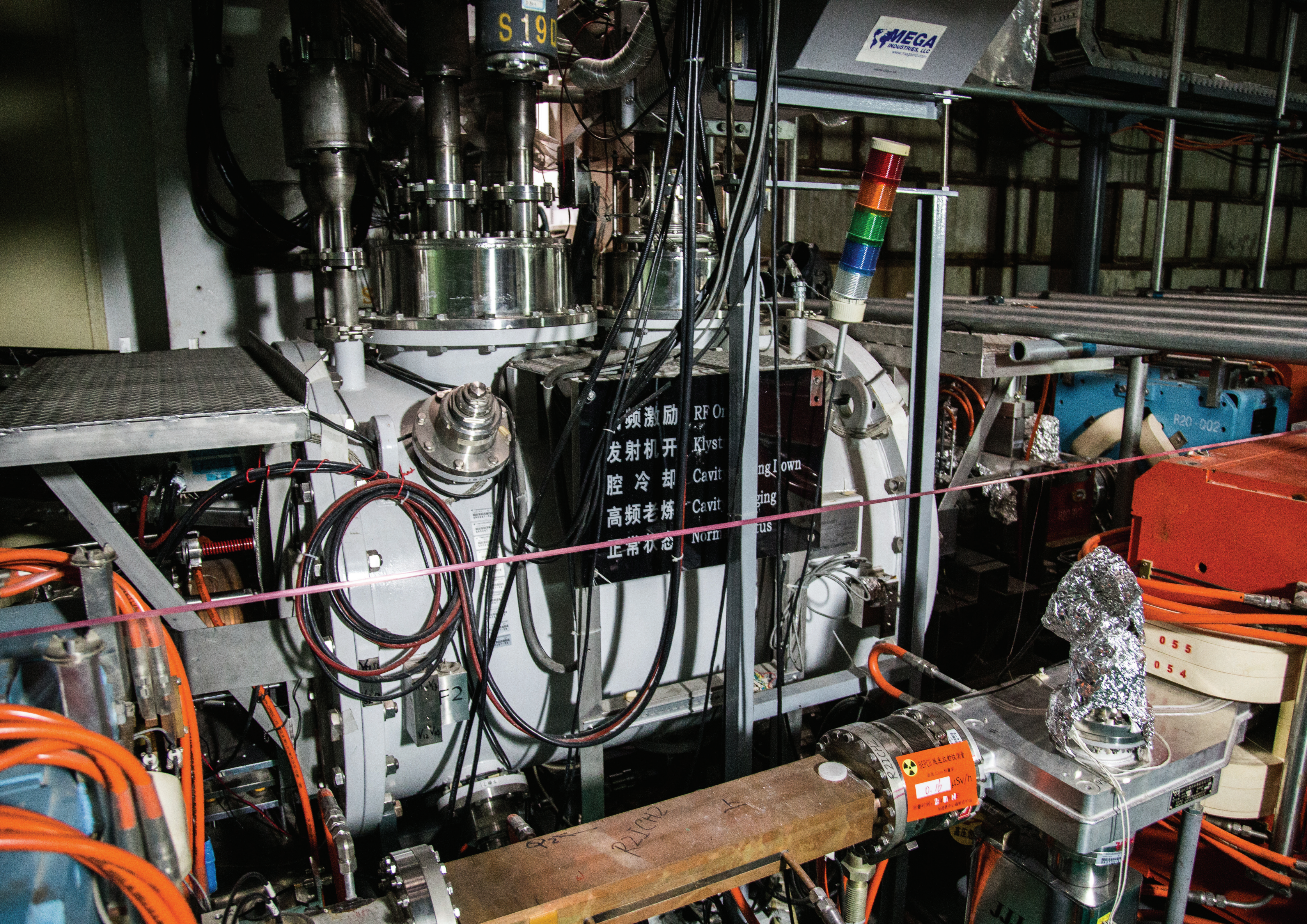
First collisions:
March 2008

Luminosity reached:
$> 1 \times 10^{33}$ $\mathrm{cm^{-2}s^{-1}}$


R3I-MB07
R3I-Q12
R3I

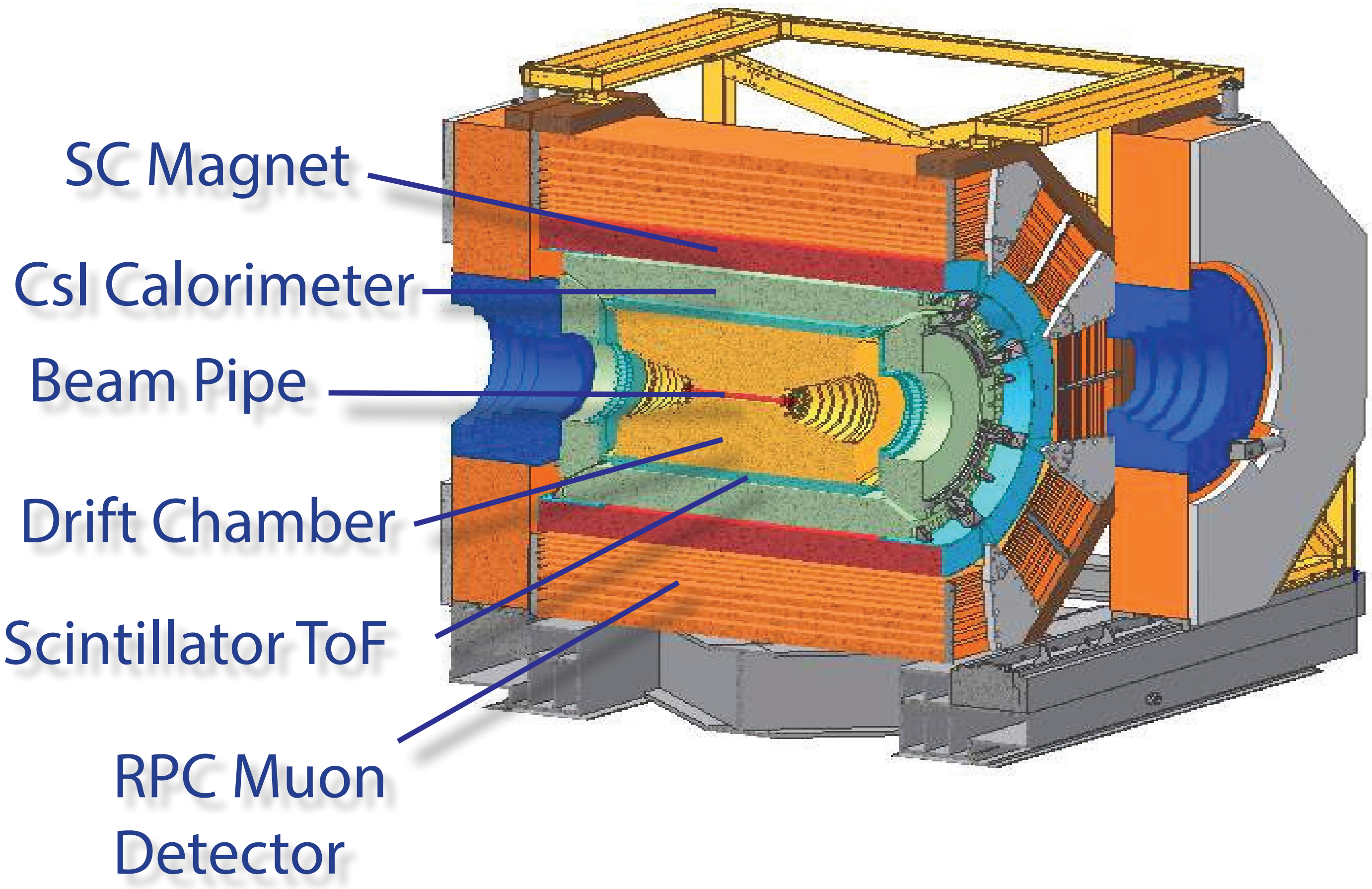

R1T-Q03
μSv/h


R10-Q09
R1T-Q09
R10-S5
S5


S19D
MEGA INDUSTRIES, LLC
频激励 RF On
发射机开 Klyst
腔冷却 Cavit ing Down
高频老炼 Cavit ging
正常状态 Norm tus
R20-Q02
F2
R21CH2
BEPCII
0.16 μSv/h
055
054


S46E
BEPCII束流损失监控器
高压危险
Diamond
F2
F1
R30 0 C T4
F3
YOKOGAWA

BES III



Excellent tracking and calorimetry:

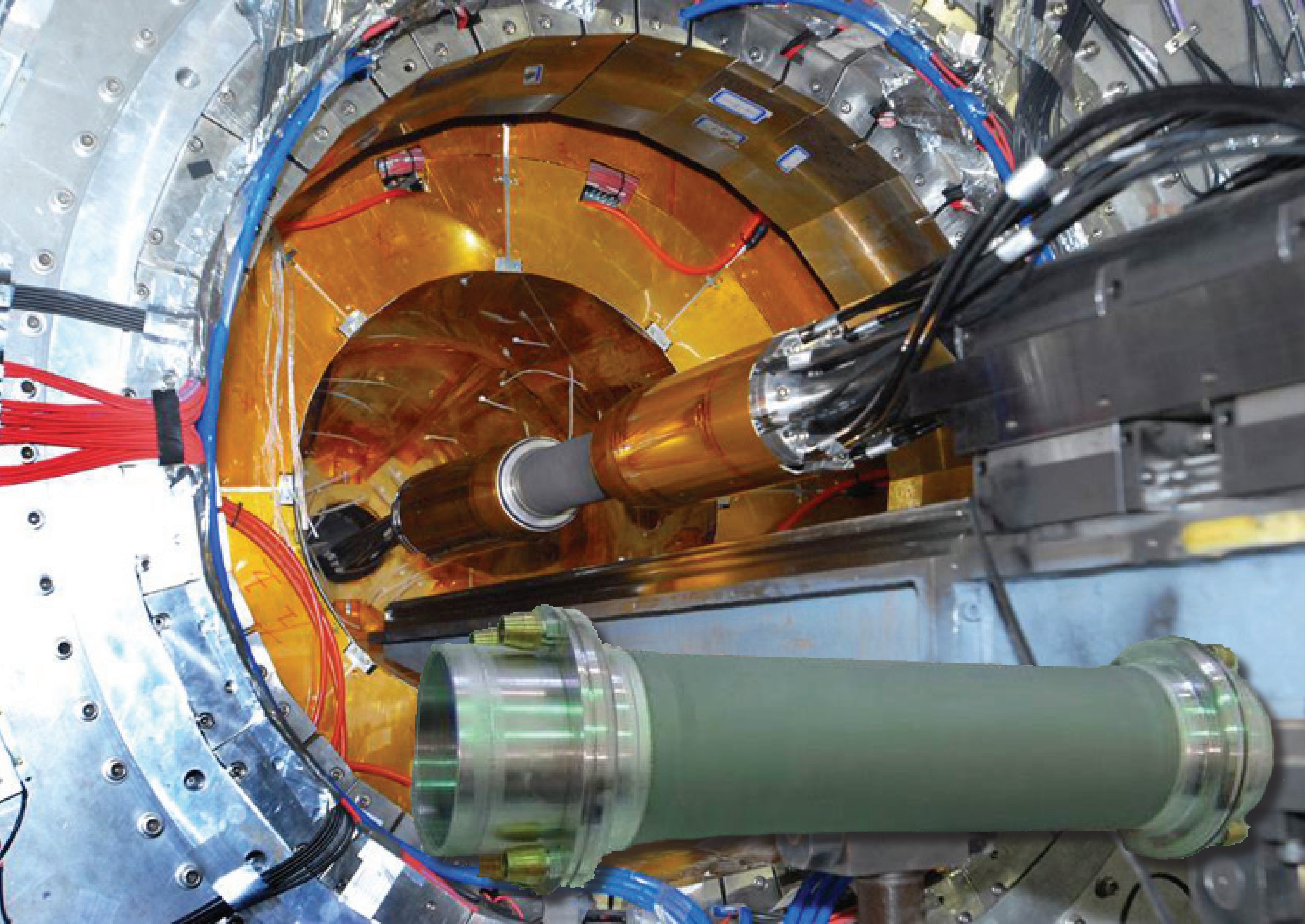
Tracks:

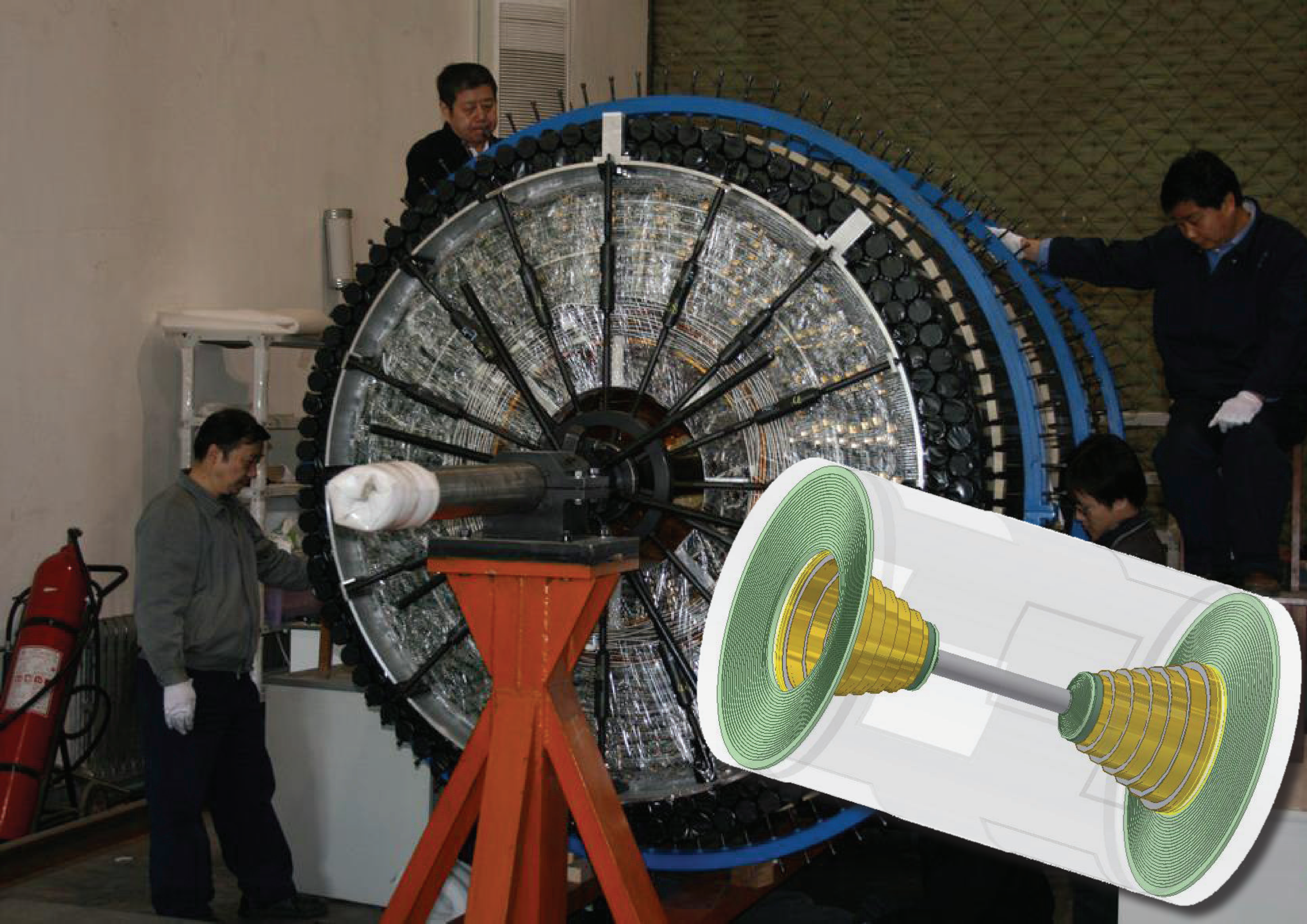
$\sigma_p/p = 0.58\%$ @ 1 GeV/c

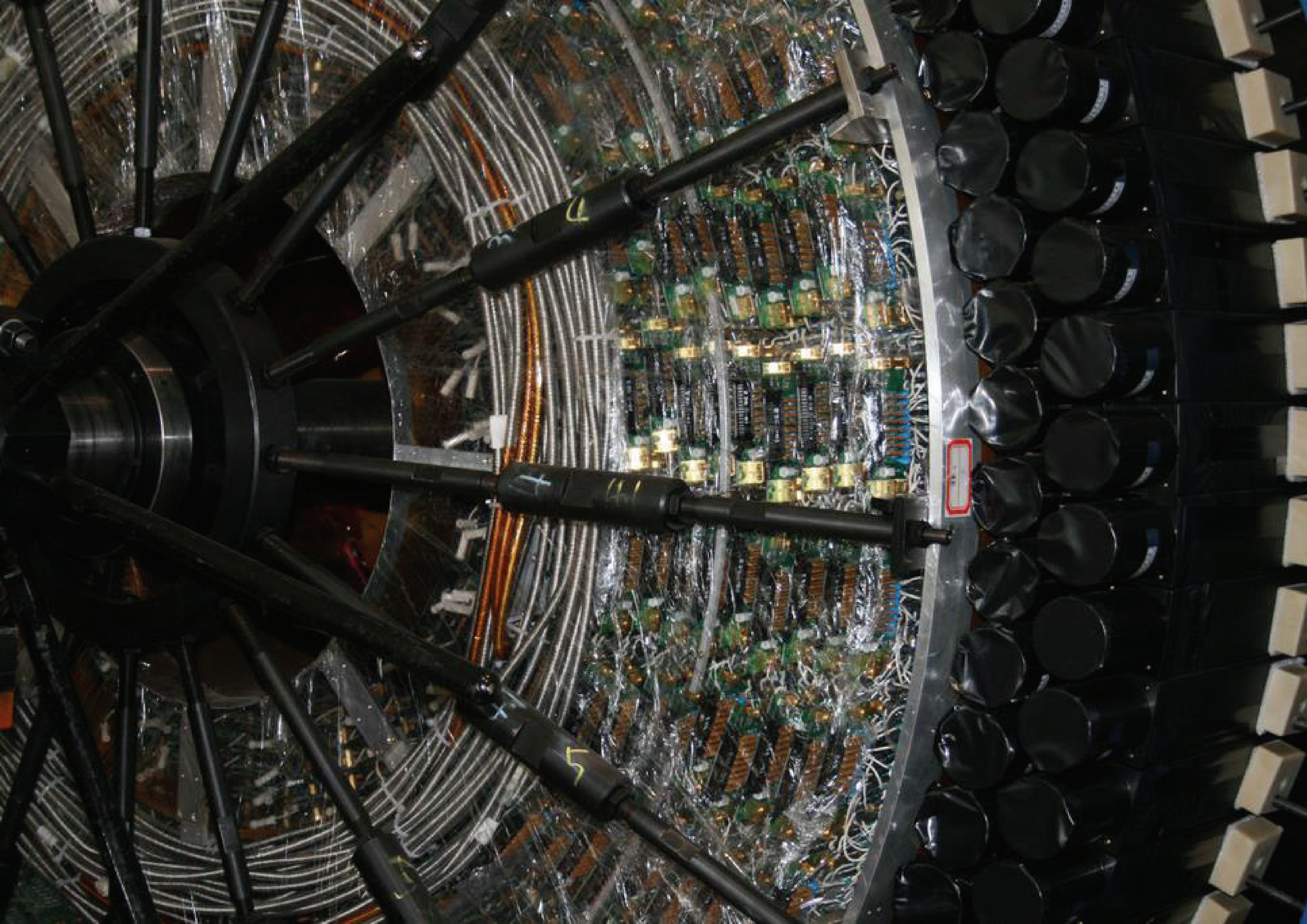
Photons:

$\sigma_E/E = 2.5\%$ @ 1 GeV

Read-out at up to 6 KHz






4
5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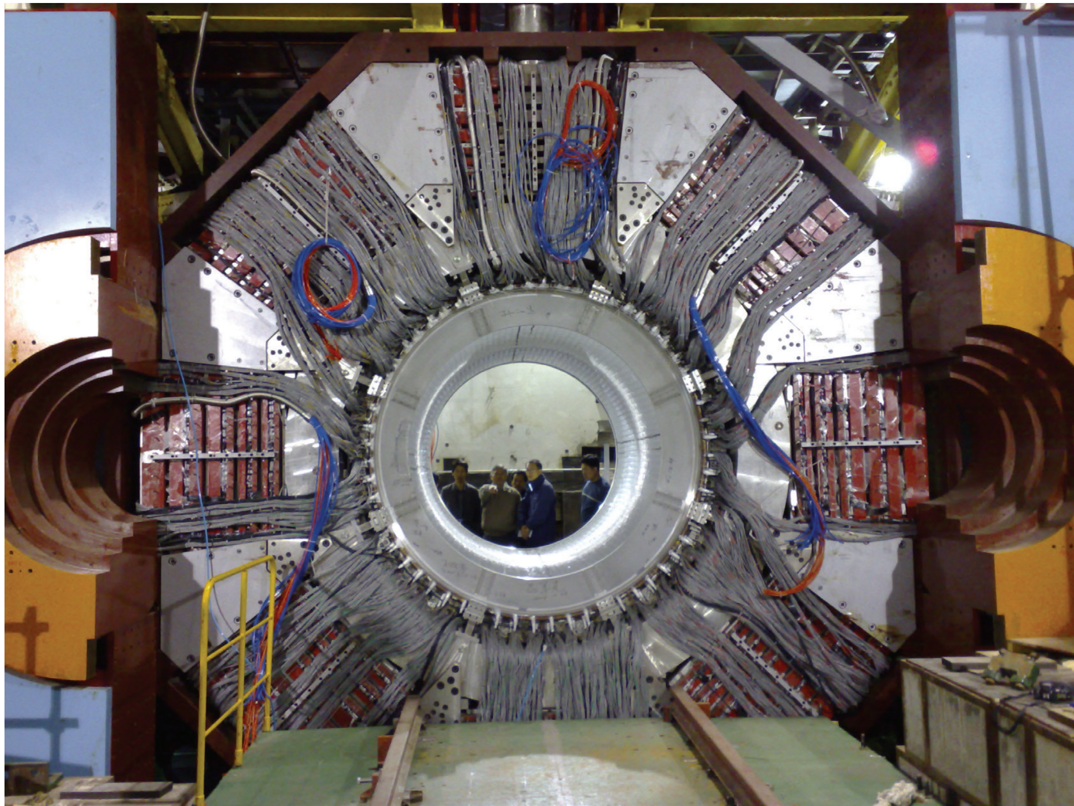
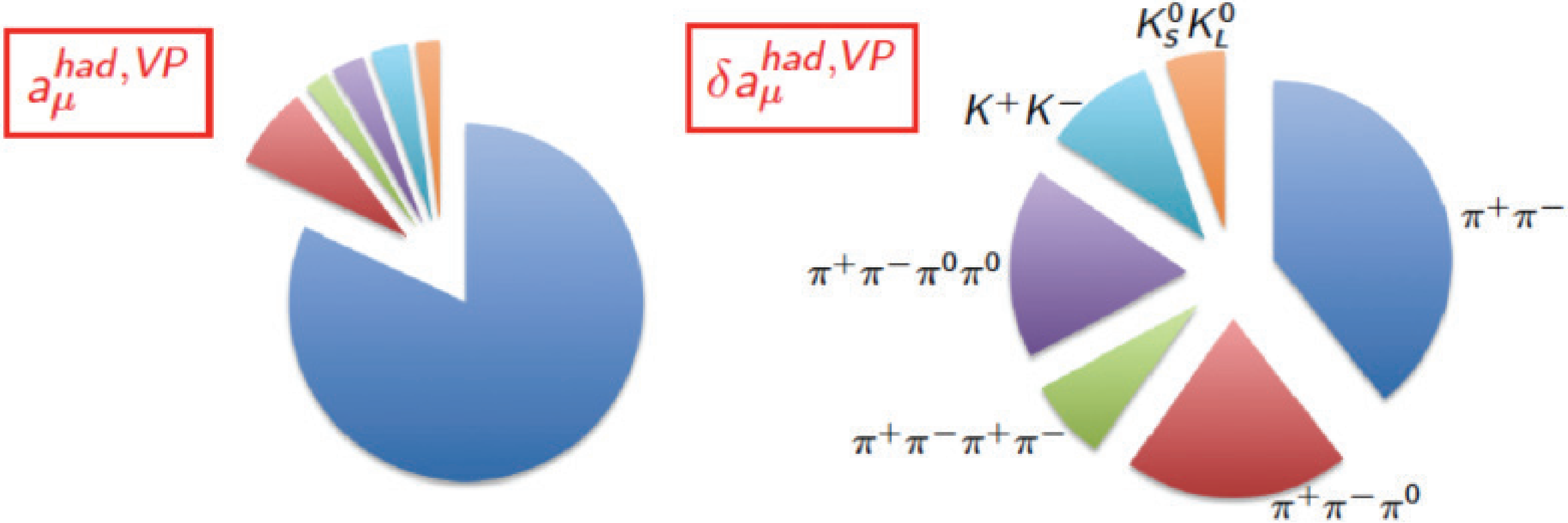
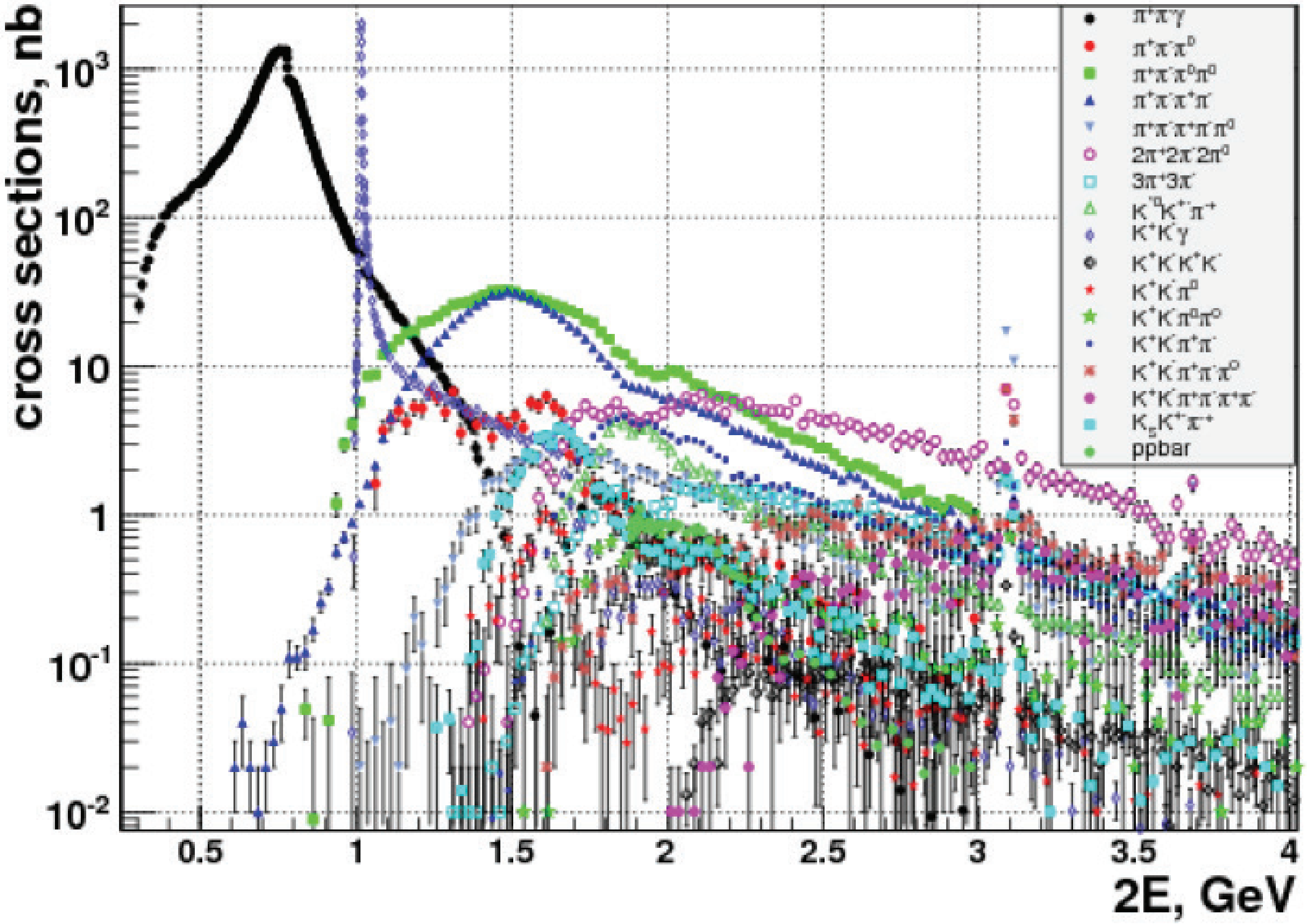



China
HongKong, China
Germany
Italy
Japan
Republic of Korea
Netherlands
Russia
Pakistan
U.S.A.



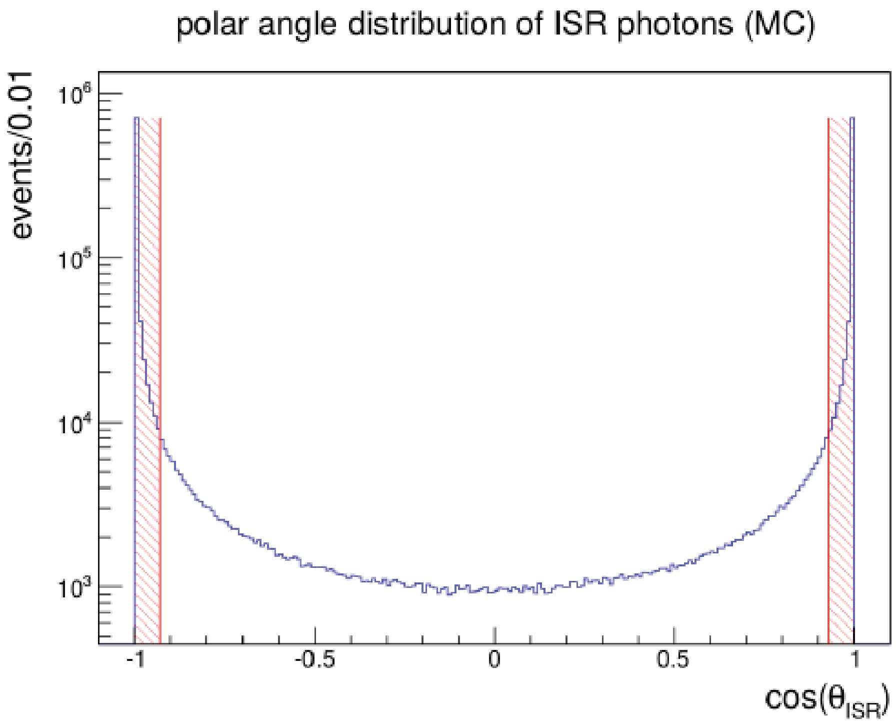
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C **71** 1515 (2011)



D. Bernard [BaBar Collaboration], PoS Hadron **2013**, 126 (2013) [arXiv:1402.0618 [hep-ex]].

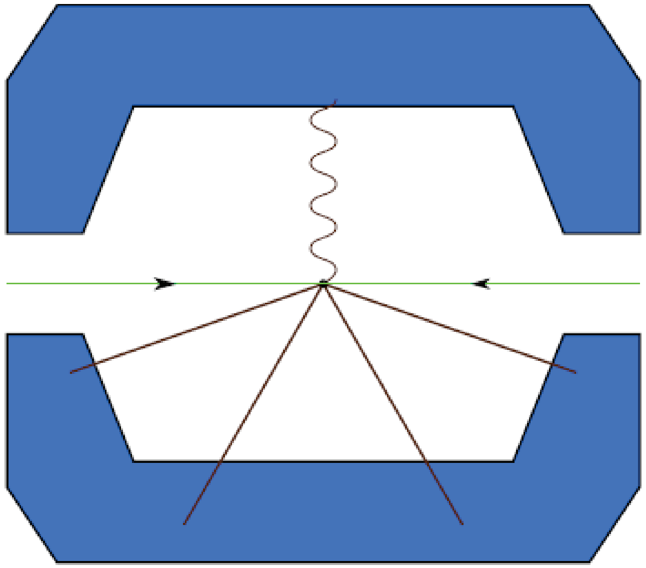
How to go to low s?

- Can tune beam energies in wide range (R-scans)
- Cannot go to threshold - particles need a minimum momentum to be detected
- Use initial state radiation (ISR) - lower s
- $e^+e^- \rightarrow e^+e^-\gamma \rightarrow X$

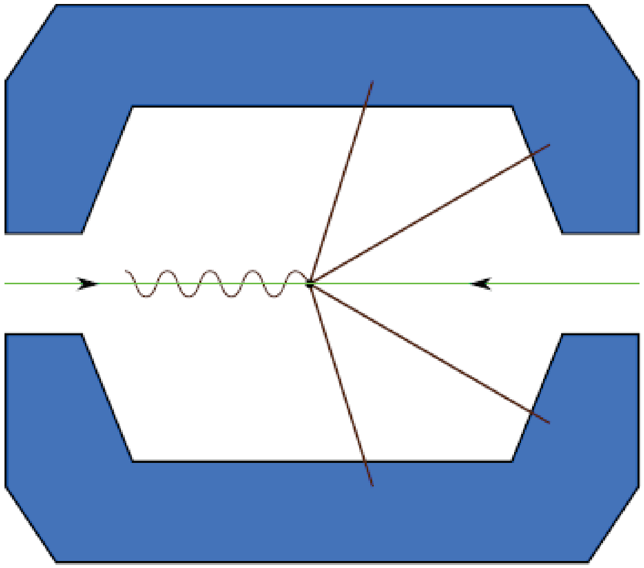


- Emission of ISR photons is suppressed by α/π
- High integrated luminosity needed for precision measurements
- Untagged analysis possible above ≈ 1 GeV

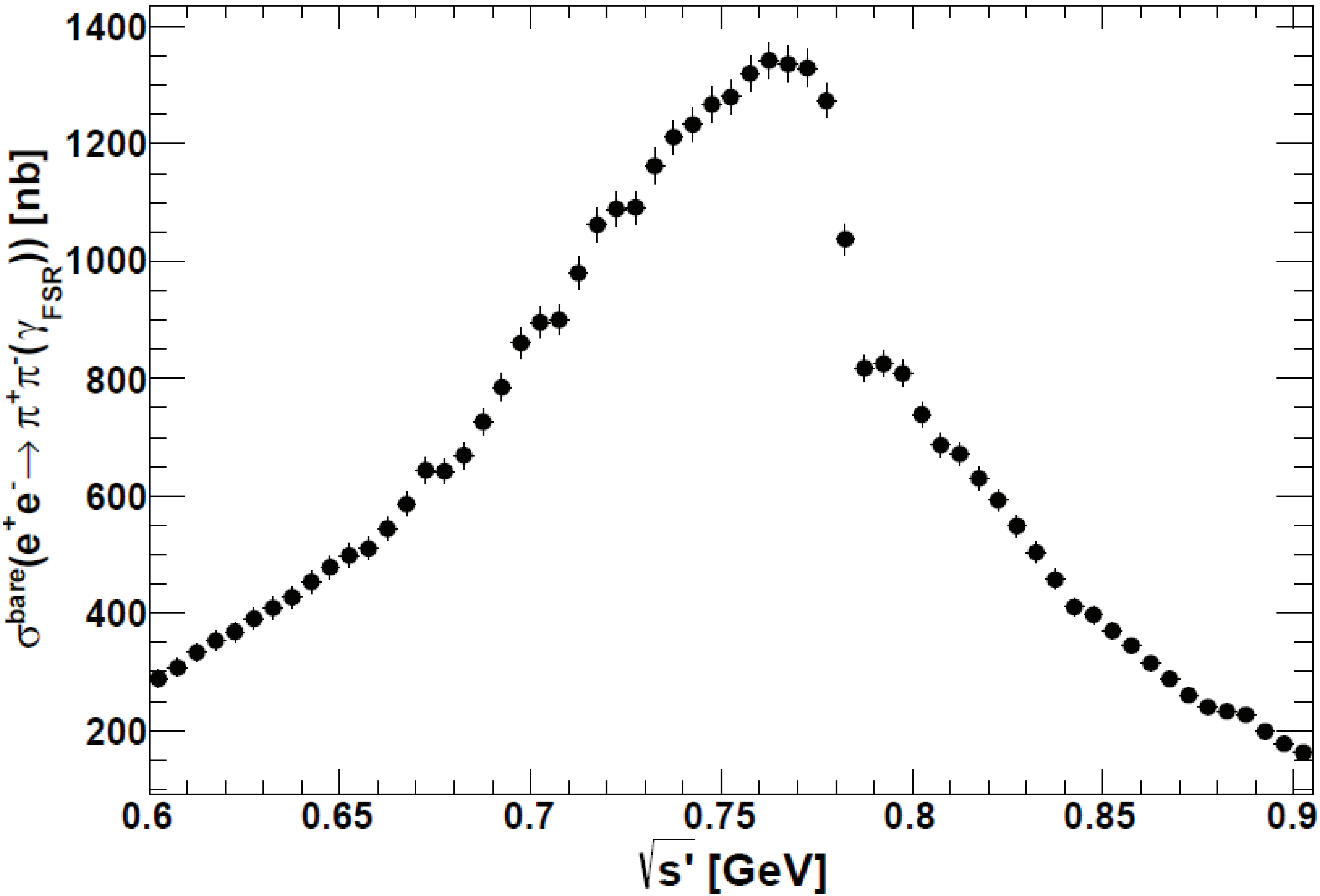
Tagged analysis

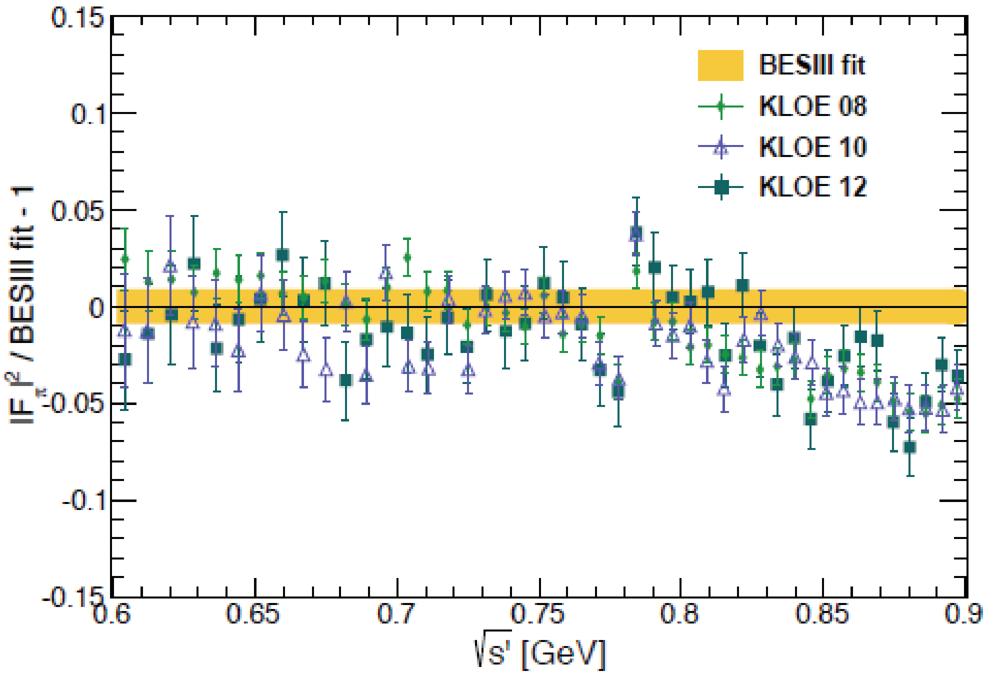


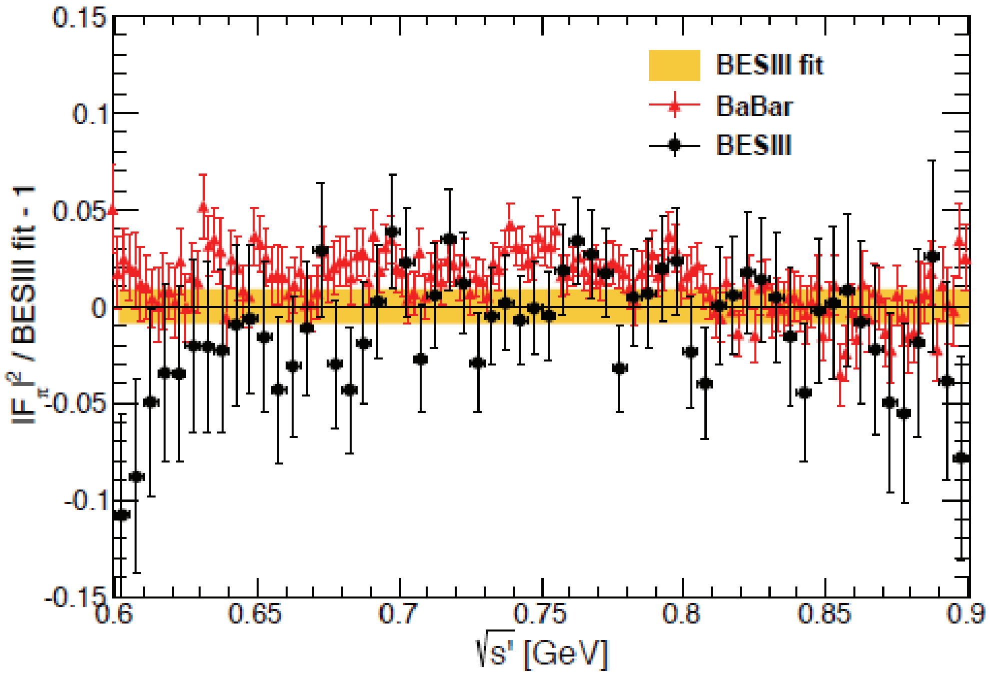
Untagged analysis

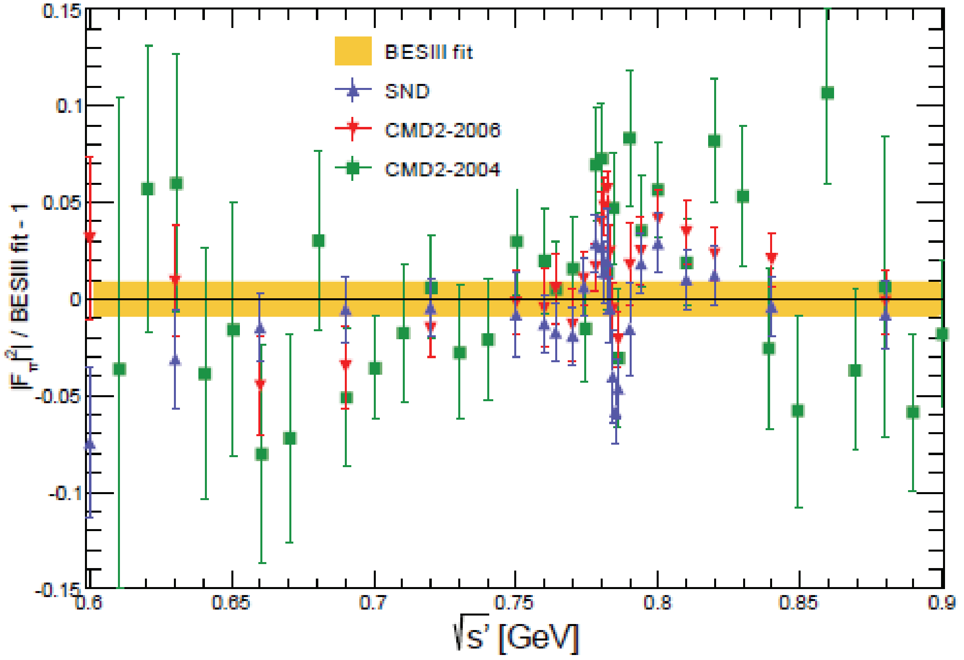


Martin Ripka, KPH Mainz


1400
1200
1000
800
600
400
200
0.6
0.65
0.7
0.75
0.8
0.85
0.9
$\sigma^{bare}(e^+e^- \to \pi^+\pi^-(\gamma_{FSR}))$ [nb]
$\sqrt{s'}$ [GeV]

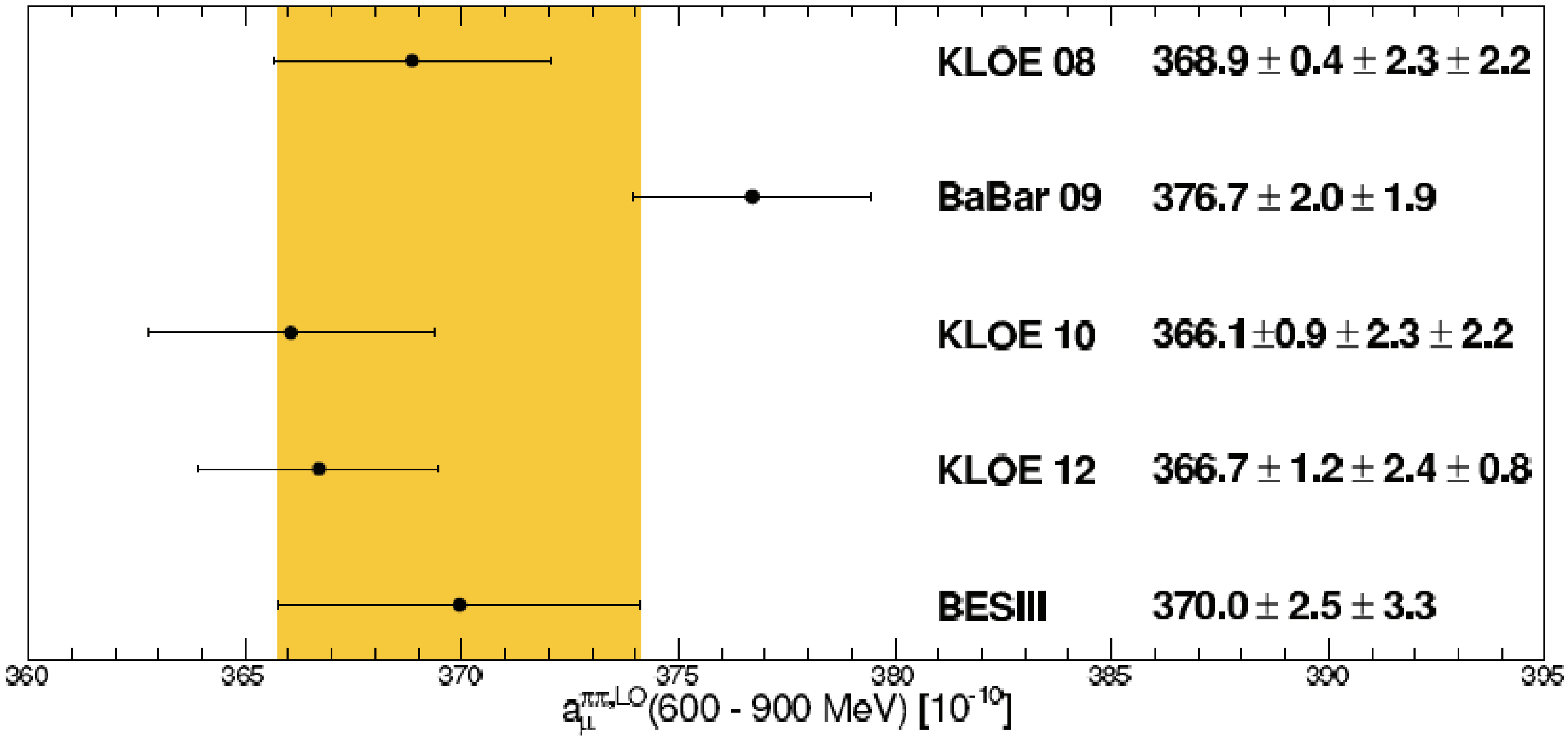




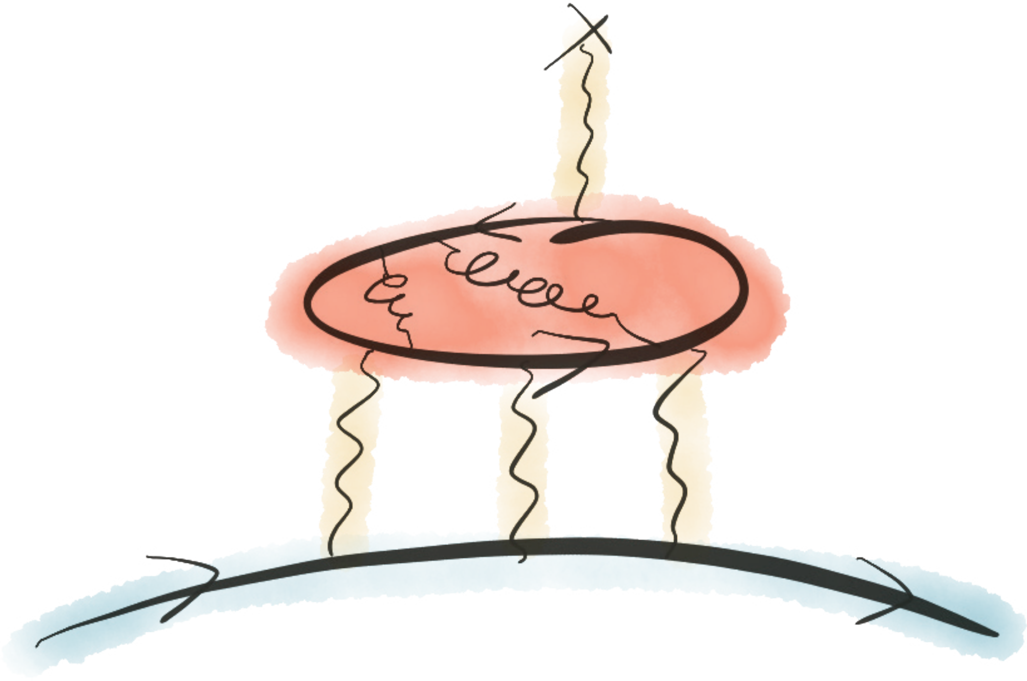


Martin Ripka, KPH

- New BESIII measurement agrees with KLOE and BaBar
- Small shift wrt. BaBar above ρ-ω interference


KLOE 08
368.9 ± 0.4 ± 2.3 ± 2.2
BaBar 09
376.7 ± 2.0 ± 1.9
KLOE 10
366.1±0.9 ± 2.3 ± 2.2
KLOE 12
366.7 ± 1.2 ± 2.4 ± 0.8
BESIII
370.0 ± 2.5 ± 3.3
360
365
370
375
380
385
390
395
$a_\mu^{\pi\pi,LO}$(600 - 900 MeV) [10^{-10}]

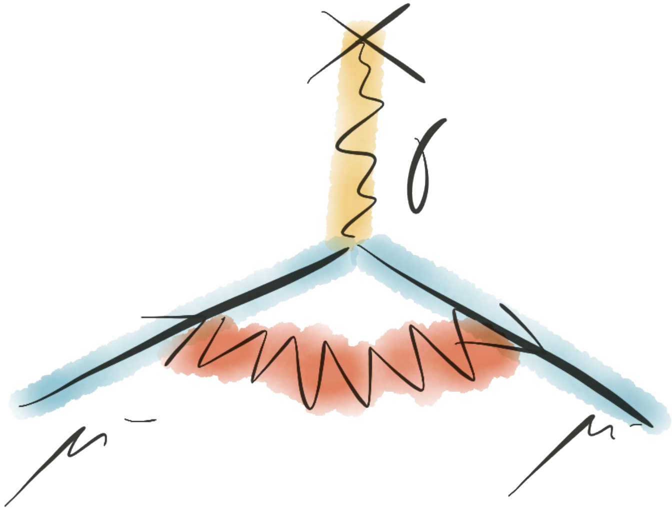
Hadronic Light-by-Light Scattering

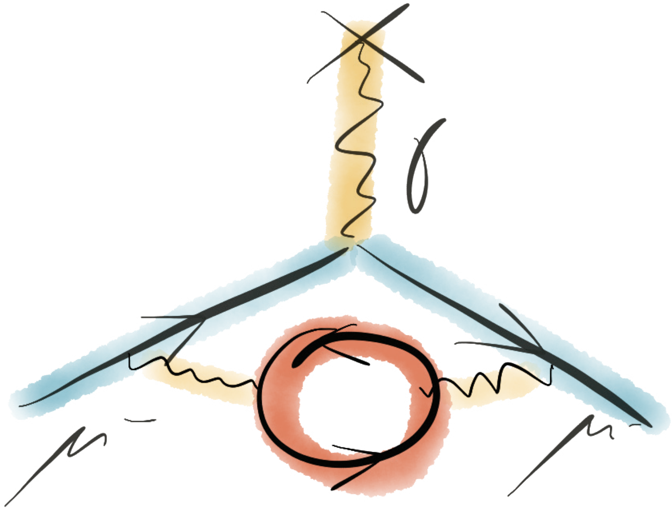


- No perturbative calculation possible
- Relies on hadronic models, where uncertainties are mostly guesswork (Glasgow consensus)
- In the works: Dispersive approach with experimental input (meson form factors) Mainz and Bern groups
- Lattice QCD also making a lot of progress might be competitive very soon

$$a_{SM} = 11\,659\,182.8(4.9) \times 10^{-10}$$

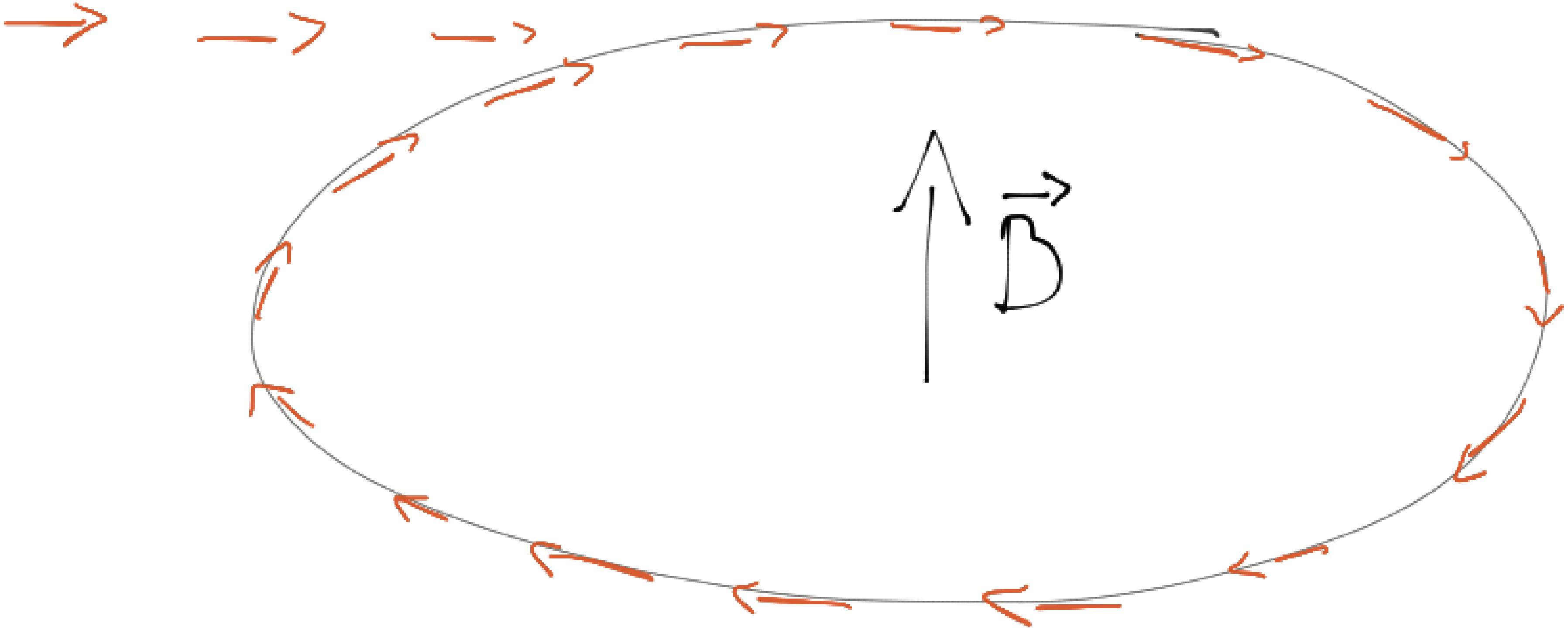
$$+a_{\text{New Physics}}?$$



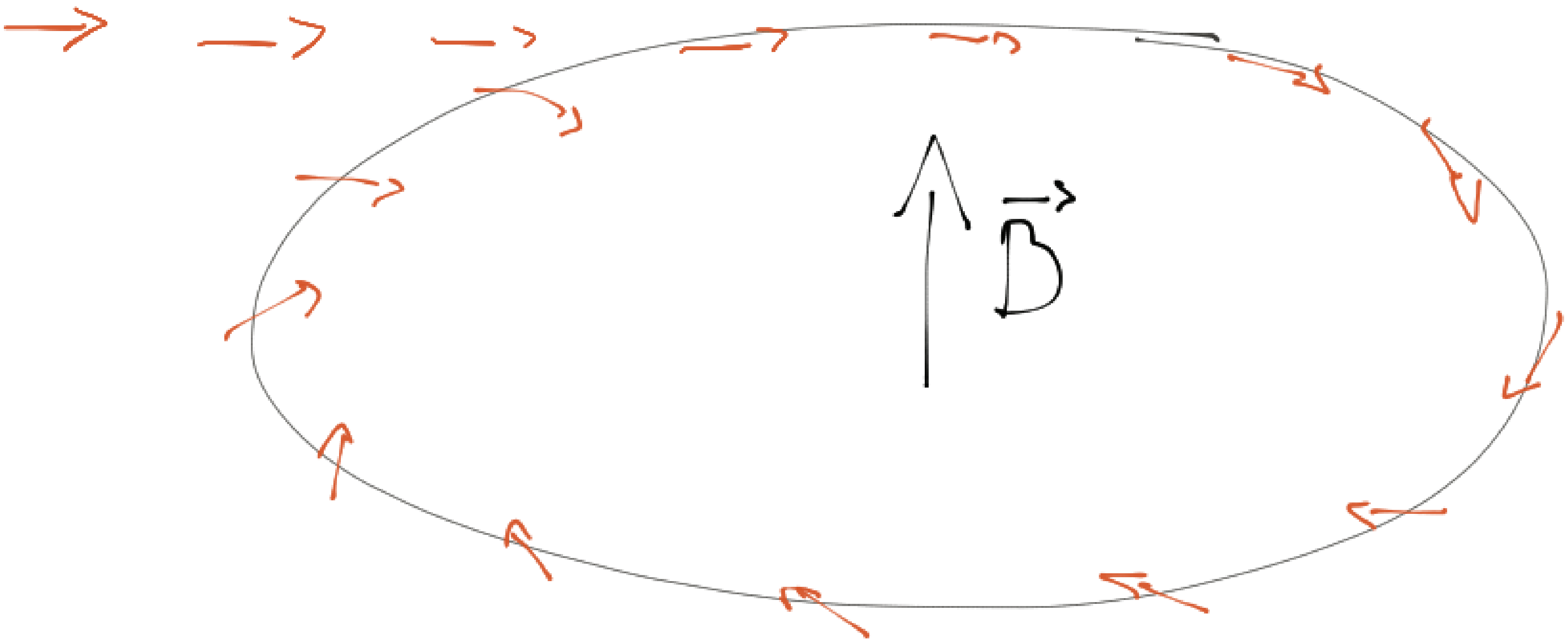


How about experiment?

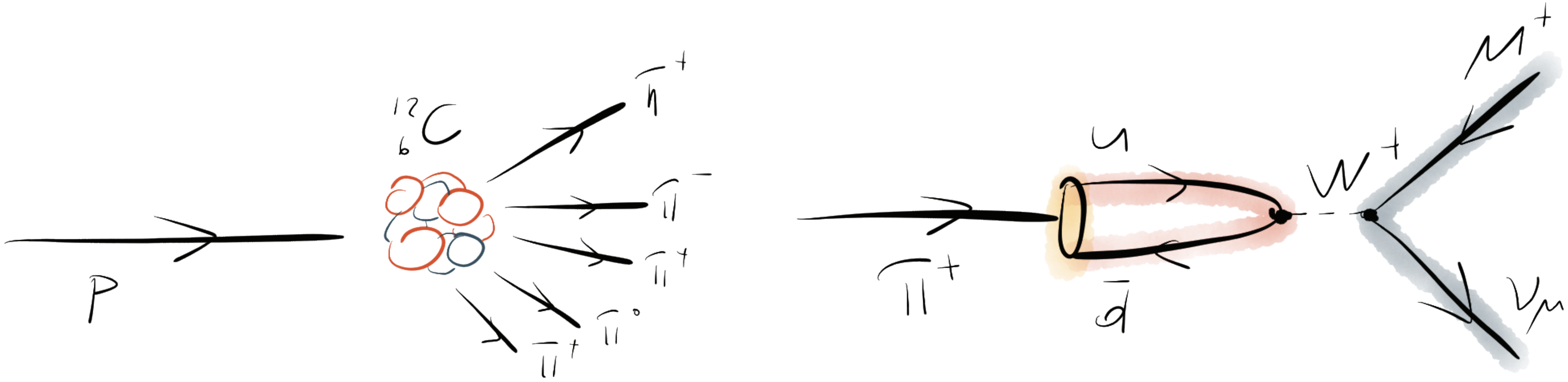
$g = 2$



g > 2



Reminder: Muons are a tertiary beam



Easy to produce with intense proton beams:

10^8 μ/s available

> 10^{10} μ/s planned

Polarized

Huge emittance

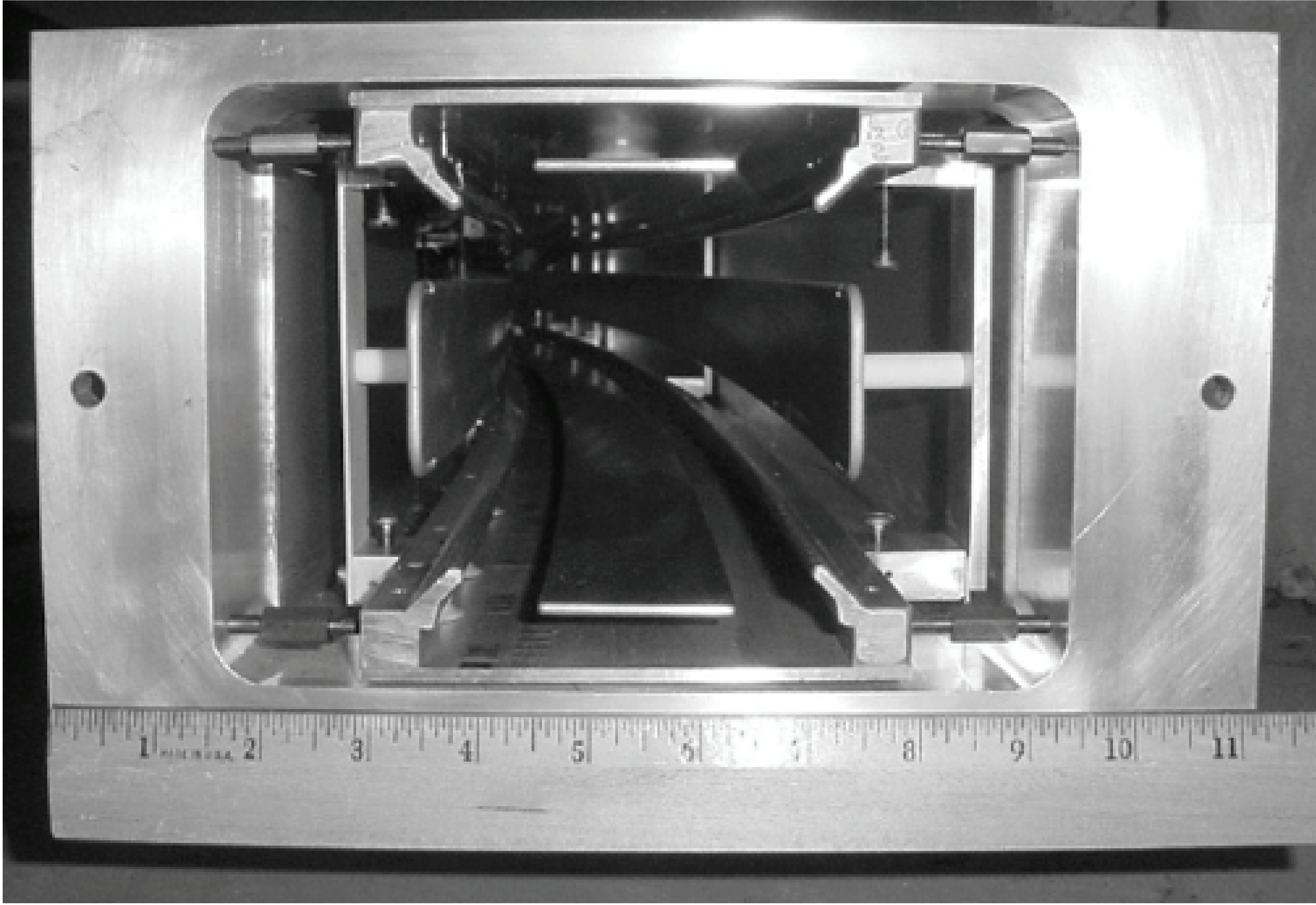
Electrical focusing

- Use electric quadrupole fields for focusing

In muon rest frame: $\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\mu} \times \vec{B}$

In lab frame (all fields perpendicular to motion):

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m} \left(a\vec{B} + (a - \frac{1}{1-\gamma^2})(\vec{v} \times \vec{E}) \right) \times \vec{s}$$


1
2
3
4
5
6
7
8
9
10
11

Electrical focusing

- Use electric quadrupole fields for focusing

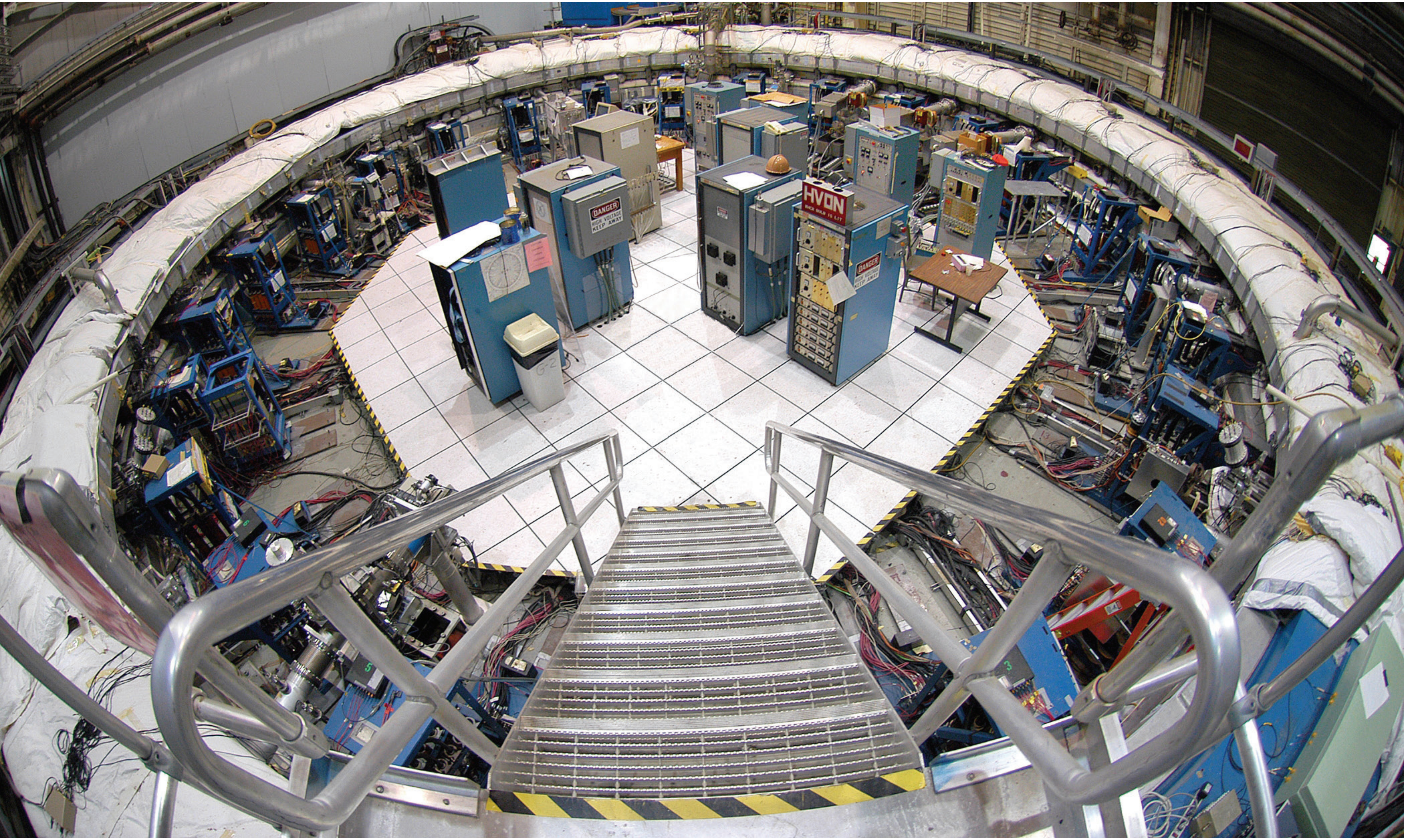
In muon rest frame: $\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\mu} \times \vec{B}$

In lab frame (all fields perpendicular to motion):

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + (a - \underset{= 0}{\cancel{\frac{1}{1-\gamma^2}}})(\vec{v} \times \vec{E})\right) \times \vec{s}$$

Run at the "magic momentum" of 3.1 GeV/c

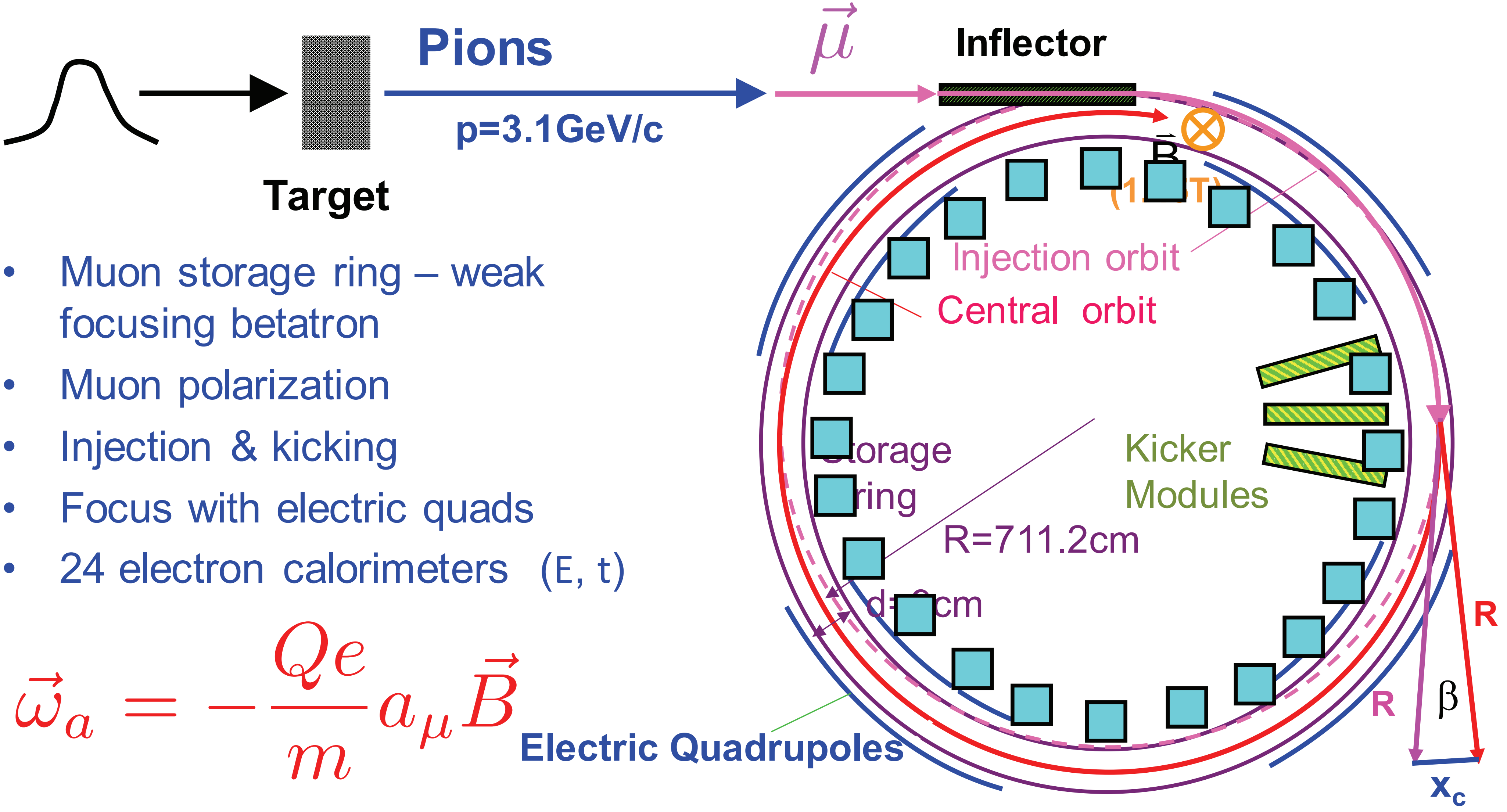
g-2 ring at Brookhaven National Lab



www.bnl.gov

narrow bunch of protons

$x_c \approx 77$ mm
$\beta \approx 10$ mrad
$B \cdot dl \approx 0.1$ Tm

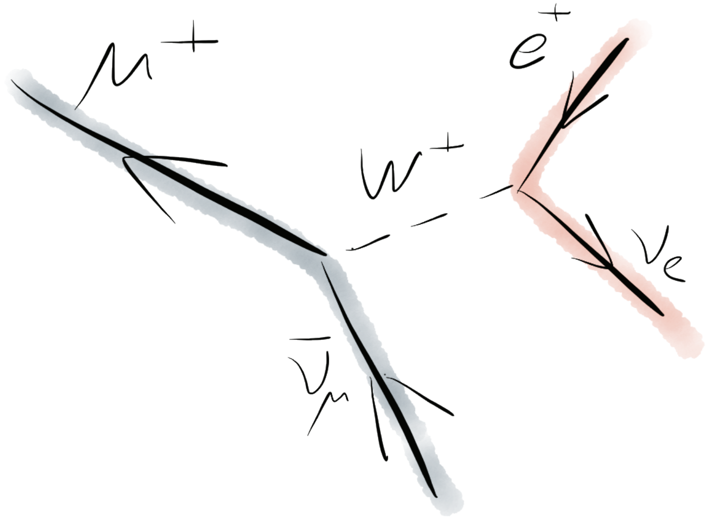


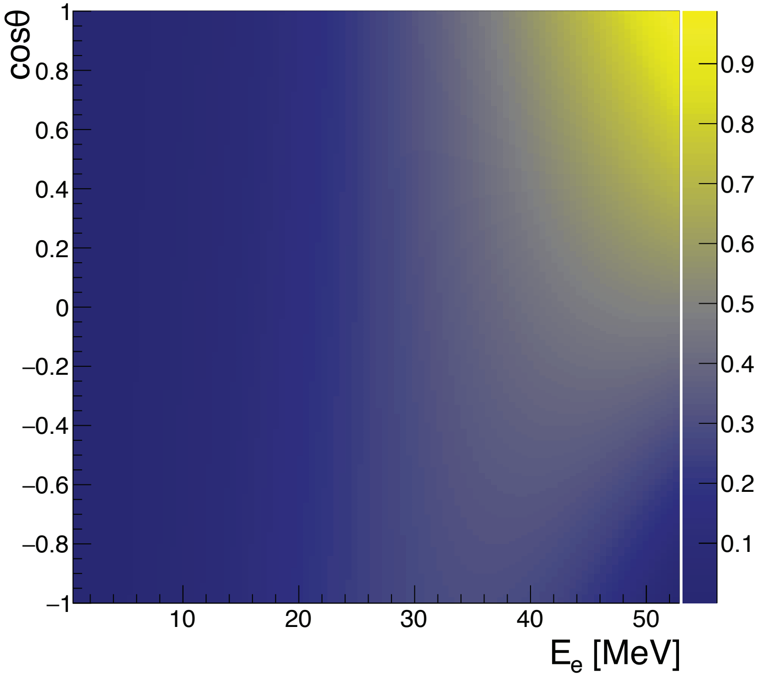
- Muon storage ring – weak focusing betatron
- Muon polarization
- Injection & kicking
- Focus with electric quads
- 24 electron calorimeters (E, t)

$$\vec{\omega}_a = -\frac{Qe}{m} a_\mu \vec{B}$$

L. Roberts

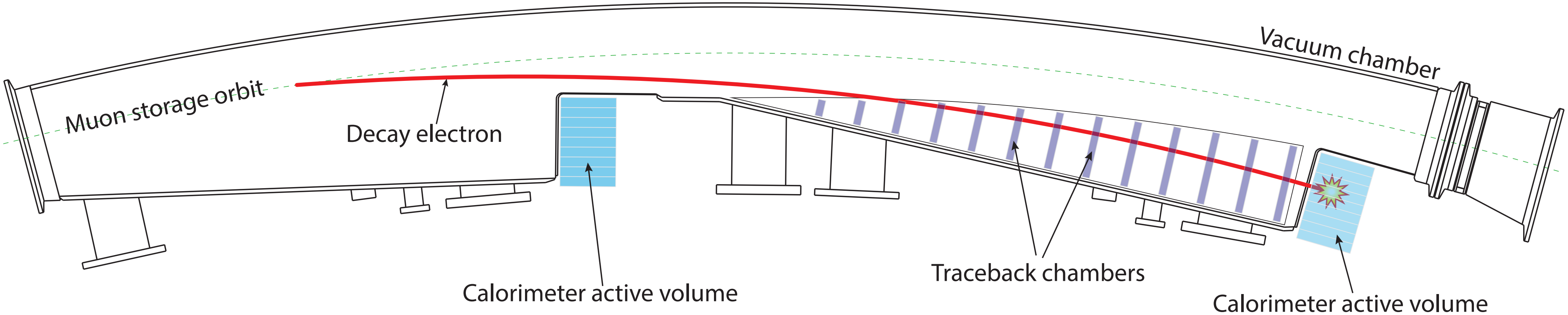
Where does the spin point?





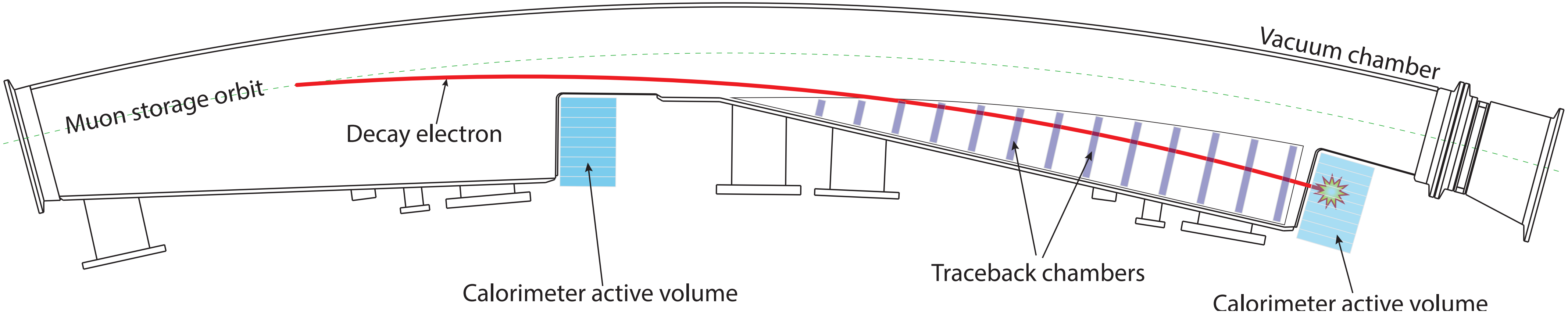
- 3-body muon decay (“Michel”-decay)
- Only electron/positron visible
- High energy e-/e+ preferentially parallel/ antiparallel to spin

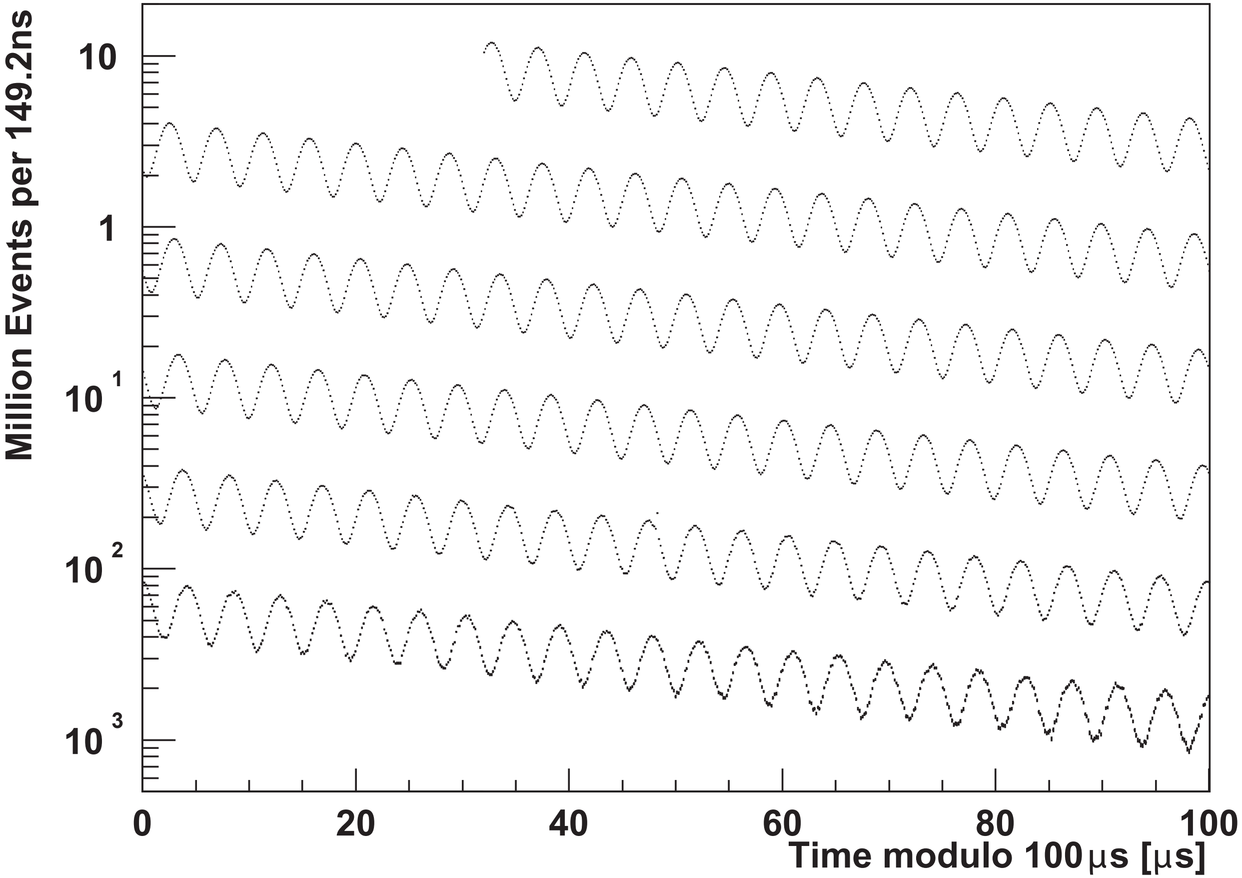
Detecting electrons



Fermilab g-2 TDR

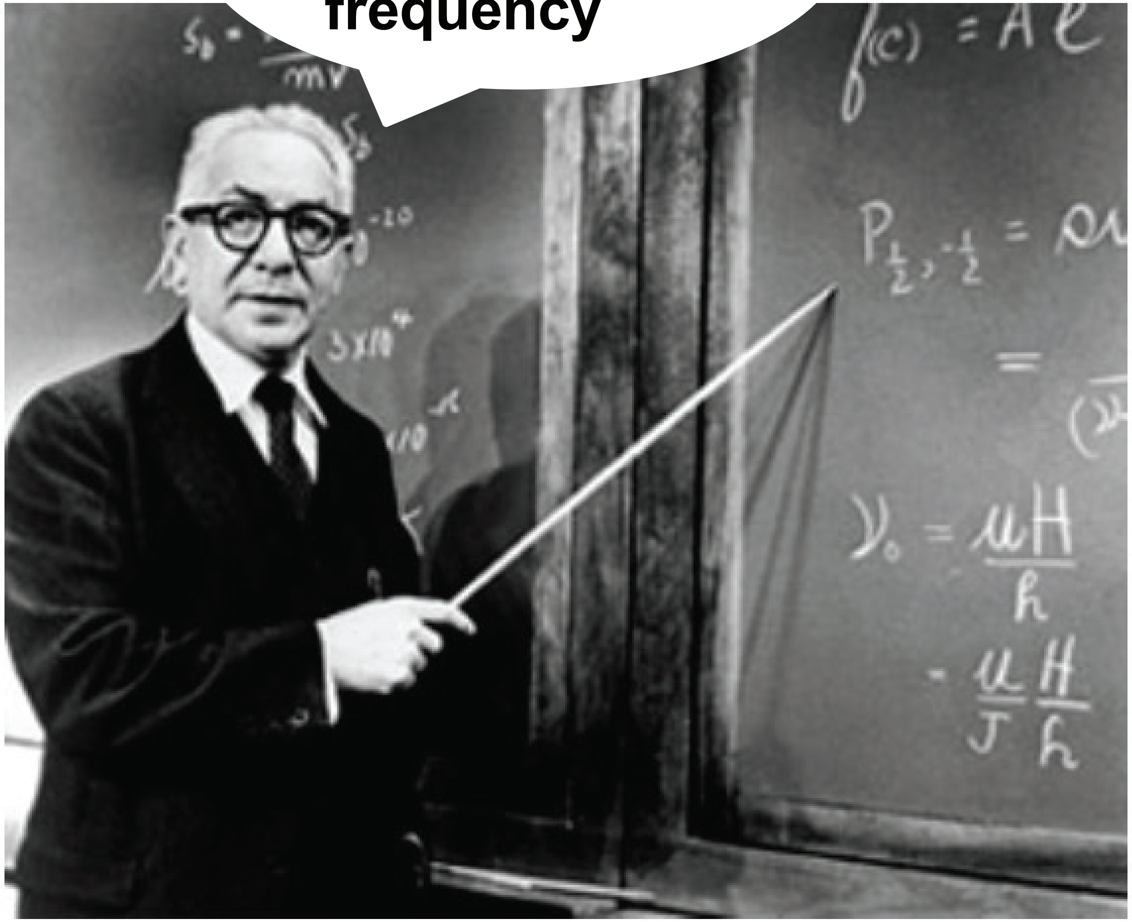
Detecting electrons





G. Bennett, et al.,
(Muon (g - 2) Collaboration),
Phys. Rev. D73, 072003 (2006).

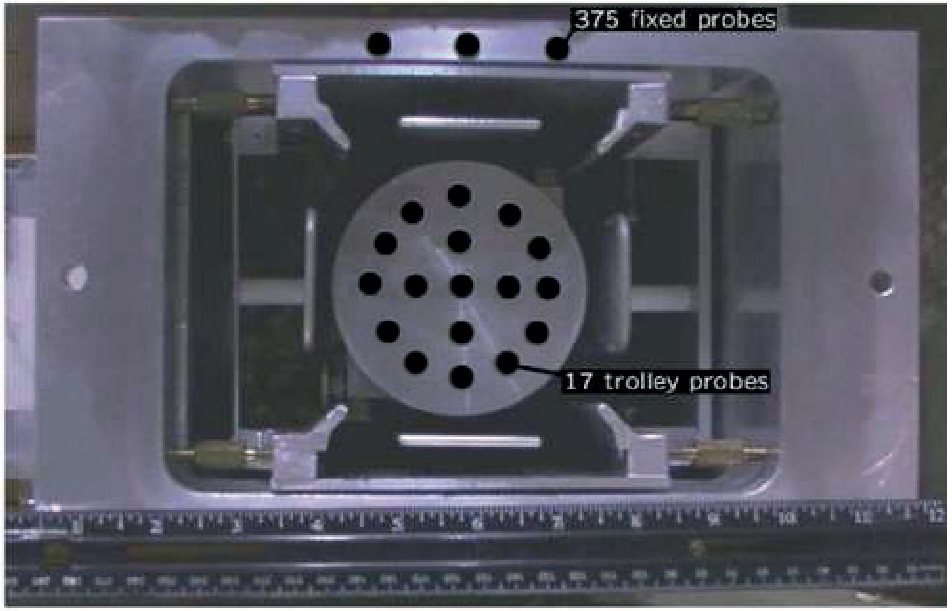
I.I. Rabi

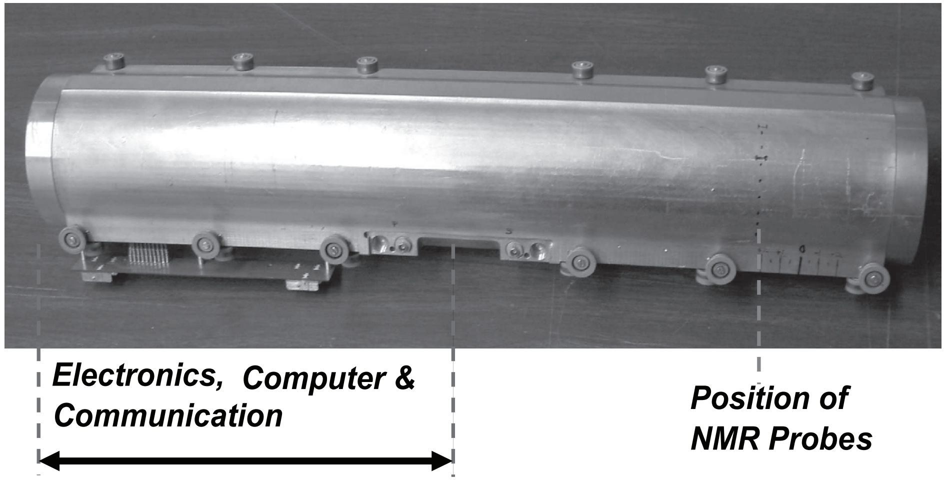


Never measure anything but frequency

Measuring the field

- Use nuclear magnetic resonance probes
- Around ring
- In trolley





K. Jungmann

We measure two frequencies: ω_a and ω_p

- The magnetic field is normalized to the Larmor frequency of a ***free*** proton.
- Spherical absolute calibration probe ties our NMR frequency to the free proton.
- We must weight the magnetic field by the muon distribution to obtain $\tilde{\omega}_p = \langle \omega_p \rangle_{\mu\,\mathrm{dist}}$

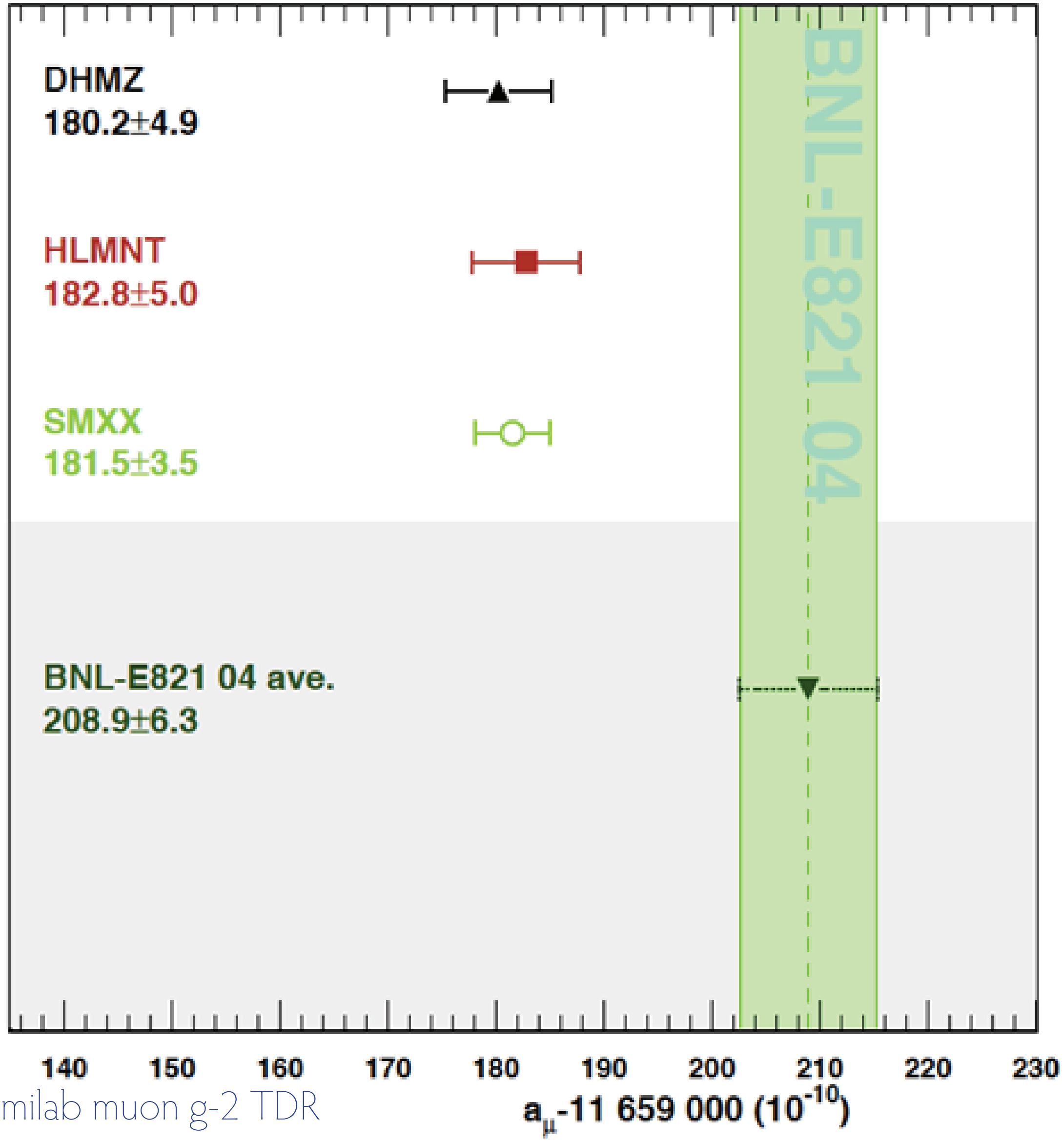
$$\boxed{a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{m_\mu}{m_e}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{\omega_a}{\tilde{\omega}_p}\right)}$$

- where the fundamental constants are known from other experiments.

L. Roberts

Putting it all together...

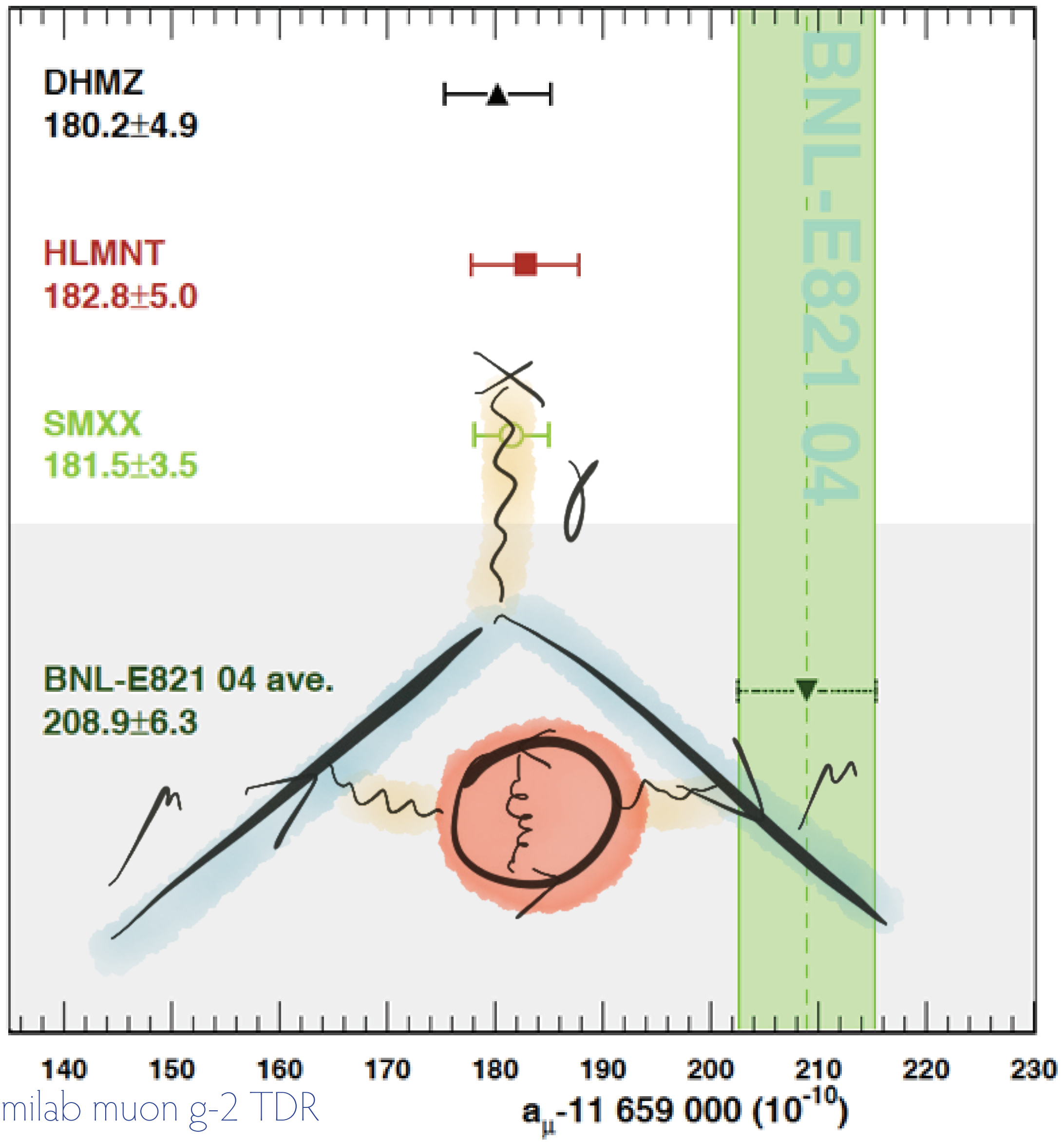
$$a_{SM} = 11\,659\,182.8(4.9) \times 10^{-10}$$
$$a_{exp} = 11\,659\,208.9(4.4)(3.3) \times 10^{-10}$$



Fermilab muon g-2 TDR
arxiv:1501.06858

- SM prediction and measurement differ by 3 - 4 σ

Putting it all together...



Fermilab muon g-2 TDR
arxiv:1501.06858

- Statistical fluctuation?
- Problem with theory?
- Lots of work ongoing
- Problem with experiment?
- New physics?
- New measurements planned

The big move ...

- Bring ring from Brookhaven to Fermilab

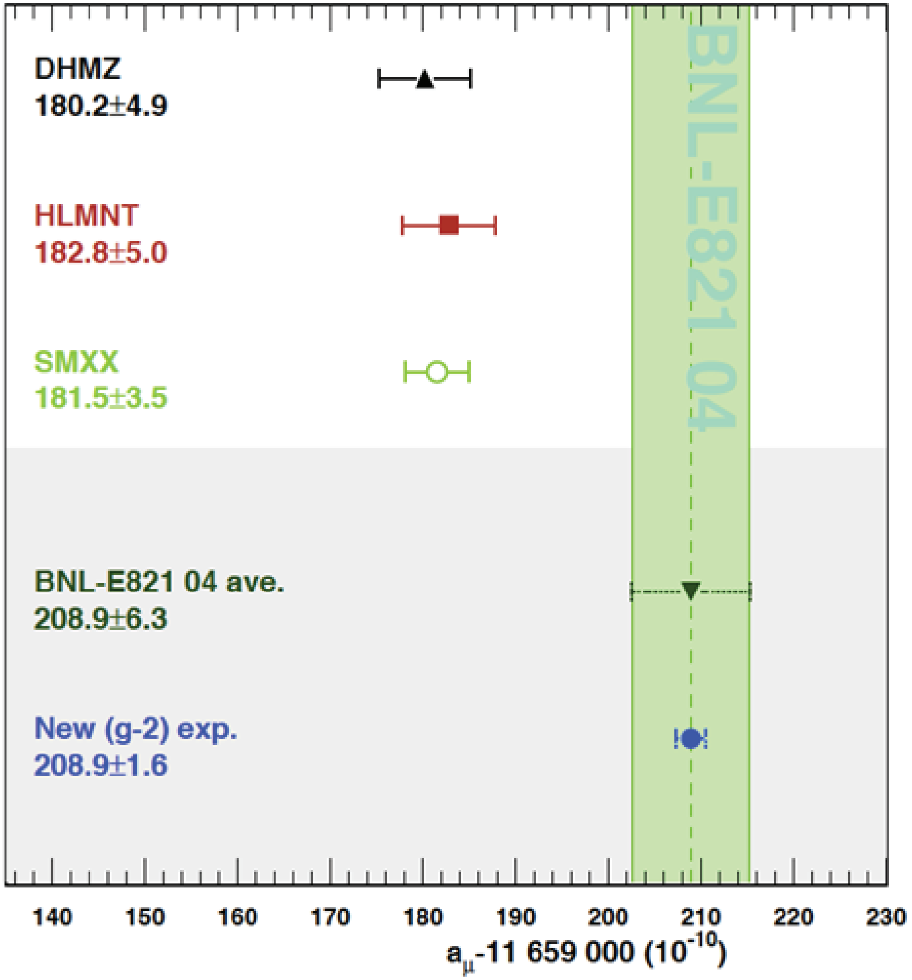

Fermilab
BROOKHAVEN NATIONAL LABORATORY
The Big Move
Travel by barge:
South along East Coast
Around tip of Florida
Northwest through Gulf of Mexico
North through Mississippi River
North through Illinois waterways

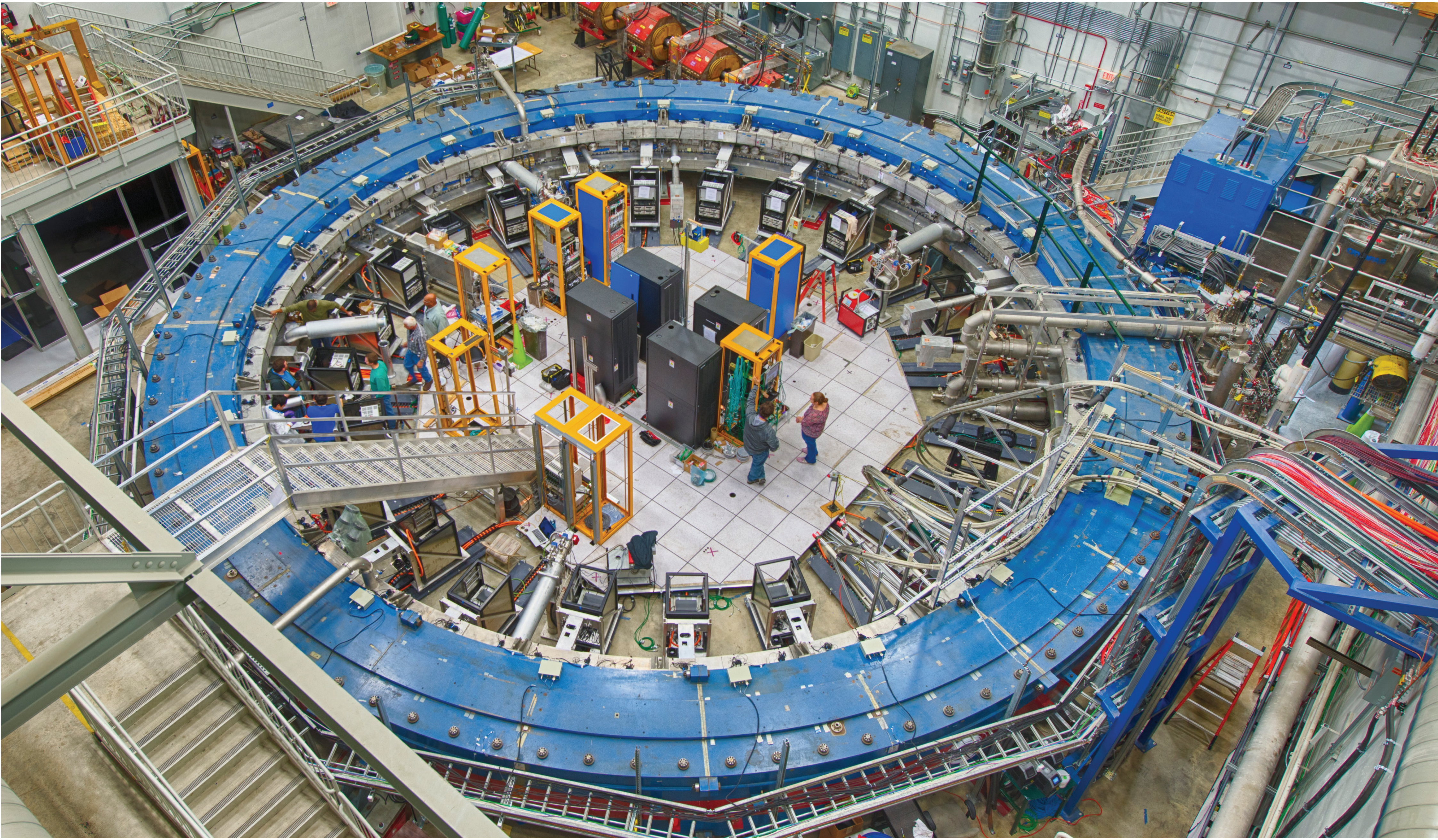
Fermilab g-2

Improve over Brookhaven with:

- 20 x more muons
- Cleaner beam
- Better calorimeters, trackers
- More field probes
- Better environment control

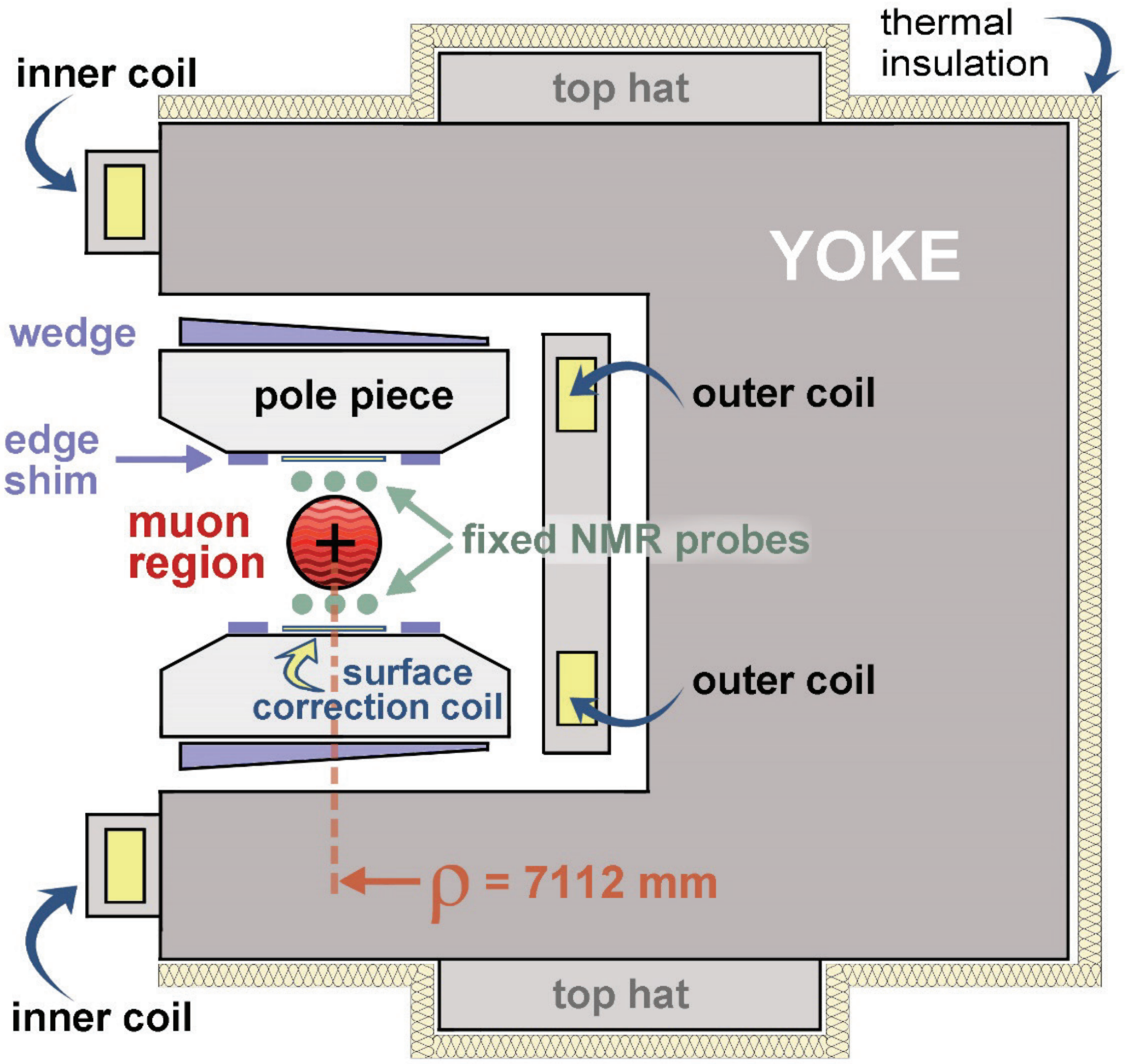
- Goal: 4 times smaller error





Getting a good field

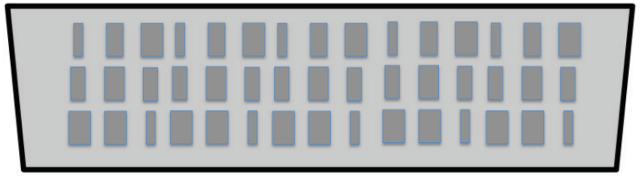
- B-field 1.45 T
- 12 Yokes
- 24 iron top hats: change effective μ
- 864 wedges: angle quadrupole and dipole
- Edge shims: quadrupole and sextupole field correction
- 8000 surface iron foils: change field locally
- Surface coils



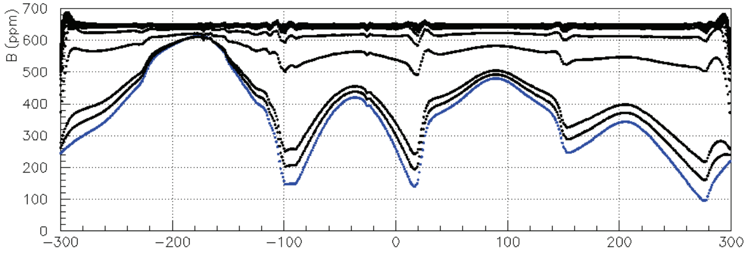
g-2 Magnet in Cross Section

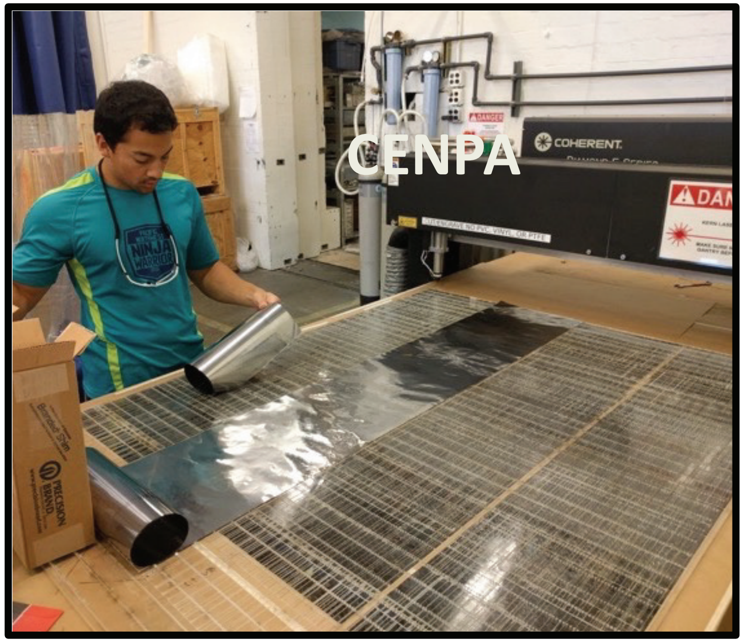
The final shimming tool: Iron Laminations

Cover each pole with a patchwork of foils in 41 azimuthal and 3 radial sections



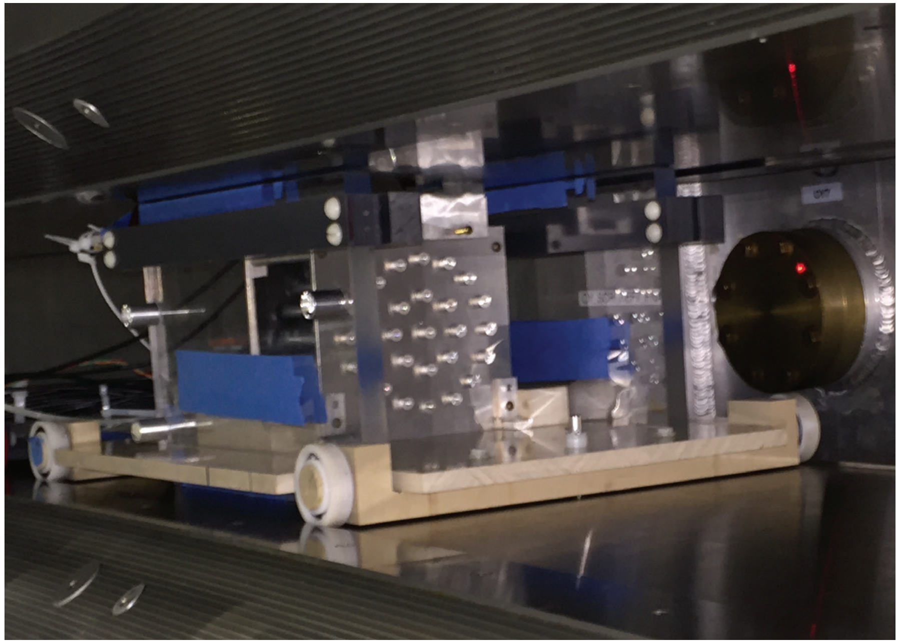
Determine optimal foil mass values by iterative procedure that minimizes field inhomogeneity around a target value – Dave Kawall U Mass

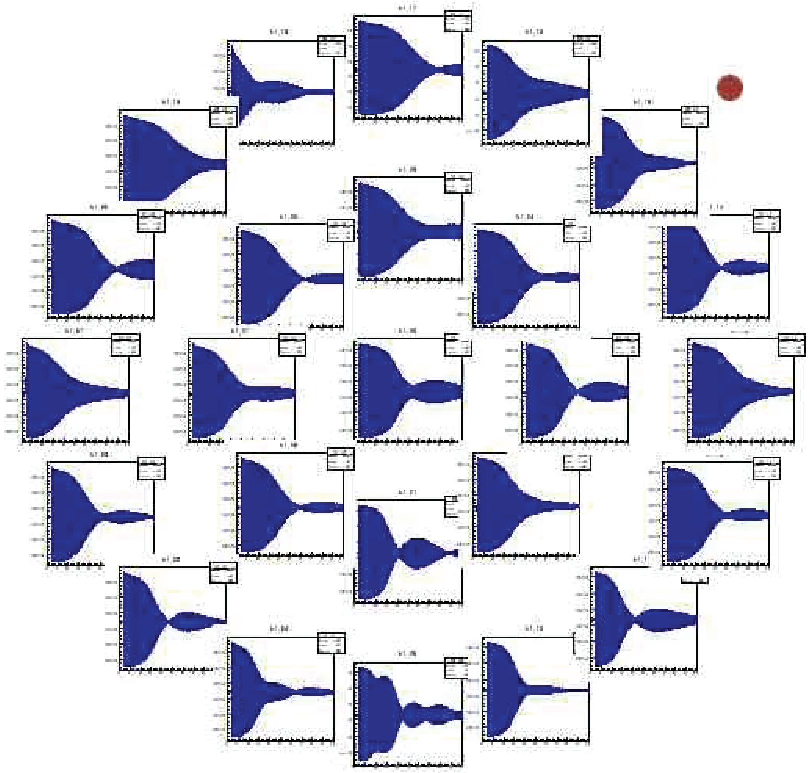




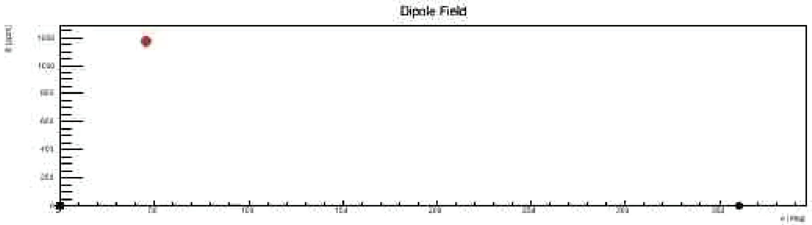
L. Roberts

- Use a special trolley





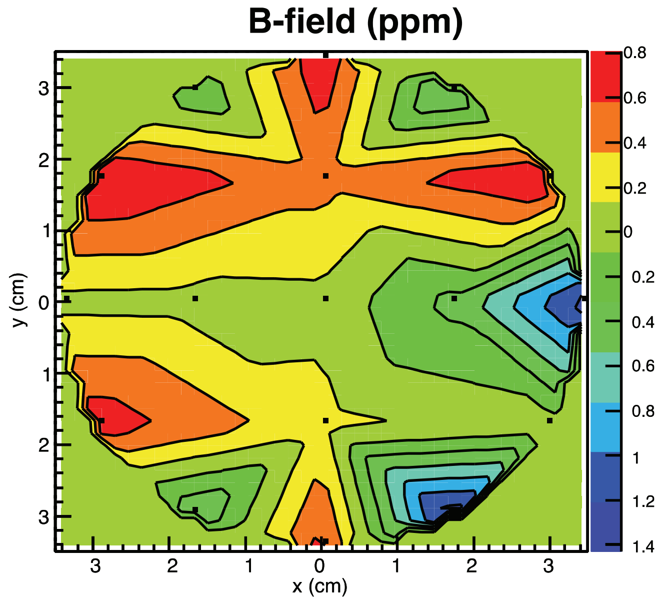
- Beating $\Longrightarrow$ gradients



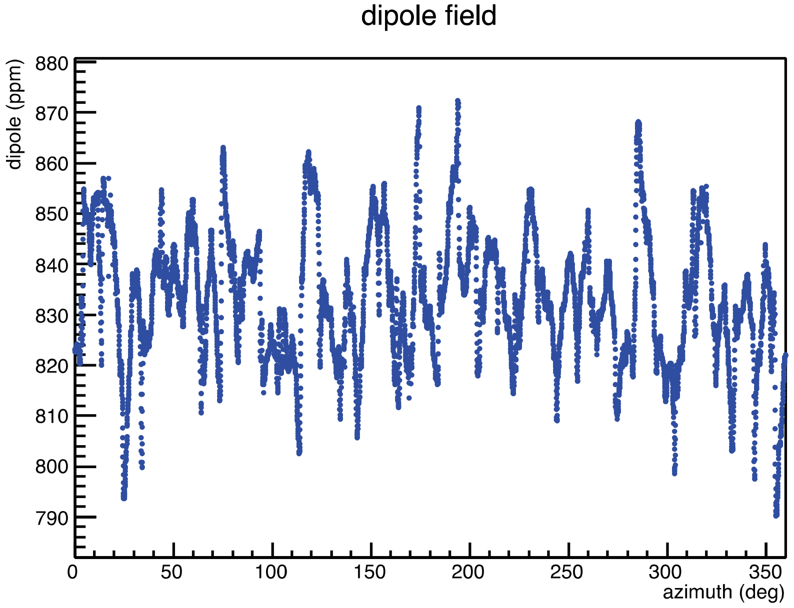
L. Roberts

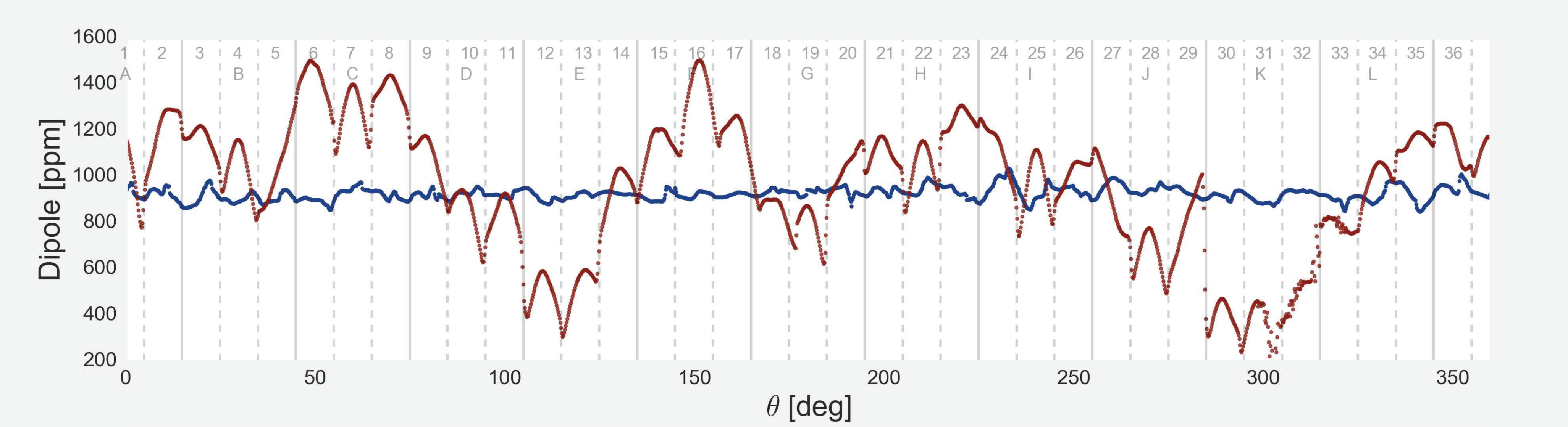
Precision field

Point-to-point < 25 ppm

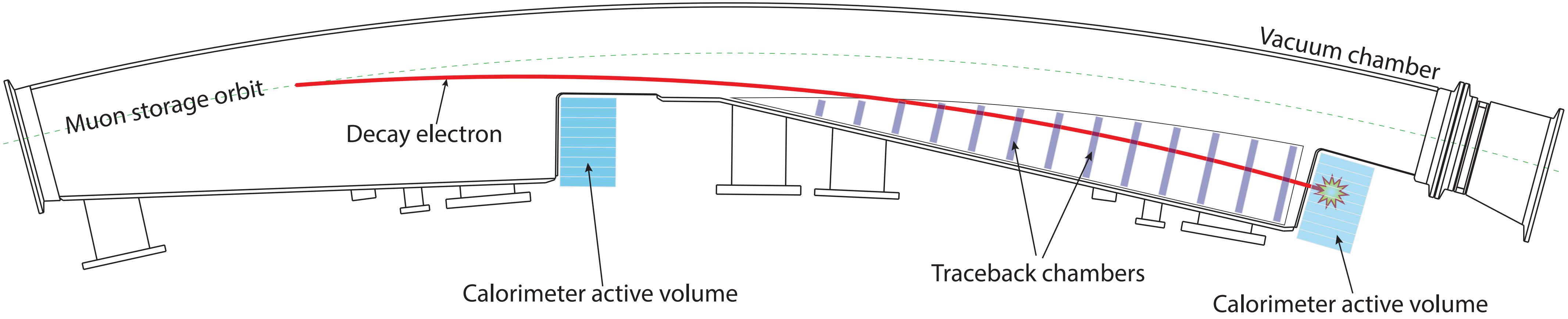


	Norm	Skew
Quad	-0.56	0.31
Sext	-0.07	0.30
Octu	-0.10	0.29
Decu	0.24	0.07
Dipole	-0.0	





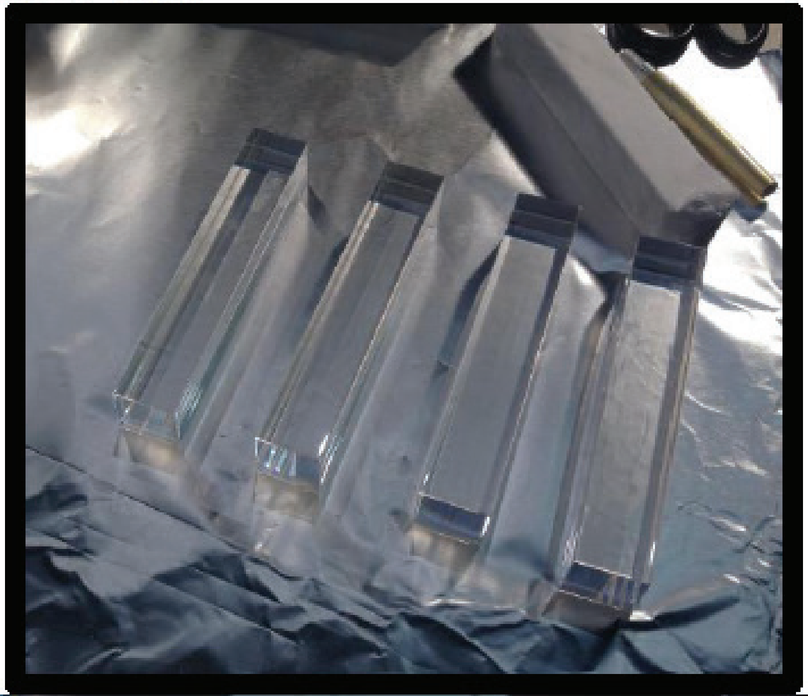
Detecting electrons

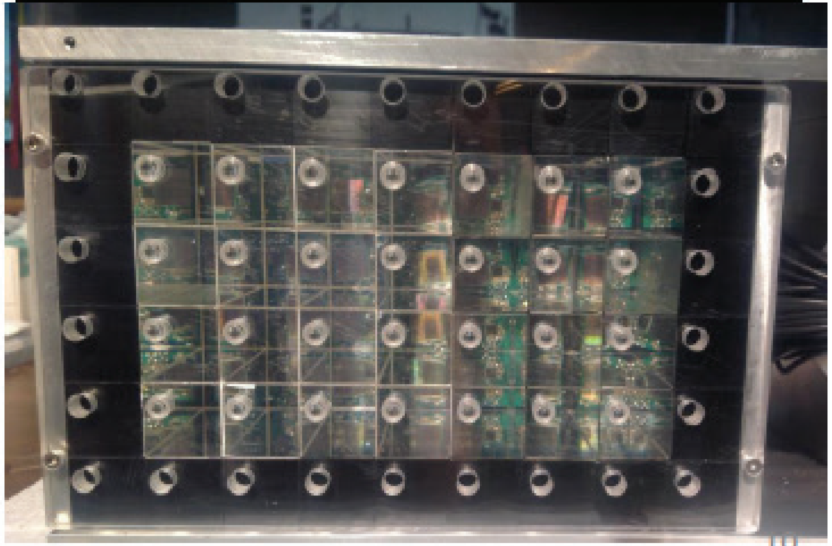


Fermilab g-2 TDR

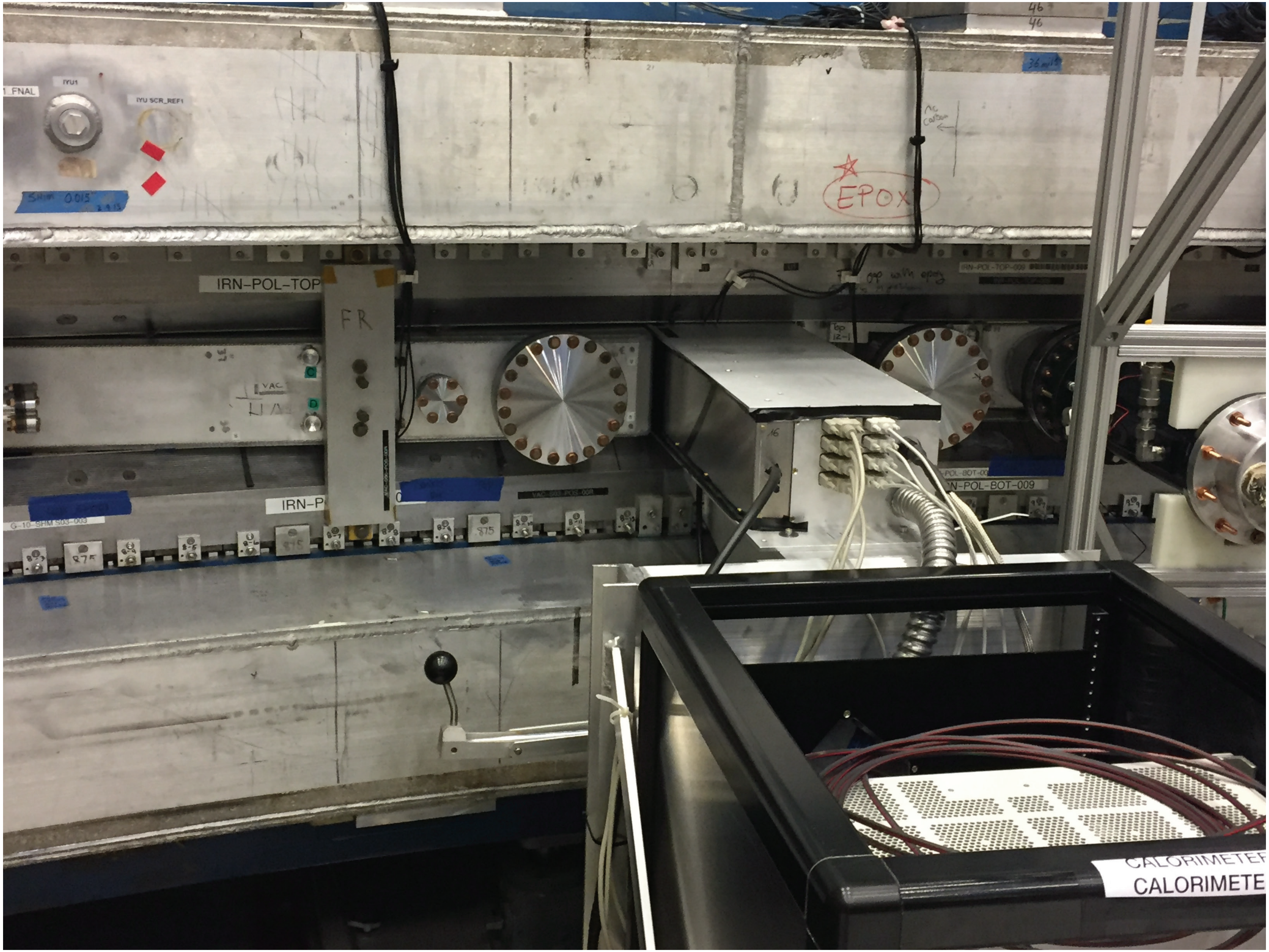
Detecting electrons: PbF_2 calorimeters

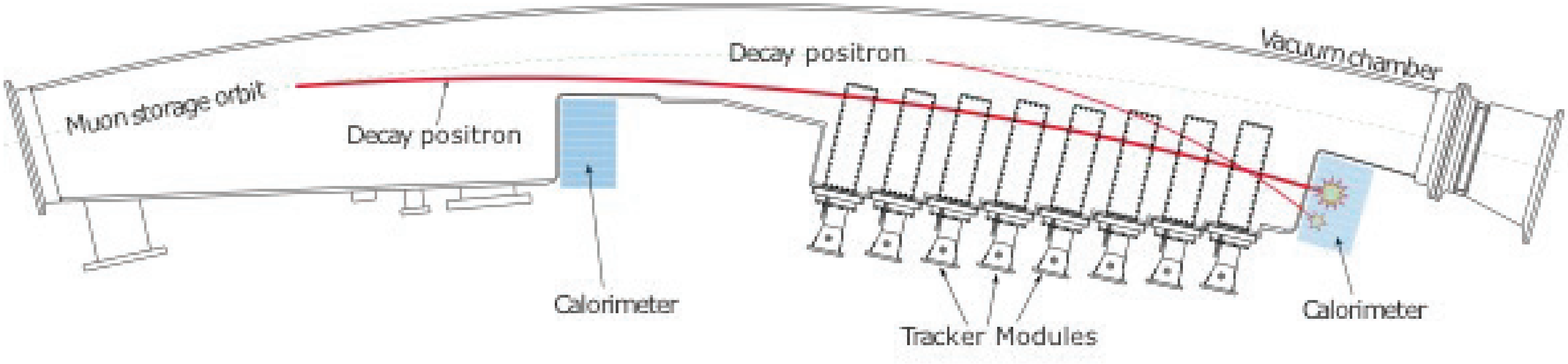
- Cherenkov light gives short pulse duration (few ns)
- High density (7.77 g/cm³), small Molière radius (2.1 cm)
- SiPMs unaffected by magnetic fields
- Segmentation reduces pileup
- Event rate in MHz range
- Few thousand pe per event (~1.5 pe/MeV)



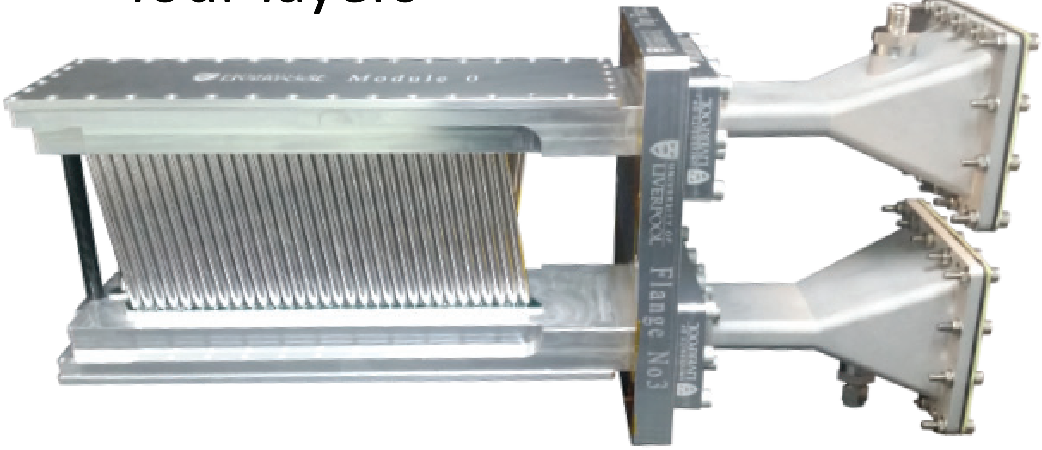


28-channel prototype calorimeter tested at SLAC


IRN-POL-TOP
IRN-POL-BOT-009
EPOX
FR
CALORIMETER
CALORIMETE

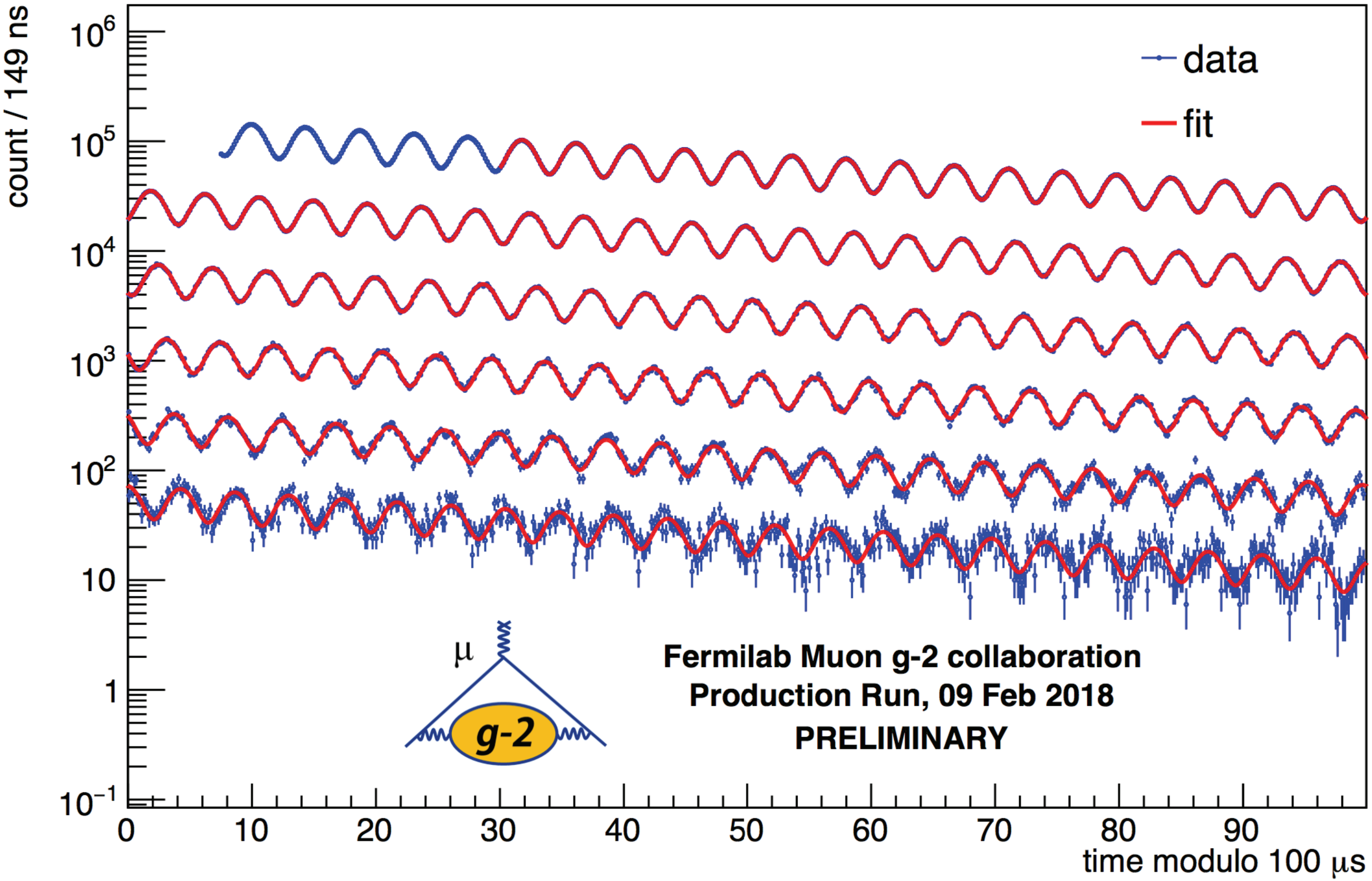


- Each module has 128 straws in four layers

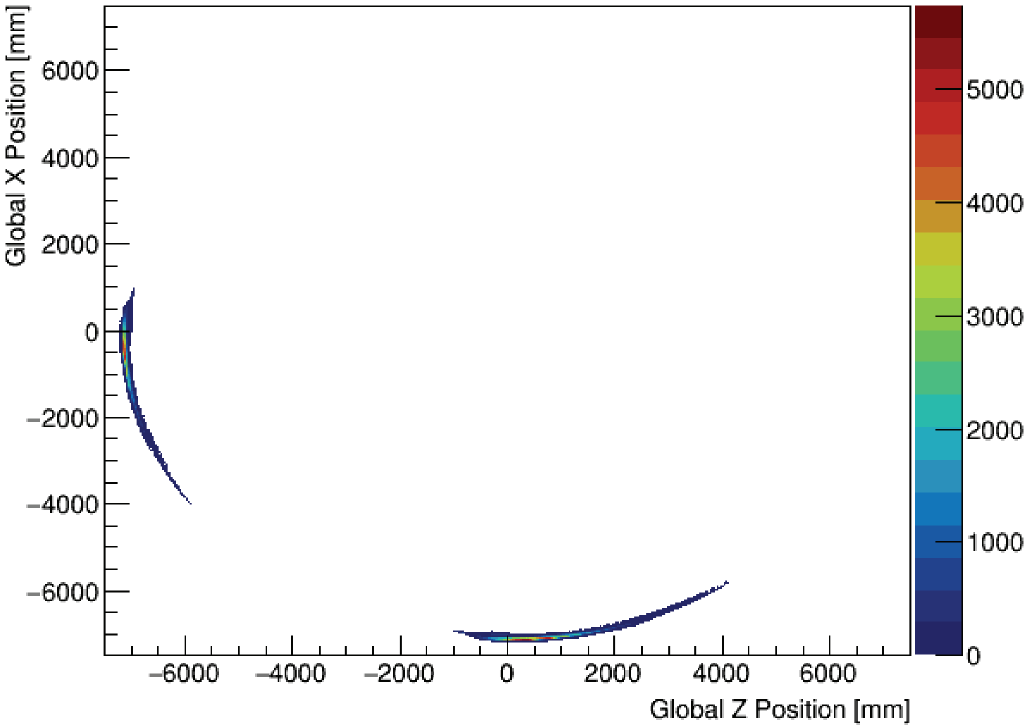


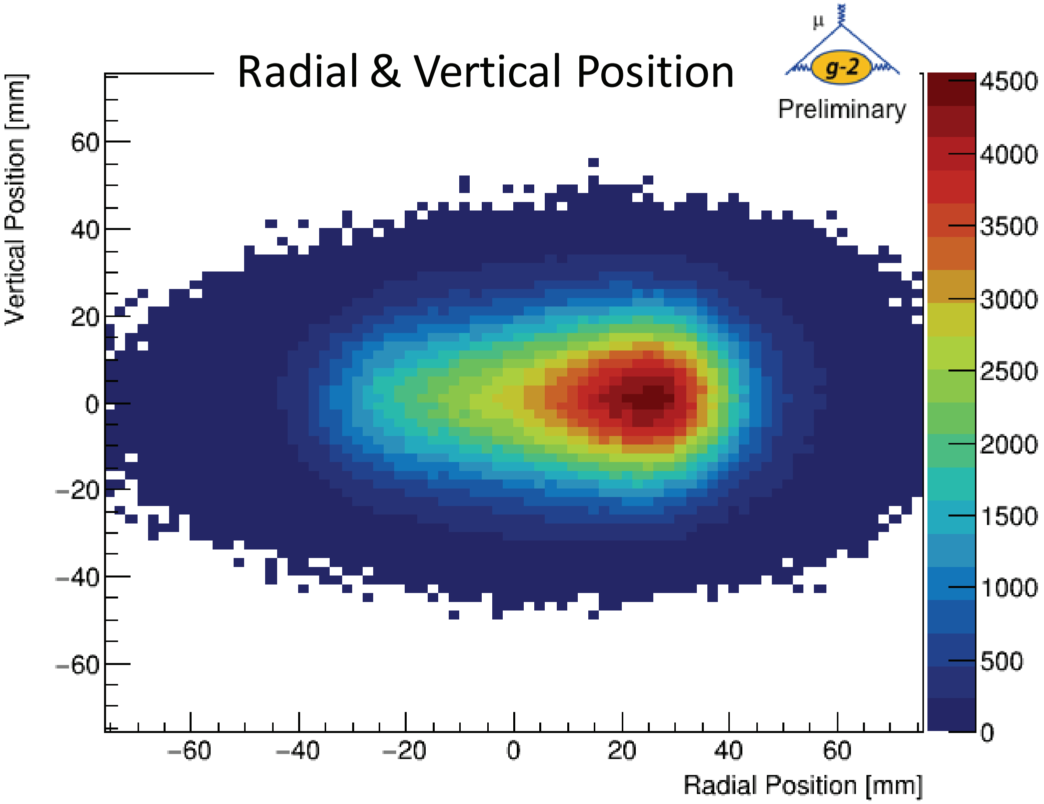
Muon's-eye view inside vacuum chamber

Beam on!

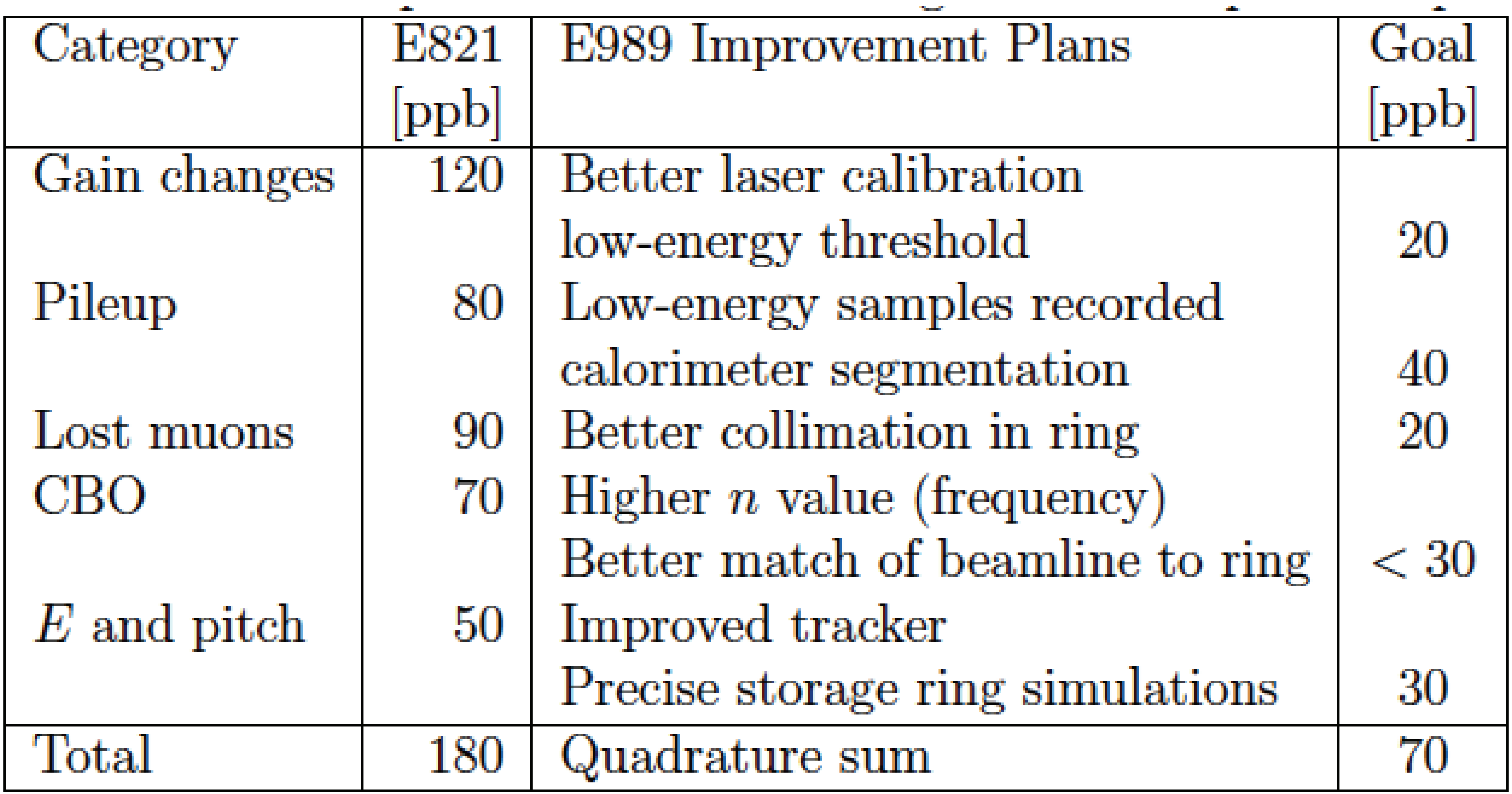

count / 149 ns
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
0
10
20
30
40
50
60
70
80
90
time modulo 100 μs
data
fit
μ
g-2
Fermilab Muon g-2 collaboration
Production Run, 09 Feb 2018
PRELIMINARY

Where are the muons? (2/3 of trackers installed)





Systematic Errors on ω_a (ppb)

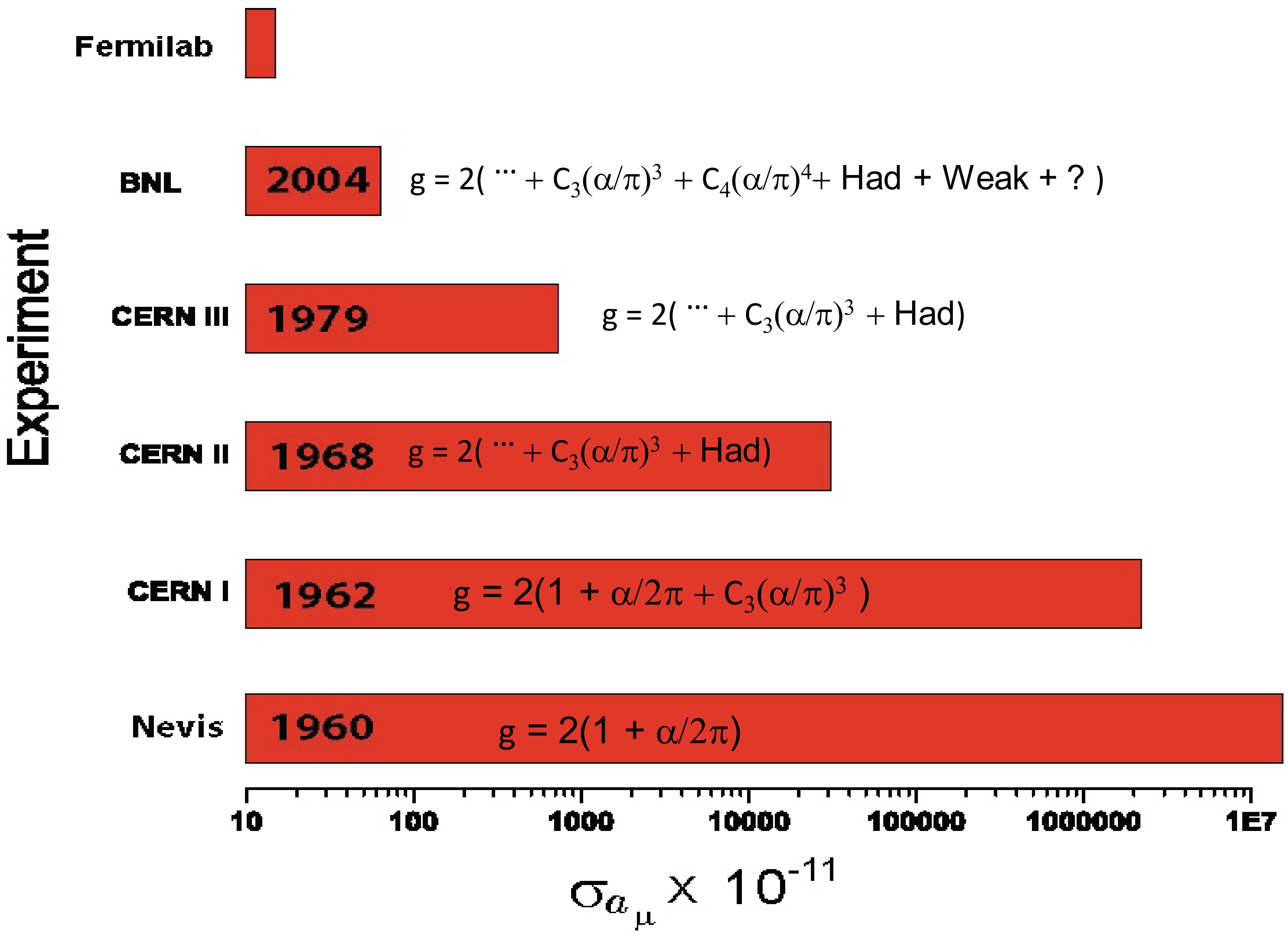


Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

Errors on the field measurement

Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	5
Others †	150	100	100	30
Total systematic error on ω_p	400	240	170	70
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

- †Higher multipoles, trolley temperature (≤ 50 ppb/° C) and power supply voltage response (400 ppb/V, ΔV=50 mV), and eddy currents from the kicker.


Fermilab
BNL
2004
$g = 2(\cdots + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + \text{Had} + \text{Weak} + ?)$
CERN III
1979
$g = 2(\cdots + C_3(\alpha/\pi)^3 + \text{Had})$
CERN II
1968
$g = 2(\cdots + C_3(\alpha/\pi)^3 + \text{Had})$
CERN I
1962
$g = 2(1 + \alpha/2\pi + C_3(\alpha/\pi)^3)$
Nevis
1960
$g = 2(1 + \alpha/2\pi)$
Experiment
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$

Can we do a different experiment for g-2?

New idea: Use cold muons

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + (a - \frac{1}{1-\gamma^2})(\vec{v} \times \vec{E})\right) \times \vec{s}$$

No vertical focusing - no electric field

New idea: Use cold muons

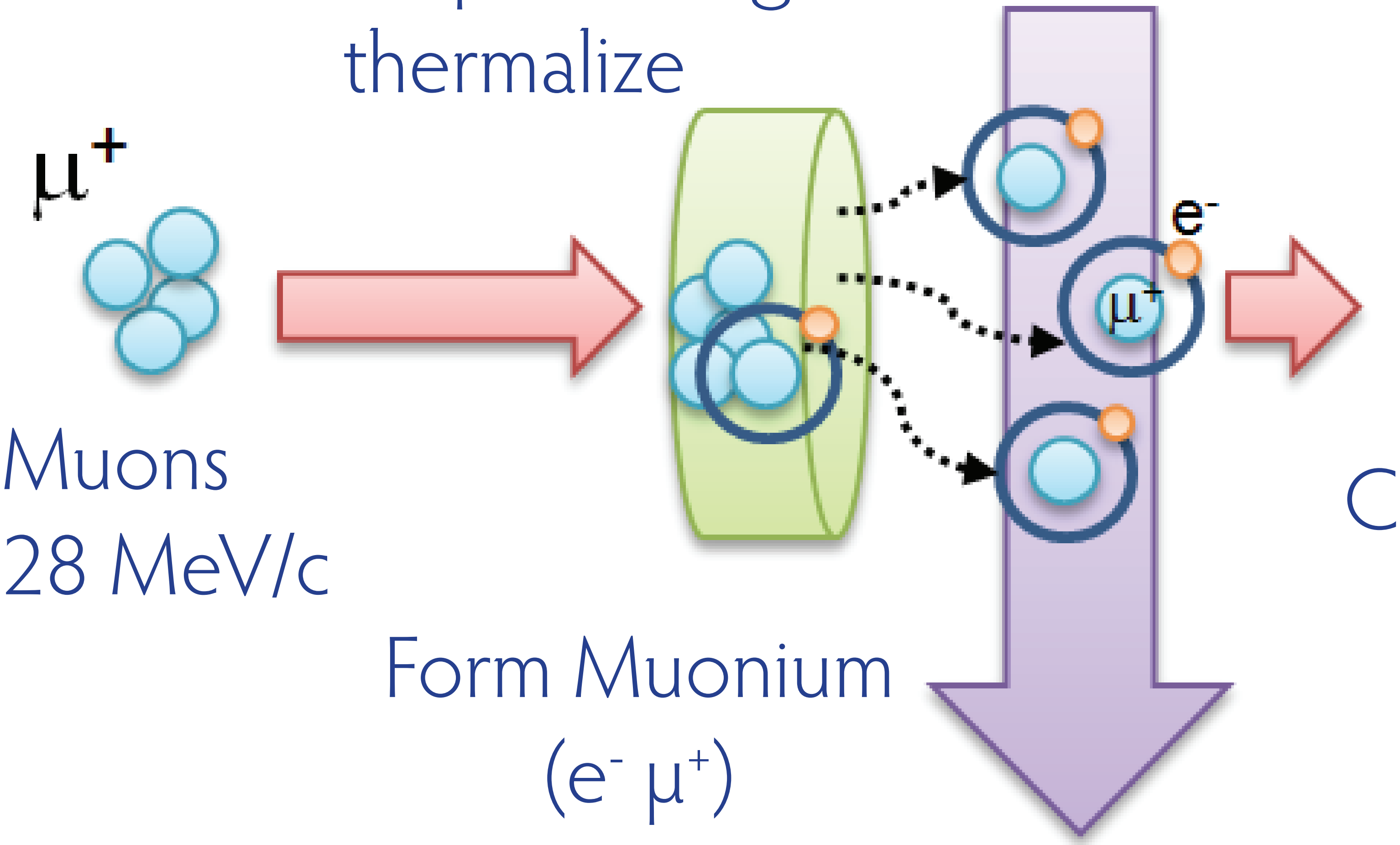
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{q}{m}\left(a\vec{B} + \left(a - \frac{1}{1-\gamma^2}\right)(\vec{v} \times \underbrace{\cancel{\vec{E}}}_{=0})\right) \times \vec{s}$$

No vertical focusing - no electric field

Can run at lower momentum - smaller magnet

Cold muons from muonium

T. Mibe



Stop in aerogel thermalize

Ionize with laser

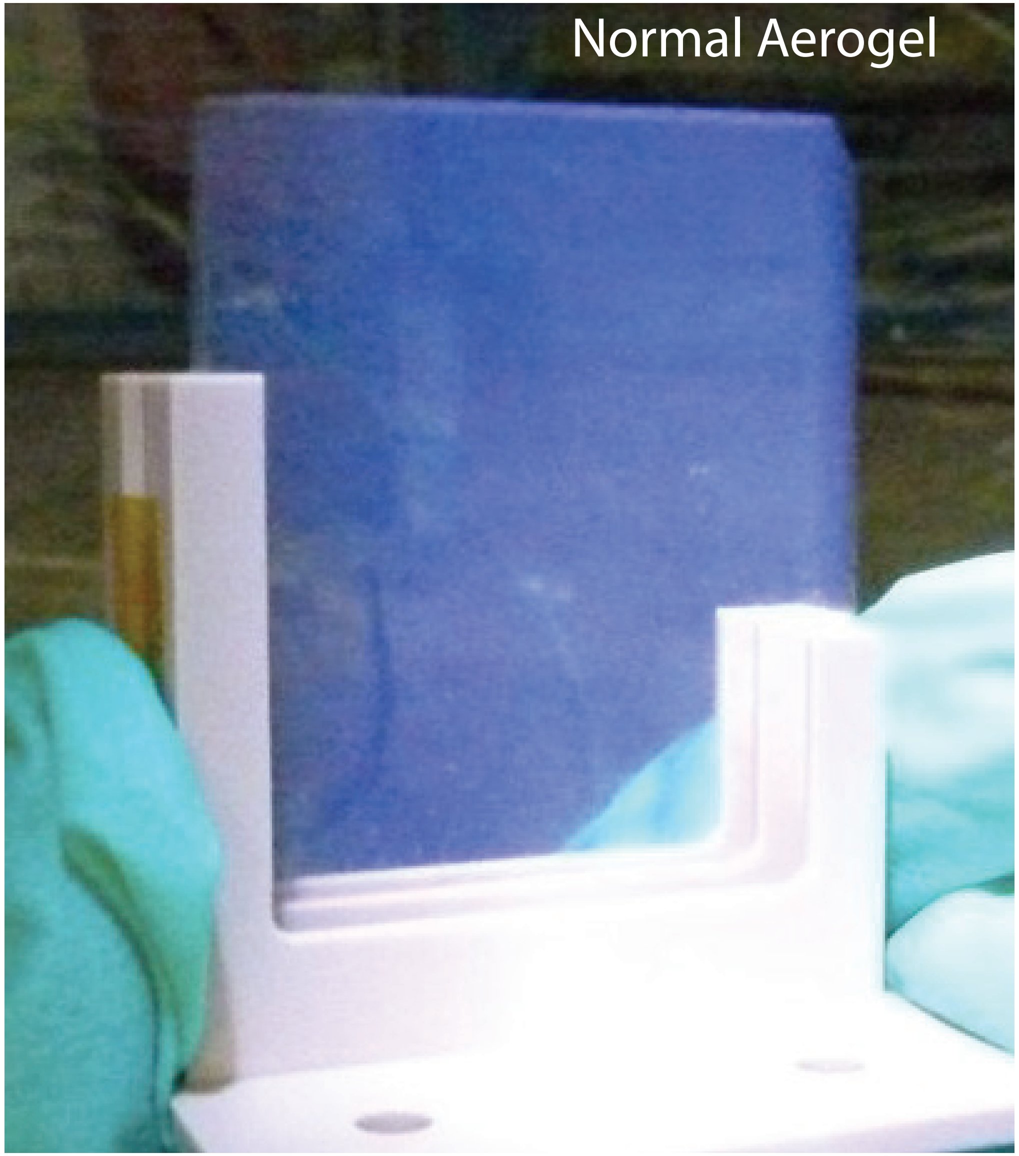
Muons
28 MeV/c

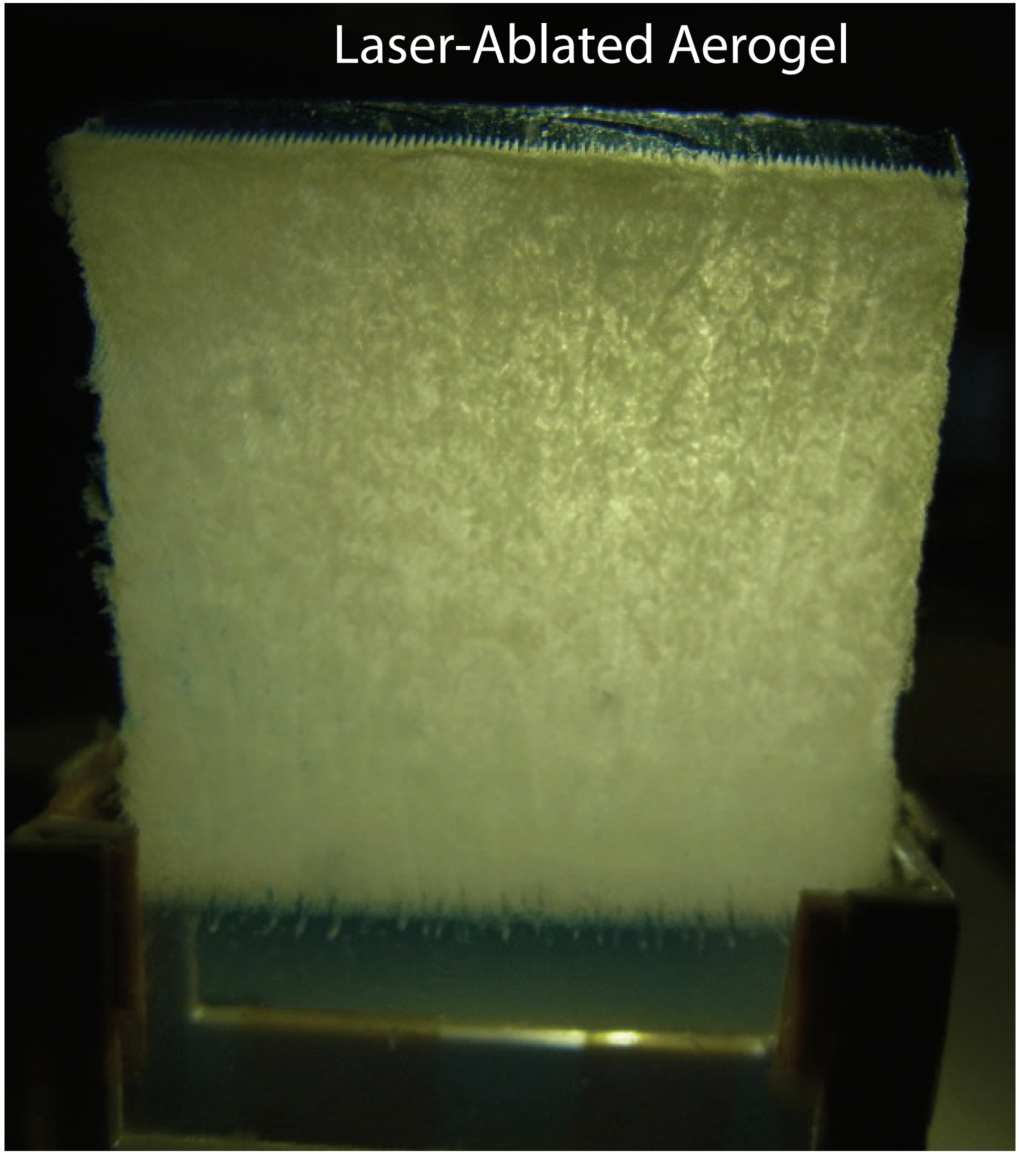
Form Muonium
($e^- \mu^+$)

Cold muons

Muonium production in aerogel

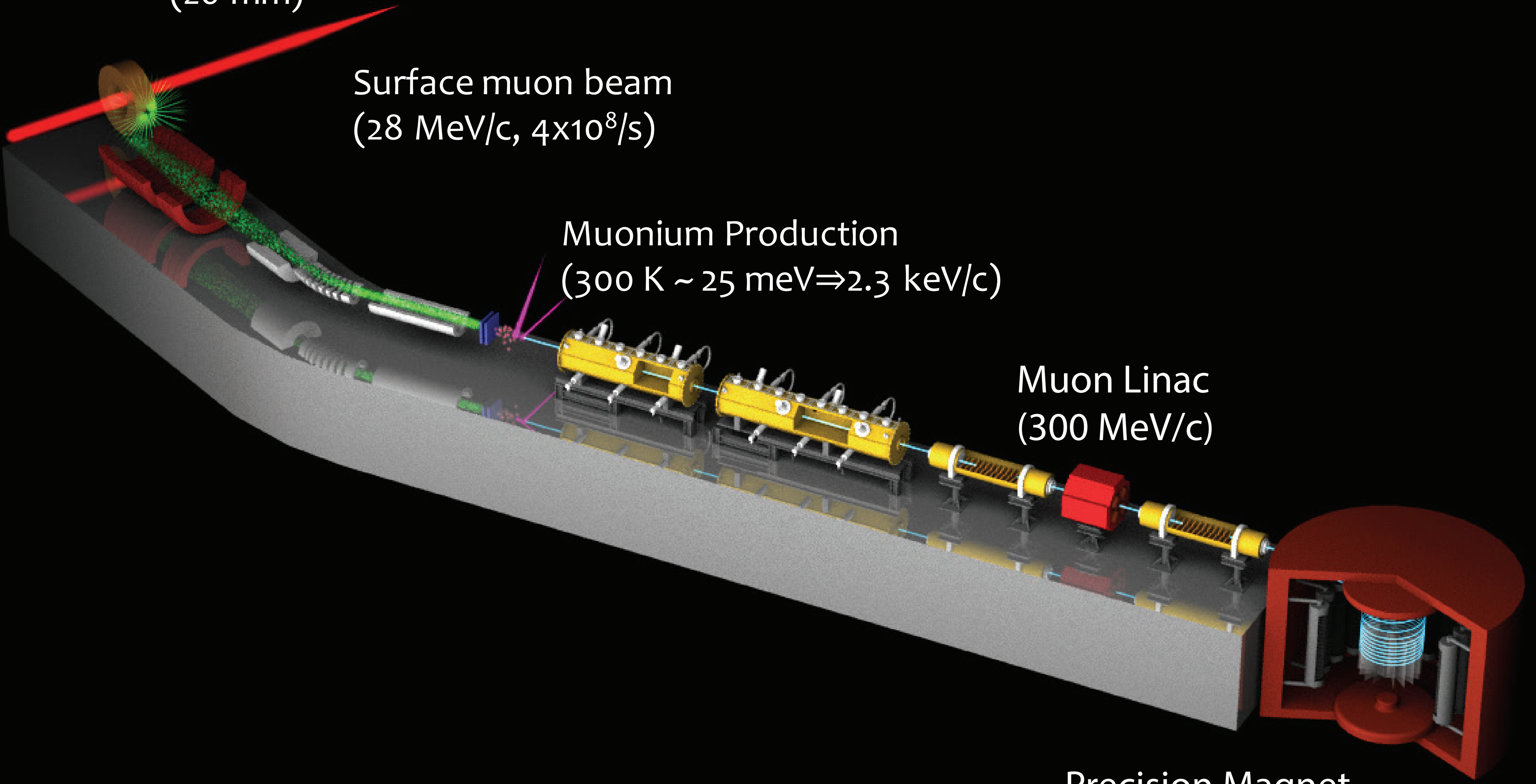
T. Mibe





1 Muonium in vacuum per 14 muon stops

T. Mibe



3 GeV proton beam
(333 uA)

Graphite target
(20 mm)

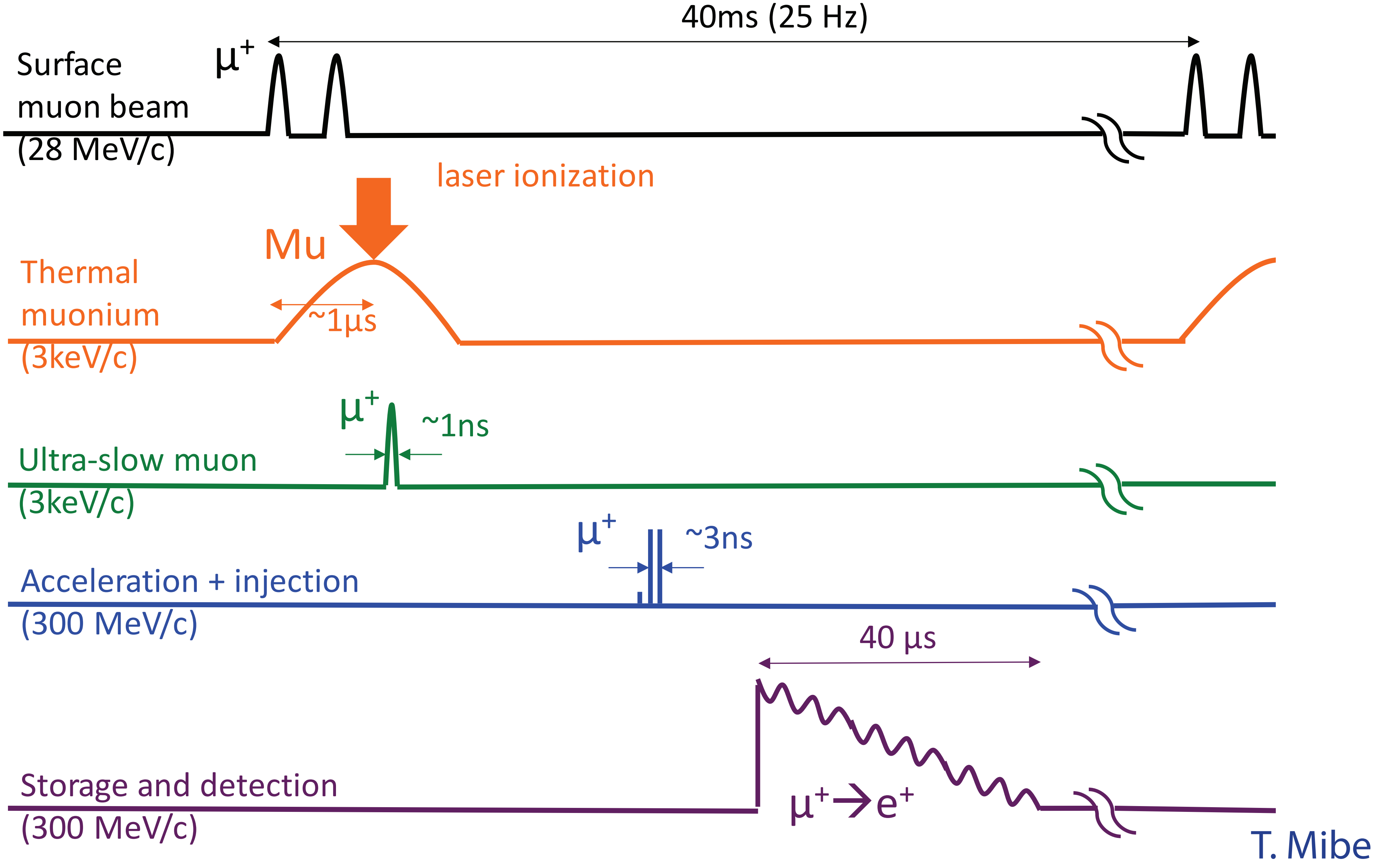
Surface muon beam
(28 MeV/c, $4\text{x}10^8$/s)

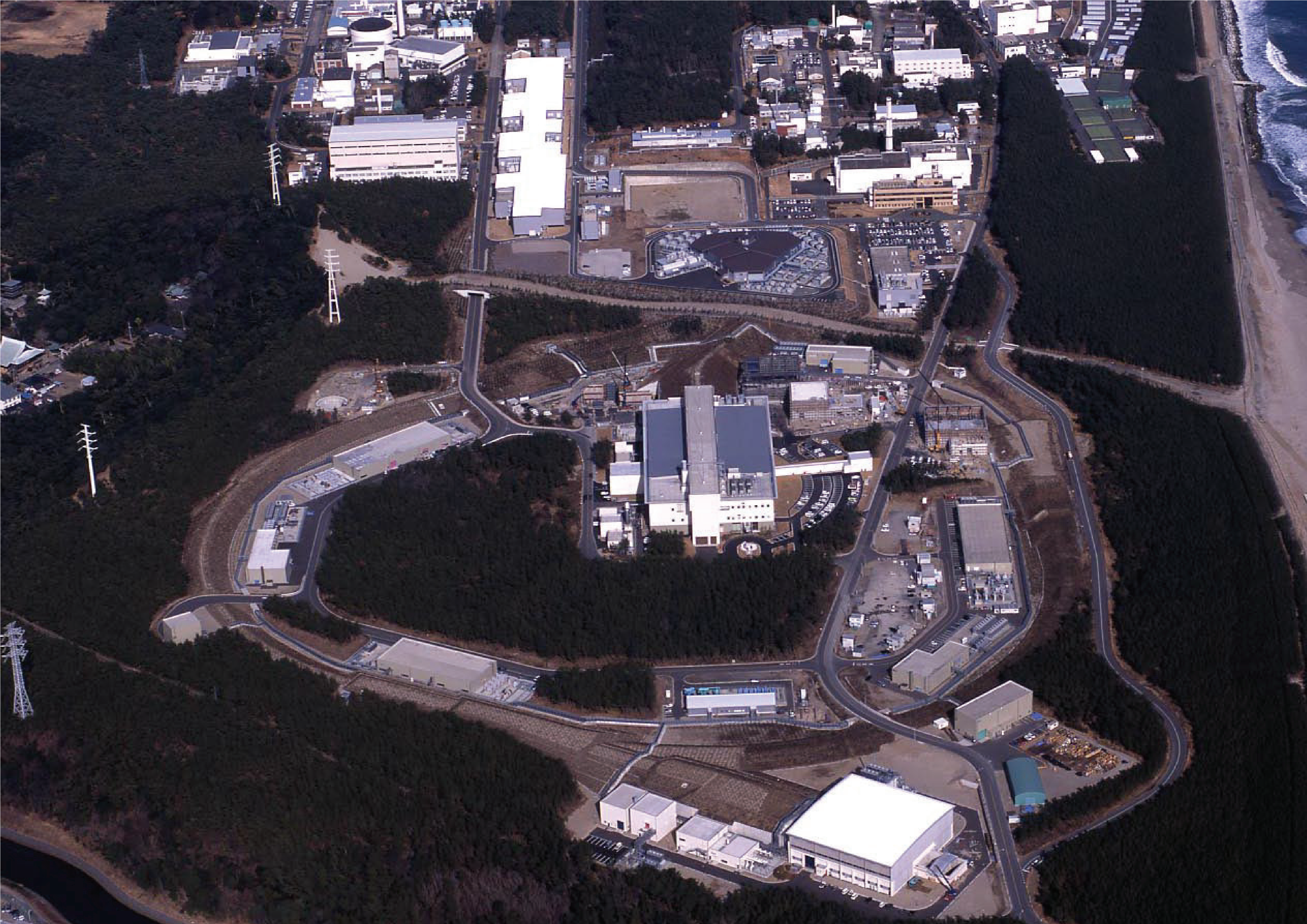
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)

Muon Linac
(300 MeV/c)

Precision Magnet
(3T, ~1 ppm local precision)

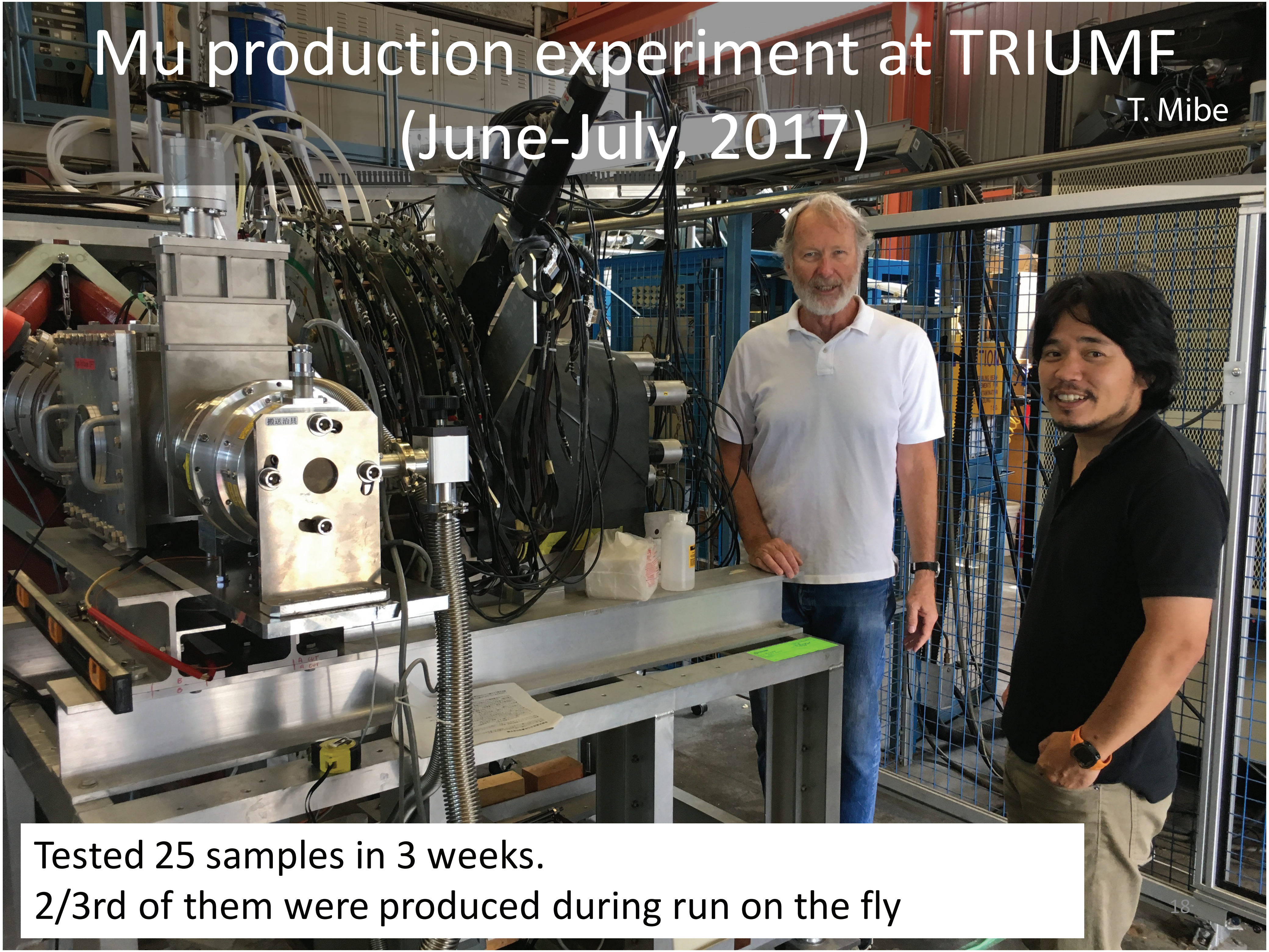
Experimental sequence





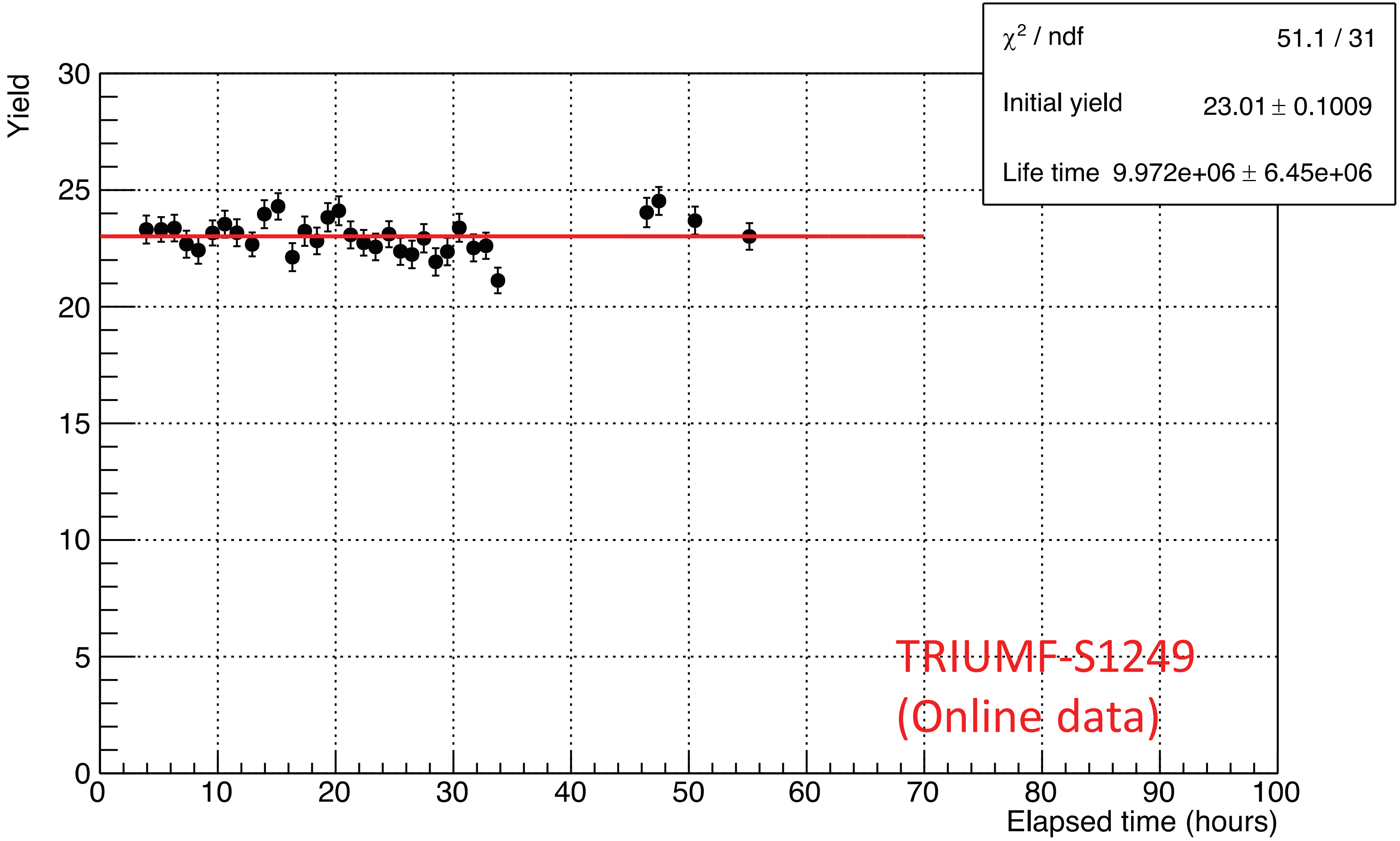
Mu production experiment at TRIUMF (June-July, 2017)

T. Mibe



Tested 25 samples in 3 weeks.
2/3rd of them were produced during run on the fly

Long-term stability of Mu yield



No hint of degradation observed for 2.5 days

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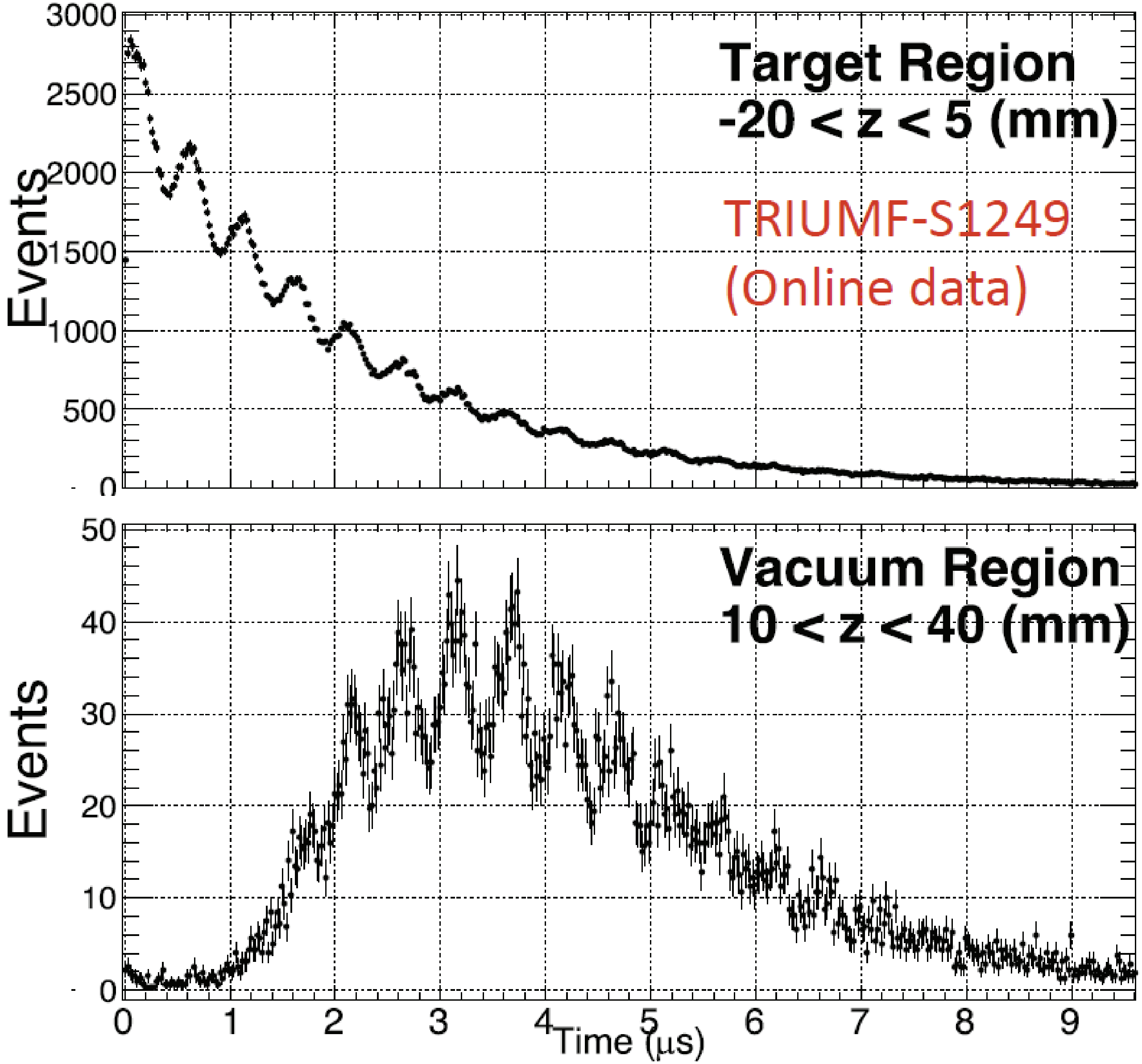
Muonium spin precession in vacuum



Reconfirmed polarization of Mu in vacuum.

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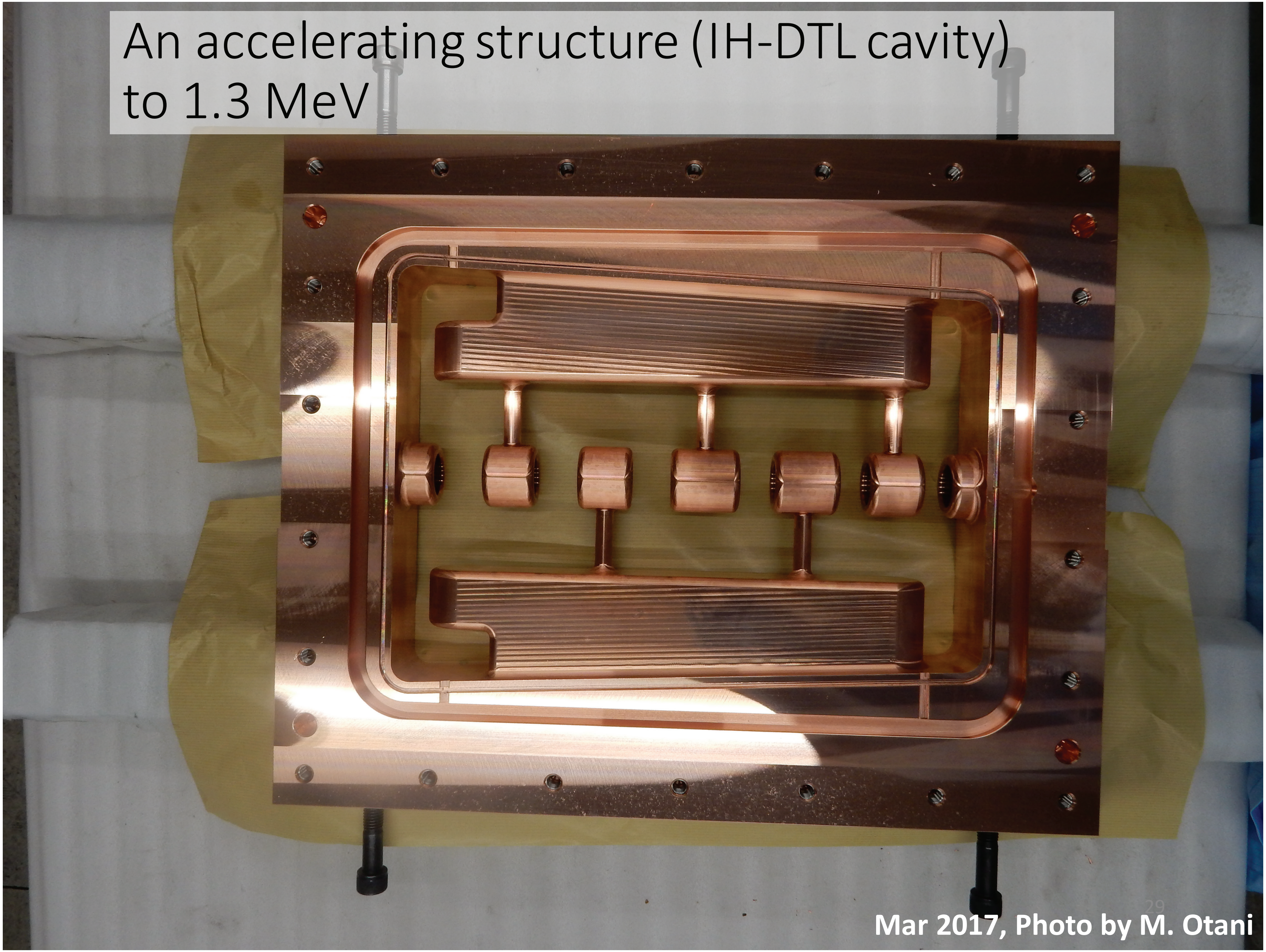
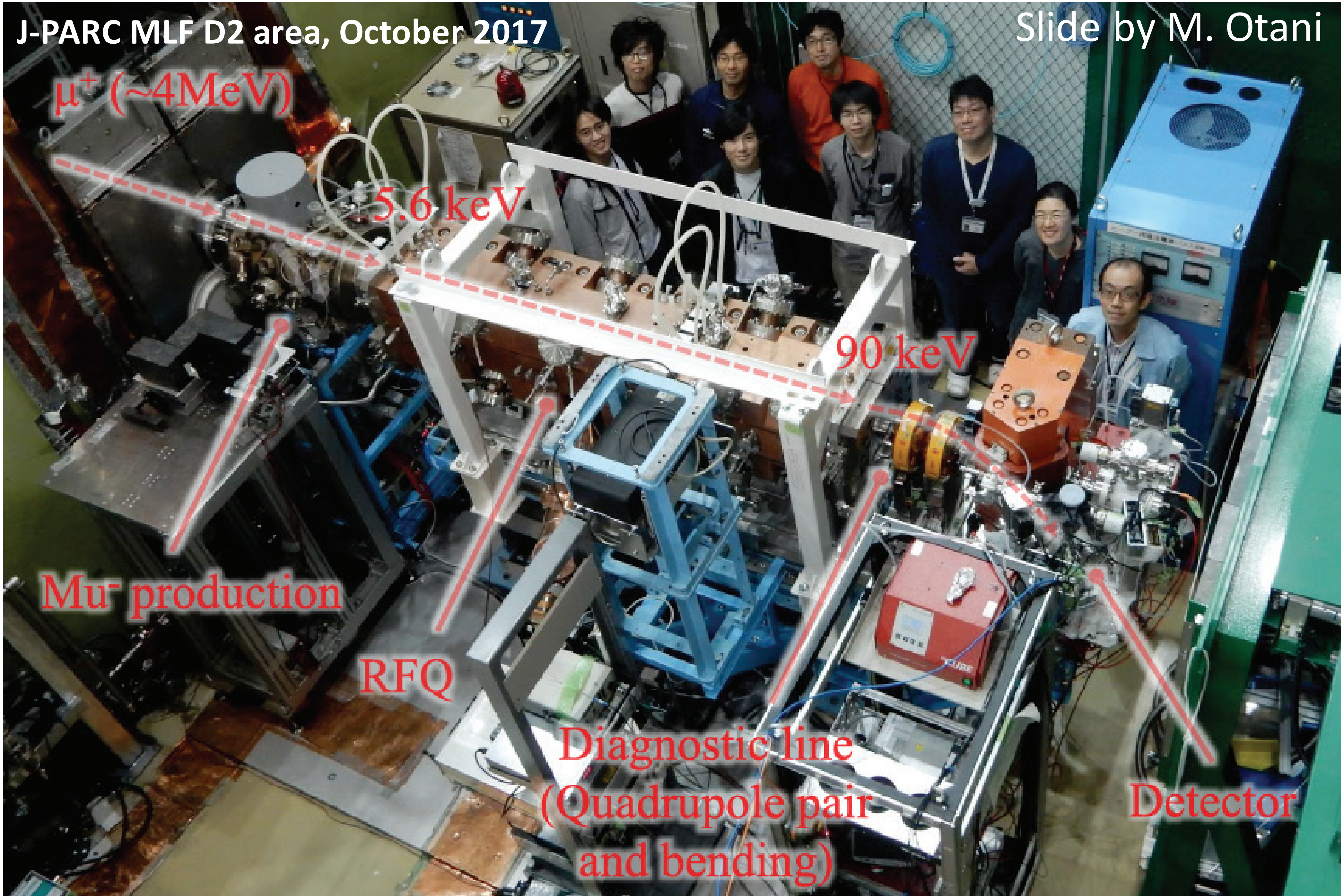
An accelerating structure (IH-DTL cavity) to 1.3 MeV

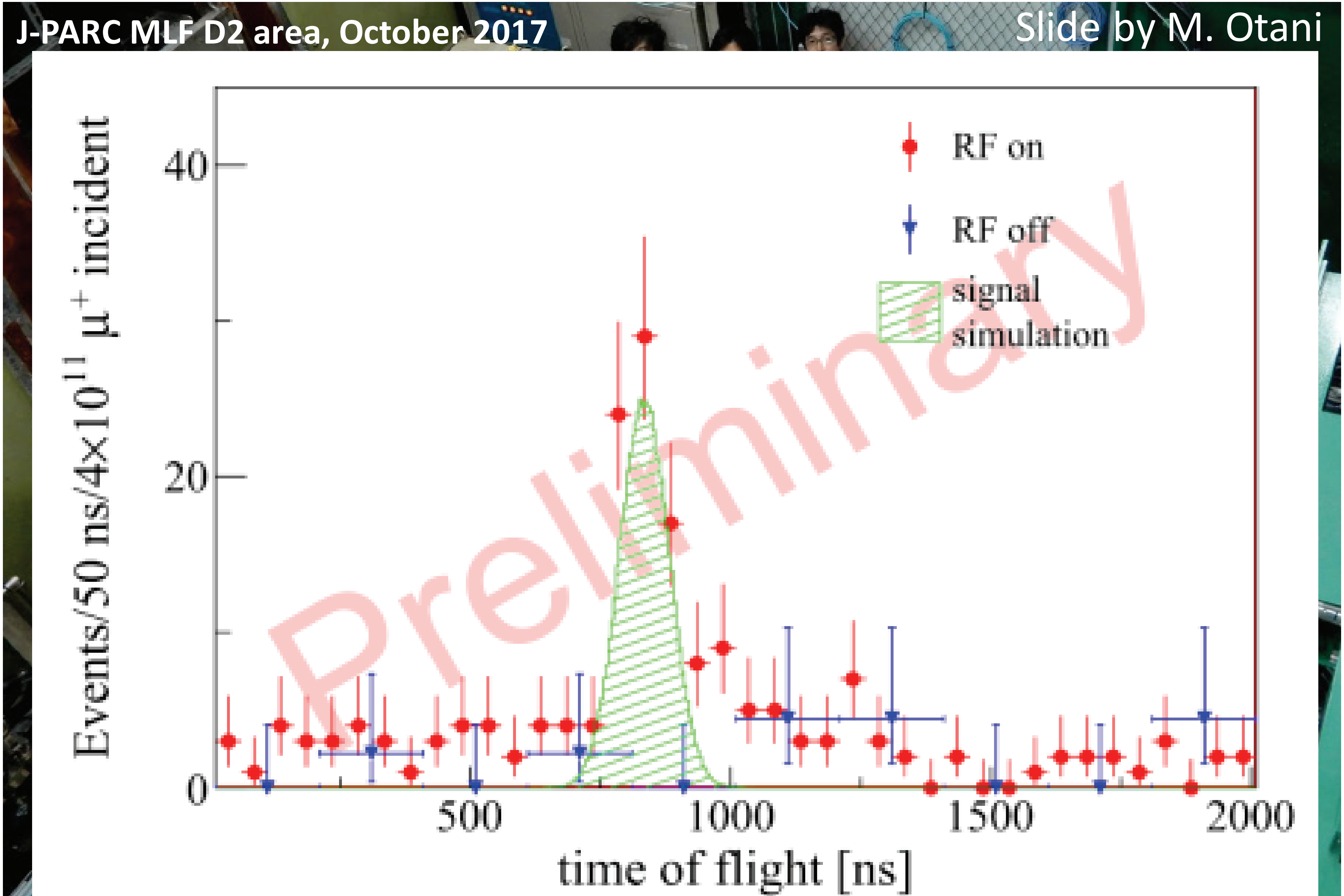


Mar 2017, Photo by M. Otani

Muon RF acceleration for the first time!



Muon RF acceleration for the first time!



Muon beam injection and storage

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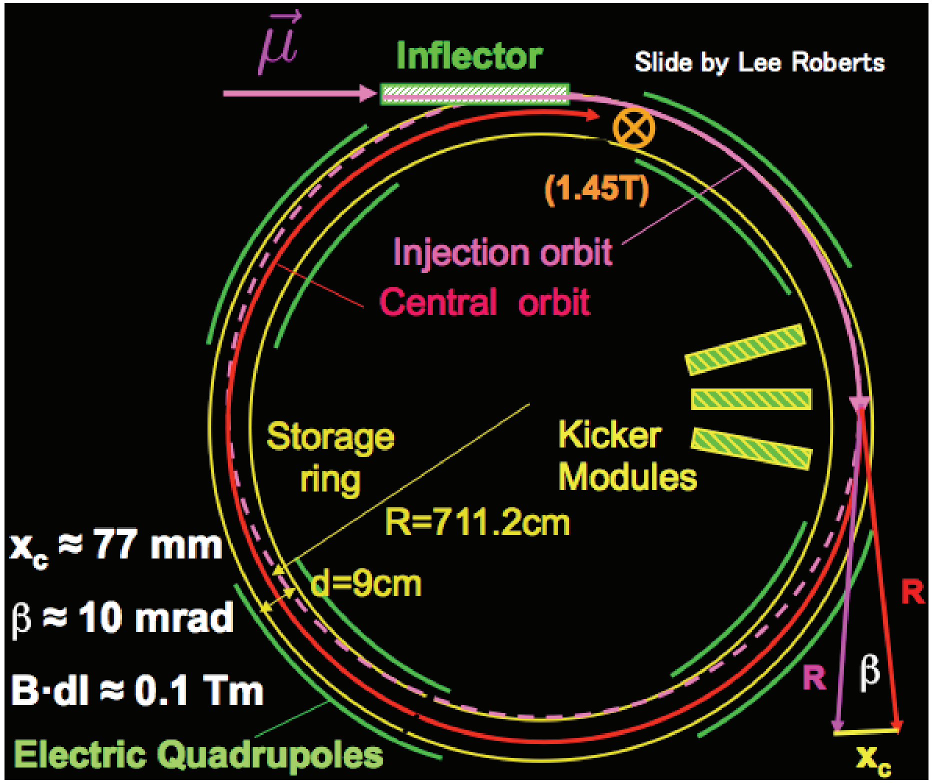
Horizontal injection + kicker

(BNL E821, FNAL E989)

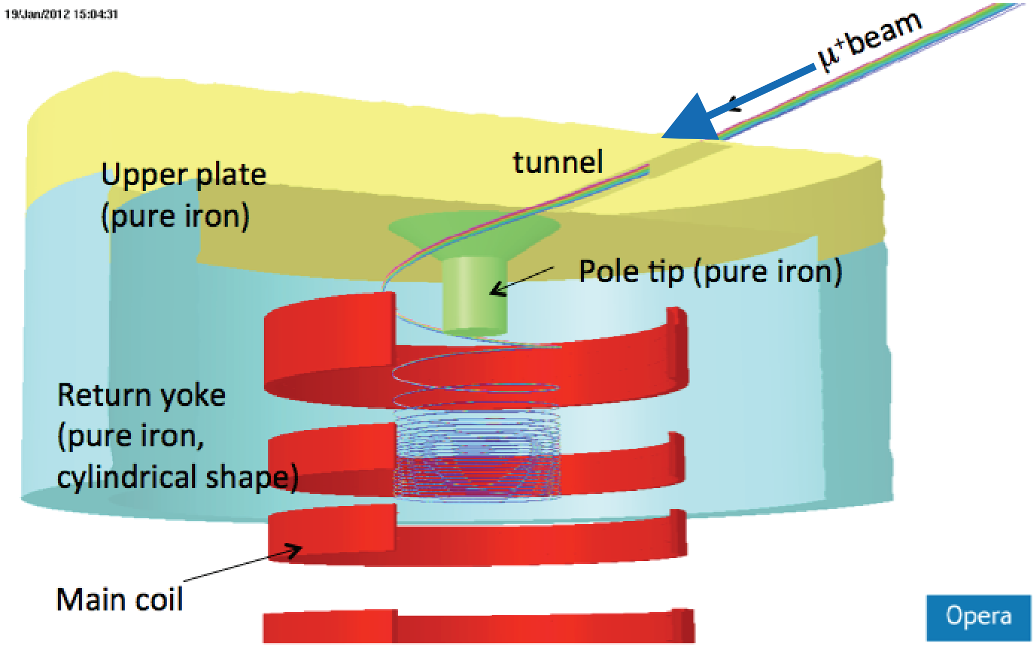


Injection efficiency : 3-5%(*)

(*) PRD73,072003 (2006)

3D spiral injection + kicker

(J-PARC E34)

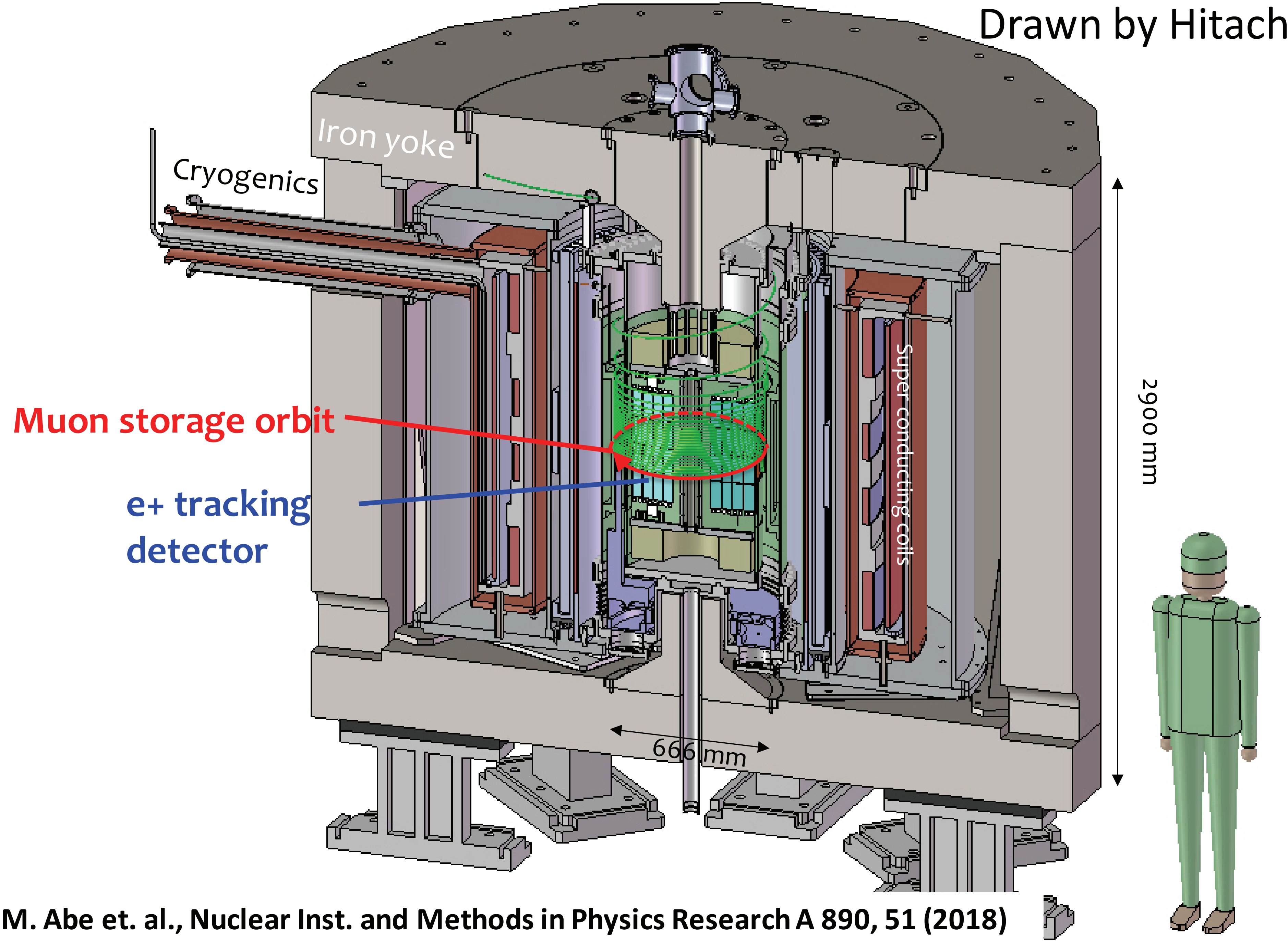


Injection efficiency : ~85%

H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

Muon storage magnet and detector

Drawn by Hitachi Co.



M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)

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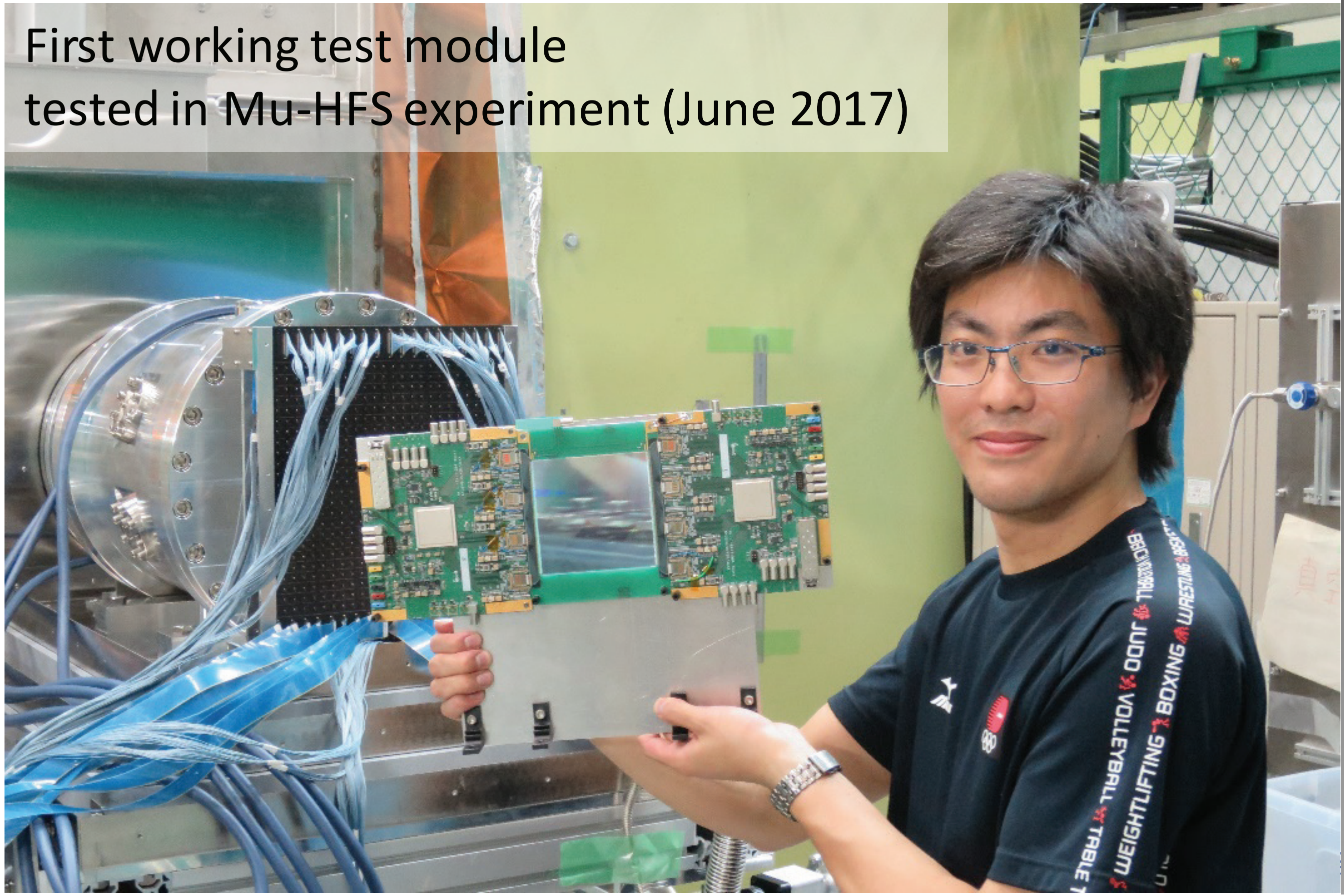
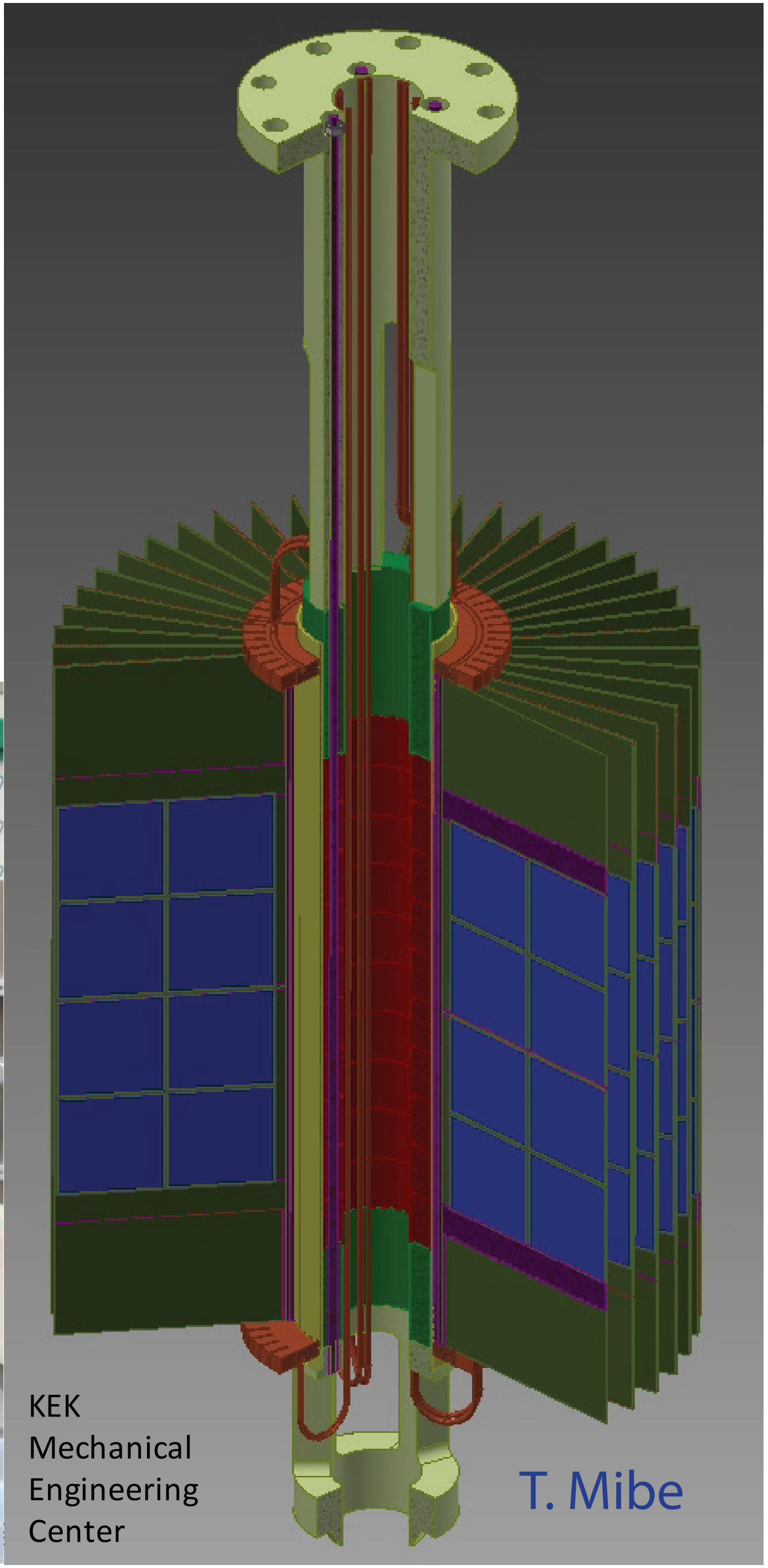
Positron tracking detector

- **A tracking detector (vs. calorimeter)**
  - Robust against pileups
- **Partial funding available to construct a part of detector system**



First working test module
tested in Mu-HFS experiment (June 2017)



KEK
Mechanical
Engineering
Center

T. Mibe

Muon g-2: The future

- First results from Fermilab soon
- Theory continuously improving
- Cold muons have a large potential
  (thus another technique next...)
- Also look for electric dipole moment of the muon

MuCool:
Another cool way to make cold muon beams?

muCool: Goals

We are building a small device to compress the phase space of a surface μ^+ beam

- Compress phase space by 10 orders of magnitude
- Energy of μ^+ <1 eV
- Beam size <1 mm^2
- Efficiency ~10^{-3}
- Tagged beam
- Conserves initial polarisation
- Add-on to existing conventional surface μ^+ beam line

A. Eggenberger

Phase Space Compression

- To reduce phase space a dissipative mechanism is needed
  - ➡ Slow down (stop) μ^+ in He gas
- After slowing down in gas:
  - ➡ low energy
  - ➡ large volume BUT: can steer μ^+ with electric and magnetic fields

In our case:

Apply $\vec{E}$x$\vec{B}$-fields in 3 successive compression stages:

1. Transverse (perpendicular to beam axis)
2. Longitudinal (along beam axis)
3. Final compression and extraction into vacuum

A. Eggenberger

Key Ingredient

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

Position-dependent drift velocity vector in He gas in the presence of crossed electric and magnetic fields

ω=eB/m: cyclotron frequency
μ=muon mobility
ν_{col}=collision frequency

3 components with different weights:
change in density (i.e. collision frequency) ➡ change in direction

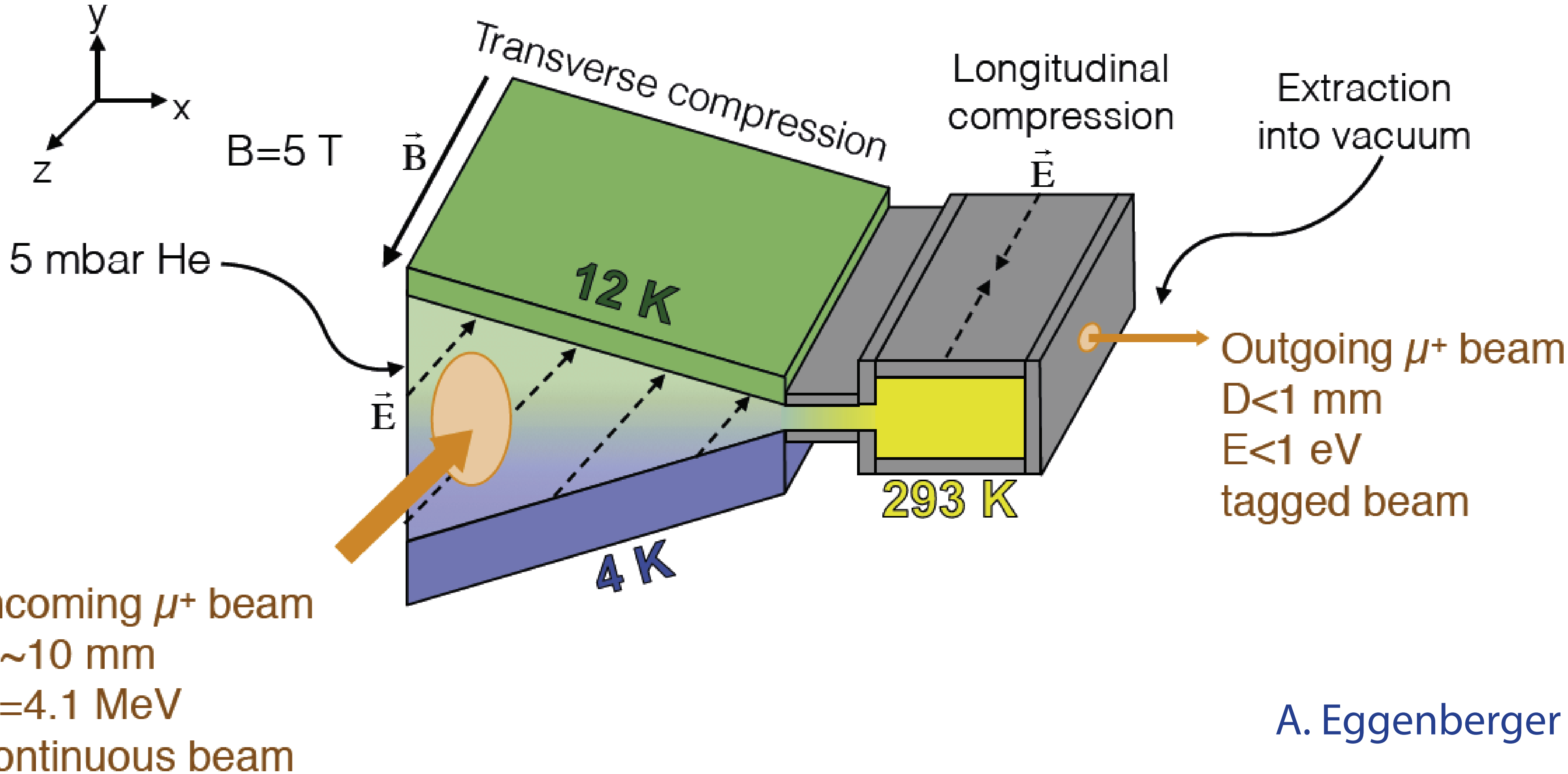
high density → v_{col} large → $\hat{E}$ dominates

low density → v_{col} small → $\hat{B}$ dominates

A. Eggenberger

3 Compression Stages

Dimensions ~ 15 x 5 x 50 cm^3



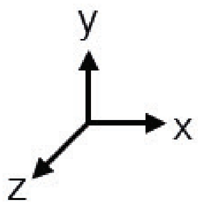
A. Eggenberger

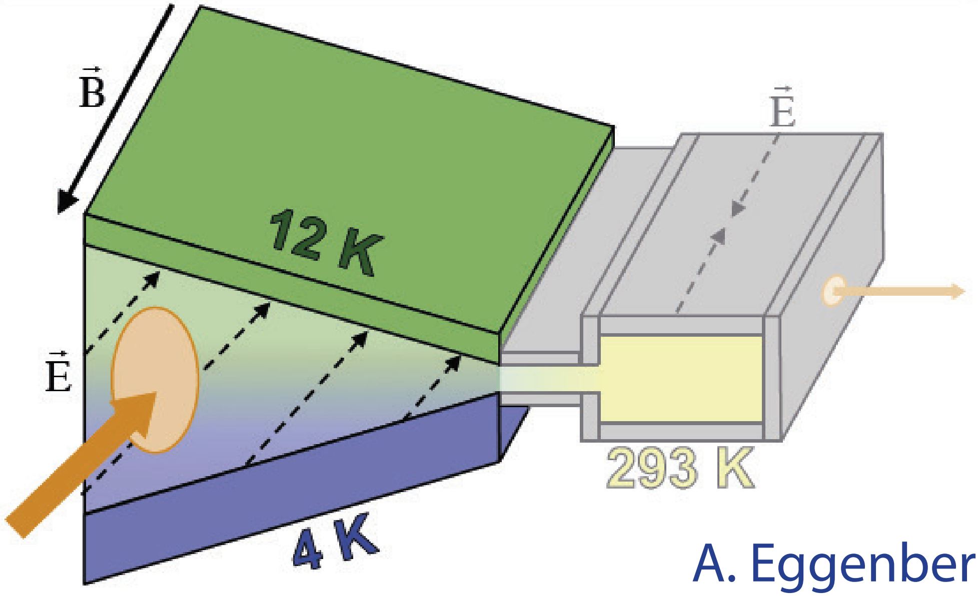
D. Taqqu, *PRL* **97**, 194801 *(2006)*
Y. Bao et al., *PRL* **112**, 224801 *(2014)*

Transverse Compression Stage

- 5 mbar He gas
- Cryogenic temperature
- Temperature gradient
- Crossed E- and B-fields

$$\hat{E} = \frac{1}{\sqrt{2}}(1,1,0)$$
$$\hat{B} = (0,0,1)$$
$$|\vec{E}| \approx 1.5\ \mathrm{kV/cm}$$



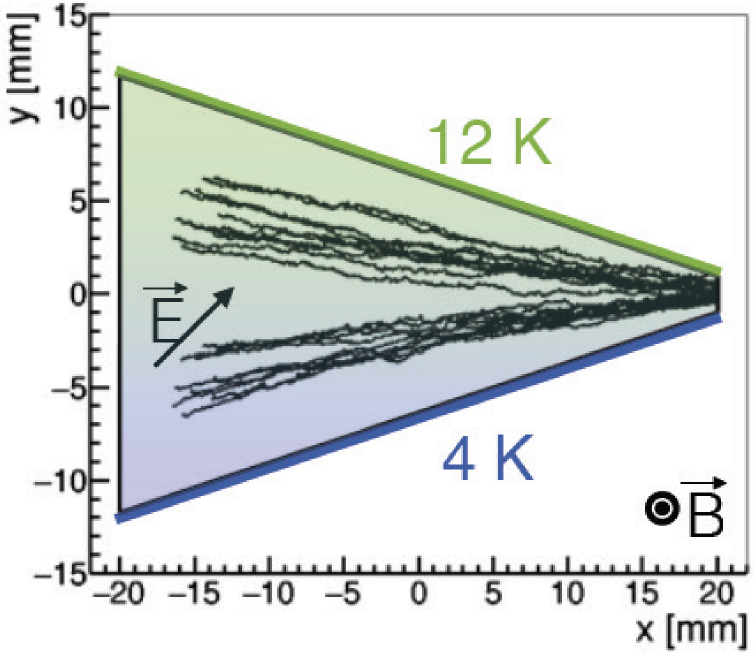


A. Eggenberger

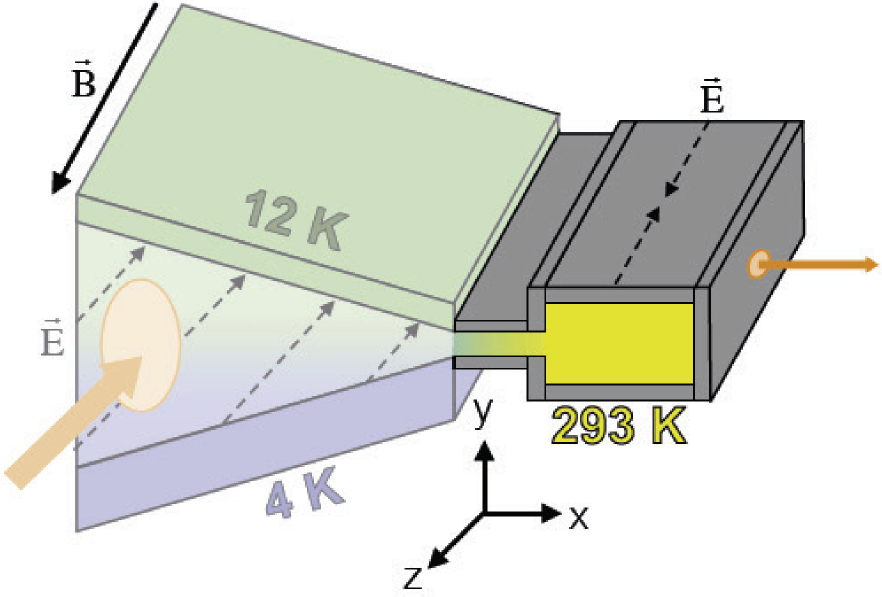
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}} \times \hat{\mathbf{B}}\right]$$

high density → v_{col} large → $\hat{E}$ dominates

medium density → v_{col} intermediate → $\hat{E} \times \hat{B}$ dominates



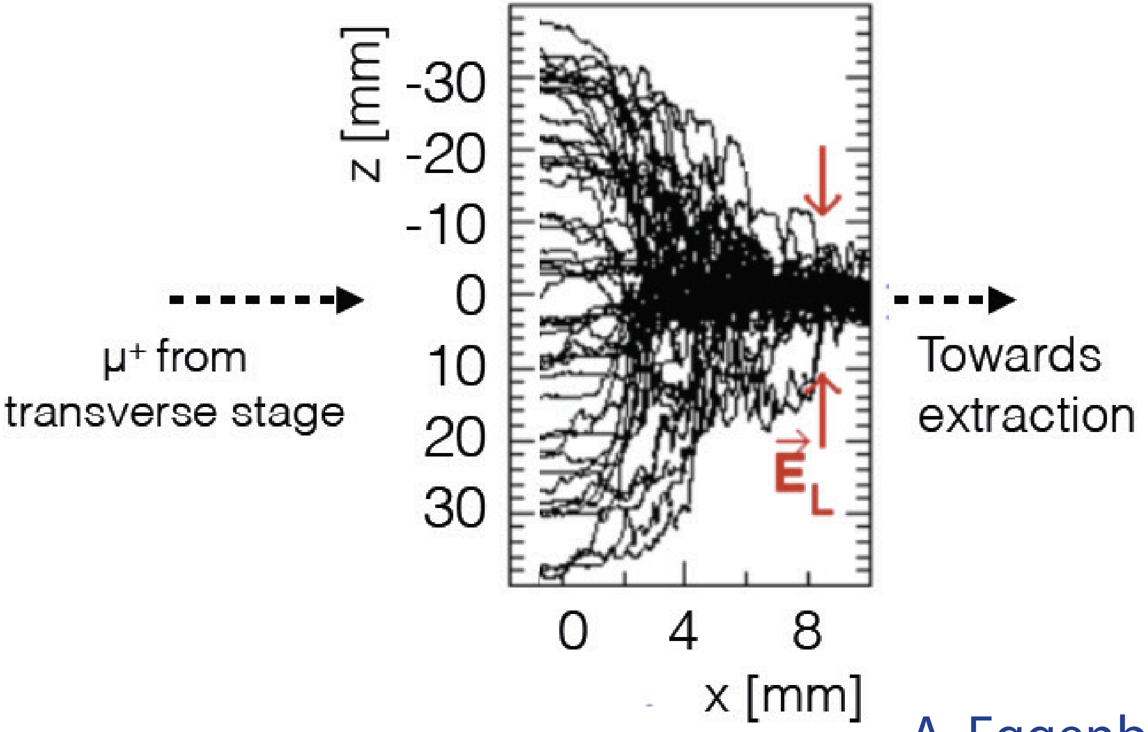
Longitudinal Compression Stage



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

low density → v_{col} small → $\hat{B}$ dominates

Simulation: Top view



μ^+ from transverse stage

Towards extraction

- 5 mbar He gas
- Room temperature
- Parallel $\vec{E}$- and $\vec{B}$-fields

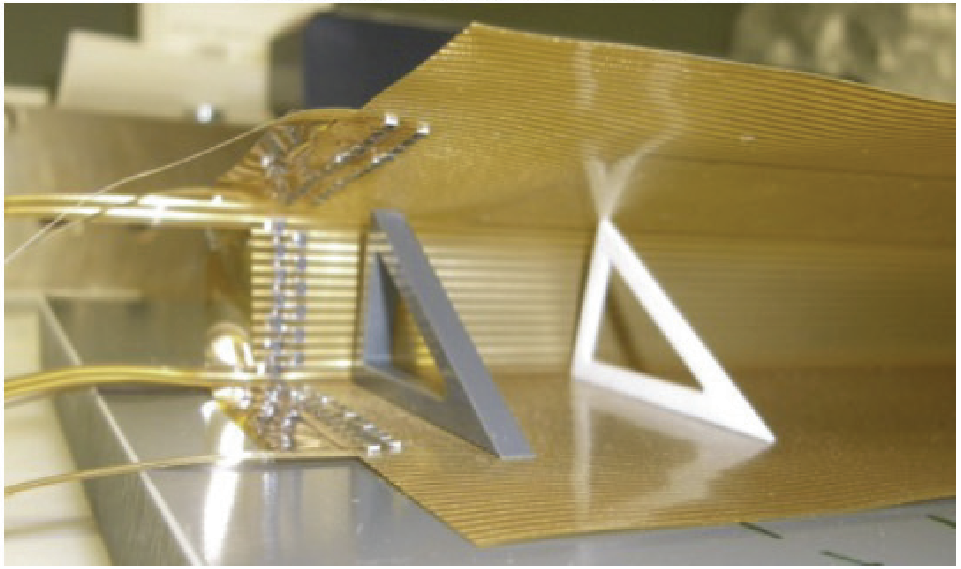
$$\hat{E} = \pm(0,0,1)$$
$$\hat{B} = (0,0,1)$$
$$|\vec{E}| \approx 60 \text{ V/cm}$$

A. Eggenberger

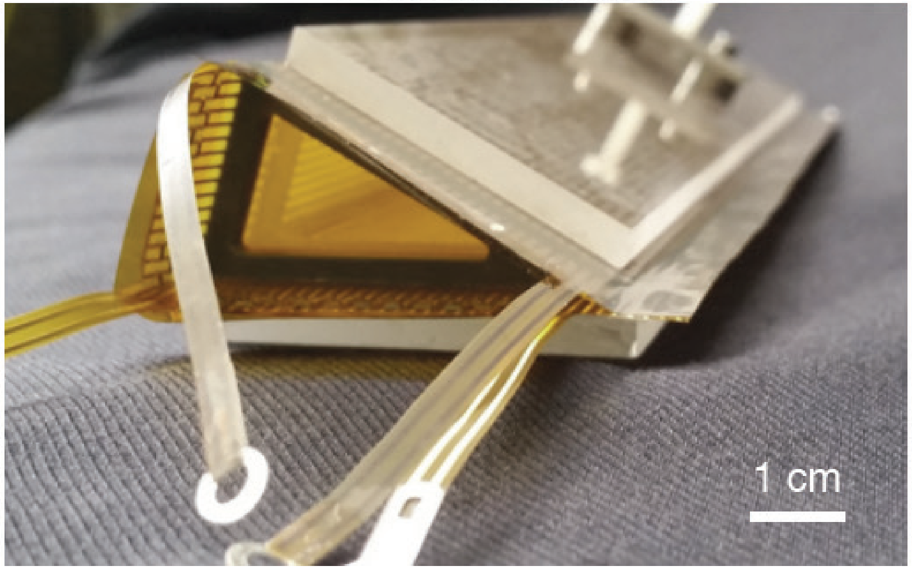
Transverse Target

A. Eggenberger

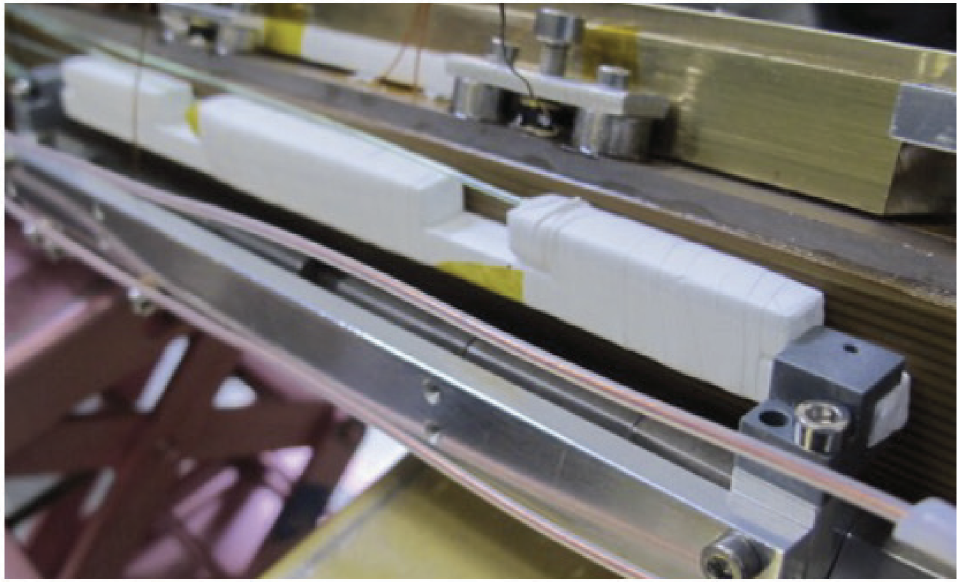
During construction



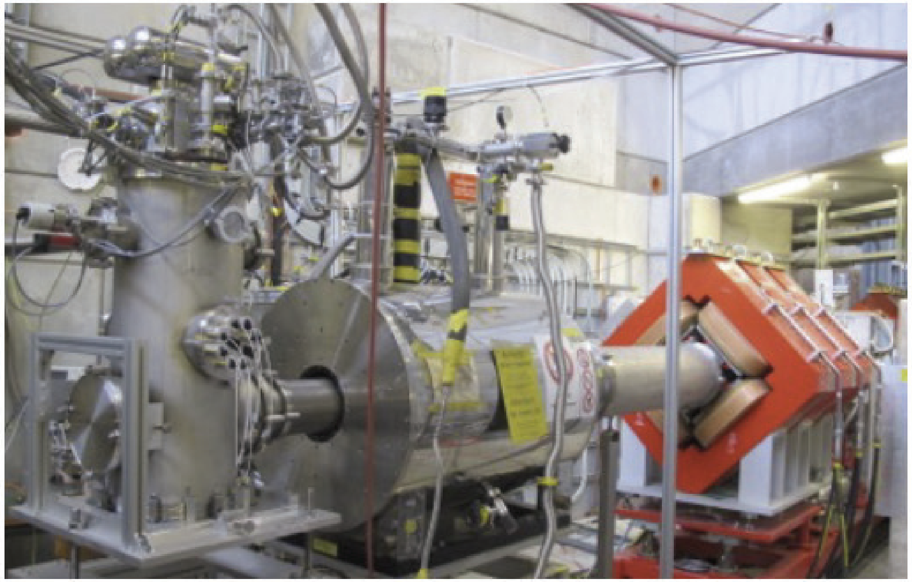
Finished target



Scintillators wrapped in Teflon



Setup at πE1



MuCool status

- Transverse and longitudinal compression demonstrated
- Both at once and extraction into vacuum to be done
- Cold beam could be used for g-2 or electric dipole moment search
- Muon EDM shows up as an out-of plane precession of the spins...