Precision Muon Experiments (and the Standard Model).

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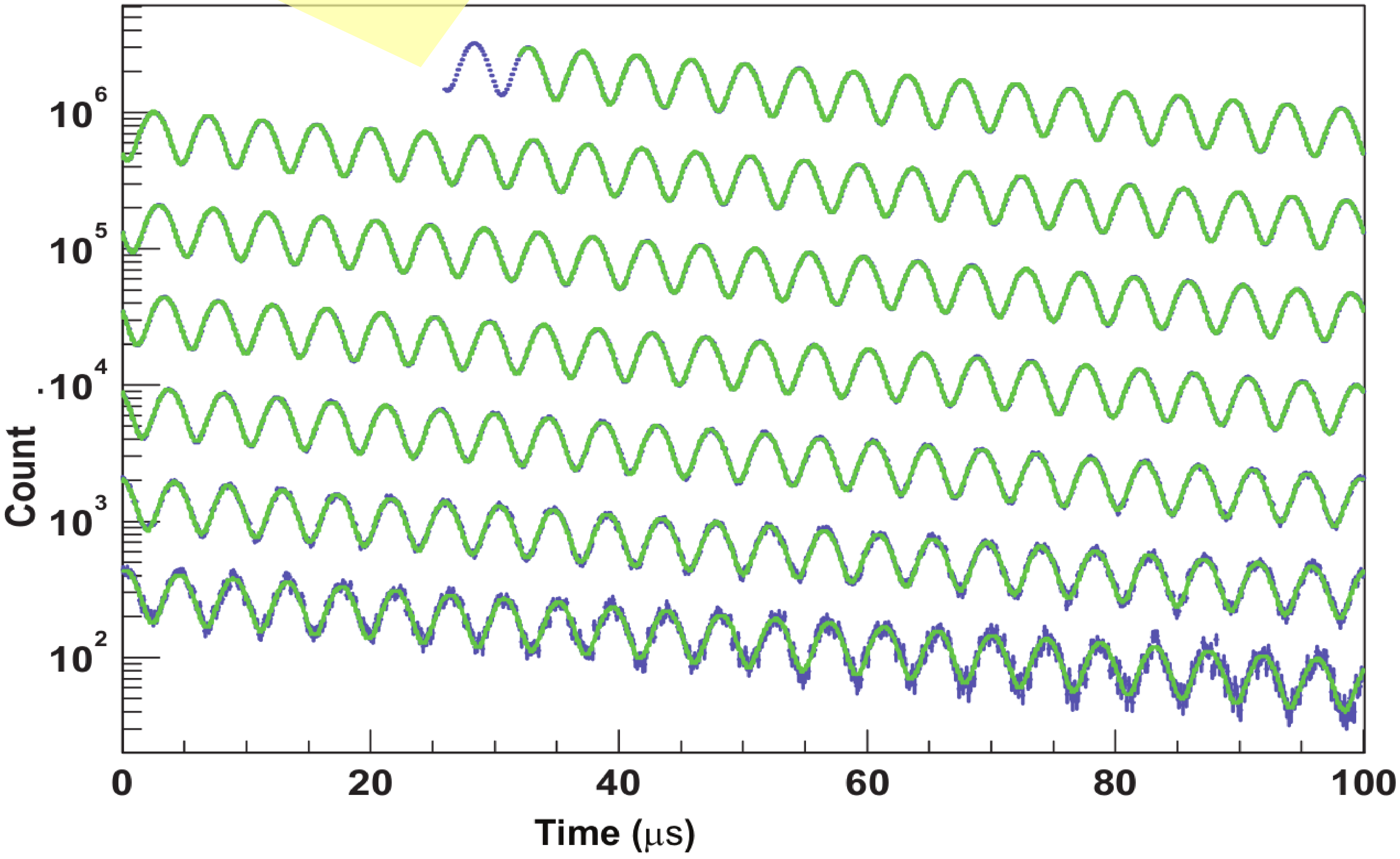
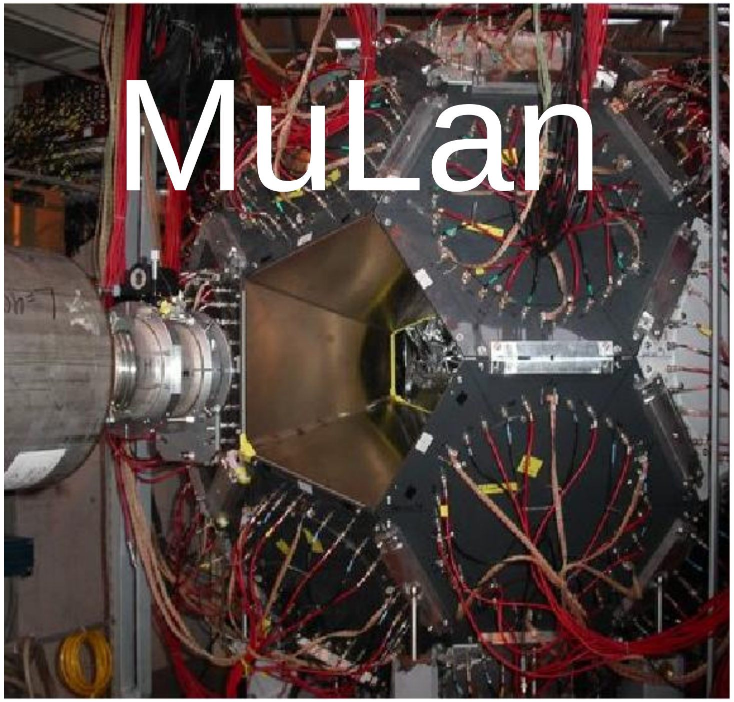
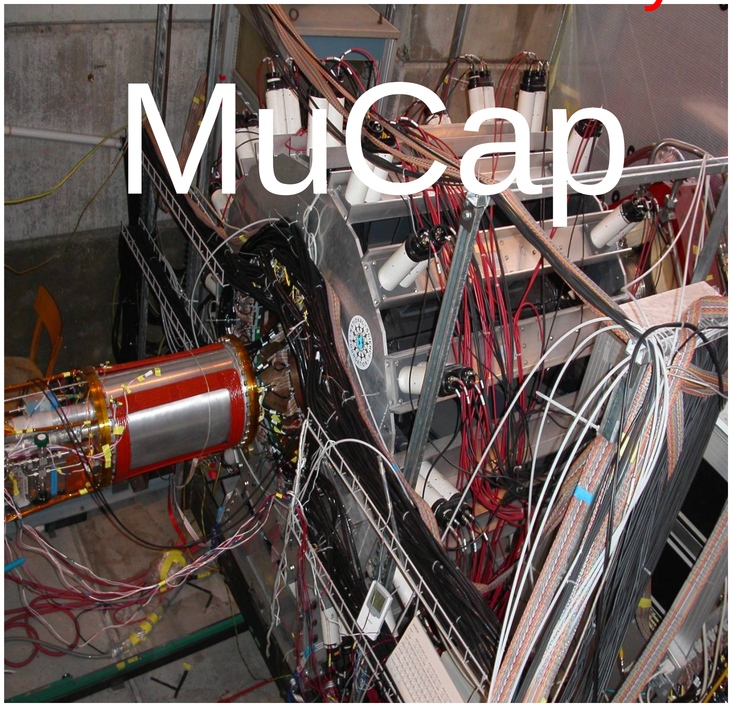
Particle Physics in Indiana, Kentucky, Illinois and Ohio,
Sept. 16, 2017, Lexington, Kentucky.

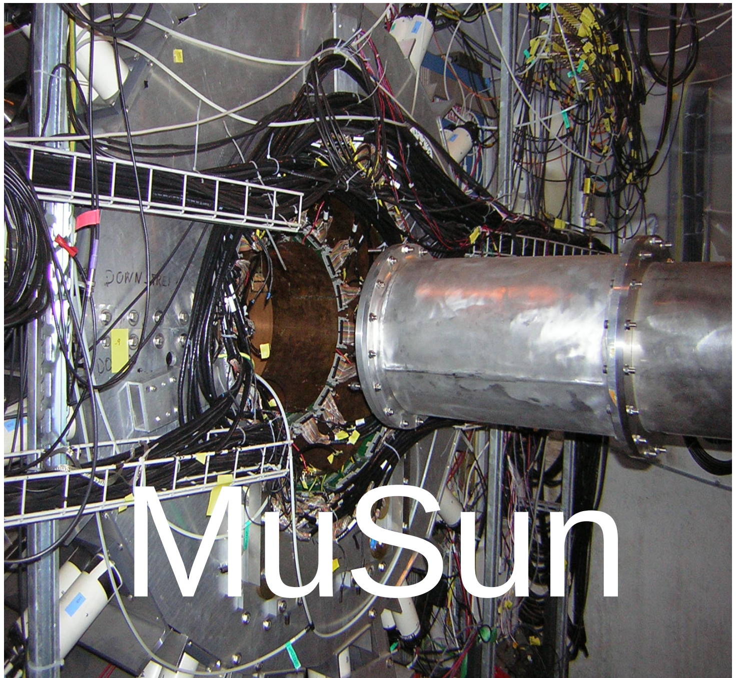
a quick tour of particle physics thru precision measurements of time distributions of μ-decay electrons with 10^{11}-10^{12} statistics, petabyte-scale datasets.



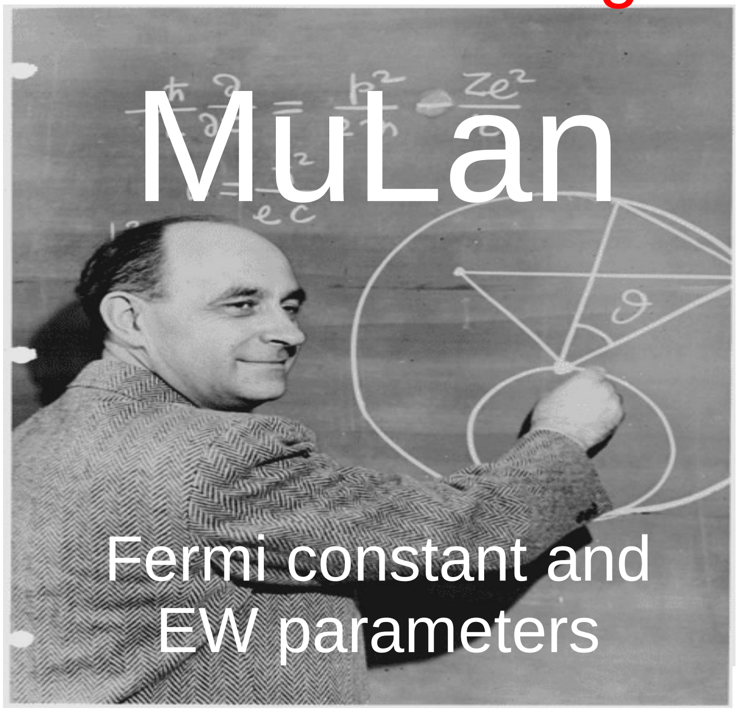
Precision measurements of electron time distributions from muon decay.

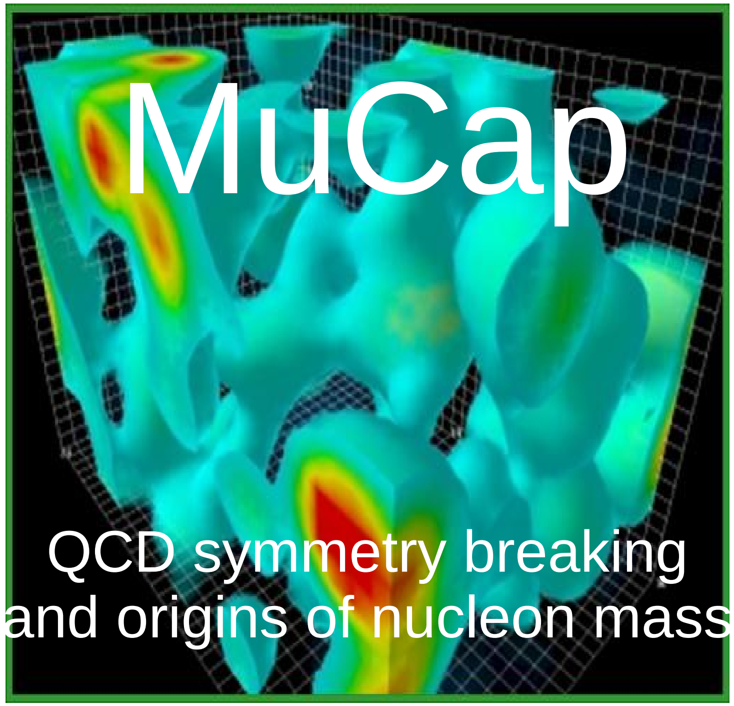


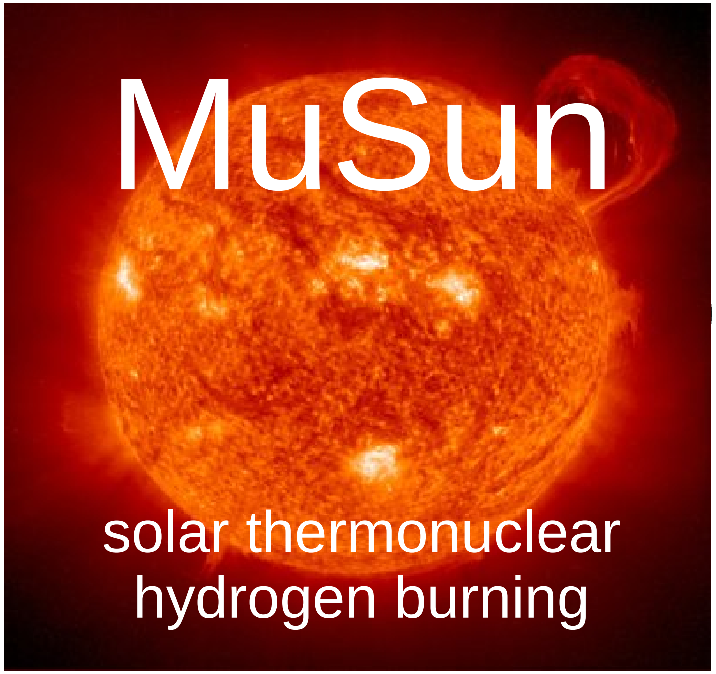




Featuring standard model, new physics, and emergent phenomena.

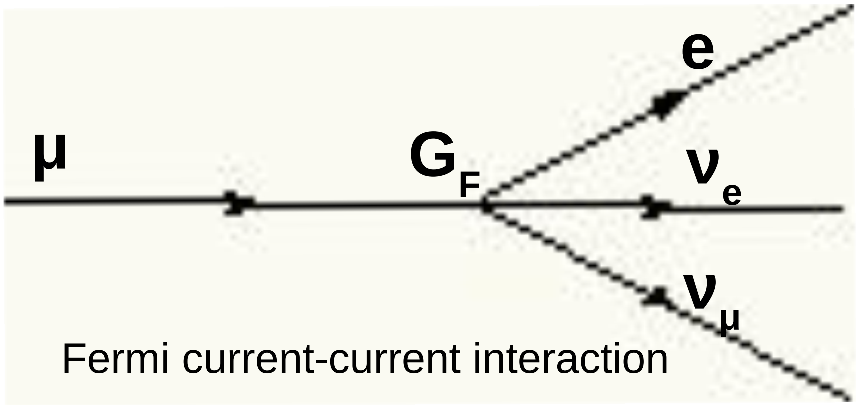




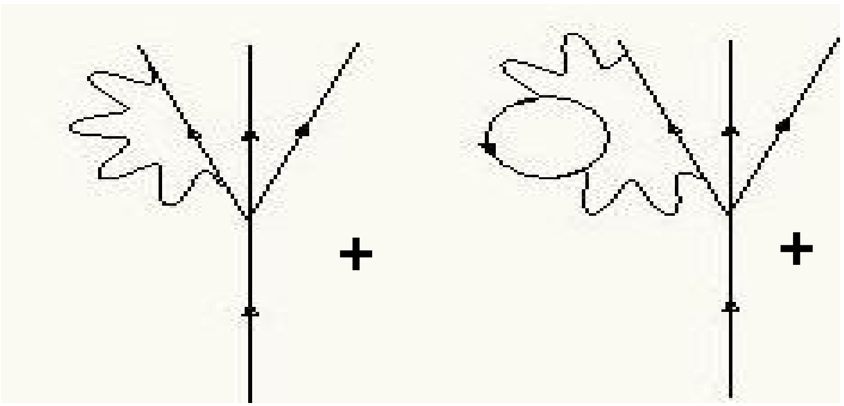


MuLan - lifetime of the positive muon $\tau_{\mu+}$

parameters of EW interaction are determined by precision measurement of α, G_F, M_Z



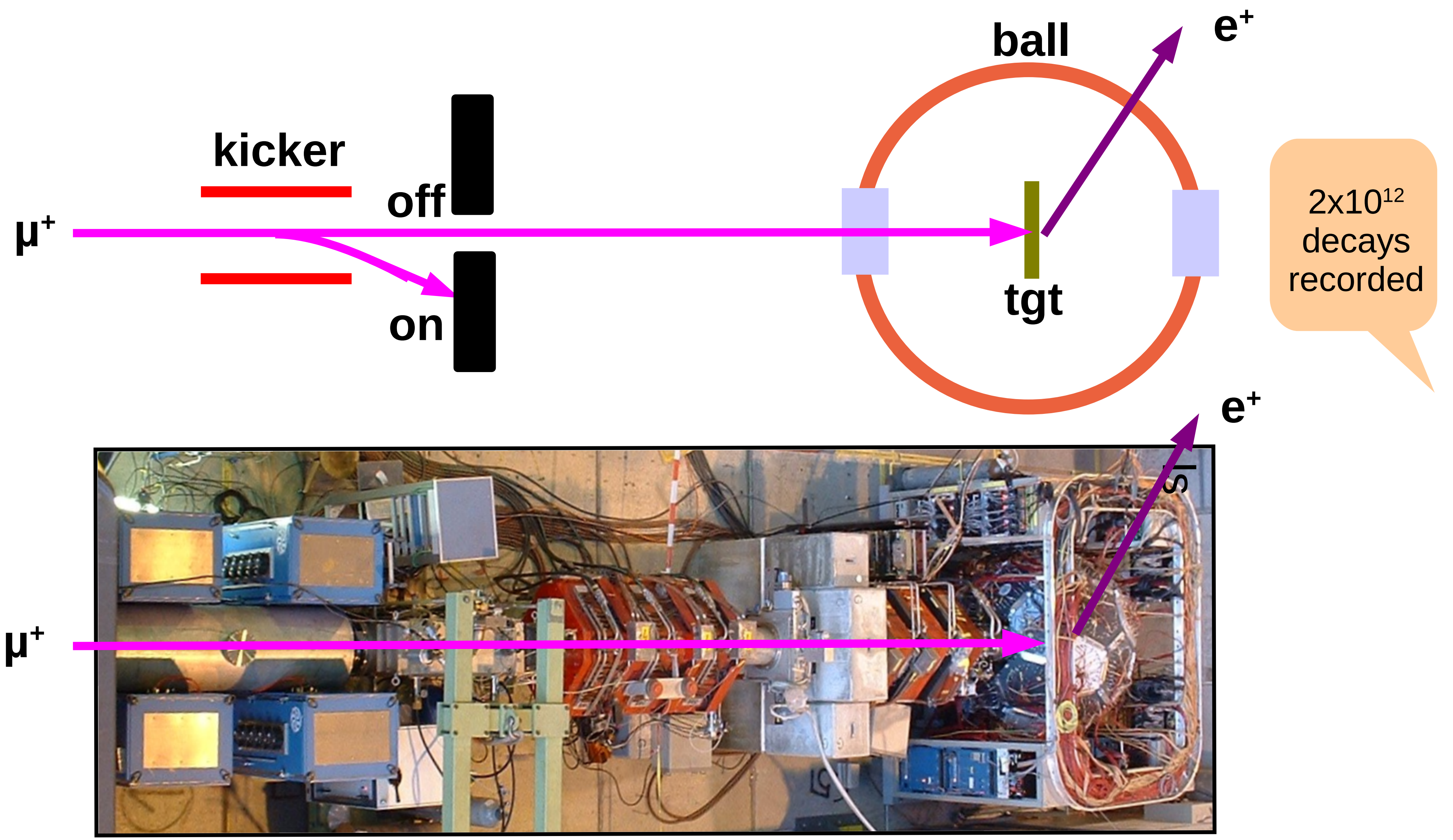
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^2}(1+\Delta q)$$



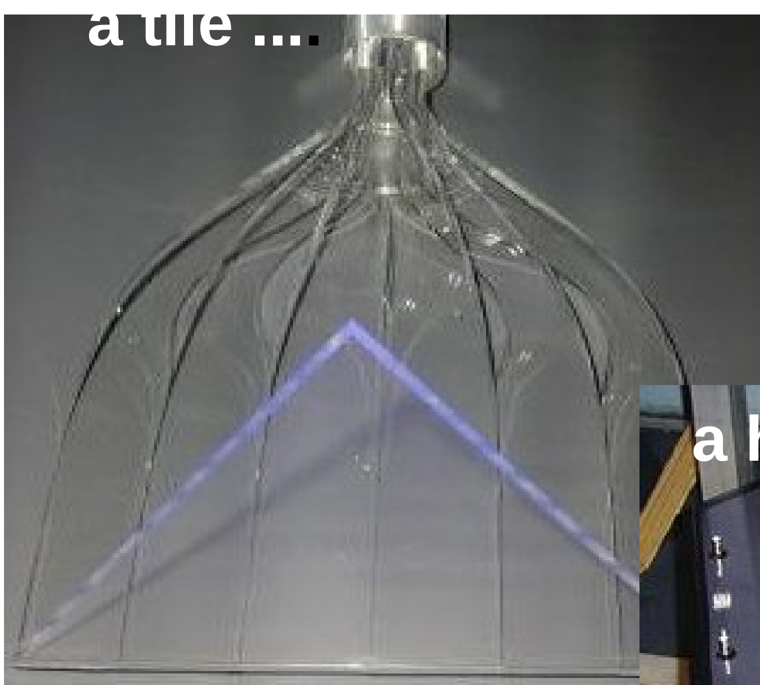
Δq contains QED, QCD radiative corrections

~ **0.1 ppm** uncertainty in $\mathbf{T_\mu}$**-**$\mathbf{G_F}$ relationship from **Δq,** $\mathbf{m_\mu}$

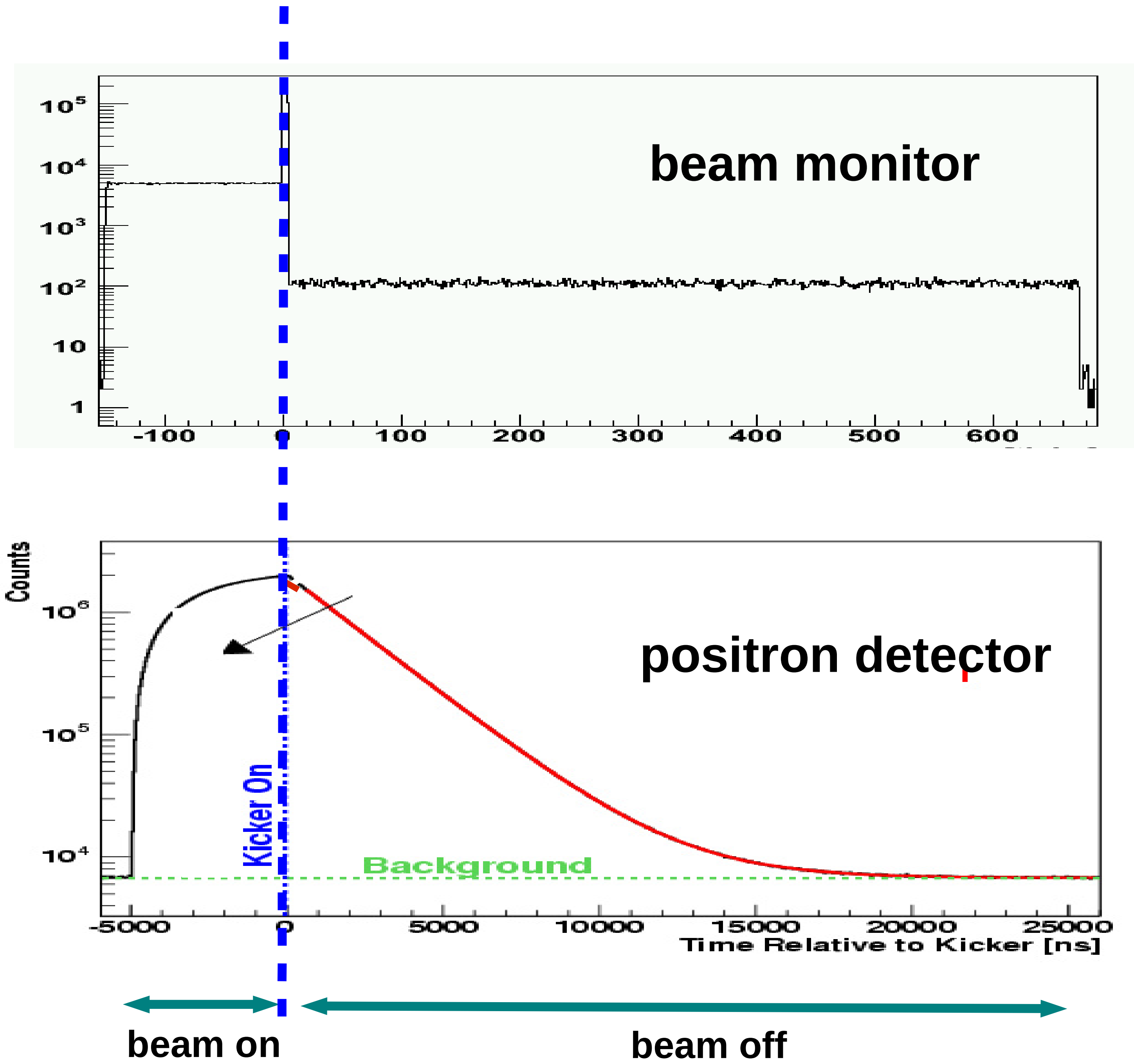
MuLan - accumulating μ⁺'s and measuring e⁺'s



MuLan detector

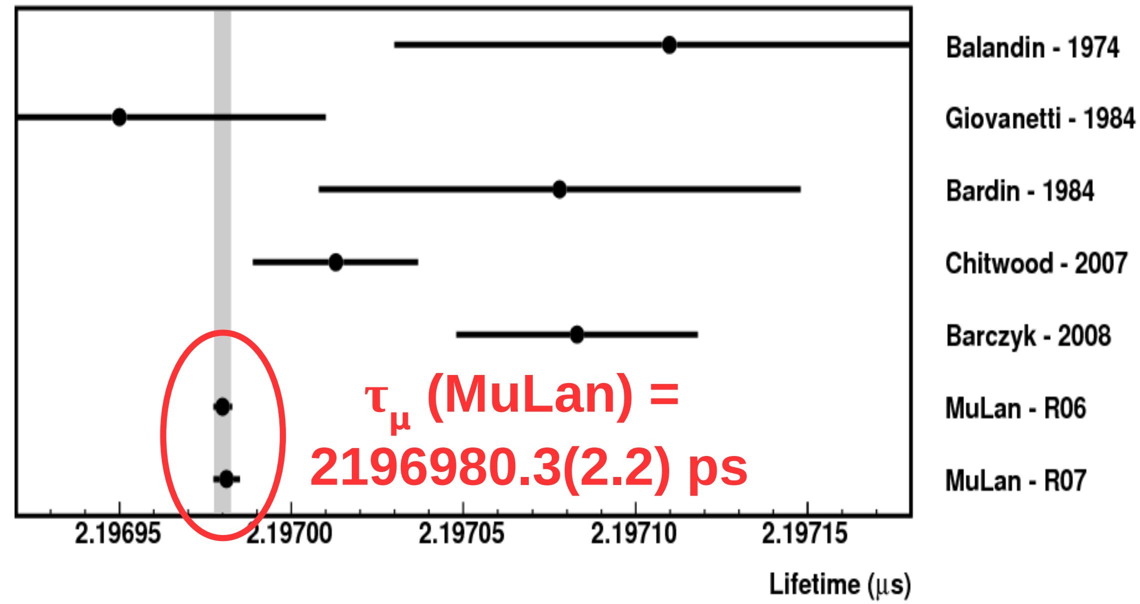


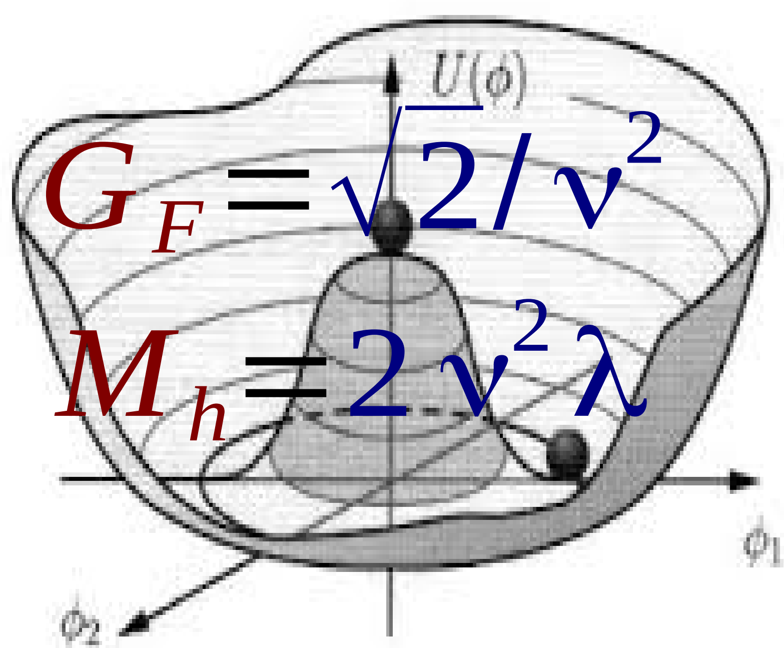
MuLan - accumulating μ⁺'s and measuring e⁺'s



MuLan Result

τ_μ is "anchor" in tests of universality using $\tau \rightarrow e\upsilon\bar{\upsilon}$, $\tau \rightarrow \mu\upsilon\bar{\upsilon}$ and studies of muon capture by lifetime techniques.



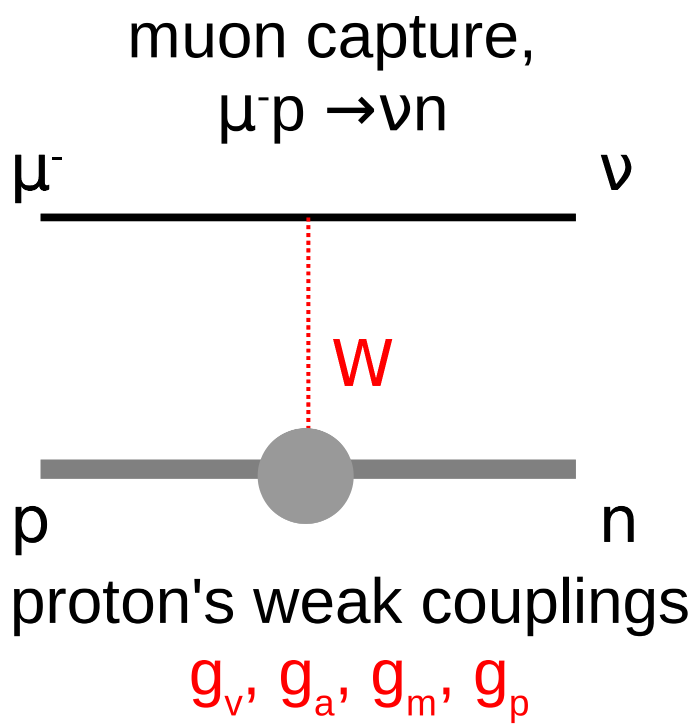


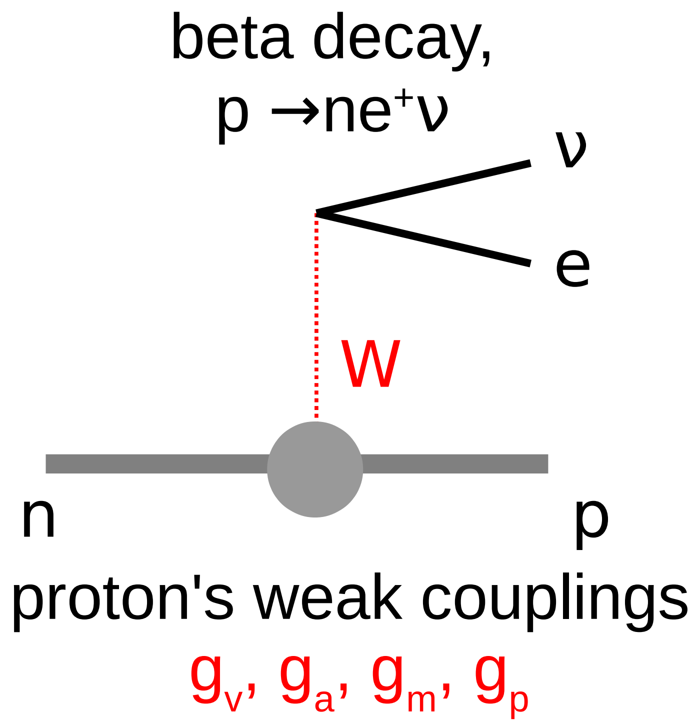
$$G_F = \sqrt{2}/v^2$$

$$M_h = 2v^2\lambda$$

'mi constant, G_F = 1.1663788(7) x10^{-5} V^{-2} [0.6 ppm], together with Higgs mass ermine the Higgs vacuum expectation ue, v, and self interaction parameter, λ.

MuCap - lifetime of muon hydrogen atom, $\tau_{\mu p}$

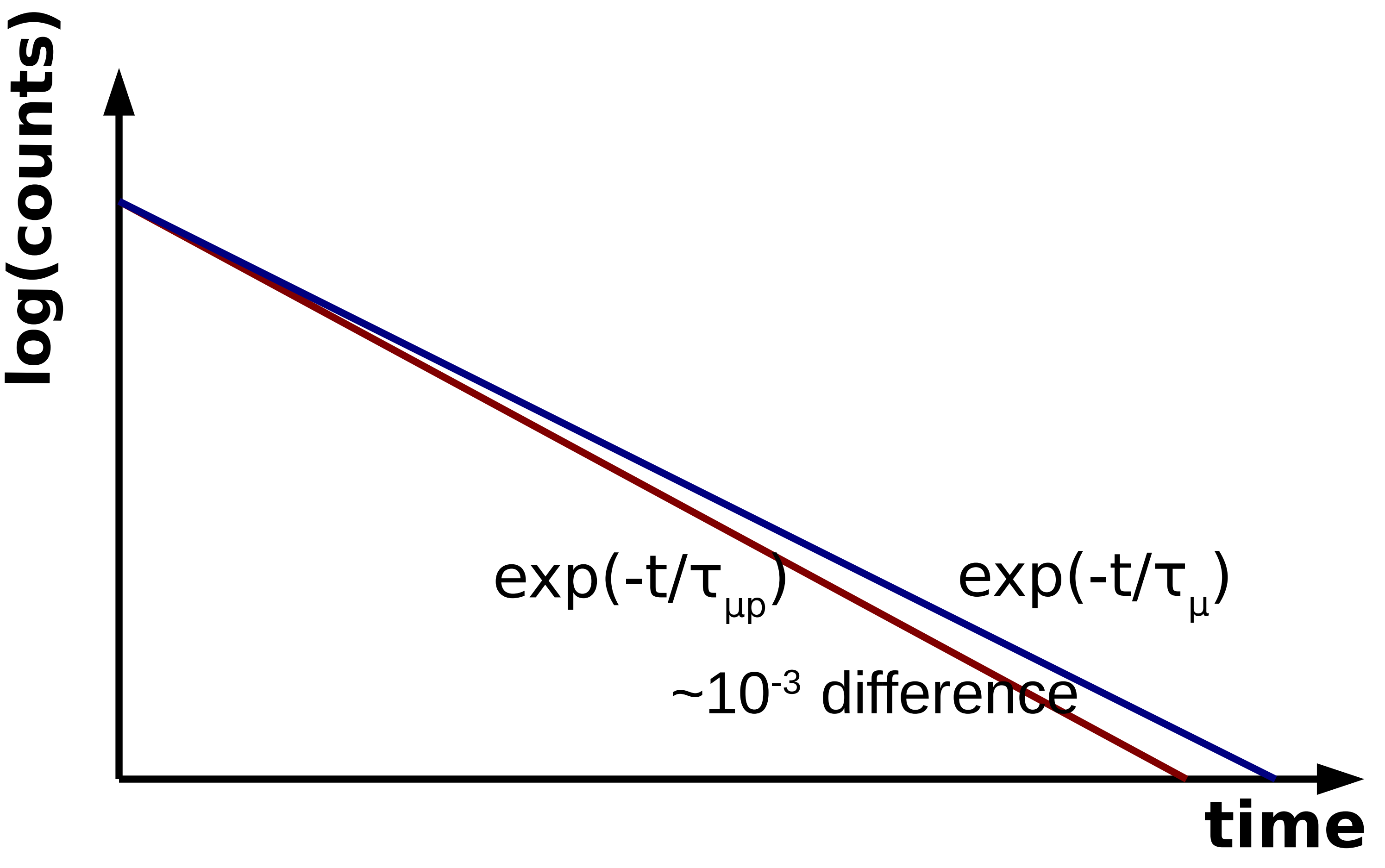




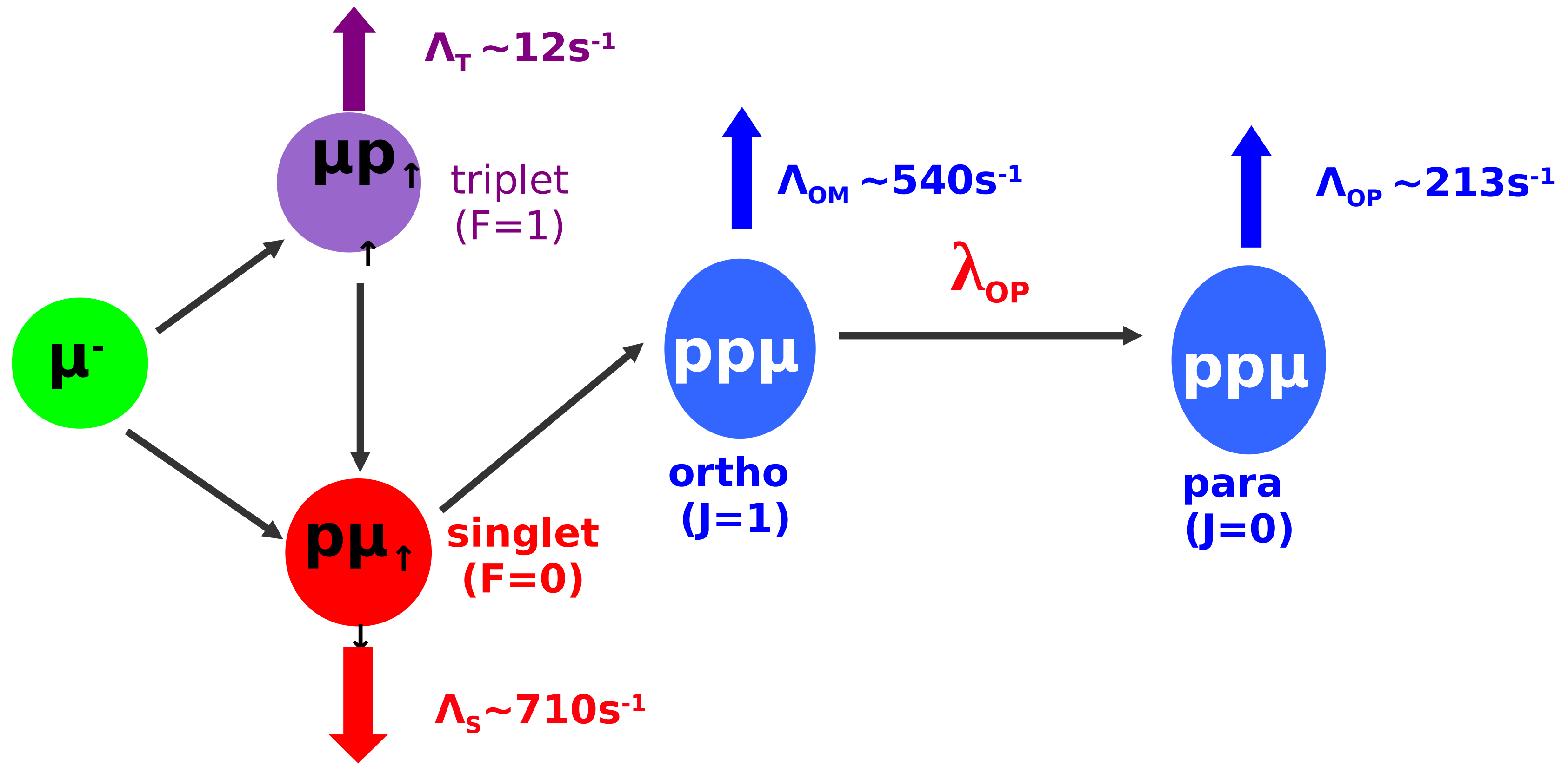
- pseudoscalar coupling g_p is fundamental quantity in description of proton's weak interaction
- relation between g_p, g_a is golden test of QCD symmetries and symmetry breaking origin of nucleon mass.

MuCap - lifetime of muon hydrogen atom, $\tau_{\mu p}$

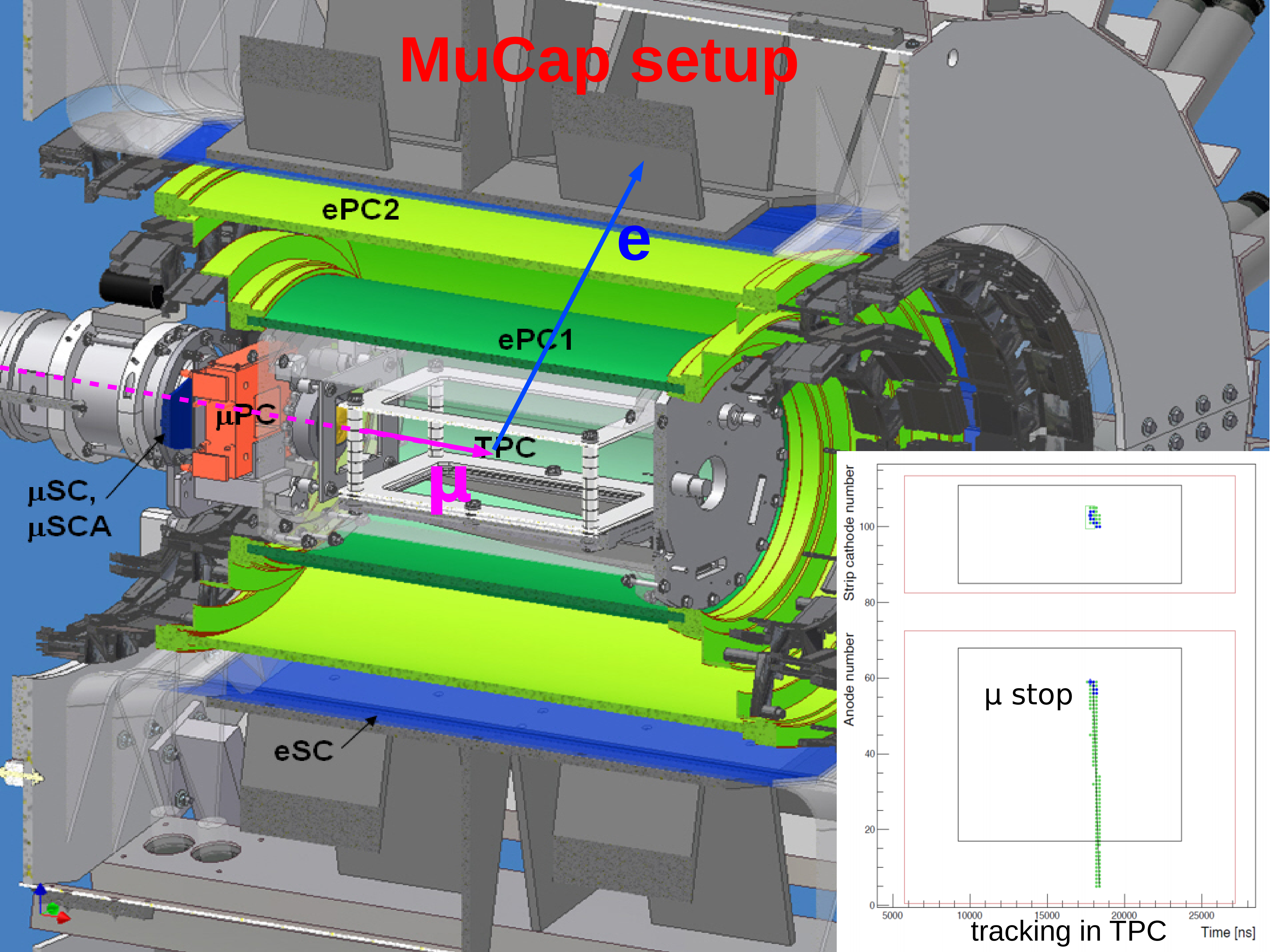
determine $\mu^- p \rightarrow \nu n$ rate
by lifetime technique $\Lambda = 1/\tau_\mu - 1/\tau_{\mu p}$



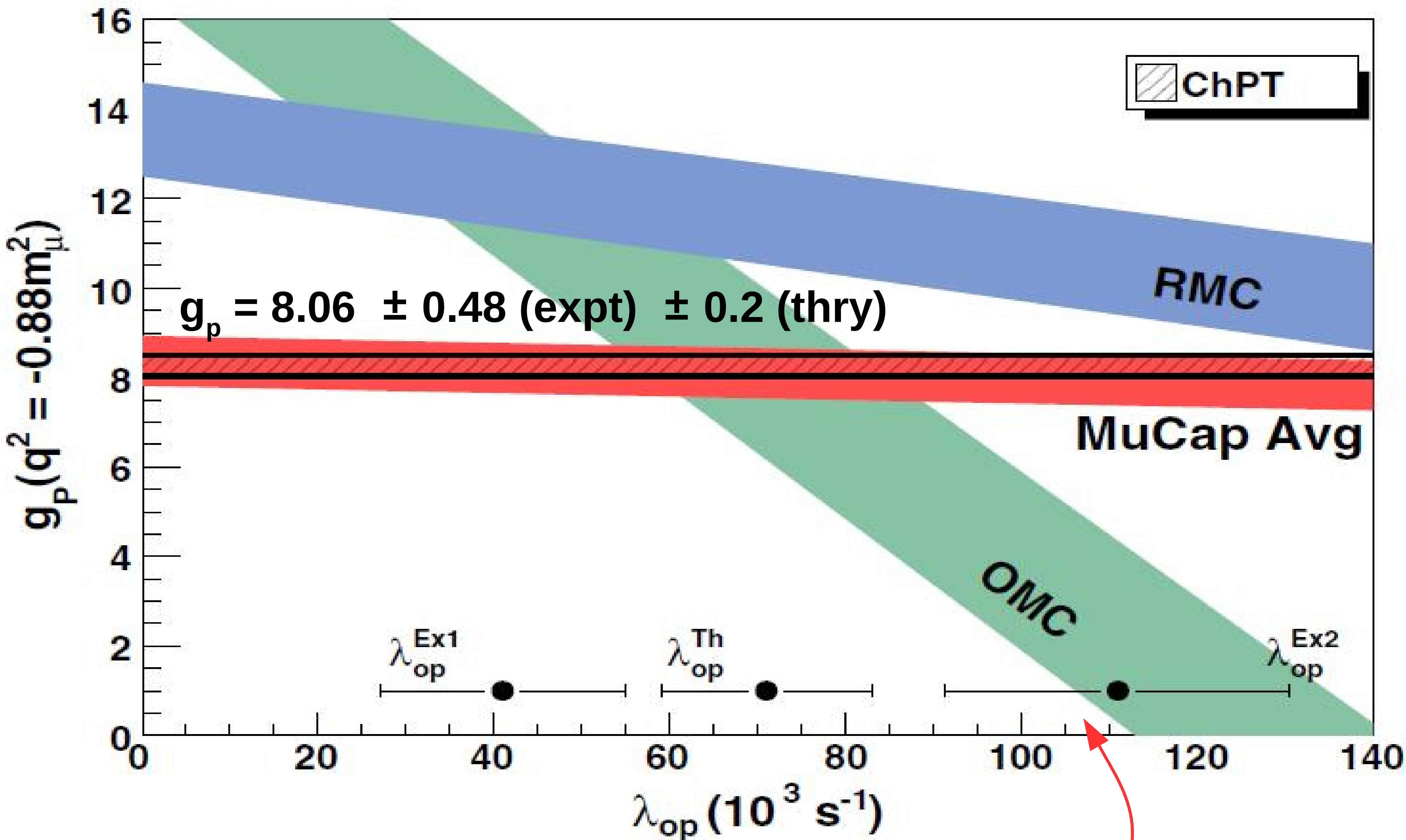
MuCap - $\mu^{-}p$ chemistry



MuCap used ultra-pure, 10 bar H_2 gas to prepare singlet atoms.


MuCap setup
ePC2
e
ePC1
μPC
TPC
μ
μSC,
μSCA
eSC
Strip cathode number
Anode number
μ stop
tracking in TPC
Time [ns]

MuCap Result, Λ_S = 715.6 ± 5.4 (stat) ± 5.1 (syst) s^{-1}

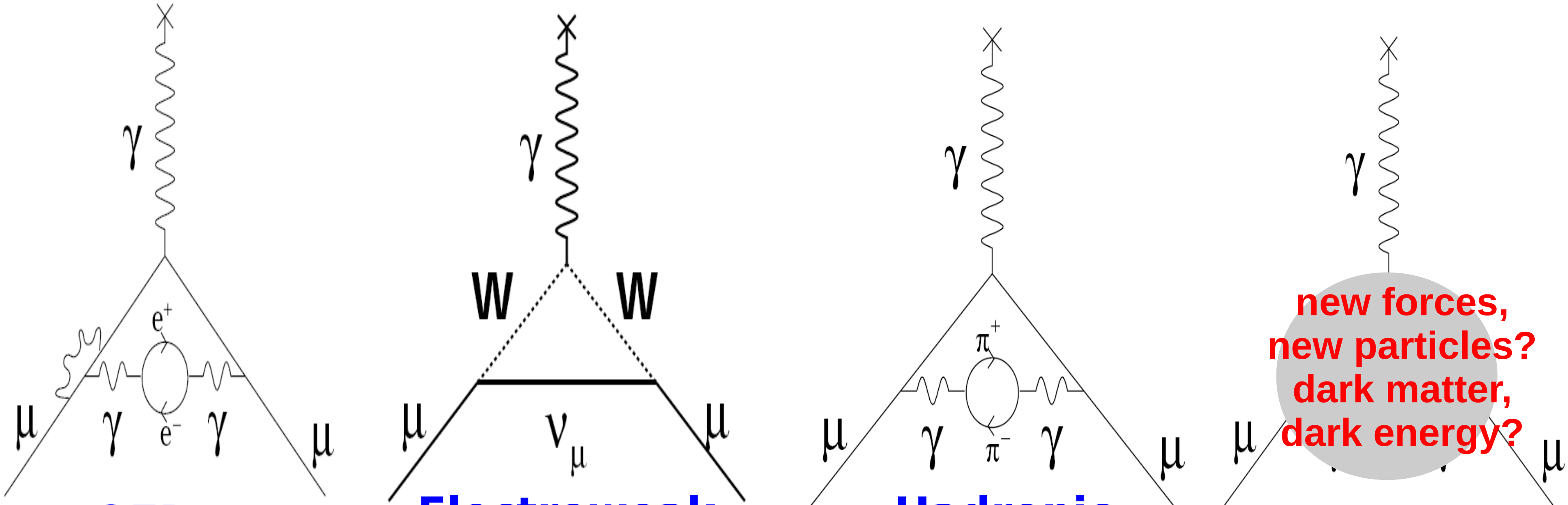


•result free of ambiguities from muonic molecule formation (λ_{op})

•verifies understanding of QCD symmetries and origins of nucleon masses

Muon g-2 – the muon's anomalous magnetic moment, a_μ.

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Strong} + a_\mu^{Weak} + a_\mu^{NP}$$



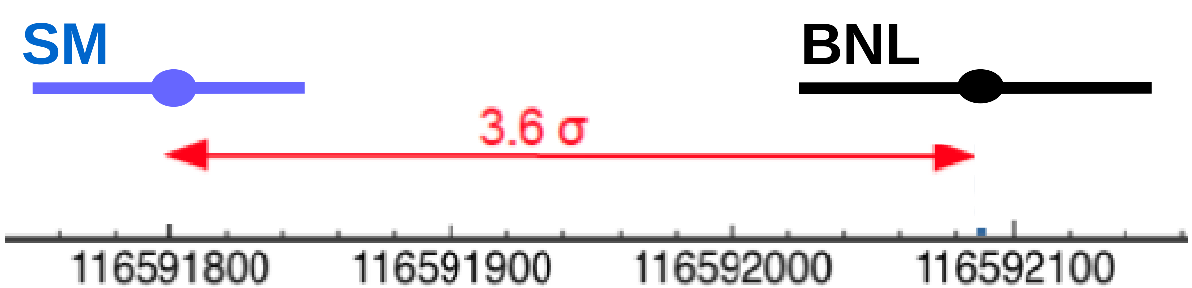
QED **Electroweak** **Hadronic**

a_μ^{QED} =
116 584 719.0 (0.1)

a_μ^{EW} =
154 (1)

a_μ^{Had} =
6983 (44)

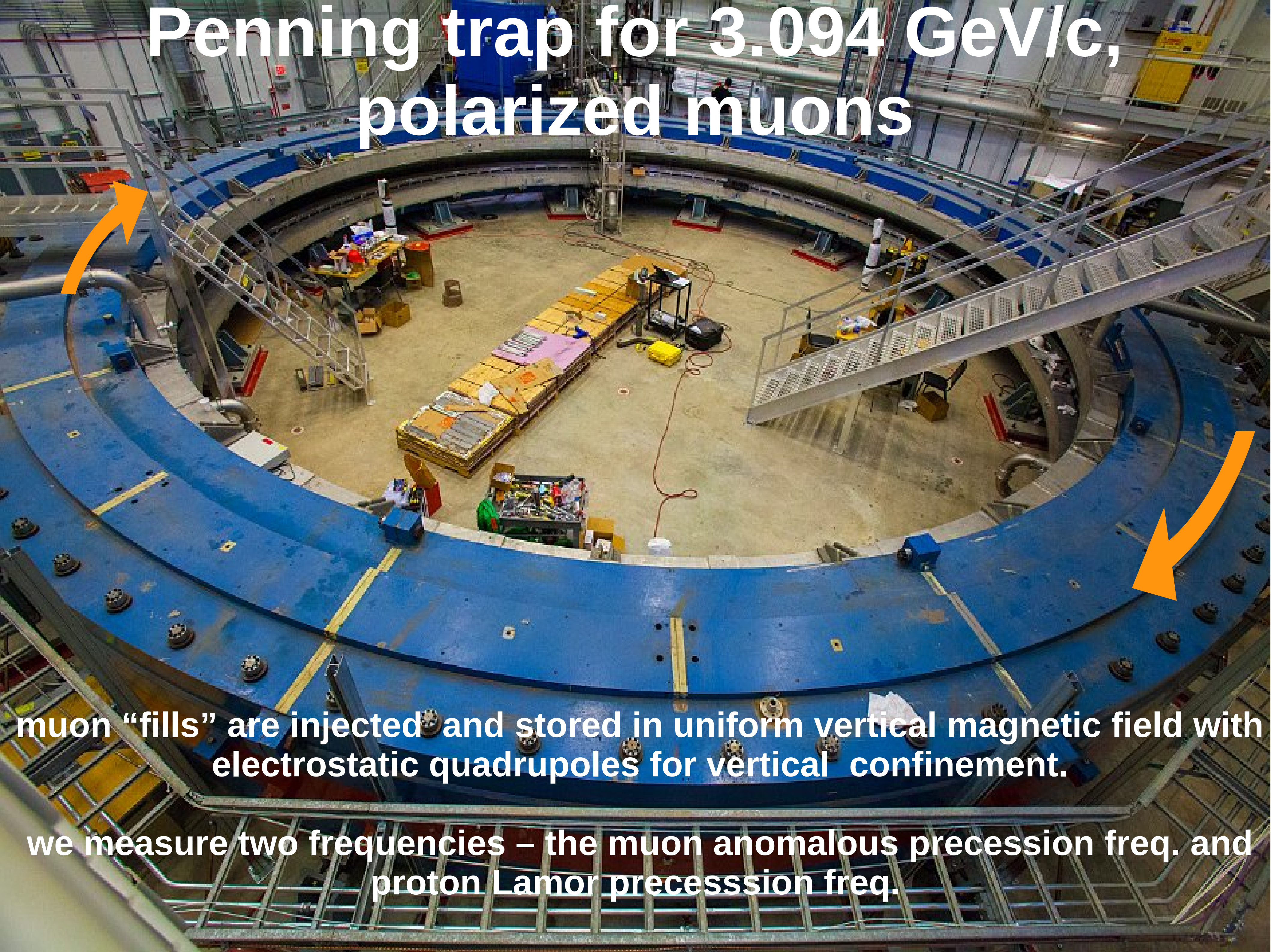
$\times 10^{-11}$



a_μ $\times 10^{-11}$

persistent,
tantalizing
discrepancy

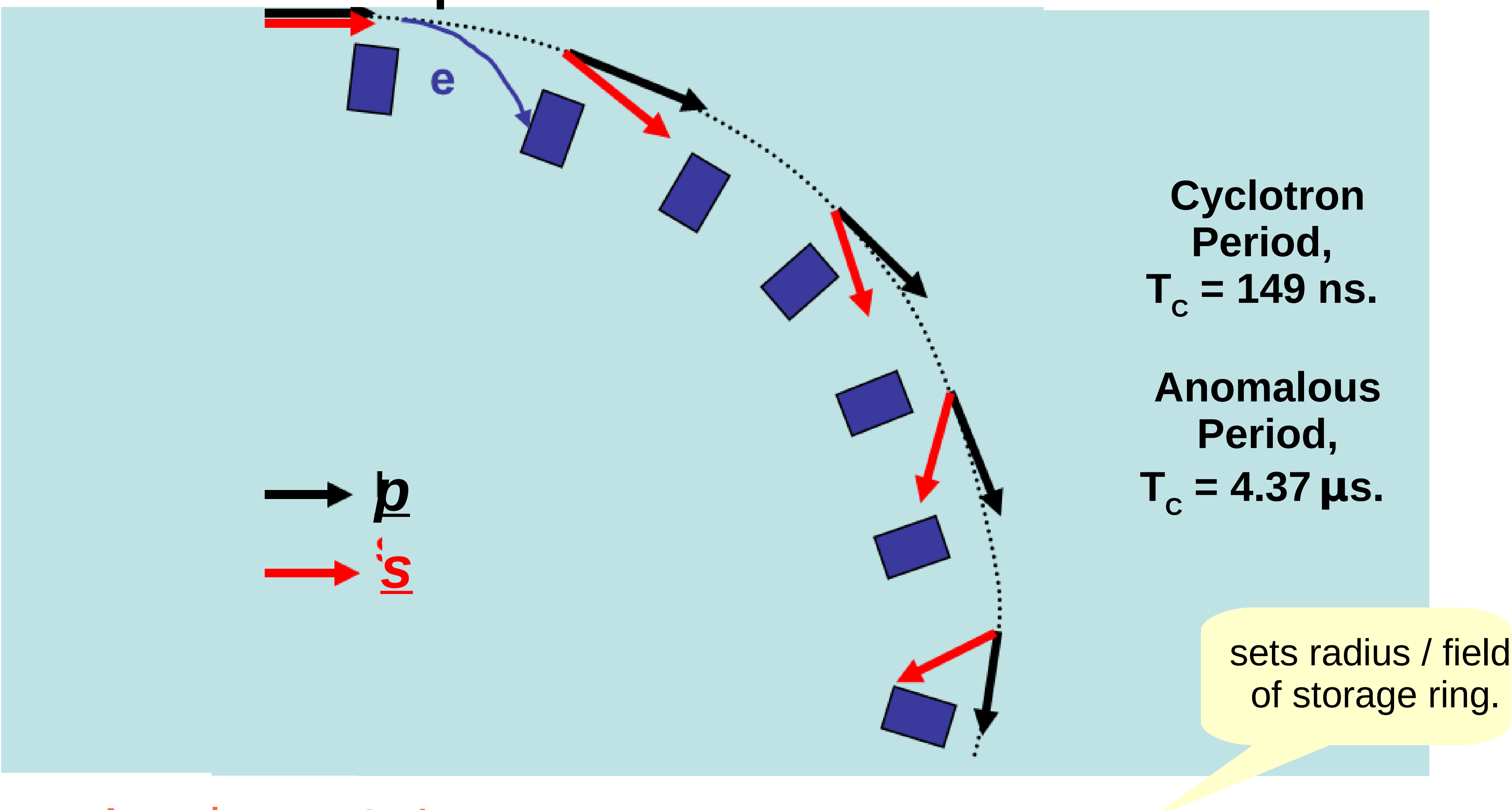
Penning trap for 3.094 GeV/c, polarized muons



muon “fills” are injected and stored in uniform vertical magnetic field with electrostatic quadrupoles for vertical confinement.

we measure two frequencies – the muon anomalous precession freq. and proton Lamor precesssion freq.

Penning trap for 3.094 GeV/c, polarized muons.



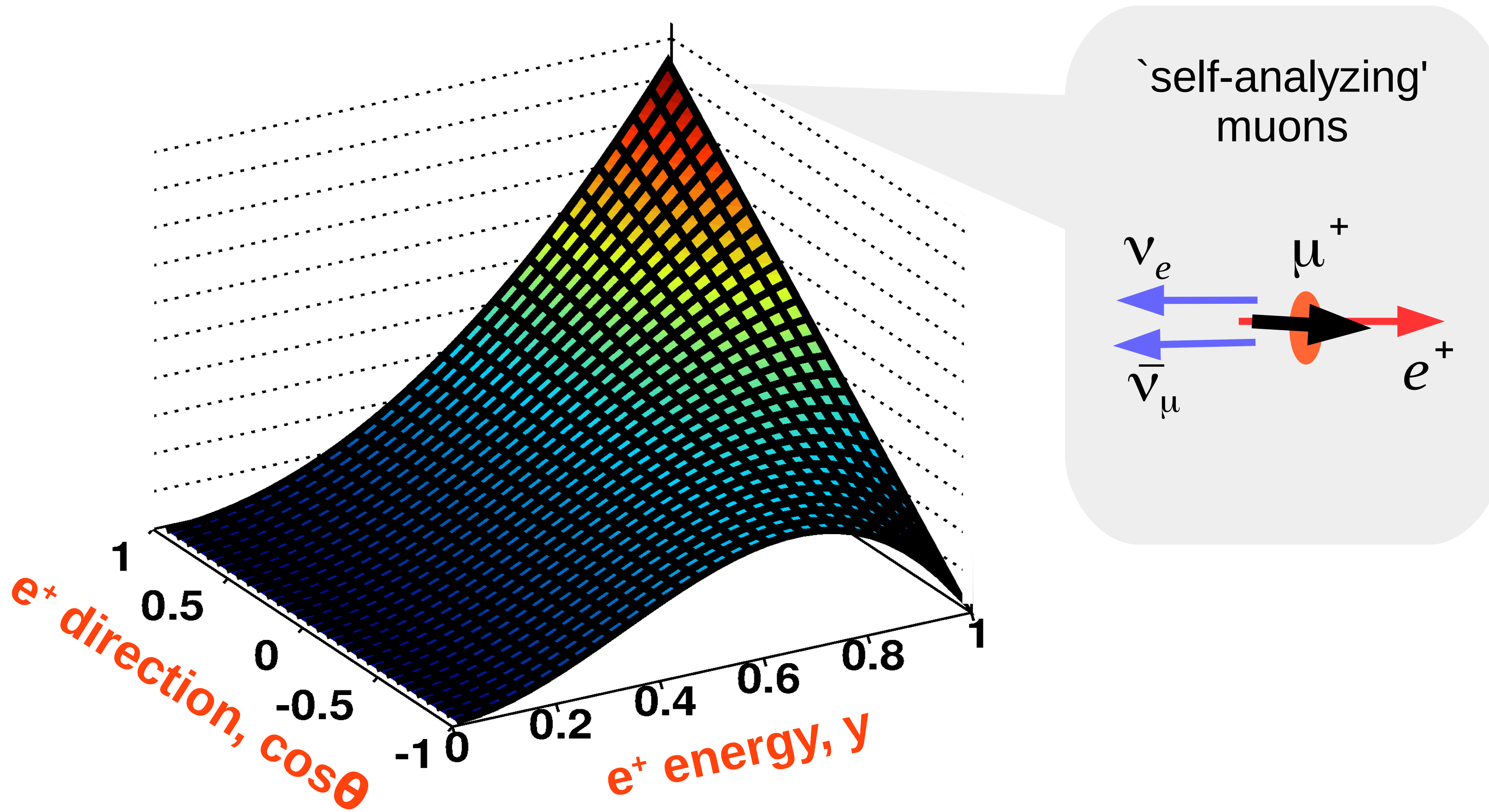
Anomalous freq. — Cyclotron freq. — Lamor freq.

γ = 29.3

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \, x \, \vec{E}}{c}\right]$$

~0

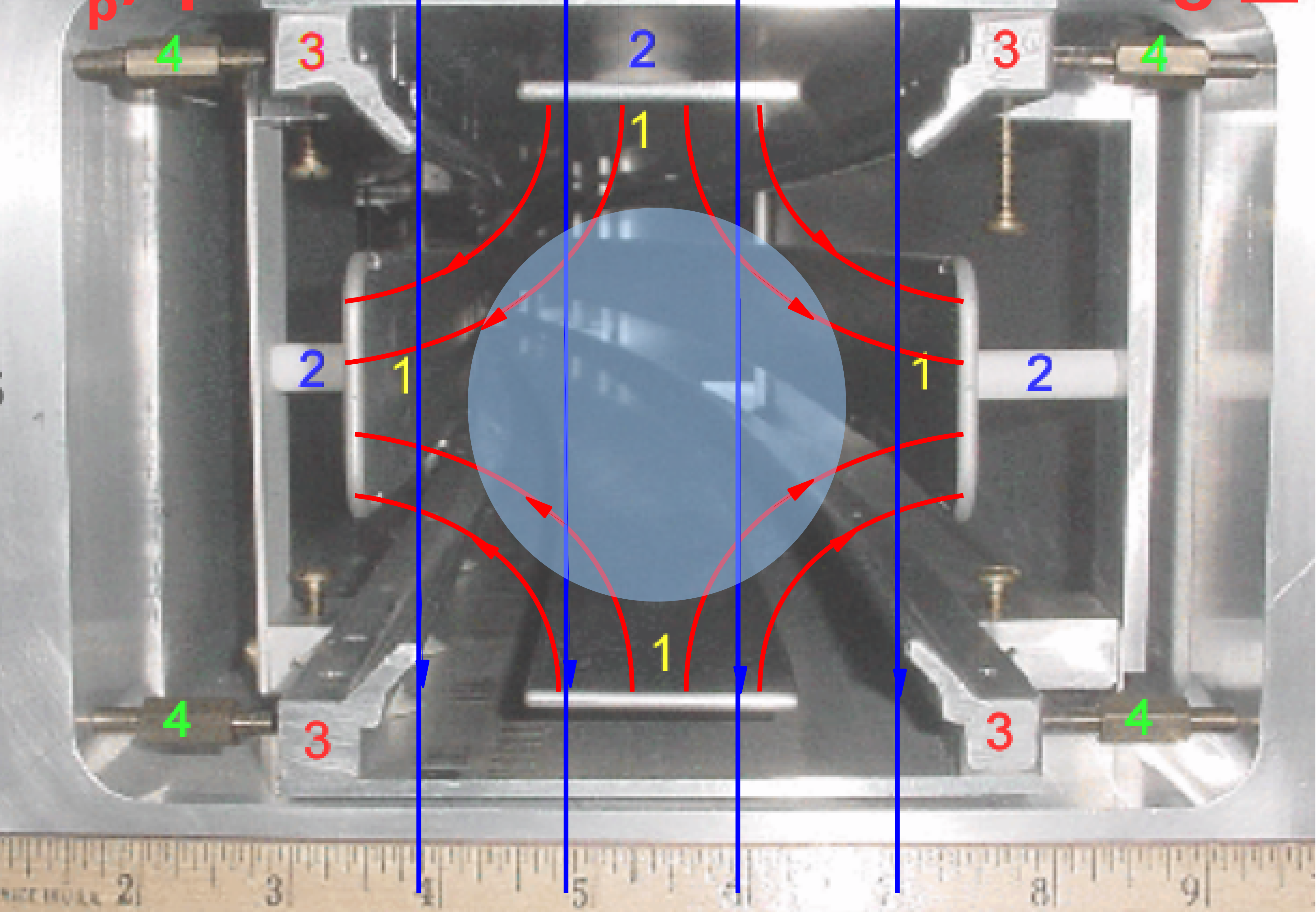
Self-analyzing muons, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$



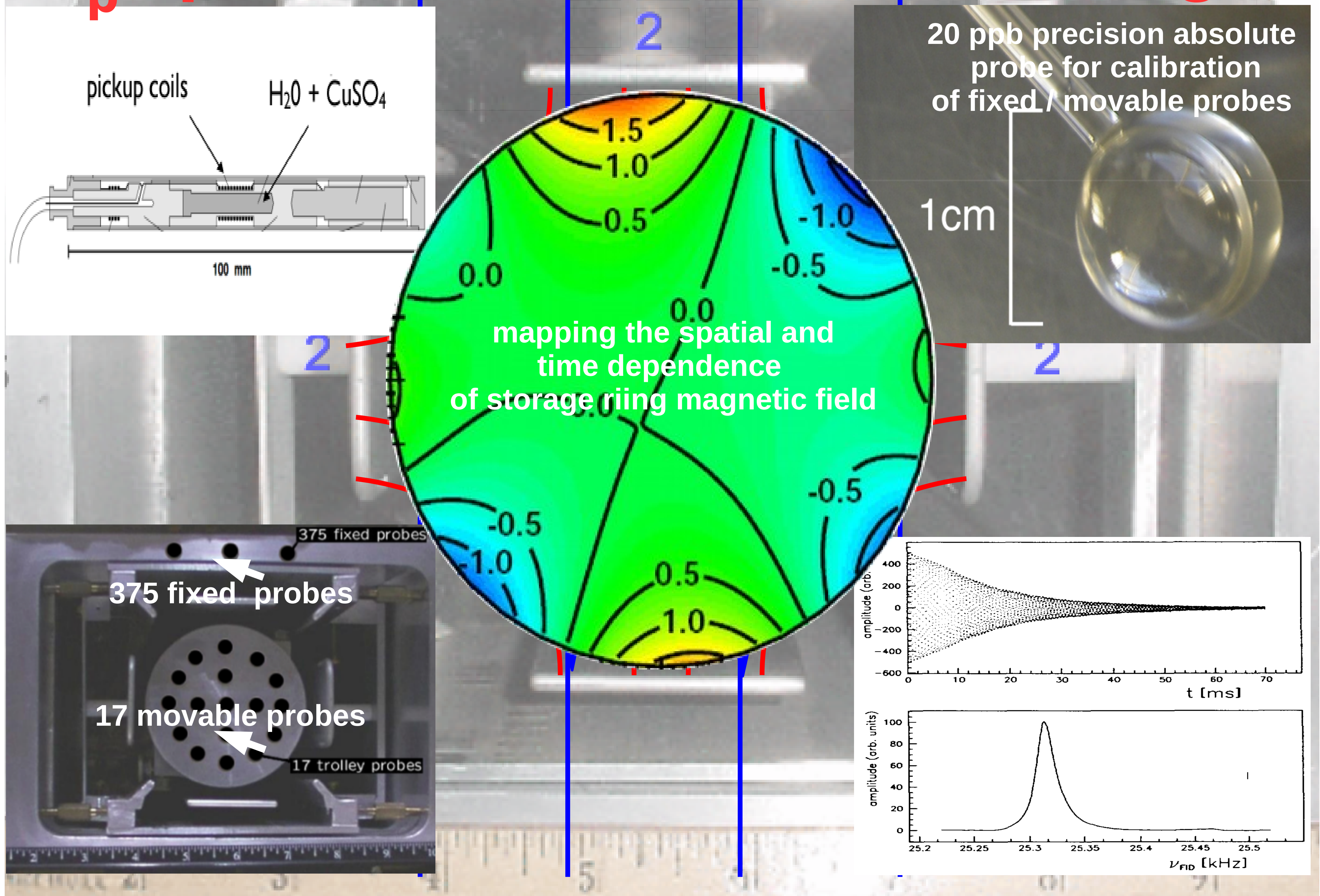
- relativistic boost from **μ** to lab frame yields higher energy positrons when emitted along **μ-orbit**

- relativistic boost from **μ** to lab frame yields lower energy positrons when emitted opposite **μ-orbit**

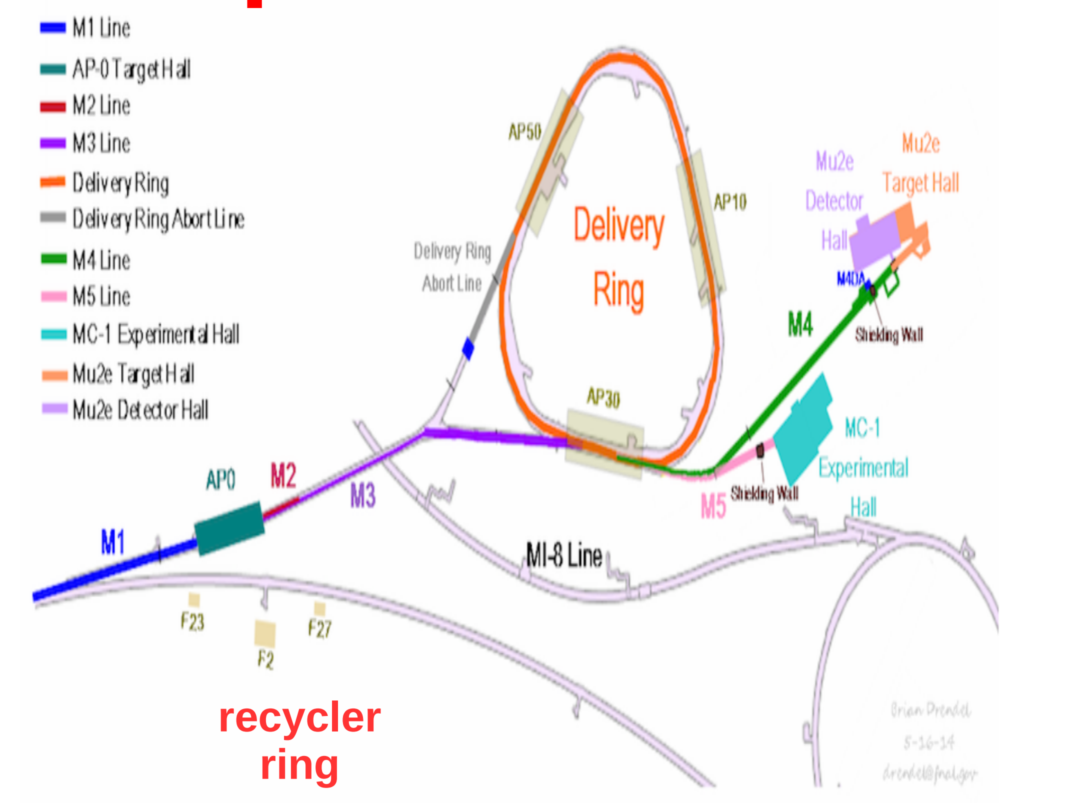
ω_p, proton NMR and measuring $\underline{B}$



ω_p, proton NMR and measuring B

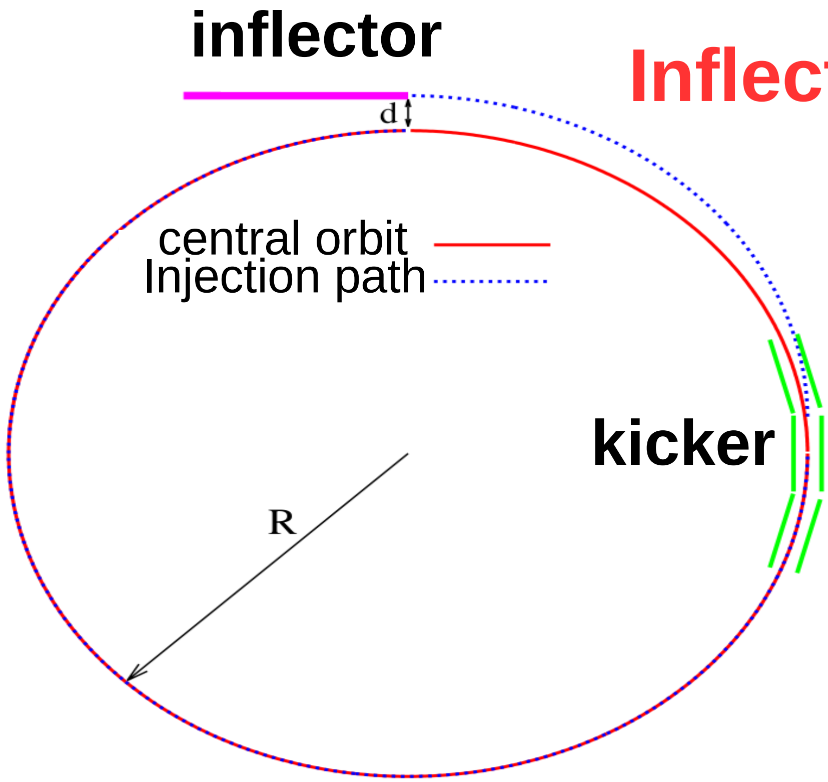


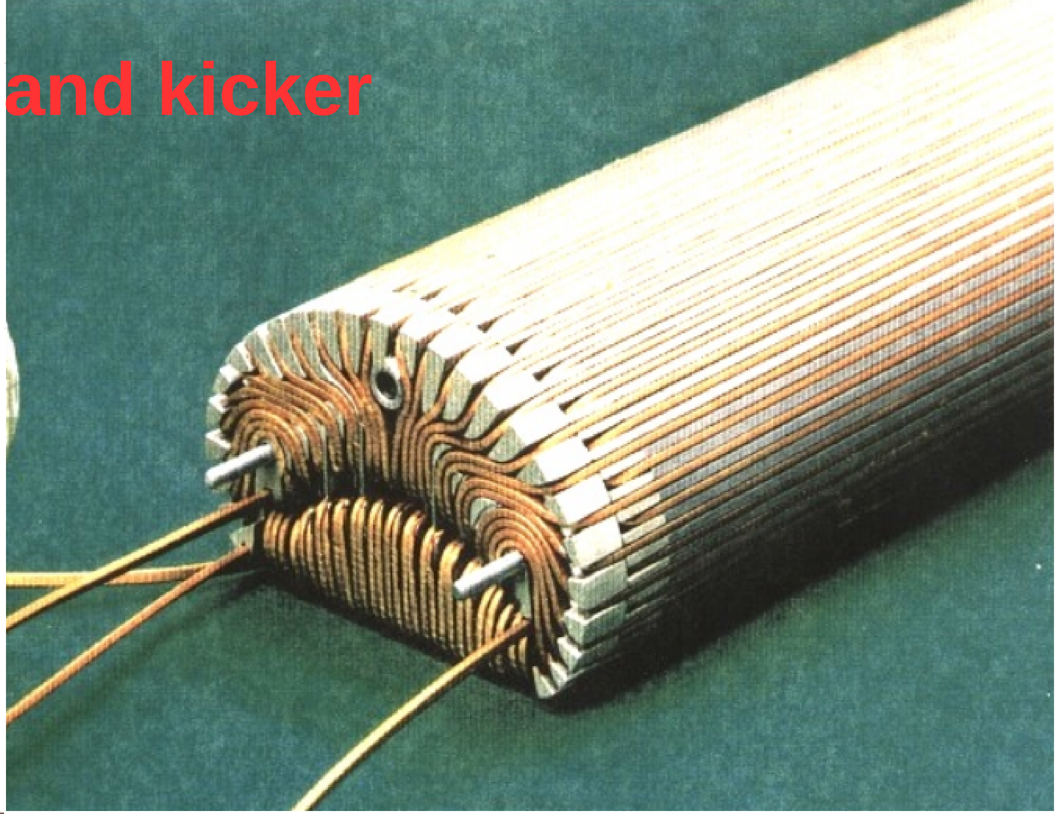
Muon Campus

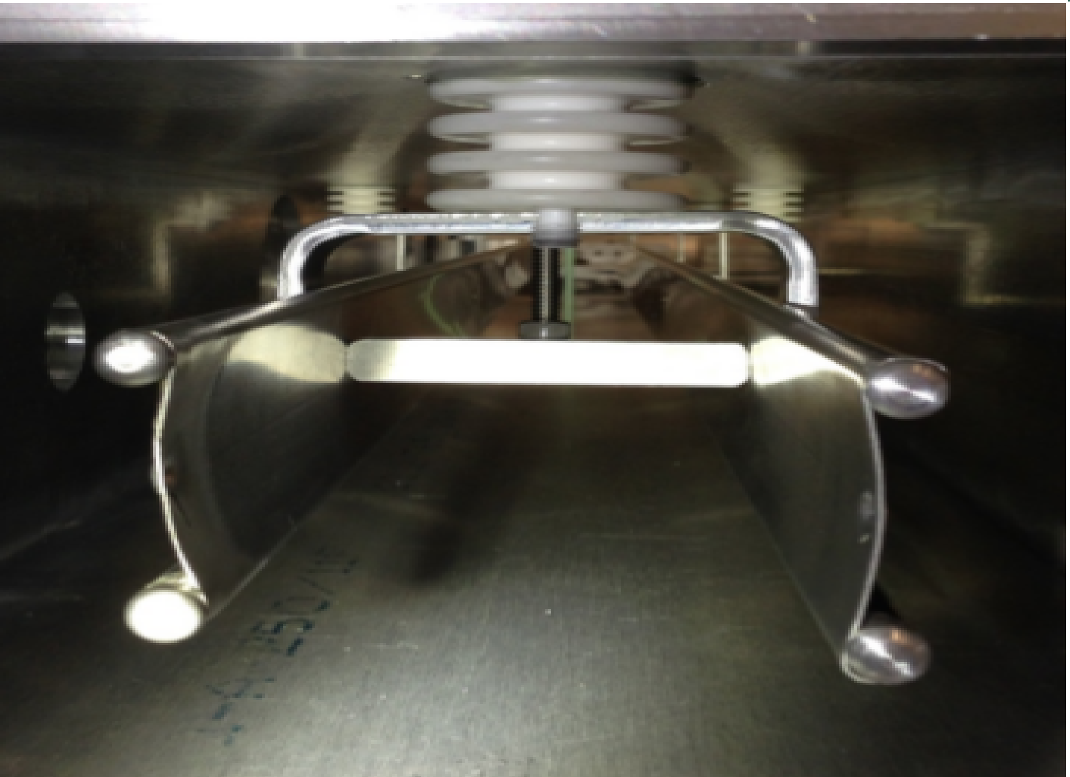


- **8 GeV protons to recycler ring for bunching**
- **extract bunches and strike the π-production target**
- **decay of π's to polarized μ's in decay line**
- **injection into delivery ring for μ, π, p separation**
- **muons extracted to g-2 storage ring**

Inflector and kicker





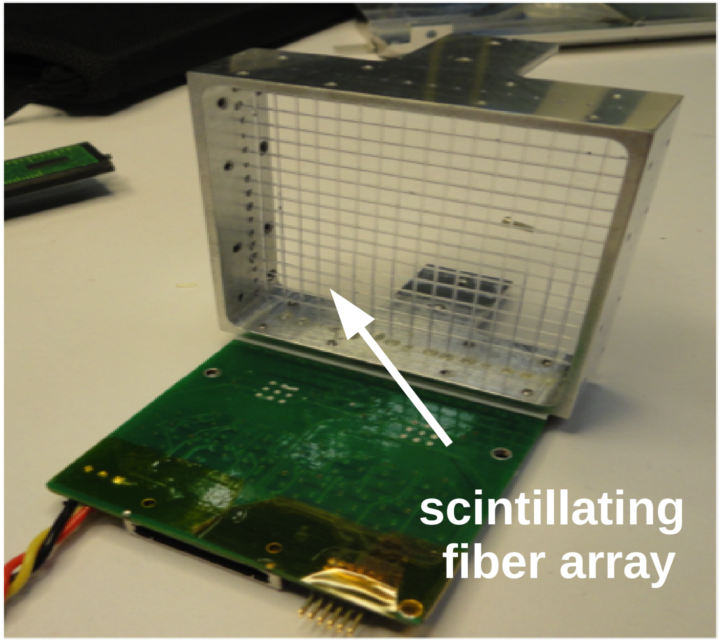


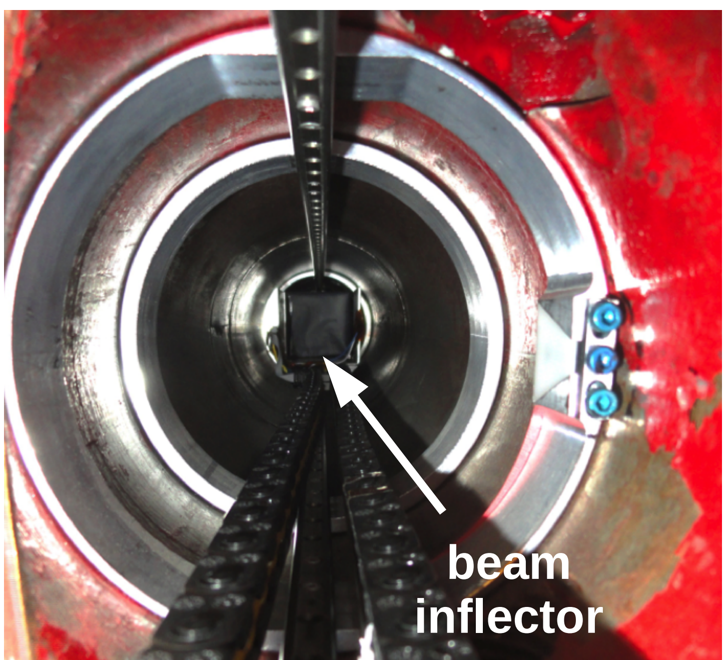
•**inflector null's storage ring 1.5T field in beamline entrance via superconducting double cosine theta coil.**

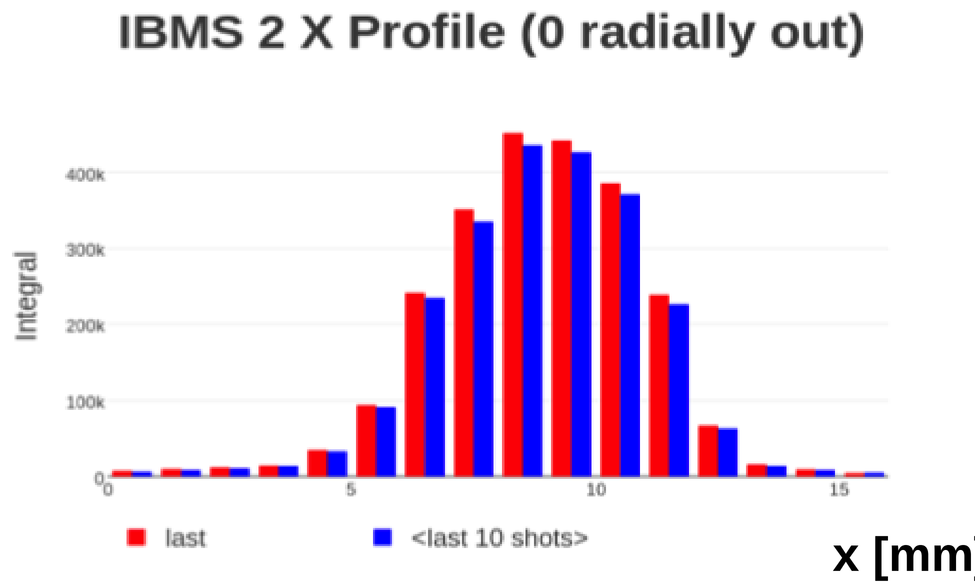
•**kicker displaces the injected beam by ~0.8 mrad to place on storage ring's ideal orbit.**

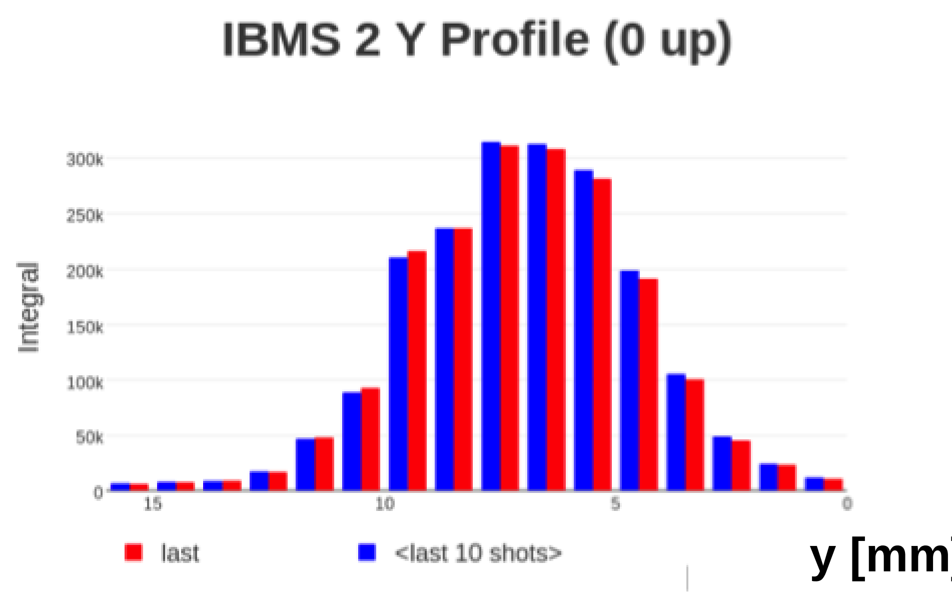
Scintillating fiber beam monitor – June 2017 commissioning run

measure beam focus at inflector



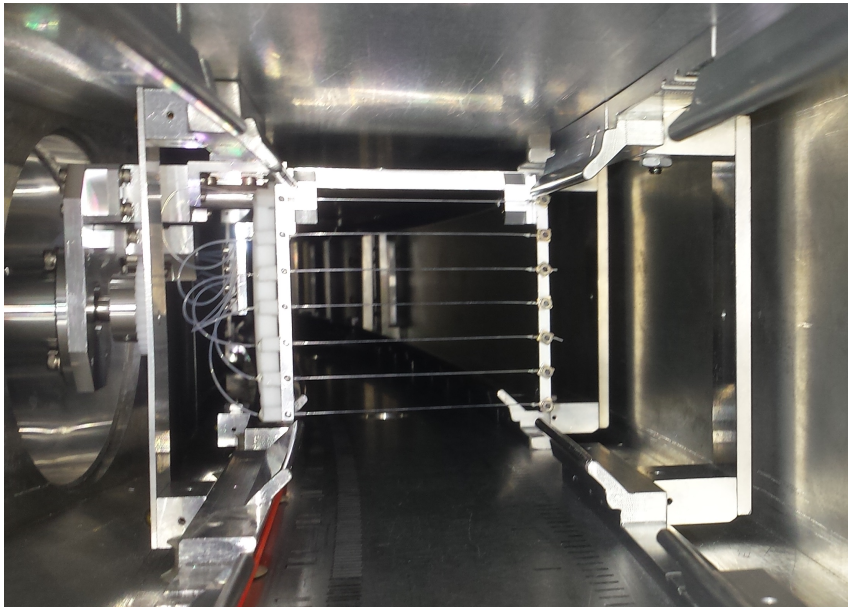


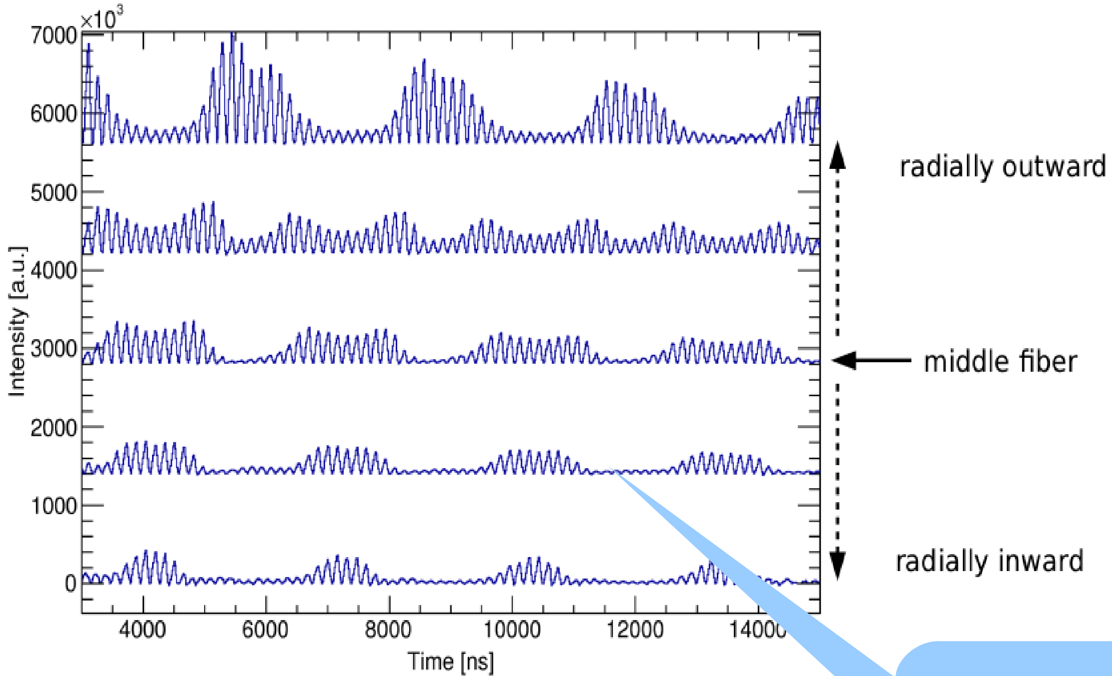




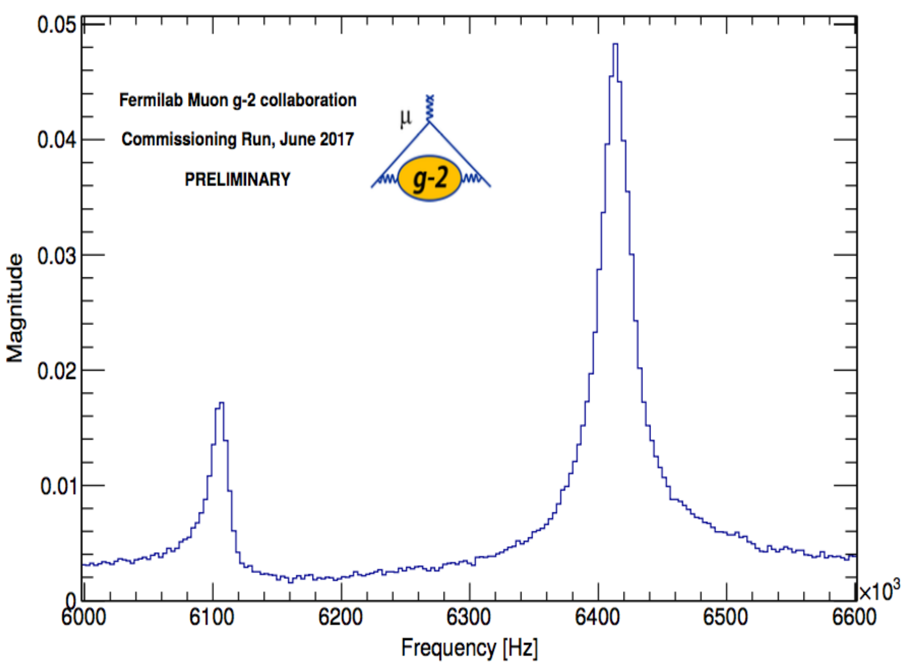
In-vacuum scintillating fiber arrays – June 2017 commissioning run

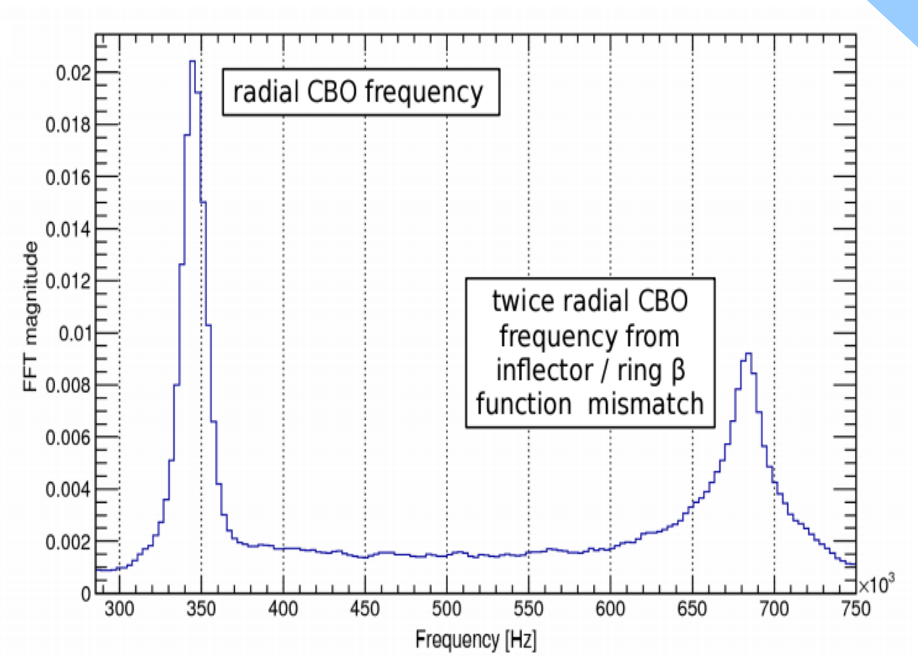
measure stored beam in ring



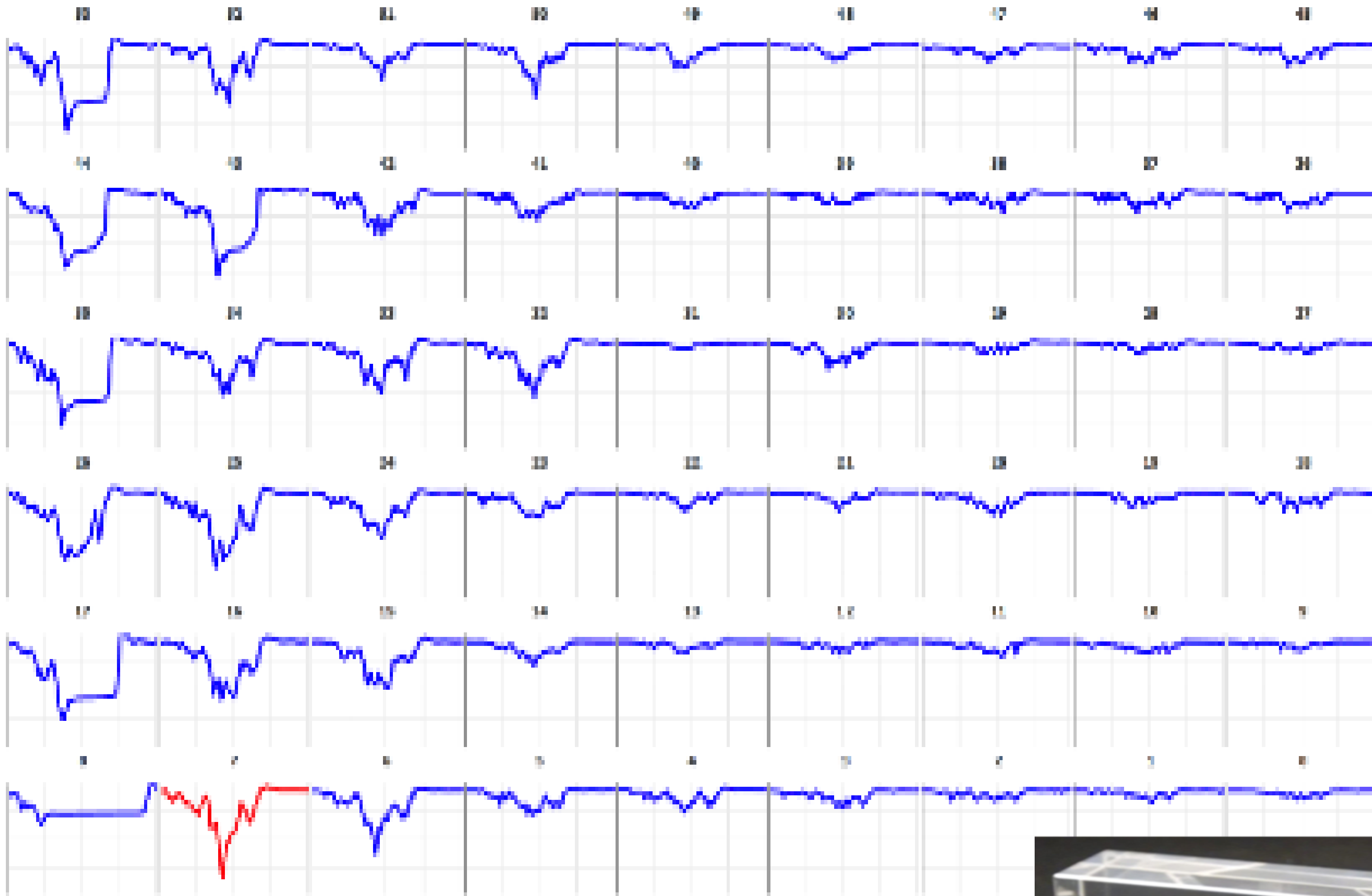


note ω_c, ω_{CBO}

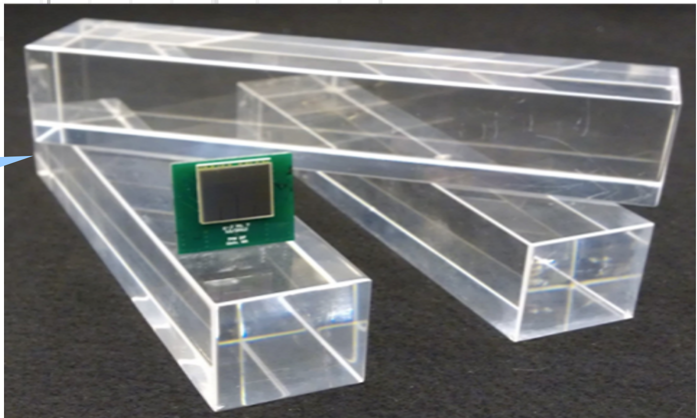




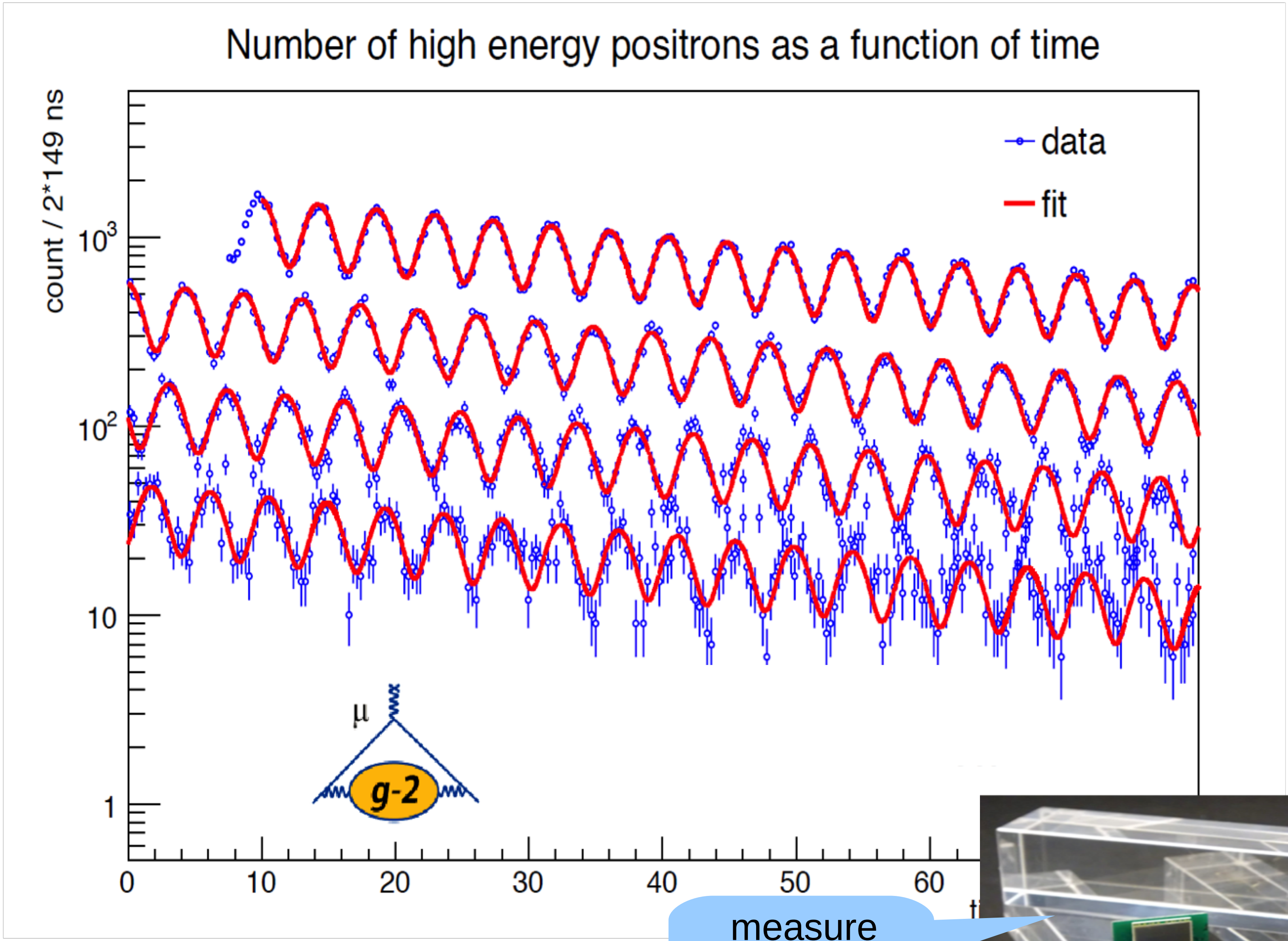
First fill – May 23, 2017 commissioning run

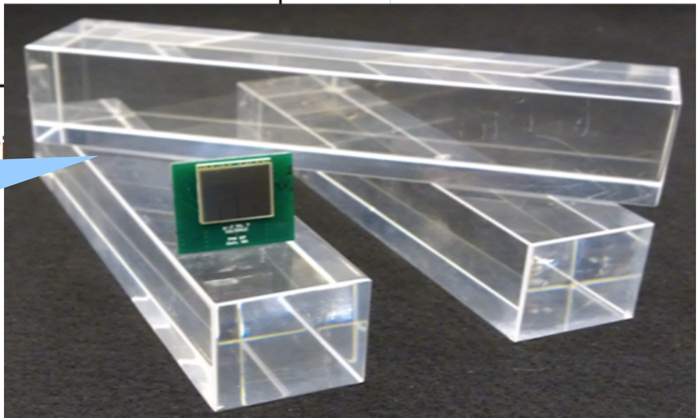


measure
decay positrons
and ω_a



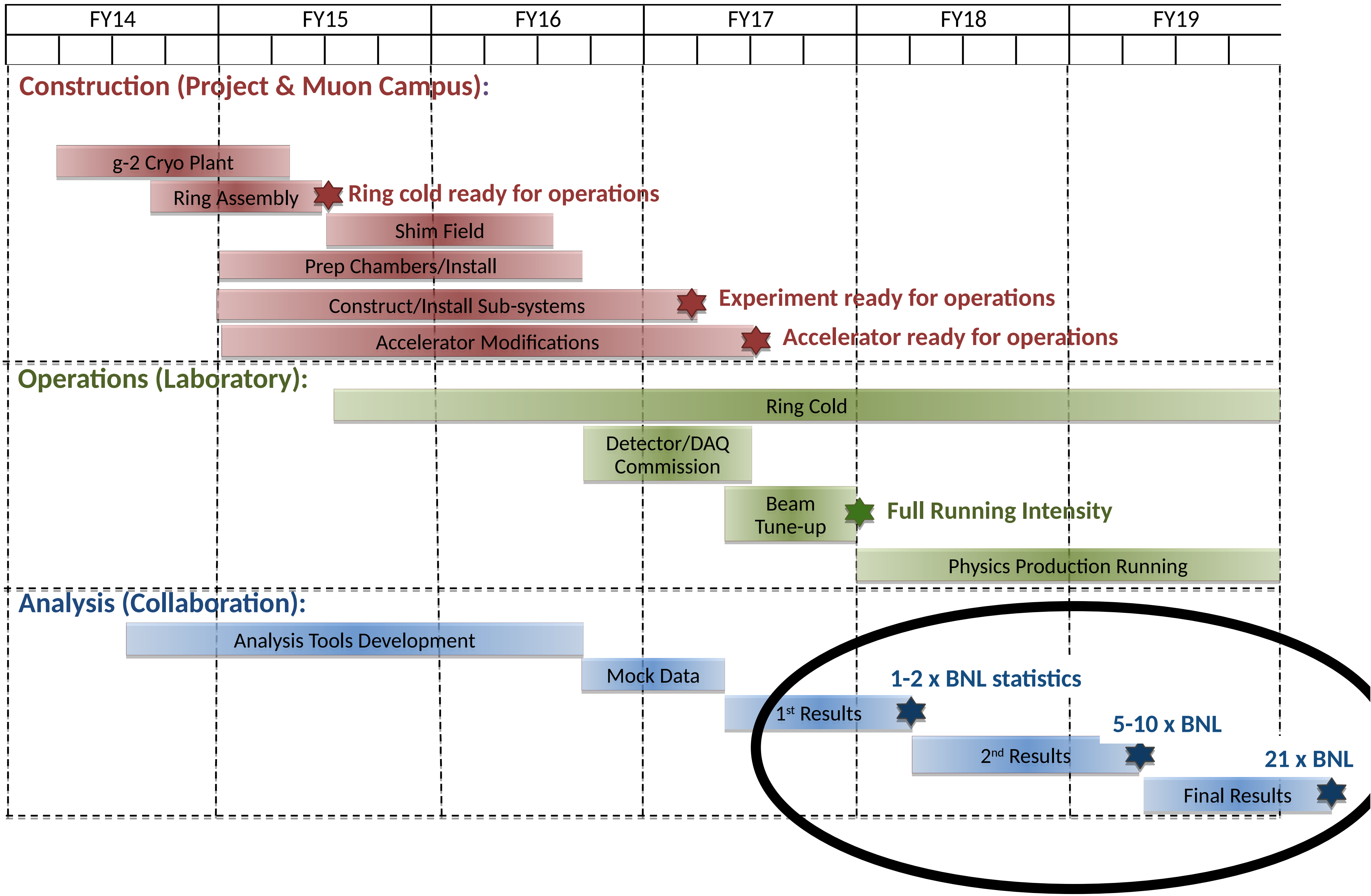
first wiggle plot – June 2017 commissioning run





measure decay positrons and ω_a

Schedule



FY14
FY15
FY16
FY17
FY18
FY19
Construction (Project & Muon Campus):
g-2 Cryo Plant
Ring Assembly
Ring cold ready for operations
Shim Field
Prep Chambers/Install
Construct/Install Sub-systems
Experiment ready for operations
Accelerator Modifications
Accelerator ready for operations
Operations (Laboratory):
Ring Cold
Detector/DAQ Commission
Beam Tune-up
Full Running Intensity
Physics Production Running
Analysis (Collaboration):
Analysis Tools Development
Mock Data
1-2 x BNL statistics
1st Results
5-10 x BNL
2nd Results
21 x BNL
Final Results