NuFact 2018 - August 12-18

WG4
Muon Physics Summary

Craig Group, MyeongJae Lee, and Frederik Wauters

Why muons at NuFact?

- Same production mechanism for muons and neutrinos.
- A neutrino factory is also a muon factory and vice versa.
- Muon experiments are complementary to each other and to searches at the Energy Frontier.
- Excellent probe for physics beyond the standard model.

So much to cover in WG4!

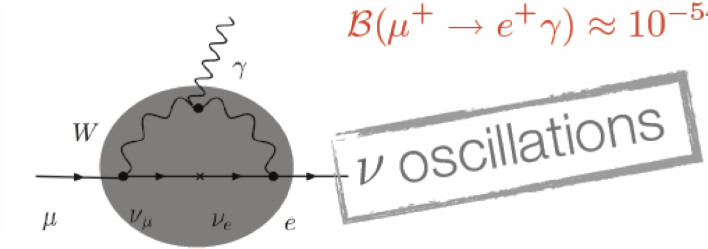
I will attempt to:

- Cover 25 talks
- Cover 18 different experiments
- Summarize the view of all group members
- Many topics:
  - CLFV (muons,colliders)
  - g-2
  - Proton radius puzzle
  - ...

CLFV evidence: A clear signature of New Physics

SM with massive neutrinos (Dirac)

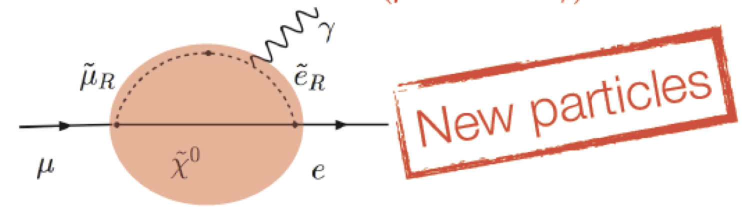
$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) \approx 10^{-54}$



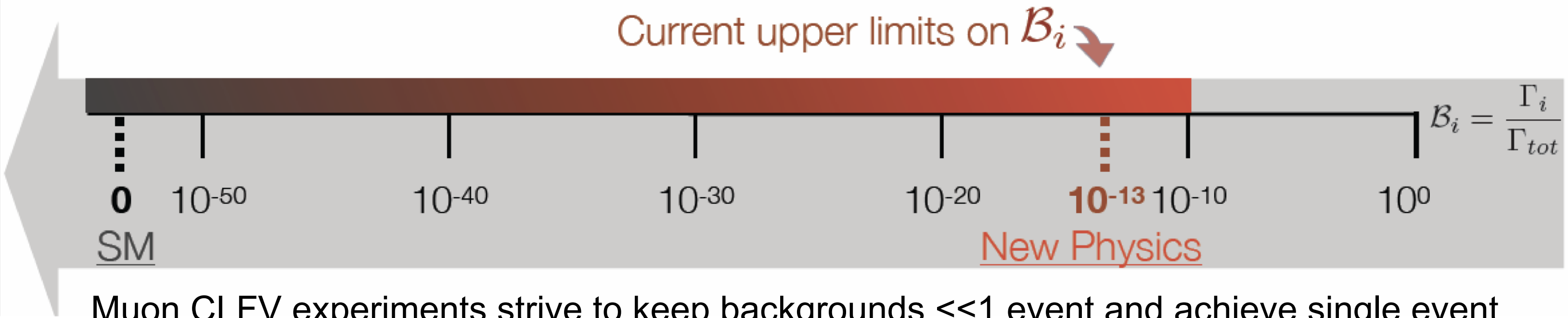
too small to access experimentally

BSM

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



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



Muon CLFV experiments strive to keep backgrounds <<1 event and achieve single event sensitivity.

Angela Papa

Pulsed v/s DC Muon Beams

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

DC or Pulsed?

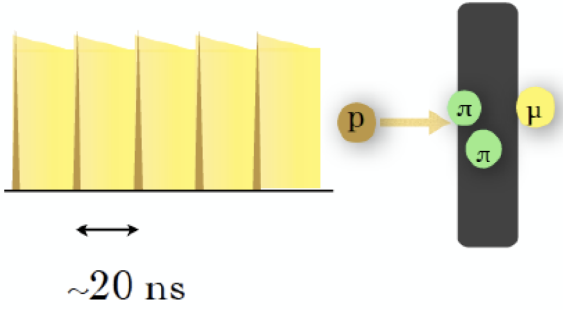
$I_{beam} \sim 10^{8} - 10^{10}\ \mu/s$

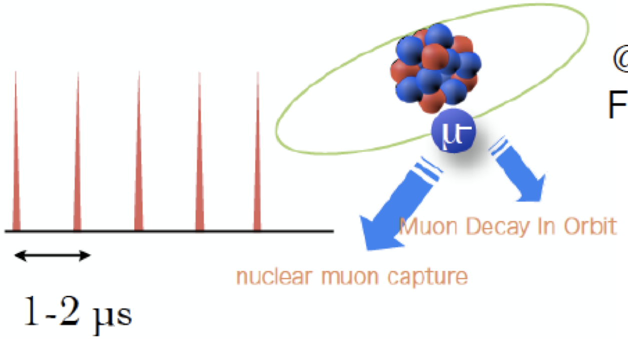
- DC beam for coincidence experiments
  - $\mu \rightarrow e\gamma$, $\mu \rightarrow e\ e\ e$

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

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

@ PSI



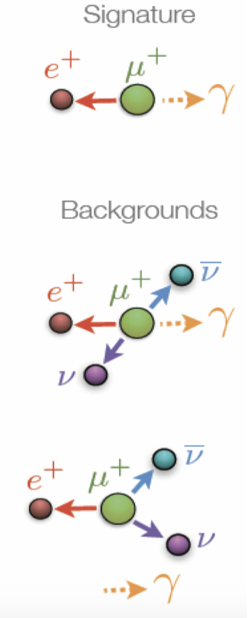


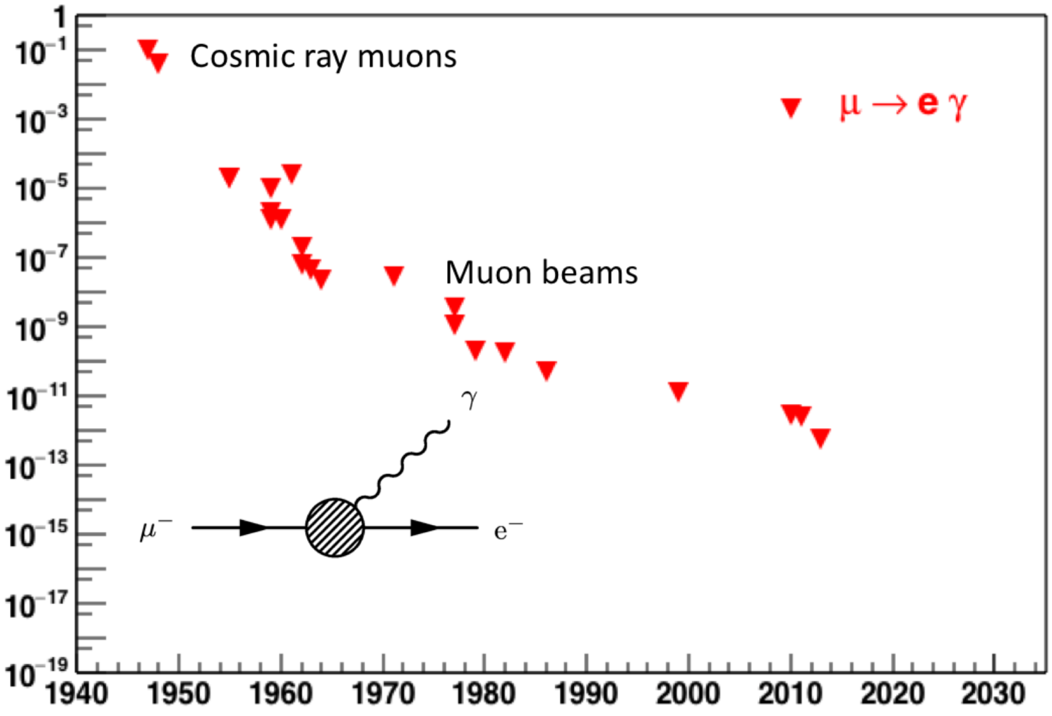
@ JPARC, FERMILAB

Angela Papa

History of CLFV Searches:

- Fully reconstruct electron and photon.
- DC beam helps control combinatorial bkg.
- Current best limit from MEG at PSI.
  → $Br<4.2 \times 10^{-13}$ MEG at PSI

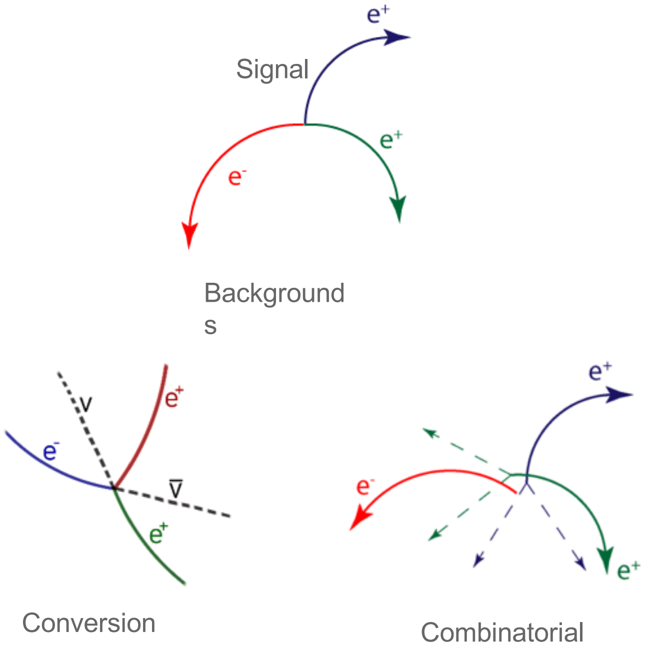


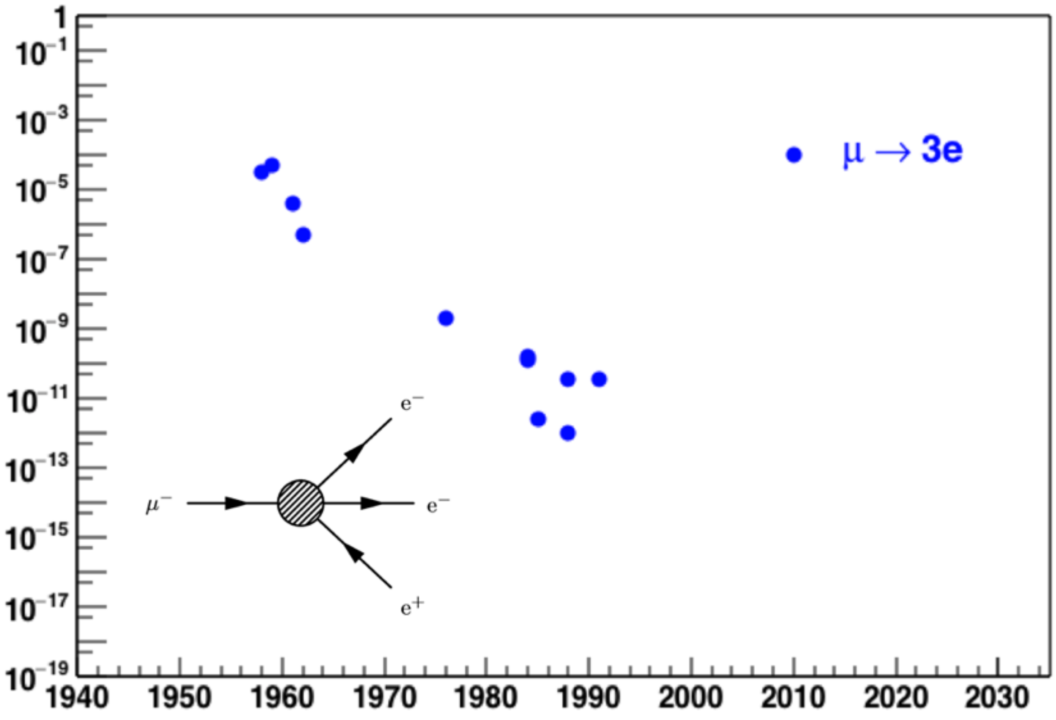


MEGA, MEG (PSI), and oth

History of CLFV Searches:

- Track all three electrons.
- DC beam helps control combinatorial bkg
- Current best limit 20 years old!

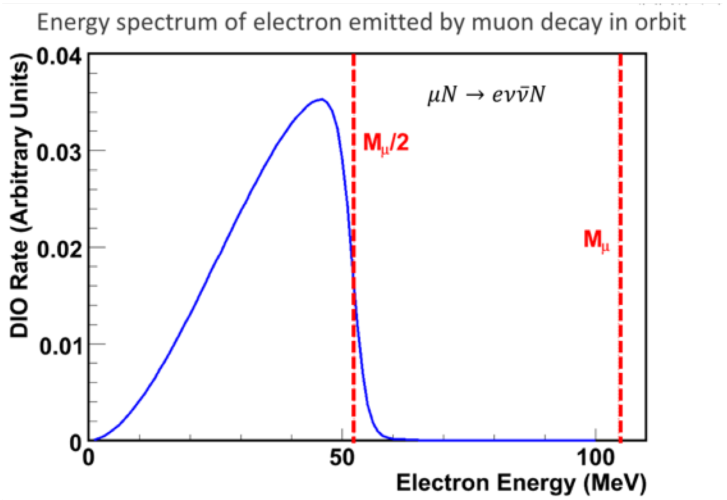


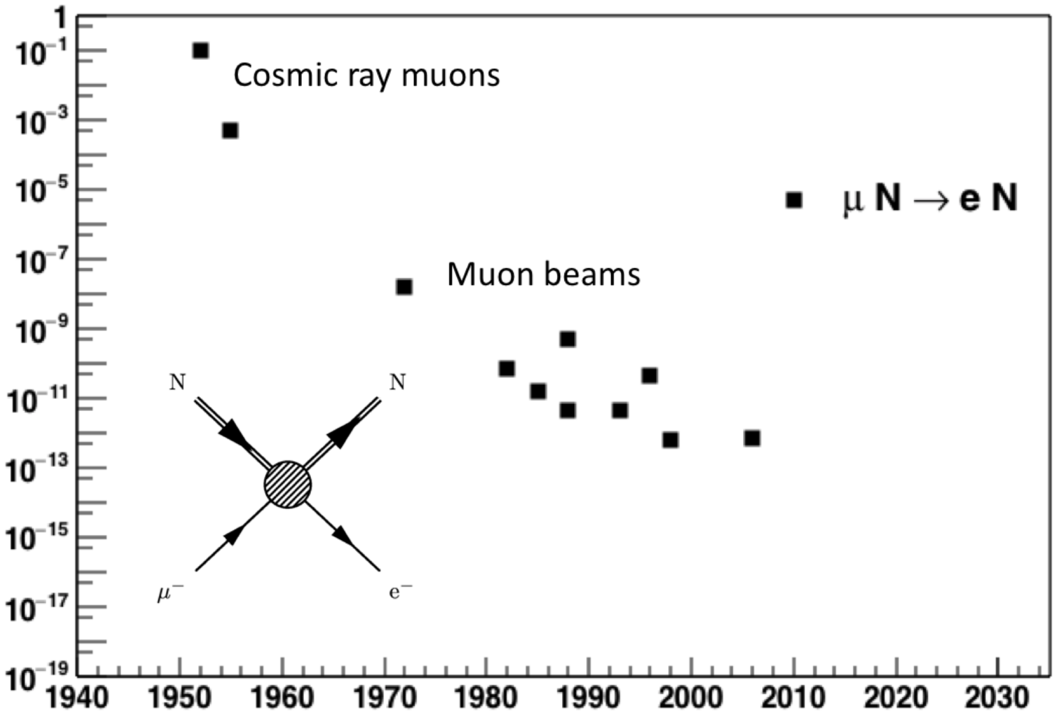


Mu3e, PSI

History of CLFV Searches:

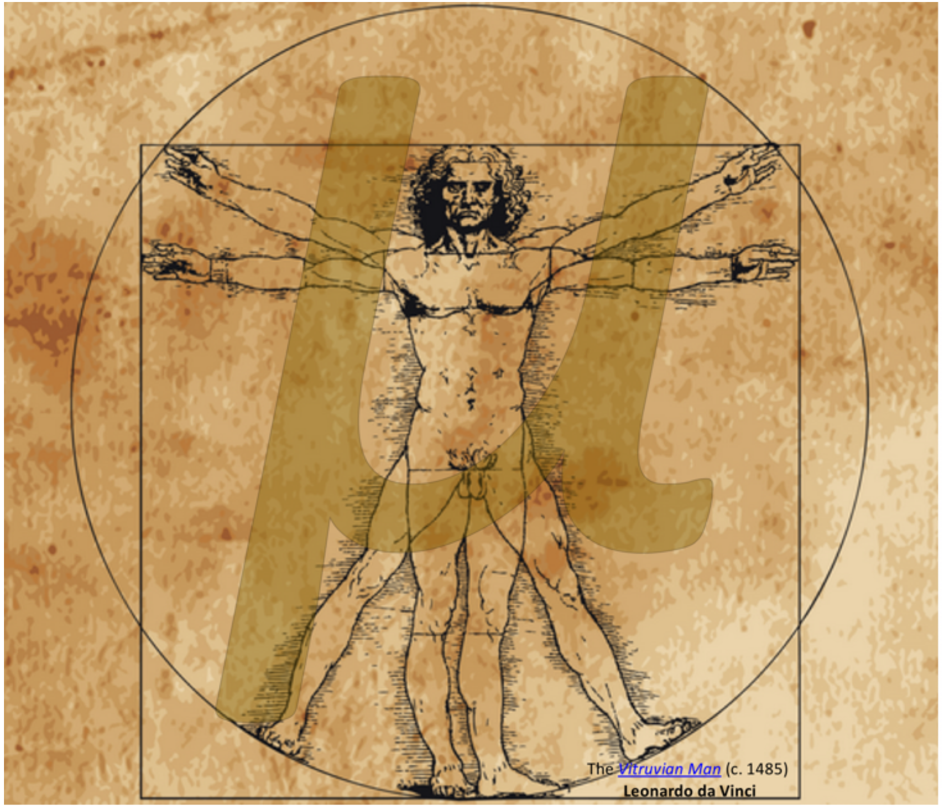
- Monoenergetic electron ~mass of muon.
- Pulsed beam controls prompt bkg
- Signal delayed by muon lifetime.
- Current best limit from SUNDRUM-II at PSI. → $7x10^{-13}$

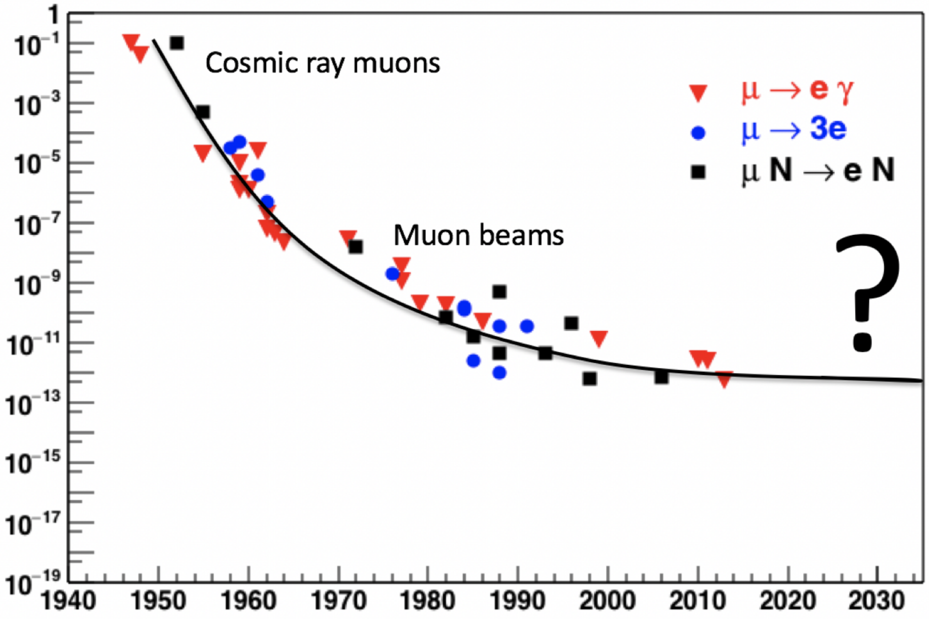




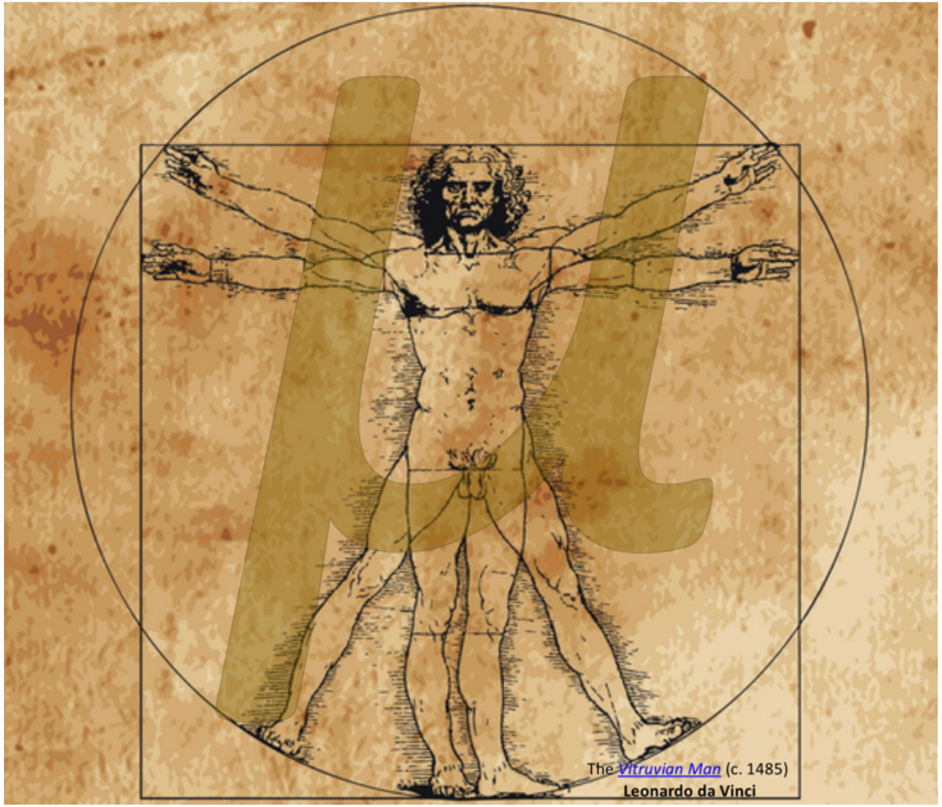
Mu2e, SINDRUM II, COMET, DeeMe,

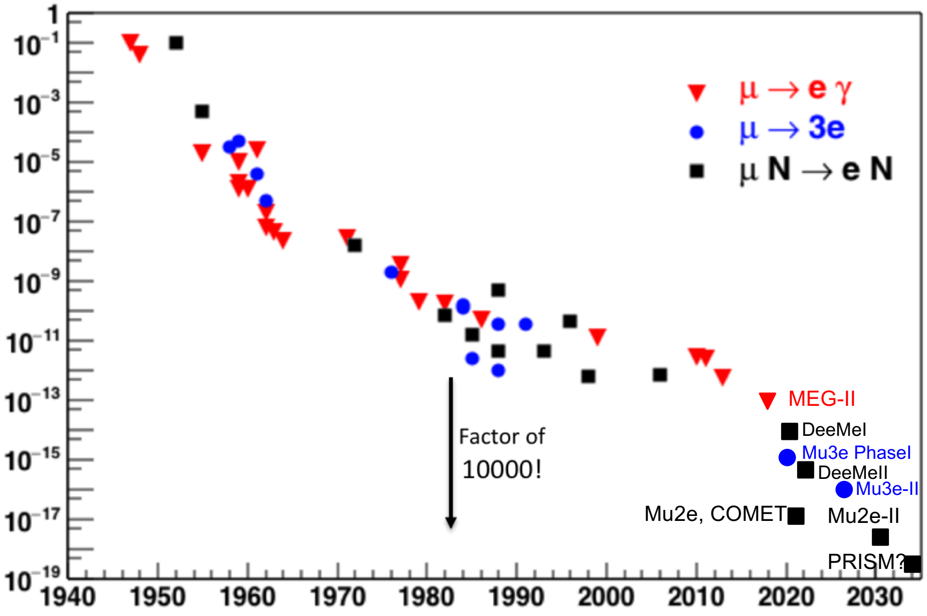
A Renaissance for Muon Physics?





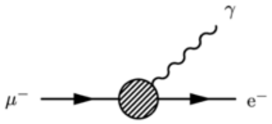
A Renaissance for Muon Physics?

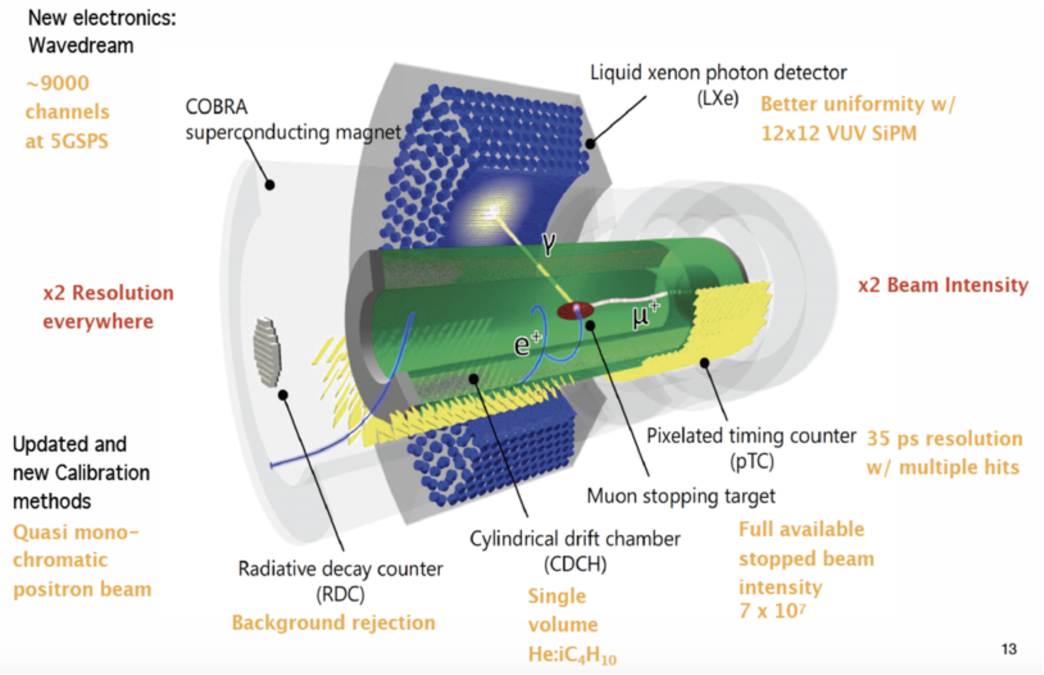


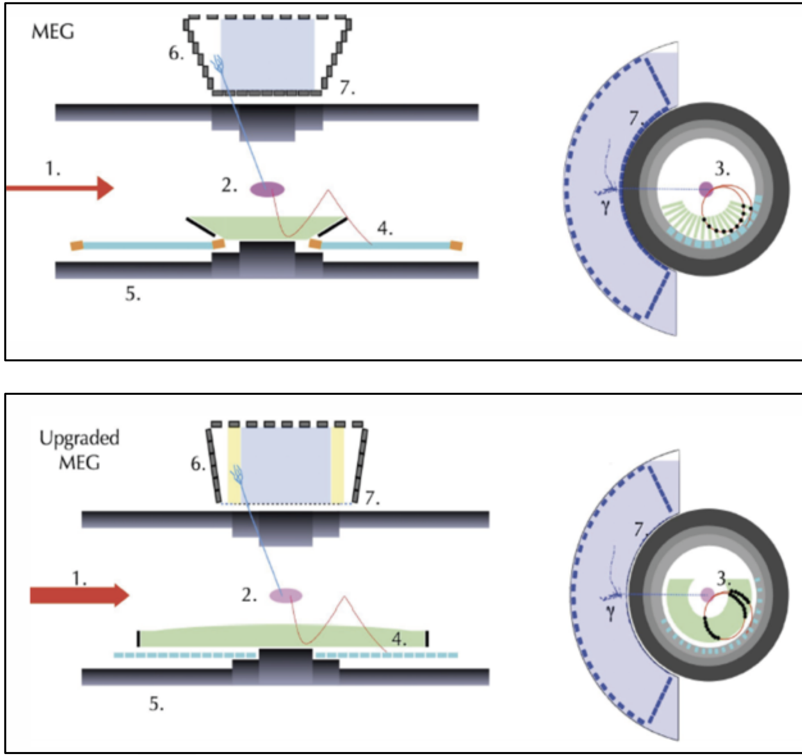


We heard updates on all of these muon CLFV experiments.

The MEG-II Experiment

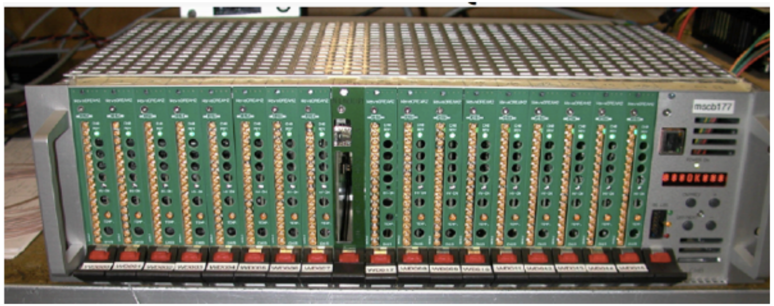




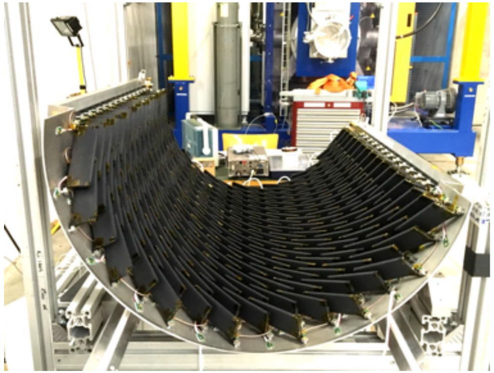


Angela Papa

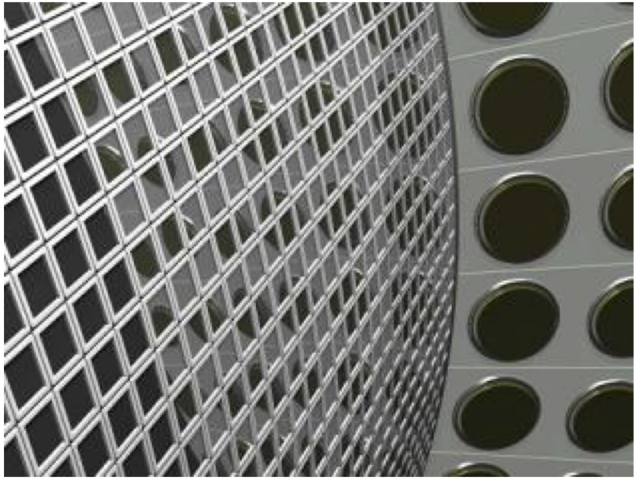
MEG-II Status



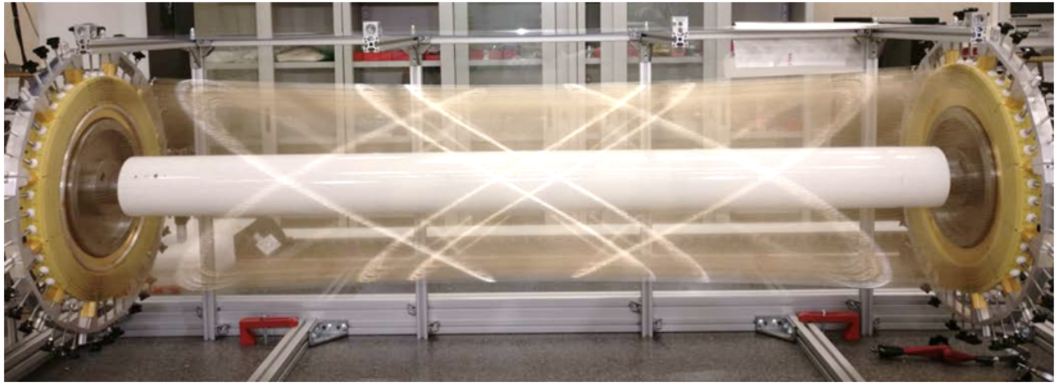
Improved electronics design ready and used in test-beam runs.



Pixel timing counters fully assembled and commissioned.

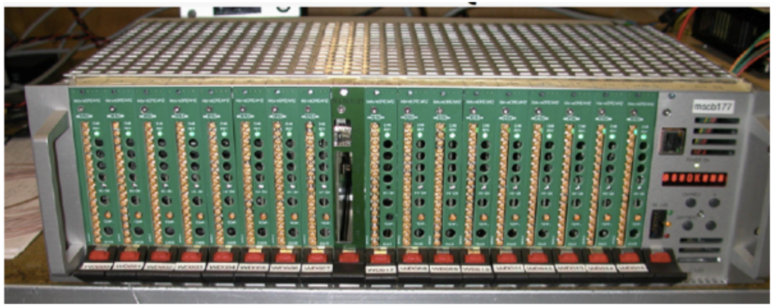


New LXe assembled and filled - commissioning ongoing.



Assembly of new single-volume chamber is complete.

MEG-II Status



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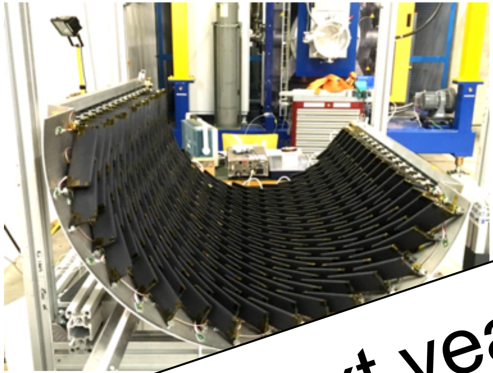
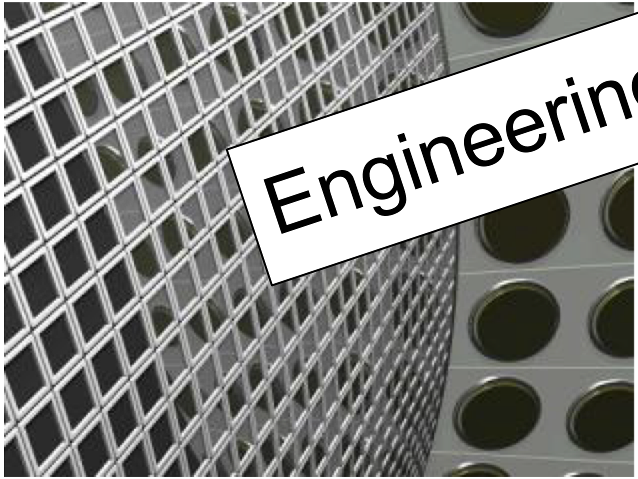


Pixel ti... and commissioned.

Engineering run should start next year!



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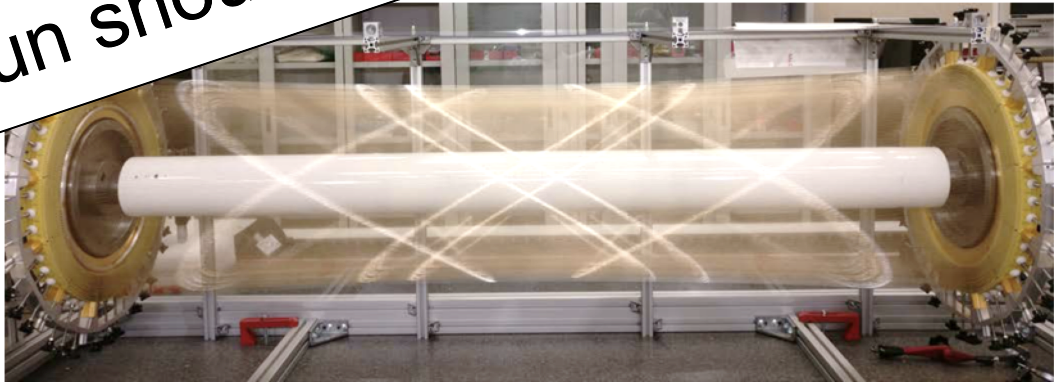

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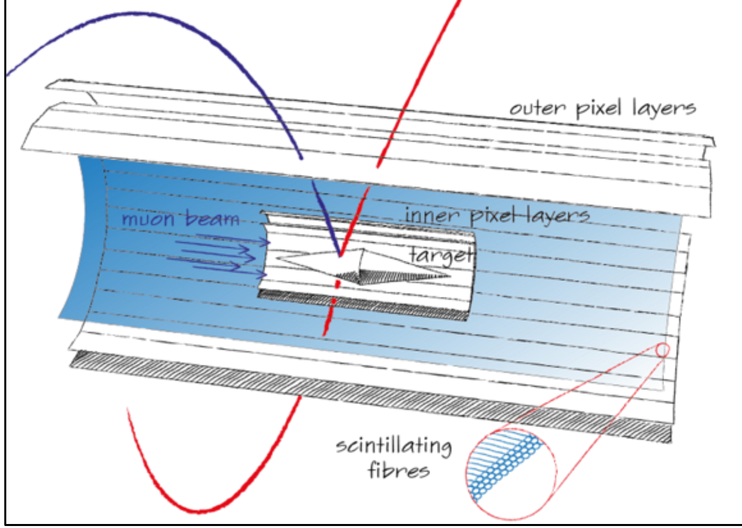
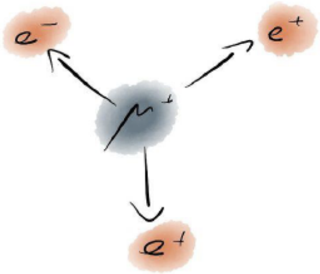
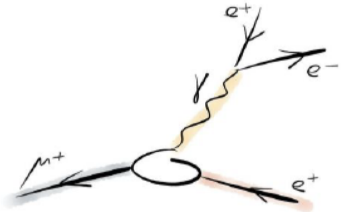
The Mu3e Experiment

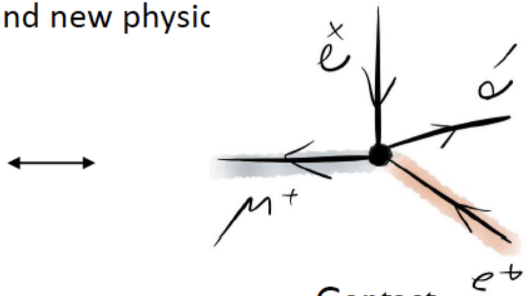




- Standard Model branching ratio $5 \cdot 10^{-55}$
- Mu3e aims for a single event sensitivity
  of $1 \cdot 10^{-16}$ (Phase II)
  of $2 \cdot 10^{-15}$ (Phase I = this talk)
  → Search for new physics
  → Previous limit $1 \cdot 10^{-12}$ (SINDRUM, 1988)
- Complementary to $\mu \to e\gamma$ and $\mu N \to e$ in technique and new physic

- 2 x double layer of Si pixel detectors
- Each layer is < 0.1 % of a radiation length
- Scintillating fiber and tile layers provide excellent timing:
  - 350 ps < 500 ps (fibres)
  - 70 ps < 100 ps (tiles)


Loop

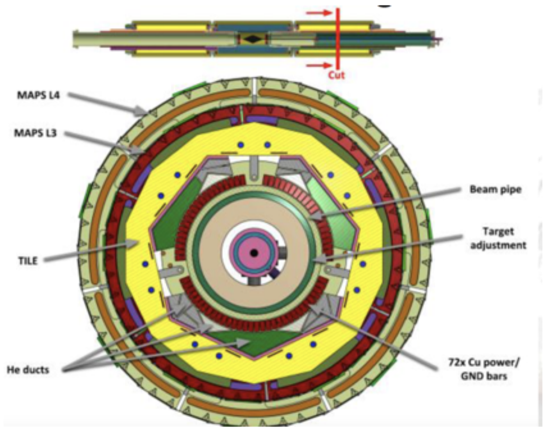


Contact

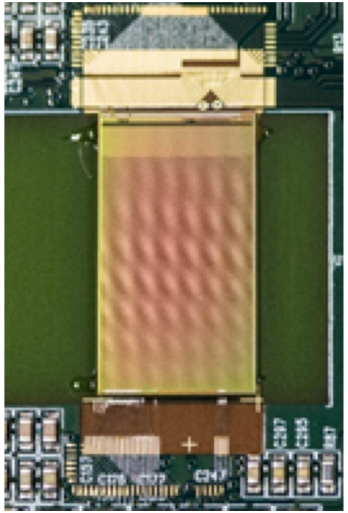
Frederik Wauters

Mu3e Status

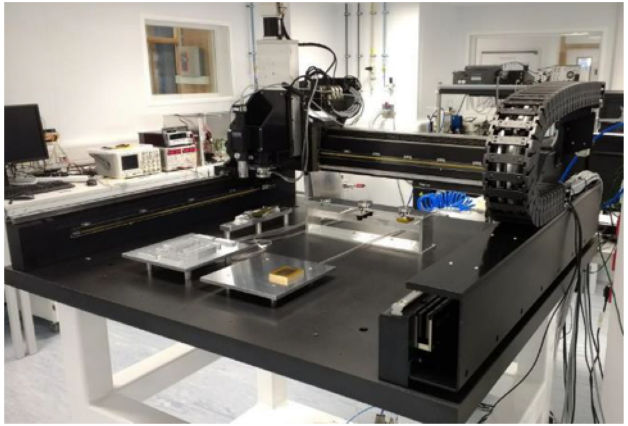
- Area/services at PSI under construction.
- Working toward vertical slice test.
- Magnet coming <1 yr.



Mechanical design is complete.



Finalizing the R&D for the HV-MAPS
High Voltage Monolithic Active Pixel Sensors



Detector production tools are underway...

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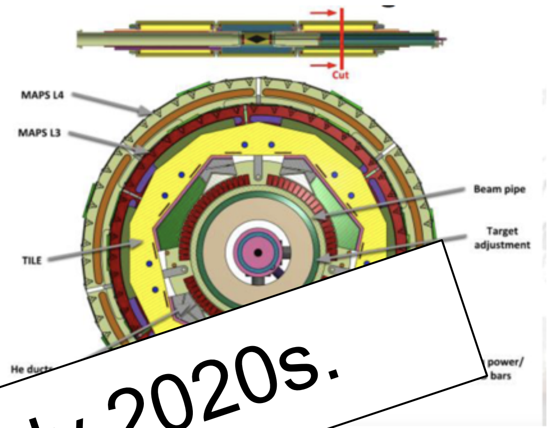
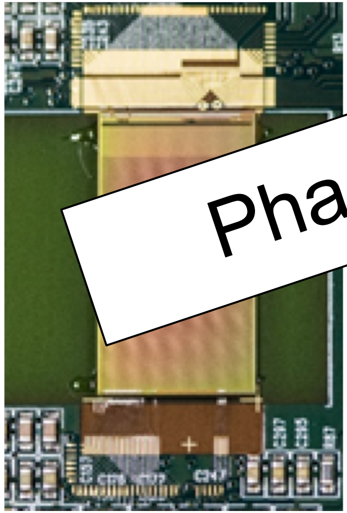


design is complete.

Phase I coming in early 2020s.



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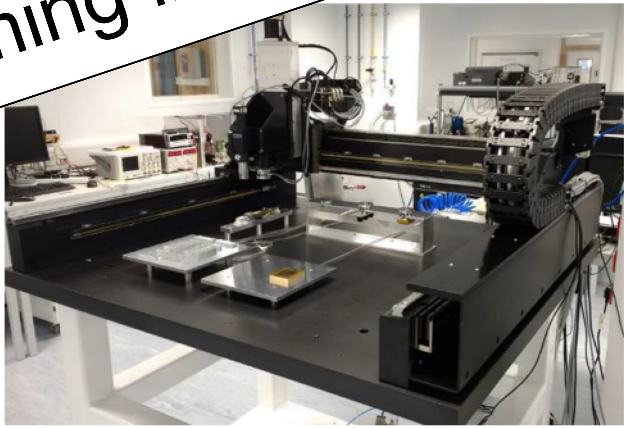
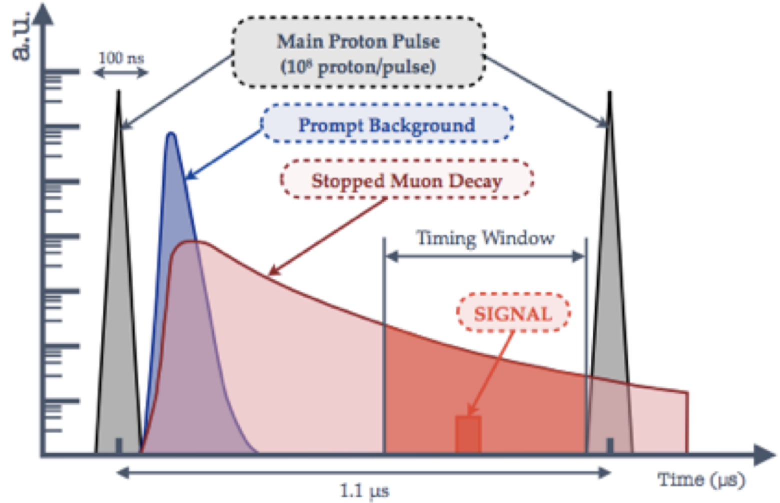
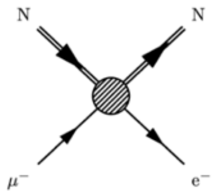


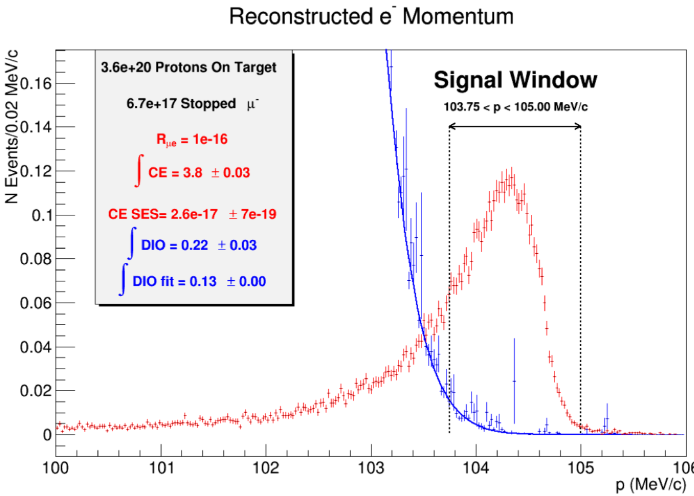
Detector production tools are underway...

μ− N → e− N Experiments

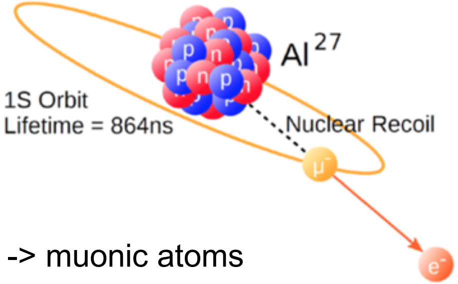


All of these experiments used pulse beams.

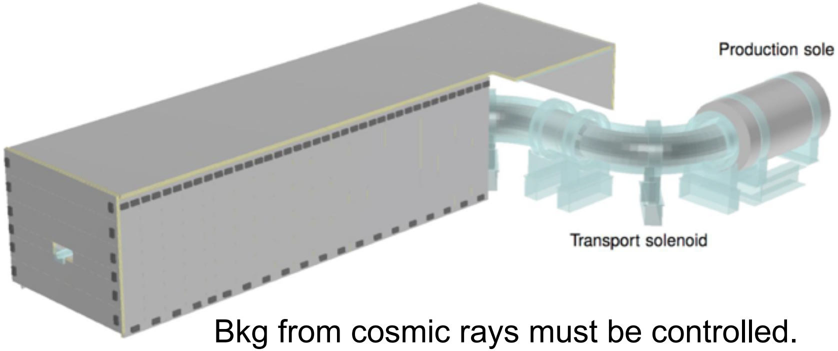




Momentum resolution must be good (typically <200 keV)



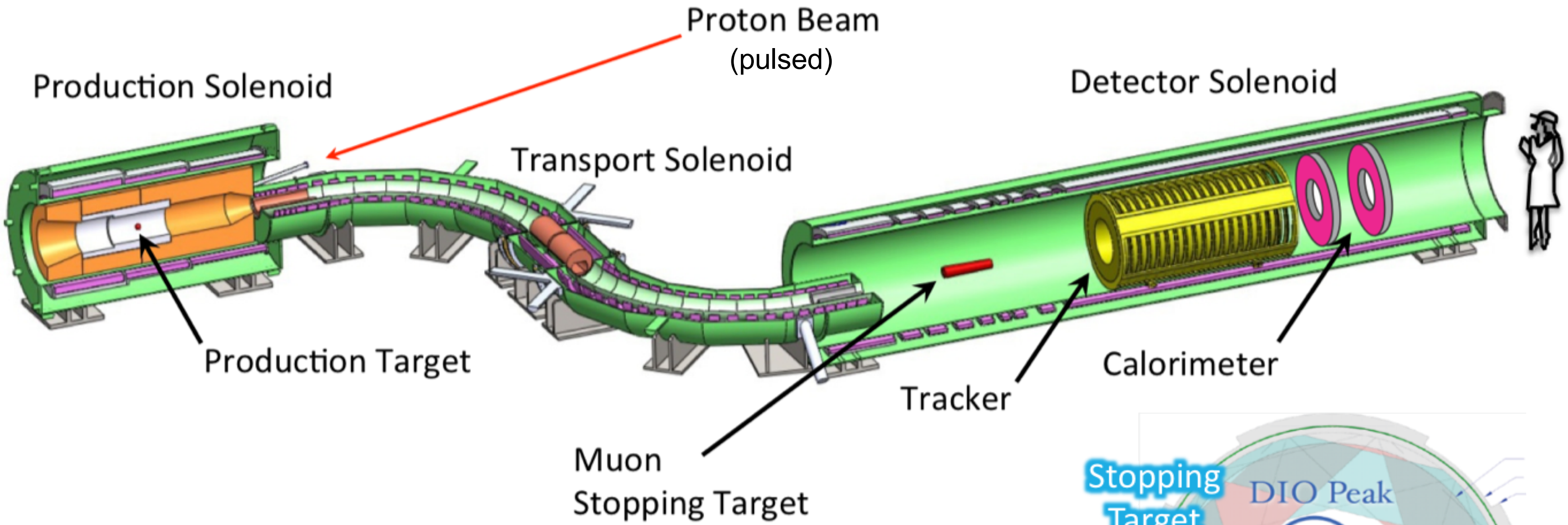
Stop muons -> muonic atoms

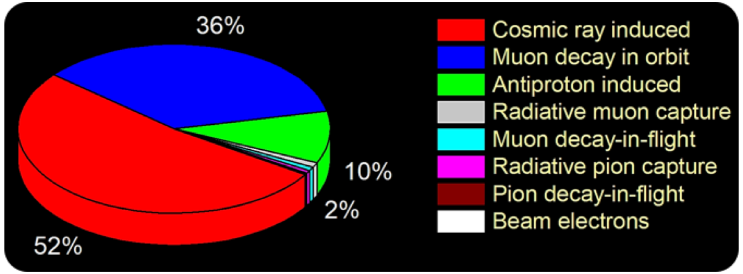


Bkg from cosmic rays must be controlled.

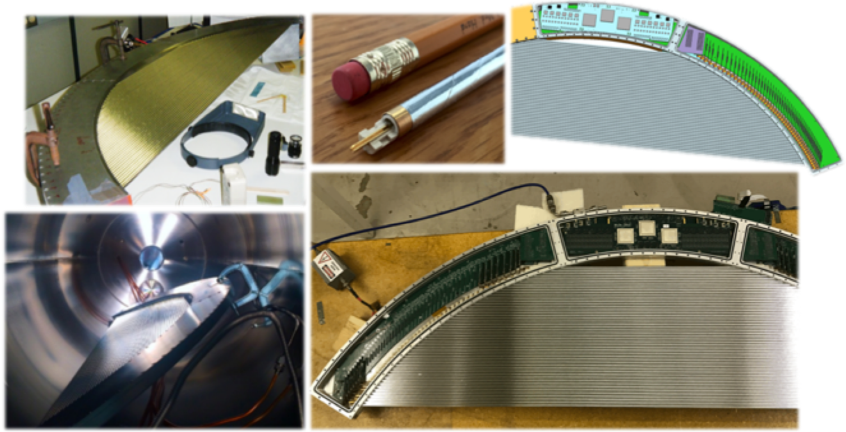
The Mu2e Experiment

SES of 3x10-17 is the target (10,000x better than current results)

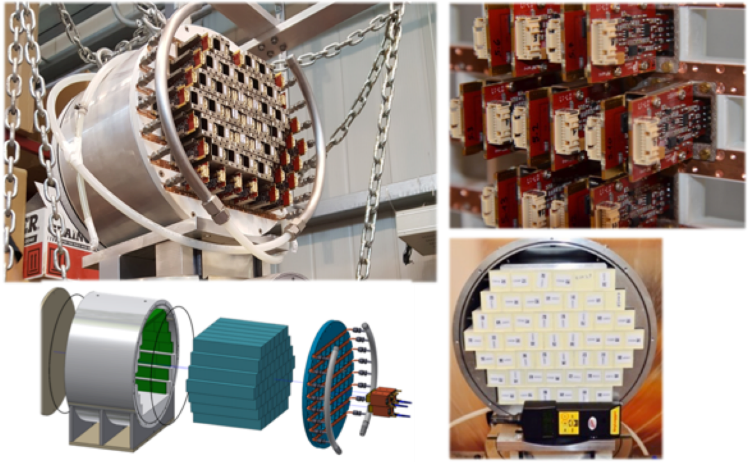




Mu2e Status

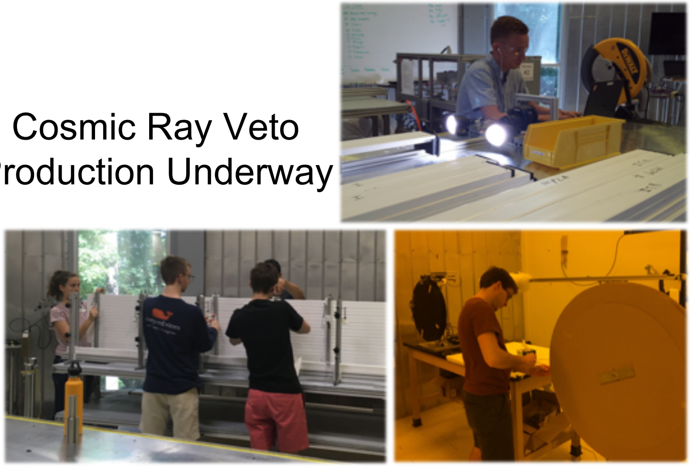


Prototype Tracker
Panels

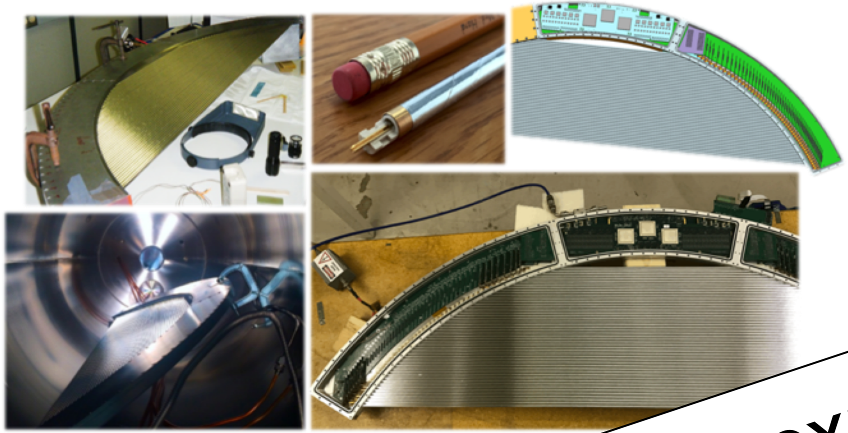


Prototype Calorimeter

Cosmic Ray Veto
Production Underway



Mu2e Status



Prototype Tracker
Panels

Prototype Calorimeter

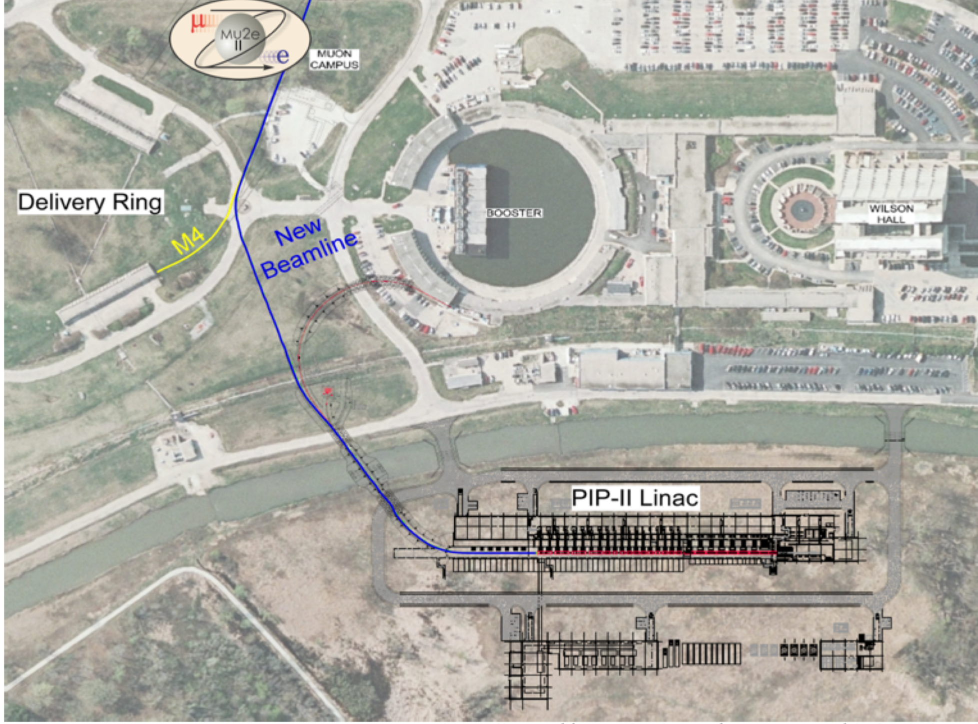
First physics expected in 2022.

Cosmic Ray Veto
Production Underway

Mu2e-II

Another factor of ten in sensitivity over Mu2e is compelling regardless of its outcome:

- If signal in Mu2e
  - <5 σ, improve statistical accuracy
  - >5 σ, use different targets to sort out nature of interaction
- If no signal in Mu2e
  - Extend sensitivity to find signal or set new limits
- Either way, BSM theories strongly constrained!

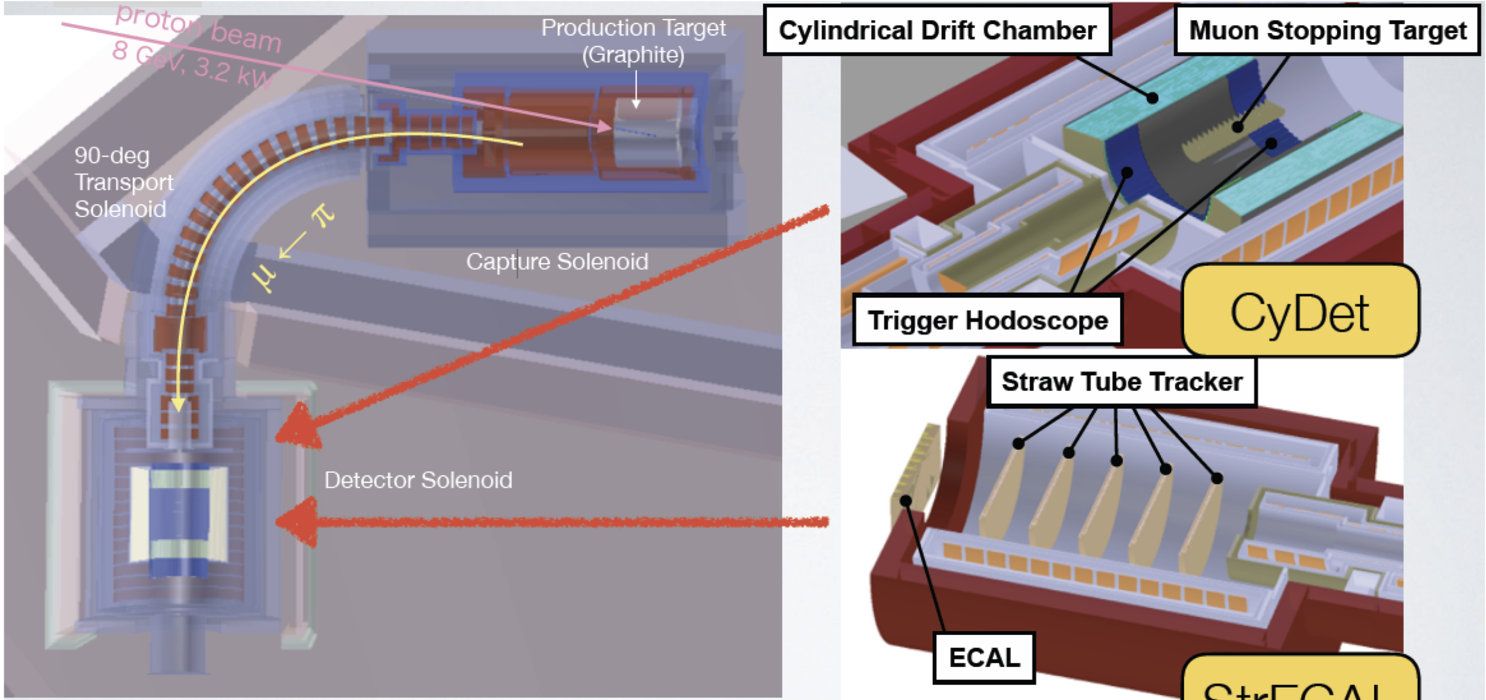


PIP-II CDR V0.01 Appendix A (http://pxie.fnal.gov/PIP-II_CDR/default.htm)

- Recent Expression of Interest.
- Upgrade to Mu2e – improve sensitivity by a factor of 10.
- Utilize the increased proton intensity afforded by PIP-II upgrade.
- Use as much Mu2e infrastructure as possible.
- Upgrade apparatus where needed to handle improved beam intensity.

→ Working to identify high-priority R&D so that work can begin soon: Mu2e workshop in two weeks at Northwestern – join us! https://indico.fnal.gov/event/17536/

The COMET Experiment (phase I)

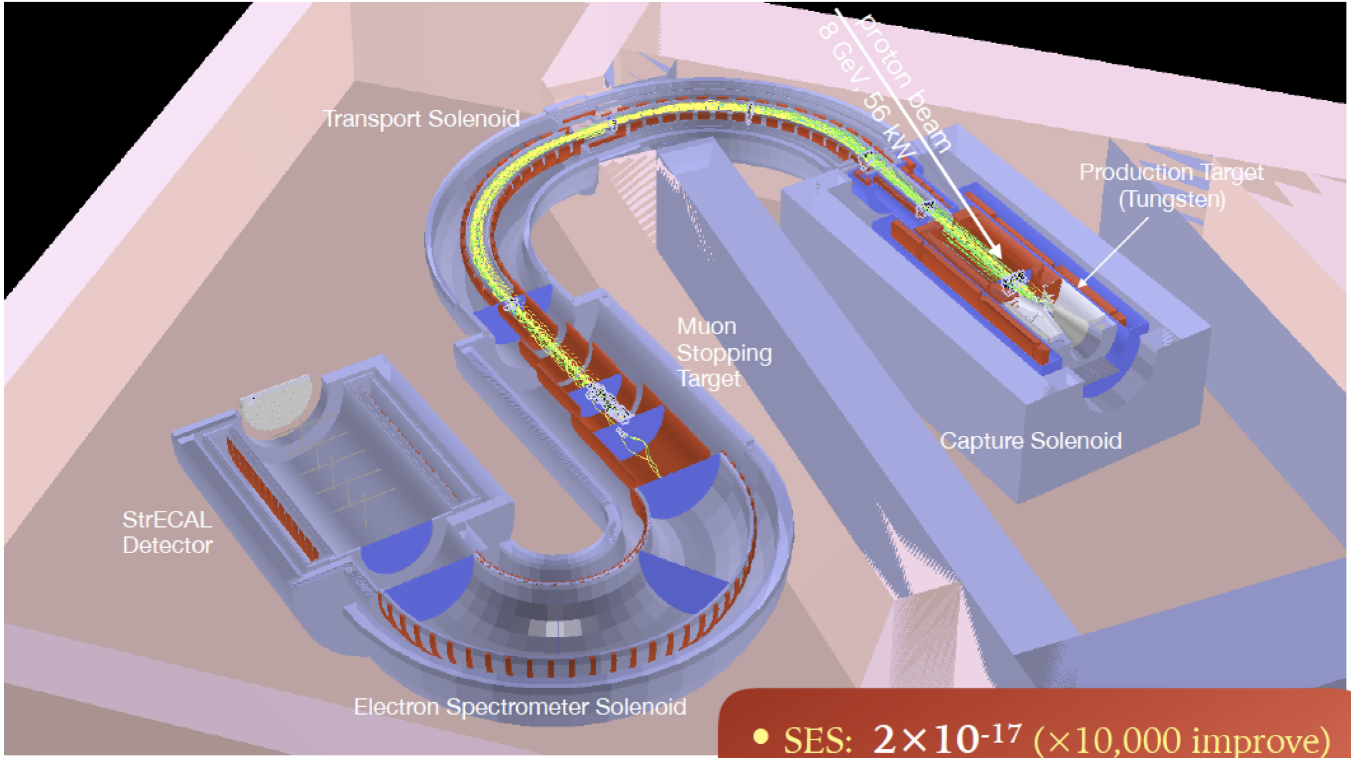


Goal of Phase-I

- ☆ **Physics measurement** → **CyDet**
  - μ-e conversion search, SES: 3×10^{-15} (×100 improve), 150 days running
- ☆ **Beam measurement** → **StrECAL**
  - to understand beam quality and background (PID, momentum, timing)

Manabu Moritzu

The COMET Experiment (phase II)



- SES: 2×10^{-17} (×10,000 improve)
- Beam: 56 kW
- 1 year running

Manabu Moritzu

COMET Status

CyDet Cylindrical Drift Chamber cosmic ray studies ongoing.
FEBs have been fabricated.

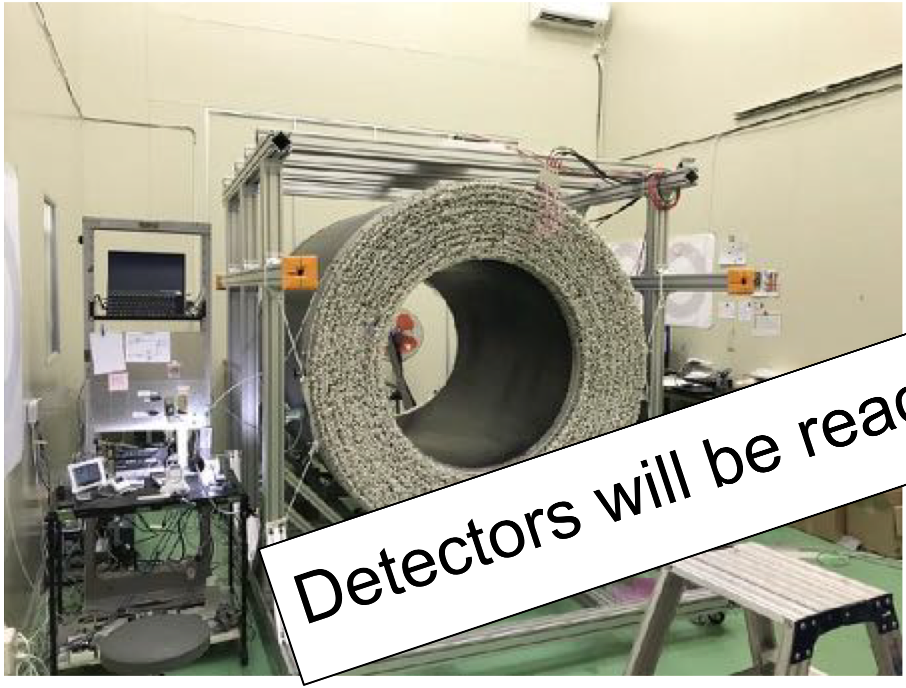
Beamline wall construction is complete.

- Transport Solenoid installed,
- Production Solenoid winding in progress, and Detector Solenoid are complete.

.

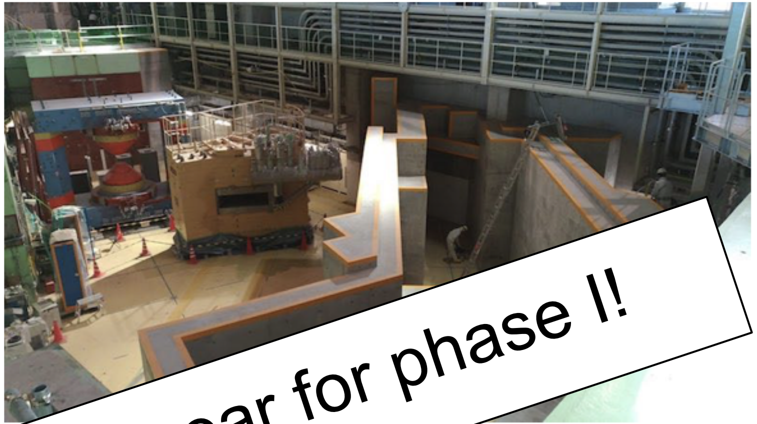
- Straws for StrECAL fabricated.
- Other StrECAL components also being produced/purchased.

COMET Status



CyDet Cylindrical Drift Chamber cosmic ray studies ongoing.
FEBs have been fabricated.

Detectors will be ready next year for phase I!



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- Beamline wall construction is complete.

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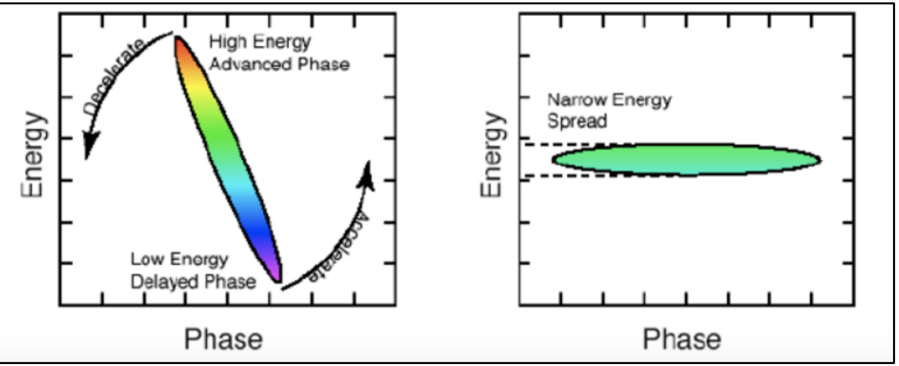
PRISM/PRIME: A Next-Generation $\mu^- N \rightarrow e^- N$ Experiments

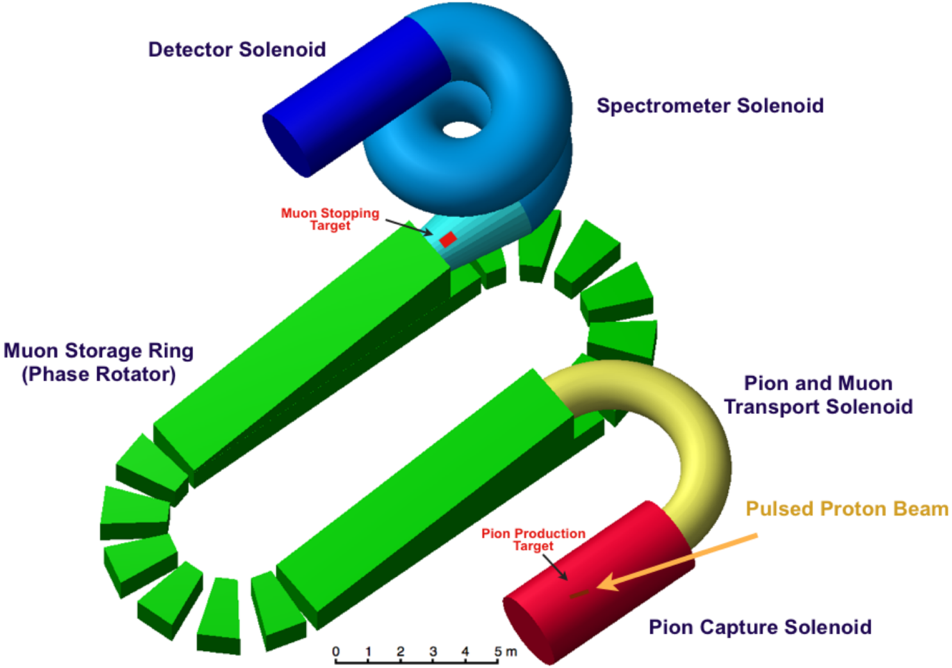
PRISM:

- Phase Rotated Intense Slow Muon beam
- Requires compressed proton bunch and high power proton beam
- Phase rotation in muon storage ring

PRISM/PRIME:

- potential upgrade to COMET
- SES 3×10^{-19} suggested with new proton driver





- R&D is ongoing…
- PRISM is becoming a serious option for the next generation cLFV experiment.
- Novel ideas in generating muon beams may open new horizons:
  - Neutrino factory
  - Muon collider
  - ...

J. Pasternak

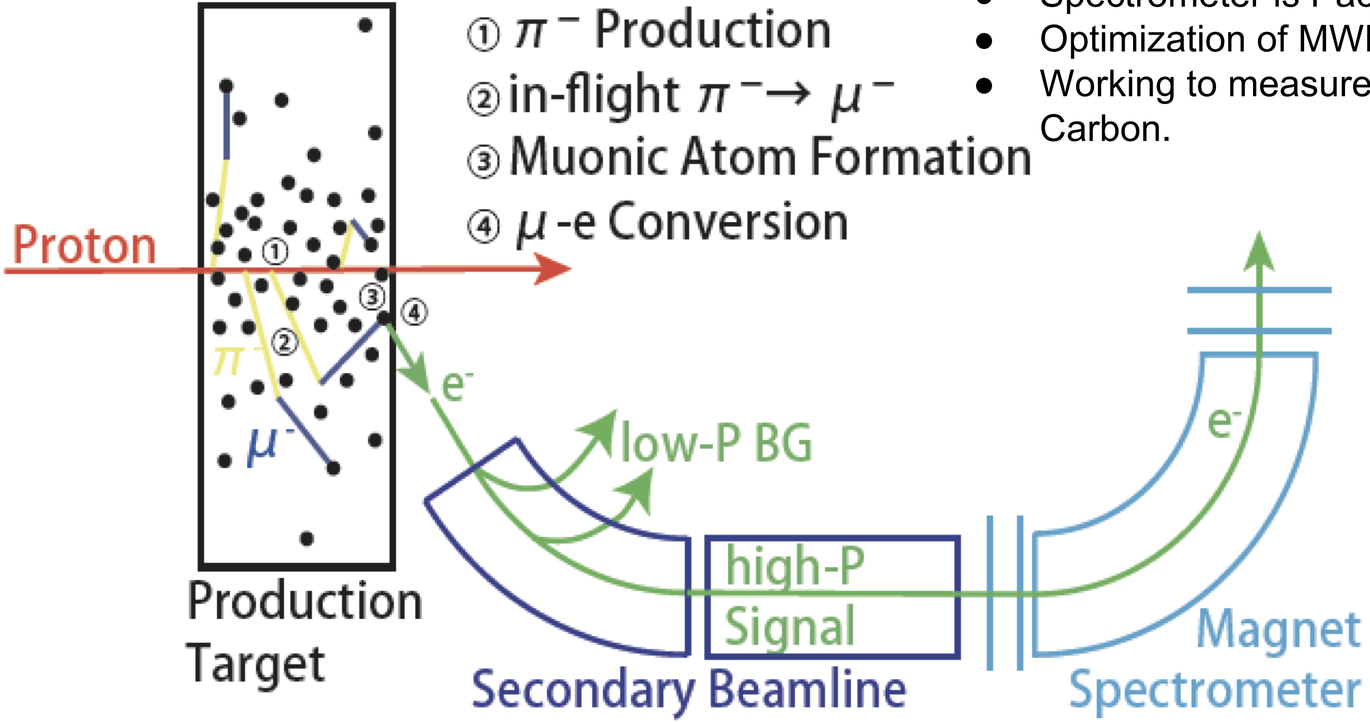
The DeeMe Experiment

- Single event sensitivity (1 year = 2×10^{7} sec)
  - 1×10^{-13}
  - 2.5×10^{-14} (4 years)

Upgrade to SiC

- 2×10^{-14}
- 5×10^{-15} (4 years)

- Unique: production target is also the stopping target.
- Spectrometer is Pacman magnet with MWPC.
- Optimization of MWPC to handle beam flash.
- Working to measure decay in orbit spectrum - Carbon.



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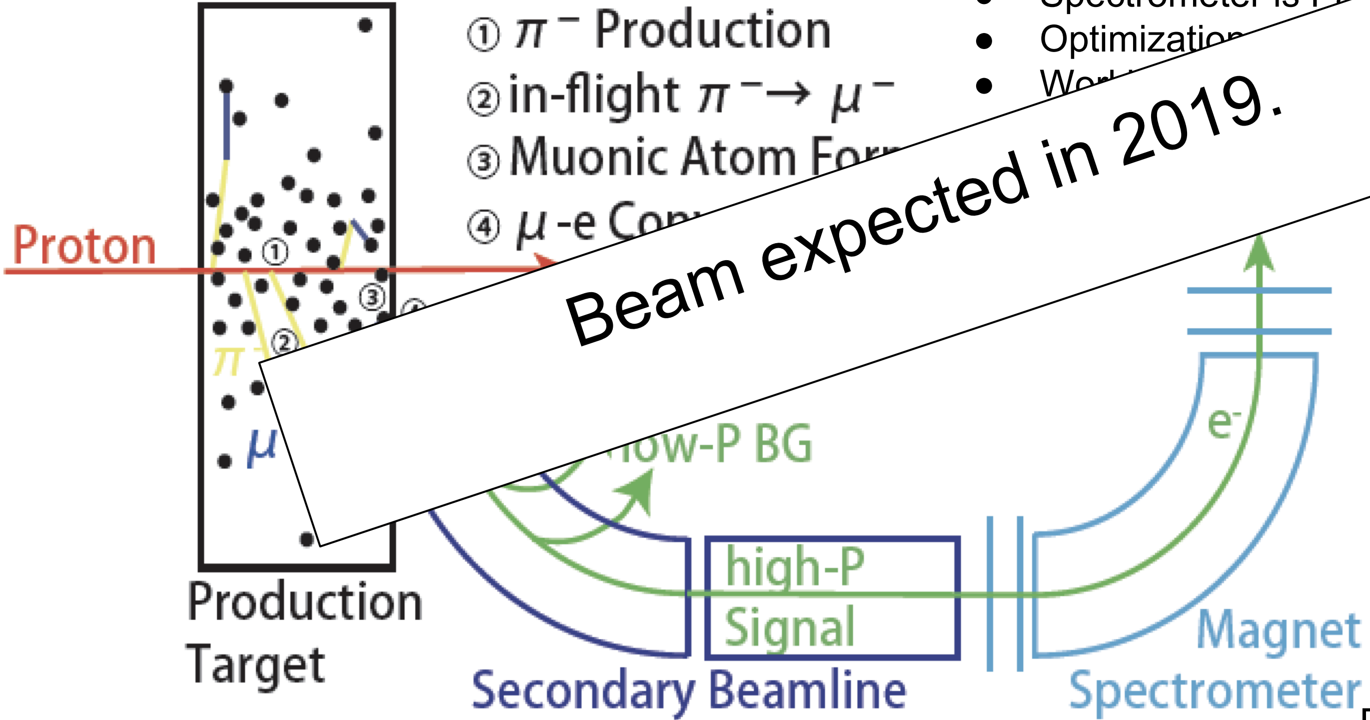
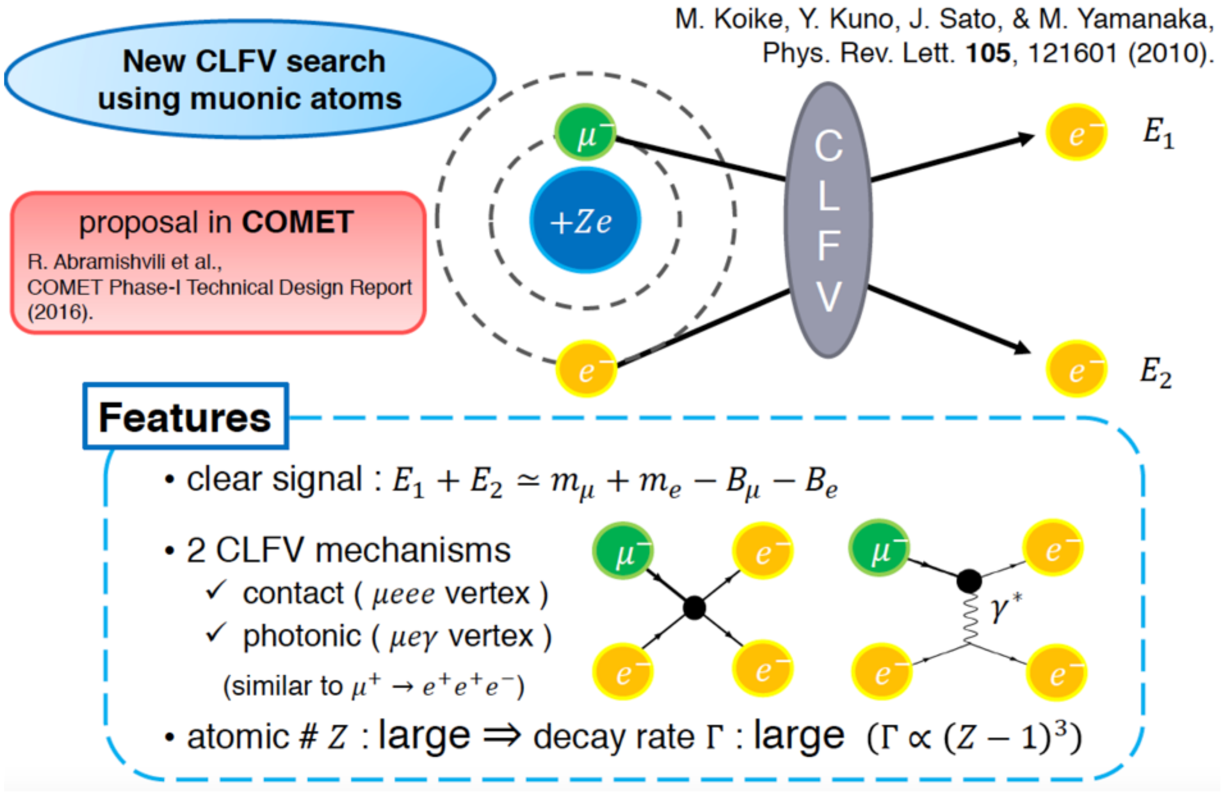
- Spectrometer is Pa... t with MWPC.
- Optimization ... beam flash.
- Wor... spectrum -



Beam expected in 2019.

Daiki Nagao

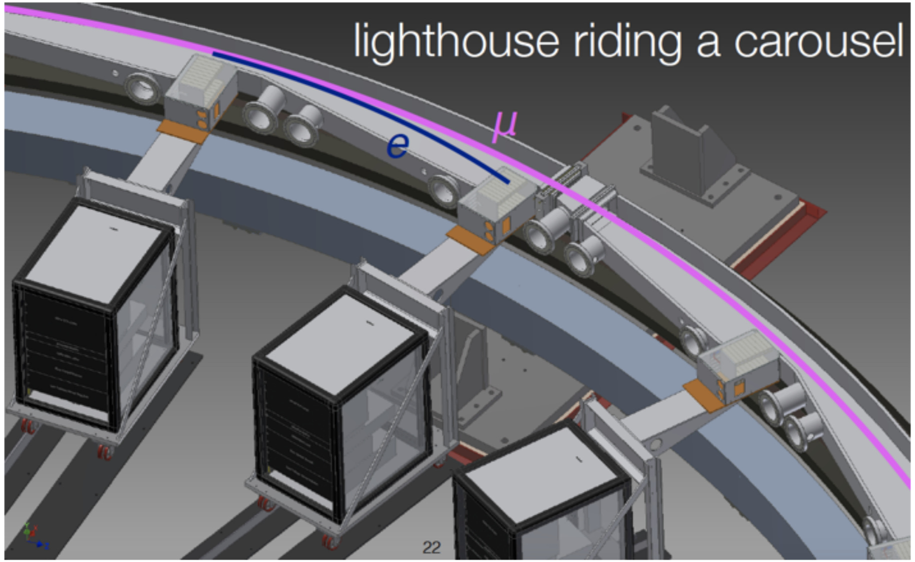
New Proposal: μ− e−→ e− e−

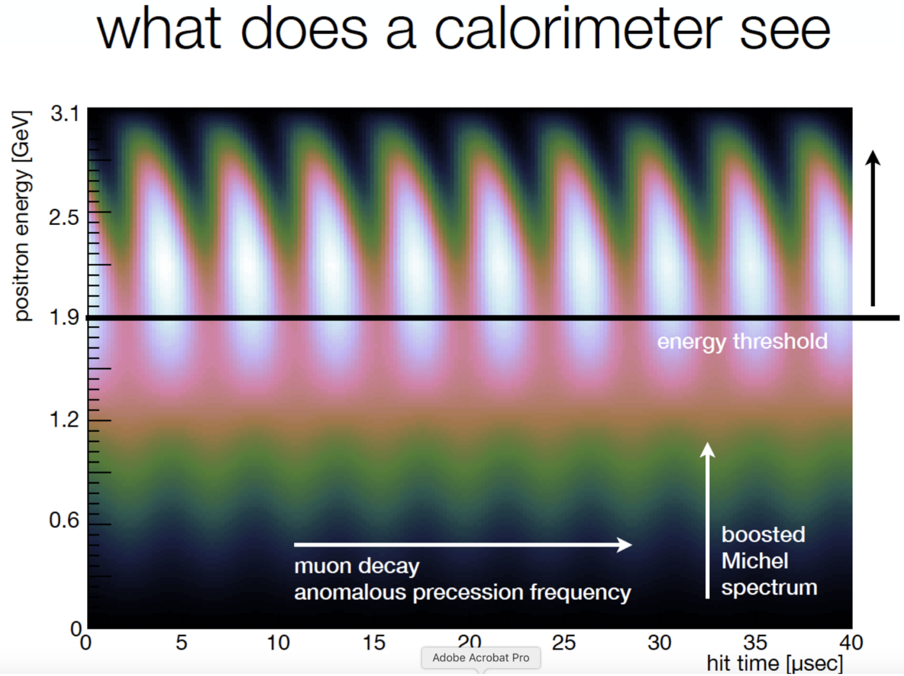


Extra CLFV channel to provide a unique handles on the type of physics interaction leading to CLFV signal.

g_μ-2 at FNAL: Experimental

1) Polarized beam
2) Precession proportional to g-2
3) "Magic" ɣ for the muon
4) Parity violating decay
   → positron (electron) prefers
   (prefers opposite) spin direction.

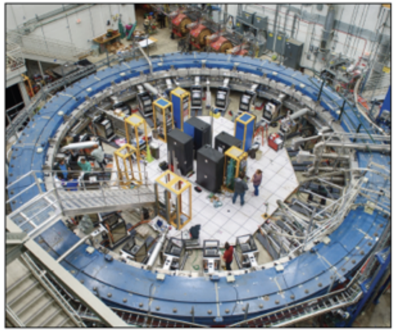


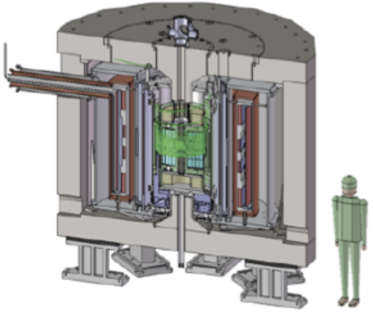


g_μ-2 Experimental Approaches

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

- Measure ω_a - want to extract a_μ
- Either:
  - E=0 (J-PARC)
  - “Magic” γ (FNAL)





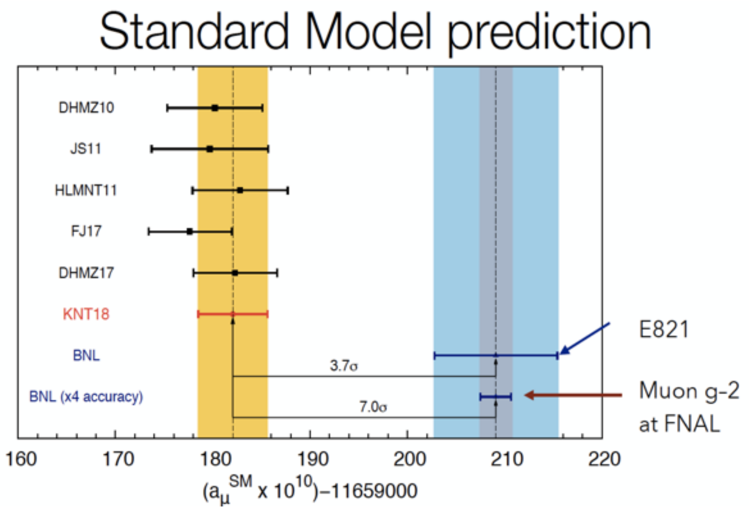
FNAL

- 7 m radius storage ring
- B = 1.45 T
- weak electric focusing
- high-rate 3 GeV/c beam
- spin polarization 97 %
- data taking 2018 - 2020
- 100 ppb by end of 2021

J-PARC

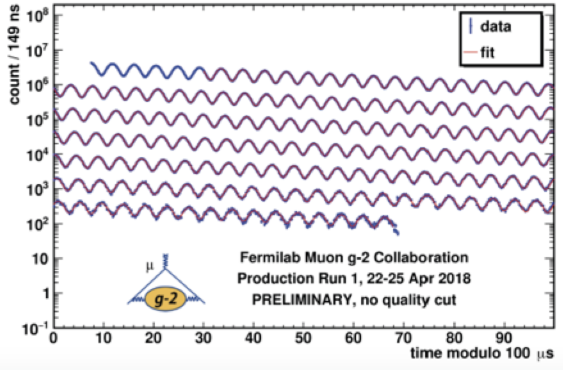
- 0.33 radius storage bottle
- B = 3 T
- no E -field, week mag. focusing
- 0.3 GeV/c beam
- spin polarization 50 %
- data taking 2020 - 2023
- 400 ppb by end of 2023

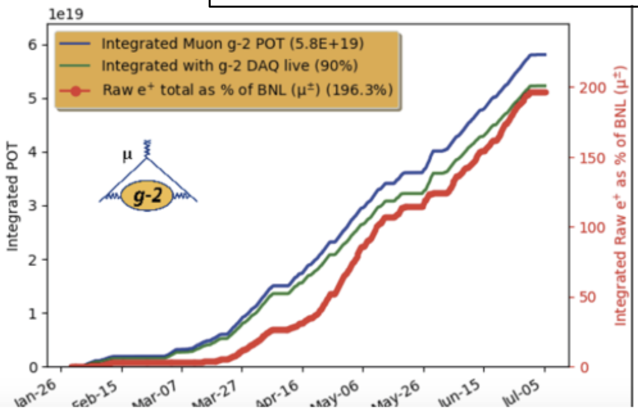
g_μ-2 at FNAL: Status



Goal is 4x improvement relative to BNL experiment

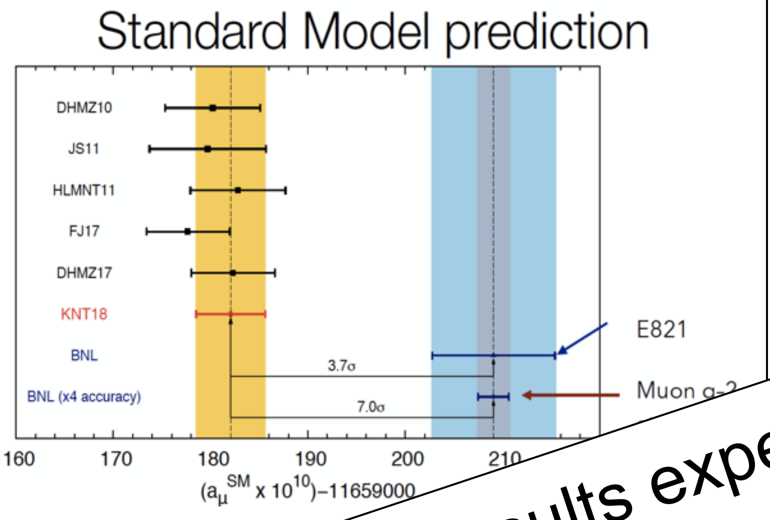
- More beam and improved purity
- Improved instrumentation:
  - Improved B field uniformity, calibration, and monitoring
  - New tracker with large azimuthal acceptance and no dead time
  - New segmented calorimeter with better timing and energy resolution
  - New laser calibration system





First physics run completed in July!

g_μ-2 at FNAL: Status

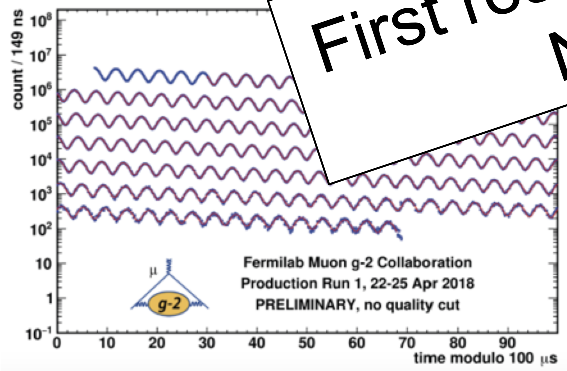


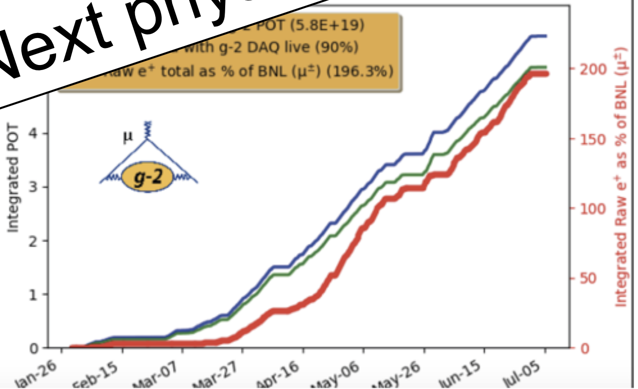
<u>Goal is 4x improvement relative to BNL experiment</u>

- More beam and improved purity
- Improved instrumentation:
  - Improved B field unif ity, calibration, and monitorin
  - New muthal
  - ime
  - calorimeter with better and energy resolution
  - New laser calibration system

First results expected soon (paper <1 yr)...

Next physics run 5-10x BNL





First physics run completed in July!

Standard Model Predictions for g_μ-2

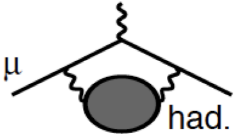
KNT18 a_μ^{SM} update [KNT18: arXiv:1802.02995, PRD (in press)]

	2011		2017	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 (2.60)	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 (2.46)	this work
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	this work
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	this work
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	this work

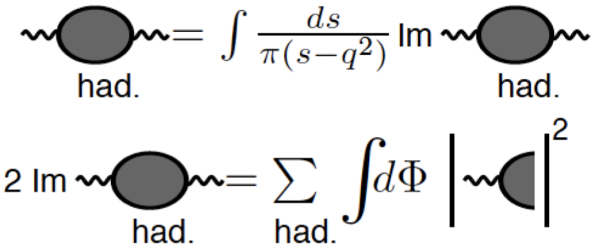
Alex Keshavarzi (KNT18) The muon $g-2$: HVP 20th June 2018 12 / 14

(HVP: Hadronic Vacuum Polarization)
(HLbL: Hadronic Light-by-Light)
Slide by A. Keshavarzi (Liverpool) at 'Muon $g-2$ Workshop' at Mainz, June 18-22, 2018

The diagram to be evaluated:



pQCD not useful. Use the dispersion relation and the optical theorem.

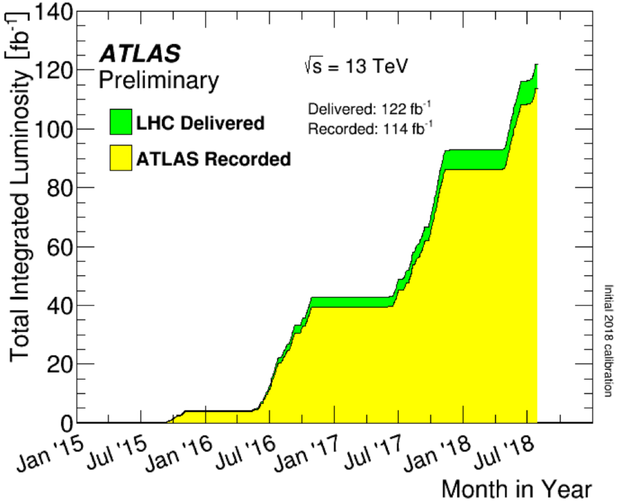


$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds \, \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)$$

- Lots of new input $\sigma(e^+e^- \to \mathrm{hadrons})$ data
- Improvements in the estimates of uncertainties due to radiative corrections (Vacuum Polarization Radiative Corrections & Final State Radiations)
- Improvements in data-combination method

Daisuke Nomura

CLFV at Colliders



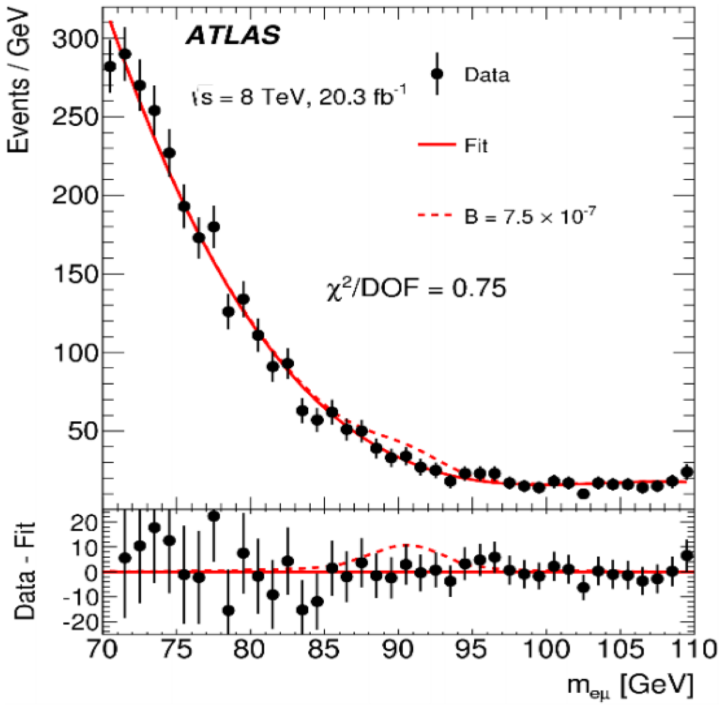
LHC experiments have enough Z bosons to compete with LEP:
- $Z \rightarrow e\mu$
- $Z \rightarrow e\tau/\mu\tau$

Can also search in Higgs boson decays:
- $H \rightarrow e\tau/\mu\tau$

Tau decays:
- $\tau \rightarrow 3\mu$

And, hypothetical channels (exclude masses above ~3TeV):
- Heavy gauge bosons (Z’)
- R-parity violating SUSY (sneutrino)
- Quantum Black Holes

CLFV at CMS and Atlas

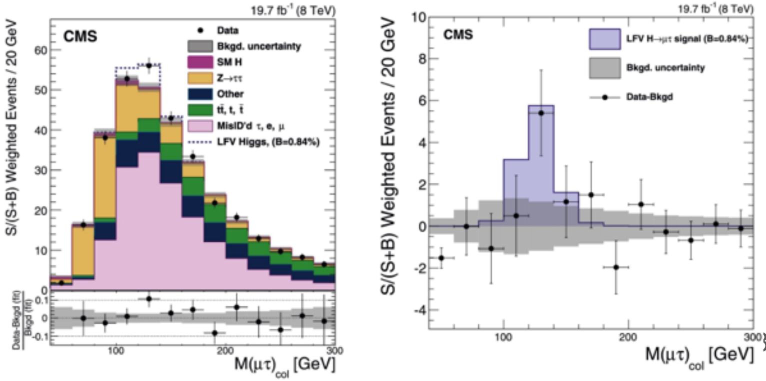


Note: Indirect low-energy Br (Z-eμ) limit: 5 x10^{-13}
(very strict, but still worth checking at high energy)

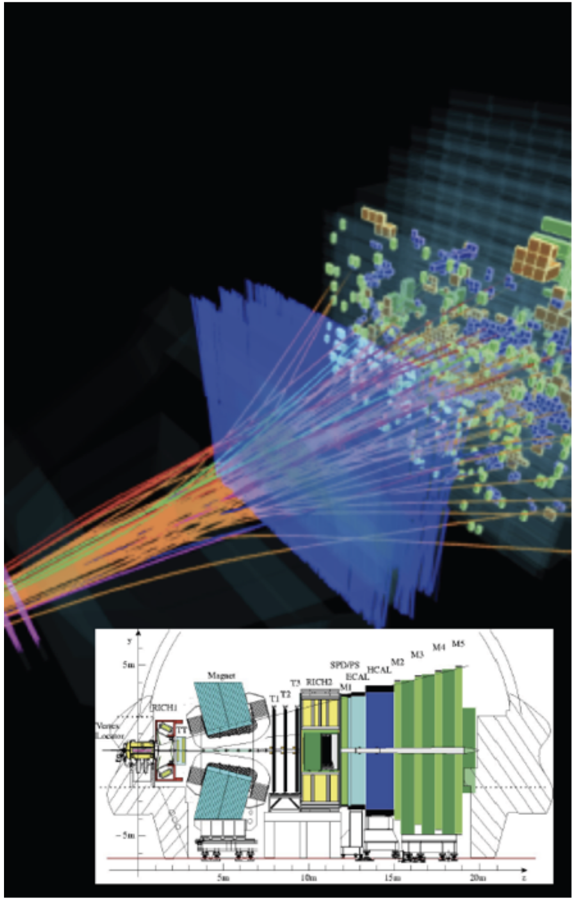
Diego Beghin (CMS) Wing Sheung Chan (Atlas)

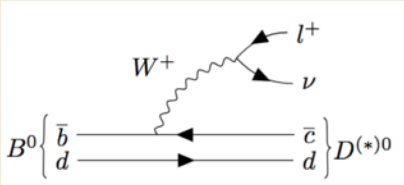
	LEP	Atlas	CMS	LHCb
$B^0_{(s)} \to e\mu$	-----	-----	-----	1.0 (5.4)×10^{-6}
$\tau \to 3\mu$	-----	3.76×10^{-7}	-----	4.6×10^{-8}
$Z \to e\mu$	1.7×10^{-6}	7.5×10^{-7}	7.3×10^{-7}	-----
$Z \to e\tau$	9.8×10^{-6}	5.8×10^{-5}	-----	-----
$Z \to \mu\tau$	1.2×10^{-5}	1.3×10^{-5}	-----	-----
$H \to e\tau$	-----	1.04×10^{-2}	0.6×10^{-2}	-----
$H \to \mu\tau$	-----	1.43×10^{-2}	0.25×10^{-2}	-----

$B(\mathrm{H} \to \mu\tau) < 1.51\%$ (2.4σ excess ↓)

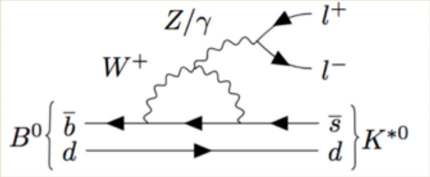


LHCB: CLFV and Lepton Universality



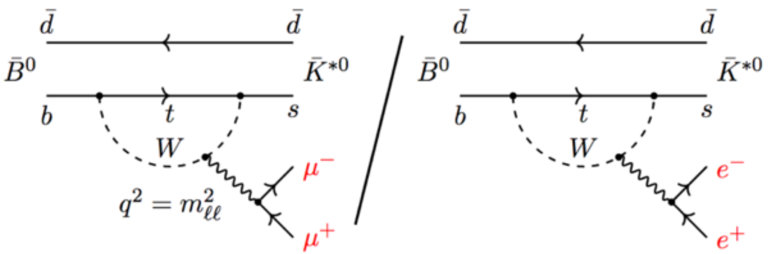


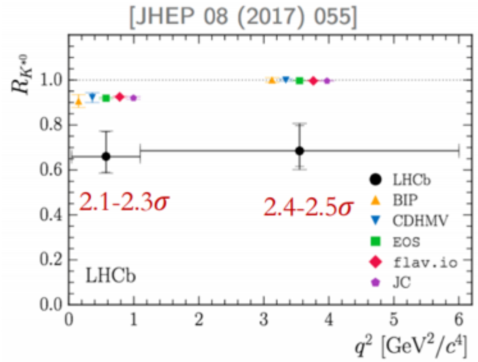
Flavour-changing CHARGED current ($b \to c\ell\bar{\nu}$)



Flavour-changing NEUTRAL current ($b \to s(d)\ell^+\ell^-$)

2-3 σ anomaly in lepton universality ratio R:





Several other 2-3 σ anomalies reported.

Will improve experimental reach significantly as dataset improves.

~2x improvement in new physics scale probed!

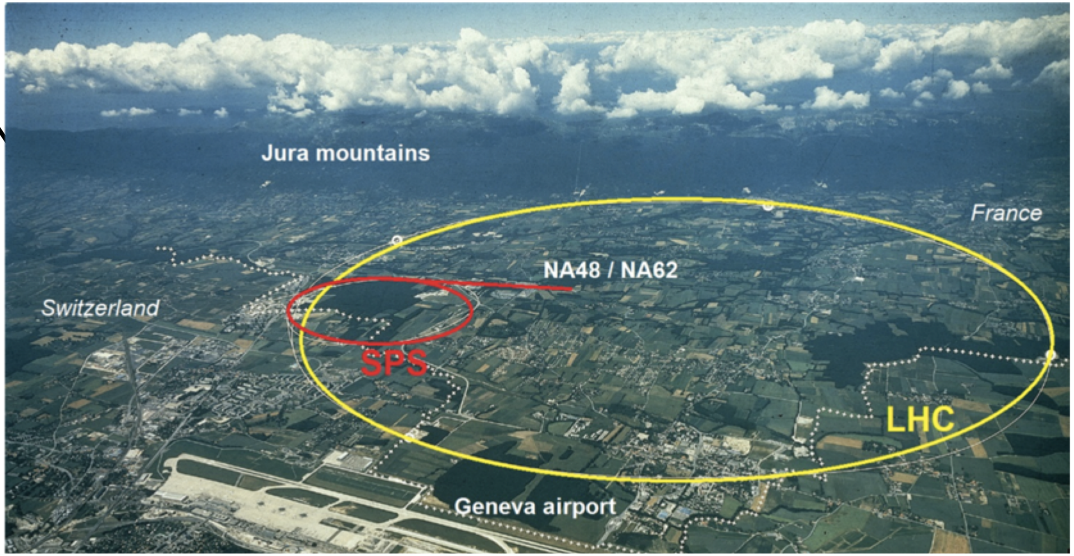
Francesca Dordei

CLFV at NA62

Kaon fixed-target experiment at CERN

NA62 (2014-2018):

- 2014: Pilot run
- 2015: Commissioning
- 2016-2018:
  - $K^+ \to \pi^+ \nu\bar{\nu}$
  - HNL
  - Rare/forbidden kaon decays
  - Exotics

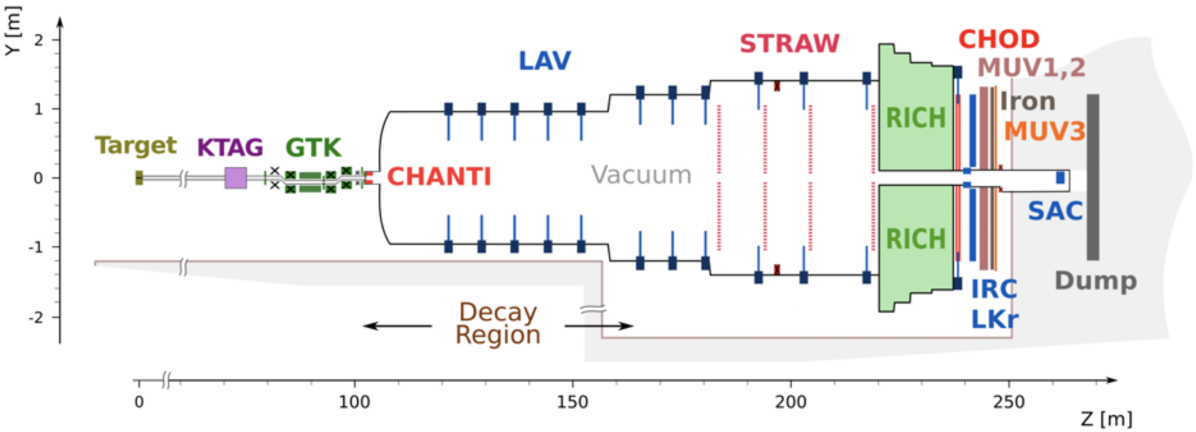


Primary beam

- 400 GeV/c protons from SPS

Secondary beam

- 6% kaons, 75 GeV/c momentum
- Rest: 70% pions, 24% protons



Stoyon Trilov

Searches for LF/LN violation at NA62

- Lepton number violating decays
  - $K^+ \to \pi^- \mu^+ \mu^+$ $(BR < 1.1\times 10^{-9})$ NA48/2@CERN [PLB 697 (2011) 107]
  - $K^+ \to \pi^- \mu^+ e^+$ $(BR < 5.0\times 10^{-10})$
  - $K^+ \to \pi^- e^+ e^+$ $(BR < 6.4\times 10^{-10})$
- Lepton flavour violating decays
  - $K^+ \to \pi^+ \mu^- e^+$ $(BR < 5.2\times 10^{-10})$

BNL E865 [PRL 85 (2000) 2877]

  - $K^+ \to \pi^+ \mu^+ e^-$ $(BR < 1.3\times 10^{-11})$ BNL E777/E865 [PRD 72 (2005) 012005]
  - $K^+ \to \pi^+ \pi^0,\ \pi^0 \to \mu^\pm e^\mp$ $(BR < 3.6\times 10^{-10})$ kTeV@FNAL [PRL 100 (2008) 131803]
  - $K^+ \to \mu^- \nu e^+ e^+ (BR < 2.1\times 10^{-8})$ Geneva-Saclay [PL 62B (1976) 485]
- $\Delta S = \Delta Q$ violating modes
  - $K^+ \to \pi^+ \pi^+ \mu^- \overline{\nu_\mu}$ $(BR < 3.0\times 10^{-6})$ LRL [PR 139 (1965) B1600]
  - $K^+ \to \pi^+ \pi^+ e^- \overline{\nu_e}$ $(BR < 1.3\times 10^{-8})$ Geneva-Saclay [PL 60B (1976) 393]

- NA62 is able to improve on most of these modes
  - Single event sensitivity $\sim 10^{-11}$

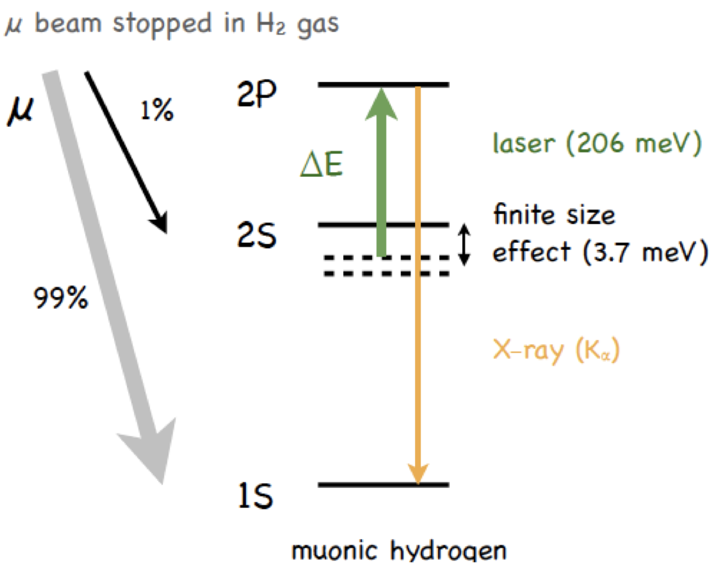
Stoyon Trilov

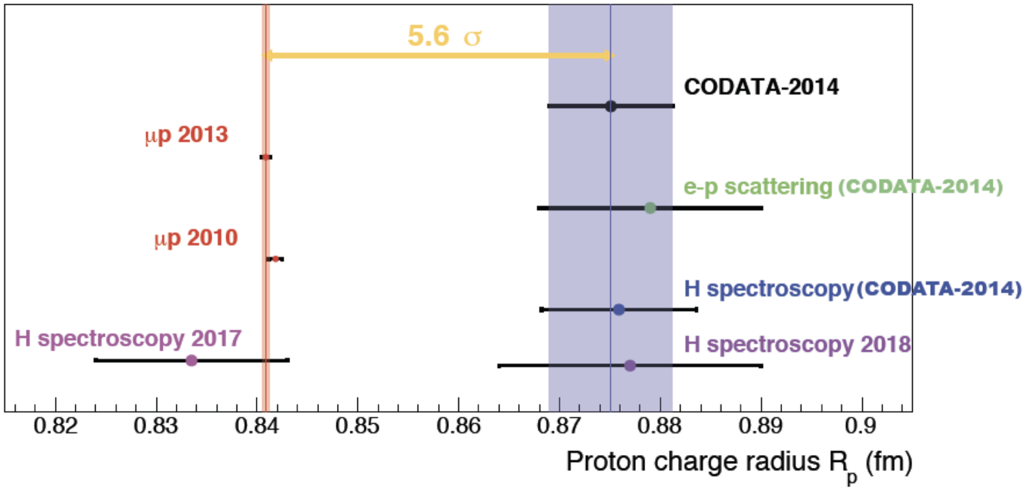
The Proton Radius Puzzle

r_p determined from:

- ep scattering
- Spectroscopy from muonic hydrogen

Results from these methods are discrepant.





Electron scattering:	0.879 ± 0.011 fm (CODATA 2014)
Muonic spectroscopy:	0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017):	0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017)6359)
H spectroscopy (2018):	0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018)183001)

Lamb shift

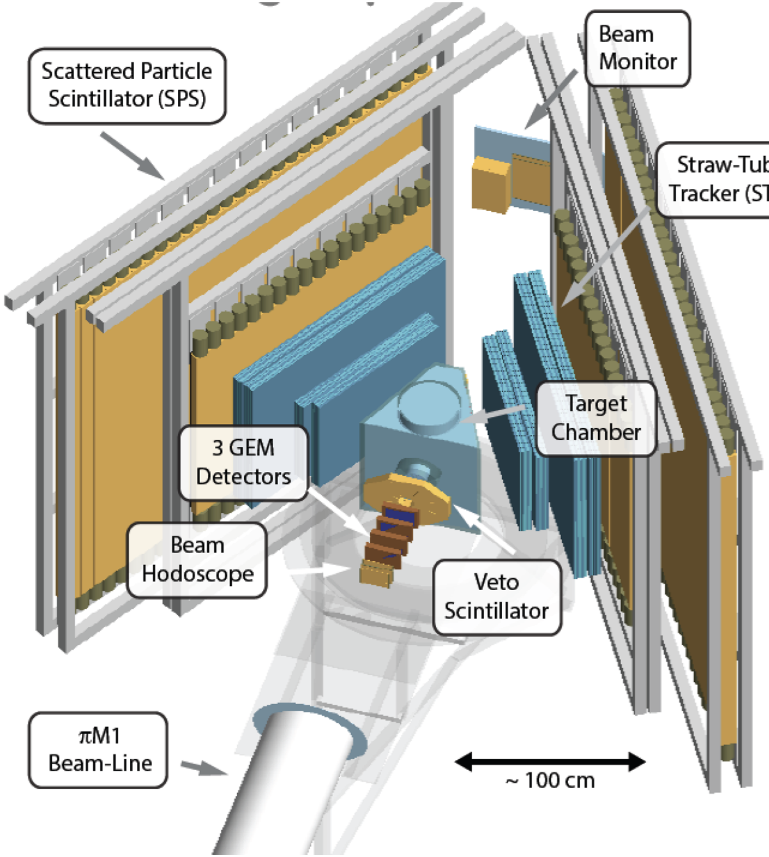
$$\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ meV}$$

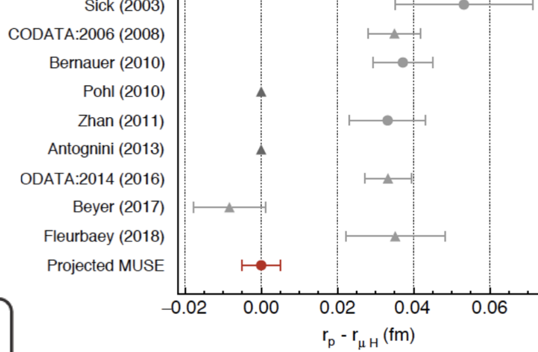
The MUSE Experiment

Measure e± and μ± elastic scattering off a liquid hydrogen target.

Challenges

- Secondary beam: identifying and tracking beam particles to target,
- Low beam flux: large angle, non-magnetic spectrometer,
- Background: e.g., Møller scattering and muon decay in flight.





Are μp and ep interactions different?

If so, does it arise from 2γ exchange effects (μ+ ≠ μ-) or beyond the standard model physics (μ+ ≈ μ- ≠ e-)?

Commissioning run with all detectors ongoing.

The MUSE Experiment

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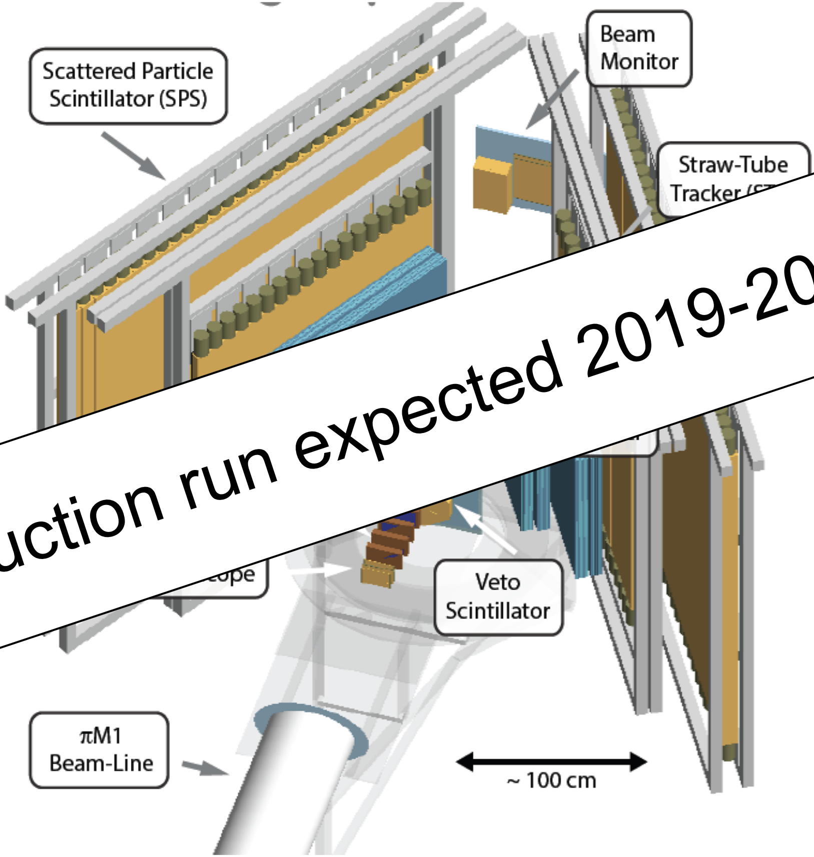
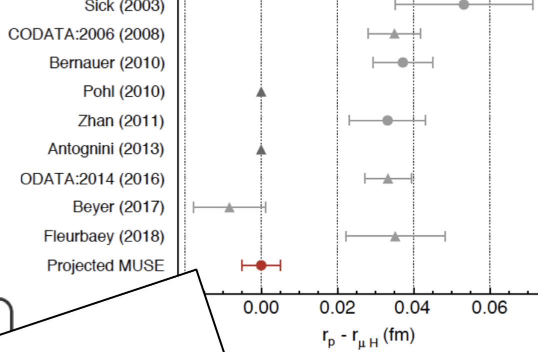


Production run expected 2019-2020.

Commissioning run with all detectors ongoing.



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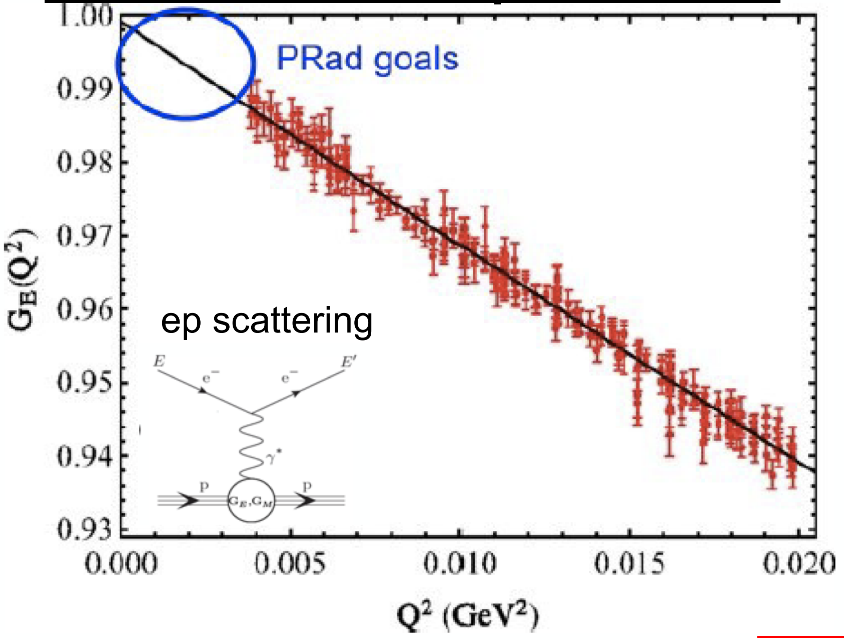
Steffen Strauch

The PRad Experiment

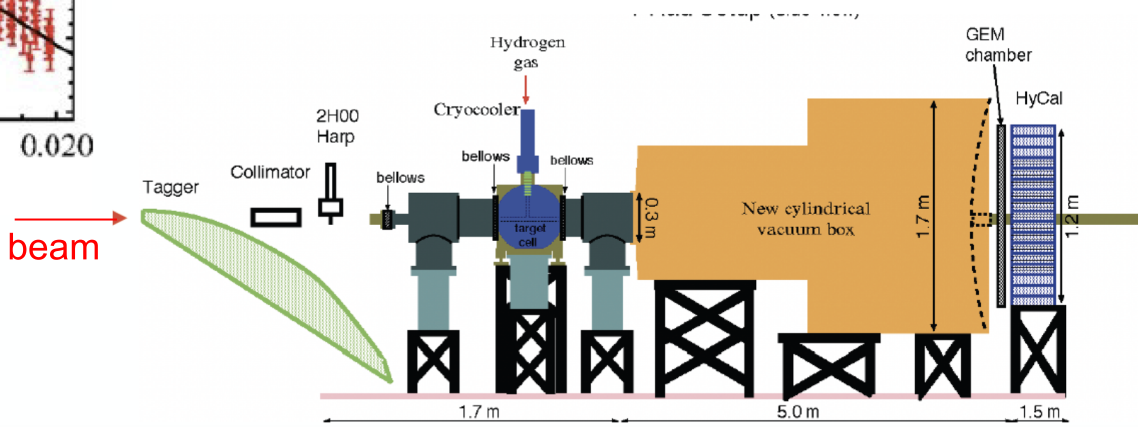


Mainz Low Q^2 data set

Phys. Rev. C 93(2016)065207

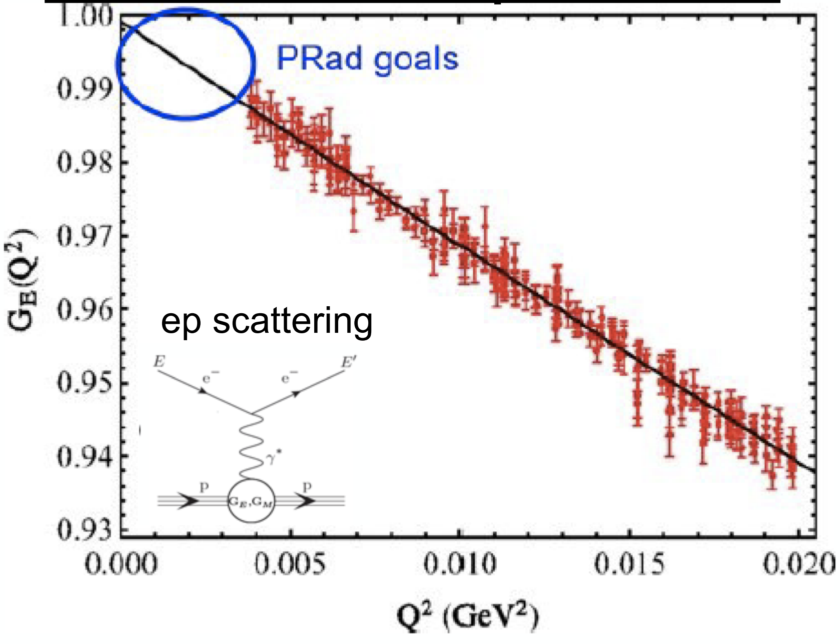
Goal: Measure proton charge radius using ep elastic scattering:

- Unprecedented low Q2 region (~2x10-4 GeV2)
- Covers two orders of magnitude in low Q2
- Normalize to the simultaneously measured Moller scattering process (control sys)
- Extract the radius with precision from subpercent cross section measurement



Chao Gu

The PRad Experiment



Mainz Low Q² data set

Phys. Rev. C 93(2016)065207

Goal: Measure proton charge radius using ep elastic scattering:

- Unprecedented low Q2 region (~2x10-4 GeV2)
- Covers two orders of magnitude in low Q2
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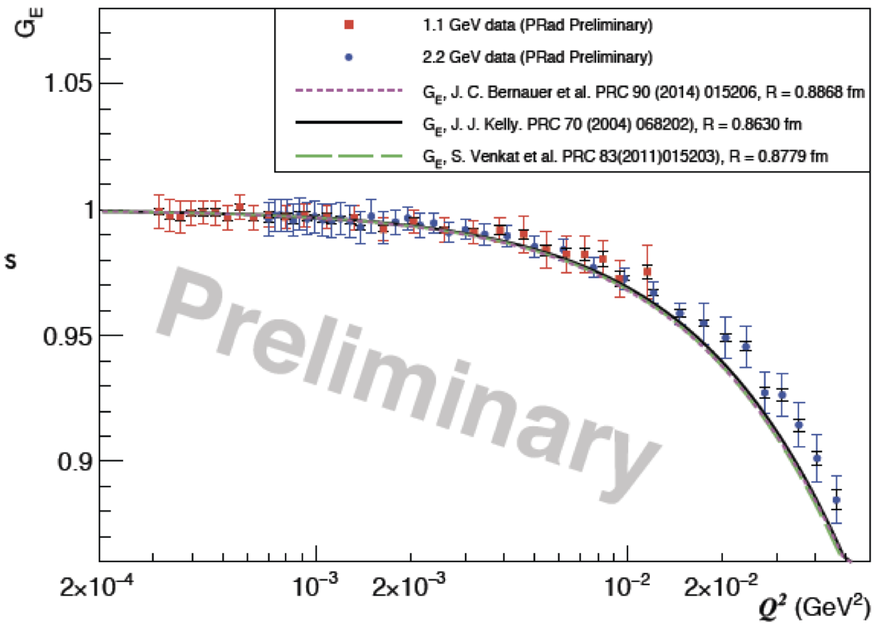
- Extract the radius with precision from subpercent cross section measurement

Proton Electric Form Factor G_E



Chao Gu

The PRad Experiment

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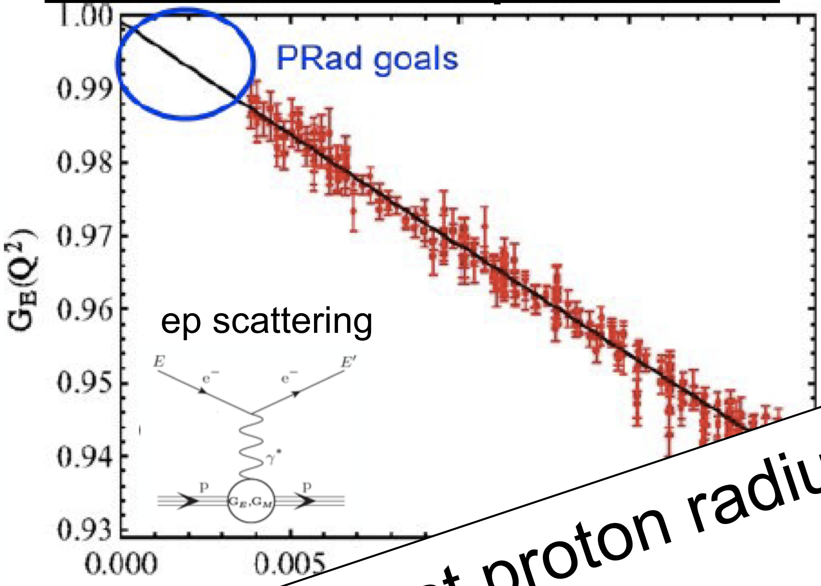
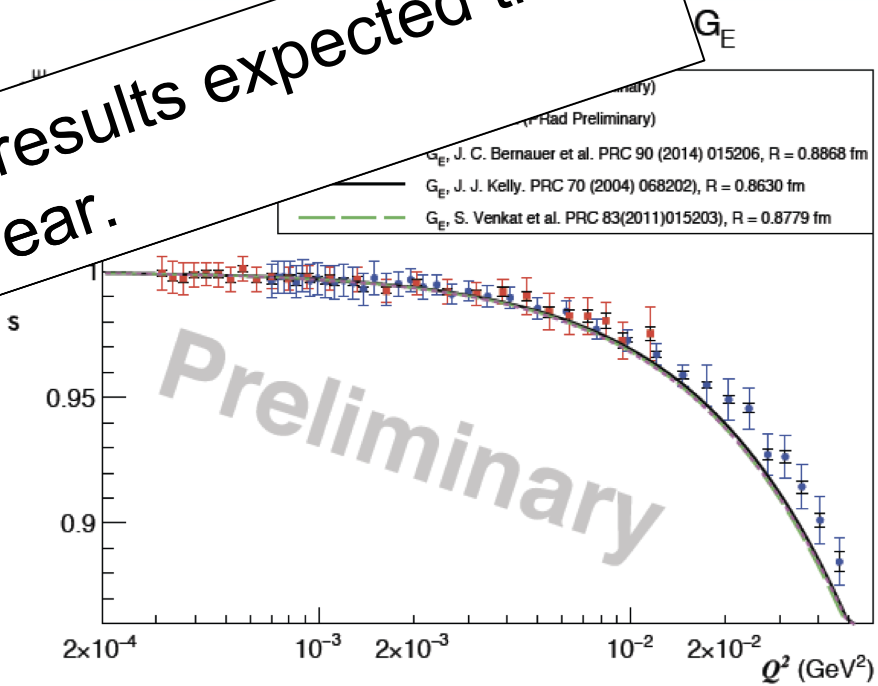


Phys. ... C 93(2016)065207

First proton radius results expected this year.

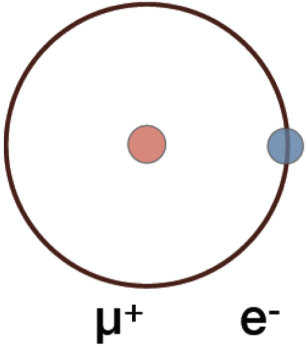


Chao Gu

Muonium and Muonic Hydrogen Experiments

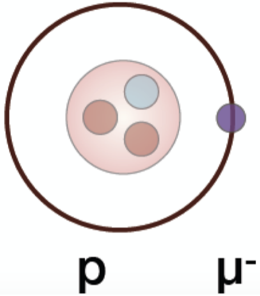
- What can we learn extract muonic atom spectroscopy?
  - Fundamental constants, QED, Nuclear physics...

Muonium



- Muon magnetic moment (HFS, μ_μ/μ_p)
- Muon mass (1S-2S, m_μ/m_e)
- Muon charge (1S-2S, q_μ/q_e)
- Fine structure constant (HFS)
- Bound-state QED theory

Muonic Hydrogen

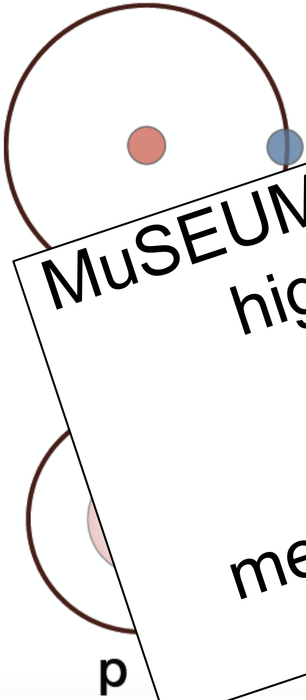


- Proton charge radius (Lamb shift)
- Proton Zemach radius (HFS)
- Proton polarizability (HFS, Lamb shift)
- Rydberg constant (Lamb shift)
- Bound-state QED theory (Sternheim interval)

Muonium and Muonic Hydrogen Experiments

- What can we learn extract muonic atom spectrosc ?
  - Fundamental constants, QED, Nuclear
    - Muon magneti
    - Muon

Muonium



Muonic Hydrogen

ability (HFS, Lamb shift)

constant (Lamb shift)

Bound-state QED theory (Sternheim interval)

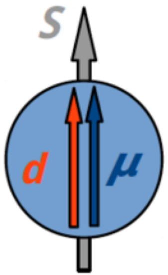
MuSEUM demonstrated HFS at zero field - high field will improve precision.

Preparing for new HFS measurement in ground-state muonic hydrogen.

The JEDI Experiment: EDMs

Baryon Asymmetry Problem: New sources of CP violation can be seen in EDM of particles.

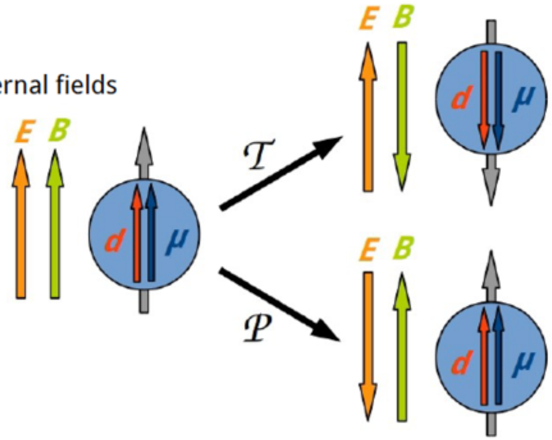
$\mathcal{CP}$-symmetry violation



$$\vec{d} = \eta \cdot \frac{q}{2mc}\vec{S}$$

$$\vec{\mu} = g \cdot \frac{q}{2m}\vec{S}$$

Pseudo vectors



The observable quantity - Energy:

- of electric dipole in electric field
- of magnetic dipole in magnetic field

$$H = H_M + H_E = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$P : H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

$$T : H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

H violates $\mathcal{T}$ and $\mathcal{P}$-symmetry if $d \neq 0$

⇓

$\mathcal{T}$ violation

⇓

$\mathcal{CP}$ violation ($\mathcal{CPT}$ conserved)

The JEDI Experiment: EDMs

JEDI goal is direct EDM measurement for charged particles: proton and deuteron
→ Very challenging technically!

OUTLOOK

2019 | COSY | 1st deuteron EDM measurement
Sensitivity: ~ 10^{-19} e·cm

Prototype ring

- Proof of principle
- Test deflectors/instrumentation
- Check lifetime
- Test CW/CCW operation
- Test frozen spin (additional B-field at low energy)

? | Dedicated ring | Highly sensitive EDM measurement

Maria Zurek

WG4 Speakers

- M. Lancaster
- Angela Papa
- Frederik Wauters
- Daiki Nagao
- Manabu Moritsu
- Steve Boi
- Craig Group
- Jaroslaw Pasternak
- Jarek Kaspar
- Daisuke Nomura
- Wing Sheung Chan
- Diego Beghin
- Francesca Dordei
- Steffen Strauch
- Chao Gu
- Sohtaro Kanda
- Hajime Nishiguchi
- Anna Soter
- Diktys Stratakis
- Maria Zurek
- Joe Sato
- Stoyan Trilov

Thanks to all the speakers for their contributions!

Focus Questions for WG4:

Color code:

Q1: Neutrino/Muon Physics: (Overlaps with WG1 and WG5)

- What overlaps exist to non-standard model neutrino interactions?
- How would these manifest in both the near term muon/precision measurements sector & in the neutrino sector?

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

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

Q3: Program Planning: (Overlaps with WG3)

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

Conclusions

- Successful muon working group!
- Great attendance including many leaders in the field.
- Some productive topics of discussion:
  - What additional measurements or searches are being considered at planned muon experiments?
  - What future upgrades are being considered for MEG, Mu2e, and Mu3e?
  - Worked to streamline focus questions for NuFact 2019.
  - Would like theory talks involving models that could solve neutrino and muon anomalies. What would these models mean for CLFV experiments? g-2?
- The muon working group is a somewhat unique aspect for NuFact, lacking from many other neutrino workshops.
- WG4 includes a **rich physics program** that naturally correlates with neutrinos from accelerators.

Suggested WG4 2019 Focus questions:

Q1: Neutrino/Muon Physics: (Overlaps with WG1 and WG5)

- What overlaps exist to BSM neutrino interactions?
- How would BSM physics manifest in the muon/precision measurements sector and in the neutrino sector?

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

- What sensitivity can be reached with current or future facilities? Improved detectors? Increased beam power? What are the implications?

Q3: Program Planning: (Overlaps with WG3)

- How do you support the physics needs for both DC and pulsed beam experiments in the planning of new facilities?