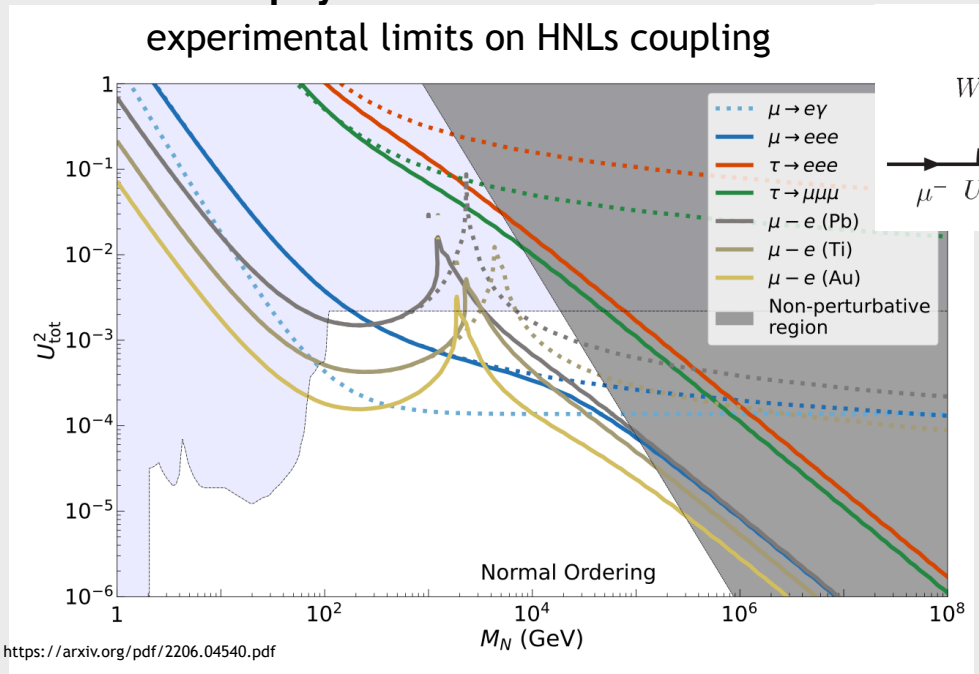
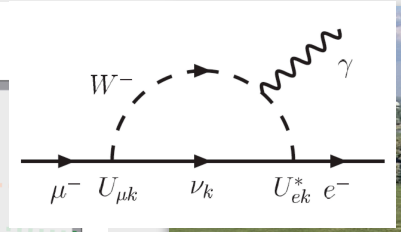
Muon Physics (WG4) summary

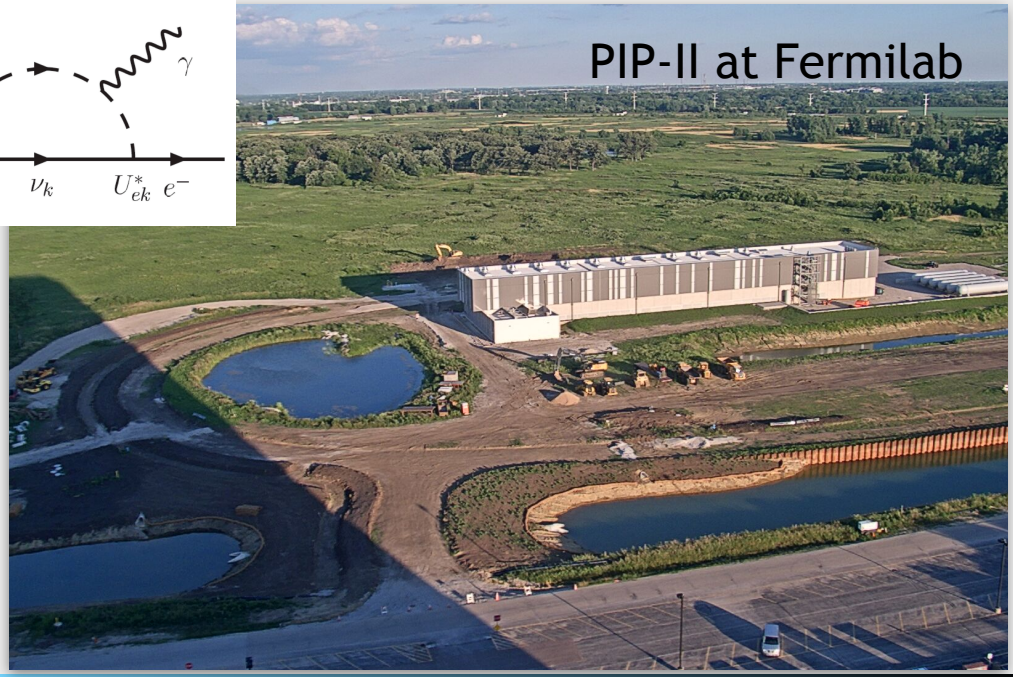
Yuri Oksuzian, Yuki Fuji, Gavin Hasketh

Muons at the neutrino conference

- Muons and neutrino beam follow a similar production mechanism
  - Dune is powered by PIP-II, but consumes only a tiny fraction of beam power
  - Other Intensity Frontier experiments like Mu2e-II will benefit from PIP-II
- We know Lepton Flavor Violation (LFV) occurs in neutrino sector
  - Are neutral and charged LFV related? Does CLFV arise from neutrino-mass generation mechanism?
  - **"Connection between neutrino mass models and muon experiments" by Julian Heeck in WG5**
- CLFV $\mu \to e + \gamma$ occurs at the rate $\sim 10^{-54}$ due to neutrino oscillation
  - Neutrino masses could be generated via New Physics: low-scale seesaws, SUSY seesaw...
- Various New Physics models suggest enhancement to $\mu \to e + \gamma$ rate
  - **An observation of CLFV would be an unambiguous sign of New Physics, and might shed light on neutrino physics**







Where is the new physics?

Craig Group

- We know the Standard Model is not complete
- So, where is the rest of the physics we need to complete it?
- **We don’t know!**
- We don't have a "no-lose" theorem to design our next discovery machine

Lepton flavour and CP violation beyond SM

Strong arguments in f(l)avour of New Physics!

Observations unaccounted for in SM: ν-oscillations, Dark matter, baryon asymmetry of the Universe (also some theoretical caveats...)

How to unveil the NP model at work?

⇒Test SM symmetries with flavour observables:

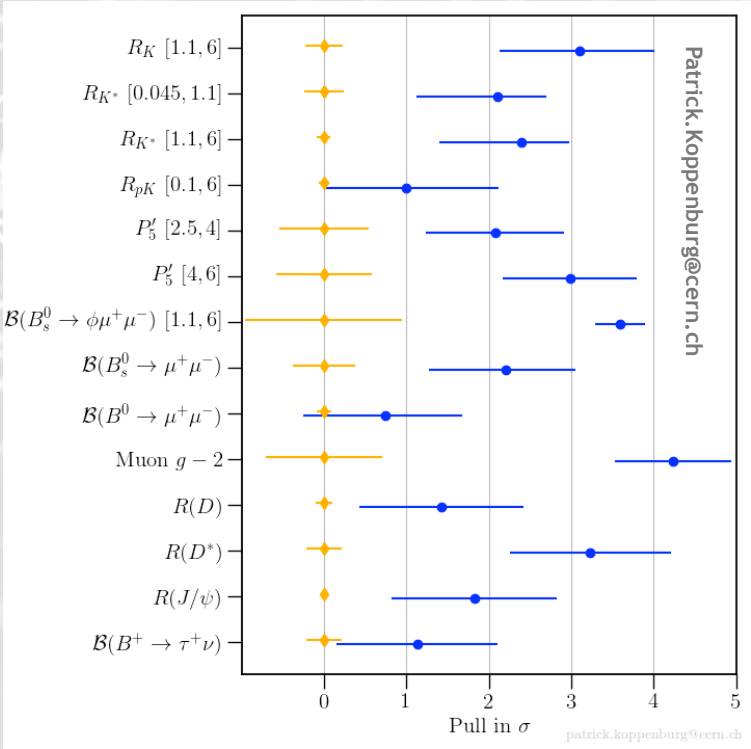
(c)LFV, lepton flavour universality violation, ...

ν-oscillations 1st laboratory *evidence* of New Physics!

- New mechanism of mass generation? Majorana fields?
- New sources of CP violation?

Currently many tensions with SM related to charged leptons

- $(g-2)_{\mu,e}$, B-meson anomalies, ...



Muons are uniquely versatile and sensitive probes of NP!

- Abundantly available, many different observables
- Unprecedented future experimental prospects

(See talks by Angela Papa & Kevin Lynch, and maaaaany WG4 contributions)

cLFV observables across all sectors and energies

Any **cLFV** signal necessarily implies the presence of **New Physics!**

- **"Purely" leptonic cLFV observables:** $\ell_\beta \to \ell_\alpha \gamma, \ell_\beta \to \ell_\alpha \ell_\gamma \ell_{\gamma'}$
  Most stringent exp. bounds: $\mathrm{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$, $\mathrm{BR}(\mu \to eee) \lesssim 10^{-12}$
- **Muonic atoms:** many **"nuclear-assisted"** cLFV observables
  e.g. neutrinoless $\mu - e$ conversion ($\mu^- N \to e^- N$) : $\mathrm{CR}(\mu - e, \mathrm{Au}) \lesssim 7 \times 10^{-13}$
- **Semi-leptonic cLFV τ decays:** $\tau \to P\ell', \tau \to V\ell'$; $\mathrm{BR}(\tau \to \phi\mu) \lesssim 8.4 \times 10^{-8}$
- **(Semi-) leptonic cLFV meson decays:** $M \to \ell_\alpha^\pm \ell_\beta^\mp$, $M \to M' \ell_\alpha^\pm \ell_\beta^\mp$;
  $\mathrm{BR}(K_L \to \mu^\pm e^\mp) \lesssim 4.7 \times 10^{-12}$, $\mathrm{BR}(B_{(s)} \to \ell_\alpha^\pm \ell_\beta^\mp) \lesssim \mathcal{O}(10^{-5})$
- **cLFV @ higher energies:** $Z \to \ell_\alpha^\pm \ell_\beta^\mp$, $H \to \ell_\alpha^\pm \ell_\beta^\mp$, high-p_T di-lepton tails $pp \to \ell_\alpha^\pm \ell_\beta^\mp$,
  $\mathrm{BR}(Z \to \ell_\alpha^\pm \ell_\beta^\mp) \lesssim \mathcal{O}(10^{-6})$

Future of CLFV Searches!!!

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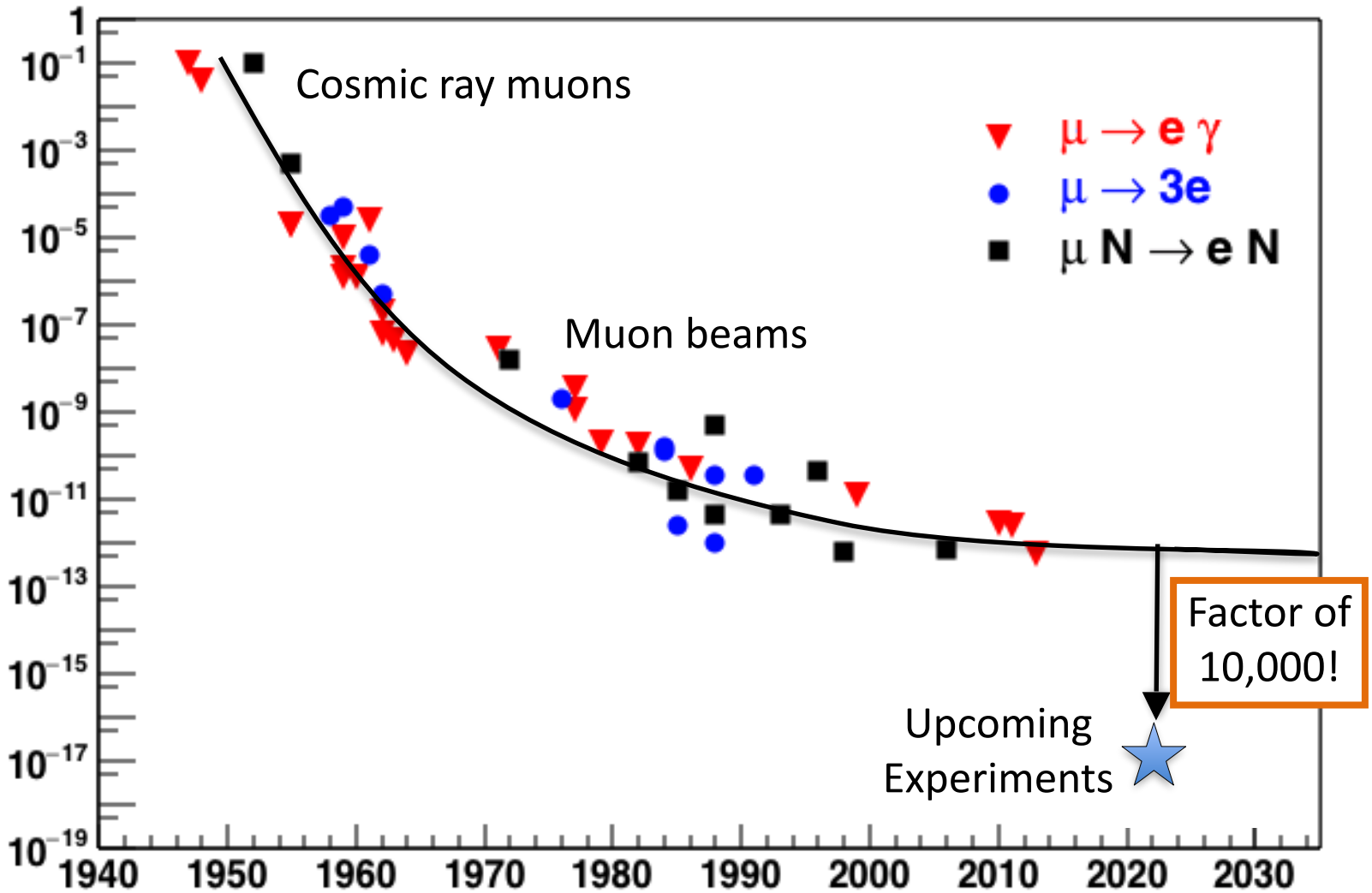
Craig Group

- We are living in a Renaissance for Muon Physics



Future CLFV experiments like Mu2e expect huge gains in sensitivity!

CLFV BSM physics

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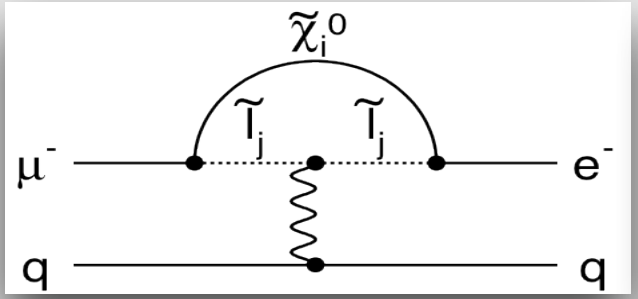
Effective CLFV Lagrangian

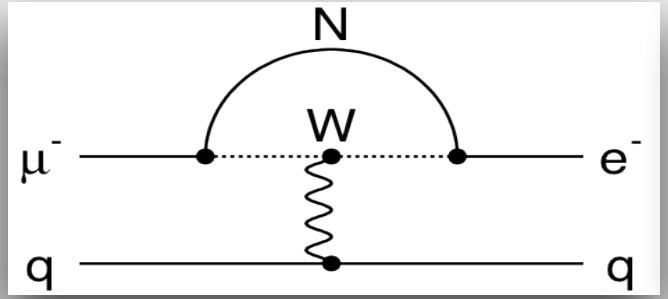
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$

Magnetic moment type operator

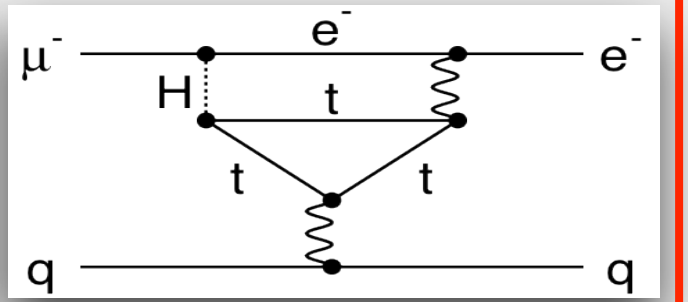
Supersymmetry



Heavy neutrinos

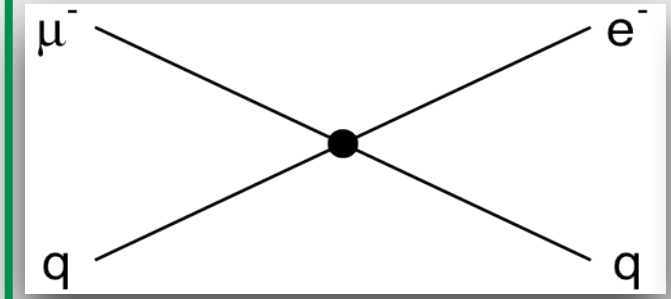


Two Higgs Doublets

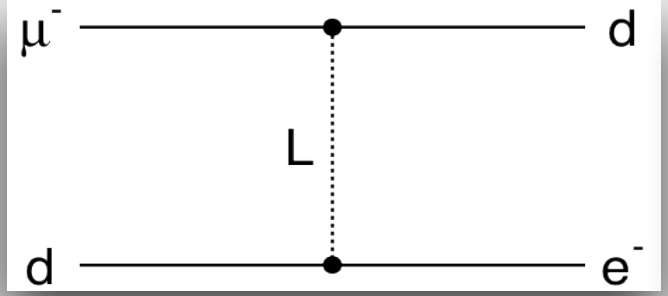


Contact term operator

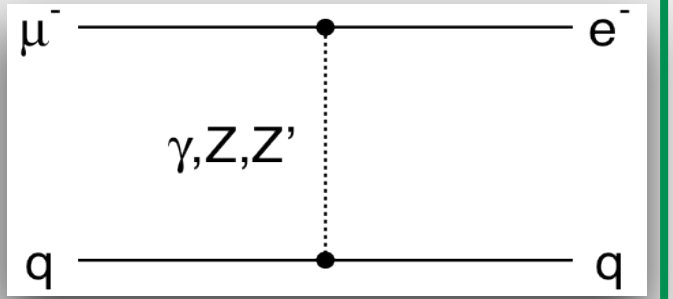
Compositeness



Leptoquarks



Heavy Z'

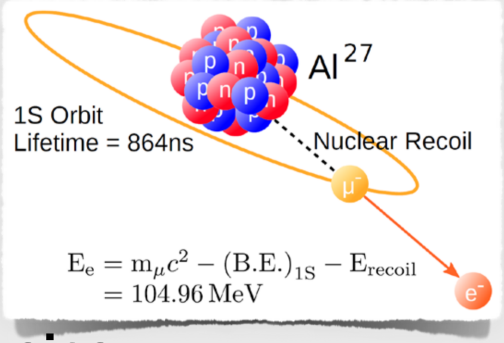


Mu2e: Concept

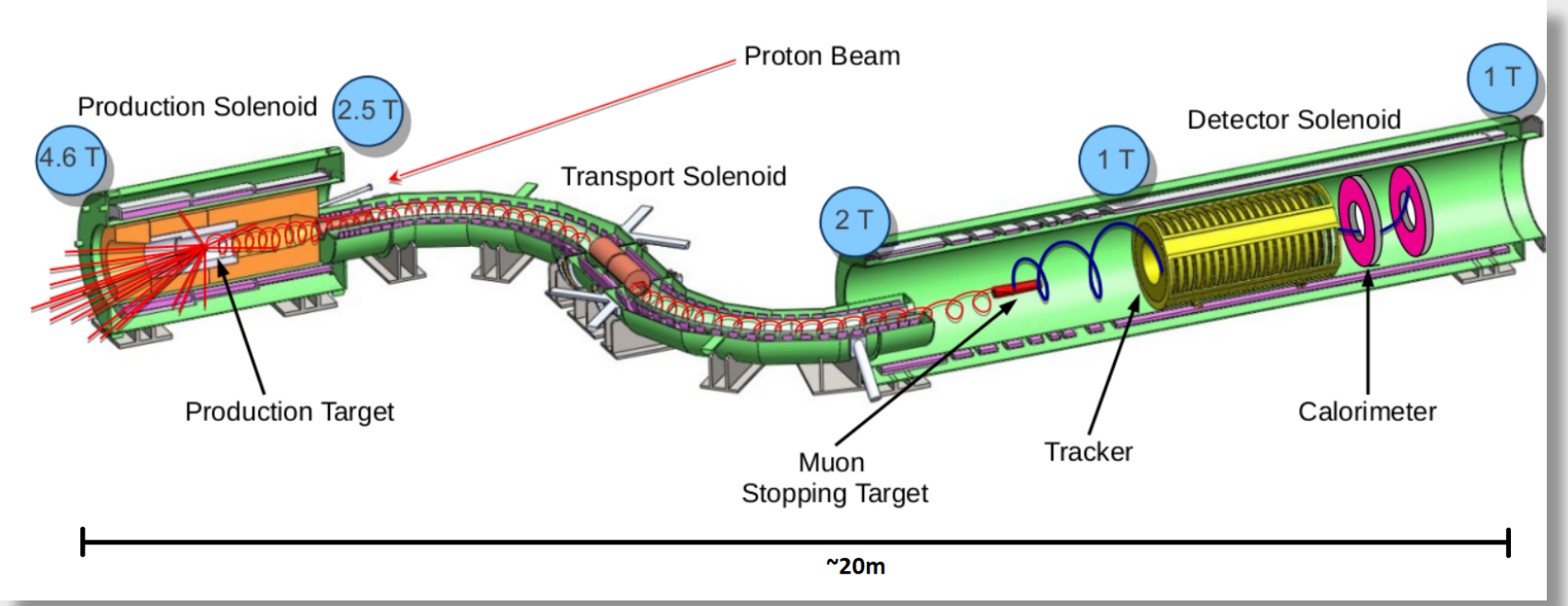
Craig Group

- Mu2e will search for a neutrino-less $\mu^- Al \rightarrow e^- Al$ conversion
- Improve the current limit on the conversion rate ($R_{\mu e}$) by **four orders** of magnitude:

$$R_{\mu\rightarrow e} = \frac{\Gamma\left(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A)\right)}{\Gamma\left(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A)\right)} < 6\times 10^{-17} \text{ (90\% CL)}$$



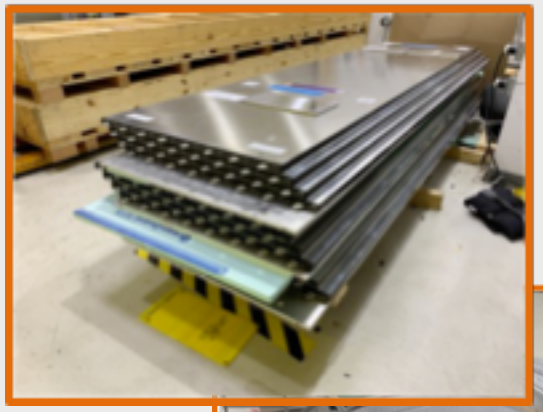
- Mu2e will produce and stop 7×10^{18} muons on aluminum foils
  - Searching for ~105 MeV electrons originating from the stopping target
  - In SM, $\mu^- N \rightarrow e^- N$ is *practically* forbidden ($R_{\mu e} \sim 10^{-54}$)
- **Signal observation at Mu2e is unambiguous sign of New Physics**

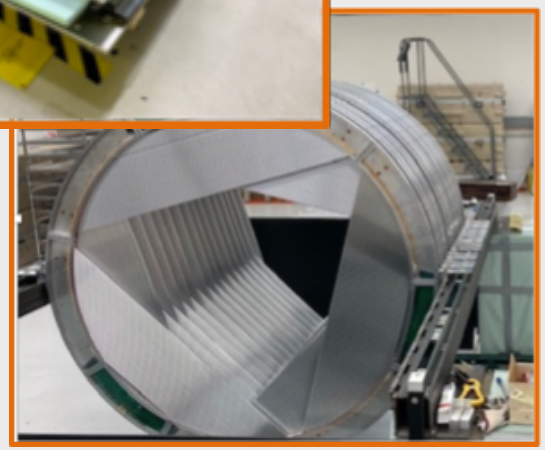


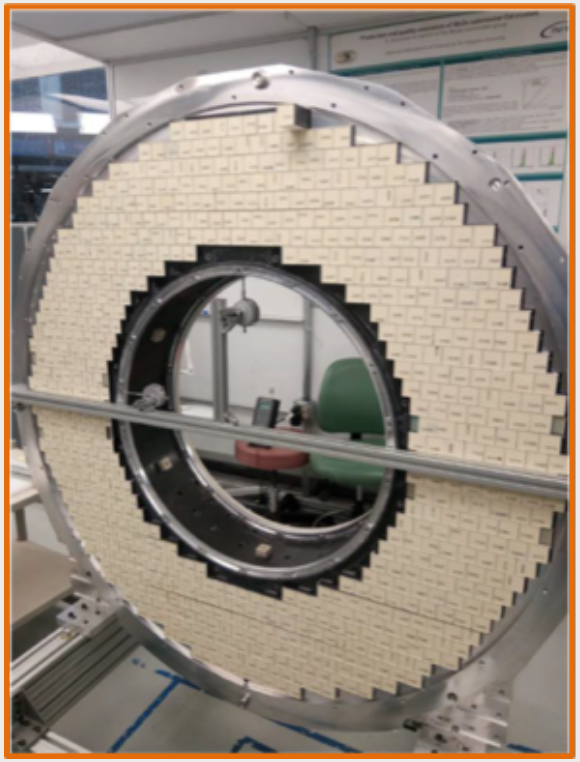
Mu2e: Status

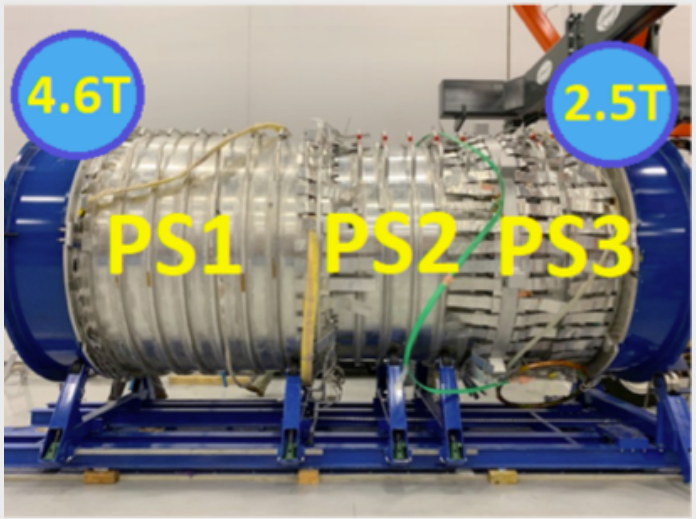
Craig Group

- Large fraction of Mu2e components have been fabricated
- Recently delivered protons to diagnostic absorber
- Detector commissioning through late 2024
- Take Run 1 data in 2025(6) until LBNF shutdown
  - x1000 improvement over SINDRUM-II
- Resume data collection in 2029





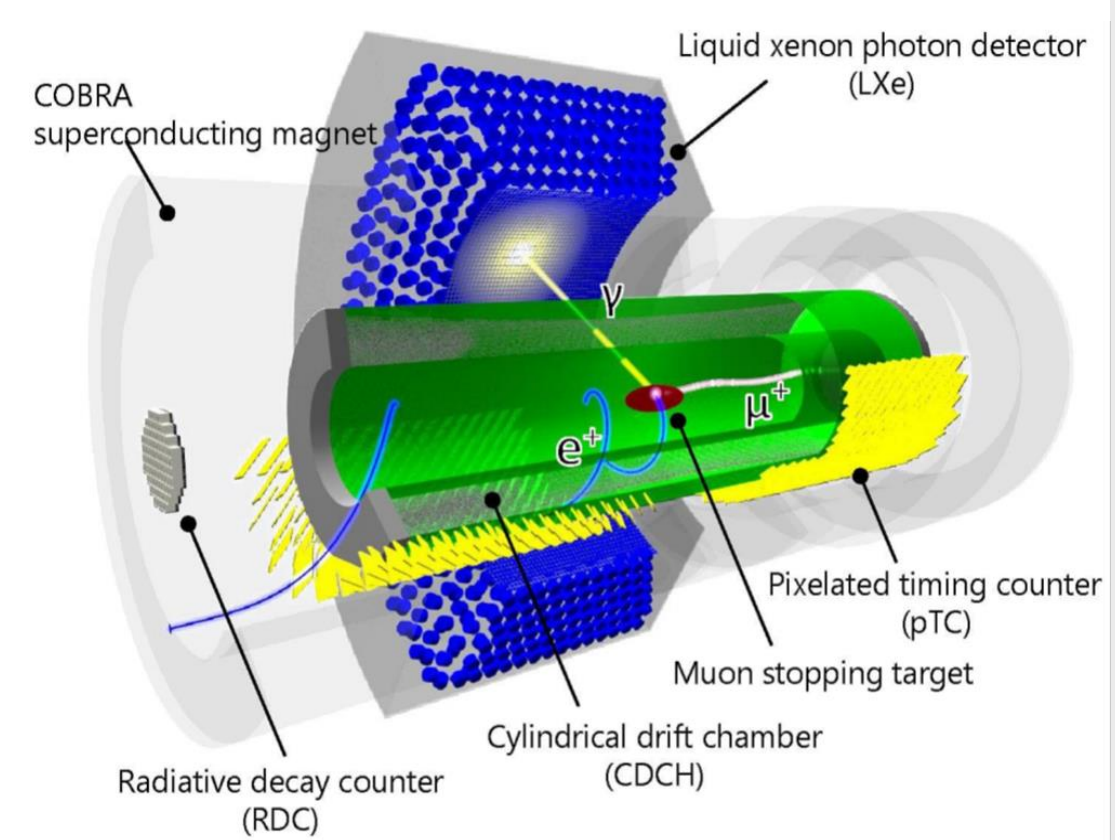


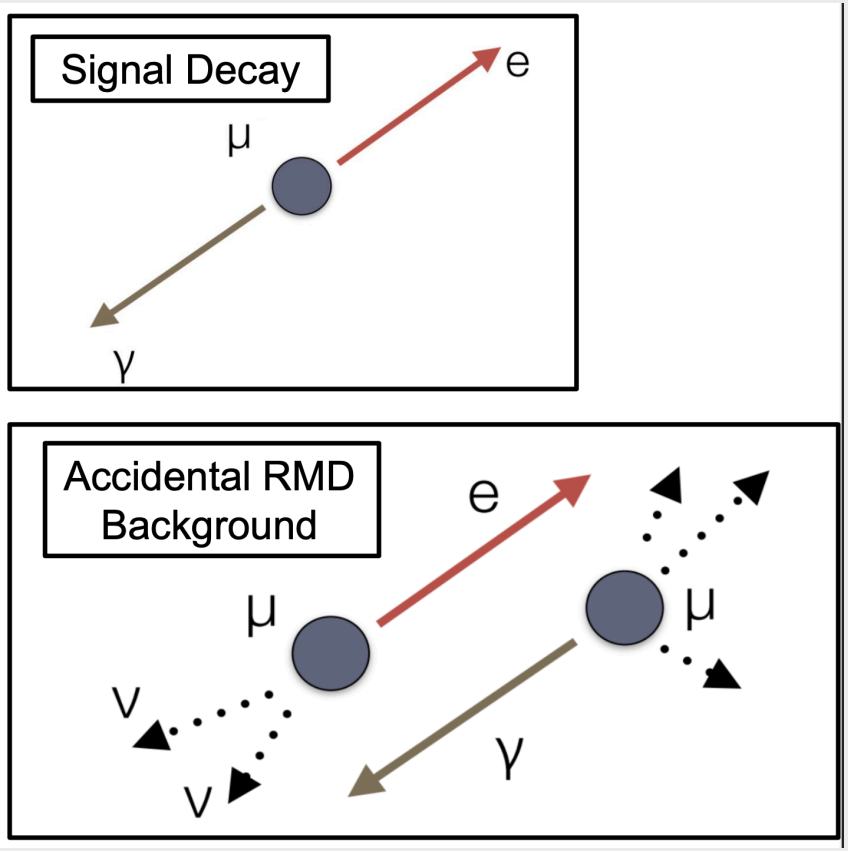


MEG-II: Concept

Dylan Palo

- MEG-I at PSI set the limit of $\mu \rightarrow e\gamma$ conversion to $4.2 \times 10^{-13} @ 90\,\%\, CL$
- MEG-II aims to increase the sensitivity by **an order** of magnitude
  - Similar design to MEG I, but all detectors have been upgraded
- Protons of 590 MeV produce un-bunched surface μ^+ at $\sim 7 \times 10^7 Hz$





MEG-II: Status

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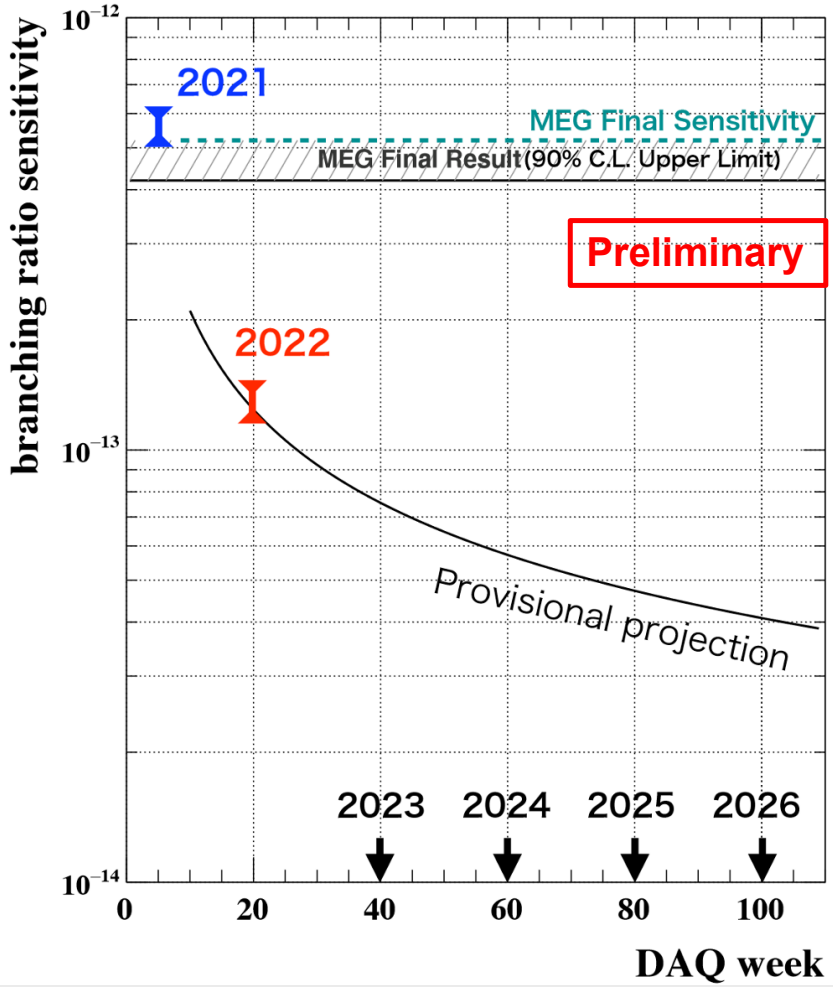
Dylan Palo

- In 2021, MEG-II had the first physics run with a complete set of instrumented electronics
- Much work ongoing to improve detector resolution (CDCH wire alignment, magnetic field, LXe calibration, algorithm optimization, etc.)

- MEG II 2021 dataset expected to approach the sensitivity limit set by MEG I
- MEG II 2021+2022 expected to surpass MEG I by a factor of ~4
- *Sensitivity hasn't yet been updated to reflect updated resolutions

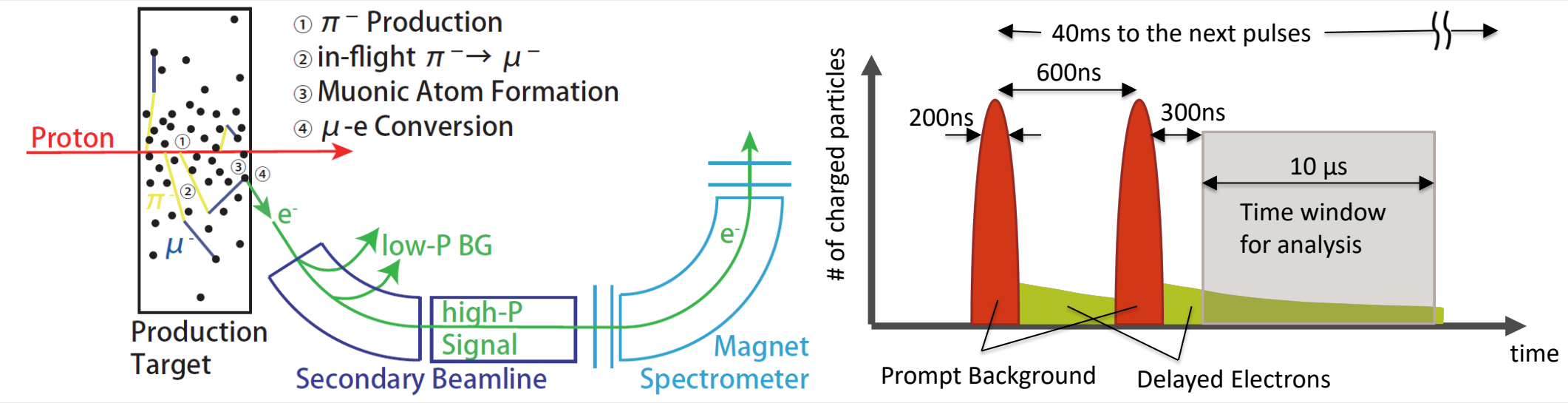
Dataset	Sensitivity (10^{-13})
MEG I Sensitivity	5.3
MEG II Preliminary 2021 Sensitivity Estimate	5.3-6.1
MEG II Preliminary 2021+ 2022 Sensitivity Estimate	1.2−1.4



Deeme: Concept

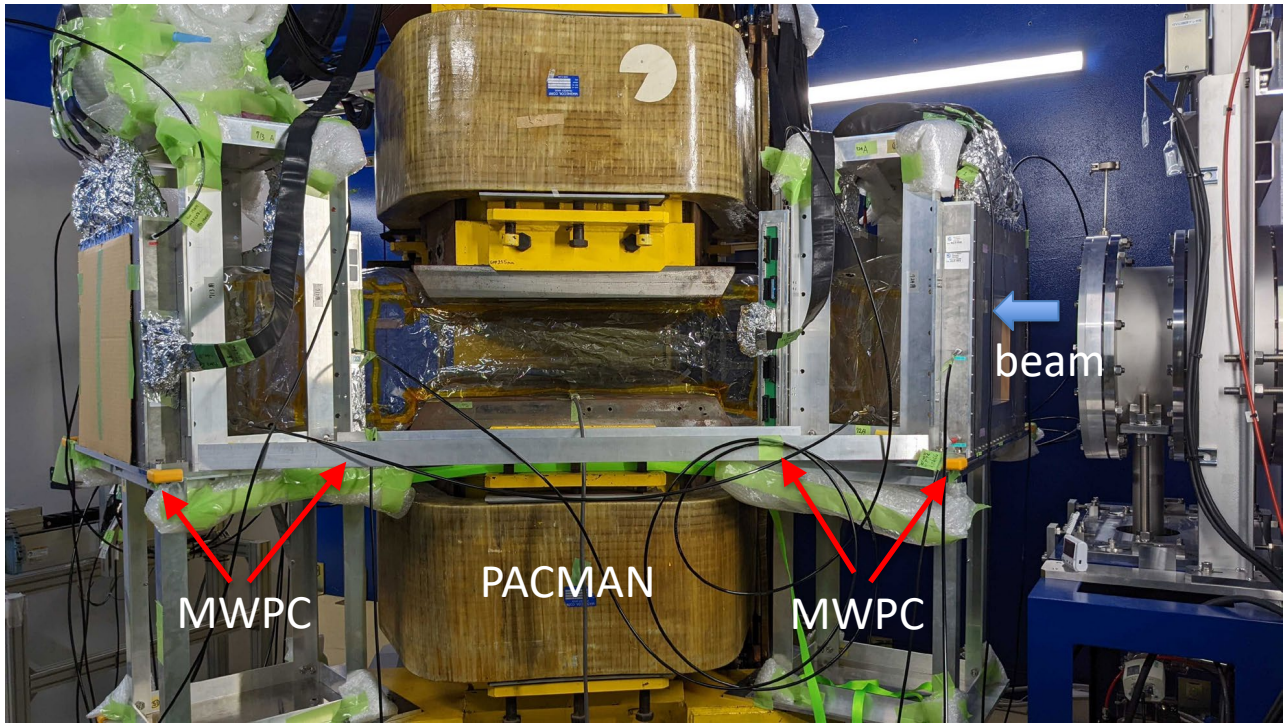
Kazuhiro Yamamoto

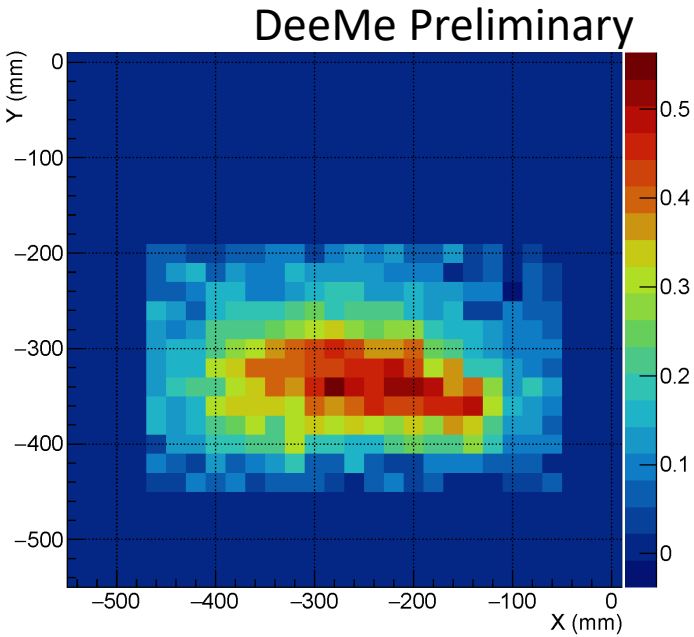
- Deeme will search for a neutrino-less $\mu^- C \rightarrow e^- C$
- Improve the current limit on $R_{\mu e}$ by an order of magnitude
- Transport signal electrons (105 MeV/c)
- Analyze momentum with spectrometer dipole magnet & MWPC)
- Main backgrounds: Decay In Orbit, delayed protons
  - Beam induced backgrounds (RPC/RMC) are suppressed by delaying the search window by 300 ns
  - Cosmic background is negligible due to short livetime
  - Beam energy is 3 GeV => $\bar{p}$ background is zero



Deeme: Status

- The DeeMe commissioning run was performed in June 2022. Kazuhiro Yamamoto
- Every system worked well.



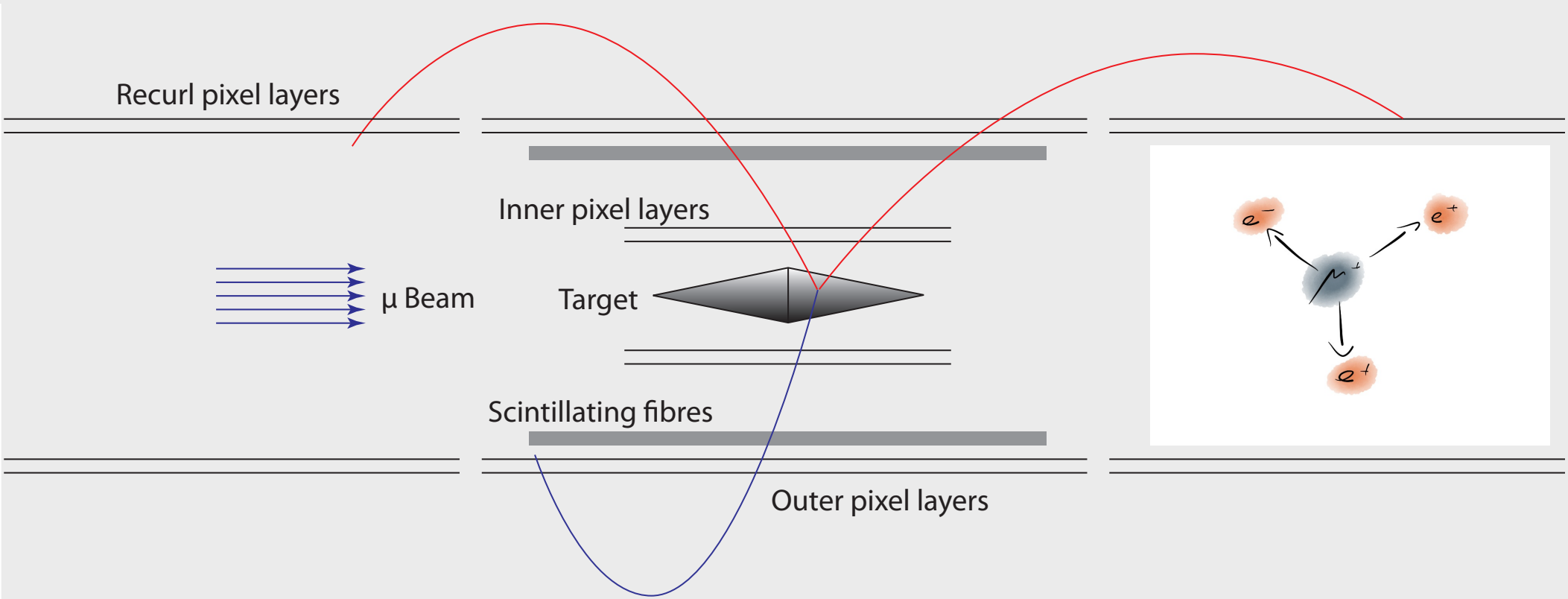


Prompt burst
105 MeV/c electron
beam profile

- Ready to take physics data.

Mu3e: Concept

Ann-Kathrin Perrevoort



- Muons stopped on target $\rightarrow$ decay at rest
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel sensors

Mu3e: Goals and Status

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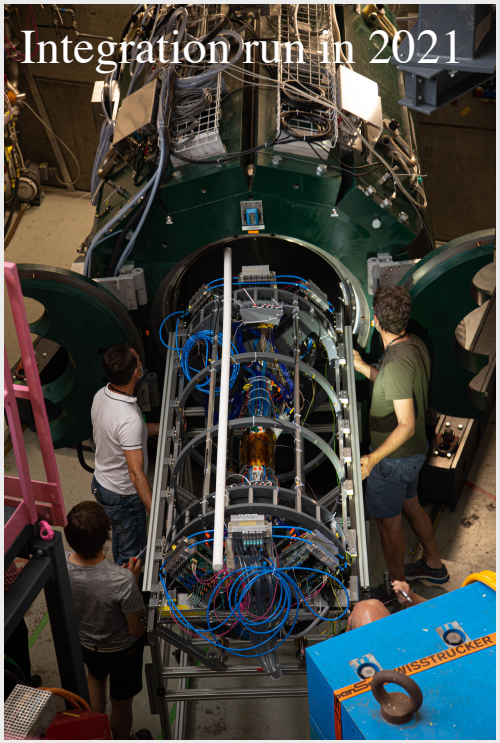
Ann-Kathrin Perrevoort

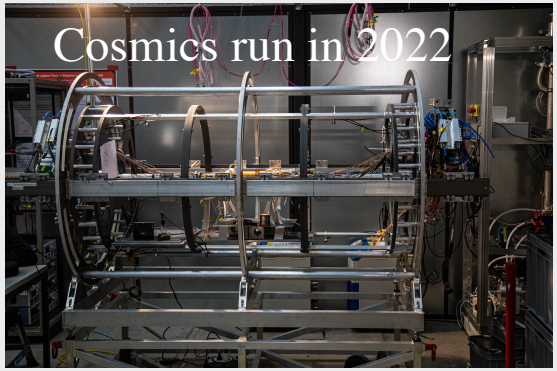
- Current strongest limit
  $\mathscr{B}(\mu \to eee) < 1.0 \times 10^{-12}$ (SINDRUM, 1988)
- Mu3e will perform a background-free search for $\mu \to eee$ and aims to find or exclude with a sensitivity in $\mathscr{B}$ of

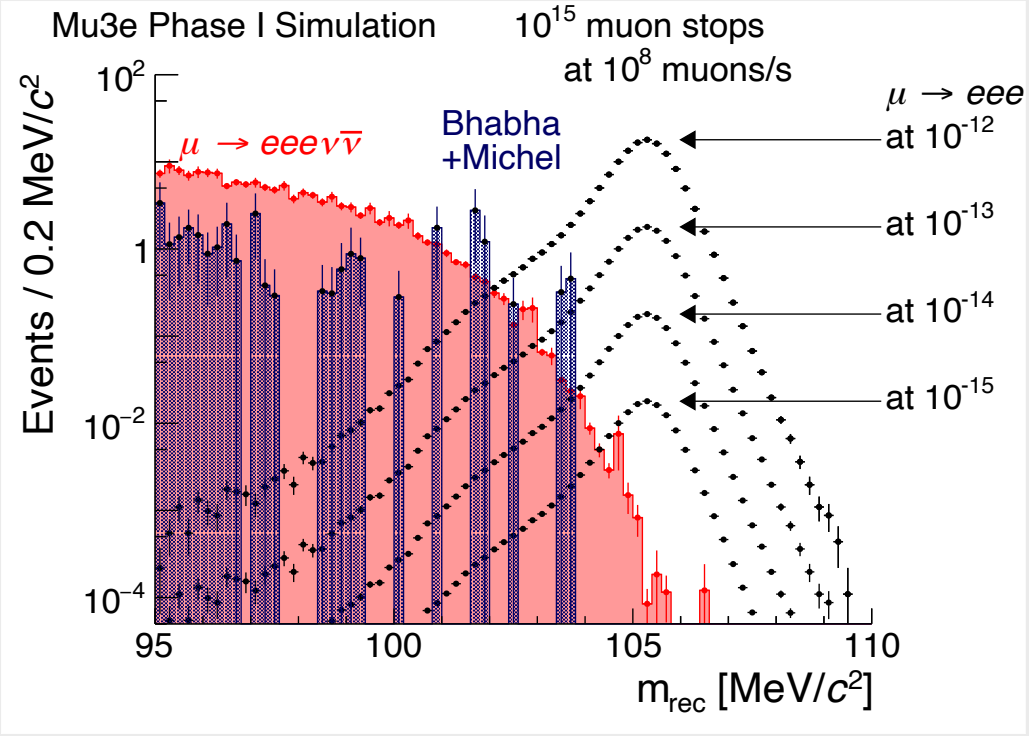
a few 10^{-15} in phase I

10^{-16} in phase II

Planning for final commissioning and first data in 2024







COMET: Concept

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Sam Dekkers

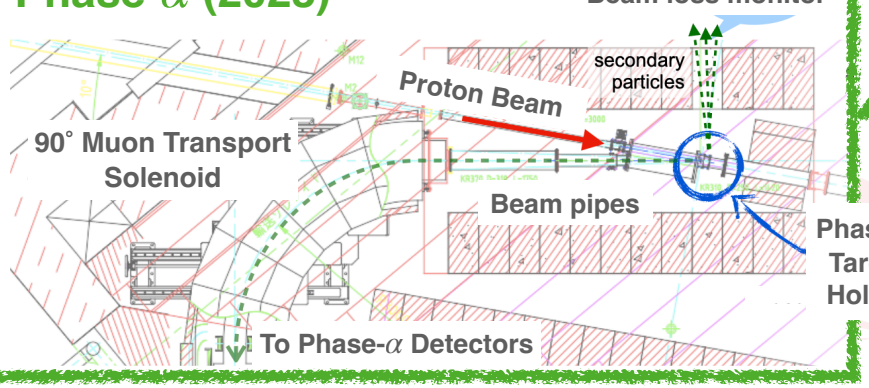
- COMET@JPARC search for a neutrino-less $\mu^- Al \rightarrow e^- Al$

The COMET Experiment

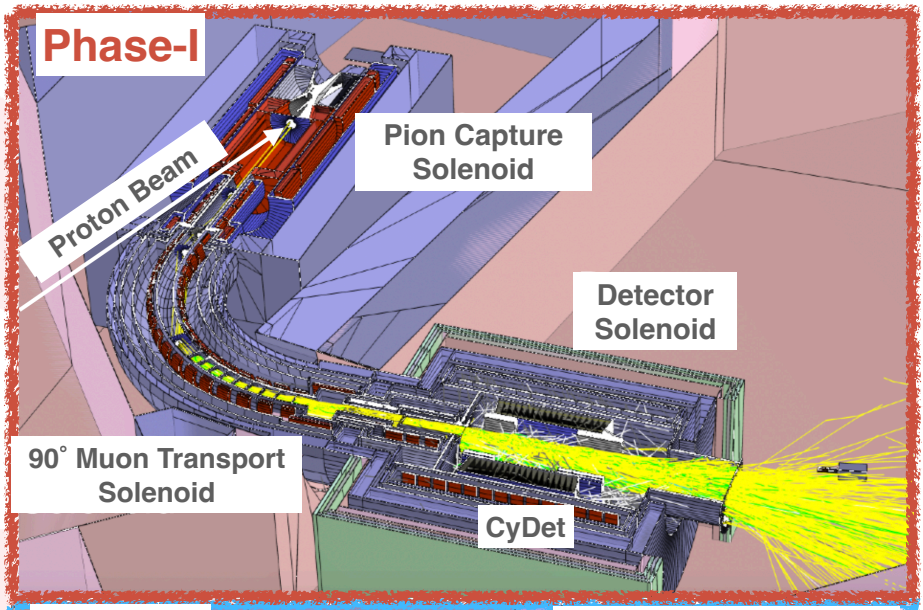
Staged Approach

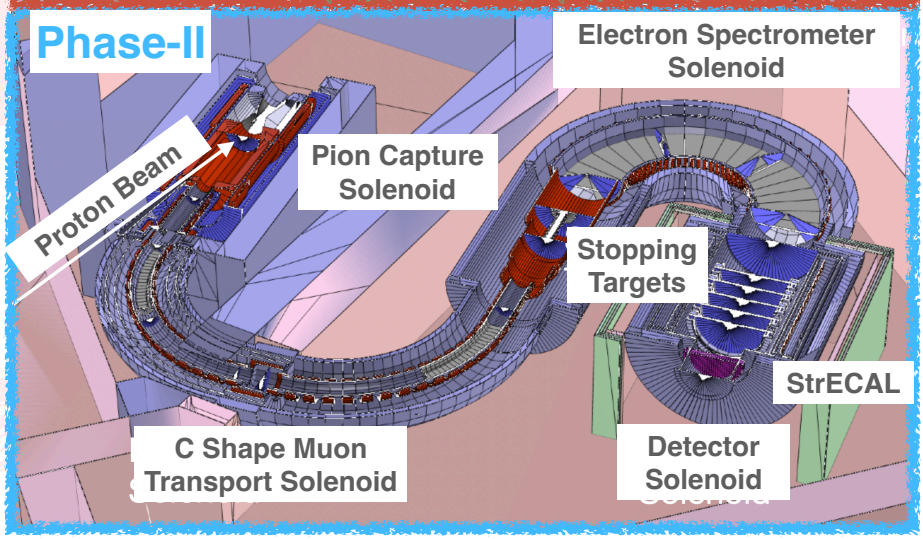
	Phase-I (2024)	Phase-II
SES	3.1×10^{-15}	1.4×10^{-17}
Proton Beam	8 GeV (3.2 kW)	8 GeV (56 kW)
Transport Solenoid	90˚ bend	C-shape
Stopped Muons	1.5×10^{16}	1.6×10^{18}
Runtime	150 days	260 days
Detectors	CyDet (physics) StrECAL (beam + background)	StrECAL (physics)

Phase-α (2023)



Initial low intensity beam run





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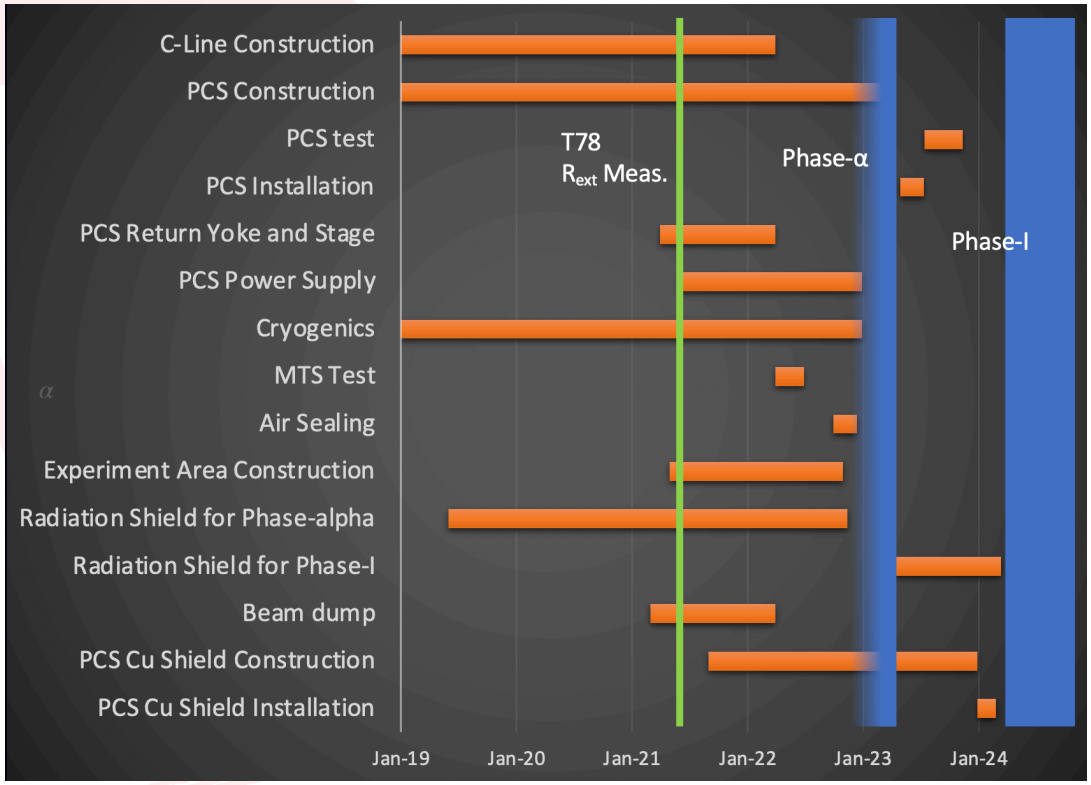
Sam Dekkers

Timeline

- All key facility and detectors on schedule for Phase-α (**2023**) and Phase-I (**2024**)
- Facility beamline to be ready for Phase-α (**2022**)
- Phase-I detectors:
  - CyDet - CDC moving to J-PARC (**2022**) and CTH construction (**2023**)
  - Phase-I StrECAL (**2023**)
  - CRV (**2023**)
- Phase-II following on from Phase-I, R&D efforts progressing now



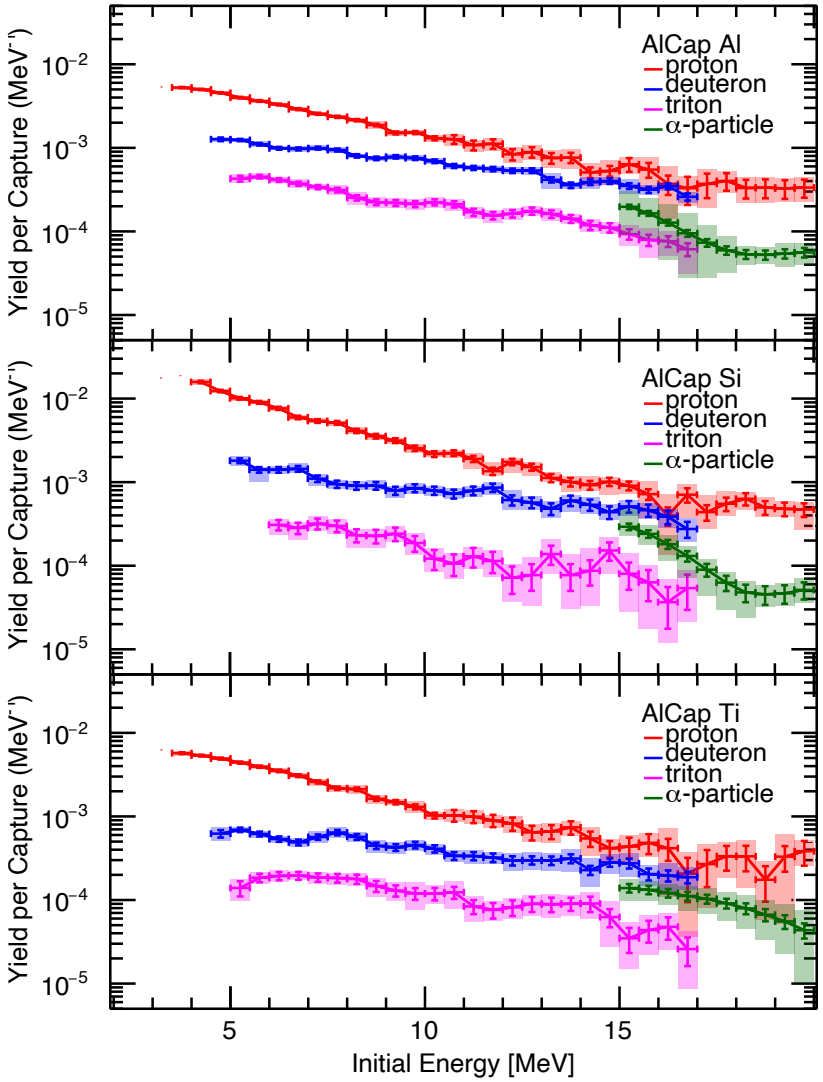
Facility timeline in lead up to Phase-α and Phase-I

26

AlCap

Andrew Edmonds

- The AlCap experiment is a joint venture between members of Mu2e and COMET to measure the yield and spectrum of individual charged particles after nuclear muon capture
- Ran at PSI and collected charged particle data on Al, Si and Ti



Results published in
Phys.Rev.C 105 (2022) 3, 035501

Found that **yields for Al were significantly lower than COMET/Mu2e had assumed**

- COMET Phase-I will forgo a proton absorber
- Mu2e proton absorber will be thinner and shorter than originally planned

g-2/EDMs

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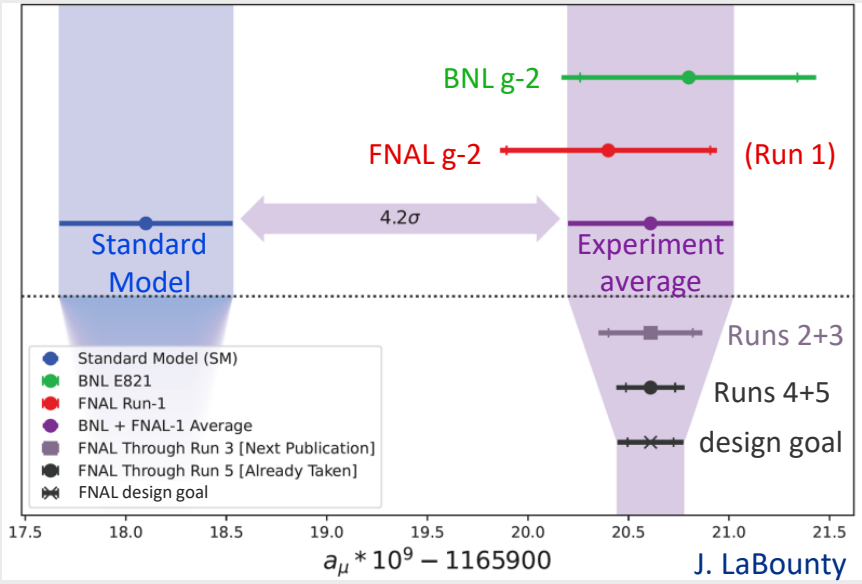
Brynn MacCoy

Fermilab Muon g-2 experiment

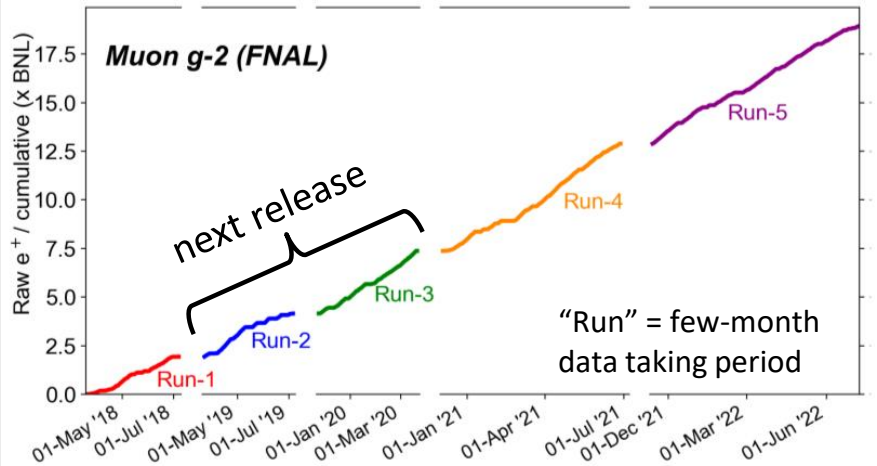
- 2006: BNL g-2 measured a_μ to 540 ppb
- 2021: FNAL g-2 measured a_μ to 460 ppb
- Combined 4.2σ discrepancy between experiment and SM prediction
- Fermilab g-2 goal: 4× higher precision than BNL



140 ppb total → 100 ppb systematic (2.8× improvement)

140 ppb total → 100 ppb statistical (4.6× improvement, 20× more muons)

- Experiment status
  - Finished Run 5 in July 2022
  - Run 2+ analysis in progress
  - Run 6 (final run) to start in fall



Very close to 20× BNL goal!

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Brynn MacCoy

Standard model prediction for muon a_μ

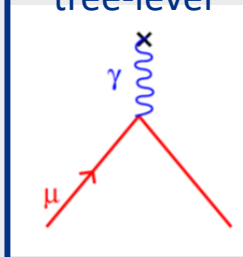
Theory prediction: include all Standard Model interactions

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$

Correction	Value (Error) $\times 10^{11}$	Error [ppb]
QED	116 584 718.931(104)	0.9
EW	153.6(1.0)	9
HVP	6845(40)	343
HLbL	92(18)	154
Total a_μ^{SM}	116 591 810(43)	369

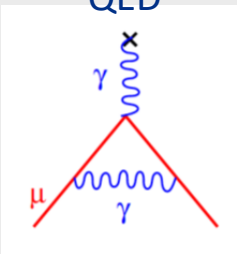
Muon g-2 Theory Initiative recommended values
T. Aoyama et. al., Phys. Rept. 887 (2020) 1-166

tree-level



g=2

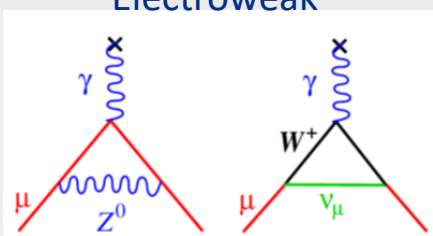
QED



Schwinger: $a \to \alpha/2\pi$

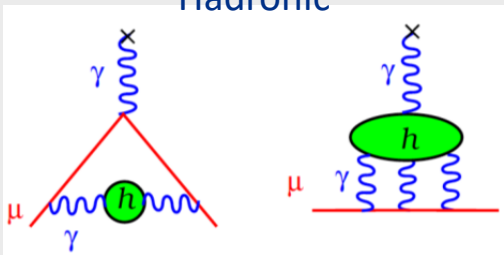
- Leptons, photons
- Terms to $O(\alpha^5)$

Electroweak



- Corrections $\sim m_\mu^2/M_W^2$
- W, Z, Higgs bosons

Hadronic



Hadronic vacuum polarization (HVP)

Hadronic light-by-light scattering (HLbL)

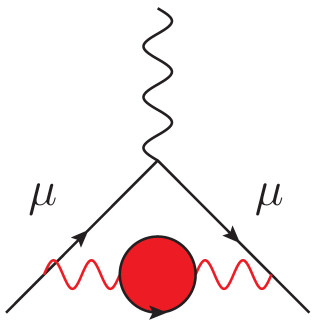
- Difficult because QCD nonperturbative
- HVP calculated from $e^+e^- \to$ hadrons cross section data
- HVP lattice calculations approaching required precision, in tension with data-driven calculations

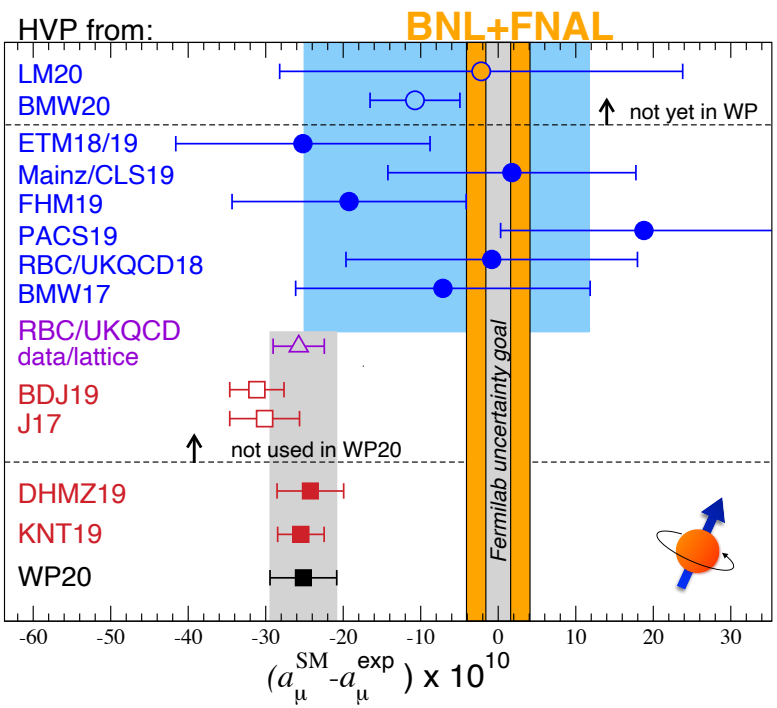
The SM value & HVP contribution

Javad Komijani

Progress to improve HVP precision:

- Current approaches:
  - Data-driven approach based on dispersive relations
  - Lattice QCD: calculations in progress
- New approaches: MUonE Experiment





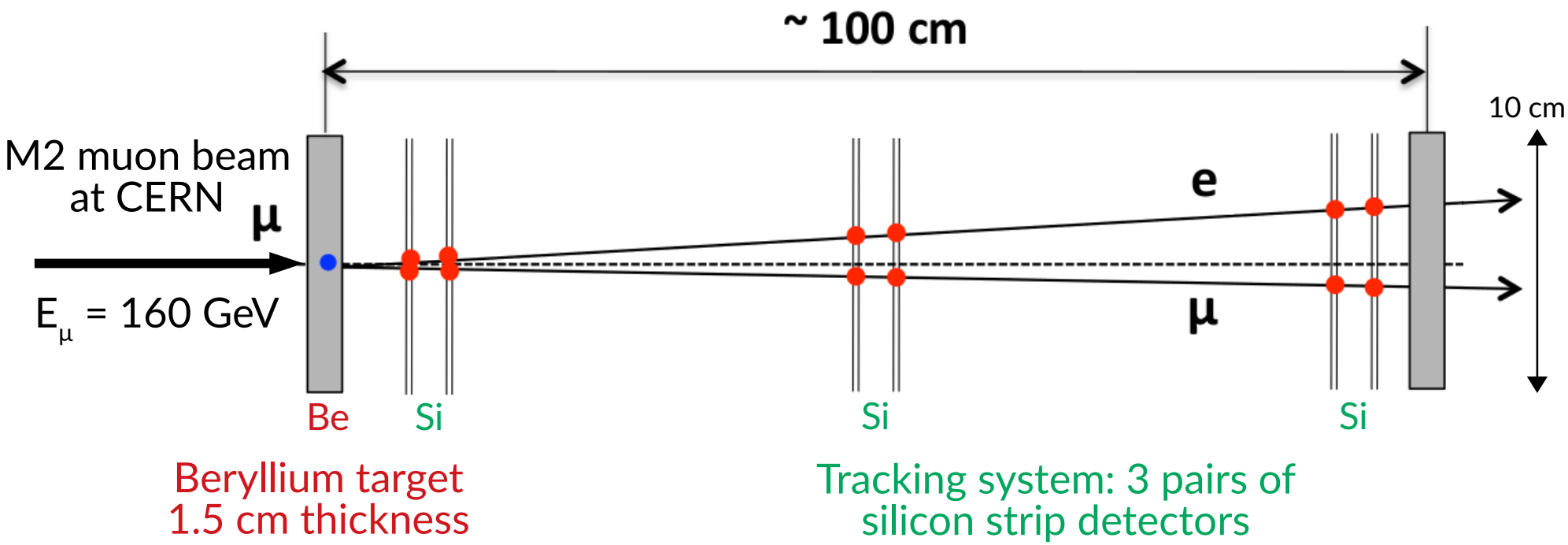
red: data-driven results
blue: lattice-QCD calculations
blue band: lattice-QCD average (WP20)
black: (& gray band) the SM prediction (WP20)
filled: included in WP20
open: not included in WP20

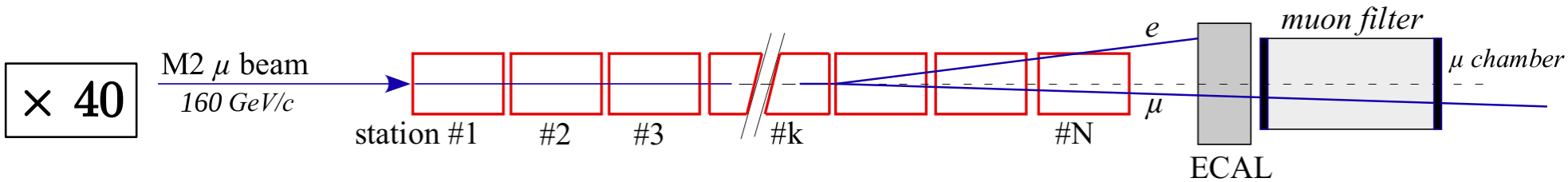
[image: arXiv:2203.15810 (Snowmass 2021)]
[WP20: arXiv:2006.04822]

MuonE

Lorenzo Capriotti

- Test run with 3 stations + calo is expected in 2023

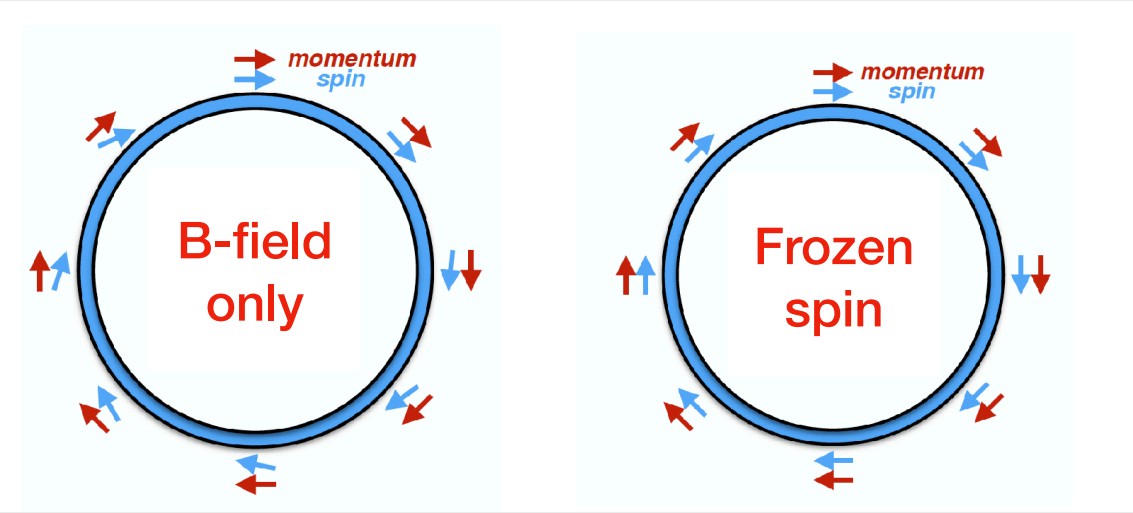


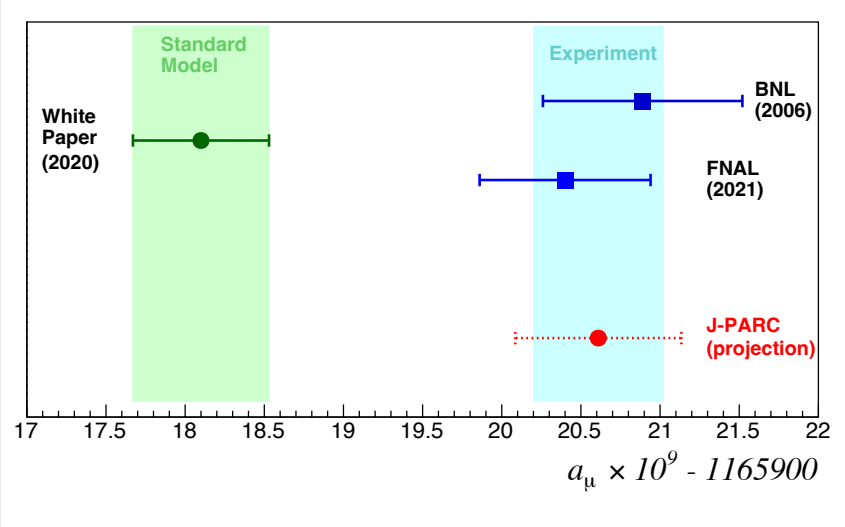


EDM

- EDMs provide a unique window into fundamental particles and their interactions
- Flavour anomalies could point to new physics which relax the constraints on the size of the muon EDM

- The Run-1 muon EDM search at Fermilab is nearing completion (Sam Grant)
- J-PARC g-2/EDM will start data taking in 2027 (Ce Zhang)
- Freeze g-2 component by applying a radial E-field (Kim Siang Khaw)
  - Up-down asymmetry measured using upper and lower detectors
  - Start phase-1 in the end of decade



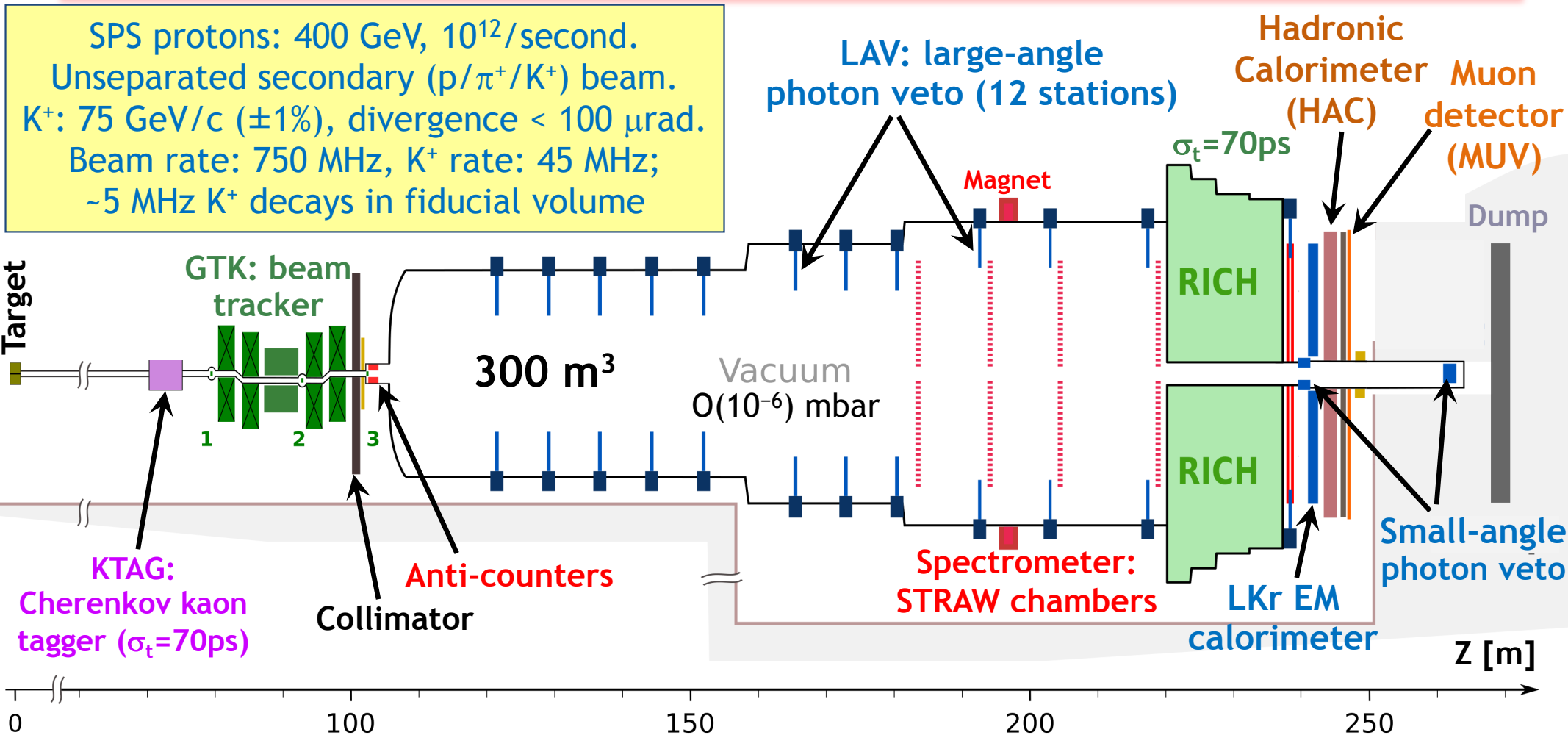


Colliders

NA62 collaboration, JINST 12 (2017) P05025

The NA62 experiment

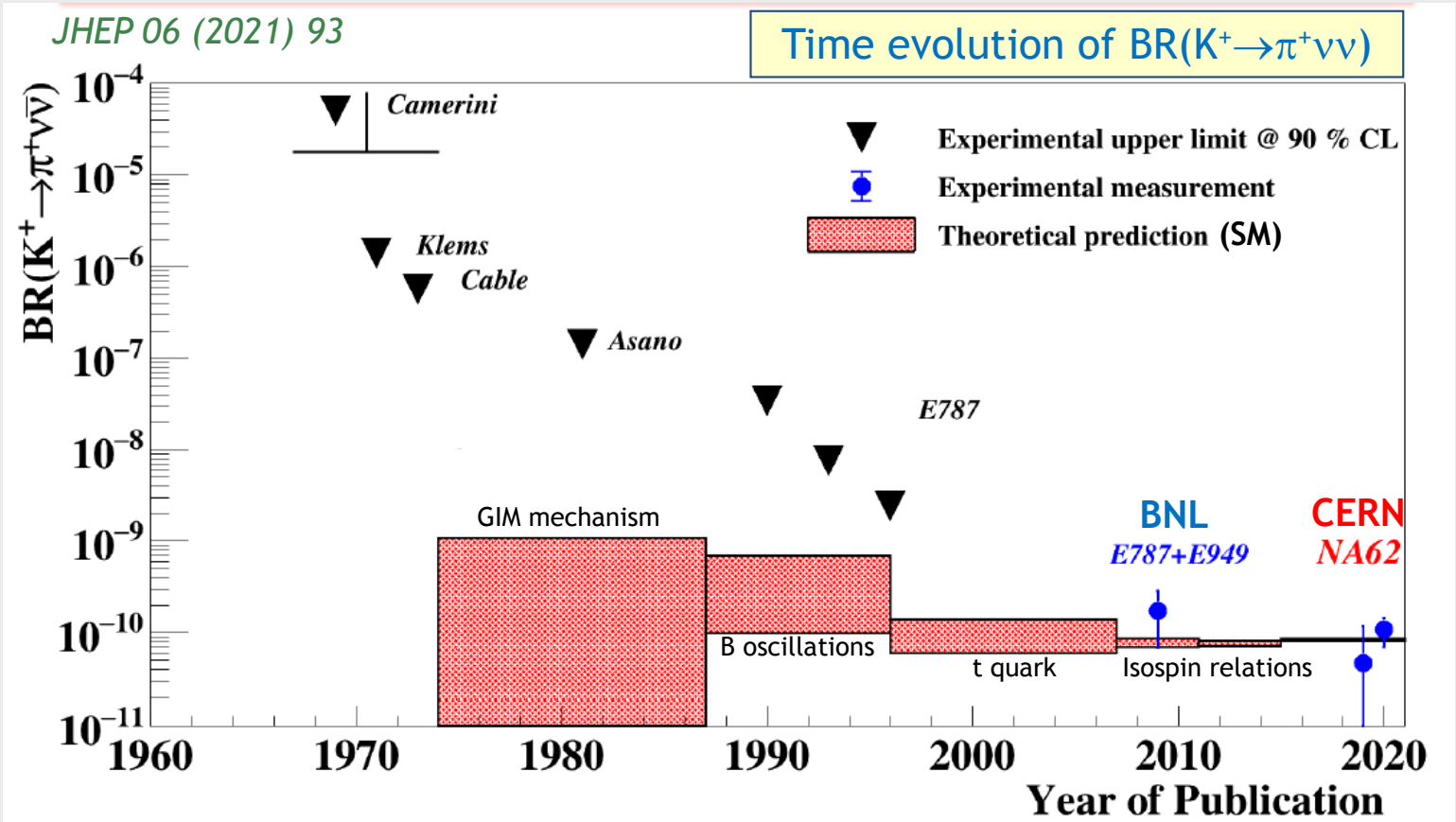
SPS protons: 400 GeV, 10^{12}/second.
Unseparated secondary ($p/\pi^+/K^+$) beam.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- In 2018, 1 year of operation ≈ 10^{18} protons on target; 4×10^{12} K^+ decays.
- Single event sensitivities for K^+ decays: approaching BR~10^{-12}.
- Kinematic rejection factors: 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi0}$>40 GeV) ~10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62

- Broad physics program in rare Kaon decays: HNL, hidden sector, LNV searches
  - No significant BSM excesses observed
- A long-term K^+ and K_L program ("HIKE") is taking shape at CERN
  - SPS fixed target operation foreseen until at least 2038



NA62 Run 1: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$

(3.4σ significance)

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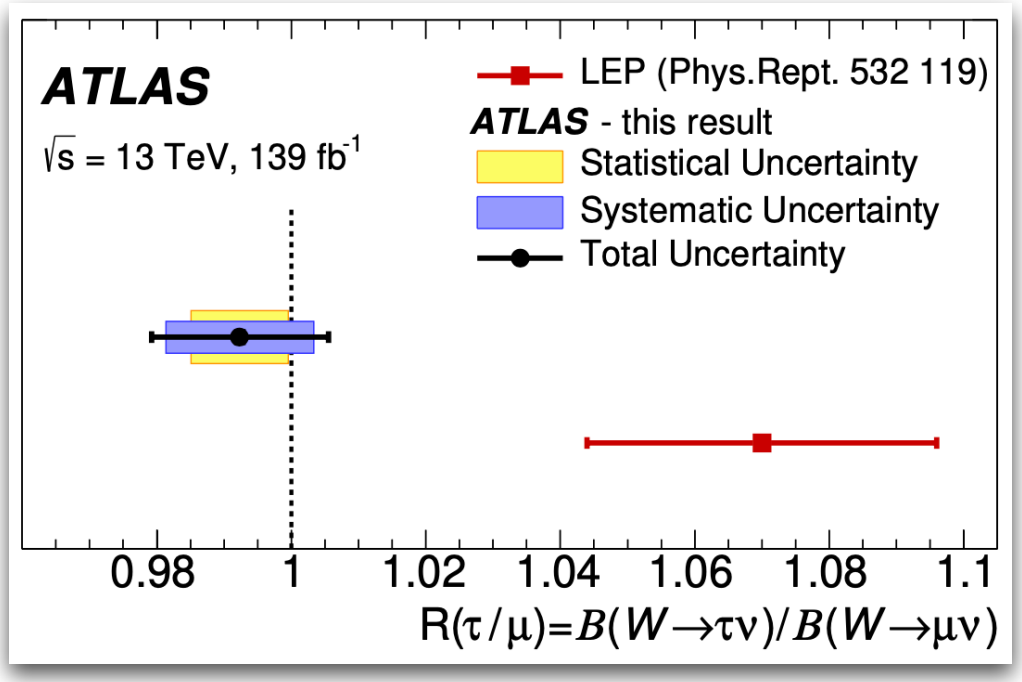
E. Goudzovski / NuFact 2022, 4 August 2022

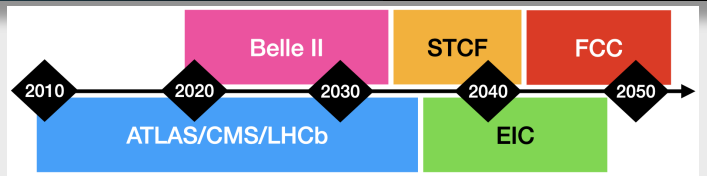
LFU test in $W\tau/\mu$ [Nat. Phys. 17 (2021) 813]

Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
μ_{prompt} and $\mu_{\tau(\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalisation	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_T spectum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\to\mu)}$ and μ_{had} d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalisation	0.0009
Other sources	0.0004
$B(\tau \to \mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**



This result surpasses the precision of the previous LEP result and resolves the tension they observed with the SM prediction of LFU

- Belle-II: e+e- B-factory operating mainly at 10.58 GeV: Y(4S)
- One of the results: will deliver the strongest limit in tau CLFV decays

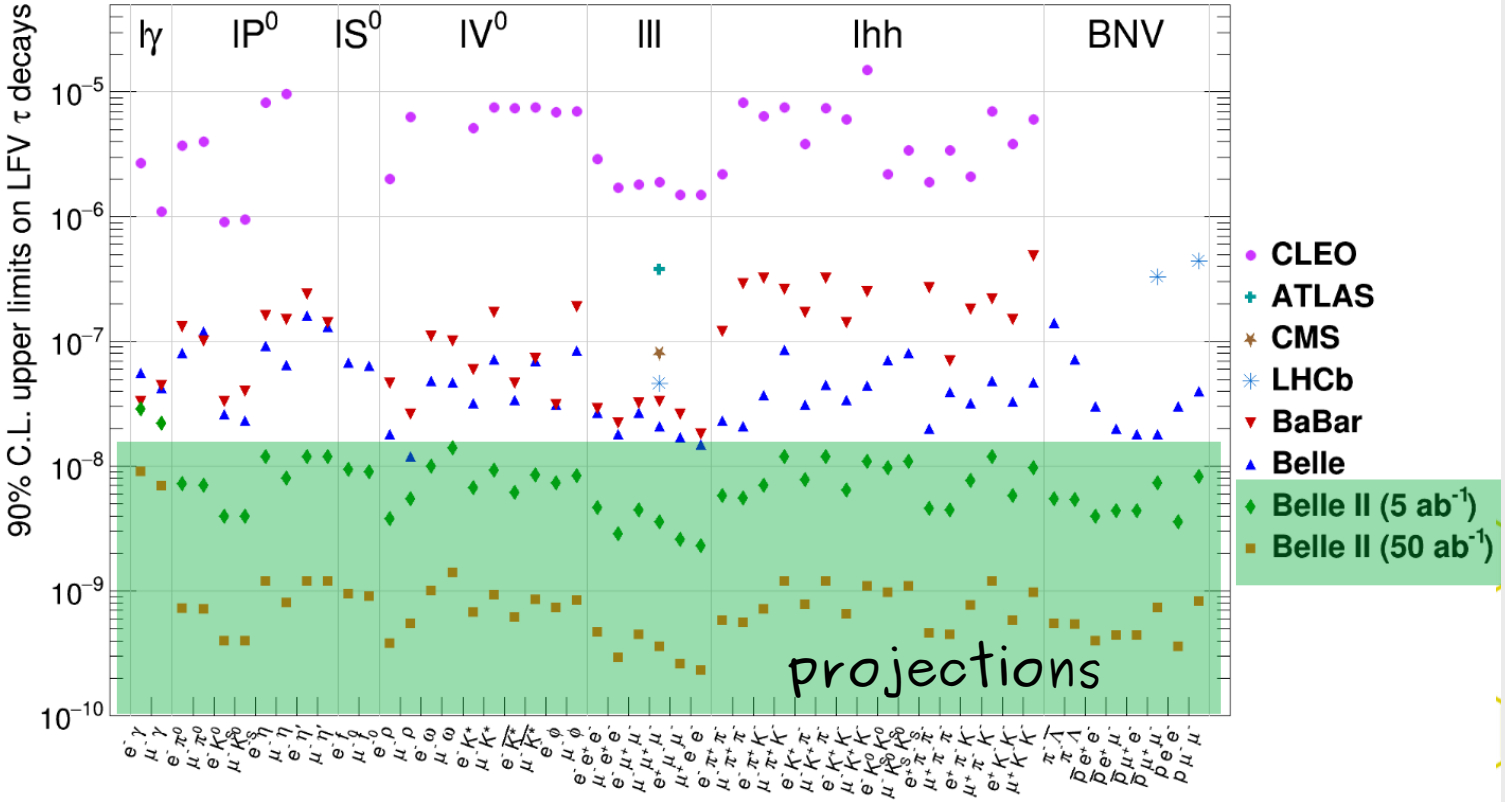


Current status

observed limits and projections

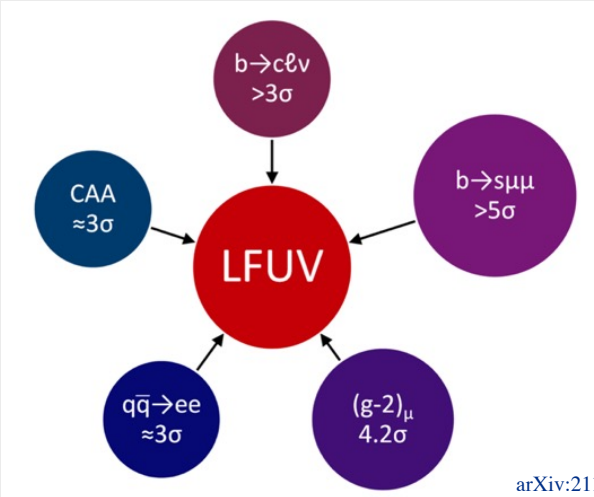
Snowmass 2021 White Paper: Charged lepton flavor violation in the tau sector arXiv:2203.14919

- 52 benchmark LFV τ decays have been searched
- modes can be classified as neutrinoless 2-body/3-body decays
- critical to probe all possible LFV modes of τ
  ⇒ any excess in single channel not provide sufficient information on underlying mechanism

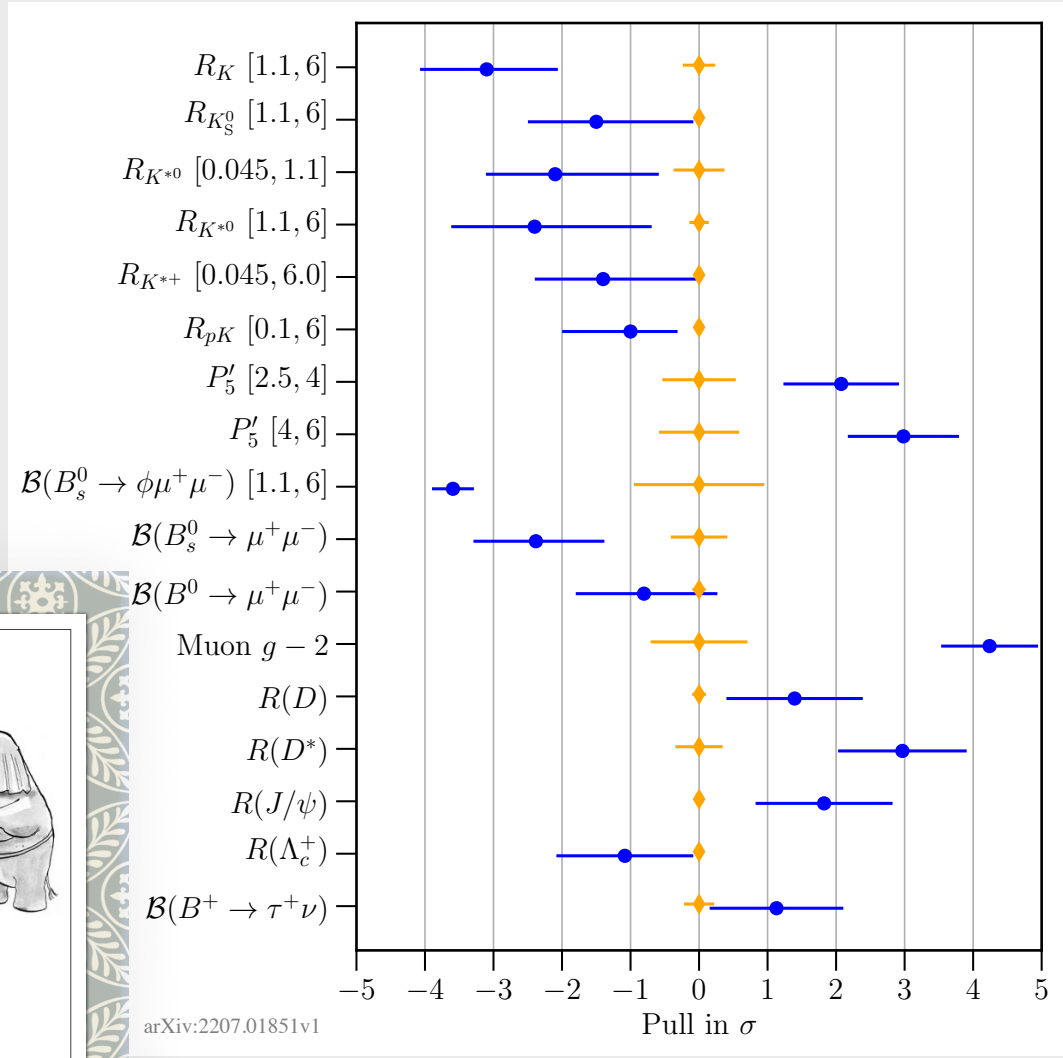


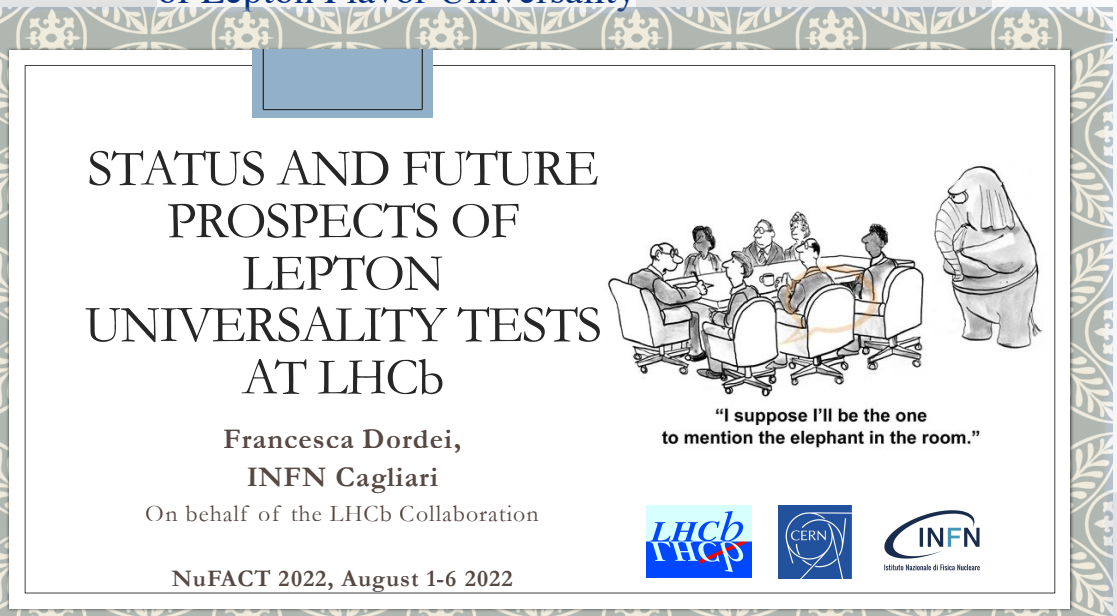
➔ Belle II detector sensitivity close to NP scenarios limits
  ➔ expected to improve the results of previous B-factories by a factor ~100 with statistics only
➔ there are additional LFV search channels with extra non-SM particles

- B-factories show indications of deviations from SM in decays of bottom hadrons



Mounting Evidence for the Violation of Lepton Flavor Universality





Measurement of R_{K^+}

- Decay used: $B^+ \to K^+\ell^+\ell^-$
- Measured in $q^2 \in [1.1, 6.0\ \mathrm{GeV}^2/c^4]$
- Using Run1 + Run 2, but still statistically limited
- Biggest systematic: fit model ~1%

Validation

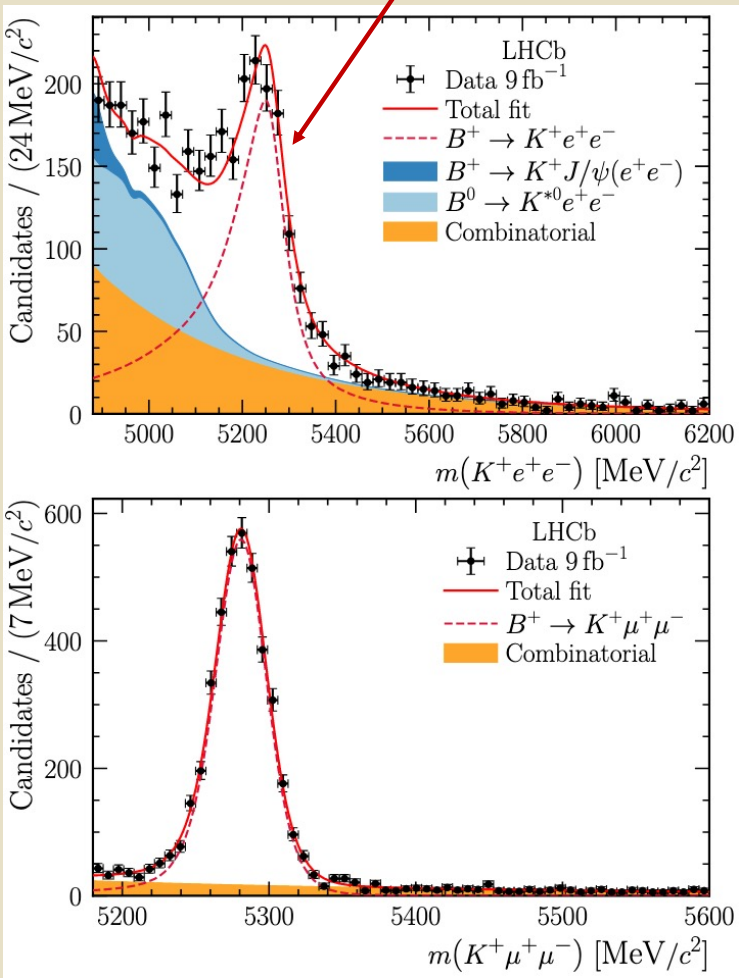
- $r_{J/\psi} = 0.981 \pm 0.020$ (stat $\oplus$ syst)
- $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat $\oplus$ syst)

Result

- $\boldsymbol{R_{K^+} = 0.846^{+0.042}_{-0.039}(\mathrm{stat})^{+0.013}_{-0.012}\ (\mathrm{syst})}$
- Tension of **3.1σ wrt the SM**

[Nat. Phys. 18, 277-282 (2022)]

resolution due to bremsstrahlung emission & recovery



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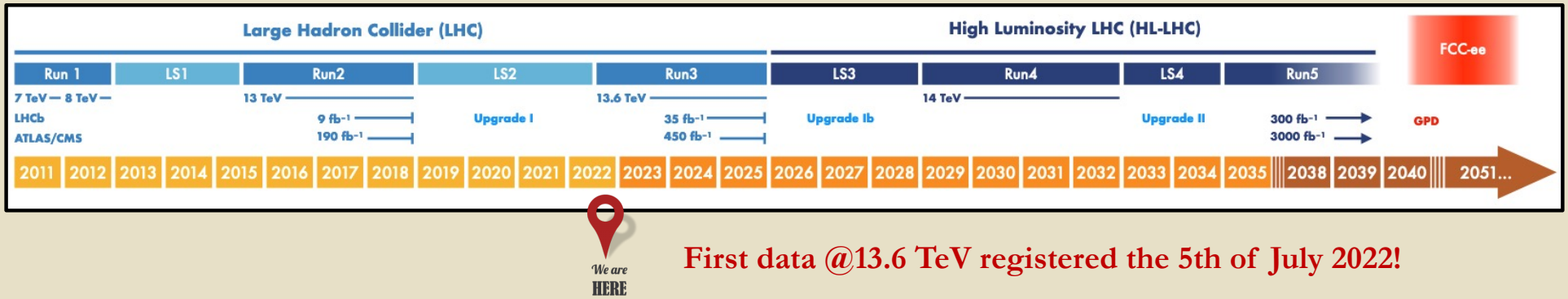
The experimental scenario



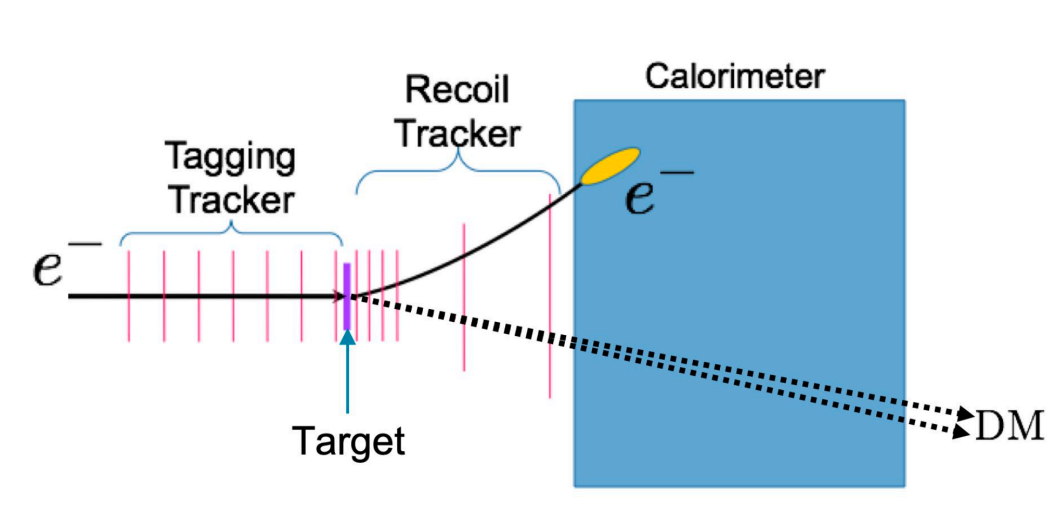
First data @13.6 TeV registered the 5th of July 2022!

LHCb Run 3 + 4: [LHCb Upgrade Physics Document]

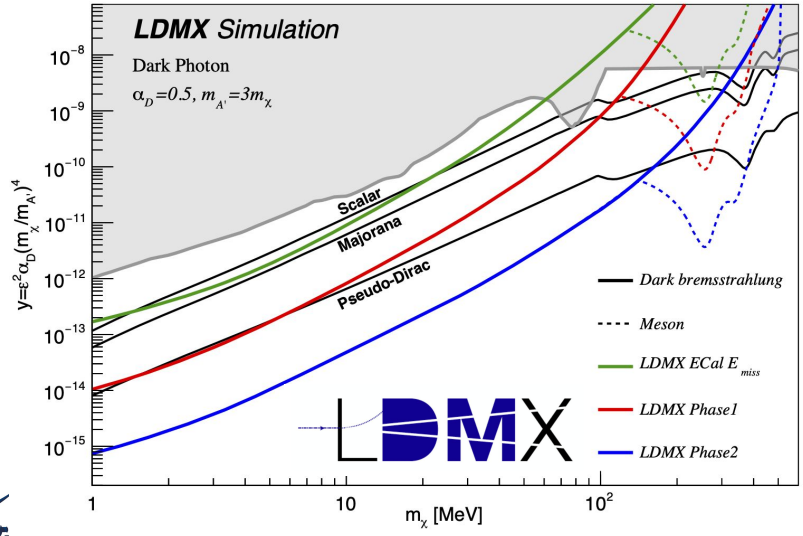
- Major upgrades of all sub-detectors
- $\mathcal{L}_{\text{peak}} = 2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$, # of pp interactions ~5
  - More measurements using full Run 1+2 dataset in preparation and using new channels.
  - Most analyses are **statistically dominated**: data from the LHCb upgrade will further improve these measurements, helping clarifying the picture.
  - **Run 3 just started**, hopefully exciting news soon!!

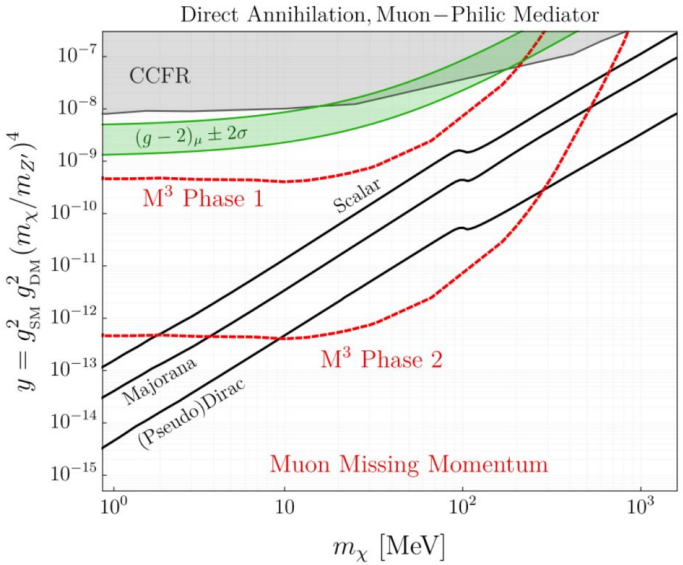
Future experiments with muon beams

LDMX/M³



- LDMX can conclusively probe many such models in the sub-GeV mass range through a missing momentum search
- Proposed M³ at Fermilab can test muonic forces motivated by muon g-2 and thermal relic models





Matt Solt

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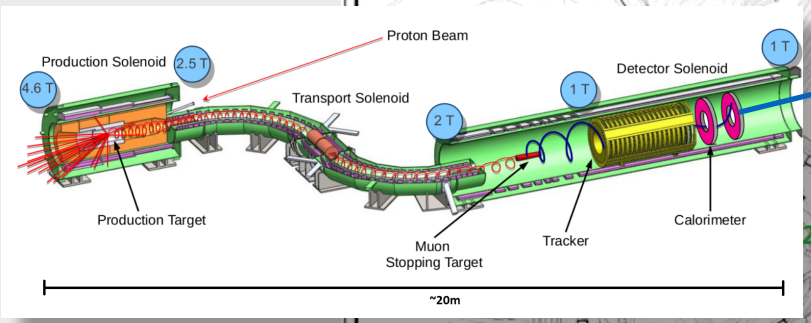
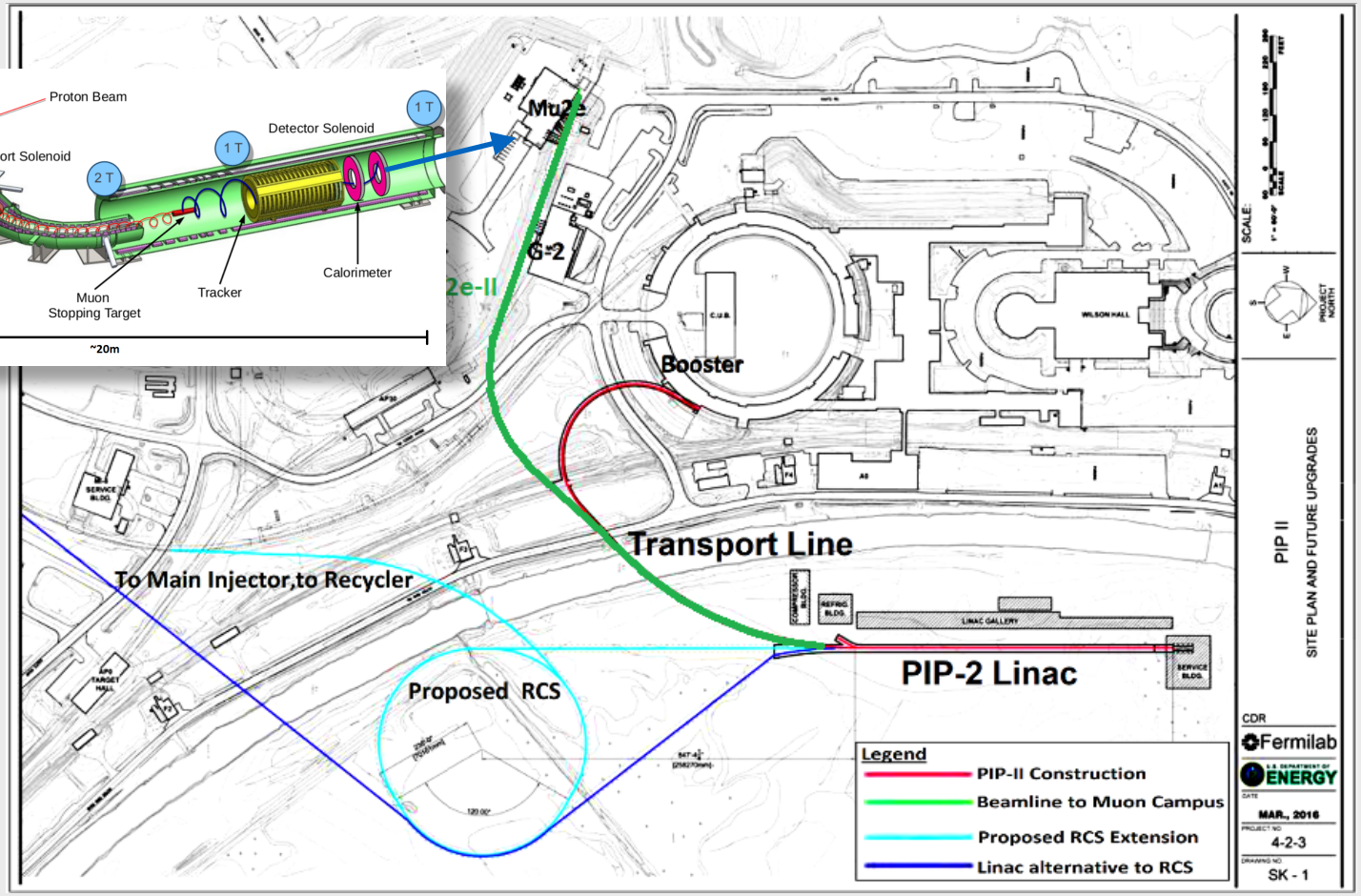
Mu2e-II@PIP-II

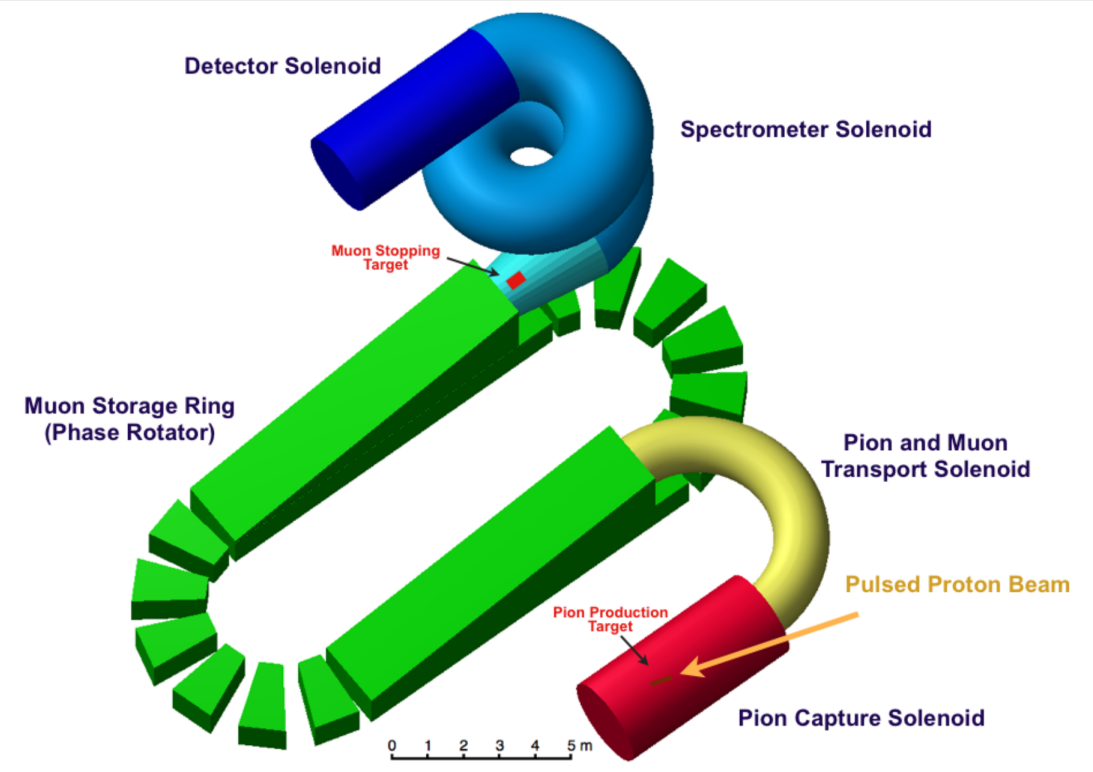
- If approved, Mu2e-II will improve $R_{\mu e}$ sensitivity by $\times 10$ beyond Mu2e limits, extending λ_{NP} reach by $\times 2$
  - Refurbish as much of Mu2e infrastructure as possible
  - Upgrade Mu2e components to handle higher beam intensity
  - Expected 5 years of physics run in the next decade
- Mu2e will utilize 100kW proton beam from Proton Improvement Plan-II (PIP-II) at Fermilab

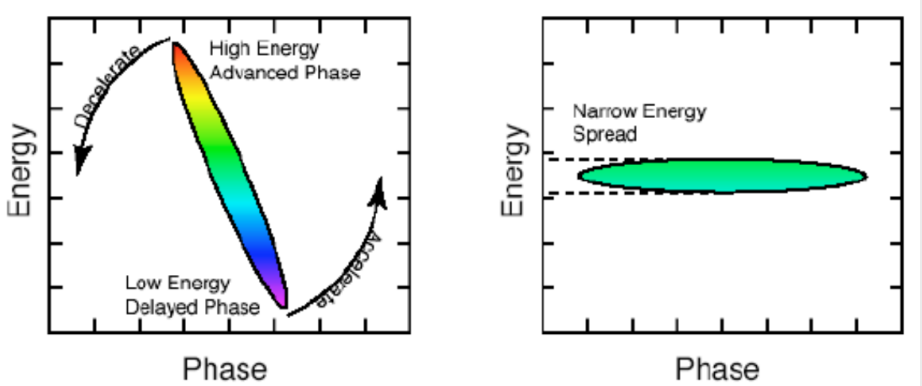




PRISM concept

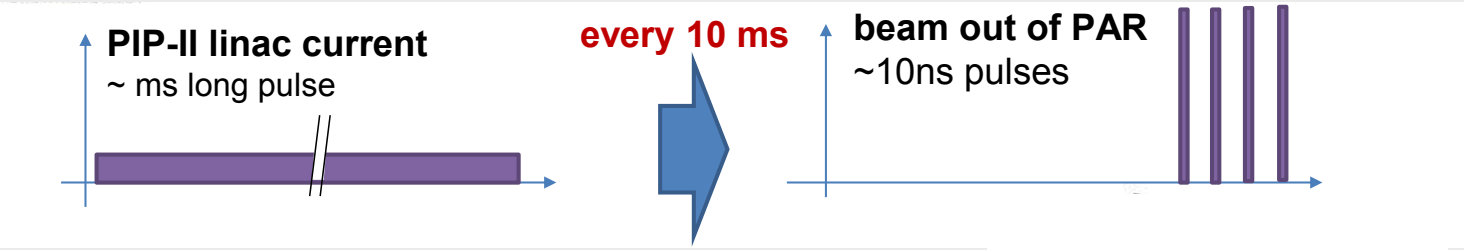
- A more ambitious option - Fixed Field Alternating gradient (FFA) ring
  - Proposed by Y. Kuno, Y. Mori
- Provides pure muon beam to detector solenoid
  - An opportunity to explore high-Z stopping targets
- Cannot fill this ring directly from PIP-II
  - Needs a “compressor ring” to provide short, intense pulses at 100-1000 Hz.

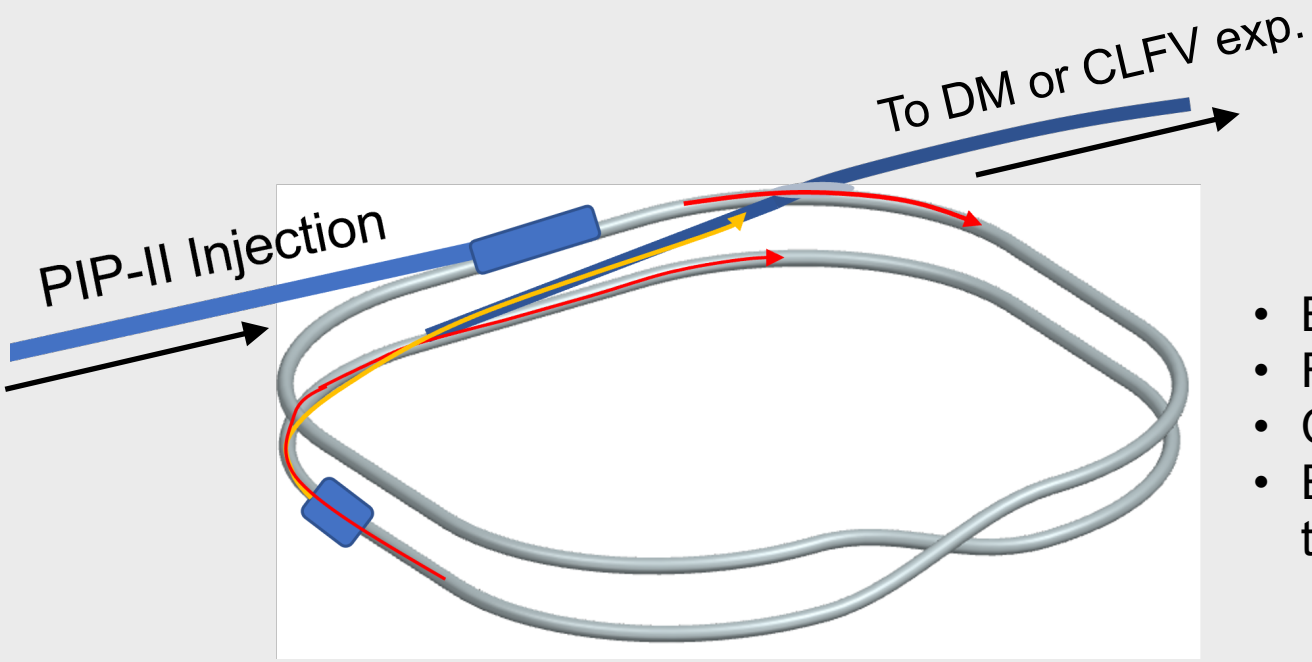




Accumulator ring

- PIP-II Accumulator Ring ( )
  - Transform a long pulse into few (4) short very intense bunches for one extraction
  - Compact version (C=120 m) would be a better option for Mu2e-II





- Beam power: >100 kW
- Frequency: 100Hz
- Circumference: 480 m
- Energy: 0.8 GeV upgradable to 1+ GeV

Beam Technical Challenges

- Things that are very hard that we know how to do:

  ● stopped muon beam at 1MW

  ■ compressor ring

  ◆◆ FFA

- Things that are very hard that we don't know how to do
  - 1MW target inside a superconducting solenoid
  - R&D here closely related to muon collider! ◆◆◆

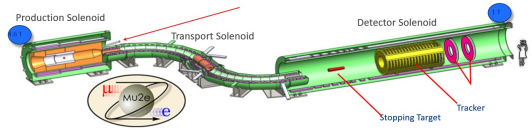
R. Bernstein, FNAL 22 Snowmass RPF5

Fermilab's vision of muon experiemnts

Argonne NATIONAL LABORATORY

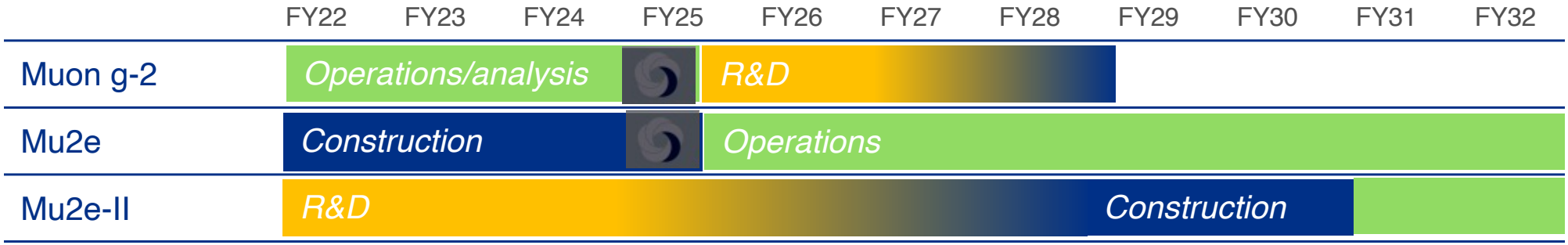
S&T Precision Science

Vision: Fermilab is a world center for accelerator-based Charged-lepton flavor violation (CLFV) and Dark Matter experiments, driven by intense particle beams and PIP-II/Booster Replacement



Major decadal goals

- Muon g-2: Complete data production, analysis, theory to achieve 5σ
- Complete Mu2e project and start science
- Design and build Mu2e-II, other upgrades



PIP-II

Questions

- Q: What are the outstanding topics in WG4:
  - g-2: requires more data, independent measurements of g-2 and HVP term, and lattice QCD validation
  - B-factories: requires more data and being patient
- Q: Overlap and complementarity between μ and ν new physics searches?
  - Presentations by Jonathan Kriewald and Julian Heeck (WG5)
- Q: Reach of upcoming experiments at current and future facilities?
  - Addressed in plenaries and parallel sessions
- Q: What do we need from P5:
  - R&D for both near term (Mu2e-II like) and longer term (AMF) experiments
  - Need to identify and pursue synergies with other frontiers. WG3: beam production, transportation, cooling and efficient shielding. WG6: low-Z tracker, fast calorimeter, rad hard components

Summary

- Thanks for Yuki, Gavin, WG3-6 conveners, speakers, and the organizers
- We might observe our next big discovery in the very near future
  - Current experiments produce intriguing hints of New Physics
  - This decade, new experiments will deliver a significant leap in the sensitivity reach