Muon Physics

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Project X Workshop, January 25–26, 2008, FNAL

Concentrate on $\mu \to e$-conversion in nuclei, and precision measurements of the muon anomalous magnetic moment.

1. Physics Case;
2. Why Here?;
3. An Integrated Approach to 8 GeV Beams;
4. $\mu \to e$-conversion with 200 kW
5. Timeline.

Physics Case: Charged Lepton Flavor Violation (CLFV) and $\mu \to e$-conversion

$$\left(B(\mu \to e - \text{conv}) \equiv \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}, \text{ is the normalized rate.} \right)$$

- Interplay with LHC – complementary information regarding new physics at the TeV scale. We learn something about the TeV scale physics in the advent of positive and negative results from $\mu \to e$ searches at 10^{-17}.
- Interplay with other CLFV – non-trivial information to be obtained by combining $\mu \to e$-conversion and other CLFV processes ($\mu \to e\gamma$, $\mu \to eee$).
- Potentially strong connection to origin of neutrino masses. In case of SUSY, may provide invaluable information that may allow one to ultimately test leptogenesis! [Also fundamental for MFV]
- Can repeat the measurement with different targets. Non-trivial information on new physics in case of positive results.

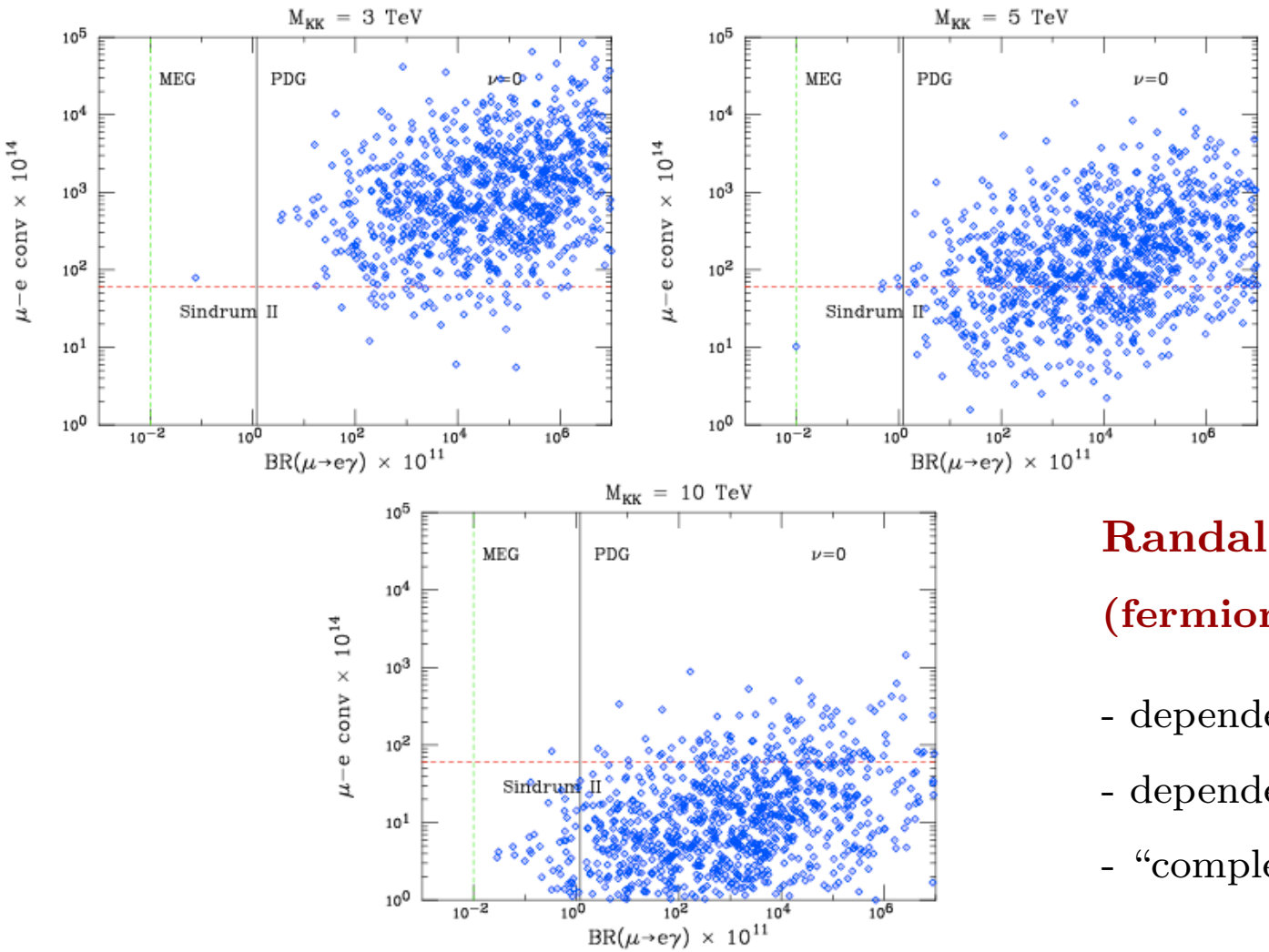


FIG. 6: Scan of the $\mu \to e\gamma$ and $\mu - e$ conversion predictions for $M_{KK} = 3, 5, 10$ TeV and $\nu = 0$. The solid line denotes the PDG bound on $BR(\mu \to e\gamma)$, while the dashed lines indicate the SINDRUM II limit on $\mu - e$ conversion and the projected MEG sensitivity to $BR(\mu \to e\gamma)$.

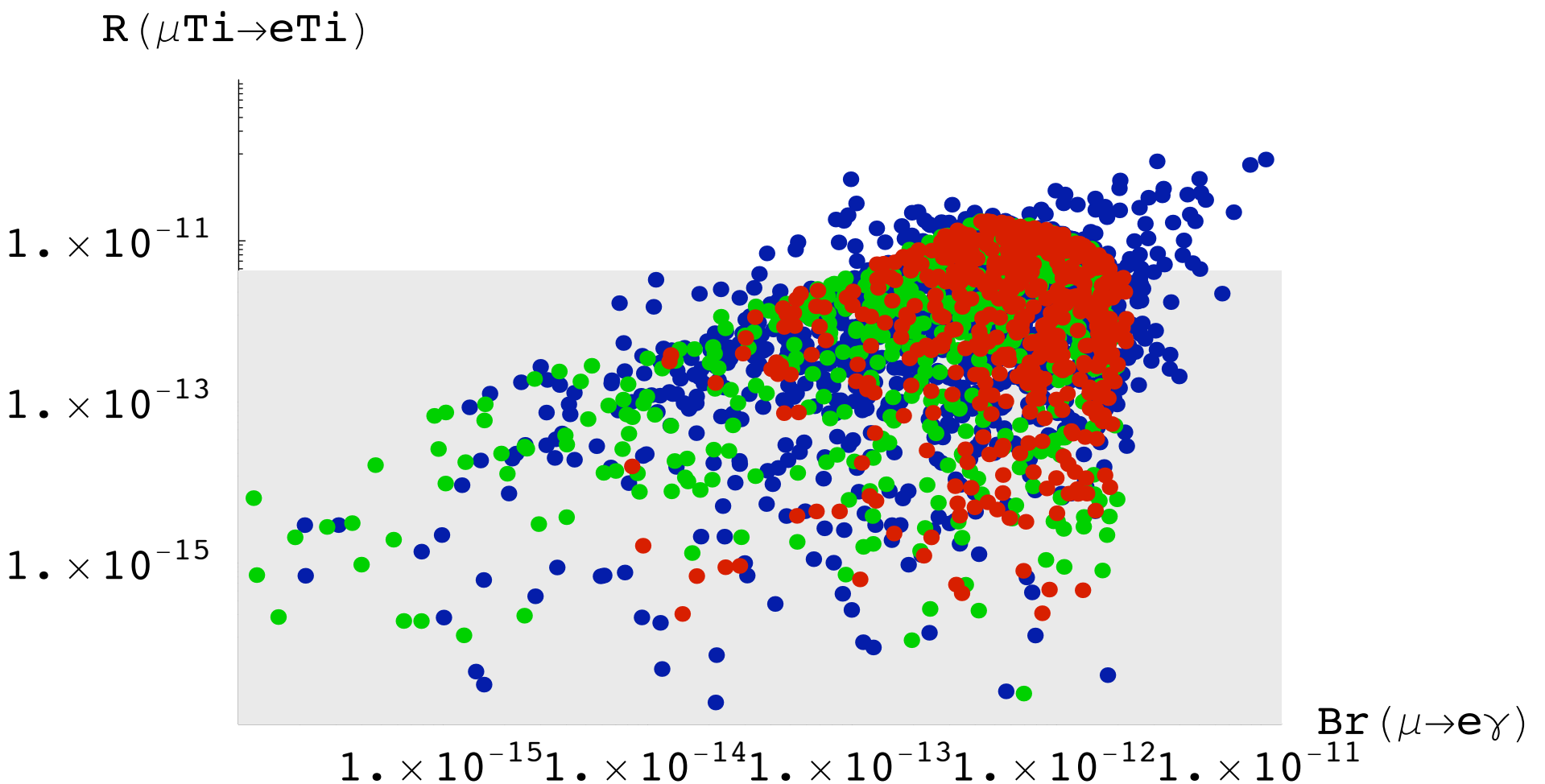
Randall-Sundrum Model

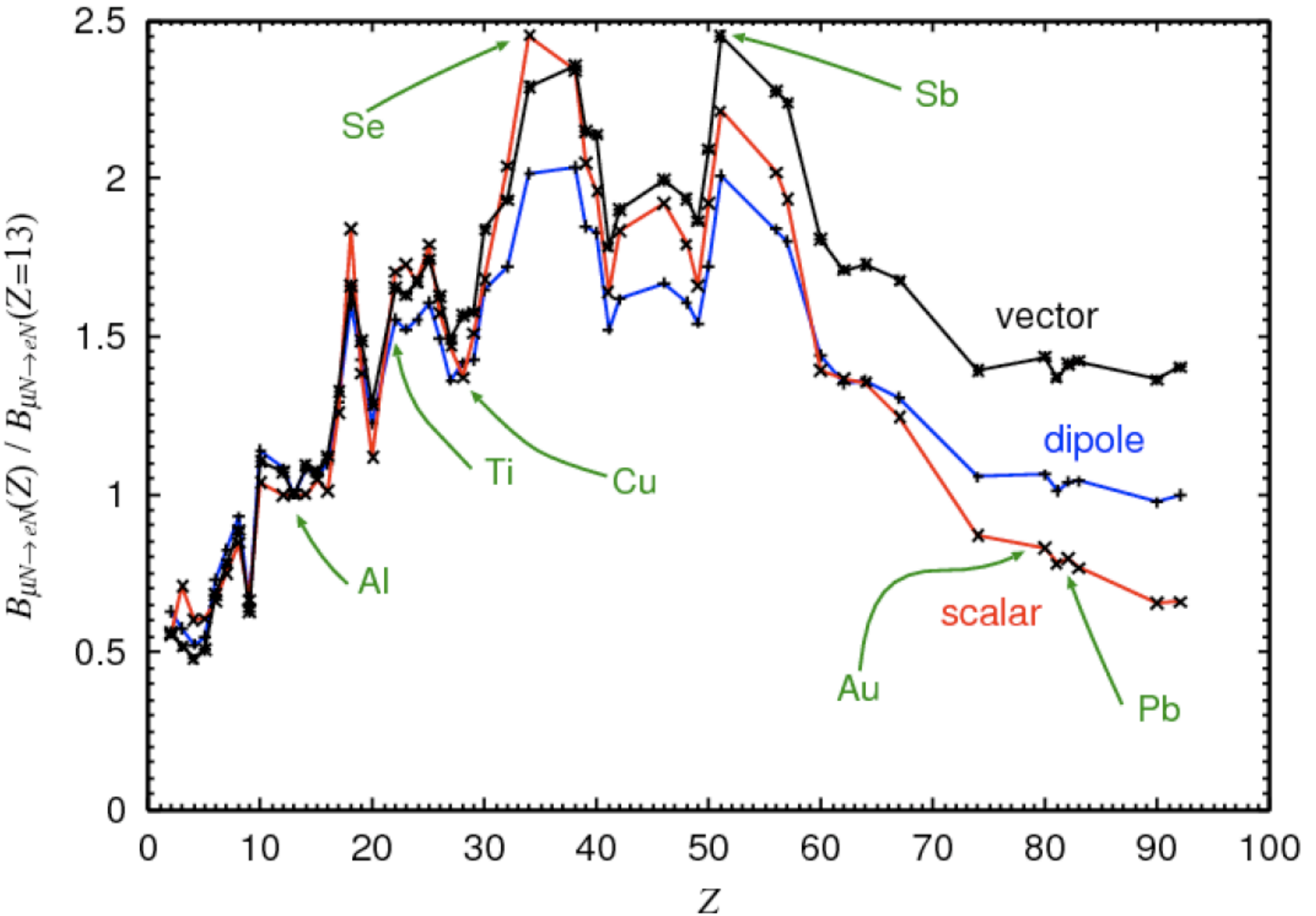
(fermions in the bulk)

- dependency on UV-completion(?)
- dependency on Yukawa couplings
- "complementarity" between $\mu \to e\gamma$, $\mu - e$ conv

[Agashe, Blechman, Petriello, hep-ph/0606021]

Little Higgs Models: L. Calibbi, *et al*, Phys. Rev. D 74, 116002 (2006).

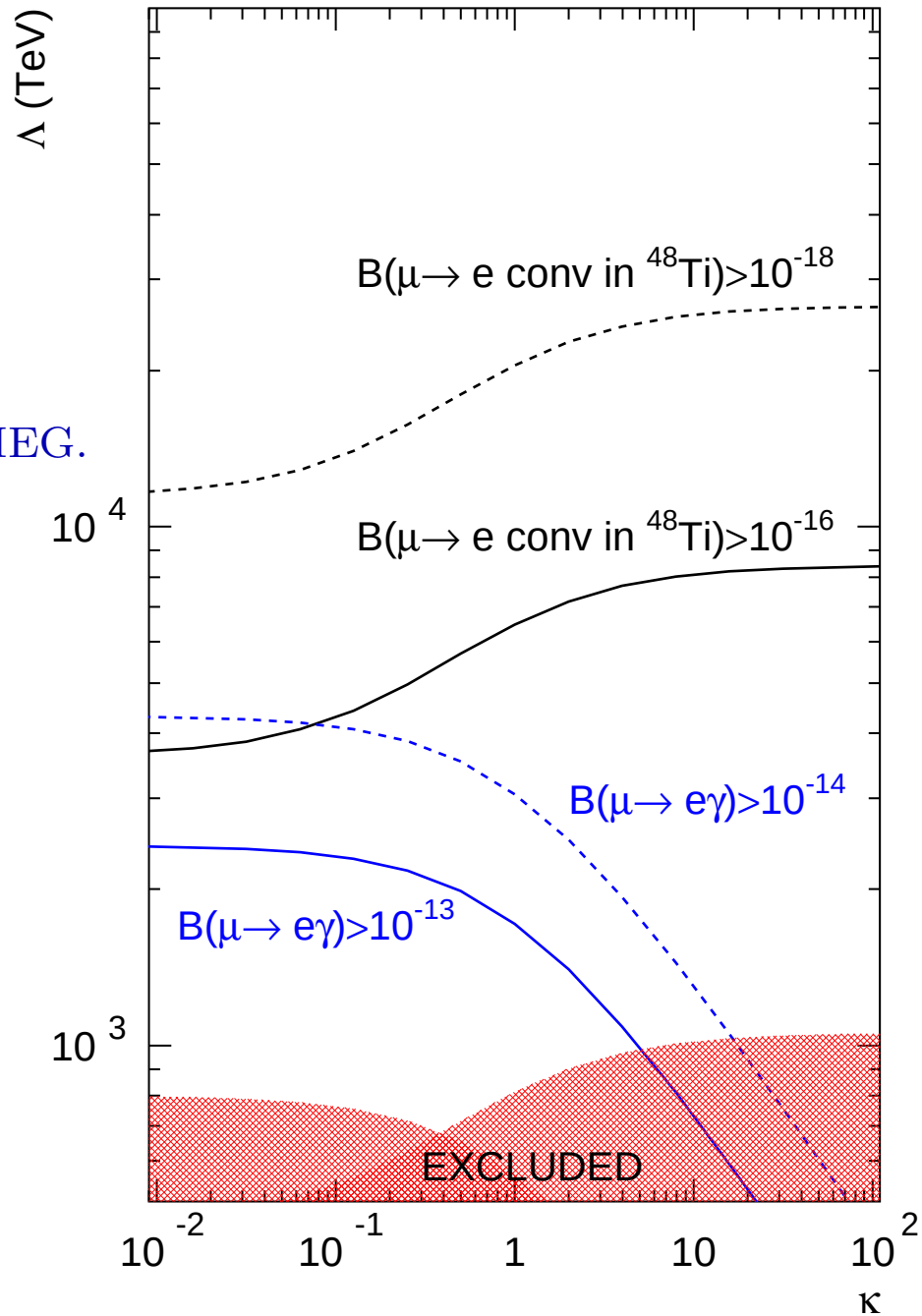



2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Z
$B_{\mu N \to eN}(Z)$ / $B_{\mu N \to eN}(Z=13)$
Se
Sb
Ti
Cu
Al
Au
Pb
vector
dipole
scalar

- $\mu \to e$-conv at 10^{-17} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.

- We don't think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$-conv "only" way forward after MEG.

- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 1000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2 \theta_{e\mu}}{M^2_{\rm new}}$.

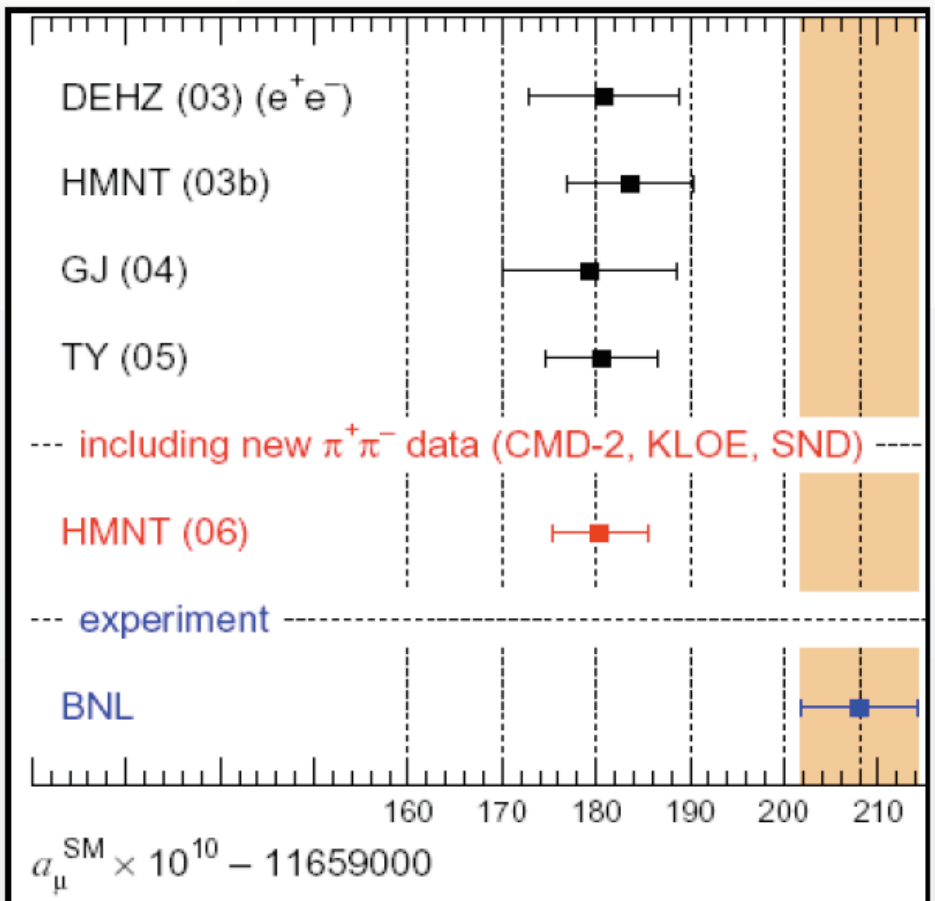


Physics Case: Anomalous Magnetic Moment of the Muon, $(g-2)/2 \equiv a_\mu$

- Current 3.4 sigma discrepancy. Is it first evidence of new physics at the TeV scale?
- Theoretical prediction "robust." Way forward clear: new e^+e^- data to improve precision of hadronic contribution, light-by-light scattering final obstacle $\Rightarrow$ lattice(?). NOTE: new experimental efforts will encourage theorists to improve on SM value.
- Interplay with LHC – if there is new physics at the TeV scale, a_μ can differentiate among different model, provide precision measurement of model parameters.

Δa_μ(expt-thy) = (295±88) x 10^{-11} (3.4 σ)

TIME



Compare

K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner Rep.Prog.Phys. 70, 795 (2007).

Muon g-2, like other precision measurements, has powerful discriminating input

10^{-11} units

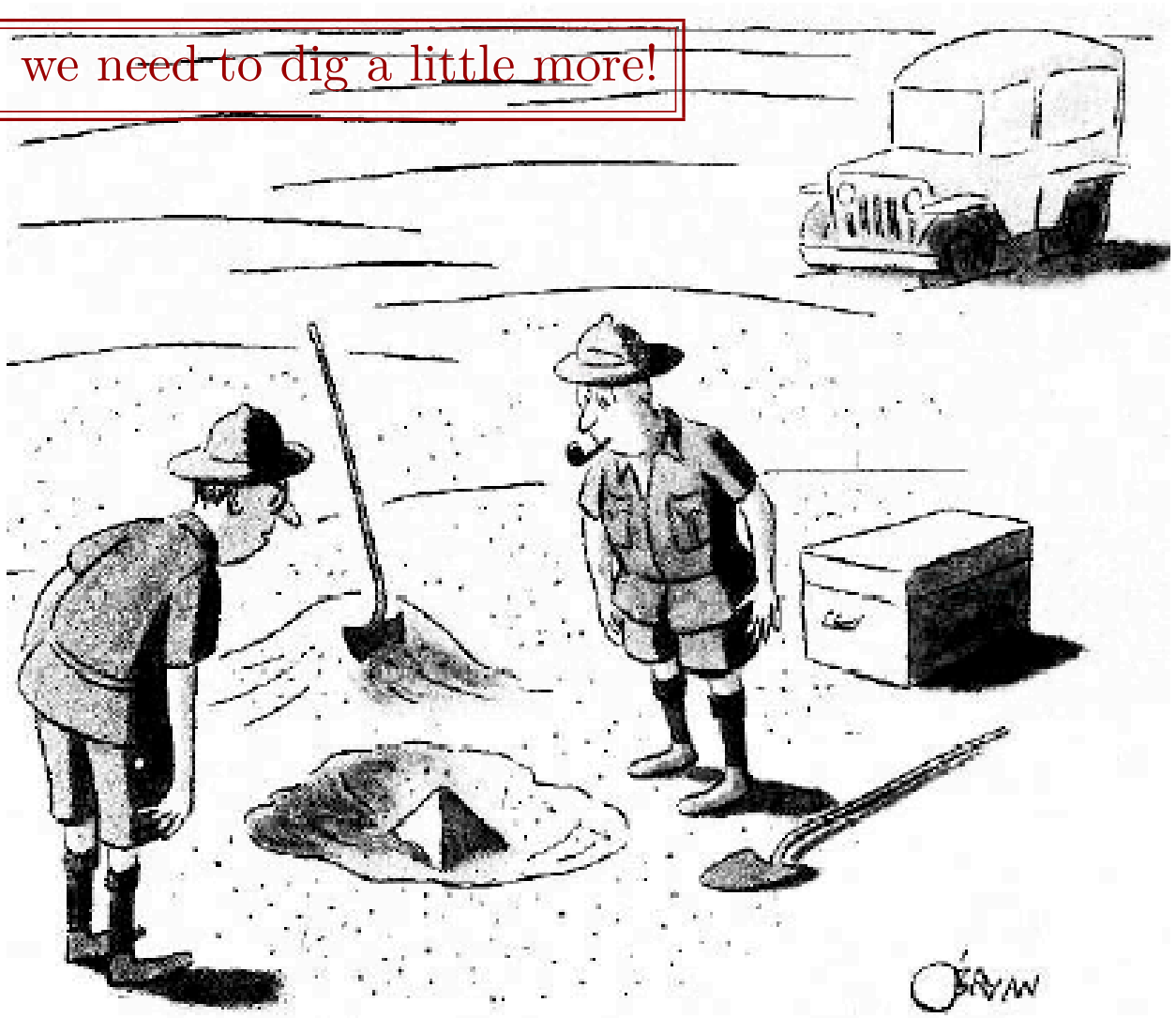
SPS Point	$a_\mu^{\mathrm{SUSY,1L}}$(improved)
SPS 1a	293
SPS 1b	318
SPS 2	16.5
SPS 3	135
SPS 4	490
SPS 5	86
SPS 6	169
SPS 7	237
SPS 8	173
SPS 9	-90

Compare to present Δa_μ =295

Compare uncertainty to $\delta\ \Delta a_\mu \sim \pm 35$

*Snowmass Points and Slopes:
http://www.ippp.dur.ac.uk/~georg/sps/sps.html

Δa_μ: we need to dig a little more!



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

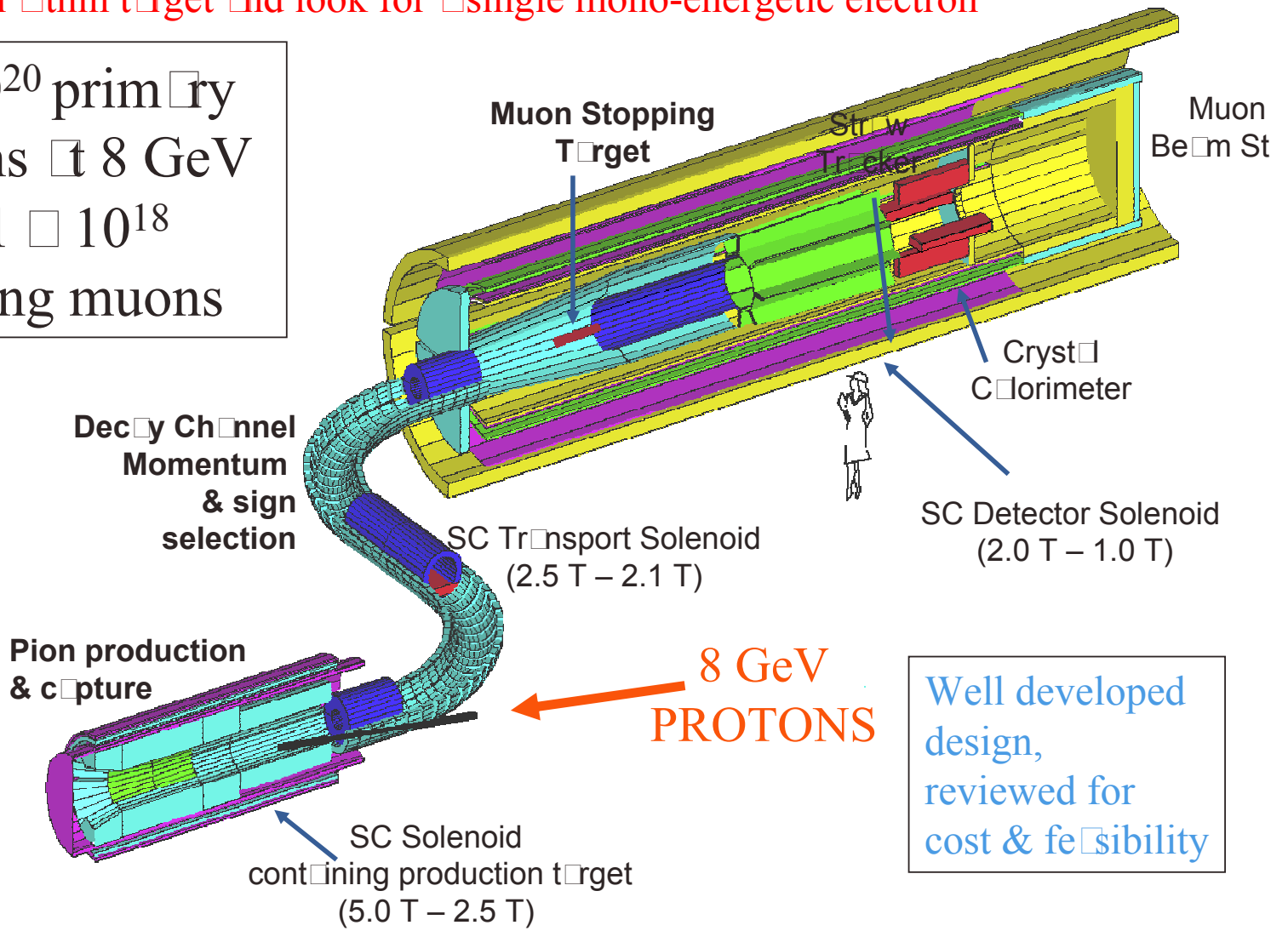
Why Here?

- $g-2$: Clear advantages from beam bunch deliver perspective and running of high-intensity protons (they do not exist at BNL anymore without 12 M upgrades to AGS. The multi-bunching at BNL is only an idea.) More muons requires a new ring and kickers to be competitive with FNAL. [Hertzog]
- $\mu \to e$-conversion: Beam has an easily produced time-structure, beam power is appropriate for a staged approach (below $10^{-16} \to 10^{-18}$). Mature, well-thought-out design, built to use this beam structure.

MECO CONCEPT (Molzon et al.)

Stop muons in a thin target and look for a single mono-energetic electron

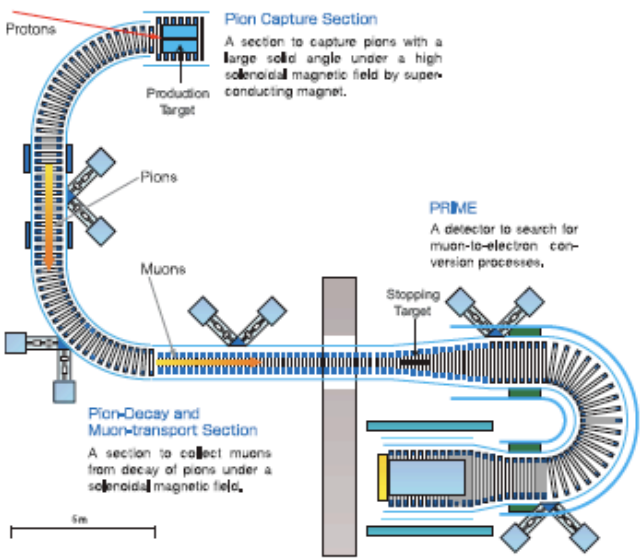
4×10^{20} primary protons at 8 GeV yield 1×10^{18} stopping muons



Well developed design, reviewed for cost & feasibility

Staging Approach to Search for Muon to Electron Conversion

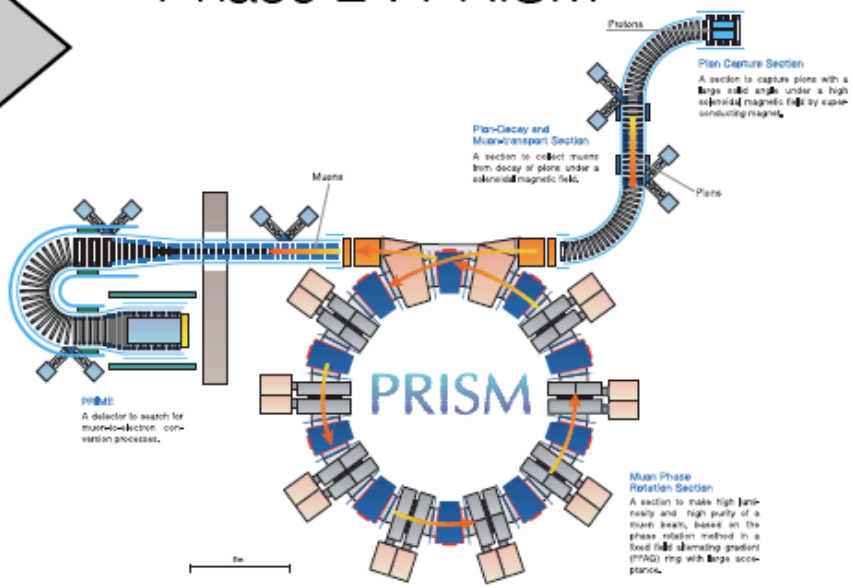
Phase 1 : COMET



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- use a slowly-extracted pulsed proton beam.
- medium proton beam power (60 kW)
- can be done at the J-PARC NP Hall.
- Early realization

Phase 2 : PRISM



$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

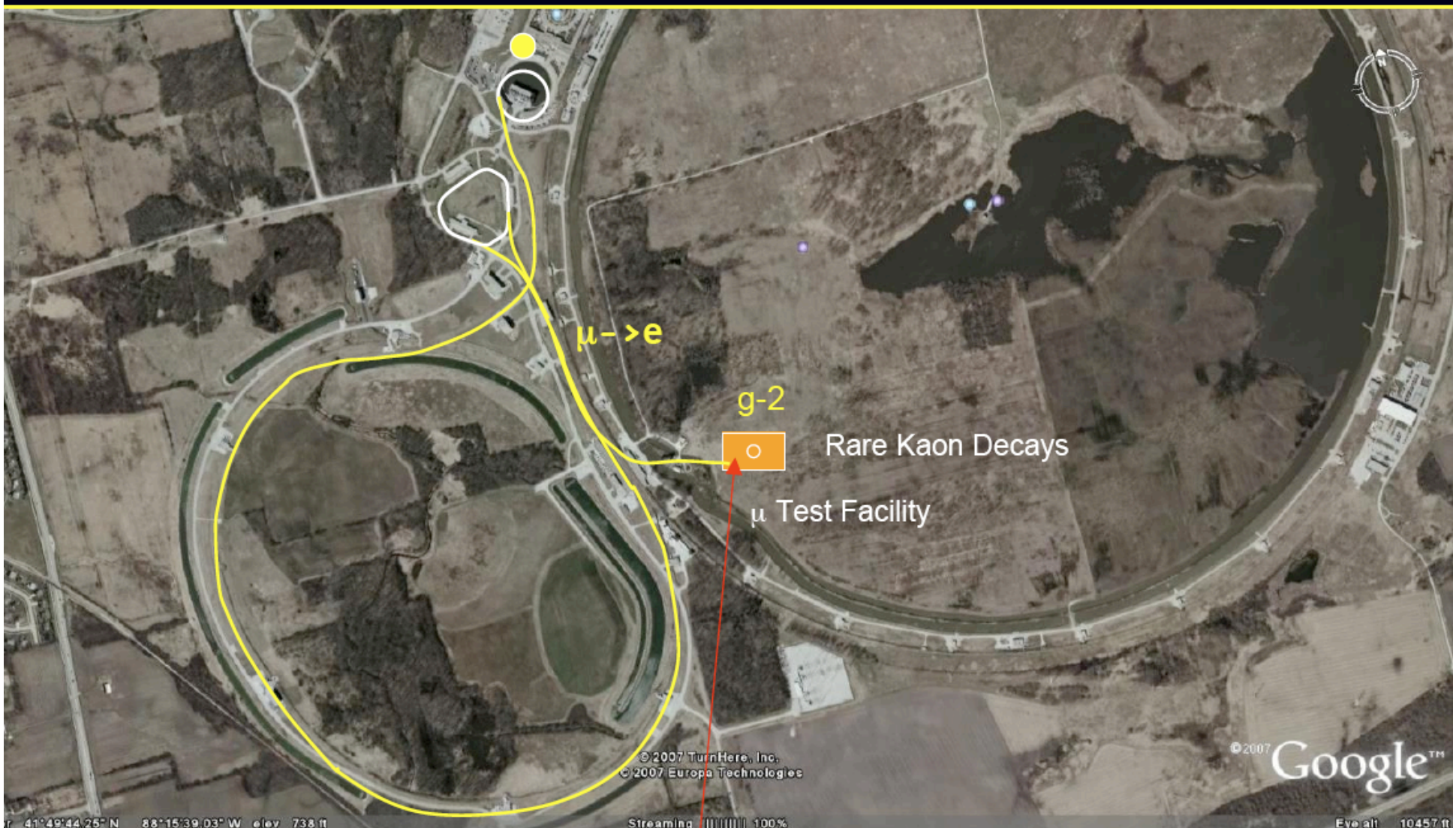
- with a muon storage ring.
- use a fast-extracted pulsed proton beam.
- very high beam pwer (>1 MW)
- need a new beamline of fast extraction.
- Ultimate search

An Integrated Approach to 8 GeV Beams:

- Work by Chuck Ankenbrandt and Milorad Popovic
- Use accumulator and debuncher both before and during Project X
- Extract all possible beams in the same general direction in existing tunnels
  - $\mu \to e$ conversion, a_μ, $K \to \pi\nu\bar{\nu}$, muon test beams,...
- Provide for beams using both Booster and Project X linac as the driver
- Scheme to put up to 200 kW through the system with ∼5 Amp circulating current (multiple transfers per 1.4s MR cycle)
- Details, e.g. number of beams transported in tunnel, locations of specific experiments to be worked out

- Important to work out the accelerator physics issues
  - Needed for all beams for all experiments with some differences: time structure, extraction
  - Concerns with intensity (instabilities, e.g. from electron cloud effects)
  - Number of person years of work should start immediately
- Real benefits from providing for multiple beams in shortly interlaced or simultaneous operation, possible ideas:
  - Formulate time structures in both accumulator and debuncher, one for $\mu \to e$-conversion, one for $g-2$ / K-decays
  - Provide for transfer into both machines from recylcer, slow or pulsed extraction from each.
- At > 200 kW, would need a new storage ring

Booster-era Beam Transfer Scheme



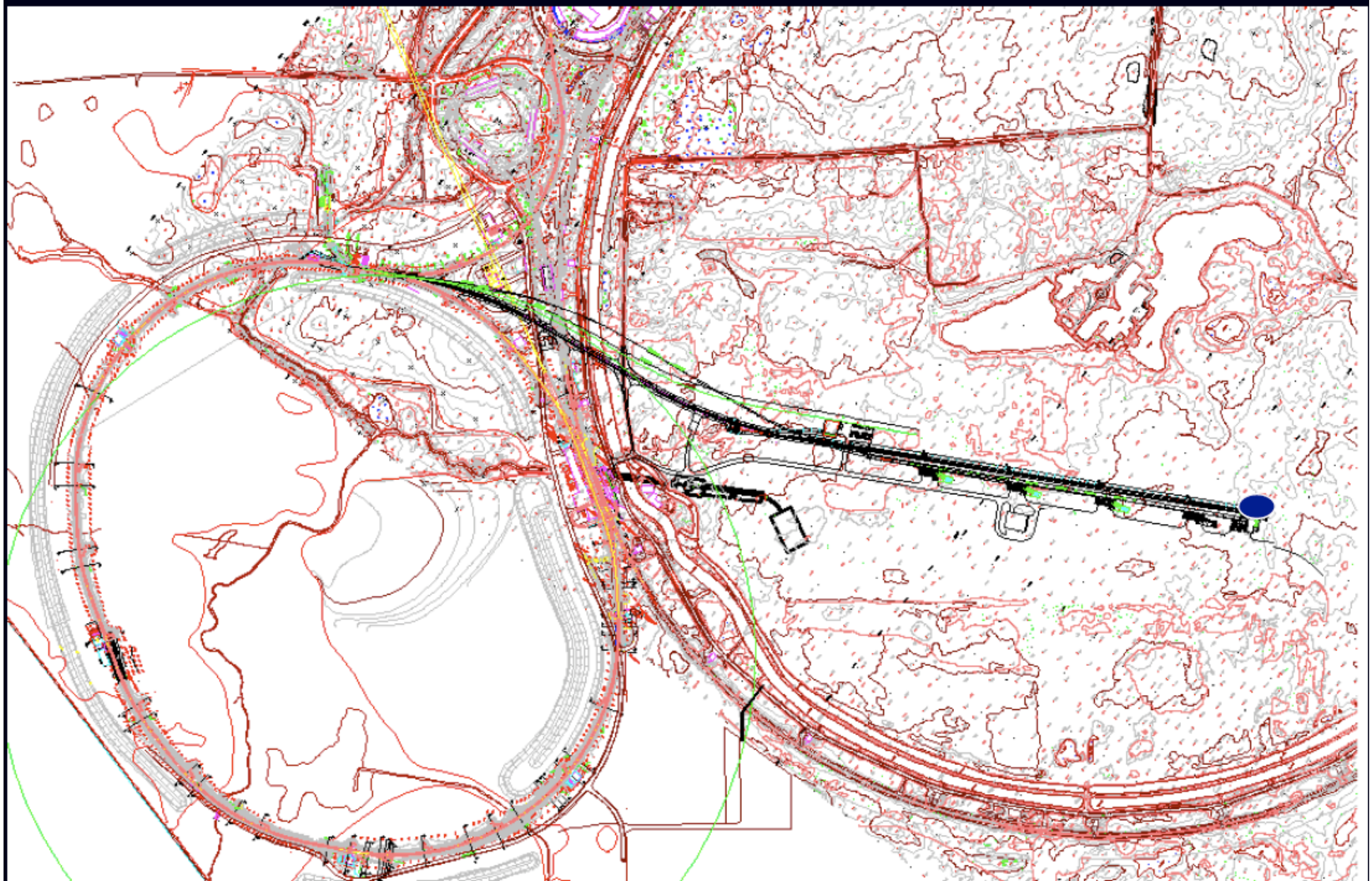
New 200-kW target station that can be upgraded to >2 MW

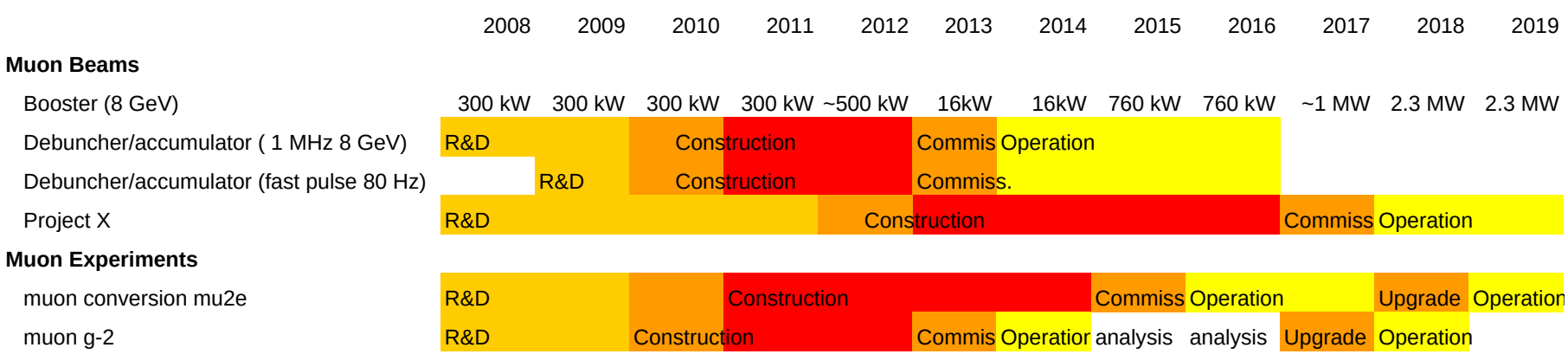
Operation of $\mu \to e$ at 200 kW:

- From operation viewpoint, MECO/$\mu 2e$ was designed for 100 kW instantaneous, 50 kW average intensity
  - Concerns about detector rates, from operation and backgrounds a concern if $2\times$ instantaneous intensity (all rate is from muon capture)
    - Rate reductions in detectors being studied with modifications to detector solenoid (curved geometry, extra length)
  - Concerns about target heating, radiation load on magnets if $4\times$ average intensity
    - Ideas for reducing rates by extra shielding of magnets, improved target cooling
    - Mostly a cost issue

- From background and sensitivity viewpoint, distinguish scenarios with a big ($> 10^{-16}$) signal:
  - For example at 3×10^{-15}, 3000 events would be detected at sensitivity of 10^{-18}, and background at the 10^{-17} level would not be a problem
  - Rates could be measured with different nuclei (Al, Ti, perhaps Ca), and the rate compared with that for $\mu \to e\gamma$
- and scenarios without a big ($> 10^{-16}$) signal:
  - Studies started on ways of improving resolution, other backgrounds
  - Will be informed by results from early running strong motivation for early start

Beam Path to 200kW Target Station in Project X Era



Possible Timeline:

- Construction of $\mu 2e$ will take 5 years, with aggressive start could begin commissioning in 2015, with 2 years running with Booster Beam – collaboration has formed and will be strengthened.
- $g-2$ could begin relatively sooner, perhaps as soon as a beam was available. Core collaboration with long experience in $g-2$ experiment exists. Running more than one experiment at a time could be beneficial in Project X era