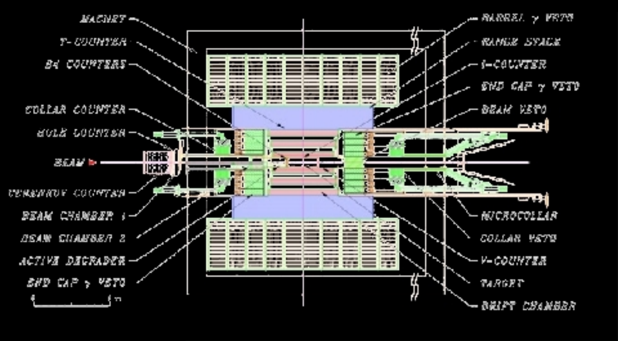
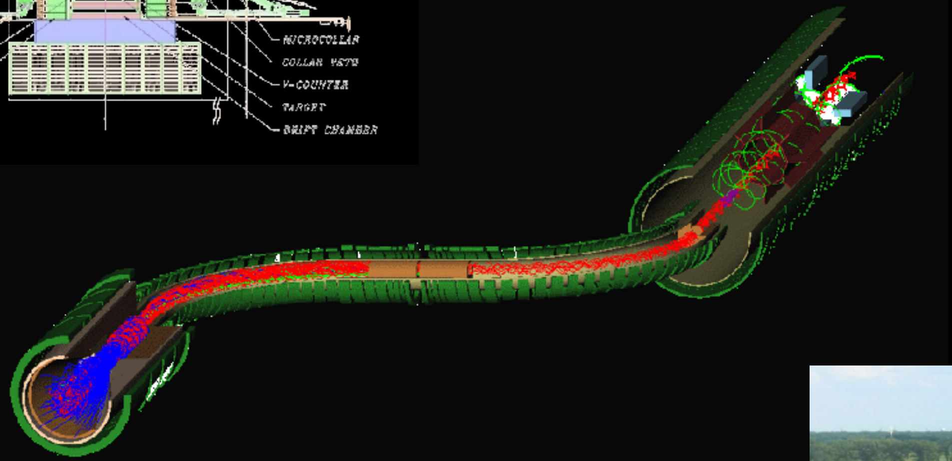
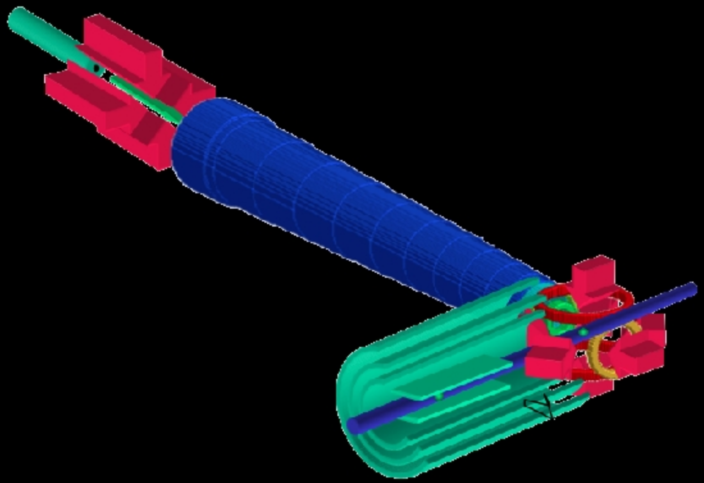
Project X Experiments at Fermilab

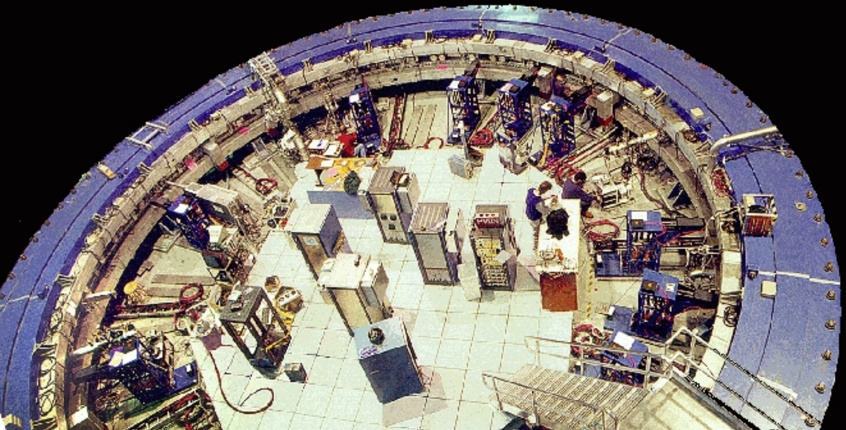
Intensity Frontier

Chris Polly, Fermilab









Two different eras in the Intensity Frontier at FNAL

75 kW Booster era (2013-2019)

- NOvA
- MicroBooNE
- Muon g-2
- Mu2e
- LBNE (700kW)

Project X era (2020-???)

- LBNE (2 MW)
- 1000 event K^+ K^0
- Muon physics
- Physics with rare beams
- Applied physics (μSR & ADS)

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Not a complete list

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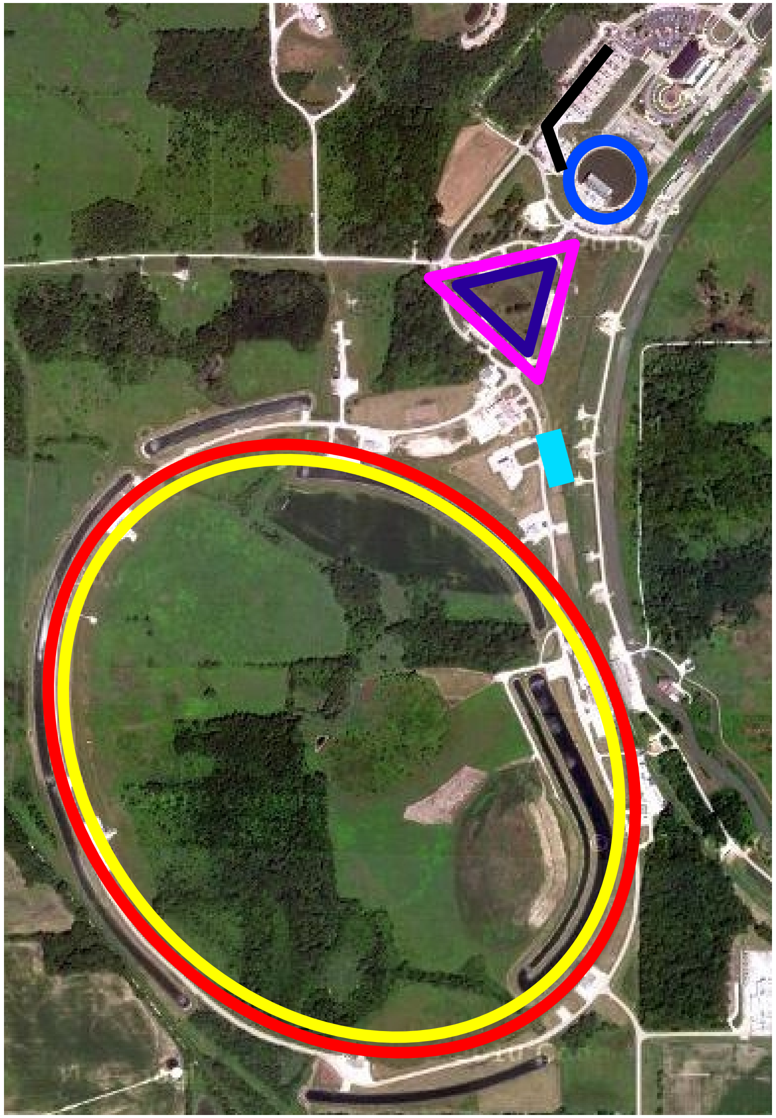
The Tevatron Legacy

In addition to 10 fb^{-1}/expt of invaluable data, generations of highly-trained physicists, and all of the spectacular physics results...

the Tevatron program leaves behind another very important legacy...

The Tevatron Legacy



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the Tevatron program leaves behind another very important legacy...

A highly-versatile accelerator complex!

Total of 8 rings & accelerators (+ TeV)
- Front-end (3 accelerators)
- Booster (8 GeV/c)
- Main Injector (120 GeV/c)
- Recycler
- Accumulator
- Debuncher

One target hall & many beamlines
- APO

The 75 kW Booster Era

The 75 kW Booster Era

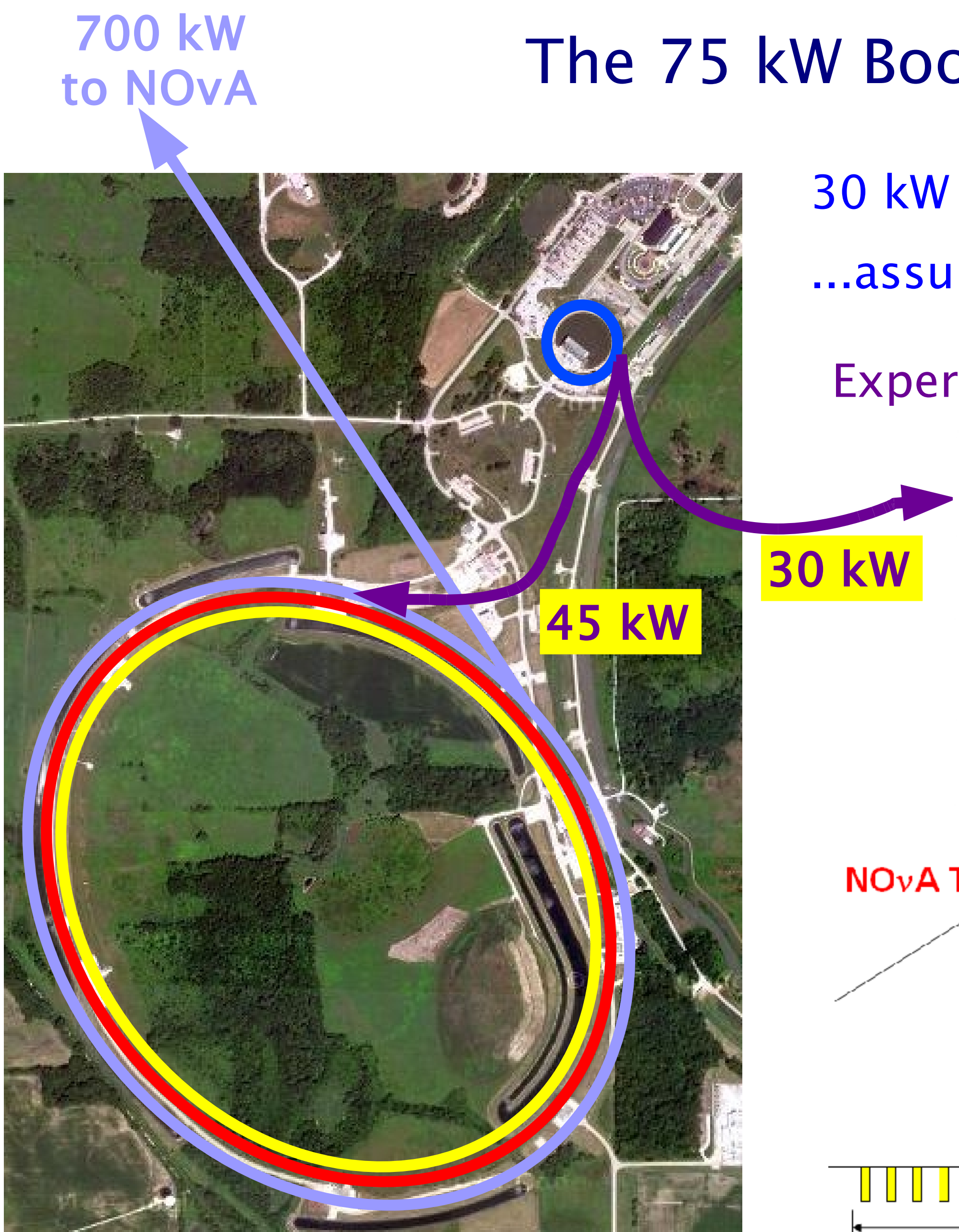
Booster is a 15 Hz harmonic oscillator

- Currently only load beam on half of the cycles

- With some relatively modest upgrades can load beam on every cycle...particularly important to change RF tubes for solid-state devices

- Total of 75 kW available

The 75 kW Booster Era



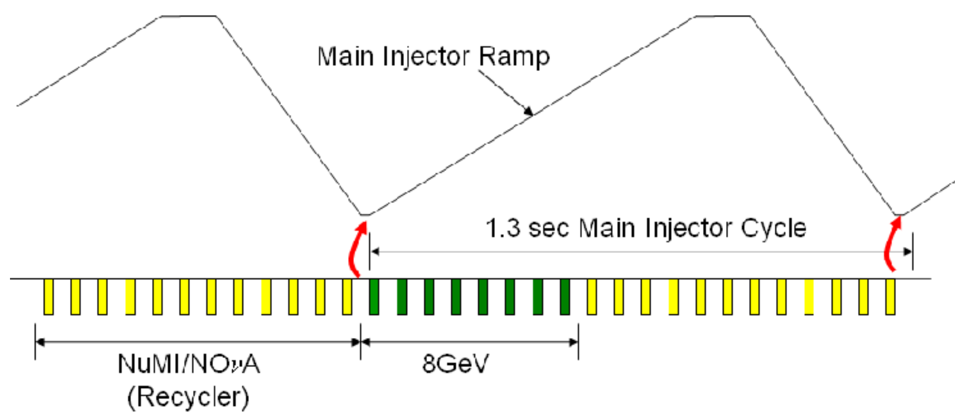
30 kW @ 8 GeV ⇒ 7.9×10^{20} POT/yr

...assume 5×10^{20} POT/yr reality (20 kW)

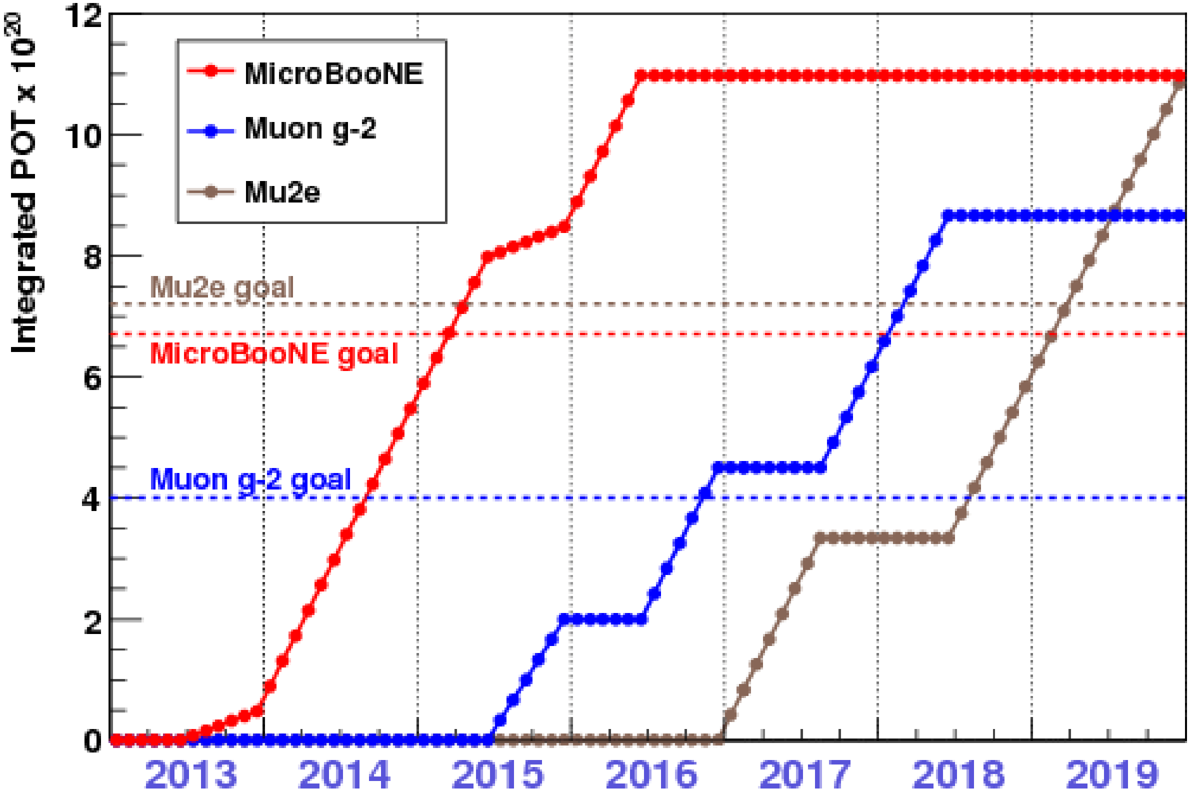
Experimental requirements...

Experiment	Total Beam Request
MicroBooNE	6.7×10^{20} POT
$g-2$	4.0×10^{20} POT
Mu2e	7.2×10^{20} POT

NOνA Time Line



Towards a realistic proton plan...



Main points:

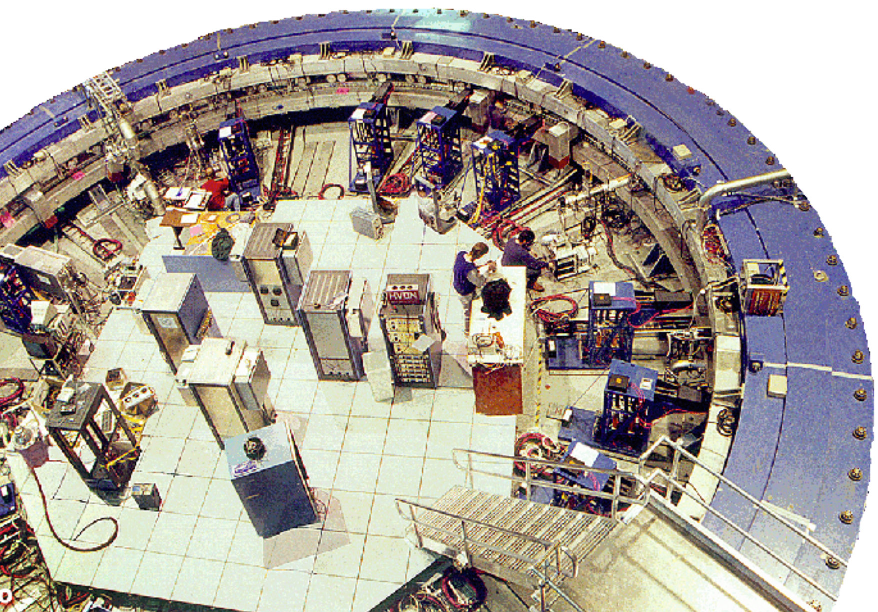
- ✔ Every experiment more than meets their proposal goals
- ✔ We won't know the reality of this until we are living it
- ✔ Designing for flexibility

Muon g-2 at Fermilab

Goal of E989...bring the apparatus from BNL to FNAL and improve the experimental precision x4

Fermilab accelerator complex allows fundamental improvements
- 21x statistics achievable
- 20x reduced hadronic background at injection
- 4x higher fill frequency

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(NP)$$



$$a_\mu^{SM} = 116\,591\,834(49) \times 10^{-11} \;\; (0.42\,\text{ppm})$$

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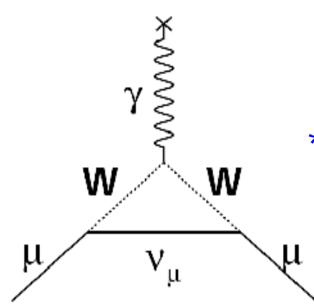
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (255 \pm 80) \times 10^{-11}$$



$$a_\mu^{EW} = 152 \pm 2 \pm 1$$

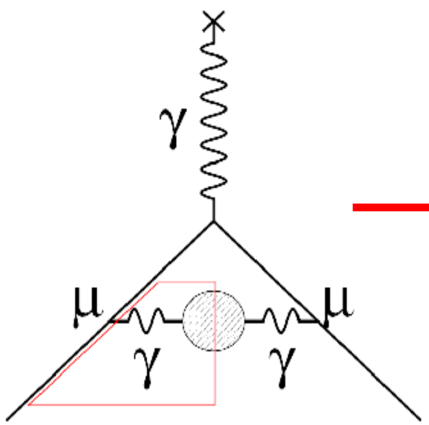
* BNL g-2 sensitive to weak loops at ~2.5σ...factor of four improvement probes weak contributions at 10σ

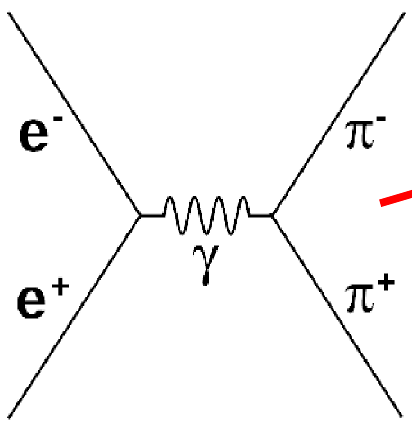
Most difficult part of theory comes from hadronic sector

CONTRIBUTION	RESULT IN 10^{-11} UNITS
QED (leptons)	$11\ 6584\ 718.09 \pm 0.14 \pm 0.04_{\alpha}$
HVP(lo)	$6\ 908 \pm 39_{\rm exp} \pm 19_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-97.9 \pm 0.9_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 785 \pm 51$

*Courtesy E. De Rafael, arXiv 0809.3025

- Theory error dominated by QCD piece
- Common to divide hadronic loops into 3 categories...
  - a_μ(had,LO) = 6908 ± 44
  - a_μ(had,HO) = -98 ± 1
  - a_μ(had,LBL) = 105 ± 26

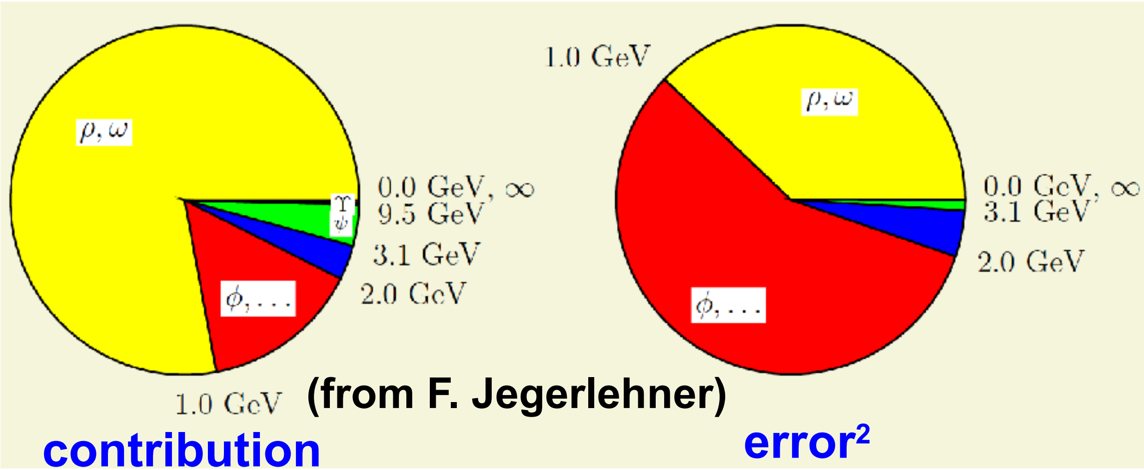




$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

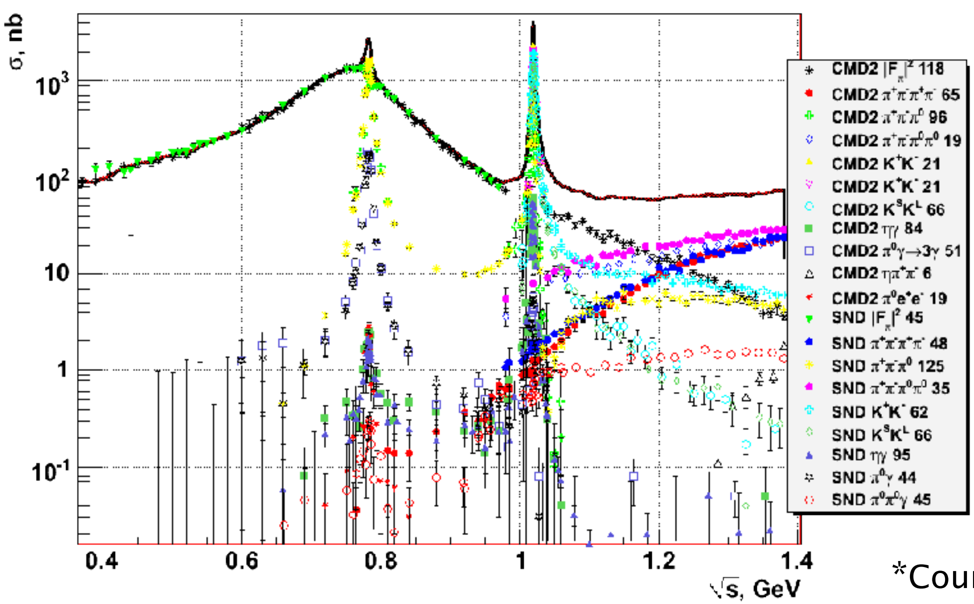
$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$

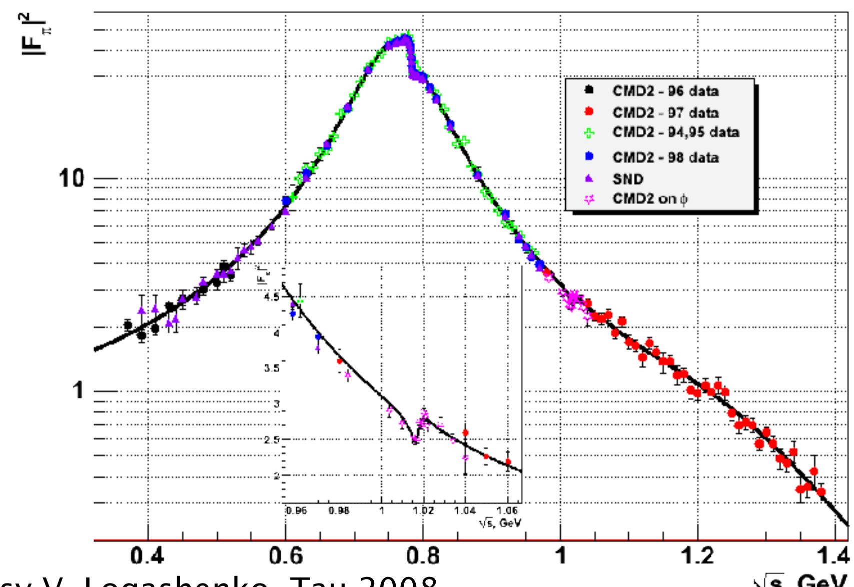
Reducing δa_μ(had,LO) requires precision e^+e^- -> hadrons



(from F. Jegerlehner)

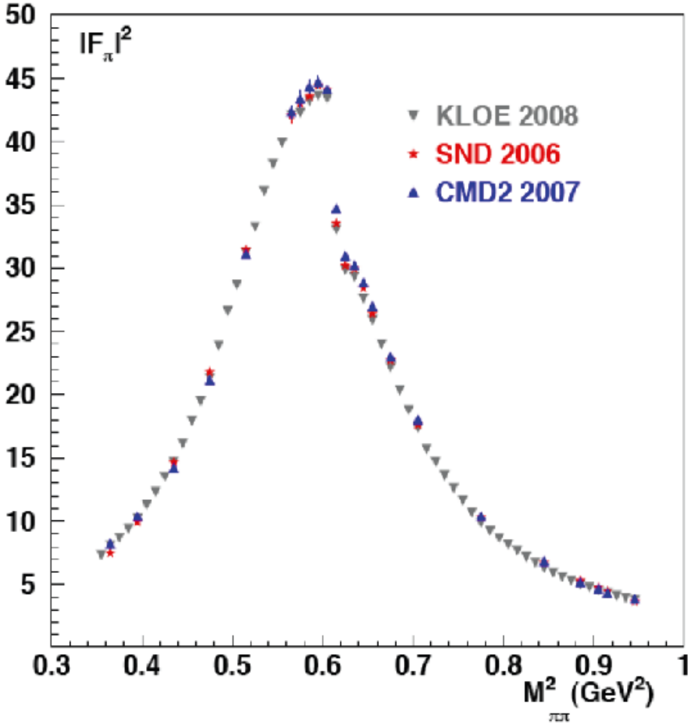
- Experiments have reduced error such that 2π region no longer dominates error
- Data from Novosibirsk (CMD2 and SND)
  - For 2π, ratio $N(2\pi)/N(ee)$, form factor to 1-2%
  - All modes but 2π, luminosity measured using Bhabha scattering

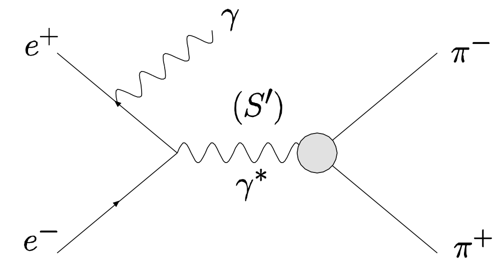


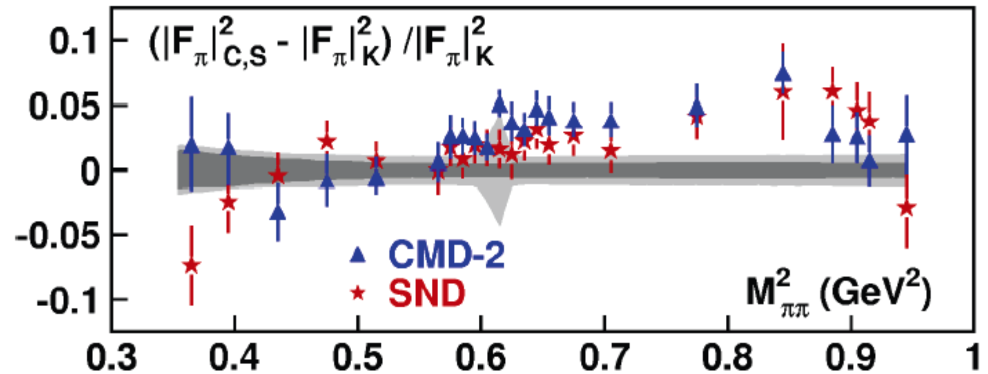


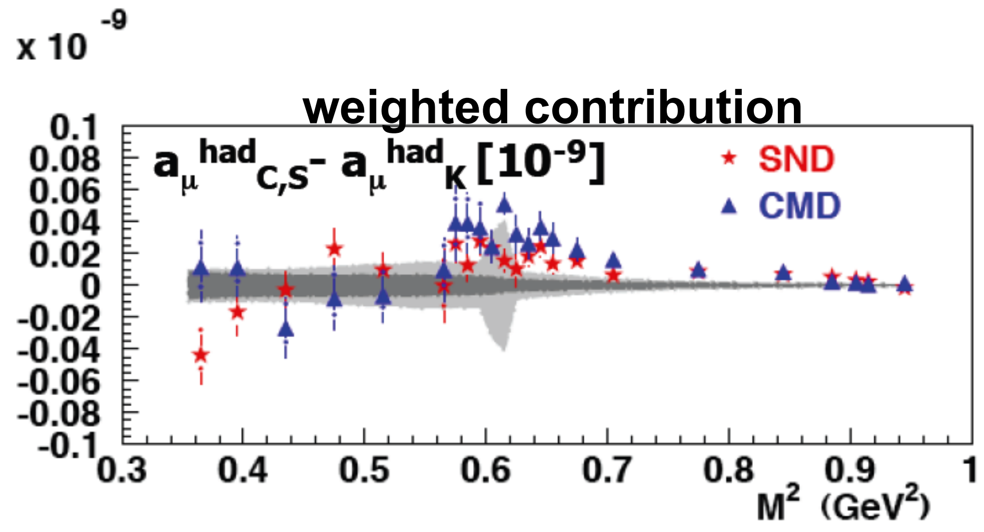
*Courtesy V. Logashenko, Tau 2008

New breakthrough pioneered by KLOE, use of ISR for a_μ





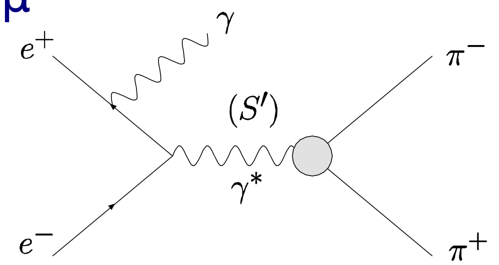




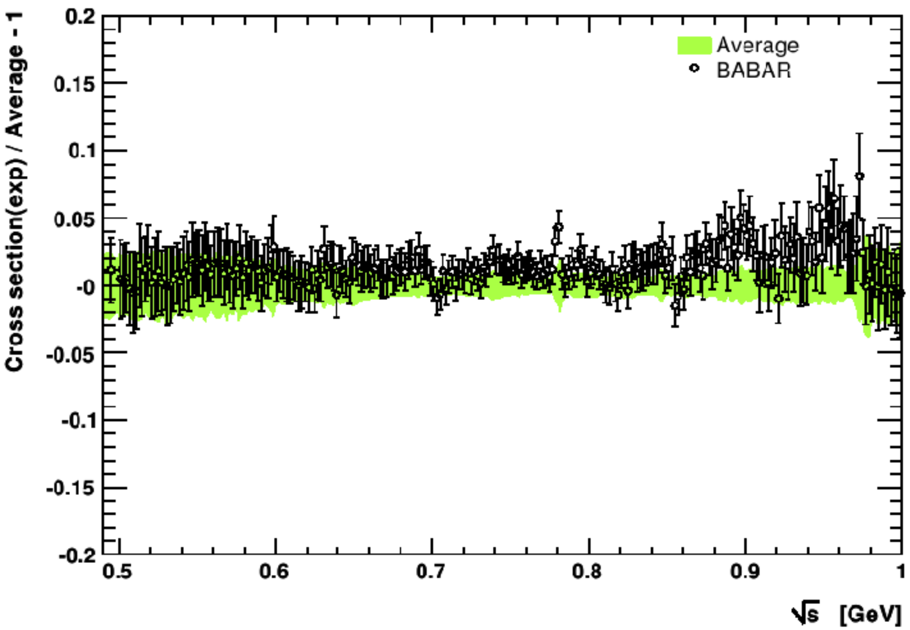
$$\sigma_{e^+e^-\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3|F_\pi|^2$$

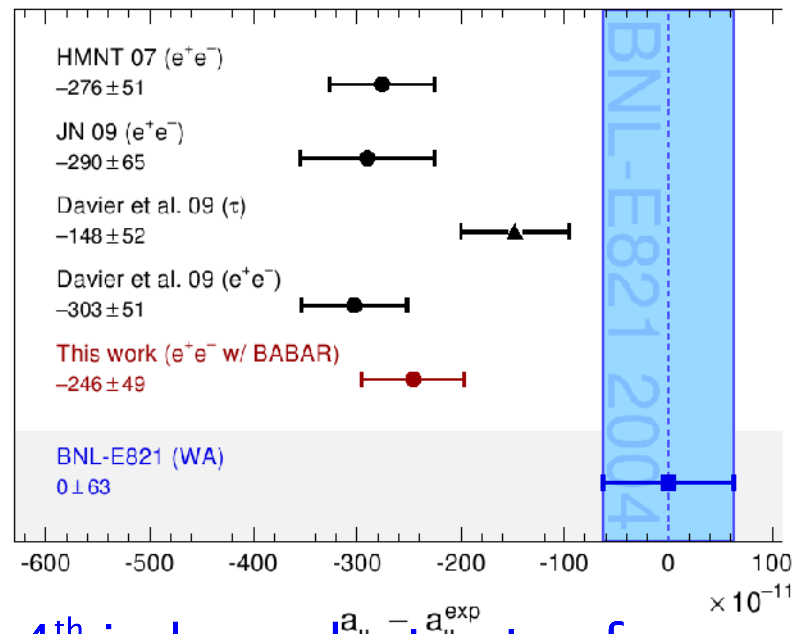
- Unbelievable statistical precision
- KLOE agrees with CMD2 & SND

Results from Babar, also using ISR for a_μ



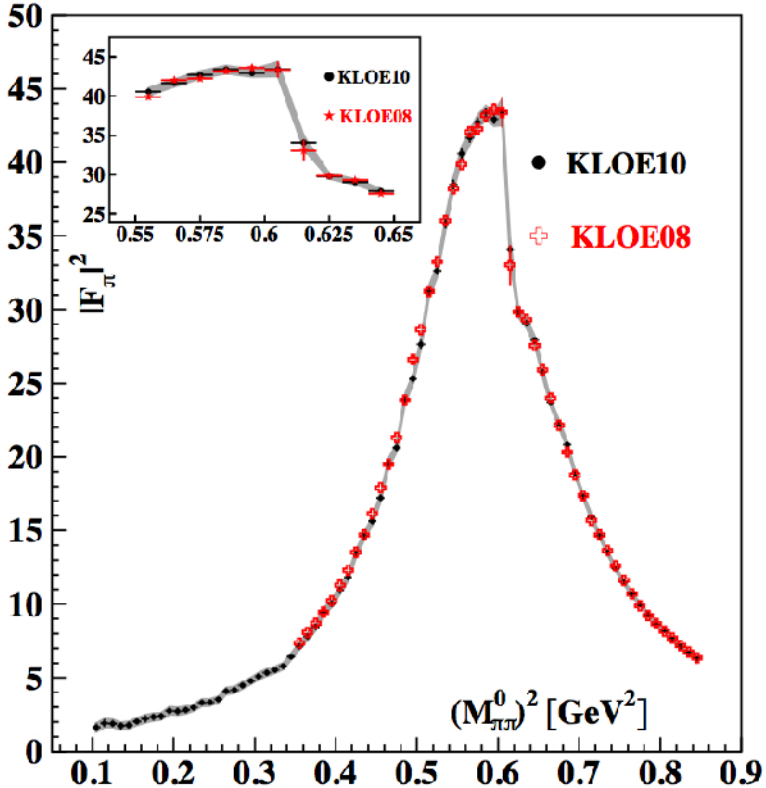
- Also, statistically precise and only 2nd expt to use ISR
- Some tension (~2σ) with KLOE result
  - Babar reconstructs the ISR photon
  - Babar also measures the denominator of R(s)

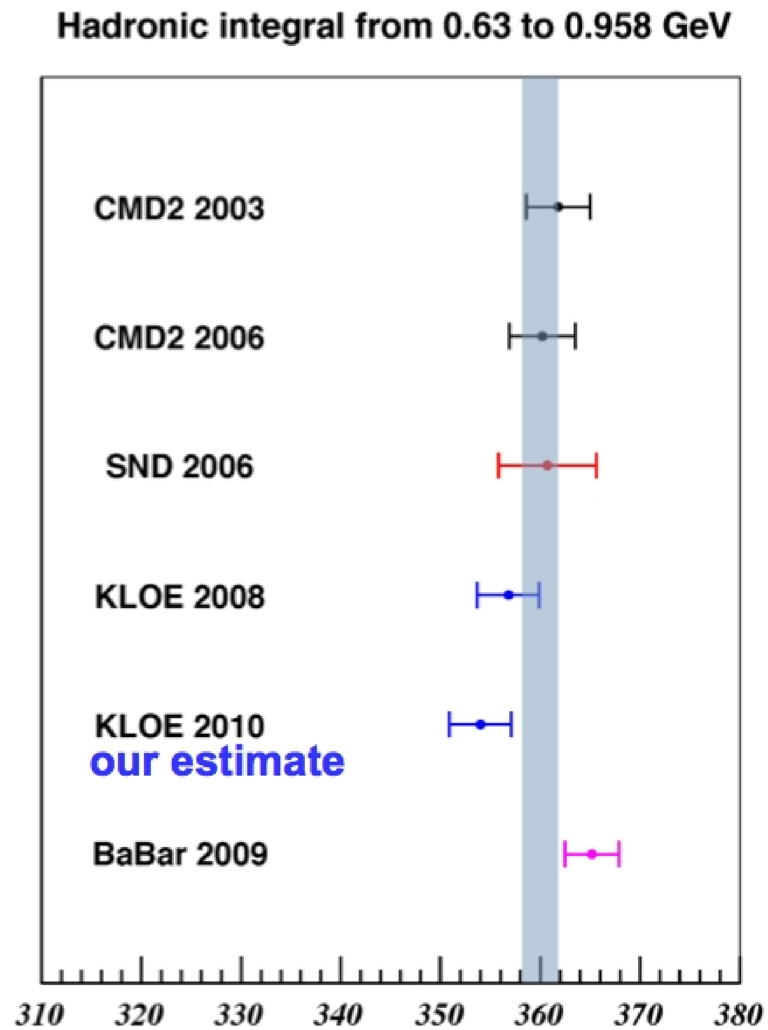




So now Babar had provided a 4th independent vote of confidence in theory...good, need that to extract new physics

Future improvements (are already here)



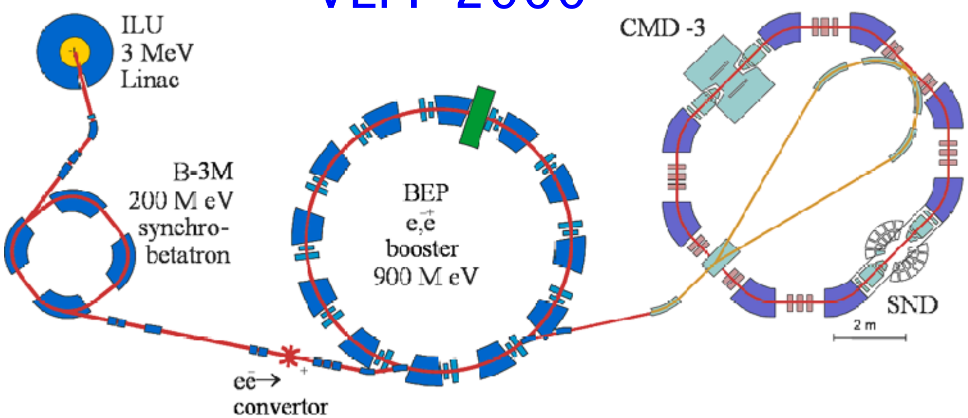


- Independent, large-angle data sample, ISR photon reconstructed
- KLOE10 in good agreement with KLOE08, still some tension with Babar09

chi2/dof=8.8/5

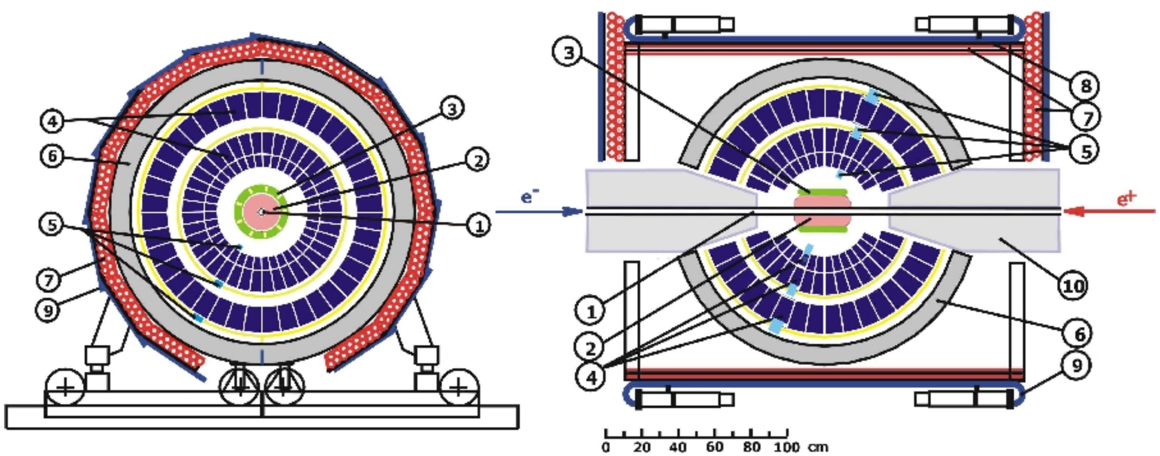
New facility VEPP-2000 and upgraded detectors

VEPP-2000

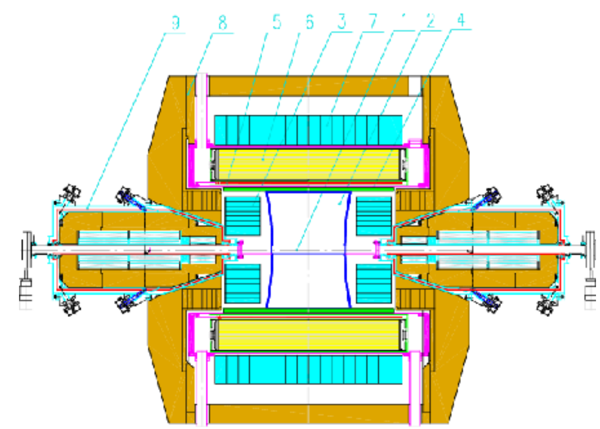


- Lots of machine and detector upgrades in Novosibirsk
  - Energy extend range up to 2 GeV
  - Experiments start in 2010!!!
- Babar & Belle multi-pion xsecs
- KLOE requestion $20M to upgrade their machine to 2 GeV

SND2000



CMD3



Muon g-2 in the LHC era

Where would we be after improvements, assuming the 255 x 10^{-11} is unchanged?

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16

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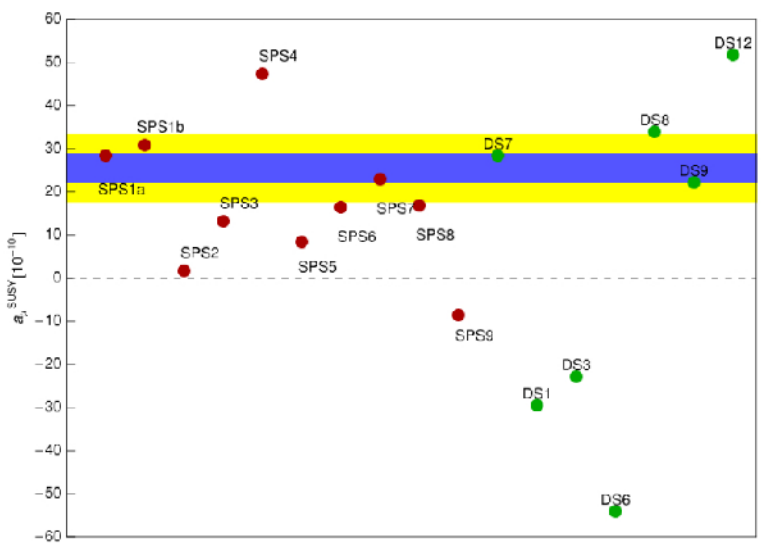
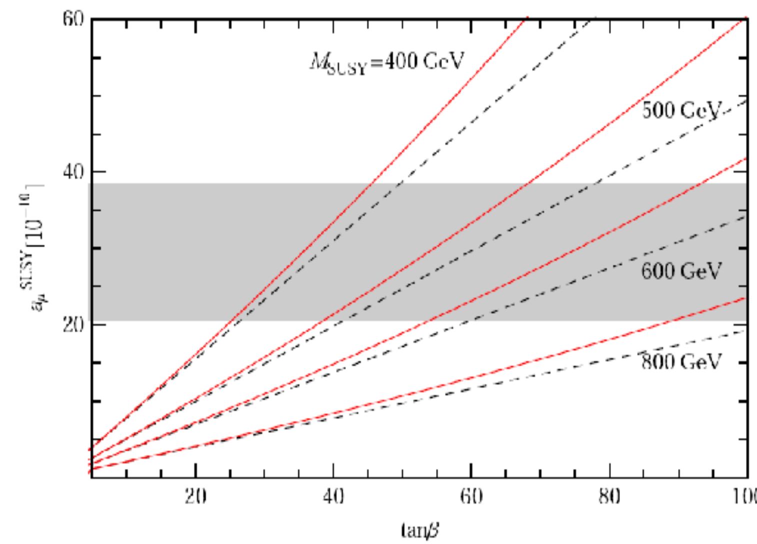
With reduction in exp. error only, discrepancy would be 5σ



SPS benchmark points LHC Inverse Problem (300fb^{-1})

[Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]
N. Arkani-Hamed, G. Kane, J. Thaler1, L. Wang



Marchetti, Mertens, Nierste, Stockinger (0808.1530)

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30

With some additional thy. progress, could be at 7.5σ!

16

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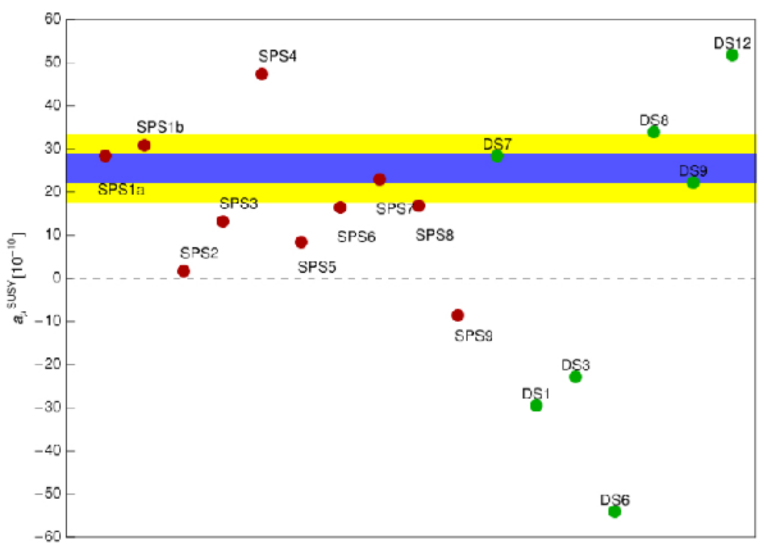

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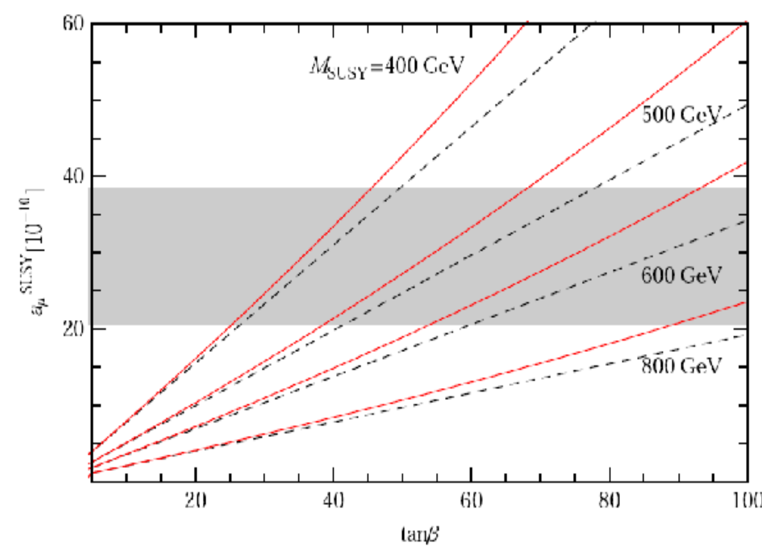

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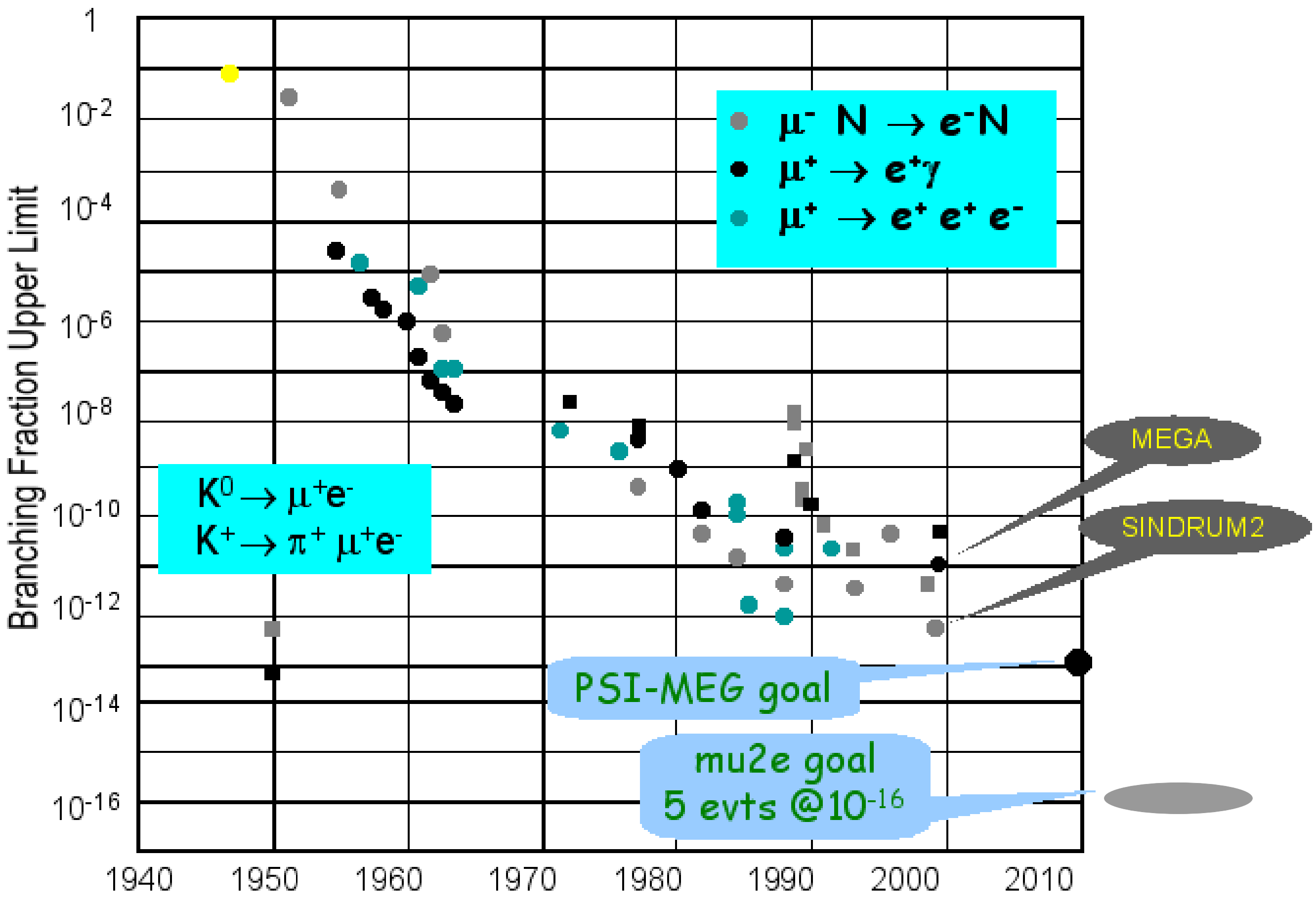
The Mu2e experiment at Fermilab

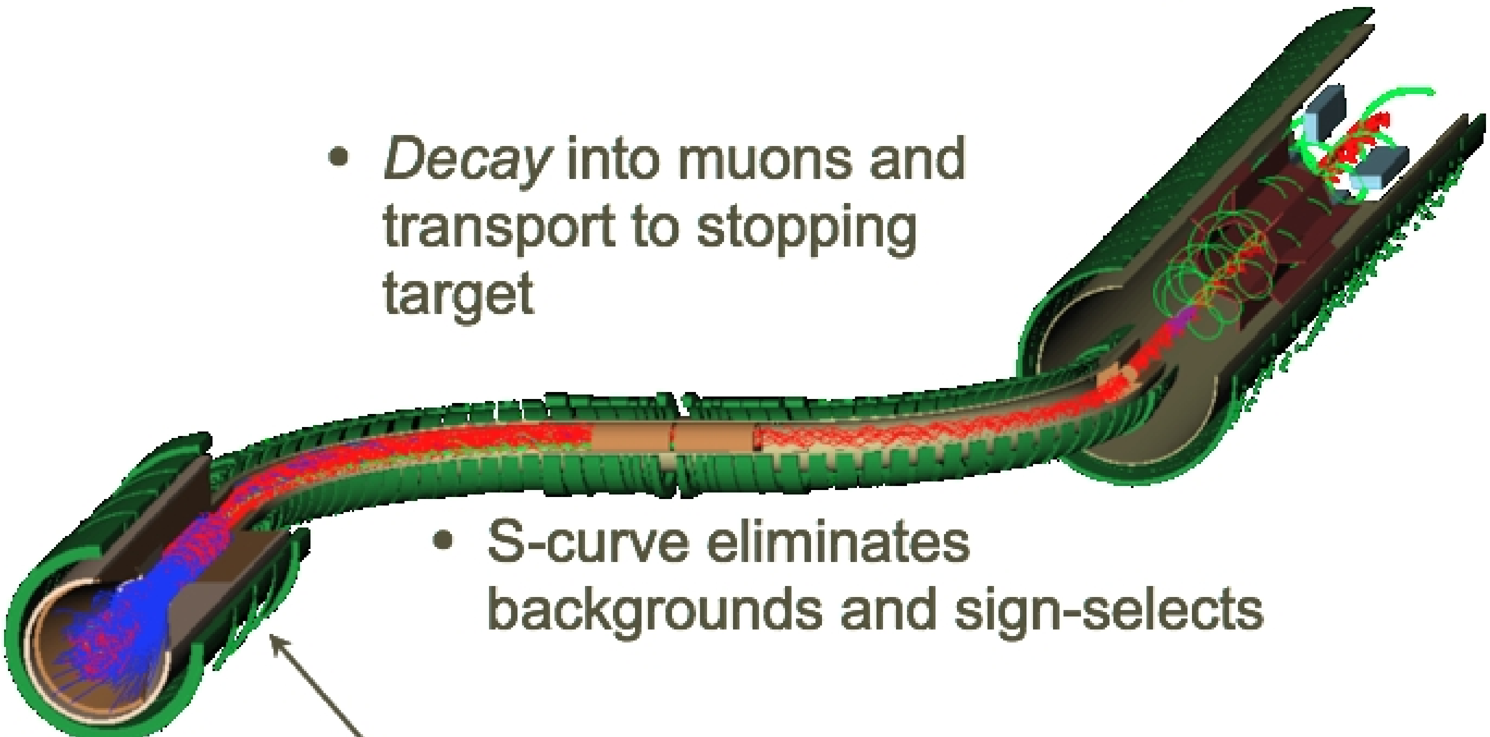
Goal of Mu2e...push the sensitivity for muon conversion in the presence of a nucleus by 4 orders of magnitude!



The Mu2e solenoids…need 10^{19} muons!

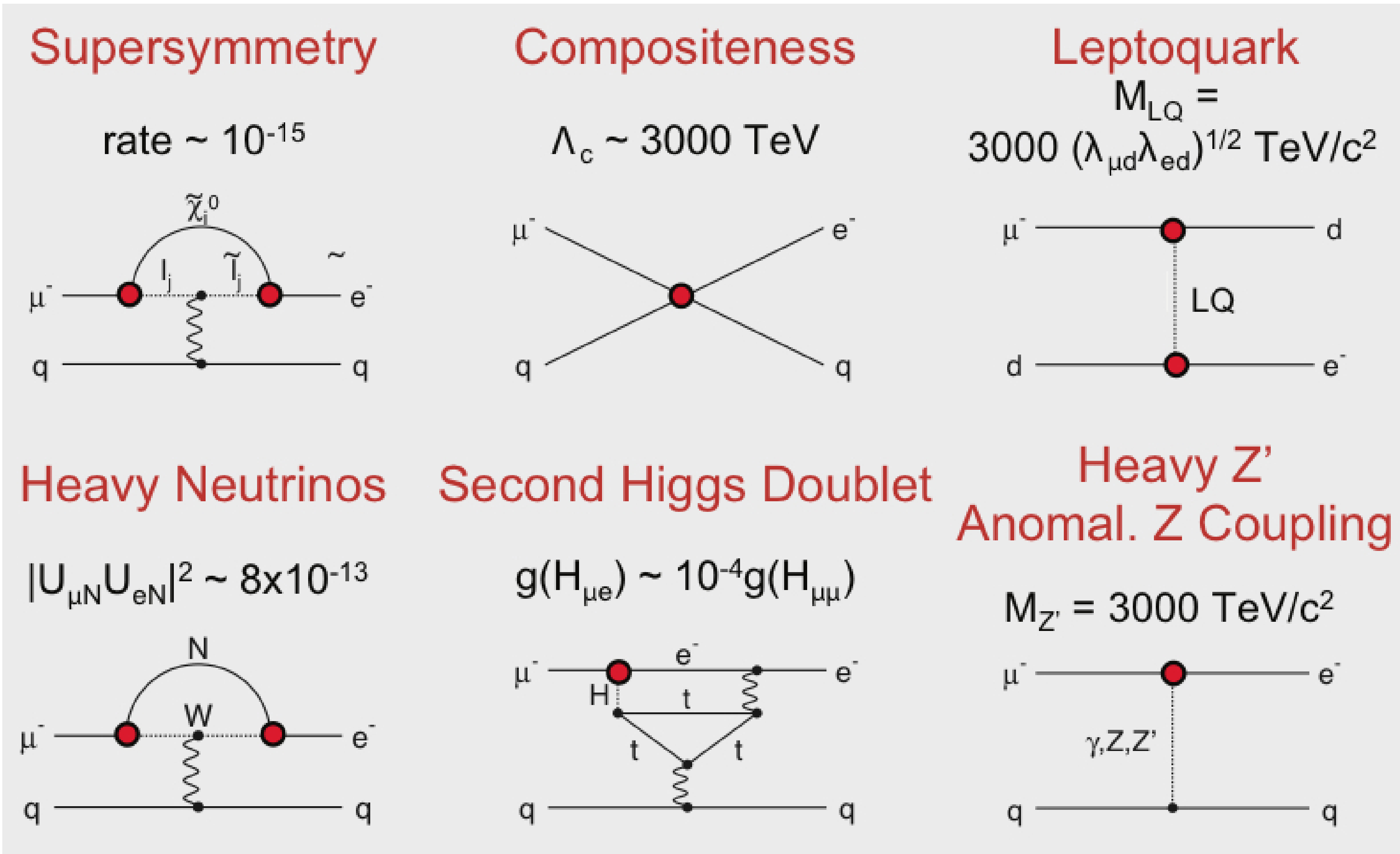
* For comparison, g-2 needs to measure 2 x 10^{11}

- *Tracking and Calorimeter*
- *Decay* into muons and transport to stopping target



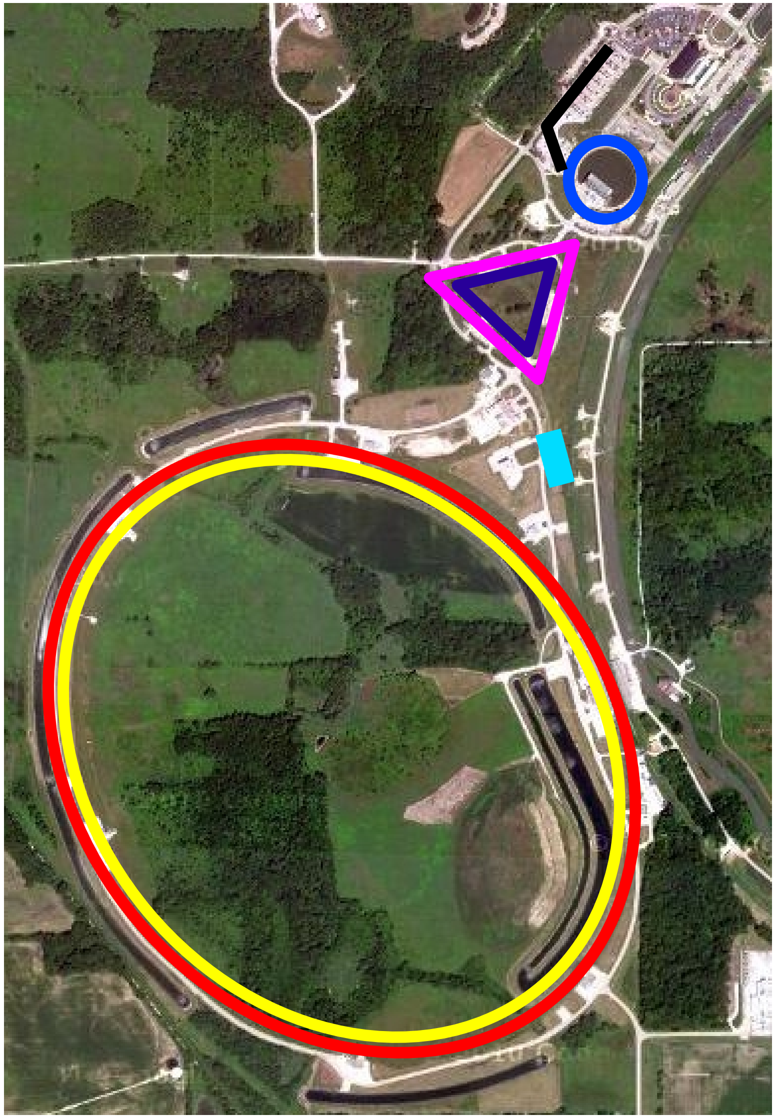
- S-curve eliminates backgrounds and sign-selects
- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ's

Mu2e sensitive to many forms of new physics



A non-zero branching ratio would be revolutionary…fuel an industry of measurements with higher precision, different targets, etc.

g-2 and Mu2e only possible due to TeV legacy



Both start with beam from the Booster

Both inject into the Recycler through the new (2012) NOvA transfer line
- g-2 rebunches beam
- Mu2e passes straight through

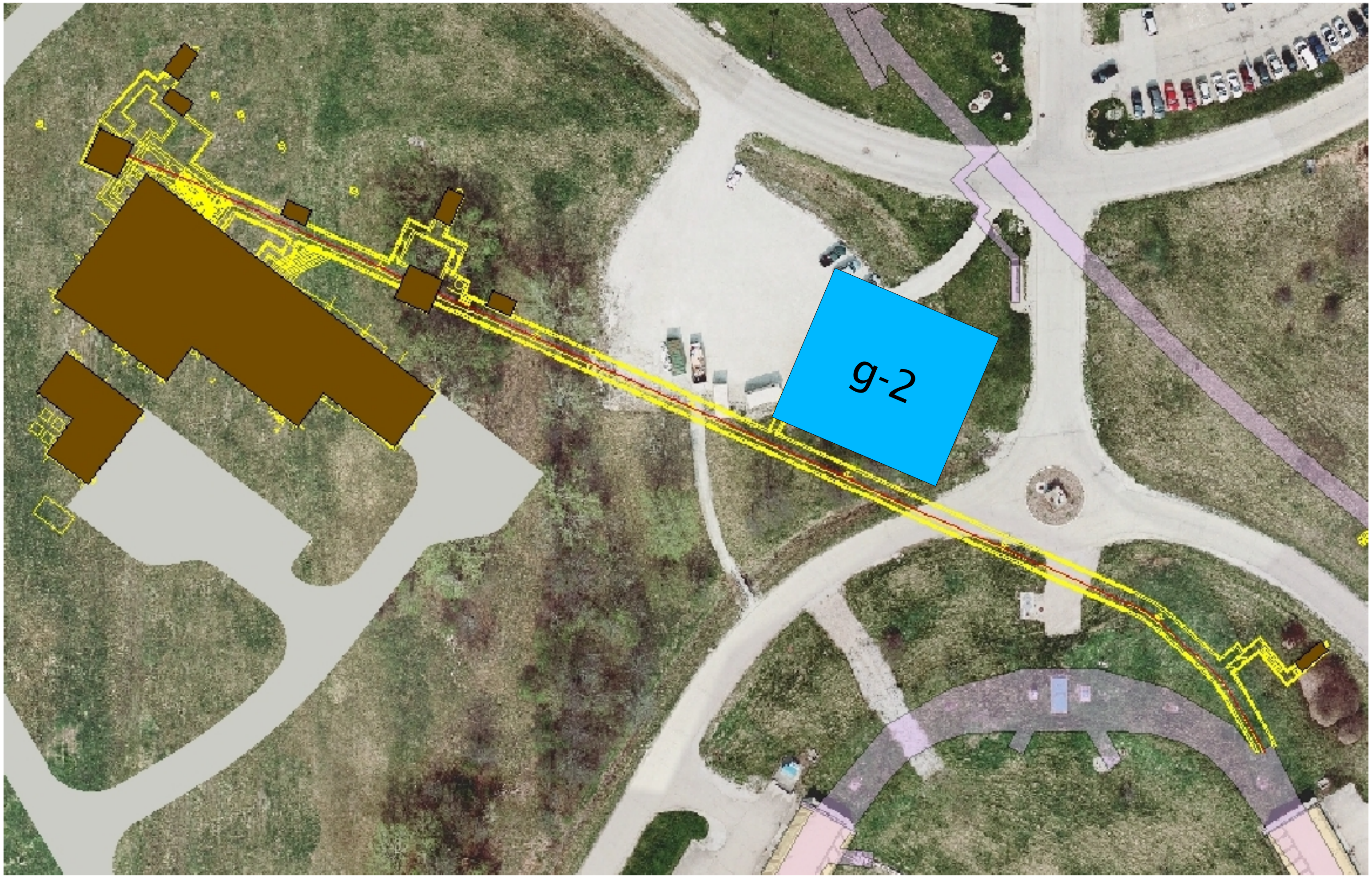
Both extract beam in new connection heading towards AP0
- g-2 hits target
- Mu2e bypasses

Mu2e injects into the Accumulator, rebunches, moves beam to Debuncher

Both use the Debuncher
- g-2 uses for once-around beamline
- Mu2e slow spills

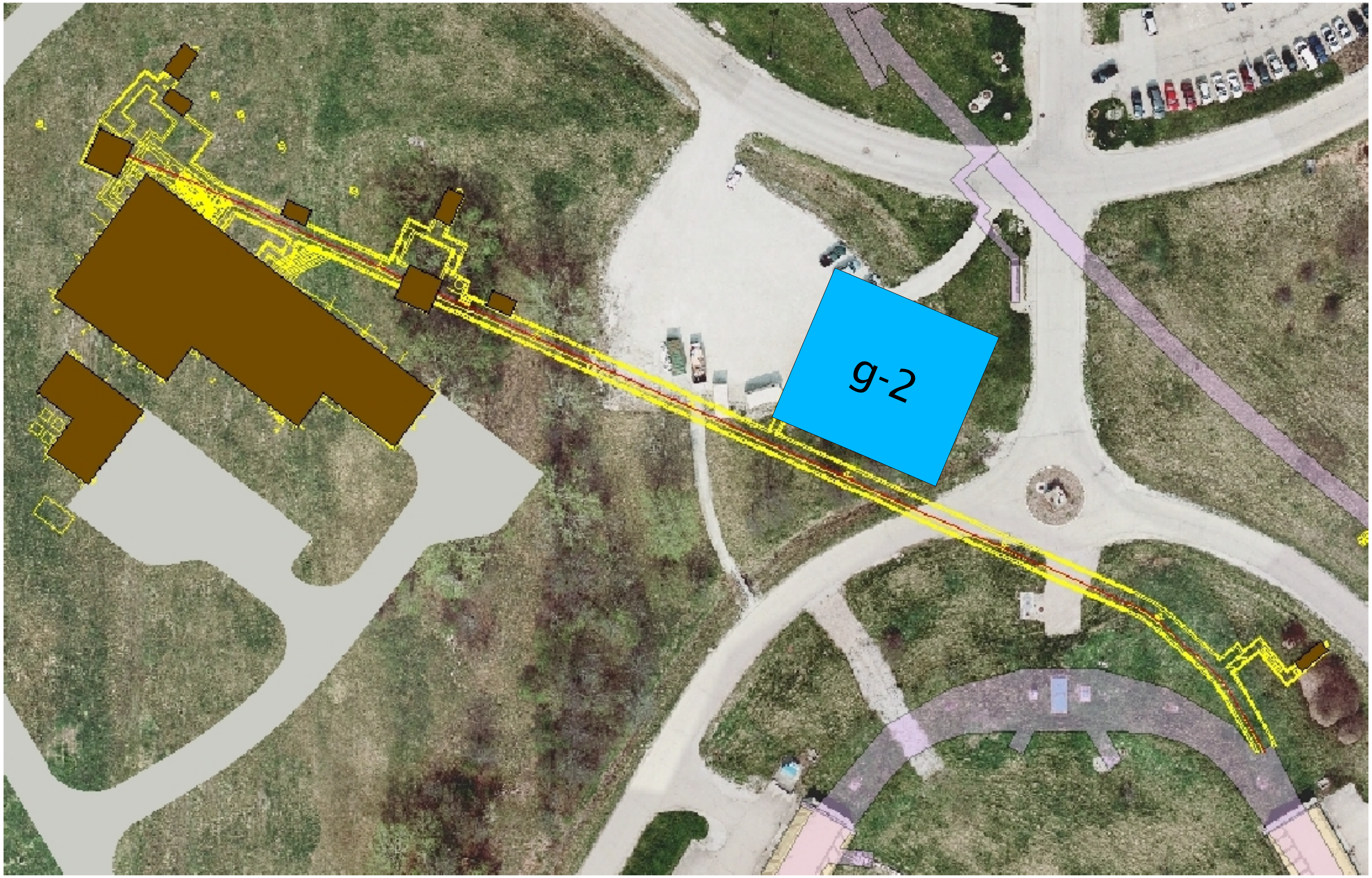
Both extract from the Debuncher towards a new experimental campus

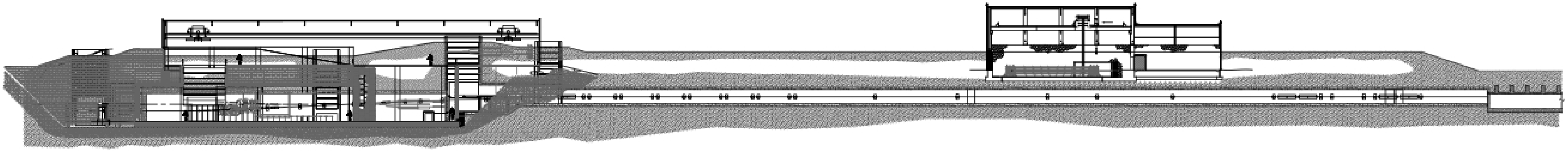
Welcome to the new muon campus!



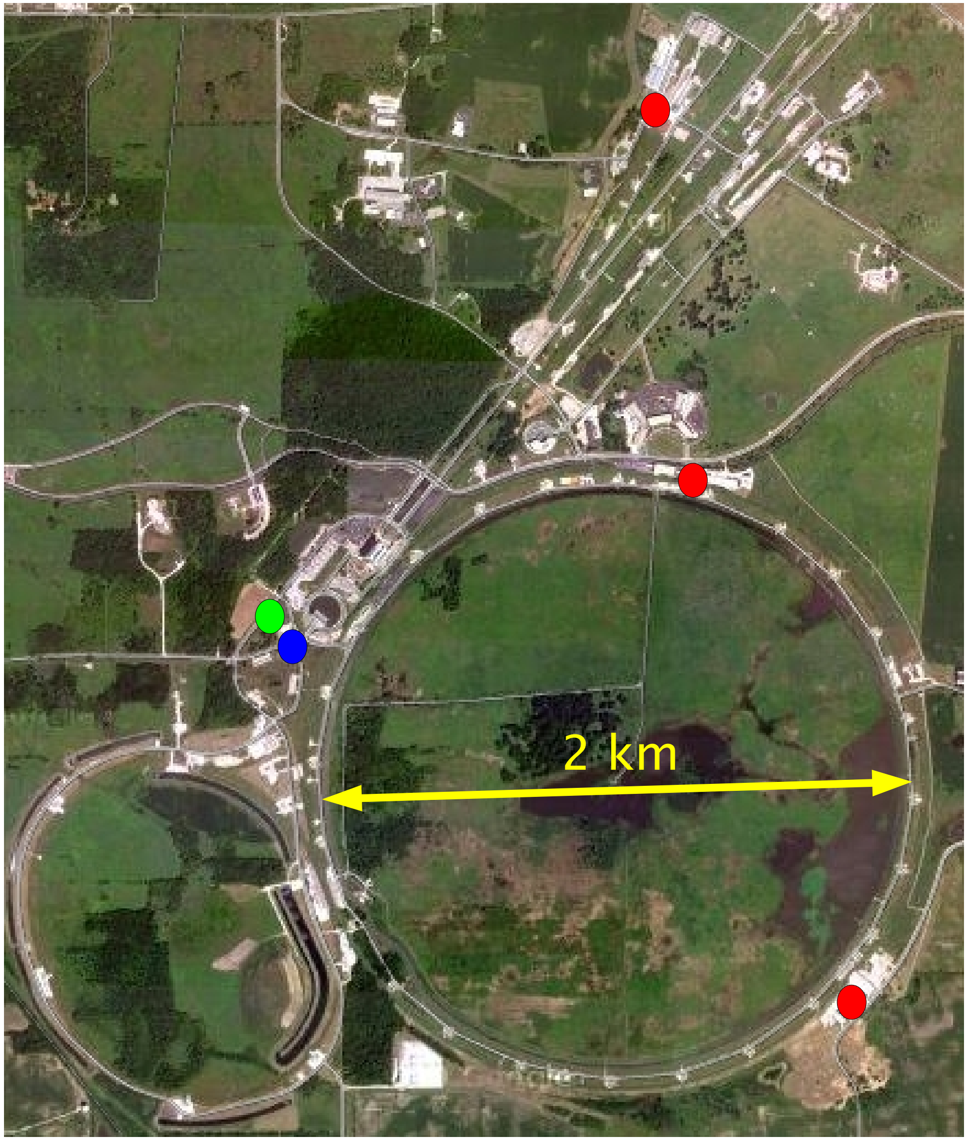
Two centrally located buildings, one with a secondary beam delivered to a surface building, the other an underground facility for primary beam

Welcome to the new muon campus!





Aren't there existing buildings?



- Beam comes out here
- Muon campus
- Buildings with enough span

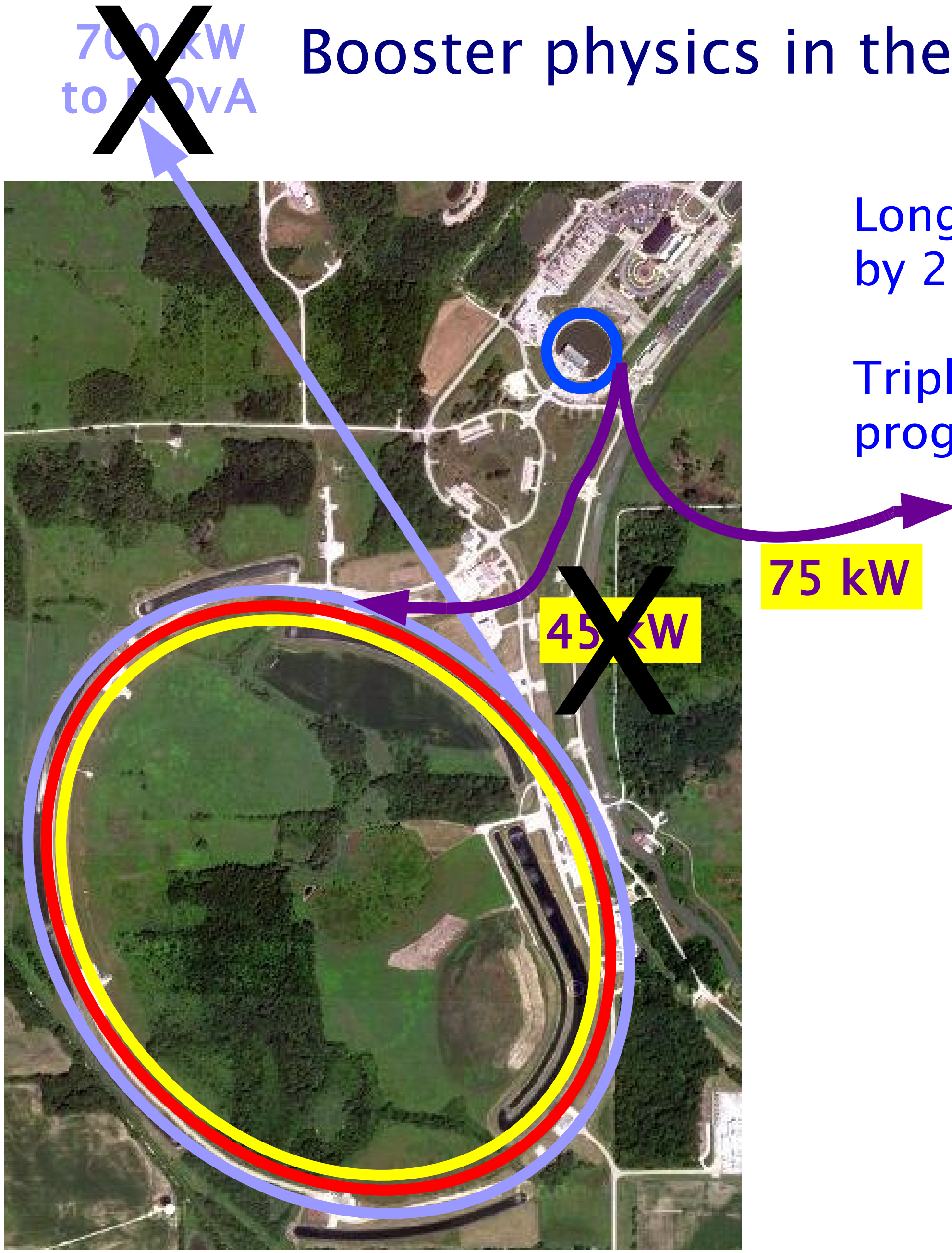
Not really...

Low-energy beams require a much denser lattice for transport, no way to even get 8 GeV primary beam to ●

On the plus side, there are a lot of other IF proposals with the same issue, e.g. μEDM (500 MeV) and μ-cooling R&D (200 MeV)

Now we will have a centrally located campus equipped with experimental halls, cryo facilities, LCW, power, etc.!

Booster physics in the Project X era...



Long-baselin neutrino program fueled by 2MW Project X beam

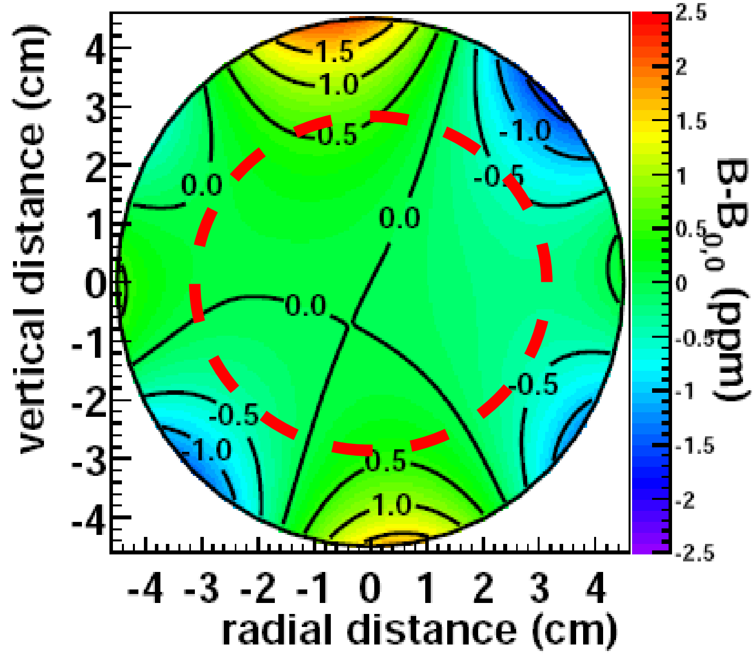
Triples beam to 75 kW for other programs

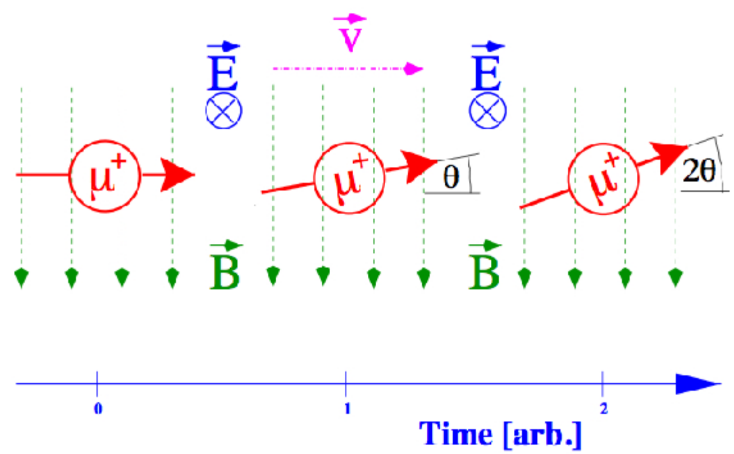
What kind of things can be done with 75 kW?

MicroBooNE + 1 kton liquid Ar
- Can triple beam to 2-detector, short-baseline, liquid Ar experiment on the Booster Neutrino Beamline

Muon g-2
- Can measure a_μ for negative muon, i.e. compensate for 2.5 x lower π^-/π^+ production at 8 GeV
- Can collimate stored muons to ultra-sweet spot in storage ring

Muon EDM
- Enough beam to mount a dedicated EDM experiment in the g-2 hall
- Need ~10^{16} 500 MeV muons
- Sensitivity to d_μ of 10^{-24}

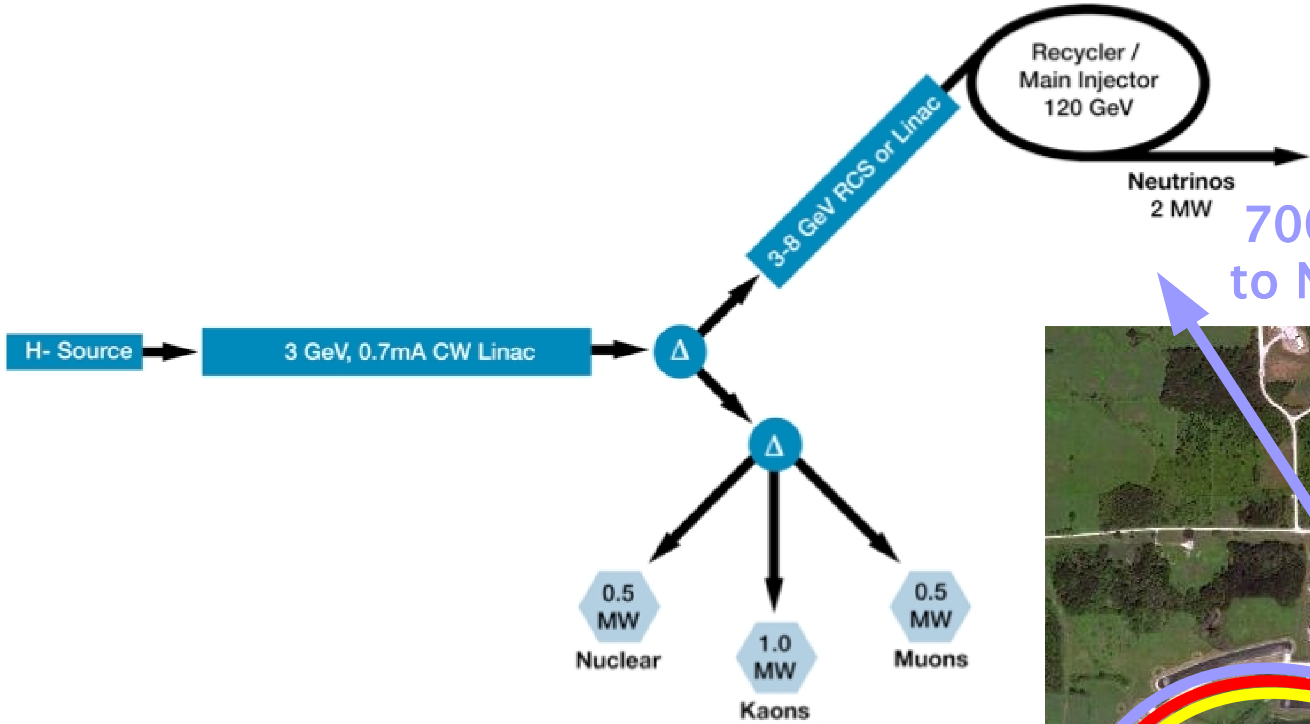


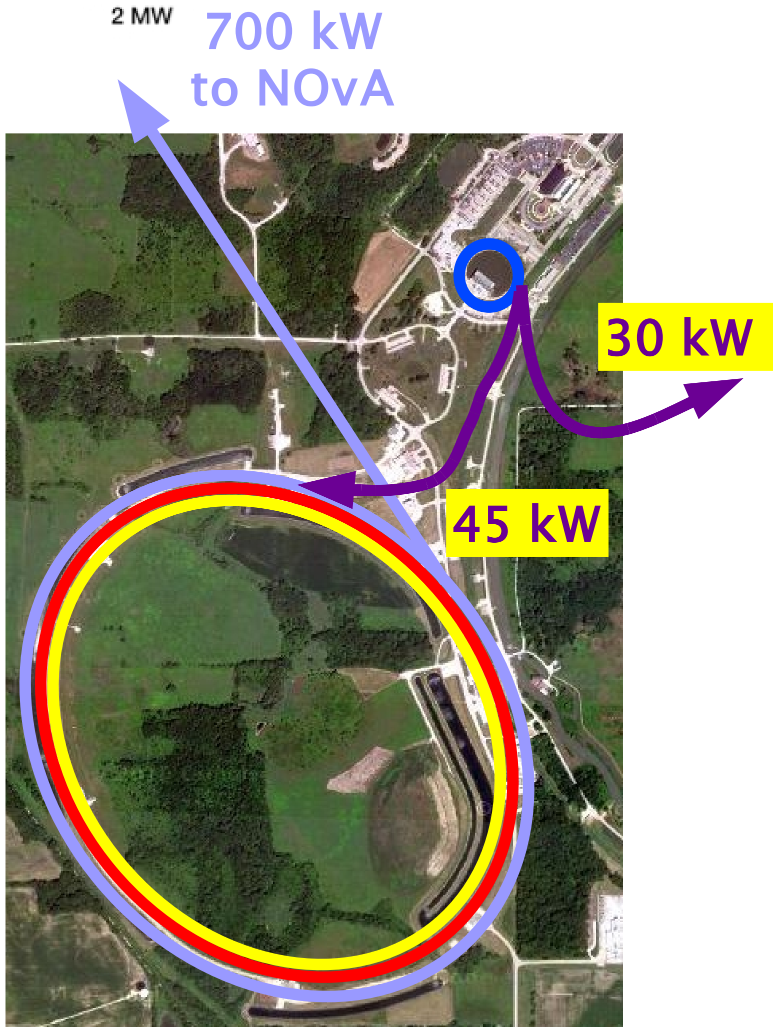


Y. Semertzidis, BNL

The Project X Era

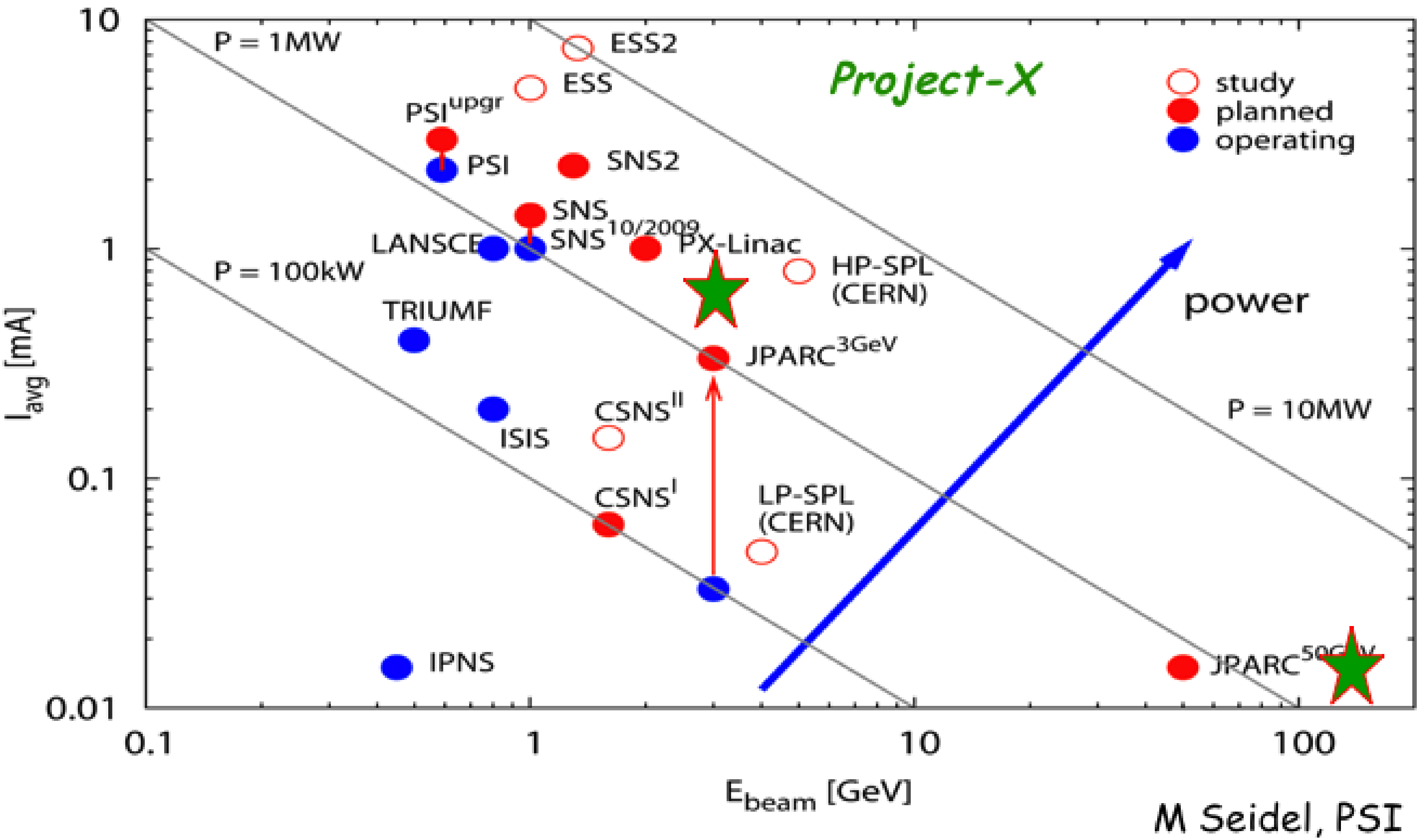
Comparing across eras...





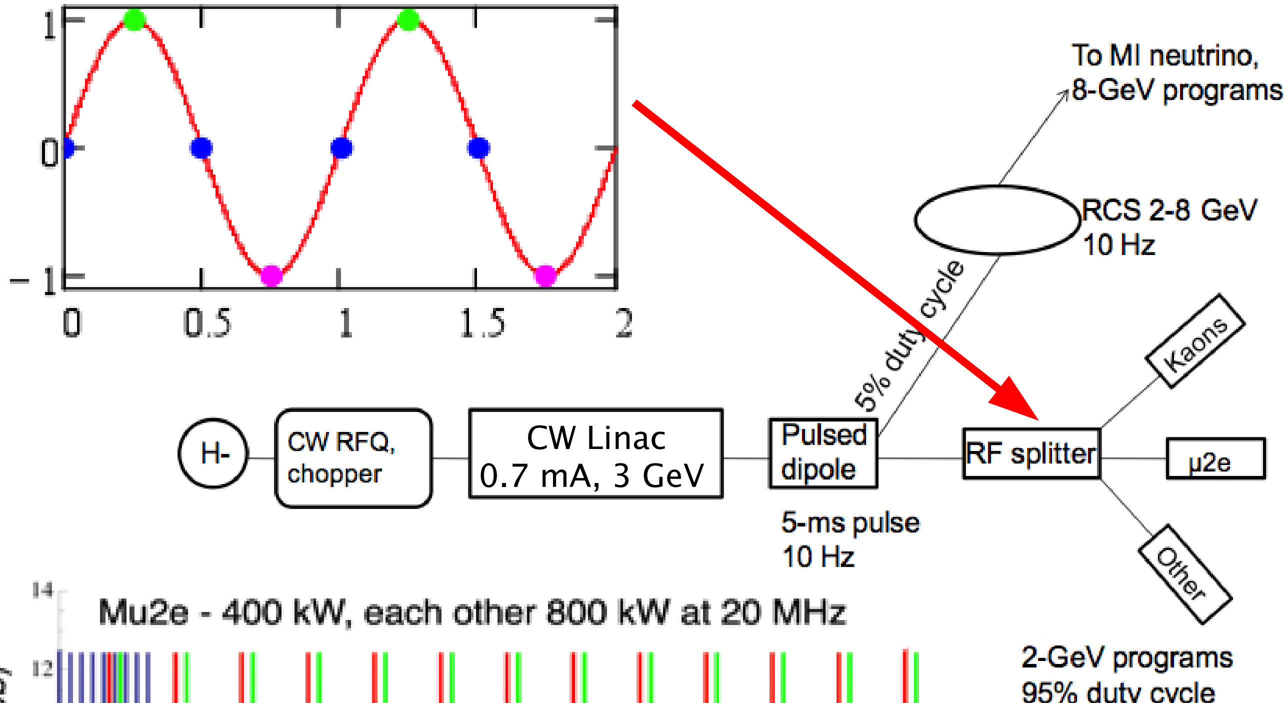
Beam power proposed in Project X would revolutionize the intensity frontier!

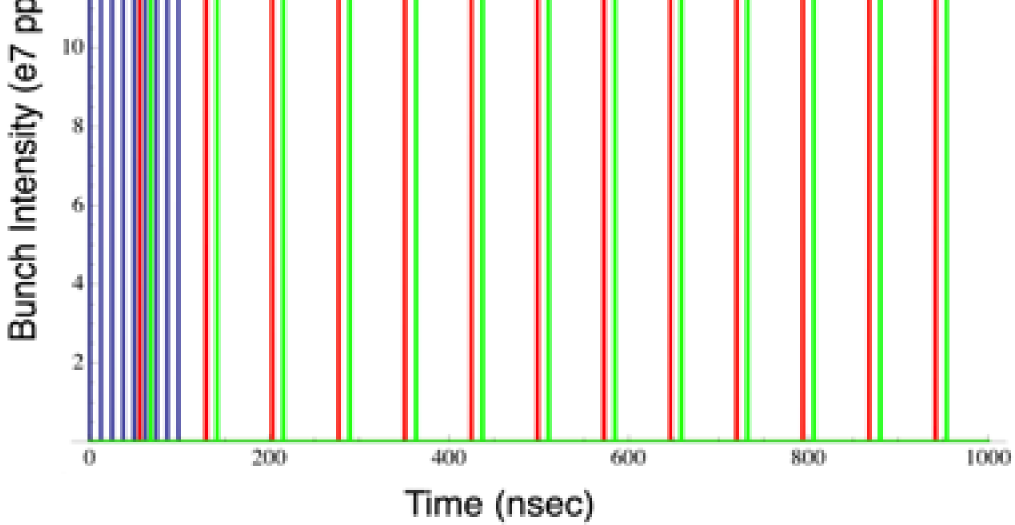
Project X compared to other intense sources



Currently only two other sources >= 1 MW, but
at energies of 1 GeV (SNS) and 590 MeV (SNS)

More than just power…unprecedented configurability

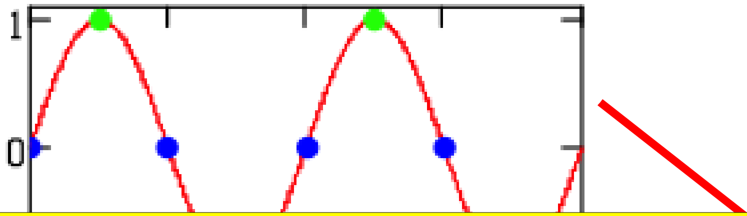


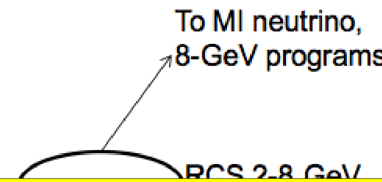


162.5 MHz CW Linac

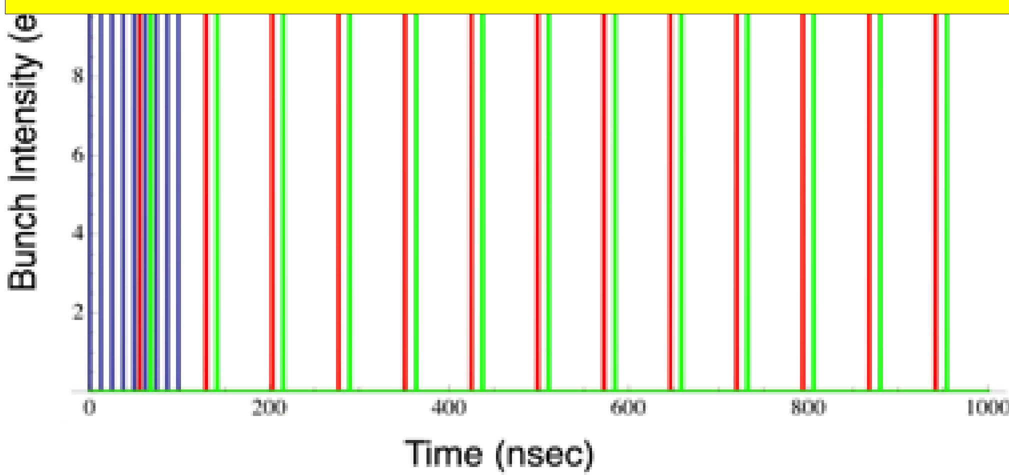
- 0.7 mA @ 3 GeV
- Pulsed dipole and RF splitter select direct beam
- Chopper creates desired time structure
- 20 ps bunch width, ~6ns spacing

More than just power...unprecedented configurability





The experiments define the accelerator parameters!



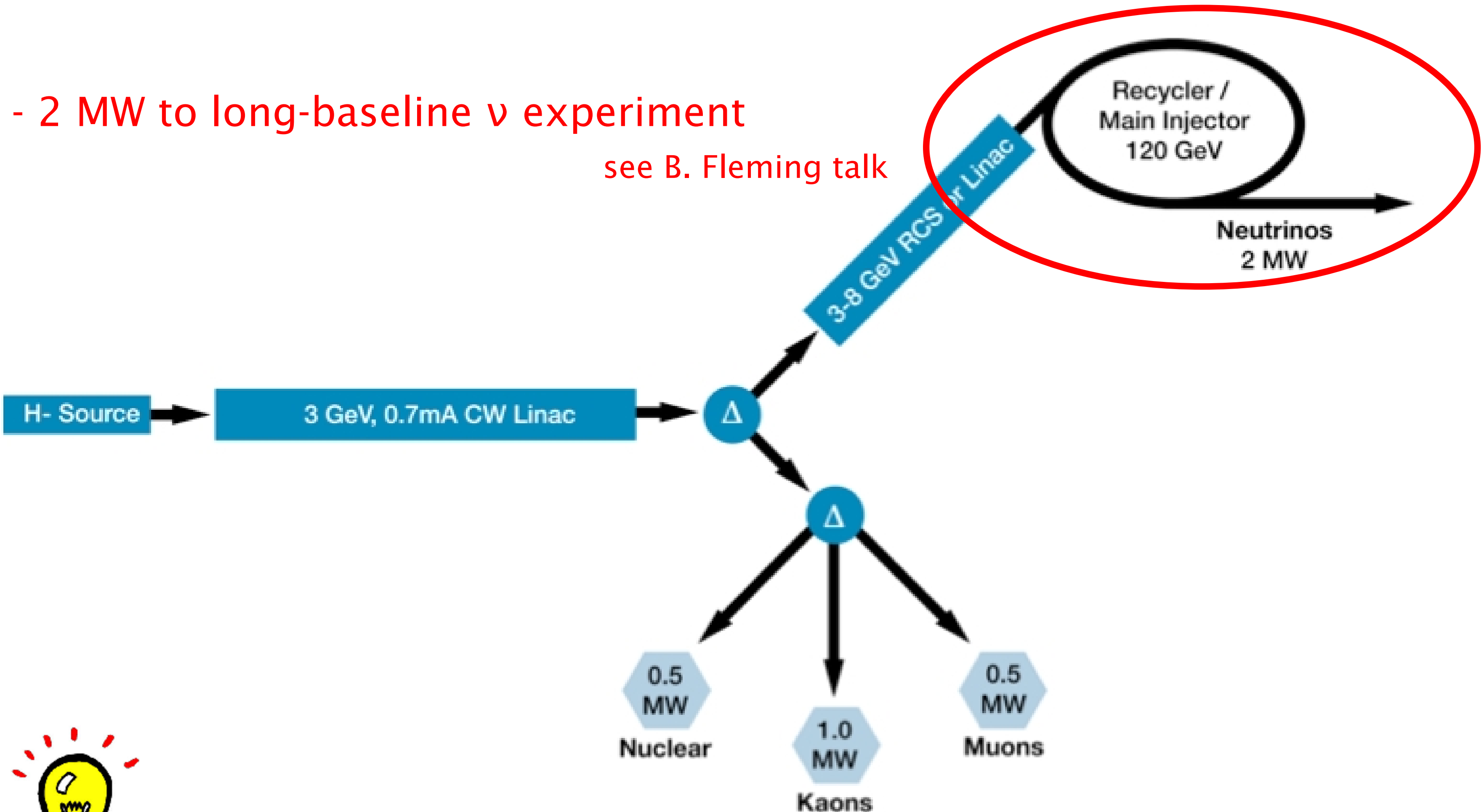
- 0.7 mA @ 3 GeV
- Pulsed dipole and RF splitter select direct beam
- Chopper creates desired time structure
- 20 ps bunch width, ~6ns spacing

3-8 GeV LINAC
NPX
NCX
SBX
MAX
BEAM LINE

Physics experiments...neutrinos

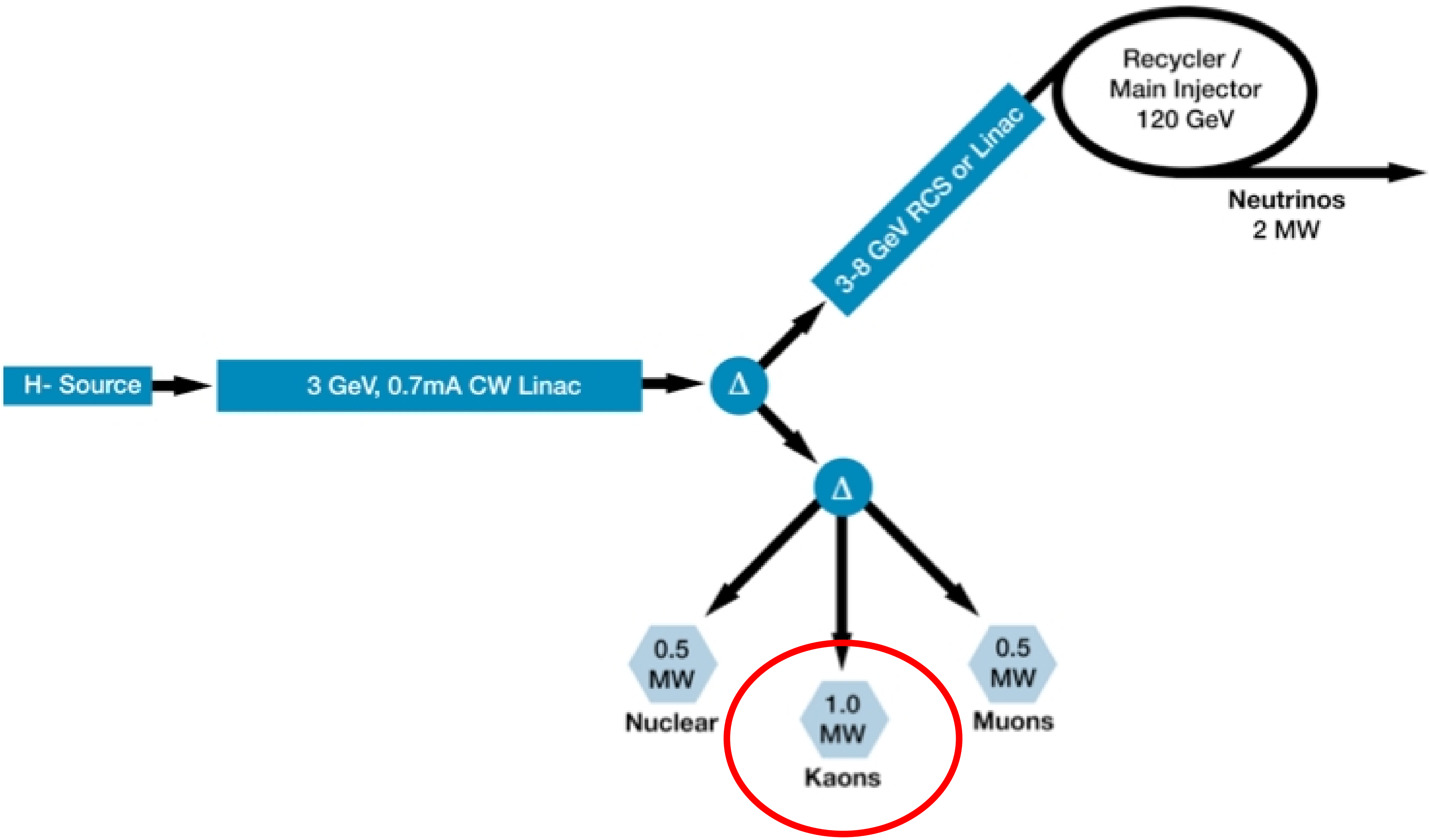
- 2 MW to long-baseline ν experiment

see B. Fleming talk

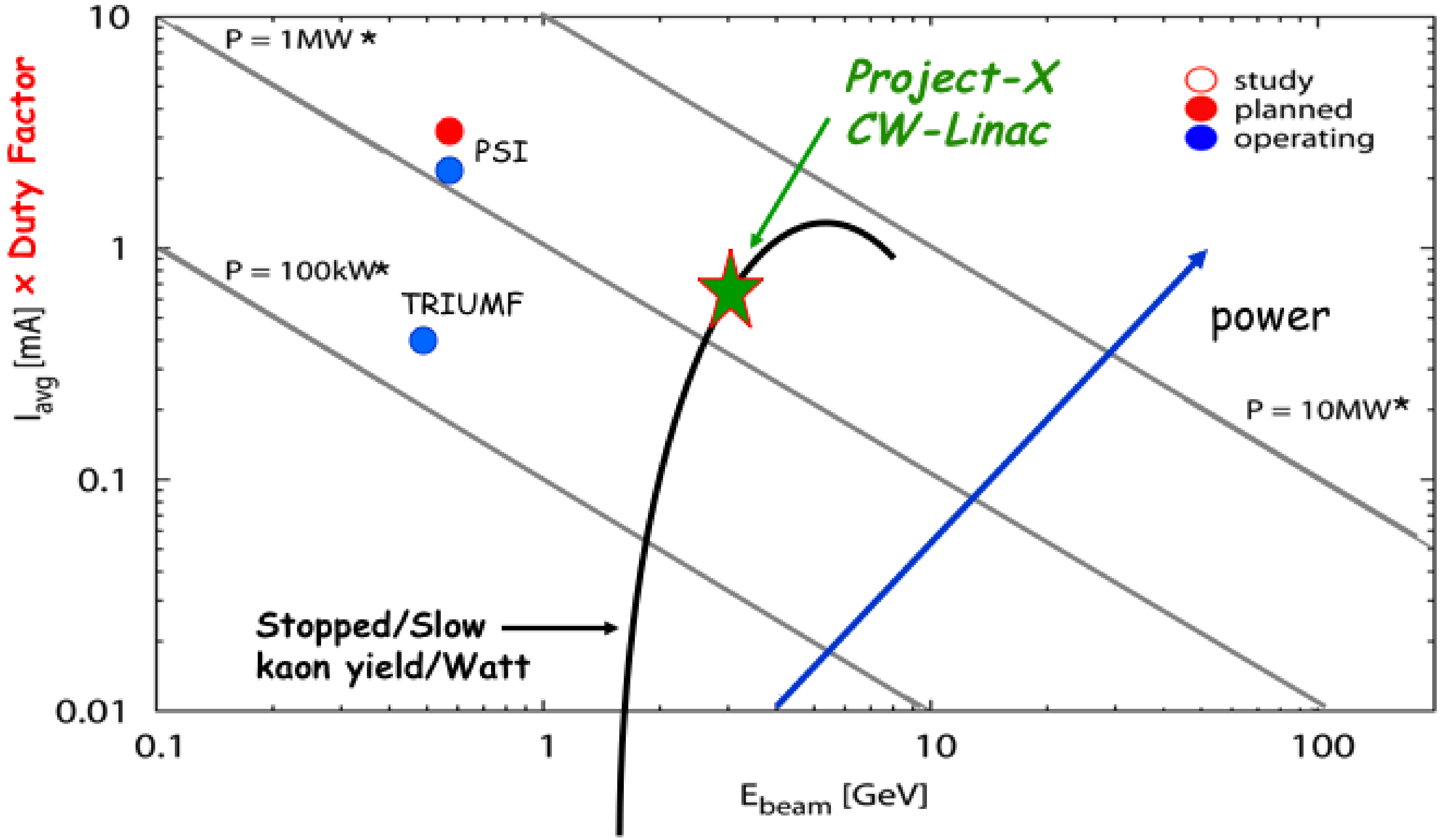


- Other ν ideas just being worked out, e.g. stopped pion source to explore sterile ν, ν_μ magnetic moment, & $\sin2(\theta_W)$ at low Q^2

Physics experiments...kaons



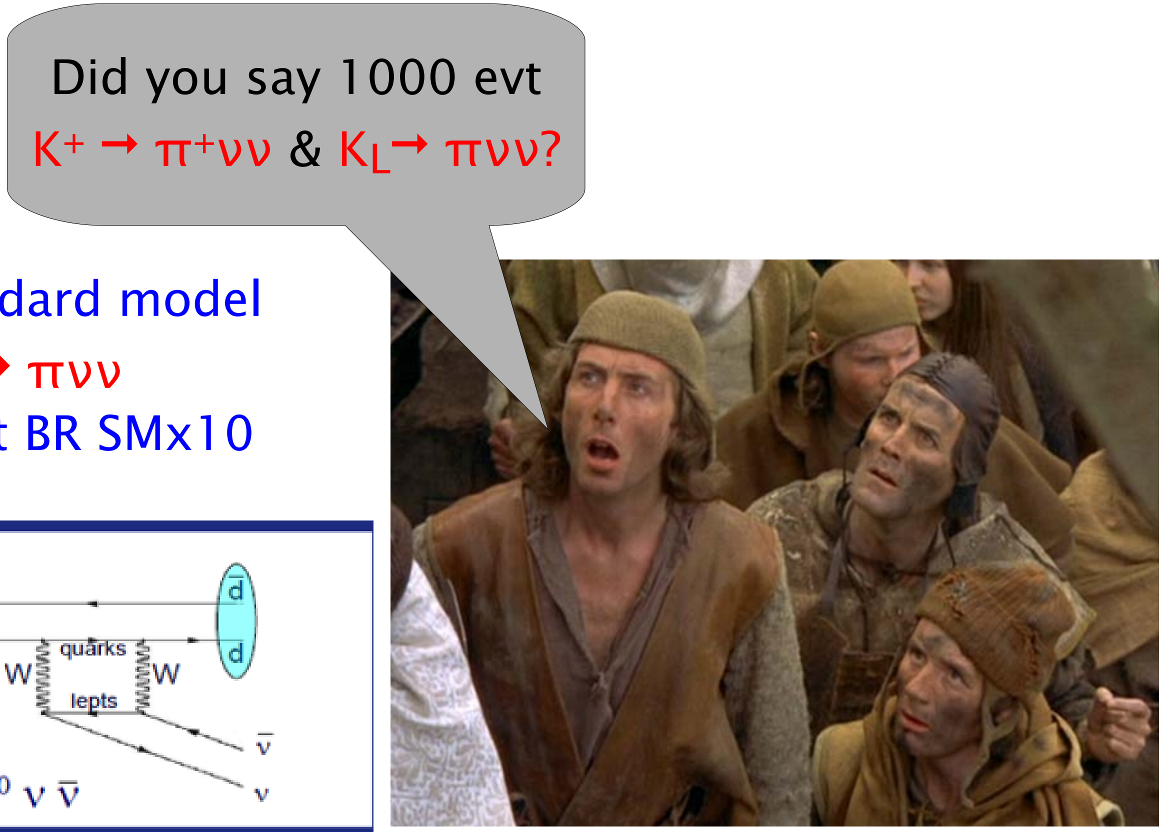
Physics experiments...kaons

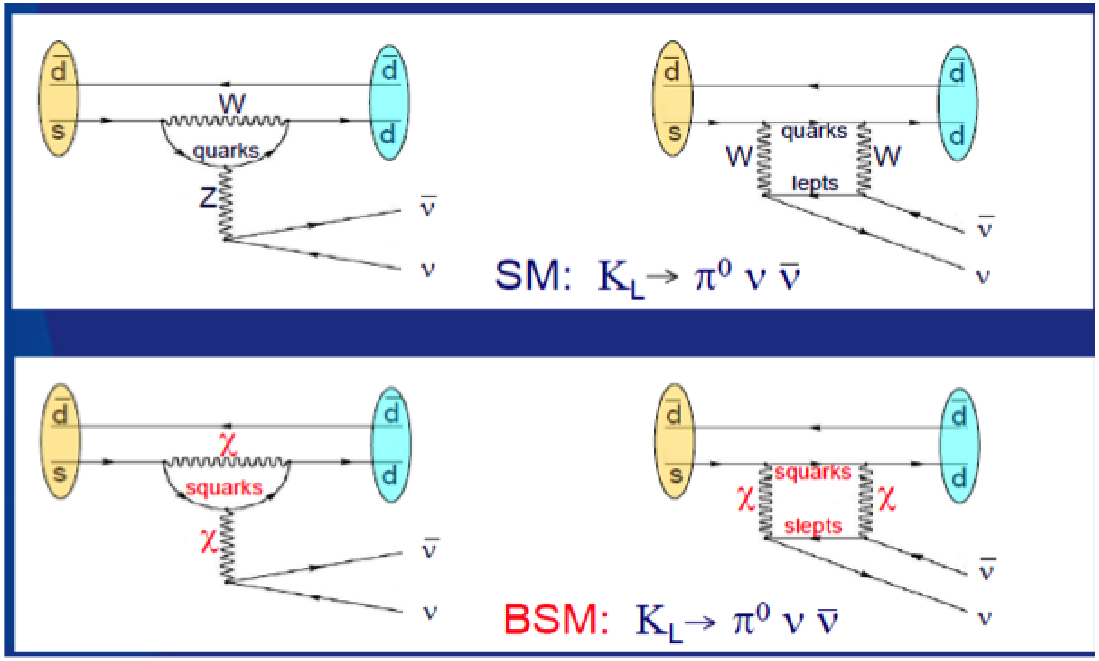


- At 3 GeV, Project X is near the maximal efficiency for producing kaons

The holy grail of kaon physics...1000 events

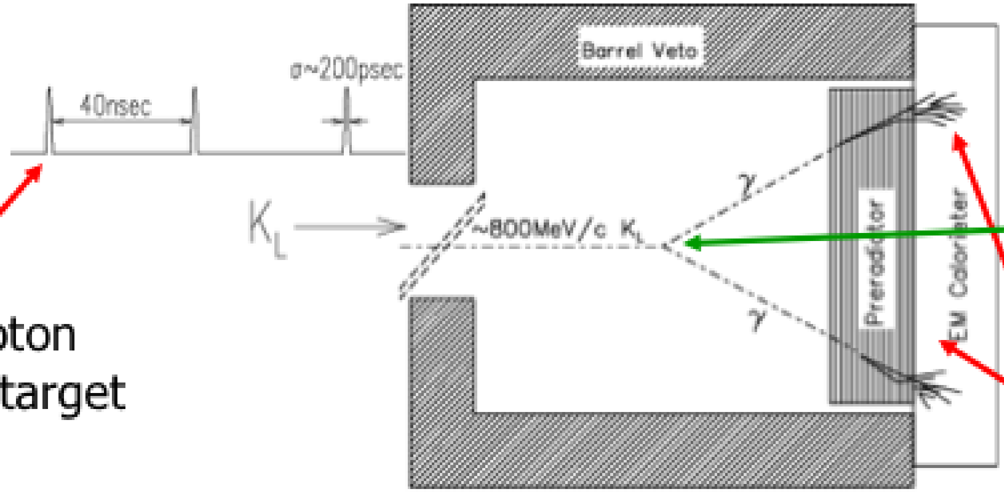
- Highly suppressed in standard model
- 30 part per trillion for $K_L \rightarrow \pi\nu\nu$
- Many BSM theories predict BR SMx10





Can see how CW linac is perfect for $K_L \rightarrow \pi\nu\nu$...

Fully reconstruct the neutral Kaon in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measuring the Kaon momentum by time-of-flight.

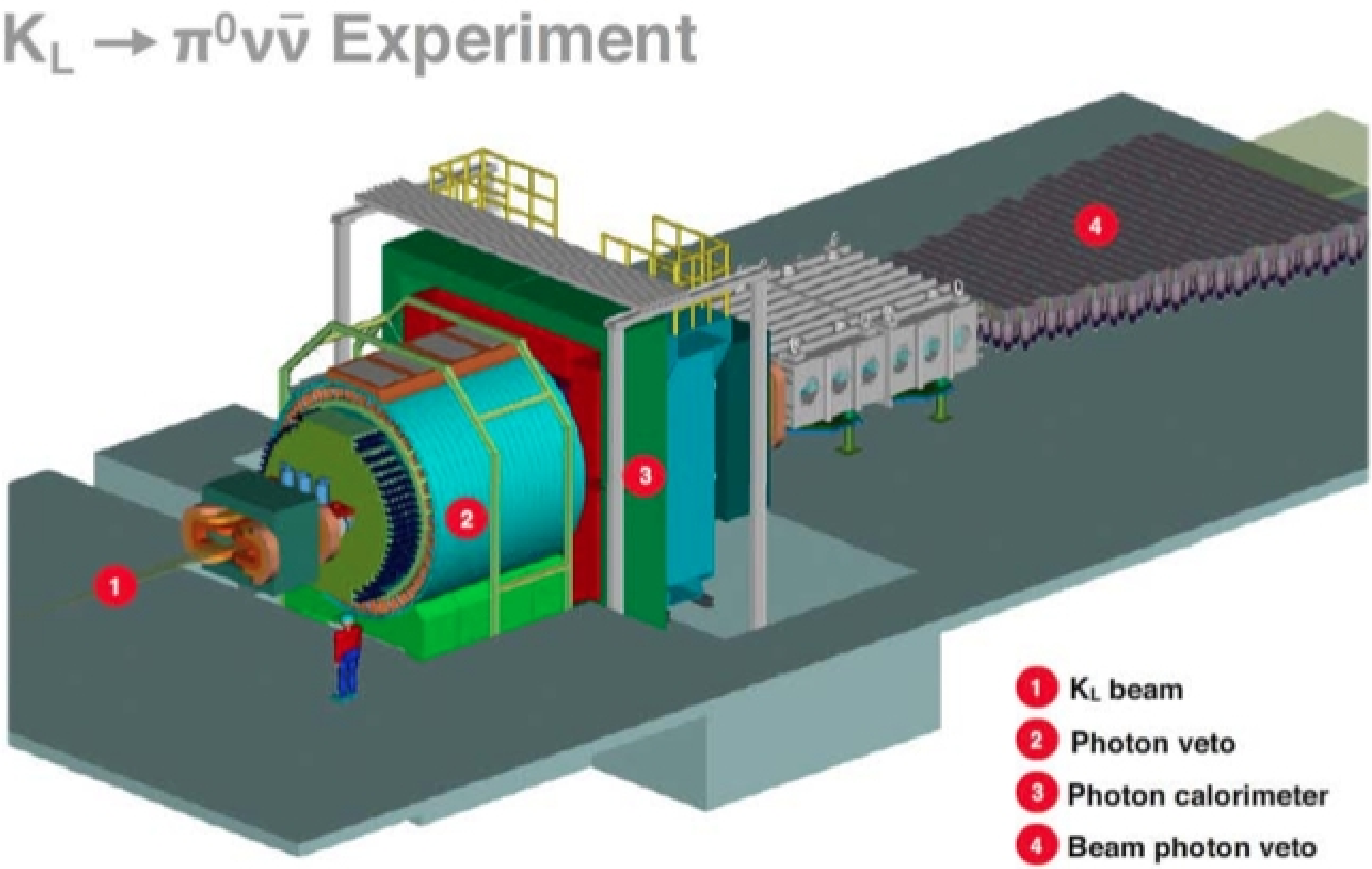


Start when proton beam hits the target

End at the decay time and decay point reconstructed from the two photons.

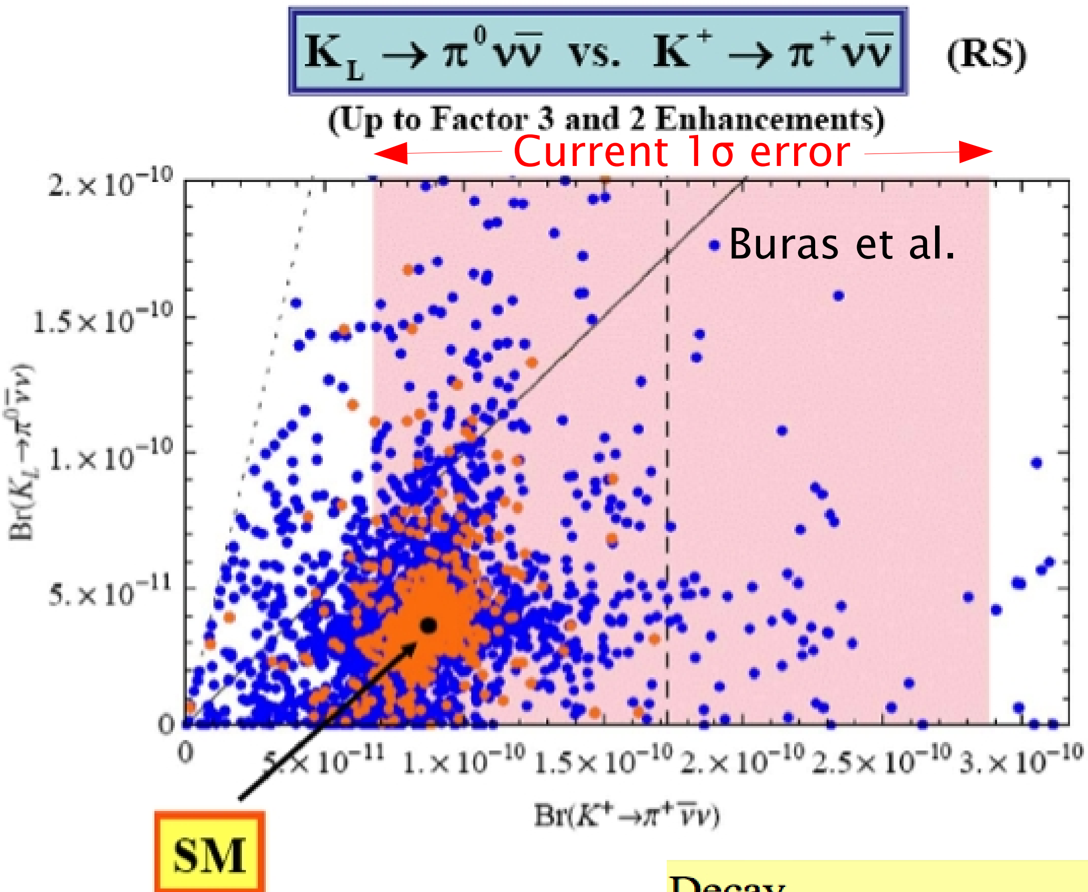
Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 50ps is intrinsic.

Actual detector conceptual design $K_L \rightarrow \pi\nu\nu$...



Probing BSM theories (not theorists)

Effect of Warped Extra Dimension Models on Branching Fractions



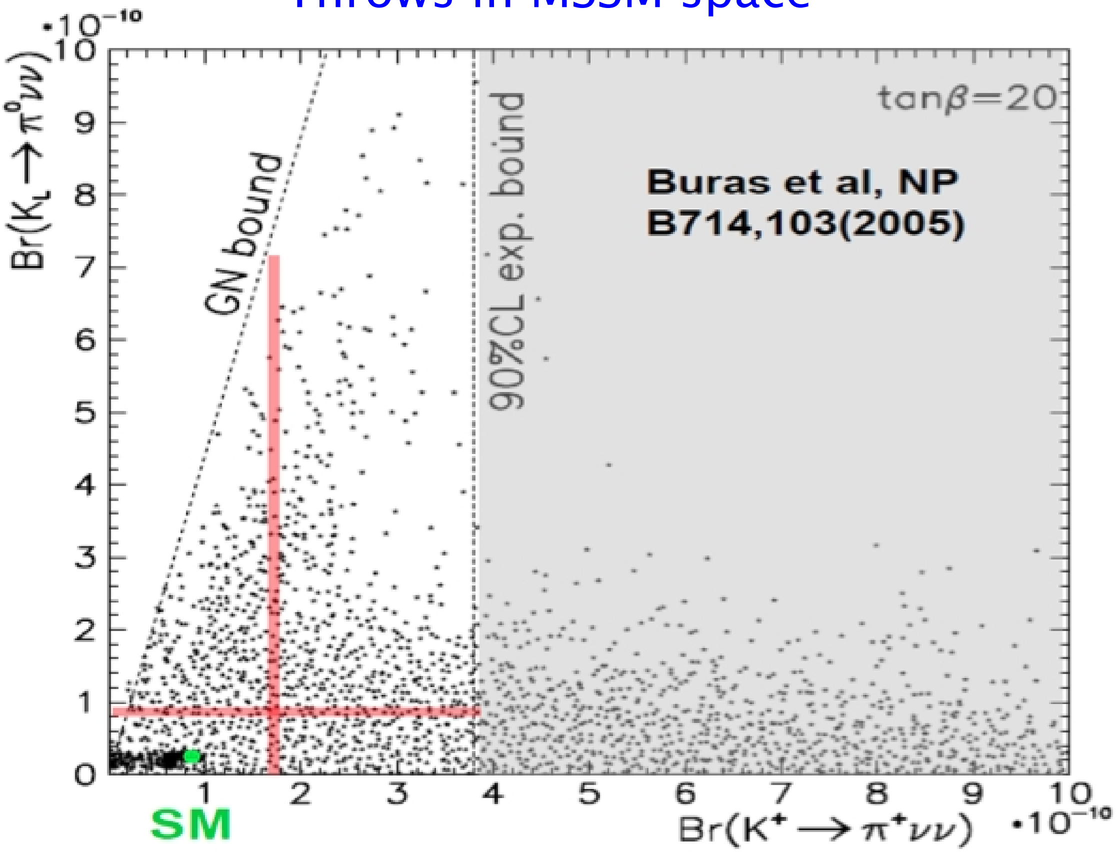
-1000 events motivated by expectation of future 5-10% theory error

- K^+ and K_L measurements very complementary in many BSM physics models

Decay	Branching Ratio ($\times 10^{10}$)	
	Theory (SM)	Experiment
$K^+ \rightarrow \pi^+ \nu\bar{\nu}(\gamma)$	0.85 ± 0.07[1]	$1.73^{+1.15}_{-1.05}$[2]
$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$	0.28 ± 0.04[3]	< 670 (90% CL)[4]

Probing BSM theories

Throws in MSSM space



-1000 events motivated by expectation of future 5-6% theory error

- K+ and KL measurements very complementary in many BSM physics models

Green dot covers theory error, width of red bands show proposed exp error, red bands placed at current measurement of K^+, and 3x SM for K^0

Decay	Branching Ratio ($\times 10^{10}$) Theory (SM)	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	0.85 ± 0.07 [1]	$1.73^{+1.15}_{-1.05}$ [2]
$K_L^0 \to \pi^0 \nu\bar{\nu}$	0.28 ± 0.04 [3]	< 670 (90% CL) [4]

Plenty of other kaon ideas for Project X

Kaon Physics:

- $K^+ \to \pi^+\nu\nu$: >1000 events, Precision rate and form factor.
- $K_L \to \pi^0\nu\nu$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \to \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \to (\pi,\mu)^+\nu_X$: Search for anomalous heavy neutrinos.
- $K_L \to \pi^0e^+e^-$: <10% measurement of CP violating amplitude.
- $K_L \to \pi^0\mu^+\mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \to X$: Precision study of a pure K^0 interferometer: Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \to$ LFV: Next generation Lepton Flavor Violation experiments

...and more

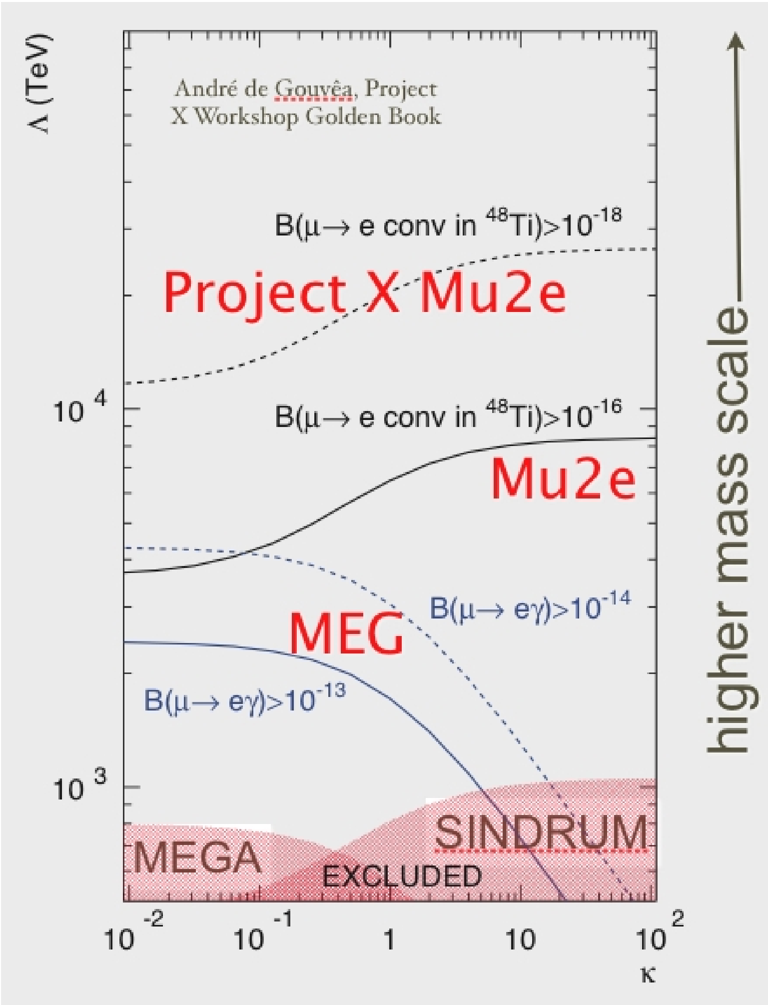
Can envision a Mu2e with 10^{-18} sensitivity...

Why?
If no discovery in current Mu2e (or LHC), then one of few experiments to extend reach. If discovery, will want to increase precision, run multiple targets

Need a factor 100 in statistics...
- -x2 acceptance (40%) for muon conversion
- -x20 POT (400 kW)
- -x10 muon capture (100 muon collider)

All are challenging R&D efforts

You can see how a Project X Mu2e would put the envelope required for a muon collider!



A. de Gouvea

Loops

Contact Interactions

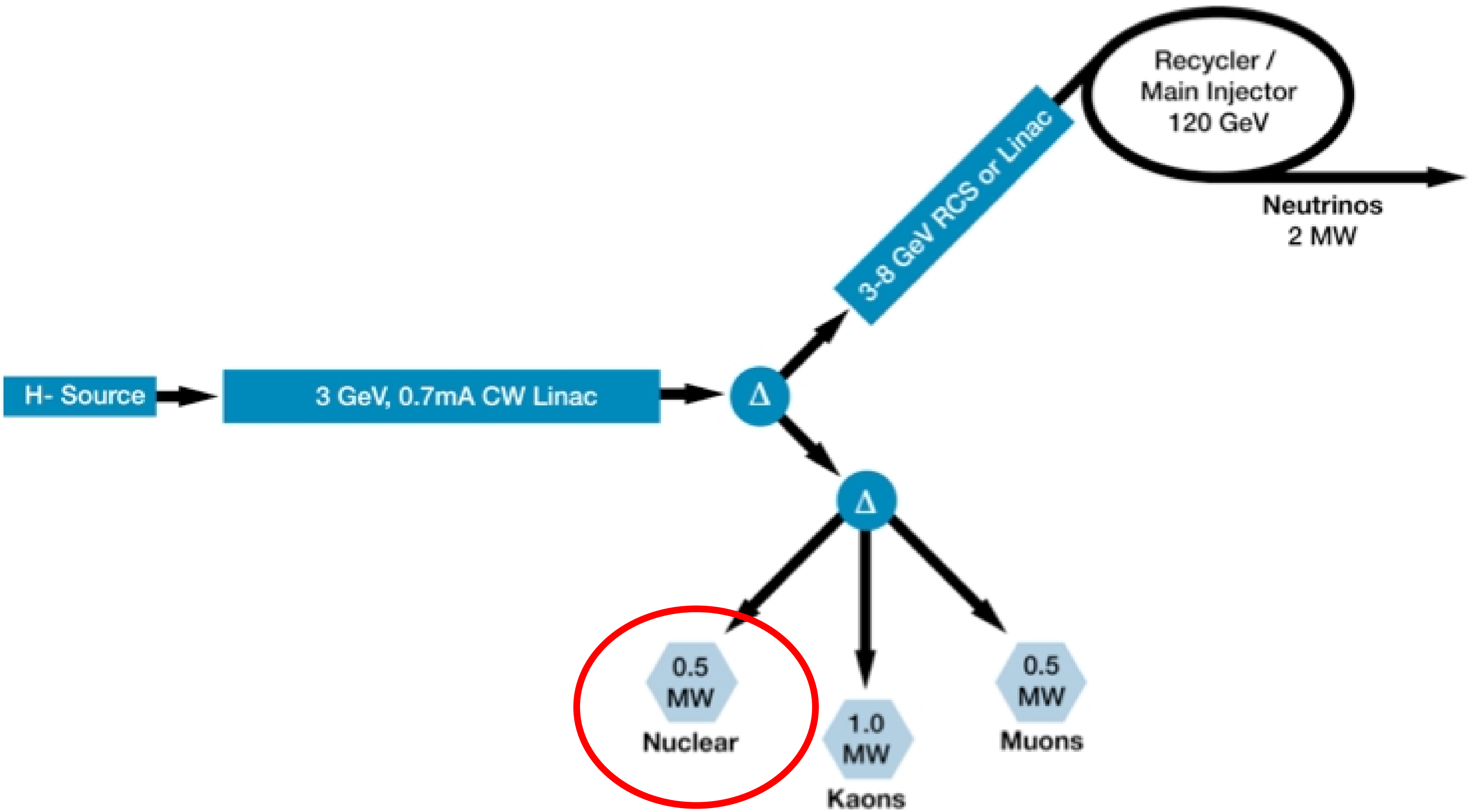
$$\mathcal{L}_{\mathcal{CFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

Plenty of other kaon ideas for Project X

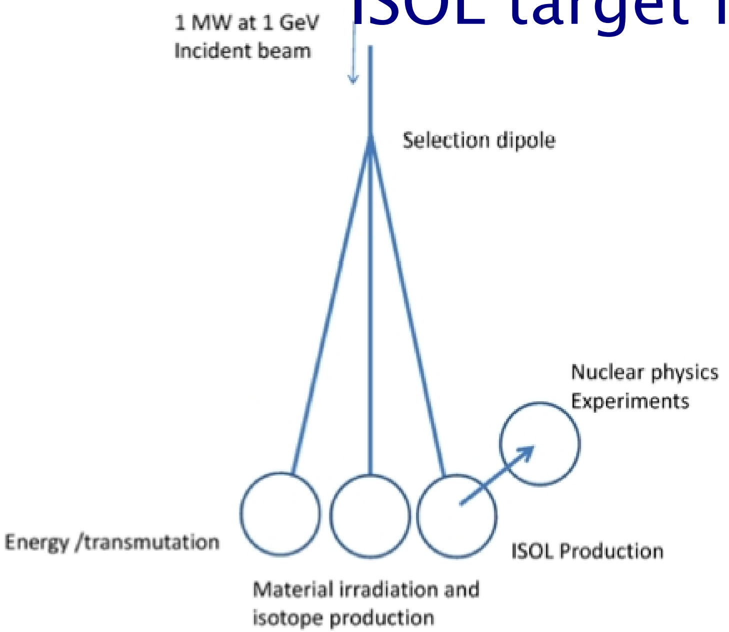
Muon Physics:

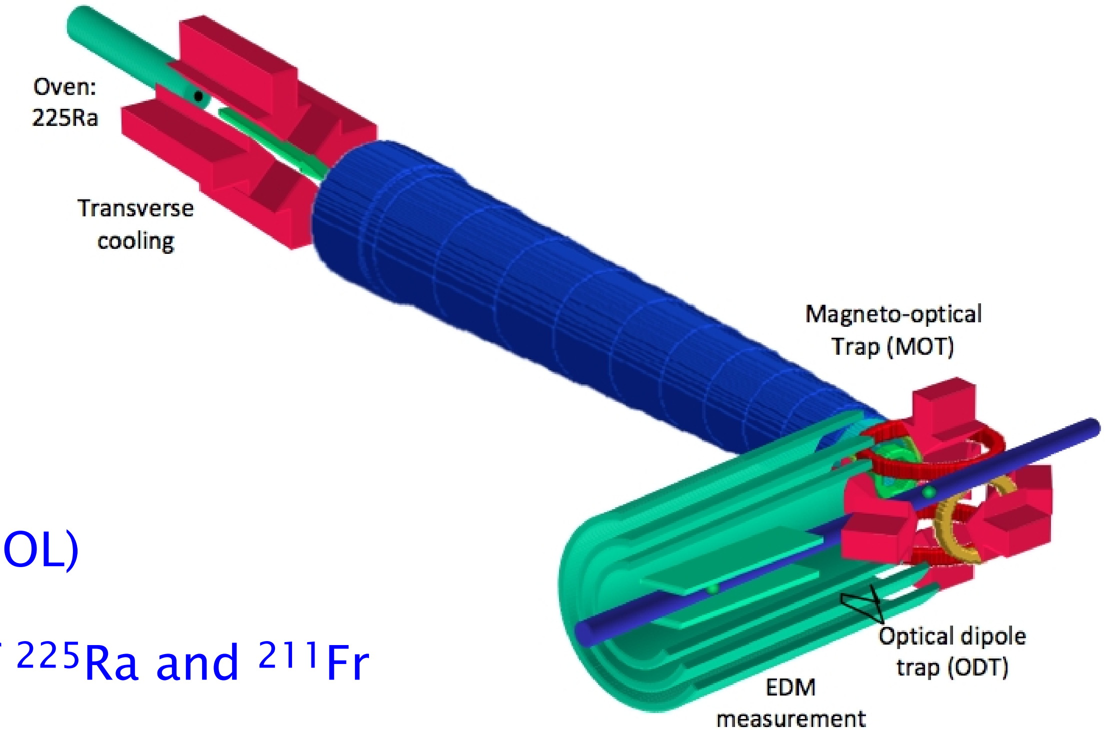
- Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.
- Next generation $(g\text{-}2)_{\mu}$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- μ edm
- $\mu \to 3e$
- $\mu^{+}e^{-} \to \mu^{-}e^{+}$
- $\mu^{-}A \to \mu^{+}A'$; $\mu^{-}A \to e^{+}A'$; $\mu^{-}\mathbf{e}^{-}(A) \to \mathbf{e}^{-}\ \mathbf{e}^{-}(A)$
- Systematic study of radiative muon capture on nuclei.

Physics experiments...nuclear



ISOL target for precision atomic EDM



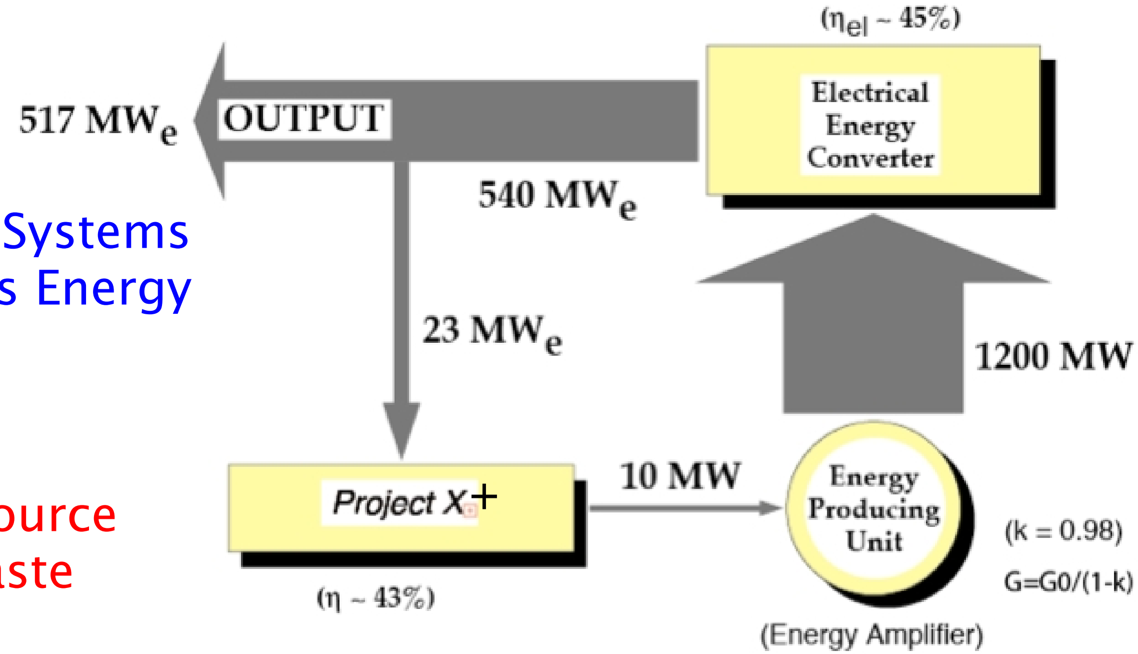


Isotope production target (ISOL)

Produce copious amounts of ^{225}Ra and ^{211}Fr for precision atomic EDM
-push EDM limits by 2 orders of magnitude

Share beam with an applied facility for material irradiation and isotope production

Physics experiments...ADS/EA basic research



Interest in Accelerator Driven Systems renewed in 90's by C. Rubbia's Energy Amplifier work...

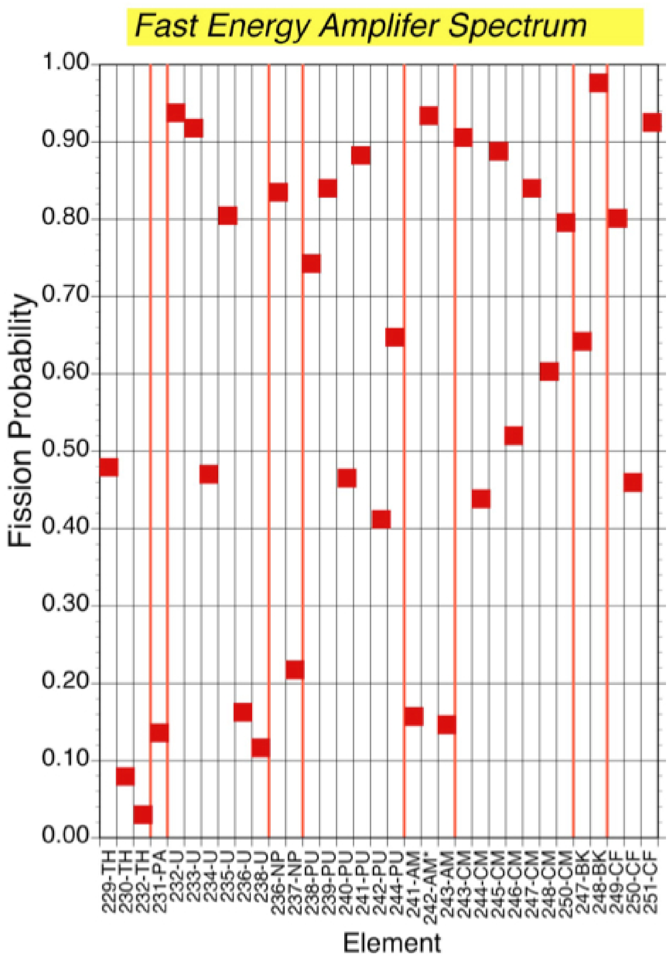
Major goals of program...
-Making Th a viable energy source
-Transmutation of nuclear waste

If proven a viable technology it would dramatically change the world's energy budget...incredible benefits
- Thorium 3-4x more abundant than Uranium in Earth's crust
- When mined, Th 6x more concentrated than U in yellowcake
- Isotopically pure, 100% burns (compare to 0.7% 235U in PWR)
- No chance of runaway reactor core
- No production of fissile (bomb-grade) materials
- Can produce a negative amount of radiological waste

* India interested in partnering with US...no yellowcake loads of Th

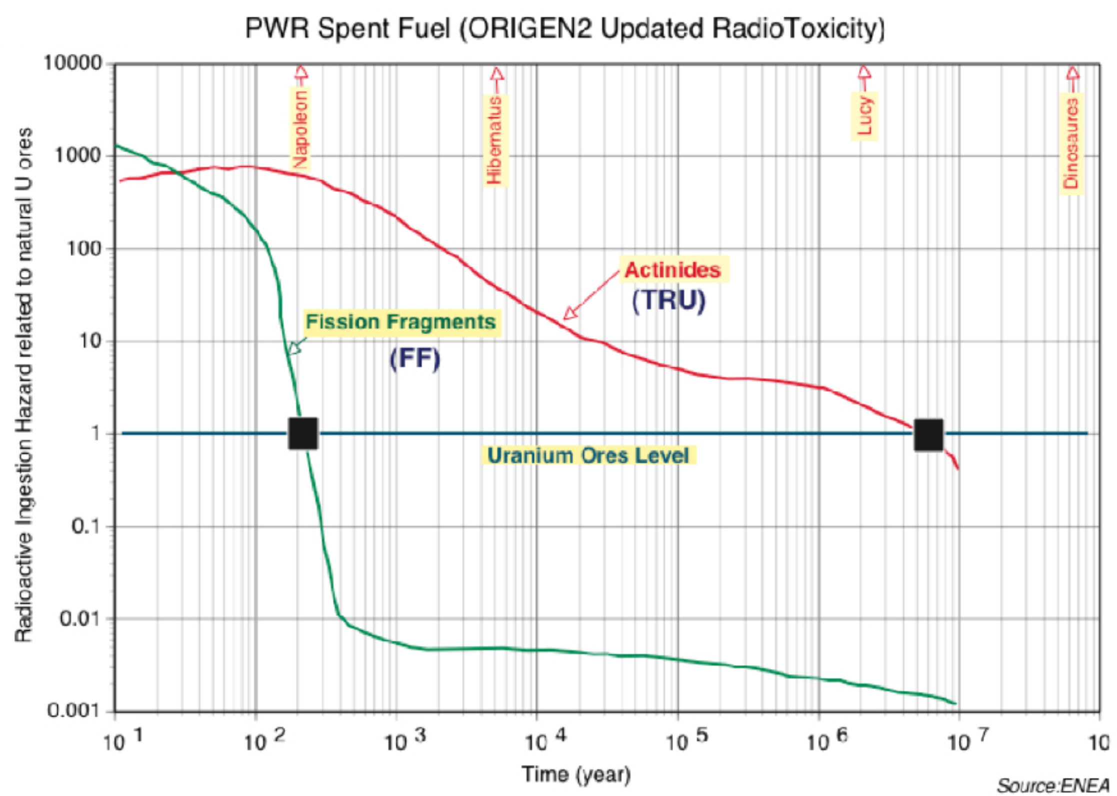
http://cas.web.cern.ch/cas/pruhonice/pdf/radermacher.pdf

Transmutation in Accelerator Driven Systems



Transuranic elements and minor actinides will fission in an ADS environment

- ~100 t/yr of ^{239}Pu produced worldwide/yr
- Not only do TRU elements fission in an ADS system, it produces heat
- Heat can be used for power generation, biofuels, oil sands, etc.



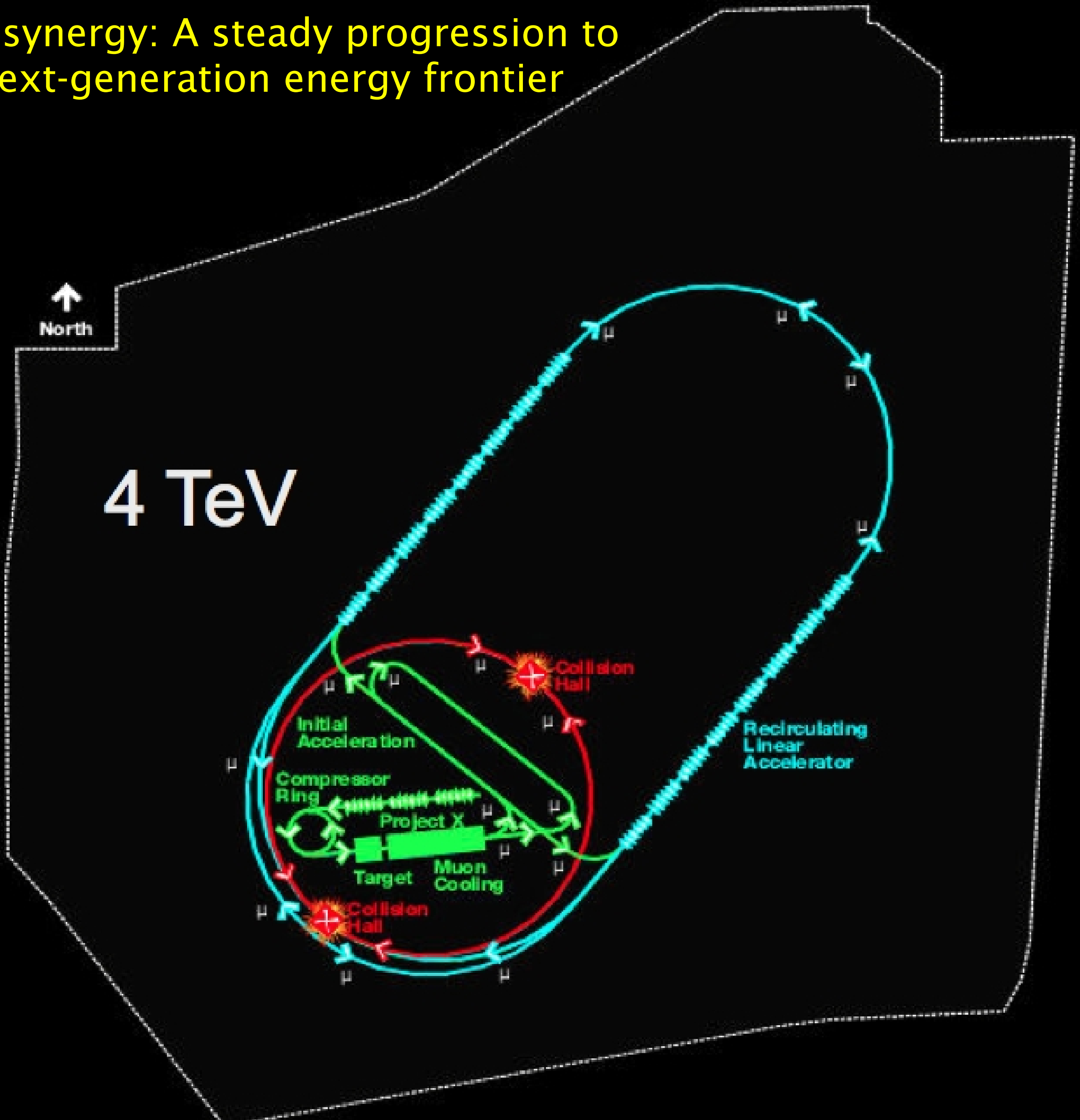
In conclusion...

Entering an immediate era where the 75 kW Booster will power some very interesting experiments...

A machine with the power and versatility of Project X will open new doors on the intensity frontier...

There are a lot of nice synergies in the program...
- Muon campus with muon g-2 and Mu2e sharing infrastructure
- Orthogonal constraints from muons and kaons in BSM theories
- Complementary with discoveries to be made at the LHC
- R&D towards the next-generation energy frontier machine

Ultimate synergy: A steady progression to the next-generation energy frontier



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.