Muon-Electron Conversion (μ2e) at FNAL

R. Bernstein
FNAL
NP'08
6 March 2008

Collaboration

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48 physicists,
11 institutions

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Experiment's 1st Stage is MECO adapted to FNAL

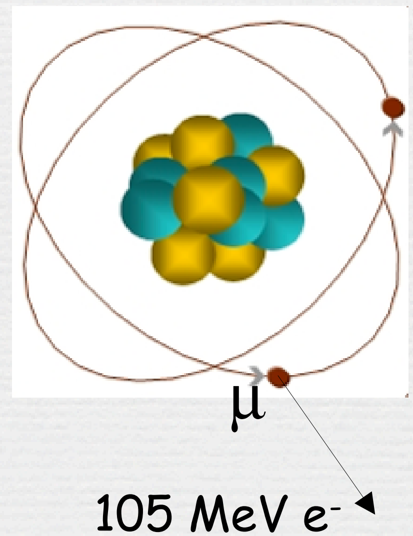
many MECO collaborators with considerable knowledge

What is μe Conversion?

$$\mu^- N \rightarrow e^- N$$

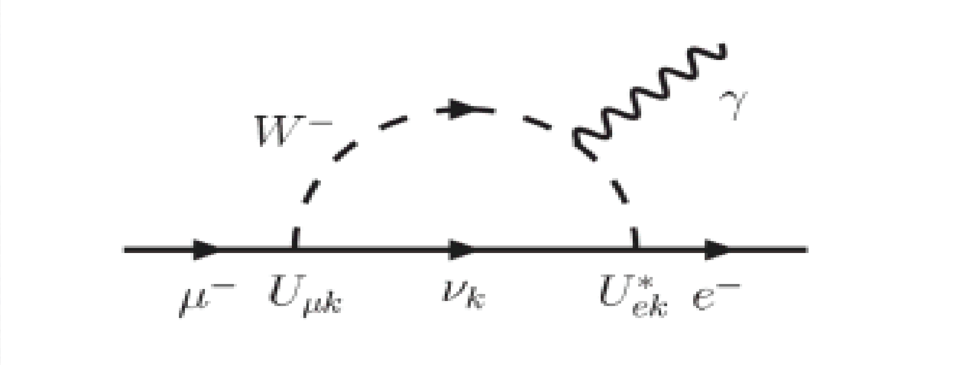
$$R_{\mu e} \equiv \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

- μ changes into e in the field of a nucleus without ν emission
- Charged Lepton Flavor Violation (CLFV)
- Related Processes: $\mu \rightarrow e\gamma$, $\mu \rightarrow e^+e^-e$, $K_L \rightarrow \mu e$



Motivation

- ν's have mass! Therefore individual lepton numbers are not good quantum numbers
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



- Except neutrinos have to change flavor in loop...

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$ ☹

- But this is good! New physics not hidden by boring old neutrino oscillations (yesterday's signal is today's calibration is tomorrow's background)

Contributions to μe Conversion

Neutrino Mass | SuperSymmetry

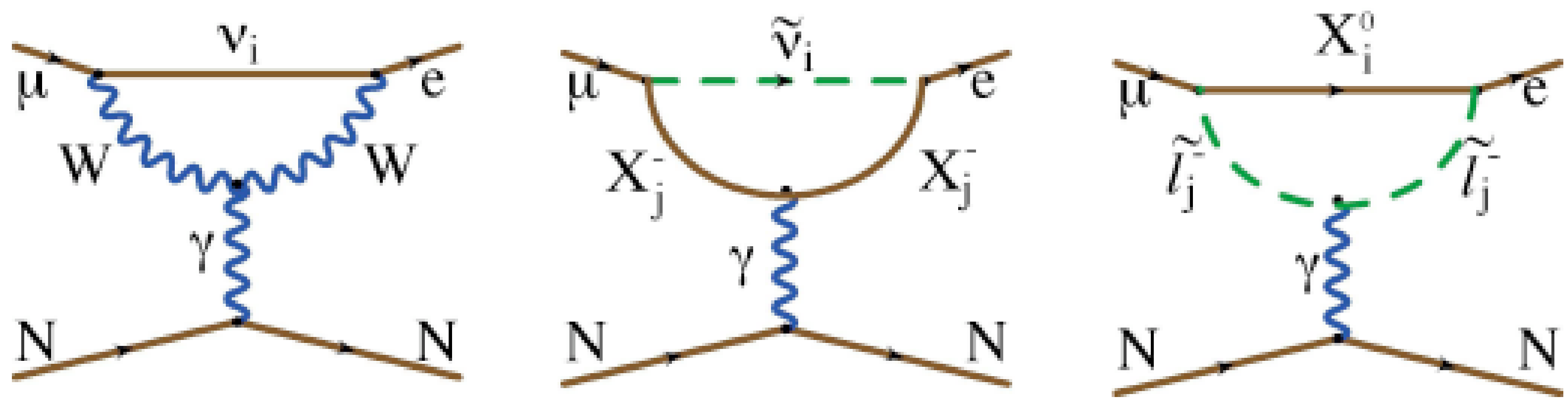
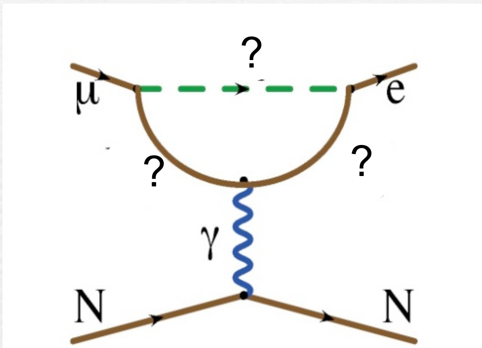


Figure 1.1: The leading Standard Model diagram for μ+N → e+N is shown on the left. The center and right figures are the dominant SUSY diagrams.

- Probe of Supersymmetry; complementary to LHC and pushes beyond LHC sensitivity
- Observation of neutrino mass, interpreted in SeeSaw, points to observable CLFV in many models [Blanke et al., hep-ph/0702136]

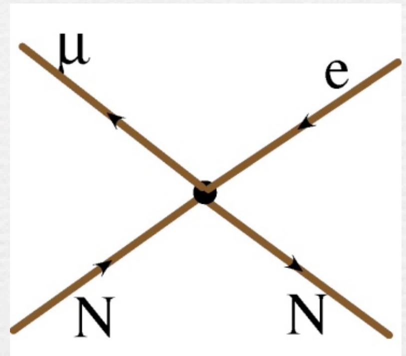
μe Conversion and $\mu \rightarrow e\gamma$

- *Dipole/Penguin*



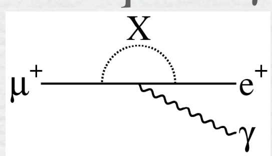
κ

- *Fermi Interaction*



Λ

- This type of diagram gives rise to small CLFV through virtual neutrino mixing
- Also contributes to $\mu \rightarrow e\gamma$ if photon real



- Corresponds to exchange of a new, massive flavor-changing neutral current particle $\frac{1}{\Lambda^2} = \frac{f^2}{16\pi^2}\frac{1}{M_{\rm new}^2}$
- ***Does not produce $\mu \rightarrow e\gamma$***

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

$\mu \rightarrow e\gamma$ and μe Conversion Experimental Differences

$\mu \rightarrow e\gamma$

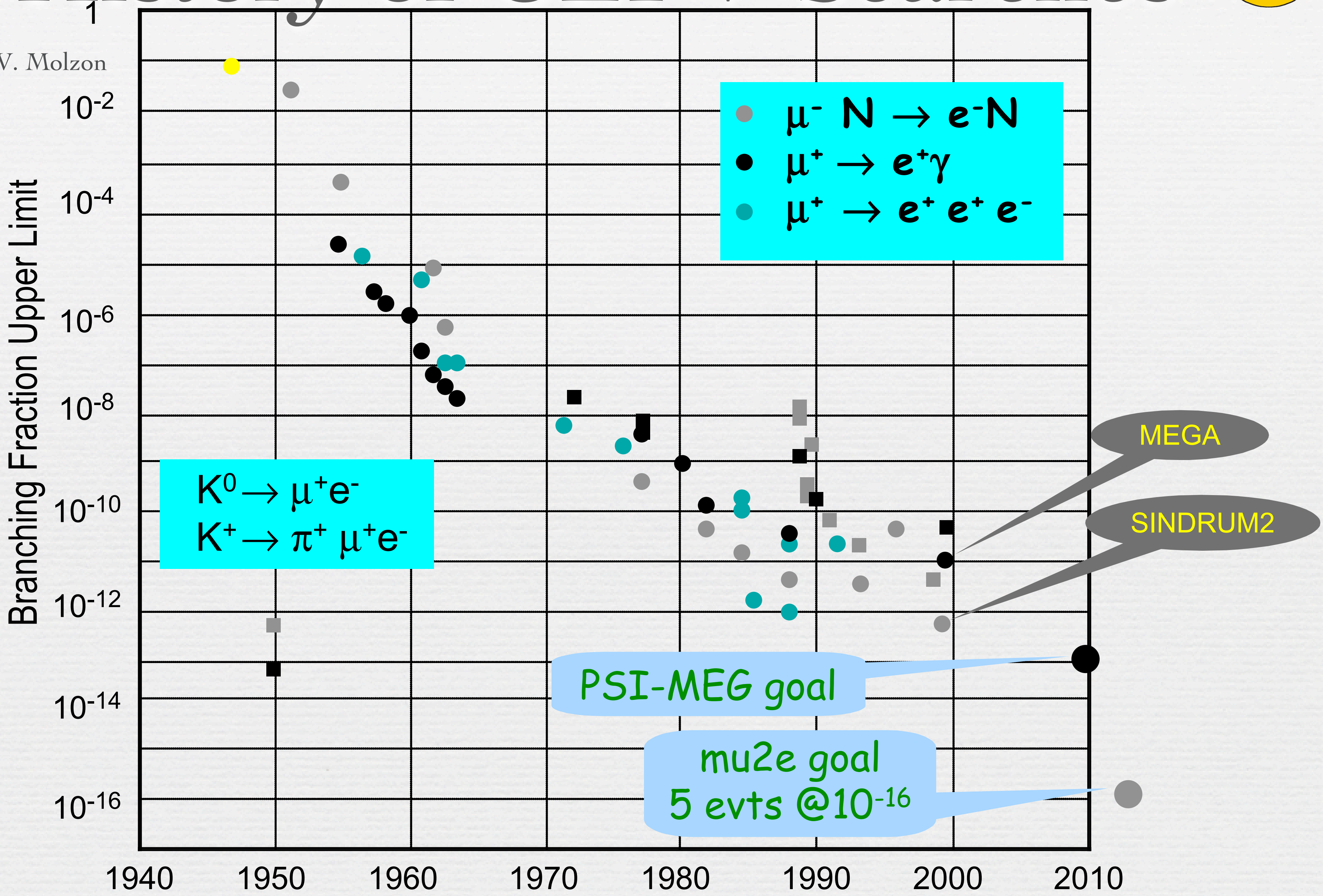
- time coincidence of back-to-back monoenergetic particles
- limited by accidental coincidences: $\mu \rightarrow e\nu\nu$ and occasional coincidence with photon leads to limit of $10^{-(13\text{-}14)}$ (for acceptable rate/running time)
- **signal e, γ in same energy region as backgrounds**

$\mu \rightarrow e$ conversion

- single, nearly monoenergetic particle
- single particle signal is a disadvantage, but:
- **signal electron at much higher energy region than almost all background**

History of CLFV Searches

from W. Molzon



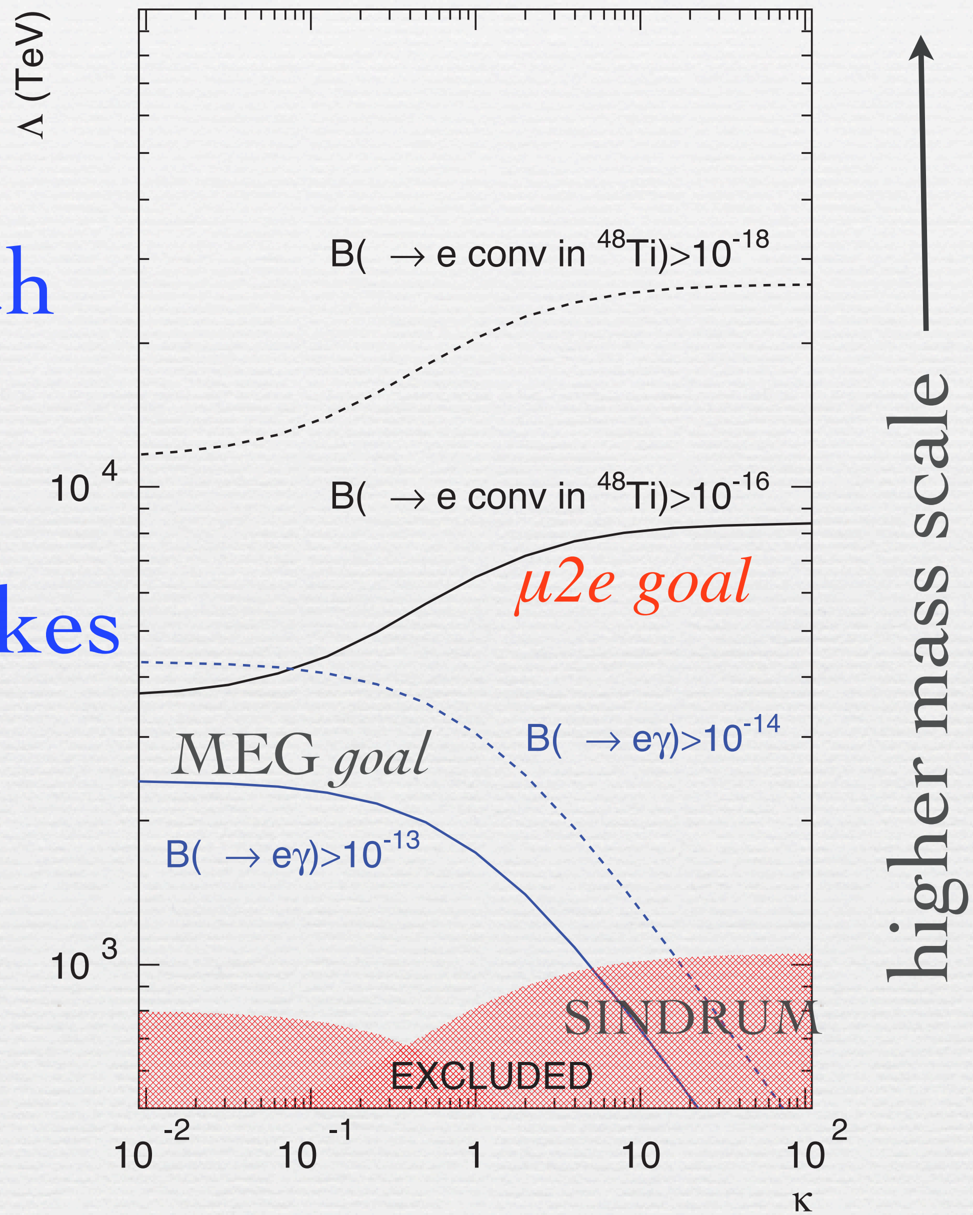
Overview of Reach

André de Gouvêa, Project X Workshop Golden Book

Two Points:

1) Mass Reach of 10^4 TeV

2) FCNC Λ capability makes for excellent combination with $\mu \rightarrow e\gamma$.



Λ four-point, κ penguin

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Λ (TeV)

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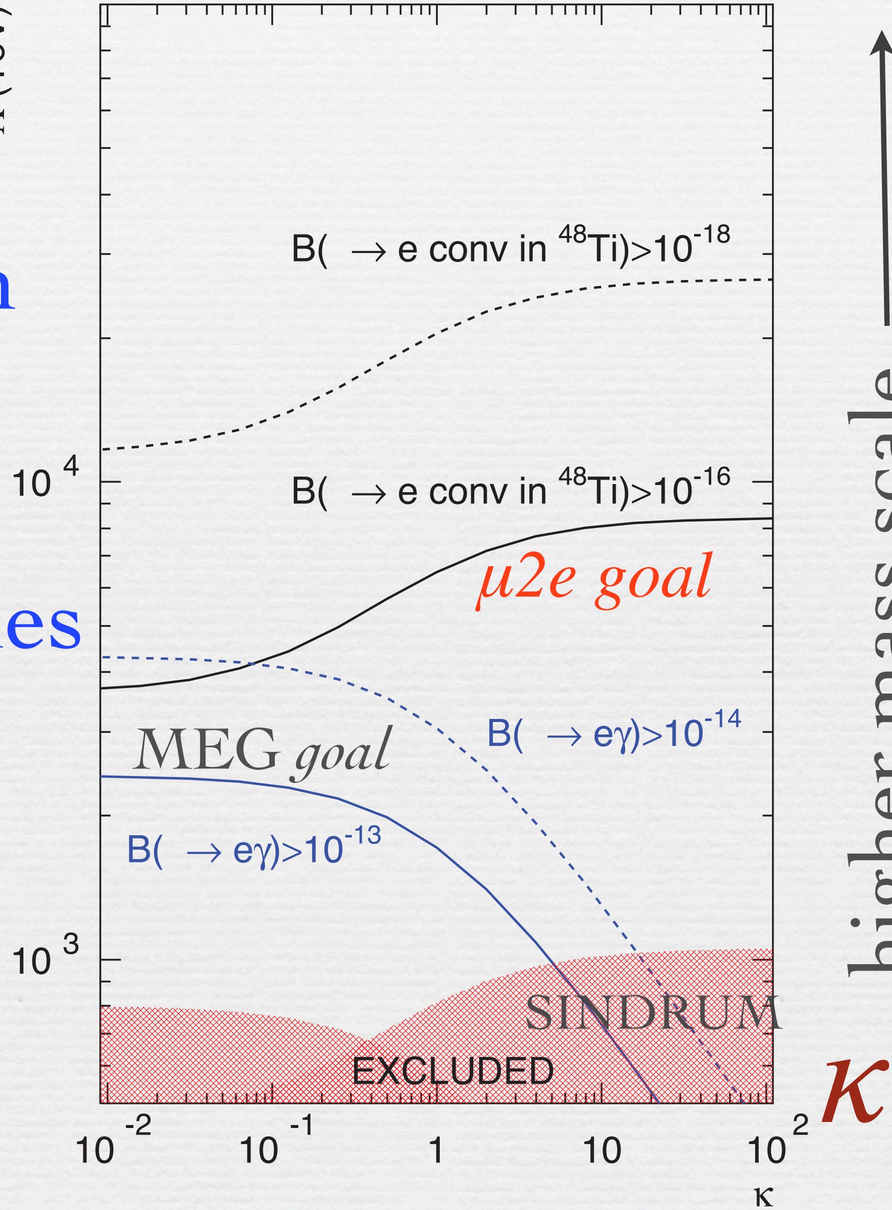

higher mass scale

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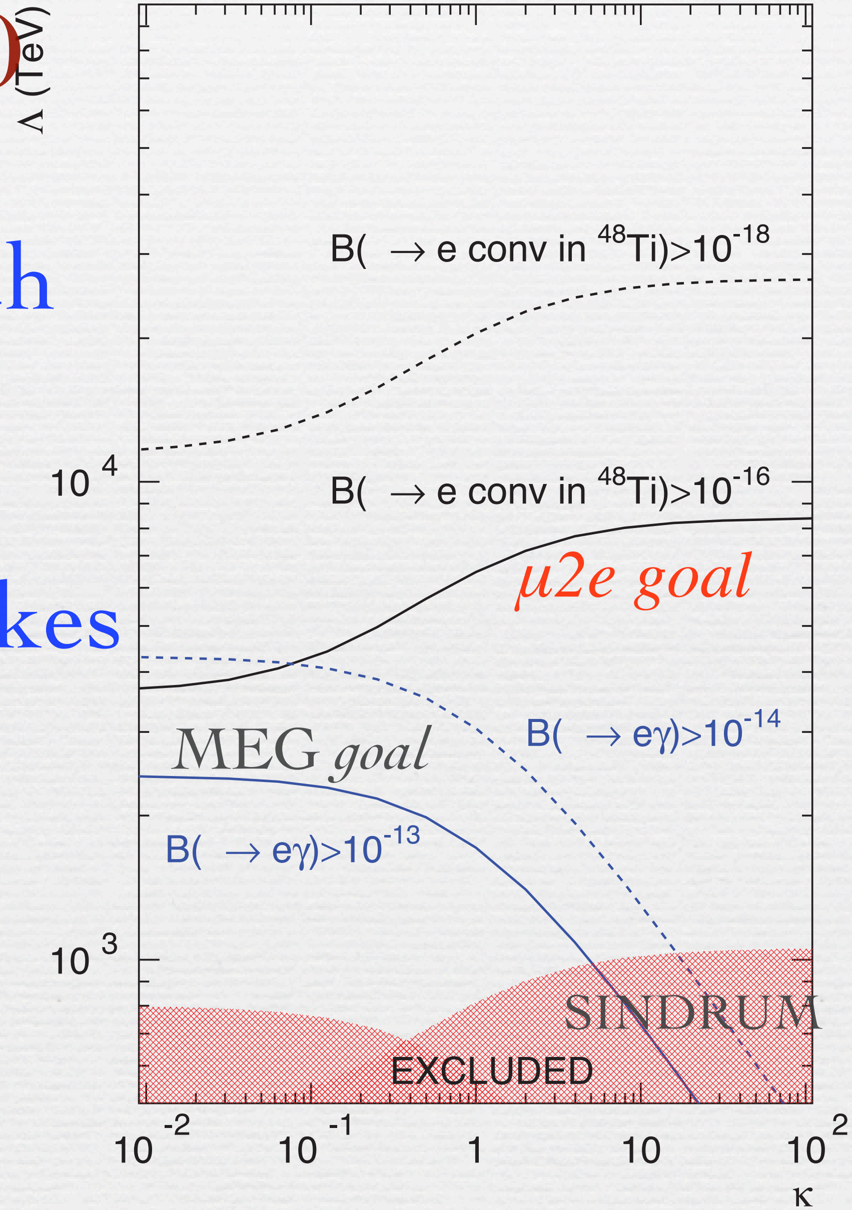

κ

higher mass scale

Λ four-point,
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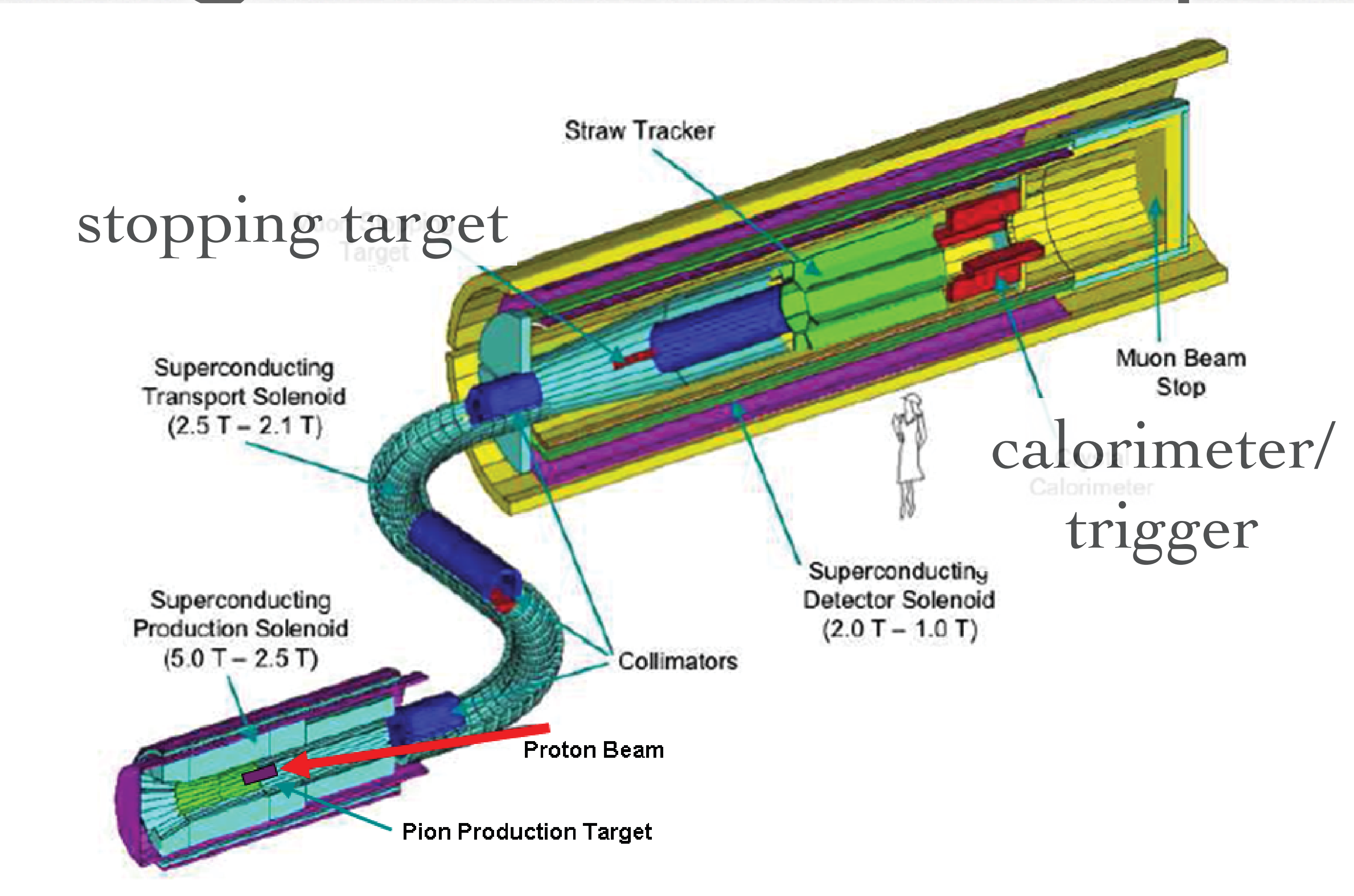
Measuring in several channels in several experiments is always better!

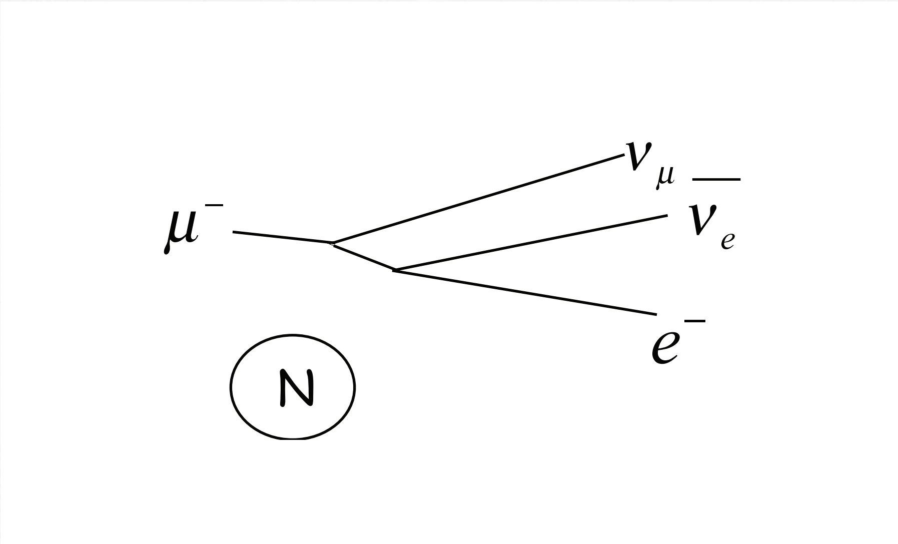
Quick Tour of Expt

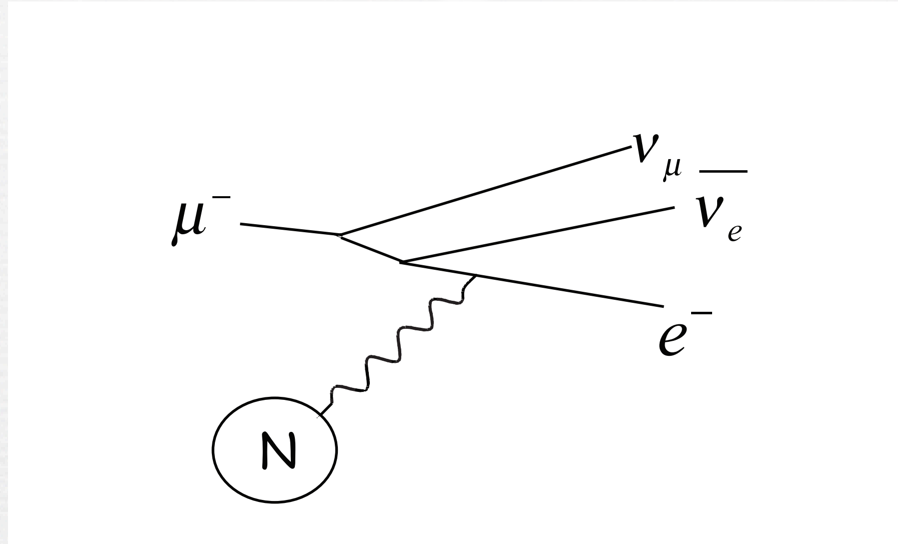


Major Background Types

- Decay In Orbit:
  - Muon Captured in Stopping Target: muon decays into electron, electron energy near signal
  - Radiative μ Capture: μ Al $\rightarrow \gamma\ \nu_\mu$ Mg
- Prompt:
  - Protons Hit Production Target, produce π's neutrons, and antiprotons which produce $\gamma \rightarrow e^+ e^-$, sometimes with energy near $\mu \rightarrow e$ signal

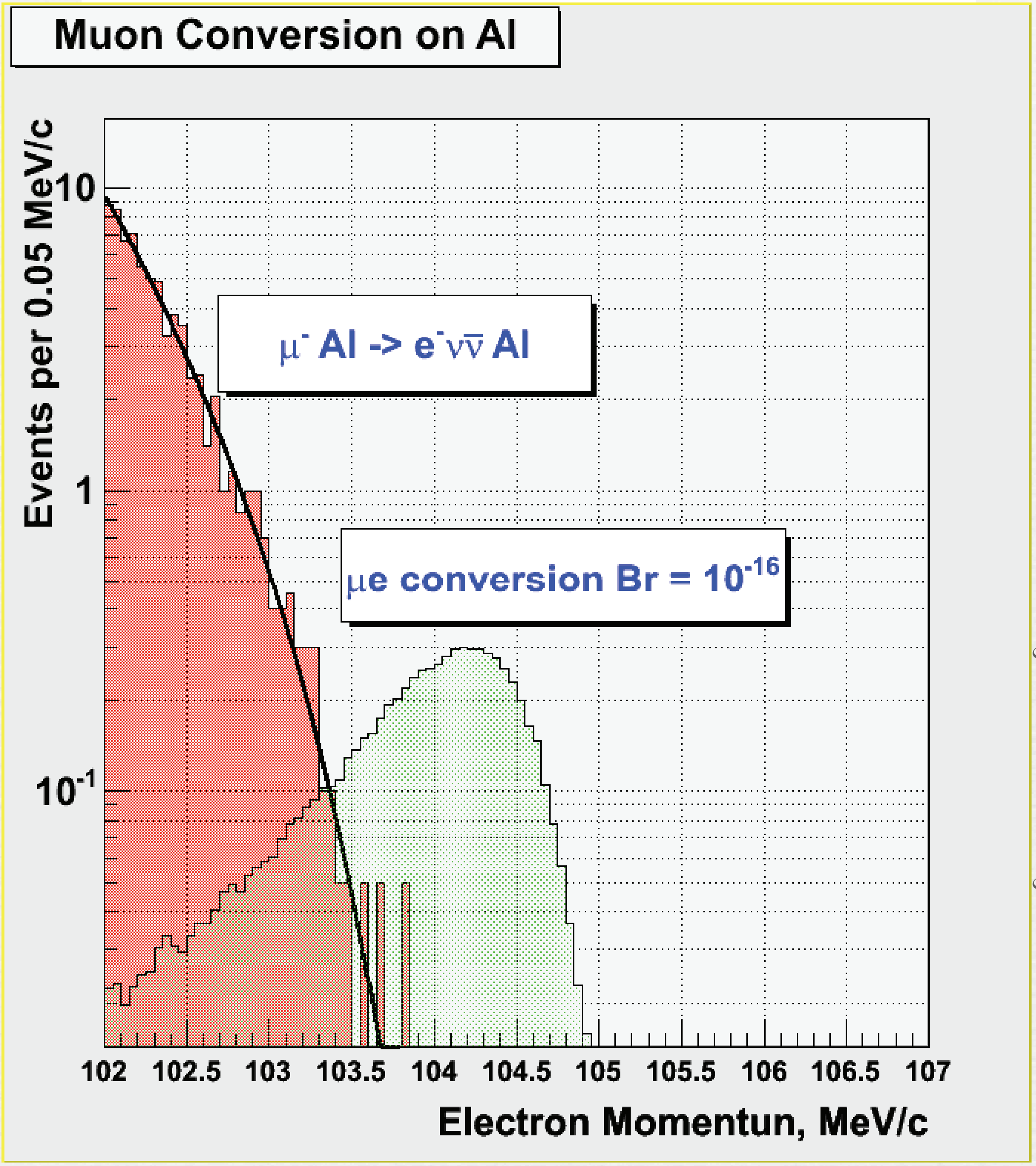
Decay-in-Orbit Background

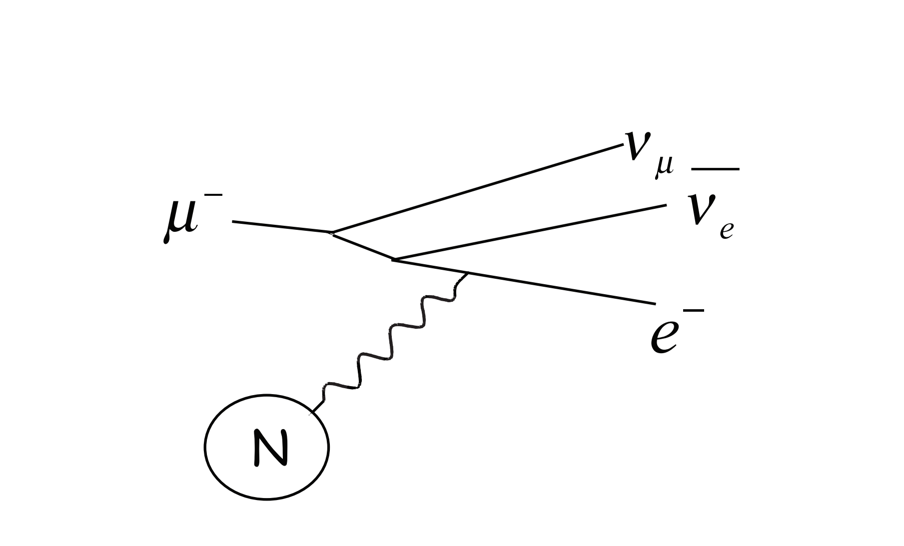




- High Rate
- Peak **52.8 MeV**
- Detector *insensitive* to these
- Fraction within 3 MeV of signal is 5 x 10^{-15}
- **Rate falls as $(E_{max} - E)^5$**
  - **Drives Resolution Requirement**

Decay-in-Orbit Background



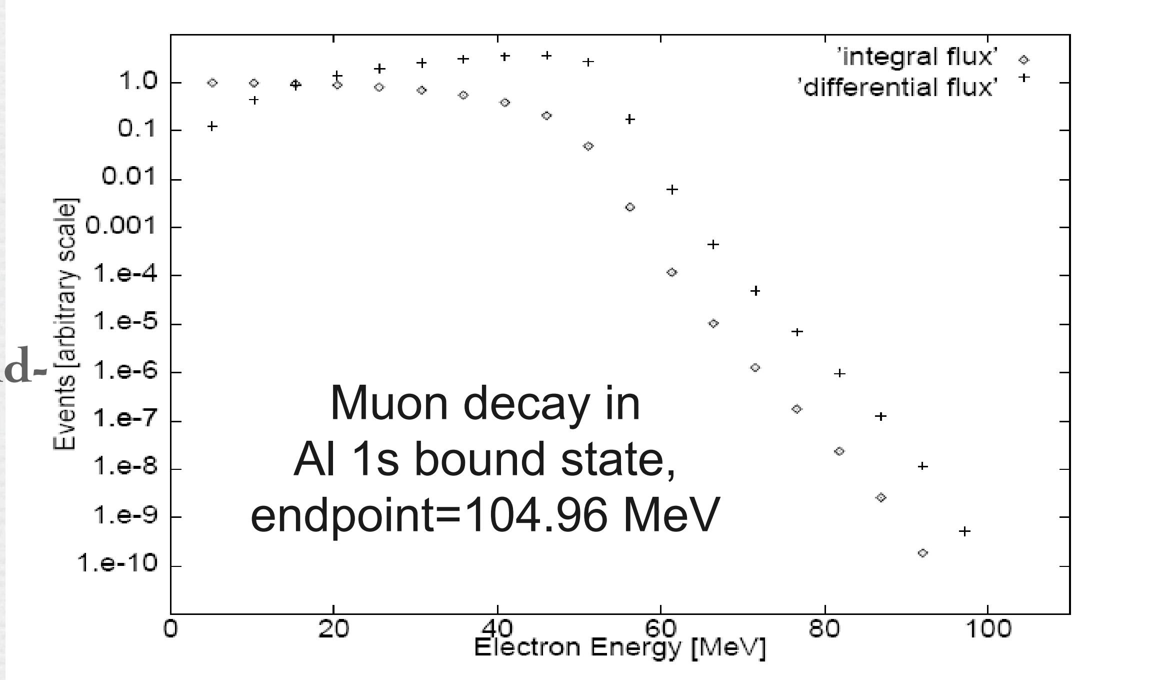


- Fraction within 3 MeV of signal is 5 x 10^{-15}
- Rate falls as $(E_{max} - E)^5$
  - Drives Resolution Requirement

Decay-In-Orbit Details

- Ee(max)= ($m_\mu c^2$ - NuclearRecoilEnergy -AtomicBindingEnergy)
- For Z=13 (Al), Atomic BE=0.529 MeV, Recoil energy=0.208 MeV →Ee(max) =104.96 MeV
- Rate near the maximum energy falls very rapidly. Near endpoint: proportional to $(Ee(max)-E)^5$
- **Major potential source of background- Discriminate against it with good electron energy resolution, ~1 MeV FWHM for μ2e**

looks exactly like signal except for electron energy



Prompt Backgrounds

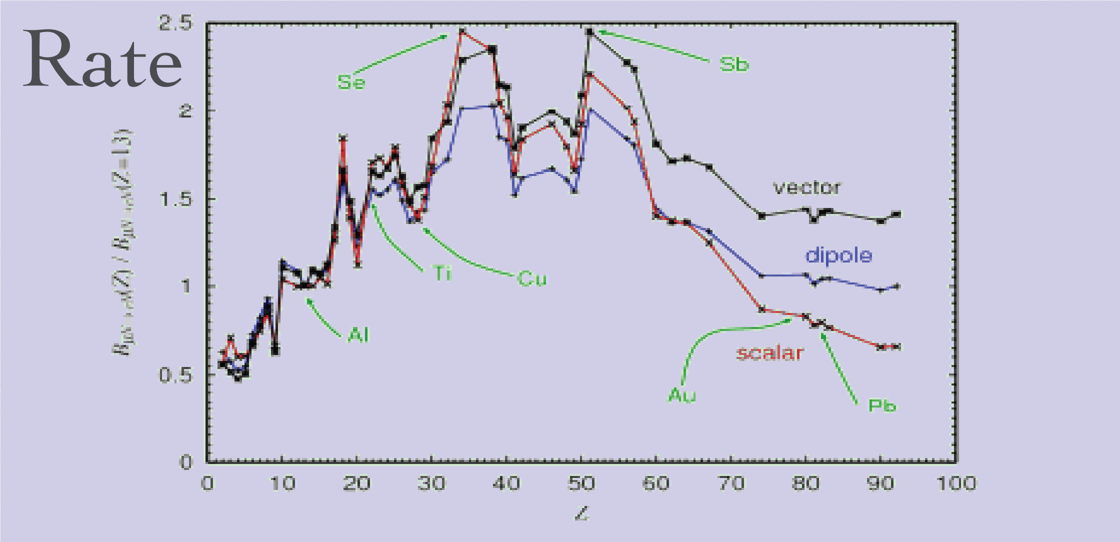
- Prompt: particles produced by proton pulse which interact almost immediately when they enter the detector region: π, neutrons, pbars

$$\pi^- \mathrm{Al} \rightarrow \gamma\ \mathrm{Mg}$$

  - Radiative pion capture, π^-+A(N,Z)->γ+X.
    - γ up to m_π; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal. Major limitation in best existing experiment, SINDRUM II.
  - Beam electrons: incident on the stopping target and scatter into the detector region. Need to suppress e^- with E>100 MeV near signal
  - In-flight muon decays yielding electrons: since not stopped, can have enough momentum to fake signal (> 76 MeV/c)

Choice of Stopping Material

- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?

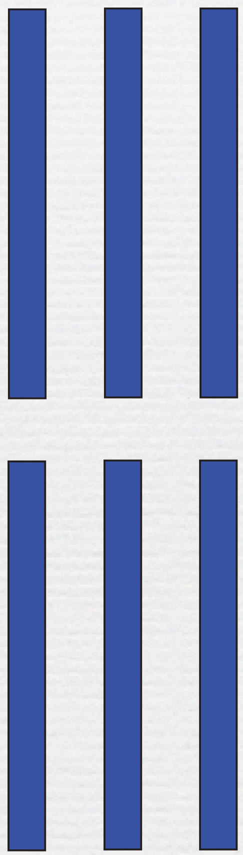


Z

rate normalized to Al

Signal in Stopping Target

target foils



Signal in Stopping Target

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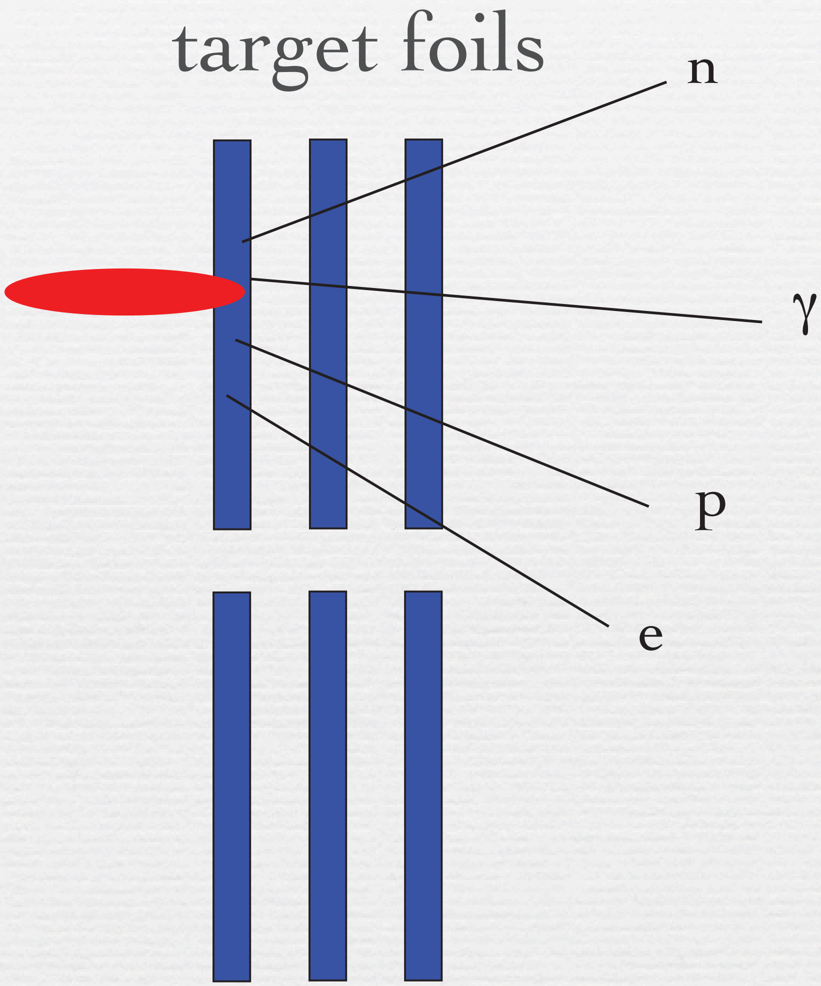
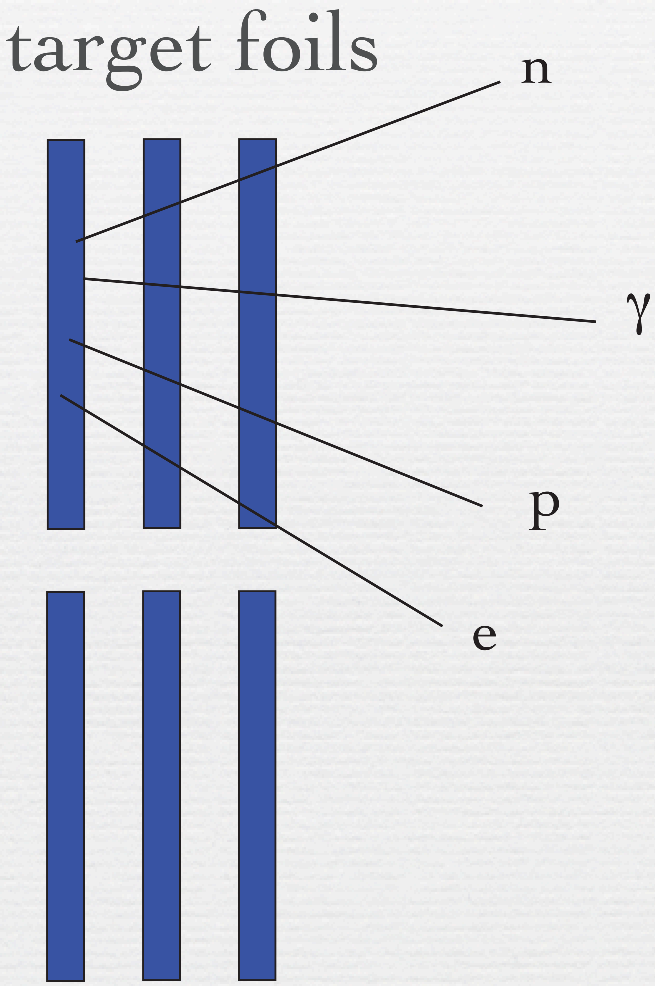
Signal in Stopping Target



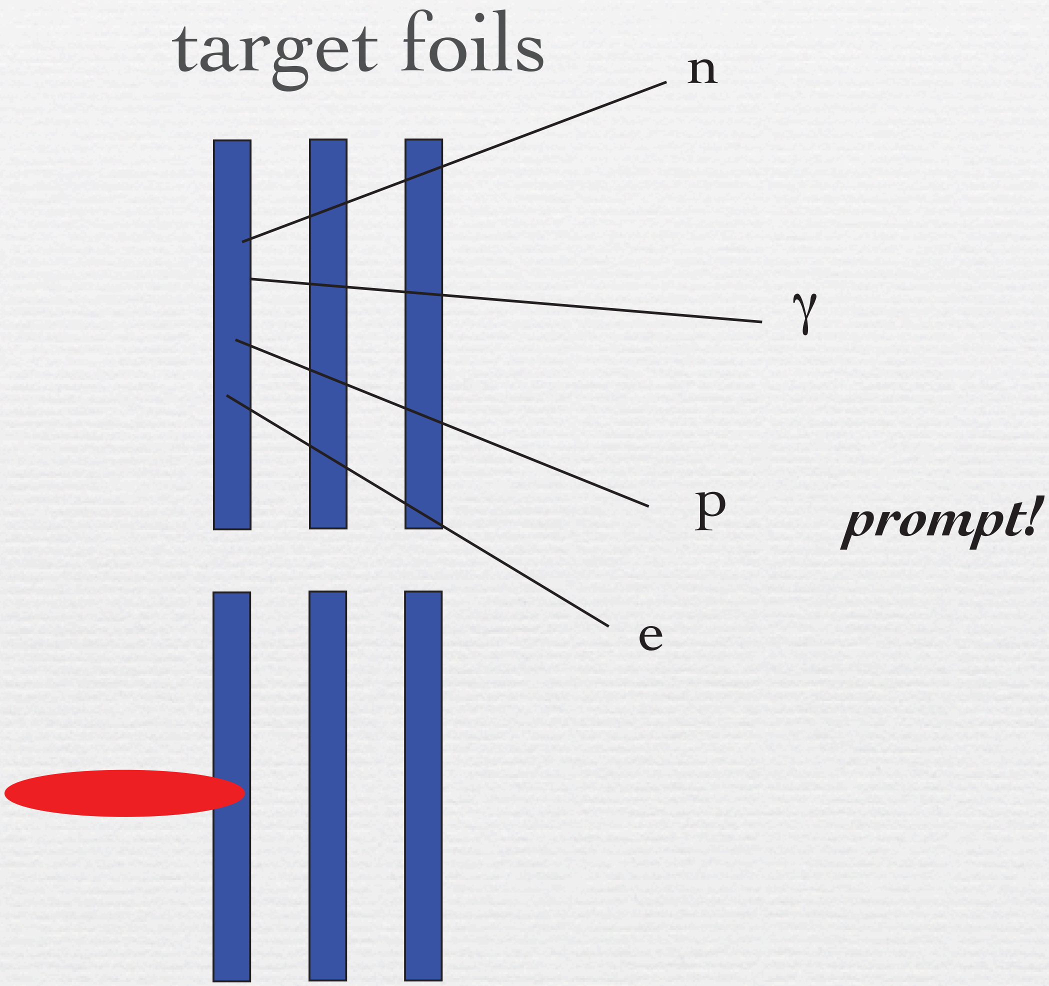
prompt!

Signal in Stopping Target

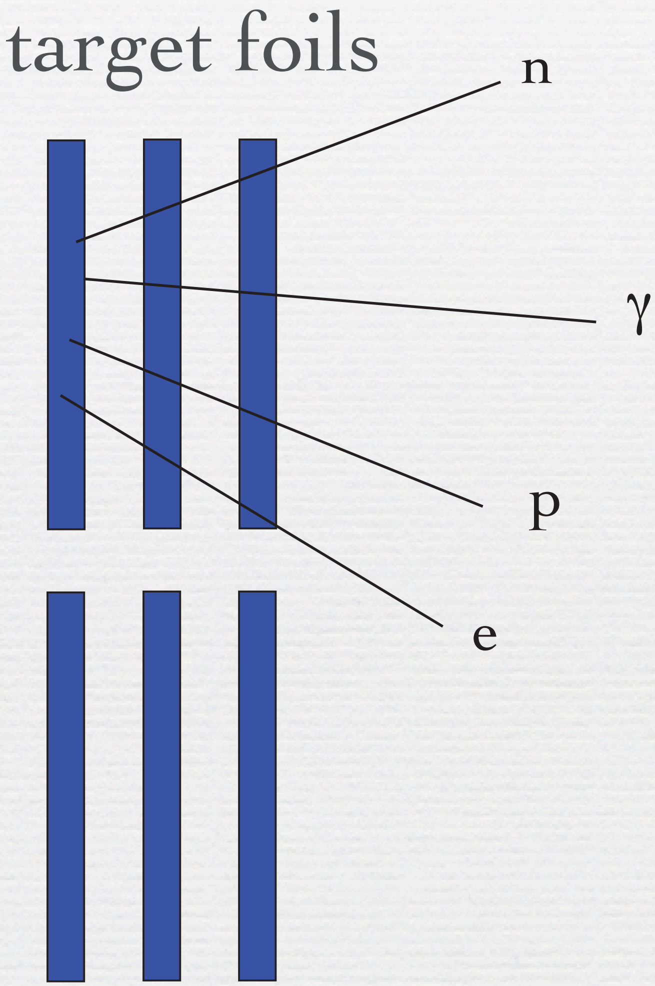


prompt!

Signal in Stopping Target

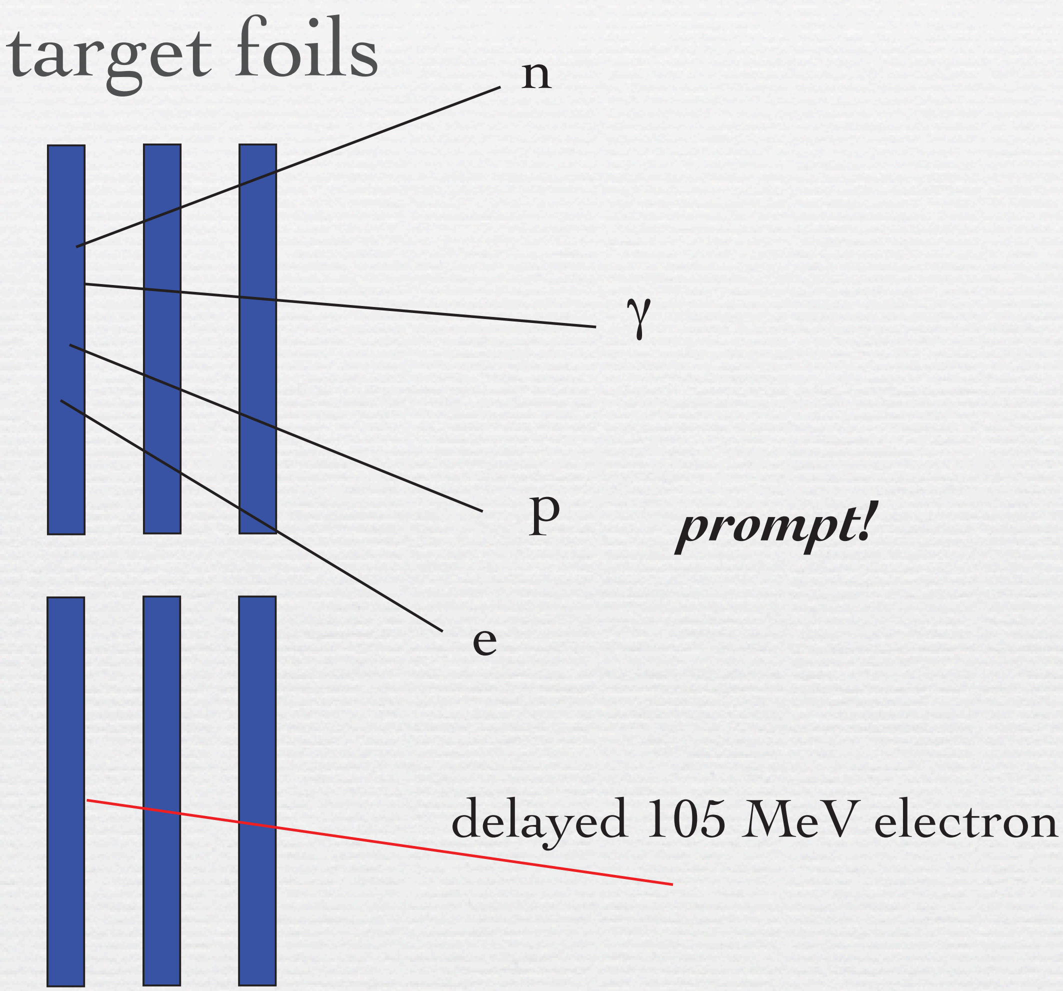


Signal in Stopping Target

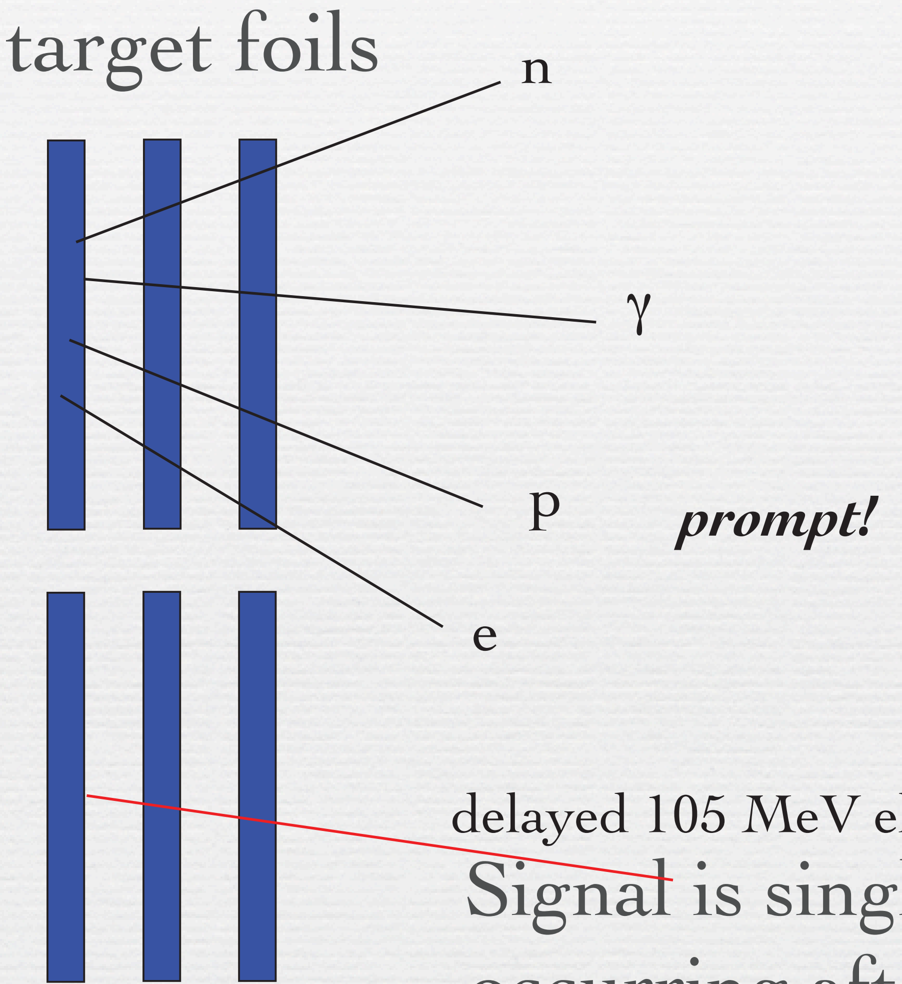


prompt!

Signal in Stopping Target

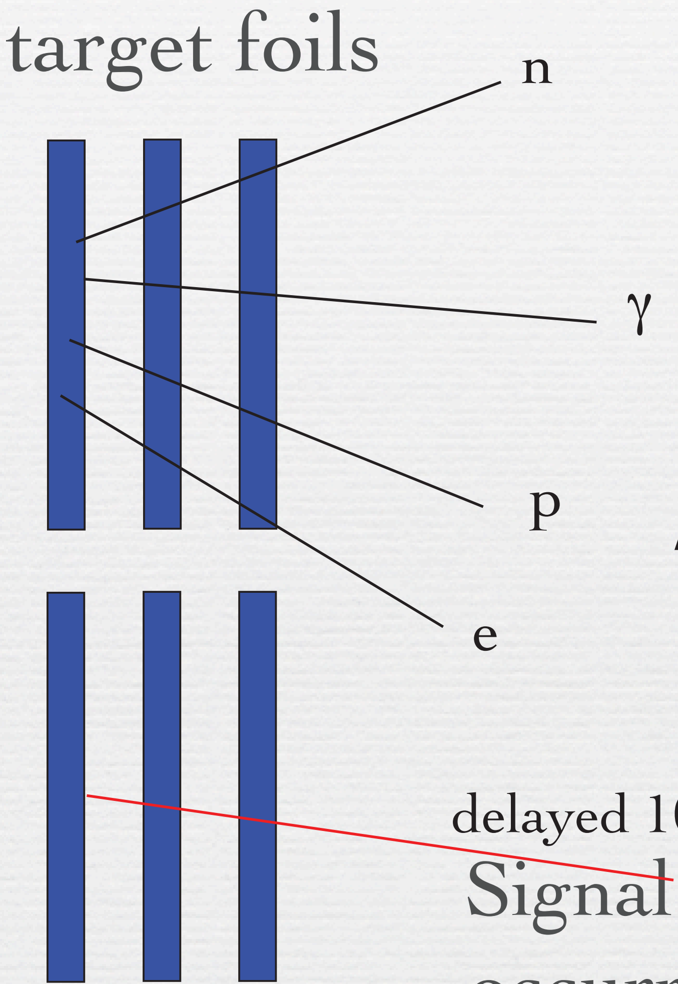


Signal in Stopping Target



Signal is single, monoenergetic electron occurring after bunch passes: want this delay to be long to reduce prompt

Signal in Stopping Target



- need good momentum resolution
- need particle ID (calorimeter)
- need a bunched beam!

prompt!

Signal is single, monoenergetic electron occurring after bunch passes: want this delay to be long to reduce prompt

Prompt Bkg and Choice of Z

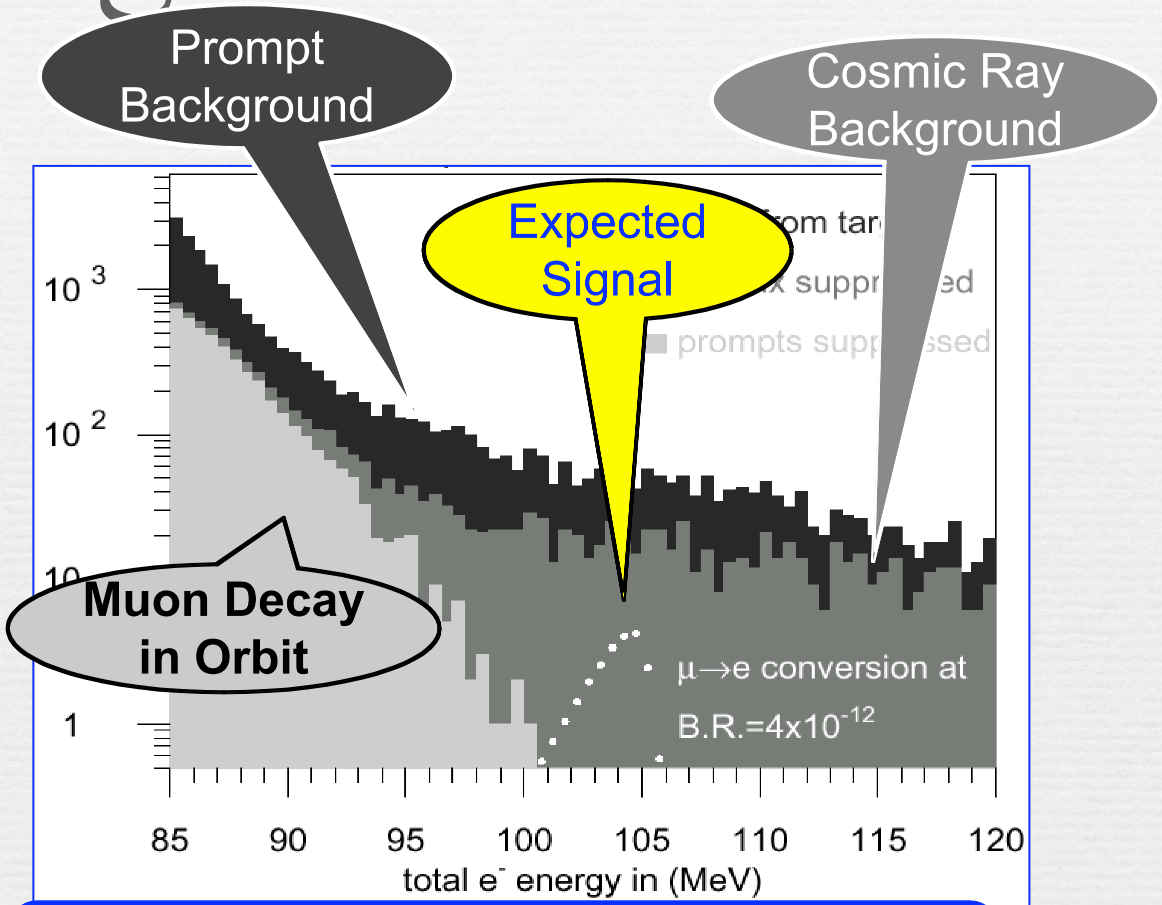
- choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

Nucleus	$R\mu e(Z)$ / $R\mu e(Al)$	Stop-to-Capture Time	Atomic Bind. Energy (1s)	Conversion Energy	Prob decay >700 ns
Al(13,27)	1.0	**880 nsec**	0.47 MeV	**104.96 MeV**	0.45
Ti(22,~48)	1.7	328 nsec	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	72.6 nsec	10.08 MeV	95.56 MeV	negligible

too short for FNAL beam pulse; need short pulse to eliminate prompt backgrounds

Existing Limits

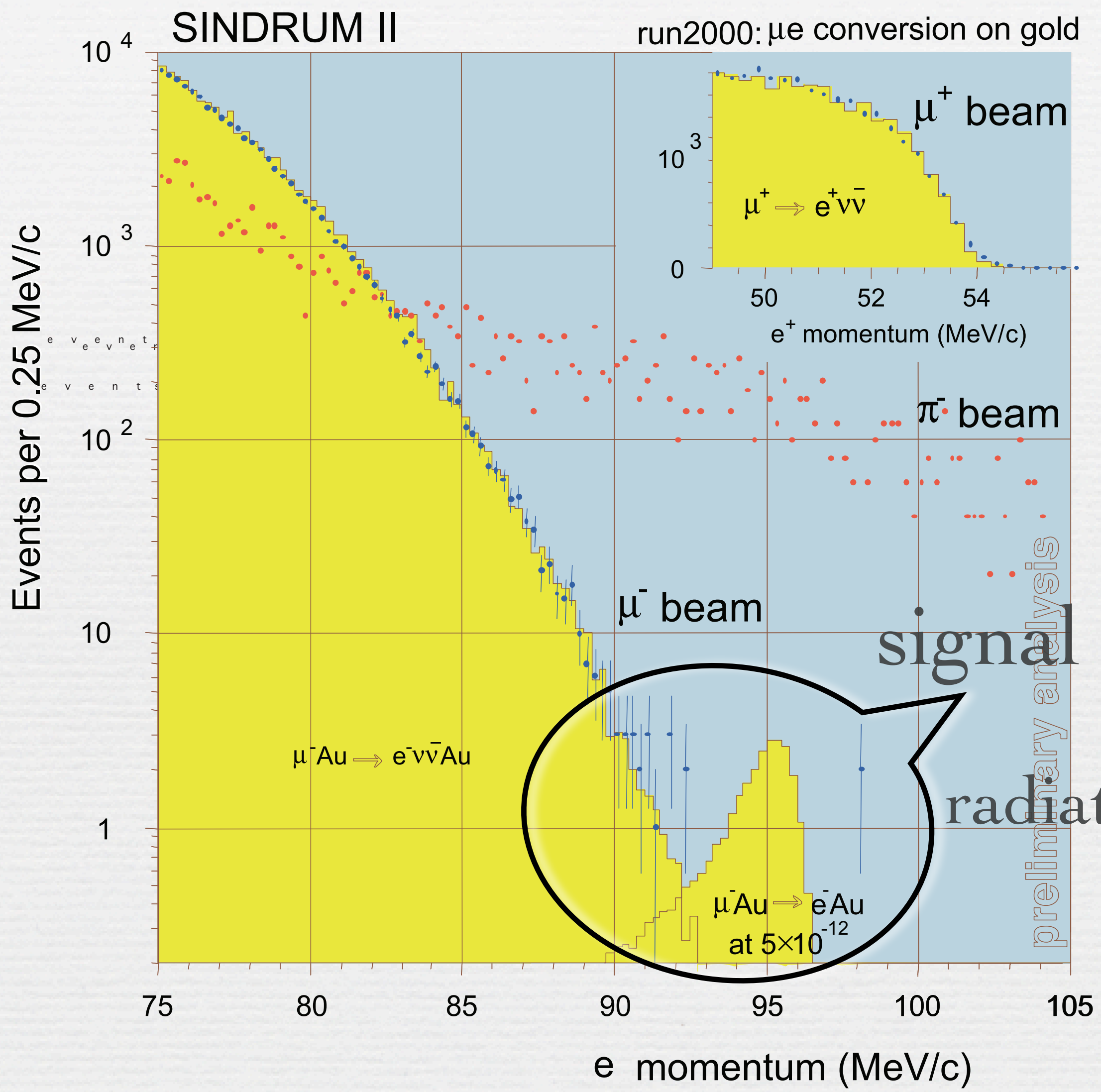
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au (SINDRUM-II)
- Want to probe to 10^{-16} or better
- Factor of $\approx 10^4$ improvement non-trivial



Experimental signature is 105 MeV e^- originating in a thin Ti stopping target

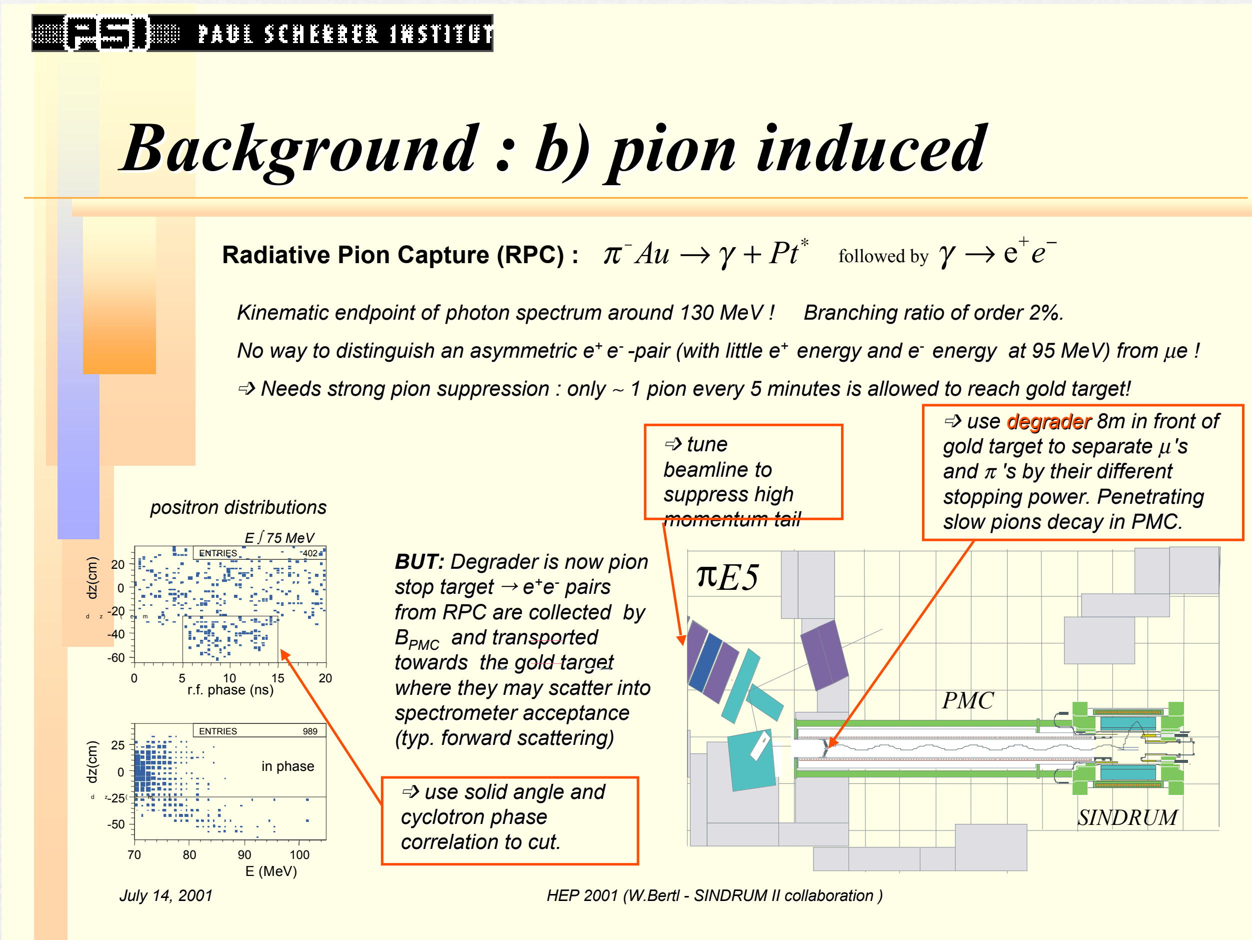
SINDRUM II Results

- Final SINDRUM-II on Au
- Note Two Background Events past Signal Region
- *Multiply Problems by 10^4 ?*



July 14, 2001 *HEP 2001 (W.Bertl - SINDRUM II collaboration)*

Key Improvement of Both COMET and $\mu 2e$



SINDRUM:

a) straight line from target to detector

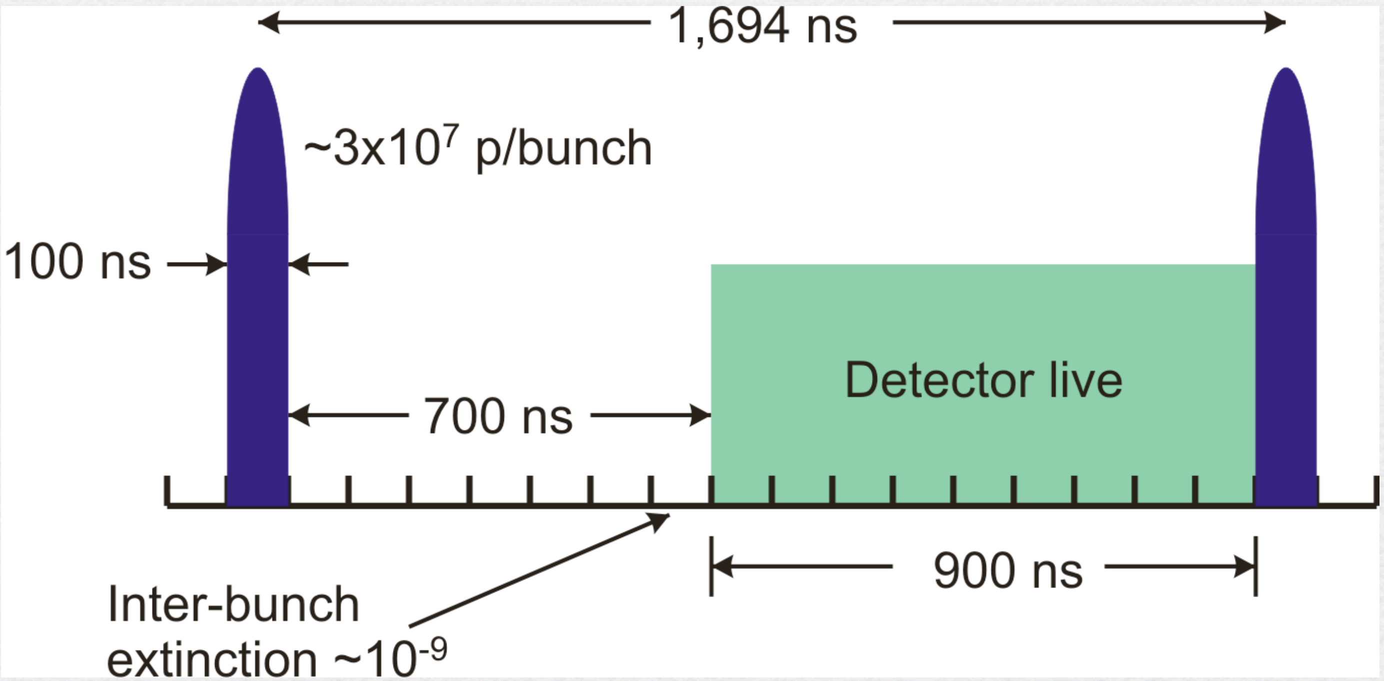
b) continuous beam

μ2e at FNAL

- Improvements:
  - **>10^3 increase in muon intensity from SINDRUM**
  - **Curved Transport Solenoid and Pulsed Beam to Eliminate prompt backgrounds(Radiative π)**
    - SINDRUM was continuous beam
    - in Mu2e, pulsed beam! but must achieve required 10^{-9} extinction *and measure it*
  - **Tracker Resolution Critical for Decay-In-Orbit Rejection**

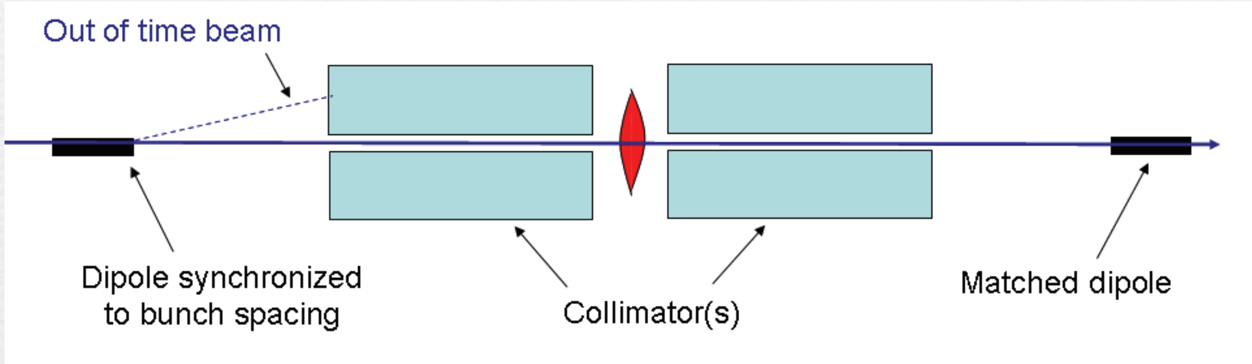
Pulsed Beam

- Beam pulse duration << τ_μ, Pulse separation ≈ τ_μ
- Large duty cycle 75-90% depending on scheme
- Extinction between pulses < 10^{-9} needed
  - # protons out of pulse/# protons in pulse



Measuring Extinction Rate

- Protons in beam between pulses:



- "Switch" dipole timing to eliminate bunches, accept out-of-time protons for direct measurement
- Other schemes under investigation
  - Measurement: off-angle collimators and telescope?

Outline of Remainder

- Beam pre- and post-Project X:
  - how do we get muons to target? how many? time structure?
- Detector:
  - How Do We Achieve Required Rejection and Resolution?
- Before we get into details on rates, how does this compare to MECO?

8 GeV Power

20 kW (current)

200 kW (Project X)

2000 kW (Project X Upgrades)

Intensity Summary

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
protons/sec	40×10^{12} (design)	18×10^{12}	70×10^{12}	160×10^{12}
average beam power	**50 kW** (design)	**23 kW**	**90 kW**	200 kW
duty factor	0.5 s on, 0.5 s off, 50%	75-90%	75-90%	75-90%
instantaneous rate	$\mathbf{80 \times 10^{12}}$ (design)	$\mathbf{20 \times 10^{12}}$	$\mathbf{77 \times 10^{12}}$	220×10^{12}
short term beam power	**100 kW** (design)	**25 kW**	**100 kW**	220 kW
Beam pulse period, msec	1.35	1.65	1.65	1.65
Data collection time interval msec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

Intensity Summary

point of this slide: if MECO worked, *μ2e* at FNAL works: pre-project X or with Project X

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
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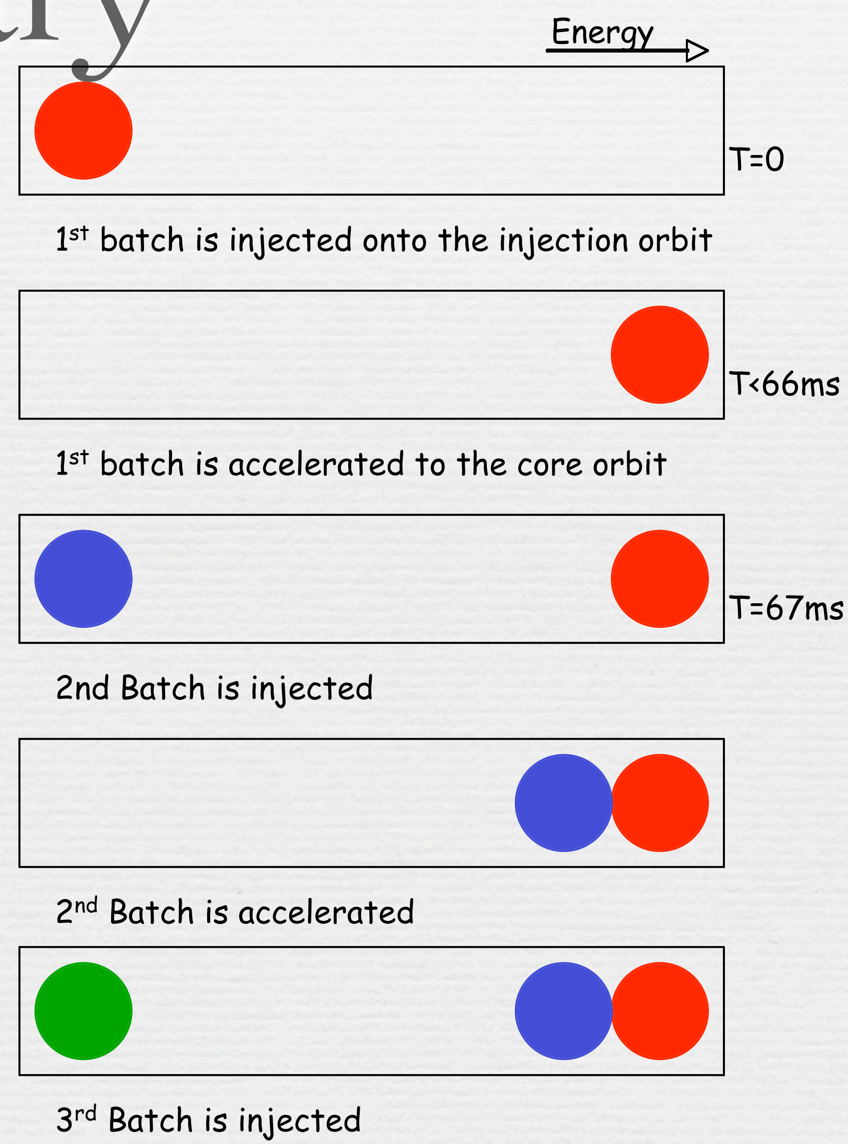
Quick Fermilab Glossary

- Booster:
  - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
  - momentum stacking successive pulses of antiprotons now, 8 GeV protons later
- Debuncher:
  - smooths out bunch structure to stack more $\bar{p}$ now; rebunch for mu2e
- Recycler:
  - holds more $\bar{p}$ than Accumulator can manage, "store" here



NovA Era and $\mu 2e$

- Load from Booster to Recycler; Booster 'ticks' at 4E12, 15 Hz

booster batches

- Single-Turn Transfer to MI

NovA Era and $\mu 2e$

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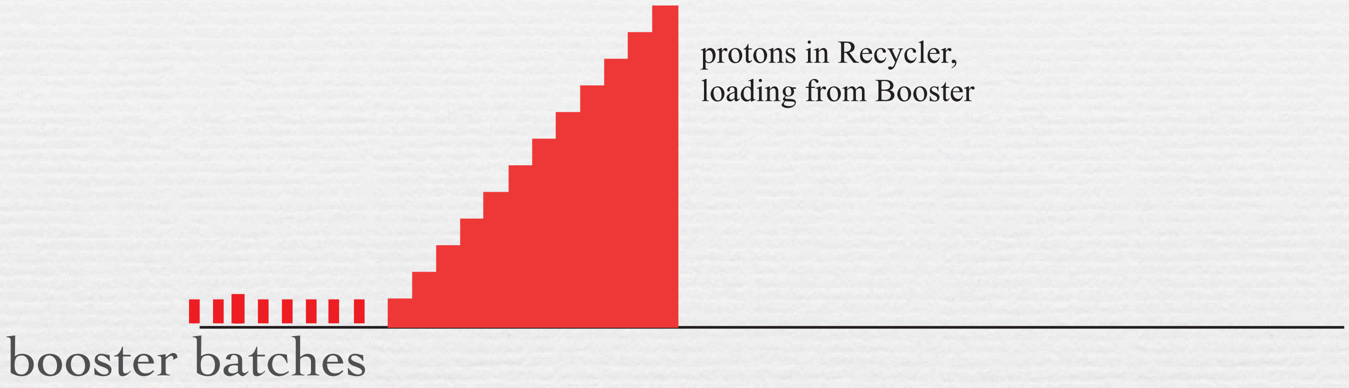

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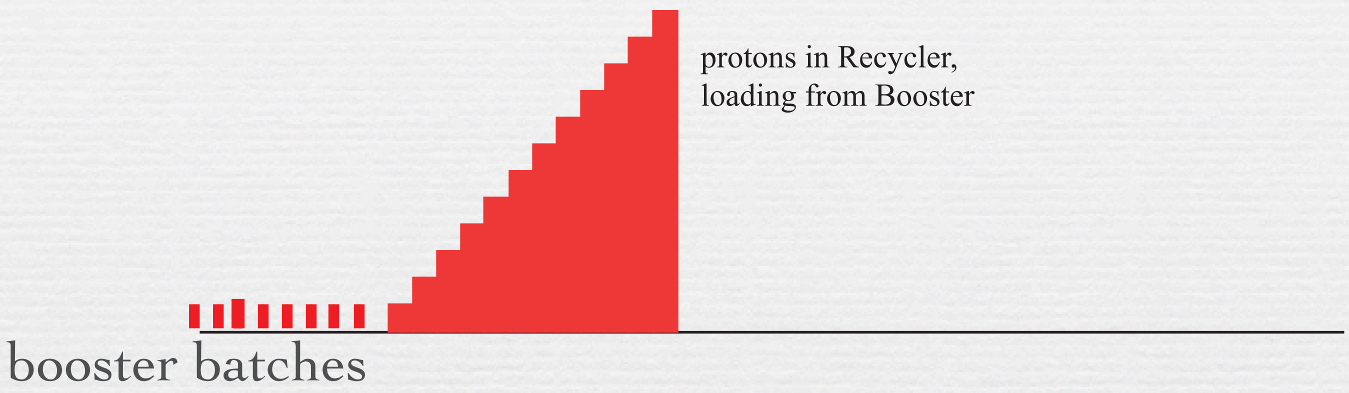

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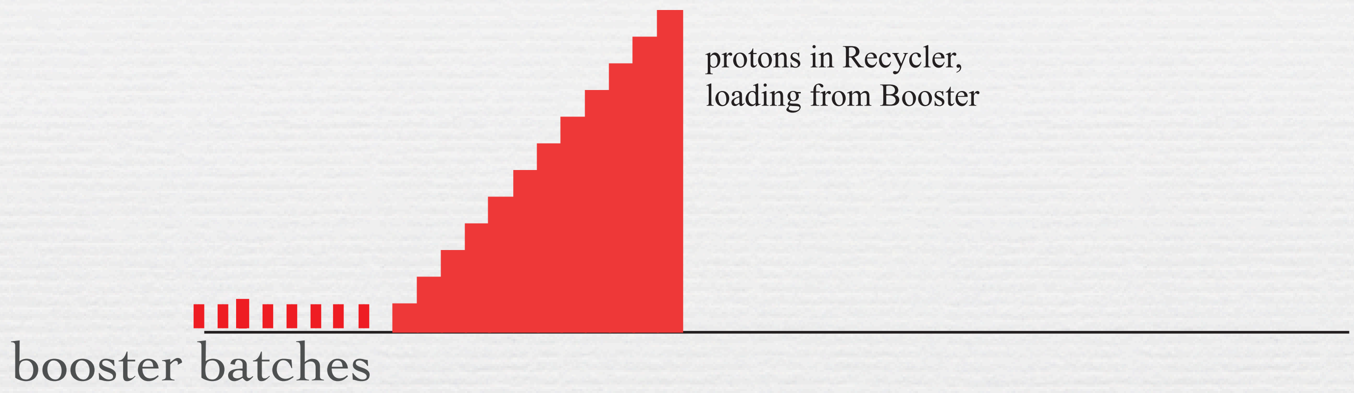

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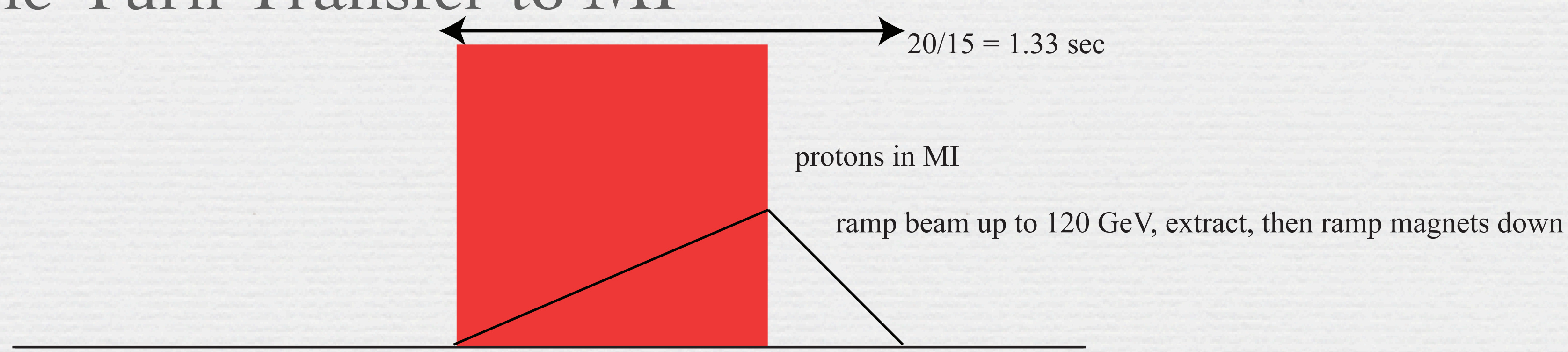
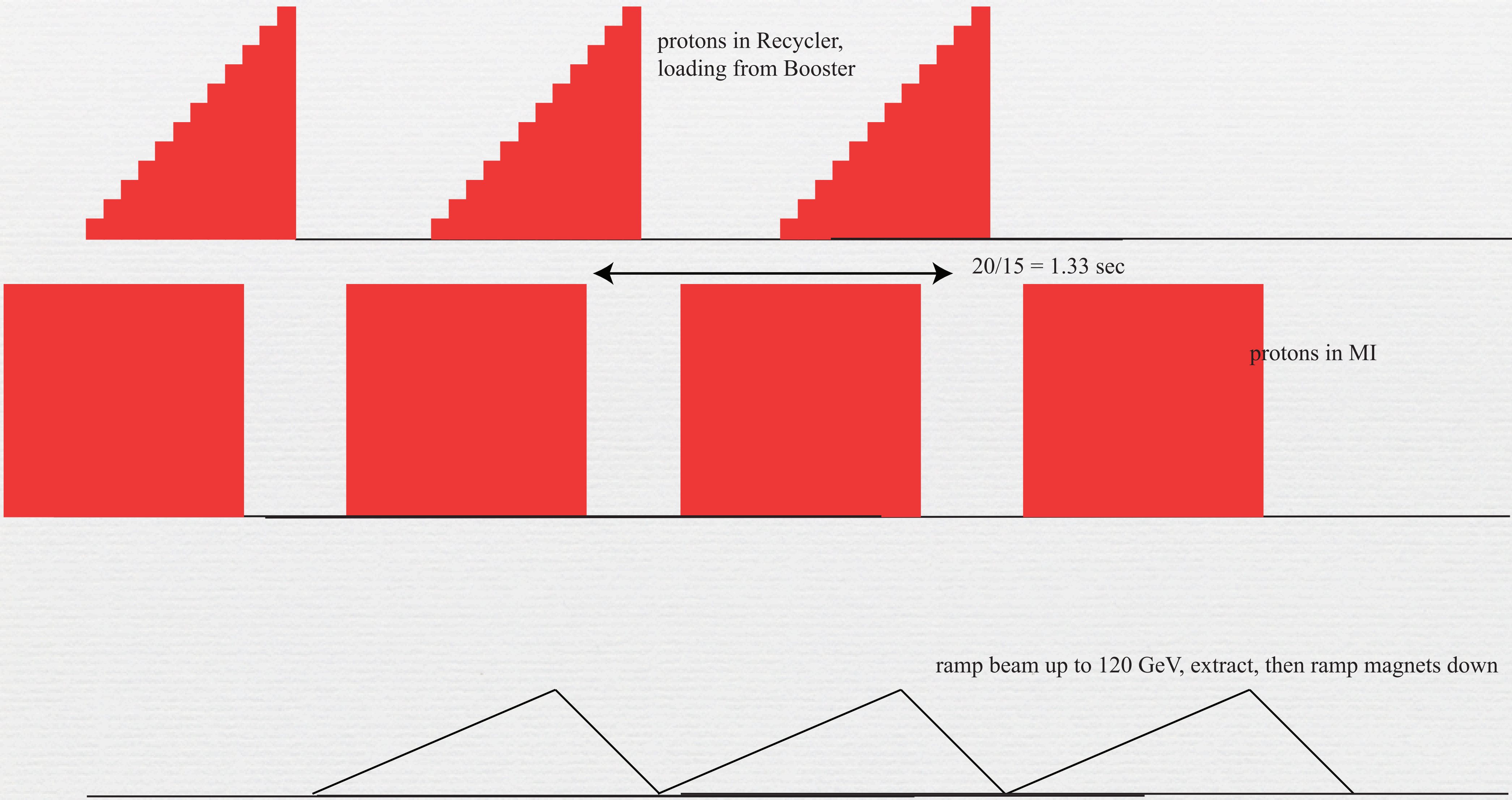


All Together...



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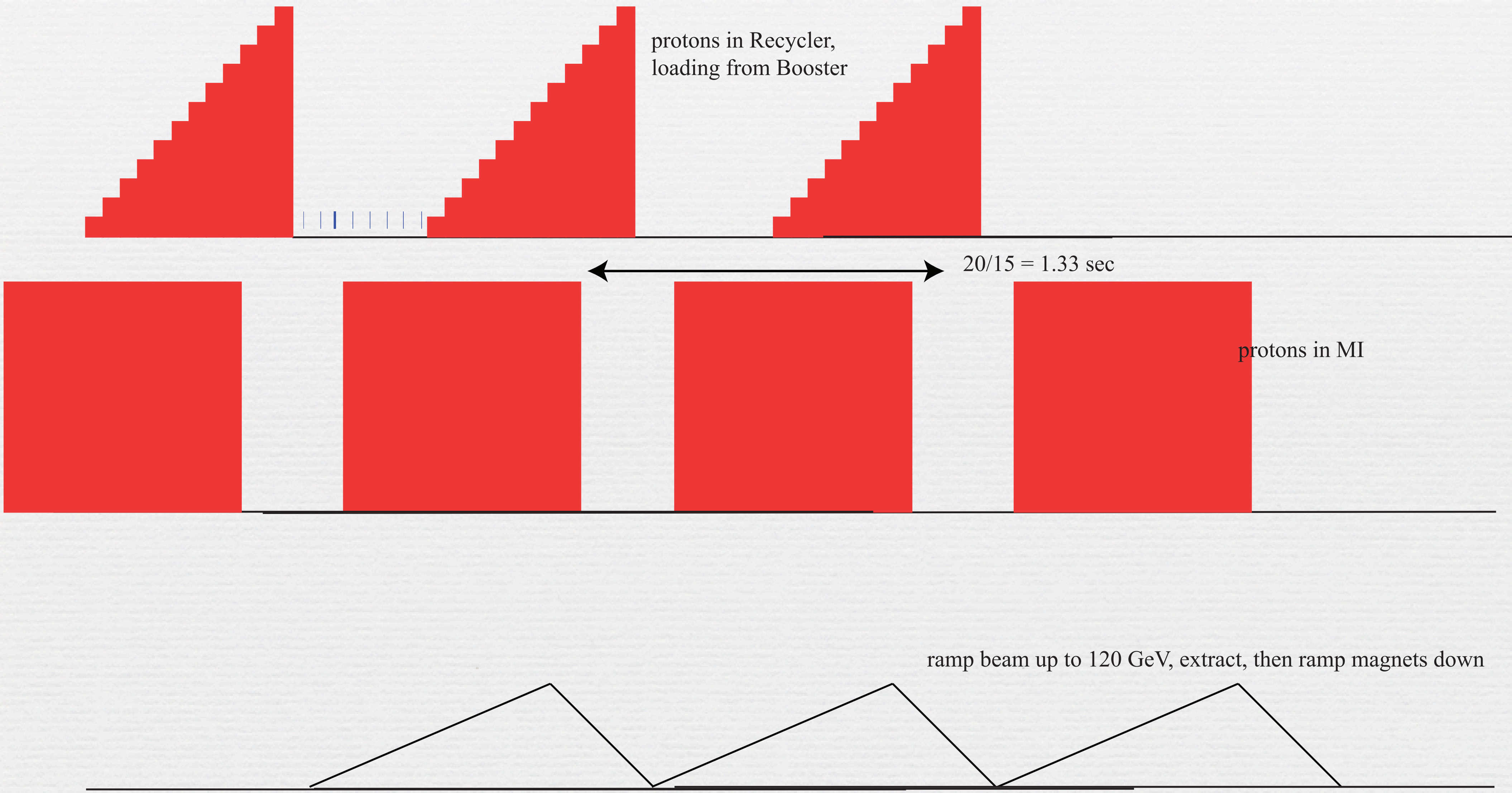
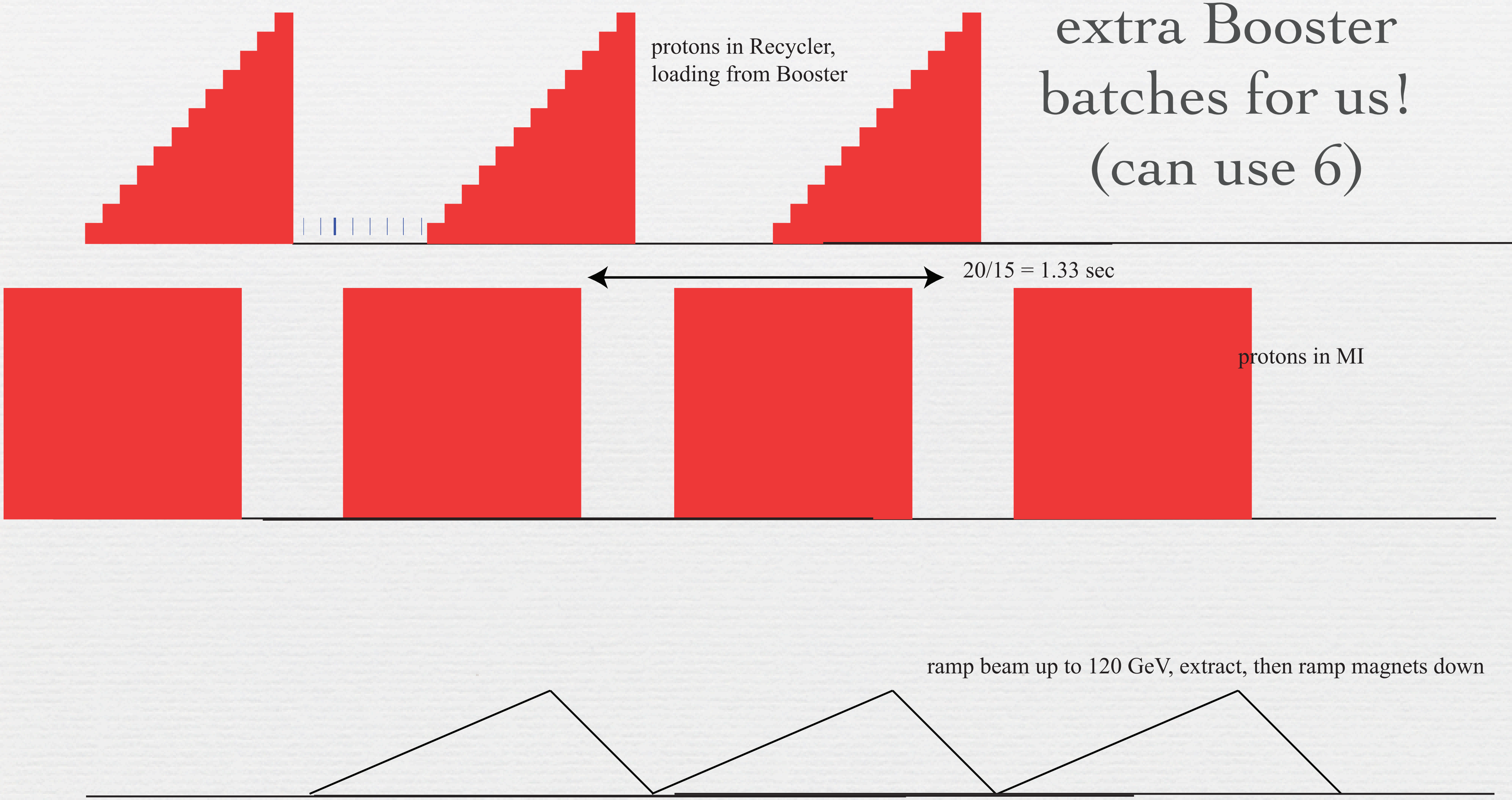
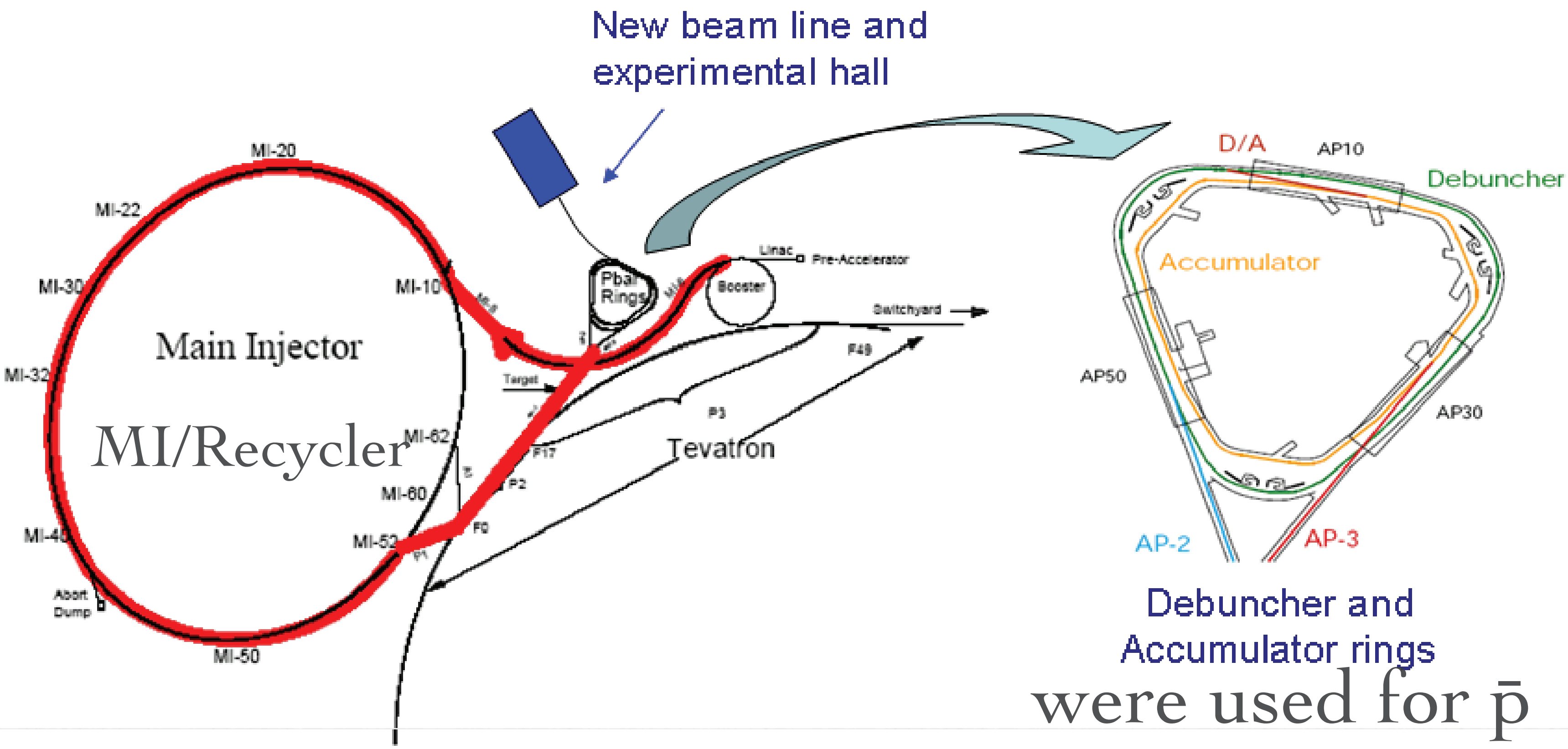


All Together...

can fit eight extra Booster batches for us! (can use 6)



Booster-Era (before Project X)



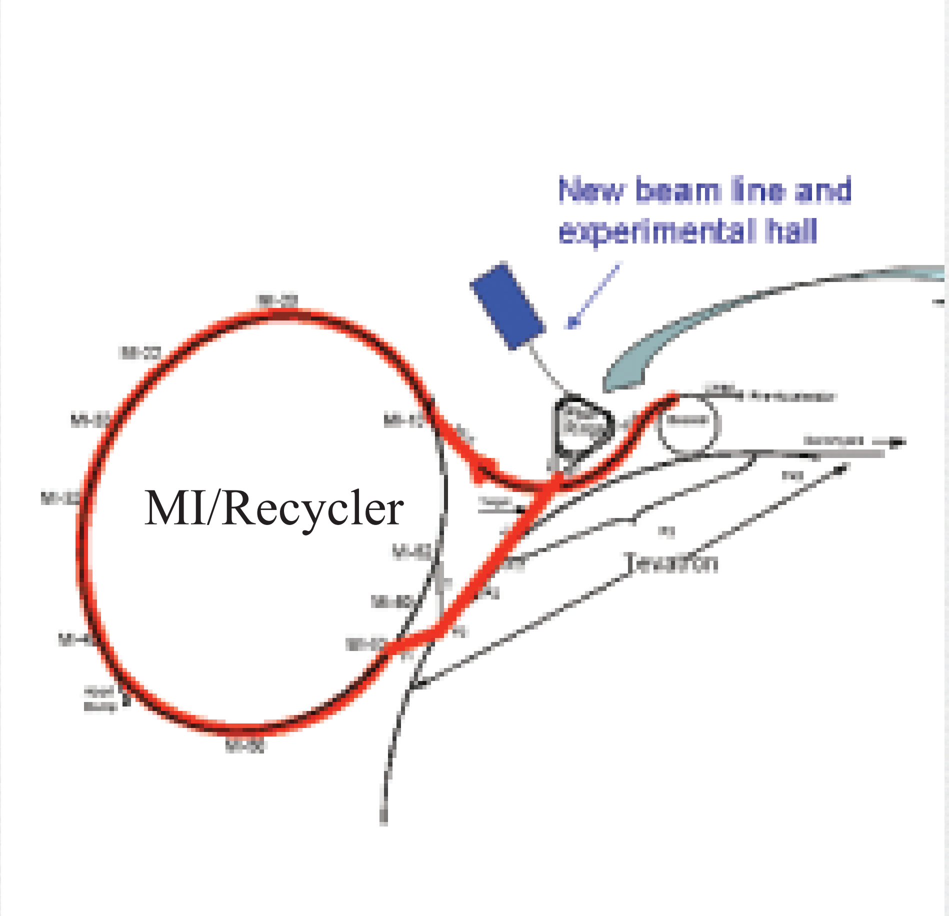
were used for $\bar{p}$

- After TeVatron shut-down, Accumulator, Debuncher, and Recycler "freed" from antiprotons

"Boomerang Scheme"

- Booster Batches transported partway through Recycler and injected directly into Accumulator
- "Momentum-Stack" batches in Accumulator
- Transfer to Debuncher
- Rebunch into Single Bunch:
  - 38 nsec RMS, ±200 MeV
- Slow Extraction: transverse, yields bunch "train"

one scheme–there are others



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one scheme–there are others

more this afternoon

Numerically,

- can get 8 Booster Batches every 1.33 sec MI cycle, or 4.8E20/yr (4E12/Booster Batch) from Booster
  - currently 10.5 Hz in Booster, need 15 Hz
  - limits of Booster RF and radiation can be overcome with some work
  - # of batches limited by longitudinal emittance in A/D to 6 of 8 (84 x .038 ev-sec)
    - Assume **3.6E20** = (6/8 × 4.8) in planning
- This manipulation can produce out-of-bucket beam
- ∴ extinction is important: must be controlled and measured

Project X Upgrades

- Ultimate sensitivity would be provided by Project X linac as proton source
  - Deliver up to 200 kW average beam current:
    - ~3 x 10^{14} protons/sec at 8 GeV (x10 previous slide)
    - 9mA, 1 msec, 5 Hz
- Three Upgrades for x10 from 200 kW to 2000 kW at 8 GeV:
  - Increase Pulse Length
  - Increase Repetition Rate
  - Increase Number of Klystrons

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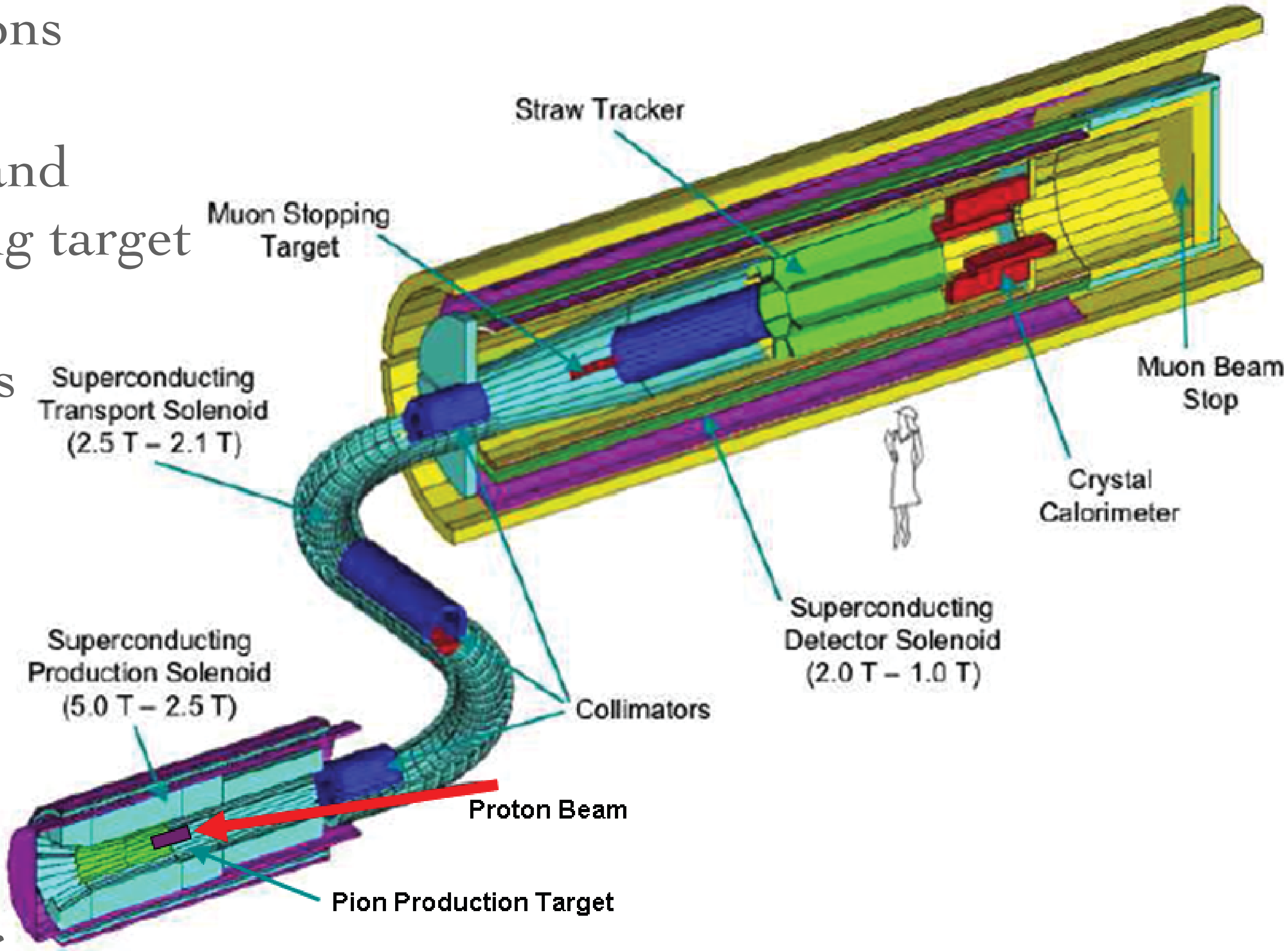
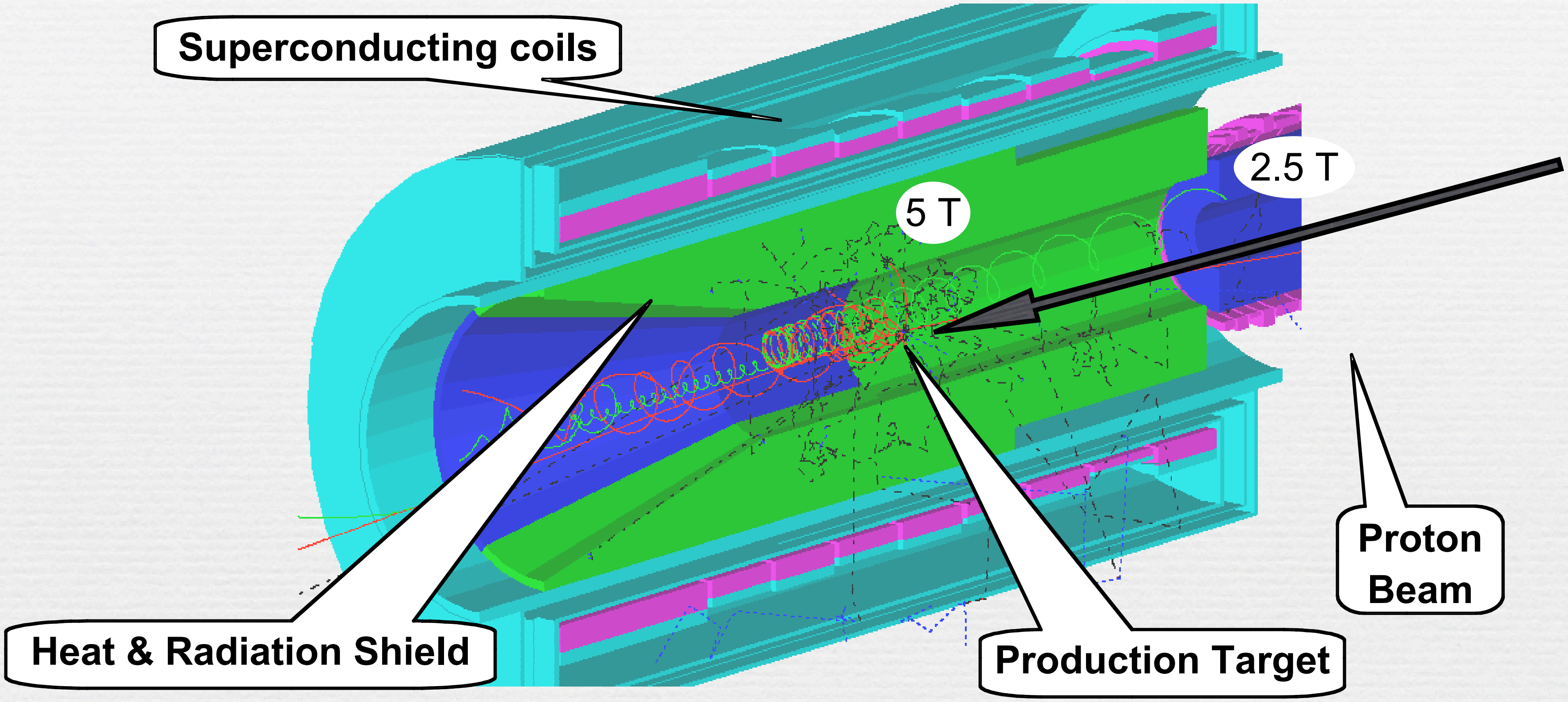
need to understand how to push single-event sensitivity to use additional capability

Overview of Experiment

- Magnetic bottle trapping backward-going pions
- Decay into muons and transport to stopping target
- "S"-curve eliminates backgrounds
- Thin windows for antiprotons
- Tracking
- Crystal Calorimeter



Production Region

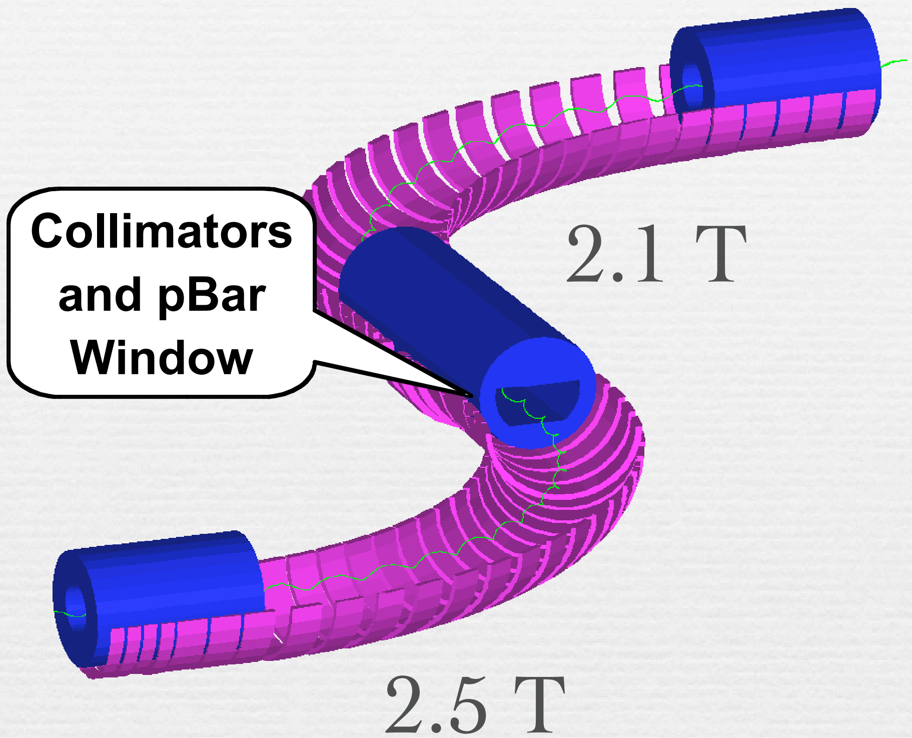


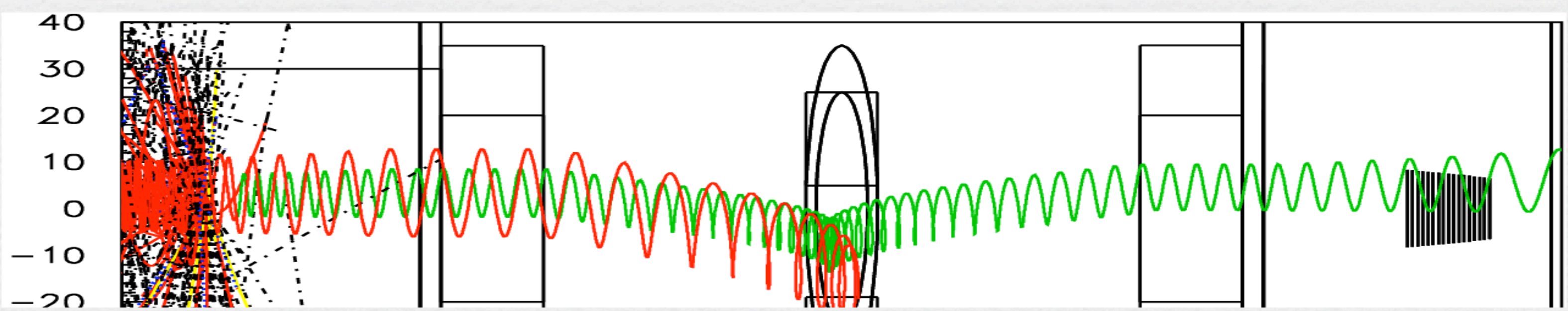
- Axially graded 5 T solenoid captures low energy backward and reflected pions and muons, transporting them toward the stopping target

- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam: need upgrade from MECO design for > 50 kW

Transport Solenoid

- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam
- dB/ds < 0 in the straight sections to avoid trapping which would result in long transit time





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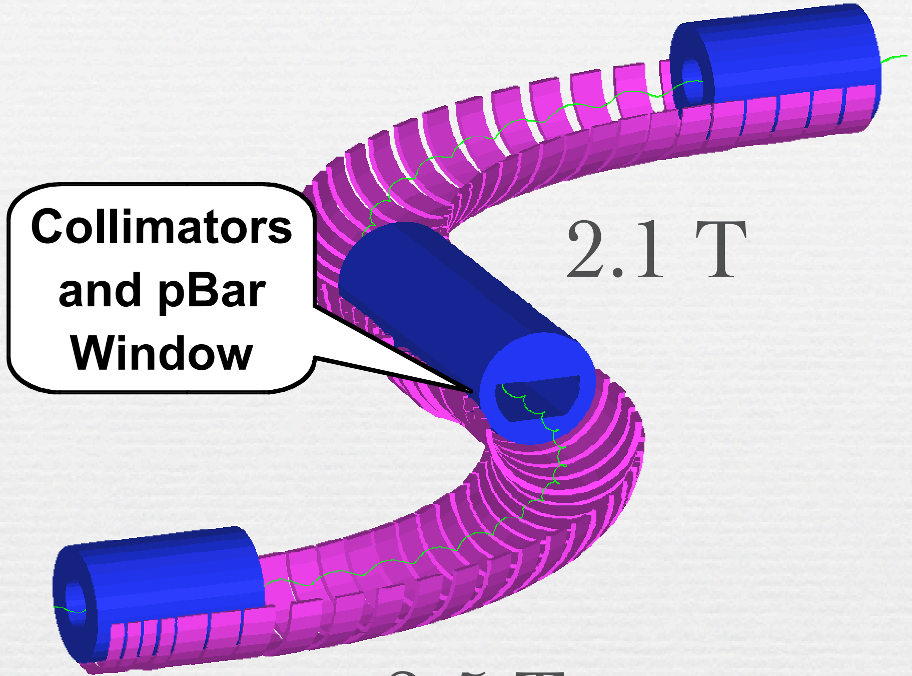
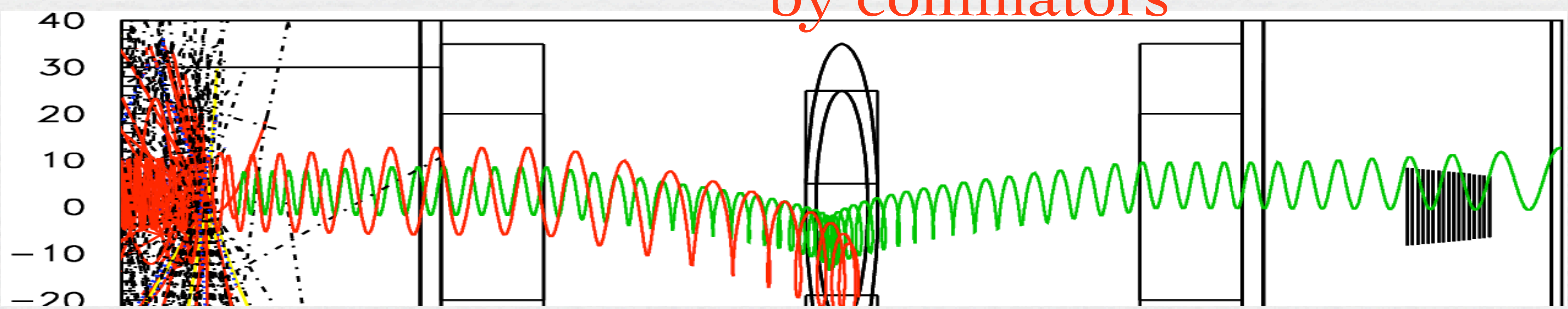


low momentum particle blocked by collimators



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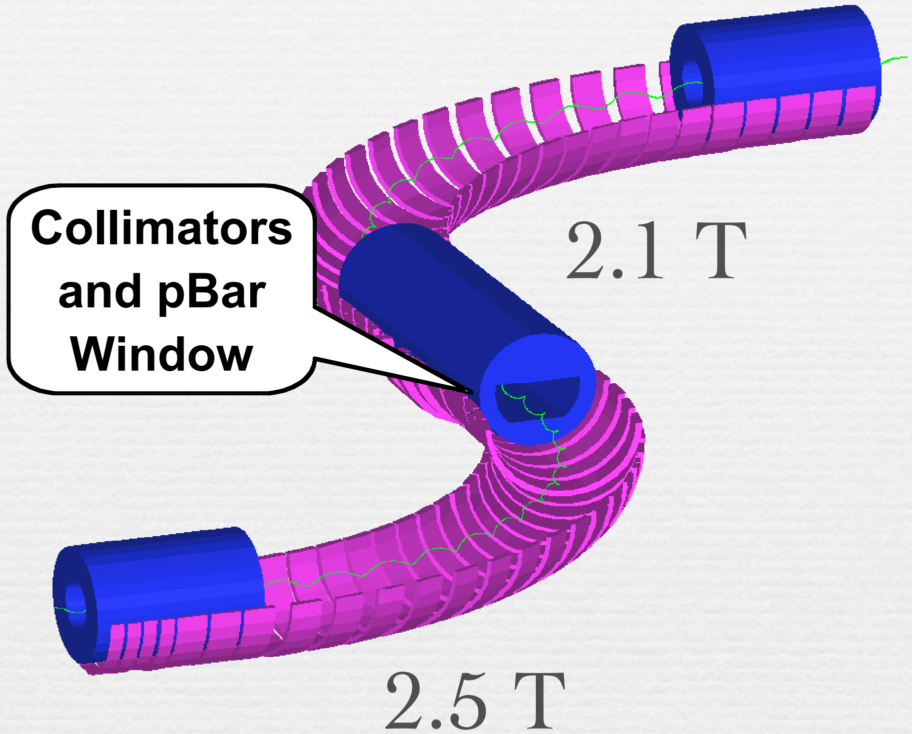
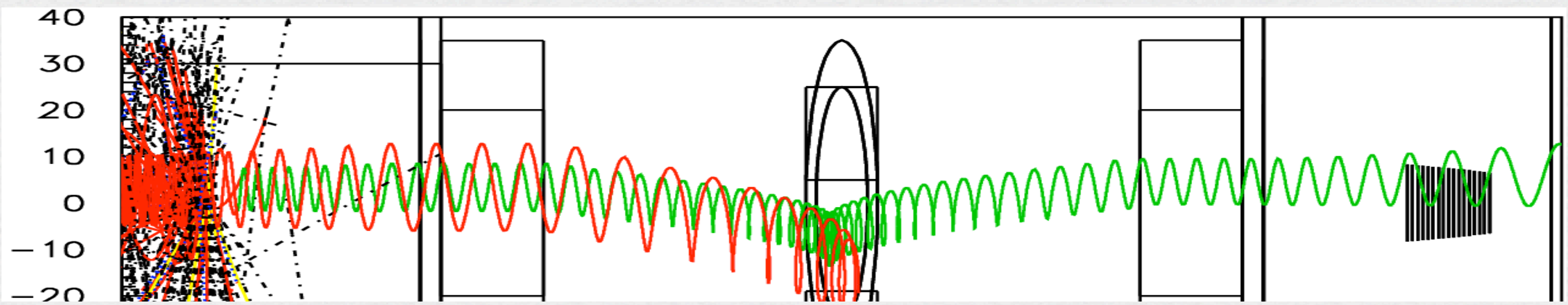
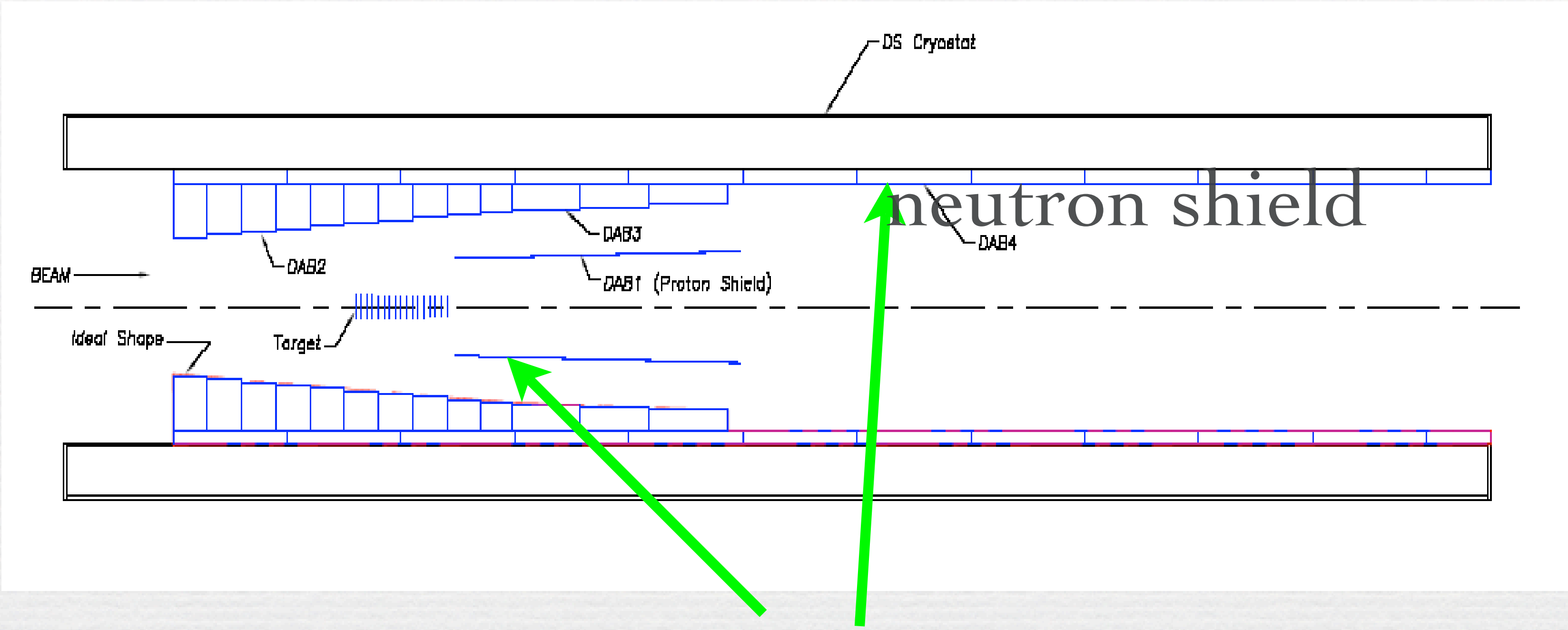




Stopping Target Region

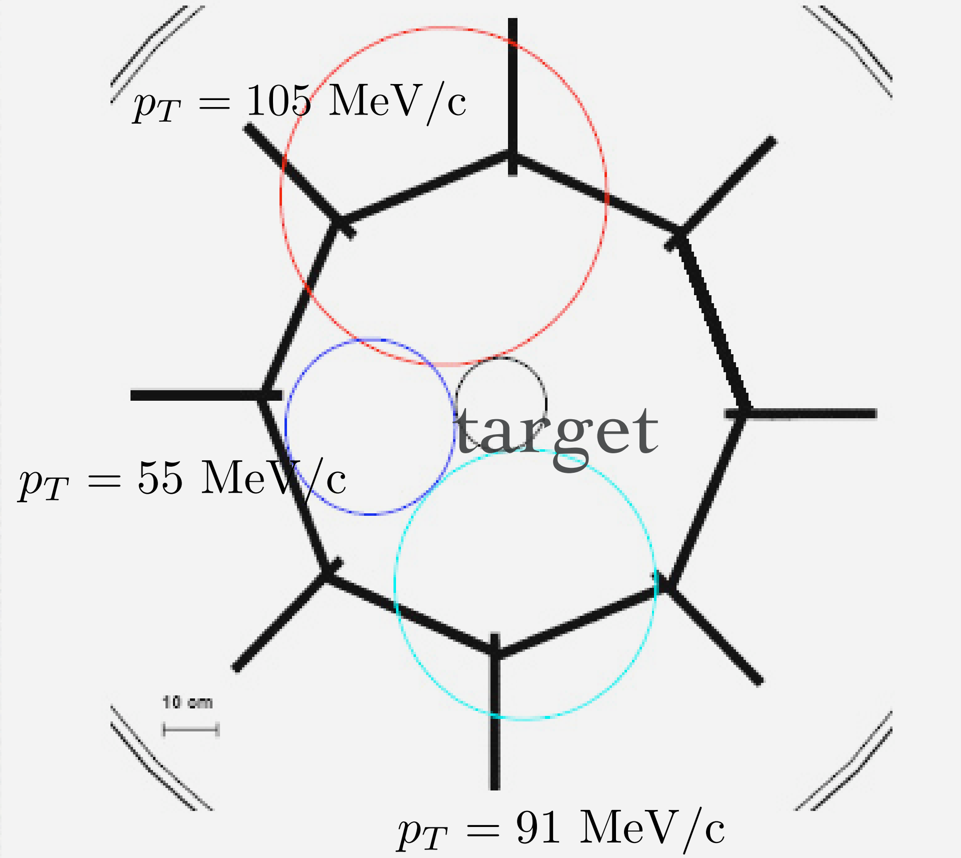


CH2 shields

- Conical Shield Reduces background and high rate from protons produced in stopping target
- Outer shield absorbs neutron cloud

Beam's Eye View of Tracker

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field
- Below p_T = 55 MeV, electron stays inside tracker and is not seen
- Looking for helix as particle propagates downstream



Note: <0.3% of e- from DIO have p_T>55 MeV/c

Detector

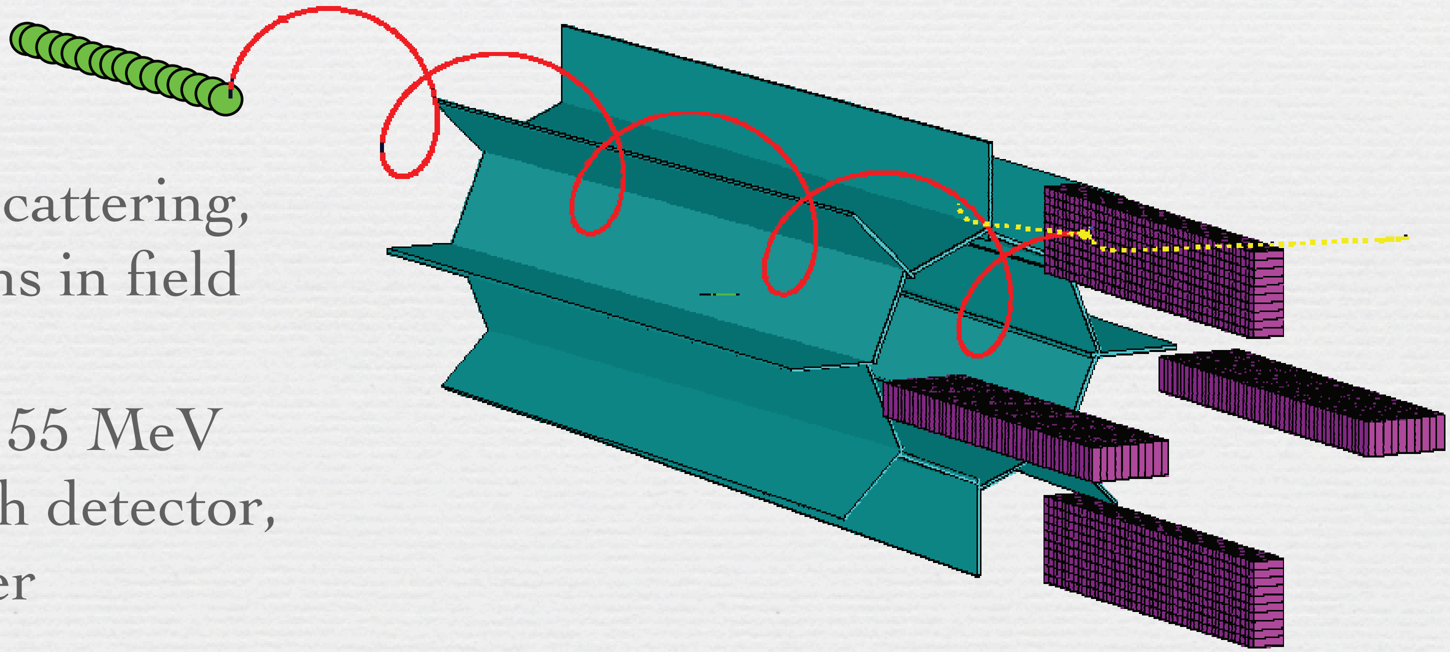
- Octagon and Vanes of Straw Tubes

σ = 200 μ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick

- Immersed in solenoidal field, so particle follows near-helical path

use return yoke as CR shield



  - up to dE/dx, scattering, small variations in field

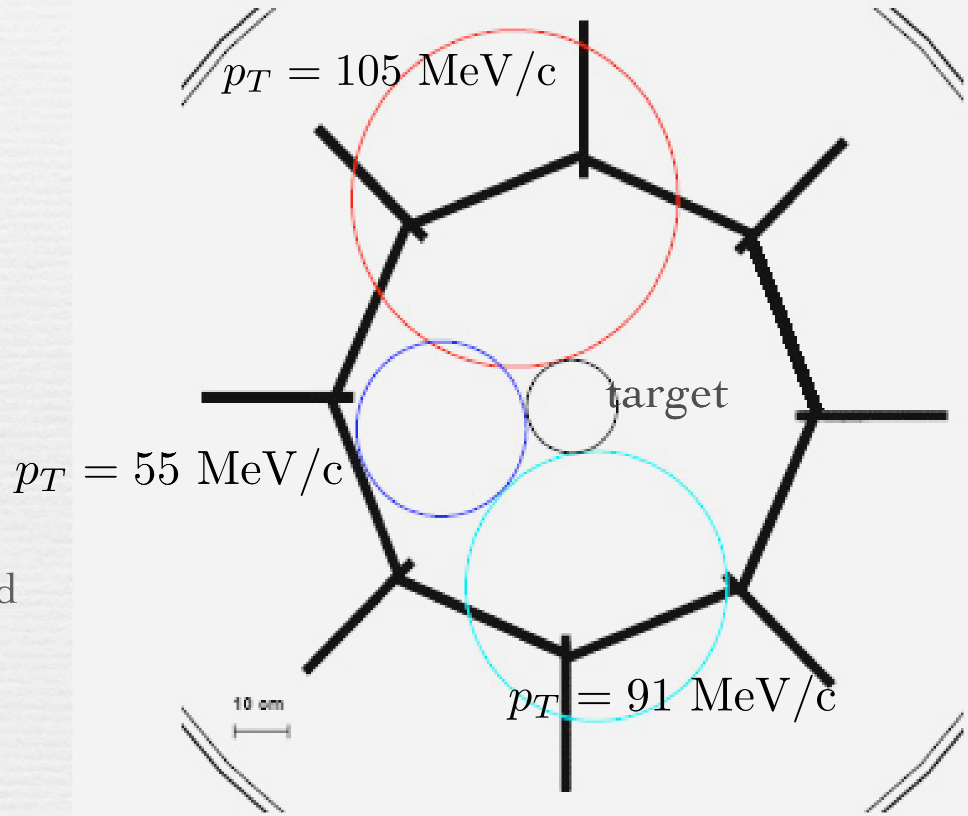
- Particles with p_T < 55 MeV do not pass through detector, but down the center

- Followed by Calorimeter

σ /E = 5%, 1200 3.5 X 3.5 X 12 cm $PbWO_4$

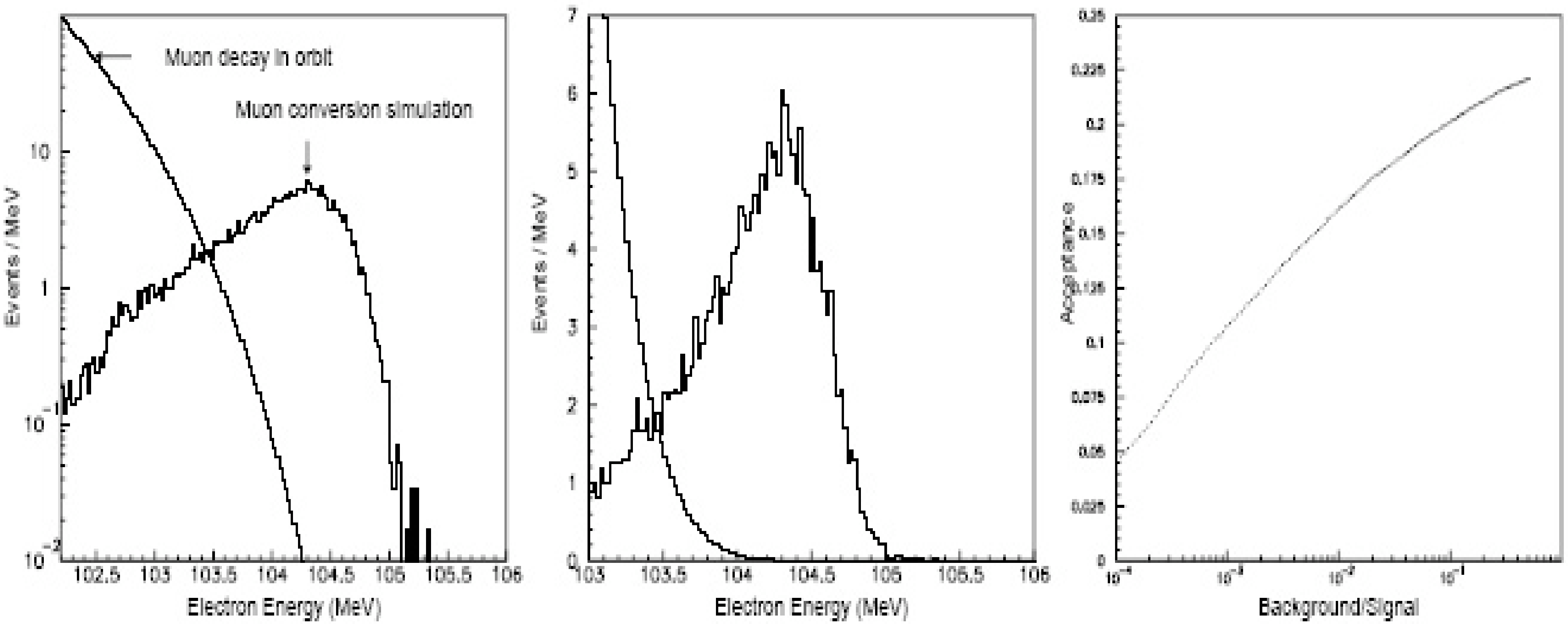
Details

- 38 -70 cm active radius
- Geometry: Octagon with eight vanes, each ~30 cm wide x 2.6 m long
- Straws: 2.9 m length 5mm dia., 25 mm wall thickness to minimize multiple scattering – 2800 total
- Three layers per plane, outer two resistive, inner conducting
- Pads: 30 cm 5mm wide cathode strips affixed to outer straws - 16640 total pads
- Position Resolution: 0.2 mm (r,φ) X 1.5 mm (z) per hit is goal
- Energy loss and straggling in the target and multiple scattering in the chambers dominate energy resolution of 1 MeV FWHM



Decay-In-Orbit

- $R_{e\mu}=1\times10^{-16}$, Momentum resolution 1 MeV (FWHM)



Log scale

Linear scale

Acceptance and S/B as E_{thresh} varied

Backgrounds...

Type	Description
e_t	beam electrons
n_t	neutrons from muon capture in muon stopping target
γ_t	photons from muon capture in muon stopping target
p_t	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, < 55 MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, > 55 MeV
n_{bd}	neutrons from muon capture in beam stop
γ_{bd}	photons from muon capture in beam stop
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, < 55 MeV
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, > 55 MeV
$e(DIF)$	DIO between stopping target and beam stop

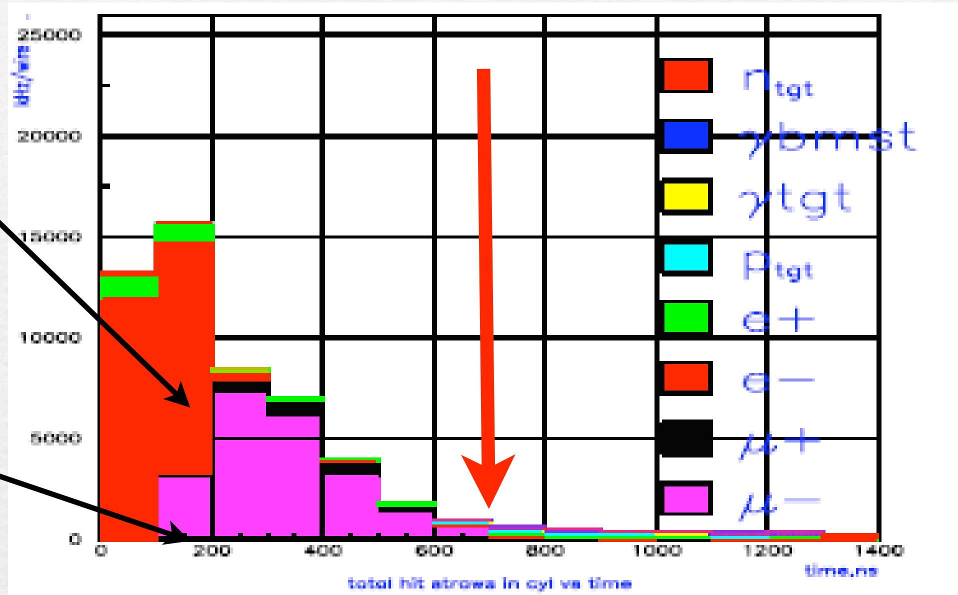
bd = albedo from beam stop (after calorimeter)

Rates vs. Time

700 nsec

beam e⁻

μ DIF



0-1400 nsec

Rate (**15 MHz/wire**)

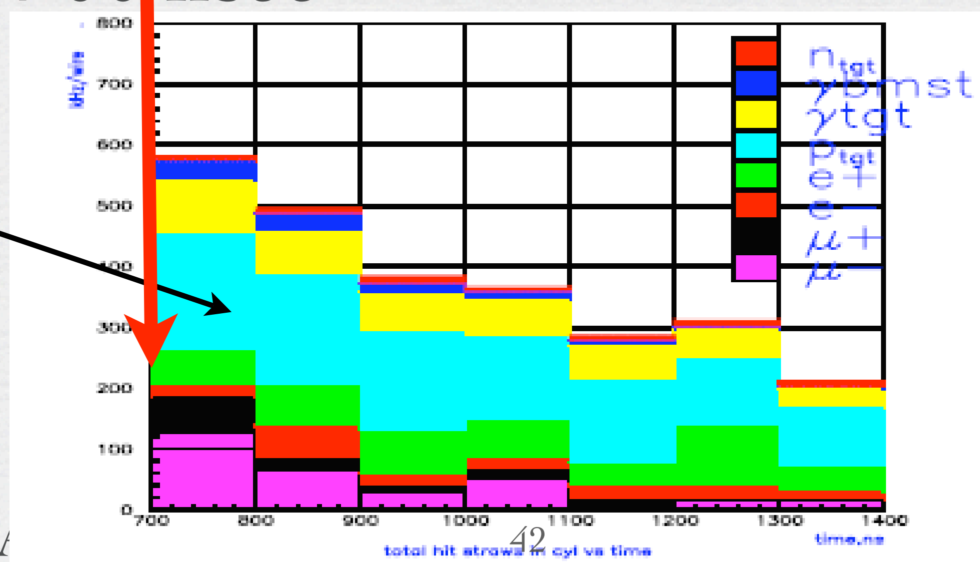
divide by 4

Rate (**560 kHz/wire**)

700-1400 nsec

700 nsec

Protons in stopping tgt



Rates In Tracker

- Rates at *Beginning* of > 700 nsec Time Window, so these are highest
- ≈ 2 hits per straw during beam flash
- Rates are manageable: (1/4 of MECO instantaneous)

Type	Rate(Hz)	$\mathcal{P}$ hit	Mean N hits/bkg part	R_{wire} (kHz)
e_t	0.62×10^{11}	0.00032	1.54	16.3
n_t	0.62×10^{11}	0.000142	2.887	12
γ_t	0.62×10^{11}	0.000248	4.524	33.4
p_t	4.5×10^{9}	0.00362	6.263	50.
$e(DIO)_t < 55$	0.2×10^{11}	9.8×10^{-5}	1.44	1.4
$e(DIO)_t > 55$	0.5×10^{8}	0.00127	22.7	0.5
n_{bd}	0.12×10^{11}	7.1×10^{-5}	5.0	1.5
γ_{bd}	0.12×10^{11}	8.3×10^{-5}	4.5	1.5
$e(DIO)_{bd} < 55$	0.5×10^{11}	8.9×10^{-5}	1.	1.65
$e(DIO)_{bd} > 55$	1.4×10^{8}	1.82×10^{-4}	1.5	0.0125
$e(DIF)$	0.69×10^{6}	1	35.84	8.6
total				116

Calculating Signal Rate

Source	Factor
Running Time (sec)	1.1×10^7
Proton Flux (Hz)	3.6×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ Stopping Probability	0.58
μ Capture Probability (normalization process)	0.60
Fraction of Capture in Time Window	0.49
Electron Trigger Efficiency	0.90
Geometrical Acceptance, Reconstruction, etc	0.19
Detected Events for $R_{\mu e} = 10^{-16}$	5.0

Final Backgrounds

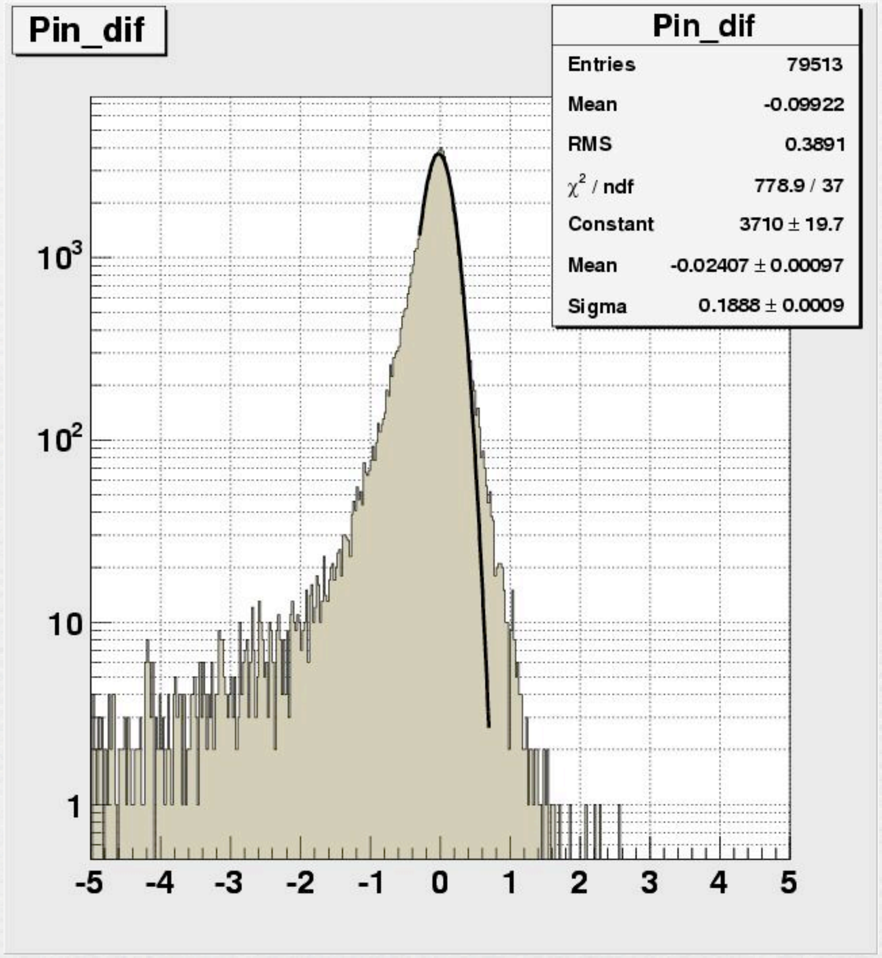
- For $R_{\mu e} = 10^{-16}$ expect 5 events to 0.5 bkg
- Extinction factor of 10^{-9}

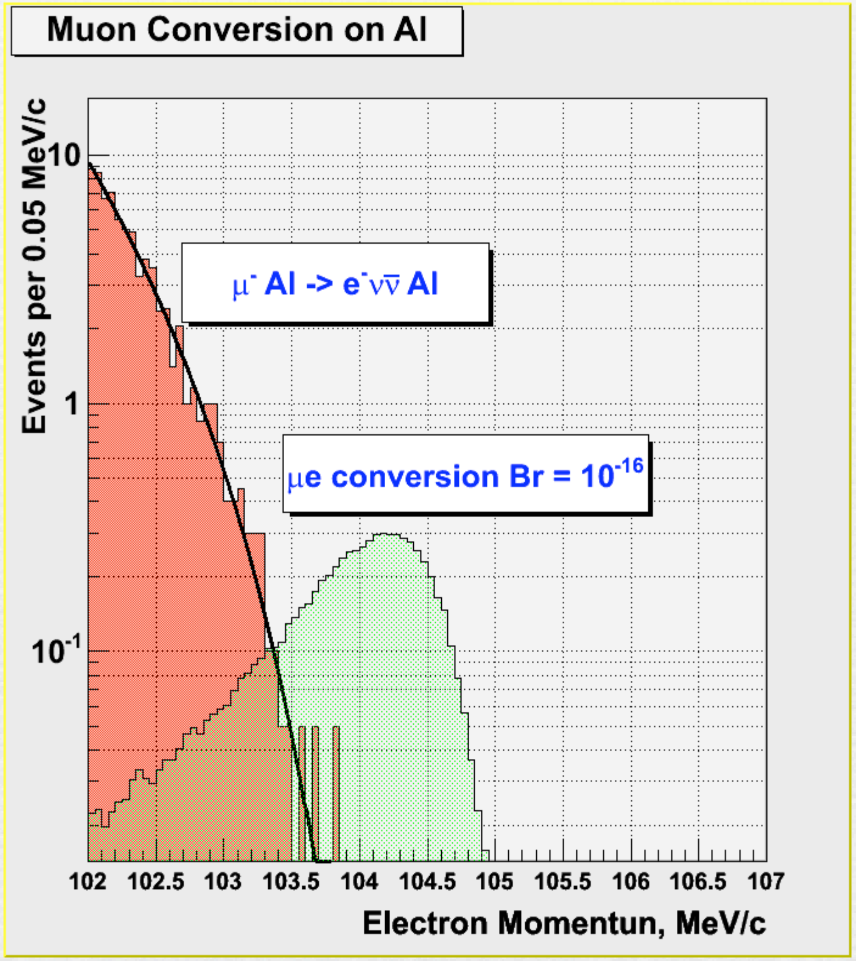
5 signal

Source	Number/ 4 x 10^{20}
DIO	0.25
Radiative π capture	0.08
μ decay-in-flight	0.08
Scattered e^-	0.04
π DIF	<0.004

Summary of Capabilities

- Resolution
- Sensitivity



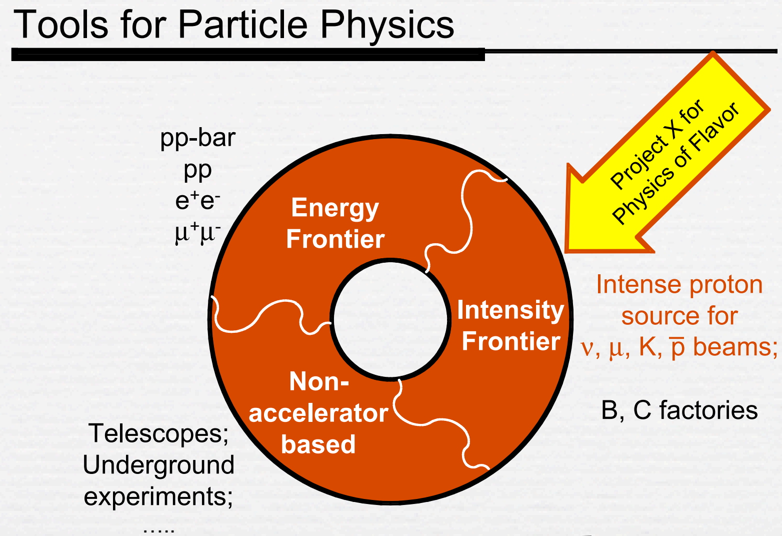


Cost and Schedule

~$100M *~2014*

- A detailed cost estimate of the MECO experiment had been done just before it was cancelled:
  - Solenoids and cryogenics: **$58M**
  - Remainder of experimental apparatus: **$27M**
  - Additional Fermilab costs have not been worked out in detail. Recent Project X era planning exercise gives ~ $130M total cost.
- Hope to begin Accelerator work along with NOvA: upgrade ~2010 (or 2011 if Run II extended)
  - Based on the original MECO proposal, we believe the experiment could be operational within five years from the start of significant funding
  - Driven by magnet construction.
- With the proposed beam delivery system, the experiment could collect the nominal 3.6×10^{20} protons on target in one to two years, with no impact on NOvA

Conclusions



- The μ2e experiment is an important measurement!
- In the initial phase (without Project X) we would either:
  - **Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6\times10^{-17}$ @ 90% C.L.)**
  - **Discover unambiguous proof of Beyond Standard Model physics**
- With a combination of Project X and/or improved muon transport, we could either
  - **Extend the limit by up to two orders of magnitude**
  - **Study the details of new physics**

Backup Slides

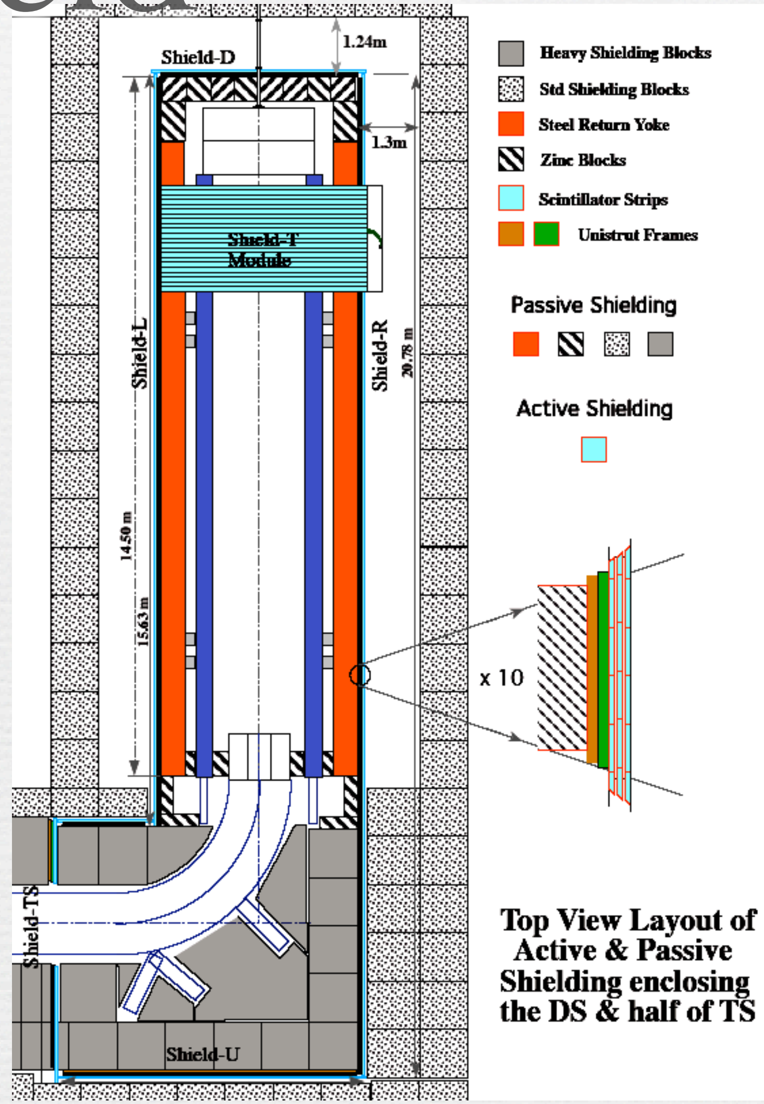
- Synergies with Neutrino Factory
- Cosmic-Ray Shield
- Acceptance of Calorimeter

Synergies with Neutrino Factory?

- There are a number of synergies between this project and muon cooling efforts
- The Debuncher beam could be extracted in a single turn to produce the short, intense bunch needed by muon production experiments
- Muon cooling studies have increased the understanding of solenoidal transport.
- It is possible that a "helical cooling channel", of the sort envisioned for muon cooling, could generate a significantly higher muon yield for this experiment.
- We will investigate these in more detail for the proposal.
- **A combination of increased flux from Project X and a more efficient muon transport line could potentially result in a sensitivity as low as 10^{-18}**

Cosmic Ray/Neutron Shield

- Three Layers of Scint
  - 2/3 coincidence
  - Inefficiency ≤ 10^{-4}



Acceptance of Calorimeter

- Note Log Scale
- High-Energy Tails of DIO do not swamp trigger