mu2e → mu2e-II
and wedge emittance exchange

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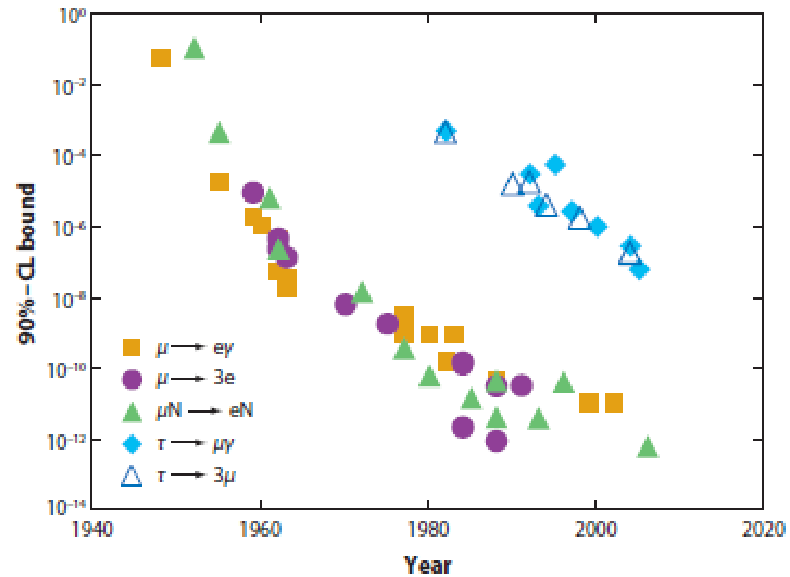
December 2017

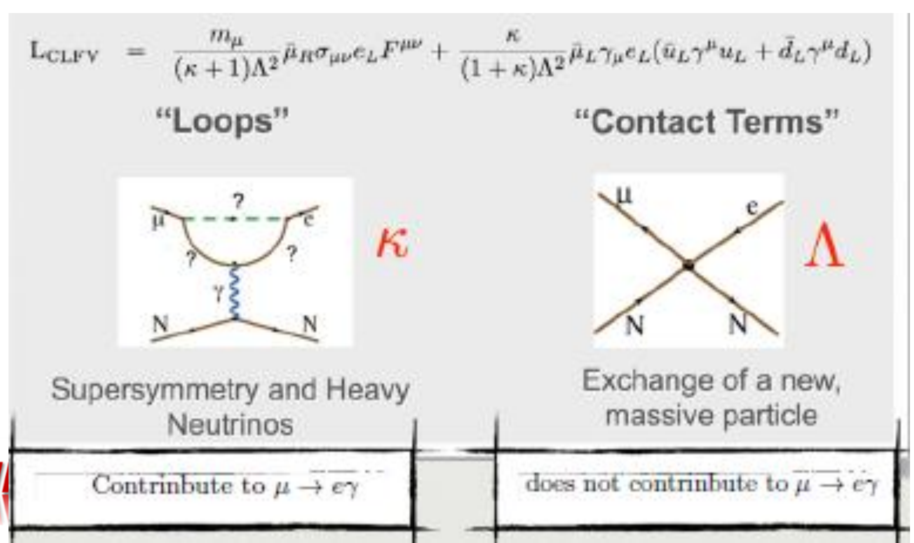
Outline

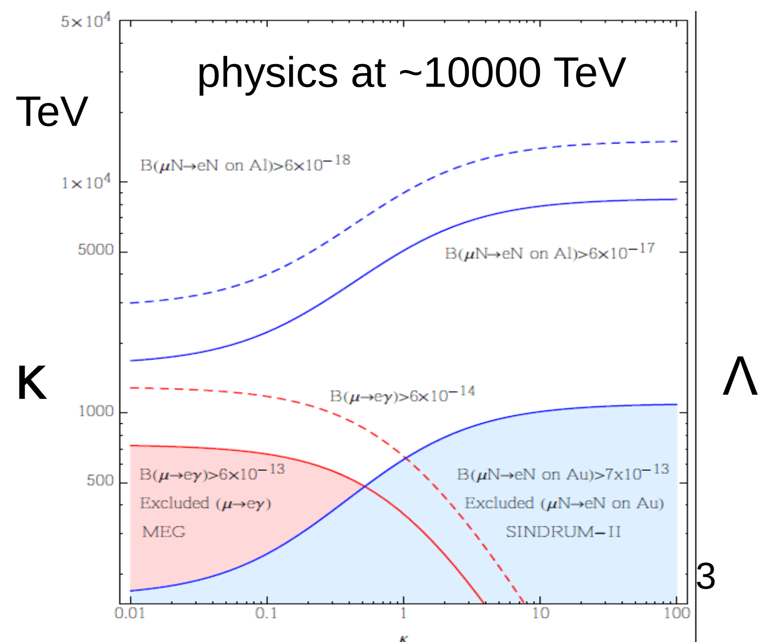
- Introduction
- Over view of mu2e
- PIP-II and mu2e-II
- mu2e-II challenges
  - Workshop on Dec. 8
  - Letter of Intent → Proposal
- Final "Cooling" Emittance Exchange
  - wedge absorbers
  - g-2 and mu2e-II

Physics goals

- **Lepton flavor violation history**
  - $\mu N \rightarrow eN < 7*10^{-13}$
  - $\mu \rightarrow e\gamma < 5.7*10^{-13}$
- **$\mu N \rightarrow eN$ Goal**
  - $\mu N \rightarrow eN < 10^{-16}$
    - mu2e Fermilab
  - $\mu N \rightarrow eN < 10^{-18}$
    - Stage 2 mu2e







mu2e Beam Scenario

- **Parameters of μ→e**
  - Proton beam – **8GeV** (~5ma)
    - $8 \cdot 10^{12}$/ 1.33s
      - 2 Booster batches/cycle
    - $6 \cdot 10^{19}$/ 10^{7} s
  - 6 years (10^{7} s)→ $3.6 \cdot 10^{20}$ p
- **Form 4 bunches in Recycler**
  - extract one by one into Delivery Ring
  - Slow extract into mu2e line
  - 0.0016 stopped μ/p
    - $5 \cdot 10^{17}$ μ / experiment

and complete the 2.5 MHz bunch formation process (see Figure 4.3).

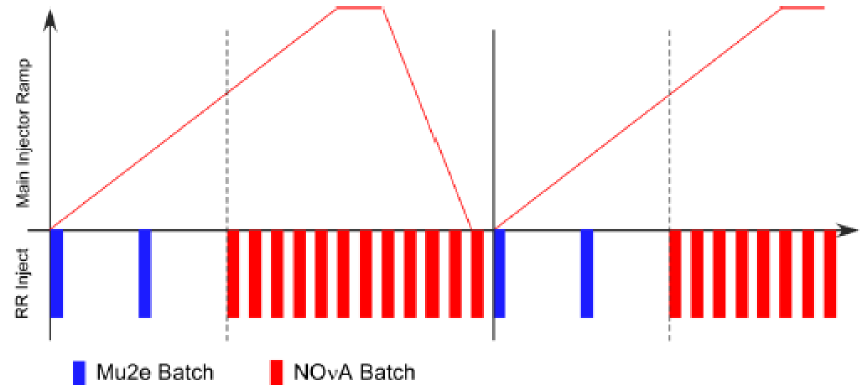
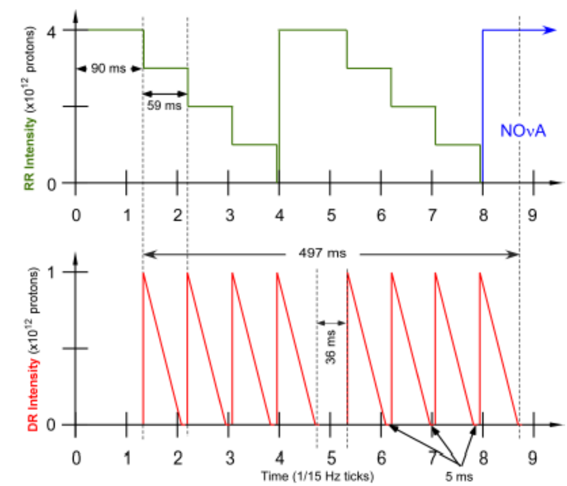


Figure 4.3. The accelerator ti
represent Mu2e and NOvA p
Recycler Ring occur in the fi
the remaining twelve 15 Hz t



Muon Campus Beam Lines

Figure 4.6 Muon Campus beam lines

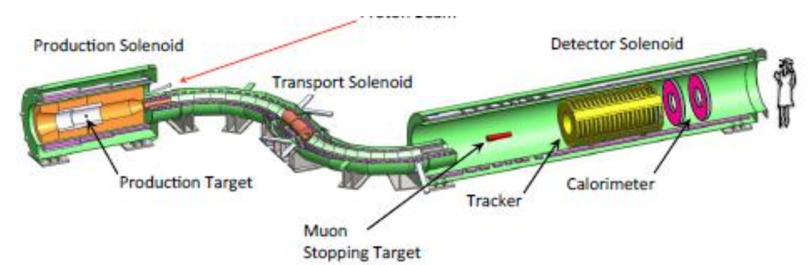


Figure 1.1. The Mu2e Detector. The cosmic ray veto that surrounds the Detector Solenoid is not shown.

mu2e scenario

- **Signal is monoenergetic**
  - 105 MeV electron
  - background is μ decay in orbit
    - π capture, μ, π decay in flight, p-bar, e^-, cosmic rays …
    - 0.4 Background Events

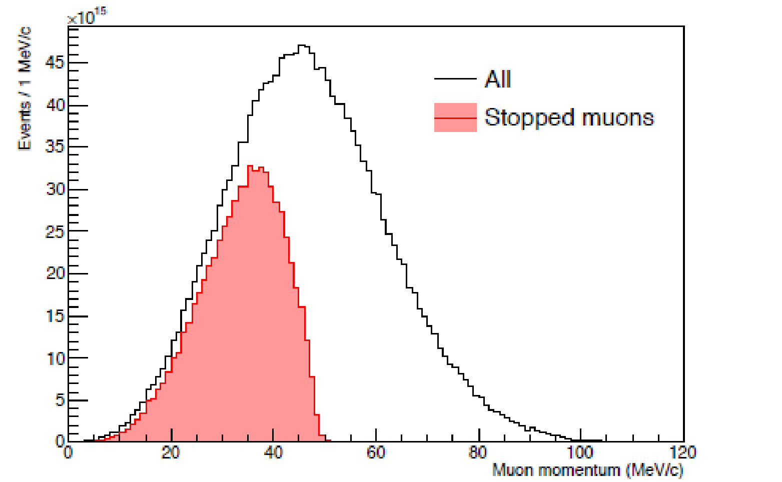
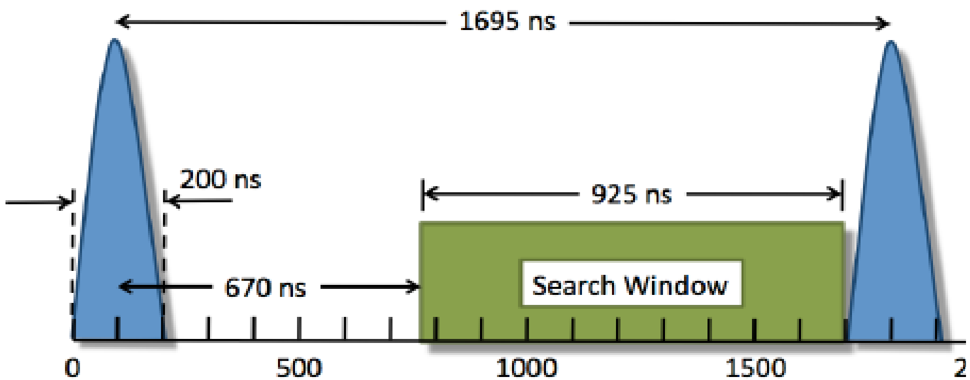
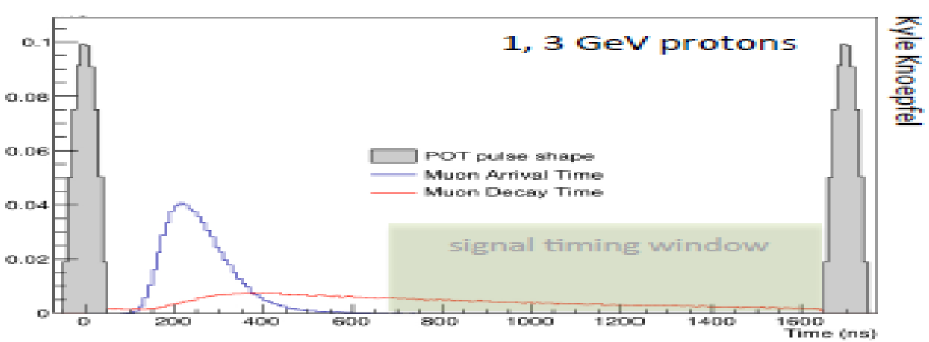
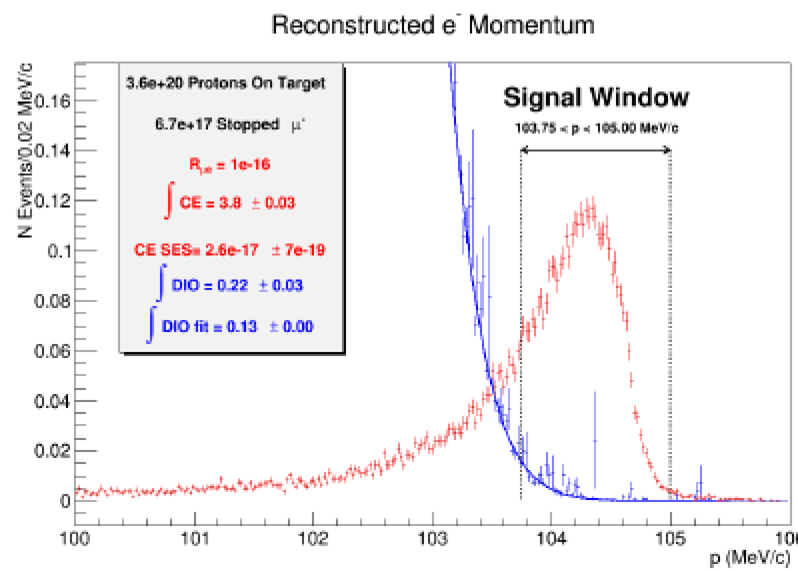


Figure 2.7 Momentum distribution of muons delivered to the stopping target as well as the distribution of muons that stop in the target.







PIP-II status

- 800 MeV-2ma cw-capable H^- linac
- On trajectory toward construction –completion in 2026
  - CD-0 → CD-1 – (CD-1 review **next week**)
  - the major accelerator project for Fermilab
- Purpose of PIP-II
  - upgraded intensity of injector for LBNF/DUNE
    - uses ~8–15 kW to produce > 1MW at 60—120 GeV
  - Platform for future high-intensity program
    - upgradeable to ~1.6MW
  - Provides up to 100 kW beam for mu2e-II
    - starting in 2026
  - with "PIP-III" (8 GeV RCS?) can provide >2MW at 60—120 GeV
- PIP-II motivation relies on mu2e-II
  - only identified user of cw linac

PIP-II Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.54	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	17	kW
Linac Upgrade potential	N/A	CW	
Mu2e Upgrade Potential (800 MeV)	**N/A**	**>100**	**kW**
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	166	kW
Beam Power to 8 GeV Program (max)	32	83	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	**0.7***	**1.0-1.2**	**MW**
LBNF Upgrade Potential @ 60-120 GeV	NA	>2.0-2.4	MW

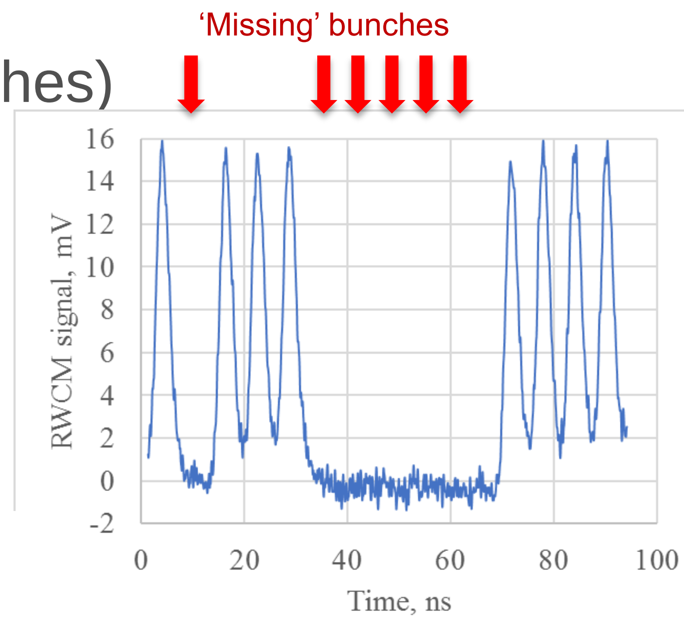
*NOvA operations at 120 GeV

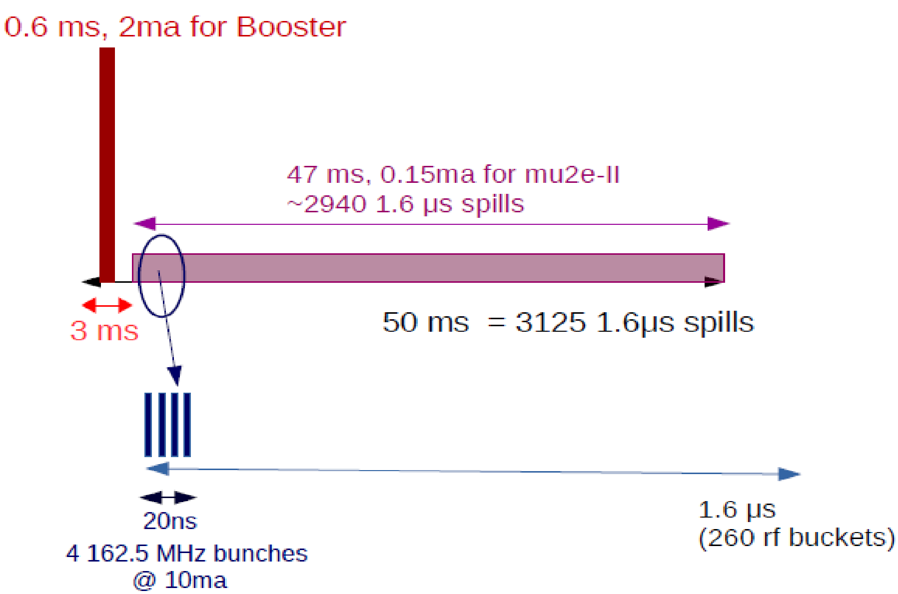
PIP-II and Next Generation Mu2e

- **India is planning to provide a cryoplant with sufficient capacity to support CW operations**
- **PIP-II front end can produce arbitrary bunch structures with:**
  - Peak current ≤10 mA
  - Average current ≤2 mA
  - This provides an opportunity for delivering 800-MeV protons directly from the SCL to a second generation Mu2e
- **Mu2e-II**
  - Use PIP-II (800 MeV) as beam source
  - Reuse as much as possible of the baseline Mu2e experiment
    - Follow similar experimental scenario
    - Improve if possible
  - Need strong Letter of Intent to support PIP-II
    - LOI will support R&D on second generation changes and improvements

PIP-II and Next Generation Mu2e

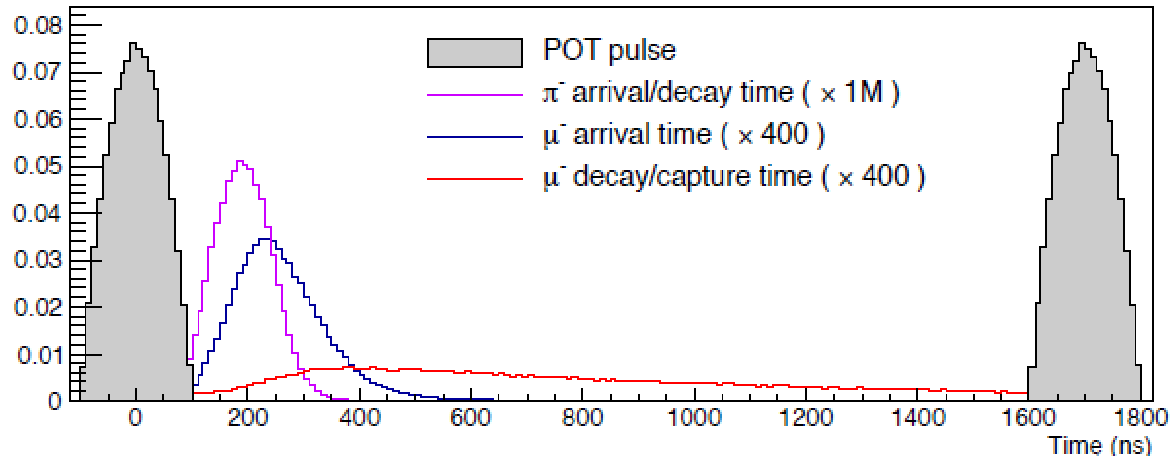
- **Possible beam structure:**
  - 162.5 MHz chopped beam
  - Beam pulse length: ~20 nsec (4 bunches)
  - Pulse repetition period: 1.6 μsec
  - Beam power: >**100 kW**
  - Three-year run achieves single event sensitivity of **2×10^{-18}**





mu2e→mu2e-II

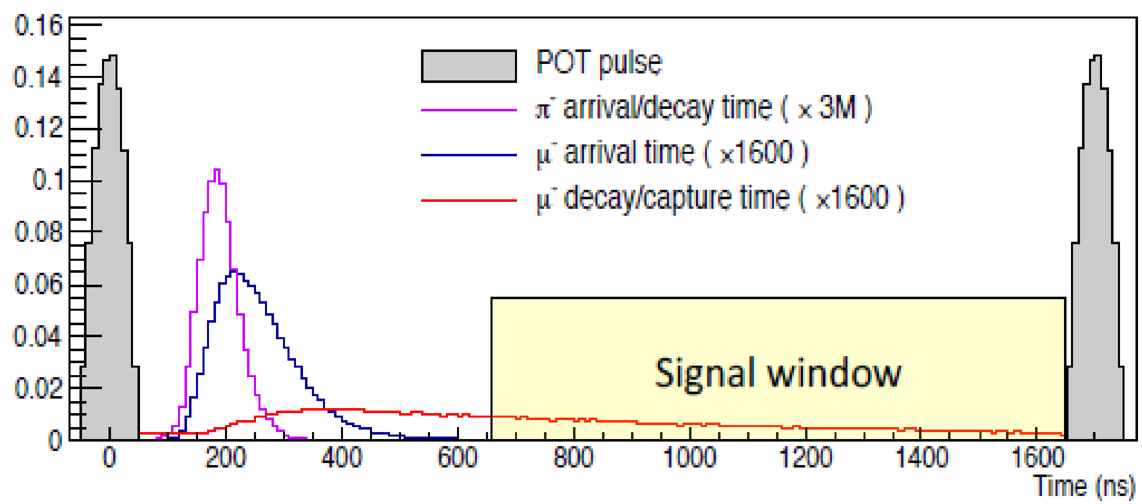
- **mu2e →mu2e-II**
  - shorter pulses
- **timing comparison**
  - K. Knoepfel



How the backgrounds change

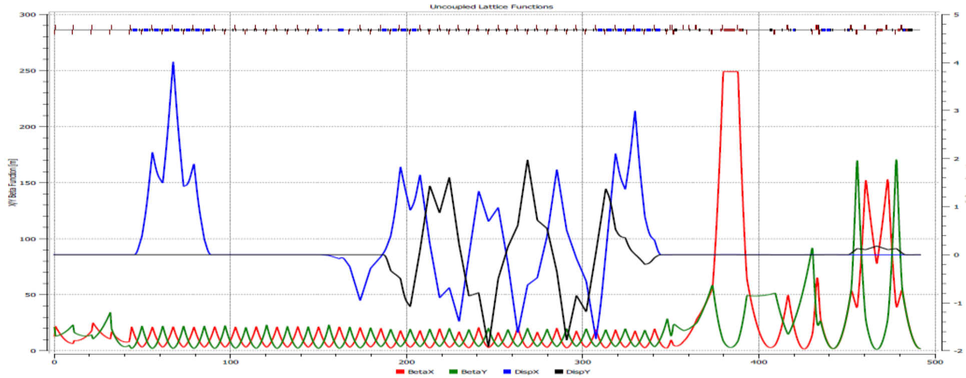
Category	Source	Events Current	Events PX (Al)
Intrinsic	μ decay in orbit	0.22	2.14
	Radiative μ capture	< 0.01	< 0.01
Late-arriving	Radiative π capture	0.03	0.04
	Beam electrons	< 0.01	< 0.01
	μ decay in flight	0.01	0.01
	π decay in flight	< 0.01	< 0.01
Miscellaneous	Antiproton	0.10	—
	Cosmic ray	0.05	0.16
	Pat. Recognition Errors	< 0.01	< 0.01
Total Background		0.41	2.36

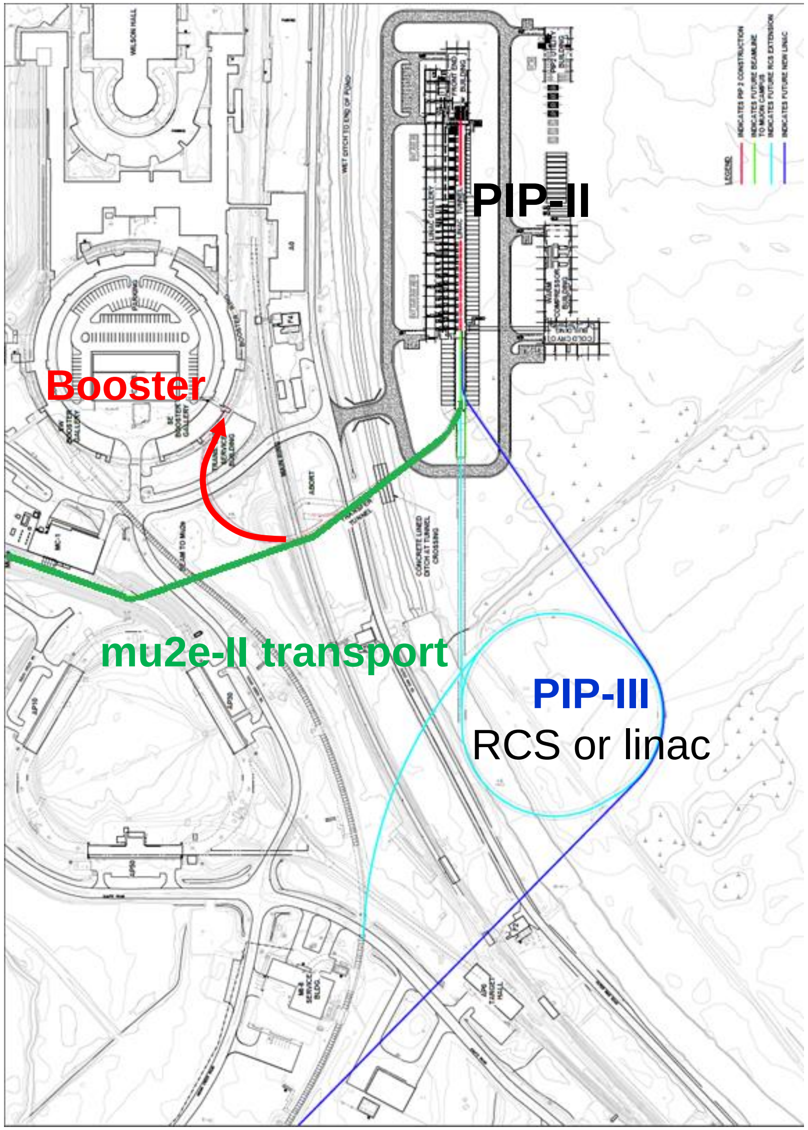
Dominant background by far is DIO for PX (Al)



New beamline to mu2e experiment

- **800 MeV beam line from linac**
  - directly to production target
  - no recycler, DR, slow extraction, no extinction
  - initial beam width shorter
    - 400ns FW → 20ns
  - 0.3 mm-mrad emittance
  - pulse to pulse chopping
    - switchyard kicker to (Booster/mu2e/dump)





PIP –II delivery on target

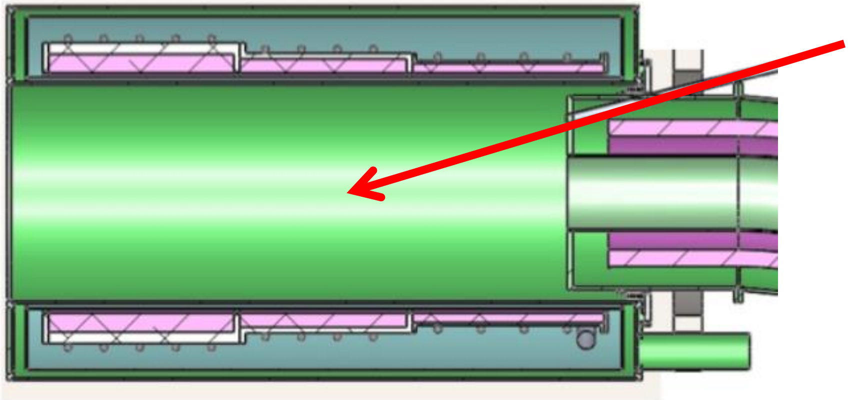
- **Linac is H⁻**

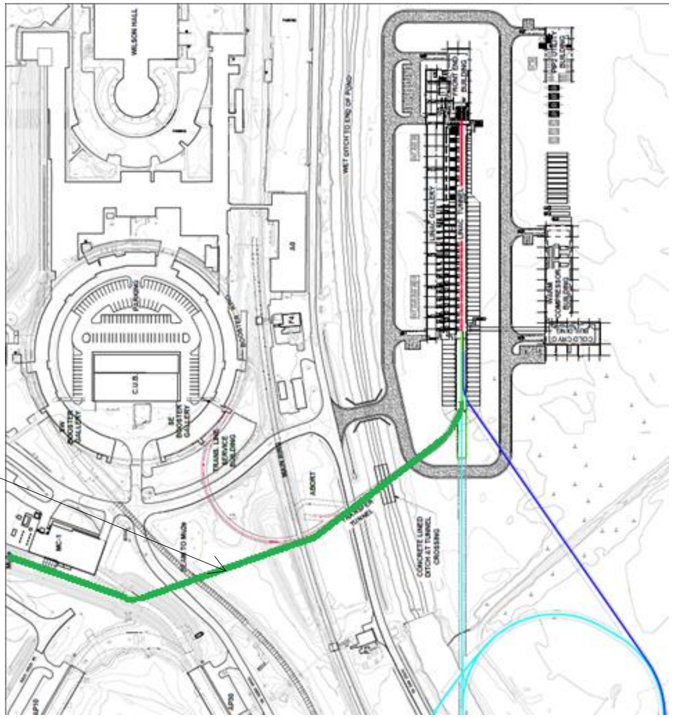
  beam enters ~4T field

  13° → 0.9 T along direction

  H_- stripping time

$$\tau = \frac{3.07 \cdot 10^{-14}}{3.2PB} \exp\left(\frac{44.14}{3.2PB}\right) s$$





$c\tau$ = ~8cm

Beam should be stripped upstream

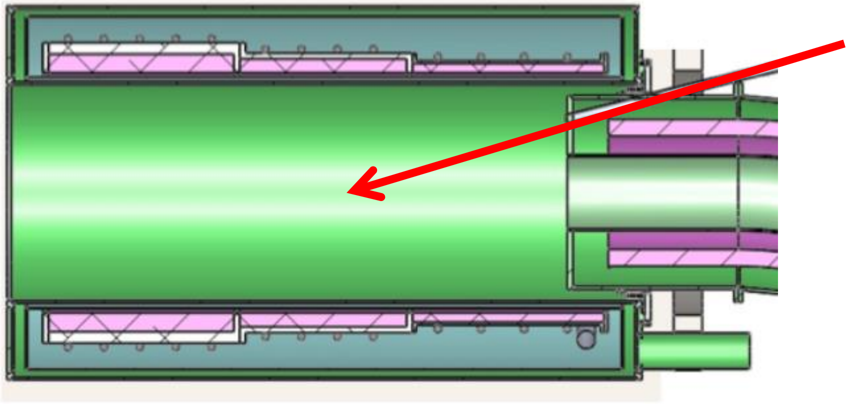
- orbit bump onto stripper foil could add to extinction (Roberts ....)

- should give much improved extinction

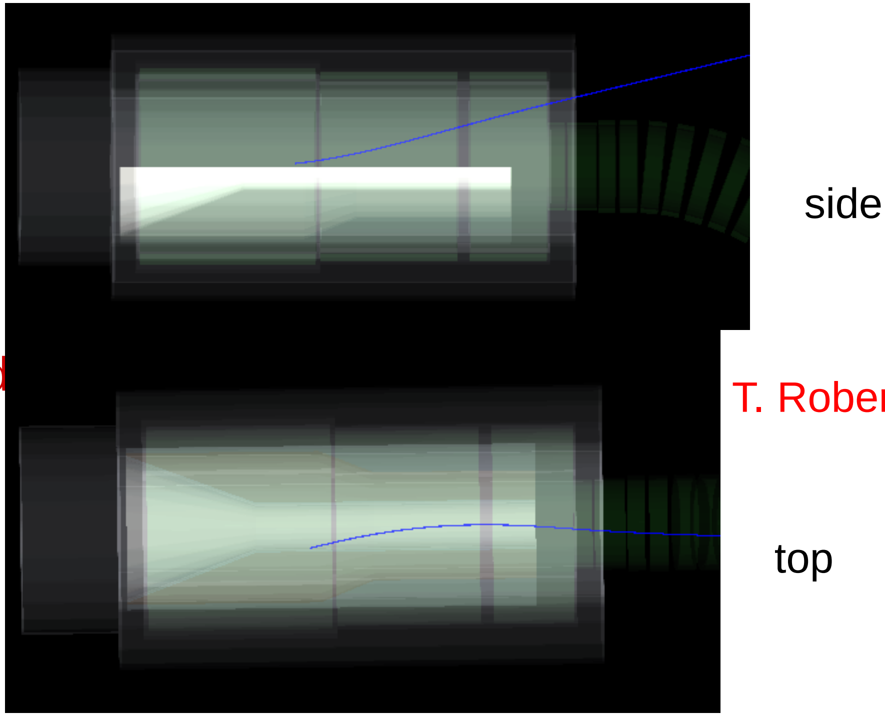
PIP-II

PIP-II beam delivery onto target

- **800 MeV beam line from linac**
  - initial beam width shorter
    - 200ns FW → 20ns
  - 0.3 mm-mrad emittance
    - smaller than 8 GeV beam



- **But 800 MeV p will not follow 8 GeV path**
  - would hit HRS shielding after target
    - modify magnet/shielding ?
  - more power deposited in target, shielding
    - new target and shielding needed
  - Will we need new Production solenoid?



T. Roberts

PIP-II

mu2e→mu2e II changes

- new injection beam line
  - from linac
- Production target
  - 8kW→100kW; 8GeV→0.8
- Production solenoid
  - internal shielding
- Transport solenoid
  - collimation …
  - →
- Detector solenoid
  - stopping target
- LOI → Proposal R&D

- mu/p estimates
  - (Matsuzawa 2015)

Kinetic Energy	Stops / POT
8 GeV	1.690×10^{-3}
800 MeV	1.035×10^{-4}

- 3 yr-100 kW =>
  - 1.5×10^{19} **μ after TS**
  - **5×10^{18} stopped μ**

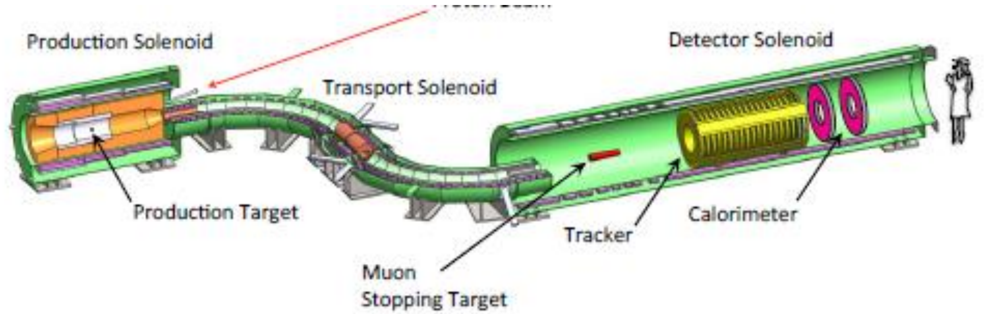
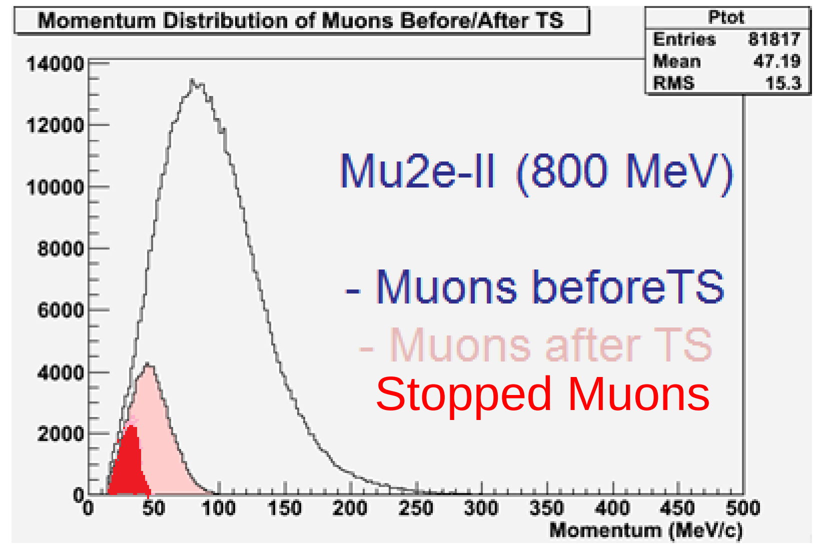


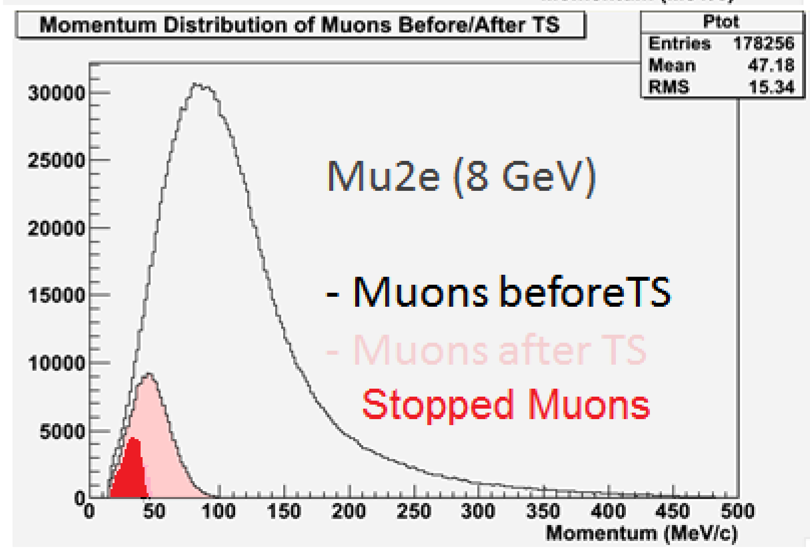
Figure 1.1. The Mu2e Detector. The cosmic ray veto that surrounds the Detector Solenoid is not shown.

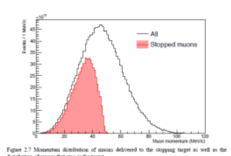
Stopped Muons

Improving stopped μ acceptance ?

- Only small fraction of μ's are stopped
  - P_μ < ~40 MeV/c (or E_μ < 7 MeV)
- Can we reduce muon momenta to < ~40MeV/c?
- If only there were a way to sort the muons by momentum and give higher momentum muons more energy loss …



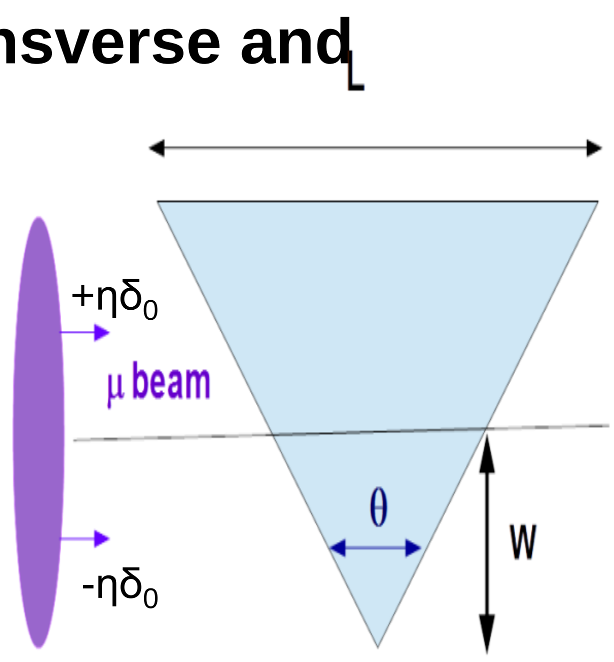




(Matsuzawa, Roberts, Prebys 2015)

Wedge absorbers and emittance exchange

- **Wedge absorbers can exchange transverse and longitudinal emittances**
  - With dispersion η , can reduce energy spread
    - **decreases ε_L, increases ε_x**
  - **with zero or opposite sign** η, can increase δE
    - increases ε_L, decreases ε_x



- **Thick wedge exchange formalism:**

Dispersion + wedge is product of two matrices

(in x – dp/p)

$$\mathbf{M}_{\delta} = \begin{bmatrix} 1 & 0 \\ -\delta' & 1 \end{bmatrix} \qquad \mathbf{M}_{\eta} = \begin{bmatrix} 1 & \eta_0 \\ 0 & 1 \end{bmatrix}$$

- wedge is $\delta' = dp/ds \; 2 \tan[\theta/2]/p$

- transport through wedge is transport of [x, δ] phase space ellipse,

$$g_0 x^2 + b_0 \delta^2 = \sigma_0 \delta_0 \quad \rightarrow \quad g_1 x^2 + 2a_1 x\delta + b_1 \delta^2 = \sigma_0 \delta_0$$

- **can get large emittance exchange**

Results of wedge transform

mucool note-003(1996)/FN-1046(2017)

$$\beta_1 = m_{11}{}^2\beta_0 + 2m_{11}m_{12}\alpha_0 + m_{12}{}^2\gamma_0$$
$$\alpha_1 = -m_{11}m_{21}\beta_0 + (m_{11}m_{22} + m_{12}m_{21})\alpha_0 - m_{12}m_{22}\gamma_0$$
$$\gamma_1 = m_{21}{}^2\beta_0 + 2m_{21}m_{22}\alpha_0 + m_{22}{}^2\gamma_0$$

- new δp/p width **($\varepsilon_{L,1} = \varepsilon_{L,0}\,(\delta_1/\delta_0)$)**

$$\delta_1 = \sqrt{g_1\sigma_0\delta_0} = \delta_0\left[(1-\eta_0\delta')^2 + \frac{\delta'^2\sigma_0{}^2}{\delta_0{}^2}\right]^{1/2}$$

- new transverse emittance **($\varepsilon_{x,1} = \varepsilon_{x,0}\,(\delta_0/\delta_1)$)**

$$\varepsilon_{x,1} = \sqrt{g_1\sigma_0\delta_0} = \varepsilon_{x,0}\left[(1-\eta_0\delta')^2 + \frac{\delta'^2\sigma_0{}^2}{\delta_0{}^2}\right]^{-1/2}$$

new η, β_x,

$$\eta_1 = -\frac{a_1}{g_1} = \frac{\eta_0(1-\eta_0\delta') - \delta'\frac{\sigma_0^2}{\delta_0{}^2}}{(1-\eta_0\delta')^2 + \delta'^2\frac{\sigma_0^2}{\delta_0{}^2}}$$

$$\beta_1 = \beta_0\left[(1-\eta_0\delta')^2 + \frac{\delta'^2\sigma_0{}^2}{\delta_0{}^2}\right]^{-1/2}$$

By choosing η_0, δ' (and δ_0, σ_0)

Can decrease ε_x and increase ε_L (or vice versa)

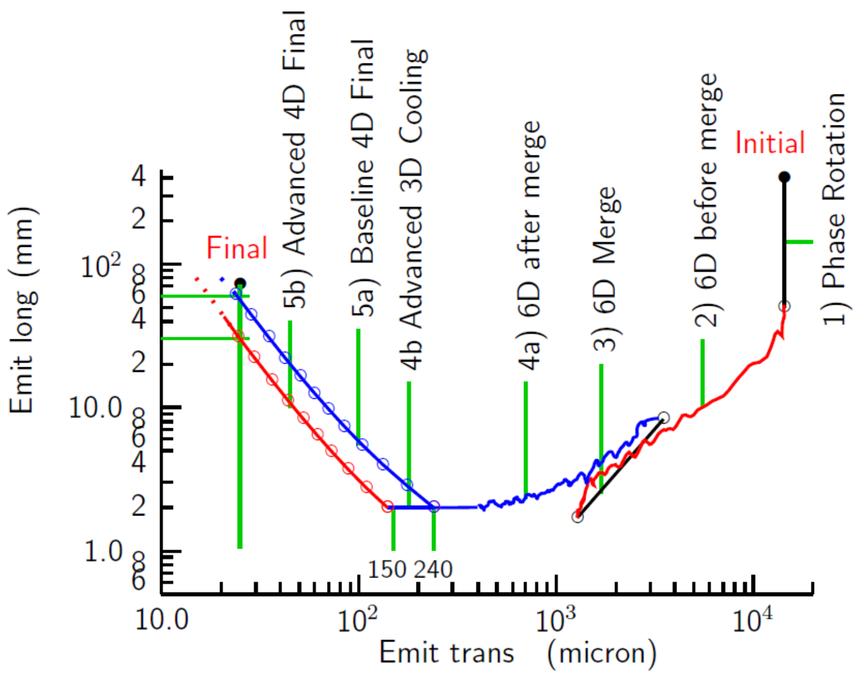
PIP-II

D. Neuffer

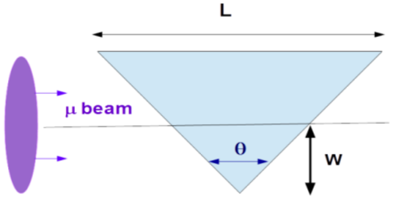
Wedges for Final Cooling

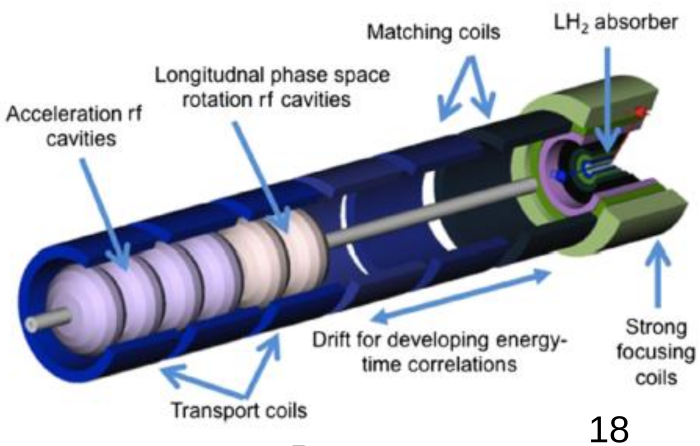
- TeV Collider wants small ε_t
  - $\varepsilon \rightarrow$ 25 μm
- "Mice" 6-D Cooling gets
  - $\varepsilon_t \rightarrow$ 200 μm
- Much further is difficult
  - …..

Mostly emittance exchange



- Can do most of this with wedge absorbers …

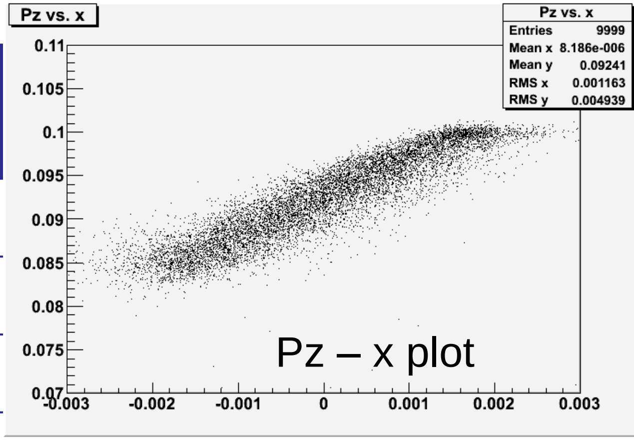




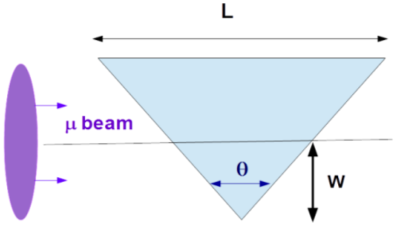
Numerical example

- **Wedge parameters**
  - Diamond, w=1.75mm, θ = 100°(4.17mm thick at center)

z(cm)	P_z	ε_x(μ)	ε_y	ε_L(mm	σ_E MeV	6-D ε increase
0	100	97	95.5	1.27	0.46	1.0
0.4	96.4	33.4	96.3	4.55	1.64	1.24
0.8	92.4	22.7	96.5	8.94	3.22	1.65



  - reduces ε_x by factor of 4.3, ε_L increases by factor of 7.0
    - first half of wedge more efficient than second half …
- **Second wedge**
  - if matched to same optics (P_z → 100 MeV/c, σ_E → 0.46 MeV)
    - ε_x : 23 →27μ; ε_y :97 → 23 μ



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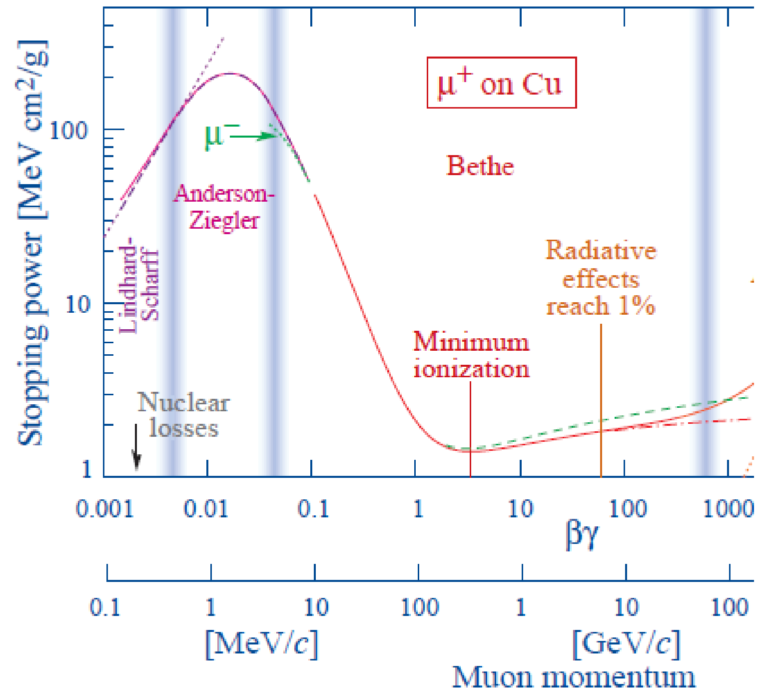
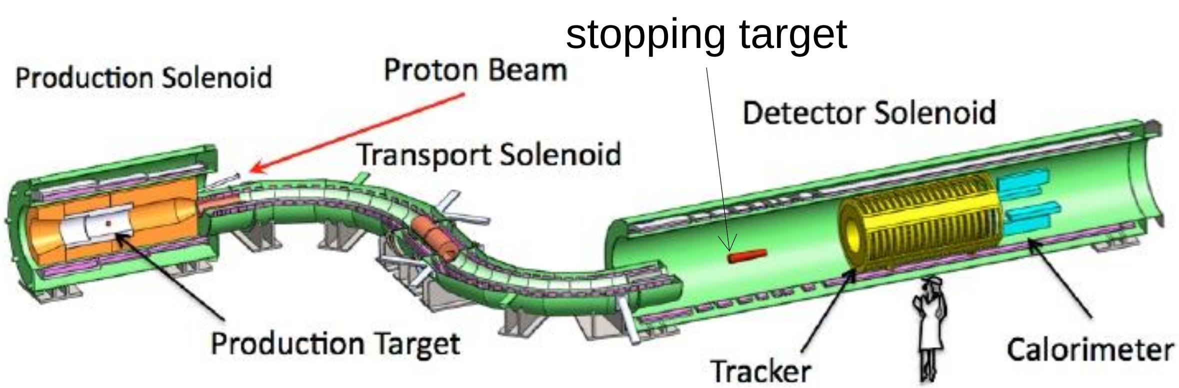
Application to mu2e

- mu2e accepts only low-E μ
  - < 40 MeV/c (7.3 MeV)
  - nearly stopped μ
    - non linear dE/dx
- Transport accepts up to >100 MeV/c (40 MeV)
- Goal is not smaller momentum spread but more nearly stopped μ's





Beam momentum sorter

- Transport solenoid
  - bent solenoid introduces vertical dispersion

position proportional to P_μ

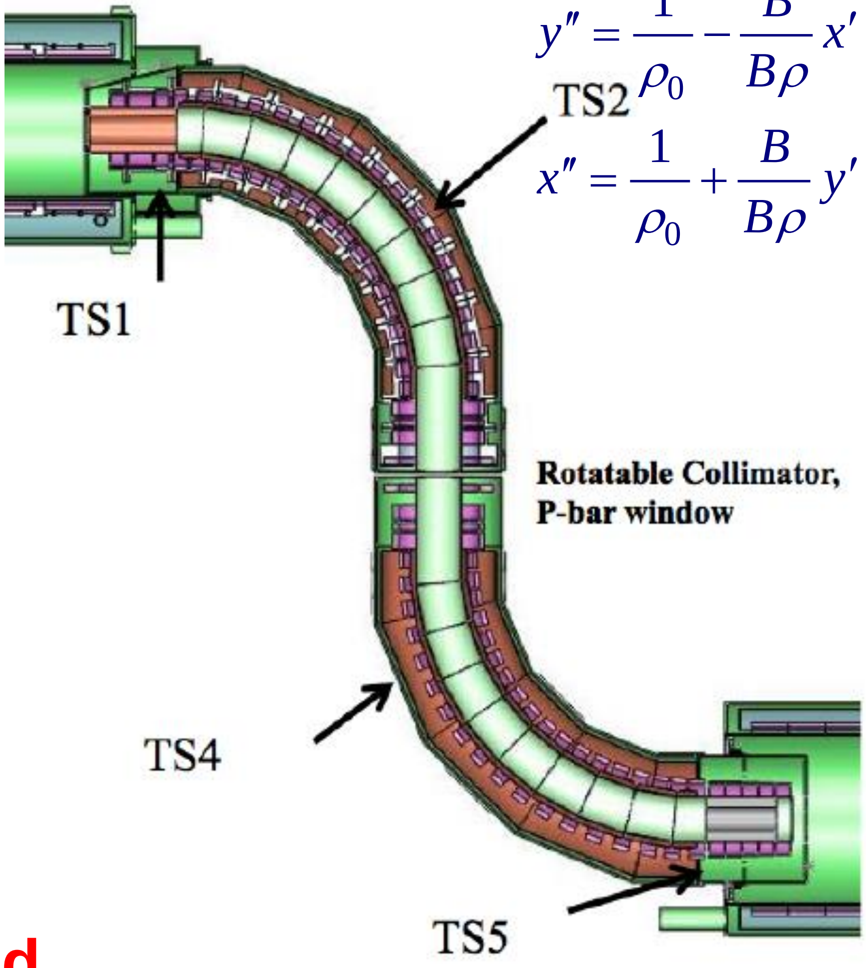
$$y(s) = P_\mu \frac{s}{0.3 B_0 \rho_0} + \ldots$$

At P-bar window y = ~0.21 P/100

- (s=4.5m, ρ_0=3m, B_0=2.5T)
  - dispersion is used to collimate muon beam
    - Could also be used to shape momentum spread

$$y'' = \frac{1}{\rho_0} - \frac{B}{B\rho} x'$$

$$x'' = \frac{1}{\rho_0} + \frac{B}{B\rho} y'$$

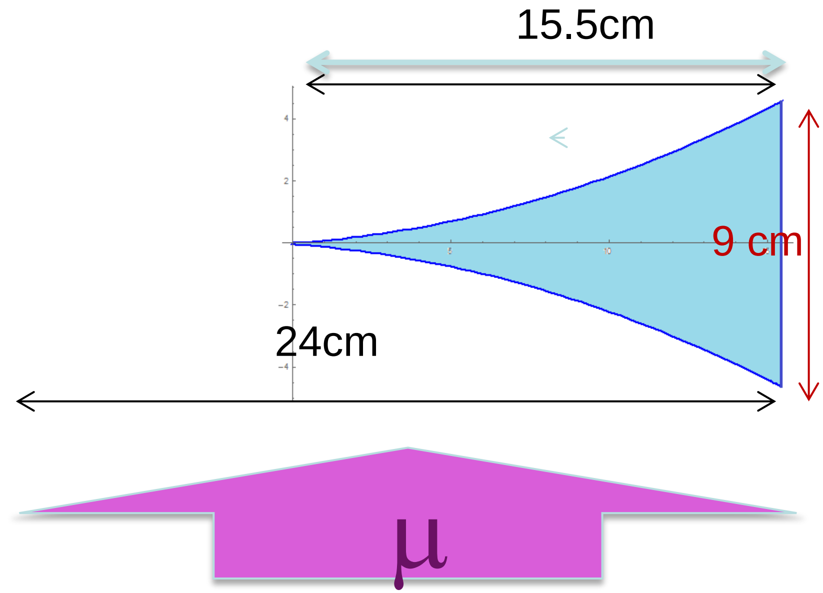


Wedge at TS center

- wedge is designed to place
  - $40 < P_\mu < 100$ MeV/c
  - at ~40 MeV/c
- Example: Polyethylene wedge
  - (~C_2H_4)
  - thickness ~0 at y< ~8.5cm
  - increases ~parabolically to aperture
    - w(y) = ~ 0.133(y-8.5) + 0.0296(y-8.5)^2 cm
  - at y=20cm , thickness ~6cm
- want low-Z material
  - Poly, C, Be, LiH,

$y(p_2)$ = ~0.213 (p_2 (MeV/c)/100) m

$$range(40, p_2) = \int_{40}^{p_2} \frac{1}{\frac{dp}{ds}(p)} dp$$

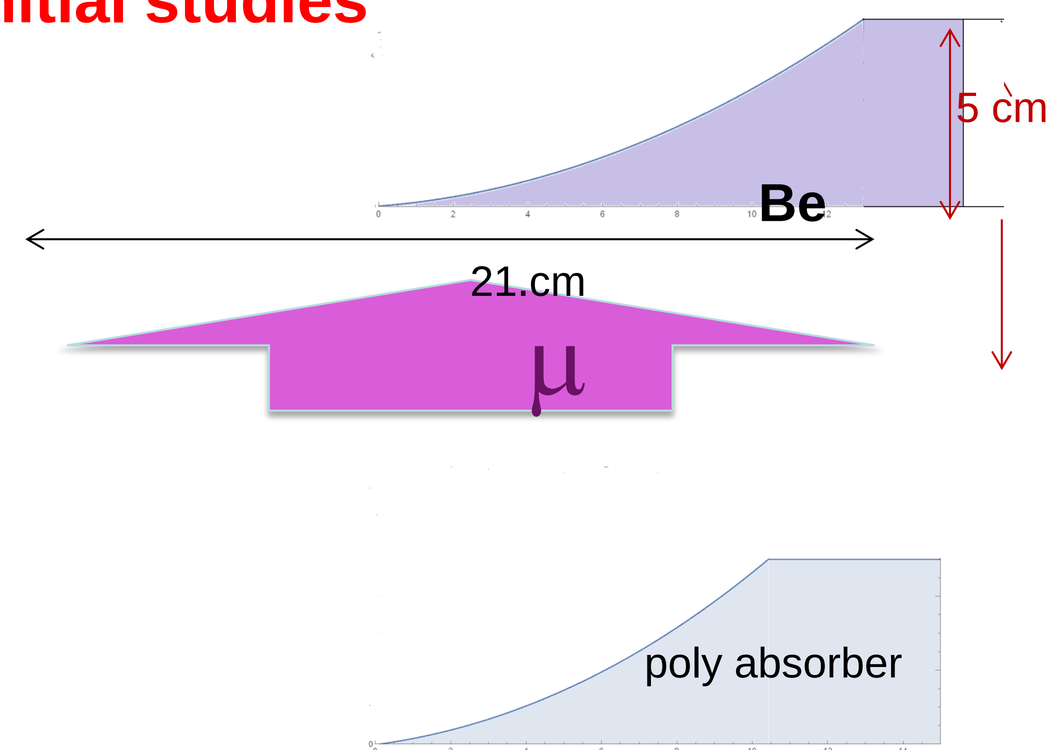


PIP-II

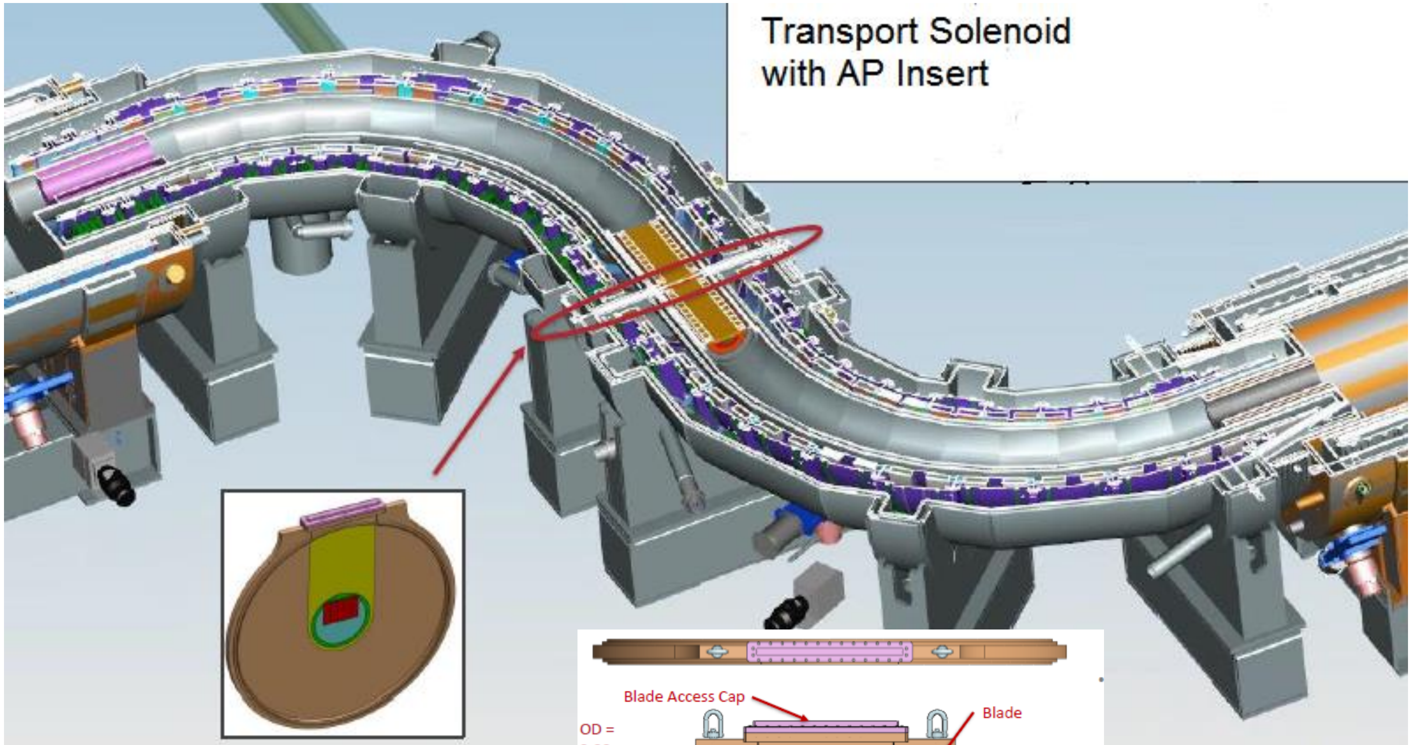
Possible wedge parameters

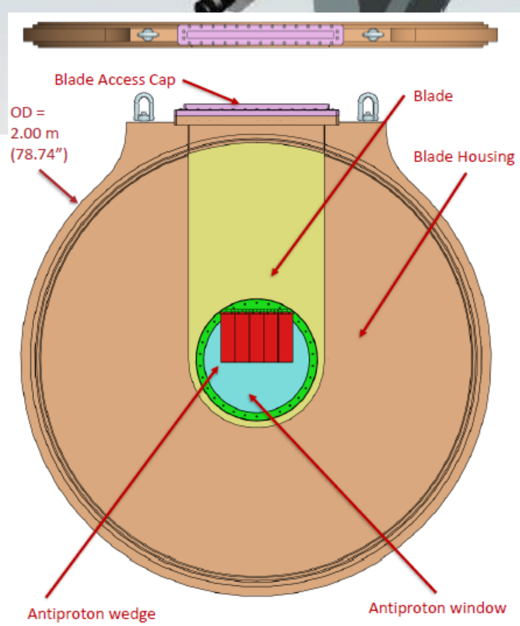
- Choose Be wedge:
  - (one sided rather than symmetric)
  - need only ~5cm thick

    matched to P_{μ}< 100 MeV/c
  - poly wedge only reaches to 88 MeV/c
    - could try poly in initial studies



location at ~AP insert ??





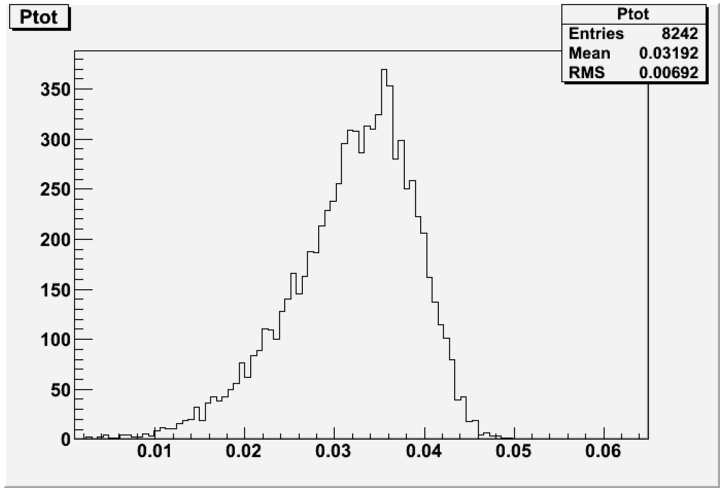
AP insert is 10cm Thick

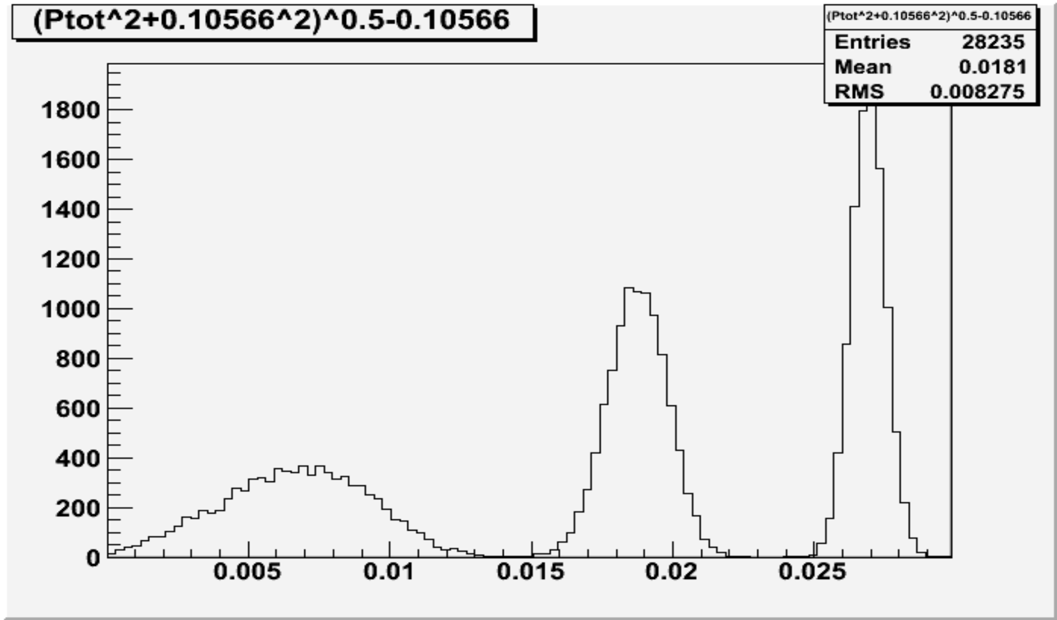
would like 5cm within that for Be/poly blade

PIP-II

Effects of New Wedge

- Momentum distribution of "nearly stopped" μ's exiting the wedge is the same as that stopped in Al target
  - ~25% lost in wedge

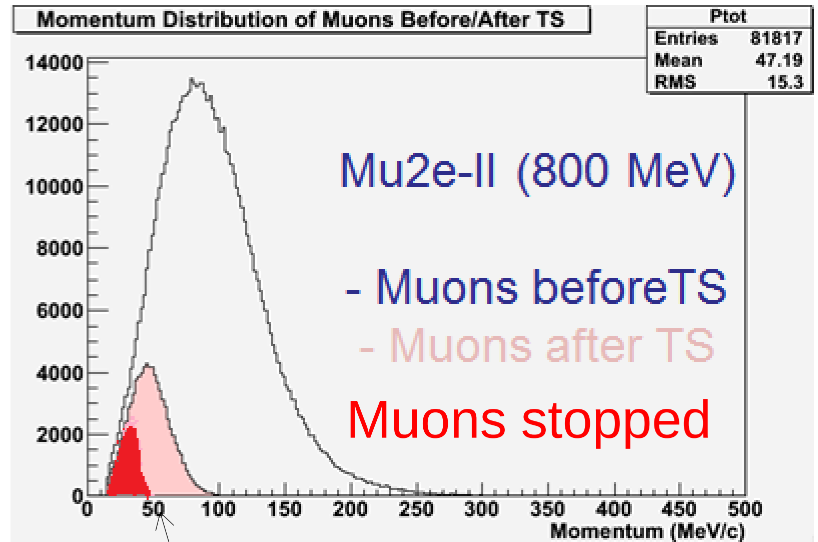




PIP-II

Potential Gain

- baseline mu2e stops only ~3% of muons produced
  - ~ all with P_{μ} < ~40MeV/c
- Tailored wedge could place ~50% of produced μ at Pμ < ~ 40 MeV/c
  - How many of these can stop for mu2e (II)?
  - reoptimize downstream fields and collimation and stopping target …



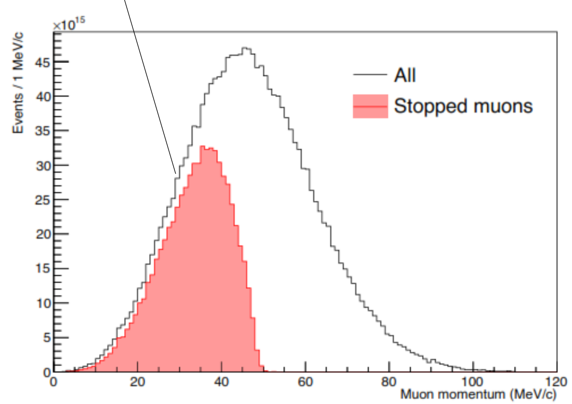
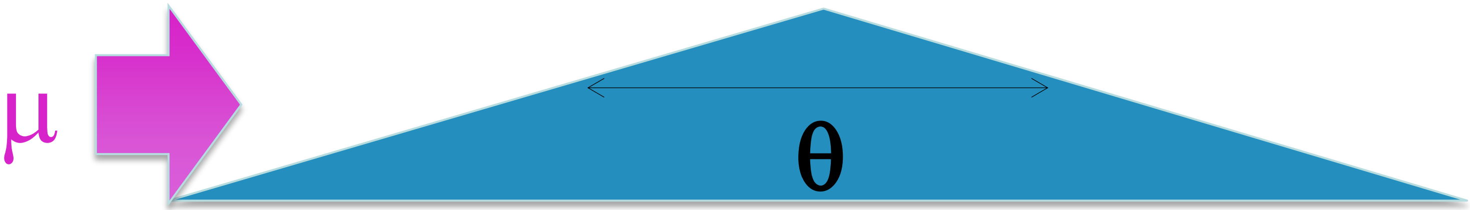


Figure 2.7. Momentum distribution of muons delivered to the stopping target as well as the distribution of muons that stop in the target.

g-2 experiment at Fermilab

- Ring accepts 3.1 GeV/c μ
  - $\delta p/p$ = 0.1 %
- Beam source and transport to Ring accepts ±1%
  - Increase beam within 0.1 %
  - with wedge absorber at dispersion (0.5—1.0 m)
  - Polyethelene absorber
    - `dp/ds = 2.56 MeV/c/cm

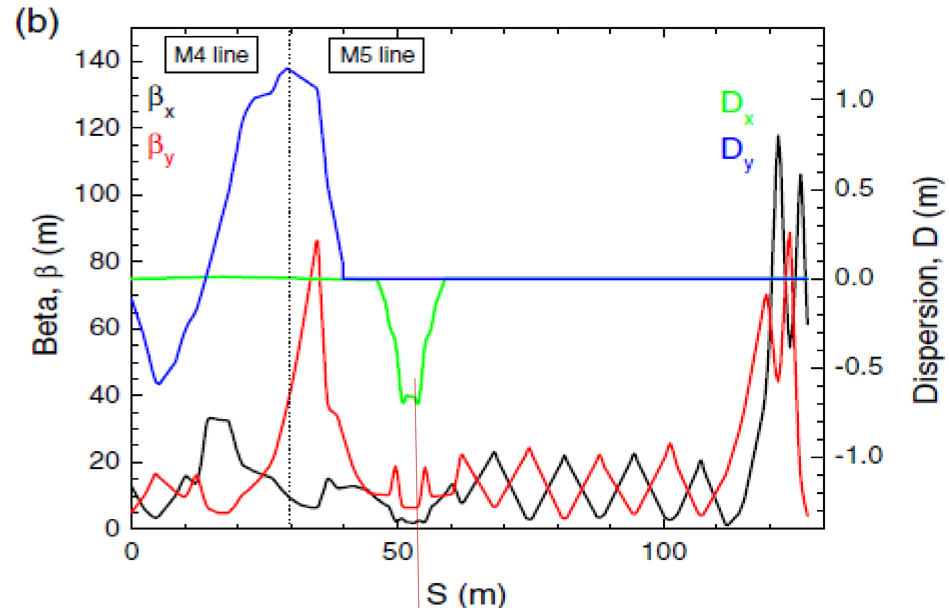


Wedge for g-2 (w. Stratakis et al.)

- Place wedge at large dispersion, small β

$$\left.\frac{\delta_1}{\delta_0}\right|_{optimum} = \left(\frac{\sigma_x^{\,2}}{(\eta\delta_0)^2+\sigma_x^{\,2}}\right) = \left(\frac{\varepsilon_x\beta_x}{(\eta\delta_0)^2+\varepsilon_x\beta_x}\right)$$

$$\frac{\theta_{opt}}{2} = \arctan\left[\frac{P_0}{2\eta\,\frac{dp}{ds}}\,\frac{(\eta\delta_0)^2}{\left((\eta\delta_0)^2+\varepsilon\beta_x\right)}\right]$$



g-2 performance

- For η=0.6m, δ_0=0.01, P_0=3.1GeV/c, $\varepsilon_{x,g}$= 16 mm-mrad, β_x= 2m :
  - $\theta_{opt}/2 = 79^\circ$
  - $\delta_1/\delta_0 = 0.69 \rightarrow$ 46% more μ's

$$F_{gain} = \left(\frac{(\eta\delta_0)^2 + \sigma_x{}^2}{\sigma_x{}^2} \right) = \left(\frac{(\eta\delta_0)^2 + \varepsilon_x\beta_x}{\varepsilon_x\beta_x} \right)$$

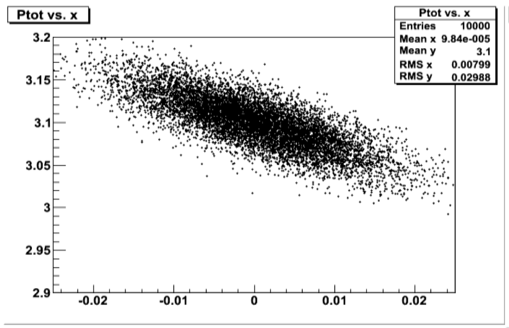
- estimate does not include multiple scattering, energy straggling
  - $\delta\varepsilon_{geom} \cong$ 4—6mm-mrad at β_t=10m

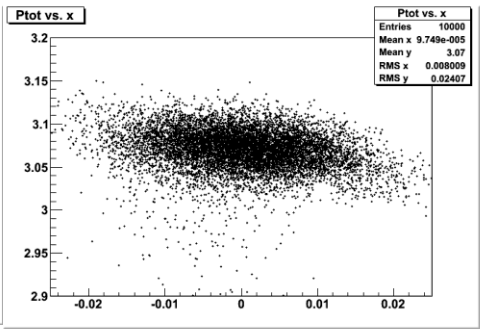
$$\delta\varepsilon_{geom} = \beta_t \frac{E_s{}^2}{2\beta^4\gamma^2(mc^2)^2} \frac{\Delta w}{L_R}$$

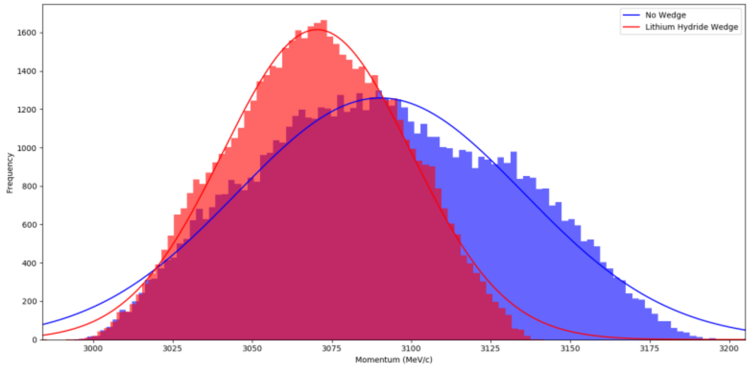
- exchange is limited by $\eta\delta/\sigma_x$
  - At η =1.2m, δ_1/δ_0= 0.43
    - 2.3 x more μ's

Simulation/optimization results

➢ **Simulation results w Bradley, Stratakis**





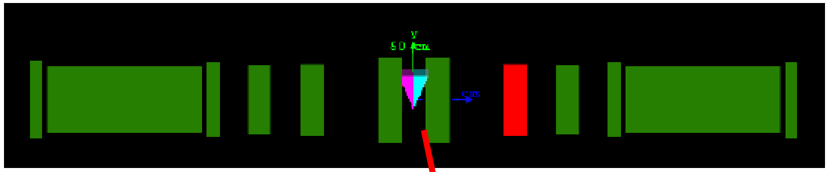


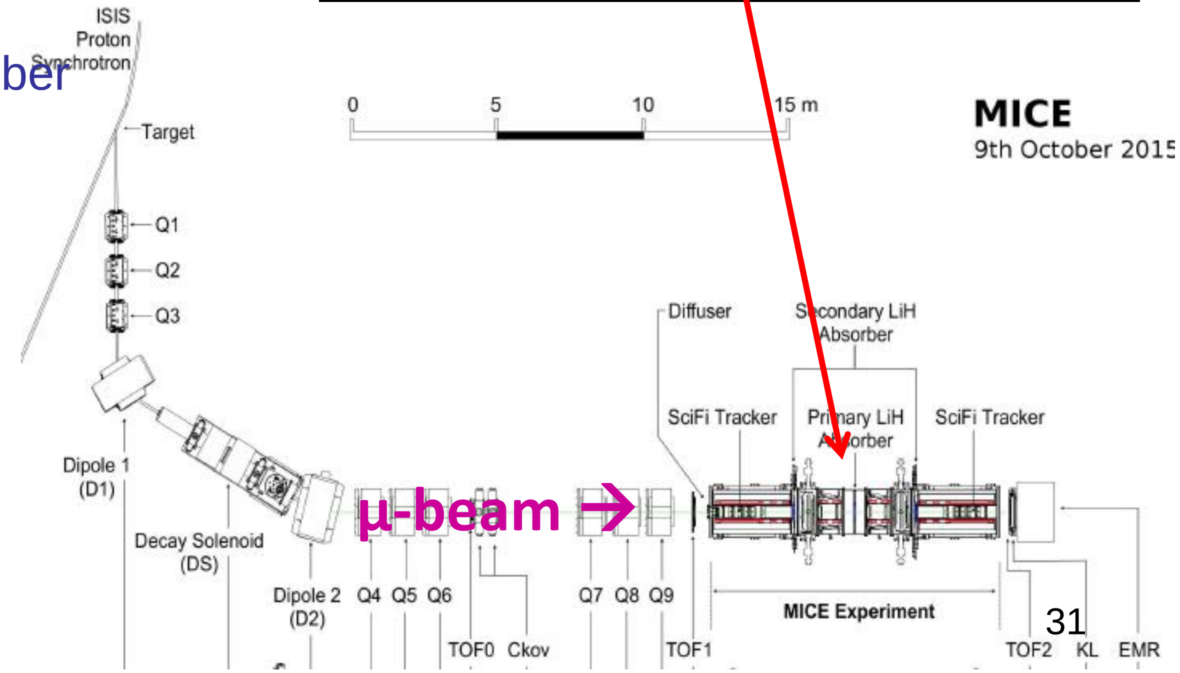
Material	Position 2 Offset /mm	Position 2 Half Angle	Position 3 Offset /mm	Position 3 Half Angle	Number in $P_0 \pm 0.1\%$
None	N/A	N/A	N/A	N/A	3889
Lithium Hydride (Single 21" Wedge)	N/A	N/A	10.0	81.5	5060 (+30%)
Vanadium (Single 21" Wedge)	N/A	N/A	1.0	57.0	4082 (+5%)
Polyethylene (Single 21" Wedge)	N/A	N/A	9.0	78.5	4911 (+26%)
Polyethylene (2 x 6" thick Wedges)	6.0	77.0	8.0	73.0	4967 (+28%)

Note:

MICE experiment (RAL)

- **Wedge absorber designed and built to be put into MICE experiment**
  - D. Summers, P. Snopok, T. Mohayai, ..
- **Polyethelyne 45º, radius ~20cm**
  - to be inserted between focus coils of MICE expt.
  - Scheduled to run December 17-20





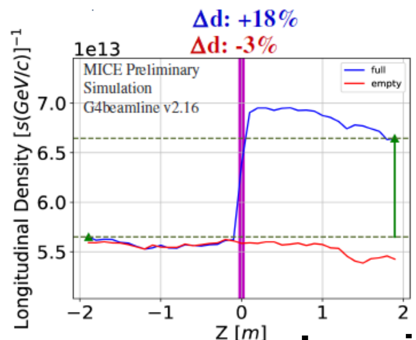
Simulations (T. Mohayai)

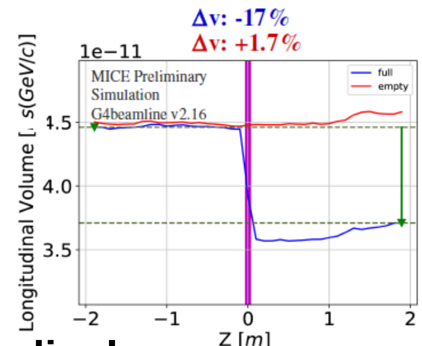
Longitudinal cooling exchange settings:

Parameters	Values
Starting sample size	20k
Cooling channel setting	**2017-02-7**
Cooling channel field [T]	**3 US, 2 DS**
Wedge angle [°]	45
Wedge on-axis length [mm]	52
$\varepsilon_\perp$ [mm]	6
$\beta_\perp$ [mm]	400
$\alpha_\perp$ [mm]	0
Dy [mm]	300
p_{ref} [MeV/c]	140

Wedge Simulation – Longitudinal Phase-space

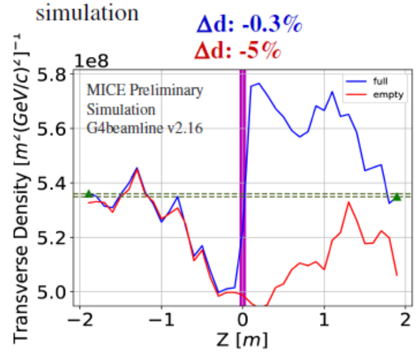
- $\varepsilon_\perp$: 6 mm; p_{ref}: 140 MeV/c; **M2D: 195A; transmission: 96%**
- Longitudinal coordinates: Δt, ΔE
- Measured the KDE-based density and volume of the 24th percentile contour (~one sigma of the distribution in 4D)
- Density ↑, volume ↓: unambiguous sign of longitudinal cooling and exchange in the case of full channel simulation

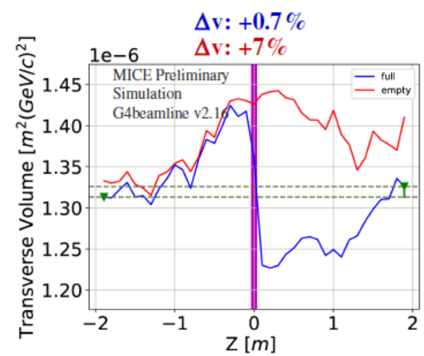




Longitudinal

- Density ↓, volume ↑: slight heating in transverse direction in case of full channel simulation





Transverse

PIP-II

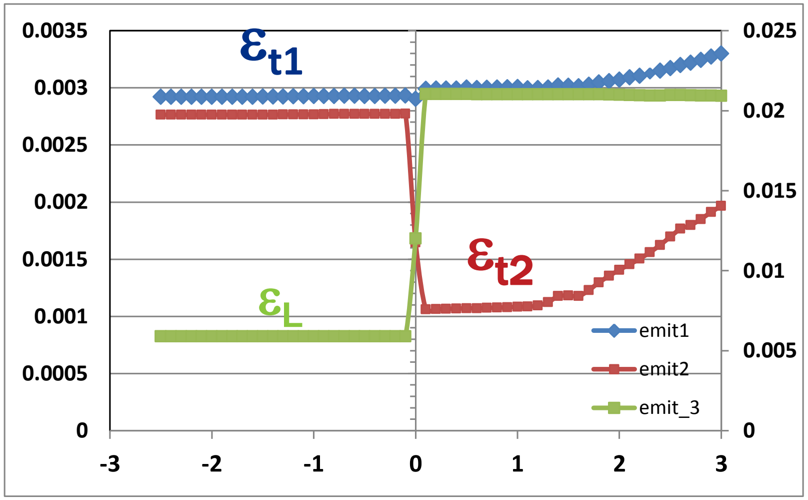
Transverse cooling…

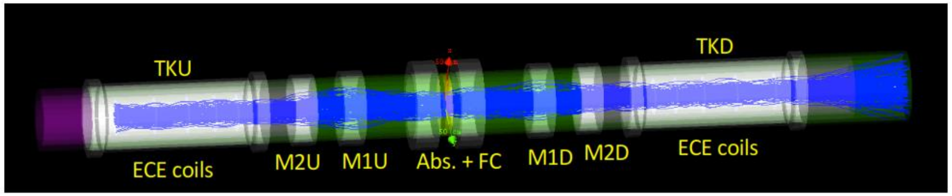
- Beam at 200 MeV/c
  - ε_t =0.003m, $\delta p/p$=1%
  - η_{in} = 0; $\beta_t \rightarrow$ 0.75m

$$\frac{\varepsilon_{t,1}}{\varepsilon_{t,0}} = \sqrt{\frac{\delta_0^2}{\delta_0^2 + \delta'^2 \sigma_0^2}}$$

- Wedge reduces transverse mode by factor of ~3;
- increases longitudinal by factor of ~3

- effect should be measurable in MICE





Questions?

Thanks for your Attention !