Delivery of Low Momentum Muons for Muon EDM Studies at Fermilab

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Muon Precision Physics Workshop

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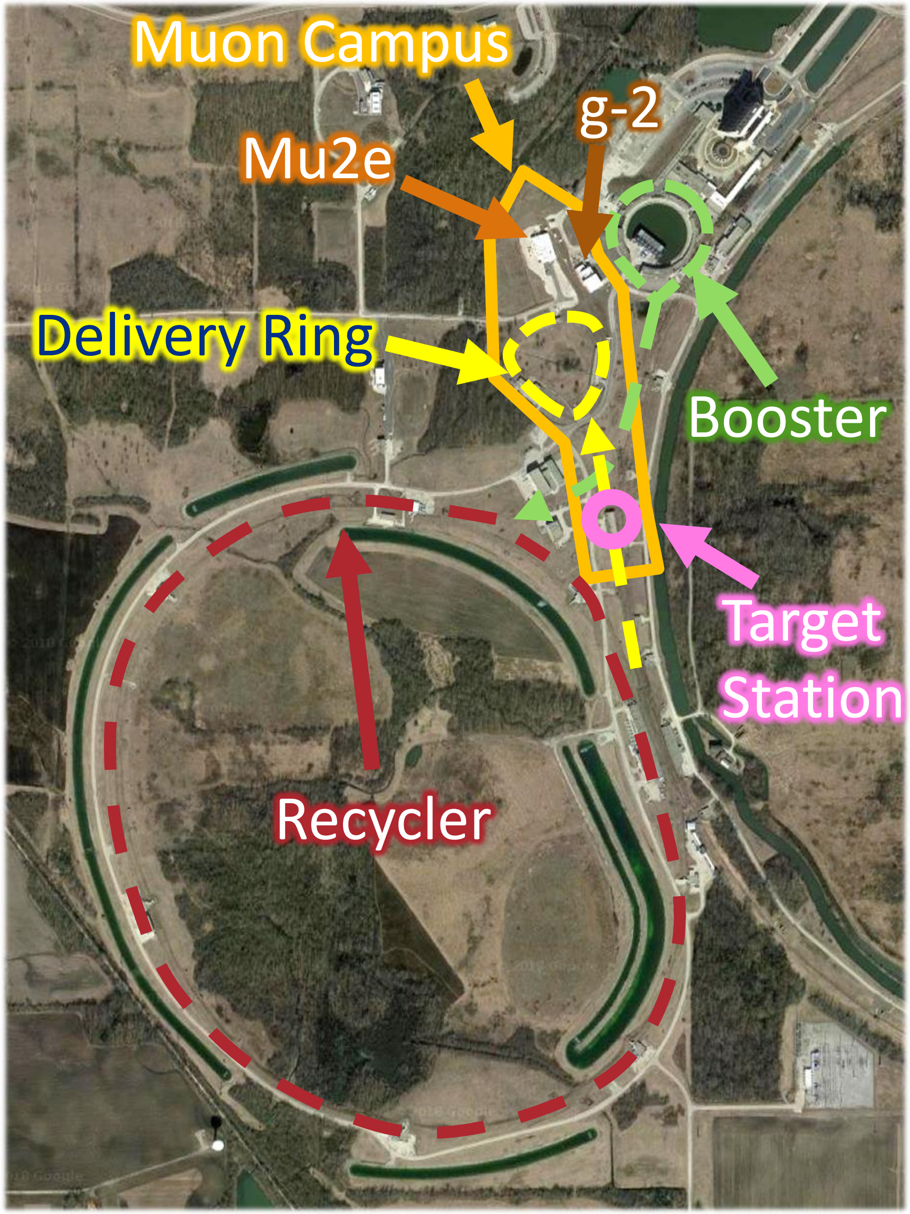
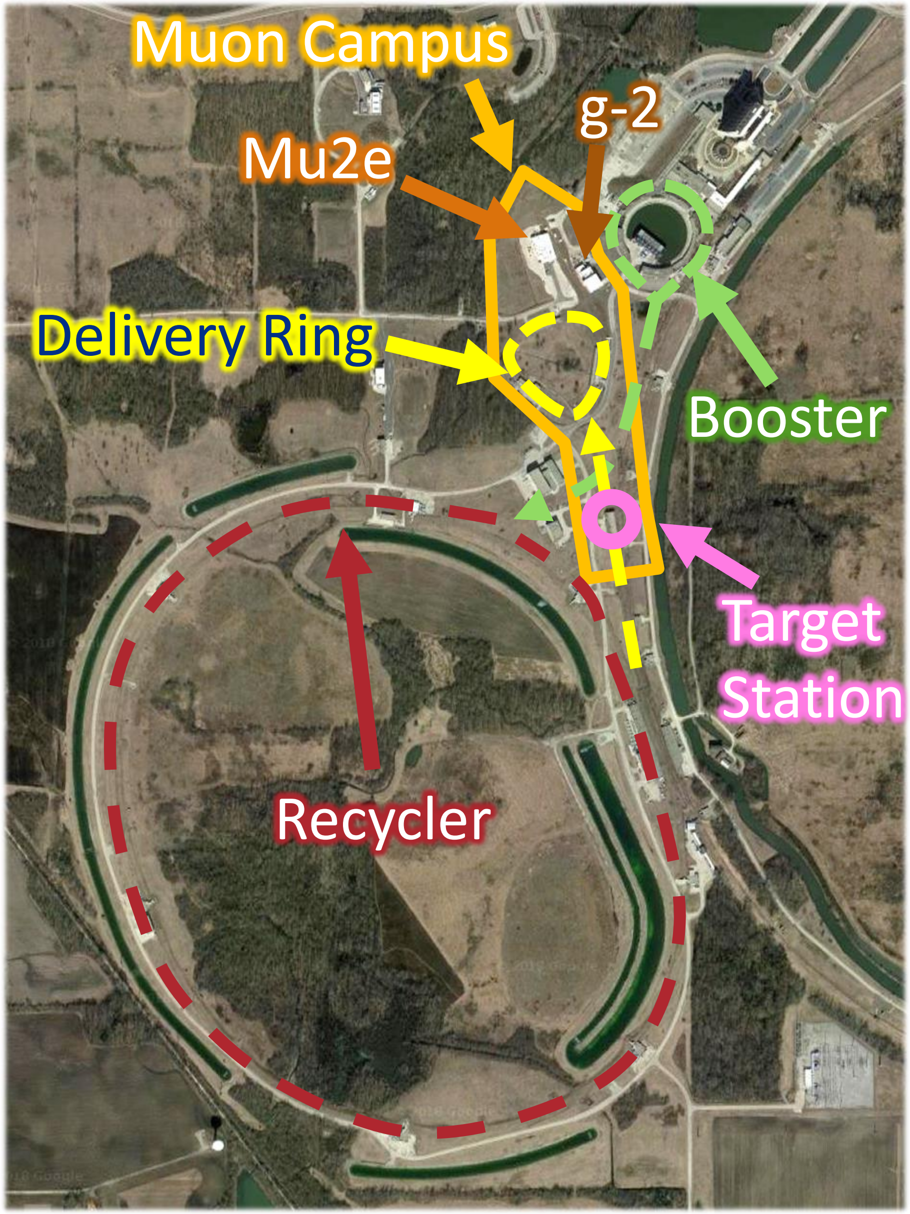
Fermilab's Muon Campus

- Originally the Antiproton Source during the Tevatron-era, the Muon Campus makes use of much of the existing infrastructure.
- **Booster** provides 8 GeV protons.
- Above the 120 GeV Main Injector is the **Recycler**, forming 8 GeV proton bunches.
- **Target Station** was for $\bar{p}$ production, now for μ production for **g-2**.
  - Mu2e-mode bypasses target.

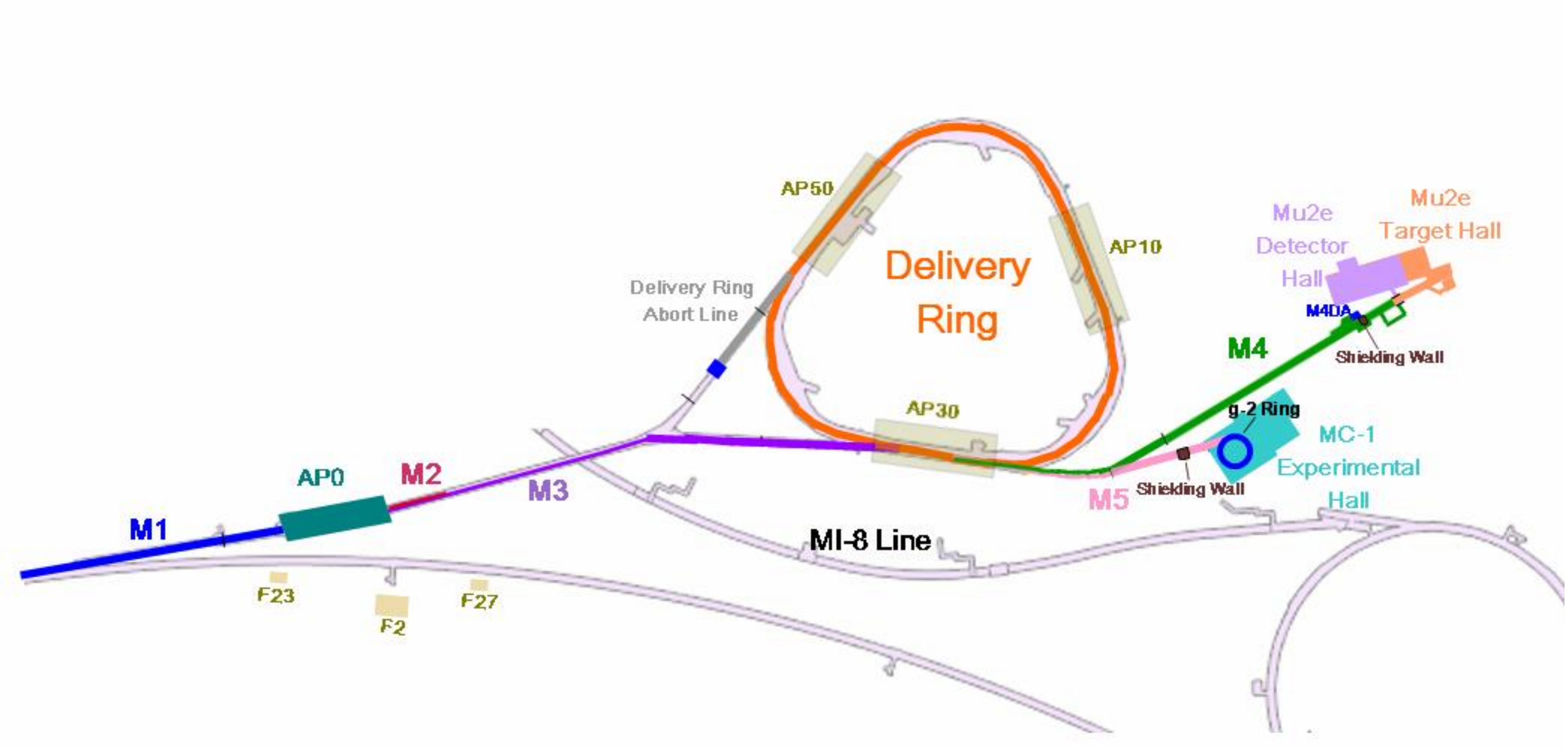


Fermilab's Muon Campus

- The $\bar{p}$ accumulator was removed and used for M4/M5.
- The $\bar{p}$ debuncher was modified into the Delivery Ring.
  - Debuncher injection line repurposed as DR abort.
  - 505 m in length, 1.695 μs revolution period.
- Two new transport lines were constructed, the M4 and M5, for beam delivery to Mu2e and g-2.



Muon Campus Beam Lines



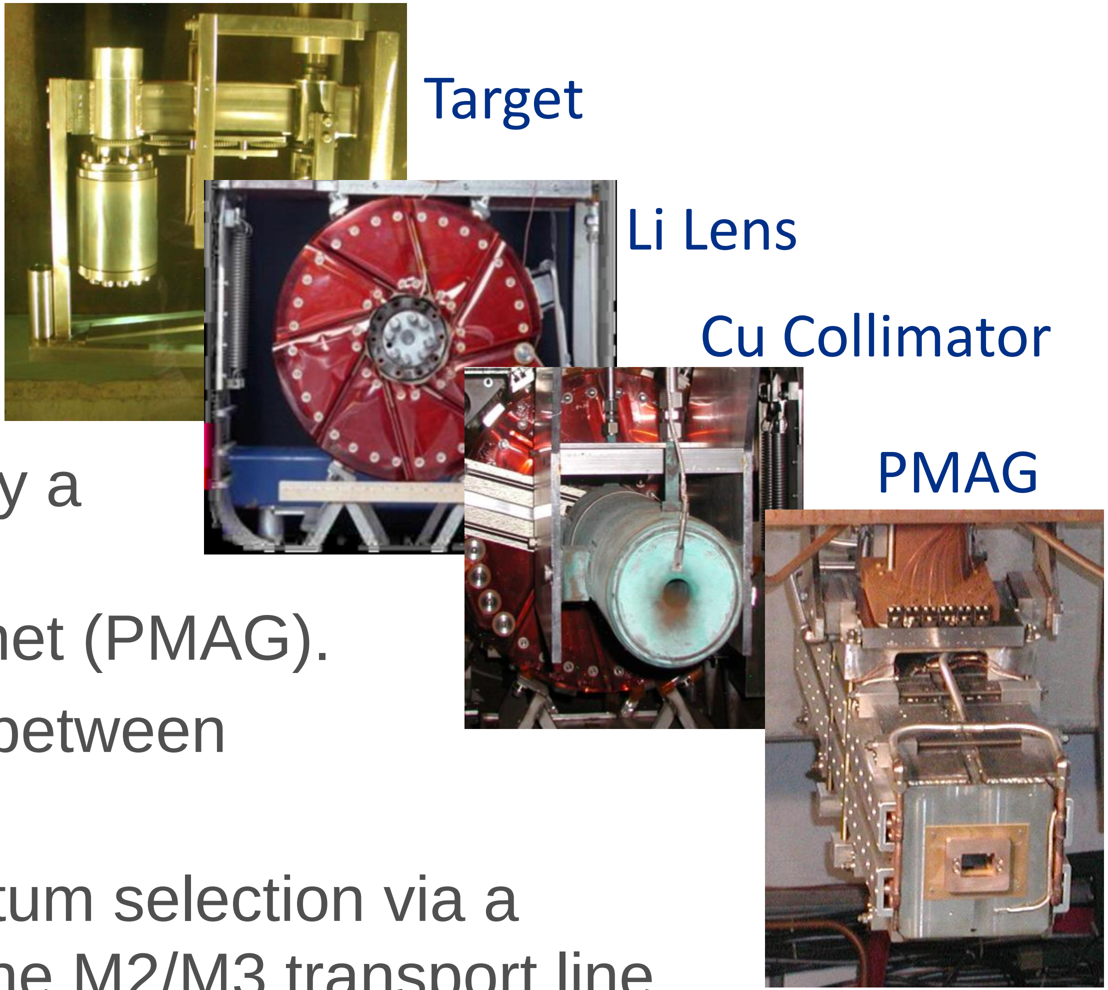
Muon Campus: g-2 Mode

- 8 GeV proton bunches (10^{12} protons/bunch) are sent to the target station from the Recycler (15.4kW).
- From the target station, only 3.1 GeV/c particles are propagated.
  - Mostly p, some π^+, and few μ^+.
  - μ^+-beam comes from π^+ decay.
- Proton contamination is removed by making 4 turns in the DR and sent to abort.
- μ^+ are extracted to g-2.

Muon Campus: Low-Momentum Mode

- 8 GeV proton bunches (10^{12} protons/bunch) are sent to the target station from the Recycler (15.4kW).
- From the target station, only 300 MeV/c particles are propagated.
  - Mostly p, some π^+, and few μ^+.
  - μ^+-beam comes from π^+ decay.
- Proton contamination is removed by making 4 turns in the DR and sent to abort.
- μ^+ are extracted to g-2.

AP0 Target Station



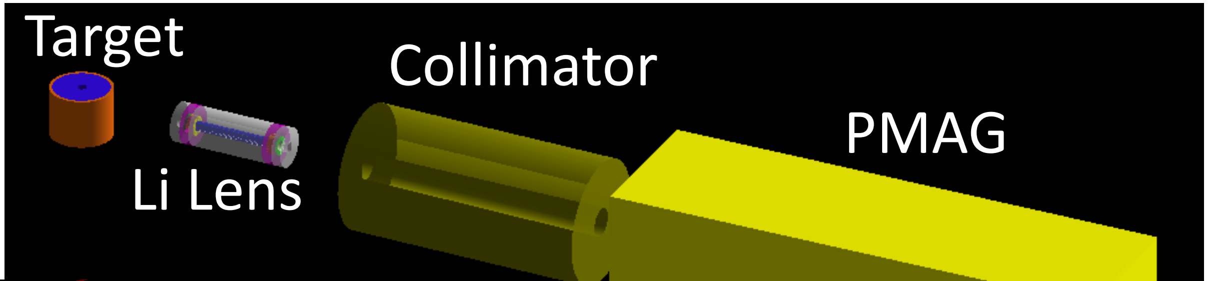
- 8 GeV primary proton beam is incident on an Inconel-600 target.
- Secondary pions are produced and focused by a lithium lens towards a horizontal bending magnet (PMAG).
- A copper collimator sits between the lens and PMAG.
- PMAG provides momentum selection via a 3° horizontal bend into the M2/M3 transport line.
  - Low momentum acceptance for transport, $\Delta p/p \approx \pm 4\%$

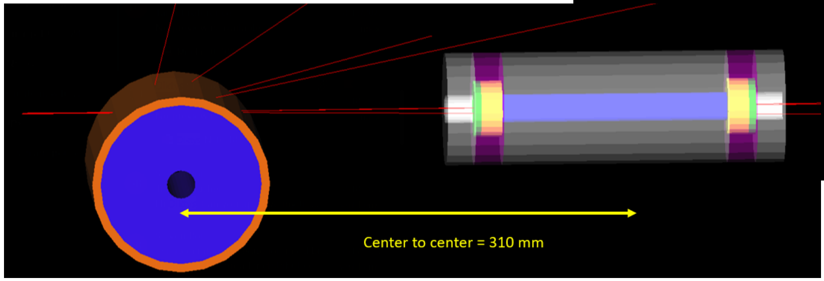
AP0 Target Station: G4Beamline

- The model begins with an 8 GeV primary proton beam incident on the production target.
- A simple model of the lithium lens is included, with the field region only extending the length of the lithium core (16cm).
  - Includes supporting titanium and beryllium windows.
  - Field goes as $B_\phi = \frac{\mu_{Li} I}{2\pi R^2} r$ for $r < R$ and $B_\phi = \frac{\mu_0 I}{2\pi r}$ for $r > R$
  - Lithium is $R = 1cm, \ell = 16cm$, spaced $310mm$ to lens (C/C)
  - Acceptance :

$$\theta = \operatorname{atan}\left(\frac{1cm}{31cm}\right)$$

$\approx$32.2mrad

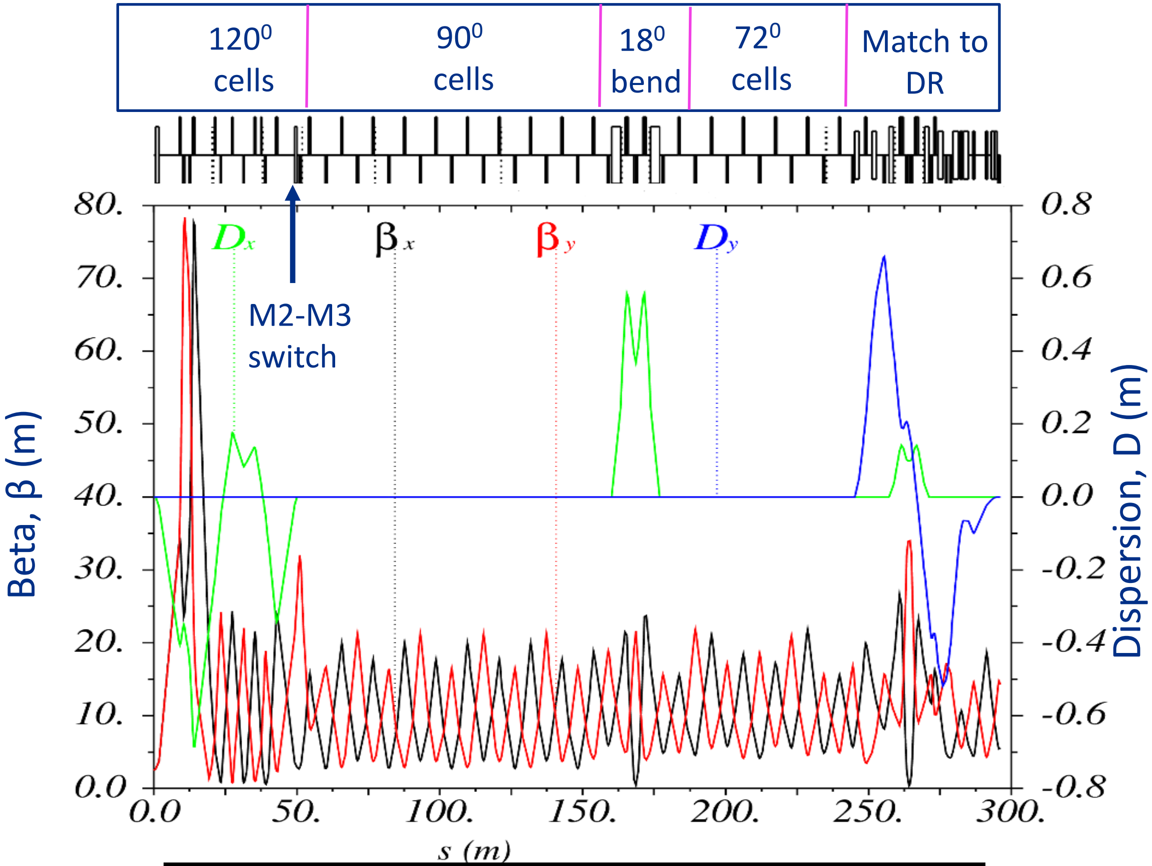


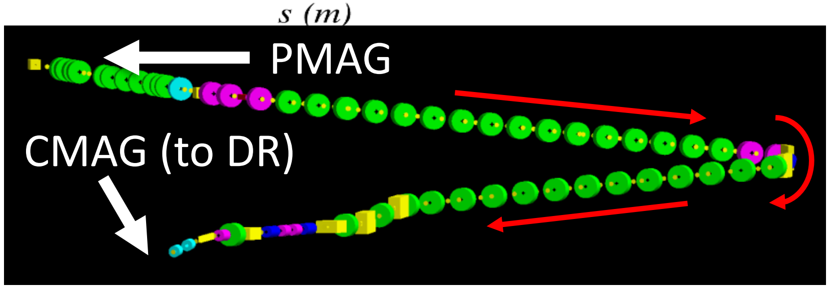


Fermilab

M2/M3 Transport Line: G4Beamline

- PMAG bends 3° into the M2/M3 transport line.
  - M2 line goes through AP0 target station. (g-2 mode)
  - M3 bypasses AP0 target station. (Mu2e mode)
  - The M2 line merges with the M3 line 47m downstream of PMAG.
- M2/M3 line transports $\Delta p/p \approx \pm 4\%$
  - Ring acceptance is much lower at $\Delta p/p \approx \pm 0.25\%$.



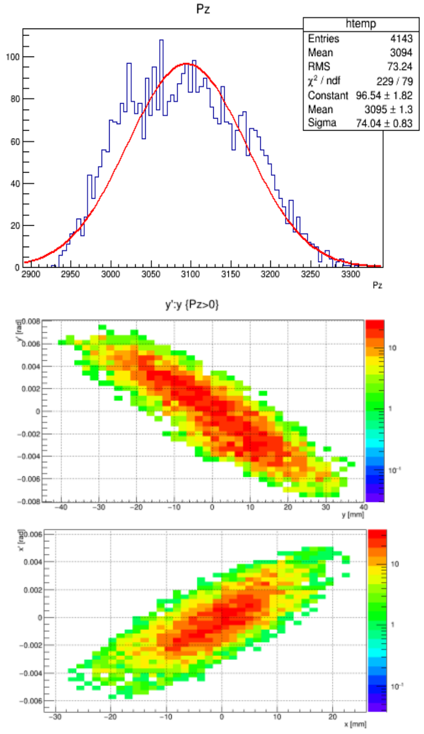


G4Beamline Key Points

- Simulated 100M protons on target (POT).
- Using physics list FTFP_BERT at the recommendation of Geant expert Vladimir Ivantchenko.
- Only considering π^+ after the production target.
  - Decays set OFF.
  - No protons or other particles propagated.
  - Momentum cuts only applied in analysis.
- World material is vacuum.
  - Effects of air in target region were not statistically significant.
- Stopped simulation at upstream of the injection-CMAG, before entering the Delivery Ring (DR).
  - From here on referred to as ‘CMAG’.

Magic Momentum Baseline

- Using 3.1GeV/c π^+ yield for comparisons:
  - Beamline optimized for 3.1GeV/c transport.
  - M2/M3 line transports $\Delta p/p \approx \pm 4\%$, so momentum cut of 3100MeV/c ± 124MeV/c is made.



Upstream CMAG

- π^+ at locations (within respective apertures):

Location		π^+ $3.1\ GeV/c \pm 124\ MeV/c$		
Lithium Lens (R=1cm)	Upstream	180229 (6806)	Per POT Yield	1.8×10^{-3} (6.8×10^{-5})
	Downstream	98845 (3674)		9.8×10^{-4} (3.6×10^{-5})
PMAG (5 x 3.5cm)	Upstream	(10089)		(1.0×10^{-4})
	Downstream	(8545)		(8.5×10^{-5})
Upstream CMAG		3808		3.8×10^{-5}

300MeV/c Baseline

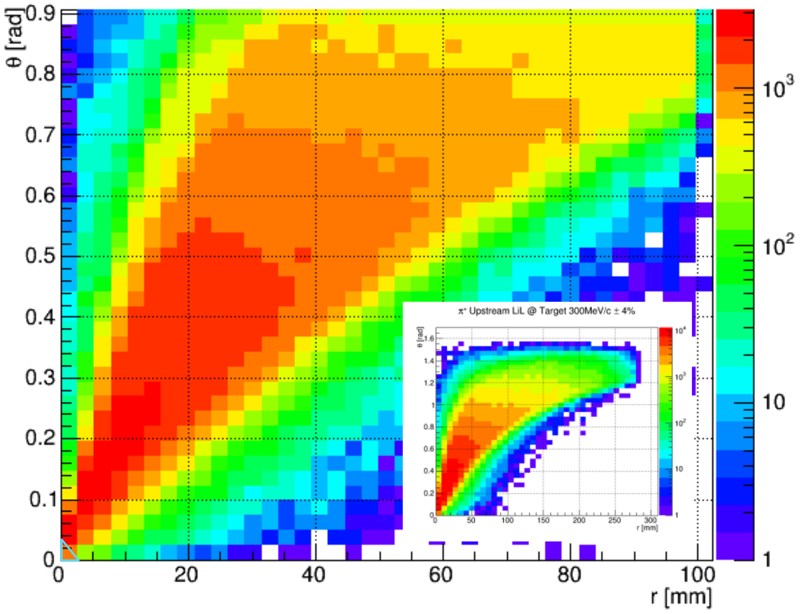
- Determine π^+ yield for 300MeV/c scenario:
  - A total of 100M POT were simulated.
    - Same data set as 3.1GeV/c case, geometry unchanged.
  - Beamline optimized for 300MeV/c transport.
    - Scaling of lithium lens and magnet strengths ($^{300}/_{3094}$ = 0.09696).
  - Momentum cut of 300MeV/c $\pm$ 12MeV/c is made ($\Delta p/p \approx \pm 4\%$).
- π^+ at locations (within respective apertures):

Location		$\pi^+ \; 300\,MeV/c \pm 12\,MeV/c$			Ratio to $3.1\,GeV/c$
Lithium Lens (R=1cm)	Upstream	895175 (1647)	Per POT Yield	8.9×10^{-3} (1.6×10^{-5})	4.97 (0.24)
	Downstream	97989 (2304)		9.7×10^{-4} (2.3×10^{-5})	0.99 (0.63)
PMAG (5 x 3.5cm)	Upstream	(1316)		(1.3×10^{-5})	(0.15)
	Downstream	(425)		(4.2×10^{-6})	(0.05)
Upstream CMAG		21		2.1×10^{-7}	0.005

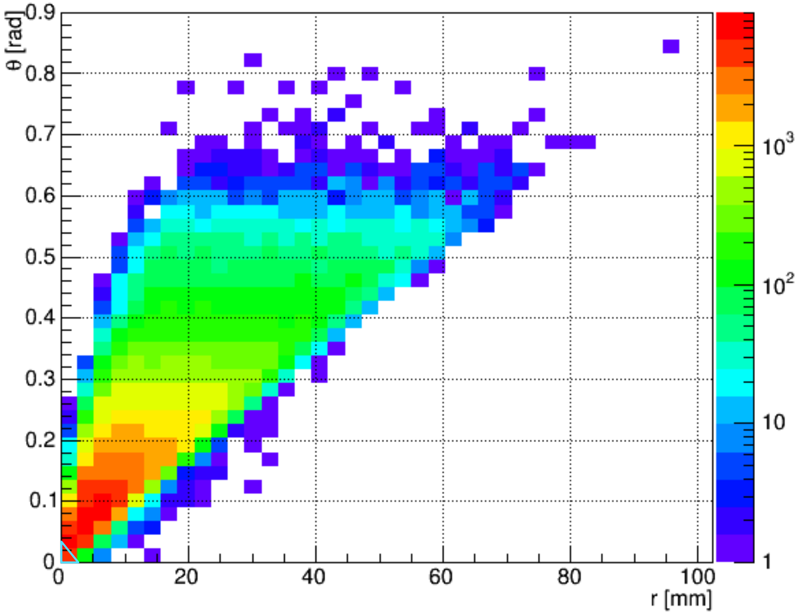
3.1GeV/c vs 300MeV/c Upstream LiL

- Upstream of the Lithium Lens (after the target), there is already a deficit of low-momentum π^+ produced at angles that can fall within the acceptance of the Lithium Lens.

$300MeV/c \pm 4\%$	$3.1GeV/c \pm 4\%$	Ratio
1647	6806	0.24



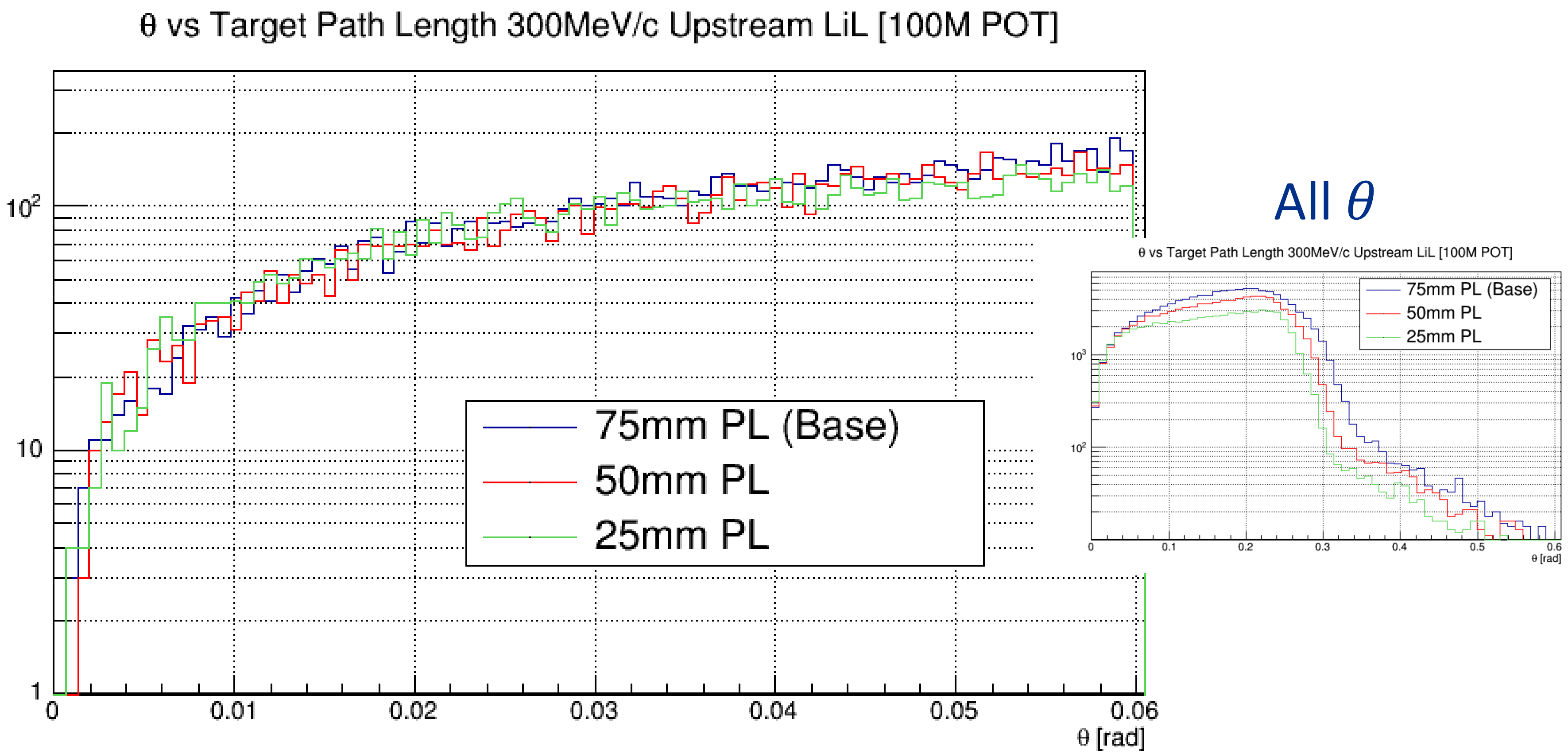
π⁺ Upstream LiL @ Target 300MeV/c ± 4%



π⁺ Upstream LiL @ Target 3.1GeV/c ± 4%

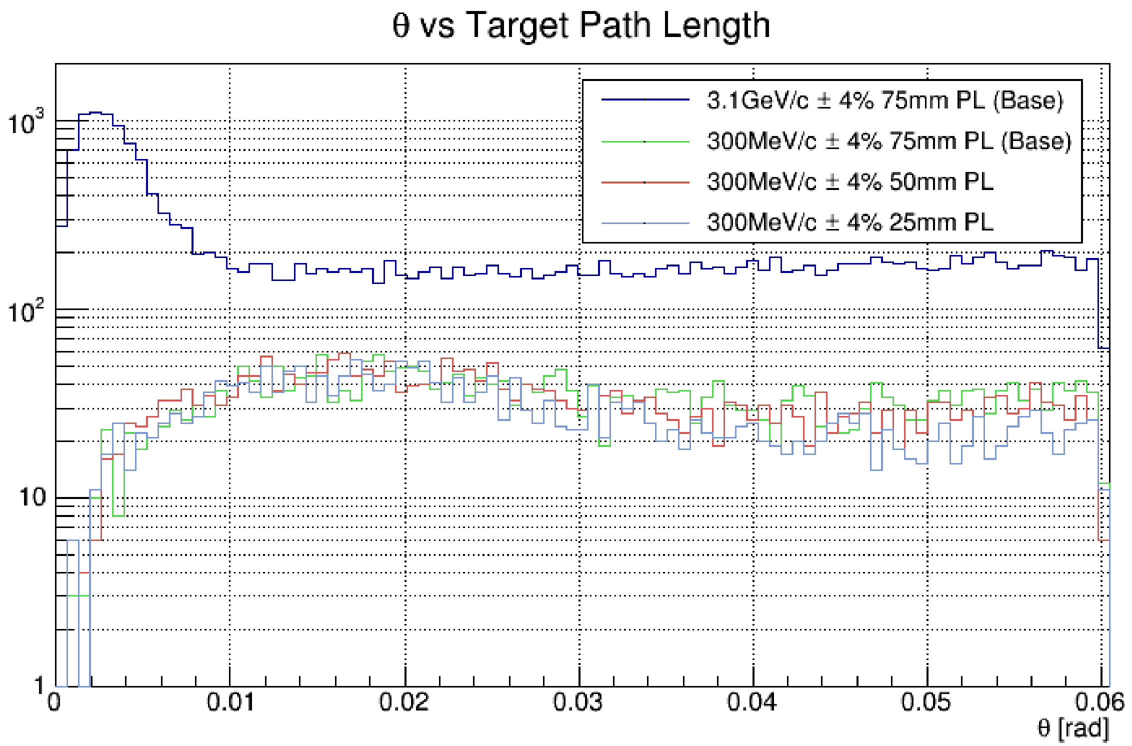
Target Path Length vs Angle @ 300MeV/c

- Scattering and yield are not significantly affected by changing the path length through the target.

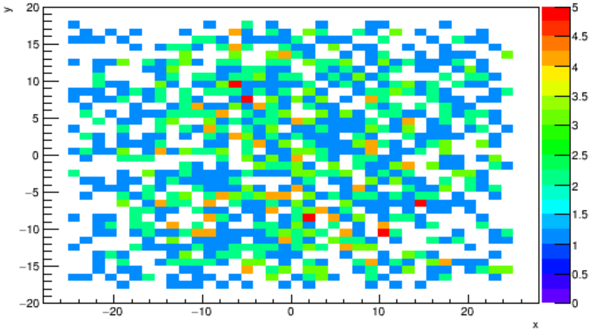


Target Path Length vs Angle Downstream LiL

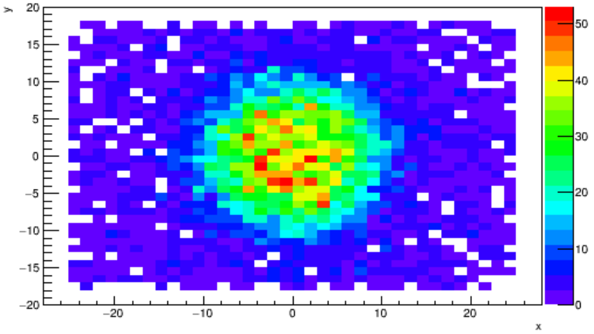
- Downstream of the LiL the yield remains unchanged.
- It appears there is difficulty adequately focusing the low-momentum π^+.
  - No improvement by varying the lens strength.


θ vs Target Path Length

XY @ PMAG 300MeV/c ± 4%

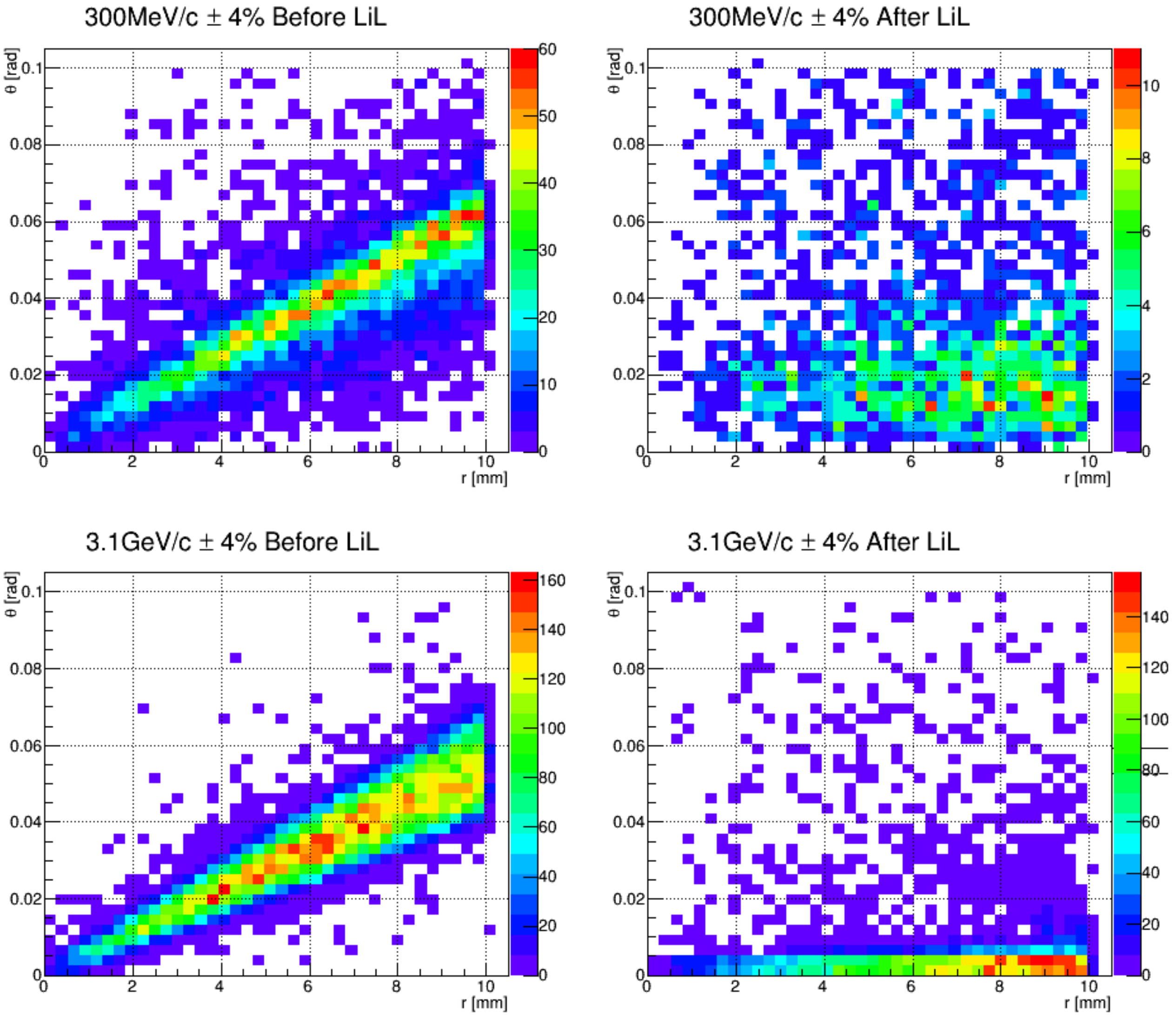


XY @ PMAG 3.1GeV/c ± 4%



Lithium Lens Effects

- Poor focusing in the 300MeV/c case.
  - Focusing strength was at the optimal value as confirmed by scanning the lens strength.
  - Material interactions with lens.


300MeV/c ± 4% Before LiL

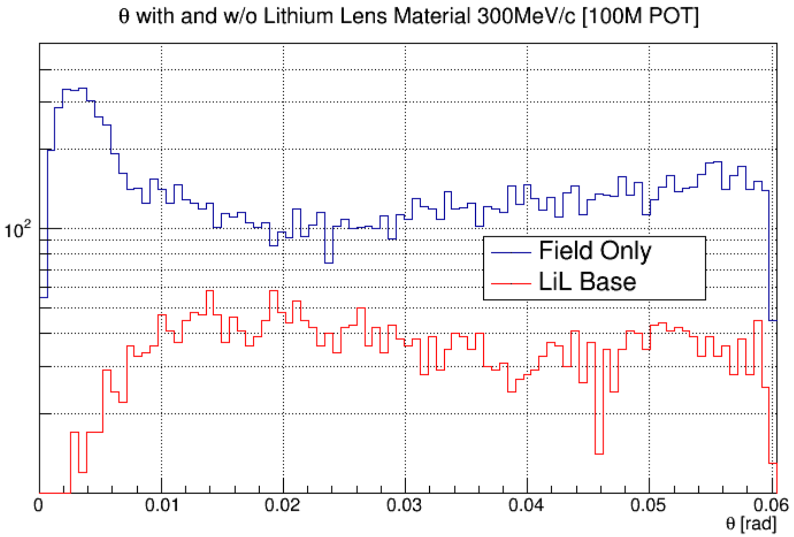
300MeV/c ± 4% After LiL

3.1GeV/c ± 4% Before LiL

3.1GeV/c ± 4% After LiL

Lithium Lens Effects

- Removal of the lens material but retaining the focusing field improves the focusing and the number of π^+ reaching CMAG.



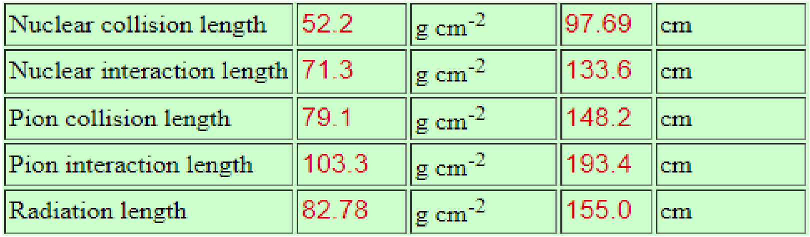
- Removal of the lens entirely (field and material) yields the same results as leaving the lens in.

π^+ @ Loc	W/Lens	Field Only	W/o Lens	3.1GeV vs w/o Lithium	
Downstream PMAG	425	3035	300	8545	9597
Upstream CMAG	21	335	22	3808	4931

Lithium Lens Materials

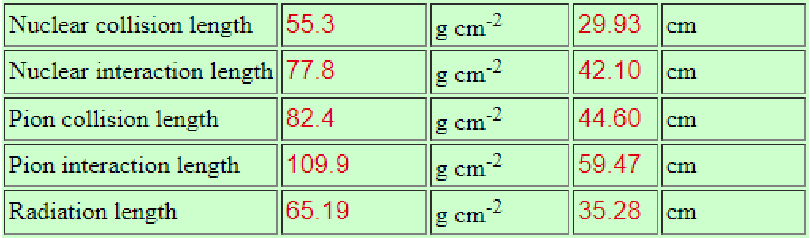
- The central region of the Lithium Lens is comprised of Beryllium windows and Lithium (obvio).
- Possible bug in materials for low-energy particles?
- From the PDG:

Lithium (16cm)



Nuclear collision length	52.2	$g\ cm^{-2}$	97.69	cm
Nuclear interaction length	71.3	$g\ cm^{-2}$	133.6	cm
Pion collision length	79.1	$g\ cm^{-2}$	148.2	cm
Pion interaction length	103.3	$g\ cm^{-2}$	193.4	cm
Radiation length	82.78	$g\ cm^{-2}$	155.0	cm

Beryllium (2cm)



Nuclear collision length	55.3	$g\ cm^{-2}$	29.93	cm
Nuclear interaction length	77.8	$g\ cm^{-2}$	42.10	cm
Pion collision length	82.4	$g\ cm^{-2}$	44.60	cm
Pion interaction length	109.9	$g\ cm^{-2}$	59.47	cm
Radiation length	65.19	$g\ cm^{-2}$	35.28	cm

Base

Location	N_{π^+}
Downstream LiL	97989
Downstream PMAG	425
Upstream CMAG	21

No Li

Location	N_{π^+}
Downstream LiL	98512
Downstream PMAG	1105
Upstream CMAG	39

No Be

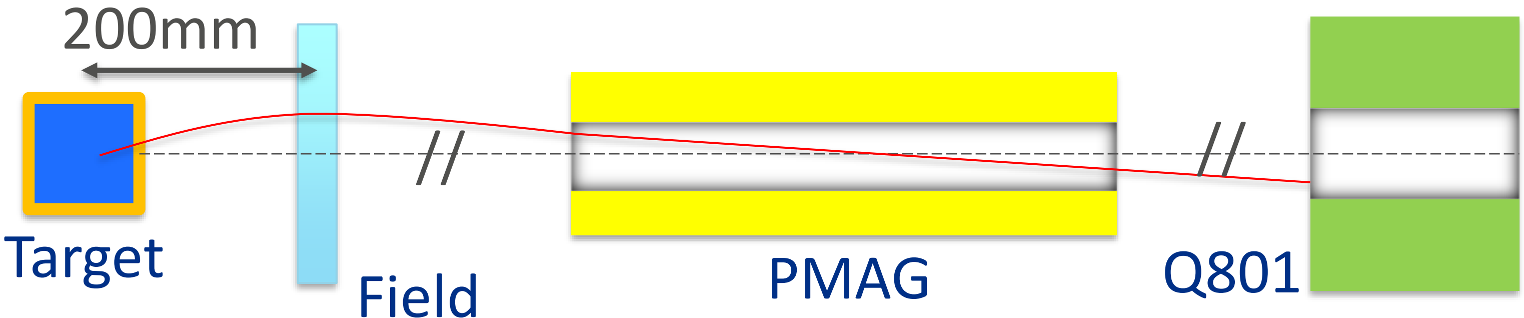
Location	N_{π^+}
Downstream LiL	98270
Downstream PMAG	709
Upstream CMAG	25

Consideration of Alternative Focusing

- As an exercise, a “thin-lens” (w/o material) focusing device was considered at approximately 200mm downstream of the target.
  - Length of the field region was 1cm, and was modeled as:

$$B_\phi = \frac{\theta(B\rho)}{\ell}$$

  - Field strength was such that it would properly focus only particles that could be geometrically within the downstream acceptance of the upstream most quadrupole (Q801) in the M2/M3 transport line.
    - Restriction by PMAG aperture, collimator removed.
  - Low-mass focusing devices generally provide weaker fields.



Consideration of Alternative Focusing

- The benefits of such a bending device is only realized at short distances to the target due to the greater solid angle for particle collection/focusing.

Li Lens Field Only

Location	N_{π^+}
Downstream LiL	106592 (2832 <1cm)
Downstream PMAG	3035
Upstream CMAG	335

π^+/POT
3.3×10^{-6}

650mm Downstream Target

Location	N_{π^+}
Downstream LiL	102948 (681 <1cm)
Downstream PMAG	3541
Upstream CMAG	154

π^+/POT
1.5×10^{-6}

200mm Downstream Target

Location	N_{π^+}
Downstream LiL	108467 (4951 <1cm)
Downstream PMAG	12353
Upstream CMAG	400

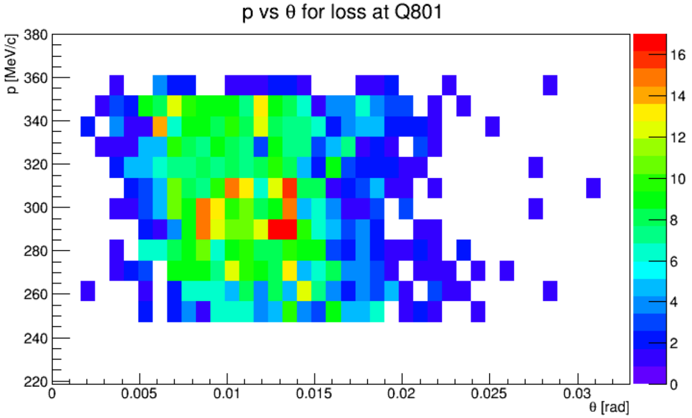
π^+/POT
4.0×10^{-6}

What about other losses?

- Recall for the baseline simulations:

Location			π^+ 300 MeV/c $\pm$ 12 MeV/c			π^+ 3.1 GeV/c $\pm$ 124 MeV/c			Ratio to 3.1 GeV/c
Lithium Lens (R=1cm)	Upstream	Per POT Yield	(1.6×10^{-5})	↑44%		(6.8×10^{-5})	↓47%		(0.24)
	Downstream		(2.3×10^{-5})		↓43%	(3.6×10^{-5})		↑170%	(0.63)
PMAG (5 x 3.5cm)	Upstream		(1.3×10^{-5})	↓67%		(1.0×10^{-4})	↓15%		(0.15)
	Downstream		(4.2×10^{-6})		↓95%	(8.5×10^{-5})		↓45%	(0.05)
Upstream CMAG			2.1×10^{-7}			3.8×10^{-5}			0.005

- The most significant loss points are at PMAG and entering the transport line.
  - The momentum acceptance for Q801 to PMAG should be ±34MeV/c (~11%).
  - Seems to imply sensitivity to focusing.
  - Losses later in transport due to poor entry.



Summary Remarks and Interpretations

- Current outlook: there is room for improvement.
  - **10^{-2} lower π^+ yield for 300MeV/c vs 3.1GeV/c.**
  - **Need MARS comparison and real beamline measurements.**
    - A beam study (or studies) will be made this run.
- It appears that the major problems is with focusing the low-momentum particles:
  - The lower momentum π^+ are at higher angles, which require more focusing.
  - Material effects of lithium lens.
    - Running w/o lens is equivalent to running w/lens.
  - Restrictive apertures.
- Proton contamination still needs to be investigated.