Studying the Proton ``Radius" Puzzle with μp Elastic Scattering
Wire Chambers

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MUSE Technical Design Review
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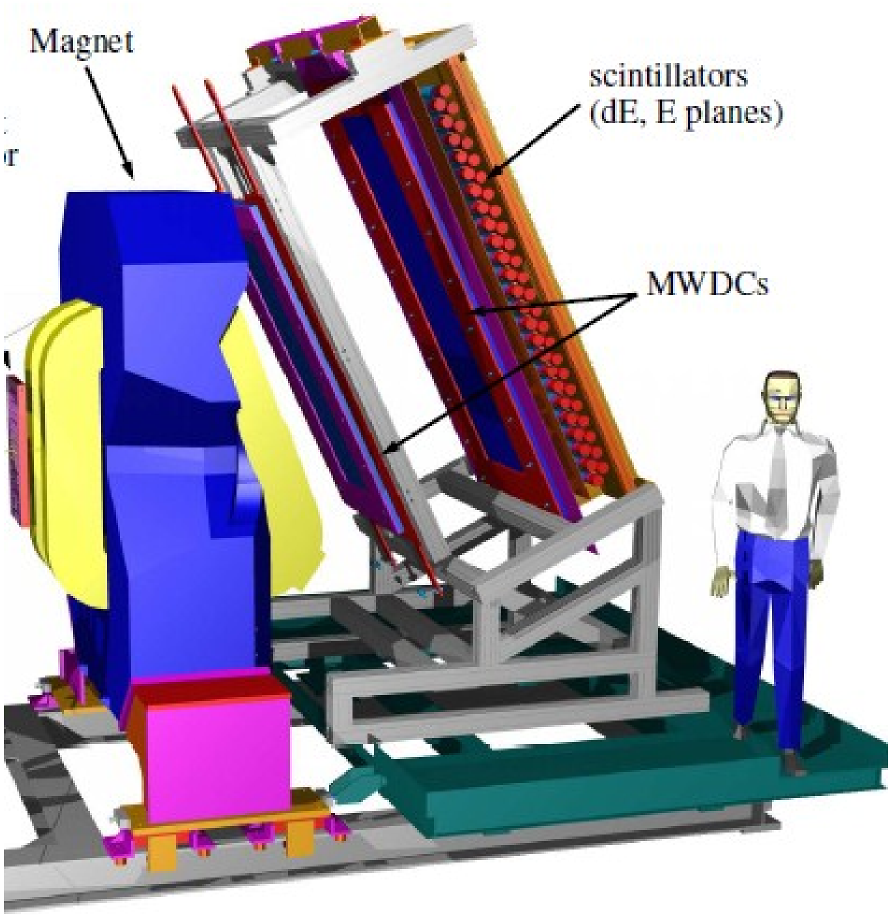
Wire Chamber Requirements

- Angular coverage: θ_H = 20 to 100 degrees
- Rates: a few hundred kHz (not an issue)
- Resolutions (neglecting multiple scattering):
  - position ≈ 100 microns
  - angular ≈ 1 mr
- Scattering angle determination: at least 1 mr
- Well determined detection and tracking efficiency
- These types of chambers have existed for a few decades

Similar to the BigBite wire chambers used at Jefferson Lab

BigBite Spectrometer

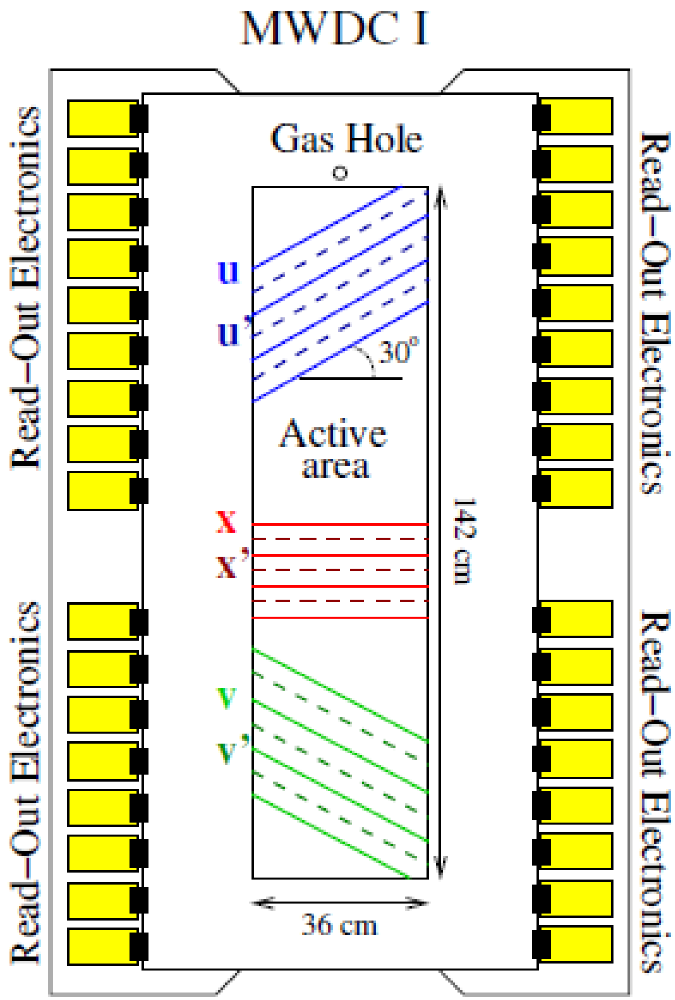


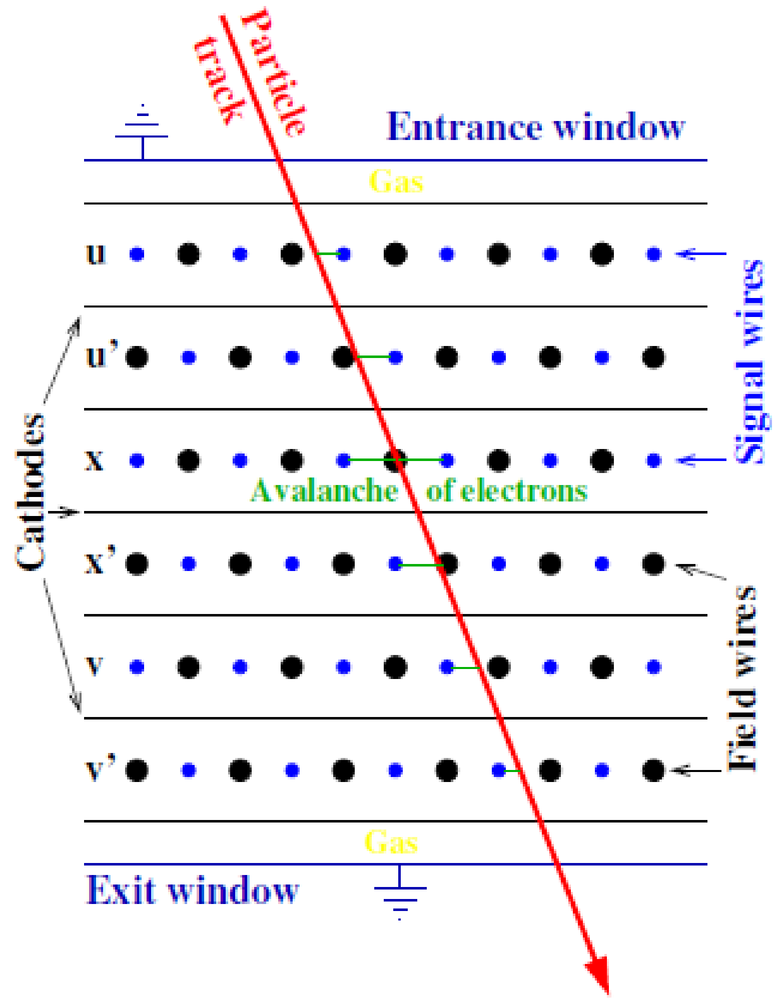
- Versatile spectrometer used to detect either hadrons or leptons

BigBite Wire Chambers

- Construction led by N. Liyanage of UVa
- Successfully used for **seven** Jefferson Lab experiments in Hall A
- Type of chambers:
  - **horizontal drift chambers** (HDC)
  - three chambers consisting of 6 wire planes: U,U'; V,V'; X,X' to remove left/right ambiguity
  - wires are oriented $+60^o$, -60^o and $+90^o$ with respect to the dispersive direction
- Alternating sense and field wires, 0.5 cm apart

BigBite Wire Chambers





- Sense wire spacing 1 cm; each B'-plane is offset by 0.5 cm from the B-plane

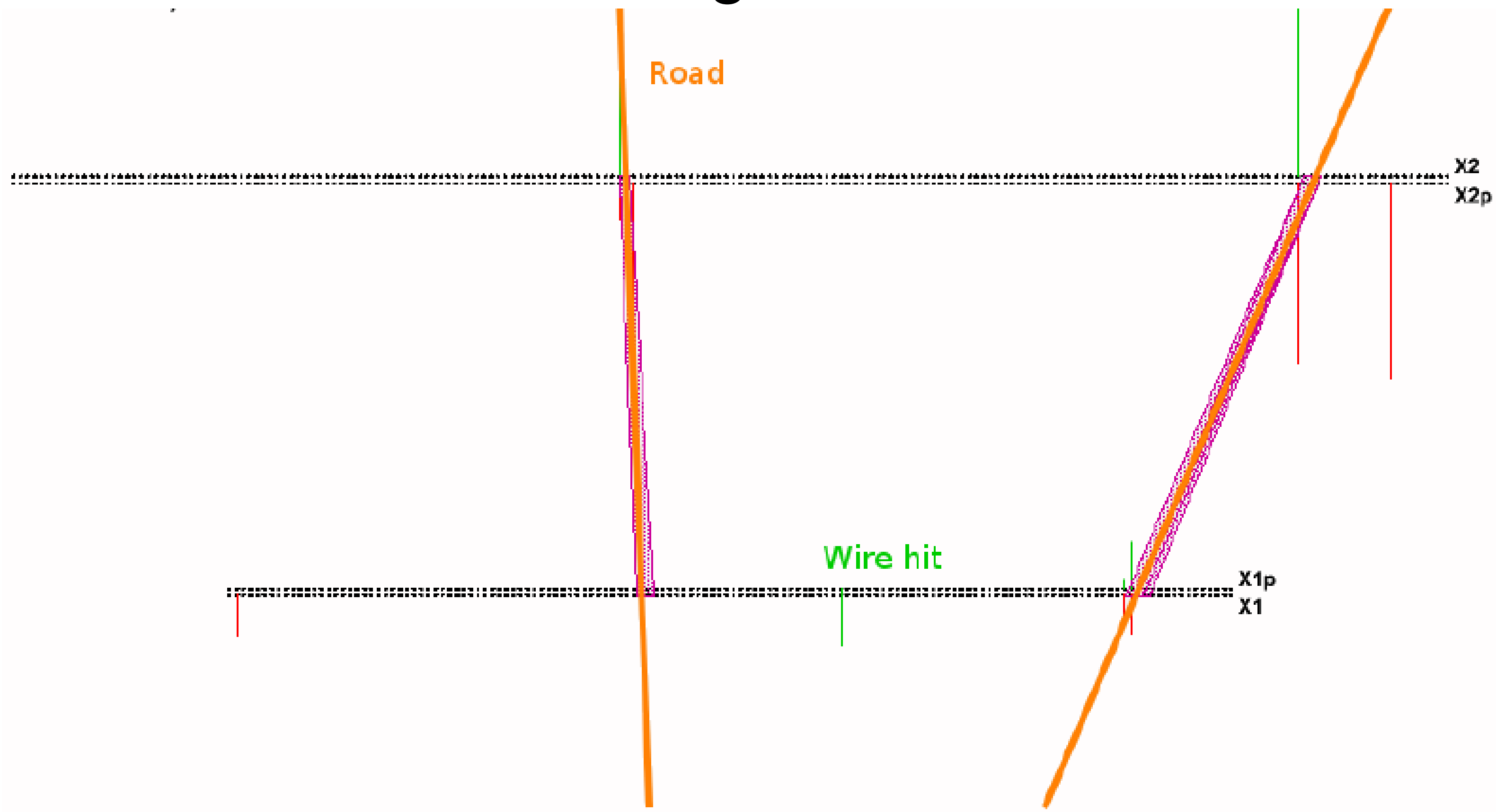
Chamber Operation & Performance

- Open geometry spectrometer ~ 75 msr solid angle acceptance
- Operated at a **luminosity** of 5×10^{36} cm^{-2} s^{-1}
- High rate conditions: 20 MHz
- Coordinate and angular resolutions:
  - $\sigma_x = 91$ µm, $\sigma_y = 200$ µm
  - $\sigma_\theta = 0.16$ mrad, $\sigma_\phi = 0.35$ mrad
  - Values from M. Mihovilovič with two chambers
- The dispersive coordinate and angle are better due to the **three wire orientations**

M. Mihovilovič et al. Nucl. Instrum. Meth. **686** (2012) 20

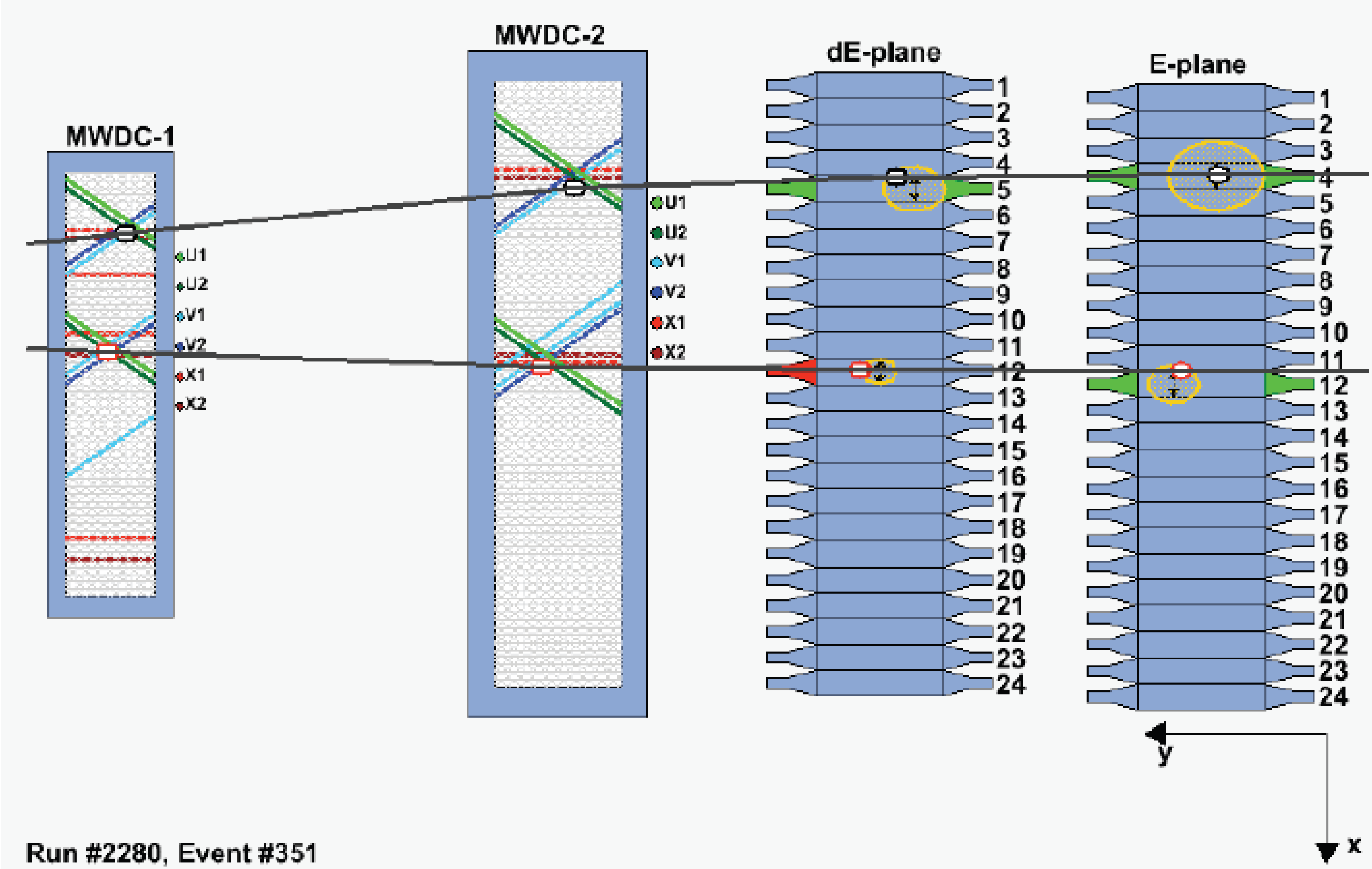
Track Reconstruction

- Tracking determination performed by a pattern match tree search algorithm



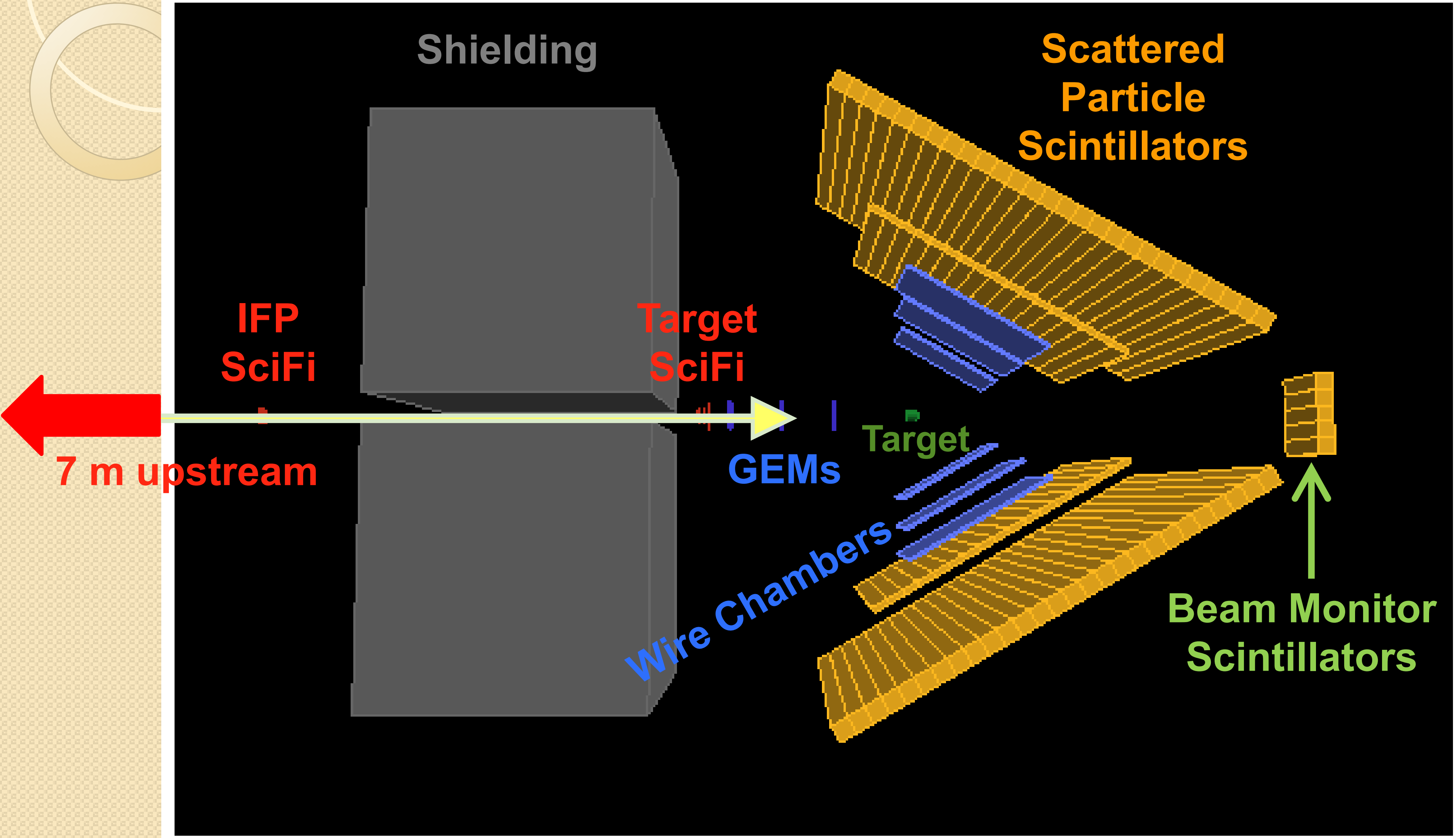
R. Mankel, Rep. Prog. Phys. **67** (2004) 553

Track Reconstruction



Less than 1% of events have two real tracks

MUSE Wire Chamber Location



Chamber Design for MUSE

- 6 chambers:
  - 3 on each side of the target
  - Containing 6 planes of UU'VV'XX' wires
  - Closely following the BigBite chamber design, though optimized for MUSE
- Chamber locations and sizes;
  - **front chamber**: 25 cm from target; 50×45 cm^2
  - **middle chamber**: 35 cm from target; 70×60 cm^2
  - **back chamber**: 45 cm from target; 90×80 cm^2
- With 100 micron resolution and a 20-cm separation, intrinsic angular determination of 0.7 mr
- Resolution will be limited by multiple scattering

Requirements for Precision Cross Sections

- Wire chambers efficiencies
- Scattering angle determination
- Solid angle determination

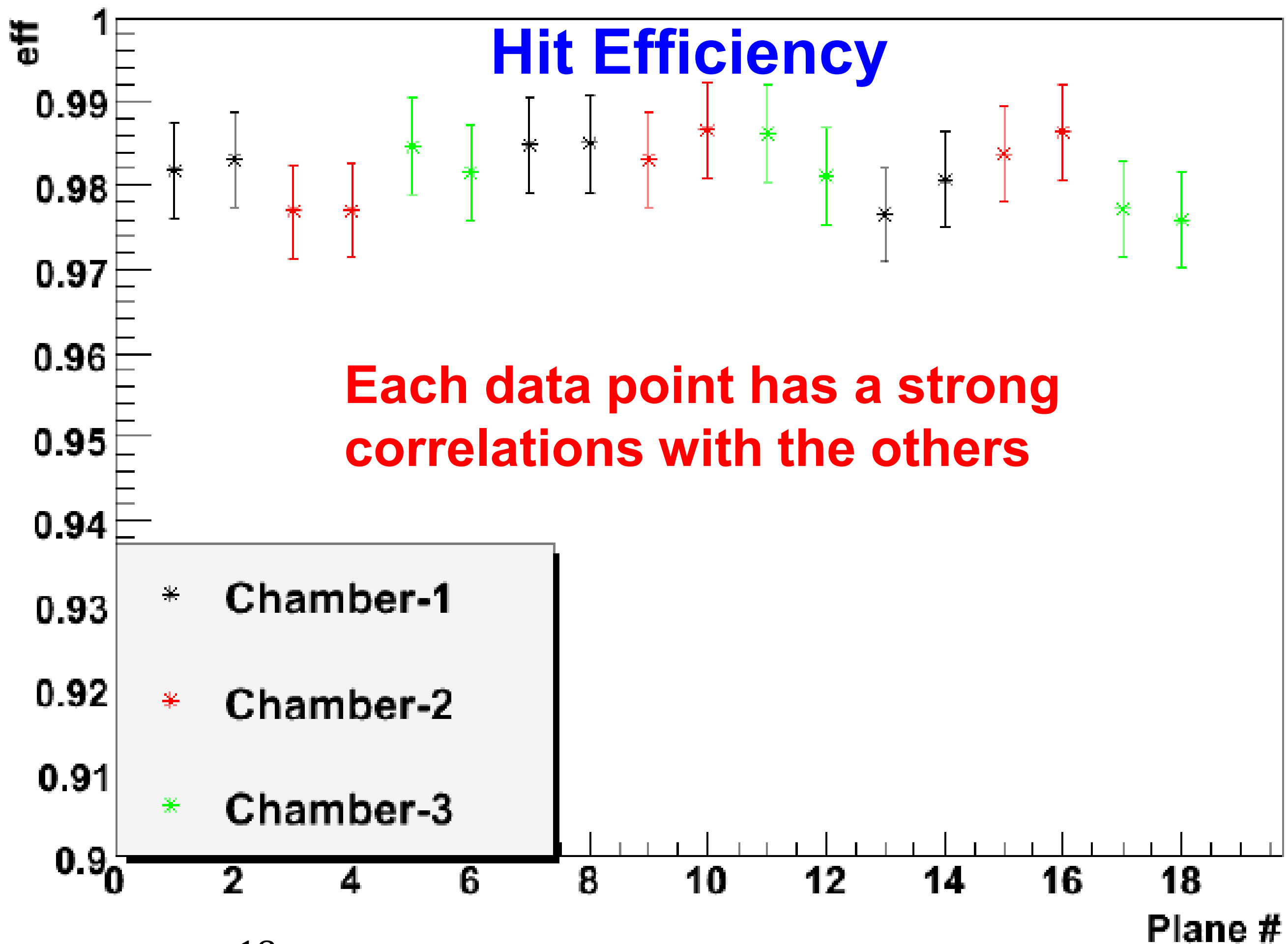
Hardware Tracking Efficiency

- Hardware efficiency can be determined by the **hit efficiency** for each plane
  - probability of a wire to fire when a charged particle passes by it

$$\epsilon_{hardware} = \sum_{n=j}^{m=18} C_m^n P^n (1-P)^{m-n}$$

  - *P*: average hit efficiency
  - *j*: minimum number of required planes
  - *m*: total number of planes
- e.g. *P* = 98% and *j* = 15, $\epsilon_{hardware} \approx 99.9\%$
- *j* = 15 is the usual requirement for the BigBite chambers

Hit Efficiency from BigBite Chambers



$$\epsilon_{hardware} = \sum_{n=j}^{m=18} C_m^n P^n (1-P)^{m-n}, \boldsymbol{j = number\ \ of\ required\ planes}$$

Hardware Tracking Efficiency

- Pattern match tree search algorithm:
  - 18 planes divided into 3 groups based on orientation
  - Tracks first searched within each group
  - If algorithm requires five out of six planes to find a valid track in each group:

$$\epsilon_{hardware} = \left(C_6^6 P^6 + C_6^5 P^5 (1-P)\right)^3 \approx 98\%, \textbf{with } \boldsymbol{P} = \mathbf{98\%}$$

- Procedure performed routinely to ensure normal performance of the wire chambers
- The efficiency has been found to be stable for several months of operation

Software Track Efficiency

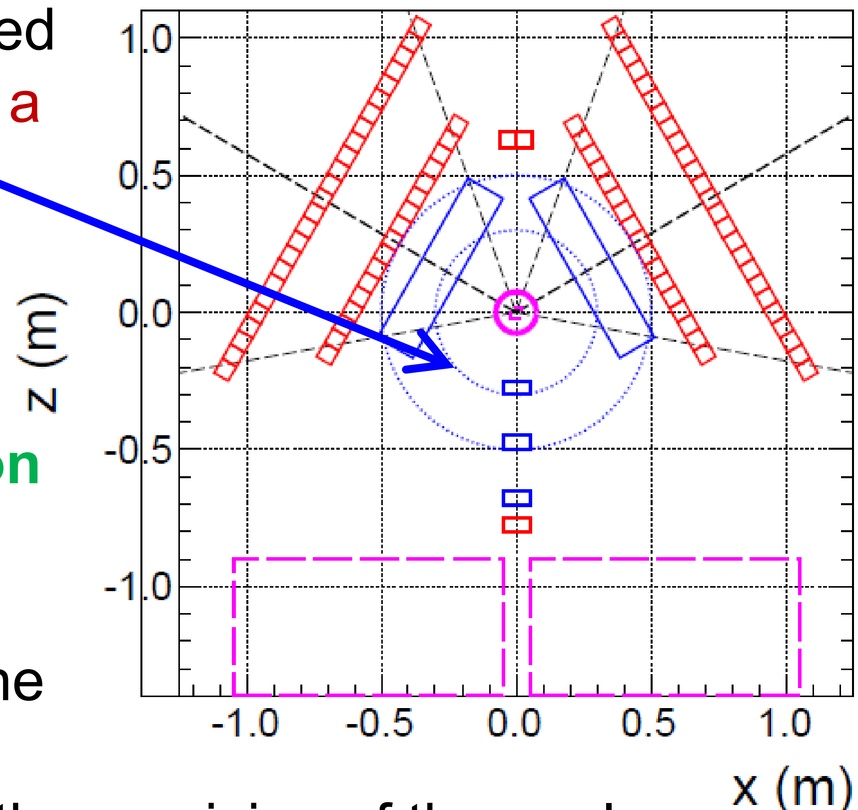
- The software tracking efficiency for the BigBite chambers was evaluated from elastic hydrogen data and a tracking Monte-Carlo
- For 2 μA beam, the efficiency was ~ 95% (3 MHz) with a 10% reduction with higher background rates at 14 μA (20 MHz)
- At the luminosity and rates at PSI, we expect greater than 99% software tracking efficiency

Plan for MUSE

- Keep the gas mixture (argon-ethane bubbled through ethanol) and high voltage stable to maintain a high efficiency for the chambers
- During commissioning at low beam rates, we will find **tracks from the GEM chambers pointing into the wire chambers** (as rotated for the angle determination) that have a signal from the rear scintillators
- These events provide a way to determine the wire and tracking efficiencies of the chambers
- Efficiency measurements will be conducted as a function of rate; since rates are much smaller than at JLab, **rates are not expected to be a problem**

Scattering Angle Determination

- **Straight-through tracks between the GEMs and wire chambers** will allow the relative angles of the GEMs and drift chambers to be calculated
- The GEMs will be mounted to a platform attached to a rotating table that the wire chambers are mounted on



- Precise angle changes are made using **precision dowel holes** (≈ 10 μm) at a radius of 50 cm
- Provides a precision of the table rotation of 0.03 mr
- Multiple scattering limits the precision of the angle determination of the GEM and drift chambers

Uncertainties on Central Angle

Drift chamber:

- Angle determination: 0.7 mr (**100 μm over 20 cm**)
- Multiple scattering adds ~ 0.5 mr
- Total chamber resolution: 0.9 mr

GEM:

- Angle determination: 0.35 mr (**100 μm over 40 cm**)
- Multiple scattering adds ~ 1.8 mr
- Total GEM resolution: 1.8 mr

Air (1 meter): multiple scattering = 1.3 mr

- Resolution for determining the relative angle is **2.4 mr** or **2.1 mr** by using a helium bag (0.6 mr)
- Values are RMS widths of the measured distributions
- Centroids of distributions can be determined better than resolutions to at least **0.5 mr** and **0.4 mm**
- Determine angle alignment in rotated position to **0.5 mr** and **rotate back** with a **precision** of **0.03 mr**

Solid Angle Determination

$$\mathrm{d}\Omega = d\left(A \cdot \frac{\cos\theta}{r^2}\right); A = x \cdot y$$

- Choose a 6.5 cm wide by 90 cm high bin
- Precision of the size and position of the chambers:
  - Wire position (~ **35 um**) at a chamber to target distance of **45 cm** (**back chamber**)
  - **dA/A ~ 5.4 × 10^{-4}** (σ_x and σ_y added in quadrature)
  - **d(r^2/r^2)** ~ 2 · dr/r ~ 2 · 0.1/450 = **4.4 × 10^{-4}**
  - $\boldsymbol{d\cos\theta/\cos\theta \sim \sin\theta \cdot d\theta/\cos\theta \sim}$ (0.34) ·(5 × 10^-4) / 0.94 = **1.8 × 10^{-4}**
- **Total uncertainty ~ 0.1%**

Systematics Summary

Systematic	Rel. Uncertainty (%)	Abs. Uncertainty (%)
Wire chamber Efficiency	0.1	0.1
Angle determination	0.3	0.5
Solid Angle	0.1	0.1

Construction Parameters

Time estimate:

- With 1 or 2 technicians plus 1-2 students,
  1.5 years for 6 chambers (based on BigBite project)
- Design: 2 months
  Order PCB board at the same time
- Etching of PCB boards: 2-3 months
- Machining of frames: 1 month
- Construction of first chamber: 3 months
- Construction of other chambers: 1-2 months each

Construction Parameters

Cost estimate:

- Design: $10k
- Infrastructure: $5k
- Materials: $150k for 6 chambers
- Labor: $200k for 6 chambers
- Mounting frames: $25k for 6 chambers
- Total: $450k for 6 chambers (including incidentals)
- **Cables and DAQ electronics not included**

Notes:

- At proposal conception, ~ **2000 wires**, for TDR has **2884 wires**
- If built, the middle plane simplifies the analysis and helps with the systematics for the absolute cross section, though it is not absolutely necessary
- Working with the David Armstrong (W&M) to reuse the electronics from the QWeak wire chambers (2232 channels)

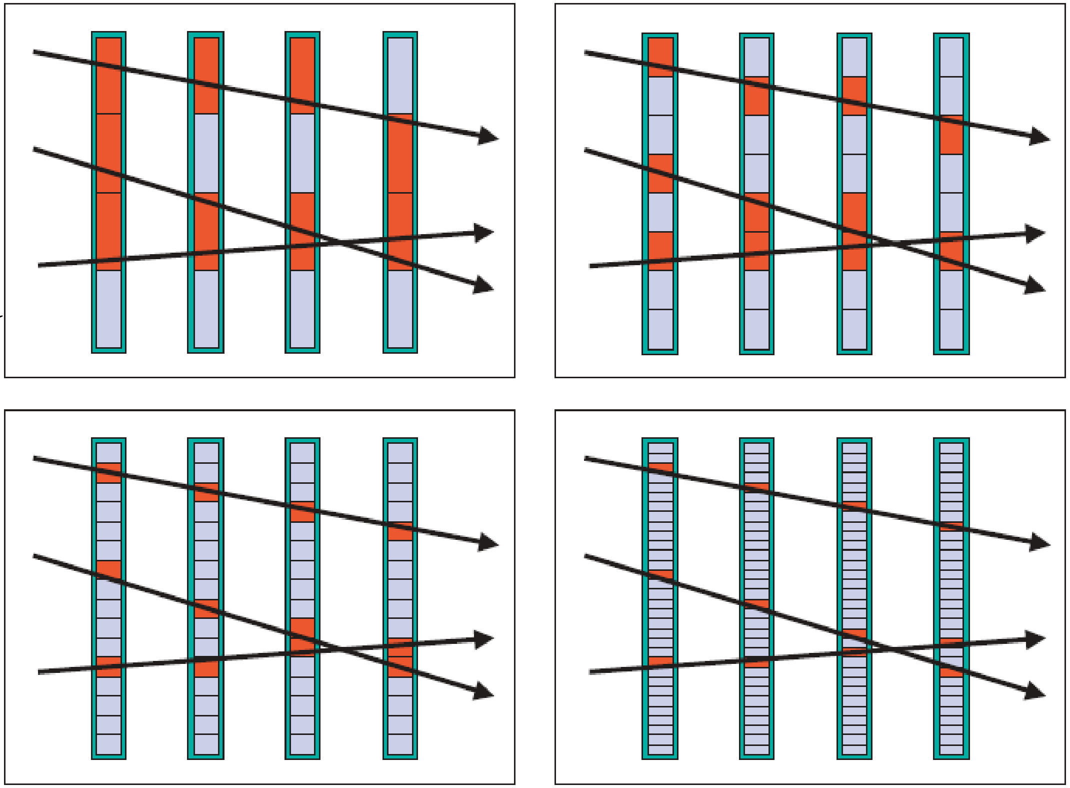
Back-up slides

Wire Chamber Experience

- Bill Bertozzi built vertical drift chambers (VDC) for the ELSSY spectrometer at Bates
- Shalev Gilad built:
  - Multi-wire proportional chambers (MWPC) at LAMPF
  - MWPC for the Bates FPPs and HDCs for the out-of-plane spectrometers (OOPS)
  - VDC for the JLab high resolution spectrometers (HRS)

Pattern Match Tree-Search Algorithm

- 18 planes divided into three groups or "projections"
- Algorithm finds 2-D tracks or "roads" within each group
- Roads are matched and the 3-D tracks are reconstructed using a fit procedure
- Iterative procedure until desired resolution is matched



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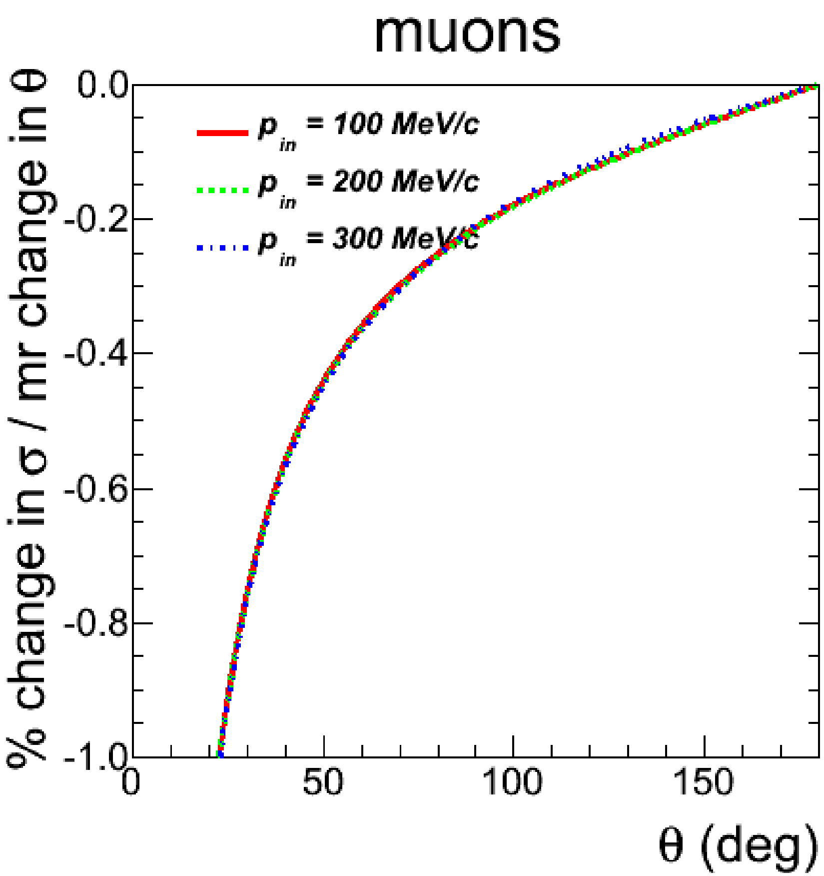
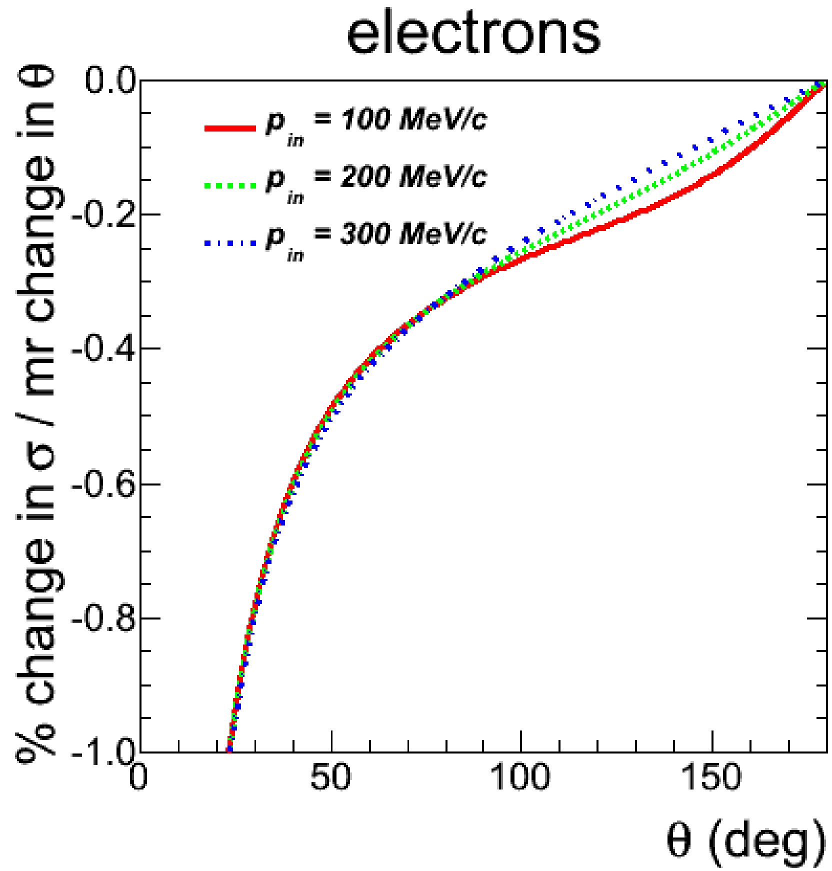
Systematics: Effect of Angle Offset





Angle offset effect is nearly energy independent. Plan to determine central angle to ±0.5 mr. Correlations between overall normalization and angle offsets will make it difficult to ``fit out" much better.

Wire Position Determination

- Optical surveying system:
  - Precision stepper motor (0.5 μm)
  - Camera resolution (35 μm)
- Absolute position to frame (100 μm)