Systematics

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for the MUSE Collaboration

Outline:

Experiment Overview for Systematics

Detector Related Systematics

Analysis Related Systematics

Kinematics Related Systematics

Corrections Related Systematics

*Supported in part by NSF grant PHY 1306126

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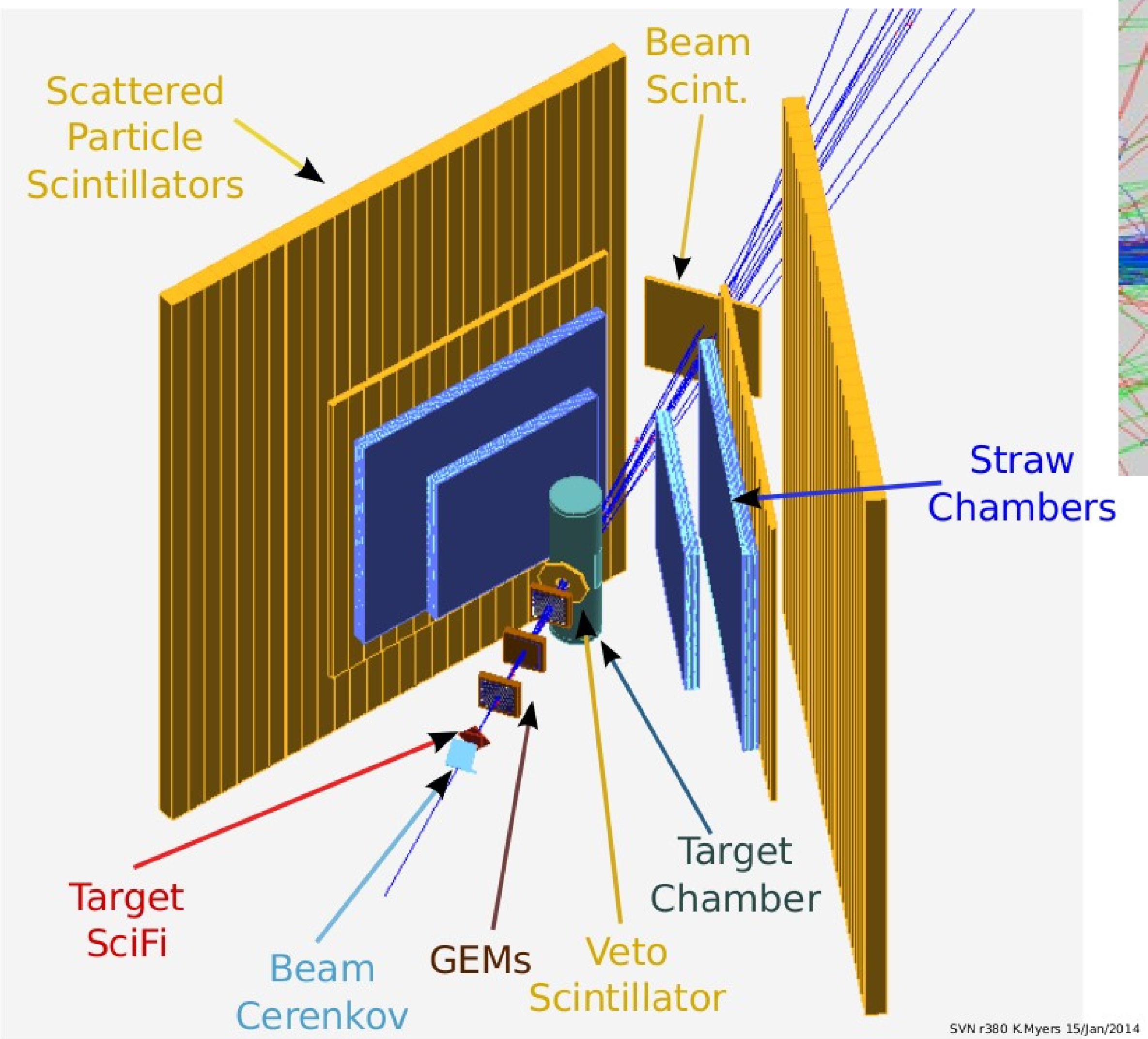
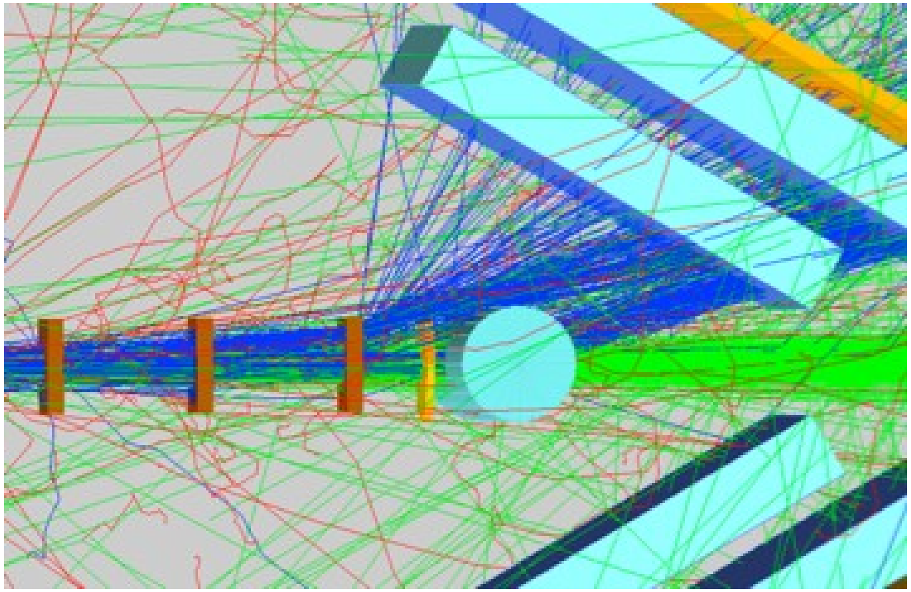
Cross Section Experiment

Detector Overview in Simulation:



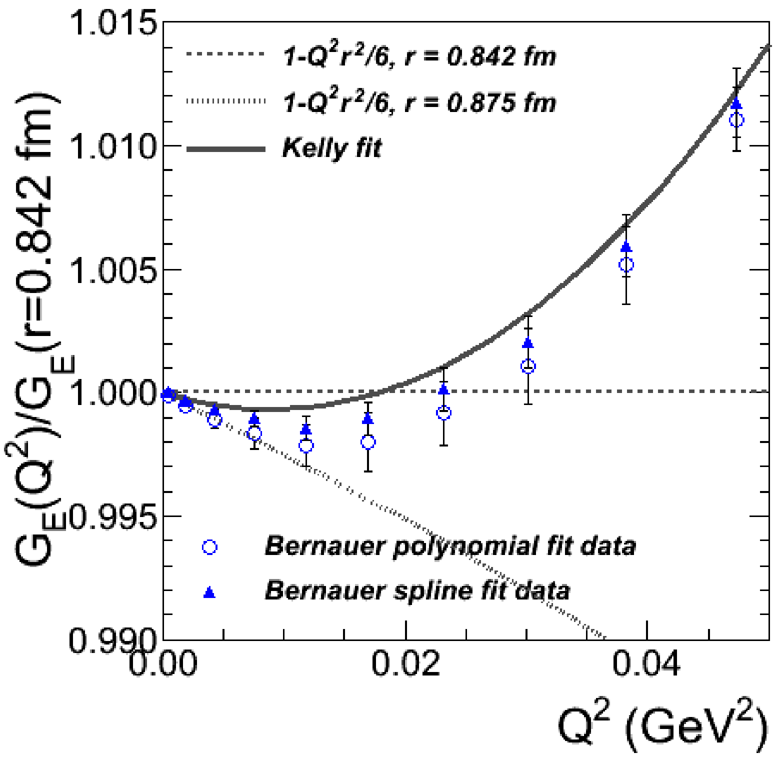


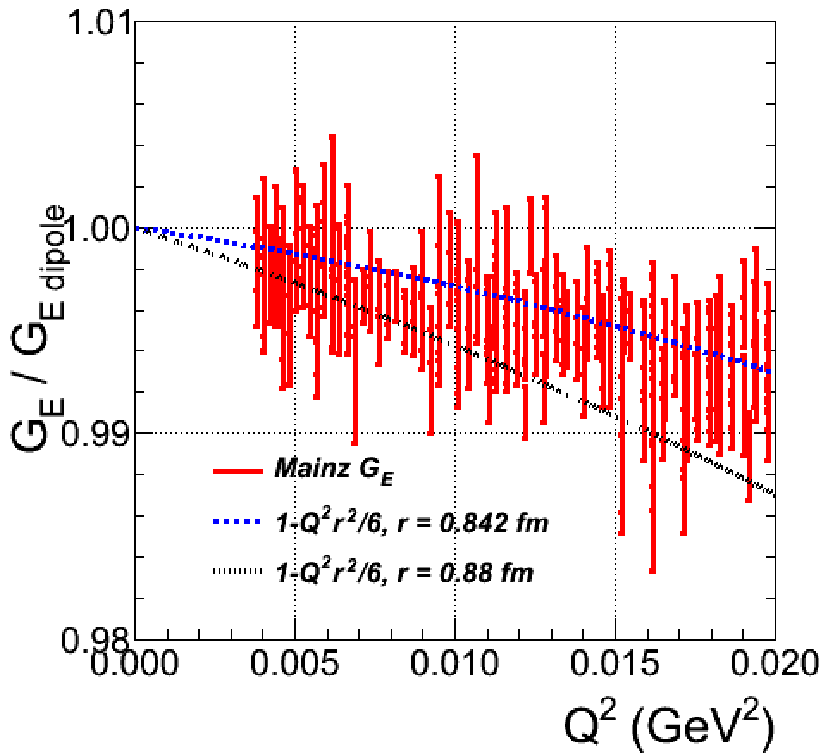
Electron tracks in simulation that trigger left arm

Beamline detector response is angle independent so does not affect relative uncertainties

Relative Cross Section Measurement

We are not an absolute cross section experiment - absolute cross sections cannot be measured well enough





Instead we focus on the relative errors that affect point-to-point uncertainties within each of our 6 primary settings.

We normalize each setting to $Q^2 = 0$ limits - everyone does this.

Cross Section Experiment

$d\sigma/d\Omega(Q^2) = N_{counts} / (\Delta\Omega \times N_{beam} \times (x\rho)_{target} \times \text{corrections} \times \varepsilon)$

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{d\sigma}{d\Omega}\right]_{ns} \times \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + \left(2\tau - \frac{m^2}{M^2}\right) G_M^2(Q^2) \frac{\eta}{1-\eta}\right]$$

$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2} \frac{1-\eta}{\eta^2} \frac{1/d}{\left[1 + \frac{2Ed}{M}\sin^2\frac{\theta}{2} + \frac{E}{M}(1-d)\right]} \qquad d = \frac{\left[1 - \frac{m^2}{E^2}\right]^{1/2}}{\left[1 - \frac{m^2}{E'^2}\right]^{1/2}}$$

$$\eta = Q^2/4EE'$$

following Preedom & Tegen, PRC36, 2466 (1987)

Relative Systematics Overview

$$d\sigma/d\Omega(Q^2) = N_{counts} / (\Delta\Omega \times N_{beam} \times (x\rho)_{target} \times corrections \times \varepsilon)$$

$\Delta\Omega$: Determined by straw chamber wire positioning

N_{beam}: Cancels! Luminosity same for all angles.

$(x\rho)_{target}$: Cancels! Luminosity same for all angles

Note: ρ_{target} comes in as a higher-order correction, as it affects the multiple scattering which varies with angle from different path lengths and momenta with angles, but it is a fraction of the multiple scattering

corrections: Non-detector corrections -- theoretical

ε (efficiencies): Detector efficiencies, dead times, reconstruction, cuts

kinematics: Beam momentum sensitivity, angle determination

Relative Systematics Table

Solid Angle	0.1%
Scintillator Efficiency	0.1%
Beam Momentum Sensitivity	0.1%
Angle Determination	0.1%
Magnetic Contributions	0.1%
Multiple Scattering	0.3%
Radiative Corrections – μ	0.1%
Radiative Corrections – e	0.5%

Total Relative Uncertainty in Cross Section*:

μ: 0.4%

e: 0.6%

- Negligible Systematics:
  - Beamline Detector Efficiency
  - Beam Flux
  - Target Thickness
  - Data set Normalization
- TBD Systematics (small)
  - Analysis Uncertainties
  - Detector Stability

* Uncertainties factor of two smaller for form factor

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Detector Systematics: $\Delta\Omega$

$$\Delta\Omega = dA/r^2 = (dxdy)/r^2$$

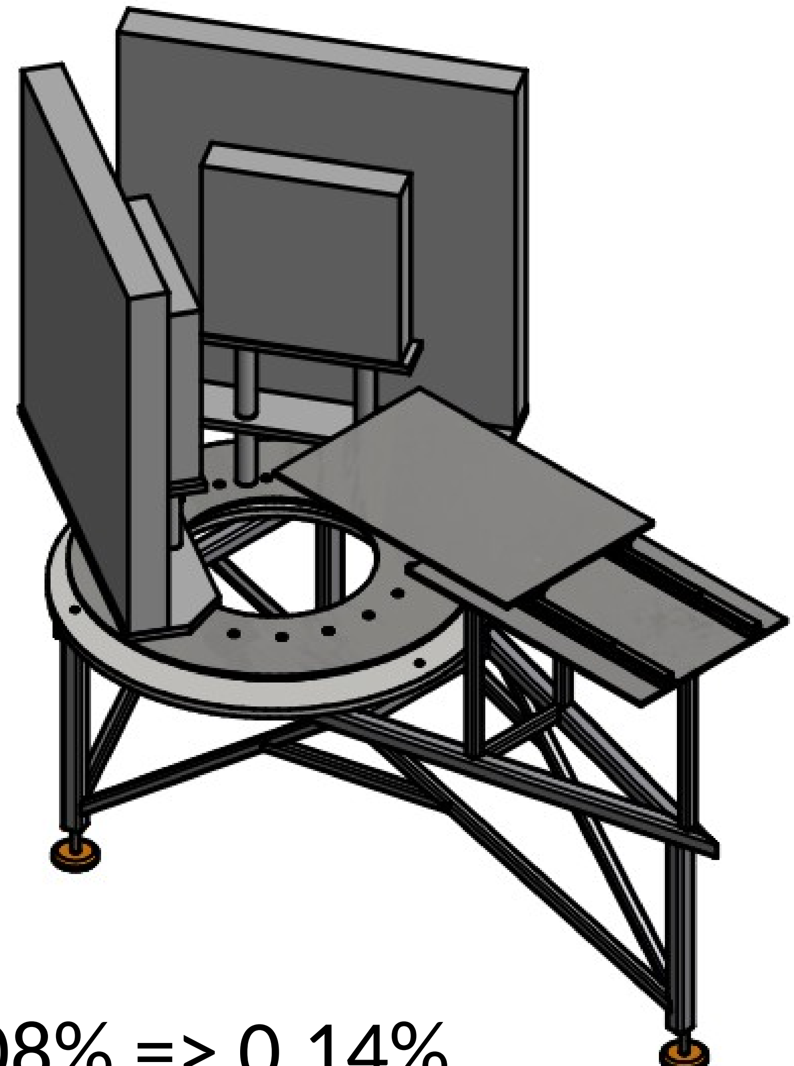
- Position of wires determined mechanically by assembly of straws into chambers. Relative positioning within chamber determined at the 25 µm level.
- Our bins will be ≈ 3 cm wide by 50 cm high, so…

  dx/x ≈ √2 x 25 µm / 3 cm = 0.12%
  dy/y ≈ √2 x 25 µm / 50 cm = 0.007%

- Note that reconstruction resolution randomly moves events between bins, but does not change solid angle.

Detector Systematics: $\Delta\Omega$

$$\Delta\Omega = dA/r^2 = (dxdy)/r^2$$



- Position of chambers (r) on table is fixed mechanically, surveyed, and calibrated by determining beam position with GEMs into rotated chambers.

  $dr/r \approx 100\ \mu m / 25\ cm = 0.04\%$

  $dr^2 / r^2 = 0.08\%$

- Thus

  $d\,\Delta\Omega/\Delta\Omega = 0.12\% + 0.007\% + 0.08\% \Rightarrow 0.14\%$

Straw Chamber Efficiencies

- Wire chambers are usually about 98% or so efficient for each plane. Straws efficiencies are reduced by a ≈ 95% geometric coverage factor.
- Each set of 5 planes needs 3 straws to fire to independently determine a track.
- High efficiency with redundant planes. Negligible relative uncert.
- Main issue: unknown inefficient straws. Need to calibrate with data, easiest if all efficiencies are high.

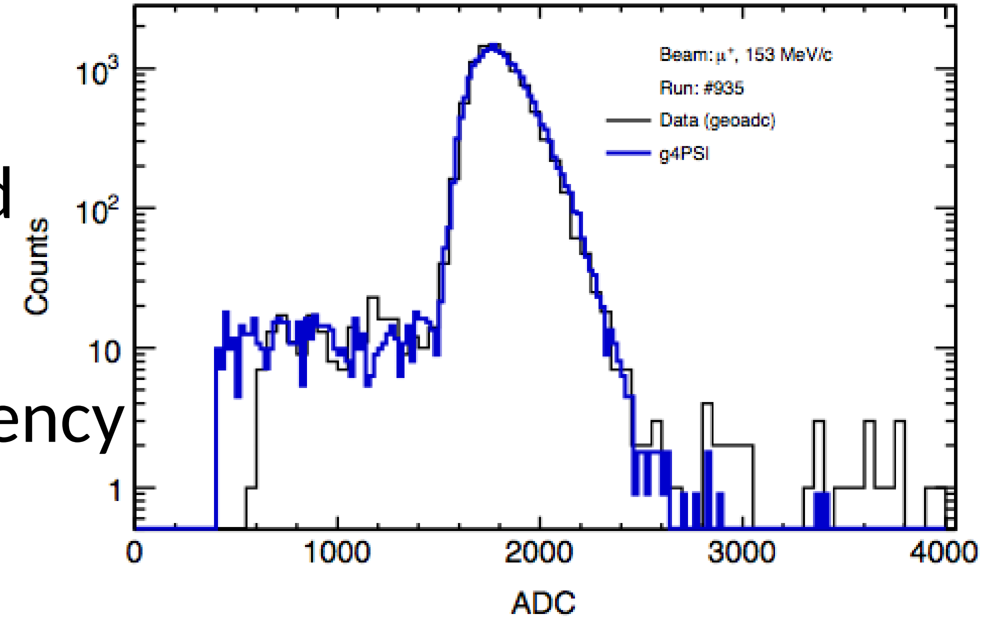
Estimate from binomial statistics:

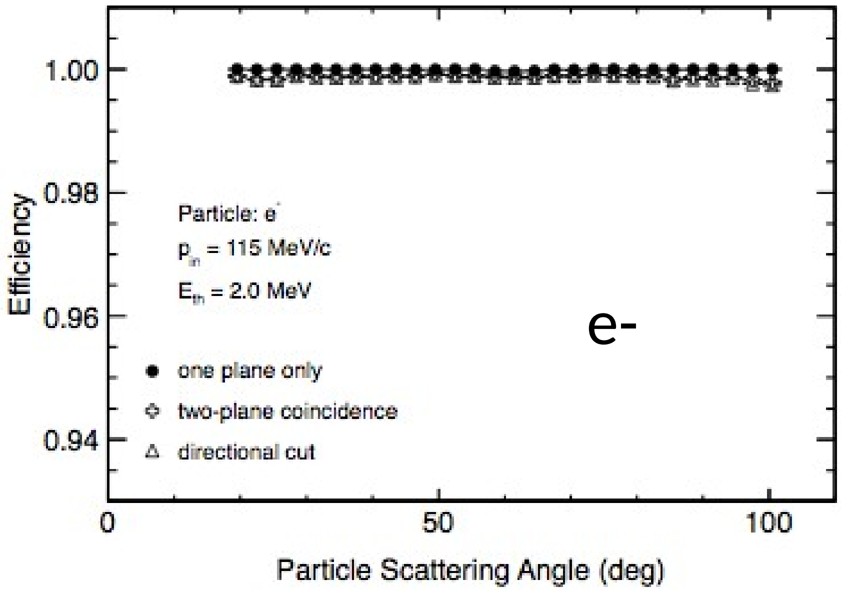
# of hits	Σ Prob.
5	69.94
>=4	95.86
>=3	99.70
>=2	99.99
>=1	~100
0	~100

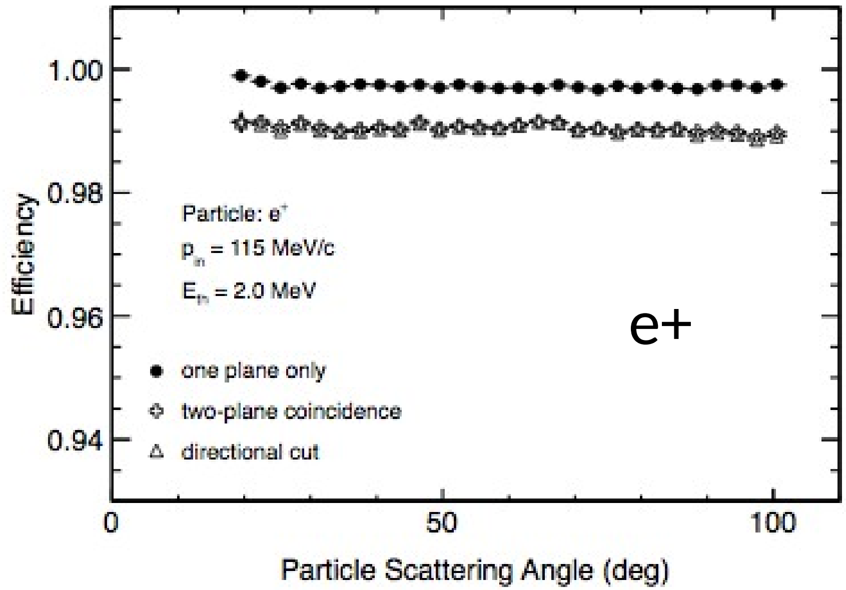
*Assumes uncorrelated efficiencies, but geometry is correlated

Scintillator Effiencies

- Scintillator efficiencies are high, angle-to-angle variations are small
- Measurements of ADC spectra and thresholds will be compared with simulation – monitor stability
- Positrons have slightly lower efficiency
- Very slight decrease in efficiency at large angle







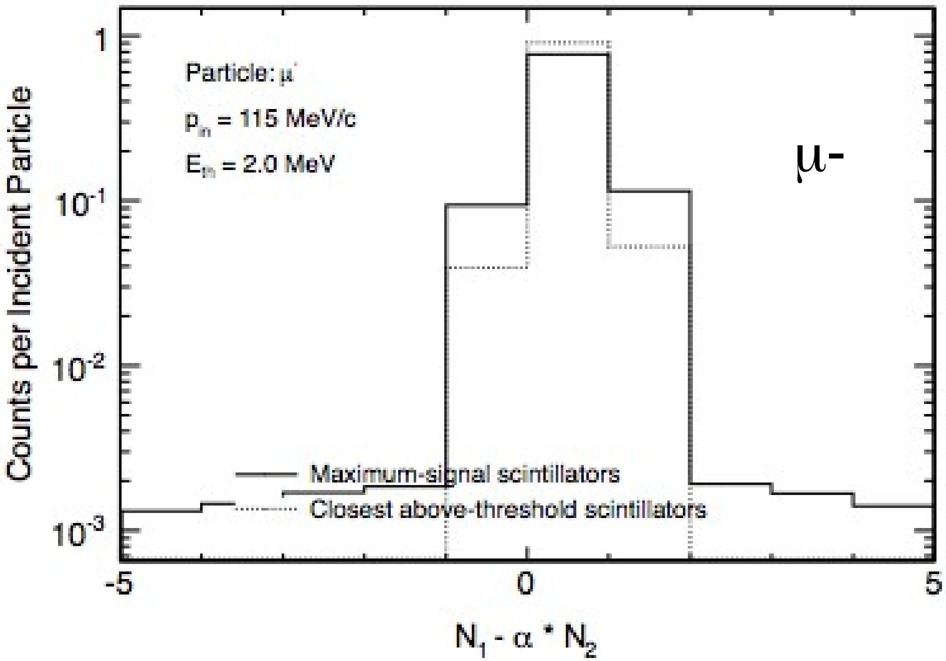
Effiency:
~100% for μ+, μ-, e-
~ 99% for e+

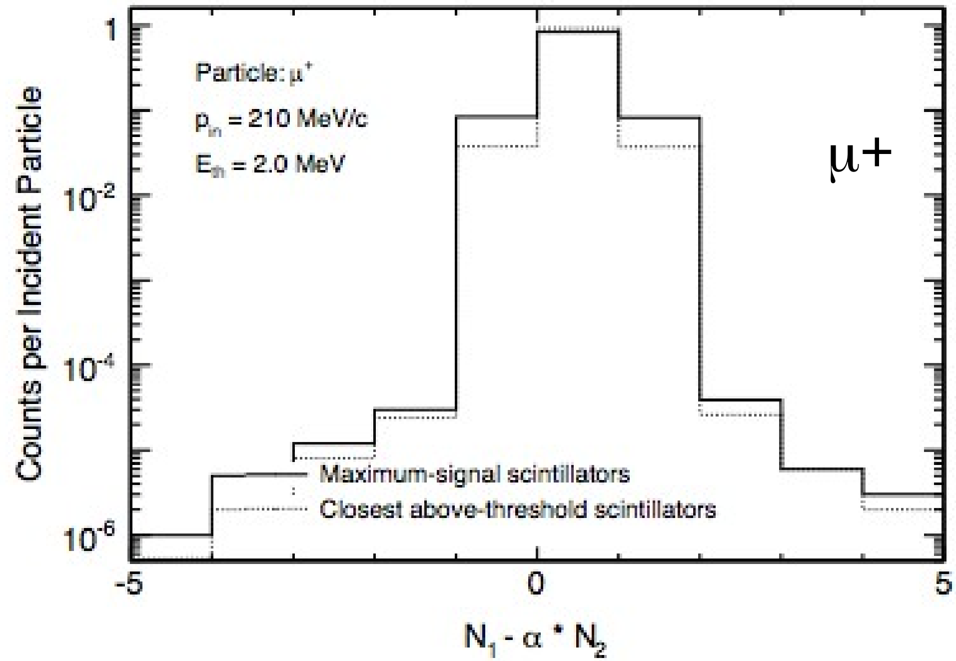
0.1% syst. error

Trigger Efficiencies

- Only the variation in scattered particle efficiency vs angle matters. Beam PID efficiency is angle-independent.
- The rear scintillator and trigger conditions are sized for high efficiency (see previous slide and below).

Efficient directional cut for trigger:



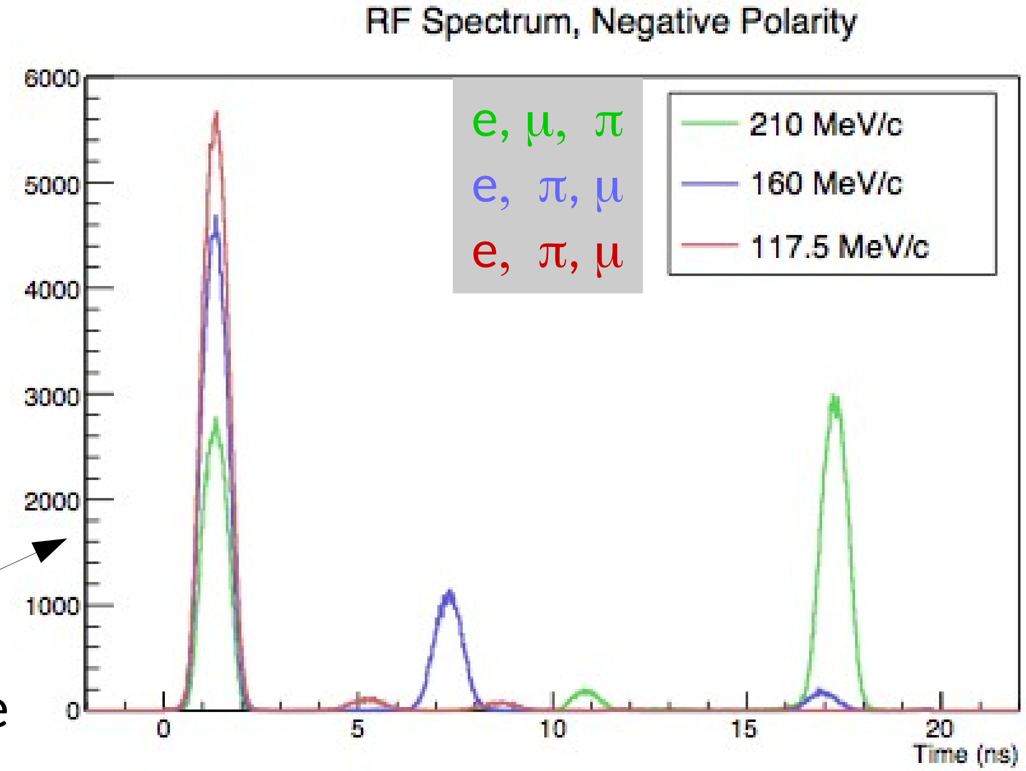


Trigger Efficiencies

Beam PID efficiency is angle-independent

This is not quite right… different particles have different scattered-particle distributions, so misidentified beam particles are a potential issue.

But our ability to ID particles at the hardware level is very good, and at the analysis level is even better (10σ).



From test measurements:
particles are well separated in RF time

Trigger Efficiencies

- The variation in scattered particle trigger efficiency versus angle also crucially depends on the FPGA programming.
- The timing is slightly different for particles of different momenta traveling different distances to the scintillators.
- Also, the front and rear scintillators have different lengths, and thus different time variations between PMTs at opposite ends.
- Knowing that the trigger programming works properly, and does not introduce angle-to-angle efficiency variations in this case, is a common issue with programmable triggers.

Trigger Efficiencies

- Triggering system and FPGA programming must be carefully studied and commissioned
- Trigger efficiency is studied by programming progressively tighter triggers and monitoring response of the system
- Initial work will be done at low rates triggering off beam particles
- The TRB data will generate the state of each input signal versus time
- We can record the state of the intermediate and final output logic versus time into spare TDC channels
- These steps give complete picture of system functionality

DAQ and Deadtime Systematics

- TRB3 counts all triggers. Estimated trigger rates up to 4 kHz, plan to limit to 2 kHz sent into the DAQ (prescaling of electron events). For 4 kHz, triggers come on average 250 μs apart.
- We run into problems if a second trigger comes within ~20 ns of the proceeding trigger. This only happens ~0.01% of the time.
    - Absolute normalization offset, but uncertainty small
    - Earlier in time particle generates the trigger
    - Both events read out and can be analyzed
- Computer DAQ deadtime is not an issue: the TRB counts all triggers sent out and all triggers read out.

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Analysis Systematics: Cuts

- Better timing at the analysis level:
  - RF time and particle TOF allow most background to be removed

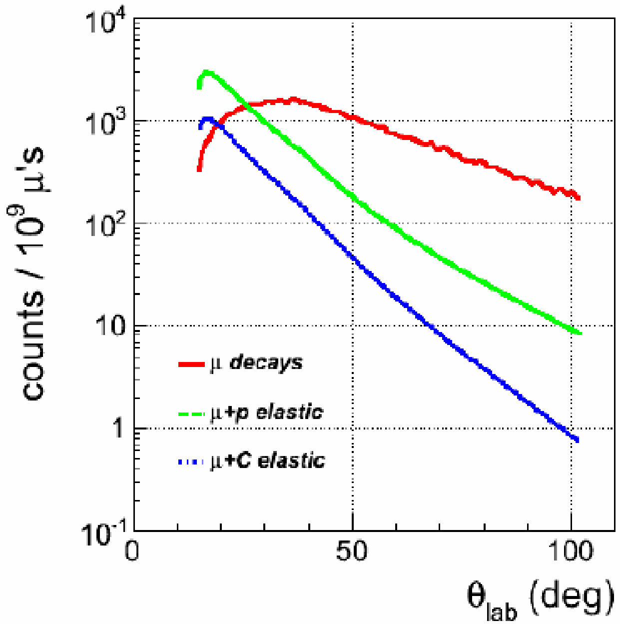
- GEM data:
  - Fiducial cuts on particles going into the LH2 target

- Remaining backgrounds:
  - Target endcap scattering
  - Muon decays coming from close to the target region

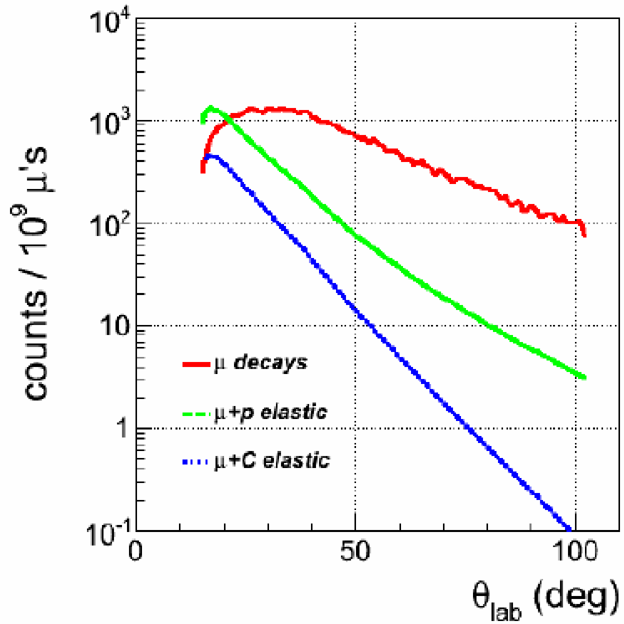
  These are removed with empty target runs coupled with simulation

Background Distributions - μ

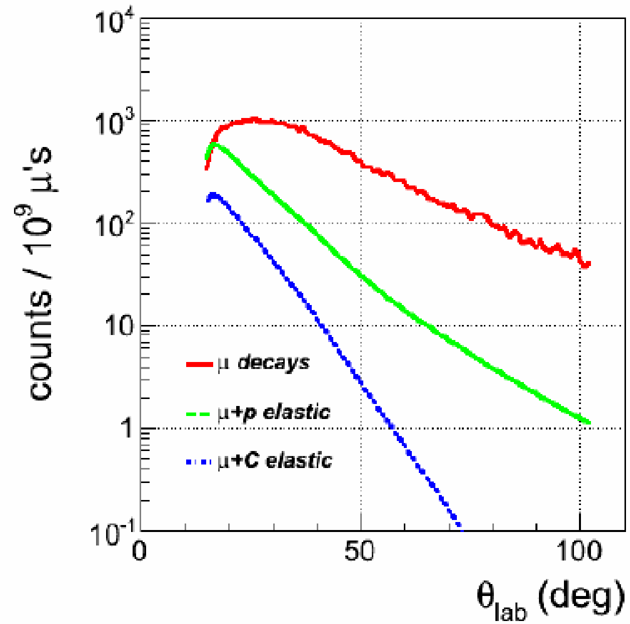
Background Distributions:



115 MeV/c



153 MeV/c

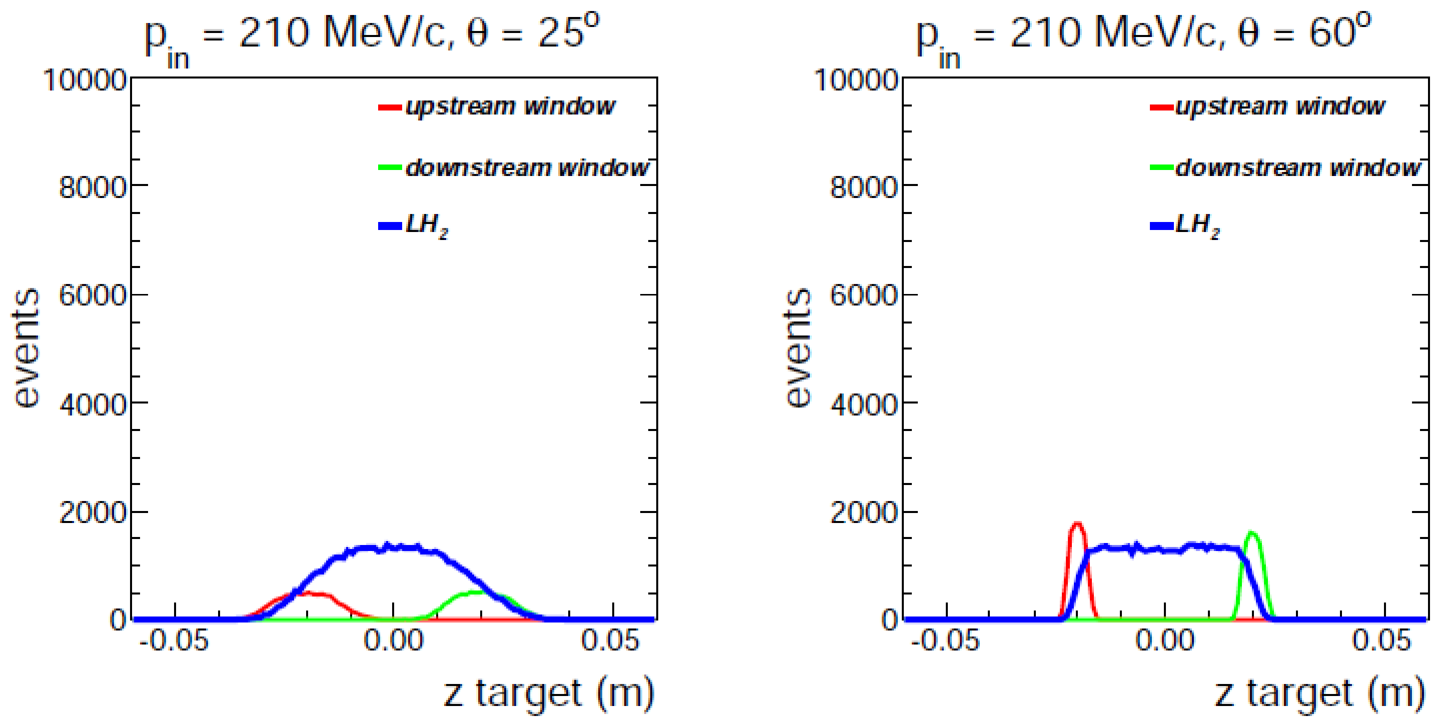


210 MeV/c

Comparison of μp (green) μC (blue) and muon decay (red)

Target Endcap Backgrounds

- Target endcap scattering:



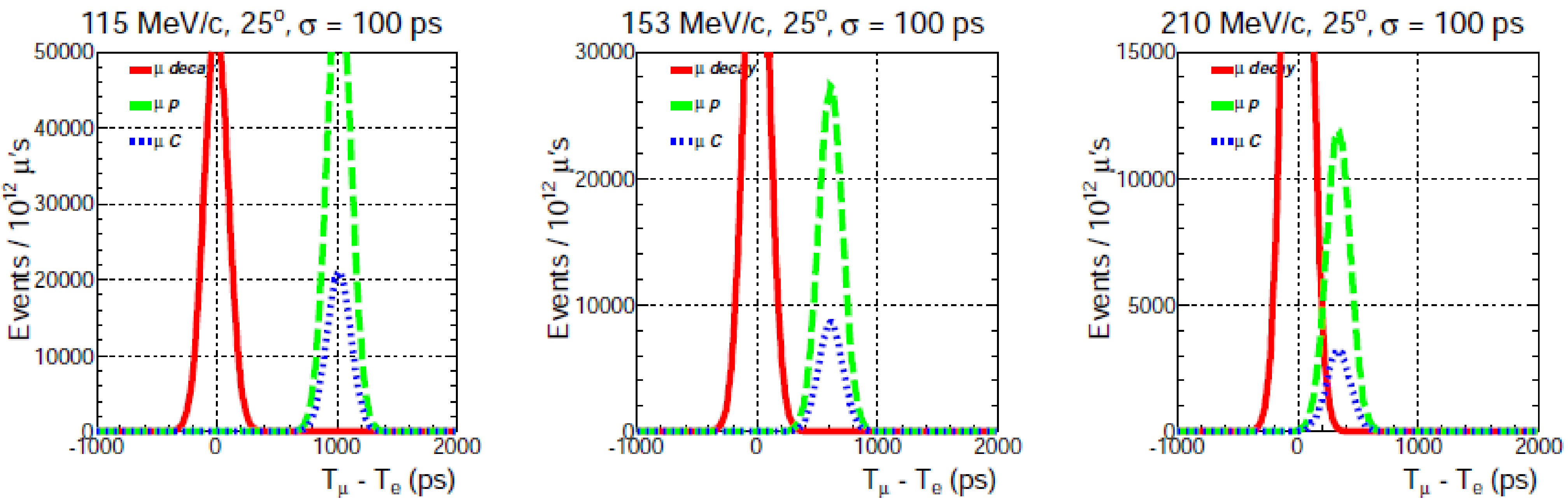
+- 5 cm cut is very safe - does not introduce angle dependence.

Resolution worse at forward angles from 1/sinθ effect

- Measurements:
  - empty target cell
  - thicker dummy target (match radiation length)

Muon Decay Backgrounds

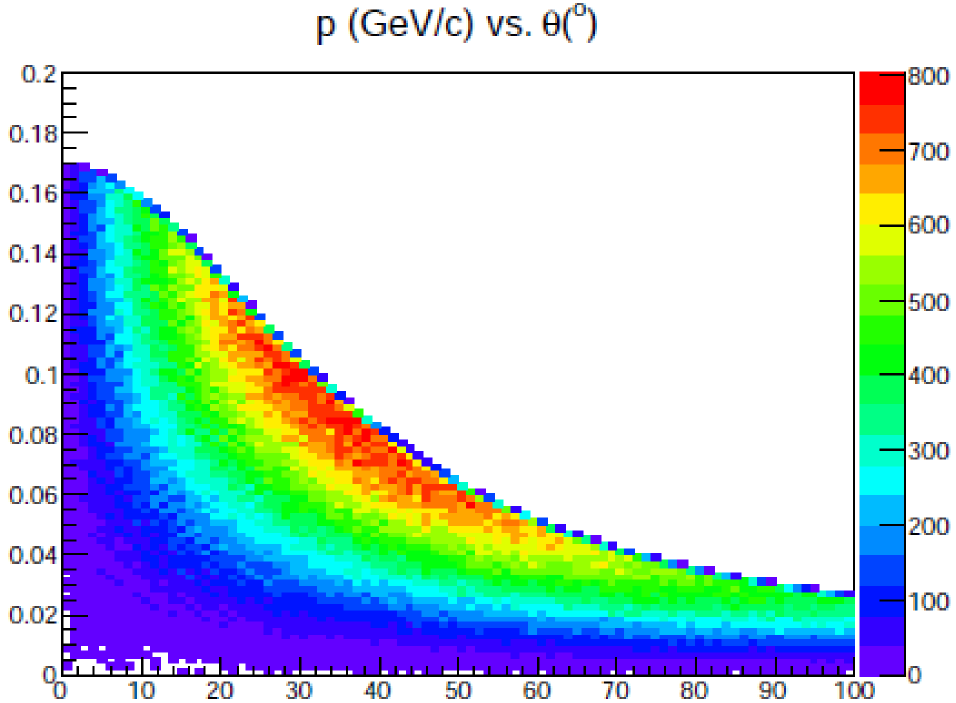
- Muon decay (red) compared to μp (green):

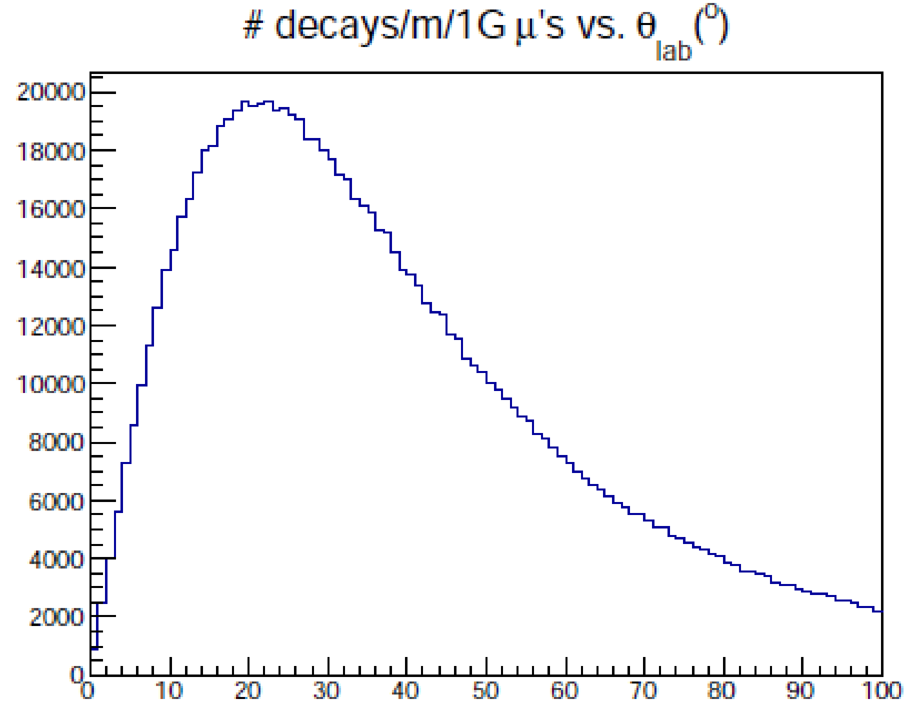


- 100% / 96% / 34% removed by TOF for 115 / 153 / 210
  - At lower momentum: TOF sufficient for removal
  - At middle and highest momentum: combination of TOF cuts and subtraction to remove

Muon Decay Backgrounds

- Muon decay lifetime and distribution known, decay rate 0.1%/m
  - Can calculate and subtract (cross check to measurement)
  - Only issue is muon polarization slightly changes the angular distribution – vary in simulation and fit to data
  - Shape of the distribution outside the target region calibrates the normalization for the subtraction





Analysis Systematics: Cuts

- Measure empty target and subtract counts in empty target run bin from counts in matched bin in full target run
- Measurements for same angular range at two separate times
  - Solid angle and beam counting the same, similar detector rates
  - Small difference in radiative corrections and multiple scattering
  - Requires good momentum stability (which we monitor)
  - Normalization different for subtraction of decays and endcap scattering
    - Can calculate decays, simulate decays, check with events coming from outside of target
    - Need relative foil thickness for endcap subtraction to ~1% uncertainty, or can cross normalize through $Q^2 = 0$ form factor.

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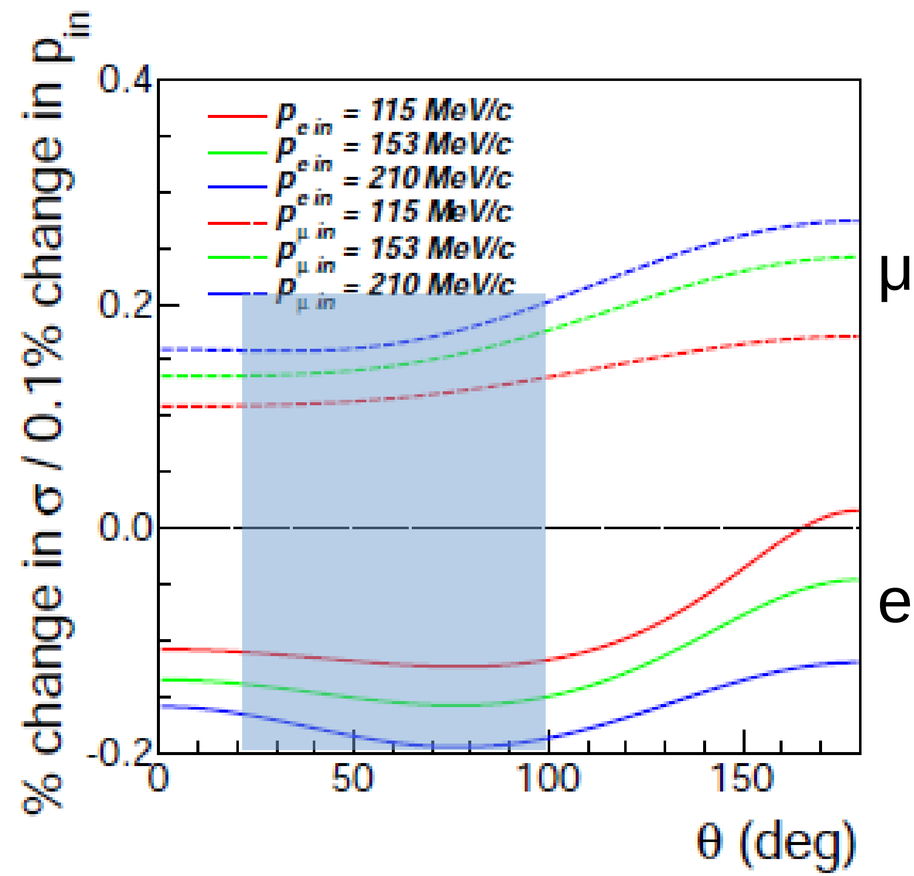
Cross Section Variations

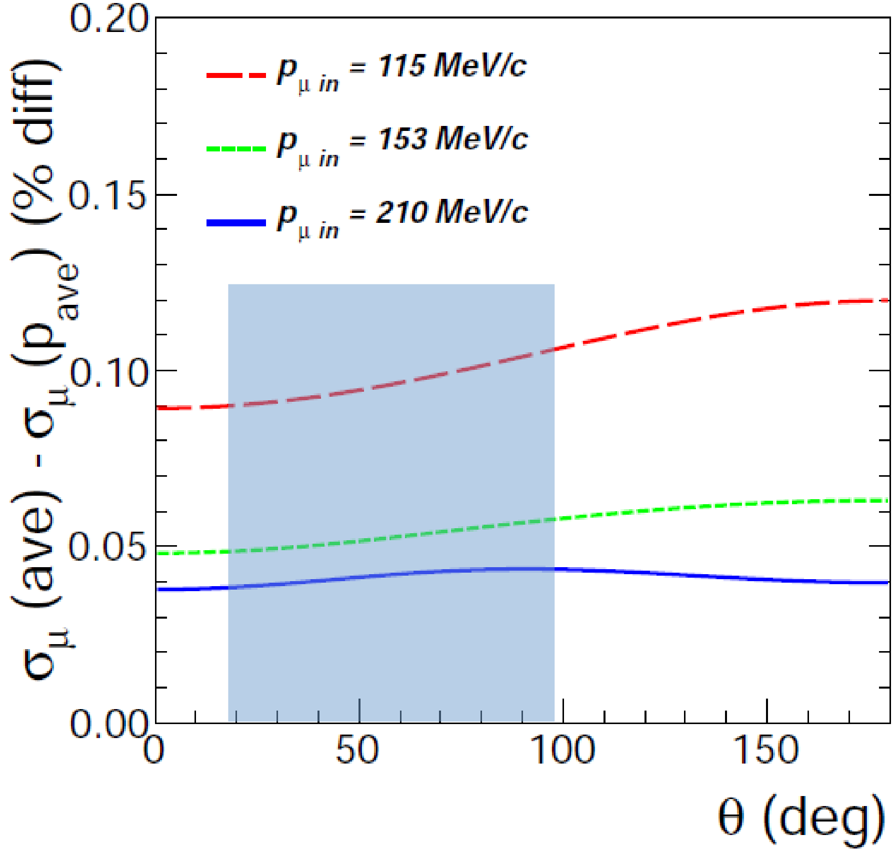
- Sensitivity to beam energy offset
  - Momentum determination to 0.1-0.2% through TOF and RF time measurements
  - Angle-to-angle variations small, <0.1% syst. uncert
  - Beam monitor scintillators will monitor shifts in π and μ peaks relative to e using random coincident particles
  - Momentum stability to 0.1%



Change in cross section for 0.1% change in beam momentum

Cross Section Variations

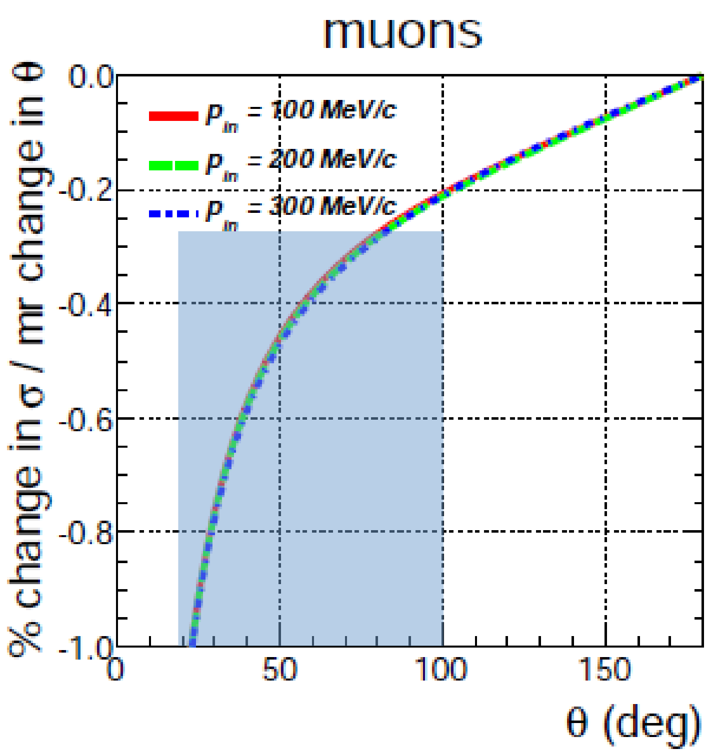
- Sensitivity to beam energy offset
  - Momentum determination to 0.1-0.2% through TOF and RF time measurements
  - Angle-to-angle variations small, <0.1% syst. uncert
  - Small effect from averaging over momentum acceptance
    - 0.05 – 0.1 %
    - Angle dependence 0.01%

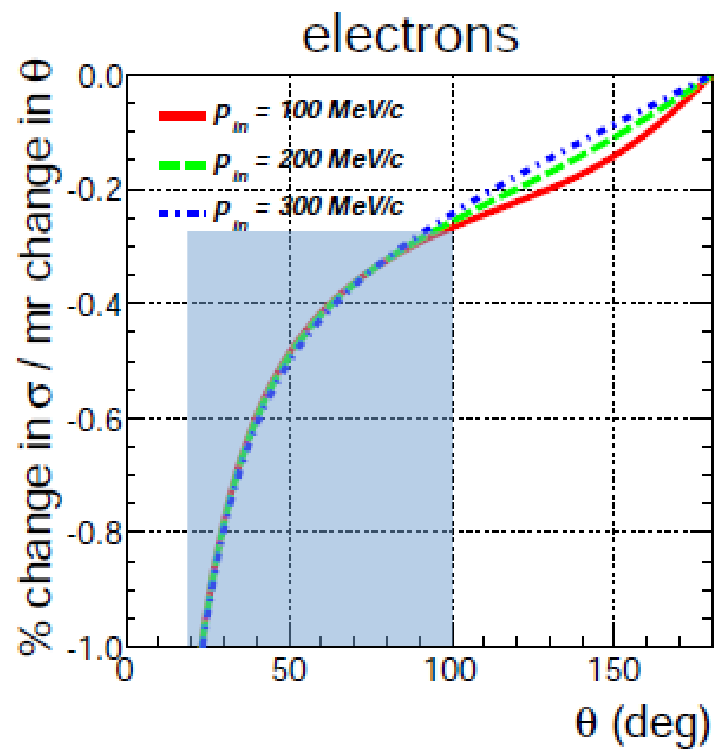


Difference in cross section for averaging over beam momentum

Cross Section Variations

- Sensitivity to scattering angle offset
  - Changes slope of the form factor versus Q^2
  - Spectrometer angle will be determined to 0.3 mr with calibration (using precision rotation of detector table to scatter particles through GEMs and chambers)

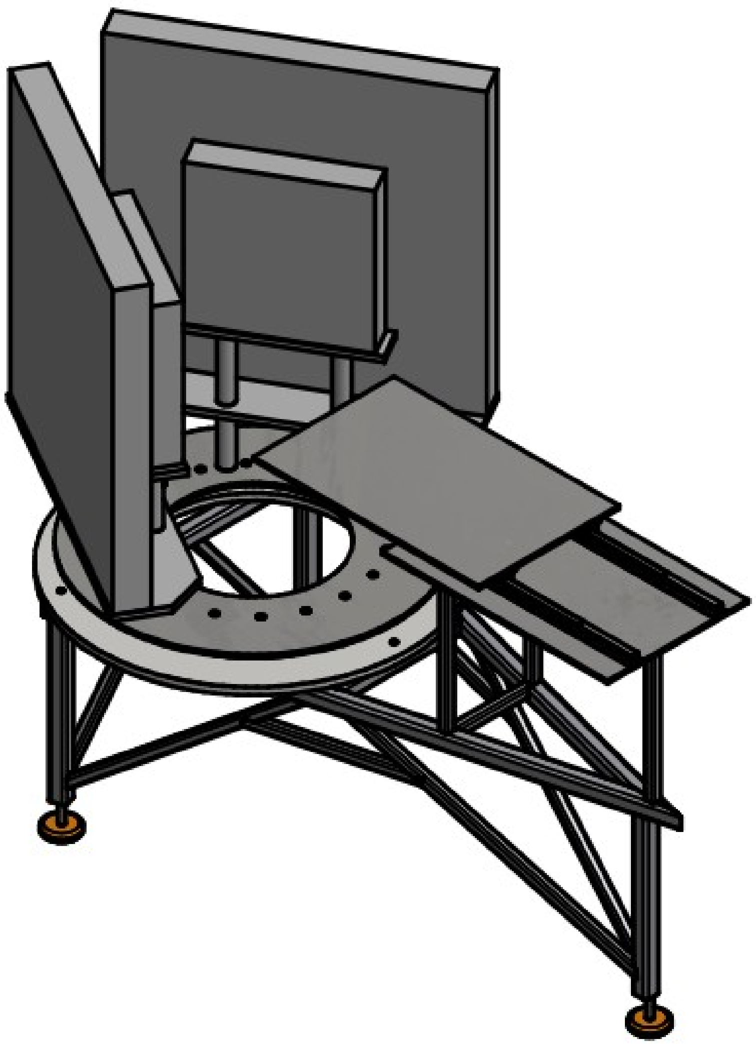




Change in cross section for 1 mr change in scattering angle

Cross Section Variations

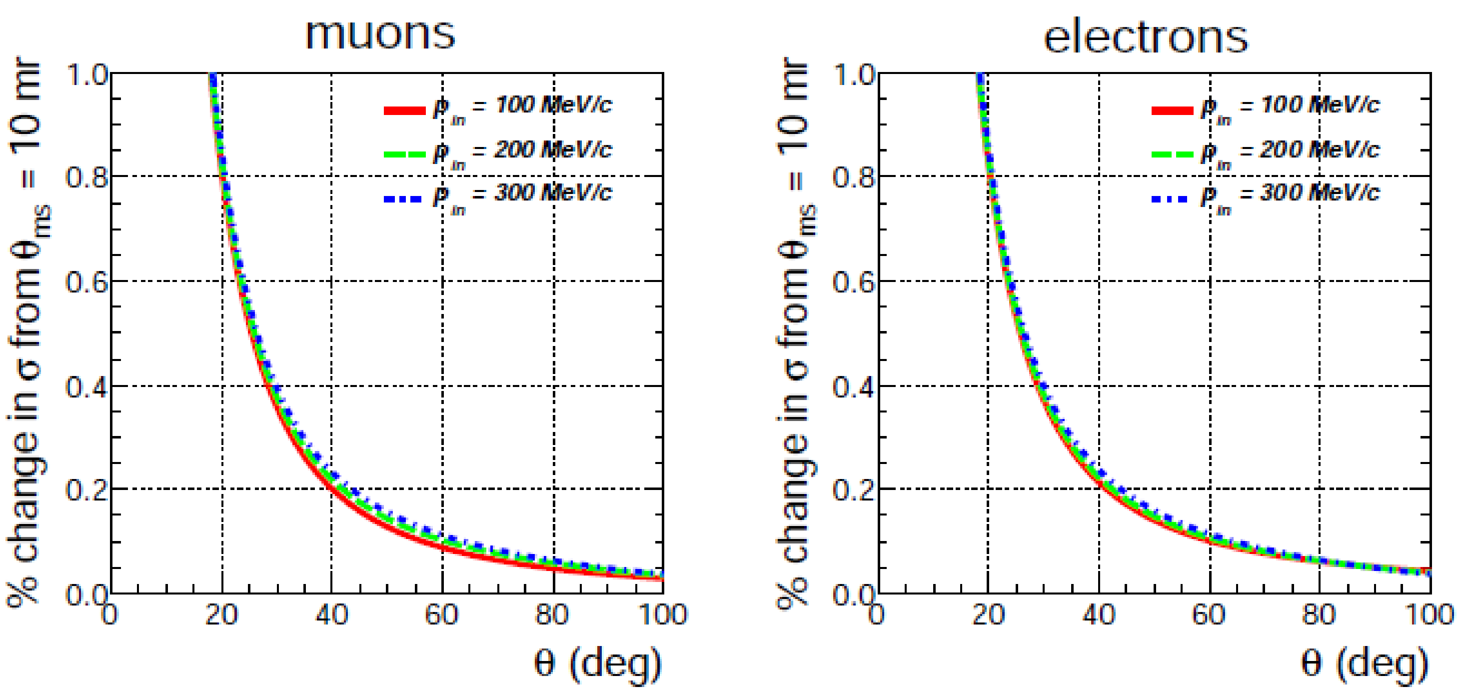
Angle Calibration:



- GEM chambers slide upstream, straw chambers can be rotated to 180^o, immediately adjacent to last GEM
- GEM track position to 100 μm, STT track position to 150 μm
- Use high-energy beam with ~3 mr multiple scattering
- Leads to position determination of STT of:
  - 300 μm for rear chamber
  - 900 μm for front chamber
- Corresponds to angular uncertainty
  - 0.8 mr for rear chamber
  - 3.1 mr for front chamber
- Centroid determined a factor of 10 better, leading to 0.3 mr

Cross Section Variations

- Sensitivity to multiple scattering
  - Averages over scattering angles
  - Limit to ~10 mr of multiple scattering: ~0.5% correction
  - Contributes ~0.3% relative systematic uncertainty (rms)
  - Will calculate multiple scattering with simulations -- with good reproduction of data, error will be smaller



Change in cross section from 10 mr of multiple scattering

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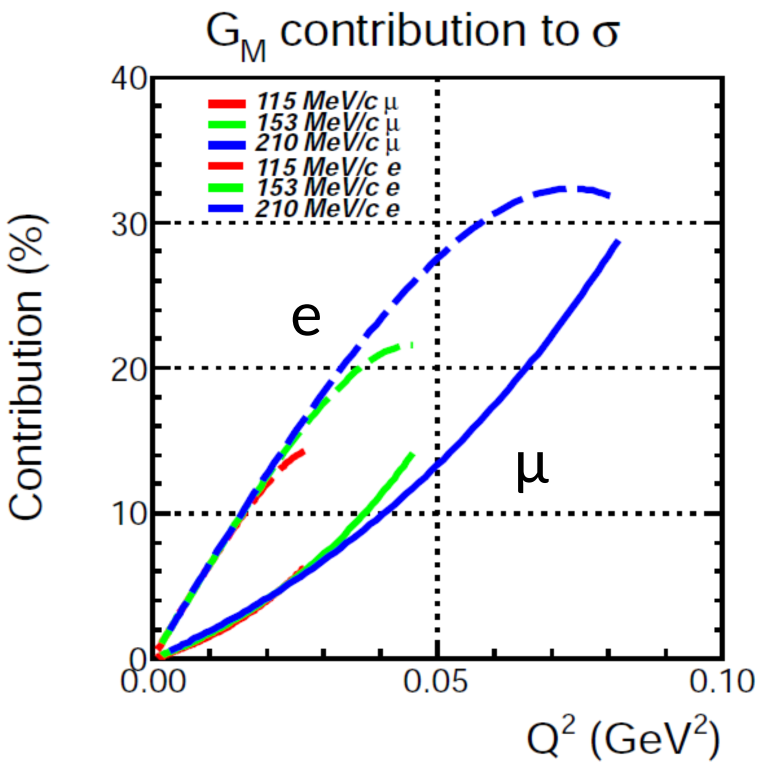
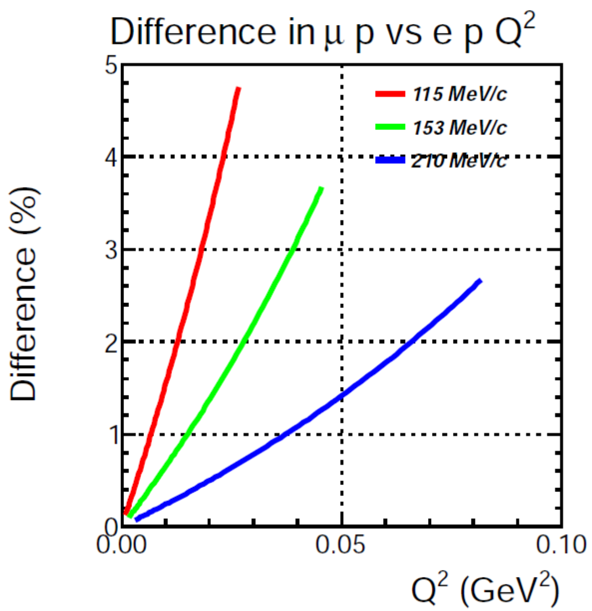
Magnetic Contribution



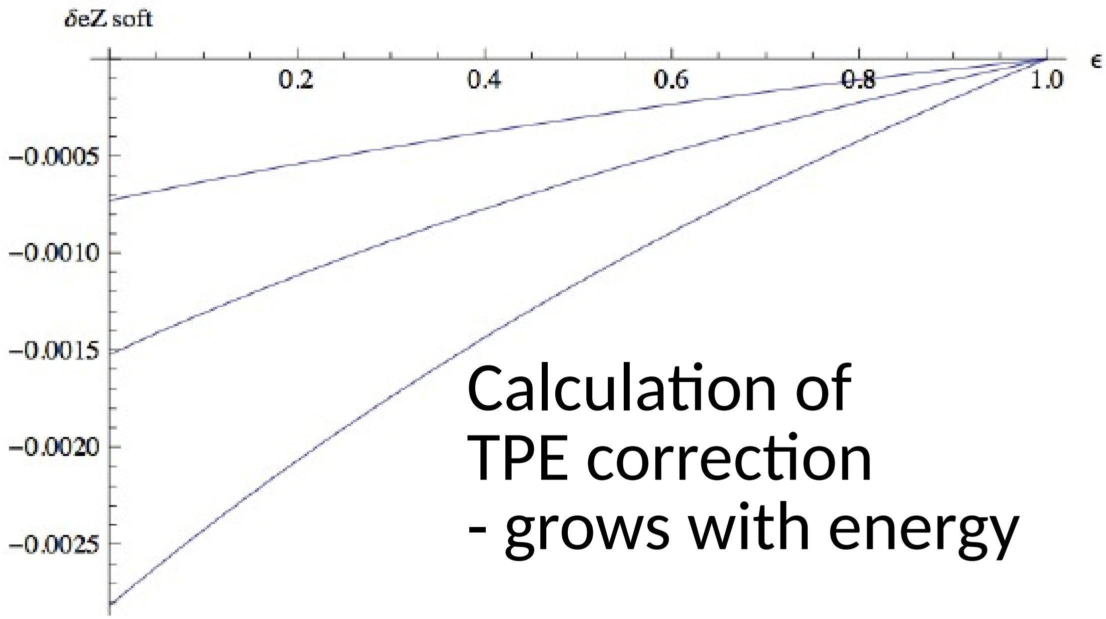
- Magnetic contribution ~30% at largest Q^2 setting
- Bernauer data: uncertainty in magnetic form factor ~0.3%
- There is a 1% difference in magnetic radius between Bernauer and Arrington (1/2 may be from different two photon corrections)



- Uncertainty 0.1-0.14% level
- Drops out in +/- comparisons
- Goes away to some degree in e/mu comparison since kinematics are similar (Q^2 different by a few percent)

TPE and Coulomb Corrections

- TPE: Not more than 0.25% effect at MUSE kinematics, uncertainty half this
  - Changes sign with polarity: we will measure TPE
  - Calculations thought to be reliable and in good agreement with a low-Q^2 TPE expansion, valid up to $Q^2 = 0.1\ GeV^2$

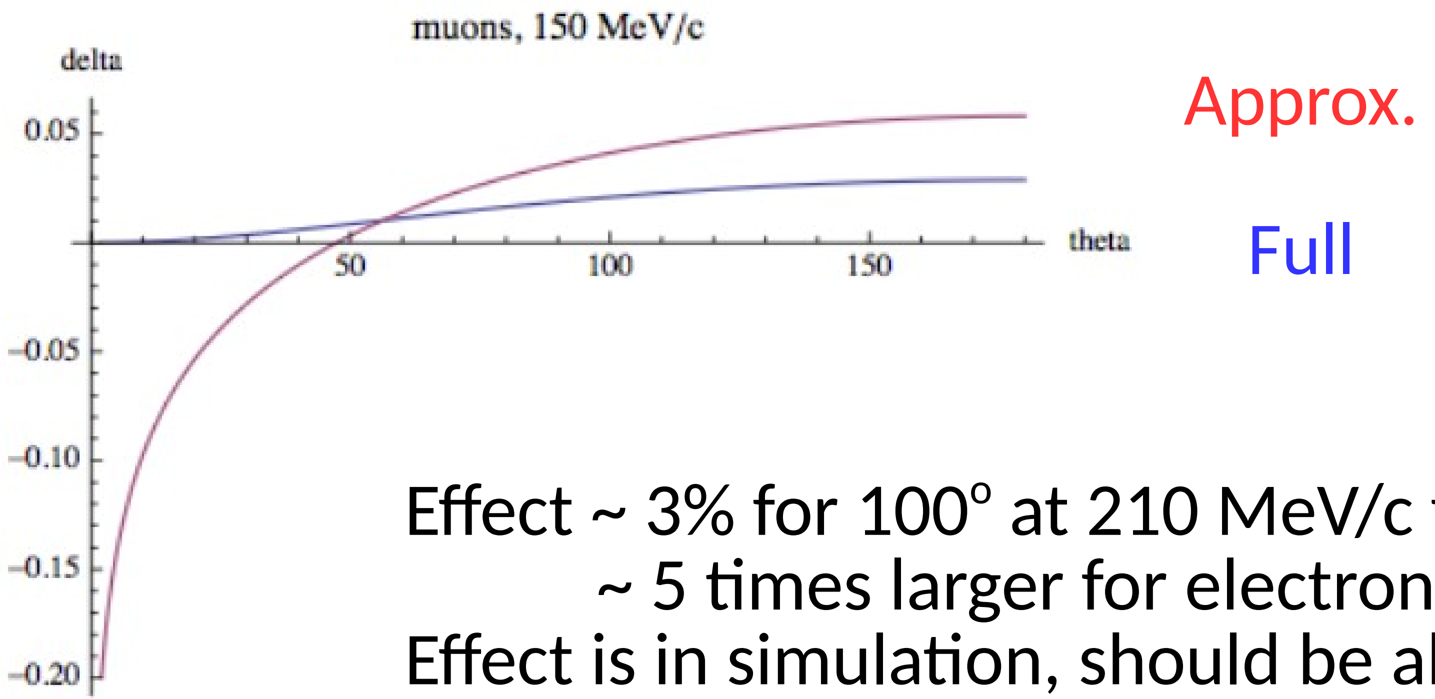


Calculation of
TPE correction
- grows with energy

- Coulomb Corrections: Standard codes exist; effects expected to be small

Radiative Corrections

Calculation of radiative correction for muon:



Effect ~ 3% for 100° at 210 MeV/c for muons
~ 5 times larger for electrons
Effect is in simulation, should be able to correct
Uncertainties over an order of magnitude smaller

Standard codes exist, but must be updated to avoid approximations (peaking, ultra-relativistic)

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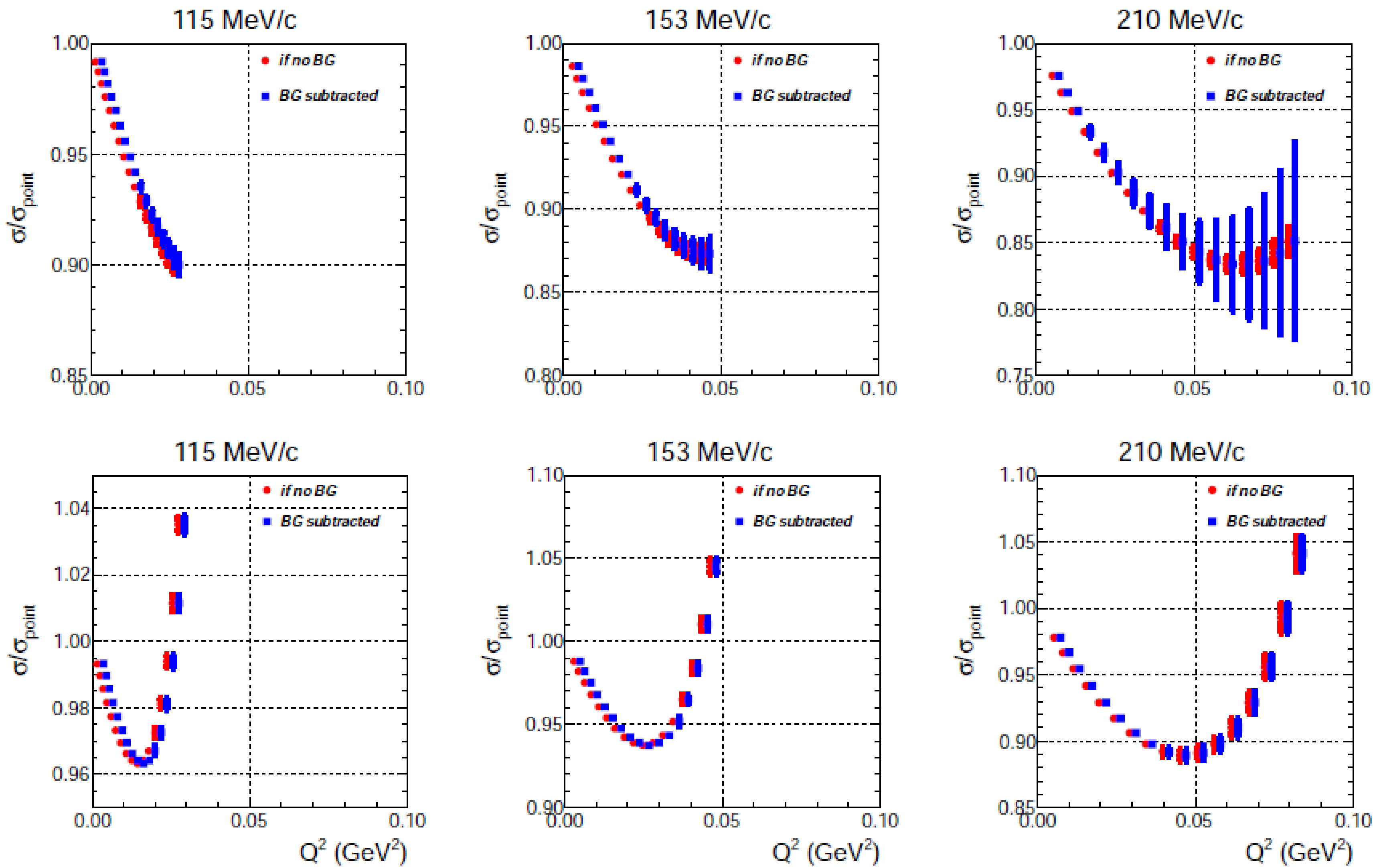
Estimated Results

Cross Sections: μ^+p (top), e^+p (bottom) [Kelly FF's]



Offset in blue points for plotting

Statistical errors only

For electrons: Stat. errors well below 1%

For muons: Stat. errors below 1% for 115 and 153, above 1% at 210.

Relative Systematics Table

Solid Angle	0.1%
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Total Relative Uncertainty in Cross Section*:

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