Projected Results

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Background / Assumptions
Optimization
Radius (J Bernauer's work)
Ratios
Summary

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Background / assumptions

- Projections are based on experience running 2022 - 2023, extrapolated out to 15×10^9 events — took ~ 1×10^9 in 2021 (no TCPV), 1×10^9 in 2022, 3×10^9 in 2023.
- Analyzed runs in each of the 6 momentum settings to determine yields per run, but yields depend on analysis techniques / cuts:
  - Tradeoffs between signal and background
  - Tradeoffs between statistical and systematic uncertainties
  - Detector analysis focussed on ensuring clean data sample, removing backgrounds — might be more recoverable events

Background / assumptions

- Projections will also depend on how we divide the beam time between the 6 momentum settings and full vs empty cell data
  - Results are not very sensitive to the division of time
  - Slightly different optimizations for different physics
    - radius
    - $\sigma_{ep}/\sigma_{\mu p}$ for lepton universality
    - two-photon exchange

Optimizing uncertainties

Look at cross section ratios for division of time between full and empty cells:

- Generate pseudodata for
  $r(Q^2) = (\sigma_{\mu p} / \sigma_{ep})_{data} / (\sigma_{\mu p} / \sigma_{ep})_{theory}$.
- Fit with $r(Q^2) \; = \; c + sQ^2$.
- Plot uncertainties for c and s.

For division of time between momenta, generate pseudodata from various parameterizations, fit with various parameterizations, examine results.

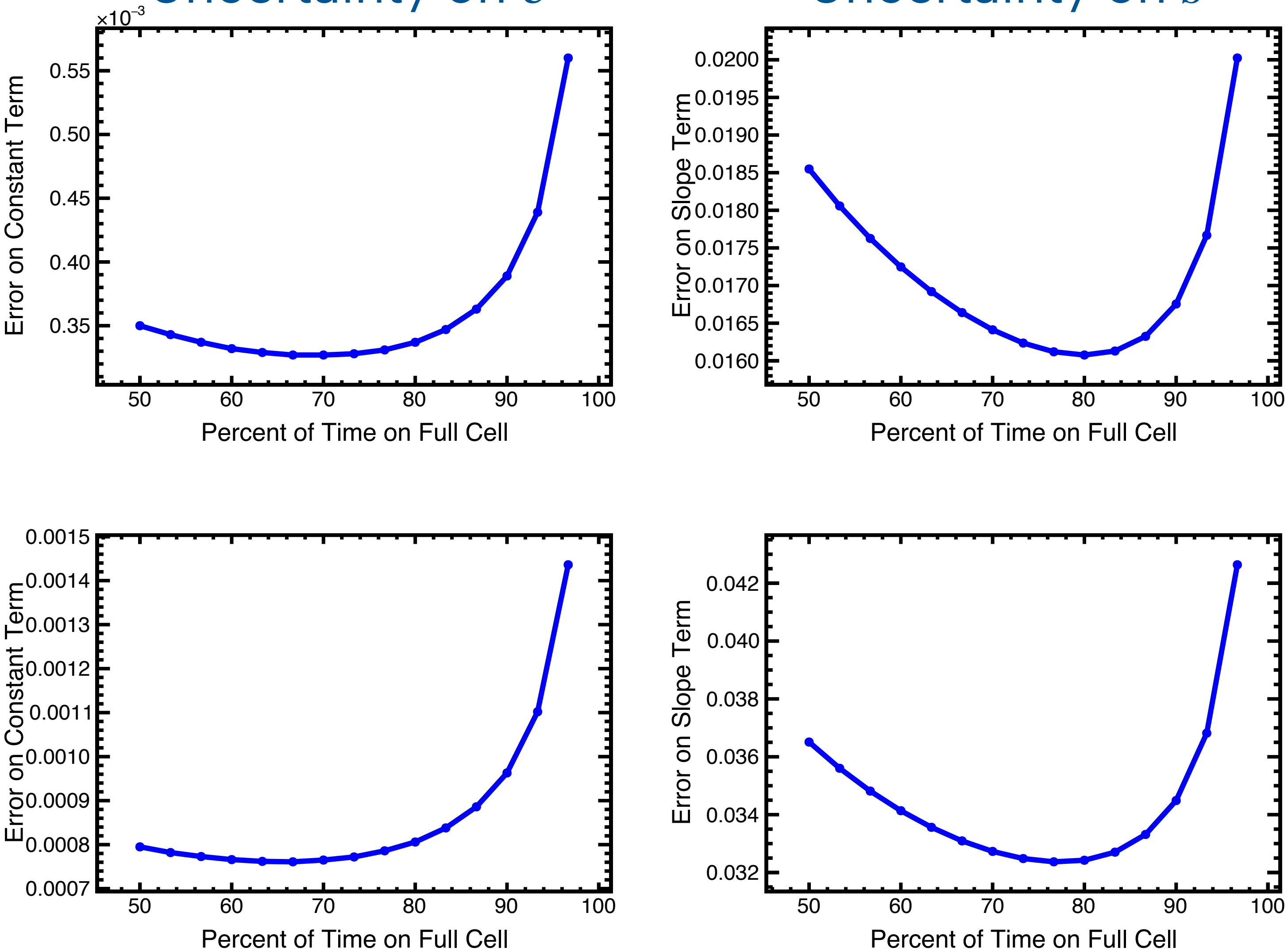
General result: optimization has shallow minimum

Uncertainties of full-vs-empty cell time

Uncertainty on c | Uncertainty on s

$\sigma_{\mu p} / \sigma_{ep}$

$\sigma_{\mu^+ p} / \sigma_{\mu^- p}$

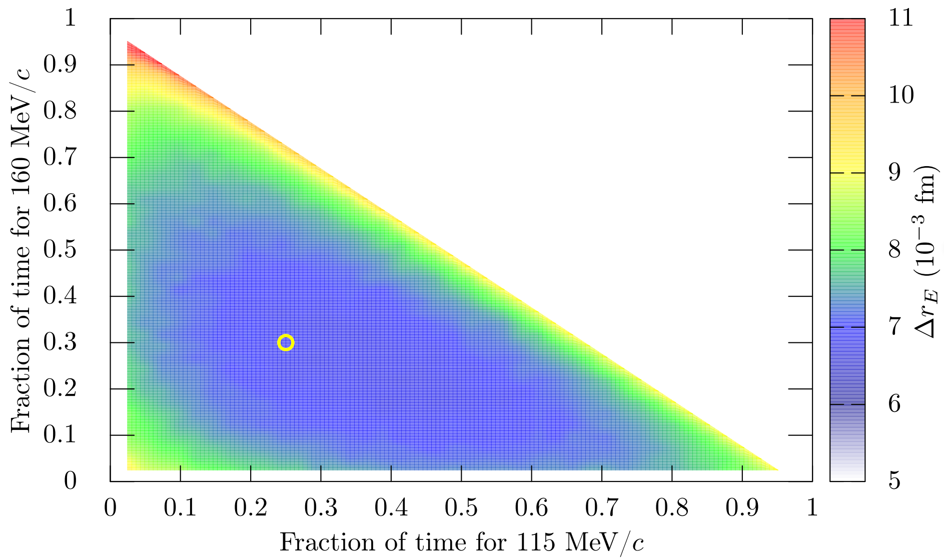


The minimum is shallow. Note suppressed 0's.

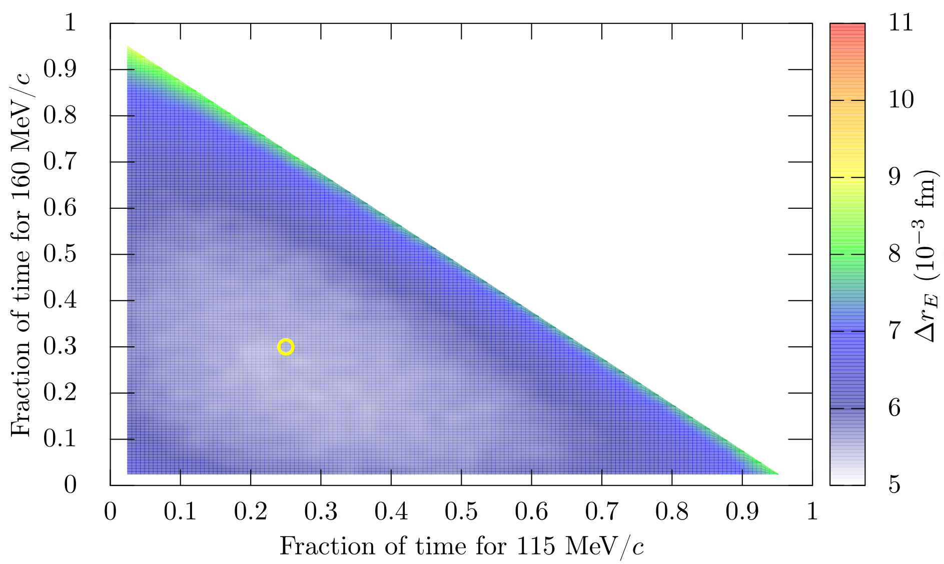
Optimum division of time depends on quantity.

Radius uncertainties

R(1, 1) / variable dipole model analysis



R(0, 2) / fixed dipole model analysis



What to take away from this analysis: ~ 15 % effect on the uncertainty from a wide range of choices of how we divide the time between momenta

Goal for uncertainty is 8 (10^{-3} fm).

Optimization summary

- The ratio analysis suggests 70% - 80% of time is spent on full cell. We typically run 60% — the final comparison to simulation will have overall lower S/N.
- Different fits lead to slightly different optimizations.
- A 10% change in statistical uncertainties is equivalent to a 20% change in amount of data taken, so it is important to try to get the division of time optimized.
- As we analyze more data, advance the analysis techniques towards those for the final data analysis, and choose exactly how we will fit the radius, we can better determine optimum.
- We will continue to revise our planned data taking to reflect our understanding of how to optimize uncertainties.

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Radius uncertainties, bias

TABLE III: Uncertainty (σ) and bias (Δ) for three input models and a series of model selections for the fits. Each model combination is fitted to a set of 10,000 variations of the input model.

Uncertainty of 8 x 10^{-3} fm corresponds to ~ 5 sigma.

Model for		Input model: JCBP10		Arr07		Std. dipole	
G_E	G_M	σ (10^{-3} fm)	Δ (10^{-3} fm)	σ (10^{-3} fm)	Δ (10^{-3} fm)	σ (10^{-3} fm)	Δ (10^{-3} fm)
$R(1,1)$	JCBP10	6.3	-2.1	5.9	2.2	6.2	8.6
$R(1,1)$	std. dipole	6.3	-4	5.9	0.3	6.2	6.6
$R(1,1)$	dipole	7.9	-0.1	7.3	8.6	7.4	8.2
$R(1,1)$	linear$\times$std. dipole	8	0.3	7.4	9.1	7.6	8.4
$R(1,1)$	$R(1,1)$	9	5.6	9	10.3	9.4	11
dipole	dipole	3.8	-21	3.8	-3.7	7.1	3.4
linear$\times$std. dipole	linear$\times$std. dipole	3.5	-25	3.4	-7.3	3.7	3.2
$R(0,1)$	std. dipole	2.5	-12.6	2.5	22	2.6	20.6
$R(0,1)$	dipole	4	-9.7	3.9	8.3	4.2	13
$R(0,1)$	$R(0,1)$	4	-11.7	4	5.8	4.2	10.7
$R(0,2)$	std. dipole	6.1	-4.2	6.1	-0.1	6.4	6.4

From analysis report. But ...

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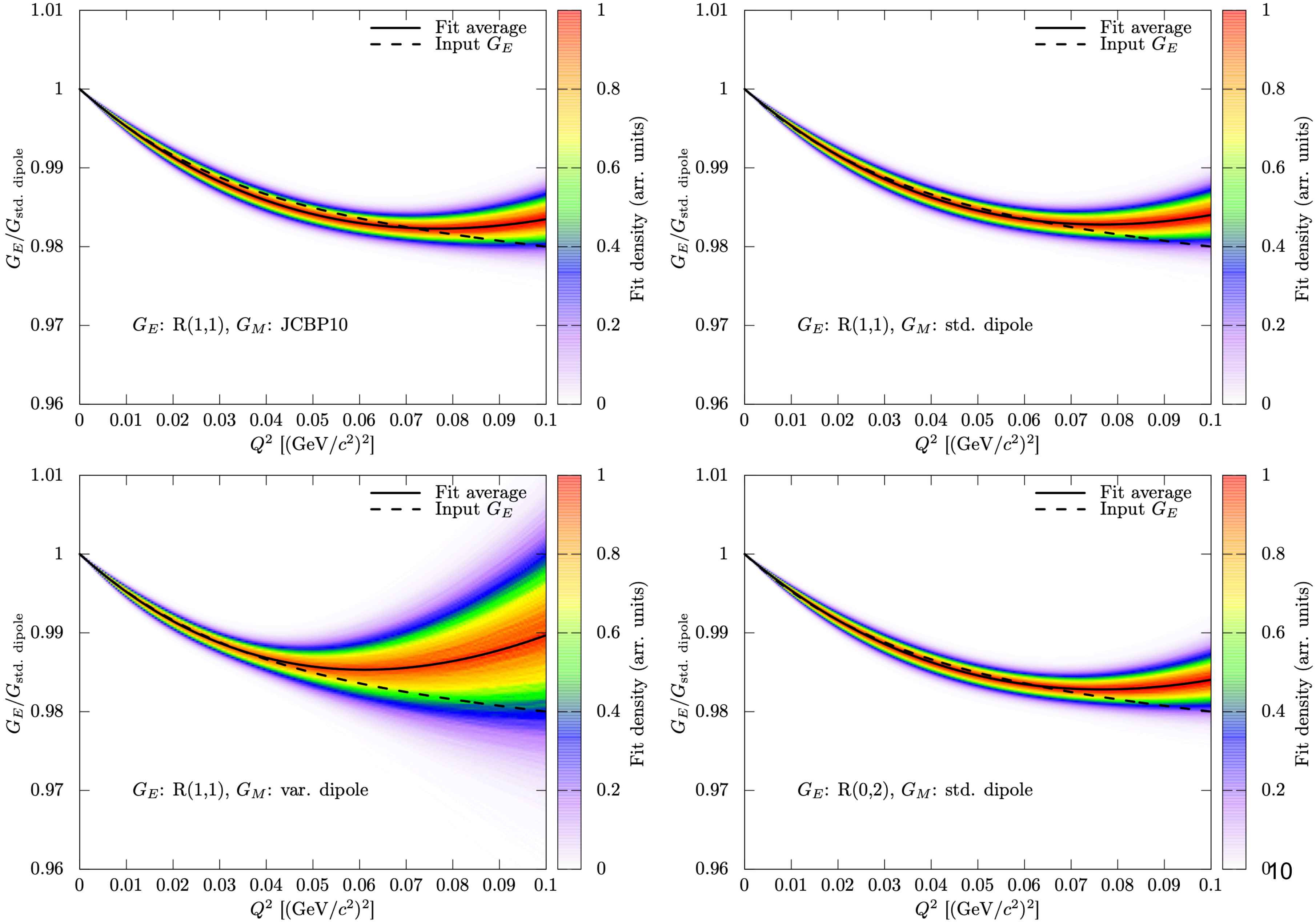
Expecting to use R(1,1) + pre-existing G_M fit.

It is fair to use multiple existing fits to study model dependence.

Q^2 dependence examples



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Conclusions on radius fits

- We have been looking in more detail at the fitting technique:
  - Uncertainties are sensitive, but not very sensitive, to the division of time.
  - Uncertainties and bias depend on choice of models.
  - Different assumptions → different optimization.
- More work needed on larger variety of fits, ensuring no pathologies.
- Best practice is to publish planned method before analysis of actual data - we expect to do this during 2024.
- Complementary, independent technique: trade off fit uncertainties for theory uncertainties by comparison to Gil-Dominguez et al.

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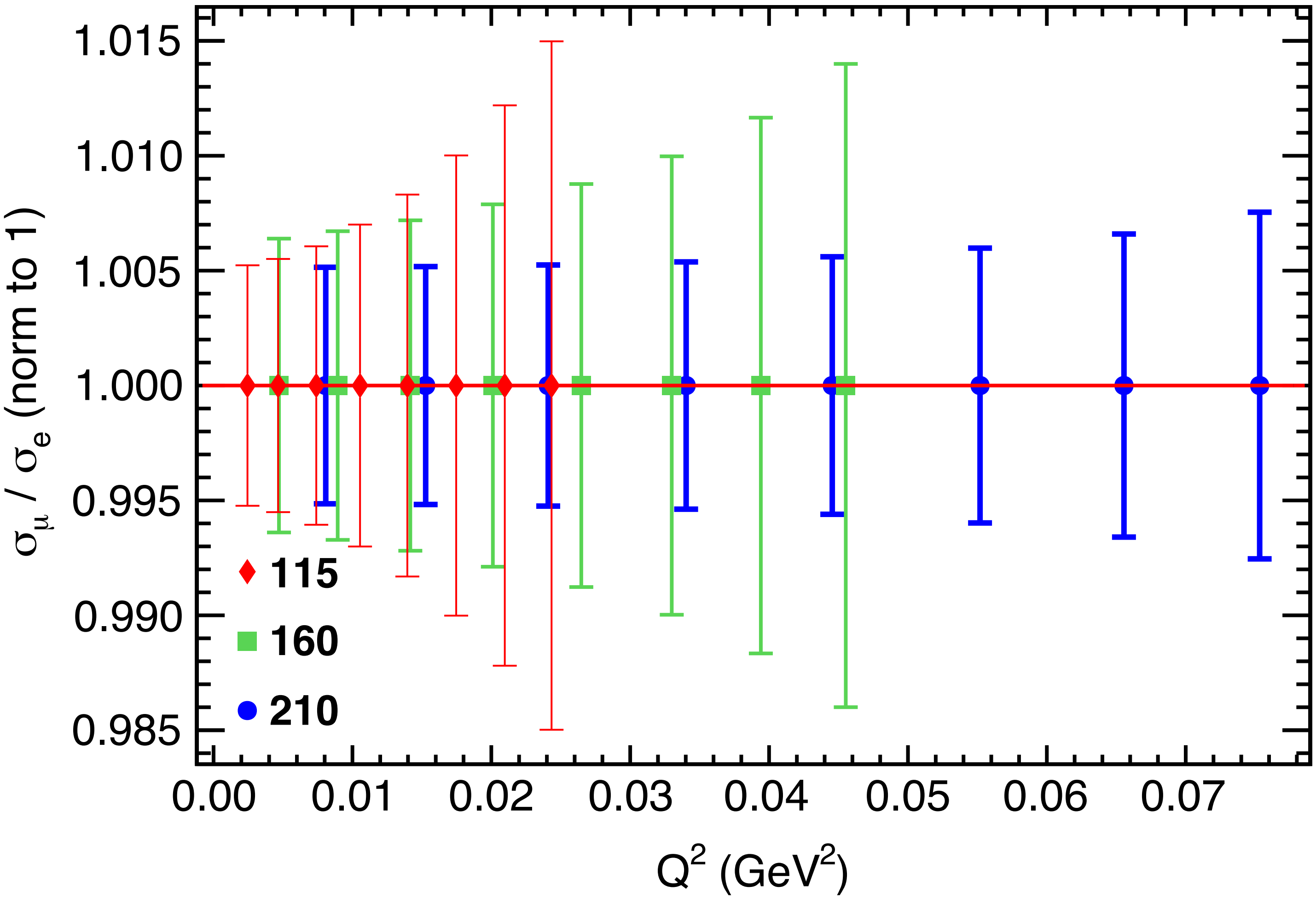
Cross section ratios

- Have also looked into cross section ratios - same statistical assumptions used for generating pseudodata as for radius determination already shown

σ_μ / σ_e

$\sigma_{\mu p} / \sigma_{ep}$ determined to 0.5 - 1.5 %. Benefit from relatively larger rates for μ's at +210 MeV/c.



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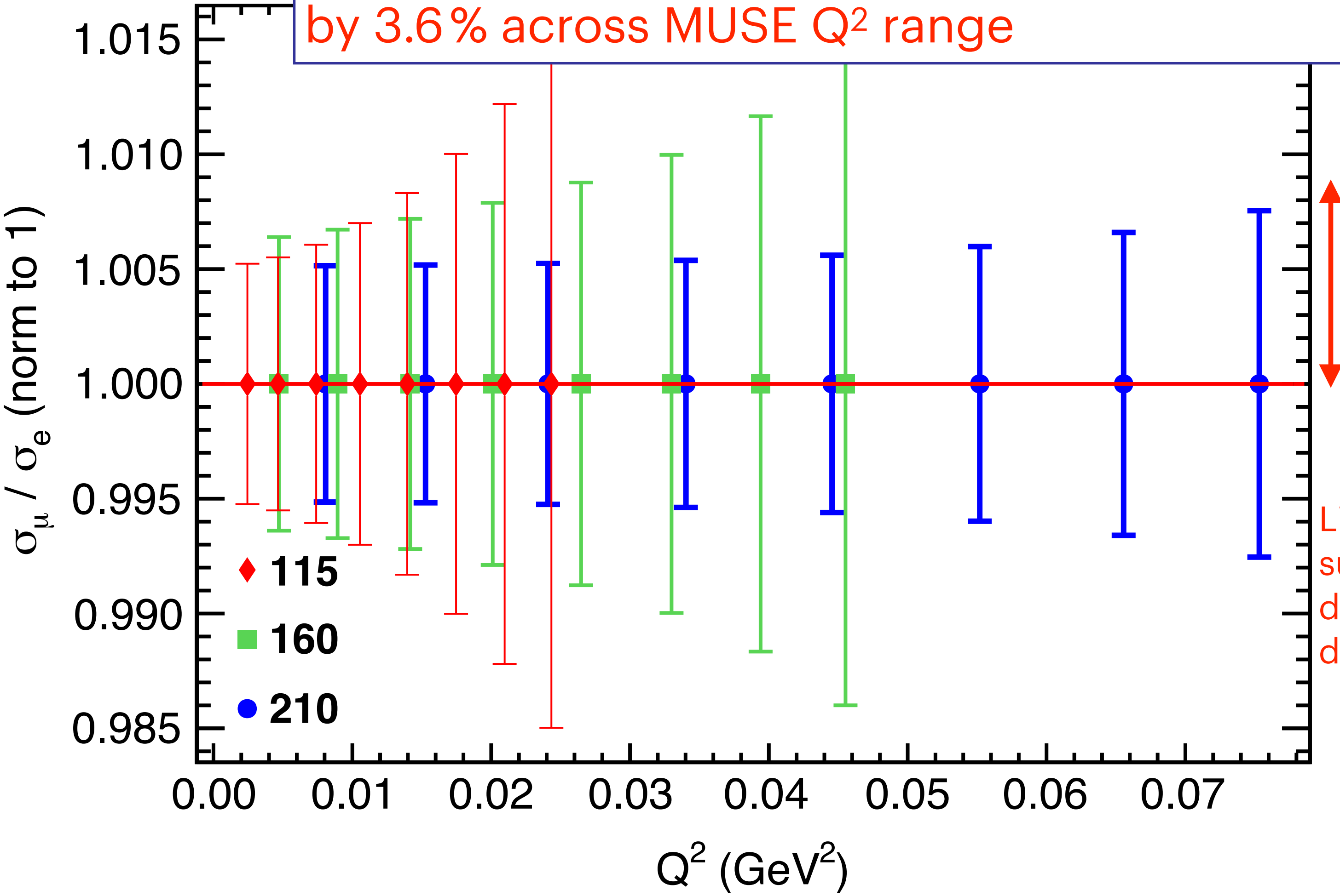
$\sigma_{\mu p} / \sigma_{ep}$ determined to 0.5 - 1.5 %. Benefit from relatively larger ra

S. Strauch overview talk, slide 5, Gil-Dominguez et al.: 0.04 fm change in radius changes fall-off of cross sections by 3.6 % across MUSE Q^2 range

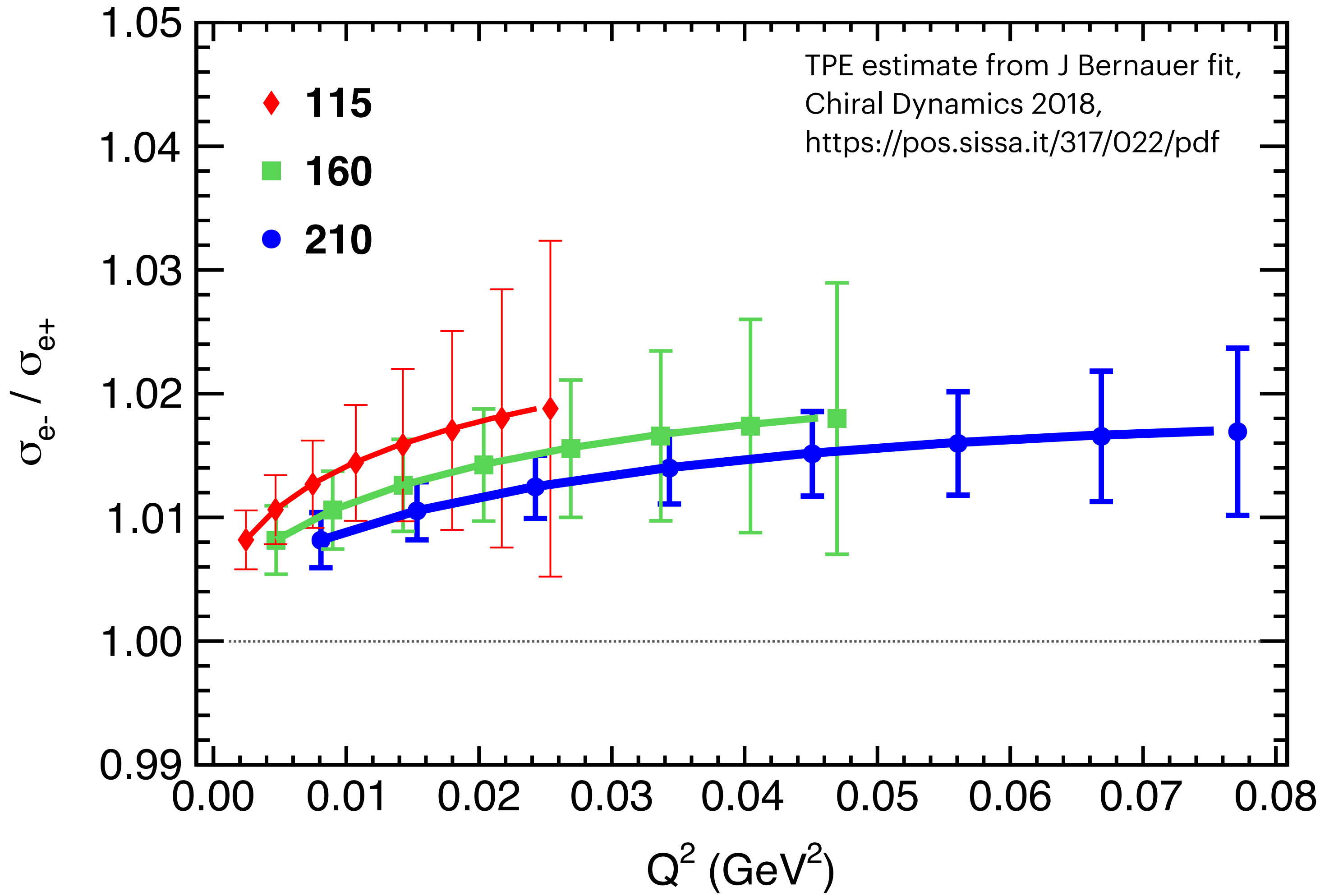


Effect of 0.01 fm radius difference

Linear fits of slide 4 suggest ratio determines radius difference to ~ 0.002 fm

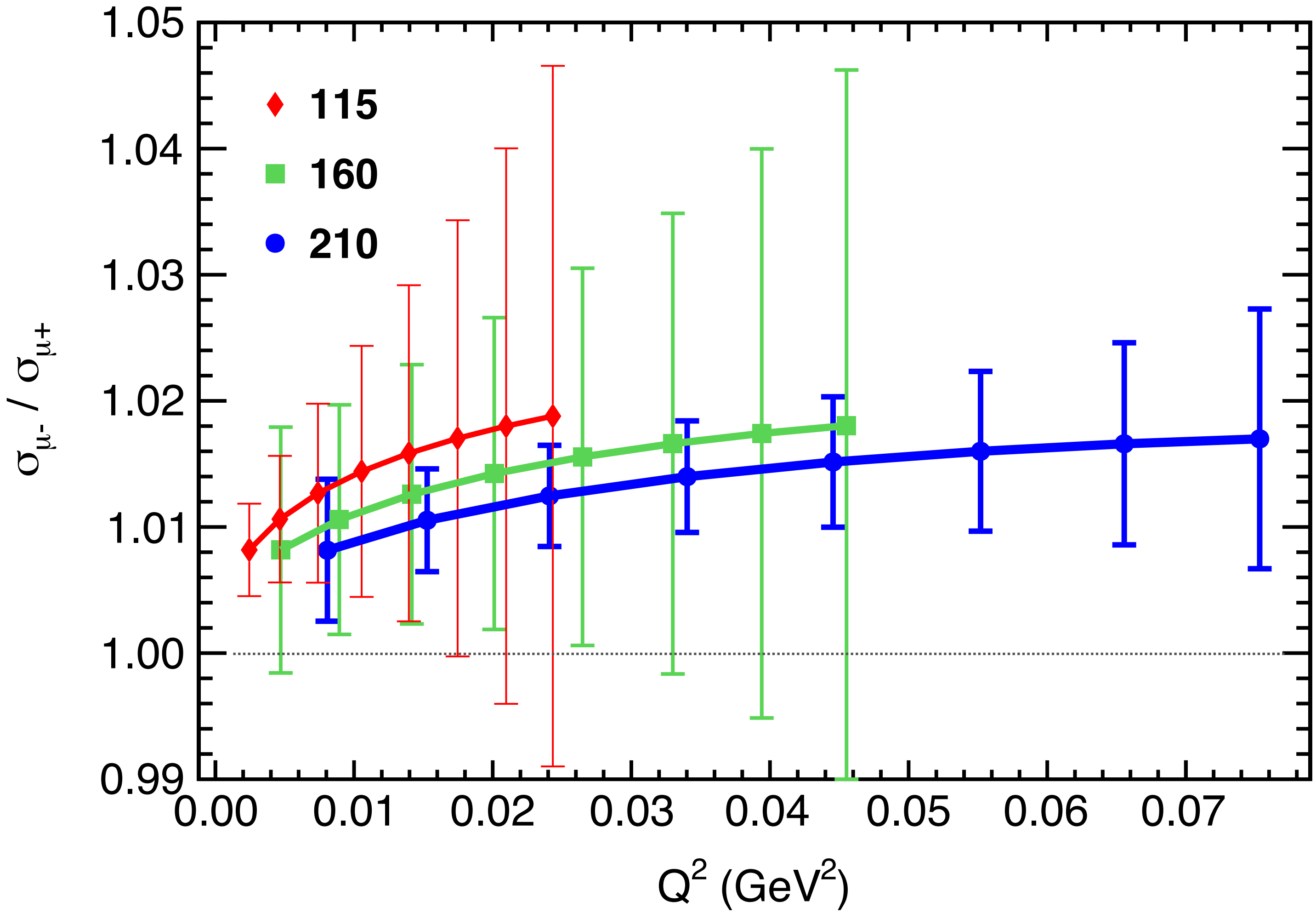
$\sigma_{e^-} / \sigma_{e^+}$

Two-photon exchange for electrons. Determine 2%* effect with 0.25 - 1.4% data. *Calculations and fits of TPE vary in size.



$\sigma_{\mu^-} / \sigma_{\mu^+}$

Two-photon exchange for muons. Determine 2%* effect with 0.4 - 3% data. *Calculations and fits of TPE vary in size.



Cross section ratio conclusions

- Ratios determined at the percent level
- Most precise comparison of $\sigma_{\mu p} / \sigma_{ep}$ by ~ an order of magnitude
  - Gil-Dominguez et al. suggest a 0.01 fm change in radius would result in about a 0.9% change in how fast MUSE cross sections fall with Q^2.
- Sufficient to determine TPE at the level it is expected to be
  - Comparison of OLYMPUS TPE data to fits and theory suggests TPE correction is sufficient to change radius extractions by ~ 0.01 fm.
- We do need more work on systematic uncertainties in the analysis

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2024 Plans

- We do have issues each time we move back into PiM1, so we need to minimize the number of times MUSE moves.
- Beam time request assumed practicum is fixed in PiM1.
- Led to plan for 2024:
  - Maintenance work in PiM1 during the spring - expecting survey, detectors, GEM DAQ, ...
  - Run through late September / October. (4.5 months)
  - October / November in staging area.
  - Back into PiM1 for November / December. (1.5 month)
  - Goal is to take ~ 6×10^9 events in scattering runs, improve balance of statistics between different momenta.

2024 Plans

- If the practicum can be moved, alternate plan for 2024:
  - Maintenance work in PiM1 during the spring - expecting survey, detectors, GEM DAQ, …
  - Run through late November. (6 months)
  - Back into PiM1 during downtime, after next BV determines 2025 schedule.
  - Goal is to take ~ 6×10^9 events in scattering runs, improve balance of statistics between different momenta.