A New Track Trigger for the Proton-Radius Measurement at COMPASS++/Amber

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Measurement of the $Q^2$ Spectrum at COMPASS

- high-intensity muon beam
  $\phi_\mu \sim 2 \cdot 10^6 / s - 2 \cdot 10^7 / s$

- would correspond to data rates of
  3 GB/s – 20 GB/s (~7-50 PB per year)

- without trigger selection only
  ~0.04‰ interesting events
  (for $Q^2 > 10^{-3}$ GeV$^2$)

→ remove the “unscattered” muons with a kink trigger
Triggering on Scattered Muons

Requirements

• reject unscattered muons below $Q^2 < \text{threshold} \ (\sim 10^{-4} - 10^{-3} \text{GeV}^2)$

• high trigger efficiency for scattered muons with $Q^2 > 10^{-3} \text{GeV}^2 \ (>90\%)$

• low material budget (source of multiple scattering)

• large active area (large beam profile)

• withstand high beam rate without pile up
Fiber-Trigger Stations: Scintillating Plastic Fibers Coupled to Silicon Photomultipliers

Tracking Station
- layers of scintillating plastic fibers with alternating orientation
- 250 fibers per layer with 200 $\mu m \times 200 \mu m$ cross section and $\sim 200 \text{ mm}$ length
- 4 layers (2 oriented horizontally, 2 oriented vertically)
- relative shift of layers by 100 $\mu m \rightarrow 100 \mu m \times 100 \mu m$ effective “pixel” size
- each fiber individually read out by two silicon photomultipliers (one on each end)
Fiber-Trigger Stations: Scintillating Plastic Fibers Coupled to Silicon Photomultipliers

- low material budget (~4% contribution)
- very fast: organic scintillator ~ 2 ns
  SiPMs ~ 10 – 100 ns
- good single-channel time resolution
- no pile-up for expected beam settings
Identification of a Scattered Muon

- determines track parameters of incoming muon

✓ only one trigger station within the scattering-sensitive measurement regime (minimize multiple scattering)
✓ simple calculation for online triggering (FPGA based)
• low-$Q^2$ resolution limited by fiber cross-section
Challenge: Having a High Detection Efficiency for the Muon

- high-energy muons are nearly minimum-ionizing: ~40 keV energy deposition in fiber
- together with scintillation efficiency, photon transport, and detection efficiency of SiPMs we expect only ~10 photoelectrons (p.e.) in average (Poisson distributed)

- noise level of SiPMs ~10 kHz @ 2 p.e.
  → reduced to a few Hz by coincidence requirement of two SiPMs
Simulation of Trigger Efficiency and Rejection Efficiency

- **efficiency**: $97\%$ @ $Q^2 = 10^{-3}$ GeV$^2$
- **rejection power**: $96.5\%$ @ $Q^2 < 10^{-3}$ GeV$^2$

**Systematic Studies**
- misalignment studies
- influence of mechanical tolerances (gaps between fibers, fiber-size variations, …)
- tune trigger threshold
- acceptance correction for measurement range
- investigate correlation between trigger efficiency and proton-radius parameters
Fitting Procedure: Markov-Chain Monte Carlo (MCMC)  
*(Work in Progress!)*

- Bayesian probabilistic analysis method

- evaluate the full posterior-probability distribution (not only a point estimate)

- update information on parameters given new data

- include acceptance corrections as nuisance parameters in the fit with informative priors

- marginalize out nuisance parameters  
  \( \rightarrow \) posterior-probability distribution of the target parameter \(<r^2>\)

- allows extended correlation studies between the parameters

\[
p(\theta|D) = \frac{L(D|\theta) \cdot \pi(\theta)}{\int L(D|\theta')\pi(\theta')} \propto L(D|\theta) \cdot \pi(\theta)
\]

\[
p(\theta_0|D) = \int p(\theta_0, \theta_n|D) \, d\theta_n
\]

Implementation using the Bayesian Analysis toolkit (BAT)  
(Caldwell et al.  
http://www.mppmu.mpg.de/bat)
Example: Fitting Polynomial Function (up to $Q^8$) to Toy MC Data

\[ r_D = 0.77 \text{ fm}^2 \]
\[ r_G = 2.63 \text{ fm}^4 \]
\[ r = 26 \text{ fm}^6 \]
\[ r = 374 \text{ fm}^8 \]

work in progress
Example: Fitting Polynomial Function (up to $Q^8$) to Toy MC Data

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→ easily visualizable how a constraint on a nuisance parameter would influence the target parameter
Quantifying Correlation

work in progress
Next Steps & Conclusion

• Include acceptance correction in MCMC Fit Procedure
  • parametrize with uncertainties (a few nuisance parameters)
  • binned template from simulation (a few thousand nuisance parameters)
    → check correlation with proton radius

• implement further acceptance corrections
  • vertex cuts
  • tracking uncertainties
  • recoil-kinematics reconstruction (muon in spectrometer & proton in TPC)

• further systematic checks of fitting procedure with different parametrizations of form factor
  • fit-range dependence

• build and test trigger stations in particle beam
Thank you for your attention!