# Charged particle spectra from $\mu^-$ capture on Al

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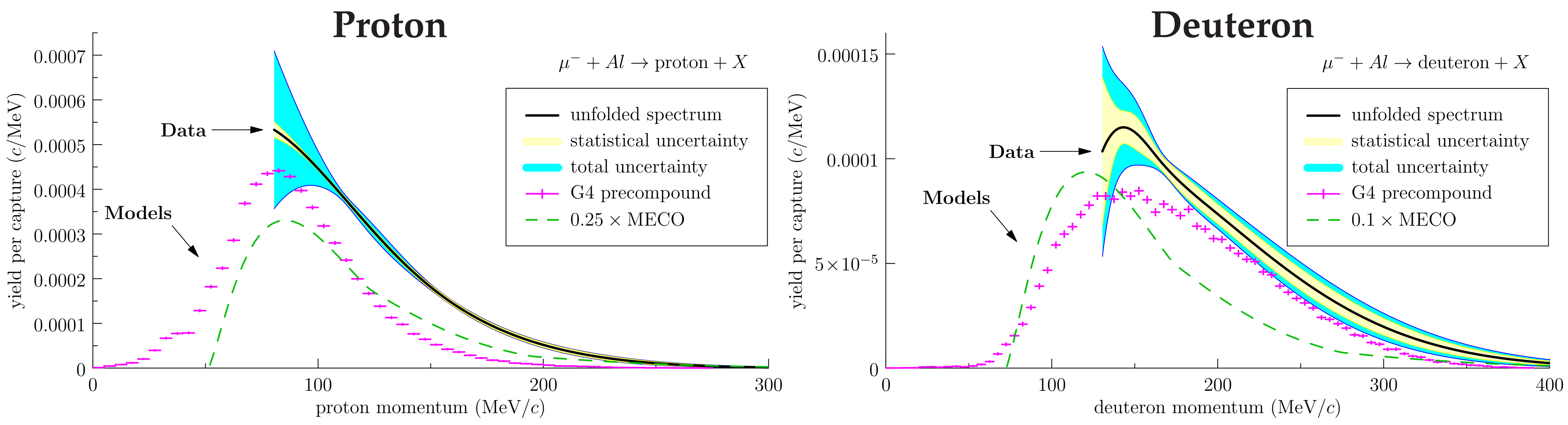
## Problem

- $\mu^-$ in matter form muonic atoms
- Nuclear capture: $\mu^- N \to \nu_\mu X$
  $X \ni \gamma, n, p$, deuteron, ...
  **What are the yields and spectra?**
- **Relevance to CLFV:** Mu2e, COMET will stop $10^{10}$ $\mu^-$/s in aluminum (Al). Charged emissions near 100 MeV/c can deaden the tracker.
- **Inform nuclear theory** for momentum transfers 100 MeV/c $\lesssim Q \lesssim$ 300 MeV/c.

## Results [arXiv:1908.06902]

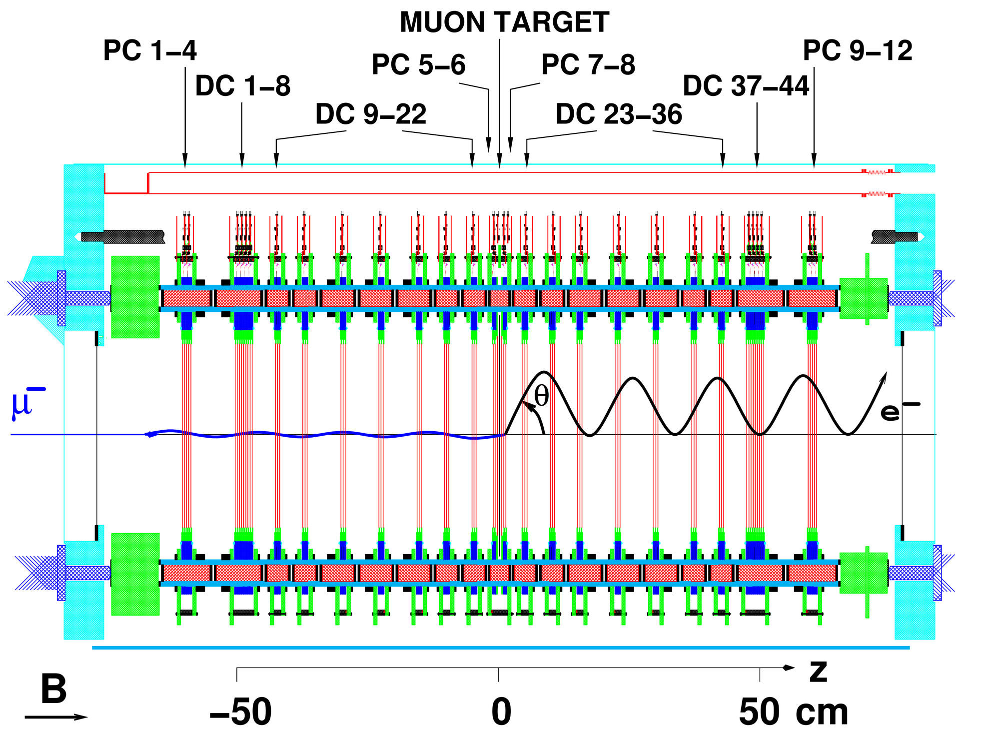



Dominant systematics: cross talk and $dE/dx$ modeling.

**Yield per capture** (most precise measurement to date)

| Proton | Deuteron |
|---|---|
| $\mathbf{0.045} \pm 0.001(\mathrm{stat}) \pm 0.003(\mathrm{syst})$ | $\mathbf{0.018} \pm 0.001(\mathrm{stat}) \pm 0.001(\mathrm{syst})$ |
| $\pm 0.001(\mathrm{extrapolation})$ | $\pm 0.002(\mathrm{extrapolation})$ |

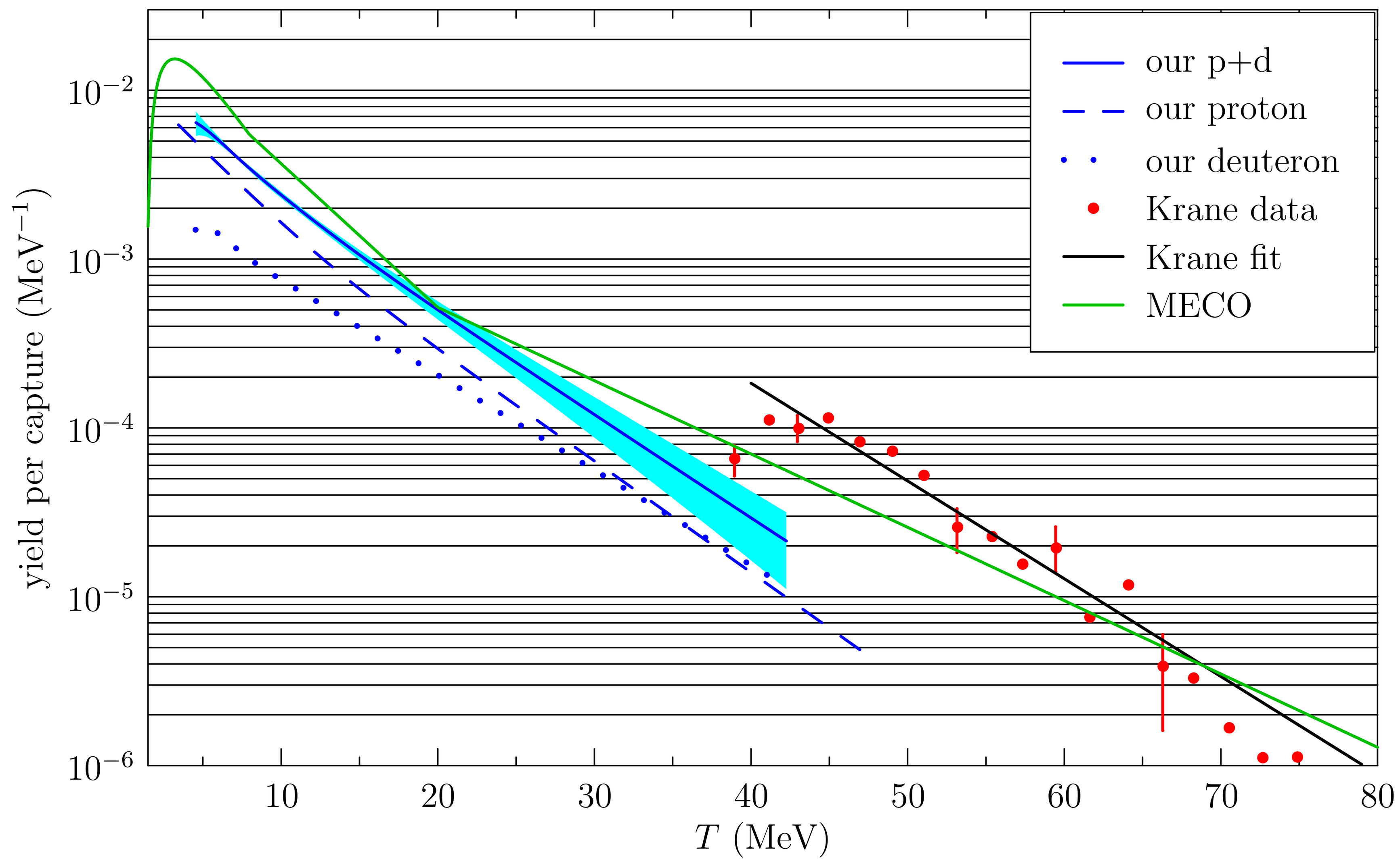
## TWIST Detector at TRIUMF




- Built for a $\mathbf{10^{-4}}$ measurement of the $\mu^+$ decay spectrum.
- Thin: 2 mg/cm$^2$ per wire chamber.
- One muon stop at a time in 71$\mu$m Al foil.

**Our data**: special run with $\mu^-$ beam, 57M triggers.

## Comparison with others




[Krane] Phys. Rev. C **20** (1979) 1873. [MECO] arXiv:1803.08403

## Data analysis

**Event selection**

- Muon stops in target
- Downstream hits after 400 ns ($\tau_{\mu^- Al} = 861$ ns)
- Veto beam accidentals

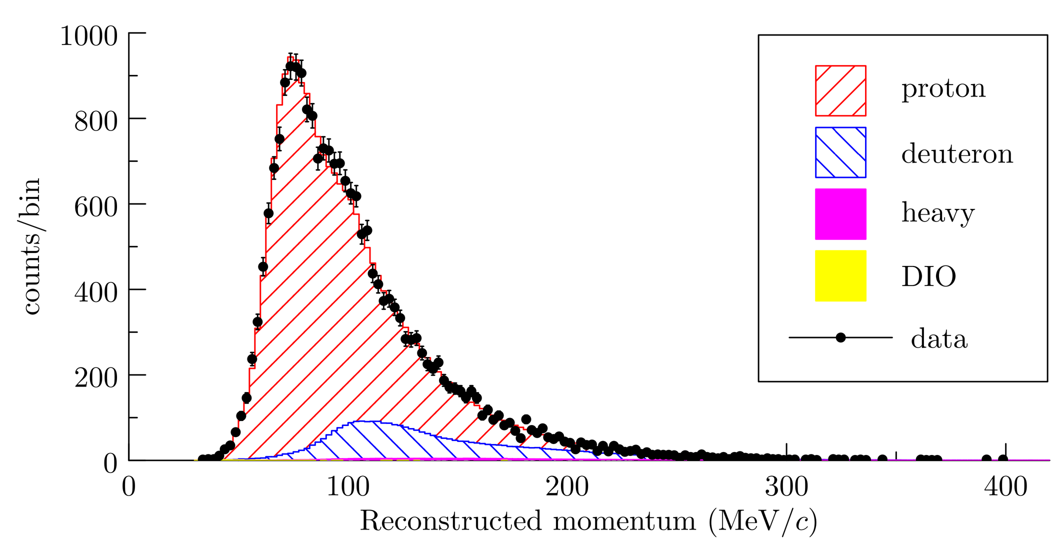
**Modified software**

- Short tracks
- Particle $\beta \approx 0.1$
- $dE/dx \gg$ MIP

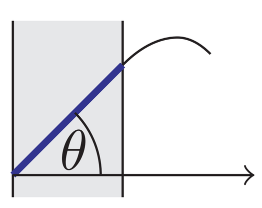
**Normalization:** $e^-$ tracks from muon decay

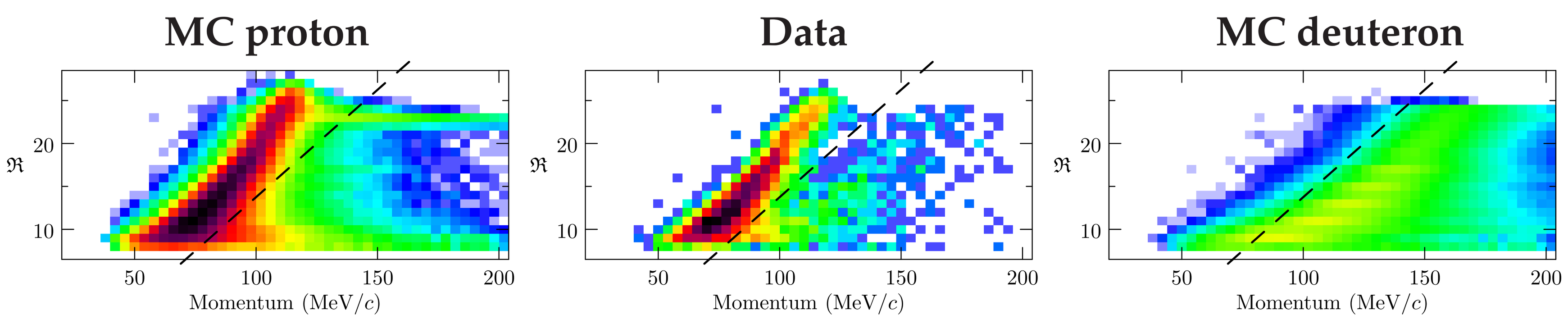
- Known spectrum and branching fraction.
- Well understood acceptance × efficiency
- Count stopped muons **in the selected event sample**
- Data/data and MC/MC uncertainty cancellations between electron and signal events.

**Reconstructed data and simulation fit**




**Particle ID:**
About 1/3 of reconstructed positive tracks range out in the detector stack.
Track range observable:
$\mathcal{R} = (\text{N crossed planes})/|\cos(\theta)|$
No PID for penetrating tracks, but use their momentum in the global fit.




## Unfolding [arXiv:1906.07918]

**Regularized unfolding:**

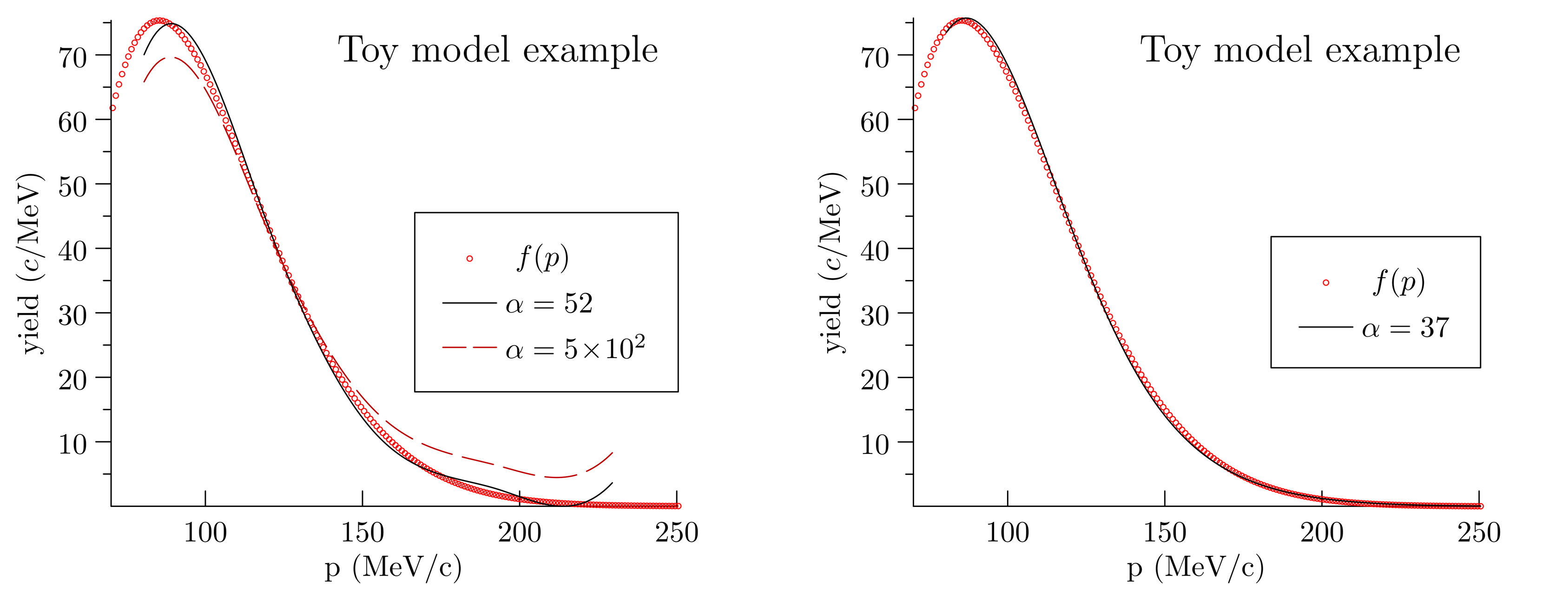
$$\text{Maximize } \mathcal{F} = \underbrace{\log \mathcal{L}(\text{data}|f)}_{\text{Likelihood of data}} + \underbrace{\alpha S\{f\}}_{\text{Regularization term}}$$

**The standard lore**

- Arbitrary $f$ = spline.
- Regularization acts on $f$, bias to a straight line.
- Zero of fixed shape continuation outside of unfolding range.

**Our approach**

- Arbitrary $f = g \times (1+\text{spline})$, problem specific $g$ may depend on fit parameters.
- Regularize *deviation* from $g$, result biased to $g$.
- Smooth continuation of fit outside of unfolding range.




## Acknowledgments

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