# Never throw away old data: using TWIST muons for Mu2e

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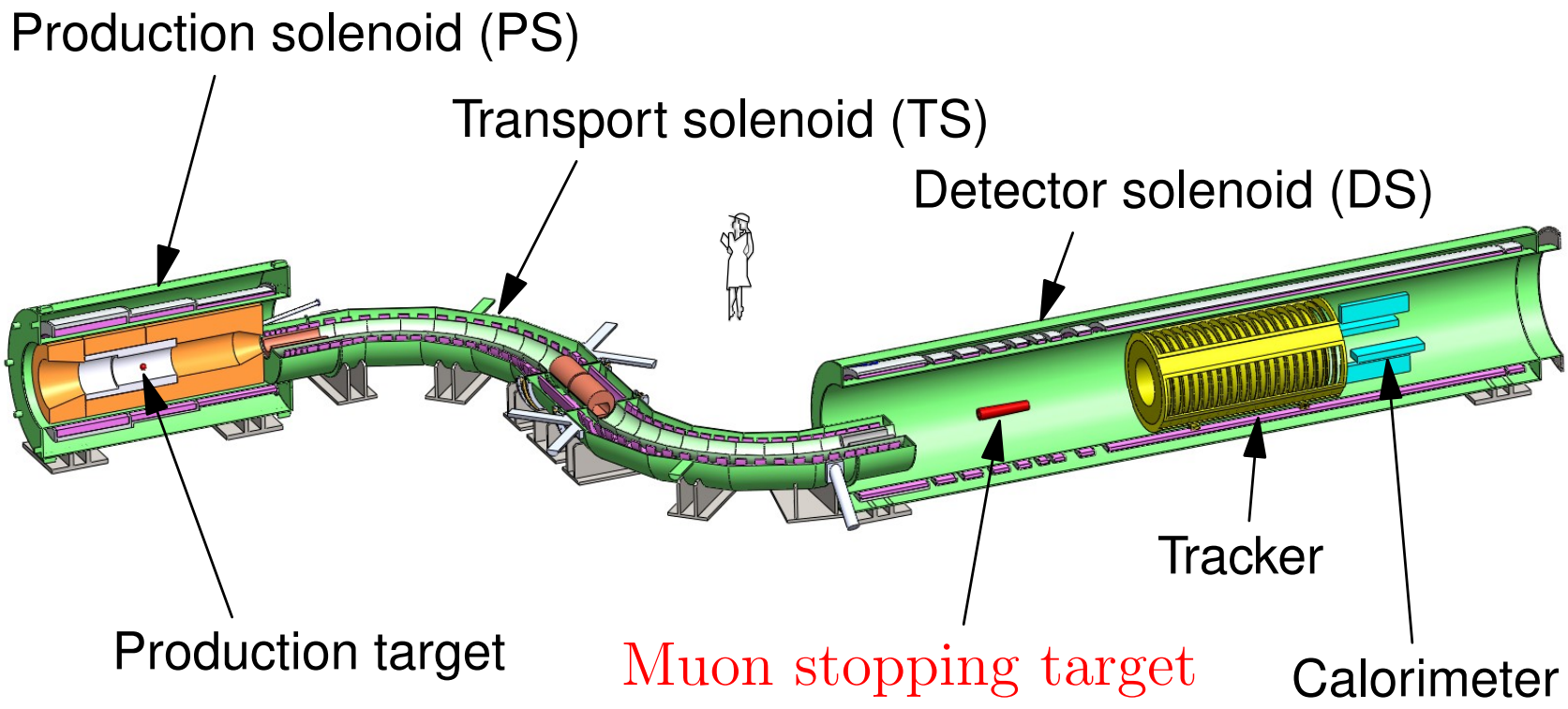
2015-02-06

# Outline

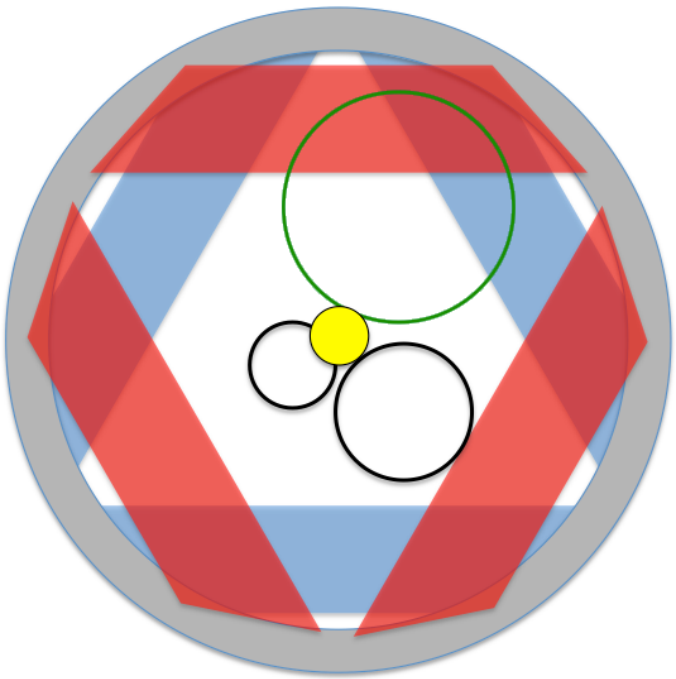
- Mu2e
- Muon nuclear capture
- TWIST
- The analysis
- Preliminary results
- Prospects: hit based channel
- Conclusion

# Mu2e reminder



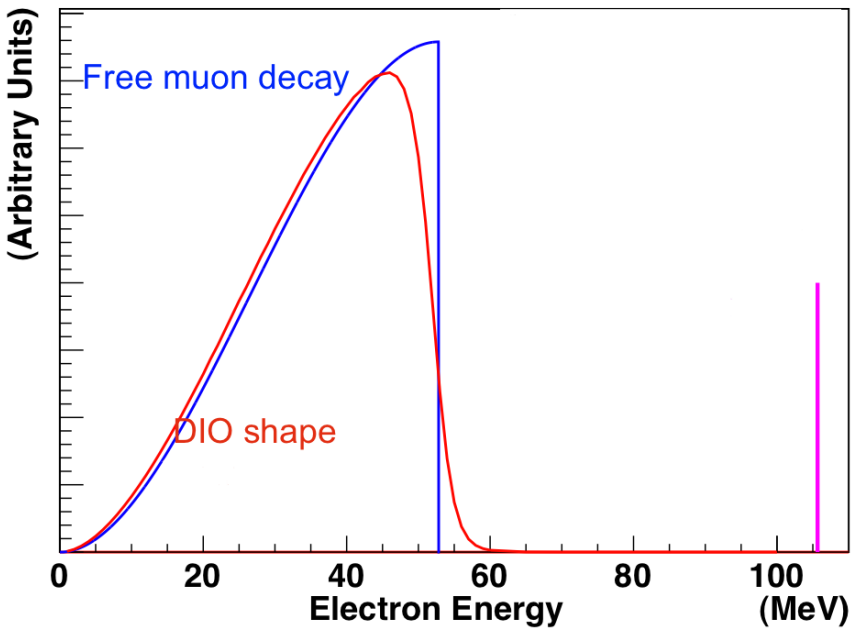

- Searches for charged lepton flavor violation $\mu N \to eN$
- New physics reach complementary and exceeding the LHC
- Almost $3 \times 10^{10}$ stopped muons/s during spill
- Muon decays and interactions produce hits in detector

# $\mu^-$ in aluminum: 40% decay and 60% capture



## Tracker design:

- Good acceptance for $p_t > 100$ MeV/c
- No hits from most electrons from muon decay in orbit (DIO)



# $\mu^-$ in aluminum: 40% decay and 60% capture

## Muon nuclear capture: a beta decay relative

$$(A, N) \rightarrow (A, N+1) + e^- + \bar{\nu}_e \qquad \text{beta decay}$$

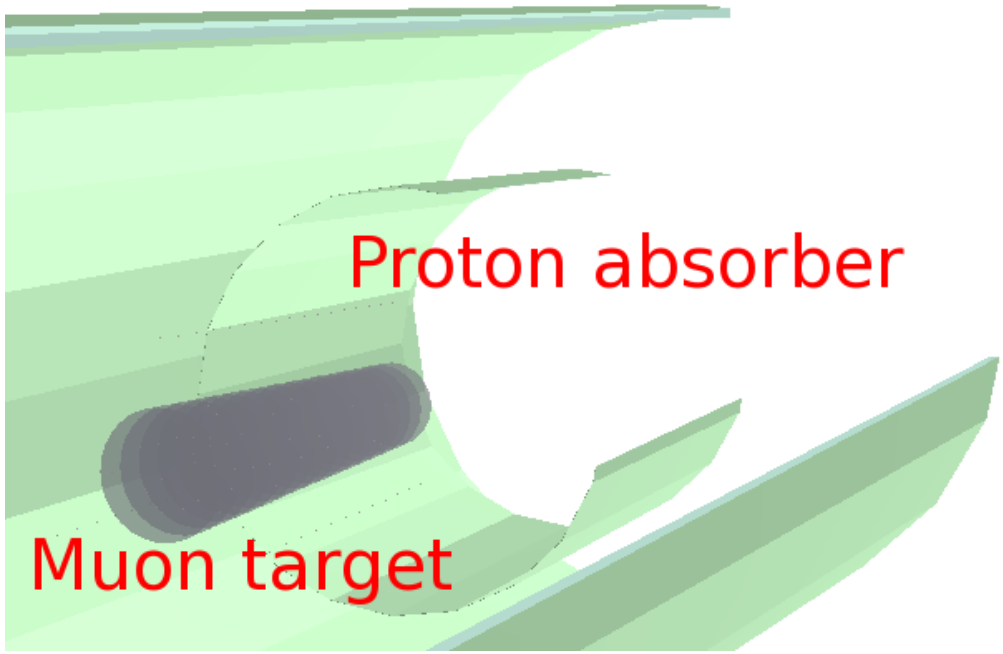
$$(A, N) + e^- \rightarrow (A, N-1) + \nu_e \qquad \text{electron capture}$$

$$(A, N) + \mu^- \rightarrow (A, N-1) + \nu_\mu \qquad \text{muon capture}$$

- Muon: 105 MeV rest mass
- Nuclear physics on steroids
- Energetic $n$, $p$, $\gamma$, deuteron, $t$, $\alpha$, ... emission
- Proton $E = 2.6$ MeV has $p = 70$ MeV/c: hits in Mu2e

# Mu2e proton absorber

- Few percent of $10^{10}$: large hit rate
- Suppression: “proton absorber”
- Plastic shell
- Stops proton and deuteron tracks
- Degrades signal resolution




How thin/small can it be to still protect the tracker?
Need to know rates and spectra of capture products.

# Previous measurements: normalization

Per-capture probabilities from activation experiments

- G. Heusser and T. Kirsten, Nucl. Phys. A **195**, 369 (1972).
  $P({}^{27}_{13}Al + \mu^- \to {}^{24}_{11}Na + \nu + p + 2n) = 3.5 \pm 0.8\%$
- A. Wyttenbach *et al.*, Nucl. Phys. A **294**, 278 (1978)
  $P({}^{27}_{13}Al + \mu^- \to {}^{25}_{11}Na + \nu + p + n) = 2.8 \pm 0.4\%$

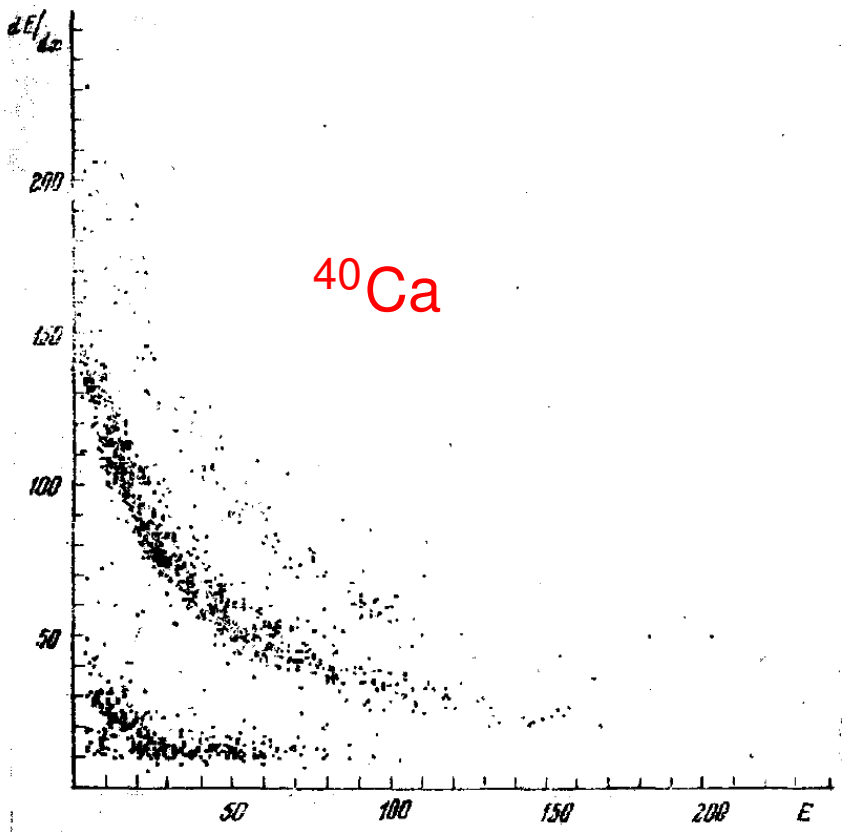
$\Longrightarrow$ at least 6% of inclusive charged particles per capture on Al

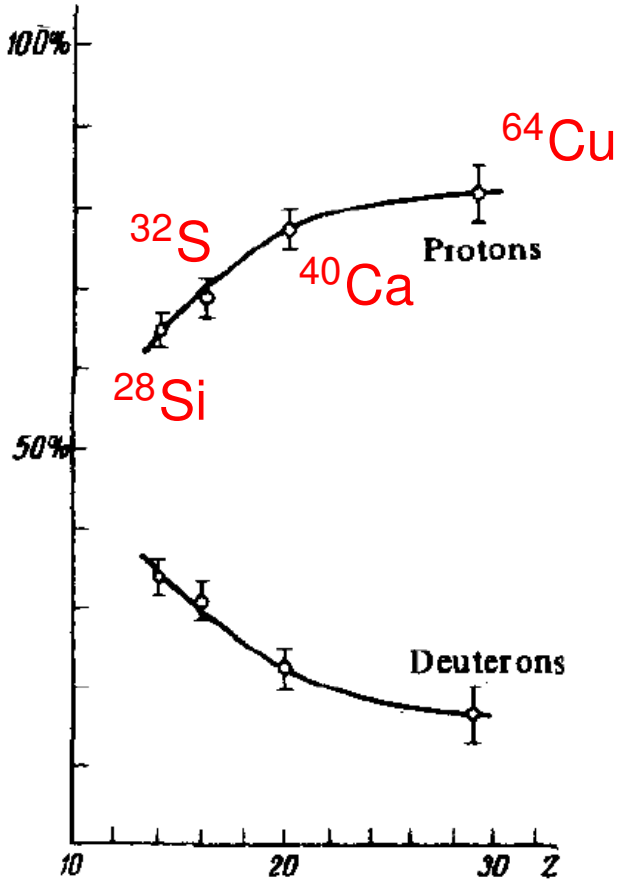
The technique does not tell *np* from *d* in the final state

Some other channels (different neutron multiplicities) may have similar probabilities.

# Previous measurements: composition

Y. G. Budyashov *et. al*, Sov. Phys. JETP **33**, 11 (1971)



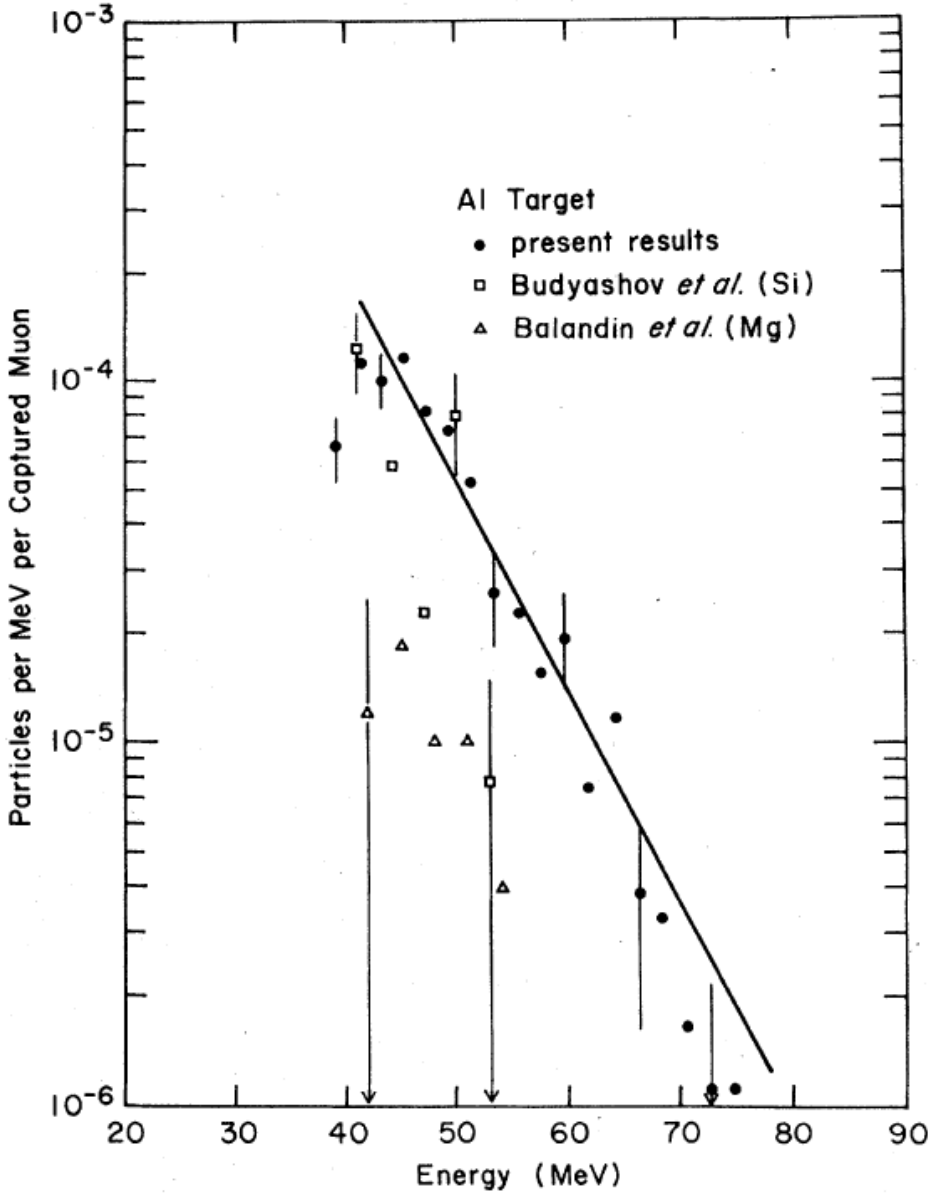




No measurement for Al

# Previous measurements: spectrum shape

K.S. Krane *et. al*, PRC20(1979)1873

- Measurement for Al
- But only the tail:
  $E > 40$ MeV
  ($p > 277$ MeV/c)
- $1.4 \times 10^{-3}$/capture integral
- No PID reported

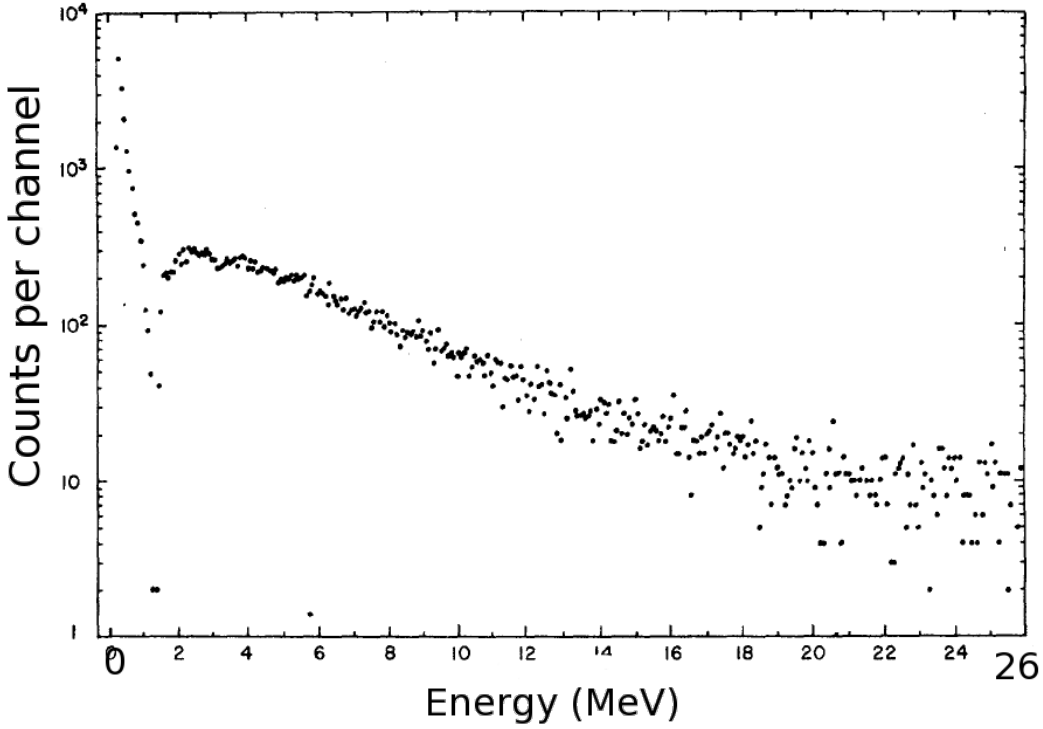


# Previous measurements: spectrum shape

S.E. Sobottka, E.L. Wills, PRL20(1968)596

- Got the peak!
  - At $\approx 2.5$ MeV
  - Caused by the Coulomb barrier of the nucleus
- Inclusive $p + d + \ldots$ spectrum (no PID)
- Measurement on Si: target $=$ detector
- 2.5 MeV proton range is 61 $\mu$m Al...

Capture in Si

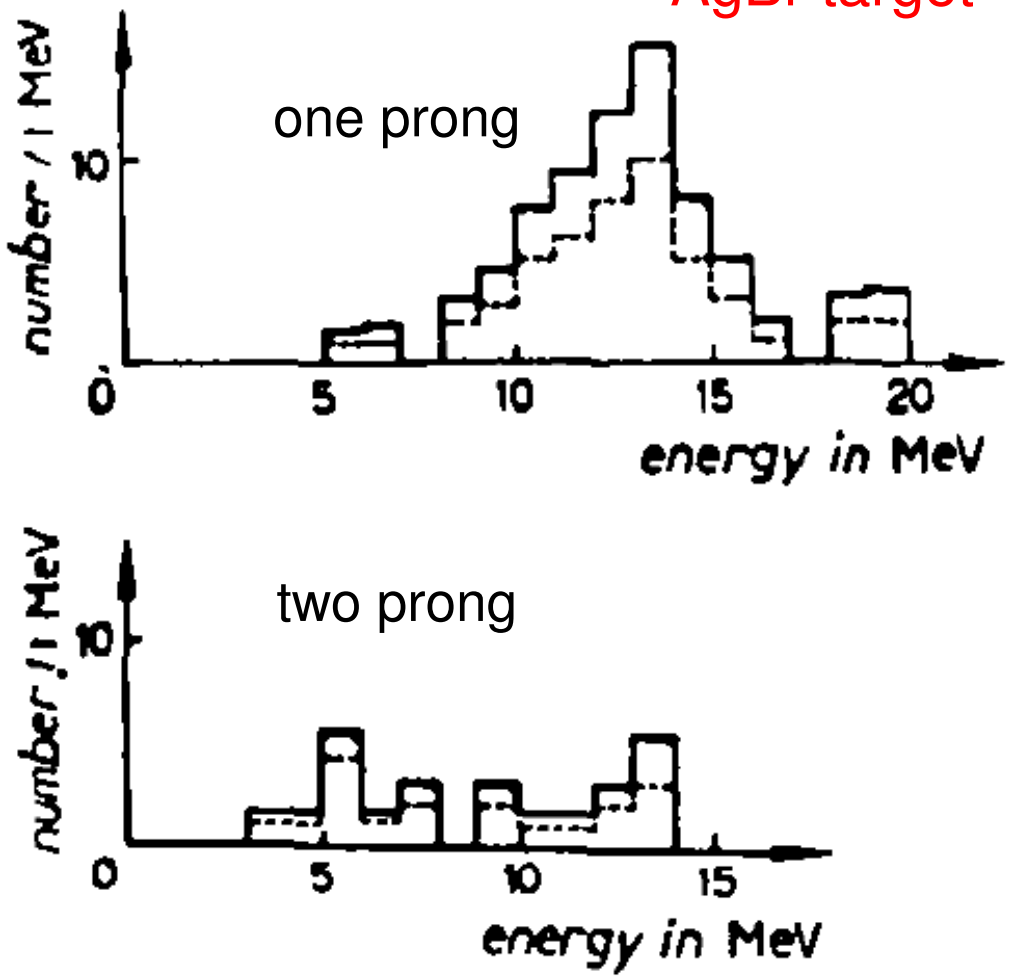


# Previous shape measurement with PID

H. Morinaga, W.F Fry, Nuovo Cimento Ser. 9 vol 10 (1953) 308

- Full spectrum shape
- Particle ID
  - "proton" vs $\alpha$
  - *d* and *t* included into "proton"
- Low statistics
- Photo emulsion: no target material choice

AgBr target




*Muons at U Chicago cyclotron*

# Summary on muon capture on aluminum

- There is a lack of experimental data on charged particle emission from $\mu^-$ capture on Al:
  - The “bulk” part of the spectra has not been measured
  - No measurement of the composition
- Mu2e cares about those “details”
- What can we do?

# “Never throw away your old data”

- Use an existing TWIST dataset to measure charged particles from $\mu^-$ capture on Al
- Extend to a lower energy range than previous Al results
- Determine both spectrum shape and normalization
- Some PID capability
- Advance understanding of the muon capture physics
- First measurement of $\mu^-$ capture with a tracker

## The competition

- The AlCap collaboration at PSI
- Dedicated setup to measure $\mu^-$ capture on Al
- Calorimetric measuremenent using Si detectors
  $\Longrightarrow$ very different backgrounds and systematics

# *TWIST* participants, past and present

## TRIUMF

Ryan Bayes ∗†
Yuri Davydov
Wayne Faszer
Makoto Fujiwara
David Gill
Alexander Grossheim
Peter Gumplinger
Anthony Hillairet ∗†
Robert Henderson
Jingliang Hu
John A. Macdonald ◇
Glen Marshall
Dick Mischke
Mina Nozar
Konstantin Olchanski
Art Olin †
Robert Openshaw
Jean-Michel Poutissou
Renée Poutissou
Grant Sheffer
Bill Shin ‡

## U Alberta

Andrei Gaponenko ∗
Robert MacDonald ∗
Maher Quraan
Nate Rodning ◇

## U British Columbia

James Bueno ∗
Mike Hasinoff
Blair Jamieson ∗

## U. Montréal

Pierre Depommier

## U. Regina

Ted Mathie
Roman Tacik

## Kurchatov Institute

Vladimir Selivanov

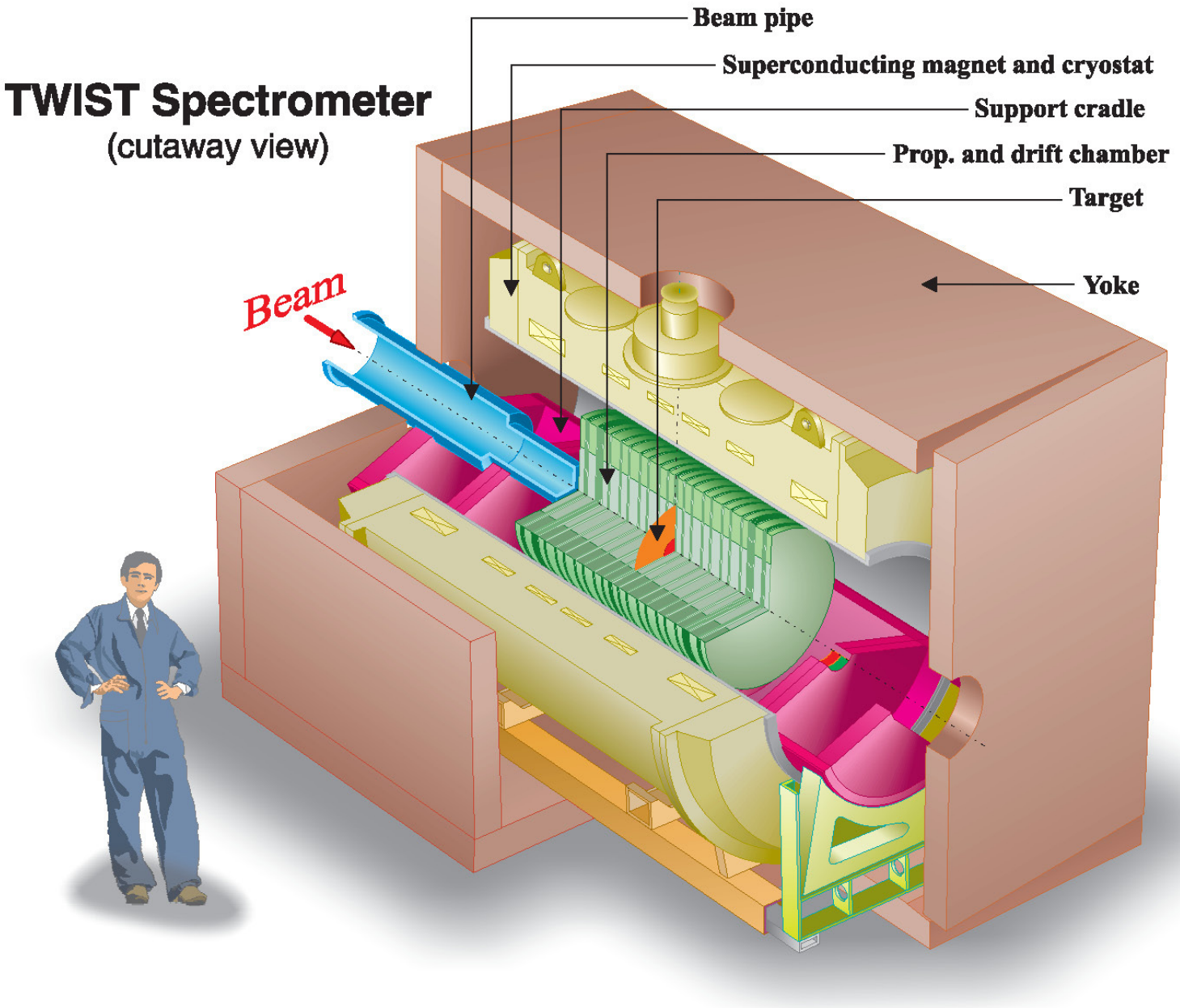
## Texas A&M U.

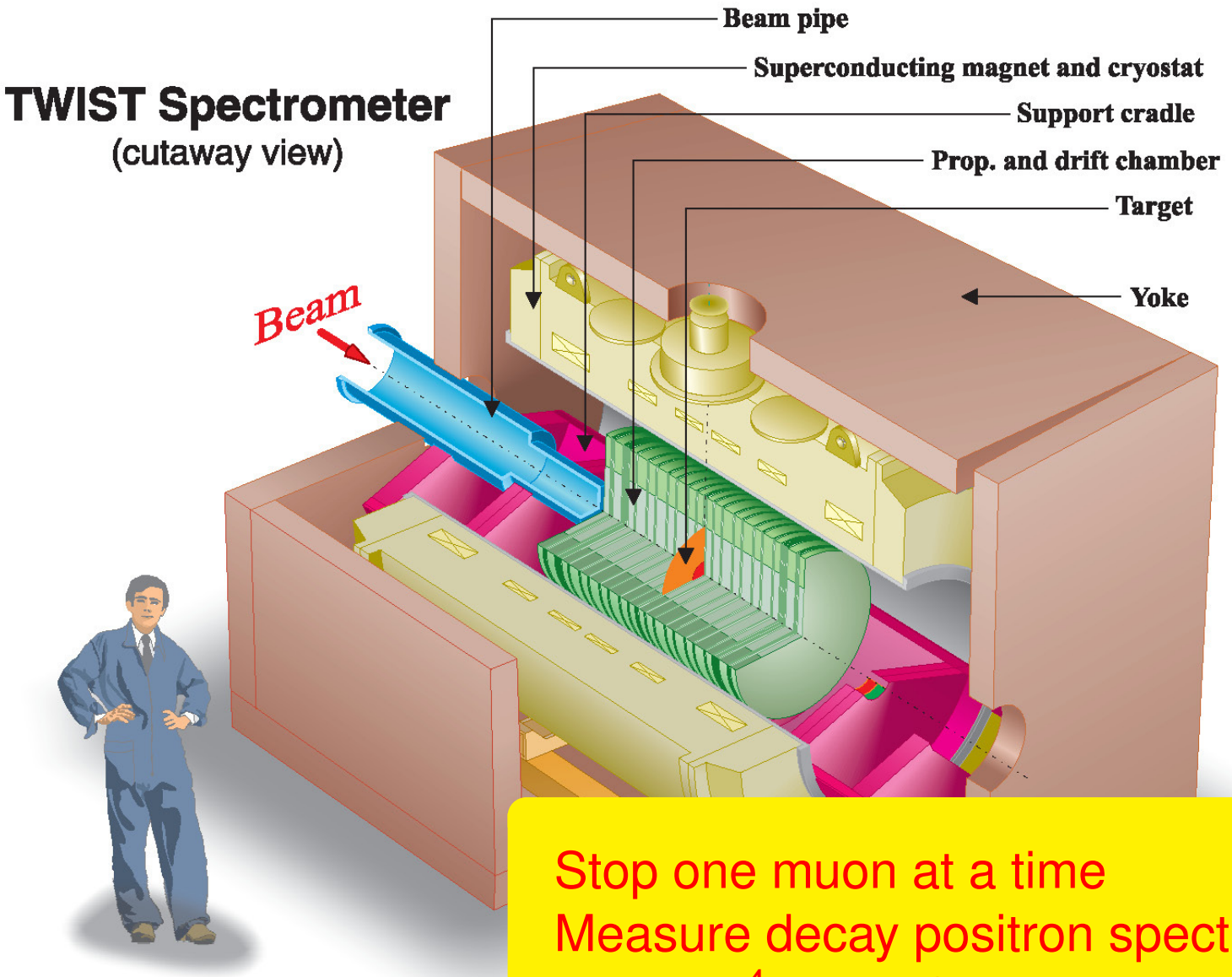
Carl Gagliardi
Jim Musser ∗
Bob Tribble

## Valparaiso U.

Don Koetke
Shirvel Stanislaus

∗ Graduated
† also U. Vic
‡ also U. Saskatchewan
◇ deceased

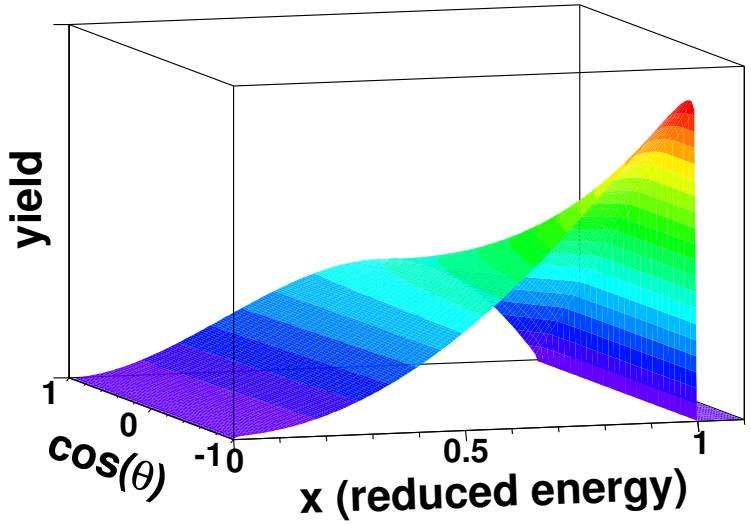

TWIST Spectrometer
(cutaway view)
Beam pipe
Superconducting magnet and cryostat
Support cradle
Prop. and drift chamber
Target
Yoke
Beam




Stop one muon at a time
Measure decay positron spectrum
At a $10^{-4}$ level of accuracy

# $\mathcal{TWIST}$ primary physics

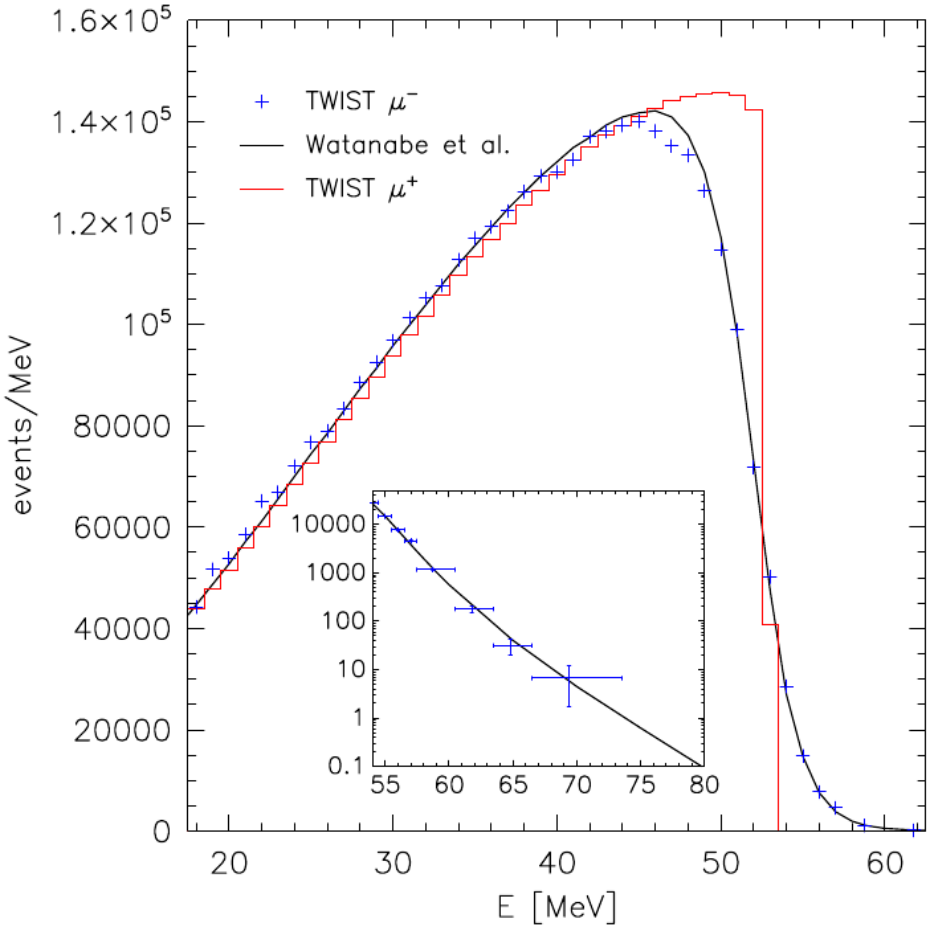
- Lorentz structure of the weak force
  - muon decay parameters $\rho$, $\eta$, $P_\mu\xi$, $\delta$
- Search for BSM physics
- Several years of $\mu^+$ data
- Detector and software understood and calibrated at a $10^{-4}$ level
- The results will dominate the field for years to come




*G. Marshall's Wine&Cheese talk on 2012-07-11*

# *TWIST* "opportunistic" dataset

- A week of $\mu^-$ beam
- 80 Hz instead of 2–5 kHz of $\mu^+$
- Primary motivation: decay in orbit spectrum
- Al target: same material as Mu2e
- Some discrepancy with the theory curve




PHYSICAL REVIEW D **80,** 052012 (2009)

**Decay of negative muons bound in $^{27}$Al**

A. Grossheim,[1,*] R. Bayes,[1,†] J. F. Bueno,[2] P. Depommier,[3] W. Faszer,[1] M. C. Fujiwara,[1,‡] C. A. Gagliardi,[4] D. R. Gill,[1] P. Gumplinger,[1] M. D. Hasinoff,[2] R. S. Henderson,[1] A. Hillairet,[1,†] J. Hu,[1] D. D. Koetke,[5] G. M. Marshall,[1] E. L. Mathie,[6] R. E. Mischke,[1] K. Olchanski,[1] A. Olin,[1,†] R. Openshaw,[1] J.-M. Poutissou,[1] R. Poutissou,[1] V. Selivanov,[7] G. Sheffer,[1] B. Shin,[1,§] T. D. S. Stanislaus,[5] R. Tacik,[6] and R. E. Tribble[4]

(TWIST Collaboration)

# Theory response

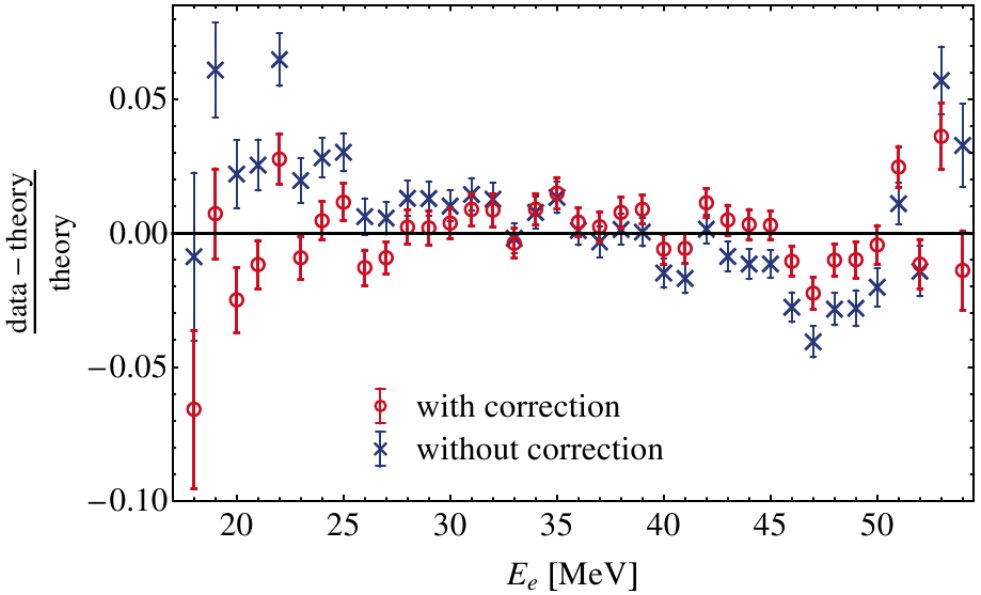
PHYSICAL REVIEW D **90,** 093002 (2014)

**Michel decay spectrum for a muon bound to a nucleus**

Andrzej Czarnecki,[1] Matthew Dowling,[1,*] Xavier Garcia i Tormo,[1,†] William J. Marciano,[2] and Robert Szafron[1]
[1]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2G7*
[2]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*
(Received 12 June 2014; published 4 November 2014)

"The spectrum of electrons from muons decaying in an atomic bound state is significantly modified by their interaction with the nucleus. Somewhat unexpectedly, its first measurement, at the Canadian laboratory TRIUMF, differed from basic theory…"

- Radiative corrections are important
- New calculation is in excellent agreement with data



# TWIST $\mu^-$ capture revival

- The possibility of measuring capture protons was discussed at the time of the DIO measurement
- Did not have resources or motivation to pursue it
- $\mathcal{TWIST}$ experiment is now officially completed

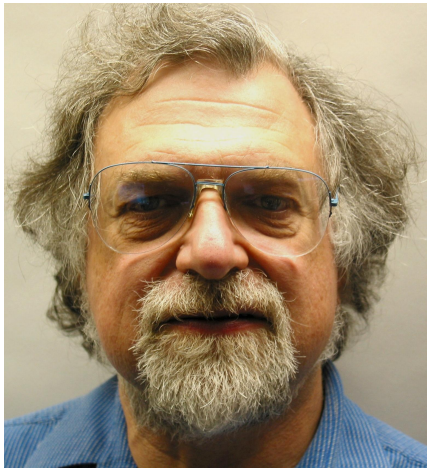
## After joining Mu2e I decided to give captures another look

- Data tapes and some computing still available
- Posted a feasibility study to TWIST mailing list in 2013
- 5 more collaborators joined; everyone is part-time
- Weekly meetings dedicated to the capture analysis
- Work towards an about 15% measurement of the proton yield and spectrum—not $10^{-4}$!

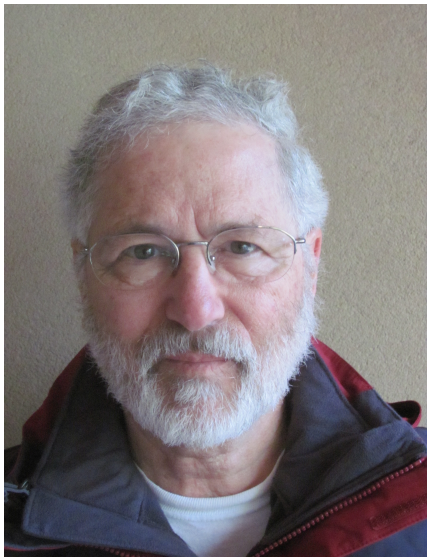
# The analysis team

G. Marshall

A. Hillairet



A. Olin



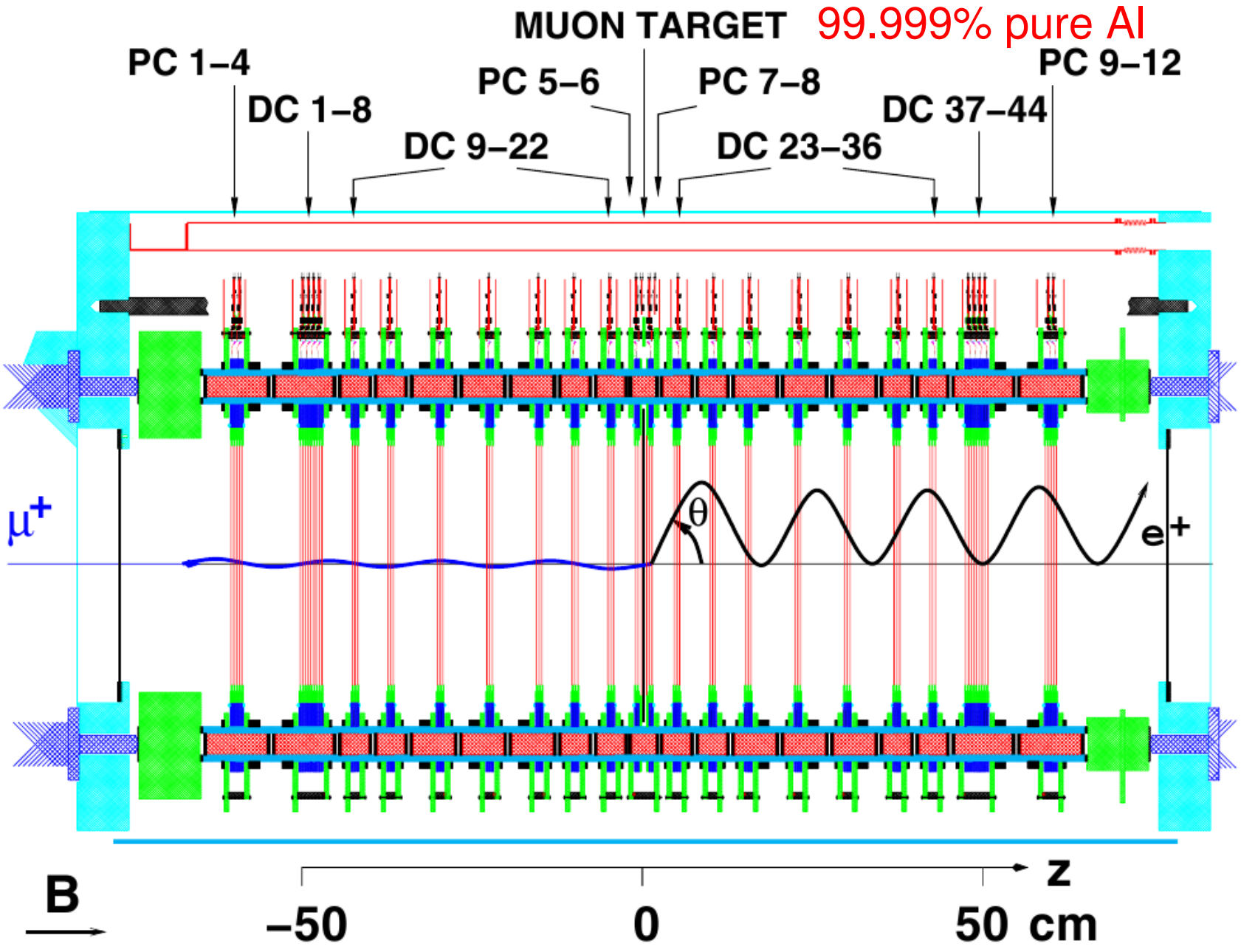
R. Mischke

A. Grossheim

A. Gaponenko

Thanks to our computer wizard K. Olchanski!

# *TWIST* detector

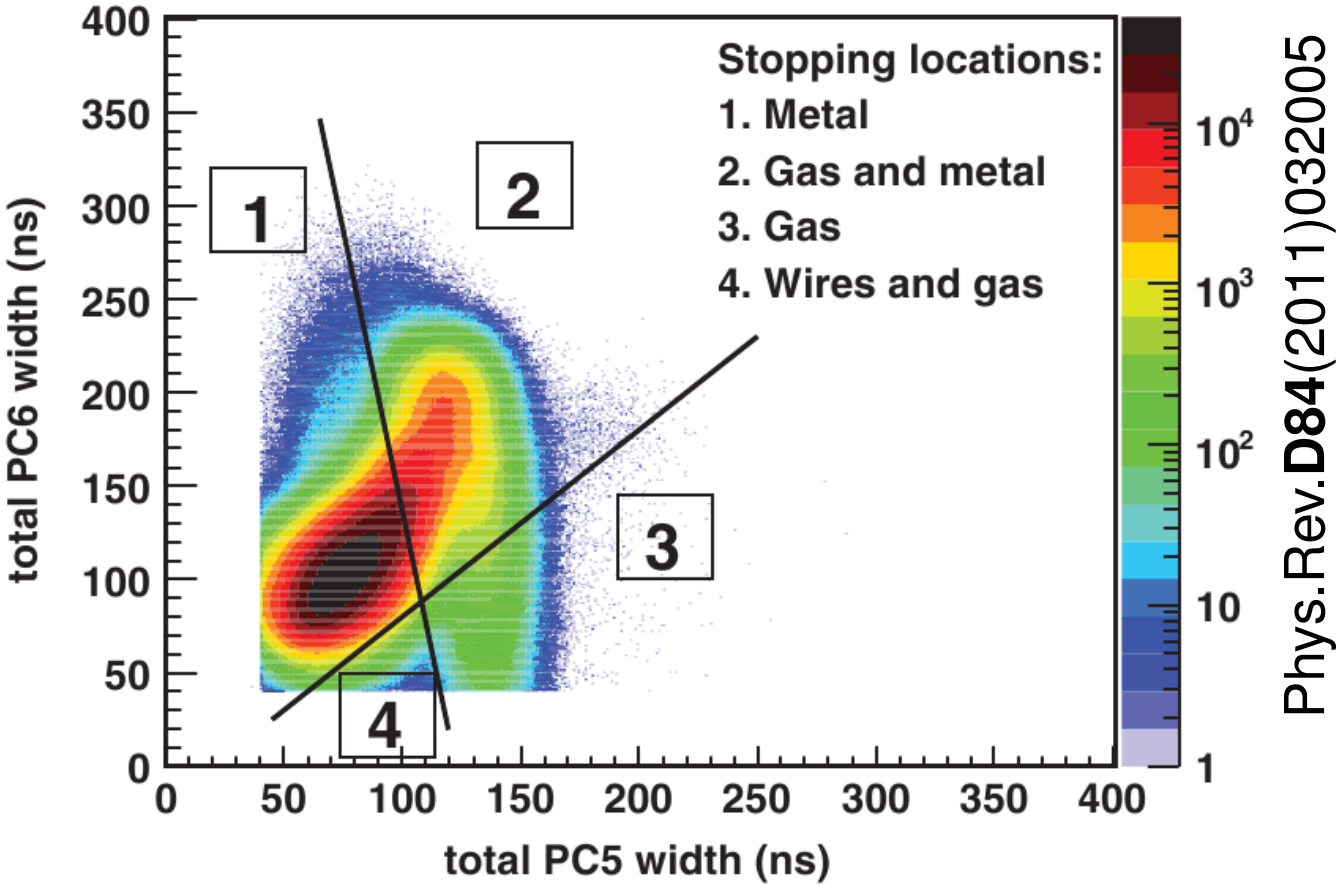


# Event selection: muon stops

- Number of triggers in the dataset: $2.1 \times 10^7$
- Identify and remove cross talk hits
- Group hits in time
- Trigger time window: require hits up to the stopping target (PC6) upstream, no hits downstream $\implies 1.1 \times 10^7$ events
- Require that the muon stopped in the target, not in gas or wires before it $\implies 7.1 \times 10^6$ events

# The target stop cut

PC5, PC6 at lowered voltage (1600 V vs 2050 V): sacrifice electron efficiency for unsaturated muon pulse width




The distribution for $\mu^-$ is similar

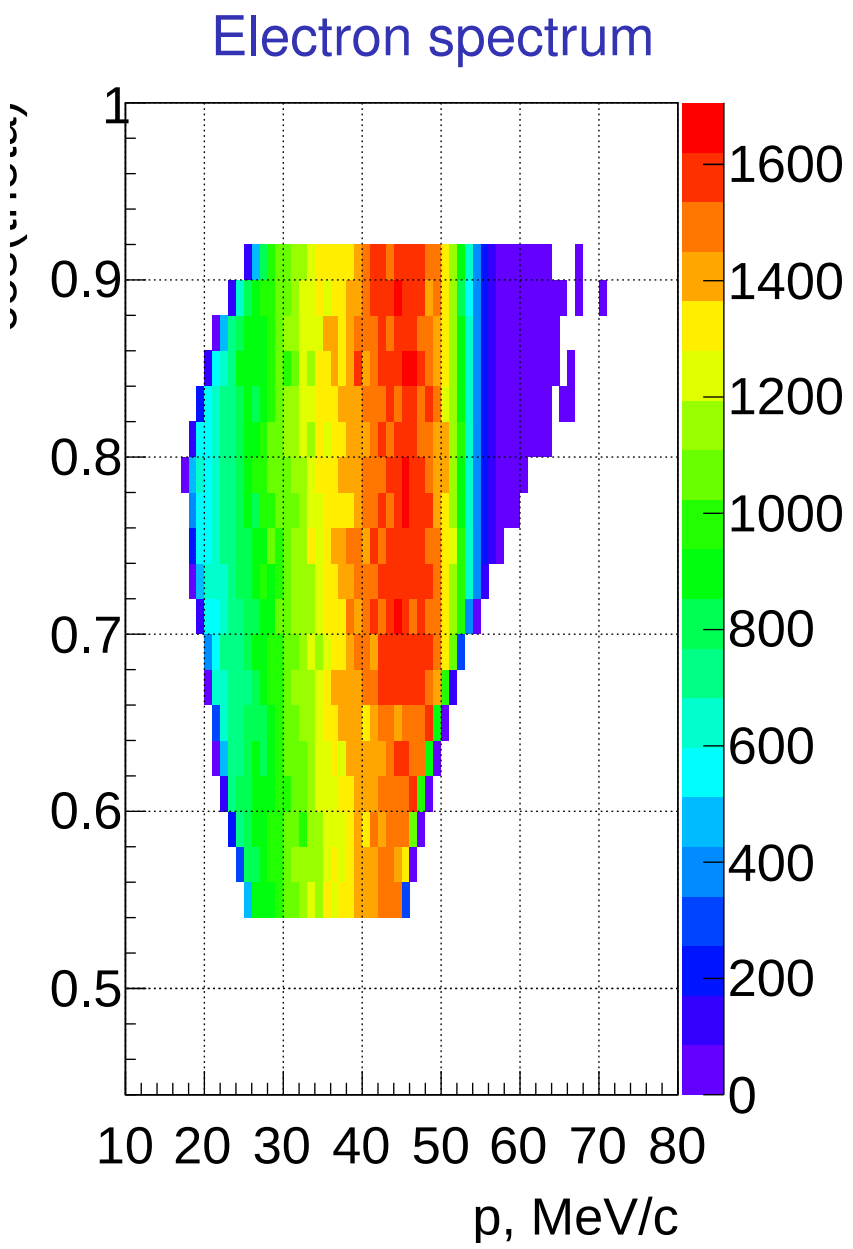
# Event selection: downstream decay candidates

First after trigger time window:

- Require a hit in PC7
- Veto beam pile-up (PC1–PC4)
- Timing cuts w.r.t trigger and pile up particles
- $\implies 2.3 \times 10^6$ "Dn candidate" events
- Efficiency of cuts up to this point is the same for DIO and reconstructable captures: reduced systematic on normalization
- Branch after this point
  - Count decays in orbit for normalization
  - Reconstruct tracks from capture particles

# Normalization: DIO tracks

- Use $\mu^- \to e^- \nu \bar{\nu}$ downstream decays
- Our $\mu^-$ sample is not polarized PRD80(2009)052012
- Electron reconstruction in $\mathcal{TWIST}$ is well understood
- From electron track count: $2.69 \times 10^7$ muon stops



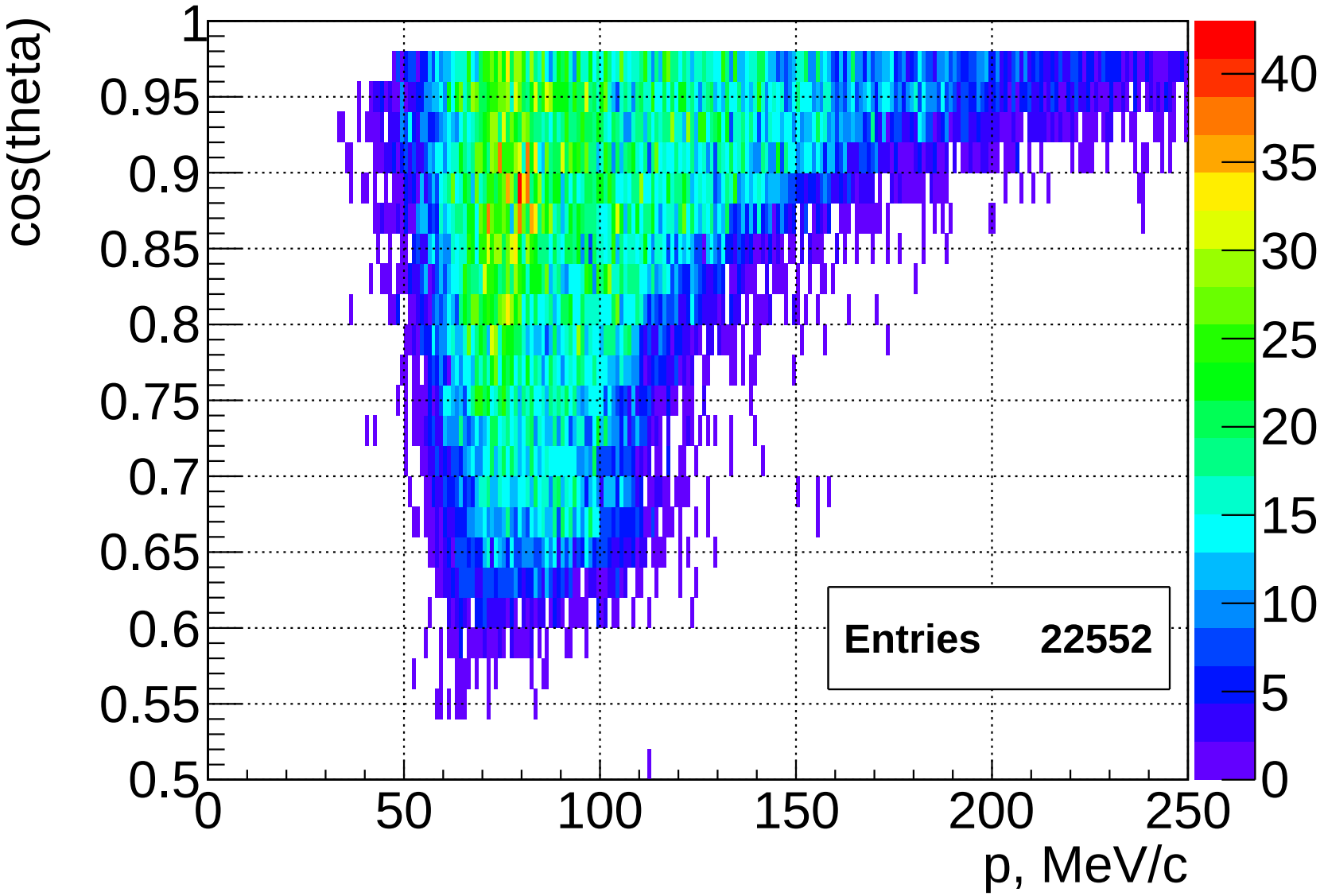
# Reconstructing proton tracks

$\mathcal{TWIST}$ was optimized to reconstruct $e^+$ tracks

Proton tracks are different:

- High momentum $\Longrightarrow$ not radially contained
  - large acceptance correction
- Large energy loss, non-helical trajectory: harder to fit
- Short range at lower energies
  - Include PCs in pattern recognition
  - The lowered HV breaks detector symmetry
  - Precludes using upstream tracks for mucapture analysis
- High ionisation density
  - cross talk is larger than for electron tracks

# Reconstructed spectrum of positive tracks

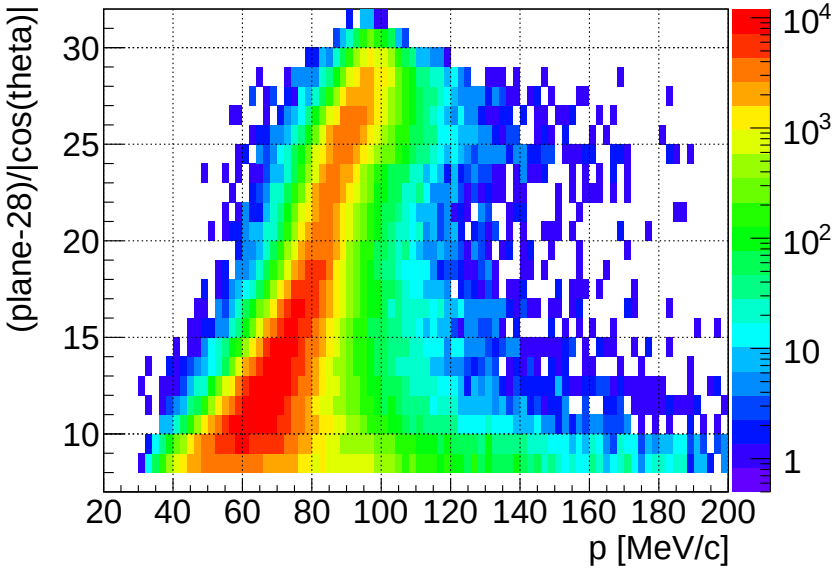


# Identifying the deuterons

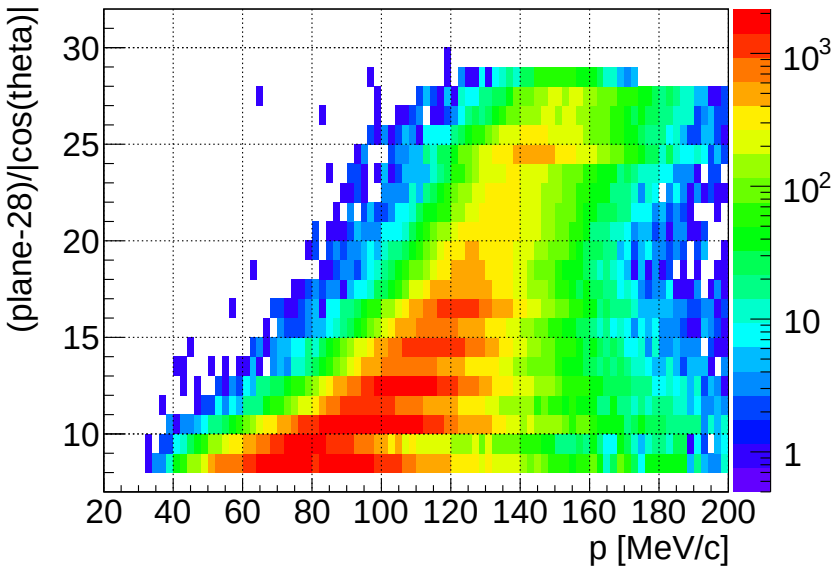
- There are proton and deuteron tracks in data
- We want to correct for detector effects
- Energy loss for $p$ and $d$ is different
- Need particle ID
- Some tracks stop in the detector
- Look at range vs momentum for that subsample

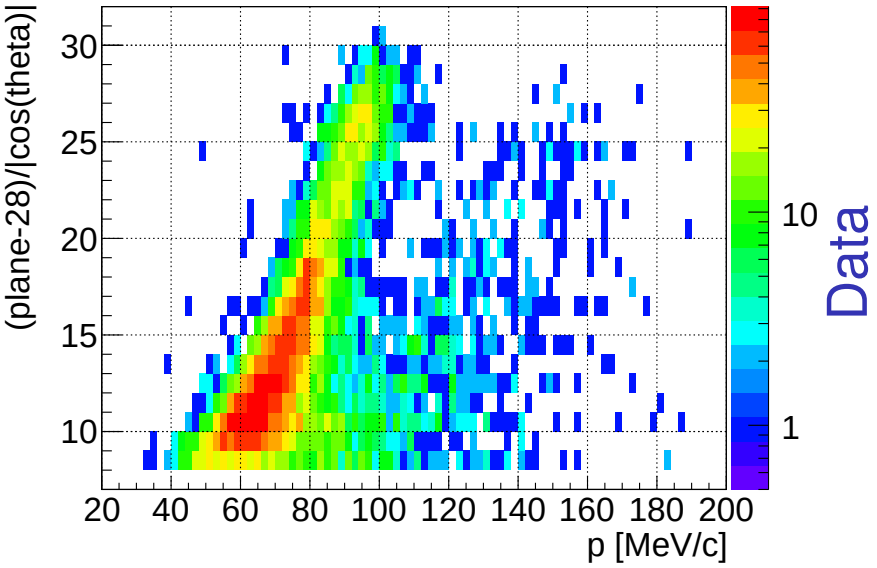
# Particle ID for contained tracks

proton MC



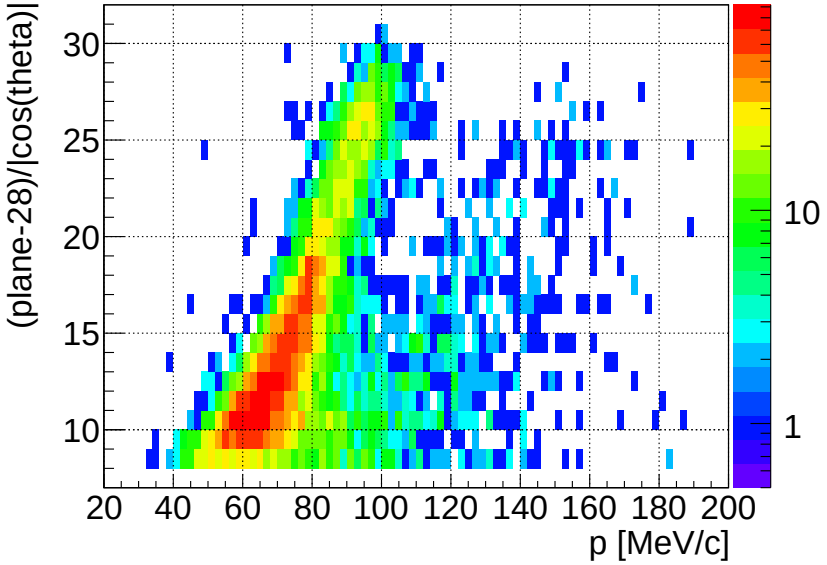

deuteron MC

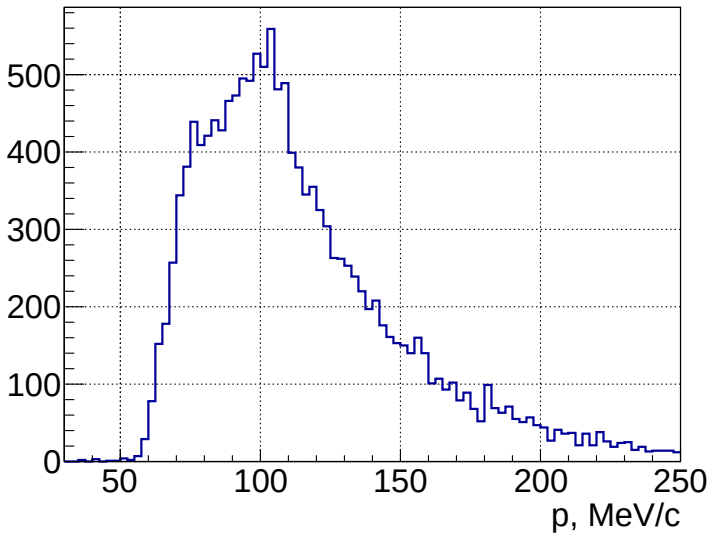


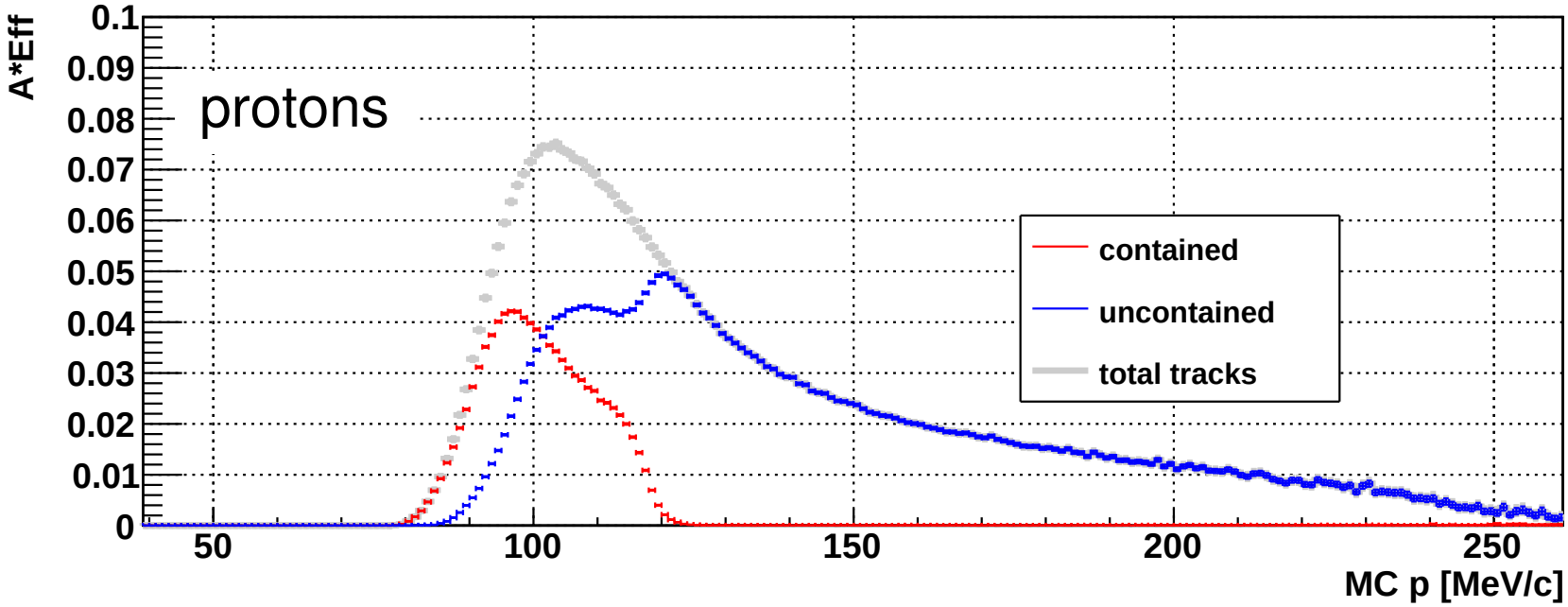
# Analysis channels

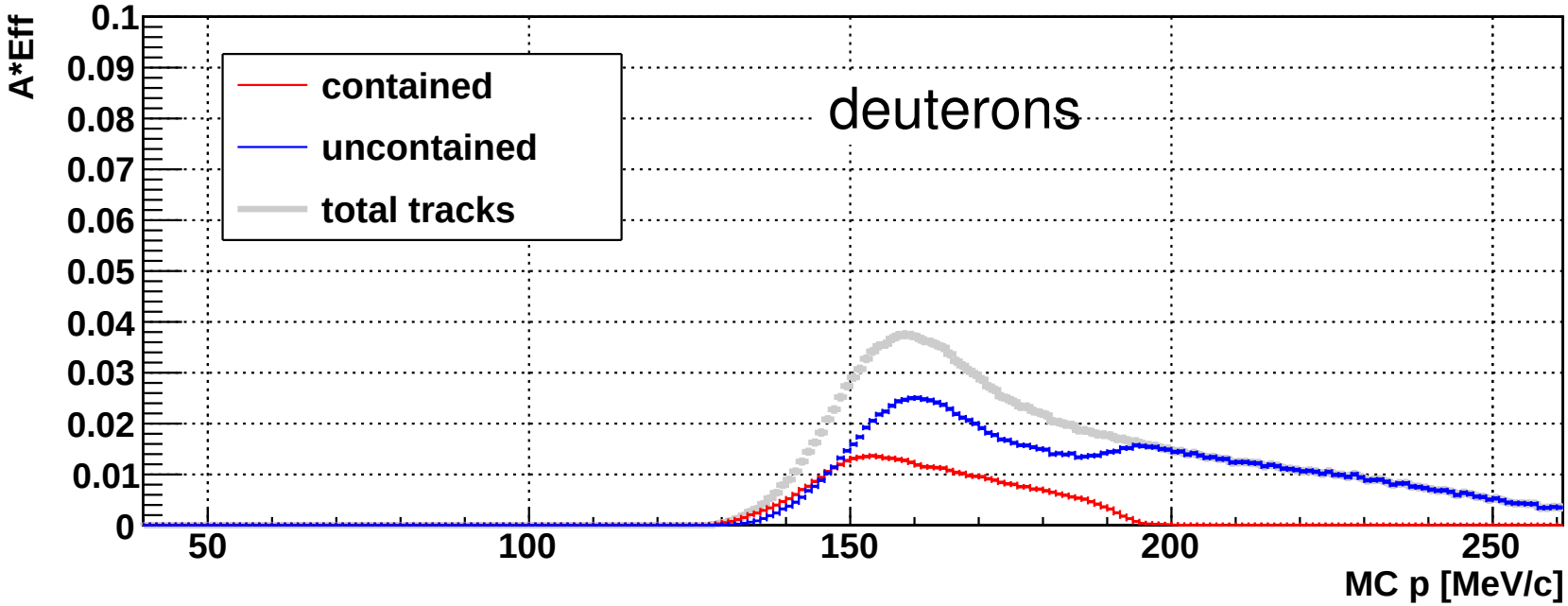
- Use track range as a PID discriminator
- Tracks exiting the detector do not provide PID
- Still carry information about momentum distribution
- Use all tracks: “contained” and “uncontained” exclusive analysis channels



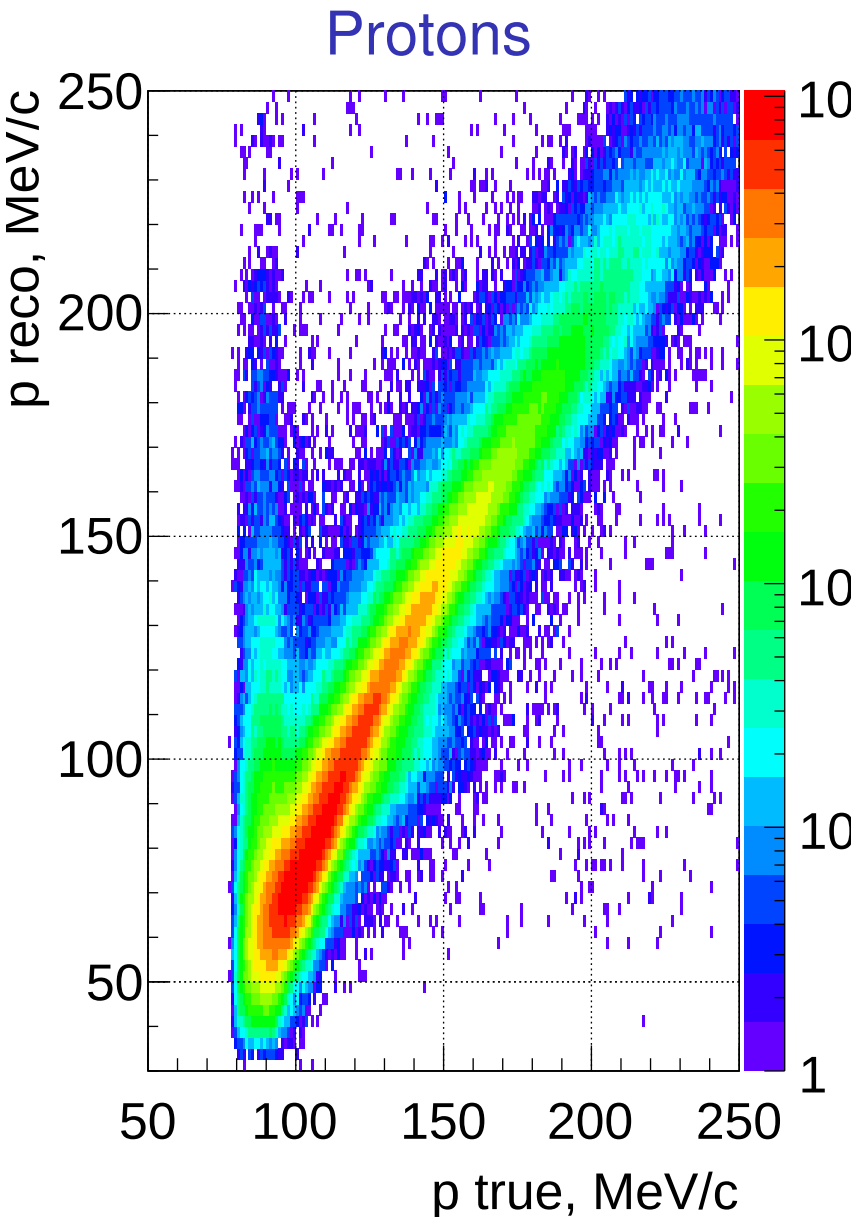



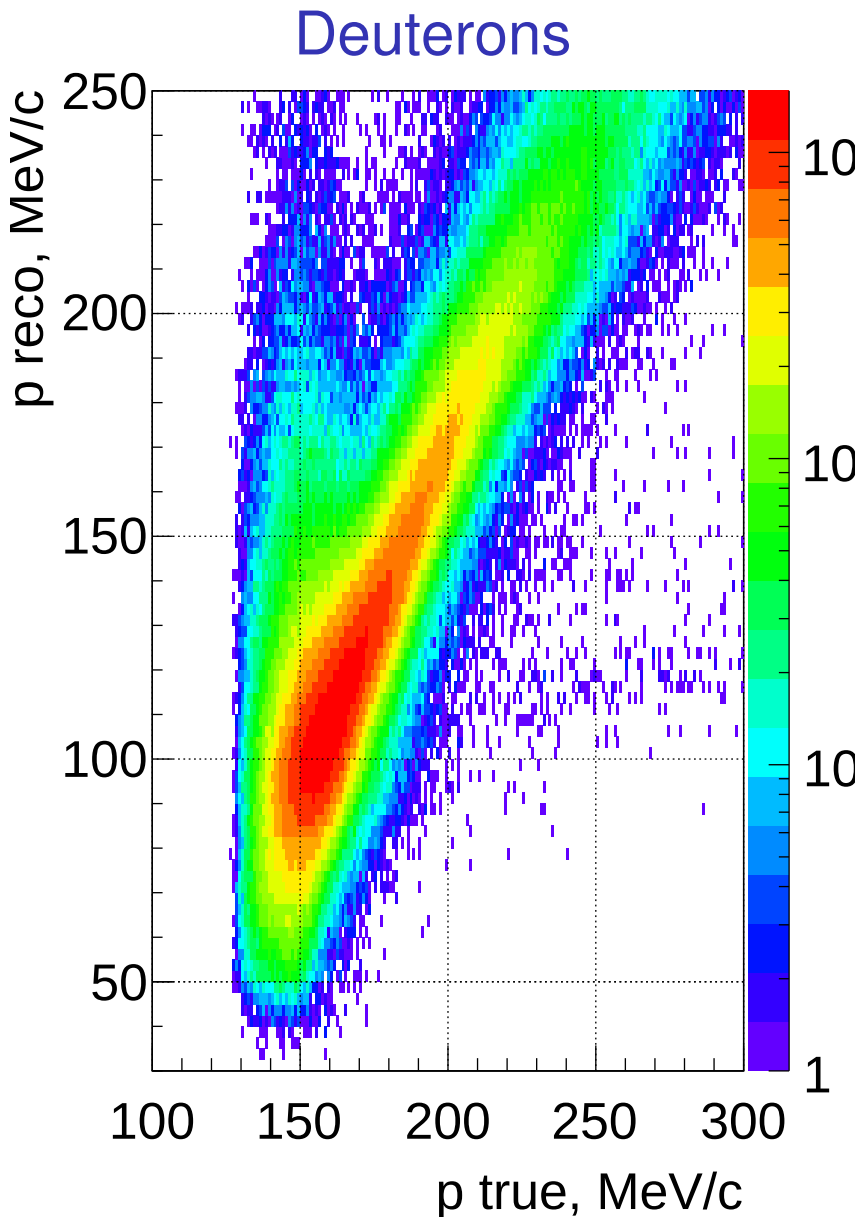
# Acceptance × efficiency



# Resolution

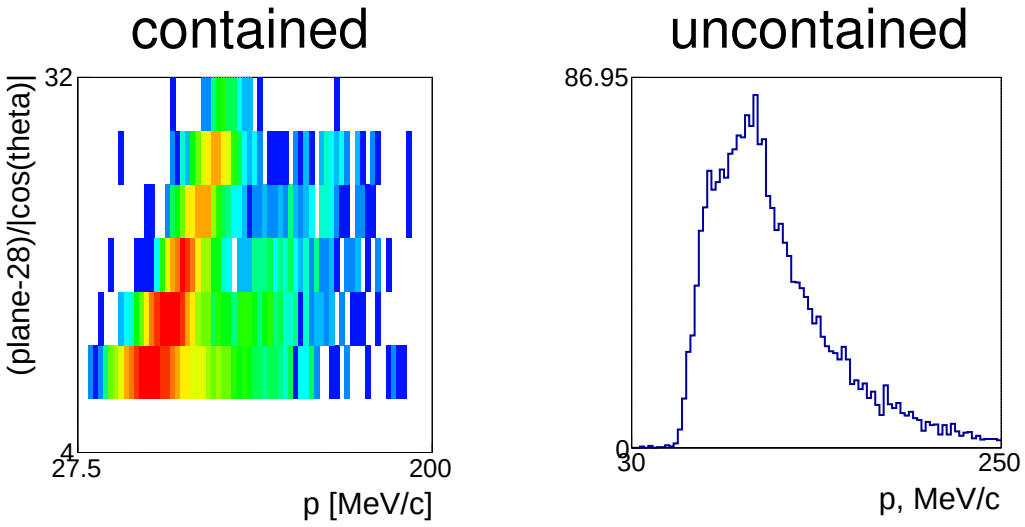

Protons
p reco, MeV/c
250
200
150
100
50
50
100
150
200
250
p true, MeV/c
10
10
10
10
1


Deuterons
p reco, MeV/c
250
200
150
100
50
100
150
200
250
300
p true, MeV/c
10
10
10
1

# From detector to physics distributions: a sketch

## Data observables

bins contents $\{m_i\}$ in the exclusive analysis channels




## Simulate detector response $R$

Generator spectrum $\{\nu_j\} \Longrightarrow$ reco expectation values $\{\mu_i\}$:

$$\mu_i = R_{ij}^{\text{proton}} \nu_j^{\text{proton}} + R_{ik}^{\text{deuteron}} \nu_k^{\text{deuteron}} + b_i$$

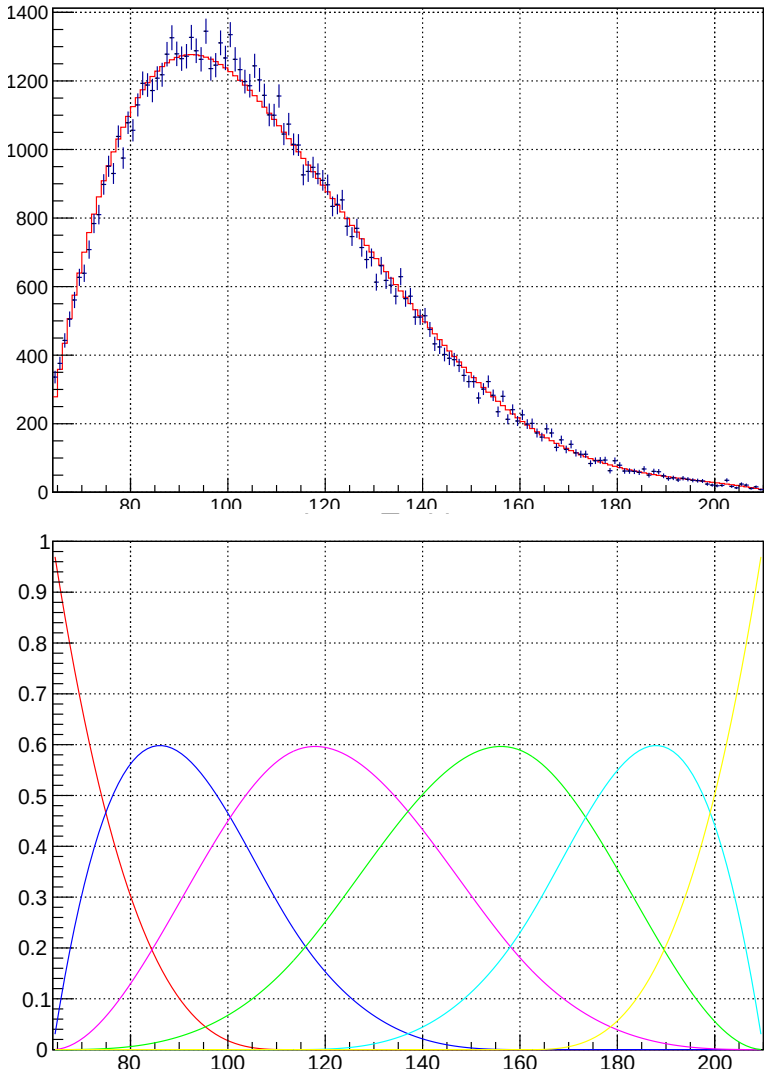
- Background: fixed shape DIO, fit normalization
- Proton and deuteron spectra $\nu$: free smooth shapes

# Sketch–2: representing free shapes

Smooth function $\nu(p)$

$$\nu(p) = \sum_k w_k B_k(p)$$

$B_k$ are basis splines,
$w_k$ are coefficients:
our fit parameters



# Sketch–3: Ill posed problem and regularization

Naïve fit

$$\text{Poisson}(\text{data}|\text{prediction}(w_k)) \to \max$$

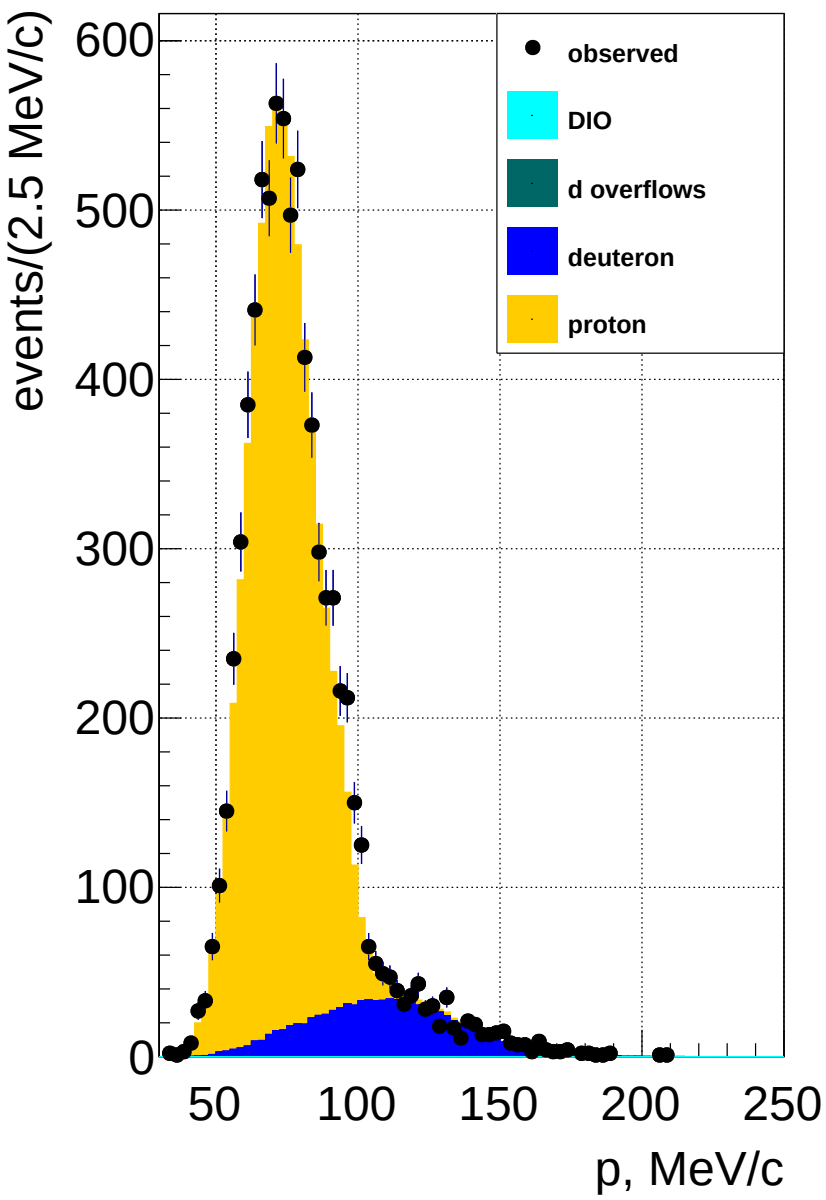
gives "random noise". Reduce the variance of $w_k$ at the expense of a bias:

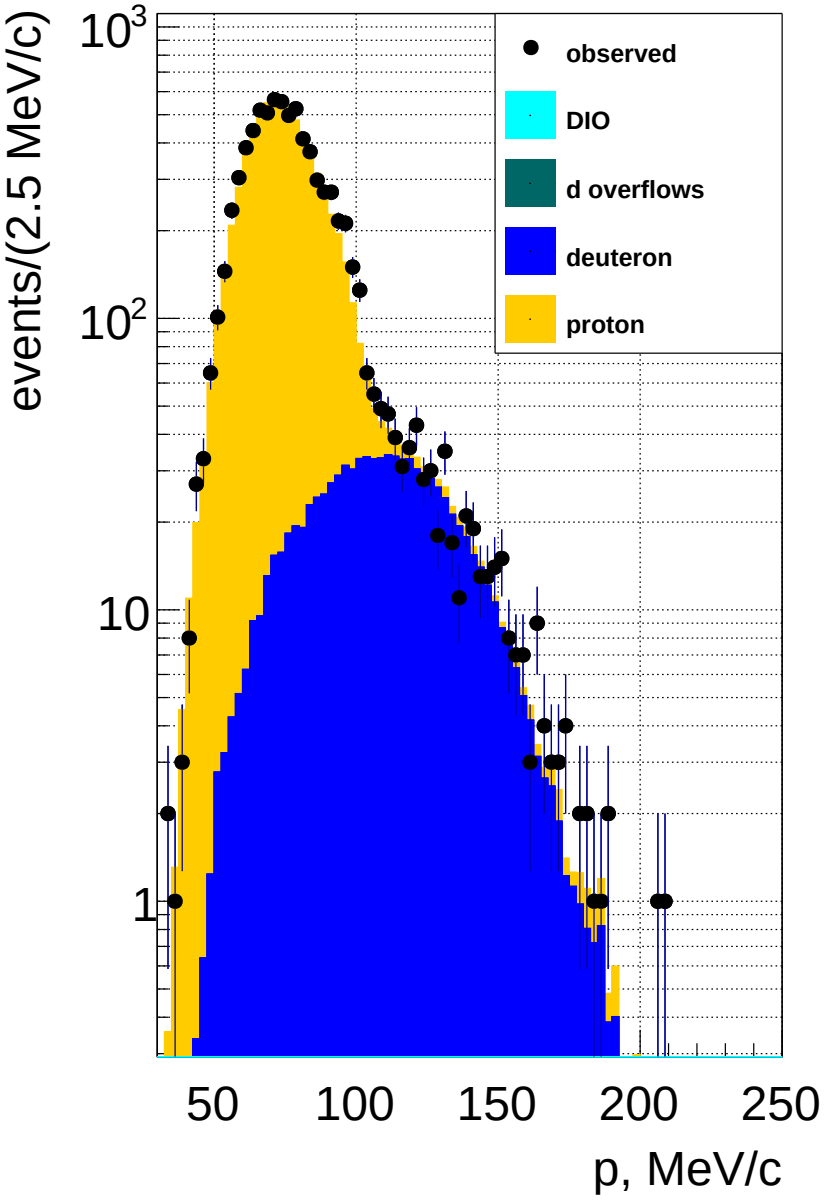
$$\text{Poisson}(\text{data}|\text{prediction}(w_k)) + \alpha S(w_k) \to \max$$

$\alpha$ is the regularization strength.
We use the maximum entropy term

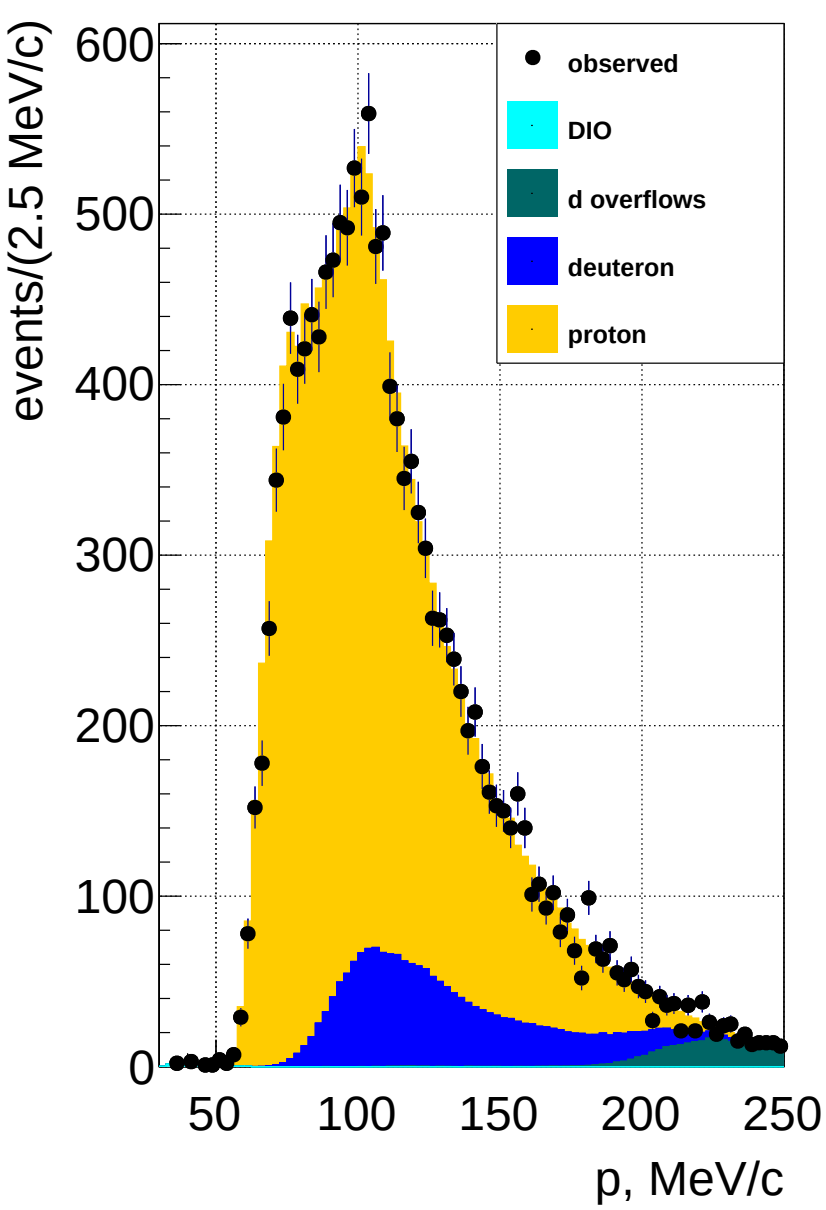
$$S(w_k) = -\sum_{\text{generator bin}} p_i \log(p_i) \quad \text{where} \quad p_i = \nu_i / \sum \nu$$

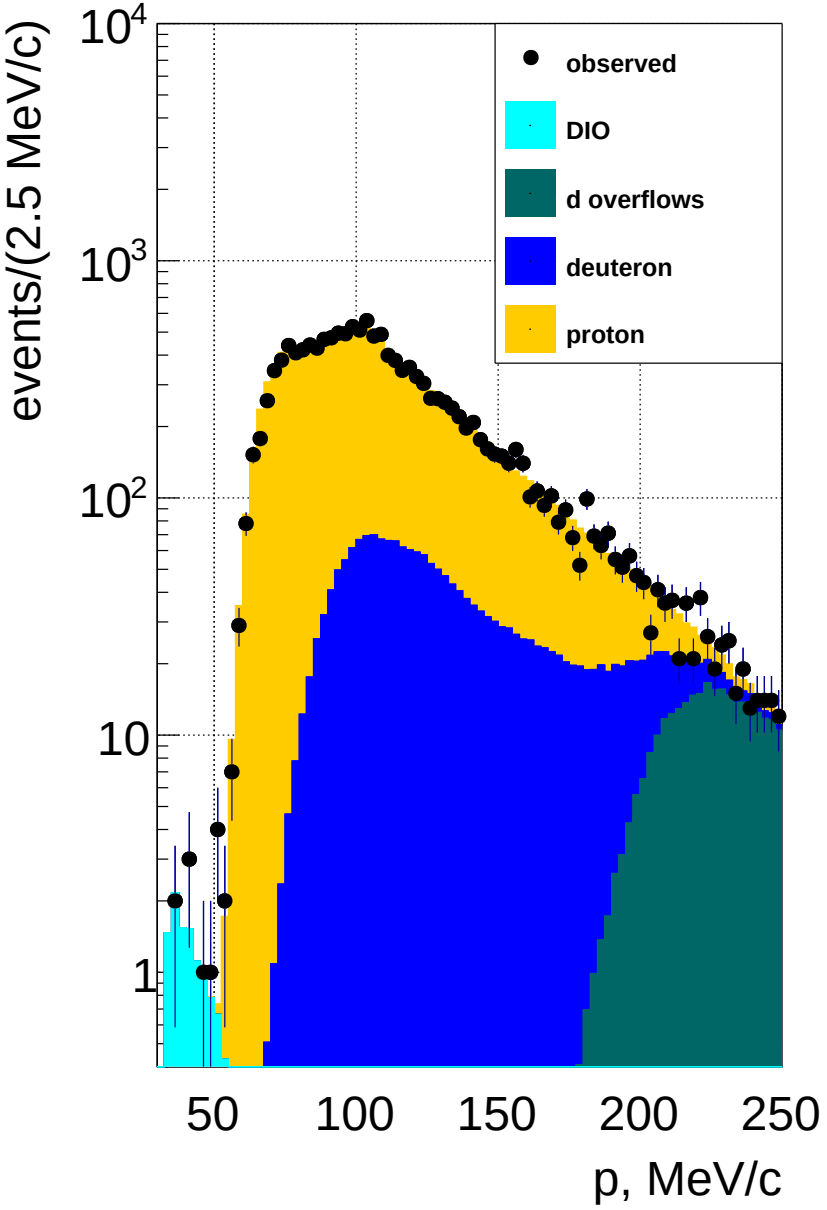
# Data spectrum: contained tracks



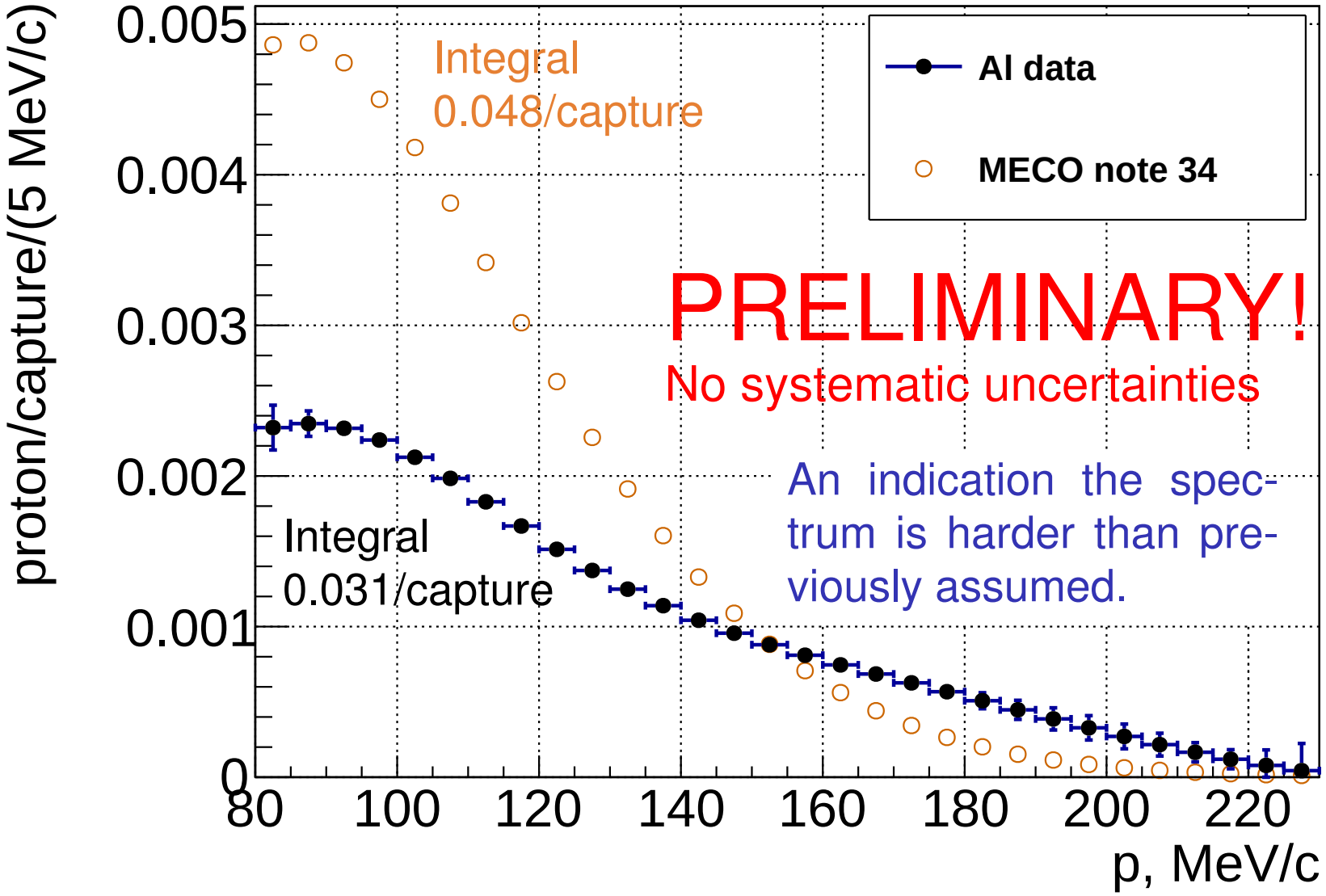



# Data spectrum: uncontained tracks



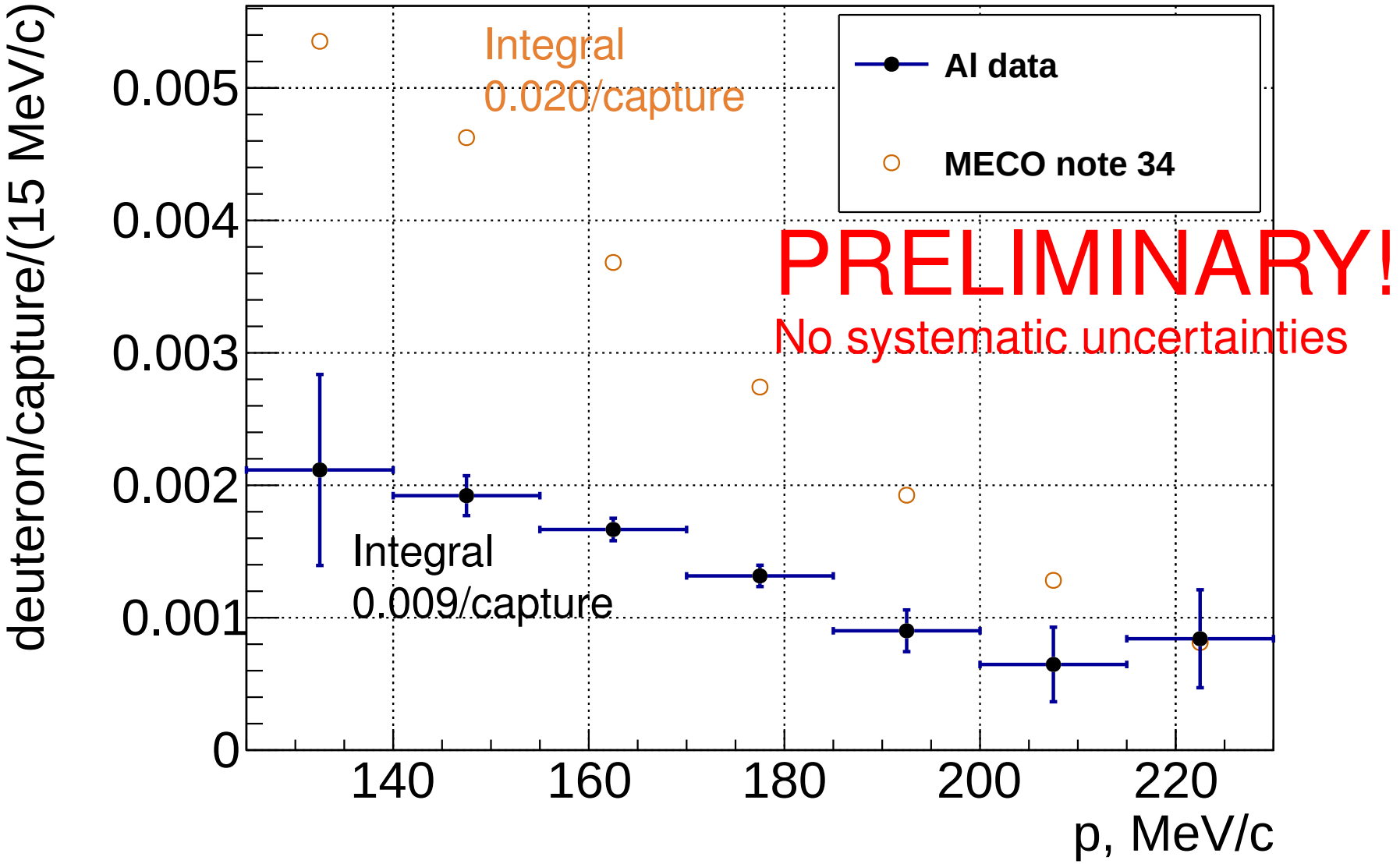



# Unfolded protons



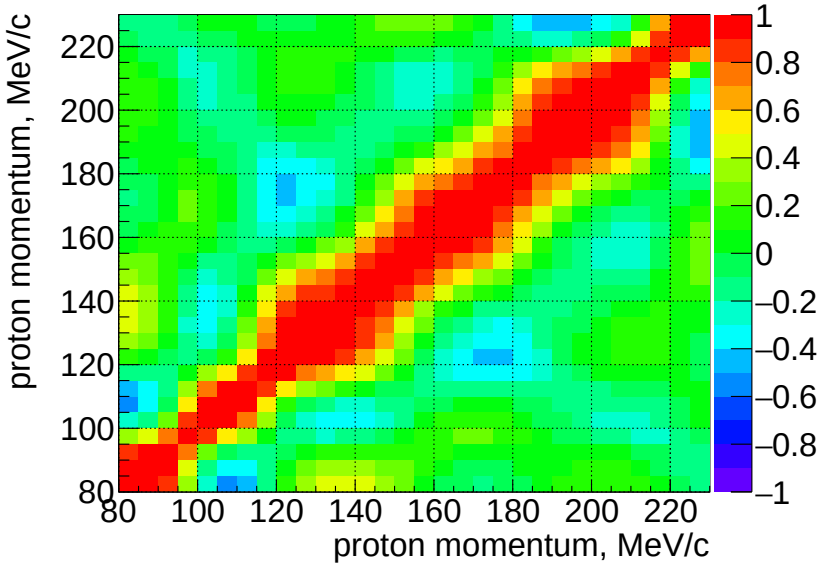

MECO note 34 by Ed Hungerford is a “best guess” based on old measurements.

# Unfolded deuterons

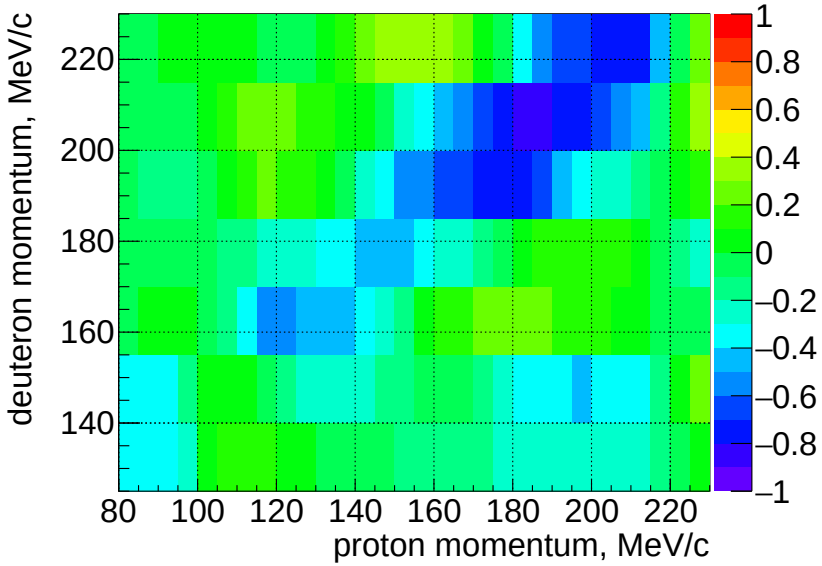


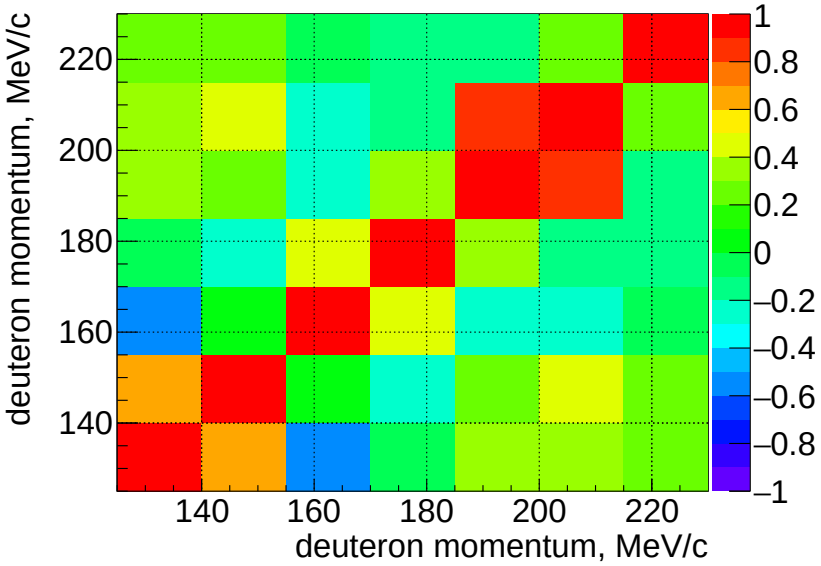

MECO note 34 by Ed Hungerford is a “best guess” based on old measurements.

# Correlations in the fitted spectra




- DIO background is not correlated with other fit parameters ($|r| < 0.3$)
- The rest of correlations is shown on this slide on a color scale



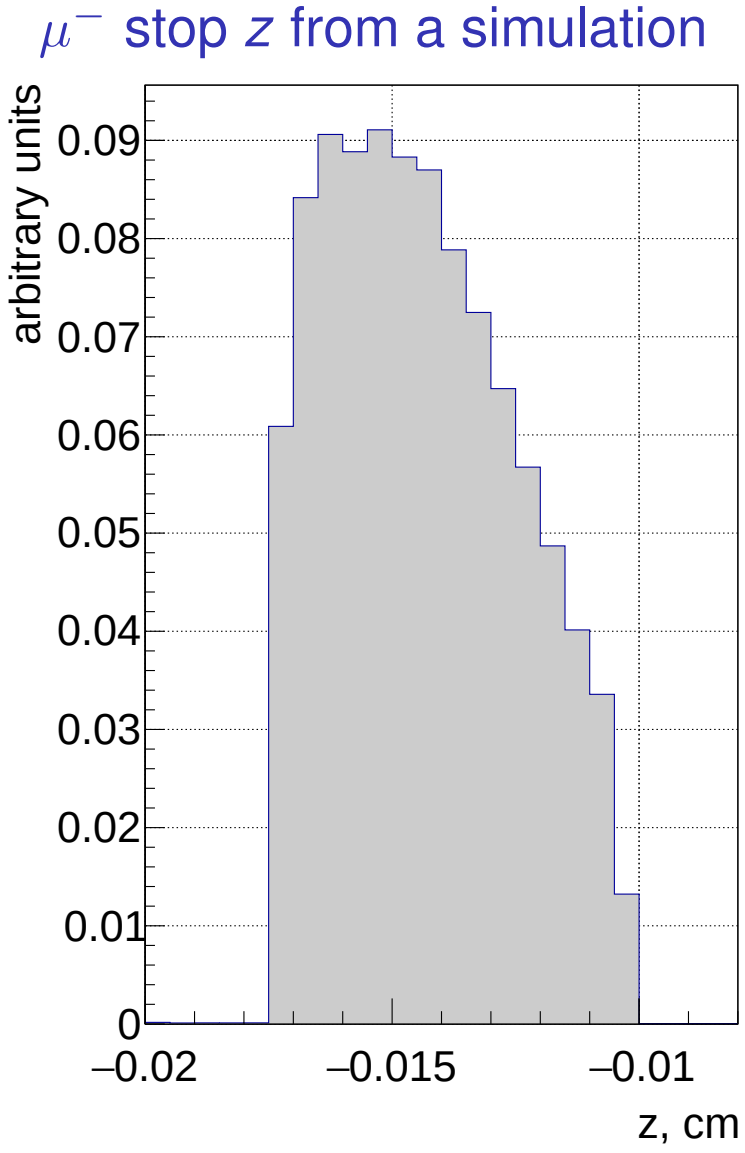



# Systematic uncertainties

- The chambers are 100% efficient for min. ionising particles
- The detector is very thin (about 2 mg/cm$^2$ per chamber)
- The materials are extremely well characterized and validated in MC
  - Expect efficiency and energy loss differences between data and MC to be small
- Cross talk
  - not simulated—does not cancel between data and MC
- Unfolding bias
- The muon stopping position systematic

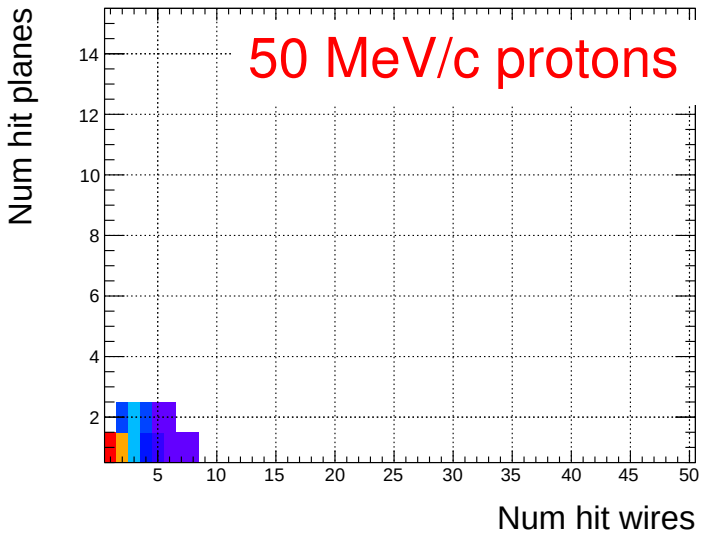
# Stopping distribution systematic

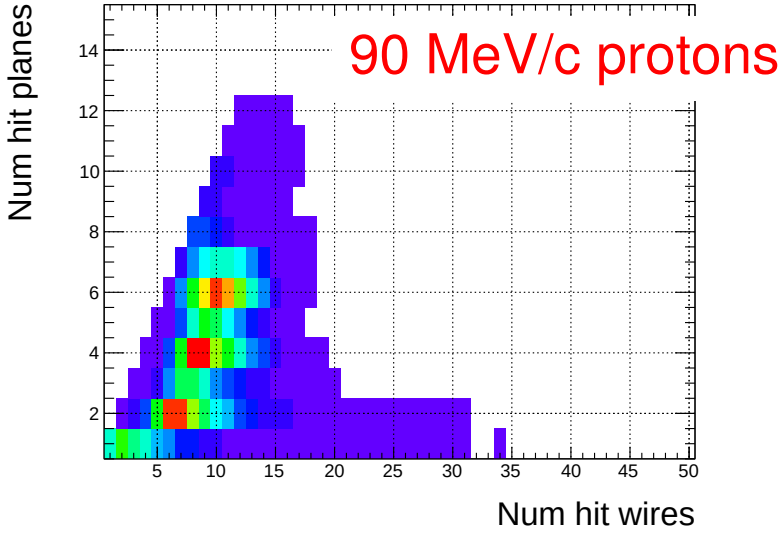
- The target is $71.6 \pm 0.5$ $\mu$m thick aluminum foil
- Muon stop positon inside the target affects the invisible $\Delta E$
- The tails of the muon stopping distribution (out of target stops) contain information about the average stopping position.
  It was known to 2 $\mu$m for the $\mu^+$ analysis
- Working to determine it for the $\mu^-$ stopping distribution

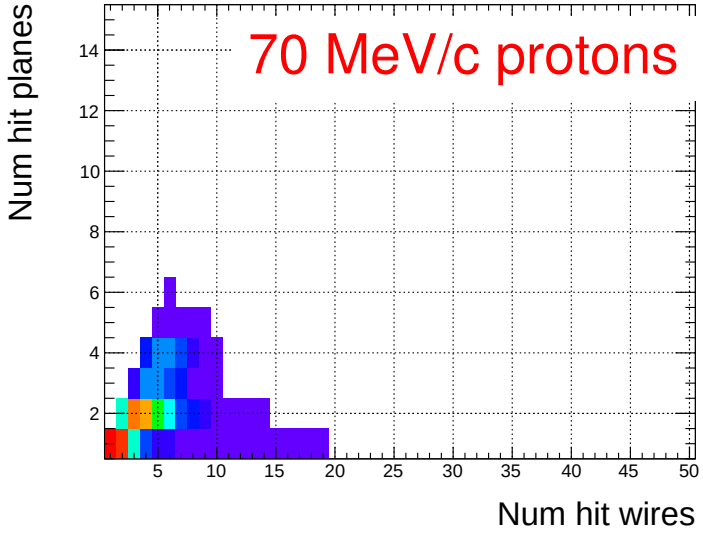


# Prospects: the hit-based channel

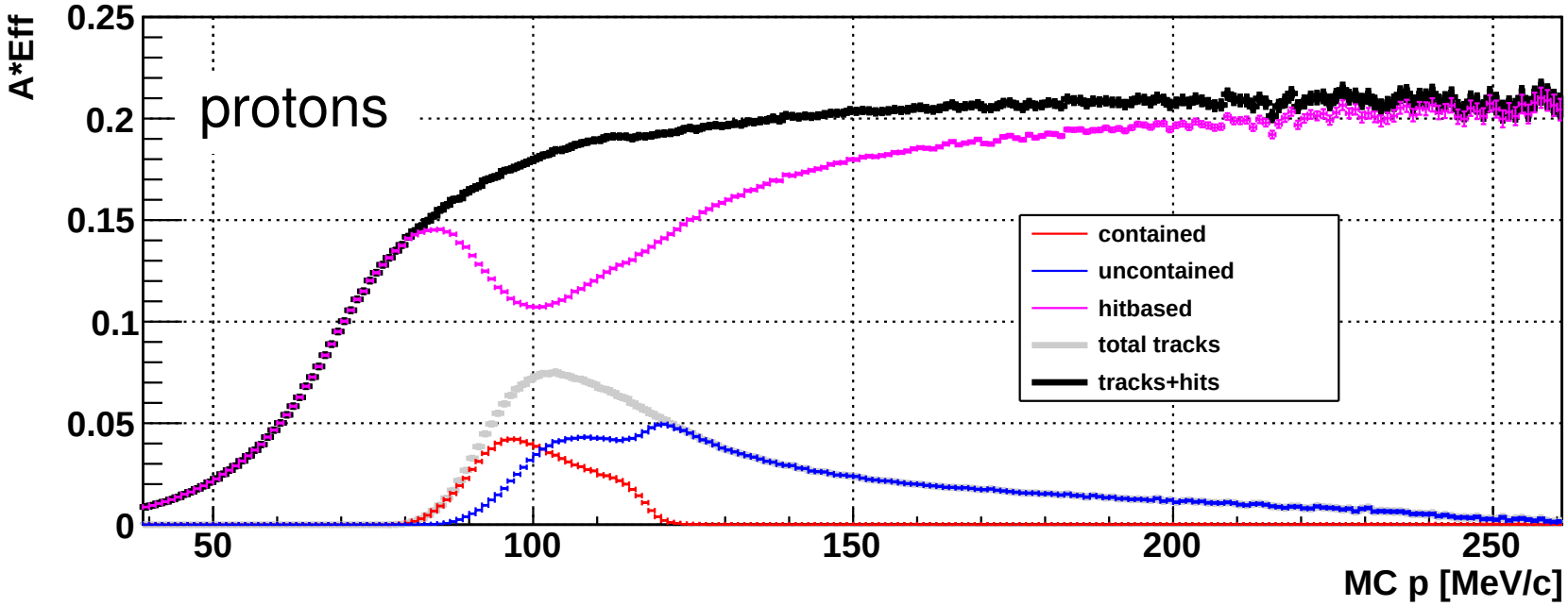
- Particle momentum is correlated to range
- Correlated to the number of hits in detector
- Use hit multiplicities to constrain the spectrum

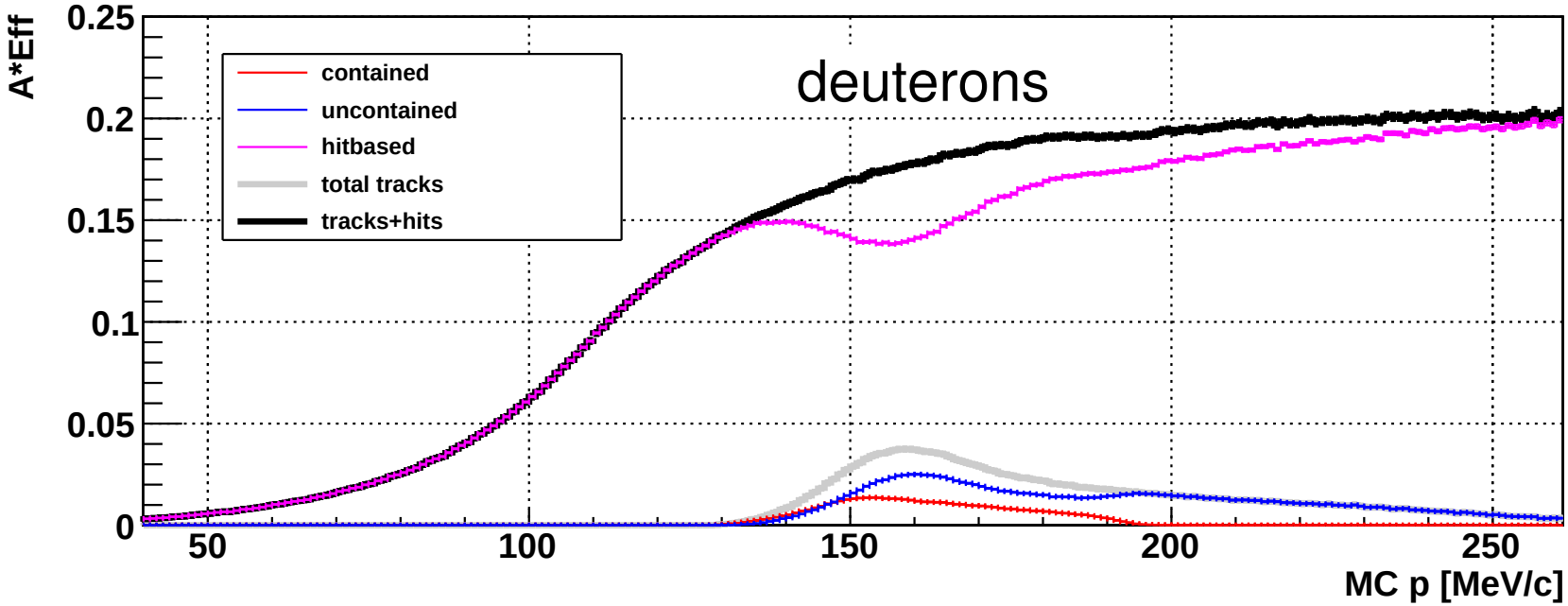


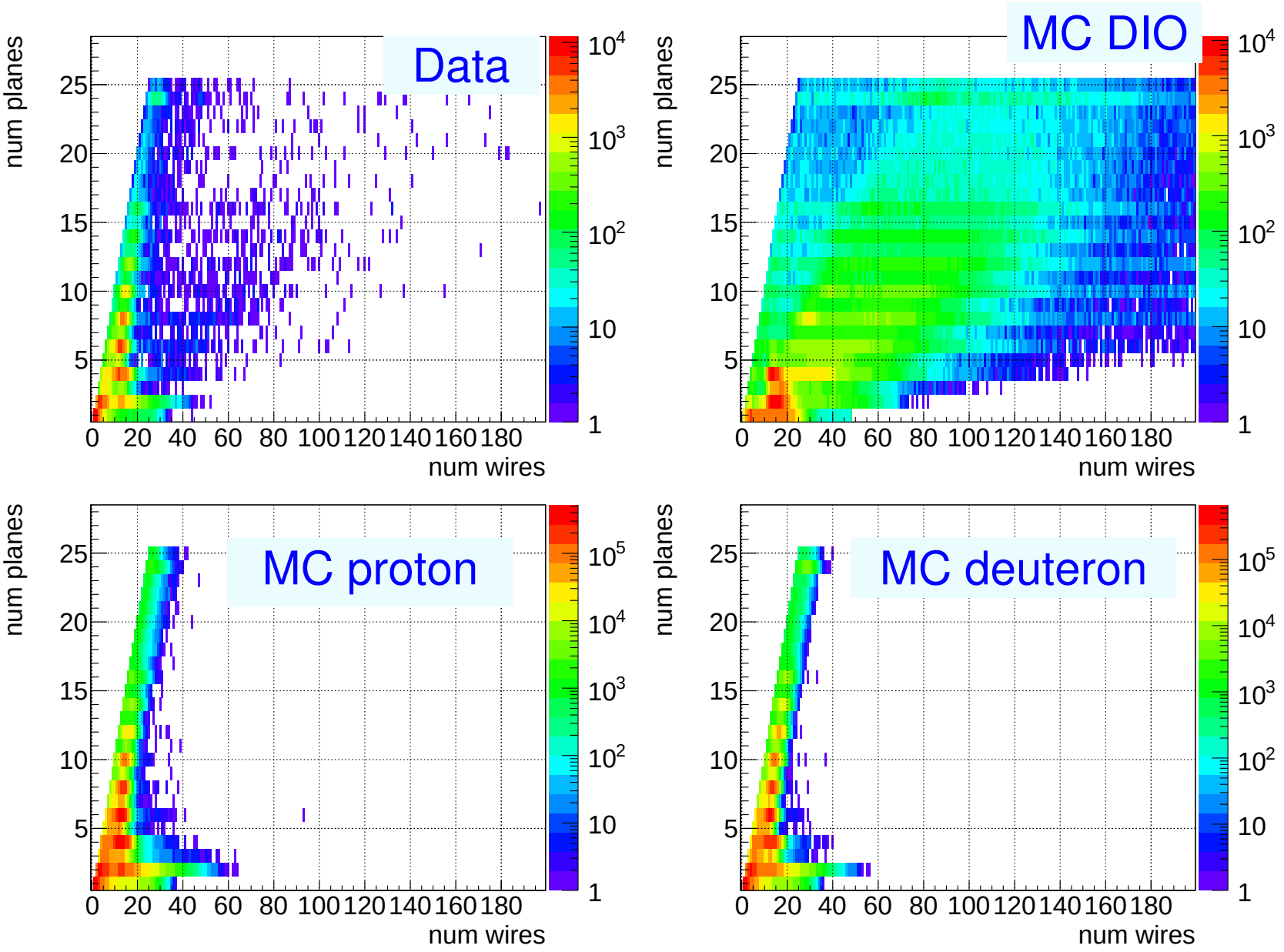



# Acceptance × efficiency with the hit-based channel



# Hit distribution in data vs MC



# Summary

- Emission of charged particles from $\mu^-$ capture on Al
  - The highest rate part of the ejected proton spectrum has not been measured until now
  - Of interest to Mu2e and COMET
- Ejected proton spectrum from $\mu^-$Al measured down to

| | | |
|---|---|---|
| $p = 80$ MeV/c | $E_k = 3.4$ MeV | Our result |
| $p = 277$ MeV/c | $E_k = 40.$ MeV | Previous measurement |

- Systematic uncertainties are being evaluated
- Adding the “hit-based” analysis channel can further extend the range and reduce uncertainties on the result
- This is a difficult measurement. Cross checks are important. We are looking forward towards AlCap results.

# Extra slides

# $\mathcal{TWIST}$ wire chambers

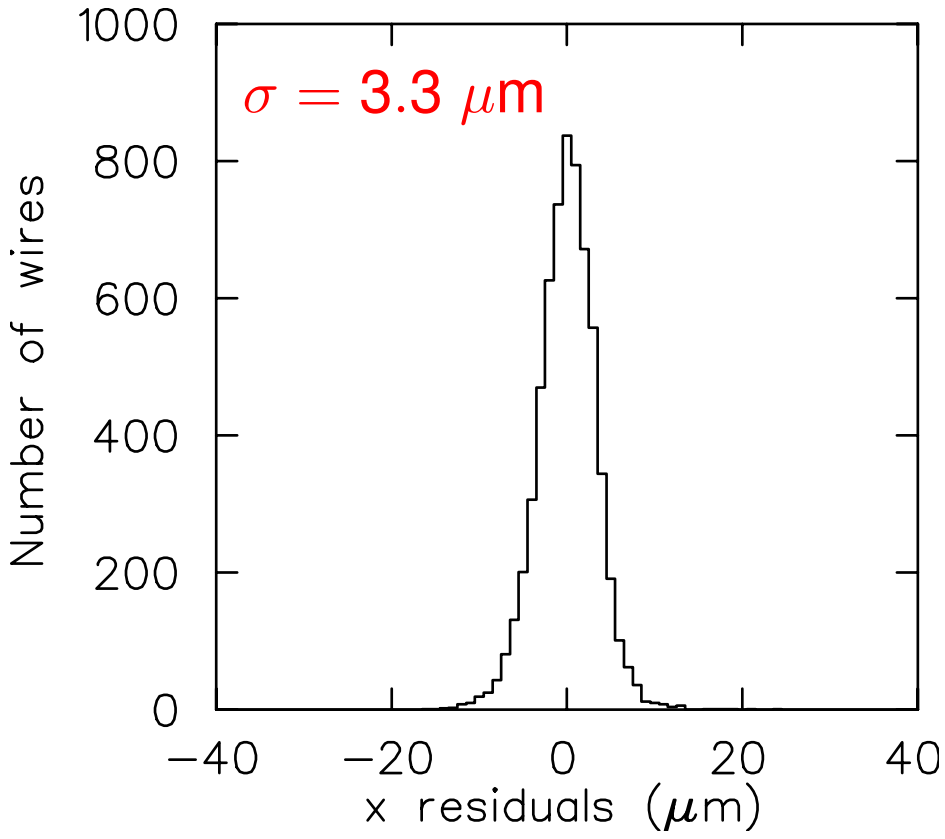
## 44 DC's

- 80 wires per plane
- 4 mm pitch
- DME gas: 50–100 $\mu$m position resolution

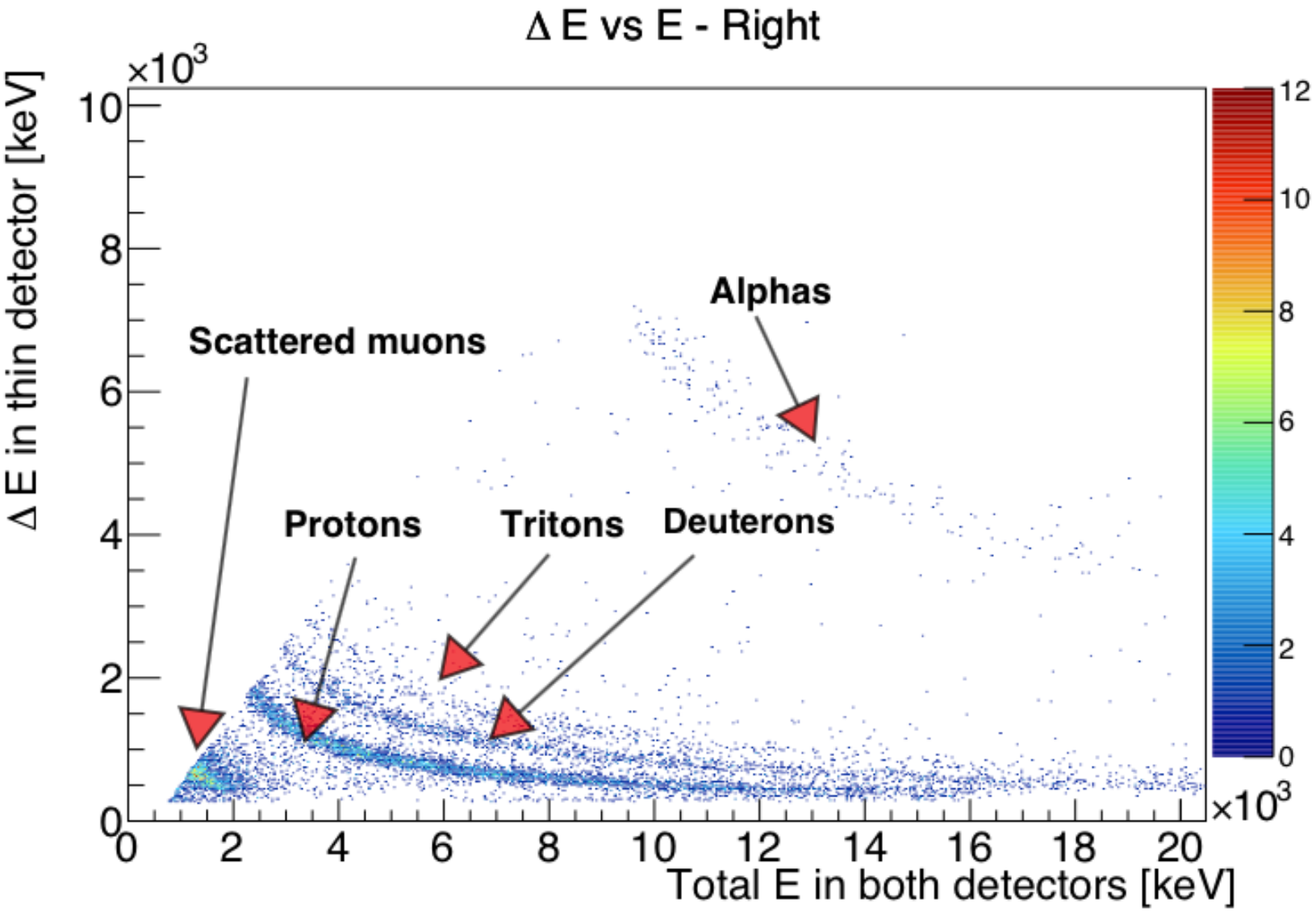
## 12 MWPC's

- 160 wires per plane
- 2 mm pitch
- $CF_4$/Isobutane: $\lesssim$ 20 ns time resolution

Wire position residuals for 70 planes




Longitudinal accuracy:
30 $\mu$m over 1 m = $3 \times 10^{-5}$

# AlCap status

See arXiv:1501.04880