A study of electron recombination using highly ionizing particles in ArgoNeuT

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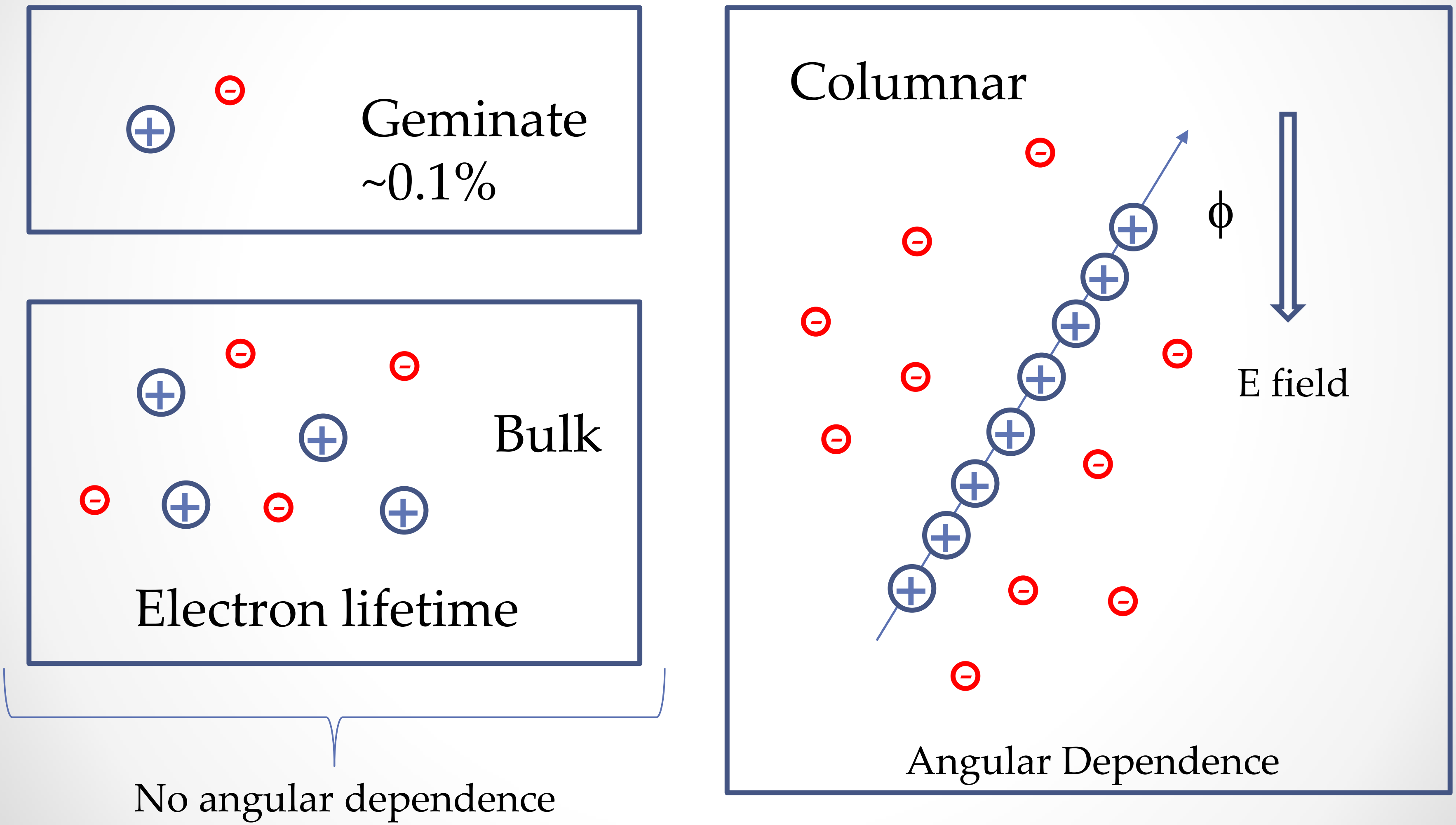
Outline

- Brief survey of recombination theory
- LAr – ideal liquid vs real liquid
- Application of Birks and Box model equations
  - Introduce a modification to the Box model
- Recombination simulation
  - Focus on angular dependence
- ArgoNeuT LAr TPC in the NuMI neutrino beam
  - track and calorimetric reconstruction
- A novel(?) stopping particle ID scheme for selecting protons and deuterons
- Angular dependence – protons
- Extend to higher stopping power - deuterons

Recombination



2. Zur Theorie der Ionisation in Kolonnen; von George Jaffé.

Leipzig, im Mai 1913.

(Eingegangen 30. Mai 1913.)

$$(32') \quad Y_3(X) = \frac{1}{1 + \frac{\alpha N_0}{8 \pi D} \sqrt{\frac{\pi}{z'}} S(z')}, \qquad z' = \frac{b^2 u^2 X^2 \sin^2 \varphi}{2 D^2}.$$

Birks model (1951)

$Y_3(X)$ = recombination factor $\mathcal{R}$
→ fraction of electrons that escape vs E field strength X

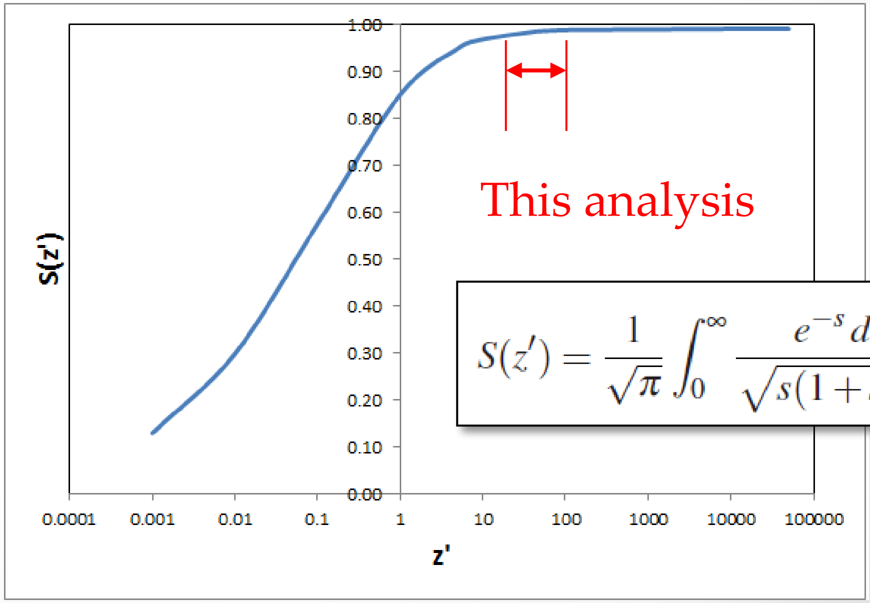
<u>Assumptions</u>

Recombination ~ charge density

No Coulomb interactions

Ion mobility = electron mobility

Electrons & ions have the same Gaussian distribution



$$S(z') = \frac{1}{\sqrt{\pi}} \int_0^\infty \frac{e^{-s} ds}{\sqrt{s(1+s/z')}}$$

Liquid Argon
A Special Medium

- High electron mobility
- Electron MFP = 20 nm
- Onsager radius = 130 nm ($E_{Coulomb} = E_{thermal}$)
- No vibration levels available → ~1 nsec thermalization time
- Electrons in Coulomb field or strong external field, $\mathscr{E}$, are not in thermal equilibrium → diffusion equations not fully applicable

Box Model

Ignore electron diffusion and ion mobility in LAr

$$\mathscr{R}_{\text{Box}} = \frac{1}{\xi} ln(\alpha + \xi).$$

$$\xi = k_{\text{Box}} N_o / 4a^2 \mu \mathscr{E}$$

$\mathscr{E}$ = E field

Thomas & Imel, Phys Rev A 36 (1987) 614

α = 1 in the canonical model.
We allow it to vary in the recombination fits

We set $\xi = \beta$ (dE/dx) and fit β in the recombination fits

Liquid Argon

As a Real Detector Medium

Measurement

Birks form

$$\mathscr{R}_{\text{ICARUS}} = \frac{A_B}{1 + k_B \cdot (dE/dx)/\mathscr{E}}$$

$A_B = 0.800 \pm 0.003$ $\neq 1$

$k_B = 0.0486 \pm 0.0006$ kV/cm (g/cm^2/MeV)

Amoruso, et al NIM A 523 (2004) 275

Impurities

Ions can attach to water molecules, screening the Coulomb field.

Debye length λ_D= distance at which screened potential E = $E_{thermal}$

λ_D= 400 – 600 nm in ArgoNeut data

Not negligible?

Measurement

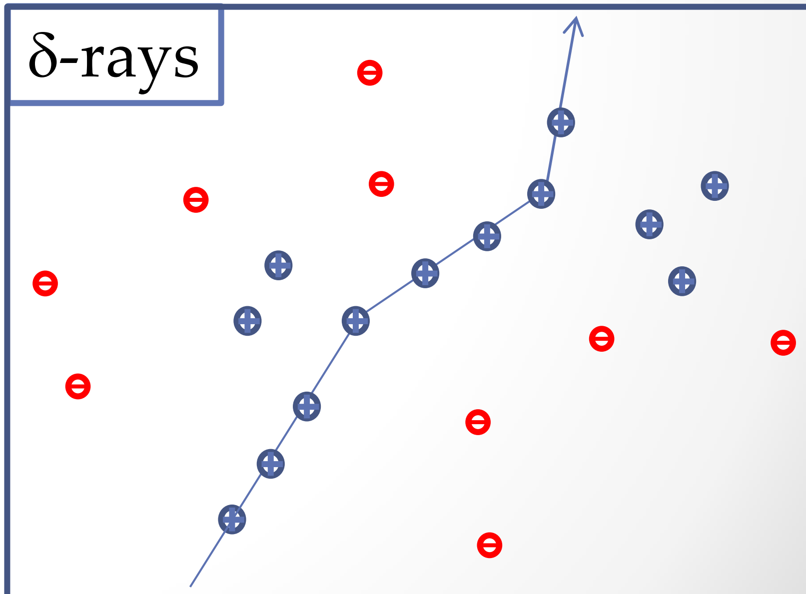
Theory $\mathcal{R} \rightarrow 0$ as $\mathscr{E} \rightarrow 0$

Heavy ions: $\mathcal{R}$= 0.003

Electrons: $\mathcal{R}$= 0.35

Doke, et al Chem. Phys. Lett 115 (1985) 3434

δ-rays



Application of Birks and Box forms to reconstruction

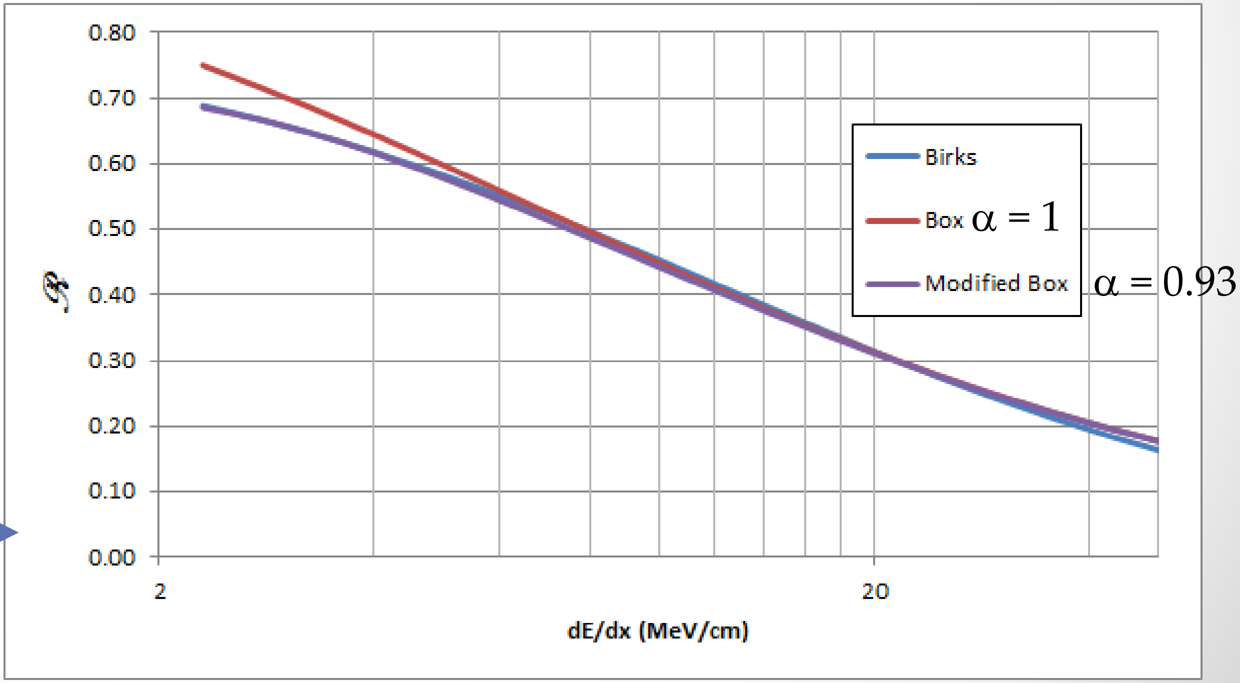
Inverse Birks equation is < 0 at large dQ/dx ⇨ $dE/dx = \dfrac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}$

Inverse Box equation is well behaved ⇨ $dE/dx = (exp(\beta W_{ion} \cdot (dQ/dx)) - \alpha)/\beta$

But Box model fails to match data at low dE/dx

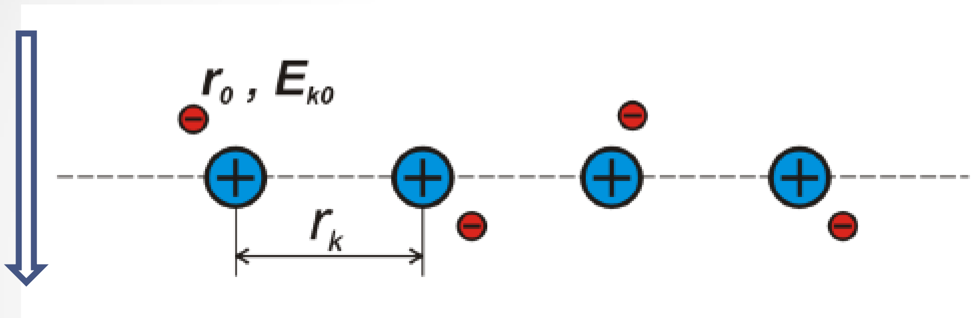
Solution: Let $\alpha < 1$
"Modified Box Model"
ala ICARUS $A_B = 0.8$

Example with $\alpha = 0.93$
$\beta = 0.32$



Recombination Simulation

E field



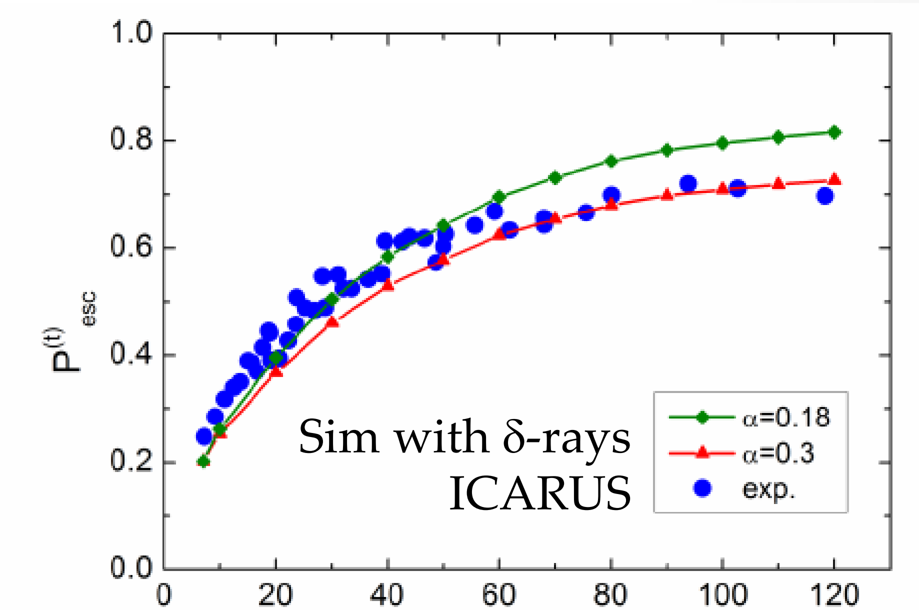
Stopping proton: dE/dx = 24 MeV/cm → r_k = 10 nm

MIP: dE/dx = 1.7 MeV/cm → r_k = 50 nm

Initial conditions:
r_o = 0.5 nm, E_{ko} = 5 eV

After thermalization:
$\langle r_o \rangle$ ~ 2500 nm, $\langle E_{ko} \rangle$ ~ 0.01 eV

Simulation includes motion due to (periodic) Coulomb field, external E field and atomic collisions, escape and recombination criteria



Jaskolski, Wojcik J. Phys. Chem. A 115 (2011) 4317

Recombination Simulation

Angular Dependence

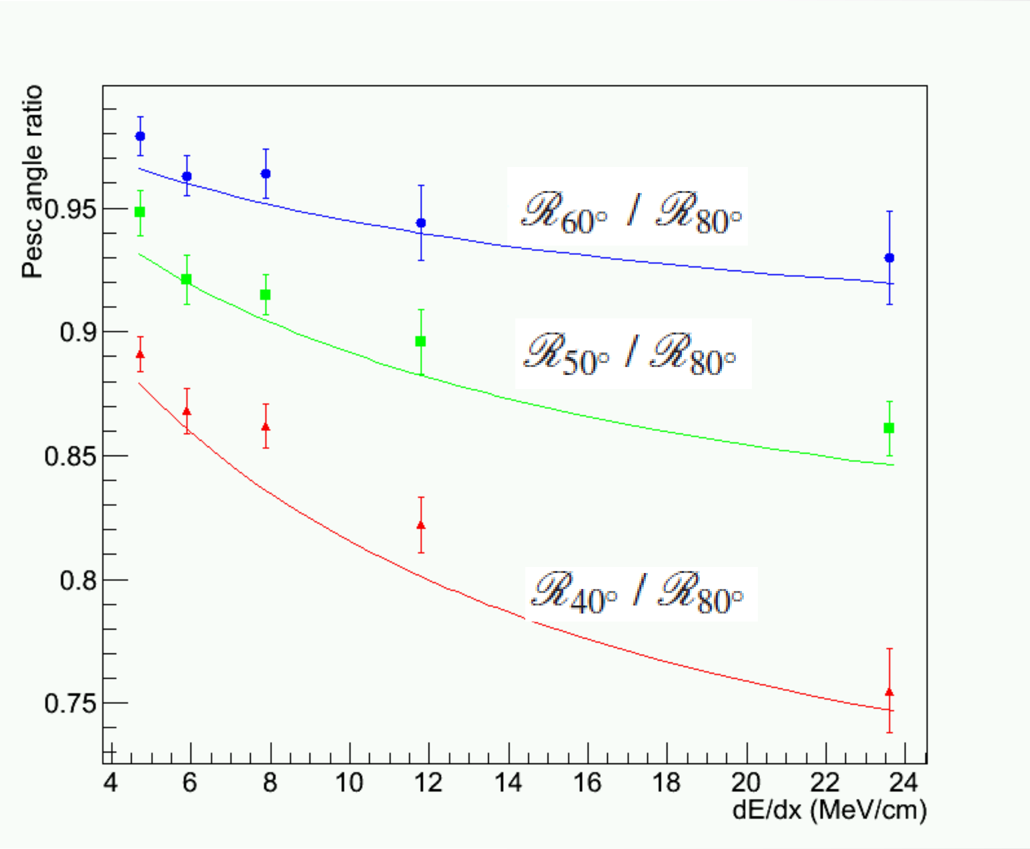
Modify simulation to allow non-perpendicular $\mathcal{E}$ field

Simulation runs for r_k = 10, 20, 30, 40, 50 nm and ϕ = 40°, 50°, 60°, 80°

Ratios of escape probability, $\mathcal{R}$, vs dE/dx →

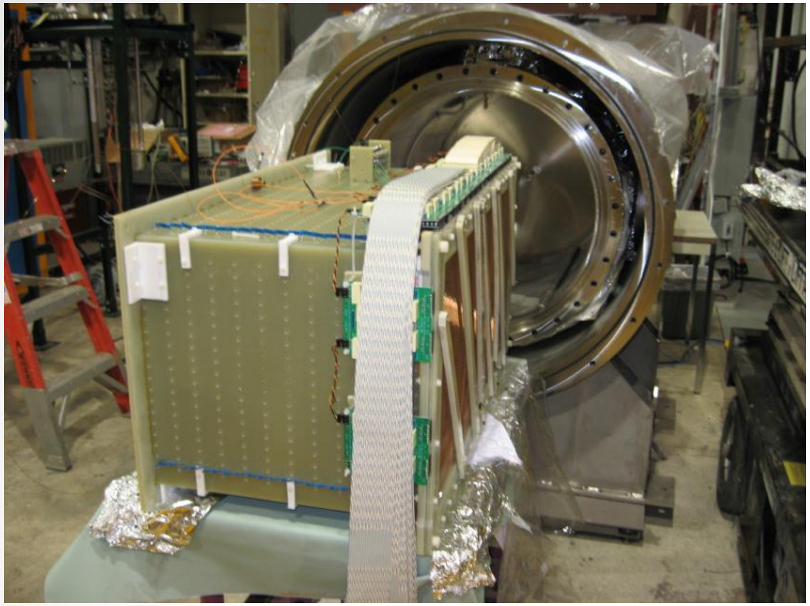
Simulation (data points) $\mathcal{R}_{ICARUS}$ with $\mathcal{E} \rightarrow \mathcal{E} \sin\phi$ (curves)

<u>Significant angular dependence expected from theory and simulation</u>

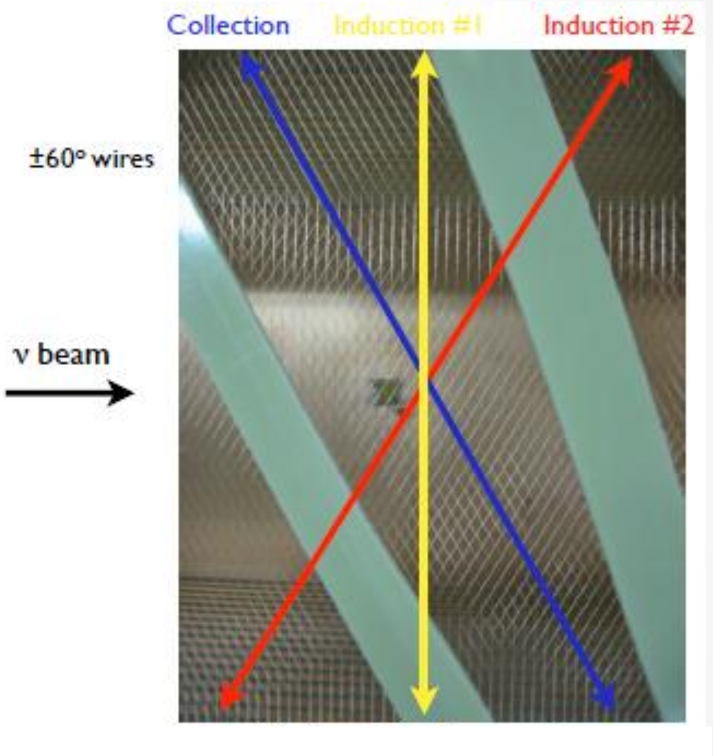


M. Wojcik

ArgoNeuT



Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Electronics Style (Temp.)	JFET (293 K)
Wire Pitch (Plane Separation)	4 mm (4 mm)
Electric Field	481 V/cm
Max. Drift Length (Time)	0.5 m (330 μs)
Wire Properties	0.15mm diameter BeCu



C. Anderson, 2012 JINST 7 P10019

Stopping Particle Stopping Power

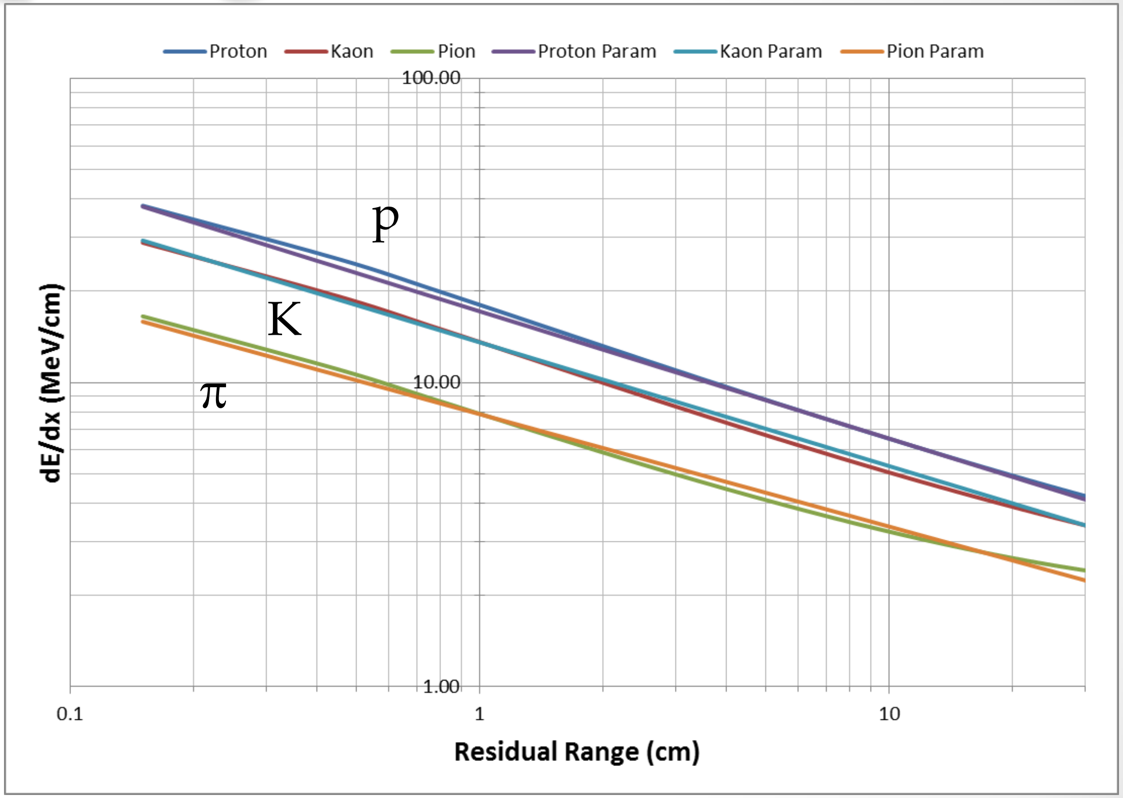
Bethe-Bloch eqn has power law dependence with residual range (R) near the stopping point

$$(dE/dx)_{hyp} = A\, R^b$$

$$T_{range} = \frac{A}{b+1} R^{b+1}$$

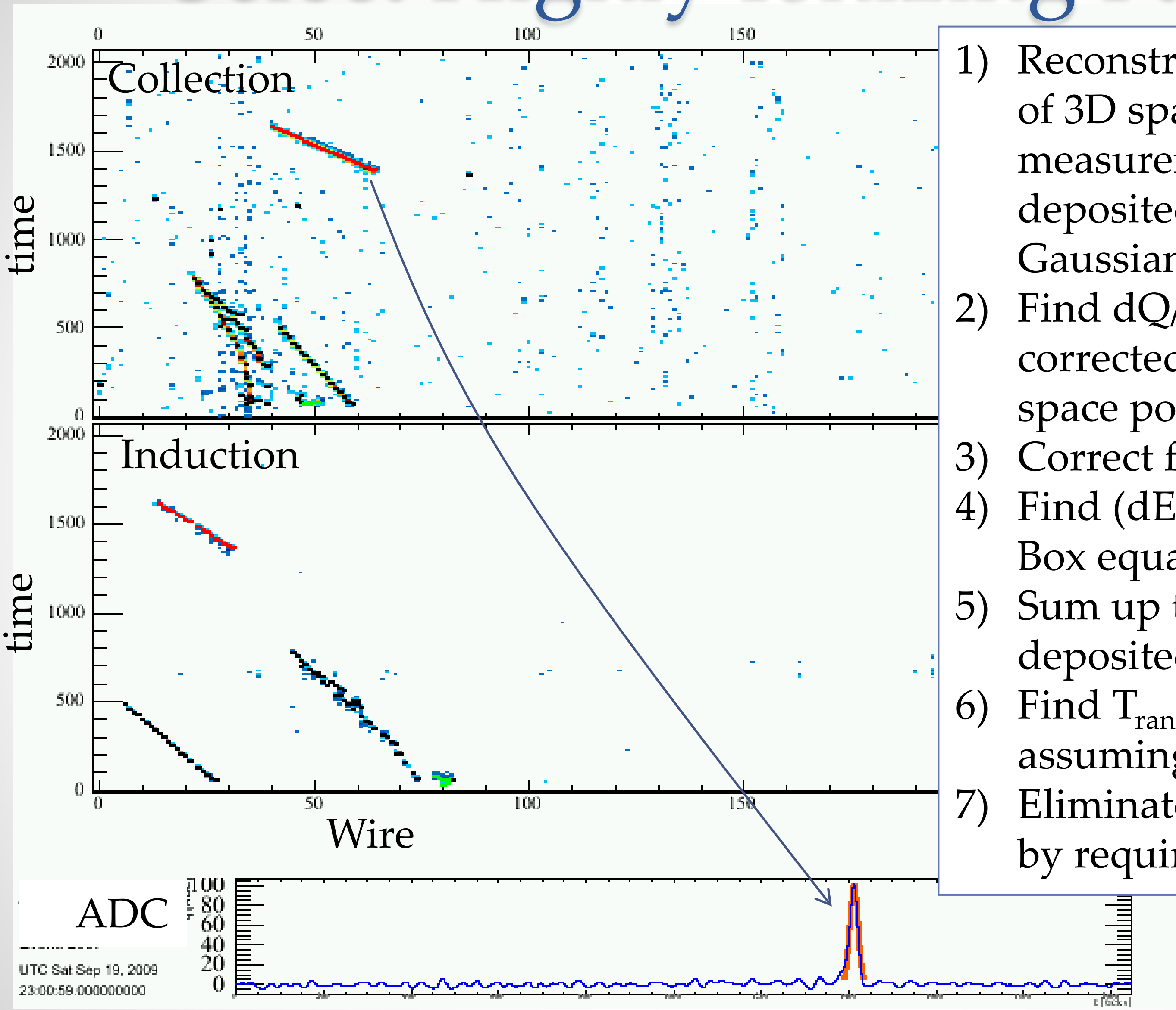
Particle	A	b
pion	7.9	-0.37
kaon	13.5	-0.41
proton	17	-0.42
deuteron	25	-0.43

T_{range} (MeV), R (cm)



Note the weak dependence on b

Select Highly Ionizing Particles



1) Reconstruct 3D tracks = cluster of 3D space points each with a measurement of charge Q deposited using the area of a Gaussian fit (collection plane)
2) Find dQ/dx using angle corrected distance between space points
3) Correct for electron lifetime
4) Find $(dE/dx)_{calo}$ using Birks or Box equation
5) Sum up to find kinetic energy deposited = T_{calo}
6) Find T_{range} using track length assuming a proton hypothesis
7) Eliminate lightly ionizing ptcls by requiring $T_{calo} > 0.5\ T_{range}$

Particle Identification
with minimal bias

Algorithm

Set b = constant = 0.42

Find $A_i = (dE/dx)_{calo} \times R^{0.42}$ for each space point i on a track

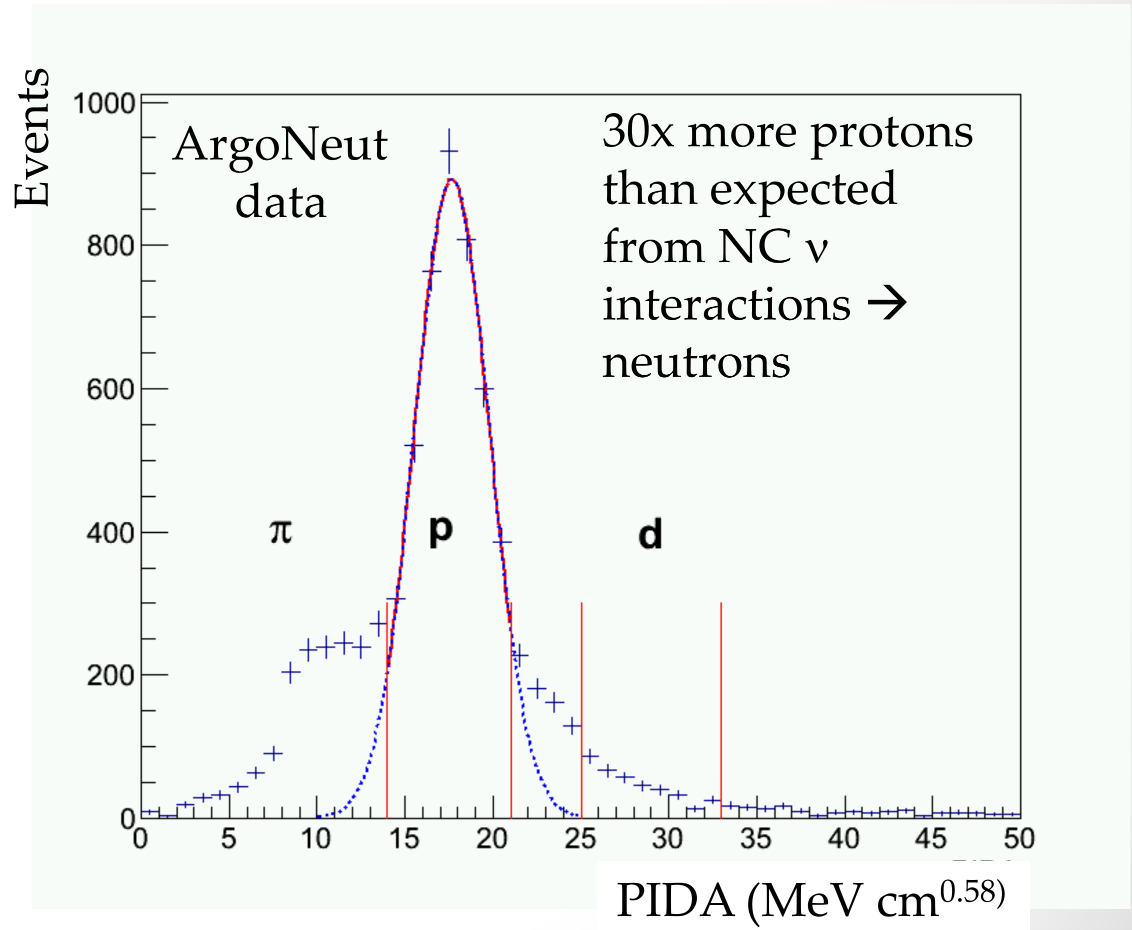
Define PIDA = $< A_i >$ = average value for the track

Histogram PIDA and look for bumps →

Requirements

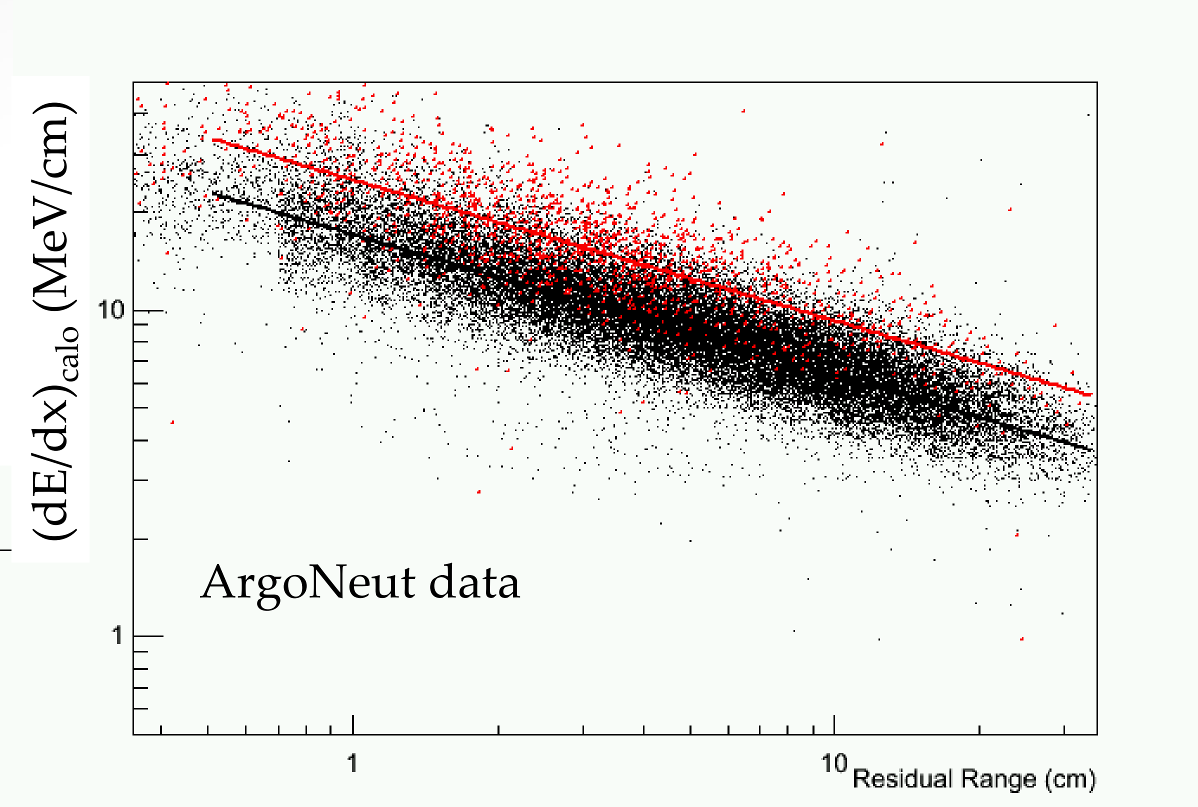
Protons: 14 < PIDA < 21

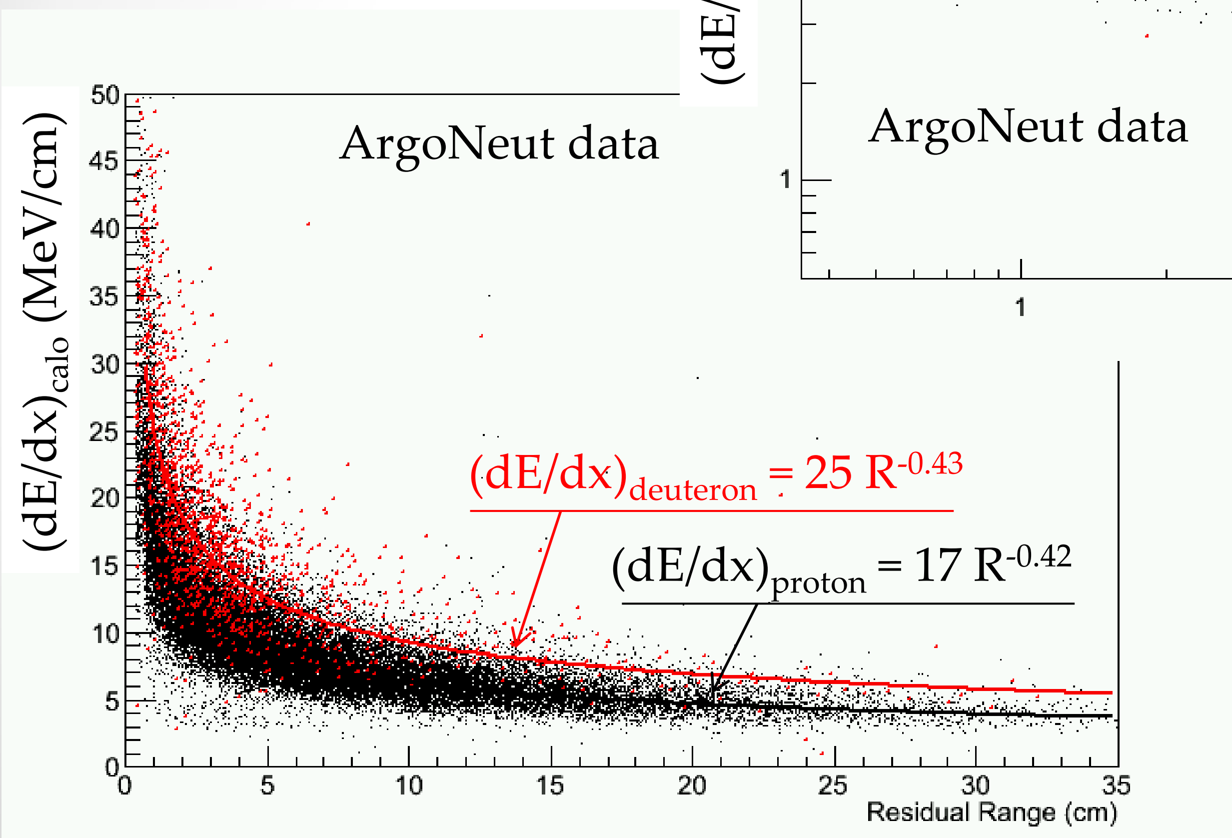
Deuterons: 25 < PIDA < 33

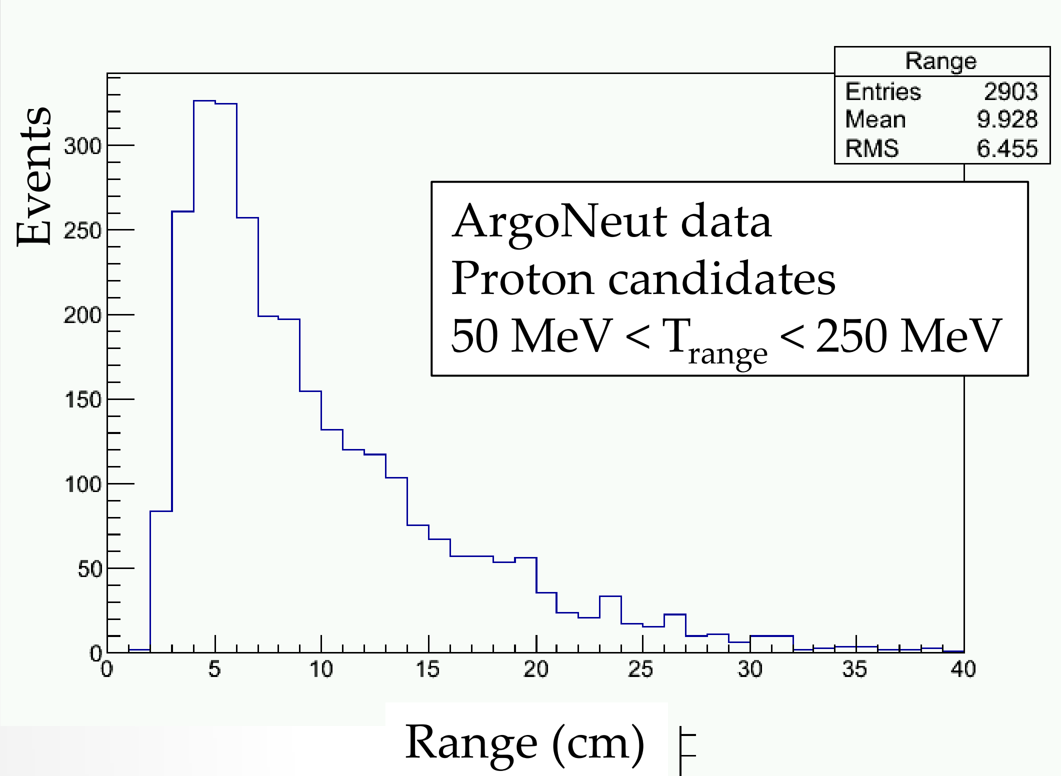


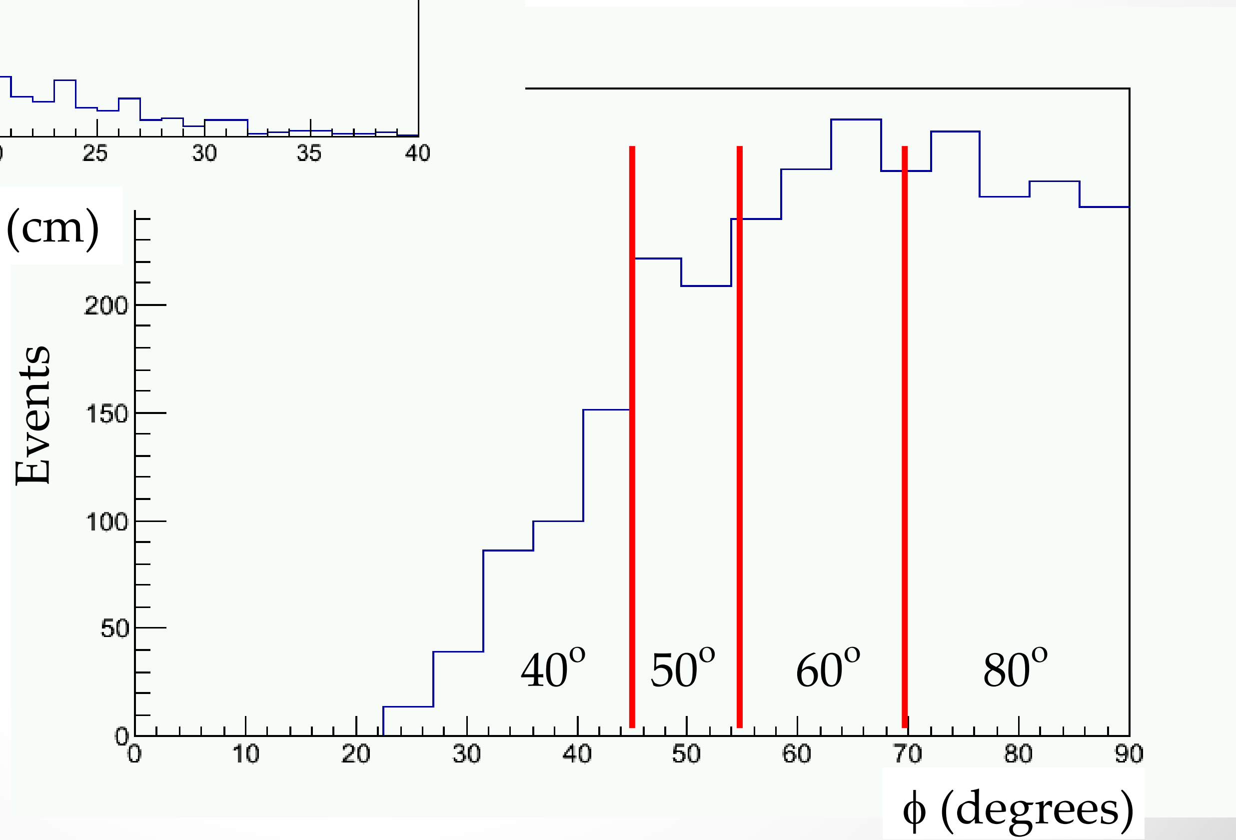
2900 proton candidates

170 deuteron candidates

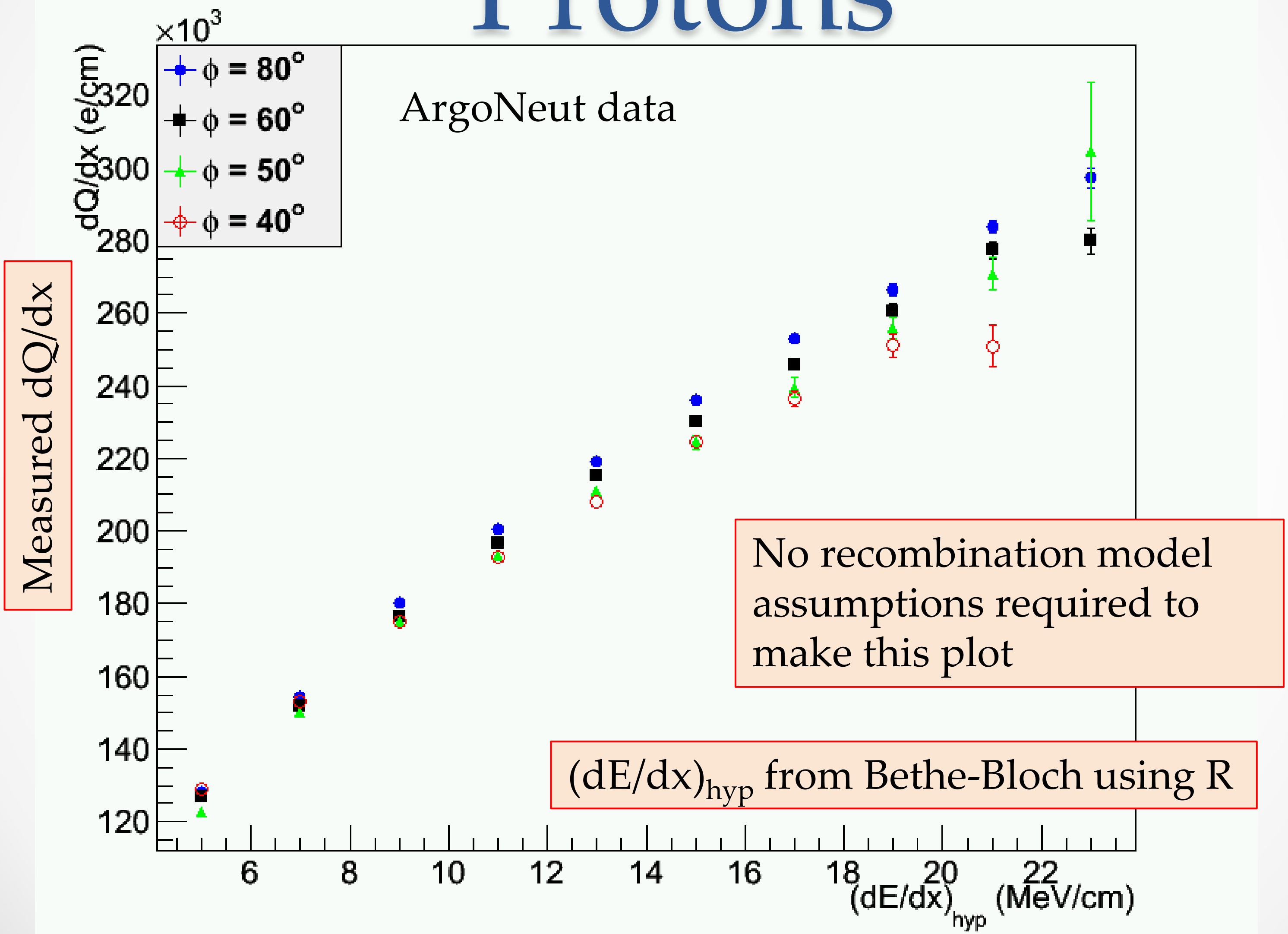




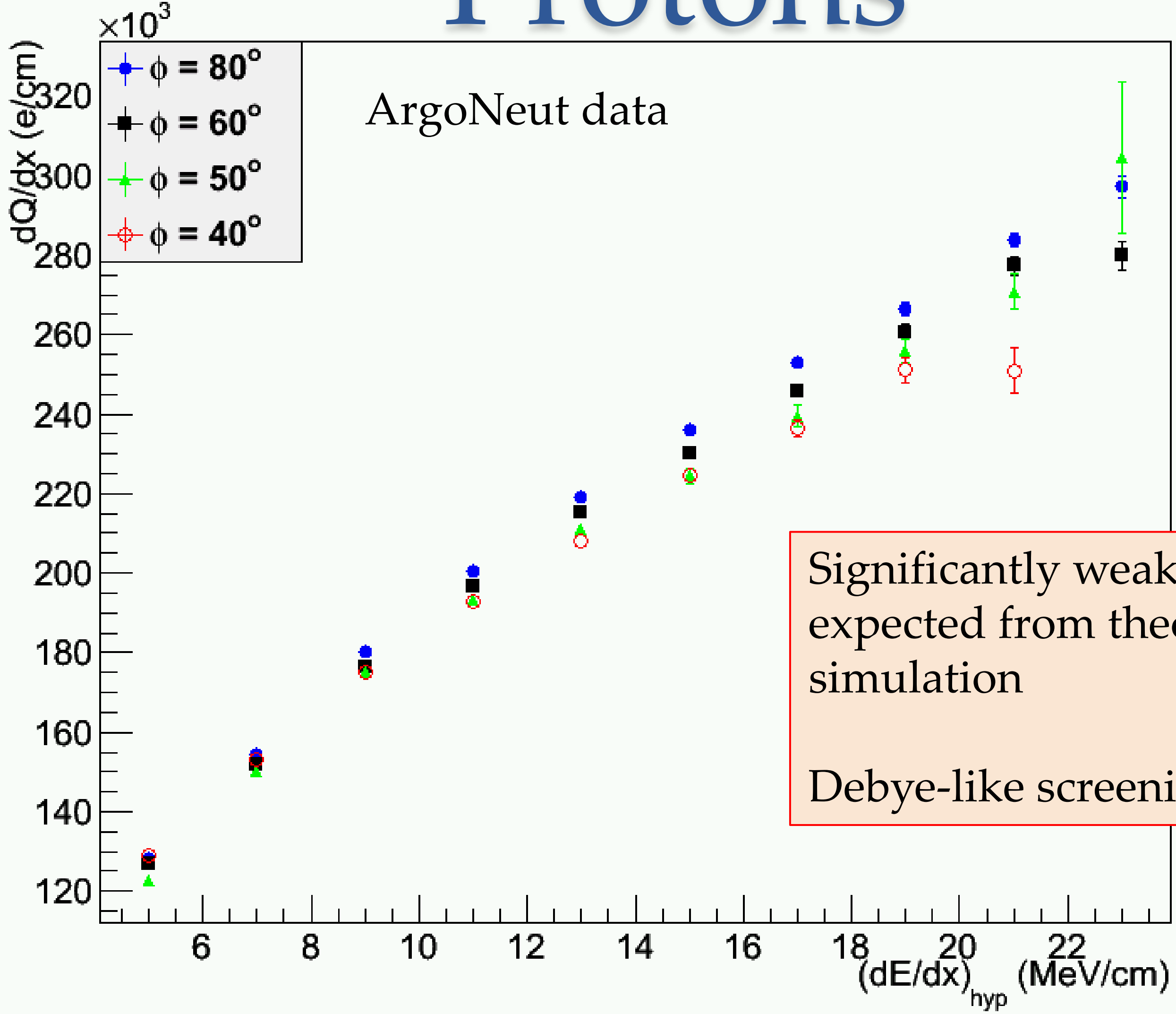

Range
Entries 2903
Mean 9.928
RMS 6.455
ArgoNeut data
Proton candidates
50 MeV < T_{range} < 250 MeV
Events
Range (cm)


Events
40^o
50^o
60^o
80^o
ϕ (degrees)

Angular Dependence Protons



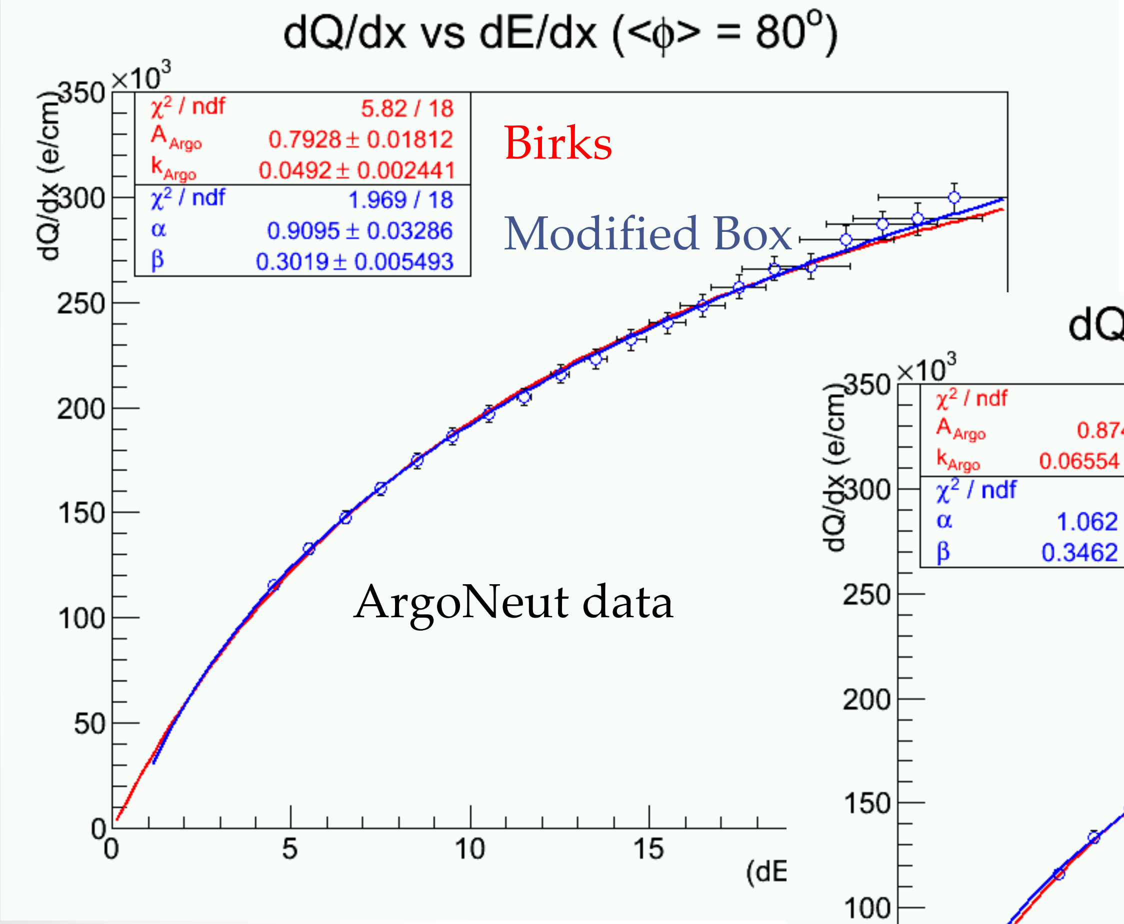
Angular Dependence Protons



Significantly weaker than expected from theory and simulation

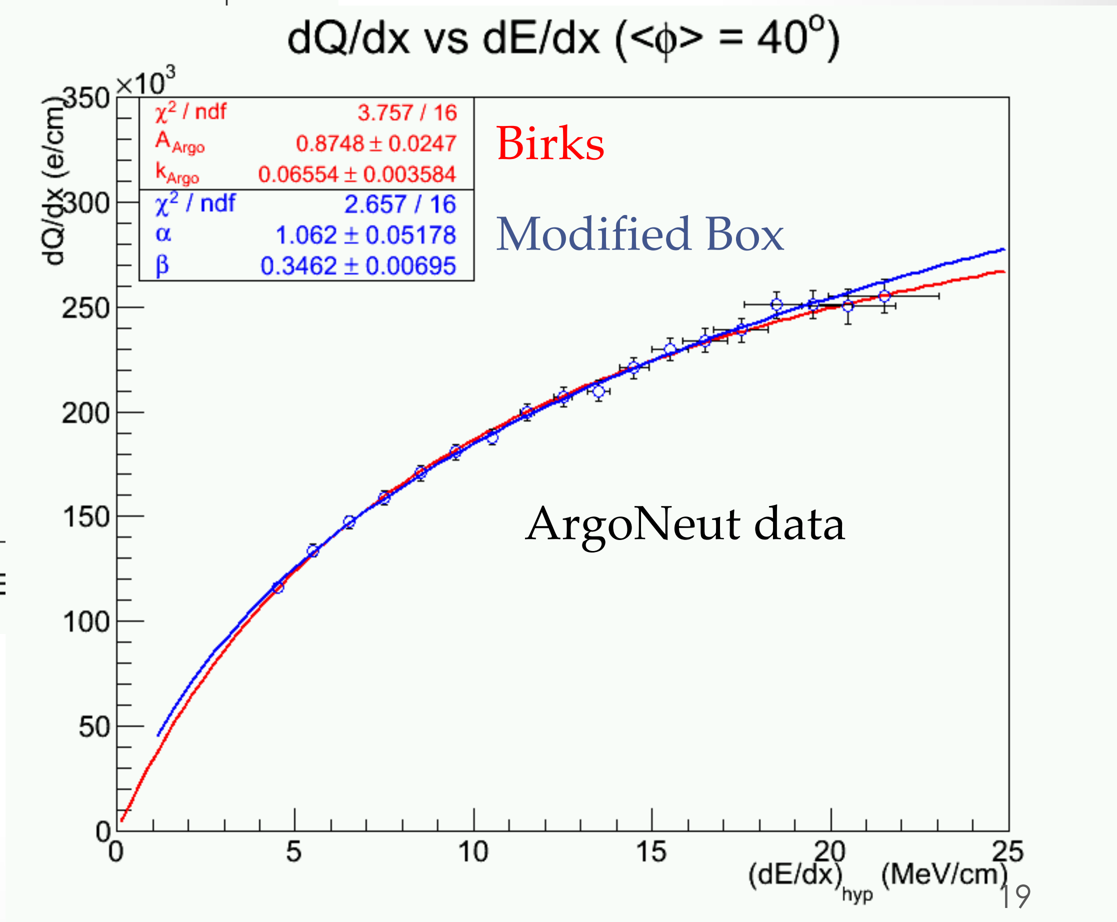
Debye-like screening effect?

Recombination Fits



Vertical bars include 2% systematic error

Horizontal bars δR = 1 mm



Data – open circles

Birks fit – red curve

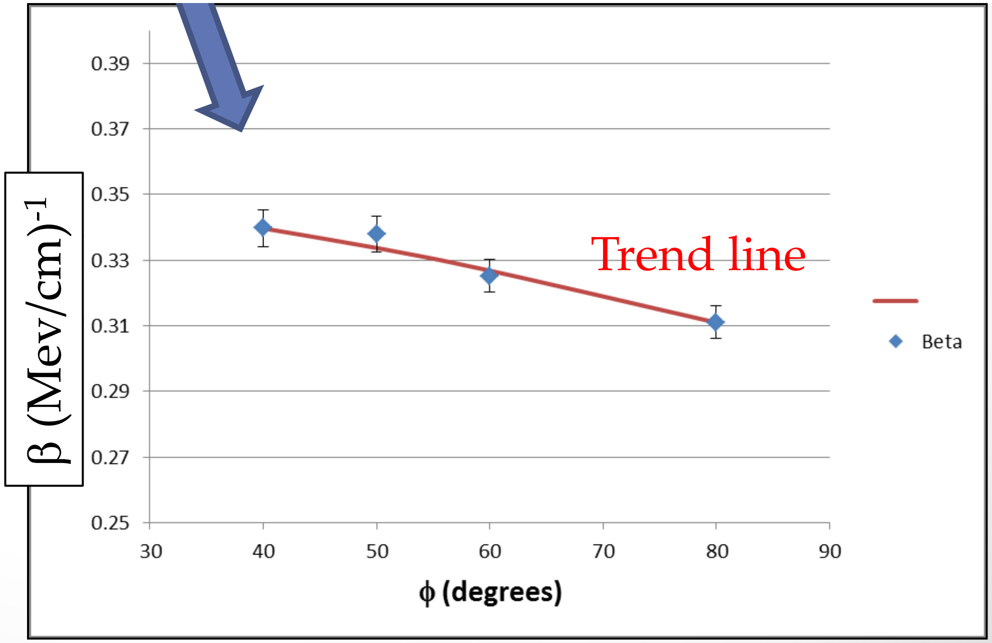
Modified Box fit – blue curve

Fit Summary Protons

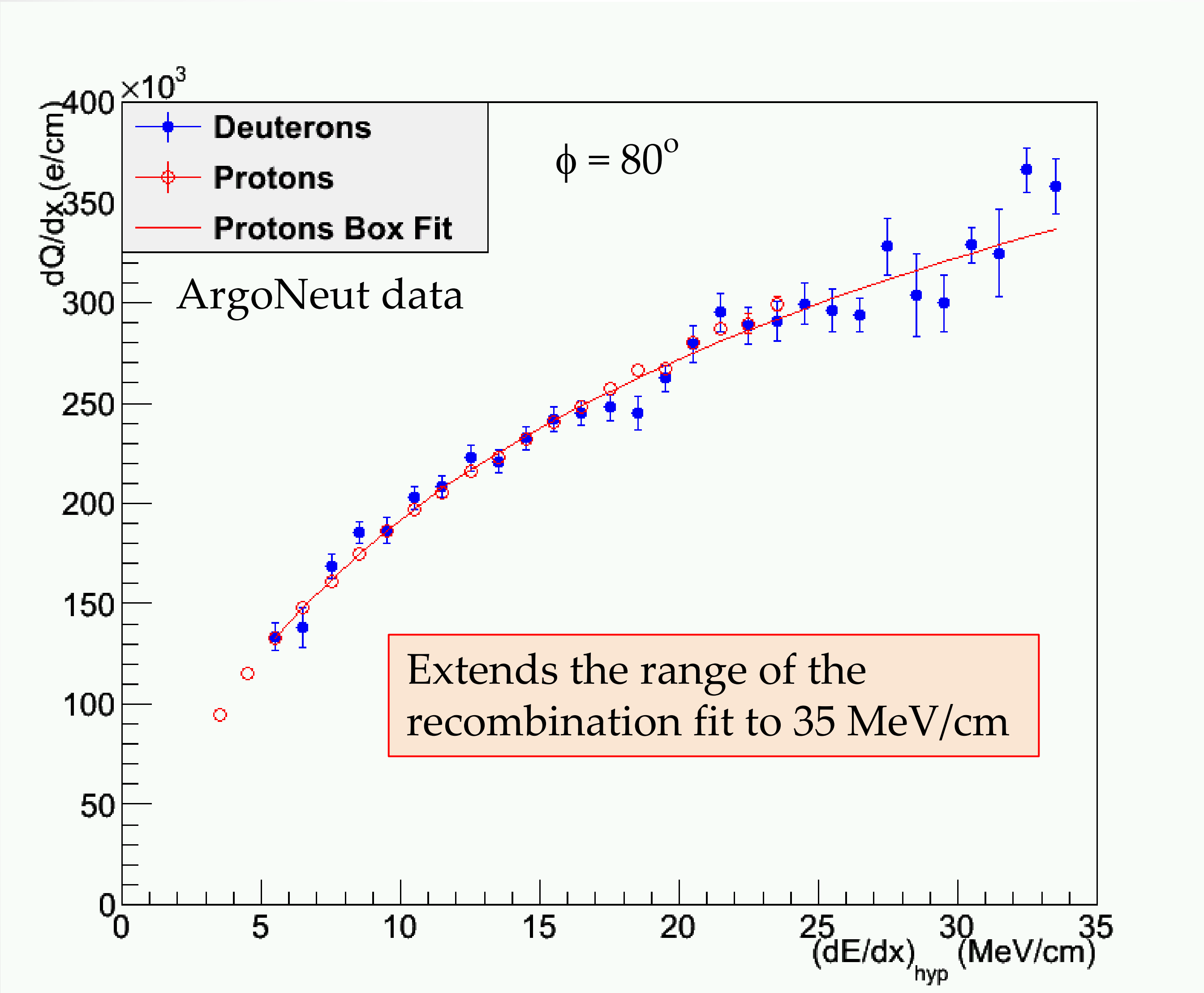
Excellent agreement with ICARUS in the 80° bin

Angle Bin	Angle Bin Range	Box α	Box β $(\mathrm{MeV/cm})^{-1}$	Birks A_{Argo}	Birks k_{Argo} $(\mathrm{kV/cm})(\mathrm{g/cm^2})/\mathrm{MeV}$
80°	70° - 90°	0.91 ± 0.03	0.302 ± 0.005	0.793 ± 0.018	0.049 ± 0.002
60°	55° - 70°	0.92 ± 0.04	0.317 ± 0.006	0.794 ± 0.019	0.052 ± 0.003
50°	47° - 55°	0.90 ± 0.04	0.327 ± 0.007	0.791 ± 0.020	0.053 ± 0.003
40°	20° - 47°	1.06 ± 0.05	0.346 ± 0.007	0.875 ± 0.025	0.066 ± 0.004

α ~ independent of angle
$\langle\alpha\rangle = 0.93 \pm 0.02$



Deuterons

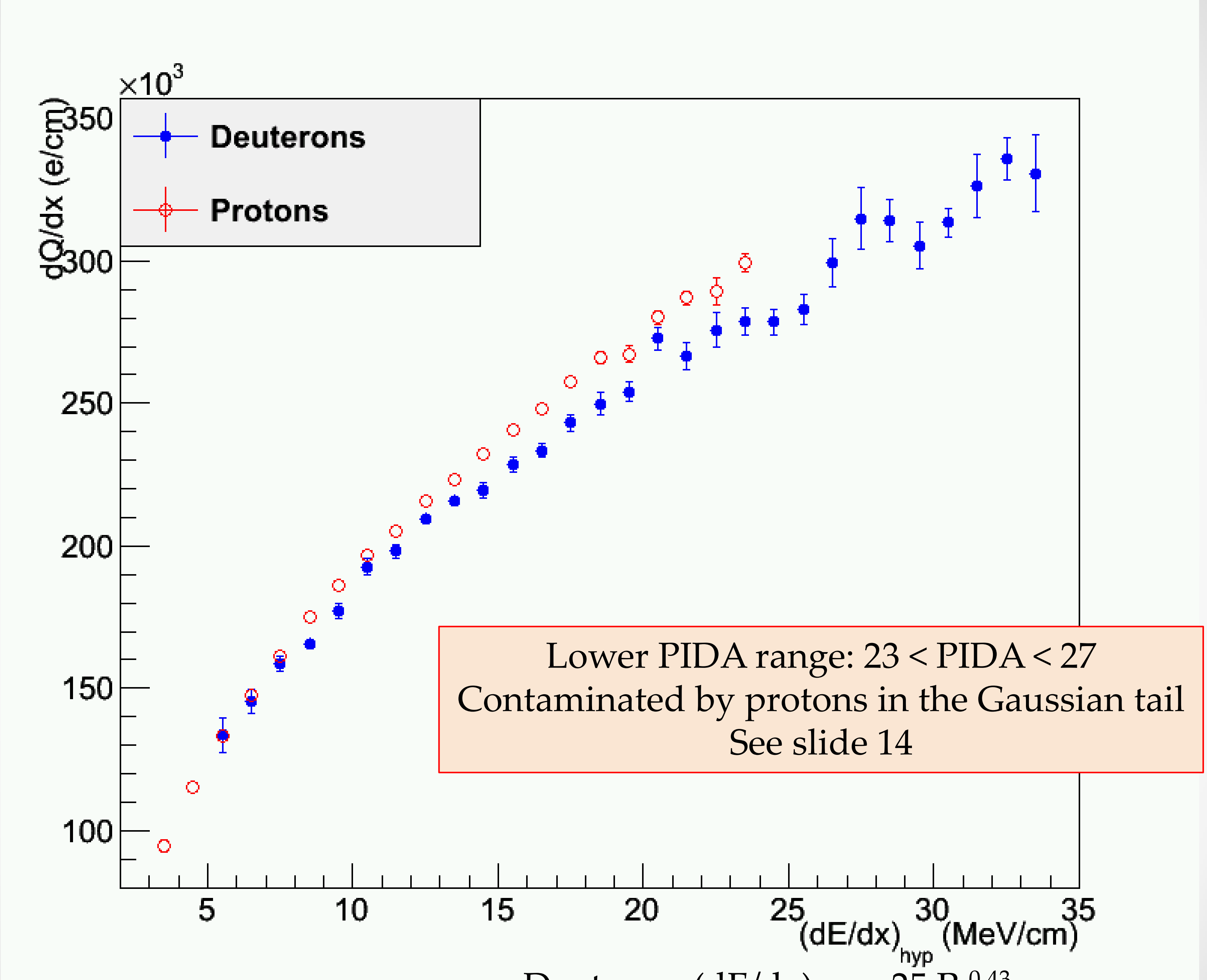


Deuteron: $(dE/dx)_{hyp} = 25\ R^{-0.43}$

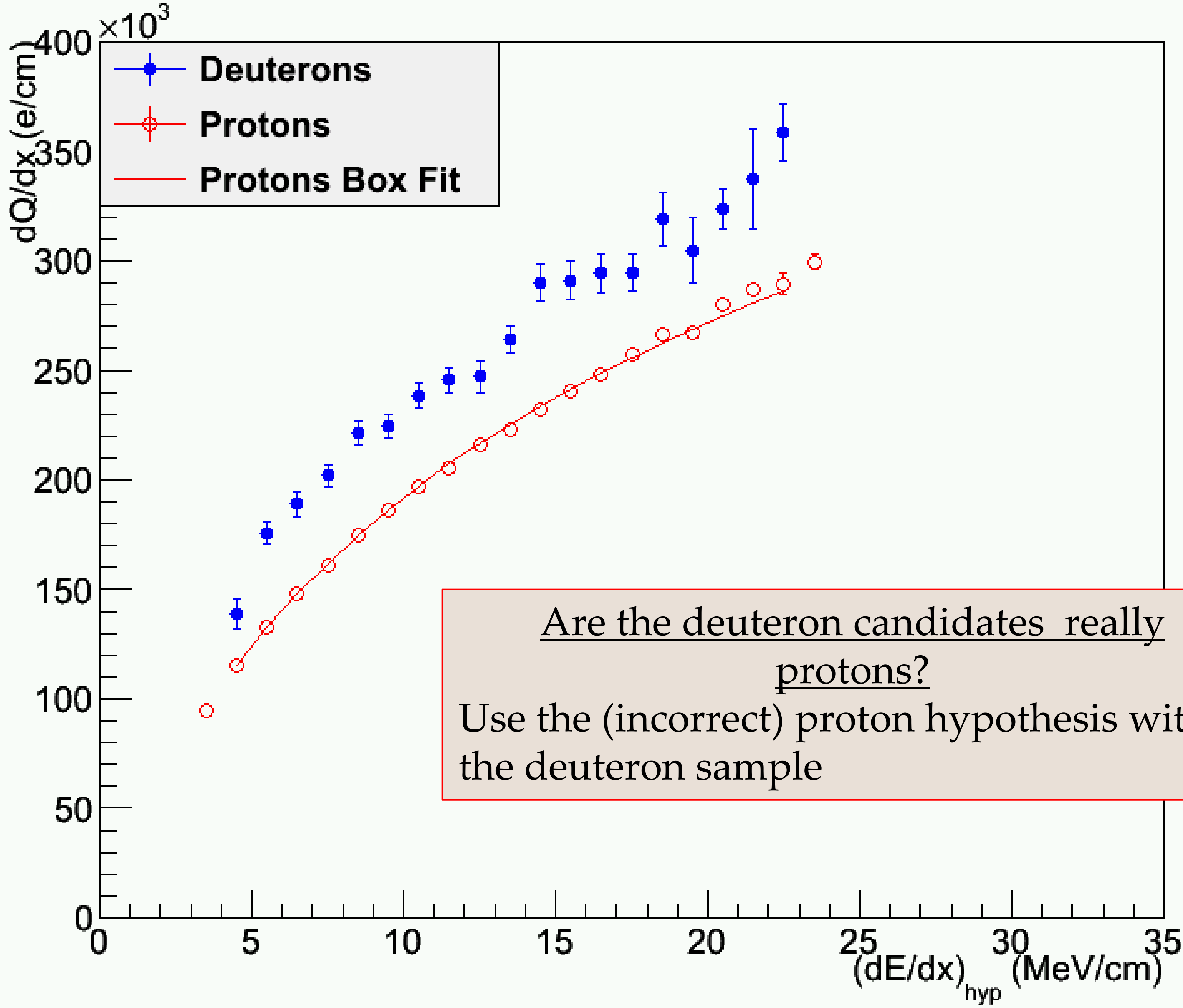
Summary

- Introduced a modified Box model
  - Excellent agreement with data and Birks model
  - Obviates the poor behavior of the Birks model at low ionization
- Significant recombination angular dependence expected from columnar theory and simulation
  - ~25% loss of charge collected at $\phi \sim 40^{\circ}$ and dE/dx ~ 24 MeV/cm compared to the same track at $\phi \sim 80^{\circ}$
- Introduced a PID scheme using the power-law behavior of stopping particle stopping power
- Charge loss is 5% - 10% in the proton sample at high dE/dx and small angle
- Extend the range of validity to 35 MeV/cm using a small sample of deuterons

Backup Slides



Deuteron: $(dE/dx)_{hyp} = 25\ R^{-0.43}$



<u>Are the deuteron candidates really protons?</u>

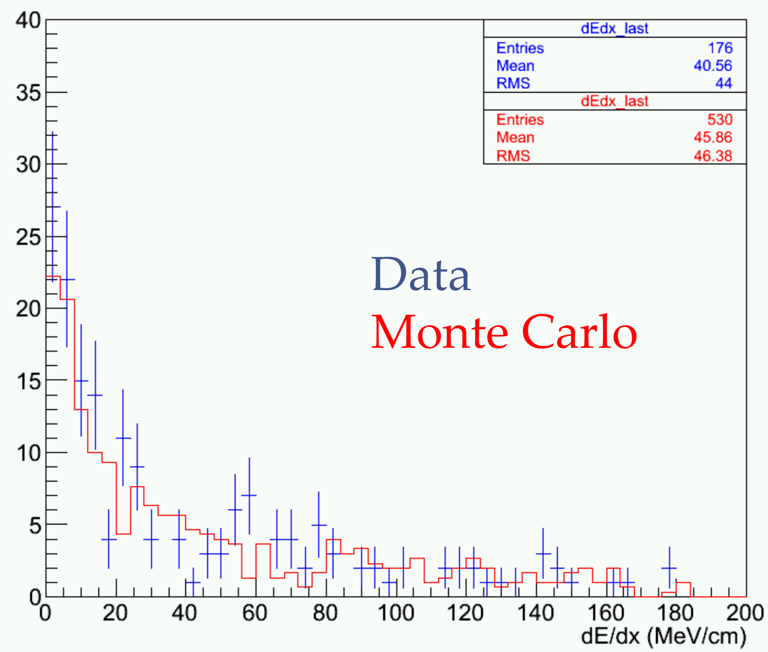
Use the (incorrect) proton hypothesis with the deuteron sample

Estimating the Stopping Point Position

- The stopping point is usually assumed to be dx/2, where dx is the distance between the last two space points
- Use the pattern of dE/dx in the last 5 space points to estimate the stopping point in the last wire cell
- Step a distance δR in the last cell ($1 < \delta R < 10$ mm) in 1 mm increments
- For each step, calculate
  - $dQ/\delta R$ for the stopping point,
  - Recombination correction → $(dE/\delta R)_{calo}$ for the stopping point,
  - $(dE/dx)_{hyp}$ for next 4 points using residual range = $\delta R + n\,dx$ (n = 1,2,3,4)
- Find rms difference between $(dE/dx)_{hyp}$ and $(dE/dx)_{calo}$ for all points
- Use the Δ value with the smallest rms

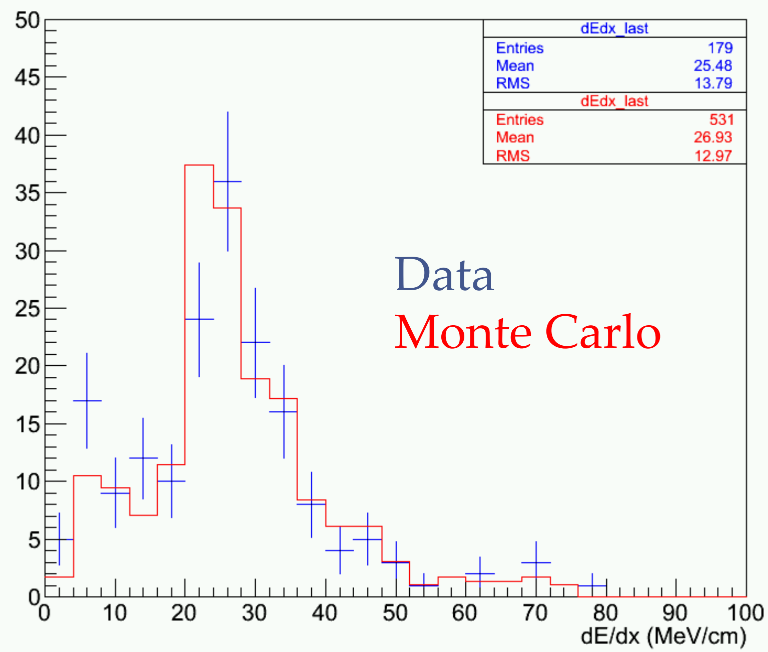
Estimating the Stopping Point Position

Assume the track stops halfway in the last cell



<dE/dx> ~ 45 ± 45 MeV/cm

After fitting to the stopping point



<dE/dx> ~ 25 ± 13 MeV/cm

Estimating the Stopping Point Position

- Stopping point error from Monte Carlo ~ 1 mm
- $(dE/dx)_{calo}$ from the last point is not included in the recombination fits
- Stopping point fit reduces the $(dE/dx)_{hyp}$ error propagated from the equation on slide 12
  - o Horizontal error bars on slide 18