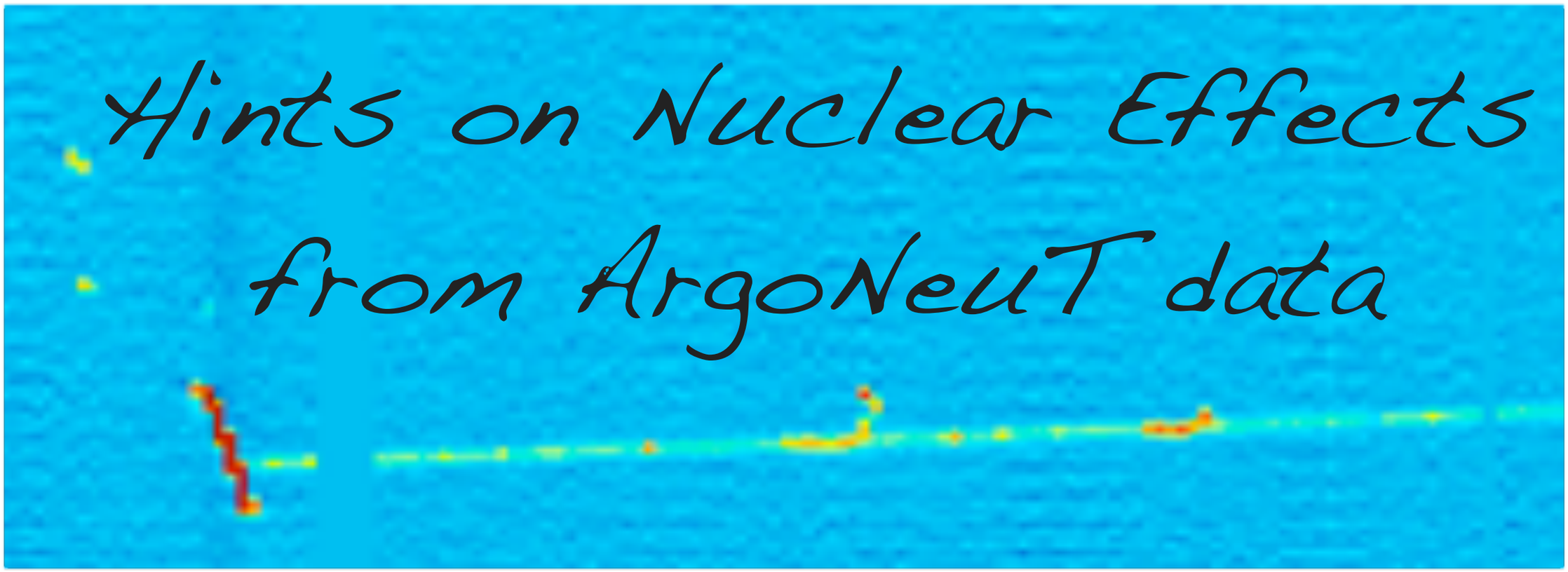
Hints on Nuclear Effects from ArgoNeuT data

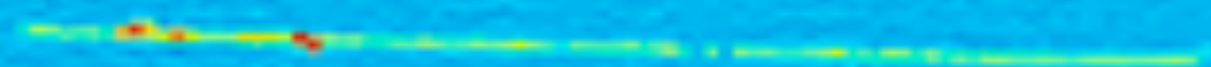


Ornella Palamara

Yale University - INFN, Laboratori Nazionali del Gran Sasso

OUTLINE

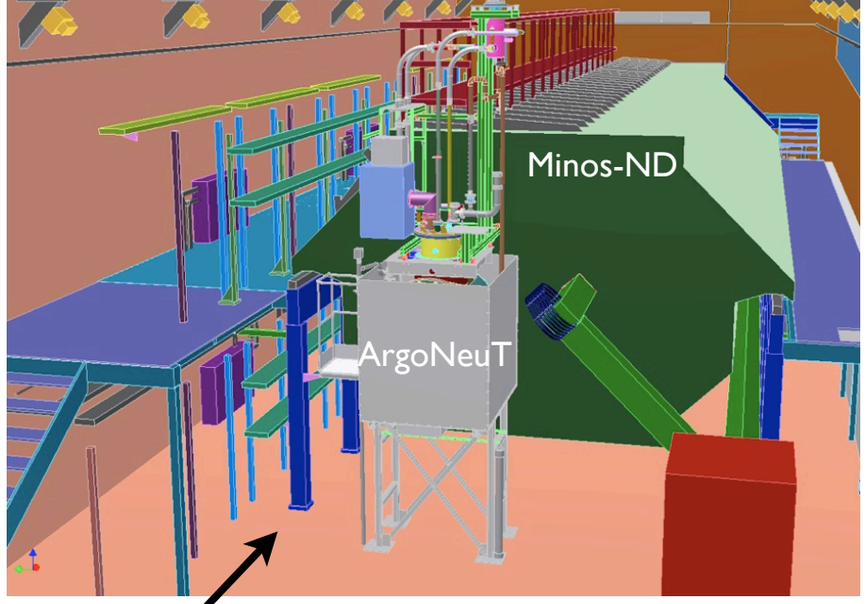
- ✓ LAr TPC ANALYSIS APPROACH
- ✓ IMPACT OF NUCLEAR EFFECTS
- ✓ MC: EFFECTS OF FSI



- ✓ DATA: EXCLUSIVE TOPOLOGIES
- ✓ DATA-MC COMPARISON

Analysis in progress:

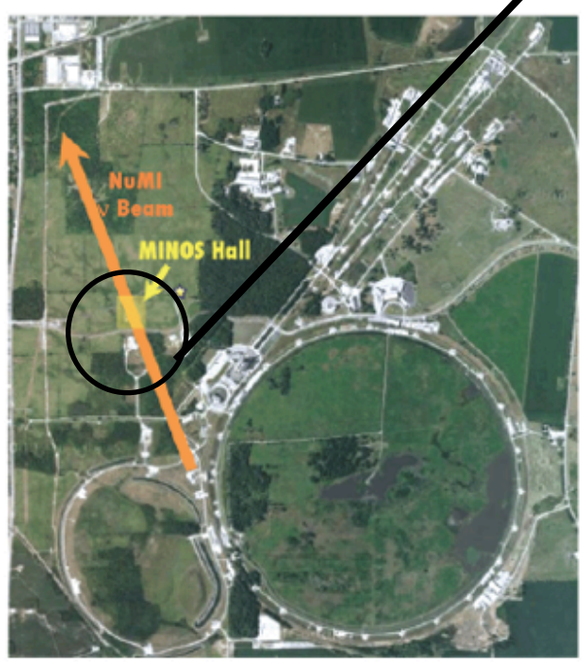
all plots and tables are preliminary



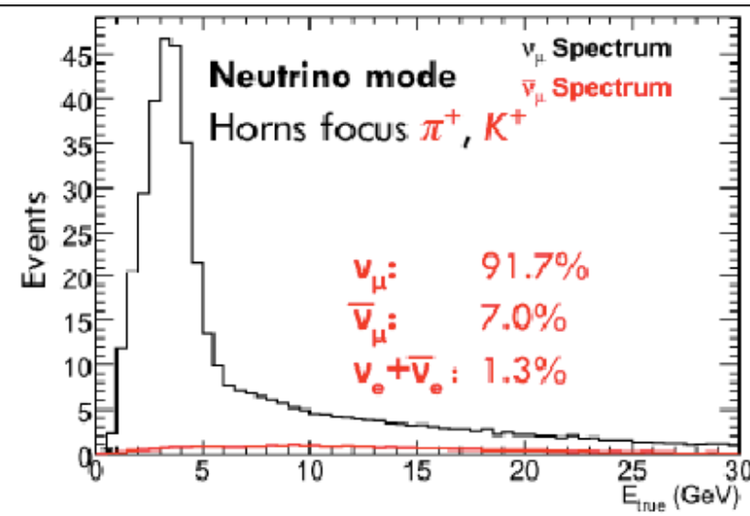
See A. Szelc presentation

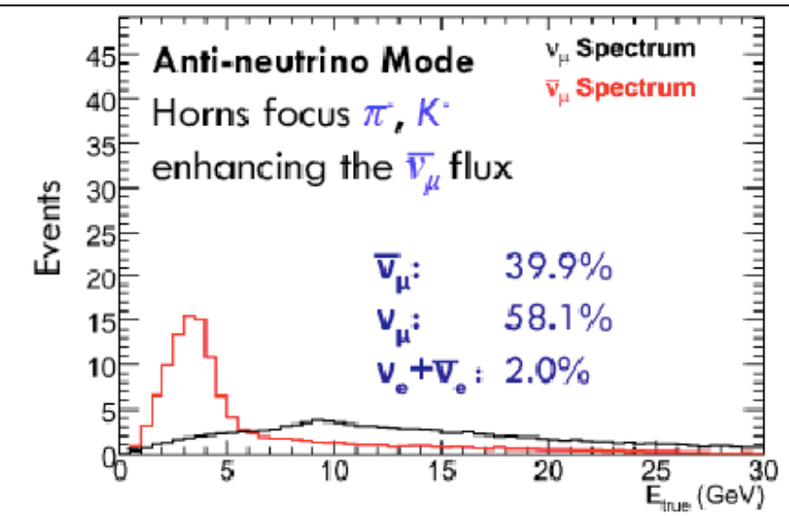
ArgoNeuT runs:
NuMI LE beam
ν–mode (2 weeks):
8.5×10^{18} POT
$\bar{\nu}$–mode (6 months):
1.20×10^{20} POT

"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab"
JINST 7 P10019 (2012)

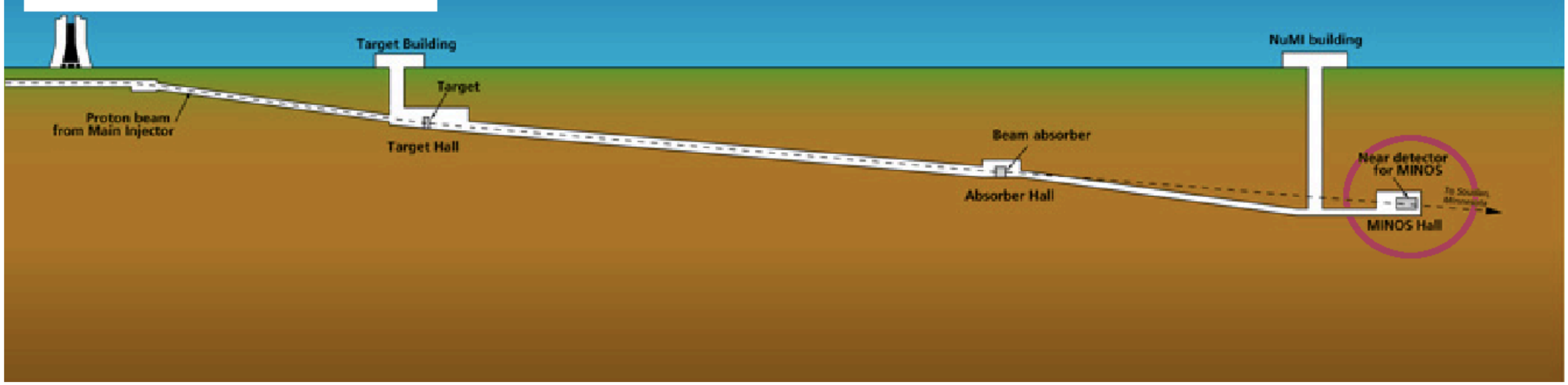


Fermilab





NuMI LE beam



LAr TPC ANALYSIS APPROACH

- Event Classification/Categorization in terms of Final State Particle Multiplicity

  See talk by K. Partyka

  - Inclusive Cross Sections

    - Final State Interactions (FSI)

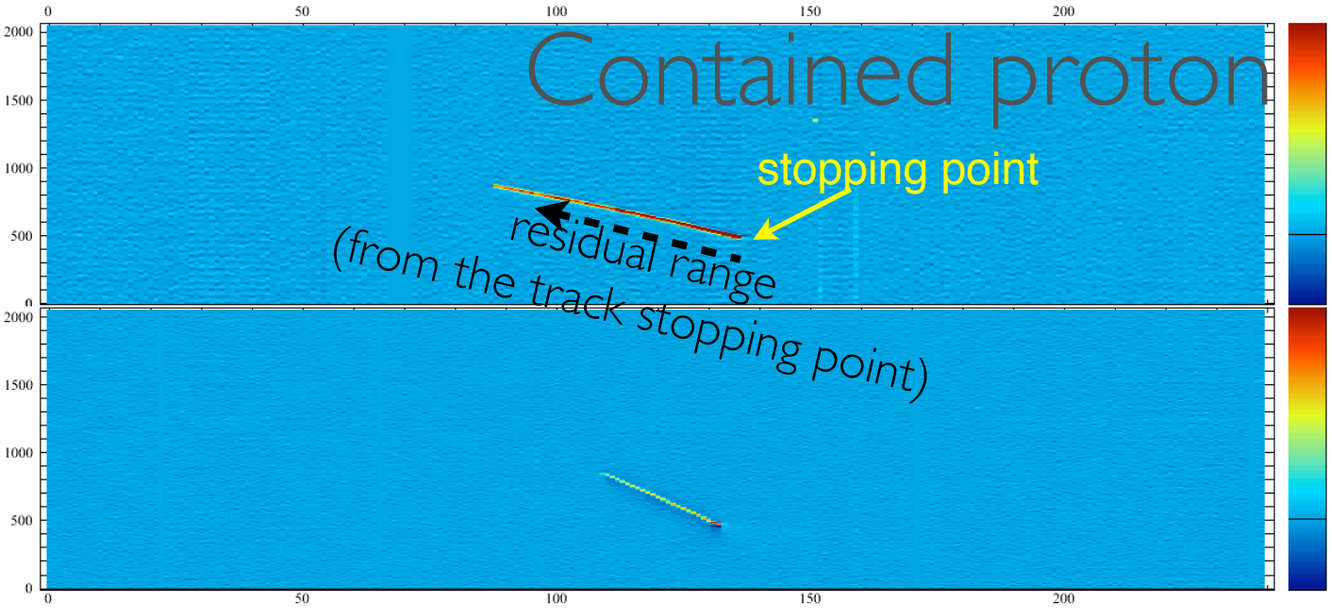
    - Exclusive Cross Sections

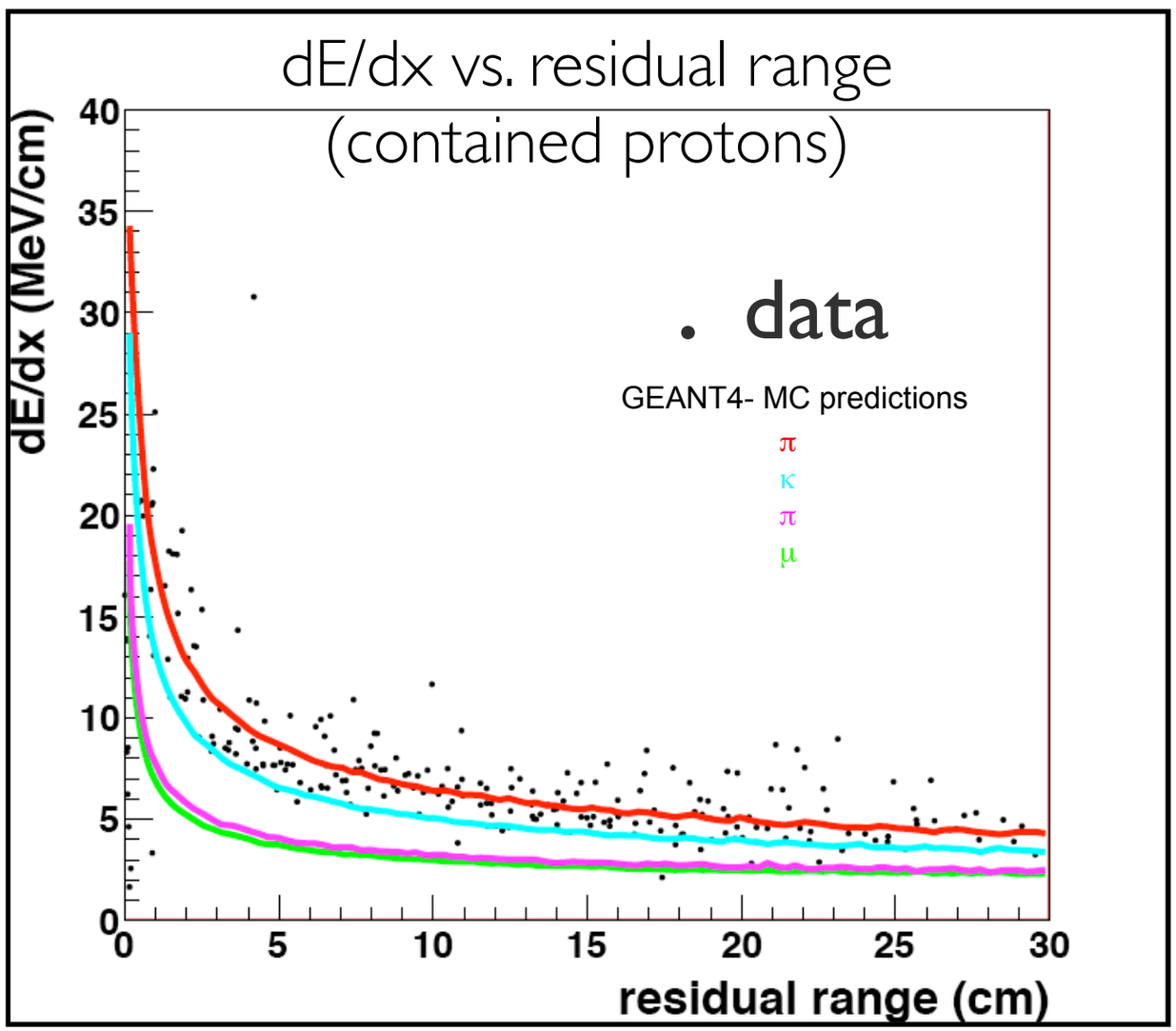
LArTPC ***when fully exploited*** allows for FSI exploration and Exclusive Topology recognition with extraordinary sensitivity

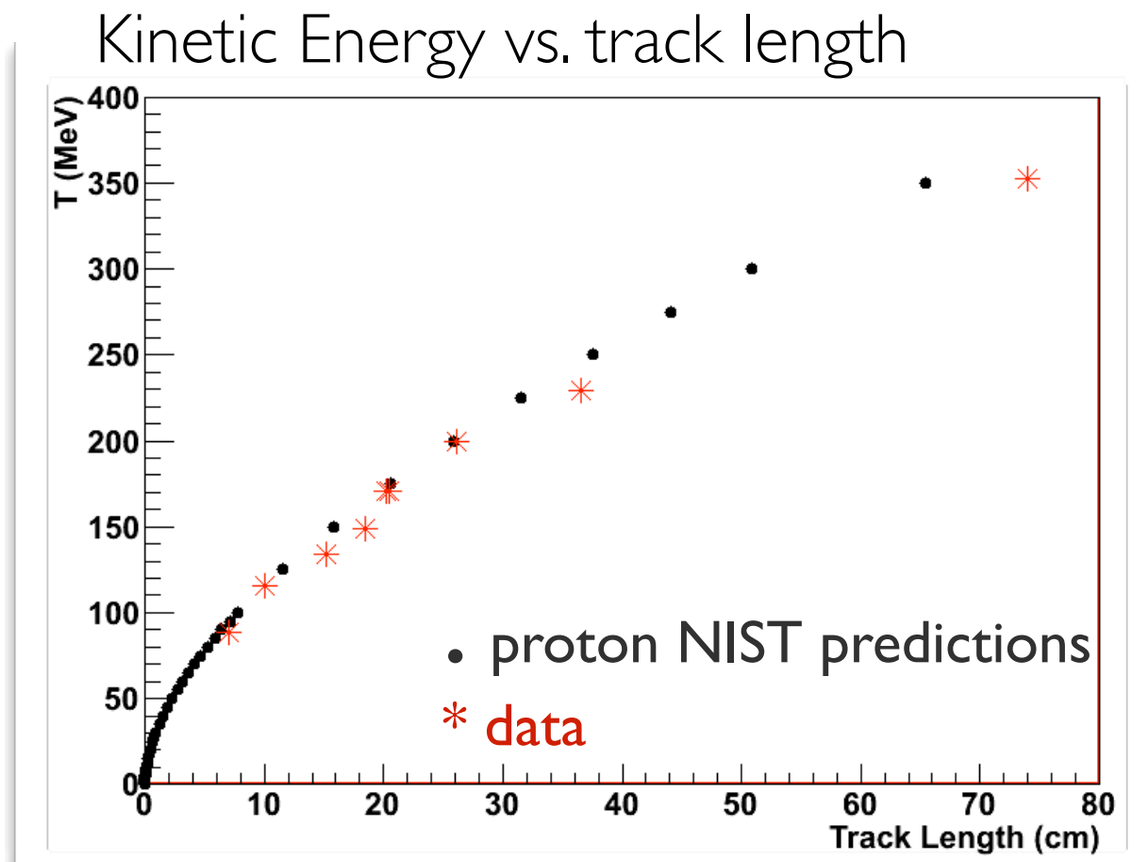
Particle Identification with LArTPC

- 3D and calorimetric reconstruction for efficient Particle Identification
- Excellent resolution for final state
- Capability of "seeing" recoil proton(s)
- Good $p/\pi^{\pm}$ identification capability

STOPPING PARTICLE - CALORIMETRIC RECONSTRUCTION and PID







Measurement of:

- dE/dx vs. residual range along the track
- kinetic energy vs. track length

DATA: EXCLUSIVE CC TOPOLOGIES*

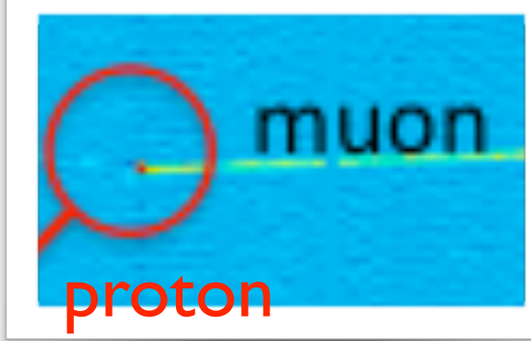
$1\ \mu^{(+/-)}\ 0p/1p/2p/...$ 0π events

(and any # of neutrons/gammas)

We measure muon and proton(s) kinematics and proton multiplicity at the neutrino interaction vertex in LAr **

for events with identified proton(s)

with kinetic energy >21 MeV



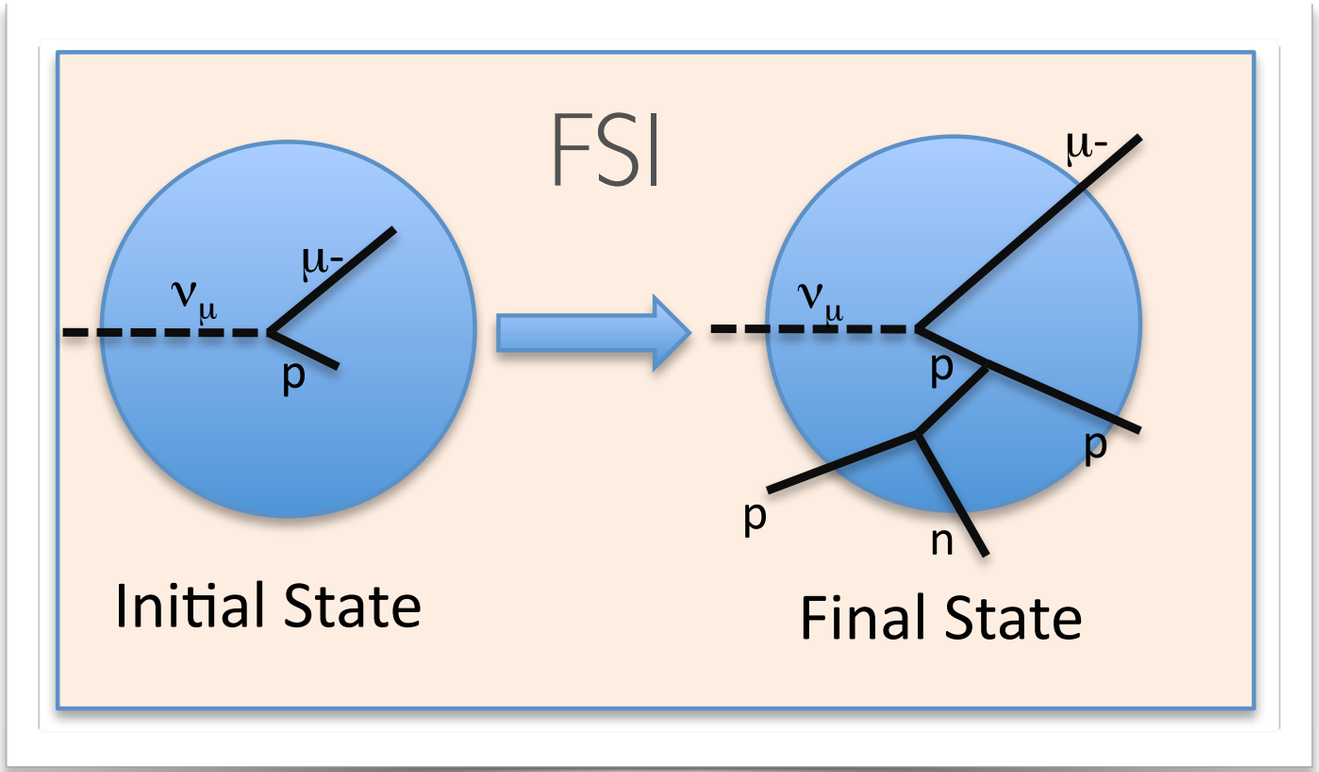
Preliminary data analysis and data-MC comparison (analysis still in progress)

See also talk by K.Partyka

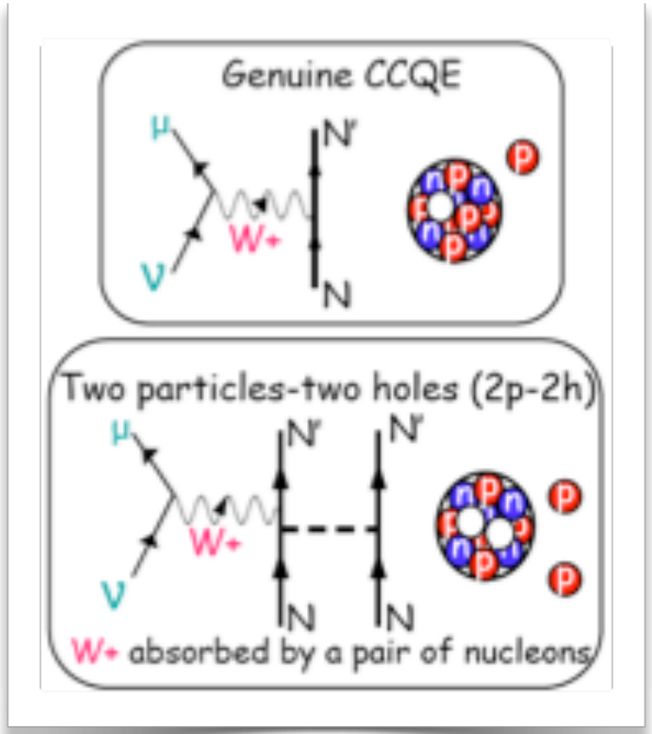
* analysis fully exploiting LAr TPC's capabilities (in Cherenkov detectors all these classes of events are 1 track "CCQE like" events)

**muon momentum and sign from MINOS-ND

IMPACT OF NUCLEAR EFFECTS



Multinucleon production (or other effects)



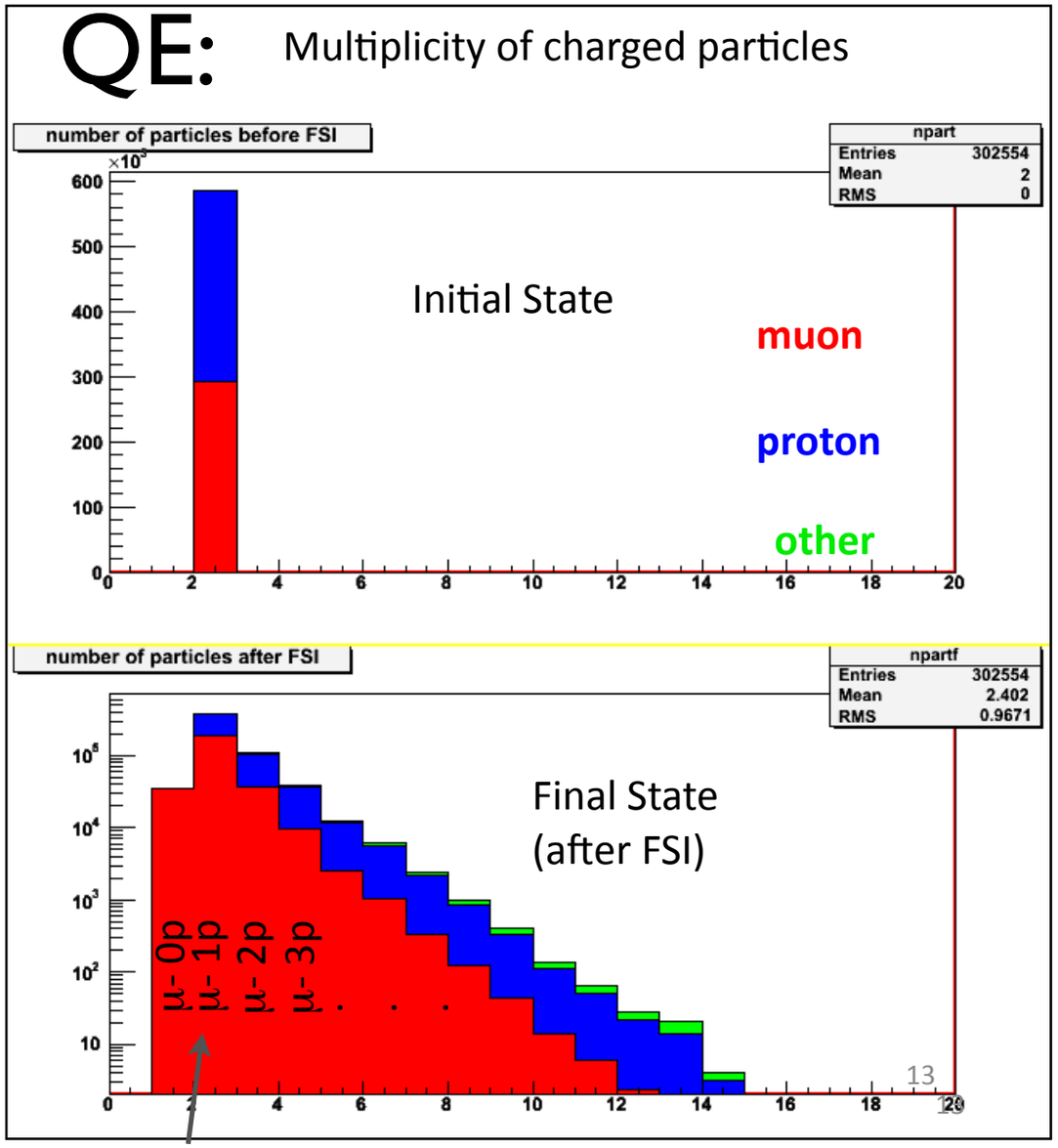
Additional difficulty is the separation of the effects of FSI from initial state correlations.

Can we disentangle them in LAr (from the distribution of specific kinematical variables in events with ≥2p and comparing data with MC including MEC production)?

MC: EFFECTS OF FSI

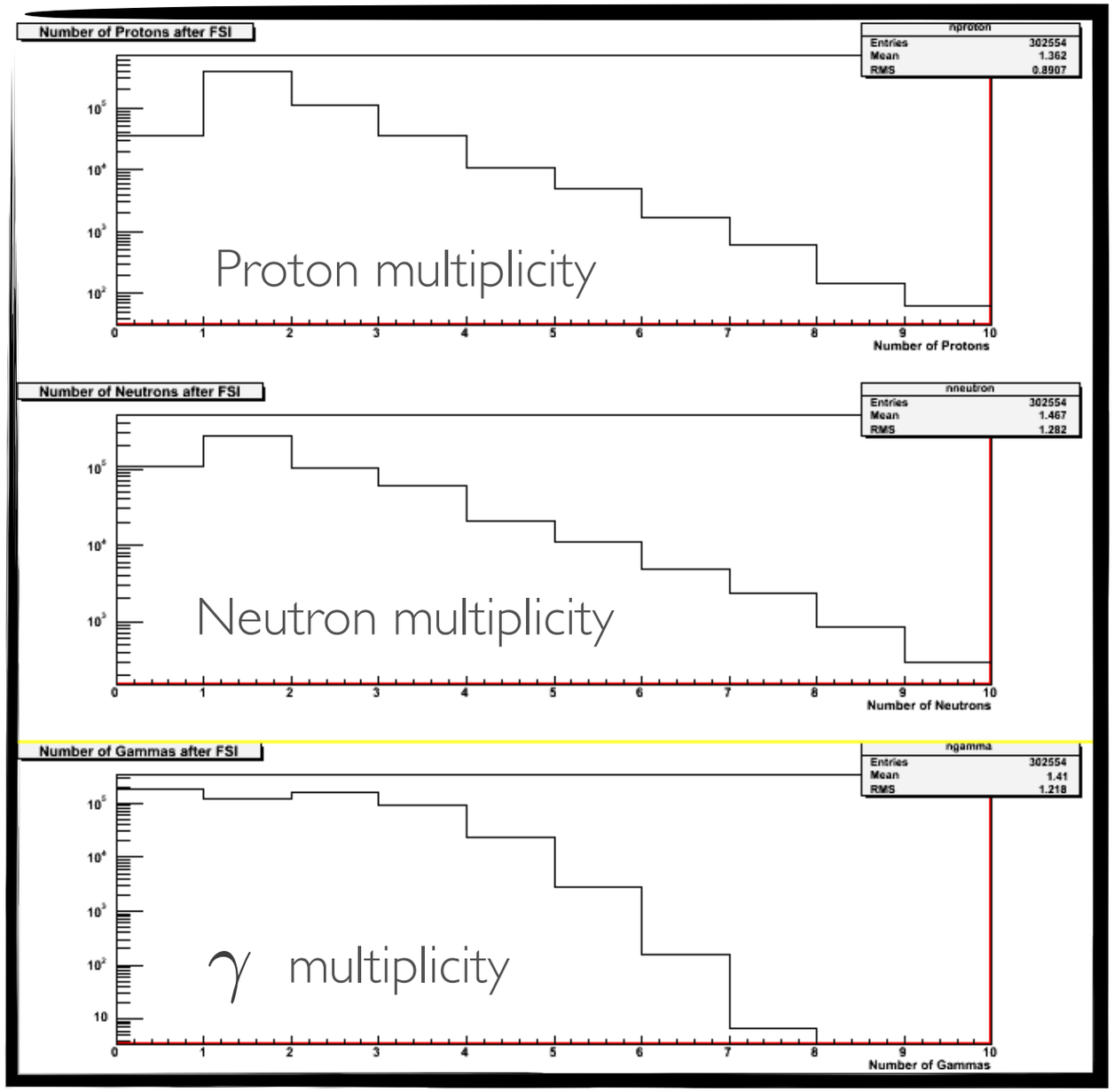
an example: **FLUKA simulation* – CCQE ν_μ events in LAr**

NuMI beam LE spectrum - neutrino mode



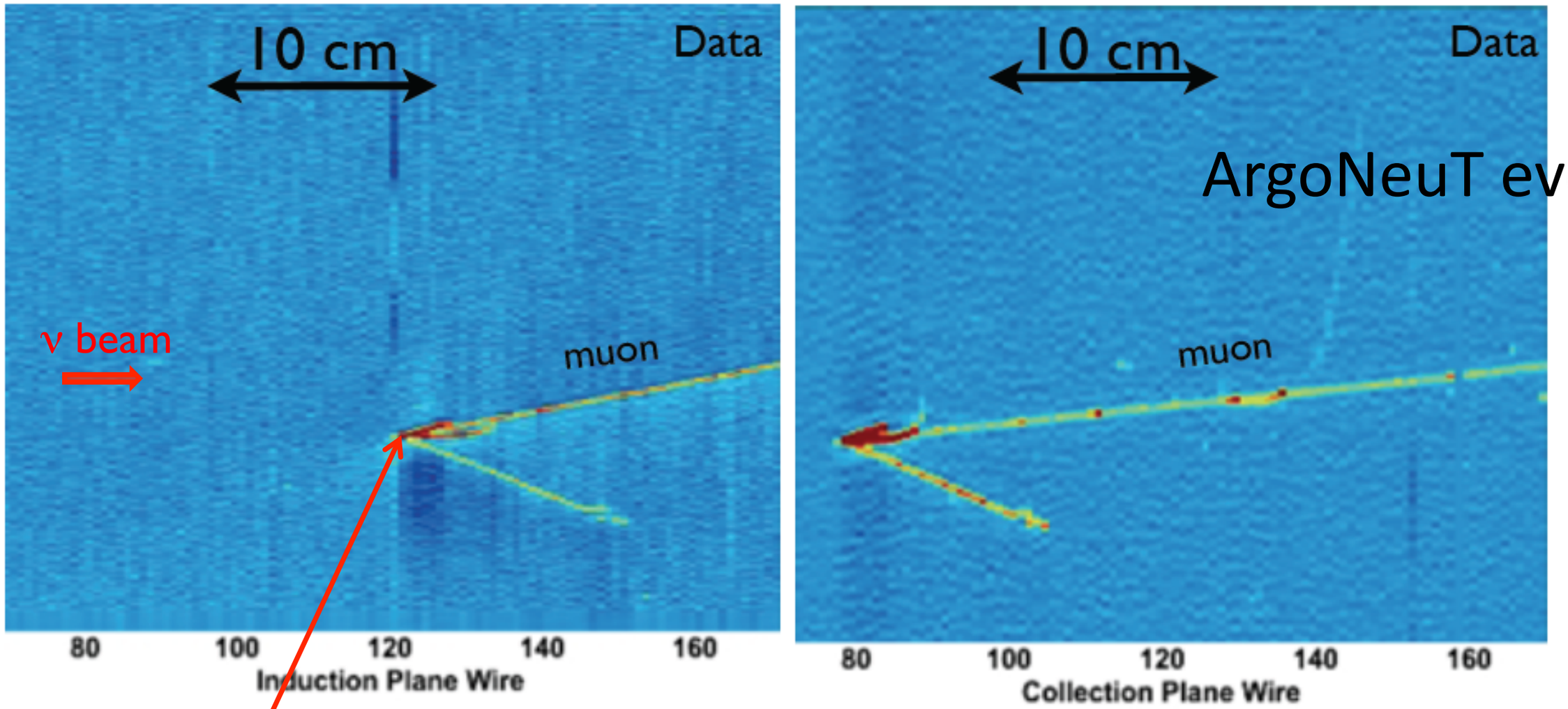
$1\mu 1p$ events

Vertex activity (multiple p at vtx., γ (→e) from nuclear de-excitation, neutrons)



* offering a full simulation of nuclear effects but not MEC

DATA: EFFECTS OF FSI



A zoomed-in view of a neutrino event with evidence of vertex activity

These products are usually neglected because not detectable,
unless…
…. a high quality imaging detector is in use !!

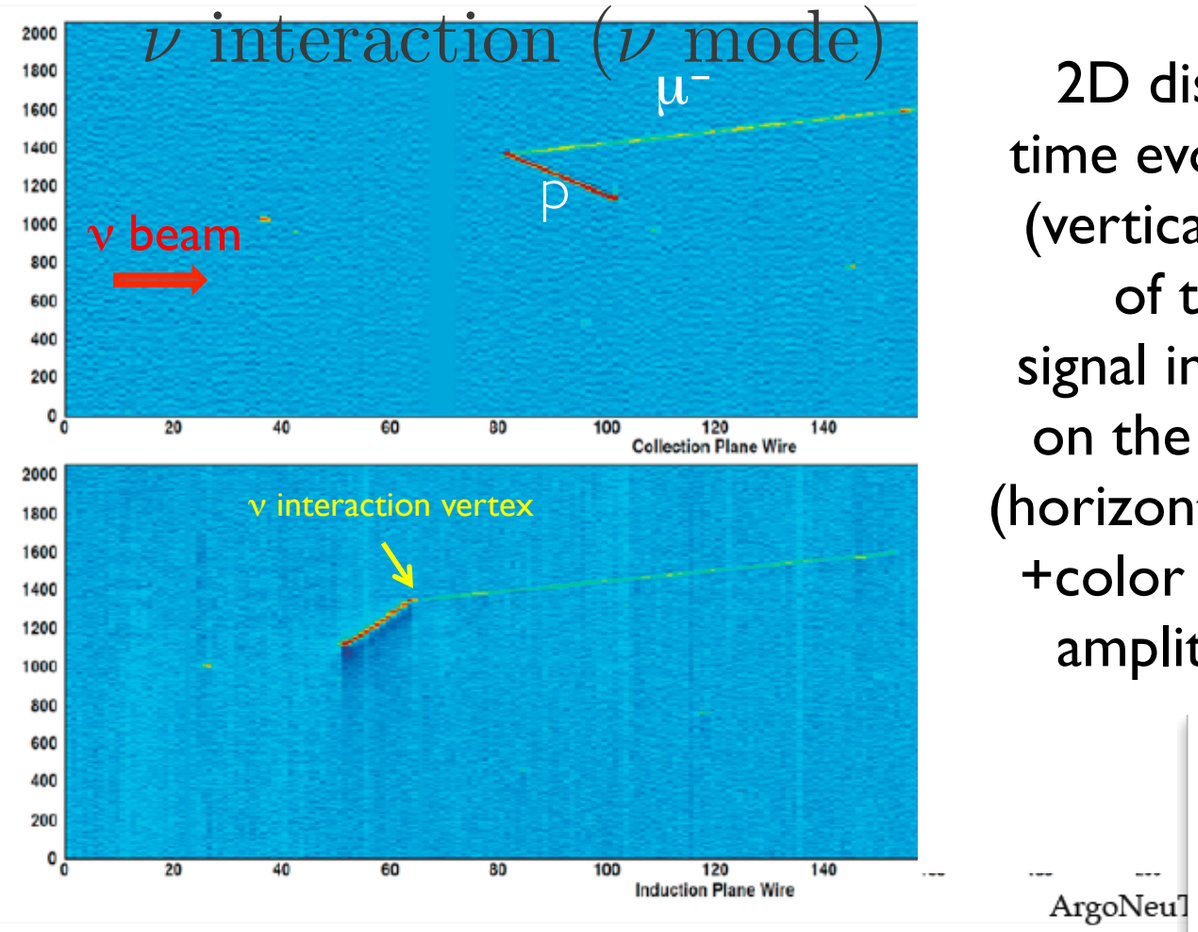
Data from LAr extremely helpful for FSI understanding

MC: EXCLUSIVE TOPOLOGIES

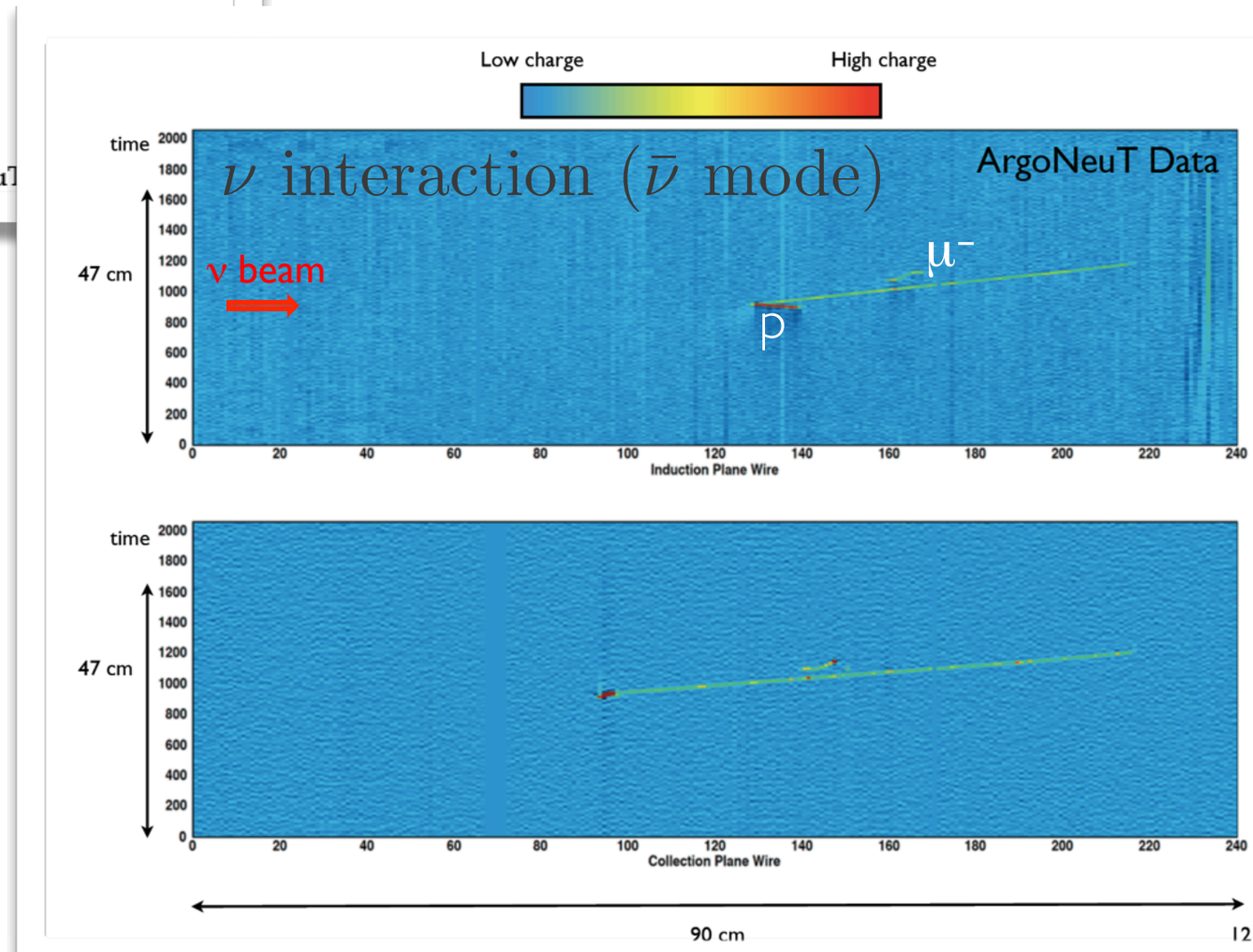
Validation of FSI models from Comparison with specialized MC generators

- Accurate and extremely detailed MonteCarlo generators are needed for comparison with LAr data
- MonteCarlo Generators: FSI models for Ar need to be cross-checked by comparison of different MC generators
- FSI in MC codes represent the most difficult present challenge in MC development
- Available versions of MC include FSI but not (yet) MEC

DATA: EXCLUSIVE TOPOLOGIES



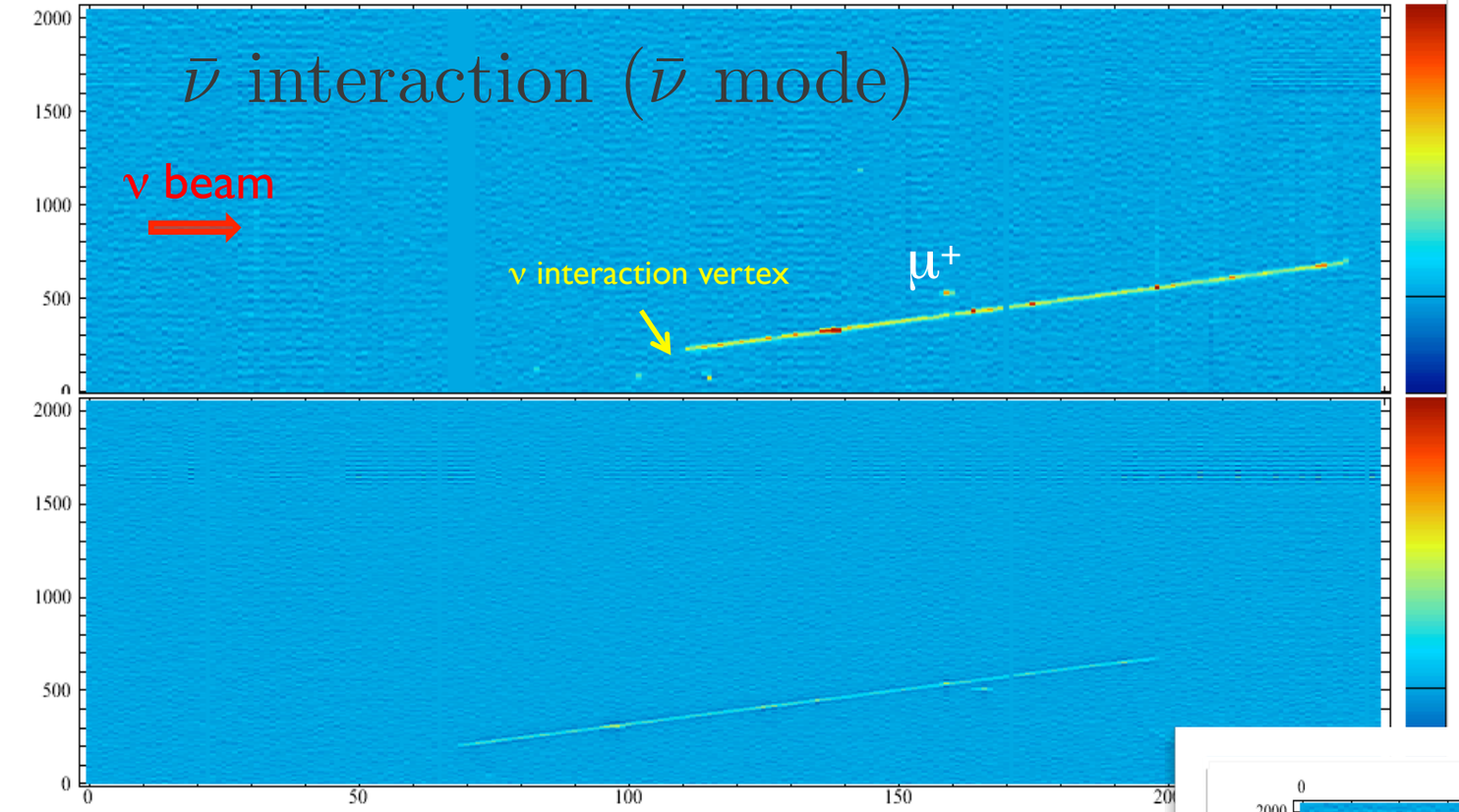
2D display: time evolution (vertical axis) of the signal induced on the wires (horizontal axis) +color (signal amplitude)

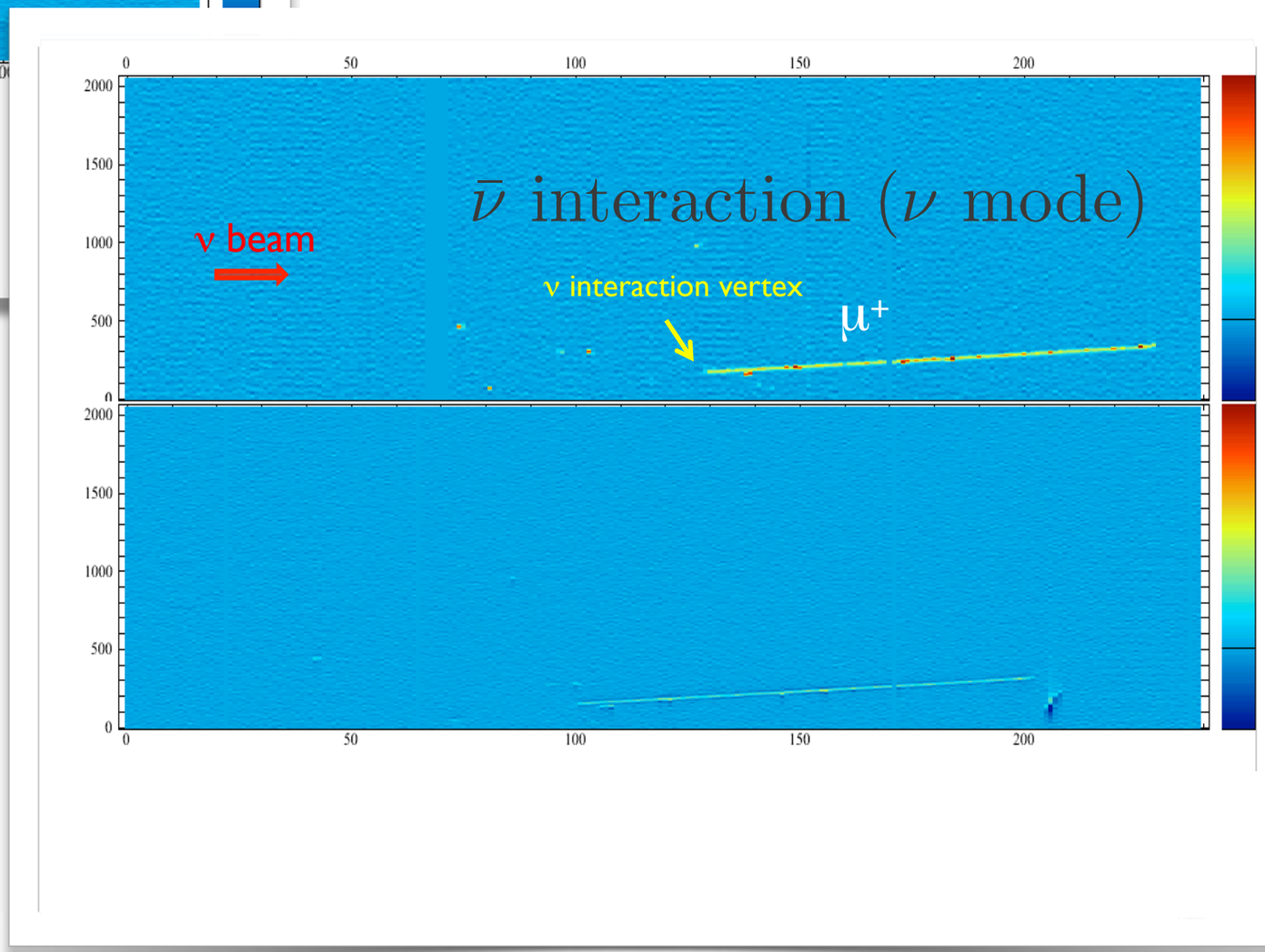


2 tracks: $\mu^- p$

ν_μ CC events: $\mu^- p$

DATA: EXCLUSIVE TOPOLOGIES





1 track: μ^+

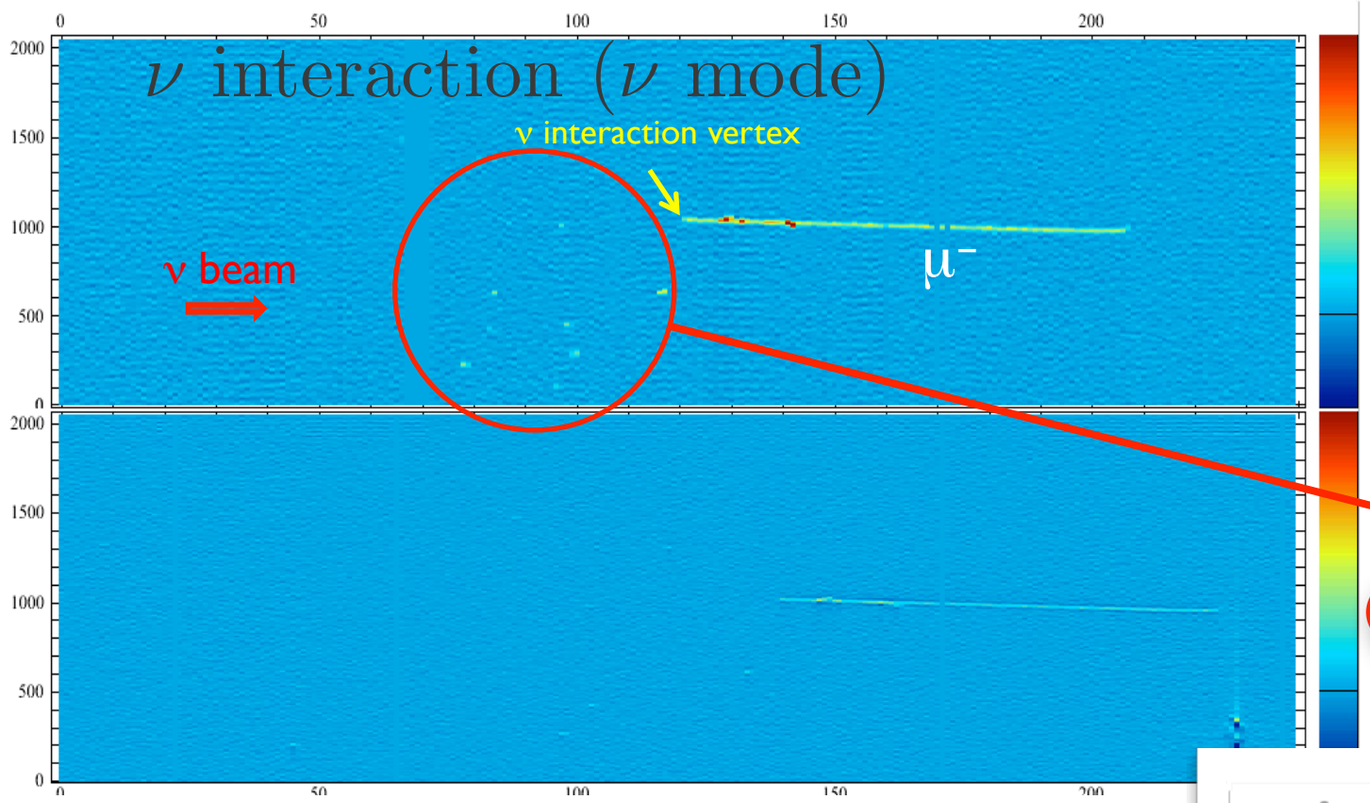
$\bar{\nu}_\mu$ CC events: μ^+n(0p)

DATA: EXCLUSIVE TOPOLOGIES

$\mu^{+/-}$ Np events
showing evidence of FSI
and/or
multi-nucleon production (or other effects)

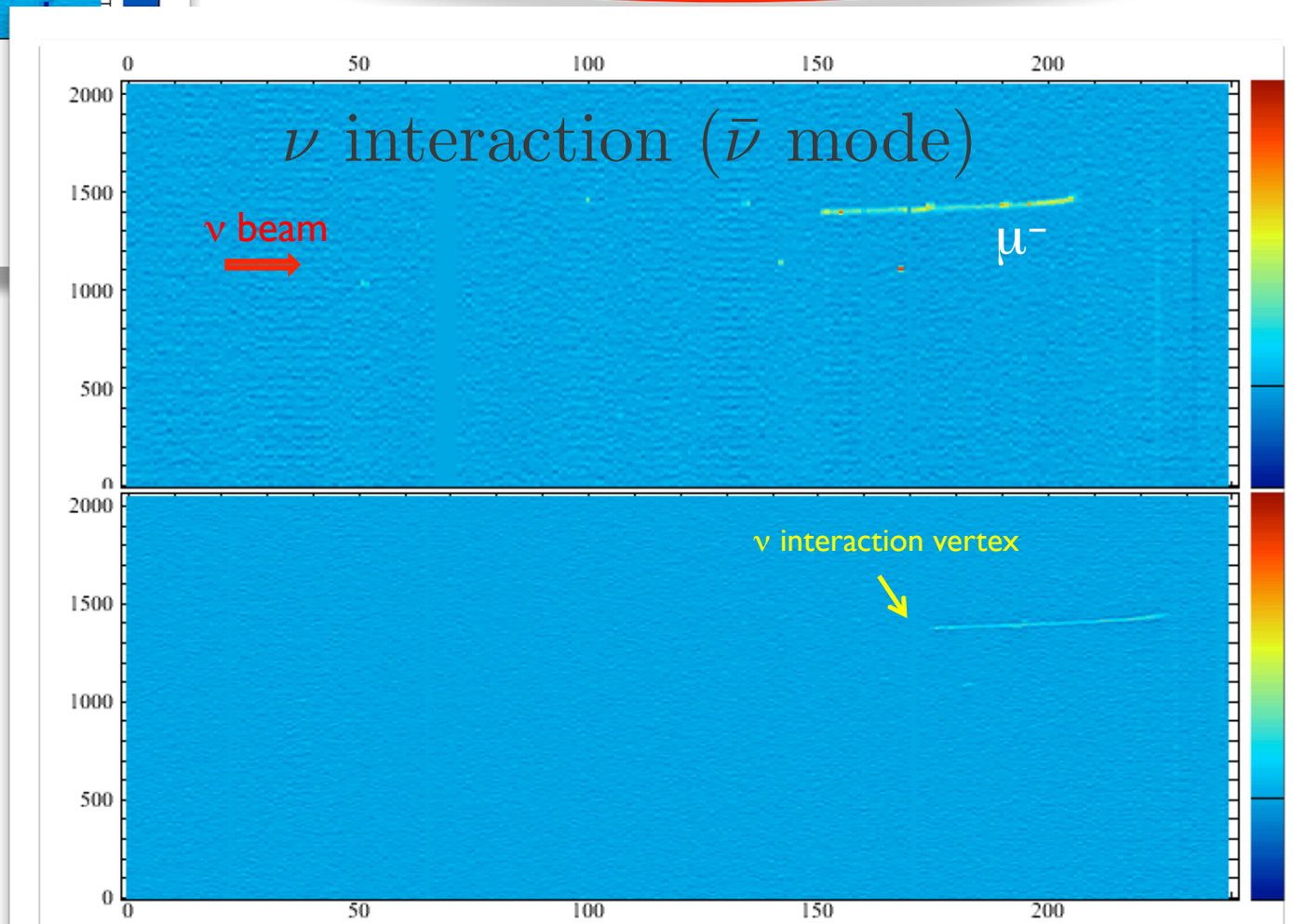
Count and reconstruct protons
at the neutrino interaction vertex

DATA: EXCLUSIVE TOPOLOGIES



Activity around the vertex

e's from nuclear de-excitation γ conversion



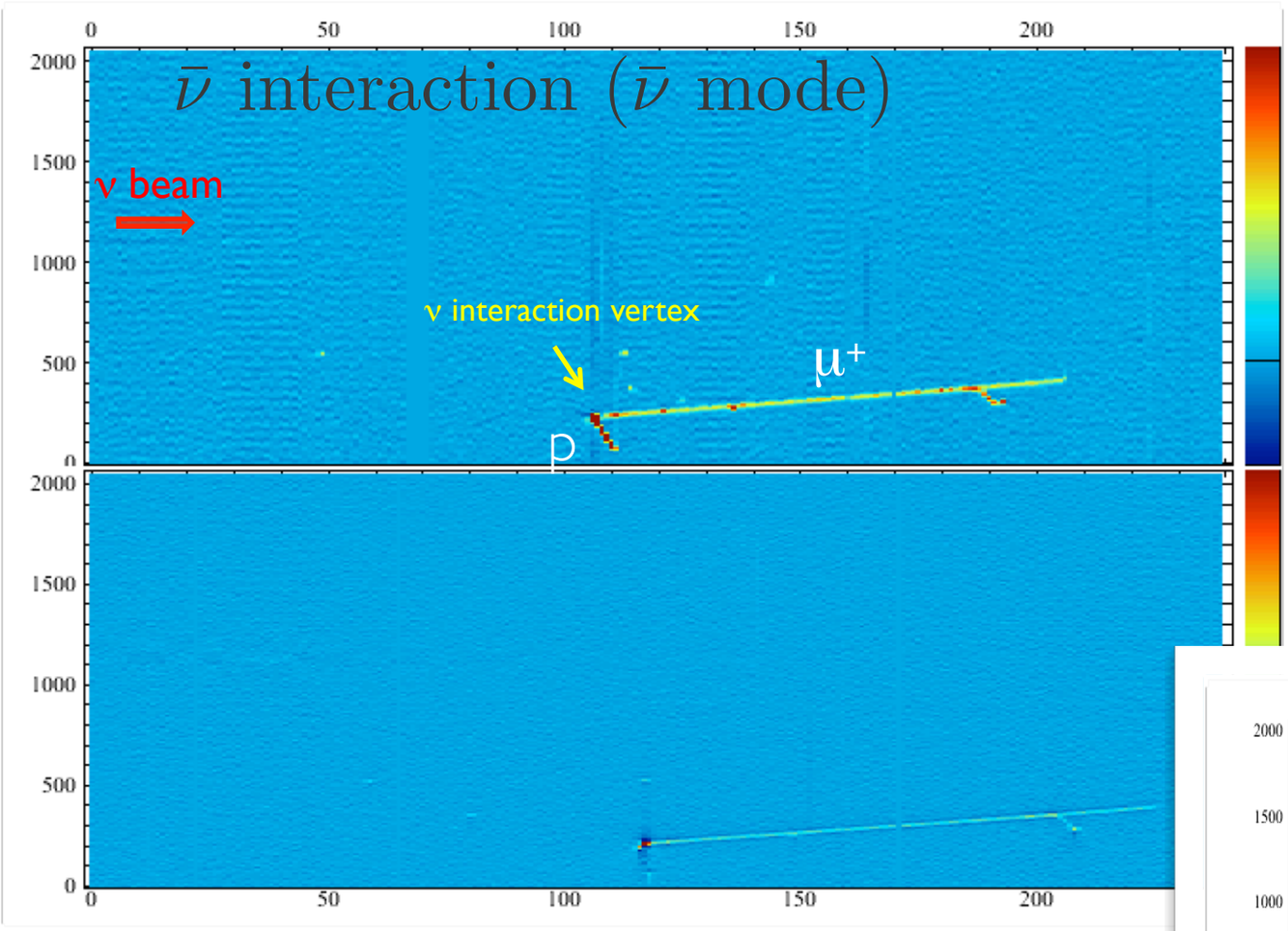
$$1 \text{ track: } \mu^-$$

μ^- track only, no p at the vertex

Evidence of FSI!

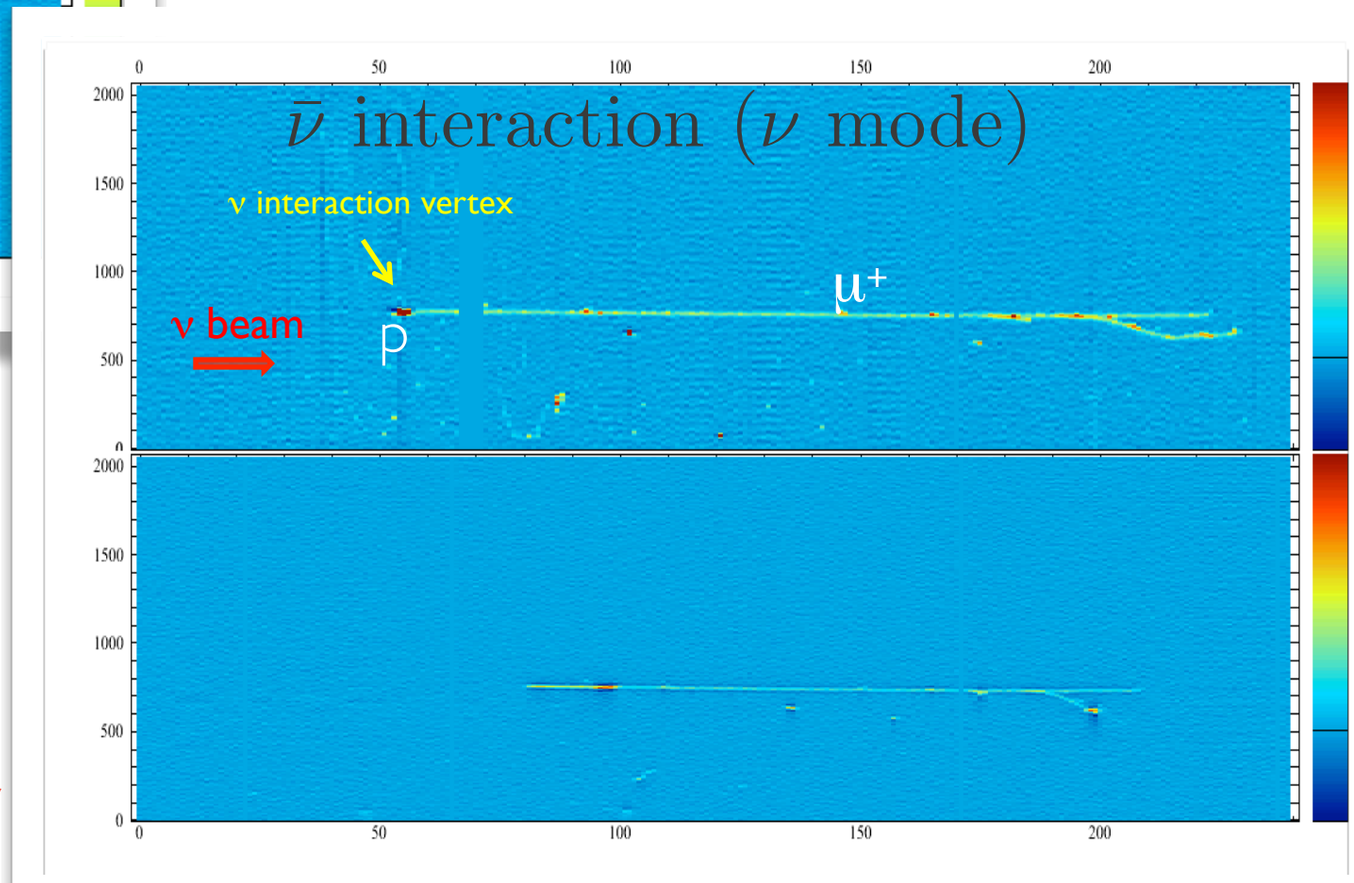
$$\nu_\mu \text{ CC events: } \mu^- 0\text{p}$$

DATA: EXCLUSIVE TOPOLOGIES



Activity around the vertex

e's from nuclear de-excitation γ conversion



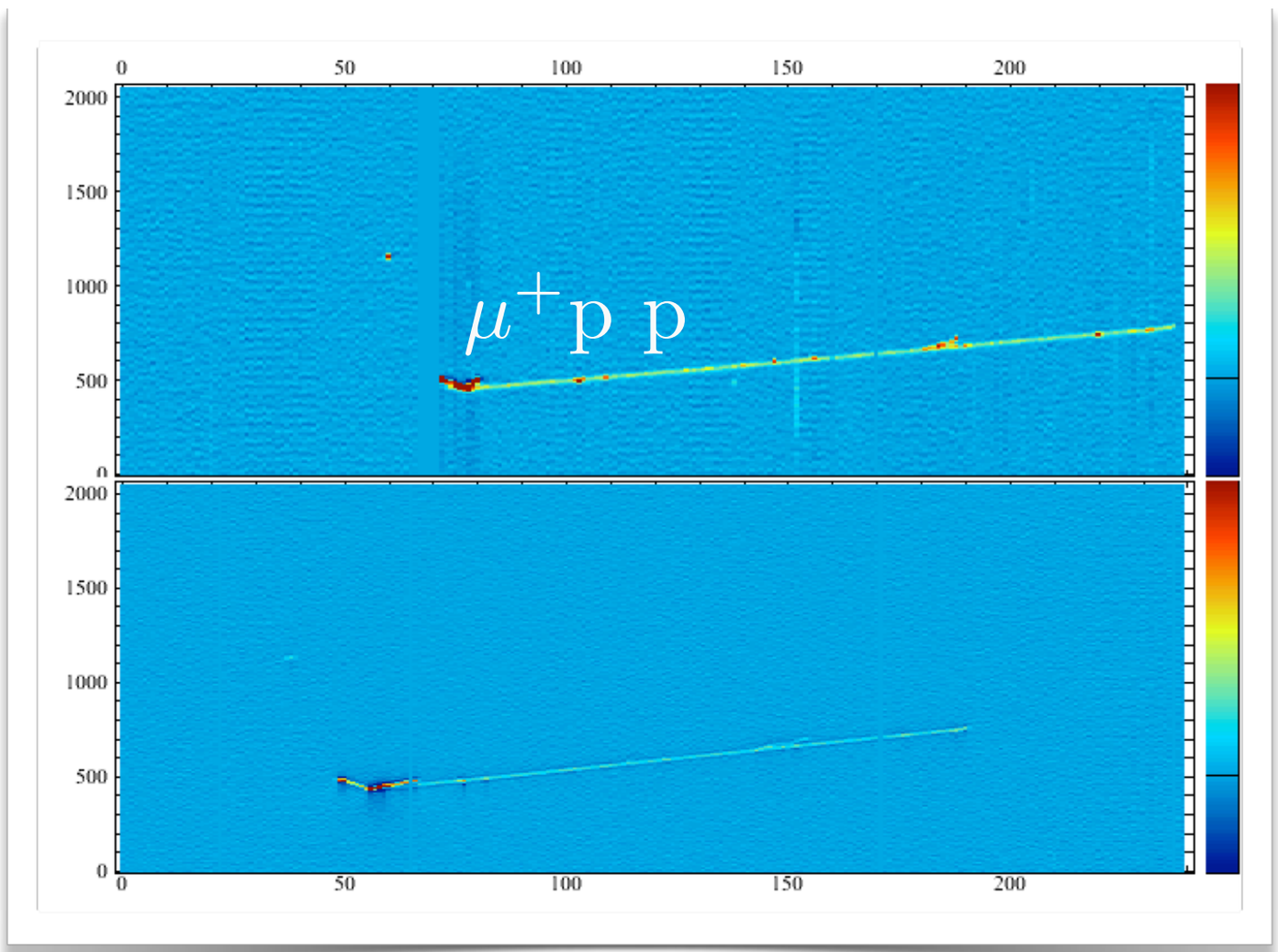
2 tracks: 1 μ^+ 1 p

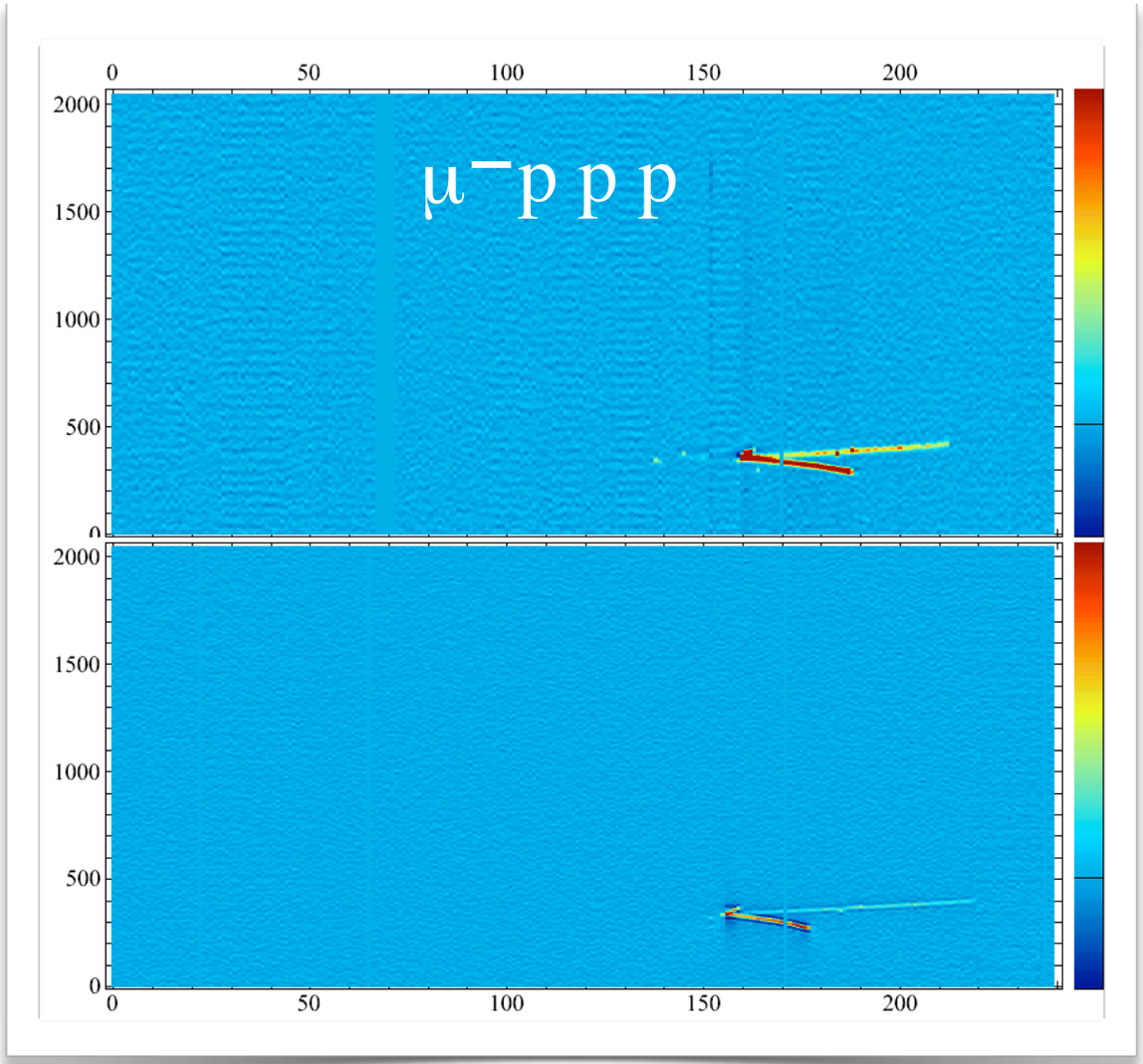
Evidence of FSI!

$\bar{\nu}_\mu$ CC events: μ^+p

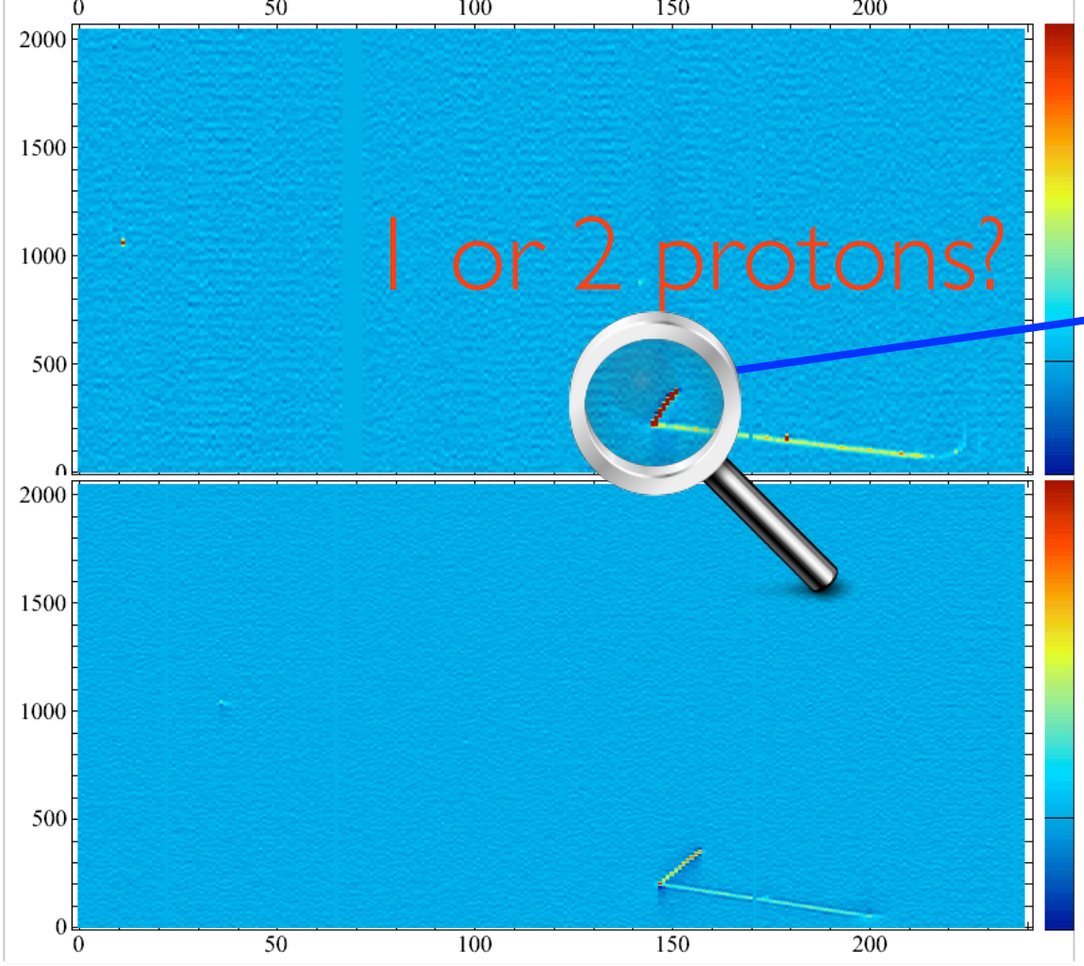
DATA: EXCLUSIVE TOPOLOGIES

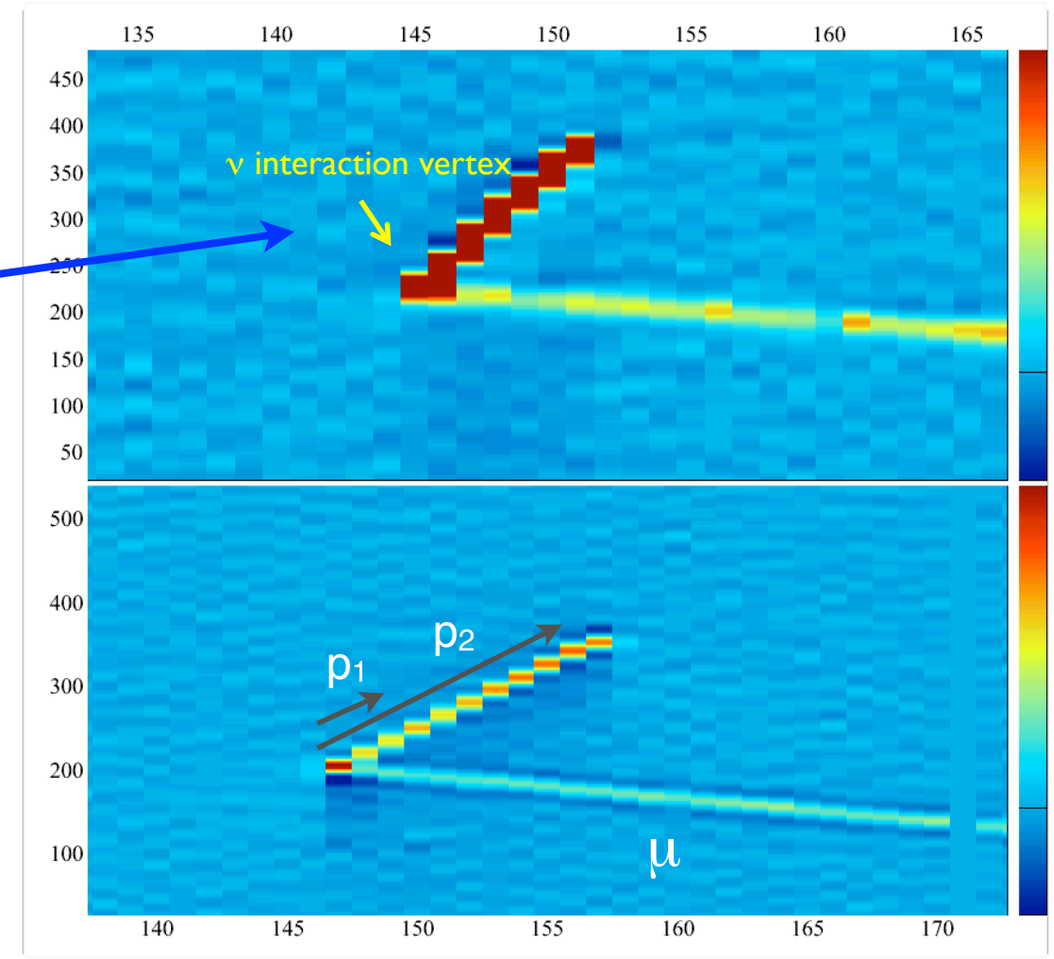
Multi-p accompanying
the leading muon
+ γ activity in the volume
around the vertex

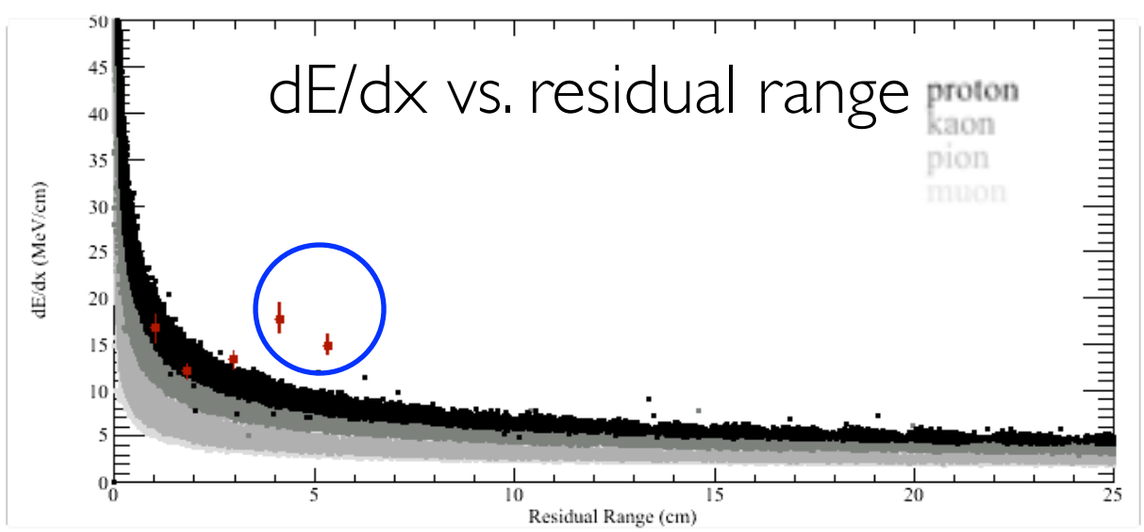


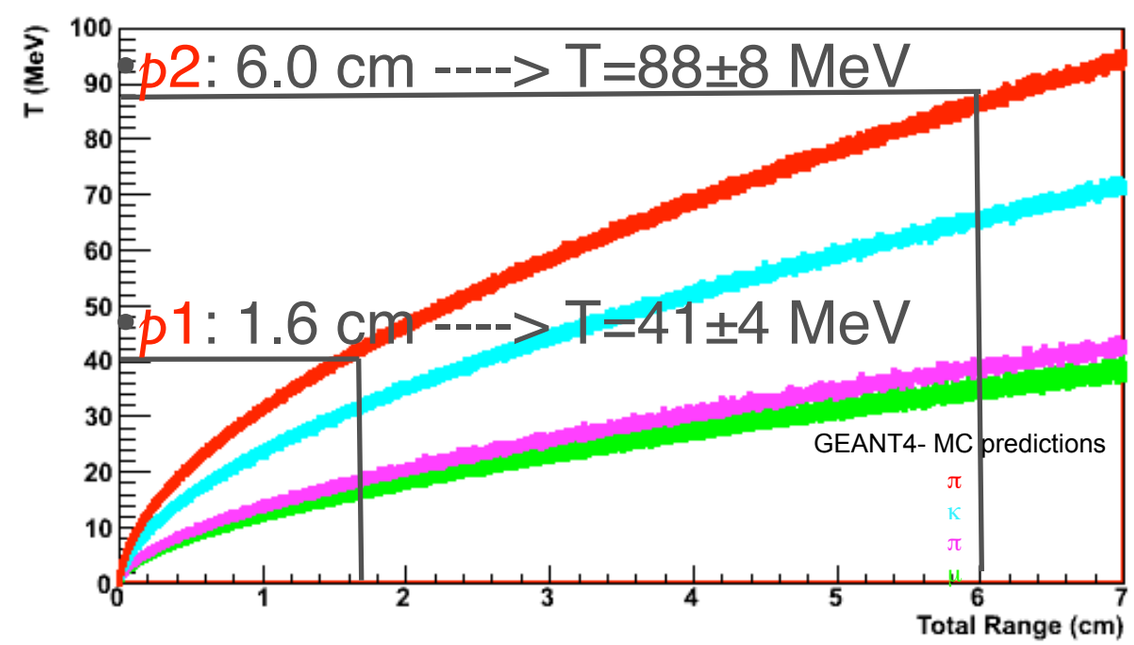


$\nu_\mu/\bar{\nu}_\mu$ CC events: $\mu^{-/+}$multi-proton



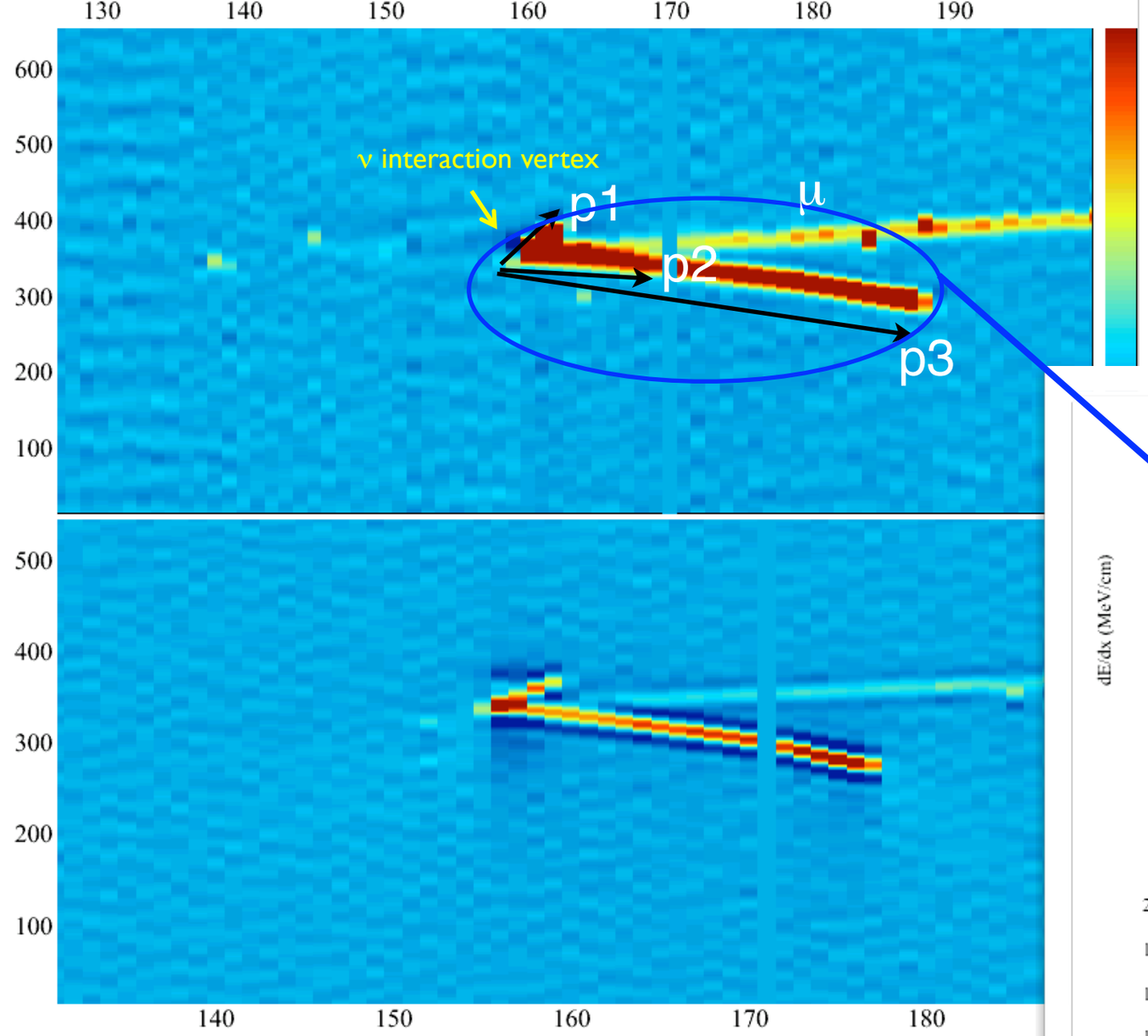


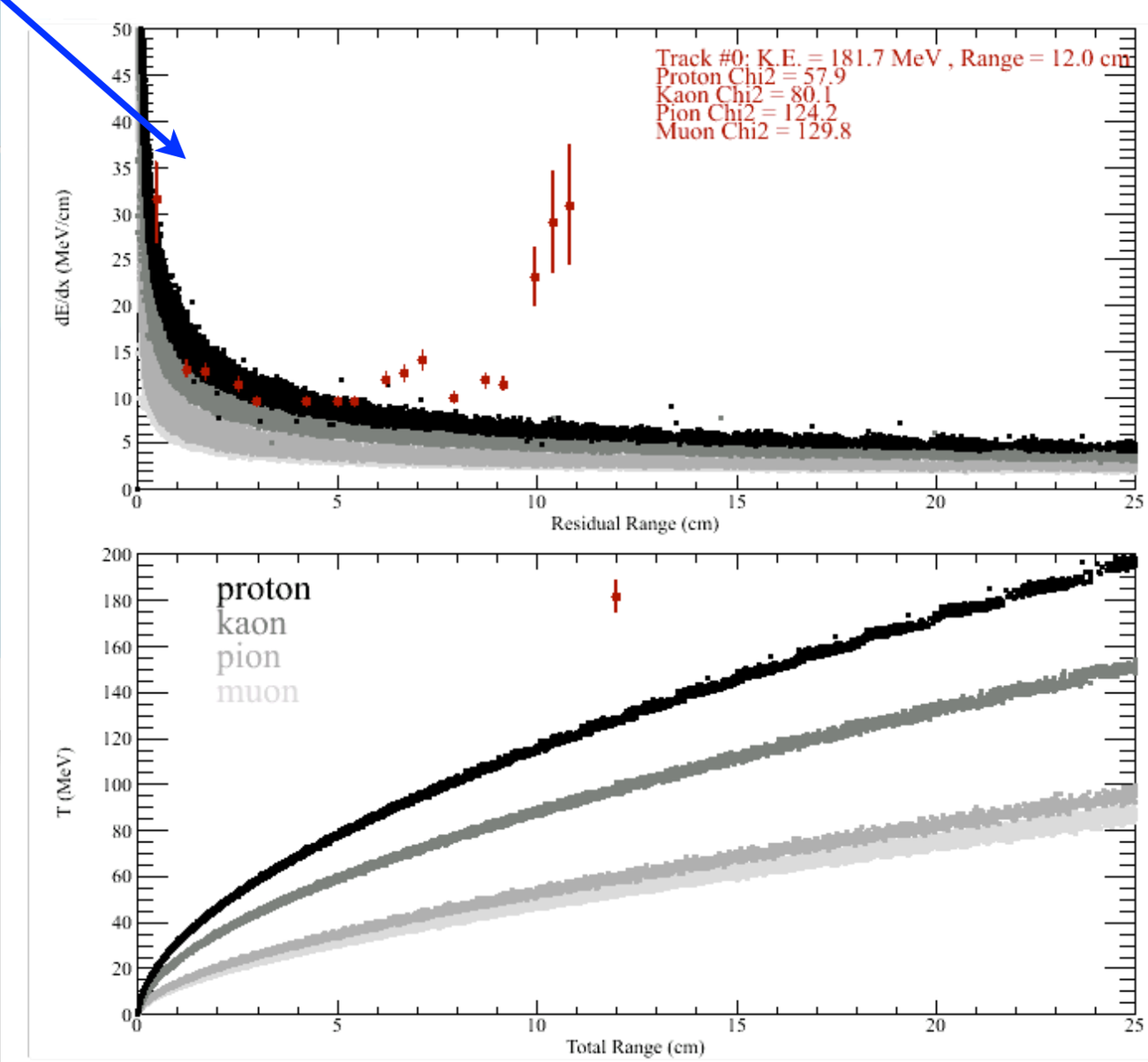




compatible with
1 μ 2p

DATA: EXCLUSIVE TOPOLOGIES



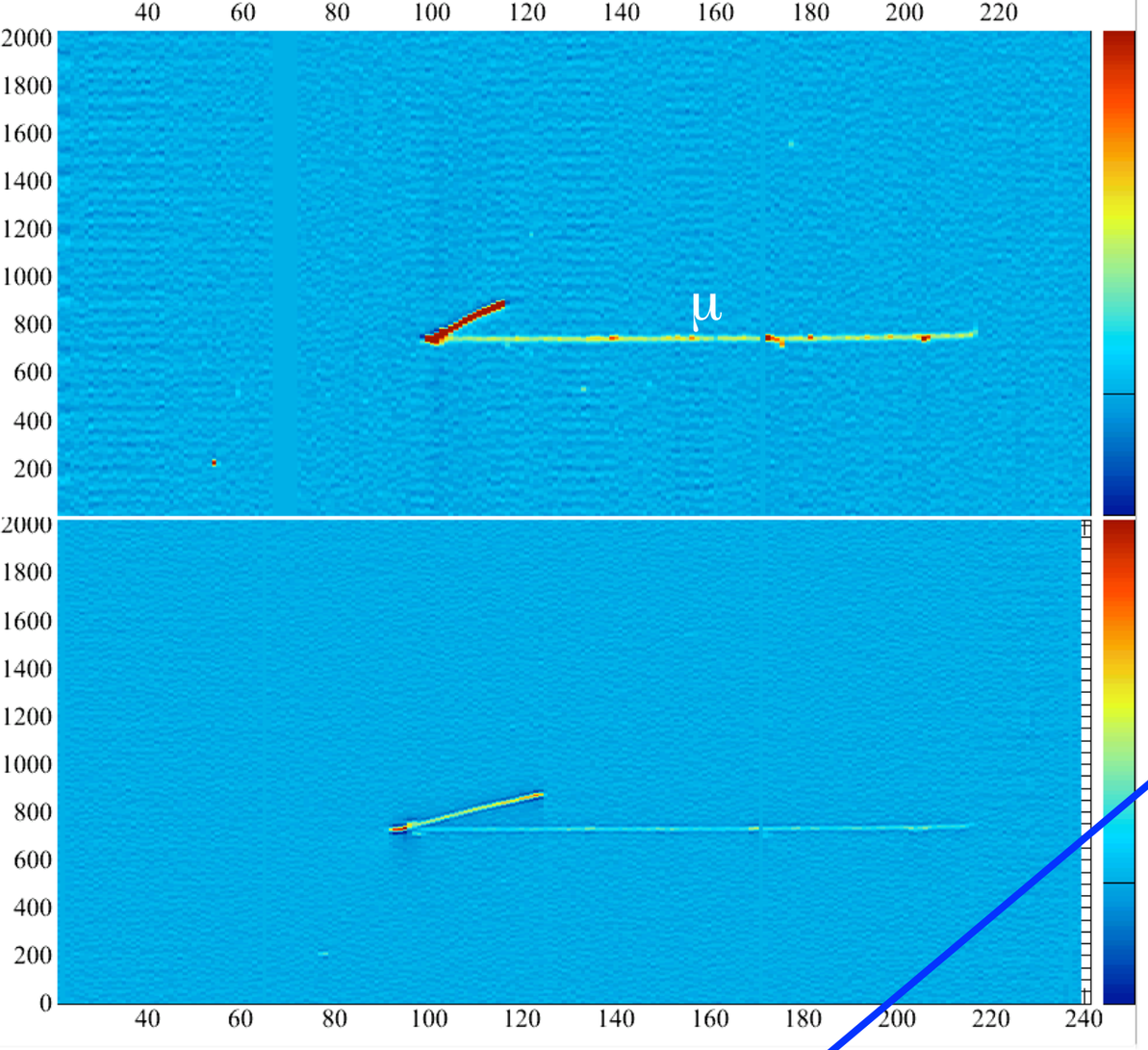


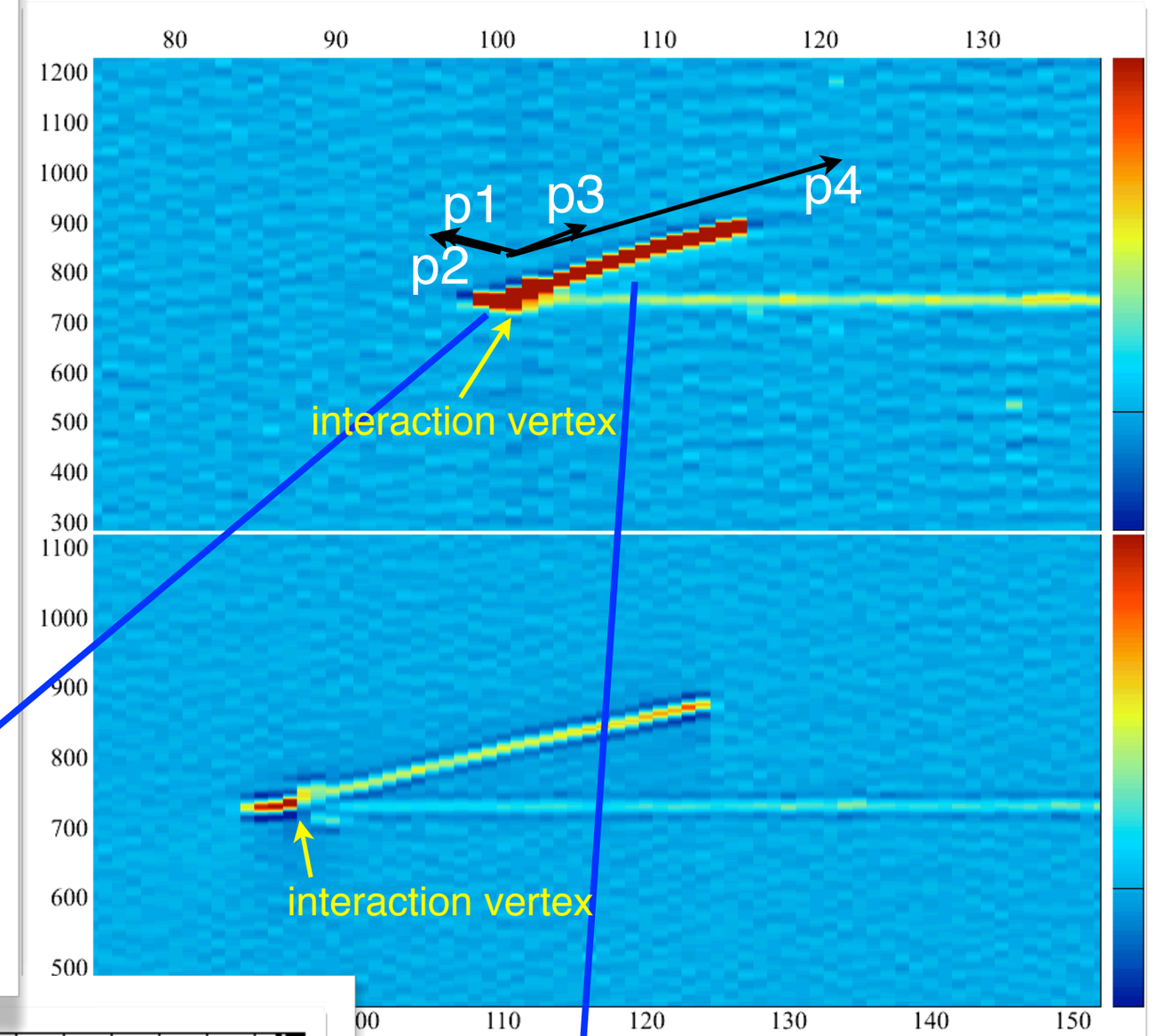
2 or 3 protons?

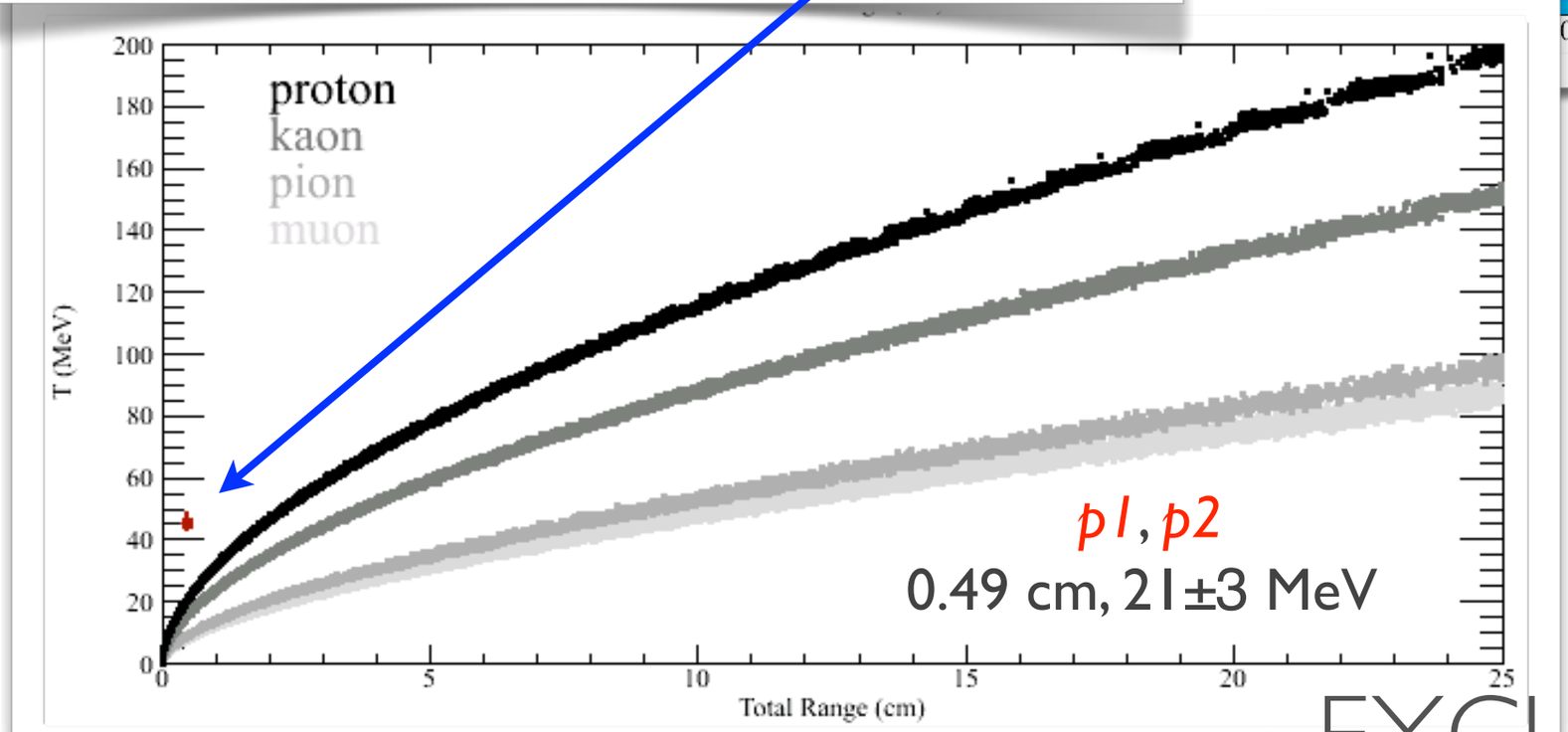
compatible with

1 μ 3p

- *p1*: 1.7 cm ----> T=42±4 MeV
- *p2*: 3.6 cm ----> T=64±5 MeV
- *p3*: 11.9 cm ----> T=126±7 MeV





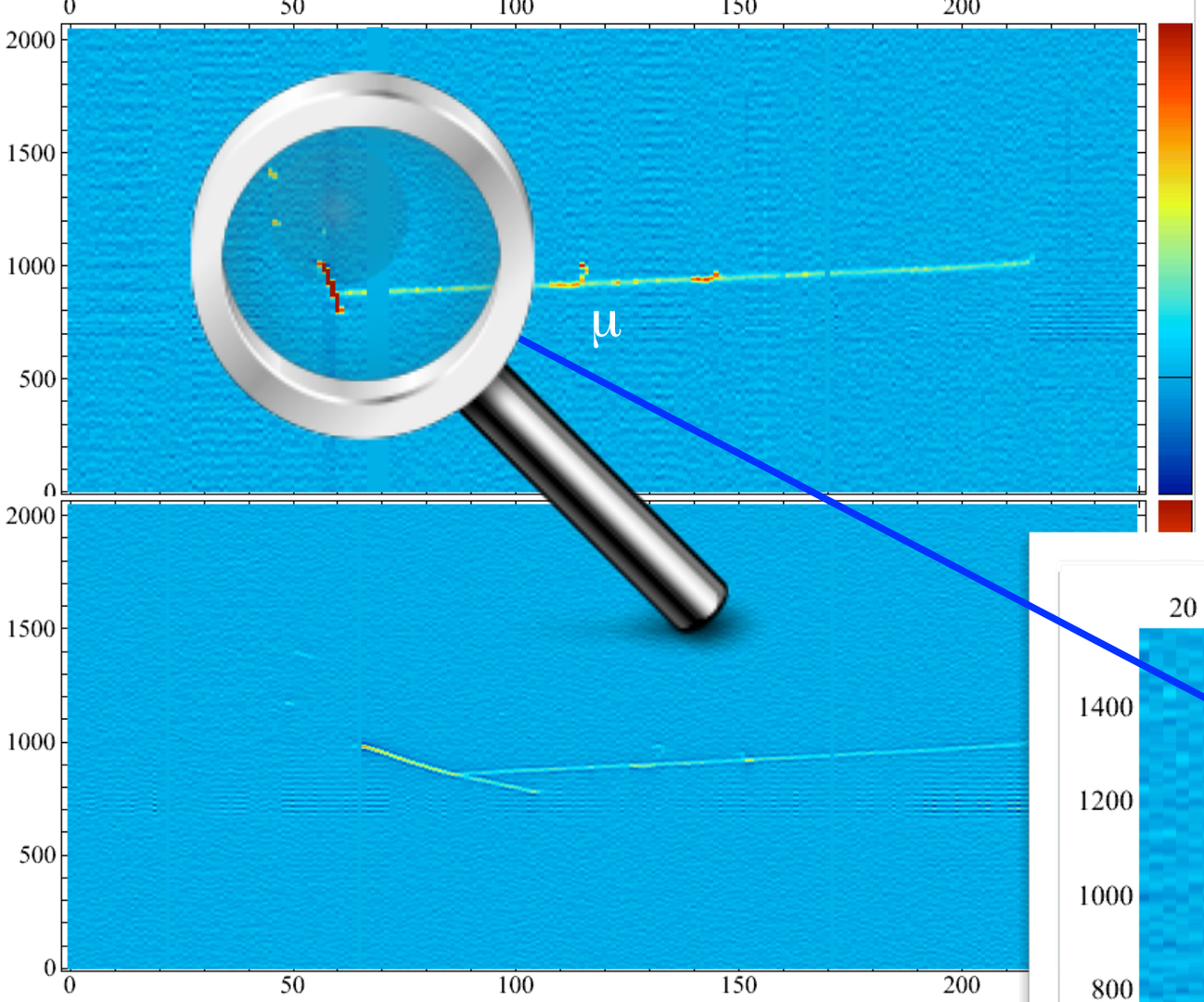


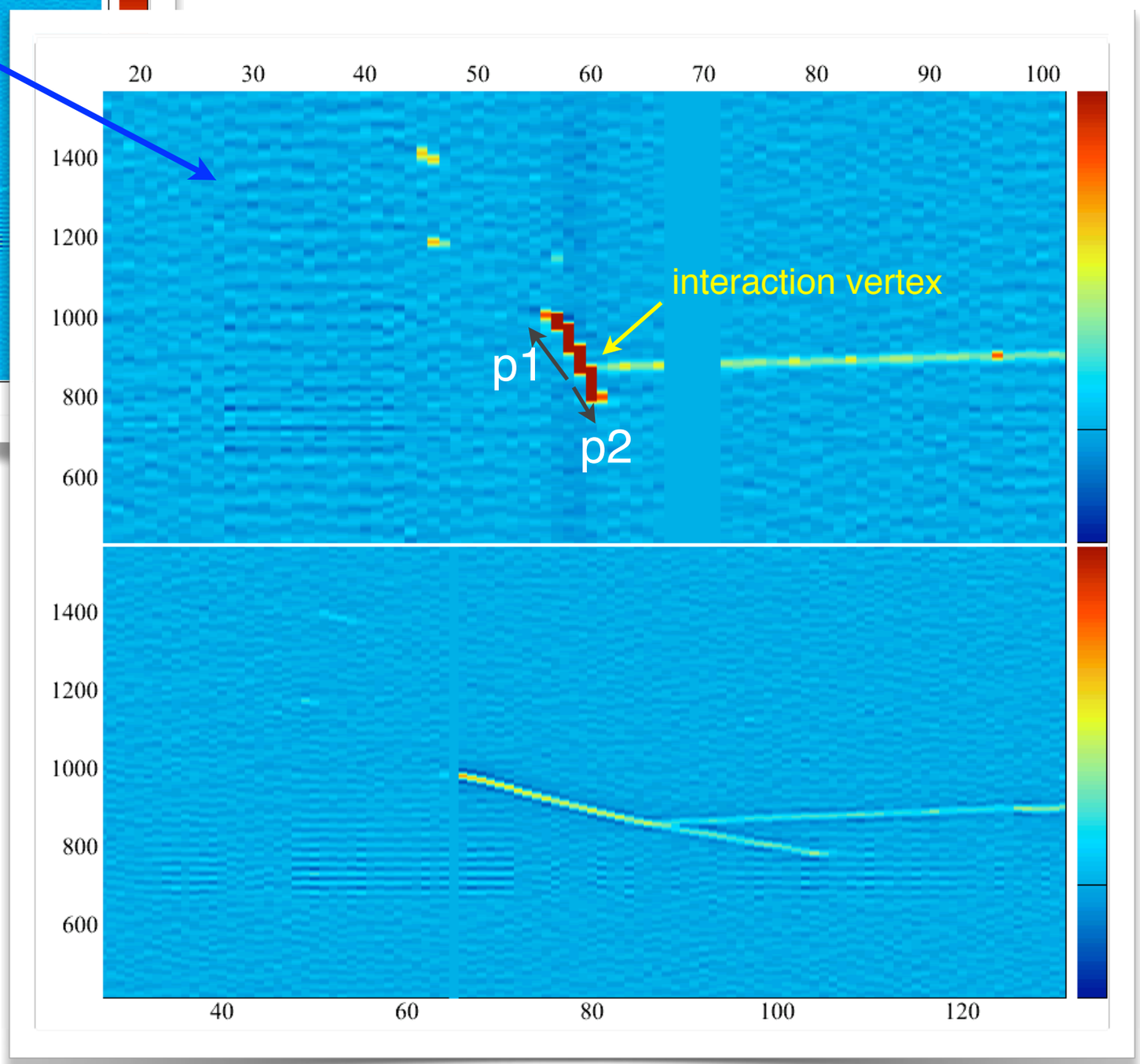
p4: 12 cm, 128±7 MeV
p3: 0.6 cm, 24±3 MeV

compatible with
1 μ 4p

DATA:
EXCLUSIVE TOPOLOGIES

DATA: EXCLUSIVE TOPOLOGIES

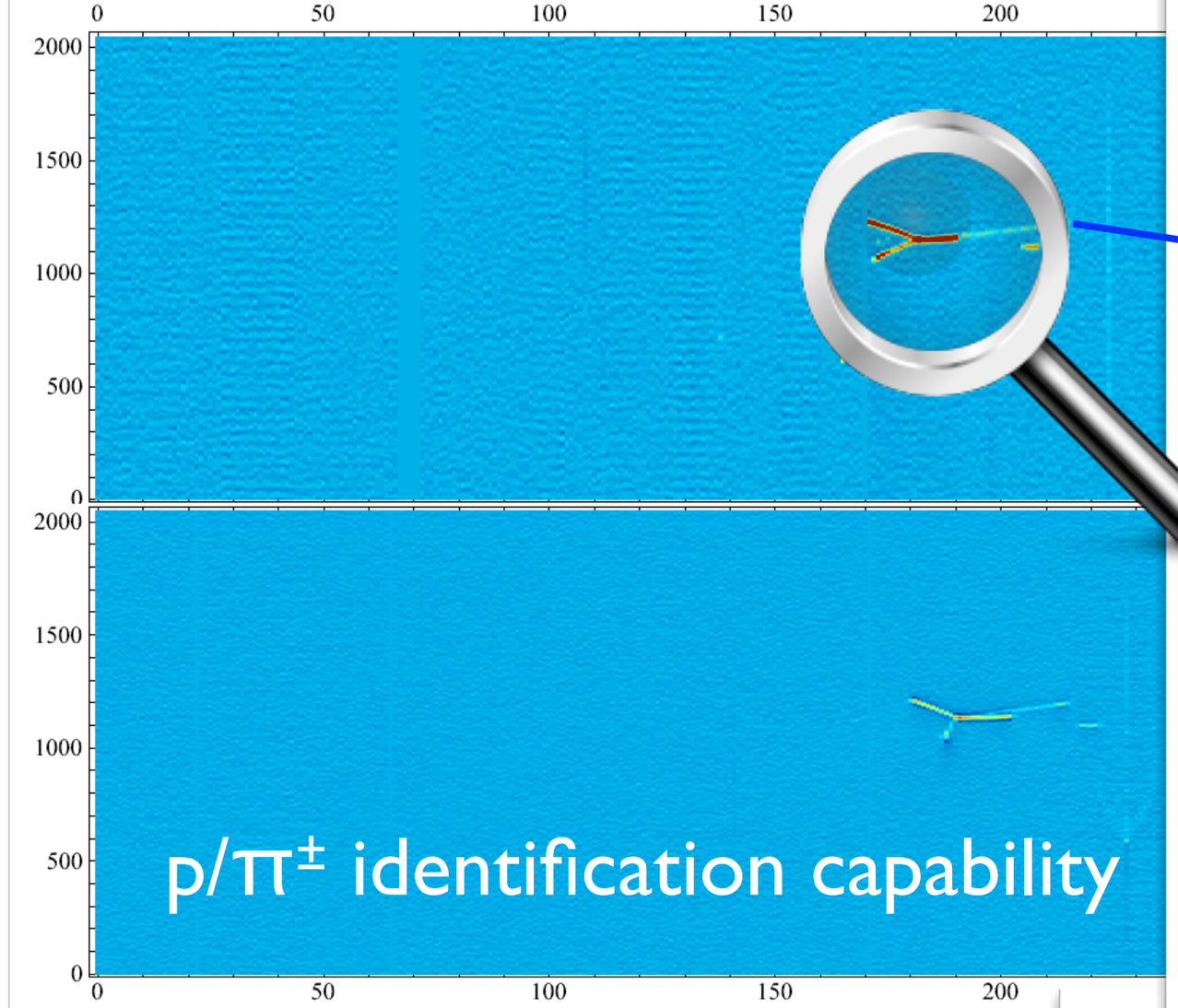


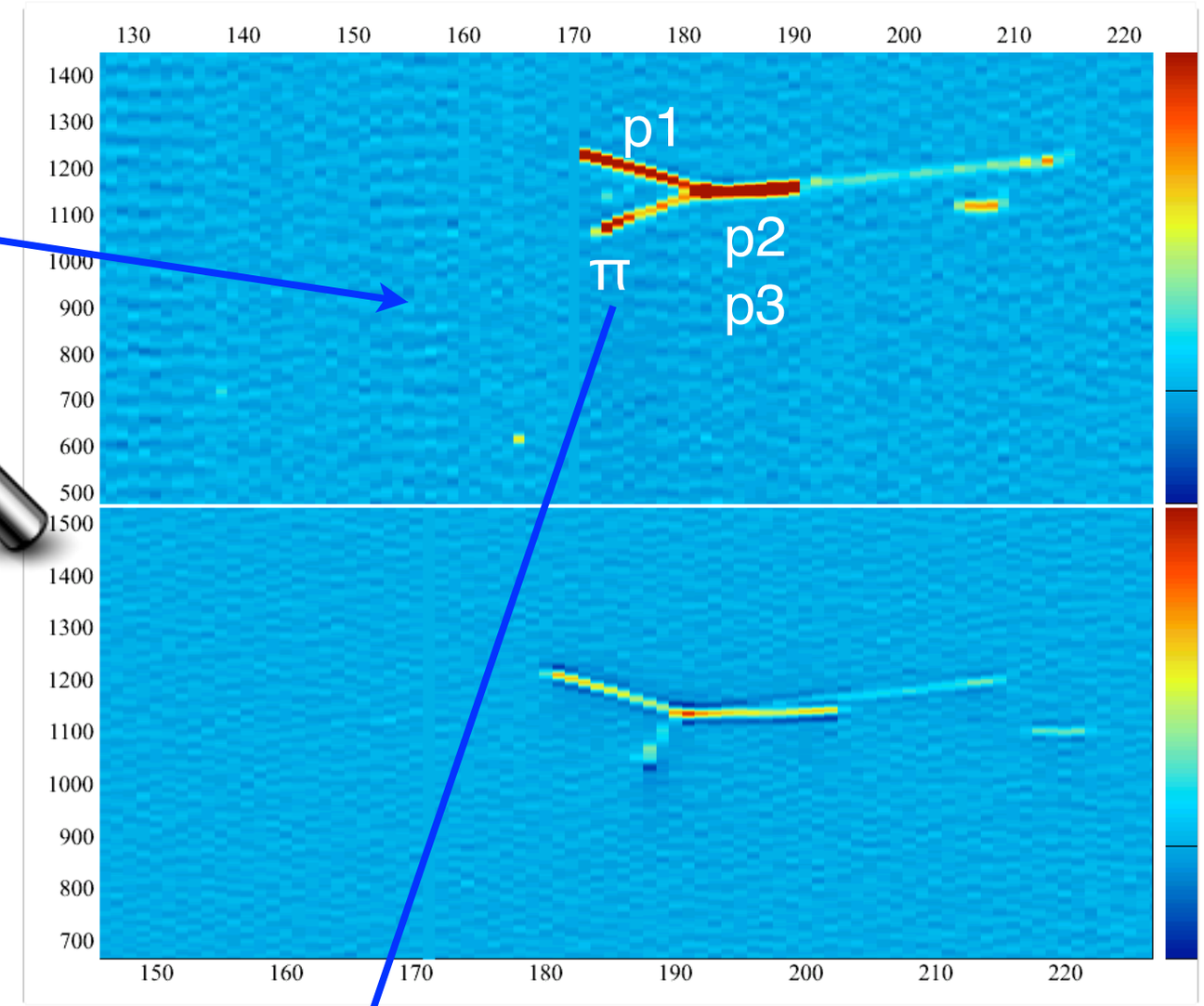


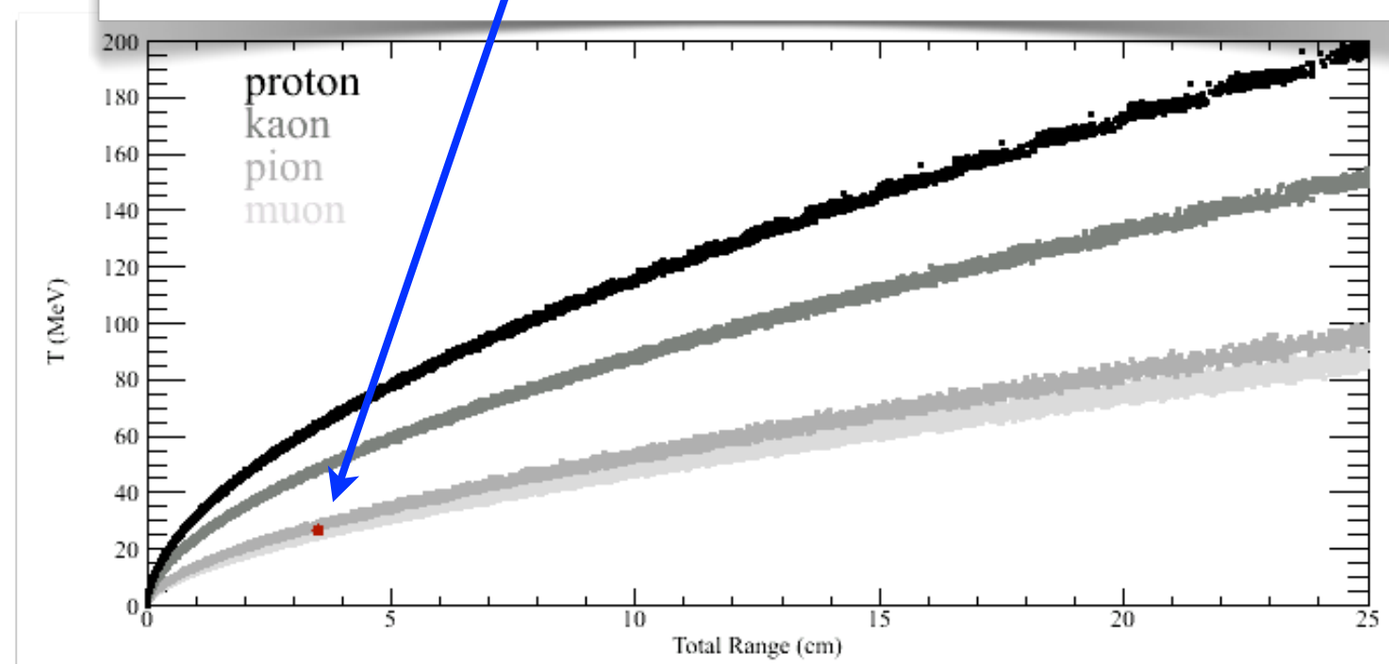
compatible with
1 **μ** 2p

- *p1* : 8.9 cm ----> T=127±7 MeV
- *p2*: 7.5 cm ----> T=80±5 MeV

p/π± identification capability







- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- **π**: 3.5 cm ----> T=26±3 MeV

compatible with

1 μ 3p 1 π

Event not in the muon+Np sample

DATA-MC COMPARISON

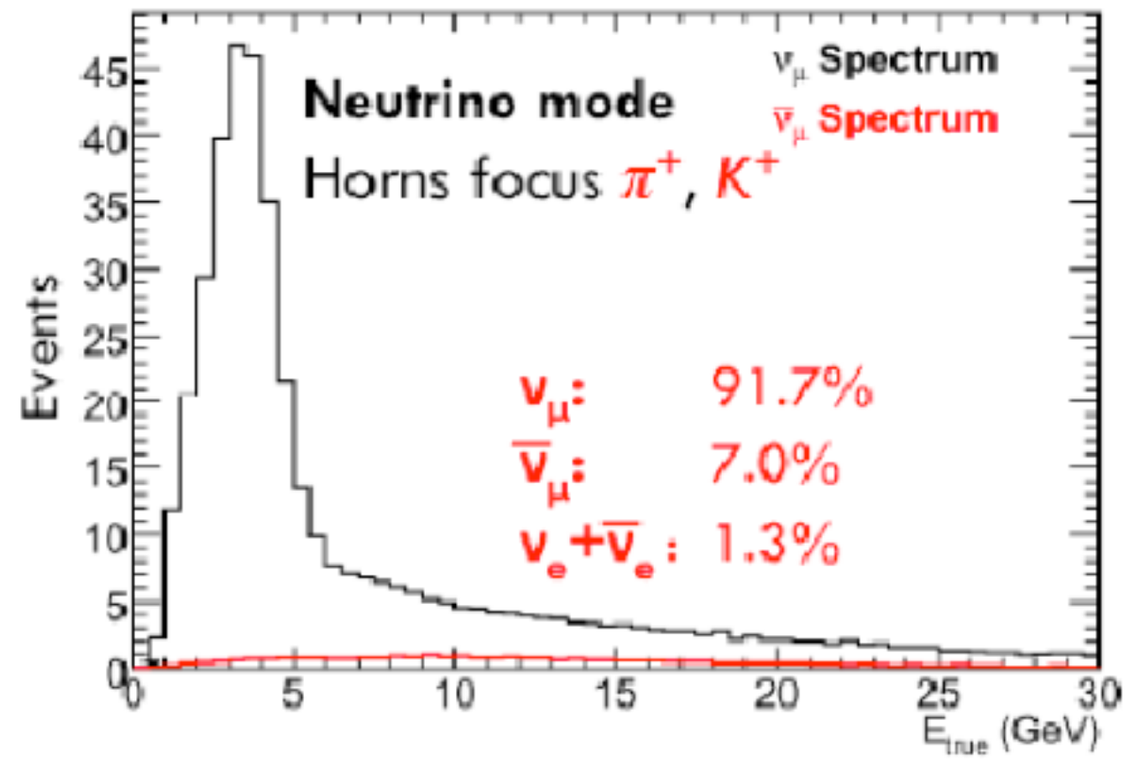
NuMI LE neutrino mode run (8.5×10^{18} POT)

Reference MC: **GENIE**

+

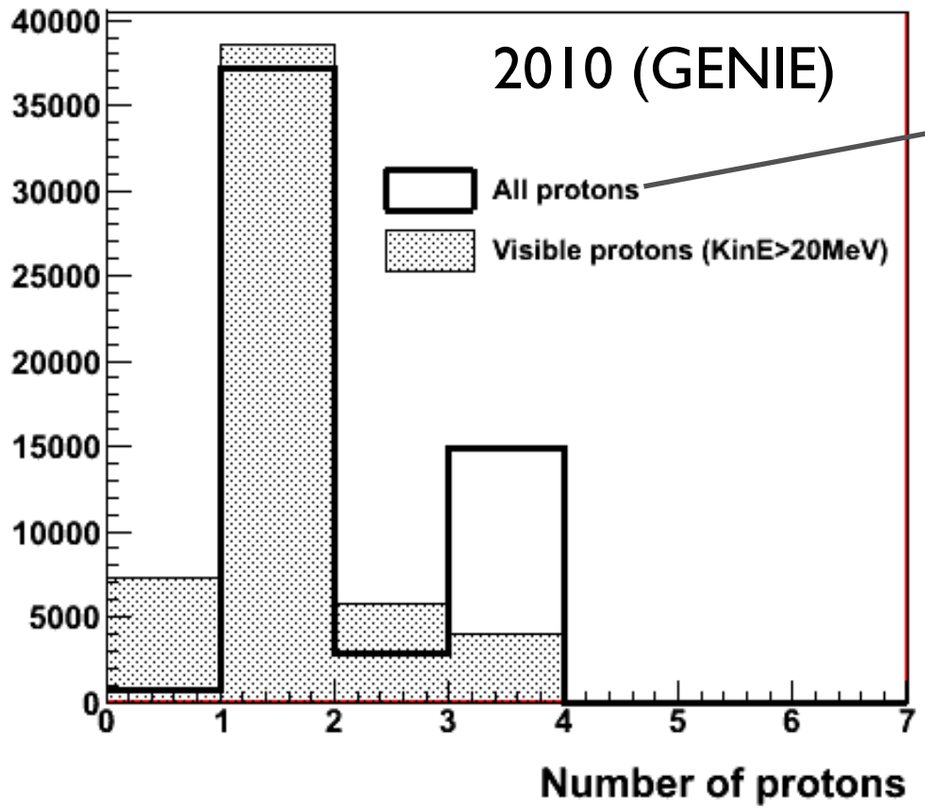
comparison with

FLUKA



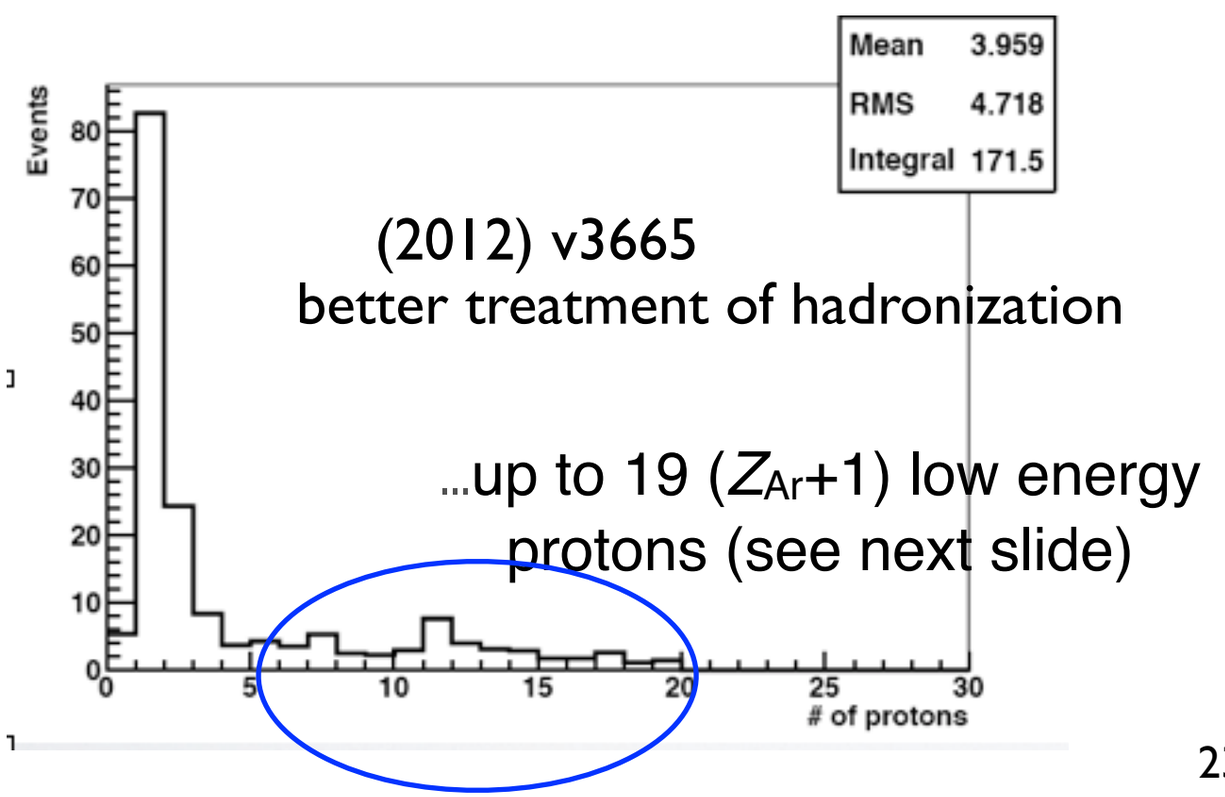
- *Efficiency for the selection of high multiplicity events not (yet) optimized*
- *Studies of background effects are ongoing and will be finalized soon*

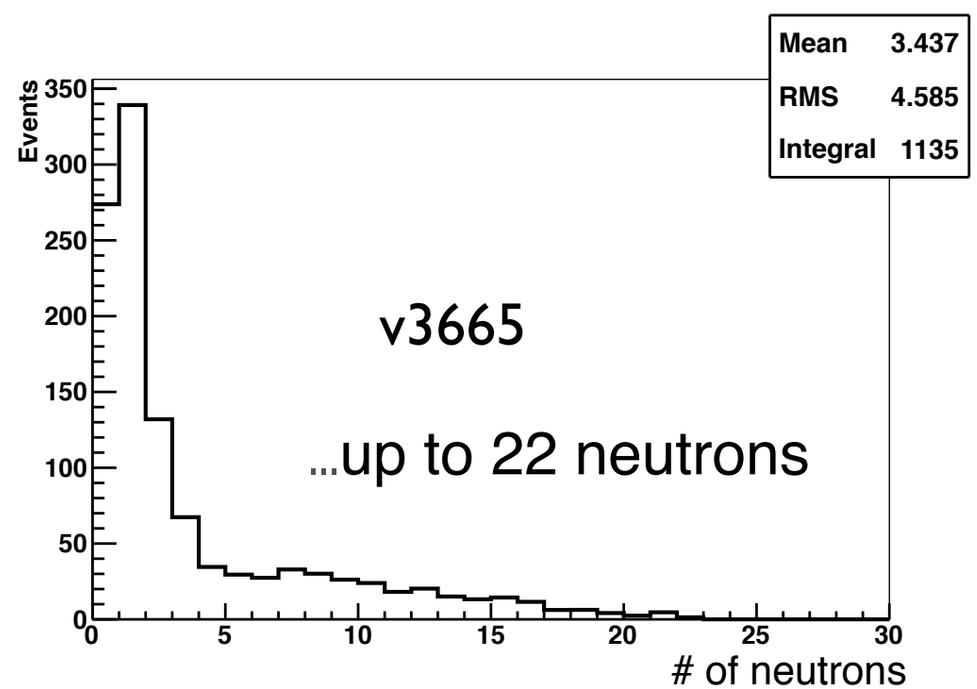
GENIE - NuMI nu mode
Proton multiplicity in μ-Np events in LAr



0p	2%
1p	69%
2p	1%
3p	28%

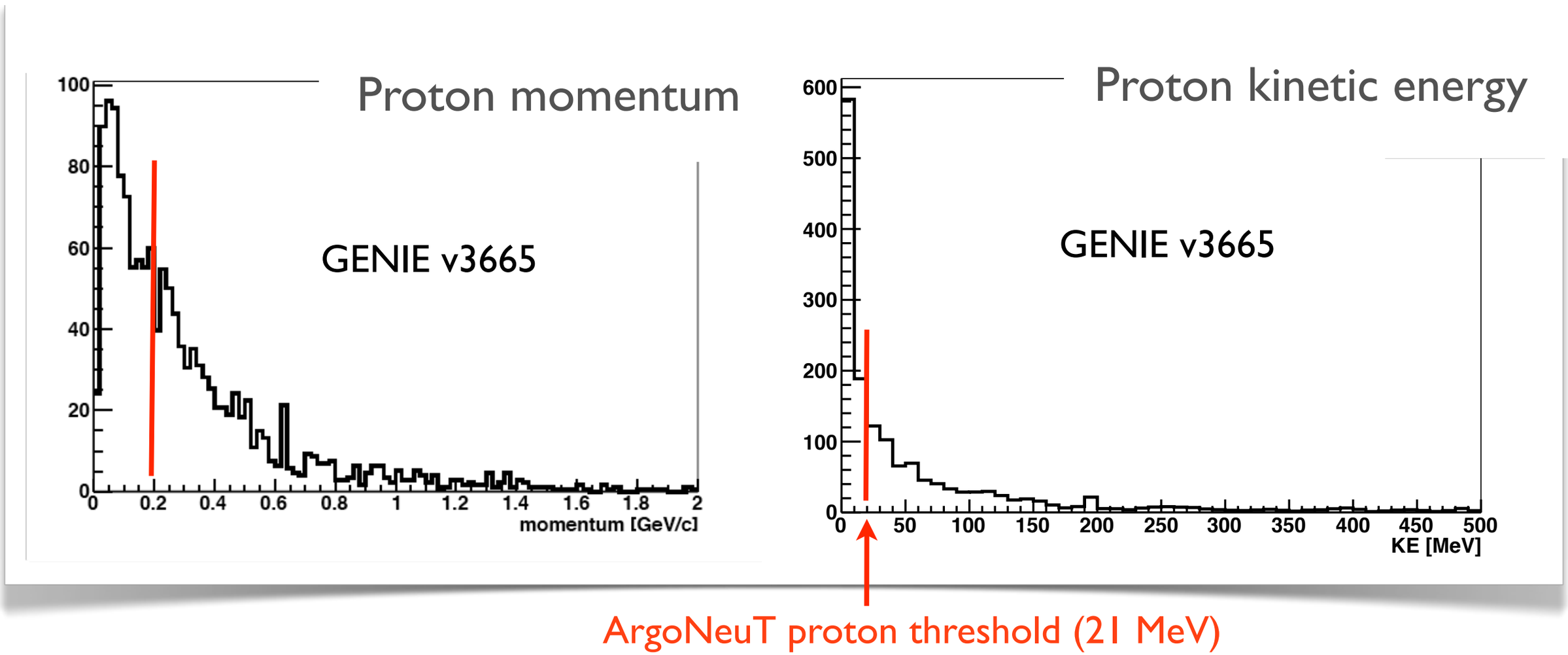
NuMI beam LE spectrum
- neutrino mode -





Genie - NuMI nu mode
Proton momentum/Kinetic energy
μ^- Np events in LAr

NuMI beam LE spectrum
- neutrino mode -



μ^- Np events - MC predictions (I)
GENIE-FLUKA comparison

ν_μ - NuMI neutrino mode run

e. g. Resonant production followed by pion absorption in the nucleus

μ^- GENIE v3665 (including FSI but not MEC)

Multiplicity	% of Total	% not CCQE
1mu+0p	3.1	0
1mu+1p	48.2	4.85
1mu+2p	14.2	40.76
1mu+3p	4.8	50.11
1mu+4p	2.1	53.7
1mu+5p	2.5	40.0
1mu+6p	2.0	32.9
1mu+7p	3.1	32
1mu+8p	1.4	69.3
1mu+9p	1.3	75.3
1mu+10p	1.7	100

μ^- FLUKA (including FSI but not MEC)*

Multiplicity	% of Total	% not CCQE
1mu+0p	4.28	0.1
1mu+1p	45.8	0.8
1mu+2p	15.74	22.2
1mu+3p	14.2	73.5
1mu+4p	9.95	90.3
1mu+5p	6.25	93.4
1mu+6p	2.4	94.7
1mu+7p	0.96	95.9
1mu+8p	0.27	97.1
1mu+9p	0.09	98.4
1mu+10p	0.03	100

MC agreement on% of total, but very different % of not CCQE

*kindly from G. Battistoni (priv. comm.)

μ^- Np events - MC predictions (II)
GENIE-FLUKA comparison

as previous slide, but with 21 MeV proton threshold

μ^- GENIE v3665

Multiplicity	% of Total	% not CCQE
1mu+0p	16.3	0
1mu+1p	47	7.8
1mu+2p	13.4	57
1mu+3p	8.3	80
1mu+4p	4.5	85
1mu+5p	3	65
1mu+6p	0.6	100
1mu+7p	1	100
1mu+8p	2.5	100
1mu+9p	1	70
1mu+10p	0.3	100

μ^- FLUKA*

Multiplicity	% of Total	% not CCQE
1mu+0p	16.5	2.7
1mu+1p	51.2	10
1mu+2p	16.4	73
1mu+3p	10.8	93
1mu+4p	3.6	95
1mu+5p	1.1	97
1mu+6p	0.28	97
1mu+7p	0.08	99
1mu+8p	0.02	100
1mu+9p	0.008	97
1mu+10p	0.003	100
1mu+Np		33

MC agreement on % of total, but very different % of not CCQE
(could be as large as ~30%, according to MC)

*kindly from G. Battistoni (priv. comm.)

μ^+ Np events - MC predictions FLUKA

$\bar{\nu}_\mu$ - NuMI neutrino mode run

μ^+ FLUKA* 21 MeV proton threshold

Multiplicity	% of Total	% not CCQE
1mu+0p	60	4
1mu+1p	21	43
1mu+2p	12	83
1mu+3p	7	93
1mu+4p	3	95
1mu+5p	1	96
1mu+6p	0.3	97
1mu+7p	0.08	100
1mu+Np		32

*kindly from G. Battistoni (priv. comm.)

Comparison with GENIE not yet available

ARGONEUT DATA-MC COMPARISON

ν_μ - NuMI neutrino mode run

Lots of infos not yet processed, e. g.

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC ratio
0p+1mu	28±4	16%	15±3	14%	0.53
1p+1mu	80±7	47%	51±10	48%	0.63
2p+1mu	23±4	13.4%	28±6	26%	1.22
3p+1mu	14±3	8.3%	13±3	12%	0.93
4p+1mu	8±2	4.5%	0	0	
TOTAL (including >4p	172±10	-	107±12	-	0.62

$(0p/1p)_{DATA}=0.29$
$(0p/1p)_{GENIE\ MC}=0.35$
$(0p/1p)_{FLUKA}=0.32$

DATA-MC quite in agreement on % of total

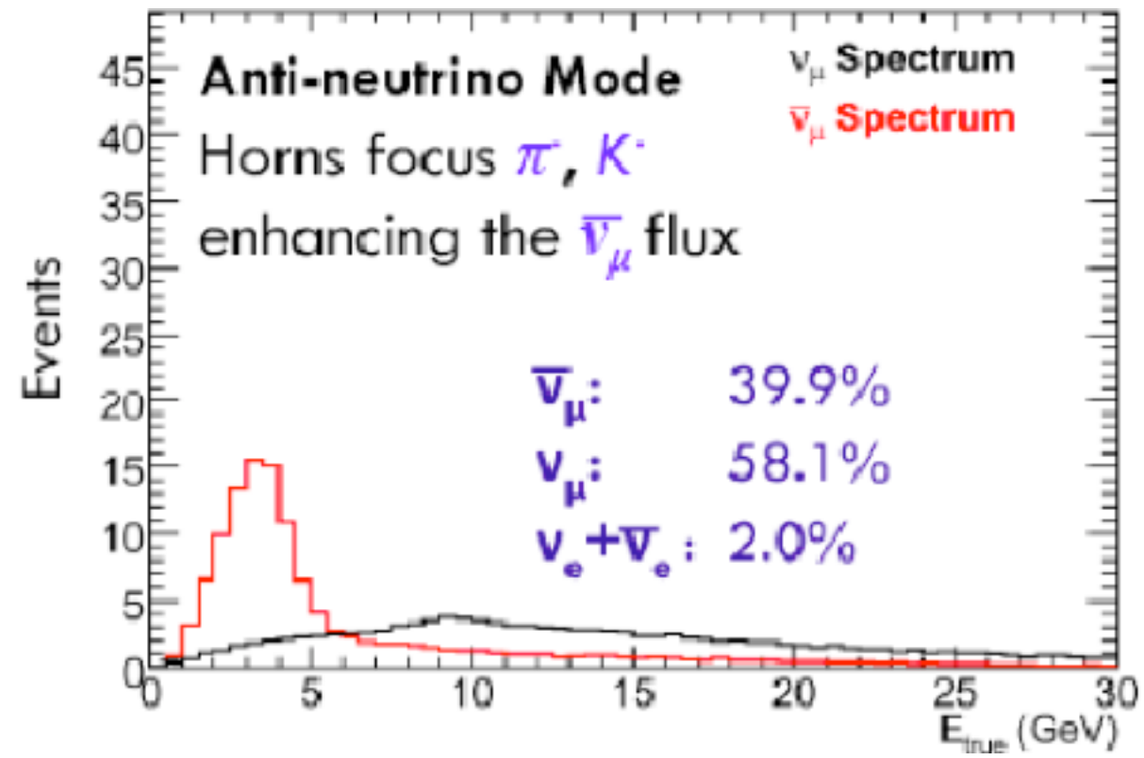
$\bar{\nu}_\mu$ - NuMI neutrino mode run

$(1p/0p)_{FLUKA}=0.35$

$\bar{\nu}_\mu$ statistics is very low in neutrino-mode run

DATA-MC COMPARISON

anti-neutrino mode run (1.2×10^{20} POT)



Reference MC: **GENIE**

+

comparison with

NUANCE

- *Uncertainties on the neutrino flux not yet included*
- *Efficiency for the selection of high multiplicity events not (yet) optimized*
- *Studies of background effects are ongoing and will be finalized soon*

$\mu^{+/-}$ Np events - MC predictions (I)
GENIE-FLUKA comparison

$\bar{\nu}_\mu$ and ν_μ - anti-neutrino mode run

μ^+ GENIE 21 MeV proton threshold

Multiplicity	% of Total	% not CCQE
1mu+0p	60	10.5
1mu+1p	17	39
1mu+2p	7	74
1mu+3p	5.4	82
1mu+4p	3.5	89
1mu+5p	2	88
1mu+6p	1.7	95.5
1mu+7p	1	95.5
1mu+8p	0.8	97
1mu+9p	0.4	100
1mu+10p	0.2	100
1mu+Np		33

μ^- GENIE 21 MeV proton threshold

Multiplicity	% of Total	% not CCQE
1mu+0p	14%	2.5%
1mu+1p	48%	5.5%
1mu+2p	13.6%	60.3%
1mu+3p	7%	76%
1mu+4p	5%	83%
1mu+5p	4%	86%
1mu+6p	2.5%	86%
1mu+7p	2%	97%
1mu+8p	1%	79%
1mu+9p	1%	94%
1mu+10p	1%	100%
1mu+Np		32

Comparison with FLUKA not yet available

ARGONEUT DATA-MC COMPARISON (I)

$\bar{\nu}_\mu$ - anti-neutrino mode run (μ^+)

Lots of infos not yet processed, e. g.

μ^-/μ^+(DATA)=0.36
μ^-/μ^+(MC)=0.36

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC RATIO
0p+1mu	553±11	60%	422±42	58%	0.76
1p+1mu	160±6	17%	266±53	37%	1.66
2p+1mu	68±4	7%	30±6	4%	0.44
3p+1mu	50±3	5%	3±1	0.4%	0.06
4p+1mu	32±3	4%	3±1	0.4%	0.09
TOTAL (including >4p	925±15	-	727±68	-	0.79

$(1p/0p)_{DATA}=0.63$
$(1p/0p)_{MC}=0.29$

0p events:
$(\mu^+/\mu^-)_{DATA}=7$
$(\mu^+/\mu^-)_{MC}=12$

ν_μ - anti-neutrino mode run (μ^-)

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC RATIO
0p+1mu	46±3	14%	60±12	23%	1.3
1p+1mu	163±6	48%	154±31	59%	0.94
2p+1mu	46±3	13.6%	33±7	13%	0.71
3p+1mu	23±2	7%	9±2	3.5%	0.39
4p+1mu	16±2	5%	4±1	1.5%	0.25
TOTAL (including >4p	337±9	-	260±34	-	0.77

$(0p/1p)_{DATA}=0.39$
$(0p/1p)_{MC}=0.28$

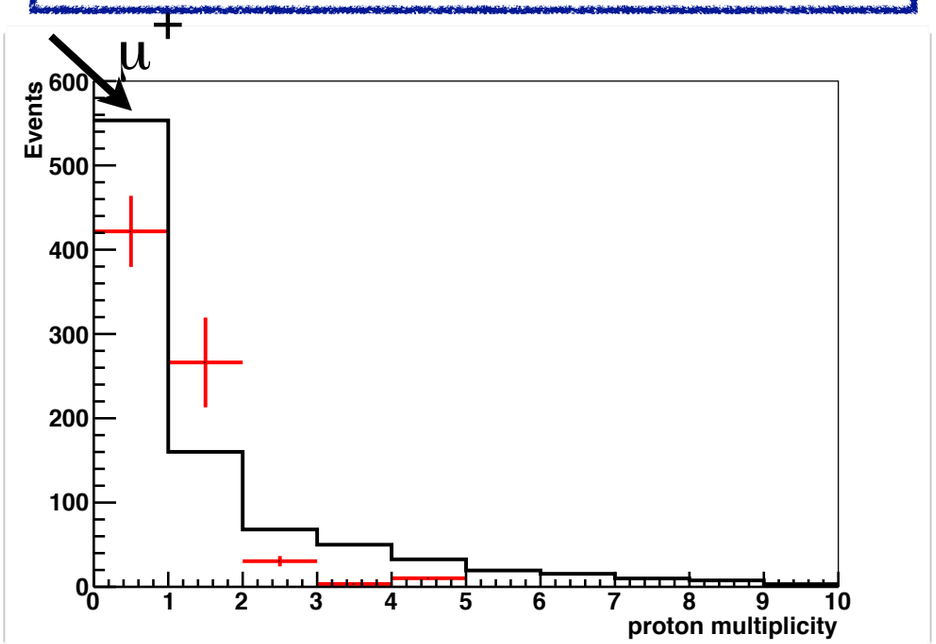
- $\frac{N_{\mu^-}}{N_{\mu^+}}$ ratio

0p events

Useful for FSI studies: indication of nucleon charge exchange in Ar nuclei, less dependent (at 1st order) on multinucleon production

ARGONEUT DATA-MC COMPARISON (II)

$\bar{\nu}_\mu$ - anti-neutrino mode run



ArgoneuT data 727±68

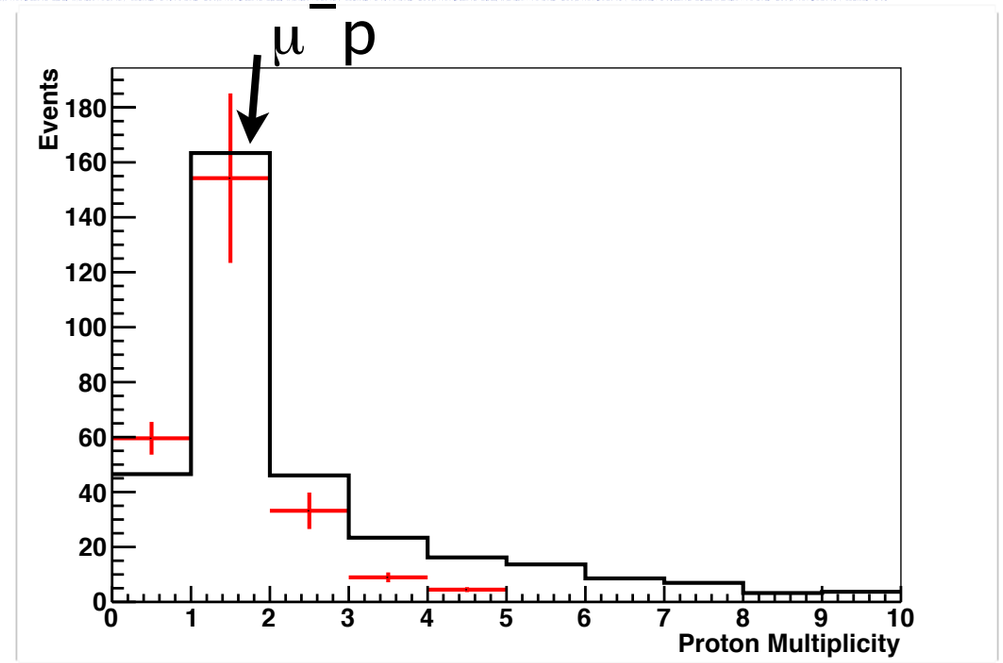
Genie 925±15

Genie: 626 CCQE events

(+ 33% contribution from not CCQE)

NUANCE: 636 CCQE events

ν_μ - anti-neutrino mode run



ArgoneuT data 260±34

Genie 337±9

Genie: 230 CCQE events

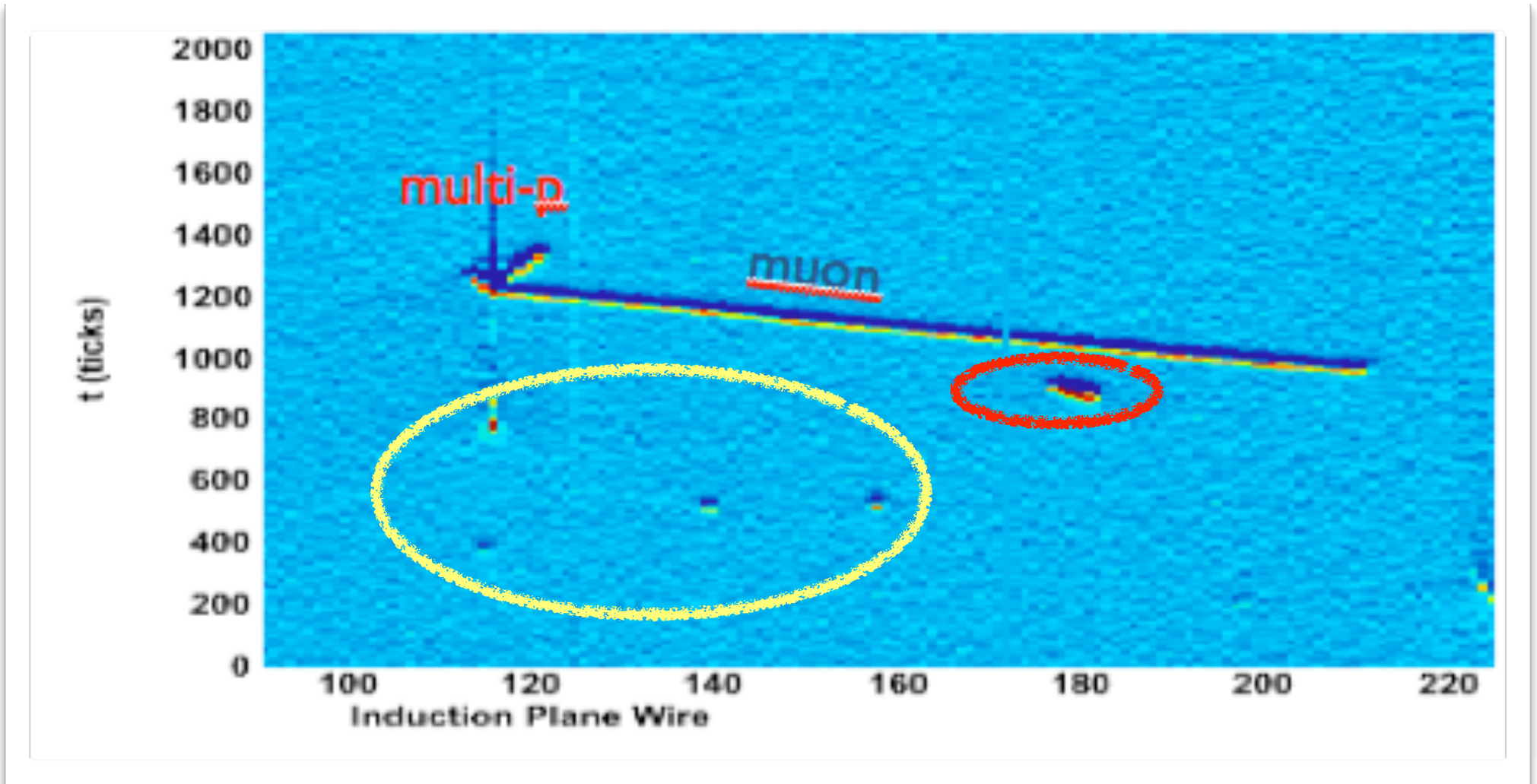
(+ 32% contribution from not CCQE)

NUANCE: 230 CCQE events

- Ratios among rates of different proton multiplicities in DATA don't agree with MC, in particular for $\bar{\nu}_\mu$
- MC agreement on total number of CCQE events
- Large (~30%) contribution from not CCQE events (FSI)

VERTEX ACTIVITY

Measurement of γ activity around the vertex and neutron → proton can also help to tune MC generators



ARGONEUT $\mu^{+/-}$ Np EVENTS ANALYSIS OUTCOMES

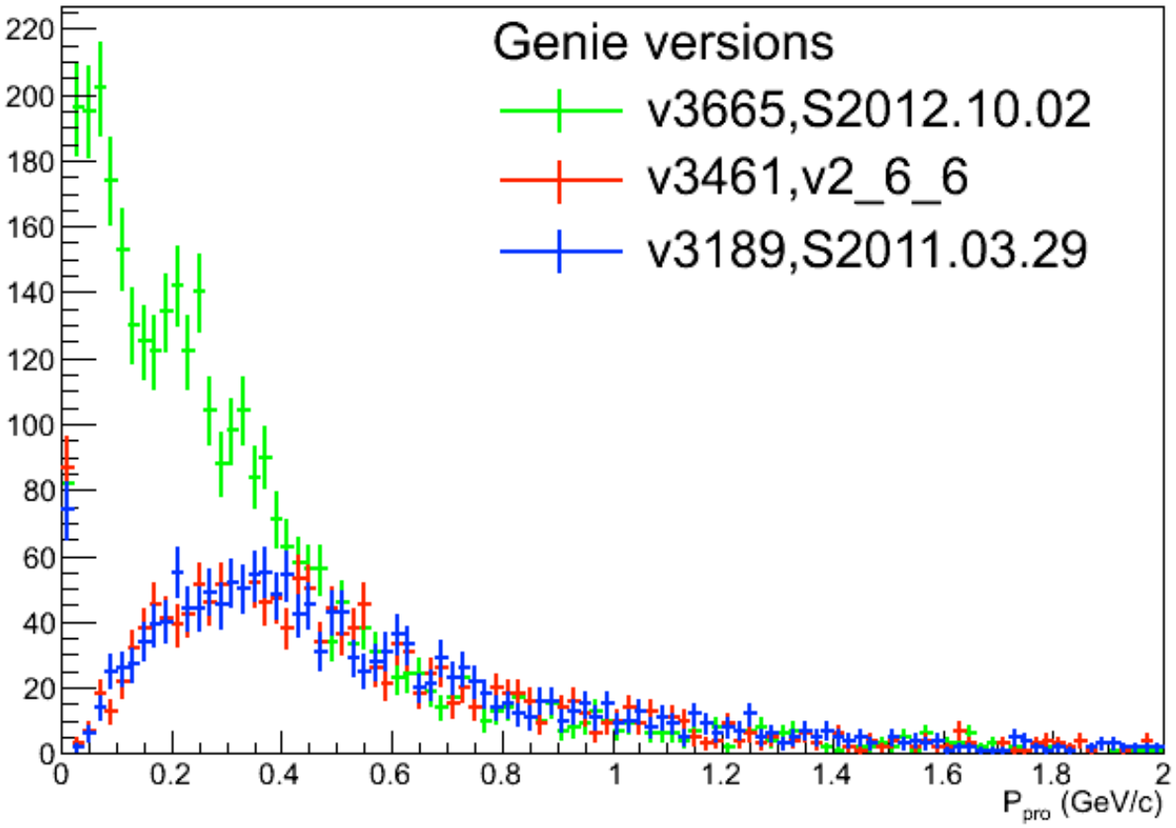
Capability to identify and reconstruct exclusive topologies
Low proton threshold: 21 MeV Kinetic Energy

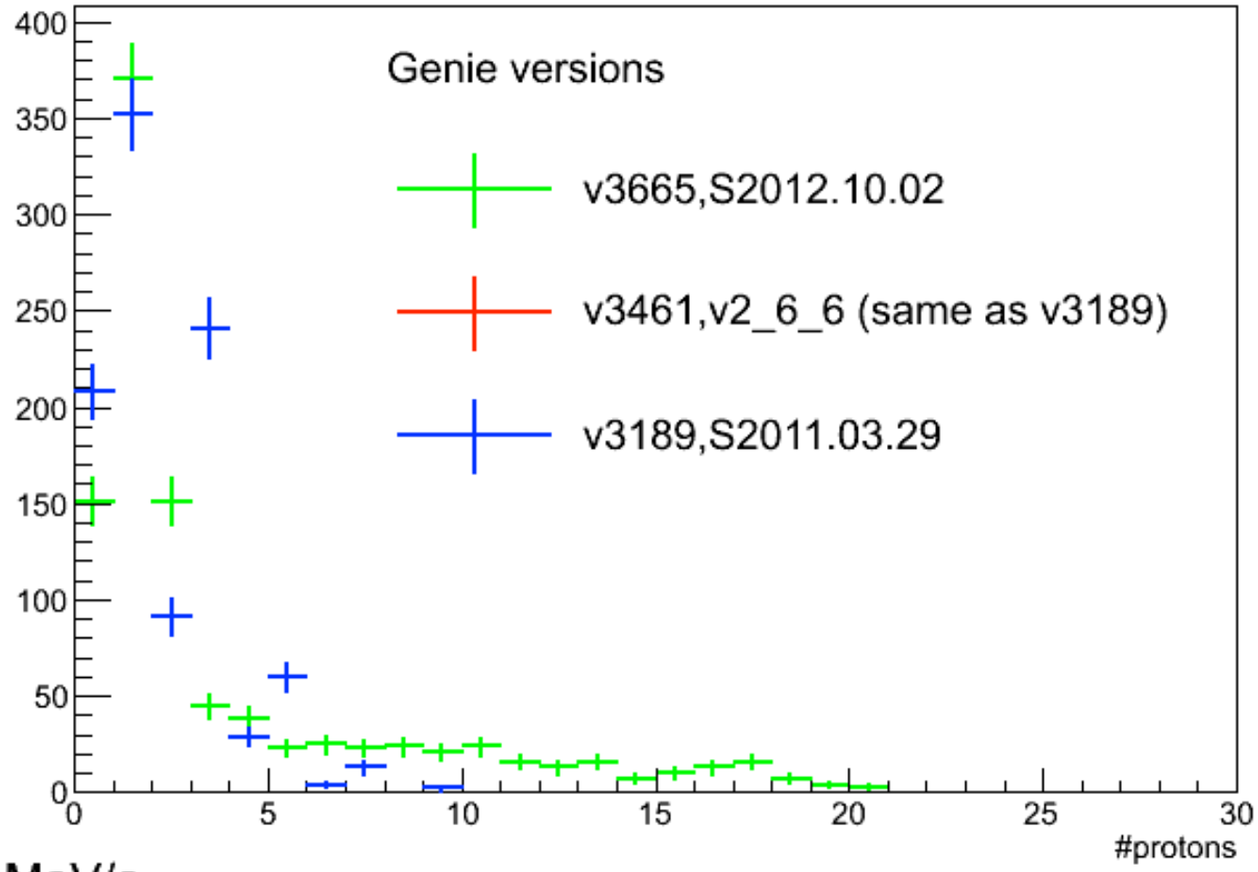
Many infos from LAr TPC..
We are learning how to deal with each class of event/topology
(e.g. reconstruction of multi-proton events)

Proton multiplicity at the neutrino interaction vertex with presence of secondary particles in ArgoNeuT events and ratios among rates of different exclusive topologies provide indications on the size of nuclear effects in LAr, like FSI (and multinucleon production) in the few GeV energy region.

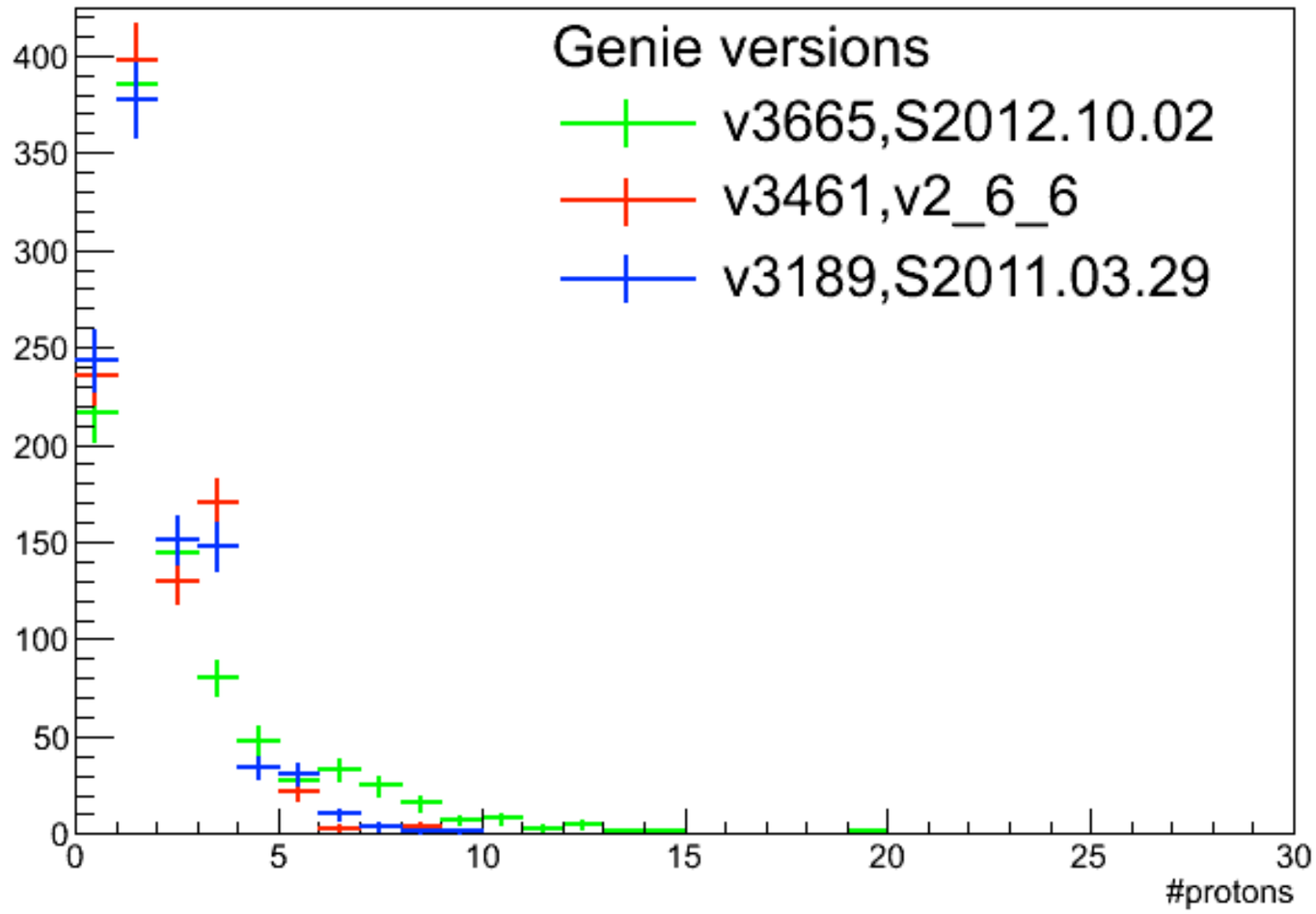
The generators predict vastly varying amounts of proton emission.
The ArgoNeuT data can provide an important discriminator among models.
This is the first time we've had this type of data available to help guide us.

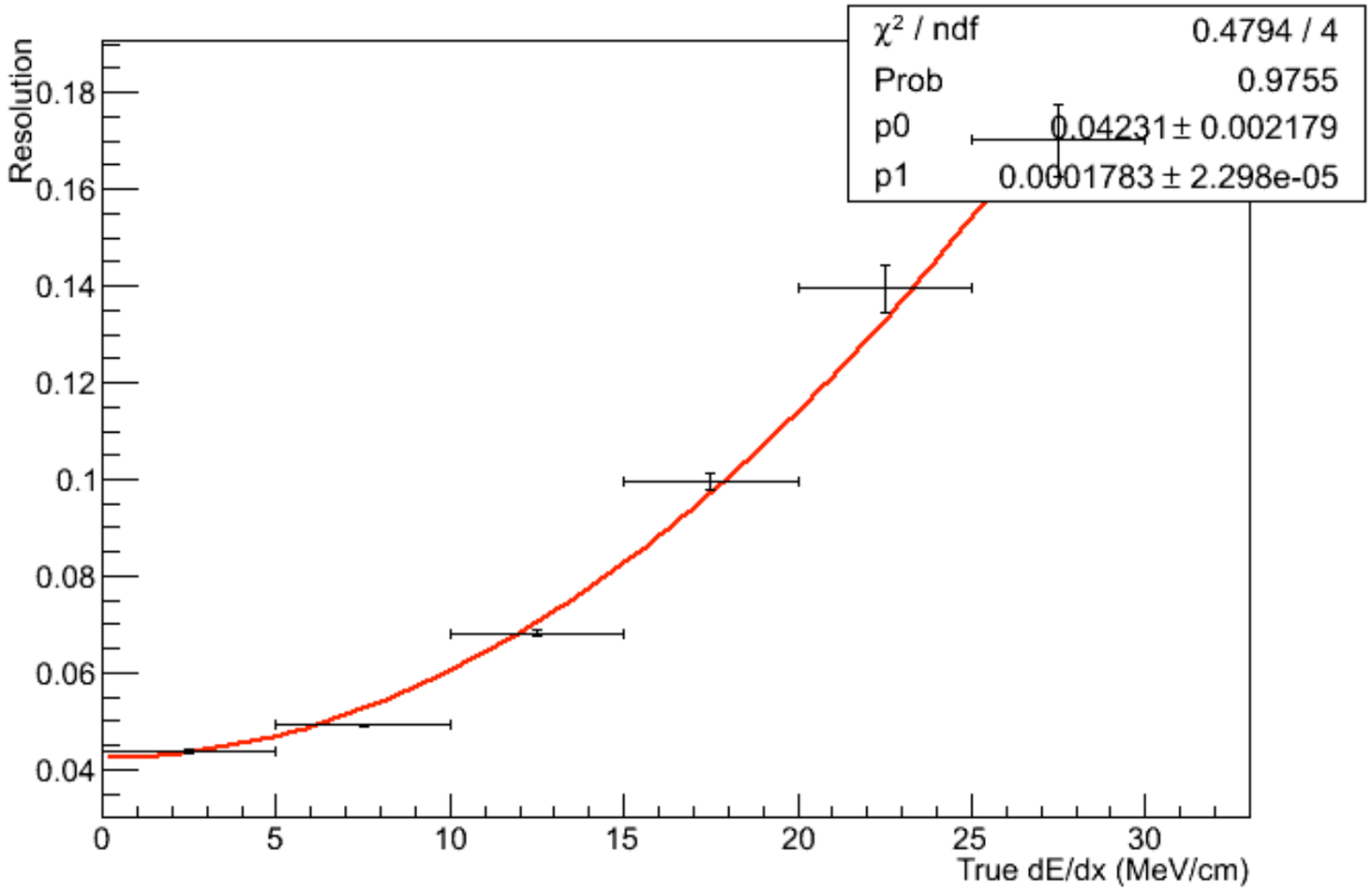
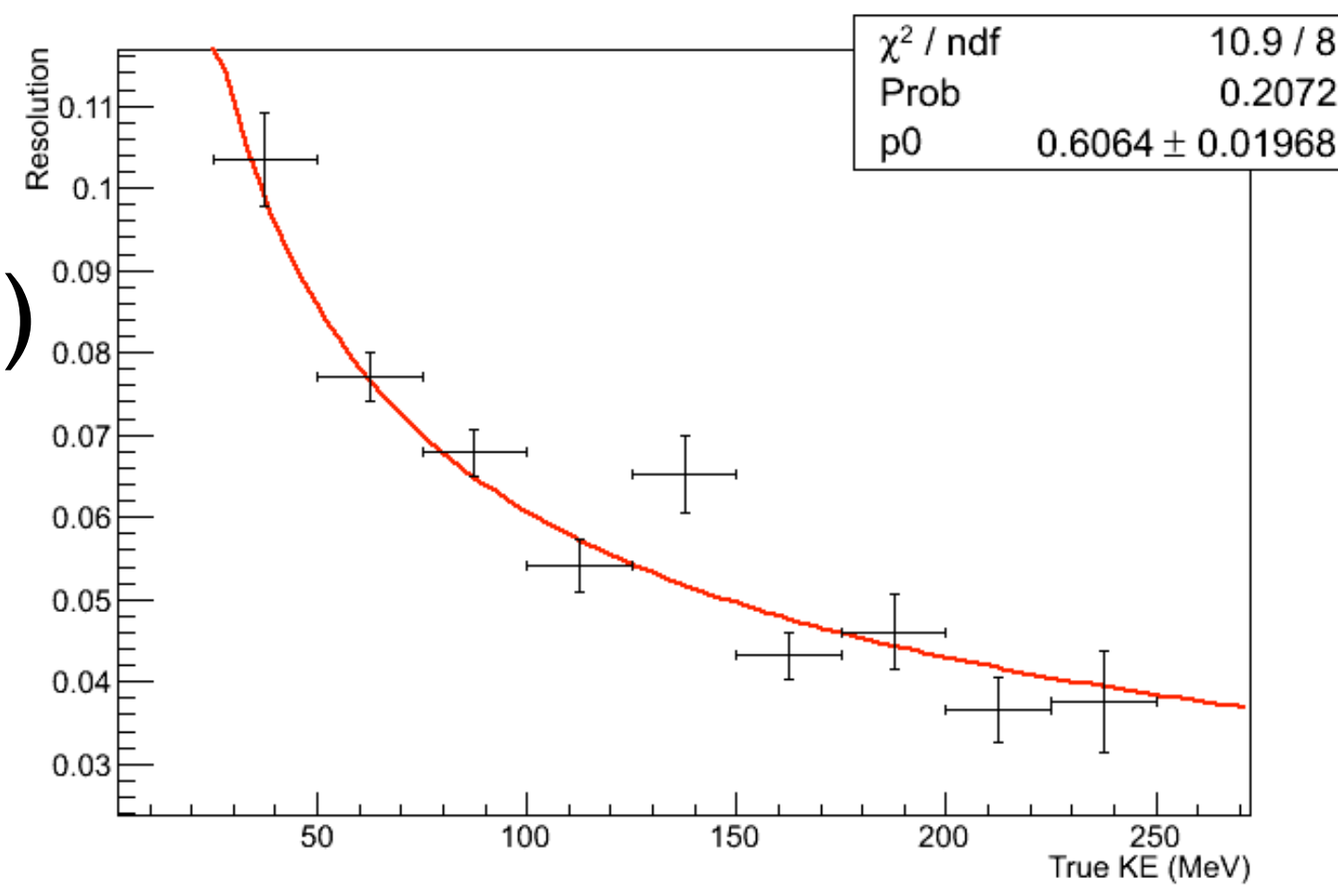
BACKUP


Genie versions
v3665,S2012.10.02
v3461,v2_6_6
v3189,S2011.03.29
P_{pro} (GeV/c)


Genie versions
v3665,S2012.10.02
v3461,v2_6_6 (same as v3189)
v3189,S2011.03.29
#protons

P>200 MeV/c


Genie versions
v3665,S2012.10.02
v3461,v2_6_6
v3189,S2011.03.29
#protons



ArgoNeuT (3 mm wire pitch) Resolution in dE/dx and Kinetic Energy