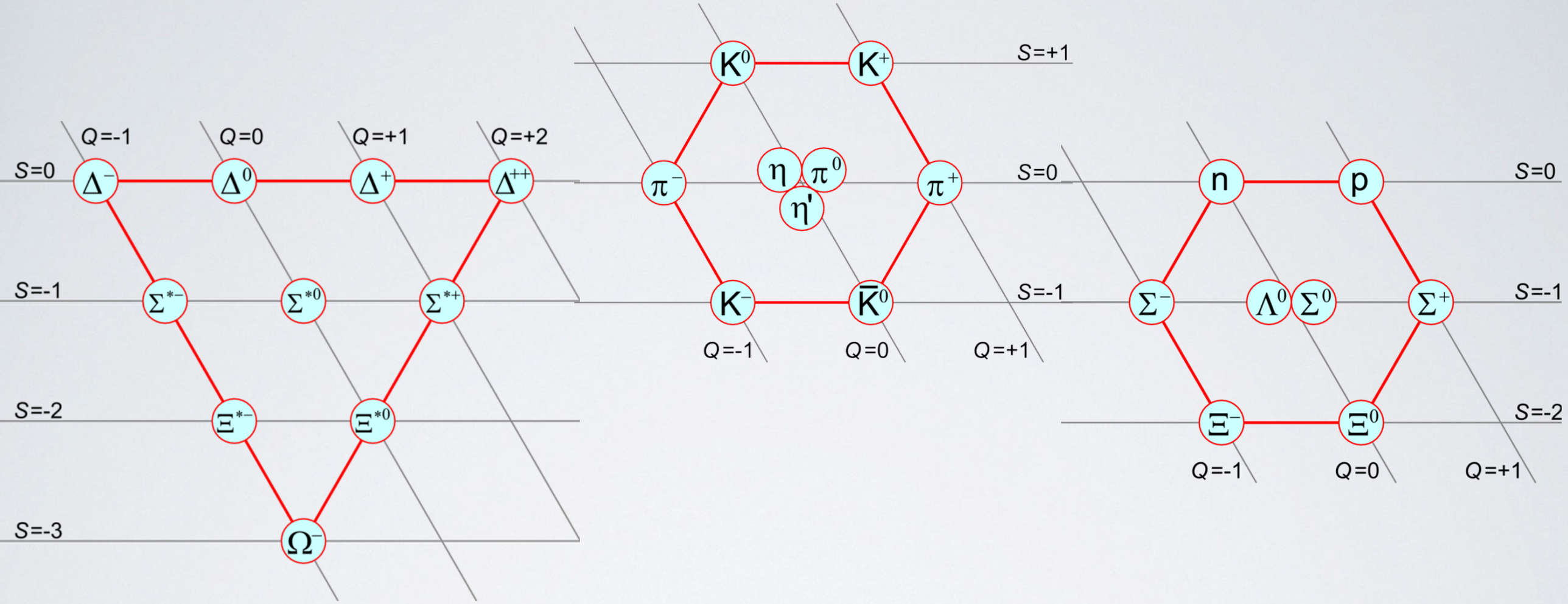
DEEP UNDERGROUND NEUTRINO EXPERIMENT

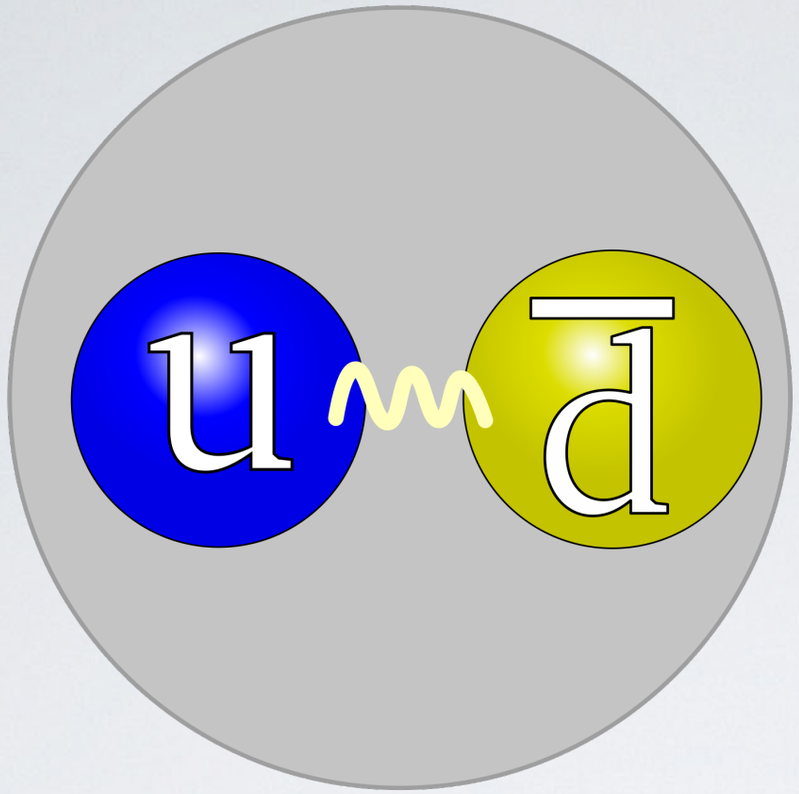
ProtoDUNE at CERN hadron interactions

ProtoDUNE Science WS at CERN

June 29, 2016 Flavio Cavanna | Fermilab



(Charged) Pion, Kaon and Proton Interaction Processes



Pion

Beyond intrinsic theoretical interest in probing the nuclear structure, pion interactions play a critical role in understanding systematic uncertainties in neutrino experiments conducted at the GeV energy scale - like the current (uB) and future (SBN and LBN-DUNE) neutrino oscillation efforts.

In the *few GeV* neutrino energy range,
neutrino-induced pion production is *“large”*.

If pions is produced, but not detected due to interactions within the target nucleus, the inferred neutrino energy will be biased,
with large impact on oscillation measurements.

- Since the ‘70s, an extensive set of pion scattering experiments have been conducted at various meson factories.
- Although these data have provided detailed measurements of differential cross sections for a variety of final state kinematic variables, the uncertainties on the inclusive cross section(s) range:

  - from 10-30% for light nuclei
  - it is even higher for heavy nuclei

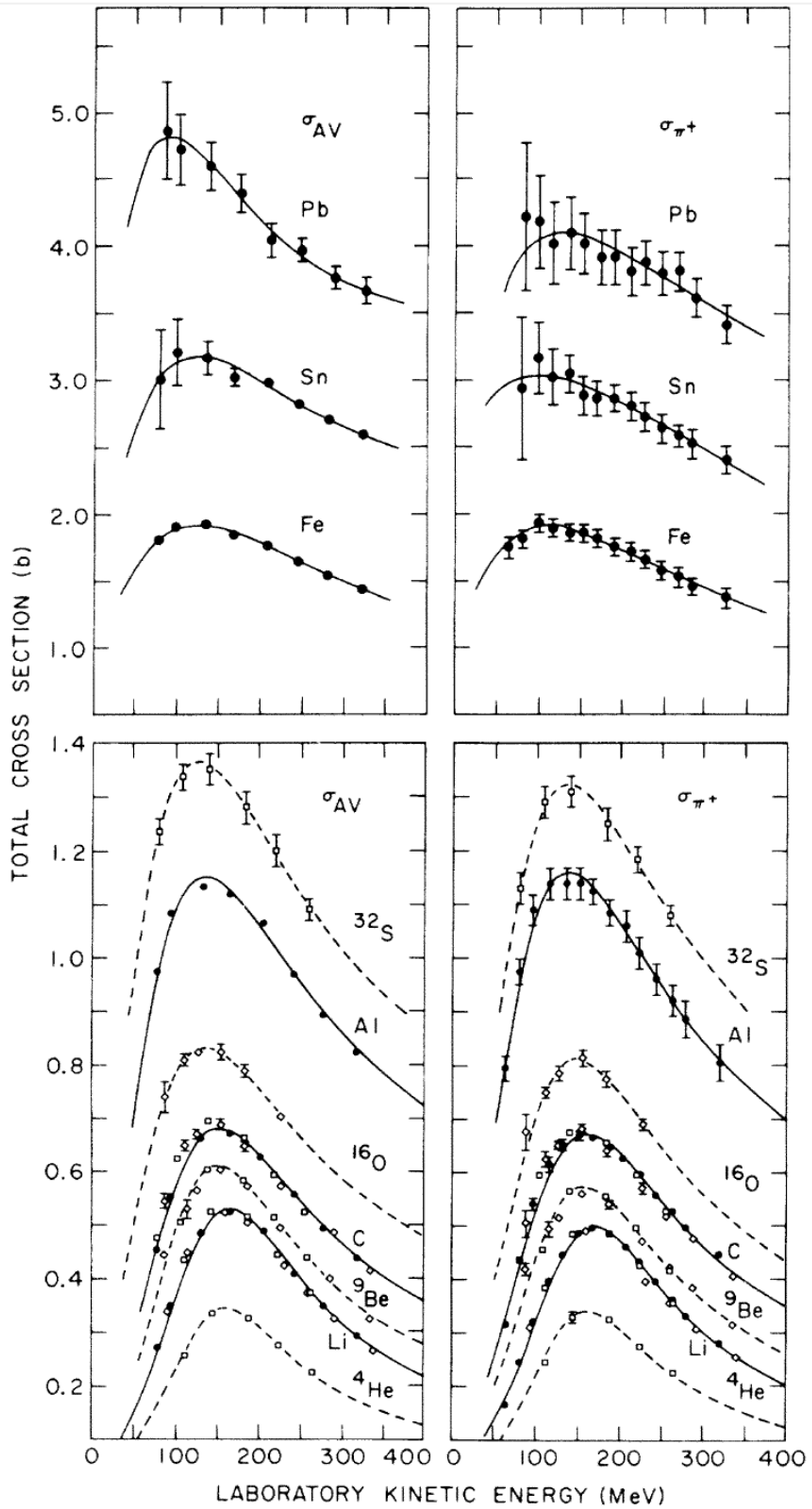
  and

  ~no-data were collected for Ar target.

- **First (π-Ar) cross section data & measurements from LArIAT (Run-I:2015 - Run-II: 2016, on going)**

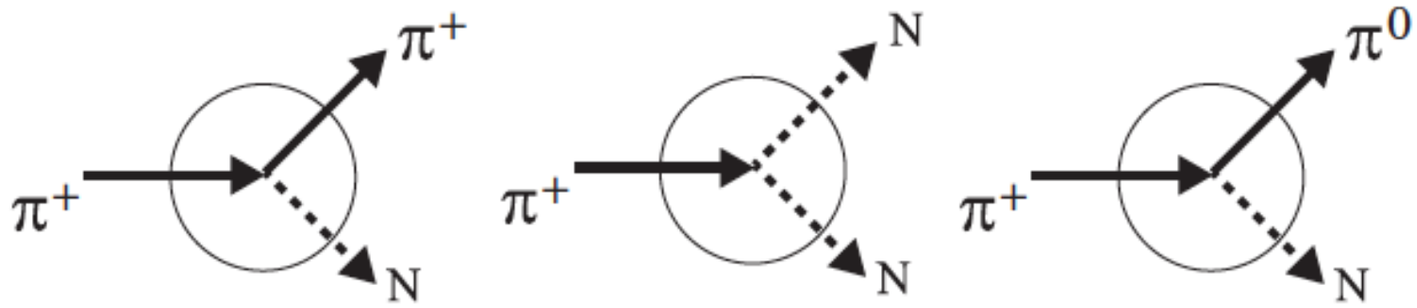
- A new era of precision Pion Xsect measurements on Ar target, performed with LArTPC technology, is now started.

- **ProtoDUNE with its the x-large size and the CERN beams at the Neutrino Platform providing pion energy up to several GeV, will overcome the intrinsic limits of the LArIAT detector (0.27t active) at FTBF (0.3 - 1.3 GeV/c):**
  - ✴Optimal complementarity of Physics achievements,
  - ✴opportunities of common development of dedicated off-line sw and evt. reconstruction/analysis tools,
  - ✴possibility of cross checks on reference set of overlapping data



Cross section increases rapidly as pion energy increases to about 160 MeV, then drops rapidly afterward: effect of Δ-resonance formation

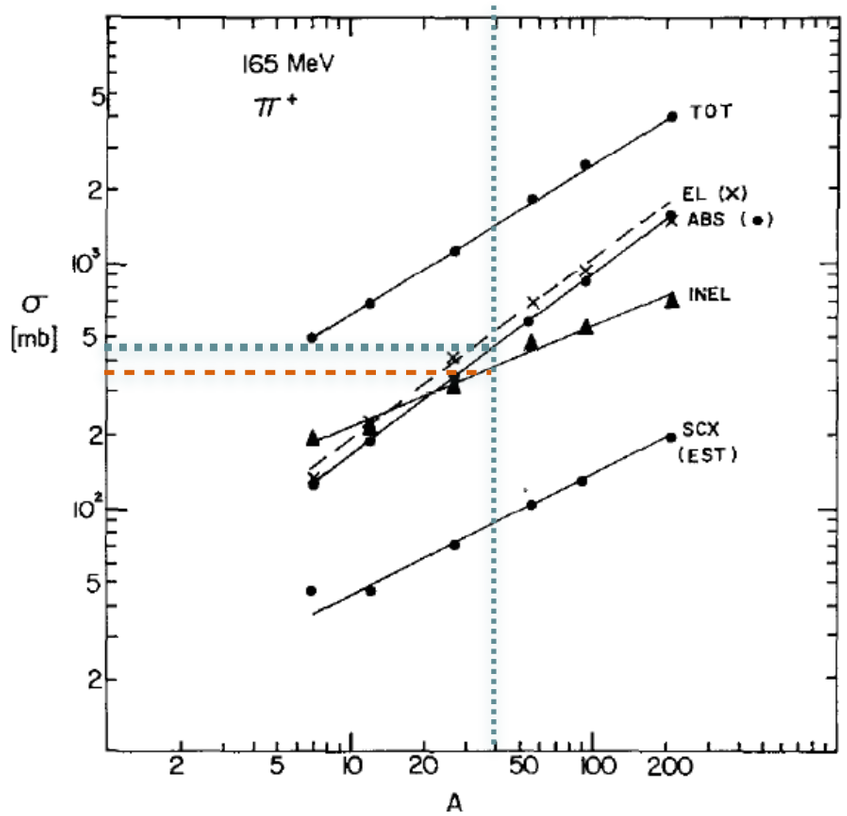
The total Pion-Nucleus interaction Xsect in [0.1 - 5.] GeV incident kin. energy may be decomposed into major channels contributions:



$$\sigma_{tot} = \sigma_{el} + \sigma_{reac}$$

$$\sigma_{reac} = \sigma_{inel} + \sigma_{abs} + \sigma_{chex} + \sigma_{\pi prod}$$

abs is the dominant process in Ar



Cross section also increases for increasing nuclear target mass

- In the lower energy range (100-500 MeV) pion interaction Cross Section - in all channels - enhanced via Δ-Resonance formation (Δ peak for pion kinetic energy of ~150 MeV).
- Above 500 MeV: π-production start to contribute to the Total Cross Section (dominant channel above 1.5 GeV)

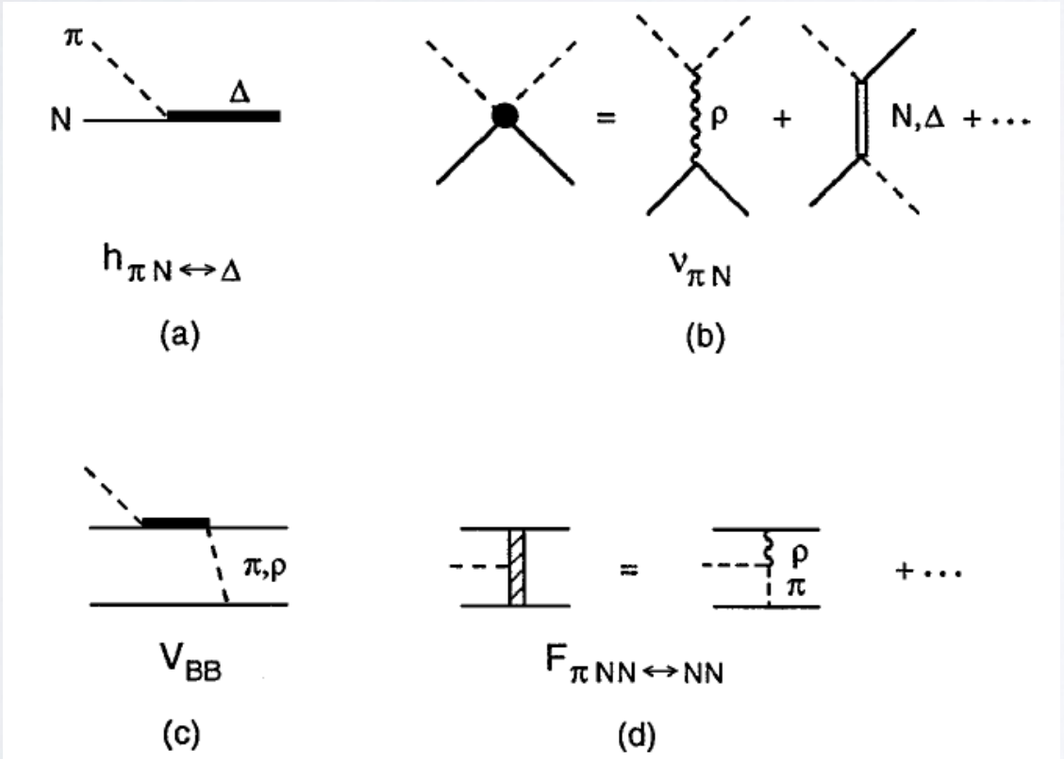
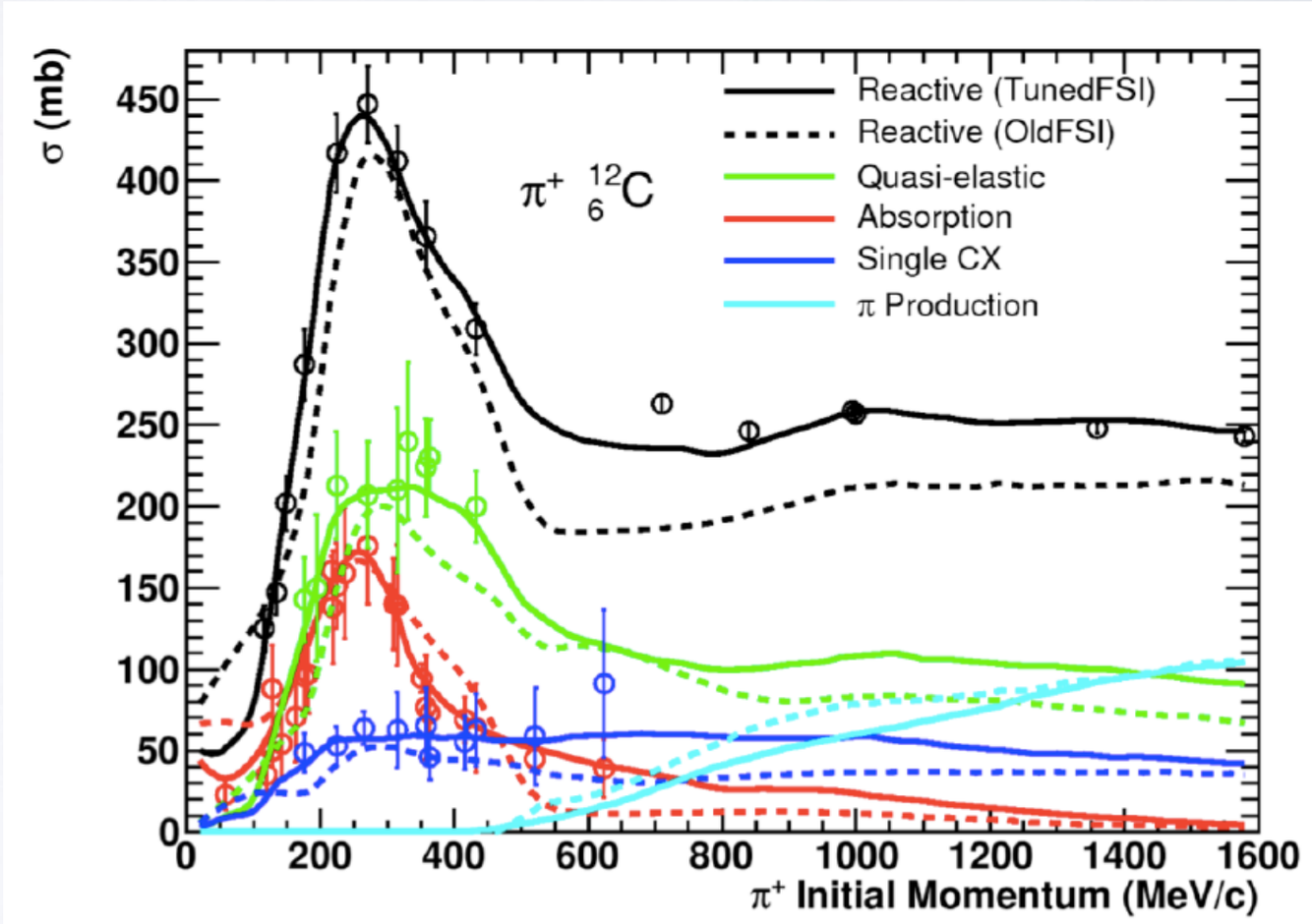
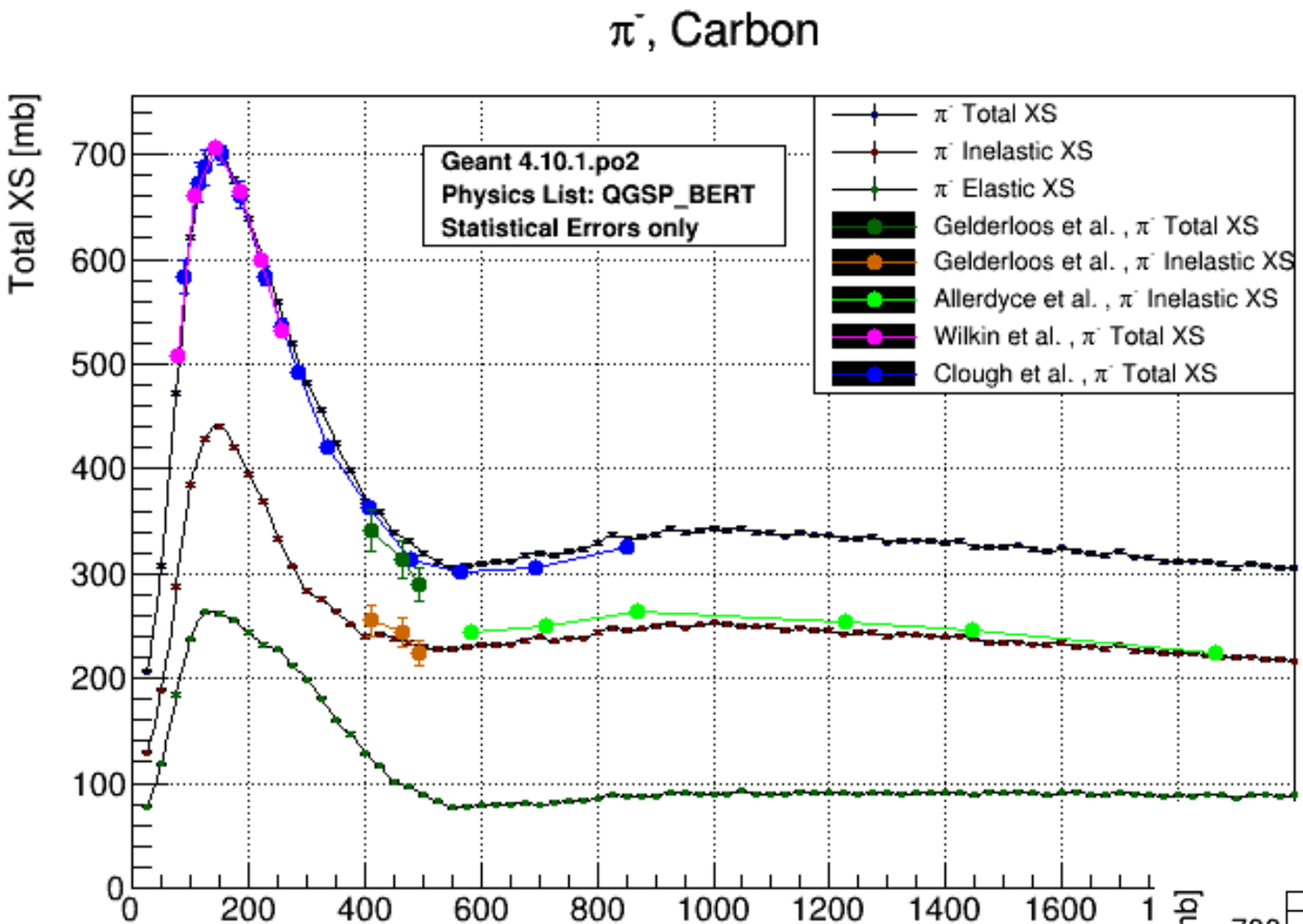
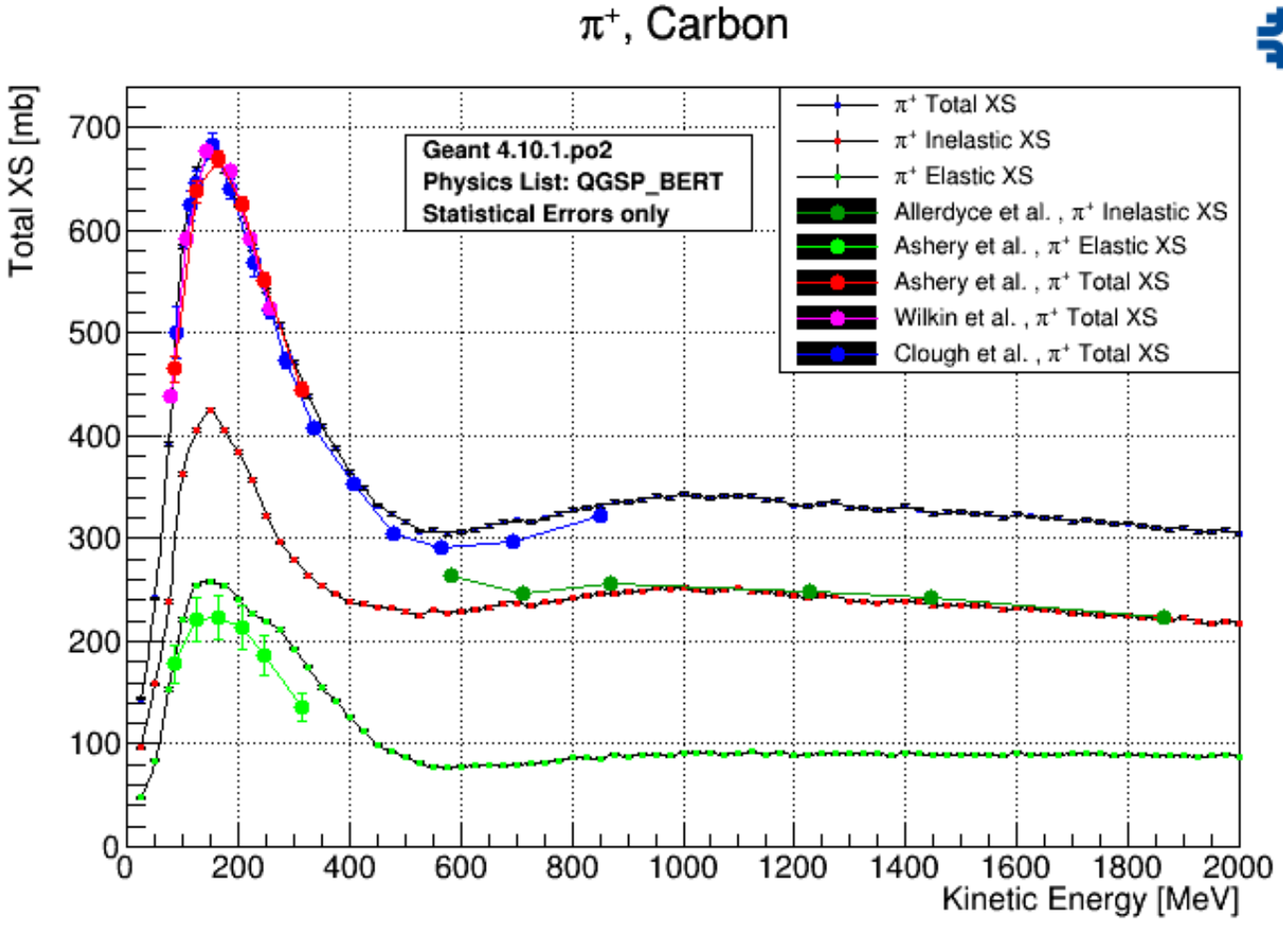


Figure 4 Graphical representations of some basic mechanisms of pion-nucleus interactions.



Geant4 Simulated Pion Cross Sections & Comparison with Experimental Data





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Geant4 Simulated Pion Cross Sections

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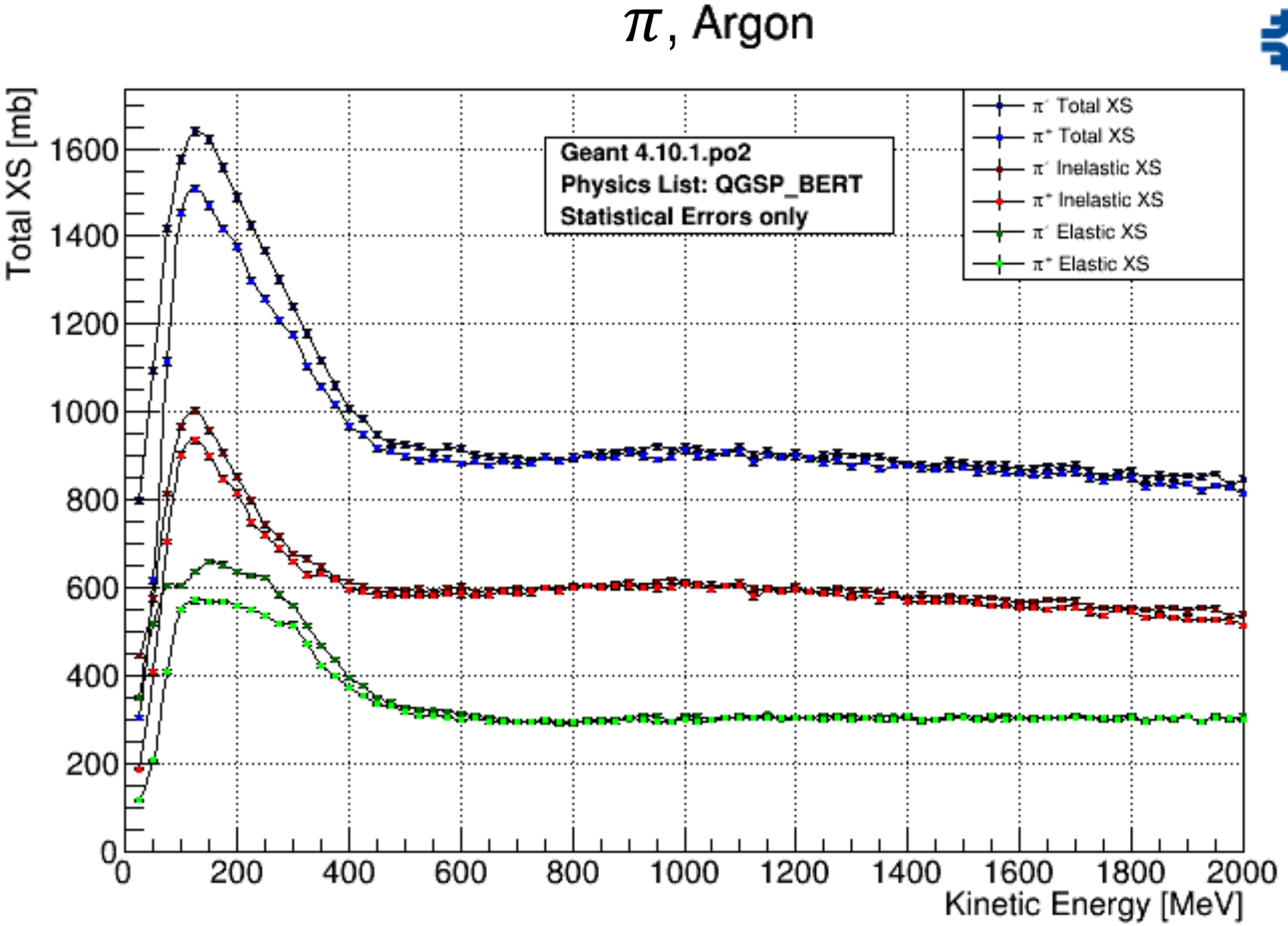

NB:
G4 “Inel” = React

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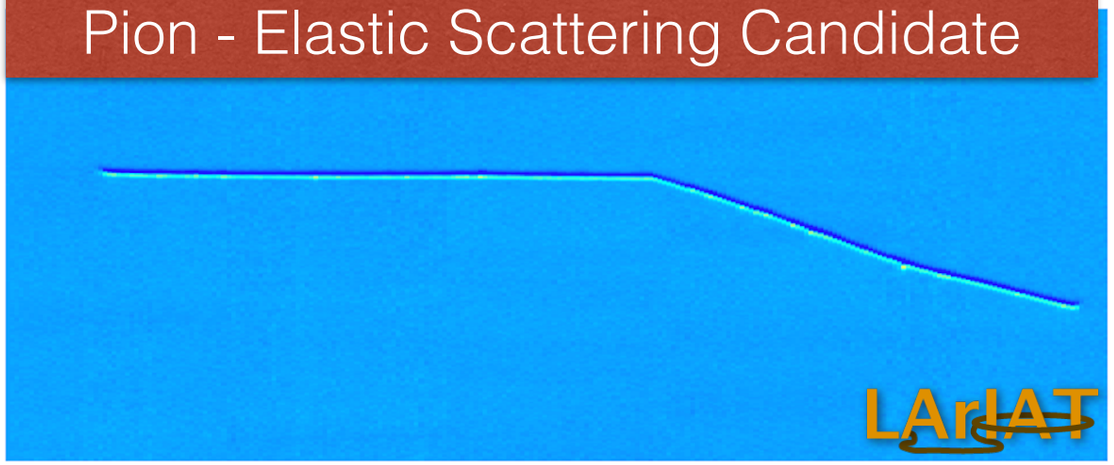
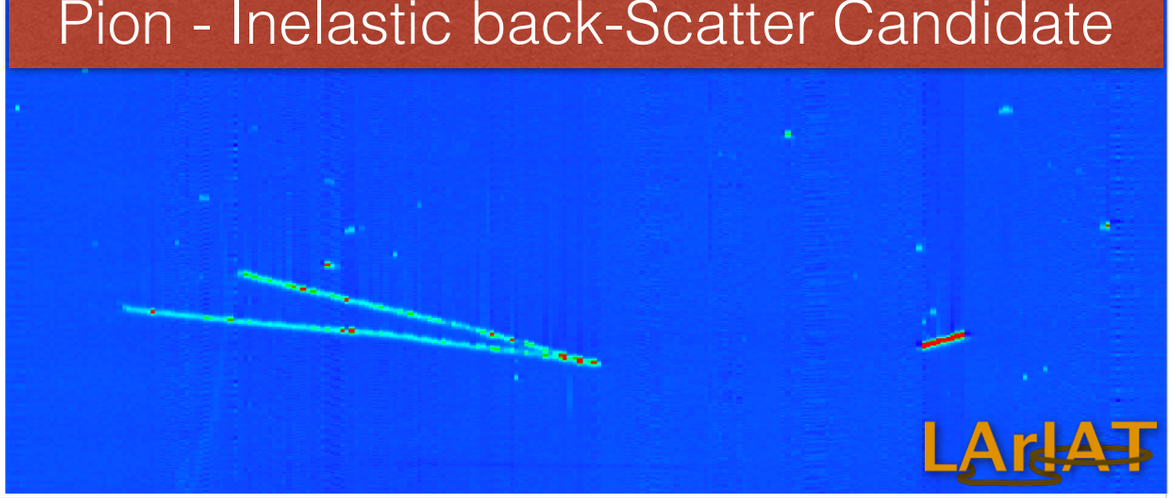
Pion REACTION		
XING	Crossing Pion	(no reaction)
ES	Elastic Scattering	$\pi^{\pm} + Ar \rightarrow \pi^{\pm} + Ar$
INEL	Inelastic Scattering	$\pi^- + n (\rightarrow \Delta^-) \rightarrow \pi^- + n$; *undetected n* $\pi^- + p (\rightarrow \Delta^0) \rightarrow \pi^- + p$ $\pi^+ + n (\rightarrow \Delta^+) \rightarrow \pi^+ + n$; *undetected n* $\pi^+ + p (\rightarrow \Delta^{++}) \rightarrow \pi^+ + p$
ABS	Pion Absorption	$\pi^+ + pn \rightarrow 2p$ $\pi^- + pn \rightarrow (2n)$; *undetected n* $\pi^+ + pnn \rightarrow 2p + (1n)$; *undetected n* $\pi^- + pnn \rightarrow (3n)$; *undetected n* $\pi^+ + ppn \rightarrow 3p$ $\pi^- + ppn \rightarrow 1p + (2n)$; *undetected n* $\pi^+ + ppnn \rightarrow 3p + (1n)$; *undetected n* $\pi^- + ppnn \rightarrow 1p + (3n)$; *undetected n* ……
CHEX	Charge Exchange	$\pi^- + p (\rightarrow \Delta^0) \rightarrow \pi^0 + n$; *undetected n* $\pi^+ + n (\rightarrow \Delta^+) \rightarrow \pi^0 + p$
π-PROD	Pion Production	$\pi^{\pm} + p \rightarrow \pi 0 + \pi^{\pm} + p$ $\pi^{\pm} + p \rightarrow \pi^+ + \pi^- + \pi^{\pm} + p$ $\pi^{\pm} + n \rightarrow \pi 0 + \pi^{\pm} + n$ $\pi^{\pm} + n \rightarrow \pi^+ + \pi^- + \pi^{\pm} + n$
π-DAR	Pion Decay at rest	$\pi^+ \rightarrow \mu^+ \rightarrow \boldsymbol{e}^+$ (100%) $\pi^- \rightarrow \mu^- \rightarrow \boldsymbol{e}^-$ (~25%)
π-CAPT	Pion Capture at rest	$\pi^- + pn \rightarrow (2n)$; *undetected n (~75%)*

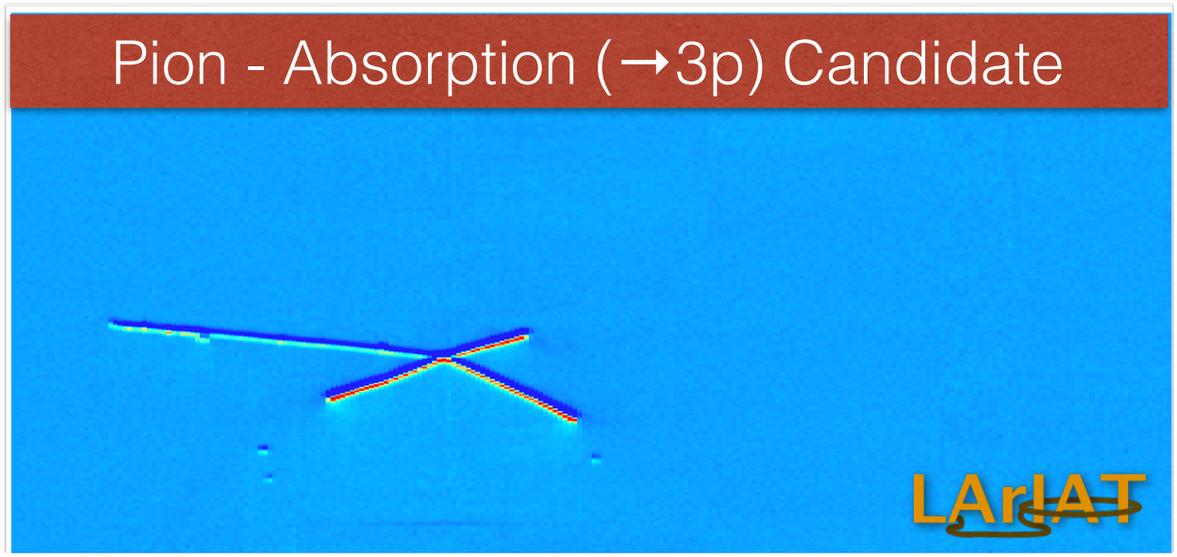
Pion - Elastic Scattering Candidate



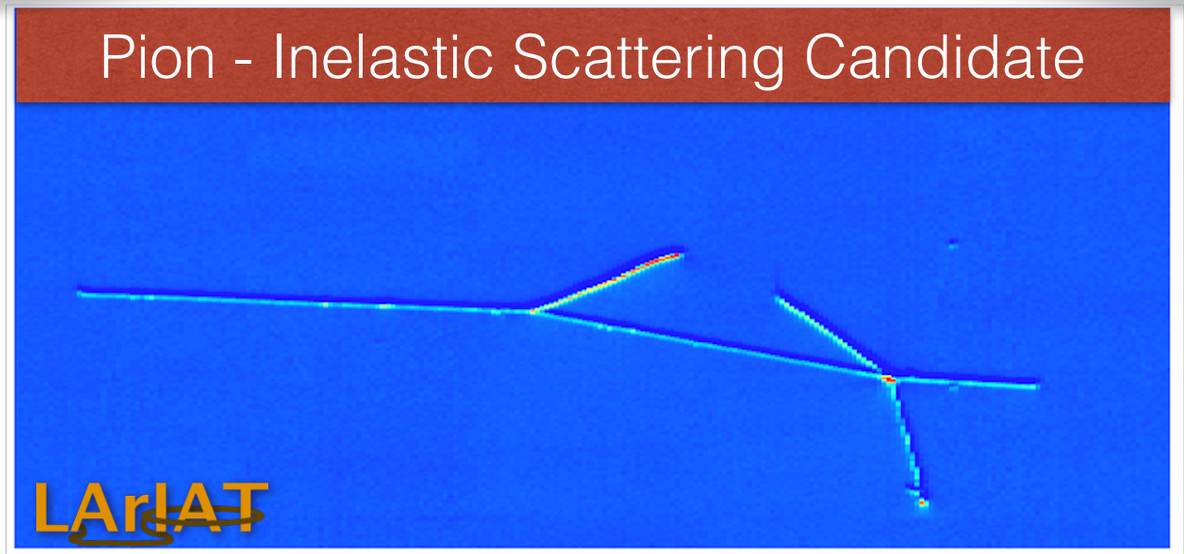
Pion - Inelastic back-Scatter Candidate



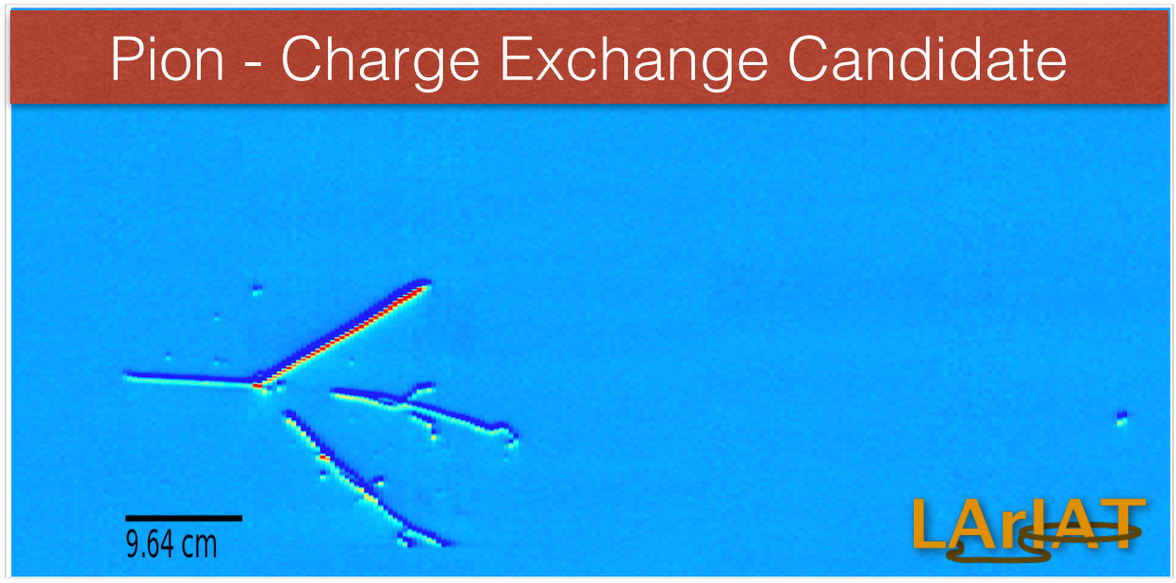
Pion - Absorption (→3p) Candidate

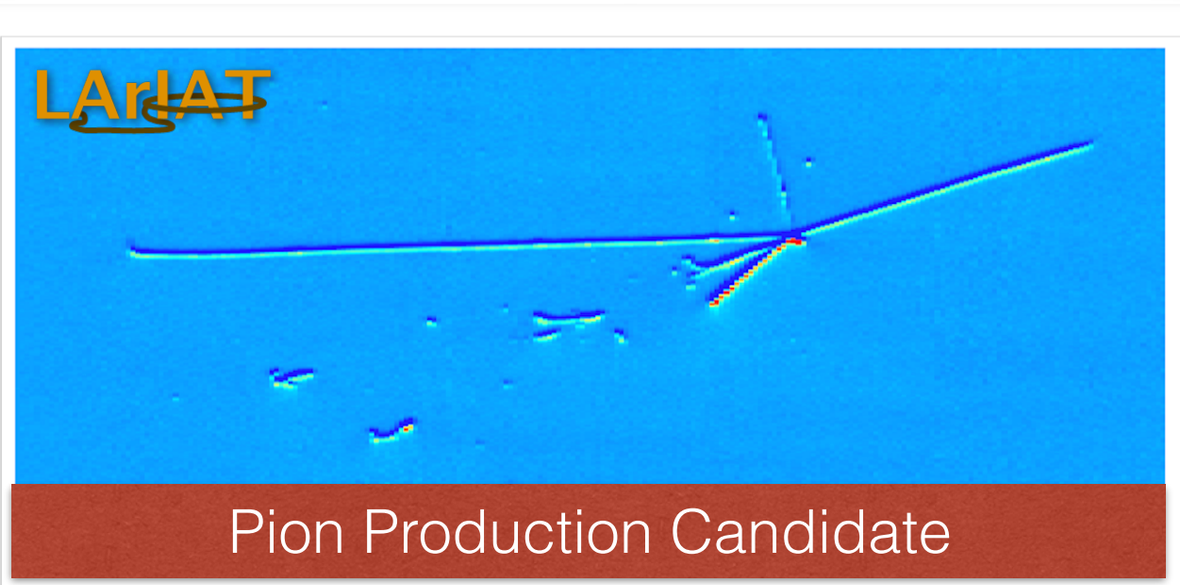


Pion - Inelastic Scattering Candidate

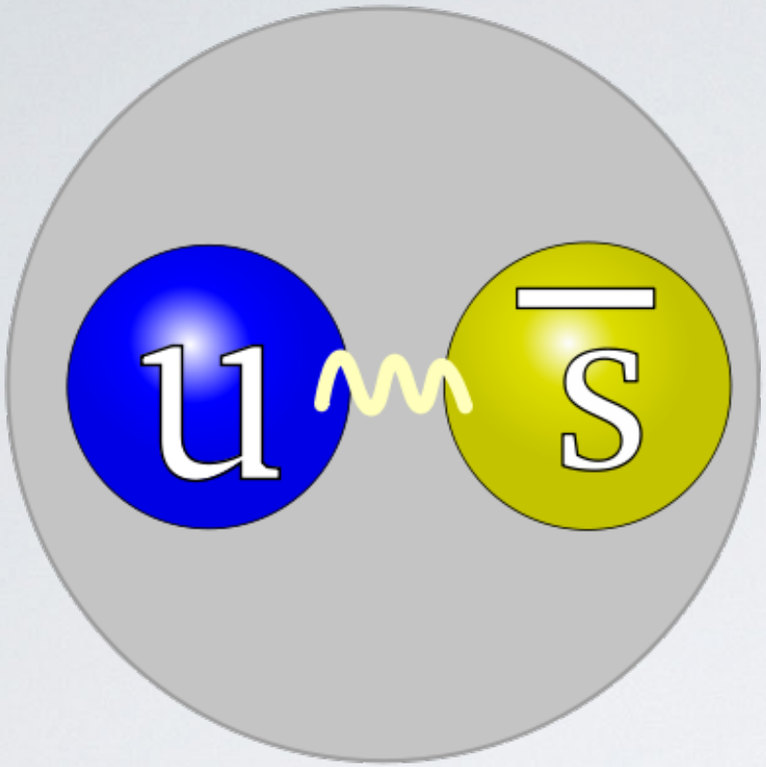


Pion - Charge Exchange Candidate





Pion Production Candidate



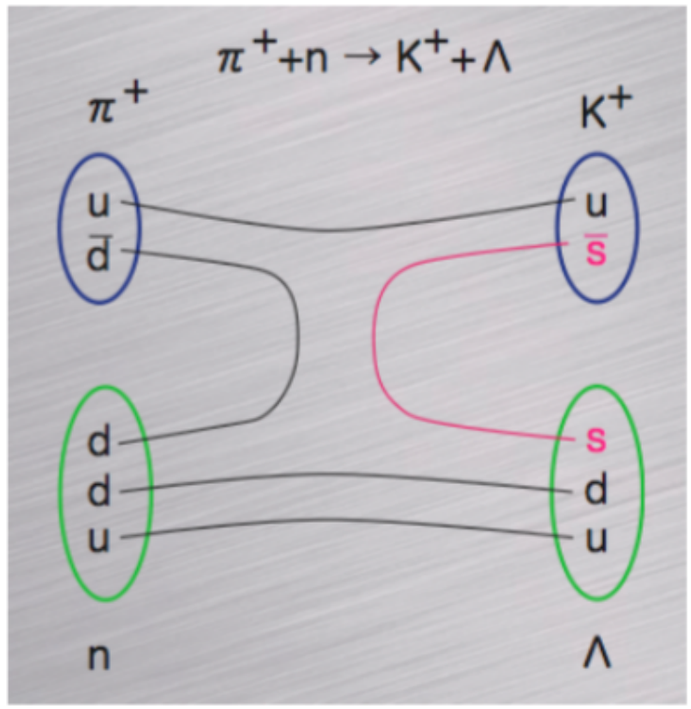
Kaon

High theoretical interest in probing constituent quark model of nuclear structure with KAON-NUCLEON INTERACTIONS

GUT models in conjunction with SUSY predict proton decay into a charged kaon and an anti-neutrino.
Kaon identification through their decay or interaction modes in argon medium is of central interest for the proton decay search with the DUNE LArTPC experiment

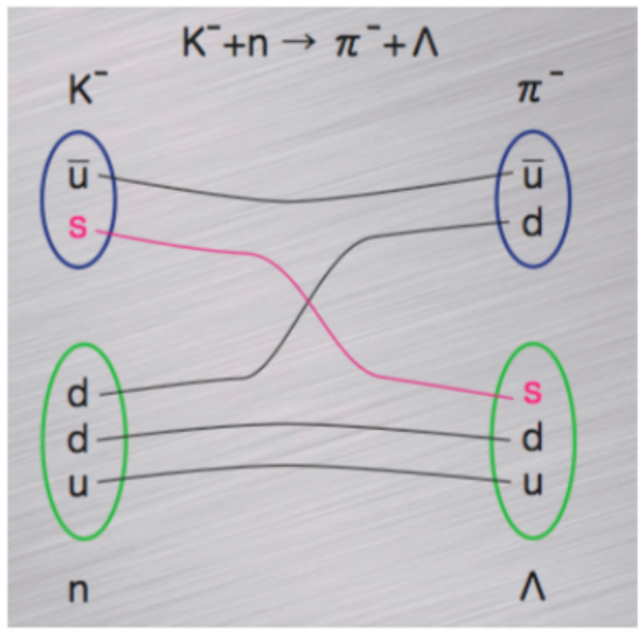
Hyperon	Quarks	I(J^P)	Mass (MeV)
Λ	uds	0(1/2$^+$)	1115
Σ^+	uus	1(1/2$^+$)	1189
Σ^0	uds	1(1/2$^+$)	1193
Σ^-	dds	1(1/2$^+$)	1197
Ξ^0	uss	1/2(1/2$^+$)	1315
Ξ^-	dss	1/2(1/2$^+$)	1321
Ω^-	sss	0(3/2$^+$)	1672

T	T_3					B	S
	$+1$	$+\frac{1}{2}$	0	$-\frac{1}{2}$	-1		
$\frac{1}{2}$		Ξ^0		Ξ^-		1	-2
1	Σ^+		Σ^0		Σ^-	1	-1
0			Λ^0			1	-1
$\frac{1}{2}$		p		n		1	0
$\frac{1}{2}$		K^+		K^0		0	$+1$
$\frac{1}{2}$		$\bar{K}^0$		K^-		0	-1
1	π^+		π^0		π^-	0	0

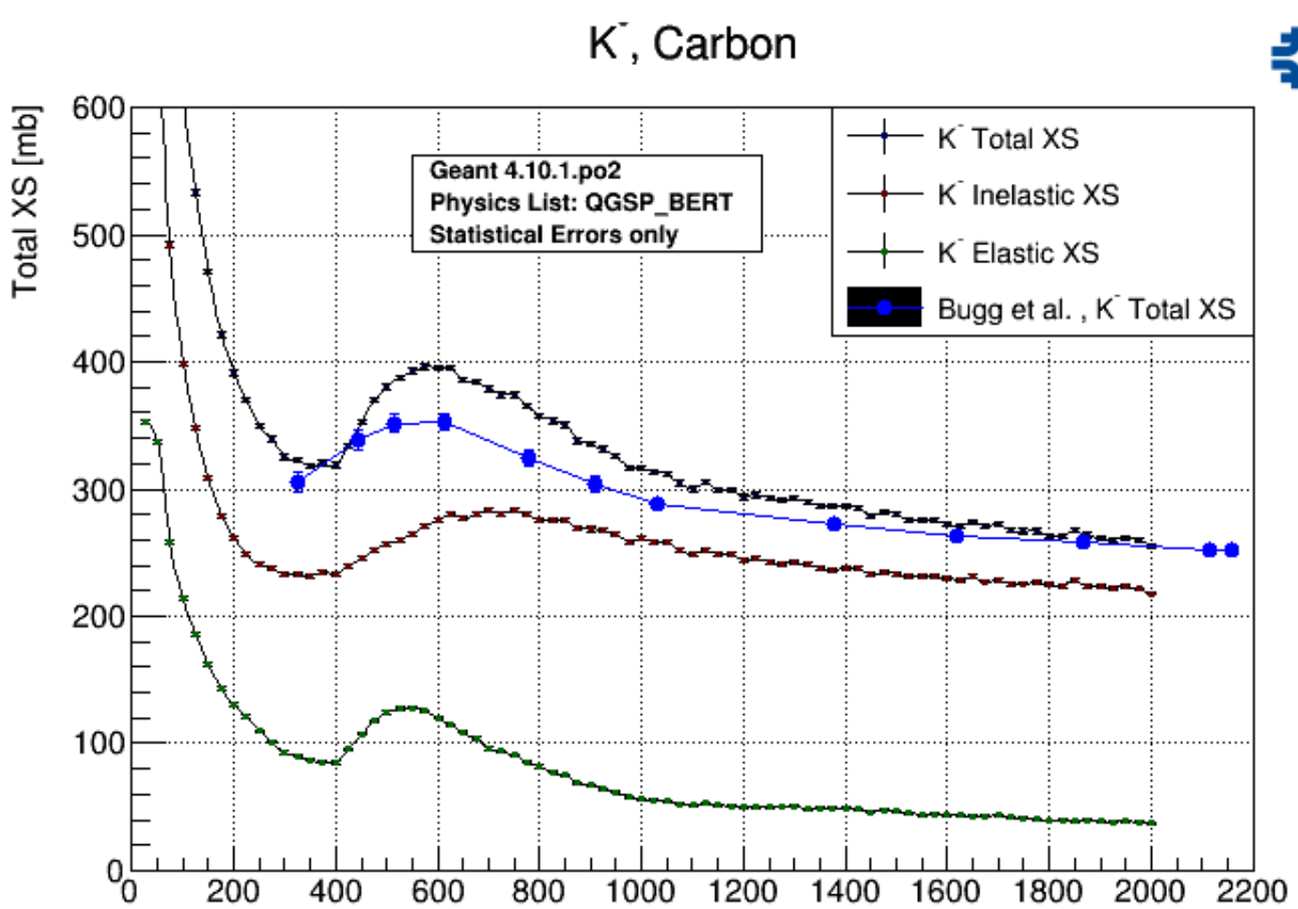


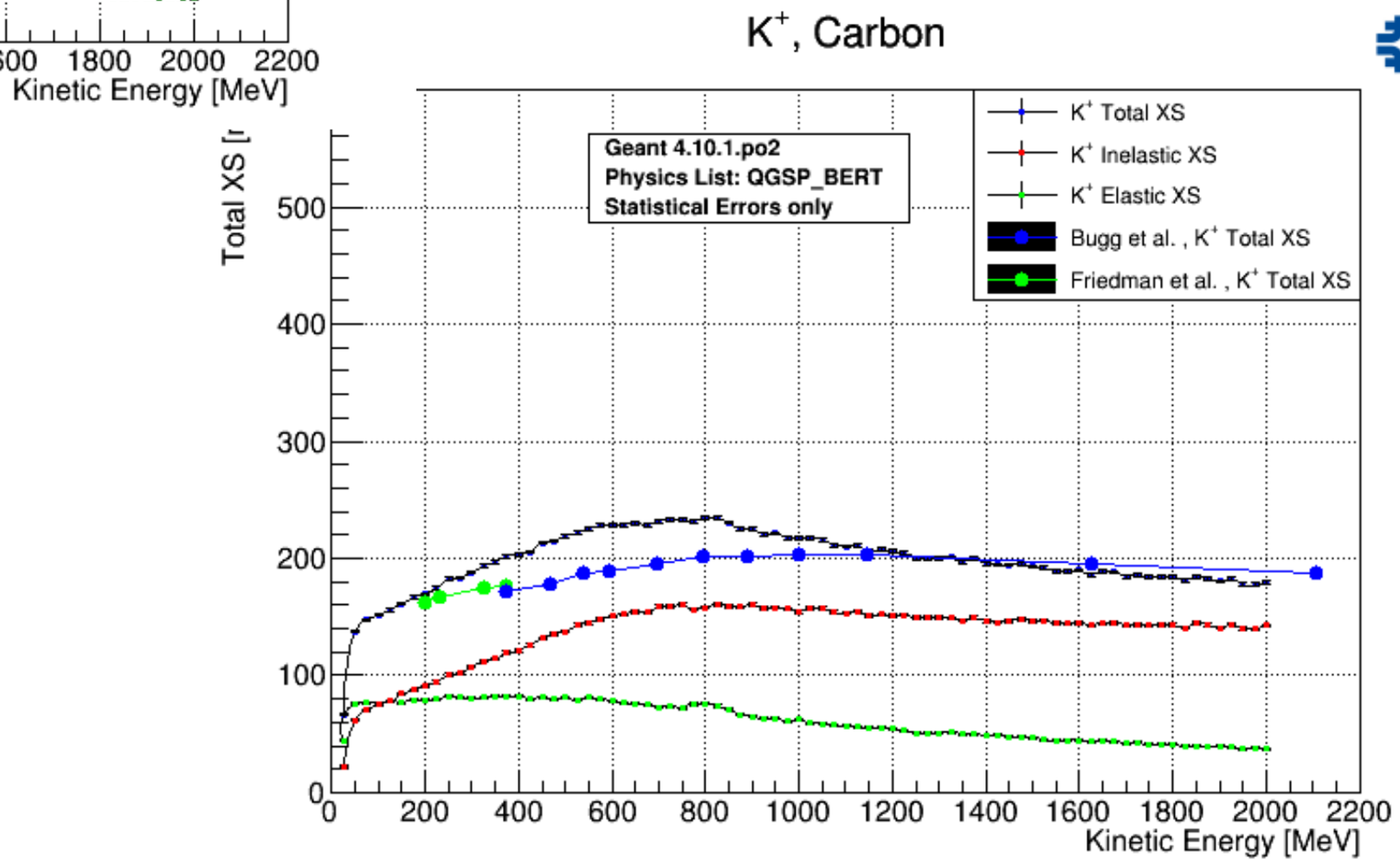
K+ production easier than K-
[K+ (s=+1) associate prod with the lighter Strange Baryons (s=-1)]

K- (s=-1) interaction Xsect larger than K+
[Strangeness Conservation favors production of the lighter Baryon (s=-1)]



Geant4 Simulated Pion Cross Sections & Comparison with Experimental Data





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K^+ REACTION

ES	Elastic Scattering	$K^+ + p \rightarrow K^+ + p$ $K^+ + n \rightarrow K^+ + n$
CHEX	Charge Exchange	$K^+ + n \rightarrow K^0 + p$
INEL	Inelastic Scattering	$K^+ + n (\rightarrow K^+ + \Delta^0) \rightarrow K^+ + \pi^- + p$ $K^+ + p (\rightarrow K^+ + \Delta^+) \rightarrow K^+ + \pi^0 + p$ $K^+ + p (\rightarrow K^+ + \Delta^+) \rightarrow K^+ + \pi^+ + n$ $K^+ + p (\rightarrow K^{+*} + p) \rightarrow K^+ + \pi^0 + p$ .....
K-DAR	Kaon Decay at rest	

Results	Mode	Branching ratio
$\mu^+ \nu_\mu$	leptonic	63.55 ±0.11%
$\pi^+ \pi^0$	hadronic	20.66 ±0.08%
$\pi^+ \pi^+ \pi^-$	hadronic	5.59 ±0.04%
$\pi^+ \pi^0 \pi^0$	hadronic	1.761 ±0.022%
$\pi^0 e^+ \nu_e$	semileptonic	5.07 ±0.04%
$\pi^0 \mu^+ \nu_\mu$	semileptonic	3.353 ±0.034%

K^- REACTION

ES	Elastic Scattering	$K^- + p \rightarrow K^- + p$ $K^- + n \rightarrow K^- + n$
CHEX	Charge Exchange	$K^- + p \rightarrow K^0 + n$
INEL	Inelastic Scattering	$K^- + p \rightarrow \pi^- + \Sigma^+$ $K^- + p \rightarrow \pi^+ + \Sigma^-$ $K^- + p \rightarrow \pi^0 + \Sigma^0$ $K^- + p \rightarrow \pi^- + \Lambda^0$ $K^- + n\ (\rightarrow K^- + \Delta^0) \rightarrow K^- + \pi^- + p$ $K^- + p\ (\rightarrow K^- + \Delta^+) \rightarrow K^- + \pi^0 + p$ $K^- + p\ (\rightarrow K^{-*} + p) \rightarrow K^- + \pi^0 + p$ …….
K-DAR	Kaon Decay at rest	

Results	Mode	Branching ratio
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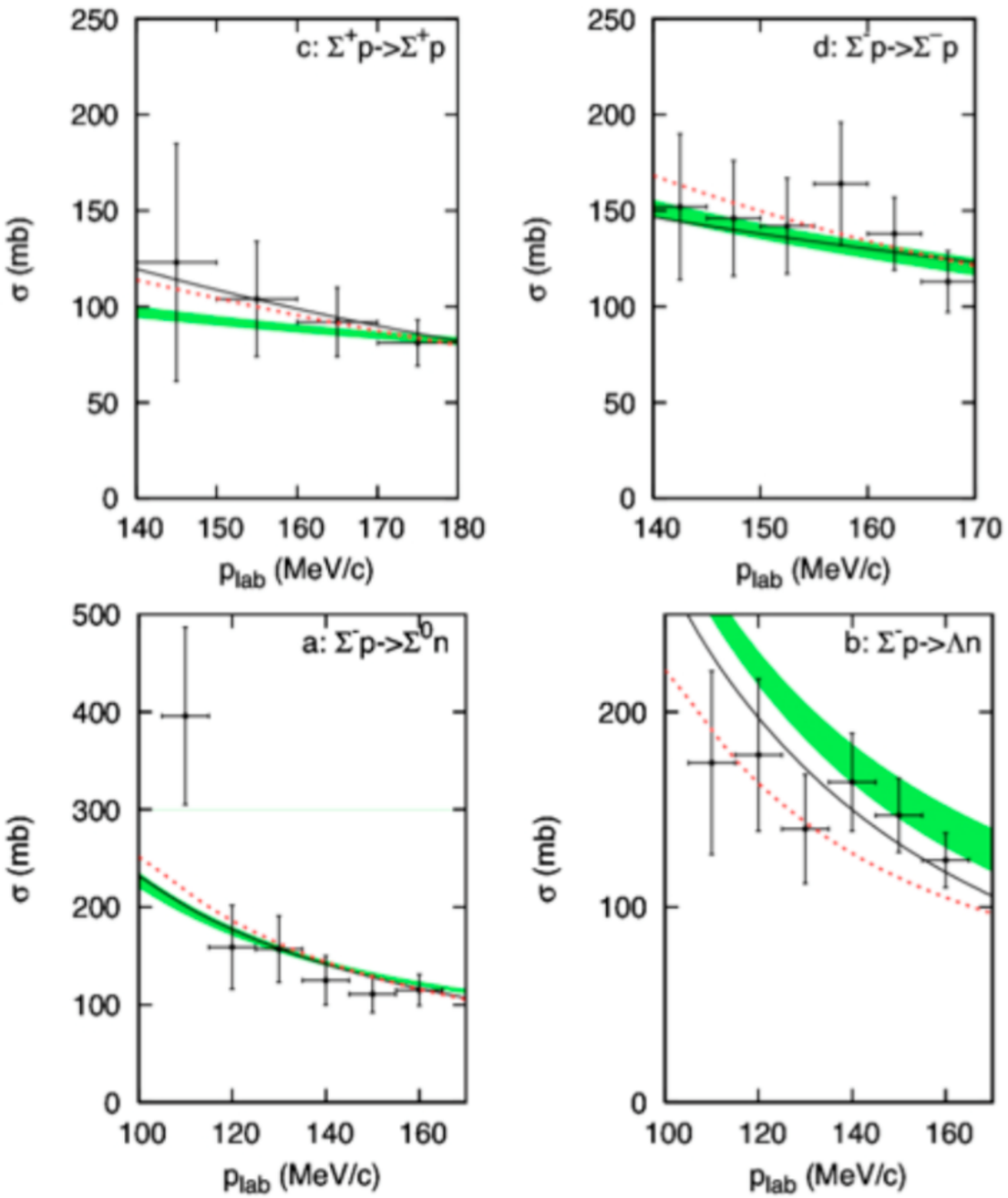
Decay modes for the K^- are charge conjugates of the ones above.

Total cross YN sections



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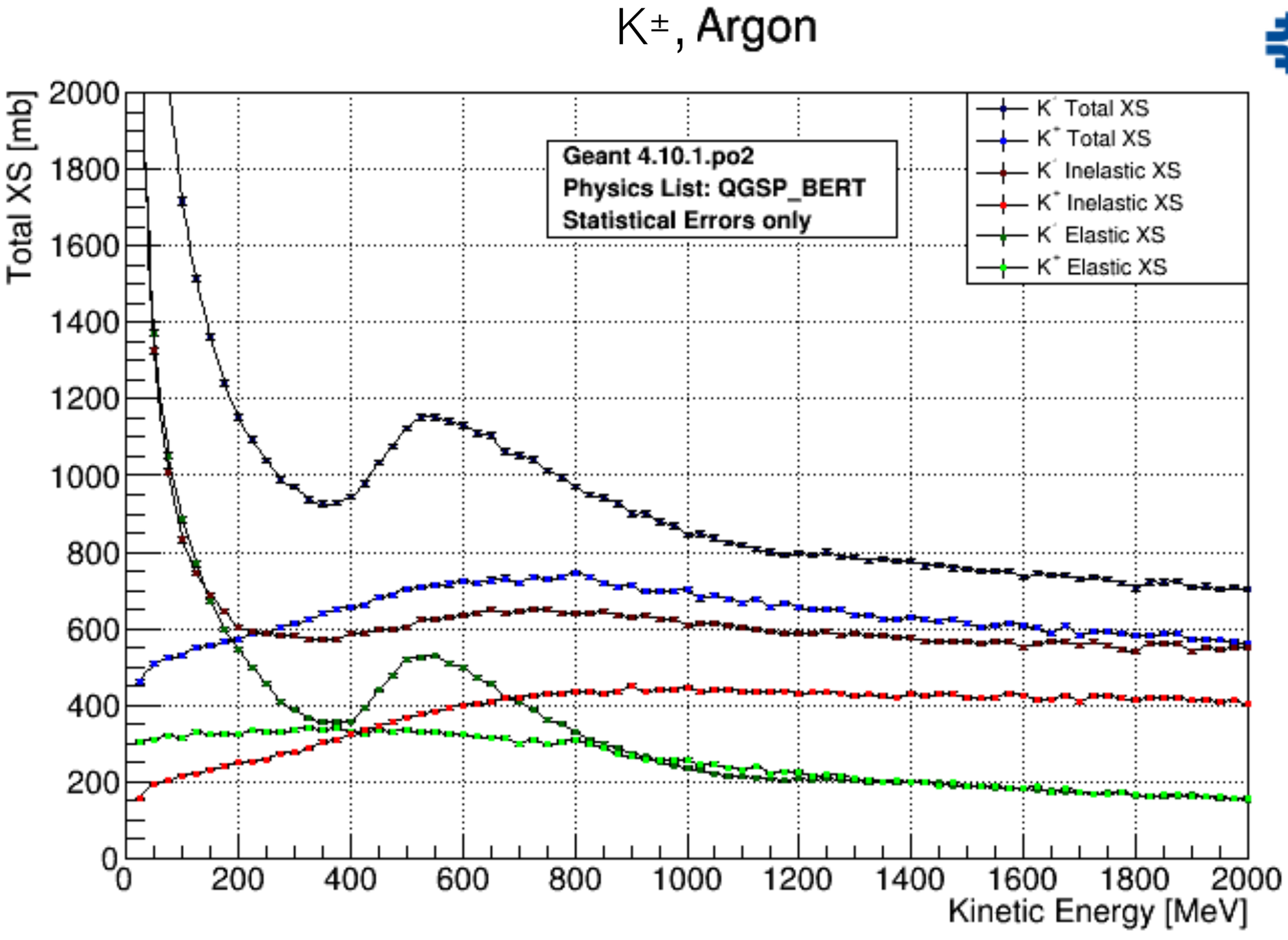

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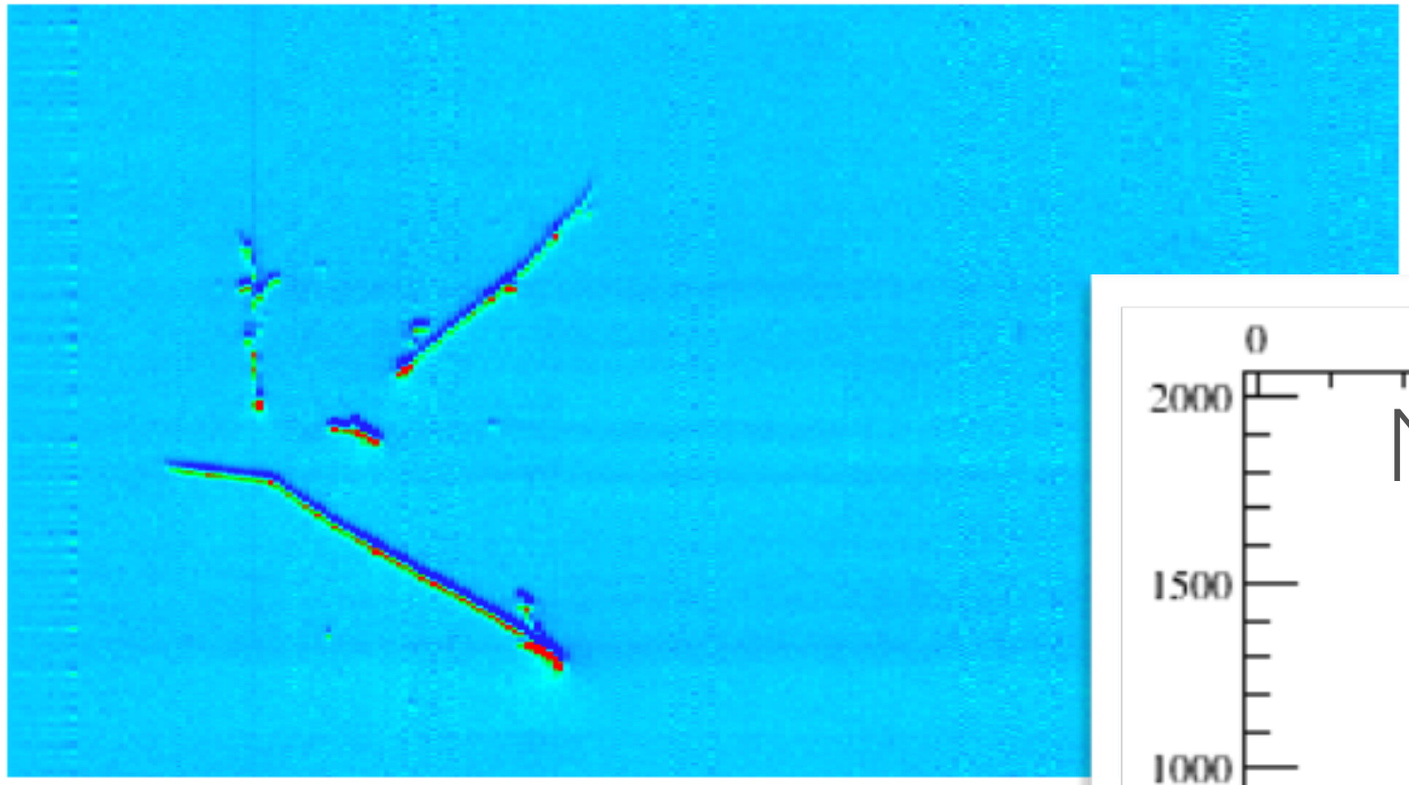
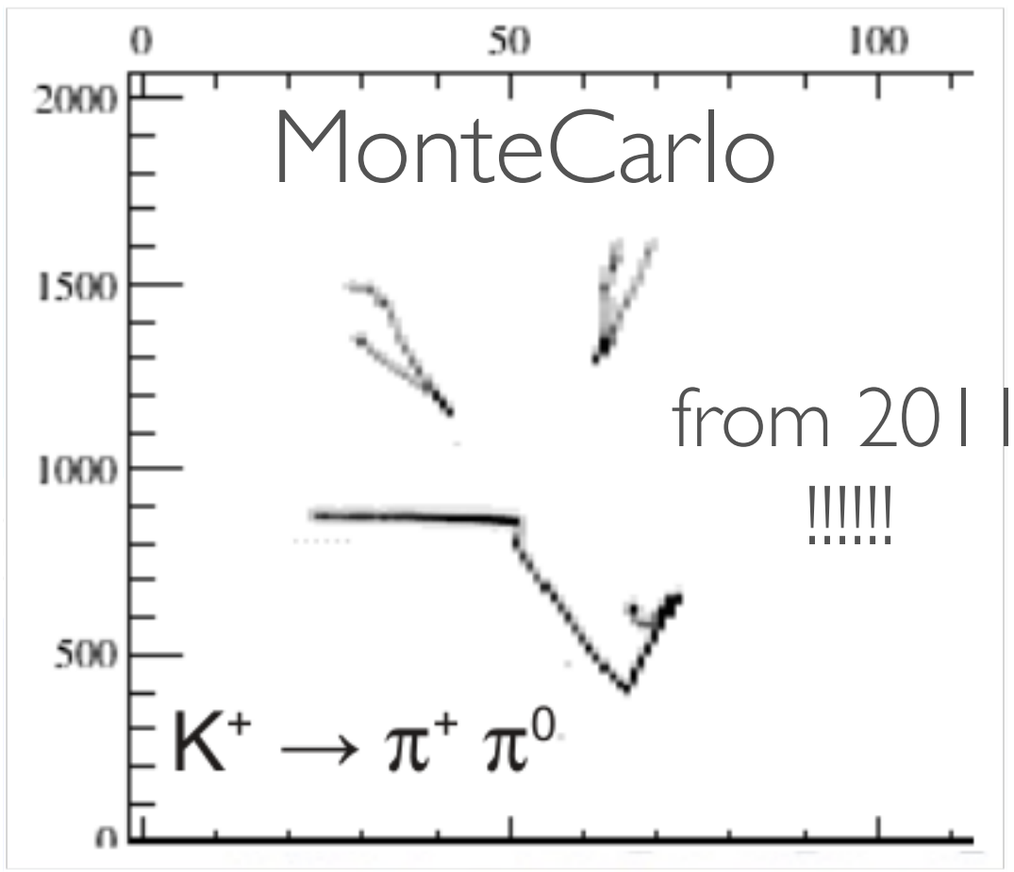


LArIAT



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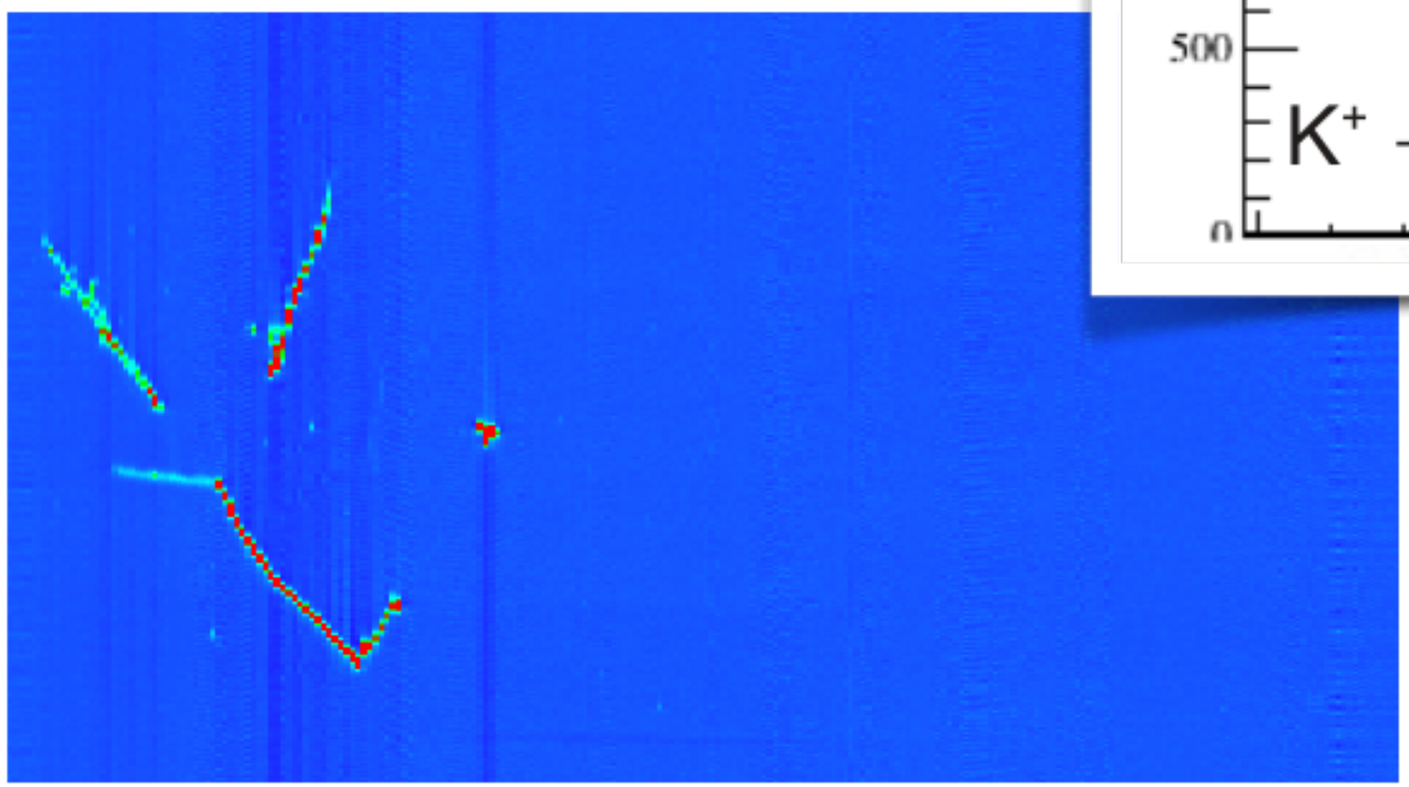

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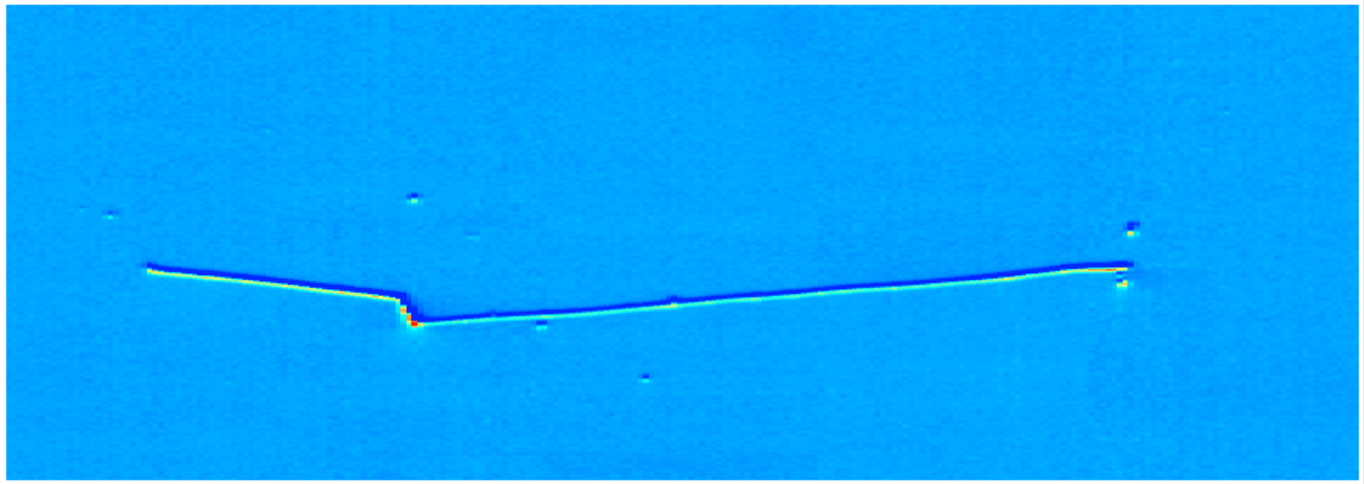

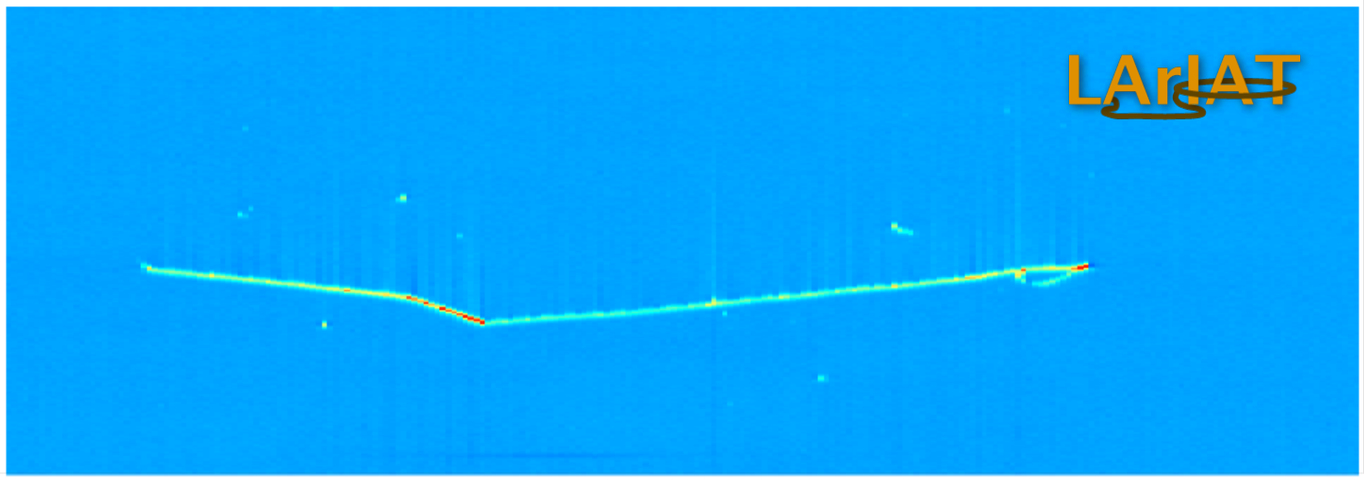

Kaon - Interaction Candidate

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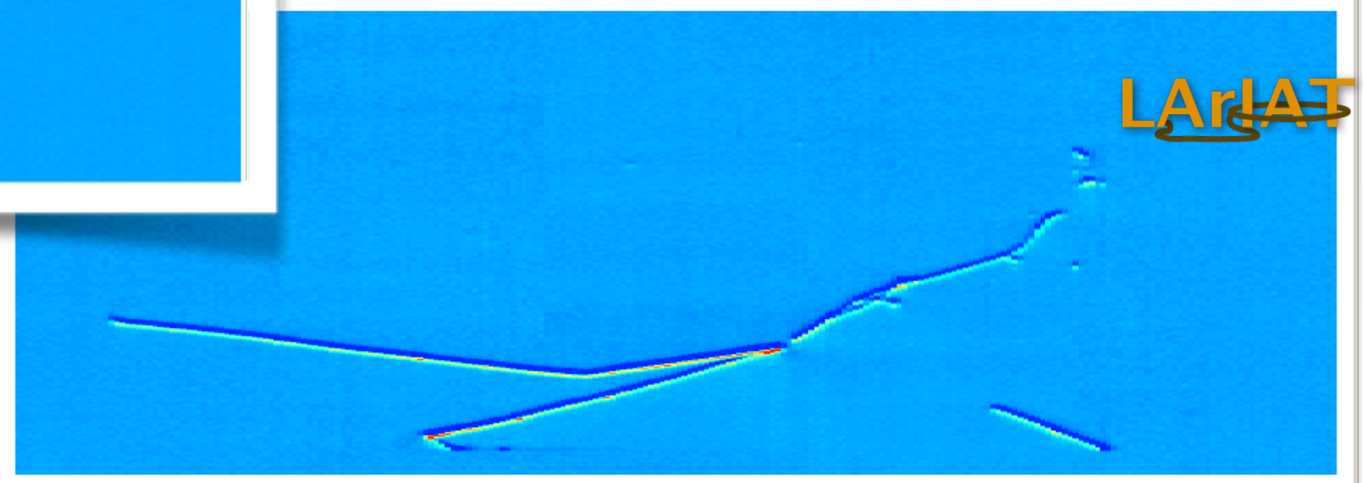
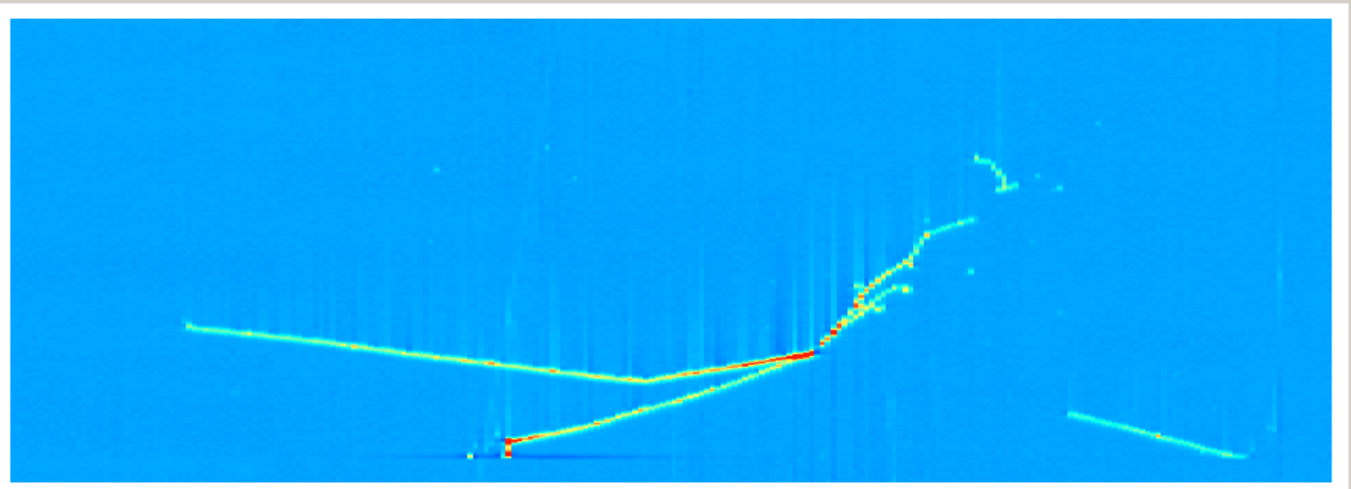
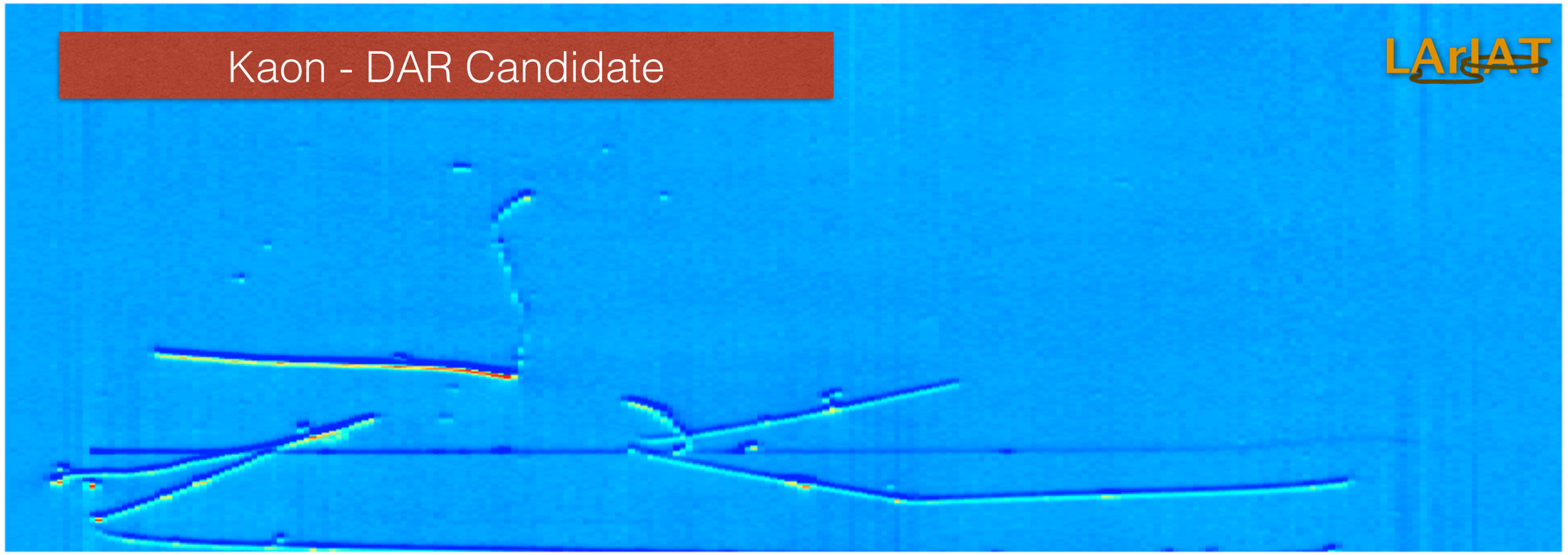
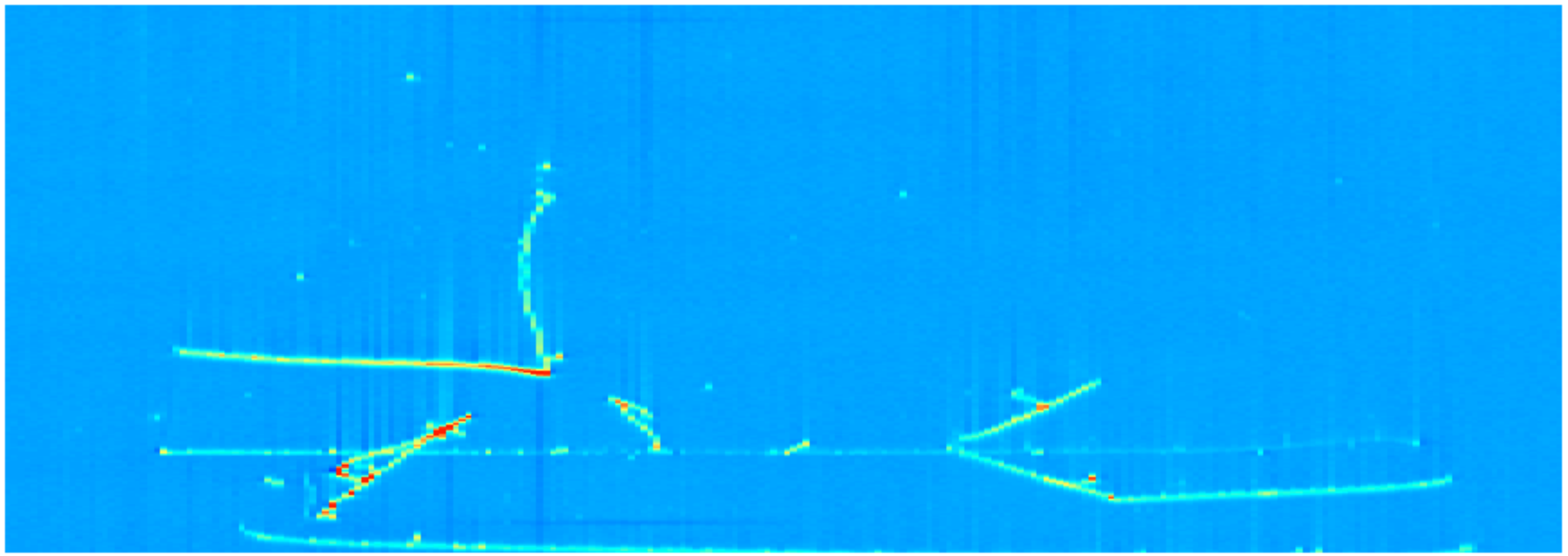
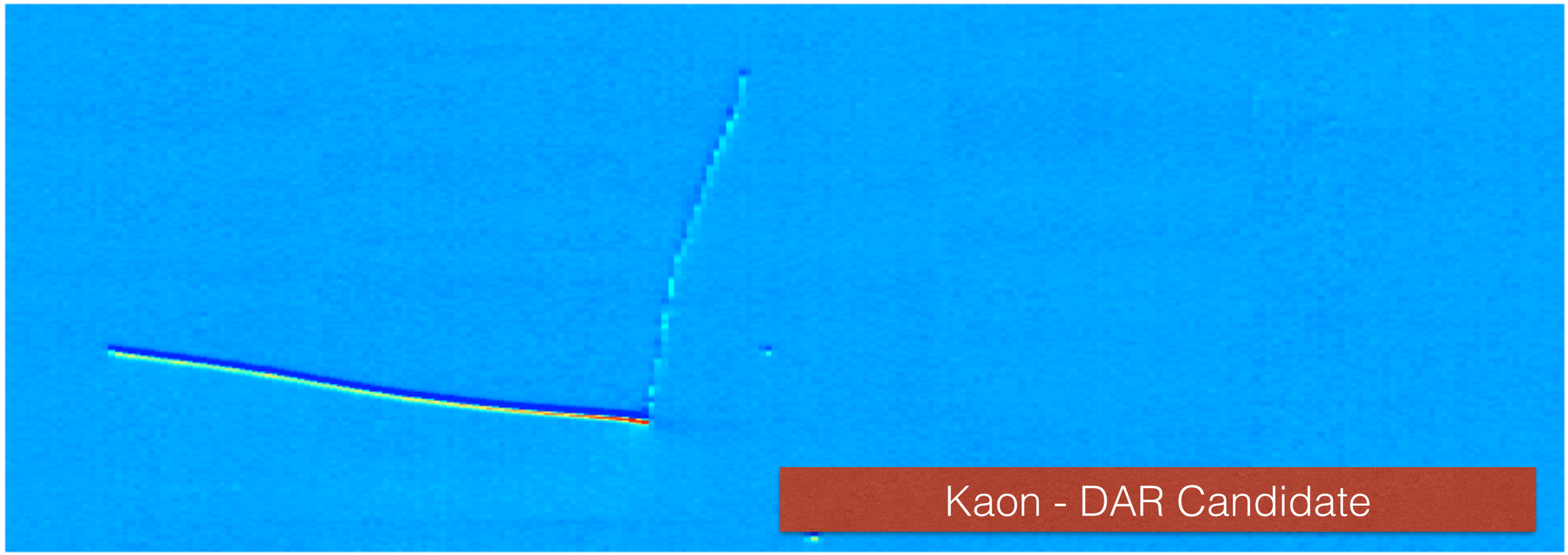


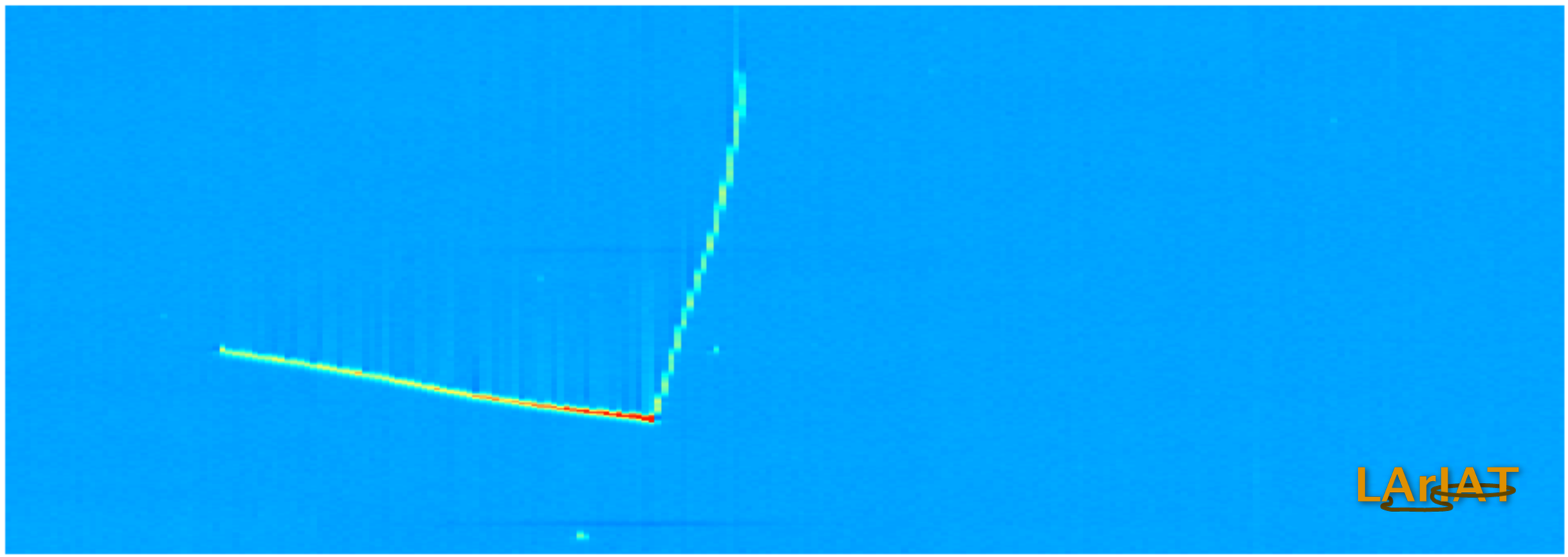


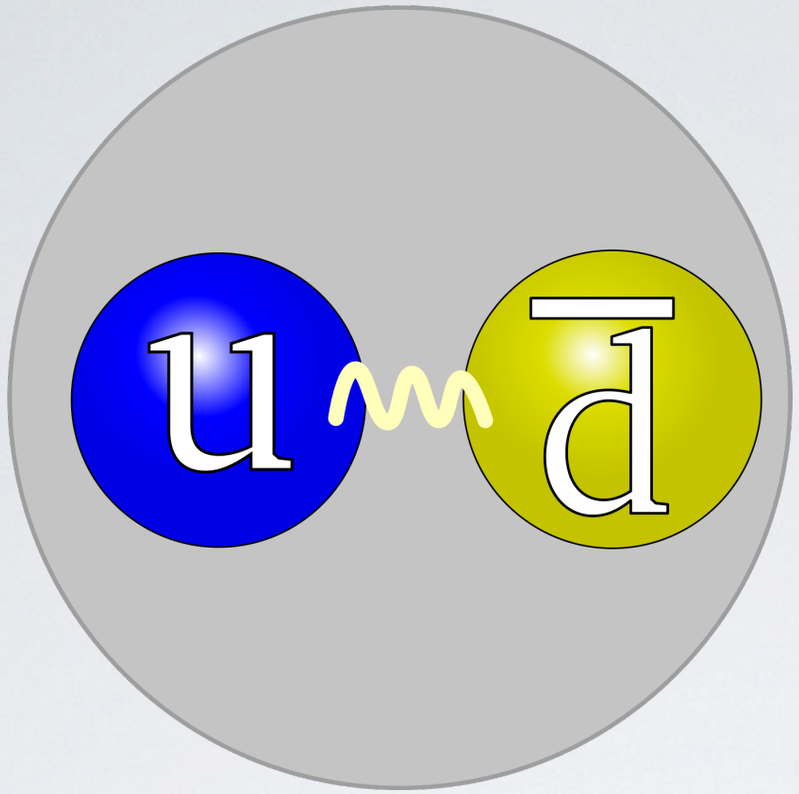
Kaon - DAR Candidate






Kaon - DAR Candidate


LArIAT



Proton

In the *few GeV* neutrino energy range,
neutrino-induced proton ejection is *“large”*.

If proton is produced, but not detected (Cherenkov Detectors), the inferred neutrino energy will be biased,
with large impact on oscillation measurements.

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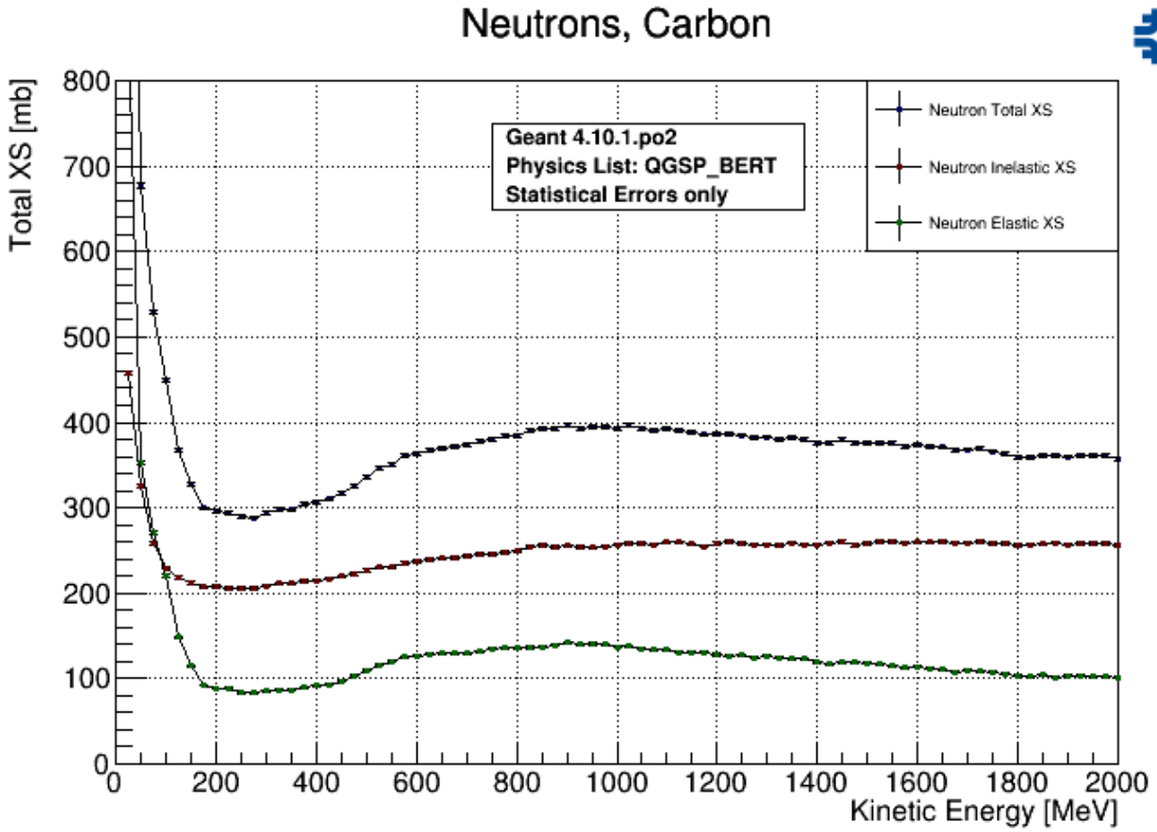

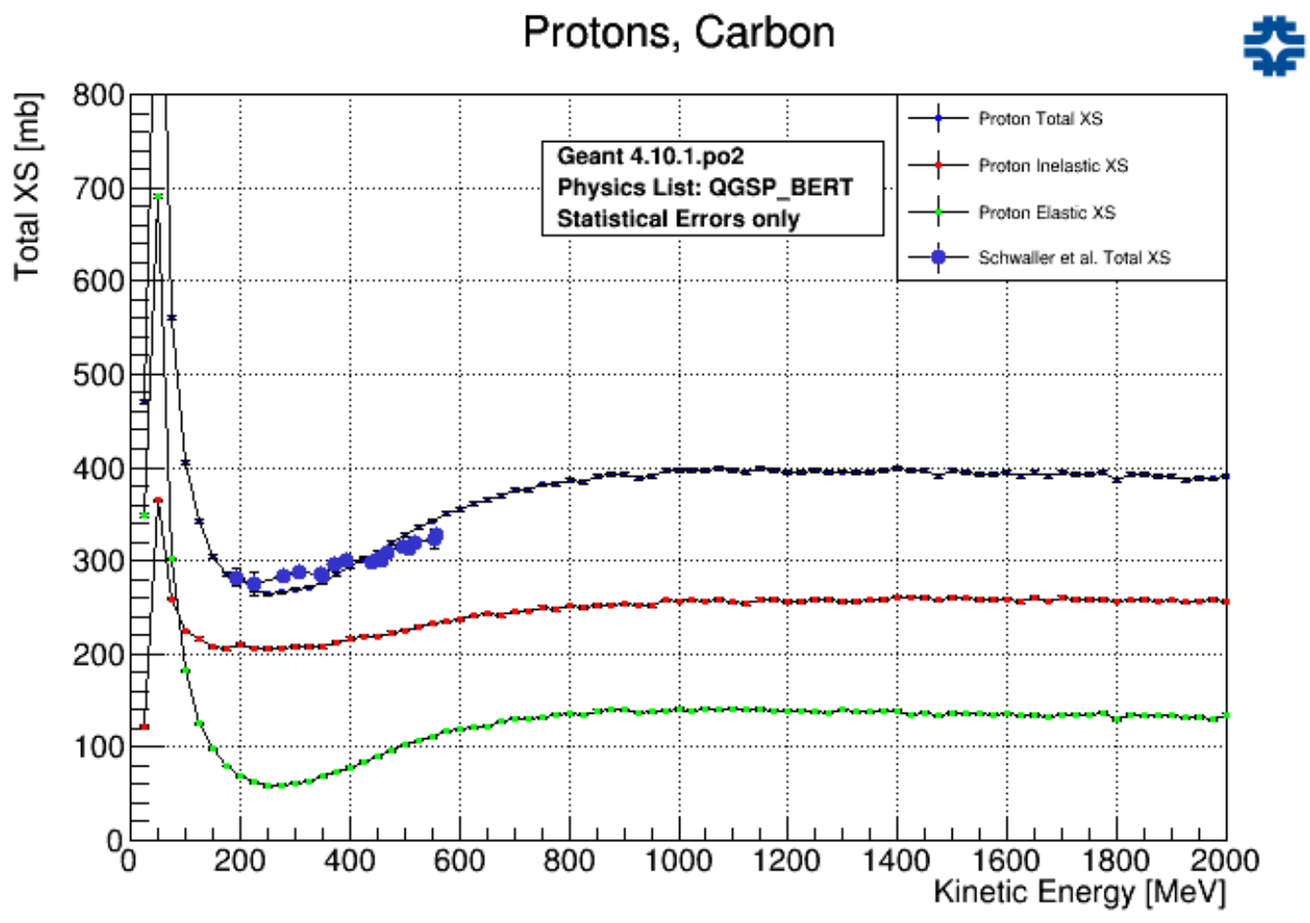

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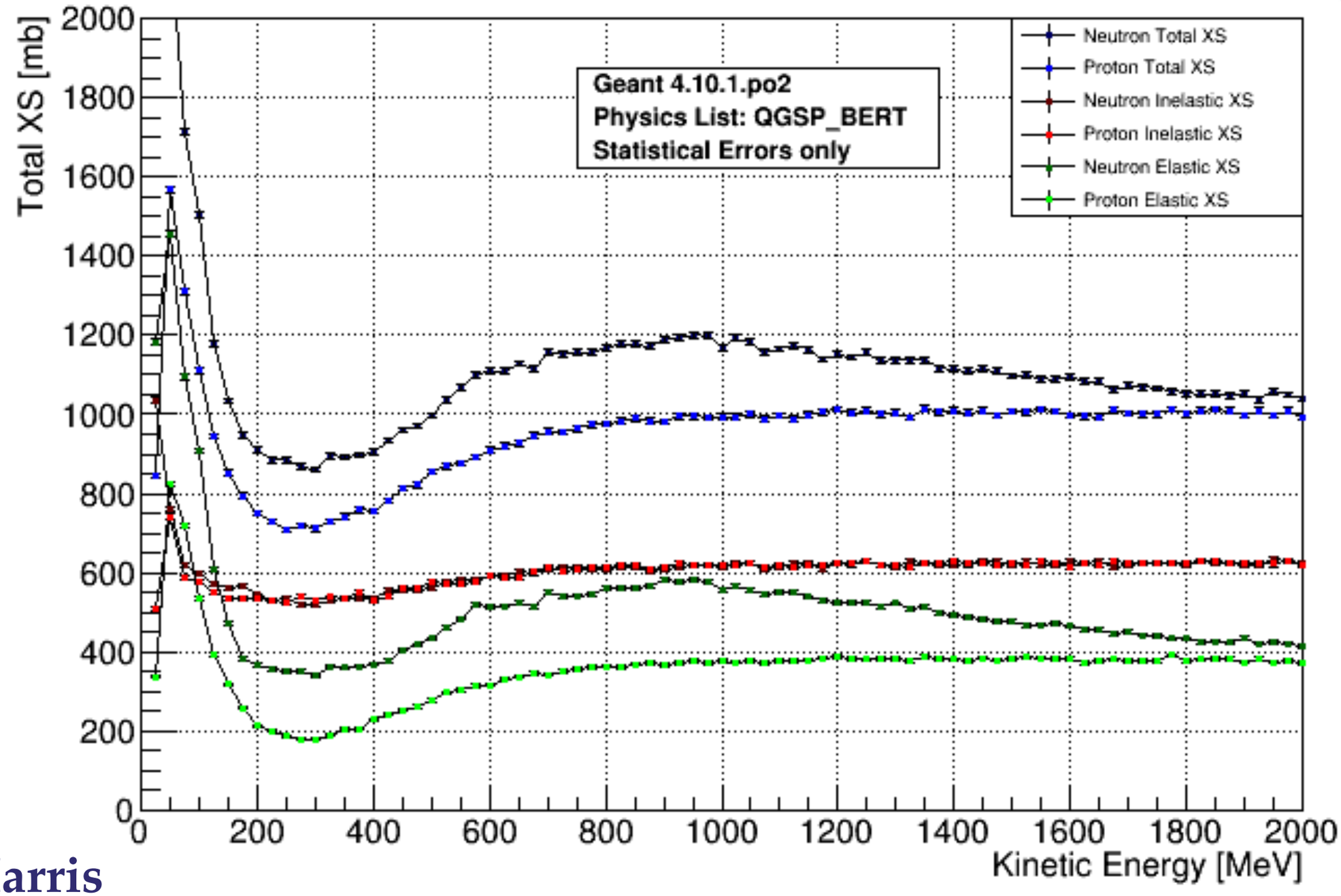
p, Argon



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