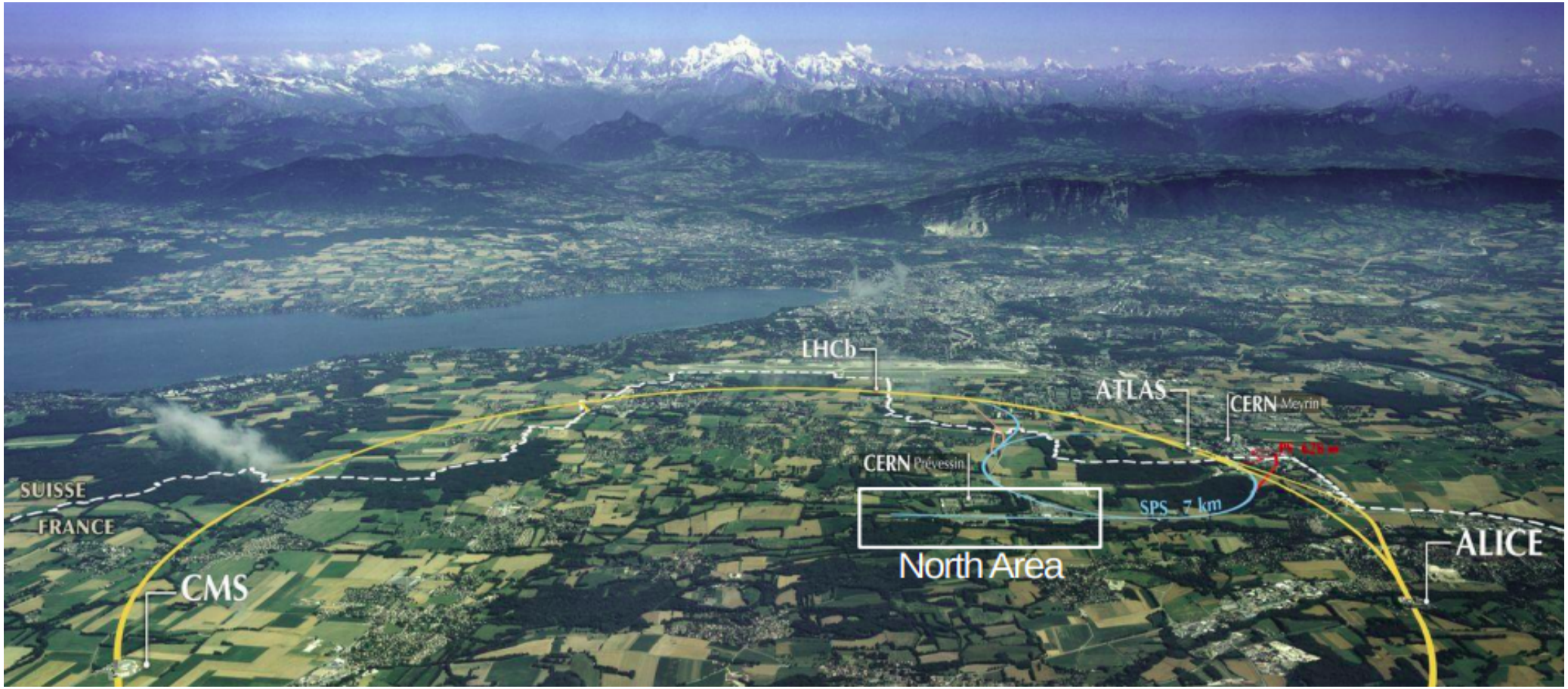
NA61/SHINE: Hadron Production Measurements for Neutrino Experiments

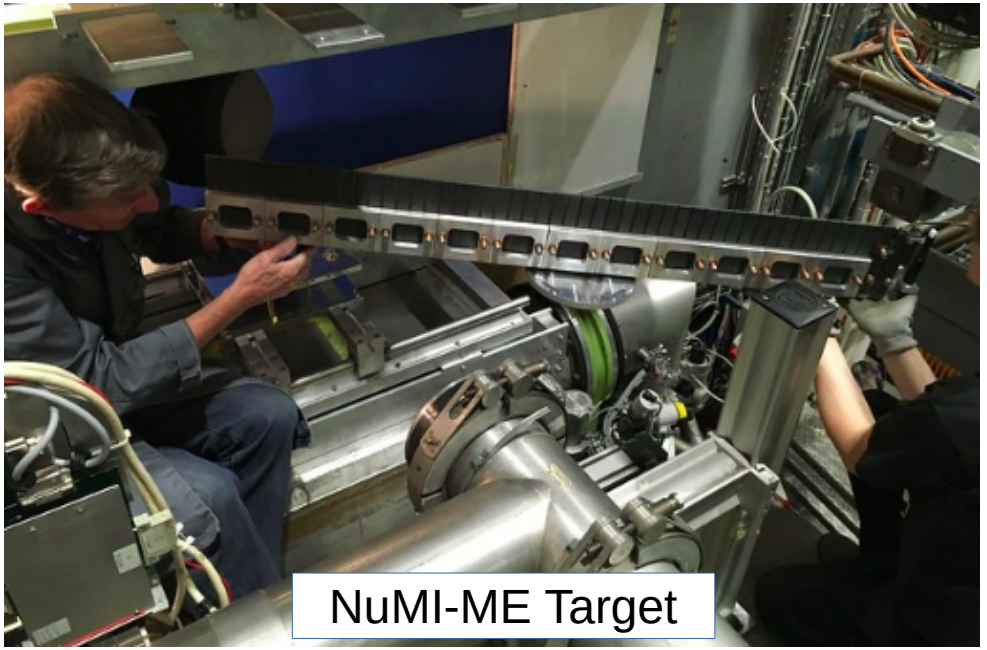
Brant Rumberger for the NA61/SHINE Collaboration
CERN Neutrino Group
NuFact Snowbird, August 5th 2022



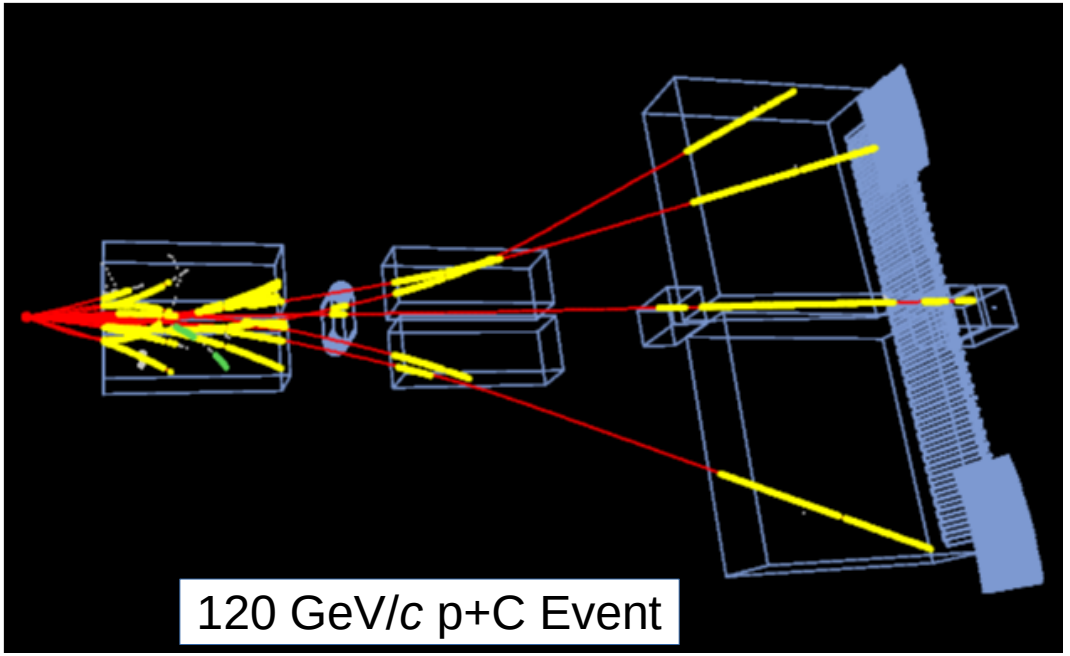
Overview

- NA61/SHINE Facility & Capabilities
- Neutrino Beam Flux Uncertainties & How to Reduce Them
- 2022 T2K Replica Target Run
- 120 GeV/*c* p+C Production Multiplicities
- DUNE Replica Target Measurement Plans

NA61 / SHINE



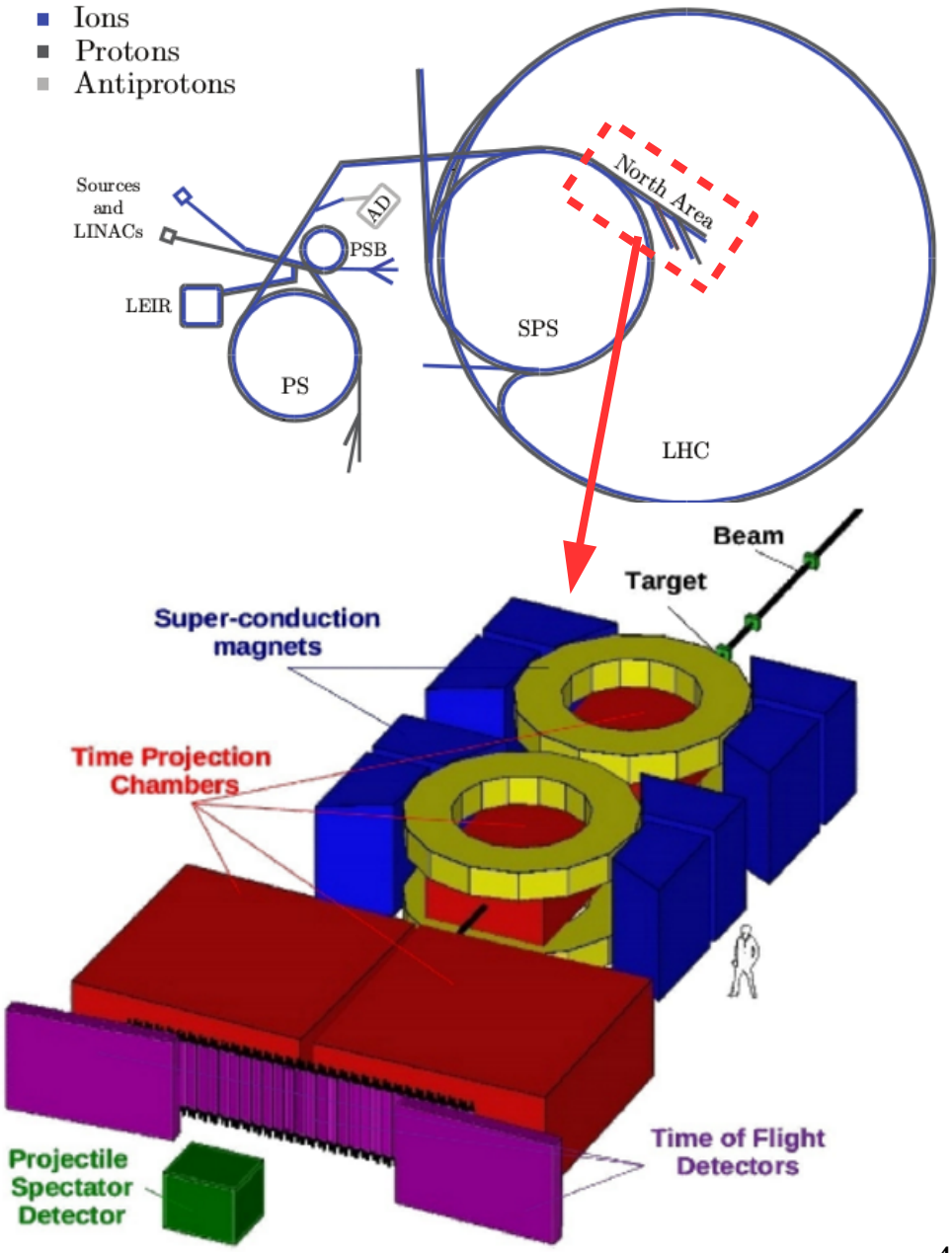
NuMI-ME Target



120 GeV/*c* p+C Event

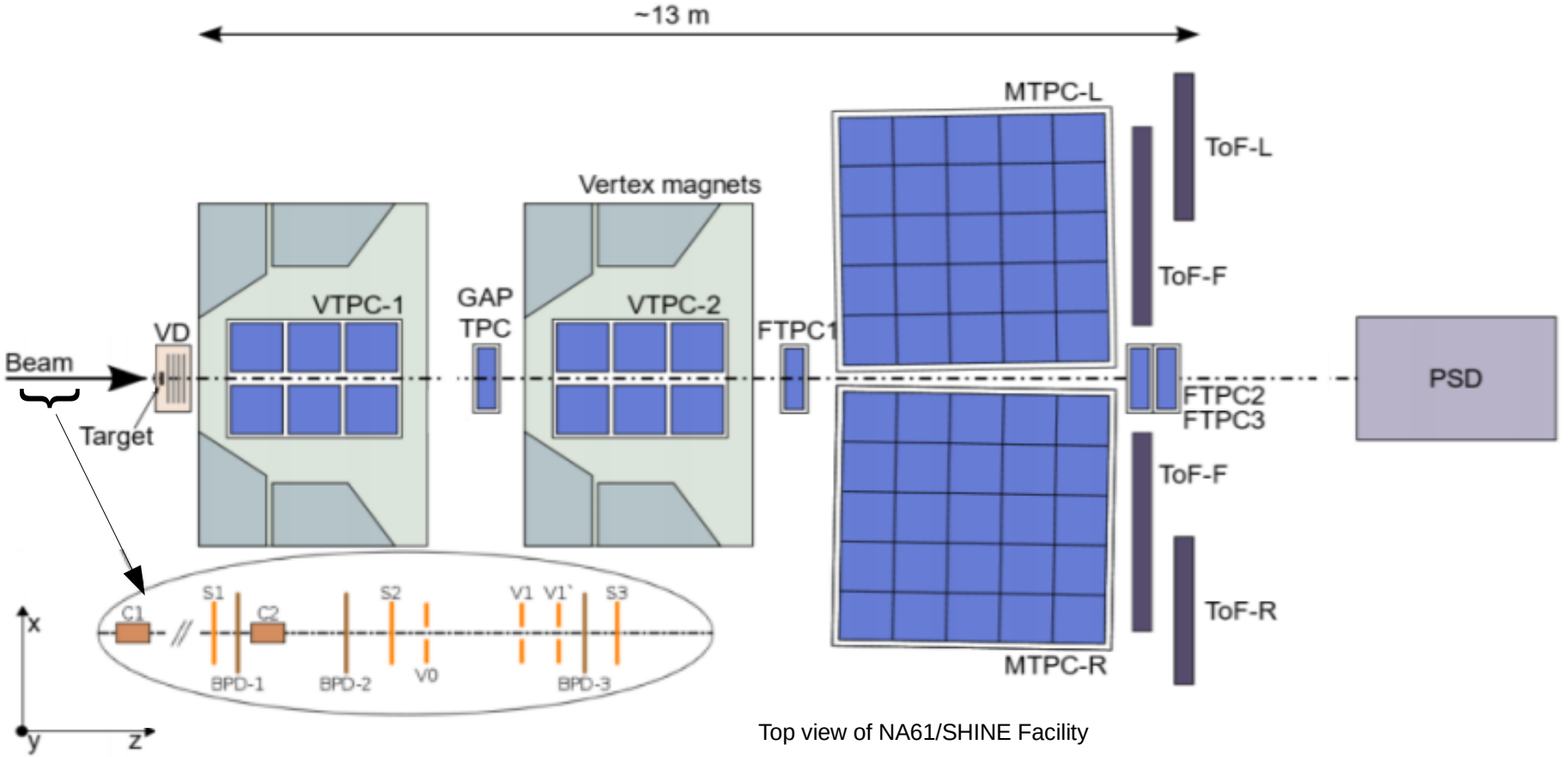
NA61 / SHINE

- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Multi-faceted physics program
  - Heavy ions
  - Cosmic-ray physics
  - Neutrino flux constraint measurements
- Beam options:
  - Primary 400 GeV/*c* protons
  - Secondary p, $K^{+/-}$, $\pi^{+/-}$, 13 - 350 GeV/*c*
- Target options:
  - Thin (~2 cm) targets, any material
  - Neutrino experiment replica targets



NA61/SHINE Detector

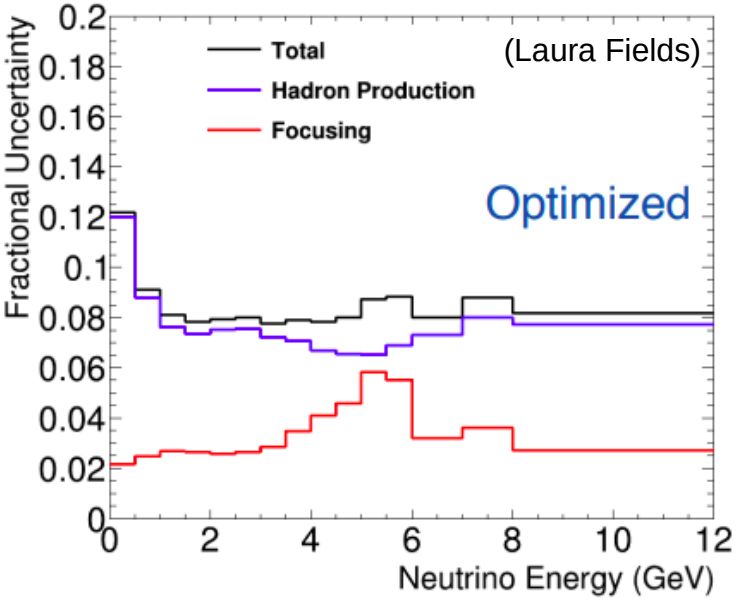
- 8 Time Projection Chambers (TPCs): 3D tracking, dE/dx measurement
- 2 superconducting magnets: momentum determination
- Cerenkov detectors: beam particle identification
- 3 Time-Of-Flight walls: mass determination
- 3 beam position detectors
- Projectile Spectator Detector (PSD): forward calorimeter

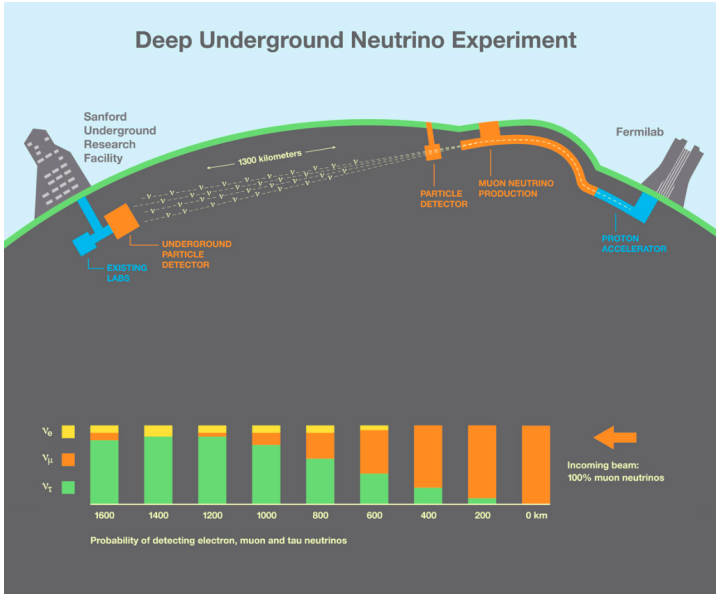


Top view of NA61/SHINE Facility

NA61/SHINE Neutrino Program: Reducing Beam Flux Uncertainties

- Long-baseline neutrino oscillation experiments typically suffer from large uncertainties associated w/ **neutrino beam flux**
- Control of general systematic uncertainties at future long-baseline experiments will be crucial to achieving physics goals
- Beam flux uncertainties should be minimized & better quantified
  - Target sensitivities still achievable if other uncertainties prove to be larger than expected
  - Precise flux knowledge crucial if results are in tension with three-flavor oscillation paradigm
- Beam flux uncertainties currently 8% - 12%
  - **Room for improvement!**

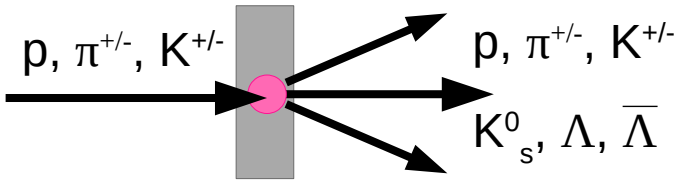




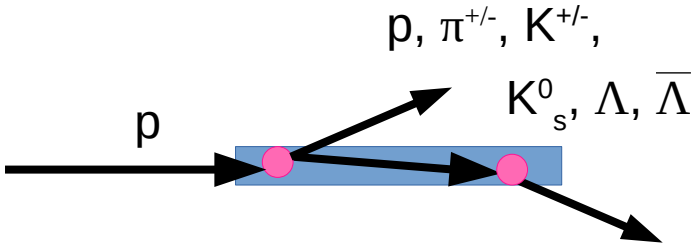
NA61/SHINE & Hadron Production Measurements

- Charged particle identification via dE/dx
  - Produced $\pi^{+/-}$, p / $\bar{p}$, $K^{+/-}$
- Weakly-decaying neutral particle identification via V^0 analysis
  - Produced K^0_s, Λ, $\bar{\Lambda}$

Thin-Target Measurements



Replica-Target Measurements



Recent Measurements for Neutrino Experiments

Year	Reaction		Number of Triggers
2016	π^+ + C 60 GeV/*c*	**Multiplicity Analysis Published**	3.0 Million
2016	π^+ + Be 60 GeV/*c*	**Multiplicity Analysis Published**	2.7 Million
2016	p + C 120 GeV/*c*	**Multiplicity Analysis Publication Pending**	4.6 Million
2016	p + Be 120 GeV/*c*		2.5 Million
2016	p + C 60 GeV/*c*	**Cross-Section Analysis Published**	3.1 Million
2016	p + Al 60 GeV/*c*	**Multiplicity Analysis Publication Pending**	3.5 Million
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2017	π^+ + Al 60 GeV/*c*	**Cross-Section Analysis Published**	2.5 Million
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2017	p + Be 120 GeV/*c*	**Calibration In Progress**	3.9 Million
2017	p + C 90 GeV/*c*	**Calibration In Progress**	3.1 Million
2018	p + NuMI-ME Target 120 GeV/*c*	**Calibration In Progress**	21.3 Million
2022	p + T2K Replica Target 31 GeV/*c*		160 Million

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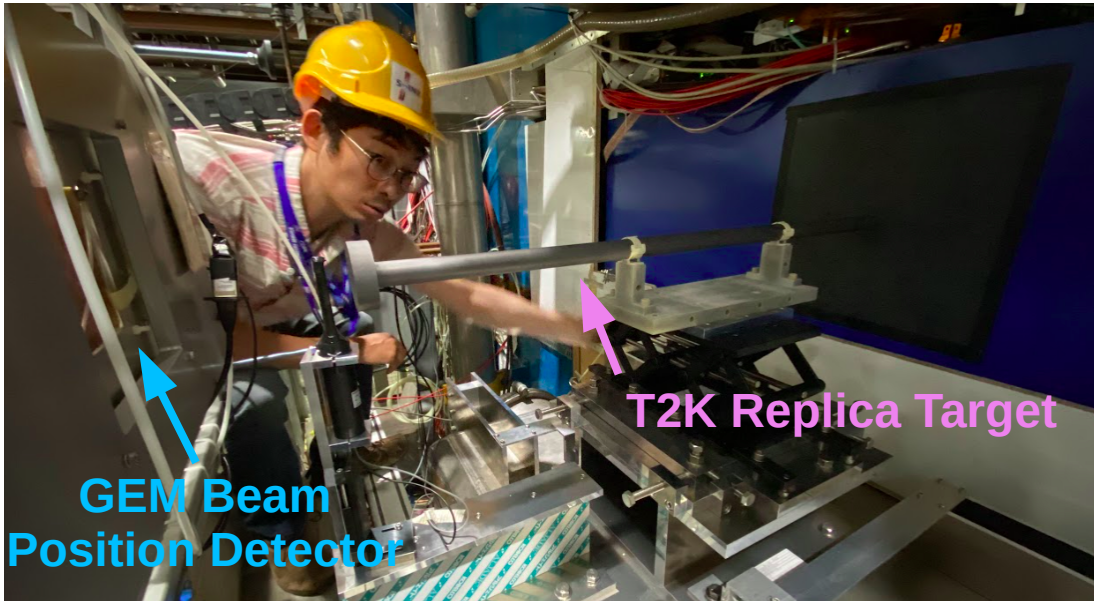
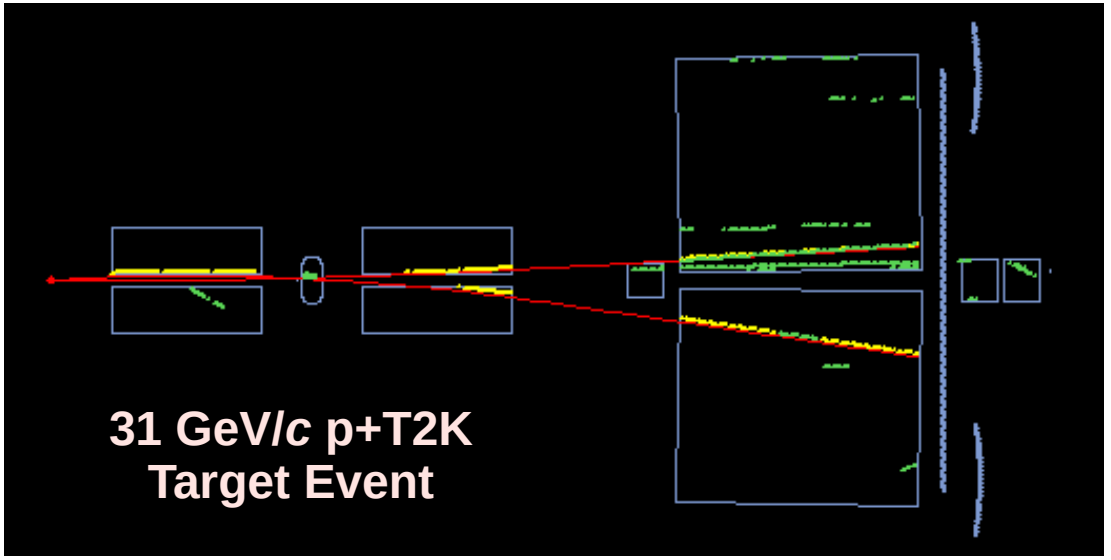
2022 p+T2K Replica Target Data Taking

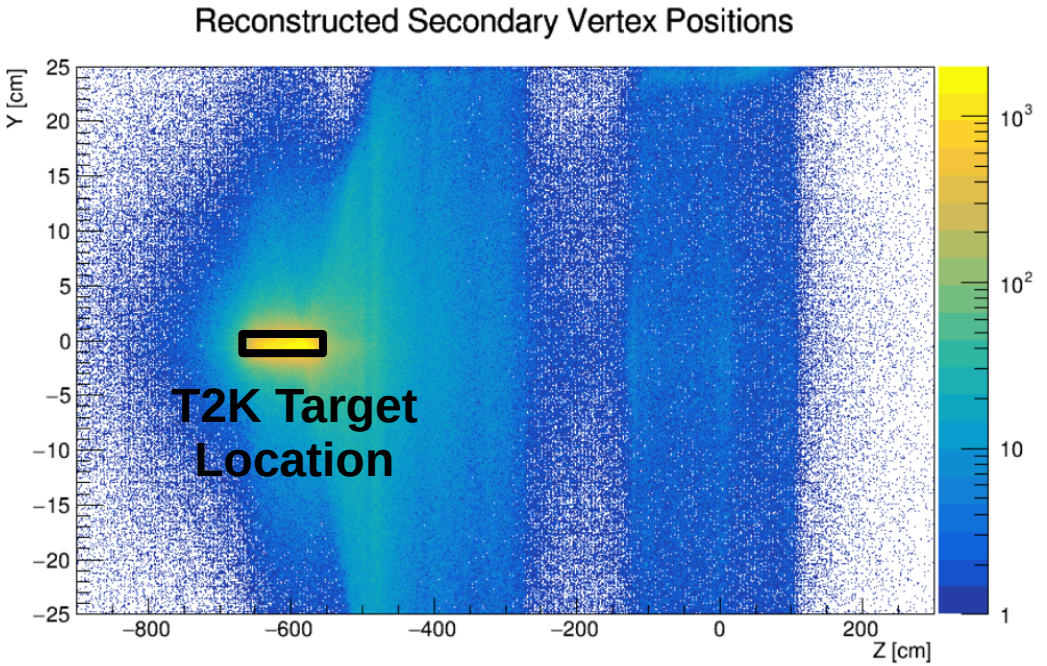
- June 22 – July 27 2022
- High-statistics 31 GeV/*c* p+T2K Target run to focus on charged kaon identification
- NA61/SHINE underwent detector-wide electronics upgrade from 2019 – 2022
- First data-taking period with new electronics

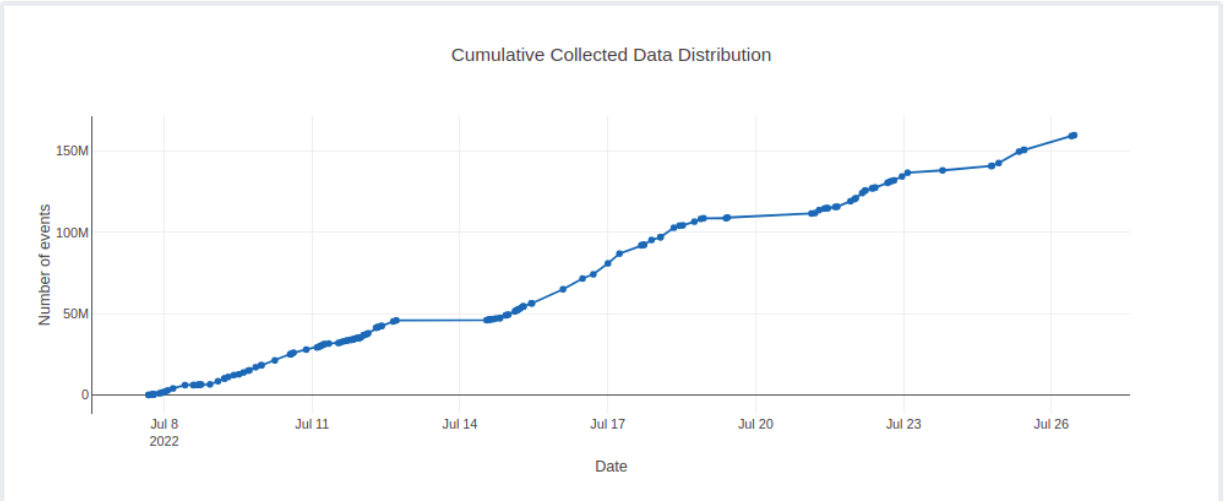




Collected Data

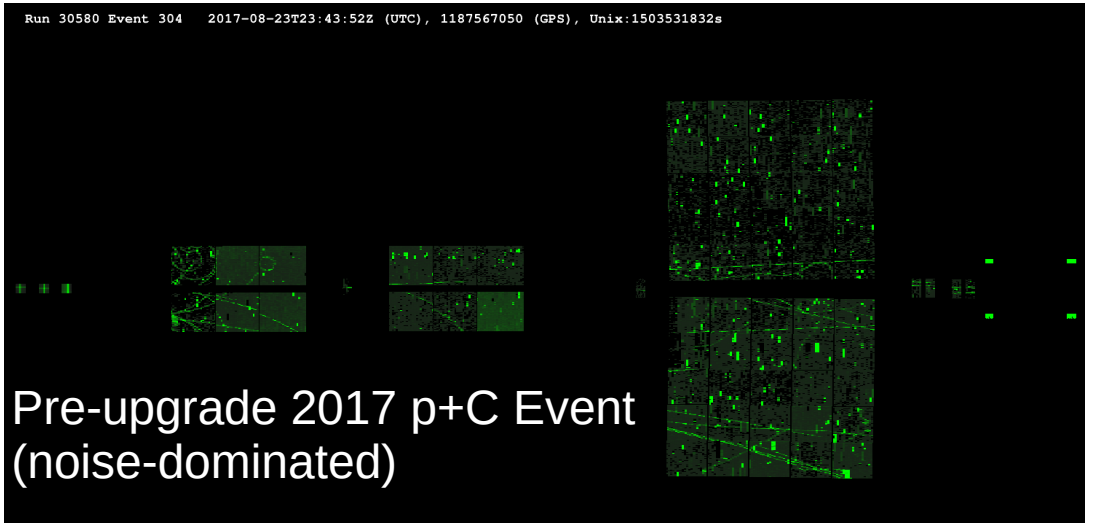
- More than **160 million events** recorded with new electronics
- New readout electronics for existing detectors
- Includes 13M events taken with 0.18 T magnetic field field for comparison with 2010 data
  - More statistics acquired in several hours than the entire 2010 run
- **DAQ rate increase: 80 Hz to 1.6 kHz**



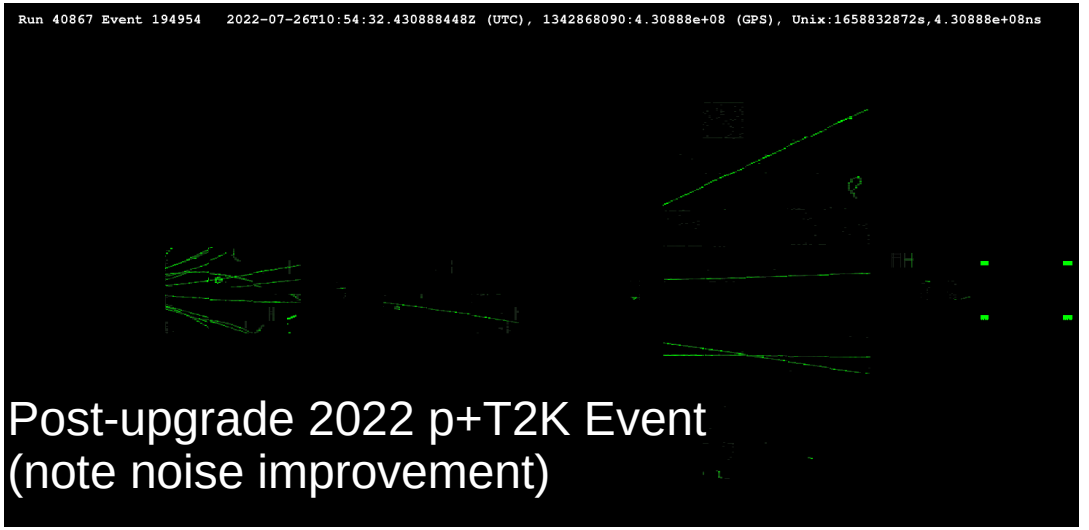


Data Quality

- Significant increase in TPC raw data quality
  - Electronics noise reduction
  - Cluster shape improvements
- Expect significant improvement in dE/dx resolution
  - dE/dx resolution crucial to performing charged hadron multiplicity measurements
  - Recent T2K run hopes to perform precise Kaon identification and will benefit from improved dE/dx resolution



Pre-upgrade 2017 p+C Event
(noise-dominated)



Post-upgrade 2022 p+T2K Event
(note noise improvement)

New Results: 120 GeV/*c* p+C Neutral Hadron Multiplicities

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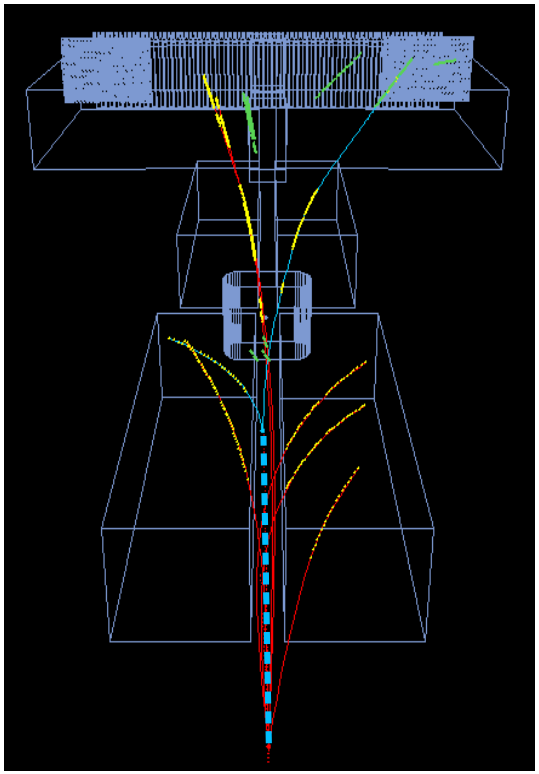
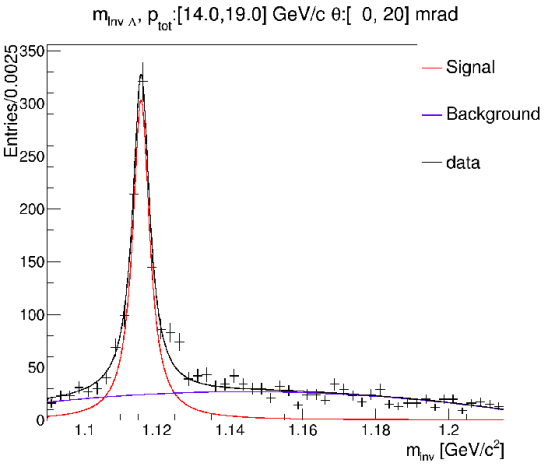
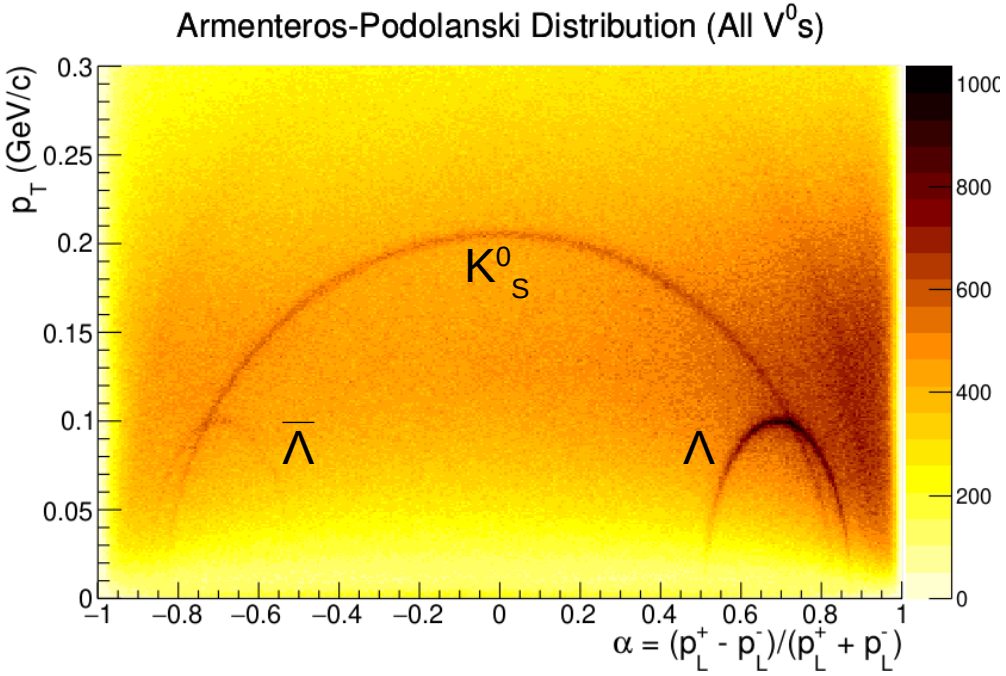
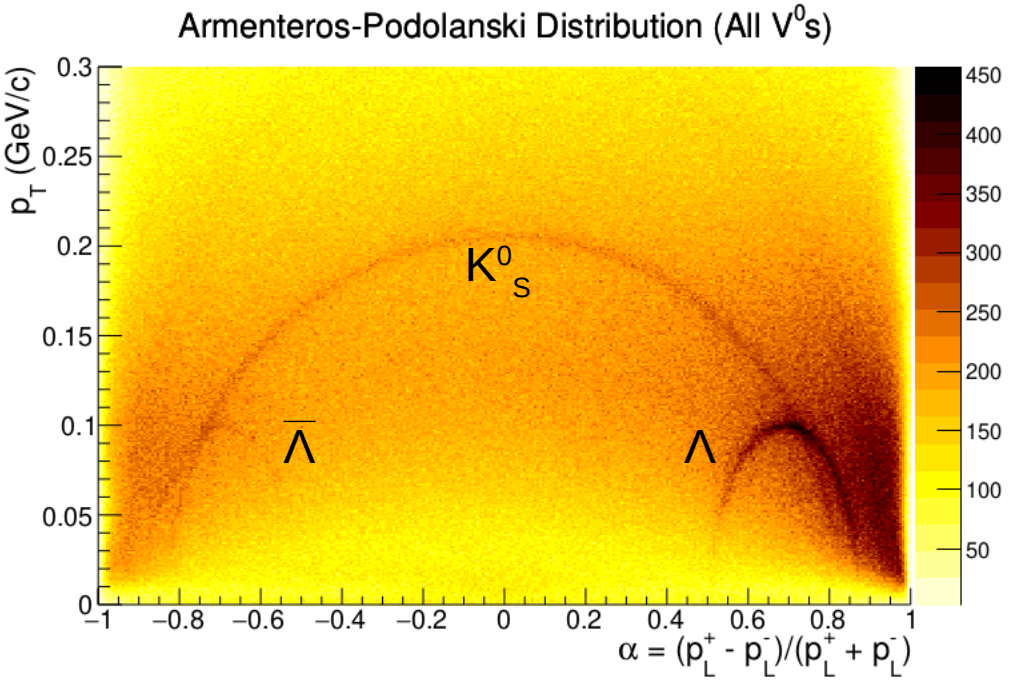
NA61 / SHINE V^0 Analysis Overview

- Reconstruct collection of V^0 candidates using V^0 finder & fitter algorithms
- Calculate neutral kinematics using decay product assumption
- Improve purity of V^0 sample by applying selection cuts
- Fit invariant mass distributions for signal yield
- Calculate & apply bin-by-bin Monte Carlo corrections
- Calculate multiplicities
- This analysis: Two independent data sets collected
  - Different detector configurations: magnetic field, more TPCs






Armenteros-Podolanski Distribution (All V0s)
K0S
Λ̄
Λ
pT (GeV/c)
α = (p+L - p-L)/(p+L + p-L)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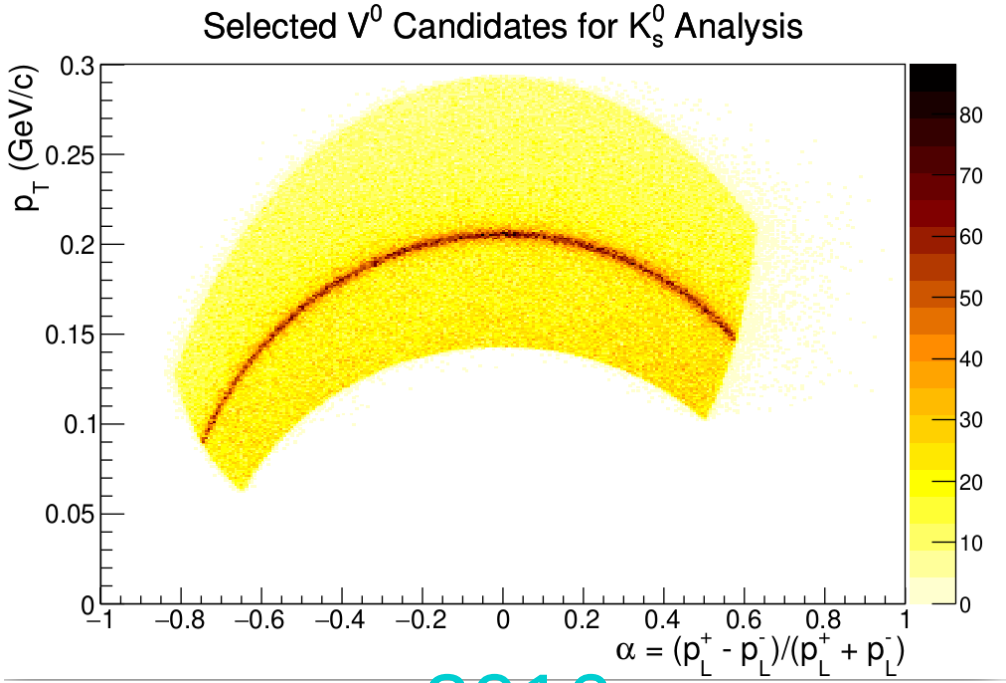
Selected V0 Candidates for K0s Analysis
pT (GeV/c)
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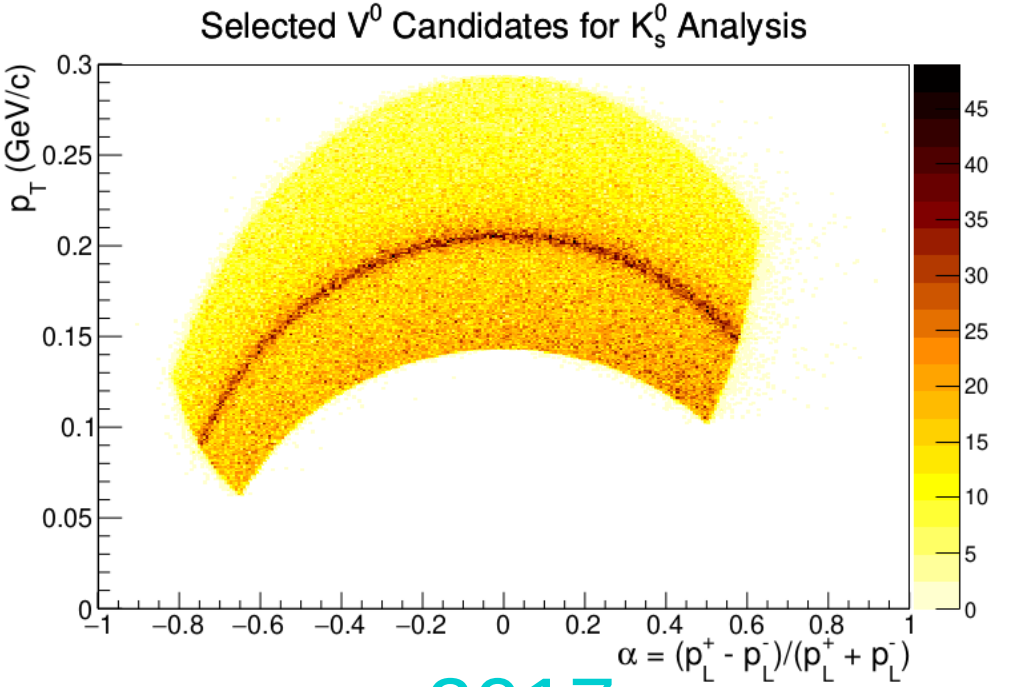
2016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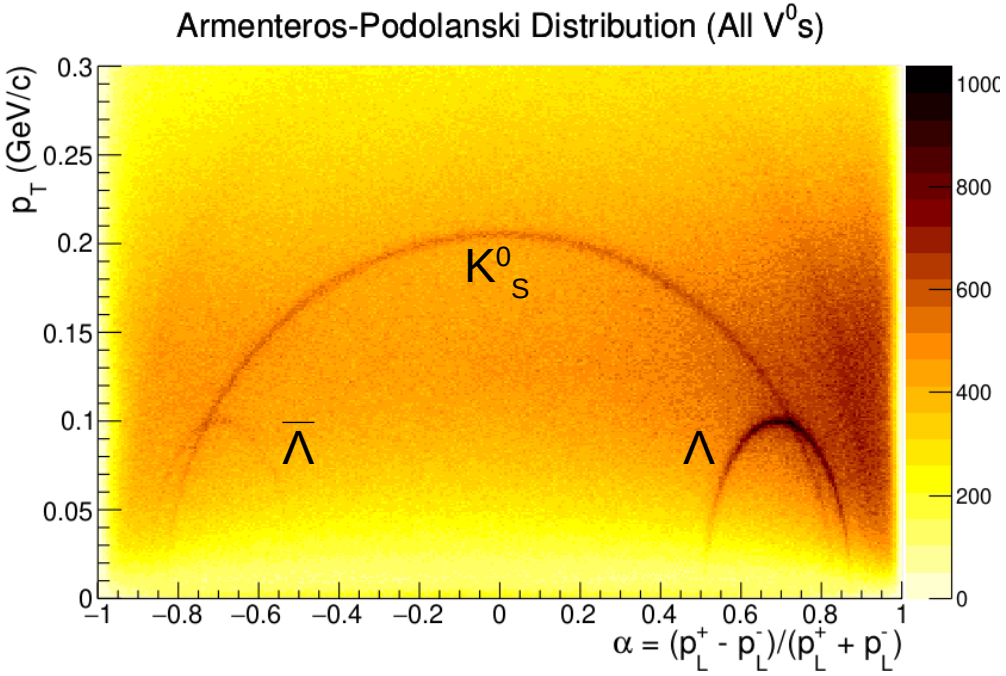
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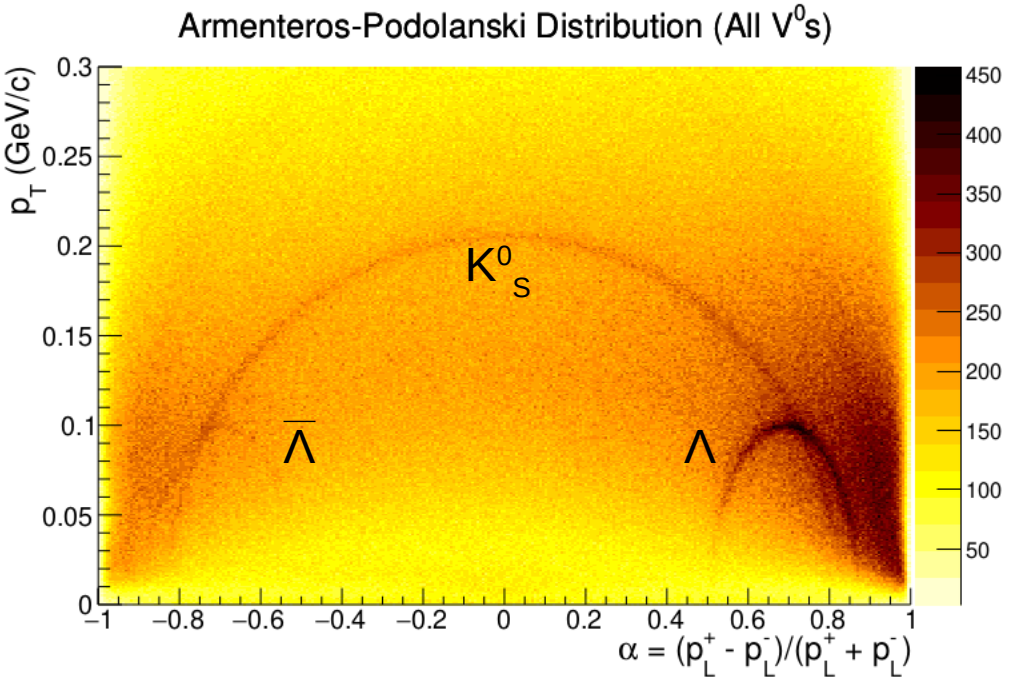
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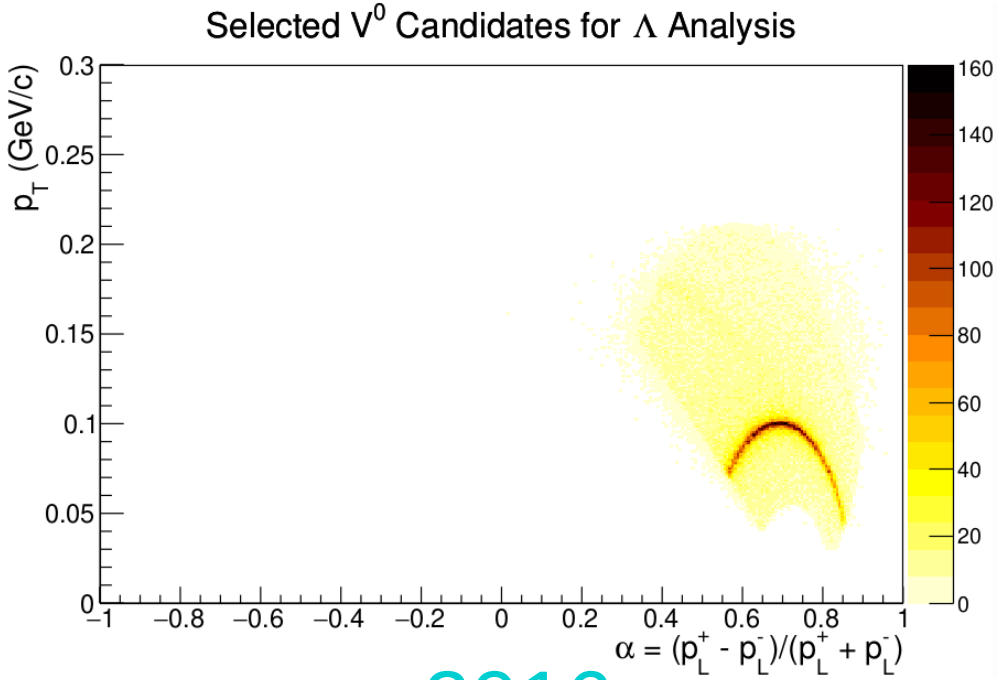
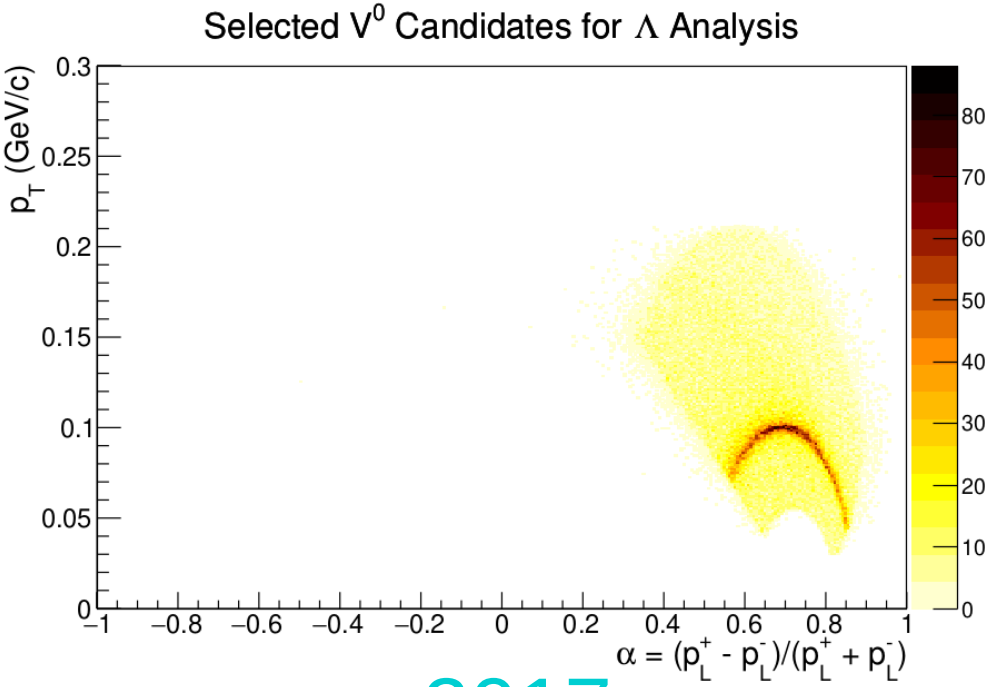

Selected V0 Candidates for Λ Analysis
pT (GeV/c)
α = (p+L - p-L)/(p+L + p-L)

2016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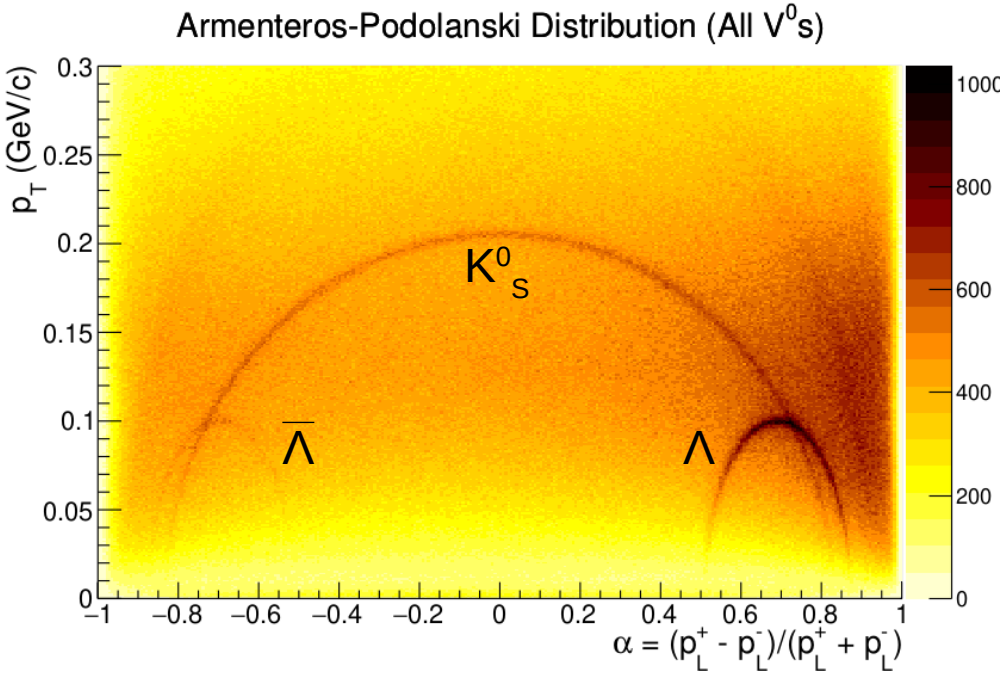
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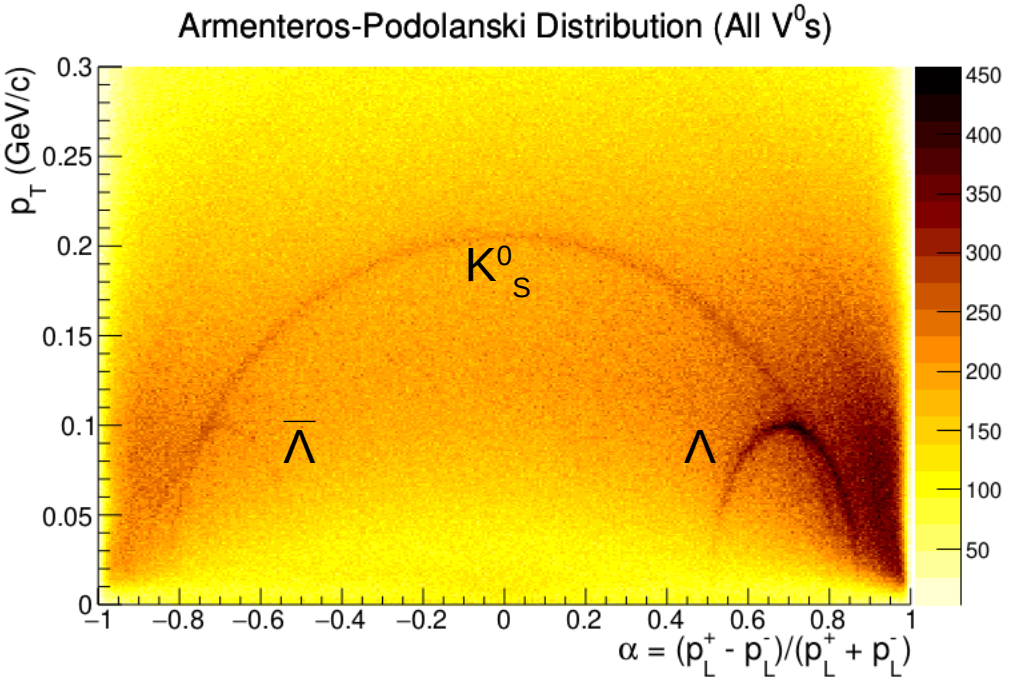
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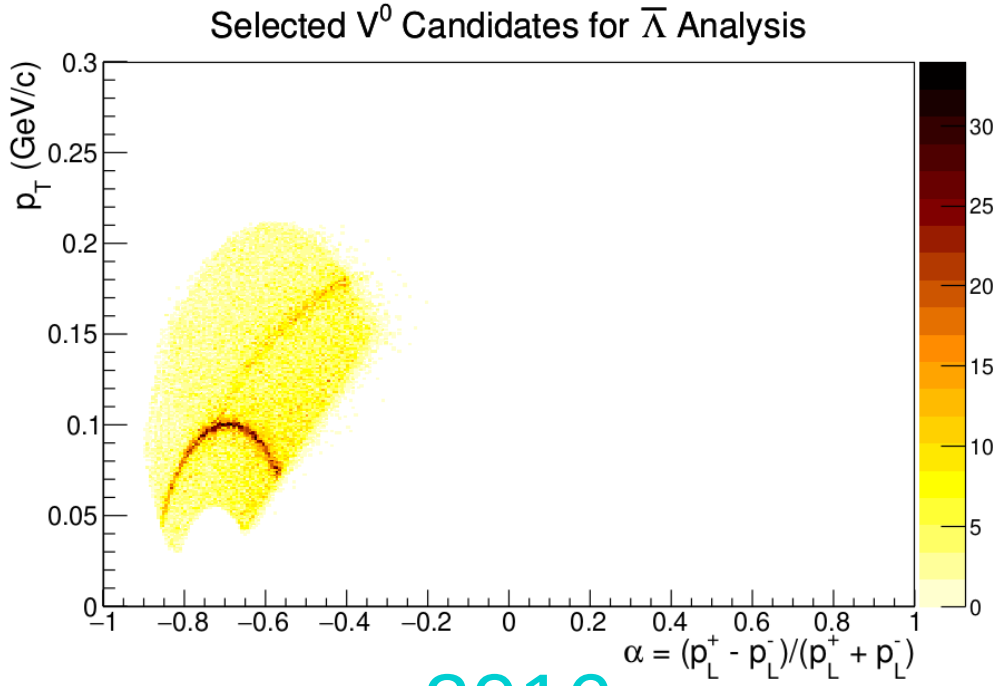
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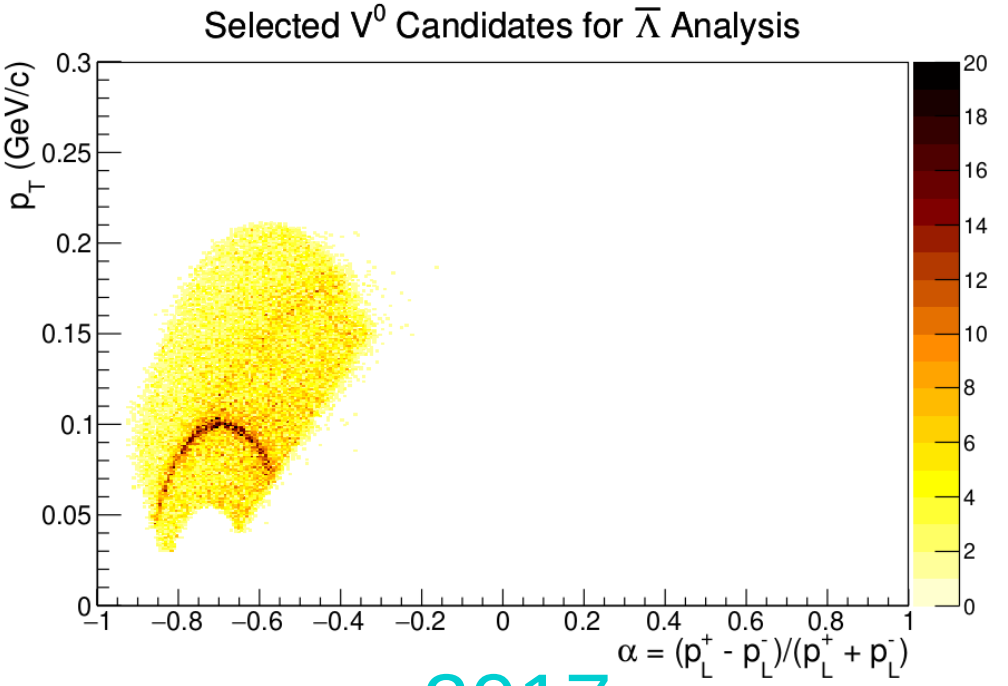
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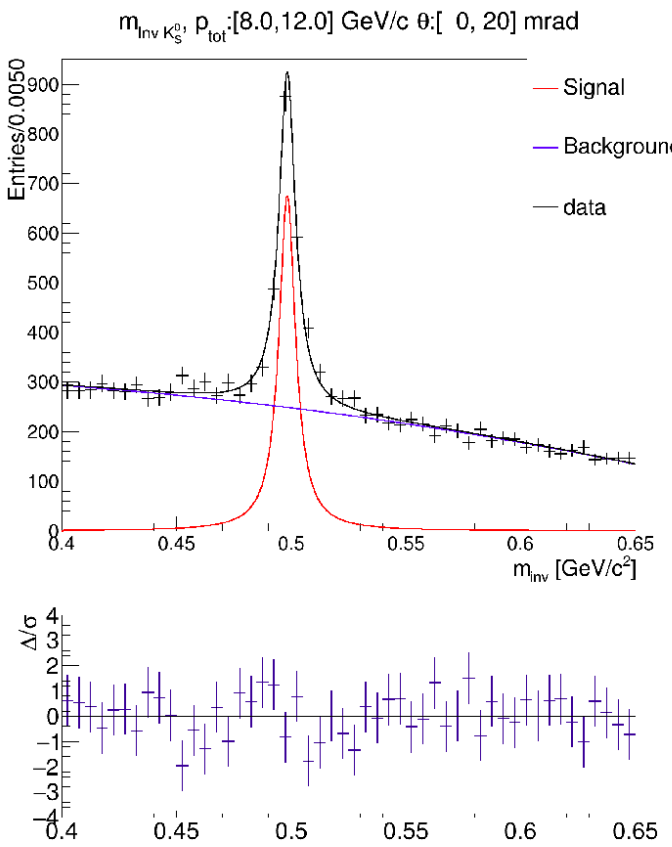
2016

2017

K^0_s Invariant Mass Fits

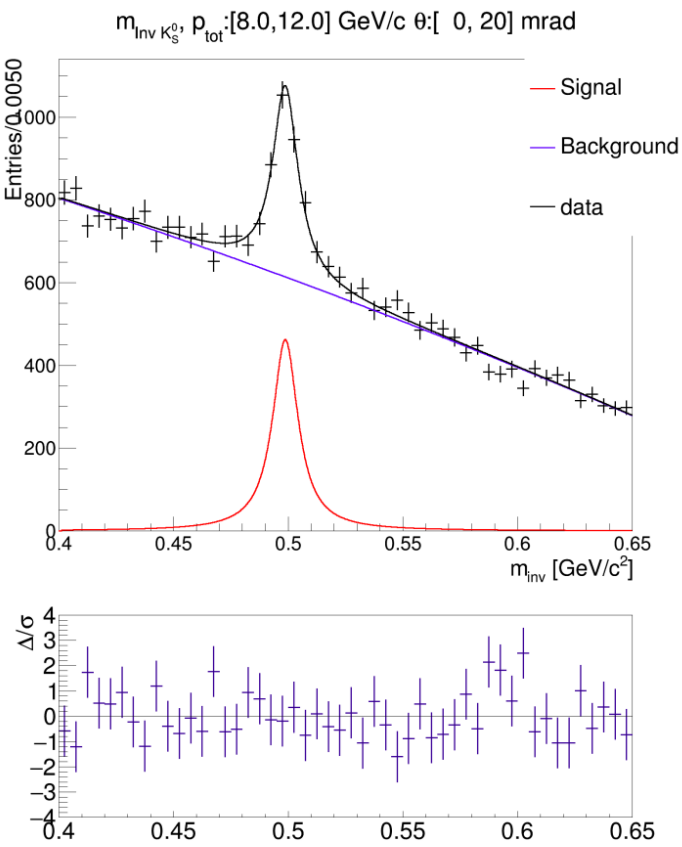
2016

	Fitted
N_S	1815.53
N_{BG}	11320.47
f_s	0.1382
m_0	0.0007
Γ	0.0044
c_1	4.0299
c_2	11.0032
c_3	-20.9510



2017

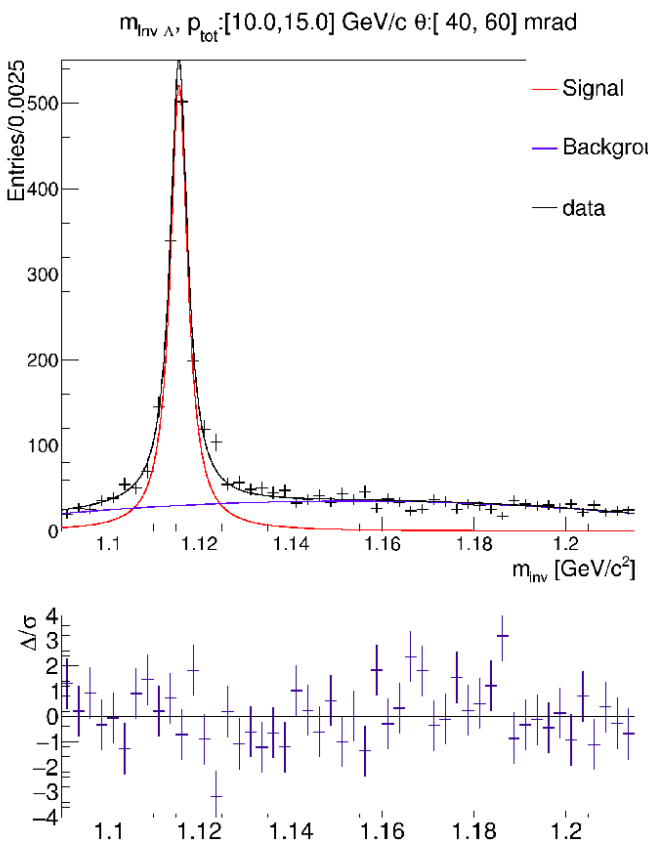
	Fitted
N_S	1886.91
N_{BG}	27671.09
f_s	0.0638
m_0	0.0011
Γ	0.0067
c_1	9.7651
c_2	-6.5116
c_3	-8.3161



Λ Invariant Mass Fits

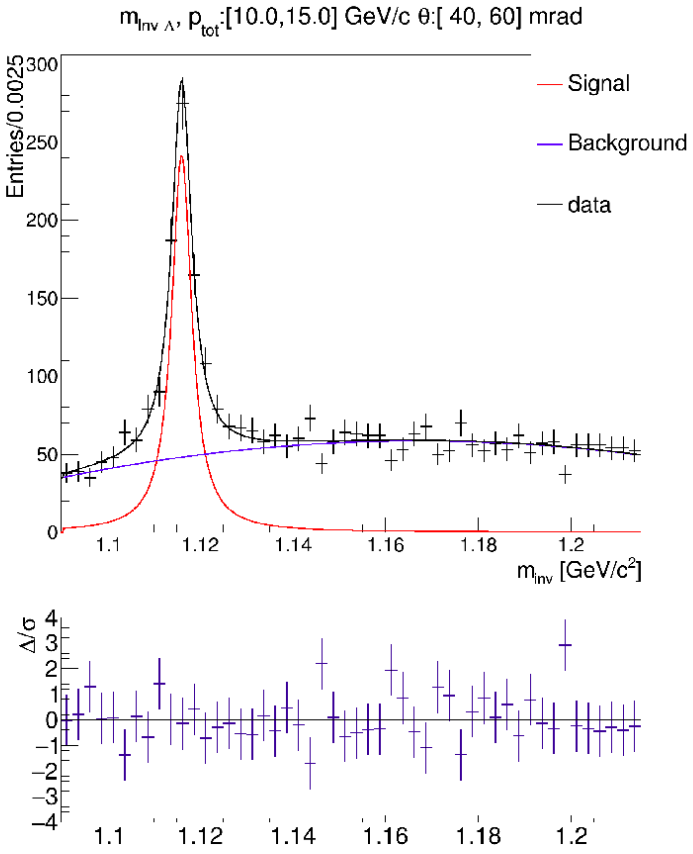
2016

	Fitted
N_S	1456.88
N_{BG}	1518.12
f_s	0.4897
m_0	0.0000
Γ	0.0023
c_1	-631.3202
c_2	1103.4291
c_3	-478.7071



2017

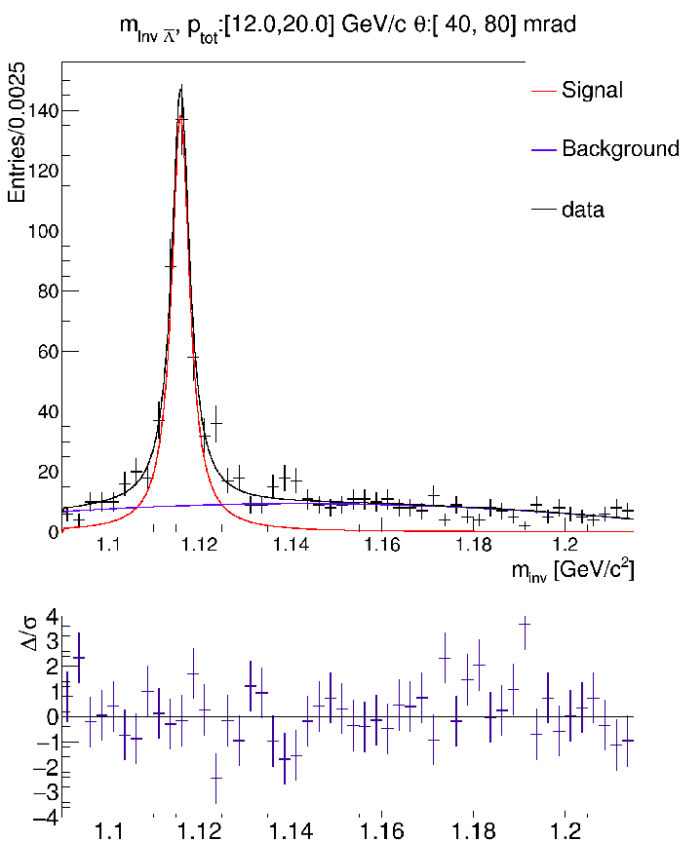
	Fitted
N_S	761.65
N_{BG}	2623.35
f_s	0.2250
m_0	0.0004
Γ	0.0026
c_1	-750.6588
c_2	1300.2512
c_3	-556.9631



$\overline{\Lambda}$ Invariant Mass Fits

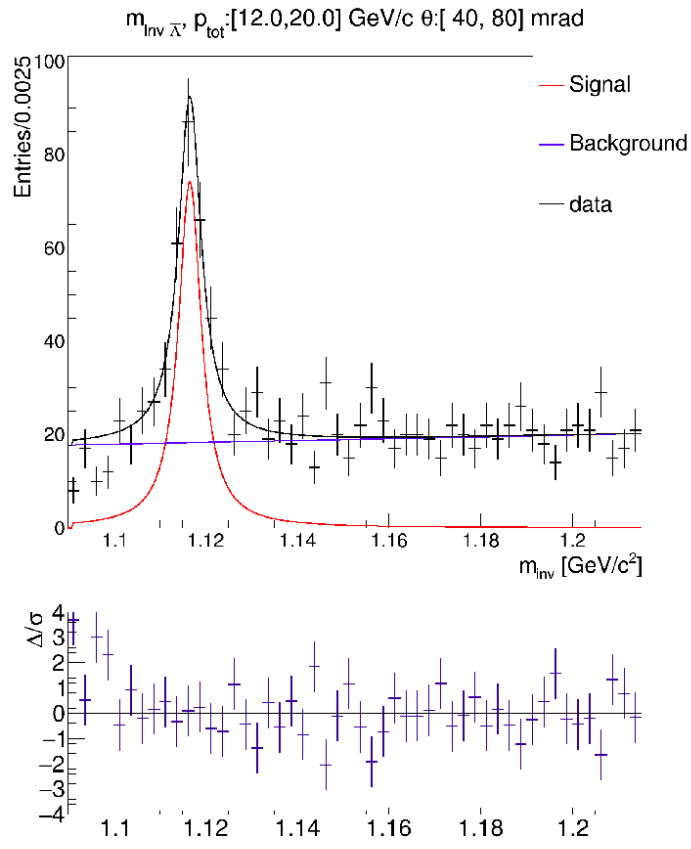
2016

	Fitted
N_S	401.00
N_{BG}	401.00
f_s	0.5000
m_0	0.0004
Γ	0.0024
c_1	-925.8070
c_2	1633.0437
c_3	-714.8490



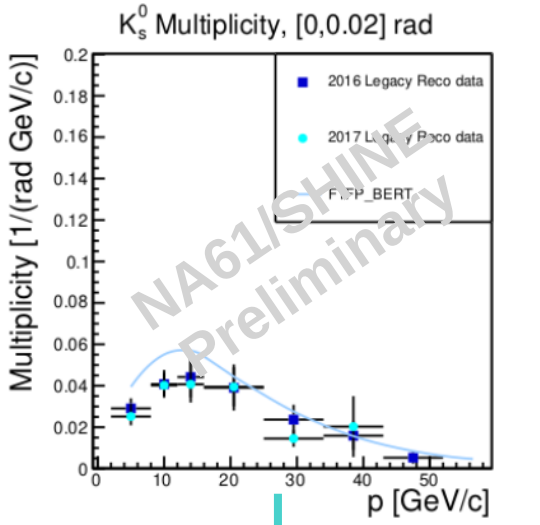
2017

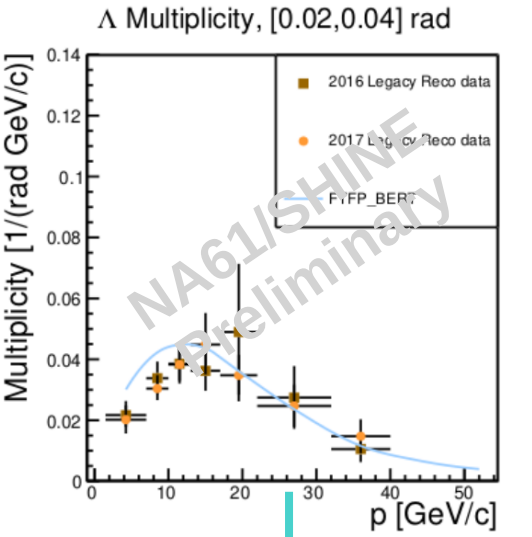
	Fitted
N_S	268.42
N_{BG}	948.58
f_s	0.2206
m_0	0.0010
Γ	0.0030
c_1	6816.5868
c_2	11109.425
c_3	9598.0664

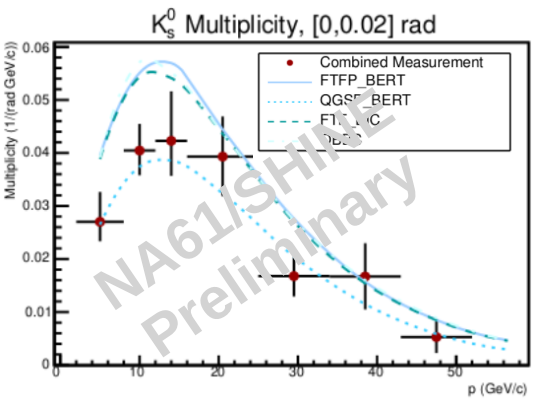


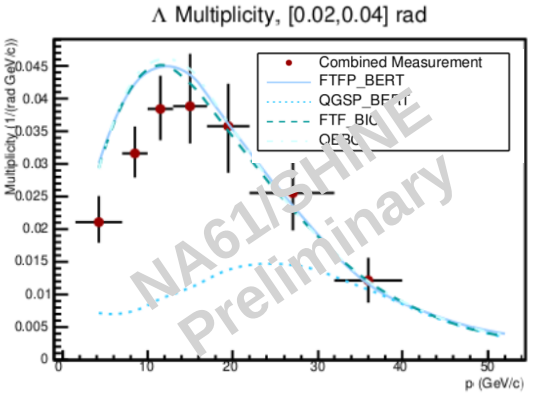
Combining Multiplicities

- Two data sets provide independent measurements in overlapping regions of phase space
- Multiplicities are weighted by uncorrelated uncertainties specific to each analysis
  - Statistical uncertainty
  - Invariant mass fit uncertainty
  - Reconstruction uncertainty
  - Selection uncertainty
  - dE/dx decay product selection uncertainty

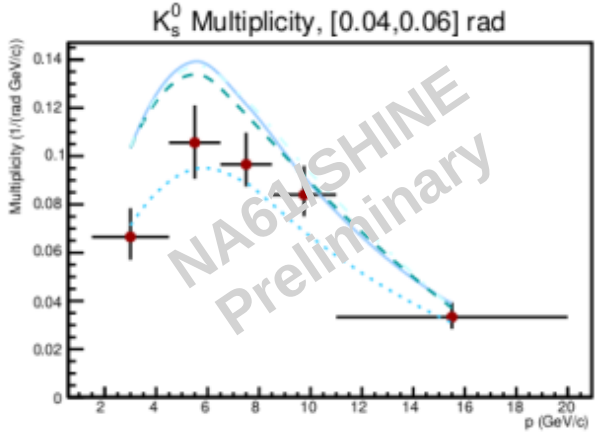


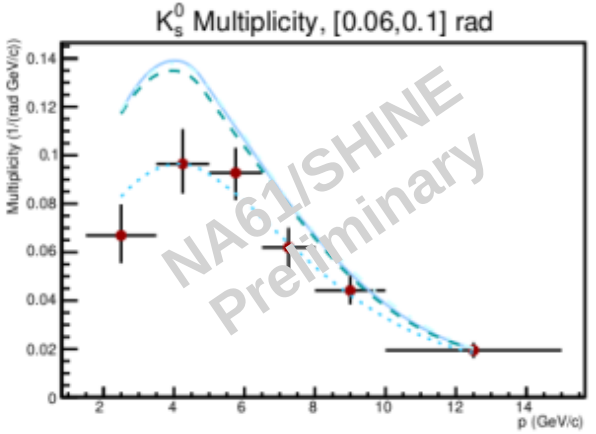


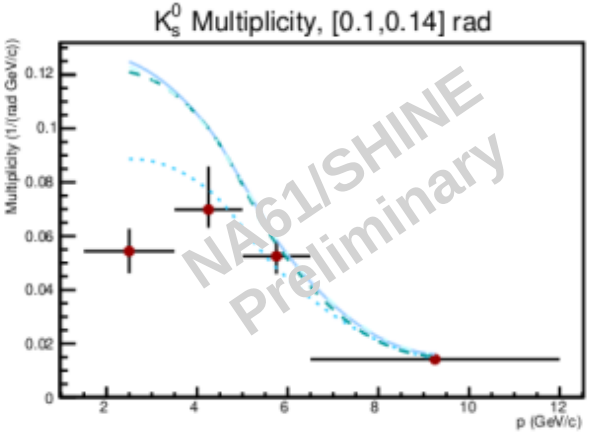


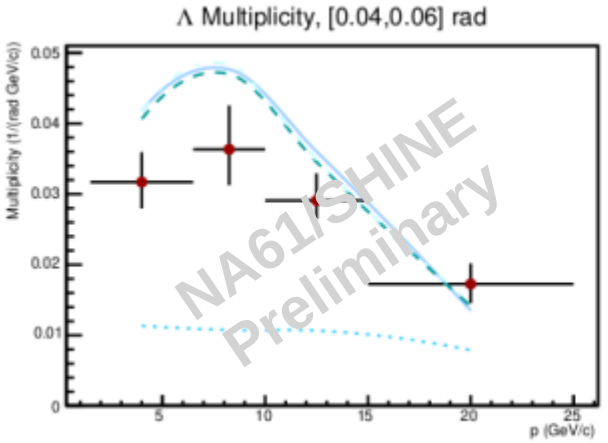


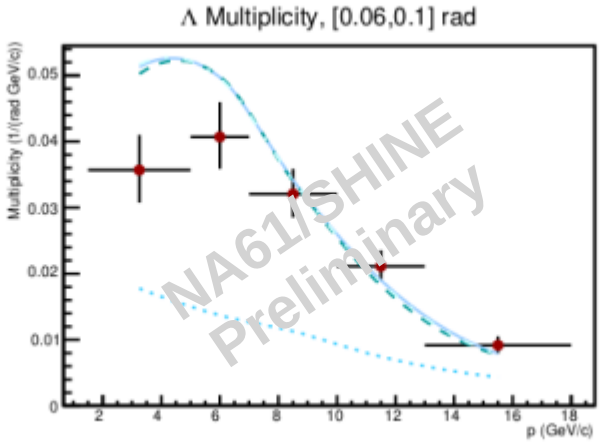
Multiplicity Measurements

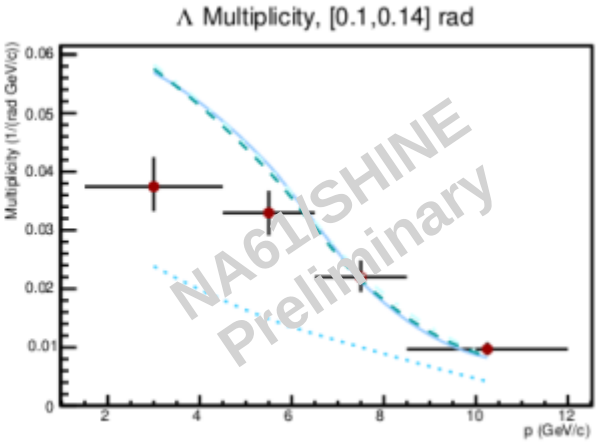


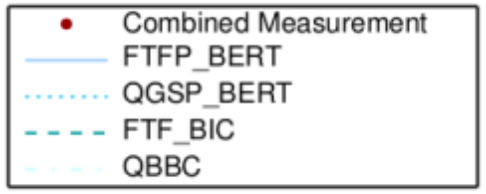


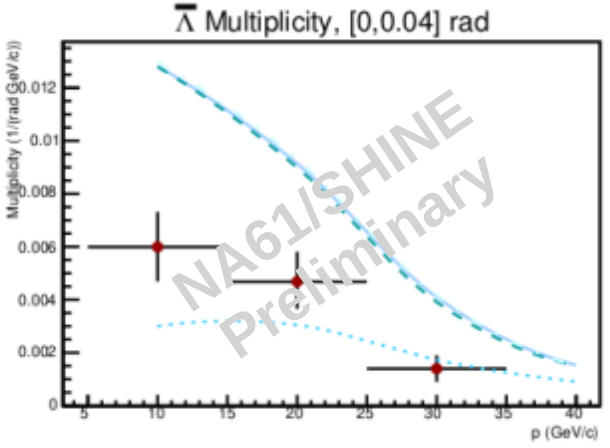


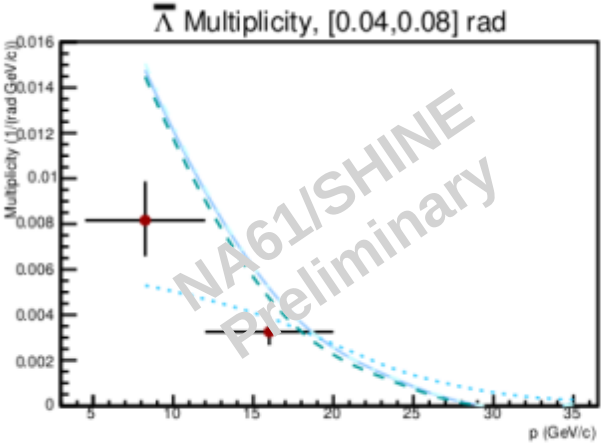






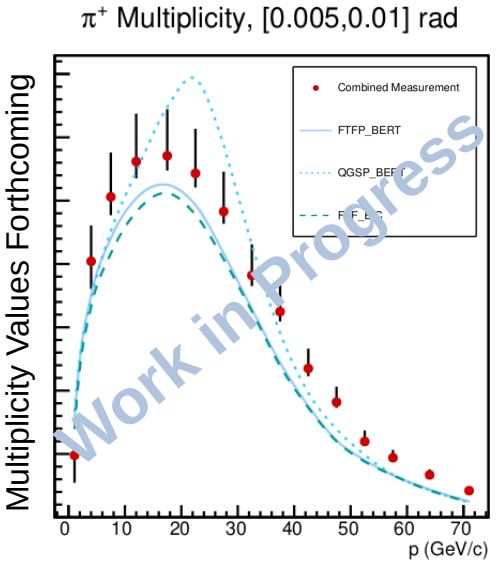


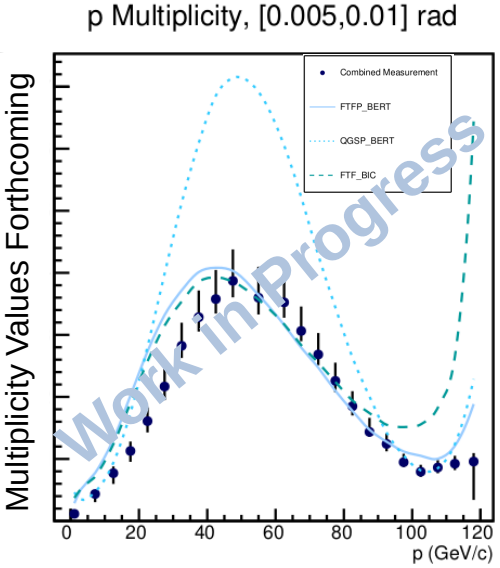


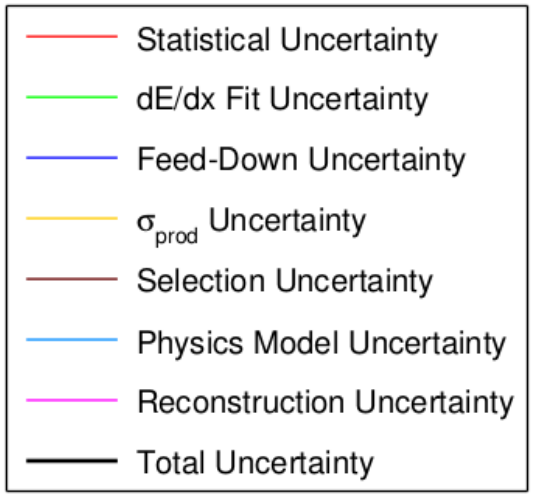


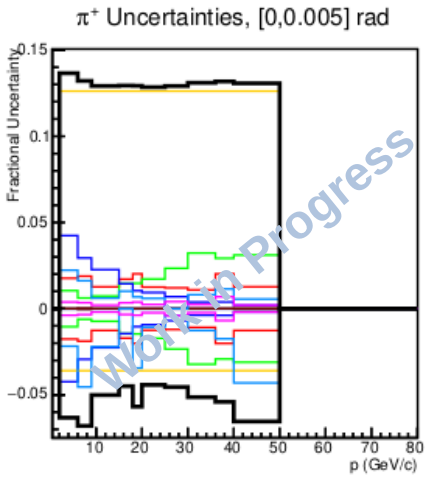
Coming Soon: Charged Hadron Multiplicities

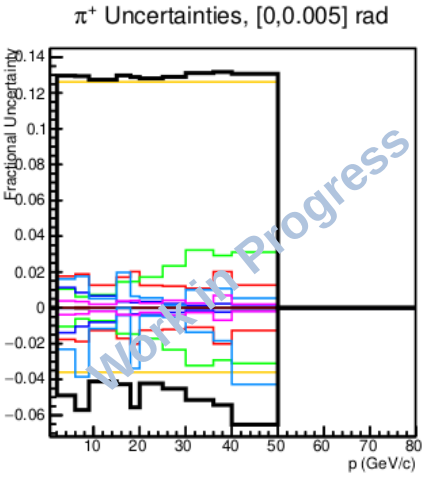
- Measured multiplicities:
  - π^+, π^-, p, $\bar{p}$, K^+, K^-
- Neutral hadron multiplicities used to reduce uncertainties associated with weak neutral decays
- Two complementary data sets again combined for final multiplicity result
- Results will soon be used to reduce DUNE beam flux uncertainties





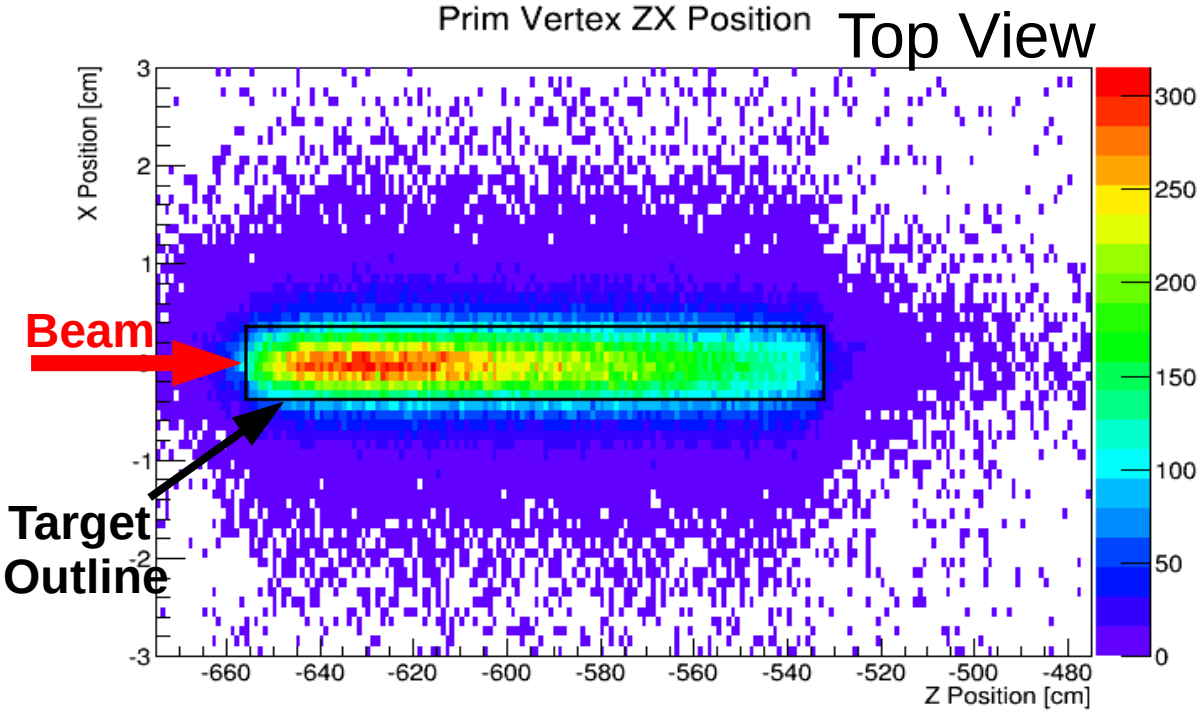






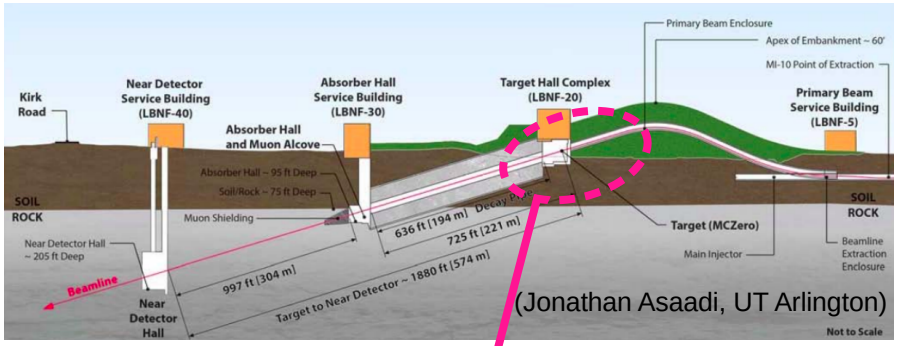
Coming Soon: NuMI Replica Target Multiplicity Analysis

- 21 M p+NuMI Target events taken in Summer / Fall 2018
- Data in final stages of calibration
- Multiplicity analyses will begin this year
- Stay tuned!

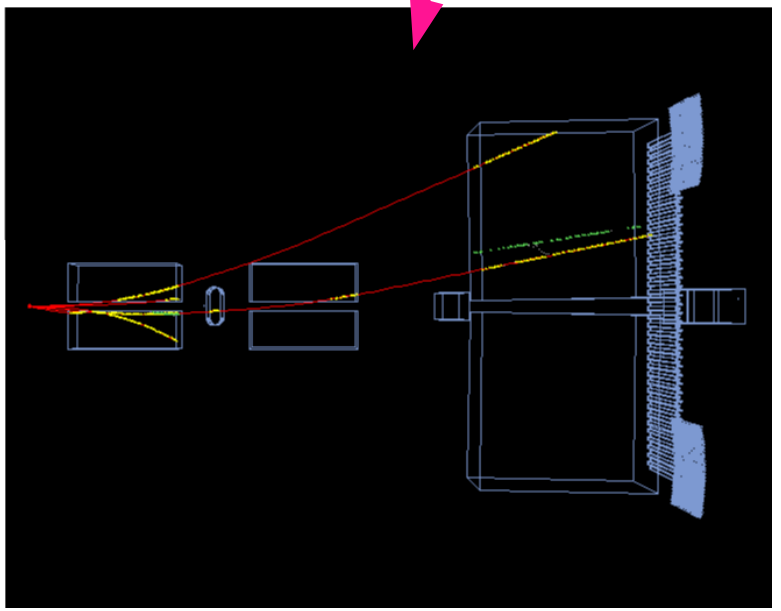


Future Campaign: DUNE Long Target Measurement

- DUNE replica target run at NA61/SHINE foreseen in next few years
  - Direct measurement of neutrino-producing hadrons in primary beam-target reaction!
- This data set will also benefit from recently-upgraded DAQ and readout electronics
  - High-quality high-statistics runs expected
- Timescale depends on DUNE target design schedule



(Jonathan Asaadi, UT Arlington)



Takeaway Points

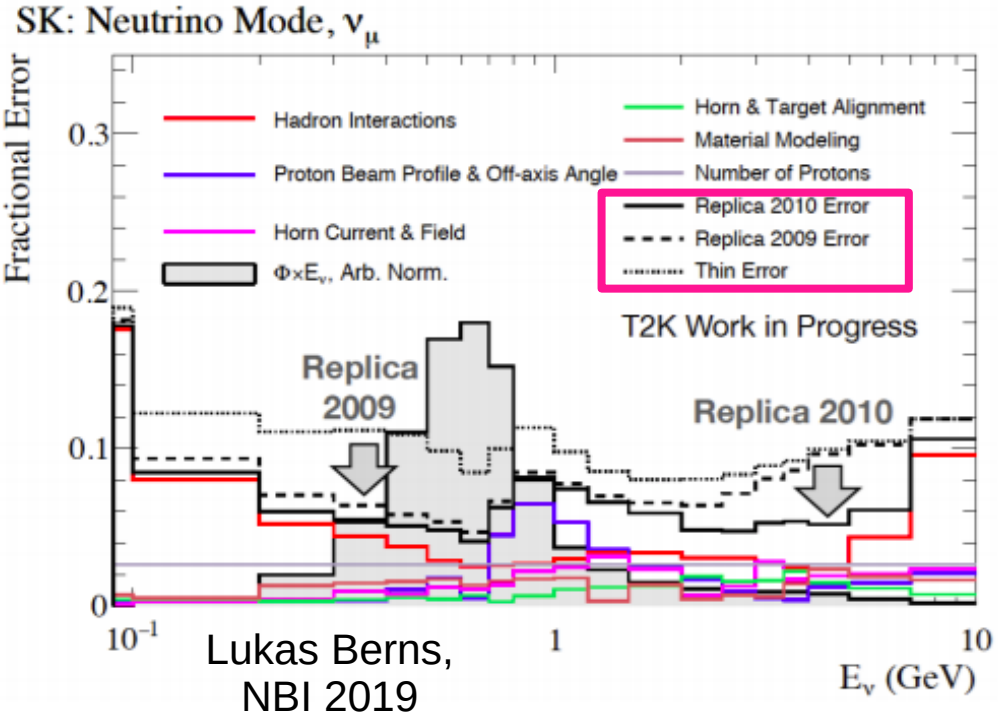
- Hadron production measurements from NA61/SHINE useful for understanding neutrino beam flux
- 120 GeV/*c* p+C multiplicities will be published this summer
- Results will be used to reduce DUNE beam flux uncertainty
- DUNE target measurement foreseen at NA61/SHINE within next ~2 years

Thanks!

BACKUP

Recent Publications for Neutrino Experiments

- **Phys. Rev. D 98, 052001 (2018):**
  - π^+ on C, Al (31 & 60 GeV/c)
  - π^+ on Be (60 GeV/c)
  - K^+ on C, Al (60 GeV/c)
- **EPJC 79, Article 100 (2019):**
  - Double differential π, p, K yields from 31 GeV/c p+T2K replica target
- **Phys. Rev. D 100, 112001 (2019):**
  - p on C, Be (60 & 120 GeV/c)
  - p on Al (60 GeV/c)
- **Phys. Rev. D 103, 012006 (2021):**
  - p+T2K replica target at 31 GeV/c (with high magnetic field)
  - Proton beam survival probability for measurement of production cross-section

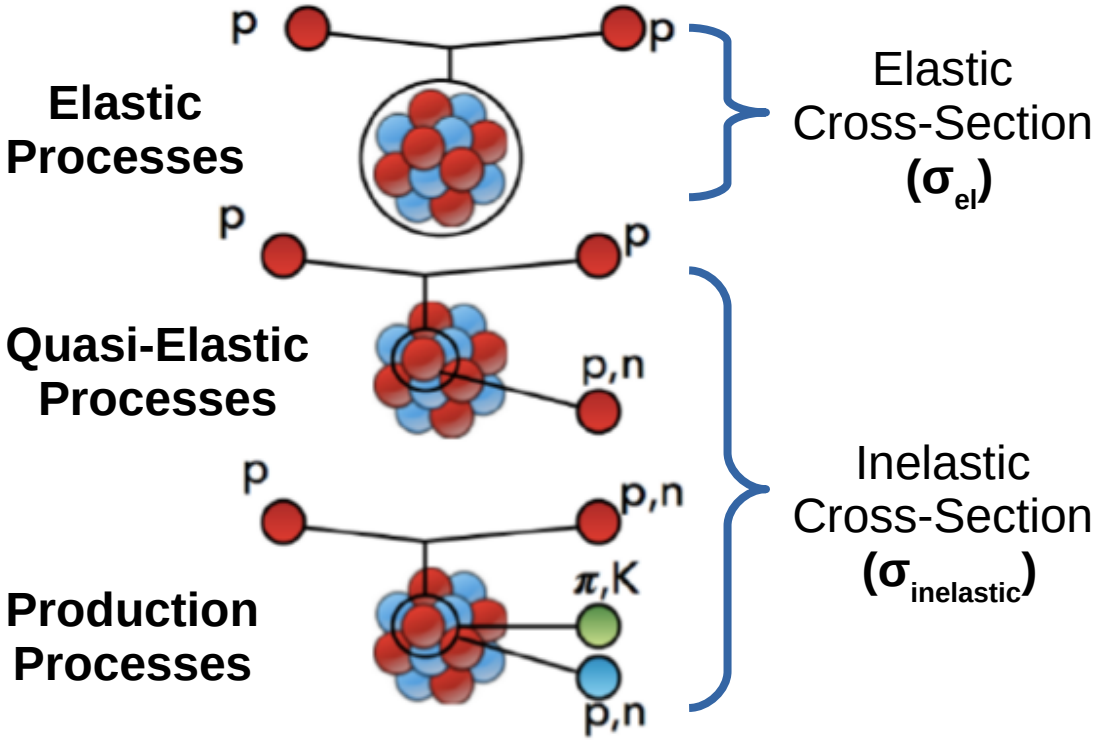


Lukas Berns, NBI 2019

Interaction Definitions

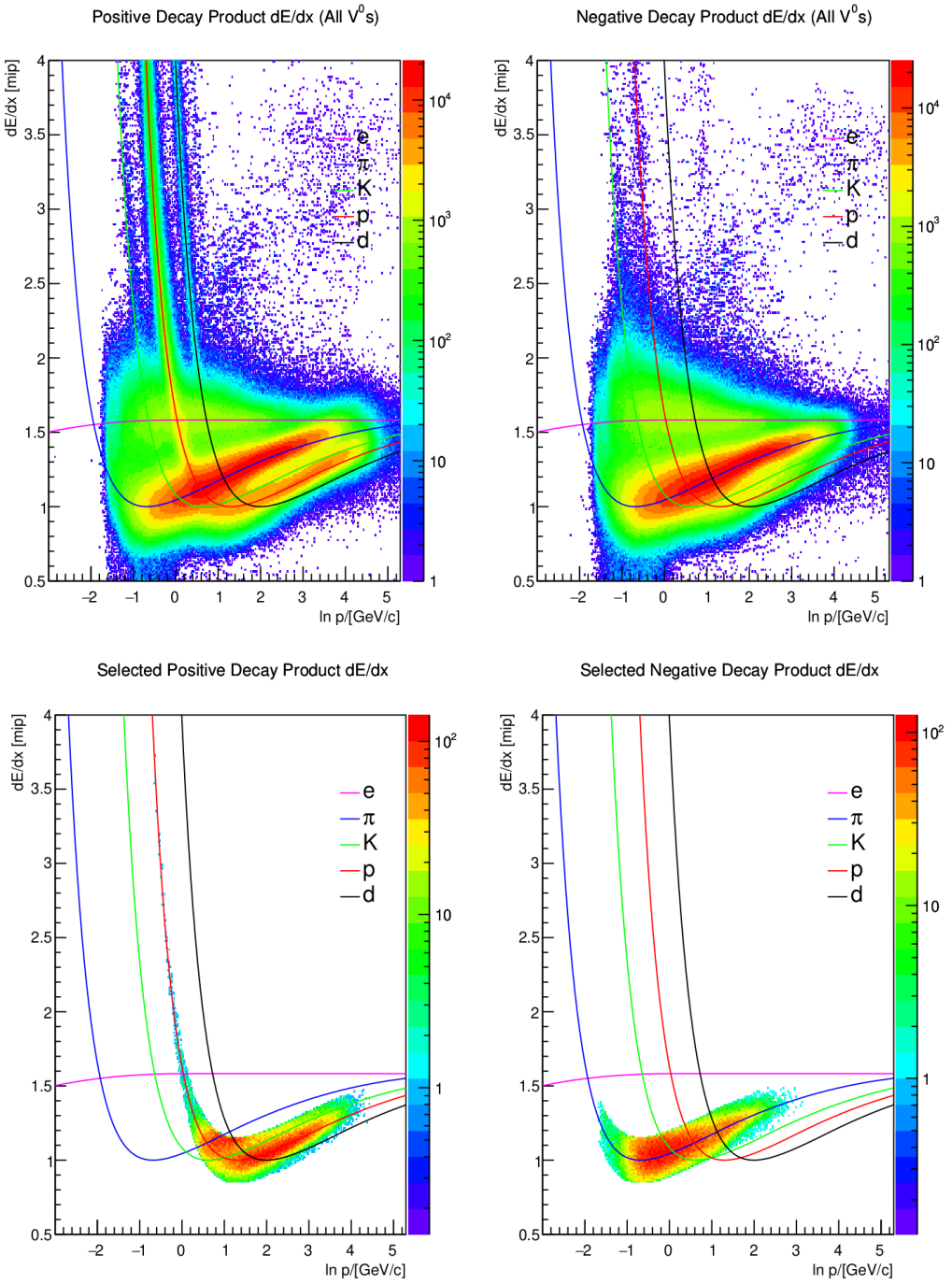
$$\sigma_{inelastic} = \sigma_{total} - \sigma_{elastic}$$

$$\sigma_{production} = \sigma_{inelastic} - \sigma_{QE}$$



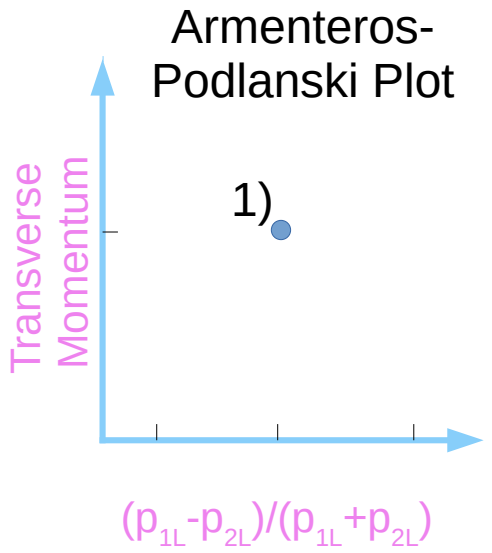
Selection Cuts

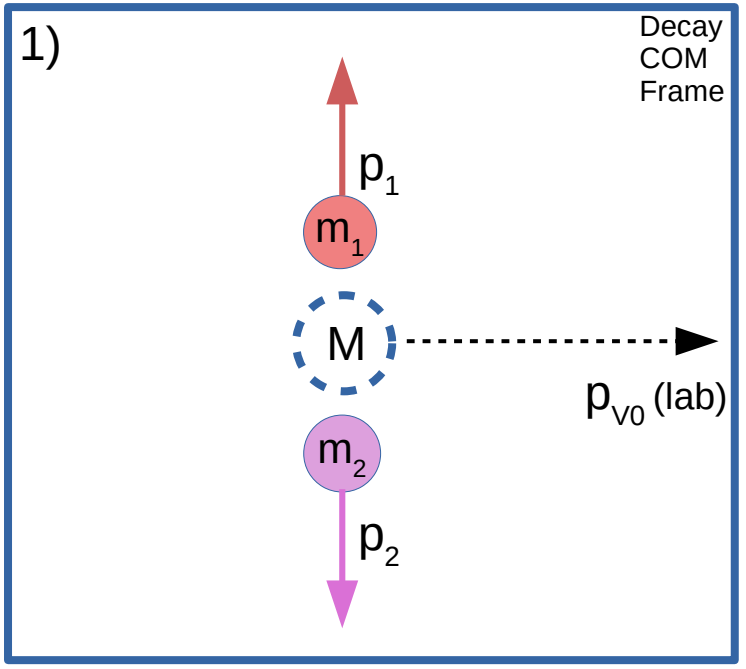
- Quality cuts
  - Sufficient number of detector measurement points
  - Reasonable impact parameter
  - Incoming beam particle trajectory well-measured
- Sample purity cuts
  - Decay product dE/dx cut (pictured right)
  - Minimum transverse momentum cut
  - Minimum & maximum decay length cut
  - Proper lifetime cut

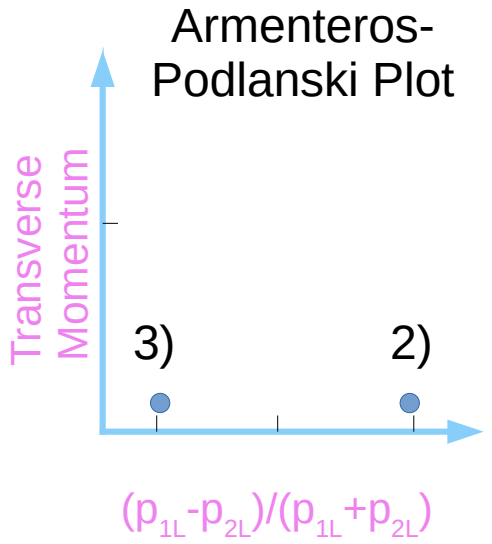


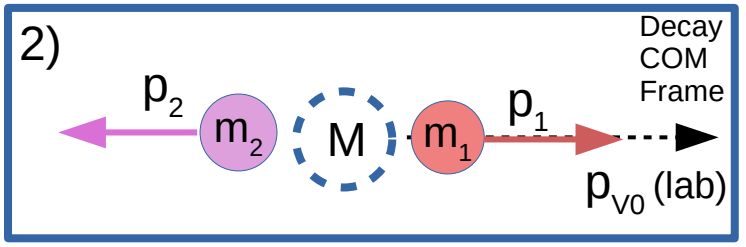
Armenteros-Podolanski Distributions

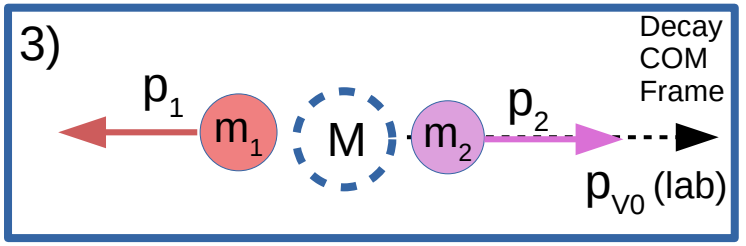
- Nice way of visually representing two-body decay kinematics
- Demonstrates species contamination after cut application
- V^0 candidates represented by points in (α, p_T) space
- Unstable particle species separate into arcs

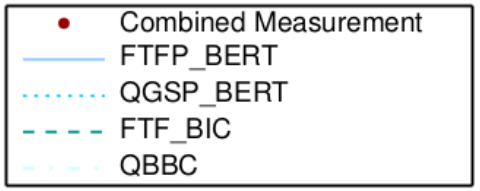


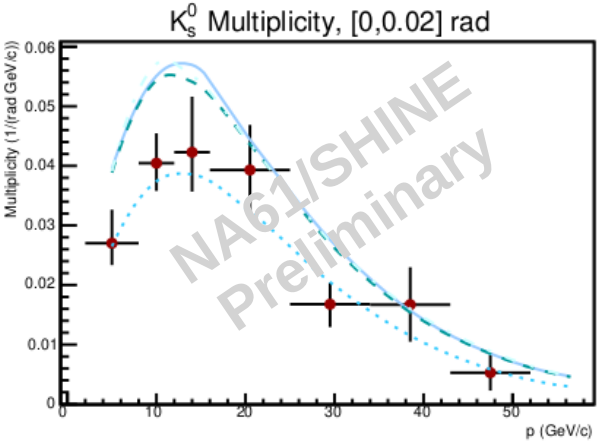


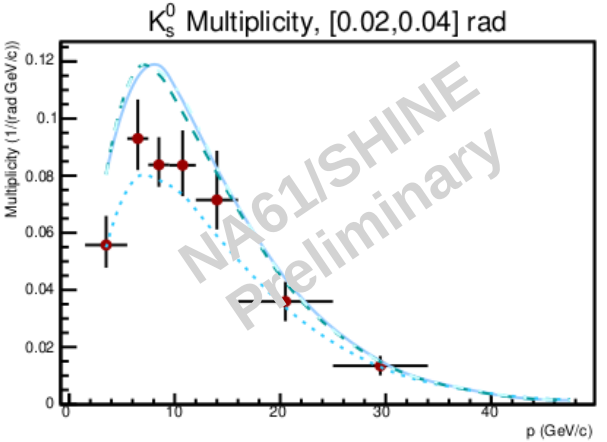







Combined Measurement
FTFP_BERT
QGSP_BERT
FTF_BIC
QBBC


K_s^0 Multiplicity, [0,0.02] rad
Multiplicity (1/(rad GeV/c))
p (GeV/c)
NA61/SHINE
Preliminary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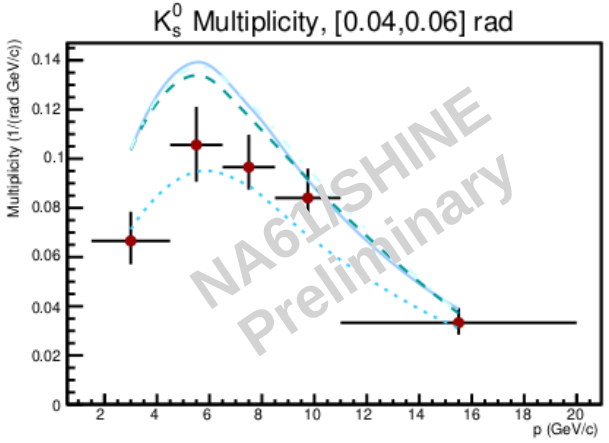
p (GeV/c)
NA61/SHINE
Preliminary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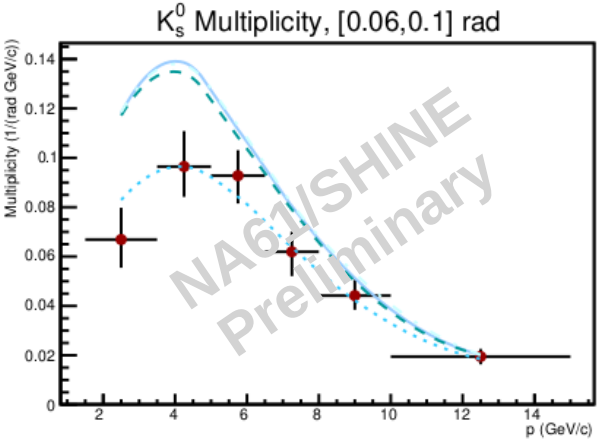
p (GeV/c)
NA61/SHINE
Preliminary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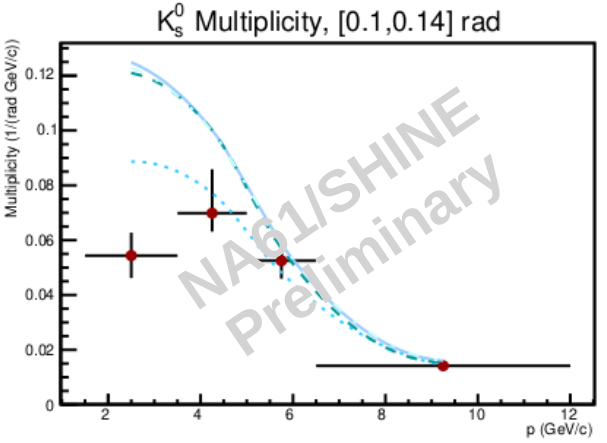
NA61/SHINE
Preliminary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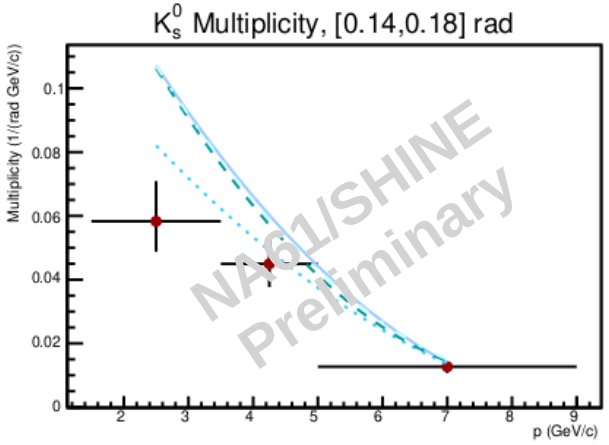
p (GeV/c)
NA61/SHINE
Preliminary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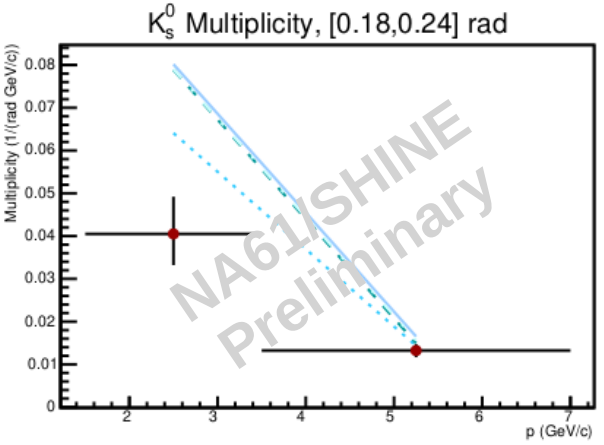
NA61/SHINE
Preliminary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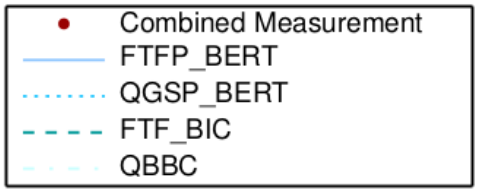
p (GeV/c)
NA61/SHINE
Preliminary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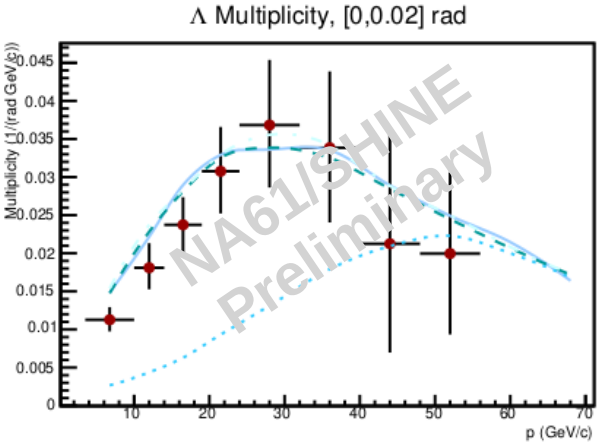
QGSP_BERT
FTF_BIC
QBBC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NA61/SHINE
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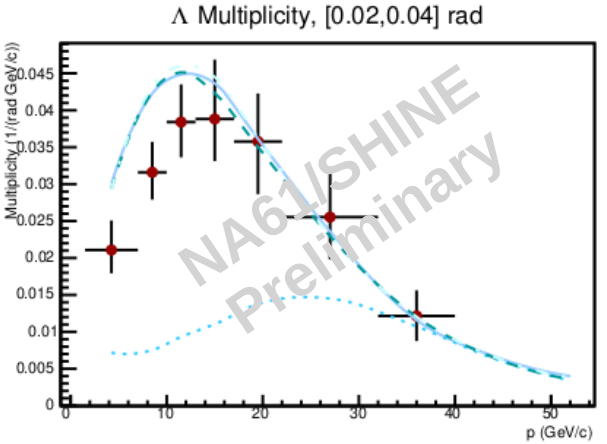
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NA61/SHINE
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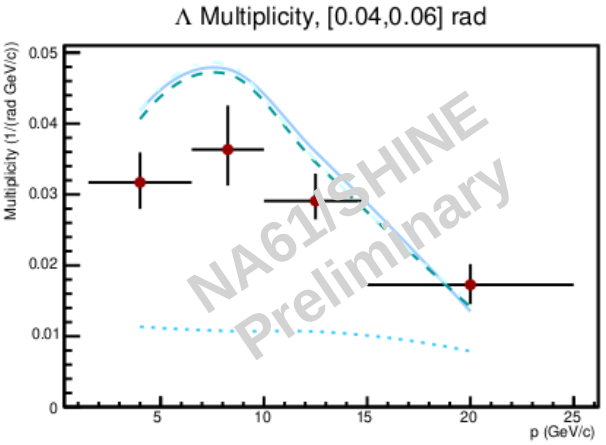
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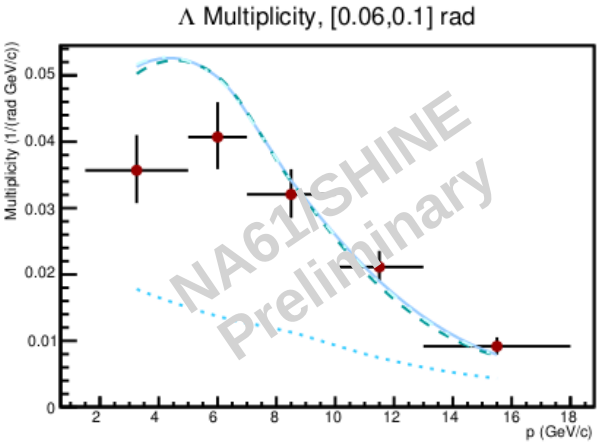
NA61/SHINE
Preliminary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p (GeV/c)
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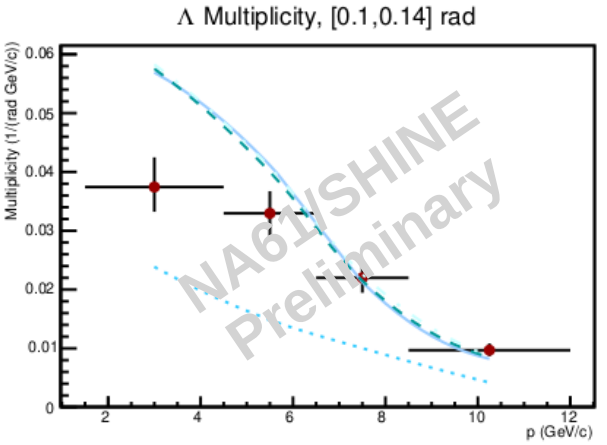
Preliminary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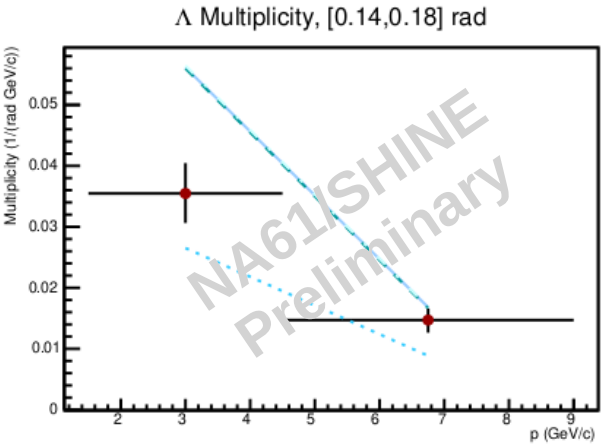
p (GeV/c)
NA61/SHINE
Preliminary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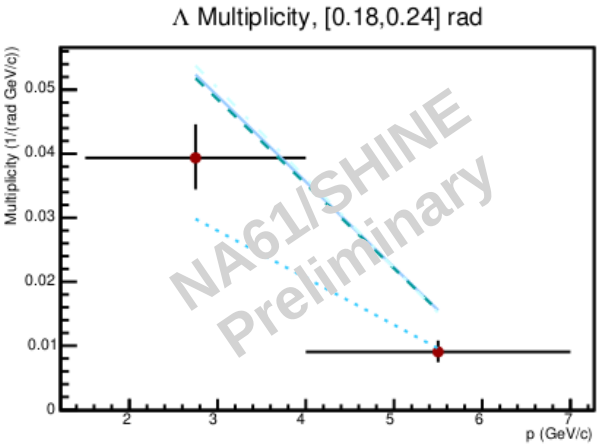
NA61/SHINE
Preliminary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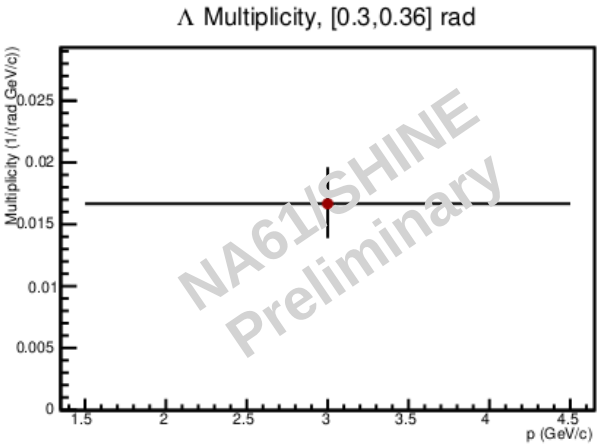
NA61/SHINE
Preliminary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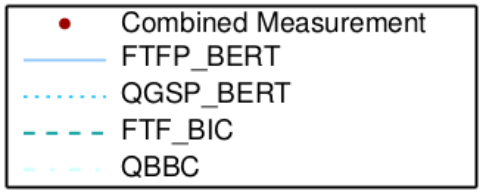
p (GeV/c)
NA61/SHINE
Preliminary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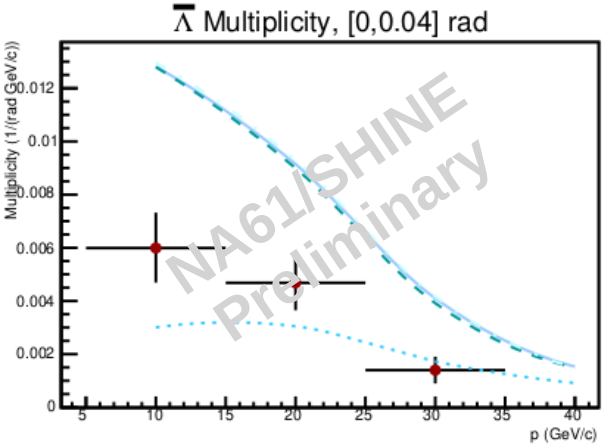
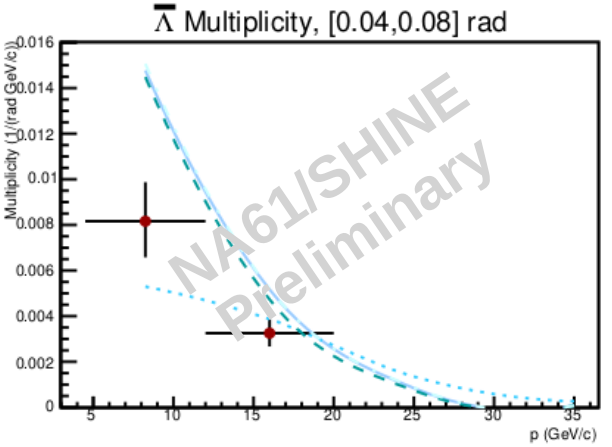
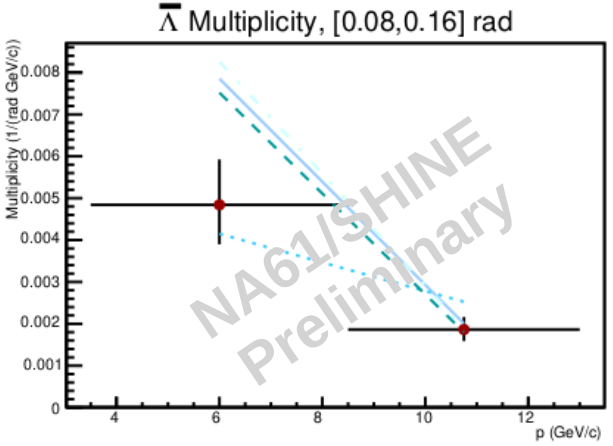
FTFP_BERT
QGSP_BERT
FTF_BIC
QBBC

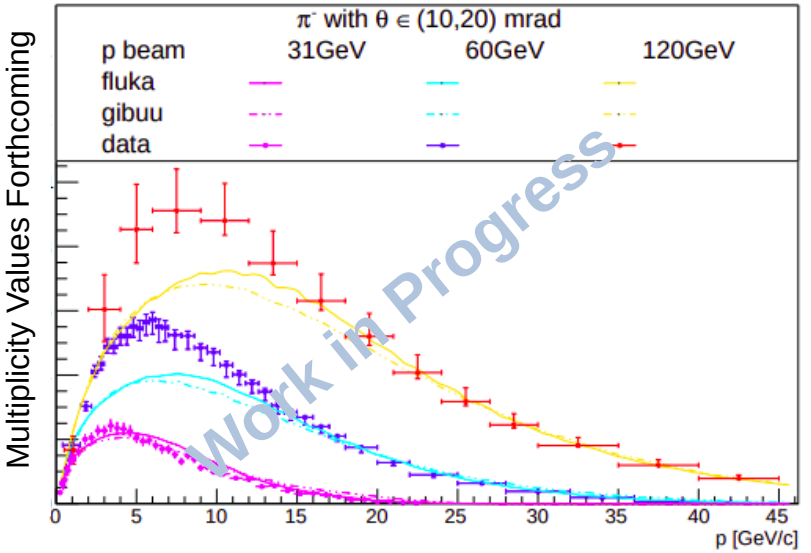

$\overline{\Lambda}$ Multiplicity, [0,0.04] rad
Multiplicity (1/(rad GeV/c))
p (GeV/c)
NA61/SHINE
Preliminary

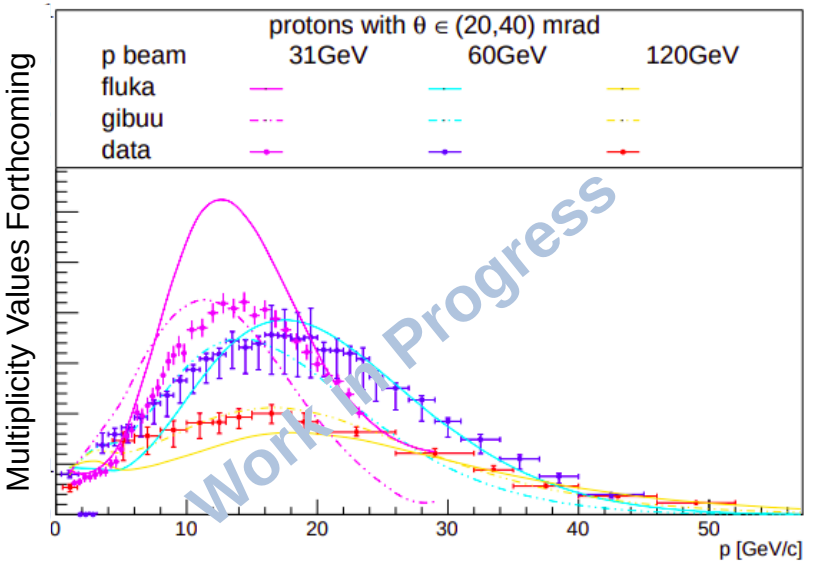

$\overline{\Lambda}$ Multiplicity, [0.04,0.08] rad
Multiplicity (1/(rad GeV/c))
p (GeV/c)
NA61/SHINE
Preliminary


$\overline{\Lambda}$ Multiplicity, [0.08,0.16] rad
Multiplicity (1/(rad GeV/c))
p (GeV/c)
NA61/SHINE
Preliminary

Coming Soon: “Evolution Plots”

- Comparisons of identical reactions at different energies allow for testing of momentum scaling assumptions
- Forthcoming comparison: 31, 60, 120 GeV/c protons & carbon
- 90 GeV/c protons & carbon analysis in preparation

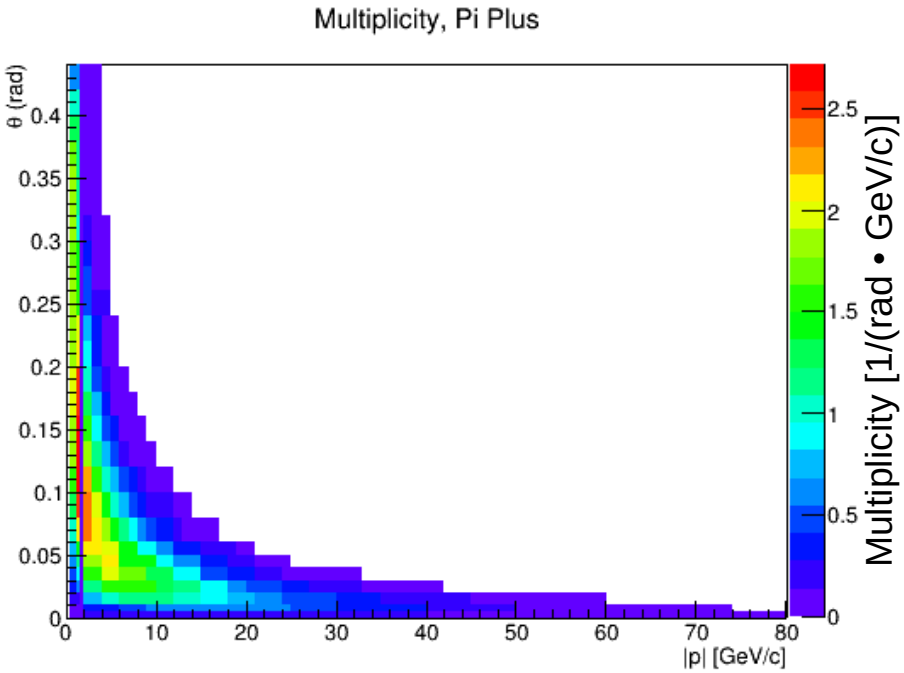


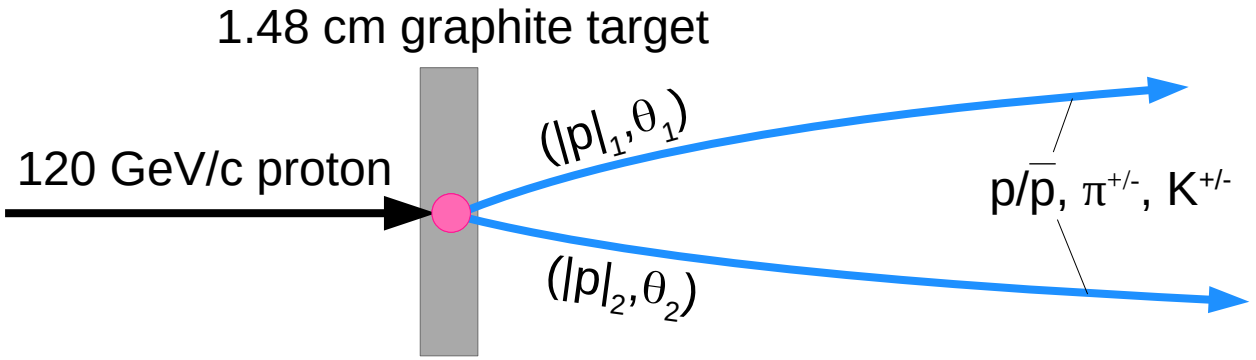


(Claire Dalmazzone)

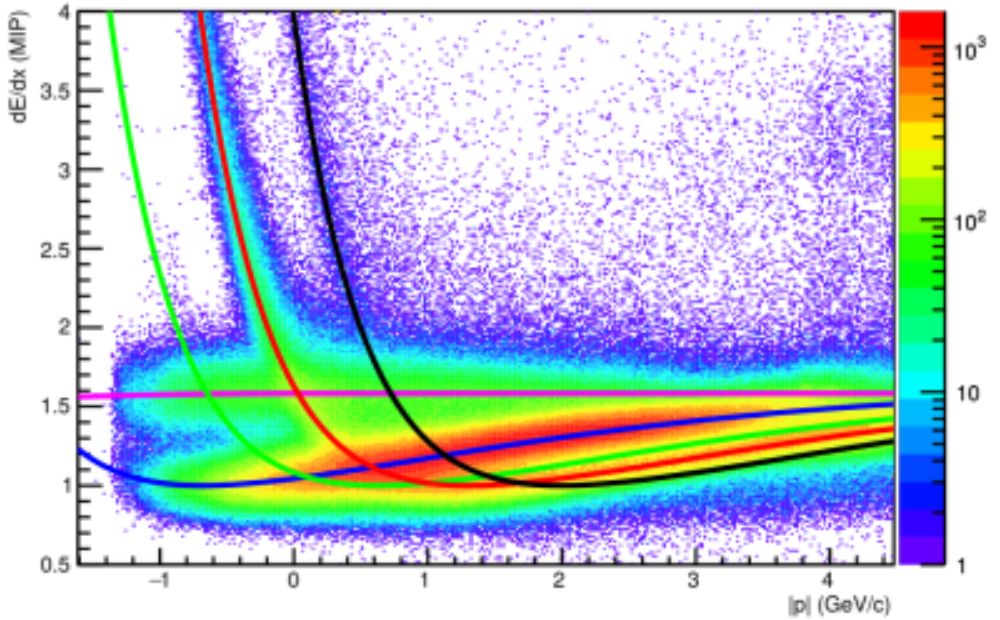
Charged Hadron Analysis Details

- Multiplicity of $p/\bar{p}$, $\pi^{+/-}$, $K^{+/-}$ studied
  - Multiplicity: Number of particle *X* produced *per production interaction*
- Differential multiplicities reported as a function of total momentum |p| and polar angle θ

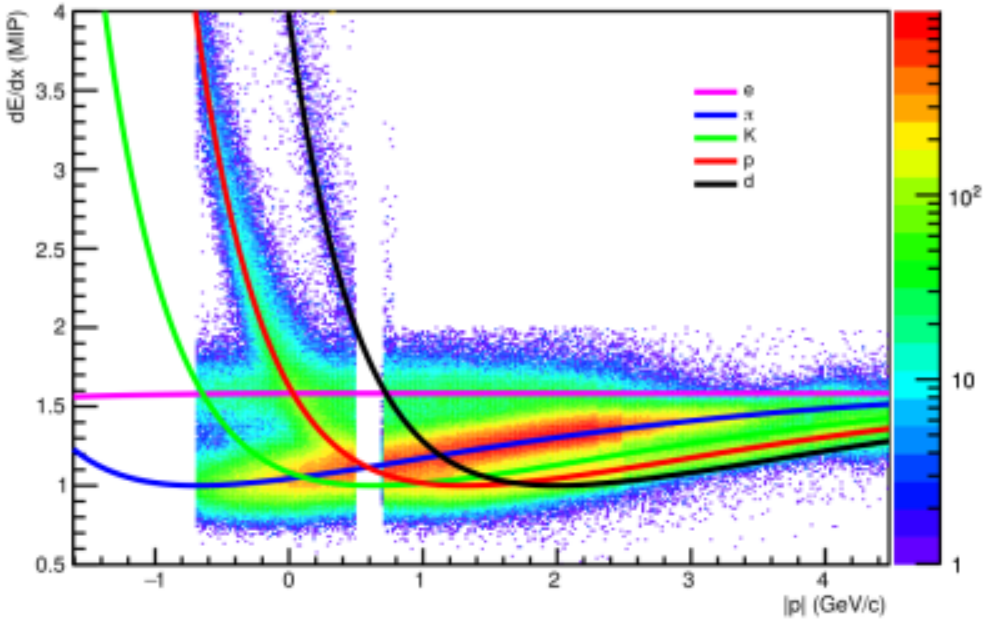




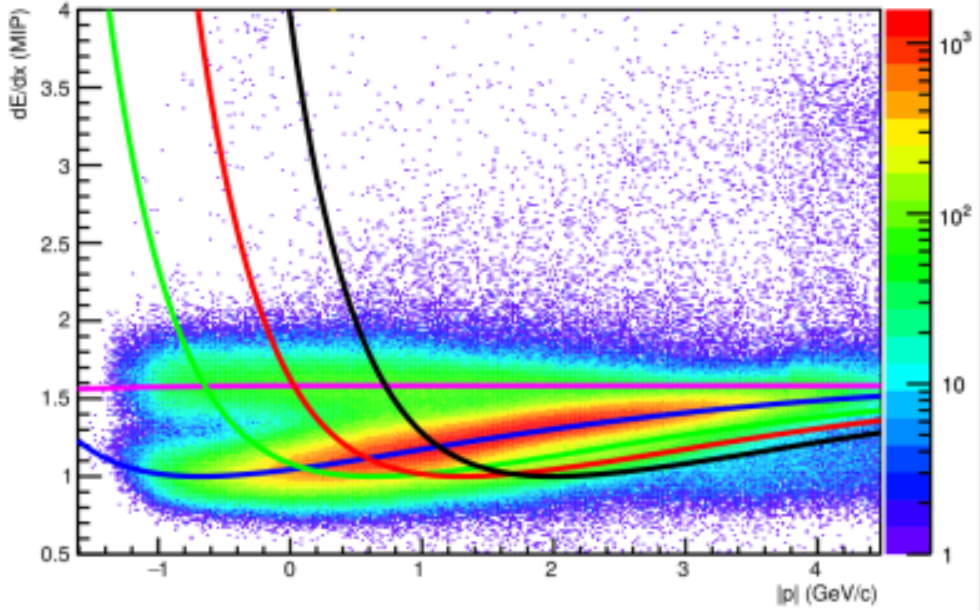
dE/dx vs. log|p|, Positive Tracks (No Cuts)



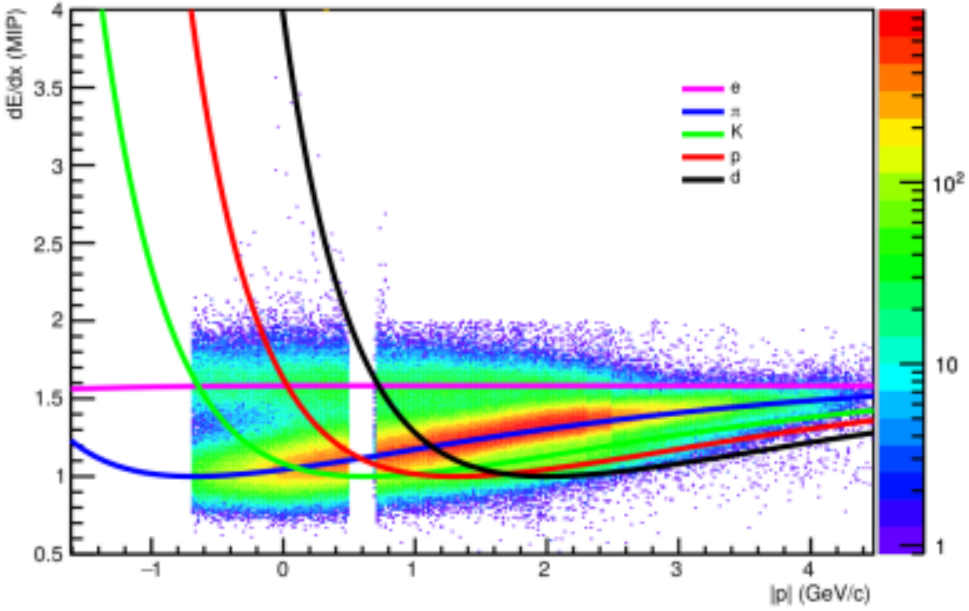
dE/dx vs. log|p|, Positive Tracks (Cuts Applied)



dE/dx vs. log|p|, Negative Tracks (No Cuts)

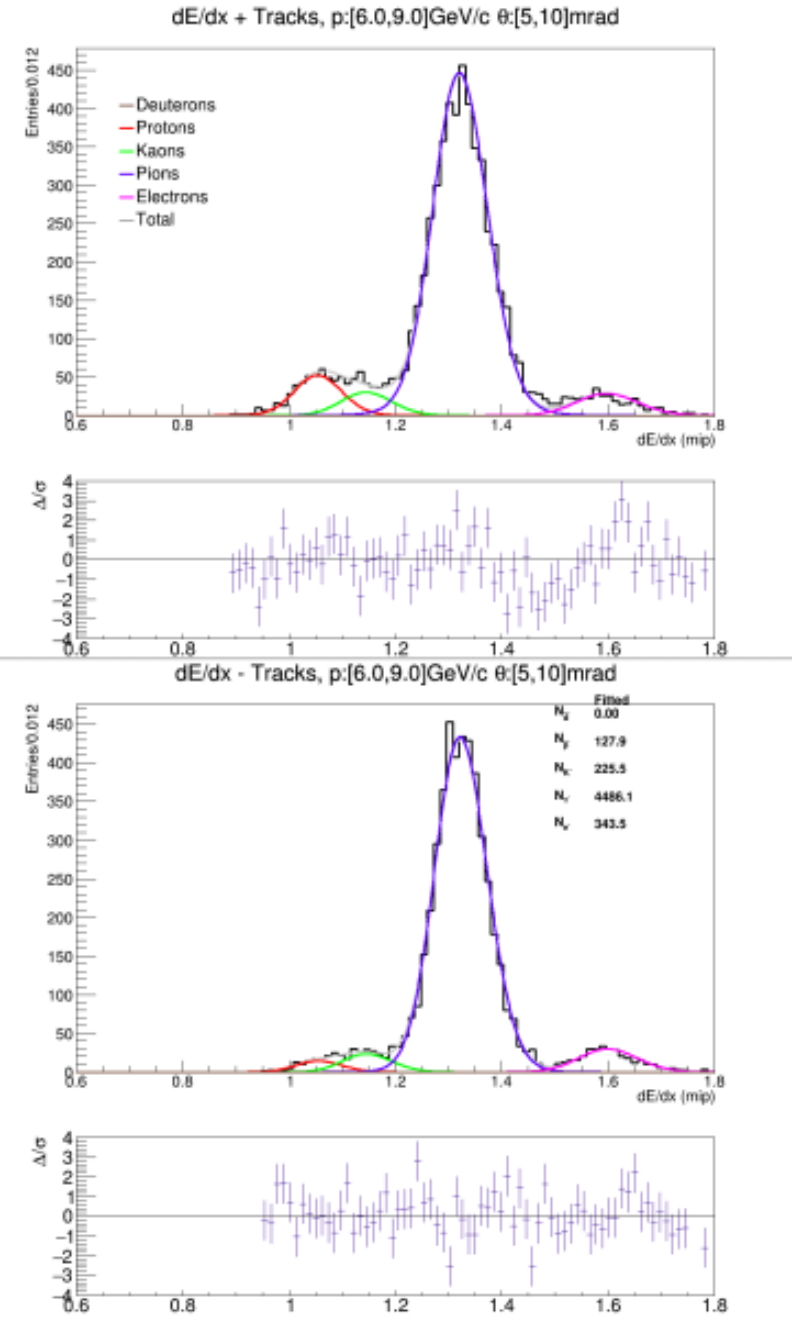


dE/dx vs. log|p|, Negative Tracks (Cuts Applied)

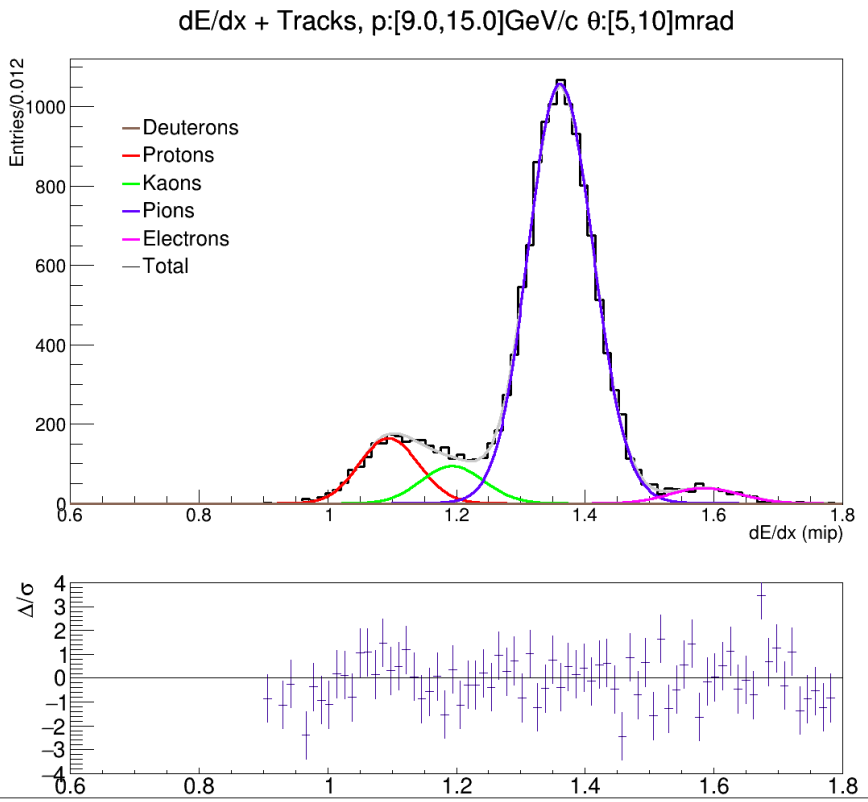


dE/dx Fits

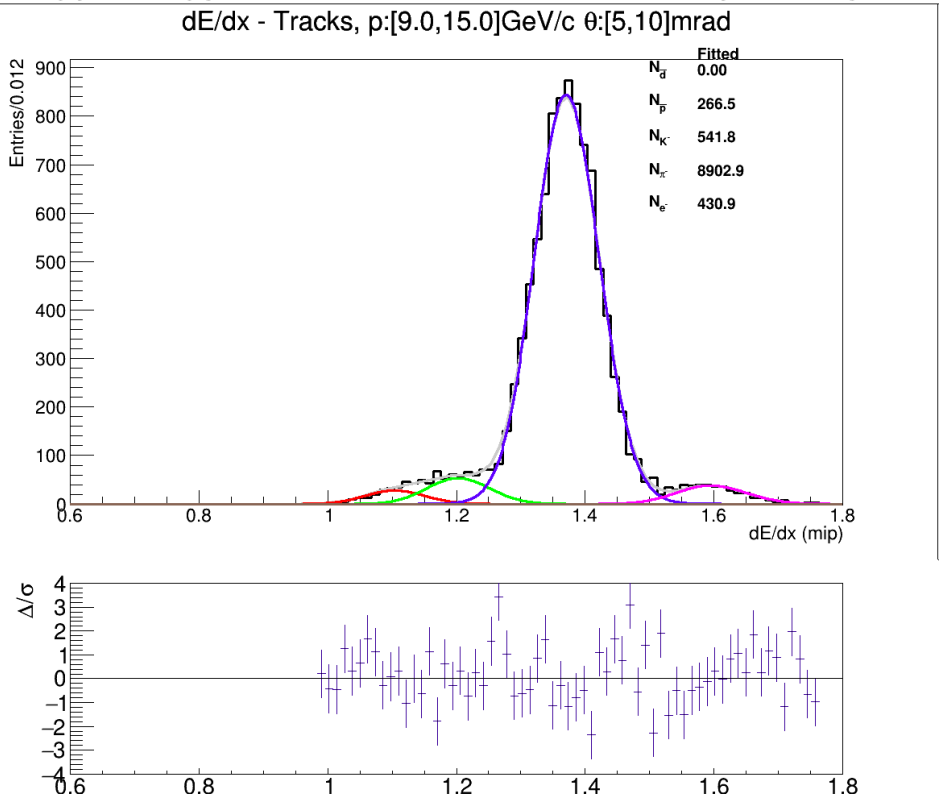
- In each kinematic bin, likelihood-based dE/dx fit performed to track dE/dx distribution
- Result: Fraction of $e^{+/-}$, $\pi^{+/-}$, $K^{+/-}$, $p/\bar{p}$, $D^{+/-}$ in each kinematic bin
  - Positive and negative tracks fit simultaneously in order to constrain calibration parameters
- Total number of each species used to calculate identified multiplicity in each bin



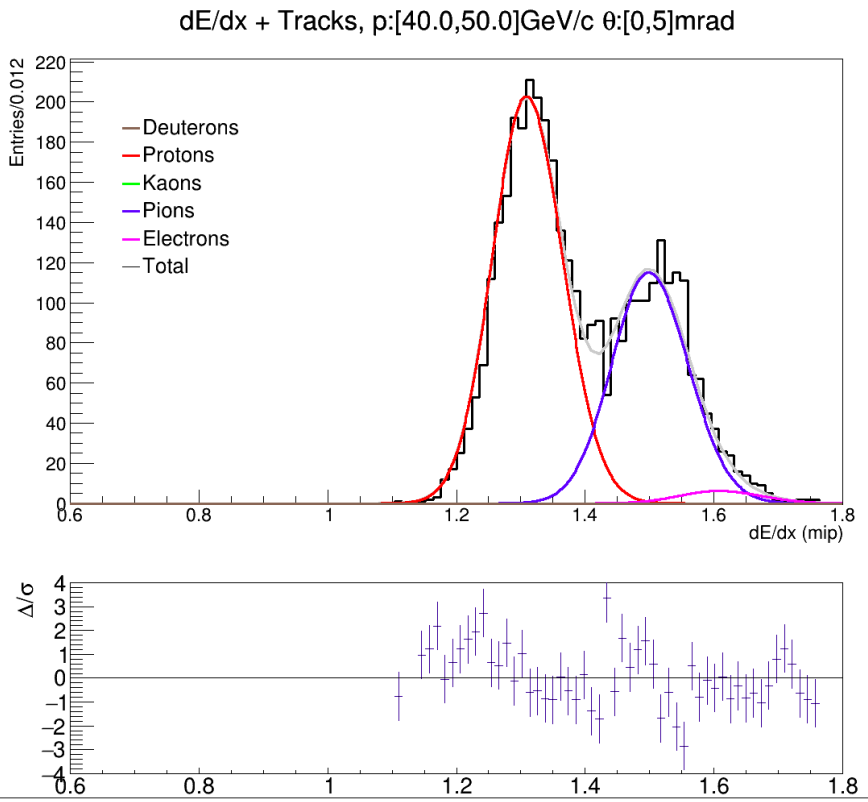
	Fitted		Fitted
N_{De}	0.00	σ^0_{Up}	0.6800
X_{De}	0.005	σ^0_{V}	0.4786
N_{Pr}	1587.34	σ^0_{M}	0.4656
X_{Pr}	-0.008	f^+_σ	1.0025
N_{K^+}	960.67	f^-_σ	1.0004
X_{K^+}	-0.003	f^e_σ	1.0230
N_{π^+}	11189.3	α	0.6524
X_{π^+}	0.005	d	0.0400
N_{e^+}	438.70	X_{π^+}	0.0051
X_{e^+}	0.005	X_{π^-}	0.0151
		X_{De}	0.0000
		X_{Pr}	-0.0135
		X_K	-0.0080
		X_e	-0.0006
		σ^0_F	0.4400



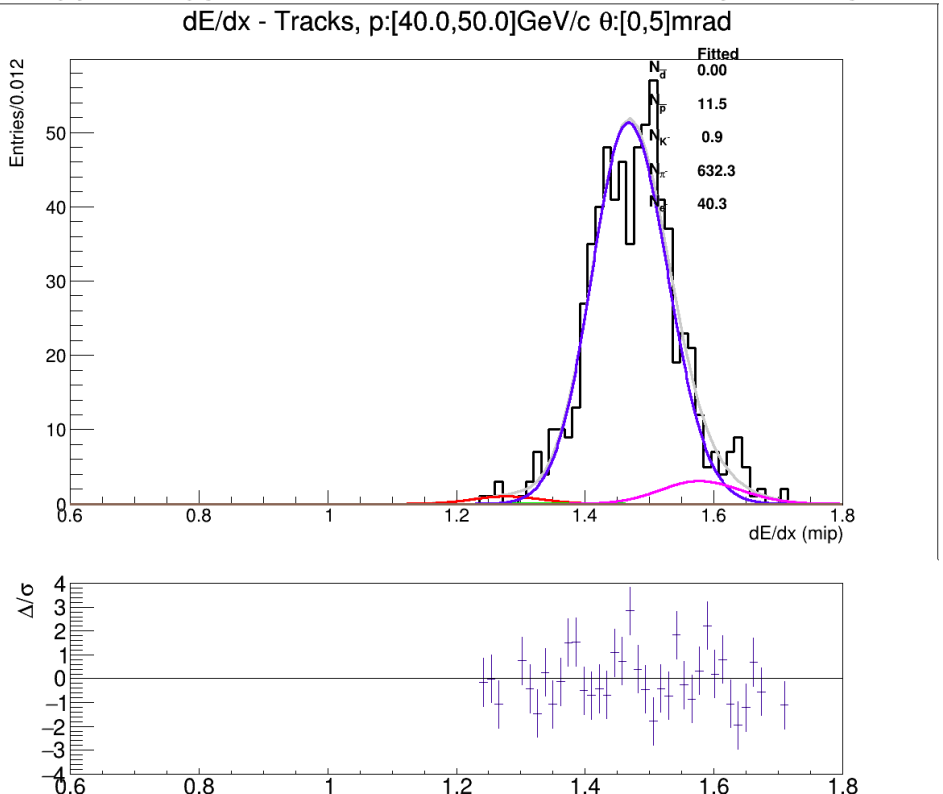
	Fitted
N_{De^-}	0.00
X_{De^-}	0.015
N_{Pr^-}	266.46
X_{Pr^-}	0.002
N_{K^-}	541.79
X_{K^-}	0.007
N_{π^-}	8902.9
X_{π^-}	0.015
N_{e^-}	430.88
X_{e^-}	0.015

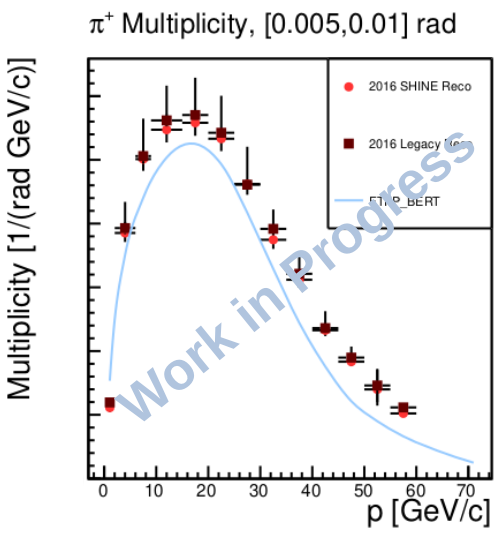


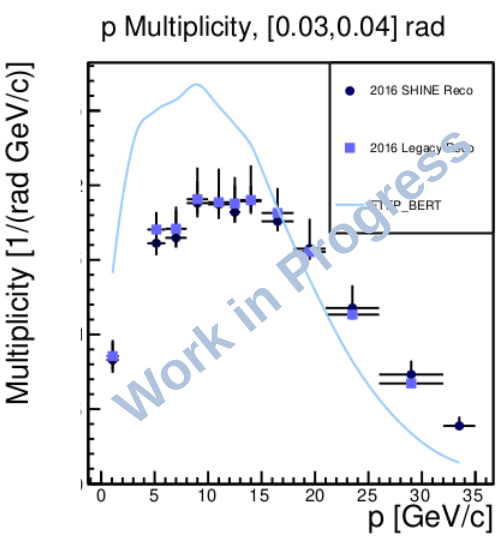
	Fitted		Fitted
N_{De}	0.00	σ^0_{Up}	0.6800
X_{De}	0.028	σ^0_{V}	0.4600
N_{Pr}	2322.75	σ^0_{M}	0.4558
X_{Pr}	0.029	f^+_σ	0.9996
N_{K^+}	0.00	f^-_σ	1.0003
X_{K^+}	0.028	f^e_σ	1.0197
N_{π^+}	1427.8	α	0.6501
X_{π^+}	0.028	d	0.0400
N_{e^+}	82.42	X_{π^+}	0.0285
X_{e^+}	0.028	X_{π^-}	-0.0021
		X_{De}	-0.0000
		X_{Pr}	0.0005
		X_{K}	-0.0000
		X_{e}	-0.0000
		σ^0_{F}	0.4430

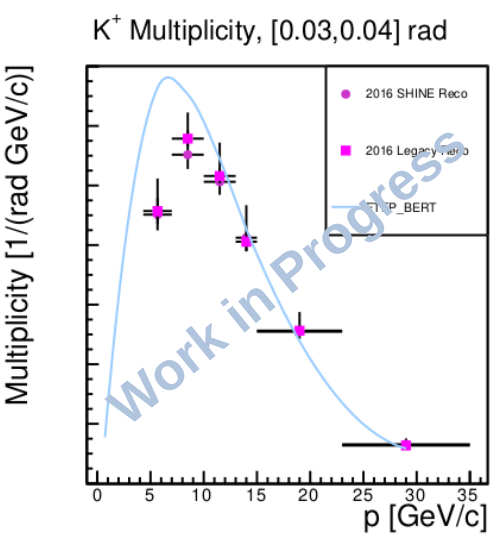


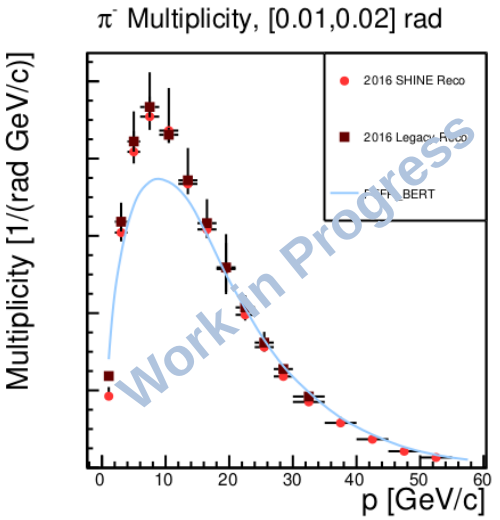
	Fitted
N_{De^-}	0.00
X_{De^-}	-0.002
N_{Pr^-}	11.47
X_{Pr^-}	-0.002
N_{K^-}	0.92
X_{K^-}	-0.002
N_{π^-}	632.3
X_{π^-}	-0.002
N_{e^-}	40.34
X_{e^-}	-0.002

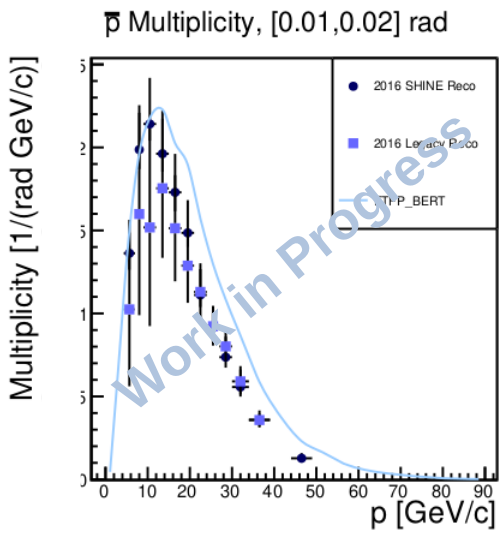


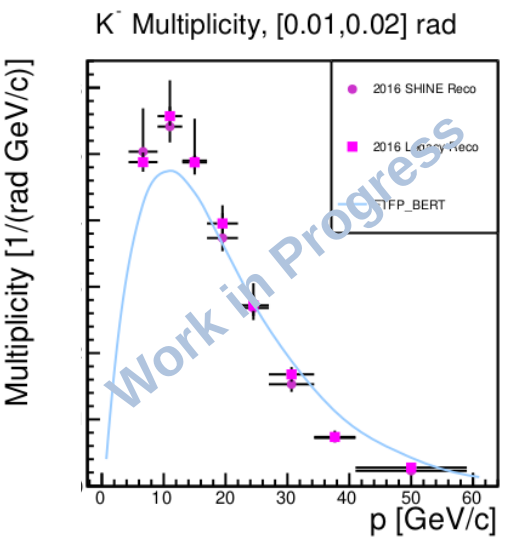

π^+ Multiplicity, [0.005,0.01] rad
Multiplicity [1/(rad GeV/c)]
p [GeV/c]
2016 SHINE Reco
2016 Legacy Reco
TFP_BERT
Work in Progress


p Multiplicity, [0.03,0.04] rad
Multiplicity [1/(rad GeV/c)]
p [GeV/c]
2016 SHINE Reco
2016 Legacy Reco
TFP_BERT
Work in Progress


K^+ Multiplicity, [0.03,0.04] rad
Multiplicity [1/(rad GeV/c)]
p [GeV/c]
2016 SHINE Reco
2016 Legacy Reco
TFP_BERT
Work in Progress


π^- Multiplicity, [0.01,0.02] rad
Multiplicity [1/(rad GeV/c)]
p [GeV/c]
2016 SHINE Reco
2016 Legacy Reco
TFP_BERT
Work in Progress

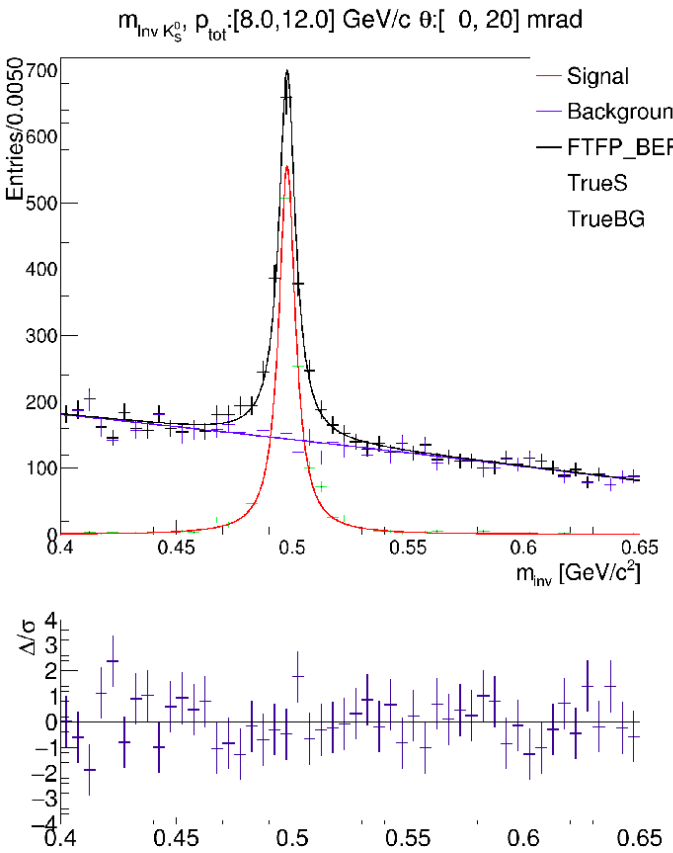

$\bar{p}$ Multiplicity, [0.01,0.02] rad
Multiplicity [1/(rad GeV/c)]
p [GeV/c]
2016 SHINE Reco
2016 Legacy Reco
TFP_BERT
Work in Progress


K^- Multiplicity, [0.01,0.02] rad
Multiplicity [1/(rad GeV/c)]
p [GeV/c]
2016 SHINE Reco
2016 Legacy Reco
TFP_BERT
Work in Progress

Invariant Mass Fits (Monte Carlo)

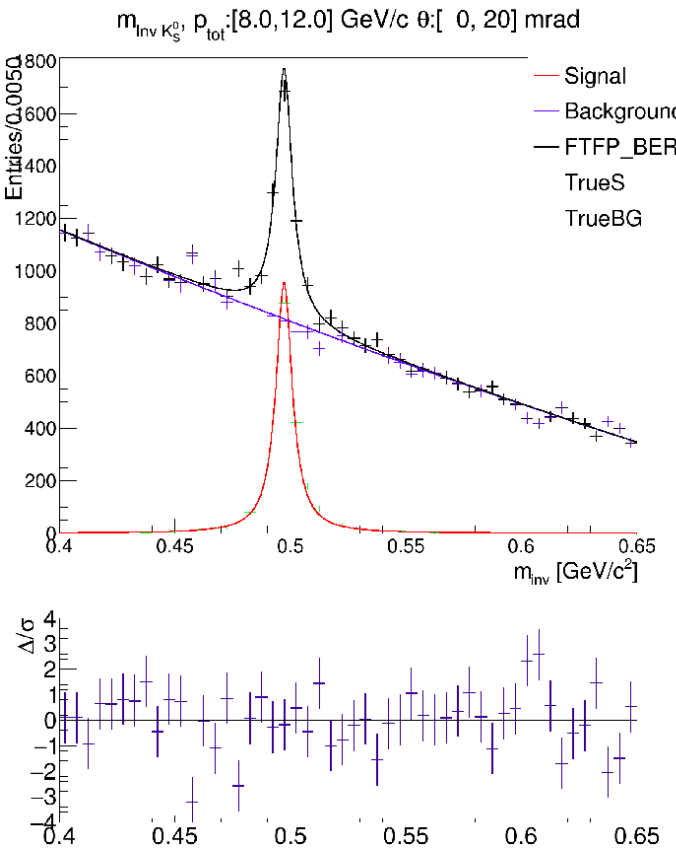
2016

	True	Fitted
N_S	1531	1473.19
N_{BG}	6572	6629.81
f_s	0.1889	0.1818
m_0		0.0002
Γ		0.0043
c_1		9.2290
c_2		-7.6759
c_3		-4.2281



2017

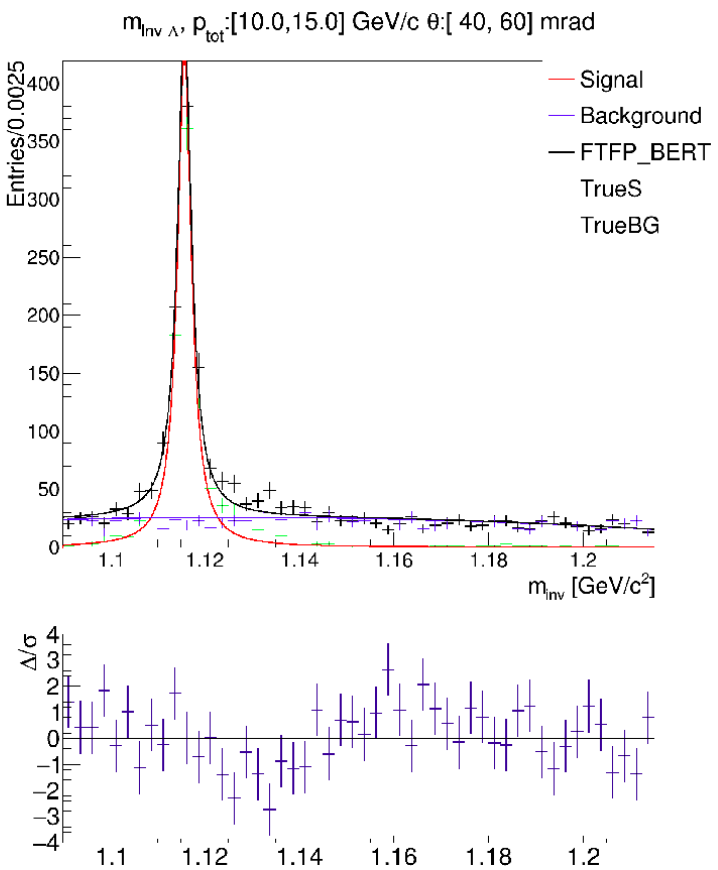
	True	Fitted
N_S	2590	2521.15
N_{BG}	36660	36728.85
f_s	0.0660	0.0642
m_0		-0.0003
Γ		0.0043
c_1		19.5094
c_2		-33.5417
c_3		11.0114



Invariant Mass Fits (Monte Carlo)

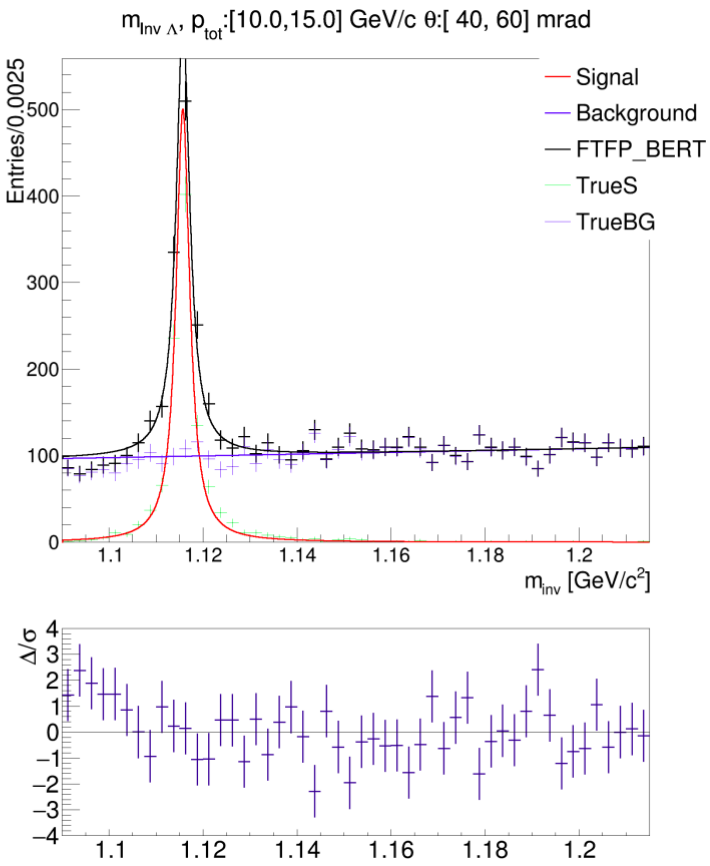
2016

	True	Fitted
N_S	1059	931.88
N_{BG}	1032	1159.12
f_s	0.5065	0.4457
m_0		0.0001
Γ		-0.0018
c_1		-472.9663
c_2		852.2031
c_3		-378.0478



2017

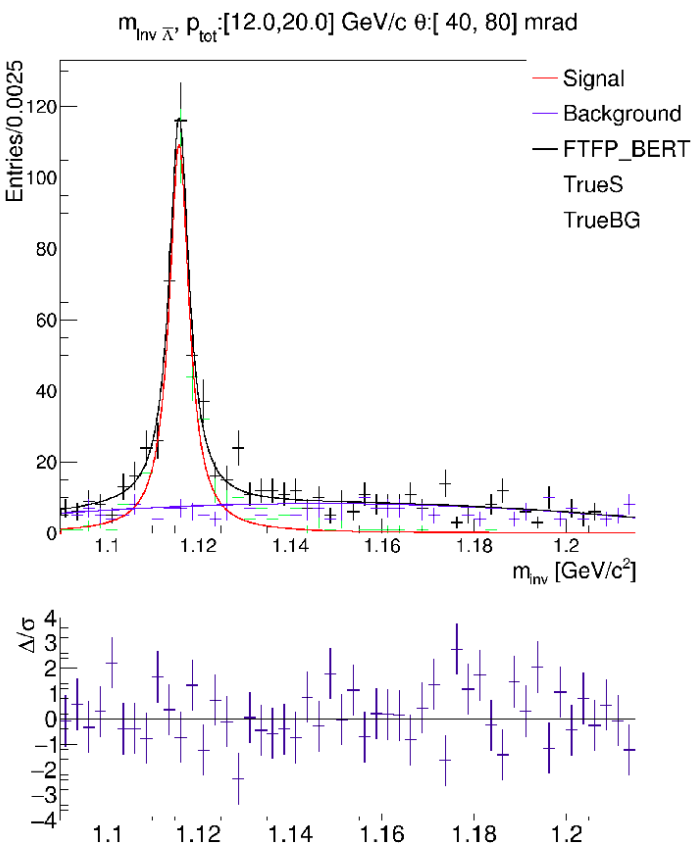
	True	Fitted
N_S	1116	1068.16
N_{BG}	5103	5150.84
f_s	0.1795	0.1718
m_0		0.0001
Γ		0.0017
c_1		13945.651
c_2		18029.242
c_3		16864.026



Invariant Mass Fits (Monte Carlo)

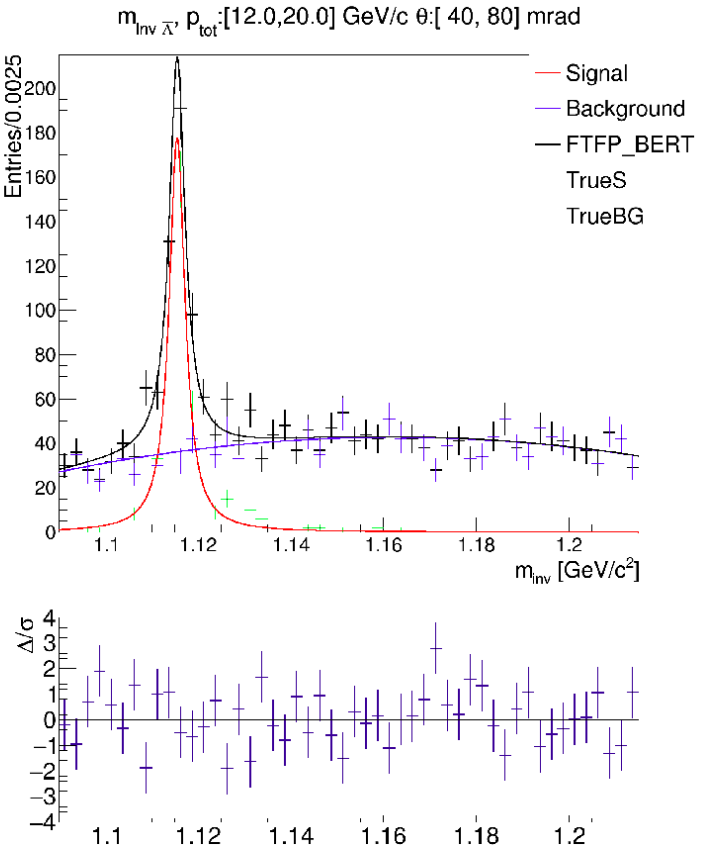
2016

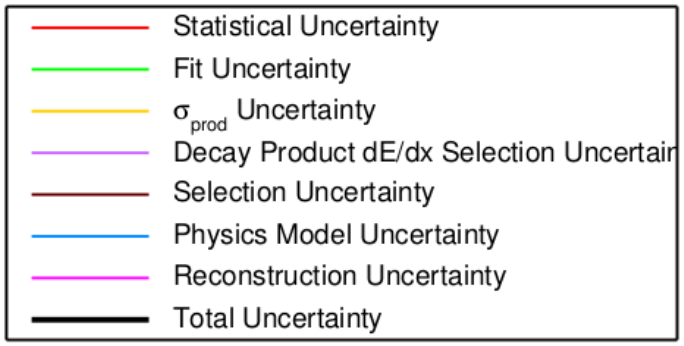
	True	Fitted
N_S	387	344.30
N_{BG}	316	358.70
f_s	0.5505	0.4898
m_0		0.0003
Γ		-0.0026
c_1		-776.2447
c_2		1363.9196
c_3		-594.6945

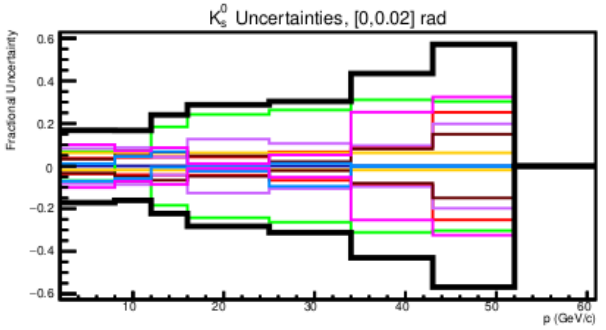


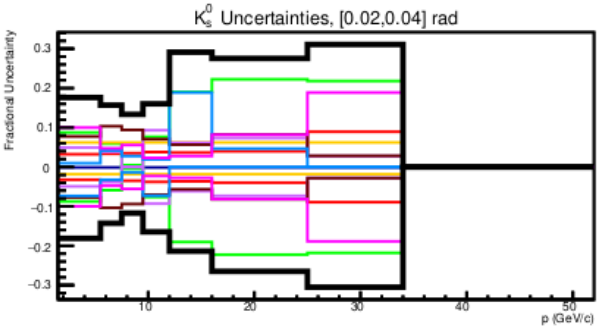
2017

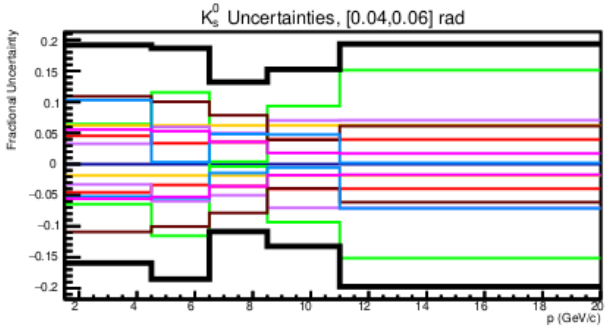
	True	Fitted
N_S	484	447.20
N_{BG}	1890	1926.80
f_s	0.2039	0.1884
m_0		-0.0001
Γ		0.0021
c_1		-688.8507
c_2		1198.1652
c_3		-515.5319

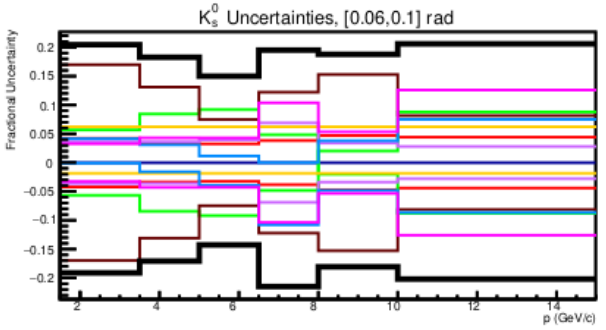


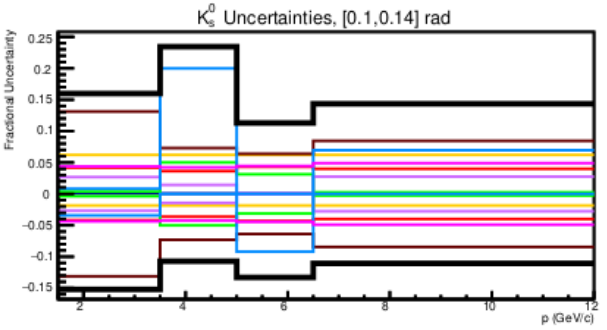

Statistical Uncertainty
Fit Uncertainty
σ prod Uncertainty
Decay Product dE/dx Selection Uncertain
Selection Uncertainty
Physics Model Uncertainty
Reconstruction Uncertainty
Total Uncertainty

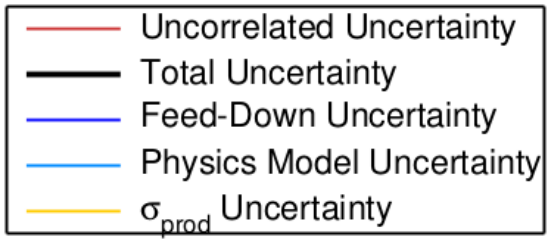

K0s Uncertainties, [0,0.02] rad
Fractional Uncertainty
p (GeV/c)

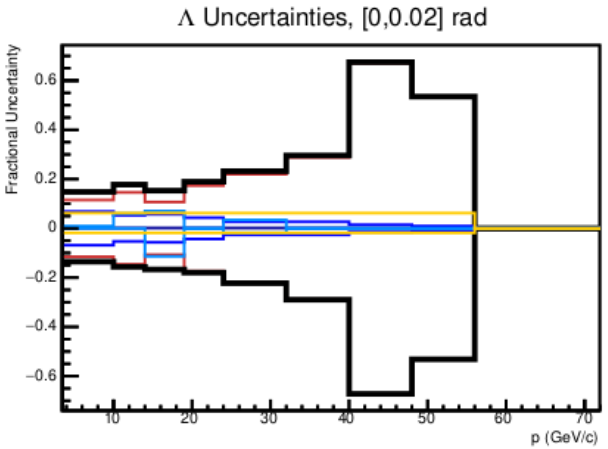

K0s Uncertainties, [0.02,0.04] rad
Fractional Uncertainty
p (GeV/c)

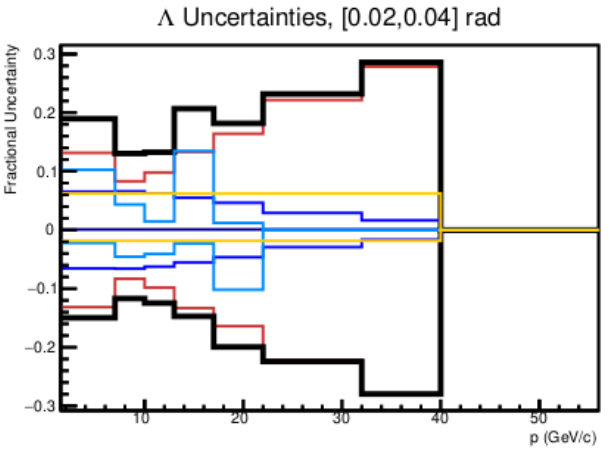

K0s Uncertainties, [0.04,0.06] rad
Fractional Uncertainty
p (GeV/c)

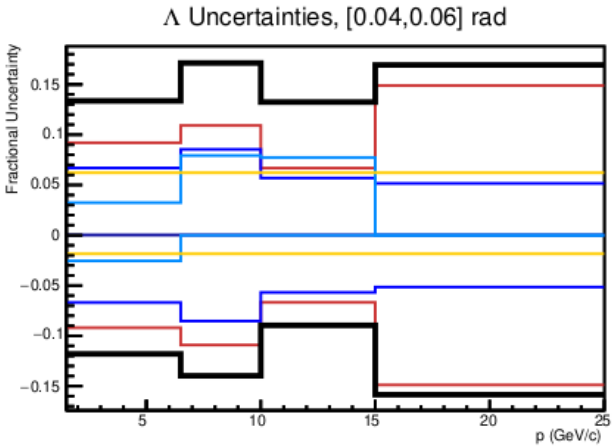

K0s Uncertainties, [0.06,0.1] rad
Fractional Uncertainty
p (GeV/c)

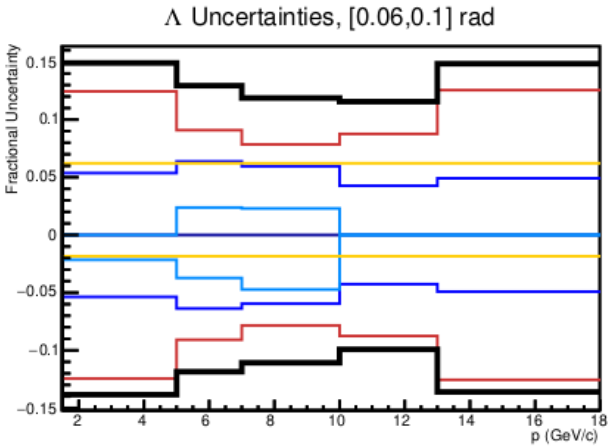

K0s Uncertainties, [0.1,0.14] rad
Fractional Uncertainty
p (GeV/c)

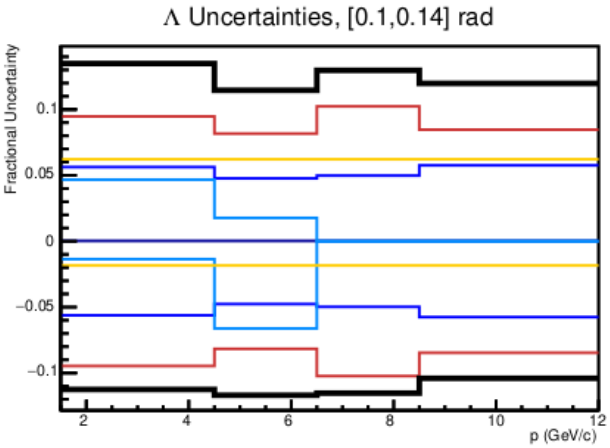

Uncorrelated Uncertainty
Total Uncertainty
Feed-Down Uncertainty
Physics Model Uncertainty
σ_{prod} Uncertainty

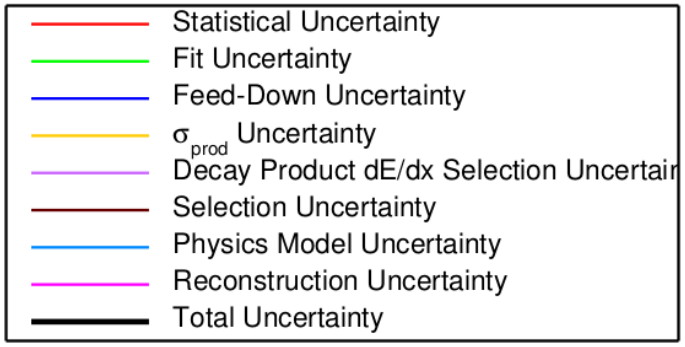

Λ Uncertainties, [0,0.02] rad
Fractional Uncertainty
p (GeV/c)

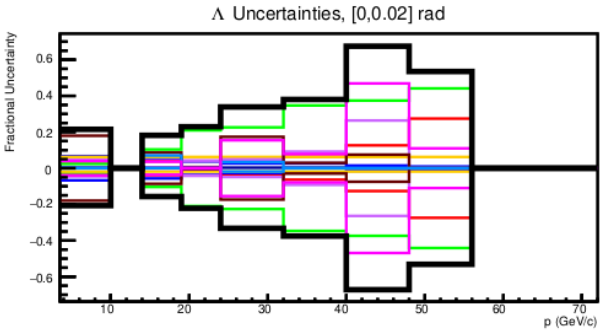

Λ Uncertainties, [0.02,0.04] rad
Fractional Uncertainty
p (GeV/c)

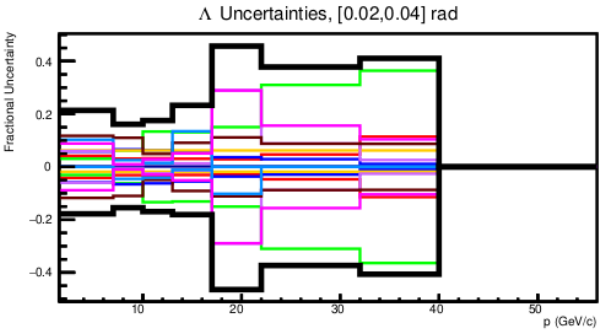

Λ Uncertainties, [0.04,0.06] rad
Fractional Uncertainty
p (GeV/c)

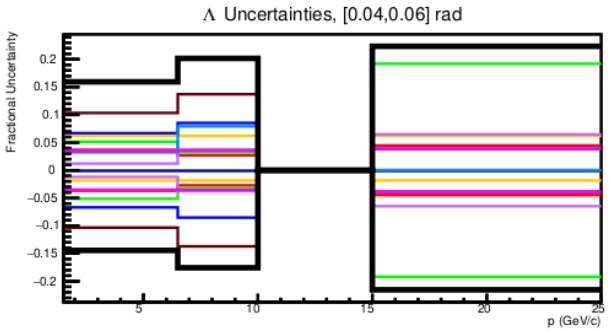

Λ Uncertainties, [0.06,0.1] rad
Fractional Uncertainty
p (GeV/c)

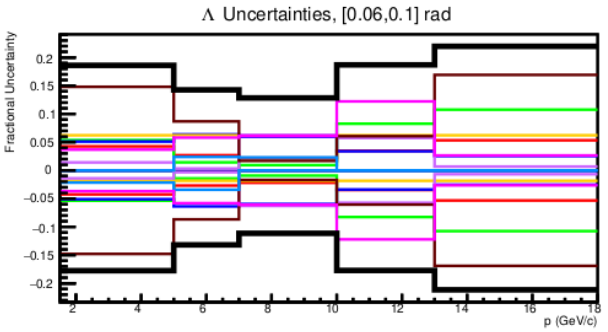

Λ Uncertainties, [0.1,0.14] rad
Fractional Uncertainty
p (GeV/c)

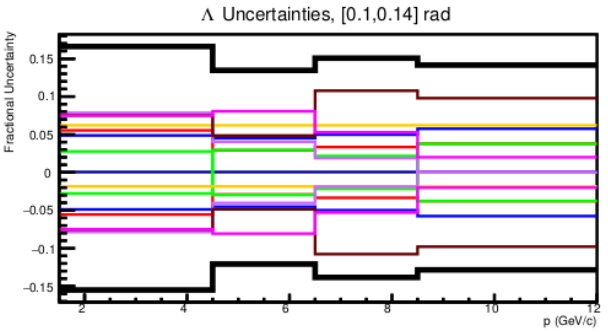

Statistical Uncertainty
Fit Uncertainty
Feed-Down Uncertainty
σprod Uncertainty
Decay Product dE/dx Selection Uncertair
Selection Uncertainty
Physics Model Uncertainty
Reconstruction Uncertainty
Total Uncertainty

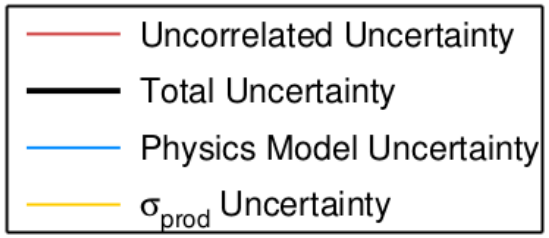

Λ Uncertainties, [0,0.02] rad
Fractional Uncertainty
p (GeV/c)

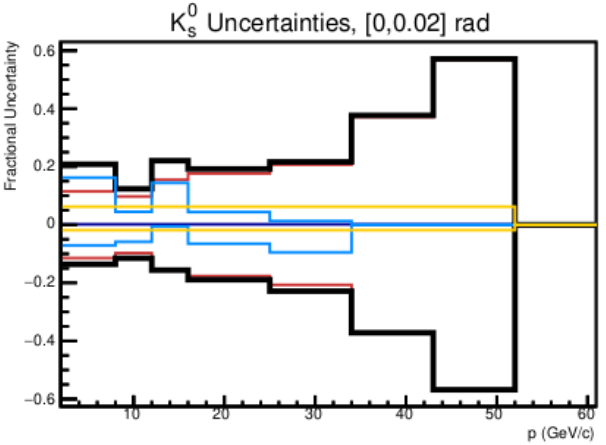

Λ Uncertainties, [0.02,0.04] rad
Fractional Uncertainty
p (GeV/c)

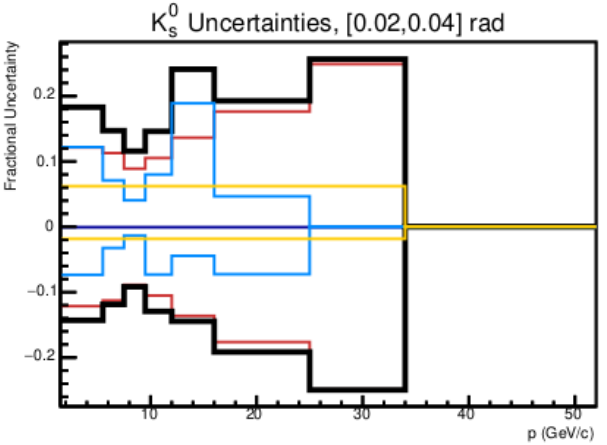

Λ Uncertainties, [0.04,0.06] rad
Fractional Uncertainty
p (GeV/c)

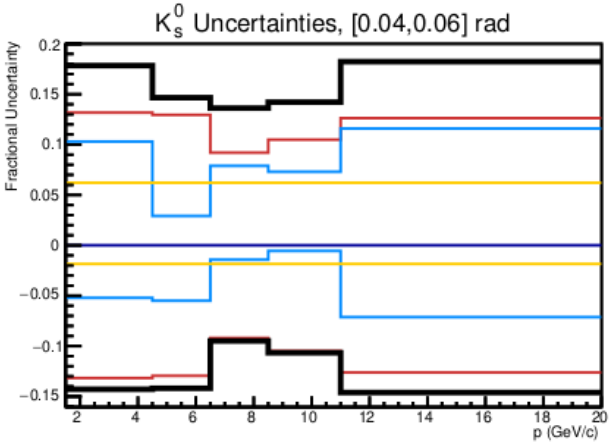

Λ Uncertainties, [0.06,0.1] rad
Fractional Uncertainty
p (GeV/c)

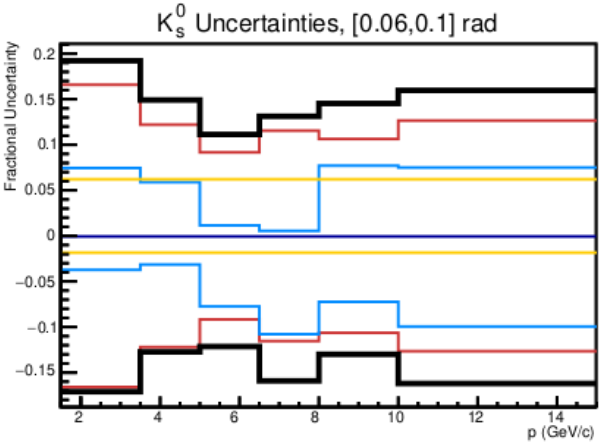

Λ Uncertainties, [0.1,0.14] rad
Fractional Uncertainty
p (GeV/c)

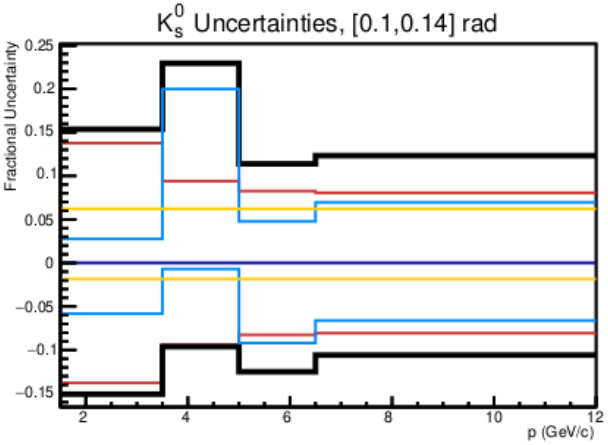

Uncorrelated Uncertainty
Total Uncertainty
Physics Model Uncertainty
σprod Uncertainty

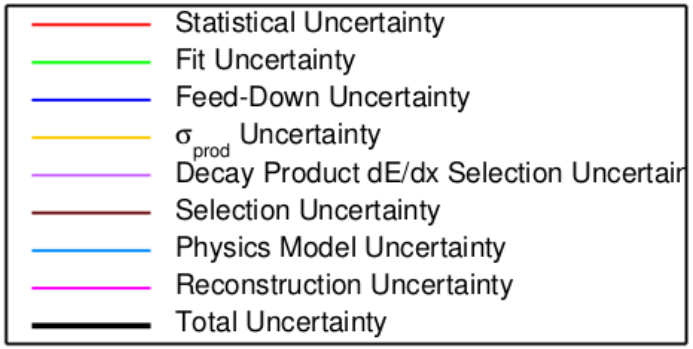

K0s Uncertainties, [0,0.02] rad
Fractional Uncertainty
p (GeV/c)

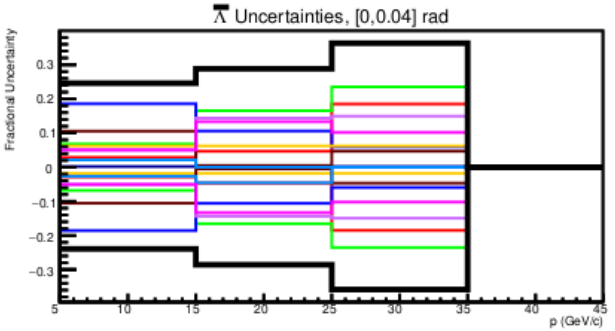

K0s Uncertainties, [0.02,0.04] rad
Fractional Uncertainty
p (GeV/c)

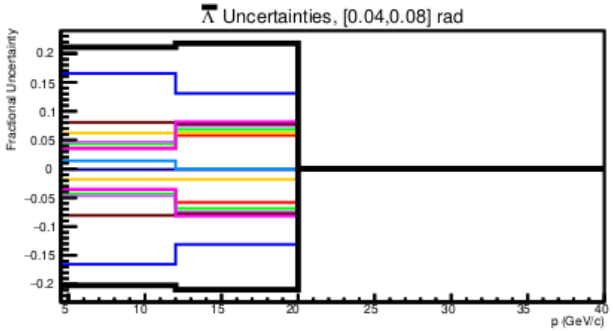

K0s Uncertainties, [0.04,0.06] rad
Fractional Uncertainty
p (GeV/c)


K0s Uncertainties, [0.06,0.1] rad
Fractional Uncertainty
p (GeV/c)


K0s Uncertainties, [0.1,0.14] rad
Fractional Uncertainty
p (GeV/c)


Statistical Uncertainty
Fit Uncertainty
Feed-Down Uncertainty
σ_{prod} Uncertainty
Decay Product dE/dx Selection Uncertair
Selection Uncertainty
Physics Model Uncertainty
Reconstruction Uncertainty
Total Uncertainty


$\overline{\Lambda}$ Uncertainties, [0,0.04] rad
Fractional Uncertainty
p (GeV/c)


$\overline{\Lambda}$ Uncertainties, [0.04,0.08] rad
Fractional Uncertainty
p (GeV/c)

Uncorrelated Uncertainty
Total Uncertainty
Feed-Down Uncertainty
Physics Model Uncertainty
σ_{prod} Uncertainty