Geant4 Physics Lists:
Optimizing for Hardron Production on Light Targets

Status Report

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Disclaimer

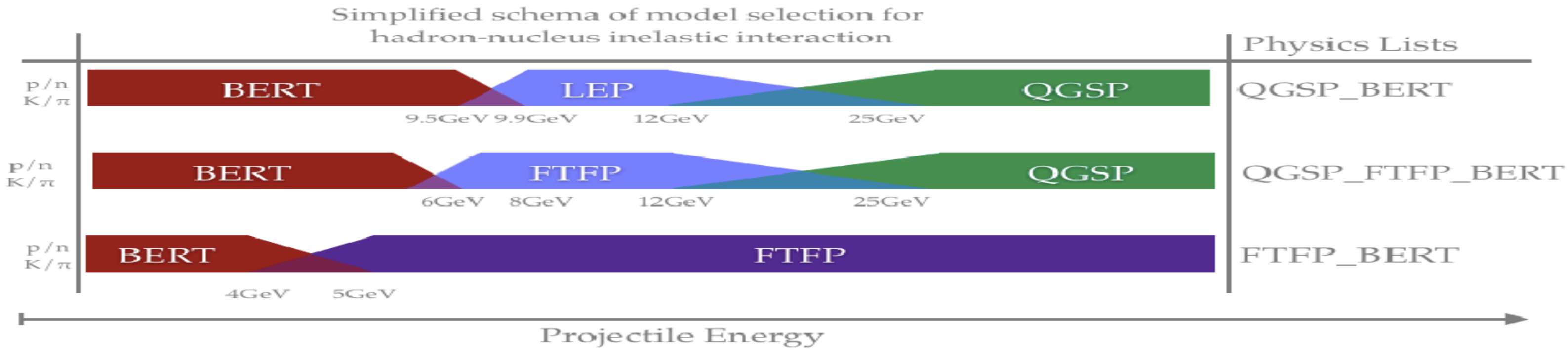
- This presentation is a status report on work in progress
- Results are preliminary
- Details may still be refined
- I my occasionally use some "Geant4 jargon" (class names, etc.)
- Feedback from the Neutrino Community is most welcome, and will help in further work towards tuning of Geant4 hadronic models

General Information (I)

- The goal of this study is to identify a beneficial combination of Geant4 hadronic models in a physics list for the needs of simulation of the Neutrino Beamline(s):
  - Subtle effects vs bulk effects
- The neutrino flux is mainly determined by pion production/decays
  - pions are mainly coming from the 1st interaction beam-target
  - re-interactions in the real target contribute substantially
- The focus is currently on pion production in p+C interactions at high energy, and subsequent re-interactions in the wide range of energies
- Study includes modeling of hadron production on Be (backup slides)
- Obviously, there're other aspects (possible future study):
  - Specific corners of the phase space, if of interest
  - Production, re-interaction, decays of other particles and flux purity
  - Etc.

General Info (II)

- There is no "unified" hadronic model in Geant4
  - Models are valid for specific energy range
  - Models may overlap in their validity range
  - Agreement with the data for specific particle-target combinations may vary
- This is reflected in the composition of Physics Lists



- Collection of ready to use Physics Lists:

  http://geant4.cern.ch/support/proc_mod_catalog/physics_lists/referencePL.shtml

- One of the current initiatives is to compose a group of Physics Lists for the Neutrino Community, including Neutrino Flux simulation

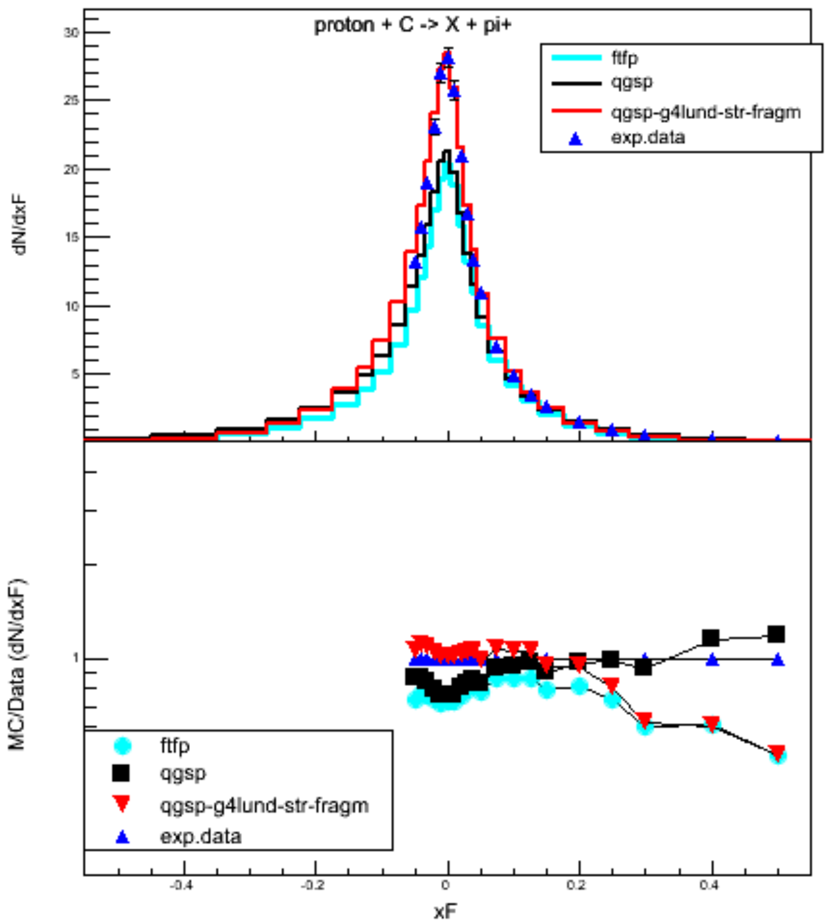
General Information (III)

- Results in this presentation are obtained with Geant4.9.6.p03
  - Latest Geant4.10 cycle contains changes to key hadronic models; the changes appear somewhat questionable and need more work
- Geant4 simulation:
  - Composition of Models: Bertini, FTFP, QGSP(+G4LundStringFragmentation)
  - Alternative to Bertini (Binary, INCLXX) have some limitations
  - Statistics: 1M events for each sample
- The MC-data agreement is judged by $\chi^2 = \Sigma\,((X_i - Y_i)/(\sigma_{xi} + \sigma_{yi}))^2$
  - assume X=sim., Y=exp.data; i=1,N, N=number of exp.data points
- Data: NA49(158GeV/c), NA61(31GeV/C), HARP(3-12GeV/c)
  - From NA49 we use both integrated spectra (dn/dxF and <pt> vs xF) and double diff. inclusive cross sections as a function of xF and pt
- To be added shortly (p, π^+, K^+ at 100GeV/c on various targets):
  - D.S. Barton et al., Phys. Rev. D27, 2580 (1983)
- Exp.data include stat. and syst. errors
- Simulation assumes 0% systematic

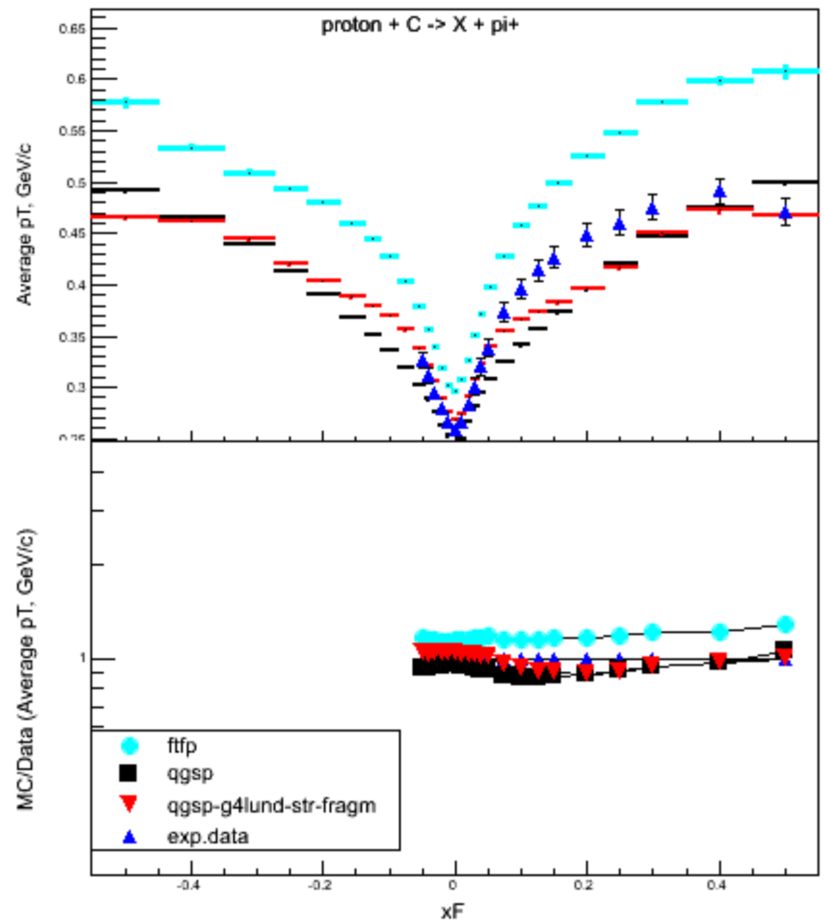
General Information (III)

- One of the factors in this study was validation of Geant4 simulation vs NA49 exp.data on hadron production in p+C at 158GeV/c, and taking inventory of Geant4 modeling options at high energy
- Secondary may re-interact in the target – this draws attention to hadron interaction/production in the intermediate energy range, and the use of data in the 3-12GeV/c range and at 31GeV/c
- Sample plots are included for illustrative purpose
- Collection of Geant4 validation plots:
  http://g4validation.fnal.gov:8080/G4ValidationWebApp/G4ValHAD.jsp
- In this presentation, most of results are included as tables, to attest Geant4 modeling options in a wide range of momenta/energies
- Tables represent integral χ^2/NDF at different beam momenta

158 GeV/c p + C $\longrightarrow$ π^+ + X (NA49)
Sample plots: dN/dxF and <pt> vs xF (incl. MC/Data)



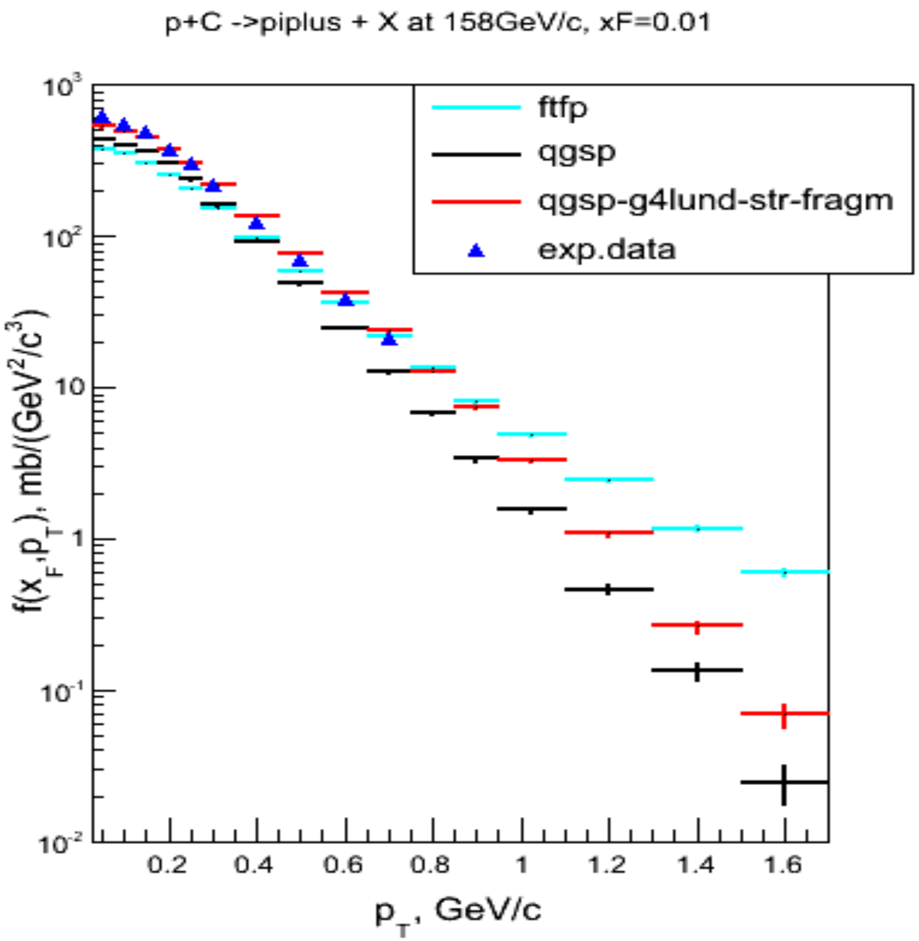
χ^2/NDF = 101.6 for ftfp vs NA49 Data
χ^2/NDF = 36.4 for qgsp vs NA49 Data
χ^2/NDF = 40.7 for qgsp-g4lund-str-fragm vs NA49 Data



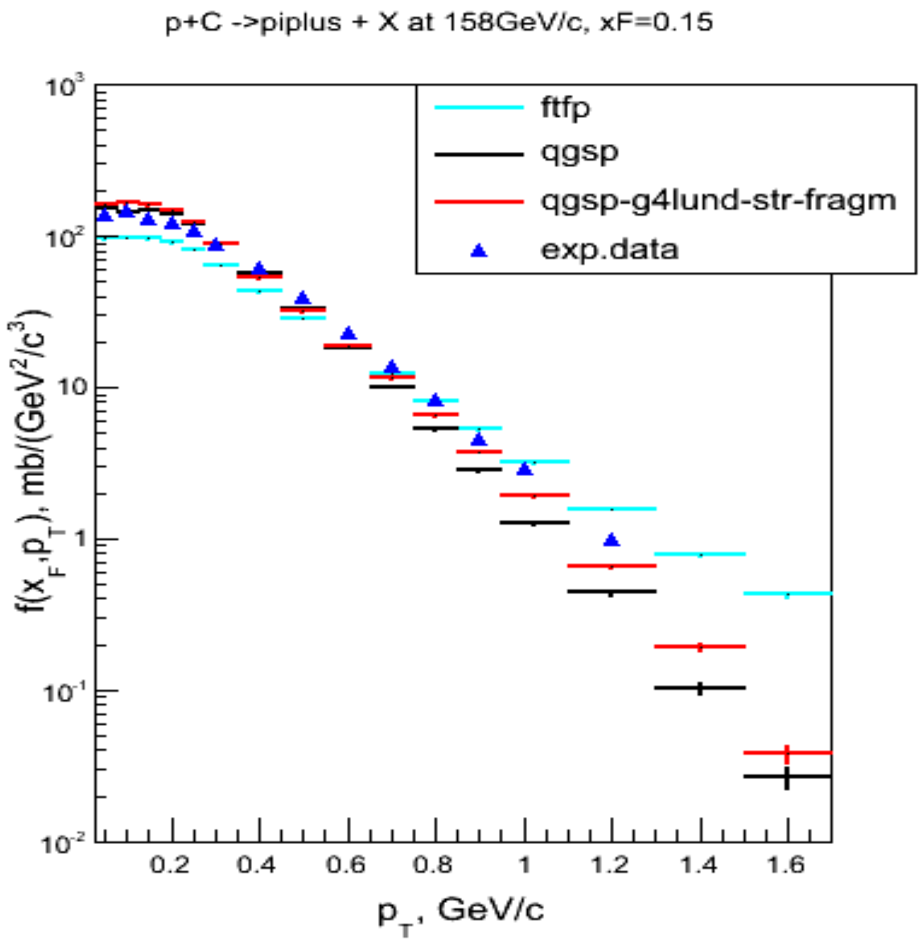
χ^2/NDF = 44.1 for ftfp vs NA49 Data
χ^2/NDF = 11.8 for qgsp vs NA49 Data
χ^2/NDF = 5.09 for qgsp-g4lund-str-fragm vs NA49 Data

158 GeV/c p + C ⟶ π^+ + X (NA49)

Sample plots: double diff. cross sections as a function of pt, at xF=0.01 or xF=0.15



χ^2/NDF = 81.5 for ftfp
χ^2/NDF = 60.1 for qgsp
χ^2/NDF = 9.28 for qgsp-g4lund-str-fragm



χ^2/NDF = 72.6 for ftfp
χ^2/NDF = 11.2 for qgsp
χ^2/NDF = 11.4 for qgsp-g4lund-str-fragm

χ^2/NDF for $p + C \longrightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c	31 GeV/c	158 GeV/c
Bertini:	10.44	22.16	16.84	19.05		
FTFP:	4.27	6.82	7.97	9.71	18.06	43.33
QGSP					33.85	26.99
QGSP+G4Lund					21.24	15.39

χ^2/NDF for $p + C \longrightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c	31 GeV/c	158 GeV/c
Bertini:	2.36	9.62	23.64	32.43		
FTFP:	3.36	4.20	5.42	5.64	12.83	40.23
QGSP					80.41	47.94
QGSP+G4Lund					49.51	10.66

For 3-31GeV/c range, χ^2 is calculated over p-spectra in all θ-bins
At 158GeV/c, χ^2 is calculated over pt-spectra in all xF-bins

χ^2 /NDF for $\pi^+ + C \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	31.16	44.57	53.84	22.59
FTFP:	17.28	15.53	18.09	3.71

χ^2 /NDF for $\pi^+ + C \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	24.49	43.90	31.94	14.04
FTFP:	11.62	15.81	9.91	2.66

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for $\pi^- + C \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	33.67	26.86	26.79	38.50
FTFP:	28.57	14.87	16.28	18.70

χ^2/NDF for $\pi^- + C \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	35.87	34.59	55.37	66.42
FTFP:	25.11	22.12	22.53	15.45

χ^2 is calculated over p-spectra in all θ-bins

Modeling p+C or p+Be Interactions with Geant4

- FTF results appear closest to the data from 3GeV (lower limit of the model's validity) and throughout tens of GeV range
- However, at 158GeV the closest fit with the data is given by QGSP outfitted with G4LundStringFragmentation
- Proposed combination of Geant4 models for protons:
  - Bertini up to 3.5GeV (overlap with FTFP at 3-3.5GeV)
  - FTFP from 3 GeV to 101GeV
  - QGSP+G4LundStringFragmentation from 100GeV
  - However, performance and overlap of Geant4 String Models at 100GeV is a subject of future benchmarking vs "Barton data"
- Geant4 documentation (Phys.Ref.Manual, ch. 28 and 29):

http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/fo/PhysicsReferenceManual.pdf

Modeling Interactions of Pions on C or Be with Geant4

- Neither FTF nor Bertini gives perfect agreement with the data in the intermediate energy range
- However, FTF results are statistically closer to the data
- Possible combination of Geant4 hadronic models:
  - Bertini up to 3.5GeV
    (overlap with FTFP at either 3-3.5GeV)
  - FTFP from 3GeV and up
- Keep an eye on other developments (e.g. INCL++)
- NOTE: having data on pion interactions with (thin) nuclear targets at high(er) energies will expand the tests and could greatly benefit tuning of Geant4

Composition of the Geant4 Hadronic Models in Physics Lists

- FTFP_BERT:
  - Bertini up to 5GeV for p,n,pi,K (overlap with FTF at 4-5GeV)
  - FTFP from 4GeV and up, for p,n,pi,K
- NuBeam:
  - Bertini up to 3.5GeV for p,pi,K
  - (overlap with FTFP at 3-3.5GeV)
  - FTFP from 3GeV and up for pi, K, 3-101GeV for p
  - QGSP+G4LundStringFragmentation from 100GeV and up for p
  - Otherwise, same as FTFP_BERT
  - Initial idea to overlap Bertini/FTFP at 7-10GeV (inspired by results with heavier targets) did not appear good for light targets
  - Alternative Bertini/FTFP overlaps 3-6GeV also tried
- QGSP_BERT is used for reference at 31GeV or higher where it is purely QGS(P) model outfitted with G4QGSMFragmentation

χ^2/NDF for $p + C \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c	31 GeV/c	158 GeV/c
FTFP_BERT	12.19	6.36	7.56			37.18
NuBeam FTFP/BERT: 7-10GeV FTFP/Bert:3-3.5GeV	12.08 7.84	19.68 6.44	10.47 7.66	8.66	4.9	13.94
QGSP_BERT					37.8	24.45

χ^2/NDF for $p + C \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c	31 GeV/c	158 GeV/c
FTFP_BERT	4.91	5.41	5.79			34.03
NuBeam: FTFP/BERT: 7-10GeV FTPF/Bert:3-3.5GeV	4.95 4.00	15.09 5.11	11.26 5.98	6.01	8.48	9.25
QGSP_BERT					78.33	38.83

For 3-31GeV/c range, χ^2 is calculated over p-spectra in all θ-bins
At 158GeV/c, χ^2 is calculated over pt-spectra in all xF-bins

χ^2/NDF for $\pi^+ + C \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	30.20	16.06	18.33
NuBeam : FTFP/Bert: 7-10GeV FTFP/Bert: 3-3.5GeV FTFP/Bert: 3-6GeV	 30.15 30.18 30.14	 33.81 16.97 15.31	 30.76 18.44 18.52

χ^2/NDF for $\pi^+ + C \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	22.60	13.28	8.75
NuBeam : FTFP/Bert: 7-10GeV FTFP/Bert: 3-3.5GeV FTFP/Bert: 3-6GeV	 22.60 22.09 22.23	 34.17 13.90 12.96	 15.20 8.96 9.12

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for $\pi^- + C \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	28.38	14.13	14.51
NuBeam : FTFP/Bert: 7-10GeV FTFP/Bert: 3-3.5GeV FTFP/Bert: 3-6GeV	 28.48 27.81 28.34	 25.33 14.28 13.62	 14.60 14.60 14.61

χ^2/NDF for $\pi^- + C \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	37.63	18.95	21.99
NuBeam : FTPF/Bert: 7-10GeV FTFP/Bert: 3-3.5GeV FTFP/Bert: 3-6GeV	 37.98 38.45 37.77	 30.33 20.26 12.40	 27.37 21.82 21.93

χ^2 is calculated over p-spectra in all θ-bins

Summary

- Geant4 collaboration is carrying studies to refine hadronic physics models included in the toolkit, and to provide a group of dedicated physics lists for the needs of the Neutrino community
- A new physics list NuBeam has been introduced as part of Geant4 standard distribution, (as of 4.10.01.b01) and is being refined
- Expansion of "test bench" (datasets) and more study is in the plans
- New experimental results, especially on thin targets, will definitely help the efforts of tuning Geant4 hadronic physics models and optimization of physics lists
- Feedback from the community will be much appreciated

BACKUP MATERIALS

χ^2 /NDF for p + Be → π^+ + X

	3 GeV/c	5 GeV/c	8 GeV/c	8.9GeV/c	12 GeV/c
Bertini	14.10	17.97	20.38	25.06	20.57
FTFP	3.80	5.93	8.76	13.09	9.93

χ^2 /NDF for p + Be → π^- + X

	3 GeV/c	5 GeV/c	8 GeV/c	8.9 GeV/c	12 GeV/c
Bertini	4.31	16.41	29.07	41.92	27.59
FTFP	5.07	7.82	10.19	17.08	13.74

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for $\pi^+ + Be \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	29.37	37.28	33.05	25.04
FTFP:	18.42	12.10	8.55	3.68

χ^2/NDF for $\pi^+ + Be \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	37.81	35.6	25.31	13.40
FTFP:	11.79	13.15	10.74	3.16

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for $\pi^- + Be \rightarrow \pi^+ + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	30.19	27.07	31.46	40.39
FTFP:	25.74	14.06	14.55	10.68

χ^2/NDF for $\pi^- + Be \rightarrow \pi^- + X$

	3 GeV/c	5 GeV/c	8 GeV/c	12 GeV/c
Bertini:	37.99	40.46	60.45	75.38
FTFP:	31.27	24.19	23.14	19.90

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for p + Be → π^+ + X

	3 GeV/c	5 GeV/c	8 GeV/c	8.9 GeV/c
FTFP_BERT	18.88	5.91	9.82	12.13
NuBeam : FTFP/Bert: 7-10GeV FTFP/Bert: 3-3.5GeV FTFP/Bert: 3-6GeV	 18.79 12.98 12.98	 17.32 6.05 5.98	 12.03 9.21 9.31	 12.14 11.90 12.37

χ^2/NDF for p + Be → π^- + X

	3 GeV/c	5 GeV/c	8 GeV/c	8.9 GeV/c
FTFP_BERT	19.94	9.00	9.29	14.86
NuBeam : FTPF/Bert: 7-10GeV FTFP/Bert: 3-3.5GeV FTFP/Bert: 3-6GeV	 19.73 15.08 15.08	 20.41 8.73 8.57	 13.37 9.64 8.76	 11.43 14.44 14.68

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for π^+ + Be → π^+ + X

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	29.28	13.88	9.09
NuBeam :			
FTFP/Bert: 7-10GeV	29.46	32.29	15.59
FTFP/Bert: 3-3.5GeV	29.08	14.23	9.22
FTFP/Bert: 3-6GeV	29.17	13.40	9.31

χ^2/NDF for π^+ + Be → π^- + X

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	33.51	10.75	2.71
NuBeam :			
FTPF/Bert: 7-10GeV	32.90	28.67	2.68
FTFP/Bert: 3-3.5GeV	32.35	10.95	2.74
FTFP/Bert: 3-6GeV	32.35	11.15	2.72

χ^2 is calculated over p-spectra in all θ-bins

χ^2/NDF for π^- + Be → π^+ + X

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	28.18	14.52	14.63
NuBeam :			
FTFP/Bert: 7-10GeV	28.04	25.63	17.84
FTFP/Bert: 3-3.5GeV	27.93	11.72	14.79
FTFP/Bert: 3-6GeV	27.87	14.94	14.71

χ^2/NDF for π^- + Be → π^- + X

	3 GeV/c	5 GeV/c	8 GeV/c
FTFP_BERT	40.06	21.19	20.42
NuBeam :			
FTPF/Bert: 7-10GeV	40.23	34.99	28.33
FTFP/Bert: 3-3.5GeV	40.49	22.70	19.81
FTFP/Bert: 3-6GeV	40.75	15.54	20.18

χ^2 is calculated over p-spectra in all θ-bins

References

- HARP data (subsets for C and Be):
  - M.G.Catanesi et al., Phys.Rev.C77:055207, 2008
  - M. Apollonio et al., Phys.Rev.C80:035208, 2009
  - M. Apollonio et al., Phys.Rev.C80:065207, 2009
  - M. Apollonio et al., Nucl. Phys. A821: 118-192, 2009
- NA61 data (31GeV/p proton beam on a thin C target):
  - N.Abgrall et al., Phys.Rev. C84:034604, 2011
- NA49 data (C target):
  - http://spshadrons.web.cern.ch/spshadrons
- To be added shortly (p, π^+, K^+ at 100GeV/c on various targets):
  - D.S. Barton et al., Phys. Rev. D27, 2580 (1983)
- Note: thin target data used in this study