



Update on Tuning FTF Model Parameters: Exploring Quark Exchange Model Parameters for the Pion Projectile

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This is work in progress which is going under the guidance of Geant4/FTF experts (Vladimir U., Alberto R.)

Results featured in this presentation are based on limited study, are very preliminary, and may change as the study advances

General Information (I)

- Ongoing activity focuses on (configurable) FTF parameters involved in modeling the following process
 - Projectile or target diffraction dissociation
 - Quark exchange (with excitation of participant in this case)
 - Nuclear target destruction
 - Details on the description/implementation of the processes in backup slides
- Earlier studies focused on proton projectile
 - <https://indico.cern.ch/event/1158833/contributions/4880823/attachments/2446731/4192593/G4HAD-VMP-May18-2022.pdf>
 - <https://indico.cern.ch/event/1178321/contributions/4972000/attachments/2483117/4262980/FTF-Parameters-July-2022-v1.pdf>
- Subsequently, similar studies for pion projectile have been requested by the G4 Hadronic group

General Information (II)

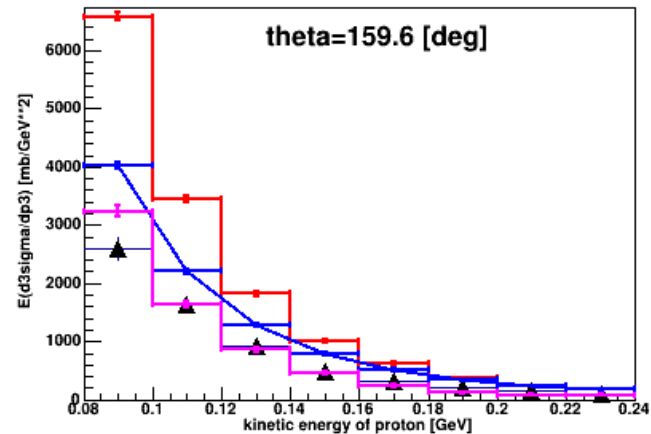
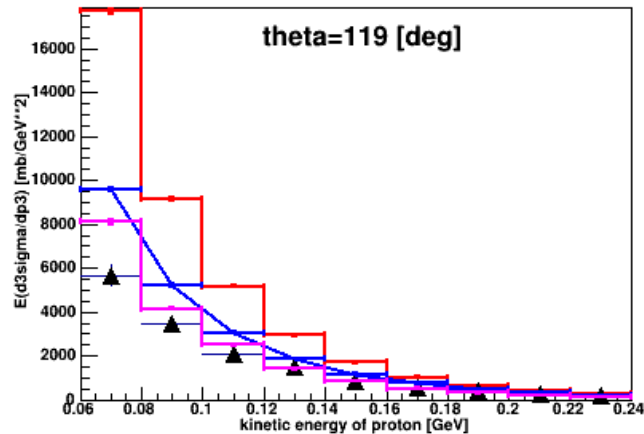
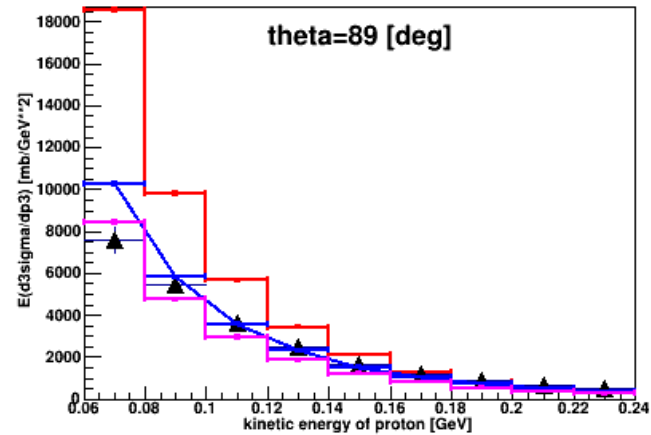
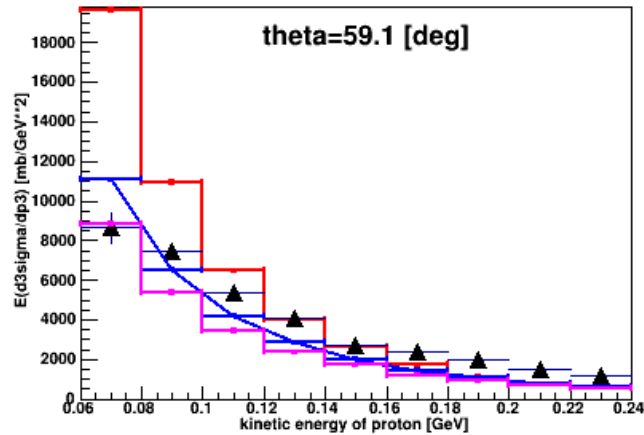
- 2-step procedure:
 - Fit parameters for the FTF nuclear target destruction
 - Beam+Target: 5, 12 GeV/c pion on C, Cu, Pb
 - Datasets: ITEP771, HARP (ref. in backup slides)
 - Topic has been preliminarily explored 3 years ago (Geant4 10.5.ref07):
<https://indico.cern.ch/event/825306/contributions/3554768/attachments/1913553/3162753/G4Workshop-FTF-API-2019.pdf>
 - FTF has evolved - selected comparison plots in backup slides
 - Use “best fit” parameters of the FTF nuclear destruction and fit parameters of the FTF quark exchange with excitation of participants (aka “proc1”)
 - Beam+Target: 5, 12, 60 GeV/c pion on C, Cu, Pb
 - Datasets: HARP, NA61 (ref. in backup slides)
 - NOTE: a subset of NA61 data for 60 GeV/c pi+ beam **newly added** to the study
 - Geant4: 11-00-ref-06
 - Fitting package: Professor (<https://professor.hepforge.org>)

Parameters of Nuclear Target Destruction (pion projectile)

- Current values of parameters in question are fairly decent for modeling interactions of pions with light nuclear targets, e.g. C, but for heavier targets, e.g. Pb, data and MC differ; for chi2 values see (e.g. slides13-14)
<https://indico.cern.ch/event/1178321/contributions/4971999/attachments/2483084/4262927/G4HAD-July20-2022.pdf>
- **Fit results** (obtained collectively for pi+ and pi-)
 - **FTFP_MESON_EXCI_E_PER_WNDNUCLN = (58.1 ± 0.7) MeV (D = 40 MeV)**
 - **FTFP_MESON_NUCDESTR_P1_TGT = $(0.001026 \pm 0.00003) * A$ (D = $0.0048 * A$)**
 - NOTE: we have also varied FTFP_MESON_NUCDESTR_P2_TGT and FTFP_MESON_NUCDESTR_P3_TGT but after some consideration they have been fixed in the fits at their default values
- Fit results are comparable, at least by the order of magnitude, with default settings, and should not result in large changes in modeling interactions of pions with light targets; for heavy targets changes are expected

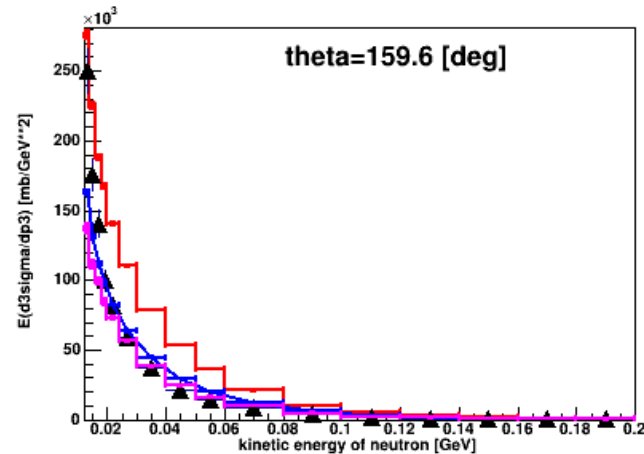
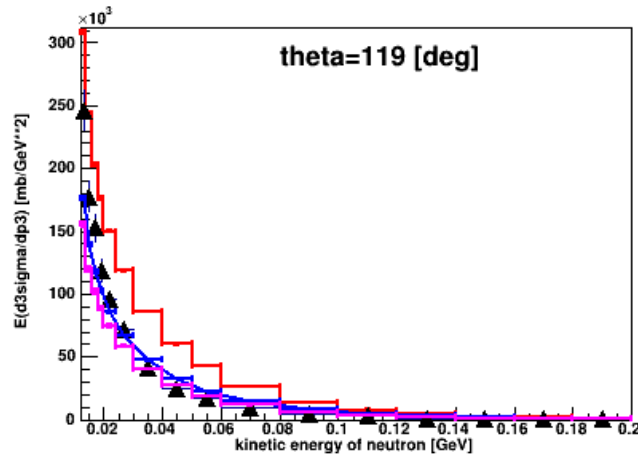
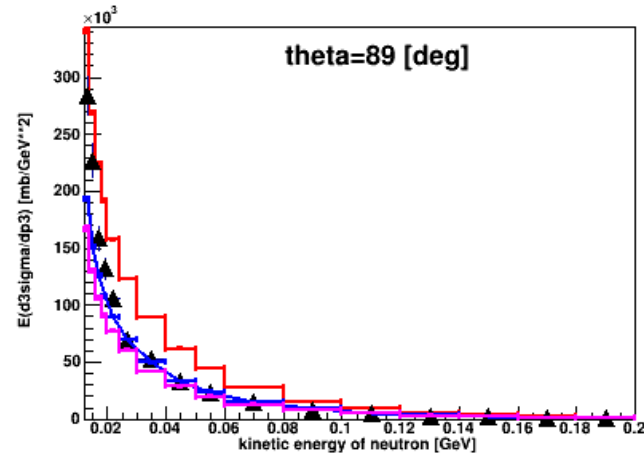
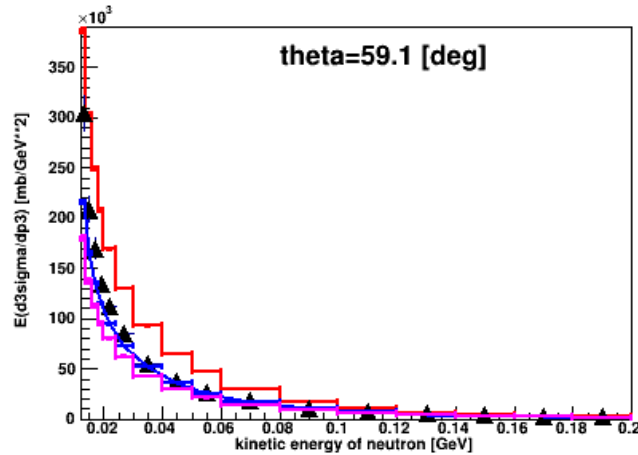
DEFAULT: $\chi^2/\text{NDF} = 108.2$ **Professor Fit:** $\chi^2/\text{NDF} = 16.7$ **Sim using Best Fit:** $\chi^2/\text{NDF} = 13.6$

G4/FTF: 5.0GeV piminus on Pb \rightarrow proton + X; data by ITEP (black triangles)



DEFAULT: $\chi^2/\text{NDF} = 123.9$ **Professor Fit:** $\chi^2/\text{NDF} = 13.1$ **Sim using Best Fit:** $\chi^2/\text{NDF} = 12.9$

G4/FTF: 5.0GeV piminus on Pb \rightarrow neutron + X; data by ITEP (black triangles)



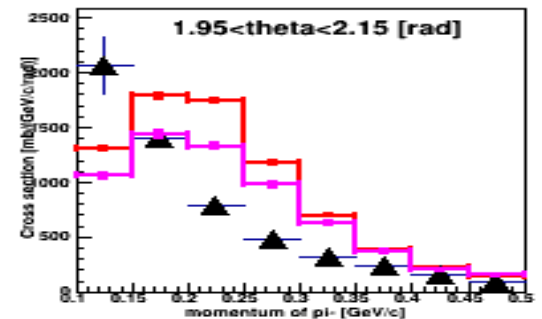
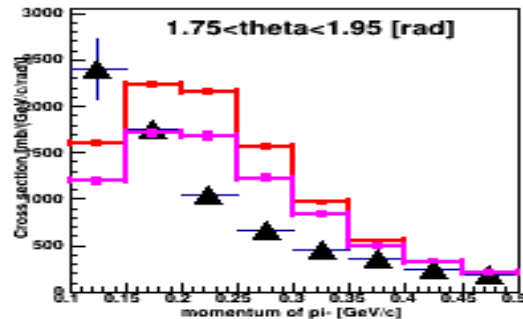
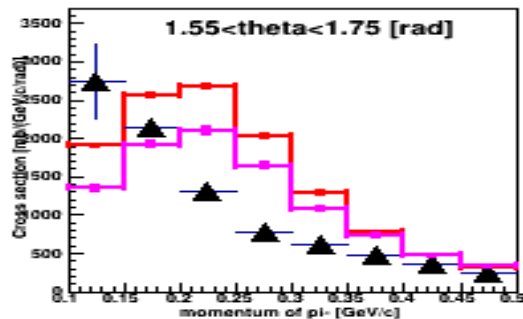
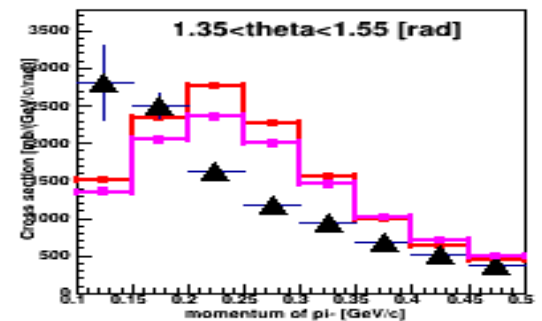
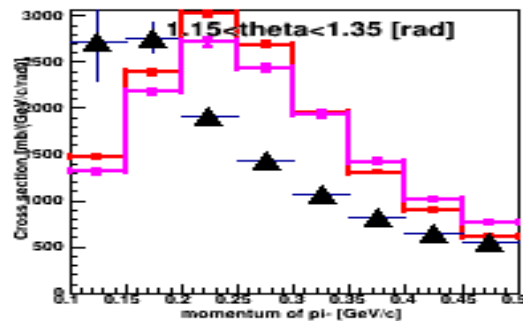
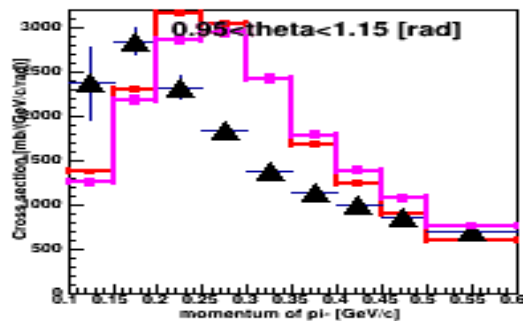
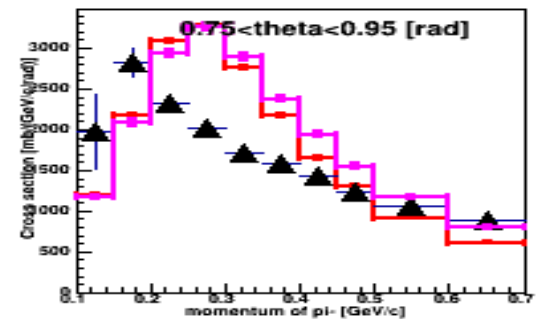
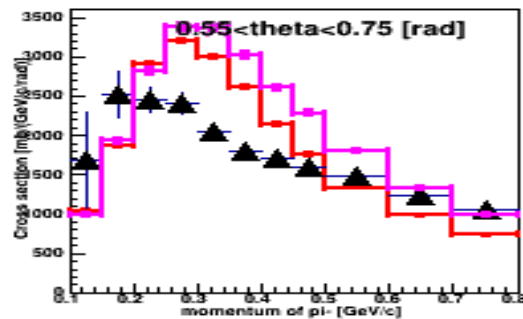
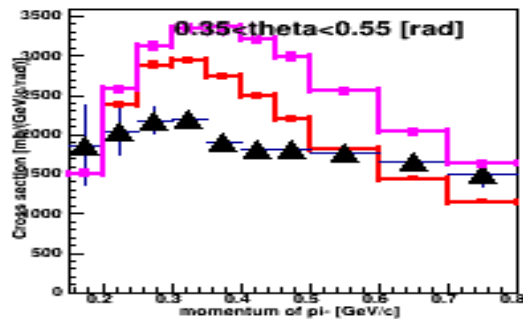
Using in Simulation Best Fit Parameters of Nuclear Target Destruction

- For pion beam we have for MC-data benchmark data that cover values of $\sim 60^\circ$ of the polar angle of the secondary protons and neutrons; we do not have enough basis to judge MC-data agreement at $\theta < 60^\circ$
- Per current benchmark, using best fit parameters in simulation results in reducing simulated yield of secondary protons and neutrons by pion beam on heavier targets which improves MC-data agreement
- At the same time, in some areas one may also note certain increase in the simulated secondary pion production on heavier targets
 - There might be different mechanisms to contribute into the observed effects
- The pattern of simulated (under/over)production of secondary pions in pion+A interactions, as compared to data, is not always the same for π^+ or π^- beam and/or for different beam momenta
 - Selected plots for 5 GeV/c pion+Pb \rightarrow pions in subsequent slides
 - Backup slides: Selected similar plots for 5 GeV/c pion+Ta \rightarrow pions, together with evolution plots (starting at 10.4.p03) and model-to-model comparisons (as of 11.0)

Default: $\chi^2/\text{NDF} = 66.6$

Sim using Best Fit: $\chi^2/\text{NDF} = 55.5$

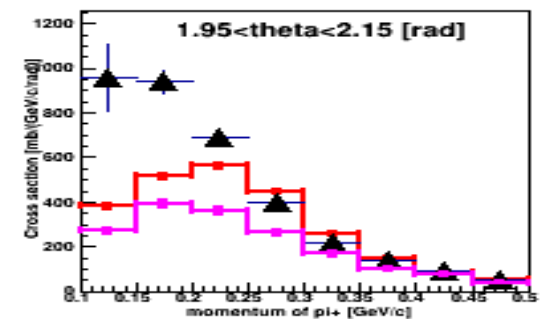
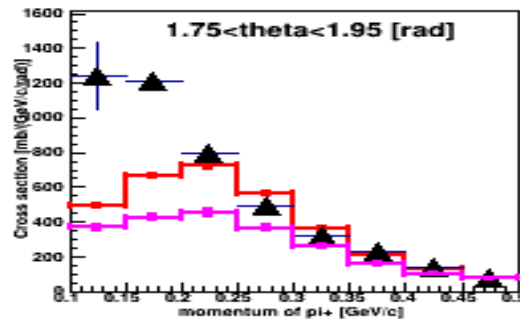
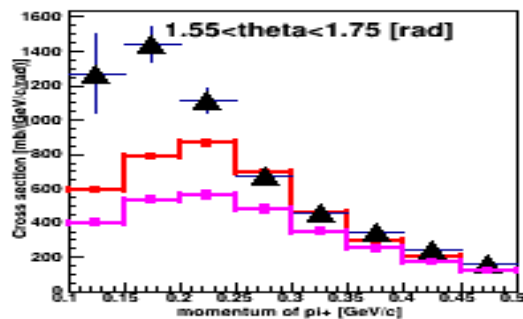
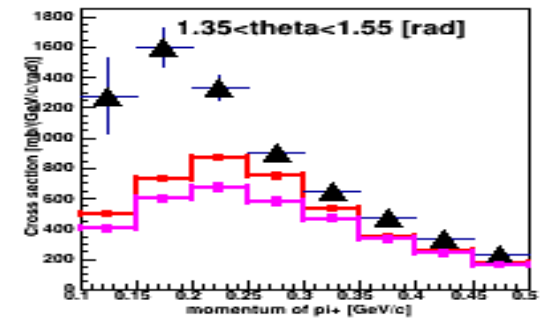
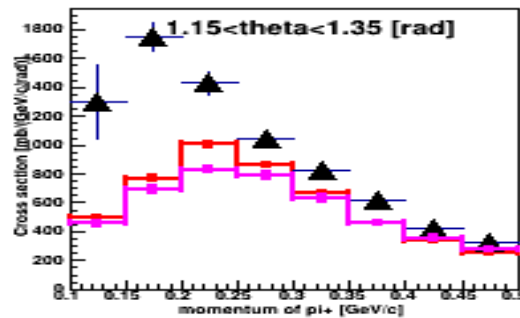
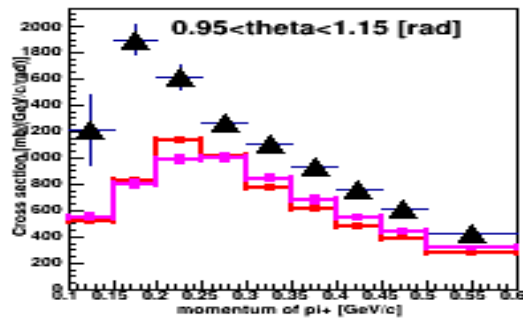
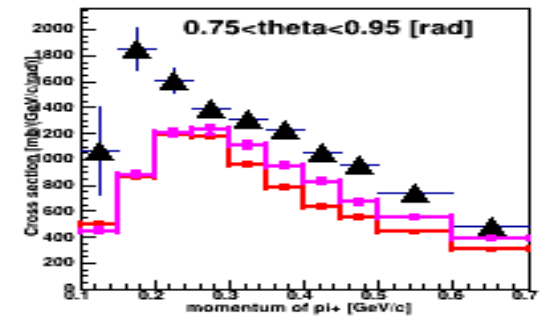
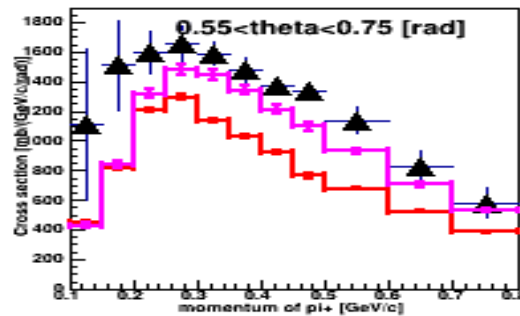
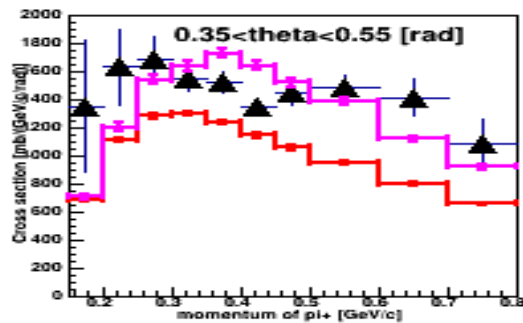
G4/FTF: 5.0GeV piminus on Pb \rightarrow piminus + X; data by HARP (black triangles)



Default: $\chi^2/\text{NDF} = 19.1$

Sim using Best Fit: $\chi^2/\text{NDF} = 18.4$

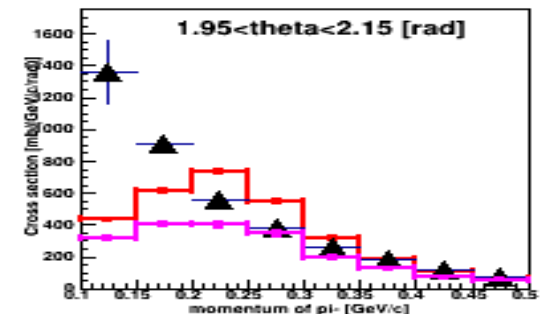
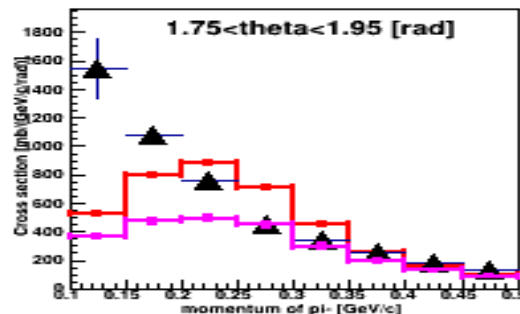
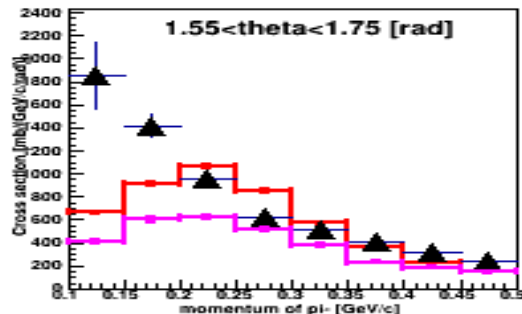
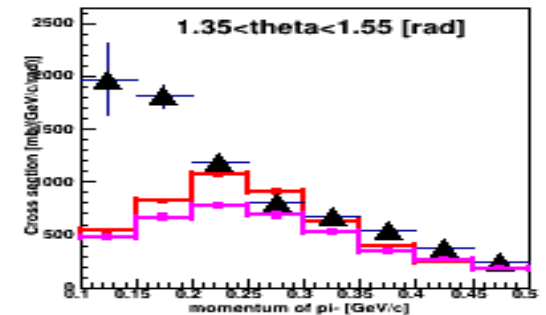
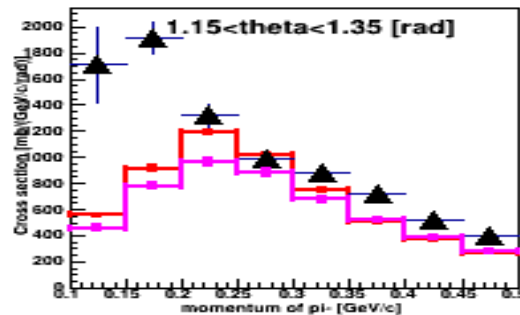
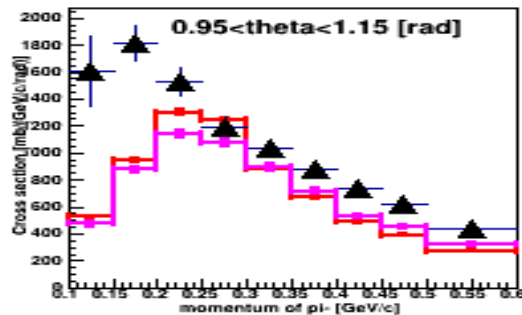
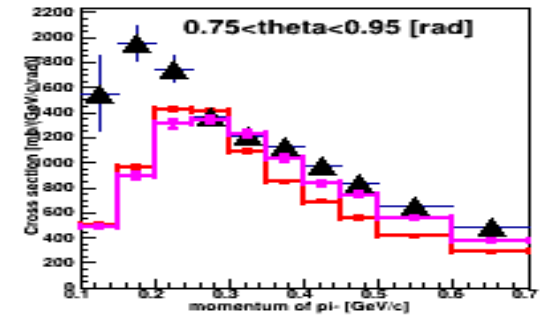
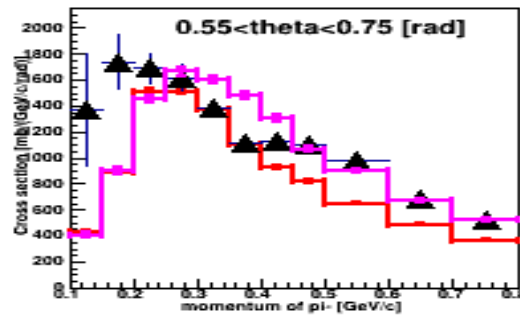
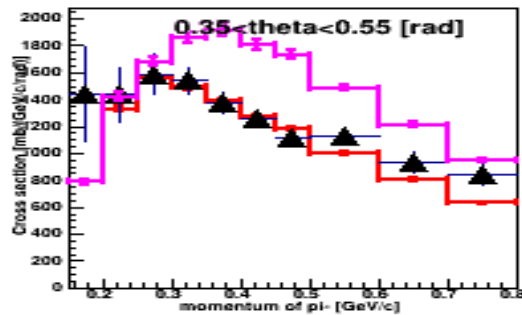
G4/FTF: 5.0 GeV piminus on Pb \rightarrow piplus + X; data by HARP (black triangles)



Default: $\chi^2/\text{NDF} = 13.6$

Sim using Best Fit: $\chi^2/\text{NDF} = 20.3$

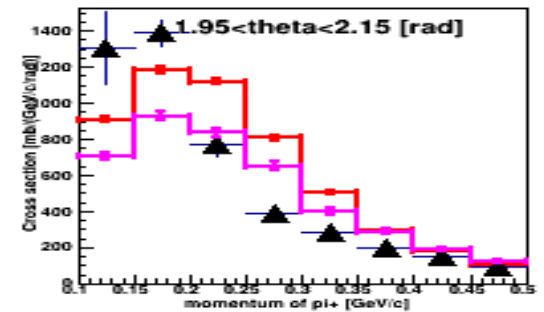
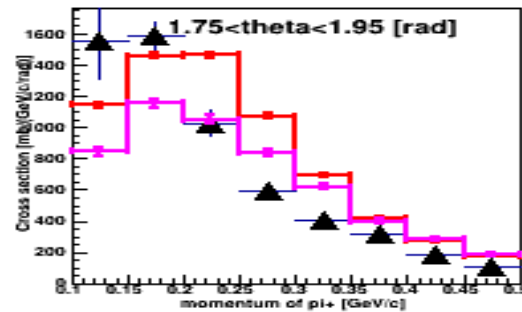
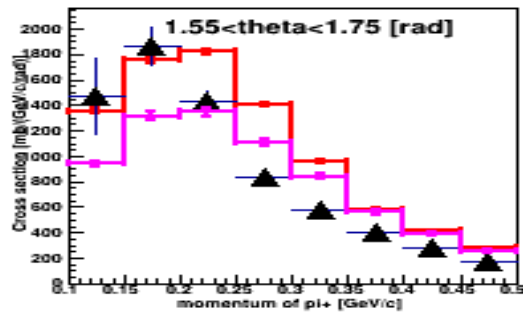
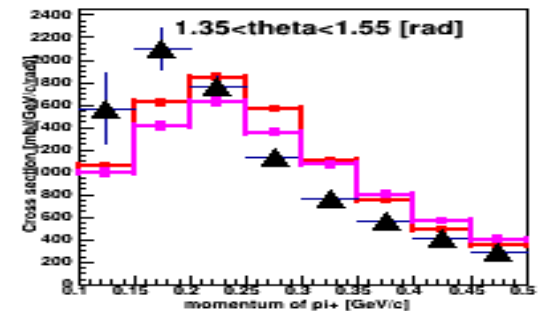
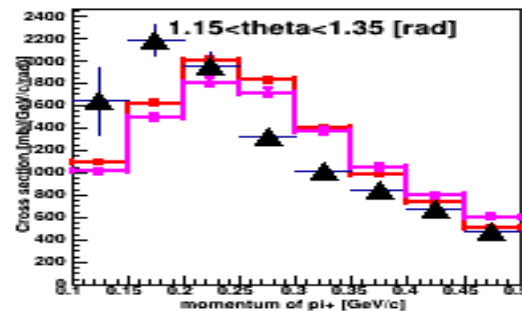
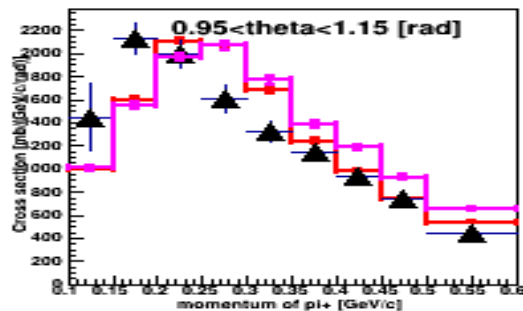
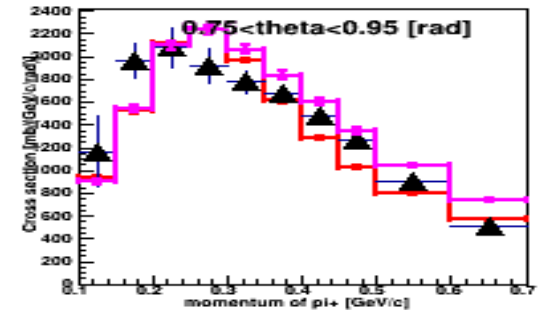
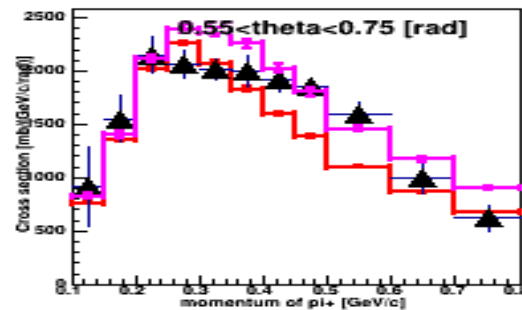
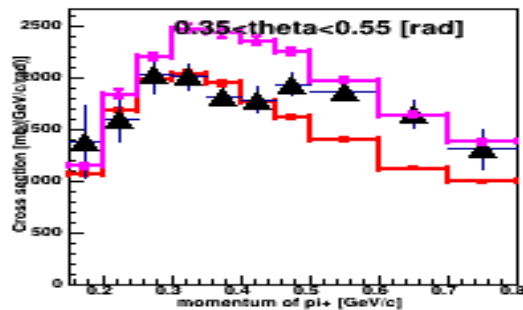
G4/FTF: 5.0GeV piplus on Pb \rightarrow piminus + X; data by HARP (black triangles)



Default: $\chi^2/\text{NDF} = 13.7$

Sim using Best Fit: $\chi^2/\text{NDF} = 12.2$

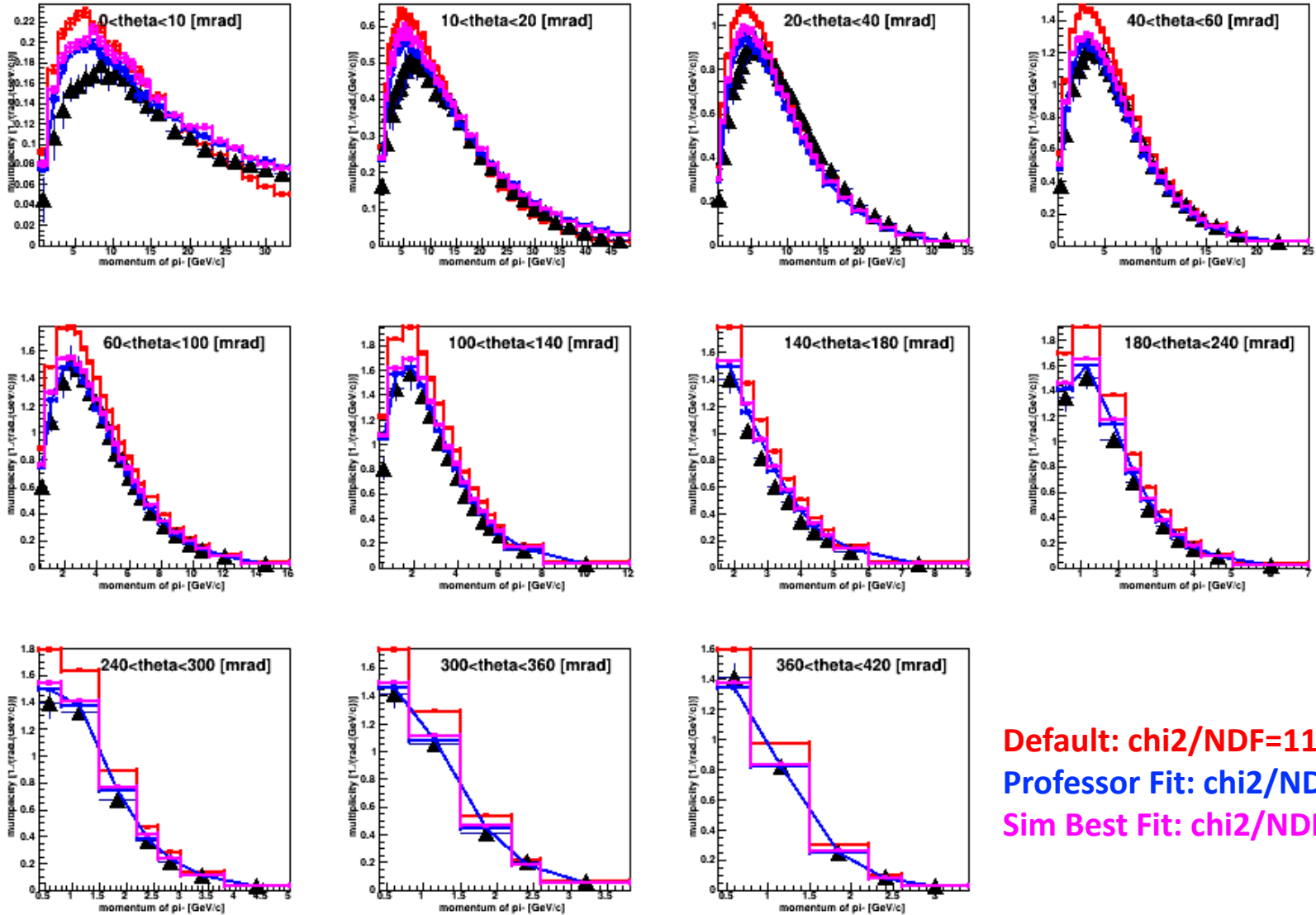
G4/FTF: 5.0GeV piplus on Pb \rightarrow piplus + X; data by HARP (black triangles)



Exploring Parameters of Quark Exchange with Excitation of Participants (“proc1”)

- Using best fit parameters obtained for nuclear target destruction
 - $\text{FTF_MESON_EXCI_E_PER_WINDNUCLN} = 58.1$
 - $\text{FTF_MESON_NUCDESTR_P1_TGT} = 0.001026 * A$
- Varying/fitting parameters of “proc1”:
 - $\text{FTF_PION_PROC1_A1} \quad 1 \quad 18 \quad D=5.77$
 - $\text{FTF_PION_PROC1_B1} \quad 0.3 \quad 0.9 \quad D=0.6$
 - $\text{FTF_PION_PROC1_A2} \quad -18 \quad -0.5 \quad D=-5.77$
 - $\text{FTF_PION_PROC1_B2} \quad 0.4 \quad 1.2 \quad D=0.8$
 - NOTE: Default calculated process probability
 ~ 0.23 @ 5 GeV/c; ~ 0.08 @ 60 GeV/c; ~ 0.06 @ 100 GeV/c (not included in this study)
- **Fit Results** (obtained collectively for pi+ and pi- projectiles):
 - $\text{FTF_PION_PROC1_A1} = 5.84 \pm 0.12$
 - $\text{FTF_PION_PROC1_B1} = 0.337 \pm 0.006$
 - $\text{FTF_PION_PROC1_A2} = -7.57 \pm 0.08$
 - $\text{FTF_PION_PROC1_B2} = 0.44 \pm 0.008$

G4/FTF: 60.0GeV piplus on C \rightarrow piminus + X; data by NA61 (black triangles)

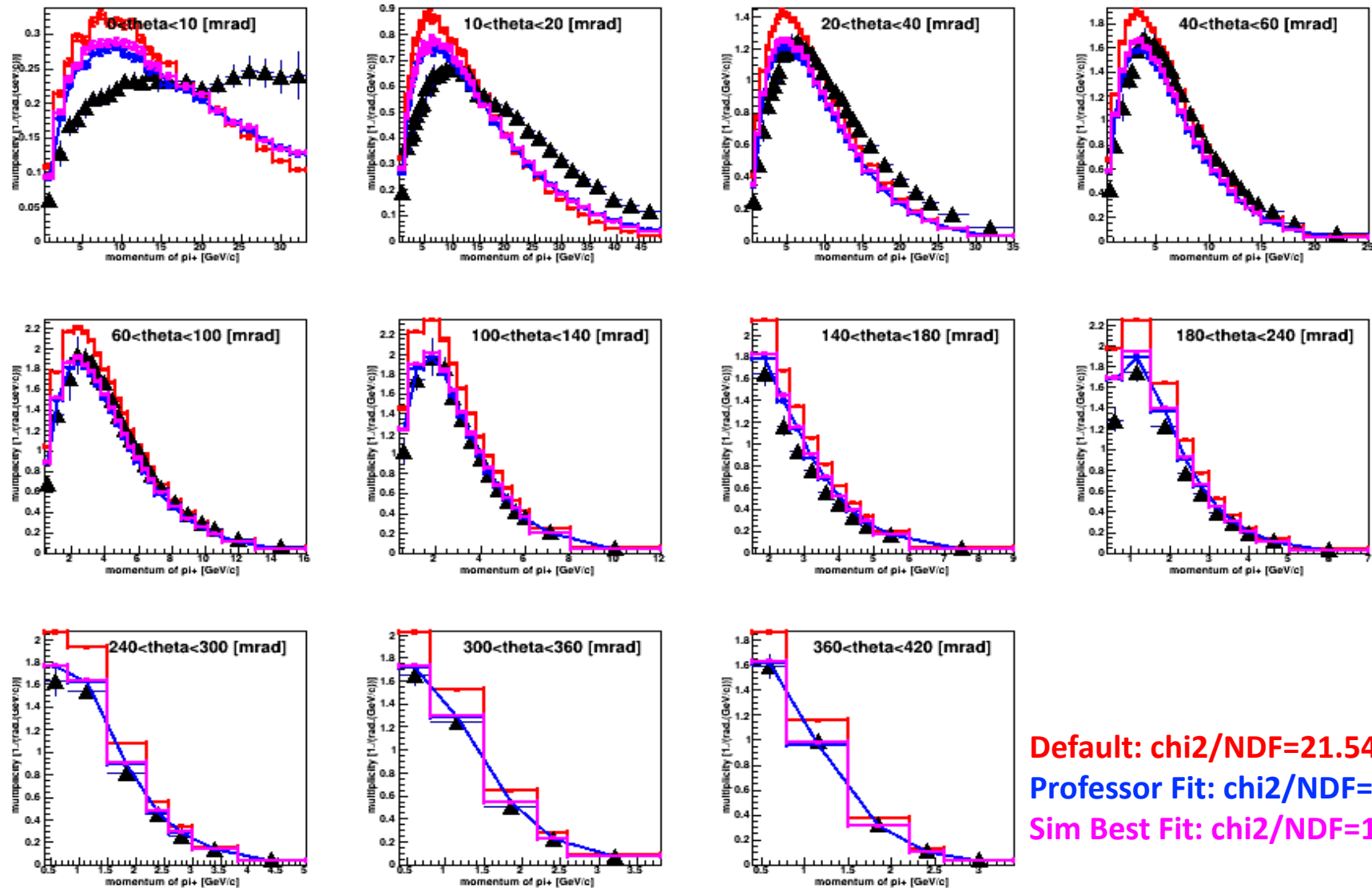


Default: $\chi^2/\text{NDF}=11.62$

Professor Fit: $\chi^2/\text{NDF}=3.25$

Sim Best Fit: $\chi^2/\text{NDF}=3.88$

G4/FTF: 60.0GeV piplus on C → piplus + X; data by NA61 (black triangles)



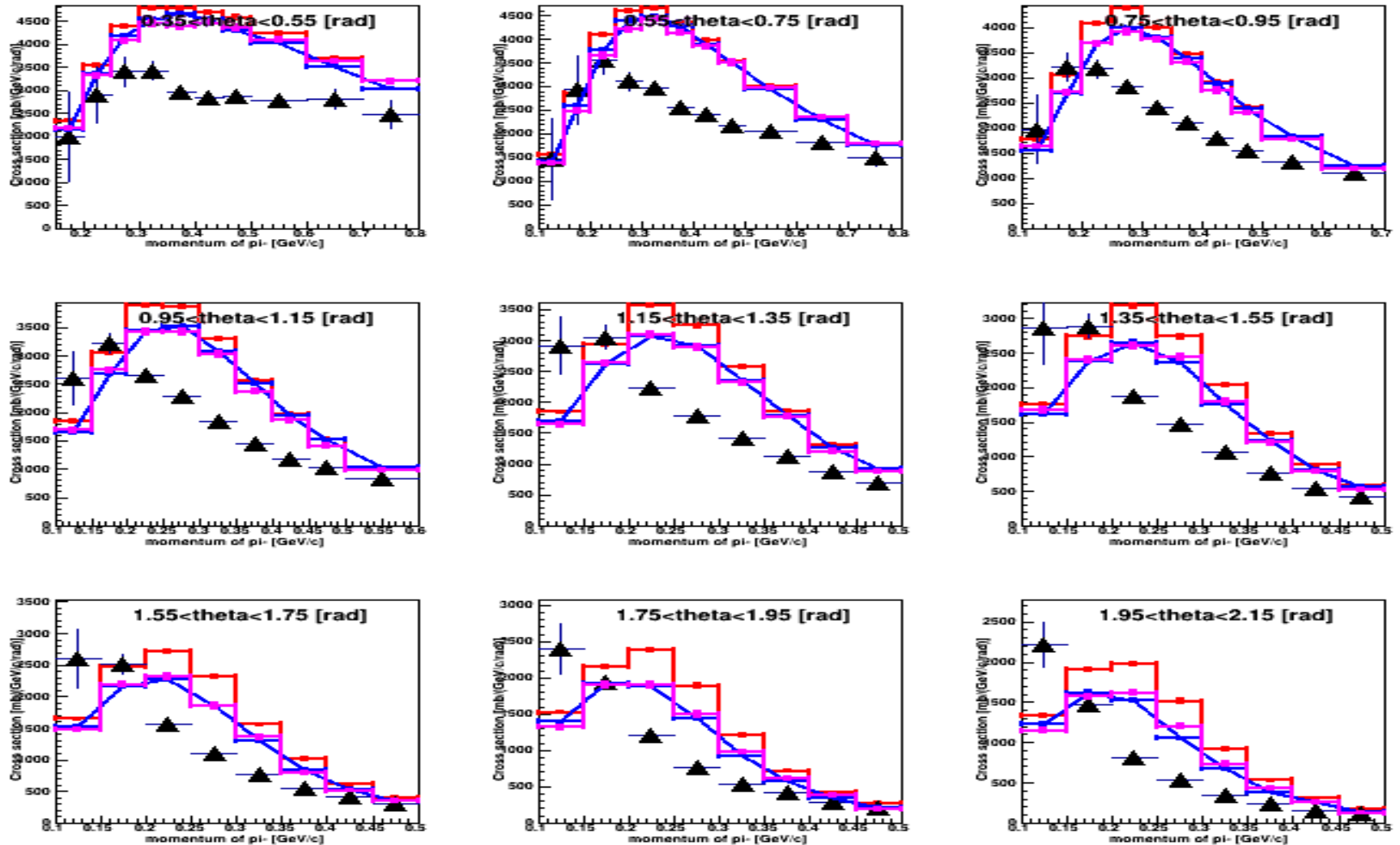
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Professor Fit: $\chi^2/\text{NDF}=11.88$

Sim Best Fit: $\chi^2/\text{NDF}=11.88$

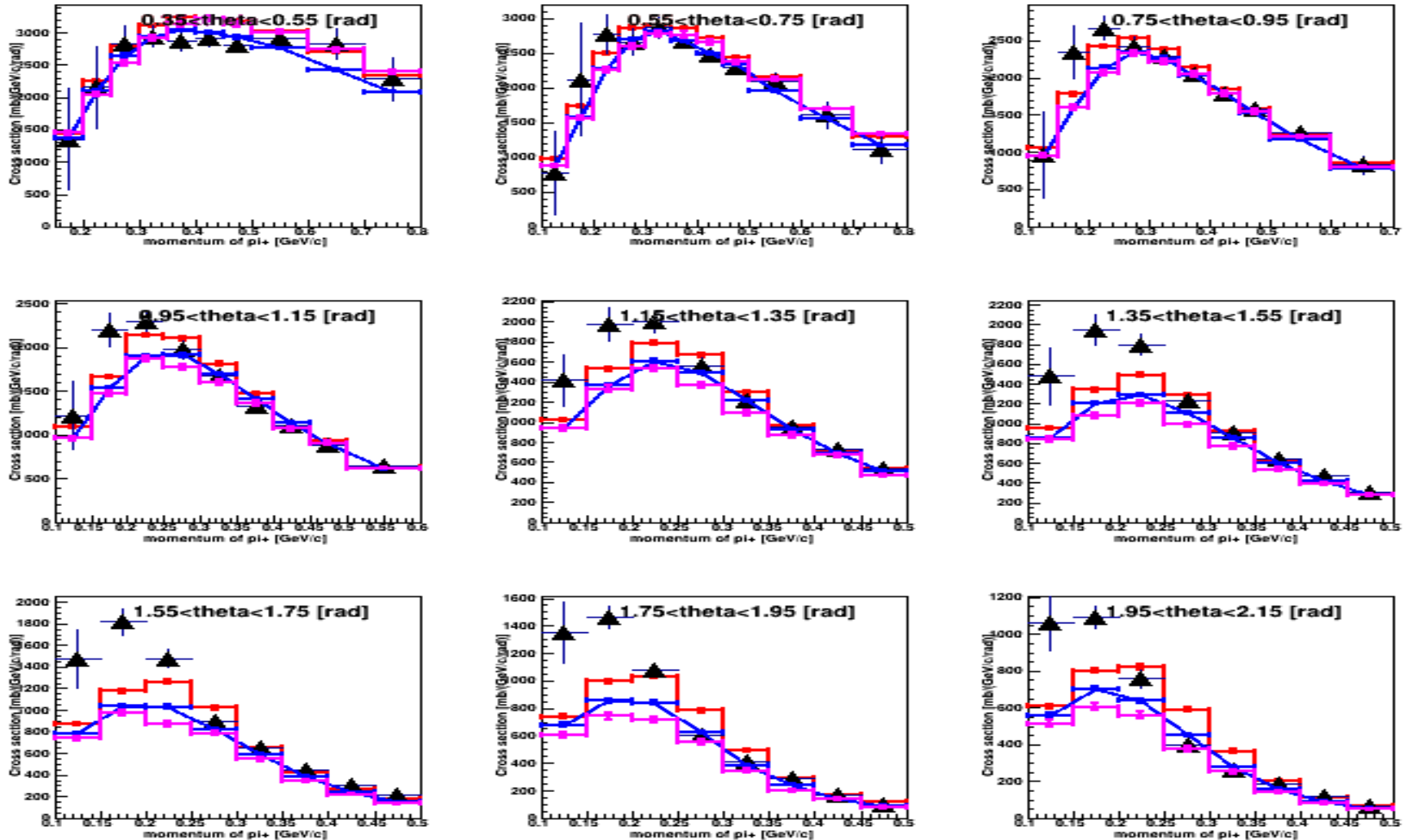
Default: $\chi^2/\text{NDF}=110.0$ Professor Fit: $\chi^2/\text{NDF}=65.0$ Sim using Best Fit: $\chi^2/\text{NDF}=54.2$

G4/FTF: 12.0GeV piminus on Pb \rightarrow piminus + X; data by HARP (black triangles)



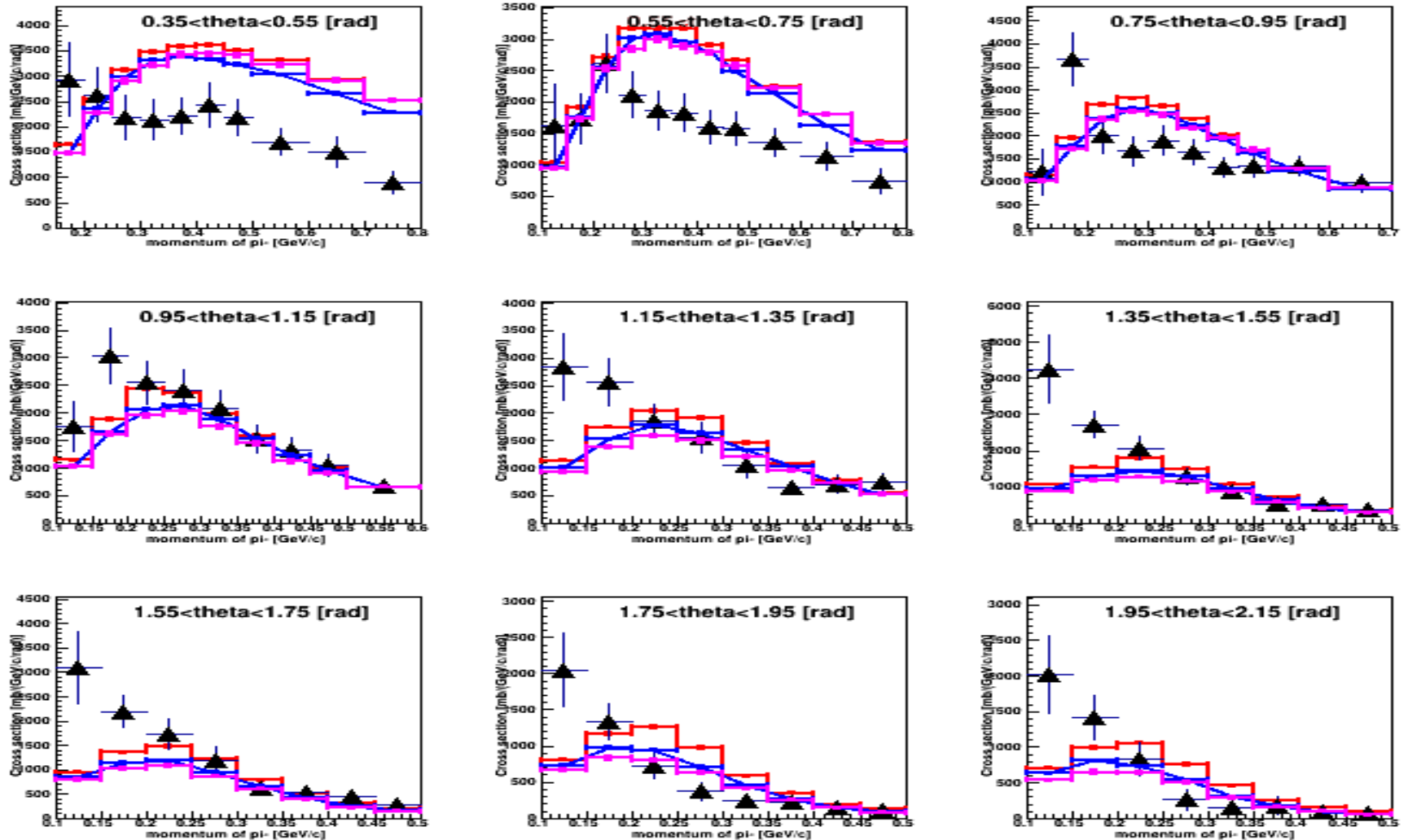
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G4/FTF: 12.0GeV piminus on Pb \rightarrow piplus + X; data by HARP (black triangles)



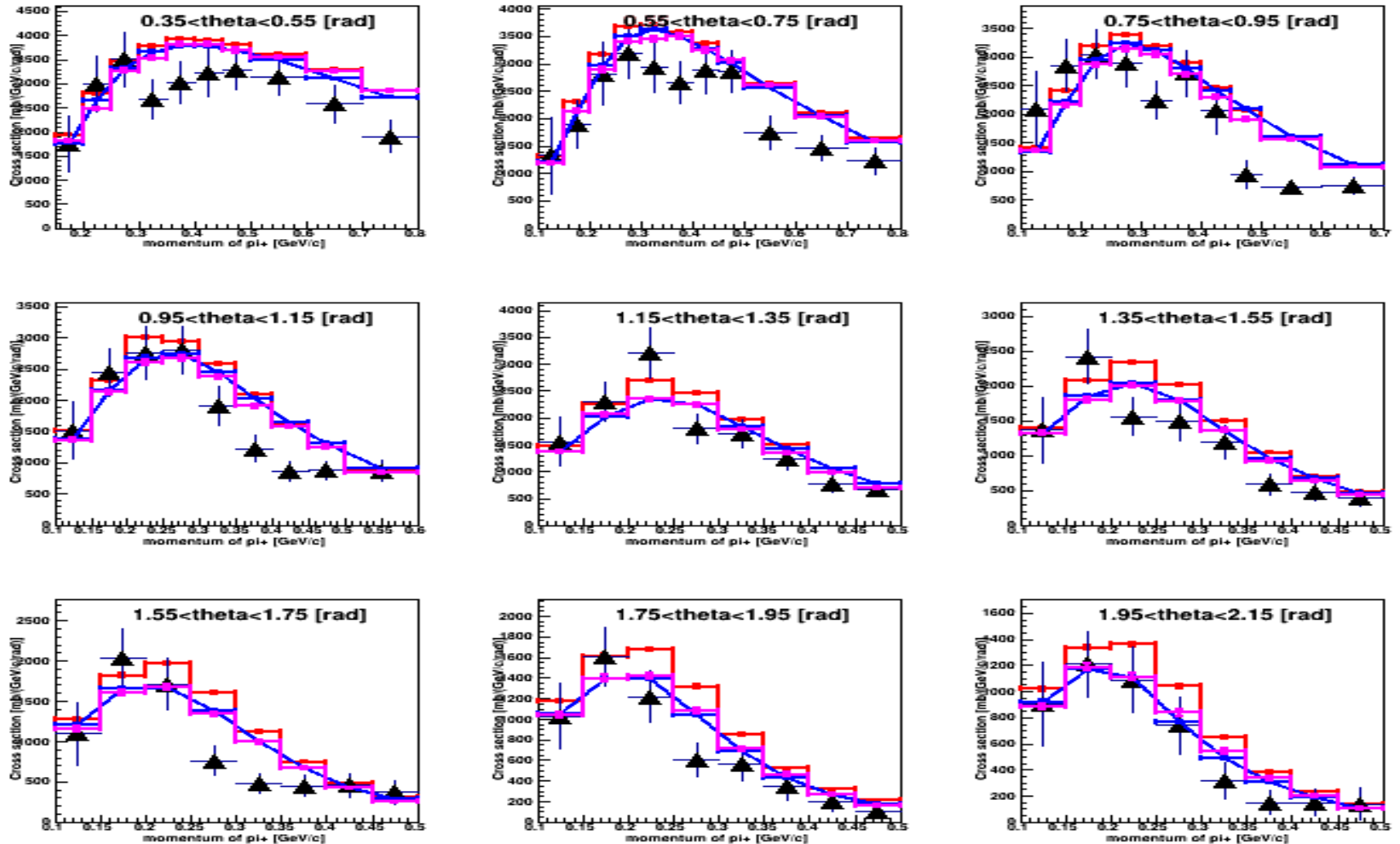
Default: $\chi^2/\text{NDF}=6.3$ Professor Fit: $\chi^2/\text{NDF}=4.8$ Sim using Best Fit: $\chi^2/\text{NDF}=5.4$

G4/FTF: 12.0GeV piplus on Pb \rightarrow piminus + X; data by HARP (black triangles)



Default: $\chi^2/\text{NDF}=4.4$ Professor Fit: $\chi^2/\text{NDF}=3.4$ Sim using Best Fit: $\chi^2/\text{NDF}=3.0$

G4/FTF: 12.0GeV pions on Pb \rightarrow pions + X; data by HARP (black triangles)



Summary

- We continue exploring FTF parameters, and how their modifications may affect various aspects of modeling hadron-nucleus interactions
- We currently concentrate on studying FTF nuclear target destruction and quark exchange with excitation of participants for the **pion projectile**
 - Subset of recent NA61 data for π^+ beam has been incorporated
 - More data by NA61 exist for π^+ projectile; will be incorporated shortly
- Initial results indicate that, through applying global fitting techniques, certain improvements in MC-data agreement can be made at least in the several tens of GeV range
- Modeling pion-nucleus interactions at intermediate energies, including benchmark vs available data, needs to be studied in more details which is planned for near term future

BACKUP SLIDES

Experimental data sets used in the study

HARP

- 3, 5, 8, 12 GeV/c proton on C, Cu, Pb targets
M. Apollonio et al., Nucl. Phys. A821 118, 2009
M. Apollonio et al., Phys.Rev.C80 065207, 2009
M. Apollonio et al., Phys.Rev.C80 035208, 2009
M.G. Catanesi et al., Phys.Rev.C77 055207, 2008
M.Apollonio et al., Phys.Rev.C82 045208, 2010

ITEP771

- Yu. D. Bayukov et al., Preprints ITEP-148-1983
and ITEP-172-1983; Sov.J.Nucl.Phys. 42 116, 1985

NA61

- 60 GeV/c proton on C
A. Aduszkiewicz et al. , Phys.Rev.D100 112004, 2019

From the documentation: <http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/ForToolkitDeveloper/html/GuideToExtendFunctionality/HadronicPhysics/hadronics.html#changing-internal-parameters-of-an-existing-model-fritiof-ftf-use-case>

Parameters to control nuclear destruction

The GEANT4 FTF model uses reggeon cascade in the impact parameter space to simulate production of fast nucleons in the hadron-nucleus interactions. After the projectile particle interacts with one of the nucleons in the target nucleus, this “wounded” nucleon may involve another nucleon in the cascade with the probability that is given as follows:

$$P(|\vec{s}_i - \vec{s}_j|) = C_{nd} \exp[-(\vec{s}_i - \vec{s}_j)^2 / R_c^2]$$

In this formula \vec{s}_i and \vec{s}_j are projections of the radii of i -th and j -th nucleons on the impact parameter plane, $R_c^2 = 1.5(fm)^2$, and the coefficient C_{nd} is defined as follows:

$$C_{nd} = P_1 e^{P_2 (y-P_3)} / [1 + e^{P_2 (y-P_3)}]$$

This is fixed (D) for baryons
but not for pions/mesons



where y is the projectile rapidity. The parameter P_1 in the above formula can be a fixed value (DEFAULT), or it can be expressed as a function of

- baryon number of the projectile in the case of the projectile destruction
- number of nucleons in the target nucleus in case of the target destruction

Modeling of momentum distributions of the nucleons involved in the cascade is described in greater details later in this document; however, one of the characteristics we would like to mention here is the average transverse momentum squared which can be expressed in a parametric way:

$$\langle P_T^2 \rangle = C_1 + C_2 \frac{e^{C_3 (y_{lab} - C_4)}}{1 + e^{C_3 (y_{lab} - C_4)}} \quad [(GeV/c)^2]$$

From the documentation: <http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/ForToolkitDeveloper/html/GuideToExtendFunctionality/HadronicPhysics/hadronics.html#changing-internal-parameters-of-an-existing-model-fritiof-fft-use-case>

The original Fritiof model contains only the pomeron exchange process shown in Fig. 44(d). It would be useful to extend the model by adding the exchange processes shown in Fig. 44(b) and Fig. 44(c), and the annihilation process of Fig. 44(a). This could probably be done by introducing a restricted set of mesonic and baryonic resonances and a corresponding set of parameters. This procedure was employed in the binary cascade model of GEANT4 (BIC) [BIC] and in the Ultra-Relativistic-Quantum-Molecular-Dynamic model (UrQMD) [UrQMD1], [UrQMD2]. However, it is complicated to use this solution for the simulation of hadron-nucleus and nucleus-nucleus interactions. The problem is that one has to consider resonance propagation in the nuclear medium and take into account their possible decays which enormously increases computing time. Thus, in the current version of the FTF model only quark exchange processes have been added to account for meson and baryon interactions with nucleons, without considering resonance propagation and decay. This is a reasonable hypothesis at sufficiently high energies.

For each projectile hadrons the following probabilities are set up:

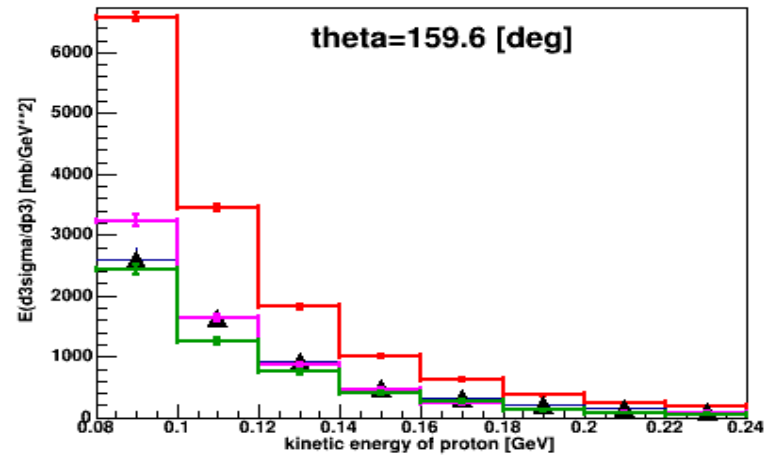
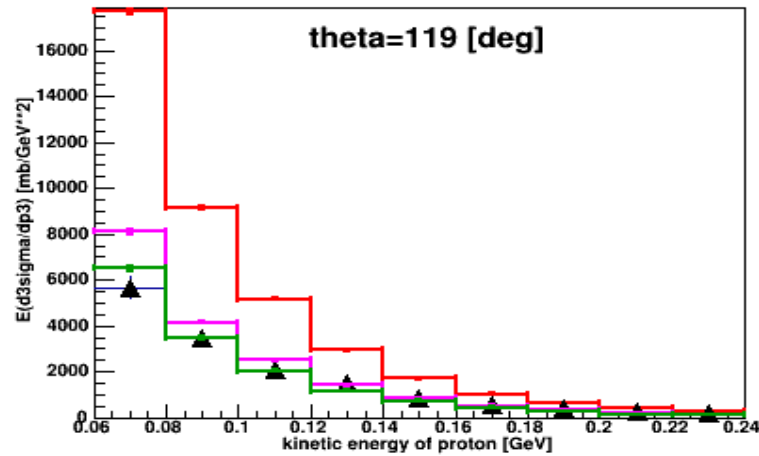
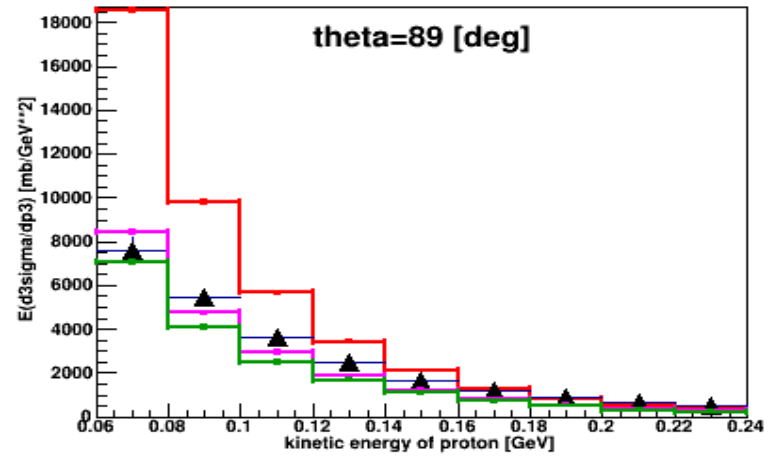
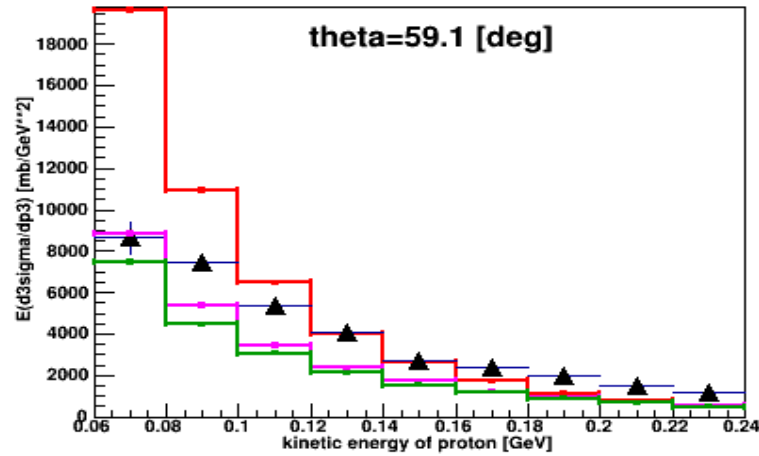
- Probability of quark exchange process without excitation of participants (Fig. 44(b)); (Proc# 0)
- Probability of quark exchange process with excitation of participants (Fig. 44(c)); (Proc# 1)
- Probability of projectile diffraction dissociation; (Proc# 2)
- Probability of target diffraction dissociation. (Proc# 3)

All these probabilities have the same functional form:

$$P_p = A_1 e^{-B_1 y} + A_2 e^{-B_2 y} + A_3,$$

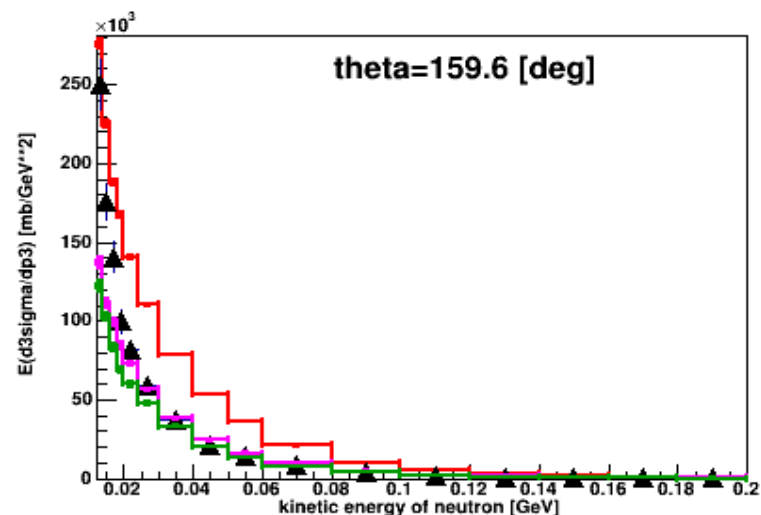
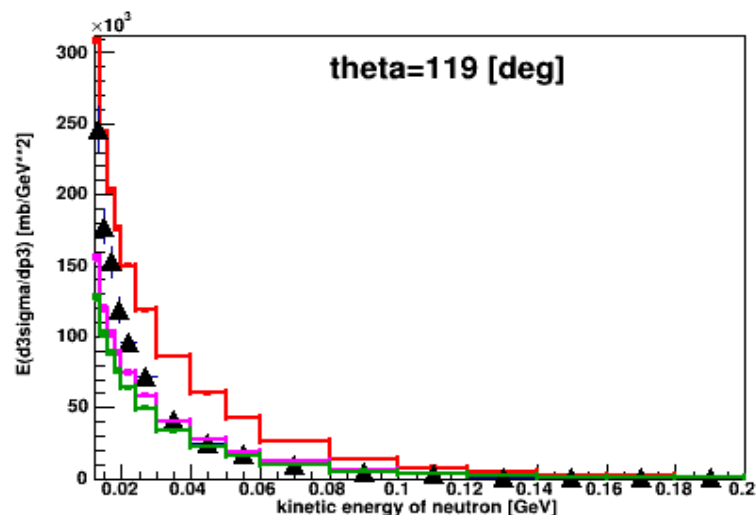
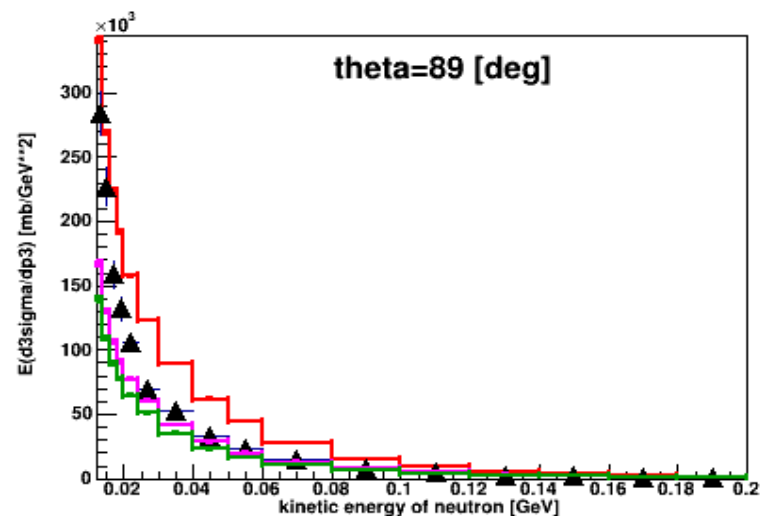
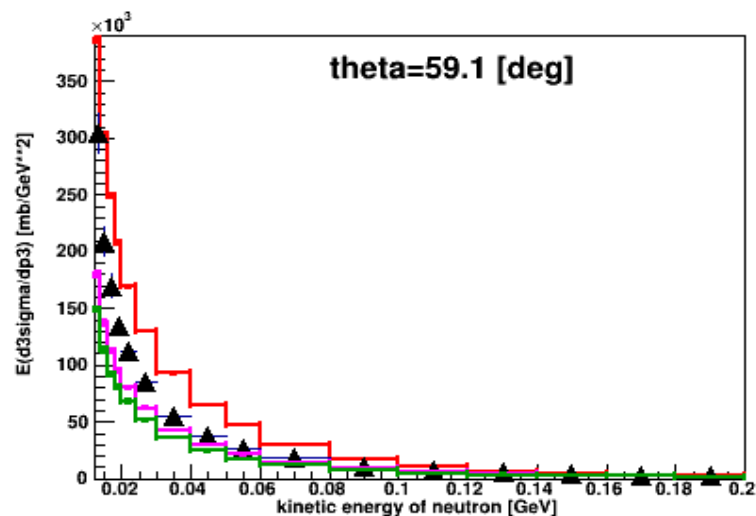
where y is the projectile rapidity in the target rest frame.

G4/FTF: 5.0GeV piminus on Pb → proton + X; data by ITEP



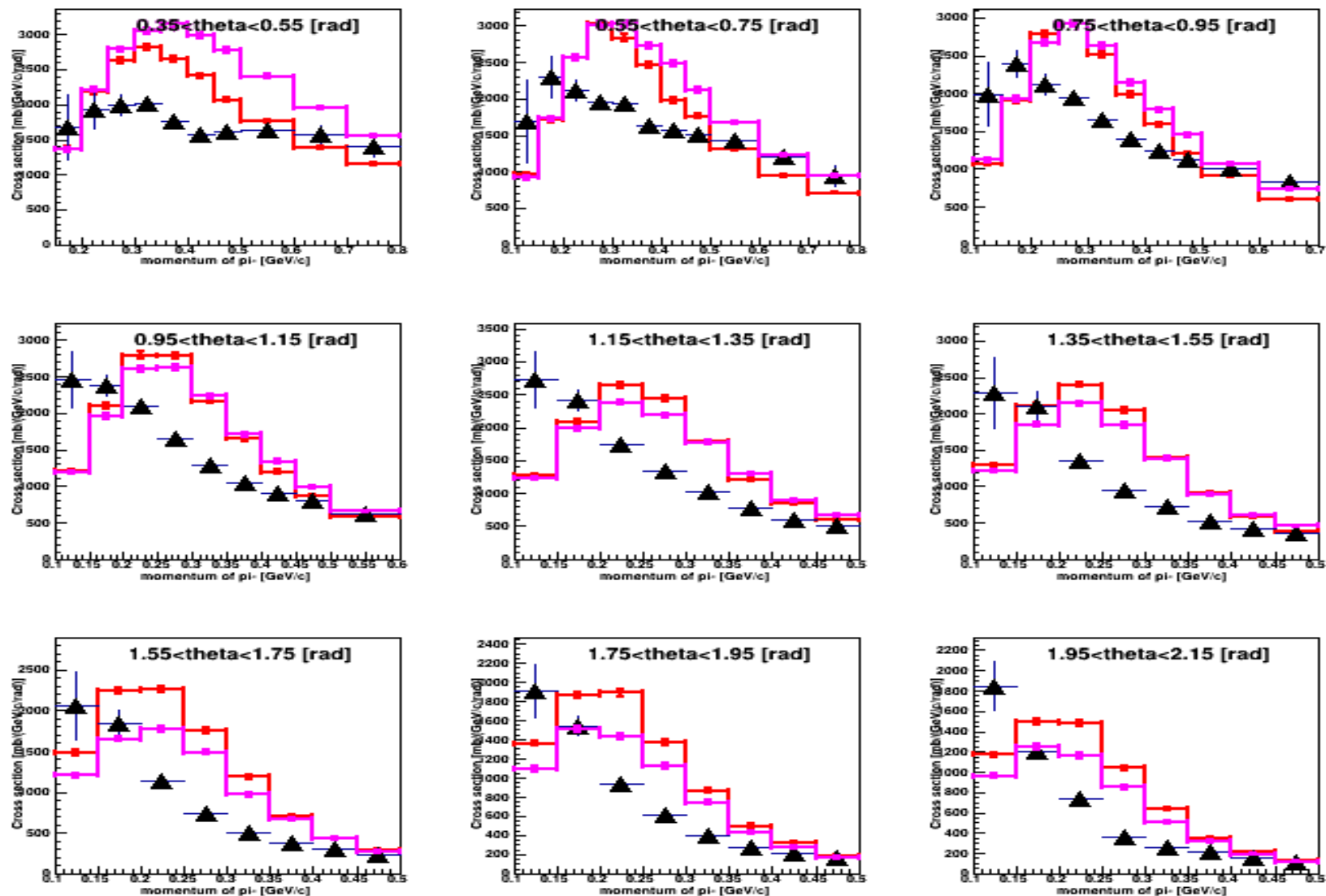
DEFAULT: $\chi^2/NDF = 108.2$ Sim Best Fit: 11.0.r06 - $\chi^2/NDF = 13.6$ 11.5.r07 - $\chi^2/NDF = 17.05$

G4/FTF: 5.0GeV piminus on Pb → neutron + X; data by ITEP

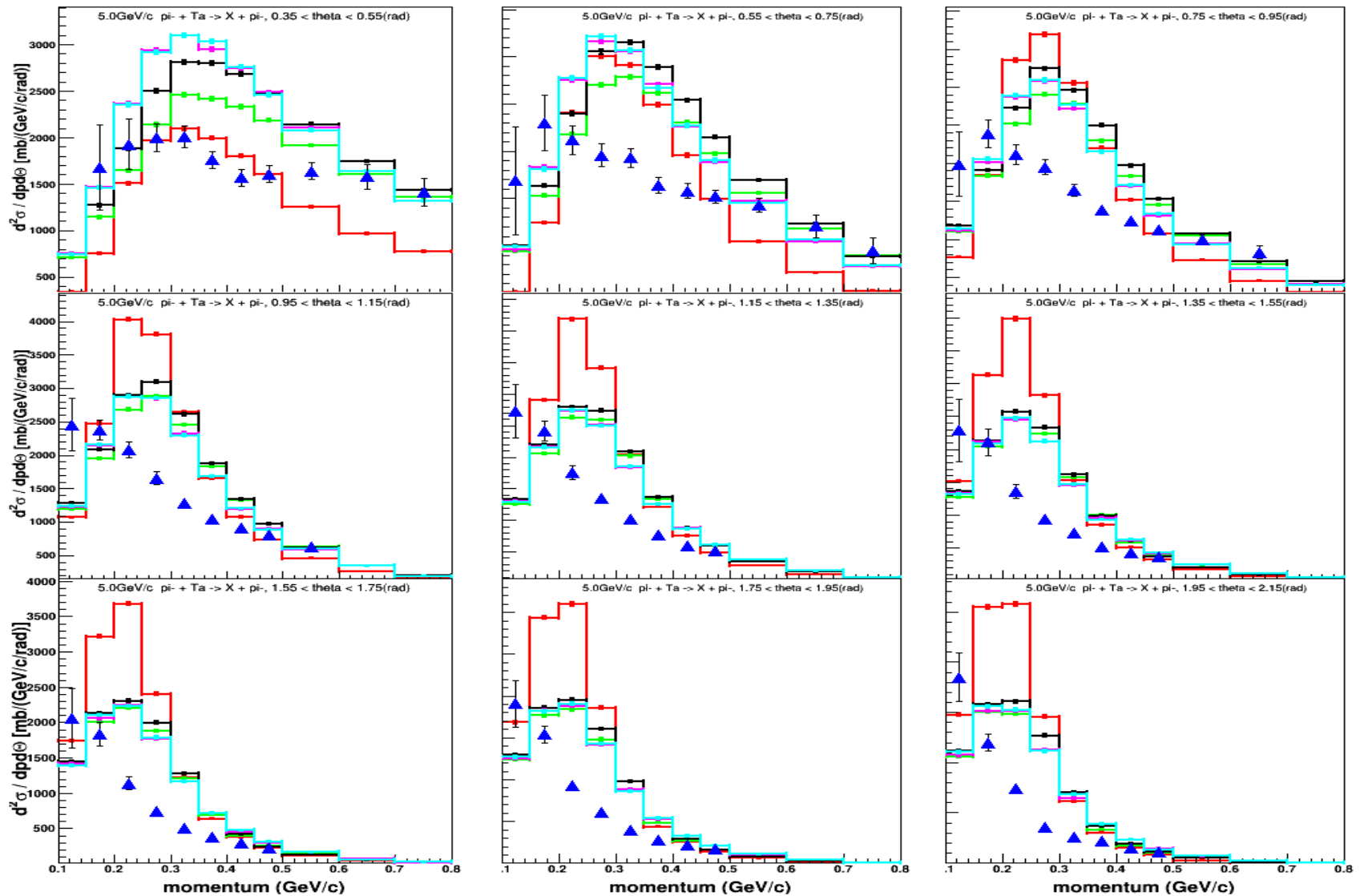


DEFAULT: $\chi^2/\text{NDF} = 123.9$ Sim Best Fit: 11.0.r06 - $\chi^2/\text{NDF} = 12.9$ 11.5.r07 - $\chi^2/\text{NDF} = 22.26$

G4/FTF: 5.0GeV piminus on Ta → piminus + X; data by HARP



DEFAULT results are for 11.0.r06 (close to 11.0 but not identical) ; **Sim Best Fit Nuc.Destr 11.6.r06 (2022)**



ftfp vs HARP Data; χ^2/NDF calculated over LA theta bins

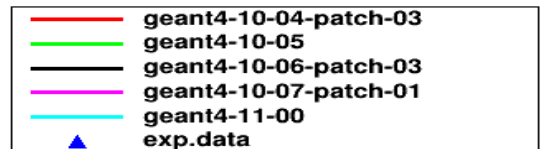
$\chi^2/\text{NDF} = 150.747$ for geant4-10-04-patch-03

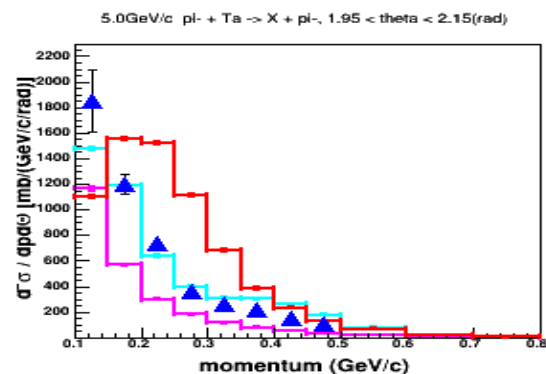
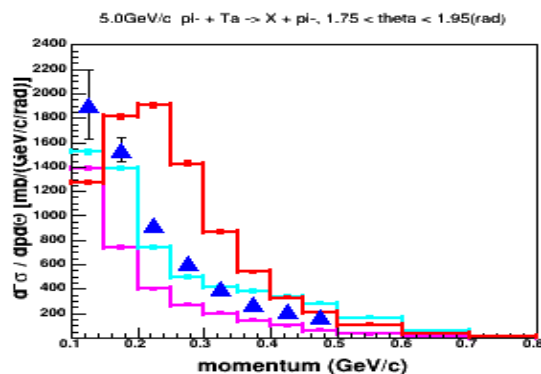
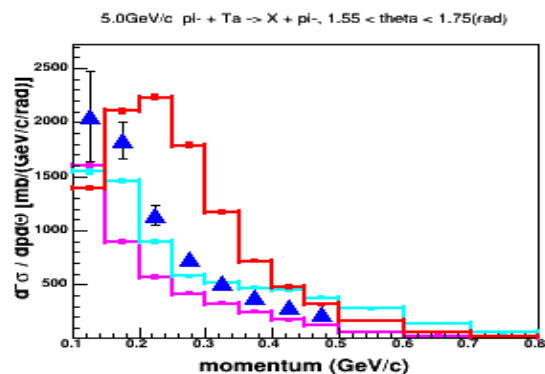
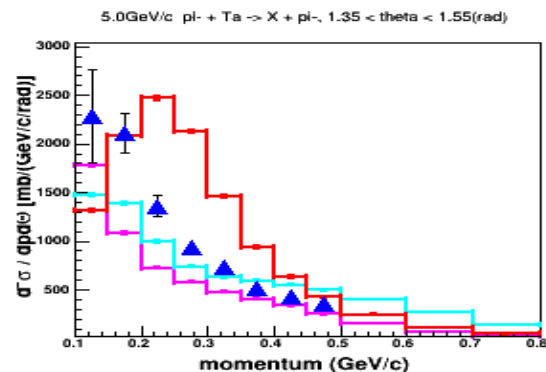
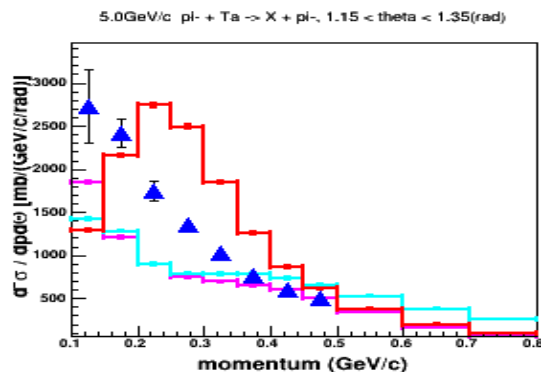
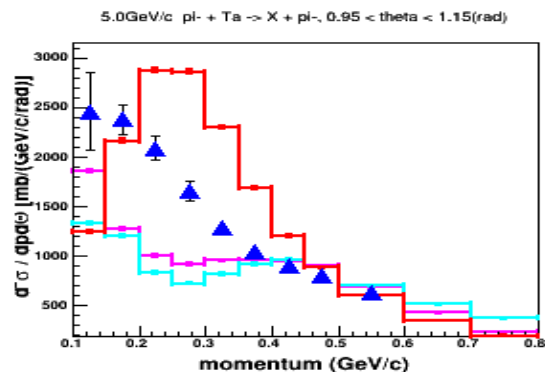
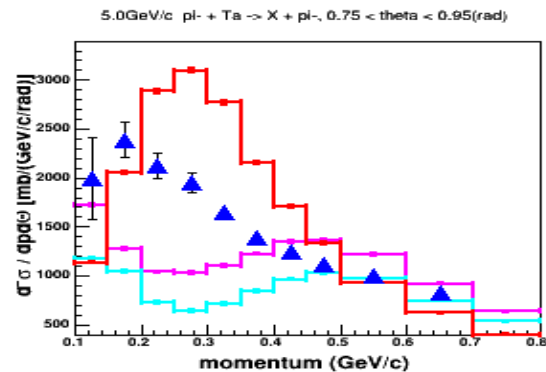
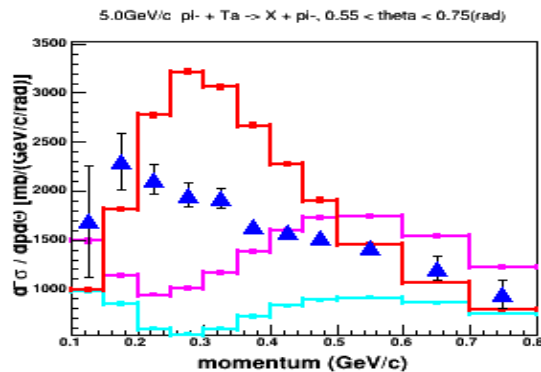
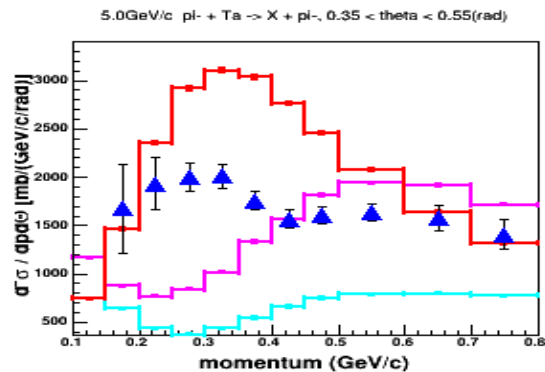
$\chi^2/\text{NDF} = 77.1672$ for geant4-10-05

$\chi^2/\text{NDF} = 103.289$ for geant4-10-06-patch-03

$\chi^2/\text{NDF} = 78.604$ for geant4-10-07-patch-01

$\chi^2/\text{NDF} = 80.129$ for geant4-11-00





MC vs HARP Data; χ^2/NDF calculated over LA theta bins

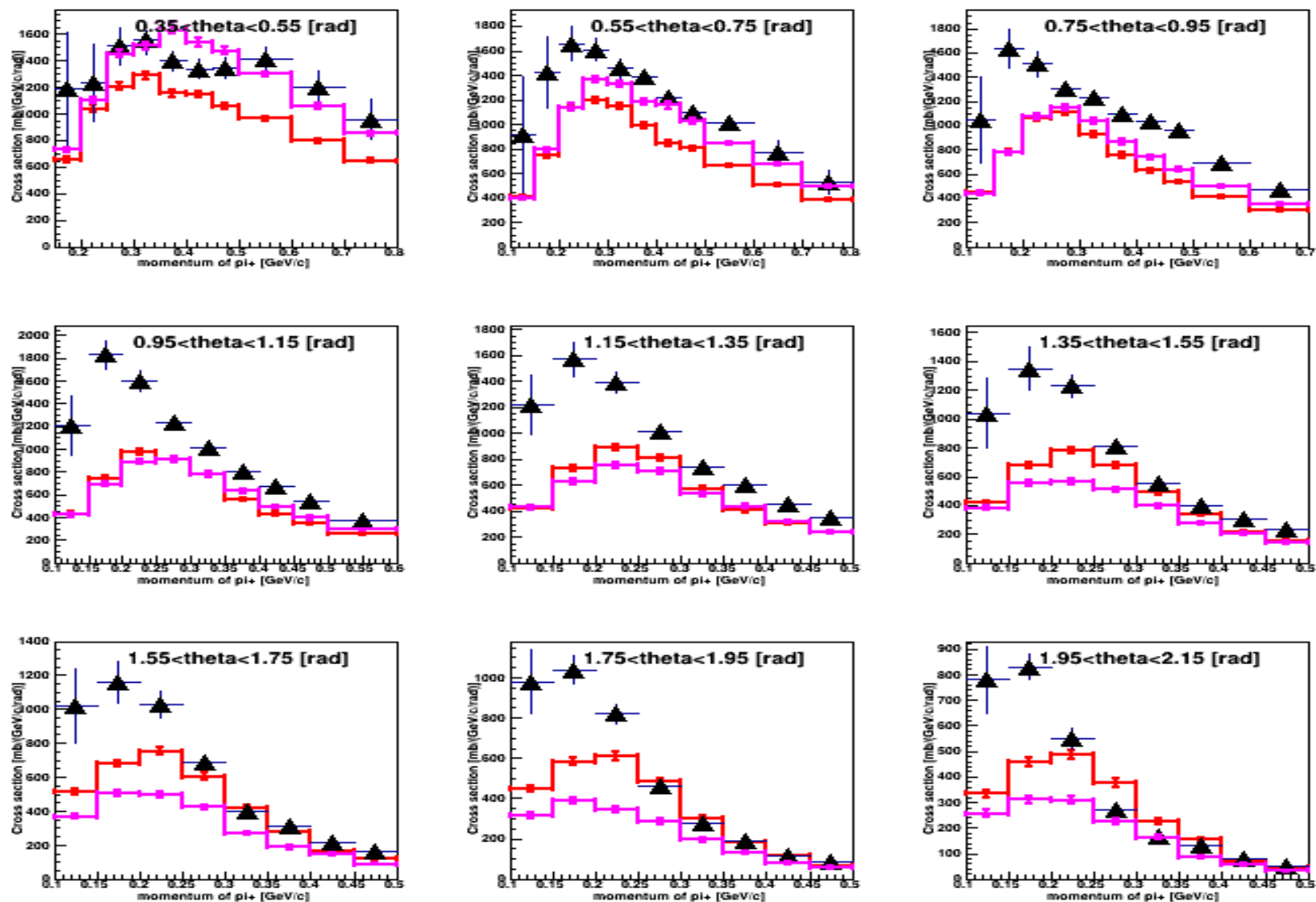
$\chi^2/\text{NDF} = 27.9507$ for inclxx

$\chi^2/\text{NDF} = 40.3521$ for bertini

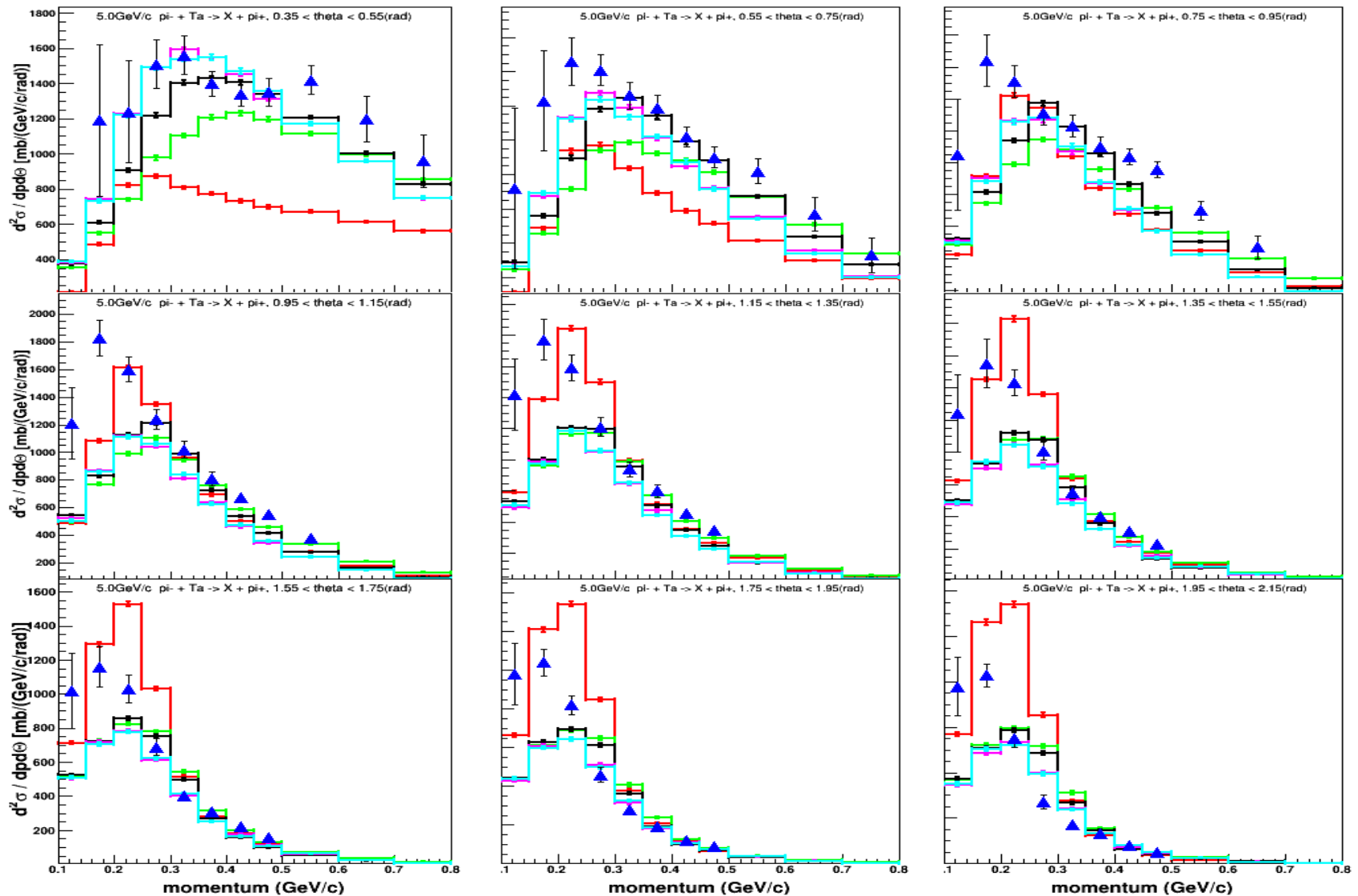
$\chi^2/\text{NDF} = 80.129$ for ftfp

— inclxx
— bertini
— ftfp
▲ exp.data

G4/FTF: 5.0GeV piminus on Ta → piplus + X; data by HARP



DEFAULT results are for 11.0.r06 (close to 11.0 but not identical) ; **Sim Best Fit Nuc.Destr 11.0.r06 (2022)**



ftfp vs HARP Data; χ^2/NDF calculated over LA theta bins

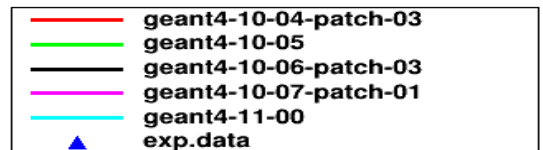
$\chi^2/\text{NDF} = 23.7324$ for geant4-10-04-patch-03

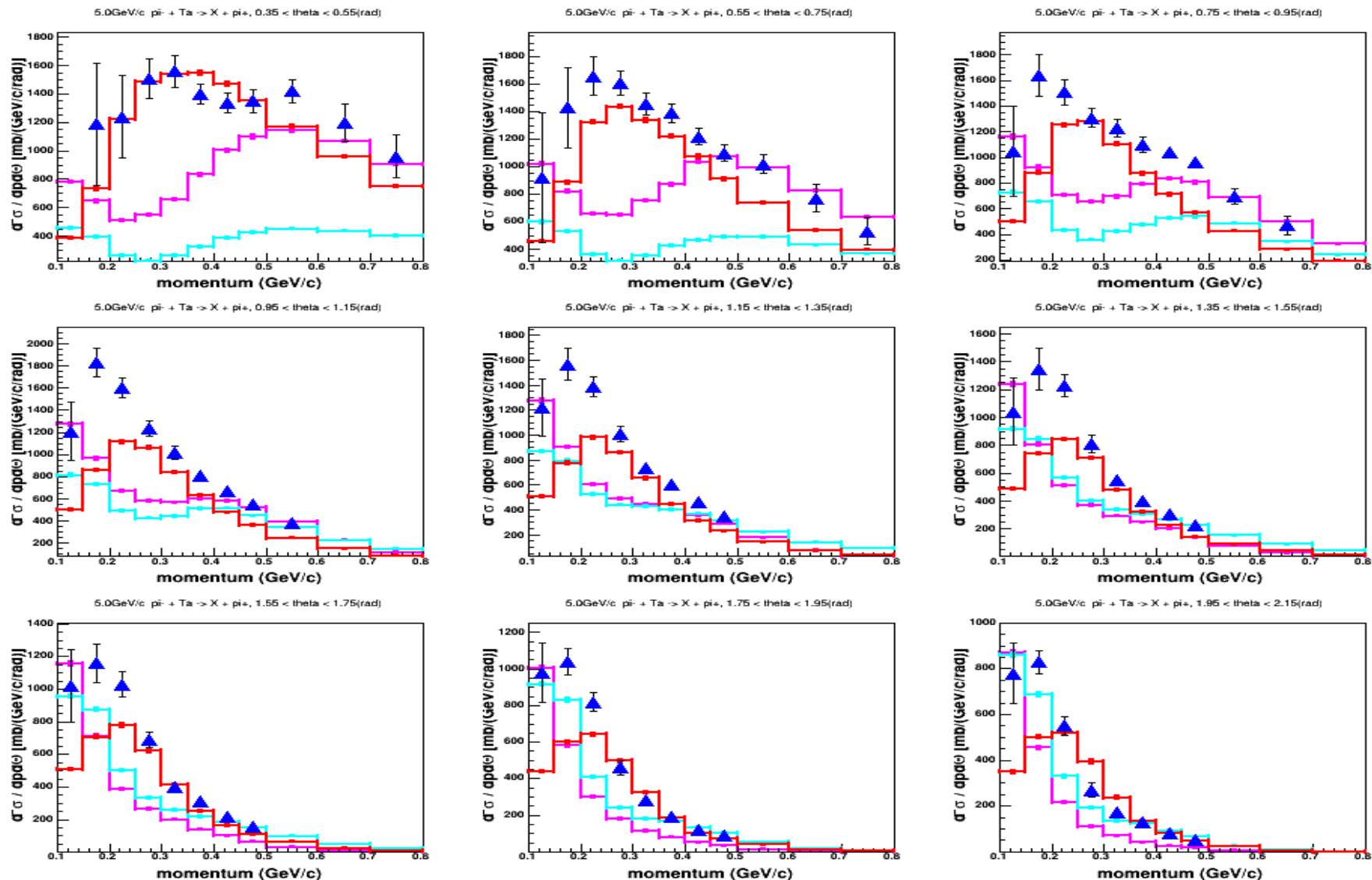
$\chi^2/\text{NDF} = 12.6294$ for geant4-10-05

$\chi^2/\text{NDF} = 9.88397$ for geant4-10-06-patch-03

$\chi^2/\text{NDF} = 11.4088$ for geant4-10-07-patch-01

$\chi^2/\text{NDF} = 11.3853$ for geant4-11-00





MC vs HARP Data; χ^2/NDF calculated over LA theta bins

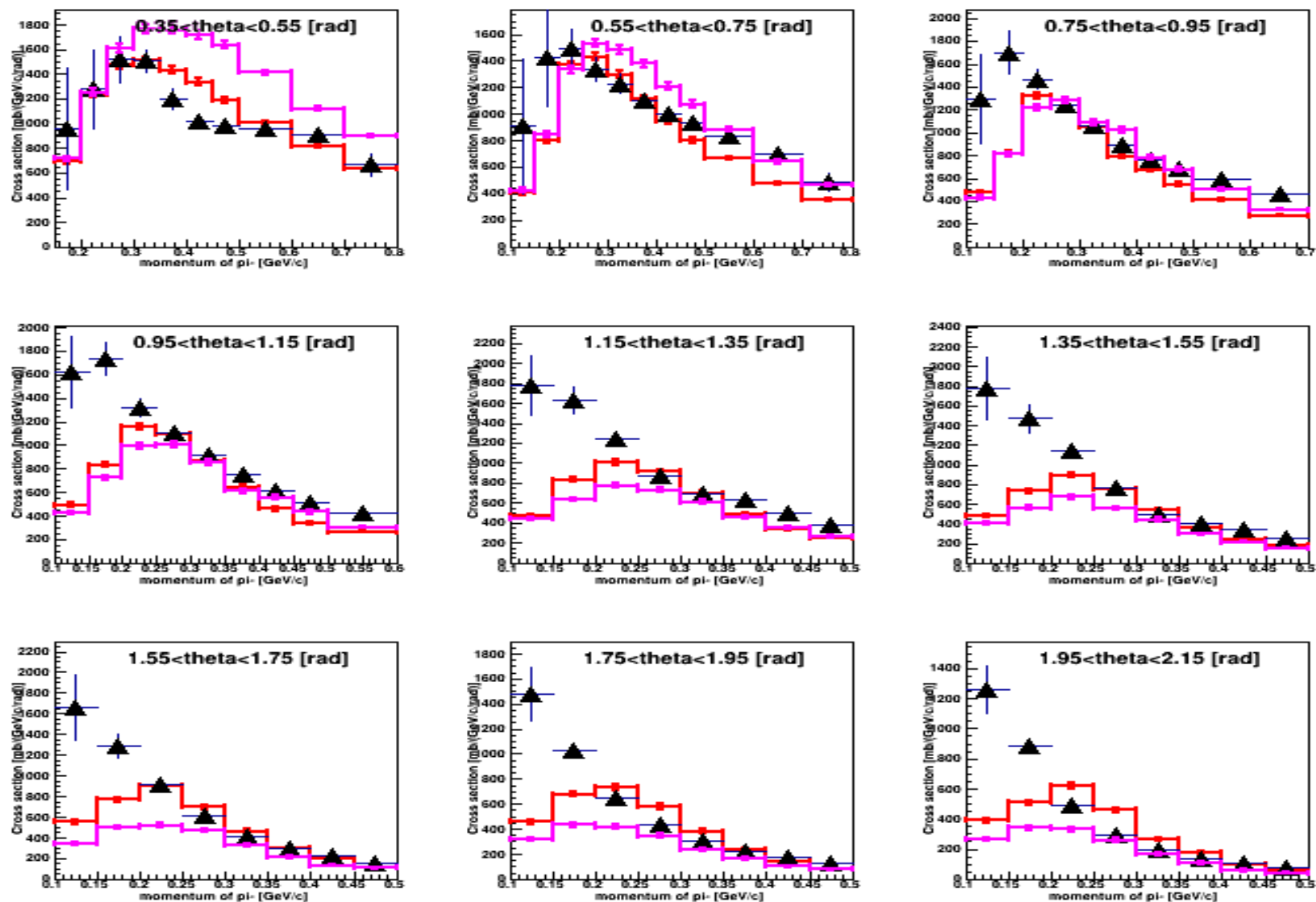
$\chi^2/\text{NDF} = 34.6272$ for inclxx

$\chi^2/\text{NDF} = 52.0291$ for bertini

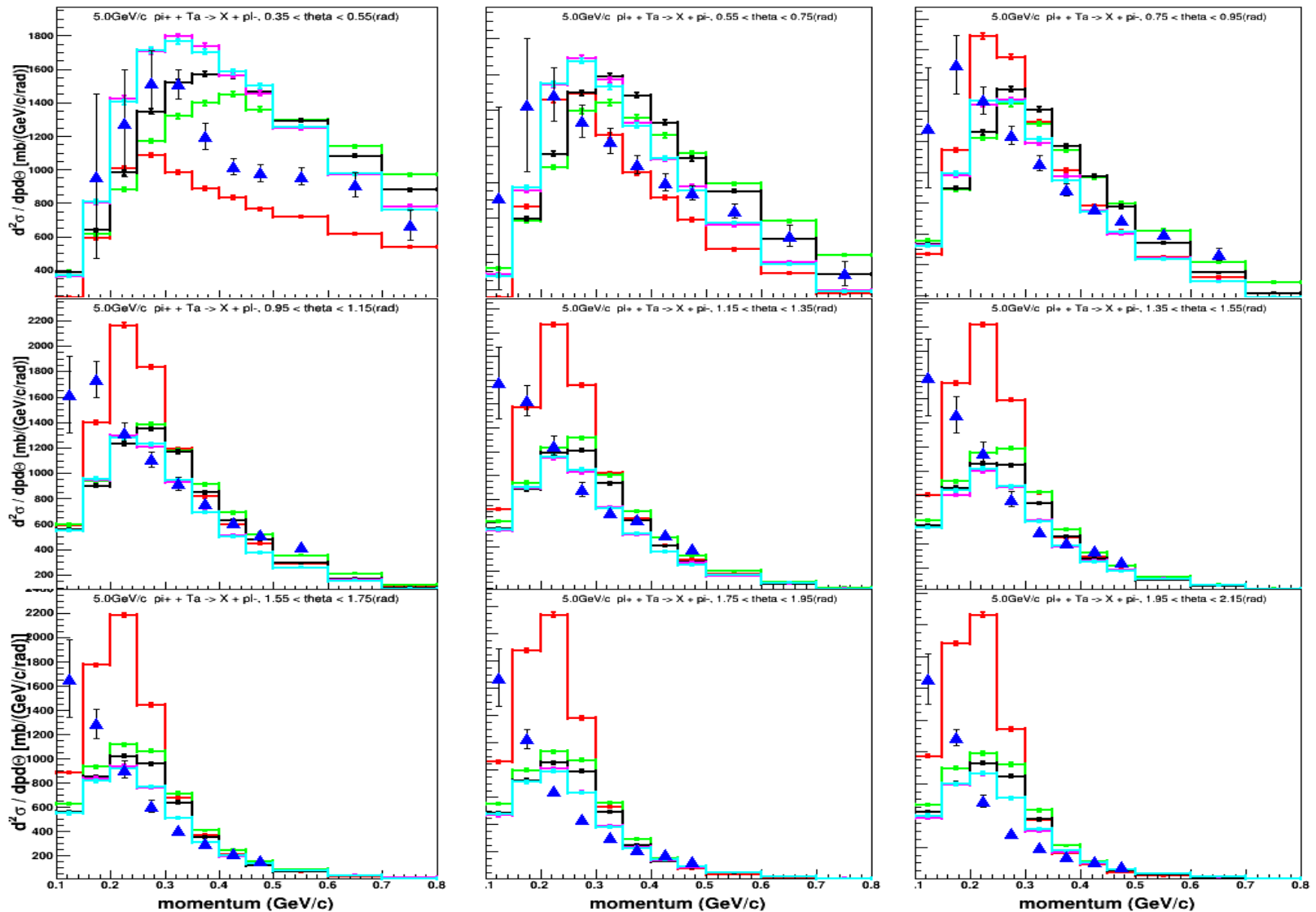
$\chi^2/\text{NDF} = 11.3853$ for ftfp

— inclxx
— bertini
— ftfp
▲ exp.data

G4/FTF: 5.0GeV piplus on Ta → piminus + X; data by HARP



DEFAULT results are for 11.0.r06 (close to 11.0 but not identical) ; **Sim Best Fit Nuc.Destr 11.0.r06 (2022)**



ftfp vs HARP Data; χ^2/NDF calculated over LA theta bins

$\chi^2/\text{NDF} = 71.5476$ for geant4-10-04-patch-03

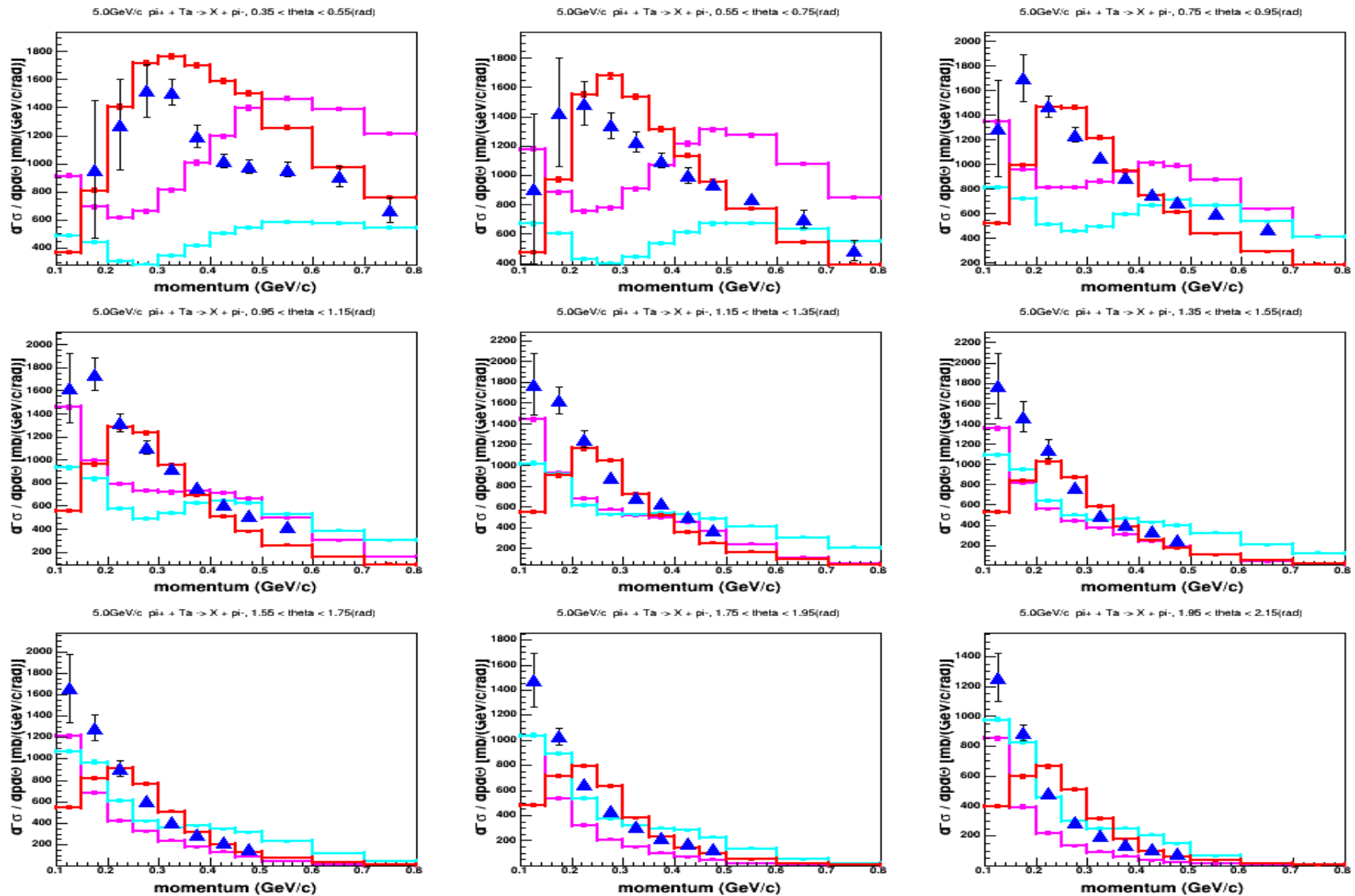
$\chi^2/\text{NDF} = 27.1707$ for geant4-10-05

$\chi^2/\text{NDF} = 23.8493$ for geant4-10-06-patch-03

$\chi^2/\text{NDF} = 15.0251$ for geant4-10-07-patch-01

$\chi^2/\text{NDF} = 15.1822$ for geant4-11-00





MC vs HARP Data; χ^2/NDF calculated over LA theta bins

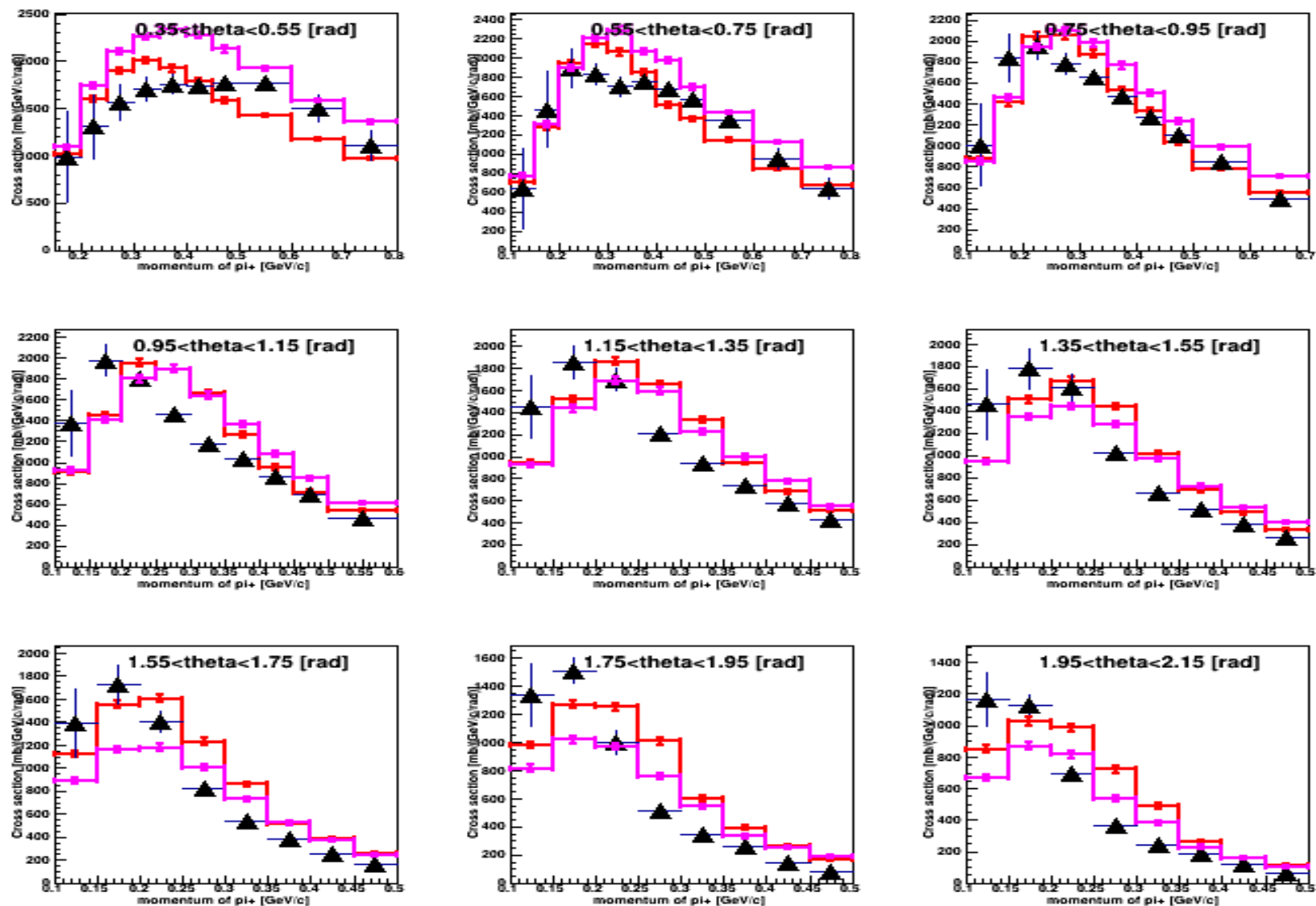
$\chi^2/\text{NDF} = 33.2666$ for inclxx

$\chi^2/\text{NDF} = 37.7825$ for bertini

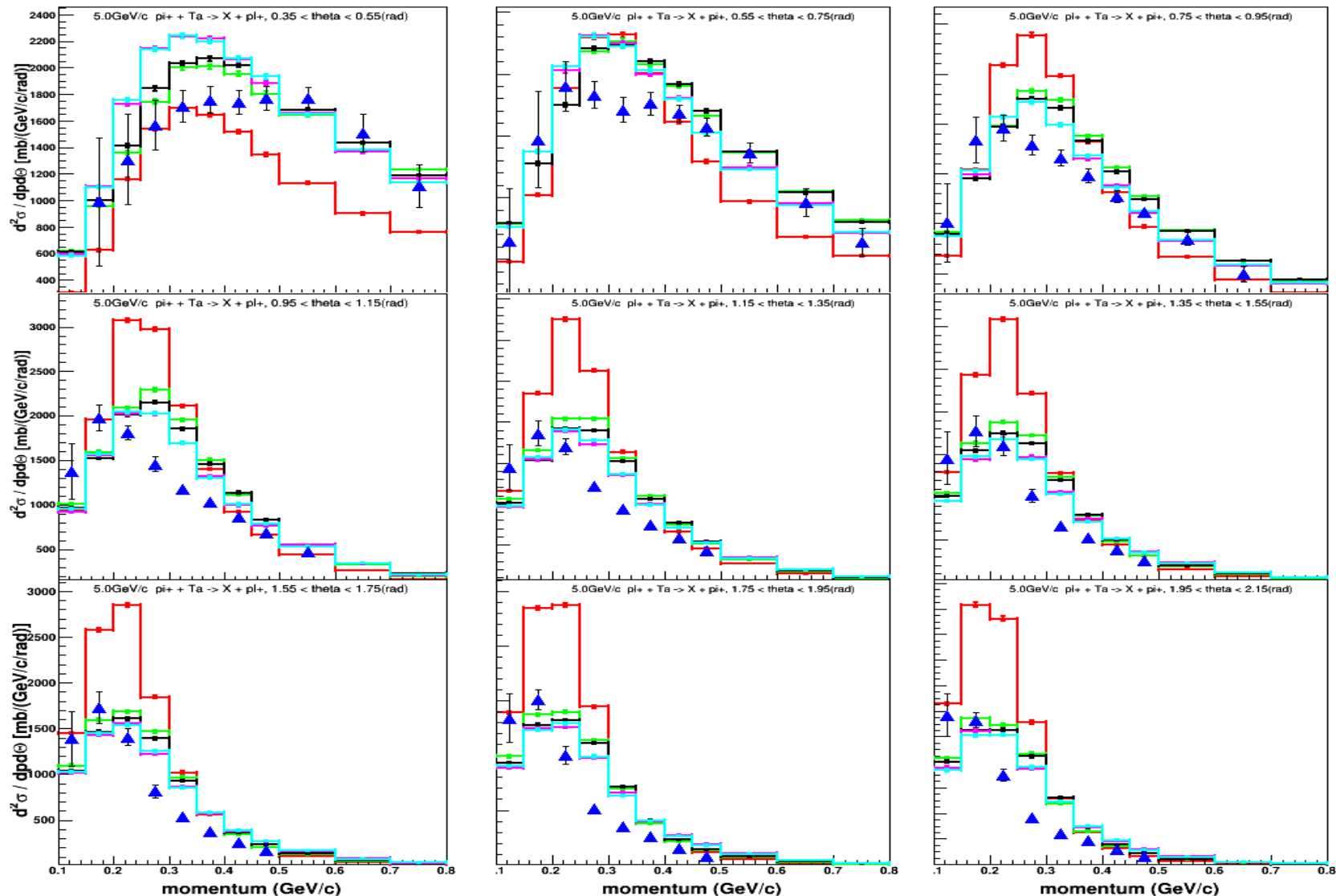
$\chi^2/\text{NDF} = 15.1822$ for ftfp

— inclxx
— bertini
— ftfp
▲ exp.data

G4/FTF: 5.0GeV pions on Ta \rightarrow pions + X; data by HARP



DEFAULT results are for 11.0.r06 (close to 11.0 but not identical) ; **Sim Best Fit Nuc.Destr 11.0.r06 (2022)**



ftfp vs HARP Data; χ^2/NDF calculated over LA theta bins

$\chi^2/\text{NDF} = 76.8791$ for geant4-10-04-patch-03

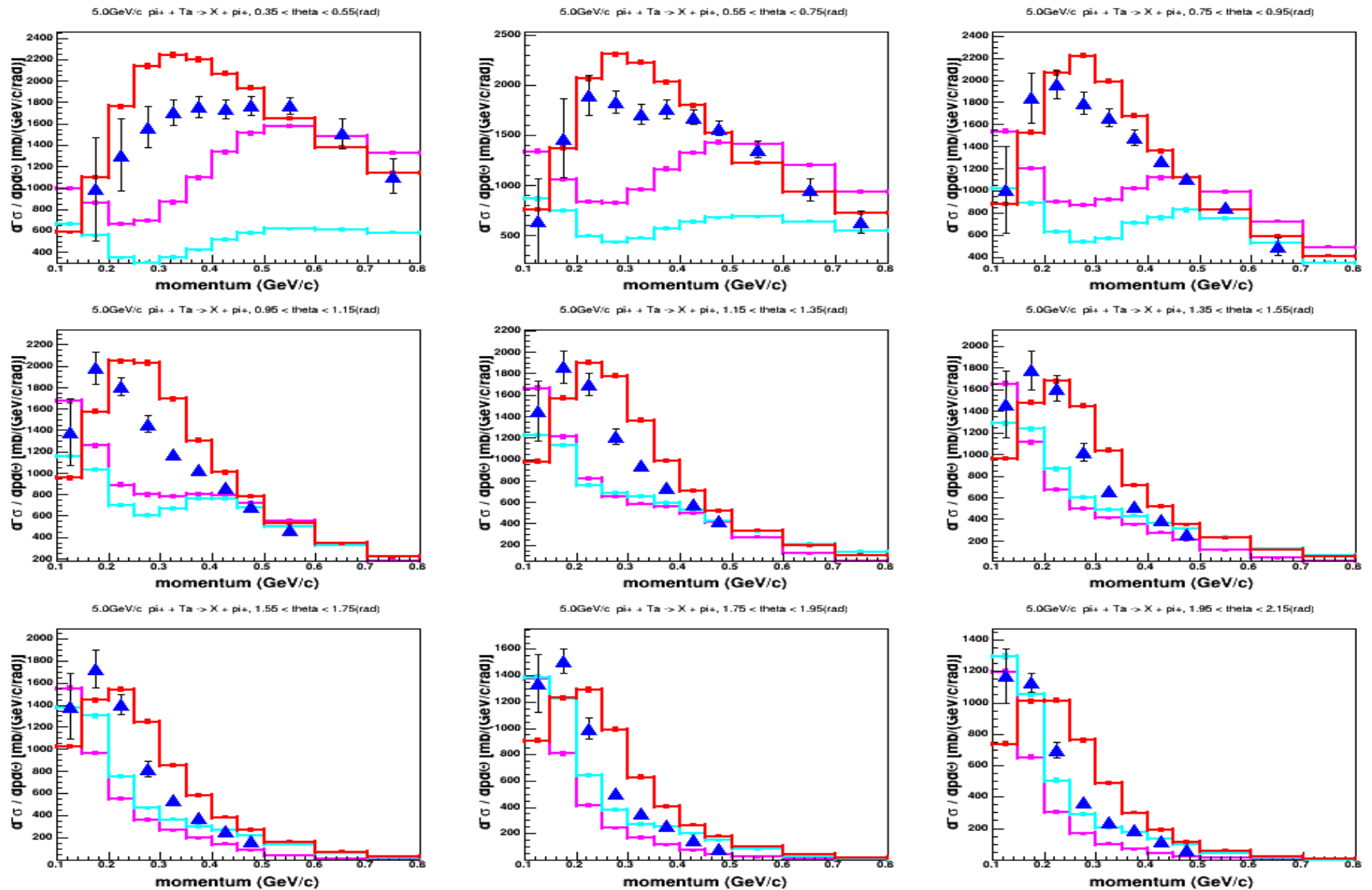
$\chi^2/\text{NDF} = 32.7555$ for geant4-10-05

$\chi^2/\text{NDF} = 31.1648$ for geant4-10-06-patch-03

$\chi^2/\text{NDF} = 23.3959$ for geant4-10-07-patch-01

$\chi^2/\text{NDF} = 23.0435$ for geant4-11-00

— geant4-10-04-patch-03
— geant4-10-05
— geant4-10-06-patch-03
— geant4-10-07-patch-01
— geant4-11-00
▲ exp.data



MC vs HARP Data; χ^2/NDF calculated over LA theta bins

$\chi^2/\text{NDF} = 30.5456$ for inclxx

$\chi^2/\text{NDF} = 46.8606$ for bertini

$\chi^2/\text{NDF} = 23.0435$ for ftfp

— inclxx
— bertini
— ftfp
▲ exp.data

Number of parameters vs polynomial order vs number of “points” in the parameter space

```
int numCoeffs(int dim, int order) {
    int ntok = 1;
    int r = min(order, dim);
    for (int i = 0; i < r; ++i) {
        ntok = ntok*(dim+order-i)/(i+1);
    }
    return ntok;
}
```

3 dimensional parameter space:

Polynomial order	Minimum samples
0	1
1	4
2	10
3	20
4	35
5	56
6	84
7	120
8	165
9	220
10	286

20 dimensional parameter space:

Polynomial order	Minimum samples
0	1
1	21
2	231
3	1771
4	10626
5	53130
6	230230
7	888030
8	3108105
9	10015005
10	30045015

50 dimensional parameter space:

Polynomial order	Minimum samples
0	1
1	51
2	1326
3	23426
4	316251
5	3478761
6	32468436
7	264385836