Preliminary Results from Exploring the FTF Quark Exchange Model Parameters

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General Information (I)

- FTF offers an API of 41 numeric parameters and boolean switches involved in modeling interactions of baryons and pions/meson with nuclei, for the following sub-processes:
  - Projectile or target diffraction dissociation
  - Nuclear destruction
- Exploring sensitivity of the predictions, incl. global fitting
  - Proton beam: JINST 15, P02025 2020 (arXiv:1910.06417)
  - Additional studies of the FTF nuclear destruction for proton and pion beam, with focus on correlations among parameter
    - https://indico.cern.ch/event/917397/contributions/3870222/attachments/2042391/3421173/G4HAD-May20-2020.pdf
    - https://indico.cern.ch/event/938303/contributions/3954369/attachments/2078467/3490663/G4HAD-July22-2020-v1.pdf

General Information (II)

- We have a reasonably good understanding of what affects modeling production of relatively low energy protons and neutrons in hadron+nucleus interactions (e.g. FTF nuclear destruction model), and that there are ways to improve agreement between MC and thin target data in this areas
- Other simulated spectra, in particular secondary pions, are likely to have contributions from other FTF processes/models, thus varying some other parameters may affect results
- There are more parameters involved in FTF modeling diffraction dissociation than we have released, i.e. parameters of the FTF quark exchange model are quite interesting to explore

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

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.

“Pilot” Study - Exploring Parameters of FTF Quark Exchange Model (I)

- From earlier attempts of varying parameters of quark exchange model with or without excitation of participants (“proc0” and “proc1”) we knew that simulated spectra of secondary pions were quite sensitive:
  - https://indico.cern.ch/event/938303/contributions/3954369/attachments/2078467/3490663/G4HAD-July22-2020-v1.pdf
- Per suggestion of Vladimir Uzh. we decided to focus on quark exchange with excitation of participants (“proc1”)
  - Specific interest from Mu2e in the production of relatively low momentum pi- in the backward hemisphere
  - Per communications with Vladimir Uzh., “we might be able to improve agreement between MC and NA61 results”

"Pilot" Study - Exploring Parameters of FTF Quark Exchange Model (II)

- Beam: proton
- Beam momentum: 5, 8, 31 GeV/c
- Targets: C, Cu, Ta, Pb
- Secondaries: pions
- Experimental datasets: HARP, NA61 (references in backup)
- Geant4: 10-06-ref-07 with custom modifications to FTF API
  - There are some changes to FTF in 10-06-ref-08, so subsequent studies will need to be done with more up-to-date release

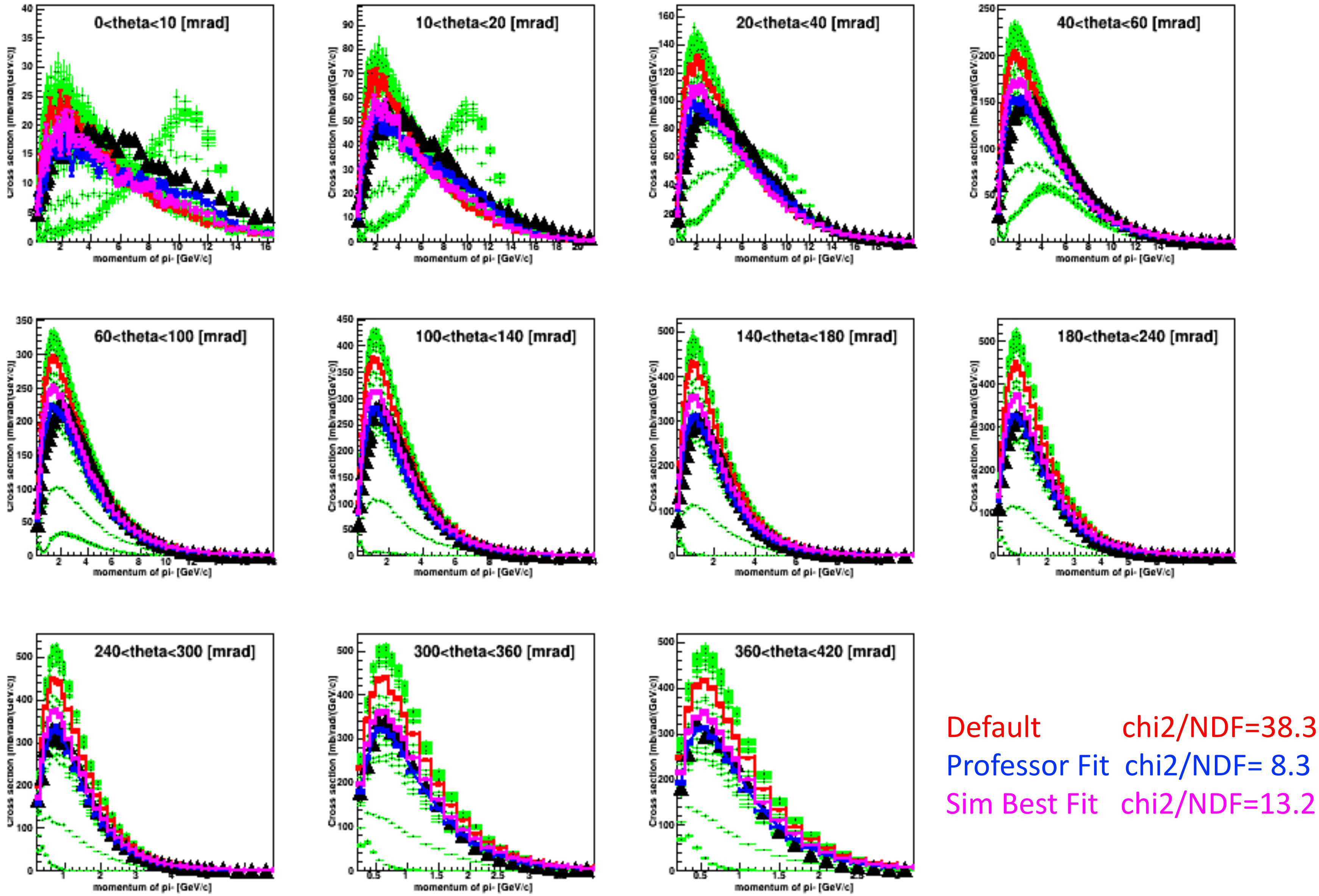
"Pilot" Study - Exploring Parameters of FTF Quark Exchange Model (III)

- Varying parameters of "proc1":
  - **FTF_BARYON_PROC1_A1 0 50 D=25.**
  - **FTF_BARYON_PROC1_B1 0 5 D=1.**
  - **FTF_BARYON_PROC1_A2 -100 0 D=-50.34**
  - **FTF_BARYON_PROC1_B2 0 5 D=1.5**
  - NOTE: When varying only the above 4 parameters, simulated "spread" was very small for pion production in backward hemisphere even for heavy target (see slide in backup)
- Parameters of the nuclear destruction model:
  - **FTF_BARYON_NUCDESTR_P1_TGT 0. 0.01 (D=1., no A-dep)**
  - **FTF_BARYON_NUCDESTR_ADEP_TGT true (D=false)**
- Simulation was done for 150 "points" in multi-parameter space, with each parameter for each "point" randomly selected from the above ranges

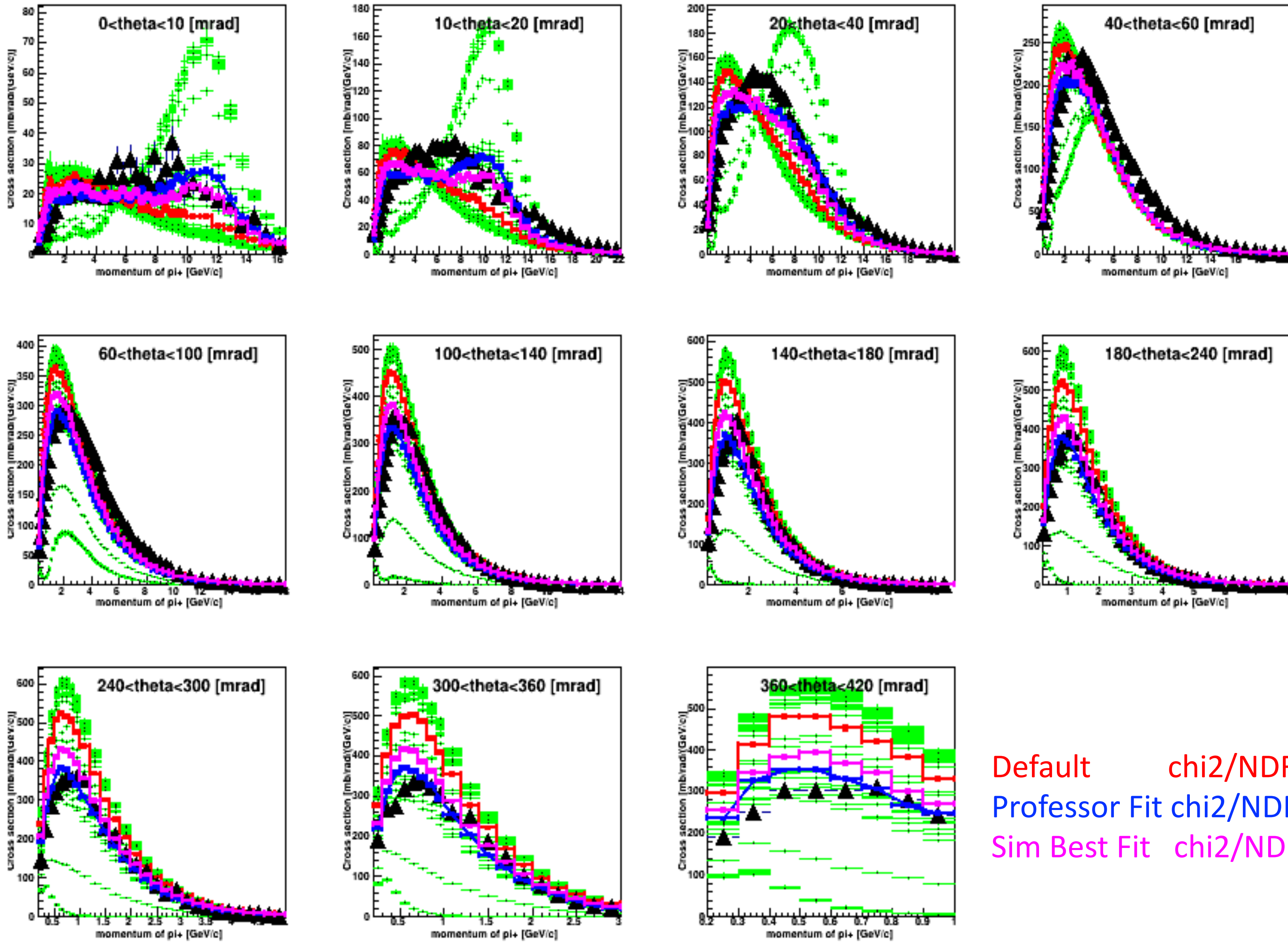
FTF Quark Exchange Parameters ("proc1") + One Nuclear Destruction Parameter

- Default
  - FTF_BARYON_PROC1_A1 = 25.
  - FTF_BARYON_PROC1_B1 = 1.
  - FTF_BARYON_PROC1_A2 = -50.34
  - FTF_BARYON_PROC1_B2 = 1.5
  - FTF_BARYON _NUCDESTR_P1_TGT = 1. (no A-dep)
- **Green is the spread in MC results due to varying FTF parameter**
- **Global Fit** vs NA61 and selected HARP data, pion spectra
  - FTF_BARYON_PROC1_A1 = 4.4 $\pm$ 0.7
  - FTF_BARYON_PROC1_B1 = 0.44 $\pm$ 0.03
  - FTF_BARYON_PROC1_A2 = -15.3 $\pm$ 1.99
  - FTF_BARYON_PROC1_B2 = 1.6 $\pm$ 0.1
  - FTF_BARYON _NUCDESTR_P1_TGT = (0.00109 $\pm$ 0.00005) * A
  - NOTE: fit result for FTF_BARYON _NUCDESTR_P1_TGT is somewhat different from what was obtained by fitting it against ITEP771 and IAEA/Ishibashi data
- Geant4 (re)simulation with the best fit parameters (above)

31.0GeV proton on C → piminus + X; data by NA61



31.0GeV proton on C → piplus + X; data by NA61

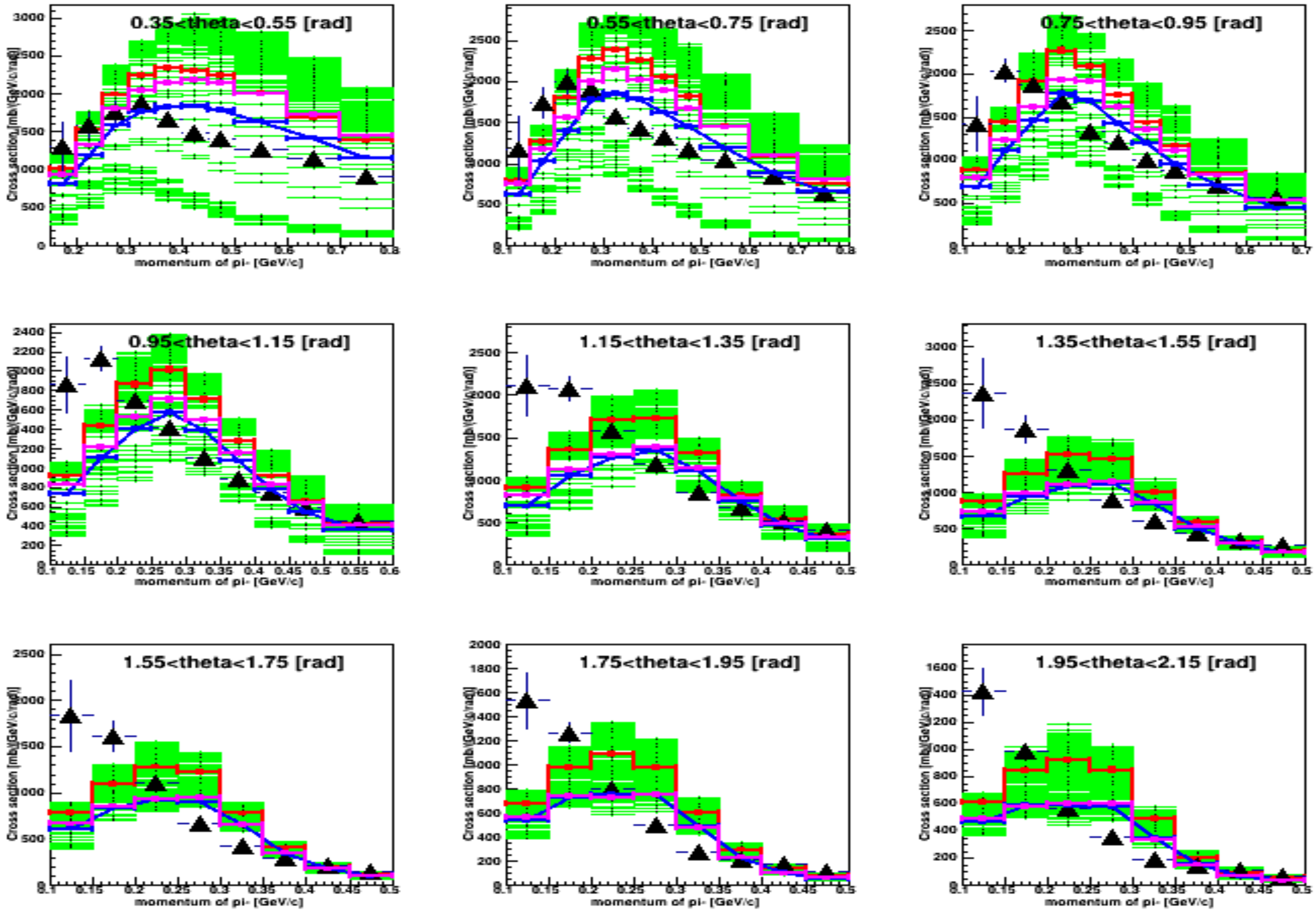


Default chi2/NDF=42.8

Professor Fit chi2/NDF=12.8

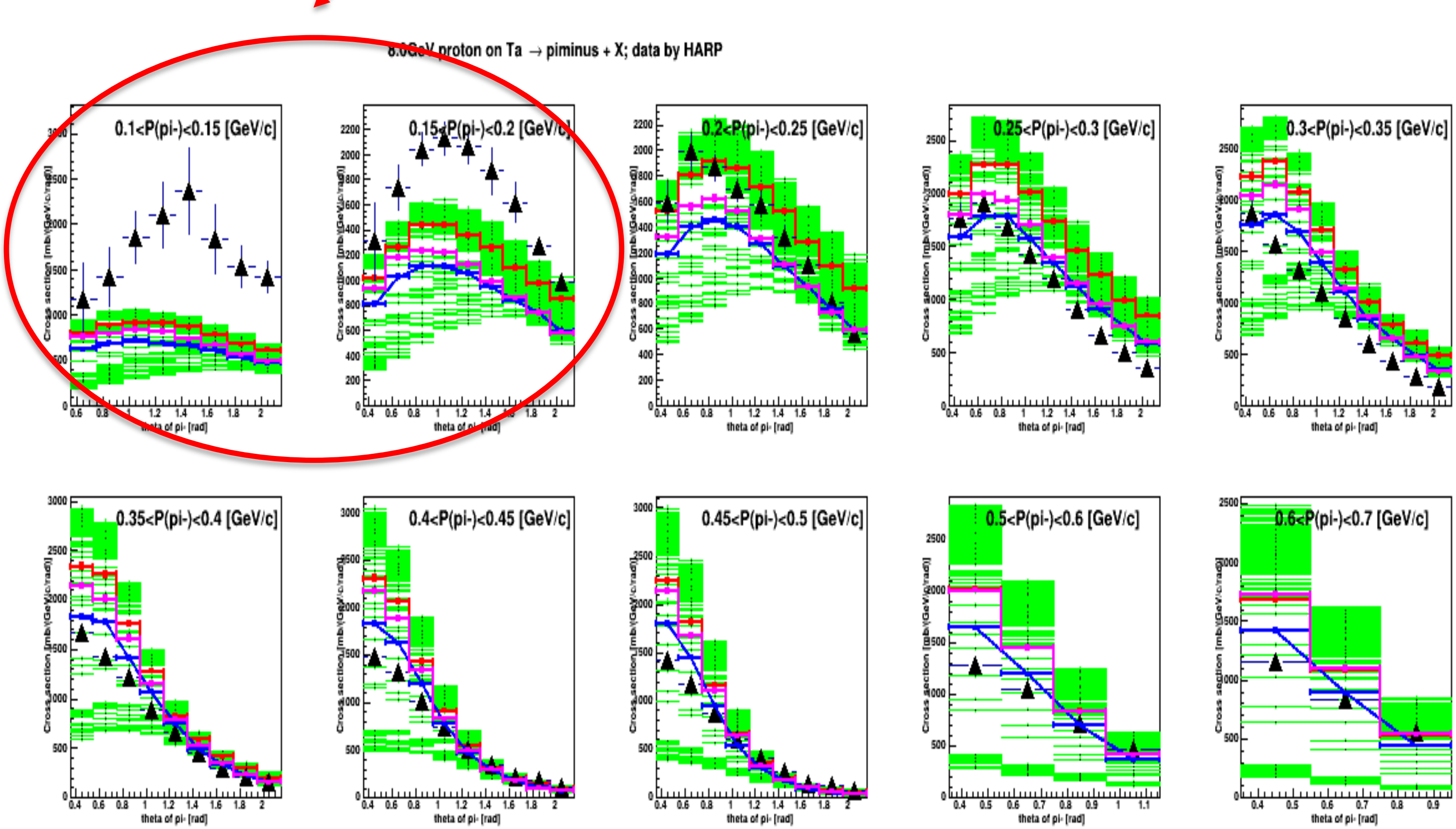
Sim Best Fit chi2/NDF=17.0

8.0GeV proton on Ta → piminus + X; data by HARP

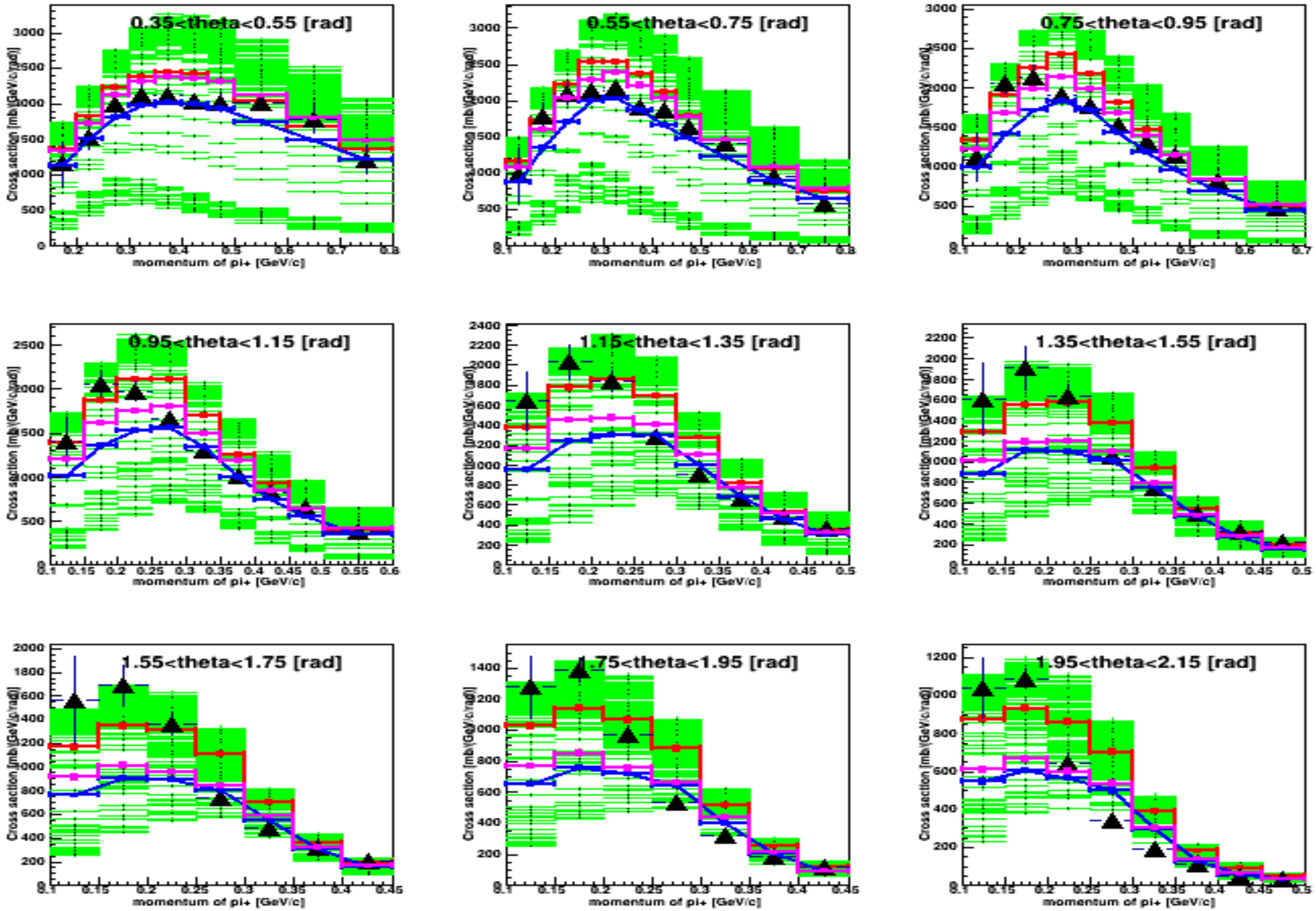


Default chi2/NDF = 41.9 Professor Fit chi2/NDF = 15.6 Sim Best Fit chi2/NDF = 25.4

Distributions of interest for Mu2e

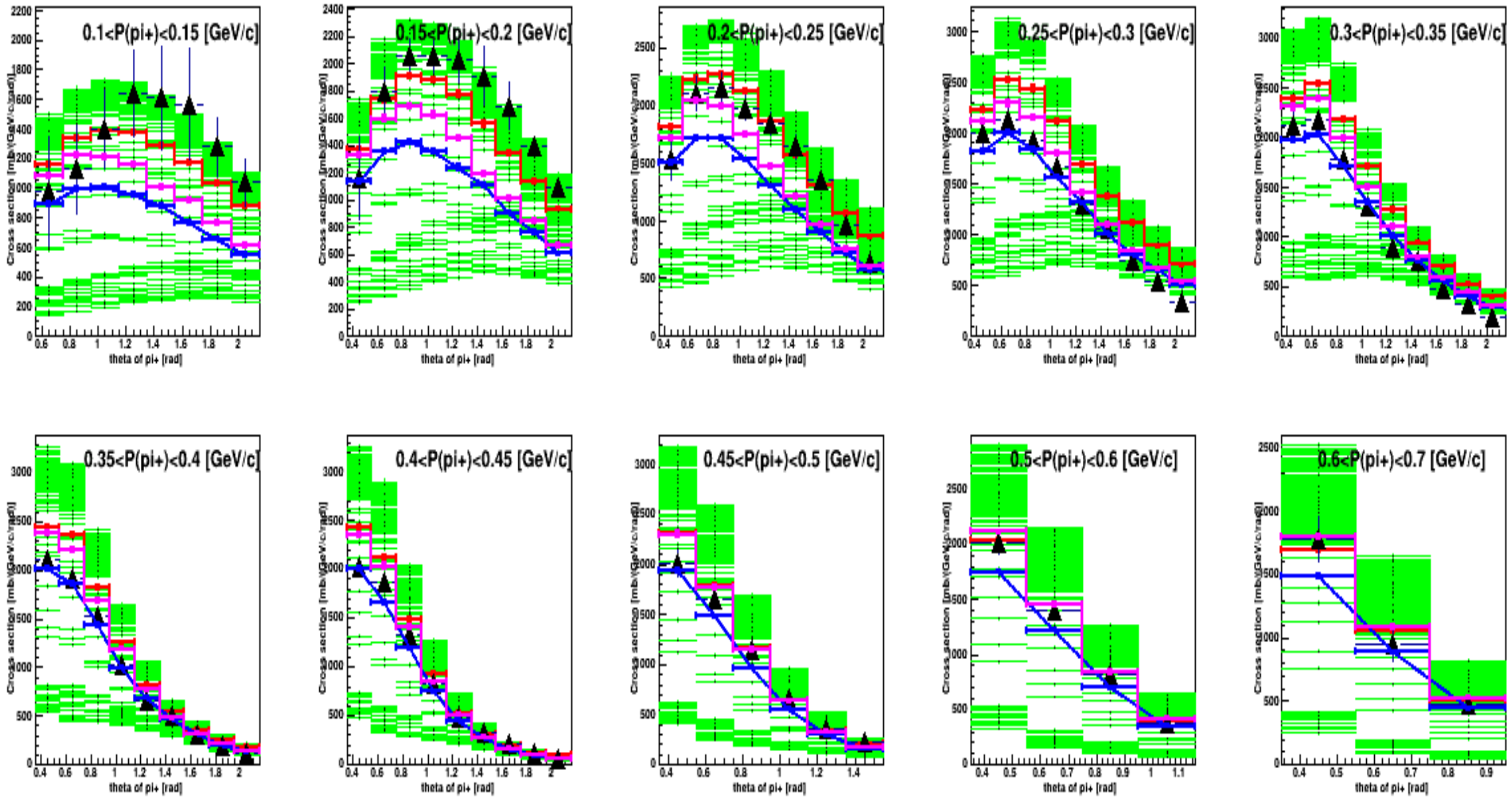


8.0GeV proton on Ta → piplus + X; data by HARP



Default chi2/NDF = 9.9   Professor Fit chi2/NDF = 7.6.   Sim Best Fit chi2/NDF = 6.1

8.0GeV proton on Ta → piplus + X; data by HARP



Some of the Early Observations

- The Professor fits seem to work reasonably well when it comes to modeling pion production by a higher momentum proton beam interacting with C target
- However, those parametrizations work only partially for modeling pion production in hadron+nucleus interactions at intermediate energy, in particular for heavier targets
- Maybe one should try separate fits in different energy ranges vs applicable datasets…
- … and subsequently consider having physics lists with multiple instances of FTF with different settings of parameters, as applicable for specific study cases ?
- Of course, other questions may also arise, and may need to be answered

Summary

- We have started exploring what FTF processes and parameters are likely to affect simulated spectra of secondary pions, e.g. FTF quark exchange model
- Initial exercise indicates sensitivity of simulated results in this area, and there seem to be ways to improve MC-data agreement, at least in some areas (e.g. with NA61 data)
- Of course, questions still remain, and a number of details need to be explored more carefully
- It is likely to be beneficial to expand FTF API and officially include parameters of the quark exchange model as it will pave ways for more extensive and detailed studies
- Documentation can be updated as appropriate, under the guidance of experts

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

NA61 – 31 GeV/c proton on C

N. Abgrall et al. , Eur.Phys.J.C 76, 2016

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

8 GeV/c proton on Ta -> piminus + X, LA production; data by HARP
Notice vary narrow spread in the simulated results due to varying only parameters of “proc1”, especially at larger values of theta