Exploring FTF Quark Exchange Model Parameters:

Quark Exchange without Excitation of Participants

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General Information (I)

- FTF offers an API to vary 85 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
- Of these, 44 parameters have been newly added in release 10.7, and are involved in modeling quark exchange with or without excitation of participants
- This group of parameters is of interest because varying them seems to significantly affect simulated spectra of secondary pions coming from hadron+nucleus interactions
  - Some of the parameters are more impactful than others

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.

Exploring Parameters of FTF Quark Exchange Model (I)

- From earlier attempts of varying parameters of quark exchange model without ("proc0") or with ("proc1") excitation of participants 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
- Subsequently, per suggestion of Vladimir Uzh. we looked at quark exchange with excitation of participants ("proc1")
  - https://indico.cern.ch/event/952890/contributions/4018013/attachments/2103644/3537527/G4Workshop-HAD-Sept16-2020-v1.pdf
  - There were indications of potentially improving MC-data agreement, e.g. for such datasets as NA61 (at least, for pion production)

Exploring Parameters of FTF Quark Exchange Model (II)

- Still it was of interest to see the effect of (separately) varying parameters of the FTF quark exchange without excitation of participants model (“proc0”)
- Preliminary study case
  - Beam: proton of 5, 8, 31 GeV/c
  - Targets: C, Cu, Pb
  - Secondaries: pions
  - Experimental datasets: HARP, NA61
  - Geant4: 10-07-ref-06

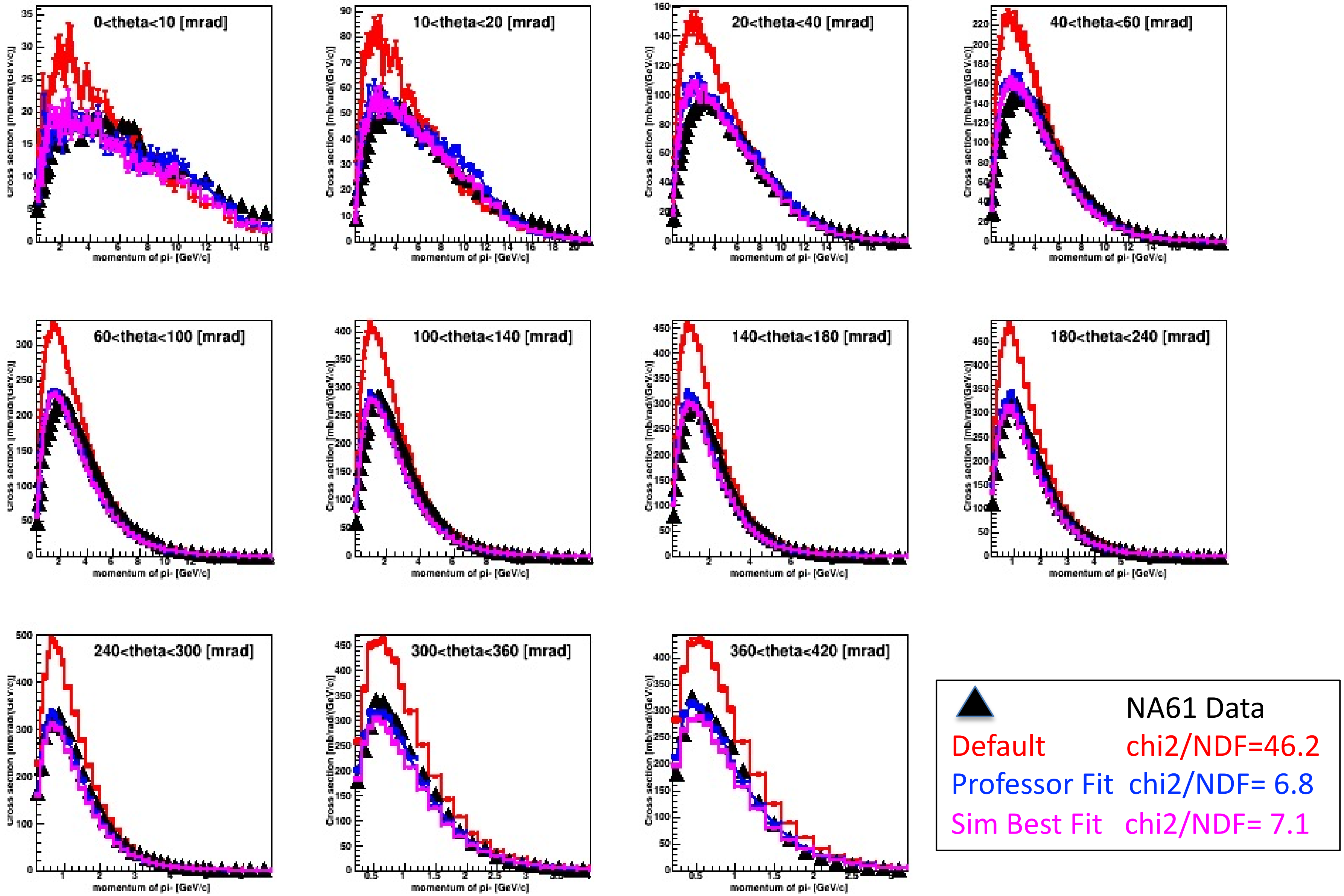
Exploring Parameters of FTF Quark Exchange Model (III)

- Varying parameters of quark exchange without excitation ("proc0"):
  - **FTF_BARYON_PROC0_A1 0 25 D=13.71**
  - **FTF_BARYON_PROC0_B1 0 5 D=1.75**
  - **FTF_BARYON_PROC0_A2 -50 0 D=-30.69**
  - **FTF_BARYON_PROC0_B2 0 5 D=3.0**
- 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)**
  - NOTE: as of now, default is 1., and the A-dependency is turned off, although there was a proposal by developers to set it to 0.0048*A
- Simulation for 100 "points" in multi-parameter space, with each parameter for each "point" randomly selected from the above ranges

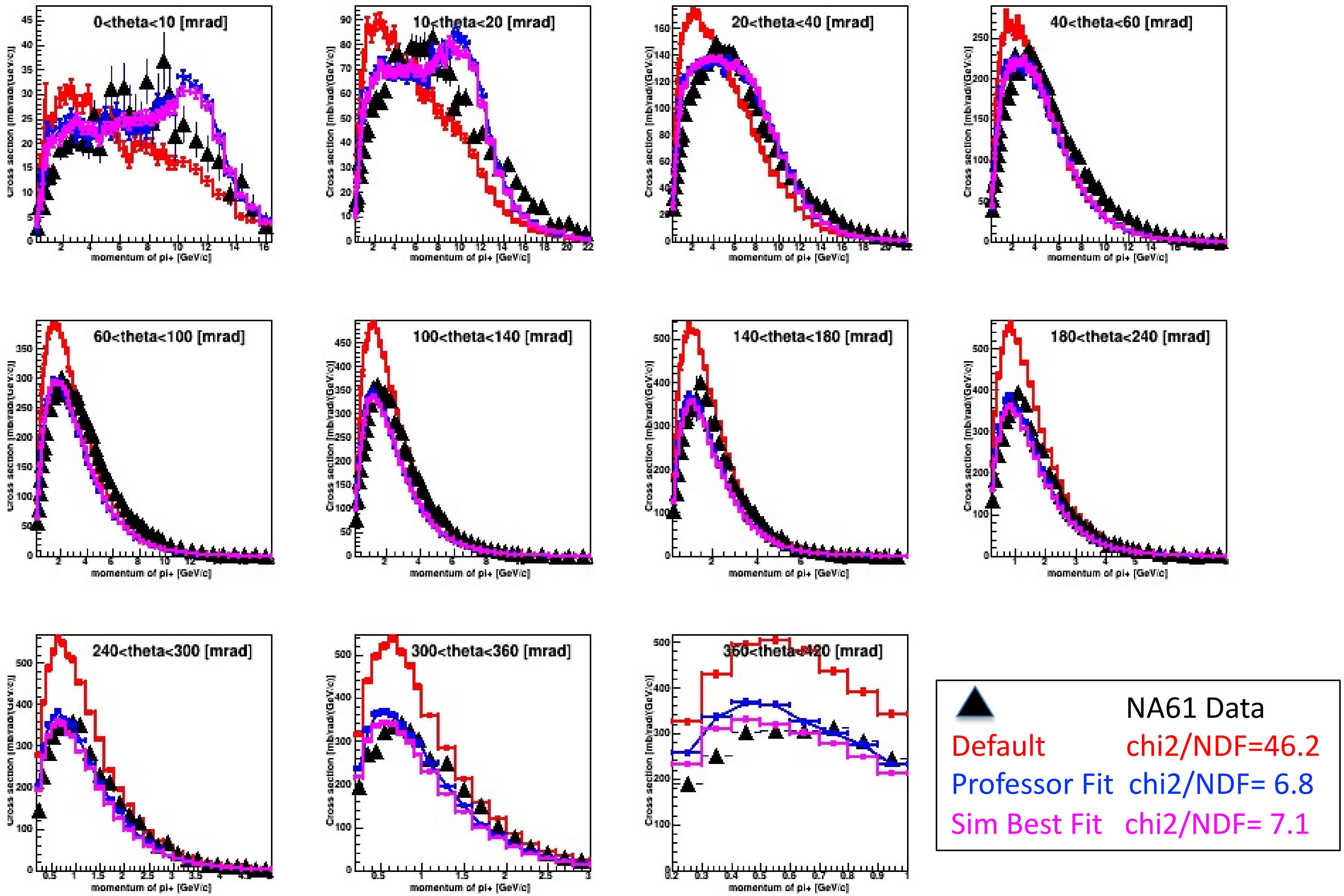
FTF Quark Exchange Parameters ("proc0") + One Nuclear Destruction Parameter

- Default
  - FTF_BARYON_PROC0_A1 = 13.71
  - FTF_BARYON_PROC0_B1 = 1.75
  - FTF_BARYON_PROC0_A2 = -30.69
  - FTF_BARYON_PROC0_B2 = 2.0
  - FTF_BARYON _NUCDESTR_P1_TGT = 1. (no A-dep)
- **Global Fit** vs NA61 and selected HARP data (only pion spectra)
  - FTF_BARYON_PROC0_A1 = 5.62 $\pm$ 0.26
  - FTF_BARYON_PROC0_B1 = 0.70 $\pm$ 0.013
  - FTF_BARYON_PROC0_A2 = -30.8 $\pm$ 1.41
  - FTF_BARYON_PROC0_B2 = 3.42 $\pm$ 0.08
  - FTF_BARYON _NUCDESTR_P1_TGT = (0.00204 $\pm$ 0.00007) * A
  - NOTE: fit result for FTF_BARYON _NUCDESTR_P1_TGT is somewhat different from what was obtained by fitting it vs ITEP771 and IAEA/Ishibashi data but comparable
- Geant4 (re)simulation with the best fit parameters (above)

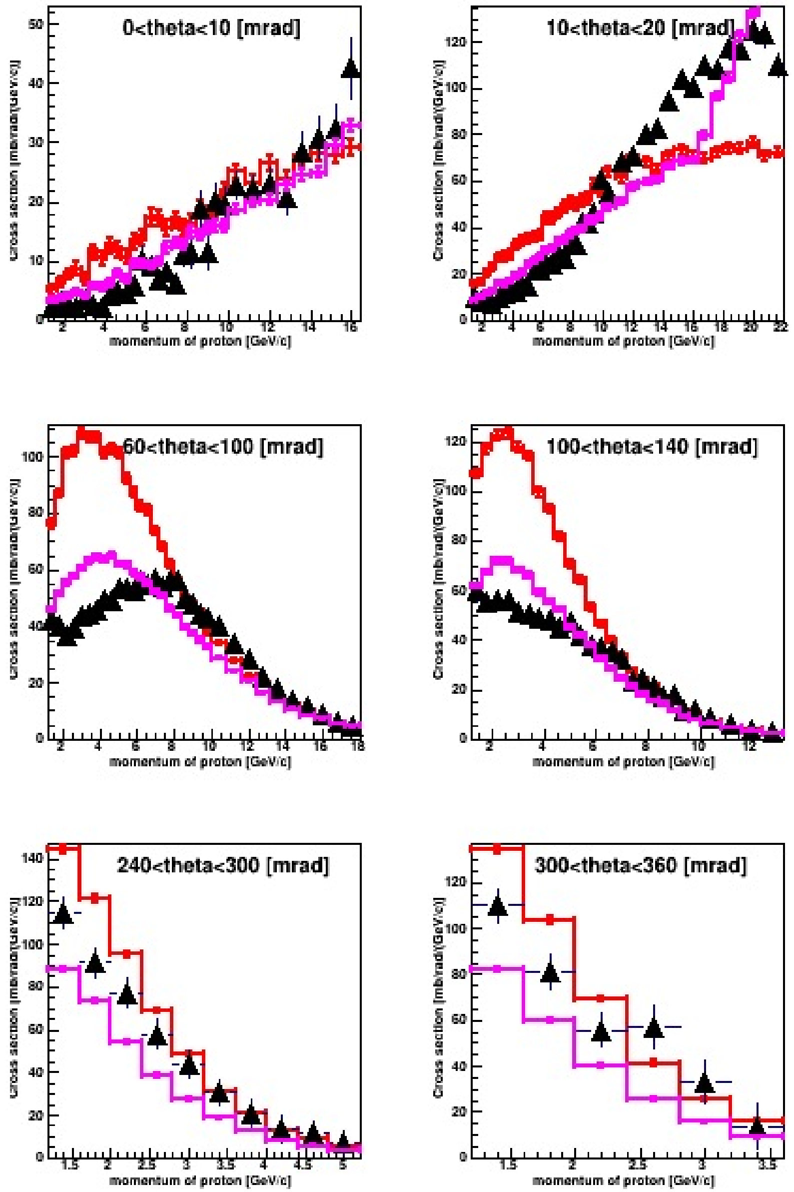
G4/FTF: 31.0GeV proton on C → piminus + X; data by NA61



G4/FTF: 31.0GeV proton on C → piplus + X; data by NA61



G4/FTF: 31.0GeV proton on C → proton + X; data by NA61



NOTE that data on proton production were NOT included in the fits, so this result is a kind of "by-product"…

NA61 data

Default chi2/NDF=44.8

Sim Best Fit chi2/NDF=11.9

Near(-and-mid?)-term Plans

- We continue exploring parameters of the FTF model, and if/how applying global fitting techniques can indicate ways to bring Monte Carlo closer to the data
- Ideally we would like to compose a consistent summary on this matter, for further consideration by developers…
- … but it requires extending/expanding the study
- (Relatively) New challenge – choice of supported global fitting package to use in the long run
  - We have been relying Professor so far – very useful
  - Professor is now **frozen**; we can keep using it for a while but not in the long run
  - There are alternative (new) tools on the market – we need to explore and choose

Summary

- We continue exploring what FTF processes and parameters and how their variations affect various aspects of modeling hadron-nucleus interactions
- Results (so far) indicate that there are ways to improve Monte Carlo to data agreement through applying global fitting techniques to model parameters
- We plan to expand the study
- We need to find a supported global fitting package to replace in the long run Professor that is now frozen

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