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Geant4 11.3 - Hadronic Physics Validation Based on Selected Tests

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Geant4 Hadronic Group Meeting

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General Information (I)

- Focus :
  - capture/annihilation processes
  - gamma-nuclear interactions (at several hundreds MeV)
  - hadron production in hadron-nucleus interactions at intermediate or high energies
- Models : Bertini, INCLXX (pbar annihalation), FTF, QGS
- Regression : 11.2.p01
- Selected regression results are shown in a form of chi2 tables
- Selected plots are included to illustrate model-to-model comparisons
  - Selected results from FLUKA.CERN are included (per single user license)
    - References : https://fluka.cern/documentation/references
    - Use of components from from Geant4 standard FlukaCern example

General Information (II)

- Use of FLUKA.CERN via interface to Geant4
  - Version 4.4.0, i.e. re-ran the same as in 2024 benchmark
    - Fix in the FlukaCern/FlukaInterface
    - Results from the latest FLUKA.CERN 4.4.1 can be added
  - In the 2024 benchmark
    - FLUKA.CERN-based application was a modified FlukaCern example
    - Geant4 interaction XSEC used in the normalization, where applicable
  - In the current round
    - **Optional** use of FLUKANuclearInelasticModel and/or G4_HP_CFLUKAHI components, together with FLUKAInelasticScatteringXS, all from FlukaCern example, are incorporated with test applications test19 and test23, test47 is in progress
    - FLUKA.CERN XSEC used with FLUKA.CERN results, Geant4 – with Geant4

Capture/annihilation and gamma-nuclear interactions

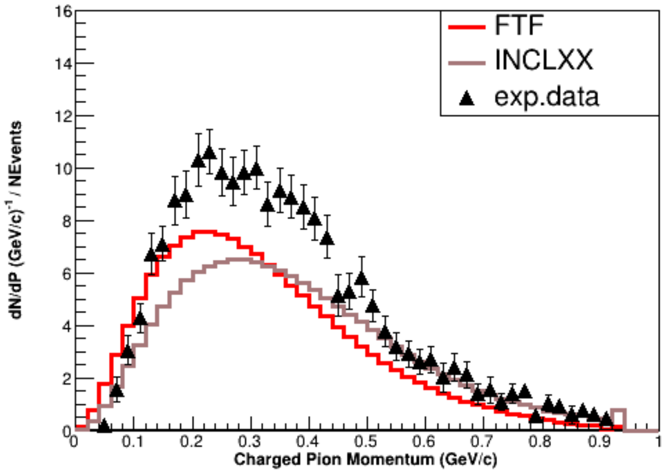
- Capture/annihilation
  - Bertini cascade model is used to model pi- and mu- capture processes
    - Changes in the code result in some changes in the simulated results although nothing major; detailed chi2 tables can be composed, if needed
  - FTF model or recently added INCLXX algorithm can be used to simulate antiproton annihilation processes (see also next slide)

    NOTE: Recently added INCLXX algorithm is included in the test for the 1st time
- Gamma-nuclear
  - Bertini cascade model is used to simulate gamma-nuclear interactions
    - Changes in the code result in some changes in the simulated results but nothing major

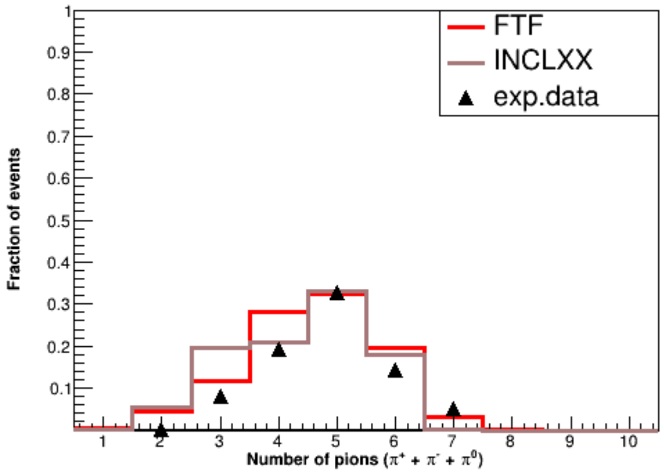
MC vs data : antiproton on H –> π

-- C. Amsler, Rev. Mod. Phys. 70, 1293 (1998)
-- C. Amsler and F. Myher, Ann. Rev. Nucl. Part. Sci. 41, 219 (1991)
-- C.B. Dover et al., Prog. Part. Nucl. Phys., Vol.29, pp.87-173 (1992)

pbar annihilation on H



χ^2/NDF = 6.99 for FTF
χ^2/NDF = 5.9 for INCLXX



χ^2/NDF = 170 for FTF
χ^2/NDF = 187 for INCLXX

NOTE: Based on this initial test, use of INCLXX is substantially more CPU expensive than FTF

Hadron-nucleus interactions at intermediate energies

- Models : Bertini (updates in 11.3) and/or FTF(P) (few updates in 11.3)
- Pion production – benchmark vs HARP data
  - The test19 application can (and does) produce simulated results on multiple nuclear target by proton or charged pion beam of momentum 3-12 GeV/c
  - However, to make the output more manageable, it appears that interactions of 8 GeV/c hadron with C or Ta target can serve as "standard candles"
- Proton and neutron production – benchmark vs ITEP(771)
  - The test47 application can produce simulated results on multiple nuclear targets by proton or charged pion beam of momentum 1.4-7.5 GeV/c
  - To make it more manageable, interactions of 5 GeV/c charged pion or 7.5 GeV/c proton with C or Pb can serve as "standard candles"

Bertini : 8 GeV/c hadron on C –> pions

chi2/NDF calculated vs HARP data

π^- beam			
		11.2.p01	11.3
π^+	FW	21.7	19.2
	LA	26.5	53.3
	Tot	25.0	43.0
π^-	FW	35.4	39.8
	LA	35.9	135
	Tot	35.7	105

π^+ beam			
		11.2.p01	11.3
π^+	FW	94.9	115
	LA	22.5	49.7
	Tot	45.3	70.4
π^-	FW	25.0	22.2
	LA	27.8	132
	Tot	26.9	97.9

proton beam			
		11.2.p01	11.3
π^+	FW	12.1	13.5
	LA	24.8	46.7
	Tot	20.9	36.4
π^-	FW	27.2	20.6
	LA	27.7	48.9
	Tot	27.6	40.9

NOTE : in this slide and through slide 10 the FW (forward) means polar angle of the secondary hadron in the range of 0.05-0.25 rad, while LA (large angle) stands for polar angle 0.35-2.15 rad

Bertini : 8 GeV/c hadron on Ta –> pions

chi2/NDF calculated vs HARP data

π^- beam			
		11.2.p01	11.3
π^+	FW	21.2	16.0
	LA	44.9	51.5
	Tot	37.4	40.3
π^-	FW	26.7	27.5
	LA	45.4	224
	Tot	39.5	162

π^+ beam			
		11.2.p01	11.3
π^+	FW	15.4	21.4
	LA	42.2	48.0
	Tot	33.7	39.6
π^-	FW	25.8	20.8
	LA	32.0	167
	Tot	30.2	123

proton beam			
		11.2.p01	11.3
π^+	FW	1.1	0.83
	LA	49.0	62.8
	Tot	33.6	42.9
π^-	FW	19.4	13.0
	LA	49.8	242
	Tot	41.8	181

FTF(P) : 8 GeV/c hadron on C –> pions

chi2/NDF calculated vs HARP data

π^- beam		11.2.p01	11.3
π^+	FW	7.9	8.0
	LA	15.7	15.8
	Tot	13.4	13.4
π^-	FW	27.6	27.5
	LA	19.9	20.4
	Tot	22.3	22.6

π^+ beam		11.2.p01	11.3
π^+	FW	73.4	73.9
	LA	3.1	3.1
	Tot	25.3	25.4
π^-	FW	5.1	5.1
	LA	14.5	14.2
	Tot	11.6	11.4

proton beam		11.2.p01	11.3
π^+	FW	13.0	13.1
	LA	7.2	7.5
	Tot	9.0	9.2
π^-	FW	8.3	8.4
	LA	15.9	15.9
	Tot	13.7	13.8

FTF(P) : 8 GeV/c hadron on Ta –> pions

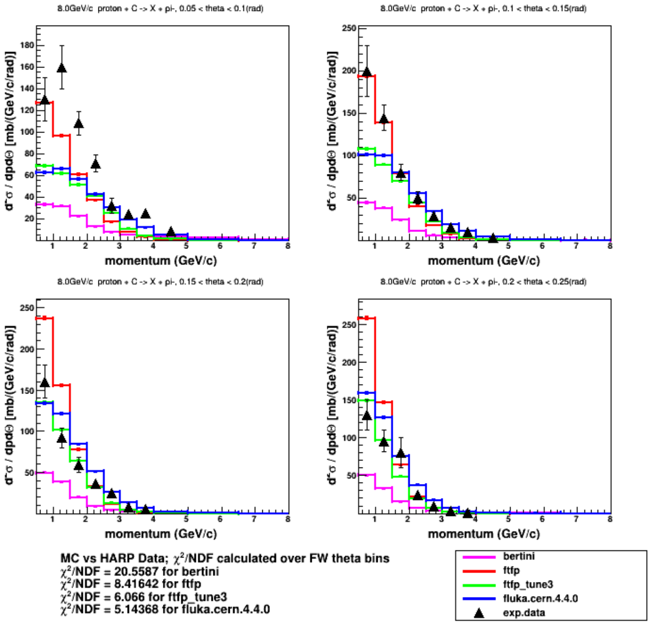
chi2/NDF calculated vs HARP data

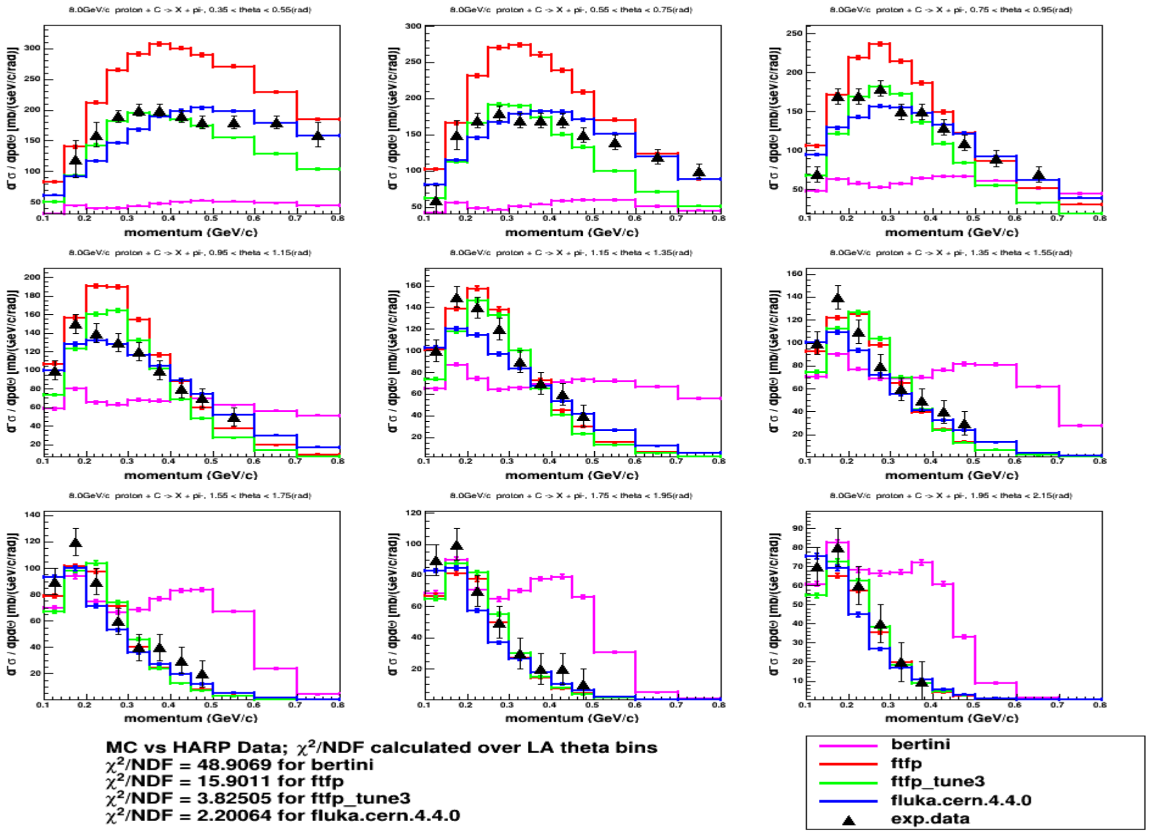
π^- beam			
		11.2.p01	11.3
π^+	FW	8.5	8.6
	LA	6.0	6.2
	Tot	6.8	6.9
π^-	FW	32.3	32.1
	LA	98.4	98.2
	Tot	77.5	77.3

π^+ beam			
		11.2.p01	11.3
π^+	FW	17.6	17.6
	LA	16.8	17.0
	Tot	17.1	17.2
π^-	FW	13.5	13.5
	LA	16.6	16.6
	Tot	15.7	15.7

proton beam			
		11.2.p01	11.3
π^+	FW	4.4	4.4
	LA	9.7	9.6
	Tot	8.0	7.9
π^-	FW	12.1	12.2
	LA	33.7	33.0
	Tot	28.0	27.5

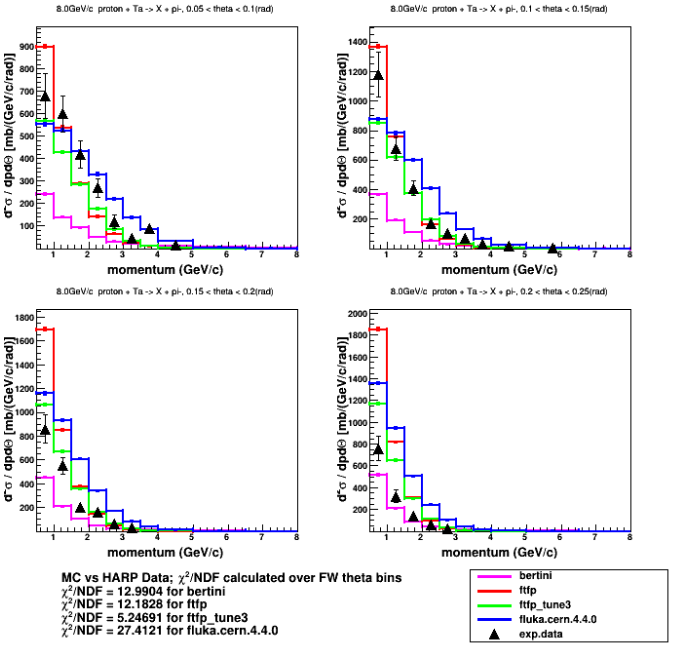
MC vs HARP data : 8 GeV/c proton on C –> π^- (FW and LA)

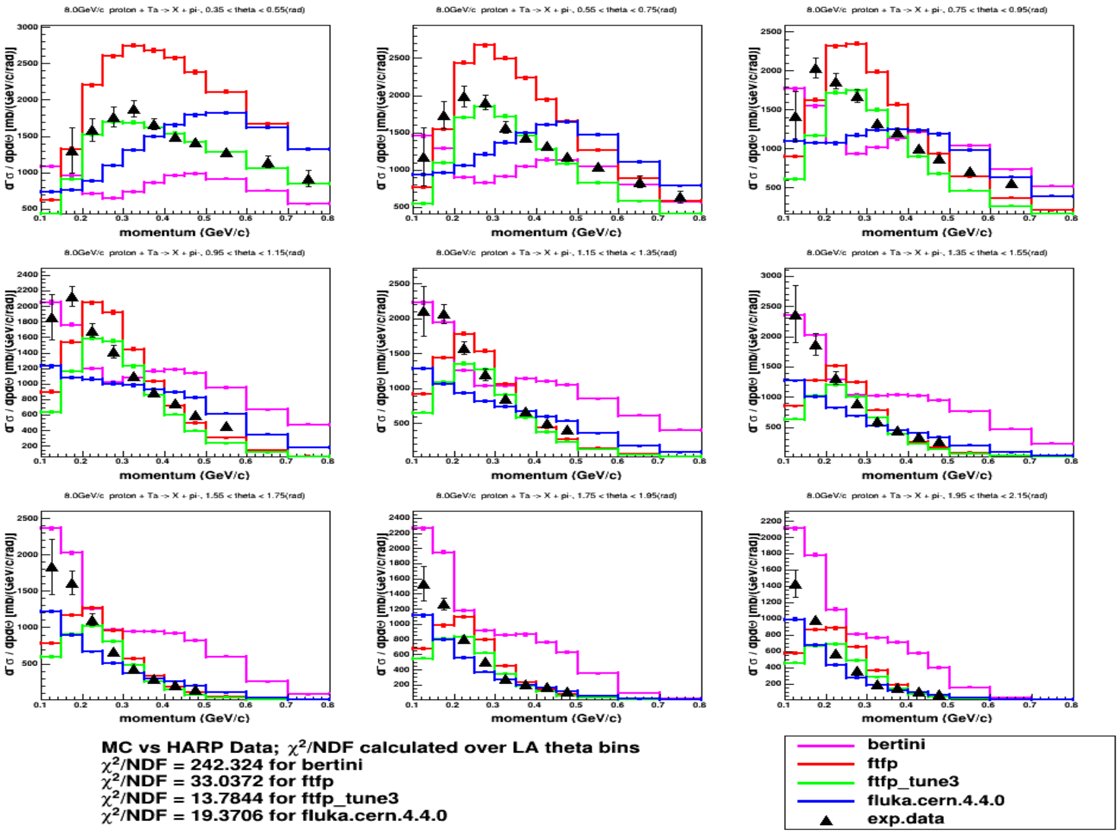




Similar plots on π^+ production are in backup slides

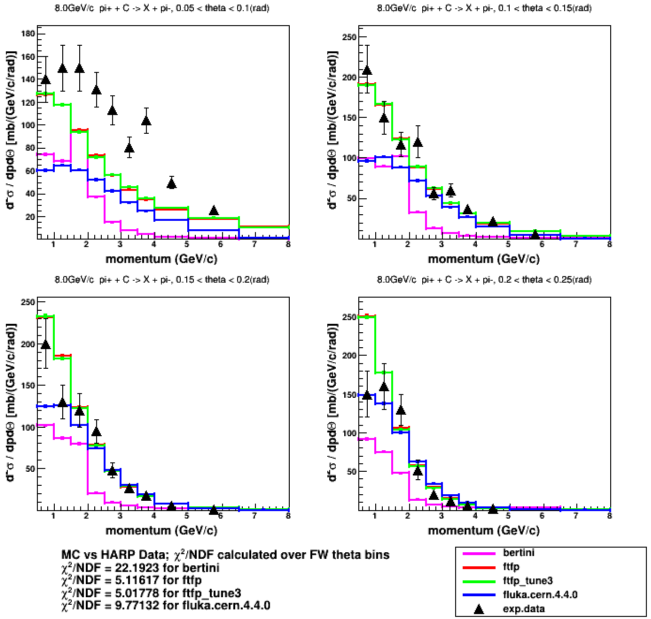
MC vs HARP data : 8 GeV/c proton on Ta –> π^- (FW and LA)

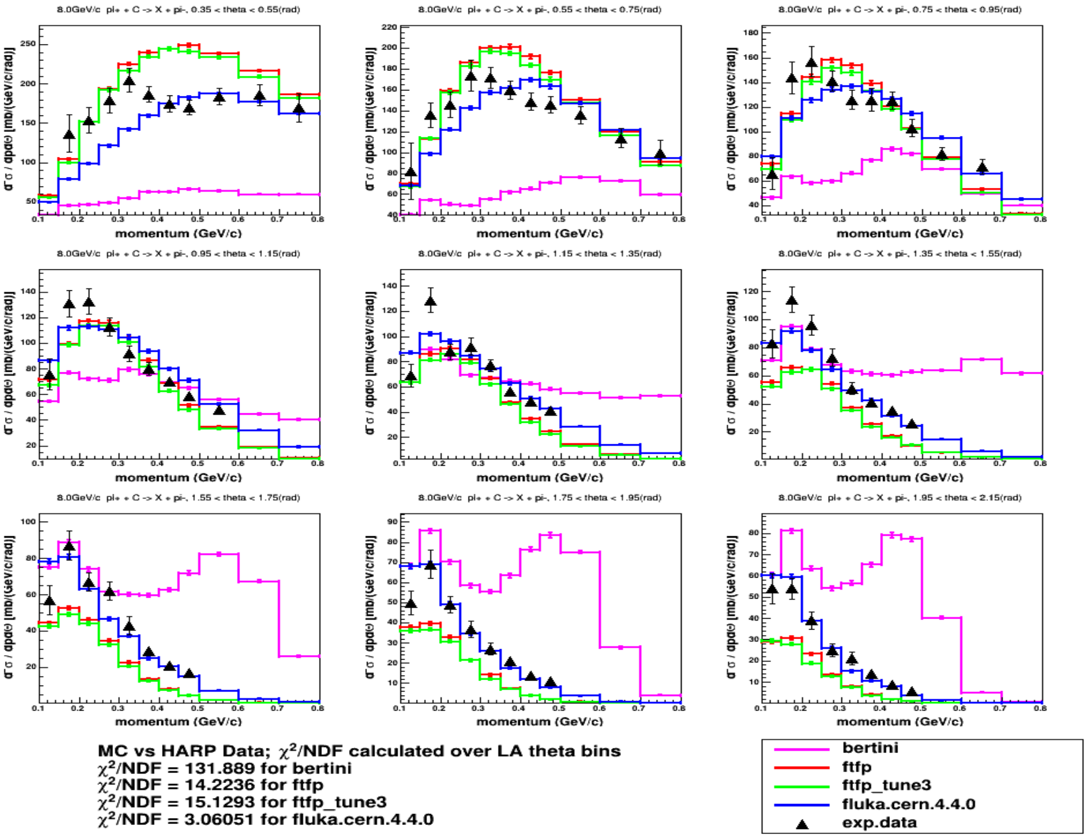




Similar plots on π^+ production are in backup slides

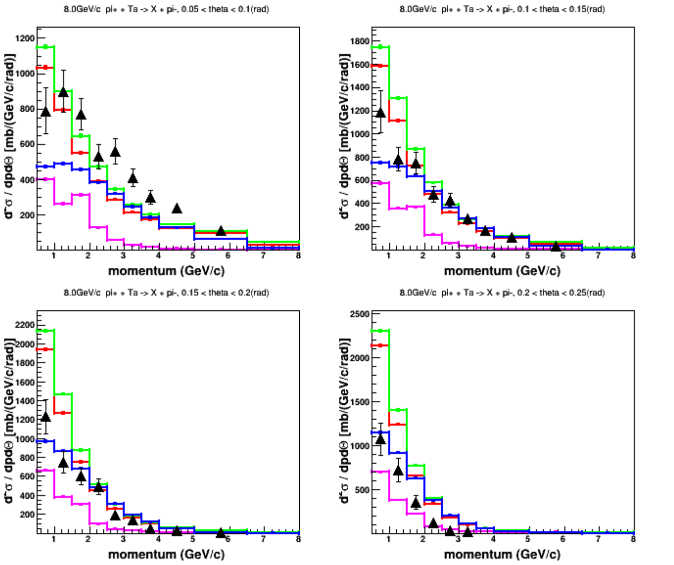
MC vs HARP data : 8 GeV/c π^+ on C –> π^- (FW and LA)





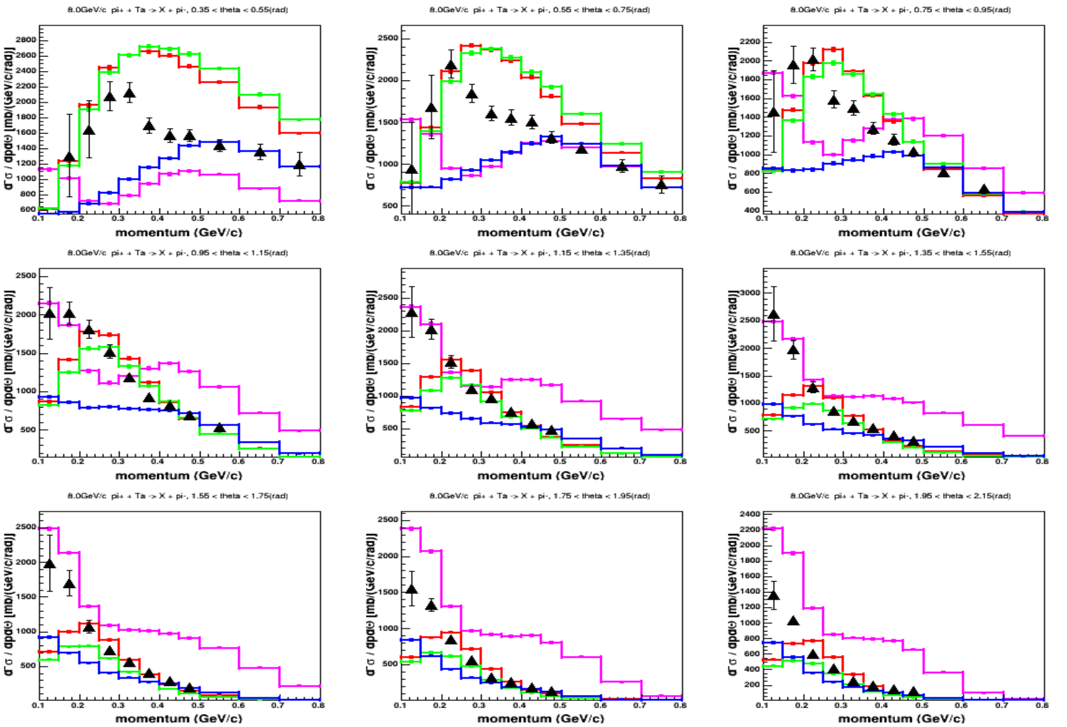
Similar plots on π^+ production are in backup slides

MC vs HARP data : 8 GeV/c π^+ on Ta –> π^- (FW and LA)



MC vs HARP Data; χ^2/NDF calculated over FW theta bins
χ^2/NDF = 20.7846 for bertini
χ^2/NDF = 13.4937 for ftfp
χ^2/NDF = 19.2734 for ftfp_tune3
χ^2/NDF = 12.8801 for fluka.cern.4.4.0

bertini
ftfp
ftfp_tune3
fluka.cern.4.4.0
▲ exp.data



Similar plots on π^+ production are in backup slides

MC vs HARP Data; χ^2/NDF calculated over LA theta bins
χ^2/NDF = 166.94 for bertini
χ^2/NDF = 16.6154 for ftfp
χ^2/NDF = 23.1814 for ftfp_tune3
χ^2/NDF = 23.3371 for fluka.cern.4.4.0

bertini
ftfp
ftfp_tune3
fluka.cern.4.4.0
▲ exp.data

Bertini : 5-7.5 GeV/c hadron on C or Pb –> proton/neutron

chi2/NDF calculated vs ITEP(771) data

5 GeV/c π^- on C		
	11.2.p01	11.3
p	8.1	8.5
n	6.4	7.0

5 GeV/c π^+ on C		
	11.2.p01	11.3
p	13.4	13.8
n	4.6	3.2

7.5 GeV/c proton on C		
	11.2.p01	11.3
p	13.2	12.1
n	3.7	3.0

5 GeV/c π^- on Pb		
	11.2.p01	11.3
p	20.0	4.5
n	26.4	14.5

5 GeV/c π^+ on Pb		
	11.2.p01	11.3
p	17.9	6.9
n	26.8	14.1

7.5 GeV/c proton on Pb		
	11.2.p01	11.3
p	57.3	12.8
n	31.6	15.3

FTF(P) : 5-7.5 GeV/c hadron on C or Pb –> proton/neutron

chi2/NDF calculated vs ITEP(771) data

5 GeV/c π^- on C		
	11.2.p01	11.3
p	5.8	7.3
n	1.4	1.6

5 GeV/c π^+ on C		
	11.2.p01	11.3
p	4.4	5.1
n	1.2	1.3

7.5 GeV/c proton on C		
	11.2.p01	11.3
p	92.6	82.1
n	71.0	64.7

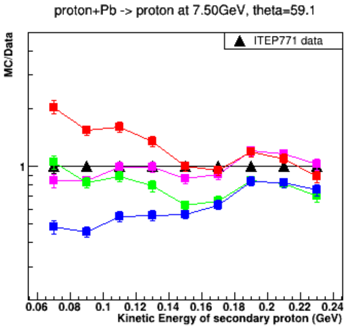
5 GeV/c π^- on Pb		
	11.2.p01	11.3
p	55.6	54.8
n	87.1	87.2

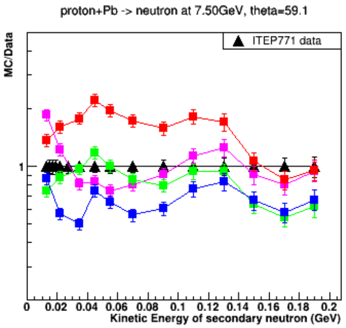
5 GeV/c π^+ on Pb		
	11.2.p01	11.3
p	19.9	21.3
n	119.2	118.2

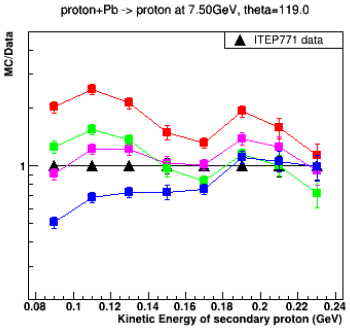
7.5 GeV/c proton on Pb		
	11.2.p01	11.3
p	96.8	95.8
n	140.2	139.3

MC vs ITEP data : 5-7.5 GeV/c hadron on Pb –> proton/neutron

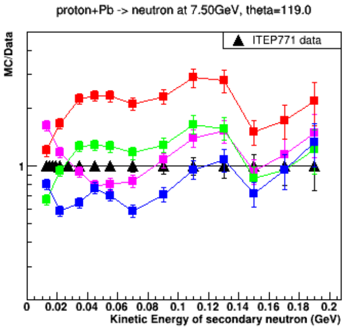
7.5 GeV/c proton beam





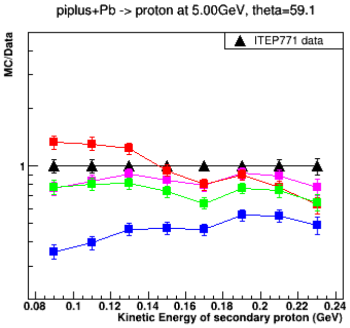


χ^2/NDF = 5.57 bertini
χ^2/NDF = 92.5 ftfp
χ^2/NDF = 15.7 ftfp_tune3
χ^2/NDF = 27.9 fluka.cern.4.4.0

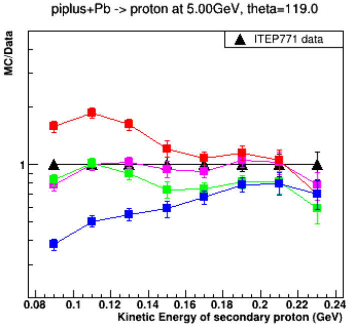


χ^2/NDF = 14.8 bertini
χ^2/NDF = 133.7 ftfp
χ^2/NDF = 9.2 ftfp_tune3
χ^2/NDF = 16.5 fluka.cern.4.4.0

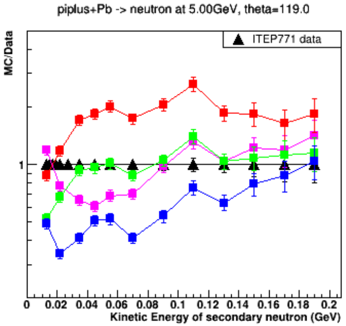
5 GeV/c π^+ beam



No experimental data on neutron production in forward hemisphere



χ^2/NDF = 3.17 bertini
χ^2/NDF = 23.8 ftfp
χ^2/NDF = 8.58 ftfp_tune3
χ^2/NDF = 38.7 fluka.cern.4.4.0



χ^2/NDF = 14.1 bertini
χ^2/NDF = 118.2 ftfp
χ^2/NDF = 10.3 ftfp_tune3
χ^2/NDF = 47.5 fluka.cern.4.4.0

Hadron-nucleus interactions at high energies

- Models : QGS(P) (no change) and/or FTF(P) (few updates in 11.3)
  - NOTE: these two models use different fragmentation algorithms
- The focus is mainly on secondary charged pions but productions of other secondary hadrons is addressed, based on availability of (or familiarity with) experimental data
- Benchmark
  - NA61 data - 31 GeV/c proton or 60 GeV/c pi+ beam on C
  - NA49 data – 158 GeV/c beam on C

FTF(P) : 31-60 GeV/c hadron on C –> hadrons

chi2/NDF calculated vs NA61 data

31 GeV/c proton beam		
	11.2.p01	11.3
π^+	36.7	36.6
π^-	27.1	26.5
K+	6.1	6.4
K-	3.2	3.1
K0s	2.3	2.3
Lambda	10.4	10.3
proton	30.9	30.6

60 GeV/c π^+ beam		
	11.2.p01	11.3
π^+	21.9	22.3
π^-	10.8	10.7
K+	4.5	4.4
K-	2.8	3.1

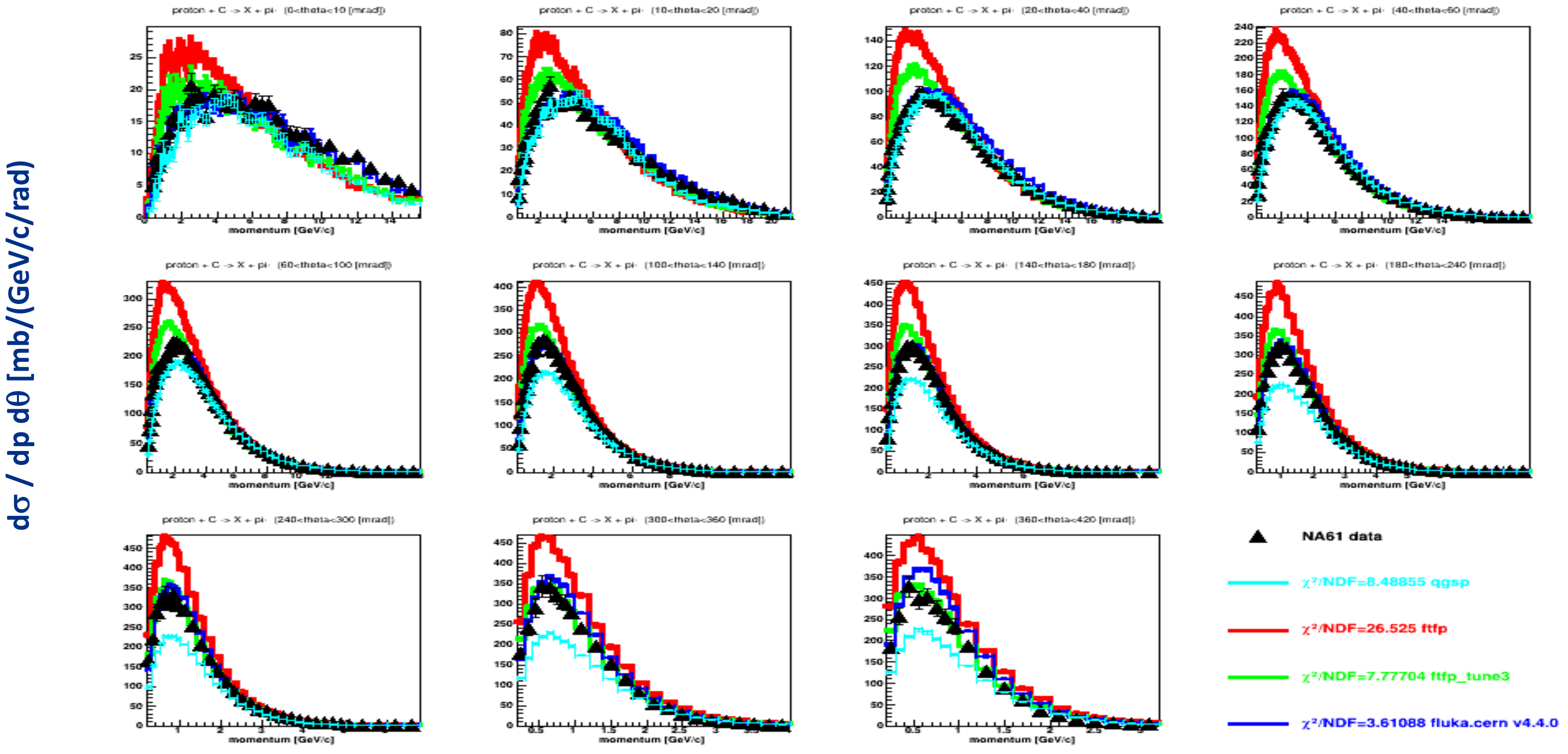
QGS(P) : 31-60 GeV/c hadron on C –> hadrons

chi2/NDF calculated vs NA61 data

31 GeV/c proton beam		
	11.2.p01	11.3
π^+	14.3	14.4
π^-	8.3	8.5
K+	8.5	8.7
K-	7.3	7.4
K0s	4.8	5.0
Lambda	21.4	21.4
proton	8.7	8.3

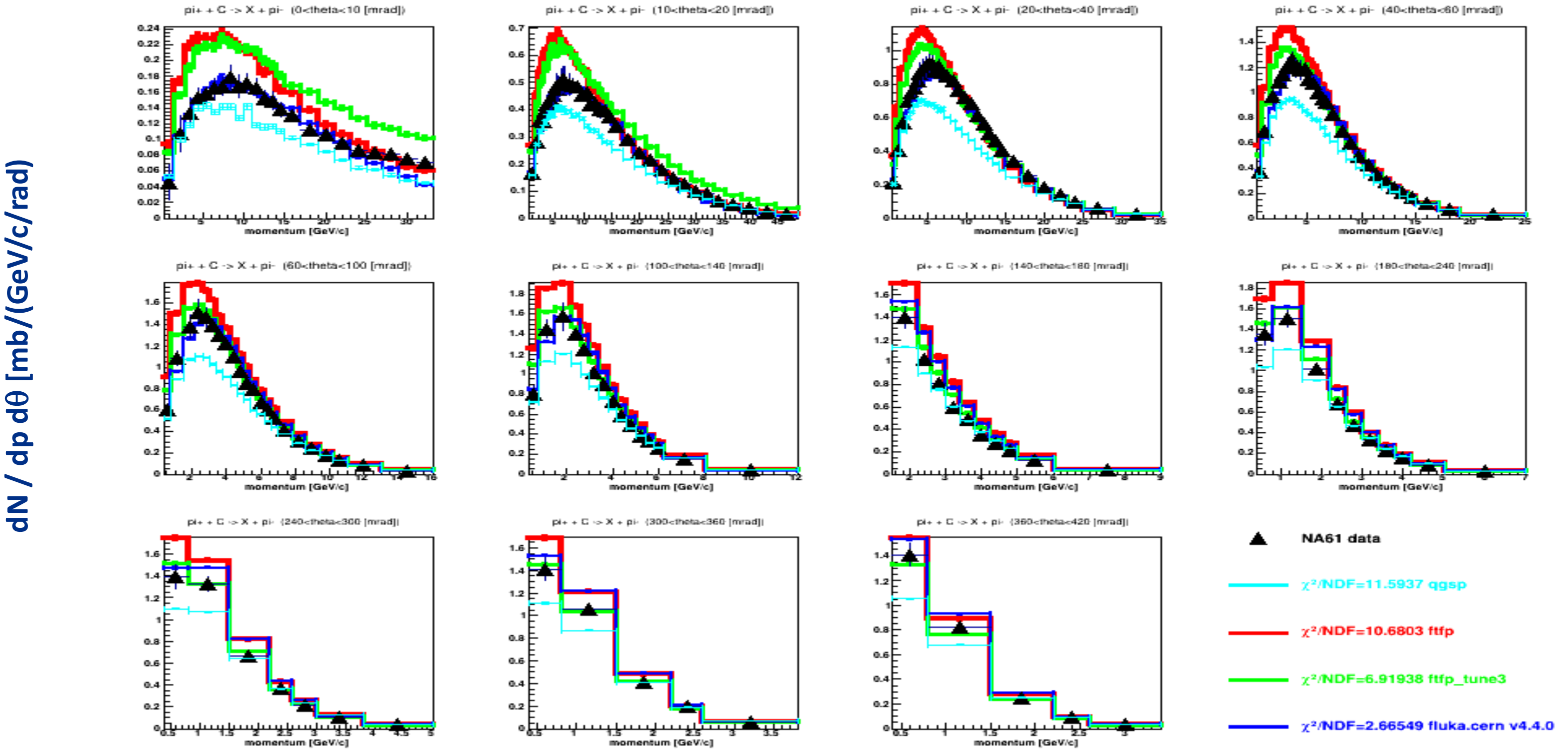
60 GeV/c π^+ beam		
	11.2.p01	11.3
π^+	13.6	13.3
π^-	12.0	11.6
K+	6.8	6.8
K-	1.5	1.5

MC vs NA61 data : 31 GeV/c proton on C –> π^-



Similar plots for π^+ productions are in backup slides

MC vs NA61 data : 60 GeV/c π^+ on C –> π^-



Similar plots for π^+ productions are in backup slides

Fermilab

FTF(P) : 158 GeV/c proton on C –> hadrons

chi2/NDF calculated vs NA49 data

dN / dx_F		
	11.2.p01	11.3
π^+	50.0	48.8
π^-	18.1	18.4
proton	93.9	89.9
pbar	25.5	24.7
neutron	2.6	2.5

$<p_T>$ vs x_F		
	11.2.p01	11.3
π^+	3.1	2.9
π^-	1.9	1.8
proton	24.7	24.1
pbar	1.2	1.3

$d^2 \sigma / dx_F \ dp_T$		
	11.2.p01	11.3
π^+	14.4	14.2
π^-	8.0	8.1
proton	35.0	33.5
pbar	4.2	4.2

QGS(P) : 158 GeV/c proton on C –> hadrons

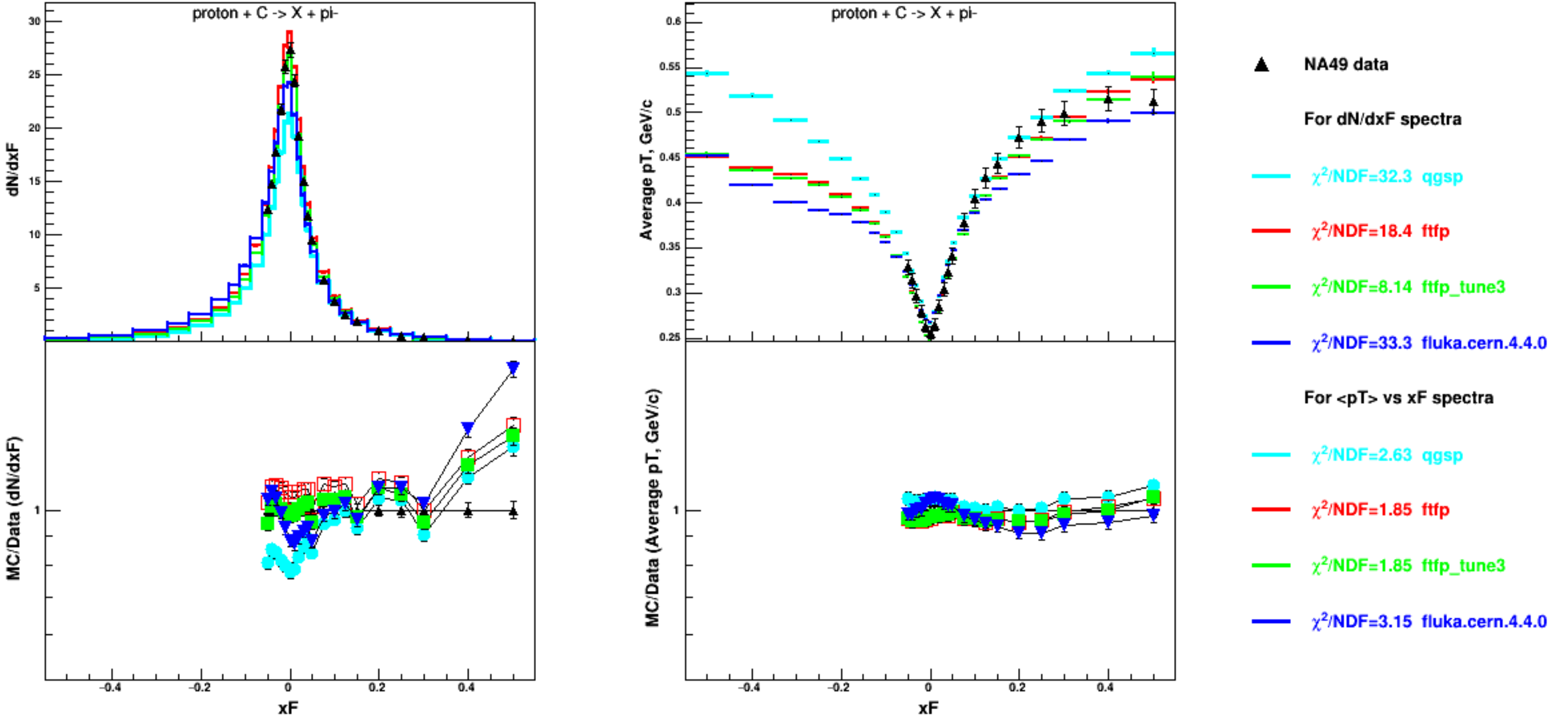
chi2/NDF calculated vs NA49 data

dN / dx_F		
	11.2.p01	11.3
π^+	69.4	69.7
π^-	31.1	32.3
proton	40.5	39.5
pbar	94.2	92.9
neutron	6.5	6.6

$<p_T>$ vs x_F		
	11.2.p01	11.3
π^+	4.3	4.3
π^-	2.8	2.6
proton	36.9	37.1
pbar	45.3	46.3

$d^2 \sigma / dx_F \; dp_T$		
	11.2.p01	11.3
π^+	18.1	18.0
π^-	11.1	11.1
proton	23.7	23.6
pbar	22.7	22.8

MC vs NA49 data : 158 GeV/c proton on C –> π^-



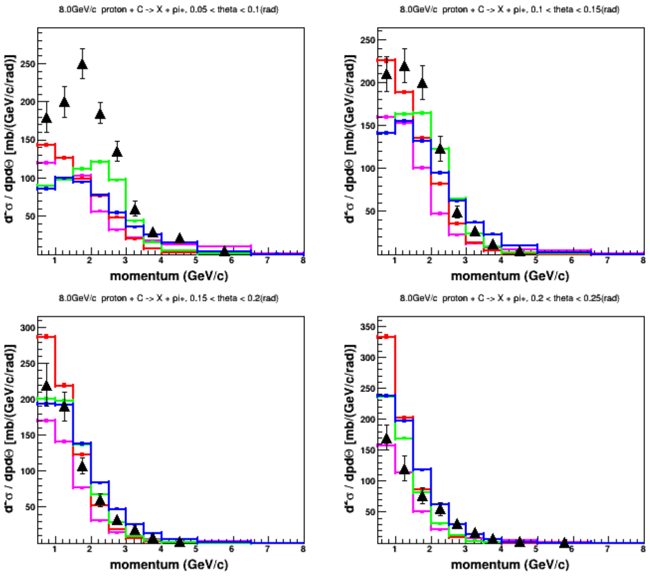
Similar plots for π^+, proton, and antiproton productions are in backup slides

Summary

- We have performed validation of Bertini, INCLXX (annihilation), FTF(P), and QGS(P) hadronic models, as of Geant4 11.3, to benchmark modeling of such processes as capture/annihilation, gamma-nuclear interactions, and hadron production in hadron-nucleus interactions at intermediate or high energies
  - Use of INCLXX annihilation modeling and comparison vs FTF(P) is a new addition to the test
- We have compared results vs those of 11.2.p01, and have observed the following :
  - Certain changes with Bertini cascade; at intermediate energies, improved MC-to-data agreement in modeling production of proton/neutron but results for simulated pion production appear to be moving away from the data; relatively small changes when modeling capture or gamma-nuclear interactions
  - Little-to-none changes with FTF(P) or QGS(P)
- We have also compared simulated results from different models, and compared them collectively vs experimental data as applicable
  - We have included in the model-to-model benchmark selected results from FLUKA.CERN 4.4.0, to see how its result compare vs those of Geant4

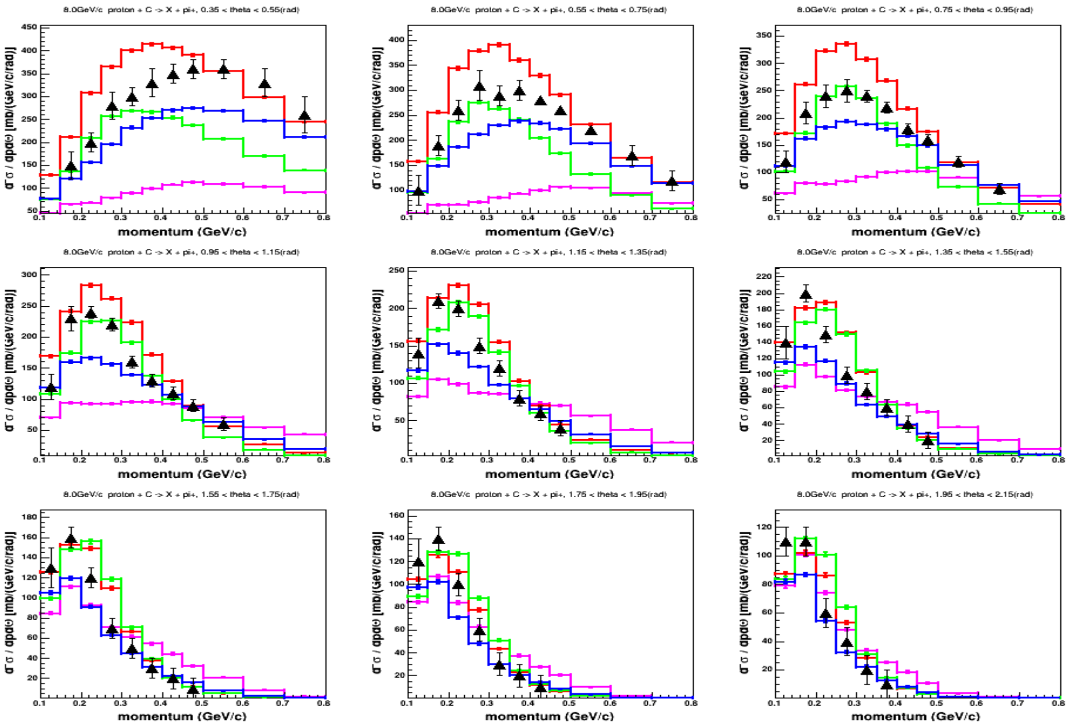
BACKUP SLIDES

MC vs HARP data : 8 GeV/c proton on C –> π^+ (FW and LA)



MC vs HARP Data; χ^2/NDF calculated over FW theta bins
χ^2/NDF = 13.5448 for bertini
χ^2/NDF = 13.079 for ftfp
χ^2/NDF = 7.69131 for ftfp_tune3
χ^2/NDF = 11.3472 for fluka.cern.4.4.0

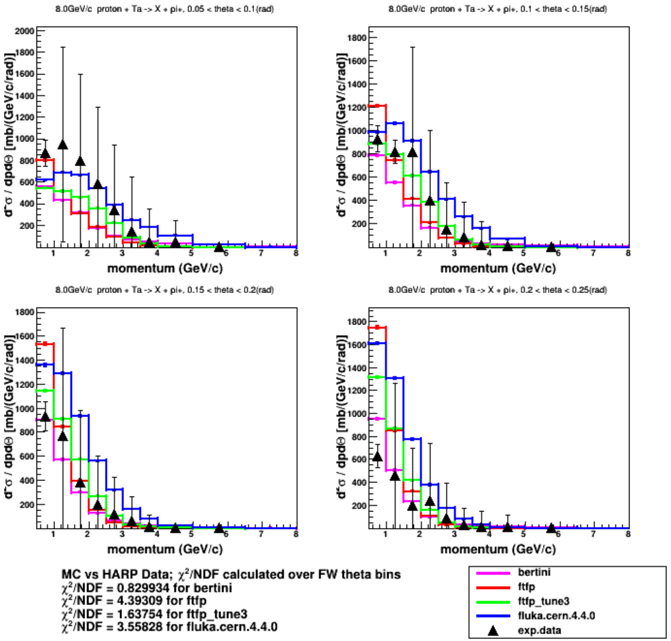
- bertini
- ftfp
- ftfp_tune3
- fluka.cern.4.4.0
- ▲ exp.data



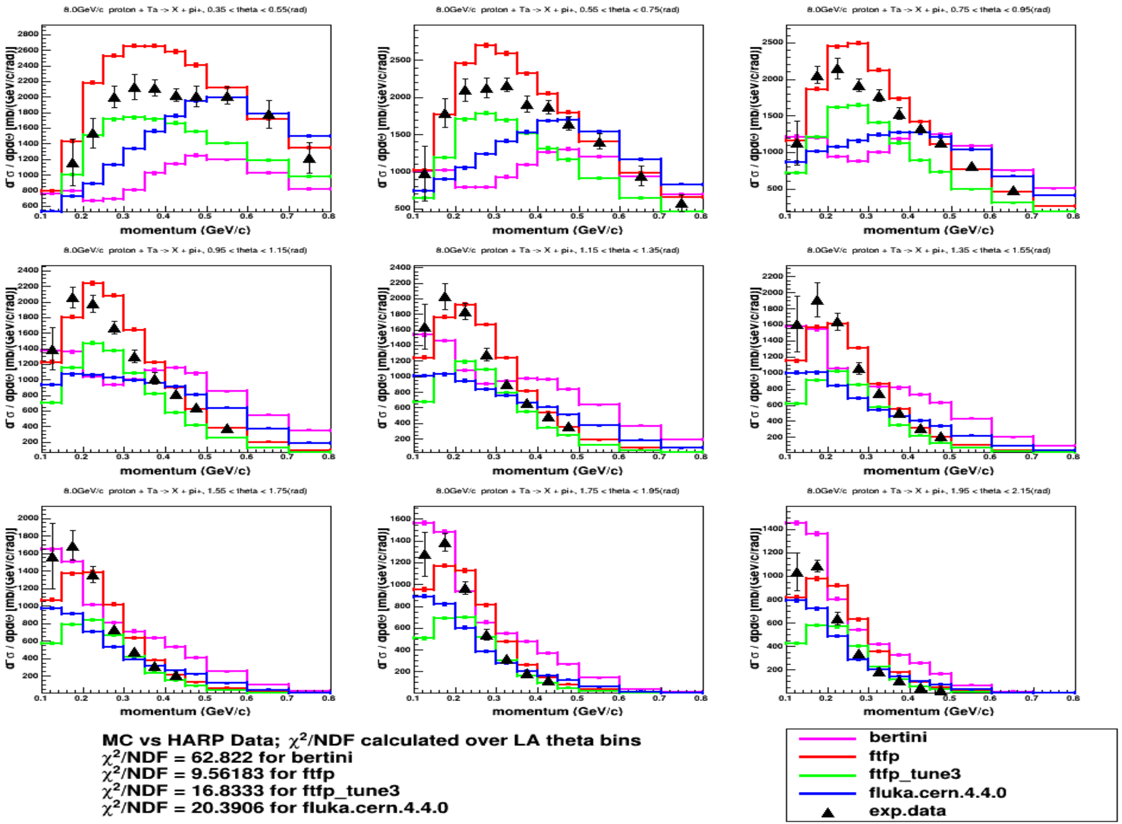
MC vs HARP Data; χ^2/NDF calculated over LA theta bins
χ^2/NDF = 46.7237 for bertini
χ^2/NDF = 7.51271 for ftfp
χ^2/NDF = 9.17002 for ftfp_tune3
χ^2/NDF = 7.62421 for fluka.cern.4.4.0

- bertini
- ftfp
- ftfp_tune3
- fluka.cern.4.4.0
- ▲ exp.data

MC vs HARP data : 8 GeV/c proton on Ta –> π^+ (FW and LA)

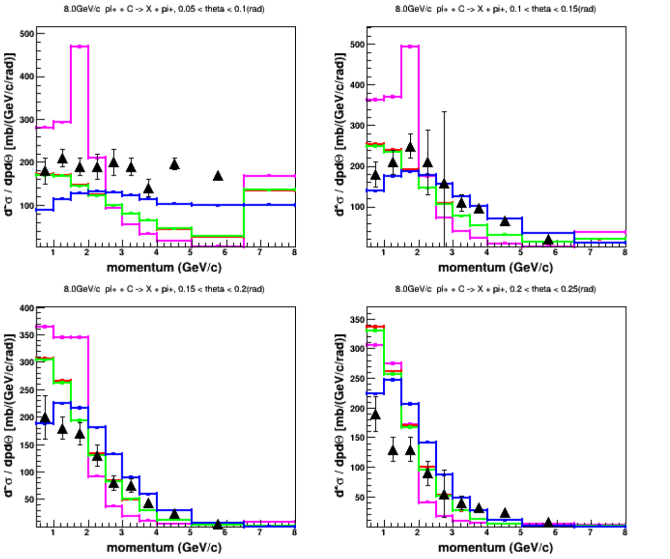


MC vs HARP Data; χ^2/NDF calculated over FW theta bins
χ^2/NDF = 0.829934 for bertini
χ^2/NDF = 4.39309 for ftfp
χ^2/NDF = 1.63754 for ftfp_tune3
χ^2/NDF = 3.55828 for fluka.cern.4.4.0



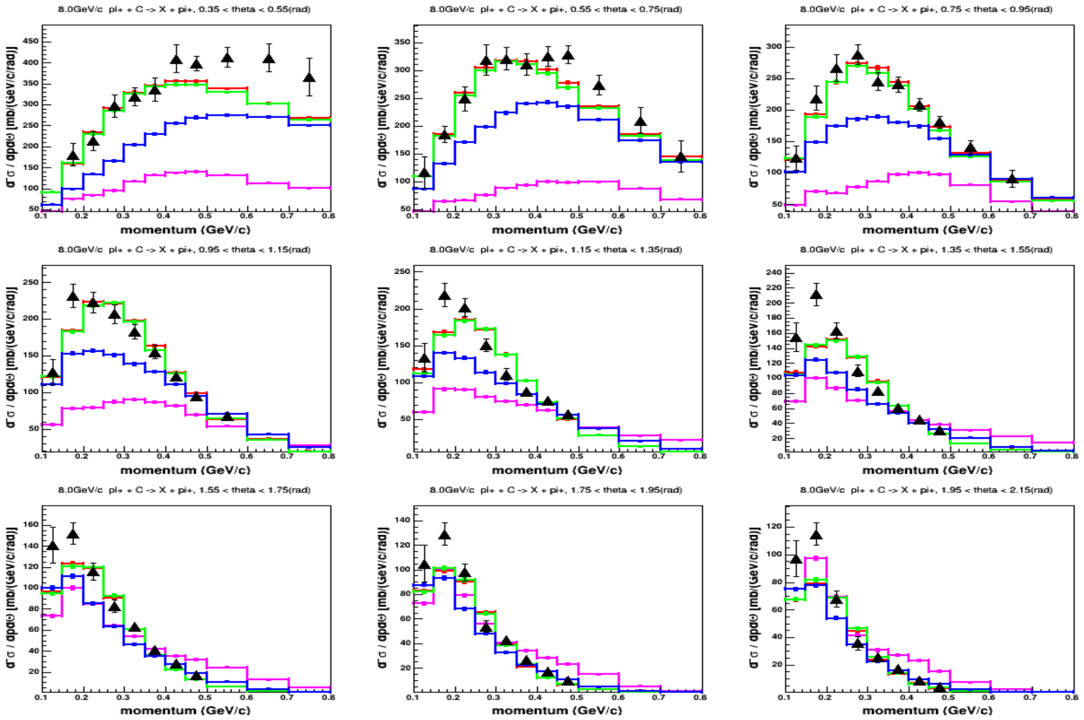
MC vs HARP Data; χ^2/NDF calculated over LA theta bins
χ^2/NDF = 62.822 for bertini
χ^2/NDF = 9.56183 for ftfp
χ^2/NDF = 16.8333 for ftfp_tune3
χ^2/NDF = 20.3906 for fluka.cern.4.4.0

MC vs HARP data : 8 GeV/c π^+ on C –> π^+ (FW and LA)



MC vs HARP Data; χ^2/NDF calculated over FW theta bins
χ^2/NDF = 115.329 for bertini
χ^2/NDF = 73.9306 for ftfp
χ^2/NDF = 72.4532 for ftfp_tune3
χ^2/NDF = 21.8384 for fluka.cern.4.4.0

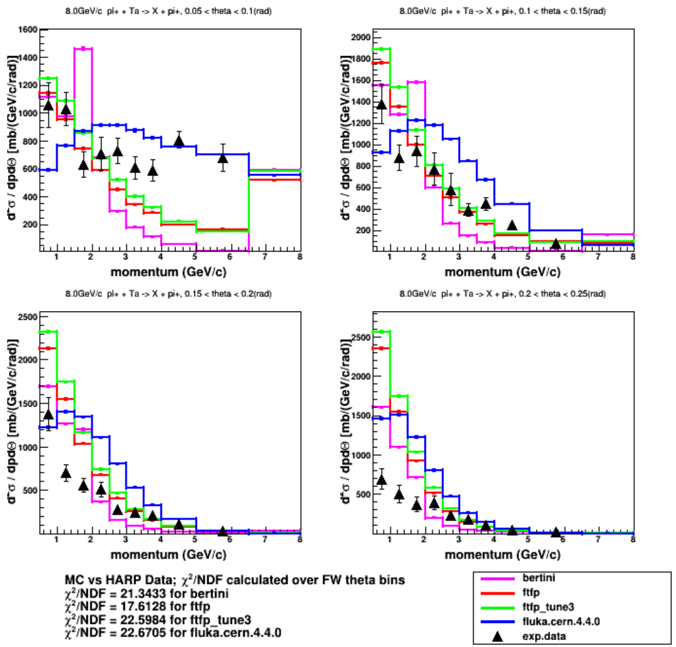
- bertini
- ftfp
- ftfp_tune3
- fluka.cern.4.4.0
- ▲ exp.data

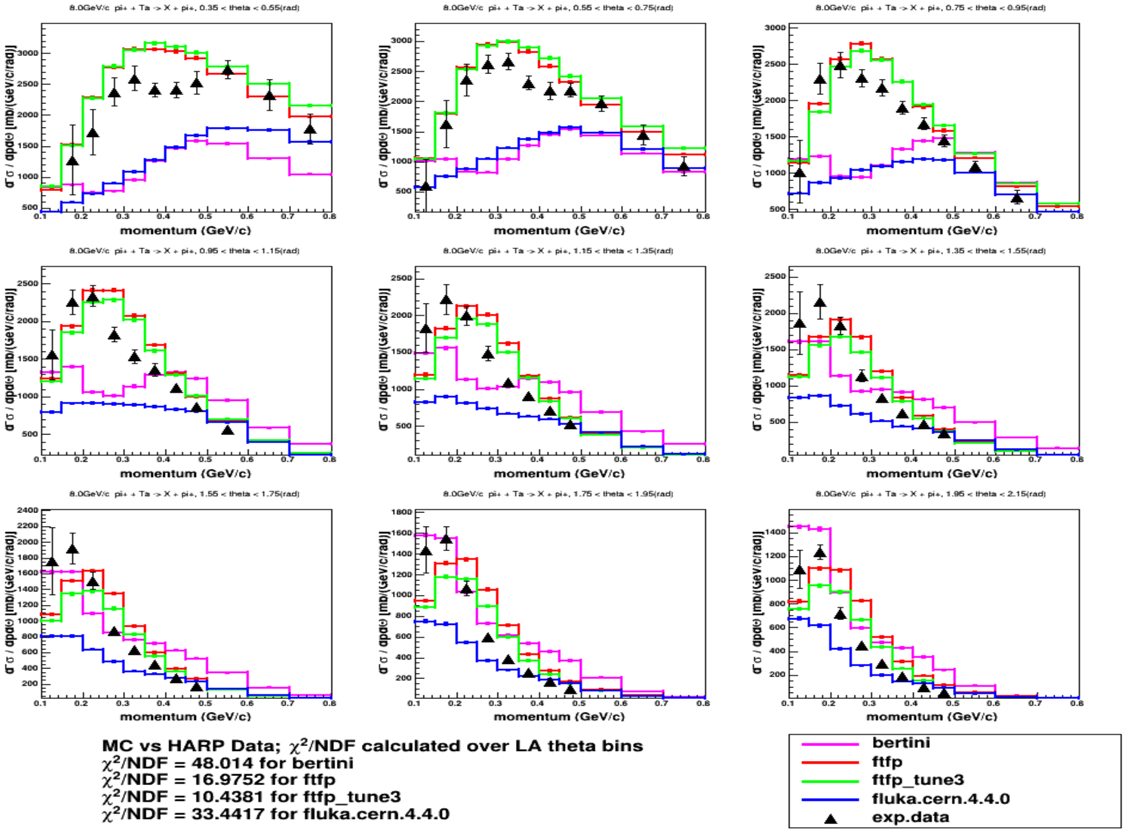


MC vs HARP Data; χ^2/NDF calculated over LA theta bins
χ^2/NDF = 49.712 for bertini
χ^2/NDF = 3.07759 for ftfp
χ^2/NDF = 3.19708 for ftfp_tune3
χ^2/NDF = 11.7733 for fluka.cern.4.4.0

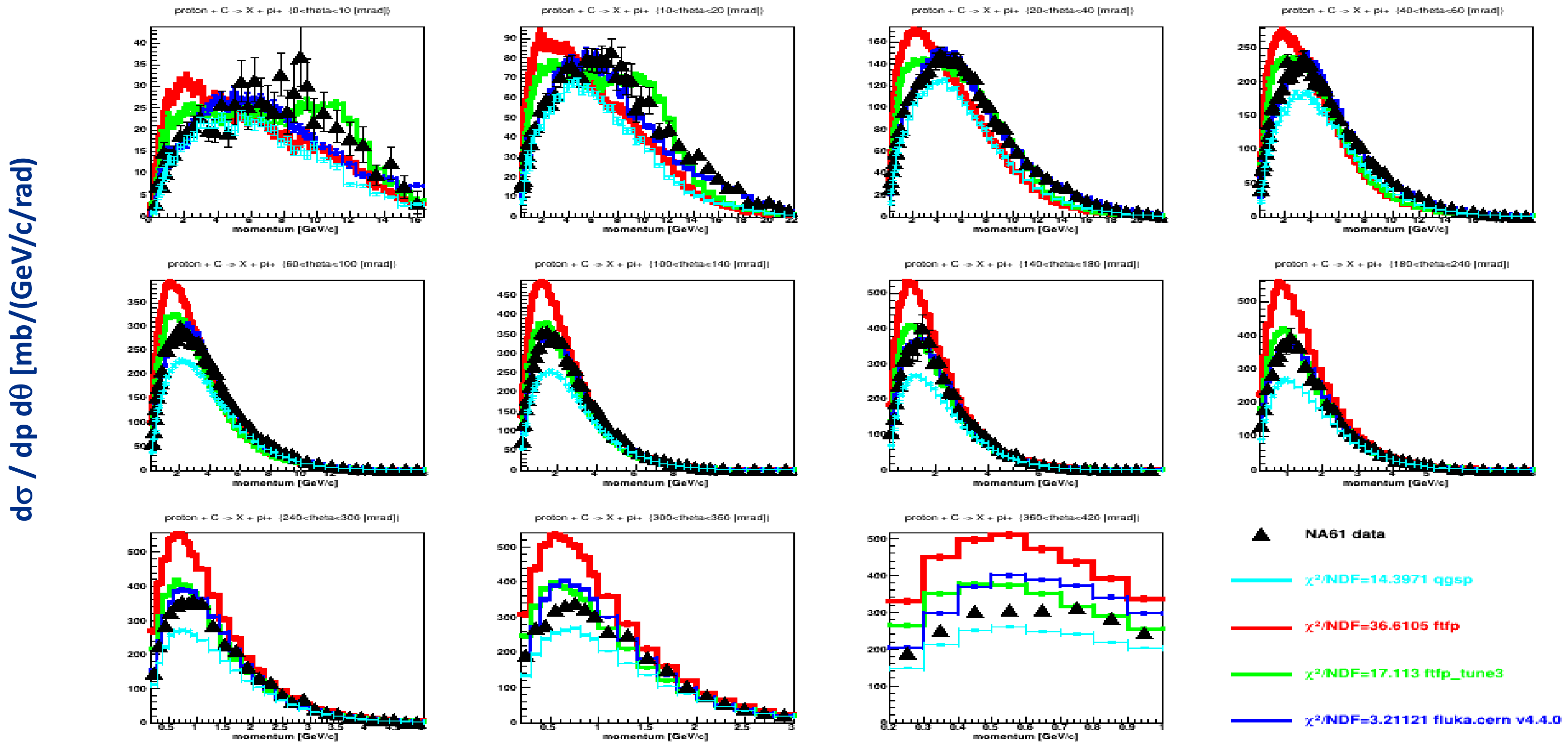
- bertini
- ftfp
- ftfp_tune3
- fluka.cern.4.4.0
- ▲ exp.data

MC vs HARP data : 8 GeV/c π^+ on Ta –> π^+ (FW and LA)

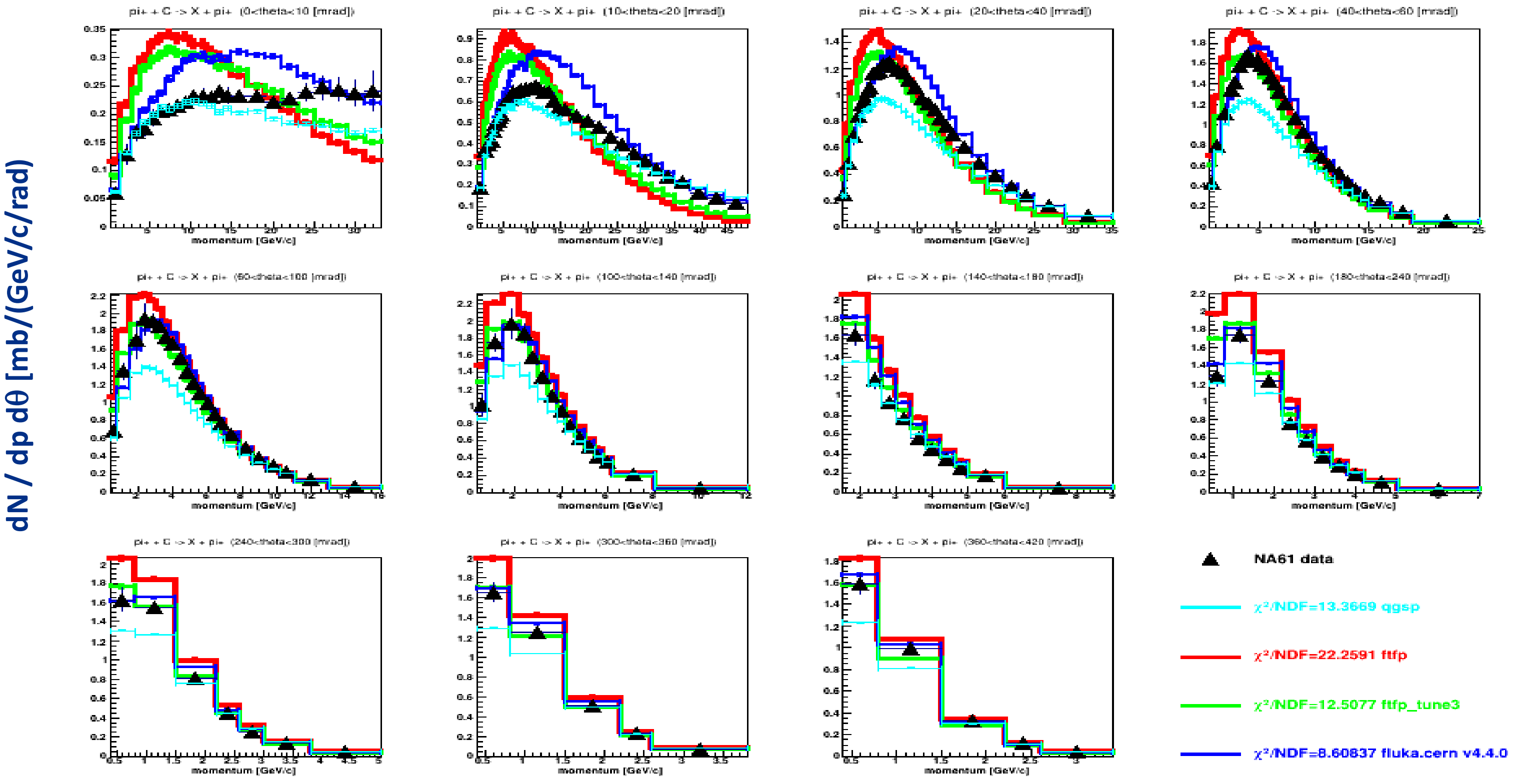




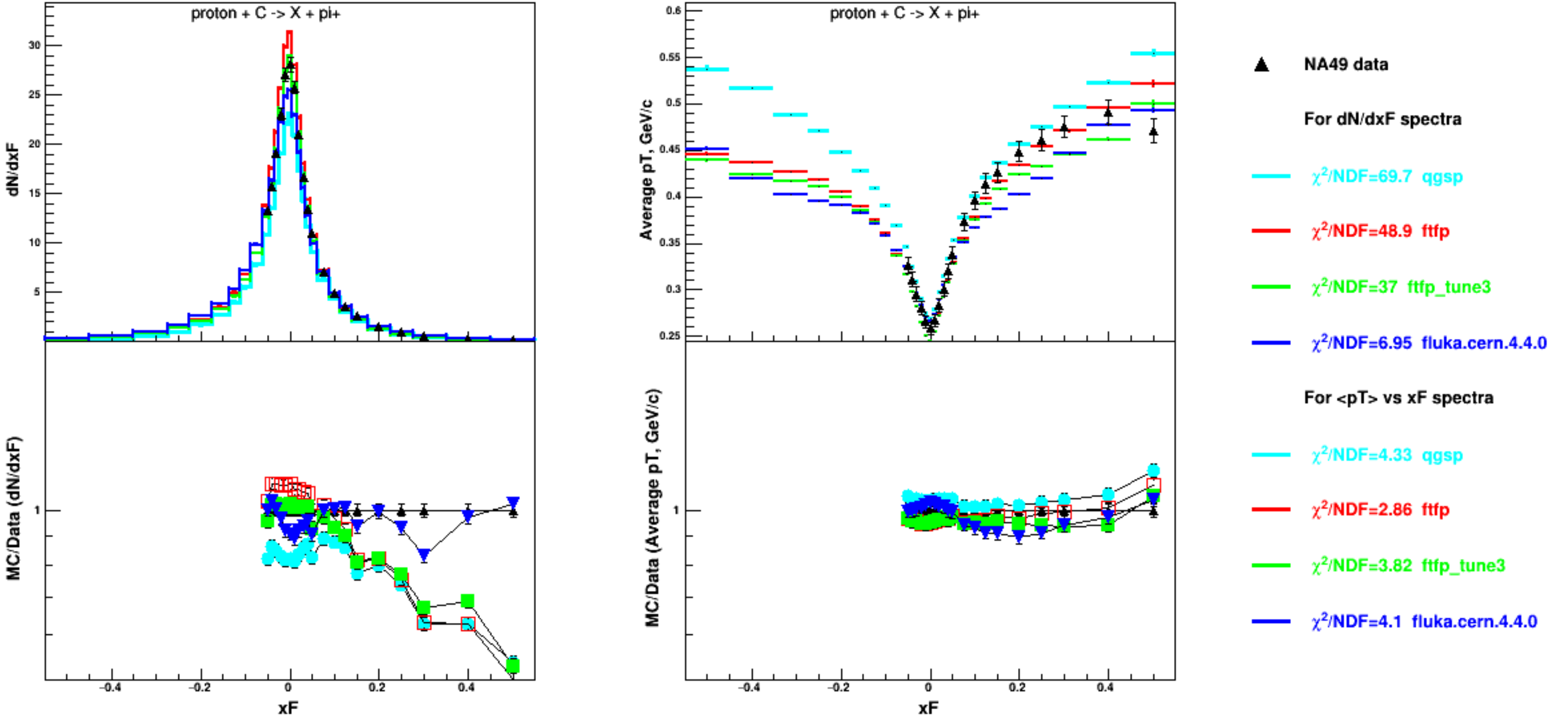
MC vs NA61 data : 31 GeV/c proton on C –> π^+



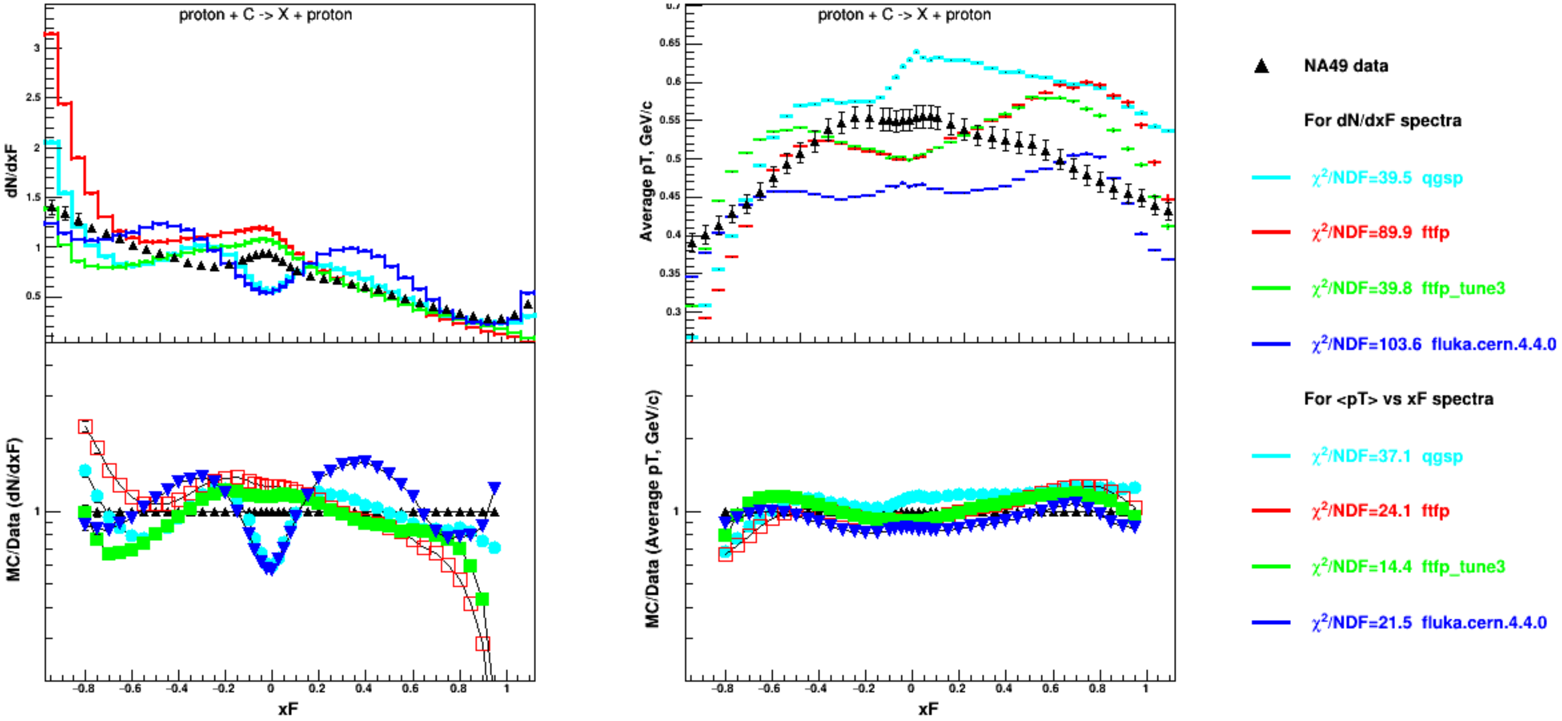
MC vs NA61 data : 60 GeV/c π^+ on C –> π^+



MC vs NA49 data : 158 GeV/c proton on C –> π^+



MC vs NA49 data : 158 GeV/c on C –> proton



MC vs NA49 data : 158 GeV/c on C –> antiproton