EUDET Annual meeting, Geneva, 19-21 October 2009

Development & Validation of Geant4 Hadronic Models in a Wide Energy Range

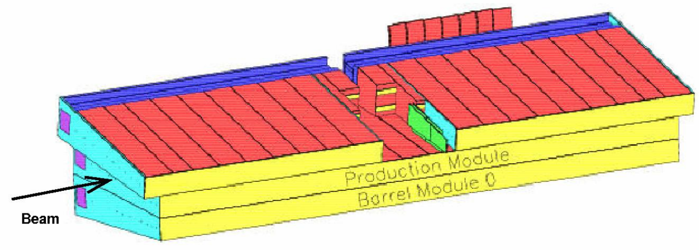
J.Apostolakis, A. Dotti, G.Folger, V.Grichine, V.Ivanchenko, M.Kossov, A.Ribon, V.Uzhinsky, D.Wright*

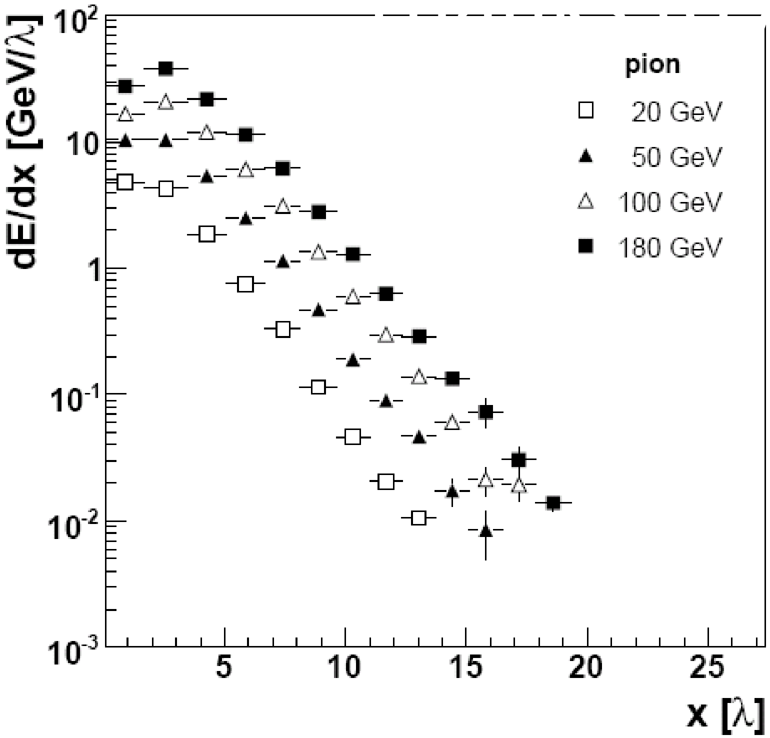
CERN PH/SFT, *SLAC

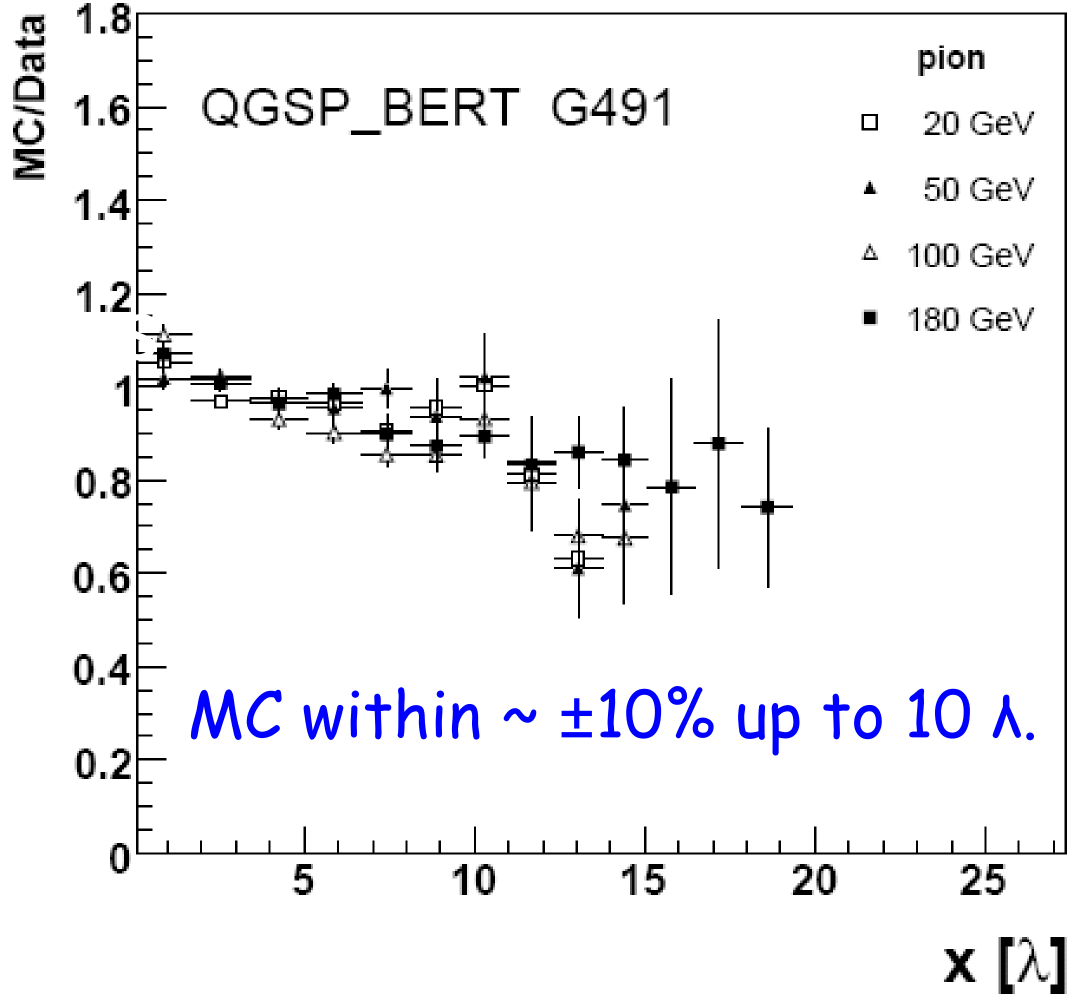
Overview

- Shower shape
- Energy response discontinuity
  - Transition between models
- Improvements of models
  - FTF (V. Uzhinksiy – EUDET support 2009)
  - Cross-section, elastic scattering

Pion longitudinal shower profile in stand-alone ATLAS TileCal test-beam at 90º ~2008-09







MC within ~ ±10% up to 10 λ.

For Protons : -(20%-40%) at 10 λ.

Motivation and Impact

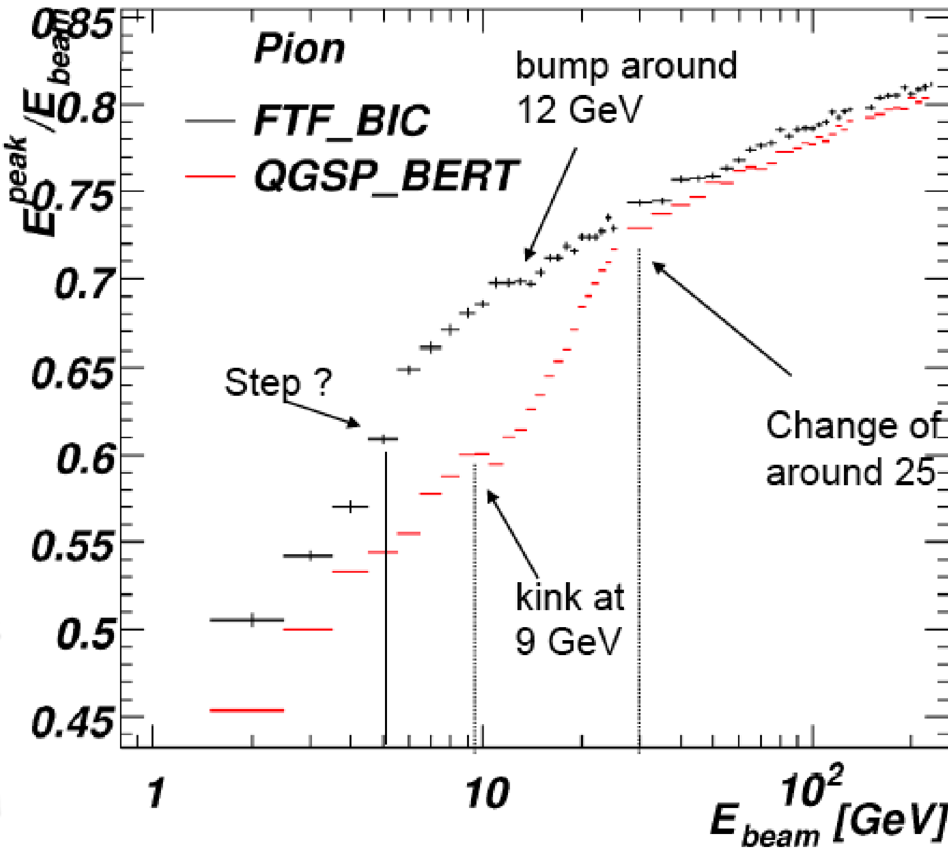
- The energy response as a function of beam energy presents some unphysical discontinuities
  - CMS reported this effect in simulations of its calorimeter test-beam set-up,
  - ATLAS confirmed and reported it also for other observables, like energy resolution vs. beam energy
- This is a worrisome feature, because jets at LHC and ILC will be composed up of hadrons of quite different energies, this could affect several analyses, and any simulation-based jet-calibration scheme.
- The reason for these unphysical discontinuties is clear: the transition between hadronic models. However, it is not trivial to fix it...

Energy response and transitions

ATLAS Tile

Problem of matching models:

- CMS & ATLAS reported energy response shows unphysical features
  - Kink (9 GeV)
  - Change of slope (25 GeV)
- These are the transition points between models
- Reproduced in simple setups
  - No detector effects



FTF_BIC is more smooth
QGSP_BERT is in better agreement to data

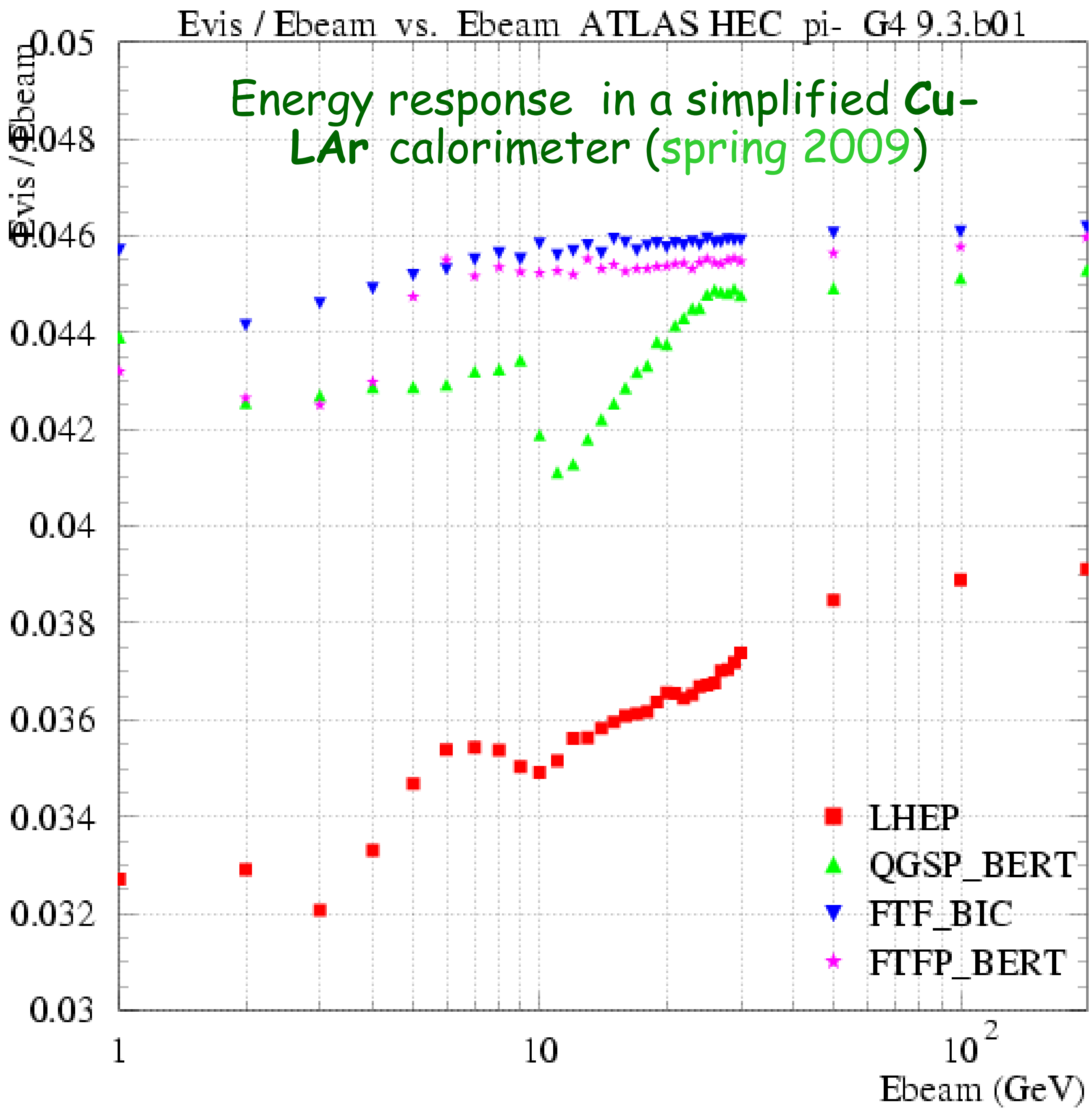
Effect of transition between models ?

QGSP_BERT:
- 0-9.9 GeV Bertini intra-nuclear cascade (BERT)
- 9.5-25 GeV low energy parameterised model (LEP)
- >12 GeV QGSP

FTF_BIC:
- 0-5 GeV binary cascade model (BIC)
- 0-5 GeV LEP for capture and fission processes
- >5 GeV Fritiof model (FTF)

Simple set-up check

- Confirmed in simple calorimeter setup



Hadronic models and Physics Lists

- Physics accuracy goals:
  - Describe known thin target data and test beam data
  - Predictive power for unmeasured regions.
- Hadronic Models have limitations and applicable energy range
  - Our physics lists mix different models

Today's physics list QGSP_BERT has transitions between:

- High-energy : string models (QGS)
- Intermediate: parameterised (LEP)
- low energy: cascade (BERTini)

All feed into de-excitation models (e.g. Preco)

The problem analysis road-map

- Reproduce the problem with simplified calorimeter
  - Compare different Physics models (from Lists)
- Understand the microscopic origins of the differences between models
  - Identify differences that are/can-be important
  - Need to confirm by comparing to thin-target data
- Improve use of hadronic models in Physics Lists:
  1. Change the transition regions between models
     - in existing Physics Lists (e.g. to avoid key deficiencies)
  2. Create novel mixtures of models in new Physics Lists
     - potentially with fewer models/transitions
  3. Improve the hadronic models (best but takes more time)

Results of Models Comparisons

(plots ->backup)

- Comparisons between models indicate
  - LEP (parameterised) differs from all other models
    - Confirmed in thin-target: aim to eliminate use
  - Bertini and Binary Cascade models produce excess energy in protons (and neutrons) above 3-5 GeV
  - Fritiof produces too many π^0 's below ~6 GeV
  - Quark-Gluon-String results stable down to ~ 9 GeV
    - Use could be extended down to 9-10 GeV
  - Energy non-conservation in FTF/BIC - being fixed
- RMS are similar for almost all models
- Suggestion on a likely better choice of the transition regions, and/or model mixing (see next slide)

New transition regions and/or combination of models

- **FTFP_BERT_TRV** : transition between Fritiof (FTF) and Bertini cascade (BERT) moved in the region **6 – 8 GeV** (originally it was 4 – 5 GeV)

- **QGSP_FTFP_BERT** : parameterized model (LEP) replaced with Fritiof/Preco model in a QGSP_BERT-like Physics List. The transition region between FTFP and BERT is **6 – 8 GeV** (instead of 9.5-9.9 GeV)

Experimental Physics Lists available in 9.3.b01

Improvements of models

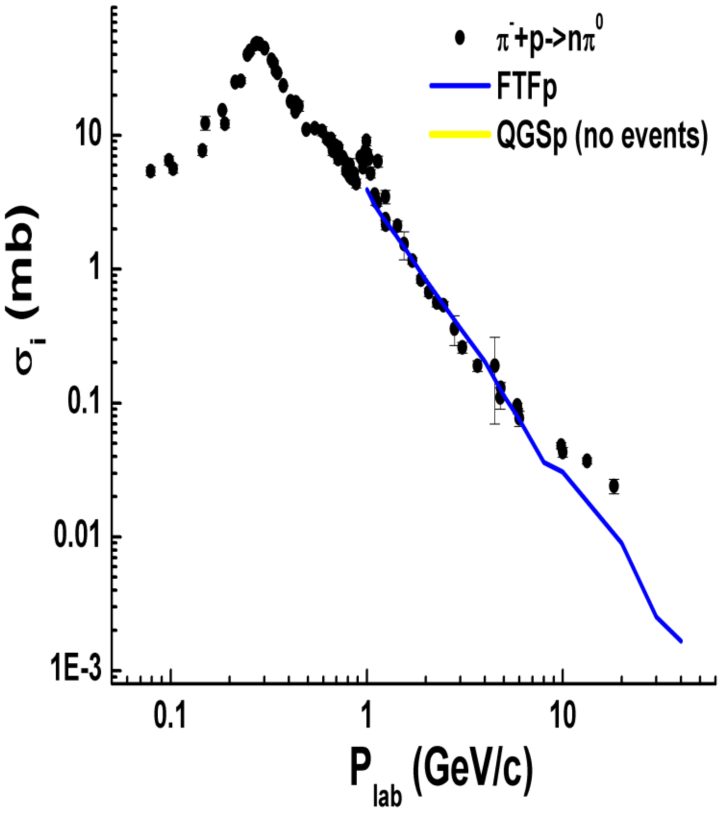
- **BERTini cascade :** improved cross-sections;
  higher multiplicity final-states;
  strange hadron production.

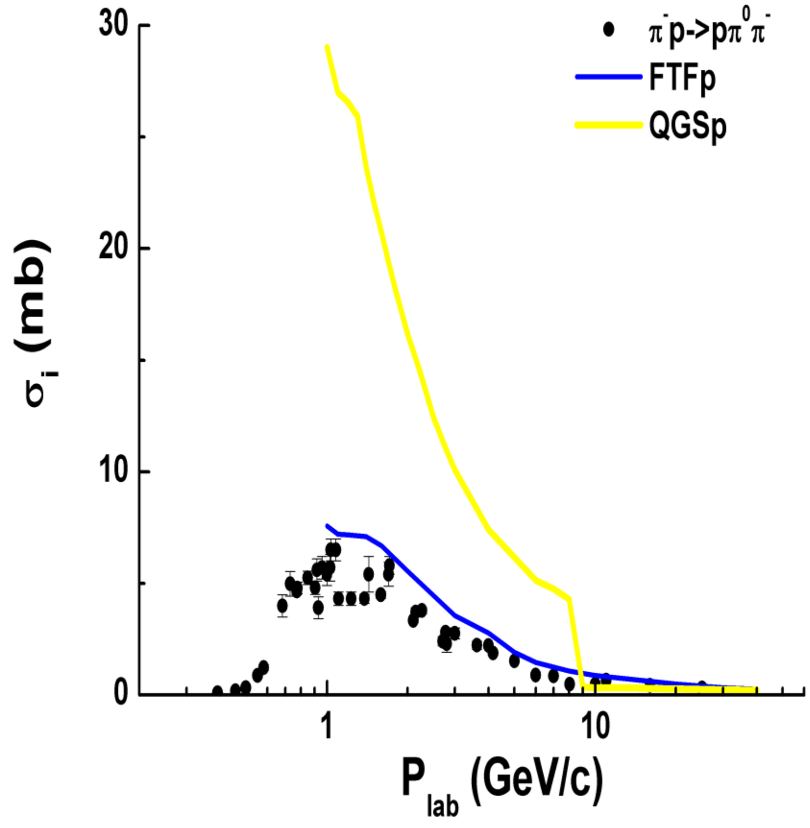
- **Fritiof** : further improved and tuned, based on
  thin-target data; FTF can be now coupled
  also to a 2-d reggeon cascade + Precompound.

- **CHIPS :** model was recently extended to all energies
  (for all hadrons and all materials);
  cross-section improvement & tuning is
  starting
  Protype Physics List QGSC_CHIPS

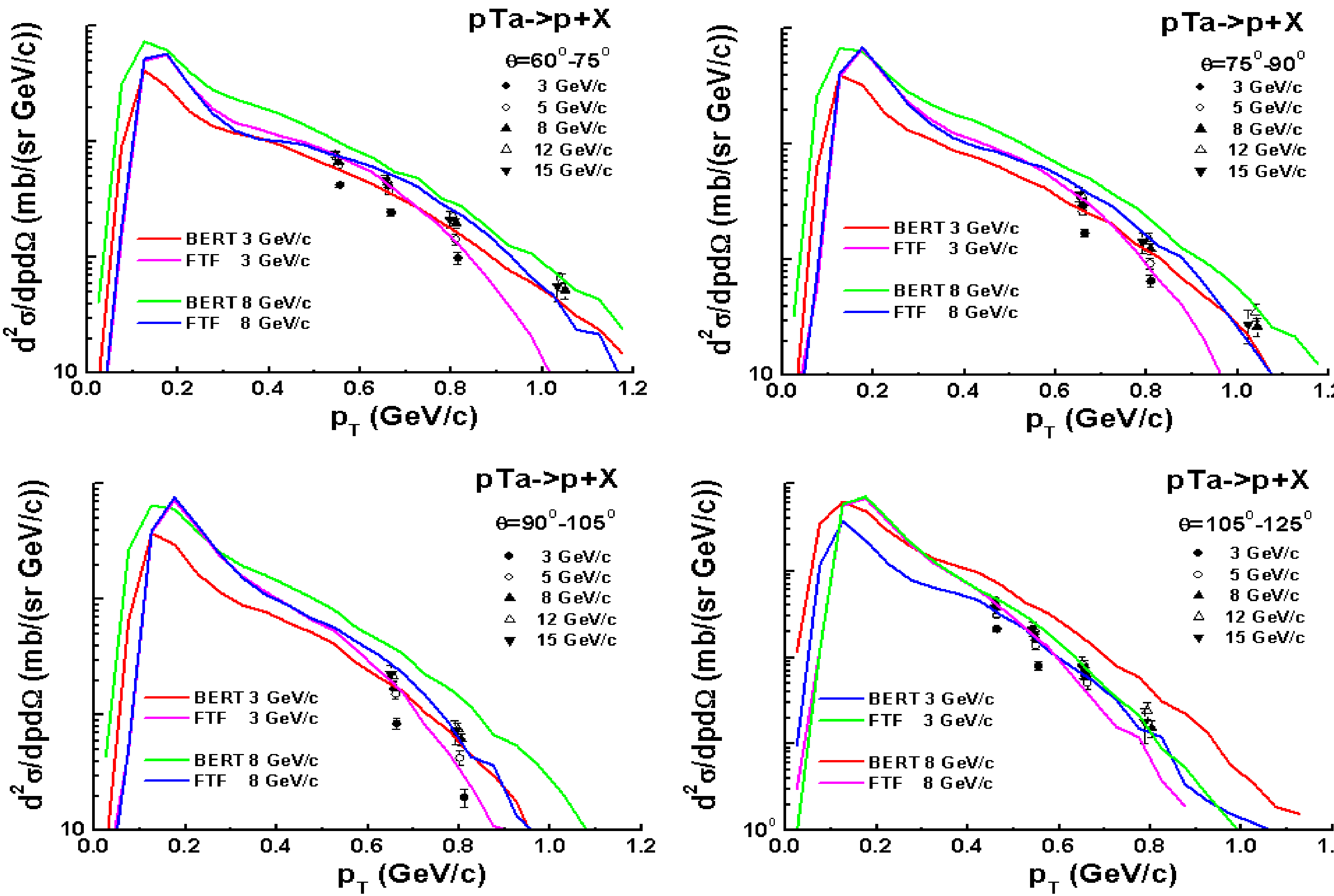
- **Other:** Cross-sections, hadron elastic scattering

Binary channel description in FTF, $\pi^- p \to \pi^o n$, $\pi^o \pi^- p$

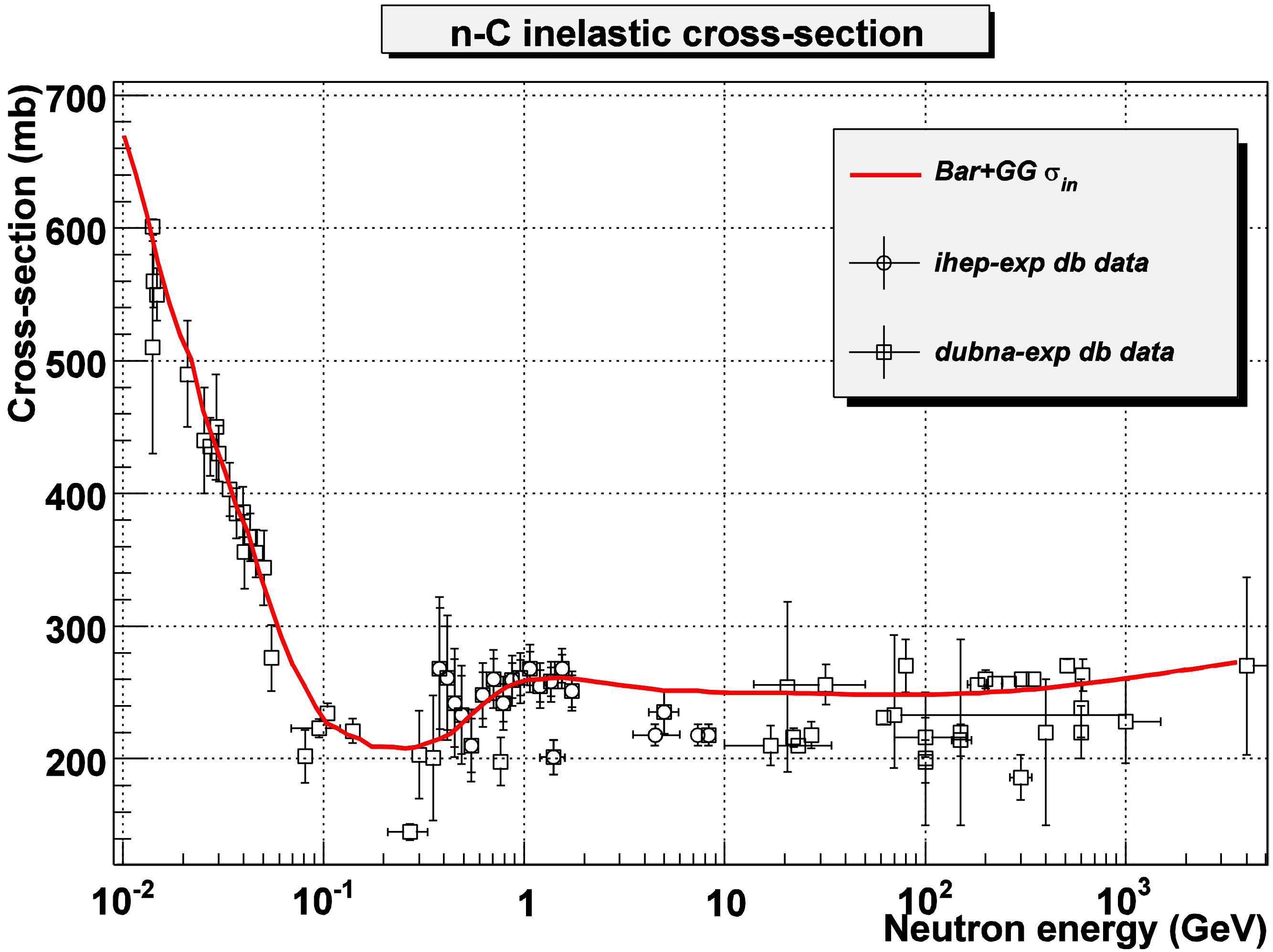


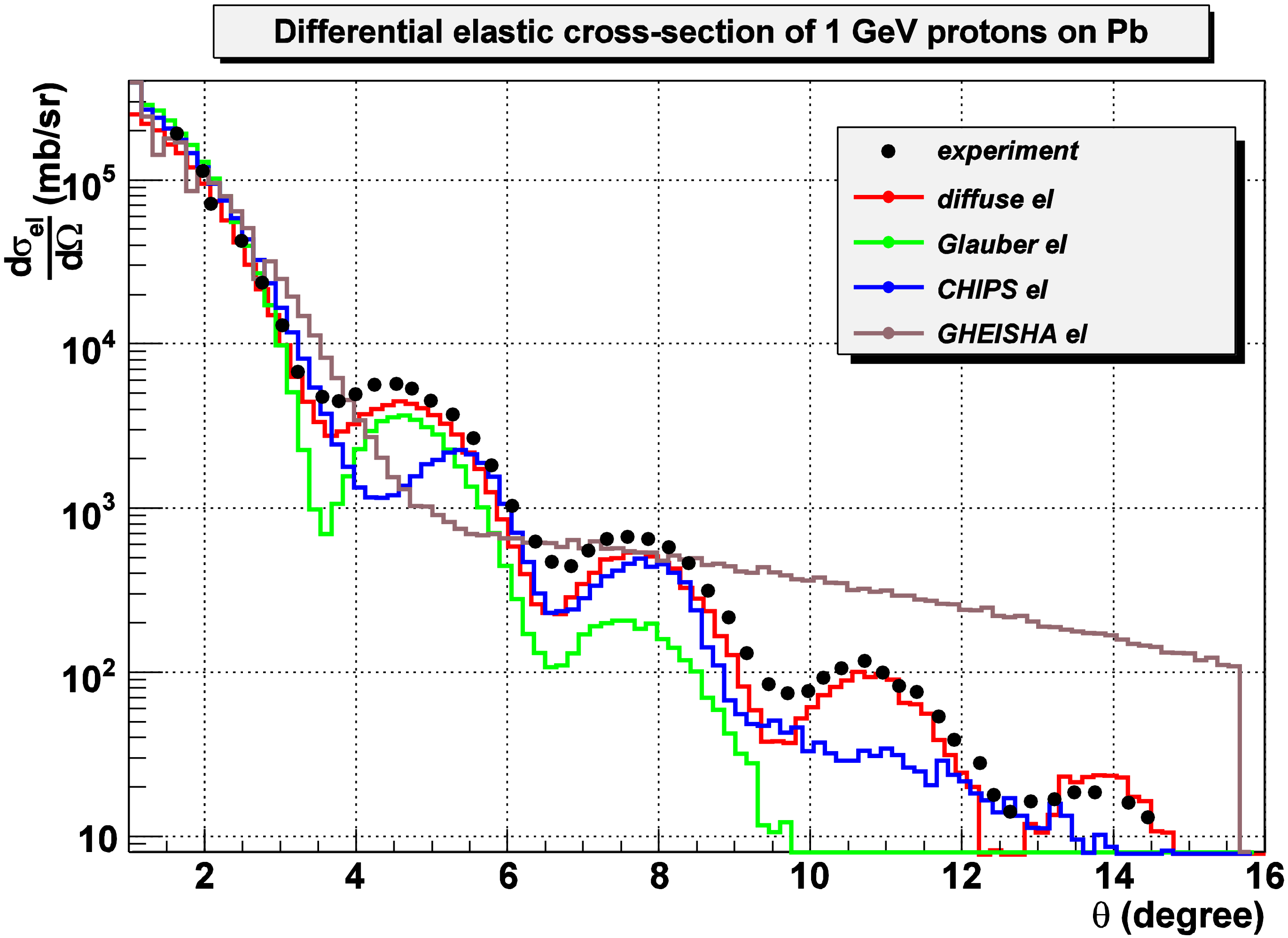


FTF & BERT proton spectra in p-A (HARP-CDP data)



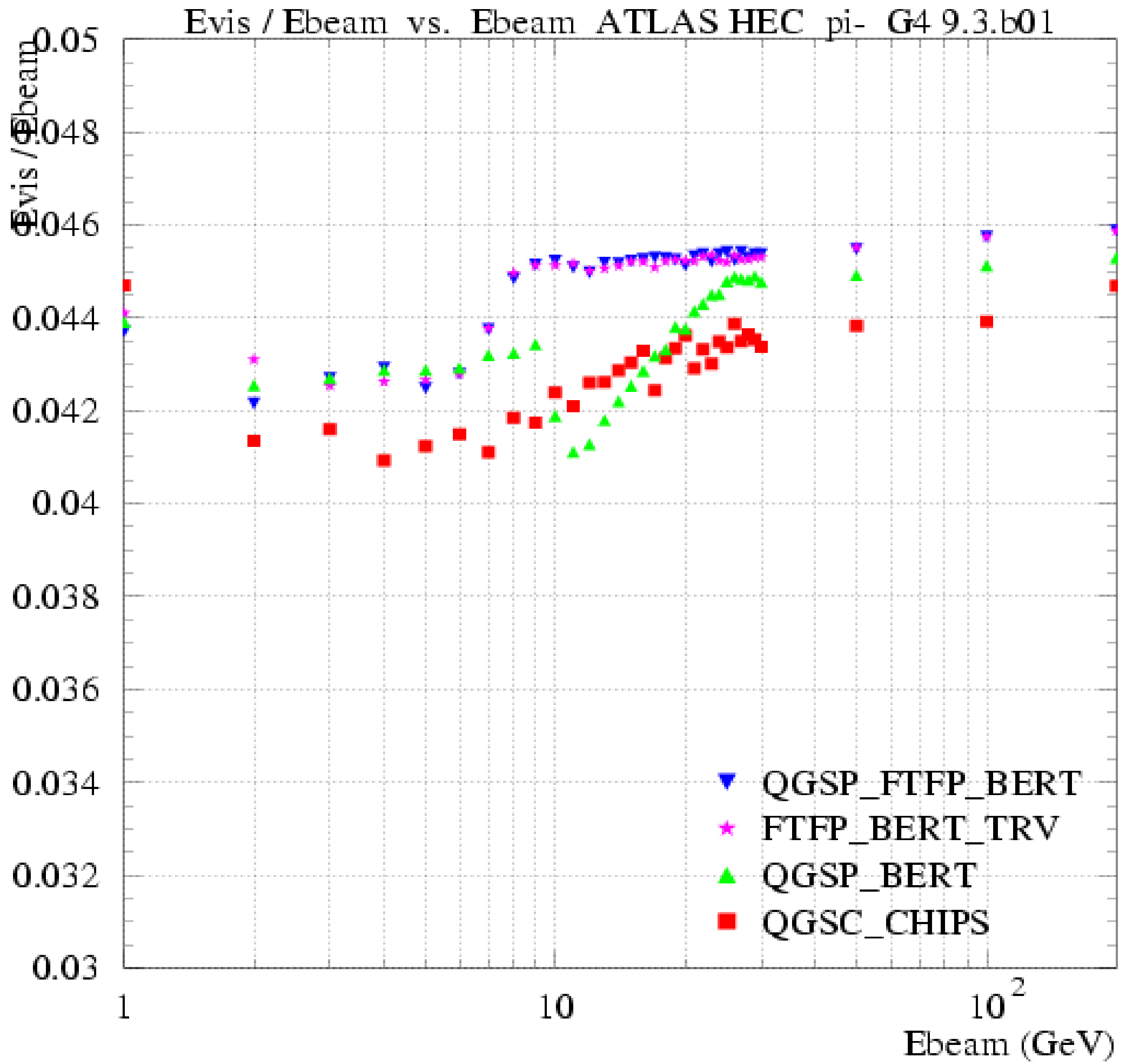
Optical & Glauber models in 10^{-2}-10^{3} GeV range





Differential elastic cross-section of 1 GeV protons on Pb
$\frac{d\sigma_{el}}{d\Omega}$ (mb/sr)
10^5
10^4
10^3
10^2
10
2
4
6
8
10
12
14
16
θ (degree)
experiment
diffuse el
Glauber el
CHIPS el
GHEISHA el

October 2009



Summary & Outlook

- Comparisons between hadronic models provide useful hints on their validity range and it can guide on the choice of the transition regions, or even new mixtures between these models in Physics Lists.

- It is interesting to compare with non-Geant4 models, like Fluka, MCNPX, Dubna cascade, etc.

- We should not forget to look at several observables, not only the energy response!

- Work to do:
  1) More validations with thin-target data in 1-20 GeV
  2) Continue to improve/extend models
  3) Try to link model-level features to calorimeter observables

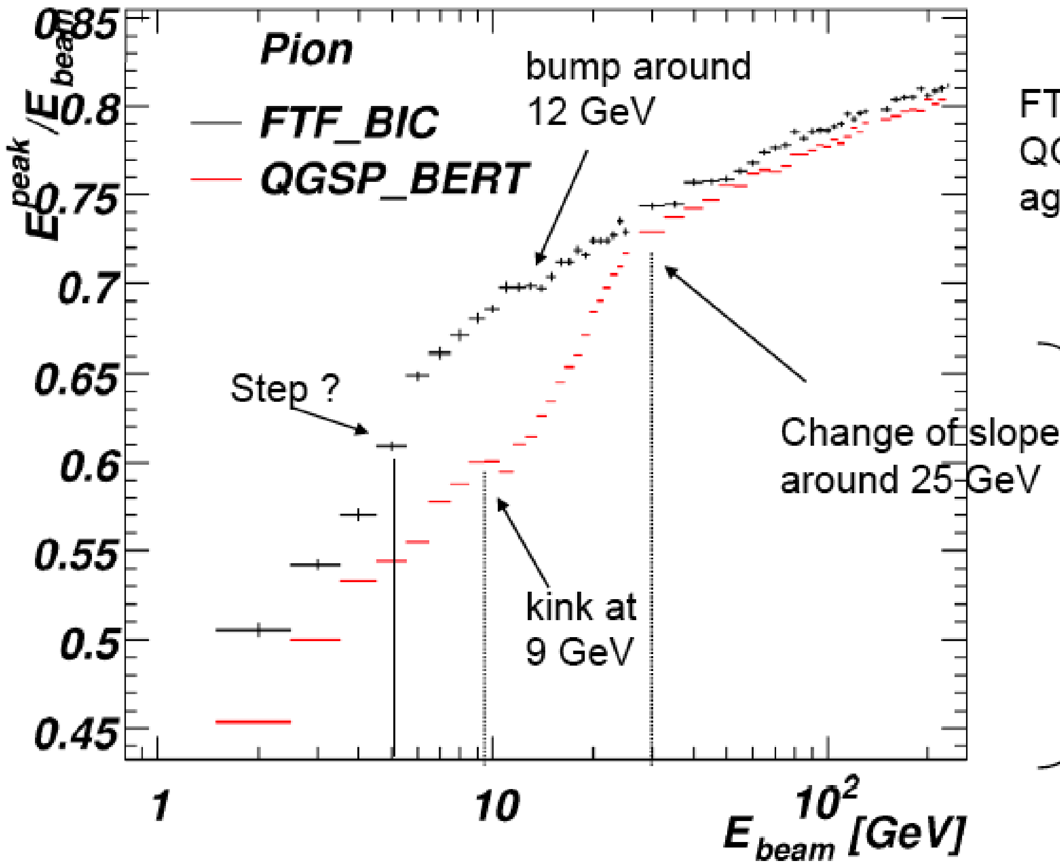
This requires a major effort of all G4 hadronic group!

BACKUP SLIDES

Energy response vs. beam energy

Problem of matching models:

ATLAS Tile

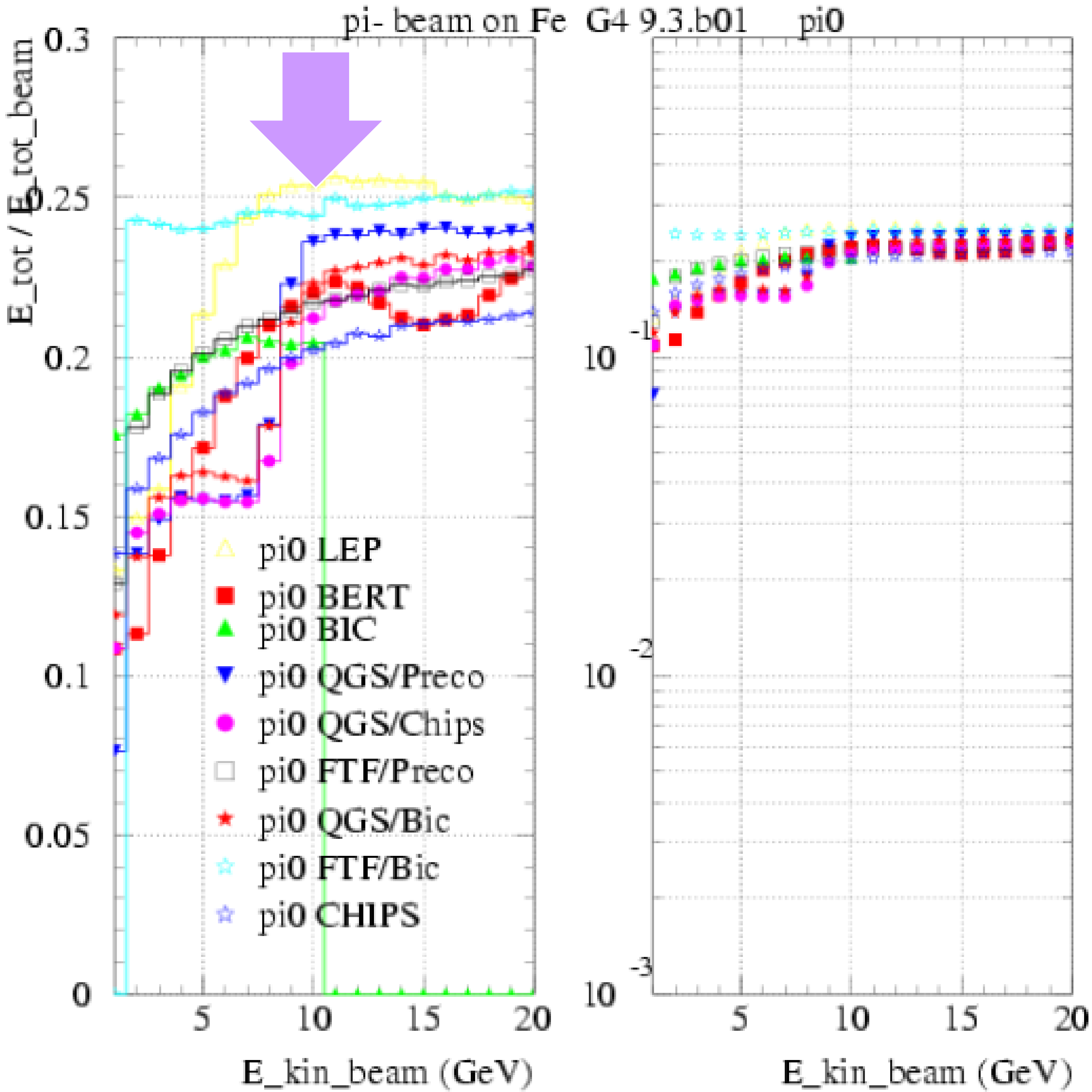


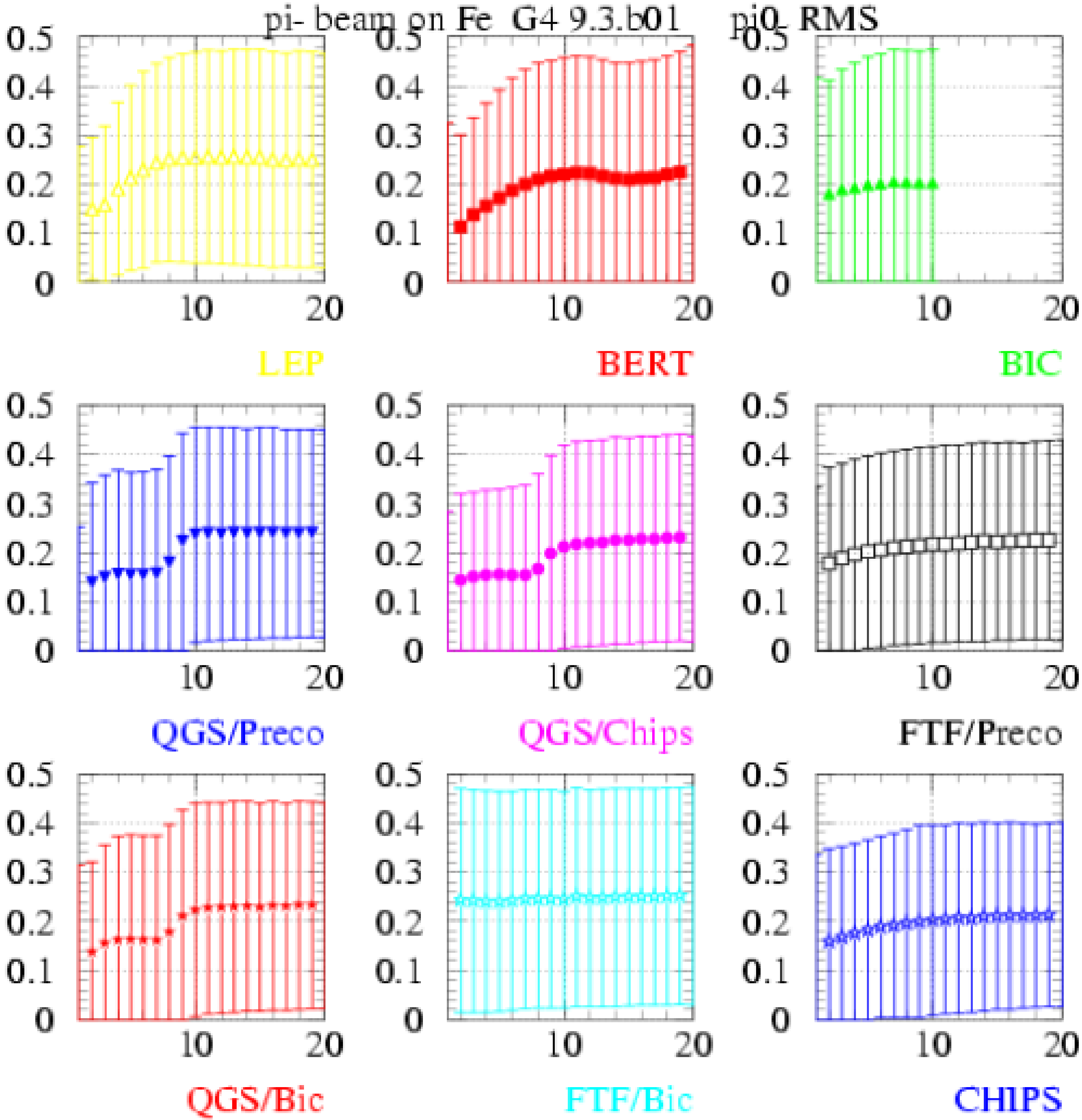
FTF_BIC is more smooth
QGSP_BERT is in better agreement to data

Effect of transition between models ?

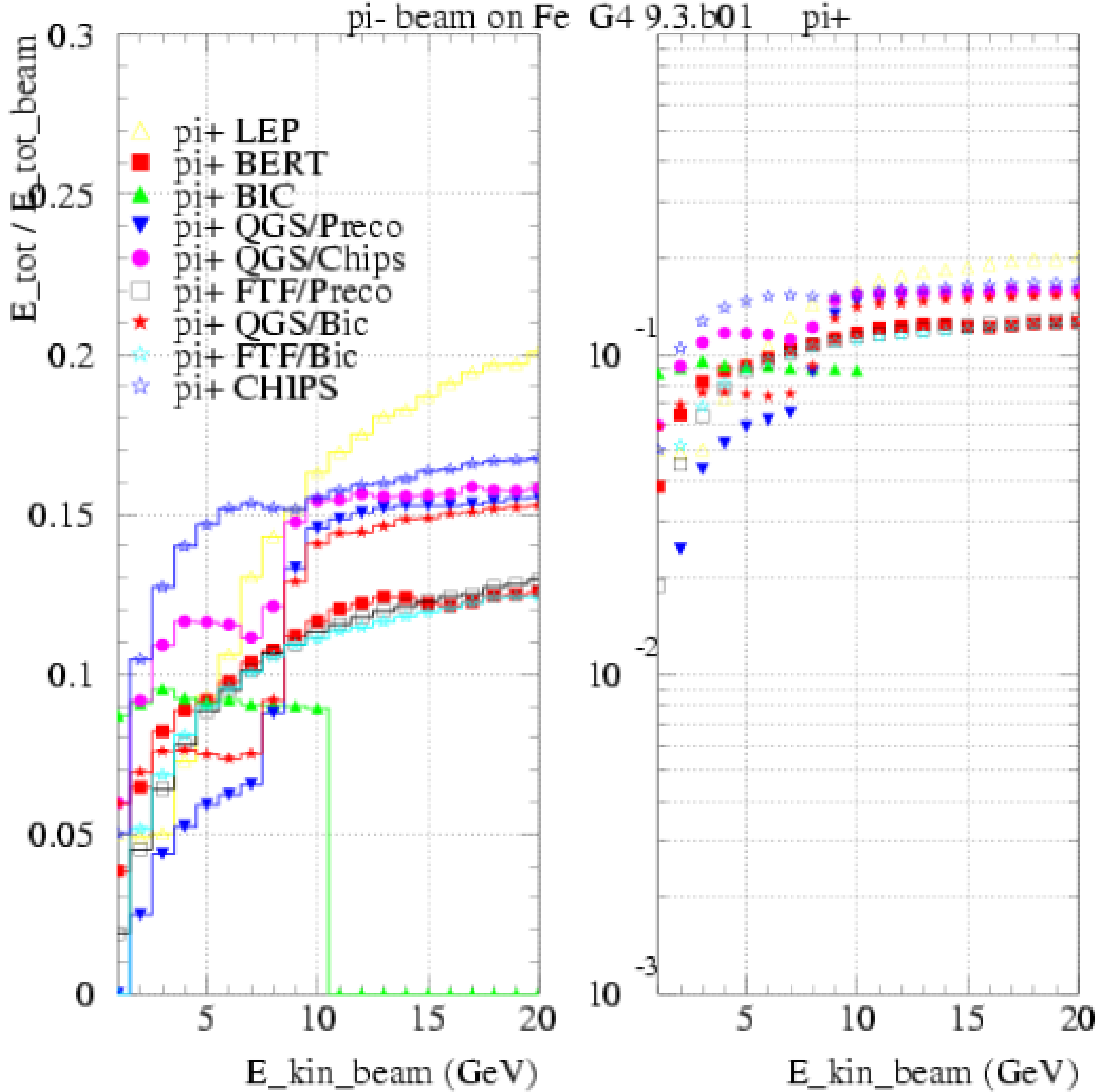
QGSP_BERT:
- 0-9.9 GeV Bertini intra-nuclear cascade (BERT)
- 9.5-25 GeV low energy parameterised model (LEP)
- >12 GeV QGSP

FTF_BIC:
- 0-5 GeV binary cascade model (BIC)
- 0-5 GeV LEP for capture and fission processes
- >5 GeV Fritiof model (FTF)

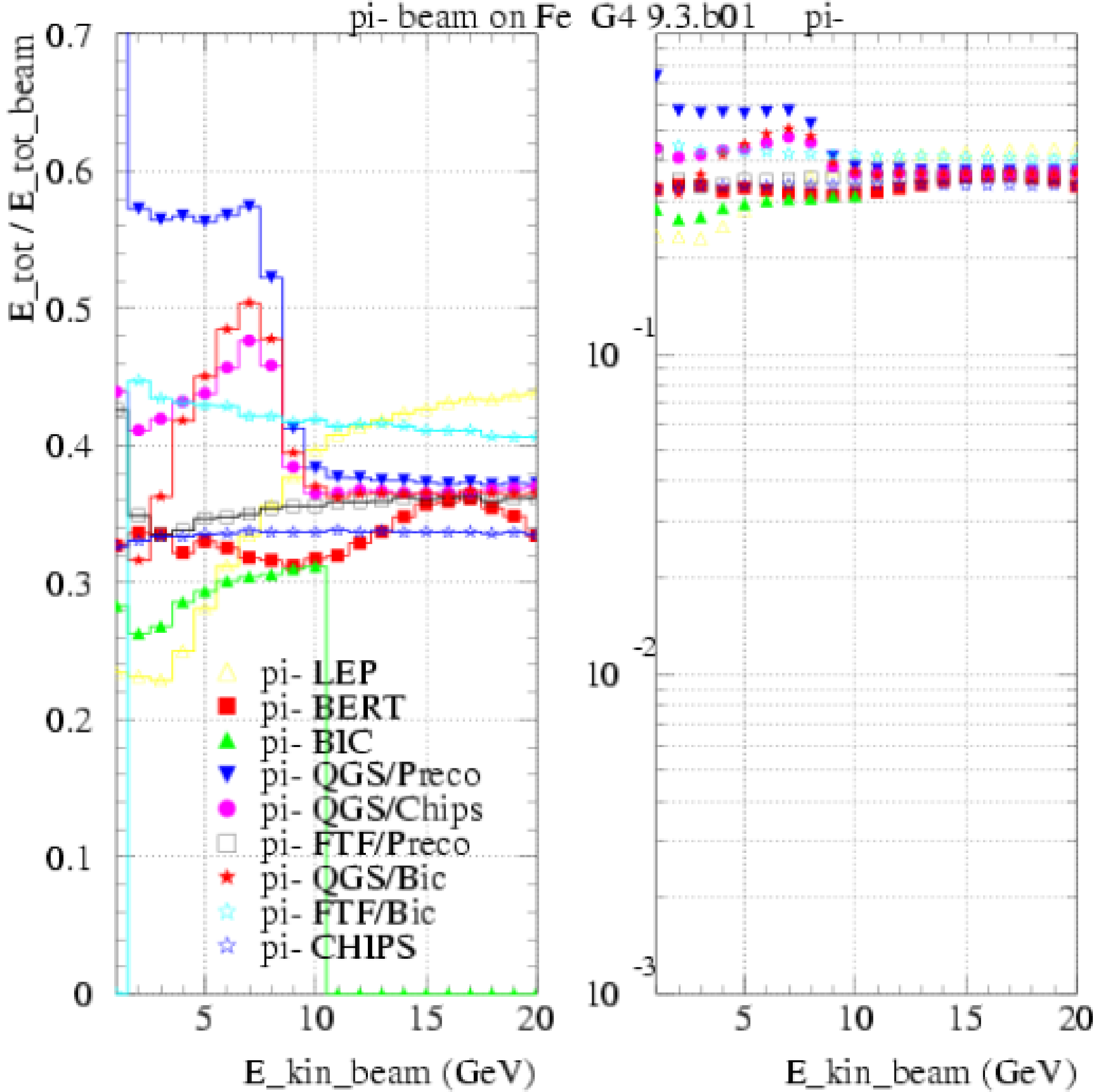

pi- beam on Fe G4 9.3.b01 pi0
E_tot / E_tot_beam
E_kin_beam (GeV)
E_kin_beam (GeV)
pi0 LEP
pi0 BERT
pi0 BIC
pi0 QGS/Preco
pi0 QGS/Chips
pi0 FTF/Preco
pi0 QGS/Bic
pi0 FTF/Bic
pi0 CHIPS



pi- beam on Fe G4 9.3.b01 pi0 RMS
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS

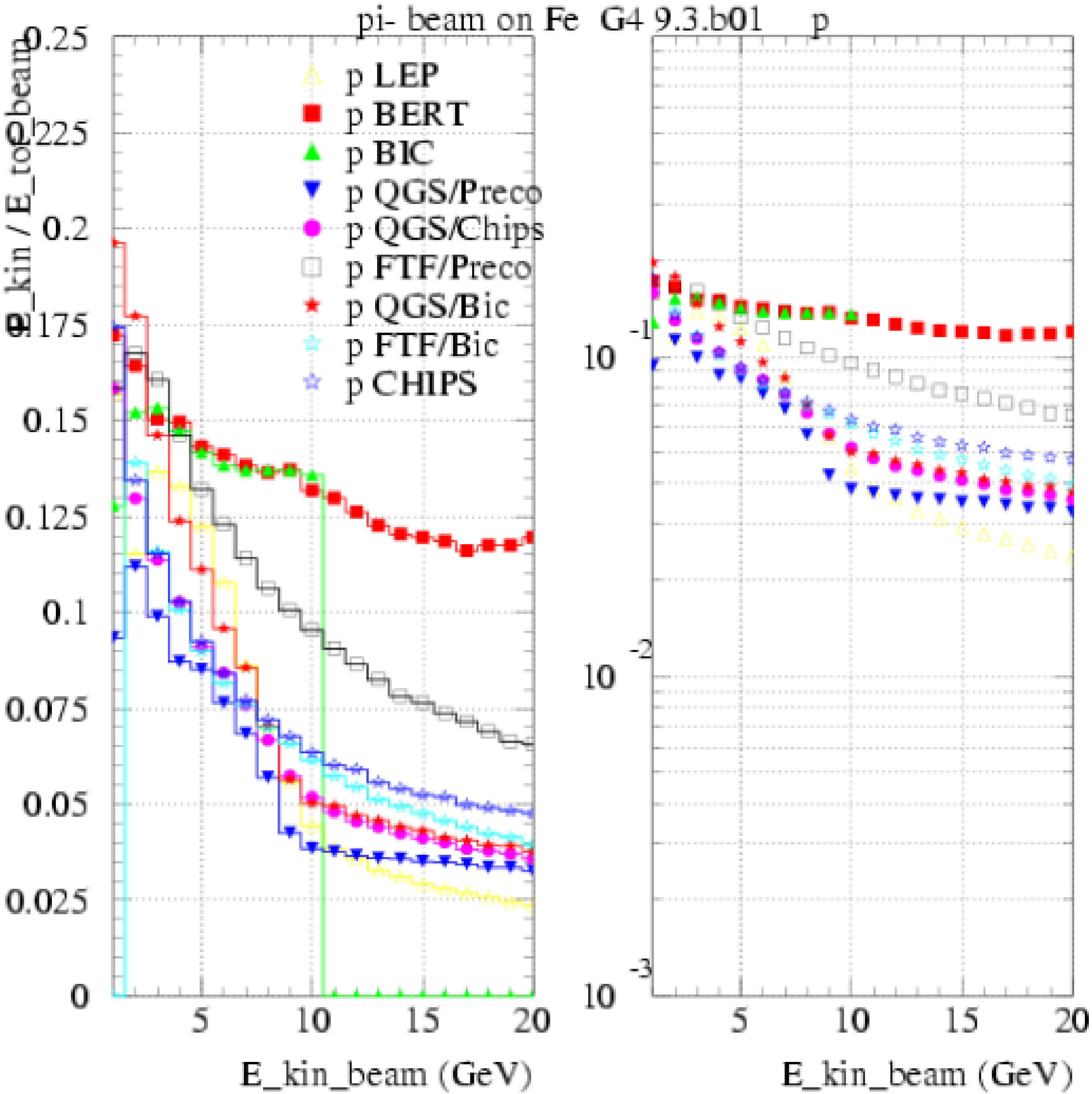


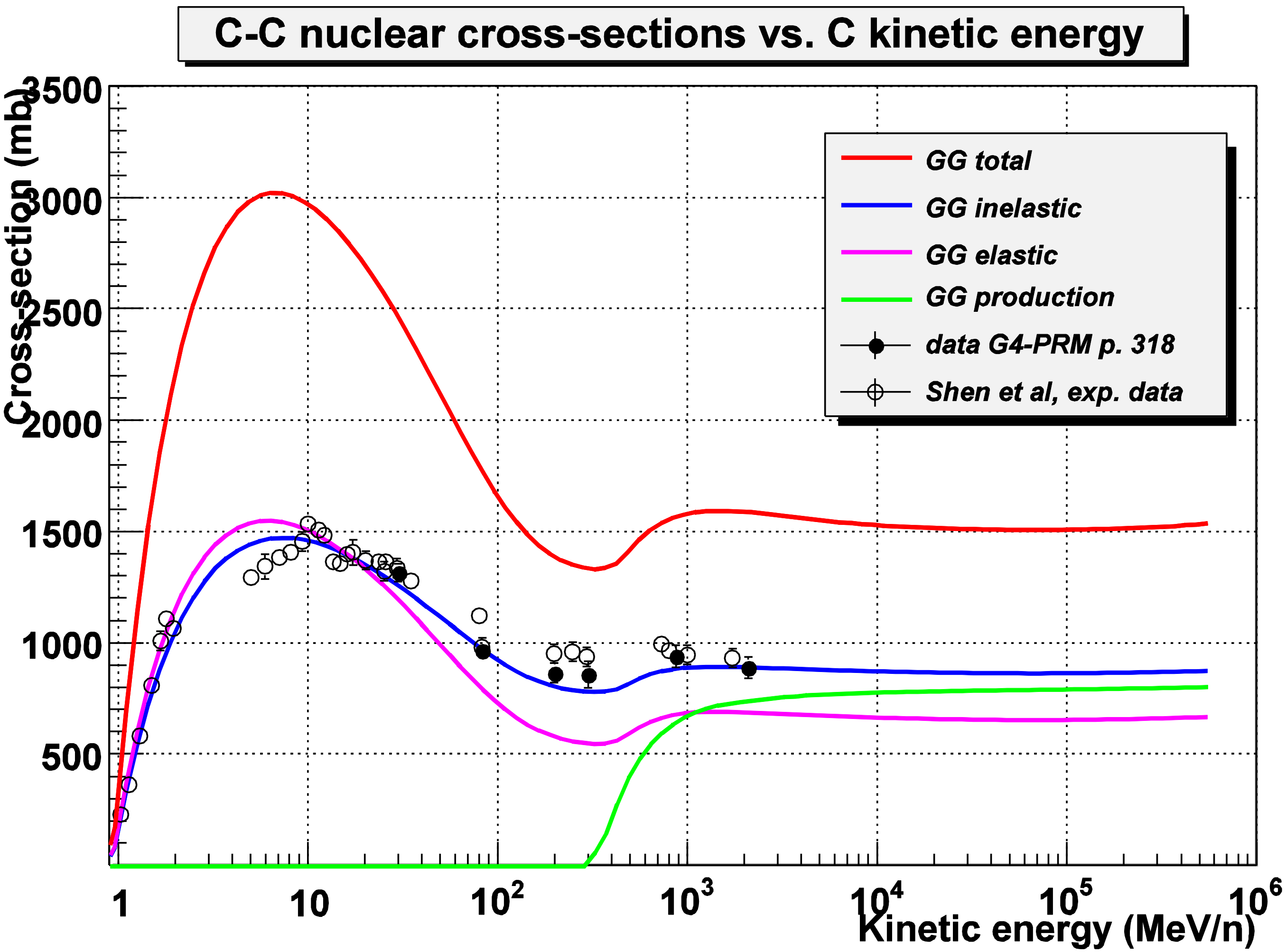
pi- beam on Fe G4 9.3.b01 pi+
E_tot / E_tot_beam
pi+ LEP
pi+ BERT
pi+ BIC
pi+ QGS/Preco
pi+ QGS/Chips
pi+ FTF/Preco
pi+ QGS/Bic
pi+ FTF/Bic
pi+ CHIPS
0.3
0.25
0.2
0.15
0.1
0.05
0
5
10
15
20
E_kin_beam (GeV)
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
E_kin_beam (GeV)

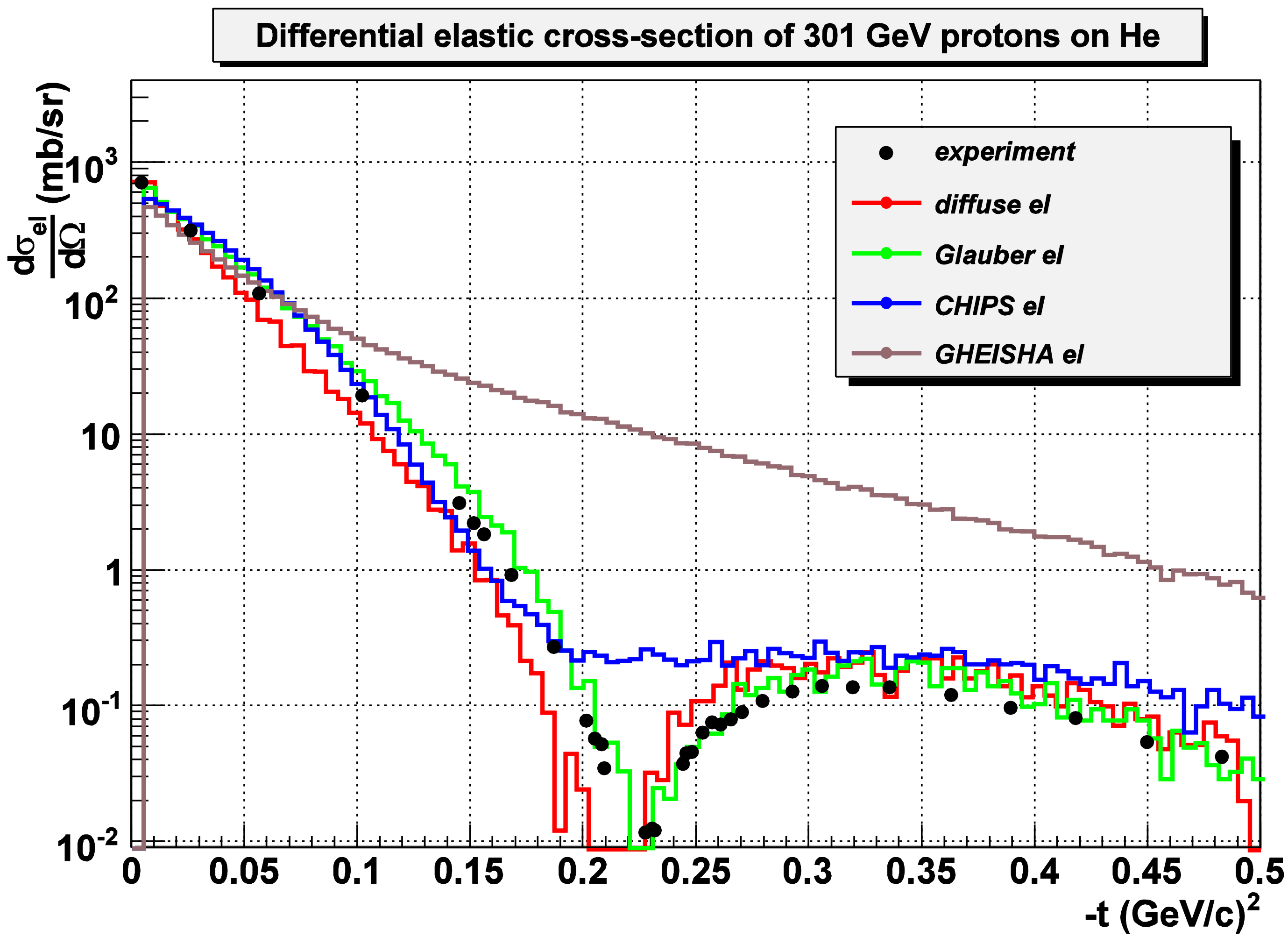


pi- beam on Fe G4 9.3.b01 pi-
E_tot / E_tot_beam
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
E_kin_beam (GeV)
pi- LEP
pi- BERT
pi- BIC
pi- QGS/Preco
pi- QGS/Chips
pi- FTF/Preco
pi- QGS/Bic
pi- FTF/Bic
pi- CHIPS
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
E_kin_beam (GeV)

Too much energy into protons for Cascade models (BERT, BIC) for $E_{kin} \geq 5GeV$

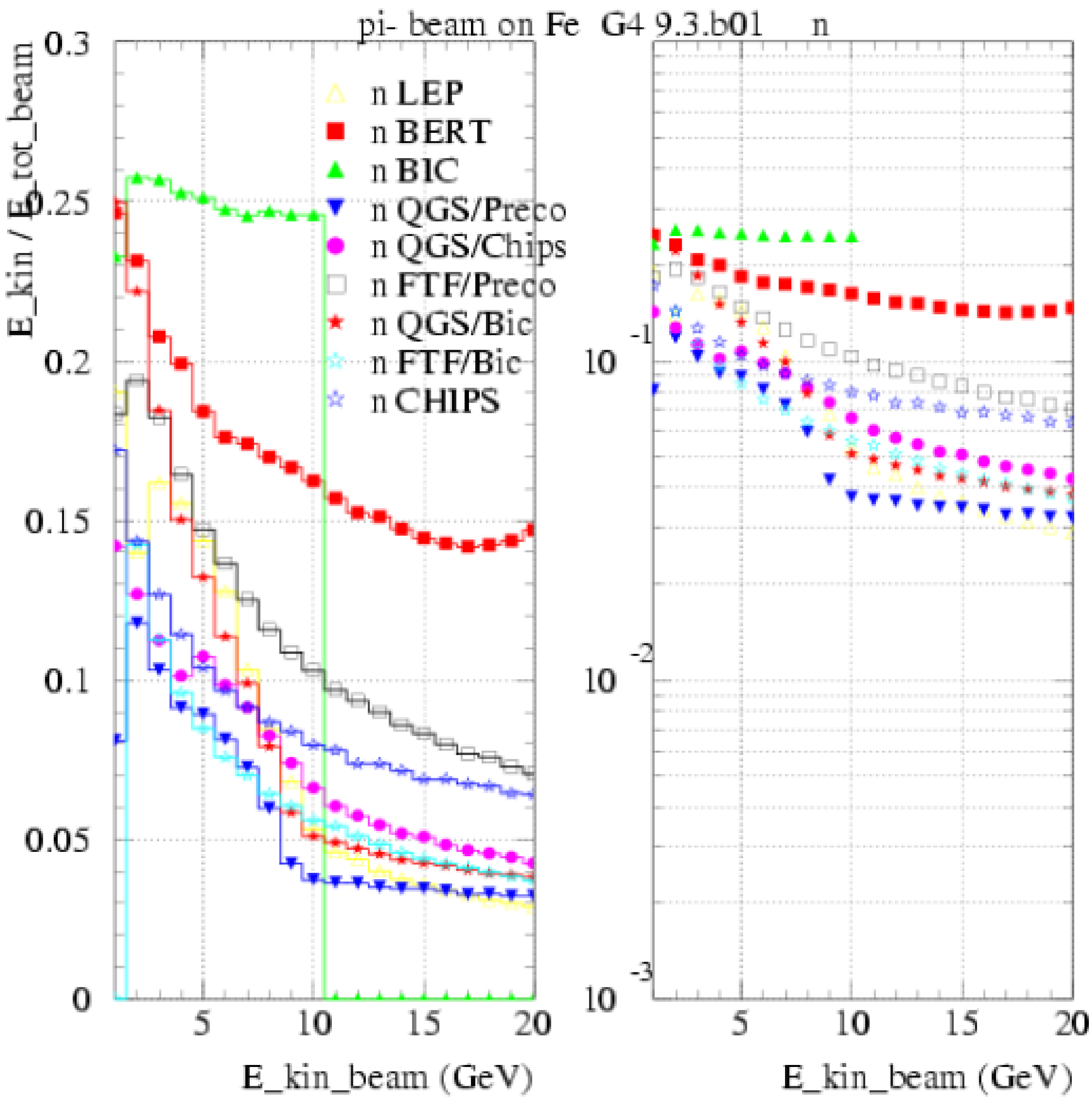


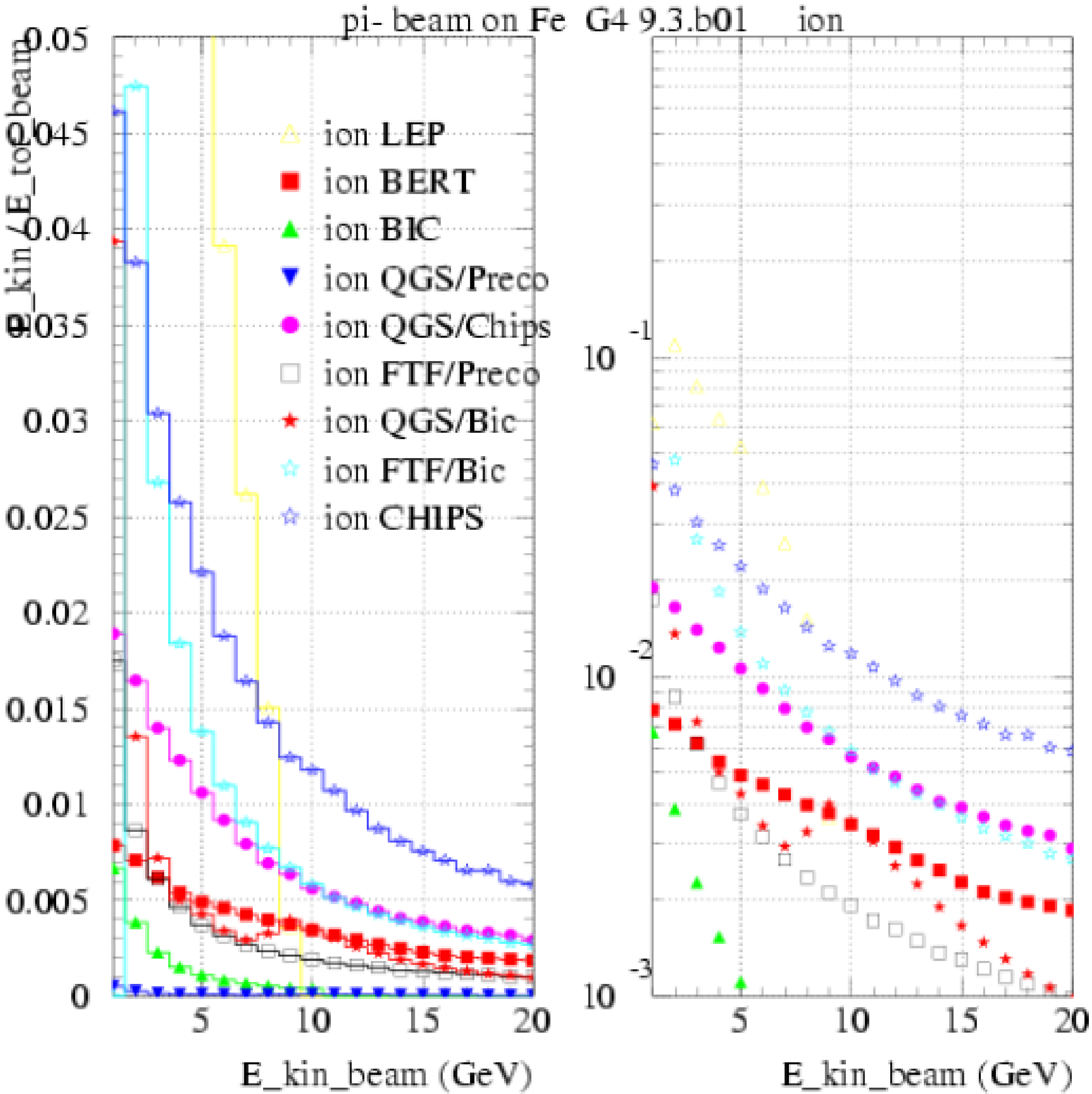

C-C nuclear cross-sections vs. C kinetic energy
Cross-section (mb)
3500
3000
2500
2000
1500
1000
500
1
10
10^2
10^3
10^4
10^5
10^6
Kinetic energy (MeV/n)
GG total
GG inelastic
GG elastic
GG production
data G4-PRM p. 318
Shen et al, exp. data



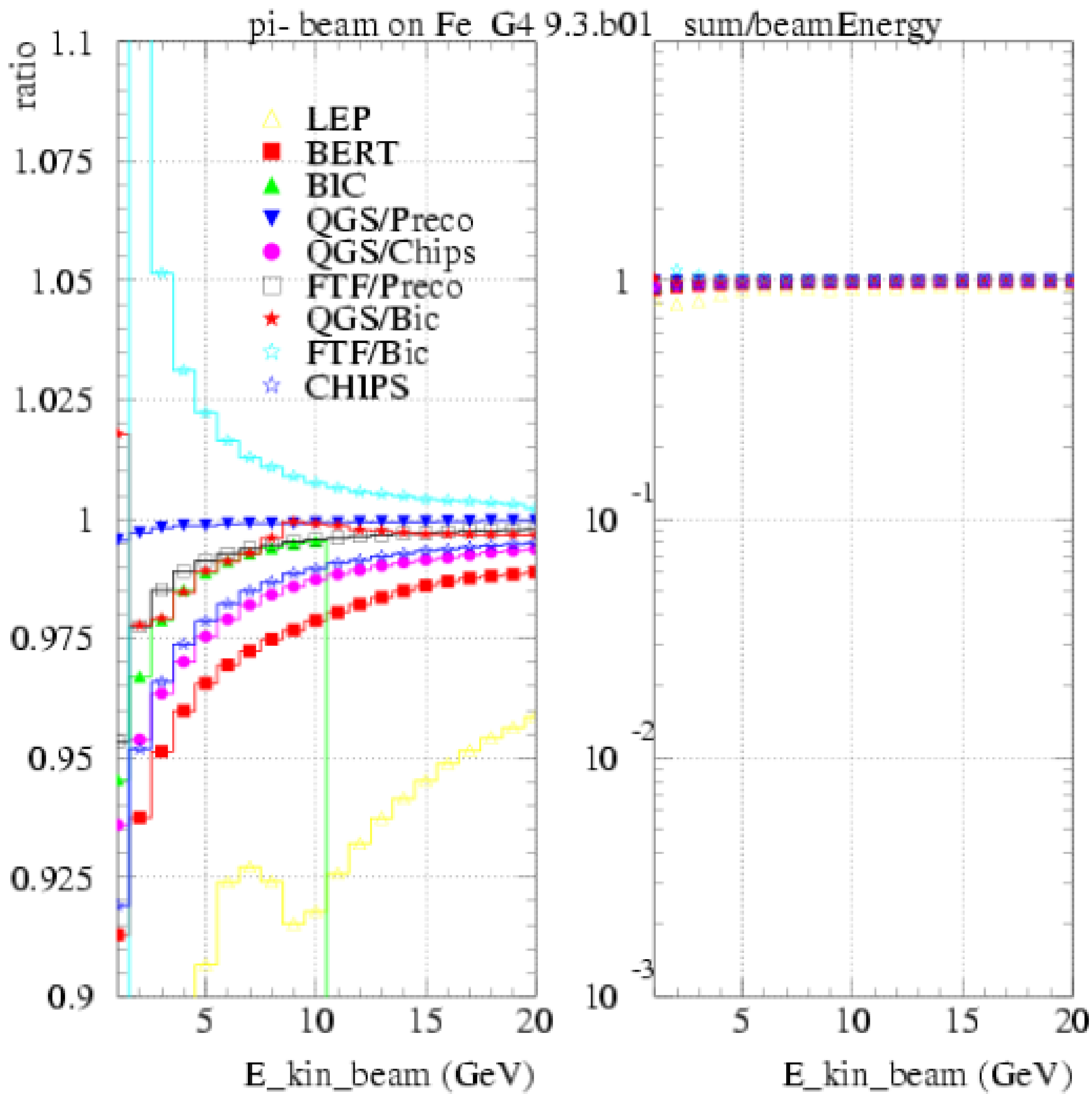
Differential elastic cross-section of 301 GeV protons on He
dσ_el/dΩ (mb/sr)
10^3
10^2
10
1
10^-1
10^-2
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
-t (GeV/c)^2
experiment
diffuse el
Glauber el
CHIPS el
GHEISHA el

Too much energy into neutrons for Cascade models (BERT, BIC) at all beam energies

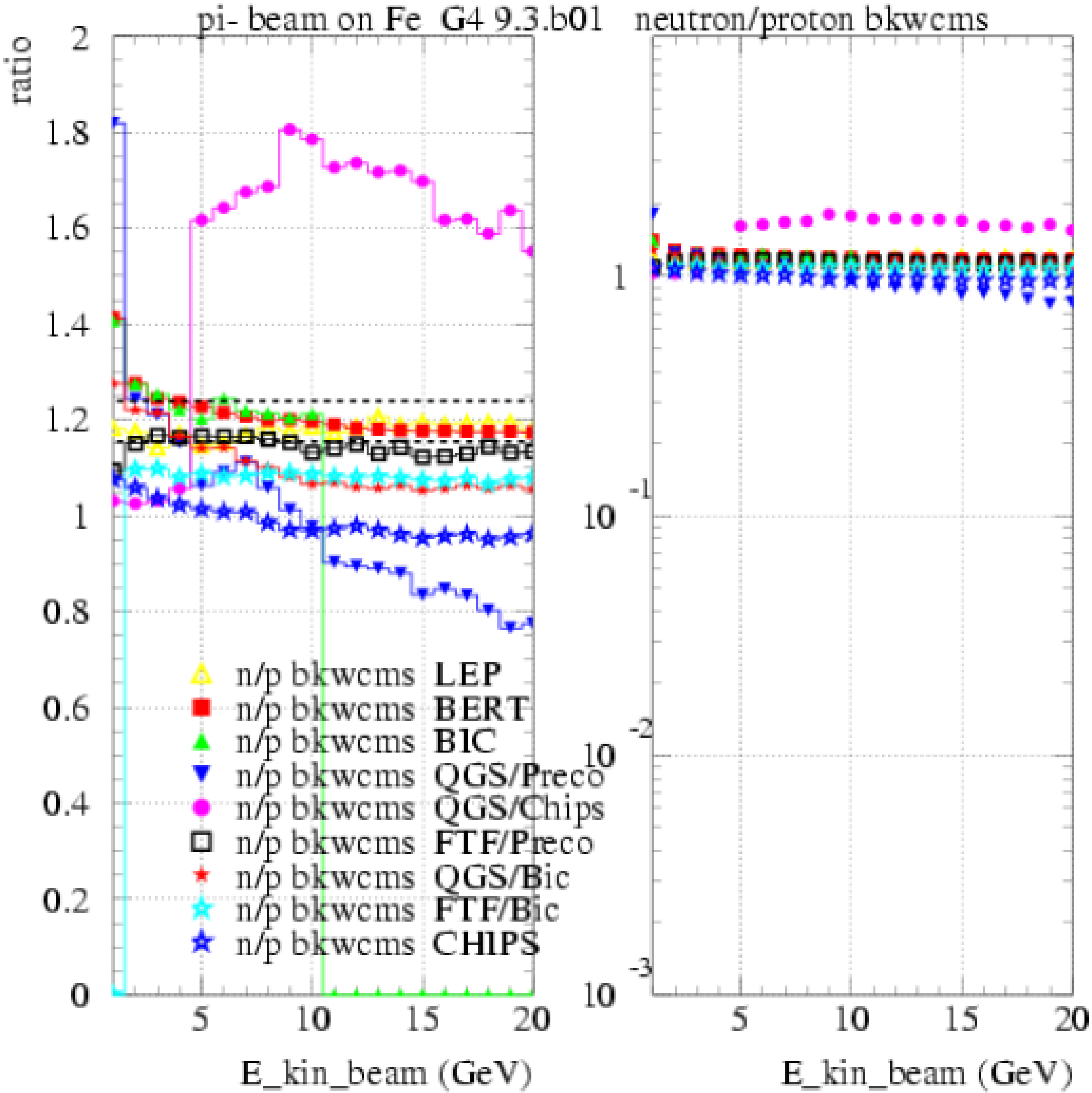




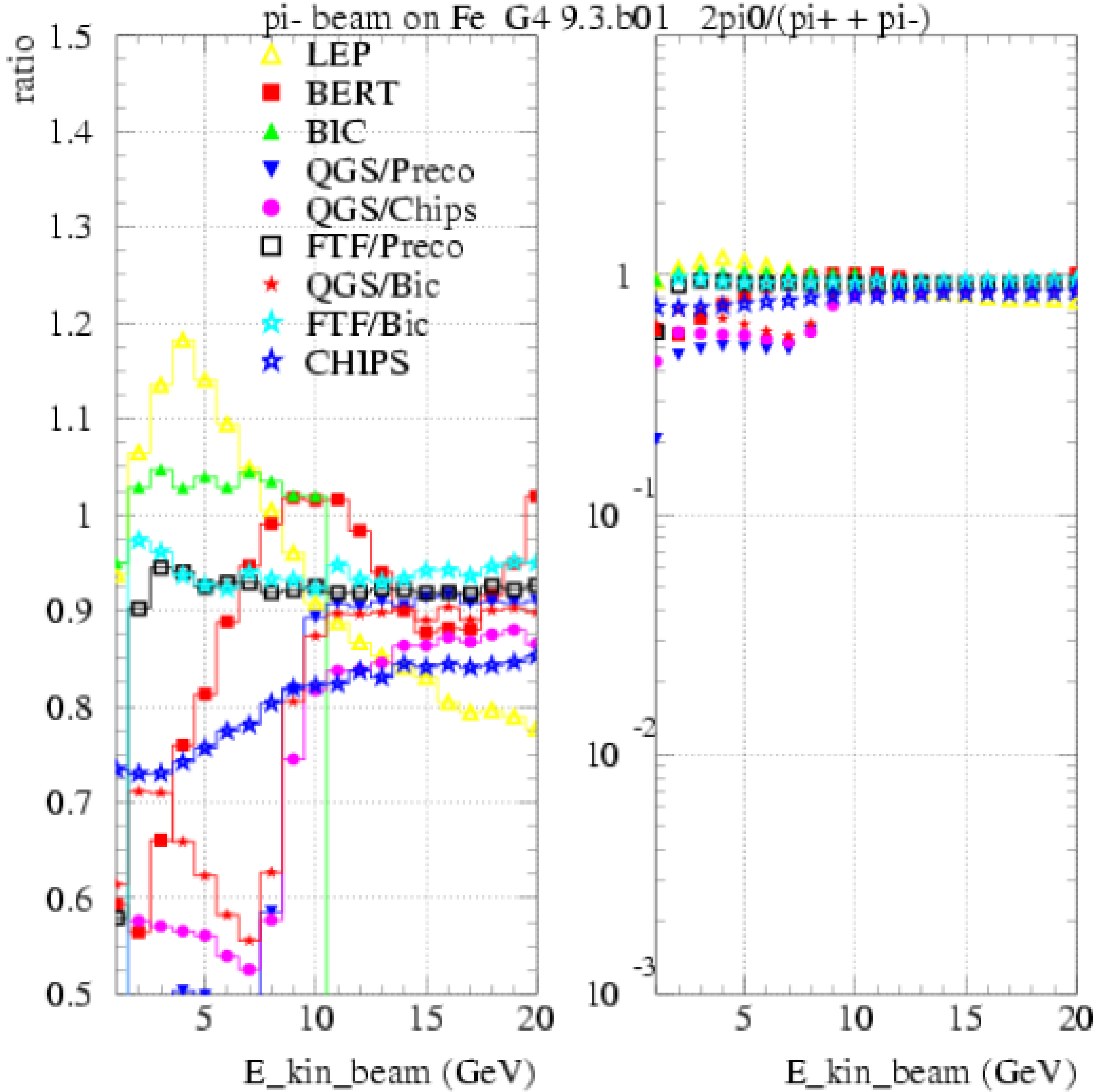
pi- beam on Fe G4 9.3.b01 ion
E_kin / E_tot beam
ion LEP
ion BERT
ion BIC
ion QGS/Preco
ion QGS/Chips
ion FTF/Preco
ion QGS/Bic
ion FTF/Bic
ion CHIPS
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
5
10
15
20
E_kin_beam (GeV)
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
E_kin_beam (GeV)

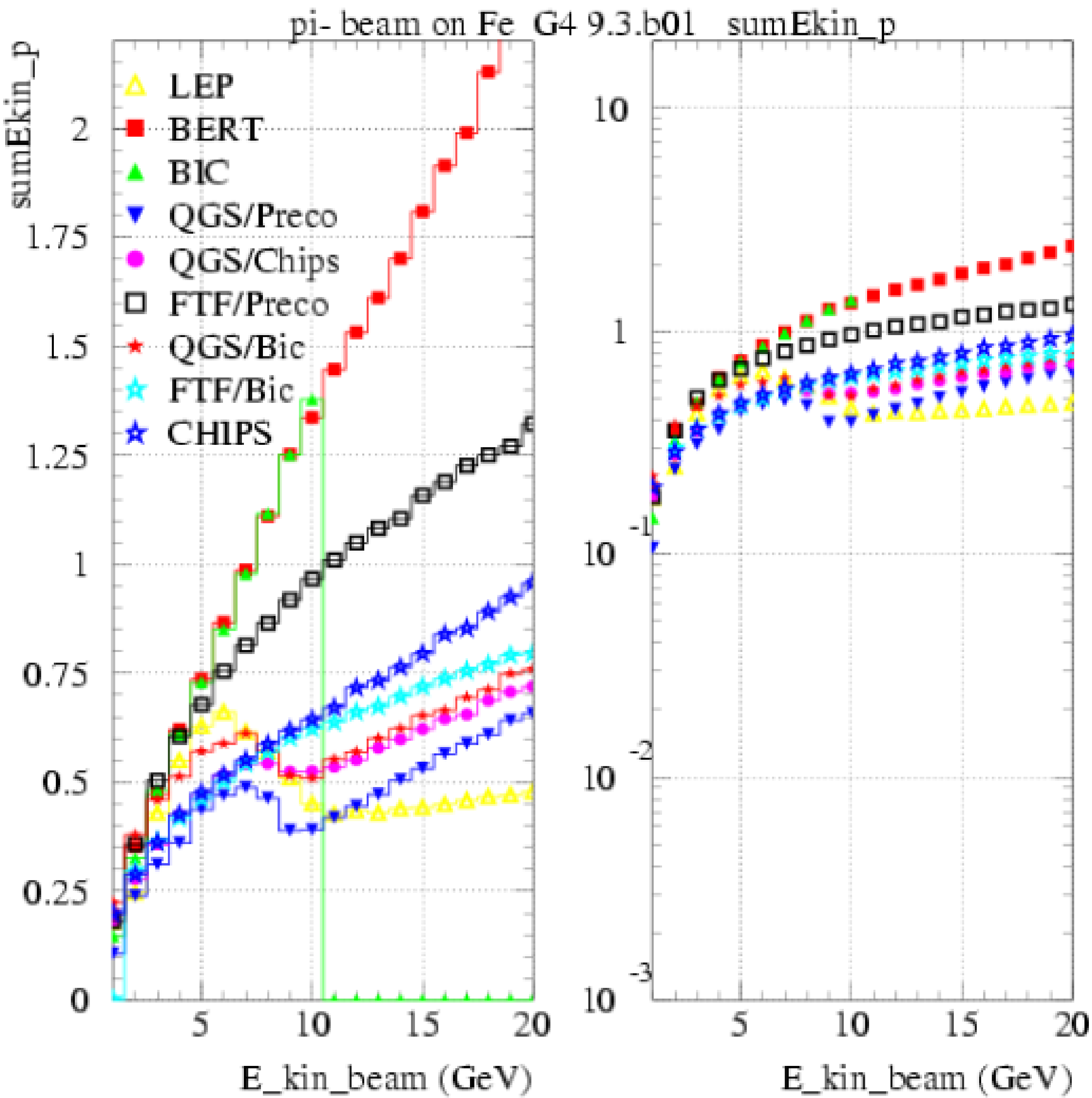


pi- beam on Fe G4 9.3.b01 sum/beamEnergy
ratio
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS
1.1
1.075
1.05
1.025
1
0.975
0.95
0.925
0.9
5
10
15
20
E_kin_beam (GeV)
1
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
E_kin_beam (GeV)

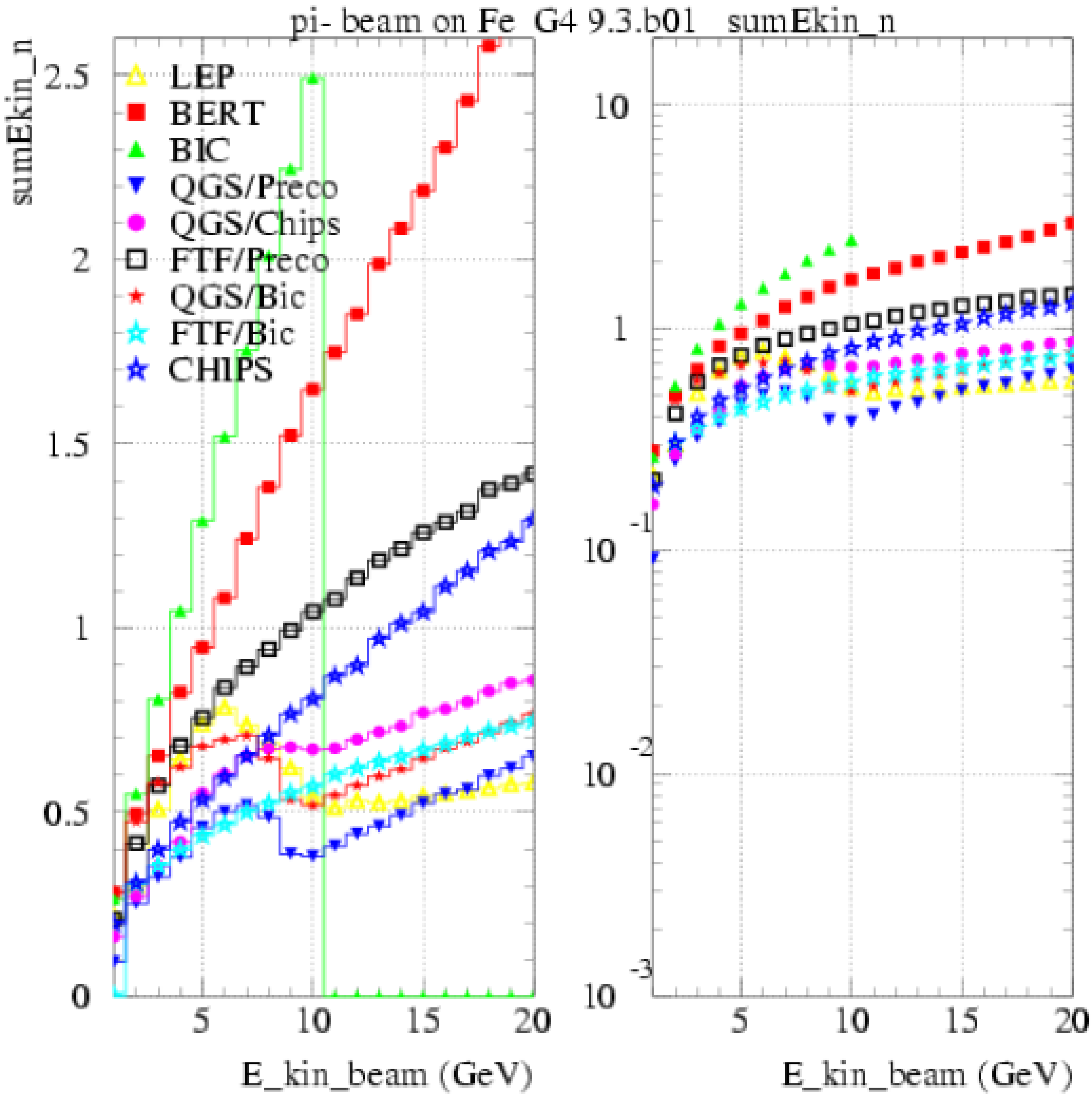


pi- beam on Fe G4 9.3.b01 neutron/proton bkwcms
ratio
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5
10
15
20
E_kin_beam (GeV)
n/p bkwcms LEP
n/p bkwcms BERT
n/p bkwcms BIC
n/p bkwcms QGS/Preco
n/p bkwcms QGS/Chips
n/p bkwcms FTF/Preco
n/p bkwcms QGS/Bic
n/p bkwcms FTF/Bic
n/p bkwcms CHIPS
1
10^-1
10^-2
10^-3
5
10
15
20
E_kin_beam (GeV)


pi- beam on Fe G4 9.3.b01 2pi0/(pi+ + pi-)
ratio
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
5
10
15
20
E_kin_beam (GeV)
1
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
E_kin_beam (GeV)

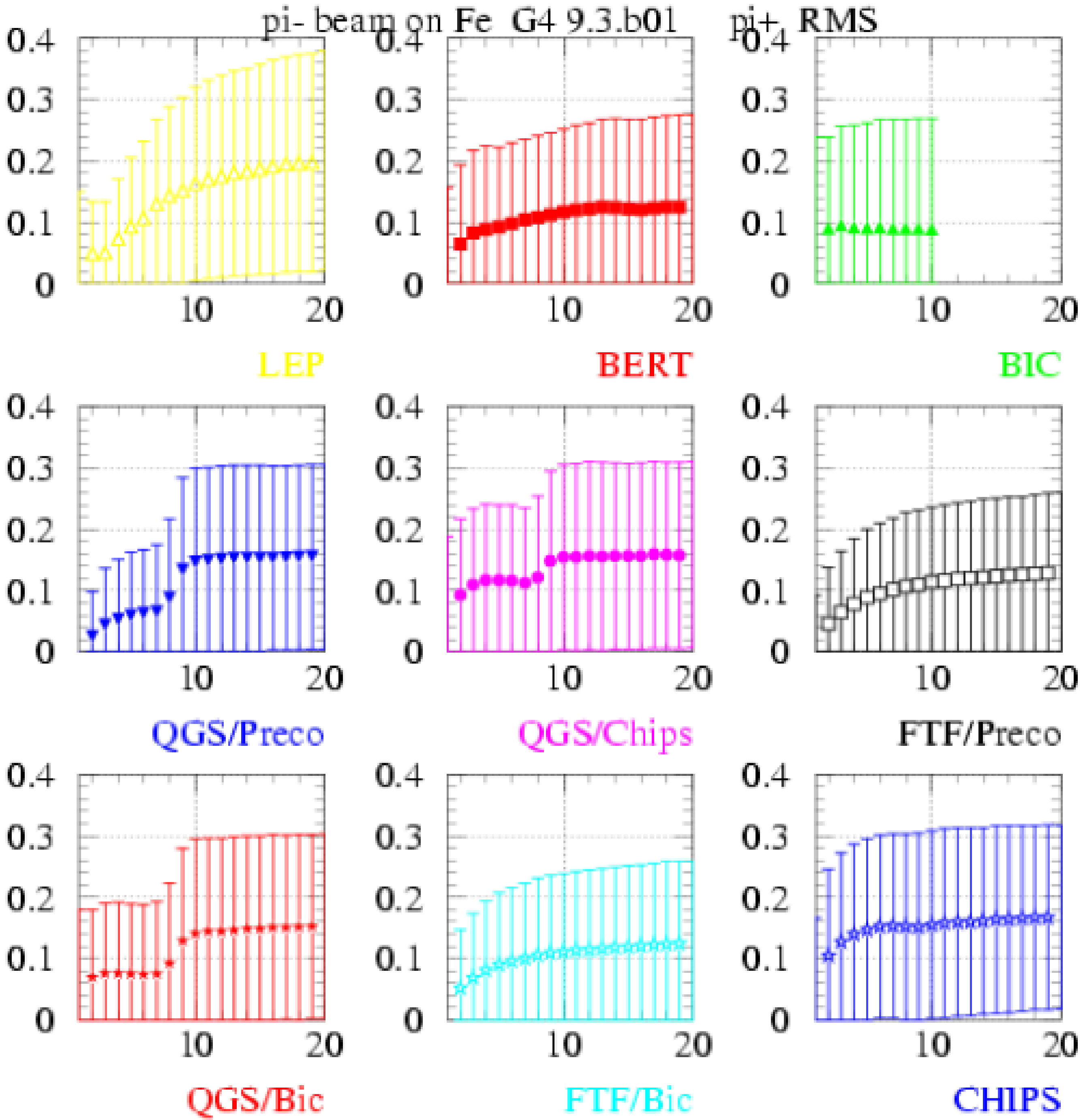


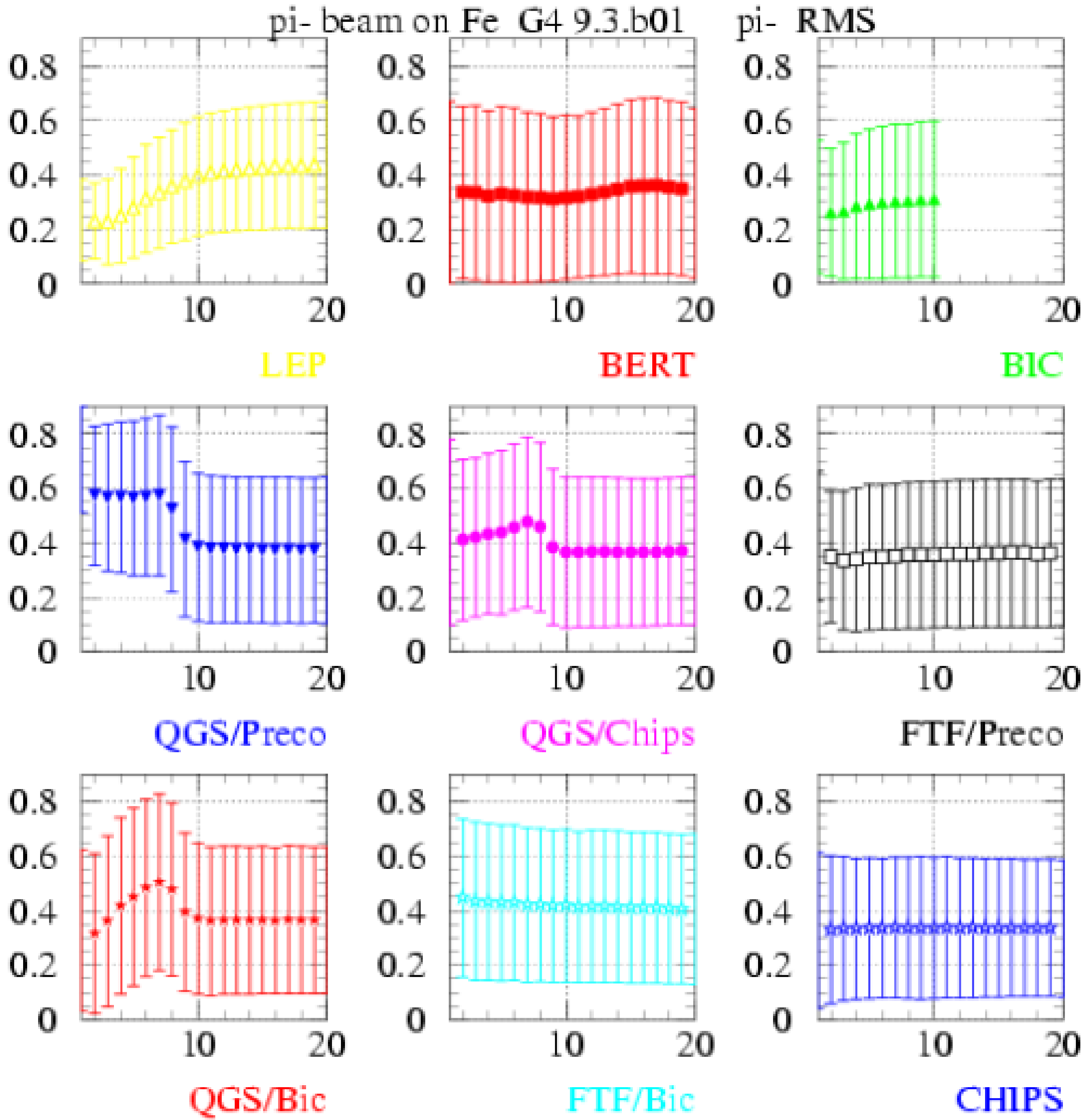
pi- beam on Fe G4 9.3.b01 sumEkin_p
sumEkin_p
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS
E_kin_beam (GeV)
E_kin_beam (GeV)

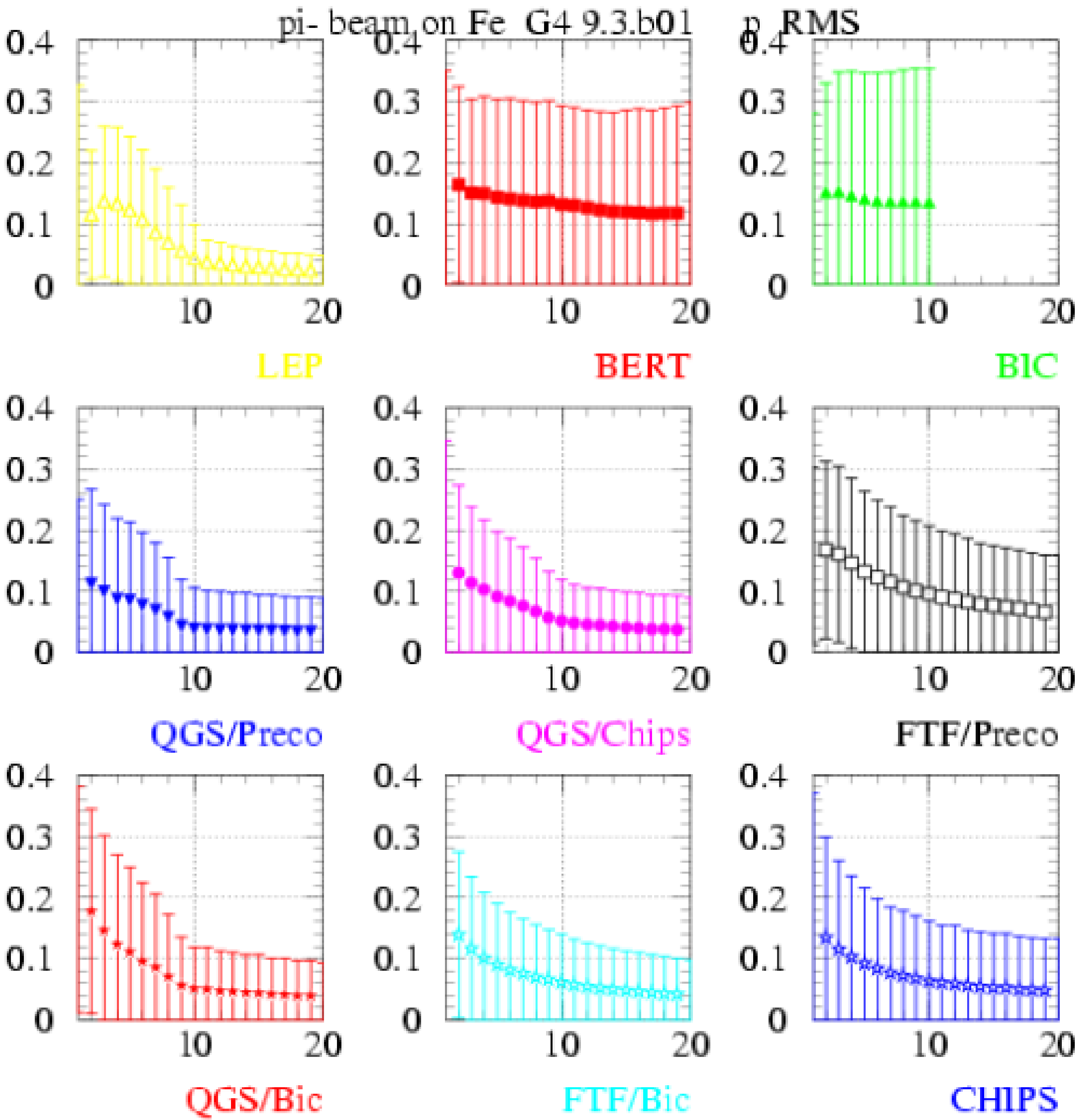

pi- beam on Fe G4 9.3.b01 sumEkin_n
sumEkin_n
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS
E_kin_beam (GeV)
E_kin_beam (GeV)

Model-level results

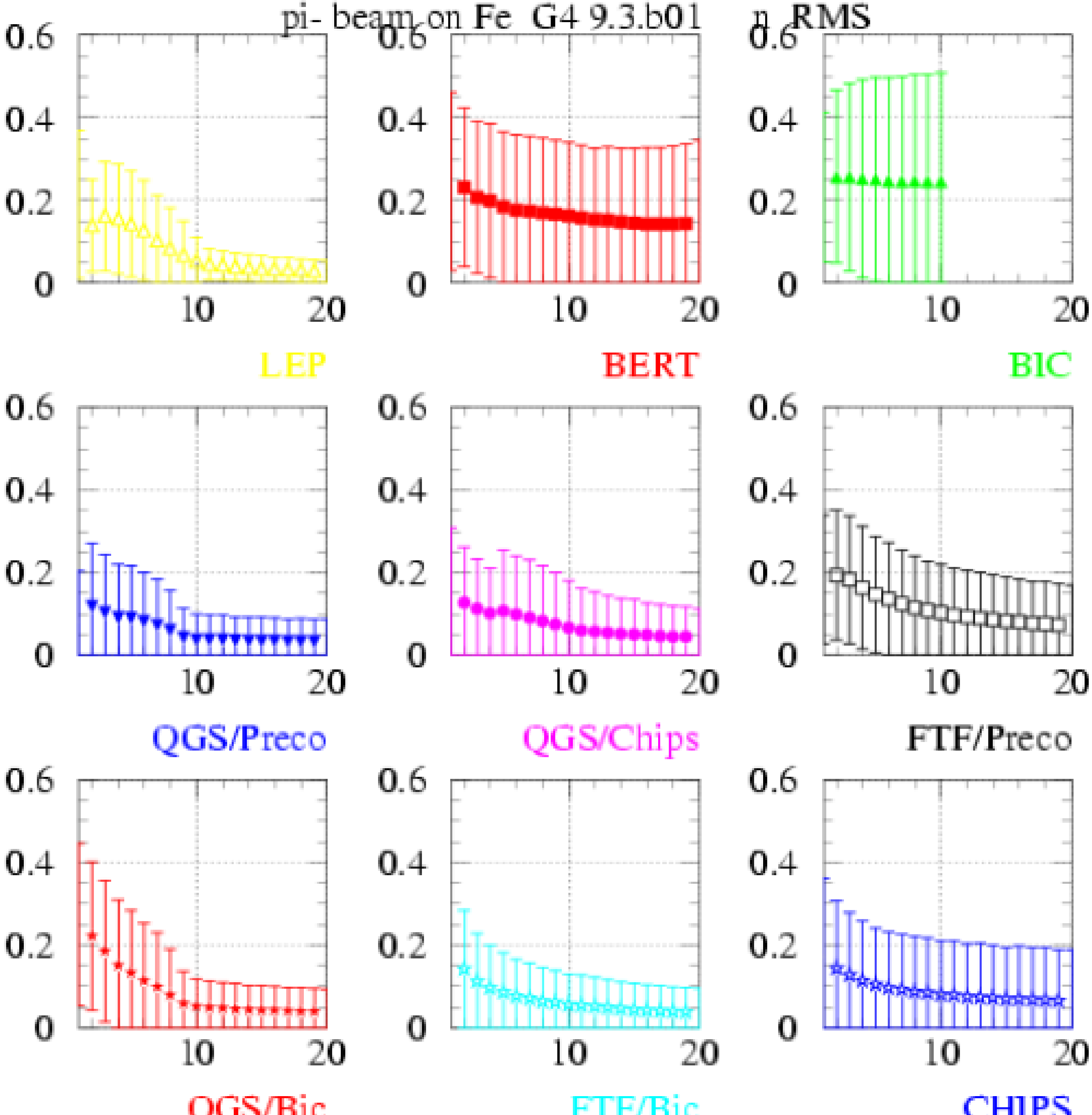
- Geant4 9.3.b01
- Beam particle: **pi-** (p, n, k, pbar)
  beam kinetic energies: **1 - 20 GeV**
  target material: **Iron** (Pb)
- Model-level only (not Physics Lists)
- 50,000 events (i.e. interactions) simulated for each considered case
- Main variables considered:
  - Average sum of total energies of **pi-** , **pi+** , **pi0**
  - Average sum of kinetic energies of **p** , **n** , light **ions** (d,t,He)
  - Average total energy
  - Ratios: n/p (backward-going), 2*pi0/(pi+ + pi-)
  - RMS of the above variables


pi- beam on Fe G4 9.3.b01 pi+ RMS
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS

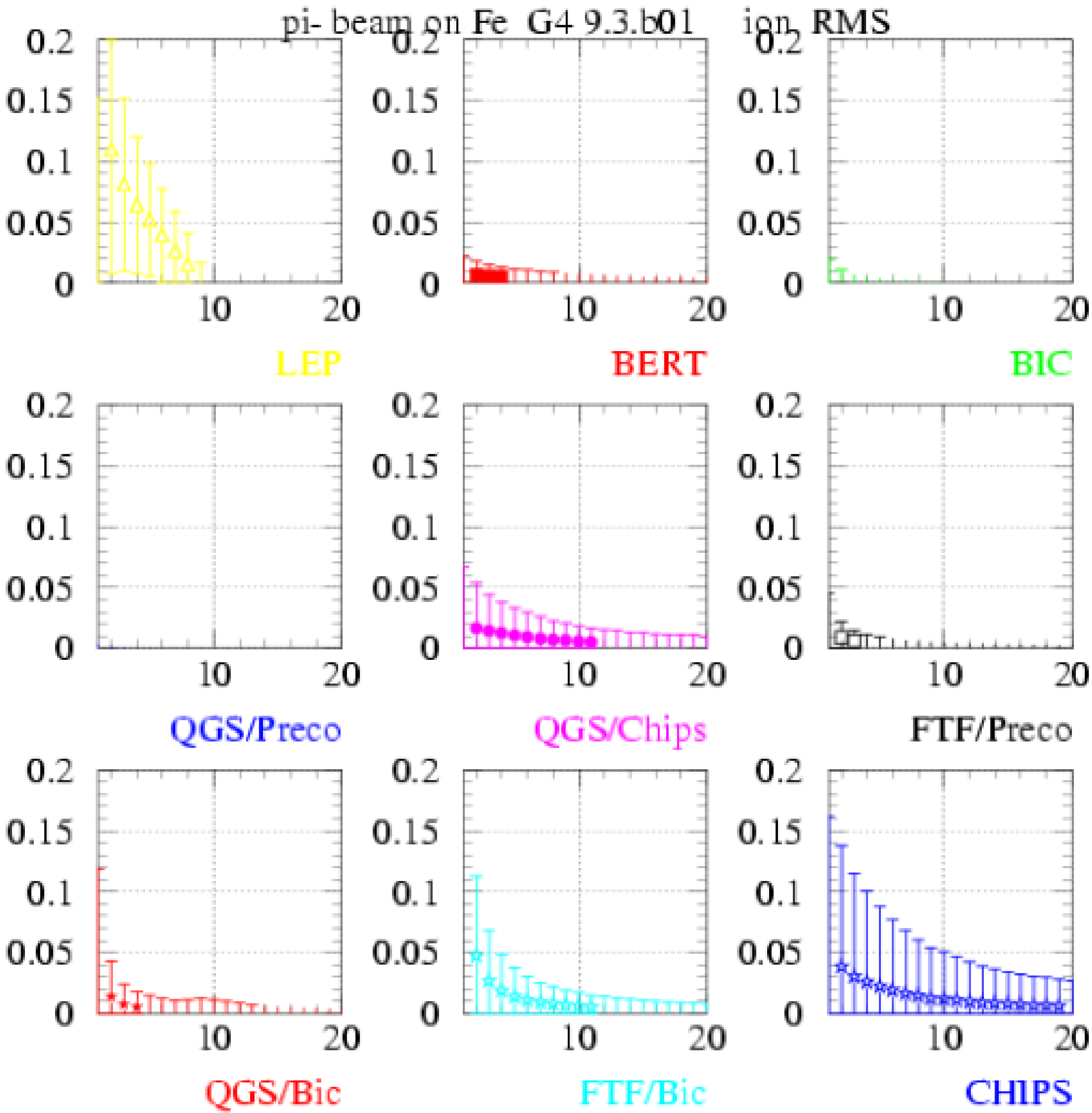

pi- beam on Fe G4 9.3.b01 pi- RMS
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS

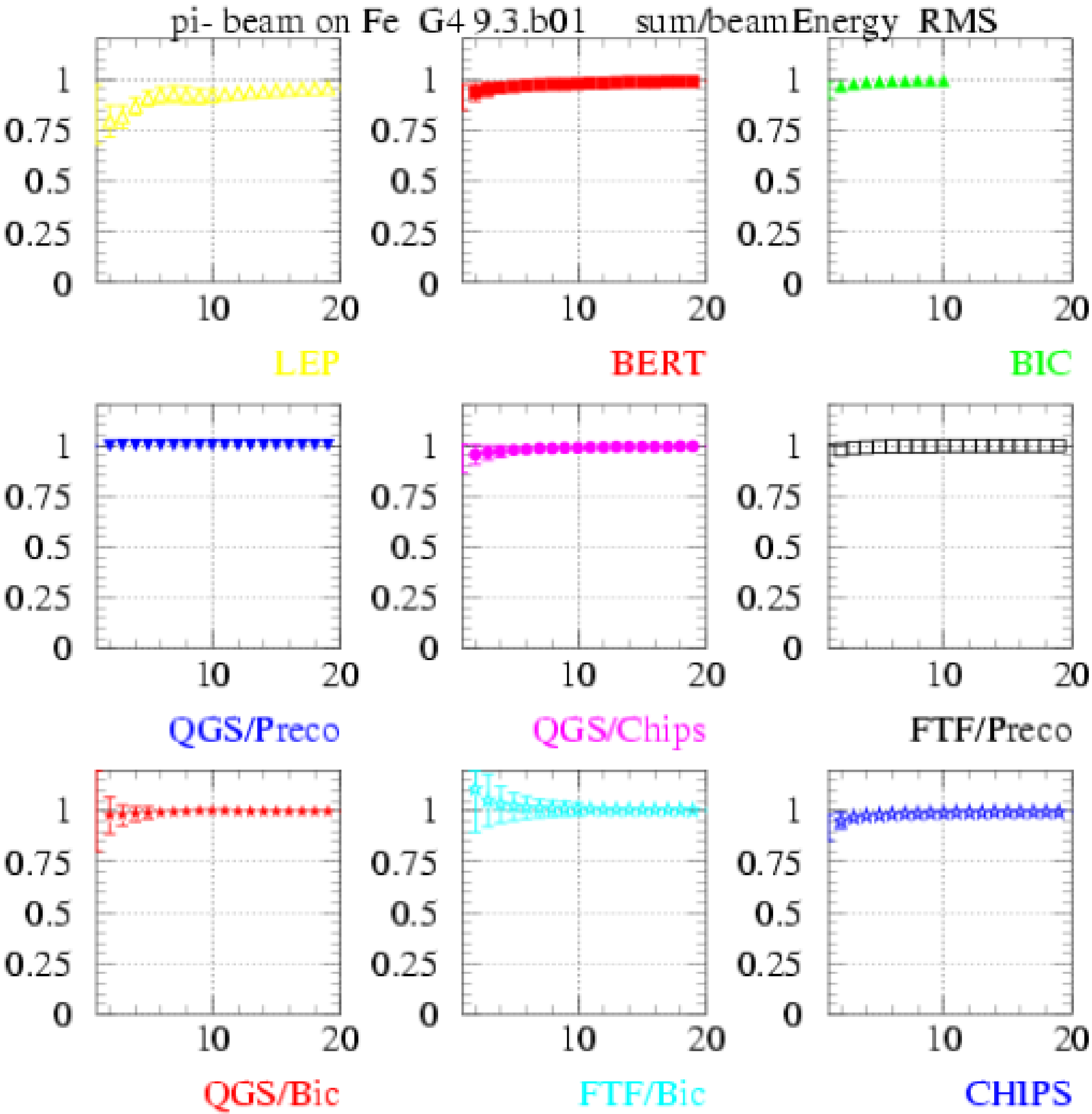


pi- beam on Fe G4 9.3.b01 p RMS
0.4
0.3
0.2
0.1
0
10
20
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS



pi- beam on Fe G4 9.3.b01 n RMS
0.6
0.4
0.2
0
10
20
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS


pi- beam on Fe G4 9.3.b01 ion RMS
0.2
0.15
0.1
0.05
0
10
20
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS


pi- beam on Fe G4 9.3.b01 sum/beamEnergy RMS
LEP
BERT
BIC
QGS/Preco
QGS/Chips
FTF/Preco
QGS/Bic
FTF/Bic
CHIPS
0
0.25
0.5
0.75
1
10
20