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Anti-proton annihilation at rest with Fritiof (FTF) in Geant4

Alberto Ribon
CERN PH/SFT

Goal

- CHIPS is used in all Geant4 physics lists (except LHEP) for nuclear capture at rest of negatively charged hadrons:
  π^- , K^- , $\underline{p}$, Σ^-, $\underline{\Sigma}^+$, Ξ^- , Ω^-

- A recent extension of Fritiof (FTF) model + Preco, in Geant4, provides nuclear interactions of anti-baryons:
  $\underline{n}$, $\underline{p}$, $\underline{\Lambda}^\circ$, $\underline{\Sigma}^+$, $\underline{\Sigma}^\circ$, $\underline{\Sigma}^-$, $\underline{\Xi}^-$, $\underline{\Xi}^\circ$, $\underline{\Omega}^-$
  valid from 0 up to TeV

- So the idea is to replace, in at least one physics list, CHIPS with FTF/Preco for anti-proton annihilation at rest

- The expected impact on LHC physics is negligible, but other experiments (e.g. AEgIS) could potentially benefit...

How?

- Created a new "**at rest**" process where FTF/Preco is used for anti-proton annihilation at rest

- Used such new process in a physics list: **FTFP_BERT_TRV**
  For the rest of captures (pi-, K-, etc.) keep using CHIPS

- New class: **G4QandFTFStoppingPhysics**
  which is almost identical to G4QStoppingPhysics , except:

```
hFTFProcess = new G4FTFCaptureAtRest();
...
if ( particle == G4AntiProton::AntiProton() ) {
  pmanager->AddRestProcess( hFTFProcess );
}
```

G4FTFCaptureAtRest

- A new class in **processes/hadronic/stopping**
  that uses FTF/Preco annihilation at rest for antiproton:
  G4FTFAnnihilation::Annihilate

- To use it, we have to go through the model interface:
  theModel->ApplyYourself(projectile, *targetNucleus);
  where

```
theModel = new G4TheoFSGenerator( "FTFP" );
theStringModel = new G4FTFModel;
theStringDecay = new G4ExcitedStringDecay( new G4LundStringFragmentation );
theStringModel->SetFragmentationModel( theStringDecay );
theCascade = new G4GeneratorPrecompoundInterface;
thePreEquilib = new G4PreCompoundModel( new G4ExcitationHandler )
theCascade->SetDeExcitation( thePreEquilib );
theModel->SetHighEnergyGenerator( theStringModel );
theModel->SetTransport( theCascade );
```

Some comments

- Now ***stopping*** depends on ***hadronic/models/parton_string***
- There is some code repetition
  - Creation/setting of the string model
  - Conversion of the final result
    - from ***G4HadFinalState*** to ***G4ParticleChange***
- This can be improved, e.g. deriving from *G4HadronicInteraction* and with *G4HadronicProcess* to be derived from *G4VRestDiscreteProcess*
- Stable
  - run several tens of thousands anti-proton annihilations in different materials
- Momentum is conserved
- Energy is sometimes violated O(10 MeV)
  - investigation is going on to understand and fix the problem (I guess it is related to how the binding energy is estimated...)

Comparing anti-proton annihilation at rest in Geant4: LEP, CHIPS, FTF/Preco

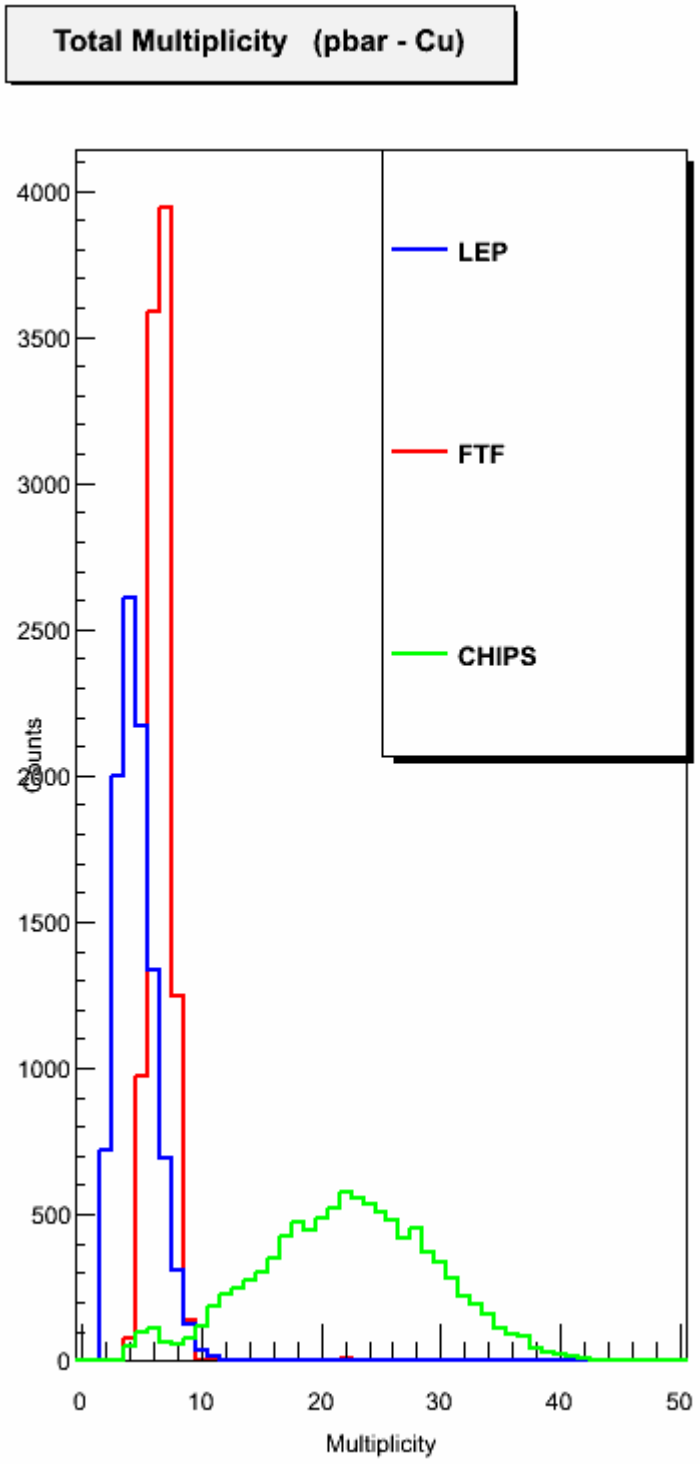
- 3 processes at rest available for anti-proton annihilation:
  - G4AntiProtonAnnihilationAtRest (LEP)
  - G4QCaptureAtRest (CHIPS)
  - G4FTFCaptureAtRest (FTF/Preco)

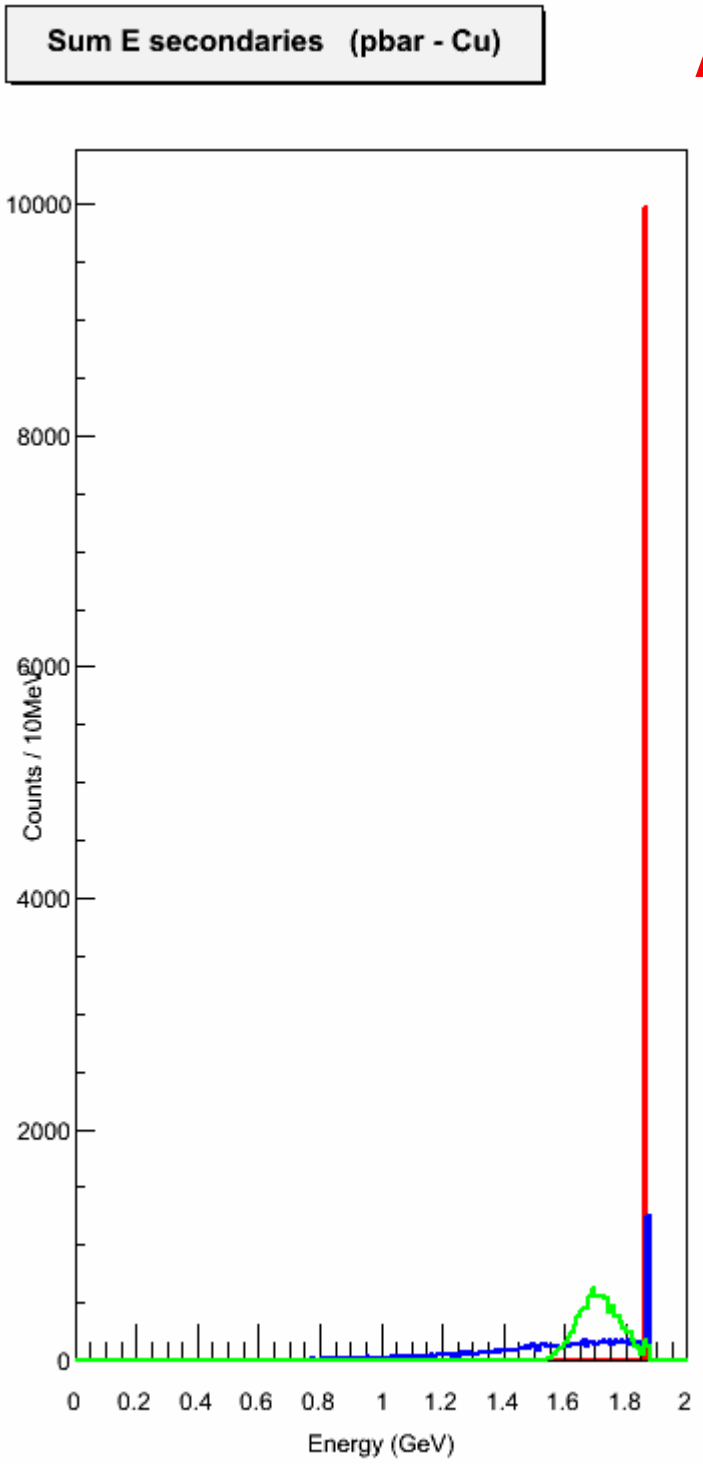
- G4 version: 9.4.ref09 (+ few tags for FTF)
- 10,000 anti-proton annihilation at rest on Copper

- Compare multiplicity and energy (kinetic or total) spectra for the secondaries produced:
  - all
  - gamma, pion-, pion-, pion0, kaons : E_tot
  - neutron, proton, light ion (d,t,3He,alpha): E_kin
  - others (mainly the residual nucleus): E_kin

- Note: no real data, only simulation!
  - Nevertheless, I am trying to make some comments based on what I would reasonably expect...

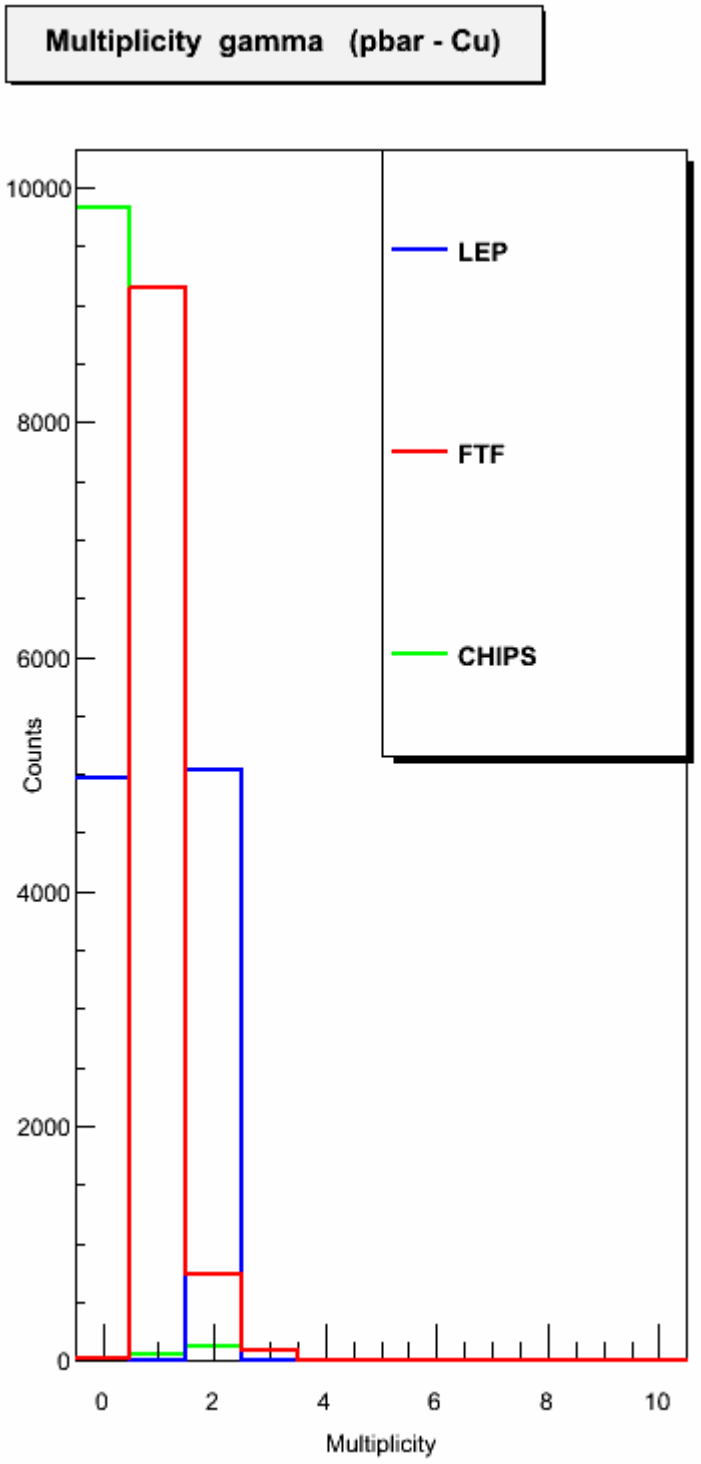
All secondaries

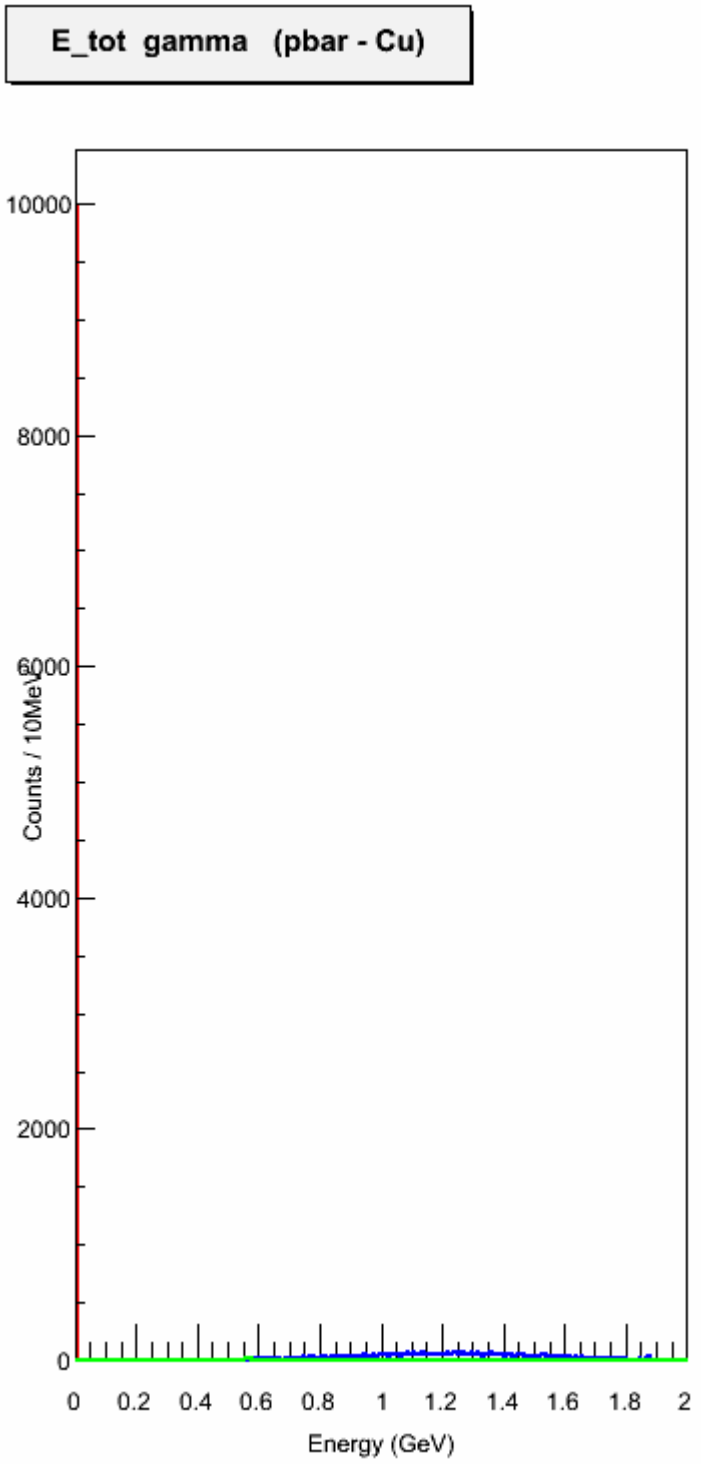




Very little fluctuation of the final-state energy in FTF

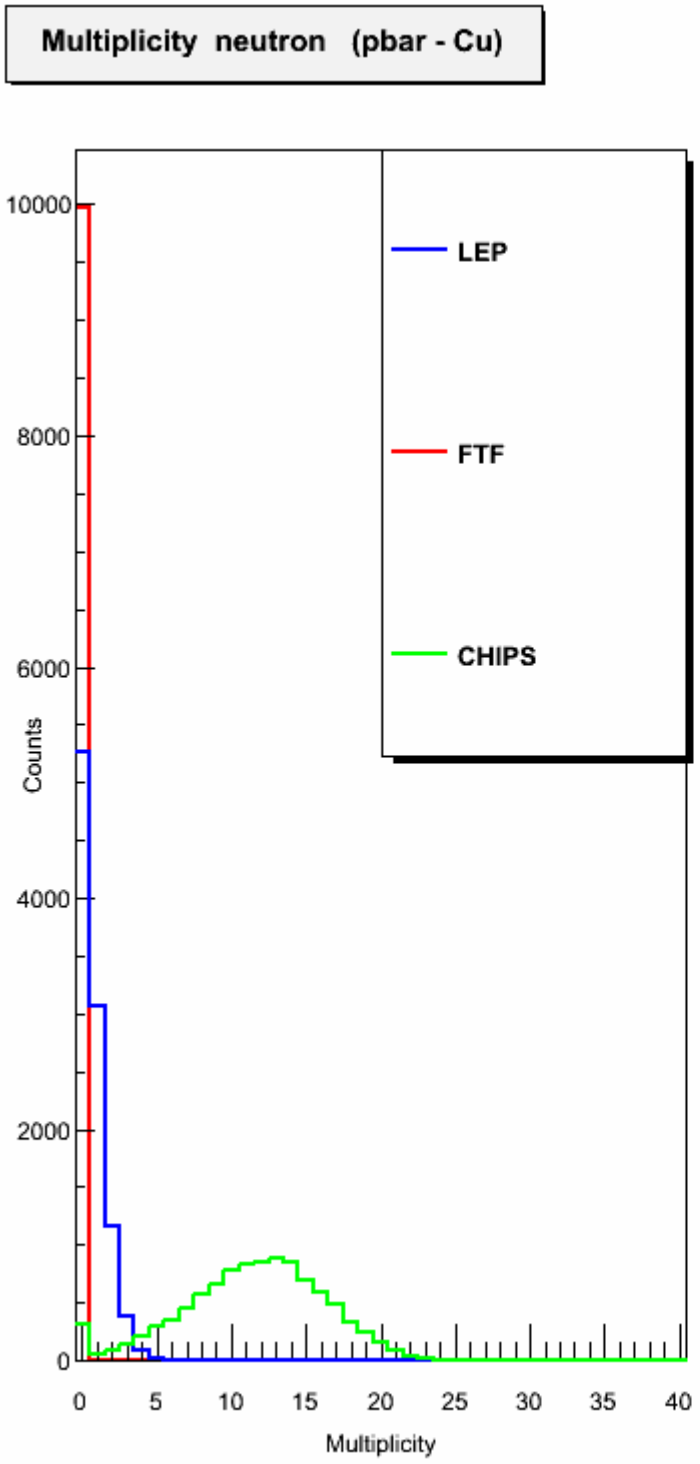
Gammas

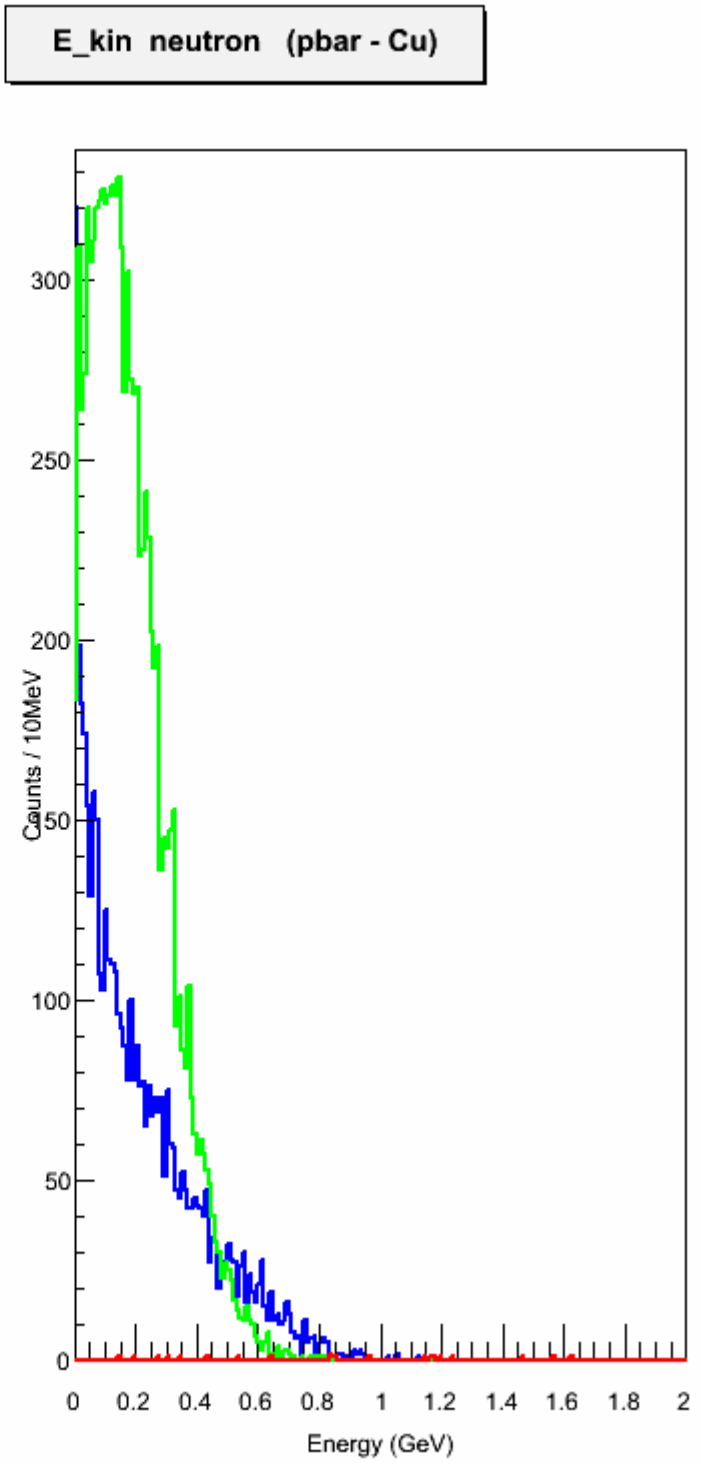




FTF/Preco produces almost always ~1 MeV gammas

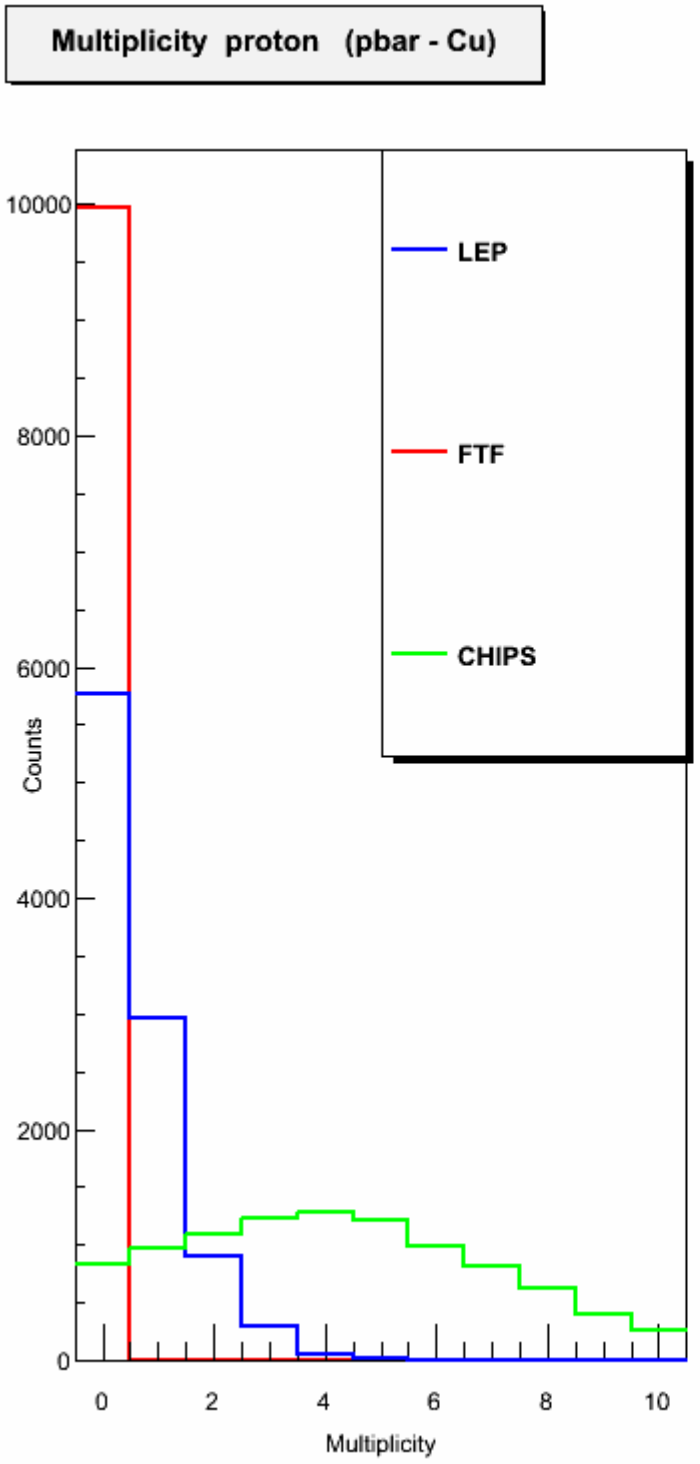
Neutrons

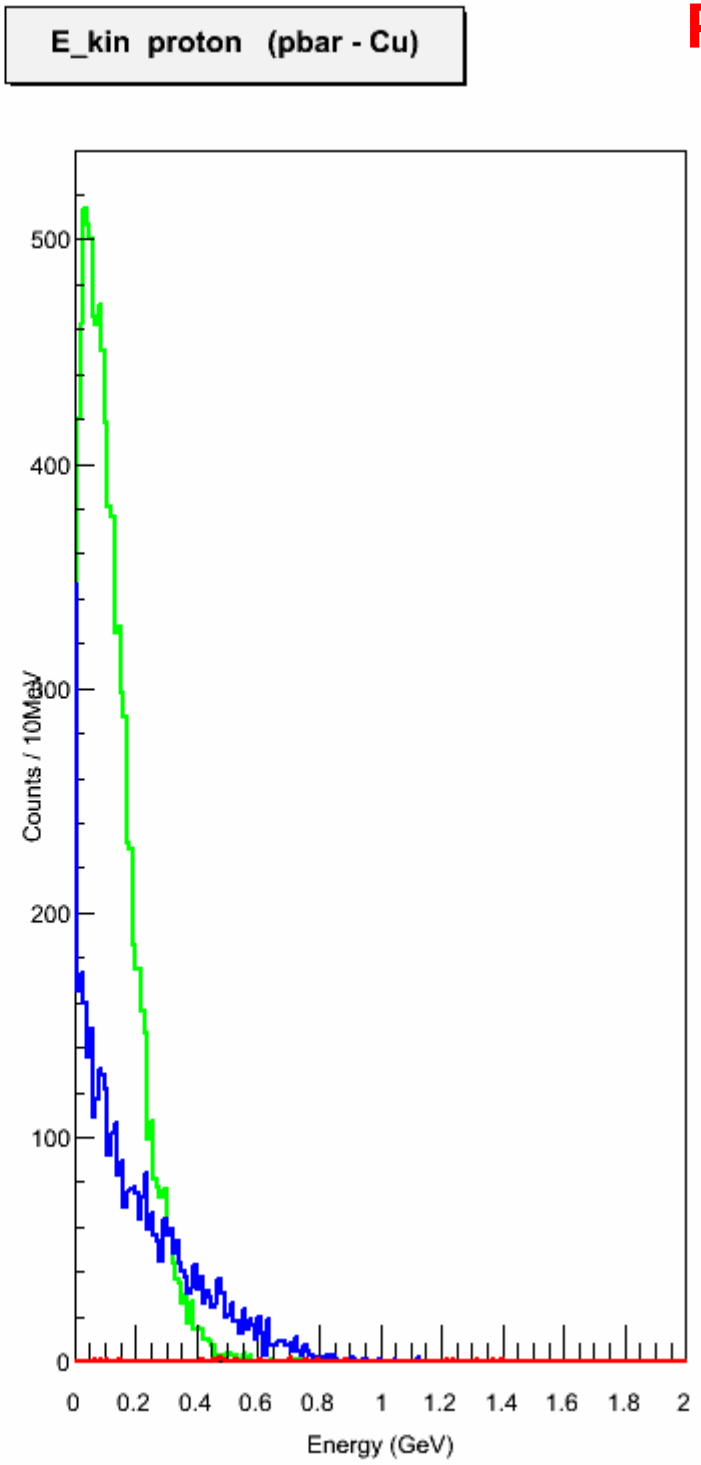




Neutrons are produced rarely by FTF/Preco

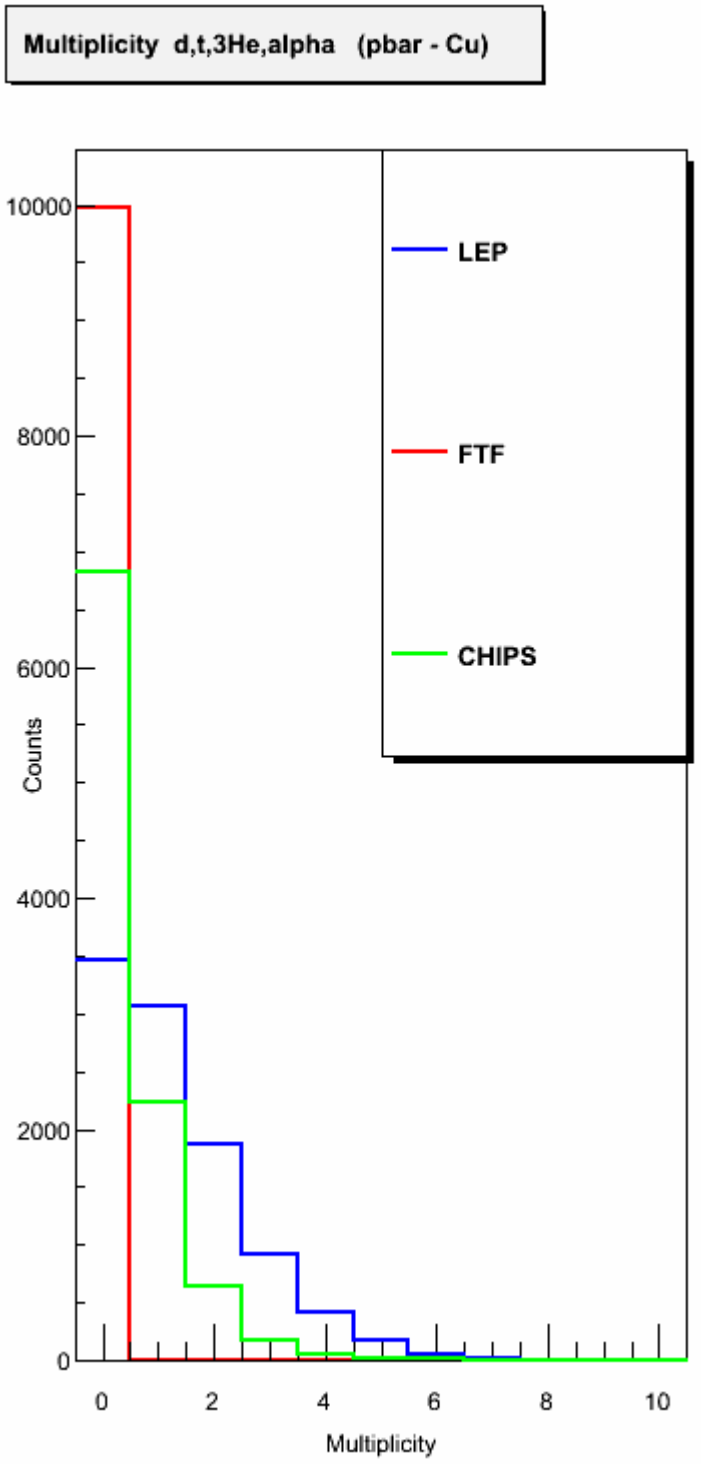
Protons

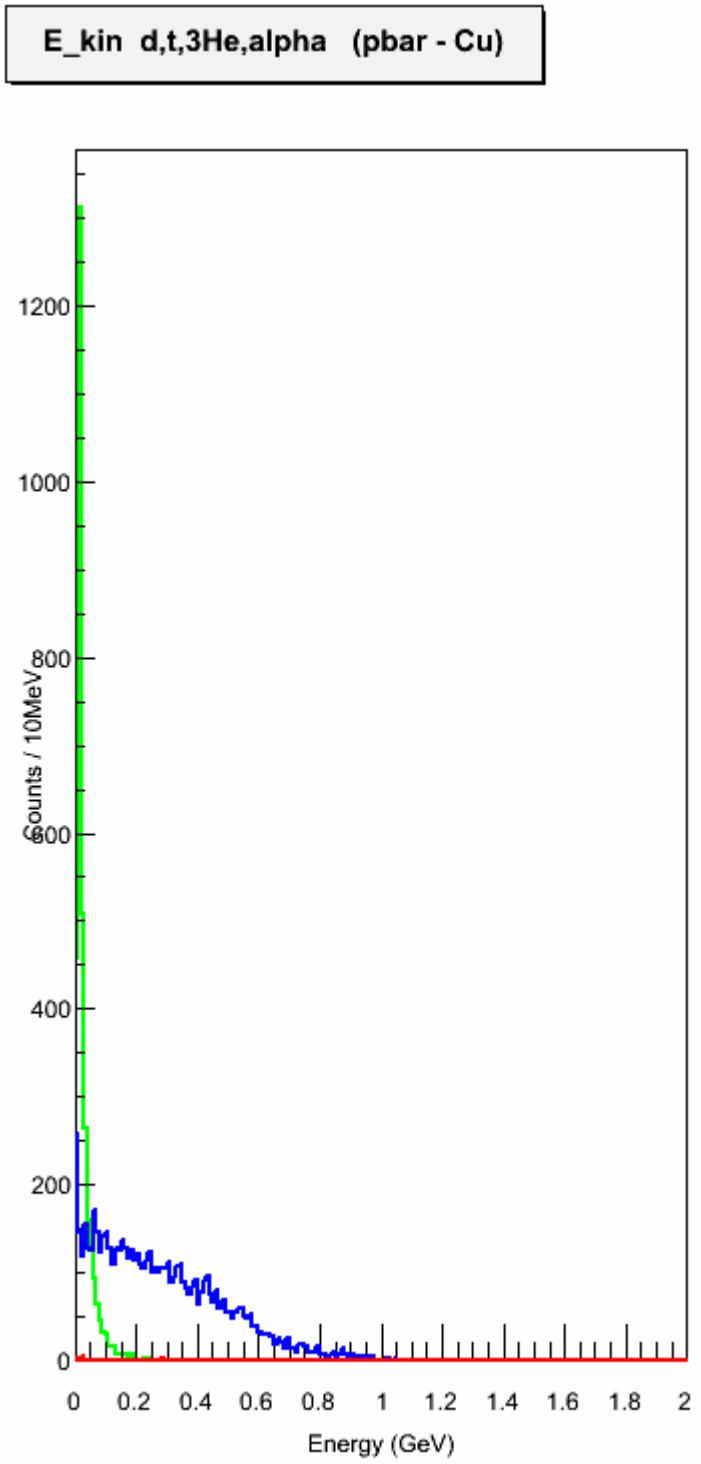




Protons are produced rarely by FTF/Preco

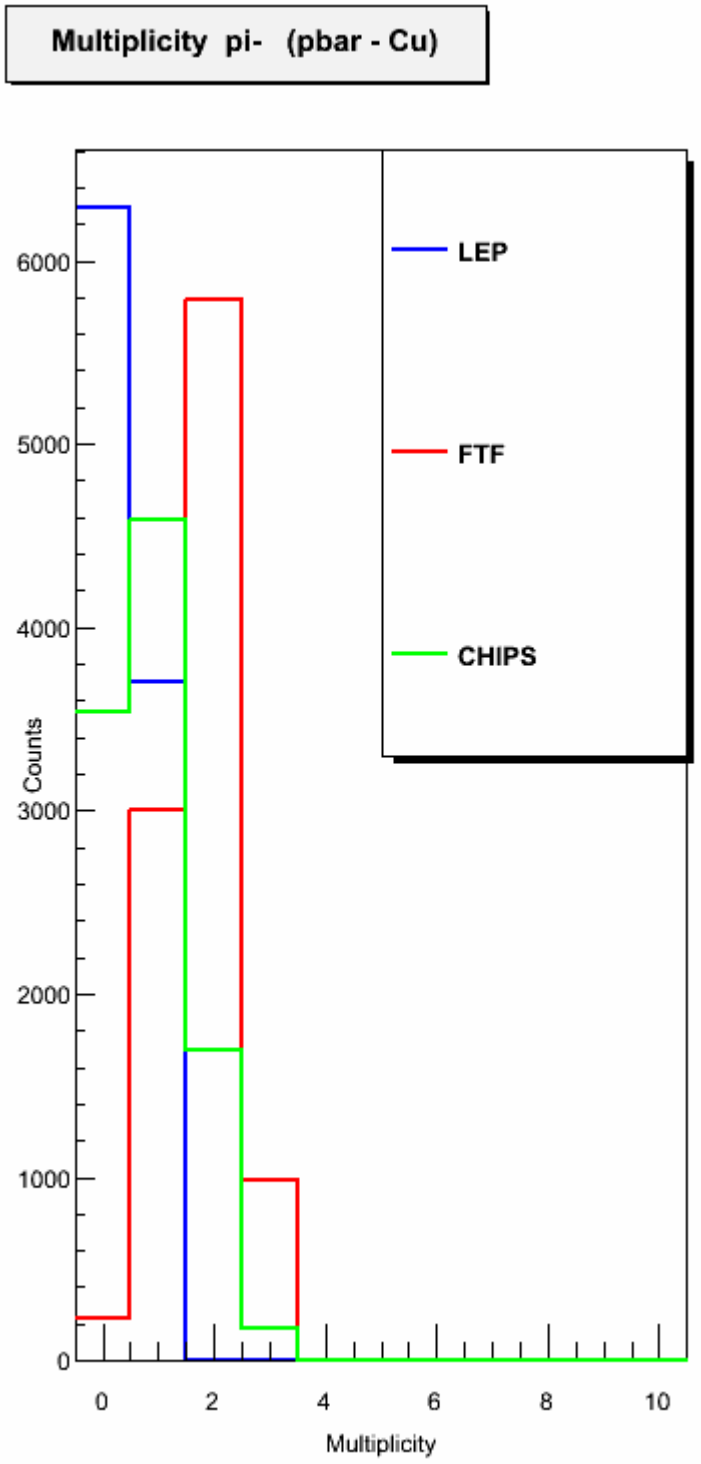
Light ions

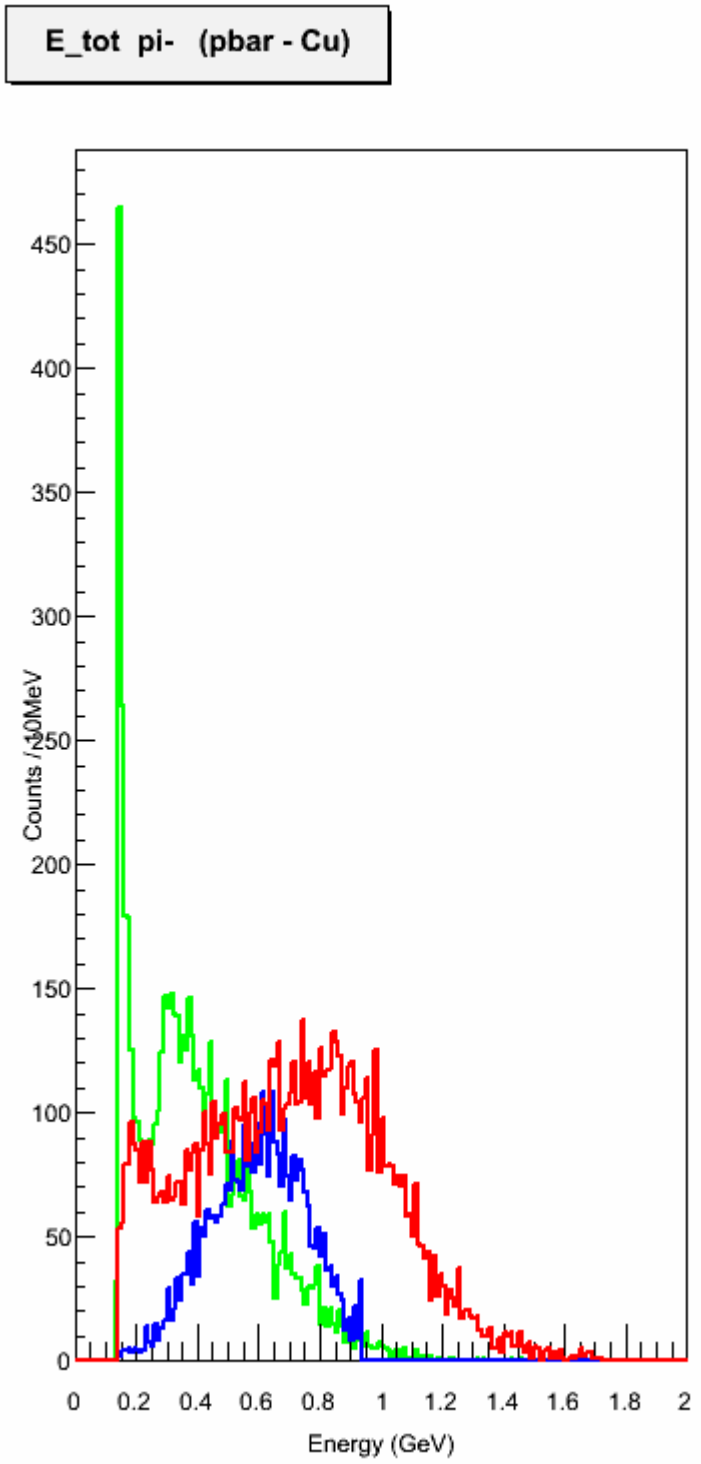




Light ions are produced rarely by FTF/Preco

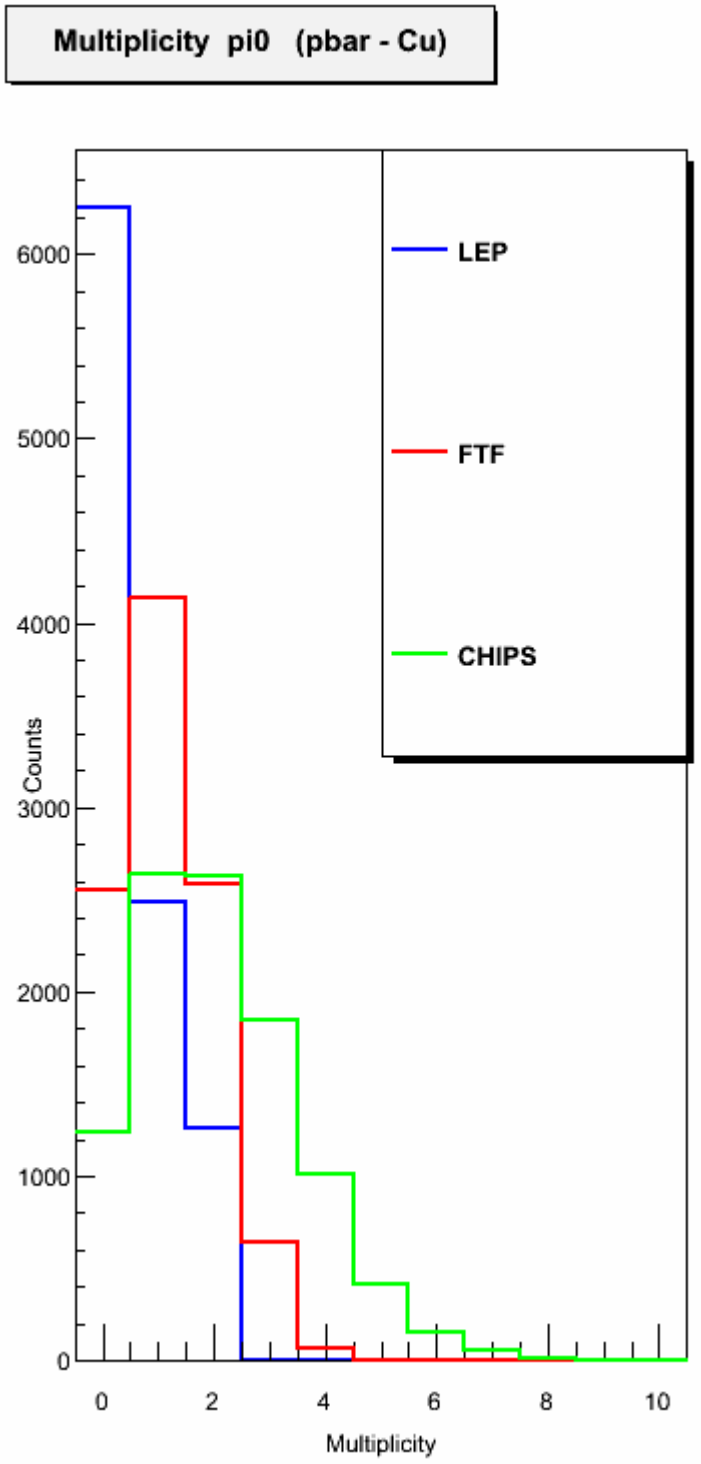
Pi-

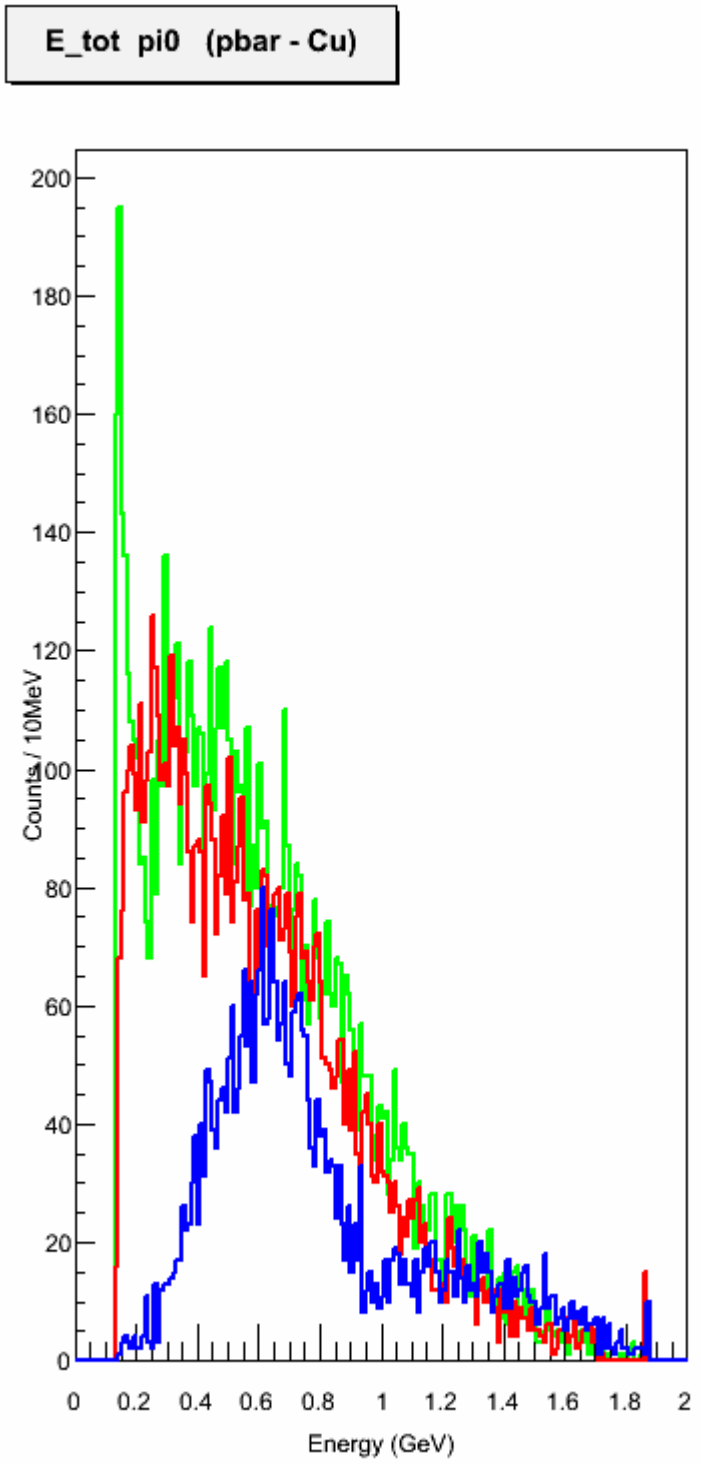




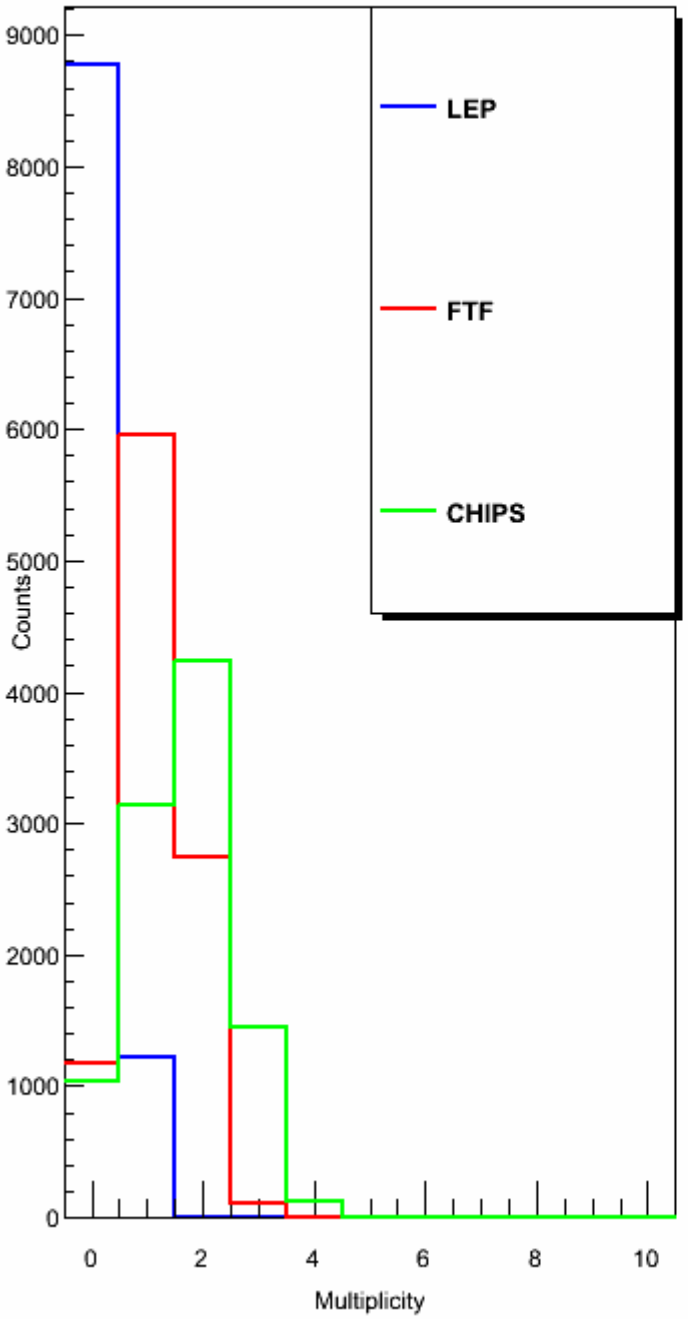
FTF produced more pi-, and with more energy than LEP and CHIPS

Pi0

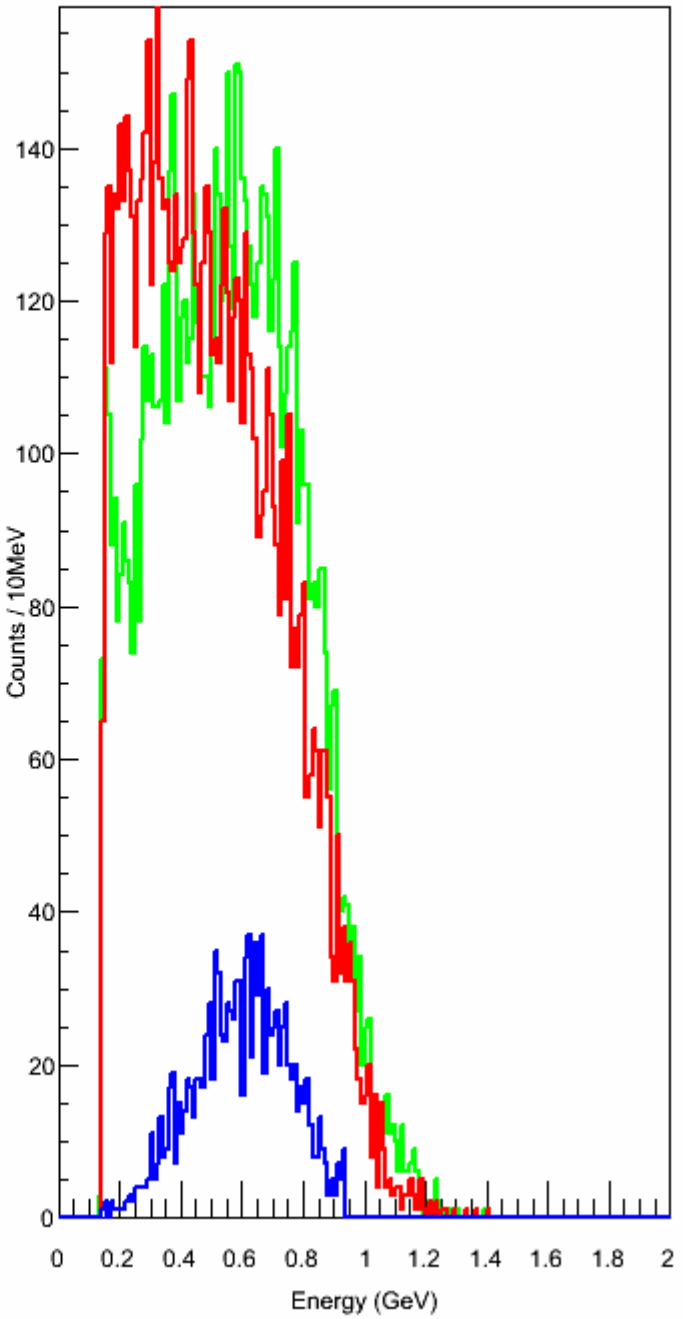

Multiplicity pi0 (pbar - Cu)
LEP
FTF
CHIPS
Counts
Multiplicity
0
1000
2000
3000
4000
5000
6000
0
2
4
6
8
10


E_tot pi0 (pbar - Cu)
Counts / 10MeV
Energy (GeV)
0
20
40
60
80
100
120
140
160
180
200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Multiplicity pi+ (pbar - Cu)

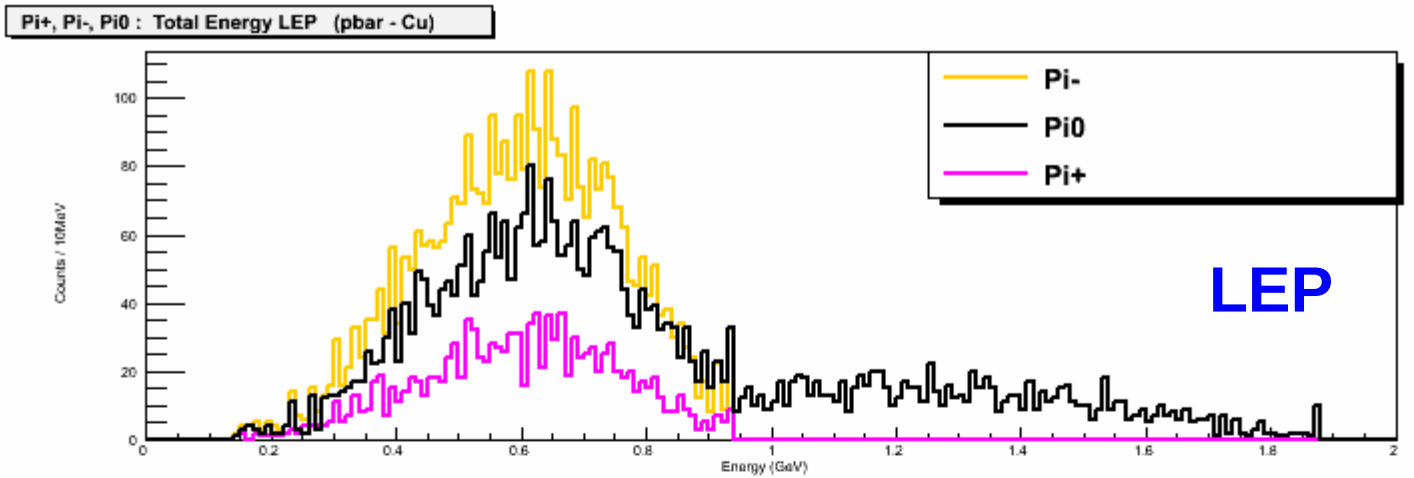


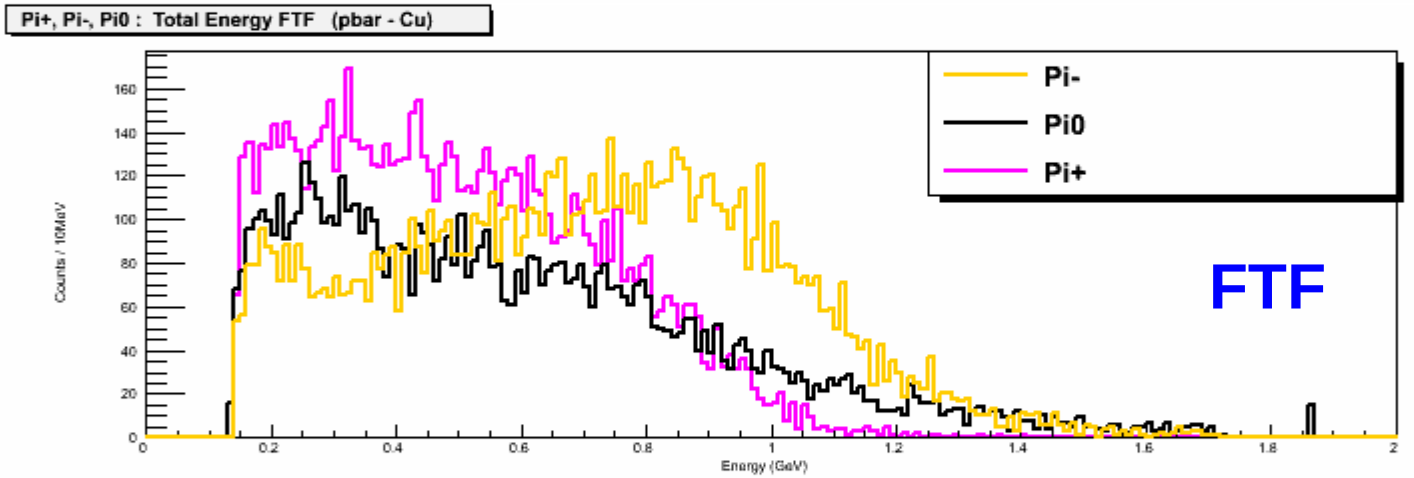
E_tot pi+ (pbar - Cu)

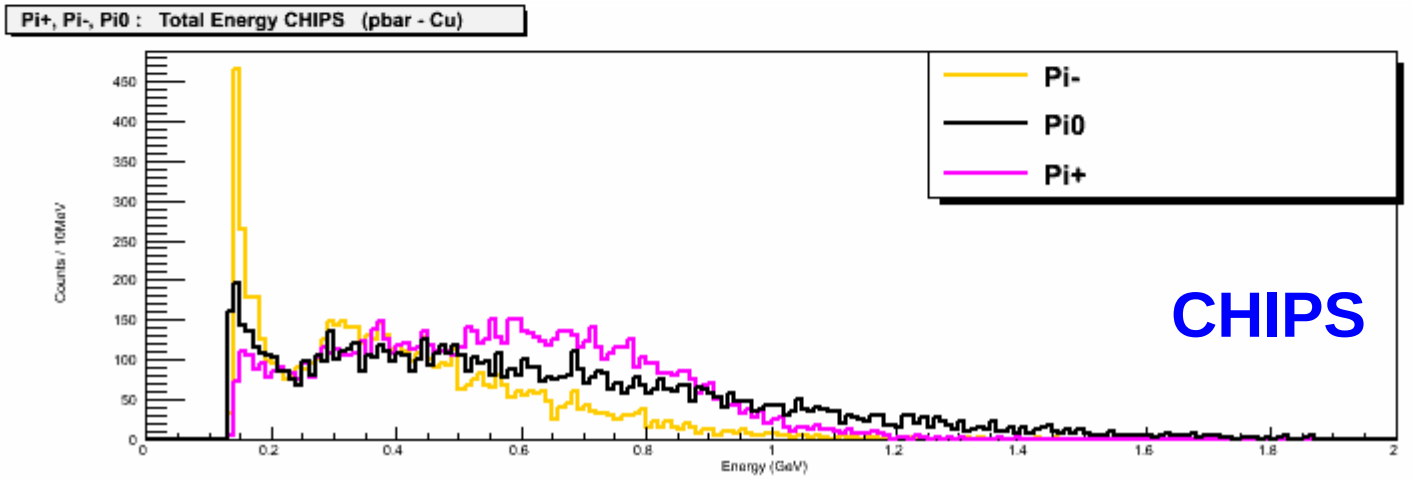


Pi+

Pi-, Pi0, Pi+

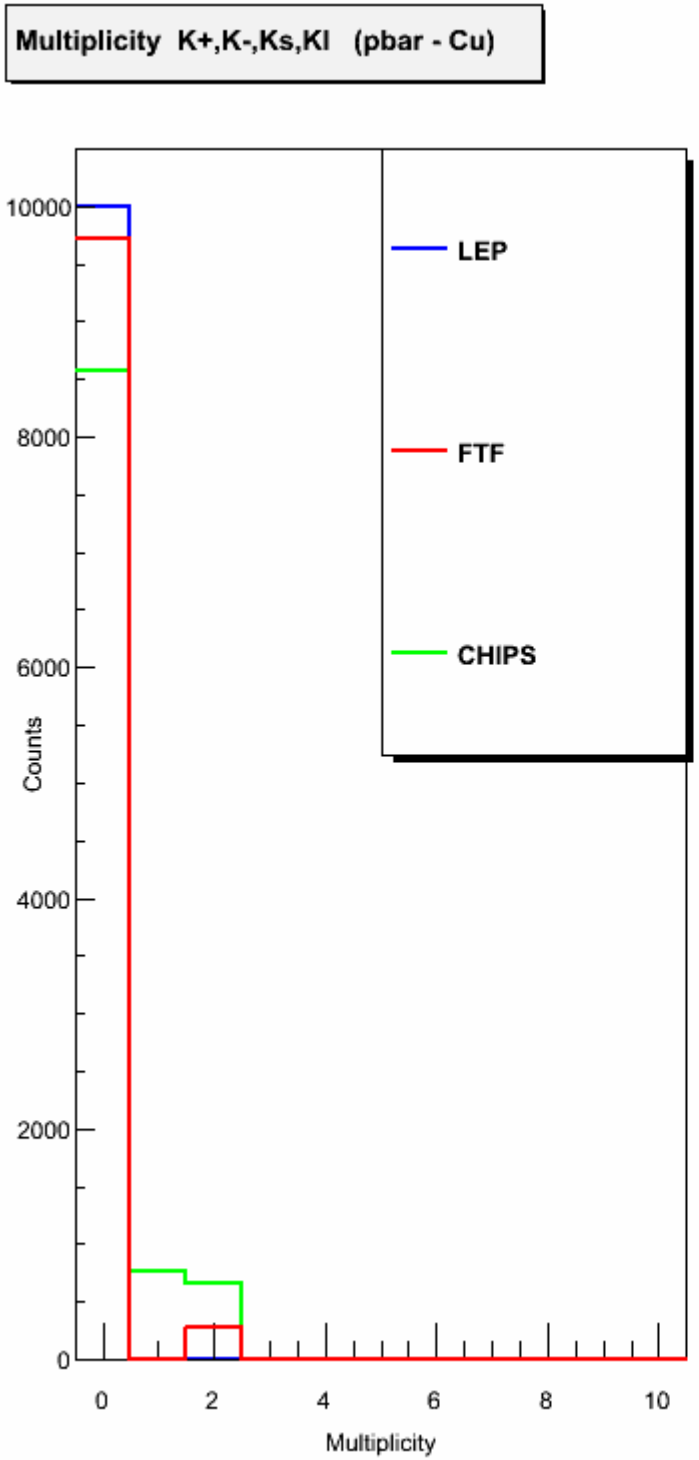


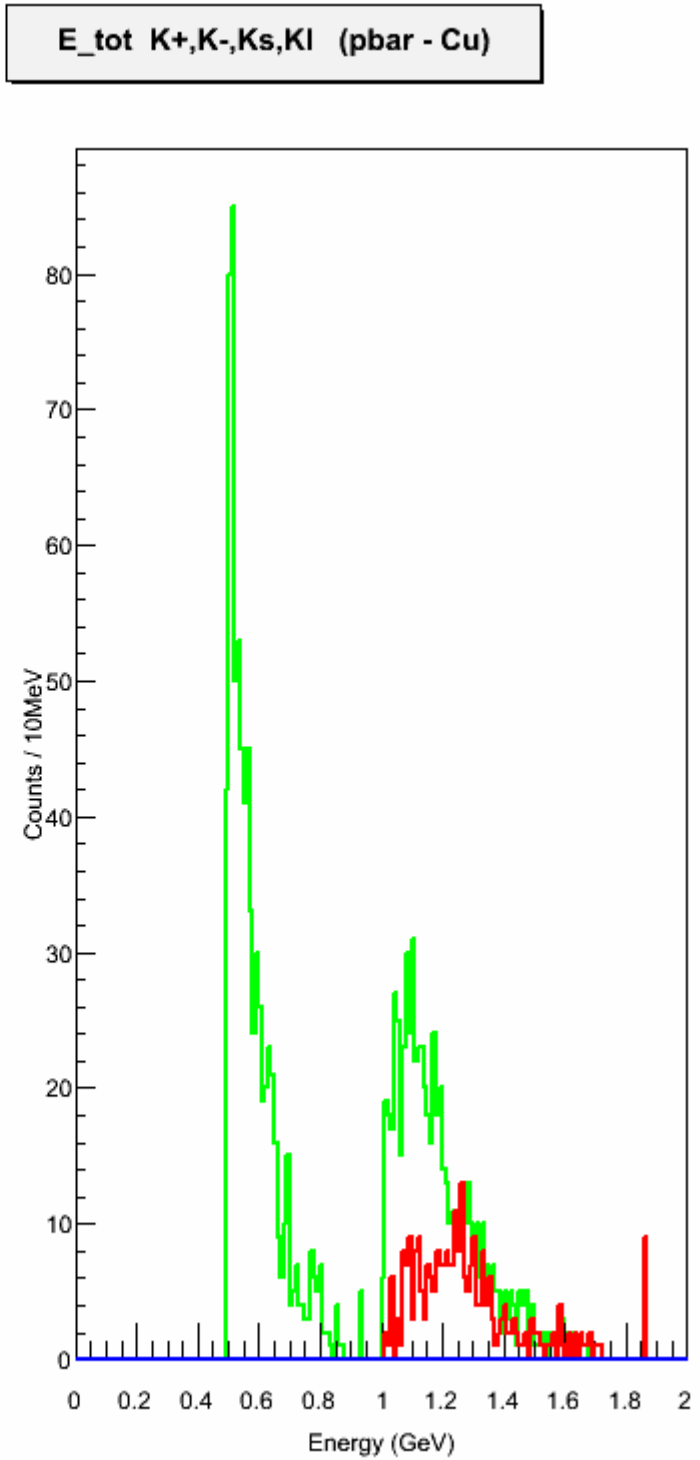




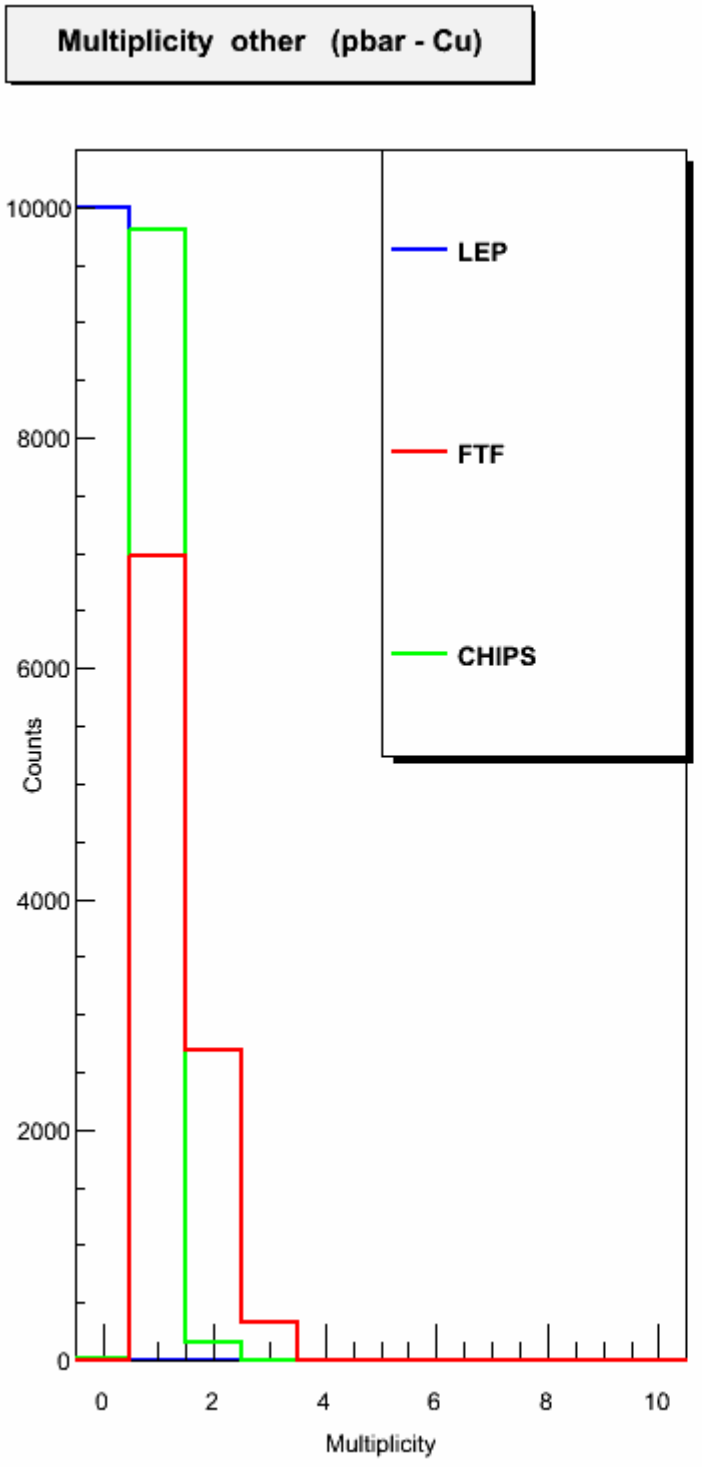
Only FTF produces more Pi- than Pi0 and Pi+, as I would expect from pbar annihilation

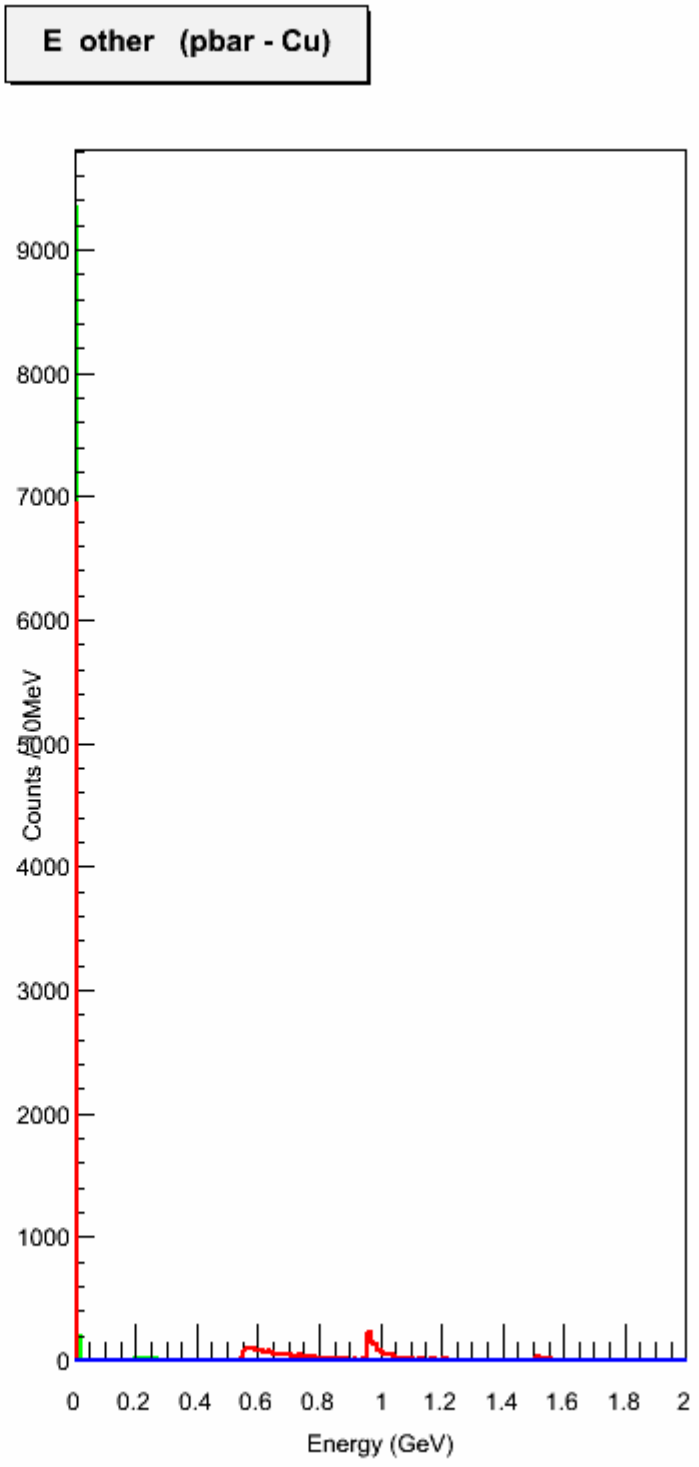
Kaons


Multiplicity K+,K-,Ks,Kl (pbar - Cu)
LEP
FTF
CHIPS
Counts
Multiplicity
0
2000
4000
6000
8000
10000
0
2
4
6
8
10


E_tot K+,K-,Ks,Kl (pbar - Cu)
Counts / 10MeV
Energy (GeV)
0
10
20
30
40
50
60
70
80
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Others





FTF/Preco always produce a residual nucleus, very often with Ekin < 1 MeV

Conclusions

- Physics list **FTFP_BERT_TRV** , starting with G4 **9.4.ref10**, will use FTF/Preco for anti-proton annihilation at rest

- Stable; momentum is conserved;
  energy is sometimes violated by O(10 MeV)
  - work in progress to understand and fix it

- First comparisons of **p – Cu** annihilation at rest between LEP , CHIPS , FTF/Preco
  + The relative energy distribution between **π^-** , **π^0** , **π^+** seems better in FTF/Preco
  - FTF/Preco gives to much energy to pions, and too little to neutrons, protons, light ions, and gammas
  - Likely too little variation in FTF/Preco for the total energy of secondaries (correlated with energy non conservation?)

- Thin-target validation is needed