Summary of the Hadronic Parallel Sessions

Alberto Ribon
(CERN EP-SFT)

Geant4 Collaboration meeting, Rennes, 30 September 2022

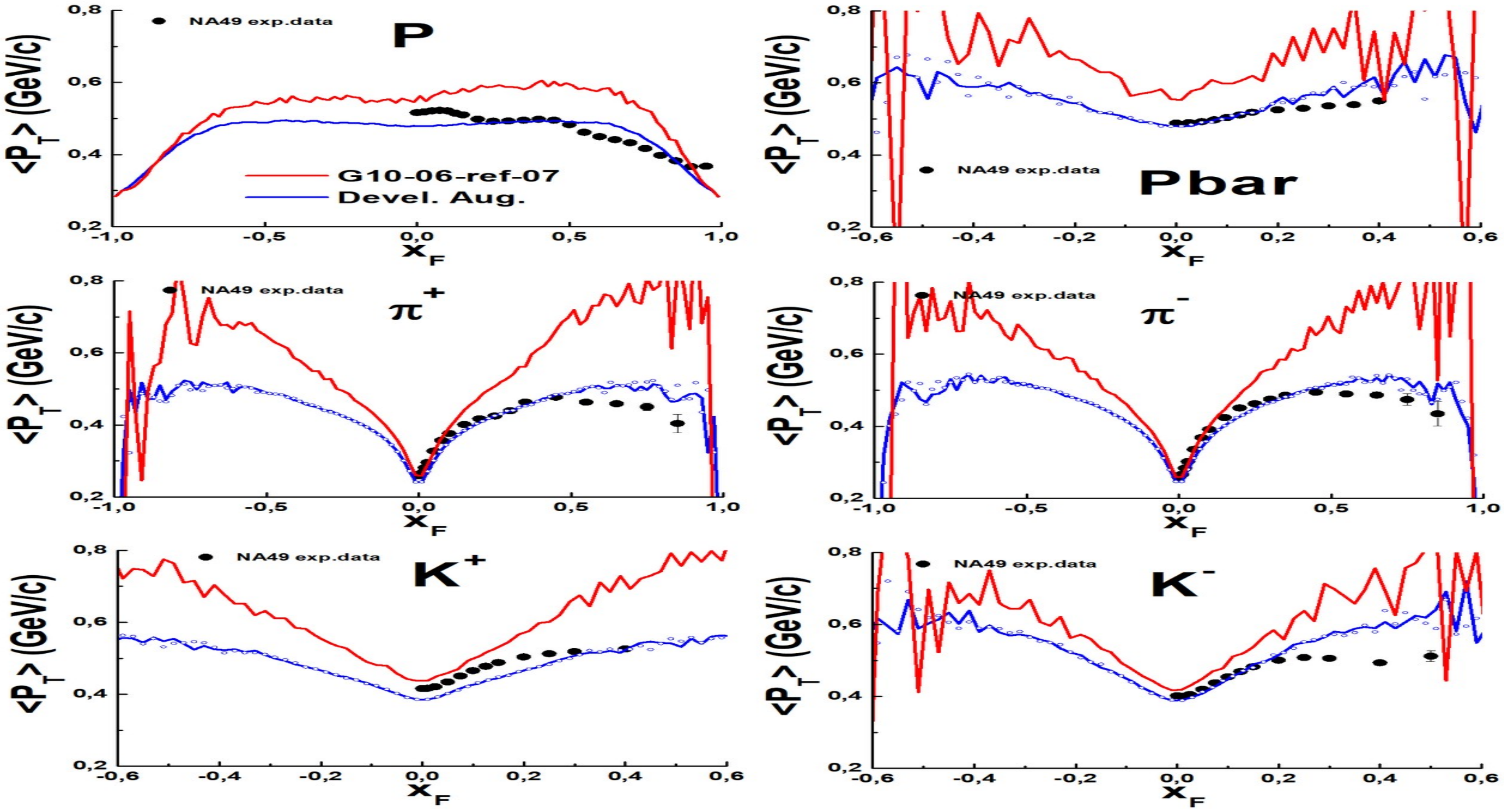
Parallel 1B : Vladimir Uzhinsky

“*Status and prospectives for the Geant4 string models, FTF and QGS*“

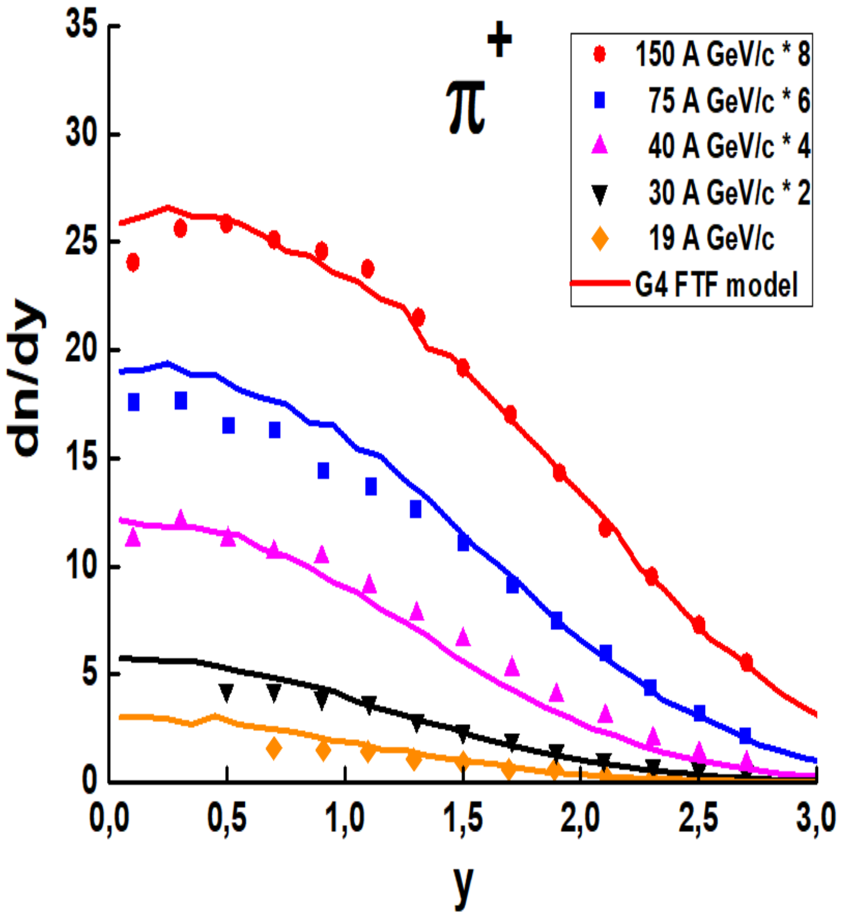
- Keep comparing FTF model performance against other MC codes
  - Based on published benchmark data (NA61/SHINE, NA49, *etc.*)
- Continuous effort to reduce disagreement between FTF model prediction and experimental data
  - Some of the progress made is shown in the following slides

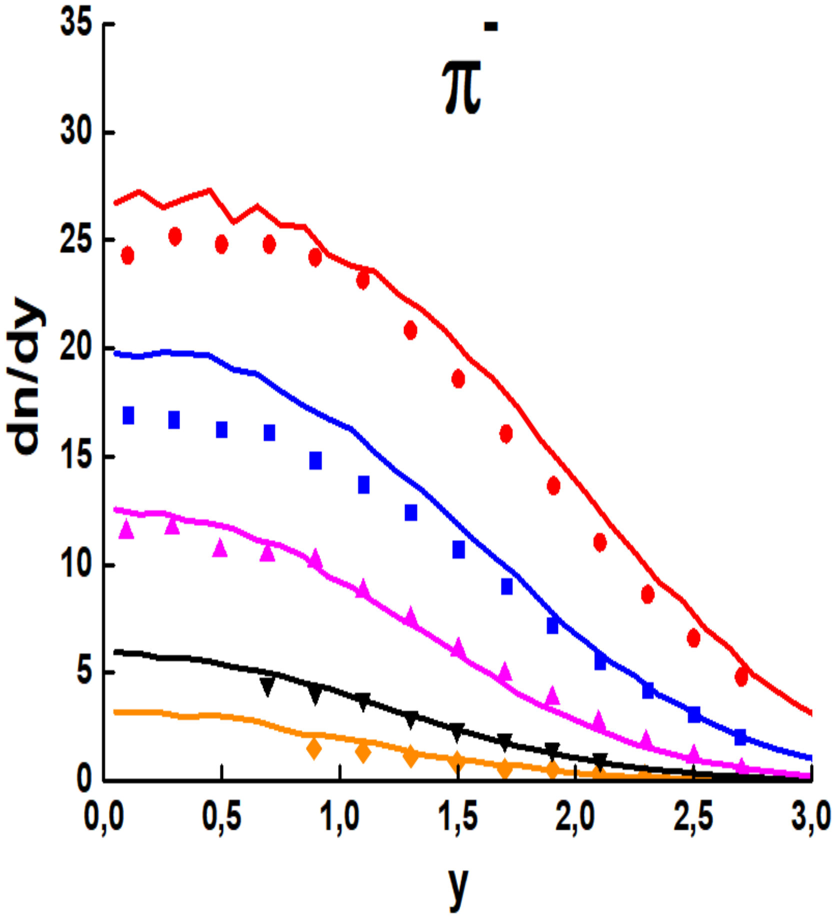
My personal opinion:
the priority of which observables to be consider first for further development depends on the type of physics one is interested in...

Final Pt – Xf correlations, 158 GeV/c

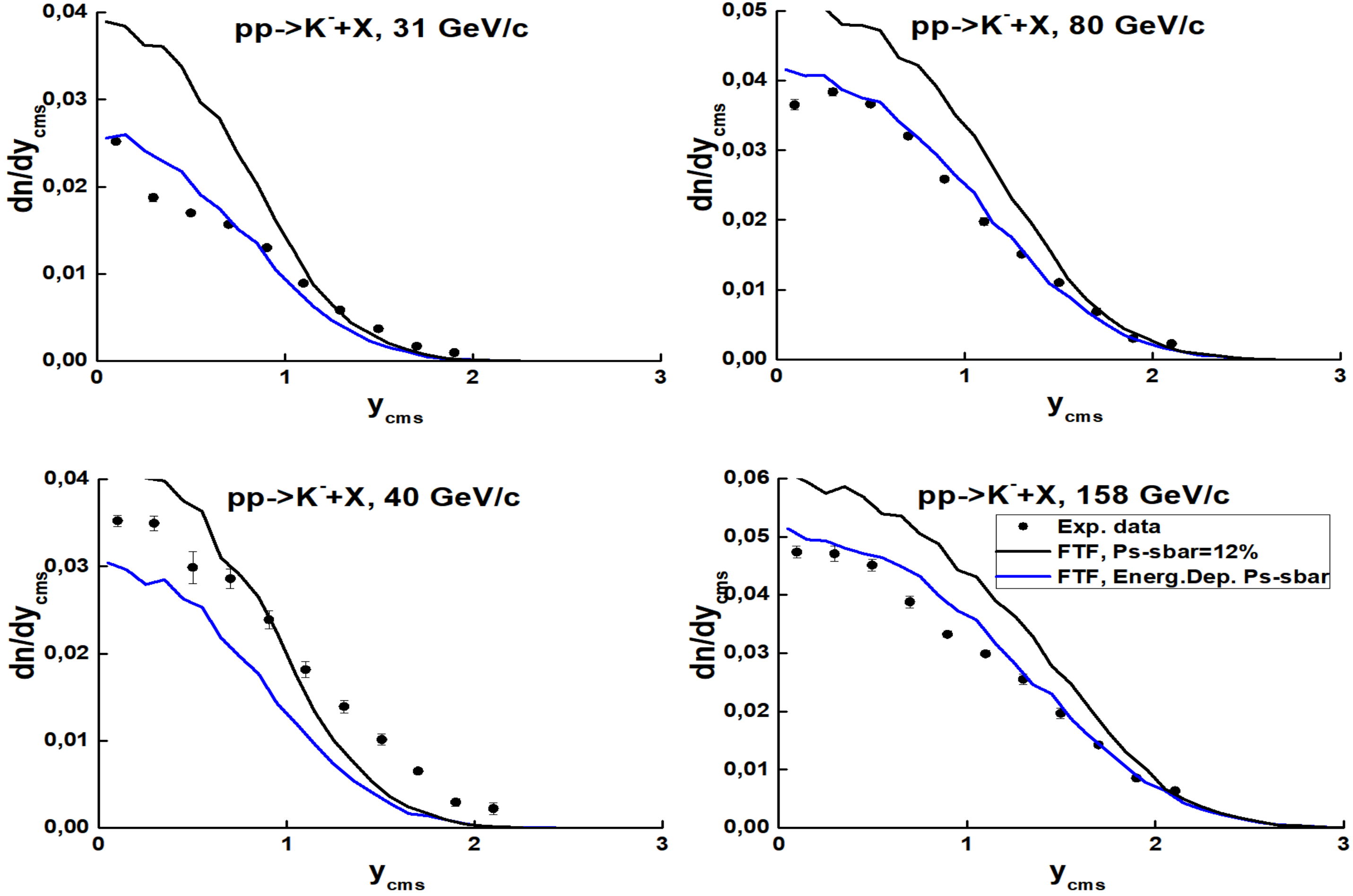


NA61/SHINE data on Be-7 + Be-9 and FTF model





Geant4 FTF model: tune of Ps-sbar (12 %)



Black lines:
Ps-sbar =12 %

Blue lines:
Ps-sbar = 0.12* [1 – (Mth/Mstr)$^{2.5}$]

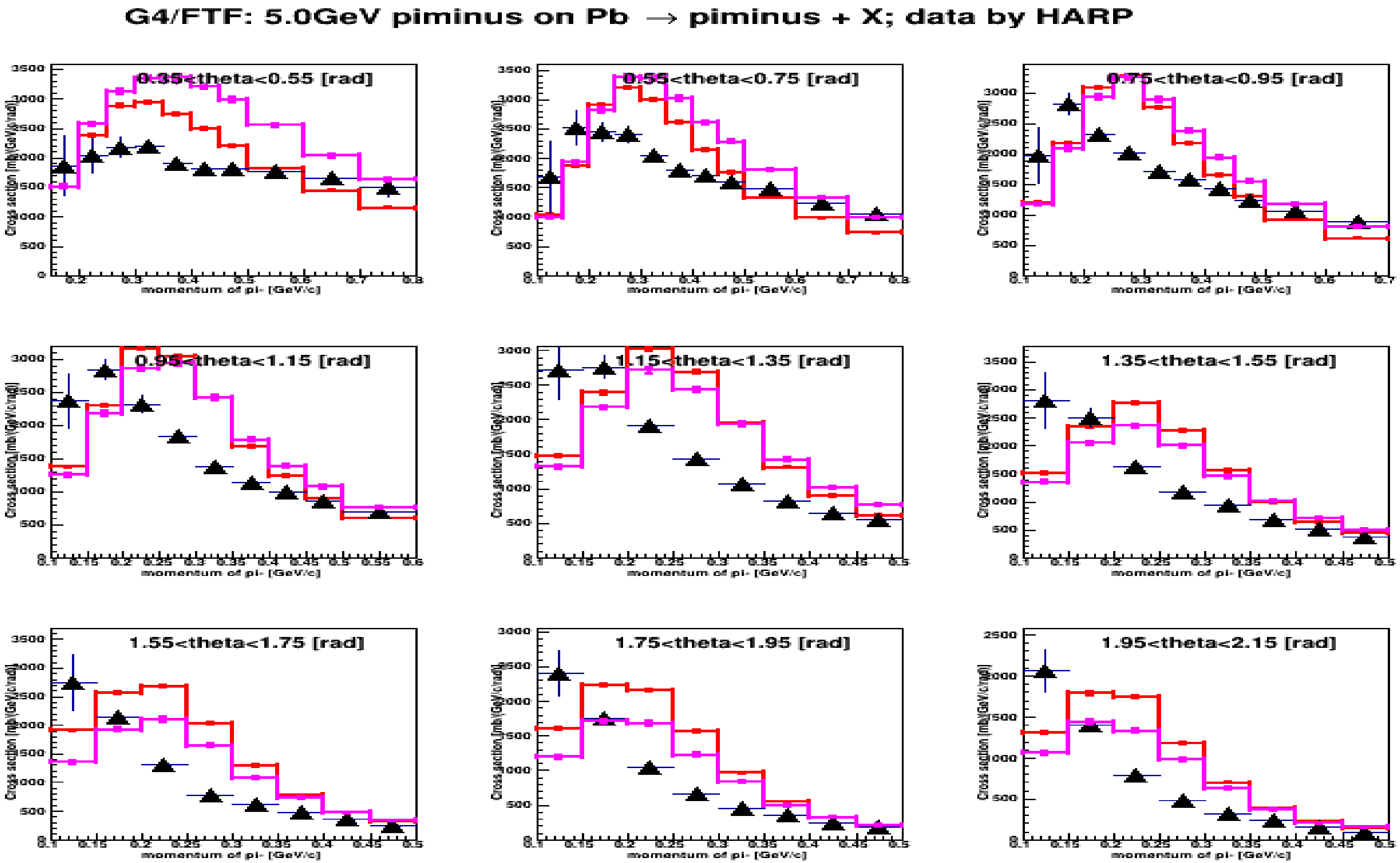
Parallel 1B : Julia Yarba “*Update on tuning FTF model parameters*“

- First FTF tuning for proton projectile available in G4 11.0.ref07
  - See plenary talk + Julia’s talk at the hadronic group meeting in July
- Started investigation of FTF tuning for pion projectiles
  - Preliminary results shown (see next slides) are encouraging!
  - Still more work is needed

Plan (private discussion after the meeting)

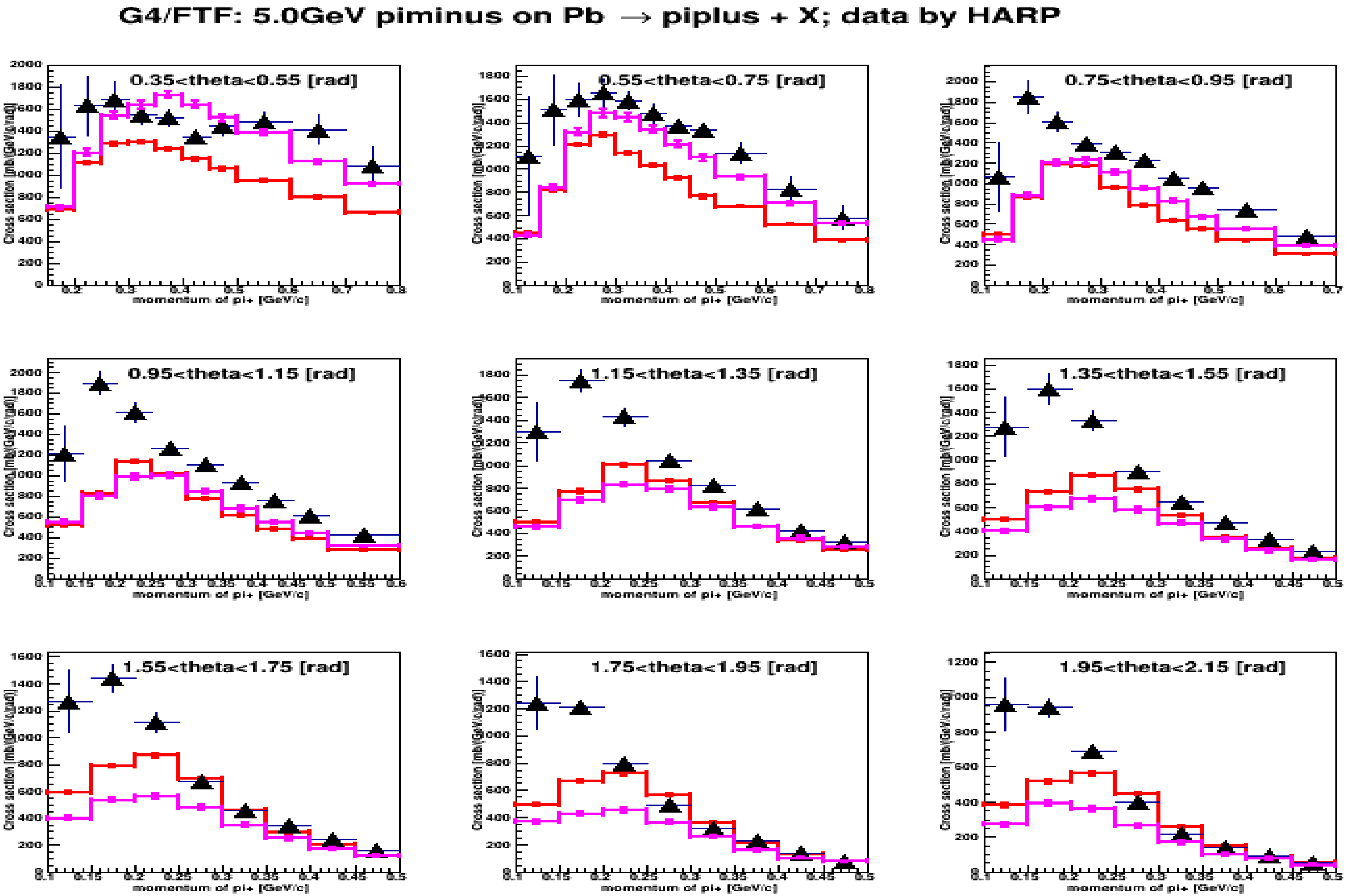
- *Aimed to find one or a few FTF tunes for pion projectiles*
  - *Either to be included in G4 11.1 as alternative tunes, or after G4 11.1*
  - *To make detailed validation studies and hadronic showers evaluations in 2023*
- *After that, start to look at QGS parameters...*

Default: chi2/NDF = 66.6 **Sim using Best Fit: chi2/NDF = 55.5**



Parallel 1B : Julia Yarba “Update on tuning *FTF model parameters*“

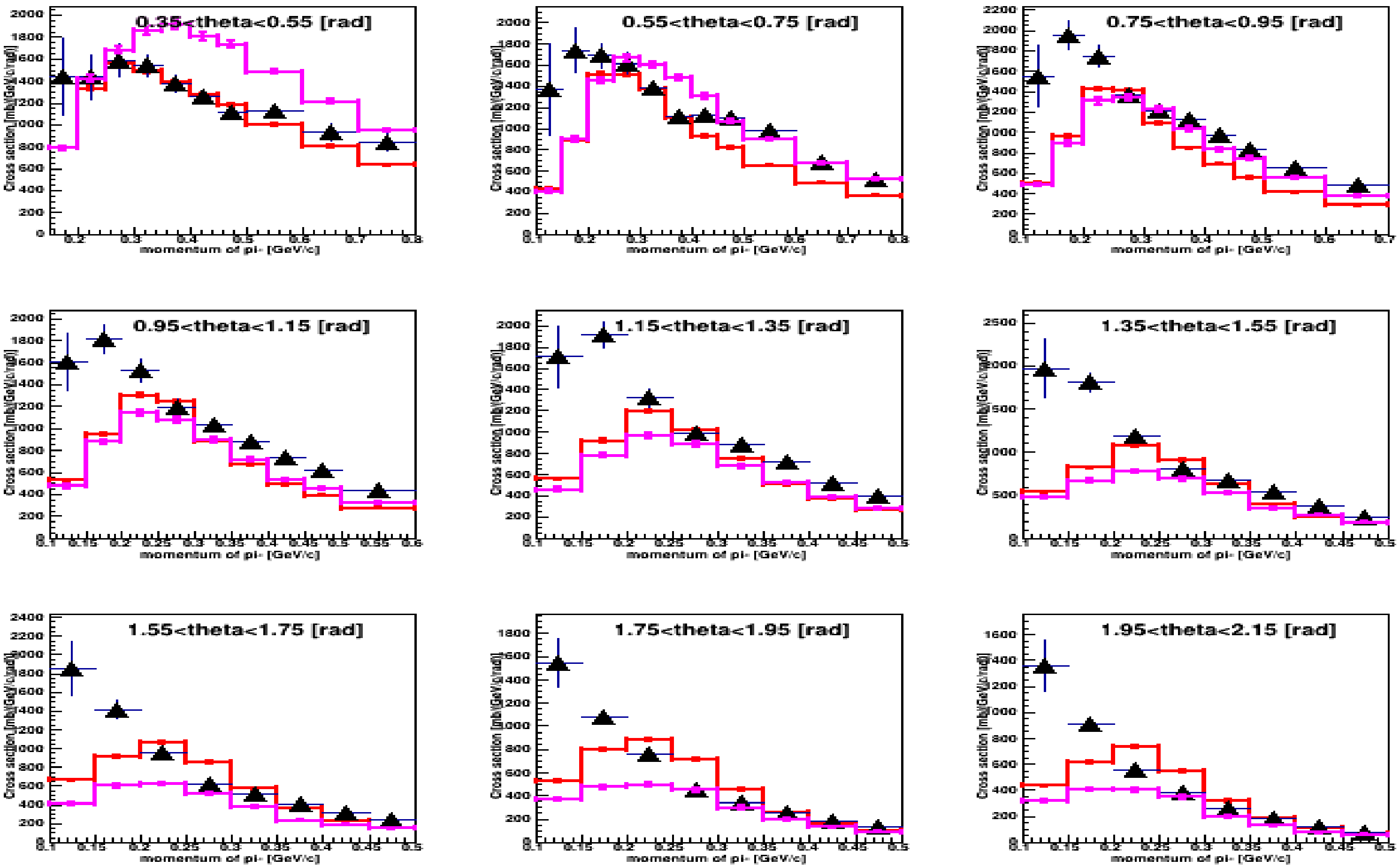
Default: chi2/NDF = 19.1 **Sim using Best Fit: chi2/NDF = 18.4**



Parallel 1B : Julia Yarba “Update on tuning *FTF model parameters*“

Default: chi2/NDF = 13.6 **Sim using Best Fit: chi2/NDF = 20.3**

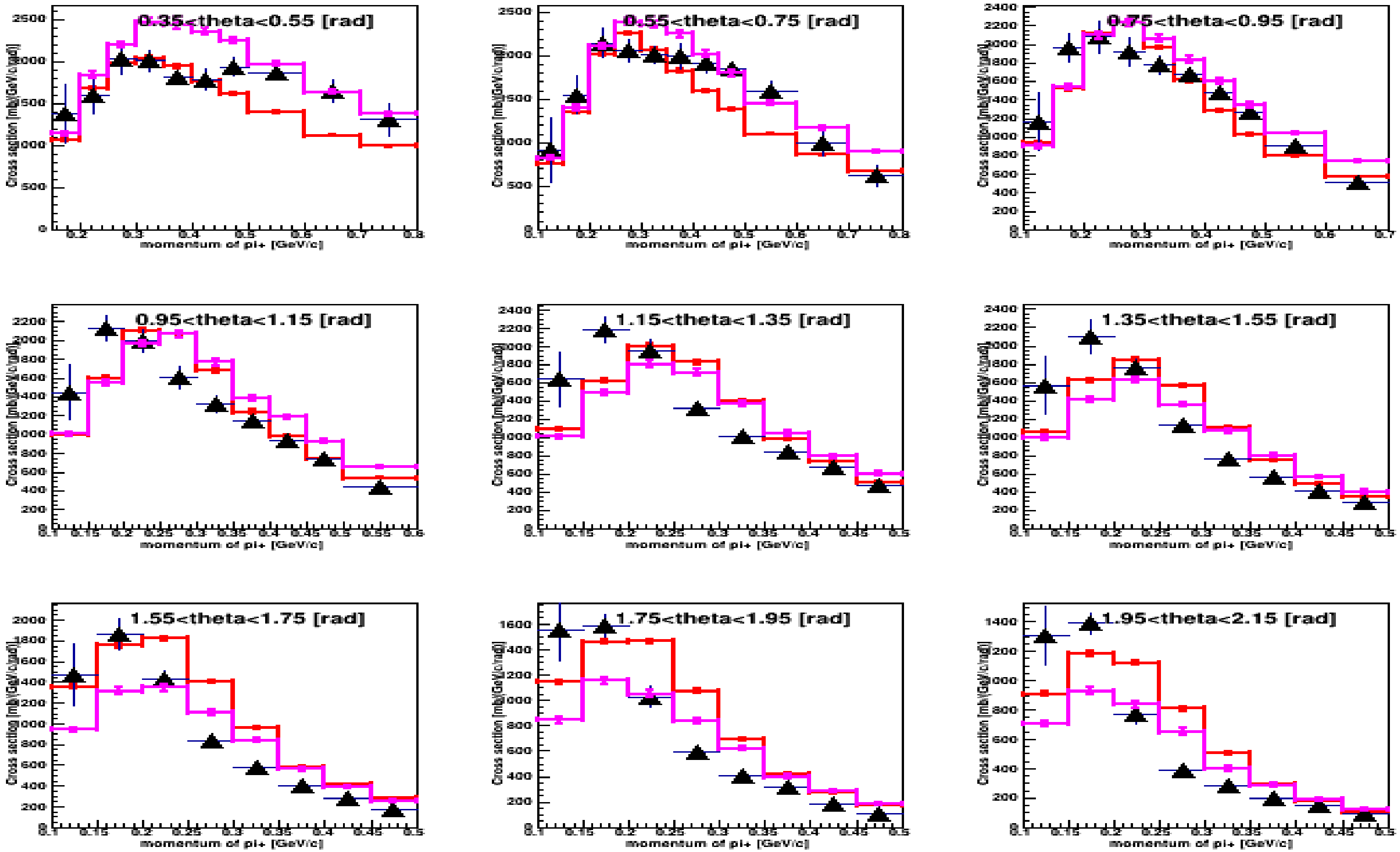
G4/FTF: 5.0GeV piplus on Pb → piminus + X; data by HARP



Parallel 1B : Julia Yarba "Update on tuning *FTF model parameters*"

Default: chi2/NDF = 13.7 **Sim using Best Fit: chi2/NDF = 12.2**

G4/FTF: 5.0GeV piplus on Pb → piplus + X; data by HARP

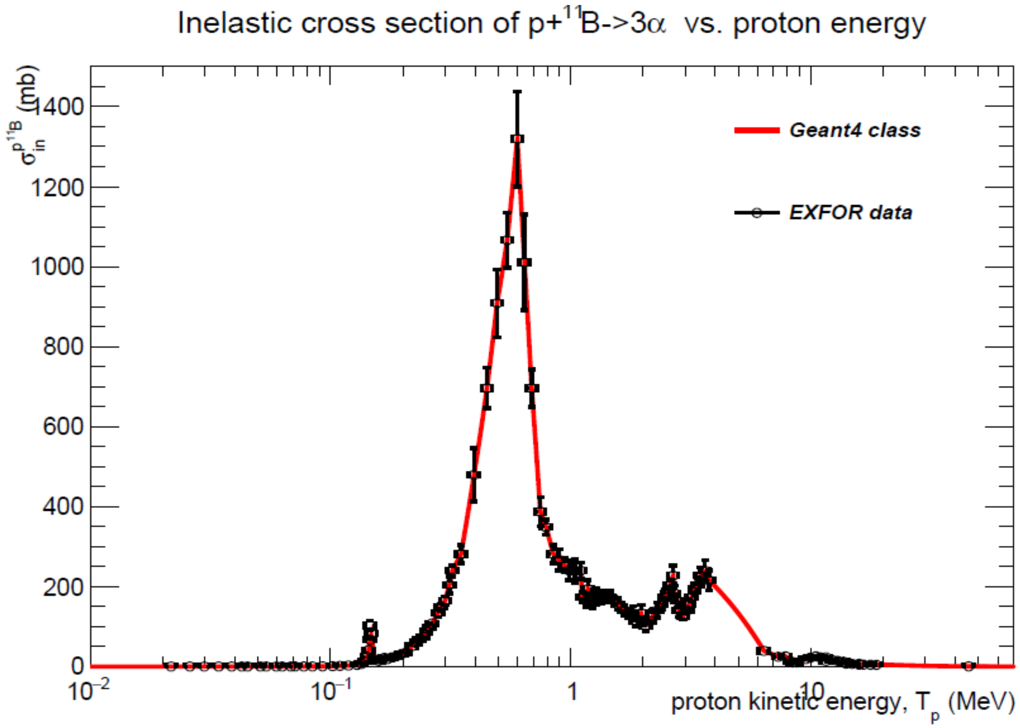


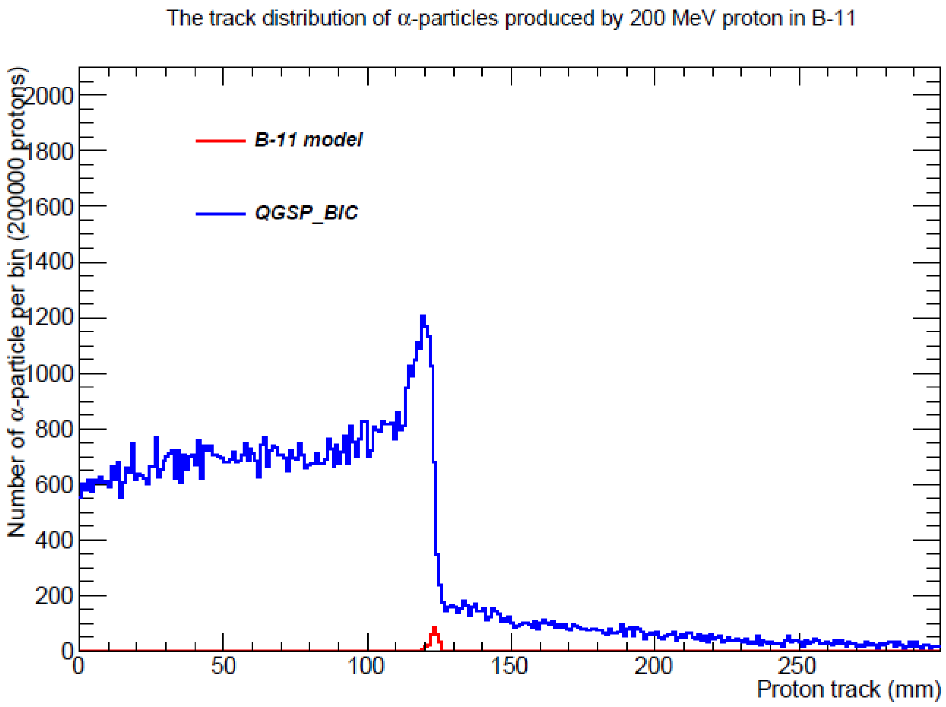
Parallel 3B : Vladimir Grichine

"Alpha particles produced by protons in 11B (Geant4)"

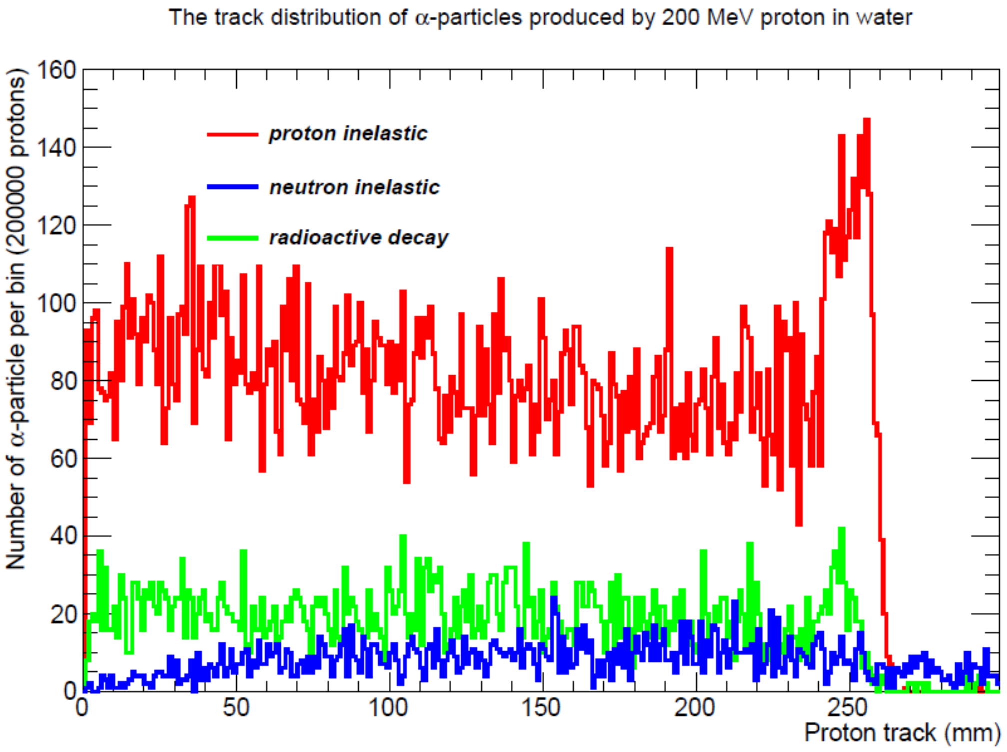
- Proposed method to enrich the energy deposition in the Bragg peak
  - 200 MeV **p + 11B --> α + 8Be* --> 3 α** + 8.79 MeV
  - A new Geant4 model is introduced for describing the reaction
  - Integral cross section according to the INFN Catania group
  - Final state created according the momentum and energy conservation, including the binding energy of the 8Be emitted
  - 2nd and 3rd alphas emitted isotropically have equal energy and opposite momenta, satisfying the total energy balance
  - Cross section and model are activated in QBBC
- "Background": α's produced by G4 intra-nuclear cascades
  - Surprisingly, ~ 30 times bigger than the "signal" !
  - To be understood… --> need experimental data !

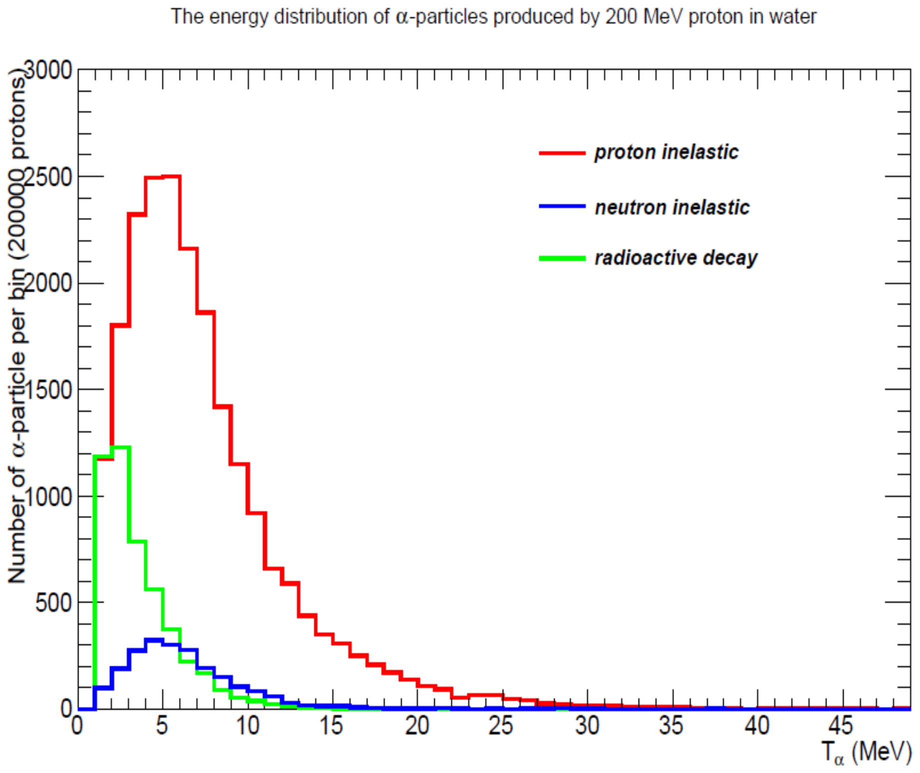
Parallel 3B : Vladimir Grichine “*Alpha particles produced by protons on B-11 (Geant4)* “

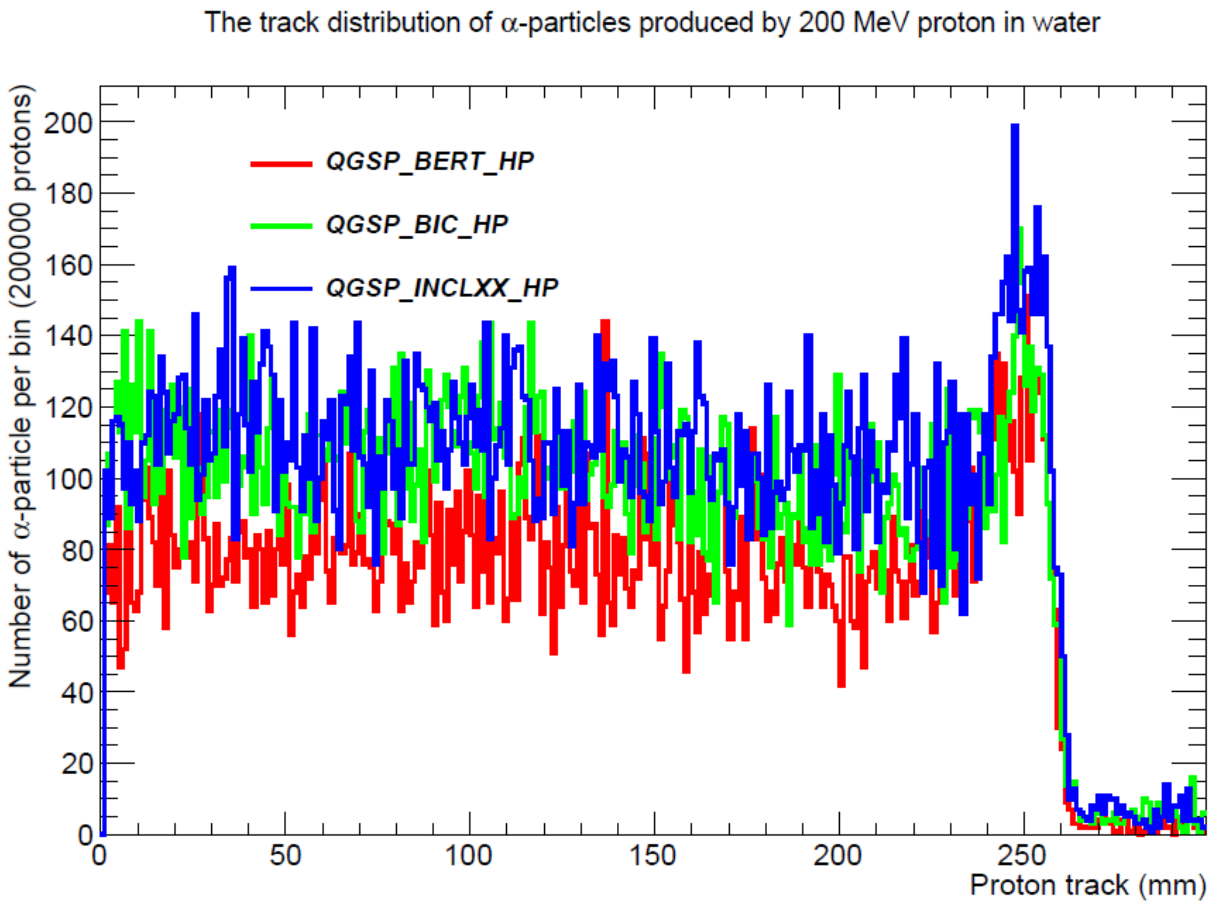




Alpha particle production along 200 MeV proton track






The track distribution of α-particles produced by 200 MeV proton in water
QGSP_BERT_HP
QGSP_BIC_HP
QGSP_INCLXX_HP
Number of α-particle per bin (200000 protons)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
Proton track (mm)

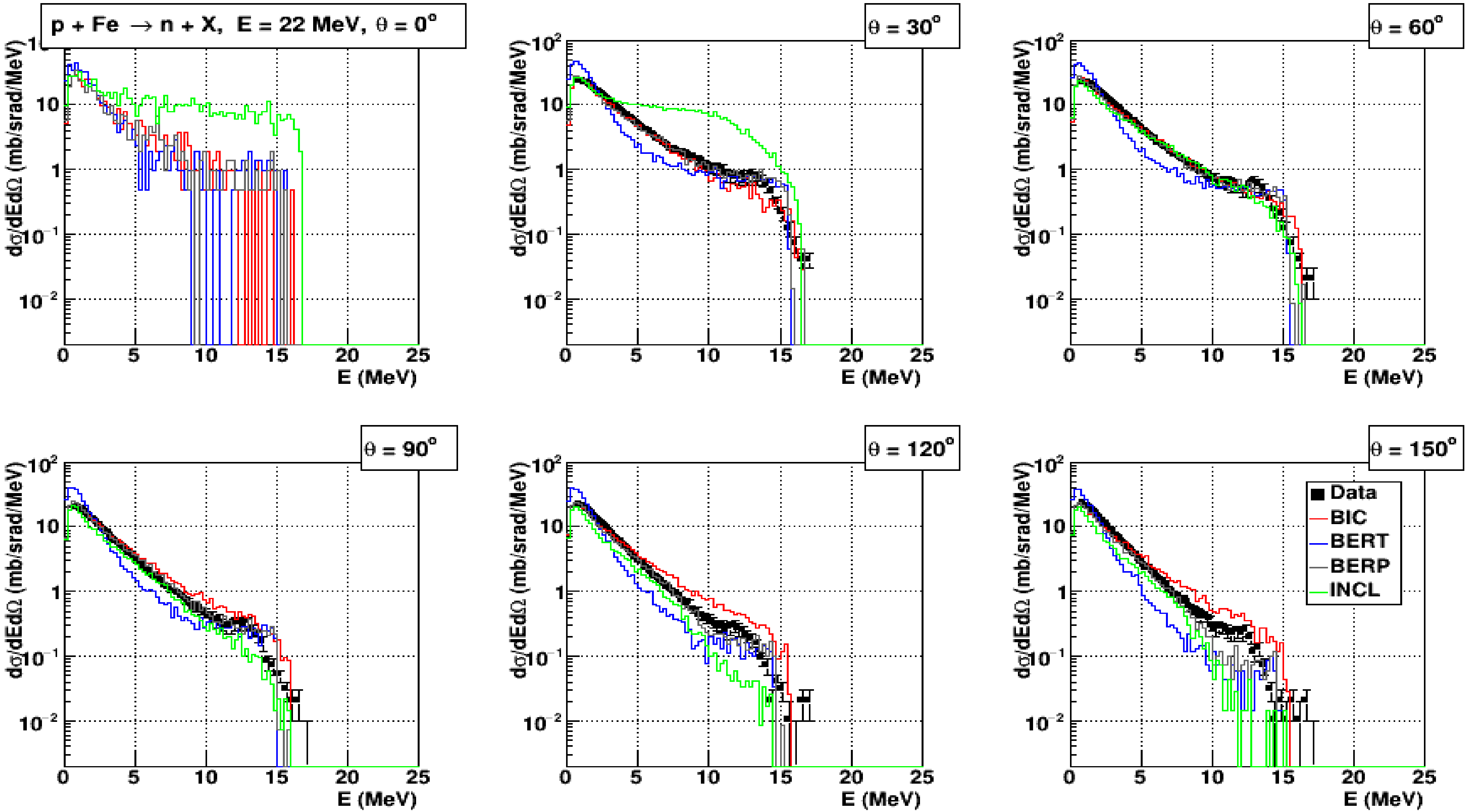
Parallel 3B : Vladimir Ivanchenko *“Recent developments in hadronics: integral approach, neutron general process, etc.“*

- Several topics included
  - Integral approach, neutron general process, improvements in nuclear de-excitation
    - Already summarized in the plenary talk on hadronic physics
- In the next slides, only a few slides are recalled
  - Some information can be very useful in practice for both developers and (advanced) users

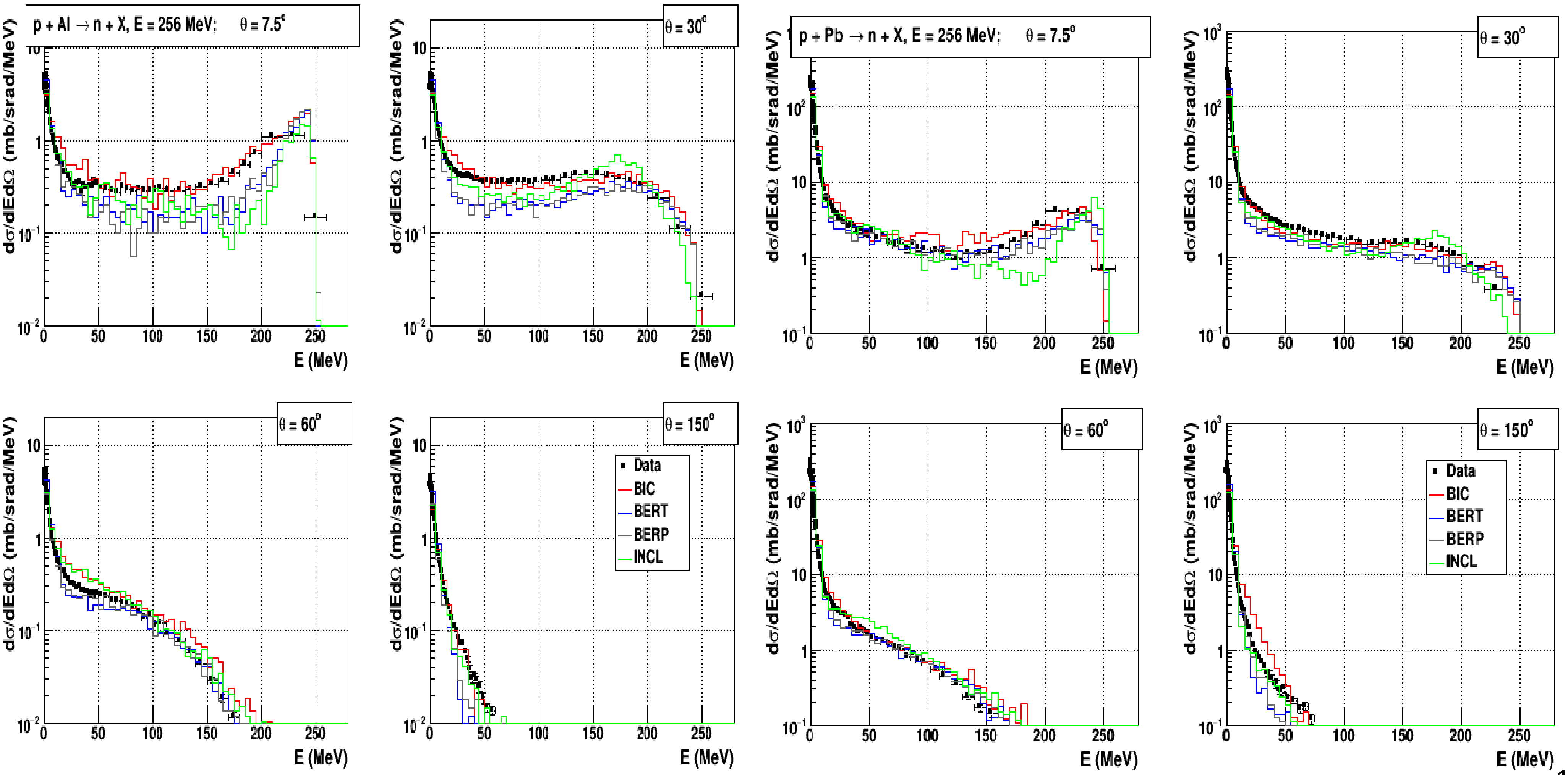
My personal comment:
modeling nuclear pre-equilibrium and de-excitation is a vast and complex area, and extremely important in all hadronic applications, from hadronic showers to nuclear and medical physics !

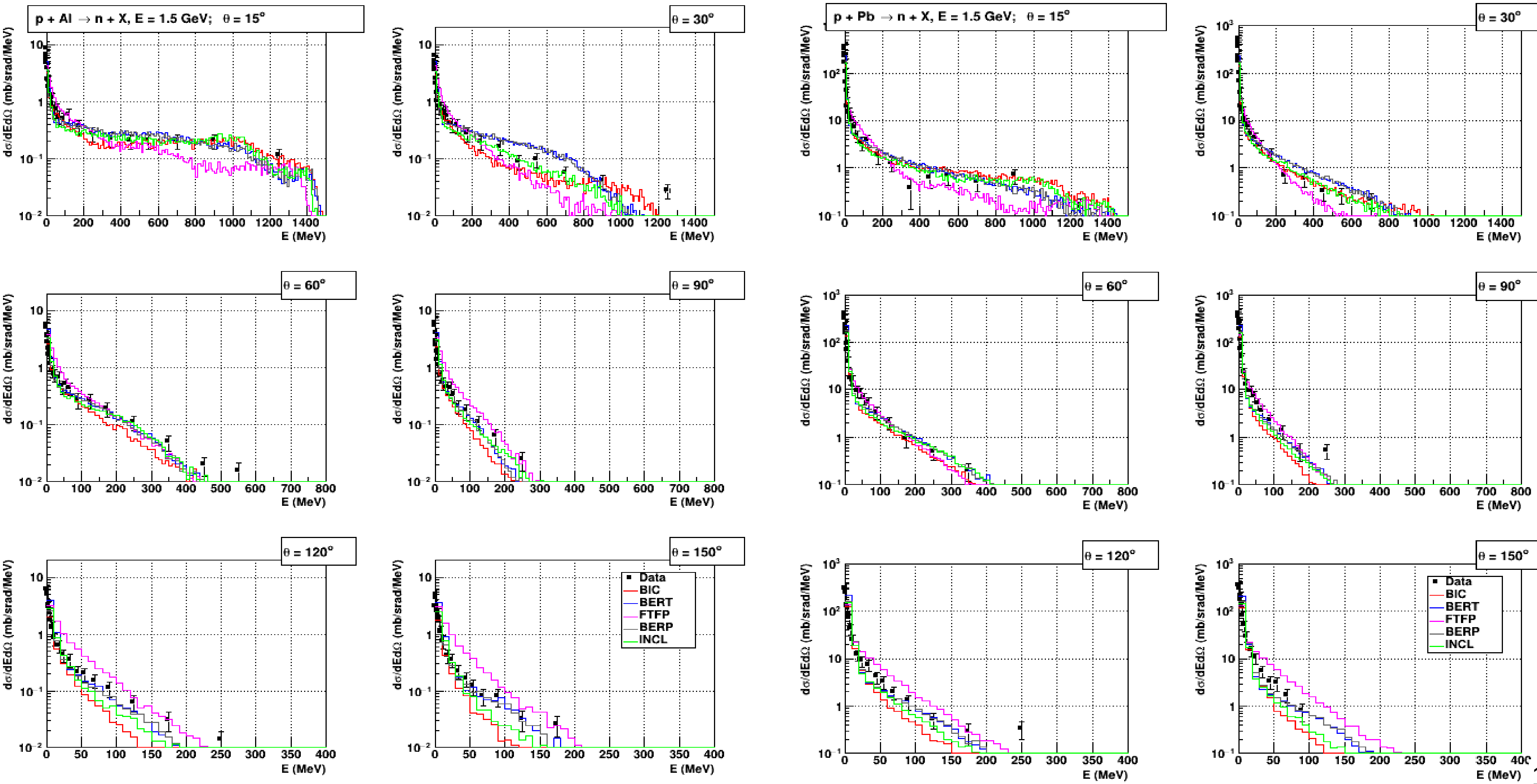
Modifications in hadronic physics lists

- To ensure **early initialization** of hadronic parameters
  - **G4PhysListUtil::InitialiseParameters()**
    - Called in several places of physics construction; Should be called in any custom physics
- To access a hadronic **process** on top of any reference Physics List, use methods of **G4PhysListUtil**
  - static G4VProcess* FindProcess(const G4ParticleDefinition*, G4int subtype);
  - static G4HadronicProcess* FindInelasticProcess(const G4ParticleDefinition*);
  - static G4HadronicProcess* FindElasticProcess(const G4ParticleDefinition*);
  - static G4HadronicProcess* FindCaptureProcess(const G4ParticleDefinition*);
  - static G4HadronicProcess* FindFissionProcess(const G4ParticleDefinition*);
  - static G4NeutronGeneralProcess* FindNeutronGeneralProcess();
- To change hadronic **cross section** of top of any reference Physics List, use methods of the **G4HadProcesses** utility
  - static G4bool AddInelasticCrossSection(const G4ParticleDefinition*, G4VCrossSectionDataSet*);
  - static G4bool AddInelasticCrossSection(const G4String&, G4VCrossSectionDataSet*);
  - static G4bool AddElasticCrossSection(const G4ParticleDefinition*, G4VCrossSectionDataSet*);
  - static G4bool AddElasticCrossSection(const G4String&, G4VCrossSectionDataSet*);
  - static G4bool AddCaptureCrossSection(G4VCrossSectionDataSet*);
  - static G4bool AddFissionCrossSection(G4VCrossSectionDataSet*);


p + Fe → n + X, E = 22 MeV, θ = 0°
θ = 30°
θ = 60°
θ = 90°
θ = 120°
θ = 150°
dσ/dEdΩ (mb/srad/MeV)
E (MeV)
Data
BIC
BERT
BERP
INCL

Parallel 3B : Vladimir Ivanchenko *“Recent developments in hadronics...“*




p + Al → n + X, E = 1.5 GeV; θ = 15°
θ = 30°
θ = 60°
θ = 90°
θ = 120°
θ = 150°
p + Pb → n + X, E = 1.5 GeV; θ = 15°
dσ/dEdΩ (mb/srad/MeV)
E (MeV)
Data
BIC
BERT
FTFP
BERP
INCL

Summary and plans for 11.1

- New features are available for 11.1
  - Neutron general process
  - Integral method for hadrons
- De-excitation module improvements
  - Resolved problems introduced in previous releases
    - Levels without data on transitions
    - Floating levels
    - Sampling of evaporation of neutrons and light ions
  - Energy response for hadronic calorimeters are back to normal
- Short term plan for 11.1
  - Establish 1 ns time limit for all components of hadronic physics
  - Do not enable multi-fragmentation by default
  - Check Fermi BreakUp model
  - To add optional X-sections and fragmentation of light hypernuclei

Parallel 4B : Pedro Arce

“*Replacing ParticleHP cross sections with user's ones*“

- First draft of a document describing ParticleHP data format
  - Available in Indico, in Pedro’s contribution (Parallel 4B)
  - Please read it and provide feedback

- Replacing ParticleHP cross sections with user’s ones
  - Nearly all the requests concern charged particles, not neutrons

First description of ParticleHP data format

- Already documented
  - Total cross sections
  - Inelastic, elastic and capture (FS and FSM6)
- Missing (coming soon)
  - Thermal
  - Fission FS/FC/
- Written in Sphinx / restructure Text format (same as Geant4 doc)
- First version of ParticleHP data format guide
  - Waiting for your opinions/suggestions (available in Indico, at Pedro's talk)
  - Where do we put it?

Simple way to change ParticleHP data (1/2)

- There is a user demand to improve the Geant4 cross sections because they do not match some experimental data that users have measured or found
- Often a user is only interested in one channel or one outgoing particle
  - Production of C11 to design a cyclotron
  - Alpha production in BNCT or other medical treatment
  - ...
- A user may want to change
  - Total cross section
  - Particle cross section(s)
  - Particle yield(s)
  - Reaction channel

Simple way to change ParticleHP data (1/2)

- Understanding ParticleHP format should make possible for a user to change some cross sections
  - Sometimes it may be cumbersome
- A simple application code to do it:
  - User just have to write a file with simple tags and a double-column list :
    energy - XS
  - Currently, code only supports **charged particle cross sections** which have **only data in the F02 directory** (all except 24 out of the 2792 isotopes)
  - Is it useful?
  - Where do we put it?

Parallel 4B : Loic Thulliez “*Recent developments in thermal neutrons*“

- Great progress in the treatment of thermal neutrons (< 4 eV) in Geant4
    - Improved the code
    - New thermal data libraries
    - Documented python tool to produce thermal data libraries
    - Two experts in neutron physics have joined the Collaboration
    - Geant4 getting on par with MCNP & Tripoli for neutrons below 20 MeV
        - Not any longer exception for neutrons below 4 eV

My personal opinion: good small group of experts in neutronics, but still missing someone who can dedicate a large fraction of FTE to maintain and develop ParticleHP (as Tatsumi did for several years)

Parallel 4B : Loic Thulliez *“Recent developments in thermal neutrons“*

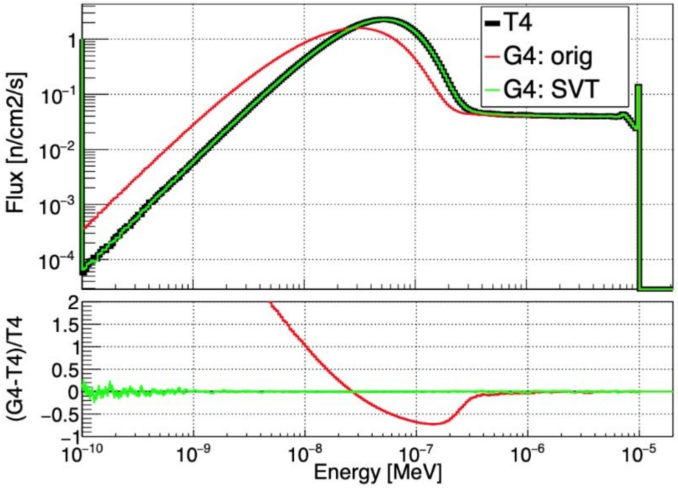


Figure 1: Neutron flux obtained with the sphere benchmark with the ENDF/B-VII.1 library for a ^{12}C free gas medium (top plot) and their relative differences using TRIPOLI-4® as the reference (bottom plot), for Geant4 original algorithm (red curve), Geant4 modified algorithm (green curve) and TRIPOLI-4® (black curve).

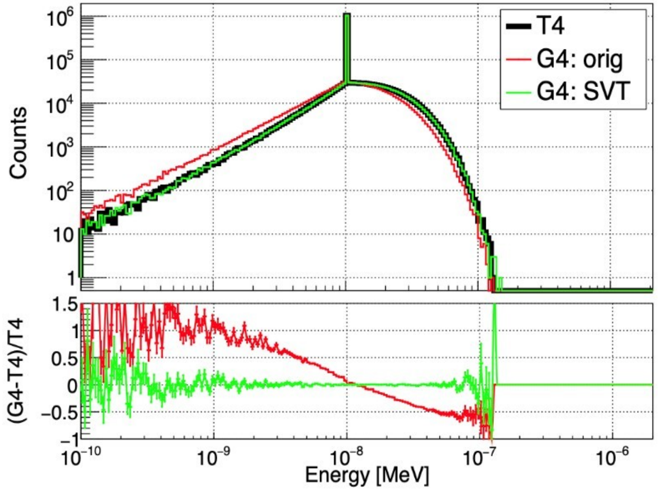


Figure 2: Scattered neutron energy spectrum obtained with the thin cylinder benchmark with the ENDF/B-VII.1 library for a ^{12}C free gas medium (top plot) and their relative differences using TRIPOLI-4® as the reference (bottom plot) for Geant4 original algorithm (red curve), Geant4 modified algorithm (green curve) and TRIPOLI-4® black curve).

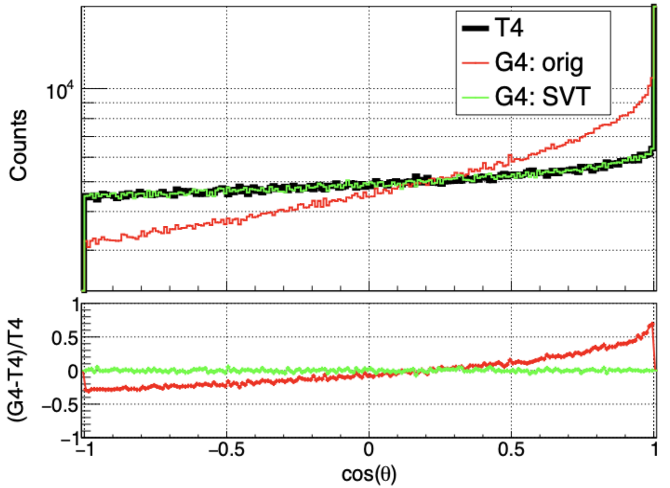


Figure 3: Scattered neutron cosinus angle obtained with the thin cylinder benchmark with the ENDF/B-VII.1 library for a ^{12}C free gas medium (top plot) and their relative differences using TRIPOLI-4® as the reference (bottom plot) for Geant4 original algorithm (red curve), Geant4 modified algorithm (green curve) and TRIPOLI-4® (black curve).

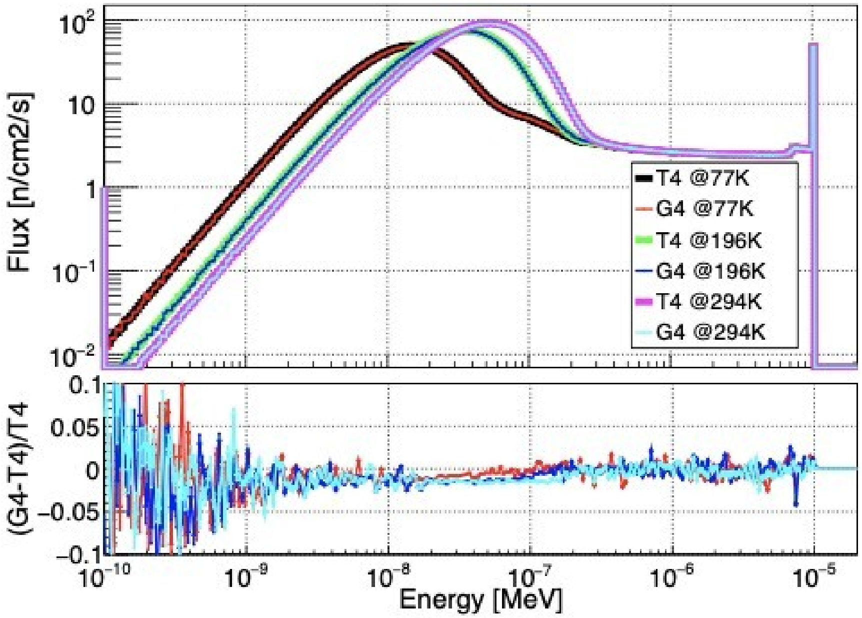


Figure 7: Neutron flux obtained with the sphere benchmark with the ENDF/B-VIII.0 library for a polyethylene (CH_2) medium as a function of the temperature (top plot) and their relative differences using TRIPOLI-4® as the reference (bottom plot).

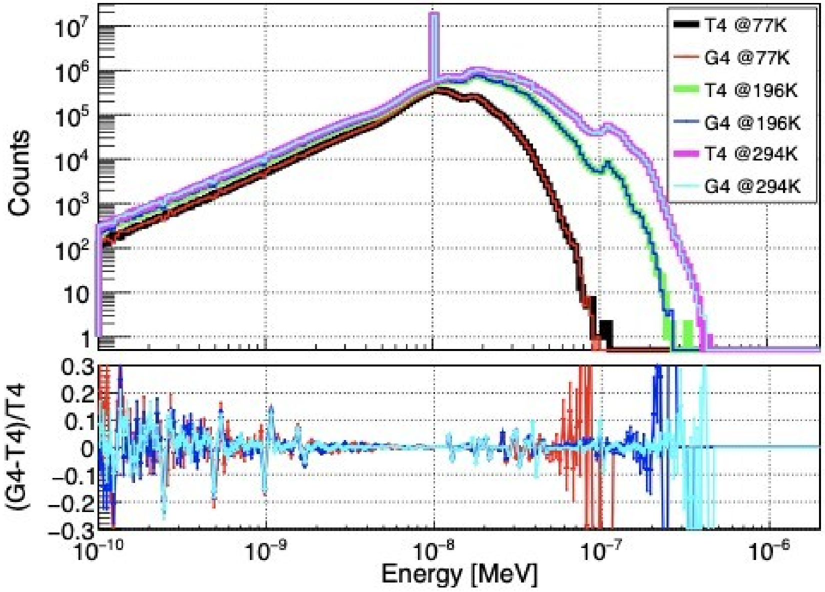


Figure 8: Scattered neutron energy spectrum obtained with the thin cylinder benchmark with the ENDF/B-VIII.0 library for a polyethylene (CH_2) medium as a function of the temperature (top plot) and their relative differences using TRIPOLI-4® as the reference (bottom plot).

WHAT ARE THE NEW LIBRARIES?

Thermal scattering data from different libraries couples to JEFF-3.3 nuclear cross-sections, i.e. with G4NDL4.6

ENDF/BVII-1:
ThermalScattering_XS_JEFF33_TSL_ENDFB71_HighPrecision
ThermalScattering_XS_JEFF33_TSL_ENDFB71_LowPrecision

ENDF/BVIII-0:
ThermalScattering_XS_JEFF33_TSL_ENDFB80_HighPrecision
ThermalScattering_XS_JEFF33_TSL_ENDFB80_LowPrecision

JEFF-3.3:
ThermalScattering_XS_JEFF33_TSL_JEFF33_HighPrecision
ThermalScattering_XS_JEFF33_TSL_JEFF33_LowPrecision

Mix JEFF-3.3 and ENDF/BVIII-0, take all TSL data from JEFF-3.3 and add the ENDF/BVIII-0 materials not in JEFF-3.3 :
ThermalScattering_XS_JEFF33_TSL_mix_JEFF33_ENDFB80_HighPrecision
ThermalScattering_XS_JEFF33_TSL_mix_JEFF33_ENDFB80_LowPrecision

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Improvement of Geant4 Neutron-HP package: From methodology to evaluated nuclear data library

L. Thulliez [a,*,1], C. Jouanne [b,1], E. Dumonteil [a,1]

[a] *IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France*

[b] *Université Paris-Saclay, CEA, Service d'études des réacteurs et de mathématiques appliquées, 91191 Gif-sur-Yvette, France*

ARTICLE INFO

Keywords:
Thermal neutrons
Thermal scattering law
Geant4
SVT method
Tripoli-4®
NJOY processing

ABSTRACT

An accurate description of interactions between thermal neutrons (below 4 eV) and materials is key to simulate the transport of neutrons in a wide range of applications such as criticality-safety, reactor physics, compact accelerator-driven neutron sources, radiological shielding or nuclear instrumentation, just to name a few. While the Monte Carlo transport code Geant4 was initially developed to simulate particle physics experiments, its use has spread to neutronics applications, requiring evaluated cross-sections for neutrons and gammas between 0 and 20 MeV (the so-called neutron High Precision – HP – package), as well as a proper offline or on-the-flight treatment of these cross-sections. In this paper we will point out limitations affecting the Geant4 (version 10.07.p01) thermal neutron treatment and associated nuclear data libraries, by using comparisons with the reference Monte Carlo neutron transport code Tripoli-4®, version 11, and we will present the results of various modifications of the Geant4 Neutron-HP package, required to overcome these limitations. Also, in order to broaden the support of nuclear data libraries compatible with Geant4, a nuclear processing tool has been developed (the code is available on a GitLab repository) and validated allowing the use of the code together with ENDF/B-VIII.0 and JEFF-3.3 libraries for example. These changes will be taken into account in an upcoming Geant4 release.

→improvements in the TSL algorithms used in Geant4

→new TSL processing tool produced to generate new TSL libraries for Geant4 users

Open source code available online:

https://gitlab.com/lthullie/geant4_tsl_processing

Parallel 4B : Eric Dumonteil

“*Variance reduction using Adaptive Multilevel Splitting (AMS)*“

- Very interesting biasing technique
  - With an apparently rather simple algorithm
    - Whereas the mathematics behind it is quite sophisticated!
  - This approach **preserves correlations between particles**
    - Contrary to (all or most?) other biasing techniques
- C++ implementation, compatible with Geant4, exists
  - Still to be integrated in Geant4 - possibly in a way compatible/consistent with the general biasing approach of Geant4
    - First discussions about it with Marc Verderi have started
  - Papers & documentation are already available
  - An example (followed later by others) is planned to show how to use it

AMS BASIC PRINCIPLES : ALGORITHM

Algorithm with 3 parameters

- **n (# of particles)**
- **k (# of particles duplicated/iteration)**
- **ξ (cost function)**

n particles simulated naturally => tracks are stored

score is assigned to each neutron track (= Max of ξ over whole trajectory)

tracks are ranked according to their score

the k-th “worst” track defines the new splitting level

the k tracks having scores lesser than this level are deleted

k tracks are randomly selected and duplicated at the splitting level

a new set of n particles is obtained, and we start the whole process again

AMS BASIC PRINCIPLES : ALGORITHM

Stopping criterium:

When n-k tracks have reached the “detector”, the algorithm stops

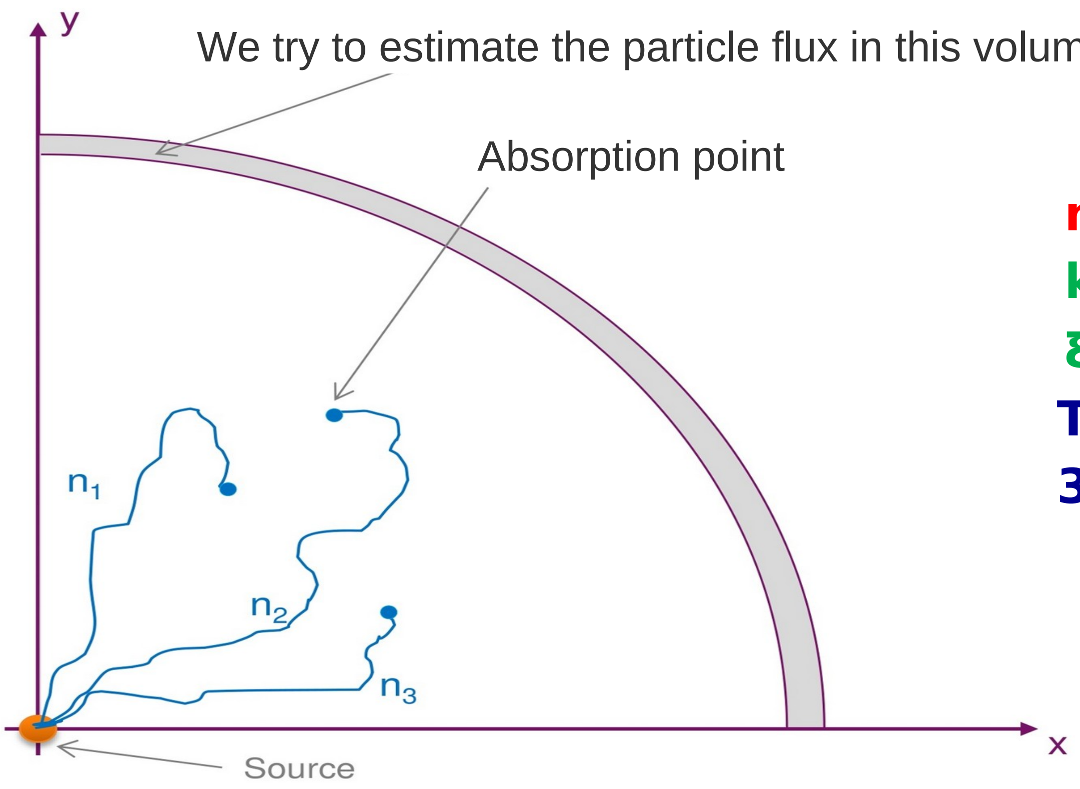
The number of iterations corresponding to reach that criterium is N

Each neutron is assigned a statistical weight α being:

$$\alpha = \left(1 - \frac{k}{n}\right)^{N}$$

An unbiased estimator of the flux is calculated “as usual” using the tracks of the last iteration

AMS BASIC PRINCIPLES : ALGORITHM



n=3

k=1

ξ: distance to the source

Target: spherical shell (purple)

3 particles simulated from the source to their absorption (blue points)

CONCLUSIONS

AMS developments within Geant4 have been verified and validated
- **on the flight scorers**
- **branching processes**

Might be useful in particle physics, and more generally in context where one is interested in:
- **Simulation of rare events / processes (multiparticles cascades)**
- **Simulation of correlated background noise**
- **Simulation of events resulting from the correlation of different particles detected in different detectors**

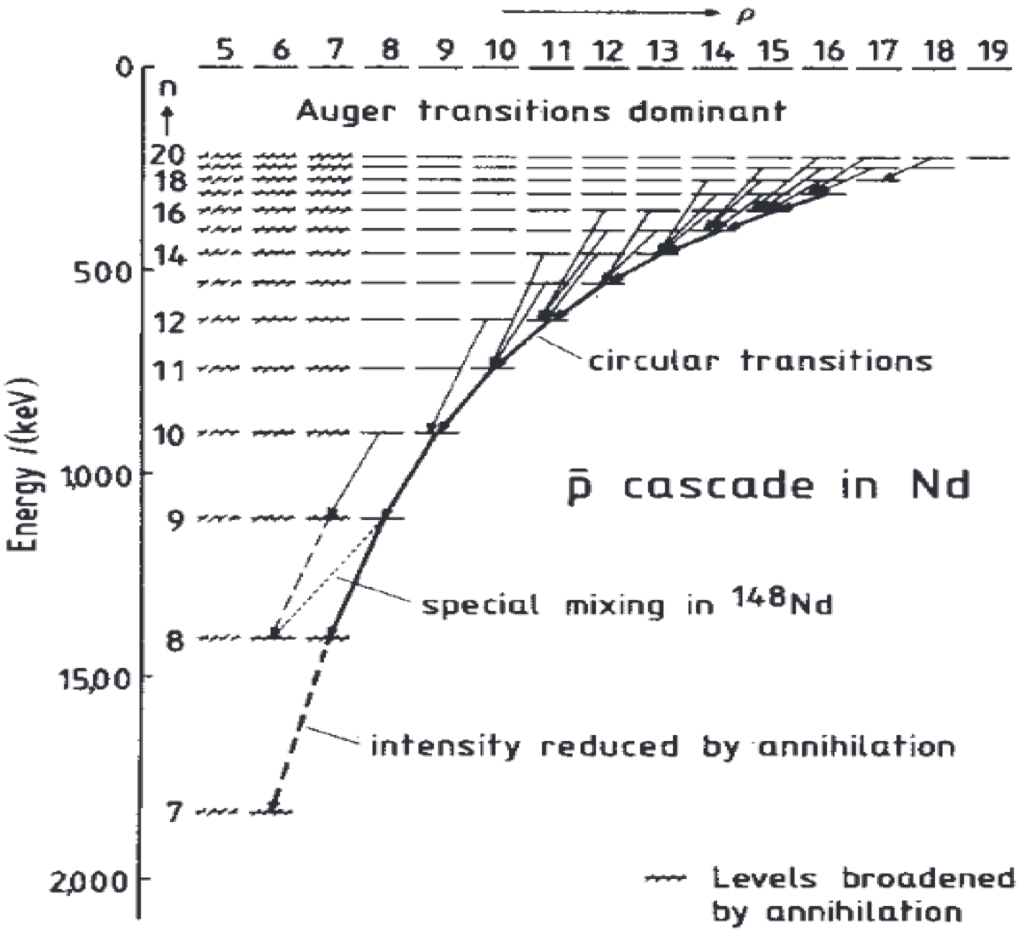
Particularily efficient when the “importance function” is unknown as it is robust

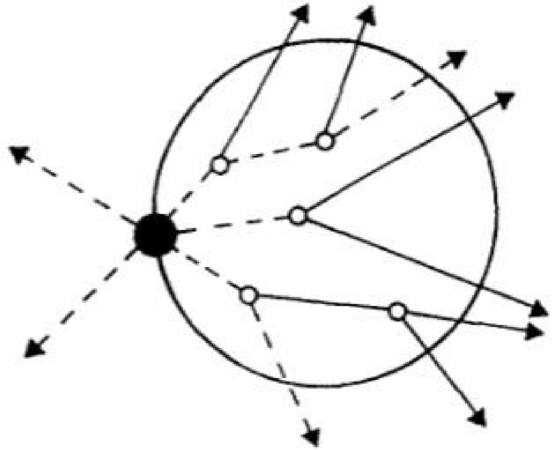
Parallel 6B : Demid Zharenov

“Update on the extension of the INCL model for antiprotons“

- Great interest for the extension of INCL to antiprotons
  - From various experiments – at rest (antiproton physics at CERN, astroparticle experiments like GAPS), high-energy (PANDA at FAIR)
  - Currently, in Geant4 we have only FTF for modeling antiproton interactions, but an intranuclear cascade model can provide a more precise modeling for at rest and low-energy antiproton annihilations
- Plan in INCL to attack first the annihilation at rest, then later in-flight interactions
  - Significant progress achieved so far, but likely not ready in time to be included in G4 11.1

At rest annihilation





Final state probabilities

TABLE 1

Probabilities of intermediate channels (in %) that were used to simulate p̄p annihilation at rest

Channel	Probability, ref.	Channel	Probability, ref.	Channel	Probability, ref.
$\eta\eta$	0.01 [17]	$\pi^+\rho^-\omega$	1.10	$\pi^+\pi^+\pi^-\pi^0\rho^-$	0.16
$\eta\omega$	0.34 [18]	$\pi^-\rho^+\omega$	1.10	$\pi^+\pi^-\pi^-\pi^0\rho^+$	0.16
$\omega\omega$	1.57 [19]	$\pi^0\rho^0\omega$	0.57	$\pi^+\pi^-\pi^0\pi^0\rho^0$	0.12
$\pi^+\pi^-$	0.40 [20]	$\eta\eta\pi^0$	0.11	$\pi^+\pi^0\pi^0\pi^0\rho^-$	0.04
$\pi^0\pi^0$	0.02 [21]	$\eta\omega\pi^0$	0.30	$\pi^-\pi^0\pi^0\pi^0\rho^+$	0.04
$\pi^+\rho^-$	1.52 [22]	$\omega\omega\pi^0$	0.37	$\pi^0\pi^0\pi^0\pi^0\rho^0$	0.01
$\pi^-\rho^+$	1.52 [22]	$\eta\eta\pi^+\pi^-$	0.07	$\pi^+\pi^+\pi^-\pi^-\eta$	0.11 [20]
$\pi^0\rho^0$	1.57 [23]	$\eta\eta\pi^0\pi^0$	0.02	$\pi^+\pi^-\pi^0\pi^0\eta$	0.22 [a]
$\rho^+\rho^-$	3.37 [a]	$\eta\omega\pi^+\pi^-$	0.04	$\pi^0\pi^0\pi^0\pi^0\eta$	0.01 [a]
$\rho^0\rho^0$	0.67 [24]	$\eta\omega\pi^0\pi^0$	0.01	$\pi^+\pi^+\pi^-\pi^-\omega$	1.80 [20]
$\pi^0\eta$	0.06 [23]	$\pi^+\pi^-\pi^0\eta$	1.22	$\pi^+\pi^-\pi^0\pi^0\omega$	2.58 [a]
$\pi^0\omega$	0.58 [23]	$\pi^0\pi^0\pi^0\eta$	0.17	$\pi^0\pi^0\pi^0\pi^0\omega$	0.10 [a]
$\rho^0\eta$	0.90 [18]	$\pi^+\pi^-\pi^0\omega$	2.84	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	2.83
$\rho^0\omega$	0.79 [22]	$\pi^0\pi^0\pi^0\omega$	0.40	$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	9.76
$\pi^+\pi^-\pi^0$	2.34 [20]	$\pi^+\pi^-\rho^0\eta$	0.06	$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	2.68
$\pi^0\pi^0\pi^0$	1.12 [25]	$\pi^+\pi^0\rho^-\eta$	0.06	$\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0$	0.07
$\pi^+\pi^-\rho^0$	2.02 [20]	$\pi^-\pi^0\rho^+\eta$	0.06	$\pi^+\pi^+\pi^+\pi^-\pi^-\rho^-$	0.02
$\pi^+\pi^0\rho^-$	2.02 [a]	$\pi^0\pi^0\rho^0\eta$	0.02	$\pi^+\pi^+\pi^-\pi^-\pi^-\rho^+$	0.02
$\pi^-\pi^0\rho^+$	2.02 [a]	$\pi^+\pi^+\pi^-\pi^-$	2.74	$\pi^+\pi^+\pi^-\pi^-\pi^0\rho^0$	0.06
$\pi^0\pi^0\rho^0$	1.01 [a]	$\pi^+\pi^-\pi^0\pi^0$	3.89	$\pi^+\pi^+\pi^-\pi^0\pi^0\rho^-$	0.06
$\pi^+\rho^-\rho^0$	1.23	$\pi^0\pi^0\pi^0\pi^0$	0.21	$\pi^+\pi^-\pi^-\pi^0\pi^0\rho^+$	0.06
$\pi^-\rho^+\rho^0$	1.23	$\pi^+\pi^+\pi^-\rho^-$	2.58 [24]	$\pi^+\pi^-\pi^0\pi^0\pi^0\rho^0$	0.03
$\pi^0\rho^+\rho^-$	1.23	$\pi^+\pi^-\pi^-\rho^+$	2.58 [24]	$\pi^+\pi^0\pi^0\pi^0\pi^0\rho^-$	0.01
$\pi^0\rho^0\rho^0$	0.54	$\pi^+\pi^-\pi^0\rho^0$	6.29 [24]	$\pi^-\pi^0\pi^0\pi^0\pi^0\rho^+$	0.01
$\pi^+\pi^-\eta$	1.50 [24]	$\pi^+\pi^0\pi^0\rho^-$	5.05 [a]	$\pi^+\pi^+\pi^-\pi^-\pi^0\eta$	0.31
$\pi^0\pi^0\eta$	0.94 [18]	$\pi^-\pi^0\pi^0\rho^+$	5.05 [a]	$\pi^+\pi^-\pi^0\pi^0\pi^0\eta$	0.17
$\pi^+\pi^-\omega$	3.03 [20]	$\pi^0\pi^0\pi^0\rho^0$	0.77 [a]	$\pi^0\pi^0\pi^0\pi^0\pi^0\eta$	0.01
$\pi^0\pi^0\omega$	0.79 [a]	$\pi^+\pi^+\pi^-\pi^-\pi^0$	2.61	$\pi^+\pi^+\pi^-\pi^-\pi^0\omega$	0.10
$\pi^+\rho^-\eta$	0.84	$\pi^+\pi^-\pi^0\pi^0\pi^0$	1.37	$\pi^+\pi^-\pi^0\pi^0\pi^0\omega$	0.06
$\pi^-\rho^+\eta$	0.84	$\pi^0\pi^0\pi^0\pi^0\pi^0$	0.07		
$\pi^0\rho^0\eta$	0.44	$\pi^+\pi^-\pi^+\pi^-\rho^0$	0.08		

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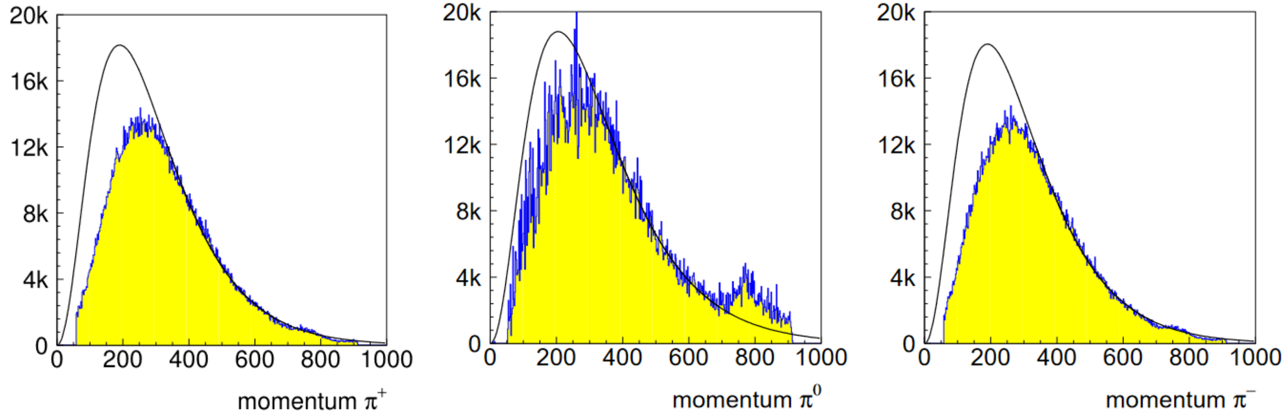
TABLE 2

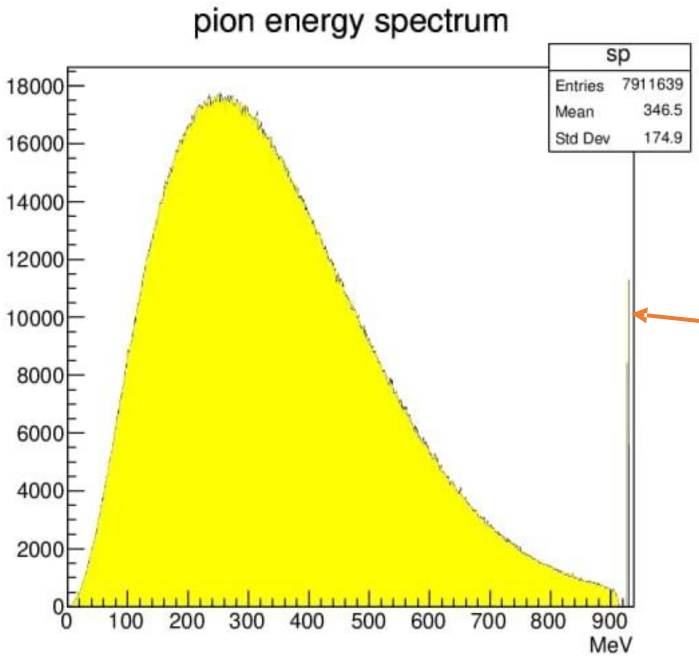
Probabilities of intermediate channels (in %) that were used to simulate p̄n annihilation at rest

Channel	Probability, ref.	Channel	Probability, ref. .	Channel	Probability
$\pi^-\pi^0$	0.49 [26]	$\eta\omega\pi^-$	0.60	$\pi^+\pi^-\pi^0\pi^0\rho^-$	0.16
$\pi^-\omega$	0.48 [27]	$\omega\omega\pi^-$	0.71	$\pi^-\pi^-\pi^0\pi^0\rho^+$	0.08
$\pi^-\rho^0$	0.47 [10]	$\eta\eta\pi^-\pi^0$	0.06	$\pi^-\pi^0\pi^0\pi^0\rho^0$	0.05
$\pi^0\rho^-$	0.47 [a]	$\eta\omega\pi^-\pi^0$	0.03	$\pi^0\pi^0\pi^0\pi^0\rho^-$	0.01
$\rho^-\rho^0$	3.51 [b]	$\pi^+\pi^-\pi^-\eta$	1.00	$\pi^+\pi^-\pi^-\pi^0\eta$	0.37
$\pi^-\eta$	0.29 [10]	$\pi^-\pi^0\pi^0\eta$	0.67	$\pi^-\pi^0\pi^0\pi^0\eta$	0.09
ρ^- .,	2.27	$\pi^+\pi^-\pi^-\omega$	10.52 [10]	$\pi^+\pi^-\pi^-\pi^0\omega$	0.40
$\rho^-\omega$	3.51 [b]	$\pi^-\pi^0\pi^0\omega$	7.01 [a]	$\pi^-\pi^0\pi^0\pi^0\omega$	0.09
$\pi^+\pi^-\pi^-$	2.86	$\pi^+\pi^-\rho^-\eta$	0.08	$\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$	8.33
$\pi^-\pi^0\pi^0$	1.90	$\pi^-\pi^-\rho^+\eta$	0.05	$\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$	6.67
$\pi^+\pi^-\rho^-$	3.62 [10]	$\pi^-\pi^0\rho^0\eta$	0.06	$\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0$	0.56
$\pi^-\pi^-\rho^+$	0.58 [10]	$\pi^0\pi^0\rho^-\eta$	0.02	$\pi^+\pi^+\pi^-\pi^-\pi^-\rho^0$	0.02
$\pi^-\pi^0\rho^0$	5.61 [a]	$\pi^+\pi^-\pi^-\pi^0$	5.51	$\pi^+\pi^+\pi^-\pi^-\pi^0\rho^-$	0.07
$\pi^0\pi^0\rho^-$	3.51 [a]	$\pi^-\pi^0\pi^0\pi^0$	1.38	$\pi^+\pi^-\pi^-\pi^-\pi^0\rho^+$	0.05
$\pi^+\rho^-\rho^-$	1.04	$\pi^+\pi^-\pi^-\rho^0$	0.99	$\pi^+\pi^-\pi^-\pi^0\pi^0\rho^0$	0.06
$\pi^-\rho^+\rho^-$	2.09	$\pi^+\pi^-\pi^0\rho^-$	1.97	$\pi^+\pi^-\pi^0\pi^0\pi^0\rho^-$	0.03
$\pi^-\rho^0\rho^0$	0.70	$\pi^-\pi^-\pi^0\rho^+$	0.99	$\pi^-\pi^-\pi^0\pi^0\pi^0\rho^+$	0.02
$\pi^0\rho^-\rho^0$	1.39	$\pi^-\pi^0\pi^0\rho^0$	0.75	$\pi^-\pi^0\pi^0\pi^0\pi^0\rho^0$	0.01
$\pi^-\pi^0\eta$	1.23	$\pi^0\pi^0\pi^0\rho^-$	0.25	$\pi^+\pi^+\pi^-\pi^-\pi^-\eta$	0.14
$\pi^-\pi^0\omega$	5.05	$\pi^+\pi^+\pi^-\pi^-\pi^-$	1.24	$\pi^+\pi^-\pi^-\pi^0\pi^0\eta$	0.30
$\pi^-\rho^0\eta$	0.78	$\pi^+\pi^-\pi^-\pi^0\pi^0$	2.72	$\pi^-\pi^0\pi^0\pi^0\pi^0\eta$	0.05
$\pi^0\rho^-\eta$	0.78	$\pi^-\pi^0\pi^0\pi^0\pi^0$	0.37	$\pi^+\pi^+\pi^-\pi^-\pi^-\omega$	0.05
$\pi^-\rho^0\omega$	1.03	$\pi^+\pi^+\pi^-\pi^-\rho^-$	0.12	$\pi^+\pi^-\pi^-\pi^0\pi^0\omega$	0.09
$\pi^0\rho^-\omega$	1.03	$\pi^+\pi^-\pi^-\pi^-\rho^+$	0.08	$\pi^-\pi^0\pi^0\pi^0\pi^0\omega$	0.01
$\eta\eta\pi^-$	0.21	$\pi^+\pi^-\pi^-\pi^0\rho^0$	0.16		

Final state particle momenta



Crystal Barrel data with Deuterium target



INCL embedded phase-space model

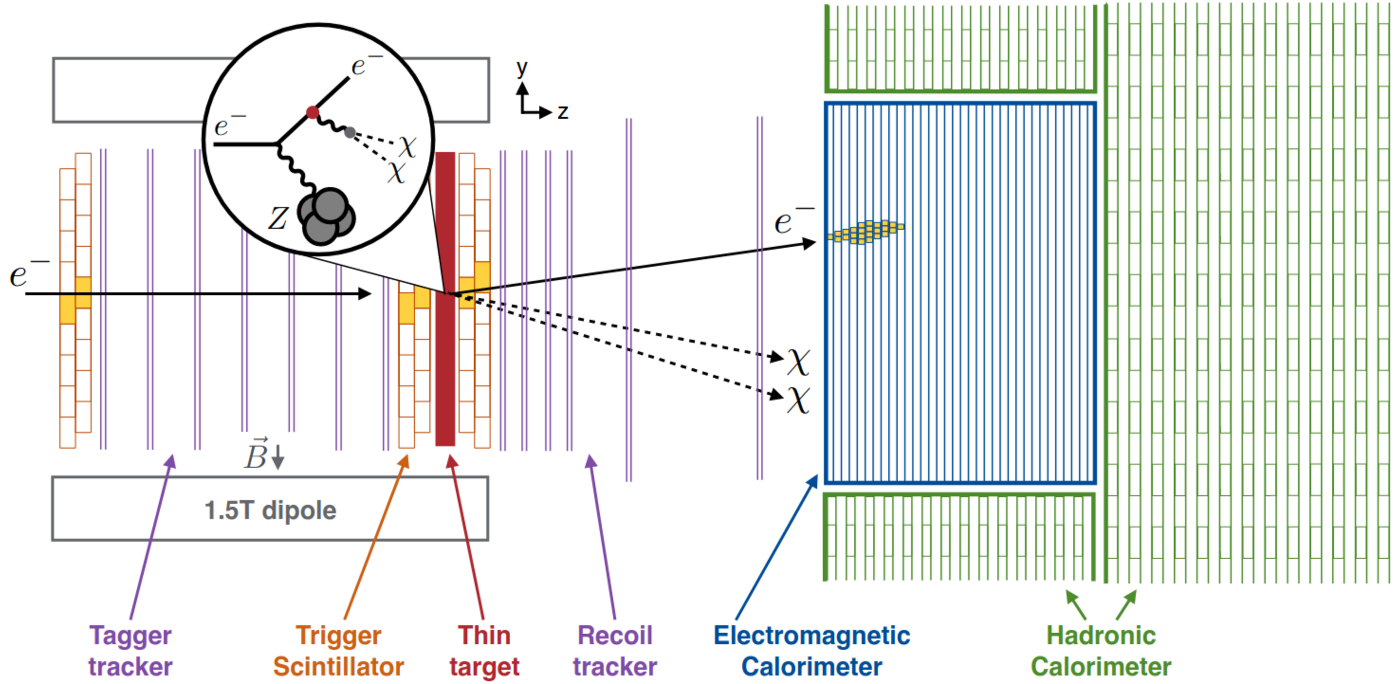
Parallel 6B : Einar Elen *“Calling Pythia8 generator to handle an interaction during a Geant4 simulation“*

- Specific need of a dark matter experiment (LDMX)
  - But of interest for many others!
- Excellent occasion to bridge between Geant4 and the strong MC event generator group in Lund
- Can be generalized/extended to other MC event generators
  - Though the coupling is done directly between Pythia8 and Geant4, not via HepMC
    - Special care is needed for particles produced by a generator which might not be recognized by Geant4...

Background & Context

LHC style experiments *typically* have clear separation between event generation and detector simulation – this is less true for other HEP applications; signal process often happens in the middle of the simulation

LDMX



Two goals:

1. Flexible signal simulation for LDMX using Pythia8 in Geant4
2. Making what we learn useful outside of our particular use-case

Pythia8 as an primary generator

Wanted a simple Geant4 component but with full-featured Pythia events:

- Picked a Pythia8-based primary generator action combined with a version of J. Yarba’s Py8Decayer example
- Can also take decays directly from Pythia event

Flexible signal simulation

Hard process simulation for experiments like LDMX.

LDMX has a simulation / reconstruction framework including Geant4 simulation with a model for dark bremsstrahlung in target (signal simulation relies on library of pre-generated events from MadGraph for various electron momenta).

Works for a given model, but changing models is non-trivial and not feasible for people outside of the LDMX software group.

Use exact kinematics of the event: requires a Pythia object set up for specific beam type and kinematics; handling creation and lifetime of such objects is challenging

Parallel 6B : Gabrielle Hugo

"*Fluka-Cern hadronic event generator interface*"

- First, important step towards the use of Fluka-Cern hadronic physics from Geant4
  - C++ interface for Geant4 to call current Fortran Fluka-Cern
- Access to (elastic and inelastic) hadron-nuclear cross sections, and final-state of inelastic hadron-nuclear interactions
  - As a function of projectile type, kinetic energy, target nucleus
  - Created already new G4 classes representing Fluka-Cern cross section, final-state, physics constructor, and physics list
    - Inheriting from, respectively: *G4VCrossSectionDataSet* , *G4HadronicInteraction* , *G4VPhysicsConstructor* , *G4VModularPhysicsList*
  - Can become an hadronic example for G4 11.2

context

GOAL

Make FLUKA physics models available to the G4 community.

General context: **increasing FLUKA openness and synergies with G4.**

PROPOSAL

Interface giving access to FLUKA PEANUT (hadronic interactions modeling) from G4.

- Give **direct access to FLUKA Physics from the G4-based user applications and experiments frameworks**.

Hadronic interactions modeling is **one of the main targets** of FLUKA Physics integration.

- To be followed by integration of additional FLUKA models (e.g. ion-nucleus).

First step in FLUKA code modernization and opening to the community.

- A second step will be to **modularize** the FLUKA code itself, to make it more maintainable, and possibly increase the granularity of the G4 integration.

DEPENDENCIES

- Interface **can be called in any G4 application** (e.g. **independent from MOIRA/FLUKA++**).
- **Registration to FLUKA and agreement to FLUKA exisiting license** is obviously needed.

Project structure

2 distinct projects:

G4↔ FLUKA interface

Standalone repository.

- Transparently **follow future FLUKA updates**.
- **Registration to FLUKA and agreement to its license** needed here.
  Need to **install FLUKA locally**, to be able to link and run the interface successfully.

G4 side

Created dedicated **Model (FlukaNuclearInelasticModel), XSDataSet (FlukaInelasticScatteringXS) [, PhysicsConstructor (FlukaHadronInelasticPhysics), PhysicsList].**

The interface can be called:

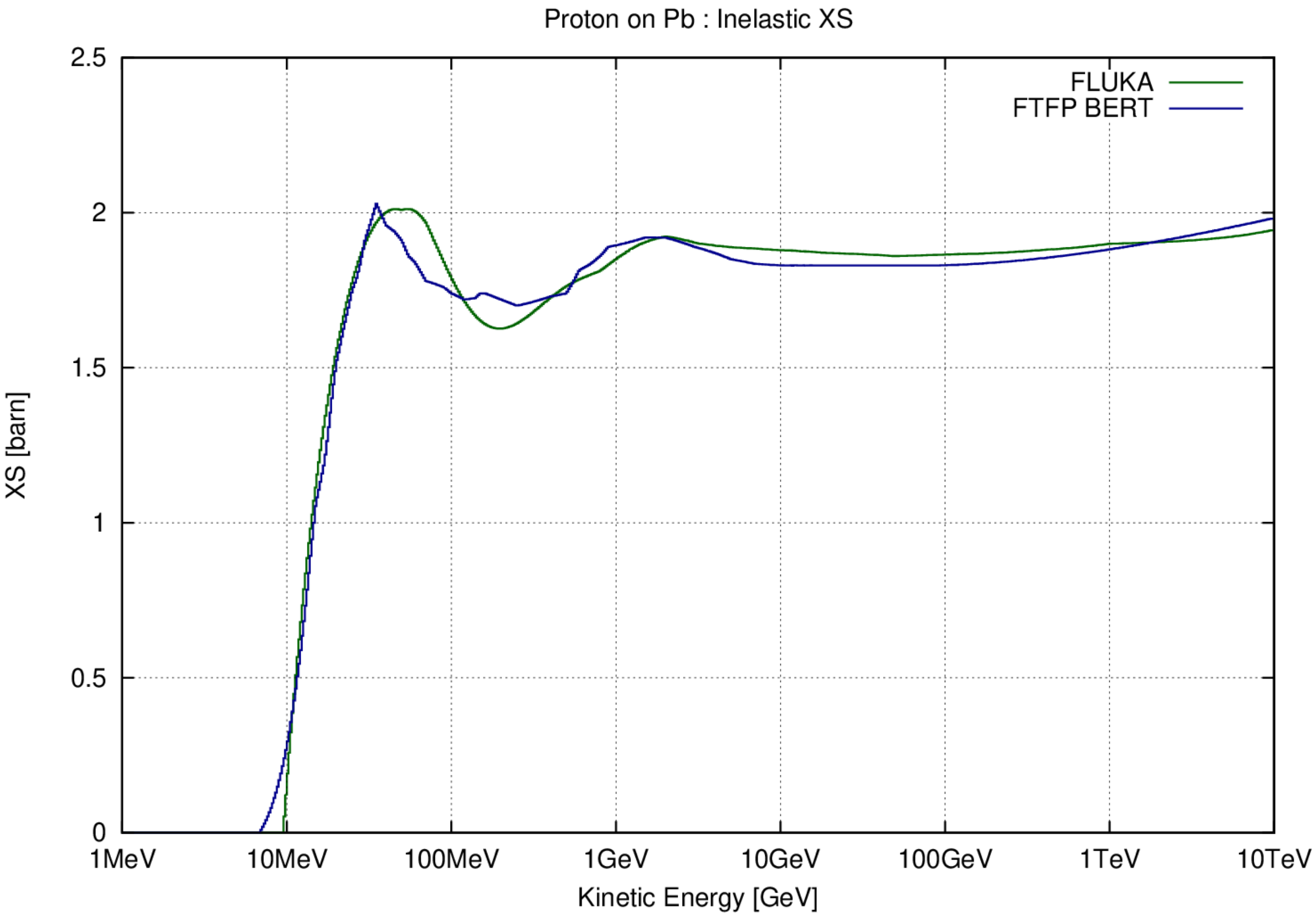
- **At the interaction level**
  Incorporated XS and final-state standalone applications as G4 examples.
- As a **comprehensive Physics list**
  `/physics_lists/select` in any G4 application (including MOIRA).

Integration to G4

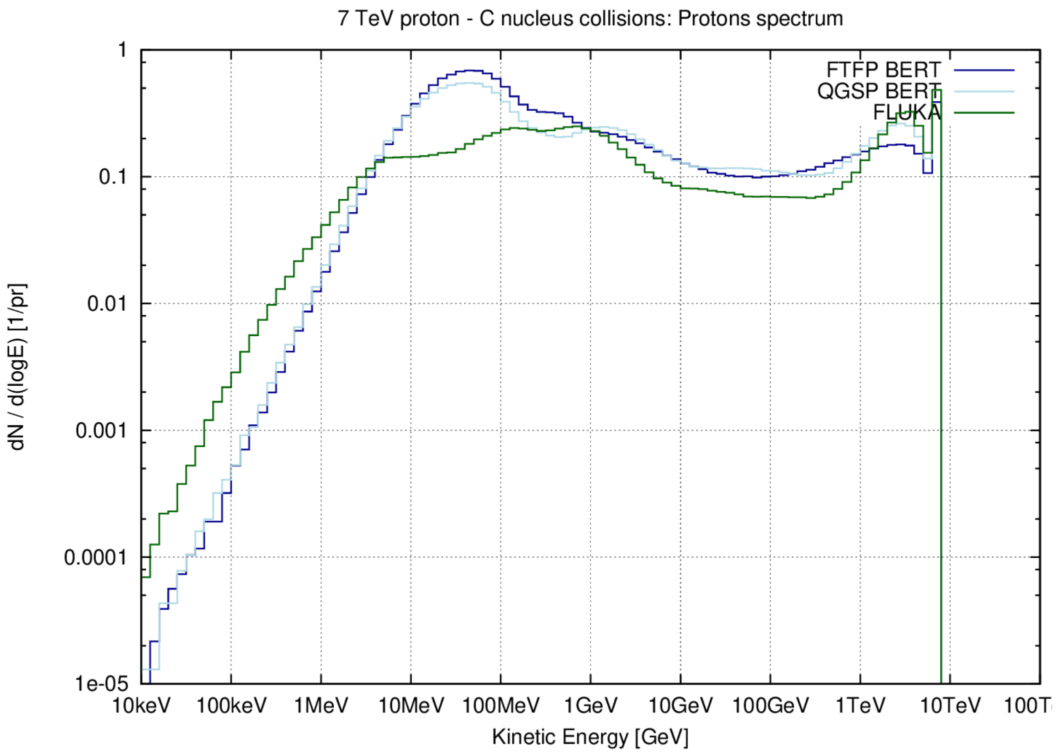
Fully open to discussion and G4 team preferences.

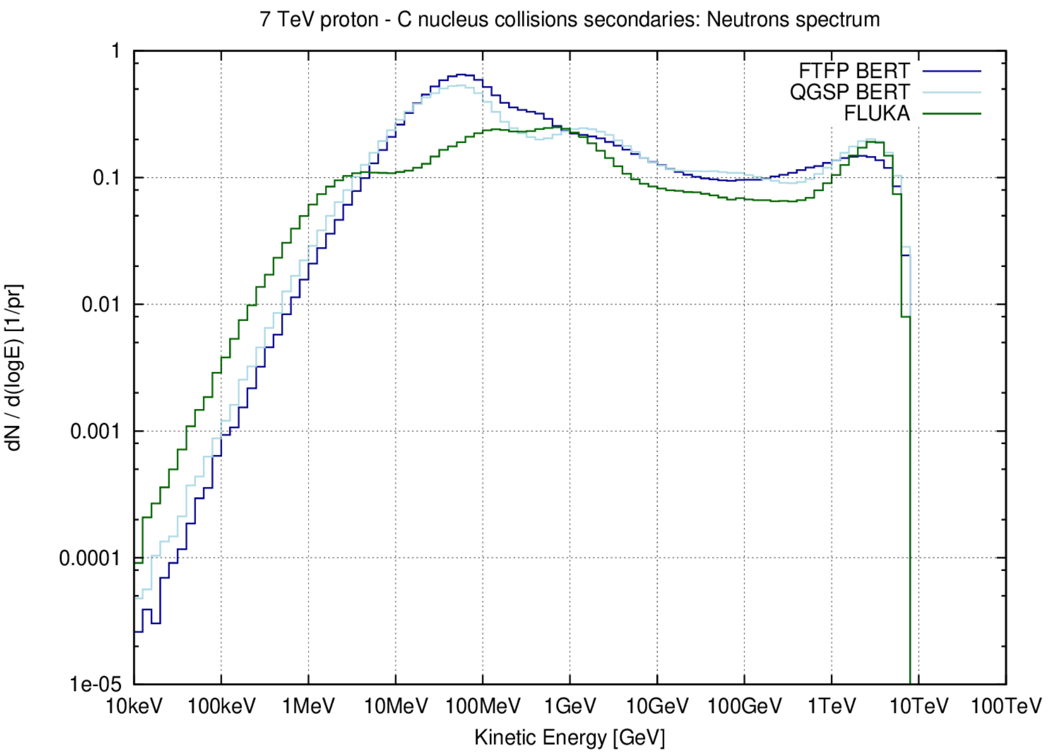
- Integrate FLUKA Model and XSDataSet
- Integrate to G4 examples the applications calling the FLUKA interface for interaction-level simulations.
- Would it also be useful to integrate the FlukaHadronInelasticPhysics PhysicsConstructor / a template PhysicsList?

Proton on Pb: inelastic xs

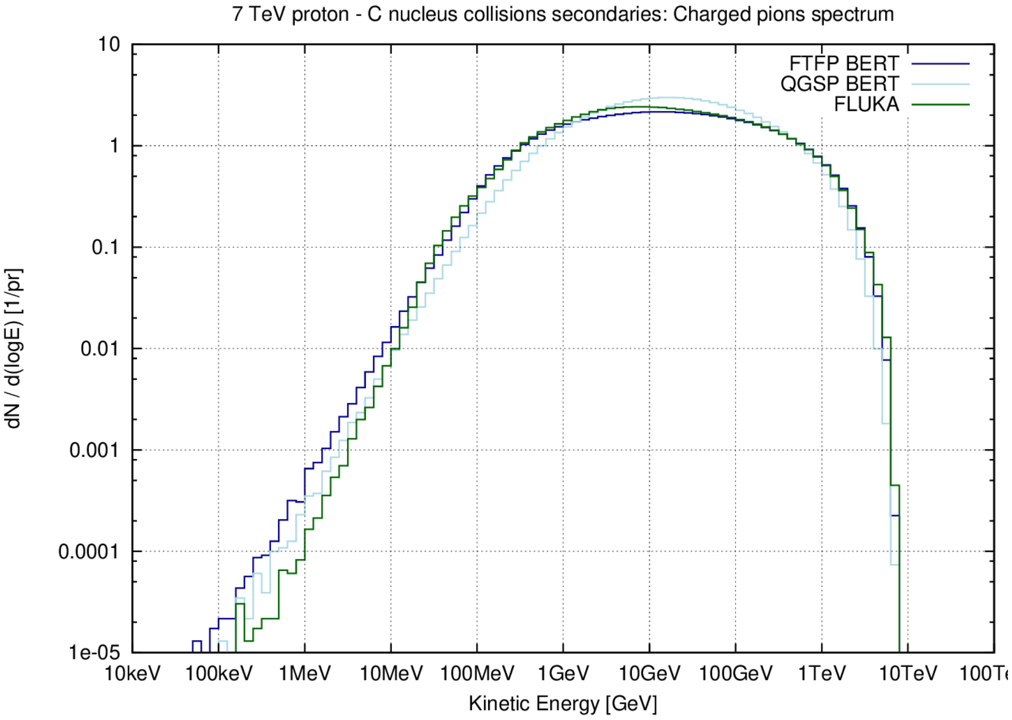


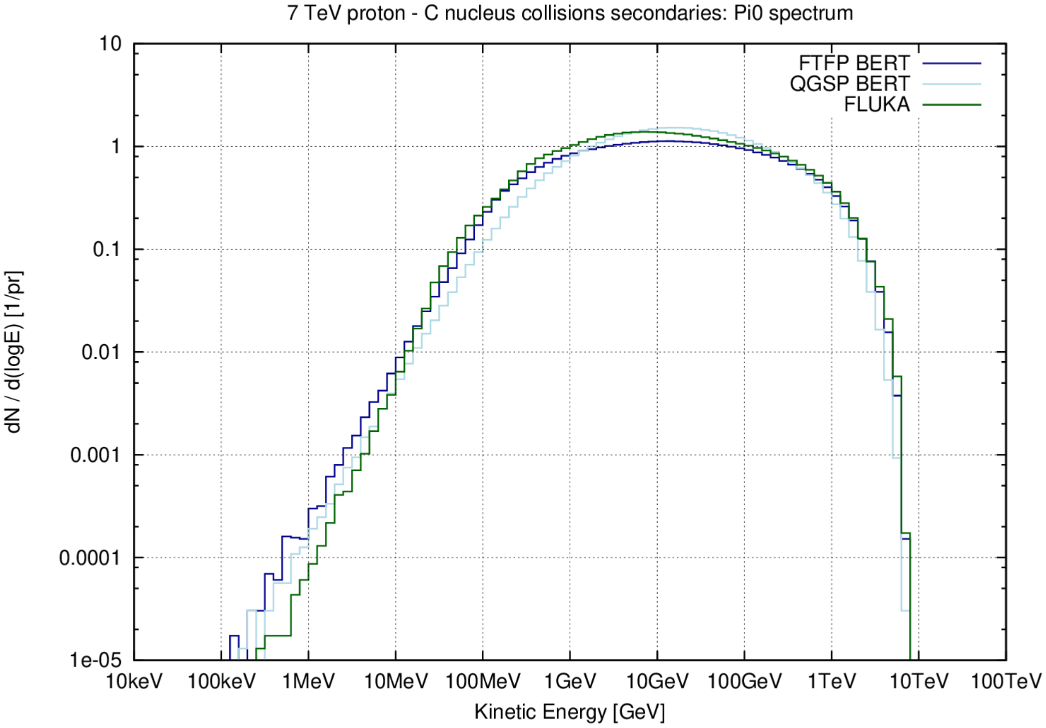
G4 ↔ FLUKA comparisons at the interaction level: FINAL states





G4 ↔ FLUKA comparisons at the interaction level: FINAL states





G4 ↔ FLUKA comparisons at the interaction level: FINAL states