GEANT4 and Pion Photo-production in the intermediate energy regime at Jefferson Lab

Sokhna Bineta Lo Amar

Advisor: Prof. Oumar Ka, UCAD
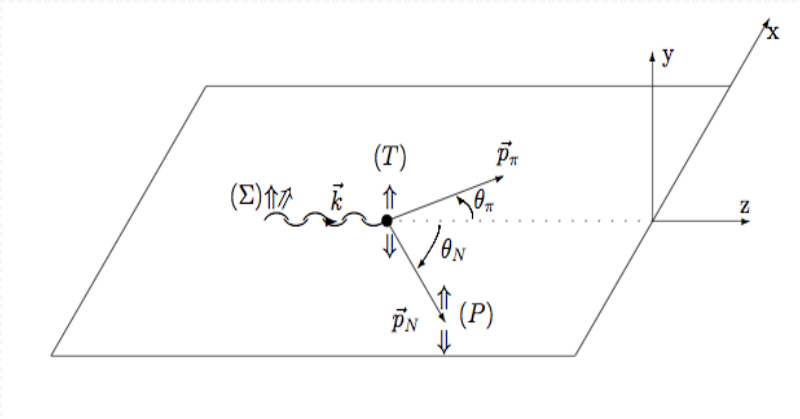**Co-Advisor: Dr. Paul Guèye, Hampton Univ./JLab/FRIB**

Université Cheikh Anta Diop, Dakar (Sénégal)

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- **Pion photo-production : alternative method for probing the matter**

  - Electromagnetic and hadronic Interactions combined

Resonances identified

  - In the intermediate energy regime

- **GEANT4,**

  - tool for simulation and data analysis
  - Validate G4 physics using Jlab data in the GeV range

Outline

- **GEANT4 Overview**

- **Cross section comparison**

- **Data comparison analysis**

- **Results**

  - ❖ **Total cross sections**

  - ❖ **Angular distribution**

  - ❖ **Total cross section integrated**

  - ❖ **Energetic distribution**

- **Conclusion & perspectives**

- **GEANT4** : **GE**ometry **AN**d **T**racking **4**

  - Developed and maintained by an international collaboration

- **Purpose**: simulate the interaction between particle and matter

- **Application**: high-energy, nuclear, space and material sciences to medical physics

- **Ingredients**

  - Large flexible set of models for physical interactions of leptons and hadrons

  - Electromagnetic and hadronic processes (both elastic and inelastic)

  - Range : eV to TeV

  - Extensive support of geometry and visualization tools + advanced scoring and tracking options
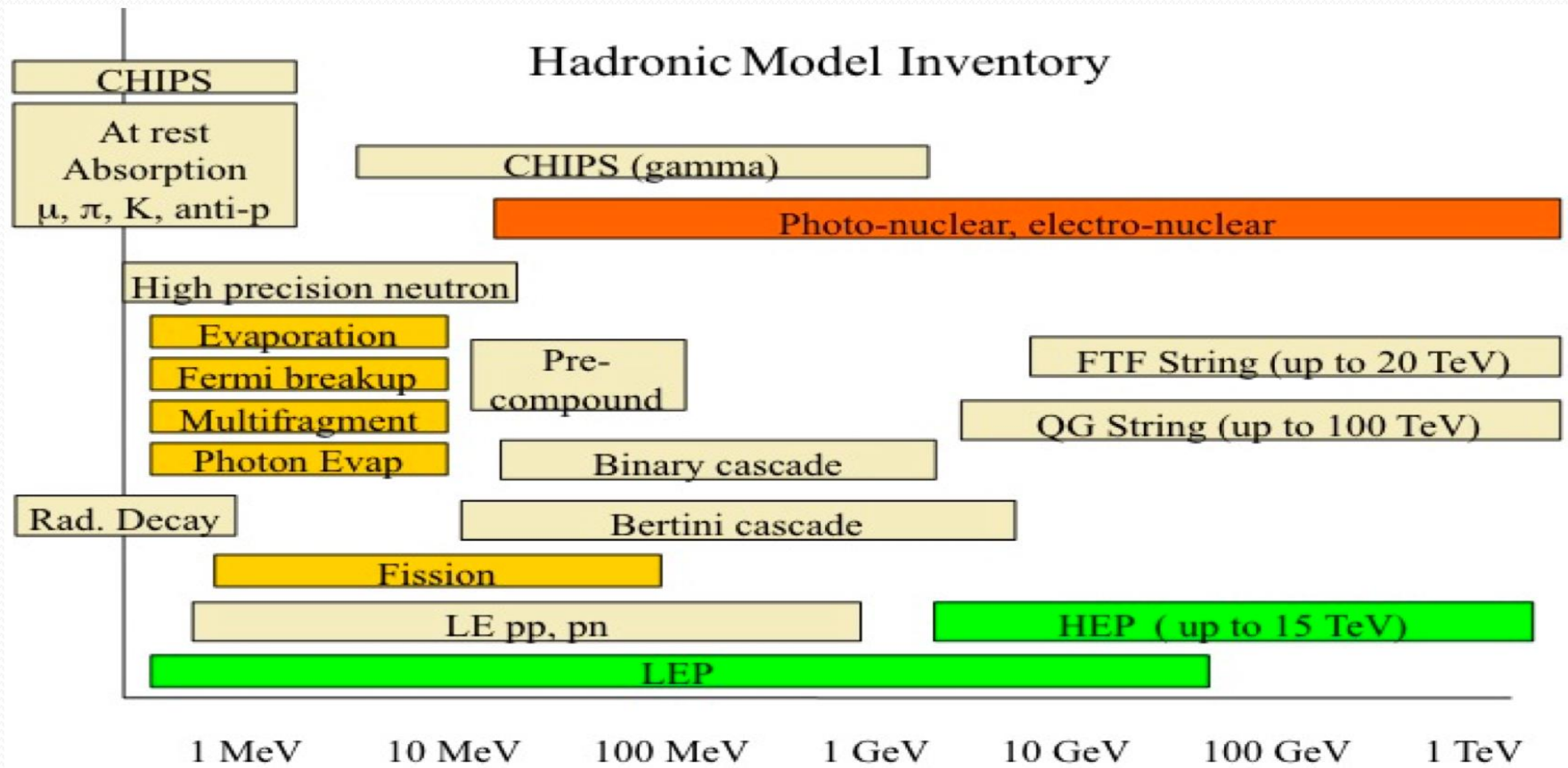
- Interactions in GEANT4 as a physical process and its associated model(s);

- Two distinct packages: electromagnetic physics and hadronic physics;

electromagnetic	hadronic
e+/-, γ, ions	fragmentation
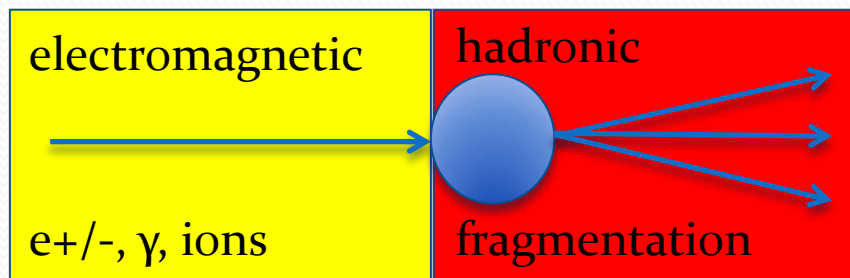
- Photo-and lepto-nuclear interactions in a hybrid process;

- Hadro-nuclear interaction in a hadronic process

- Tens of categories of hadronic models (Geant4 .9.6.po2)

Hadronic Model Inventory

CHIPS

At rest
Absorption
μ, π, K, anti-p

CHIPS (gamma)

Photo-nuclear, electro-nuclear

High precision neutron

Evaporation
Fermi breakup
Multifragment
Photon Evap

Pre-compound

FTF String (up to 20 TeV)

QG String (up to 100 TeV)

Binary cascade

Rad. Decay

Bertini cascade

Fission

LE pp, pn

HEP (up to 15 TeV)

LEP

| 1 MeV | 10 MeV | 100 MeV | 1 GeV | 10 GeV | 100 GeV | 1 TeV |

- Different models considering incidents particles

Model	Incident Particles	Incident Energy	Applications
Parameterized Low Energy Parameterized (LEP) High Energy Parameterized (HEP)	p, n, π, K, Λ, Σ, Ω, Ξ, α, t, d.	$0 \to \sim 30$ GeV $\sim 10 \to 15$ TeV	Describing showers in detectors
Pre-compound (PRECO)	p, n	$0 \to 170$ MeV	- Used for nucleus interactions at low energies
Cascade **Bertini (BERT)** Binary Invariant Cascade (BIC)	p, n, π, K, Λ, Σ^+, Σ^- Ω^-, Ξ^-, Ξ^0 p, n., **Gamma** π^+, π^-	$0 \to 10$ GeV $0 \to 10$ GeV $0 \to 1.3$ GeV	For intermediates energies
String Quark –Gluon –String (QGS) Fritiof (FTF)	p, n, K, π.	$\sim 10 \to \ \sim$ TeV Down to much lower ~ 3 GeV	Recommended for use in shielding applications as well in High energy
Chiral – Invariant – Phase – Space (CHIPS)	μ, π, K, anti-p, anti-baryon **Gamma**	At rest ~ 1MeV $\to \ \sim 1$GeV	For low to medium range energies
High Precision neutron (HP)	Neutrons	< 20 MeV	- Requires detailed for neutron transport - Can be used for radiation protection
Low Background experiments (LBE)		Low energies	
Other Capture Fission Isotope production	In a nucleus Modeling Sequence for π^-; Validation of CHIPS for Pion Neutron	At rest Low energies < 100 MeV From100 MeV down to thermal	Useful for activation studies

Cross sections comparison (1/3)

- **Jefferson Lab:** Pion photo-production experimental data from Hall B

- **Comparison:** PDG and GEANT4 (CHIPS & BERT)

  - **PDG:** Particle Data Group

    Large collaboration aimed at summarizing data for particle physics and related fields
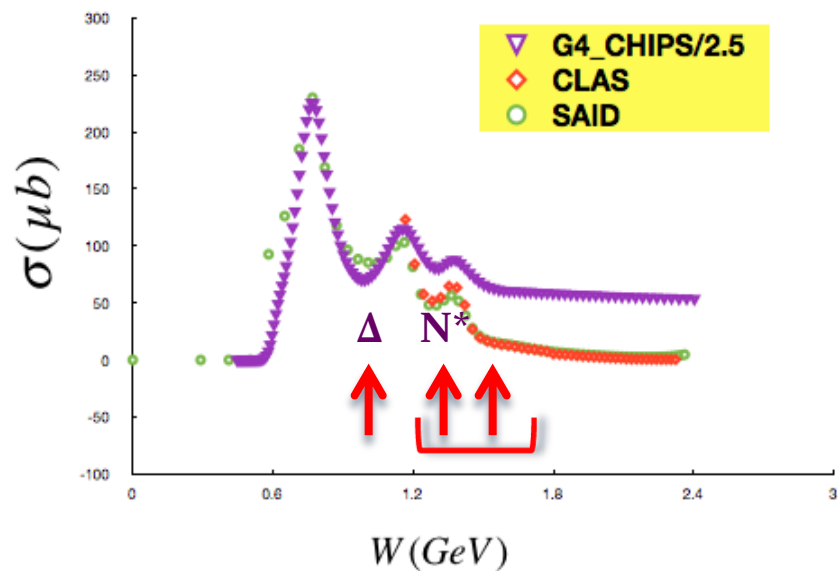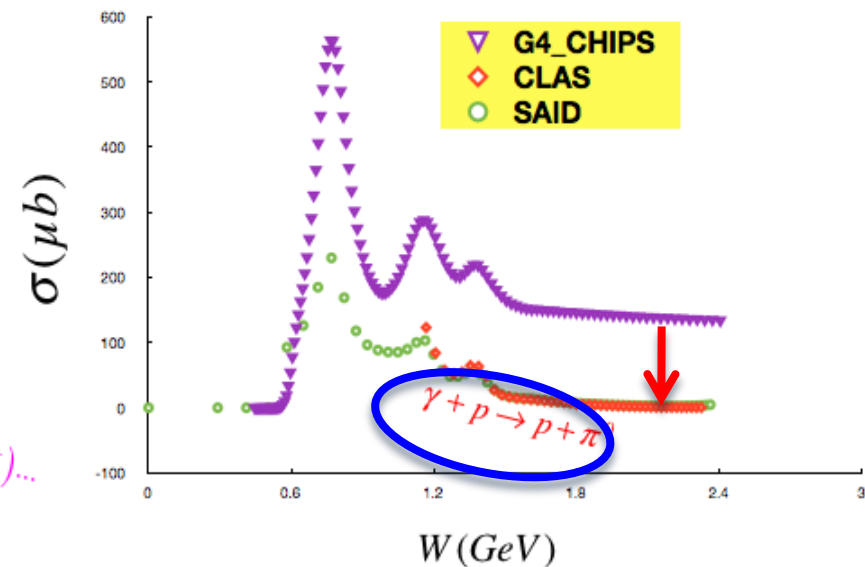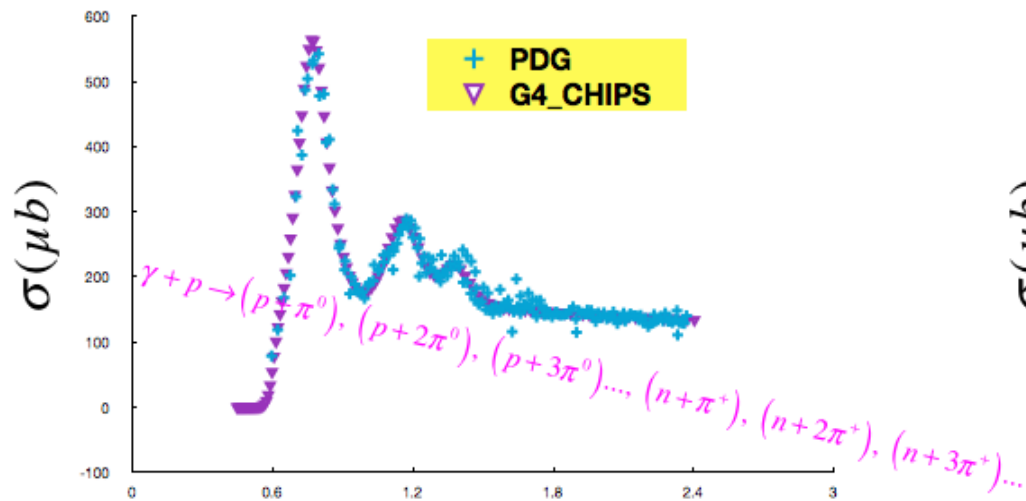   Database that includes various compilations and evaluations of elementary particles properties

  Comparison: GEANT4 and SAID+Jefferson Lab experimental data
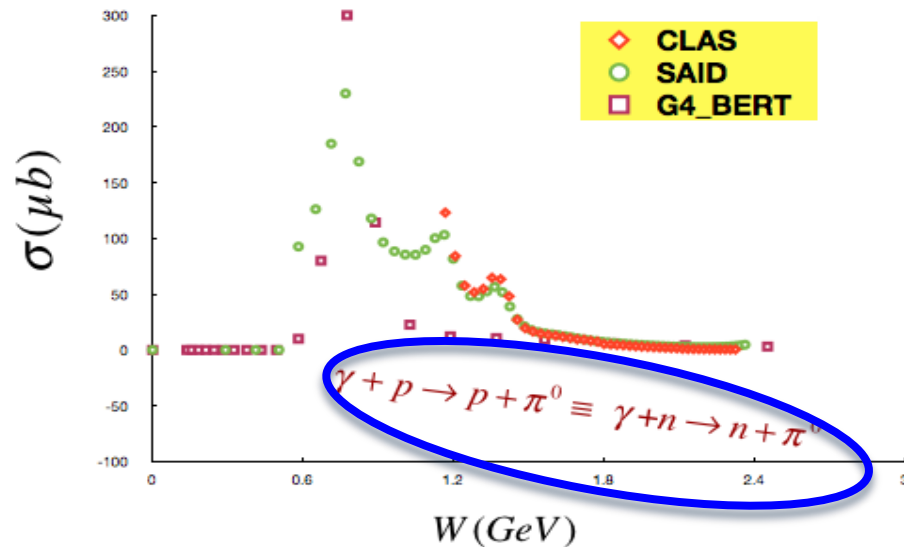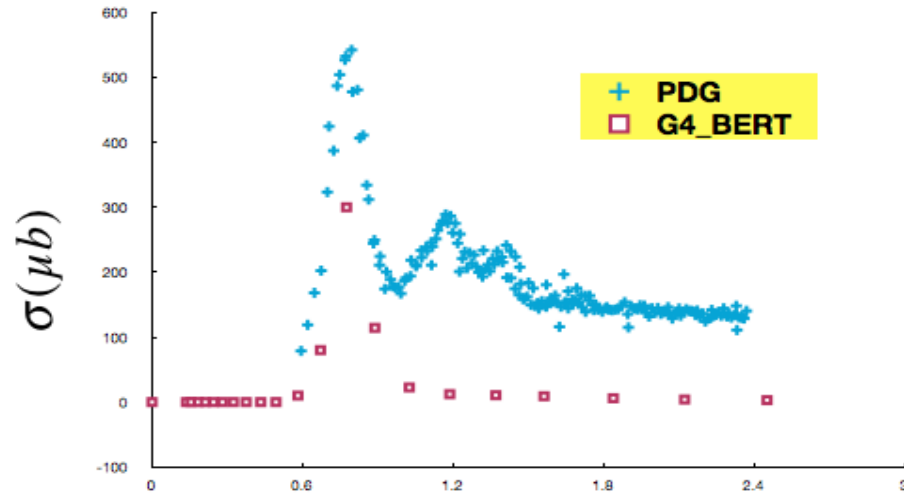
  - **SAID:** Scattering Analysis Interactive Dial-in

    (Phenomenological model driven from world-wide experimental data and maintained by GWU)

$\gamma + p \to (p+\pi^0), (p+2\pi^0), (p+3\pi^0)..., (n+\pi^+), (n+2\pi^+), (n+3\pi^+)...$

$\gamma + p \to p + \pi$

Δ   N*

- G4_CHIPS
  - fits perfectly with PDG;
  - reproduce correctly the experimental resonances (G4_CHIPS/2.5)

- G4_BERT

  - Describes relatively well Δ resonances but few data in this range

  - Limitation: same results for photo-production of $\gamma(p,p)\pi^0$ and $\gamma(n,n)\pi^0$

 - More simulation and comparison with data using this model is highly desirable

Data comparison analysis(1/2)

1. Generate 2 histograms with same binning

2. Perform χ^2 minimization
   ① Follow the prescription from Gagunashvili
   ② N. D. Gagunashvili, *Chi square goodness of fit tests for weighted histograms*, Journal of Instrumentation 10 (2015) P0500

3. Check normalized residuals for low statistics issue

<u>Notes</u>
- Example: total cross section CHIPS vs. PDG
- Similar approach for all work:
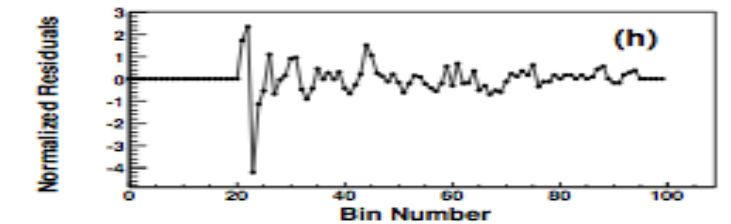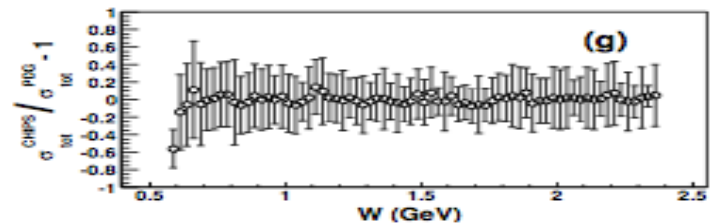 ✓ Geant4 vs. SAID
  ✓ Angular & energy distributions
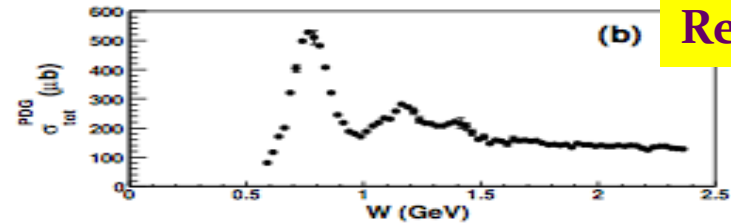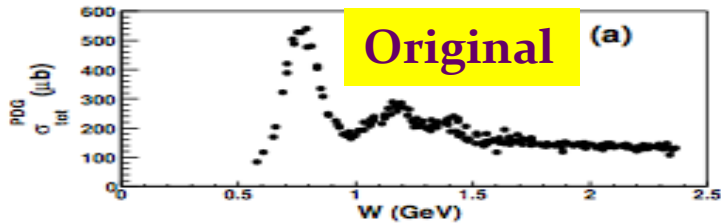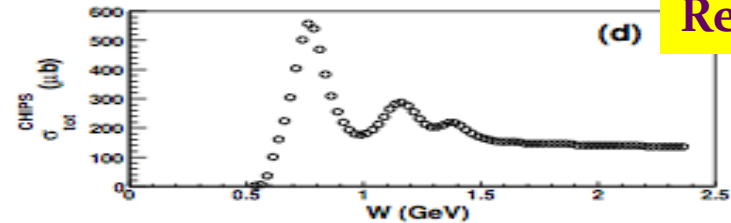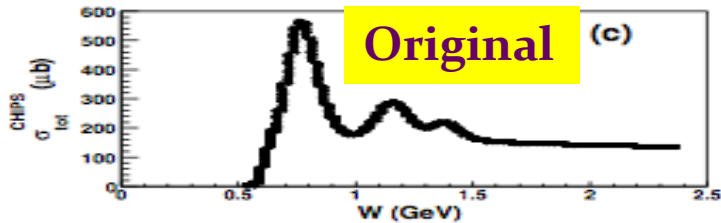
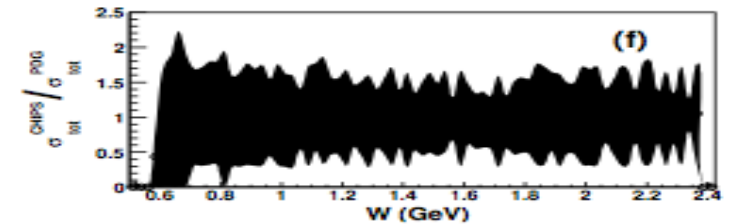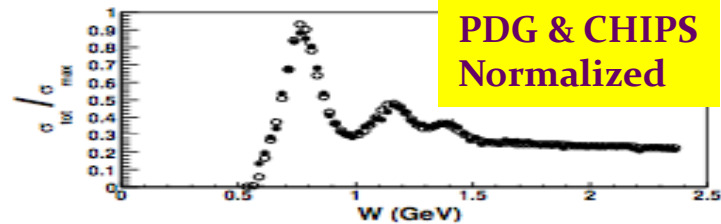| χ^2	42.342
Ndf	73
p-value	99.846%

Total Cross sections

$$\gamma + p \rightarrow p + \pi^0$$
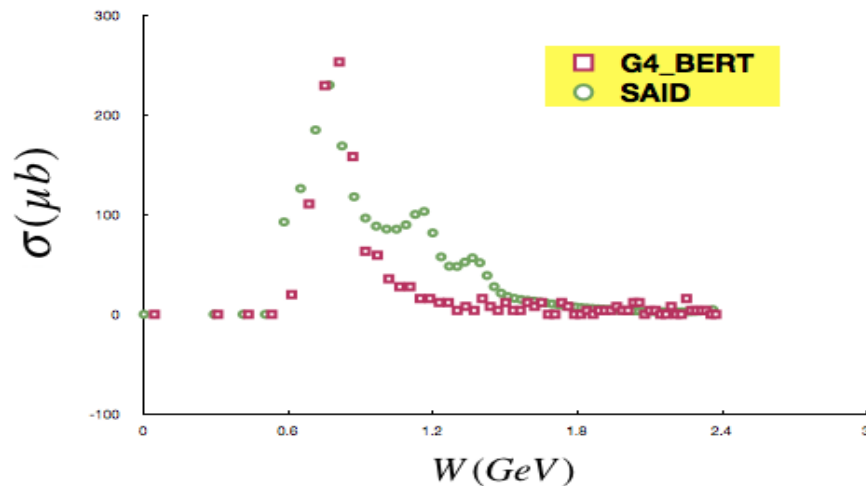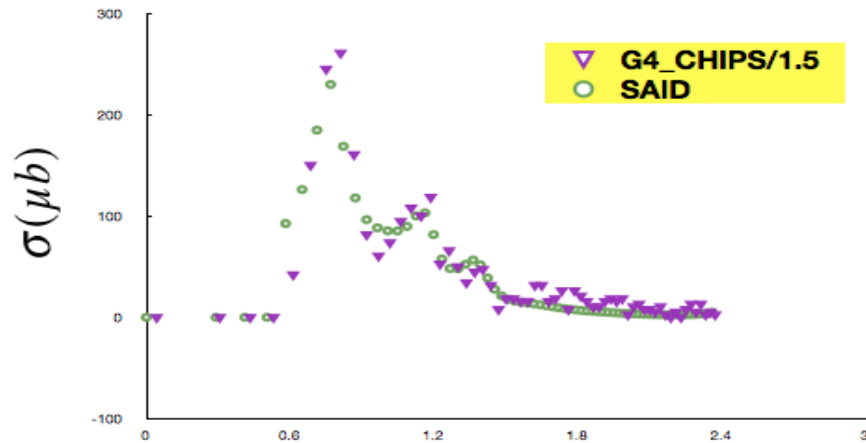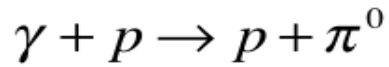
- **G4_CHIPS**
  - Confirmation that CHIPS describes very well the fitting model, hence the experimental data

  - Simulation is improved but over estimation with a smaller coefficient

  - Lots of fluctuations after the second resonance

  (see differential cross section simulation)

- **G4_BERT**
  - Tabulated data fit with simulation results

  - Geant4 database only for protons

  - Recommendation: do not use for neutrons

Differential Cross sections

- JLab experiments total cross sections : obtained from $\Sigma d\sigma/d\Omega$

- Differential cross section : generated both angular and energetic distributions

- **Objective :** detailed comparison between Geant4 and Jlab/SAID data for σ_{Tot} and $d\sigma/d\Omega$

  → simulate number of events under scattering angle theta in the lab frame

From the kinematics data, we calculate theta in the center of mass frame following the relation
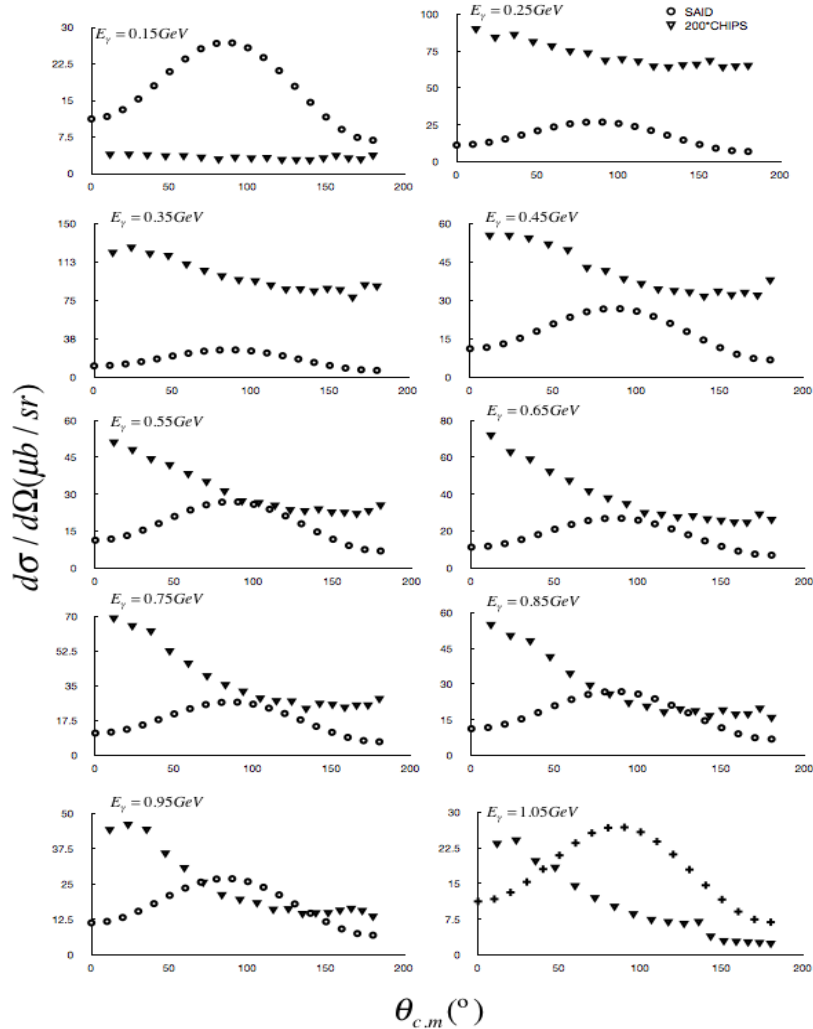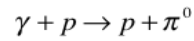
$$q_{c.m} = a\tan\left(\frac{\sin(q_{lab})}{\cos(q_{lab}) - \left(\frac{m_{p^{\pm,0}} \, {}^{\star}\, E_{lab}^{g}}{m_{prot} \, {}^{\star}\, P_{p^{\pm,0}}}\right)}\right) \quad (5)$$

- Differential cross section calculated for :
  - a given energy and variable angle: angular distribution
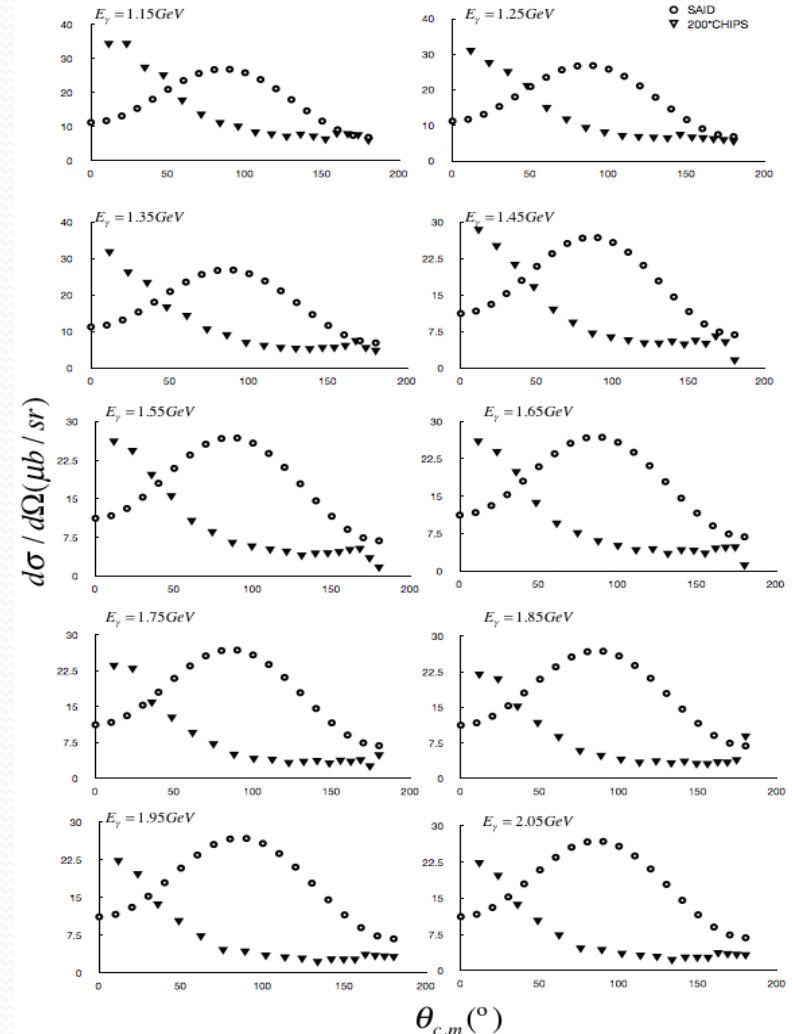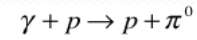 - a given angle and variable energy: energetic distribution
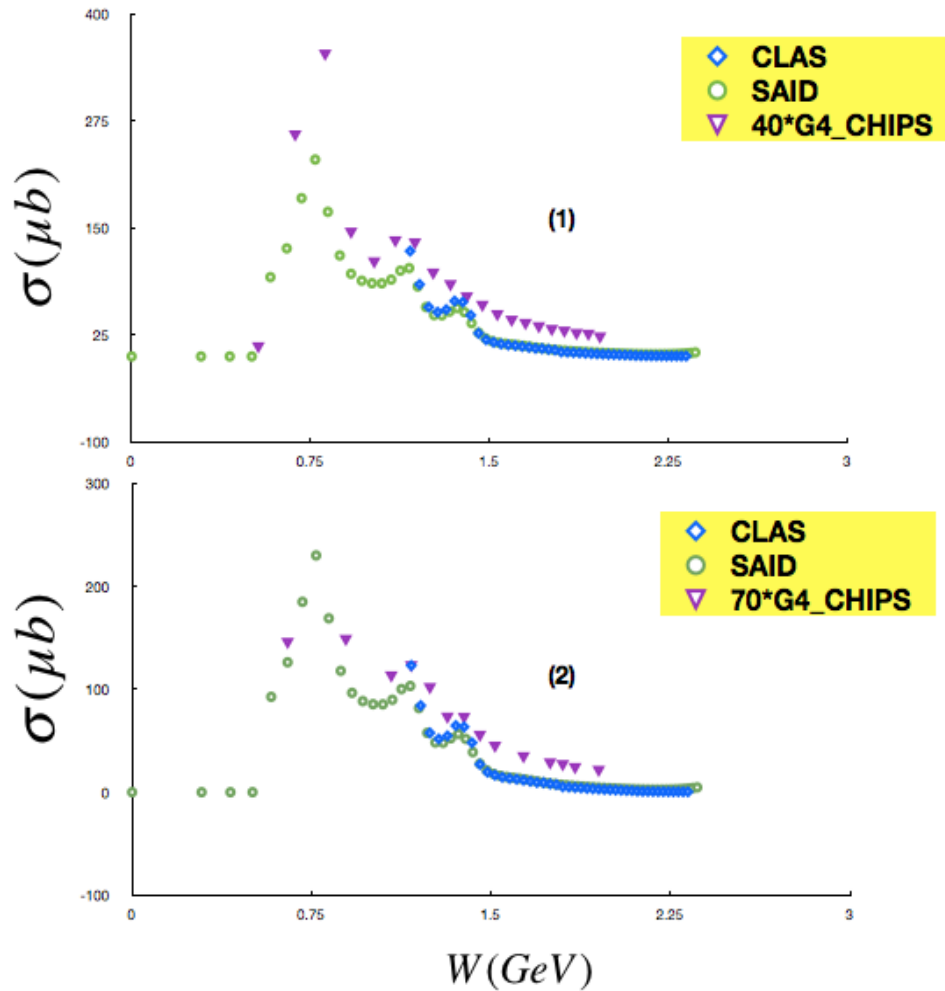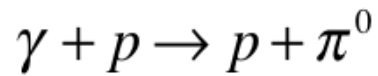
Results
Angular Distributions

"Low Energy" $\gamma + p \rightarrow p + \pi^0$

"High Energy" $\gamma + p \rightarrow p + \pi^0$

Very different distributions!!

Total Cross sections integrated

$$\gamma + p \rightarrow p + \pi^0$$

- Differential cross section integrated over scattering angles

  (1): Third resonance not well-described

    (Energy step used is not the same as Jlab)

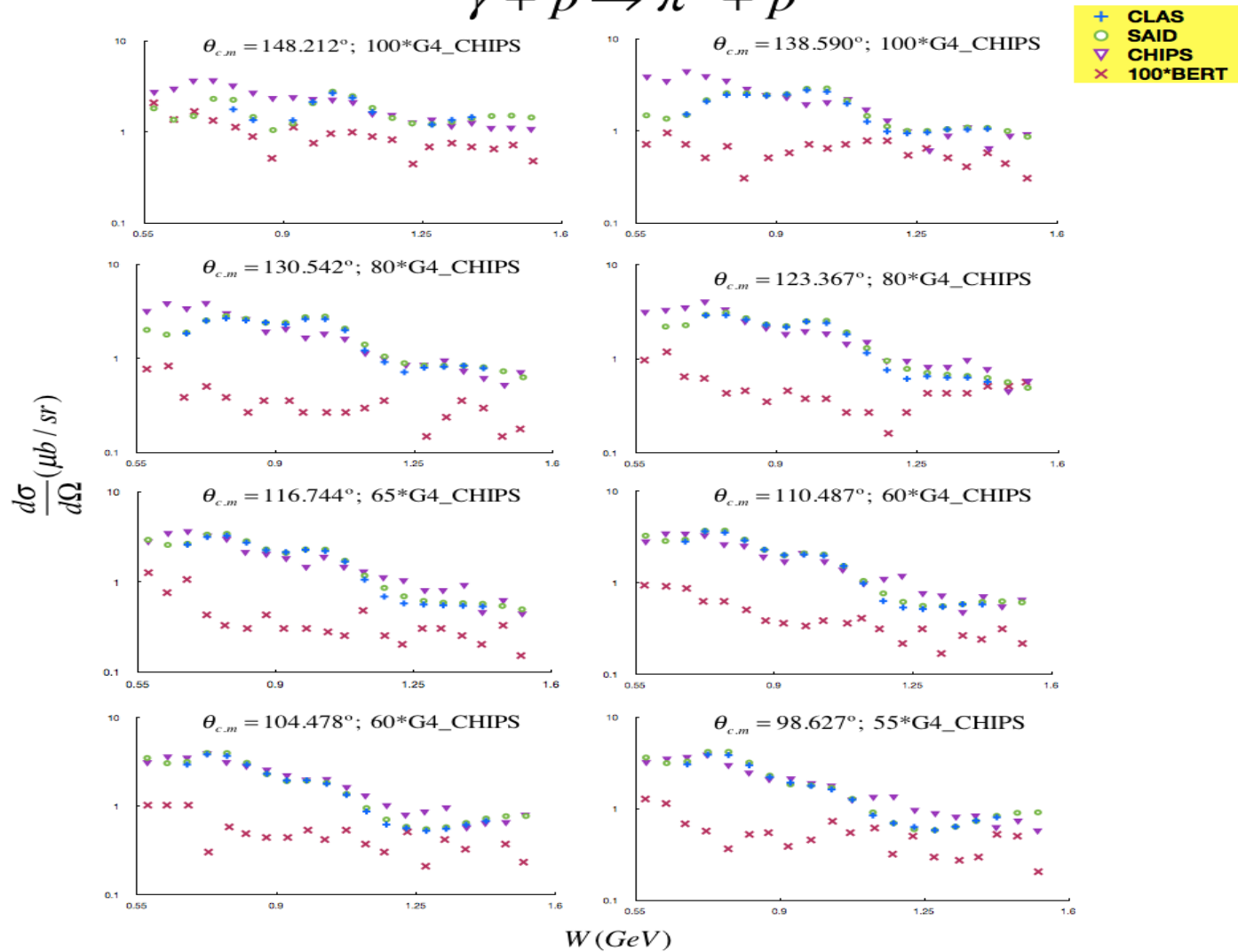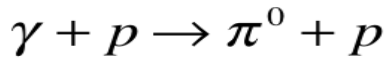 (2): Rebinning shows good agreement

    In process ...

(1)
Different binning

(2)
Same binning

Energetic Distributions (1/2)

Backward Angle

$$\gamma + p \rightarrow \pi^0 + p$$

Legend:
- **+ CLAS**
- **○ SAID**
- **▽ CHIPS**
- **✕ 100*BERT**

Panels:
- $\theta_{c.m} = 148.212°$; 100*G4_CHIPS
- $\theta_{c.m} = 138.590°$; 100*G4_CHIPS
- $\theta_{c.m} = 130.542°$; 80*G4_CHIPS
- $\theta_{c.m} = 123.367°$; 80*G4_CHIPS
- $\theta_{c.m} = 116.744°$; 65*G4_CHIPS
- $\theta_{c.m} = 110.487°$; 60*G4_CHIPS
- $\theta_{c.m} = 104.478°$; 60*G4_CHIPS
- $\theta_{c.m} = 98.627°$; 55*G4_CHIPS

$\frac{d\sigma}{d\Omega}(\mu b / sr)$

$W (GeV)$

Preliminary

Energetic Distributions (2/2)

Forward Angle

$$\gamma + p \longrightarrow \pi^0 + p$$
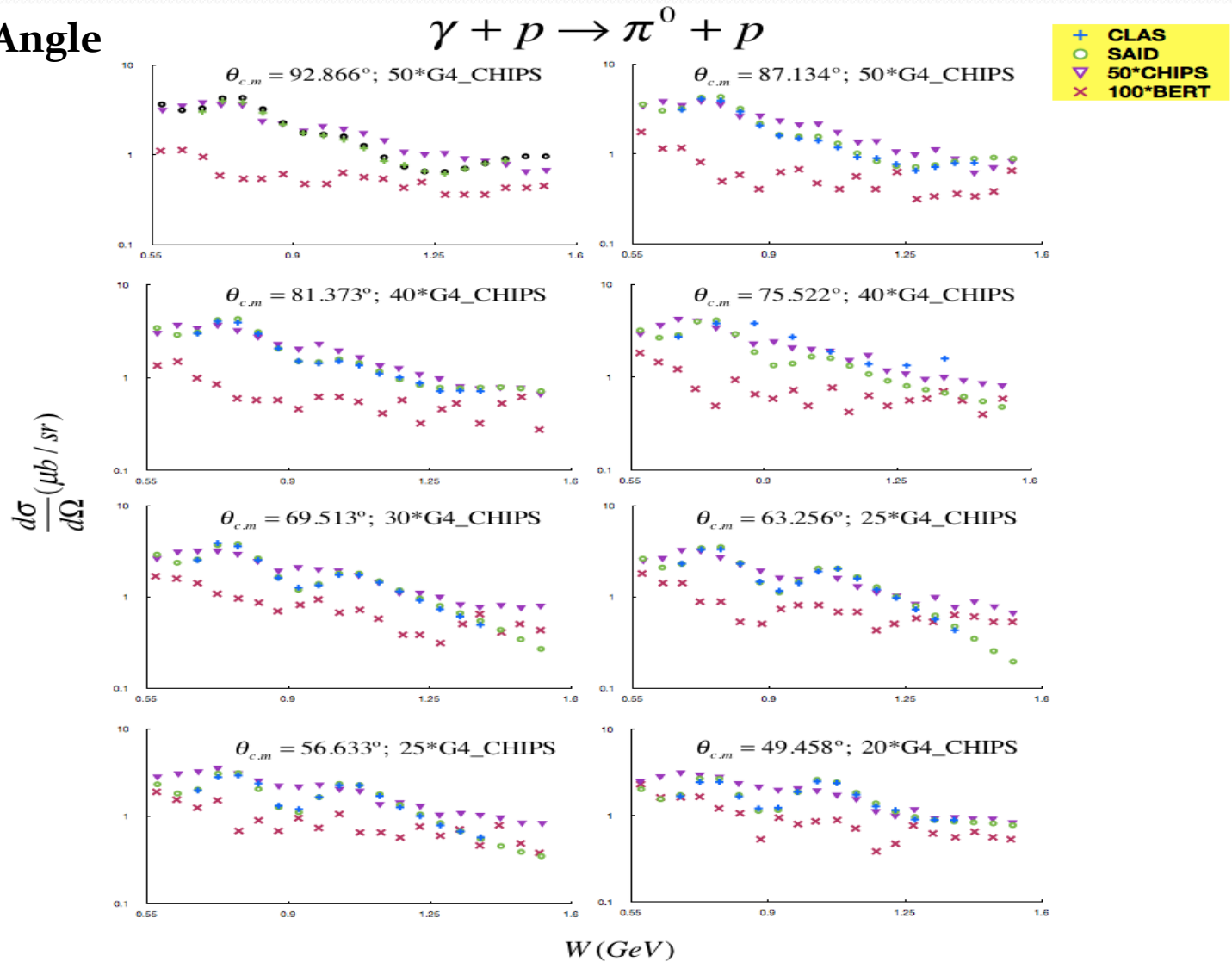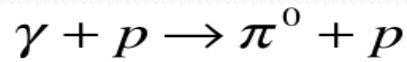
Preliminary

Conclusion & Perspectives

- **Conclusion**

  - Study of pion photo-production off hydrogen in Geant4 using JLab/SAID data

  - Comprehensive comparison of differential and total cross sections

  - Qualitative analysis: seems OK – Quantitative: with chi-square (next step)

  - CHIPS model: reasonable in the intermediate energy range

  - BERT model: necessary to perform more comparison/improvement

- **Perspectives**

  - Finish the simulation for the proton target (in progress)

  - Same exercises for the neutron target (very near future)

  - Applications to heavier targets (if time allows it)

  - Provide recommendation for the users of Geant4 models in mesons photo-production within the intermediate energy regime