Electro and gamma nuclear physics in geant4.

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Outline

- Cross-section calculations
  - The modeling, and restrictions of applicability
- Final state generation
  - The modeling, and restrictions of applicability
- Verification

Gamma nuclear reaction cross-sections

- Modeling the following regions:
  - GiantDipoleResonance regime
    - O(100MeV)
  - Roper regime
    - the intermediate energy ‘desert’
  - Delta regime
    - O(1-2GeV)
  - Reggeon-pomeron regime

GDR regime

- GDR from power law (chiral invariant phase space decay prediction), and nuclear barrier reflection function.

$$GDR(e,p,b,c,s) = T(e,b,s)\exp(c - pe)$$

$$T(e,b,s) = 1 \Big/ 1 + \exp((b-e)/s)$$

- Here e is log(E_g).
- Parameters p, b, c, s are tuned on experimental data (From He to U), H and deuterium are treated as special cases

Delta isobar region

- The delta isobar region is modeled as a Breit Wiegner function with a production threshold:

$$\Delta(e,d,f,g,r,q) = \frac{d \cdot T(e,f,g)}{1 + r \cdot (e-q)^2}$$

- Here q can be viewed as the position of the delta resonance, and r as it's inverse width.
- The parameters are tuned on before mentioned experimental data as a function of log(A).

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Roper region

- This regime was parametrized using the same functional form as for the Delta region, but dropping the pion threshold factor

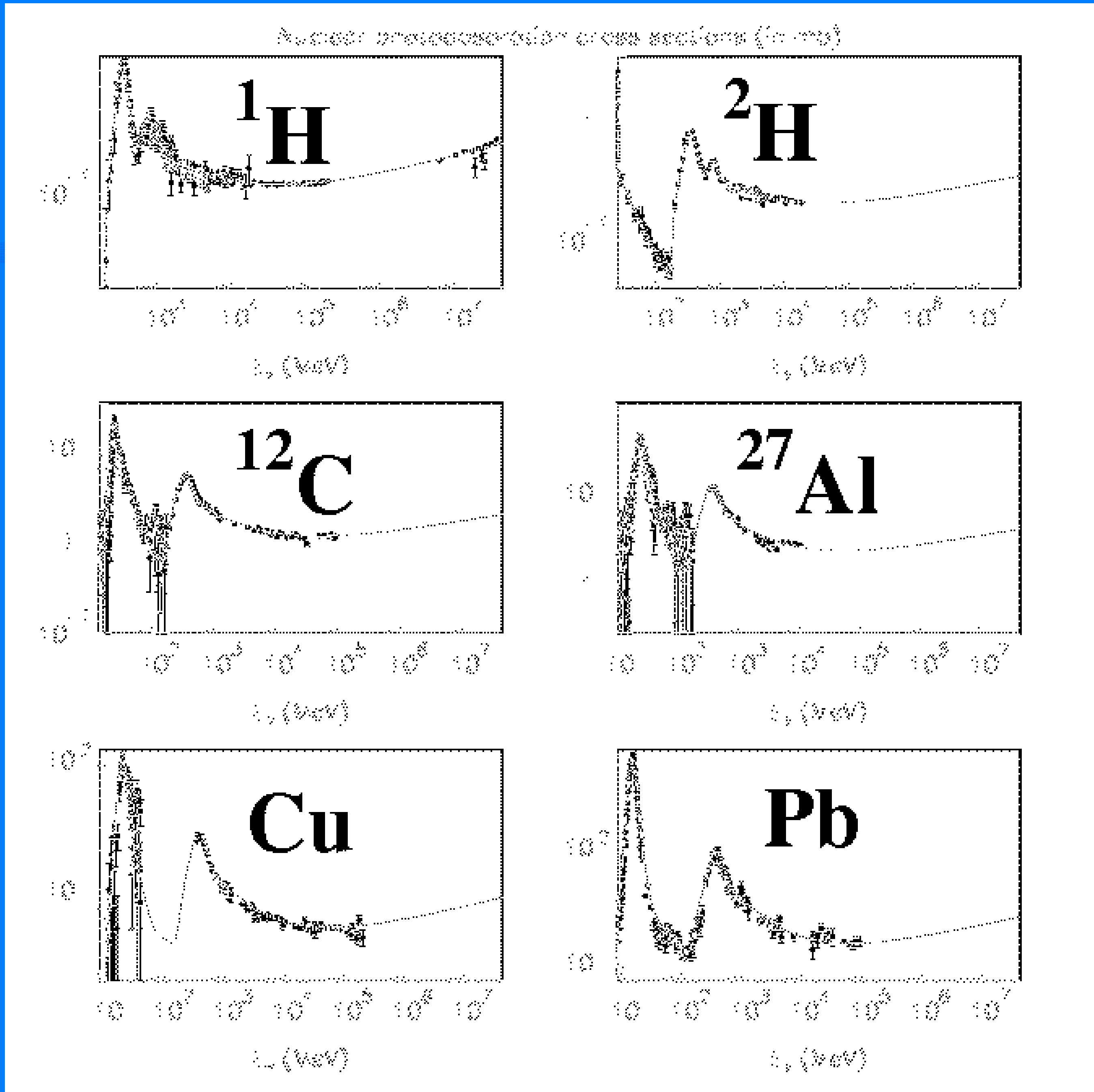
$$Ro(e,v,w,u) = \frac{v}{1 + w \cdot (e-u)^2}$$

Reggeon-Pomeron region

- In the reggeon-pomeron region, we use

$$RP(e,h) = h \cdot T(e,7.0,0.2) \cdot (0.0116 \cdot \exp(0.16 \cdot e) + 0.4 \cdot \exp(-0.2 \cdot e)), with$$

$$h = A \cdot \exp(-\log(A) \cdot (0.885 + 0.0048 \cdot \log(A)))$$



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Implementation restrictions:

- None.
- Details are currently being prepared for publication in a refereed journal.

Final state generation:

- Energies above 3 GeV: Kaidalov's quark gluon string model (see talk presented by Gunter Folger).
- Energies below 3GeV: Chiral invariant phase-space deay

Chiral Invariant Phase-space Decay.

- A quark level 3-dimensional event generator for fragmentation of excited hadronic systems (quasmons) into hadrons.
- Based on the QCD idea of asymptotic freedom
- Local chiral invariance restoration lets us consider quark partons massless, and we can integrate the invariant phase-space distribution of quark partons and quark exchange (fusion) mechanism of hadronization
- The only non-kinematical concept used is that of a temperature of the quasmon.

Vacuum CHIPS

- Or how to calculate the decay of free excited hadronic systems:
- In an finite thermalized system of N partons with total mass M, the invariant phase-space integral is proportional to M^{2N-4}, and the statistical density of states is proportional to $e^{-M/T}$. Hence we can write the probability to find N partons with temperature T in a state with mass M as

$$dW \propto M^{2N-4} e^{-M/T} dM$$

- Note that for this distribution, the mean mass square is $\langle M^2 \rangle = 2N(2N-2)T^2$

Vacuum CHIPS

- We use this formula to calculate the number of partons in the quasmon, and obtain the parton spectrum

$$\frac{dW}{kdk} \propto \left(1 - \frac{2k}{M}\right)^{N-3}$$

- To obtain the probability for quark fusion into hadrons, we can compute the probability to find two partons with momenta q and k with the invariant mass μ.

$$P(k, M, \mu) = \int \left(1 - \frac{2q}{M\sqrt{1 - 2k/M}}\right)^{N-4} \times \delta\left(\mu^2 - \frac{2kq(1 - \cos\theta)}{\sqrt{1 - 2k/M}}\right) qdqd\cos\theta$$

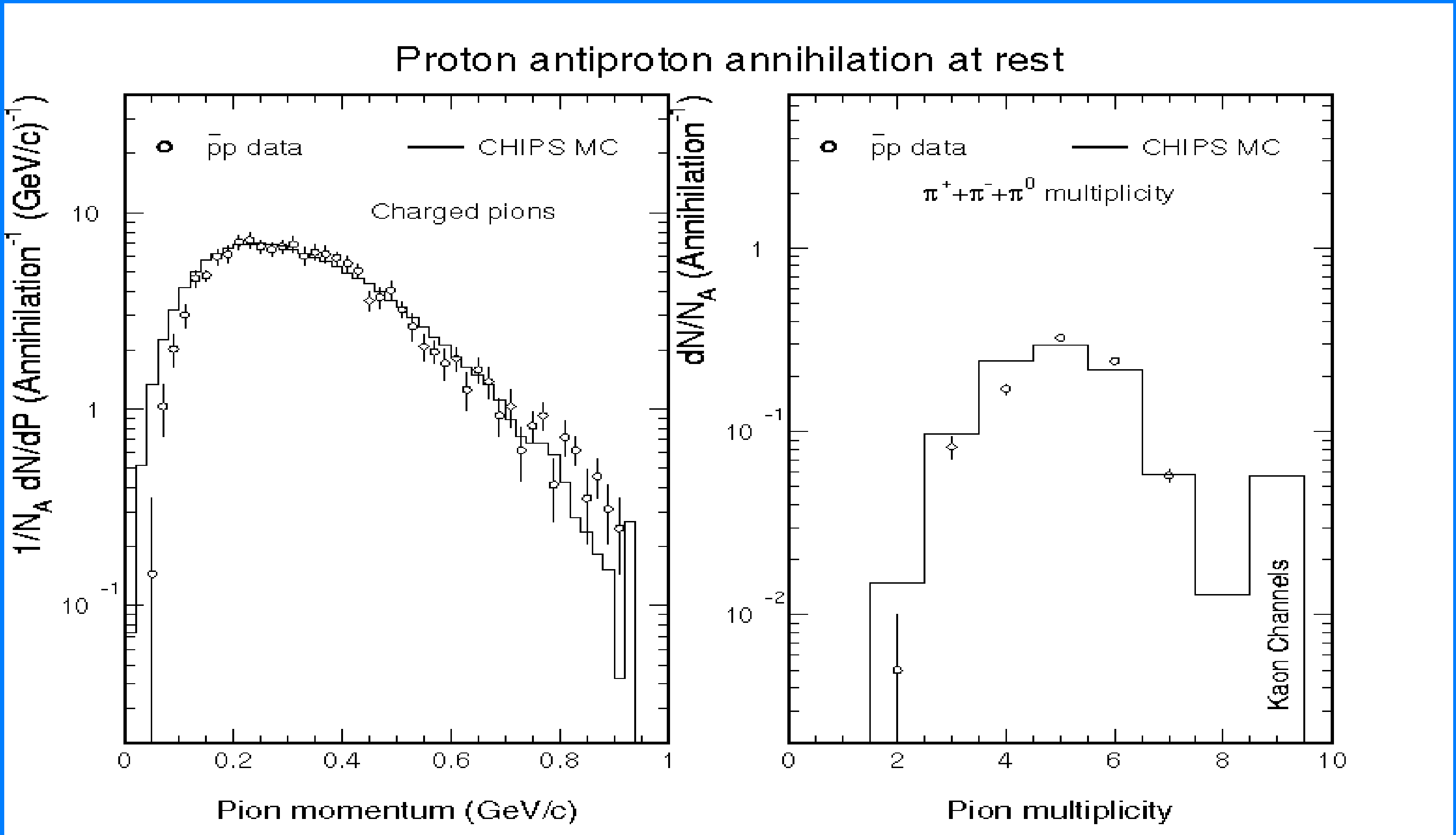
Vacuum CHIPS

- Using the delta function to perform the integration and the mass constraint, we find the total kinematical probability of hadronization of a parton with momentum k into a hadron with mass μ:

$$\frac{M-2k}{4k(N-3)}\left(1-\mu^2/2kM\right)^{N-3}$$

- Accounting for spin and quark content of the final state hadron adds (2s+1) and a combinatorial factor.
- At this level of the language, CHIPS can be applied to p-pbar annihilation

For more information see: Eur.Phys.Journal A8,217(2000)



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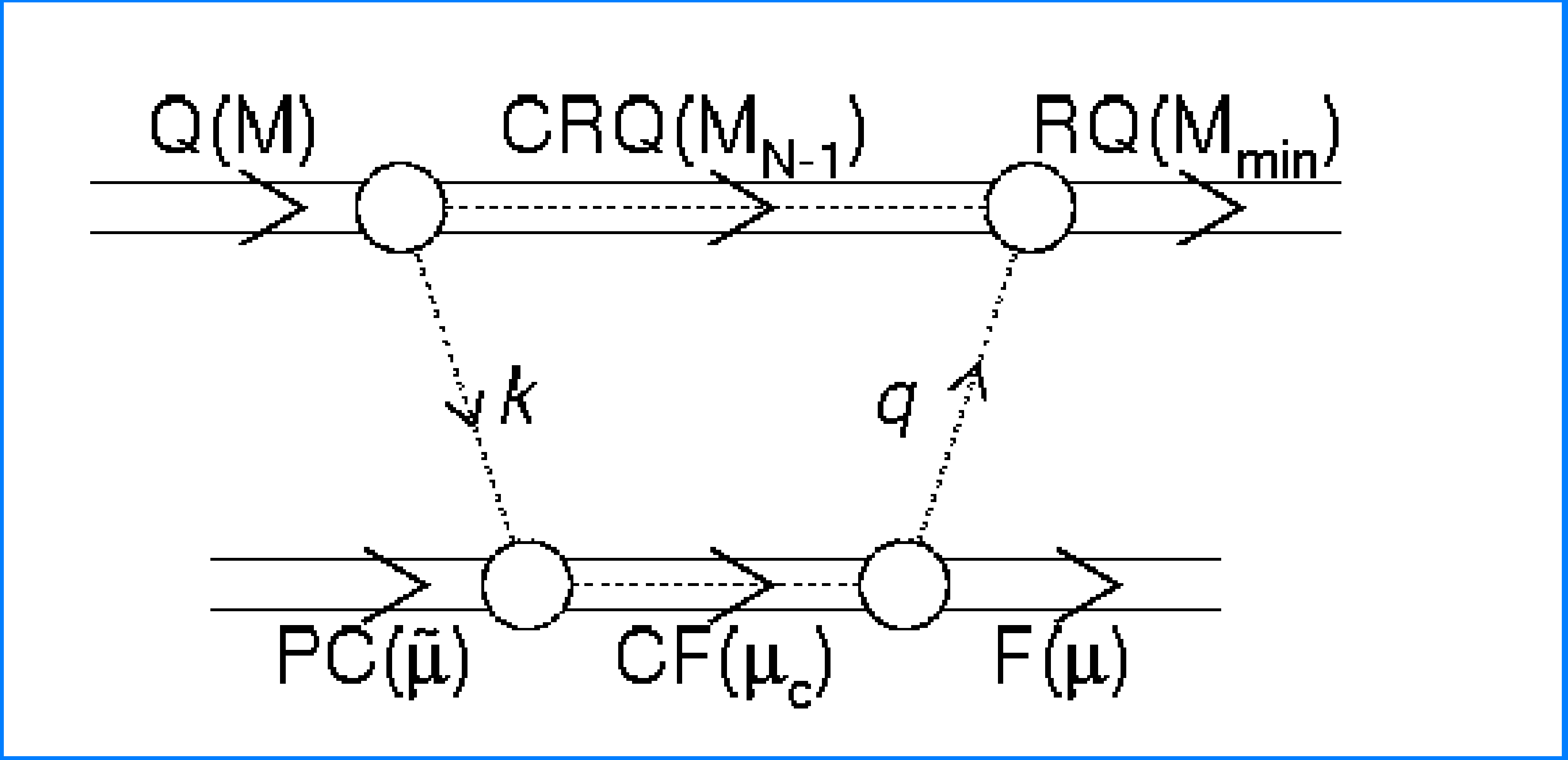
Nuclear CHIPS

- In order to apply CHIPS for an excited hadronic system within nuclei, we have to add parton exchange with nuclear clusters to the model
- The kinematical picture is, that a color neutral quasmon emits a parton, which is absorbed by a nucleon or a nuclear cluster. This results in a colored residual quasmon, and a colored compound.
- The colored compound then decays into an outgoing nuclear fragment and a 'recoil' quark that is incorporated by the colored quasmon.

The parton exchange diagram



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Nuclear CHIPS

- Applying mechanisms analogue to vacuum CHIPS, we can write the probability of emission of a nuclear fragment with mass μ as a result of the transition of a parton with momentum k from the quasmon to a fragment with mass μ' as:

$$P(k,\mu',\mu) = \int \left(1 - \frac{2(k-\Delta)}{\mu' + k(1-\cos\theta_{kq})}\right)^{n-3} \frac{\mu'(k-\Delta)}{2\left[\mu' + k(1-\cos\theta_{kq})\right]^2} d\cos\theta_{kq}$$

- Here, n is the number of quark-partons in the nuclear cluster, and Δ is the covariant binding energy of the cluster, and the integral is over the angle between parton and recoil parton.

Nuclear CHIPS

- To calculate the fragment yields it is necessary to calculate the probability to find a cluster of ν nucleons within a nucleus. We do this using the following assumptions:
  - A fraction $\varepsilon 1$ of all nucleons is not clusterising
  - A fraction $\varepsilon 2$ of the nucleons in the periphery of the nucleus is clustering into two nucleon clusters
  - There is a single clusterization probability ω
- and find, with a being the number of nucleons involved in clusterization

$$P_\nu = \frac{C_\nu^a \omega^{\nu-1}}{(1+\omega)^{a-1}}$$

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Nuclear CHIPS

- At this level of the language, CHIPS can be applied to reactions of pions and photo-nuclear reactions.

A few results: For more information see: Eur.Phys.Journal A9,411(2000) and Eur.Phys.Journal A9,421(2000)

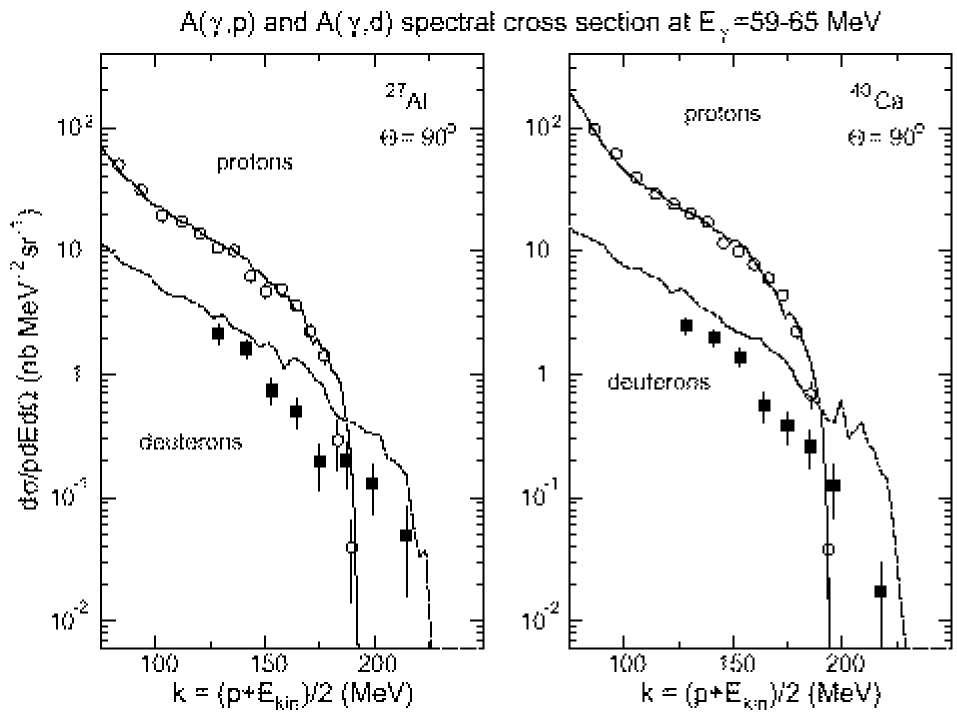
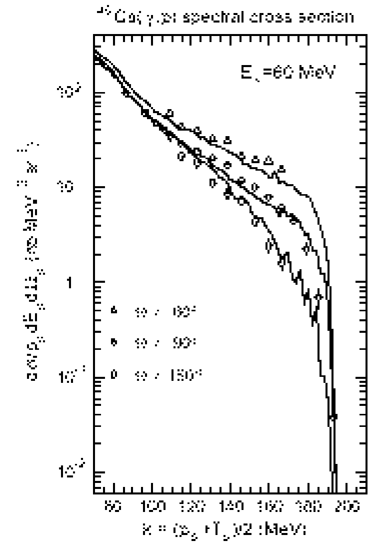
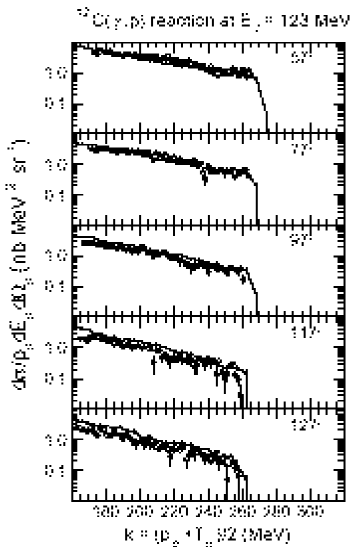
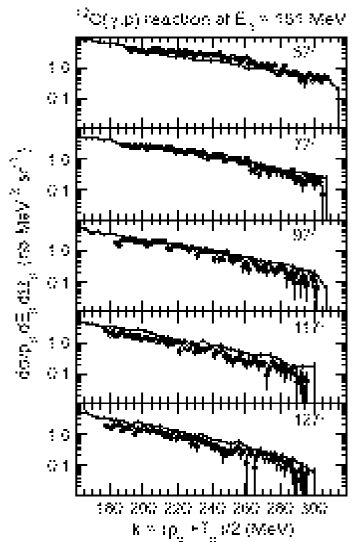


Fig. 7. Comparison of CHIPS model with experimental data [15] on proton and deuteron production at 90° in photonuclear reactions on ^{27}Al and ^{40}Ca at 59–65 MeV. Open circles and solid squares represent the experimental proton and deuteron spectra, respectively. Solid and dashed lines show the results of the corresponding CHIPS model calculation. Statistical errors in the CHIPS results are not shown and can be judged by the point-to-point variations in the lines. The comparison is absolute, using the values of total photonuclear cross-section 3.6 mb for Al and 5.4 mb for Ca, as given in ref. [16].





4 Comparison with data



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Electro-nuclear scattering: reaction cross-sections

- Based on Fermi's method of equivalent photons, as developed by Weitzsaecker and Williams:

$$dN_\gamma = -\frac{2\alpha}{\pi}\log(y)d\log(y), y = \nu/E_e$$

- Folding this flux with the gamma reaction cross-section (as described above) and integrating the gamma spectrum, we obtain:

$$\sigma(eA \to X) = \log(E_e)\int\frac{2\alpha}{\pi}\sigma_{\gamma A}(\nu)d\log(\nu) - \int\frac{2\alpha}{\pi}\log(\nu)\sigma_{\gamma A}(\nu)d\log(\nu)$$

Restrictions

- The modeling assumptions in the equivalent photon spectrum.
  - The DIS part was recently added.
- To smoothen the electro-nuclear cross-section at 2 GeV, the following PR term was used

$$RP(e,h) = h \cdot (0.0116 \cdot \exp(0.16 \cdot e) + 1.0 \cdot \exp(-0.26 \cdot e))$$

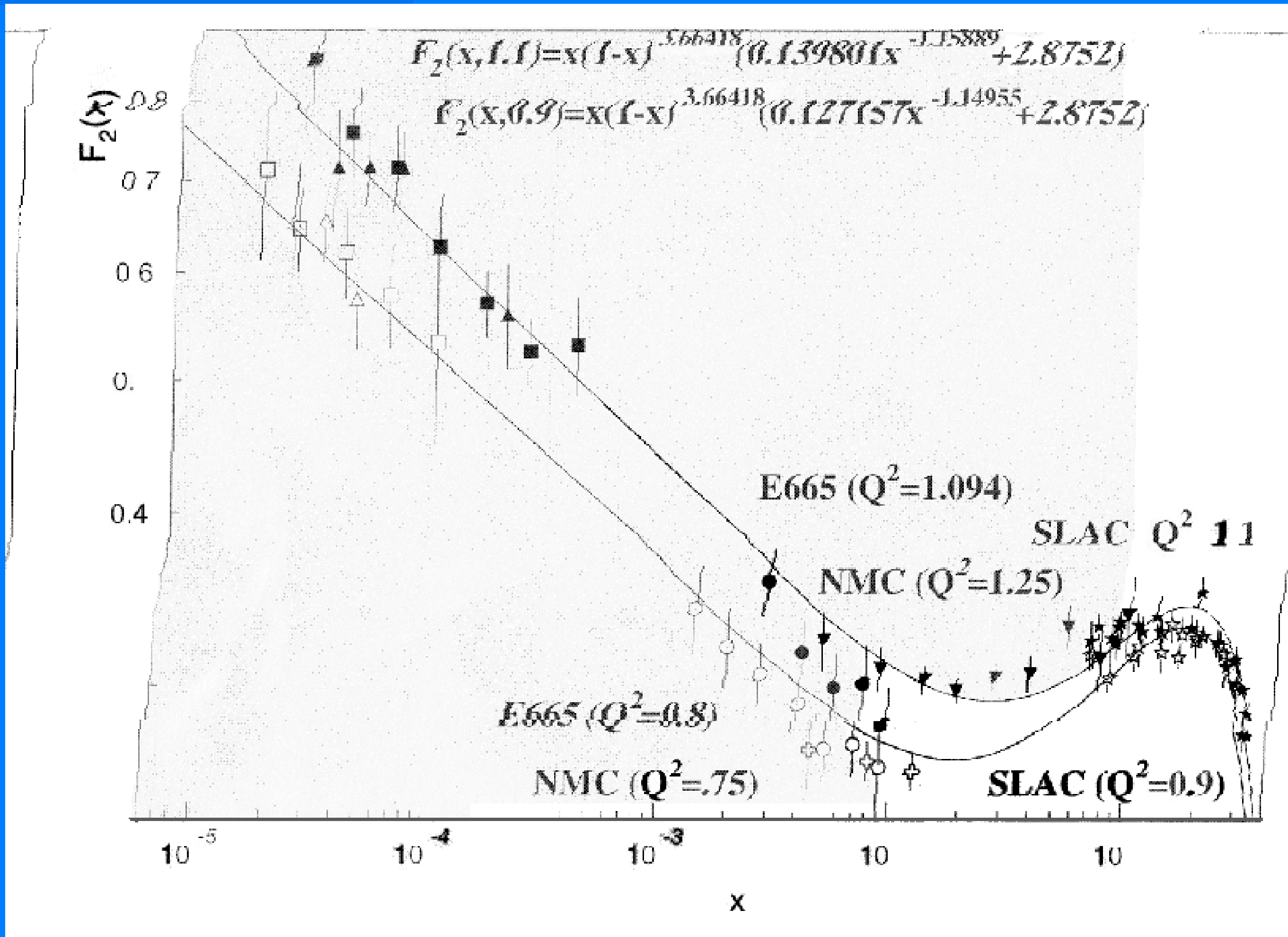
Electro-nuclear scattering: final state modeling

- The formulas presented in the cross-section section can be used to calculate the probability distribution of the equivalent photons.
- This distribution is sampled to calculate the energy transfer of the nuclear reaction
- The energy is assumed to be transferred by gamma exchange, and the models for gamma nuclear reaction (CHIPS, QGString) are used.

Implementation restrictions

- Assumption of equivalent photon.
- Otherwise none.
  - For energy transfers below 3 GeV per collision, CHIPS is used
  - above quark gluon string model is used.
- DIS is included

Hard scattering in electro-nuclear



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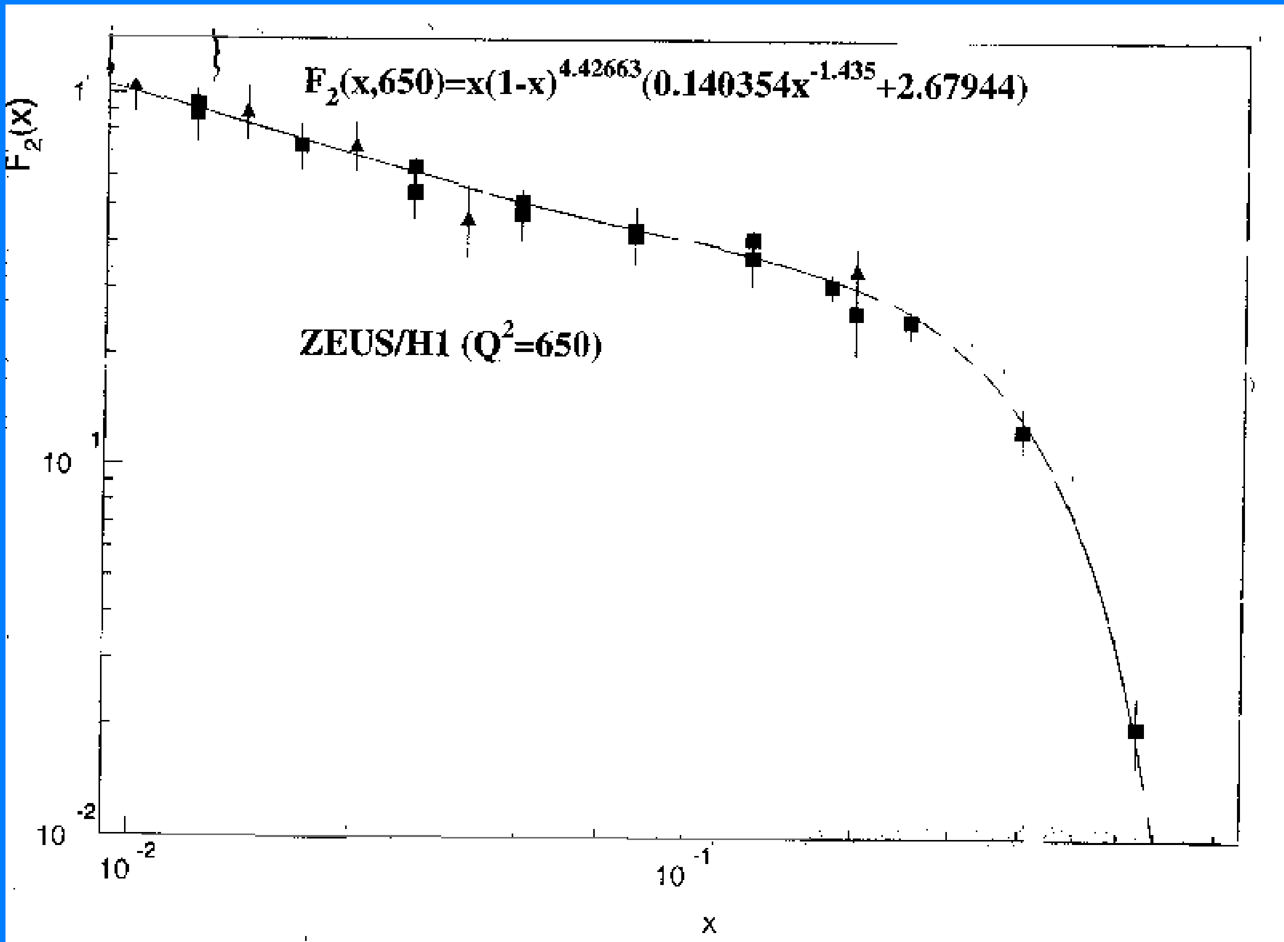
Hard scattering in electro-nuclear



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Conclusions

- Geant4 physics modeling is now equipped to deal with linear collider or Jefferson Lab radiation environment, and LHC precision gamma identification use-cases.