Verification and development of nH interaction in Geant4.

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1. **Elastic and inelastic cross-sections of np interaction.**
2. **Differential np elastic cross-sections.**
3. **Inelastic $n(p,d)\gamma$ and $n(p,np)\gamma$ interactions.**

Signifi cance of nH interactions

1. In High Energy Physics it's very important for scintillator detectors.
2. In medical simulation Hydrogen is an element of watter.
3. The neutron production is very different for different hadronic models of Geant4, so the response of detectors to neutrons is very important.

At Low Energies there are three main processes:

1. *Elastic np scattering (recoil protons or nuclei).*
2. *Binary $n(p,d)\gamma$ reaction (radiative capture).*
3. *Hard bremsstrahlung of neutrons: $n(p,np)\gamma$ reaction.*

RED/PINK is CHIPS parameterization of np elastic (direct/integrated). BLUE is GHAD cross-section, BLACK is HP cross-section. Dashed lines correspond to inelastic processes (RED is for CHIPS, BLUE is for GHAD).

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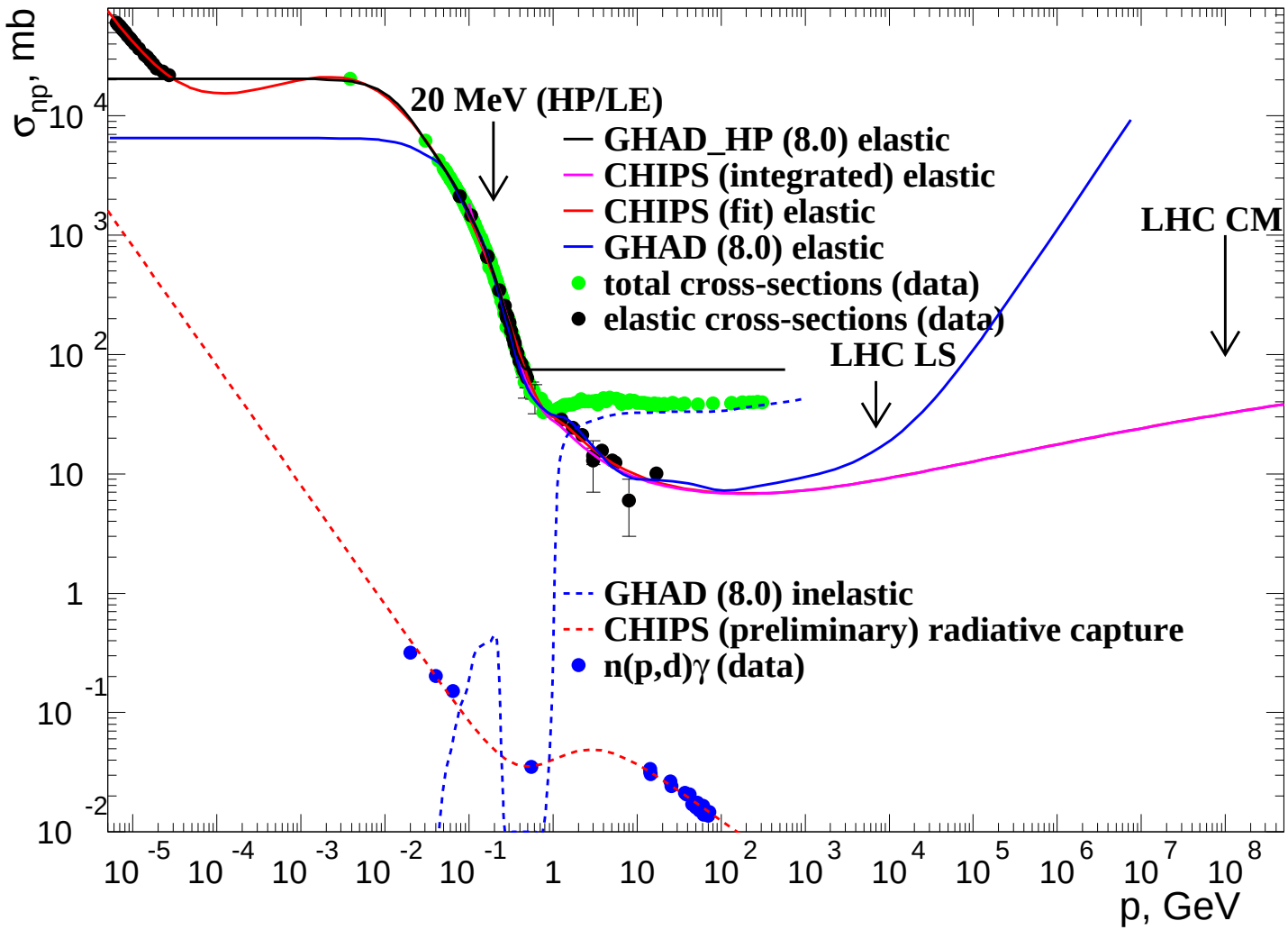

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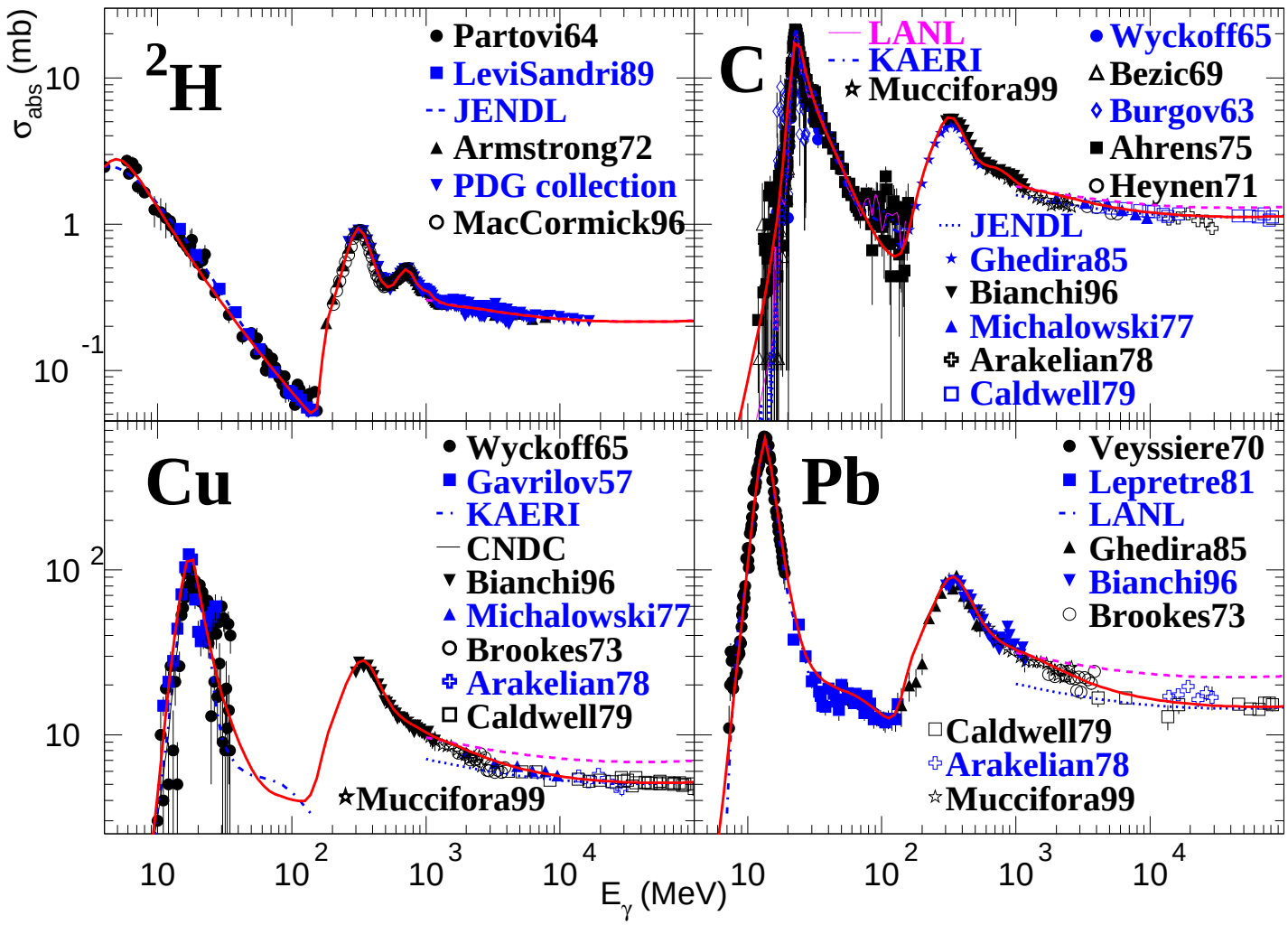

Exponential approach for elastic cross-sections

$$\frac{d\sigma}{dt} = A_1 \cdot e^{B_1 \cdot t} + A_2 \cdot e^{B_2 \cdot u}$$

1. *Diffraction (a π^0 exchange, t-channel).*
2. *Charge exchange (a π^- exchange, u-channel).*
3. *Vacuum pole diffraction (High Energy: a Pomeron exchange).*

GREEN LINES correspond to $G4LElastic$ model (with np filter to kill pp and one particle final states, it does not work above 3 GeV/c, no charge exchange above .4 GeV/c: solid lines on the ERROR figure). The $G4LElasticB$ process produces $n(p,p)p$ events (a bug) so it is not shown (dashed lines on the ERROR figure). BLUE LINES correspond to $G4LEnp$ model (not used in Geant4 8.0 PhysLists, bad below .25 GeV/c and above 2 GeV/c). RED/PINK is CHIPS parameterization of the np elastic ($G4LElastic$ process corrected by cross-sections/ CHIPS fit).

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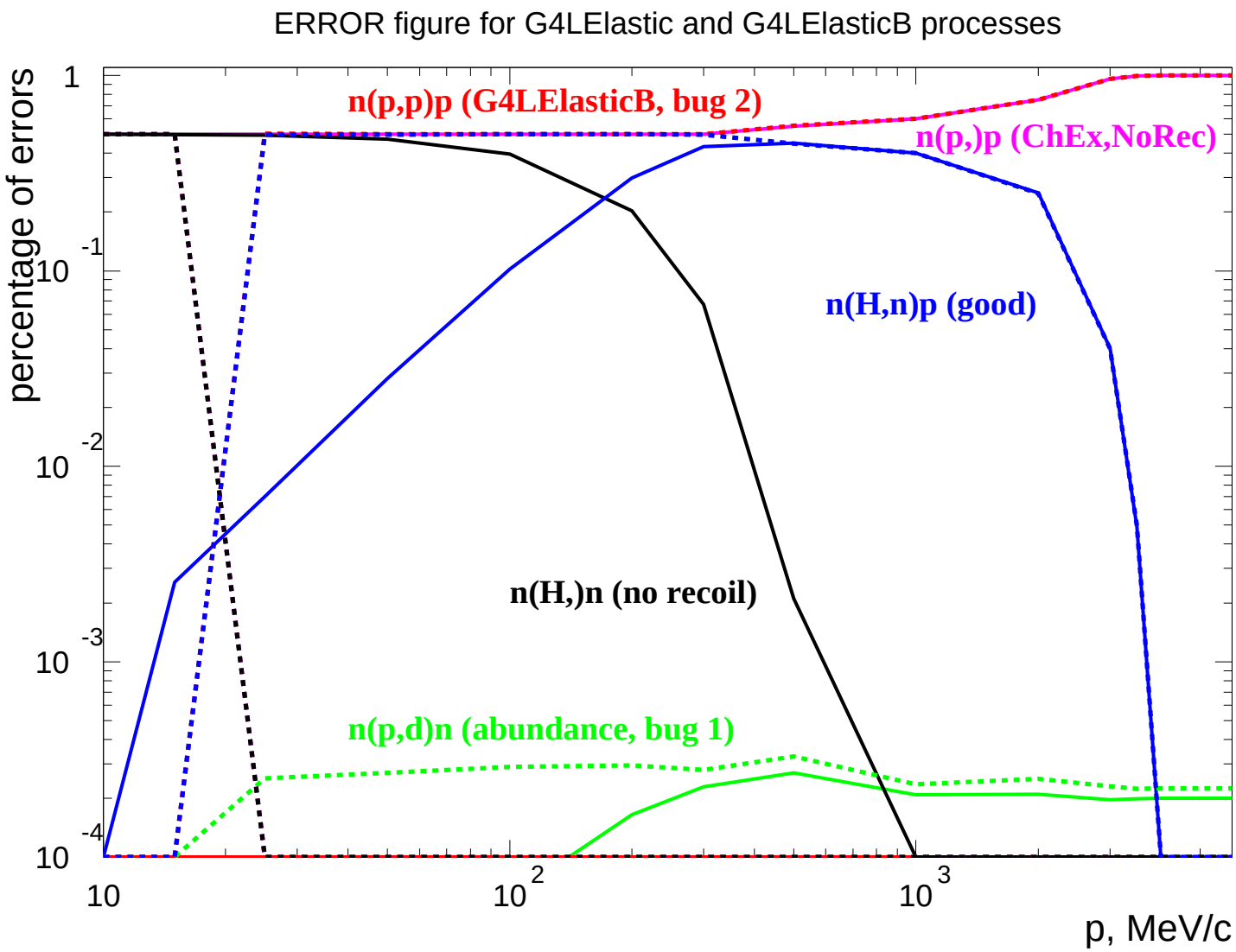

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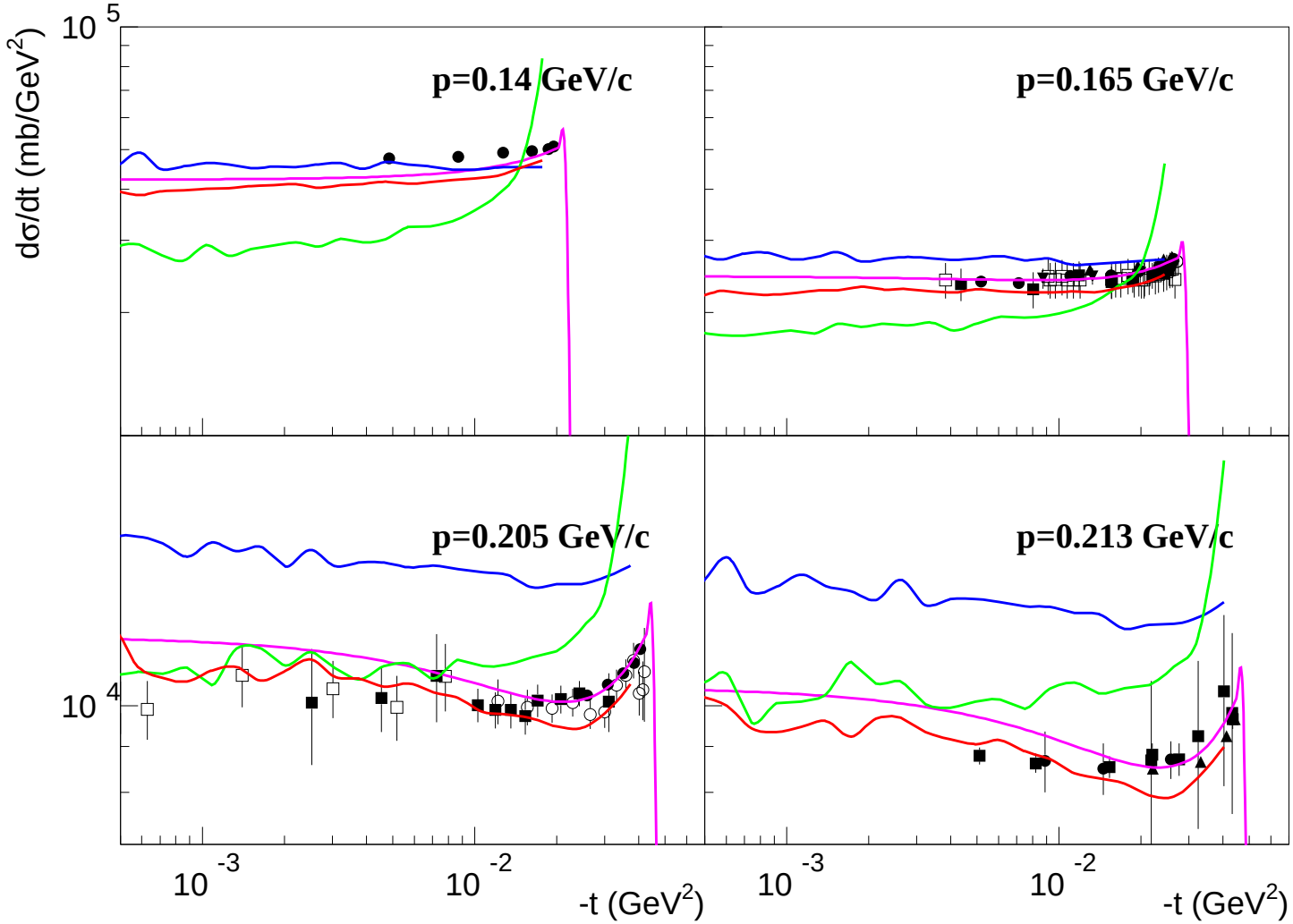

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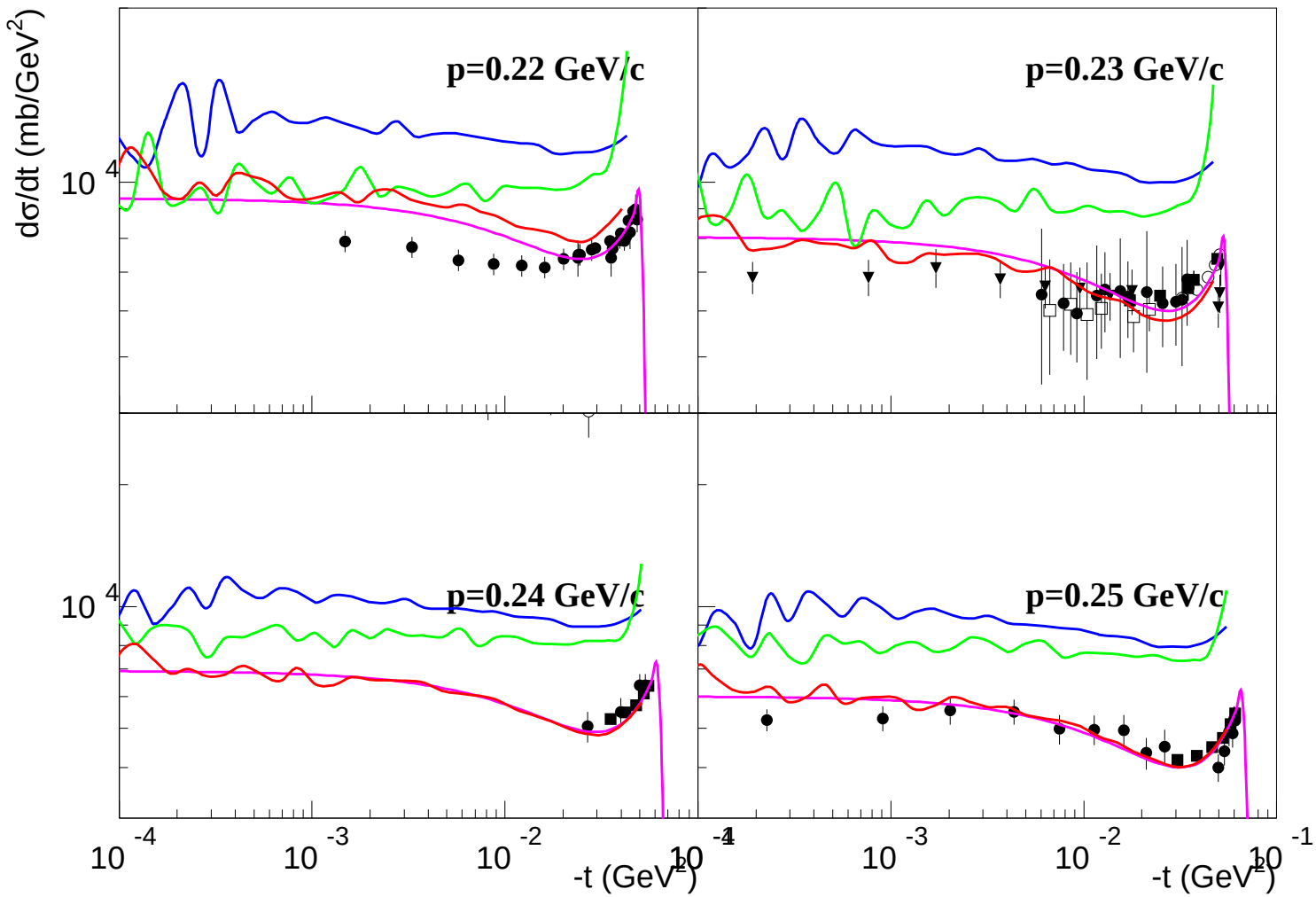

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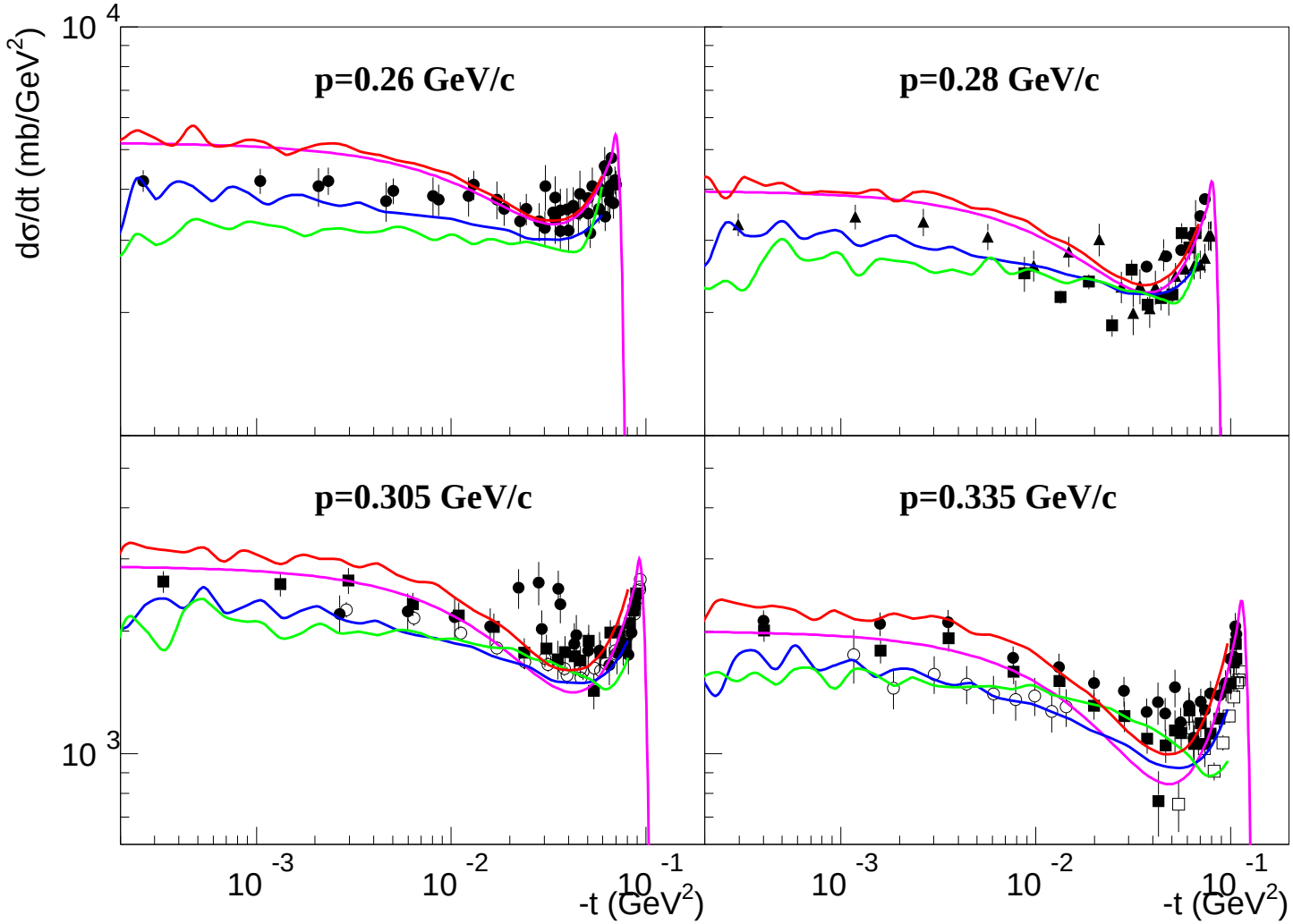

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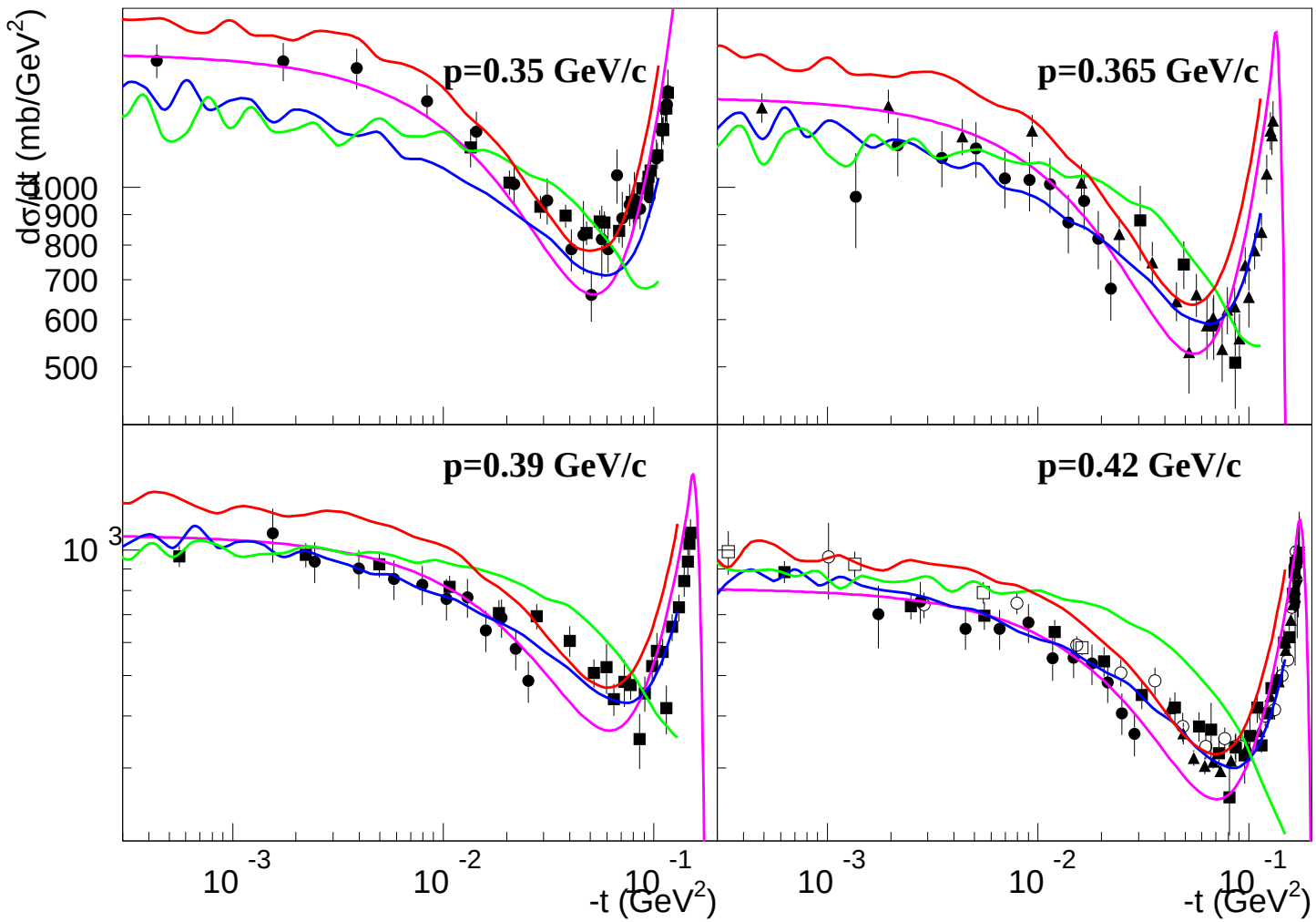

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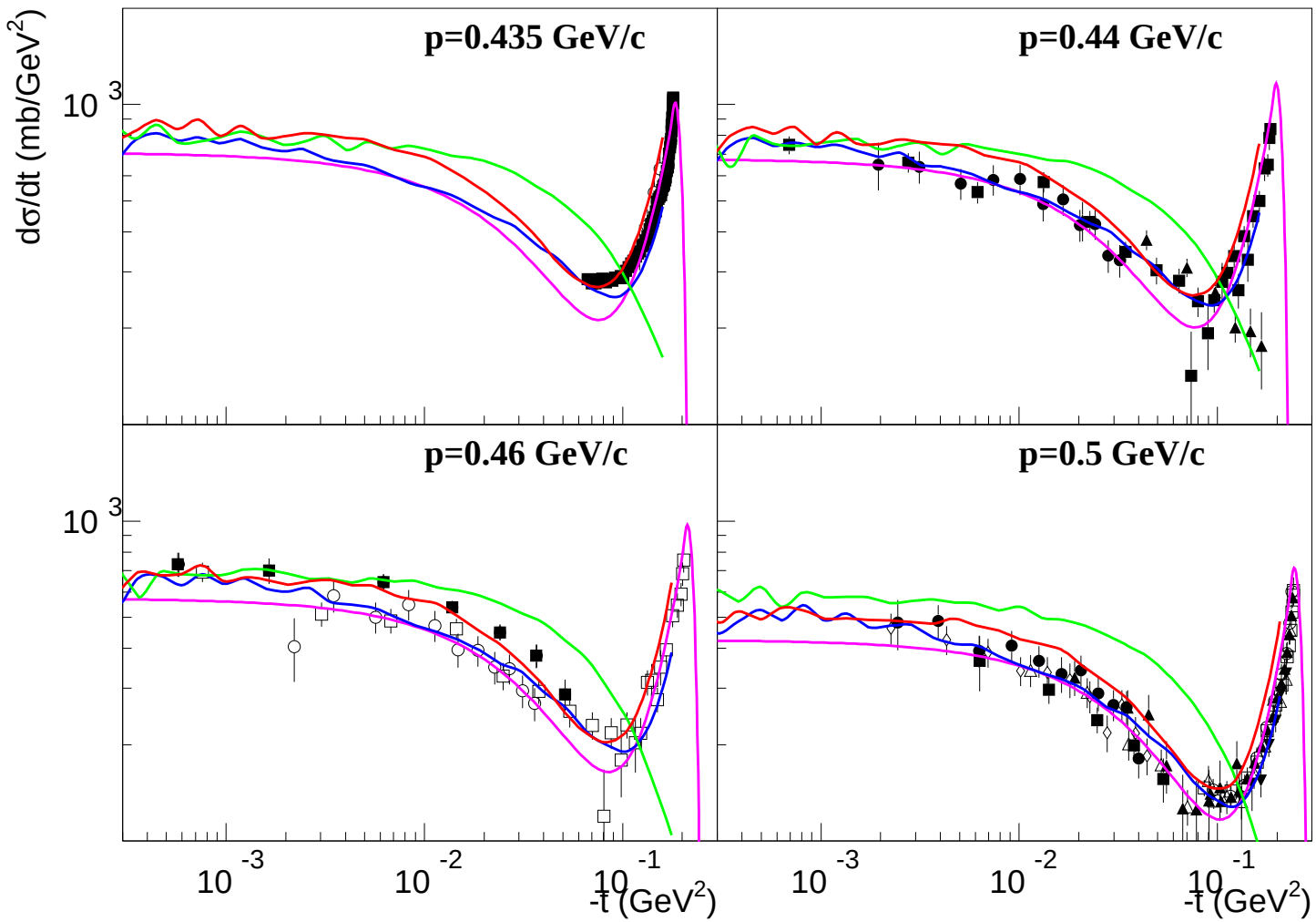

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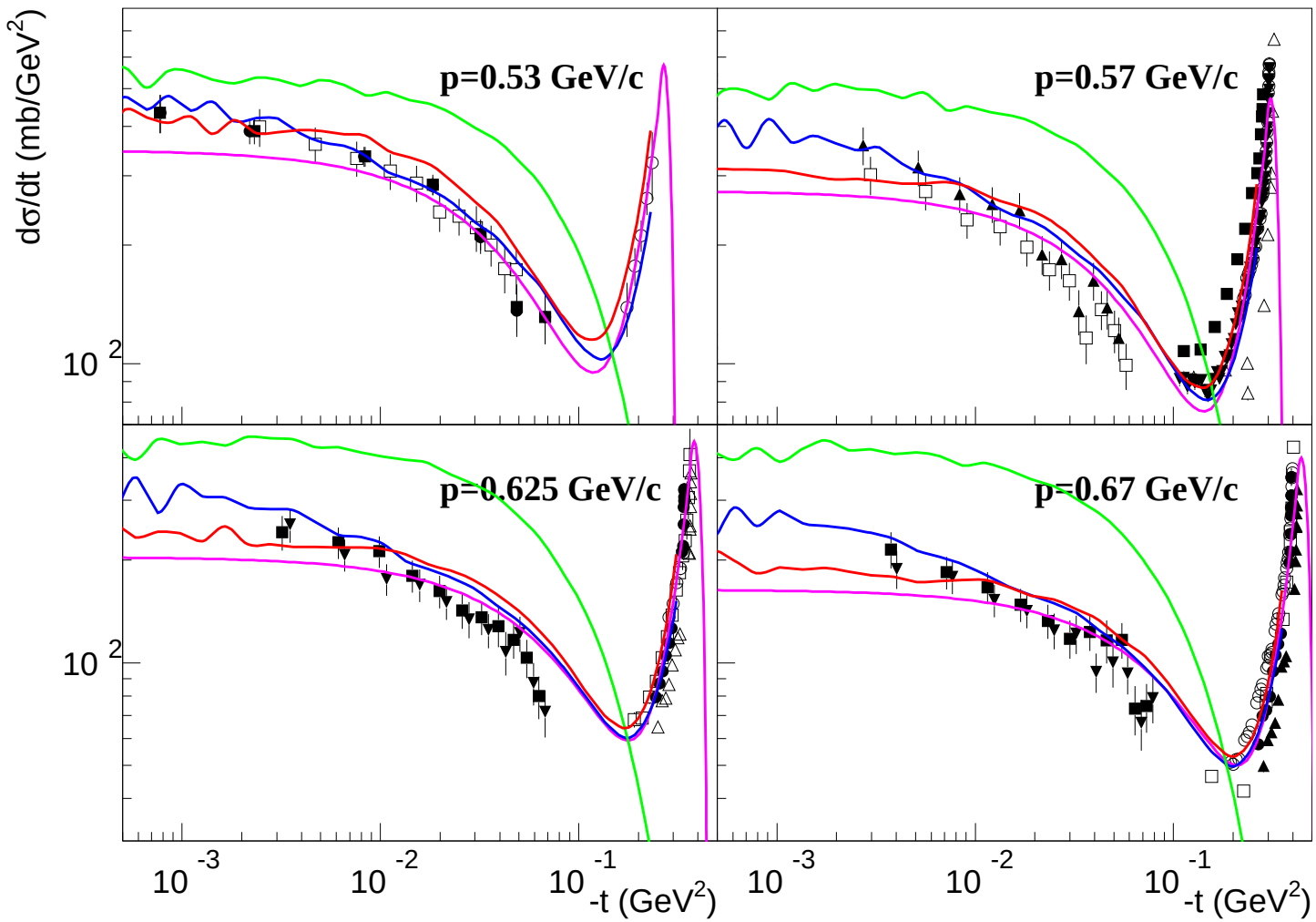

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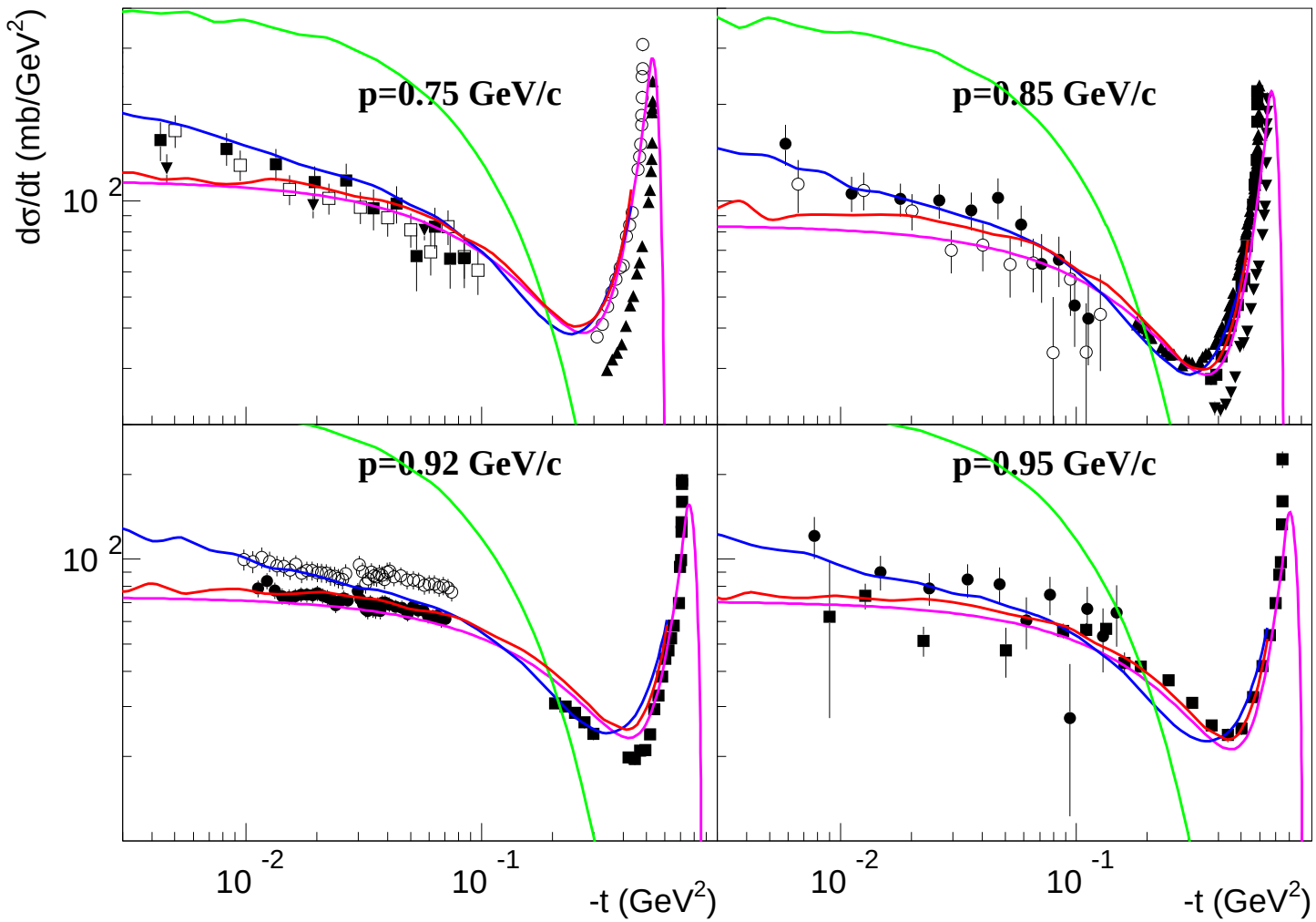

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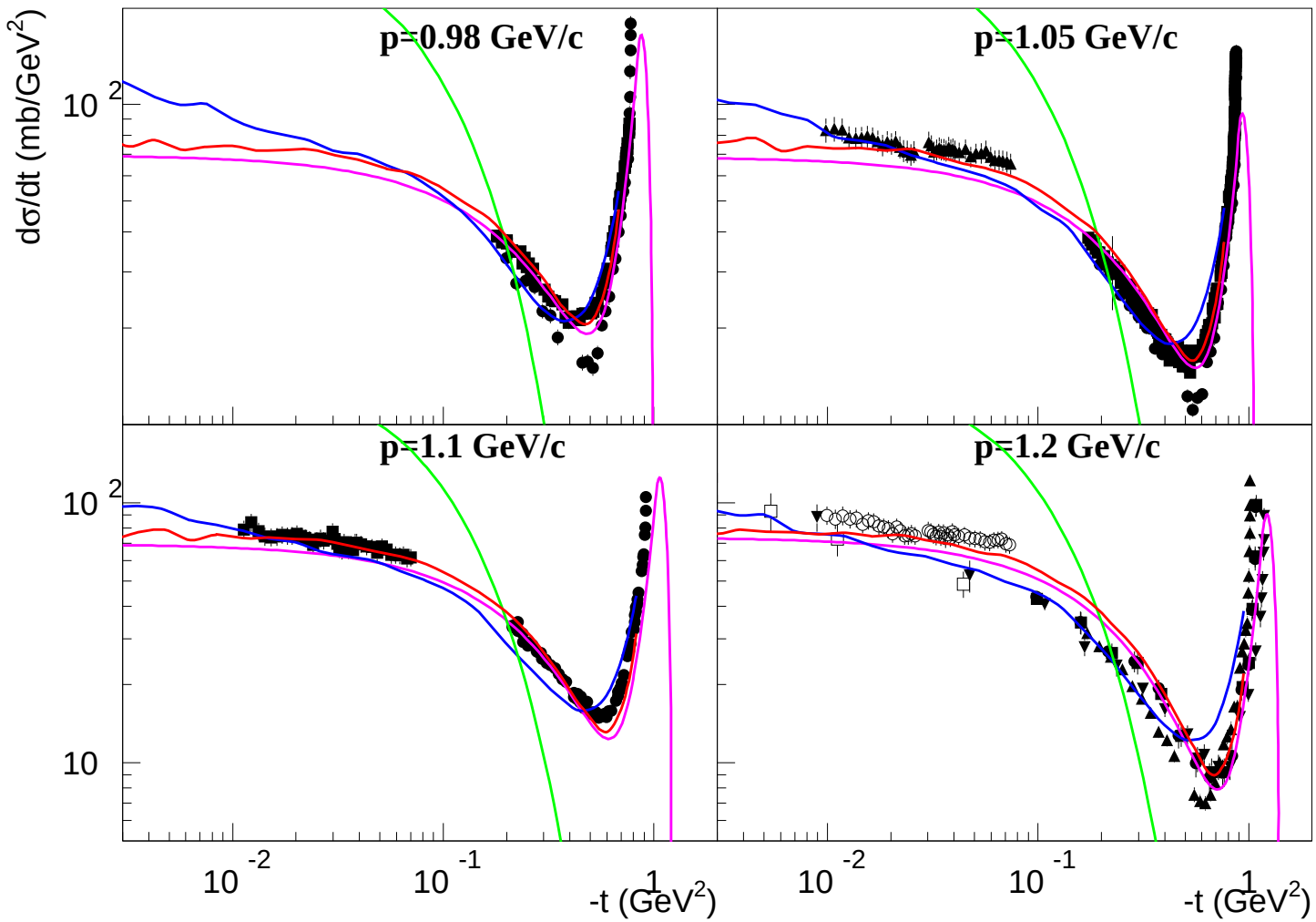

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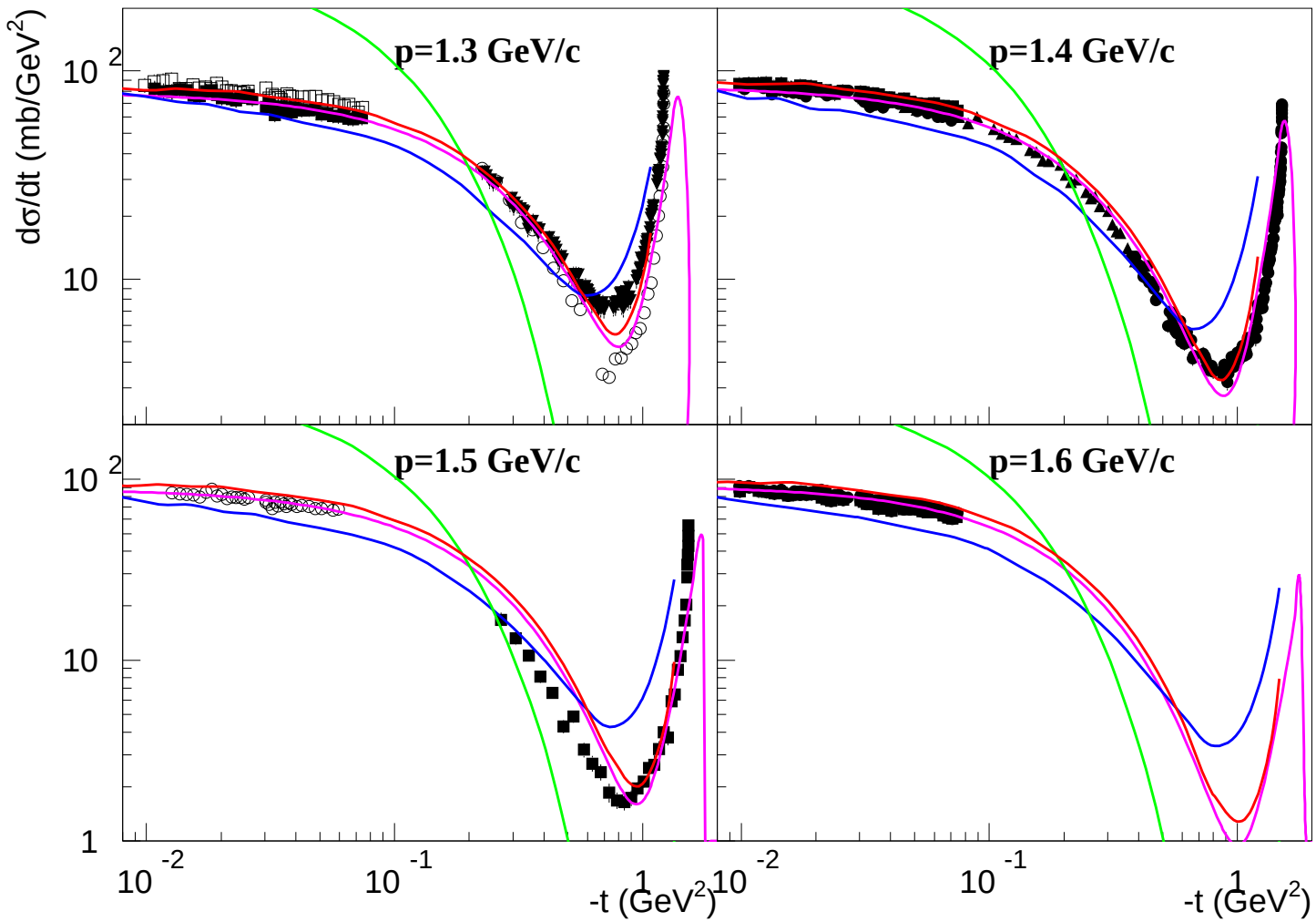

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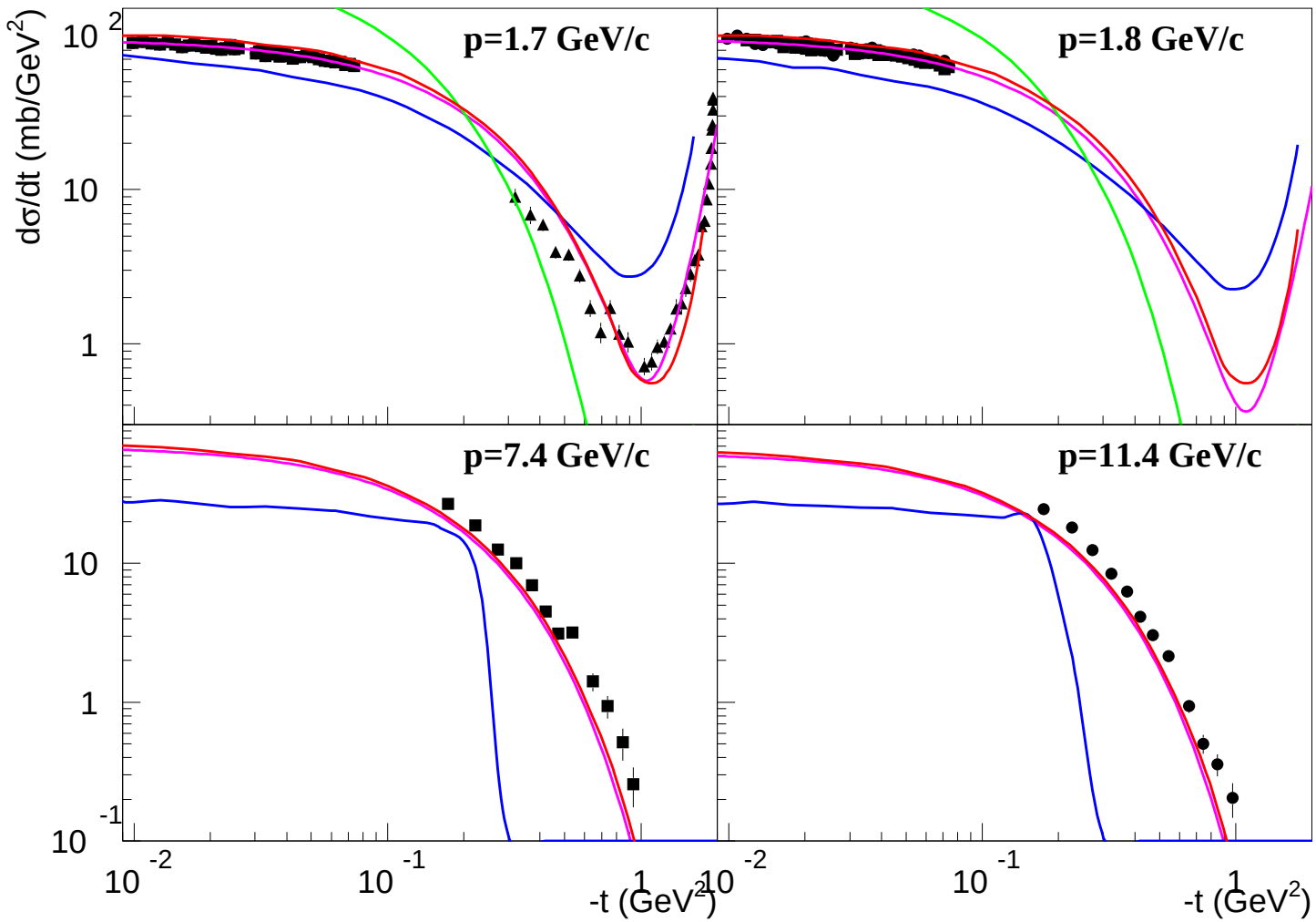

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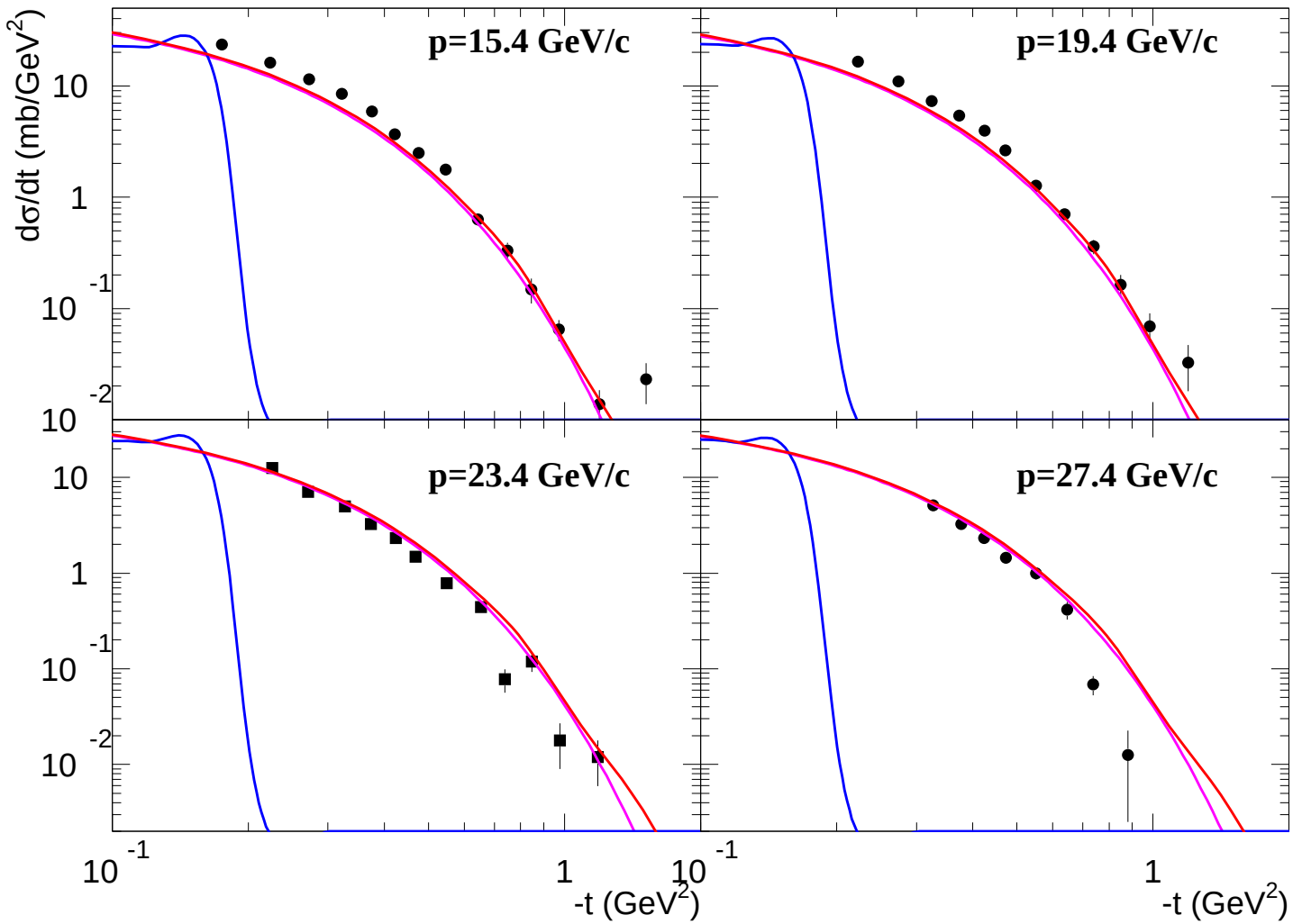

Inelastic nH reactions at low energies

Below the pion threshold the main inelastic reactions are $n(p,d)\gamma$ (radiative absorption) and $n(p,np)\gamma$ (hard Bremsstrahlung of neutrons).

$$\frac{\mathbf{d}\sigma_{(\mathbf{d}\gamma)}}{\mathbf{d\Omega}} = \mathbf{A_0} + \mathbf{A_1} \cdot \mathbf{cos}(\theta) + \mathbf{A_2} \cdot \mathbf{cos}(\theta)^{\mathbf{2}} + \mathbf{A_3} \cdot \mathbf{cos}(\theta)^{\mathbf{3}}$$

Using the detailed balance one can use $\gamma(d,n)p$ measured reactions.

The $n(p,np)\gamma$ reaction is not well measured and the energy dependence is practically unknown, while it is known that at low energies the cross-section of this reaction is much smaller than the cross-section of the $n(p,d)\gamma$ reaction. Can it be described by γnp phase space?

$$\frac{\mathbf{d}\sigma_{(\mathbf{np}\gamma,\theta=\mathbf{0})}}{\mathbf{dE}} = \mathbf{C} \cdot \left(\frac{\mathbf{T}}{\mathbf{T_{max}}}\right)^{\mathbf{12}} \cdot \left(\mathbf{1} - \frac{\mathbf{T}}{\mathbf{T_{max}}}\right)^{\mathbf{16}}$$

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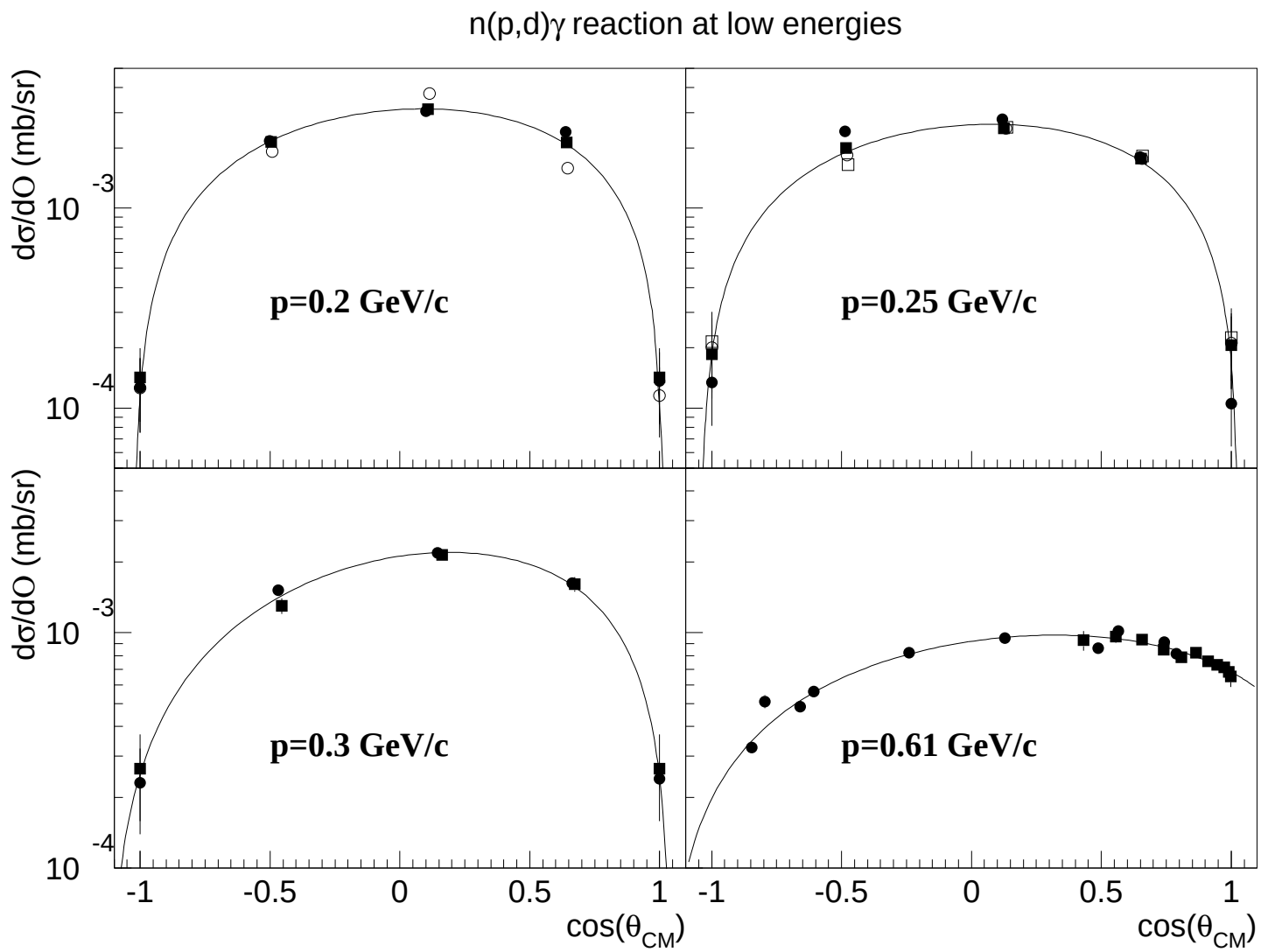

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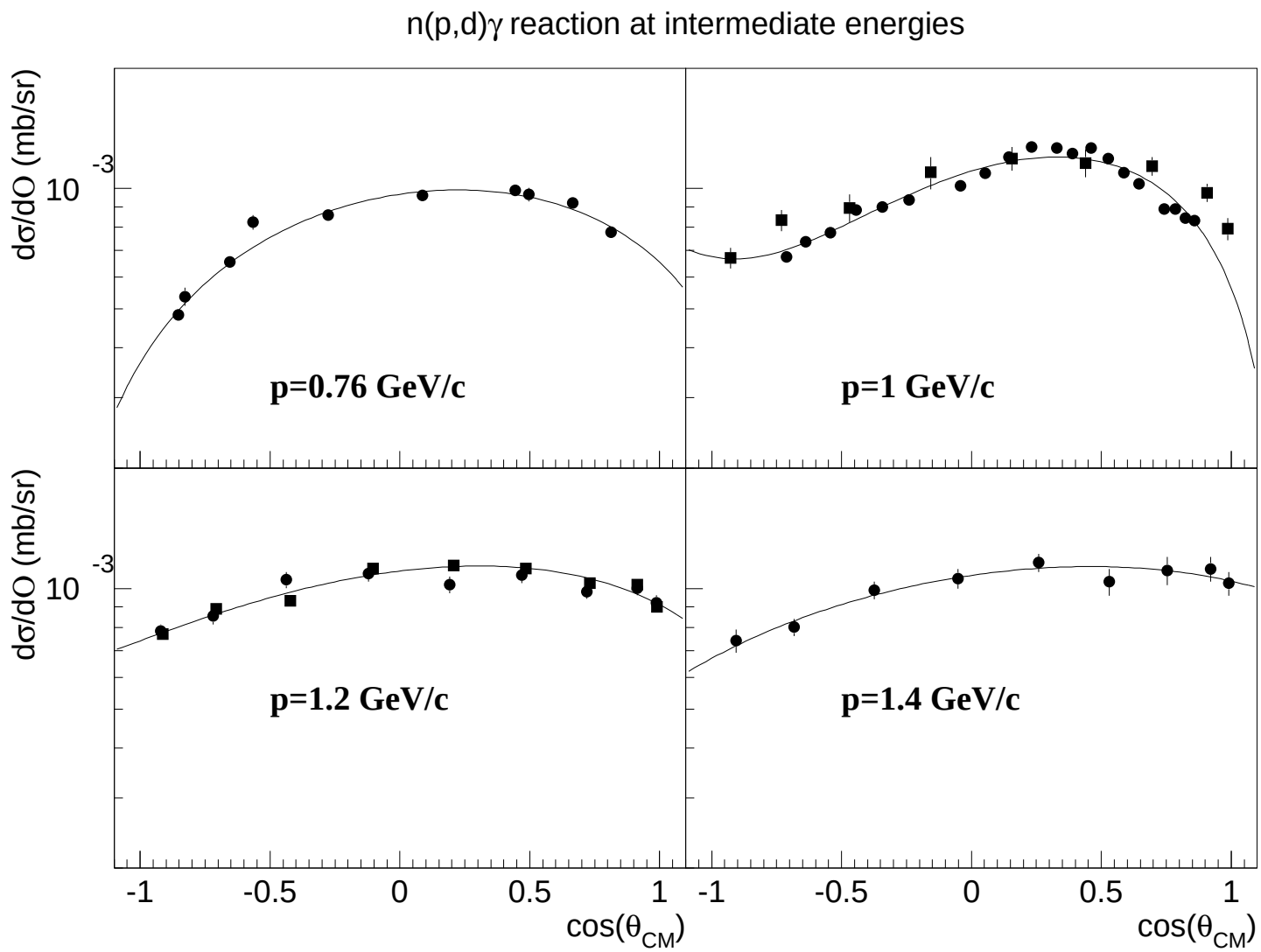

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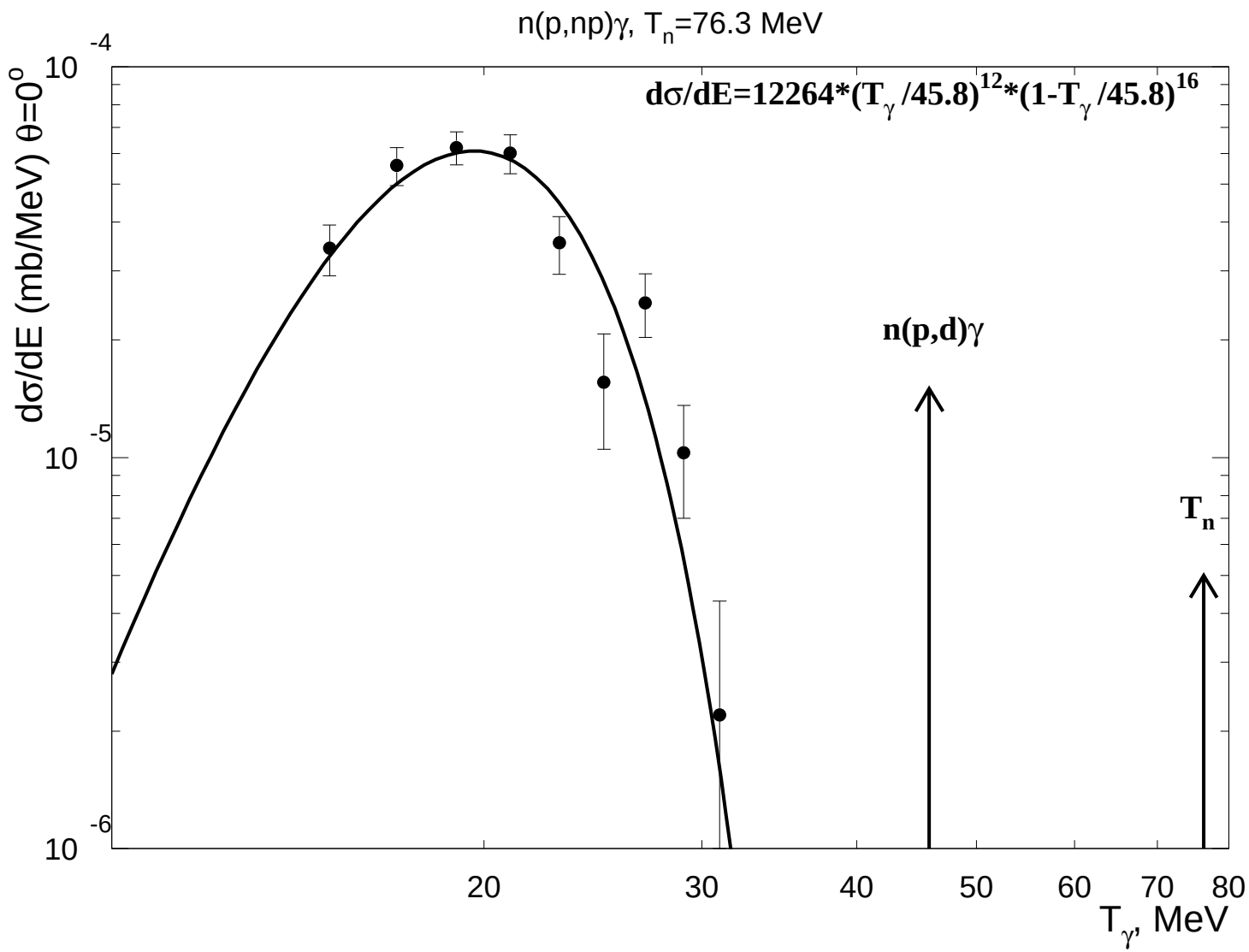

Conclusion

- The $G4QElastic$ (CHIPS) process covers all energies for nH elastic.
- The existing HP/LE np elastic cross-section combination (not just LE!) looks good except for p $>$ 200 GeV/c and p $<$ 30 keV/c.
- The Geant4 8.0 $G4LElastic$ model converts n to p (killing n) or keep n practically unchanged in about 50% of events at low energies and practically always at p $>$ 3 GeV/c. The rest of selected np final states do not include a charge exchange process for p $>$ .4 GeV/c.
- The $G4LElasticB$ model provides pp (?!) final states for np elastic scattering (pseudo charge exchange). It is not analyzed in details.
- The existing in Geant4 (but not used in physics lists) $G4LEnp$ model is close to data above .25 GeV/c (XS) and below 2 GeV/c (t-dep).
- $n(p,d)\gamma$ reaction must be upgraded, $n(p,np)\gamma$ reaction must be added.