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.**

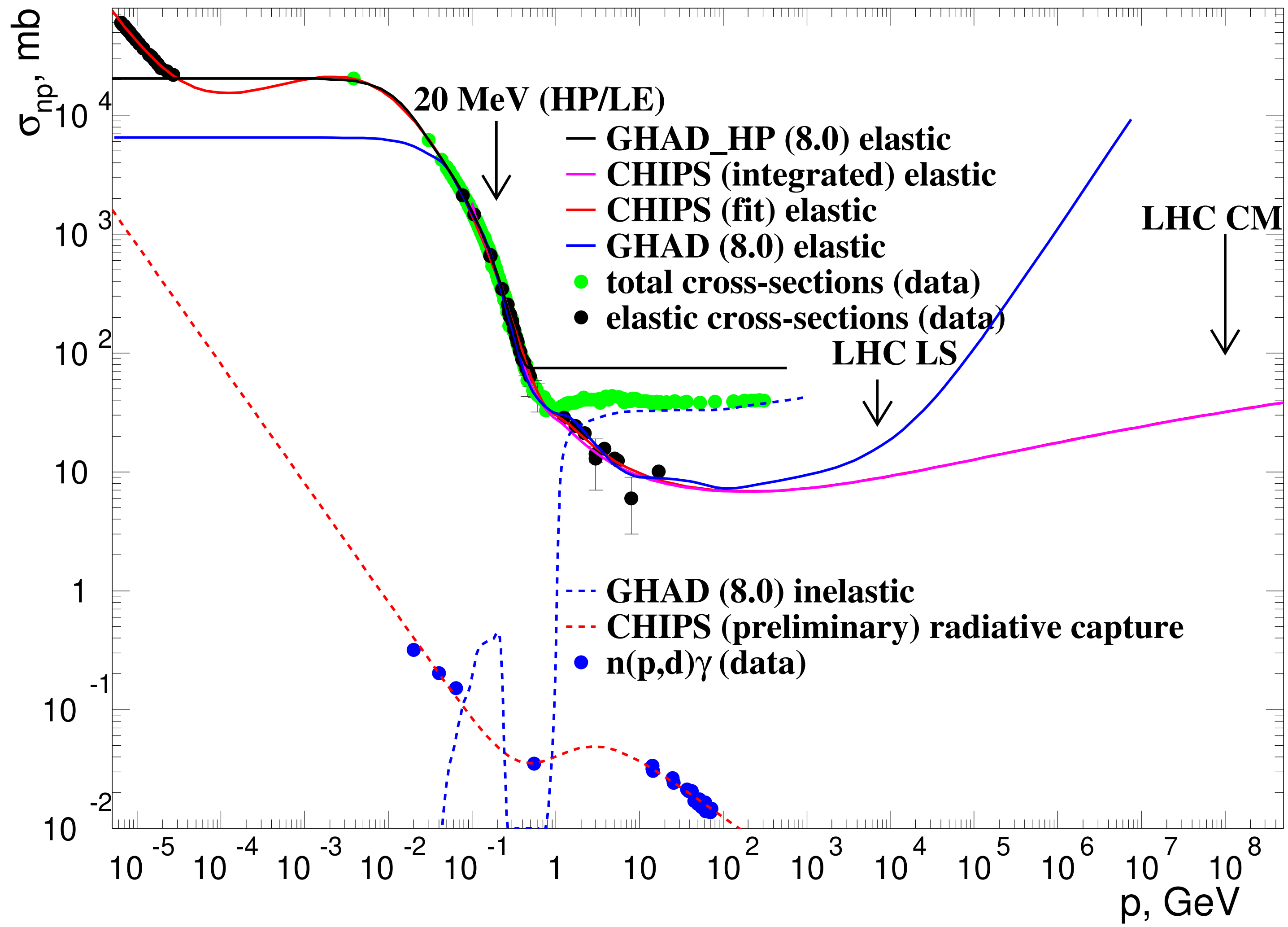
Significance of nH interactions

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.

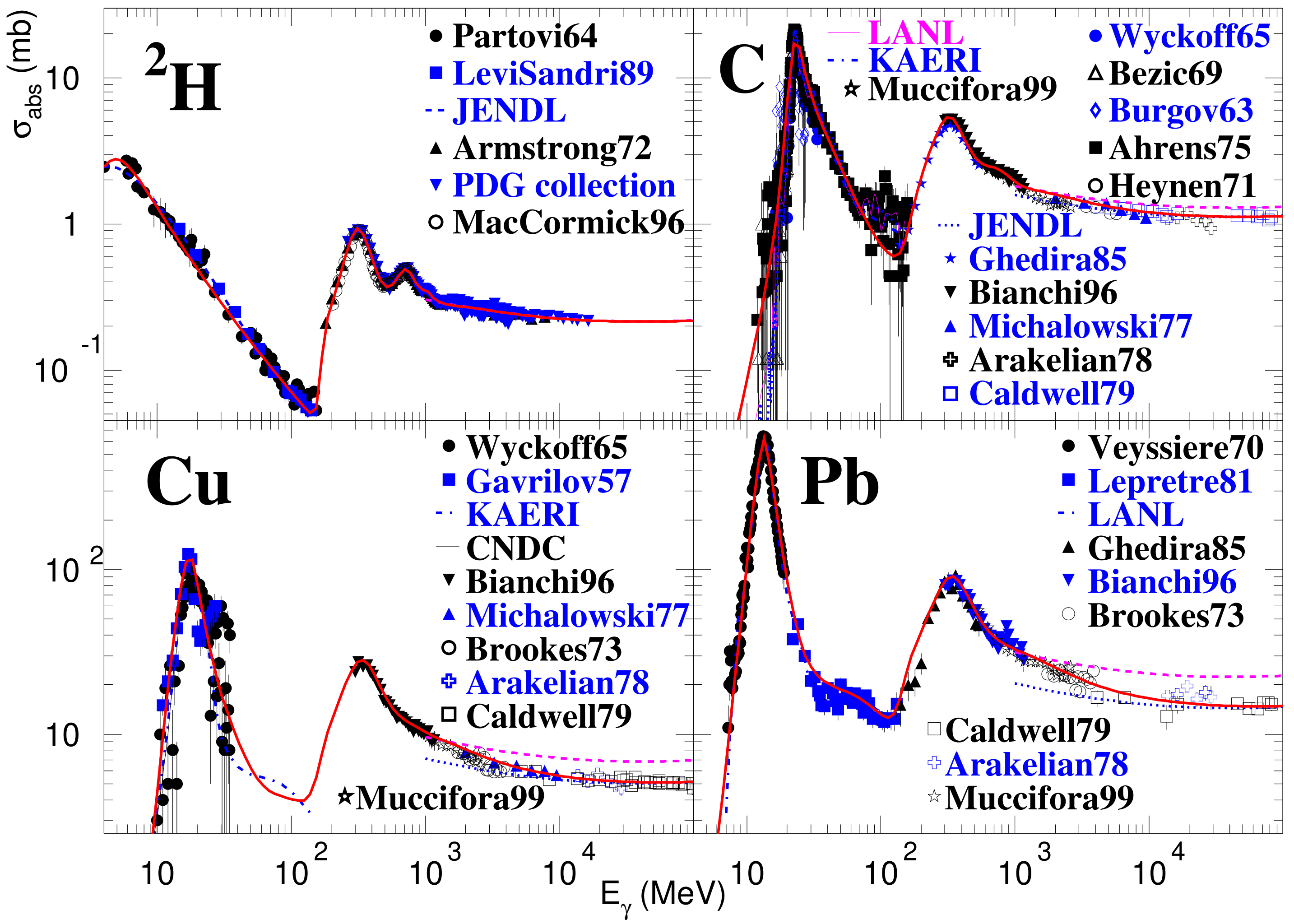
At Low Energies there are three main processes:

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).



σ_{np}, mb
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8
p, GeV
20 MeV (HP/LE)
GHAD_HP (8.0) elastic
CHIPS (integrated) elastic
CHIPS (fit) elastic
GHAD (8.0) elastic
total cross-sections (data)
elastic cross-sections (data)
LHC CM
LHC LS
GHAD (8.0) inelastic
CHIPS (preliminary) radiative capture
n(p,d)γ (data)



σ_{abs} (mb)
^{2}H
Partovi64
LeviSandri89
JENDL
Armstrong72
PDG collection
MacCormick96
C
LANL
KAERI
Muccifora99
Wyckoff65
Bezic69
Burgov63
Ahrens75
Heynen71
JENDL
Ghedira85
Bianchi96
Michalowski77
Arakelian78
Caldwell79
Cu
Wyckoff65
Gavrilov57
KAERI
CNDC
Bianchi96
Michalowski77
Brookes73
Arakelian78
Caldwell79
Muccifora99
Pb
Veyssiere70
Lepretre81
LANL
Ghedira85
Bianchi96
Brookes73
Caldwell79
Arakelian78
Muccifora99
E_γ (MeV)

Exponential approach for elastic cross-sections

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

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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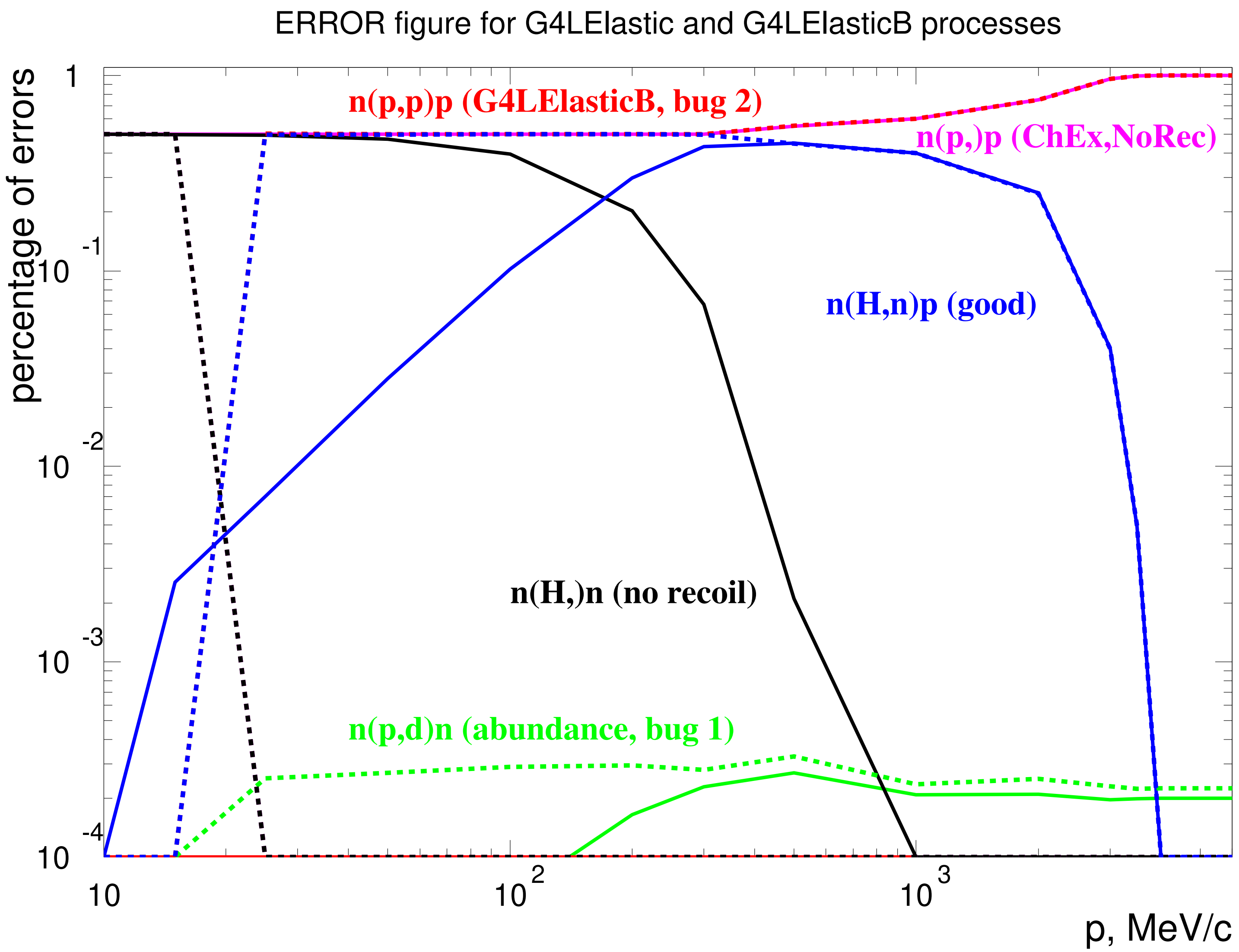
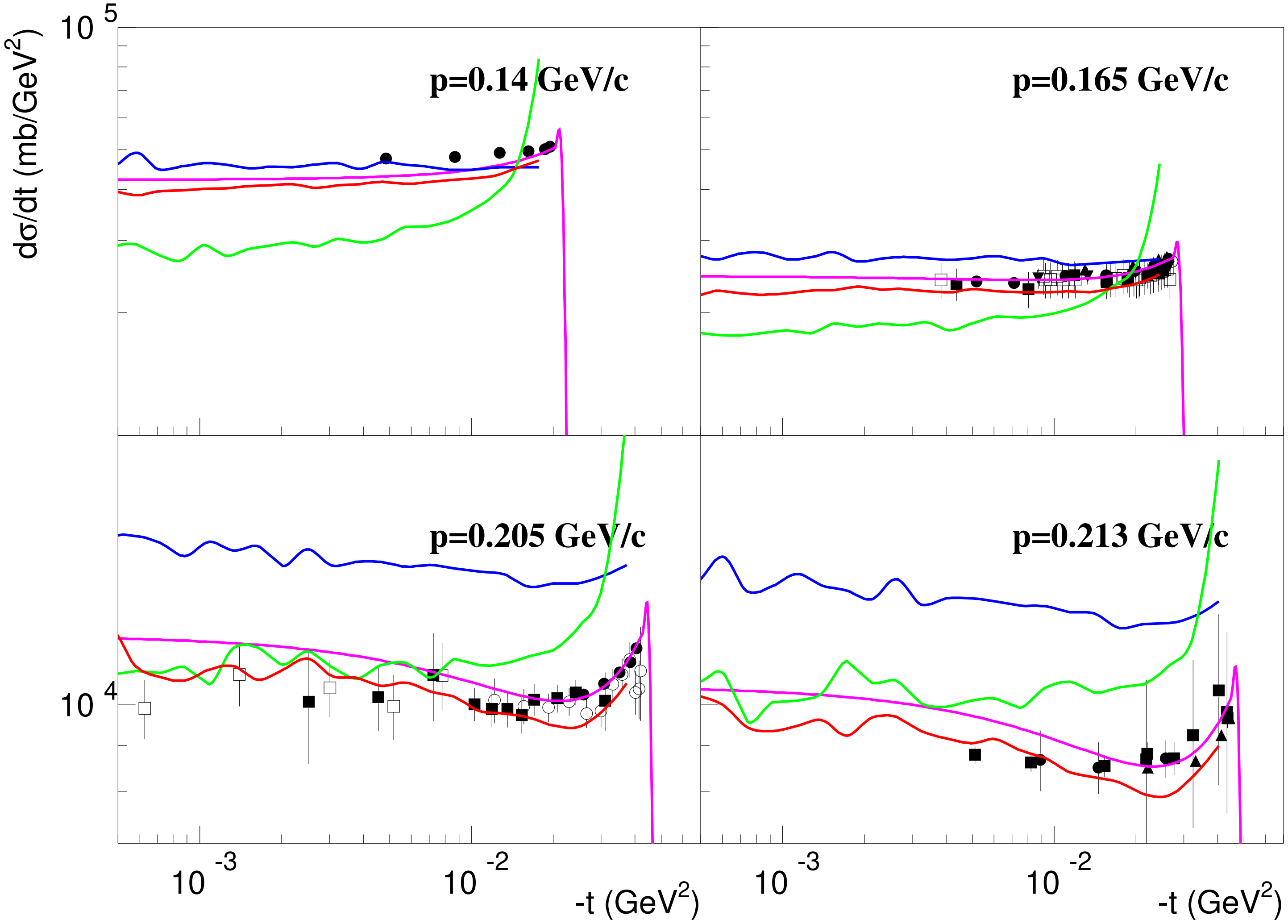
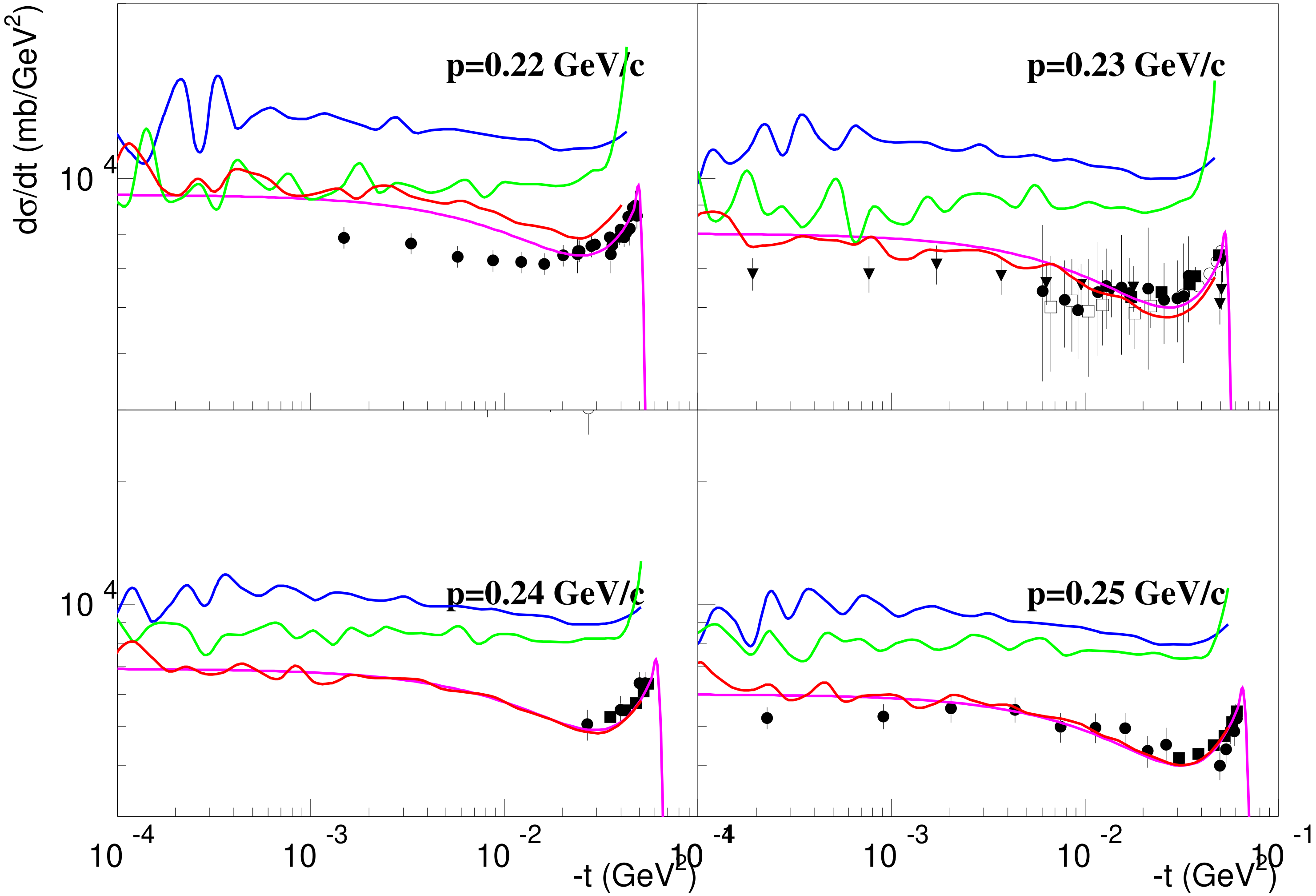
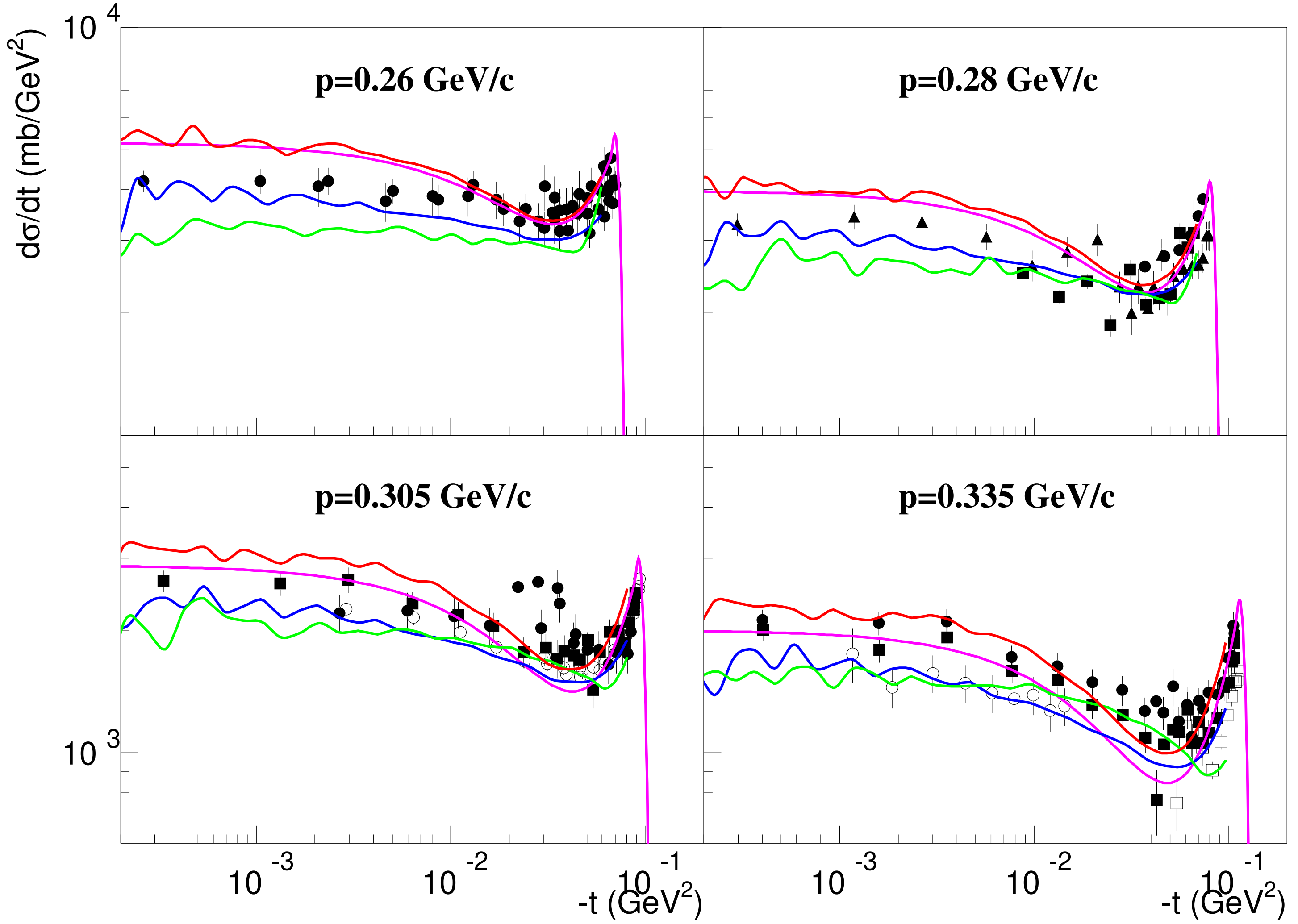
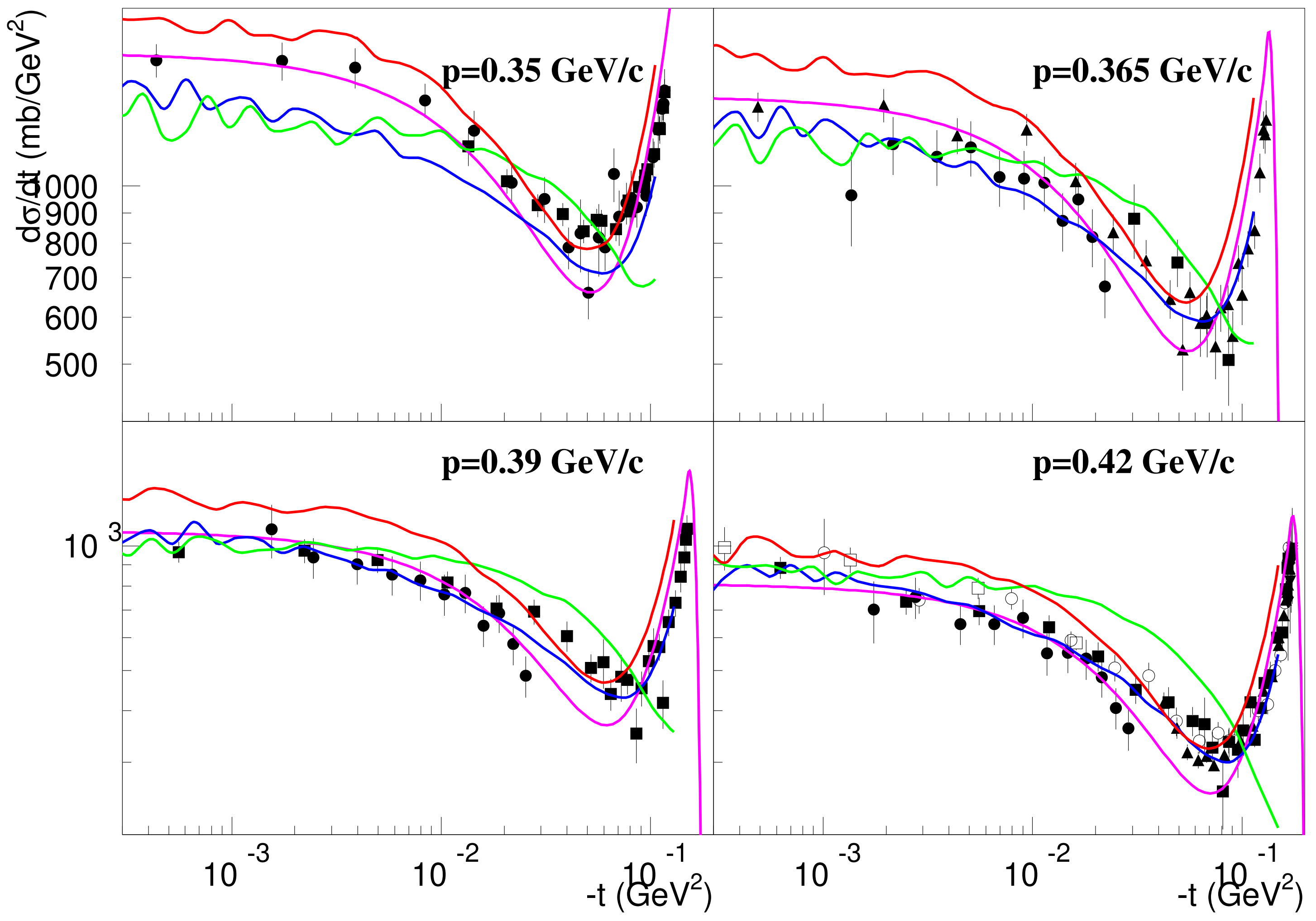
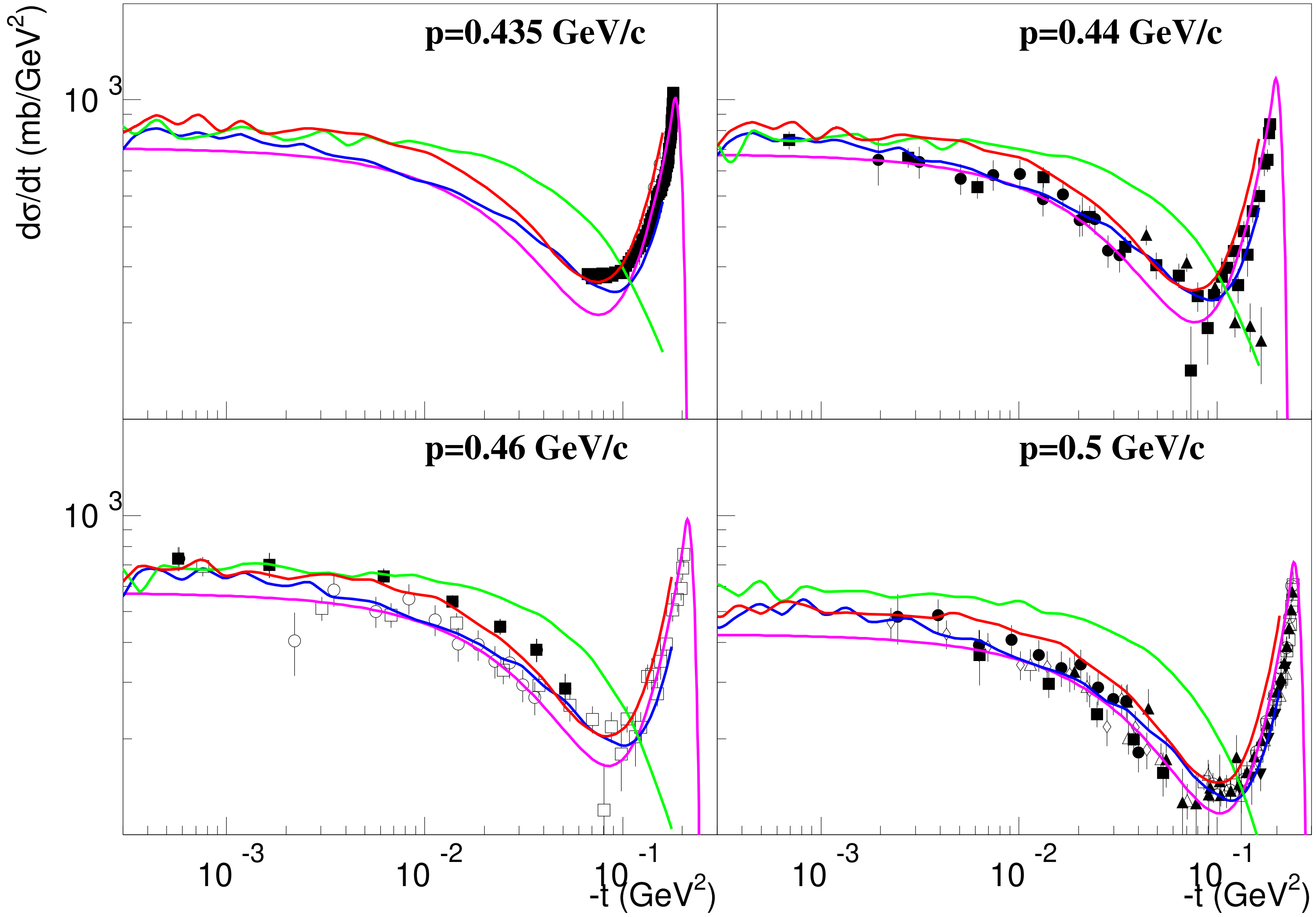

ERROR figure for G4LElastic and G4LElasticB processes
percentage of errors
1
10^-1
10^-2
10^-3
10^-4
10
10^2
10^3
p, MeV/c
n(p,p)p (G4LElasticB, bug 2)
n(p,)p (ChEx,NoRec)
n(H,n)p (good)
n(H,)n (no recoil)
n(p,d)n (abundance, bug 1)


dσ/dt (mb/GeV^2)
10^5
10^4
p=0.14 GeV/c
p=0.165 GeV/c
p=0.205 GeV/c
p=0.213 GeV/c
10^{-3}
10^{-2}
-t (GeV^2)
10^{-3}
10^{-2}
-t (GeV^2)


p=0.22 GeV/c
p=0.23 GeV/c
p=0.24 GeV/c
p=0.25 GeV/c
dσ/dt (mb/GeV^2)
10^4
10^4
10^{-4}
10^{-3}
10^{-2}
10^{-1}
-t (GeV^2)
-t (GeV^2)


p=0.26 GeV/c
p=0.28 GeV/c
p=0.305 GeV/c
p=0.335 GeV/c
dσ/dt (mb/GeV²)
-t (GeV²)
10^4
10^3
10^-3
10^-2
10^-1


p=0.35 GeV/c
p=0.365 GeV/c
p=0.39 GeV/c
p=0.42 GeV/c
dσ/dt (mb/GeV^2)
1000
900
800
700
600
500
10^3
10^{-3}
10^{-2}
10^{-1}
-t (GeV^2)


p=0.435 GeV/c
p=0.44 GeV/c
p=0.46 GeV/c
p=0.5 GeV/c
dσ/dt (mb/GeV²)
10 3
10 -3
10 -2
10 -1
-t (GeV²)

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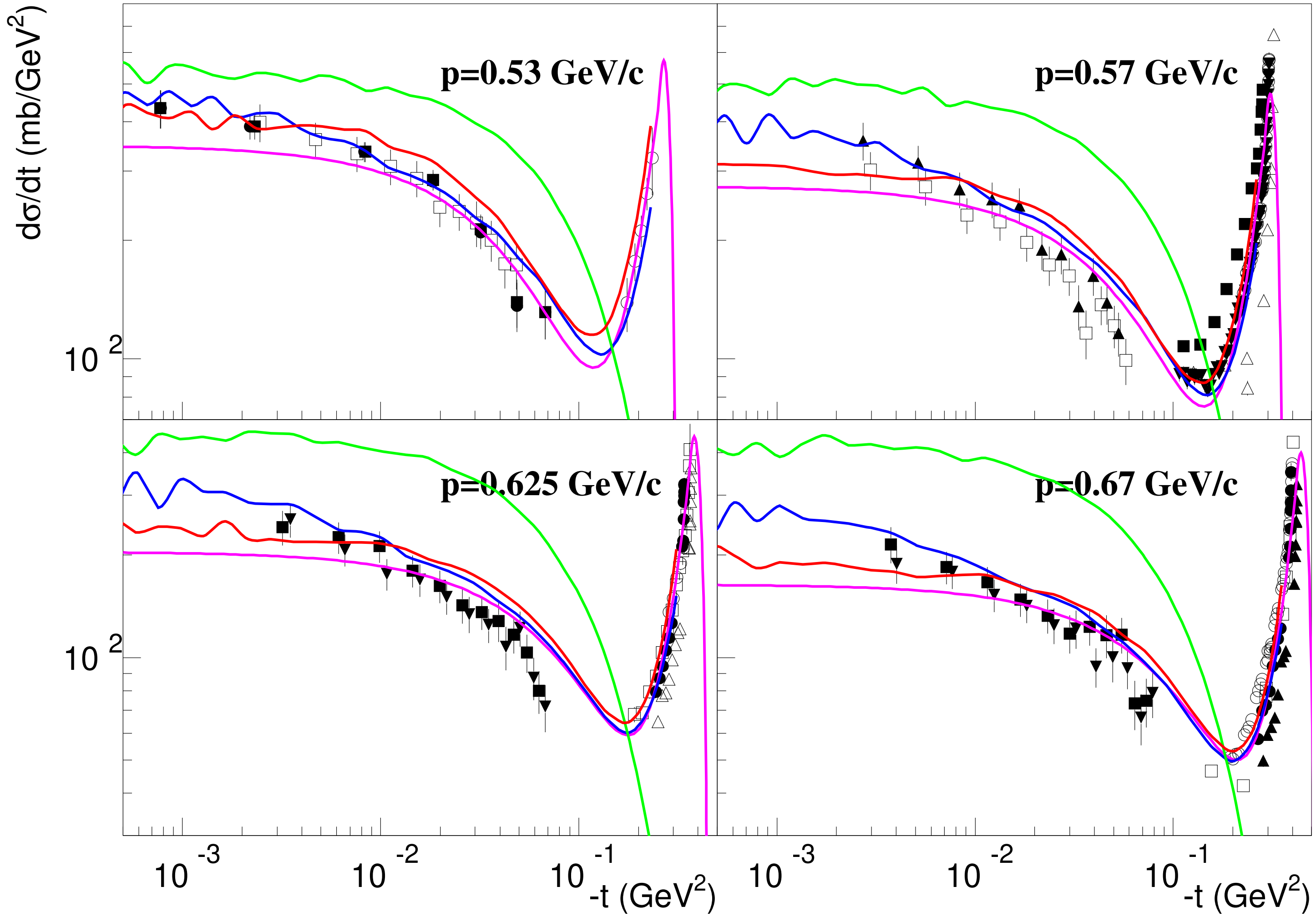
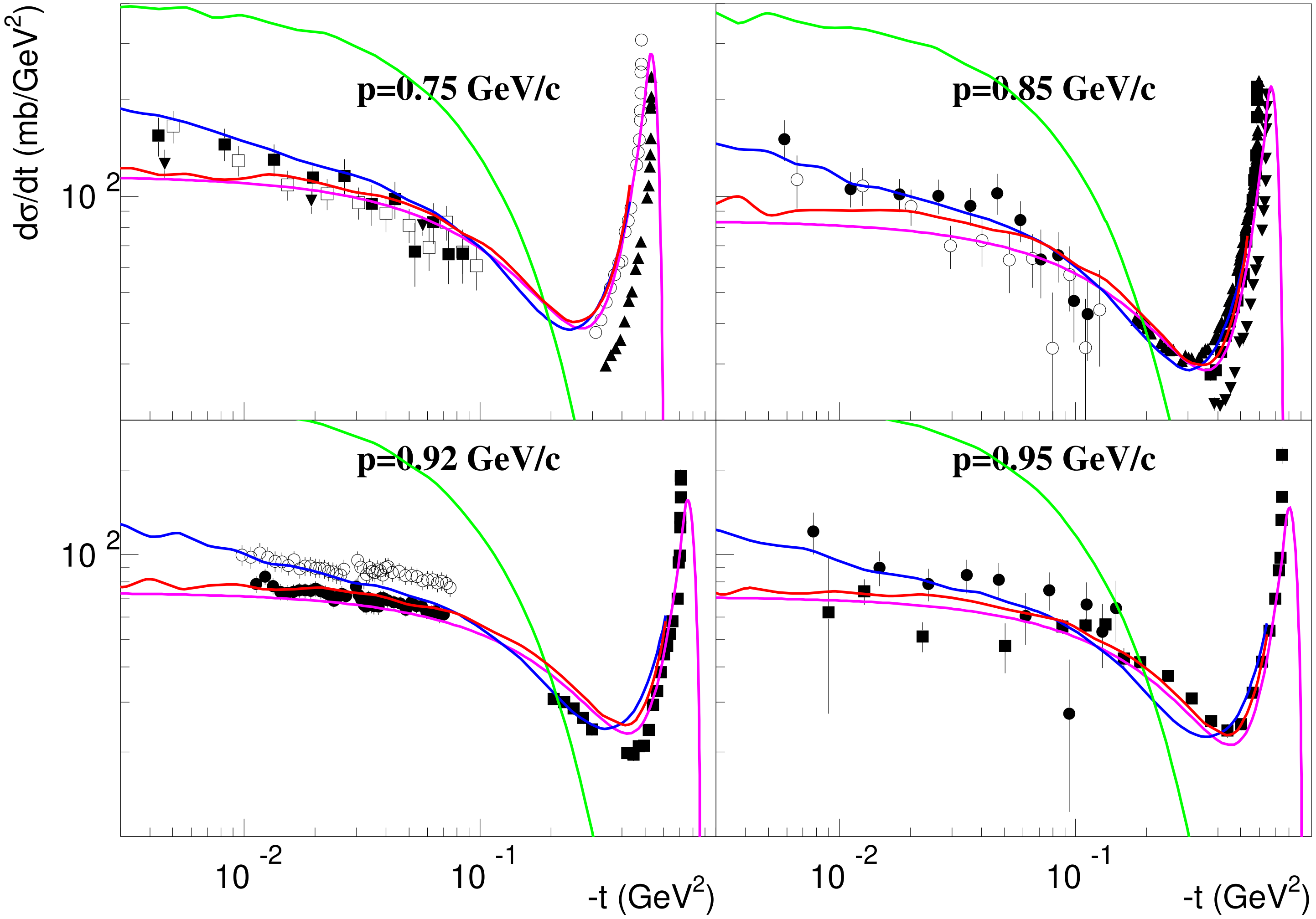
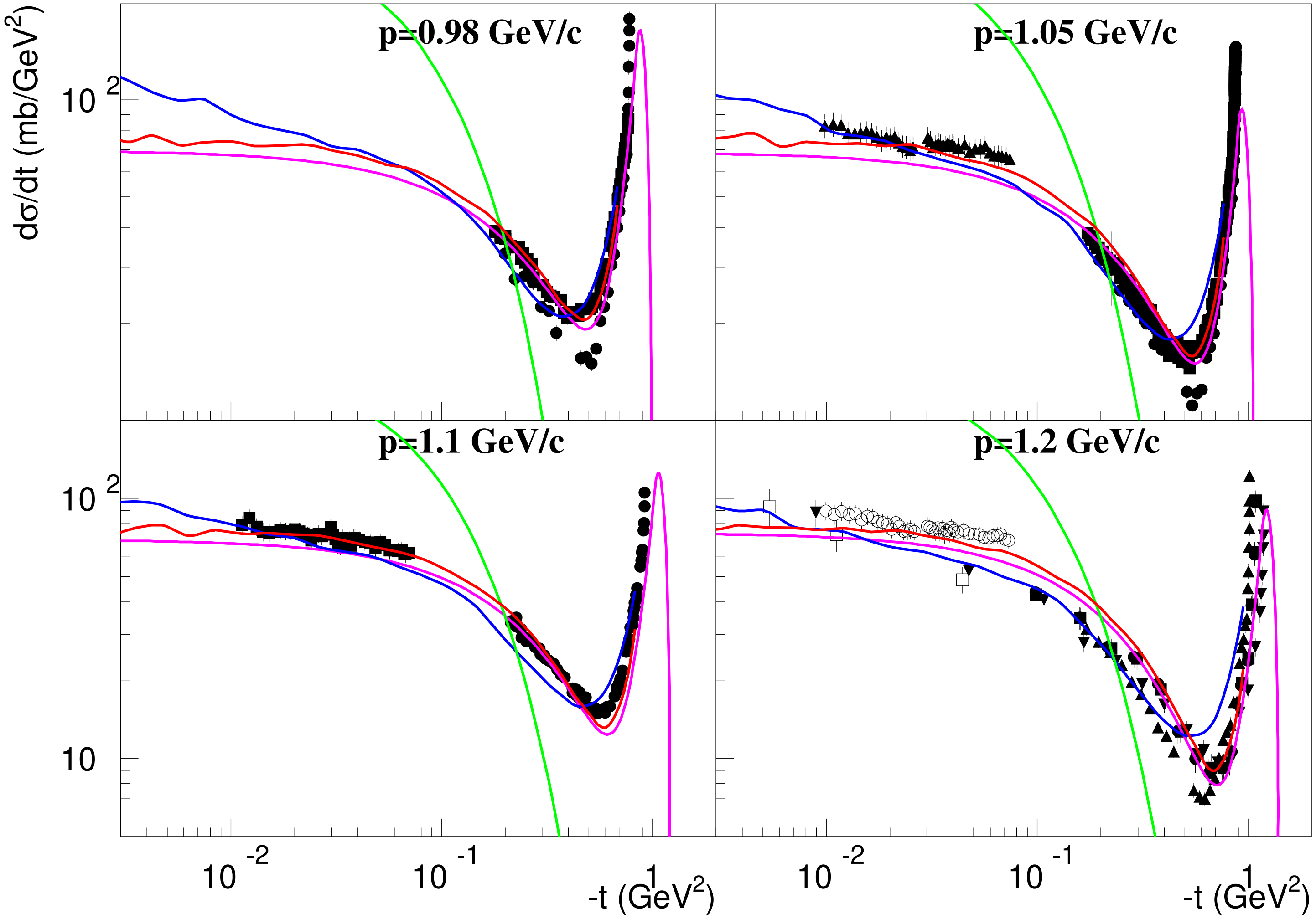
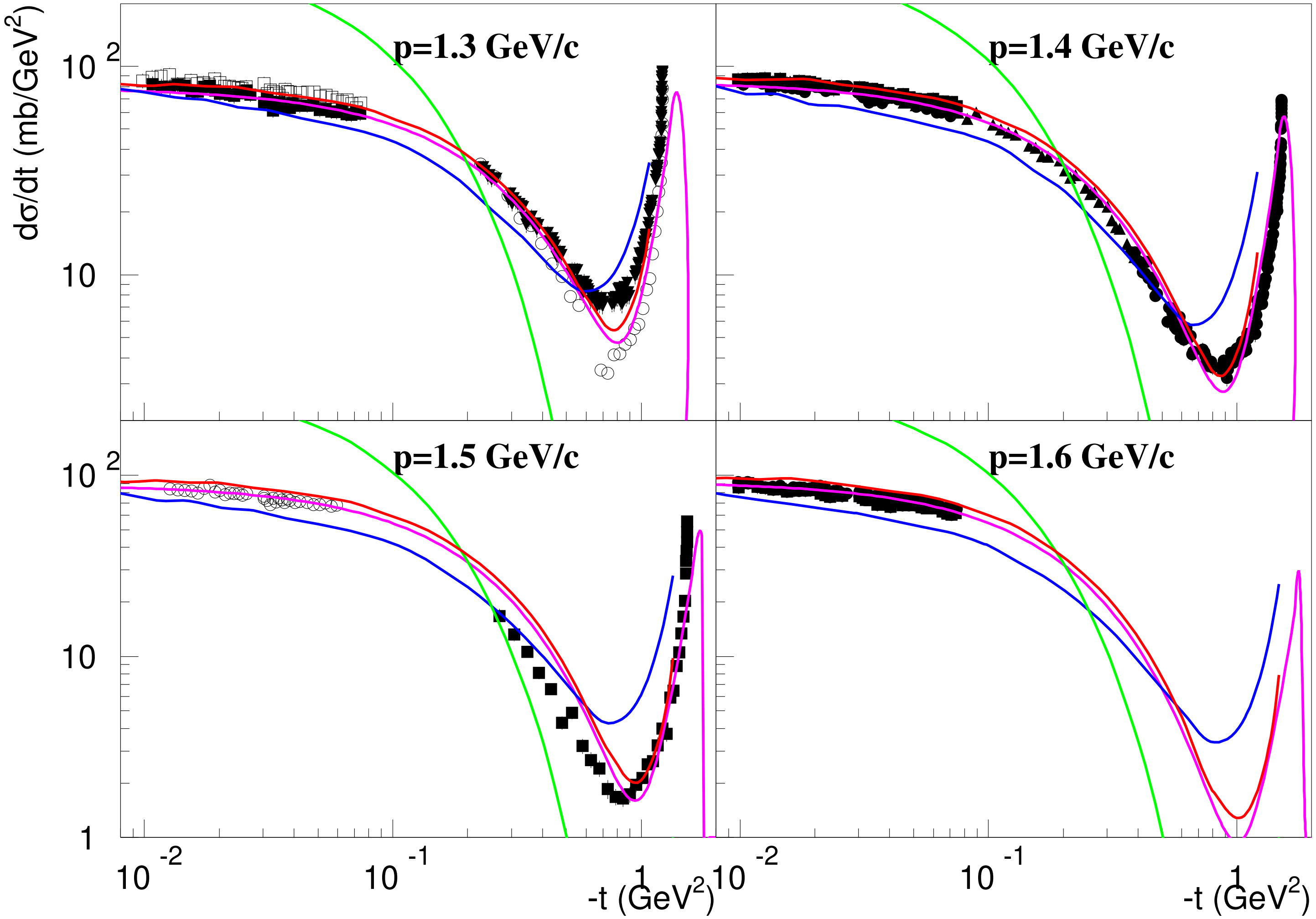


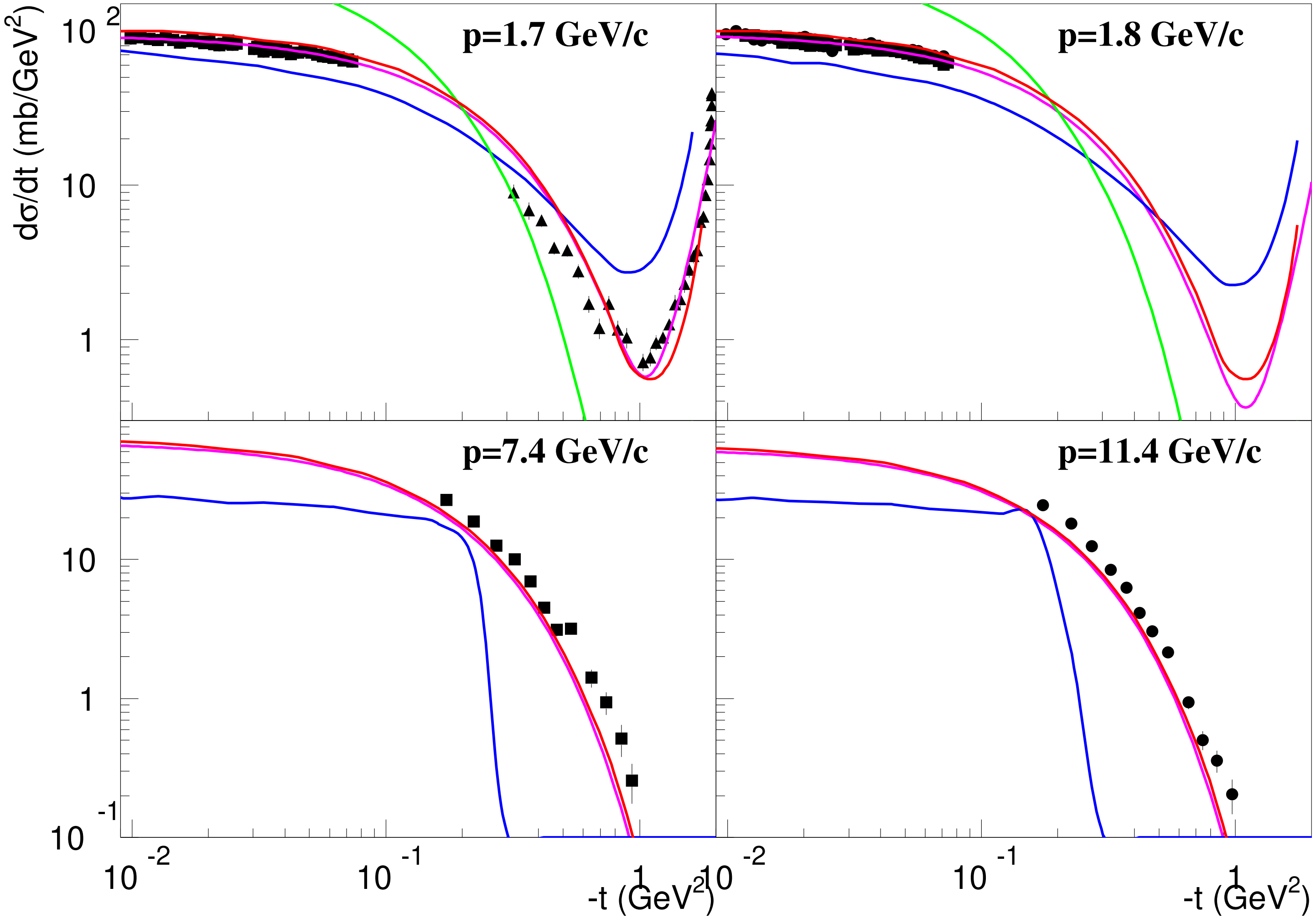
dσ/dt (mb/GeV²)
p=0.53 GeV/c
p=0.57 GeV/c
p=0.625 GeV/c
p=0.67 GeV/c
10²
10²
10⁻³
10⁻²
10⁻¹
-t (GeV²)
10⁻³
10⁻²
10⁻¹
-t (GeV²)


dσ/dt (mb/GeV^2)
p=0.75 GeV/c
p=0.85 GeV/c
p=0.92 GeV/c
p=0.95 GeV/c
10^2
10^2
10^{-2}
10^{-1}
-t (GeV^2)
10^{-2}
10^{-1}
-t (GeV^2)


p=0.98 GeV/c
p=1.05 GeV/c
p=1.1 GeV/c
p=1.2 GeV/c
dσ/dt (mb/GeV^2)
10^2
10
10^{-2}
10^{-1}
1
-t (GeV^2)



p=1.3 GeV/c
p=1.4 GeV/c
p=1.5 GeV/c
p=1.6 GeV/c
dσ/dt (mb/GeV^2)
-t (GeV^2)
-t (GeV^2)



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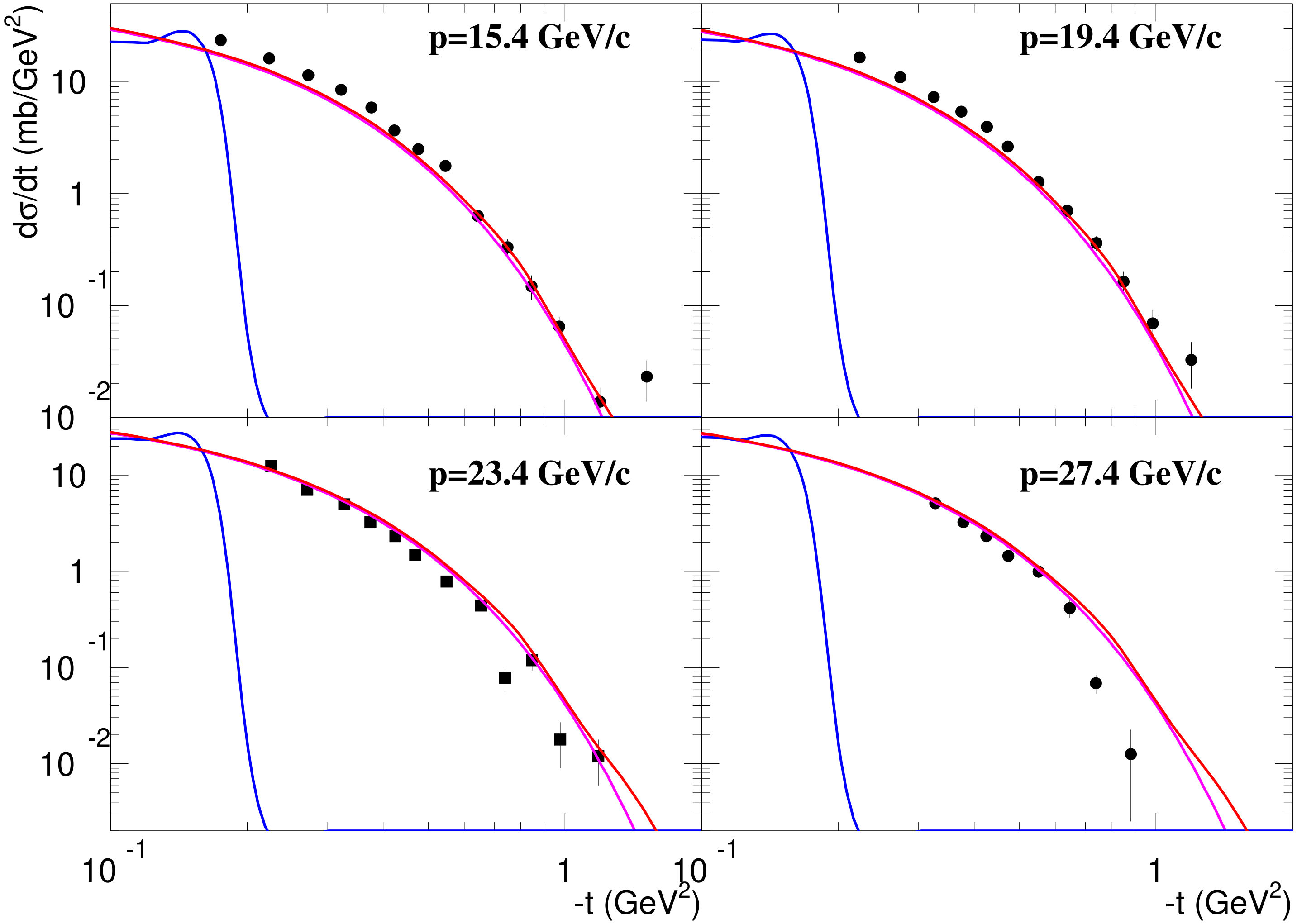
p=15.4 GeV/c
p=19.4 GeV/c
p=23.4 GeV/c
p=27.4 GeV/c
dσ/dt (mb/GeV^2)
-t (GeV^2)
-t (GeV^2)

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).

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

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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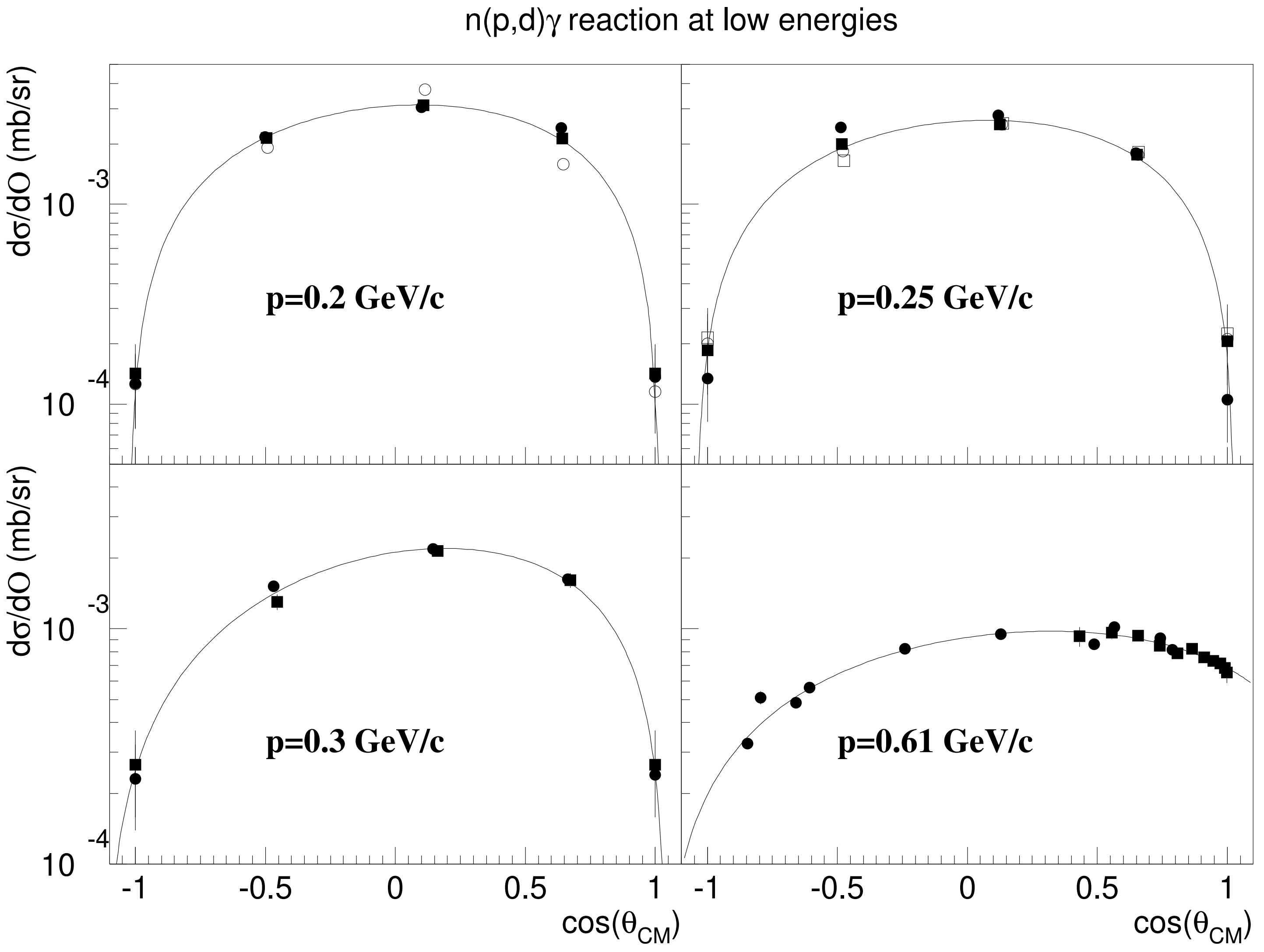
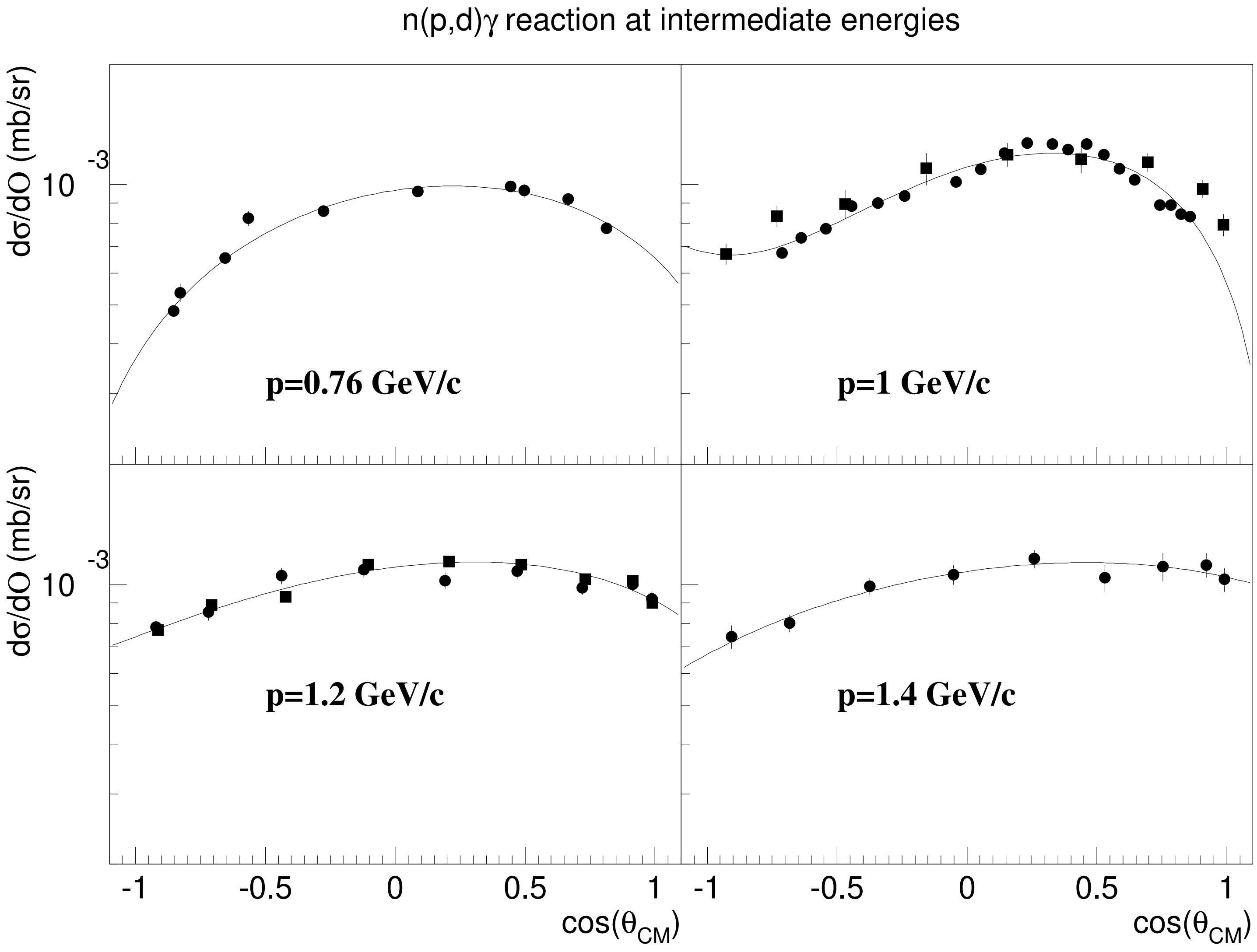
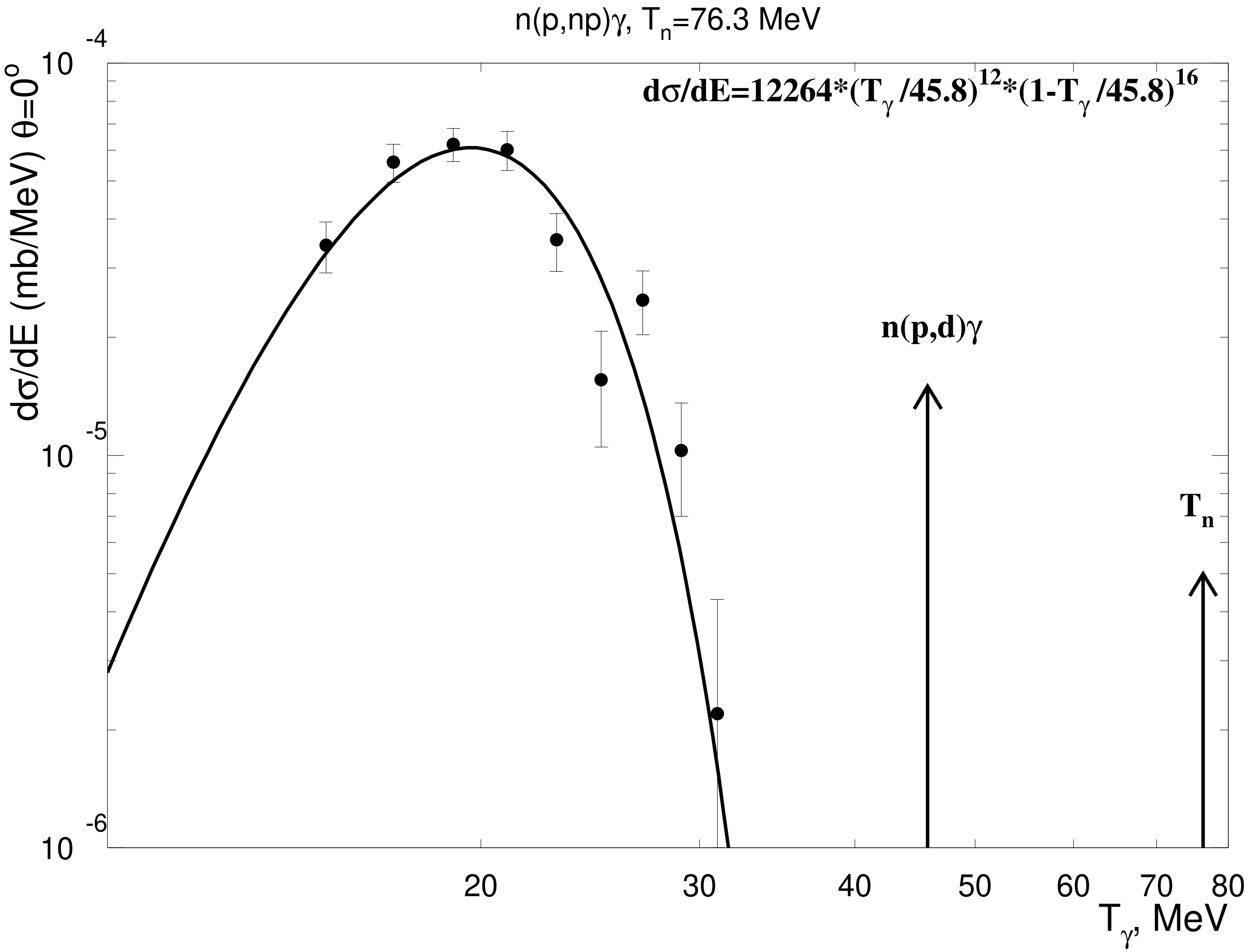

n(p,d)γ reaction at low energies
dσ/dO (mb/sr)
p=0.2 GeV/c
p=0.25 GeV/c
p=0.3 GeV/c
p=0.61 GeV/c
cos(θCM)
cos(θCM)


n(p,d)γ reaction at intermediate energies
dσ/dO (mb/sr)
10^{-3}
p=0.76 GeV/c
p=1 GeV/c
p=1.2 GeV/c
p=1.4 GeV/c
-1
-0.5
0
0.5
1
cos(θ_CM)


n(p,np)γ, T_n=76.3 MeV
dσ/dE=12264*(T_γ /45.8)^12*(1-T_γ /45.8)^16
dσ/dE (mb/MeV) θ=0°
10^-4
10^-5
10^-6
n(p,d)γ
T_n
20
30
40
50
60
70
80
T_γ, MeV

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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.