Single-Pion Photoproduction Contribution to Gerasimov – Drell – Hearn Sum Rule & Related Integrals

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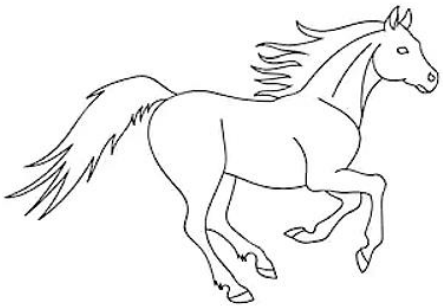
The George Washington University

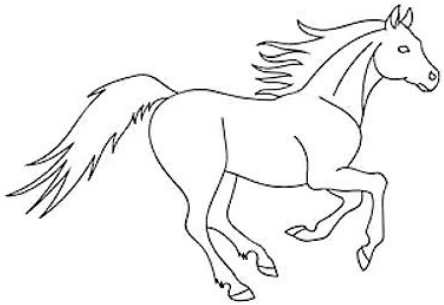
IS, S. Sirca, W.J. Briscoe, A, Deur, R.L. Workman, Phys Rev C **105**, 045202 (2022)

*Supported by DE-SC0016583

Outline



- Sum Rules:
  - *GDH*.
  - *Baldin*.
  - *GGT*.
- Photoabsorption cross sections.
- Double-pol observable ***E***.
- Differences of total cross sections.
- Running integrals.
  - *GDH*.
  - *Baldin*.
  - *GGT*.
- Future experiment(s).
- Summary.



Sum Rules

- Study of *polarized lepton* scattering on *polarized nucleons* provides information on *spin composition of nucleon*.

- In *real*-*photon* *limit* of *lepton*-*nucleon* interaction, process can be characterized either
  - in terms of *integrals* of *cross-sections* with various weights,
  - in terms of *static nucleon properties* or

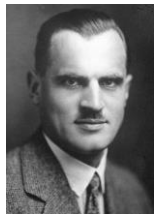
  resulting in "*Sum Rules*."

- Relevant quantities of interest are $\sigma_{3/2}$ & $\sigma_{1/2}$, *photon*-*nucleon* *total absorption cross-sections* for *circularly polarized photons* on *longitudinally polarized nucleons*, with total helicity *3/2* & *1/2* from which either
  - *difference*, $\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$, or
  - *sum*, $\sigma_{\rm tot} = \sigma_{3/2} + \sigma_{1/2}$,

  can be constructed.

- Our Phys Ref C **105**, 045202 (2022) gives ***comprehensive review*** of status of
  - *Gerasimov*-*Drell*-*Hearn* (*GDH*),
  - *Baldin*, &
  - *Gell-Mann*-*Goldberger*-*Thirring* (*GGT*) sum rules.

GDH Sum Rule



- *Gerasimov – Drell – Hearn* (*GDH*) sum rule, formulated in 1960s, rests upon *fundamental physics principles* or *first principles* (*Lorentz* & gauge invariances, crossing symmetry, rotational invariance, causality, & unitarity) & unsubtracted *dispersion relations* applied to forward ***Compton*** amplitude.

- Because of its *fundamental* character, *GDH* sum rule requires *experimental verification* which has been awaiting technical developments that have only recently been attained.

- *GDH* sum rule relates *proton* (*neutron*) *anomalous magnetic moment* to integral of total photon-nucleon total absorption cross-sections for *circularly polarized photons* on *longitudinally polarized nucleons*, with total helicity *3/2* & *1/2*, $\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$, weighted by photon energy in lab frame, E_γ:

$$I_{\rm GDH} = \int_{E_\gamma^{\rm thr}}^{\infty} \frac{\Delta\sigma}{E_\gamma}\, dE_\gamma = \frac{2\pi^2\alpha}{M^2}\kappa^2$$

- For *nucleon*, all ***static quantities*** appearing in Eq. (right-hand) are known very precisely.
  204.784482(35) μb for *proton*
  232.25159(13) μb for *neutron*

where $\kappa_p = \mu_p - 1 \approx 1.793\,\mu_N$ $(\kappa_n = \mu_n \approx -1.913\,\mu_N)$ is *anomalous magnetic moment*;
μ_N is *nuclear magneton*;
$E_\gamma^{\rm thr}$ is *photon energy* corresponding to pion photoproduction *threshold*;
$\alpha = e_0^2/4\pi$ is *fine structure constant*;
M is *nucleon* mass.

S.B. Gerasimov, Sov J Nucl Phys **2**, 430 (1966)
S.D. Drell & A.C. Hearn, Phys Rev Lett **16**, 908 (1966)
L.I. Lapidus & Chou Kuang-chao [Zhou Guangzhao], , Sov Phys JETP **14**, 352 (1962)

Possible Causes of Violation of GDH

- *Gerasimov – Drell – Hearn* sum rule rests upon *first principles:*
  Lorentz & gauge invariances, crossing symmetry, rotational invariance, causality, unitarity & unsubtracted ***dispersion relations*** applied to forward ***Compton*** amplitude.

- Possible causes for *GDH sum rule violation* — or its apparent violation when integral is "measured" over finite E_γ range.

- Most often considered are (all proposed mechanisms would manifest themselves at high E_γ):
  - Existence of unknown high-energy phenomena, such as quark substructure (non-zero quark anomalous moments)
  - Existence of **J** = **1** pole of nucleon ***Compton*** amplitude, &
  - Chiral anomaly.

- *Weinberg* stated that usefulness of *GDH* sum rule was really underappreciated & community should realize that.

S. Weinberg, Lect. Notes Phys. **452**, 1 (1995)

- Wealth of new data has been both informative & challenging for theory, & we look forward to further experimental & theoretical advances in our *quest* to understand *nucleon's spin structure* in realm of nonperturbative *QCD*.

Baldin Sum Rule

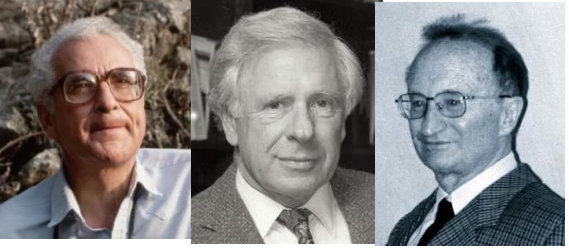
- *Baldin* sum rule, formulated in 1960s, relates sum of *electric* α & *magnetic* β *polarizabilities* of *nucleon* to total *photo-absorption* cross section $\sigma_{\rm tot} = \sigma_{3/2} + \sigma_{1/2}$,

$$I_{\rm Baldin} = \frac{1}{4\pi^2} \int_{E_\gamma^{\rm thr}}^{\infty} \frac{\sigma_{\rm tot}}{E_\gamma^2}\, dE_\gamma = \alpha + \beta$$

- As pion photoproduction *PWA* does not allow for model independent separation of *electric* & *magnetic* *polarizabilities* of *nucleon*, we shall compare our results for *sum* of α & β, determined from ***Compton*** scattering:

$\alpha+\beta$ is $(14.2 \pm 0.5) \times 10^{-4}\,\mathrm{fm}^3$ for *proton*
$(15.5 \pm 1.6) \times 10^{-4}\,\mathrm{fm}^3$ for *neutron*

A.M. Baldin, Nucl Phys **18**, 310 (1960)
L.I. Lapidus, Sov Phys JETP **16**, 964 (1963)



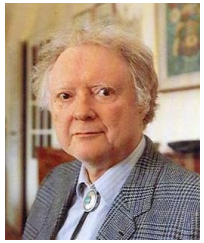
GGT Sum Rule

- Third sum rule, introduced by *Gell-Mann–Goldberger–Thirring* (*GGT*) in 1950s, involves $\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$ in integrand, & results in *forward spin polarizability*, γ_0, of *nucleon*:

$$I_{\mathrm{GGT}} = -\frac{1}{4\pi^2}\int_{E_\gamma^{\mathrm{thr}}}^{\infty}\frac{\Delta\sigma}{E_\gamma^3}\,dE_\gamma = \gamma_0$$

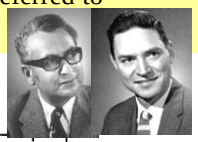
M. Gell-Mann, M.L. Goldberger, & W.E. Thirring, Phys. Rev. **95**, 1612 (1954)
M. Gell-Mann & M.L. Goldberger, Phys Rev **96**, 1433 (1954)

Photoabsorption Cross-Section

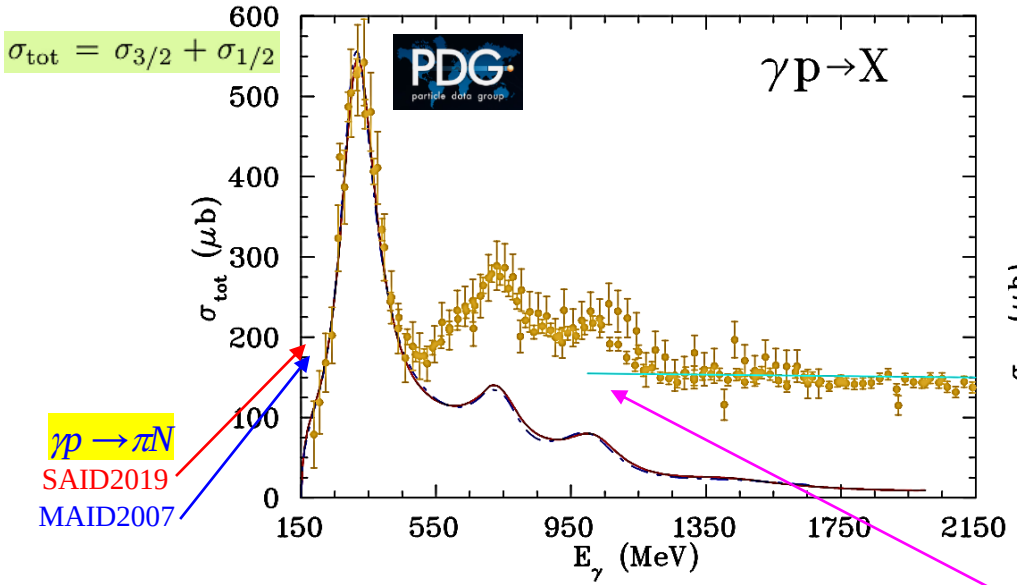



- Sum rules considered in our Phys Ref C **105**, 045202 (2022), call for both $\Delta\sigma$ & σ_{tot}, & it is important to note that @ energies far above *nucleon resonance region* (not far beyond invariant masses of several GeV), unpolarized total photoabsorption cross-section, σ_{tot}, appears to rise indefinitely.
- In *Regge theory*, this rise can be explained in terms of processes involving *pomeron exchange*, but it results in non-convergent integral of σ_{tot}, which puts into question asymptotic behavior of $\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$ as well.

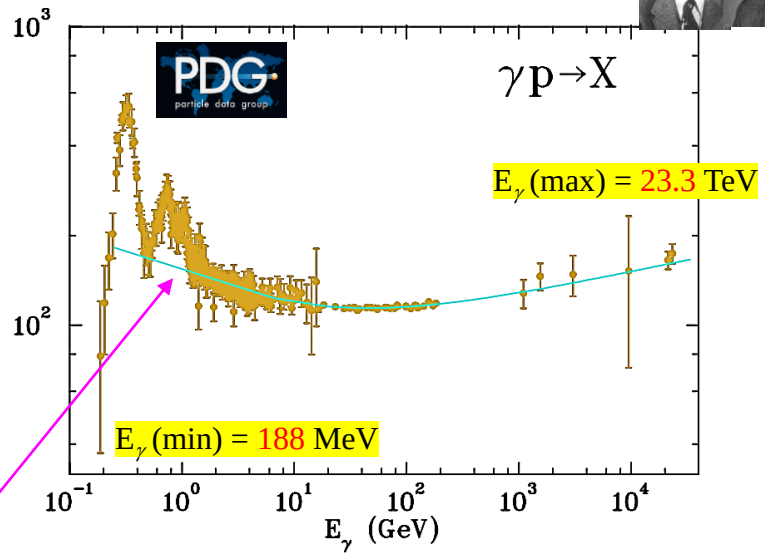
Name "Pomeron" for vacuum pole was coined by *Murray Gell-Mann*, who referred to *Geoffrey Chew* as inventor.



$\sigma_{tot} = \sigma_{3/2} + \sigma_{1/2}$

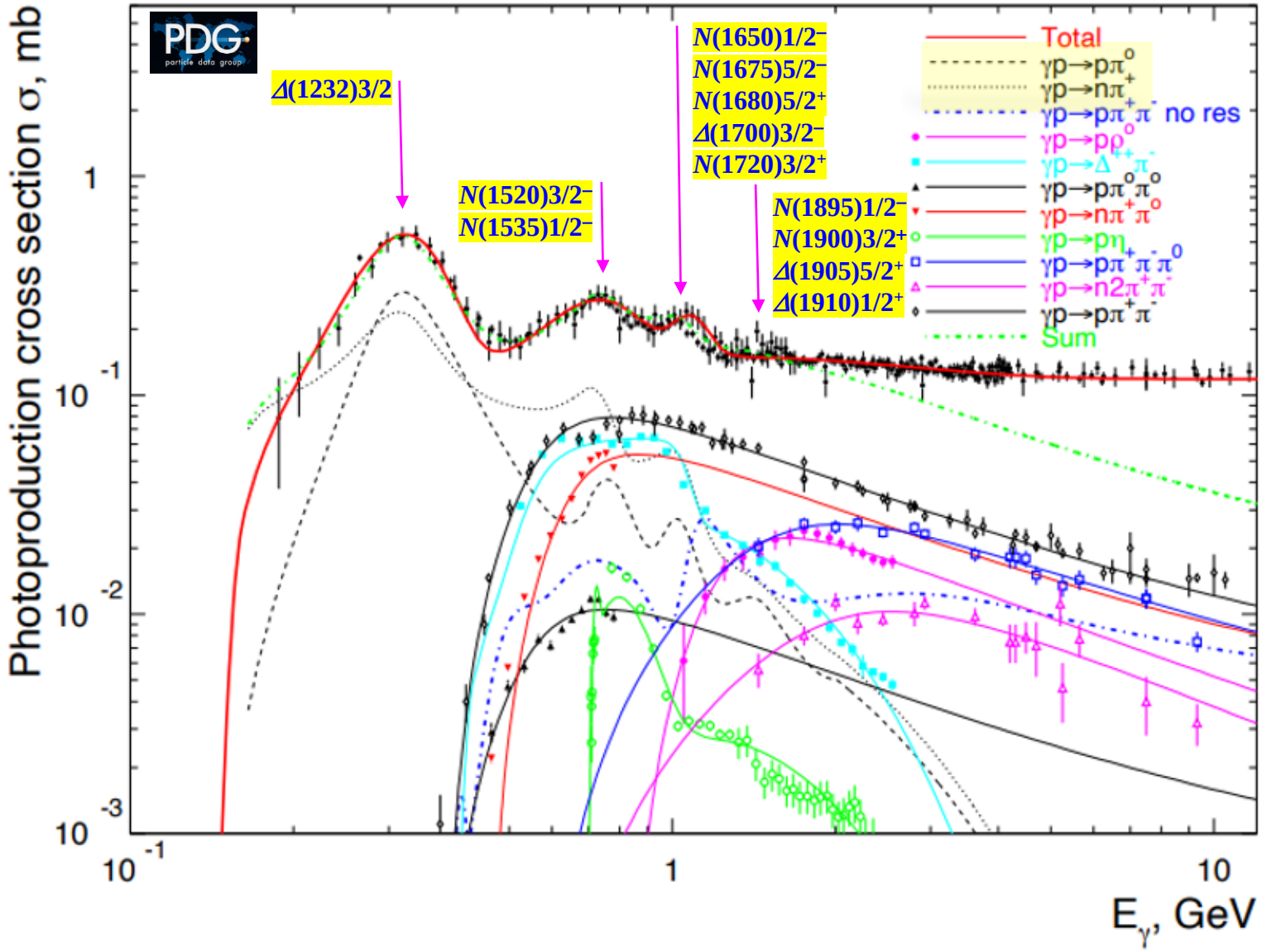


γp → πN
SAID2019
MAID2007

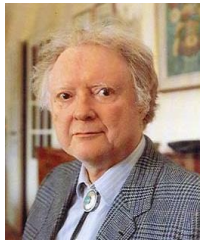
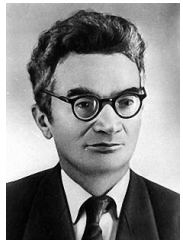


Regge

Photoabsorption Cross-Section



Photoabsorption Cross-Section

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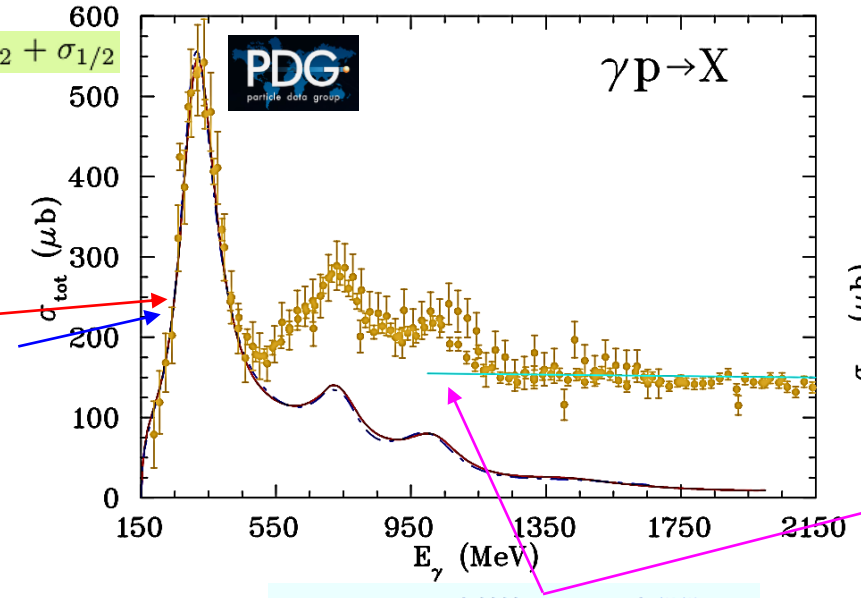
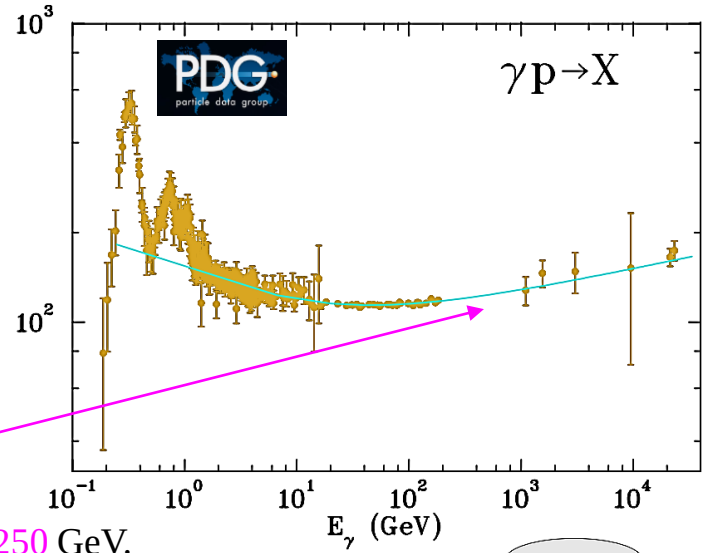
$\sigma_{tot} = \sigma_{3/2} + \sigma_{1/2}$



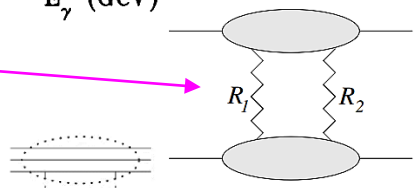
$\gamma p \to \pi N$
SAID2019
MAID2007





- *Regge* empirical fit $\sigma_{tot} = \left(67.7\, s^{+0.0808} + 129\, s^{-0.4545}\right)\ \mu b$ to W = 250 GeV.
  - *First* term is associated with *gluonic pomeron exchange*,
  - *Second* term is associated with *vector* ω & ρ *trajectories*.

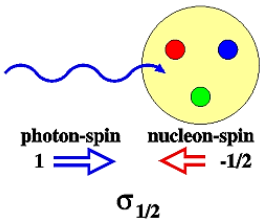
S.D. Bass, M. Skurzok, & P. Moskal, Phys. Rev. C **98**, 025209 (2018)

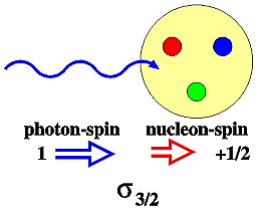


- Early estimates of *GDH* integral used phenomenological ***single-pion*** photoproduction amplitudes & crude estimates for ***two-pion*** & *mesons* other than pion production.

Double-Polarized Observable E

Circular Polarized Photon *Beam*
Longitudinally Polarized Nucleon *Target*





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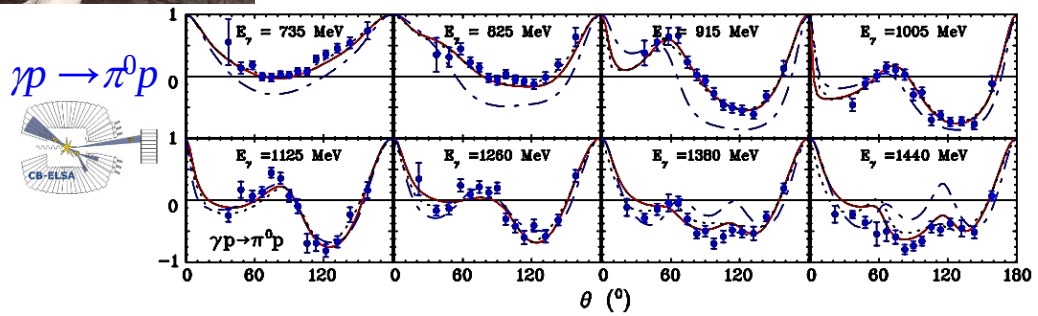
$$\frac{d\sigma_{1/2}}{d\Omega} = \frac{q}{k}\left(|H_2|^2 + |H_4|^2\right)$$

where *q* & *k* are *pion* & *photon* c.m. momenta. Their sum & difference can then be used to construct *beam-target* polarization quantity ***E***:

$$E = \frac{|H_2|^2 + |H_4|^2 - |H_1|^2 - |H_3|^2}{|H_2|^2 + |H_4|^2 + |H_1|^2 + |H_3|^2}$$

Double-Polarized Observable E



Circular Polarized Photon *Beam*

Longitudinally Polarized Nucleon *Target*

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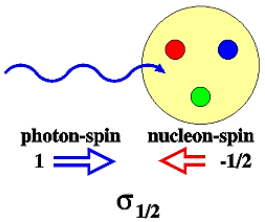
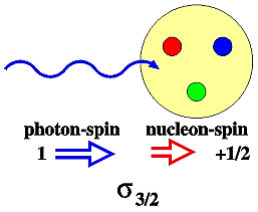
Double-Polarized Observable E

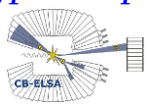
Circular Polarized Photon *Beam*

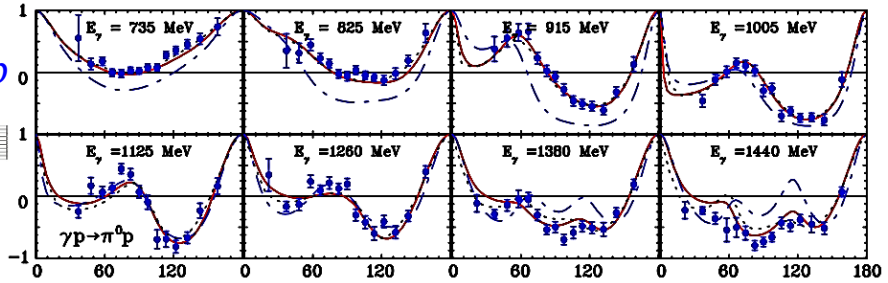
Longitudinally Polarized Nucleon *Target*



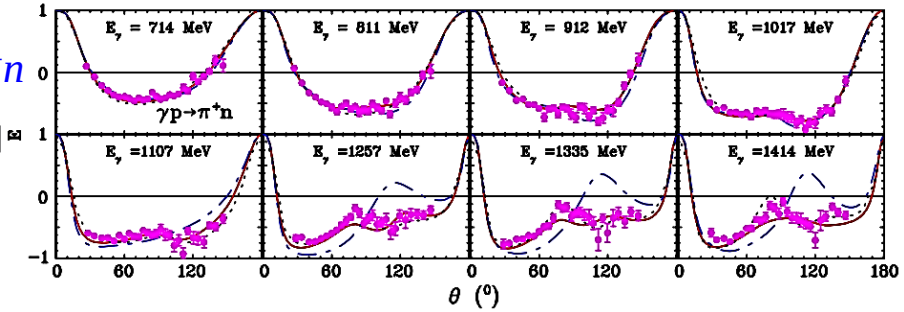


$\gamma p \to \pi^0 p$





$\gamma p \to \pi^+ n$



- Difference of cross-sections for helicity states *3/2* & *1/2*, that is, $\Delta(d\sigma/d\Omega) = (d\sigma_{3/2}/d\Omega - d\sigma_{1/2}/d\Omega)$ for $\vec{\gamma}\vec{N} \to \pi N$, is given in terms of helicity amplitudes:

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where *q* & *k* are *pion* & *photon* c.m. momenta. Their sum & difference can then be used to construct *beam-target* polarization quantity ***E***:

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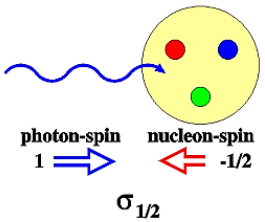
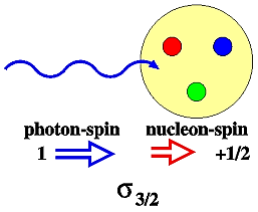
Double-Polarized Observable E

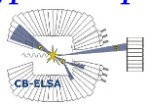
Circular Polarized Photon *Beam*

Longitudinally Polarized Nucleon *Target*



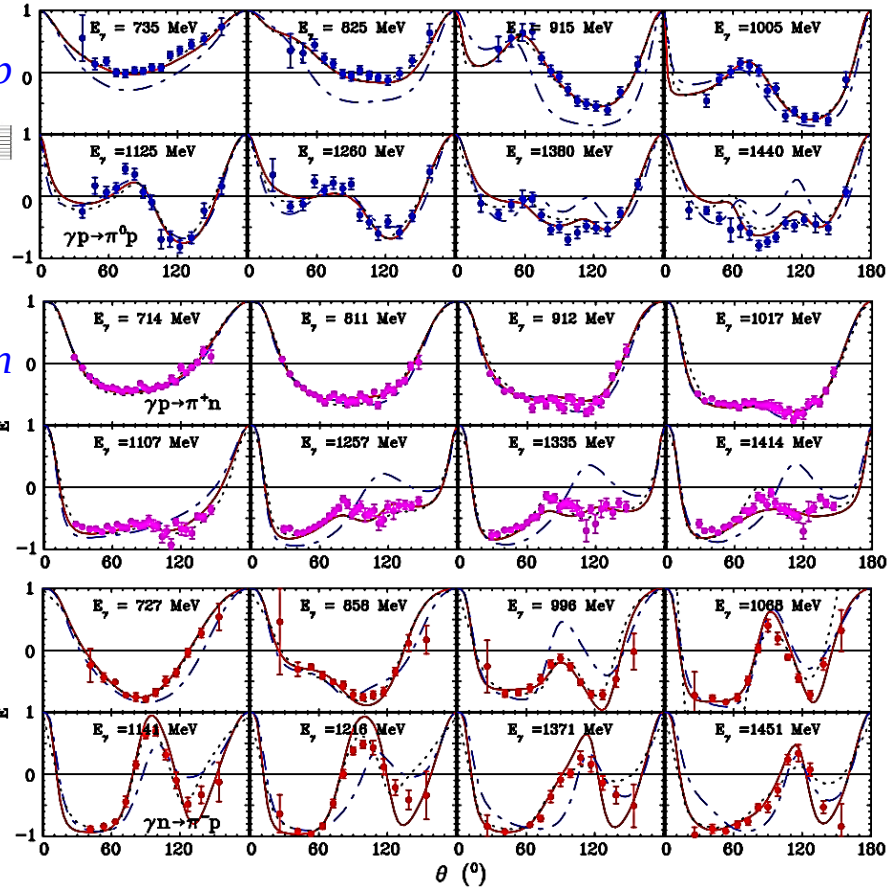


$\gamma p \to \pi^0 p$



$\gamma p \to \pi^+ n$

$\gamma n \to \pi^- p$



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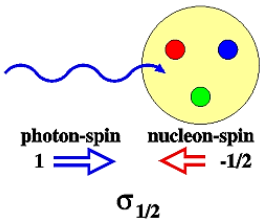
Double-Polarized Observable E

715 – 1450 MeV

Circular Polarized Photon *Beam*
Longitudinally Polarized Nucleon *Target*



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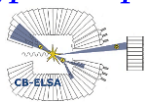
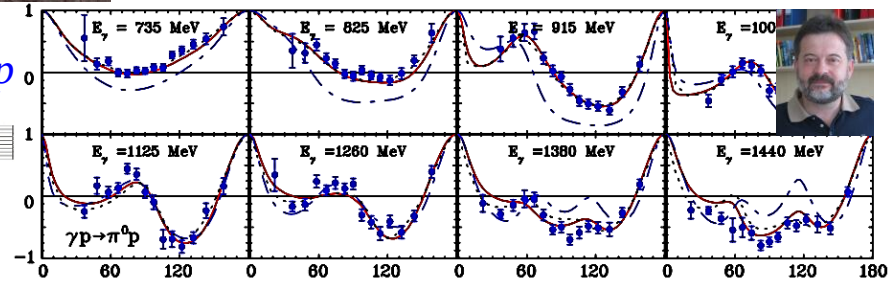
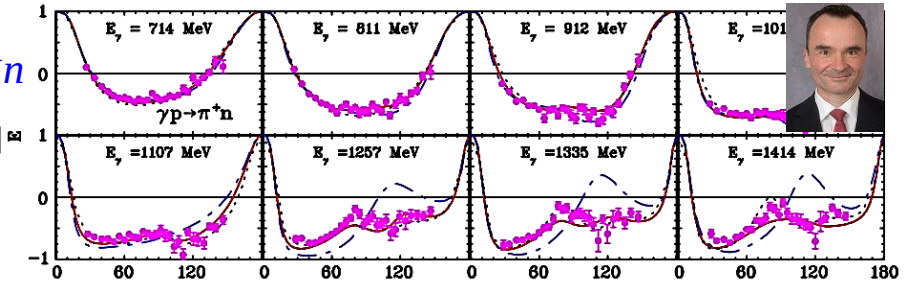


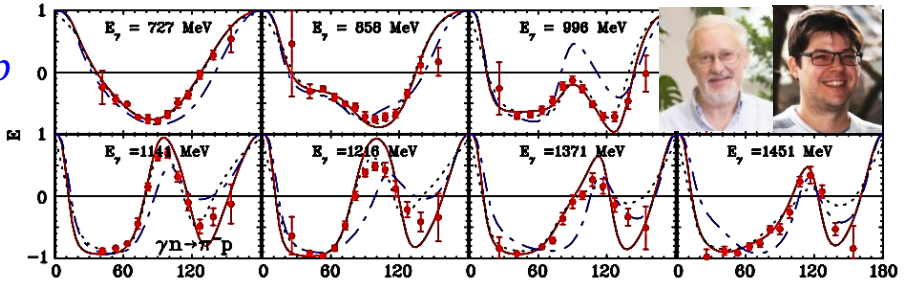


$\gamma p \to \pi^+ n$

clas

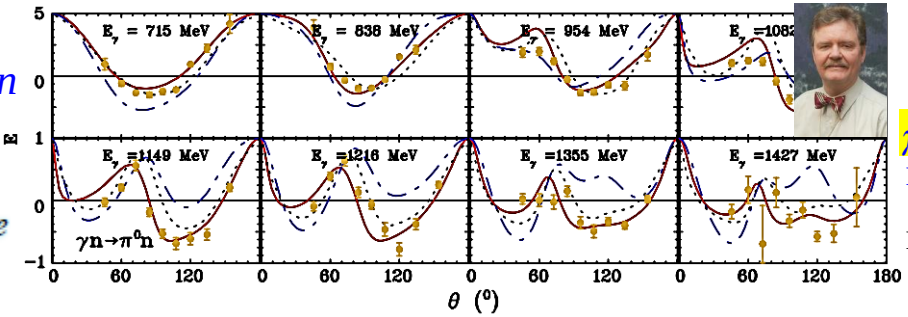


$\gamma n \to \pi^- p$



$\gamma n \to \pi^0 n$

clas



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$$\frac{d\sigma_{3/2}}{d\Omega} = \frac{q}{k}\left(|H_1|^2 + |H_3|^2\right)$$
$$\frac{d\sigma_{1/2}}{d\Omega} = \frac{q}{k}\left(|H_2|^2 + |H_4|^2\right)$$

where *q* & *k* are *pion* & *photon* c.m. momenta. Their sum & difference can then be used to construct *beam-target* polarization quantity ***E***:

$$E = \frac{|H_2|^2 + |H_4|^2 - |H_1|^2 - |H_3|^2}{|H_2|^2 + |H_4|^2 + |H_1|^2 + |H_3|^2}$$

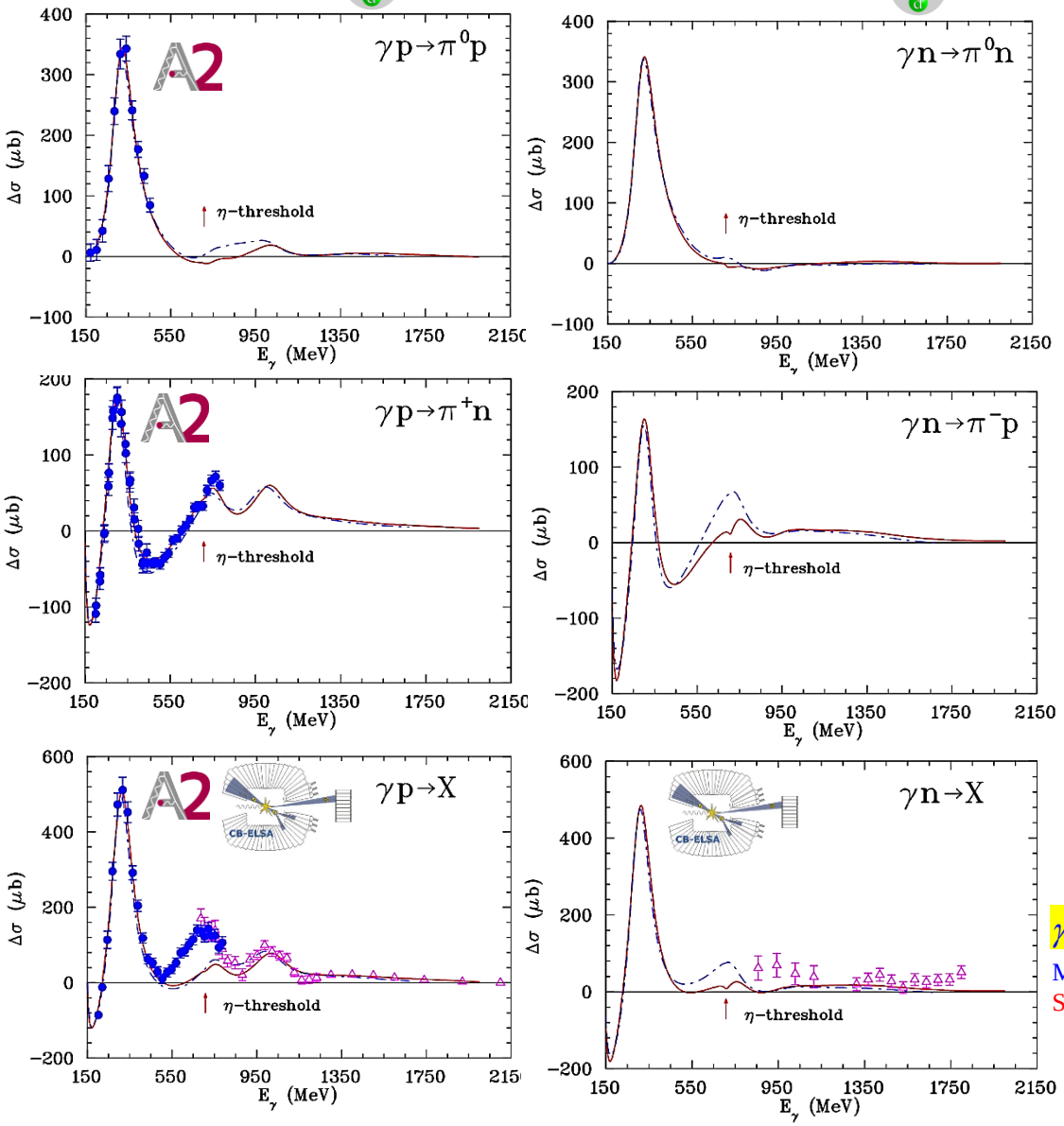
$\gamma N \to \pi N$
MAID2007
SAID2019
BnGa2019

This solution uses *E* DB in fit.

Differences of Total Cross Section for Helicity States 3/2 & 1/2

Proton

Neutron



$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

- In *SAID* & *MAID* PWAs, *second* (& η-threshold) as well as *third* resonance regions around 700 & 1000 MeV are very pronounced for *charged* pions in final state, whereas they are weak in case of *neutral* pions.
- In Δ-*isobar* region, predictions for both cases are the same.
- Around η-threshold, deviation becomes more apparent.

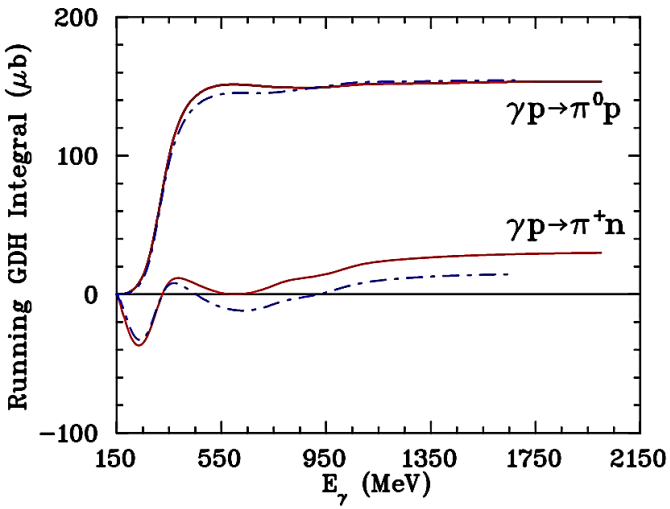
$\gamma N \to \pi N$

MAID2007

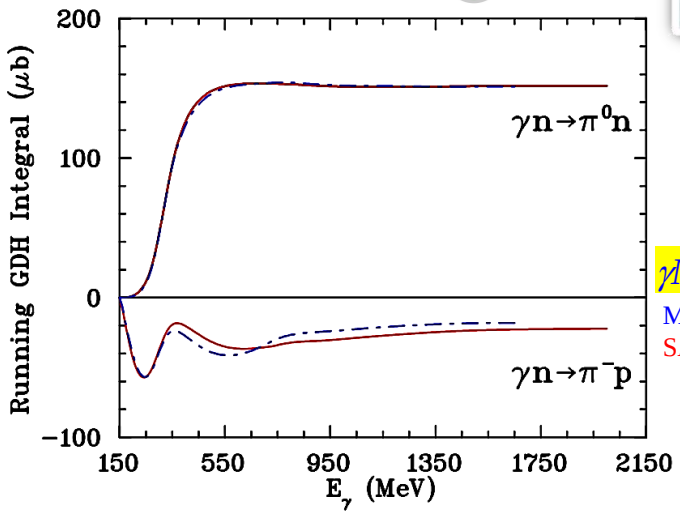
SAID2019

GDH Running Integral

Proton



Neutron



$$I_{GDH} = \int_{E_\gamma^{thr}}^{\infty} \frac{\Delta\sigma}{E_\gamma}\, dE_\gamma = \frac{2\pi^2 \alpha}{M^2}\kappa^2$$

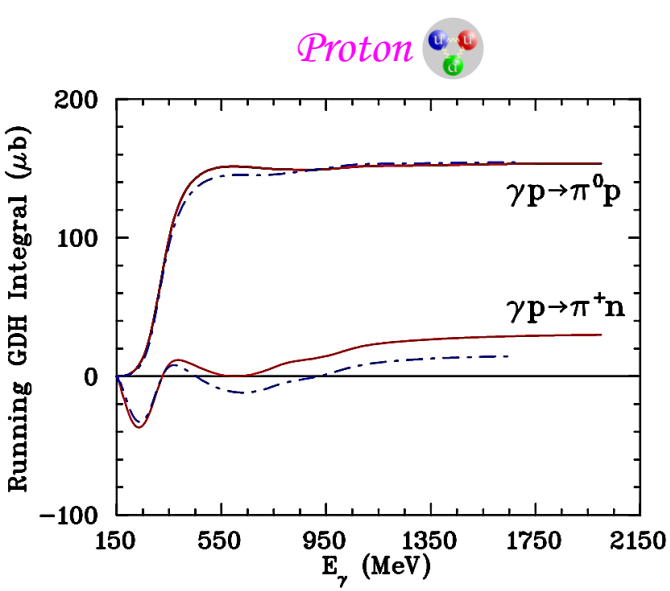
$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

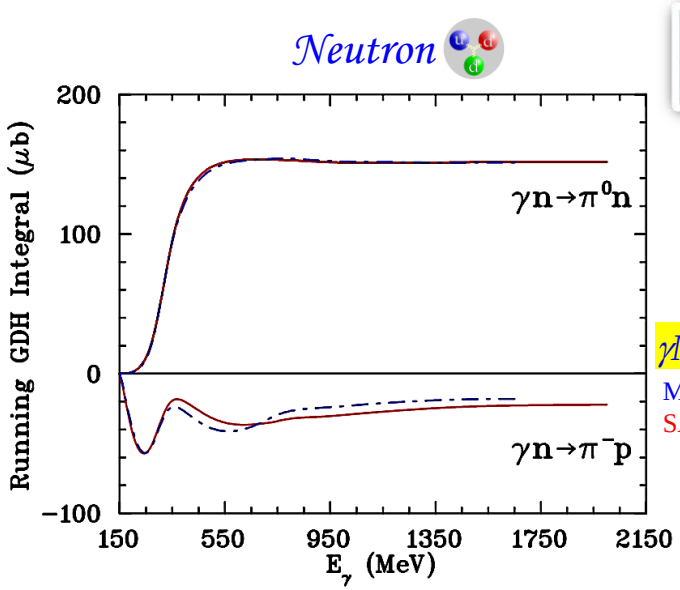
$\gamma N \rightarrow \pi N$

MAID2007

SAID2019

GDH Running Integral





$$I_{GDH} = \int_{E_\gamma^{thr}}^{\infty} \frac{\Delta\sigma}{E_\gamma}\, dE_\gamma = \frac{2\pi^2 \alpha}{M^2}\kappa^2$$

$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

$\gamma N \to \pi N$

MAID2007

SAID2019

- How we know *anomalous magnetic moment* of nucleon:

- ***Penning trap*** is device for storage of *charged particles* using *axial magnetic field* & *quadrupole electric field*.

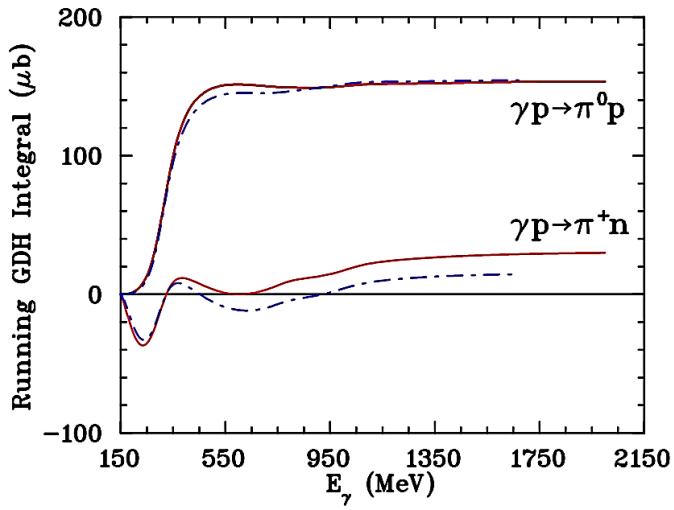
- Measuring *magnetic moment* of ^{11}Be & detecting *nuclear magnetic resonance* signals in beryllium crystal lattice.

GDH Running Integral

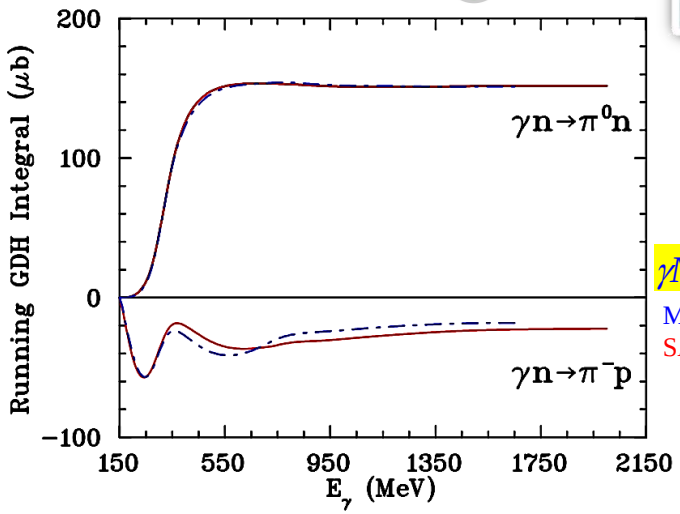
$$I_{GDH} = \int_{E_\gamma^{thr}}^{\infty} \frac{\Delta\sigma}{E_\gamma}\, dE_\gamma = \frac{2\pi^2 \alpha}{M^2}\kappa^2$$

$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

Proton



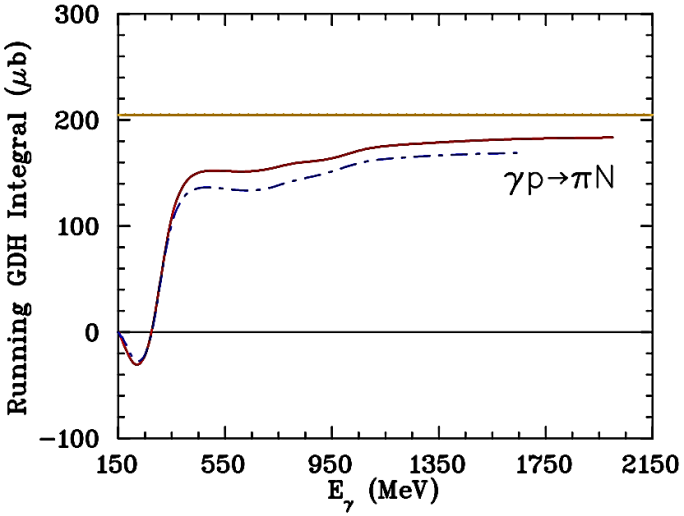
Neutron



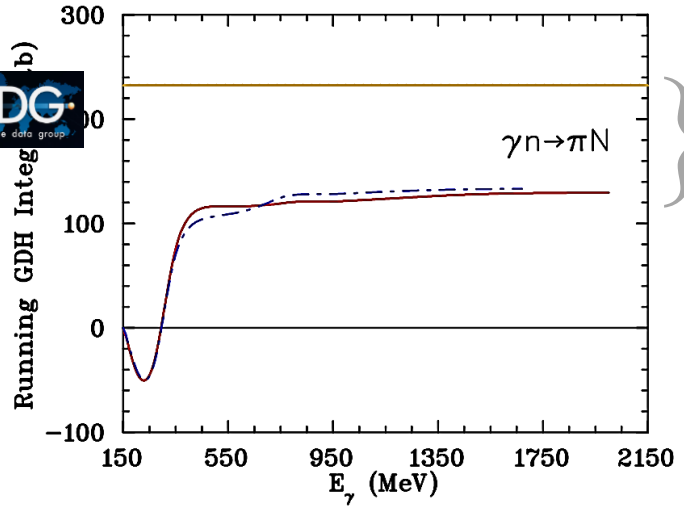
γN → πN

MAID2007

SAID2019



PDG particle data group



Static properties of nucleons

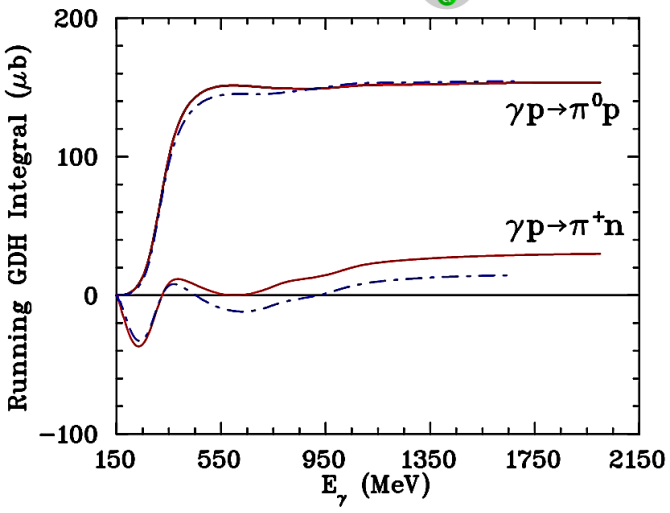
- In *proton* case, **21** μb strength (which is about **10%** of right-hand-side of eq.) is missing & can be attributed to non-single-pion processes, while gap is much larger in *neutron* case, where **104** μb are missing (about **44%** of right-hand-side of eq.)

GDH Running Integral with Regge

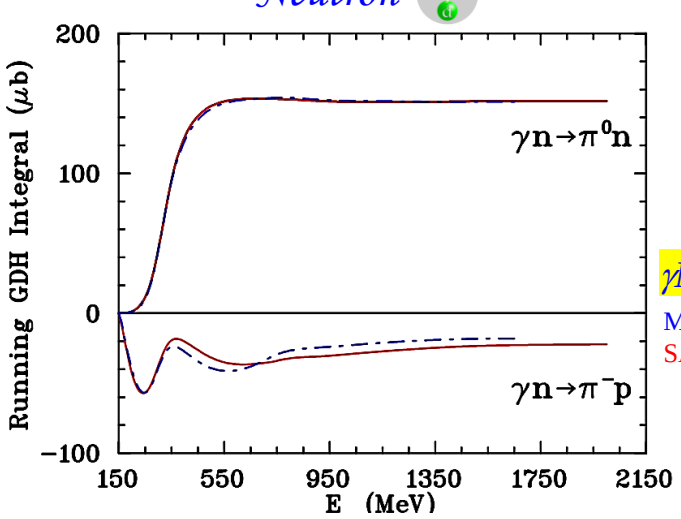
$$I_{GDH} = \int_{E_\gamma^{thr}}^{\infty} \frac{\Delta\sigma}{E_\gamma}\, dE_\gamma = \frac{2\pi^2\alpha}{M^2}\kappa^2$$

$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

Proton



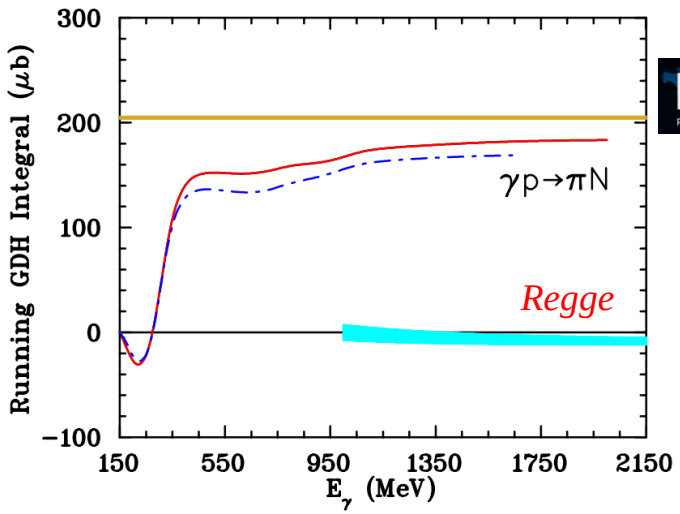
Neutron



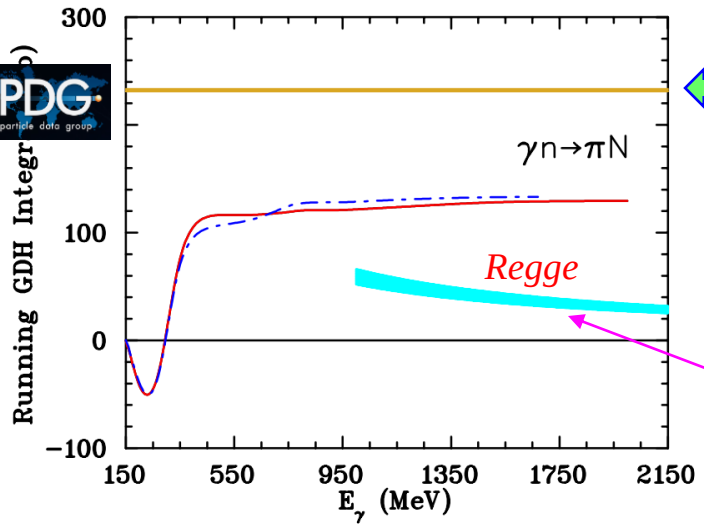
γN →πN

MAID2007

SAID2019



PDG particle data group



Static properties of nucleons

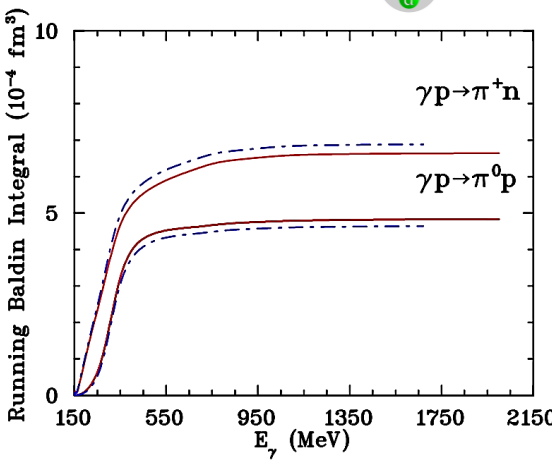
- Since *Regge* theory only becomes applicable @ energies far above resonance region, this dependence is shown only above E_γ = 1 GeV.
- These (negative) *Regge* values need to be added to (positive) *SAID* & *MAID* curves.

Baldin Running Integral

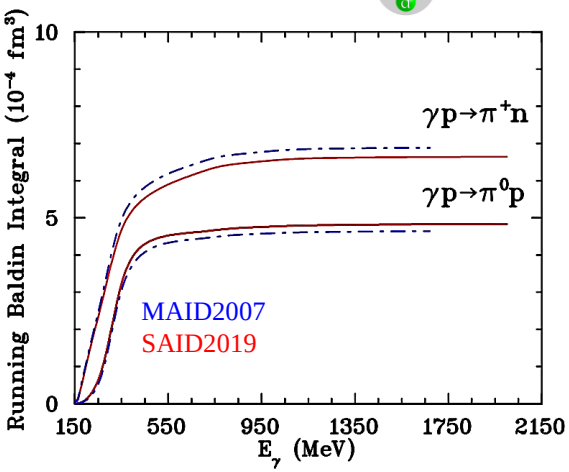
$$I_{\text{Baldin}} = \frac{1}{4\pi^2} \int_{E_\gamma^{\text{thr}}}^{\infty} \frac{\sigma_{\text{tot}}}{E_\gamma^2}\, dE_\gamma = \alpha + \beta$$

$$\sigma_{\text{tot}} = \sigma_{3/2} + \sigma_{1/2}$$

Proton



Neutron



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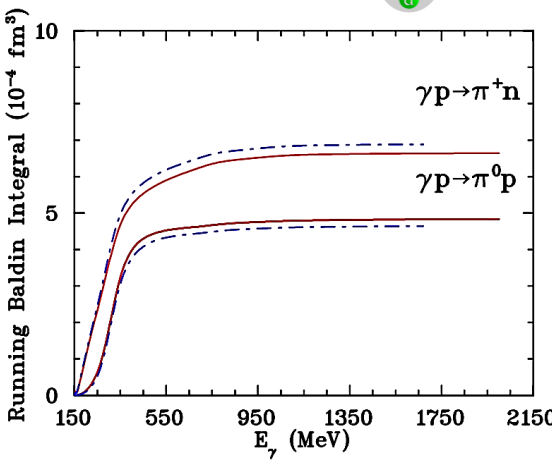
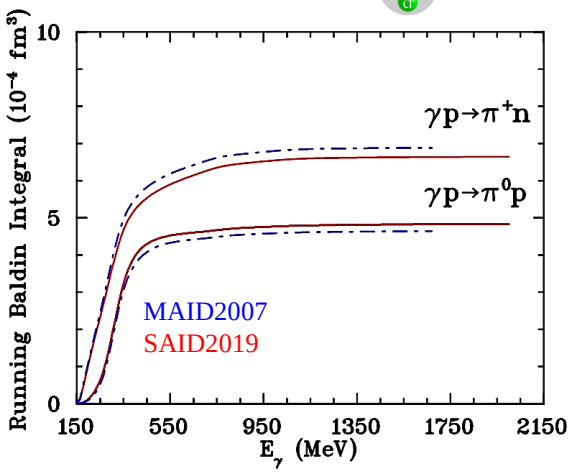
$$\sigma_{\text{tot}} = \sigma_{3/2} + \sigma_{1/2}$$

Proton



Neutron



Compton Scattering

PDG particle data group

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

p ELECTRIC POLARIZABILITY α_p

For a very complete review of the "polarizability of the nucleon and Compton scattering," see SCHUMACHER 05.

VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
11.2 ±0.4 OUR AVERAGE			

p MAGNETIC POLARIZABILITY β_p

The electric and magnetic polarizabilities are subject to a dispersion sum-rule constraint $\overline{\alpha} + \overline{\beta} = (14.2 \pm 0.5) \times 10^{-4}$ fm^3. Errors here are anticorrelated with those on $\overline{\alpha}_p$ due to this constraint.

VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
2.5 ±0.4 OUR AVERAGE	Error includes scale factor of 1.2.		

n ELECTRIC POLARIZABILITY α_n

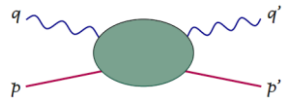
Following is the electric polarizability α_n defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_n\mathbf{E}$. For a review, see SCHMIED-MAYER 89.

For very complete reviews of the polarizability of the nucleon and Compton scattering, see SCHUMACHER 05 and GRIESSHAMMER 12.

VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
11.8 ± 1.1 OUR AVERAGE			

n MAGNETIC POLARIZABILITY β_n

VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
3.7 ±1.2 OUR AVERAGE			



Baldin Running Integral

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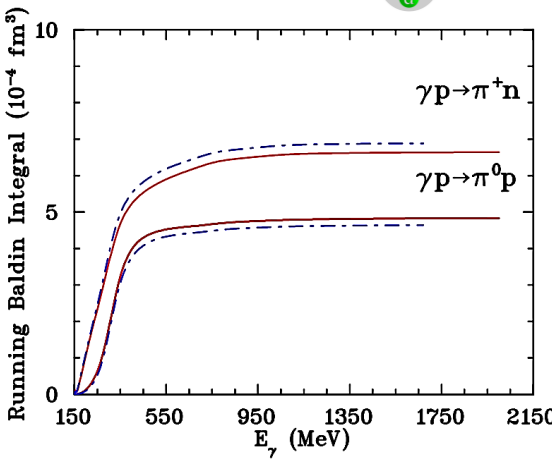
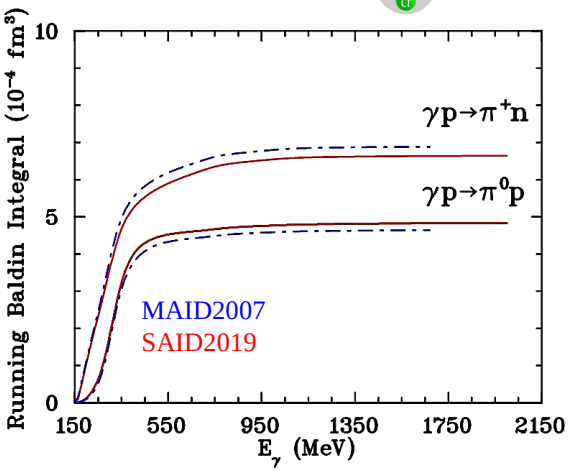
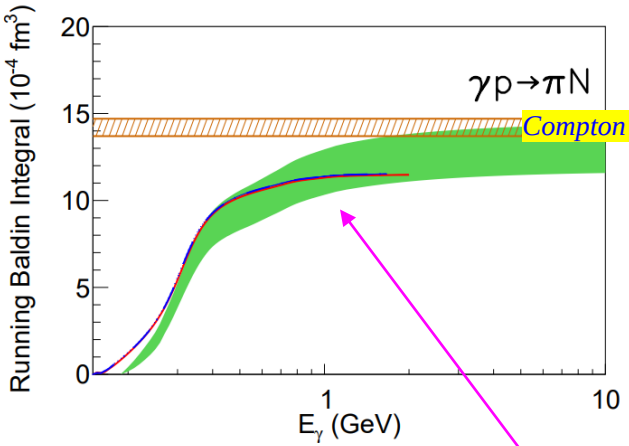
$$\sigma_{\text{tot}} = \sigma_{3/2} + \sigma_{1/2}$$

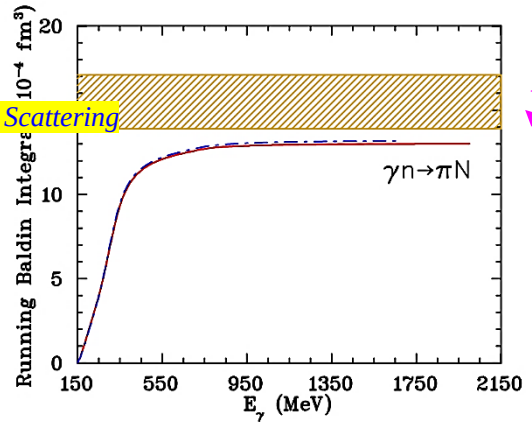
Proton



Neutron







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VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
11.2 ±0.4 OUR AVERAGE			

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For very complete reviews of the polarizability of the nucleon and Compton scattering, see SCHUMACHER 05 and GRIESSHAMMER 12.

VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
11.8 ± 1.1 OUR AVERAGE			

n MAGNETIC POLARIZABILITY β_n

VALUE (10^{-4} fm^3)	DOCUMENT ID	TECN	COMMENT
3.7 ±1.2 OUR AVERAGE			

- We fitted data PDG that spans photon energies from 188 MeV to 23.3 TeV.
- Evaluation yields (13.1 ± 1.4) x 10^{-4} fm^3, that agrees well with *Compton* estimate of (14.2 ± 0.5) x 10^{-4} fm^3.

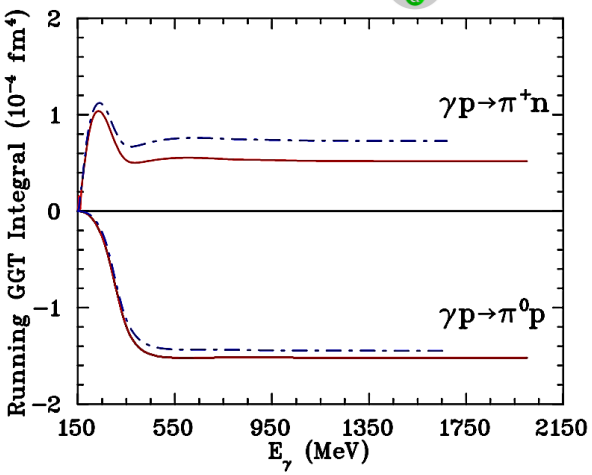
PDG

GGT Running Integral

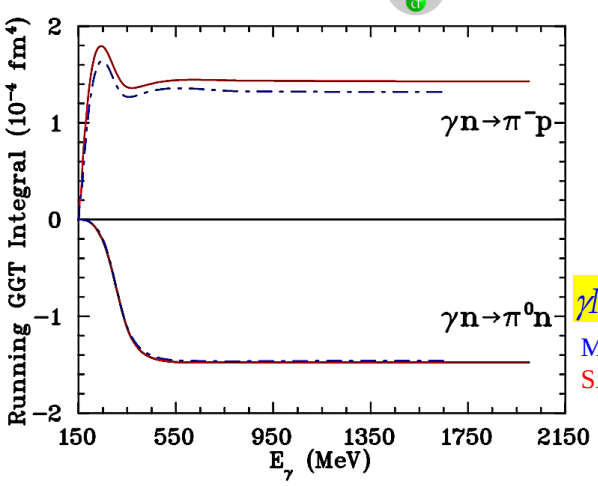
$$I_{GGT} = -\frac{1}{4\pi^2}\int_{E_\gamma^{thr}}^{\infty}\frac{\Delta\sigma}{E_\gamma^3}\,dE_\gamma = \gamma_0$$

$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

Proton



Neutron



$\gamma N \to \pi N$

MAID2007

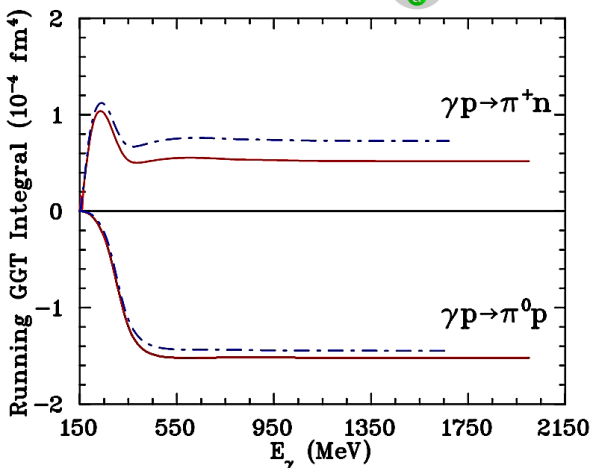
SAID2019

GGT Running Integral

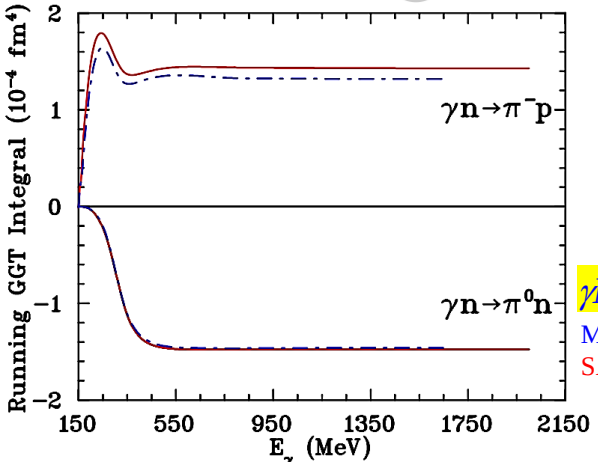
$$I_{GGT} = -\frac{1}{4\pi^2}\int_{E_\gamma^{thr}}^{\infty}\frac{\Delta\sigma}{E_\gamma^3}\,dE_\gamma = \gamma_0$$

$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$$

Proton



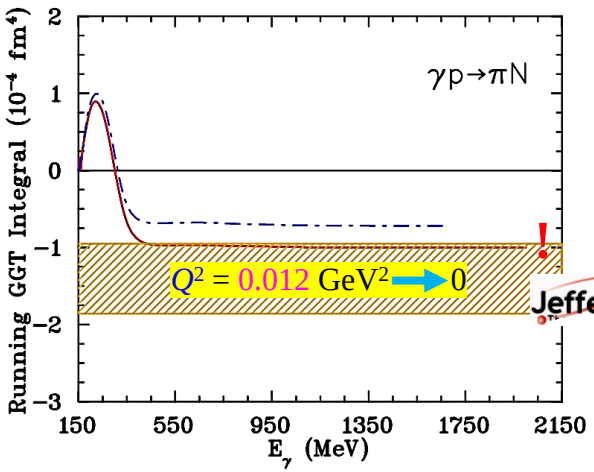
Neutron

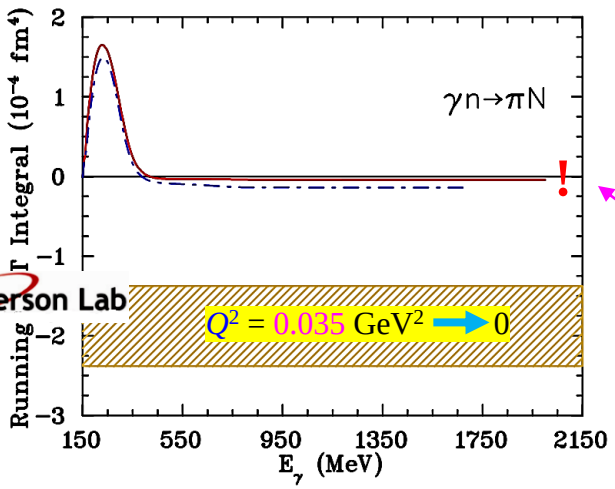


$\gamma N \to \pi N$

MAID2007

SAID2019





Jefferson Lab

- For *GGT*, single-pion contribution converges to **0** for *neutron* case, while **–1** for *proton* case.

- New determination of *Regge* theory parameters by extending $\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$ measurements both on *proton* & *neutron* (*deuteron*) targets to $E_\gamma \approx 12$ GeV is one of aims of recently approved REGGE *Experiment* in Hall D of Jefferson Lab.

M.M. Dalton, A. Deur, C.D. Keith, S. Sirca, & J. Stevens,
Measurement of the high-energy contribution to the Gerasimov-Drell-Hearn sum rule,
JLab Proposal **E12-20-011** [arXiv:2008.11059 [nucl-ex]].

S&T visit: Hall D plans - summary

Scheduling Outlook

13

Activity, experiment running	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	scheduled									
Run PRIMEX-η	■	■								
Run SRC	■									
Installation CPP		■								
Run CPP-NPP		■								
Run GlueX-II		■								
Installation FCAL2			■							
Run GlueX-II+JEF				■						
Installation KLF (K_L beam)					■					
Commissioning, Run KLF						■	■	■		
Back to photon beam								■		
Installation of REGGE									■	
Commissioning, Run REGGE									■	

- Assumed 25 weeks/year for Hall D running
- Assumed timely budgeting for KLF and REGGE
- Assumed timely construction of JEF,KLF,GDH

13

Jefferson Lab

E.Chudakov GlueX Meeting, 2022 Feb Hall D Status Update 12 / 12

33 PAC days

- Evaluation of *GDH*, *Baldin*, & *GGT sum rules* involving difference of helicity dependent total photoabsorption cross-sections, $\Delta\sigma = \sigma_{3/2} - \sigma_{1/2}$, shows that ***single-pion*** photoproduction off nucleon is dominant contribution to these *sum rules*.

- In all cases, ***single-pion*** contribution *converges* above $E_\gamma \sim 1.7$ GeV.

- In *GDH* sum rule for *proton*, ***single-pion*** contribution saturates *sum rule* to 90%, while in *neutron* case, missing strength amounts to 44%.

- Situation is most favorable for *Baldin* sum rule where – to attainable levels of precision – ***single-pion*** photoproduction off nucleon comes closest to agreeing with ***Compton*** scattering & *EFT* calculations for *neutron* case.

- In case of the *GGT* sum rule, lack of precise calculations & size of experimental uncertainties preclude clear statement of agreement.

- Direct experimental *verification* of *GDH* sum rule are difficult because of need to extend measurements to sufficiently high E_γ despite $1/E_\gamma$ weighting, & to reliably cover not only *single*- & *double*-pion photoproduction but all possible *photon-induced* processes.

THANKS