GDH sum rule on the neutron

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The GDH collaboration

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SUMMARY

- Physics motivation
- Experimental set-up
- **Results**

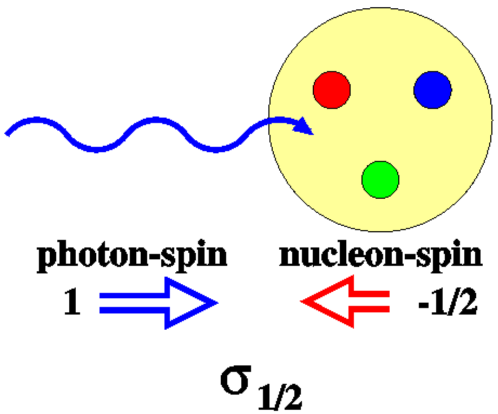
$$\vec{\gamma}\vec{d} \rightarrow \begin{cases} X & \text{for } E_\gamma < 2 \text{ GeV (GDH sum rule)} \\ N\pi(\pi)N_{Spect} & \text{for } E_\gamma < 800 \text{ MeV} \\ pn & \end{cases}$$

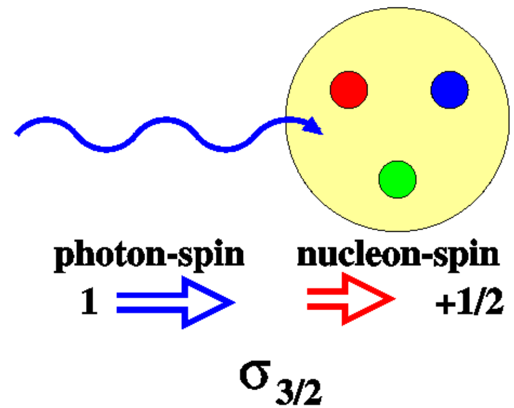
- Conclusions

Gerasimov-Drell-Hearn sum rule

- Proposed in 1966 (and never verified up to now…)

- Prediction on the absorption of circularly polarized photons by longitudinally polarized nucleons





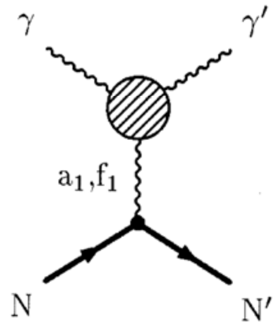
- **Based on very general quantum mechanical principles (causality, optical theorem, gauge and Lorentz invariance)**

Anomalous magnetic moment of the nucleon

$$I_{GDH} = \int_{m_\pi}^{\infty} \frac{\sigma_{3/2}(E_\gamma) - \sigma_{1/2}(E_\gamma)}{E_\gamma} dE_\gamma = \frac{2\pi^2\alpha}{m^2}\kappa^2$$

Why could the GDH sum rule be violated ?

- The only "weak" hypothesis is the assumption that **Compton scattering $\gamma N \rightarrow \gamma' N'$ becomes spin independent when $\nu \rightarrow \infty$**
- A violation of this assumption can not be easily explained
- Possible hypotheses for violation:
  - ✓ Exchange of **a1**-like (J=1+) mesons between γ and N



  - ✓ Non pointlike (constituent) quarks ?
  - ✓ Photoproduction of gravitons ?

GDH sum rule:

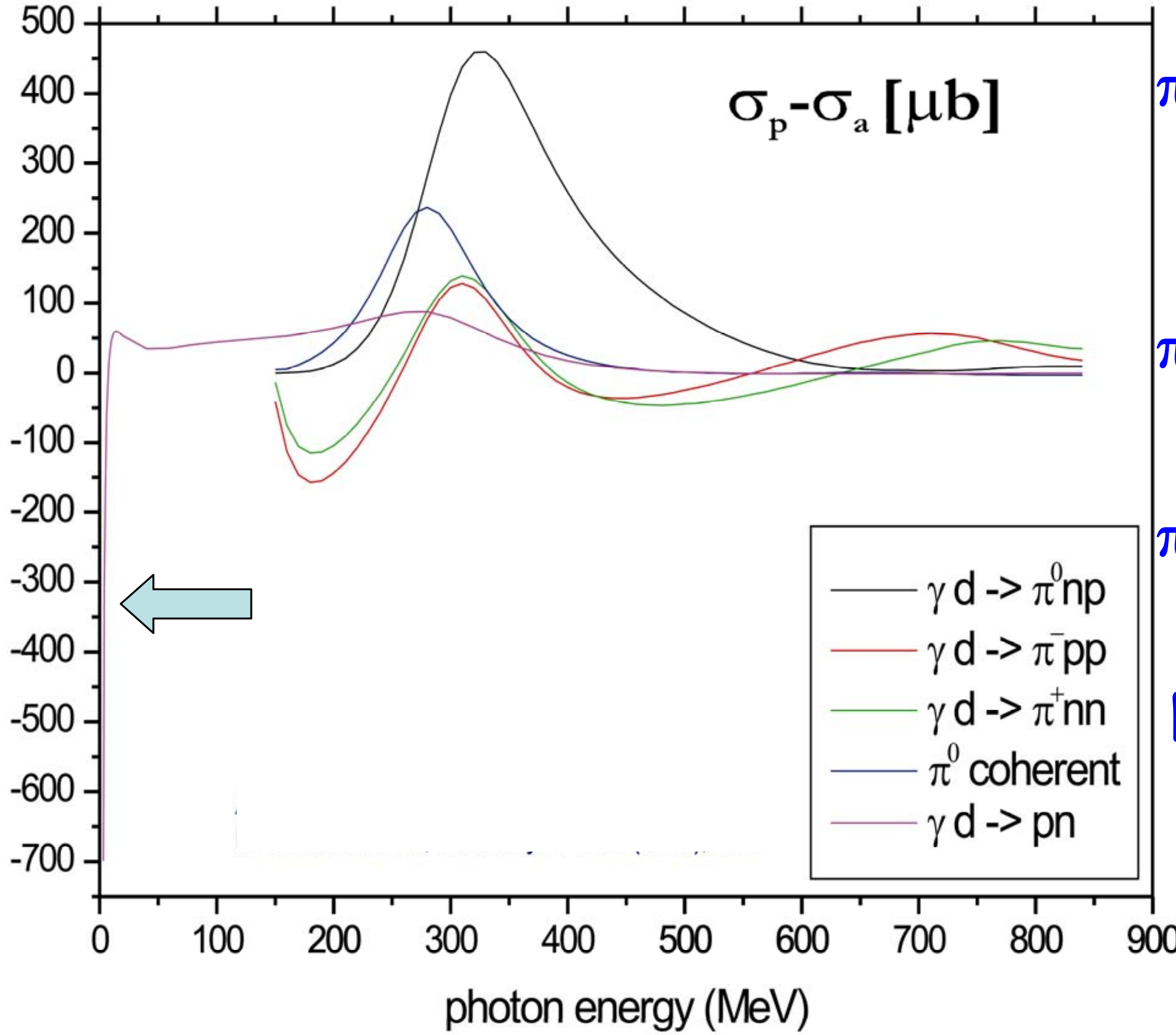
- ✓ Fundamental check of our knowledge of the γN interaction
- ✓ Important comparison for photoreaction models
- ✓ Helicity dependence of partial channels (pion photoproduction) is an essential tool for the study of the baryon resonances (interference terms between different electromagnetic multipoles)
- ✓ Valid for any system with **k** $\neq 0$ (^{2}H, ^{3}He) . "Link" between nuclear and nucleon degrees of freedom

$$I_{GDH}^{deut} = \int_{2.2\,MeV}^{\infty} \frac{\sigma_p - \sigma_a}{E_\gamma} dE_\gamma = 0.6\ \mu b << I_{GDH}^{proton} + I_{GDH}^{neutron} \quad (\approx 430\ \mu b)$$

$$\left(\kappa_{deut} = -0.14\ n.m.\right)$$

AFS model

Arenhoevel, Fix, Schwamb, PRL 93, 202301 (04)



πNN πN from MAID +nuclear effects

ππNN EPJA 25,114 (05)

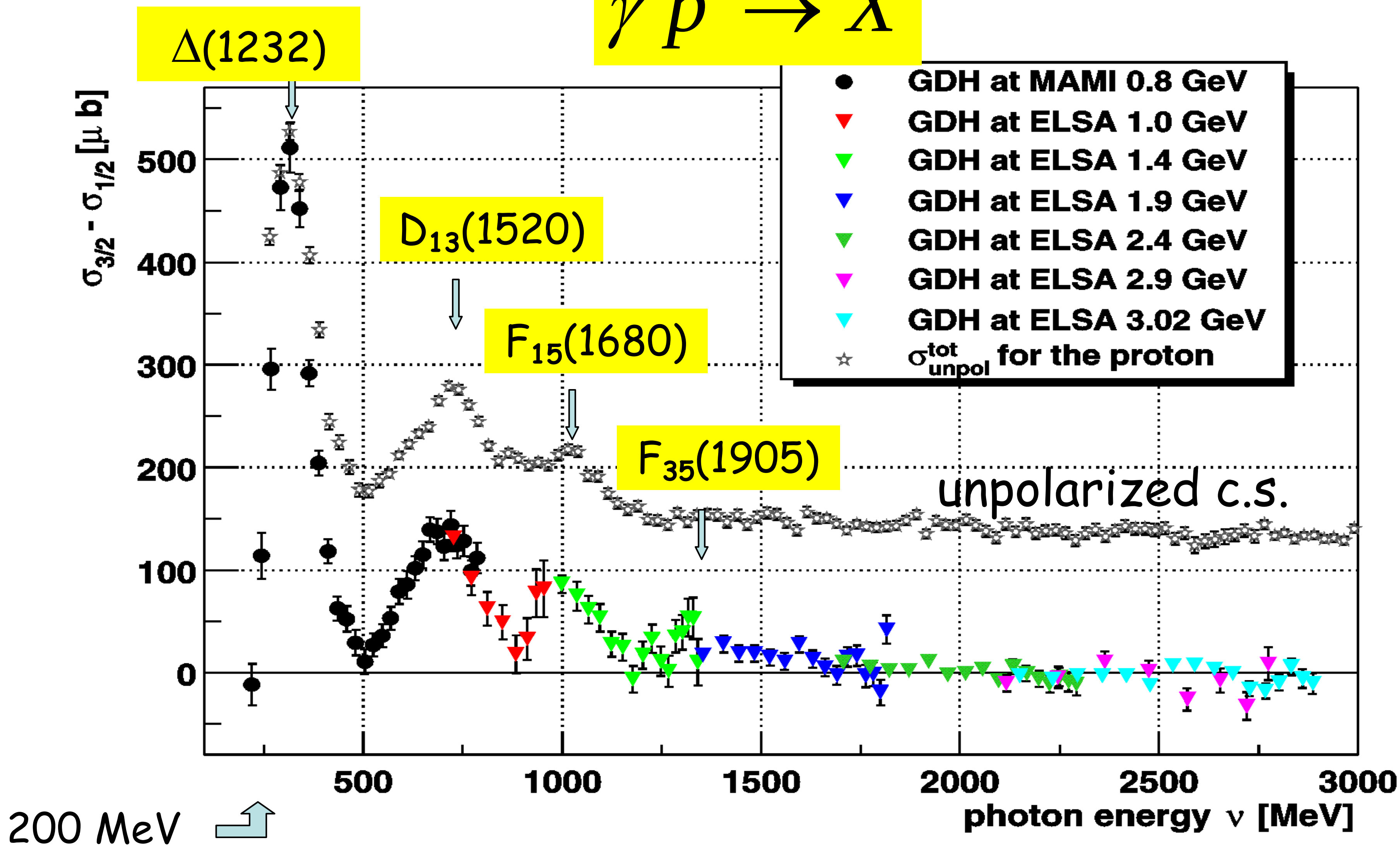
π^0d PLB 407,1 (97)

pn NPA 690,682 (01)

$$\left[I^{deut}_{GDH}\right]_{AFS} = 27\ \mu b$$

Experimental status

$$\vec{\gamma}\,\vec{p} \rightarrow X$$



MAMI data: J. Ahrens et al., Phys. Rev. Lett. 87 (2001) 022003
ELSA data: H. Dutz et al., Phys. Rev. Lett 91 (2003) 192001
H. Dutz et al., Phys. Rev. Lett 93 (2004) 032003

GDH sum rule on the proton

E_γ (GeV)		I_{GDH} (mb)
0.14-0.20 *	MAID03 SAID04	-29 -28
0.20-2.90	Measured (Mainz+Bonn)	254±5±12
> 2.90 (Regge approach)	Simula et al. Bianchi-Thomas	~ -13 ~ -14
Total		~ 211
GDH sum rule		205

* Low energy theorems in the Nπ threshold region (multipole analyses not very wrong ...)

GDH sum rule: predictions (2005)

Proton	I_{GDH} (μb)	Neutron	I_{GDH} (μb)
$\gamma\, p \to N\pi$	172	$\gamma\, n \to N\pi$	133
$\gamma\, p \to N\pi\pi$	94	$\gamma\, n \to N\pi\pi$	82
$\gamma\, p \to N\eta$	-8	$\gamma\, n \to N\eta$	-6
$\gamma\, p \to K\Lambda\,(\Sigma)$	-4	$\gamma\, n \to K\,\Lambda(\Sigma)$	2
$\gamma\, p \to N\rho(\omega)$	0	$\gamma\, n \to N\rho(\omega)$	2
Regge contrib. (E_γ > 2 Gev)	~ -15	Regge contrib. (E_γ > 2 Gev)	~ 20
TOTAL	~ 240	TOTAL	~ 230
GDH	**205**	**GDH**	**233**

Nπ : SAID KΛ(Σ) : Sumowidagdo et al., PRC 65,0321002 (02)

Nη : MAID Nππ : Fix, Arenhoevel EPJA 25, 114 (2005)

Nρ : Zhao et al., PRC 65, 032201 (03) Regge : Bianchi-Thomas , PLB 450,439(99)

GDH sum rule on the neutron

- **No Free neutron target available**
- Model dependent results from nuclear targets
- Experimental goal: have a "small" and "reliable" model dependence
- Two different (and complementary) targets

  =) Deuterium (deuterated butanol /^{6}LiD)

  =) ^{3}He (high pressure gas target - under development)
- Measurement of partial channels like

$$\vec{\gamma}\vec{d} \to pn$$

$$\vec{\gamma}\vec{d} \to p\pi^- p_s \; (n\pi^+ n_s) \; (p\pi^0 n_s)$$

Experimental set-up

- **Tagged photon beam** Mainz: $m_\pi \leq E_\gamma \leq 800 MeV$

  Bonn: $0.6\ GeV \leq E_\gamma \leq 2.9\ GeV$

- **Circularly polarized photons**

  from bremsstrahlung of linearly polarized electrons

- **Longitudinally polarized protons and neutrons**

  Frozen spin (deut.)butanol/^{6}LiD target (Bonn, Bochum, Nagoya)

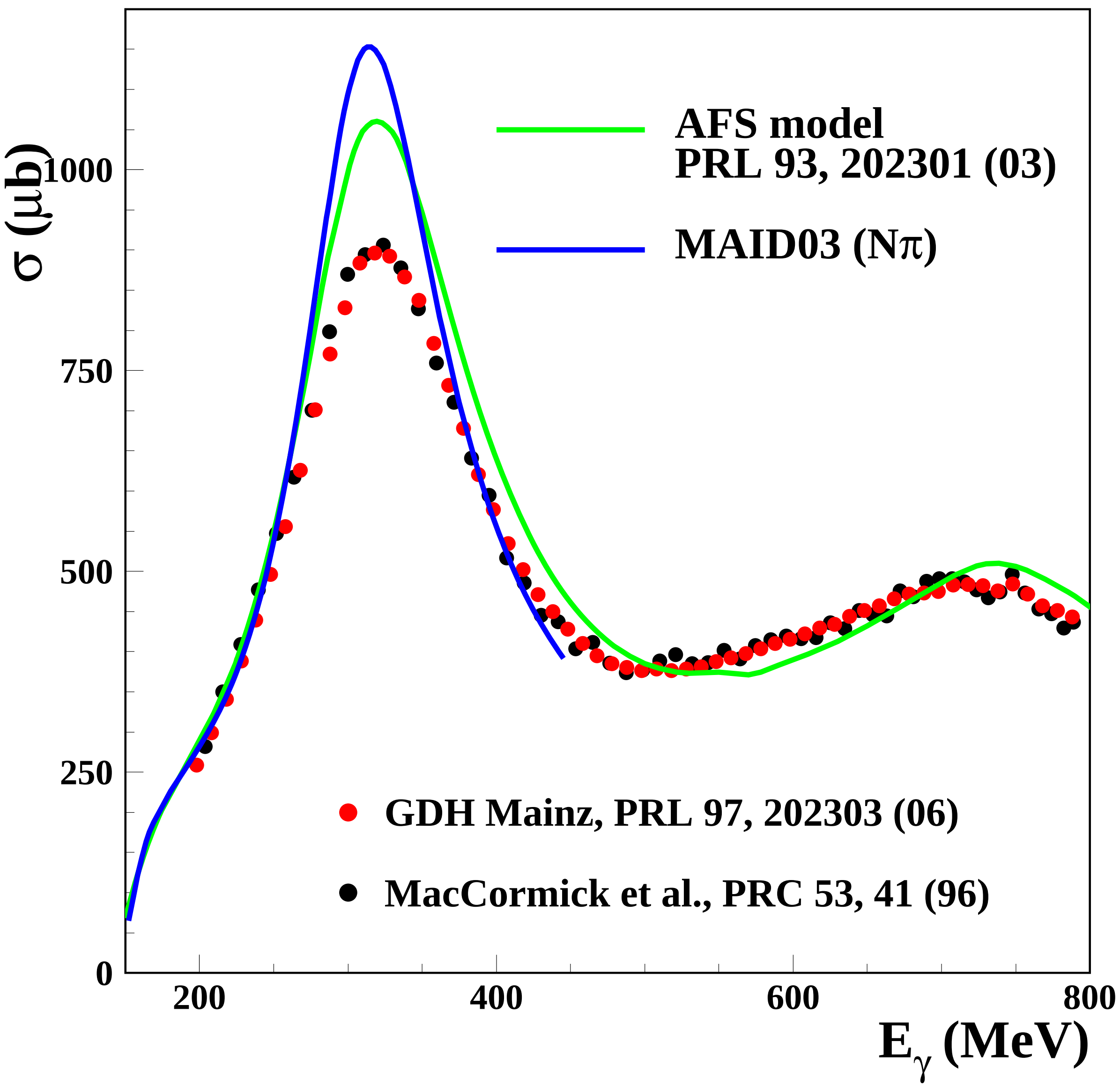
- **Large acceptance hadron detector**

  - Mainz: DAPHNE detector (Pavia,Saclay) + forward angle detectors (Pavia, Mainz)
  - Bonn: GDH Detector (Erlangen, Tuebingen, Gent)

Total inclusive cross section on the deuteron

$$\gamma d \rightarrow X$$

unpolarized data

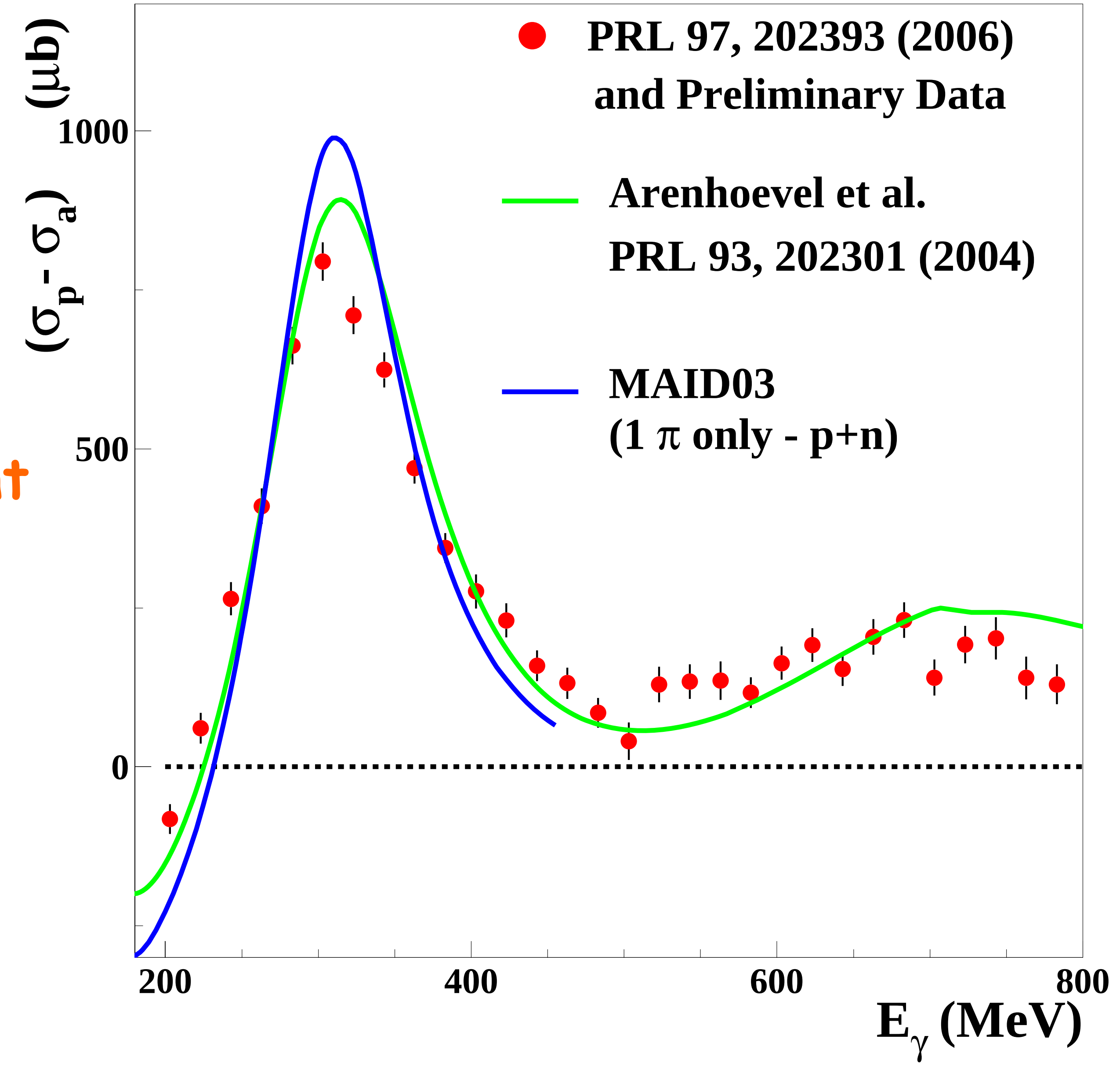


Total inclusive cross section

$\vec{\gamma}\vec{d} \rightarrow X$

helicity dependent data

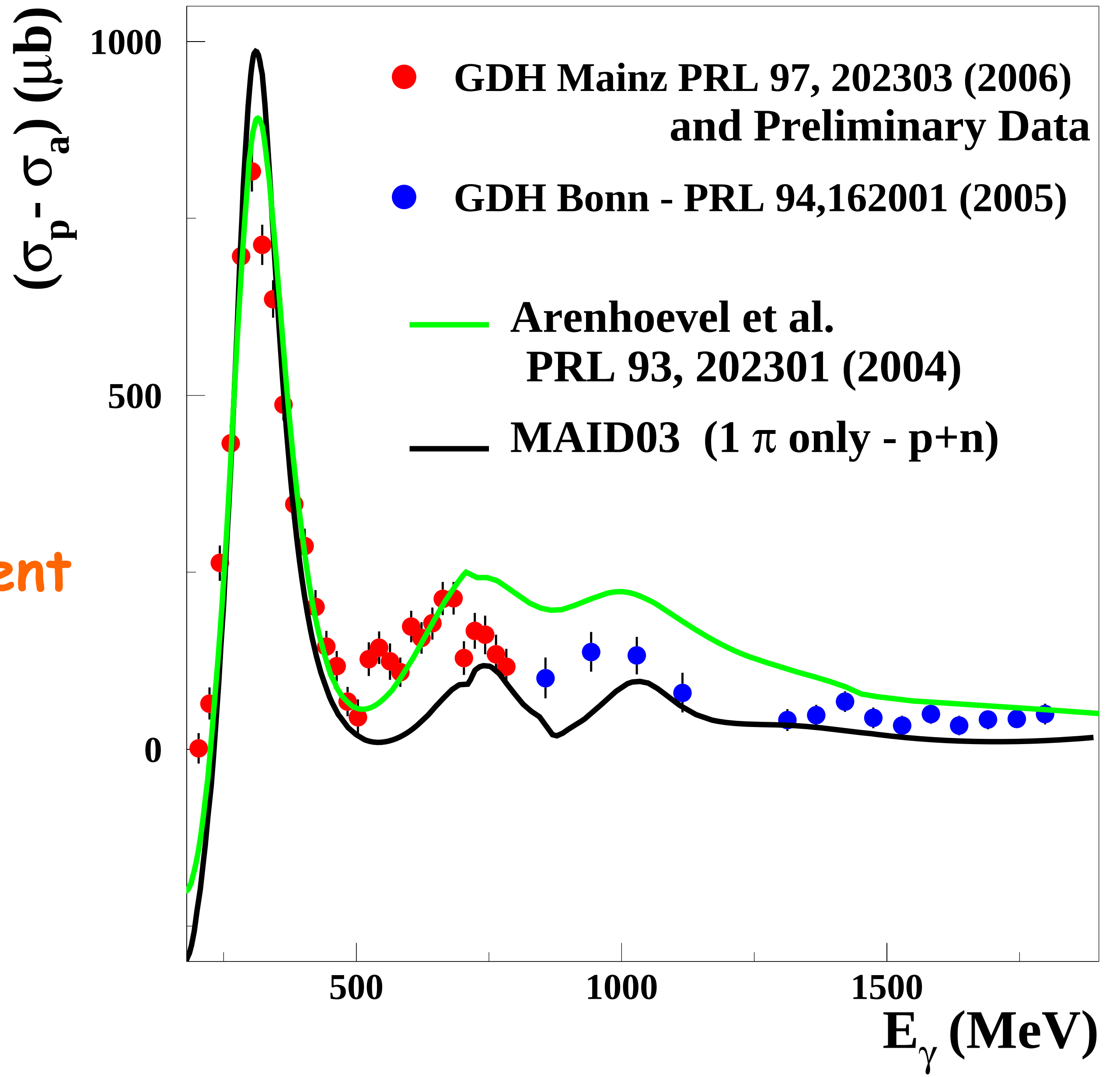
(full statistics)



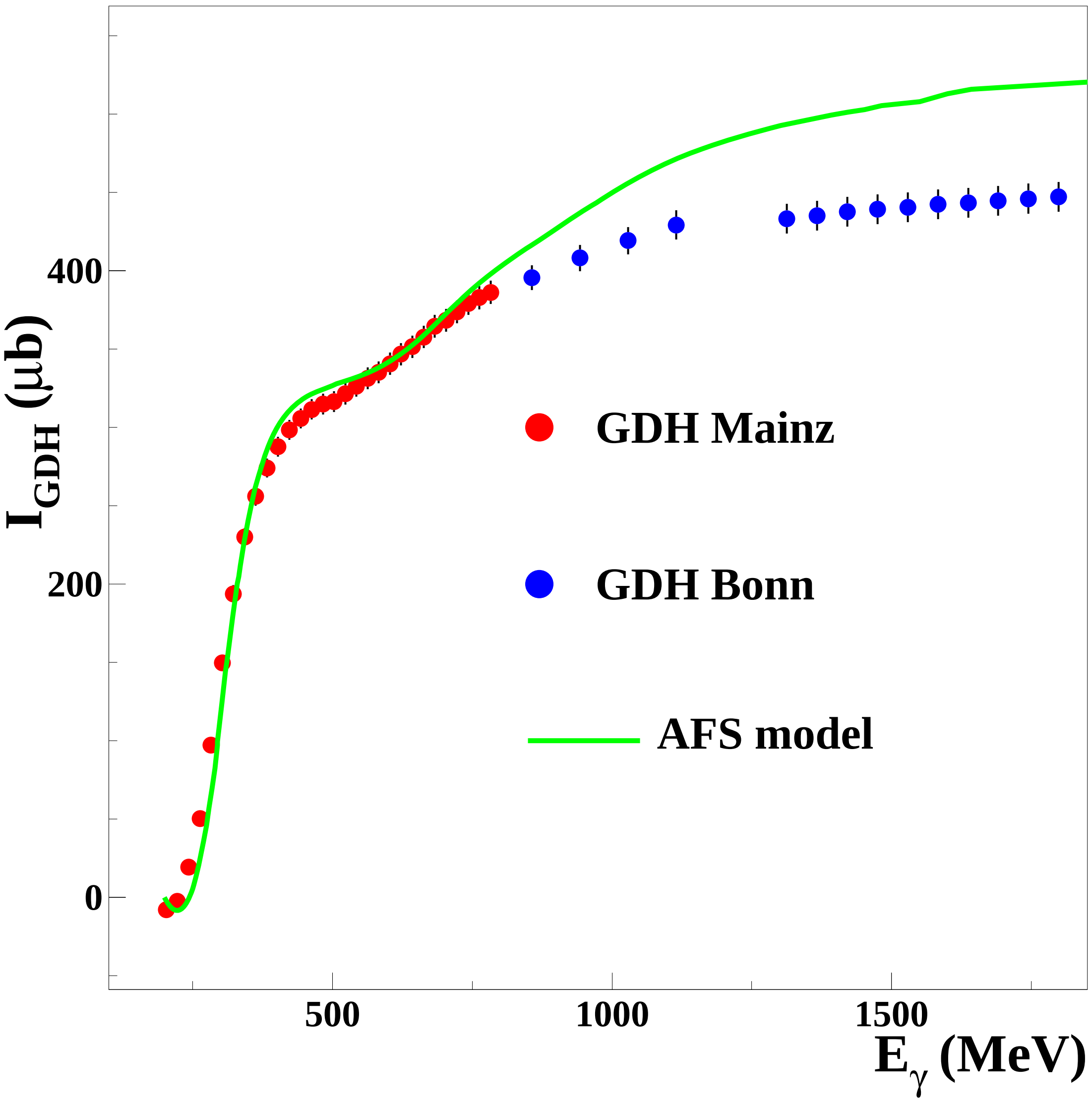
Total inclusive cross section on the deuteron

$\vec{\gamma}\vec{d} \to X$

helicity dependent data



GDH sum rule on the deuteron



Running GDH integral for the deuteron

For 0.5-2.0 GeV

(nuclear effects are expected to be "small")

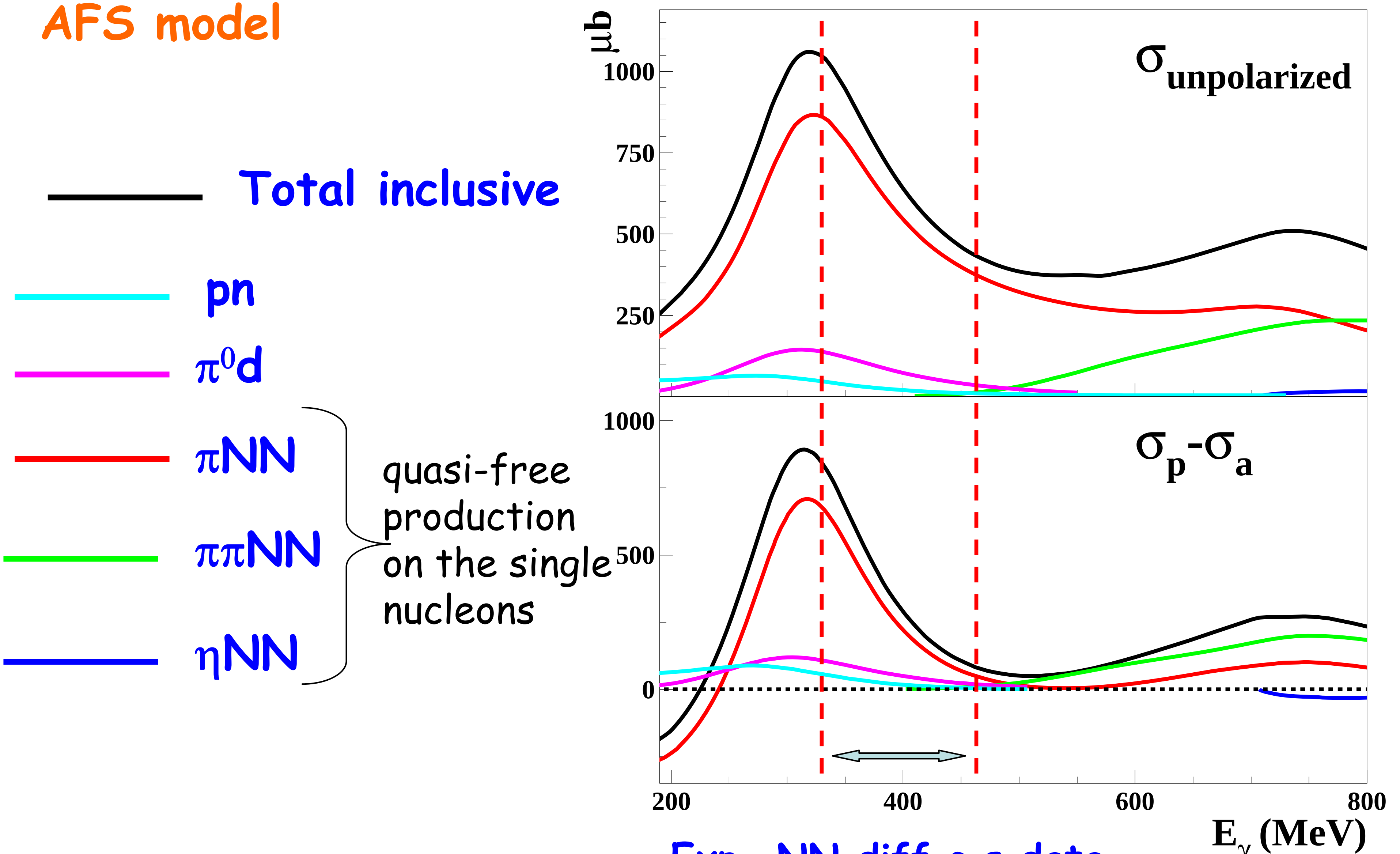
$$I_{GDH}^{Exp-Deuteron} \cong 2 \cdot I_{GDH}^{Exp-proton}$$

$$\Downarrow$$

$$I_{GDH}^{neutron} \approx I_{GDH}^{proton}$$

Study of Partial channels

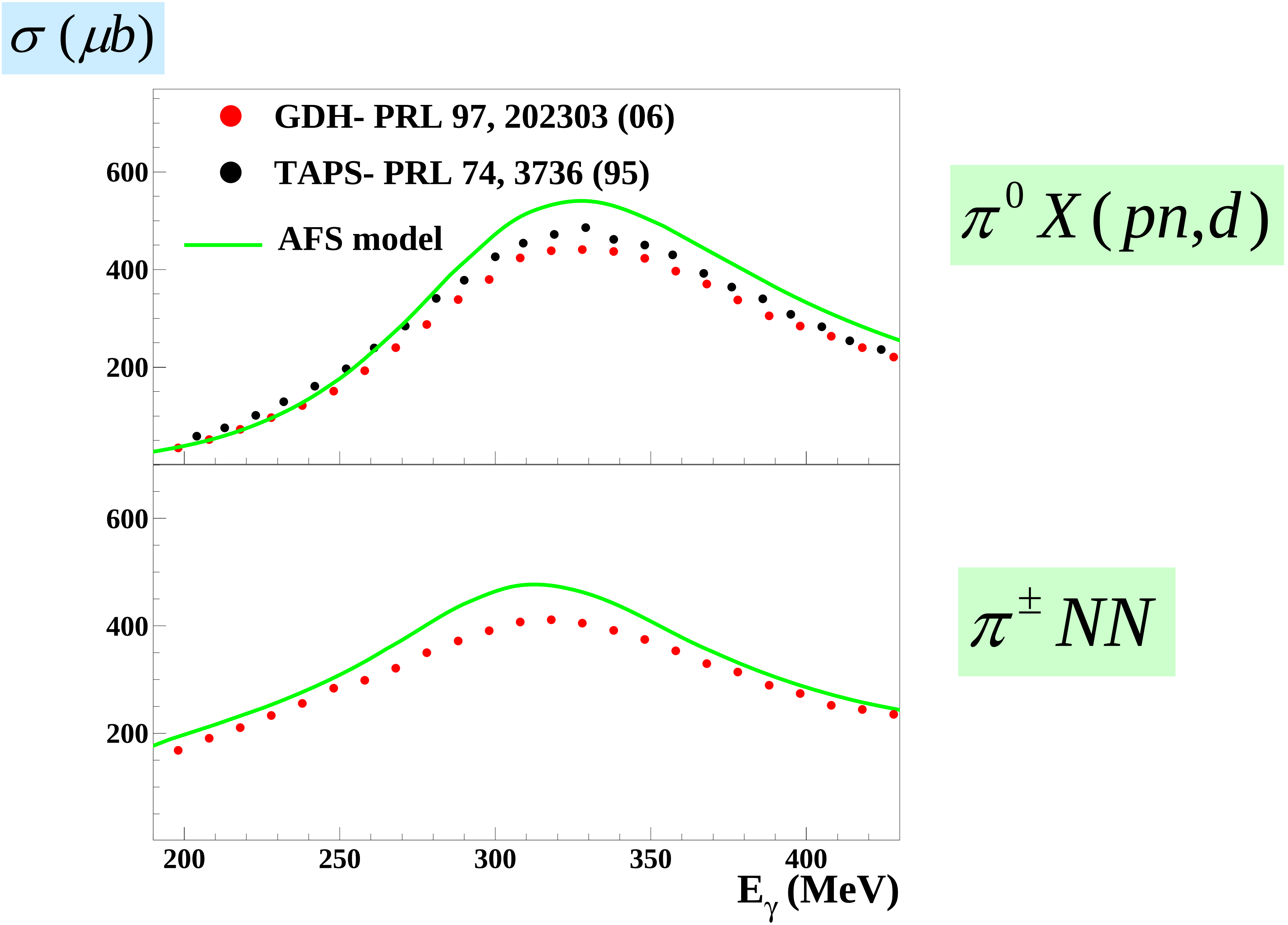
AFS model



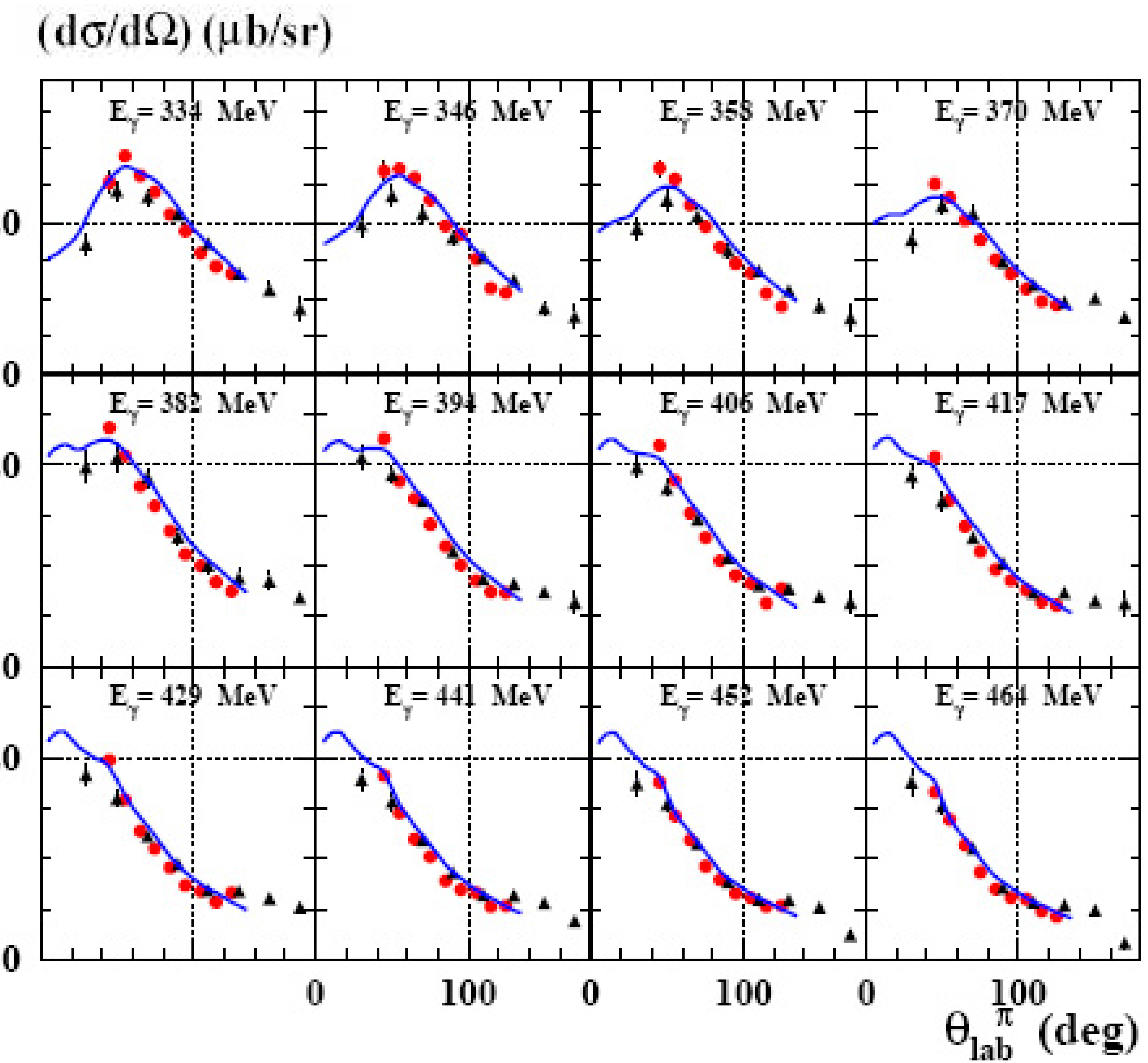
Exp.πNN diff.c.s.data

200 400 600 800

Unpolarized cross sections



$$\gamma d \rightarrow p \pi^- p_s$$



● GDH Preliminary

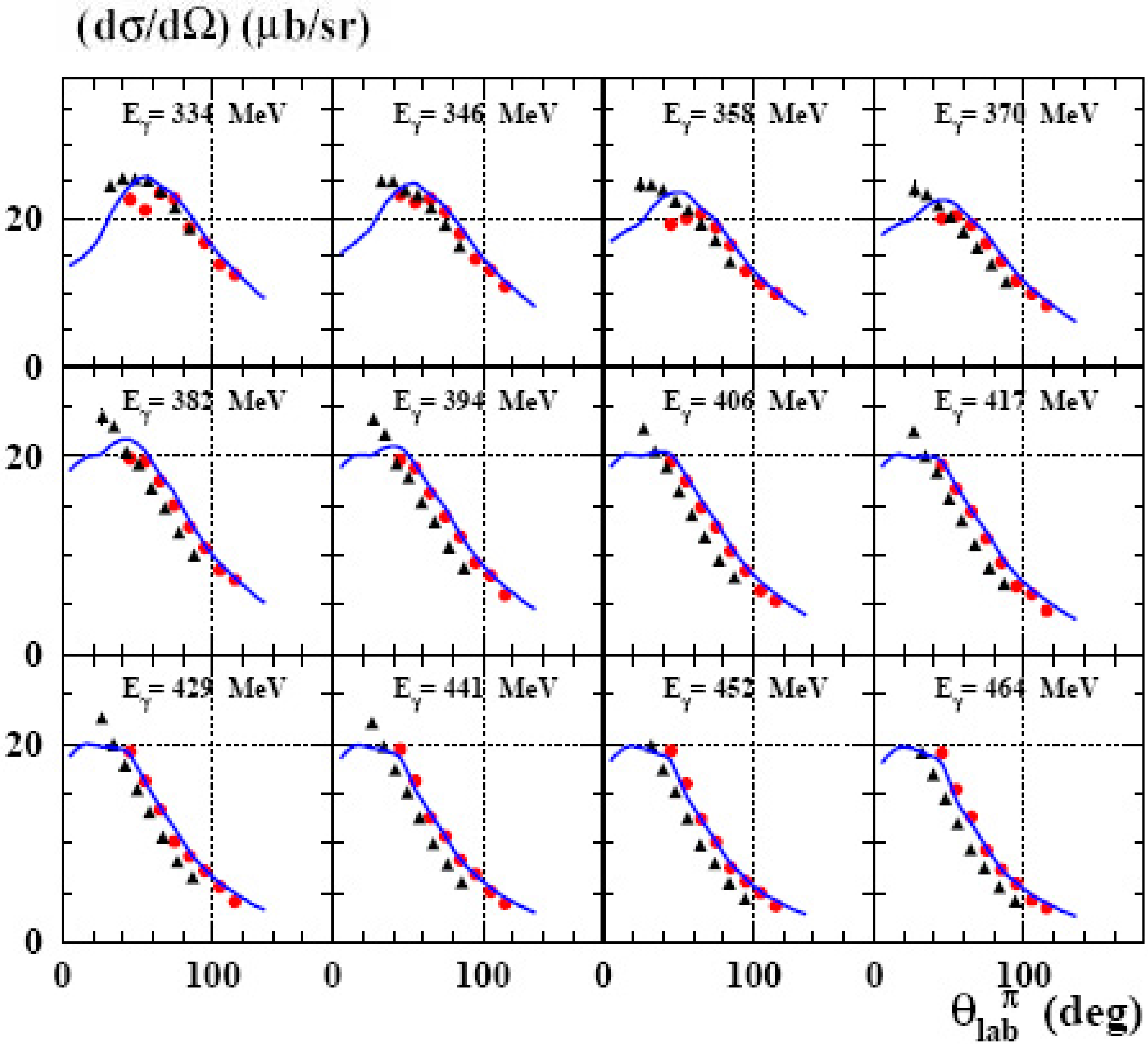
— AFS model

▲ Benz et al., NPB 65, 158 (73)

Preliminary

$$\gamma d \rightarrow n \pi^+ n_s$$

quasi –free reaction on the proton



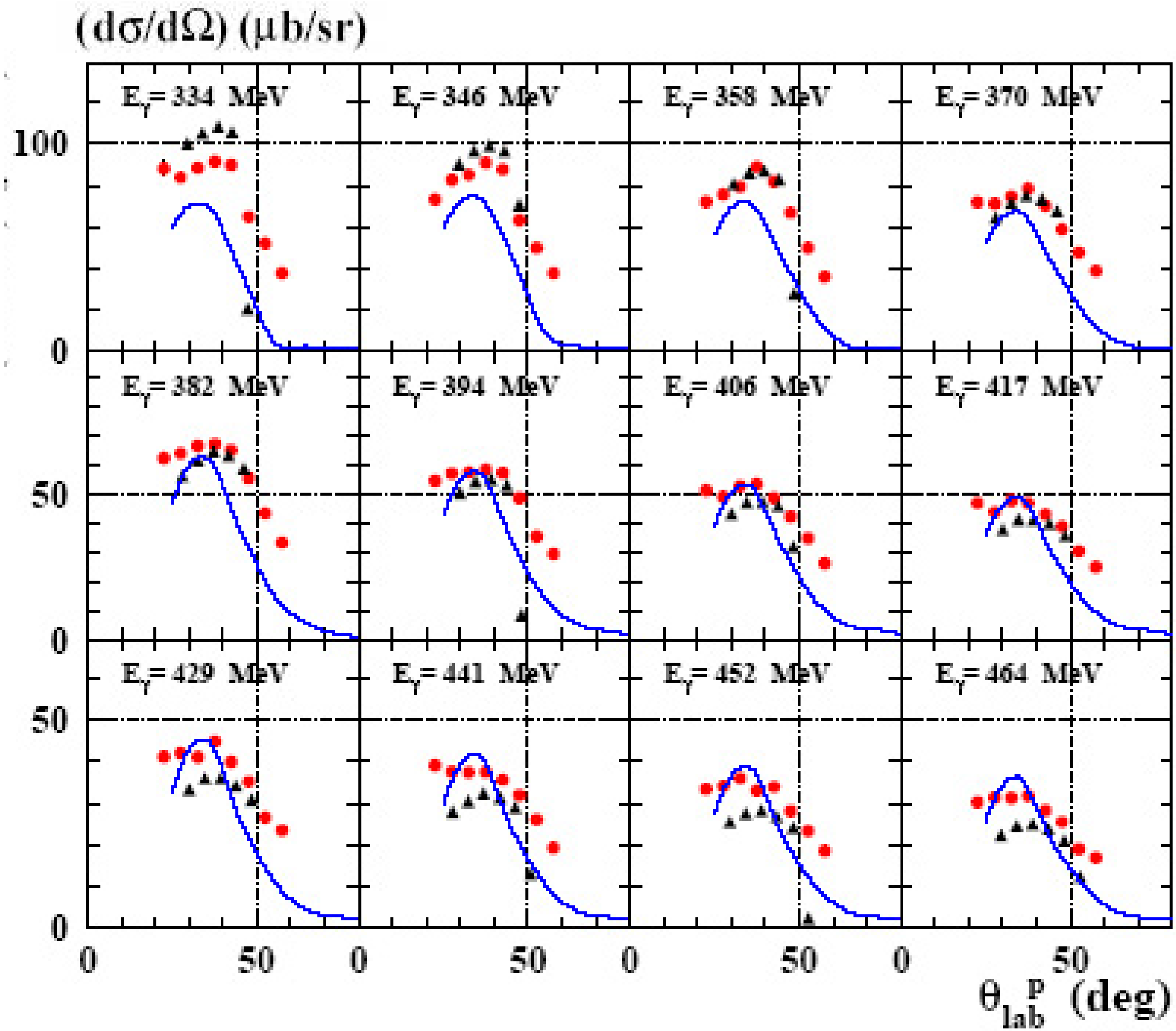
● GDH Preliminary

— AFS model

▲ GDH $\gamma p \to n \pi^+$
Ahrens et al.,
EPJA 26, 135 (05)

Preliminary

$$\gamma d \rightarrow p \pi^0 n_s$$



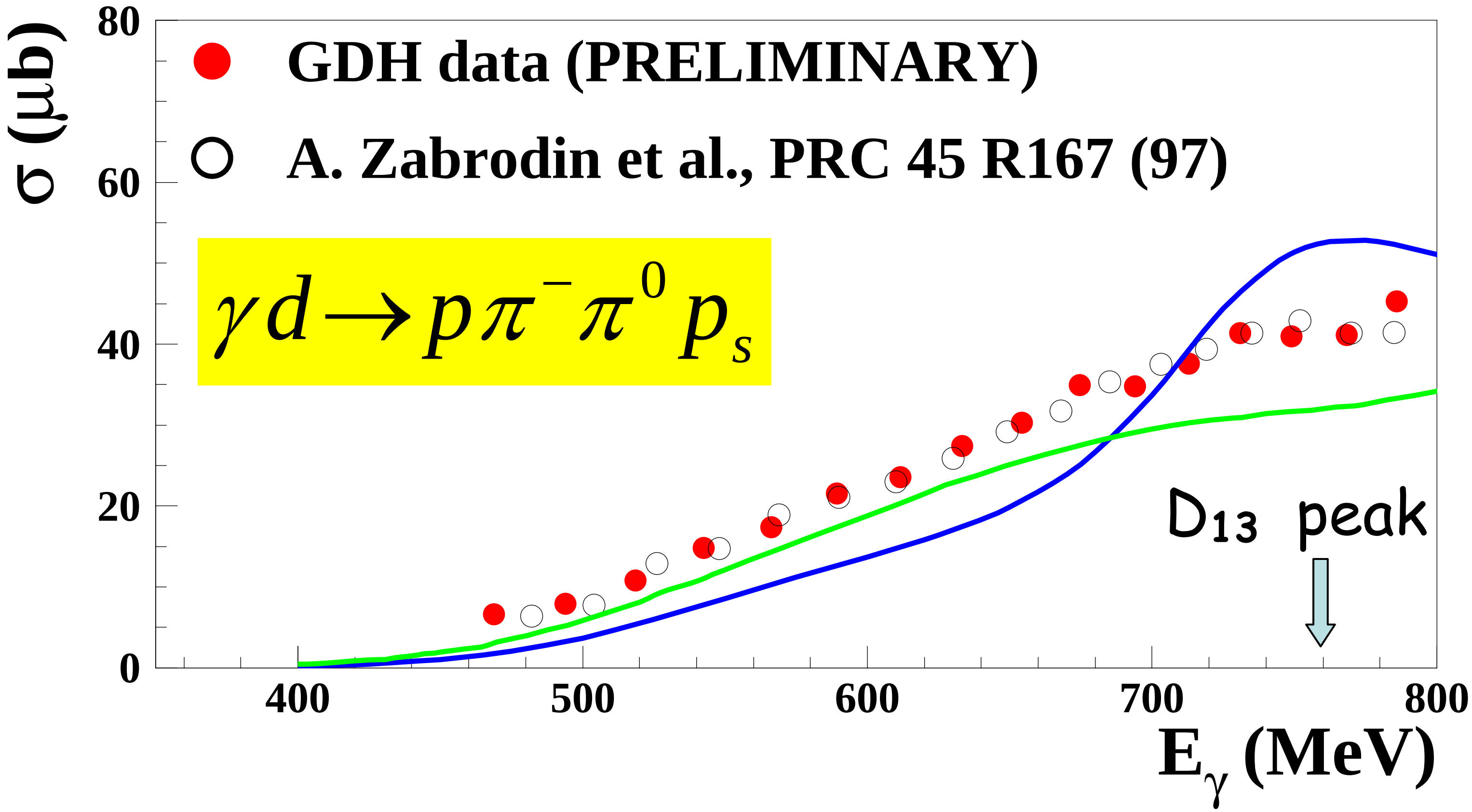
● GDH Preliminary

— AFS model

▲ GDH γ p -> p π^0
Ahrens et al.,
EPJA 26, 135 (05)

Preliminary

Double pion photoproduction

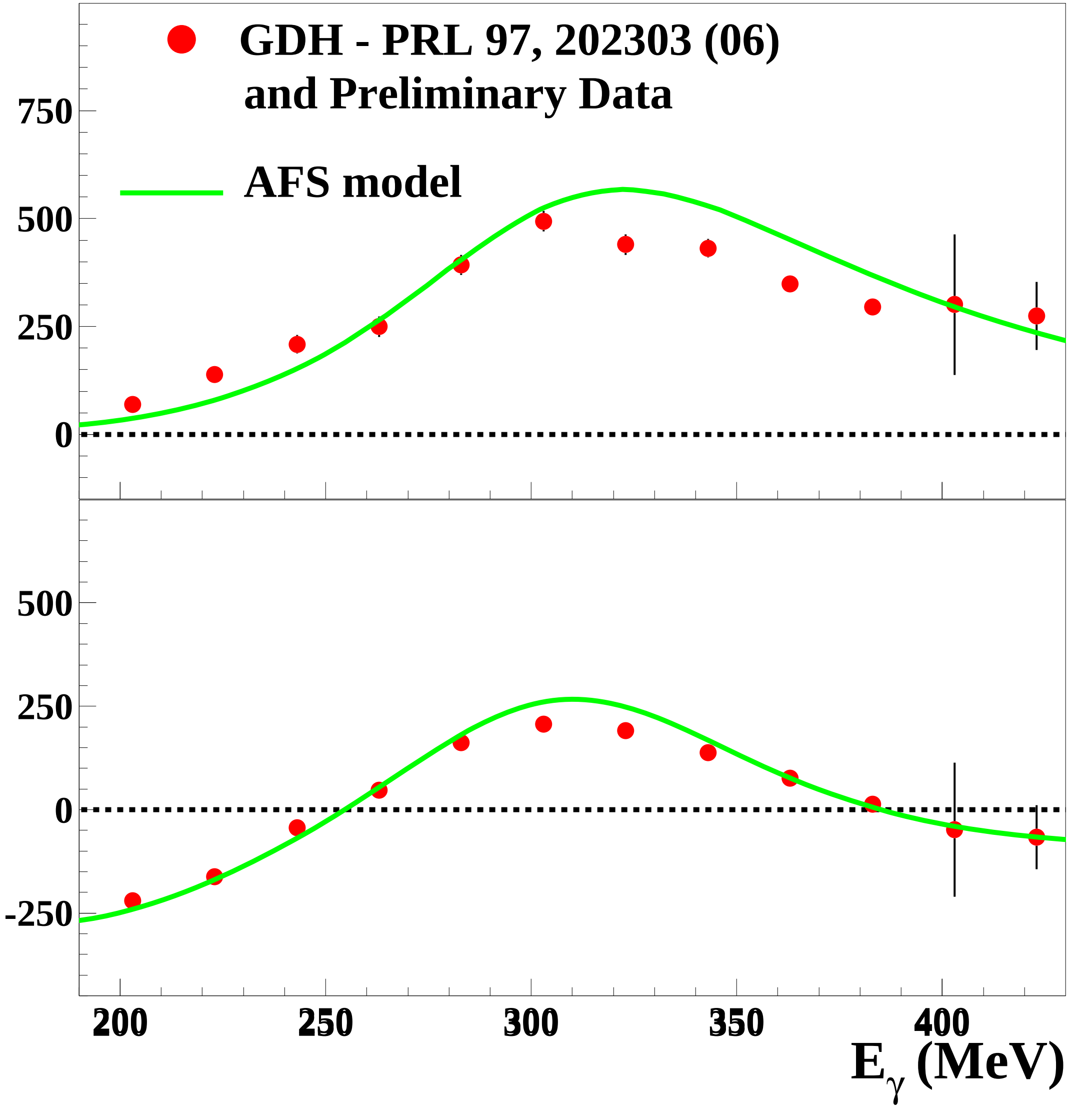


Fix-Arenhovel model, EPJA 25, 114 (05) — dominant mechanism $\gamma n \rightarrow D_{13}(1520) \rightarrow p\pi^- \pi^0$

Valencia model, NPA 600, 413 (96) — dominant mechanism $\gamma n \rightarrow \Delta^+ \pi^- \rightarrow p\pi^- \pi^0$

Helicity dependent cross sections

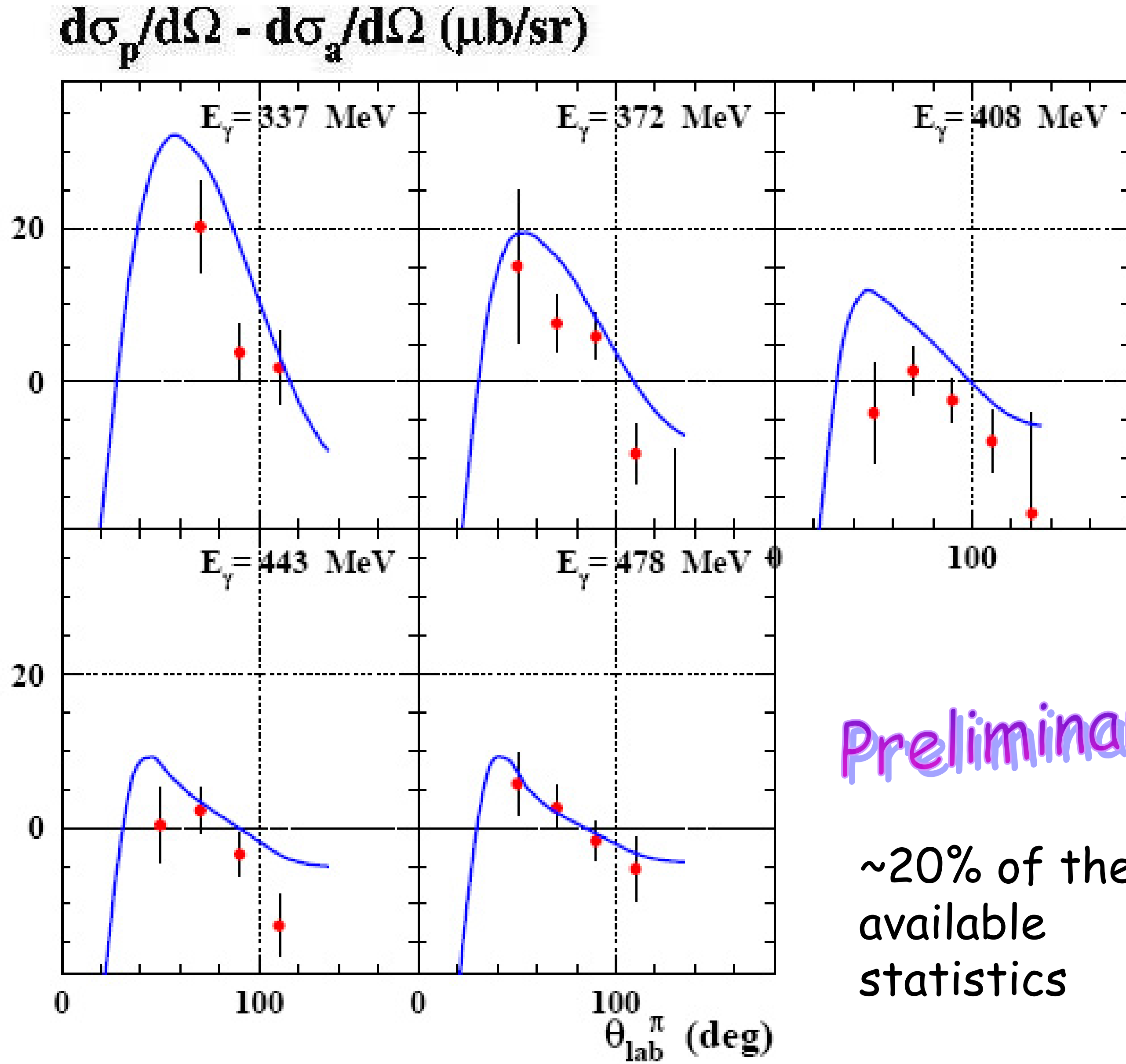
$\sigma_p - \sigma_a \; (\mu b)$



$\pi^0 X(pn, d)$

$\pi^\pm NN$

$$\vec{\gamma}\vec{d} \rightarrow p\pi^- p_s$$



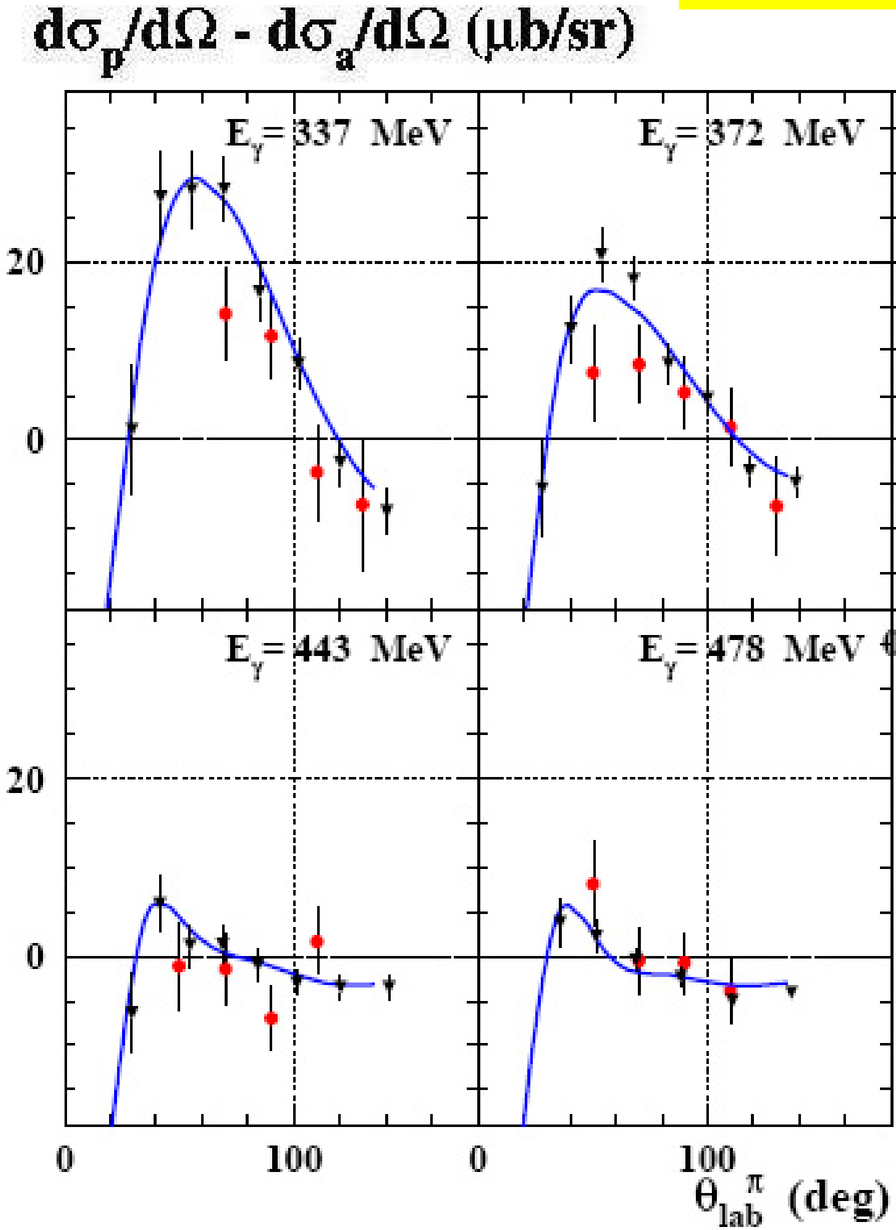
● GDH Preliminary

— AFS model

Preliminary

~20% of the available statistics

$\vec{\gamma}\vec{d} \rightarrow n\pi^+ n_s$



● GDH Preliminary

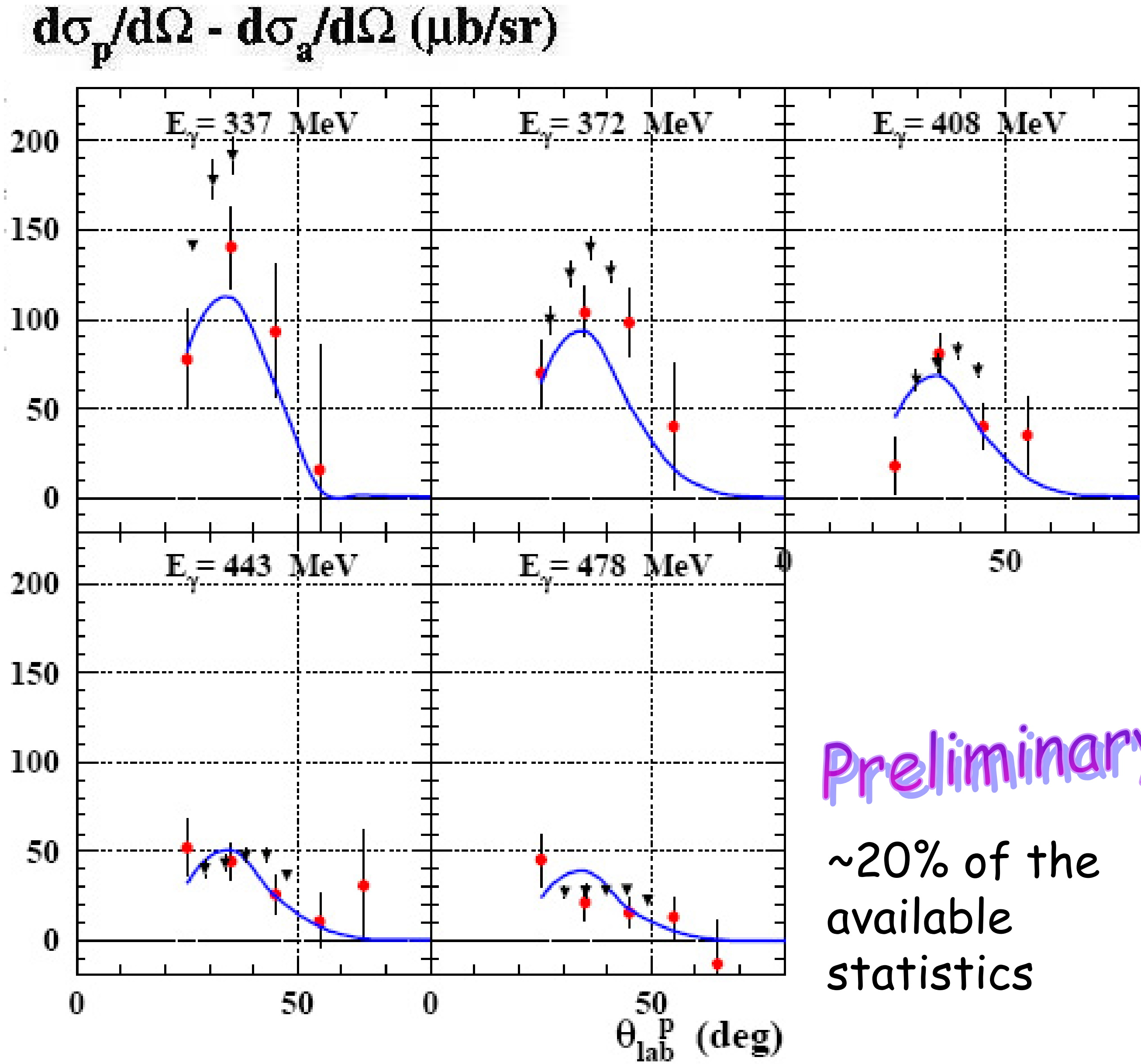
— AFS model

▲ GDH $\gamma\, p \rightarrow n\, \pi^+$
Ahrens et al., EPJA 26, 135 (05)

Preliminary

~20% of the available statistics

$$\vec{\gamma}\vec{d} \rightarrow p\pi^0 p_s$$



● GDH Preliminary

— AFS model

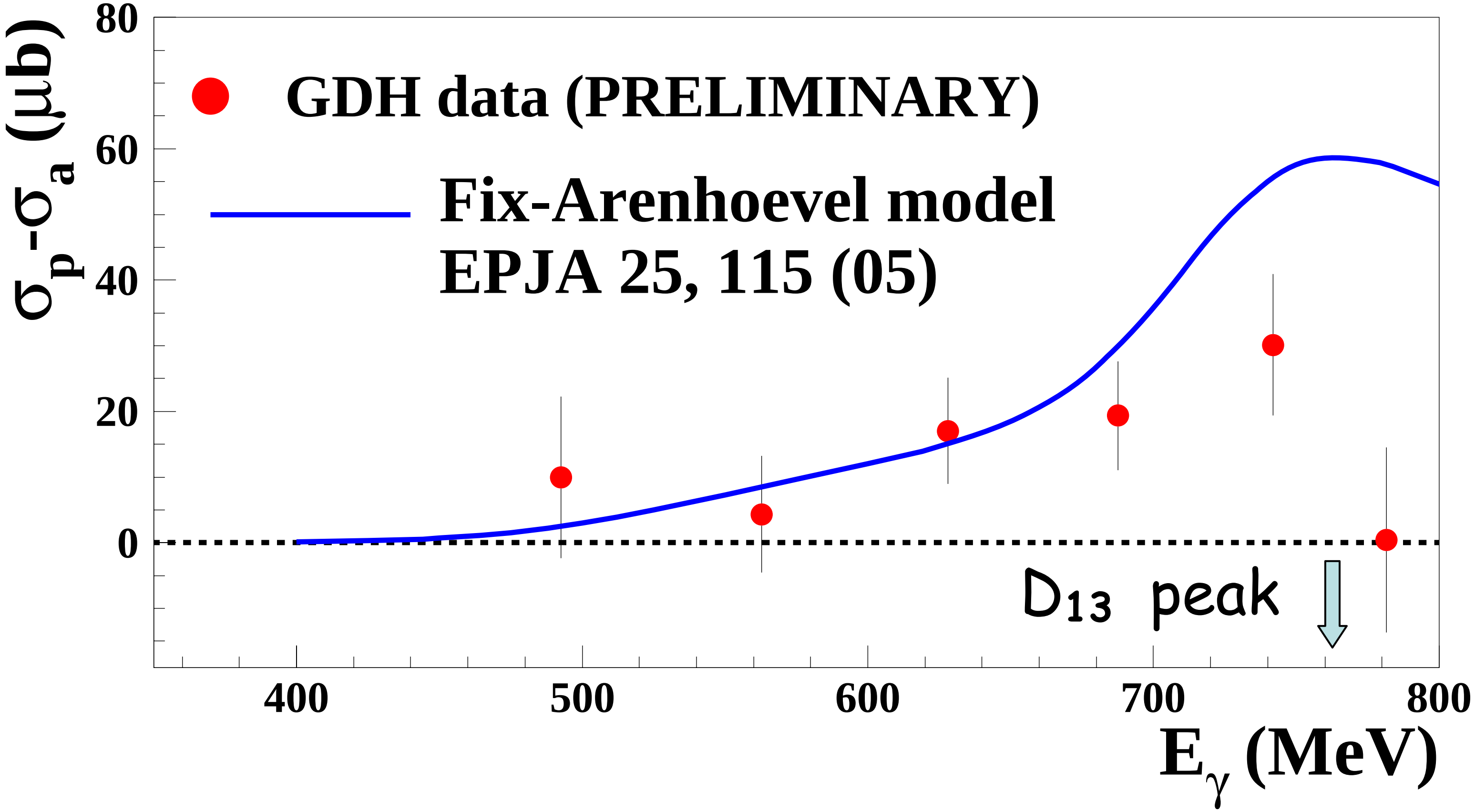
▲ GDH $\gamma p \to p \pi^0$
Ahrens et al., EPJA 26, 135 (05)

Preliminary

~20% of the available statistics

$$\vec{\gamma}\vec{d} \rightarrow p\pi^- \pi^0 p_s$$

quasi –free reaction on the neutron



Effects due to the intermediate excitation of the D_{13}(1520) resonance are much smaller than the AFS model predictions

$$\vec{\gamma}\,\vec{p} \rightarrow n\pi^{+}\pi^{0}$$

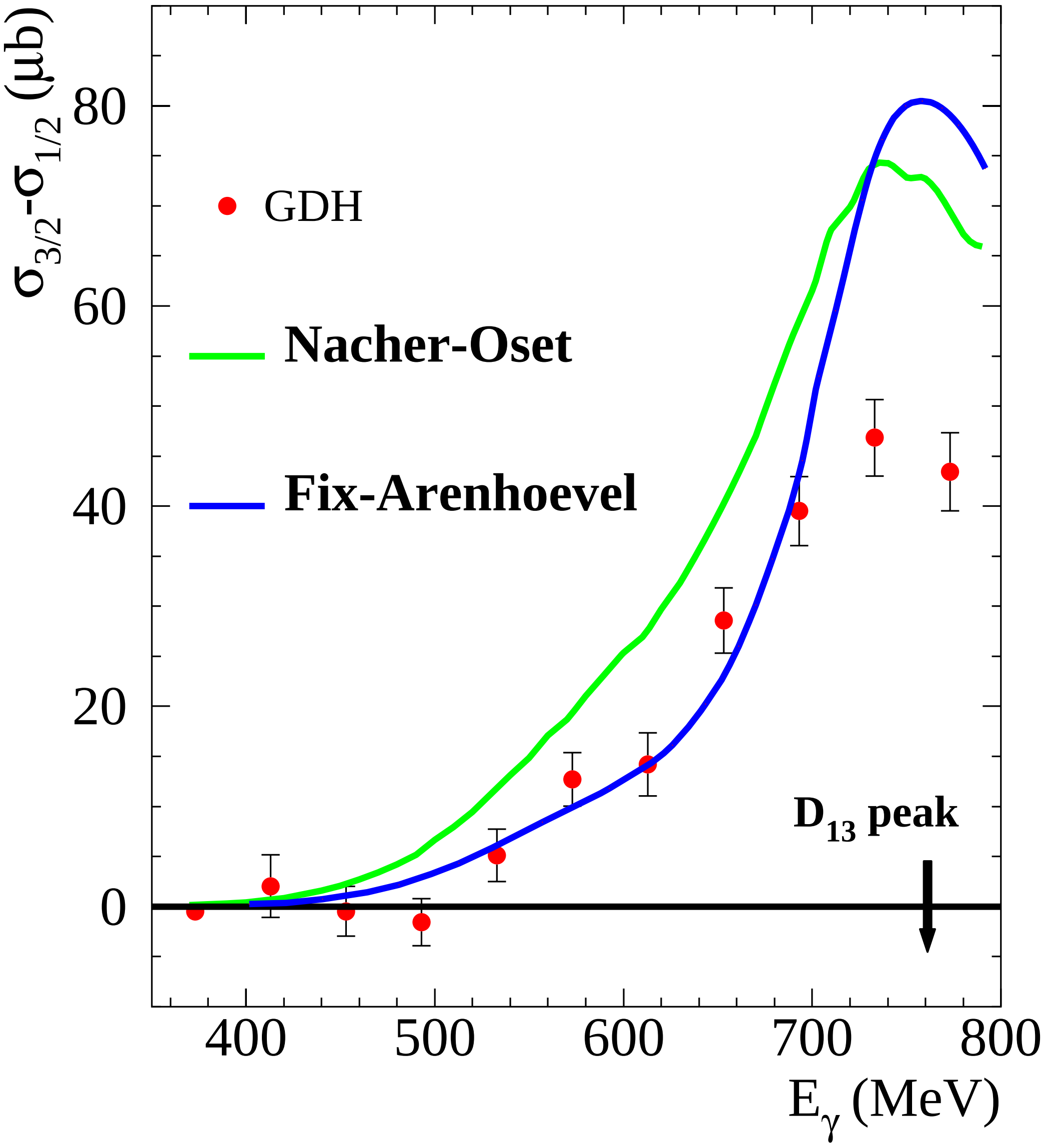
■ GDH data

PLB 551, 49 (2003)

➢ D_{13} plays a significant role ($\gamma p \rightarrow D_{13} \rightarrow N\rho$)

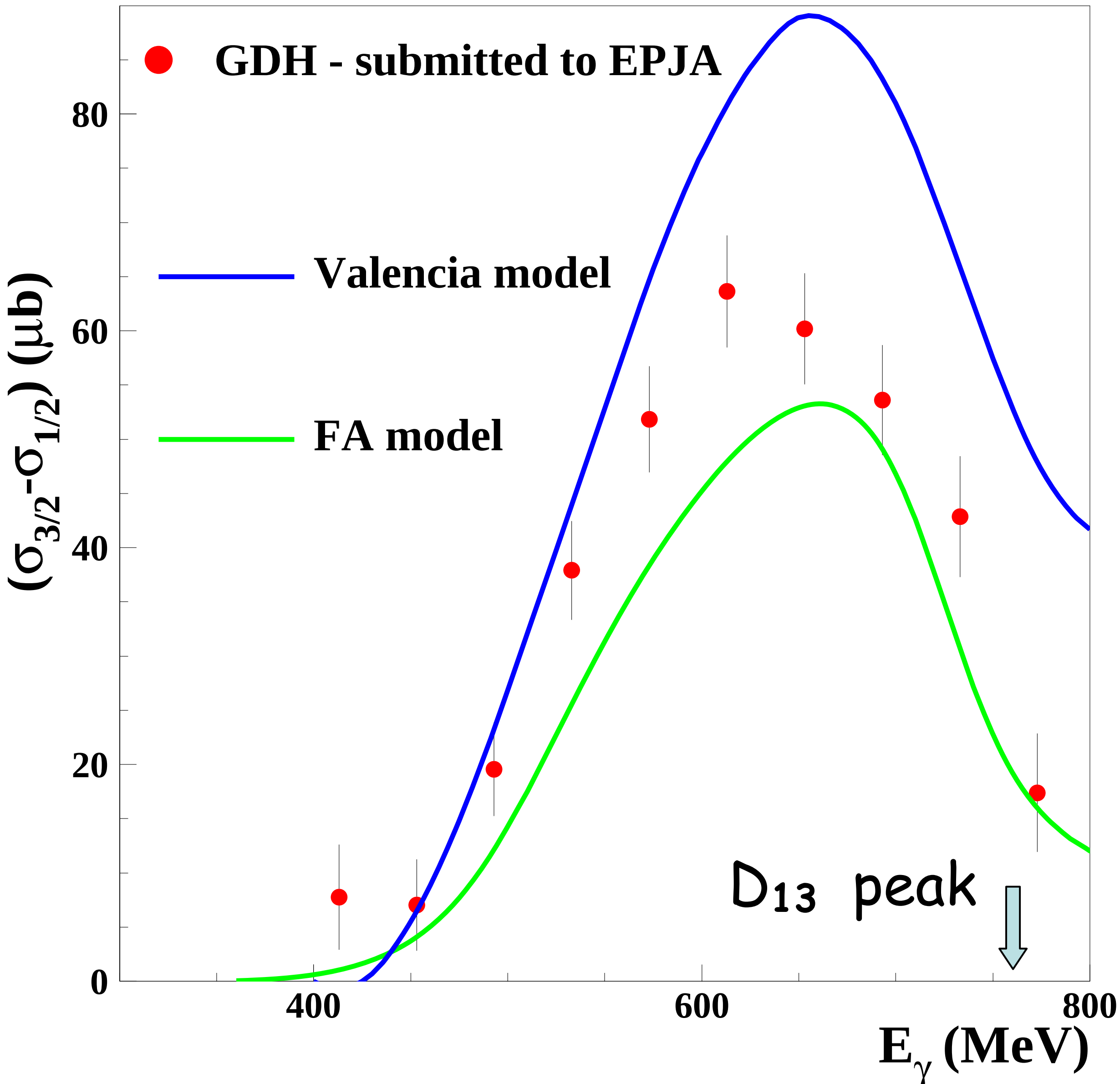
➢ Nacher-Oset model: NPA 695, 295 (01)

➢ Fix- Arenhoevel model: EPJA 25, 114 (05)

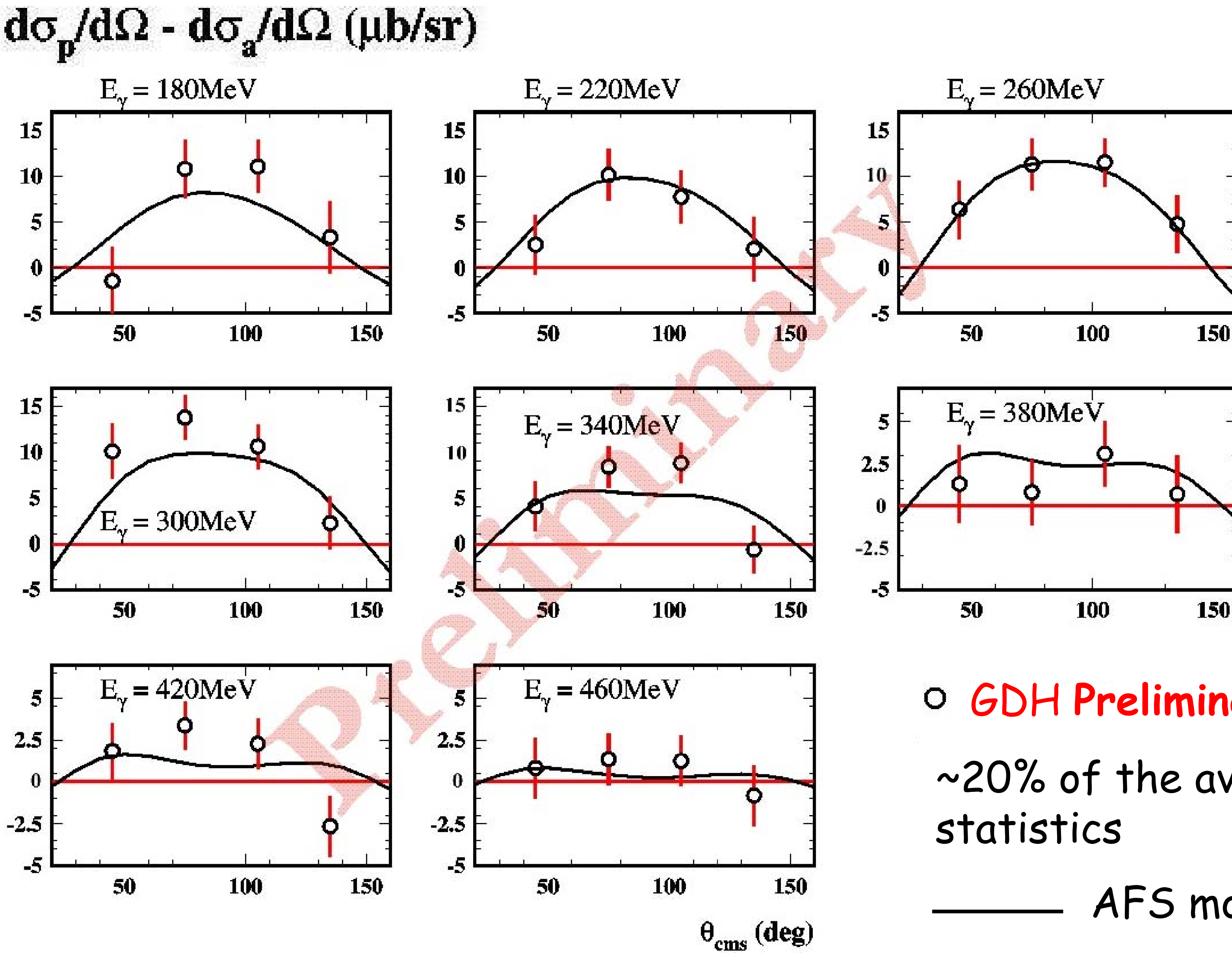


$\vec{\gamma}\,\vec{p} \rightarrow p\pi^{+}\pi^{-}$

- D_{13} plays a small role
- Most important mechanism $\gamma \mathbf{p} \rightarrow \Delta\pi$
- S-wave $\pi \Rightarrow \sigma_{3/2}$ is dominant



$\vec{\gamma}\vec{d} \to pn$



○ GDH **Preliminary**

~20% of the available statistics

——— AFS model

Conclusions

- After a long "hunt" for the GDH sum rule, we are almost there …
  - -) **proton :** sum rule ~ verified
  - -) **neutron:** first data available on the deuteron (nuclear corrections !)

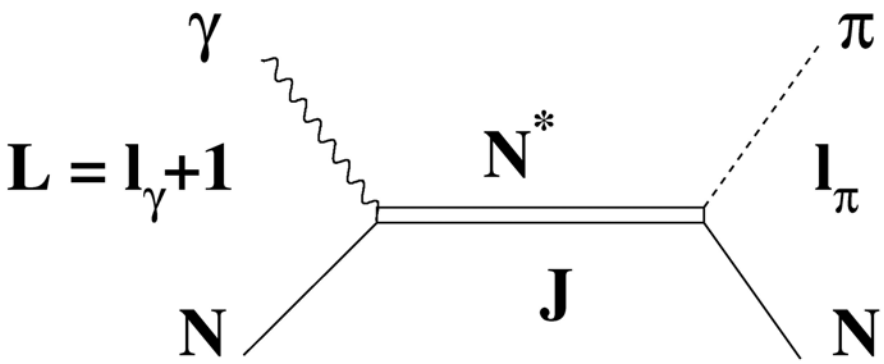
- Helicity dependent observables are a powerful (and essential) tool for a precise measurement of the baryon resonance properties

- At Mainz: CB@MAMI collaboration will improve/exend up to 1.5 GeV the $N\pi(\pi)(N\eta)$ GDH data (two proposals rated "A" by the PAC)

- **The game has just started ……**

Riserva

Connection between resonances and multipoles

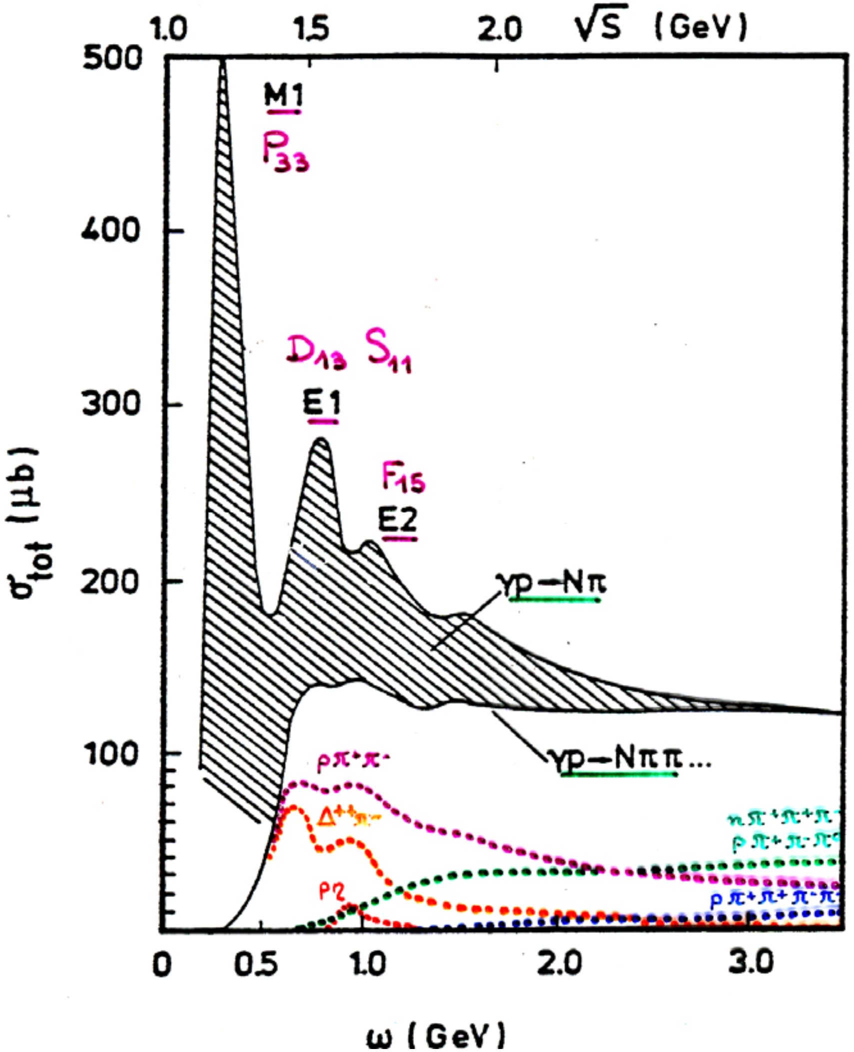


Photon L	Photon Multipole	J	P	Pion l_π	Pion Multipole	Resonance
1	E1	1/2	-	0	E_{0+}	S_{11}
		3/2	-	2	E_{2-}	D_{13}
	M1	1/2	+	1	M_{1-}	P_{11}
		3/2	+	1	M_{1+}	P_{33}
2	E2	3/2	+	1	E_{1+}	P_{33}
		5/2	+	3	E_{3-}	F_{15}
	M2	3/2	-	2	M_{2-}	D_{13}
		5/2	-	2	M_{2+}	D_{15}

- Unpolarized cross section

$$\sigma = |E_{0+}|^2 + |M_{1-}|^2 + 6|E_{1+}|^2 + 2|M_{1+}|^2 + 6|M_{2-}|^2 + 2|E_{2-}|^2 + \ldots$$

Only the (few) most relevant multipoles can be accessed



Total photoabsorption cross section on the proton

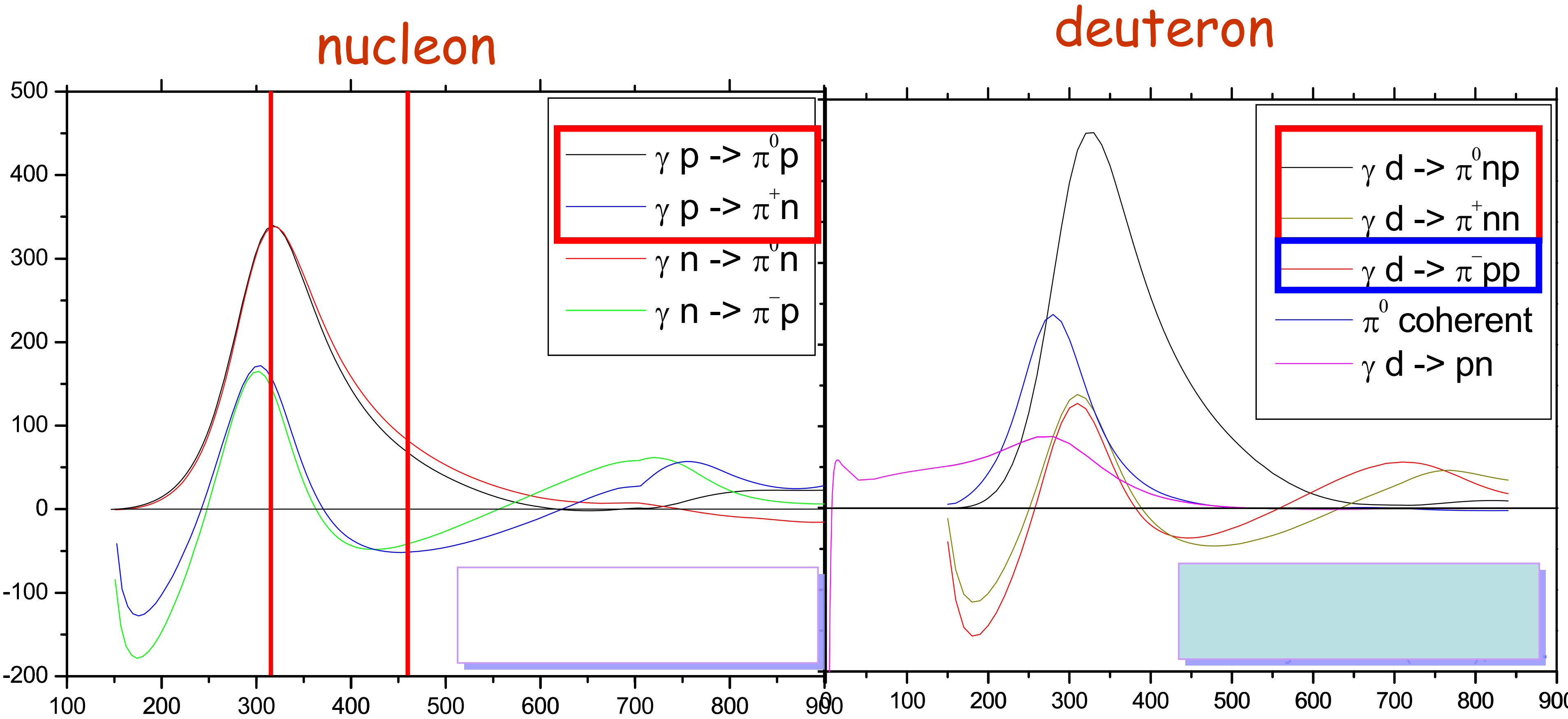
- Helicity dependent cross section $(\sigma_{3/2}-\sigma_{1/2})$

$$(\sigma_{3/2}-\sigma_{1/2}) = -|E_{0+}|^2 - |M_{1-}|^2 - 3|E_{1+}|^2 + |M_{1+}|^2 - 6E_{1+}^{*}M_{1+} + $$
$$- 3|M_{2-}|^2 + |E_{2-}|^2 + 6E_{2-}^{*}M_{2-} + \dots$$

Change of sign / Interference terms between multipoles

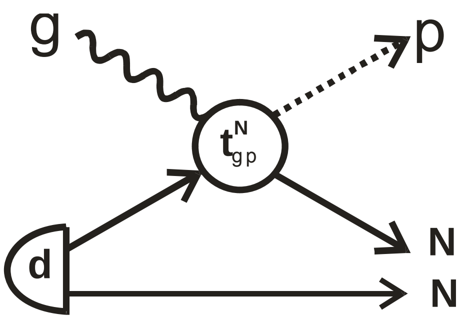
Single pion photoproduction

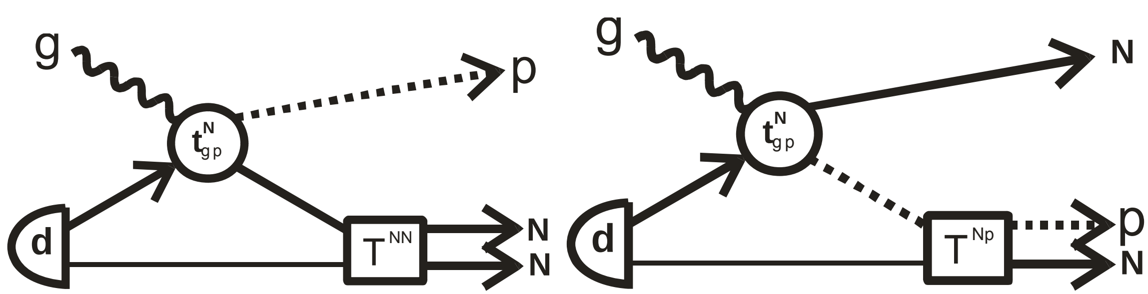
Helicity dependence of the photoabsorption reactions



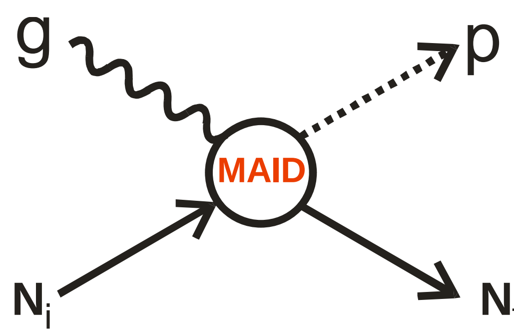
Deuteron Model

Impulse Approximation + Final State Interaction





- Elementary amplitude from MAID



- NN : Paris potential, partial waves up to ${}^{2s+1}L_j = {}^3D_3$
- pN : model of S. Nozawa *et al.*, partial waves up to $L_{2T\,2J} = D_{35}$

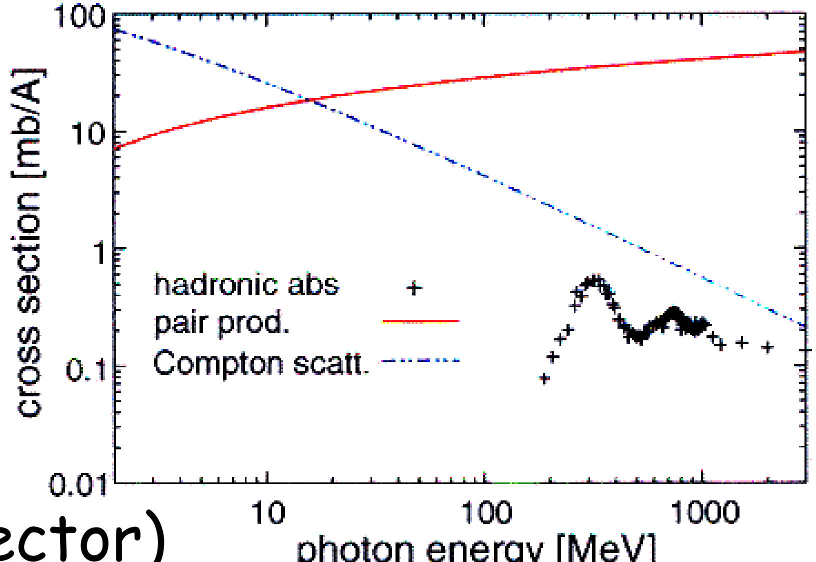
Total inclusive cross section

$$\sigma_{total} = \sum \text{partial channels}$$ (not feasible)

$$\sigma_{total} = \sum \text{hadrons}$$ (inclusive method)

For each partial reaction channel, at least one reaction product has to be detected with (almost) complete acceptance (solid angle & efficiency)

a) detector with a very high acceptance/particle detection efficiency (DAPHNE: 94% of 4π)



b) Suppression of e.m. events (pair prod./Compton) at forward angles (Cerenkov detector)

Derivation of the GDH sum rule

- Forward (ϑ =0) Compton scattering amplitude (Lorentz and gauge invariance)

$$f(\nu) = f_1(\nu)\vec{\varepsilon}_f \cdot \vec{\varepsilon}_i + f_2(\nu)\vec{\sigma} \cdot (\vec{\varepsilon}_f \times \vec{\varepsilon}_i)$$

Spin independent　　　Spin dependent

($\vec{\varepsilon}$ = photon polarization vector　σ = nucleon spinor)

- Dispersion relation without subtraction for the spin dependent part of the amplitude

$$\mathrm{Re}\, f_2(\nu) = \frac{2\nu}{\pi} \cdot \int_0^\infty \frac{\mathrm{Im}\, f_2(\nu')}{(\nu'^2 - \nu^2)} d\nu'$$

$f_2 \rightarrow 0$ when $\nu \rightarrow \infty$

- Optical theorem

$$\mathrm{Im}\, f_2(\nu) = \frac{\nu}{8\pi}\left[\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right]$$

- Low energy theorem

$$\lim_{\nu\to 0} f_2(\nu) = -\frac{\alpha}{2m^2}\kappa^2\nu$$

$$\mathrm{Re}\, f_2(\nu) = \frac{2\nu}{\pi}\int_0^\infty \frac{\mathrm{Im}\, f_2(\nu')}{(\nu'^2 - \nu^2)}d\nu' \underset{\nu\to 0}{\Rightarrow} \int_0^\infty \frac{\sigma_{3/2}(\nu') - \sigma_{1/2}(\nu')}{\nu'}d\nu' = \frac{2\pi^2\alpha}{m^2}\kappa^2$$

Why could the GDH sum rule be violated ?

- The only "weak" hypothesis is: $f_2 \to 0$ when $\nu \to \infty$
- Violation:

=) Im $f_2(\nu) = (\sigma_{3/2} - \sigma_{1/2}) \to 0$ when $\nu \to \infty$

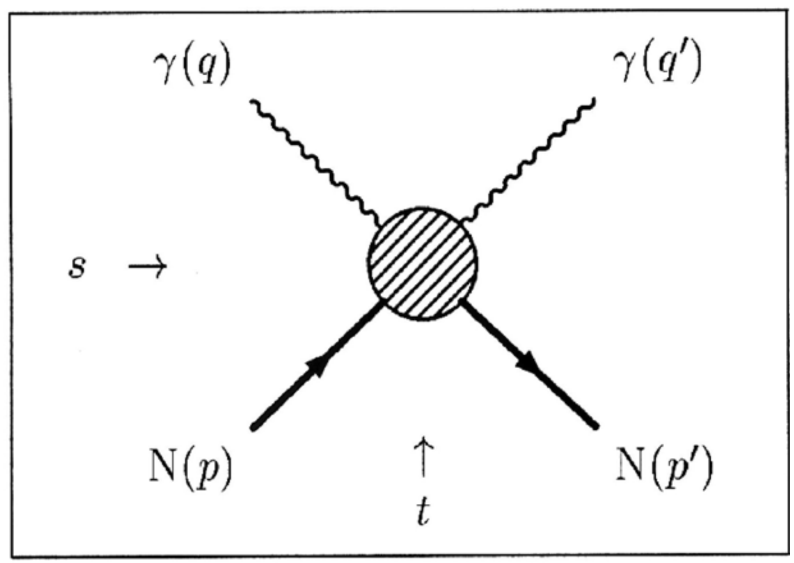
(from Regge theory $(\sigma_{3/2} - \sigma_{1/2}) \Rightarrow s^{-k}$, $k>0$)

=) Re $f_2(\nu) \not\to 0$ when $\nu \to \infty$

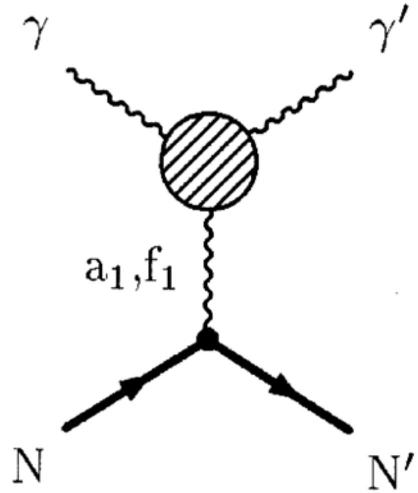
Compton scattering amplitude is spin dependent when $\nu \to \infty$

Scattering amplitude has a fixed J=1+ pole in the t channel

$$f_2(0) = f_2(\infty) + \int_0^\infty \frac{\operatorname{Im} f_2(\nu')}{\nu'} d\nu$$



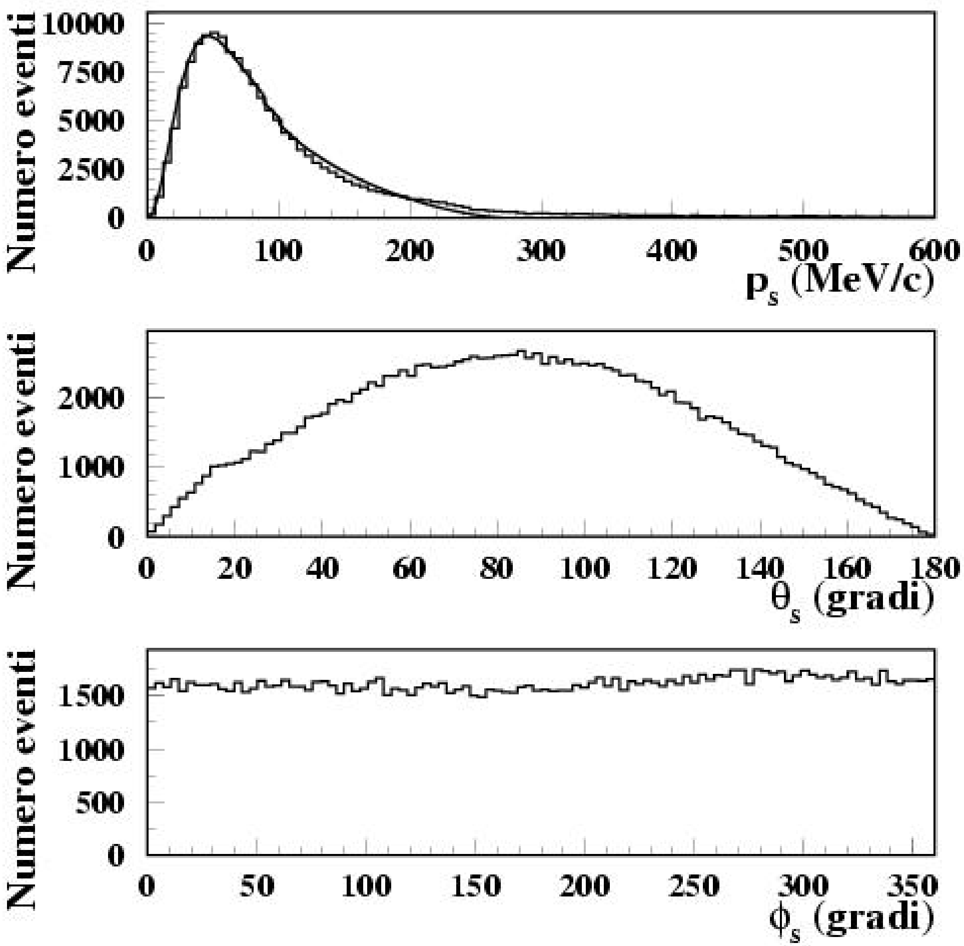
- Exchange of a_1-like (J=1+) mesons between γ and N ?



- Non pointlike (constituent) quarks ?

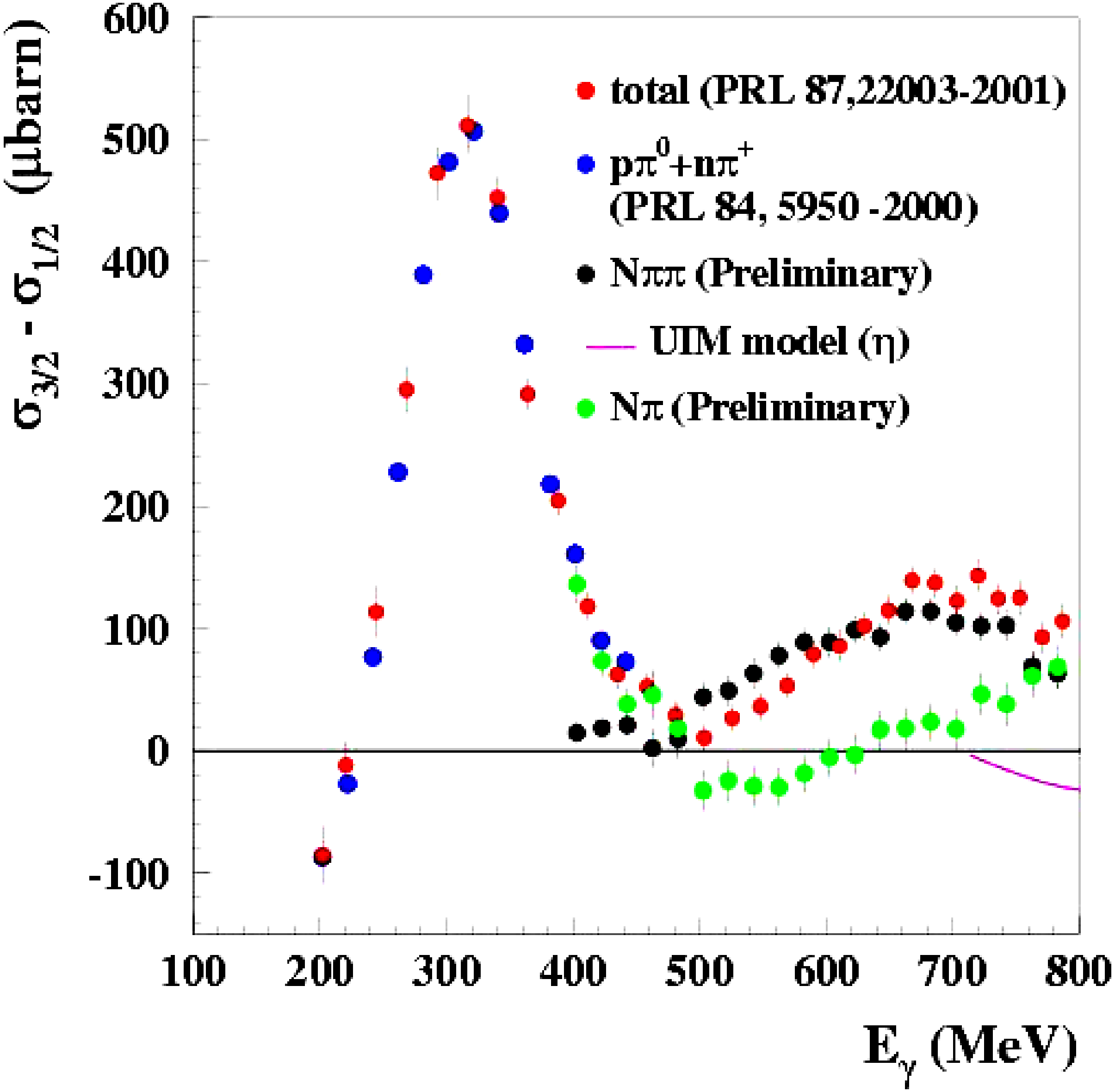
- photoproduction of graviton ?

(dσ/dΩ) (μb/sr)



Numero eventi
10000
7500
5000
2500
0
0
100
200
300
400
500
600
p_s (MeV/c)
Numero eventi
2000
1000
0
0
20
40
60
80
100
120
140
160
180
θ_s (gradi)
Numero eventi
1500
1000
500
0
0
50
100
150
200
250
300
350
ϕ_s (gradi)

Esclusive reactions



$$\vec{\gamma}\,\vec{p} \rightarrow X,\, N\pi(\pi),\, p\eta$$

$\vec{\gamma}\,\vec{p} \rightarrow N\pi$

Δ resonance region

■ GDH data

EPJA 31, 323 (04)

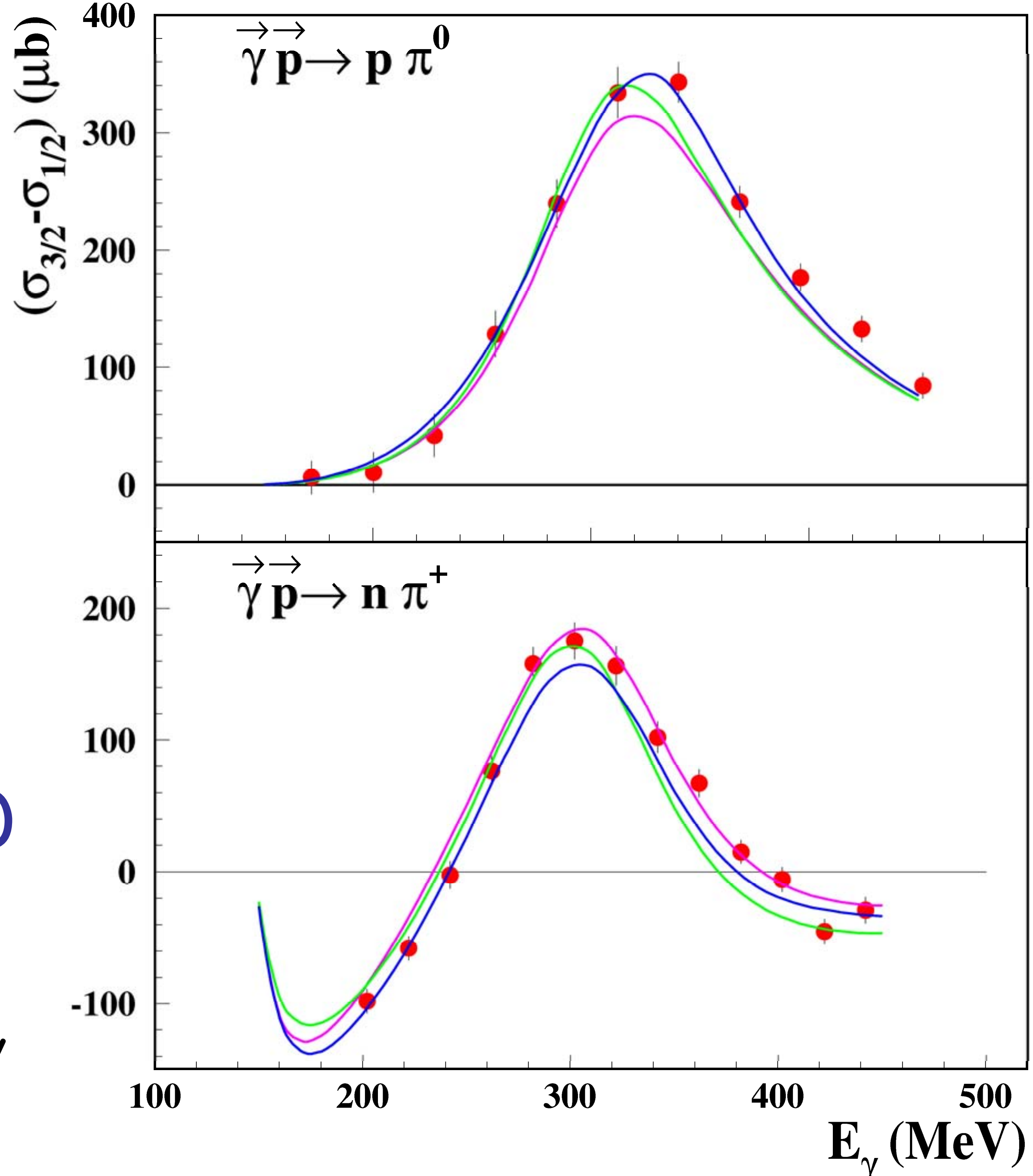
SAID (SM02k)

HDT

MAID

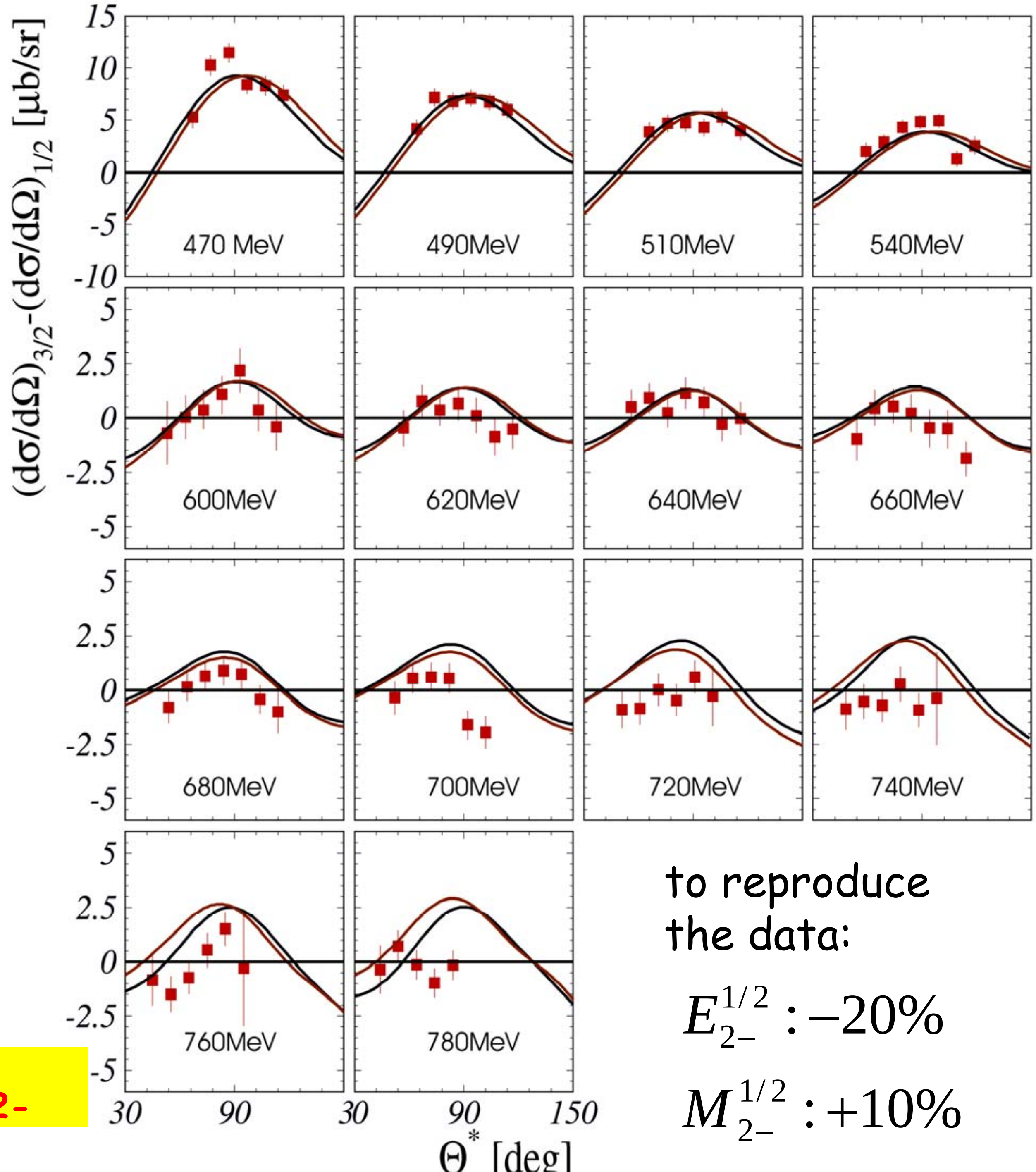
As expected, no (big) discrepancies

(several precise measurements already performed)



$$\vec{\gamma}\,\vec{p} \rightarrow p\pi^0$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{3/2} - \left(\frac{d\sigma}{d\Omega}\right)_{1/2} (\mu b)$$



■ GDH data

PRL 88, 232002, 2002

SAID (SM01)

MAID2000

to reproduce the data:

$E_{2-}^{1/2}: -20\%$

$M_{2-}^{1/2}: +10\%$

Sensitivity to $E_{2-}{}^{*}M_{2-}$

$$\vec{\gamma}\,\vec{p} \rightarrow n\pi^+$$

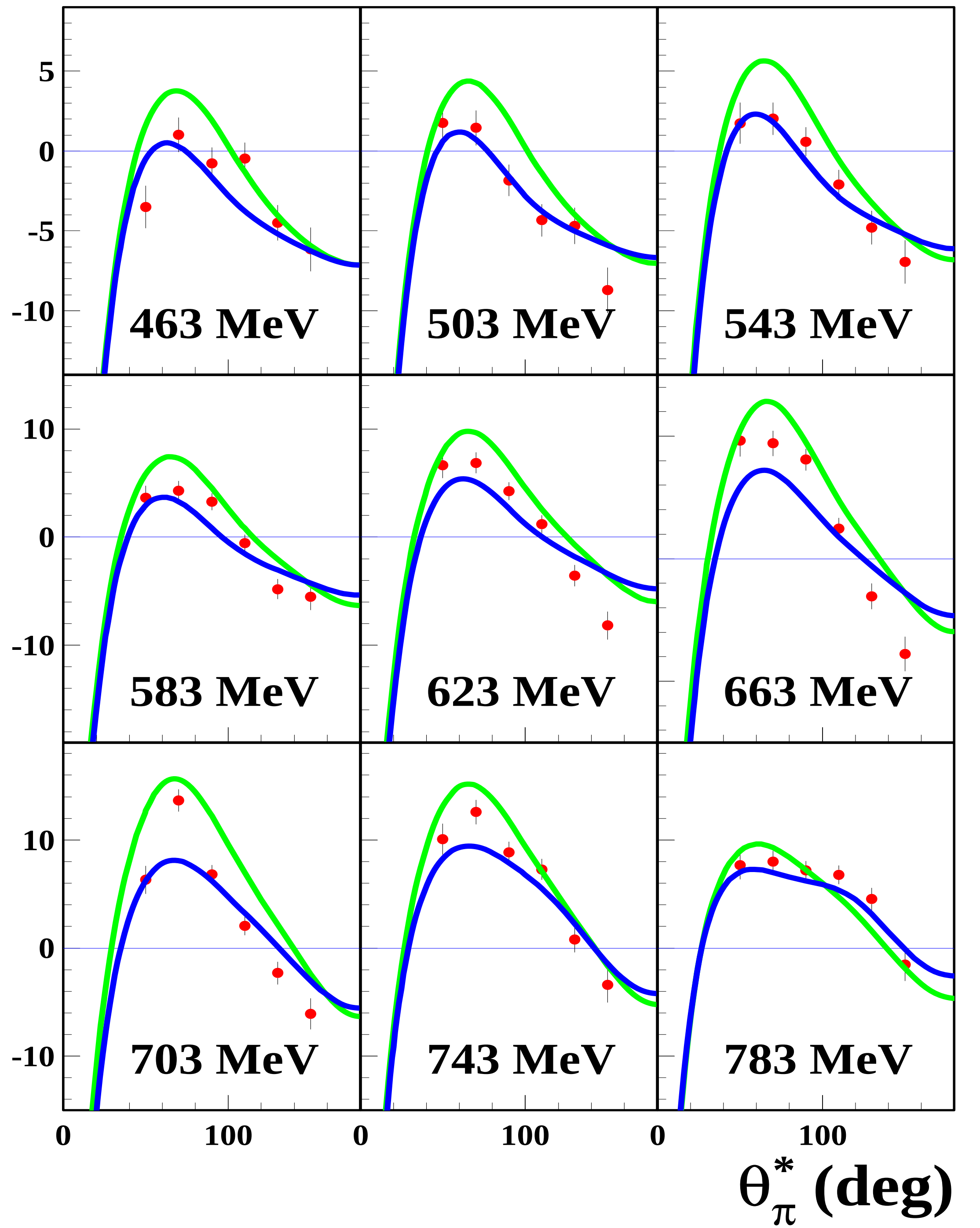
$$\left(\frac{d\sigma}{d\Omega}\right)_{3/2} - \left(\frac{d\sigma}{d\Omega}\right)_{1/2} (\mu b)$$

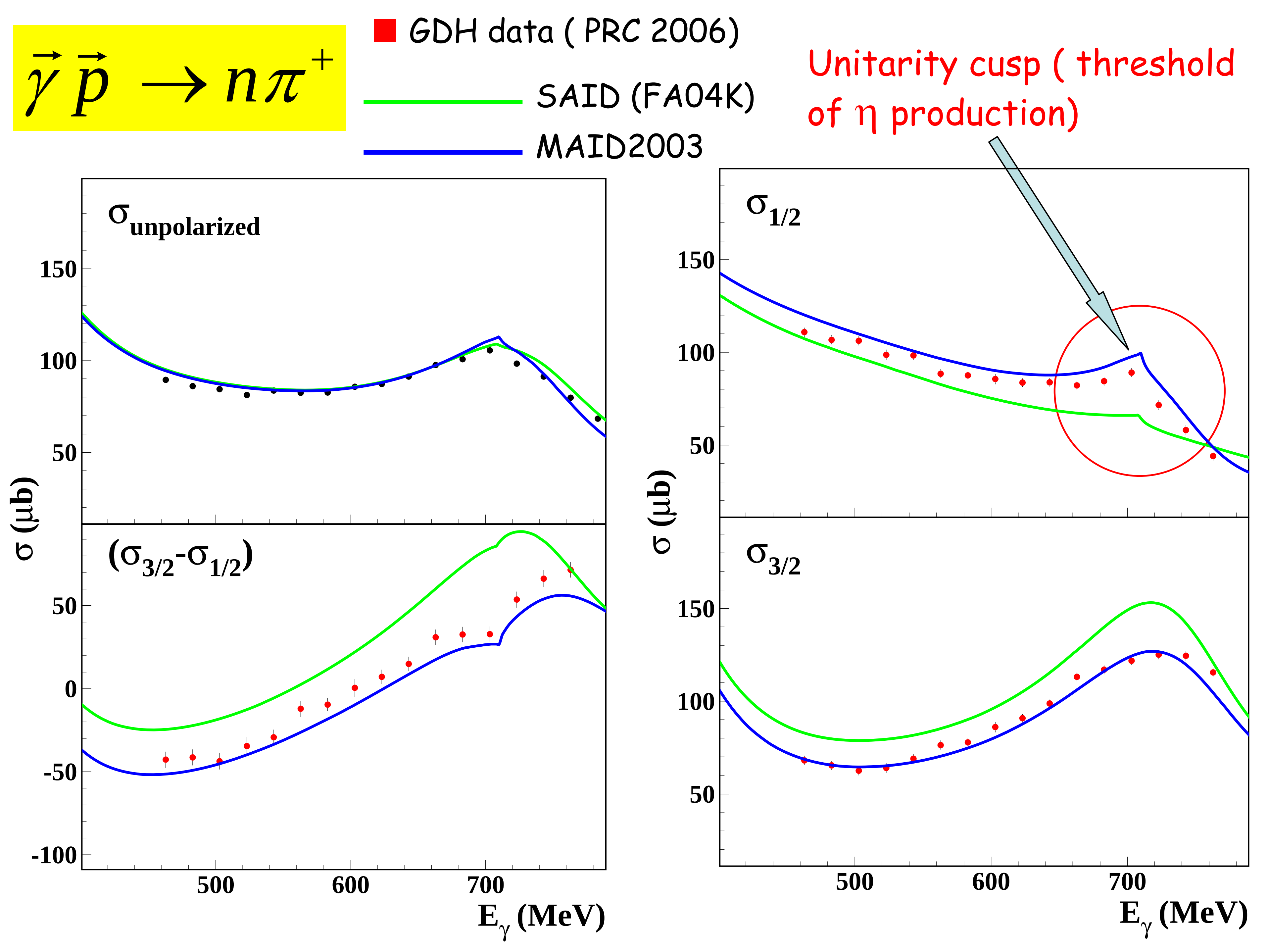
■ GDH data (submitted to PRL)

SAID (FA04K)

MAID2003

different contributions from E_{0+}, E_{2-} give now different model predictions





$\vec{\gamma}\,\vec{p} \rightarrow n\pi^+$
GDH data (PRC 2006)
SAID (FA04K)
MAID2003
Unitarity cusp (threshold of η production)
σunpolarized
(σ3/2-σ1/2)
σ1/2
σ3/2
σ (μb)
150
100
50
0
-50
-100
500
600
700
Eγ (MeV)

$\vec{\gamma}\,\vec{p} \rightarrow p\pi^0\pi^0$

GDH data

PLB 624, 173 (05)

■ $\sigma_{3/2}$

■ $\sigma_{1/2}$

- D_{13} plays a significant role
- **Which mechanisms do contribute to $\sigma_{1/2}$? (P_{11}, ...)**