Meson production dynamics and properties of excited nucleon states

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  - Current status of N^*'s
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  - Jülich hadron-exchange model: ingredients & main features
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  - $\pi N \to \eta N$, ΛK, ΣK cross sections & polarizations
  - $\gamma N \to \pi N$ cross sections, single & double polarizations
  - Resonances extracted
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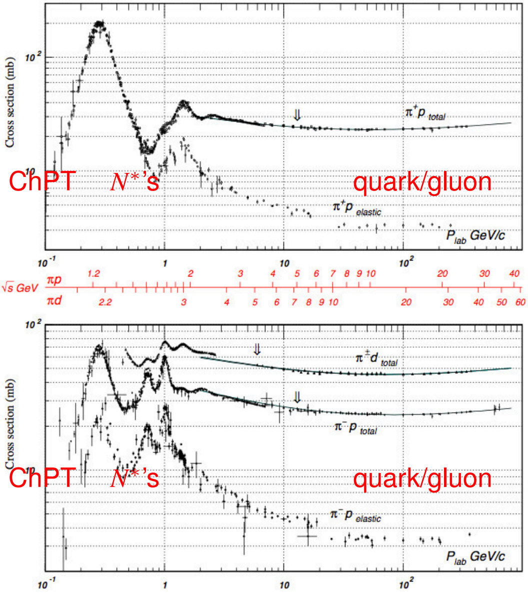
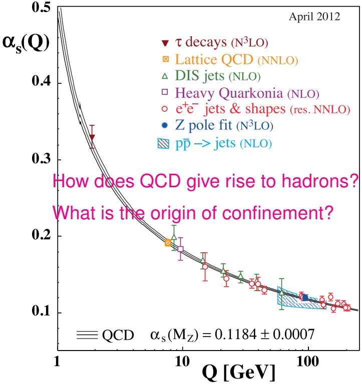
Why N^*'s





How does QCD give rise to hadrons?

What is the origin of confinement?

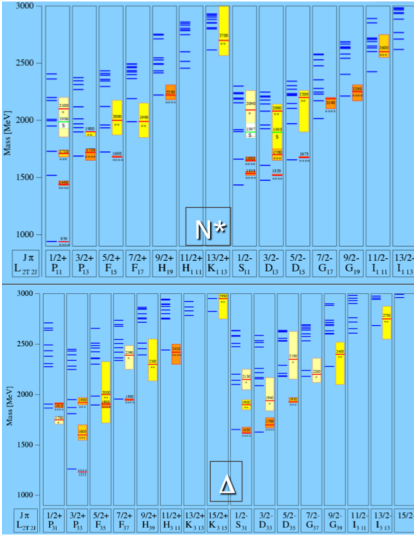
Explaining the excitation spectrum of nucleons is central to our understanding of non-perturbative QCD.

Why N^*'s

N. Isgur, NSTAR 2000, Newport News, 2000, USA:

- Nucleons are the stuff of which our world is made. As such they must be at the center of any discussion of why the world we actually experience has the character it does.
- Nucleons are the simplest system in which the quintessentially nonabelian character of QCD is manifest. There are, after all, N_c quarks in a proton because there are N_c colors.
- While relatively simple, baryons are sufficiently complex to reveal physics hidden from us in the mesons. One famous example: Gell-Mann and Zweig were forced to the quarks by $3 \times 3 \times 3$ giving the octet and decuplet, while mesons admitted of many possible solutions.

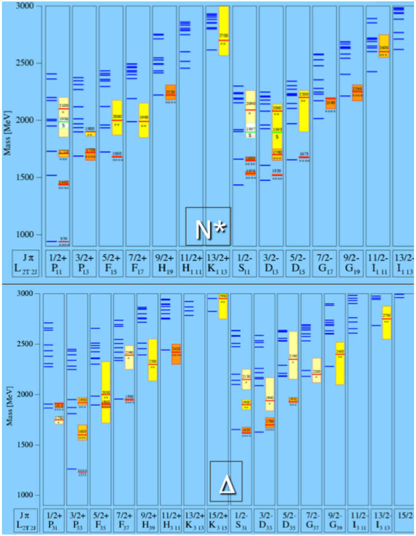
"I am convinced that completing this chapter in the history of science will be one of the most interesting and fruitful areas of physics for at least the next thirty years."



S. Capstick & N. Isgur, Phys. Rev. D 34 (1986) 2809.

"Missing resonances" problem

Current status of N^*'s



S. Capstick & N. Isgur, Phys. Rev. D 34 (1986) 2809.

"Missing resonances" problem

Particle J^P		overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*								
$N(1880)$	$1/2^+$	**	*								
$N(1895)$	$1/2^-$	**	*								
$N(1900)$	$3/2^+$	***	*								
$N(1990)$	$7/2^+$	**	*								
$N(2000)$	$5/2^+$	**	*								
$N(2040)$	$3/2^+$	*									
$N(2060)$	$5/2^-$	**	*								
$N(2100)$	$1/2^+$	*									
$N(2150)$	$3/2^-$	**	*								
$N(2190)$	$7/2^-$	****	*								
$N(2220)$	$9/2^+$	****	*								
$N(2250)$	$9/2^-$	****	*								
$N(2600)$	$11/2^-$	***	*								
$N(2700)$	$13/2^+$	**	*								

PDG 2012

Particle J^P		overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	o					*	***
$\Delta(1620)$	$1/2^-$	****	****	***	r					***	***
$\Delta(1700)$	$3/2^-$	****	****	****	b					**	***
$\Delta(1750)$	$1/2^+$	*	*		i						
$\Delta(1900)$	$1/2^-$	**	**	**	d				**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****	d				***	**	**
$\Delta(1910)$	$1/2^+$	****	****	**	e				*	*	**
$\Delta(1920)$	$3/2^+$	***	***	**	n				***		**
$\Delta(1930)$	$5/2^-$	***	***								
$\Delta(1940)$	$3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**			r						**
$\Delta(2150)$	$1/2^-$	*	*		b						
$\Delta(2200)$	$7/2^-$	*	*		i						
$\Delta(2300)$	$9/2^+$	**	**		d						
$\Delta(2350)$	$5/2^-$	*	*		d						
$\Delta(2390)$	$7/2^+$	*	*		e						
$\Delta(2400)$	$9/2^-$	**	**		n						
$\Delta(2420)$	$11/2^+$	****	****	*							
$\Delta(2750)$	$13/2^-$	**	**								
$\Delta(2950)$	$15/2^+$	**	**								

4-star	17
3-star	8
2-star	15
1-star	8

Problems in N^* study

- Where are the missing resonances?
- Do 1-star & 2-star resonances exist?
- How many resonances in total?
- Resonance structures?
- Resonance parameters?
- ......

Volker Credé:

N^*'s: only the tip of the iceberg has been discovered?

Experimental efforts

- JLab
- ELSA
- MAMI
- GRALL
- BES
- COSY
- Spring-8
- LEGS
- BATES
- ...

Status of meson photoproduction @ JLab

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton target																
$p\pi^0$	✔	✓	✓	✓ (grey)	✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓	✓ (grey)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	✓ (grey)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	✓ (grey)	✓	✓	✓	✓								
$p\omega$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓	✓	✓ (grey)	✓	✓	✓	✓								
"Neutron" target																
$p\pi^-$	✔	✓	✓		✓	✓	✓	✓								
$p\rho^-$	✓	✓	✓		✓	✓	✓	✓								
$K^+\Sigma^-$	✔	✓	✓		✓	✓	✓	✓								
$K^0\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

✔ - published ✓ - acquired

Courtesy of E. Pasyuk, MESON 2012, Poland

Methodology for theoretical studies

Theory: N^*'s unstable & couple strongly to baryon-meson states

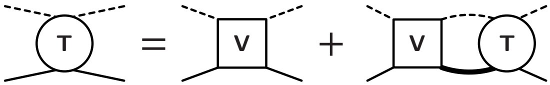
$$\Downarrow$$

Build coupled-channels meson-baryon reaction models:

- meson production data analysis
- understand the reaction mechanisms
- extract N^* parameters
- understand N^* structures and dynamical origins

Most widely used models (hadron level): K matrix approximation, chiral unitary approach, dynamical coupled-channels model, et al.

Theoretical approaches



T = V + V G$_0$ T

T: amplitude

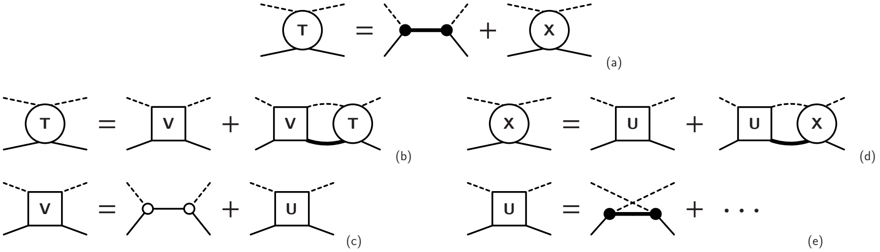
V: pseudo-potential

G$_0$: free propagator

Sum over all channels and partial waves, and **integrate** over intermediate momenta.

- K matrix approximation $G_0 = \frac{1}{E - H_0 + i\epsilon} = \frac{\mathcal{P}}{E - H_0} - i\pi\delta(E - H_0) \approx -i\pi\delta(E - H_0)$
    - Principle-value part of the loop integral neglected $\Rightarrow$ off-shell intermediate states omitted $\Rightarrow$ integral equation reduced to algebraic equation
    - Unitarity satisfied, analyticity violated
- Chiral unitary approach $V \propto C\,\bar{u}(p')\gamma^\mu u(p)(k_\mu + k'_\mu) \approx C\,(k_0 + k'_0)$
    - V: contact interaction, momentum-dependent terms neglected $\Rightarrow$ S-wave
    - Resonances are dynamically generated
- Dynamical coupled-channels model
    - On-shell & off-shell effects considered
    - Resonance dynamical generation allowed
    - Unitarity & analyticity respected
    - Examples: Jülich model, ANL-Osaka model

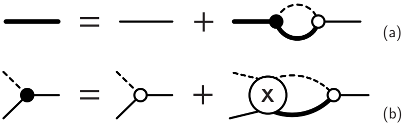
Jülich hadron-exchange model ingredients



(a) $T = |F\rangle\, S\, \langle F| + X$
(b) $T = V + V\, G_0\, T$
(c) $V = |f\rangle\, S_0\, \langle f| + U$
(d) $X = U + U\, G_0\, X$

T: full amplitude
X: non-pole amplitude
U: driving term of X
V: driving term of T

S: dressed res. propagator
S_0: bare res. propagator
$|F\rangle$: dressed res. vertex
$|f\rangle$: bare res. vertex



(a) $S = S_0 + S\, \underbrace{\langle F|\, G_0\, |f\rangle}_{\text{“self energy" } \Sigma}\, S_0$

(b) $|F\rangle = |f\rangle + X\, G_0\, |f\rangle$

Main features of Jülich hadron-exchange model

- Two-body unitarity guaranteed by scattering equation
- Analyticity (no on-shell factorization); resonance dynamical generation allowed
- Channels & partial waves correlated through t- & u-channel interactions $\Rightarrow$ dynamical generation not easy; no need to model background with resonances
- Effective interaction based on chiral Lagrangians of Wess & Zumino, supplemented by additional terms for including Δ, ω, η, a_0, σ
- **GAUGE INVARIANCE**

Generalized Ward-Takahashi Identity (GWTI) for π production current

$$k_\mu M^\mu = -\left|F_s\tau\right\rangle S_{p+k} Q_i S_p^{-1} + S_{p'}^{-1} Q_f S_{p'-k} \left|F_u\tau\right\rangle + \Delta_{p-p'+k}^{-1} Q_\pi \Delta_{p-p'} \left|F_t\tau\right\rangle$$

$\Downarrow$ on shell

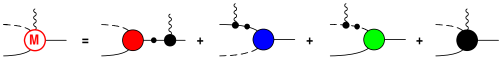
Current conservation

$$k_\mu M^\mu = 0$$

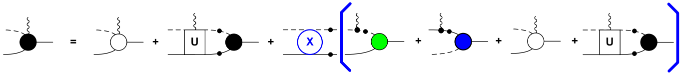
Current conservation necessary but not sufficient!

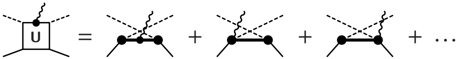
The vast majority of existing models does not satisfy gauge invariance!

Prescription for gauge invariance



$$M^\mu = M_s^\mu + M_u^\mu + M_t^\mu + M_{\text{int}}^\mu$$





$$M_{\text{int}}^\mu = M_c^\mu + X\, G_0 \left(M_u^\mu + M_t^\mu + M_c^\mu \right)_{\mathsf{T}}$$

$$M_c^\mu = \Gamma_{NN\pi}(q)\, C^\mu + M_{KR}^\mu f_t$$

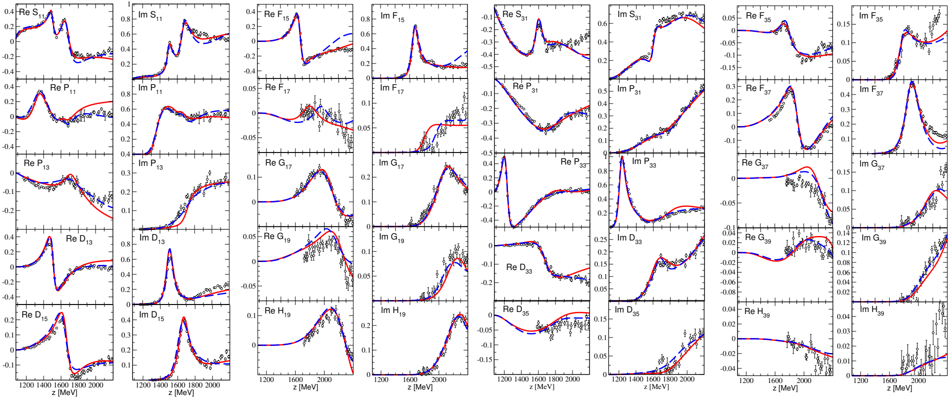
$$C^\mu = e_\pi \frac{(2q-k)^\mu}{t-q^2}\left(f_t - \hat{F}\right) + e_f \frac{(2p'-k)^\mu}{u-p'^2}\left(f_u - \hat{F}\right) + e_i \frac{(2p+k)^\mu}{s-p^2}\left(f_s - \hat{F}\right)$$

$$\hat{F} = 1 - \hat{h}\left(1-\delta_s f_s\right)\left(1-\delta_u f_u\right)\left(1-\delta_t f_t\right)$$

Recent progress: $\pi N \to \pi N$, ηN, ΛK, ΣK & $\gamma N \to \pi N$

- Channel space: $\gamma N \oplus \pi N \oplus \eta N \oplus \pi\Delta \oplus \rho N \oplus \sigma N \oplus K\Lambda \oplus K\Sigma$
- Resonances considered: $J = 1/2,\ 3/2,\ 5/2,\ 7/2,\ 9/2$
- Reactions and observables investigated:
  - $\pi N \to \pi N$: partial wave amplitudes up to $J = 9/2$
  - $\pi^- p \to \eta n,\ K^0\Lambda,\ K^0\Sigma^0,\ K^+\Sigma^-$: $d\sigma/d\Omega$, P, σ (up to $\sim$ 2.4 GeV)
  - $\pi^+ p \to K^+\Sigma^+$: $d\sigma/d\Omega$, P, σ (up to $\sim$ 2.4 GeV)
  - $\gamma p \to \pi^0 p,\ \pi^+ n$: $d\sigma/d\Omega$, Σ, σ (up to $\sim$ 1.65 GeV)
  - $\gamma n \to \pi^- p,\ \pi^0 n$: $d\sigma/d\Omega$, Σ, σ (up to $\sim$ 1.65 GeV)
  - $\gamma p \to \pi^0 p,\ \pi^+ n$: $d\sigma/d\Omega$, Σ, T, P, G, H, E, $C_{x'_L}$, $C_{z'_L}$
    (phenomenological parametrization of photo-coupling vertices, up to $\sim$ 2.4 GeV)
- Quantities extracted for N^*'s: pole positions, residues, photo-couplings

$\pi N \to \pi N$ partial wave amplitudes



S_{11}: 1535, 1650
P_{11}: 1440, 1710, 1750
P_{13}: 1720
D_{13}: 1520
D_{15}: 1675

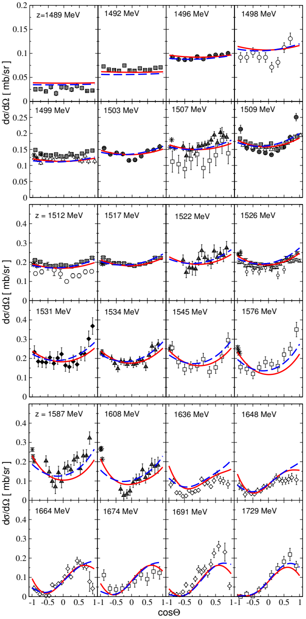
F_{15}: 1680
F_{17}: 1990
G_{17}: 2190
G_{19}:
H_{19}:

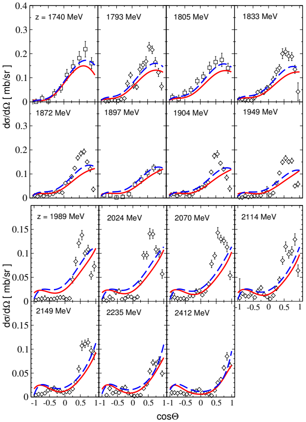
S_{31}: 1620
P_{31}: 1910
P_{33}: 1232, 1600
D_{33}: 1700
D_{35}:

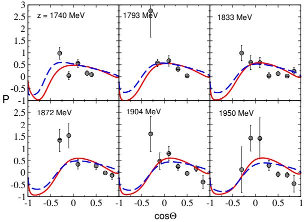
F_{35}: 1905
F_{37}: 1950
G_{37}: 2200
G_{39}:
H_{39}:

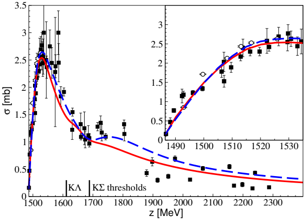
****	***	**	*	no star

$\mathrm{d}\sigma/\mathrm{d}\Omega$, P & σ for $\pi^- p \to \eta n$





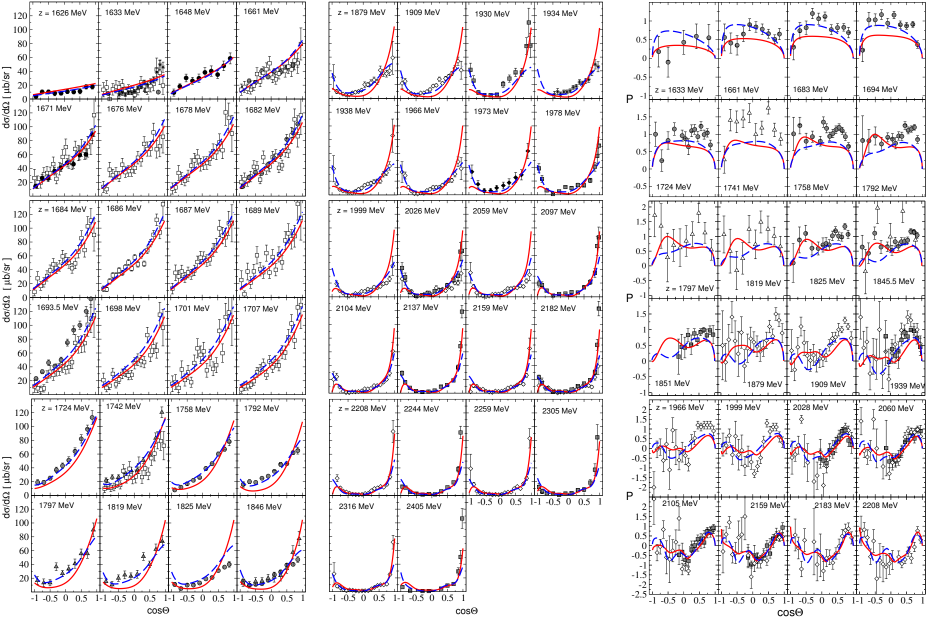




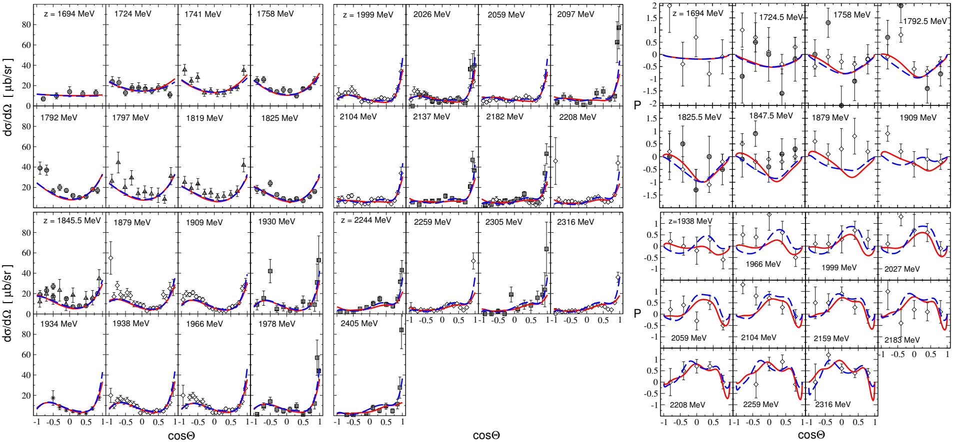
⇓

Data highly problematic (mis-calibration of beam momentum) & not included in the fit.

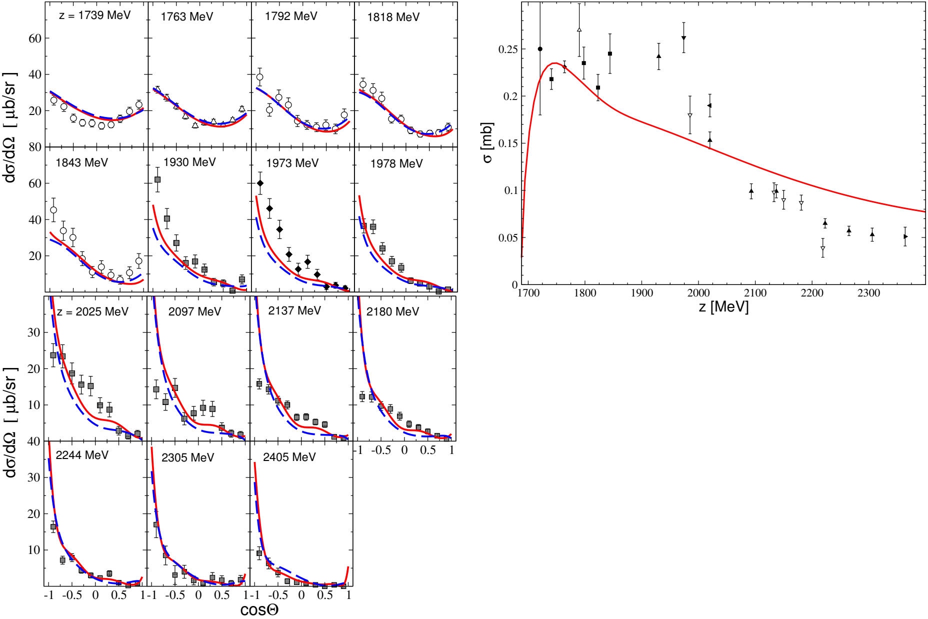
$d\sigma/d\Omega$ & P for $\pi^- p \to K^0\Lambda$



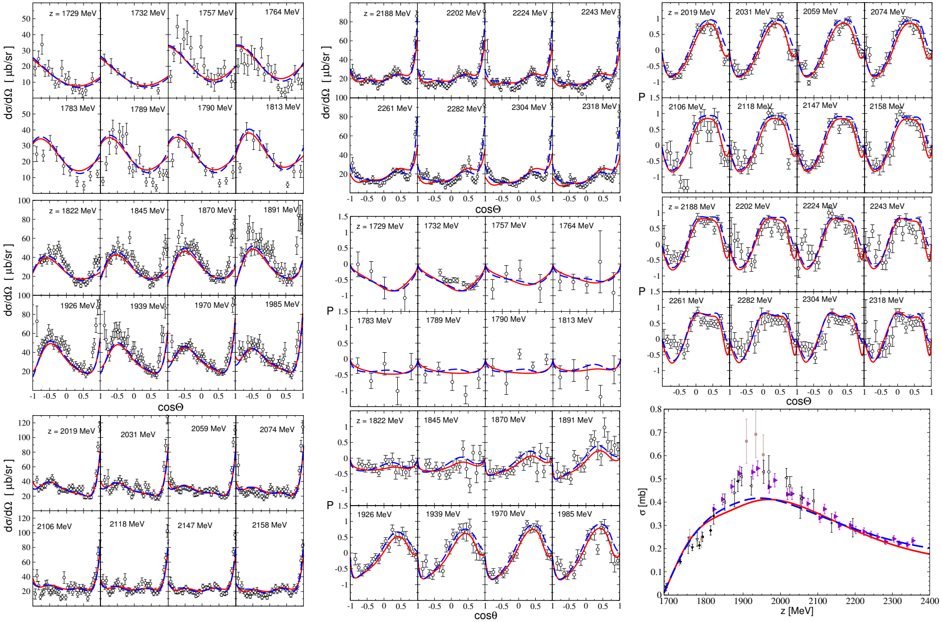
$d\sigma/d\Omega$ & P for $\pi^- p \to K^0 \Sigma^0$



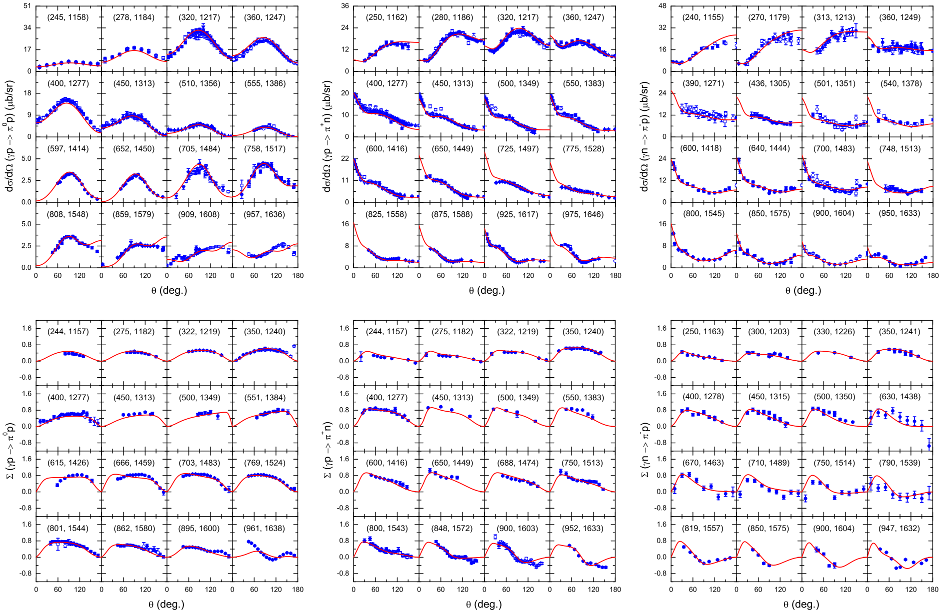
$d\sigma/d\Omega$ & σ for $\pi^- p \to K^+\Sigma^-$



$d\sigma/d\Omega$, P & σ for $\pi^+ p \to K^+\Sigma^+$

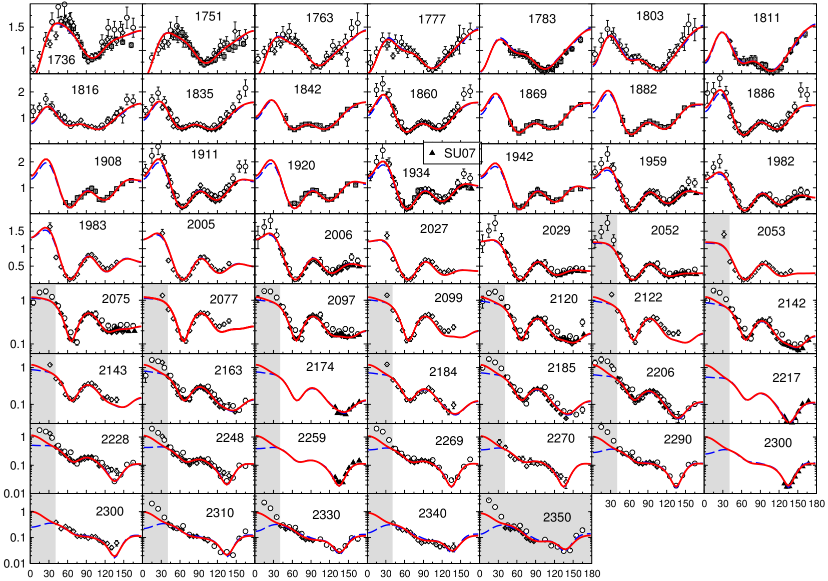


$d\sigma/d\Omega$ & Σ_γ for $\gamma p \to \pi^0 p$, $\gamma p \to \pi^+ n$ & $\gamma n \to \pi^- p$



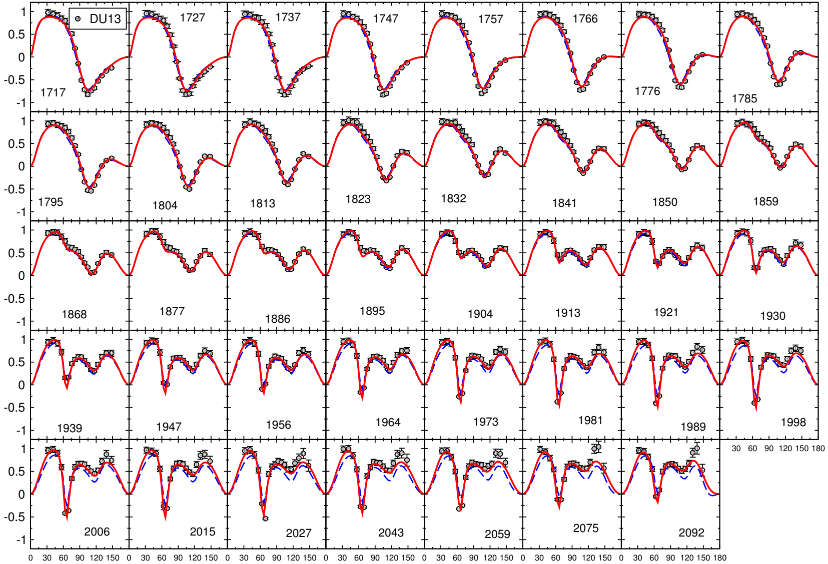
Selected results for $\gamma p \to \pi^0 p$ (phenomenological parametrization of Γ_γ)

$d\sigma/d\Omega$ [μb/sr] as a function of θ [deg]



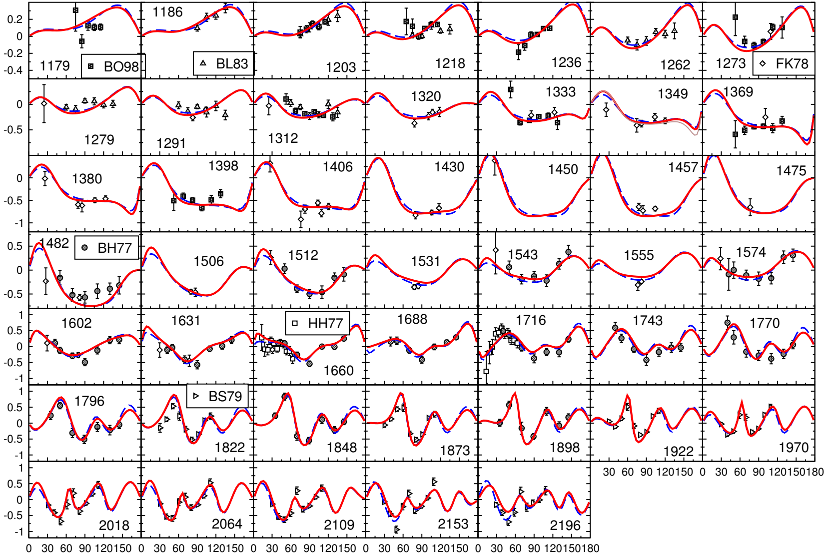
Selected results for $\gamma p \to \pi^0 p$ (phenomenological parametrization of Γ_γ)

Σ as a function of θ [deg]



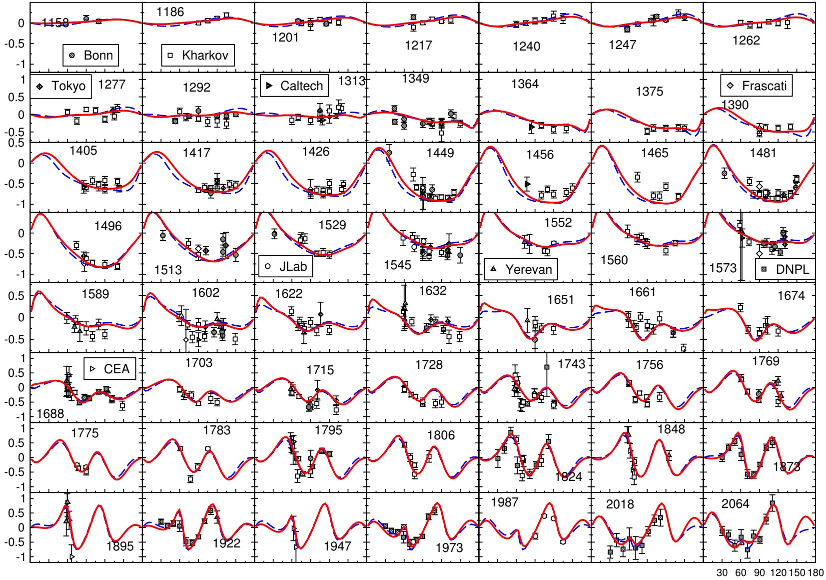
Selected results for $\gamma p \to \pi^0 p$ (phenomenological parametrization of Γ_γ)

T as a function of θ [deg]



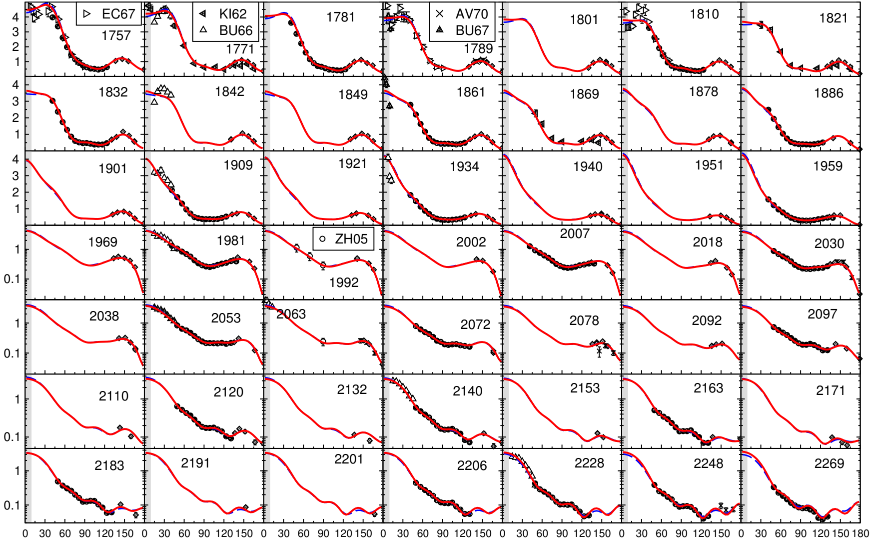
Selected results for $\gamma p \to \pi^0 p$ (phenomenological parametrization of Γ_γ)

P as a function of θ [deg]



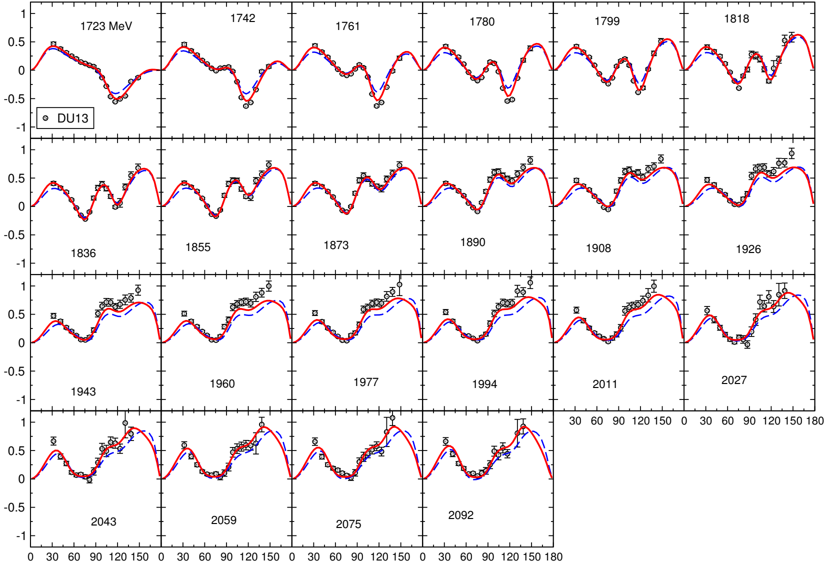
Selected results for $\gamma p \to \pi^+ n$ (phenomenological parametrization of Γ_γ)

$d\sigma/d\Omega$ [μb/sr] as a function of θ [deg]



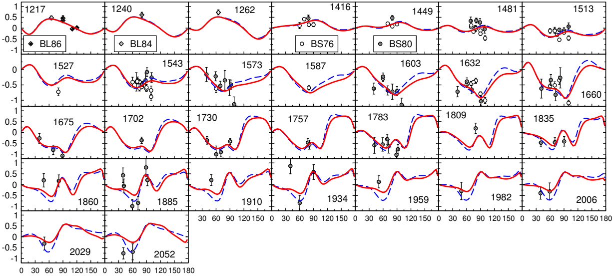
Selected results for $\gamma p \to \pi^+ n$ (phenomenological parametrization of Γ_γ)

Σ as a function of θ [deg]

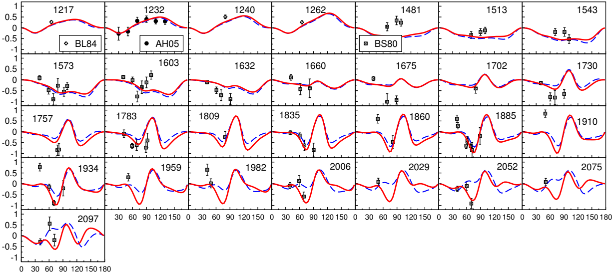


Selected results for $\gamma p \to \pi^+ n$ (phenomenological parametrization of Γ_γ)

H as a function of θ [deg]



G as a function of θ [deg]



Resonances and their structures

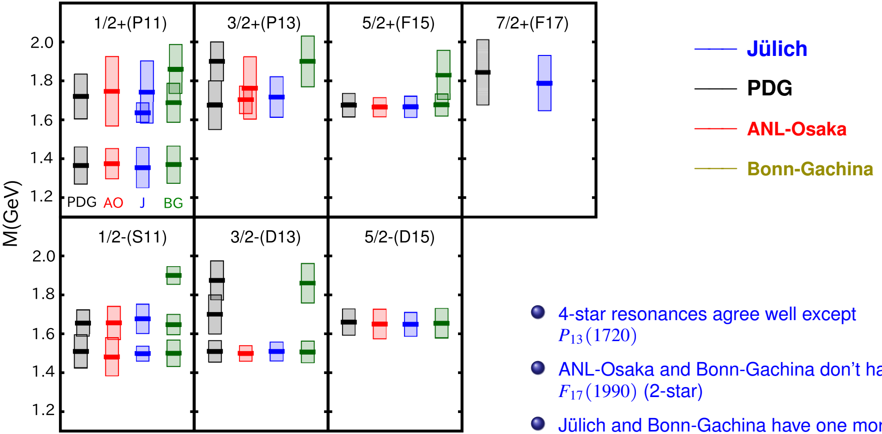
Resonances found:

- 4-star resonances: 14 (17 in PDG):
  $P_{33}(1232)$, $\underline{P_{11}(1440)}$, $D_{13}(1520)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $\overline{D_{33}(1700)}$, $P_{13}(1720)$, $F_{35}(1905)$, $P_{31}(1910)$, $F_{37}(1950)$, $G_{17}(2190)$
- 3-star resonances: 2 (8 in PDG):
  $P_{11}(1710)$, $\underline{P_{33}(1600)}$
- 2-star resonances: 1 (15 in PDG):
  $F_{17}(1990)$
- 1-star resonance: 1 (8 in PDG):
  $G_{37}(2200)$
- resonance not listed in PDG:
  $\underline{P_{11}(1750)}$

Resonance structures:

- $P_{11}(1440)$, $P_{33}(1600)$, $P_{11}(1750)$: dynamically generated
- Others: genuine resonances

Pole positions ($I = 1/2$)



Courtesy of T. Sato, Nstar 2013, Spain

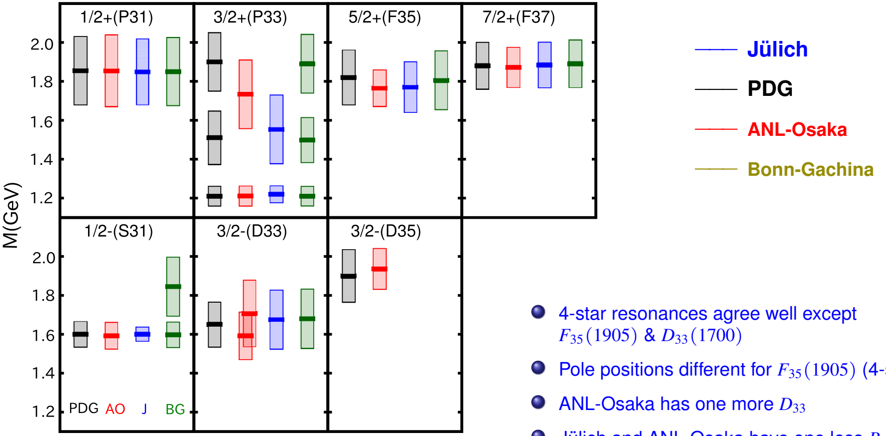
4-star resonances compared:

$P_{11}(1440)$, $P_{13}(1720)$, $F_{15}(1680)$

$S_{11}(1535)$, $S_{11}(1650)$, $D_{13}(1520)$, $D_{15}(1675)$

- 4-star resonances agree well except $P_{13}(1720)$
- ANL-Osaka and Bonn-Gachina don't have $F_{17}(1990)$ (2-star)
- Jülich and Bonn-Gachina have one more P_{11} and one less P_{13}
- Bonn-Gachina has one more F_{15} and one more S_{11}
- Bonn-Gachina and PGD have more D_{13}'s

Pole positions ($I = 3/2$)



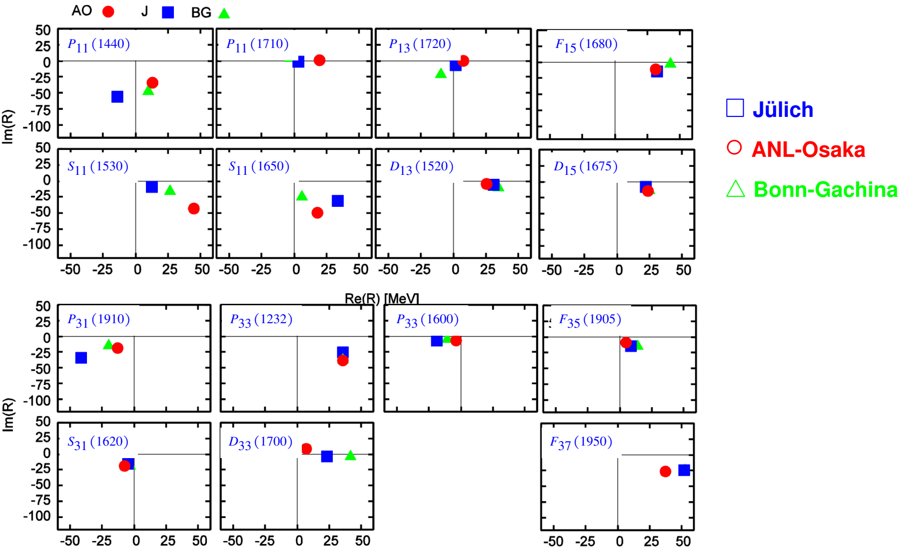
Courtesy of T. Sato, Nstar 2013, Spain

4-star resonances compared:

$P_{31}(1910)$, $P_{33}(1232)$, $F_{35}(1905)$, $F_{37}(1950)$
$S_{31}(1620)$, $D_{33}(1700)$

- 4-star resonances agree well except $F_{35}(1905)$ & $D_{33}(1700)$
- Pole positions different for $F_{35}(1905)$ (4-star)
- ANL-Osaka has one more D_{33}
- Jülich and ANL-Osaka have one less P_{33}
- Bonn-Gachina has one more S_{31}
- Jülich and Bonn-Gachina don't have D_{35}

Residues of πN amplitudes at pole positions

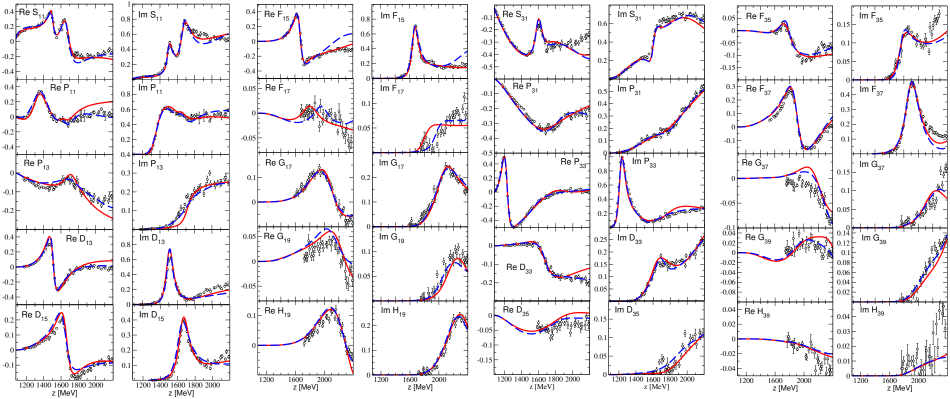


Courtesy of T. Sato, Nstar 2013, Spain

Summary & perspectives

- Channel space: $\pi N \oplus \eta N \oplus \pi\Delta \oplus \rho N \oplus \sigma N \oplus K\Lambda \oplus K\Sigma \oplus \gamma N$
- Unitarity; Analiticity; Gauge invariance
- Channels & partial waves correlated
- Recent progress: $\pi N \to \pi N$, ηN, ΛK, ΣK & $\gamma N \to \pi N$
  - $\pi N \to \pi N$ partial wave amplitudes ($J = 1/2,\ 3/2,\ 5/2,\ 7/2,\ 9/2$)
  - $\pi N \to \eta N,\ \Lambda K,\ \Sigma K$ cross sections & polarizations
  - $\gamma N \to \pi N$ cross sections, single & double polarizations
- Resonances extracted
  - 4-star resonances (14/17): $G_{19}(2250)$, $H_{19}(2220)$, $H_{311}(2420)$ not found
  - 3-star resonances (2/8): $P_{11}(1710)$, $P_{33}(1600)$
  - 2-star resonances (1/15): $F_{17}(1990)$
  - 1-star resonance (1/8): $G_{37}(2200)$
  - resonance not listed in PDG: $P_{11}(1750)$
  - Pole positions & residues extracted
- Next step work
  - $\pi N \to \omega N, \pi\pi N$
  - $\gamma N \to \eta N, K\Lambda, K\Sigma, \omega N, \pi\pi N$
  - $eN \to e\pi N$

πN amplitudes: comparison with GWU/SAID



S_{11}: 1535, 1650

P_{11}: 1440, ~~1710~~, ~~1750~~

P_{13}: 1720

D_{13}: 1520

D_{15}: 1675

F_{15}: 1680 **+ 1860**

F_{17}: ~~1990~~

G_{17}: 2190

G_{19}:

H_{19}:

S_{31}: 1620

P_{31}: 1910

P_{33}: 1232, 1600

D_{33}: 1700

D_{35}:

F_{35}: 1905

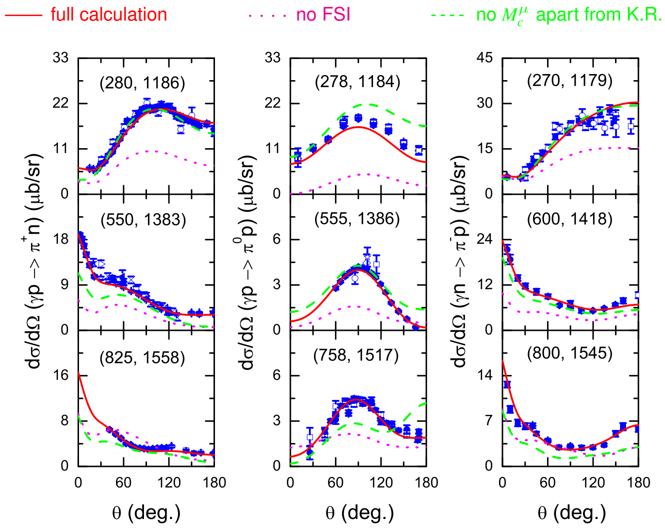
F_{37}: 1950

G_{37}: ~~2200~~

G_{39}:

H_{39}:

Relevance of FSI & gauge invariance

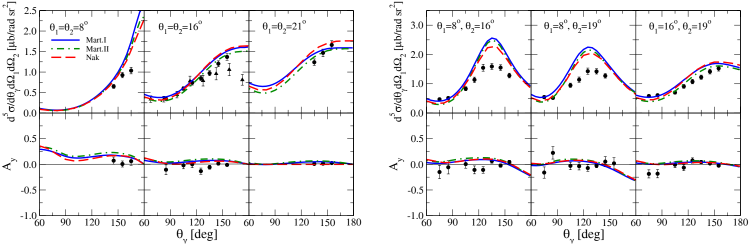


The effects of both FSI & gauge invariance are important!

Relevance of gauge invariance in $p\,p \to p\,p\,\gamma$

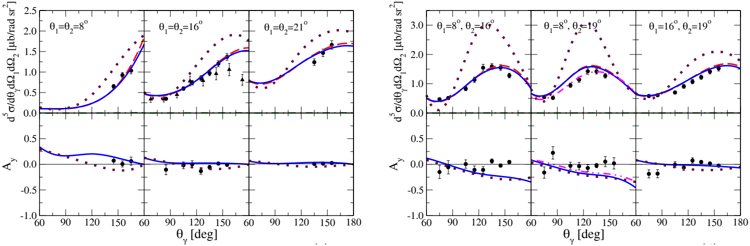
None of the existing models can describe high-precision KVI data for coplanar geometries involving small p scattering angles.

Lines: Martinus, Scholten, Tjon, PRC 58, 686 (1998); PRC 56, 2945 (1997); Herrmann, Nakayama, Scholten, Arellano, NPA 582, 568 (1995)



Construct the contact current $\to$ full amplitude obeys WTI

(gauge invariant) [K. Nakayama & H. Haberzettl, PRC 80, 051001 (2009)]



It is important to properly take into account the interaction current for NN bremsstrahlung reaction!

Covariance & 3-D integral equation

- Jülich πN model — TOPT

$$T_{\rm TO}(\mathbf{p}',\mathbf{p};\sqrt{s}) \;=\; V_{\rm TO}(\mathbf{p}',\mathbf{p};\sqrt{s}) \;+\; \int d^3p''\, V_{\rm TO}(\mathbf{p}',\mathbf{p}'';\sqrt{s})\, G_{\rm TO}(\mathbf{p}'',\sqrt{s}) T_{\rm TO}(\mathbf{p}'',\mathbf{p};\sqrt{s})$$

$$G_{\rm TO}(\mathbf{p}'',\sqrt{s}) \;=\; \frac{1}{\sqrt{s}-E(\mathbf{p}'')-\omega(\mathbf{p}'')+i0}$$

- Converting to a covariant 3-D reduction like equation

$$V(\mathbf{p}',\mathbf{p};\sqrt{s}) \;\equiv\; (2\pi)^3\sqrt{2E(\mathbf{p}')\,2\omega(\mathbf{p}')}\sqrt{2E(\mathbf{p})\,2\omega(\mathbf{p})}\; V_{\rm TO}(\mathbf{p}',\mathbf{p};\sqrt{s})$$

$$T(\mathbf{p}',\mathbf{p};\sqrt{s}) \;\equiv\; (2\pi)^3\sqrt{2E(\mathbf{p}')\,2\omega(\mathbf{p}')}\sqrt{2E(\mathbf{p})\,2\omega(\mathbf{p})}\; T_{\rm TO}(\mathbf{p}',\mathbf{p};\sqrt{s})$$

$$T(\mathbf{p}',\mathbf{p};\sqrt{s}) \;=\; V(\mathbf{p}',\mathbf{p};\sqrt{s}) \;+\; \int \frac{d^3p''}{(2\pi)^3}\, V(\mathbf{p}',\mathbf{p}'';\sqrt{s})\, G_0(\mathbf{p}'',\sqrt{s})\, T(\mathbf{p}'',\mathbf{p};\sqrt{s})$$

$$G_0(\mathbf{p}'',\sqrt{s}) \;\equiv\; \frac{1}{2E(\mathbf{p}'')\,2\omega(\mathbf{p}'')}\;\frac{1}{\sqrt{s}-E(\mathbf{p}'')-\omega(\mathbf{p}'')+i0}$$

- Similarly, make 3-D reduction of the covariant photoproduction equation