Experimental Challenges for the Study of Light Baryons

Takashi NAKANO

(RCNP, Osaka University)

- Introduction [1)]
- Photoproduction Experiments [1)]
- Reaction Dynamics and Resonance [2)]
- π beam experiment at J-PARC
- Summary

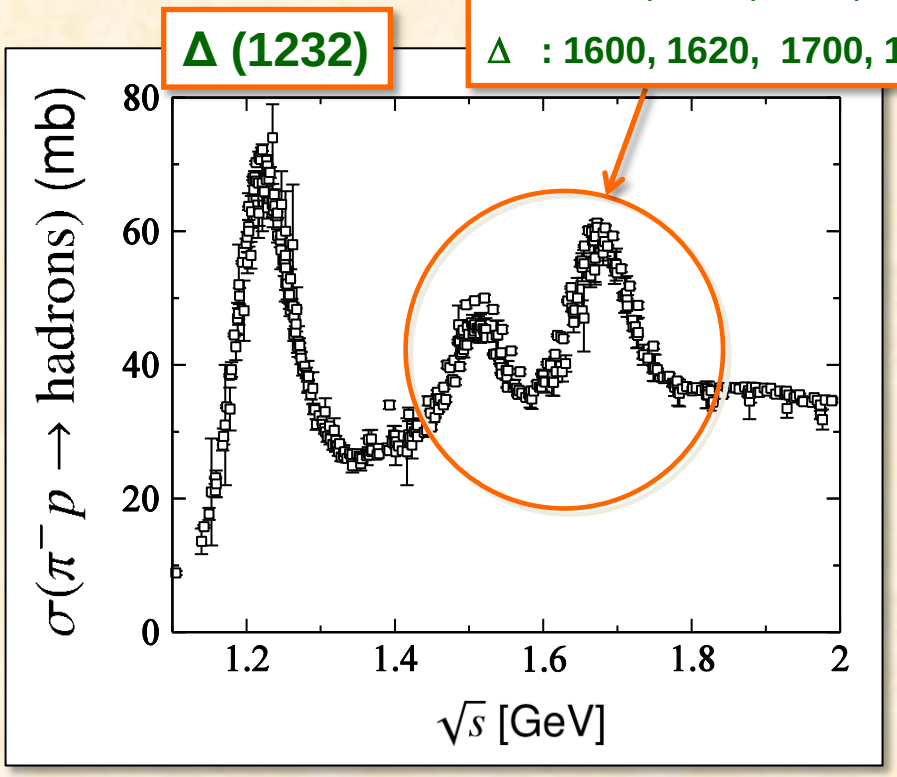
1) presented with permission courtesy of U. Thoma (Bonn)
2) presented with permission courtesy of H. Kamano (Osaka)

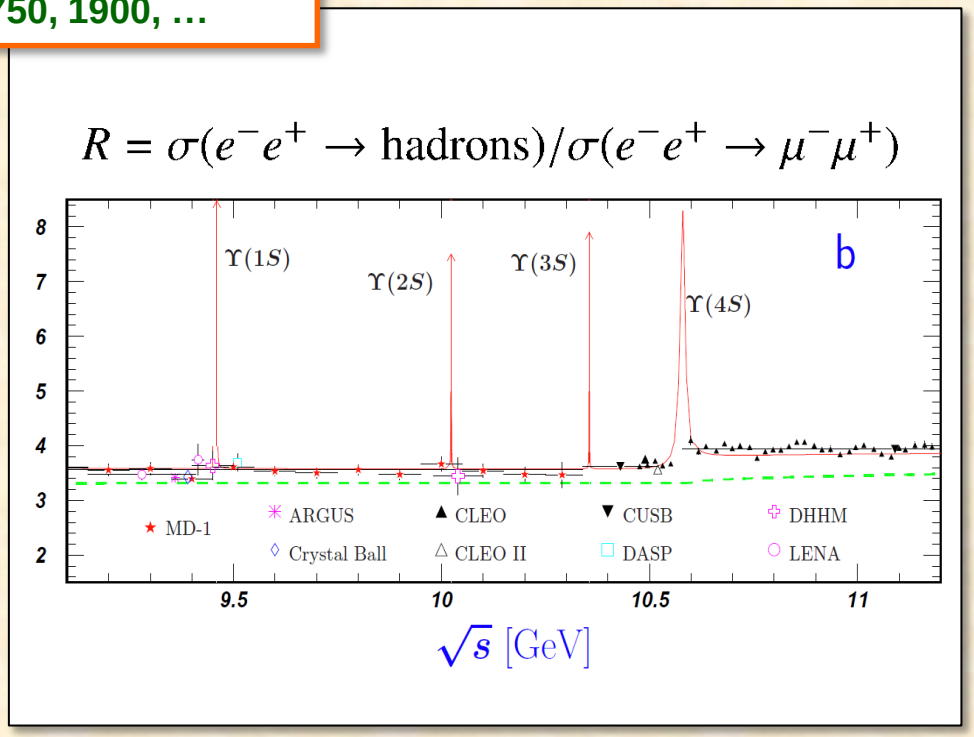
Resonance in QCD@GSI, October 13th, 2015.

N* spectroscopy :
Physics of broad & overlapping resonances

N* : 1440, 1520, 1535, 1650, 1675, 1680, ...

Δ : 1600, 1620, 1700, 1750, 1900, …





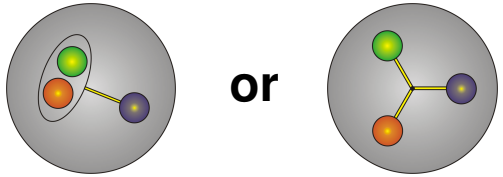
- ✓ Width: a few hundred MeV.
- ✓ Resonances are highly overlapped in energy except Δ(1232).

- ✓ Width: ~10 keV to ~10 MeV
- ✓ Each resonance peak is clearly separated.

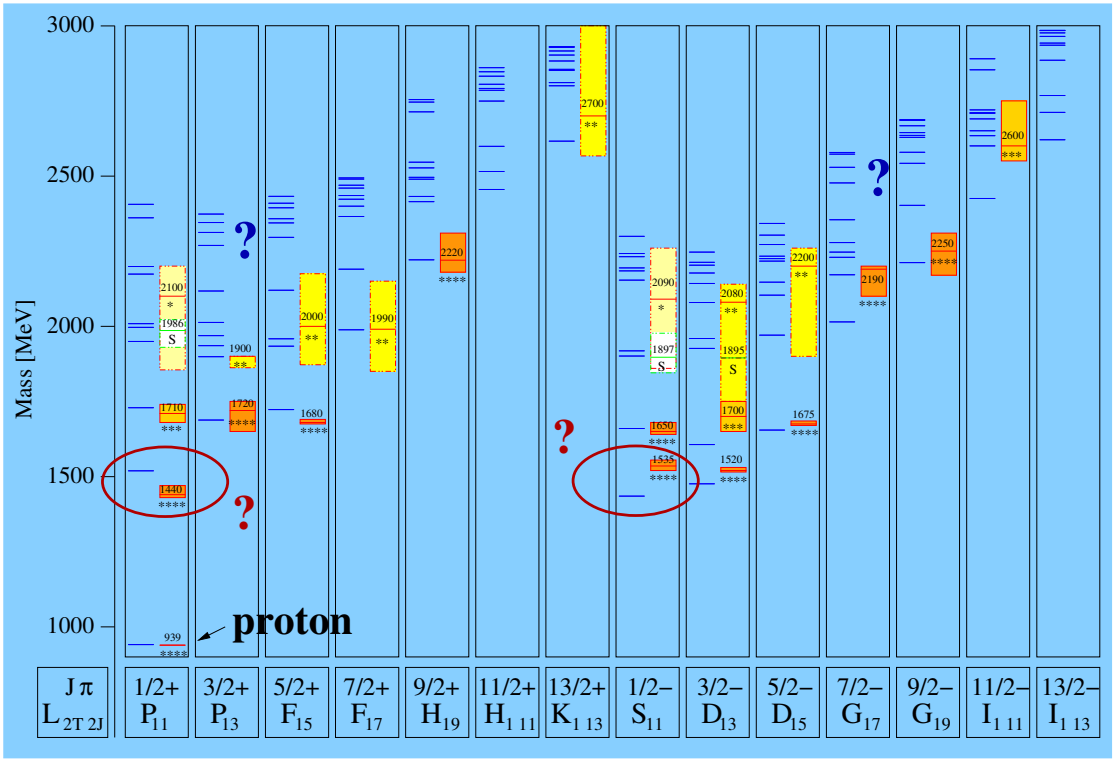
Baryon Spectroscopy

Aim: Good understanding of the spectrum and the properties of baryon resonances $\leftrightarrow$ bound states of QCD

- What are the relevant degrees of freedom ?
- Effective forces between them ?

e.g.:  **or** **?**

Symmetric quark models:
$\rightarrow$ many more resonances expected than observed yet



U. Loering, B. Metsch, H. Petry et al.

relativistic quark model

Constituent quarks, confinement potential
+ residual interaction

non-strange N*-resonances

$\leftrightarrow$ $\mathbf{J^P}$

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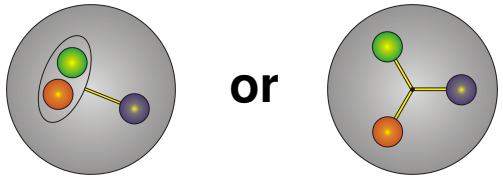
e.g.:  **or** **?**

Symmetric quark models:
$\rightarrow$ many more resonances expected than observed yet (certain configurations completely missing)

- **Certain configurations not realised by QCD ? Why ?**
- **Experimentally not found yet (resonances might decouple from πN)**

  $\leftrightarrow$ Big discovery potential of photoproduction experiments

Baryon Spectroscopy

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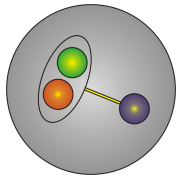
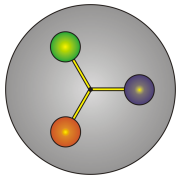
e.g.:  **or**  **?**

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- **Certain configurations not realised by QCD ? Why ?**
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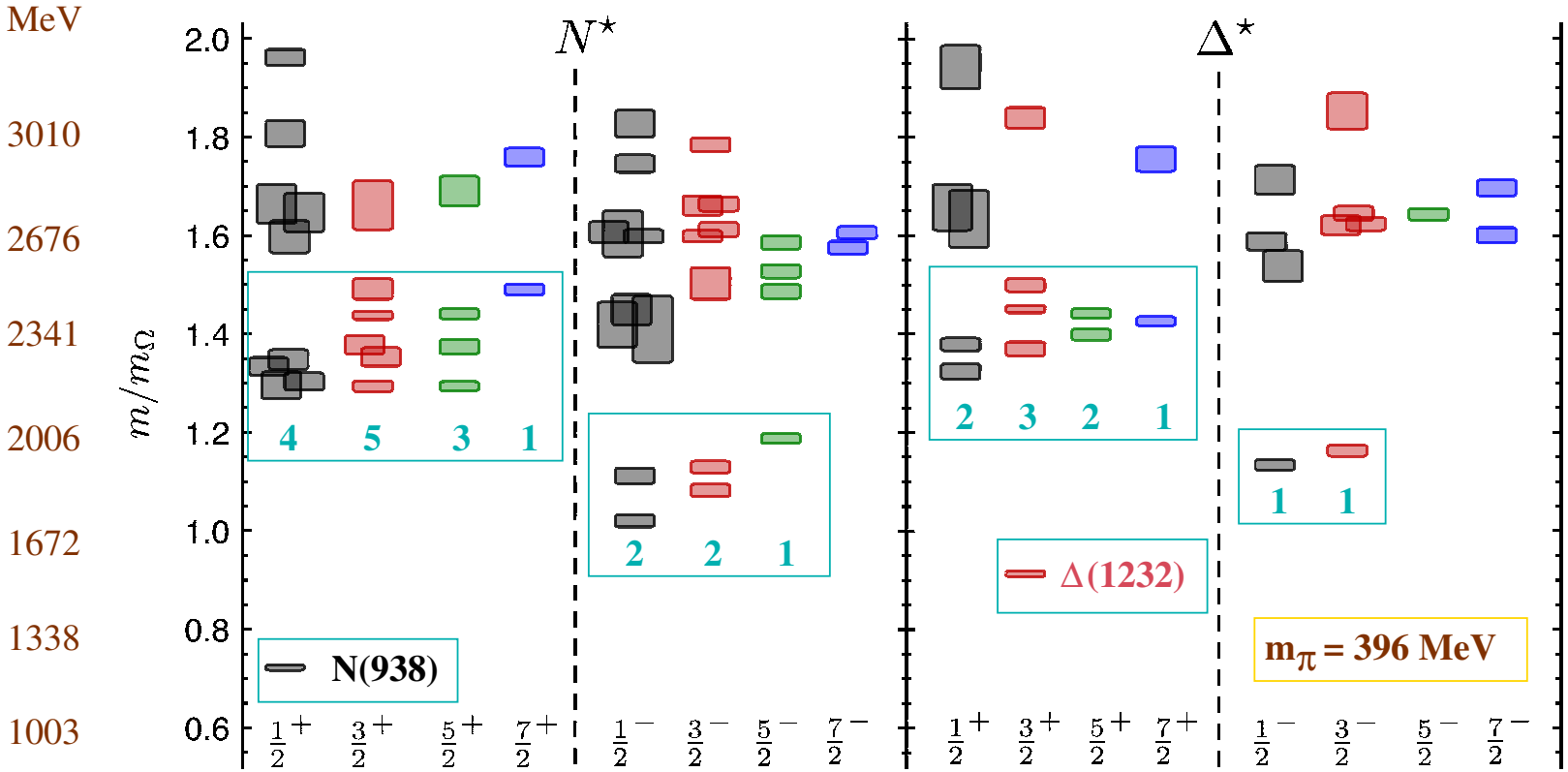
Or does the quark model just use the wrong degrees of freedom?

Baryon Spectroscopy

Excited baryons from Lattice QCD:



R.Edwards et al., Phys. Rev. D84 (2011) 074508

Exhibits the broad features expected from SU(6)⊗O(3)-symmetry

→ **Counting of levels consistent with non-rel. quark model**

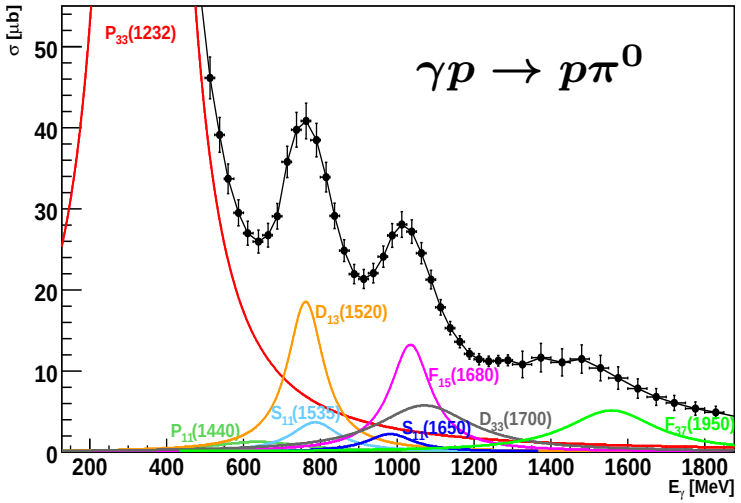
→ **no parity doubling**

Of course there are also approximations made by lattice QCD (e.g. m_π=396 MeV)

Baryon Spectroscopy

⇒ Good understanding of the spectrum and the properties (e.g. decays) of the resonances needed !

Experimentally:
Broad and strongly overlapping resonances

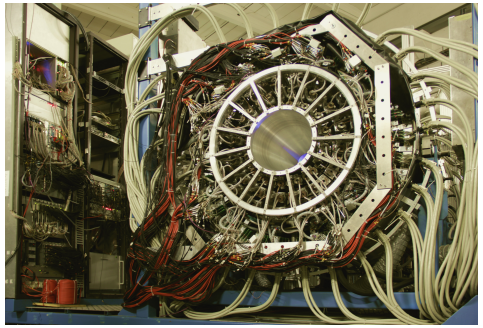


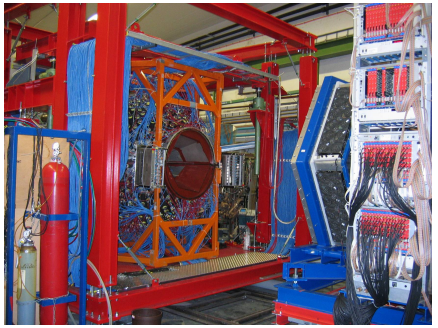
Important:
→ Investigation of different final states
→ Measurement of polarization observables (unambiguous PWA)

⇓

vigorous experimental program underway worldwide:

CLAS (JLab), CBELSA/TAPS (ELSA), CBALL (MAMI), LEPS (Spring-8), ...



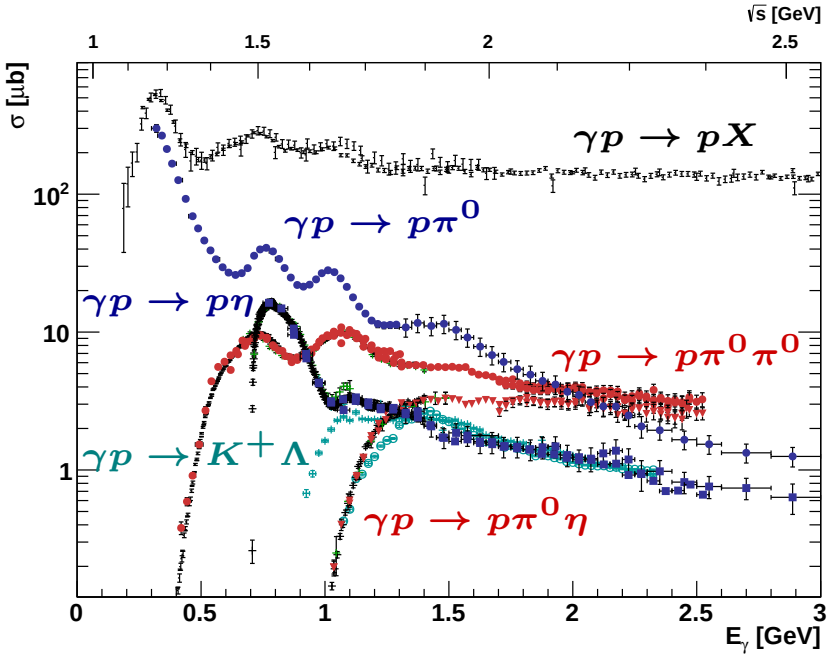


performing photoproduction experiments

⇔ polarized beam, polarized target

Baryon Spectroscopy

⇒ **Good understanding of the spectrum and the properties (e.g. decays) of the resonances needed !**



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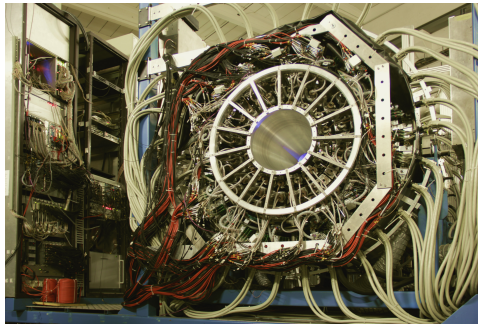
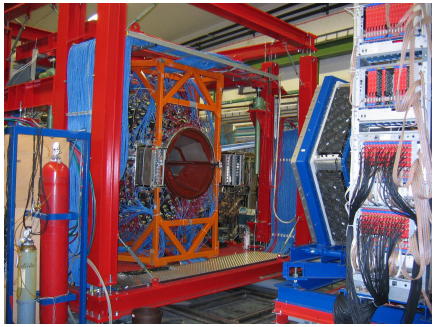




performing photoproduction experiments

⇔ **polarized beam, polarized target**

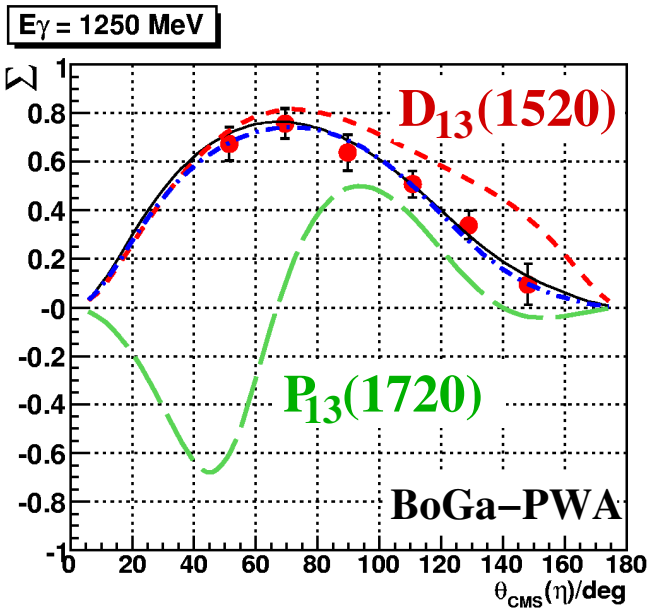
Polarization Observables - Why are they important ?

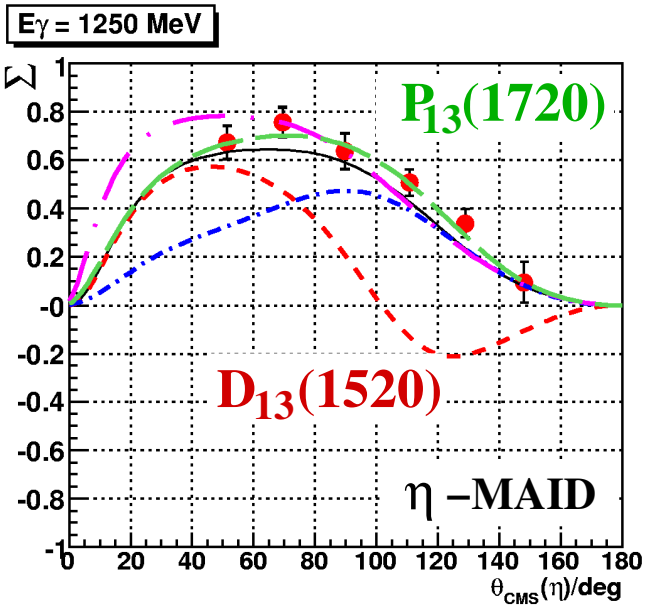
Example : $\gamma p \to pM$ (M: pseudoscalar meson):

8 well chosen observables need to be measured to determine the contributing amplitudes = basis for an unambigious PWA (Chiang & Tabakin, Phys. Rev. C55, 2054 (1997))

Problem otherwise: e.g. for $\gamma p \to p\eta$:

Two different PWA-solutions: both describing $d\sigma/d\Omega$ and Σ nicely, but:





CBELSA/TAPS collaboration:
D.Elsner et al.,EPJ. A33 (2), 147 (2007)

→ quite different resonance contributions ...

→ solution not unambiguous

⇒ **further polarisation observables needed !**

Double Polarization Experiments - Selected Results -

Circularly polarized photons, longitudinally polarized target

CBELSA/TAPS

$\gamma p \rightarrow p\pi^0$:

PWAs:

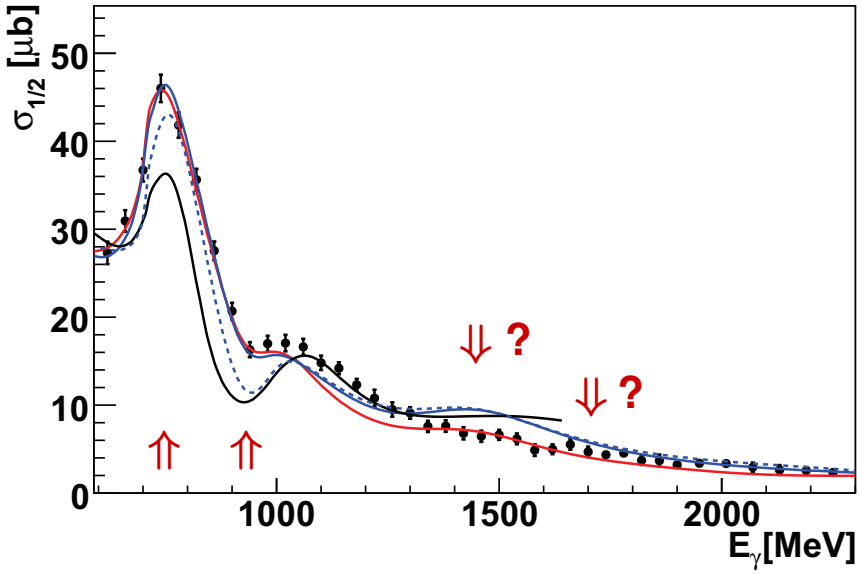
SAID (SN11, CM12), **MAID**

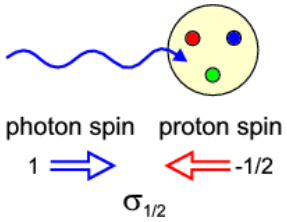
BnGa (2011_2)

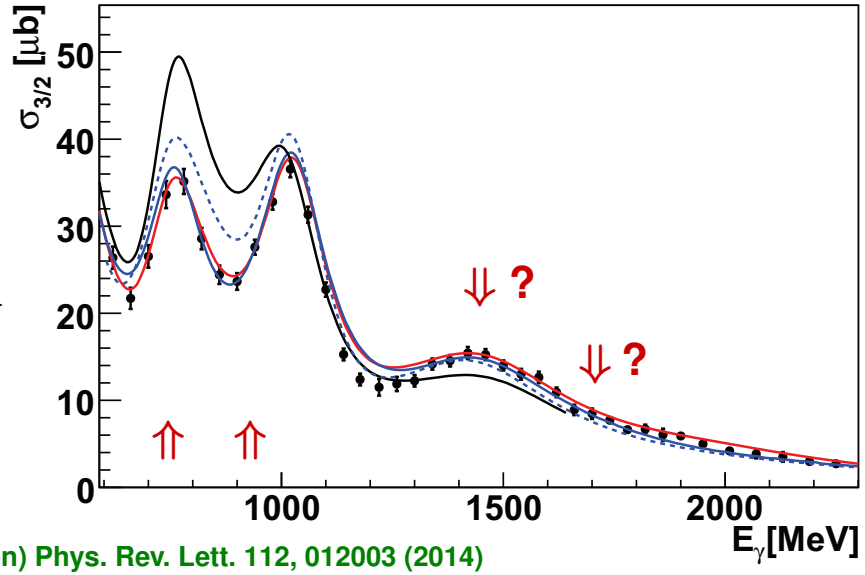
$\leftrightarrow$ **describe the so far existing photoproduction data, but ...**

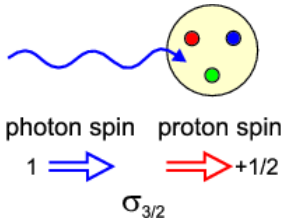
large deviations observed $\rightarrow$

Differences even at low energies where everything was thought to be well understood ... $\rightarrow$









$\Rightarrow$

Sensitivity on high mass resonances !

M. Gottschall et al. (CBELSA/TAPS-collaboration) Phys. Rev. Lett. 112, 012003 (2014)

Double Polarization Experiments - Selected Results -

Circularly polarized photons, longitudinally polarized target: **CBELSA/TAPS**

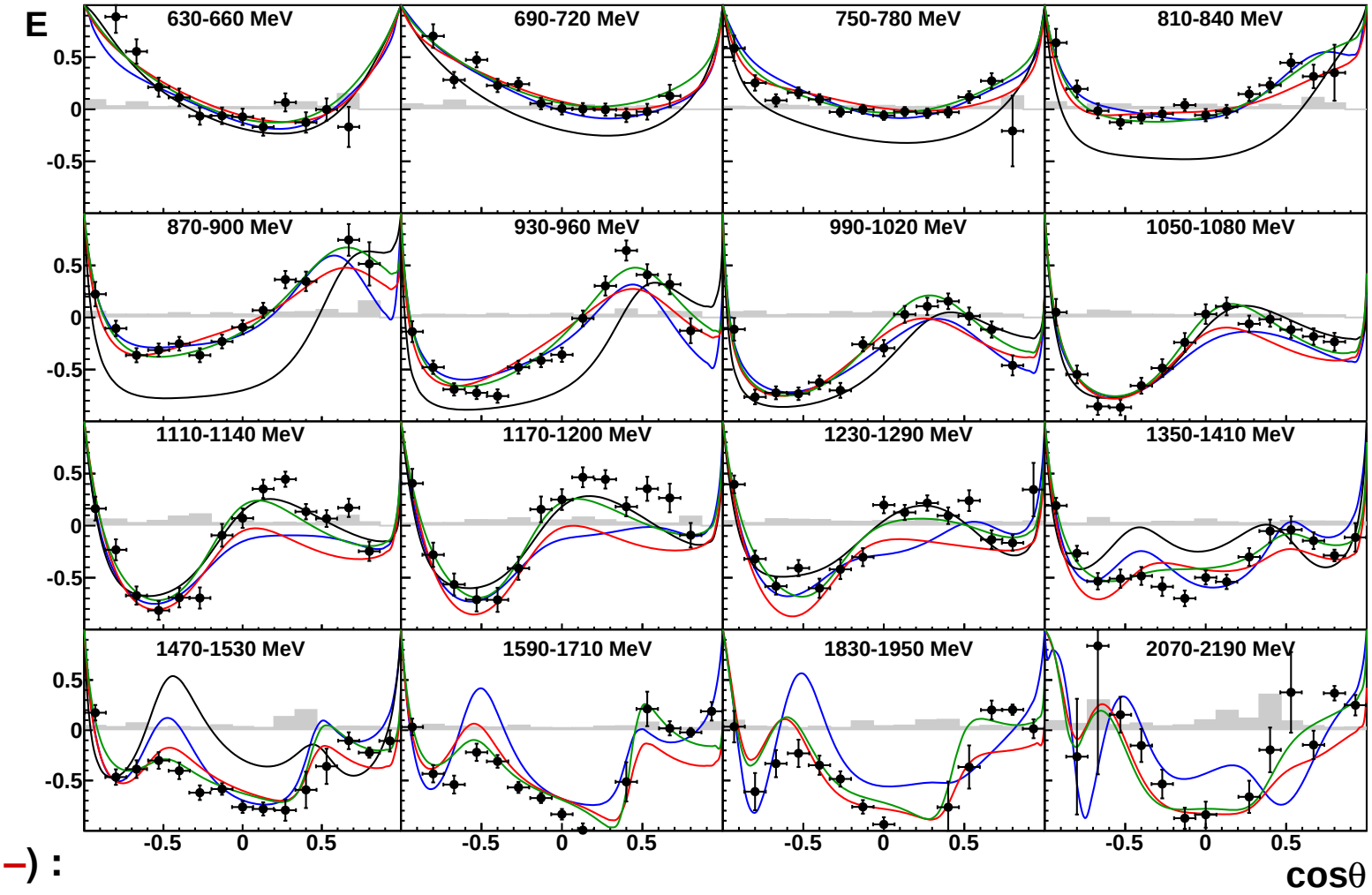
$\gamma p \rightarrow p\pi^0$:

(only every second bin shown)

$$\mathbf{E} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

PWAs predictions:
- **MAID,**
- **SAID** (CM12),
- **BnGa** (2011_2)

Fit:
- **BnGa**



Predictions (–, – , –) :

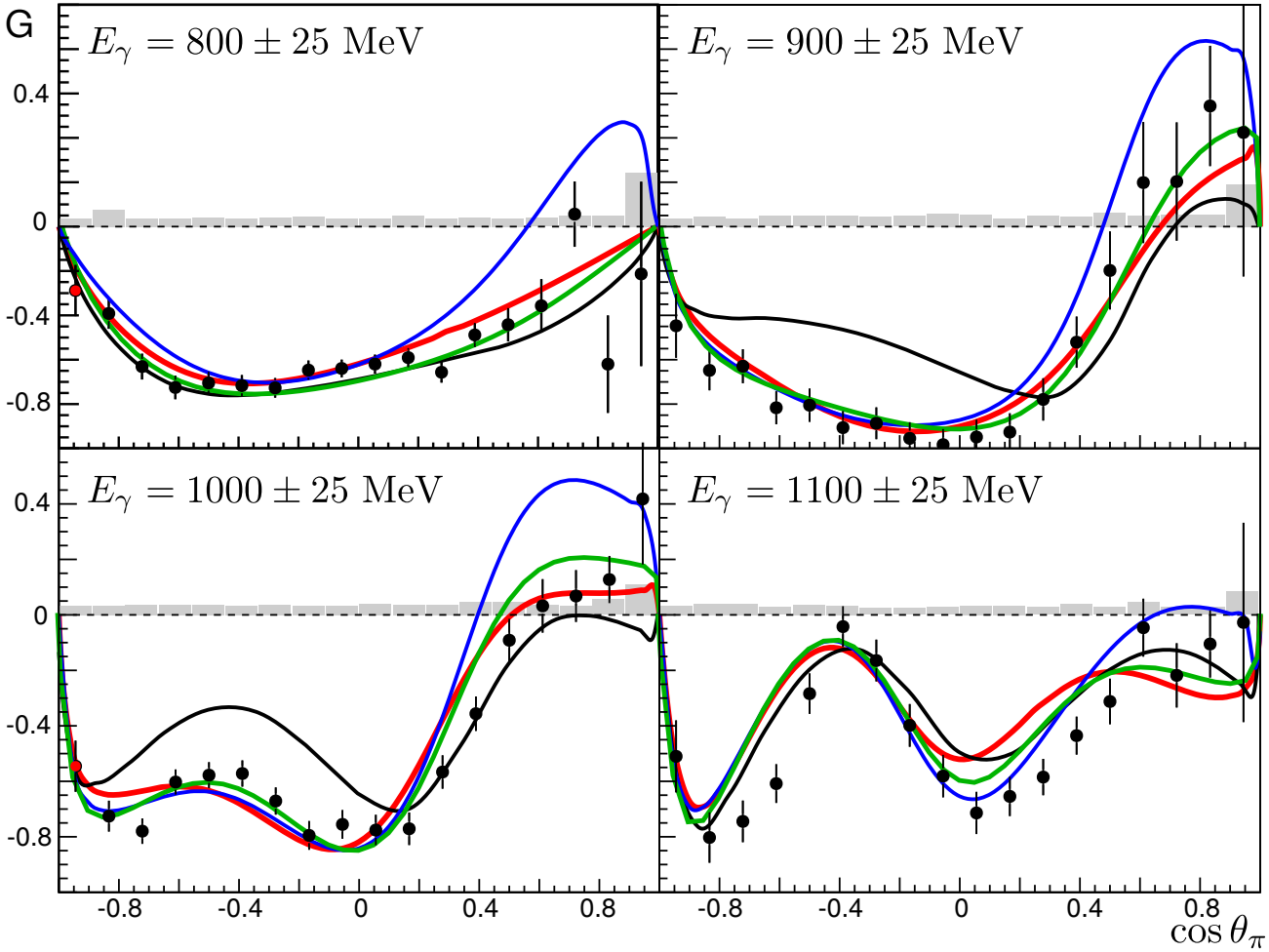
⇒ **Large deviations observed :**
High sensitivity of the data on the contributing amplitudes

M. Gottschall et al. (CBELSA/TAPS-collaboration) Phys. Rev. Lett. 112, 012003 (2014)

Double Polarization Experiments - Selected Results -

Linearly polarized photons, longitudinally polarized target: **CBELSA/TAPS**

$$\frac{d\sigma}{d\Omega}(\Phi) = \frac{d\sigma}{d\Omega_0} \cdot \left(1 - P_\gamma^{lin} \Sigma \cos(2\phi) + P_\gamma^{lin} P_z G \sin(2\phi)\right)$$



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

(only few bins shown)

already in the second resonance region: significant differences !

related to the E_{0+}, E_{2-} -multipoles

$\leftrightarrow 1/2^-, 3/2^-$

-partial waves

Further data on the polarisation observables T, P, H also available.

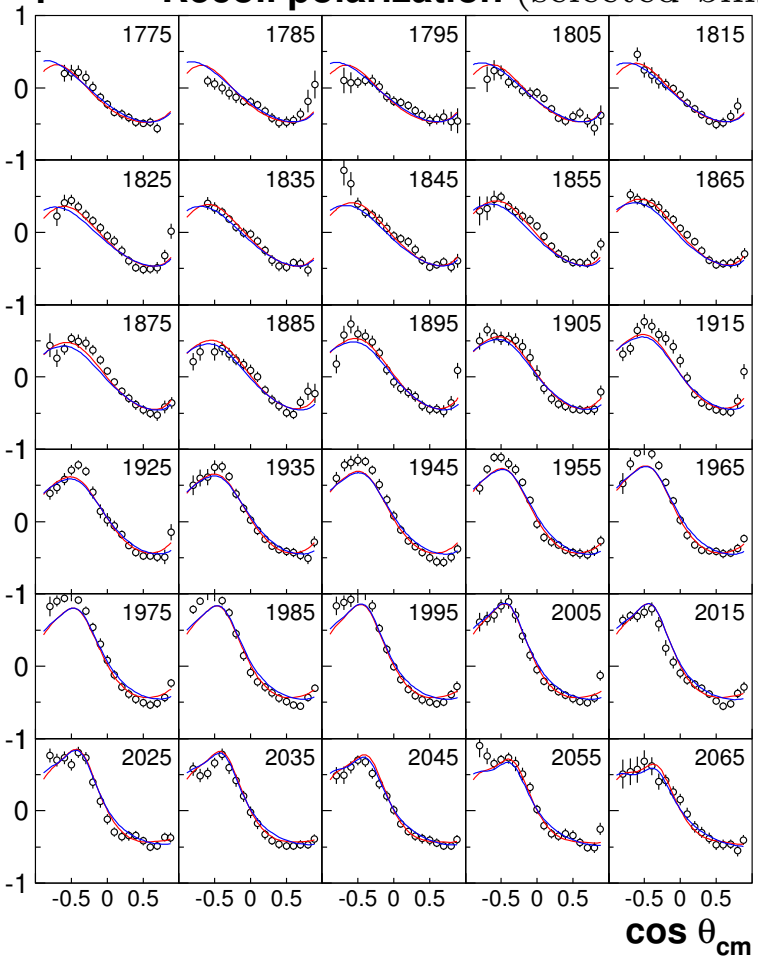
Predictions: – MAID – BnGa – SAID (CM12) **Fit: – BnGa**

A. Thiel et al. (CBELSA/TAPS)
Phys. Rev. Lett. 109, 102001 (2012)

Strangeness Photoproduction: $\gamma p \to K^+\Lambda \to K^+ p \pi^-$

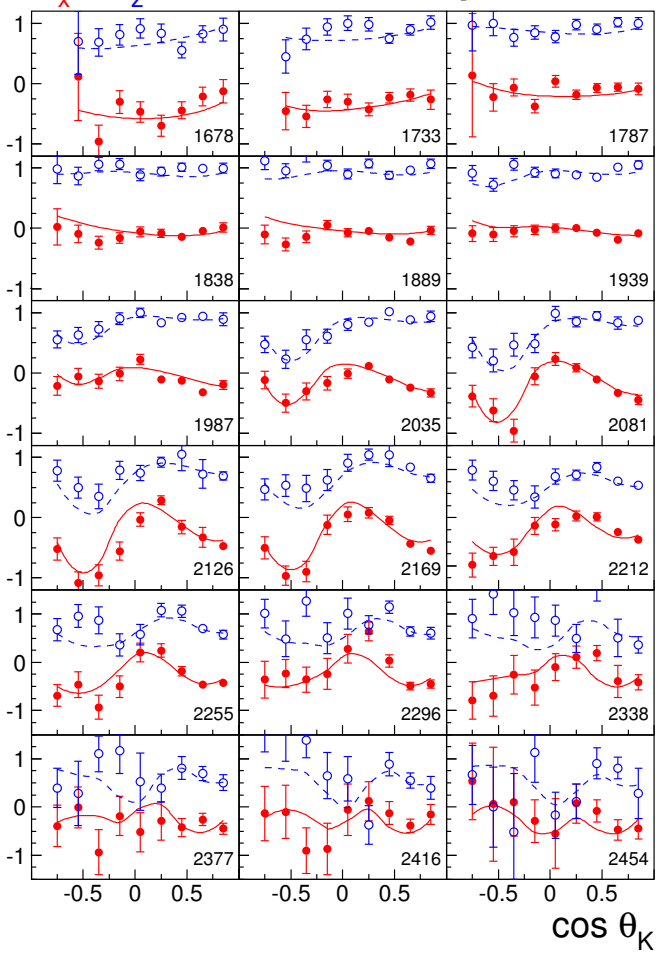
CLAS

P **Recoil polarization** (selected bins):



M. E. McCracken et al. (CLAS) PRC81, 025201 (2010)

C_x C_z **Beam-Recoil polarization:**



R. K. Bradford et al. (CLAS), PRC75, 035205 (2007)

data for all possible 16 observables has been taken

(only 8 needed for the complete experiment)

⇔ **much more to come!**

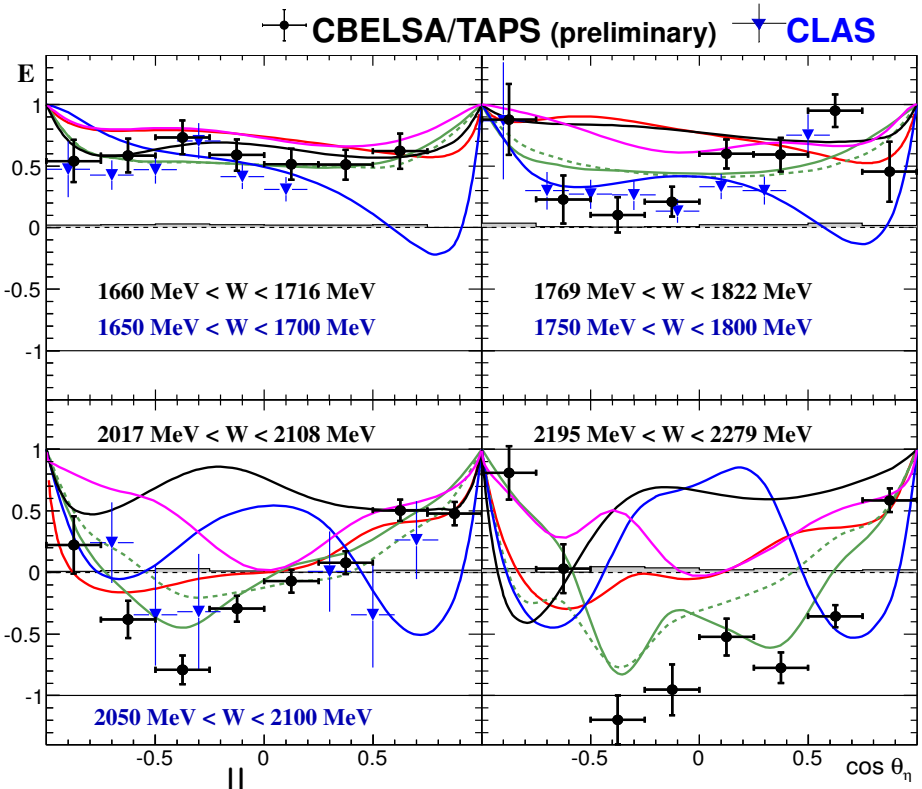
Fit within the Bonn-Gatchina multi-channel PWA: Favours the existence of the $P_{13}(1900)$

(confirmed by O. V. Maxwell, PRC85, 034611 (2012), T. Mart, M. Kholili, PRC86, 022201 (2012))

⇔ **Evidence against the quark-diquark model**

$\vec{\gamma}\vec{p} \to p\eta$ - Selected Polarization Observables -

circ. pol. photons, long. pol. target

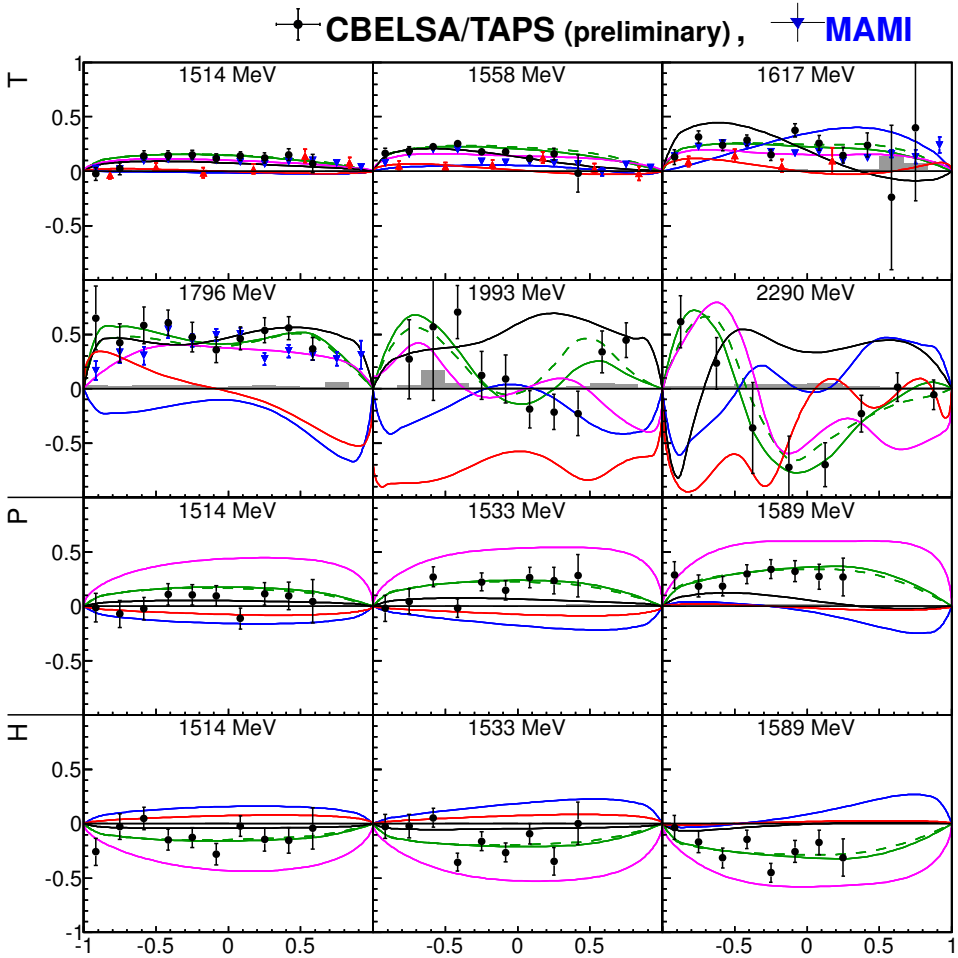


⇓

⇔ **Large sensitivity!** (also true for G (CBELSA/TAPS) and F (MAMI))

⇒ **approaching also the high mass region**

linear pol. photons, transv. pol. target



Predictions : — Maid , — Said , — BoJü, — BnGa

— new BnGa-fit : Determination of precise $p\eta$-branching ratios for resonances
indications for a new resonance (no PDG entry) at 2200 MeV

The Spectrum of Baryon Resonances

Multi-channel Bonn-Gatchina PWA, including data from ELSA, JLab, MAMI and other labs $\leftrightarrow$ **confirmation known resonances, search for new resonances**

	Particle Data Group 2010	our analyses	Particle Data Group 2012	GWU'06
N(1860)5/2$^+$		*	**	
N(1875)3/2$^-$		***	***	
N(1880)1/2$^+$		**	**	
N(1895)1/2$^-$		**	**	
N(1900)3/2$^+$	**	***	***	no evidence
N(2060)5/2$^-$		***	**	
N(2150)3/2$^-$		**	**	
Δ(1940)3/2$^-$	*	*	**	no evidence

A.V. Anisovich et al. (BnGa-PWA), EPJA 48 (2012) 15

from 2000-2010 not one new baryon resonance was considered by the PDG

$\leftrightarrow$ **Results from photoproduction (Bonn-Gatchina PWA) do now enter the PDG and determine the properties of baryon resonances !**

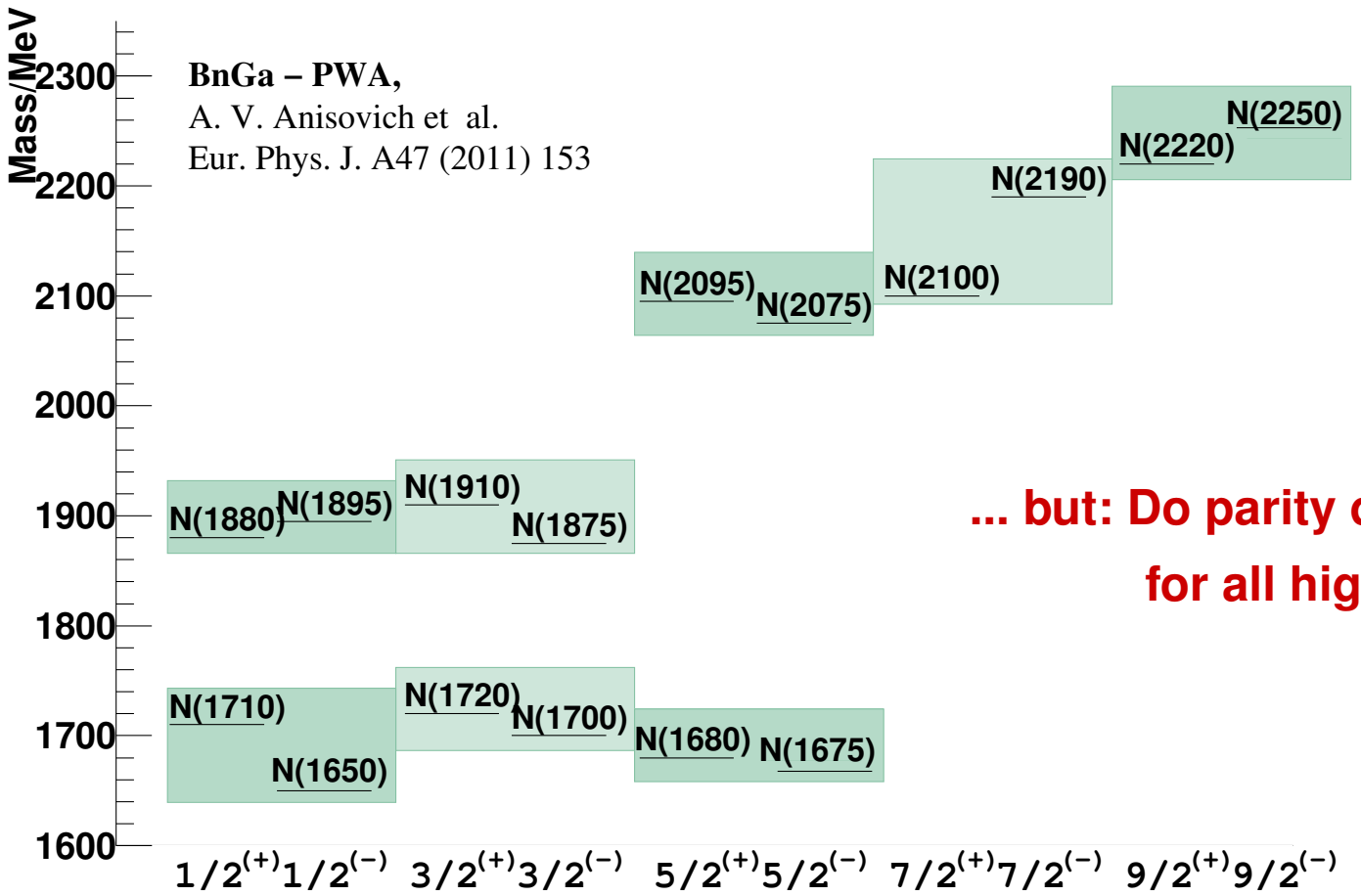
(before: almost entirely πN-scattering and some π-photoproduction)

Photoproduction provides access to the "inelastic channels"

$\Rightarrow$ **better determination of resonance properties**

The Spectrum of Baryon Resonances - Parity Doublets -

Parity doublets occur:



... but: Do parity doublets exist for all high mass states ?

Not expected by:

- present lattice QCD calculations or constituent quark-models

⇔ QCD not yet understood !

Search for Parity Doublets $\leftrightarrow$ Chiral Symmetry Restoration?

Idea (L. Y. Glozman): chiral symmetry restoration in highly excited baryon states.

$\Leftrightarrow$ **Mass-gaps due to spontaneous chiral symmetry breaking like:**
ρ**(770)** $\leftrightarrow$ a_1**(1260)** **or** **N(940)**$1/2^+$ $\leftrightarrow$ **N(1535)**$1/2^-$
no longer present in highly excited baryon states

$\Rightarrow$ **ALL high mass states should have a parity partner!**

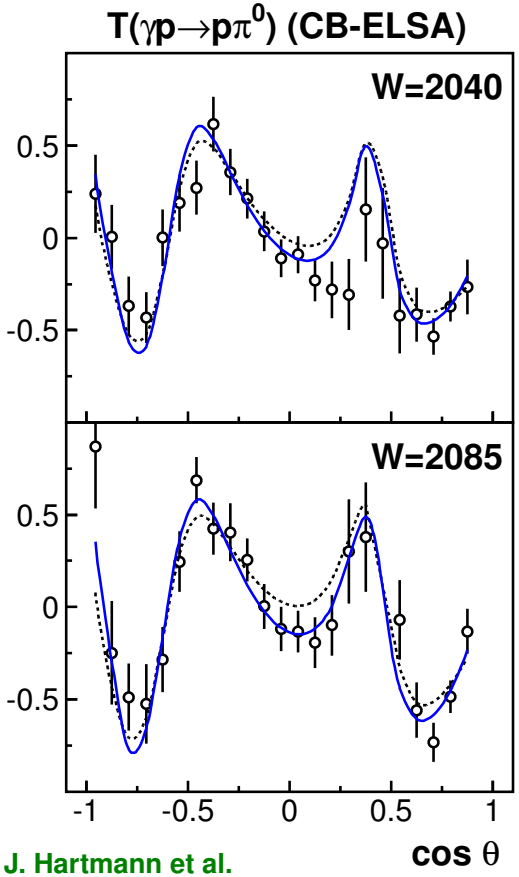
$\Downarrow$

Δ**(1910)**$1/2^+$	Δ**(1920)**$3/2^+$	Δ**(1905)**$5/2^+$	Δ**(1950)**$7/2^+$
Δ**(1900)**$1/2^-$	Δ**(1940)**$3/2^-$	Δ**(1930)**$5/2^-$	**???** $7/2^-$

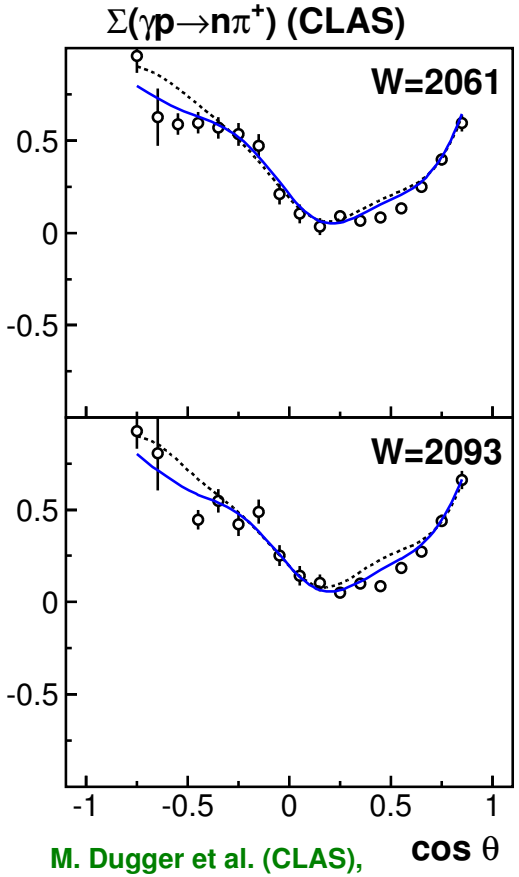
Search for the parity partner of the well known Δ(1950)$7/2^+$ (4*)

Precise Measurements of Polarisation Observables

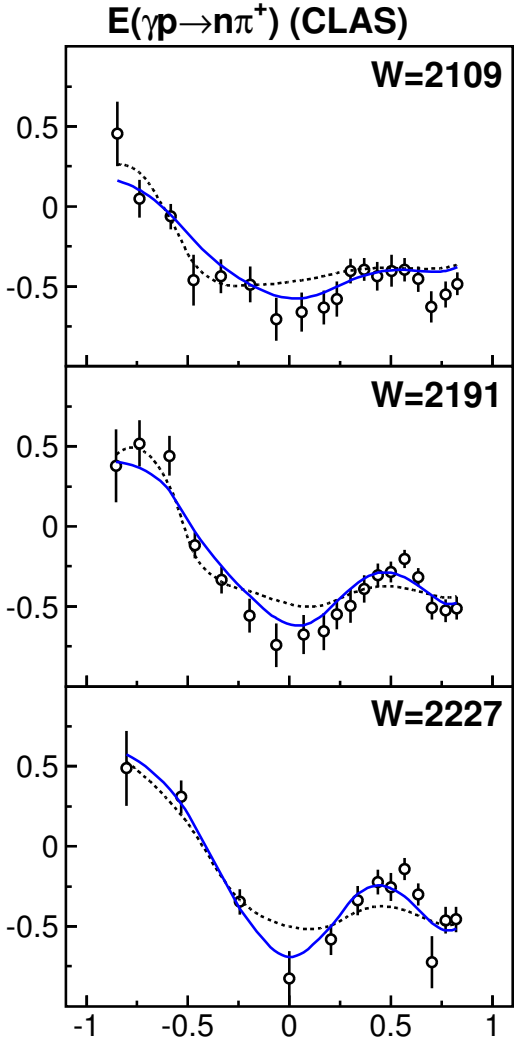
CBELSA/TAPS, CLAS-data (only a few of the measured bins shown:)



J. Hartmann et al. (CBELSA/TAPS), PLB 748, 212 (2015)



M. Dugger et al. (CLAS), PRC 88, 065203 (2013)



S. Strauch et al. (CLAS), arXiv:1503.05163 (2015)

data included in the multi-channel BnGa-PWA:
fit with (——) / without (- - - -) $\Delta(2200)7/2^-$

Search for Parity doublets

Idea (L. Glozman): chiral symmetry restoration in highly excited baryon states.

⇔ Mass-gaps due to spontaneous chiral symmetry breaking like:
ρ(770) ↔ a_1(1260) or N(940)$1/2^+$ ↔ N(1535)$1/2^-$
no longer present in highly excited baryon states

⇒ ALL high mass states should have a parity partner!

⇓

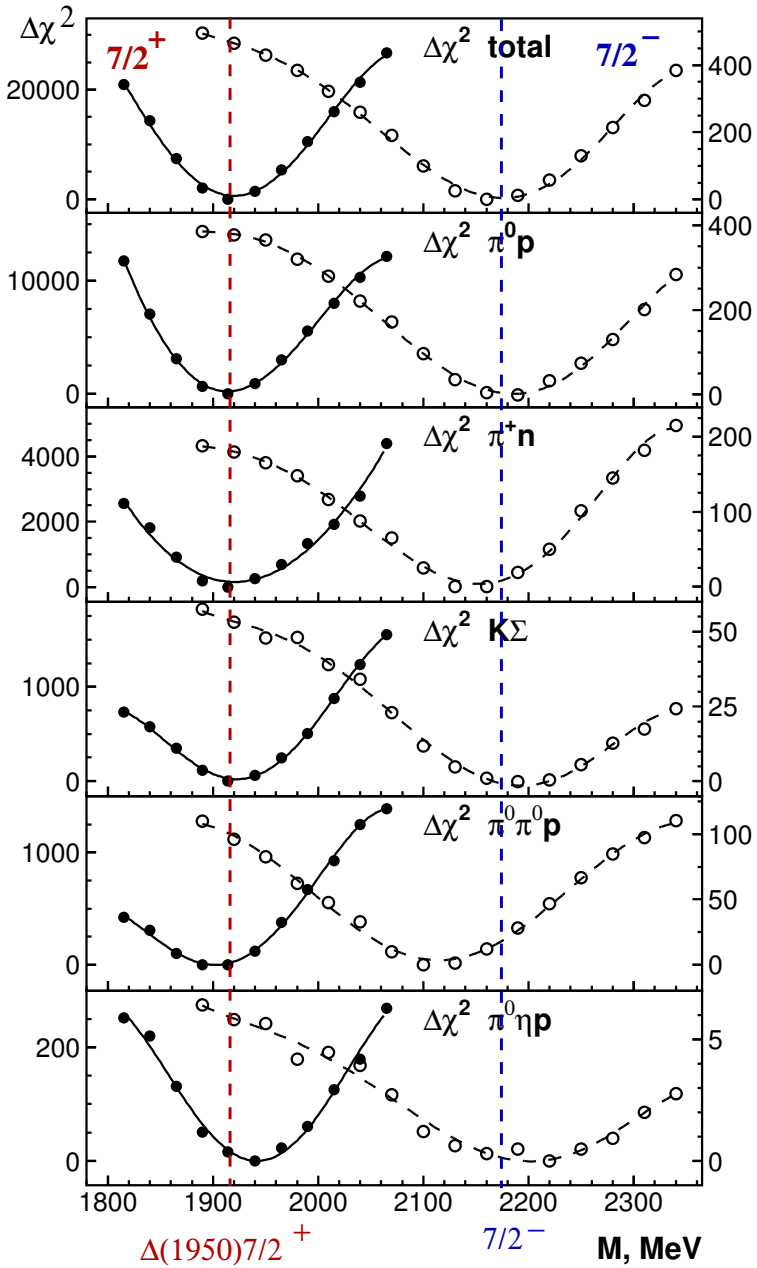
Δ(1910)$1/2^+$ Δ(1920)$3/2^+$ Δ(1905)$5/2^+$ Δ(1950)$7/2^+$
Δ(1900)$1/2^-$ Δ(1940)$3/2^-$ Δ(1930)$5/2^-$??? $7/2^-$

Search for the parity partner of the well known Δ(1950)$7/2^+$ (4*) ⟹

⇒ J^P = 7/2$^-$-state found at a significantly higher mass: m = 2200 MeV

(7/2$^-$ (2200) - (1*)-resonance (PDG) confirmed)

⇔ No parity-partner found



V. Anisovich et al. (BnGa-PWA), arXiv:1503.05774 (2015)

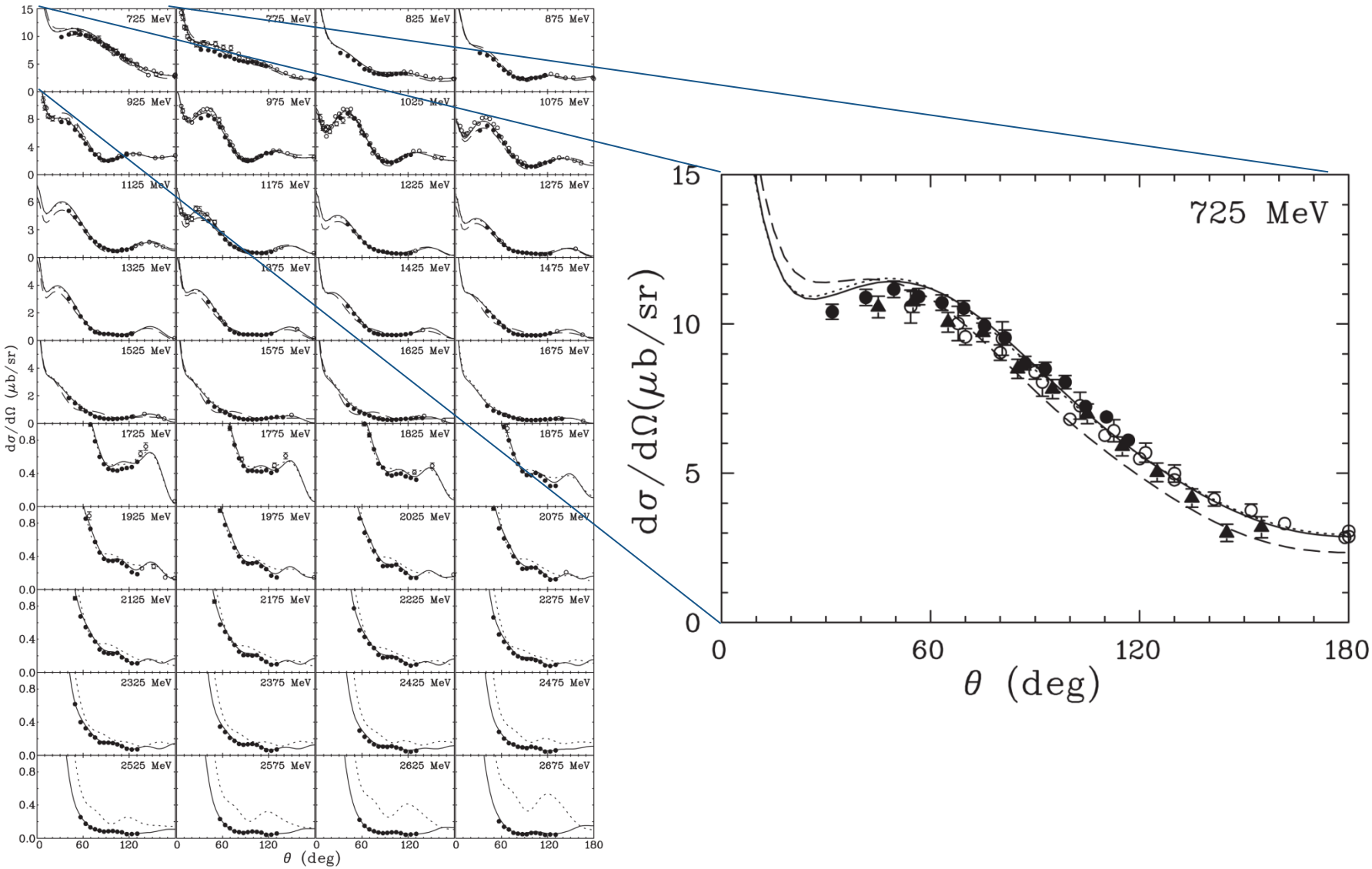
N* photoproduction program at CLAS

	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 targets																
$p\pi^0$	✔	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓		✓	✓	✓	✓								
$p\eta$	✔	✓	✓		✓	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$p\omega/\varphi$	✔	✓	✓		✓	✓	✓	✓								
$N\pi\pi$	✓	✓														
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$K^{+*}\Sigma^0$	✔	✓														
Neutron targets																
$p\pi^-$	✔	✓			✓	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^-\Sigma^+$	✓	✓			✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓				✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓				✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

Data taking completed May 18, 2012

✓-published, ✓-acquired

Channel: $\gamma + p \rightarrow \pi^+ + n$;Cross-section

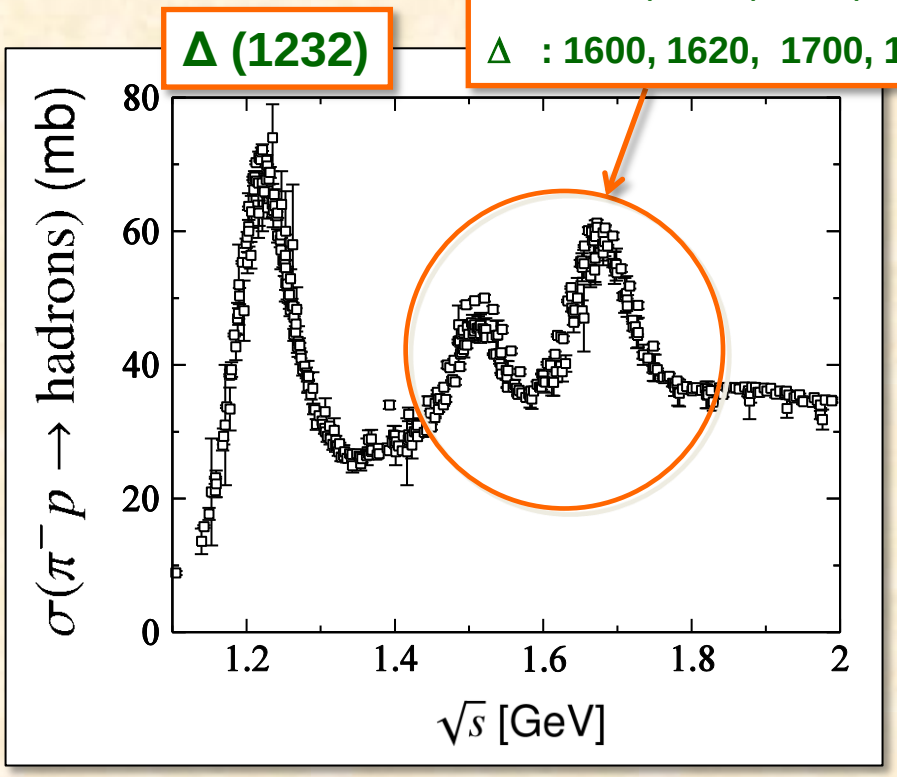


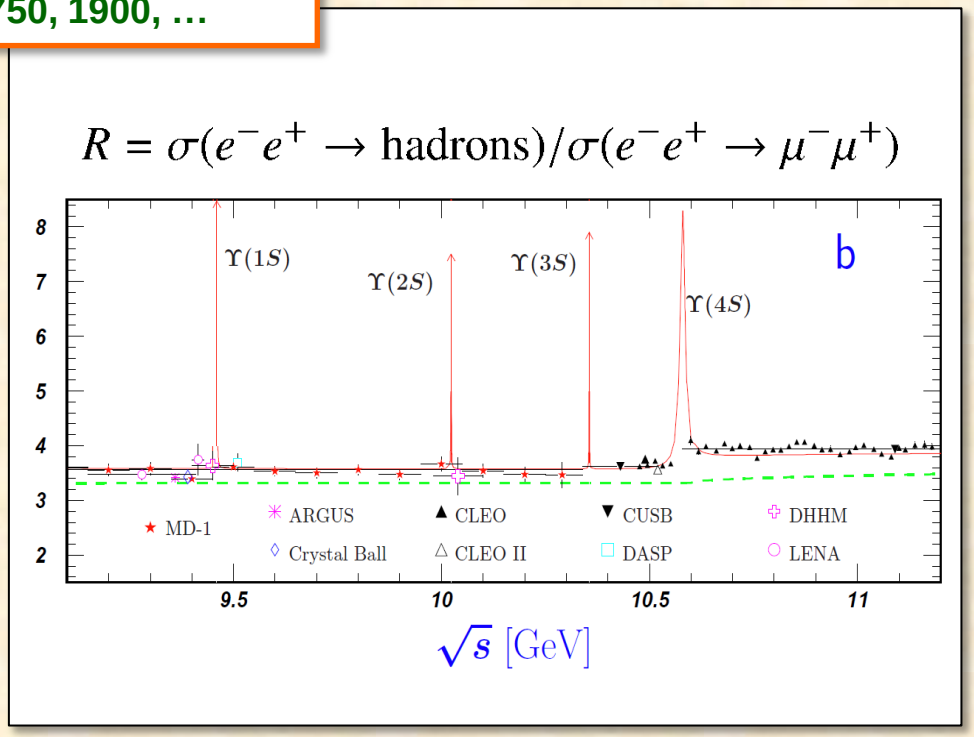
M. Dugger et al. (CLAS), Phys. Rev. C 79, 065206, 2009

N* spectroscopy :
Physics of broad & overlapping resonances

N* : 1440, 1520, 1535, 1650, 1675, 1680, ...

Δ : 1600, 1620, 1700, 1750, 1900, …





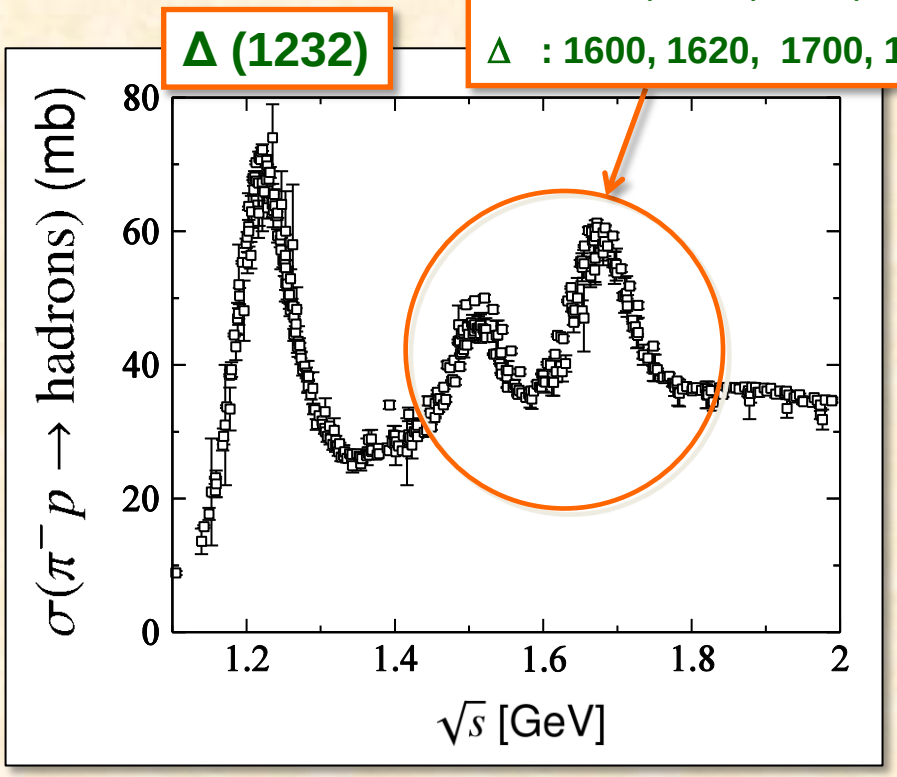
- ✓ Width: a few hundred MeV.
- ✓ Resonances are highly overlapped in energy except Δ(1232).

- ✓ Width: ~10 keV to ~10 MeV
- ✓ Each resonance peak is clearly separated.

N* spectroscopy :
Physics of broad & overlapping resonances

N* : 1440, 1520, 1535, 1650, 1675, 1680, ...

Δ : 1600, 1620, 1700, 1750, 1900, …



First step is to make an extensive partial-wave analysis to disentangle resonance contributions in different J^P states.

Need huge amount of high precision data (dσ/dΩ, polarization obs., etc.) covering wide energy & kinematical regions

- ✓ Width: a few hundred MeV.
- ✓ Resonances are highly overlapped in energy except Δ(1232).

N* states and PDG *s

Particle	J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	N				
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***					
$N(1520)$	$3/2^-$	****	****	****	***						
$N(1535)$	$1/2^-$	****	****	****	****						
$N(1650)$	$1/2^-$	****	****	***	***						
$N(1675)$	$5/2^-$	****	****	***	*						
$N(1680)$	$5/2^+$	****	****	****	*	**					***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	?			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	? *			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**		
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*		
$\Delta(1232)$	$3/2^+$	****	****	****	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					(se	
$\Delta(1950)$	$7/2^+$	****	****	****	o					***	
$\Delta(2000)$	$5/2^+$	**			?	r					**

All of these studies essentially agree on the existence and (most) properties of the 4-star states. For the 3-star and lower states, however, even a statement of existence is problematic.

—— **Arndt, Briscoe, Strakovsky, Workman PRC 74 045205 (2006)**

Most of the N*s were determined from

$$\pi N \to \pi N\ , \quad \gamma N \to \pi N$$

Need *comprehensive analysis* of

$$\pi N,\ \eta N,\ \pi\pi N,\ KY,\ \omega N, \ldots$$

channels !!

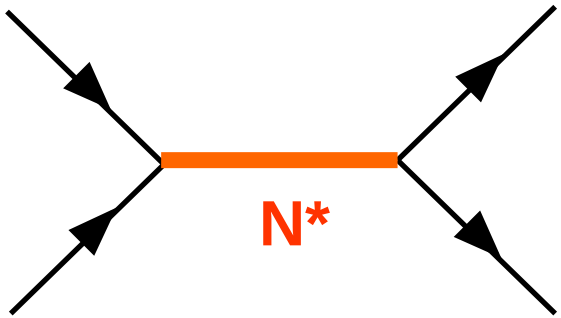
Hadron spectrum and reaction dynamics

✓ Various *static* hadron models have been proposed to calculate hadron spectrum and form factors.

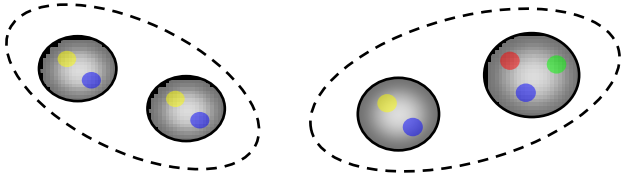
- Quark models, Bag models, Dyson-Schwinger approaches, Holographic QCD,…
- Excited hadrons are treated as stable particles. → The resulting masses are *real*.

✓ In reality, excited hadrons are "unstable" and can exist only as resonance states in hadron reactions.

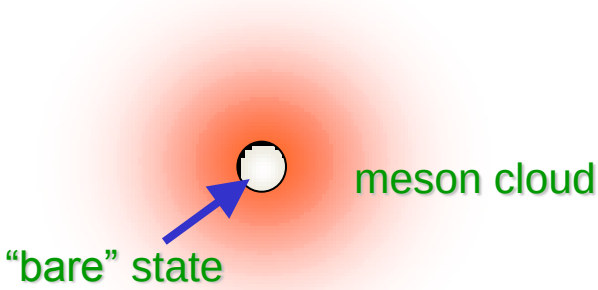
"Mass" becomes complex !!
→ "pole mass"



"molecule-like" states



core (bare state) + meson cloud



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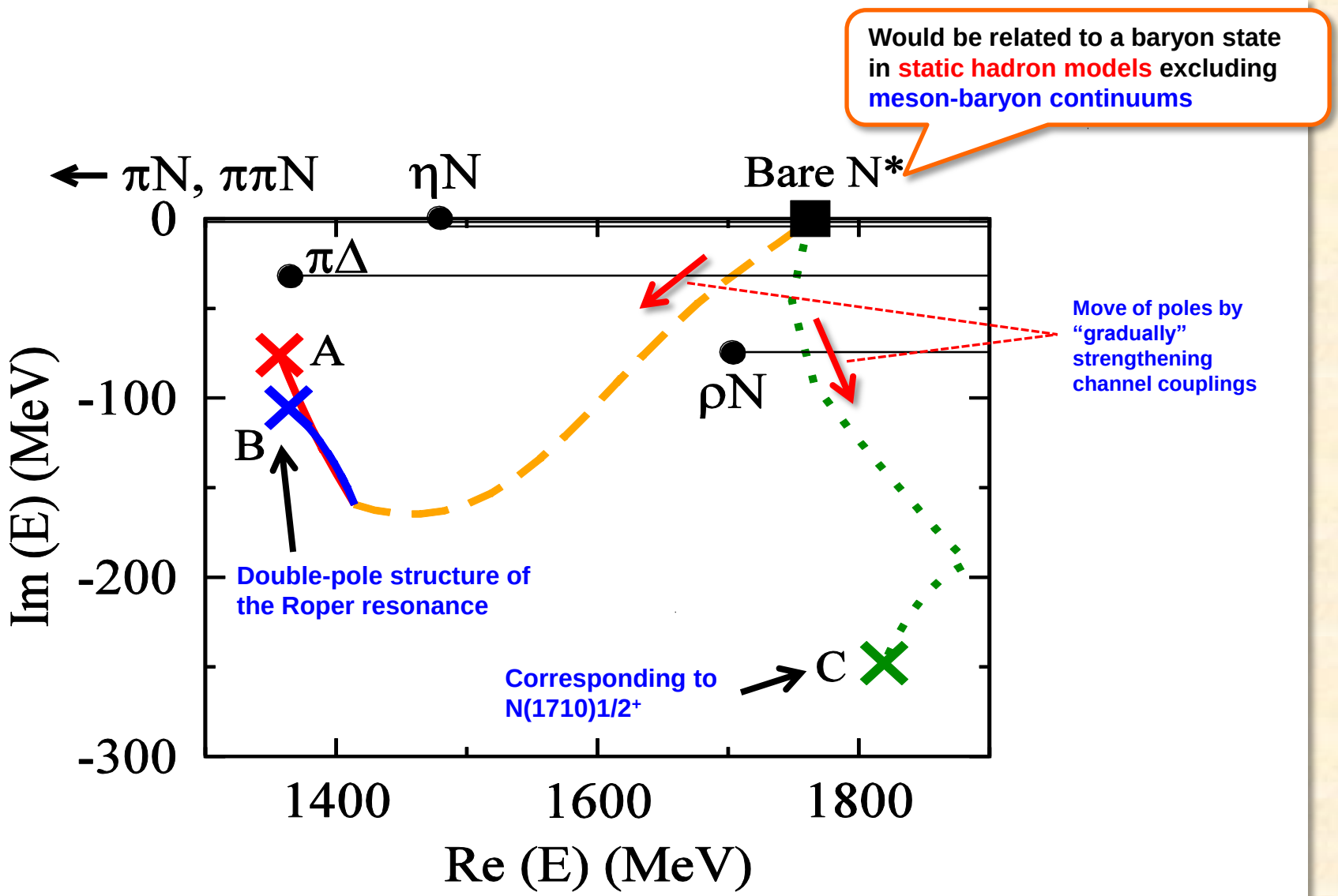
What is the role of reaction dynamics in interpreting the spectrum, structure, and dynamical origin of hadrons??

Dynamical origin of P11 N* resonances

(example of nontrivial nature of multichannel reaction dynamics)



Suzuki, Julia-Diaz, HK, Lee, Matsuyama, Sato, PRL104 042302 (2010)

Dynamical origin of P11 N* resonances

(example of nontrivial nature of multichannel reaction dynamics)

To explore role of reaction dynamics for hadron resonances, one needs:

- **Modeling appropriately reaction processes with a model Hamiltonian.**
  (➔ not a simple "pole + polynomial" parametrization, etc.)

- **Solving coupled-channels equations so that the amplitudes satisfy the multichannel unitarity.**
  (➔ key to having proper analytic structure [branch points, cuts,…] in complex energy plane)

We employ Dynamical Coupled-Channels approach !!

J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors, arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222 [on-line]

Quark core masses

- Argonne Osaka DCC model: Preliminary attempt to identify quark-core mass by isolating and removing meson-cloud contribution
- Semi-quantitative agreement:
  Cloud-subtracted masses
  ≈ DSE dressed-quark core masses
- Level ordering is particularly interesting:
  Cloud-substracted & DSE core masses agree on
  $\frac{1}{2}^+ \ldots \frac{1}{2}^+ \ldots \frac{1}{2}^-$
  Level ordering for core masses;
  Evidently, adding cloud does not change ordering

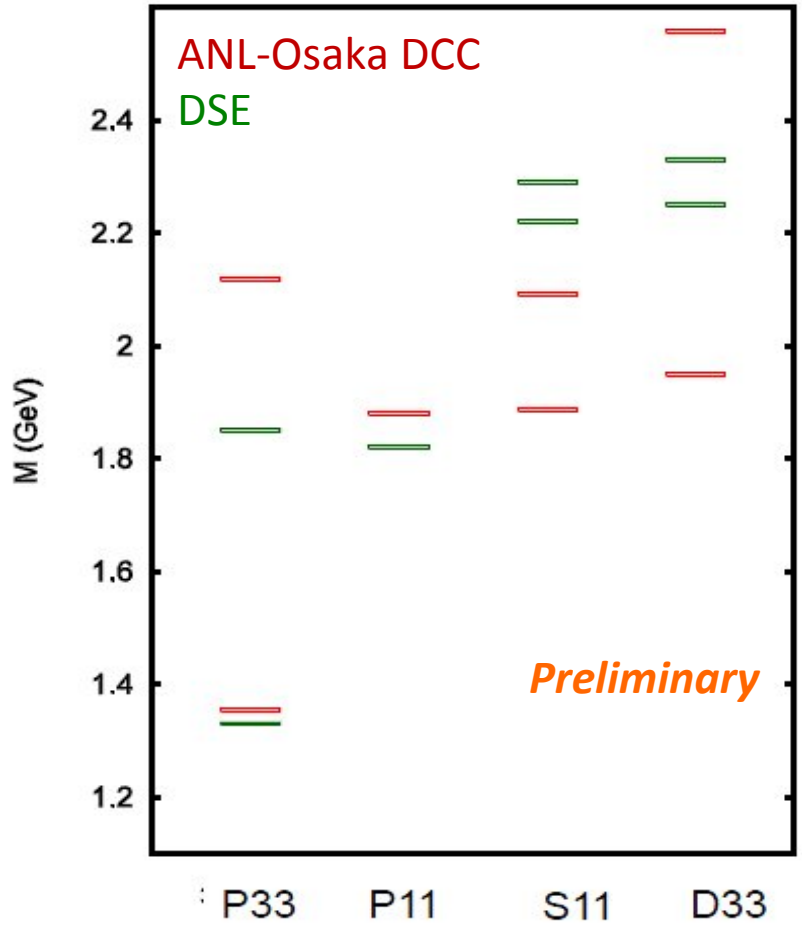
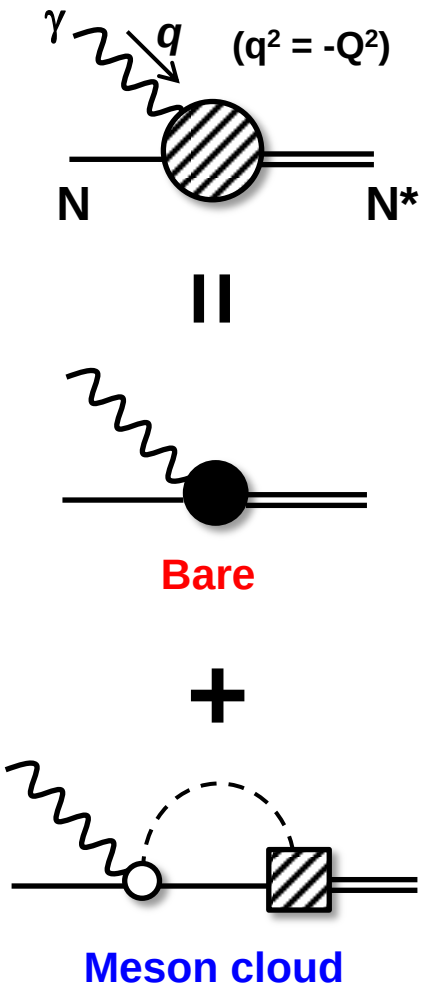


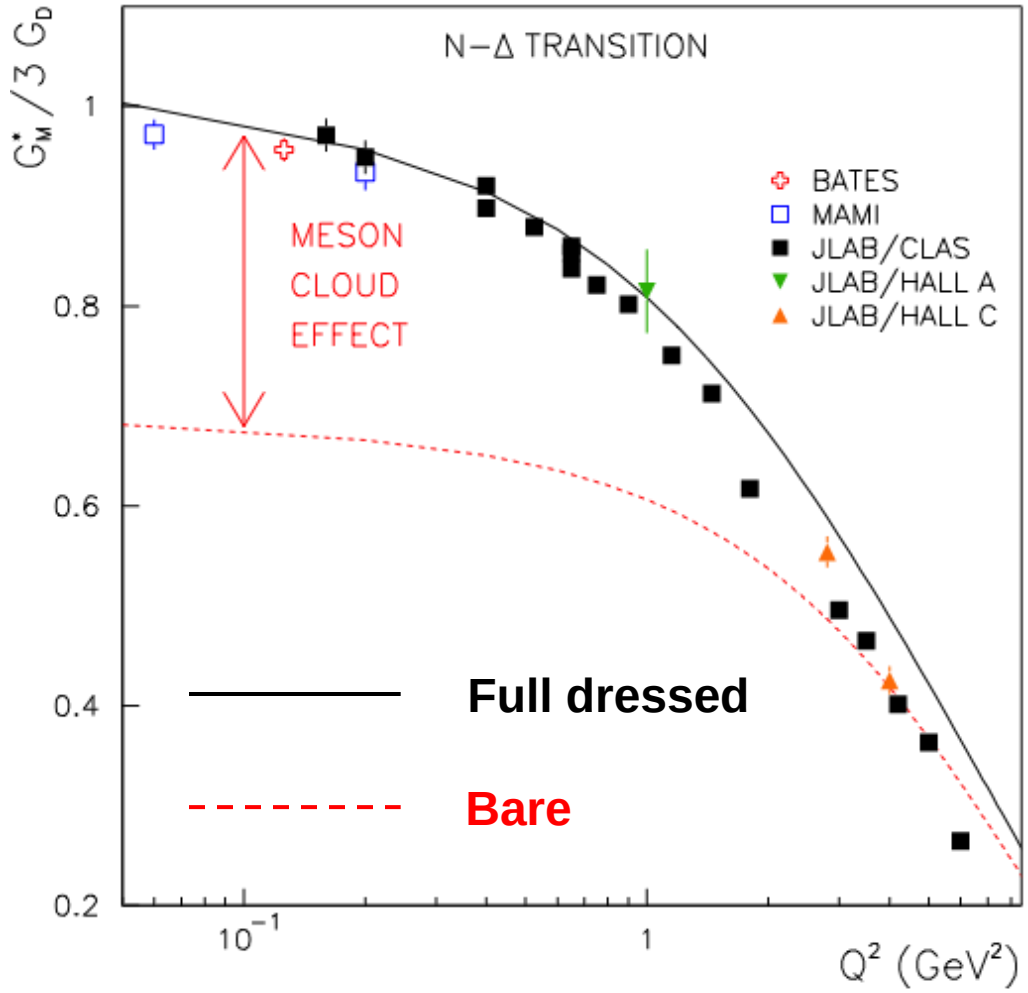
Image courtesy of T. Sato, H. Kamano, S. Nakamura and T.-S. H. Lee

Consequences of reaction dynamics: Meson cloud effect

N-N* e.m. transition form factor



Re[$G_M(Q^2)$] for γ N → Δ (1232) transition



Julia-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

Consequences of reaction dynamics: Meson cloud effect

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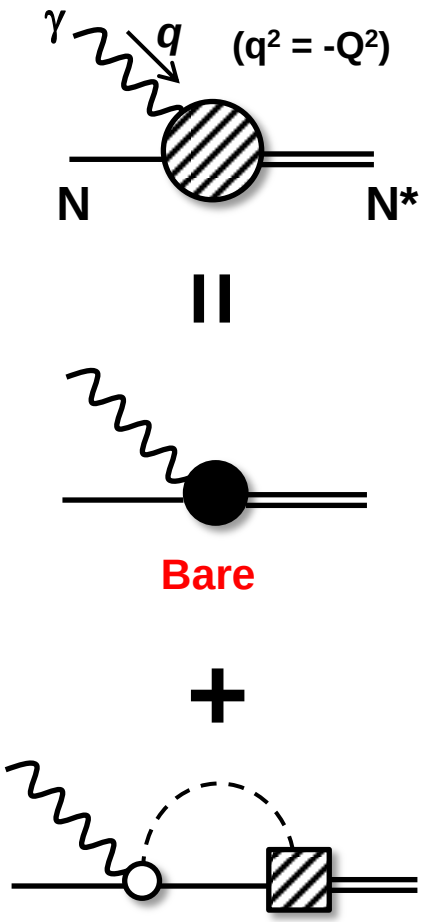
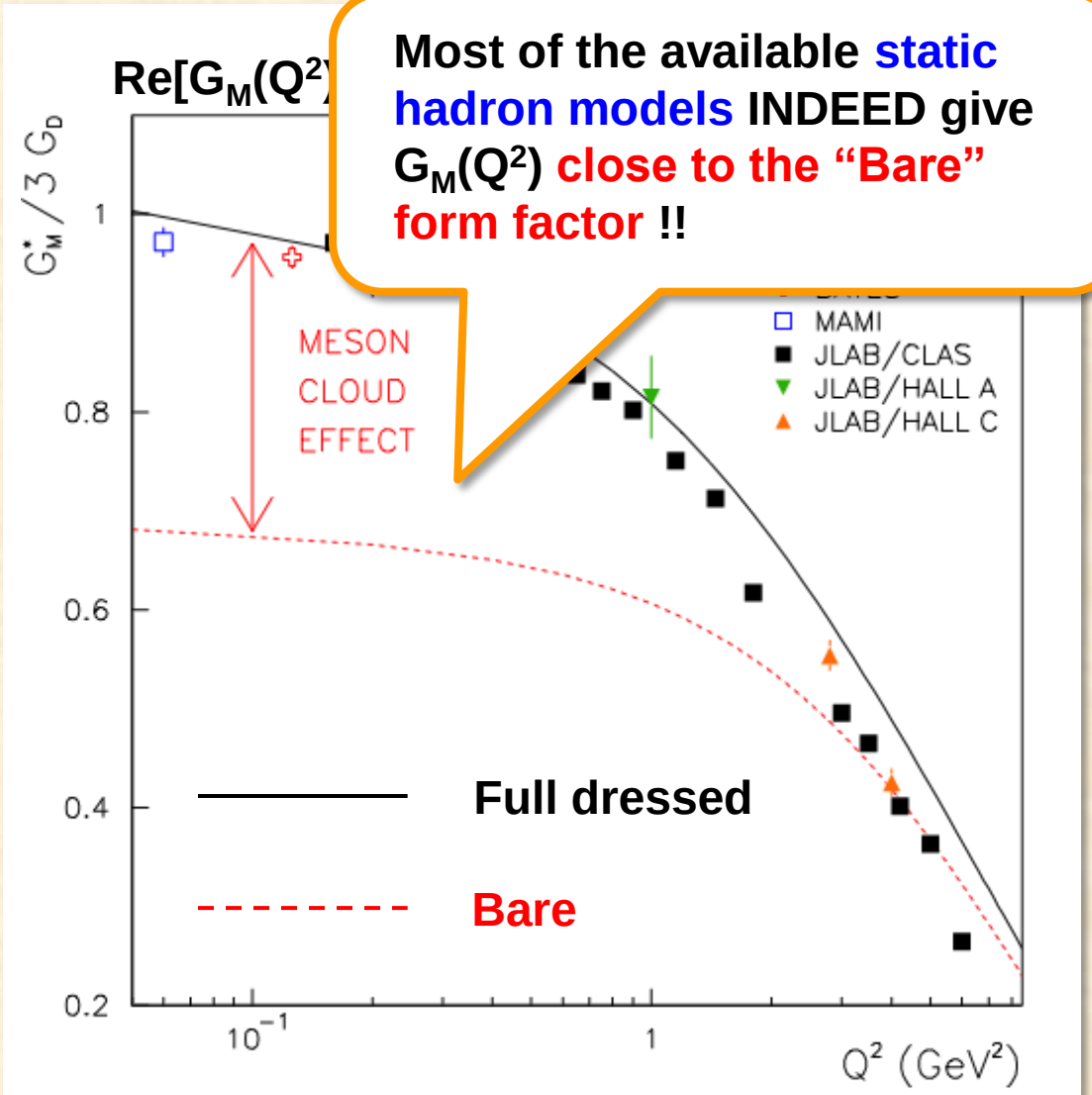
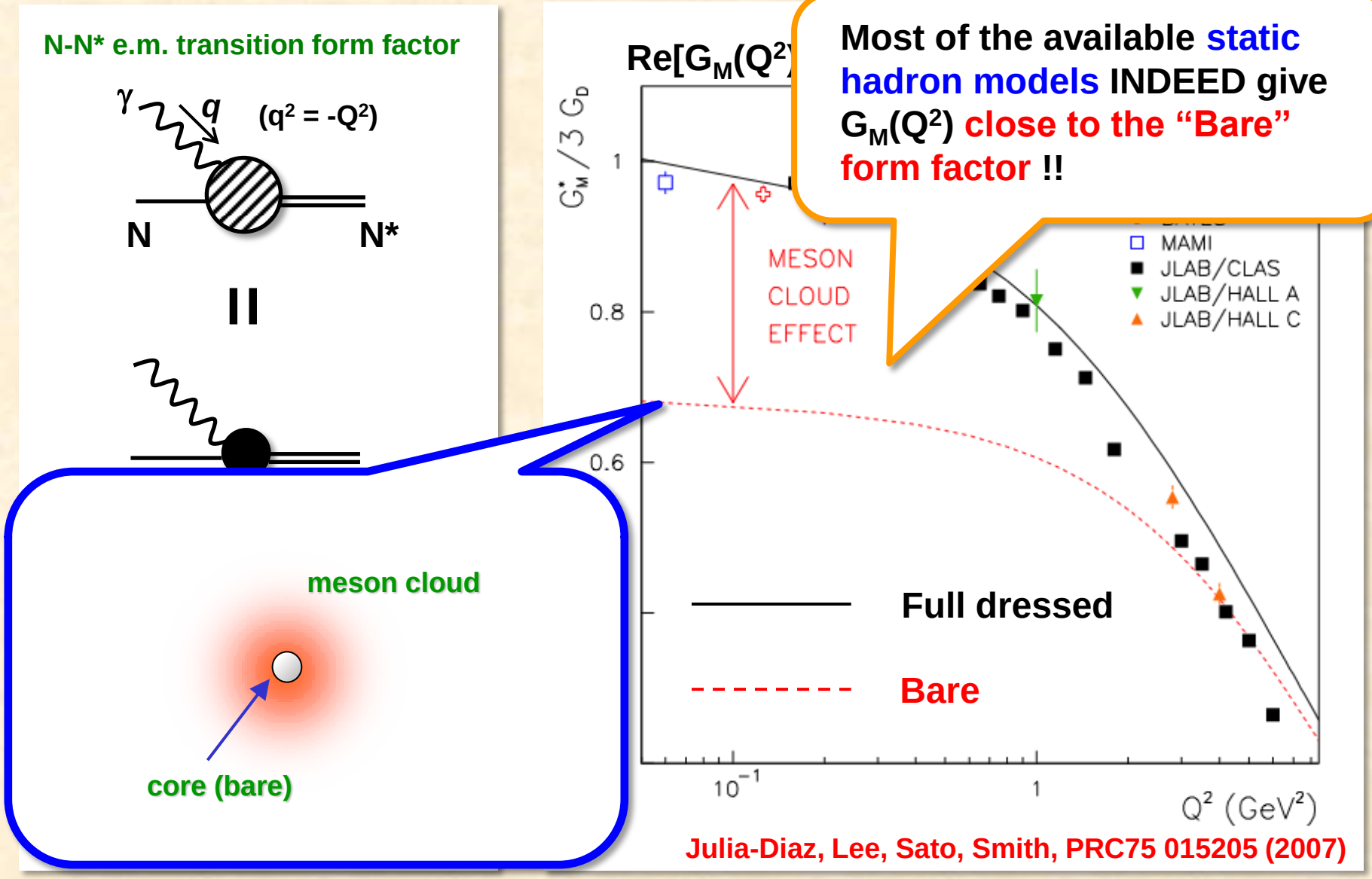




Most of the available static hadron models INDEED give $G_M(Q^2)$ close to the "Bare" form factor !!

Julia-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

Consequences of reaction dynamics: Meson cloud effect



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Julia-Diaz, Lee, Sato, Smith, PRC75 015205 (2007)

ANL-Osaka DCC approach to N* and Δ*

Dynamical coupled-channels model [Matsuyama, Sato, Lee, Phys. Rep. 439(2007)193]

$$T^{(LSJ)}_{a,b}(p_a,p_b;E) = V^{(LSJ)}_{a,b}(p_a,p_b;E) + \underbrace{\sum_c}_{\text{CC effect}} \underbrace{\int_0^\infty q^2 dq V^{(LSJ)}_{a,c}(p_a,q;E) G_c(q;E) T^{(LSJ)}_{c,b}(q,p_b;E)}_{\text{off-shell effect}}$$

$$a,b,c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N,\ K\Lambda,\ K\Sigma,\cdots)$$

$\pi\pi N$

Region our model can cover

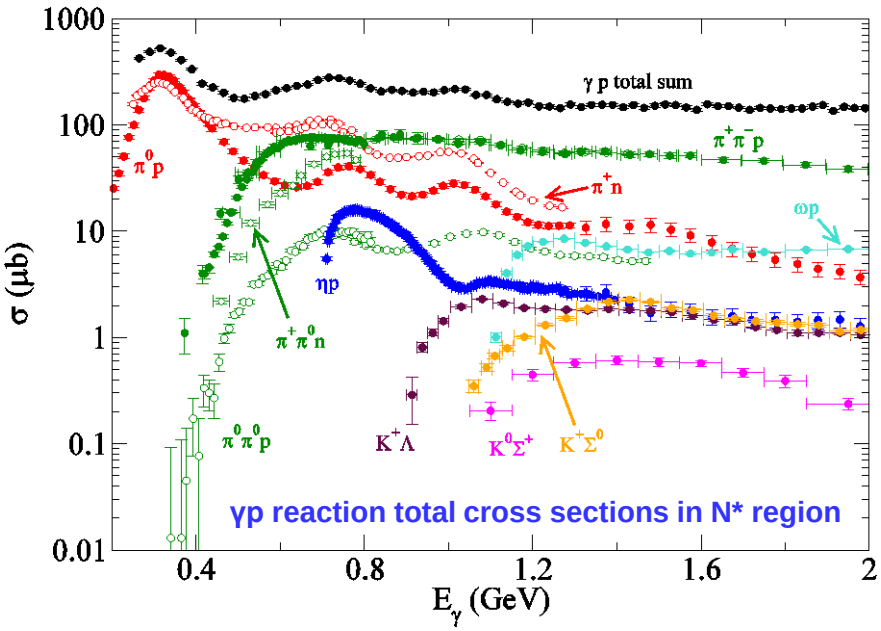
Latest published model (8-channel):

HK, Nakamura, Lee, Sato, PRC88(2013)035209

Constructed by simultaneous analysis of

- **πN SAID PW amps. (W < 2.3 GeV)**
- **πp → ηN, KΛ, KΣ (W < 2.1 GeV)**
- **γp → πN, ηN, KΛ, KΣ (W < 2.1 GeV)**

(including dσ/dΩ & polarization obs. data)



Need of inelastic reaction data for establishing high-mass N* and Δ* spectrum

To establish the spectrum of high-mass resonances, inelastic reaction (particularly double pion production) data are highly desirable:

πN, γN → ππN, KΛ, KΣ, ηN, η'N, ωN, ΦN,…

Measurements of πN → ππN, … :

HADES

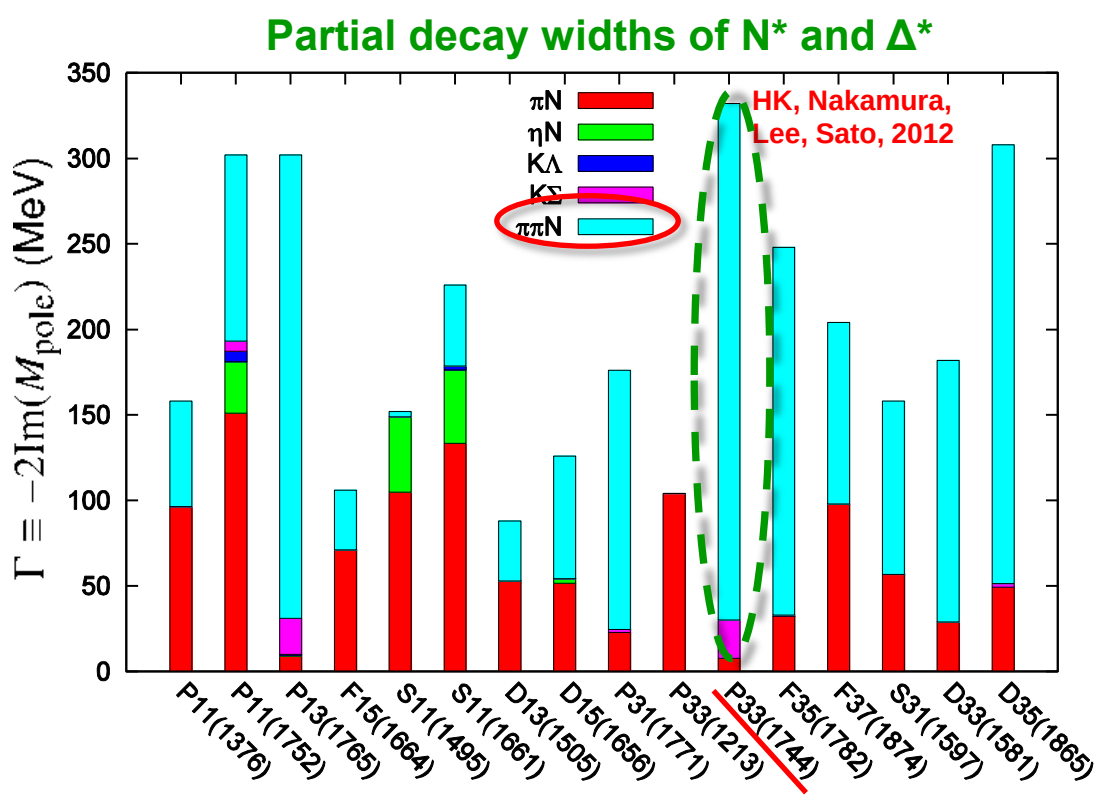
[➔ e.g., talk by W. Przygoda @NSTAR2015]

http://www.rcnp.osaka-u.ac.jp/~nstar15/talks/27_P2/27_P2_Przygoda.pdf

J-PARC E45

[➔ e.g., talk by K. Hosomi @NSTAR2015]

http://www.rcnp.osaka-u.ac.jp/~nstar15/talks/27_A2/27_A2_Hosomi.pdf



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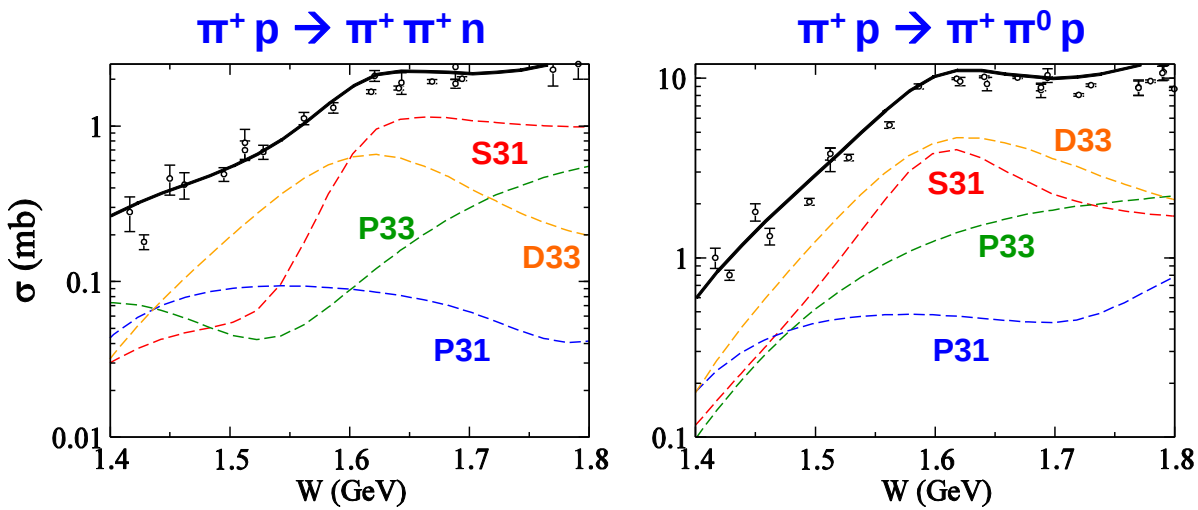
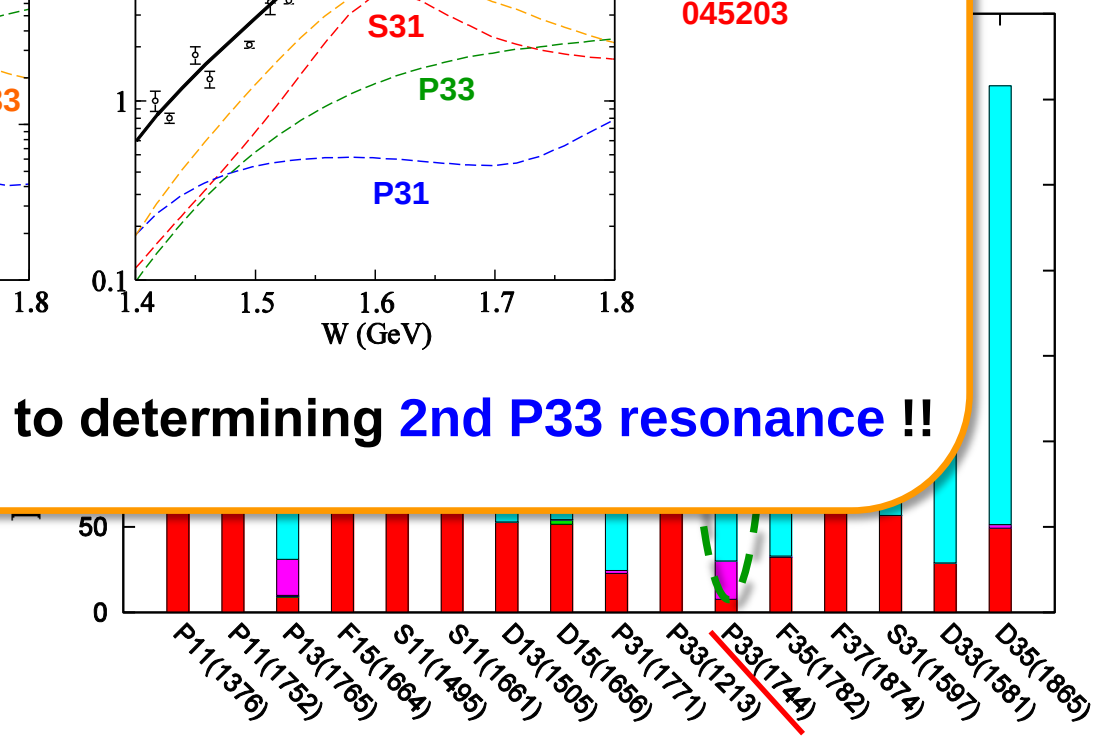


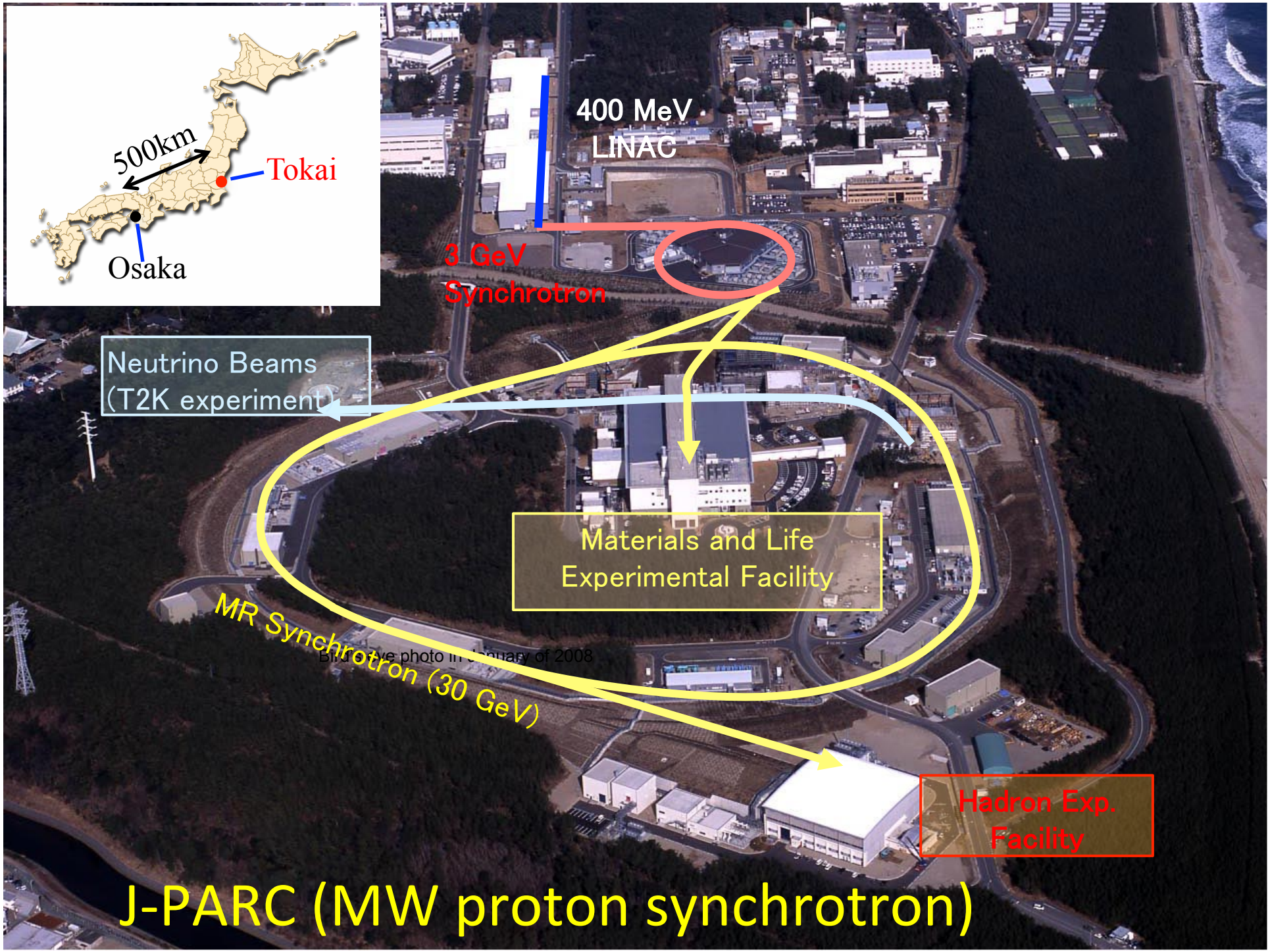
HK PRC88(2013) 045203

$\pi^+ p \rightarrow \pi\pi N$ will be a key to determining 2nd P33 resonance !!

[➔ e.g., talk by K. Hosomi @NSTAR2015]

http://www.rcnp.osaka-u.ac.jp/~nstar15/talks/27_A2/27_A2_Hosomi.pdf





J-PARC (MW proton synchrotron)

E45 HypTPC Spectrometer

Measure (π,2π) in large acceptance TPC in dipole magnetic field

$\pi^- p \rightarrow \pi^+ \pi^- n$, $\pi^0 \pi^- p$

$\pi^+ p \rightarrow \pi^0 \pi^+ p$, $\pi^+ \pi^+ n$

2 charged particles + *1 neutral particle*

→*missing mass technique*

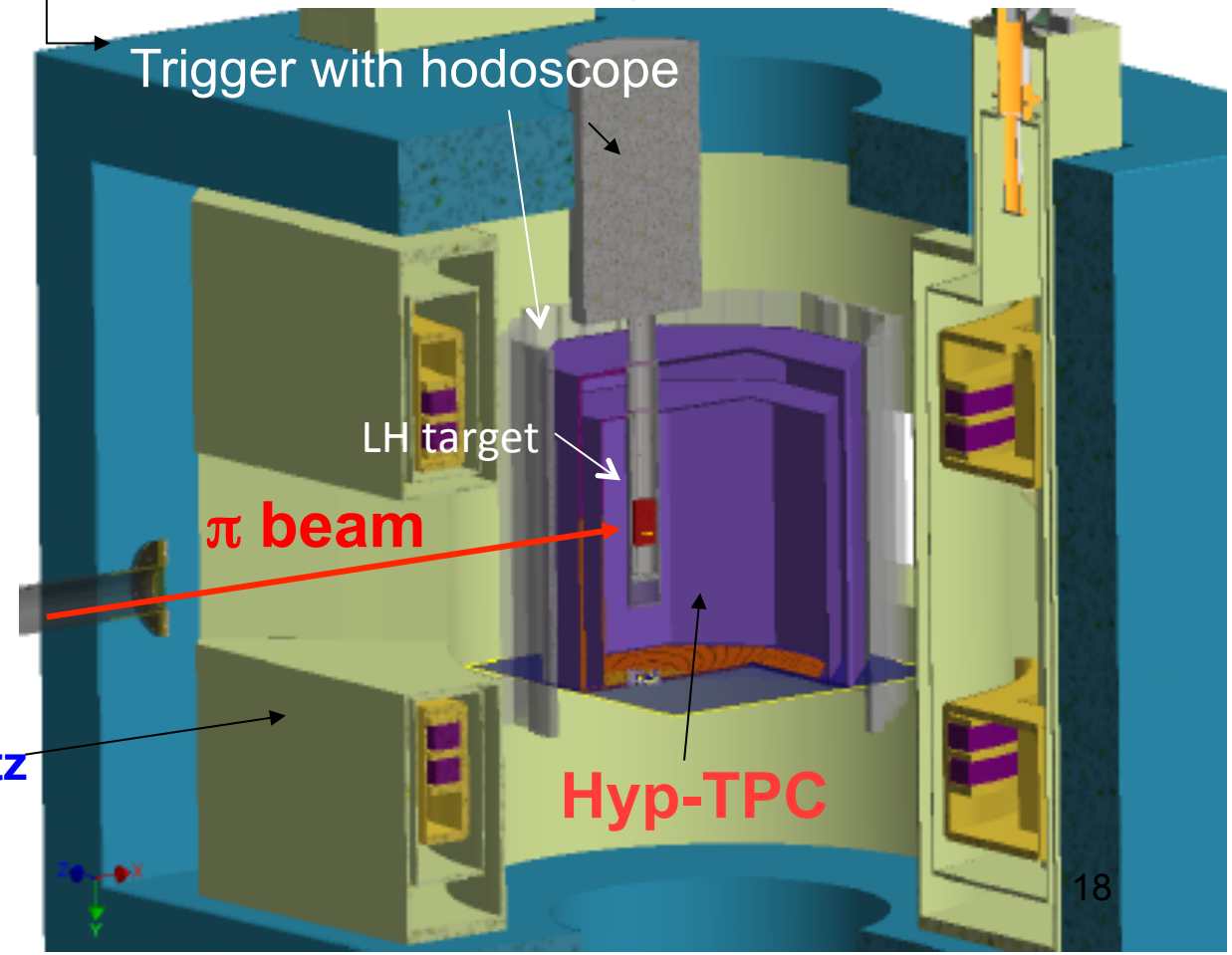
$\pi N \rightarrow KY$ *(2-body reaction)*

$\pi^- p \rightarrow K^0 \Lambda$,

$\pi^+ p \rightarrow K^+ \Sigma^+$ $(I=3/2, \Delta^*)$

π^{+-} beam on liquid-H target
(p= 0.73 – 2.0 GeV/c
W=1.5-2.15 GeV)

LH target: Φ5cm



Superconducting Helmholtz Dipole magnet (1.5 T)

High-res., High-momentum Beam Line

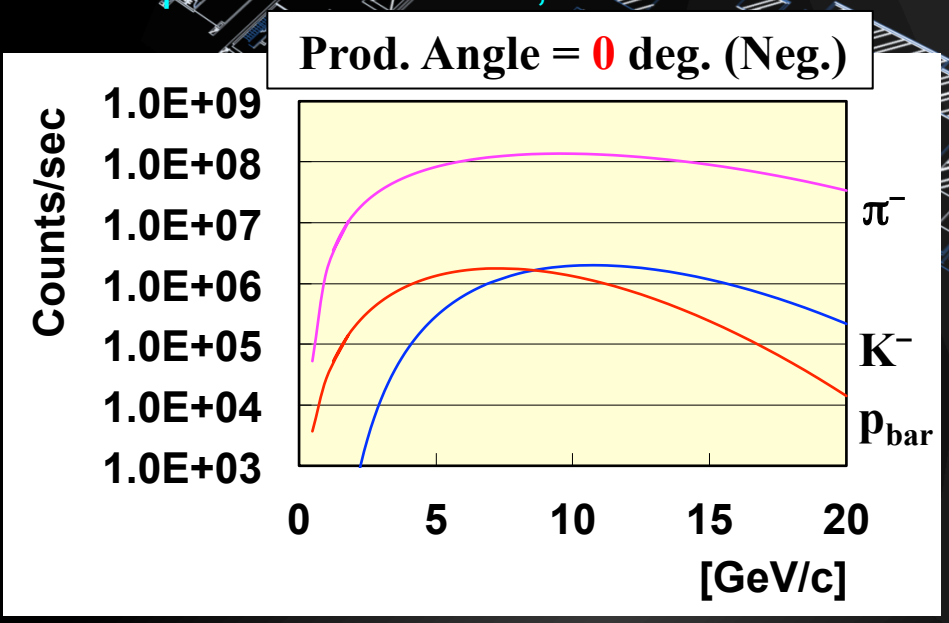
- High-intensity secondary Pion beam
  - 1.0 x 10^7 pions/sec @ 20GeV/c
- High-resolution beam: $\Delta p/p \sim 0.1\%$

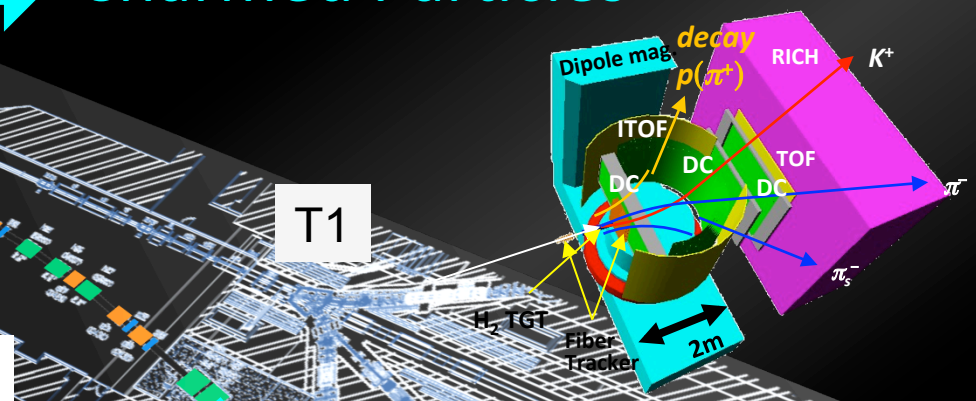
Charmed Particles

30 GeV proton beam

Production Target

Sanford-Wang
15 kW Loss on Pt
Acceptance :1.5 msr%, 133.2 m



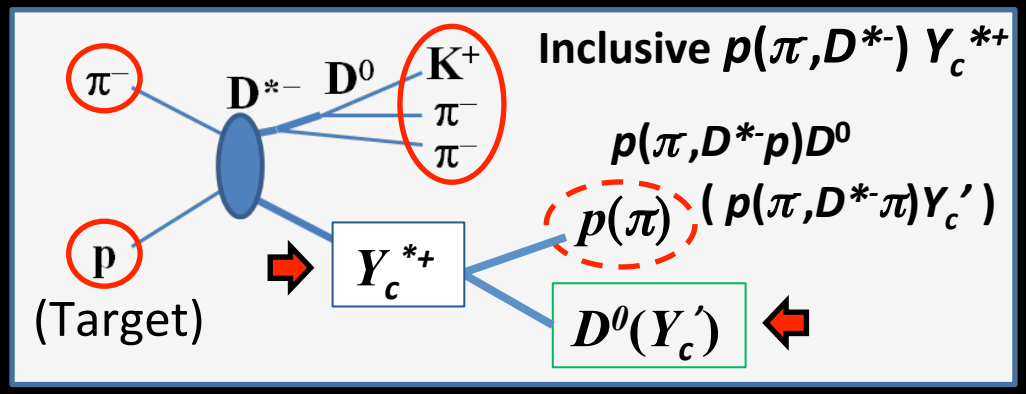


T1

Pion Beam
Up to 20 GeV/c

Spectrometer

CHARM Spectrometer Design



Cross Section:

$\sigma(\Lambda_c) \sim$ 1 nb (no meas.)

PTEP2014, 103D01(2014)

Large Acceptance:

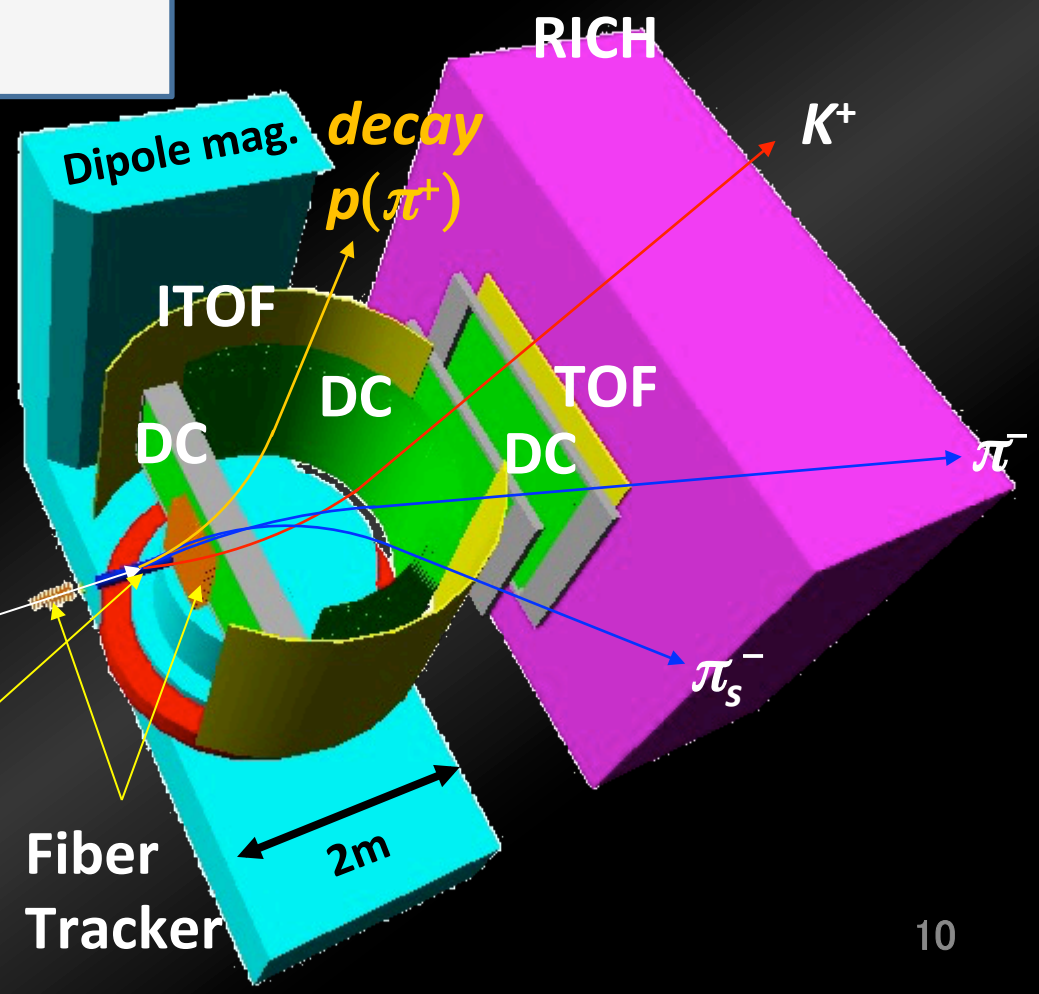
~ 60% for D^*,

~ 80% for decay π^+

Good Resolution:

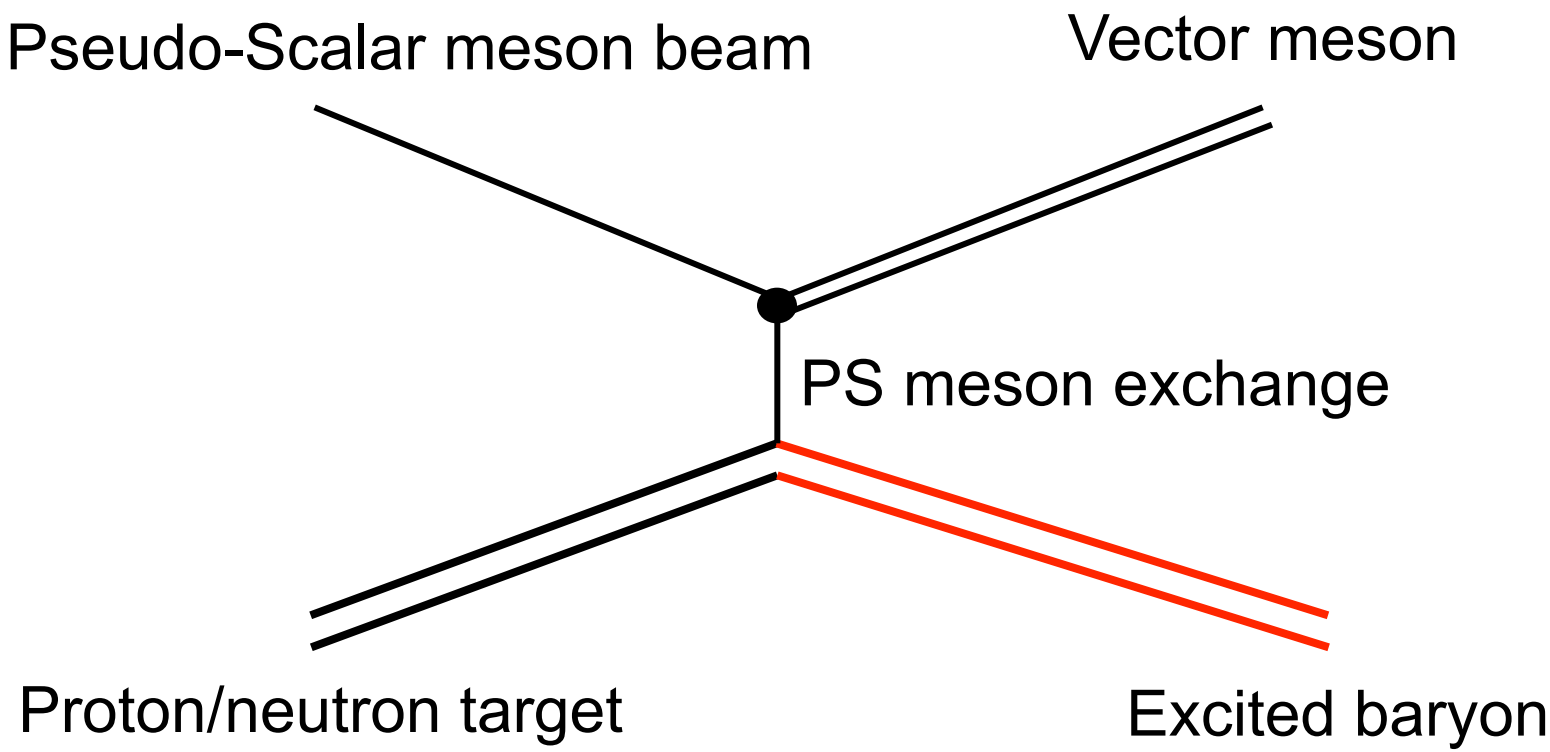
$\Delta p/p$~0.2% at ~5 GeV/c

(Rigidity: ~2.1 Tm)

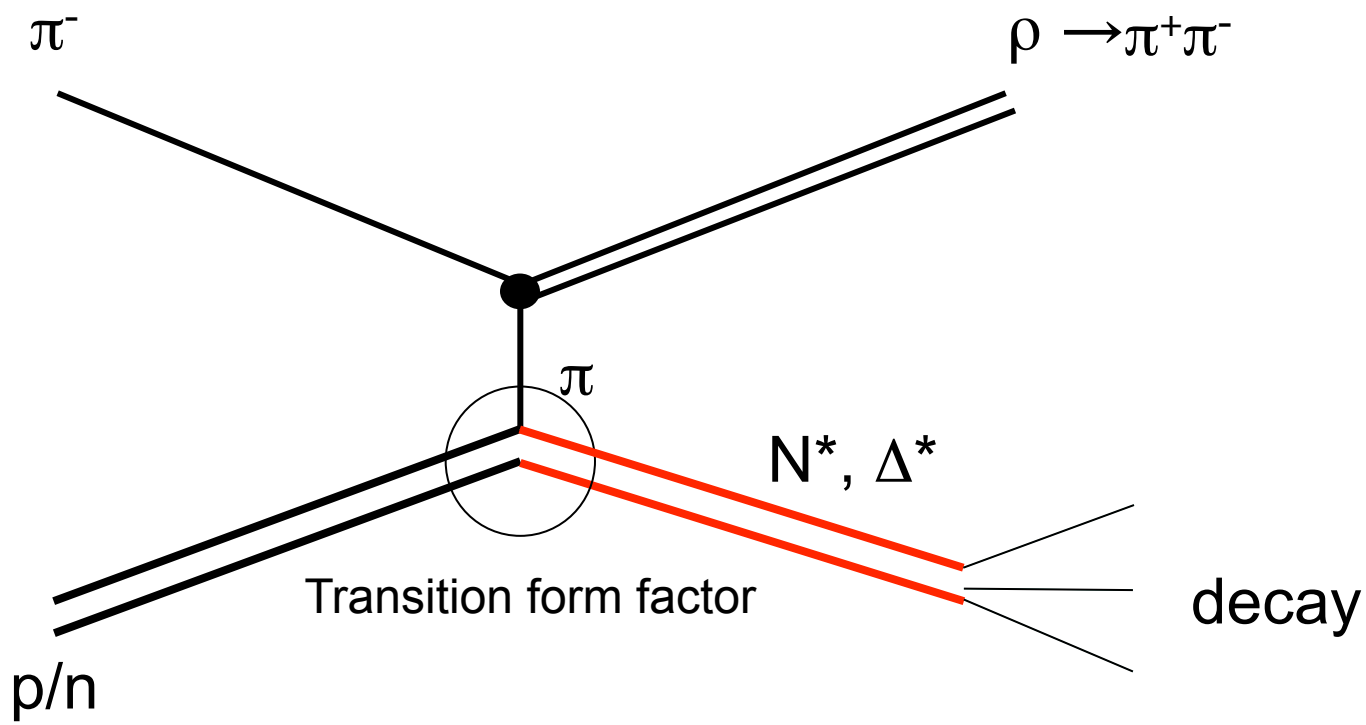


R&D works in progress.

V production with PS beam

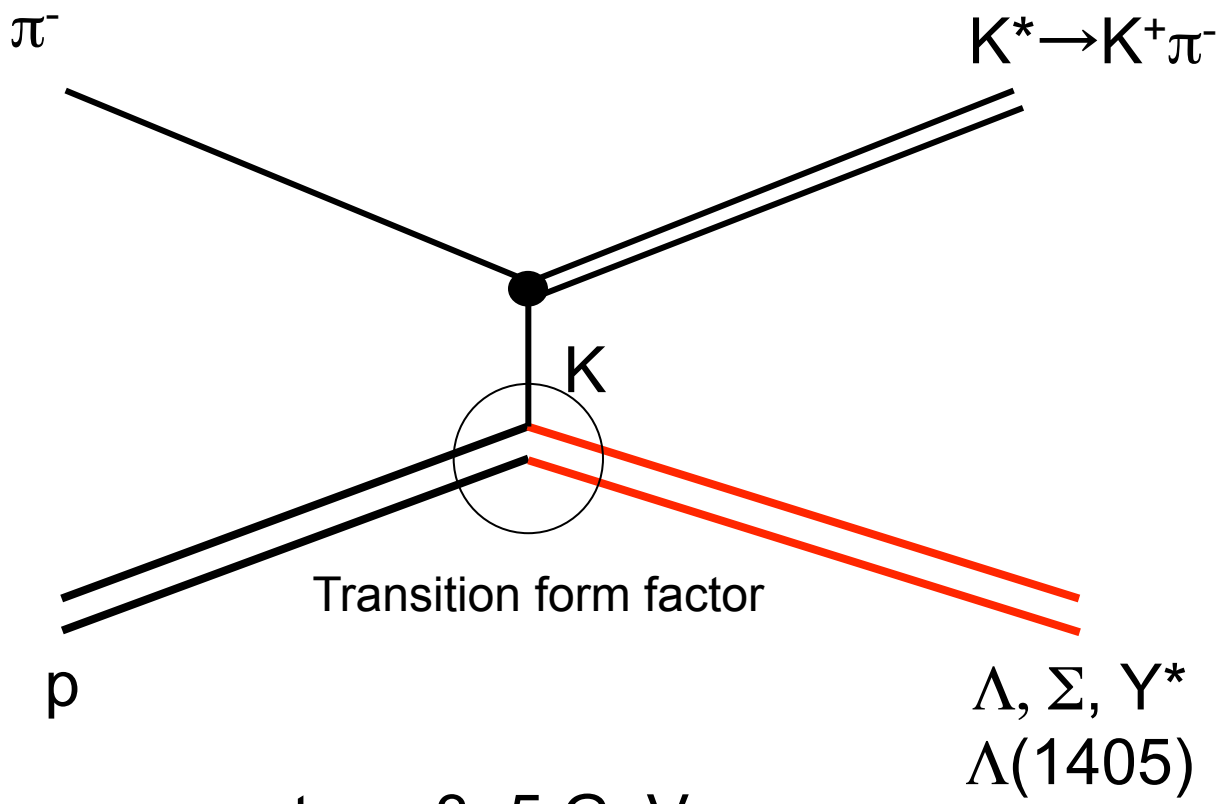


(π, ρ) reaction



ππN data can be obtained for free.
Detect forward ππ and decay particles

(π^-, K*) reaction

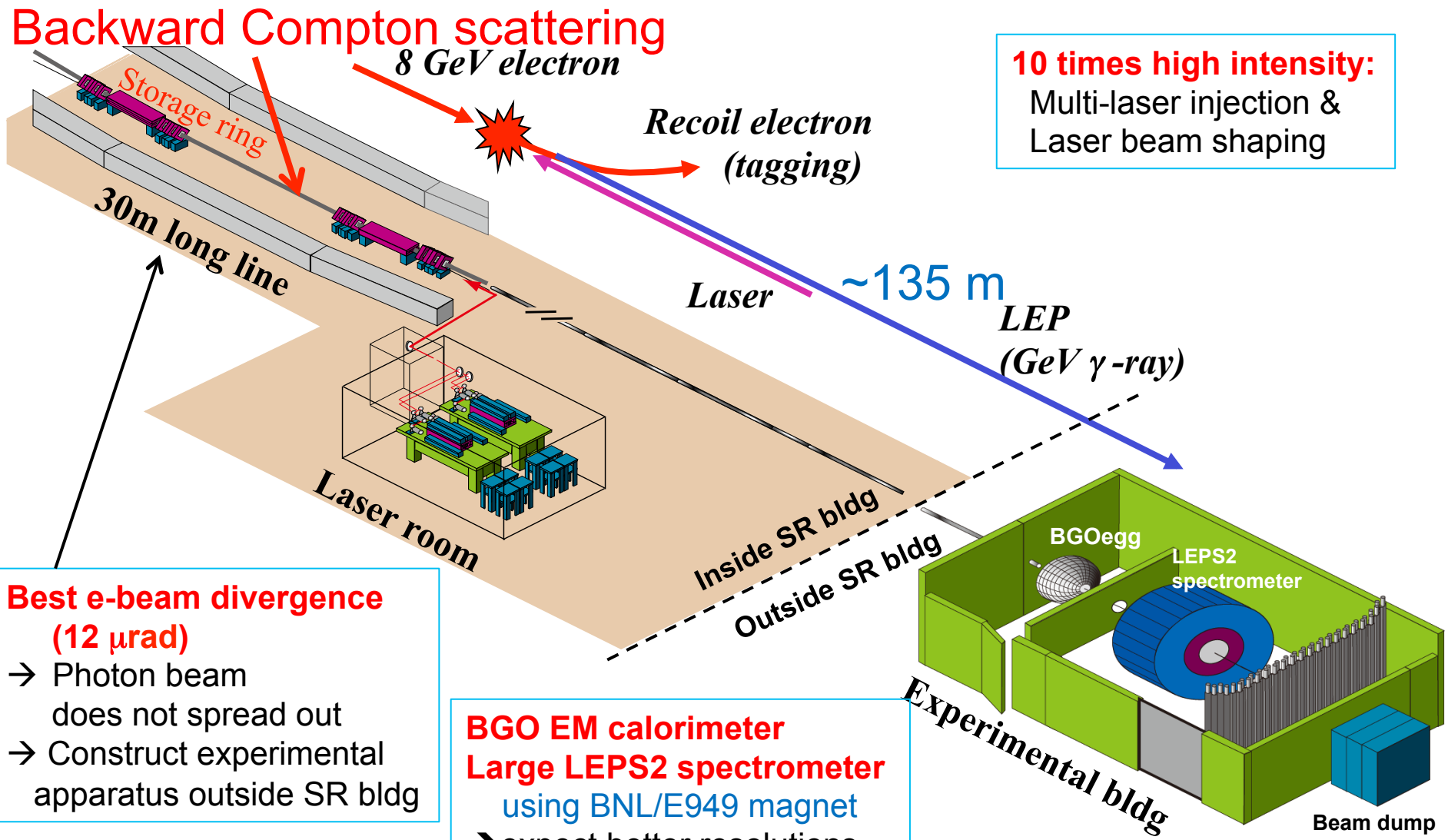


Beam momentum: 3~5 GeV
Large solid angle detector to detect Kπ
and decay products of a hyperon.

Summary

- Recent high statics photoproduction experiments have made important contributions to the study of light baryons. → Confirmation of many resonances and new findings such as parity doublets.
- The key elements are single and double polarization observables in wide energy and angle coverage for PWA analyses to detangle overlapped resonance contributions. → More data are coming soon!
- Dynamical approach is important for the comparison with various static baryon models and lattice calculations.
- For the study of high mass resonances, we need more data with multi-pion productions with pion beam. → J-PARC will start to contribute.

Outline of the LEPS2 facility



10 times high intensity:
Multi-laser injection &
Laser beam shaping

Best e-beam divergence
(12 μrad)
→ Photon beam
does not spread out
→ Construct experimental
apparatus outside SR bldg

BGO EM calorimeter
Large LEPS2 spectrometer
using BNL/E949 magnet
➔expect better resolutions

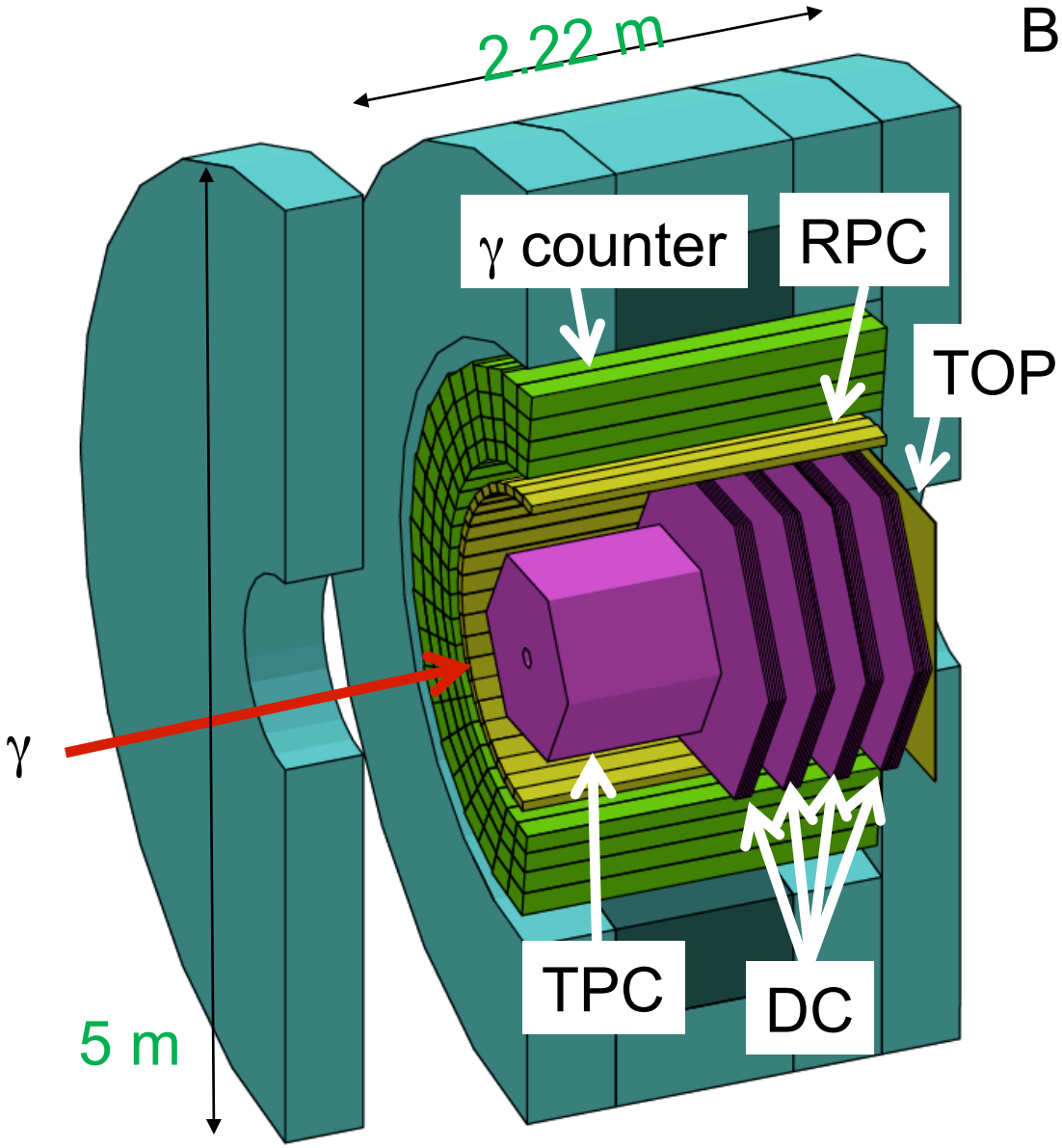
Exp. hall was constructed. (2010.Oct-2012Jan)

Installation of the E949 magnet (2011.Nev-Dec)

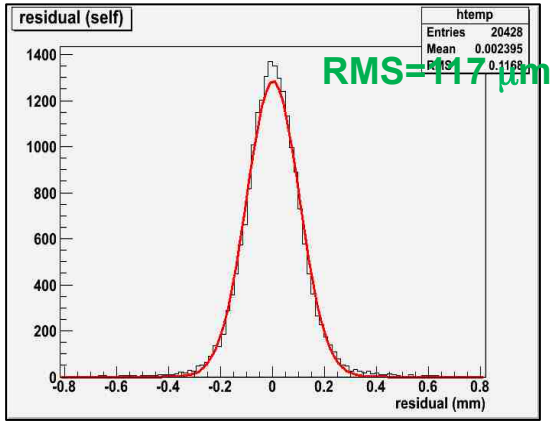
γ counters were installed. (2012.June)

Beam pipe (2012.May)

LEPS2 Detector

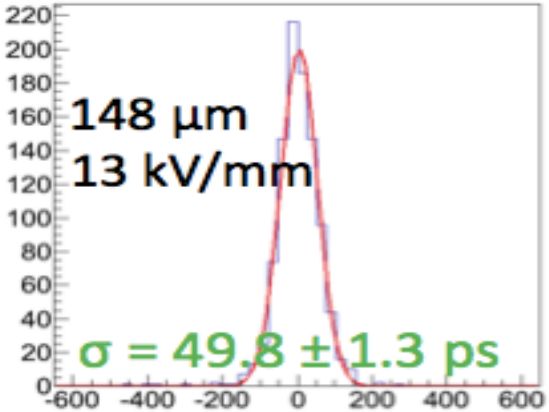


B=1 T : **Δp/p ~ 1%** for θ >7°



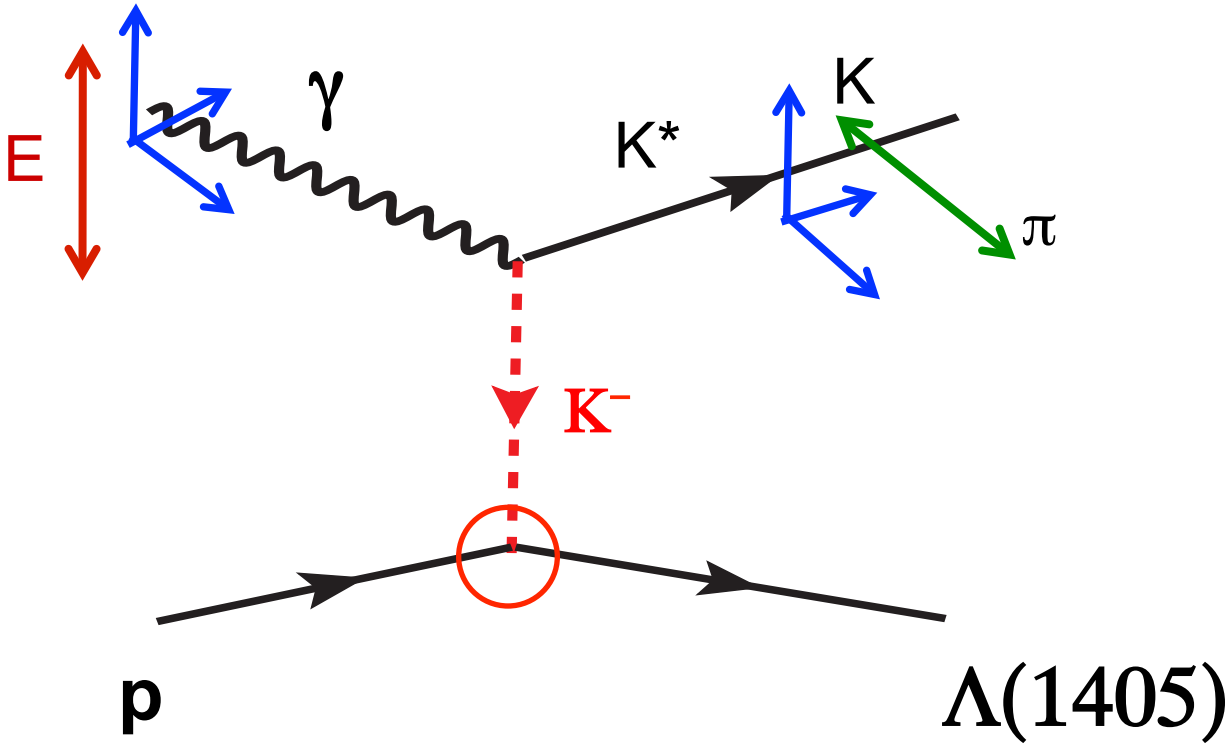
TPC Prototype Residual

RPC ToF time distribution



>3σ K/π separation
@1.1 GeV/c^2

K*(890) Λ(1405) photoproduction with linearly polarized photon



Commissioning of LEPS2 detector will start in 2017.