UNIVERSITEIT GENT

FACULTY OF SCIENCES

# The Regge-plus-Resonance (RPR) model for Kaon Production on the Proton and the Neutron


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# Outline

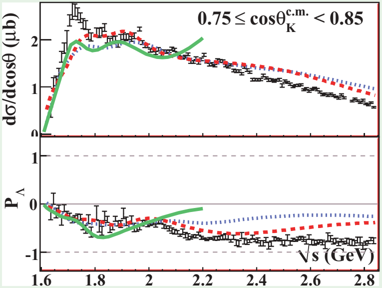
- Motivation (Why should one study $N(\gamma, K)\Lambda$ and $N(\gamma, K)\Sigma$?)
- Models for open strangeness production
- Regge-plus-resonance (RPR) approach to kaon photoproduction
- Kaon production on the proton
  1. RPR results for kaon photoproduction
     **DESCRIPTION** AND **PREDICTION**
  2. RPR results for kaon electroproduction
     **PREDICTION**
- Kaon photoproduction on the neutron (deuteron)
  1. RPR results for kaon photoproduction
     **PREDICTION**
- Conclusions and outlook

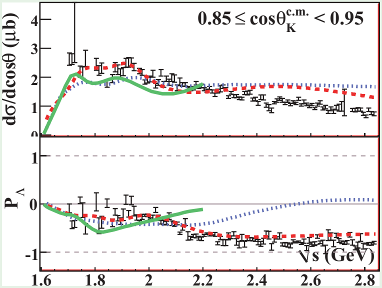
# Models for open strangenes production I

**Challenges for model builders**

- $\gamma$ cross sections are of the order of $\mu$b (pion production is mb)
- threshold $\sqrt{s} \approx 1.6$ GeV (overlapping resonances)
- no obvious indications for dominant resonance(s) in the energy dependence of the cross section (BACKGROUND DIAGRAMS!)

## $p(\gamma, K^+)\Lambda$ results from CLAS (PRC **81**, 025201 (2010))




KAON-MAID Bonn-Gatchina RPR (Ghent)

# Models for open strangeness production II

## Models for electromagnetically induced kaon production

- single-channel (single-step) approaches (KAON-MAID, ...)
- coupled-channel (multi-step) approaches
  1. Bonn-Gatchina (coupled-channel partial wave analysis ($\pi N, \eta N, KY$)) (Sarantsev, Anisovich, Nikonov, Klempt, Thoma ; EPJA **34**, 243 (2007))
  2. Giessen: (Shklyar, Lenske, Mosel ; PRC **72**, 015210 (2005))
  3. EBAC: (Saghai, David, Julá-Diaz, Lee ; EPJA **31**, 512 (2007))

## Issues with regard to coupled-channel approaches

- highly multidimensional in parameter space
- centered on the real photon data ($\gamma^*$ ????)
- demanding analysis framework: HR and computer time consuming
- constraining background contributions in the weak channels is challenging

# Models for open strangeness production III

**???? Economical model for $N(\gamma, K)Y$ and $N(e, e'K)Y$ with few parameters and predictive power????**

- **predict results for "neutron" targets from parameters of "proton" targets**
- **predict $N(e, e'K)Y$ from fitted $N(\gamma, K)Y$**
- **simple enough such that it can be used in hypernuclear calculations, neutrino-nucleus response calculations, . . .**

**???? Economical model for $N(\gamma, K)Y$ and $N(e, e'K)Y$ with few parameters and predictive power????**

- **predict results for "neutron" targets from parameters of "proton" targets**
- **predict $N(e, e'K)Y$ from fitted $N(\gamma, K)Y$**
- **simple enough such that it can be used in hypernuclear calculations, neutrino-nucleus response calculations, . . .**

## Regge-inspired models

PHYSICAL REVIEW C **68**, 058201 (2003)

**Exclusive electromagnetic production of strangeness on the nucleon: Regge analysis of recent data**

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[1]*IPN Orsay, F-91406 Orsay, France*
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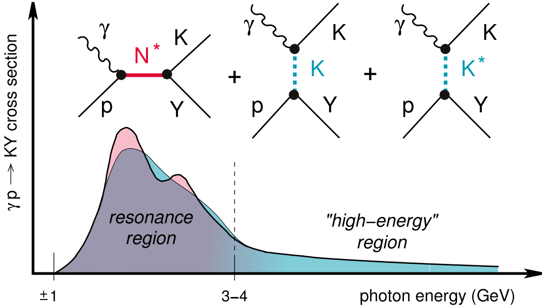
[3]*University Mainz, D-55099 Mainz, Germany*
(Received 11 August 2003; published 10 November 2003)

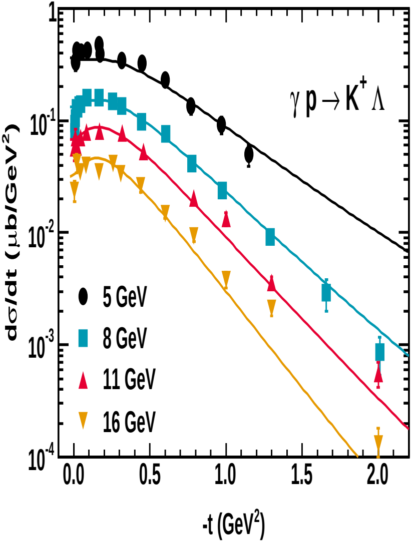
# The Regge-plus-resonance model I



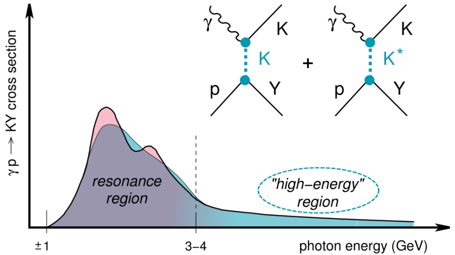

**The RPR strategy: PRC73, 045207 (2006)**

1. Construct Regge model for high-energy (=background) amplitude, and constrain parameters to the available high-energy data.
2. Add resonance contributions ($N^*$ and/or $\Delta^*$) to obtain the full RPR amplitude, and fit parameters to the resonance region data.

# The Regge-plus-resonance (RPR) model II



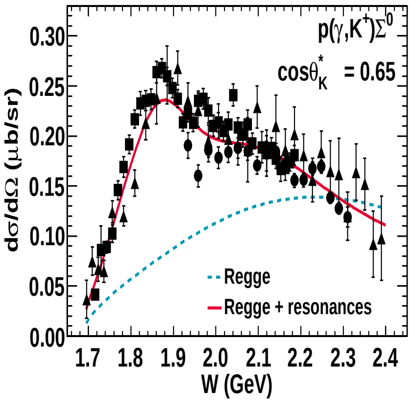

**3 parameters**

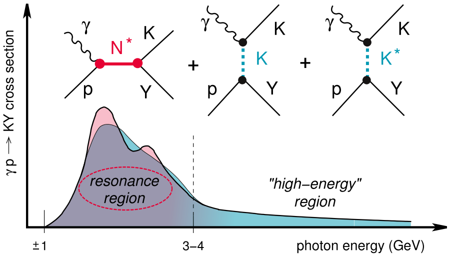



## Background contributions

- Exchange of $K(494)$ and $K^*(892)$ Regge trajectories in $t$ channel
- Valid for $s \gg$ and forward angles
- Describes gross features of data in the resonance region (duality)

# The Regge-plus-resonance (RPR) model III




## Resonant contributions

- enrich Regge background with nucleon and delta resonances
- standard Feynman s-channel diagrams
- EM form factors from Bonn CQM

# Resonance physics with the RPR model: the $p(\gamma, K^+)\Lambda$ case I

## Resonances used in this analysis:

| | | | |
|---|---|---|---|
| $S_{11}(1535)^{\star\star\star\star}$ | $S_{11}(1650)^{\star\star\star\star}$ | $P_{11}(1710)^{\star\star\star}$ | $P_{11}(1900)^{m}$ |
| $D_{13}(1700)^{\star\star\star}$ | $P_{13}(1720)^{\star\star\star\star}$ | $D_{13}(1900)^{m}$ | $P_{13}(1900)^{\star\star}$ |
| $D_{15}(1675)^{\star\star\star\star}$ | $F_{15}(1680)^{\star\star\star\star}$ | $F_{15}(2000)^{\star\star}$ | |

$\star$: PDG status

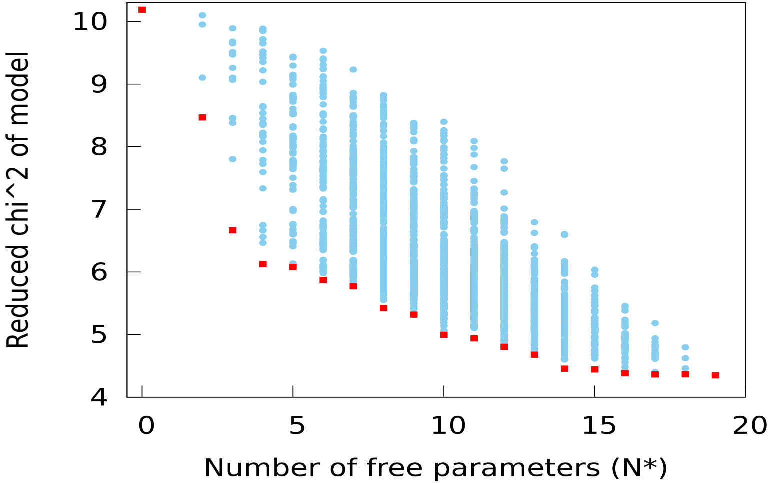
*m*: missing resonance, predicted by CQMs

## Strategy

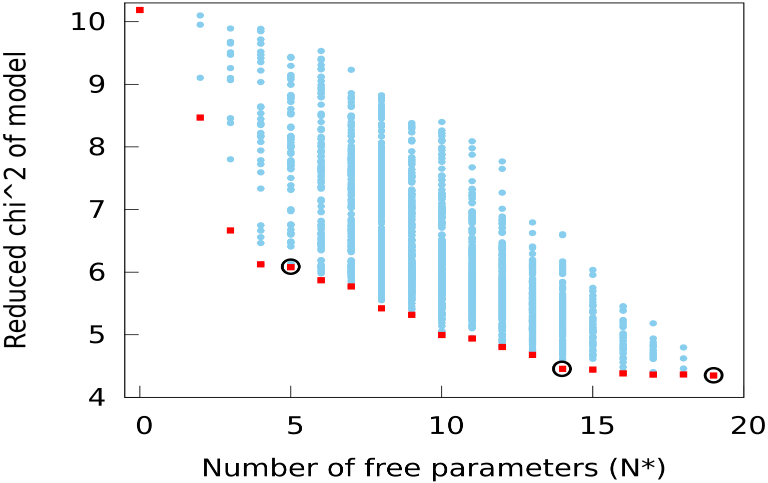
- consider all possible combinations of above list of resonances
- use a genetic algorithm to find optimum model and its parameters
- the fitness of a particular $N^*$ combination and corresponding parameters $\vec{a}$ is determined by: $f_{fitness} = \frac{1}{1+\chi^2(\vec{a})}$

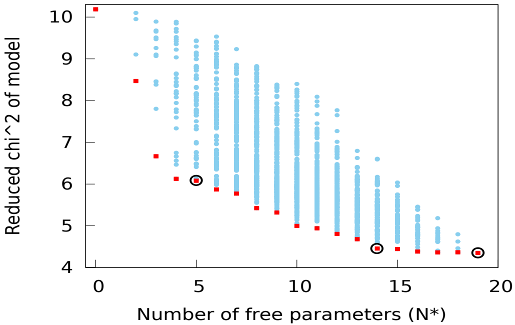
CHALLENGE: there are 2048 possible combinations to evaluate !!!

# Figure of merit for the 2048 $N^*$ combinations



# Figure of merit for the 2048 $N^*$ combinations






Fitted parameters:

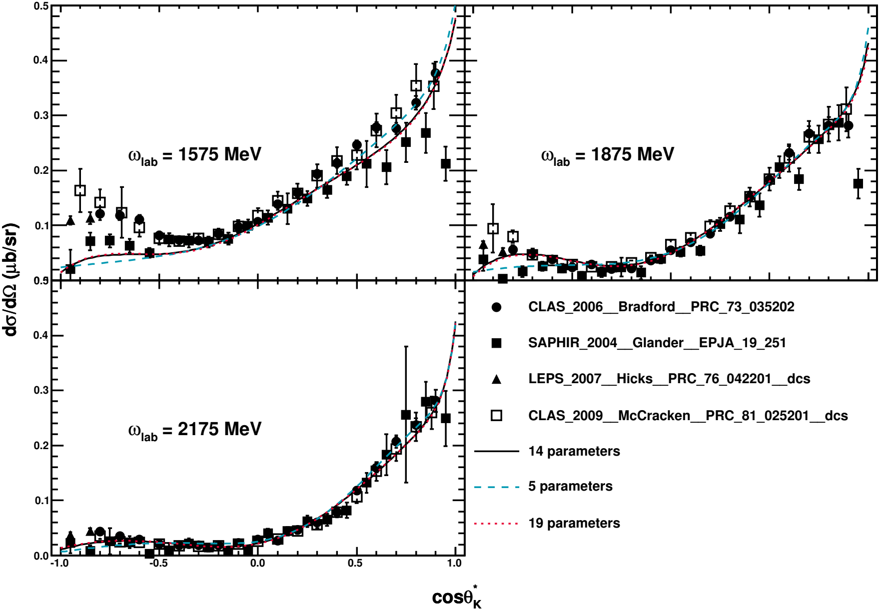
- cutoff parameter $\Lambda$ in the hadronic form factor
- coupling strengths:
  - 1 for $J = \frac{1}{2}$
  - 3 for $J \geq \frac{3}{2}$

**5 parameters:** $\mathbf{S}_{11}(1650)$ **+** $\mathbf{P}_{11}(1710)$ **+** $\mathbf{P}_{13}(1900)$

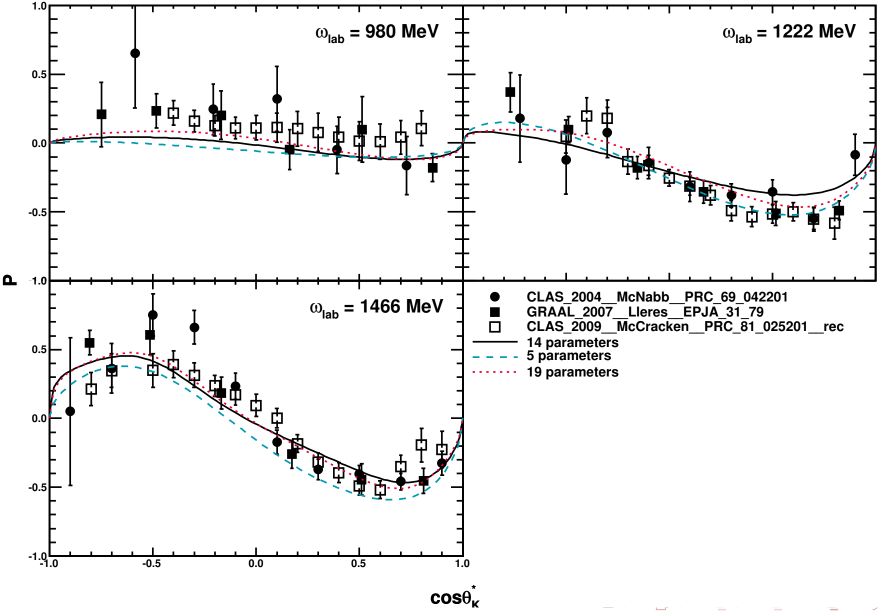
**14 parameters:** $\mathbf{S}_{11}(1535)$ **+** $\mathbf{S}_{11}(1650)$**+** $\mathbf{P}_{13}(1720)$ **+** $\mathbf{D}_{13}(1900)$ **+** $\mathbf{P}_{13}(1900)$ **+** $\mathbf{P}_{11}(1900)$ **+** $\mathbf{F}_{15}(1680)$ **+** $\mathbf{D}_{15}(1675)$

**20 parameters:** **all 11 $N^*$'s**

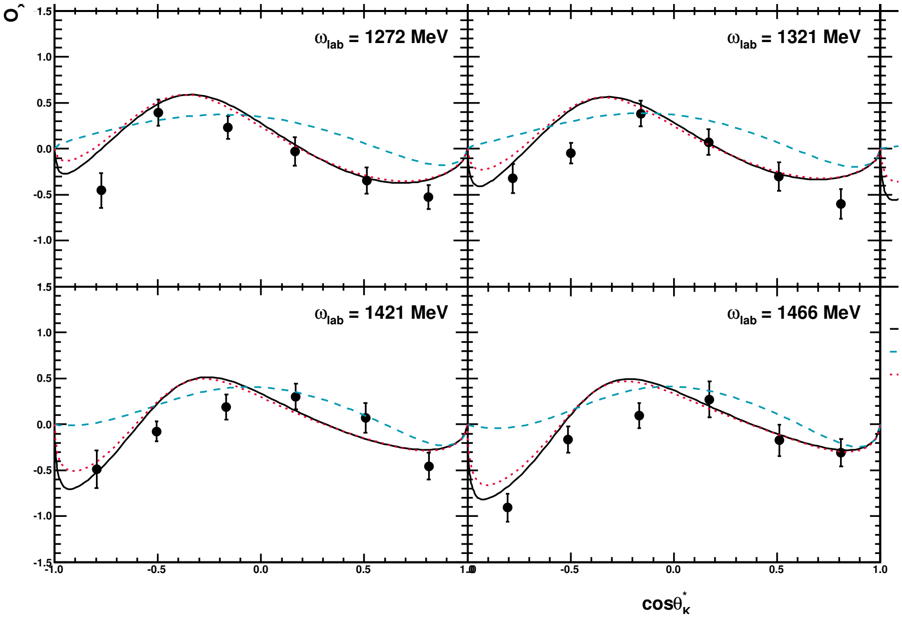
# $p(\gamma, K^+)\Lambda$: differential cross sections



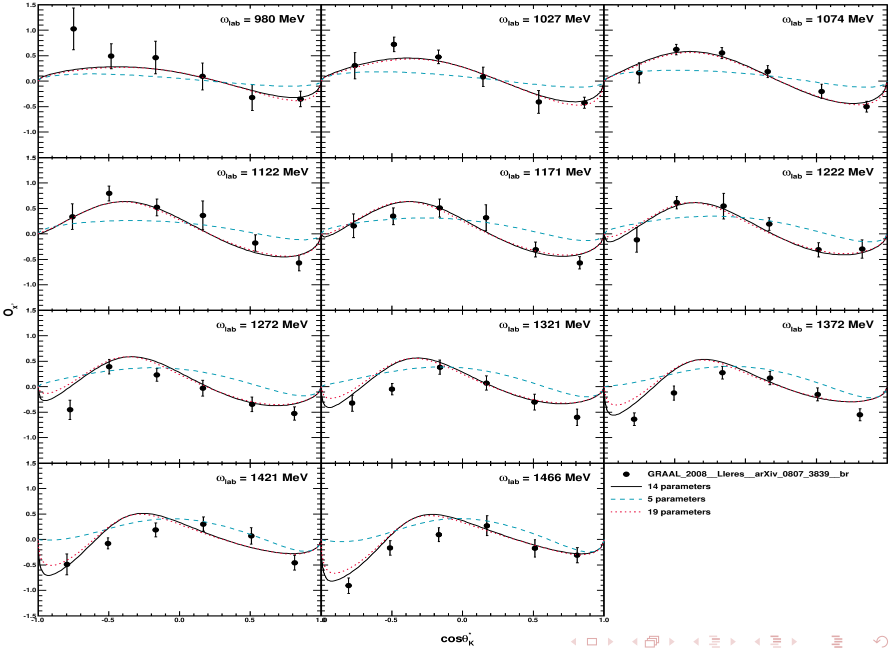
# $p(\gamma, K^+)\vec{\Lambda}$: recoil polarisation



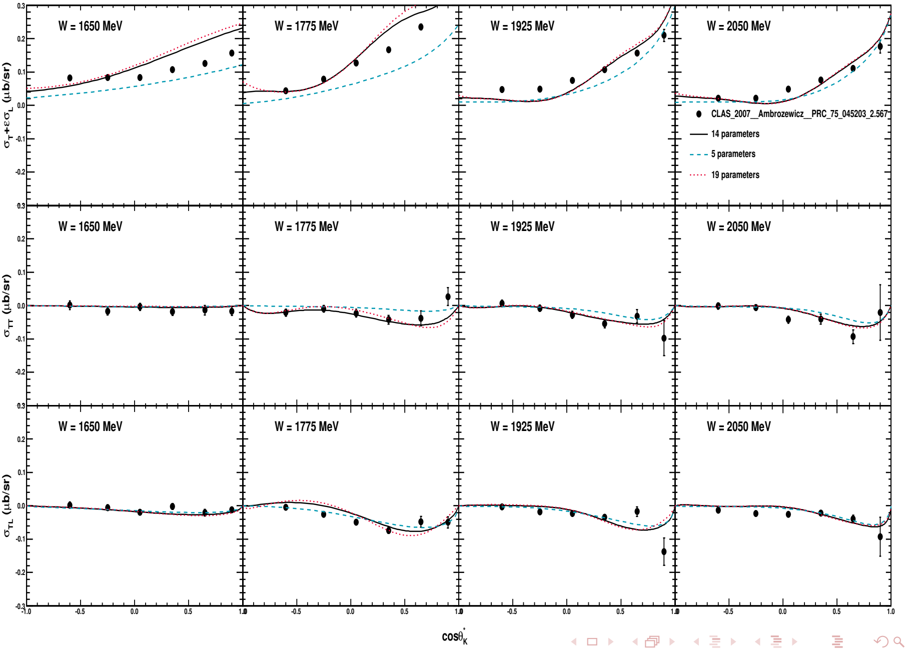
# $p(\vec{\gamma}, K^+)\vec{\Lambda}$: beam-recoil polarisation $O_{x'}$



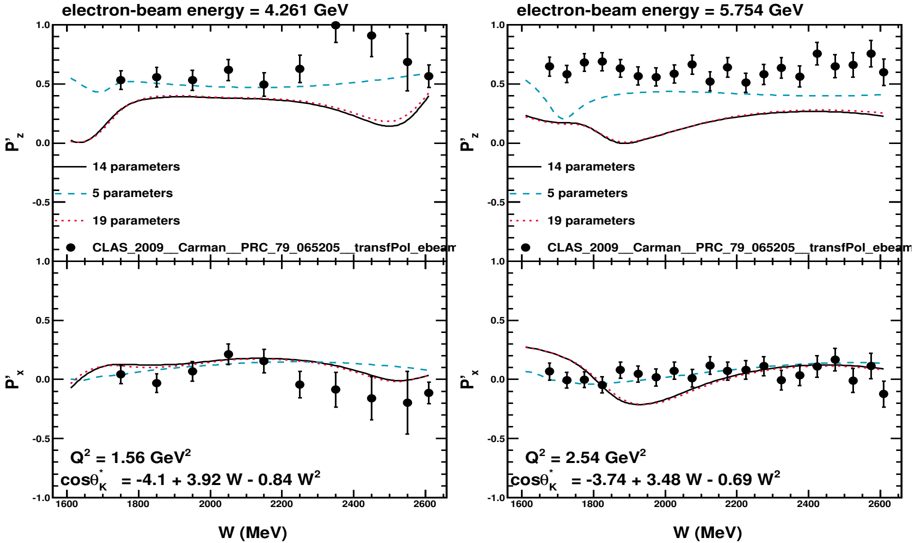
# $p(\vec{\gamma}, K^+)\vec{\Lambda}$: beam-recoil polarisation $O_{x'}$



# $p(e, e'K^+)\Lambda$: structure functions for $Q^2 = 0.65\ GeV^2$

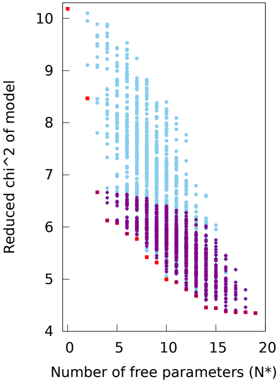


# $p(\vec{e}, e' K^+)\vec{\Lambda}$: transferred polarisation

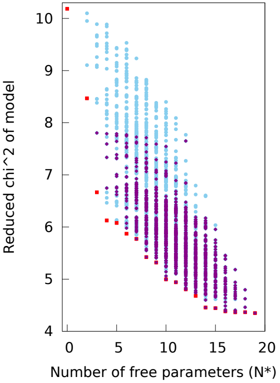


# Importance of the $P_{13}(1900)$ / $D_{13}(1900)$

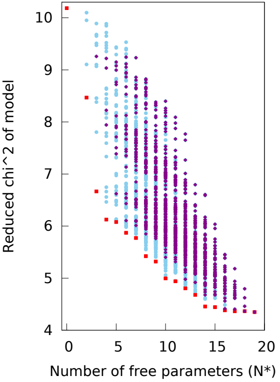
Models that include $P_{13}(1900)$




Models that include $D_{13}(1900)$



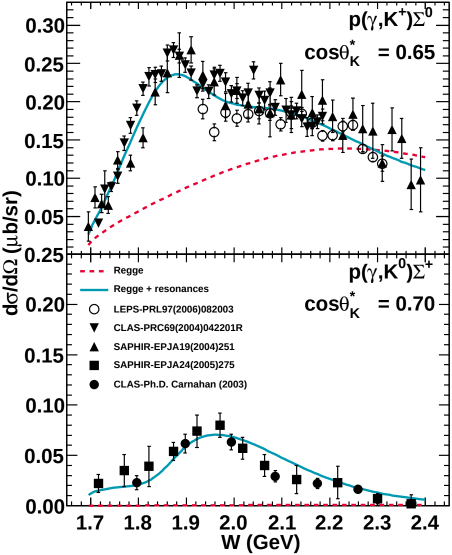

By comparison: $D_{13}(1700)$




$P_{13}(1900)$: ⋆⋆ PDG status

$D_{13}(1900)$: missing resonance

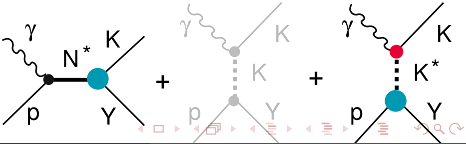
# Neutral-kaon production: $p(\gamma, K^0)\Sigma^+$ I




## $p(\gamma, K^+)\Sigma^0 \longrightarrow p(\gamma, K^0)\Sigma^+$

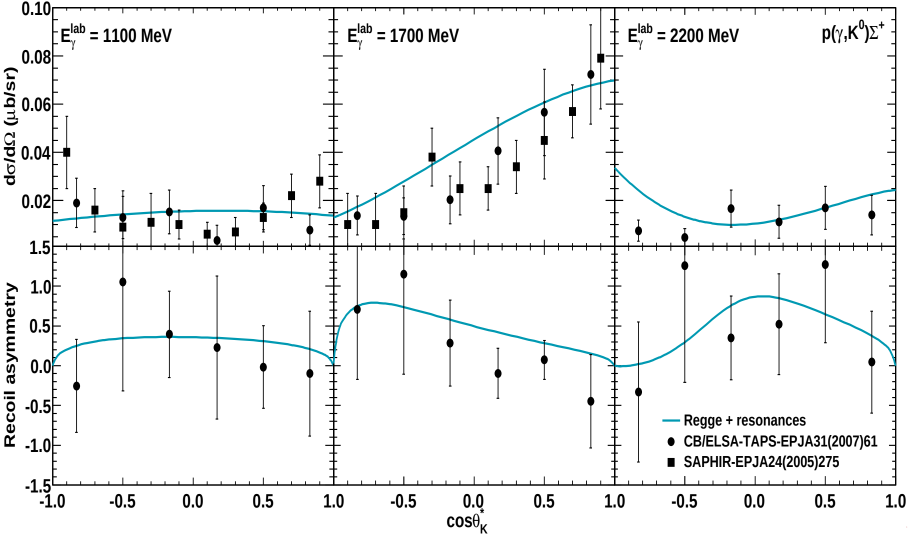
- $K(494)$-exchange vanishes
- isospin relations at strong vertex
  $$g_{K^{(*)0}\Sigma^+N^{(*)}} = \sqrt{2} g_{K^{(*)+}\Sigma^0 N^{(*)}}$$
- Fit ratio of EM coupling constants
  $$\frac{\kappa_{K^{*0}(892)K^0(494)}}{\kappa_{K^{*+}(892)K^+(494)}} = 0.05 \pm 0.01$$

Fair description of data ($\chi^2/n.d.f. = 3.4$).

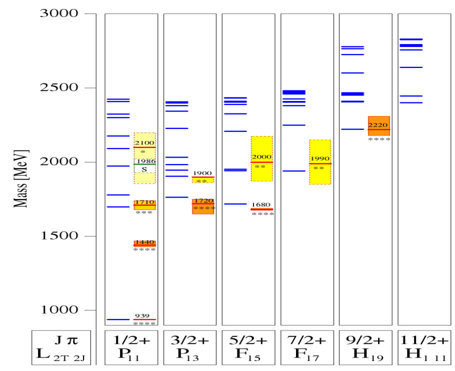


# Neutral-kaon production : $p(\gamma, K^0)\Sigma^+$ II

## Differential cross section and photon asymmetry



## Why studying kaon production on the neutron?

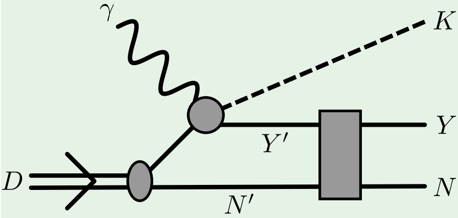



**The $N^*$ spectrum according to the Relativistic Constituent Quark Model of the Bonn group**

- extract the $n(\gamma, K)Y$ amplitude: complementary information about $N^*$
- investigate nuclear-medium effects
- study of the hyperon-nucleon potential
  - hypernuclear spectroscopy
  - final-state interactions in $^2$H$(\gamma, KY)N$

# Kaon production from the neutron (deuteron) II

## An RPR model for kaon production on the neutron (deuteron)




- Elementary-production operator: RPR model
  - Describes $K^+\Lambda$ and $K^+\Sigma^0$ channels from the proton
  - Parameters for the neutron derived from the ones of the proton (isospin!)
- *Dnp*-vertex: relativistic
- FSI: $YN \longrightarrow Y'N'$

# Kaon production from the free neutron $n(\gamma, K^+)\Sigma^-$ I

| Resonance | | SAID PRC53(1996)430 |
|---|---|---|
| $S_{11}(1650)$ | $\frac{\kappa_{N^*n}}{\kappa_{N^*p}}$ | $-0.22 \pm 0.07$ |
| $P_{11}(1710)$ | $\frac{\kappa_{N^*n}}{\kappa_{N^*p}}$ | $-0.29 \pm 2.23$ |
| $P_{13}(1720)$ | $\frac{\kappa^{(1)}_{N^*n}}{\kappa^{(1)}_{N^*p}}$ | $-0.38 \pm 2.00$ |
| | $\frac{\kappa^{(2)}_{N^*n}}{\kappa^{(2)}_{N^*p}}$ | $-0.50 \pm 1.08$ |
| | | Unknown |
| $P_{13}(1900)$ | $\frac{\kappa^{(1)}_{N^*n}}{\kappa^{(1)}_{N^*p}}$ | $0.00 \pm 2.00$ |
| | $\frac{\kappa^{(2)}_{N^*n}}{\kappa^{(2)}_{N^*p}}$ | $0.00 \pm 2.00$ |

**Photocoupling helicity amplitudes from SAID analysis**

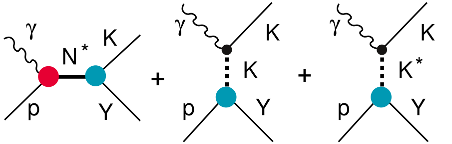
### $p(\gamma, K^+)\Sigma^0 \longrightarrow n(\gamma, K^+)\Sigma^-$

- isospin relations at strong vertex

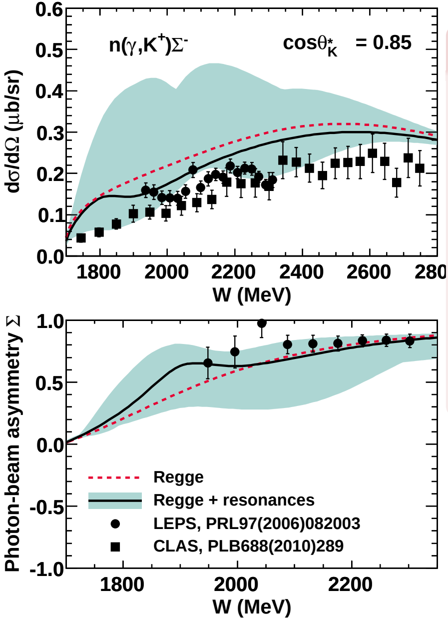
$$g_{K^{(*)+}\Sigma^- N^{(*)0}} = \sqrt{2}\, g_{K^{(*)+}\Sigma^0 N^{(*)+}}$$
$$\sqrt{2}\, g_{K^+\Sigma^-\Delta^{*0}} = g_{K^+\Sigma^0\Delta^{*++}}$$

- ratio of helicity amplitudes at EM vertex

$$\frac{\kappa_{nN^*}}{\kappa_{pN^*}} = \frac{\mathcal{A}^n_{1/2}}{\mathcal{A}^p_{1/2}}, \ldots$$



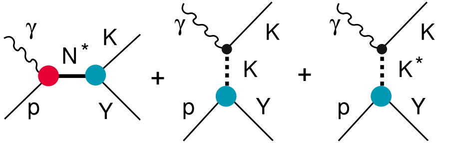
# Kaon production from the free neutron $n(\gamma, K^+)\Sigma^-$ II



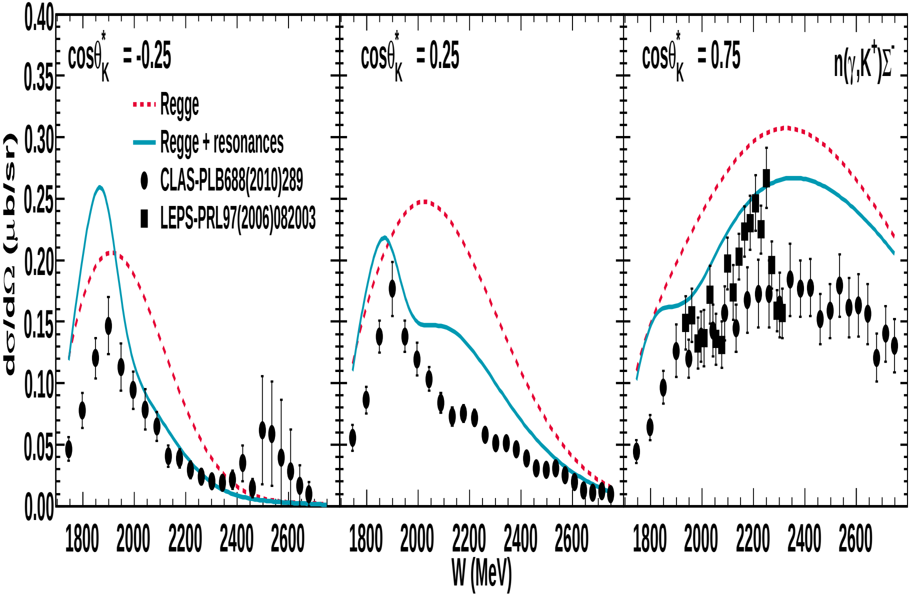

$p(\gamma, K^+)\Sigma^0 \longrightarrow n(\gamma, K^+)\Sigma^-$

- isospin relations at strong vertex
- ratio of helicity amplitudes at EM vertex

$N^*$ helicity amplitudes subject to error bars!
P. Vancraeyveld *et al.* PLB681(2009)428

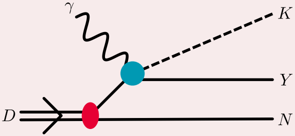


# Kaon production from the free neutron $n(\gamma, K^+)\Sigma^-$ III



# Kaon production from the deuteron: formalism (I)

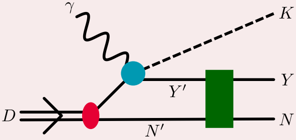
## Plane-wave impulse approximation




- **covariant *Dnp*-vertex**
- **elementary-production operator: Regge-plus-resonance model**

+

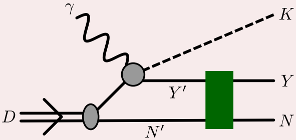
## Hyperon-nucleon final-state interactions




- **hyperon-nucleon interaction: Juelich model**

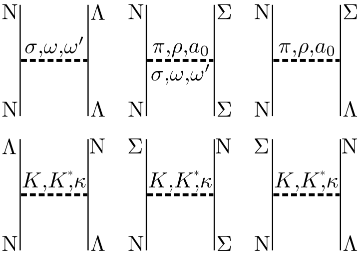
# Kaon production from the deuteron: formalism (II)

## Hyperon-nucleon final-state interactions




$$= \frac{-i}{32\pi^2} \int d\Omega_{N'} \frac{|\vec{p}^{\,*}_{N'}|}{W_{YN}} \mathcal{M}(YN \rightarrow Y'N')$$

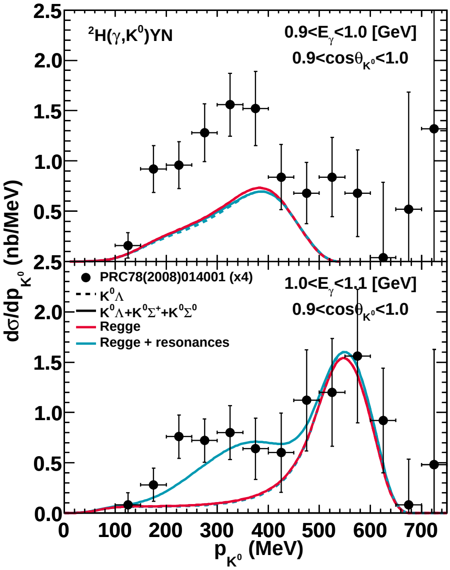
$$\times\ \overline{u}_{Y'}\ \Gamma^{\lambda_\gamma}_{\mathrm{RPR}}\ \frac{m_N + \not{p}_T}{m_N^2 - p_T^2}\ \Gamma^{\lambda_D}_{\mathrm{Dnp}}\ \mathcal{C}\overline{u}^T_{N'}$$




## Hyperon-nucleon interaction

- Juelich model (PRC72(2005)044005)
- elastic + inelastic rescattering
- restrict to on-shell rescattering
- no sub-threshold production

# RPR predictions for $^2H(\gamma, K^0)\,YN$



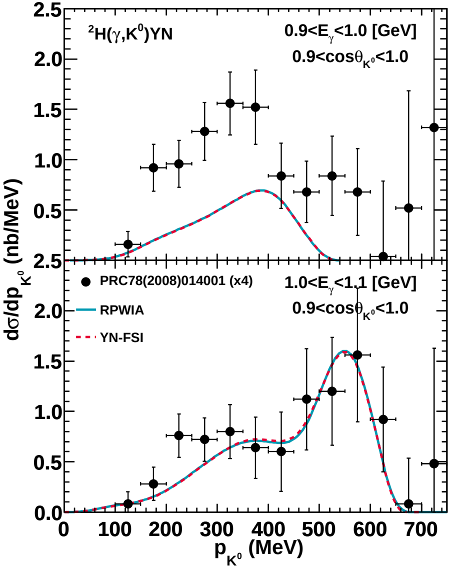

## LNS: PRC78 (2008) 014001

- Semi-inclusive $K^0$ production $= K^0\Lambda + K^0\Sigma^0 + K^0\Sigma^+$
- Only forward angles $\frac{d\sigma}{dp_K} = 2\pi \int_{0.9}^{1.0} \frac{d\sigma}{dp_K\, d\Omega_K} d\cos\theta_K$

## RPR predictions

- $\langle E_\gamma^{lab} \rangle = 950\,\text{MeV}$
  - near $K^0\Sigma$ threshold
  - data is underpredicted
- $\langle E_\gamma^{lab} \rangle = 1050\,\text{MeV}$
  - 2 quasi-elastic peaks
  - good predictions

# RPR predictions for $^2H(\gamma, K^0)\,YN$

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## RPR predictions

- $\langle E_\gamma^{lab} \rangle = 950\,\text{MeV}$
  - near $K^0\Sigma$ threshold
  - data is underpredicted
- $\langle E_\gamma^{lab} \rangle = 1050\,\text{MeV}$
  - 2 quasi-elastic peaks
  - good predictions
- effect of "YN" FSI is small

# Conclusions

**These are exciting times for modelers in open strangeness production (high-quality data over extended energy range, proton AND neutron targets, single and double polarization data, complete measurements, hypernuclear results at the horizon)**

## Regge-plus-resonance (RPR) approach

- fixes Regge background at **high energies**
- adds $N^*$'s and $\Delta^*$'s in the **resonance region**
- economical and gauge-invariant description of $K^+\Lambda$ and $K^+\Sigma^0$ channels for threshold $\leq E_\gamma^{lab} \leq 16\,\text{GeV}$
- **RPR has predictive power**
  - $K^0$ production
  - electroproduction
  - $K$ production from the neutron (deuteron)


THANK YOU!