Weak Pion Production in Baryon ChPT

NuSTEC

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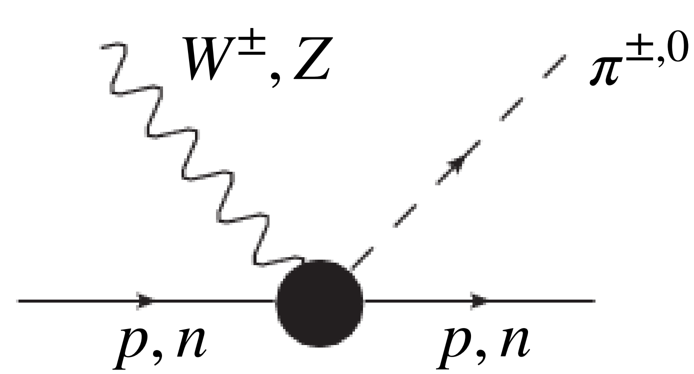
Why single-pion production?

- $\nu_l(\bar{\nu}_l)N \to \pi^{\mp}N'$ gives leading contributions to $\nu_l(\bar{\nu}_l)N$ cross sections.
- Extremely relevant for **precision in neutrino oscillation experiments.**
- **Charged-pion production** needs to be well tackled because of risk of **misidentification as quasi-elastic** channels $\nu_l(\bar{\nu}_l)N \to l^{\mp}N'$. This would lead to bias in neutrino energy reconstruction.
- **Neutral-pion production** contributes to the **electron-like background** in $\nu_\mu \to \nu_e$ oscillation measurements.
- Single-pion production in oscillation analyses still taken with 20-30% errors.



What can we learn close to threshold?

- Neutrino-induced pion production is not monochromatic:
  need to integrate over wide energy bins.
- The more one can get predictive constraints from theory models,
  the more reliable the analyses will be.
- Chiral perturbation theory (ChPT) can predict the low-energy region.

Baryon chiral perturbation theory: an introduction

First studies: pion photoproduction

Pion electro-weak production

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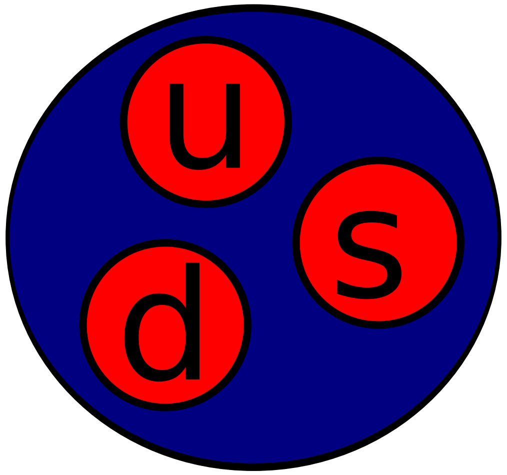
Chiral perturbation theory

- Effective field theory of QCD for large distances (low energies):
  quarks and gluons integrated out, hadrons are our elementary particles.

- We're in the region in which perturbative QCD breaks down.
  Instead of α_s we need new **expansion** parameters:
  small masses (pions) and **external momenta** (close to threshold)
  when compared to the scale (~1 GeV).



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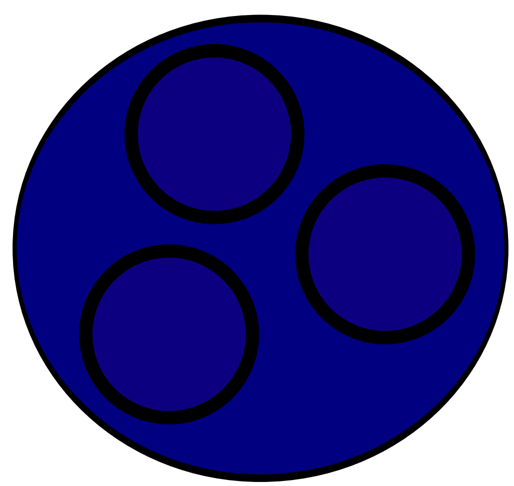
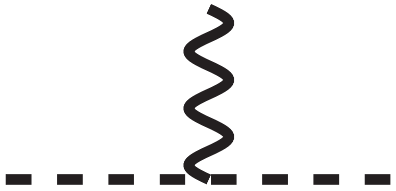


Example Lagrangian terms

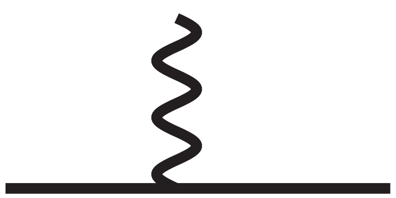
- Lowest-order meson couplings ~ $p_{\text{ext}}^2, m_\phi^2$:

$$\mathscr{L}^{(2)}_{\phi\phi\gamma} = \frac{F_\phi^2}{4} \left\langle \nabla_\mu U \, \nabla^\mu U + \chi_+ \right\rangle$$



- Lowest-order baryon couplings ~ p_{ext} :

$$\mathscr{L}^{(1)}_{\phi B\gamma} = \left\langle \bar{B}(\mathrm{i}\not{D} - m)B \right\rangle + \frac{D}{2}\mathrm{Tr}\left(\bar{B}\gamma^\mu \left\{u_\mu, B\right\} \gamma_5\right) + \frac{F}{2}\mathrm{Tr}\left(\bar{B}\gamma^\mu \left[u_\mu, B\right] \gamma_5\right)$$



- Low-energy constants (LECs) appear order by order — have to be fitted to data, but many already well known!

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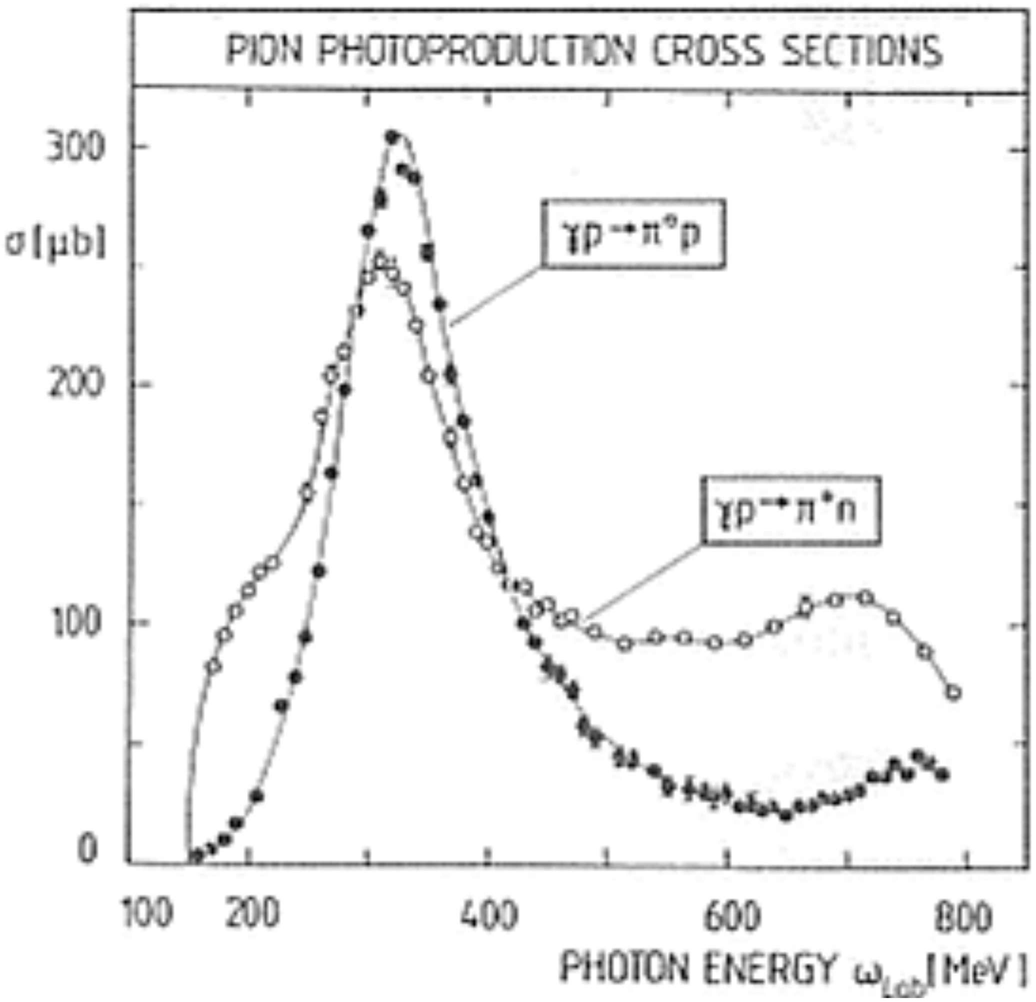
Pion electro-weak production

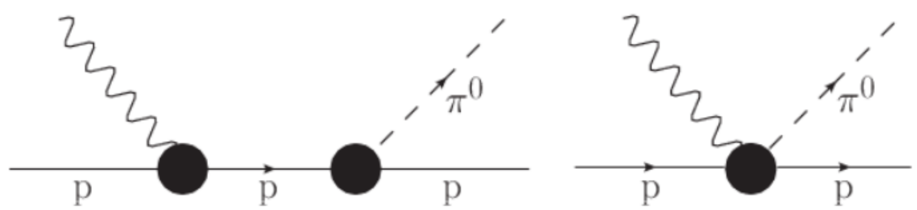
“Simple” case: neutral pion photoproduction

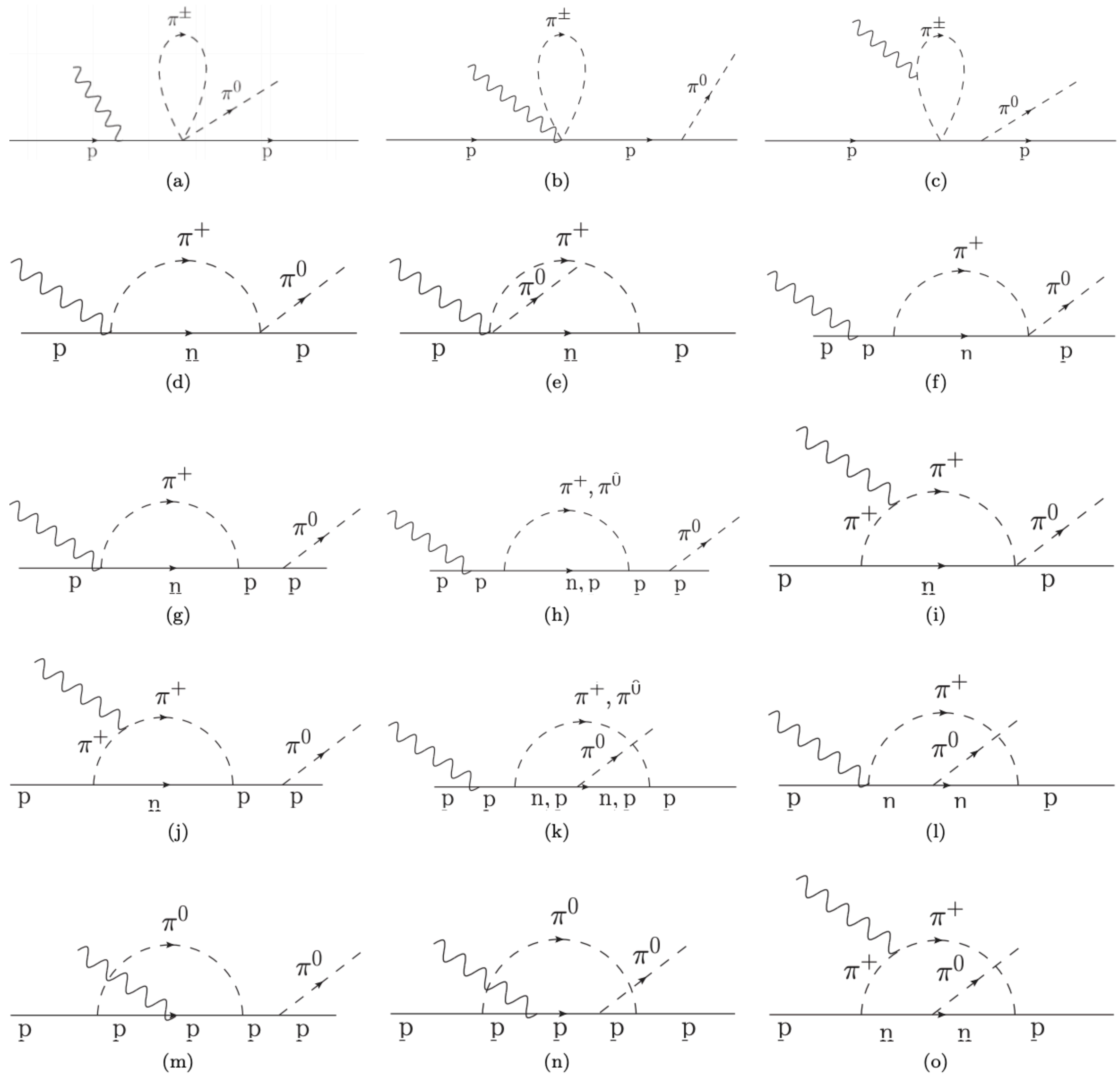


- Neutral pion production cross section much smaller than for charged channels at threshold.
- Charged channels well described at tree level; **neutral channel NOT, loops needed!**
  Bernard et al., Nucl.Phys. B383 (1992) 442
- Need $\Delta(1232)$ even very close to threshold.
  Hemmert et al., Phys.Lett. B395 (1997) 89

Precise low-energy data from MAMI re-analysis of previous ChPT works:
even $\mathcal{O}(p^4)$ calculations could not describe data beyond 20 MeV from threshold!
Hornidge et al., Phys.Rev.Lett. 111 (2013) 062004

Our approach: $\mathcal{O}(p^3)$ calculation with $\Delta(1232)$





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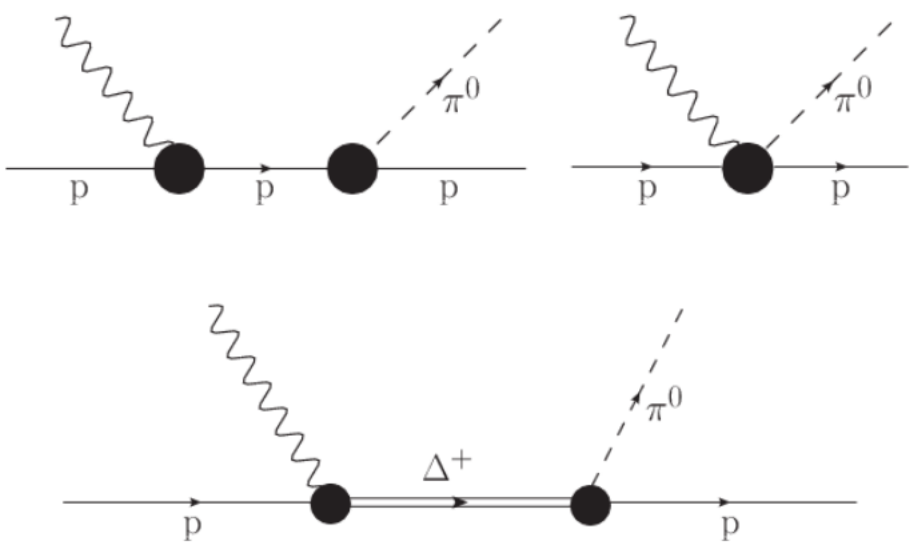
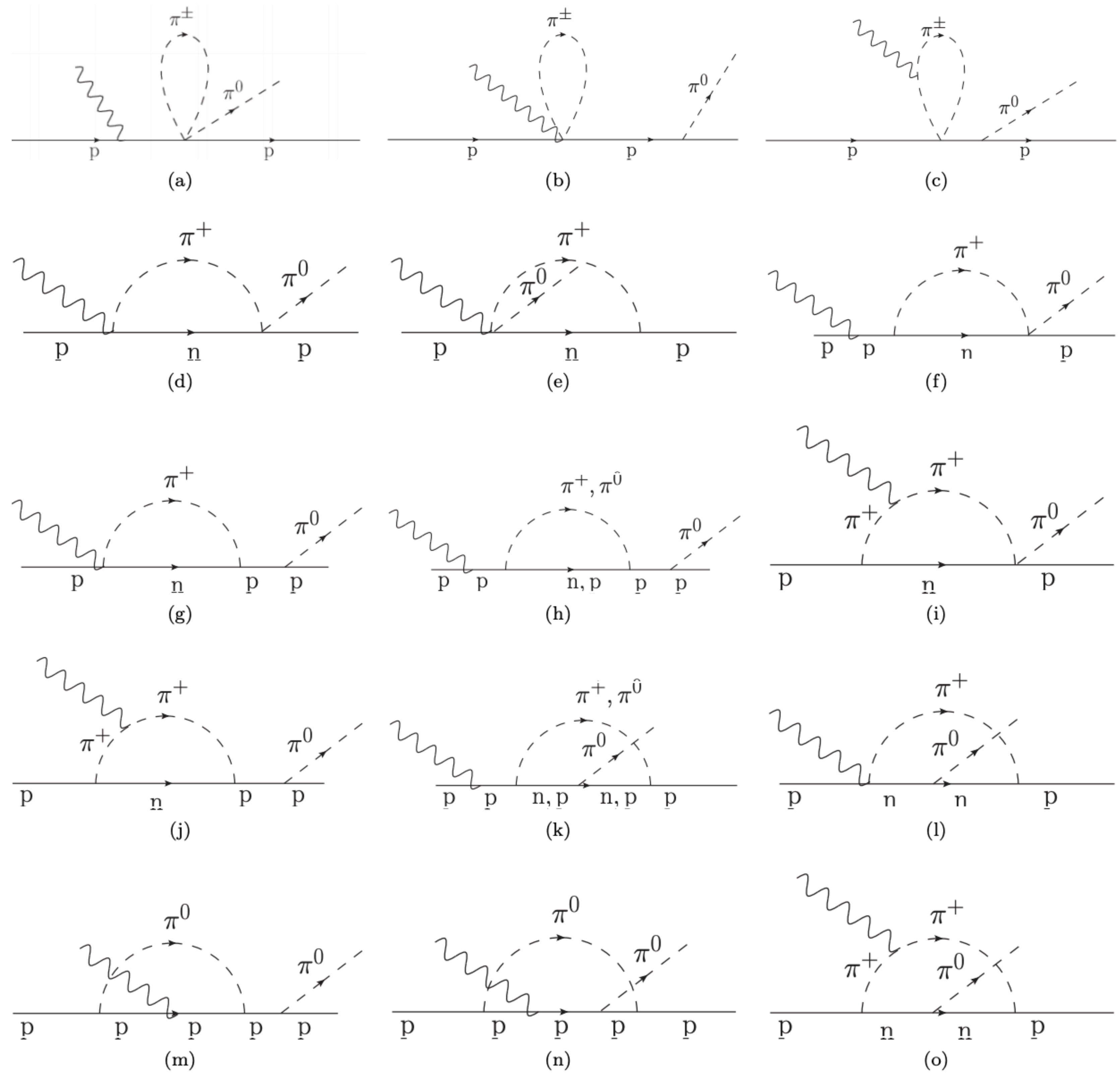
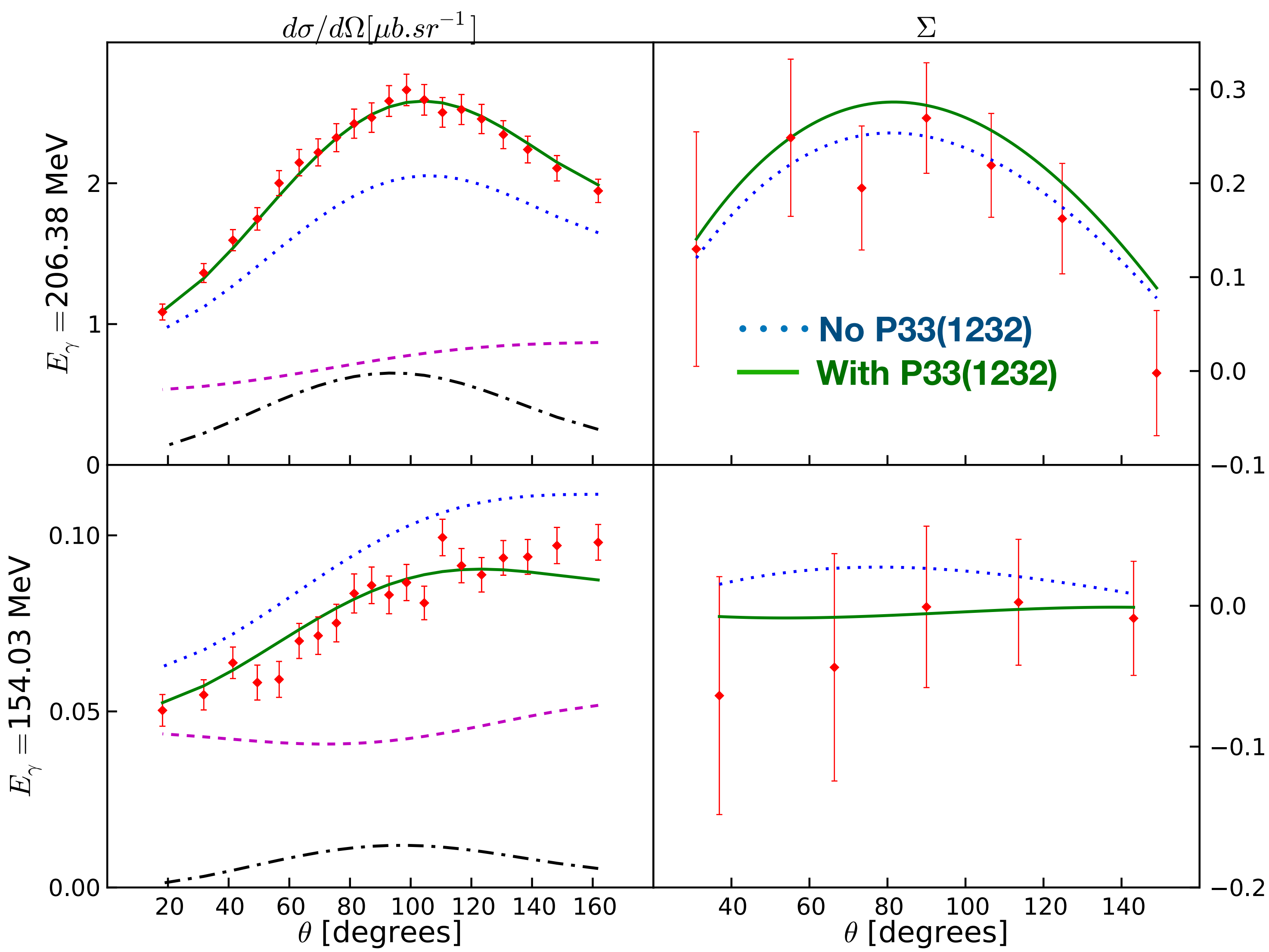




Confronting results with and without $\Delta(1232)$ resonance

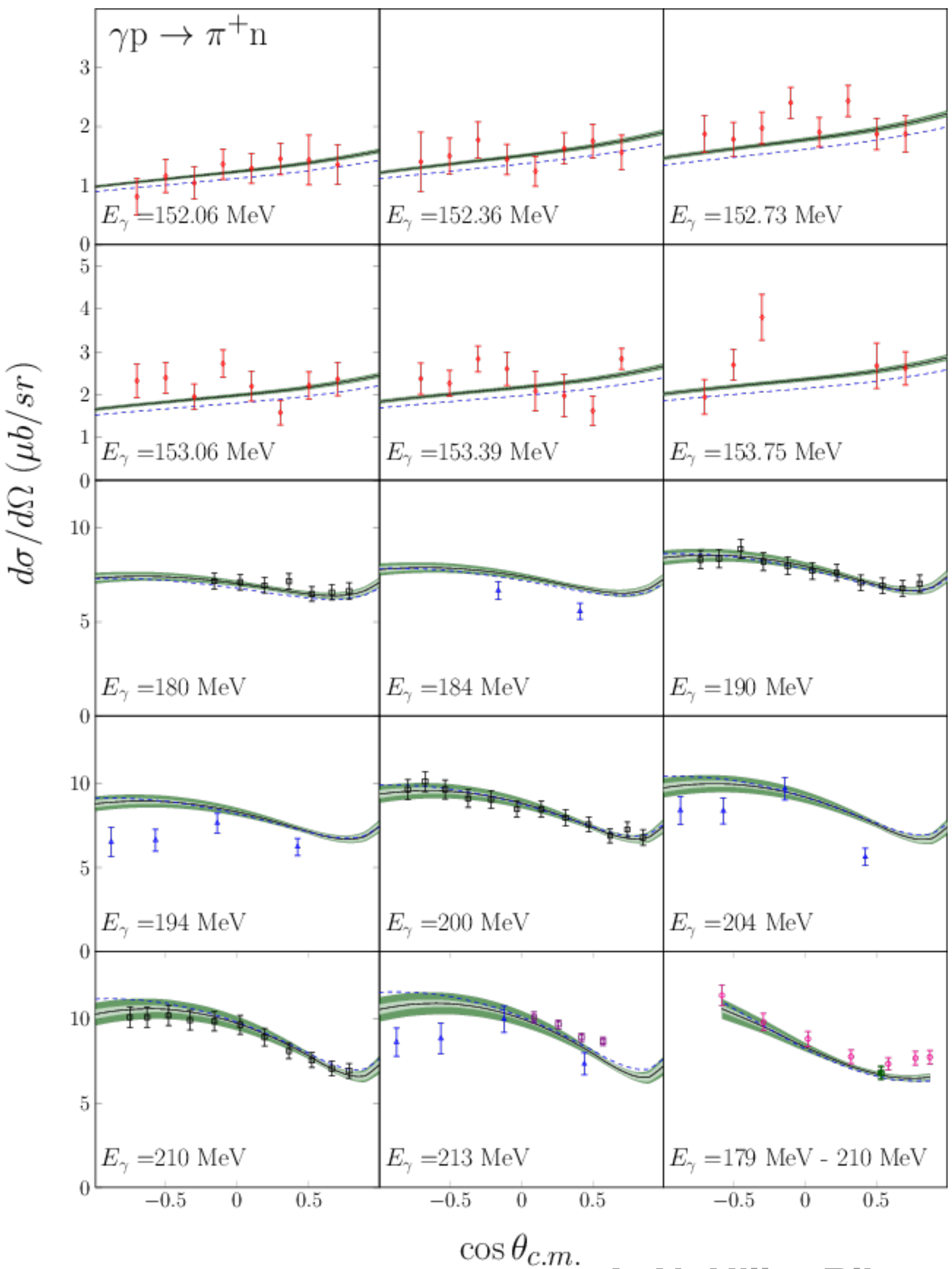


- Angular distribution described well without $\Delta(1232)$.
- But steep increase of cross sections: **order of magnitude within 50 MeV!**
- Achieved excellently only when including $\Delta(1232)$.

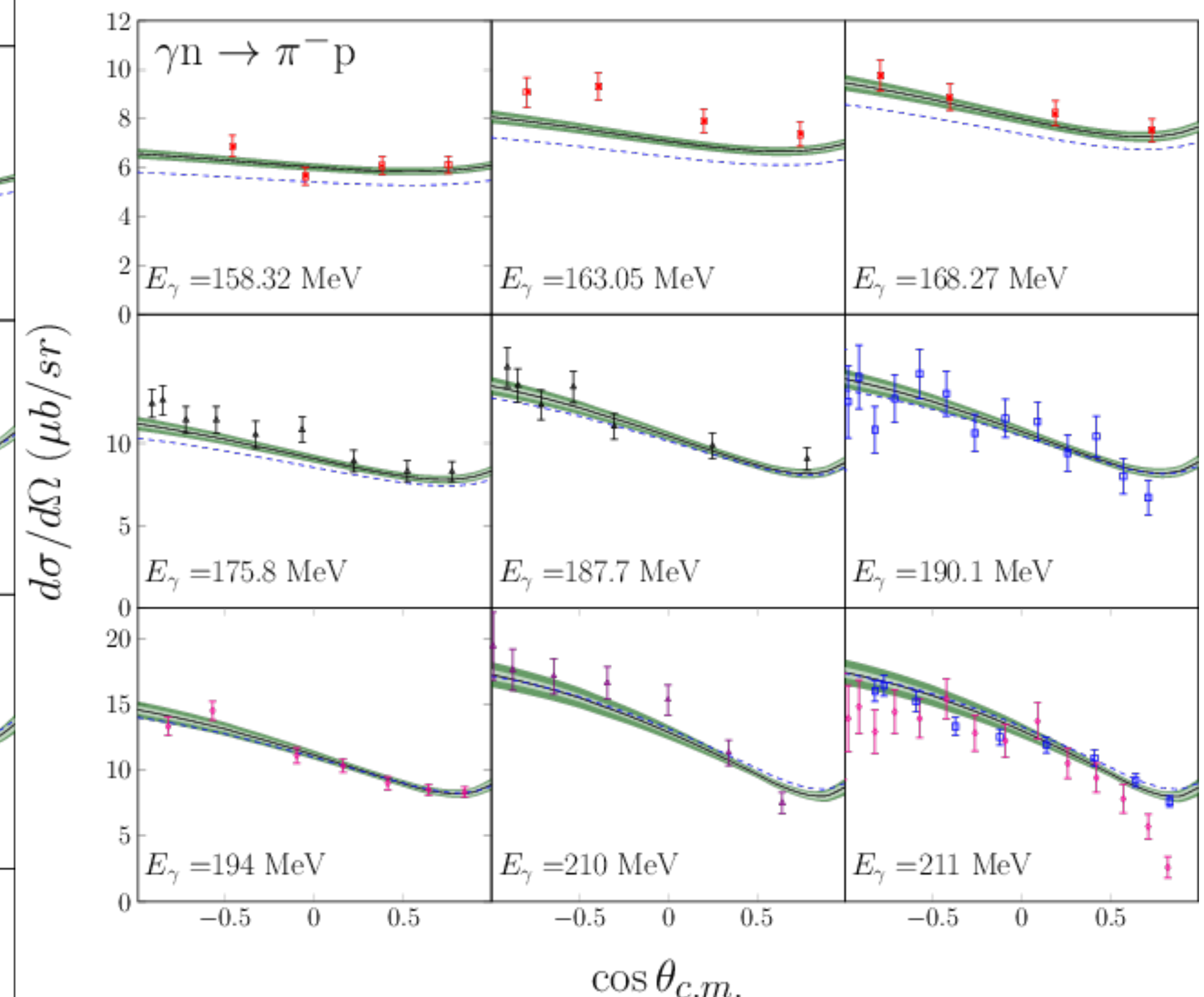
ANHB, Ledwig, Vicente Vacas, Phys.Lett. B747 (2015) 217
ANHB, Ledwig, Vicente Vacas, Phys.Rev. D93 (2016) 094018

- **800** data points: only **3** fitting parameters!
- Important constraints on reaction-specific LECs.

Charged pion photoproduction



The combined fit of charged an neutral pion photoproduction data allowed for further constraints/disentagling of LECs.



Guerrero Navarro, Vicente Vacas, ANHB, Yao, Phys.Rev. D100 (2019) 094021

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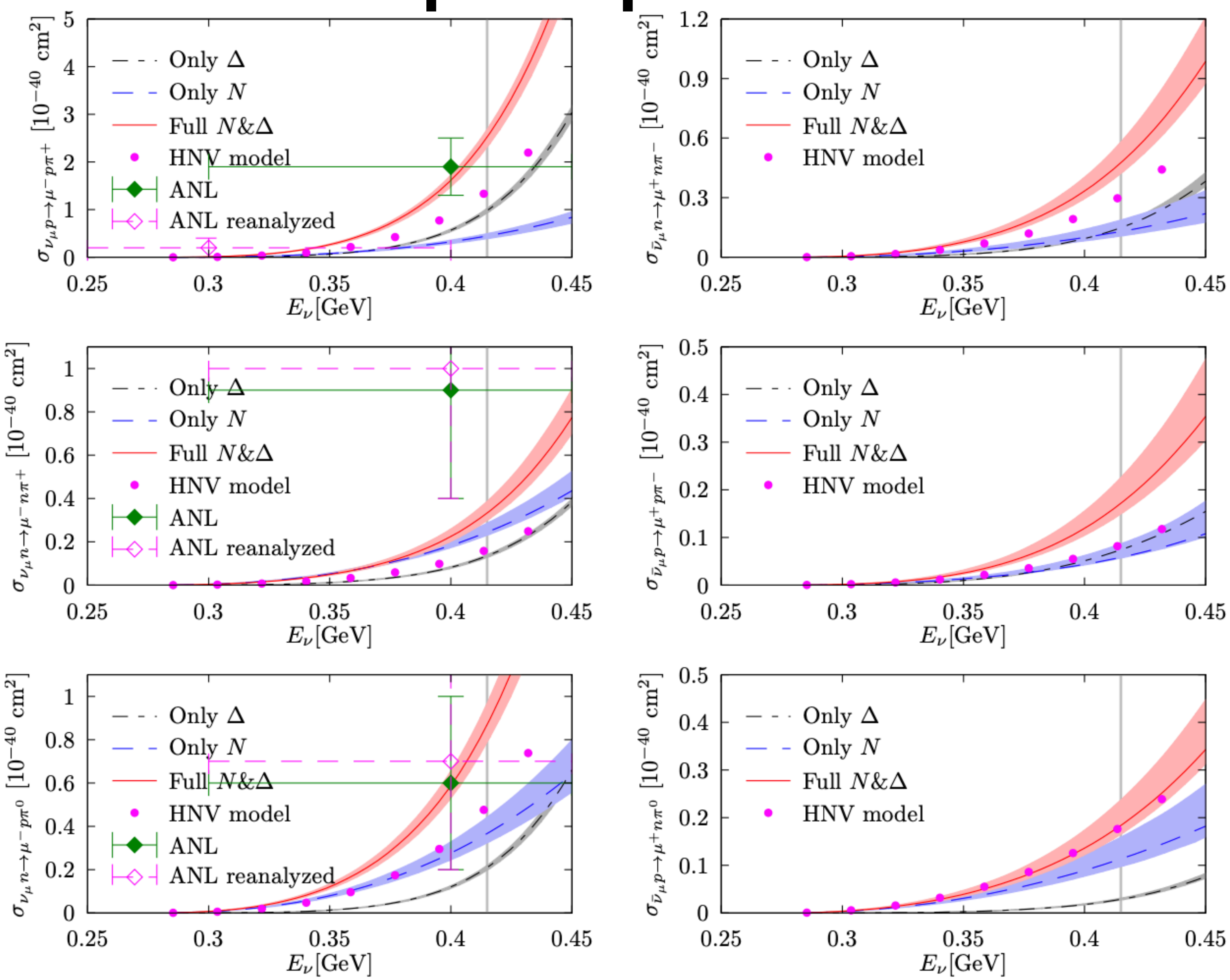
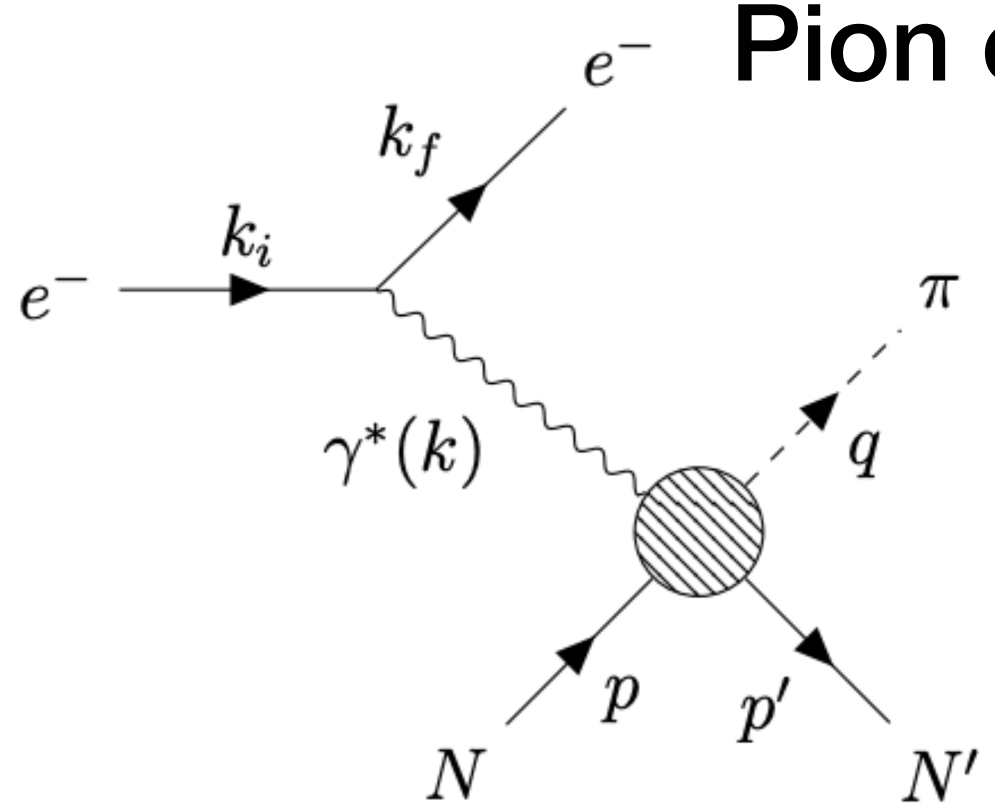
<u>Pion electro-weak production</u>

Weak pion production

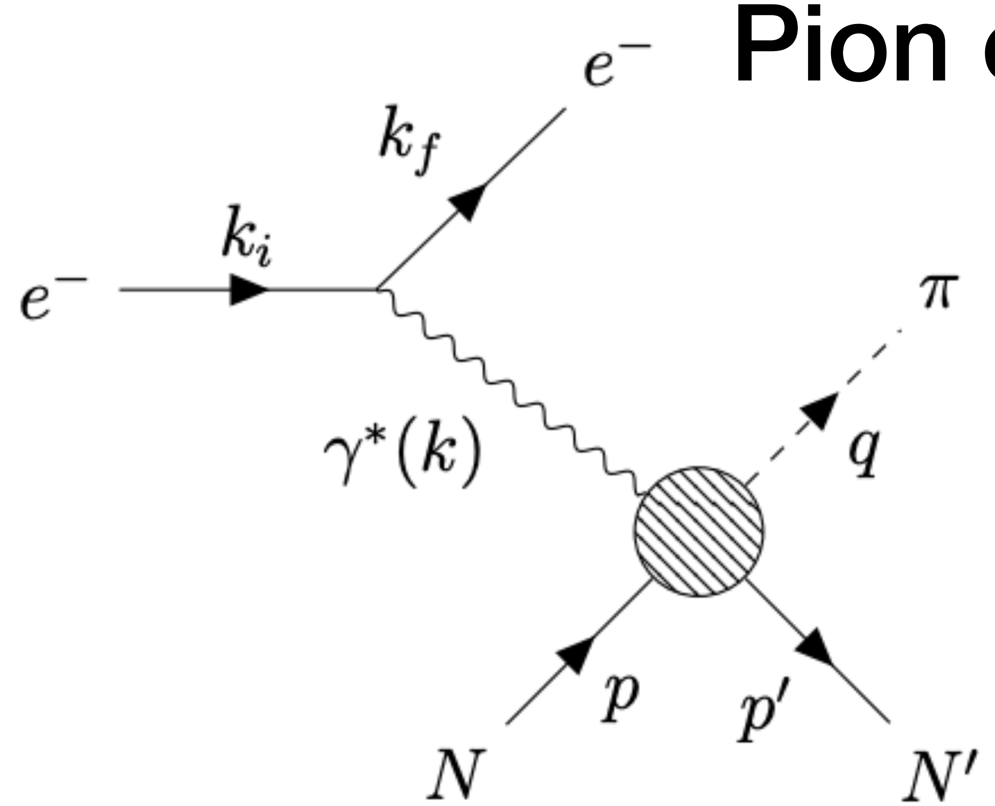


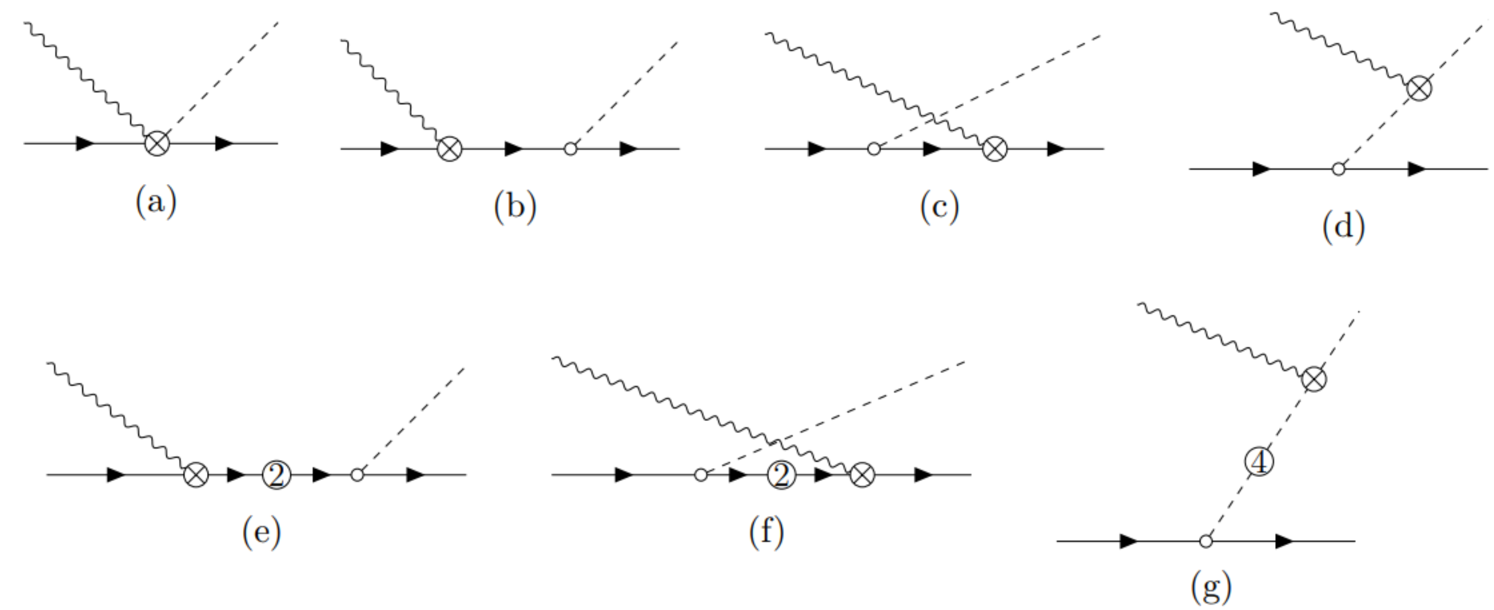
- Here, fits cannot really be made: most LECs known, others taken with natural size.
- $\Delta(1232)$ contributes significantly to all channels: relevant for data reproduction.
- Most other LECs can be determined from electroproduction studies.

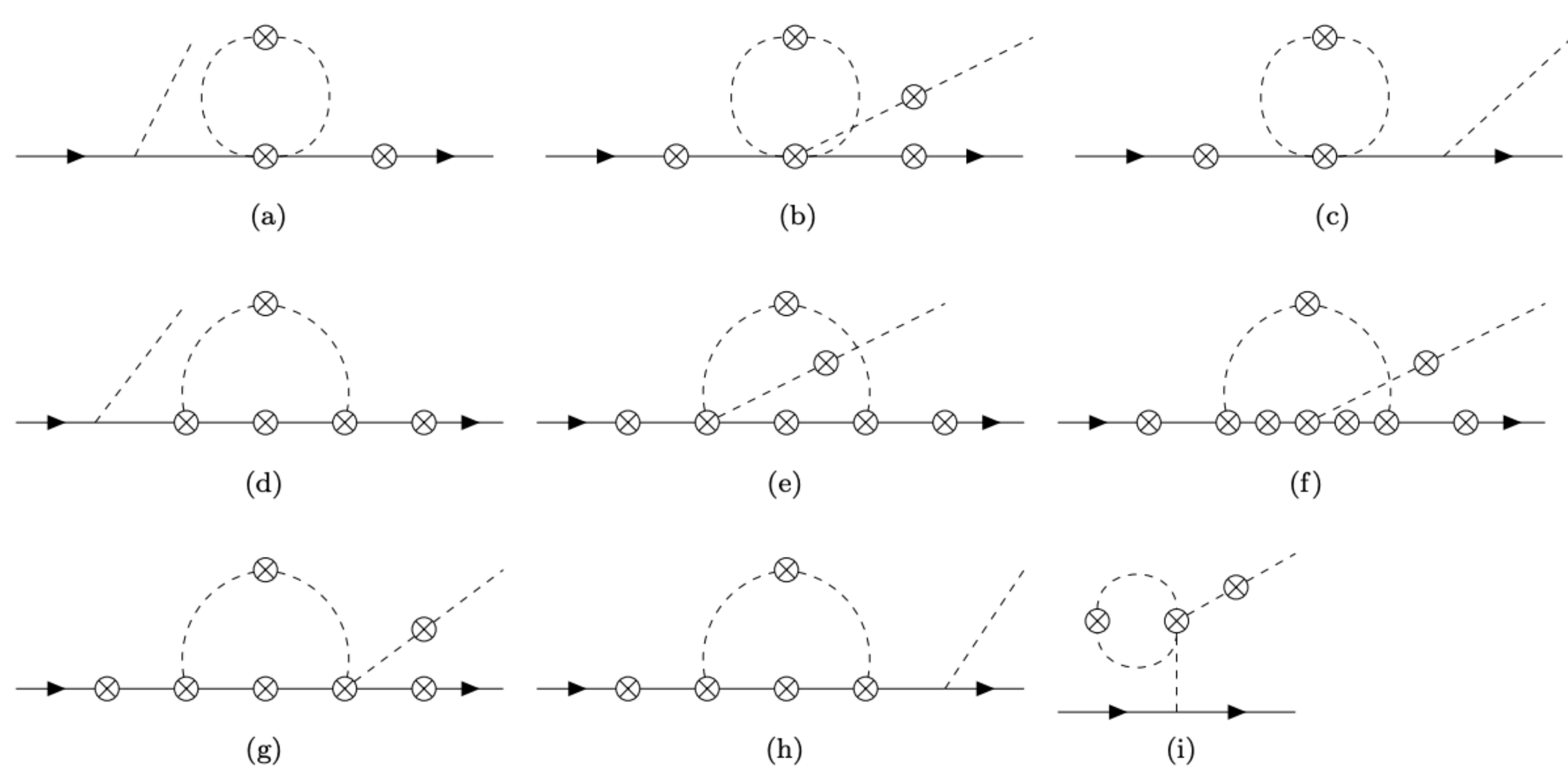
Pion electroproduction



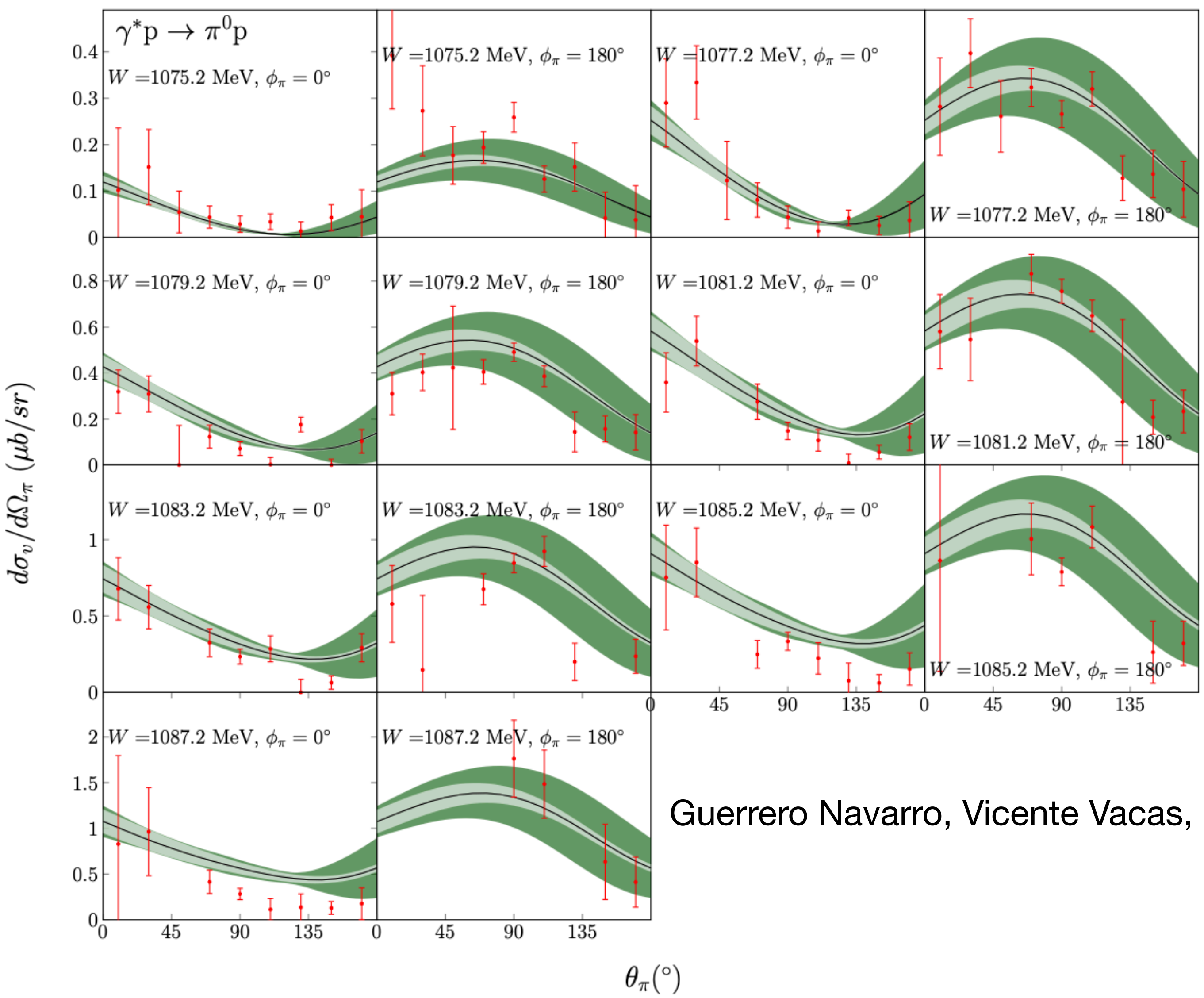
Pion electroproduction

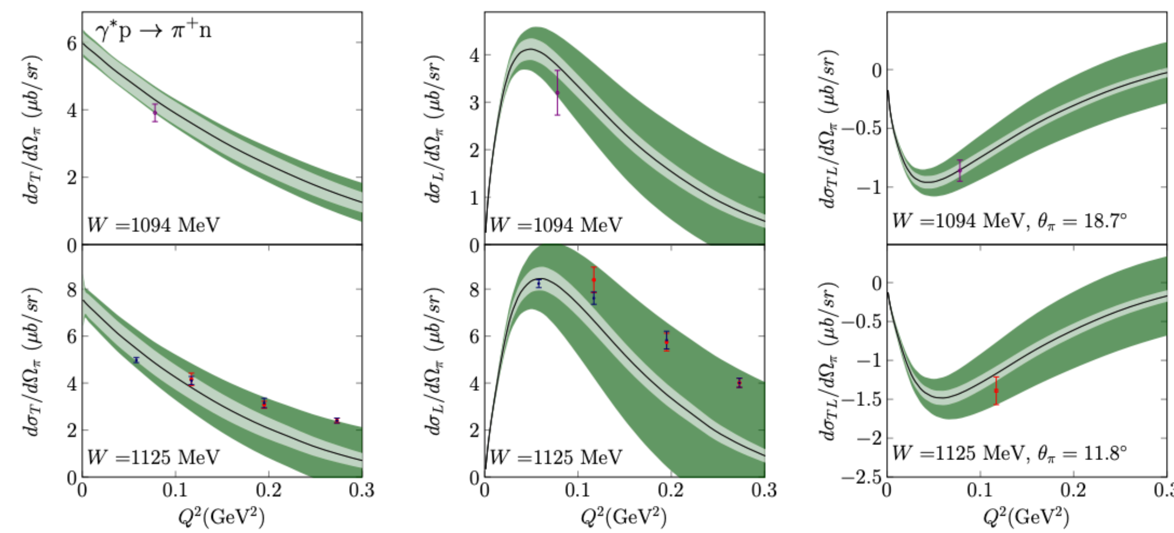




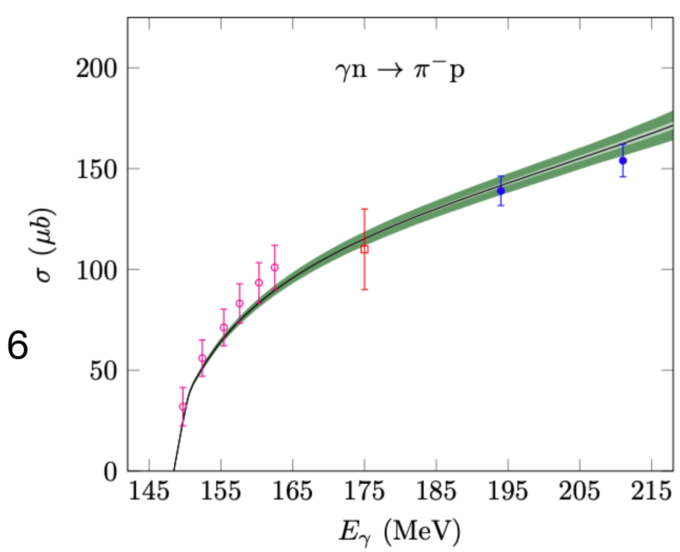


Pion electroproduction at $Q^2 < 0.15$ GeV





Guerrero Navarro, Vicente Vacas, Phys.Rev. D102 (2020) 113016



- The description of virtual photons paves half the way towards weak production.
- Many more data available than for weak pion production.
- Combined with fit to pion photoproduction, most LECs can already be constrained.

Summary and outlook

- Low-energy pion production can be determined with predictive methods of ChPT.
- Described well **neutral pion photoproduction** at low energies for the first time: the **inclusion of $\Delta(1232)$ is crucial** for the steep rise of cross sections with energy.
- Extended to charged pion photoproduction to tackle better LECs.
- **Weak and electroproduction of pions** extremely similar in concept: additional topologies and LECs.
- Very important for **neutrino-oscillation experiments**: disentangle from quasi-elastic channels and electron-like background.
- Predicting the low-energy behaviour helps with overall determination of neutrino-nucleon cross sections **integrated over broad energy ranges**!
- Outlook: **combined analyses** of electro-, photo- and weak production.

Backup

$\Delta(1232)$ Lagrangians

The spin-3/2 states **couple strongly** to the spin-1/2 baryons — mainly **magnetic** transition!

Geng et al., Phys. Lett. B 676 (2009) 63

$$\mathcal{L}^{(1)}_{\Delta\phi B} = \frac{-i\sqrt{2}\,\mathcal{C}}{F_0 M_\Delta} \bar{B}^{ab} \varepsilon^{cda} \gamma^{\mu\nu\lambda} (\partial_\mu \Delta_\nu)^{dbe} (D_\lambda \phi)^{ce} + \text{H.c.}$$

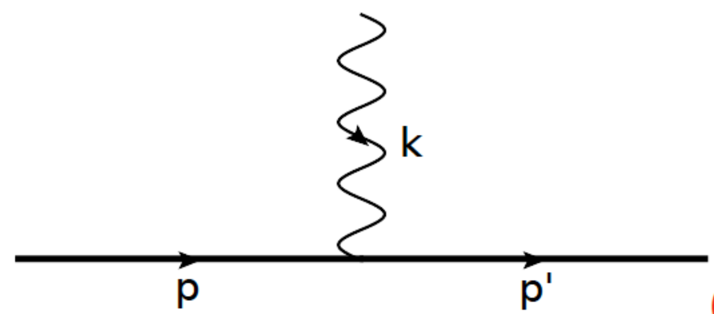
$$\mathcal{L}^{(2)}_{\Delta\gamma B} = -\frac{3ie\, g_M}{\sqrt{2} m (m + M_\Delta)} \bar{B}^{ab} \varepsilon^{cda} Q^{ce} (\partial_\mu \Delta_\nu)^{dbe} \tilde{F}^{\mu\nu} + \text{H.c.}$$

Higher-order Lagrangians

$$\mathcal{L}_N = \bar{\Psi}\Bigg\{ \frac{1}{8m}\left(c_6 f^+_{\mu\nu} + c_7 \mathrm{Tr}\left[f^+_{\mu\nu}\right]\right)\sigma^{\mu\nu} + \frac{\mathrm{i}}{2m}\varepsilon^{\mu\nu\alpha\beta}\left(d_8 \mathrm{Tr}\left[\tilde{f}^+_{\mu\nu} u_\alpha\right] + d_9 \mathrm{Tr}\left[f^+_{\mu\nu}\right] u_\alpha + \mathrm{h.c.}\right)\mathrm{D}_\beta + \frac{\gamma^\mu\gamma_5}{2}\left(d_{16}\mathrm{Tr}\left[\chi_+\right] u_\mu + \mathrm{i}\, d_{18}[\mathrm{D}_\mu, \chi_-]\right)\Bigg\}\Psi + \ldots$$

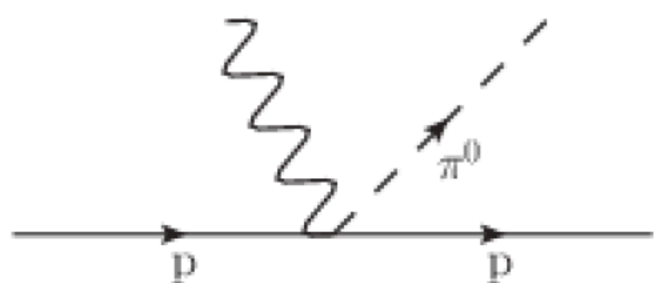
Fettes et al., Ann. Phys. 283 (2000) 273

$\mathcal{O}(\mathbf{p}^2)$

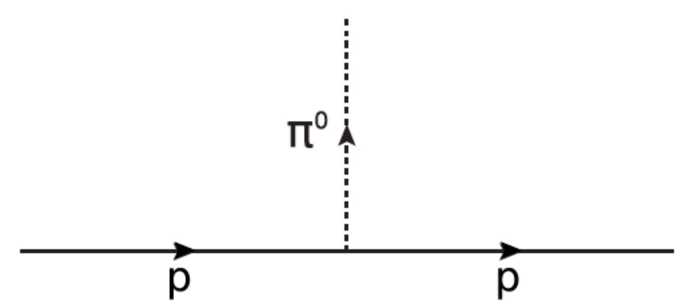


c_6, c_7

$\mathcal{O}(\mathbf{p}^3)$

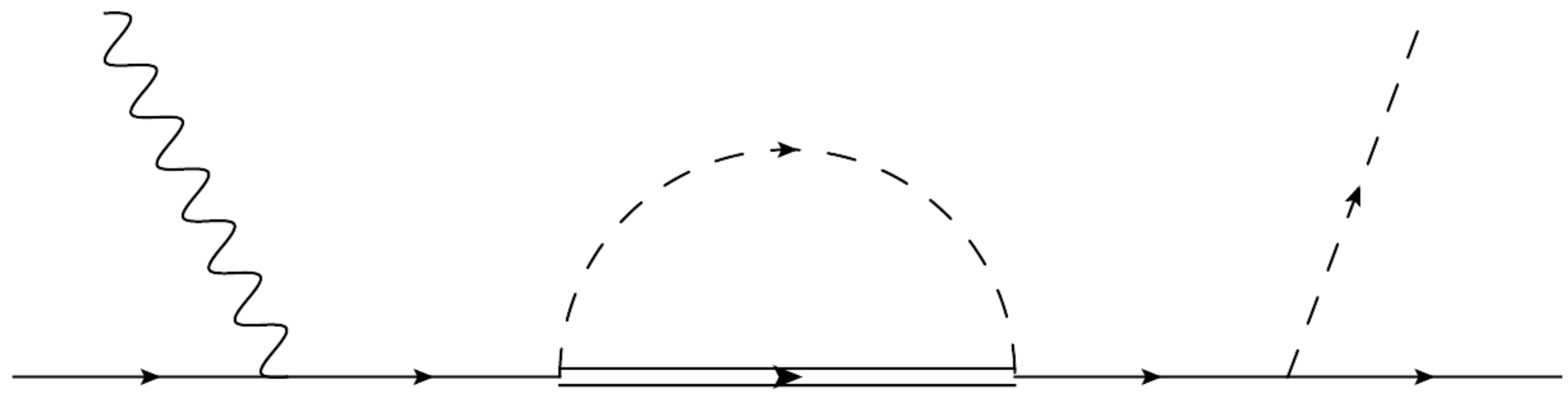


d_8, d_9



d_{16}, d_{18}

Matching a diagram to a specific order



$$O = 4L + \sum kV_k - \mathbf{2N_\pi} - \mathbf{N_N} - N_\Delta \cdot \frac{1}{2}$$

- Propagators: meson $\sim \mathbf{m_\pi^{-2}}$, spin-1/2 baryon $\sim \mathbf{p_{ext}^{-1}}$
- Spin-3/2 baryon: new scale $\delta = M_\Delta - m_N \approx 0.3$ GeV $> m_\pi$
- $(\delta/m_p)^2 \approx (m_\pi/m_p) \Longrightarrow$ far from resonance mass: $\frac{1}{2}$

Pascalutsa and Phillips, Phys. Rev. C 67 (2003) 055202

Renormalization: order by order

- Loop diagrams:
  divergences and **power counting breaking terms**

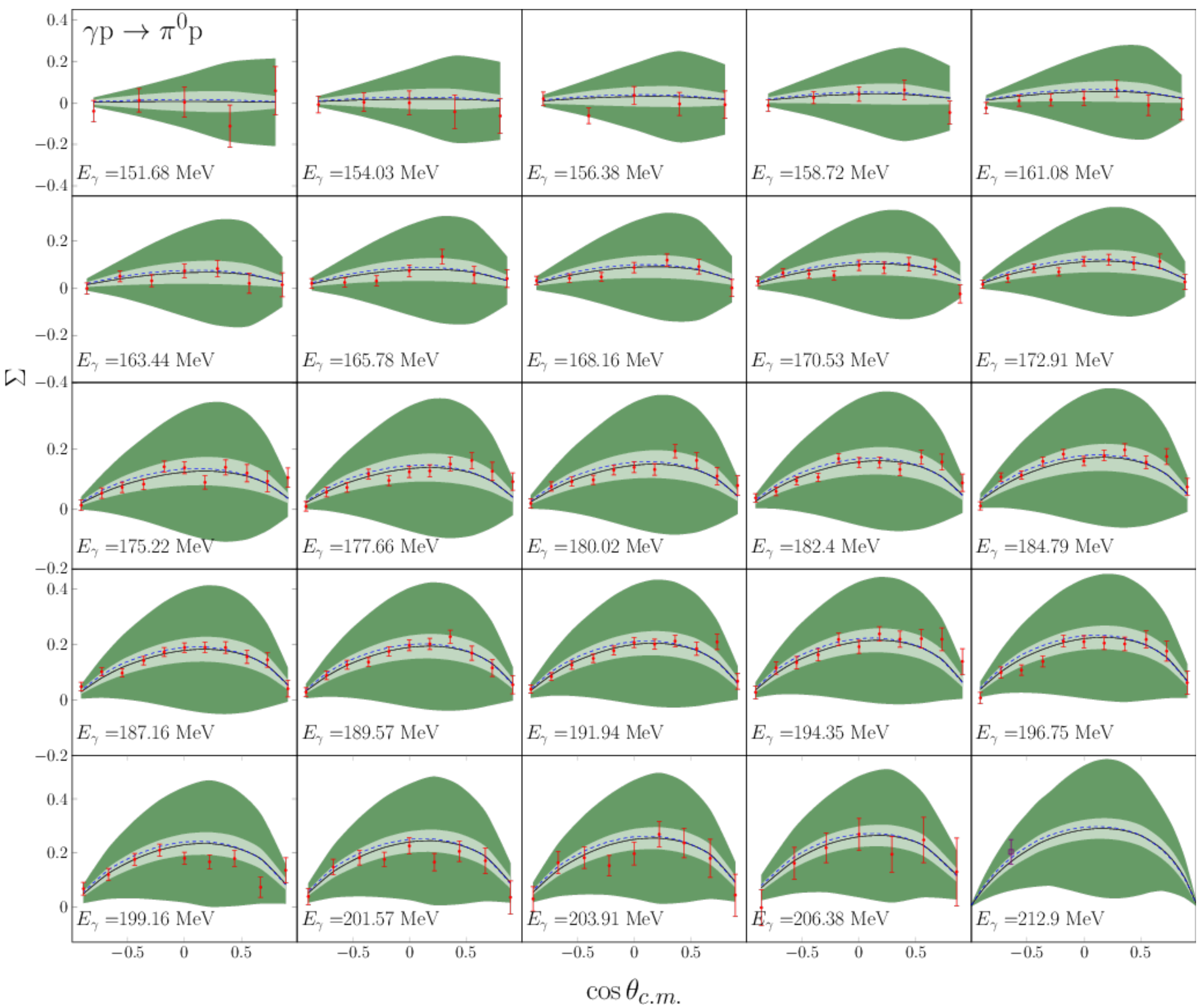
$$\frac{1}{\epsilon} = \frac{1}{4-\text{dim}} \qquad \text{and} \qquad \text{e.g. terms } \propto p^2 \text{ at } \mathcal{O}(p^3)$$

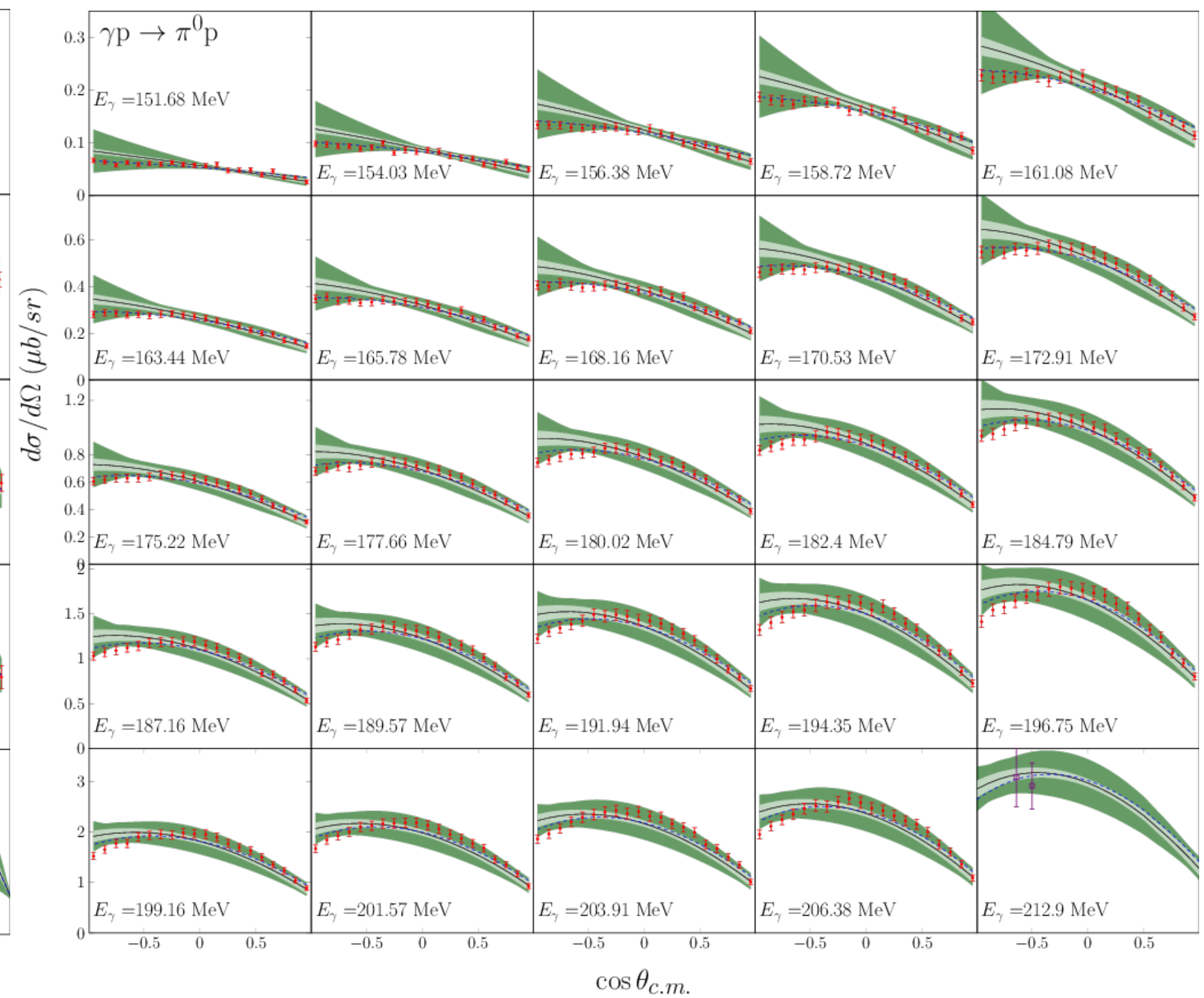
- Fully analytical $\Longrightarrow$ match with **Lagrangian terms**
- **Low-energy constants** of these terms a priori unknwon
- EOMS-renormalization prescription:

Gegelia and Japaridze, Phys. Rev. D 60 (1999) 114038

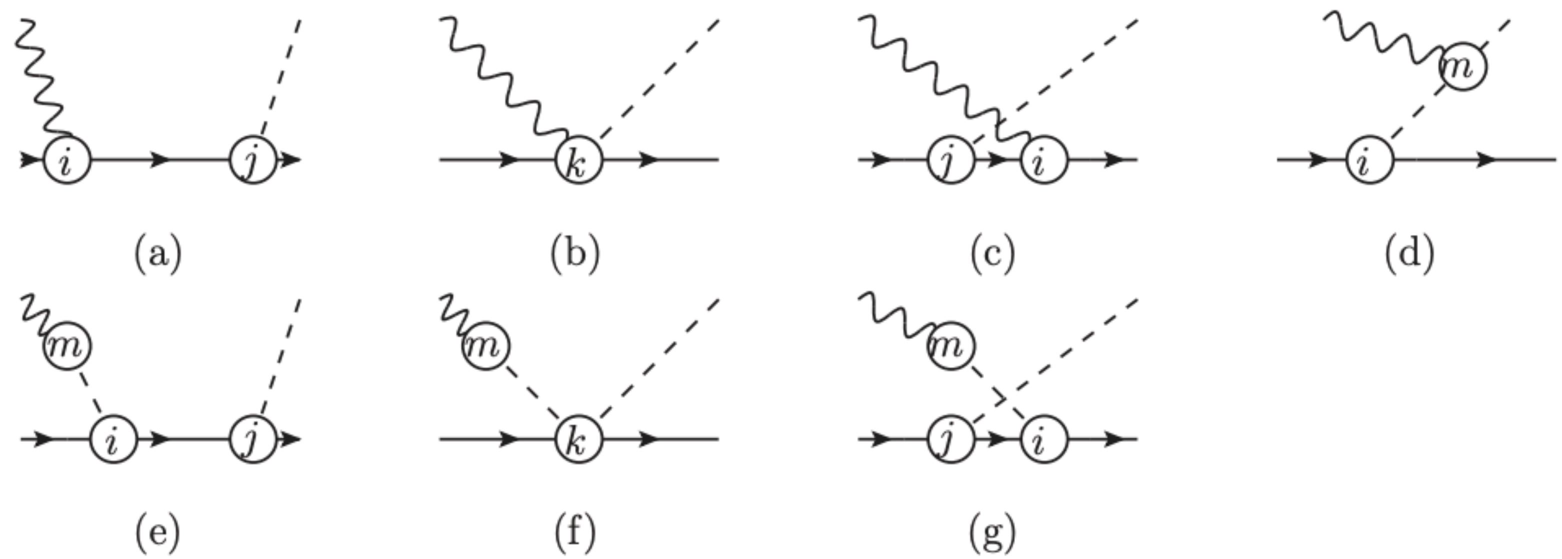
  - $\overline{MS}$ absorbs $L = \frac{2}{\epsilon} + \log(4\pi) - \gamma_E$ into LECs
  - Also subtracts PCBT by redefinition of LECs
  - Usually converges faster than other counting schemes (relativistic or not)

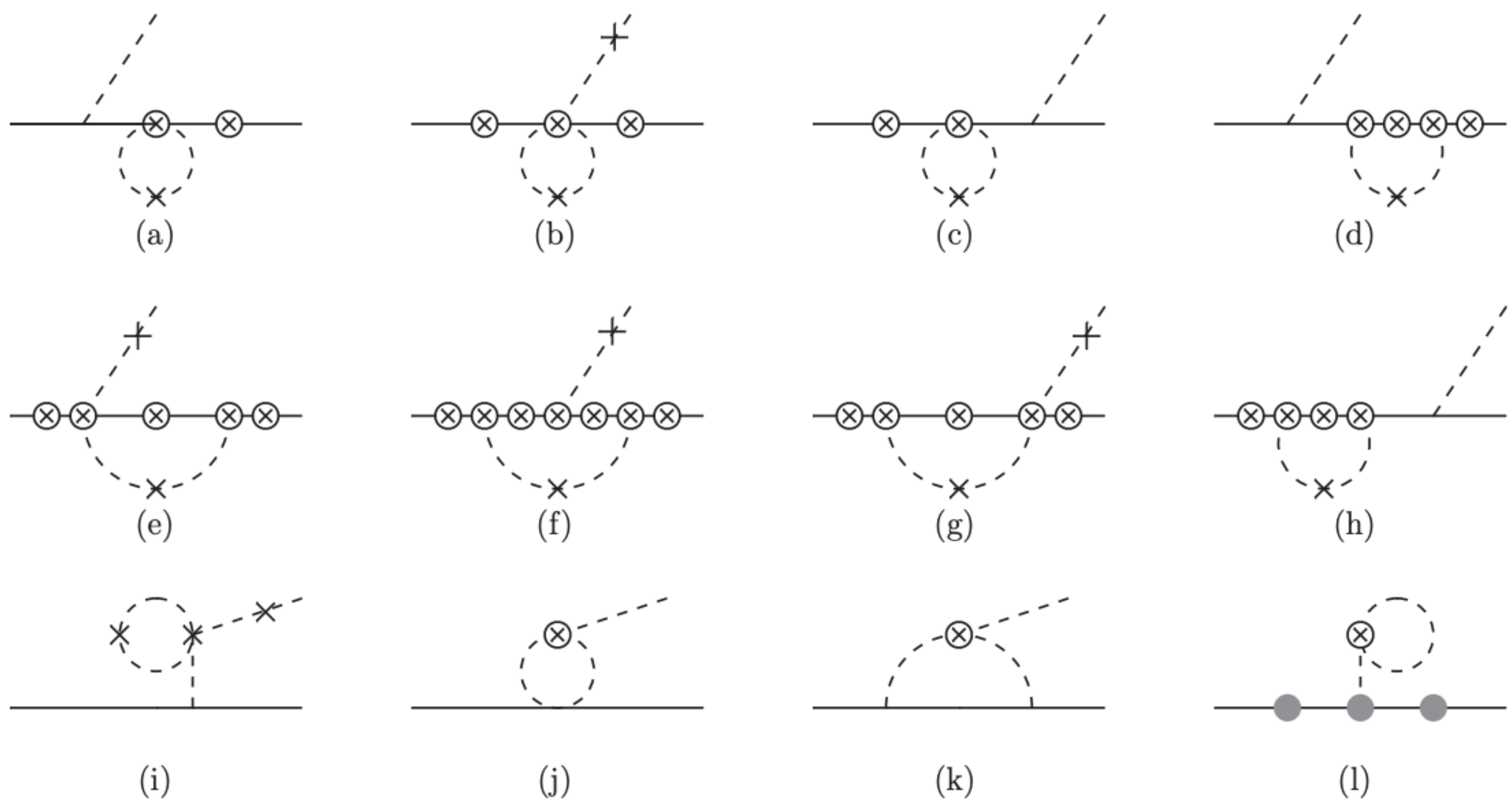
Pion photoproduction





Additional topologies for weak production





Estimation of uncertainties

- Statistical uncertainties in LECs from data uncertainties:

$$\delta\mathcal{O}_{\mathrm{LECs}} = \left(\sum_{i,j} \left[\mathrm{Corr}(x_i, x_j) \right] \frac{\partial\mathcal{O}(\bar{x}_i)}{\partial x_i} \delta x_i \frac{\partial\mathcal{O}(\bar{x}_j)}{\partial x_j} \delta x_j \right)^{1/2}$$

- Systematical theory error from truncation of chiral series:

$$\delta\mathcal{O}_{\mathrm{Th}}^{(n)} = \max\left(\left|\mathcal{O}^{(n_{LO})}\right| B^{n-n_{LO}+1}, \left\{ \left|\mathcal{O}^{(k)} - \mathcal{O}^{(l)}\right| B^{n-l} \right\} \right)$$