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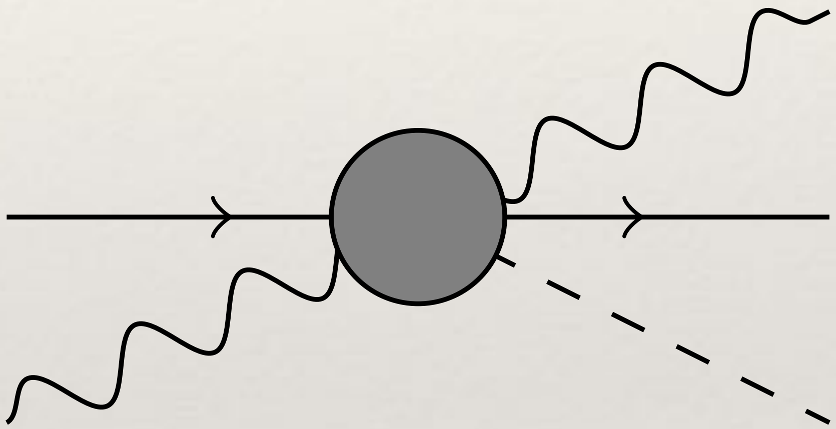
Radiative Pion-Photoproduction in Covariant Chiral Perturbation Theory



Trento, 02.07.2018

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Low-energy Quantum Chromodynamics

The QCD coupling is not small in the low-energy limit — traditional perturbation theory is not applicable

QCD describes the interaction of quarks and gluons. In the low-energy regime, we cannot observe free quarks and gluons, they are confined into hadrons.

An effective theory that describes the interaction of hadrons can allow for low-energy calculations.

From QCD to chiral perturbation theory

The chiral symmetry of QCD

The QCD Lagrangian reads $\mathcal{L}_{\mathrm{QCD}} = \bar{q}(\mathrm{i}\not{D} - M)q - \frac{1}{4}\mathcal{G}_a^{\mu\nu}\mathcal{G}_{a,\mu\nu}$

In the chiral limit (zero u and d mass), the Lagrangian decouples with

$q_{L/R} = \frac{1}{2}(\mathbb{1} \mp \gamma^5)q$ into two parts.

$$\mathcal{L}_{\mathrm{QCD}}^0 = \bar{q}_L \not{D} q_L + \bar{q}_R \not{D} q_R - \frac{1}{4}\mathcal{G}_a^{\mu\nu}\mathcal{G}_{a,\mu\nu}$$

These obey the chiral symmetry: $\mathrm{U}(2)_L \times \mathrm{U}(2)_R \cong \mathrm{SU}(2)_V \times \mathrm{SU}(2)_A \times \mathrm{U}(1)_V \times \mathrm{U}(1)_A$

$\mathrm{U}(1)_A$ is anomalously broken

$\mathrm{SU}(2)_A$ is spontaneously broken

⇒ three Goldstone Bosons (pions)

The Goldstone Bosons have only derivative couplings.

⇒ there are small scales in the theory (mass, energy)

Chiral Lagrangians

Weinberg, 1979; Gasser, Leutwyler, 1984. Deltas: Hemmert, Holstein, Kambor 1998; Fettes, Meißner, Mojžiš, 2000

Effective Lagrangian: All possible terms that obey chiral symmetry (and Lorentz symmetry etc.). The contributions are classified according to orders of $\epsilon \in \{|\vec{k}|/\Lambda_\chi, M_\pi/\Lambda_\chi, \Delta/\Lambda_\chi\}$

Leading order pion/nucleon Lagrangians:

$$\mathcal{L}_\pi^{(2)} = \frac{1}{2}(\partial_\mu \boldsymbol{\pi} \cdot \partial^\mu \boldsymbol{\pi} - M_\pi^2 \boldsymbol{\pi}^2) + \mathcal{O}(\boldsymbol{\pi}^4) \qquad \mathcal{L}_{\pi N}^{(1)} = \bar{N}(\mathrm{i}\not{\partial} - m_N - \frac{g_A}{2F_\pi}(\not{\partial}\boldsymbol{\pi}) \cdot \boldsymbol{\tau}\gamma^5)N + \mathcal{O}(\boldsymbol{\pi}^2)$$

Power of ε for a given diagram:

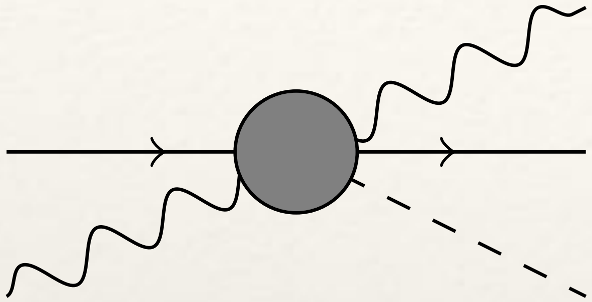
$$D = 1 + 2L + \sum_n (2n-2)V_{2n}^M + \sum_d (d-1)V_d^B$$

Power counting formula restricts the number of loops at a given order

The low energy constants (LECs) of ChPT must be determined

Radiative pion-photoproduction chiral perturbation theory

Radiative pion-photoproduction

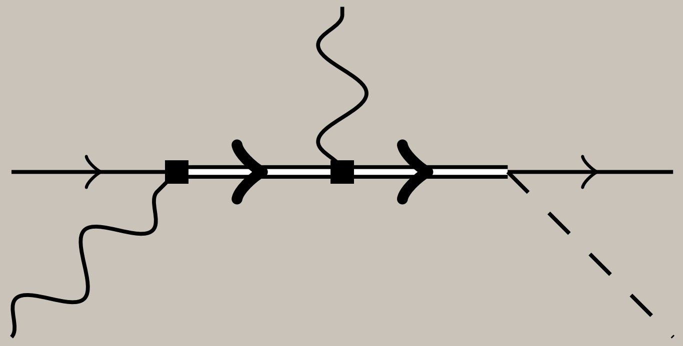


$$\gamma(k,\lambda)N(p,s) \to \gamma(k',\lambda')N(p',s')\pi_a(q)$$

Why is it interesting to look at this reaction?

- ChPT is regarded to be universal — checking it for several processes is crucial for its validation.
- This reaction is of interest since the channel $p+\gamma \to p+\gamma+\pi^0$ includes the Δ^+ magnetic moment which is so far poorly known.

Minimal order: ε^3



State of the art

Pascalutsa, Vanderhaeghen; Phys.Rev. D77 (2008) 014027

Basics done by Pascalutsa and Vanderhaeghen:

They calculated the absorptive part and used a different power-counting scheme $M_\pi/\Lambda_\chi \sim (\Delta/\Lambda_\chi)^2$ (δ scheme).

Available data points lie too far off the delta poles. This procedure gives only weak restrictions to the magnetic moment.

The inclusion of the complete dynamics is needed to determine the delta's properties. Therefore, I am calculating the full amplitude in a fully covariant framework using the ε scheme.

First step: Calculate the diagrams

Contributing Lagrangians: $\mathcal{L}^{\text{eff}} = \sum_{i=1}^{\infty} \mathcal{L}_{\pi}^{(2i)} + \sum_{i=1}^{\infty} (\mathcal{L}_{\pi N}^{(i)} + \mathcal{L}_{\pi N \Delta}^{(i)} + \mathcal{L}_{\pi \Delta}^{(i)})$

$$\mathcal{L}_{\pi N}^{(2)} = \sum_{j=1}^{7} c_j O_j^{(2)} \qquad \mathcal{L}_{\pi N}^{(3)} = \sum_{j=1}^{23} d_j O_j^{(3)} \qquad \mathcal{L}_{\pi}^{(4)} = \sum_{j=1}^{7} l_j o_j^{(4)}$$

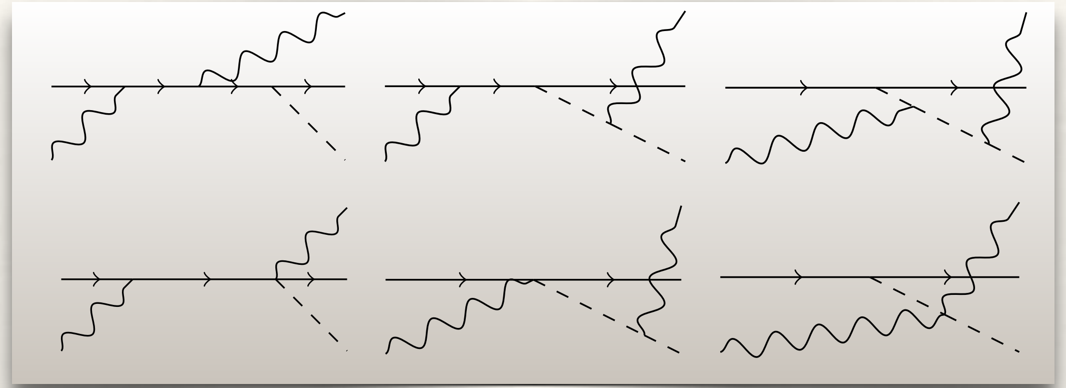
$$\mathcal{L}_{\pi N \Delta}^{(2)} = \sum_{j=1}^{7} b_j \tilde{O}_j^{(2)} \qquad \mathcal{L}_{\pi N \Delta}^{(3)} = \sum_{j=1}^{67} h_j \tilde{O}_j^{(3)} \qquad \mathcal{L}_{\pi \Delta}^{(2)} = \sum_{j=1}^{12} c_j^{\Delta} \bar{O}_j^{(2)}$$

There are 19 q^1, 20 q^2, 93 q^3 tree and 419 q^3 loop diagrams built out of 21 different vertices.

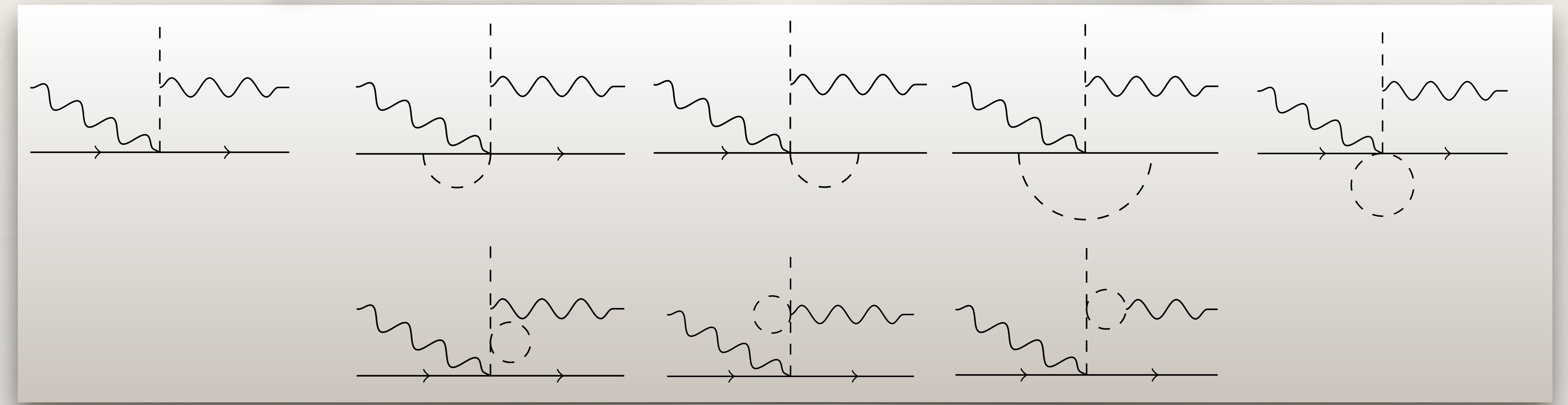
Delta diagrams arise from non-delta diagrams by considering all possibilities to exchange nucleon lines by those of deltas. This leads to hundreds of diagrams.

Examples of Feynman diagrams

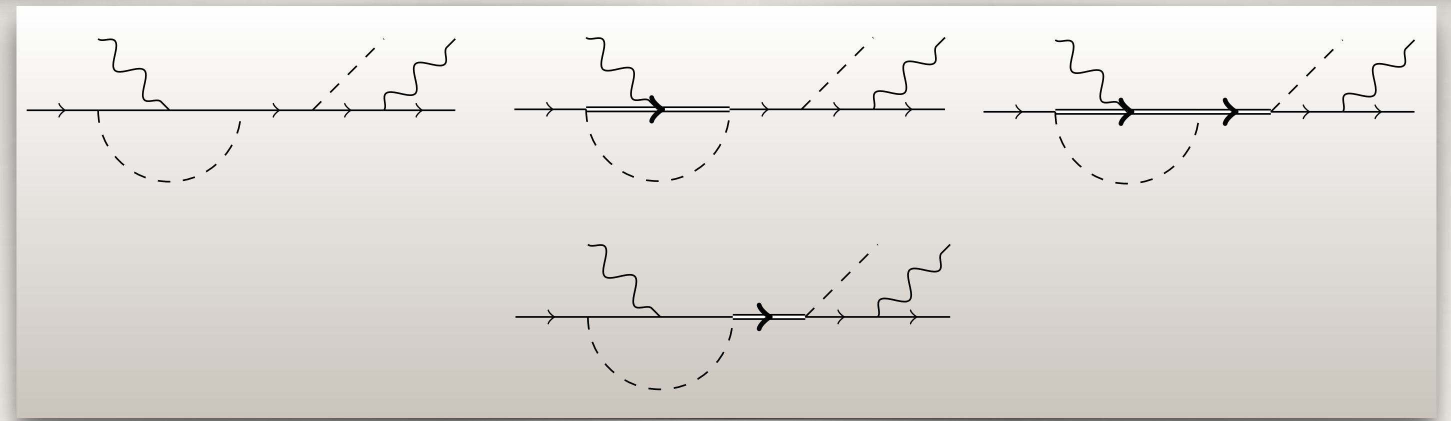
Tree diagram basic structures



Ways to introduce loops



Ways to introduce deltas



Second Step: Renormalisation

In ChPT, renormalisation up to a certain order is possible. However, in the covariant scheme, expressions contain also higher order terms.

Furthermore, baryon loop diagrams are known to violate power-counting with lower order terms, in the covariant formalism.

In general these violations can be absorbed into LECs.

Fuchs, Gegelia, Japaridze, Scherer; Phys.Rev. D68 (2003) 056005

The other way round: if a vertex at a certain order vanishes, the violations of power counting have to cancel.

This holds for $\gamma N \to \gamma N$, $\gamma N \to \pi N$ and $\gamma N \to \gamma \pi N$.
Dimensional regularisation with on-shell renormalisation secures the cancellation of all violations.

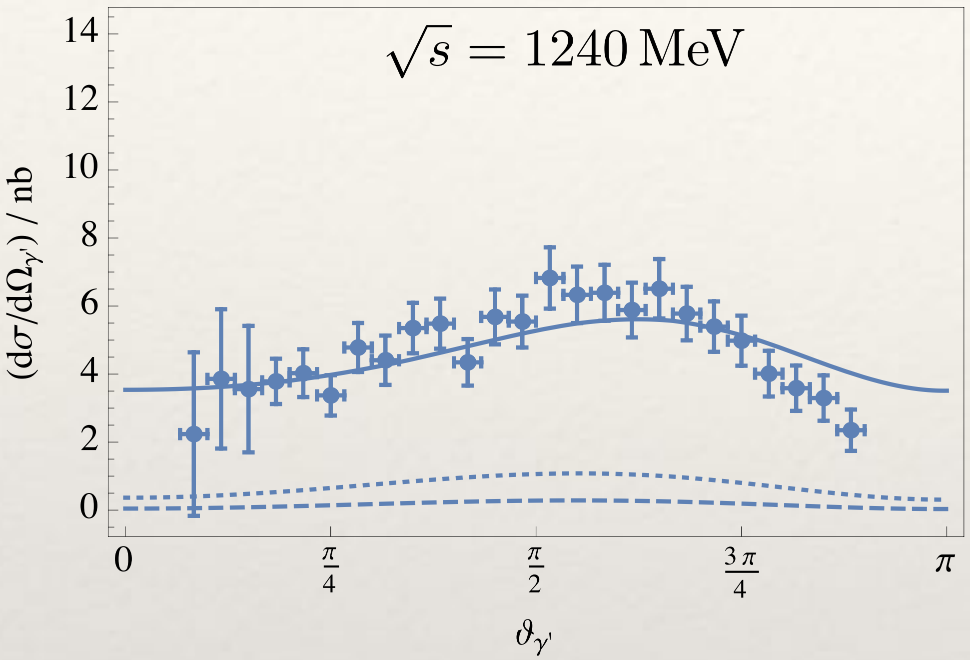
Third step: Calculation of observables

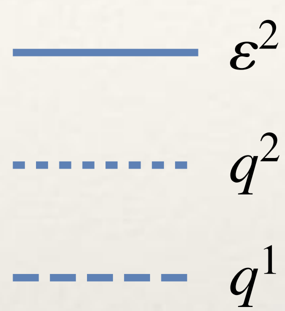
Some characteristics of the calculation (Preview results for ε²)

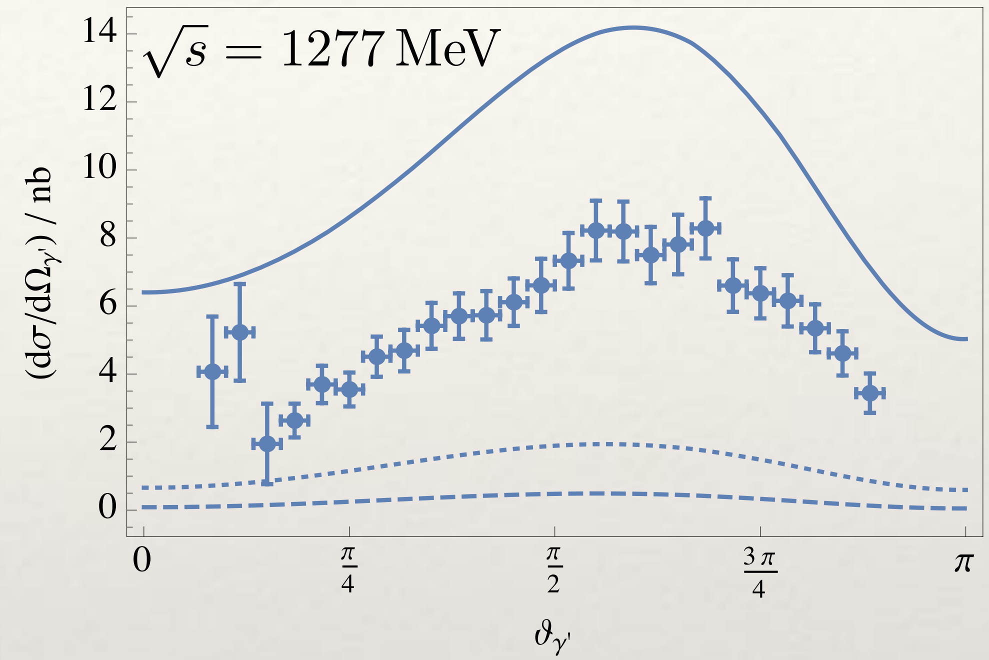
- Up to this point: only symbolic computations. Now: numerical integration
- Dimensional regularisation, on-shell renormalisation with $\mu = m_N$
- There is a bremsstrahlung pole in the amplitude. In accordance with the measured values, the integration over the outgoing photon's energy runs from $E_{\gamma'} = 30\,\mathrm{MeV}$.
- Remaining LECs starting from ε² are c_6 , c_7 (magnetic moment of the nucleon) and b_1 .

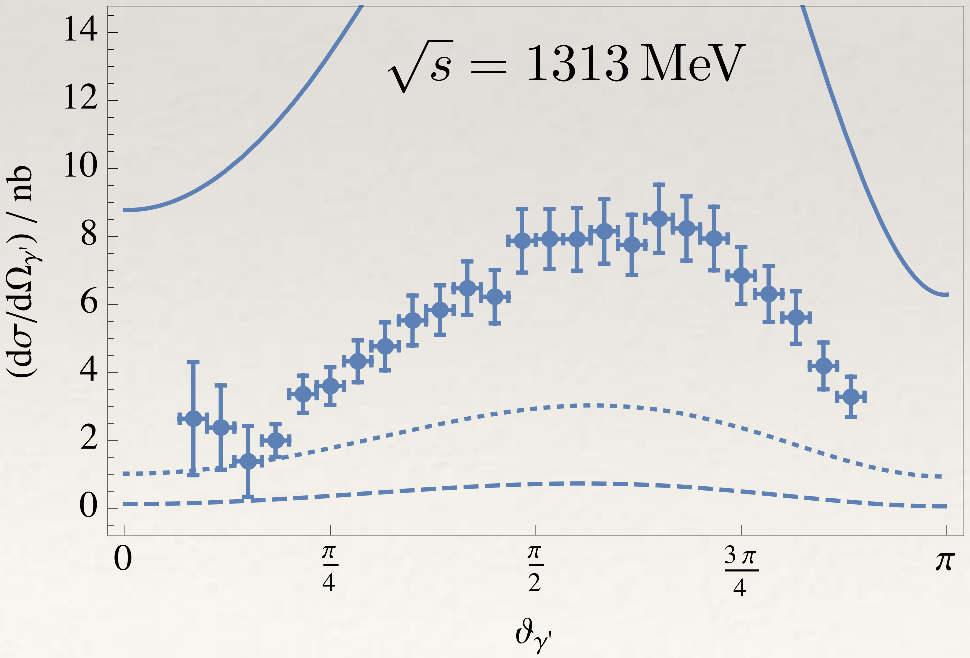
Plots for channel 1 ($\gamma p \to \gamma p \pi^0$): $d\sigma/d\Omega_{\gamma'}$

Data from MAMI Schumann et al.; Eur.Phys.J. A43 (2010) 269-282



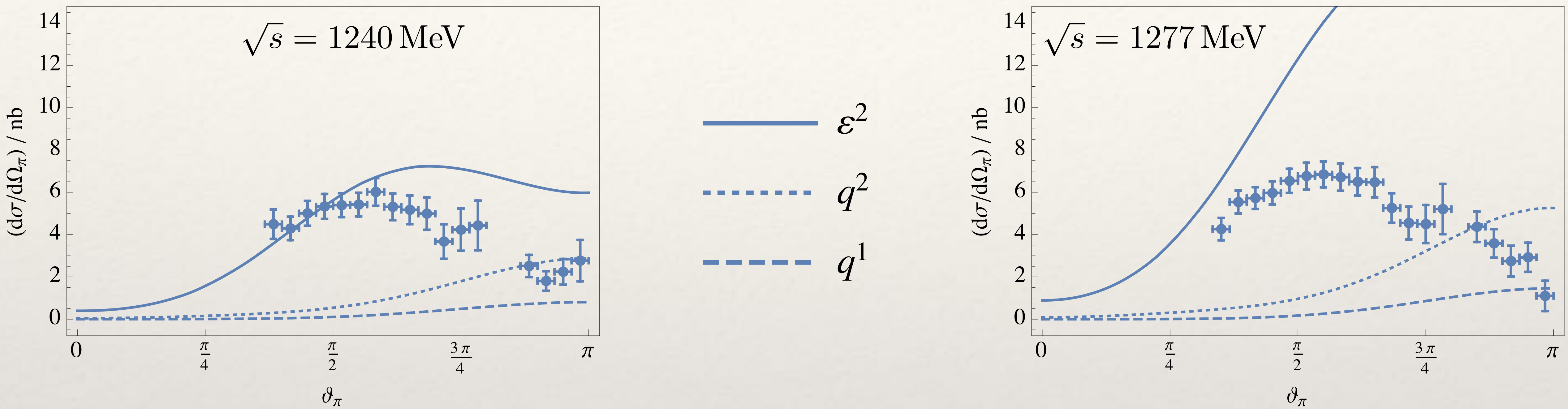


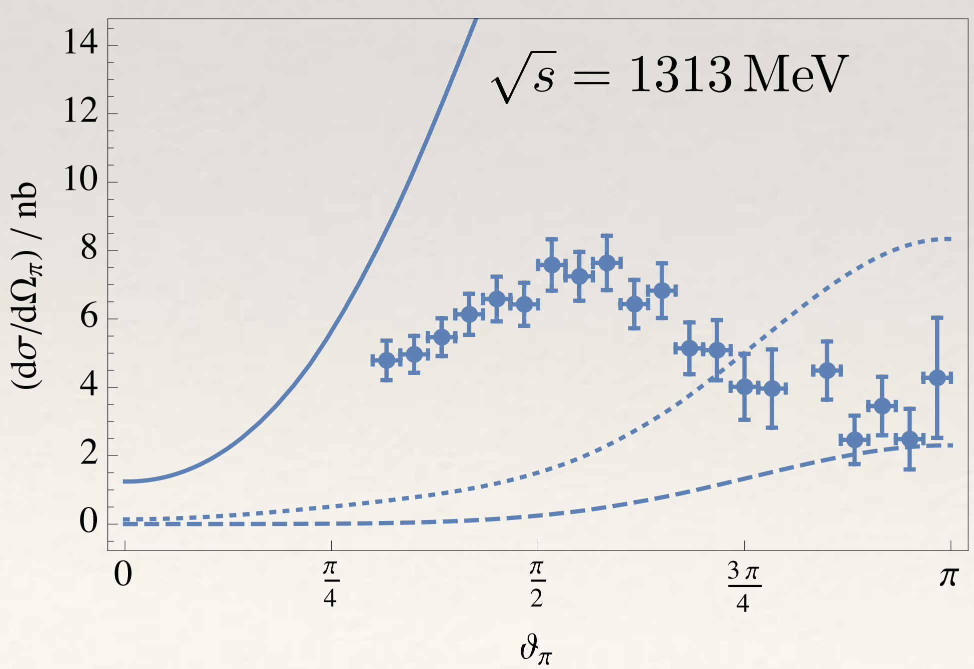




- Curves match the shape of data points distribution
- Results are too large for high energies

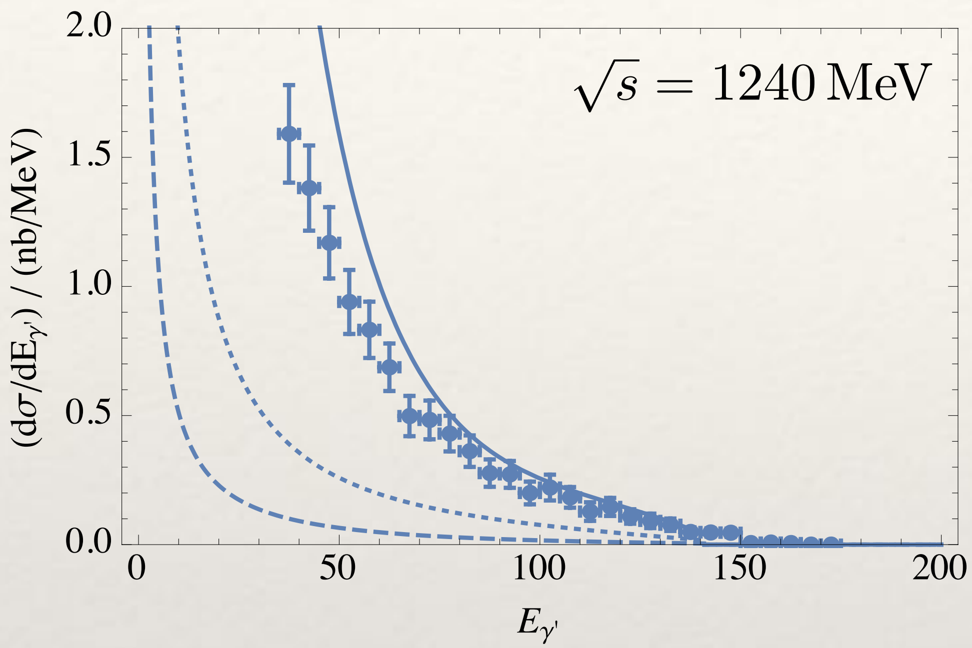
Plots for channel 1 ($\gamma p \rightarrow \gamma p \pi^0$): $d\sigma/d\Omega_\pi$

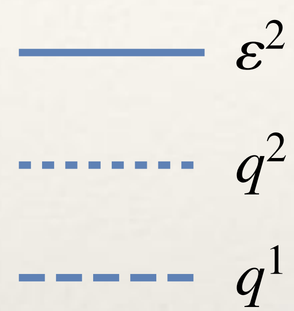


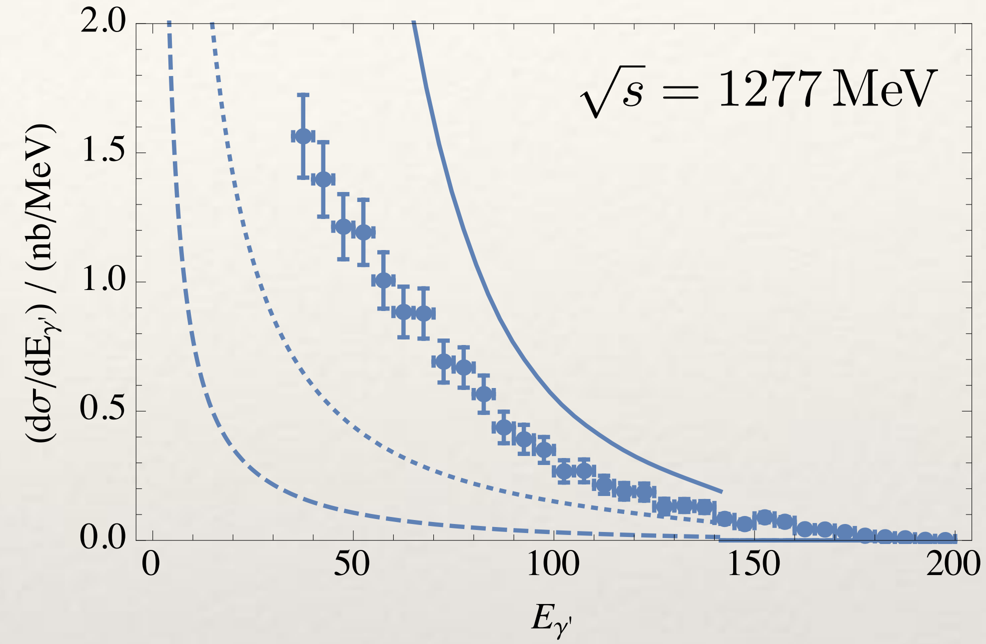


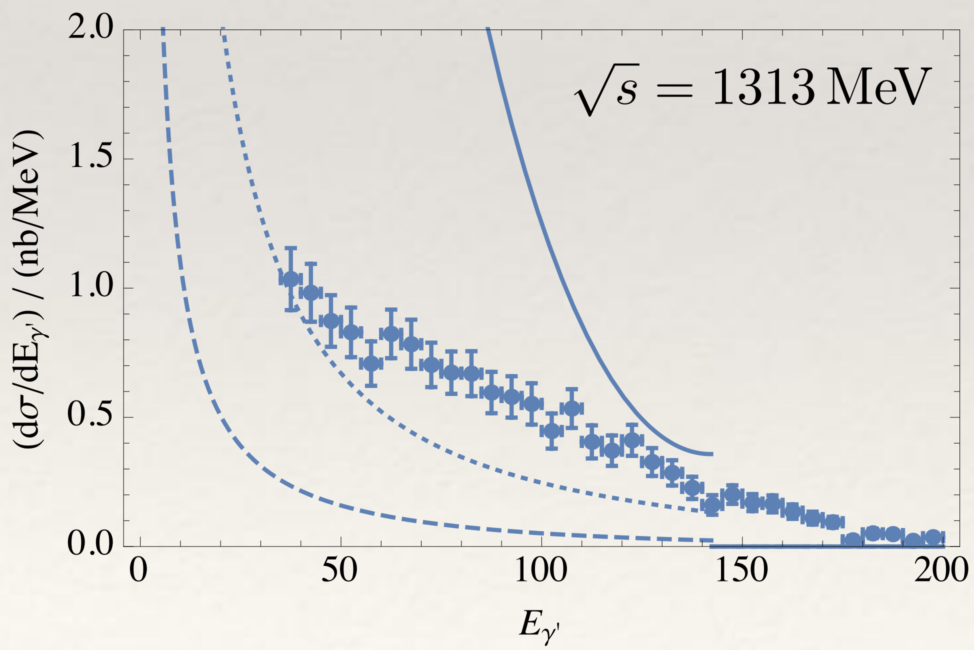
- Agreement is much worse
- Results are far too large for high energies and angles >π/2

Plots for channel 1 ($\gamma p \rightarrow \gamma p \pi^0$): $d\sigma/dE_{\gamma'}$









- Quite good agreement for the lowest energy
- Disagreement for the shape grows with CM energy

Summary and Outlook

Summary and Outlook

The first two orders have been calculated in a fully covariant way with explicit deltas included.

- The delta plays a crucial role
- Observe slow convergence at higher energies

The leading loop order (ε^3) is yet to be done.

- This complicates the calculation significantly.
- The LECs that then have to be fitted include those related to the MDM of the delta
- Inclusion of other intermediate states (ρ, Roper)