An exemplary case of ChEFT with resonances - the Delta(1232)

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Presented @ 6th Workshop on Chiral Dynamics (Bern, July 9, 2009)

Low-lying resonances in chiral EFT

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The chiral PT with pion and nucleon fields is limited by a lowest-lying resonance:

- Meson sector: rho-meson
  - excitation energy $\approx m_\rho - m_\pi \simeq 640\mathrm{MeV}$
- Baryon sector: Delta-isobar
  - excitation energy $\approx M_\Delta - M_N \simeq 300\,\mathrm{MeV}$

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- PT: explicit field (d.o.f.) with M>2m (or, $M > \sum_i m_i$) and $g \neq 0$
  - e.g., muon, tau, W-, Z-bosons
- Non-PT: quasibound state from a Dyson-Schwinger, Bethe-Salpeter eqs
  - e.g., positronium

Effective Lagrangians with Δ(1232) (I=3/2, $J^P=3/2^+$)

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Lagrangian: $\mathcal{L}_\Delta^{(1)} \;=\; \bar{\psi}_\mu \, (i\gamma^{\mu\nu\alpha}\, \partial_\alpha - \gamma^{\mu\nu}\, M_\Delta\,)\, \psi_\nu$

where $\gamma^{\mu\nu\alpha} = \frac{1}{2}(\gamma^\mu\gamma^\nu\gamma^\alpha - \gamma^\alpha\gamma^\nu\gamma^\mu)$, $\gamma^{\mu\nu} = \frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.

The kinetic term is invariant under the gauge transformation:

$$\psi_\mu(x) \to \psi_\mu(x) + \partial_\mu \varepsilon(x)$$

leading to 2 spin d.o.f. for massless theory. The mass term breaks the symmetry to raise the # of spin d.o.f. to $2s+1=4$.

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$$\mathcal{L}_\pi^{(2)} = \frac{f^2}{4}\,\mathrm{tr}\big(\partial^\mu U \partial_\mu U^\dagger + 2B_0(UM^\dagger + MU^\dagger)\big),$$

$$\mathcal{L}_N^{(1)} = \overline{N}\,(i\partial\!\!\!/ - M_N + v\!\!\!/ + g_A\, a\!\!\!/\, \gamma_5)\, N,$$

$$\mathcal{L}_\Delta^{(1)} = \overline{\Delta}_\mu\,(i\gamma^{\mu\nu\lambda}\,\partial_\lambda - M_\Delta\,\gamma^{\mu\nu})\,\Delta_\nu + \frac{h_A}{2M_\Delta}\left[i\overline{N}\,T_a\,\gamma^{\mu\nu\lambda}\,(\partial_\mu\Delta_\nu)\,\mathrm{tr}(a_\lambda\tau^a) + \mathrm{H.c.}\right]$$

Spin-3/2 aspects:

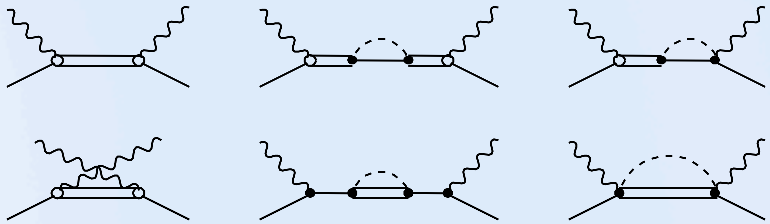
[V.P., PRD (1998), PLB (2001); V.P. & Timmermans, PRC (1999); Deser, V.P. & Waldron PRD (2000); Lenske & Shklyar (2009); Krebs, Epelbaum & Meissner (2009)]

1. Power counting for Delta propagators
and

Compton scattering,
pion-nucleon scattering,
pion photo- and electro-production

Chiral Lagrangians with Δ and power counting

How to count



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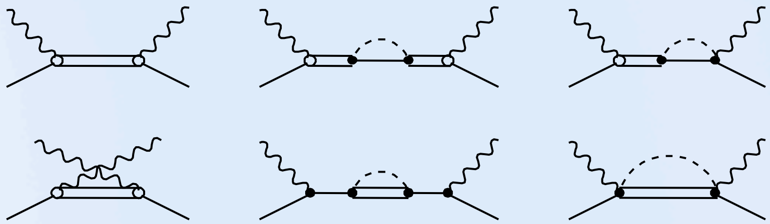

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[Jenkins & Manohar (1991), Hemmert, Kambor & Holstein (1998) ... (2006)]

$p \sim m_\pi \sim \Delta << \Lambda_{\chi SB}$

$\epsilon = (\frac{p}{\Lambda_{\chi SB}}, \frac{m_\pi}{\Lambda_{\chi SB}}, \frac{\Delta}{\Lambda_{\chi SB}})$

"ϵ-expansion"

N and Δ propagators:

$S_N \sim \frac{1}{p} = O(\epsilon^{-1})$

$S_\Delta \sim \frac{1}{p-\Delta} = O(\epsilon^{-1})$

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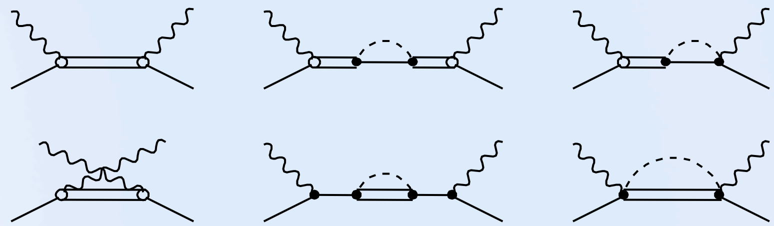

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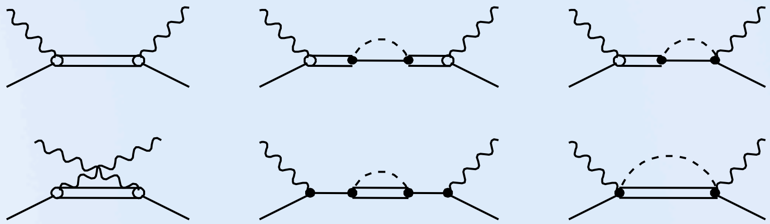

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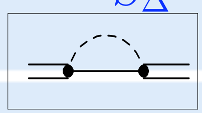
p $\sim$ **m_π**, $S_N \sim 1/p = O(1/\delta^2)$

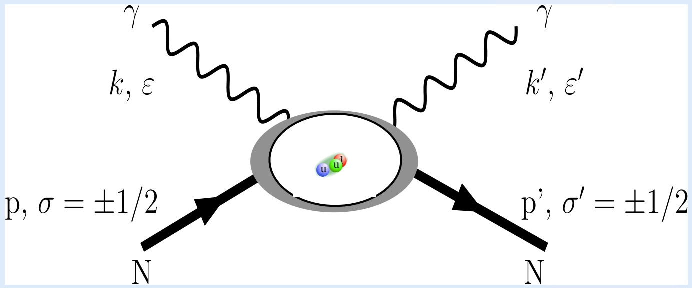
$S_\Delta \sim 1/\Delta = O(1/\delta)$

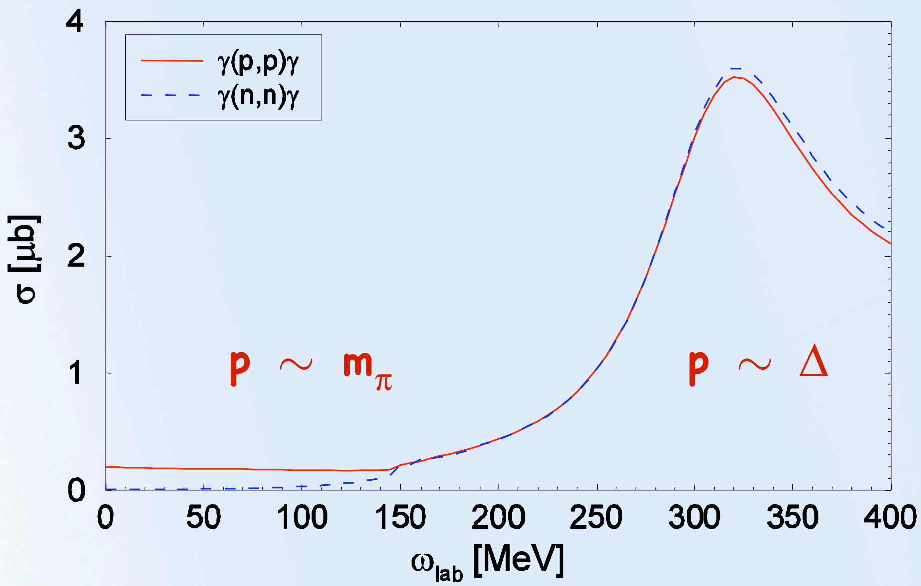
p $\sim$ **Δ**, $S_N \sim 1/p = O(1/\delta)$

$S_\Delta \sim 1/(p-\Delta-\Sigma) = O(1/\delta^3)$

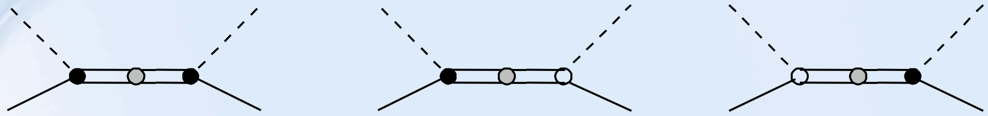
$\Sigma =$  $+ \ldots = O(p^3) = O(\delta^3)$

Total cross-section for Compton scattering at NLO





Pion-nucleon scattering in the resonance region



(LO) (NLO)

Renormalized NLO propagator

$$S_{\alpha\beta}(p) = \frac{-1}{(\not{p} - M_\Delta)[1 - i\,\mathrm{Im}\Sigma'(M_\Delta)] - i\,\mathrm{Im}\Sigma(M_\Delta)} P^{(3/2)}_{\alpha\beta}(p)\,.$$

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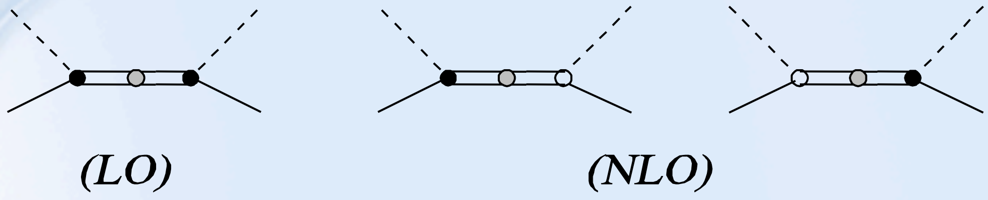

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K-matrix in the resonant channel:

$$K_{P33} = \frac{\mathrm{Im}\Sigma(M_\Delta)}{W - M_\Delta} + \mathrm{Im}\Sigma'(M_\Delta),$$

$W = \sqrt{s}.$

Partial-wave S-matrix:

$$S_l = \frac{1 + iK_l}{1 - iK_l} = e^{2i\delta_l}\,,$$

phase-shift:

$$\delta_l = \arctan K_l$$

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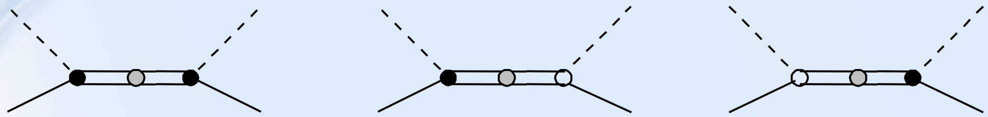

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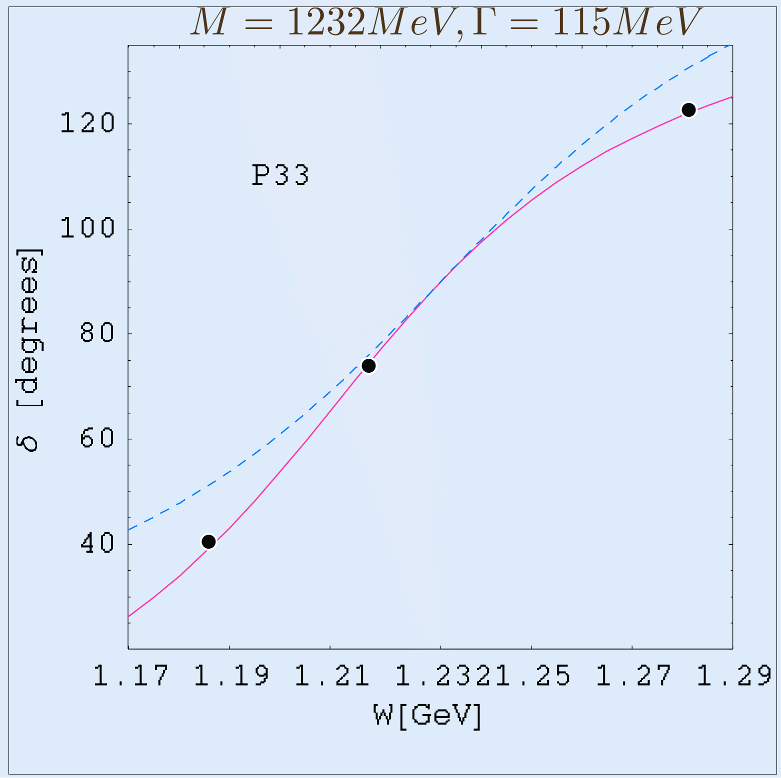
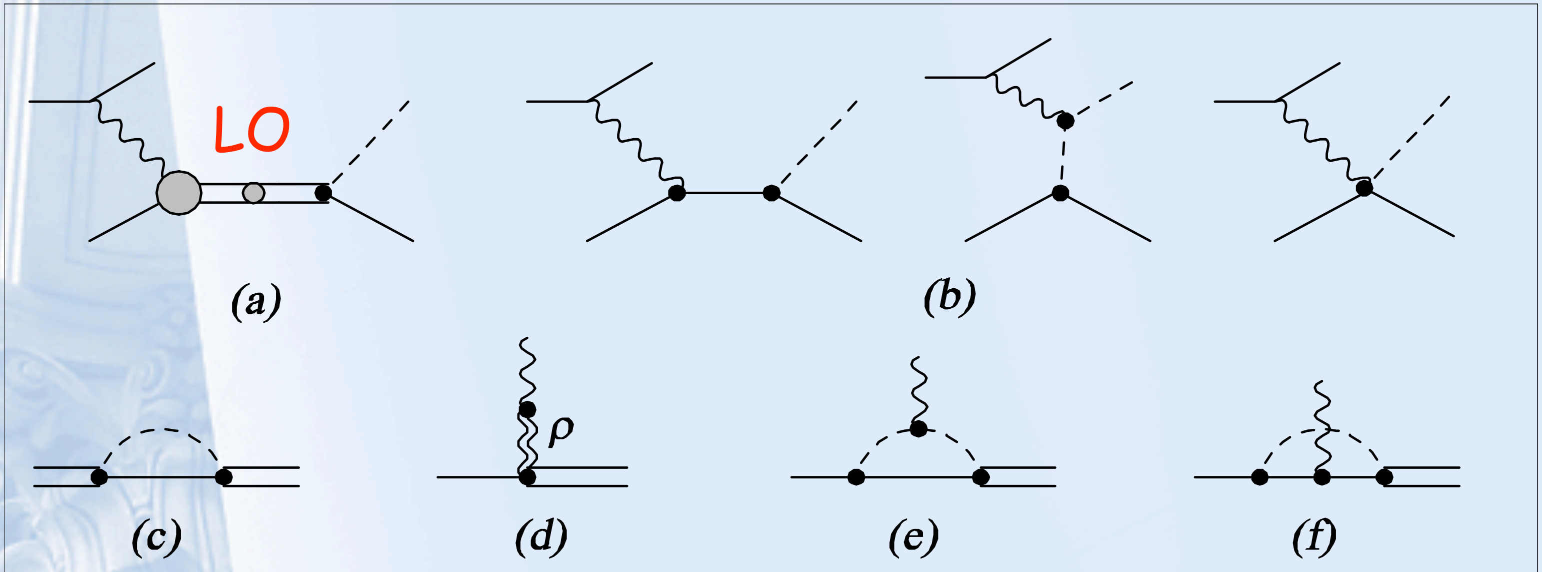


Data: SAID

Pion Electroproduction (e N -> e N π) in Δ(1232) region

[V.P. & Vanderhaeghen, PRL 95 (2005); PRD 73 (2006)]

Calculation to NLO in the δ expansion:



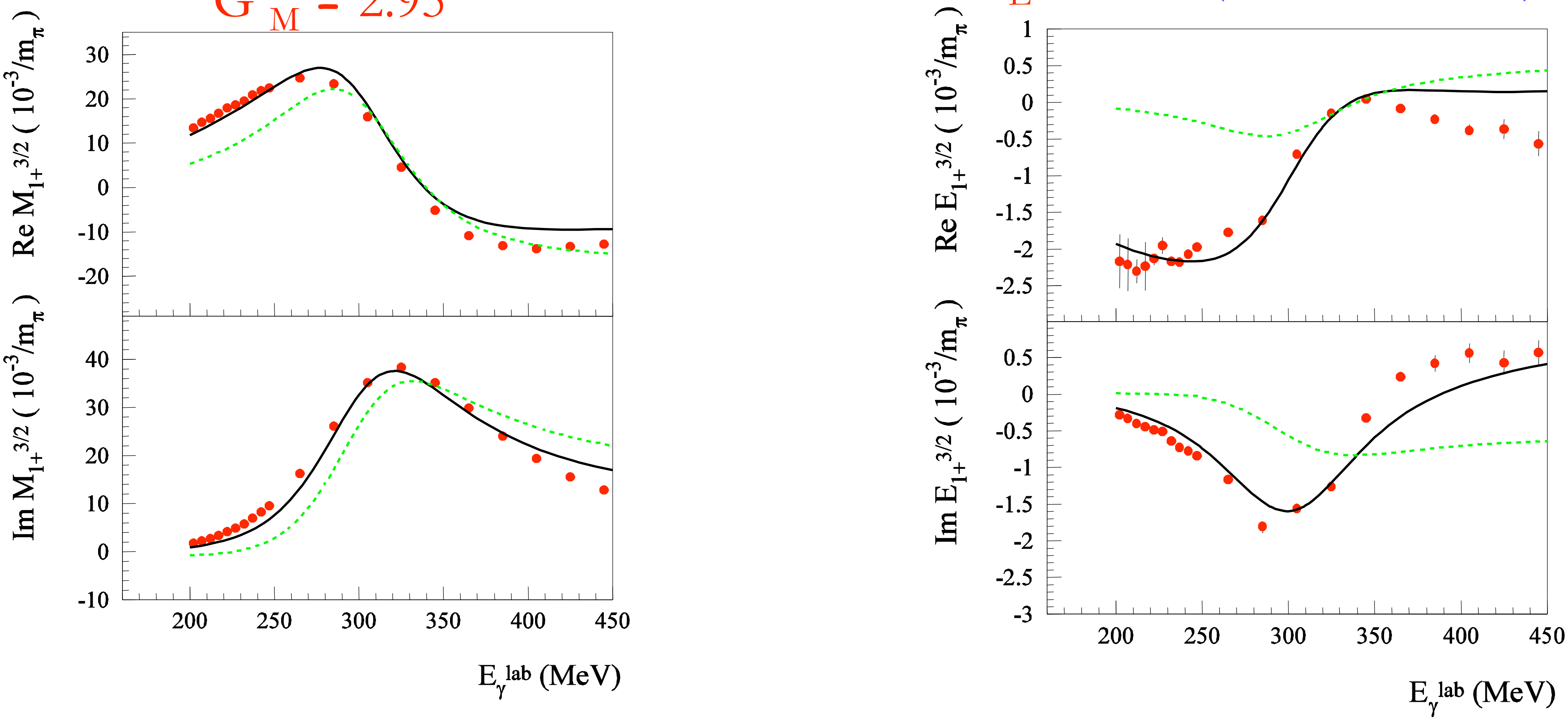
4 free parameters – LECs corresponding to G_M, G_E, G_C at Q^2=0, and G_M radius

magnetic (M1) & electric (E2) N - Δ transition resonant multipoles

2 free parameters at NLO

$G^*_M = 2.95$

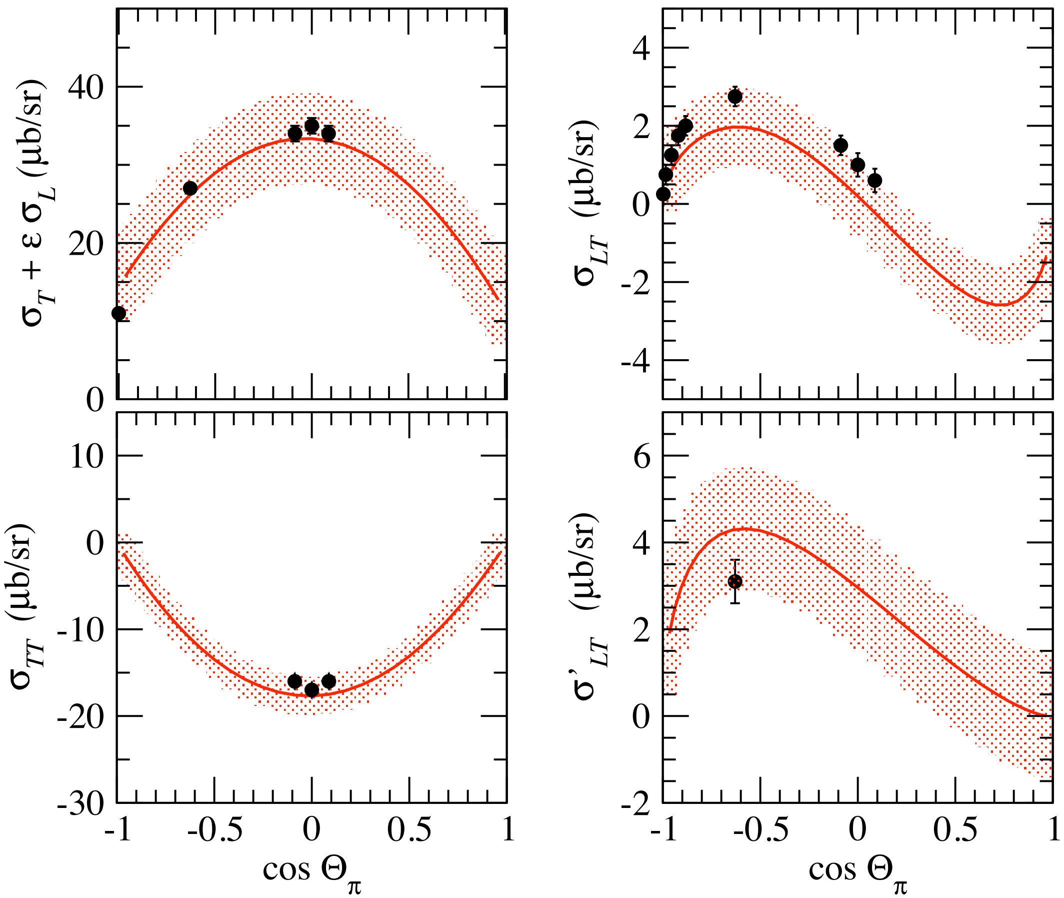
$G^*_E = 0.07$ (E2/M1 = -2.4 %)



Data: MAID 2003

e p -> e p π in Δ(1232) region: observables

W = 1.232 GeV , Q^2 = 0.127 GeV^2



data points :

MIT-Bates

(Sparveris et al., 2005)

NLO ChEFT (4 LECs)

theory error bands due to NNLO

$$R_{err} = |R|_{av}\,\tilde{\delta}$$

$$\tilde{\delta} = \frac{1}{3}\left[\frac{\Delta}{M_N} + \left(\frac{m_\pi}{M_N}\right)^{1/2} + \left(\frac{Q^2}{M_N^2}\right)^{1/2}\right]$$

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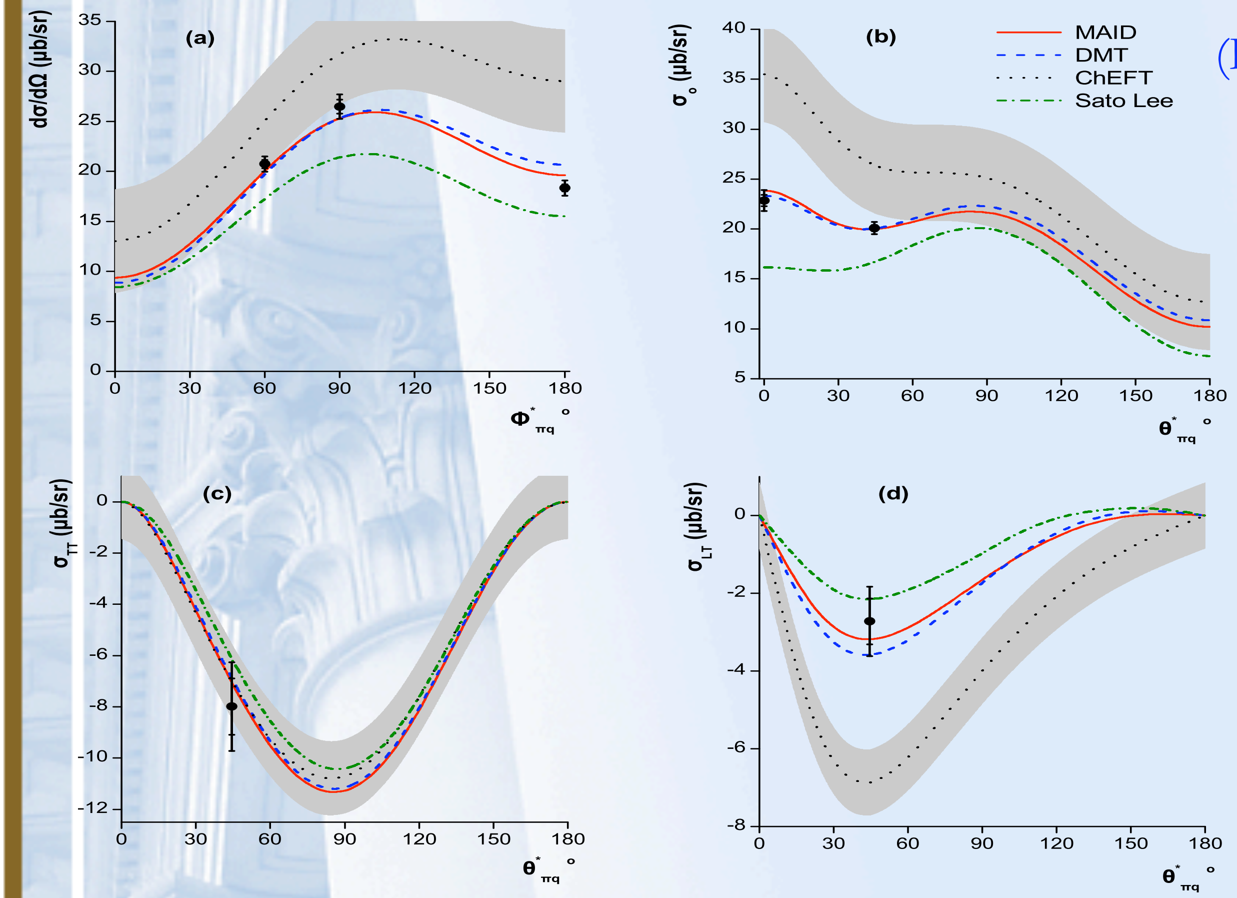

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(Kirkpatrick et al, 2008)

NLO ChEFT (4 LECs)

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2. NNLO Compton scattering and nucleon polarizabiltites:
BChPT vs. HBChPT

Power couniting in BChPT (Nucleon mass)

Leading order pion-nucleon interaction:

$$\mathcal{L}_{\pi N}^{(1)} = \frac{g_A}{2f_\pi} \bar{N}\, \gamma^\mu \gamma^5\, \tau^a\, N\, (\partial_\mu \pi^a)$$

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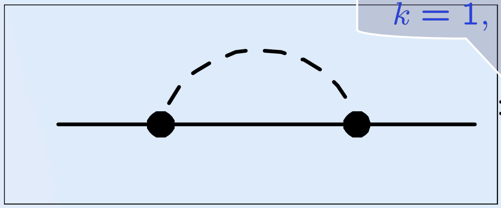
Power counting index: $n = \sum_k k V_k + 4L - 2N_\pi - N_N$

tells us that a graph is of O(p^n)

$k = 1,\ V_k = 2,\ L = 1,\ N_\pi = 1,\ N_N = 1$

LO nucleon self-energy =  $= O(p^{1\cdot 2 + 4 - 2\cdot 1 - 1}) = O(p^3)$

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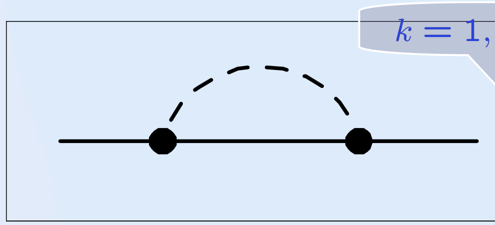


$= O(p^{1\cdot 2 + 4 - 2\cdot 1 - 1}) = O(p^3)$

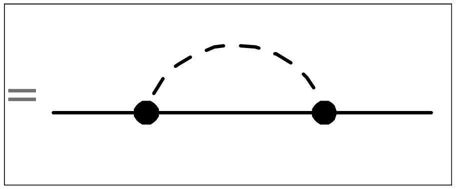
$$M_N = M_N^{(0)} + c_1\, m_\pi^2 + \left(\frac{g_A}{4\pi f_\pi}\right)^2 \left[a_0 + a_1\, m_\pi^2 + \chi m_\pi^3 + \ldots\right]$$

$O(m_\pi^4 / M_N^{(0)})$

LECs

[Gasser, Sainio, Svarc (1988); Jenkins & Manonar (1991); Becher & Leutwyler (1999); Gegelia & Japaridze (1999); Gegelia, Scherer et al. (2003)]; VP & Vanderhaeghen (2006)]

Analyticity in energy vs. the quark mass

LO nucleon self-energy =  $\equiv \Pi^{(3)}(s, m_\pi^2) = O(p^3)$

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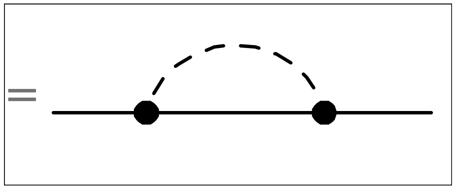
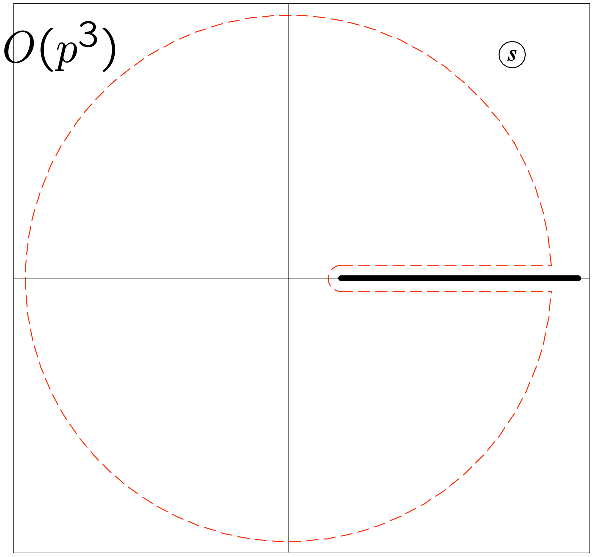
LO nucleon self-energy =  $\equiv \Pi^{(3)}(s, m_\pi^2) = O(p^3)$



Dispersion in energy:

$$\Pi(s, m_\pi^2) = \frac{1}{2\pi i} \oint ds' \, \frac{\Pi(s', m_\pi^2)}{s' - s}$$

$$\Pi^{(n)}(s, m_\pi^2) = \frac{1}{\pi} \int_{M^2}^{\infty} ds' \, \frac{\mathrm{Im}\, \Pi^{(n)}(s', m_\pi^2)}{s' - s} \left(\frac{s - M^2}{s' - M^2} \right)^{n-1}$$

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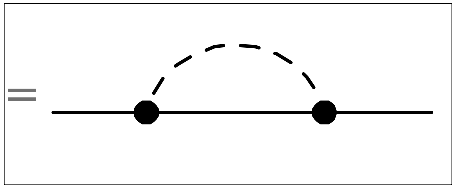
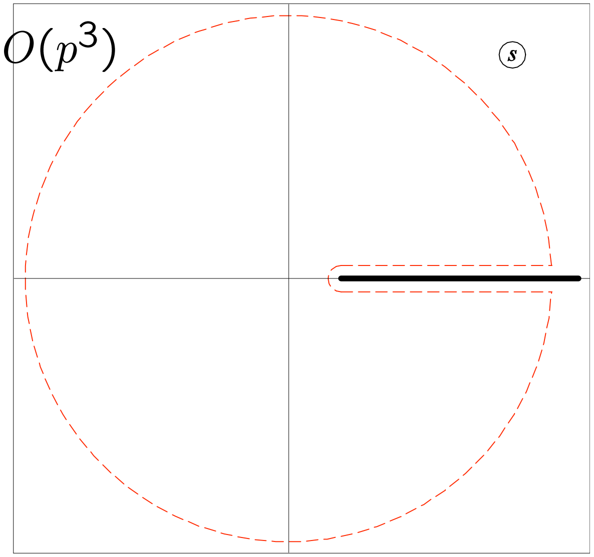
LO nucleon self-energy =  $\equiv \Pi^{(3)}(s, m_\pi^2) = O(p^3)$



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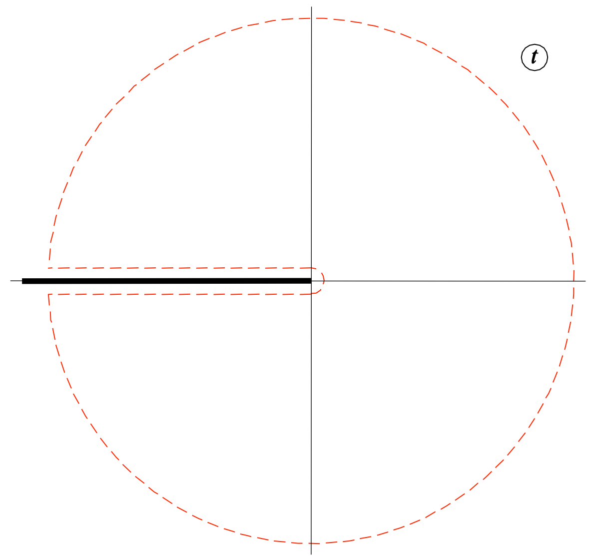

Dispersion in $t = m_\pi^2 \sim m_q$:

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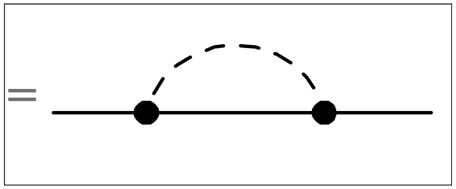
LO nucleon self-energy =  $\equiv \Pi^{(3)}(s, m_\pi^2) = O(p^3)$

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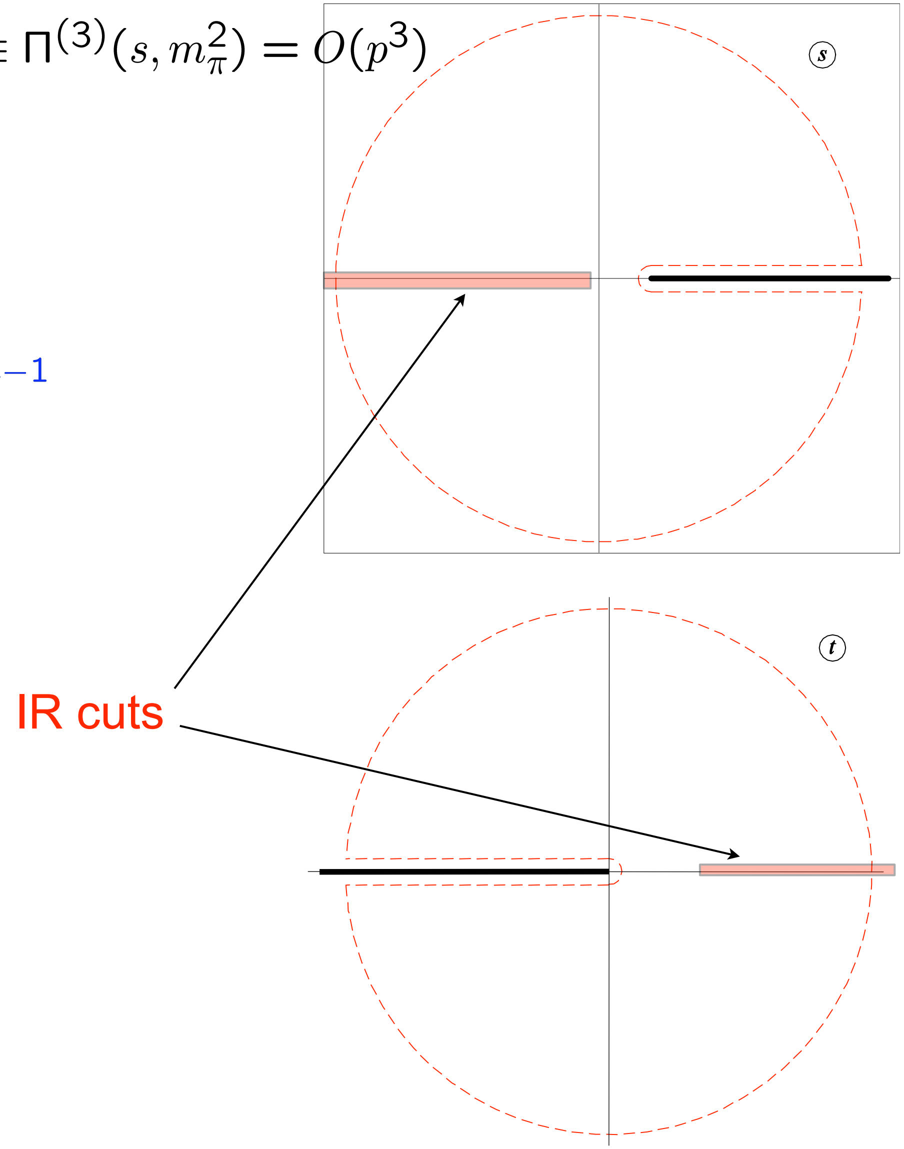
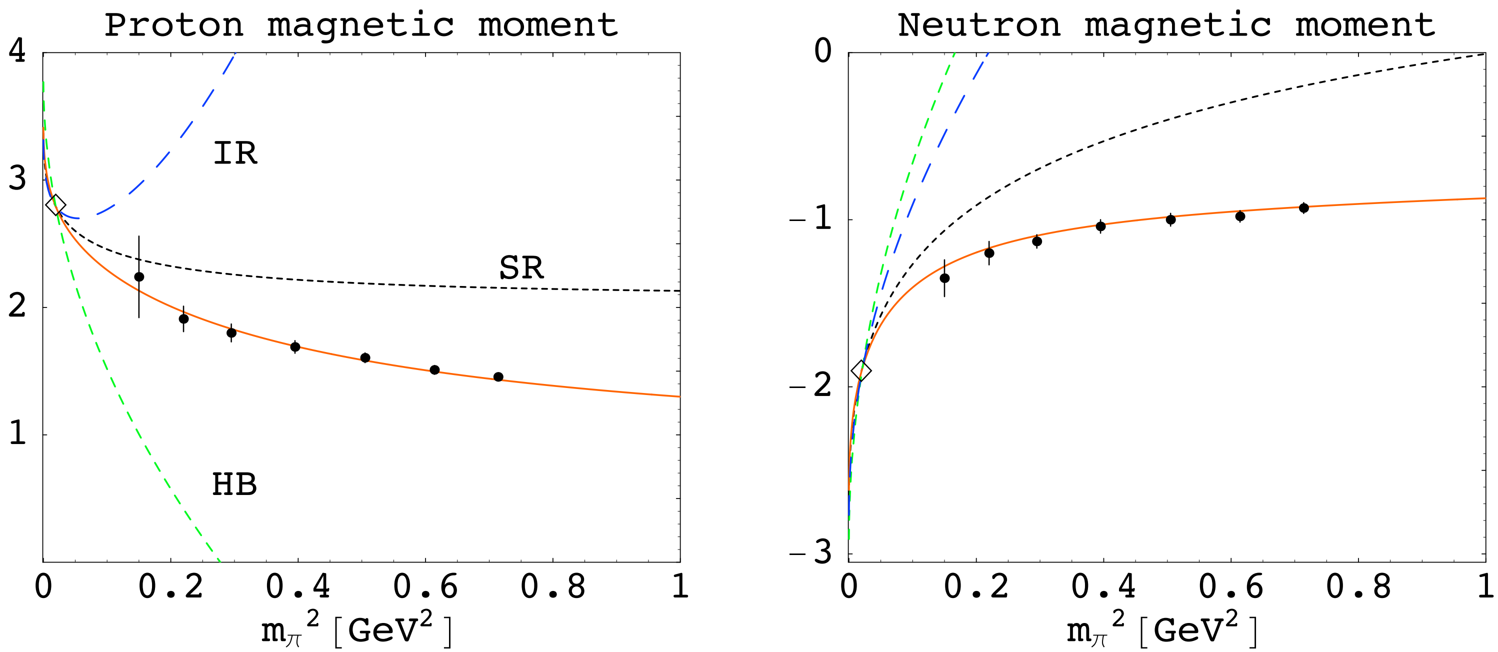


O(p3) calculations of the nucleon magnetic moment



IR = Infrared regularization [Kubis & Meissner (2001)]

SR = 1st derivative of the GDH sum rule or BChPT [Holstein, VP, Vanderhaeghen PLB (2005)]:

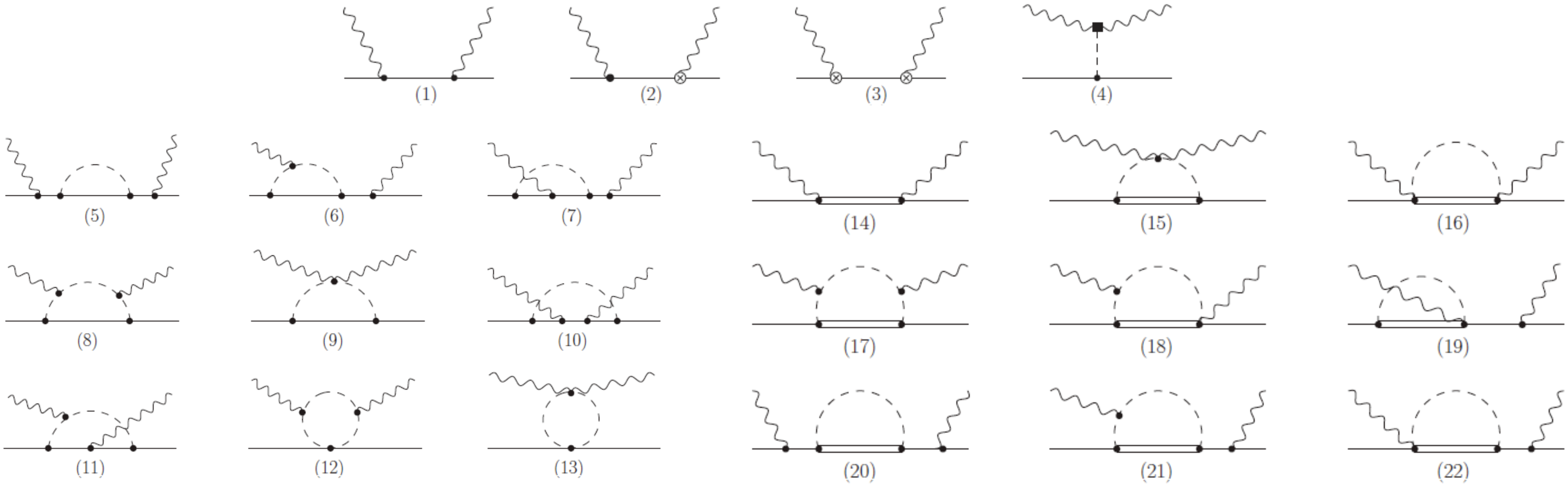
$$\mu_p = (1 + \kappa_{0p} + \kappa_p^{(\text{loop})})(e/2M)$$

$$\kappa_p^{(\text{loop})} = \frac{M^2}{\pi e^2} \int_{\omega_{\text{th}}}^{\infty} \frac{d\omega}{\omega} \Delta\sigma_{1p}^{(p)}$$

$$= \frac{g^2}{(4\pi)^2} \left\{ 1 - \frac{\mu\,(4 - 11\mu^2 + 3\mu^4)}{\sqrt{1 - \frac{1}{4}\mu^2}} \arccos\frac{\mu}{2} - 6\mu^2 + 2\mu^2 \left(-5 + 3\,\mu^2\right) \ln\mu \right\}$$

$$= \frac{g^2}{(4\pi)^2} \left\{ 1 - 2\pi\mu - 2\,(2 + 5\ln\mu)\,\mu^2 + \frac{21\pi}{4}\,\mu^3 + O(\mu^4) \right\} \qquad \mu = m_\pi/M_N$$

Compton scattering to NNLO [V.Lensky & VP, JETP Lett. (2009), arXiv:0907.0451]



$\mathcal{O}(p^2)$	$\frac{e^2}{4\pi} = \frac{1}{137}$, $M_N = 938.3$ MeV, $\hbar c = 197$ MeV$\cdot$fm
$\mathcal{O}(p^3)$	$g_A = 1.267$, $f_\pi = 92.4$ MeV, $m_\pi = 139$ MeV, $m_{\pi^0} = 136$ MeV, $\kappa_p = 1.79$
$\mathcal{O}(p^4/\Delta)$	$M_\Delta = 1232$ MeV, $h_A = 2.85$, $g_M = 2.97$, $g_E = -1.0$
$\mathcal{O}(p^4)$	$\alpha_0, \beta_0 = \pm\frac{e^2}{4\pi M_N^3}$

Compton scattering cross sections

Data points:
MAMI/TAPS (2001)
SAL (1993)
Illinois (1991)

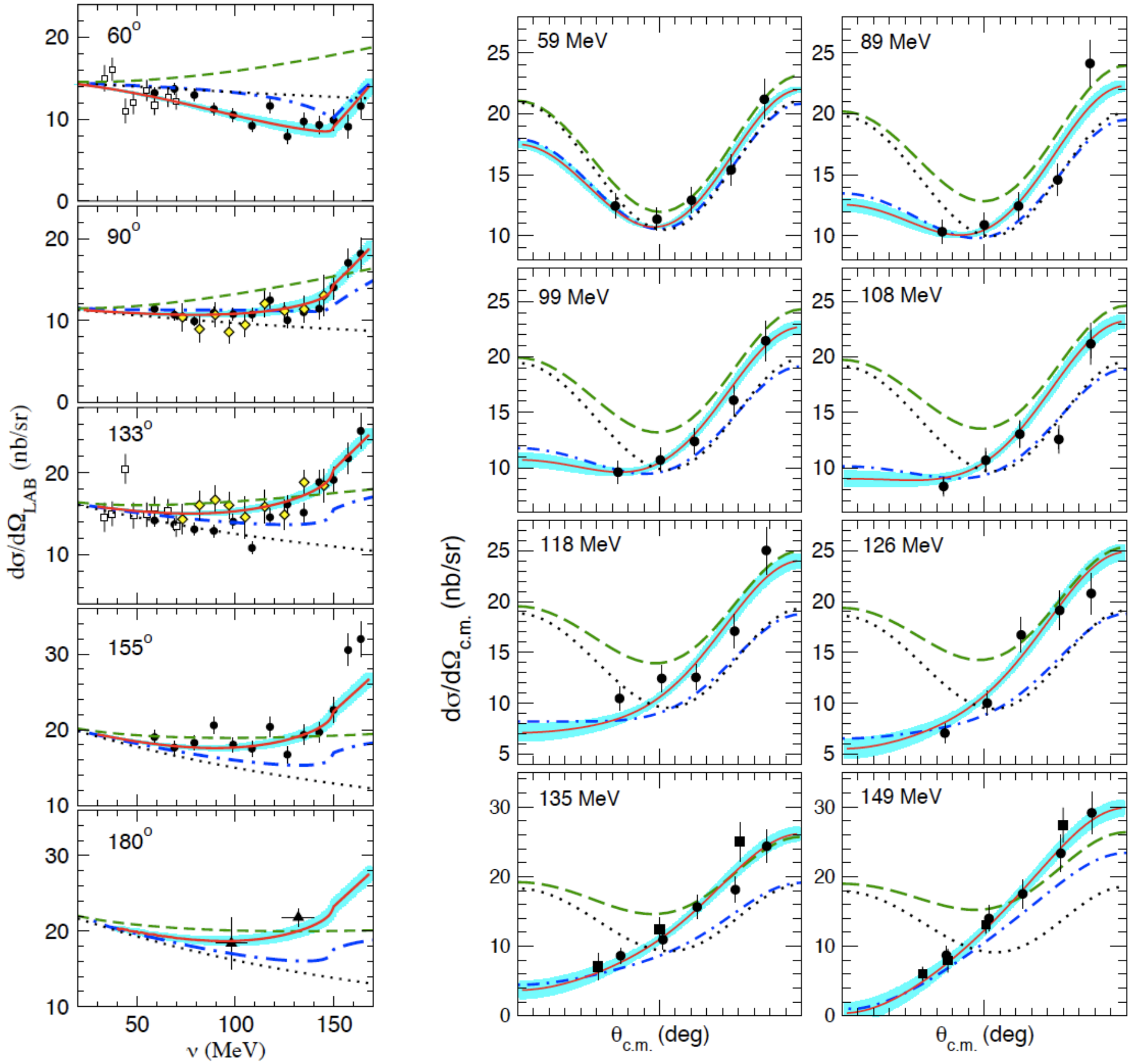
Curves:

.... Klein-Nishina

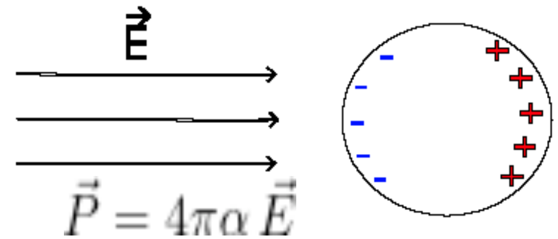
— — — Born + WZW

— · — + p-qube

(red line with cyan band) + Delta



Scalar Polarizabilities



$$\vec{P} = 4\pi\alpha\,\vec{E}$$

	BχPT (HBχPT)			PDG
	$\mathcal{O}(p^3)$	$\mathcal{O}(p^3) + \mathcal{O}(p^4/\Delta)$	$\mathcal{O}(p^4)$ est.	[45]
$\alpha^{(p)}$	6.8 (12.2)	10.8 (20.8)	± 0.7	12.0 ± 0.6
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$$\Delta = M_\Delta - M_N \approx 300\text{MeV}$$

TABLE I: Predictions of baryon χPT for electric (α) and magnetic (β) polarizabilities of the proton in units of 10^{-4} fm^3, compared with the Particle Data Group summary of experimental values.

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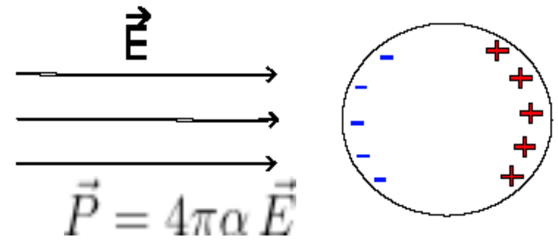

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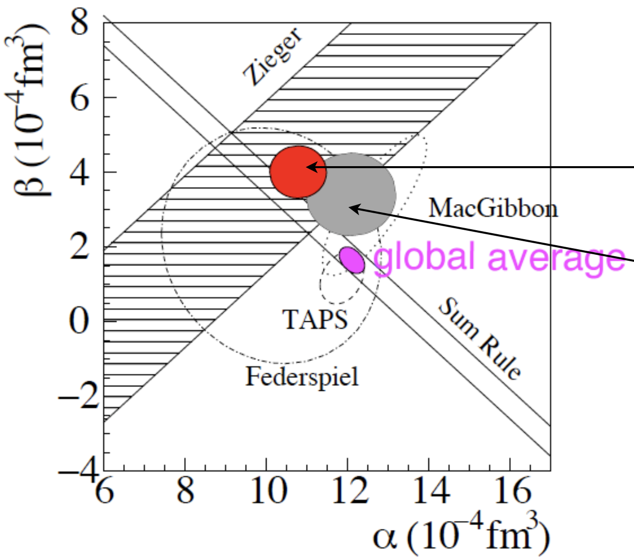

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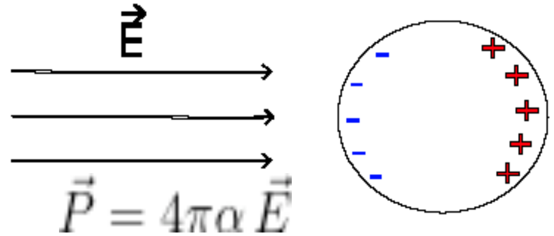

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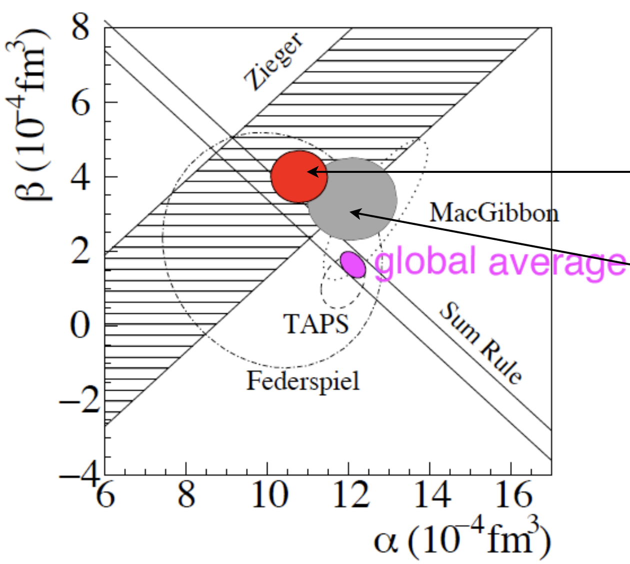

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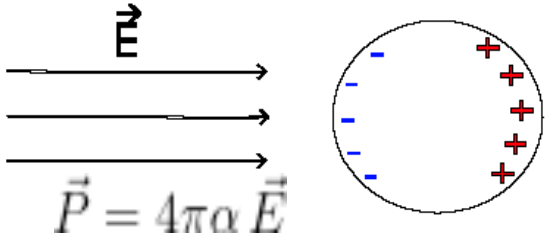

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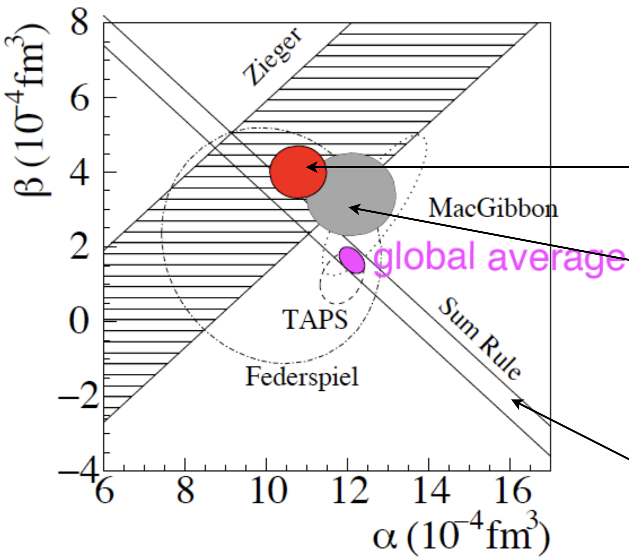

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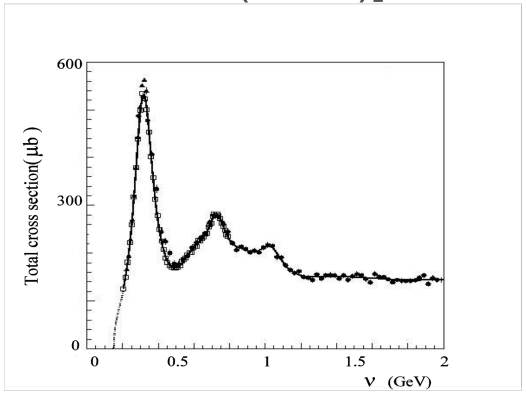
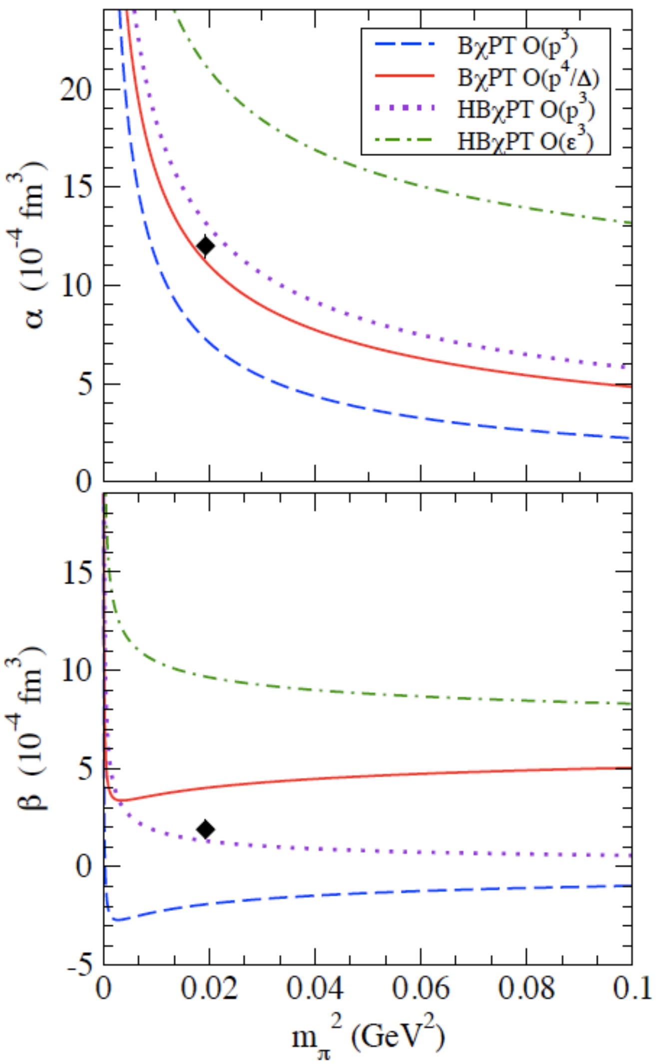
$$\alpha + \beta = \frac{1}{4\pi^2}\int_{\nu_0}^{\infty} d\nu' \, \frac{(\sigma_{1/2} + \sigma_{3/2})}{\nu'^2}$$

[Baldin (1960)]



Chiral behavior: HBChPT vs BChPT



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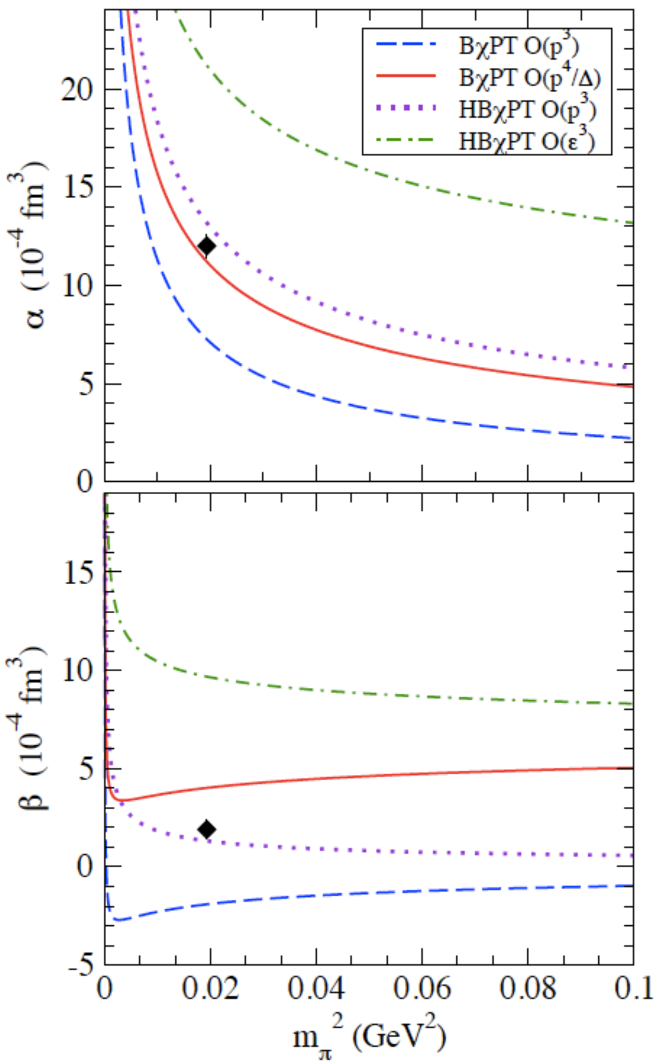

$$\mu = m_\pi / M_N$$

$$(\bar\alpha+\bar\beta)_n = \frac{e^2 g^2}{(4\pi)^2 M^3}\frac{11}{48\mu}\left(1+\frac{4(1+12\ln\mu)}{11\pi}\mu-\frac{117}{88}\mu^2+\ldots\right)$$

$$(\bar\alpha+\bar\beta)_p = \frac{e^2 g^2}{(4\pi)^2 M^3}\frac{11}{48\mu}\left(1+\frac{48(4+3\ln\mu)}{11\pi}\mu-\frac{1521}{88}\mu^2+\ldots\right)$$

or, numerically,

$$(\bar\alpha+\bar\beta)_n = 14.5-5.5-0.4+\ldots = 8.7$$
$$(\bar\alpha+\bar\beta)_p = 14.5-5.2-5.5+\ldots = 5.3$$

in units of 10^{-4} fm^3.

$$\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu}+18\log\mu+\frac{63}{2}-\frac{981\pi\mu}{32}-(100\log\mu+\frac{121}{6})\mu^2+\mathcal{O}(\mu^3)\right]$$

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- BChPT (w/ Delta's) at NNLO for **Compton scattering** has a uncertainty comparable to experiment and is consistent with experimental cross-sections upto the threshold, but **not** with the PDG value for magnetic polarizability.