Experimental results from MAMI

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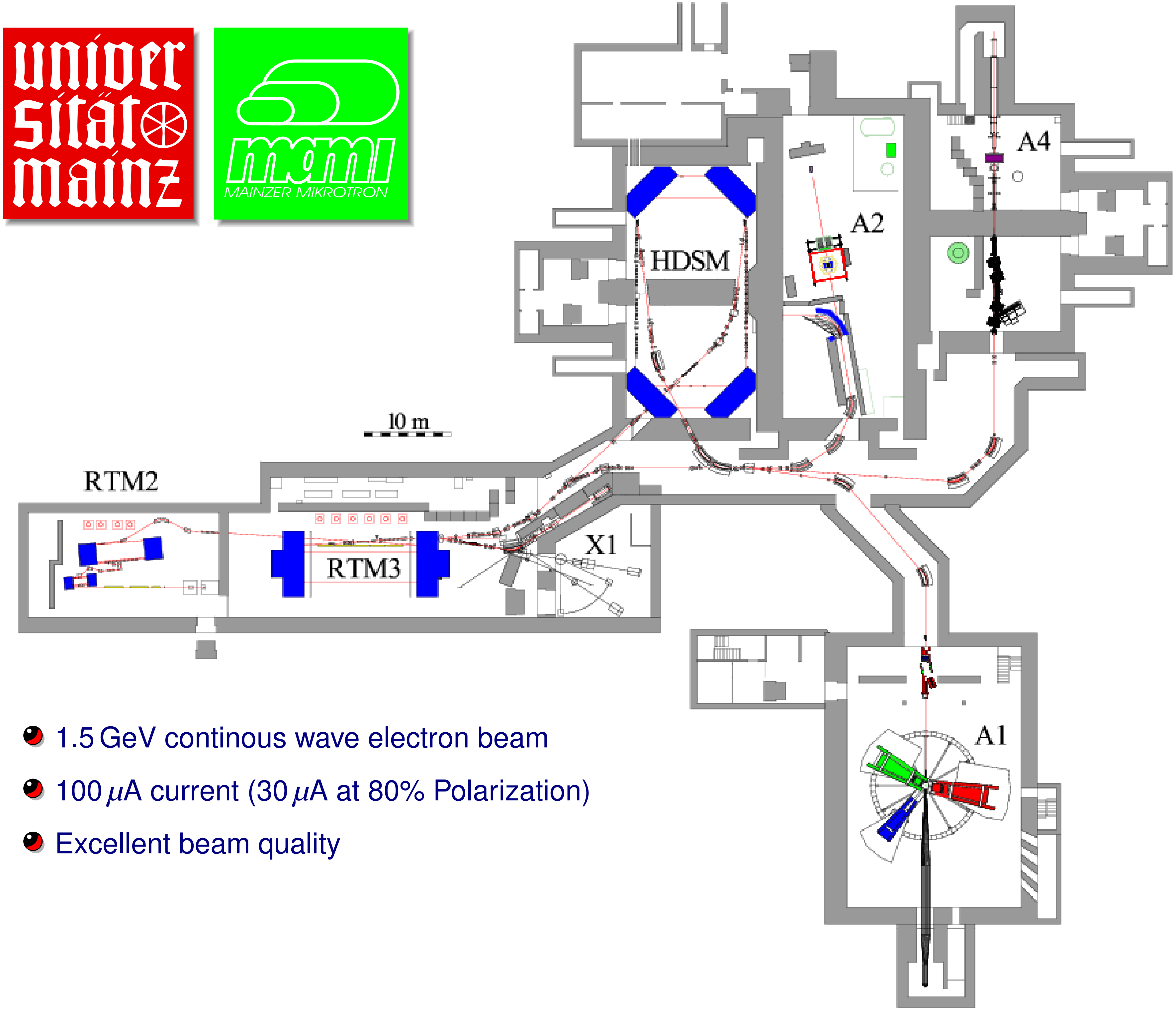
- η and η' Decays
  - $\eta \to \pi^0\pi^0\pi^0$
  - Cusp in η decays
- Polarizabilities of the Nucleon
  - Virtual Compton Scattering
  - Spin Polarizabilities
- Threshold Pion Production
  - Q^2 Dependence
  - Polarized Beam Asymmetry Σ



- 1.5 GeV continous wave electron beam
- 100 μA current (30 μA at 80% Polarization)
- Excellent beam quality

η and η' Decay

Motivation: η and η' Decay

$\eta,\ \eta' \to \pi^0\pi^0\pi^0$

- Isospin violating $\Delta I = 1 \Rightarrow \quad \sim$ light quark mass difference $m_u - m_d$
- Calculations in ChPT
  - Decay amplitude at $O(p^2)$ (J. Gasser, H. Leutwyler NPB250, 539 (1985)):

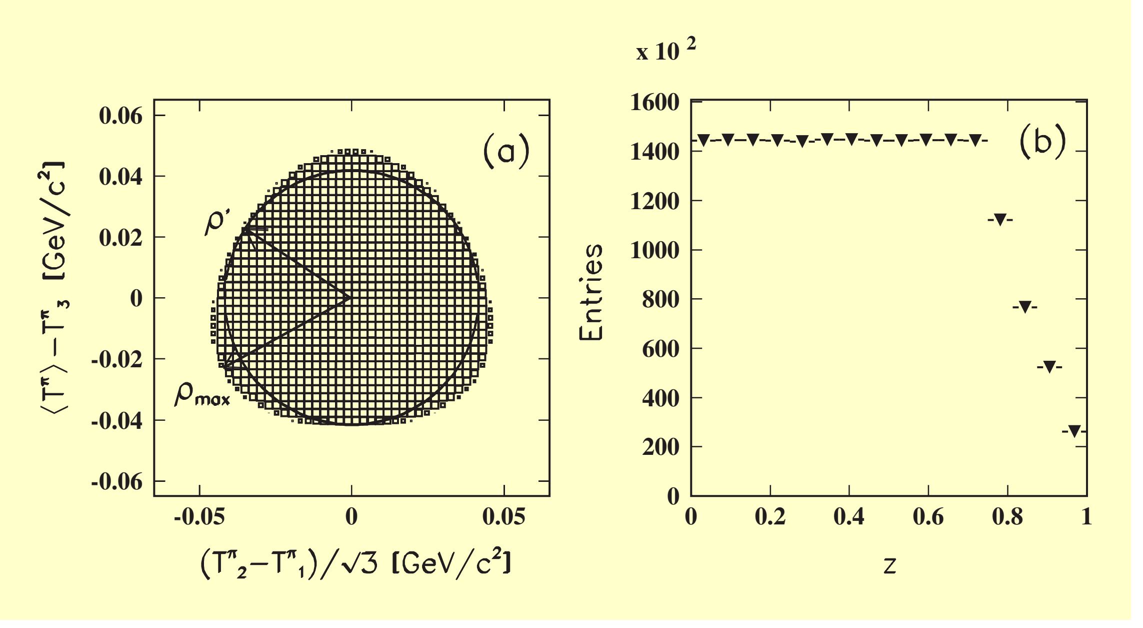
$$A(s,t,u) \;=\; \frac{B_0(m_u-m_d)}{3\sqrt{3}F_\pi^2}\left[1+\frac{3(s-s_0)}{M_\eta^2-M_\pi^2}\right] \sim \frac{m_d-m_u}{m_s-\hat{m}}$$

  - ChPT $O(p^6) \Rightarrow$ in disagreement with data
  - Structure of the η, *e.g.* $\eta_1 - \eta_8$ mixing?
  - Final State Interaction, unitary chiral approach
- Cusp in $3\pi^0$ Dalitz plot $\Rightarrow \pi^0\pi^0 \to \pi^+\pi^-$ Scattering length

Decay $\eta \to 3\pi^0$: slope parameter α

$$|A_{\eta\to 3\pi^0}|^2 \sim 1 + 2\alpha z + \cdots$$

with $$z = 6\sum_{i=1}^{3} \frac{(E_i - m_\eta/3)^2}{(m_\eta - 3m_{\pi^0})^2} = \frac{\rho^2}{\rho^2_{max}}$$



Experimental technique:

- Identified $3\pi^0$ decay $\Rightarrow$ 4π detector for photons
- Comparison of decay slope with Monte-Carlo-Simulation

A2 Crystal Ball and TAPS Photon Spectrometer

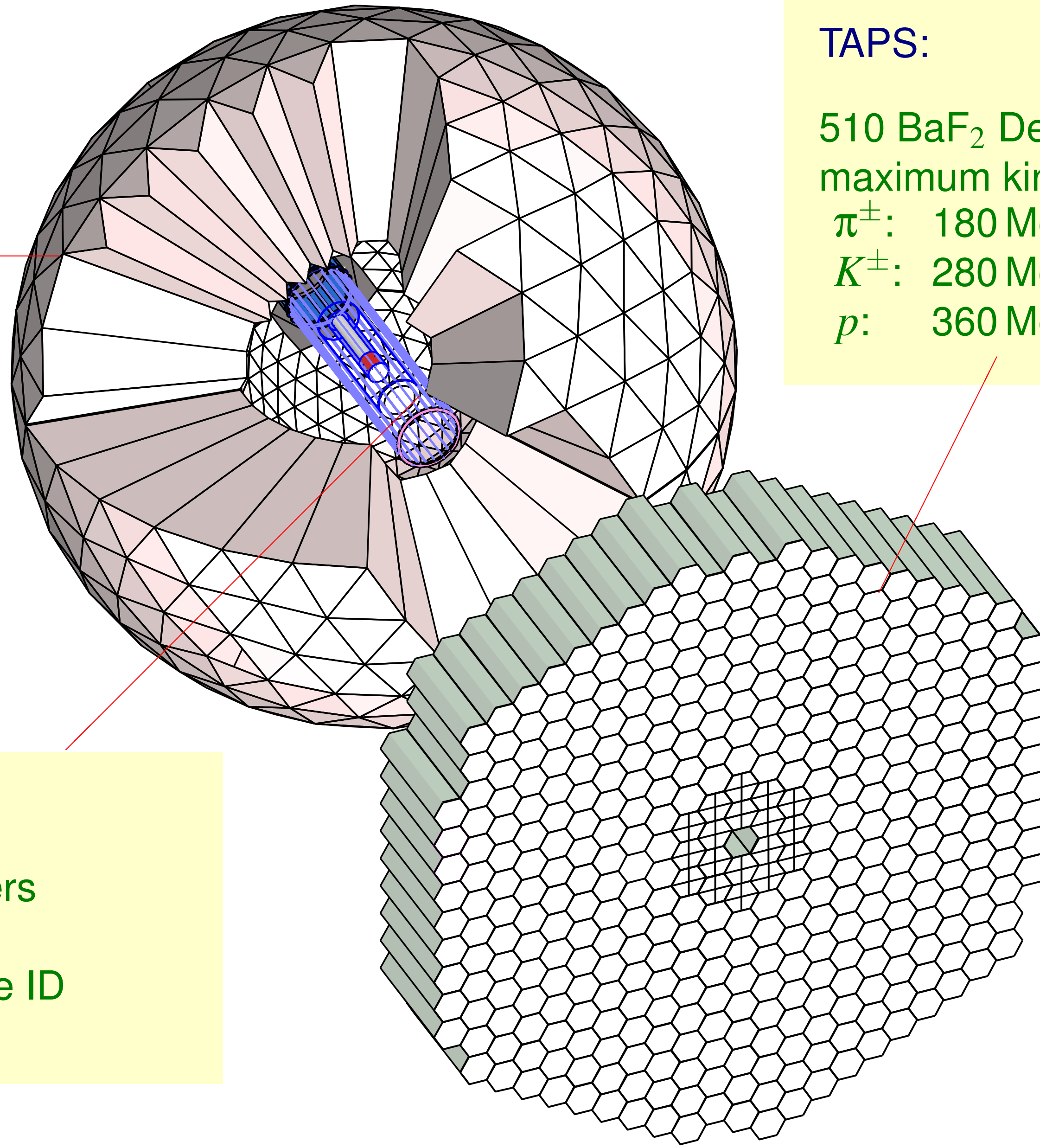
Cystal Ball:

672 NaJ Detectors

$20^\circ \leq \theta \leq 160^\circ$

max. kin. Energy

$\mu^{\pm}$:	233 MeV
$\pi^{\pm}$:	240 MeV
$K^{\pm}$:	341 MeV
p:	425 MeV



TAPS:

510 BaF_2 Detectors

maximum kin. Energy:

$\pi^{\pm}$:	180 MeV
$K^{\pm}$:	280 MeV
p:	360 MeV

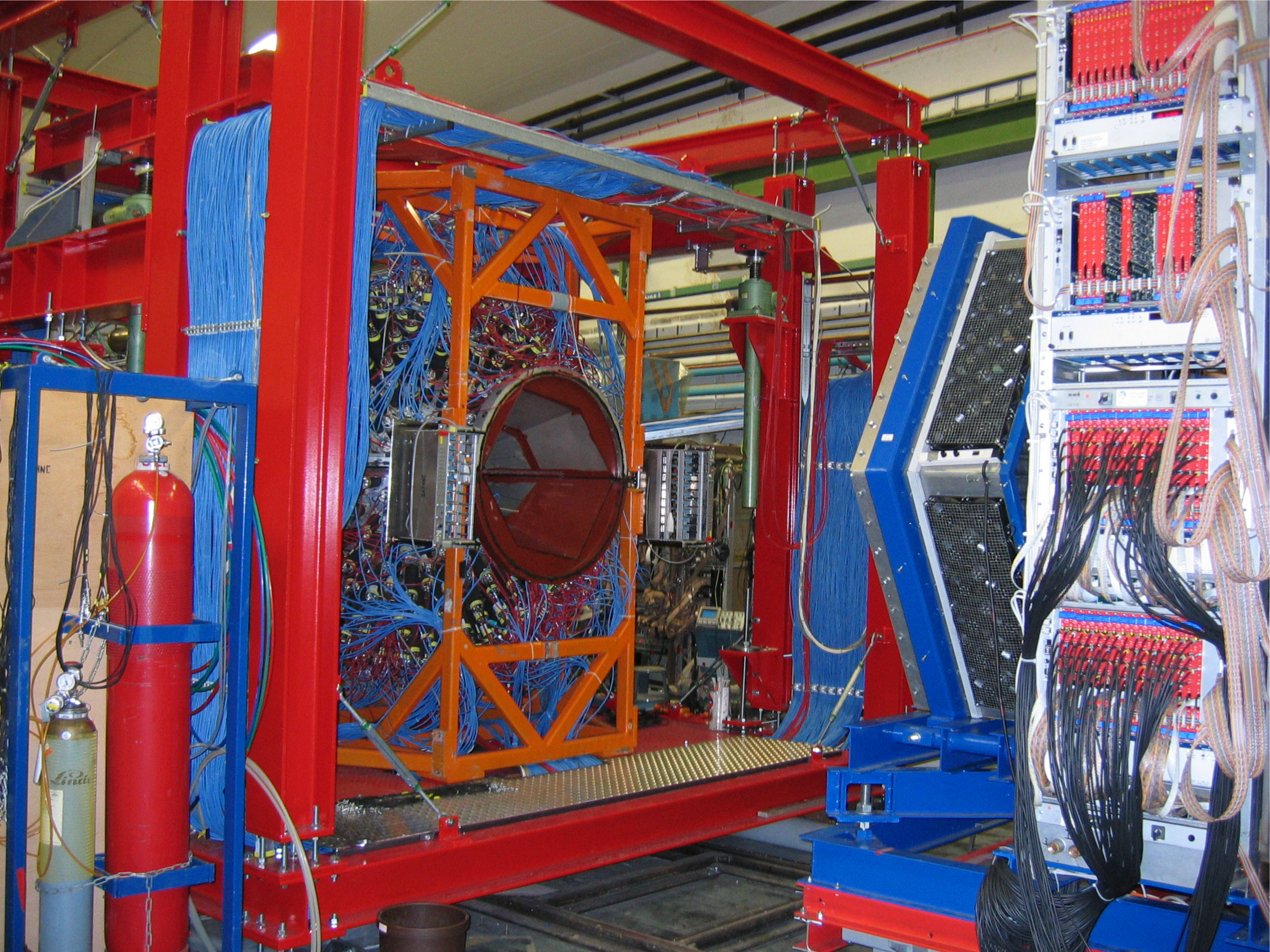
Vertex Detectors:

2 cylindrical wire chambers

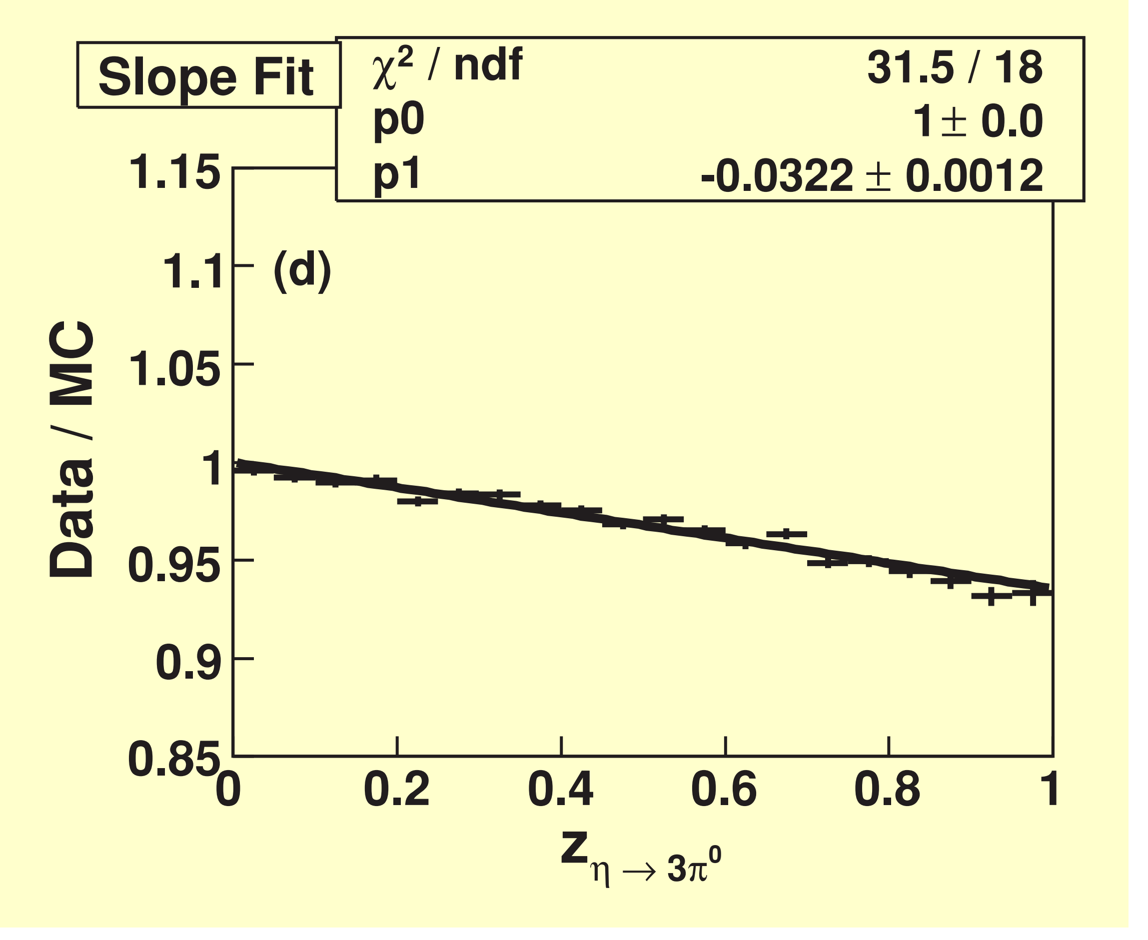
480 wires, 320 stripes

24 Scintillators for particle ID

$$\sigma_E/E = 2\%/\sqrt[4]{E(GeV)}$$



Decay $\eta \to 3\pi^0$

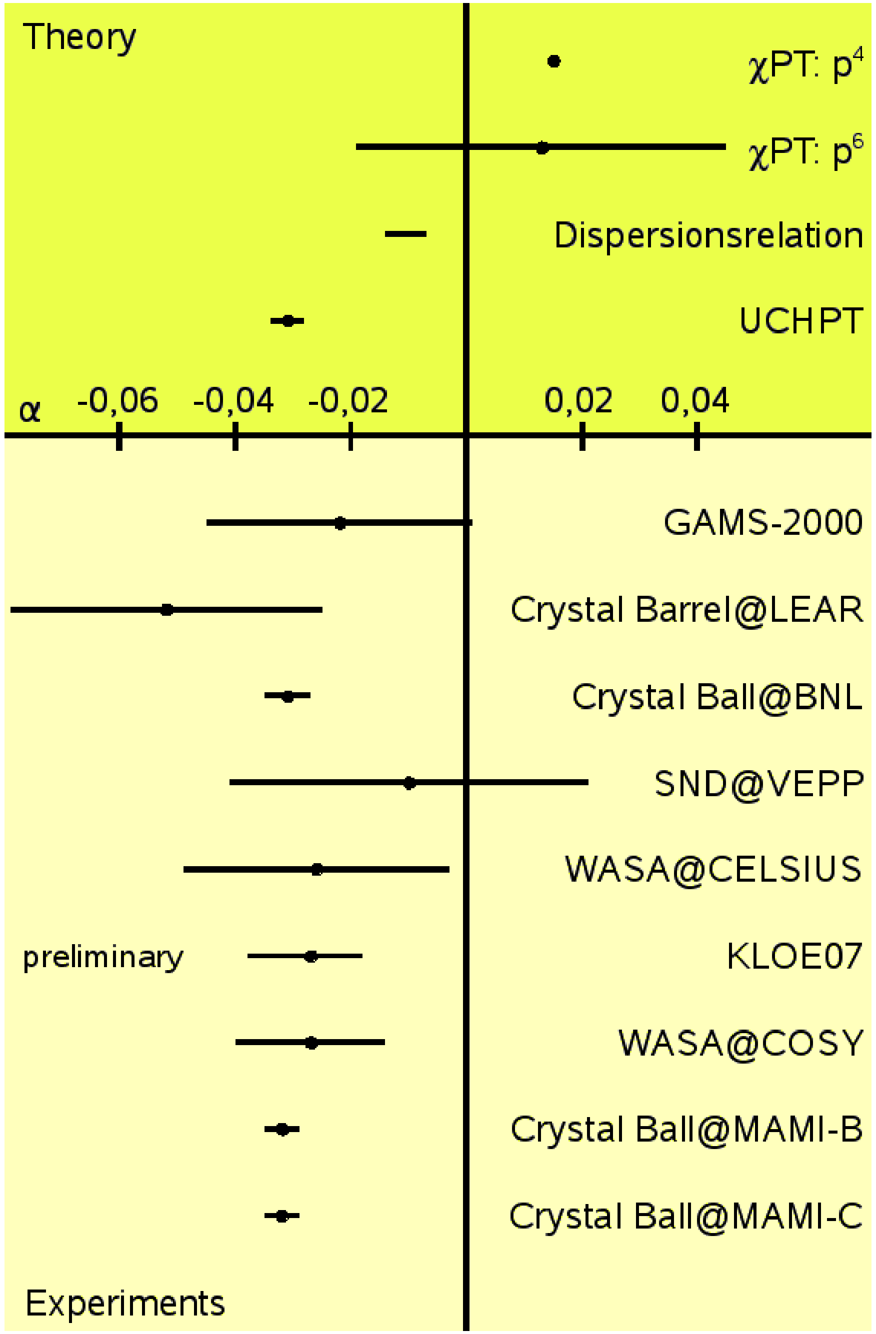


$$\alpha = -0.0322 \pm 0.0012 \pm 0.0022$$

S. Prakhov *et al.*, Phys. Rev. C79, 035204 (2009)

Details → Talk by Sergey Prakhov (Tuesday)

Decay $\eta \rightarrow 3\pi^0$



Dalitz Plot Parameter α:

- MAMI-B

$$\alpha = -0.0319 \pm 0.0015 \pm 0.0016$$

- MAMI-C

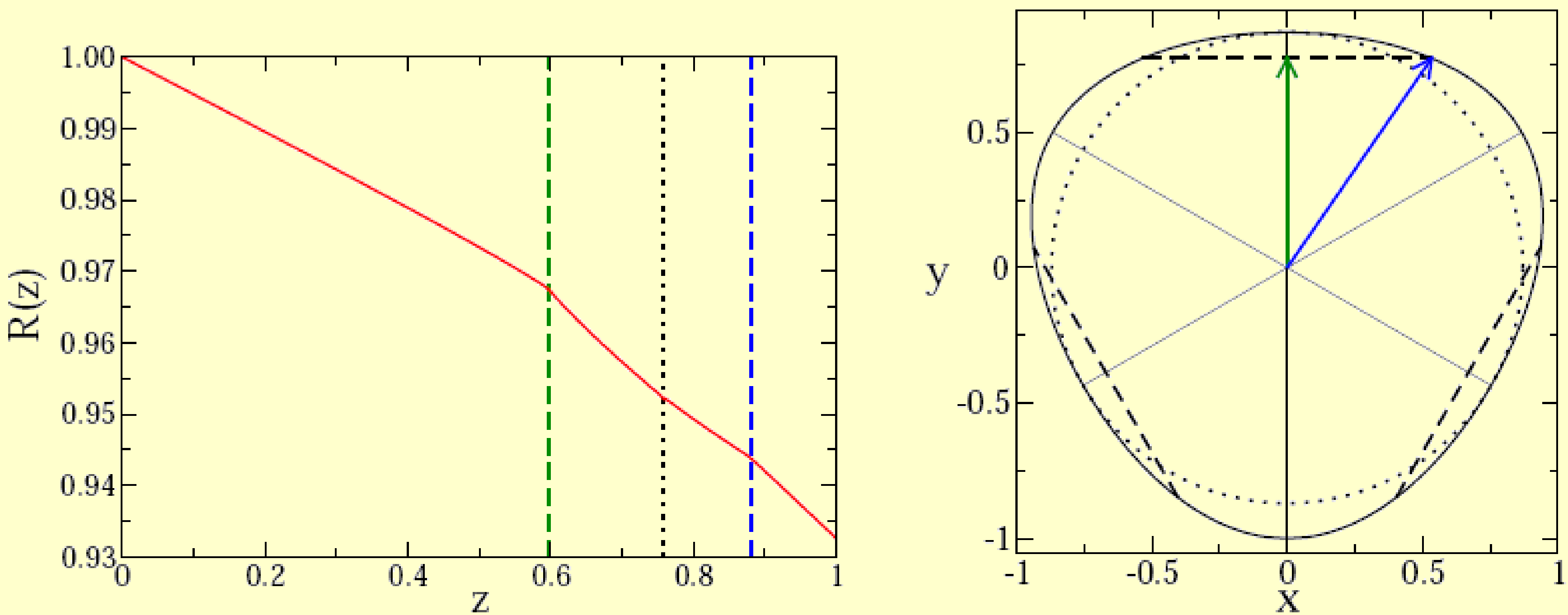
$$\alpha = -0.0322 \pm 0.0012 \pm 0.0022$$

- Consistent with Crystal Ball@BNL / KLOE
- Theory: UChPT
- Cusp on slope?

MAMI-B: M. Unverzagt *et al.*, Eur. Phys. J. A39, 169-177 (2009)
MAMI-C: S. Prakhov *et al.*, Phys. Rev. C79, 035204 (2009)
UChPT: B. Borasoya and R. Nißler, Eur. Phys. J. A 26, 383-398 (2005)

Cusp in slope

- Rescattering $\eta \to \pi^0\pi^+\pi^- \to \pi^0\pi^0\pi^0$ at threshold
- Cusp in Dalitz plot slope $\Rightarrow$ $\pi\pi$ scattering length:

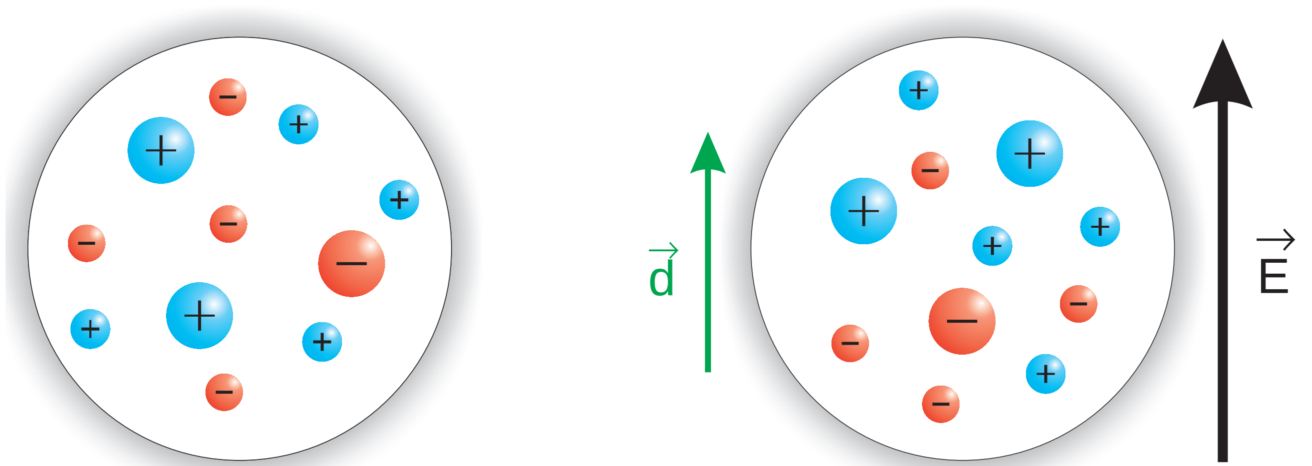


- Near future: $3 \cdot 10^6 \to 30 \cdot 10^6$ detected η-Decays
- Also visible in $\eta' \to \eta\pi^0\pi^0$, larger effect

R. Nißler, PhD-Thesis, HISKP Bonn University

Polarizabilities of the Nucleon

Electromagnetic Polarizabilities



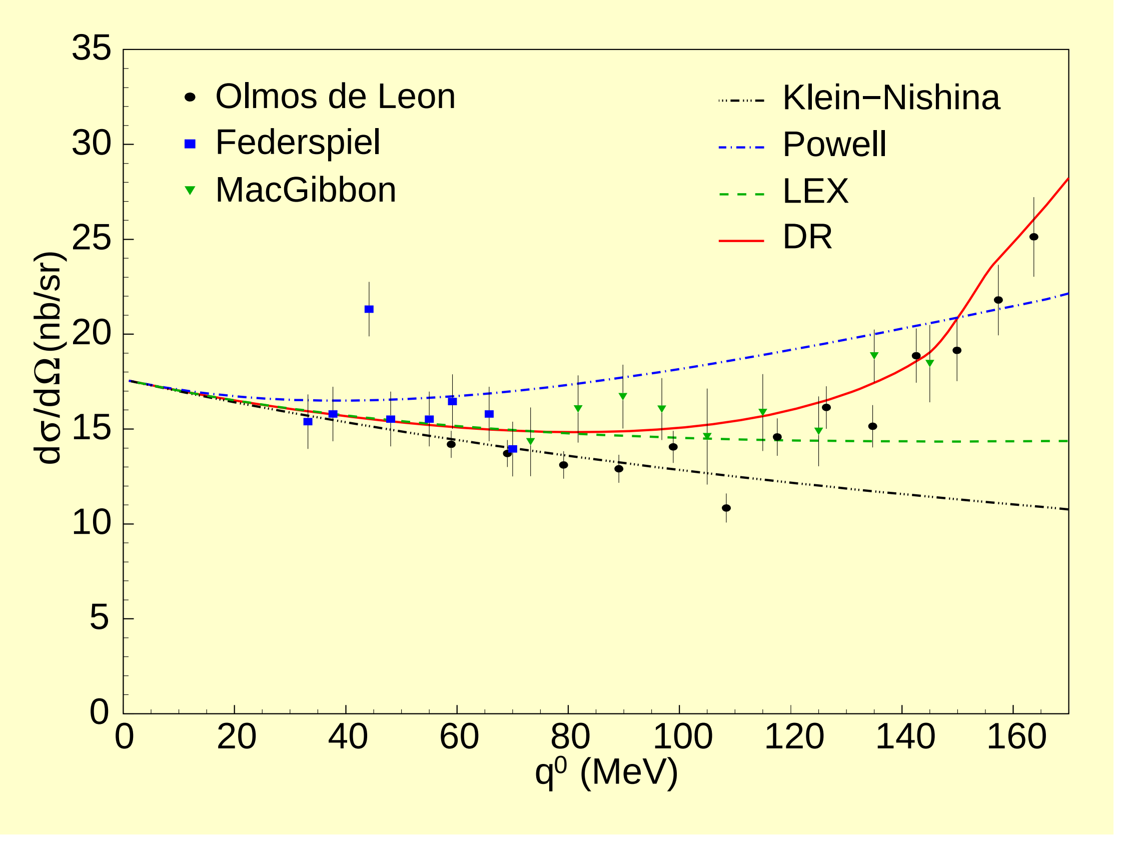
Polarizability α: induced dipole moment $\vec{d} = \alpha \vec{E}$

- Direct measure of electric (α) and magnetic (β) stiffness of nucleon
- Fundamental static properties of the nucleon
- Spin polarizabilities

Dynamical Measurement

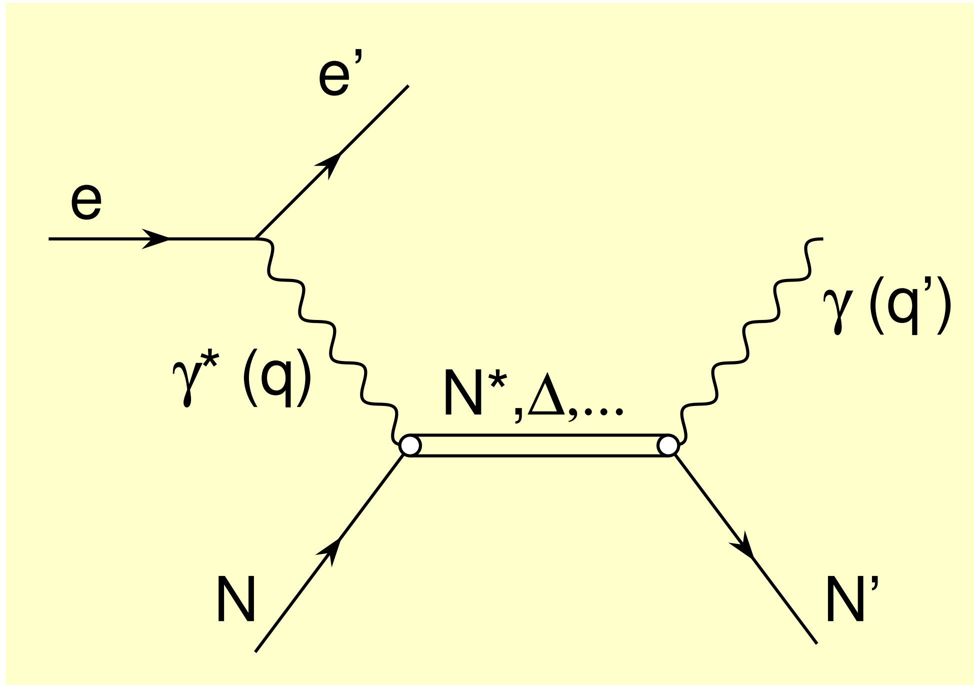
COMPTON SCATTERING ⇒ Polarizabilities in static limit $q' \to 0$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} - \frac{e^2}{4\pi m_p}\left(\frac{q'}{q}\right)^2 q q' \left\{\frac{1}{2}(\bar{\alpha}+\bar{\beta})(1+\cos\theta)^2 + \frac{1}{2}(\bar{\alpha}-\bar{\beta})(1-\cos\theta)^2\right\} + \cdots$$



Data/(10^{-4}fm^3)				HBChPT $(\mathcal{O}(p^4))$
α	=	12.1	$\pm 0.3_{stat} \pm 0.5_{syst}$	10.5 ± 0.2
β	=	1.6	$\pm 0.4_{stat} \pm 0.6_{syst}$	3.5 ± 3.6

Virtual Compton Scattering



- Polarizabilities depend on photon virtuality Q^2
  $\Rightarrow$ Generalized Polarizabilities
- Interpretation of GP(Q^2):
  $\Rightarrow$ "Form Factor" measurement in external field
  $\Rightarrow$ Fouriertransform of local distribution of polarizabilities

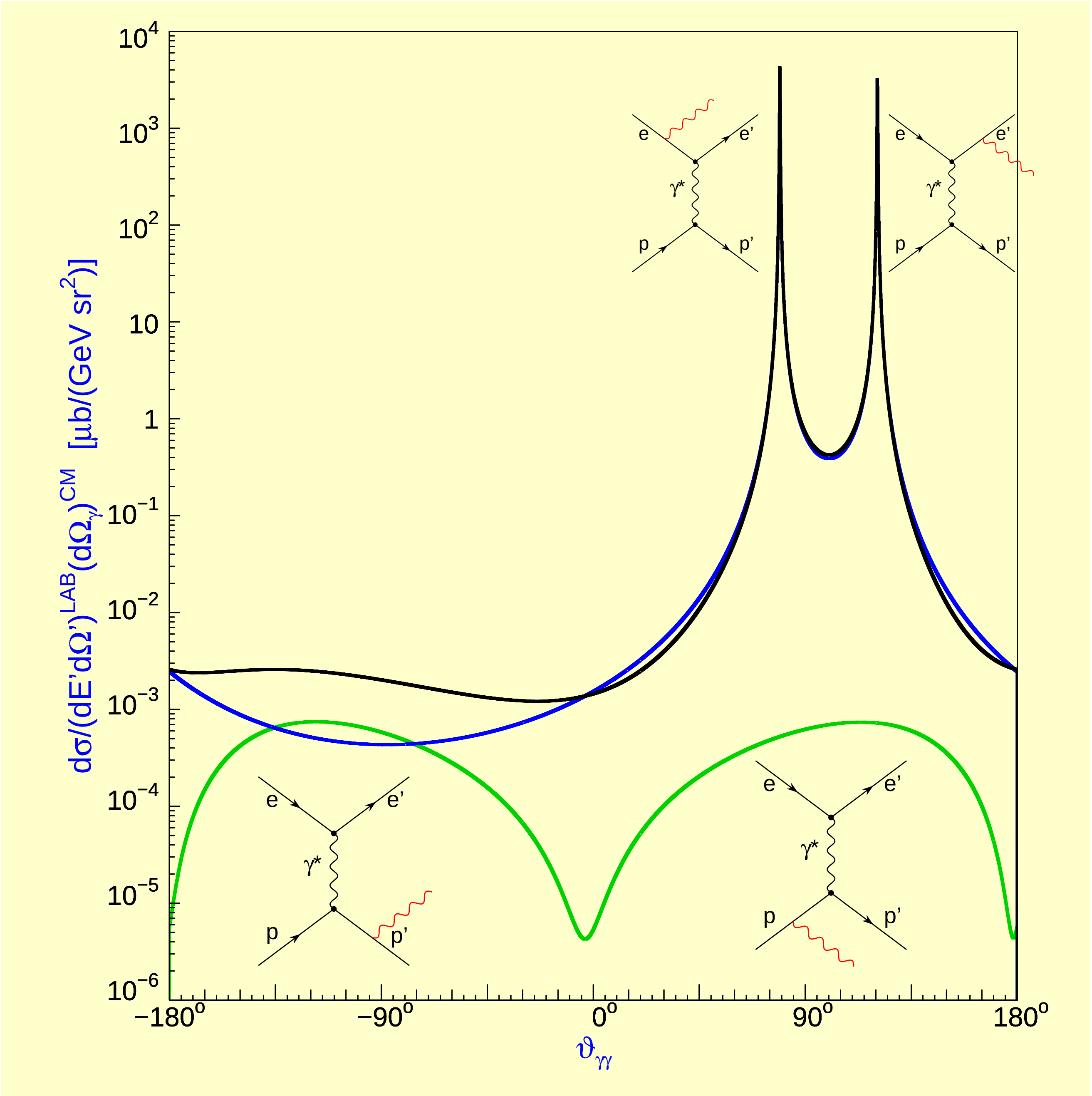
Polarizabilities in Virtual Compton Scattering

VCS[1]	EM transition	Spin flip	RCS[2]	Resonance
$P^{(01,01)0}$	C1 $\longrightarrow$ E1	S=0	$-\frac{1}{\alpha}\sqrt{\frac{2}{3}}\,\alpha_E$	D13, S11
$P^{(11,11)0}$	M1 $\longrightarrow$ M1	S=0	$-\frac{1}{\alpha}\sqrt{\frac{8}{3}}\,\beta_M$	P33, P11
$P^{(01,12)1}$	M2 $\longrightarrow$ E1	S=1	$-\frac{1}{\alpha}\frac{\sqrt{2}}{3}\,\gamma_3$	D13
$P^{(11,02)1}$	C2 $\longrightarrow$ M1	S=1	$-\frac{1}{\alpha}\sqrt{\frac{8}{27}}\,(\gamma_2+\gamma_4)$	P33
$P^{(11,00)1}$	C0 $\longrightarrow$ M1	S=1		P11
$P^{(11,11)1}$	M1 $\longrightarrow$ M1	S=1		P33, P11
$P^{(01,01)1}$	C1 $\longrightarrow$ E1	S=1		D13, S11
$\hat{P}^{(11,2)1}$	C2, E2 $\longrightarrow$ M1	S=1		P33
$\hat{P}^{(01,1)1}$	C1, E1 $\longrightarrow$ E1	S=1		D13, S11
$\hat{P}^{(01,1)0}$	C1, E1 $\longrightarrow$ E1	S=0		D13, S11

- Defined only in limit $q' \longrightarrow 0$, linear in q'
- Angular momentum conservation $\Rightarrow$ 10 Generalized Polarizabilities
- Charge-conjugation, crossing[3] $\Rightarrow$ Only 6 independent GP's

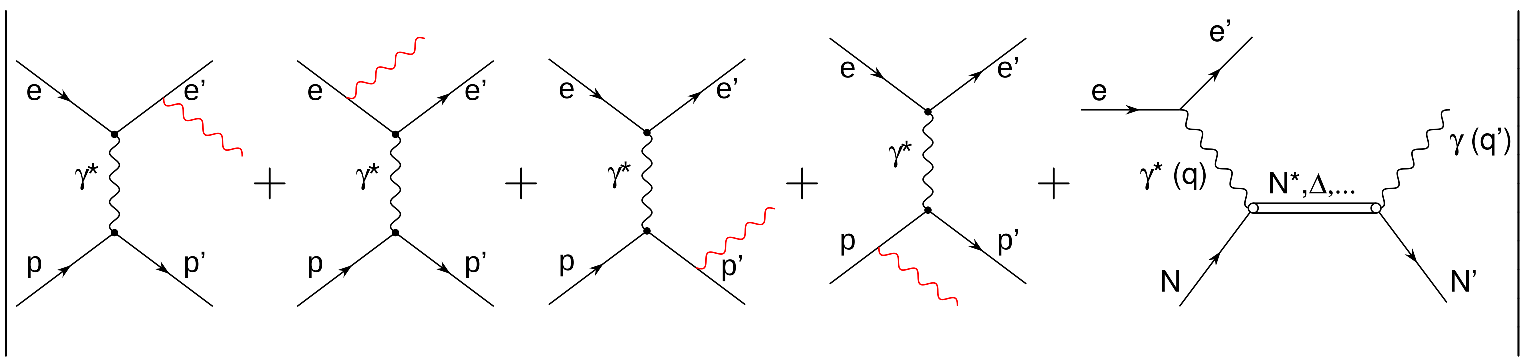
1) P. A. M. Guichon, G. Q. Liu, A. W. Thomas, Nucl. Phys. A 591 606 –638 (1995)
2) S. Ragusa, Phys. Rev. D **47**, 3757 (1993)
3) D. Drechsel *et al.*, Phys. Rev. C **57**,**2**, 941 (1998)

Bethe-Heitler and Born Amplitudes



Extraction of Polarizabilities

$$\frac{d\sigma}{dE'd\Omega'd\Omega_\gamma} = \left| \quad \right|^2$$



- Low Energy Expansion (LEX)
  - Expansion in outgoing photon momentum q'

$$\frac{d^5\sigma}{dE'd\Omega'd\Omega_\gamma^{cm}} = d^5\sigma^{BH+Born} + \phi q' \Psi_0(q,\varepsilon,\theta,\phi) + O(q'^2)$$

  - First order given by Bethe-Heitler + Born
  - First non trivial term in q' expansion: Interference between Bethe-Heitler + Born and VCS

- Dispersion Relations (DR)
  - Connects π-Photo- and Electroproduction with VCS
  - Two parameter: $\Lambda_\alpha(Q^2)$ and $\Lambda_\beta(Q^2)$

LEX: P. A. M. Guichon, G. Q. Liu, A. W. Thomas, Nucl. Phys. A 591 606 –638 (1995)
DR: B. Pasquini *et al.*, Eur. Phys. J. **A 11**, 185 – 208 (2001)

Unpolarized Virtual Compton Scattering

- Low Energy Expansion (LEX)

$$\frac{d^5\sigma}{dE'd\Omega' d\Omega_\gamma^{cm}} = d^5\sigma^{BH+Born} + \phi q' \Psi_0(q,\varepsilon,\theta,\phi) + O(\mathrm{q}'^2)$$

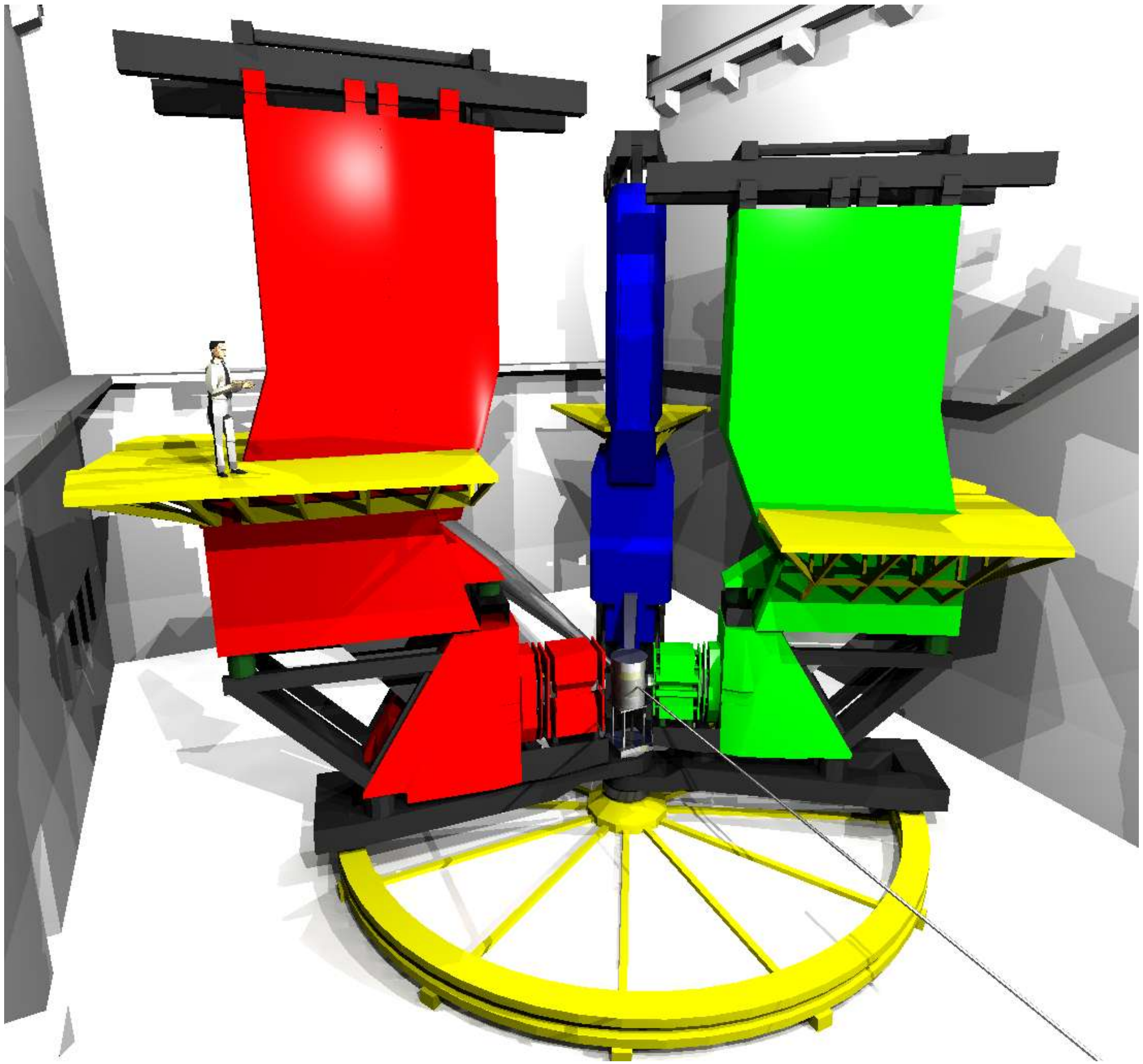
- Unpolarized experiment:

$$\Psi_0 = v_1(\theta,\phi,\varepsilon)(\mathrm{P_{LL}}(\mathrm{q}^2) - \mathrm{P_{TT}}(\mathrm{q}^2)/\varepsilon) + v_2(\theta,\phi,\varepsilon)\mathrm{P_{LT}}(\mathrm{q}^2)$$

- Varying $\theta,\phi,\varepsilon \Rightarrow$ 3 Structure functions:

$$\begin{aligned}
\mathrm{P_{LL}}(\mathrm{q}^2) &= -2\sqrt{6}\, m_N\, G_E\, P^{\mathrm{C1}\to\mathrm{E1}} \\
\mathrm{P_{TT}}(\mathrm{q}^2) &= 3\, G_M\, |\vec{q}|^2 \left(\sqrt{2} P^{\mathrm{C2}\to\mathrm{E1(S)}} - \frac{1}{q_0} P^{\mathrm{M1}\to\mathrm{M1(S)}}\right) \\
\mathrm{P_{LT}}(\mathrm{q}^2) &= \sqrt{\frac{3}{2}\frac{|\vec{q}|}{Q}}\, m_N\, G_E P^{\mathrm{M1}\to\mathrm{M1}} + \frac{\sqrt{3}}{2}\frac{Q}{|\vec{q}|}\, G_M \left(P^{\mathrm{C0}\to\mathrm{M1(S)}} + \frac{|\vec{q}|^2}{\sqrt{2}} P^{\mathrm{C2}\to\mathrm{M1(S)}}\right)
\end{aligned}$$

A1: 3-Spectrometer-Setup at MAMI



Spectrometer A:

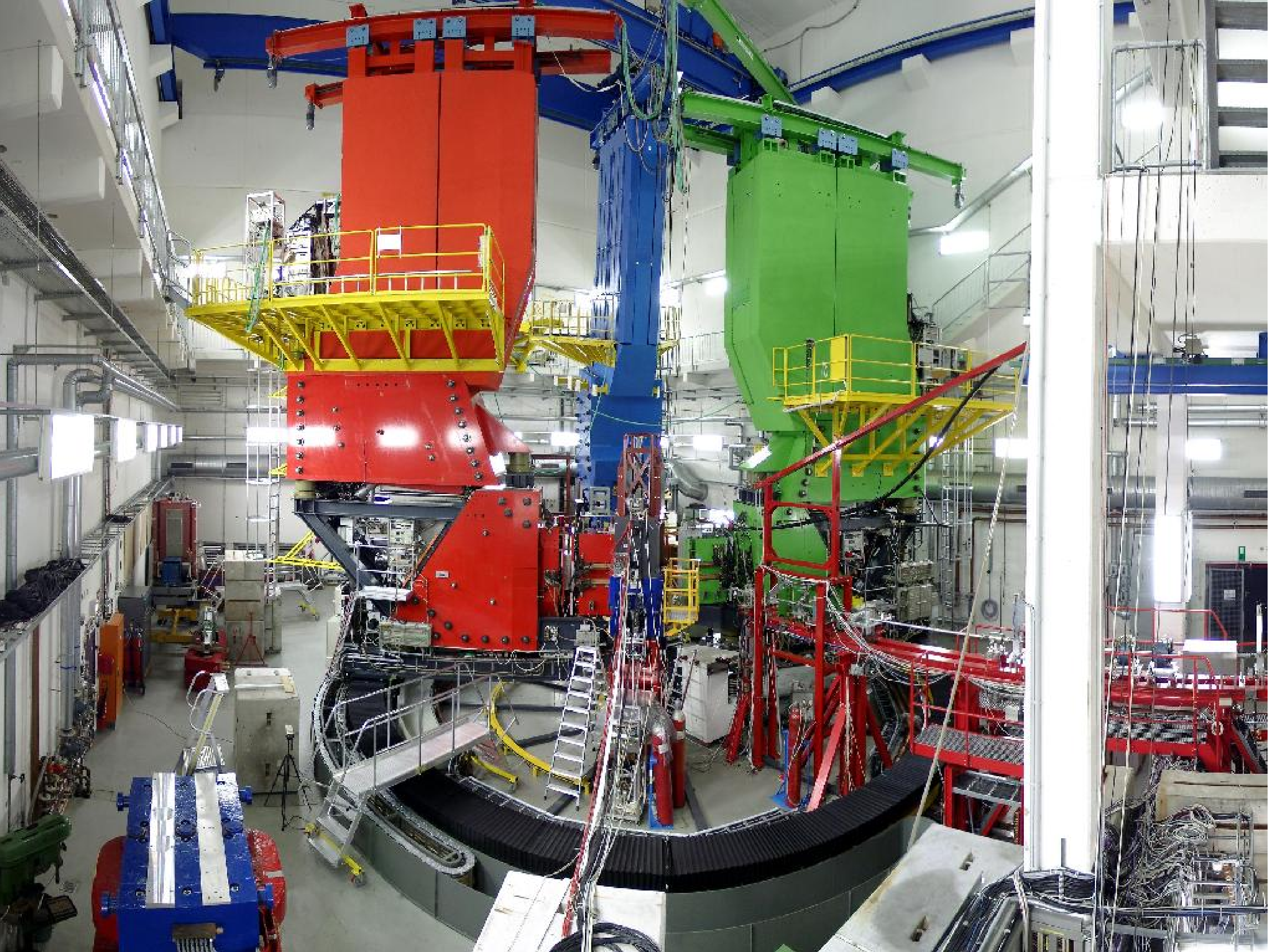
$$\begin{aligned} \alpha &> 20^\circ \\ p &< 735\,\frac{\text{MeV}}{c} \\ \Delta\Omega &= 28\,\text{msr} \\ \Delta p/p &= 20\% \end{aligned}$$

Spectrometer B:

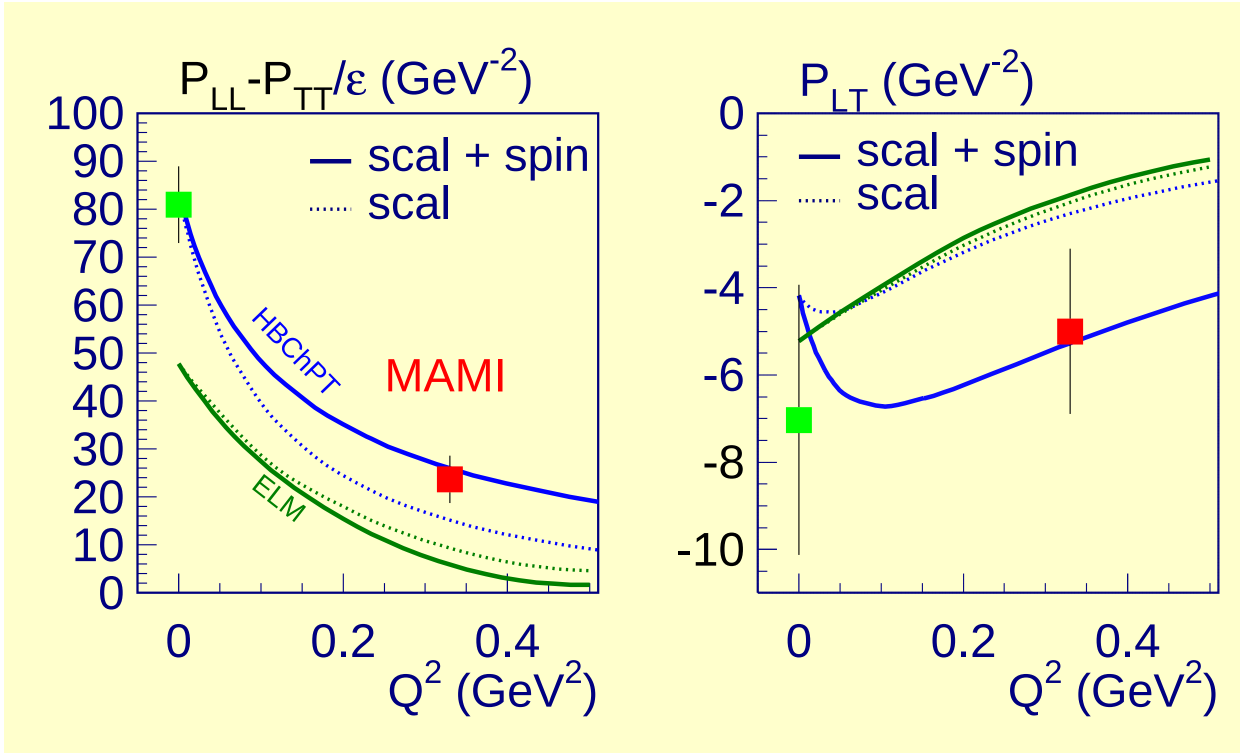
$$\begin{aligned} \alpha &> 8^\circ \\ p &< 870\,\frac{\text{MeV}}{c} \\ \Delta\Omega &= 5.6\,\text{msr} \\ \Delta p/p &= 15\% \end{aligned}$$

Spectrometer C:

$$\begin{aligned} \alpha &> 55^\circ \\ p &< 655\,\frac{\text{MeV}}{c} \\ \Delta\Omega &= 28\,\text{msr} \\ \Delta p/p &= 25\% \end{aligned}$$



Results unpolarized VCS at $Q^2 = 0.33, \varepsilon = 0.62$

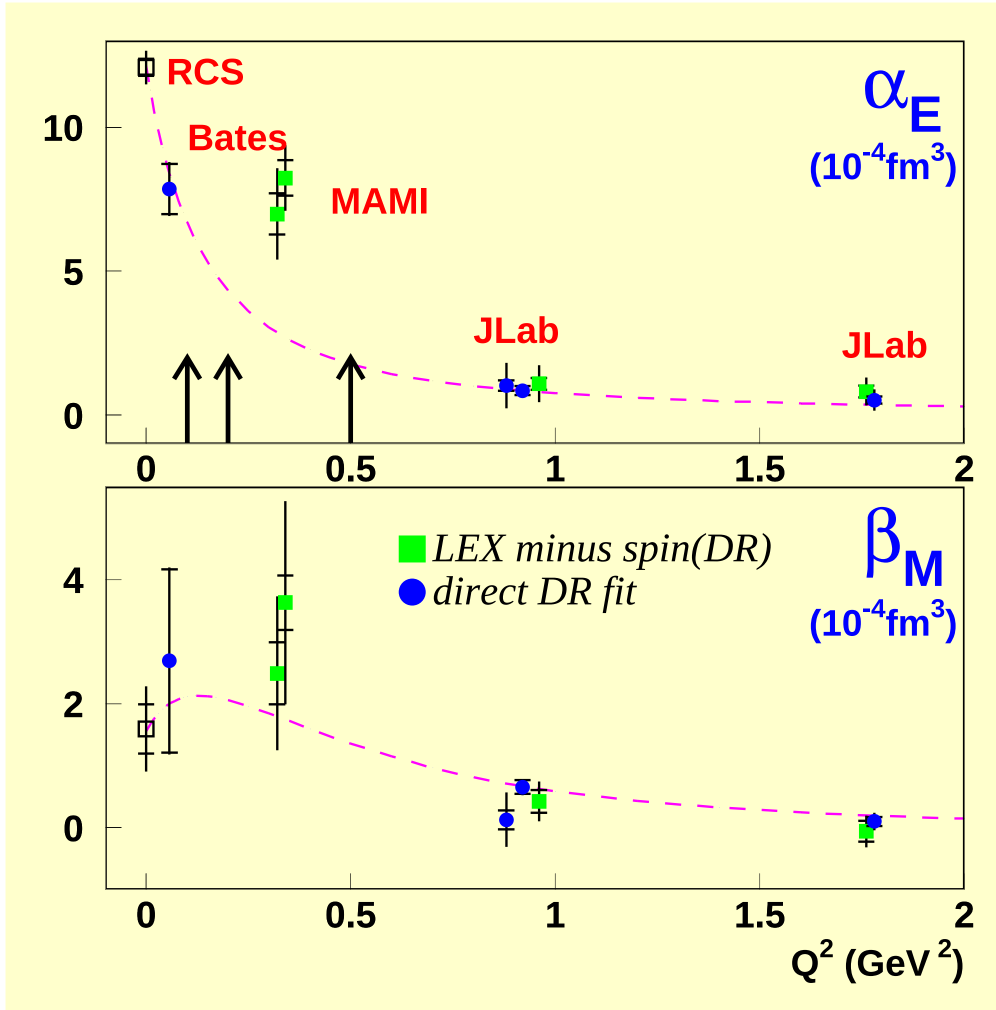


	$P_{LL}(Q^2) - \frac{1}{\varepsilon}P_{TT}(Q^2)$ [GeV^{-2}]	$P_{LT}(Q^2)$ [GeV^{-2}]
MAMI	$23.7 \pm 2.2 \pm 4.3$	$-5.0 \pm 0.8 \pm 1.8$
HBChPT	26.0	-5.3
ELM	5.9	-1.9
LSM	11.5	0.0
NRCQM1	11.1	-3.5
NRCQM2	14.9	-4.5

- (green) V. Olmos de Leon *et al.*, EPJ A **10** 207-215 (2001)
- (red) J. Roche *et al.*, Phys. Rev. Lett **85,4** 708 (2000)

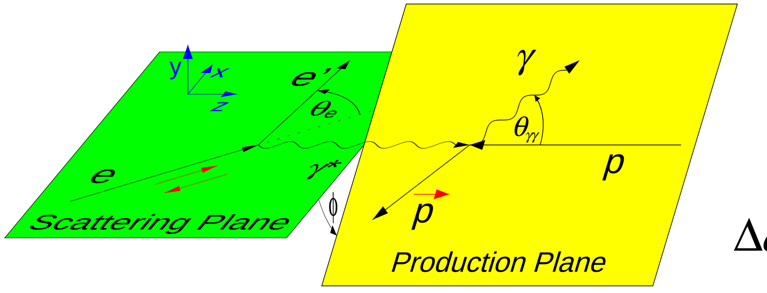
HBChPT	Heavy Baryon Chiral Perturbation Theory Th. Hemmert, et al. Phys. Rev. Lett. **79** (1997), **D 55** (1997)
ELM	Effective Lagrangian Model M. Vanderhaeghen, Phys. Lett. **B 368** (1996)
LSM	Linear Sigma Model A. Metz, D. Drechsel, Z. Phys. **A356** (1996), **A 359** (1997)
NRCQM1	Non Relativistic Constituent Quark Model G. Q. Liu, et al. Aust. J. Phys. **49** (1996)
NRCQM2	Non Relativistic Constituent Quark Model B. Pasquini, et al., Phys. Rev. C **63** 025205 (2001)

Results on Polarizabilities α and β



- DR: Extraction of α and β with Dispersion Relations
- LEX: Low Energy Expansion
- Proposal MAMI-A1-1-09: $Q^2 = 0.1,\ 0.2,\ 0.5\,\mathrm{GeV}^2/c^2$

Beam-Recoil Polarization



$$P_{x,y,z} = \frac{d^5\sigma^{\uparrow\uparrow} + d^5\sigma^{\downarrow\downarrow} - d^5\sigma^{\uparrow\downarrow} - d^5\sigma^{\downarrow\uparrow}}{d^5\sigma^{\uparrow\uparrow} + d^5\sigma^{\downarrow\downarrow} + d^5\sigma^{\uparrow\downarrow} + d^5\sigma^{\downarrow\uparrow}} = \frac{d^5\sigma^{h\uparrow} - d^5\sigma^{h\downarrow}}{2\, d^5\sigma}$$

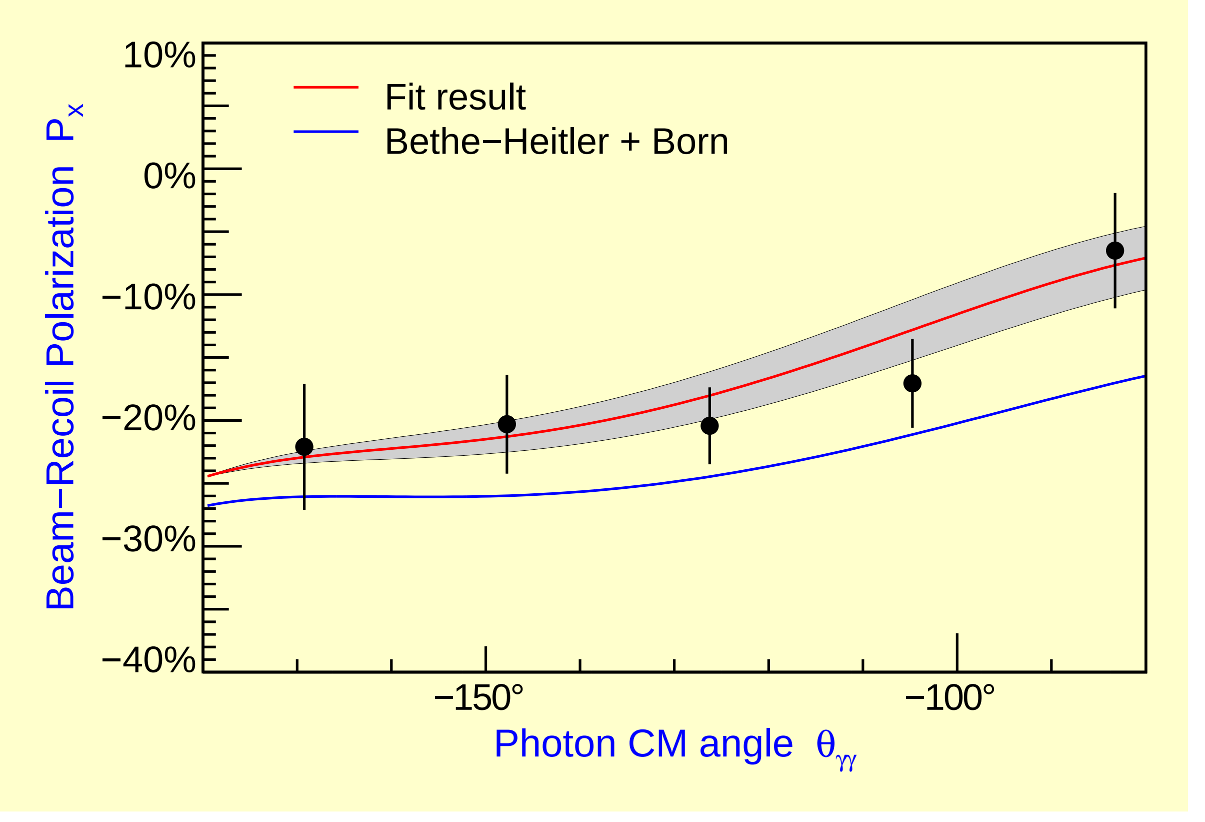
$$\Delta d^5\sigma^h_{x,y,z} = \Delta d^5\sigma^{BH+Born}_{x,y,z} + \phi \mathrm{q}' \Delta\Psi_0^{x,y,z} + \phi O(\mathrm{q}'^2)$$

$$\begin{aligned}
\Psi_0 &= v_1(\mathbf{P_{LL}} - \mathbf{P_{TT}}/\varepsilon) + v_2 \mathbf{P_{LT}} \\
\Delta\Psi_0^z &= 4\,h\,[v_1^z\, \mathbf{P_{TT}} + v_2^z \mathbf{P^z_{LT}} + v_3^z\, \mathbf{P'^z_{LT}}] \\
\Delta\Psi_0^x &= 4\,h\,[v_1^x\, \mathbf{P^\perp_{LT}} + v_2^x\, \mathbf{P^\perp_{TT}} + v_3^x\, \mathbf{P'^\perp_{TT}} + v_4^x\, \mathbf{P'^\perp_{LT}}] \\
\Delta\Psi_0^y &= 4\,h\,[v_1^y\, \mathbf{P^\perp_{LT}} + v_2^y\, \mathbf{P^\perp_{TT}} + v_3^y\, \mathbf{P'^\perp_{TT}} + v_4^y\, \mathbf{P'^\perp_{LT}}]
\end{aligned}$$

$$\begin{aligned}
\mathbf{P_{LL}} &= aP^{\mathrm{C1\to E1}} \\
\mathbf{P_{TT}} &= c_1 P^{\mathrm{M1\to M1(S)}} + c_2\, P^{\mathrm{M2\to E1(S)}} \\
\mathbf{P_{LT}} &= bP^{\mathrm{M1\to M1}} \quad + c_3 \left[P^{\mathrm{C0\to M1(S)}} + d_1 P^{\mathrm{C2\to M1(S)}}\right] \\
\mathbf{P^z_{LT}} &= c_4 P^{\mathrm{M1\to M1(S)}} + c_3 \left[P^{\mathrm{C0\to M1(S)}} + d_1 P^{\mathrm{C2\to M1(S)}}\right] \\
\mathbf{P'^z_{LT}} &= c_5 P^{\mathrm{M1\to M1(S)}} + c_6 \left[P^{\mathrm{C0\to M1(S)}} + d_1 P^{\mathrm{C2\to M1(S)}}\right] \\
\mathbf{P'^\perp_{LT}} &= \left[d_2\, P^{\mathrm{C0\to M1(S)}} + d_3 P^{\mathrm{C2\to M1(S)}}\right]
\end{aligned}$$

$\Rightarrow$ Out-of-Plane measurement to access $P'^{\perp}_{LT}$

Double Polarized virtual Compton Scattering



	Structure Function (GeV^{-2})			HBχPT (GeV^{-2})
$P_{LL} - P_{TT}/\varepsilon$	25.6	$\pm$ 2.9	$\pm$ 2.8	26.3
P_{LT}	-5.0	$\pm$ 1.1	$\pm$ 2.1	-5.5
$P_{LT}^{\perp}$	-14.2	$\pm$ 2.8	$\pm$ 2.2	-10.7

Data: L. Doria *et al.*, in preparation
HBChPT: C.-W. Kao *e*t al., Phys. Rev. D 70 (2004) 114004

Threshold Pion Photo- and Electroproduction

Motivation: Threshold Pion Photo-/Electroproduction

- Clean test of Chiral dynamics with heavy baryons
  - Photo-/Electroproduction $\Rightarrow$ well known initial state
  - π^+ dominated by Kroll-Rudermann-Term $\Rightarrow \quad \gamma p \to \pi^0 p$
  - Experiments close to production threshold $\Rightarrow$ s- and p-waves

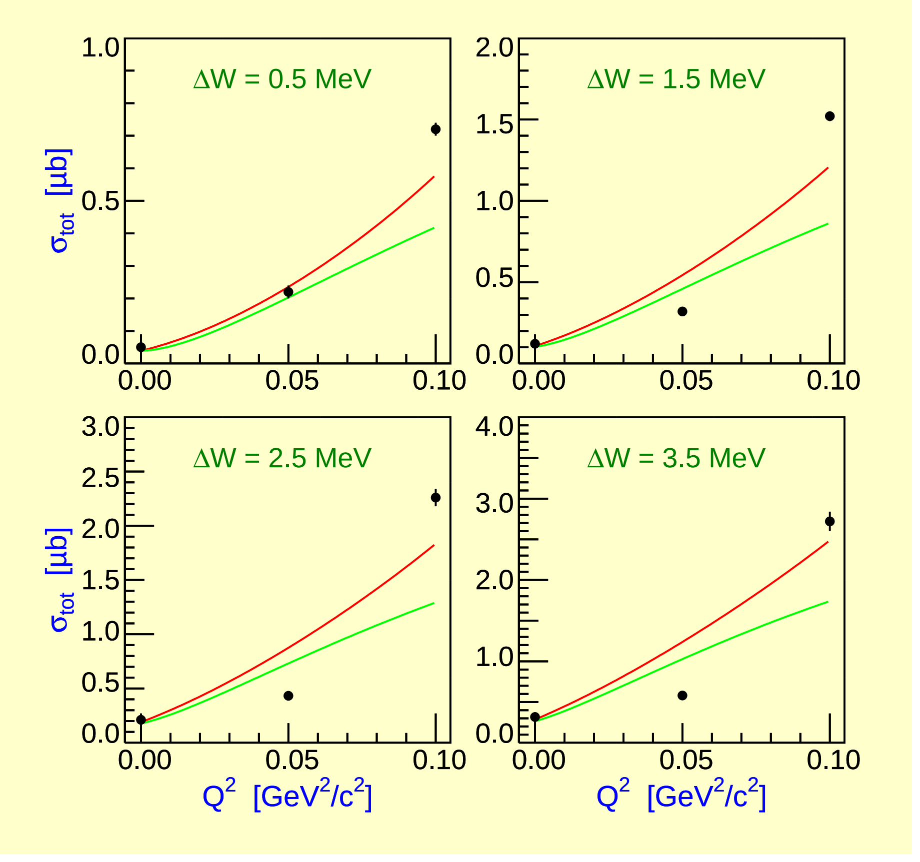
$$\sigma(\theta) \;=\; \frac{q}{k}\left(A + B\cdot\cos\theta + C\cdot\cos^2\theta\right)$$

$$A = E_{0+}^2 + \frac{1}{2}({P_2}^2 + {P_3}^2) \qquad B = 2\cdot Re(E_{0+}{P_1}^*) \qquad C = {P_1}^2 - \frac{1}{2}({P_2}^2 + {P_3}^2)$$

  - Known energy dependence for p-waves
  - Electroproduction $\Rightarrow$ additional longitudinal multipoles

- Physics addressed:
  - p-waves: fast converging in HBChPT $\to$ p-wave low energy theorem
  - s-waves: cusp effect of $\gamma p \to \pi^+ n \to \pi^0 p$ rescattering
  - Convergence in photon virtuality Q^2

Open Problem Q^2 Dependence



— HBChPT, V. Bernard *et al.*, Nucl. Phys. A 607 (1996) 379-401

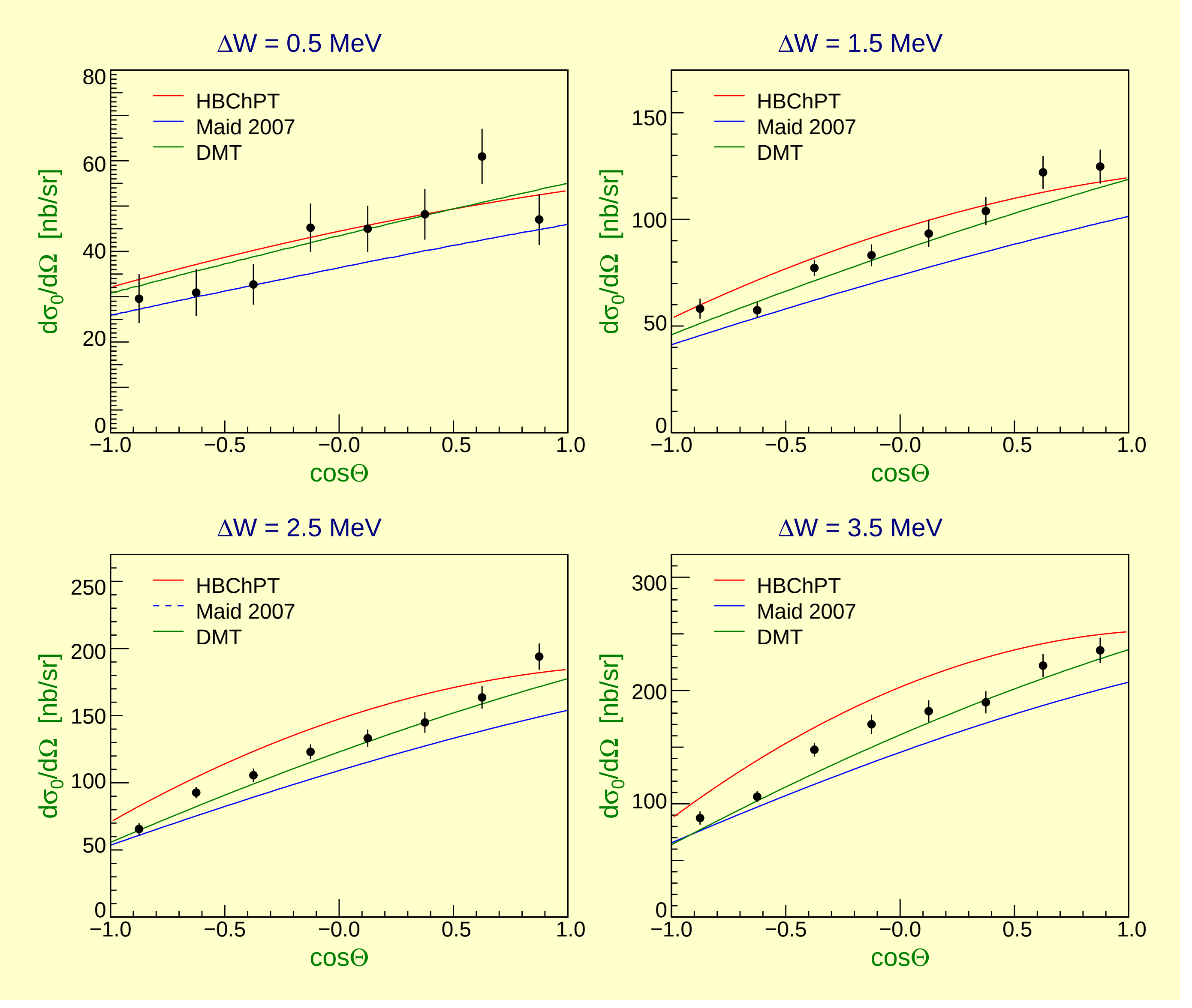
— MAID, D. Drechsel *et al.*, Nucl. Phys. A645 (1999) 145-174

• A. Schmidt *et al.*, $Q^2 = 0$
H.M. *et al.*, $Q^2 = 0.05\,\mathrm{GeV}^2/\mathrm{c}^2$
M. O. Distler *et al.*, $Q^2 = 0.1\ \mathrm{GeV}^2/\mathrm{c}^2$

- Statistical error only
- Rapid variation with Q^2 possible?
  - Separate measurements at different Q^2
  - Data dominated by systematic error

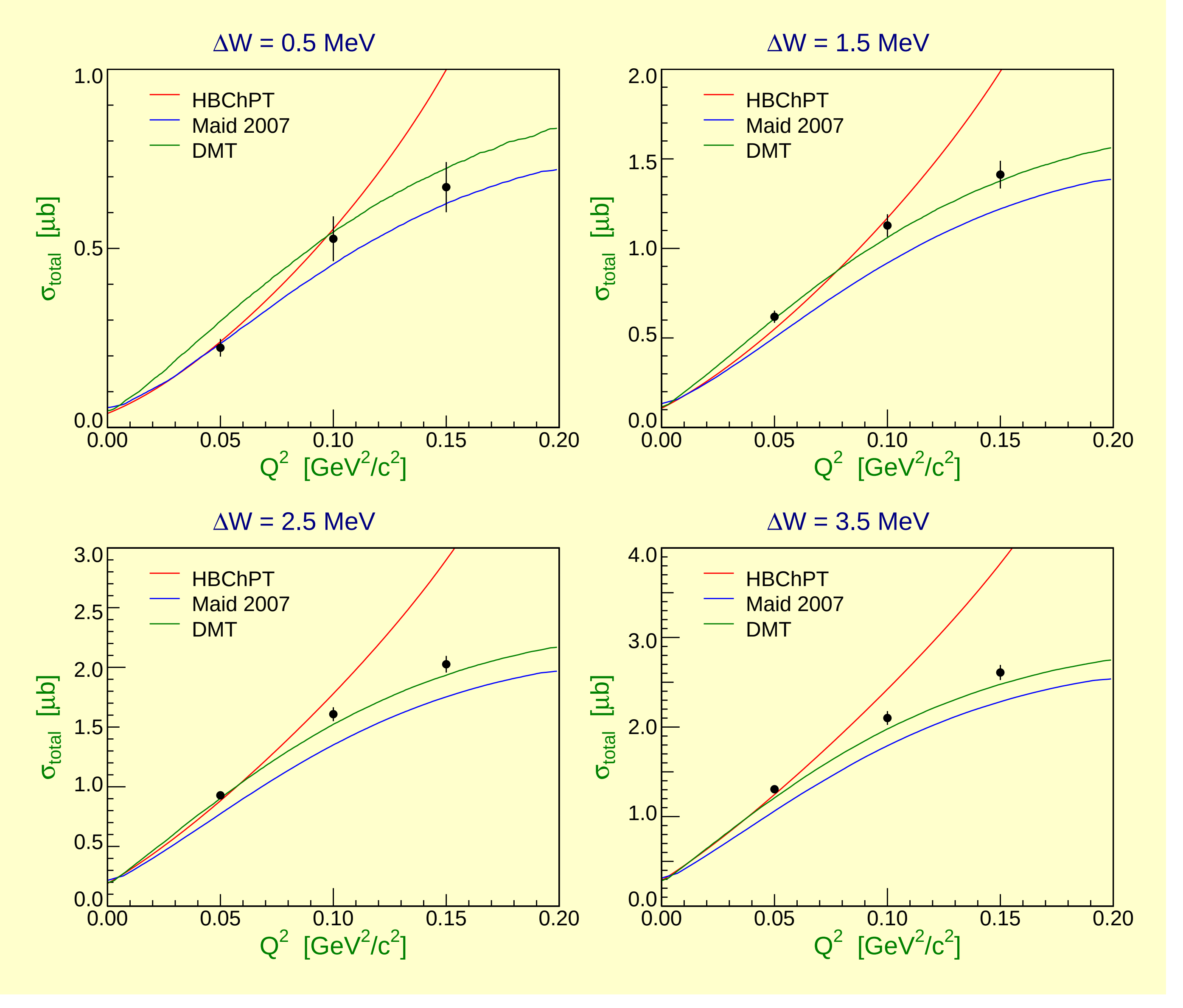
$\Rightarrow$ Check with 1. improved systematics
2. consistent Q^2 coverage

π^0 Threshold Production (Angular dependence)



Data: H.M. *et al.*, in preparation
HBChPT: V. Bernard, N. Kaiser, U.-G.Meißner, Phys. Lett. **B 378**, 337 (1996)
MAID: D. Drechsel *et al.*, Nucl. Phys. A645 (1999) 145-174, 2007 fit
DMT: S.S. Kamalov *et al.*, Phys. Rev. Lett. 83, (1999) 4494, Phys. Rev. C 64 (2001) 032201

Q^2 Dependence of π^0 Threshold Production



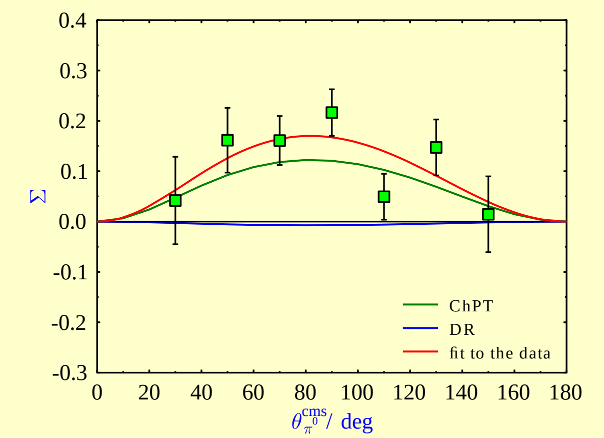
Data: H.M. *et al.*, in preparation
HBChPT: V. Bernard, N. Kaiser, U.-G.Meißner, Phys. Lett. **B 378**, 337 (1996) (fit to old data, new fit would improve agreement!!!)
MAID: D. Drechsel *et al.*, Nucl. Phys. A645 (1999) 145-174, 2007 fit
DMT: S.S. Kamalov *et al.*, Phys. Rev. Lett. 83, (1999) 4494, Phys. Rev. C 64 (2001) 032201

Meson Threshold Production – Current and Future Experiments

Polarized Beam Asymmetry:

$$\sigma(\theta,\phi) = \sigma(\theta)\left(1 - P_\gamma \cdot \Sigma(\theta) \cdot cos2\phi\right)$$

- High statistics experiment
- Analysis in progress



A. Schmidt *et al.*, PRL 87, 232501 (2001)

Transverse Polarized Target

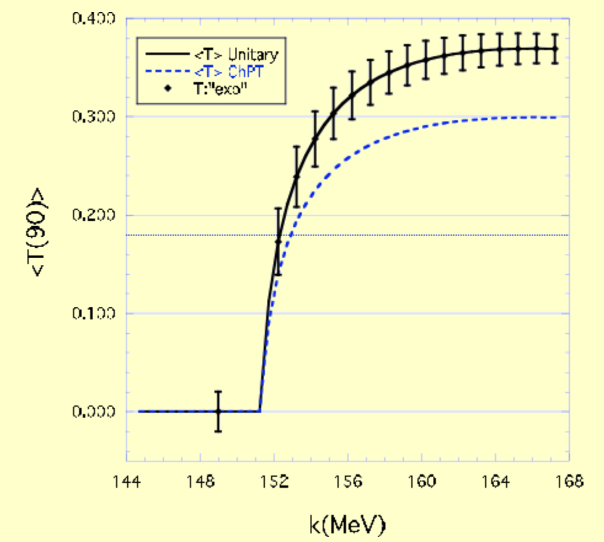
- Target Asymmetry T

$$T \Rightarrow ImE_{0+} \Rightarrow a_{cex}(\pi^+ n \longrightarrow \pi^0 p)$$

- Beam-Target-Asymmetry

$F \Rightarrow$ Test of d-wave contribution

→ C. Fernández-Ramírez



Kaon Production $\gamma^* p \longrightarrow K + \Lambda, K + \Sigma$

- $SU(3)$
- K^* exchange in t-channel $\Rightarrow$ electroproduction
- Coupled channels ...

Summary

- η, η' Decays
  - Slope parameter α
  - Rescattering Cusp in Dalitz plot
  - High statistics in the next years

- Nucleon Polarizabilities
  - Q^2 Dependence in Virtual Compton Scattering
  - Polarization Experiments
  - Spin Polarizabilities in Real Compton Scattering

- Threshold Pion Photo-/Electroproduction
  - Stringent test of ChPT including Heavy Baryons
  - Consistent Q^2 evolution
  - Photoproduction will be completed