Theoretical Aspects of Baryon Form Factors

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by VolkswagenStftung

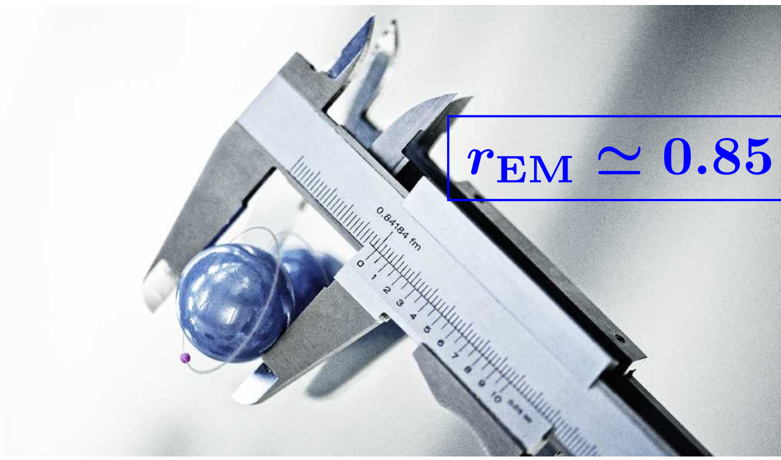
CONTENTS

- Introductory remarks
- Theoretical framework: Dispersion relations
- Discussion of the spectral functions
- Results for space- and time-like ffs
- The proton radius controversy
- Proton form factors in the timelike region
- Λ form factors in the timelike region
- Once more on the isovector spectral functions
- Summary and outlook

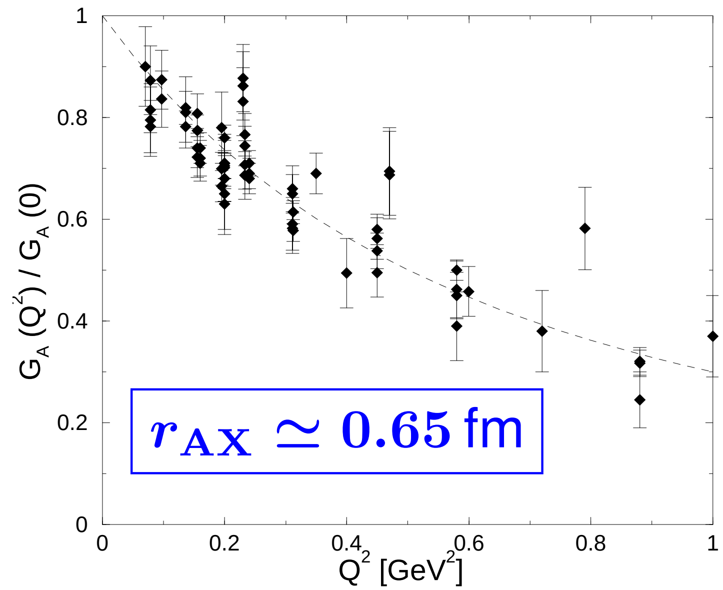
Introduction

FACETS of the NUCLEON / of BARYONS

- Basic objects of QCD in the strong coupling regime
- Various probes (electromagnetic, weak) see different facets/scales



$r_{\mathrm{EM}} \simeq \mathbf{0.85}$ fm



$r_{\mathrm{AX}} \simeq \mathbf{0.65}$ fm

$\hookrightarrow$ use the nucleon to develop methods

$\hookrightarrow$ gain insight $\rightarrow$ testbed for hyperons/cascades

$\hookrightarrow$ important role of final-state-interactions (FSI)

$\hookrightarrow$ beautiful link between electromagnetic and hadronic interactions

WHY DISPERSION RELATIONS for the NUCLEON FFs ?

- Model-independent approach $\to$ important non-perturbative tool to analyze data
- Dispersion relations are based on fundamental principles: unitarity & analyticity
- Connect data from small to large momentum transfer
  as well as time- and space-like data
- Allow for a **simultaneous analysis** of all four em form factors
- Spectral functions encode perturbative and non-perturbative physics
  e.g. vector meson couplings, multi-meson continua, pion cloud, . . .
- Spectral functions also encode information on the strangeness vector current
  $\to$ sea-quark dynamics, strange matrix elements
- Allow to extract nucleon electric and magnetic radii
- Can be matched to chiral perturbation theory [and not the other way around!]

Theoretical framework

BASIC DEFINITIONS

- Nucleon matrix elements of the em vector current J_μ^I

$$\boxed{\langle N(p')|J_\mu^I|N(p)\rangle = \bar{u}(p')\left[F_1^I(t)\,\gamma_\mu + i\,\frac{F_2^I(t)}{2m}\,\sigma_{\mu\nu}q^\nu\right]u(p)}$$

⋆ isospin $I = S, V$ (isoScalar, isoVector) $[= (p \pm n)/2]$

⋆ four-momentum transfer $t \equiv q^2 = (p' - p)^2 \equiv -Q^2$

⋆ F_1 = Dirac form factor, F_2 = Pauli form factor

⋆ Normalizations: $F_1^V(0) = F_1^S(0) = 1/2$, $F_2^{S,V}(0) = (\kappa_p \pm \kappa_n)/2$

⋆ Sachs form factors: $G_E = F_1 + \frac{t}{4m^2}F_2\ ,\ \ G_M = F_1 + F_2$

⋆ Nucleon radii: $F(t) = F(0)\ \left[1 + t\langle r^2\rangle/6 + \ldots\right]$ [except for the neutron charge ff]

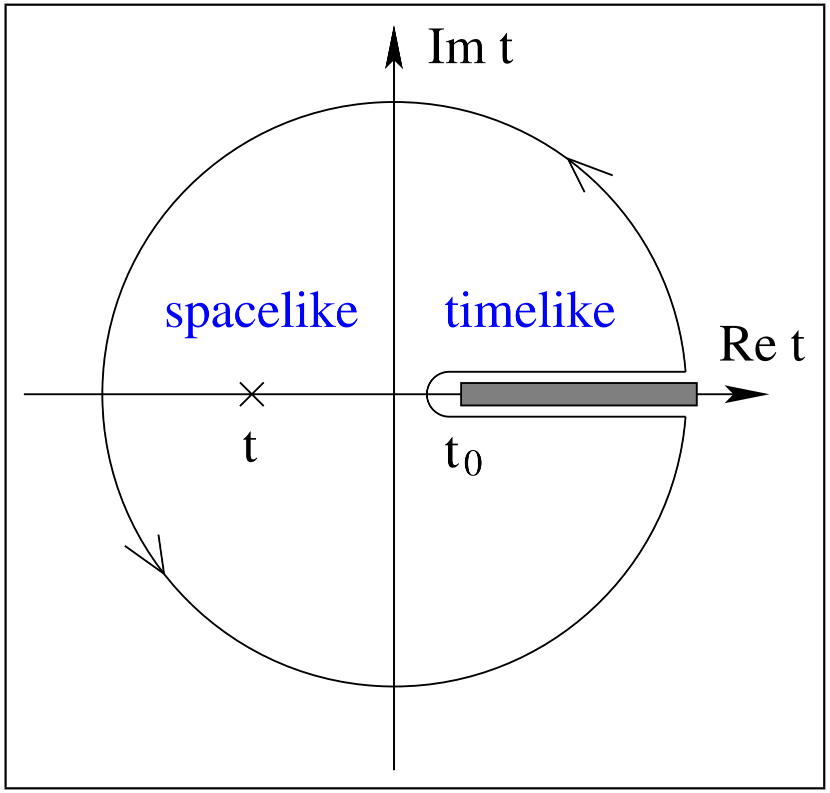
DISPERSION RELATIONS

Federbush, Goldberger, Treiman, Drell, Zachariasen, Frazer, Fulco, Höhler, . . .

- The form factors have cuts in the interval $[t_n, \infty[\ \ (n = 0, 1, 2, \ldots)$ and also poles

$\Rightarrow$ Dispersion relations for $F_i(t)$ $(i = 1, 2)$:

$$\boxed{F_i(t) = \frac{1}{\pi}\int_{t_0}^{\infty} dt' \, \frac{\mathrm{Im}\, F_i(t')}{t' - t}}$$



- no subtractions
  [only proven in perturbation theory]
- suppression of higher mass states
- central objects: spectral functions

$$\boxed{\mathrm{Im}\, F_i(t)}$$

– cuts $\triangleq$ multi-meson continua
– poles $\triangleq$ vector mesons

SPECTRAL FUNCTIONS – GENERALITIES

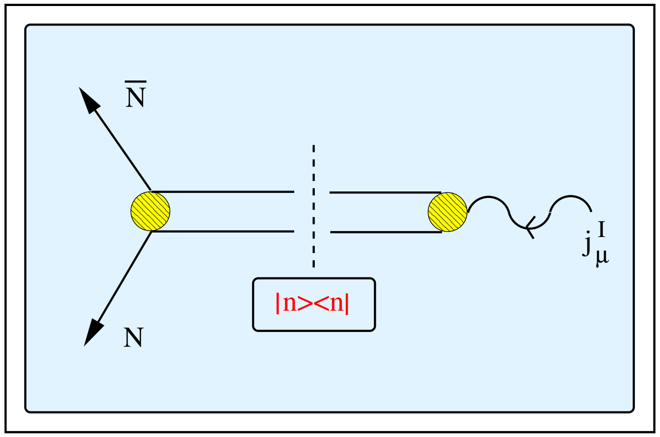
- Spectral decomposition:

$$\boxed{\mathrm{Im}\,\langle \bar{N}(p')N(p)|J_\mu^I|0\rangle \sim \sum_n \langle \bar{N}(p')N(p)|n\rangle\langle n|J_\mu^I|0\rangle \Rightarrow \mathrm{Im}\,F}$$

⋆ on-shell intermediate states

⋆ generates imaginary part

⋆ accessible physical states



- *Isoscalar* intermediate states: $3\pi, 5\pi, \ldots, K\bar{K}, K\bar{K}\pi, \pi\rho, \ldots +$ poles $\rightarrow t_0 = 9M_\pi^2$

- *Isovector* intermediate states: $2\pi, 4\pi, \ldots +$ poles $\rightarrow t_0 = 4M_\pi^2$

- Note that some poles are *generated* from the appropriate continua

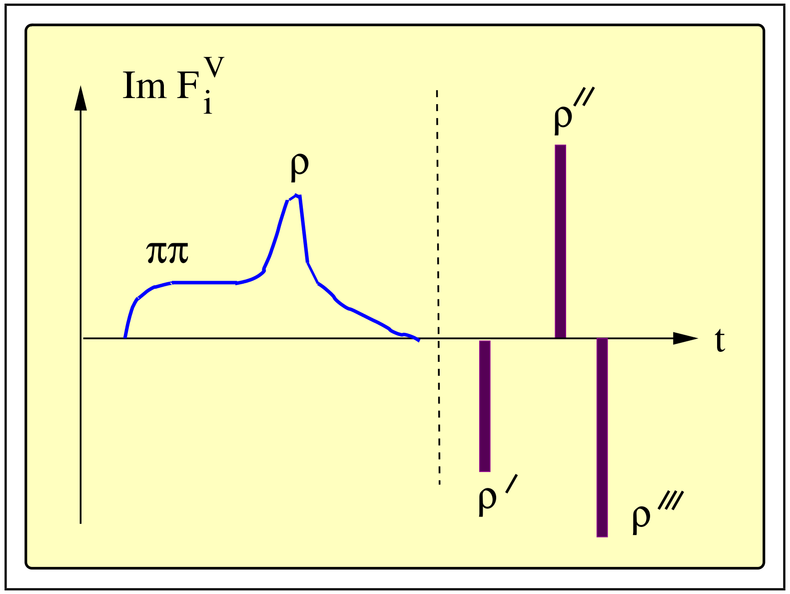
ISOVECTOR SPECTRAL FUNCTIONS

Frazer, Fulco, Höhler, Pietarinen, . . .

- exact 2π continuum is known from threshold $t_0 = 4M_\pi^2$ to $t \simeq 40\, M_\pi^2$

$$\boxed{\mathrm{Im}\, G^V_{E/M}(t) = \frac{q_t^3}{(m_N/\sqrt{2})\sqrt{t}} F_\pi(t)^\star f^1_{+/-}(t)}$$

  - ⋆ $F_\pi(t)$ = pion vector form factor
  - ⋆ P-wave pion-nucleon partial waves in the t-channel [$\sim f^1_\pm(t)$]



- Spectral functions inherit singularity on the second Riemann sheet in $\pi N \to \pi N$

$$\boxed{t_c = 4M_\pi^2 - M_\pi^4/m^2 \simeq 3.98\, M_\pi^2}$$ → strong shoulder → isovector radii

- This singularity can also be analyzed in CHPT

Bernard, Kaiser, UGM, Nucl. Phys. A **611** (1996) 429

- For a recent determination of the 2π continuum, see HKRHM, EPJA **52** (2016) 331

- Higher mass states represented by poles (not necessarily physical masses)

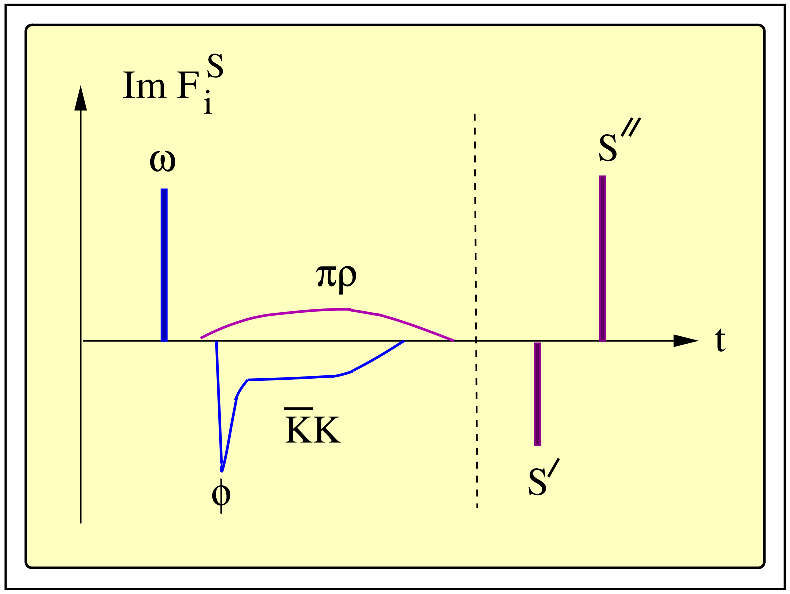
ISOSCALAR SPECTRAL FUNCTIONS

- $K\bar{K}$ continuum can be extracted from analytically cont. KN scattering amplitudes

  $\rightarrow$ analytic continuation must be stabilized

  $\rightarrow$ generates most of the ϕ contribution

  Hammer, Ramsey-Musolf, Phys. Rev. C **60** (1999) 045204, 045205



- Further strength in the ϕ-region generated by correlated $\pi\rho$ exchange

  $\rightarrow$ strong cancellations ($K\bar{K}, K^*K, \pi\rho$)

  $\rightarrow$ takes away sizeable strength from the ϕ

  UGM, Mull, Speth, van Orden, Phys. Lett. B **408** (1997) 381

- Spectral functions exhibit anomalous threshold (analyzed in 2-loop CHPT)

$$\boxed{t_c = M_\pi^2 \left(\sqrt{4 - M_\pi^2/m^2} + \sqrt{1 - M_\pi^2/m^2}\right)^2 \simeq 8.9\, M_\pi^2}$$

$\rightarrow$ effectively masked

Bernard, Kaiser, M, Nucl. Phys. A **611** (1996) 429

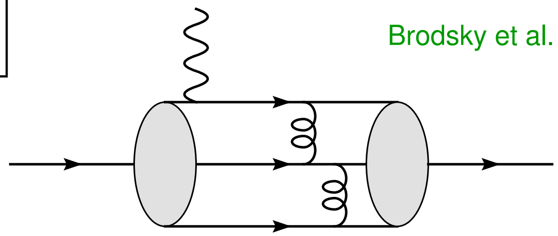
- Higher mass states represented by poles (with a finite width)

CONSTRAINTS ON THE SPECTRAL FUNCTIONS

- Normalizations: electric charges, magnetic moments
- Radii *not* imposed [can be done using subtracted DR]
- Superconvergence relations $\cong$ leading pQCD behaviour

$$\boxed{F_1(t) \sim 1/t^2\ ,\ F_2(t) \sim 1/t^3\ \ (\text{helicity} - \text{flip})}$$

Brodsky et al.



$$\Rightarrow\ \boxed{\int_{t_0}^{\infty} \text{Im}\ F_1(t)\, dt = 0\ , \quad \int_{t_0}^{\infty} \text{Im}\ F_2(t)\, dt = \int_{t_0}^{\infty} \text{Im}\ F_2(t)\, t\, dt = 0}$$

- Various ways of implementing the asymptotic QCD behaviour

$\Rightarrow$ severely restricts the number of fit parameters

SUMMARY: SPECTRAL & FIT FUNCTIONS

- Representation of the pole contributions: vector mesons
  [NB: can be extended for finite width]

$$\boxed{\mathrm{Im}\, F_i^V(t) = \sum_v \pi a_i^v \,\delta(t - M_v^2)\ , \quad a_i^v = \frac{M_v^2}{f_V} g_{vNN} \ \Rightarrow\ F_i(t) = \sum_v \frac{a_i^v}{M_v^2 - t}}$$

- *Isovector* spectral functions:

$$\mathrm{Im}\, F_i^V(t) = \mathrm{Im}\, F_i^{(2\pi)}(t) + \sum_{v=v_1,v_2,\ldots} \pi\, a_i^v \delta(t - M_v^2)\ , \quad (i = 1, 2)$$

- *Isoscalar* spectral functions:

$$\mathrm{Im} F_i^S(t) = \mathrm{Im} F_i^{(K\bar{K})}(t) + \mathrm{Im} F_i^{(\pi\rho)}(t) + \sum_{v=\omega,\phi,s_1,s_2,\ldots} \pi\, a_i^v \delta(t - M_v^2)$$

- Parameters: 2 for the ω, ϕ, 3 (4) for each other V-mesons minus # of constraints

- Ill-posed problem $\rightarrow$ extra constraint: minimal # of poles to describe the data

Results

Belushkin, Hammer, UGM, Phys. Rev. **C 75** (2007) 035202 [hep-ph/0608337]

GENERAL COMMENTS ON THE FITS

- large MC sampling for initial values, successive improvement by pole reduction, new MCs, ...
- theoretical uncertainty (error bands) from $\chi^2_{\rm min} + 1.04$ [1-σ devs.]

$\rightarrow$ first time: dispersive analysis w/ error bars !

	this work	HM 04	recent determ.
r_E^p [fm]	0.844 (0.840...0.852)	0.848	0.880(15) [1,2,3]
r_M^p [fm]	0.854 (0.849...0.859)	0.857	0.855(35) [4]
$(r_E^n)^2$ [fm^2]	$-$0.117 ($-$0.11...$-$0.128)	$-$0.12	$-$0.115(4) [5]
r_M^n [fm]	0.862 (0.854...0.871)	0.879	0.873(11) [6]

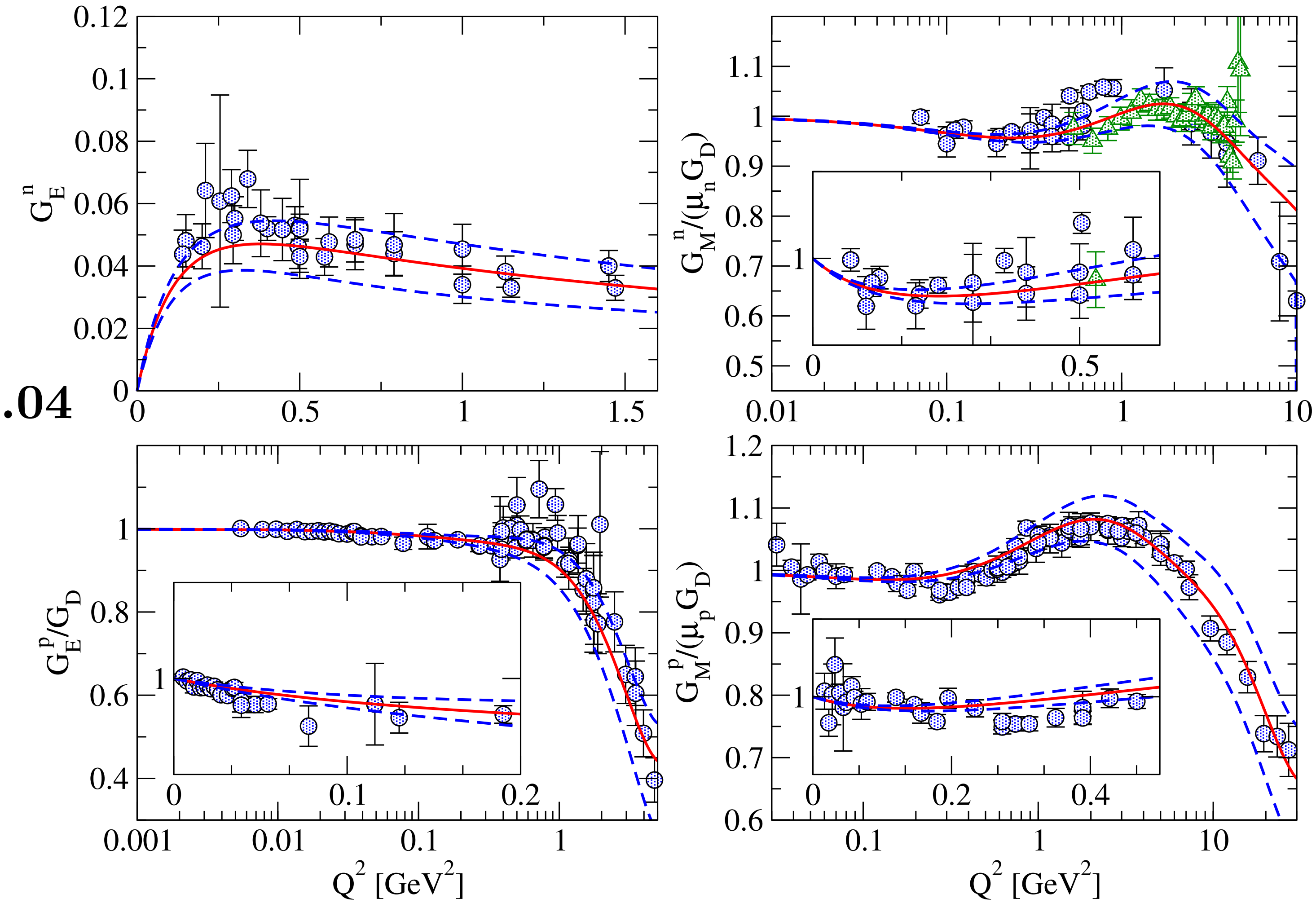
[1] Rosenfelder, Phys. Lett. B **479** (2000) 381
[2] Sick, private communication
[3] Melnikov, van Ritbergen, Phys. Rev. Lett. **84** (2000) 1673
[4] Sick, Phys. Lett. B **576** (2003) 62
[5] Kopecky et al., Phys. Rev. C **56** (1997) 2229
[6] Kubon et al., Phys. Lett. B **524** (2002) 26

$\star$ Magnetic radii in good agreement with recent determinations

$\star$ Proton electric radius comes out $\lesssim$ 0.855 fm

SPACE-LIKE FORM FACTORS

- present best fit
  incl. time-like data
- ω, ϕ + 2 eff. IS poles
- 5 effective IV poles
- weighted χ^2/dof = 1.8
  error bands: $\chi^2_{\text{min}} + \mathbf{1.04}$



Improved description

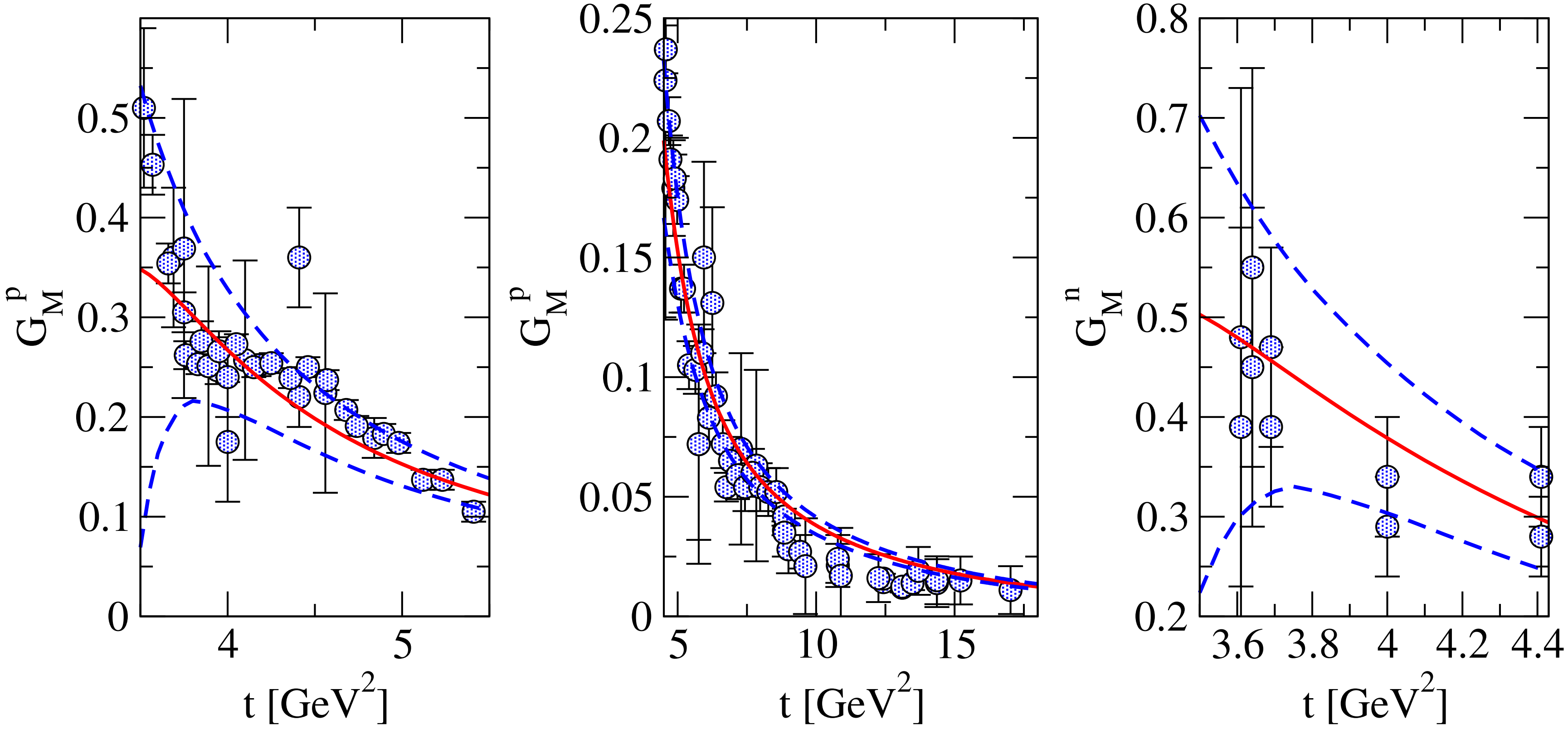
⋆ JLab data described

⋆ higher mass poles
not at physical values

MMD 96, HMD 96, HM 04

$$G_D(Q^2) = \left(1 + \frac{Q^2}{0.71\ \text{GeV}^2}\right)^{-2}$$

TIME-LIKE FORM FACTORS



- Only proton data participate in the fits
- All data within one sigma – first time consistent fit w/ space-like ffs

$\Rightarrow$ Need more data on time-like G_M^n & E/M separation

The proton radius

Lorenz, Hammer, UGM, Eur. Phys. J. **A 48** (2012) 151 [arXiv:1205.6628 [hep-ph]]

Lorenz, UGM, Phys. Lett. **B 737** (2014) 57 [arXiv:1406.2962 [hep-ph]]

Lorenz, UGM, Hammer, Dong, Phys. Rev. **D 91** (2015) 014023 [arXiv:1411.1704 [hep-ph]]

A SHORT HISTORY

- Dispersion relations always found a "small" radius

$r_E^p = 0.847$ fm — Mergell, UGM, Drechsel 1995

$r_E^p = 0.848$ fm — Hammer, UGM 2004

$r_E^p = 0.844\,(0.840\ldots0.852)$ fm — Belushkin, Hammer, UGM 2007

- CODATA 2008: $r_E^p = 0.8768(69)$ fm

- Muonic hydrogen at PSI: $r_E^p = 0.84184(67)$ fm — Pohl et al. 2010

$r_E^p = 0.84087(39)$ fm — Antognini et al. 2013

- Electron-proton scattering at MAMI: $r_E^p = 0.876(8)$ fm — Bernauer et al. 2010

$\Rightarrow$ zillions of papers, different levels of sophistication, ...

$\Rightarrow$ reanalyze Mainz data including constraints from analyticity and unitarity

$\Rightarrow$ study various sources of uncertainties (2π continuum, radiative corrections, etc.)

DIRECT CROSS SECTION FITS

- is the small radius in the DR approach consistent with the Mainz data?
- Fit directly to ep Xsections (and other world data & also the neutron FF data)

$\star$ use the recent MAMI data $\rightarrow$ slide

$\star$ floating normalizations for individual data sets w/ different kinematical conditions [as done by the Mainz group, see PhD thesis J. Bernauer]

$\star$ include new and improved TPE corrections

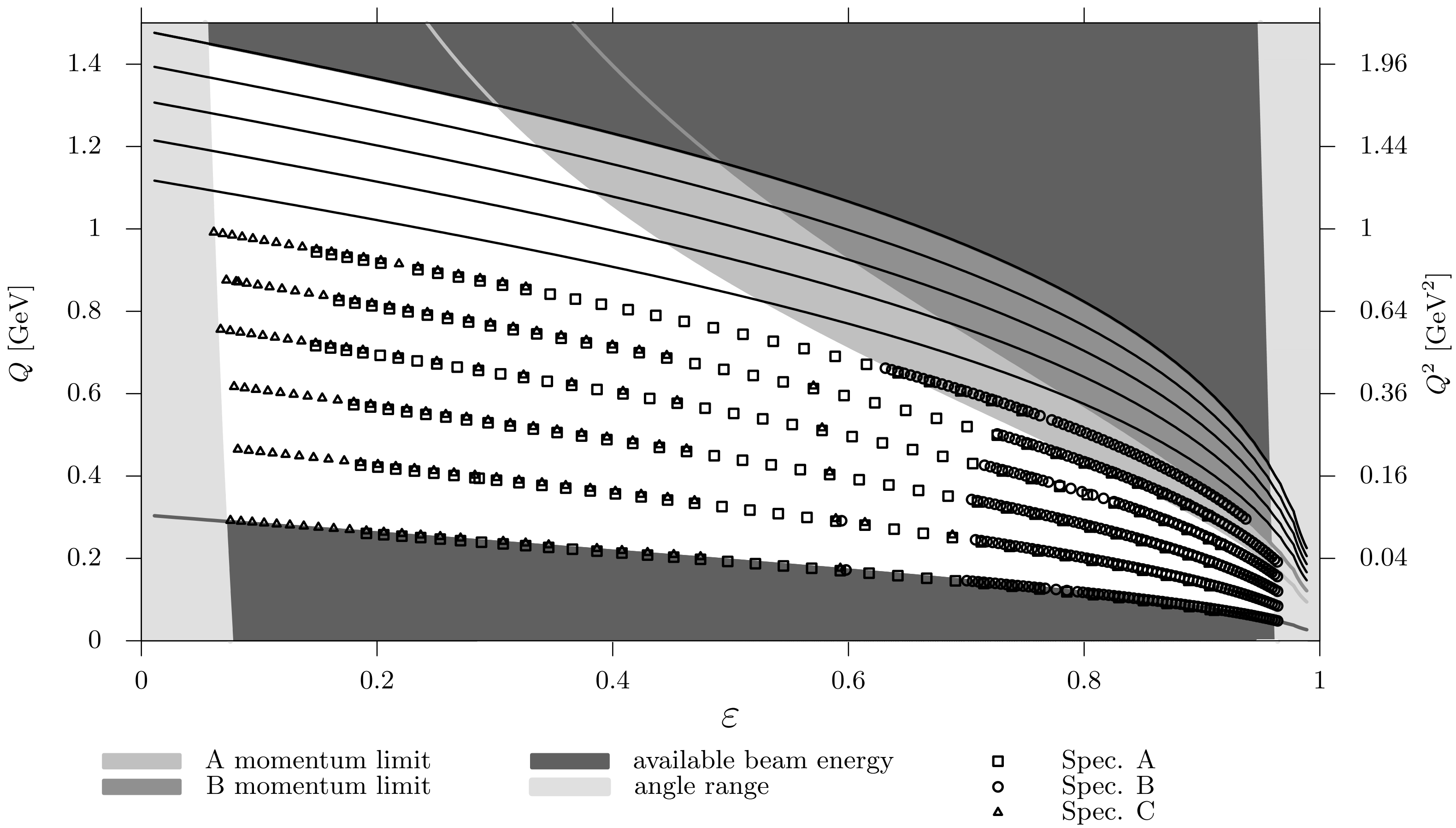
$\star$ include error correlations and use bootstrap methods to estimate fit errors
$\Rightarrow$ improves the earlier methods based on χ^2 only

$\star$ perform also purely statistical fits based on a conformal mapping (not including all physics constraints, not discussed here)

Will we still obtain a small radius?

NEW MAINZ DATA

- Kinematical coverage of the new MAMI data (1422 data pts)



A1 collaboration, J. Bernauer et al., Phys. Rev. C **90** (2014) 015206

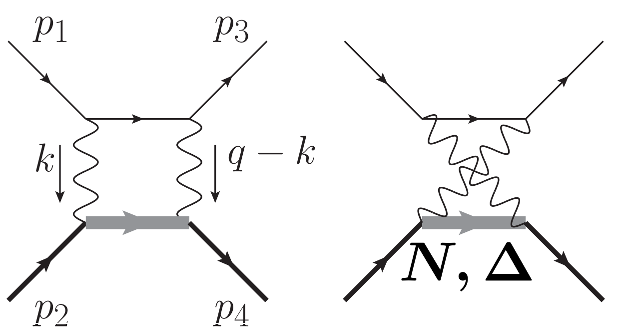
NEW DEVELOPMENTS: TPE CORRECTIONS

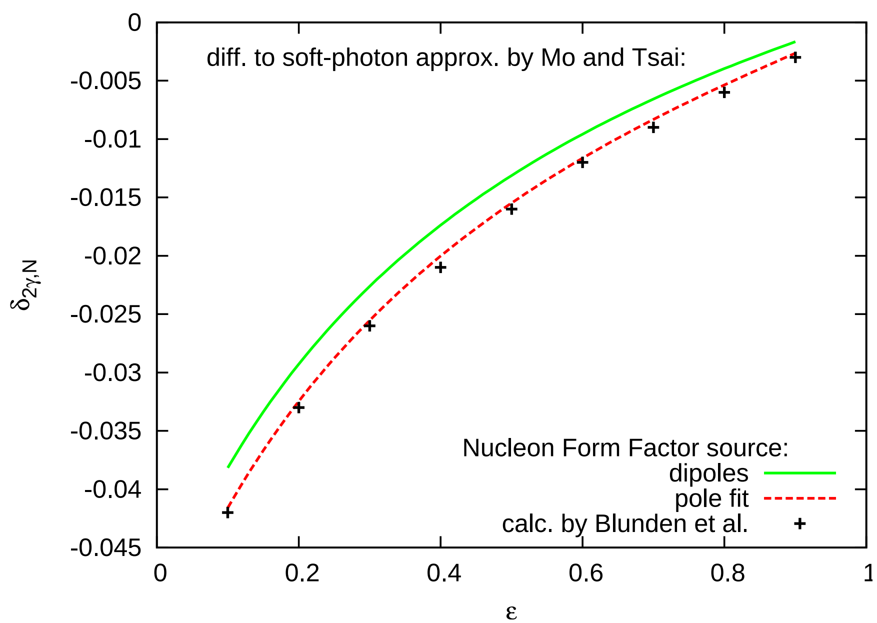
Lorenz, UGM, Hammer, Dong, Phys. Rev. D **91** (2015) 014023 [arXiv:1411.1704v1]

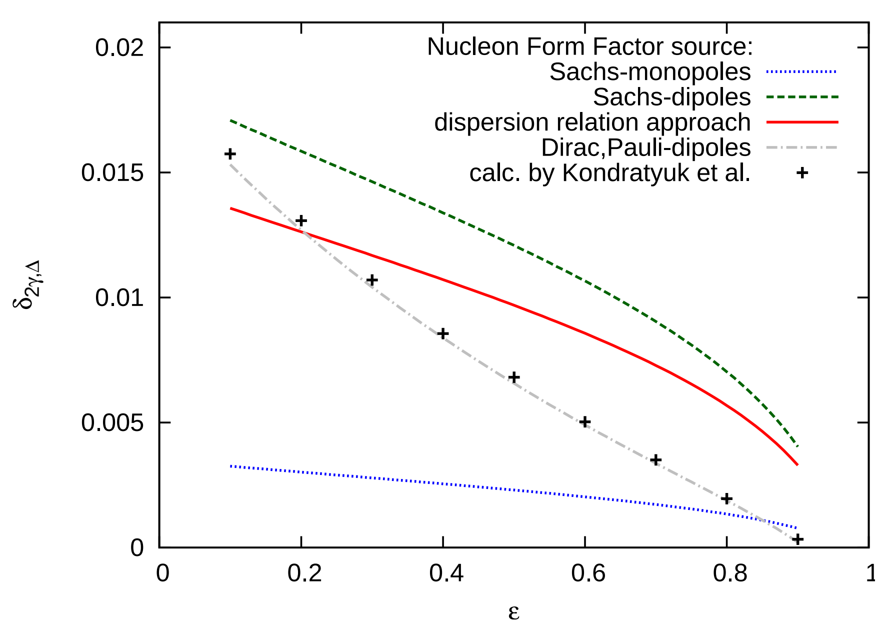
- improved calculation of two-photon exchange effects incl. the $\boldsymbol{\Delta}$
  - $\longrightarrow$ study dependence on nucleon ffs! [never done before]

- TPE correction: $\boldsymbol{\delta_{2\gamma} = \delta_{2\gamma,N} + \delta_{2\gamma,\Delta}}$

- $\boldsymbol{\delta_{2\gamma,\Delta}}$ more sensitive to ffs than $\boldsymbol{\delta_{2\gamma,N}}$







NEW TPE CORRECTIONS versus MAMI DATA

- Mainz uses the old Feshbach/Kinley approximation

$$\delta_F = Z\alpha_{\rm EM}\pi \frac{\sin\theta/2 - \sin^2\theta/2}{\cos^2\theta/2}$$

incorrect for some kinematics Arrington 2011

- our TPE correction: $\delta_{2\gamma} = \delta_{2\gamma,N} + \delta_{2\gamma,\Delta}$

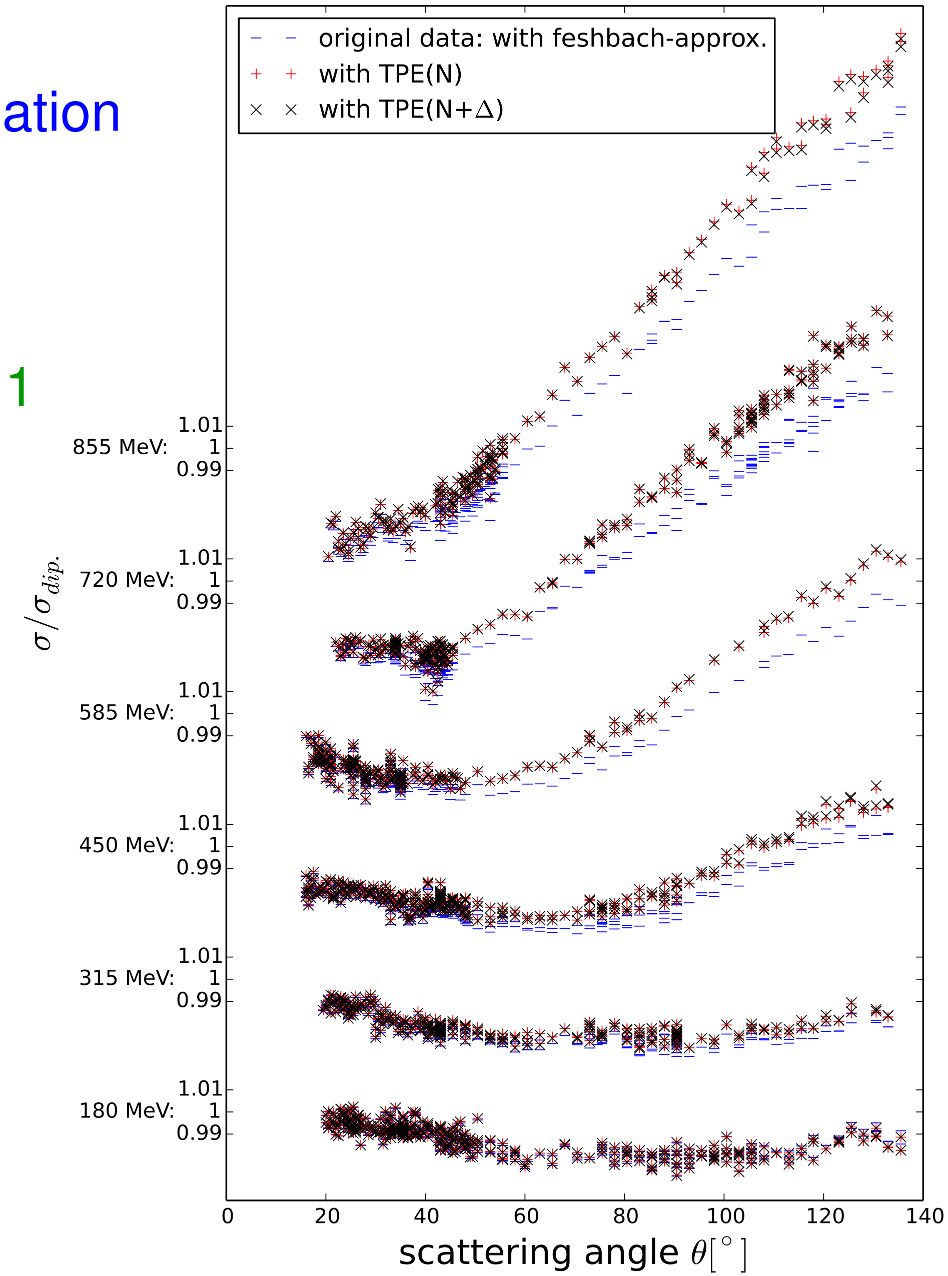
- $\delta_{2\gamma,\Delta}$ effects small for MAMI data

  $\to$ important for world data at higher Q^2

  Sick, priv. comm.

- $\delta_{2\gamma,N}$ quite different from Feshbach approx.

  $\to$ important for the error budget!



NEW DISPERSIVE FITS to MAMI & WORLD DATA

- Fit to the Mainz data and also the world data on ep scattering at higher Q^2
- Float the normalizations similar what was done by the Mainz group
- Good fit requires 5 IS and 5 IV poles (28 + 31 + 23 parameters)

$\rightarrow$ show plots next slide

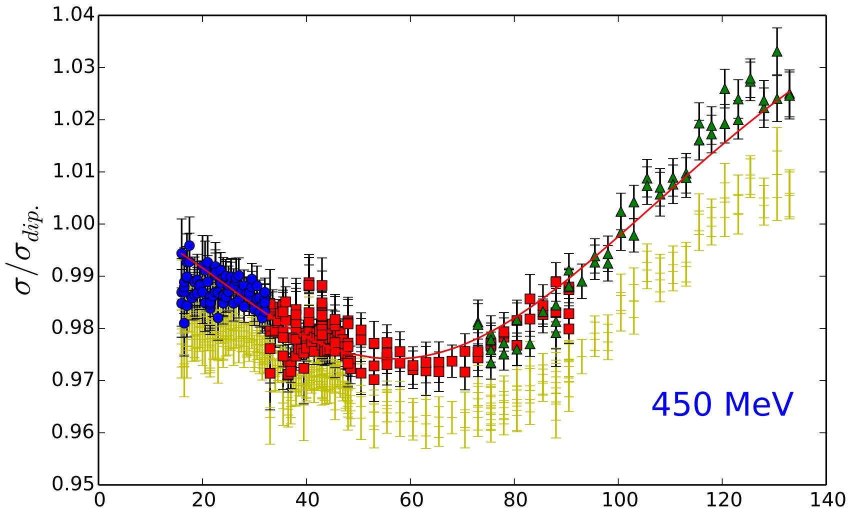
$\rightarrow$ achieve good χ^2/ndf = 1.37 (1422 + 1922 data points)

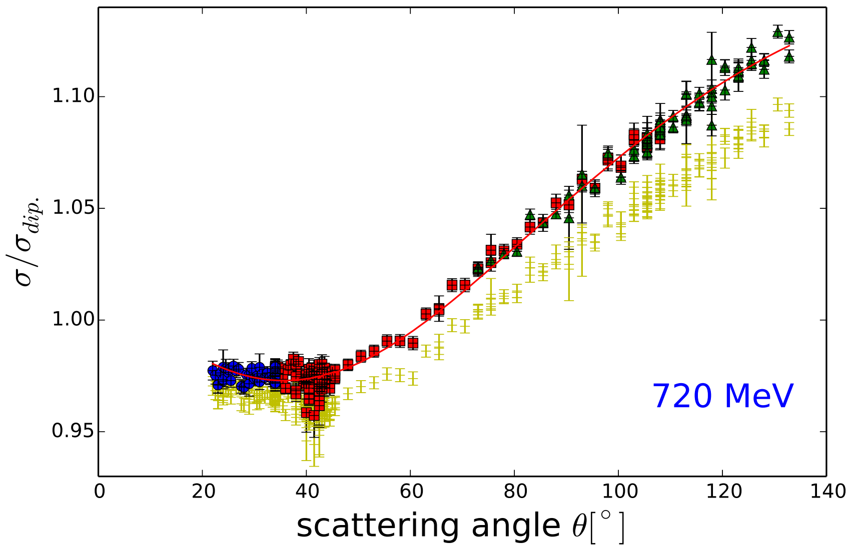
$\rightarrow$ radii with 3σ uncertainties from bootstrap:

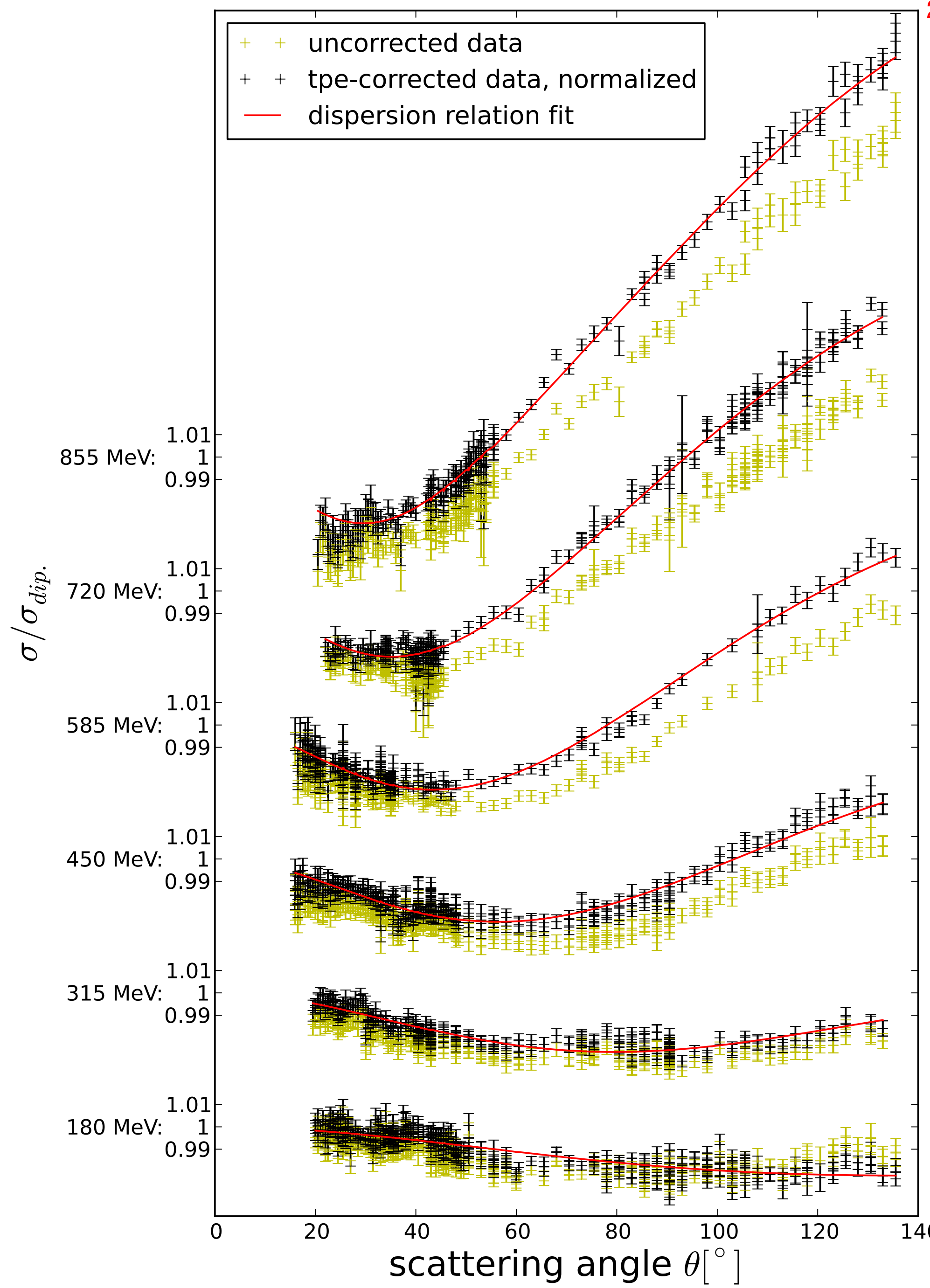
$$\boxed{\begin{aligned} r_E^p &= 0.840\ (0.828 - 0.855)\ \text{fm} \\ r_M^p &= 0.848\ (0.843 - 0.854)\ \text{fm} \end{aligned}}$$

- perfectly consistent with earlier DR determinations
- consistency check: predict the ff ratio G_E^p/G_M^p measured at JLAB $\rightarrow$ slide

NEW FITS to MAMI DATA

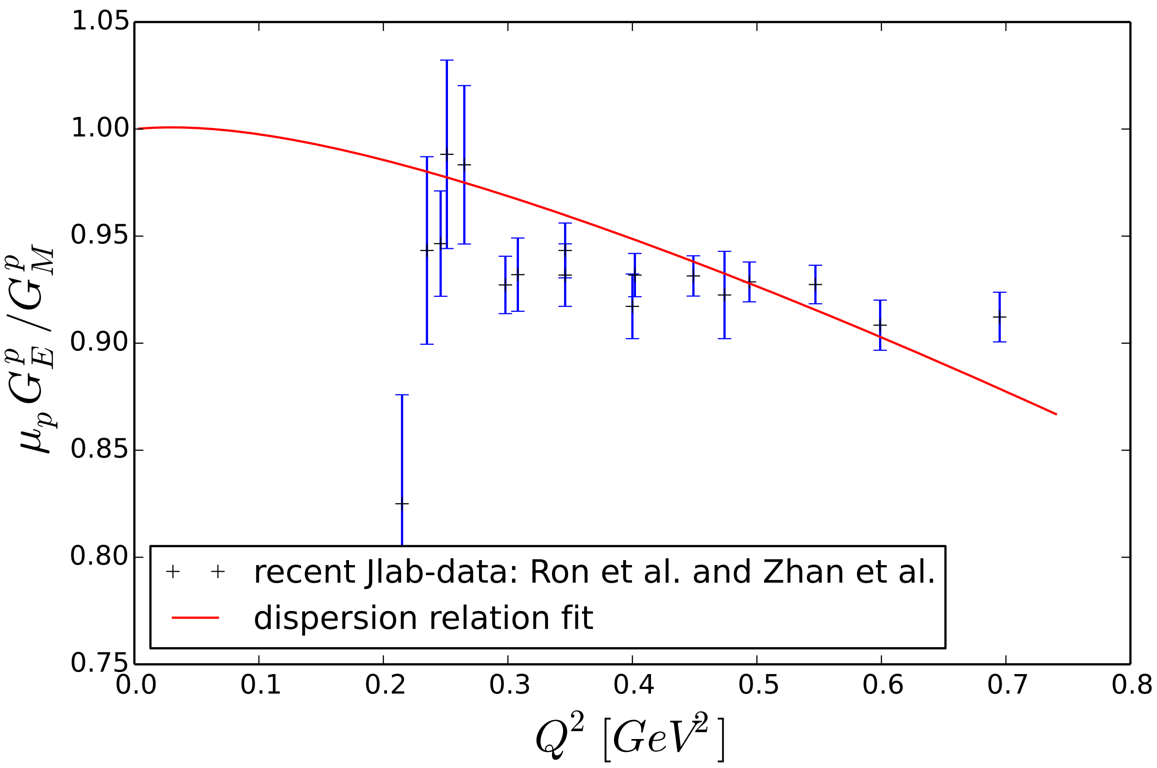






PREDICTON of the JLAB DATA

- Polarisation measurements at low Q^2 give directly $\mu_p G_E^p / G_M^p$



Ron et al., Phys. Rev. C **84** (2011) 055204

Zhan et al., Phys. Lett. B **705** (2011) 59

The proton form factors in the timelike region

Haidenbauer, Kang, UGM, Nucl. Phys. A **929** (2014) 102 [arXiv:1405.1628 [nucl-th]]

BASIC DEFINITIONS and FACTS

- differential Xsection for $e^+e^- \leftrightarrow \bar{p}p$ in the one-photon approximation

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{\rm EM}^2 \beta}{4s}\, C_p(s) \left[|G_M(s)|^2 \left(1+\cos^2\theta\right) + \frac{4M_p^2}{s} |G_E(s)|^2 \sin^2\theta \right] , \quad \beta = \frac{k_p}{k_e}$$

- $G_{E,M}(s)$ are complex for $s \geq 4M_p^2$

- threshold constraint: $\quad G_E(4M_p^2) = G_M(4M_p^2)$

- Gamov-Sommerfeld factor:

$$C_p = \frac{y}{1-e^{-y}} , \quad y = \frac{\pi\alpha_{\rm EM} M_p}{k_p} , \quad \sqrt{s} = 2\sqrt{M_p^2 + k_p^2}$$

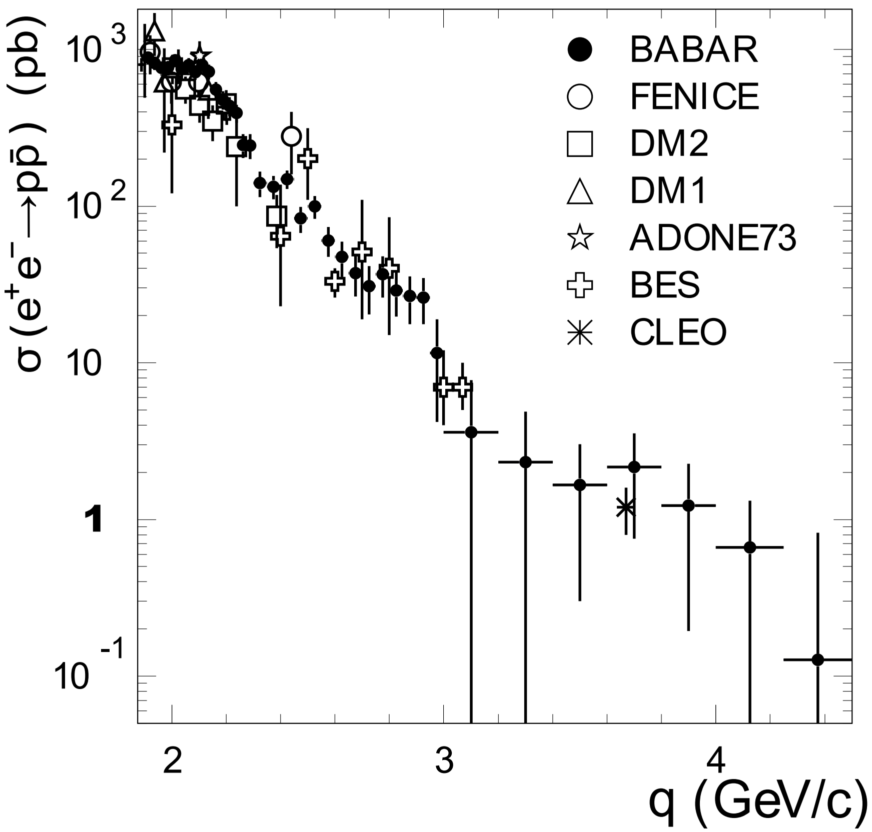
- Data from $e^+e^- \to \bar{p}p$ and $\bar{p}p \to e^+e^-$

  $\to$ extraction of ffs difficult, strong threshold enhancement

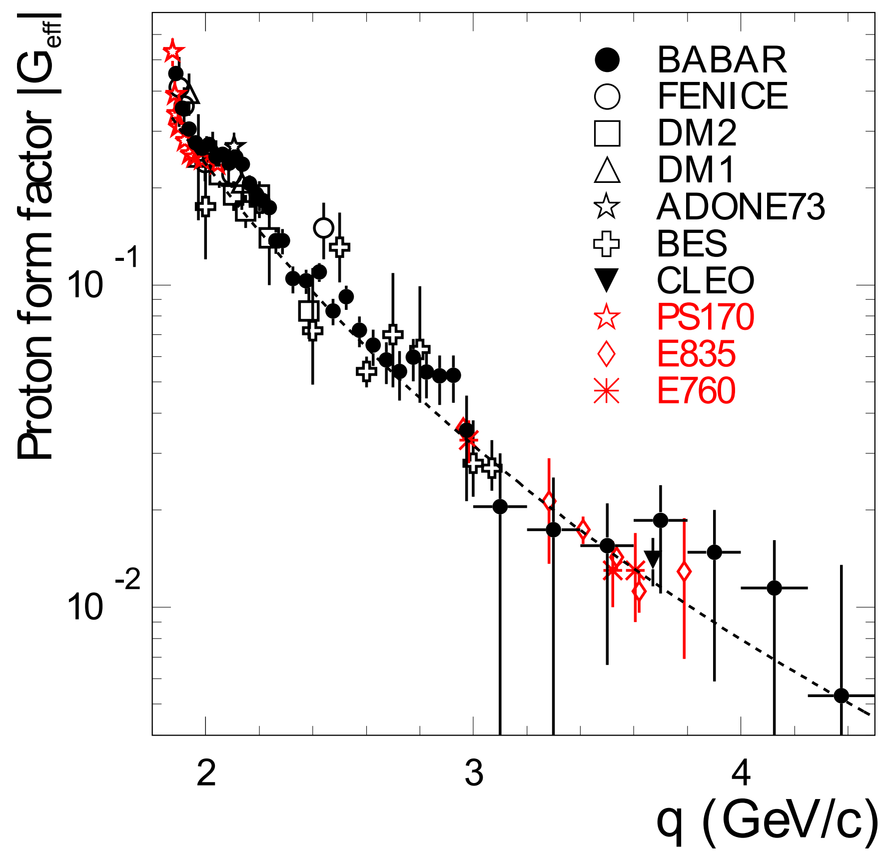
WORLD DATA

Denig, Salme, Prog. Part. Nucl. Phys. **68** (2013) 113

- X section



- effective FF ($\sigma \sim |G_{\rm eff}|^2$)



- strong enhancement in the threshold region $q \sim 2M_p$
- effective form factor consistent with data from $\bar{p}p \to e^+e^-$ (mod. norm.)
- threshold enhancement also seen in $J/\psi \to \bar{p}p\gamma$, $\psi(3686) \to \bar{p}p\gamma$, $J/\psi \to \bar{p}p\omega$, $B^+ \to \bar{p}pK^+$

FINAL-STATE INTERACTIONS

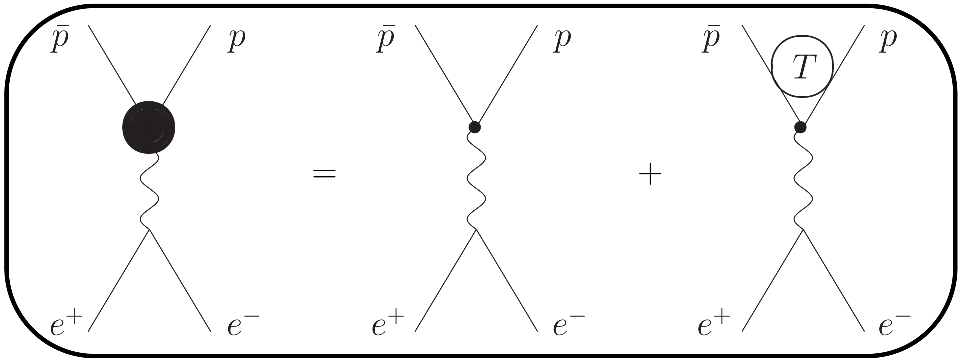
- threshold enhancement appears to be an universal phenomenon

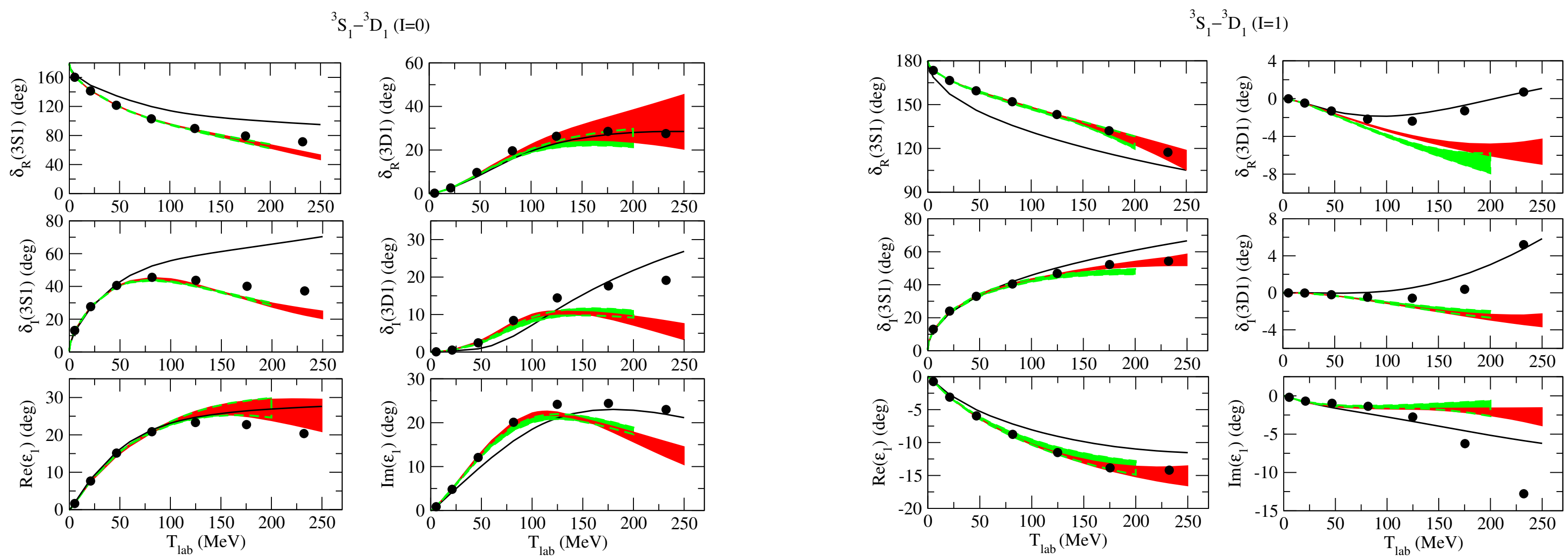
- hypothesis: it is generated by the strong $\bar{p}p$ FSI

- bare ffs dressed by FSI, and these generated all the Q^2 dependence $\to$ one number to be fitted

- FSI from chiral EFT

  $\to$ only $^3S_1$ and $^3D_1$ partial waves





Kang, Haidenbauer, UGM, JHEP **1402** (2014) 113

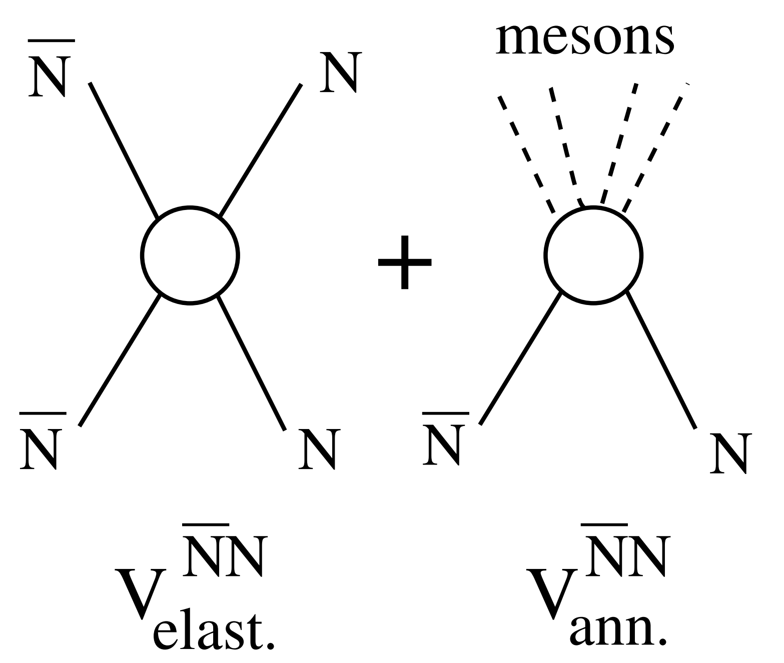
Dai, Haidenbauer, UGM, JHEP **1707** (2017) 078

CHIRAL NUCLEON–ANTINUCLEON POTENTIAL

Kang, Haidenbauer, UGM, JHEP **1402** (2014) 113; Dai, Haidenbauer, UGM, JHEP **1707** (2017) 078

- $\bar{\mathrm{N}}\mathrm{N}$ potential has two parts:

$$V^{\bar{\mathrm{N}}\mathrm{N}} = V^{\bar{\mathrm{N}}\mathrm{N}}_{\mathrm{elast.}} + V^{\bar{\mathrm{N}}\mathrm{N}}_{\mathrm{ann.}}$$



- Elastic part from G-parity transformation:

$$V^{\mathrm{NN}} = +V_{1\pi} + V_{2\pi} + V_{3\pi} + \ldots + V_{\mathrm{cont}}$$
$$\to V^{\bar{\mathrm{N}}\mathrm{N}}_{\mathrm{elast.}} = -V_{1\pi} + V_{3\pi} - V_{3\pi} + \ldots + V_{\mathrm{cont}}$$

$\hookrightarrow$ can be taken over from the chiral EFT NN potential

- Annihilation potential accounts for the open annihilation channels

$$V^{\bar{\mathrm{N}}\mathrm{N}}_{\mathrm{ann.}} = \sum_{\mathrm{X}} V^{\bar{\mathrm{N}}\mathrm{N}\to\mathrm{X}}\,, \quad \mathrm{X} = \pi, 2\pi, 3\pi, 4\pi, \ldots$$

$\hookrightarrow$ describe annihilation by a few effective two-body channels (with 3/2/1/1 LECs for S/P/D/F)

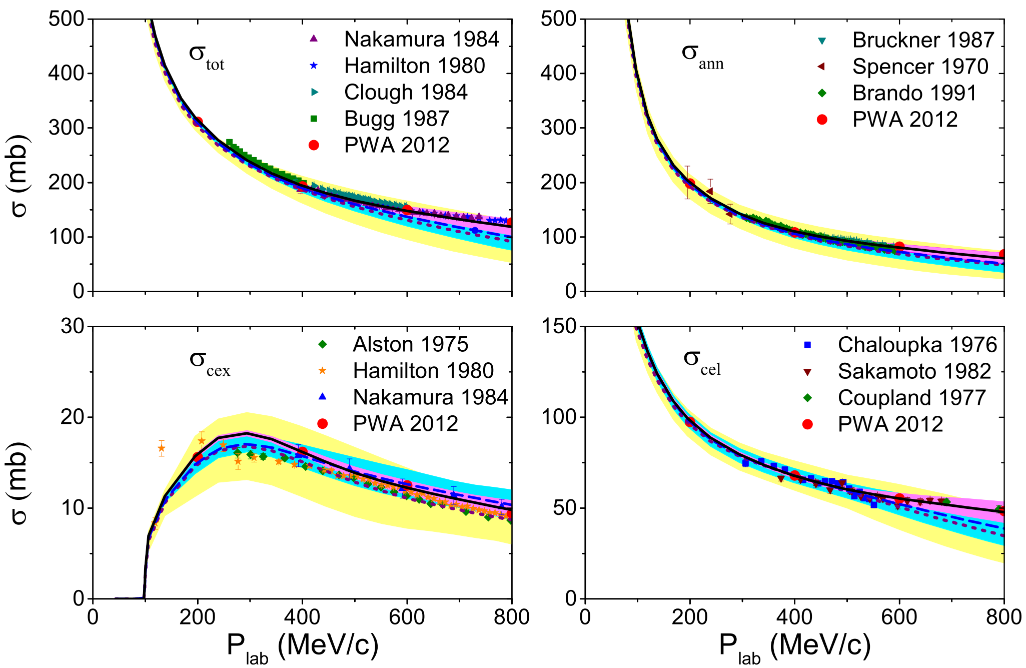
$\hookrightarrow$ preserves unitarity!

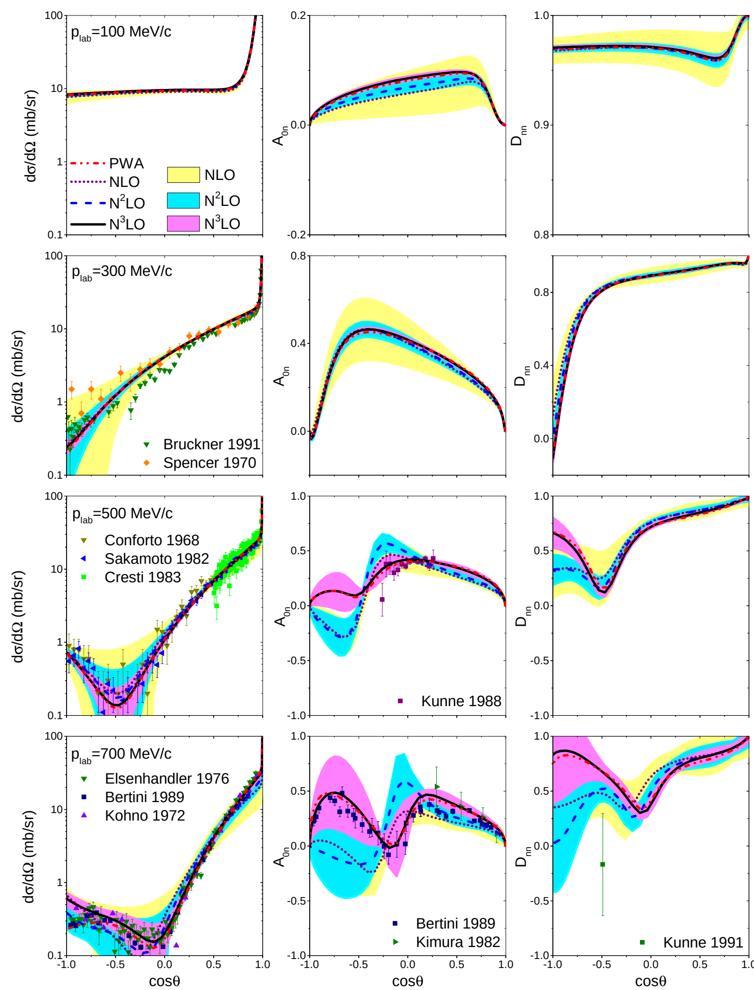
PROTON-ANTIPROTON ANNIHILATION

Dai, Haidenbauer, UGM, JHEP **1707** (2017) 078

- Results from chiral EFT at NNNLO
- Uncertainties as developed for the NN system

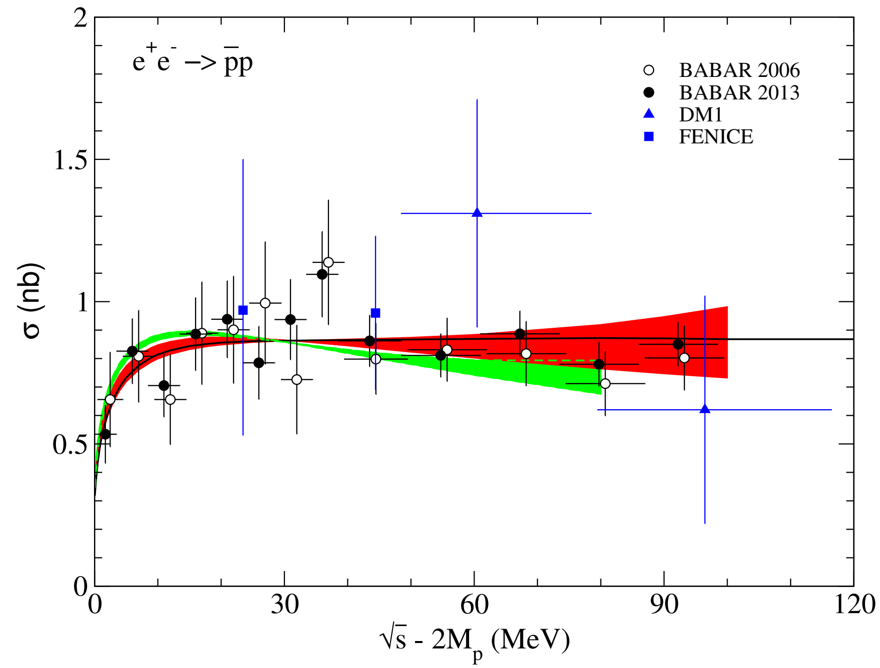
Epelbaum, Krebs, UGM, EPJA **51** (2015) 53



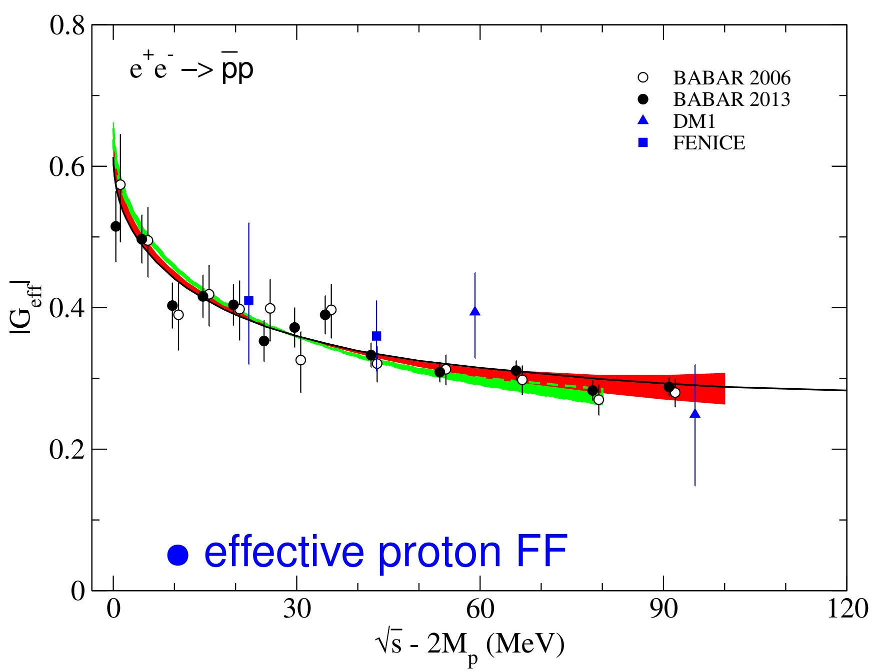


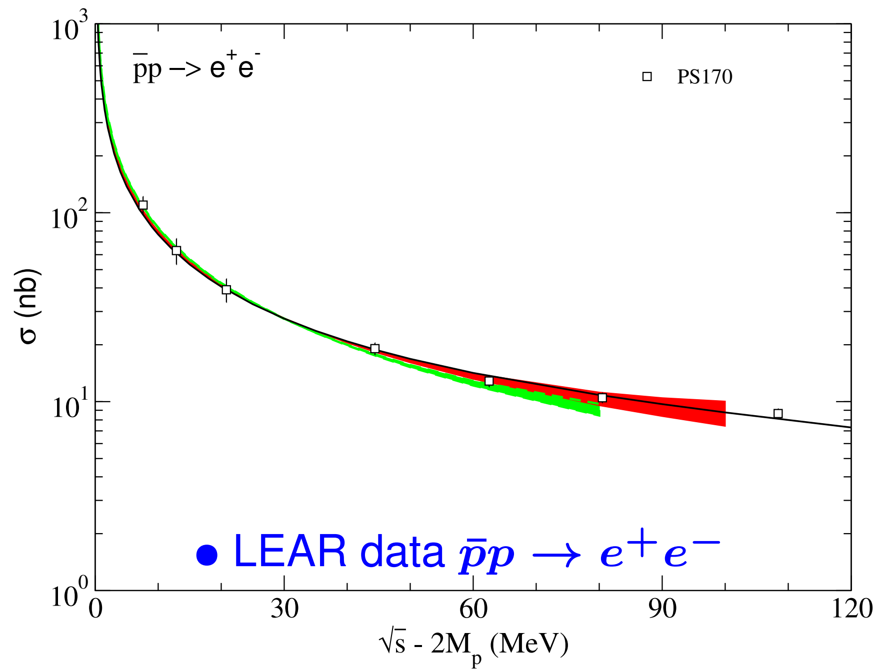
FIT and PREDICTIONS

- one parameter fitted for
  excess energies smaller than 60 MeV



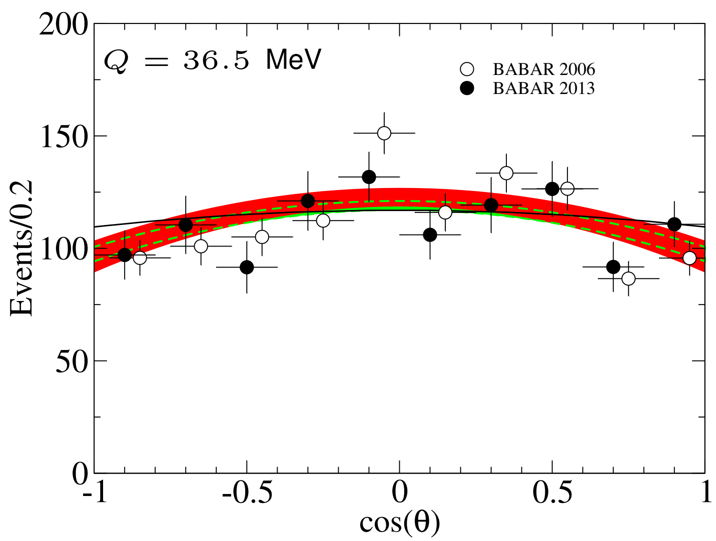
- Predictions:

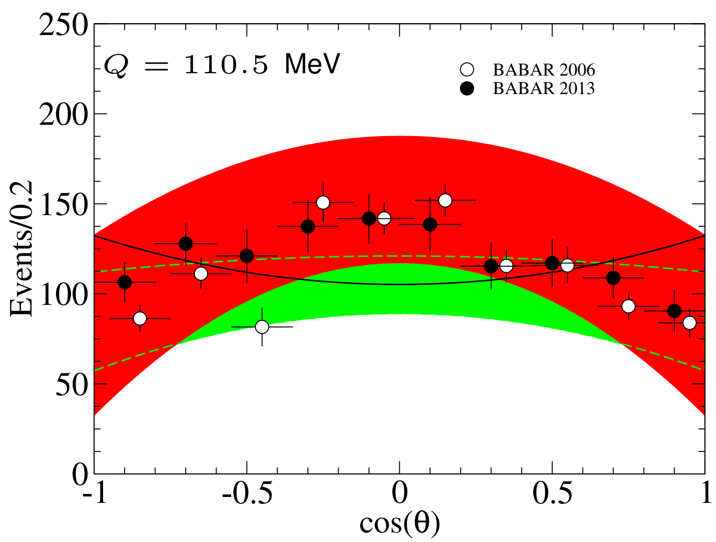


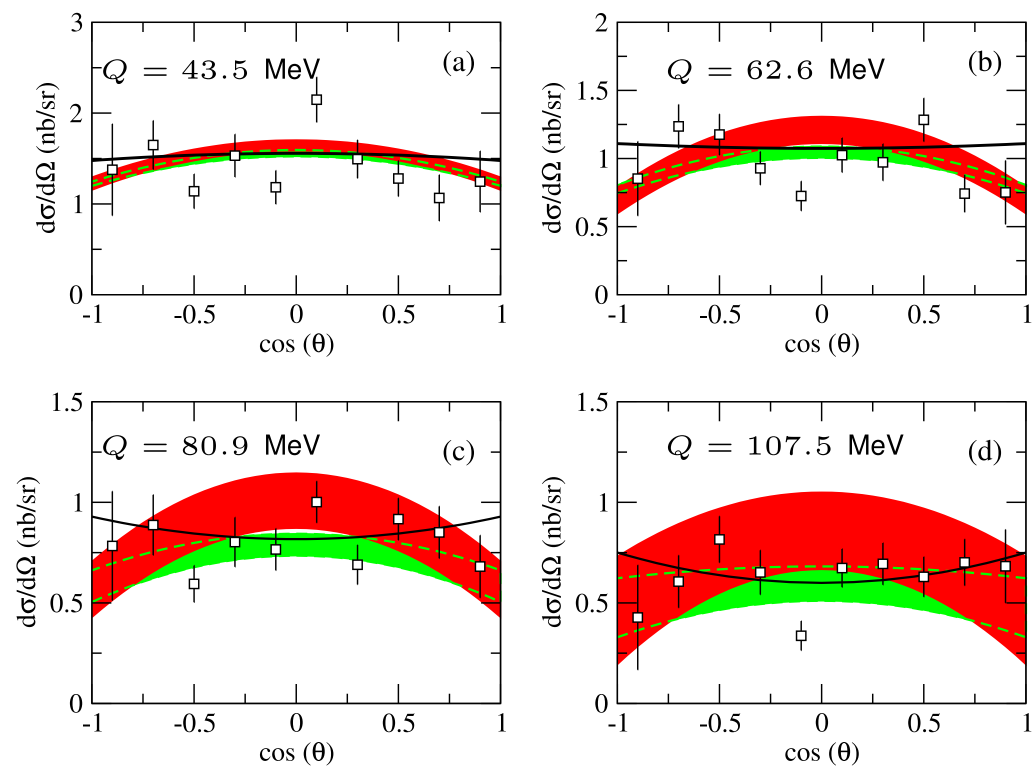


PREDICTIONS: DIFFERENTIAL XS

- differential X sections from BaBar and PS170 $\quad [Q = \sqrt{s} - 2M_p]$







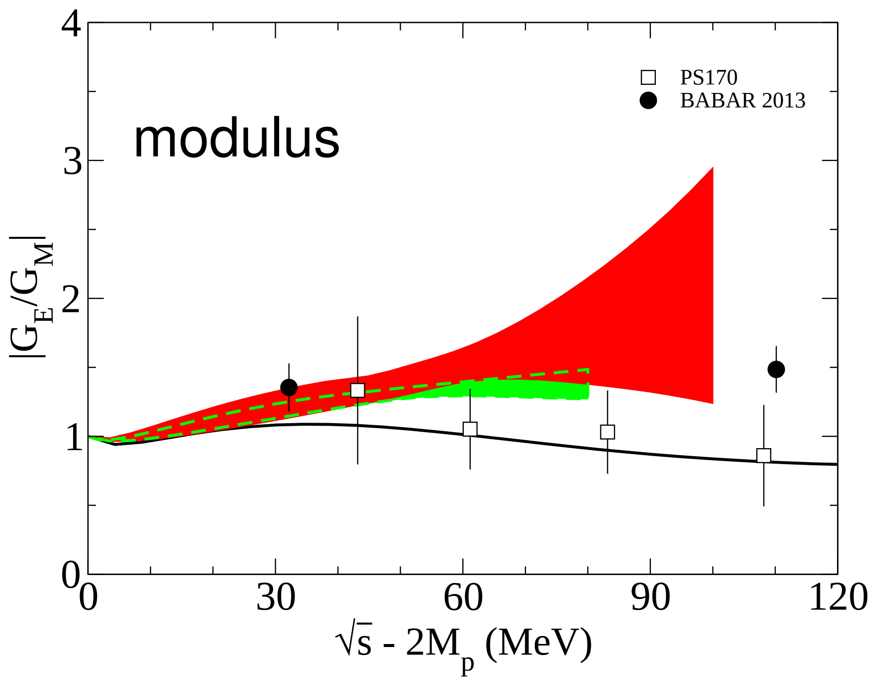
PS170: Bardin et al., Nucl. Phys. B **411** (1994) 3

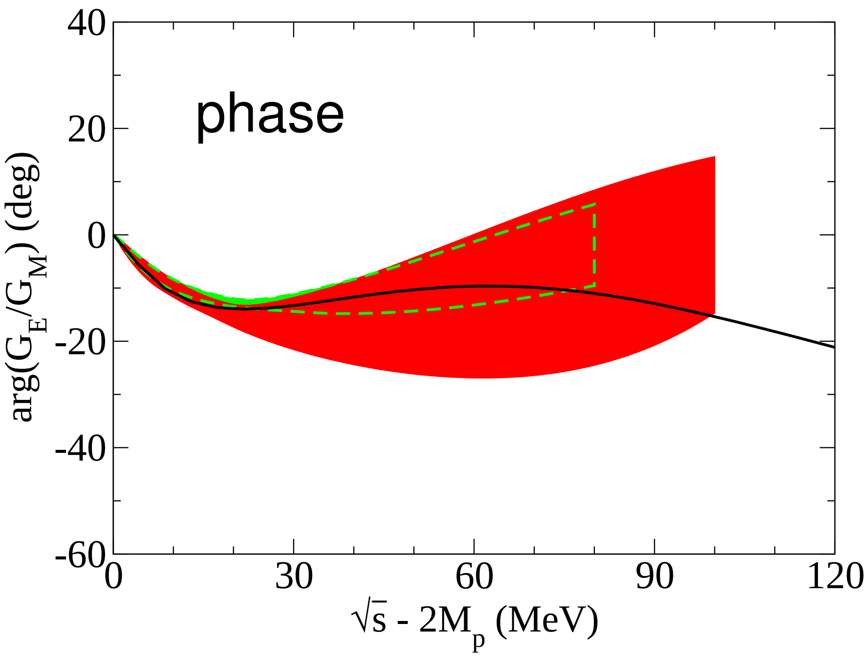
BaBar: Aubert et al., Phys. Rev. D **73** (2006) 012005

BaBar: Lees et al., Phys. Rev. D **87** (2013) 092005

FURTHER PREDICTIONS

- complex form factor ratio





- ratio and phase are to be determined w/ PANDA at FAIR

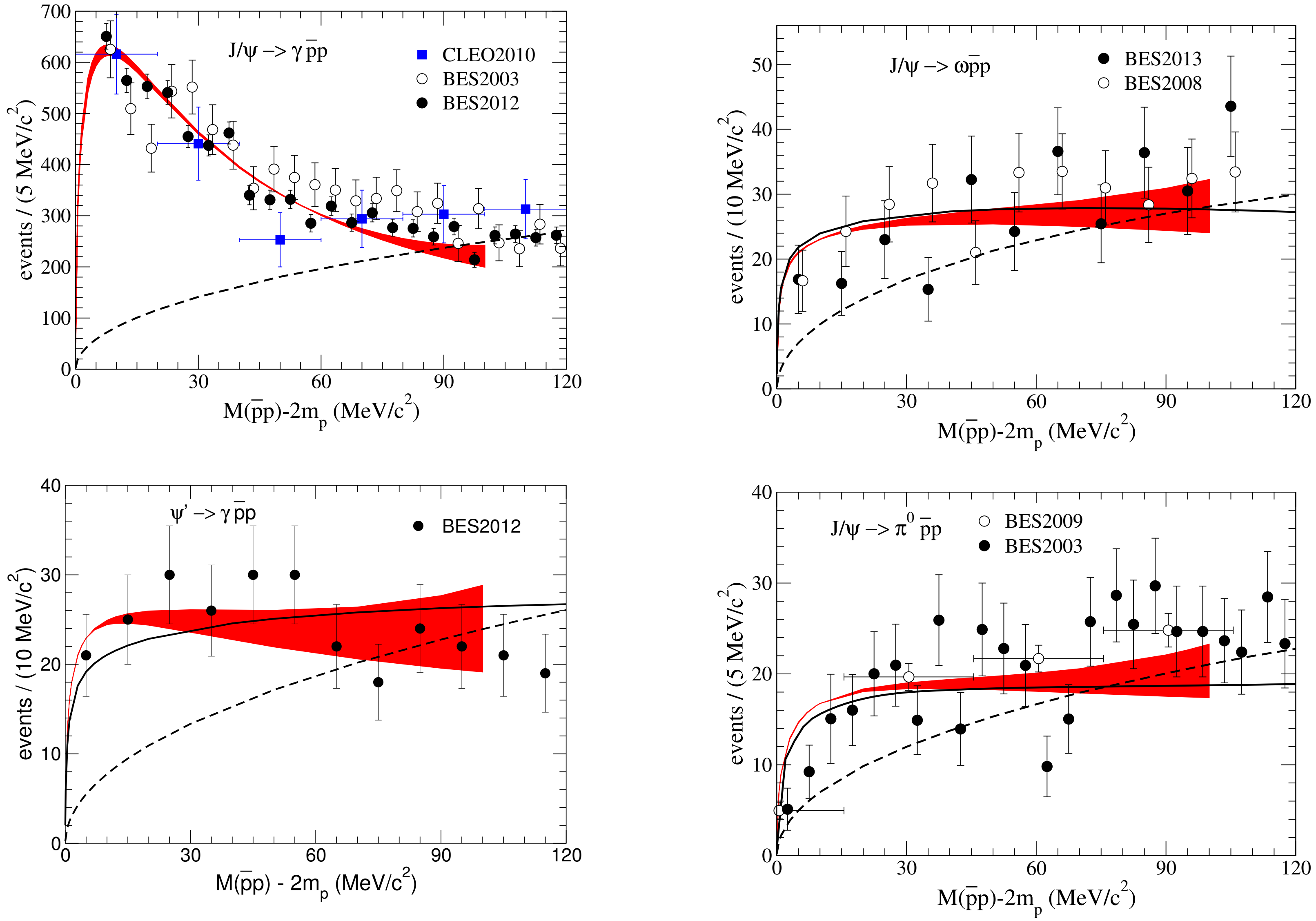
- also predictions for the analyzing power and spin correlation coefficients

$\hookrightarrow$ see Haidenbauer, Kang, UGM, Nucl. Phys. A **929** (2014) 102

$\hookrightarrow$ spares

UNIVERSALITY of the FSI MECHANISM

- explains a large number of threshold enhancements



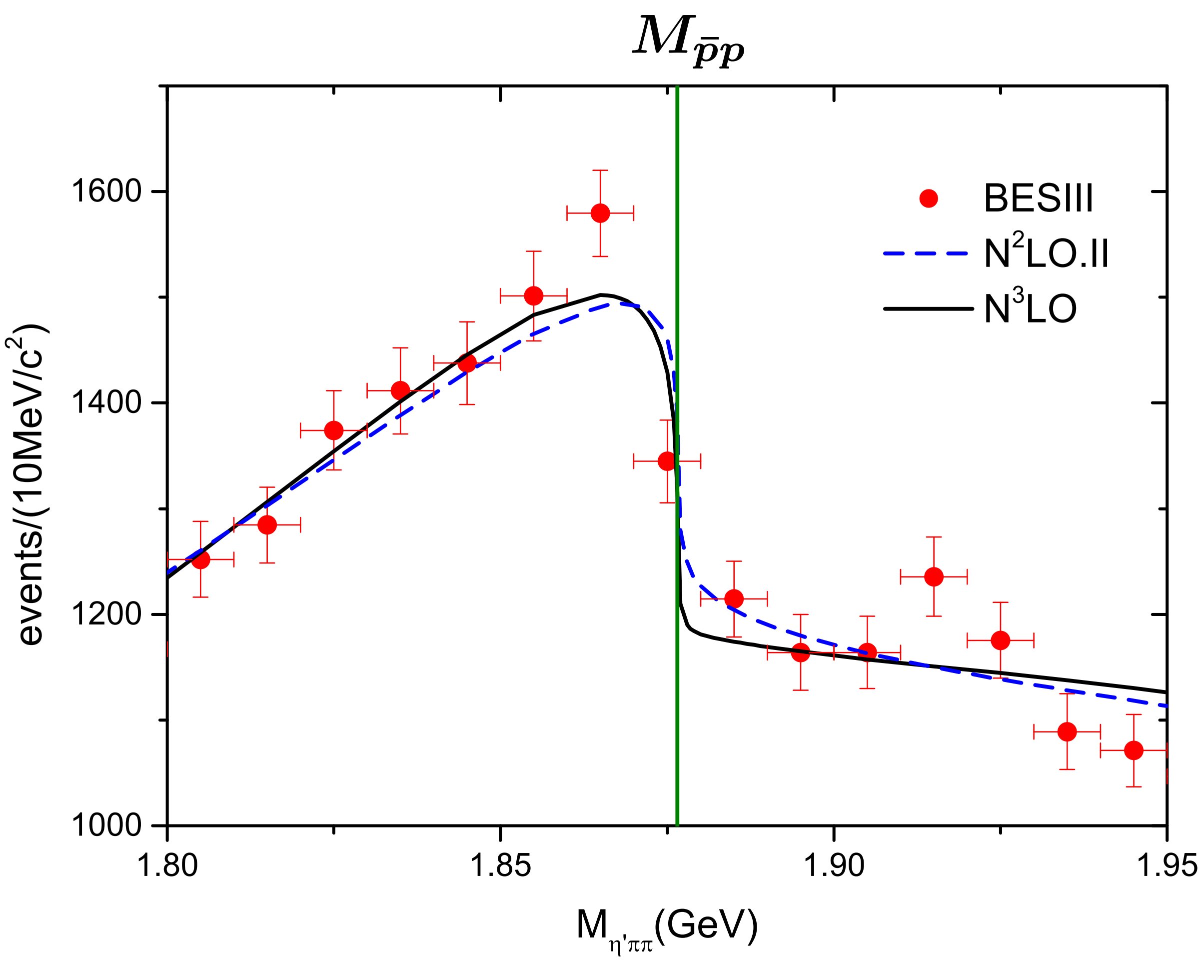
Kang, Haidenbauer, UGM, Phys. Rev. D **91** (2015) 074003

UNIVERSALITY of the FSI MECHANISM cont'd

Dai, Haidenbauer, UGM, Phys. Rev. D **98** (2018) 014005

- and even the structure observed by BESIII in $J/\psi \to \gamma\eta'\pi^+\pi^-$ at the $\bar{p}p$ threshold (coupled channel calculation)

M. Ablikim et al. (BESIII Coll.), Phys. Rev. Lett. **117** (2016) 042002 (2016)



The Λ form factors in the timelike region

Haidenbauer, UGM, Phys. Lett. B **761** (2016) 456 [arXiv:1608.02766 [nucl-th]]

BASIC DEFINITIONS and FACTS

- Consider the reaction $e^+e^- \to \bar{\Lambda}\Lambda$
- Formalism identical to the proton case, just change labels $[C_p(s) = 1]$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{\rm EM}^2 \beta}{4s} \left[|G_M(s)|^2 \,(1+\cos^2\theta) + \frac{4M_\Lambda^2}{s} \,|G_E(s)|^2 \sin^2\theta \right]$$

- As usual, define an effective ff:

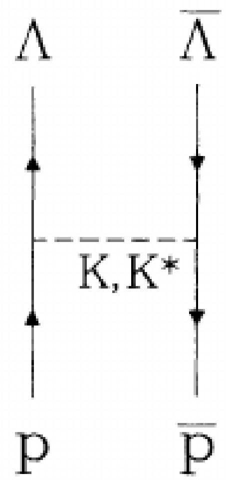
$$|G_{\rm eff}(s)| = \sqrt{\frac{\sigma_{e^+e^-\to\bar{\Lambda}\Lambda}(s)}{\frac{4\pi\alpha_{\rm EM}^2\beta}{3s}\left[1+\frac{2M_\Lambda^2}{s}\right]}}$$

- The $\bar{\Lambda}\Lambda$ interaction must be modelled

  $\to$ describe all PS185 data on $\bar{p}p \to \bar{\Lambda}\Lambda$

  Haidenbauer et al., Phys. Rev. C **45** (1992) 931

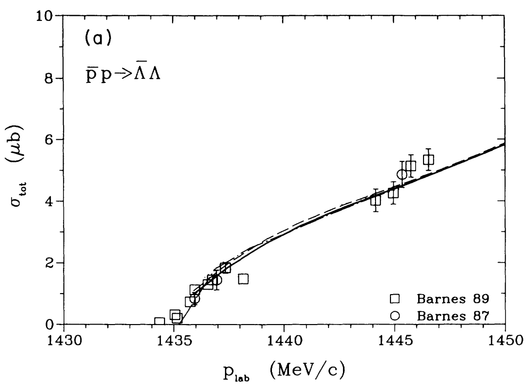
  Haidenbauer et al., Phys. Rev. C **46** (1992) 2158

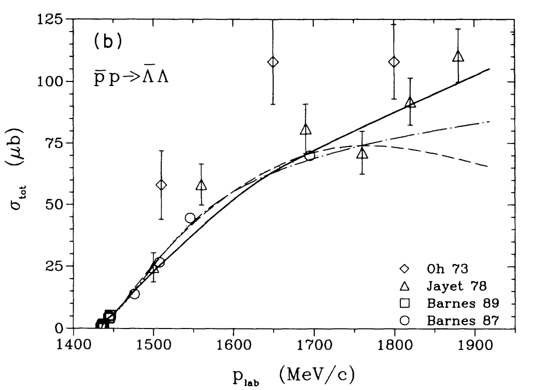


$+V_{\rm annihilation}$

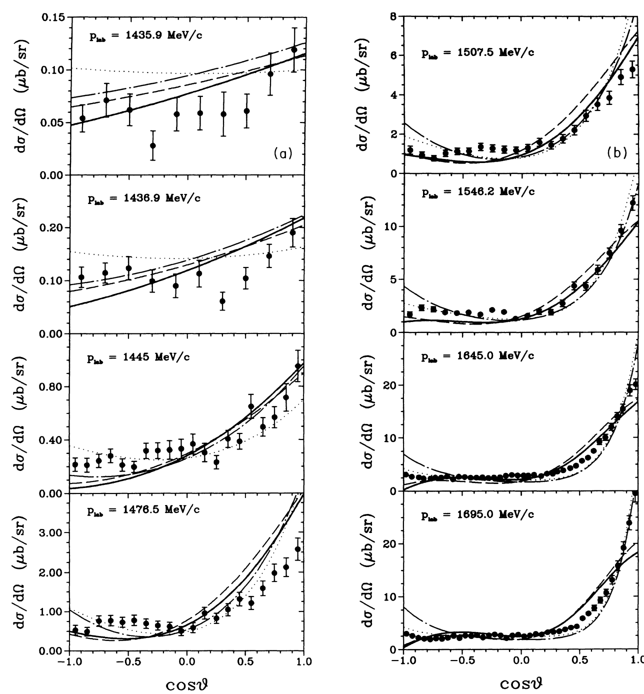
SOME OLD RESULTS

total XS

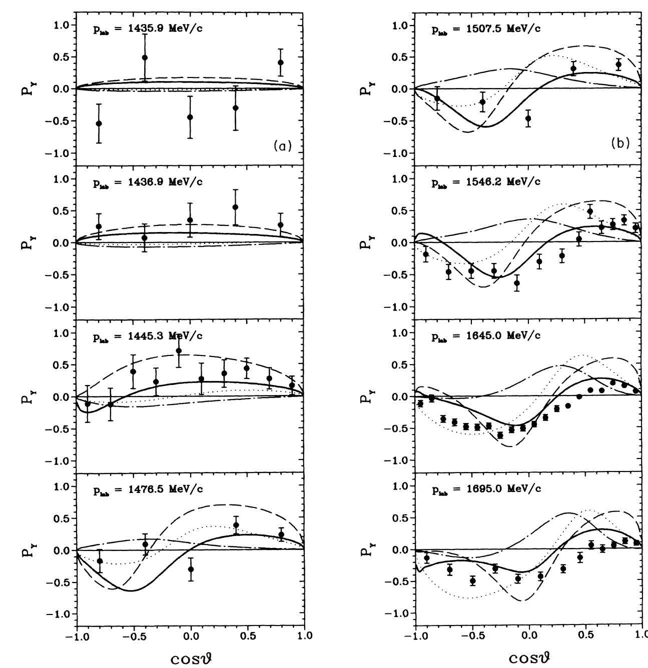




diff. XS



Polarizations



- various lines corresponds to different model versions

Haidenbauer, Holinde, Mull. Speth, Phys. Rev. C **46** (1992) 2158

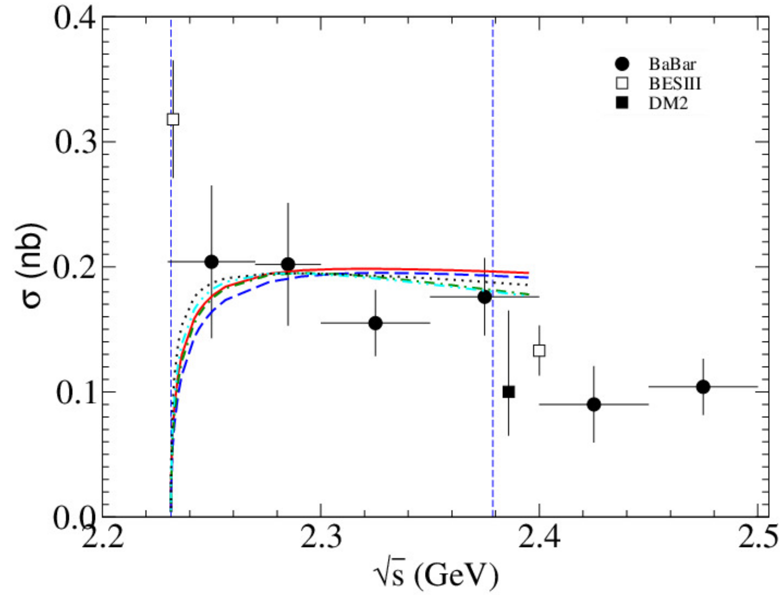
FIT and PREDICTIONS

- Fit: one parameter fitted to the value at the maximum

DM2: Bisello et al., Z. Phys. C **48** (1990) 23

BaBar: Aubert et al., Phys. Rev. D **76** (2007) 092006

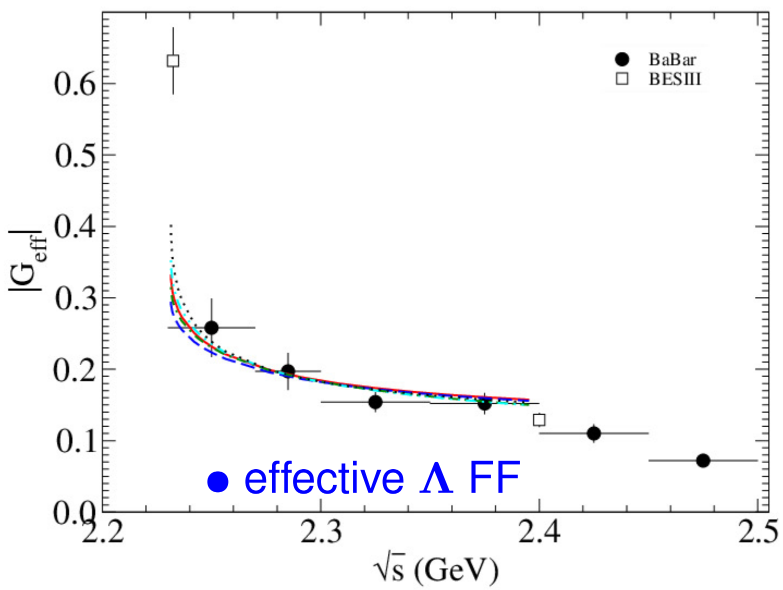
BESIII: P. Larin et al., PoS Hadron2017 (2018) 158



- Effective form factor:

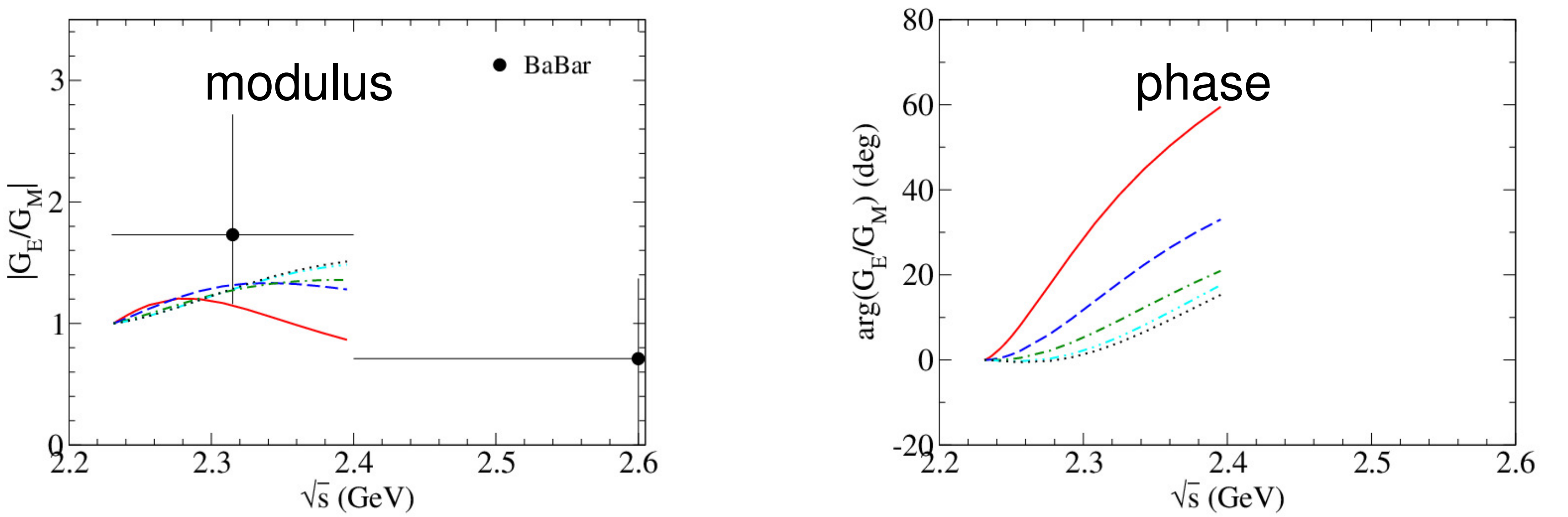
$\hookrightarrow$ good description of the data $\surd$

$\hookrightarrow$ threshold BESIII datum a mystery



FURTHER PREDICTIONS

- complex form factor ratio



- stronger model predictions, PANDA at FAIR? or BESIII? or ...

- also predictions for differential XS and spin correlation parameters

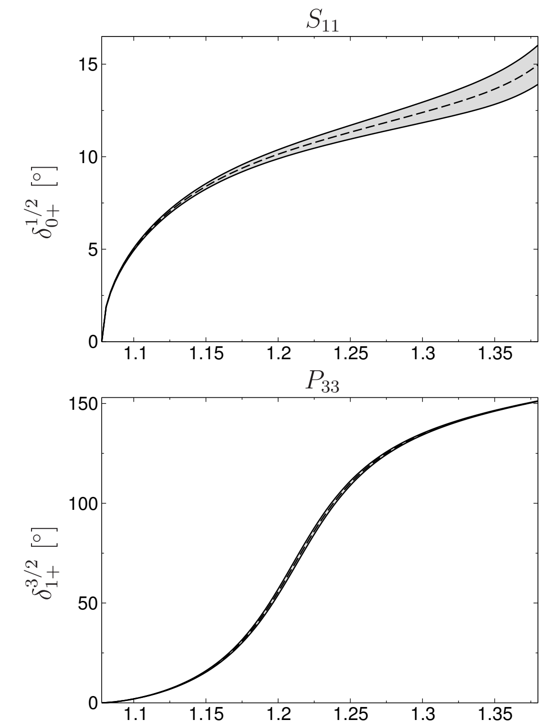
$\hookrightarrow$ see Haidenbauer, UGM, Phys. Lett. B **761** (2016) 456

$\hookrightarrow$ spares

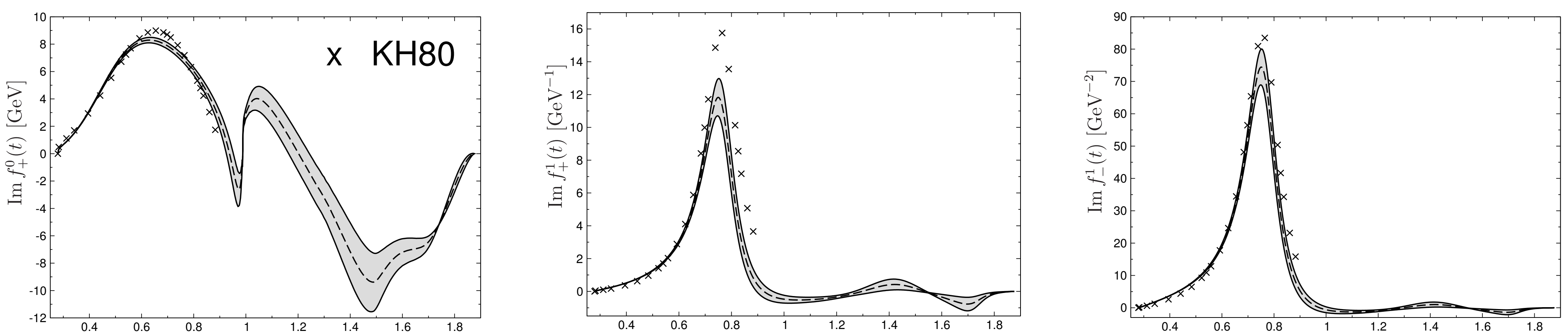
Once more on the isovector spectral functions

Hoferichter, Kubis, Ruiz de Elvira, Hammer, UGM, Eur. Phys. J. A **52** (2016)331 [arXiv:1609.06722 [nucl-th]]

ROY-STEINER EQUATION ANALYSIS



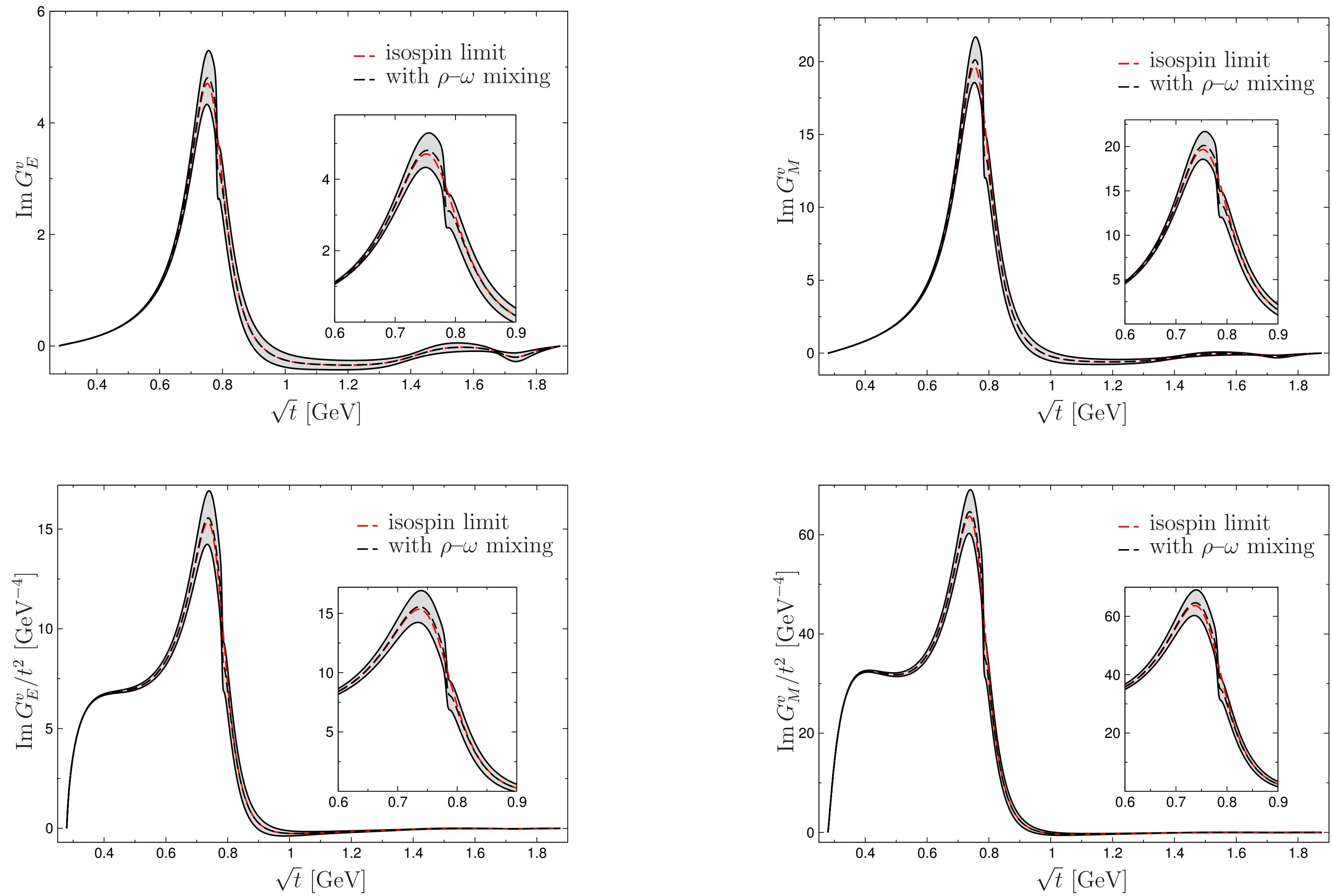
- improve the isovector spectral functions by
  - ↪ updated πN amplitudes from Roy-Steiner equations
  - ↪ include modern data (esp. pionic hydrogen & deuterium)
  - ↪ better treatment of isospin-violating effects
  - ↪ construct the pion FF from precise knowledge of $\delta_1^1(s)$
  - ↪ perform systematic error analysis



Hoferichter, Ruiz de Elvira, Kubis, UGM, Phys. Rev. Lett. **115** (2015) 092301; Phys. Rev. Lett. **115** (2015) 192301; Phys. Rept. **625** (2016) 1; J.Phys. G**45** (2018) 024001

NEW ISOVECTOR SPECTRAL FUNCTIONS

- Precise determinations of the isovector spectral functions



MODELLING ISOVECTOR TRANSITIONS

- For hyperons, combine CHPT with dispersion relations
- consider e.g. $\Sigma^0 \to \Lambda\gamma^\star$
- include only the 2π intermediate state

$\hookrightarrow$ dispersive representation for the form factor(s)

$\hookrightarrow$ best use MO scheme for pion rescattering

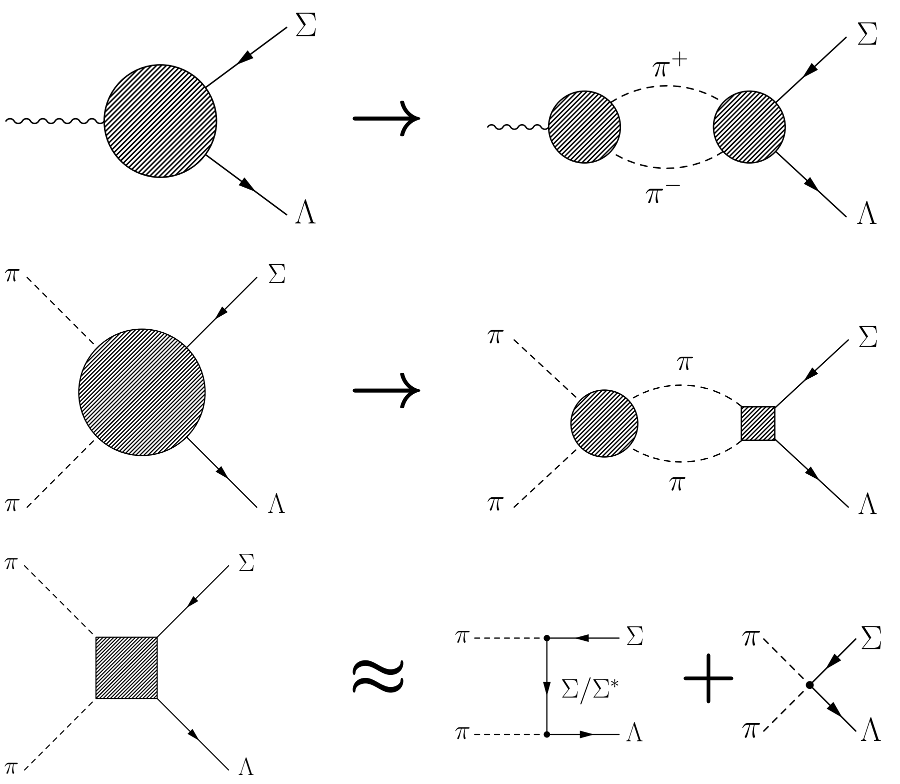
$\hookrightarrow$ induces some cutoff dependence ($1 \leq \Lambda \leq 2$ GeV)

- use baryon CHPT to describe pion-baryon scattering

$\hookrightarrow$ must include the decuplet

$\hookrightarrow$ known from connecting the threshold with the subthreshold region

Siemens et al., Phys. Lett. B **770** (2017) 27



- only applicable for isovector transitions

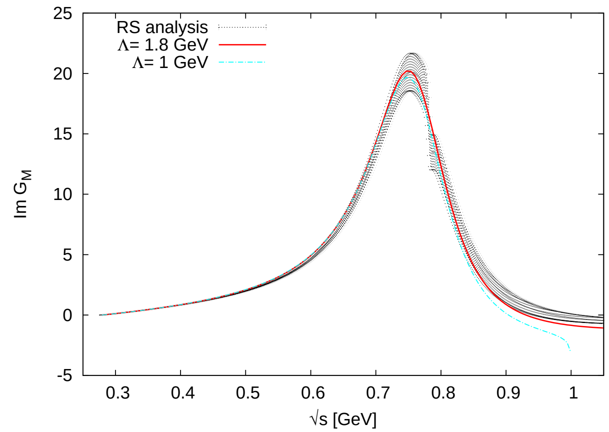
$\hookrightarrow$ must gauge on the nucleon case!

Granados, Leupold, Perotti, EPJA **53** (2017) 117

Leupold, EPJA **54** (2017) 1

TESTING on the NUCLEON

- If the modelling should make sense, one must recover the isovector spectral functions based on the RS analysis!



- clearly the case for the MO approach to pion rescattering

  Leupold, Eur. Phys. J. A **54** (2017) 1

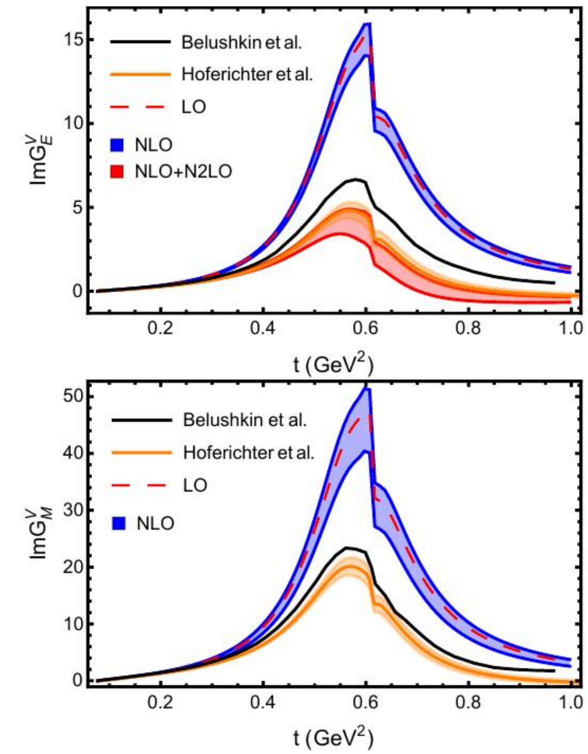
- Alternative: use the N/D approach to describe pion rescattering

  $\hookrightarrow$ clearly at odds with the exact description

  $\hookrightarrow$ overshoots the IV radius by far!

  $\hookrightarrow$ should be abandoned!

  Alarcon, Weiss, Phys. Rev. C **97** (2018) 055203



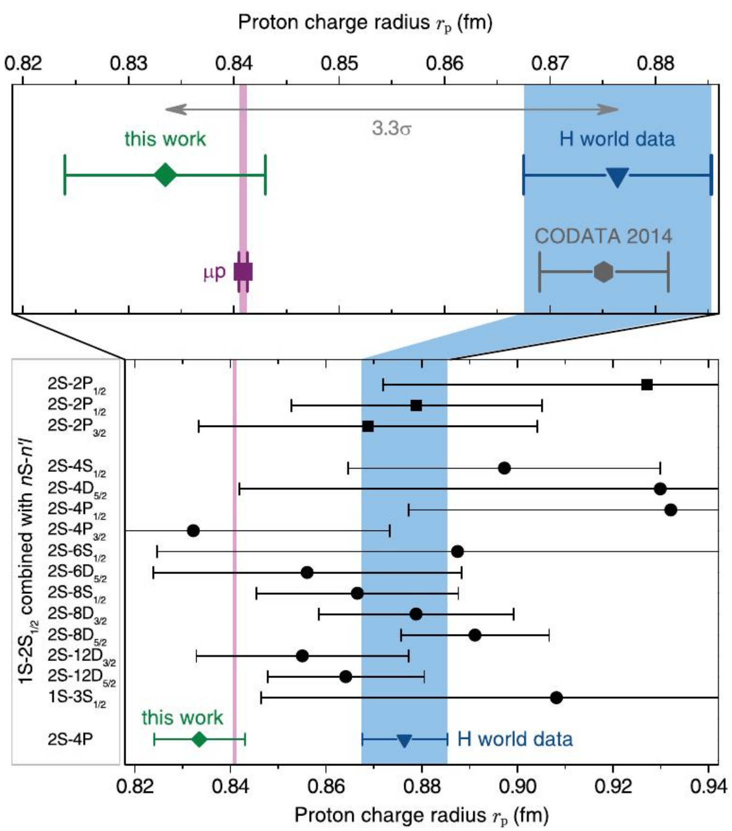
- isoscalar case less well constrained (see earlier discussion)

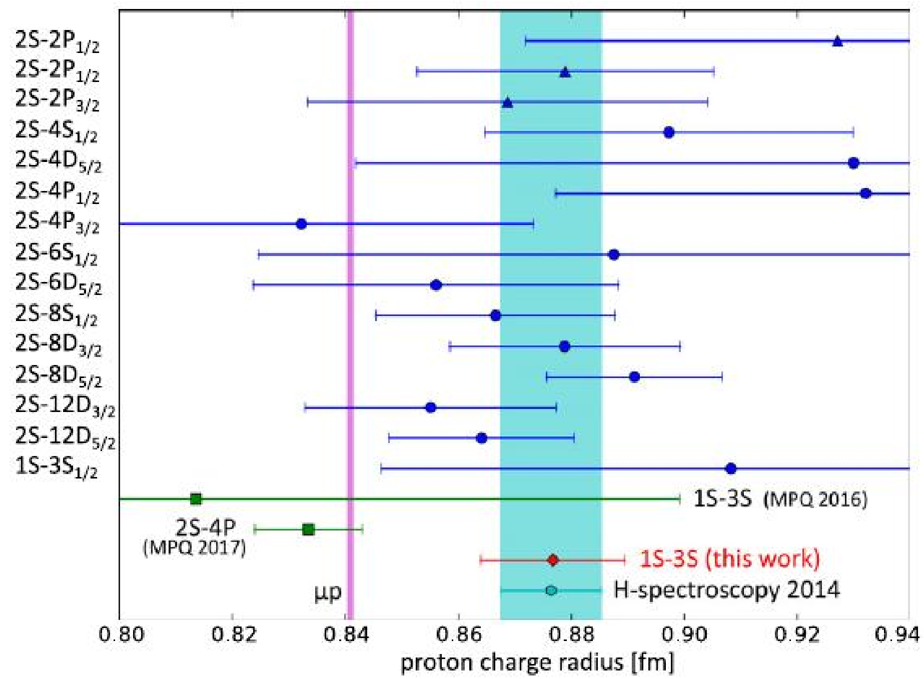
SUMMARY & OUTLOOK

- Dispersion theory is the best tool to analyze the nucleon em FFs
  $\hookrightarrow$ always a small radius, status of electronic hydrogen unclear $\rightarrow$ slide
  $\hookrightarrow$ more data in the time-like region are needed
- Proton time-like FFs show a strong threshold enhancement $\rightarrow$ $\boldsymbol{p\bar{p}}$ FSI
  $\hookrightarrow$ $\boldsymbol{p\bar{p}}$ FSI can be described in chiral EFT
  $\hookrightarrow$ appears to be a universal phenomenon
- $\boldsymbol{\Lambda}$ time-like FFs can be modelled in a similar way $\rightarrow$ no chiral EFT so far
  $\hookrightarrow$ works well, but puzzling datum just at the threshold from BESIII
- CHPT and dispersive approaches together allow for predictions of hyperon FFs
  $\hookrightarrow$ so far, only for the isovector transitions
  $\hookrightarrow$ must gauge on the well-determined nucleon IV spectral functions
- Nice interplay of electromagnetic & hadronic physics $\rightarrow$ interesting times ahead!

ELECTRONC LAMB SHIFT

- Recent results from PSI and ENS





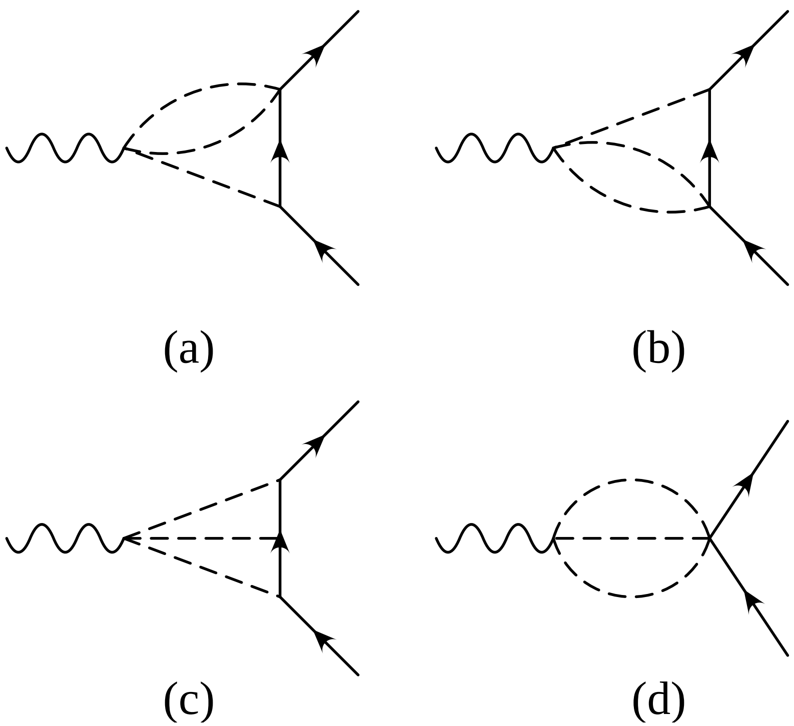
PSI: Beyer et al., Science **358** (2017) 79   ENS: Fleurbaey et al., Phys. Rev. Lett. **120** (2018) 183001

Spares

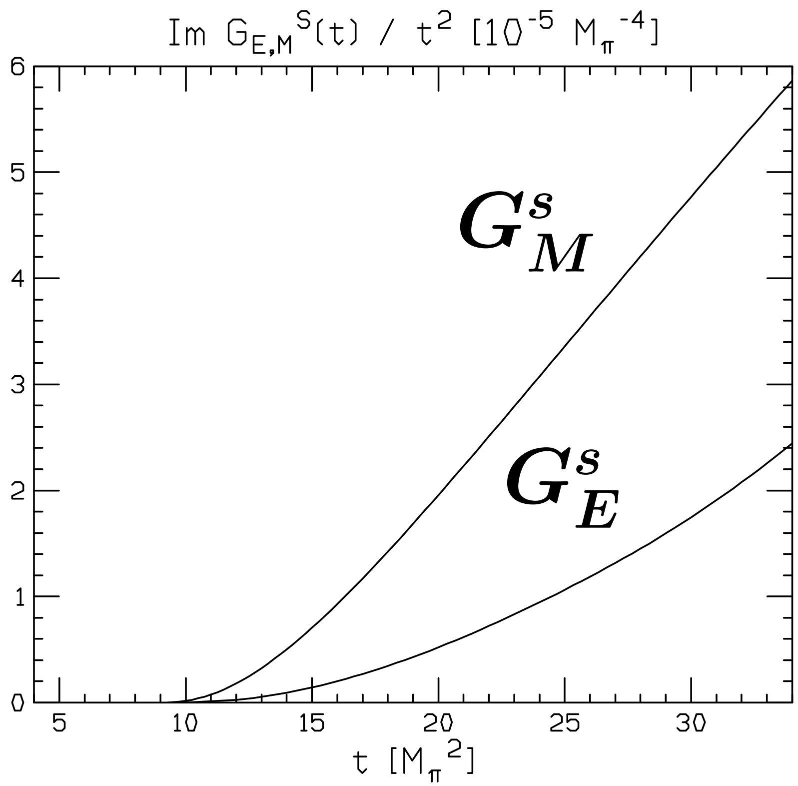
ISOSCALAR SPECTRAL FUNCTION

Bernard, Kaiser, UGM, Nucl. Phys. A **611** (1996) 429 [hep-ph/9607428]

- Two-loop CHPT calculation



- Electric/magnetic spectral fcts



⋆ **no** shoulder on the left wing

⋆ **clean** omega-pol dominance

RADIUS EXTRACTION

- We include the following **uncertainties** in the radius extraction:
  - variations in the 2π-continuum (F_π^V and f_+^1) $\rightarrow$ slide/spares
  - variations of the isoscalar ($\pi\rho$, $\bar{K}K$) continua
  - different #s of effective iso-scalar/vector poles
  - variations of the fit range ($Q^2_{\rm max}$) $\rightarrow$ slide/spares
  - inclusion of superconvergence relations
  - inclusion of data from polarization measurements $\rightarrow$ slide/spares
  - different available approximations for the radiative corrections

$\Rightarrow$ values for the extracted proton radii:

$$\boxed{r_E^p = 0.84^{+0.01}_{-0.01}\ \text{fm}\ , \quad r_M^p = 0.86^{+0.02}_{-0.03}\ \text{fm}}$$

PARAMETERS of the NEW DISPERSIVE FITS

- Vector meson parameters (5 IS, 5 IV needed)

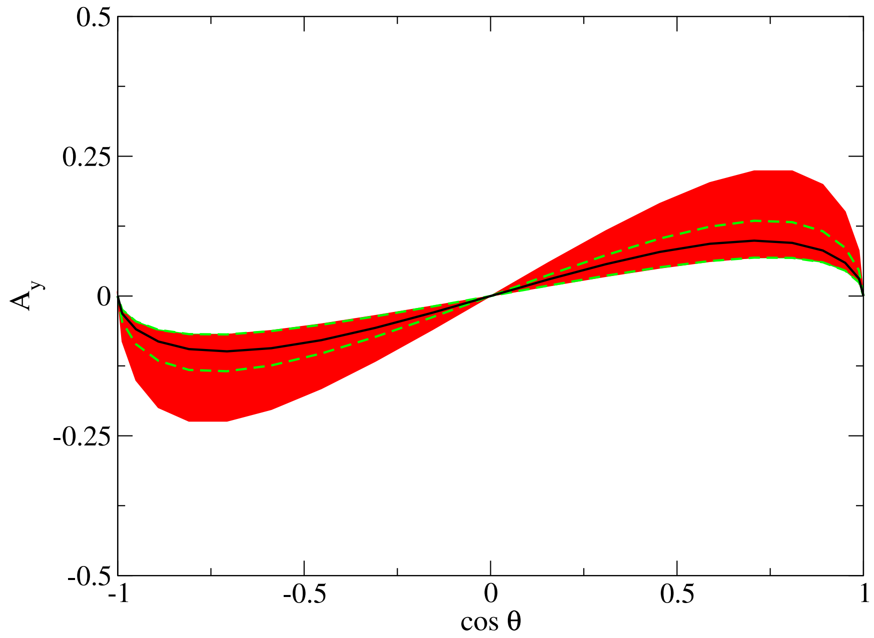
$V_{\rm IS}$	m_V	a_1^V	a_2^V	$V_{\rm IV}$	m_V	a_1^V	a_2^V
ω	0.783	0.500	−0.190	v_1	2.330	−1.911	0.314
ϕ	1.019	0.375	−0.861	v_2	2.192	0.644	2.265
s_1	3.052	−0.446	0.512	v_3	4.272	0.173	−0.322
s_2	1.571	0.095	−2.388	v_4	2.454	0.158	0.064
s_3	2.580	0.760	−0.538	v_5	2.492	0.142	−0.372

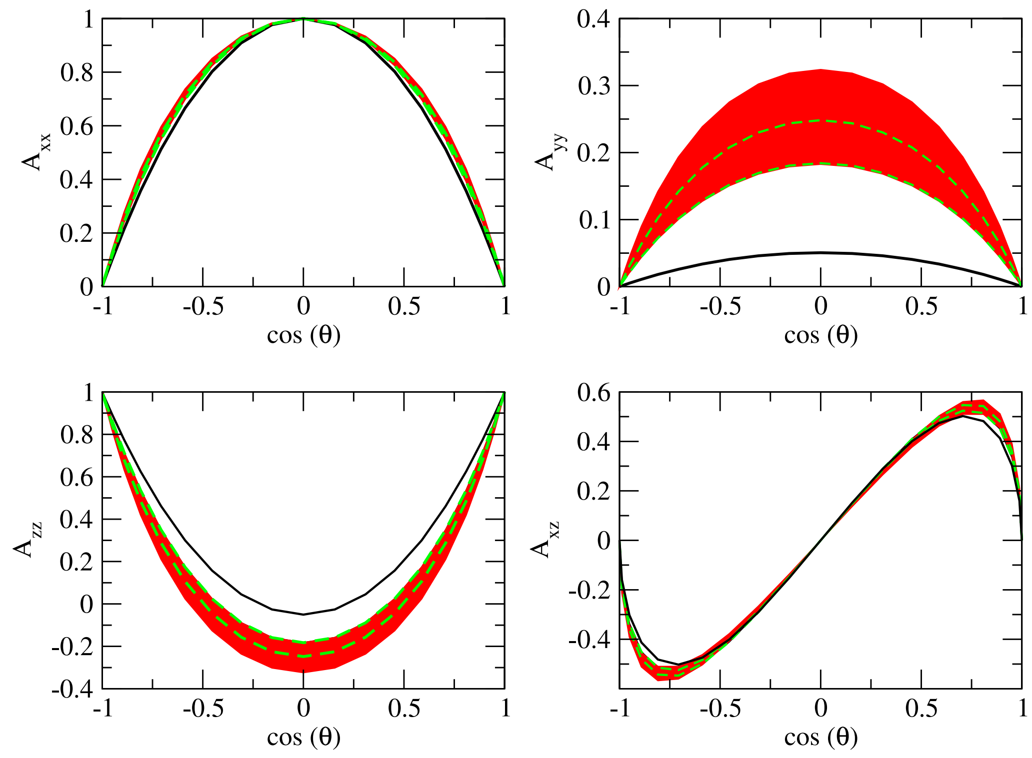
- Normalization parameters

n1	0.9982	n5	1.0059	n9	1.0056	n13	1.0052	n17	1.0008
n2	0.9928	n6	1.0017	n10	1.0025	n14	1.0044	n18	1.0076
n3	1.0051	n7	1.0003	n11	1.0000	n15	1.0023	n19	1.0055
n4	1.0078	n8	0.9975	n12	1.0031	n16	1.0006	n20	1.0035
n21	0.9995	n22	0.9975	n23	0.9996	n24	0.9984	n25	1.0056
n26	1.0080	n27	1.0004	n28	1.0011	n29	1.0078	n30	0.9985
n31	1.0060								

FURTHER PREDICTIONS for $p\bar{p} \to e^+e^-$

- Analyzing power at $Q = 45$ MeV
- Spin correlation parameters at $Q = 45$ MeV





FURTHER PREDICTIONS for $\Lambda\bar{\Lambda} \to e^+e^-$

- Diff. XS & polarization [$Q = 90$ MeV]
- Spin correlation parameters [$Q = 90$ MeV]