Compton Scattering: How to Optimise Experiments?

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1. How To Spend Your Time & Money Wisely?
2. Two-Photon Response Explores System Dynamics
3. A Plethora of Observables To Determine 6 Parameters $\alpha_{E1}, \beta_{M1}, \gamma_i$
4. How To Spend Your Time & Money Wisely?

Office of Science U.S. DEPARTMENT OF ENERGY

How do constituents of the nucleon react to external fields?

How to reliably extract proton, neutron, spin polarisabilities?

How to plan effective experiments & test theory?

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Polarisabilities & Bayes in χEFT for lattice-QCD: hg/JMcG/DRP *Eur. Phys. J.* **A52** (2016) 139
Comprehensive proton/neutron observables: hg/JMcG/DRP *Eur. Phys. J.* **A54** (2018) 37
^{3}He $\mathcal{O}(\delta^3)$: Margaryan/Strandberg/hg/JMgG/DRP/Shukla: *Eur. Phys. J.* **A54** (2018) 125

1. How To Spend Your Time & Money Wisely?

Optimise suite of future measurements! – Sequence may depend on future results.

Goals: improve/validate existing data; test theoretical descriptions; extract parameters.

Money & time & workforce & reputation $\Longrightarrow$ Careful planning needs to integrate

theory $\oplus$ experimental facts $\oplus$ likeliness of success

Given Effective Field Theory: predictions of finite accuracy; also validate prior parameter determinations.

Given prior data: noisy, $\lesssim 100$ points with varying degrees of quality & reliability. $\Longrightarrow$ **Curate!**

3-10% point-to-point (statistical, Gaußian) error

3-10% correlated (systematic, non-Gaußian) error (beam flux,. . .) differ between sets ("floating norms").

Often under-/over-estimated. $\Longrightarrow$ May have to **reconstruct/validate likely correlated error**. . .

Need to find "Sweet-Spot", given constraints & tensions:

Detector location (walls), difficulty of observables, parameter combinations "known" with varying confidence, . . .

High energy: high count rates $\Longrightarrow$ short runs, high statistics —— theory less accurate

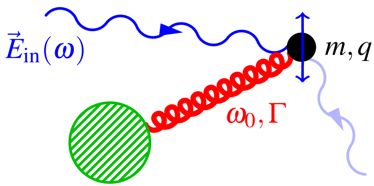
Low energy: low count rates $\Longrightarrow$ long runs for adequate statistics —— theory more accurate

Desired Outcome: **"Optimal Impact Machine" (generally accepted/well-defined/reproducible/canned)**
for sequence of experiments with high(est) impact: Figures of Merit, validations of theory/data,. . .

2. Two-Photon Response Explores System Dynamics

(a) Polarisabilities: Stiffness of Charged Constituents in El.- Mag. Fields

Example: induced electric dipole radiation from harmonically bound charge, damping Γ Lorentz/Drude 1900/1905



$$\vec{d}_{\text{ind}}(\omega) = \underbrace{\frac{q^2}{m} \frac{1}{\omega_0^2 - \omega^2 - \mathrm{i}\Gamma\omega}}_{=:\, 4\pi\, \alpha_{E1}(\omega)} \vec{E}_{\text{in}}(\omega)$$

$=: 4\pi\, \alpha_{E1}(\omega)$ "displaced volume" $[10^{-4}\ \text{fm}^3]$

electric scalar dipole polarisability

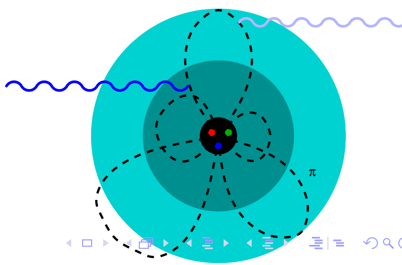
$$2\pi \Big[\underbrace{\alpha_{E1}\, \vec{E}^2 + \beta_{M1}\, \vec{B}^2}_{\text{electric, magnetic scalar dipole}} + \underbrace{\gamma_{E1E1}\, \vec{\sigma} \cdot (\vec{E} \times \dot{\vec{E}}) + \gamma_{M1M1}\, \vec{\sigma} \cdot (\vec{B} \times \dot{\vec{B}}) + 2\gamma_{M1E2}\, \sigma^i B^j E_{ij} + 2\gamma_{E1M2}\, \sigma^i E^j B_{ij}}_{\text{spin-dependent dipole response of nucleon-spin constituents}} + \dots \Big]$$

electric, magnetic scalar dipole

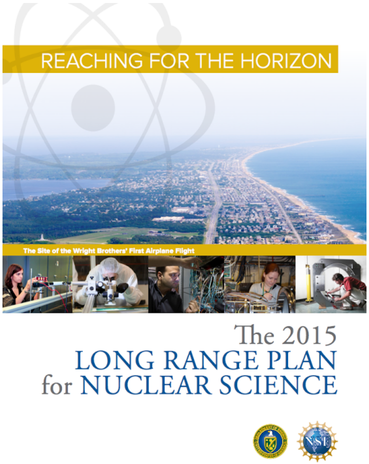
spin-dependent dipole response of nucleon-spin constituents

Dis-entangle *interaction scales, symmetries & mechanisms* with & among constituents.

Fundamental hadron properties, like charge, mass, mag. moment, $\langle r_N^2 \rangle \dots$ PDG



(b) A Word from Our Sponsors: The US Long Range Plan



The special status of pions and kaons in QCD and their marked impact on the long-distance structure of hadrons can be systematically encoded in an effective theory, applicable to processes at low energy. This effective theory, as well as emerging LQCD calculations, can provide benchmark predictions for so-called polarizabilities that parameterize the deformation of hadrons due to electromagnetic fields, spin fields, or even internal color fields. Great progress has been made in determining the electric and magnetic polarizabilities. Within the next few years, data are expected from the High Intensity Gamma-ray Source (HIγS) facility that will allow accurate extraction of proton-neutron differences and spin polarizabilities. JLab also explores aspects

[US NSAC LRP 2015 p. 14]

HIγS (DOE): a central goal; > 3000 hrs committed at $60 - 100\ \mathrm{MeV}$

proton doubly & beam pol. (E-06-09/10) deuteron beam pol. (E-18-09, running)

^{3}He unpol & doubly pol. (E-07-10, E-08-16) ^{4}He unpol ^{6}Li unpol. (E-15-11, first!)

A2 @ MAMI (DFG: 5-year SFB): running, data cooking and planned

proton $100 - 400\ \mathrm{MeV}$: beam & target pol. deuteron, ^{3}He, ^{4}He unpol., beam & target pol.

MAXlab: data cooking deuteron $100 - 160\ \mathrm{MeV}$: unpol.

(c) All 1N Contributions to N^4LO

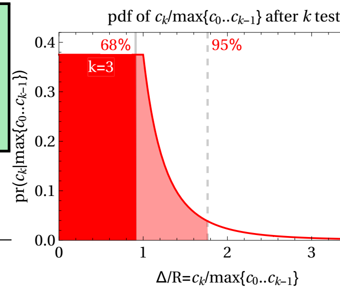
Bernard/Kaiser/Meißner 1992-4, Butler/Savage/Springer 1992-3, Hemmert/… 1998
McGovern 2001, hg/Hemmert/Hildebrandt/Pasquini 2003
McGovern/Phillips/hg 2013

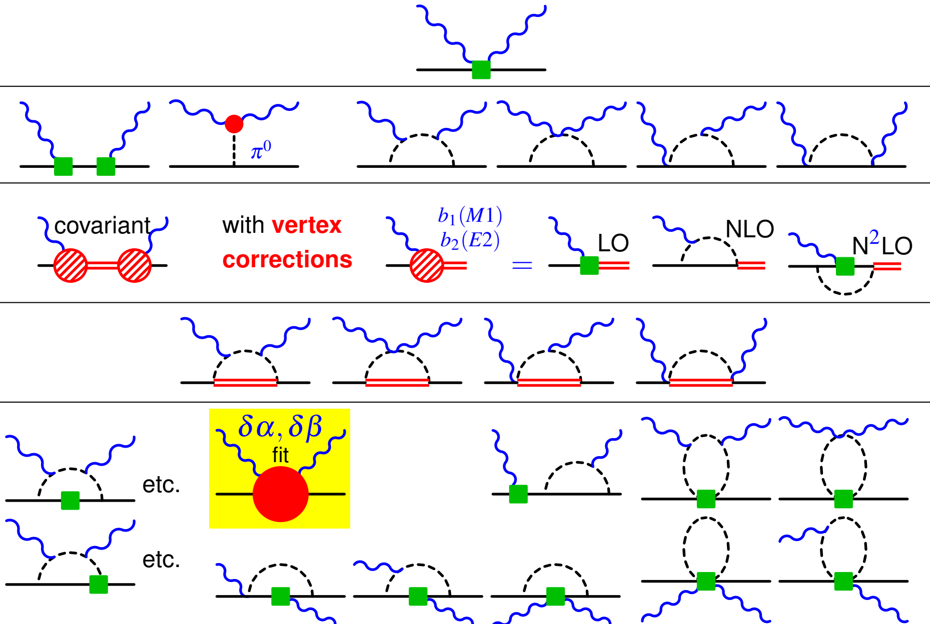
Effective Field THEORY: Finite accuracy with "known" residual theory uncertainties: non-Gaußian pdfs.

Low numerical cost, but $\alpha_{E1}, \beta_{M1}, \gamma_i$ are *shadowed by larger effects, dependence largely linear.*

Unified Amplitude: accuracy decreases with ω:

	in low régime	$\omega \lesssim m_\pi$	at least N^4LO $(e^2\delta^4)$:	accuracy $\delta^5 \lesssim 2\%$;
or	in high régime	$\omega \sim M_\Delta - M_N$	at least NLO $(e^2\delta^0)$:	accuracy $\delta^2 \lesssim 20\%$.



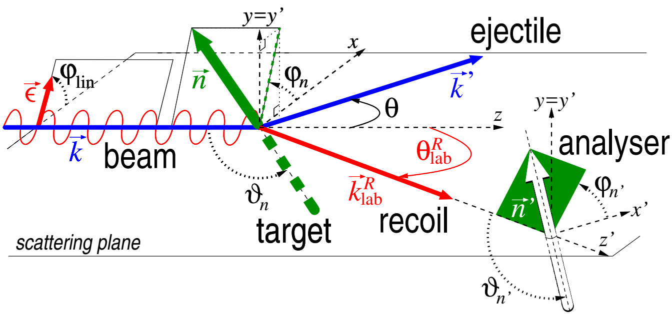


3. A Plethora of Observables To Determine 6 Parameters $\alpha_{E1}, \beta_{M1}, \gamma_i$

Arbitrary cross section given by linear combination of independent observables parameterising set-ups with Unpolarised/linear/circular beam on scalar/vector/tensor target/recoil:

Proton/^{3}He (spin-$\frac{1}{2}$): 7 Asymmetries: **1 beam, 1 target, 2 circpol. double, 3 linpol. double**

5 Polarisation Transfers: **2 circpol. beam on pol. recoil, 3 linpol. beam on pol. recoil**



$$
\left.\frac{d\sigma}{d\Omega}\right|_{\text{unpol}} \times \Bigg[1 + \Sigma^{\text{lin}}(\omega,\theta) P^{(\gamma)}_{\text{lin}} \cos 2\phi_{\text{lin}}
+ \sum_{\substack{J=1,\dots,2S\\ 0\le M\le J}} T_{JM}(\omega,\theta) P^{(\text{d})}_J d^J_{M0}(\theta) \cos[M\phi - \tfrac{\pi}{2}\delta_{J\text{odd}}]
+ \sum_{\substack{J=1,\dots,2S\\ 0\le M\le J}} T^{\text{circ}}_{JM}(\omega,\theta) P^{(\gamma)}_{\text{circ}} P^{(\text{d})}_J d^J_{M0}(\theta) \sin[M\phi + \tfrac{\pi}{2}\delta_{J\text{odd}}]
+ \sum_{\substack{J=1,\dots,2S\\ -J\le M\le J}} T^{\text{lin}}_{JM}(\omega,\theta) P^{(\gamma)}_{\text{lin}} P^{(\text{d})}_J d^J_{M0}(\theta) \cos[M\phi - 2\phi_{\text{lin}} - \tfrac{\pi}{2}\delta_{J\text{odd}}] \Bigg]
$$

6 p & n polarisabilities + constraints on $\alpha_{E1}+\beta_{M1}$, γ_0,…; experiment: detector settings, feasibilities,…

"At present, single and double polarised data is sorely missing." **Theory letter [arXiv:1409.1512]**

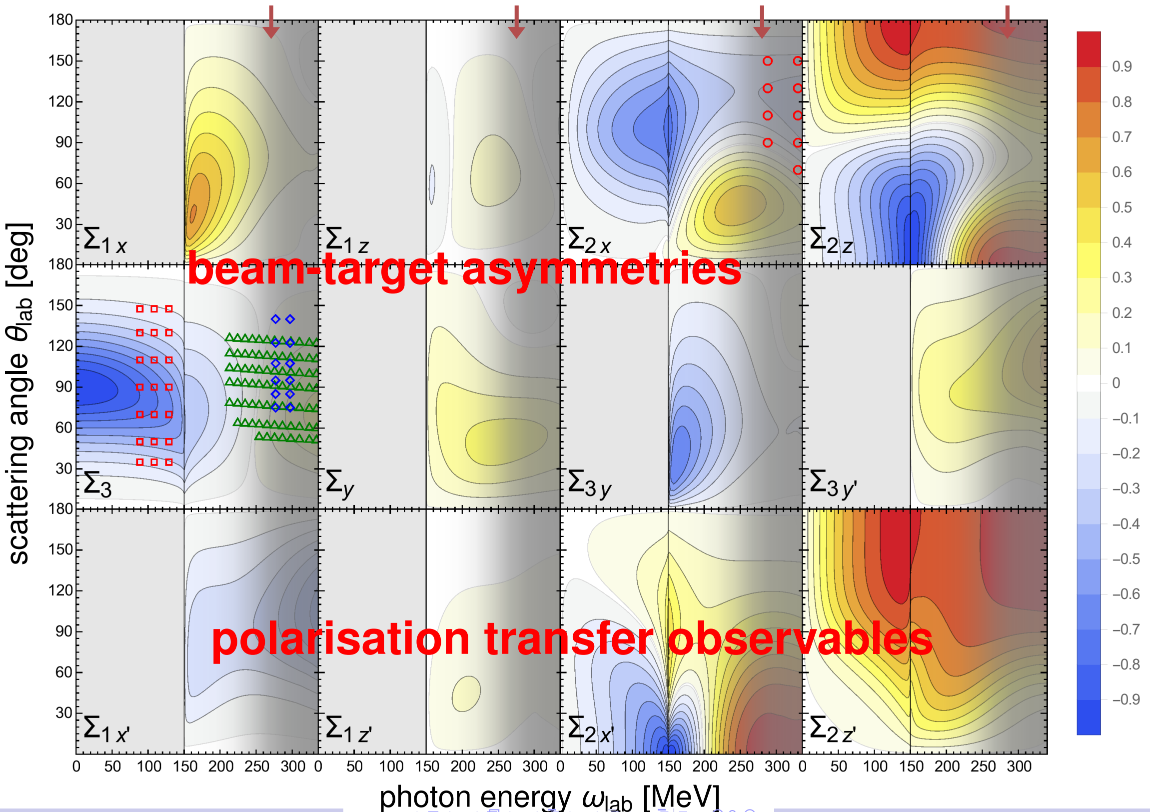
No single measurement to provide definitive answers: multi-parameter extractions, systematics, validation.

$\Longrightarrow$ **Experiment & Theory must collaborate to identify *observables with biggest impact.***

(a) The 12 Proton Observables: Not Lots Of Data, and Wrong Region

JMcG/hg/DRP
1711.11546

Fading Colours for $\omega \gtrsim 250$ MeV indicate breakdown of χEFT expansion.

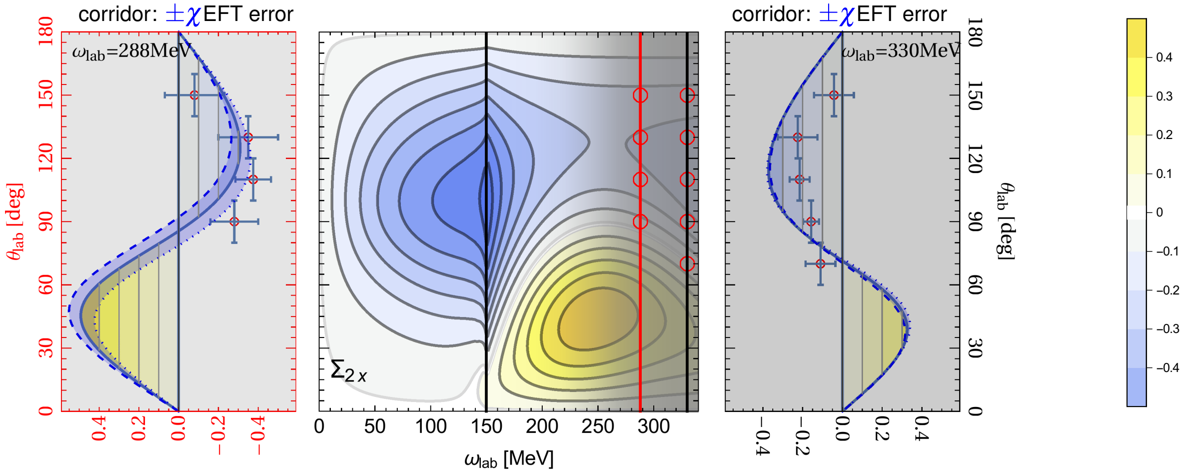


(b) Proton Spin Polarisabilities from Polarised Photons

$\mathcal{O}(e^2\delta^3)$: hg/Hildebrandt/...2003
$\mathcal{O}(e^2\delta^4)$: hg/McG/Ph 1511.0952&1711.11546
exp MAMI: Martel/...PRL 2014; Collicott/...t.b.a.

Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

Σ_{2x} :



$\mathcal{O}(e^2\delta^4)$ χEFT prediction hg/McGovern/Phillips 2014 **vs. MAMI extraction** Martel/...2014

static $[10^{-4}\ \text{fm}^4]$	γ_{E1E1}	γ_{M1M1}	γ_{E1M2}	γ_{M1E2}
MAMI 2014 proton	-3.5 ± 1.2	3.2 ± 0.9	-0.7 ± 1.2	2.0 ± 0.3
χEFT proton **predicted**	$-1.1\pm1.9_{\text{th}}$	$2.2\pm0.5_{\text{stat}}\pm0.6_{\text{th}}$	$-0.4\pm0.6_{\text{th}}$	$1.9\pm0.5_{\text{th}}$

(b) Proton Spin Polarisabilities from Polarised Photons

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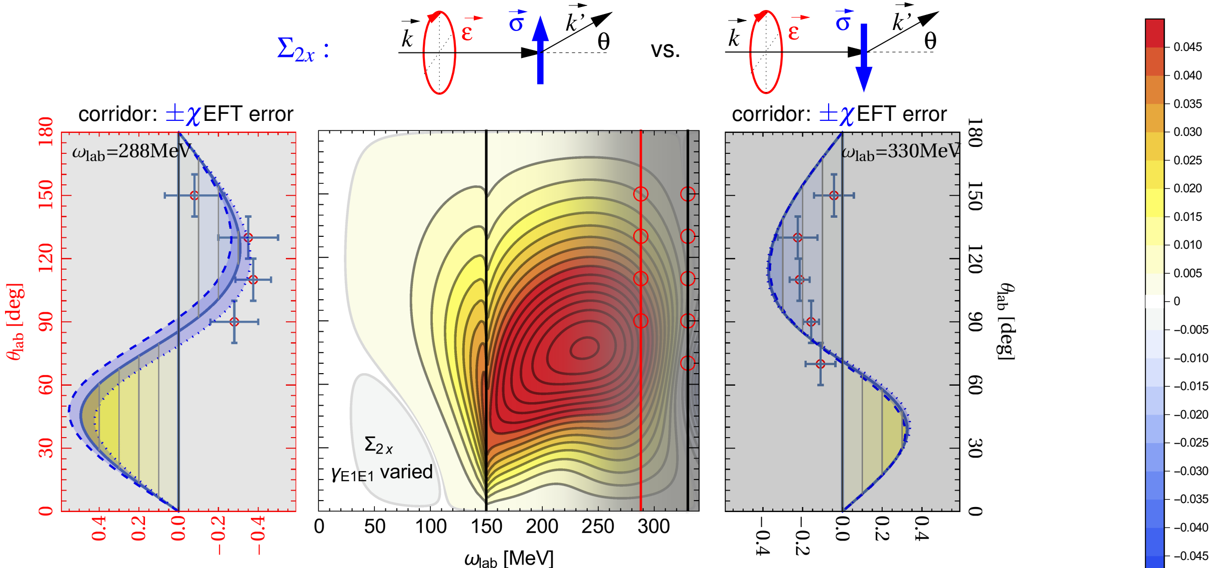

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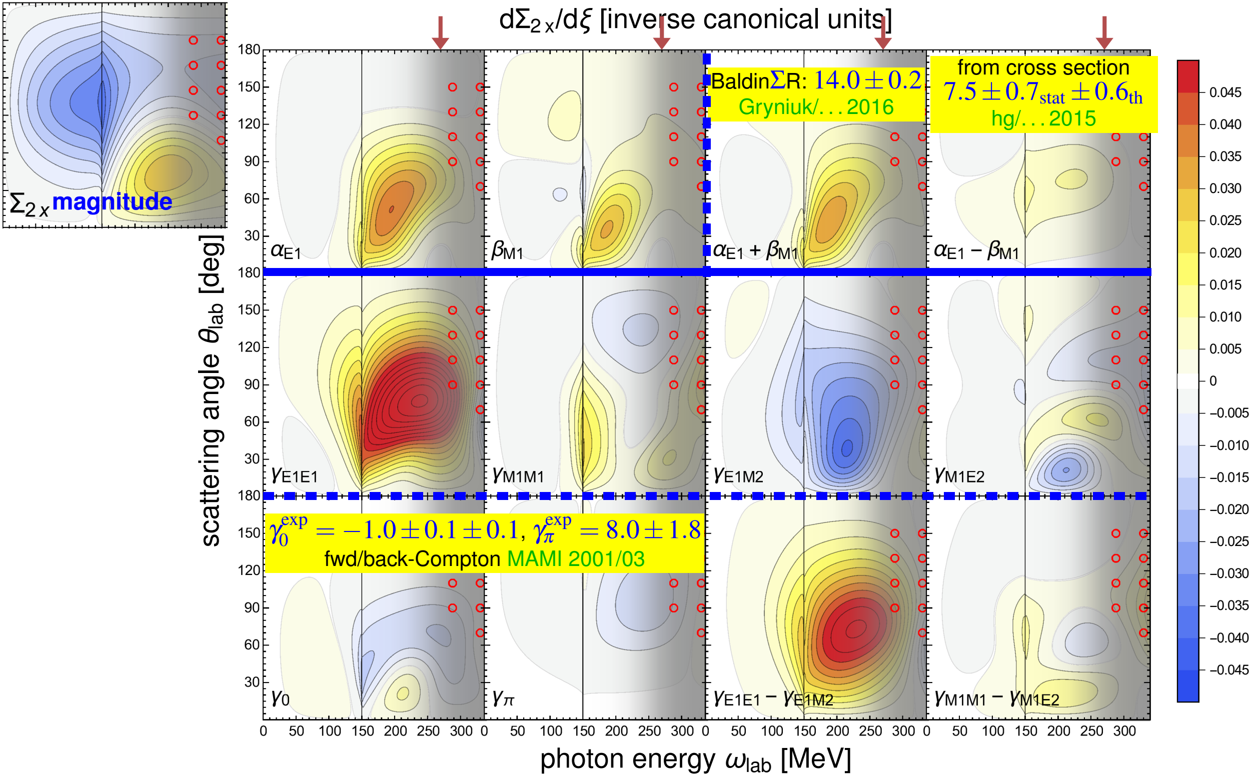
Theory: uncertainty on magnitude $\neq$ uncertainty on sensitivity.

Experiment: magnitudes determine beamtime – sensitivities & *efficiencies* determine success.

(c) Proton: Sensitivity of Σ_{2x} (Circpol Beam on Linpol$_x$ Target)

Fading Colours for $\omega \gtrsim 250$ MeV: breakdown of χEFT expansion $\Longrightarrow$ *prefer data below.*

6 parameters, constraints on $\alpha_{E1} \pm \beta_{M1}$, γ_0, γ_π,... $\Longrightarrow$ ***Sensitivities to linear combinations – validation!***



(d) Inverting the Question: One Polarisability per Experiment?

Instead of optimising a set of observables to a linear combination of polarisabilities,
optimise 9 continuous parameters (kinematics & polarisations) to *one* polarisability!?

Photon energy ω=120MeV | Reference frame: cm | lab

Deuteron vector polarisation $P_1^{(d)}$=1.1`
Deuteron tensor polarisation $P_2^{(d)}$=0.53`
Photon right–circular polarisation $P_{circ}^{(\gamma)}$=−0.5 (−0.5)
Photon linear polarisation $P_{lin}^{(\gamma)}$=1.`

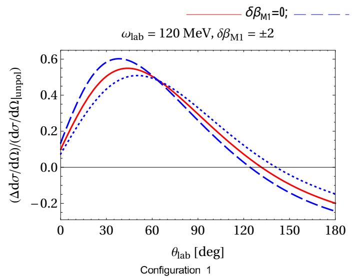
Configuration 1
Deuteron polarisation quantisation axis Θ_{d1}=0°
ϕ_{d1}=0°
Photon linear polarisation angle ϕ_{lin1}=90°

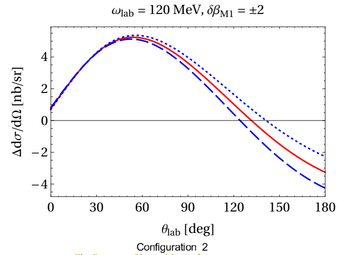
Configuration 2
Deuteron polarisation quantisation axis Θ_{d2}=90°
ϕ_{d2}=270°
Photon linear polarisation angle ϕ_{lin2}=90°

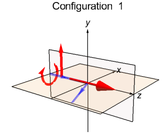
Variation by ±2 of: $\delta\beta_{M1}$
χEFT order: $e^2\delta^3=\epsilon^3$: with $\Delta(1232)$ | $e^2\delta^2=Q^3$: no $\Delta(1232)$
Deuteron wave function: NNLO Epelbaum 650MeV | AV18 — NN potential: AV18
Range on y–axis: All
Normalise left plot to: $\frac{d\sigma}{d\Omega}\big|_{unpol}$ | $\Sigma\frac{d\sigma}{d\Omega}$: sum of configurations

Export $\Delta\frac{d\sigma}{d\Omega}$ and $\Sigma\frac{d\sigma}{d\Omega}$ of this configuration? — File name: "out.dat"

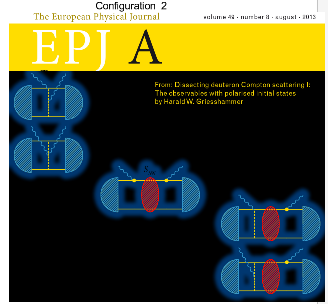
Example double-polarised on deuteron







Probability of spin projection $M_{\vec{d}}$:
Cartesian polarisation along $\vec{d}$:



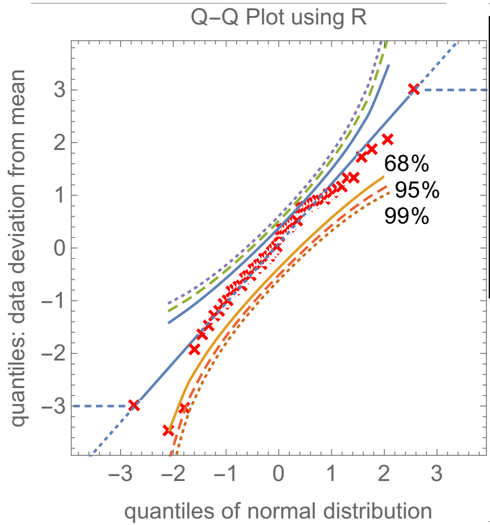
hg EPJA**49** (2013) 100
Europhysics News HIGHLIGHT May 2013
errata A**53** (2017) 113, A**54** (2018) 57

Cross section difference of configurations: $\Delta\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega}\big|_{unpol}\times[0+0.78\,T^{lin}_{1,-1}-0.55\,T^{circ}_{1,0}-0.78\,T_{1,1}+0.78\,T^{lin}_{1,1}-0.32\,T^{lin}_{2,-2}+0.8\,T_{2,0}-0.8\,T^{lin}_{2,0}+0.32\,T_{2,2}-0.32\,T^{lin}_{2,2}]$

Cross section sum of configurations: $\Sigma\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega}\big|_{unpol}\times[2+-2.\,\Sigma^{lin}+-0.78\,T^{lin}_{1,-1}-0.55\,T^{circ}_{1,0}+0.78\,T_{1,1}-0.78\,T^{lin}_{1,1}+0.32\,T^{lin}_{2,-2}+0.26\,T_{2,0}-0.26\,T^{lin}_{2,0}-0.32\,T_{2,2}+0.32\,T^{lin}_{2,2}]$

(e) Curating: The Good, The Bad, and The Ugly Data

Illinois 1994 •, Lund 2003 ▲, Saskatoon 2000 ♦, **Lund 2014** × —— $N\pi + \Delta +$ stat. error, Baldin constrained

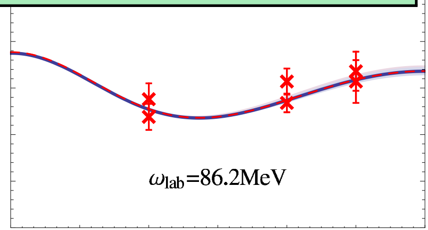


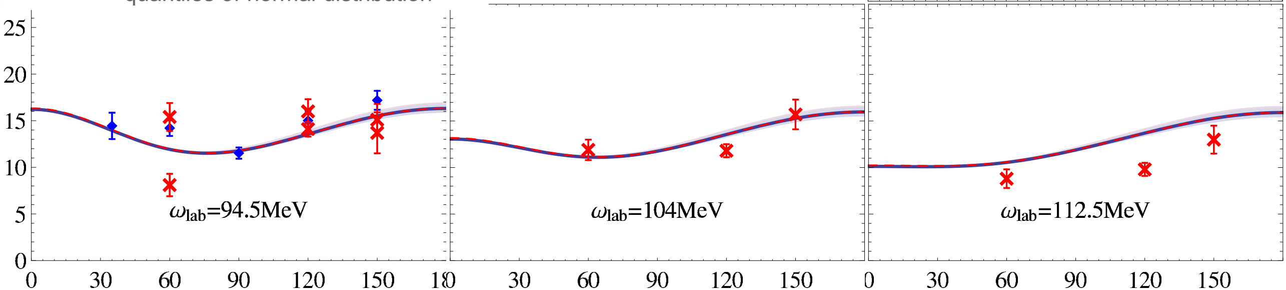
How to *reproducibly* prune database with *minimal* theory bias?

Tension to data cluster in kinematic proximity ("Majority Rules"?),
but not when isolated ("Could be Physics")?

What about "creeping": data consistent in one region,
increasingly inconsistent in another?

Traditional methods like Q-Q seem blind and compare to theory.





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Detector location (walls), difficulty of observables, parameter combinations “known” with varying confidence, . . .

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Desired Outcome: **“Optimal Impact Machine” (generally accepted/well-defined/reproducible/canned) for sequence of experiments with high(est) impact: Figures of Merit, validations of theory/data,. . .**

The efficient person gets the job done right. The effective person gets the right job done.

B. The Promise of Reliable Error Bars

(a) (Dis)Agreement Significant Only When All Error Sources Explored

Editorial PRA 83 (2011) 040001

PHYSICAL REVIEW A **83**, 040001 (2011)

Editorial: Uncertainty Estimates

The purpose of this Editorial is to discuss the importance of including uncertainty estimates in papers involving theoretical calculations of physical quantities.

It is not unusual for manuscripts on theoretical work to be submitted without uncertainty estimates for numerical results. In contrast, papers presenting the results of laboratory measurements would usually not be considered acceptable for publication

The question is to what extent can the same high standards be applied to papers reporting the results of theoretical calculations. It is all too often the case that the numerical results are presented without uncertainty estimates. Authors sometimes say that it is difficult to arrive at error estimates. Should this be considered an adequate reason for omitting them? In order to answer this question, we need to consider the goals and objectives of the theoretical (or computational) work being done. Theoretical papers

physical effects not included in the calculation from the beginning, such as electron correlation and relativistic corrections. It is of course never possible to state precisely what the error is without in fact doing a larger calculation and obtaining the higher accuracy. However, the same is true for the uncertainties in experimental data. The aim is to estimate the uncertainty, not to state the exact amount of the error or provide a rigorous bound.

Theoretical uncertainty: Truncation of Physics

EFT claim: systematic in $Q = \dfrac{\text{typ. low scale } p_{typ}}{\text{typ. high scale } \overline{\Lambda}_{EFT}}$

Does Nuclear Structure emerge from QCD?

Beyond-Standard-Model Physics from Supernovae?

Religion — Thou Shalt Believe!

Science: Degree of Belief — ***Conjecture*** ⟲ ***Evidence***

Scientific Method: Quantitative results with corridor of theoretical uncertainties for *falsifiable predictions*.

Need procedure which is established, economical, reproducible: room to argue about “error on the error”.

“Double-Blind” Theory Errors: Assess with pretense of no/very limited data.

(b) What Does "Conservative" Theory Uncertainty Mean?

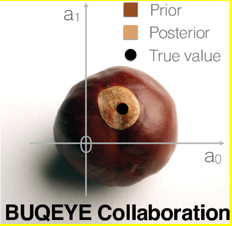
BUQEYE 1506.01343
hg/JMcG/DRP 1511.01952

χEFT $\alpha_{E1}^{(p)} - \beta_{M1}^{(p)}$ $[10^{-4}\ \mathrm{fm}^3]$: $7.5 \pm ???_{\text{th}} = 11.2_{\text{LO}} - 3.6_{\text{NLO}} - 0.1_{\text{N}^2\text{LO}} \pm ???_{\text{th}}$

Observable as series: $\mathcal{O} = c_0 + c_1\,\delta^1 + c_2\,\delta^2 +$ unknown $\times\,\delta^3$

Assuming $\delta \simeq 0.4$: $11.2 - 9.1\,\delta^1 - 0.6\,\delta^2 +$ unknown $\times\,\delta^3$

$\Longrightarrow$ **Estimate next term *"most conservatively"* as** $|$unknown $c_3| \lesssim \max\{|c_0|;|c_1|;|c_2|\}$.



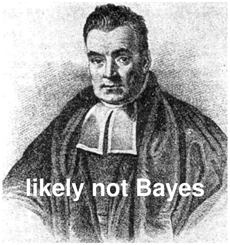
Call upon the Reverend Bayes for probabilistic interpretation!

see e.g. **BUQEYE collaboration** Furnstahl/Phillips/... 1506.01343+more

New information increases level of confidence.

$\Longrightarrow$ **Smaller corrections, more reliable uncertainties.**

Clearly state your premises/assumptions – including *naturalness*.



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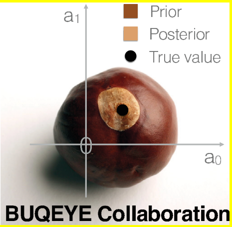

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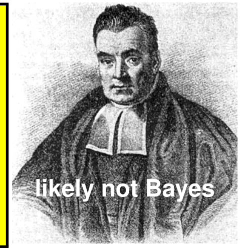
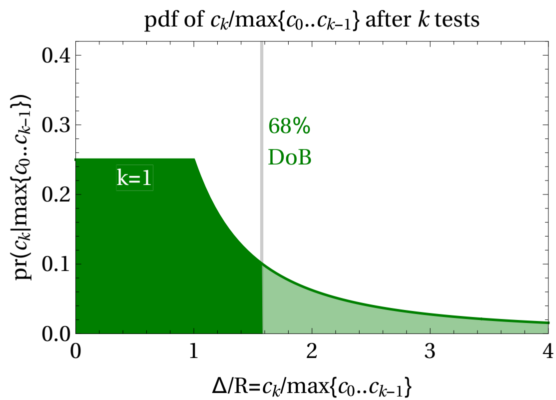




Priors: all c_n "equally likely", "any upper bound" $\bar{c}$.

order	DOB in $\pm R$	σ: 68%	$\Delta(95\%)$
LO	$\frac{1}{2} = 50\%$	$1.6\,R$	$11R = 7\sigma$
Gauß	68.27%	$1.0\,R$	2.0σ

Posterior pdf *not Gauß'ian:* Plateau & power-law tail.

(b) What Does "Conservative" Theory Uncertainty Mean?

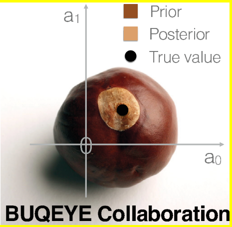
BUQEYE 1506.01343
hg/JMcG/DRP 1511.01952

χEFT $\alpha_{E1}^{(p)} - \beta_{M1}^{(p)}\ [10^{-4}\ \text{fm}^3]: 7.5 \pm ???_{\text{th}} = 11.2_{\text{LO}} \mathbf{-3.6}_{\text{NLO}} - 0.1_{\text{N}^2\text{LO}} \pm ???_{\text{th}}$

Observable as series: $\mathcal{O} = c_0 + c_1\ \delta^1 + c_2\ \delta^2 + \text{unknown} \times \delta^3$

Assuming $\delta \simeq 0.4$: $11.2\ \mathbf{-9.1}\ \delta^1 - 0.6\ \delta^2 + \text{unknown} \times \delta^3$

$\Longrightarrow$ **Estimate next term *"most conservatively"* as** $|\text{unknown } c_3| \lesssim \max\{|c_0|;|c_1|;|c_2|\}$.



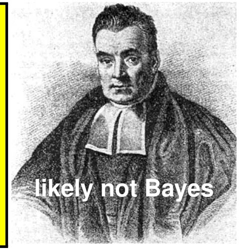
Call upon the Reverend Bayes for probabilistic interpretation!

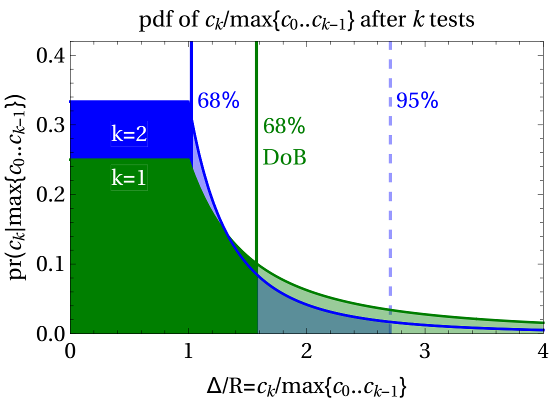
see e.g. **BUQEYE collaboration Furnstahl/Phillips/... 1506.01343+more**

New information increases level of confidence.

$\Longrightarrow$ **Smaller corrections, more reliable uncertainties.**

Clearly state your premises/assumptions – including *naturalness*.





Priors: all c_n "equally likely", "any upper bound" $\bar{c}$.

order	DOB in $\pm R$	σ: 68%	$\Delta(95\%)$
LO	$\frac{1}{2} = 50\%$	$1.6\ R$	$11R = 7\sigma$
NLO	$\frac{2}{3} = 66.7\%$	$1.0\ R$	$2.7R = 2.6\sigma$
Gauß	68.27%	$1.0\ R$	2.0σ

Posterior pdf *not Gauß'ian:* Plateau & power-law tail.

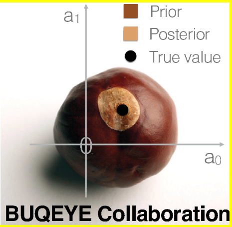
(b) What Does "Conservative" Theory Uncertainty Mean?

χEFT $\alpha_{E1}^{(p)} - \beta_{M1}^{(p)}$ $[10^{-4}\ \text{fm}^3]$: $7.5 \pm 0.6_{\text{th}} = 11.2_{\text{LO}} - 3.6_{\text{NLO}} \mathbf{-0.1}_{\text{N}^2\text{LO}} \pm 0.6_{\text{th}}$

Observable as series: $\mathcal{O} = c_0 + c_1\,\delta^1 + c_2\,\delta^2 + \text{unknown} \times \delta^3$

Assuming $\delta \simeq 0.4$: $11.2 \quad -9.1\,\delta^1 \quad \mathbf{-0.6}\,\delta^2 \quad \pm(11.2 \times \delta^3 \approx 0.7??)$

$\Longrightarrow$ **Estimate next term *"most conservatively"* as** $|\text{unknown } c_3| \lesssim \max\{|c_0|;|c_1|;|c_2|\}$.



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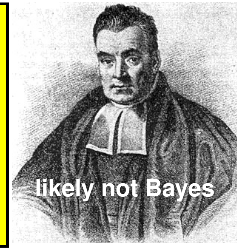
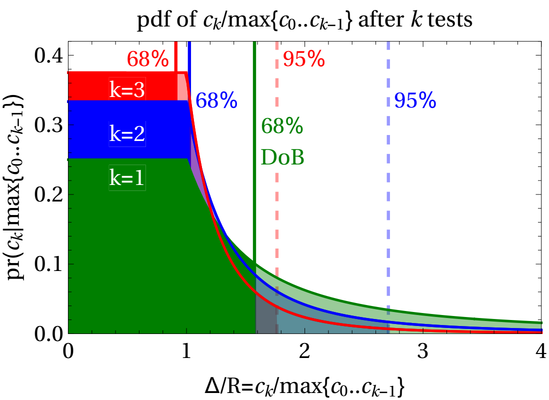




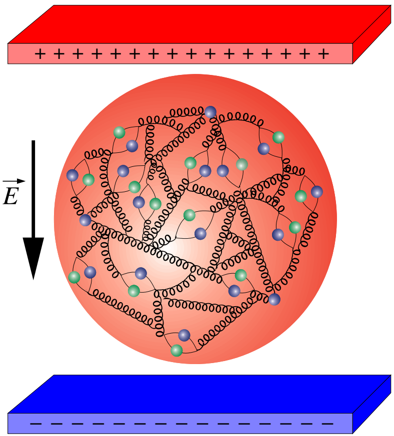
Priors: all c_n "equally likely", "any upper bound" $\bar{c}$.

order	DOB in $\pm R$	σ: 68%	$\Delta(95\%)$
LO	$\frac{1}{2} = 50\%$	$1.6\,R$	$11R = 7\sigma$
NLO	$\frac{2}{3} = 66.7\%$	$1.0\,R$	$2.7R = 2.6\sigma$
N^{2}LO	$\frac{3}{4} = 75\%$	$0.9\,R$	$1.8R = 1.9\sigma$
k	$\dfrac{k}{k+1}$	$0.68\dfrac{k+1}{k}R(k \geq 2)$	
Gauß	68.27%	$1.0\,R$	2.0σ

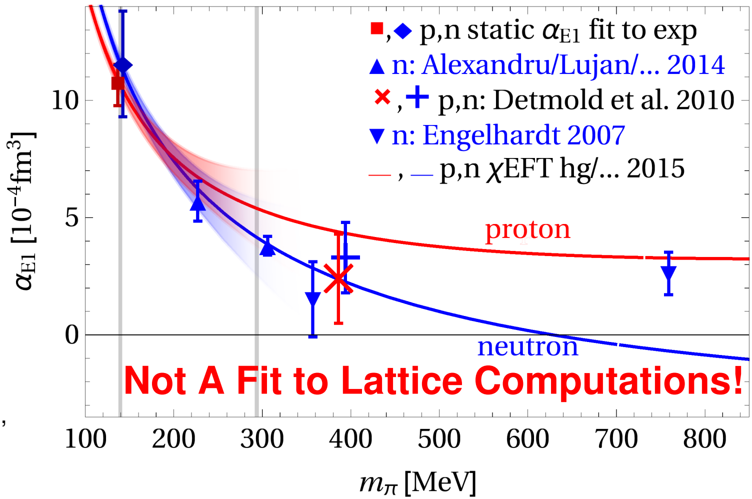
Posterior pdf *not Gauß'ian:* Plateau & power-law tail.

Towards comparable uncertainties in experiment, χEFT and lattice QCD.

χEFT: reliable error estimate for $\frac{m_\pi}{\Lambda_\chi}$ extrapolation. $\Longrightarrow$ ***Fading corridors beyond*** ~ 250 MeV.



Example: static electric polarisability α_{E1}



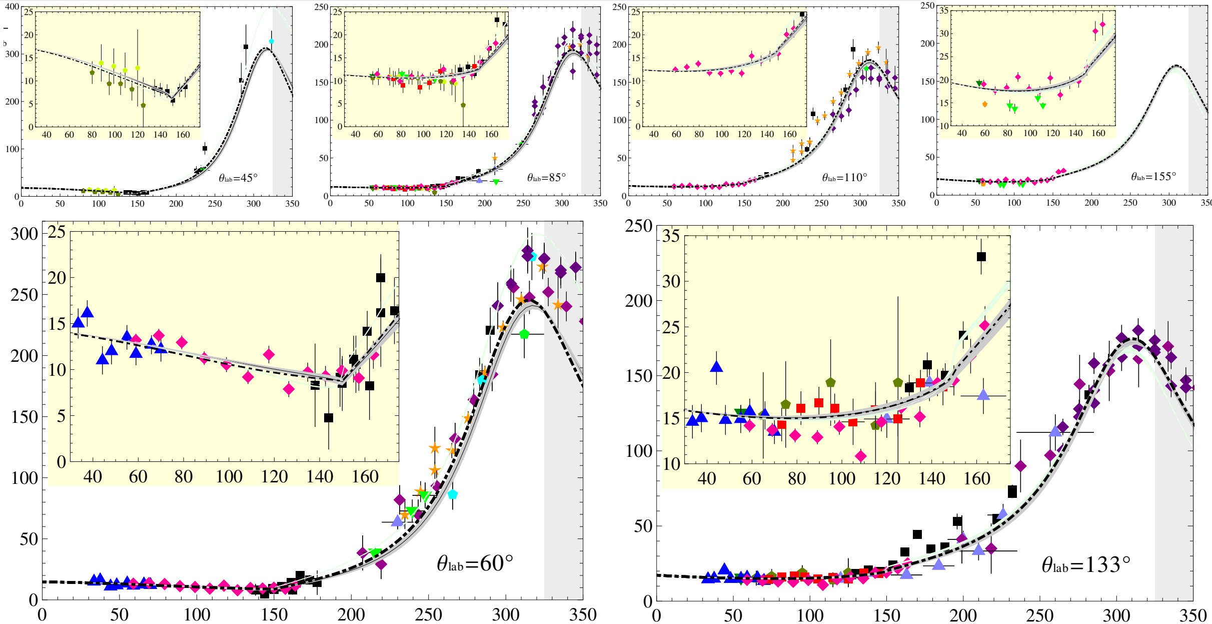
Ongoing: charged sea, $m_\pi \searrow 200$ MeV, larger volumes, more statistics,. . .

Active lattice groups:

Alexandru/Lee/. . . 2005-;
Engelhardt/LHPC 2006-;
EMC/NPLQCD 2006-, 2015-;
Leinweber/Primer/Hall/. . . 2013-

(d) Nucleon Polarisabilities from a Consistent Database

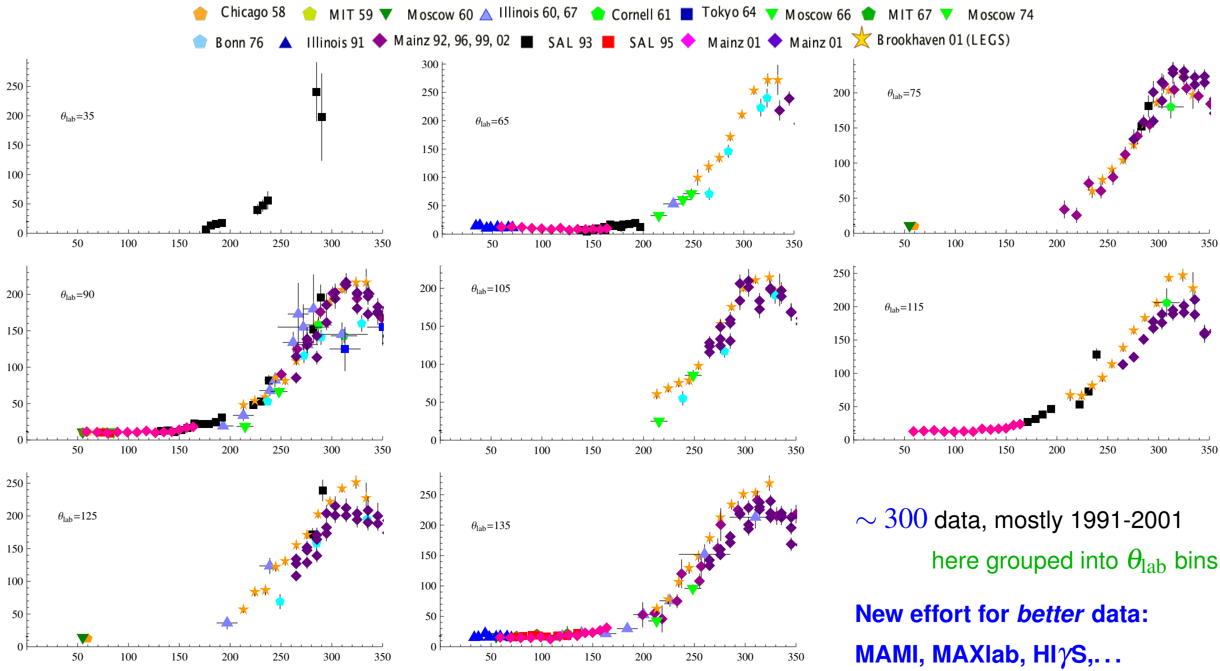
McGovern/Phillips/hg 2013
database: +Feldman PPNP 2012



Noisy database, partially conflicting $\Longrightarrow$ reproducible trimming necessary.

Fit focuses on different Physics in different regions:

> 200 MeV: $\Delta(1232)$ **fit** $b_1 = 3.61 \pm 0.02 \Longleftrightarrow < 170$ MeV: **polarisabilities**



~ 300 data, mostly 1991-2001

here grouped into θ_{lab} bins

New effort for *better* data:

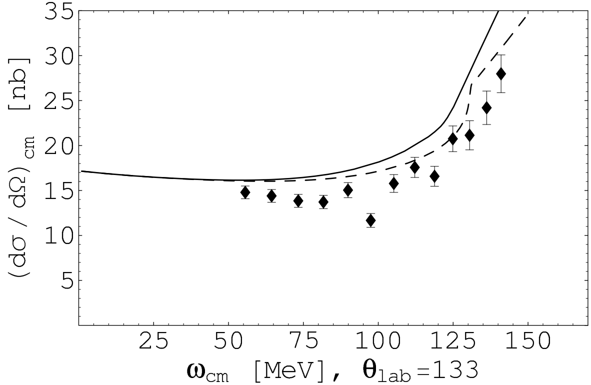
MAMI, MAXlab, HIγS,. . .

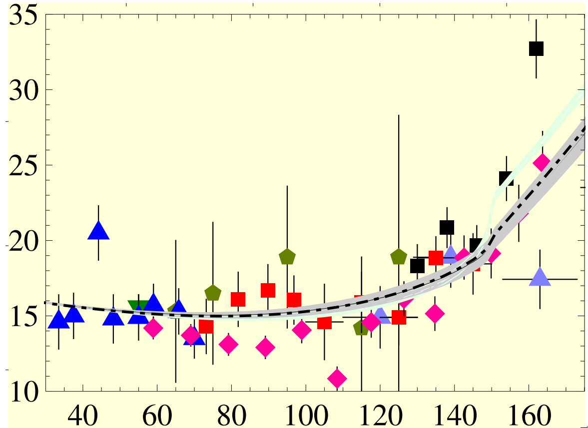
Quoted stat+sys too small for quoted fluctuations; tensions MAMI vs. LEGS; etc. $\Longrightarrow$ $\frac{\chi^2}{\text{d.o.f.}} \approx 1$ **needs *pruning***.

Not *more*, but *more reliable* data needed for unpolarised proton.

(f) The Good, The Bad and the Ugly Data

One MAMI dataset seems not to fit into the picture. Whose problem?



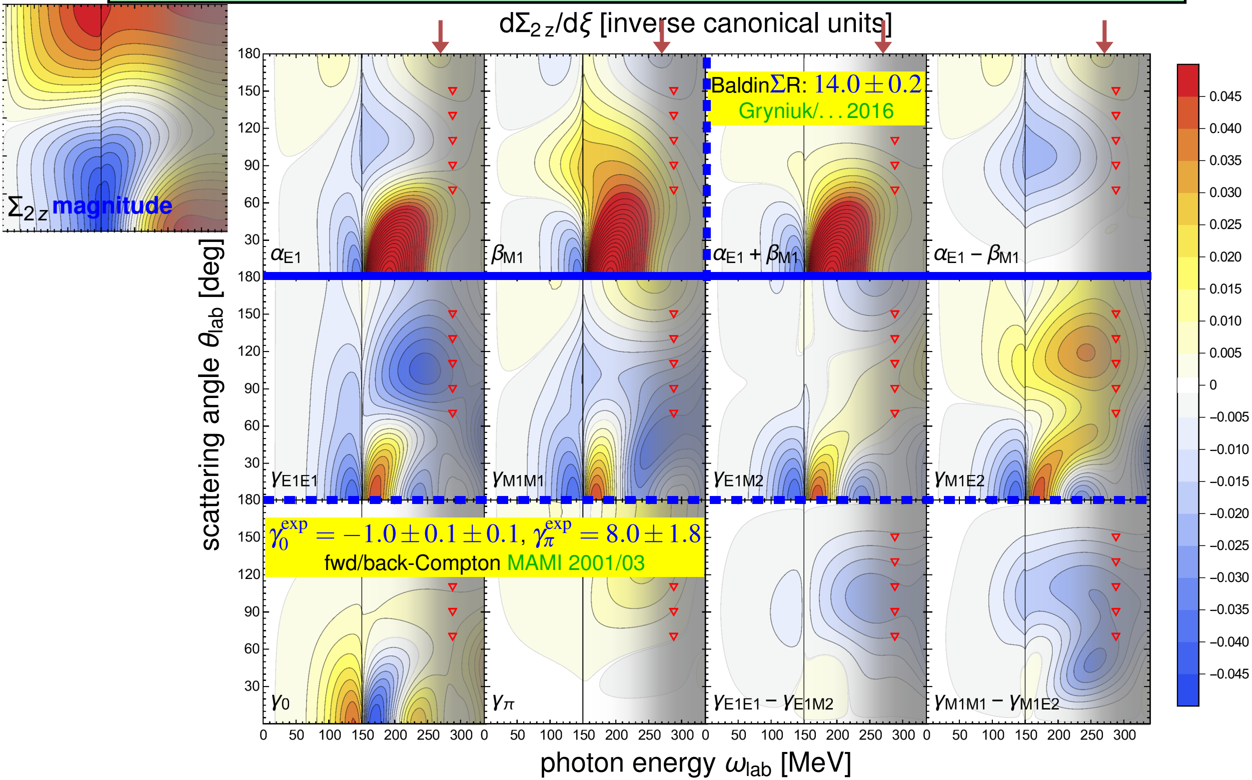


(g) Proton: Sensitivity of Σ_{2z} (Circpol Beam on Linpol$_z$ Target)

JMcG/hg/DRP
1711.11546

Fading Colours for $\omega \gtrsim 250$ MeV: breakdown of χEFT expansion $\Longrightarrow$ *prefer data below.*

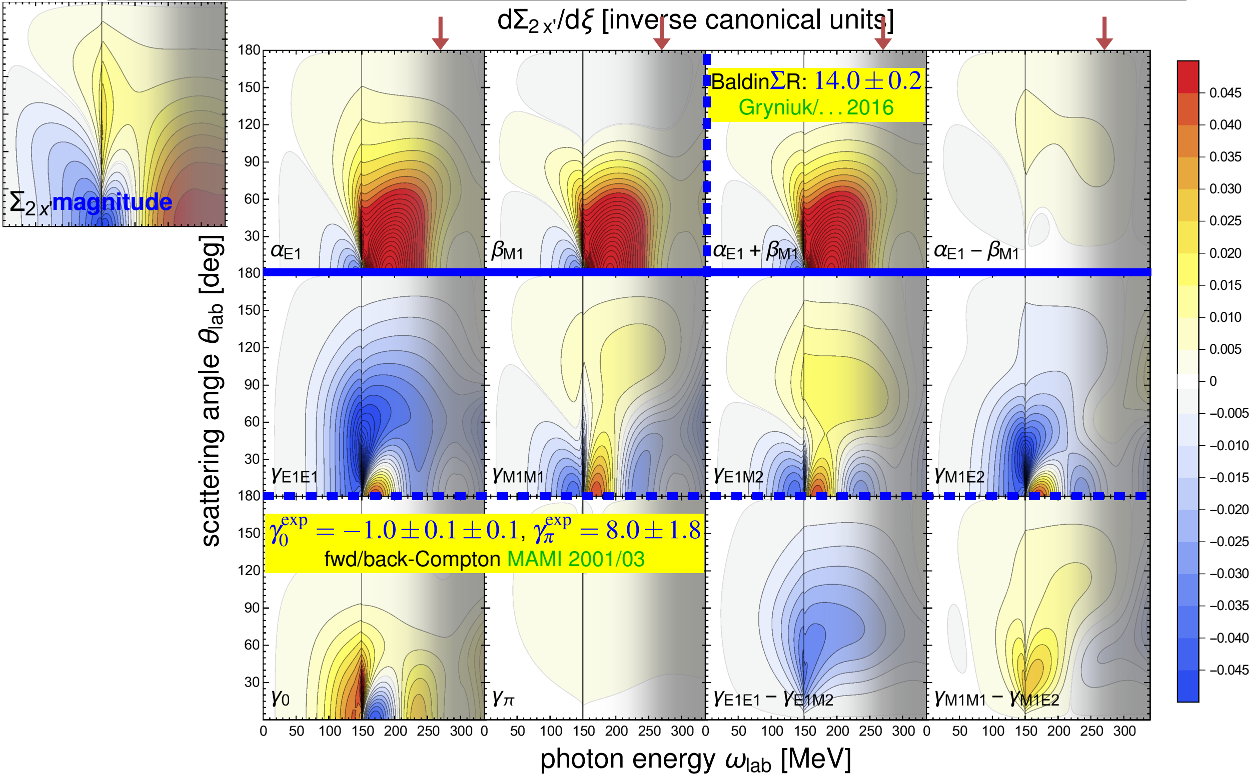
6 parameters, constraints on $\alpha_{E1}+\beta_{M1}$, γ_0, γ_π,... $\Longrightarrow$ *Sensitivities to linear combinations.*



(h) Proton: Sensitivity of $\Sigma_{2x'}$ (Transfer Circpol Beam→Linpol$_{\mathbf{x'}}$ Recoil)

Fading Colours for $\omega \gtrsim 250$ MeV: breakdown of χEFT expansion $\Longrightarrow$ *prefer data below.*

6 parameters, constraints on $\alpha_{E1}+\beta_{M1}$, γ_0, γ_π,... $\Longrightarrow$ *Sensitivities to linear combinations.*



(i) Proton: Sensitivity of Beam Asymmetry Σ_3

JMcG/hg/DRP 1711.11546

Fading Colours for $\omega \gtrsim 250$ MeV: breakdown of χEFT expansion $\Longrightarrow$ *prefer data below.*

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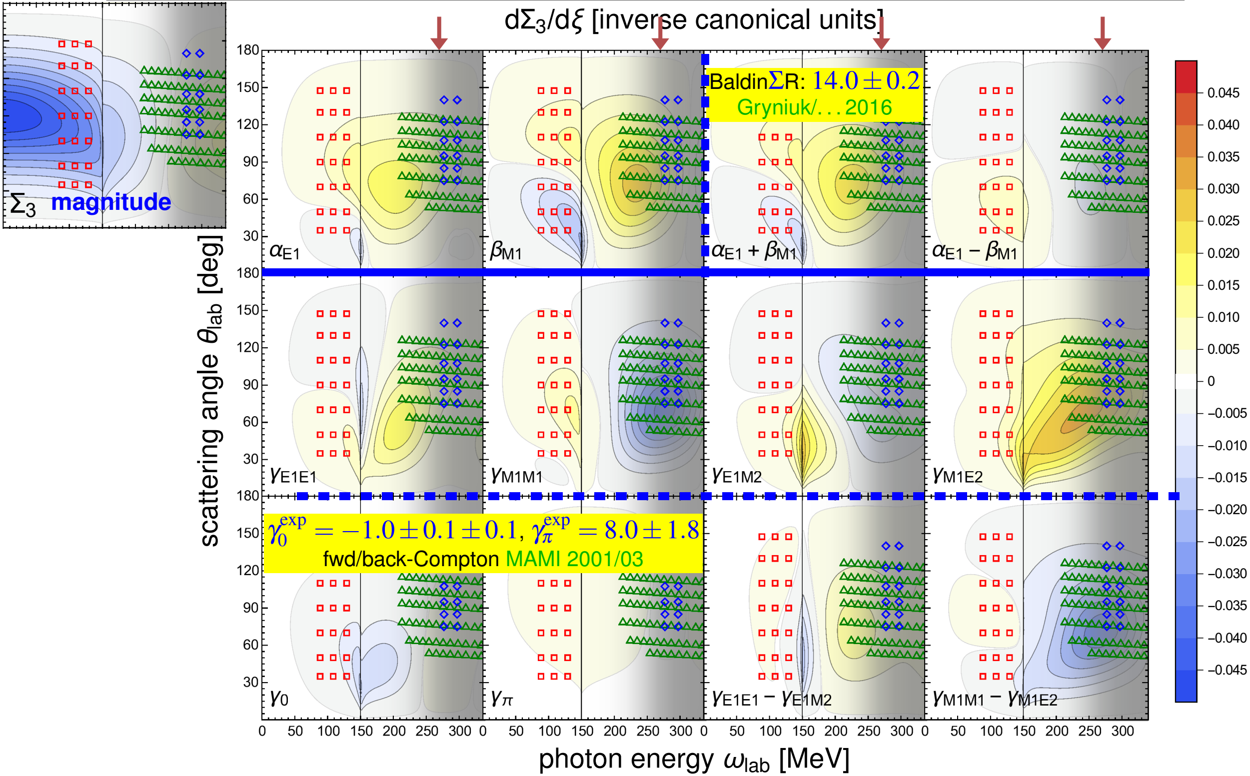
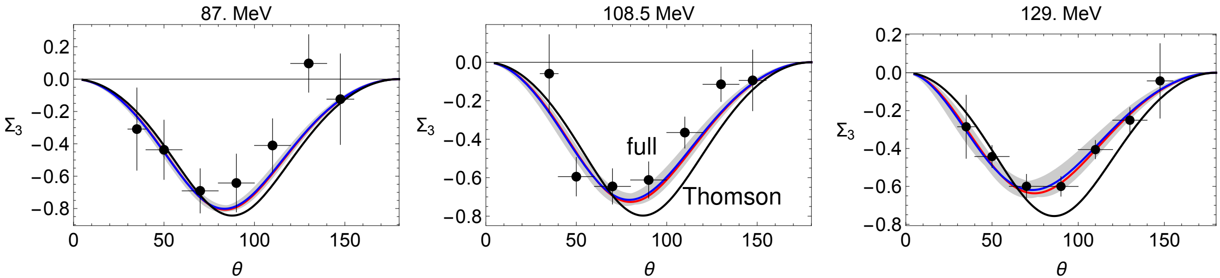


(i) Proton: Sensitivity of Beam Asymmetry Σ_3

Σ_3 for $\omega \lesssim 200$ MeV dominated by Thomson. $\Longrightarrow$ Theory check; polarisabilities need high accuracy.

Rule of Thumb: Thomson dominates large asymmetries. Polarisabilities dominate small ones.

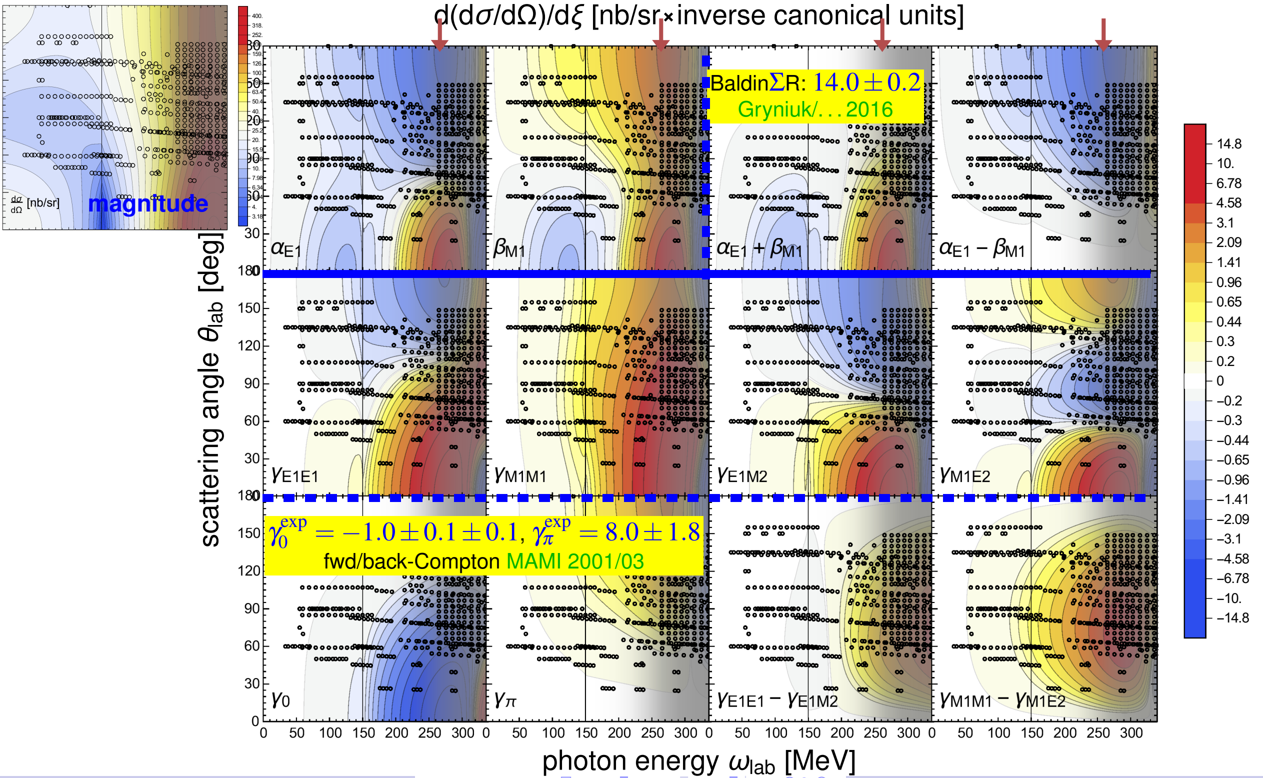
Thomson only — fit with/without Baldin $\Longrightarrow \beta_{M1} = 3.7^{+2.5}_{-2.3}$ large error — Sokhoyan/...MAMI 2017



(j) Proton: Sensitivity of Unpolarised Cross Section

Fading Colours for $\omega \gtrsim 250$ MeV: breakdown of χEFT expansion $\Longrightarrow$ *prefer data below.*

6 parameters, constraints on $\alpha_{E1}+\beta_{M1}$, γ_0, γ_π,… $\Longrightarrow$ *Sensitivities to linear combinations.*



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