

# Compton Scattering: How to Optimise Experiments?



THE GEORGE  
WASHINGTON  
UNIVERSITY  
WASHINGTON DC

H. W. Griebhammer

Institute for Nuclear Studies  
The George Washington University, DC, USA



Institute for Nuclear Studies  
THE GEORGE WASHINGTON UNIVERSITY  
WASHINGTON, DC

- 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?



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?



Polarisabilities & Bayes in  $\chi$ EFT 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  
 $^3\text{He } \mathcal{O}(\delta^3)$ : Margaryan/Strandberg/hg/JMcG/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  $\Rightarrow$  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.  $\Rightarrow$  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.  $\Rightarrow$  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  $\Rightarrow$  short runs, high statistics — theory less accurate

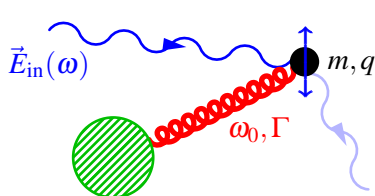
**Low energy:** low count rates  $\Rightarrow$  long runs for adequate statistics — theory more accurate

**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  $\Gamma$  Lorentz/Drude 1900/1905



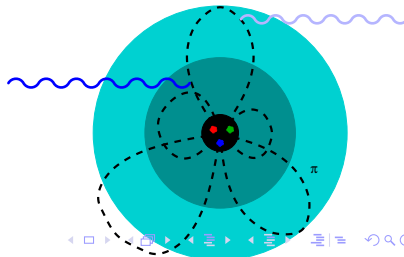
$$\vec{d}_{\text{ind}}(\omega) = \underbrace{\frac{q^2}{m} \frac{1}{\omega_0^2 - \omega^2 - i\Gamma\omega}}_{=: 4\pi \alpha_{E1}(\omega) \text{ "displaced volume" } [10^{-4} \text{ fm}^3]} \vec{E}_{\text{in}}(\omega)$$

**electric scalar dipole polarisability**

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

**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 2015  
**LONG RANGE PLAN**  
for NUCLEAR SCIENCE



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 MeV

proton doubly & beam pol. (E-06-09/10)

deuteron beam pol. (E-18-09, running)

<sup>3</sup>He unpol & doubly pol. (E-07-10, E-08-16)

<sup>4</sup>He unpol

<sup>6</sup>Li unpol. (E-15-11, first!)

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

proton 100 – 400 MeV: beam & target pol. deuteron, <sup>3</sup>He, <sup>4</sup>He unpol., beam & target pol.

**MAXlab:** data cooking

deuteron 100 – 160 MeV: unpol.



# (c) All 1N Contributions to $N^4\text{LO}$

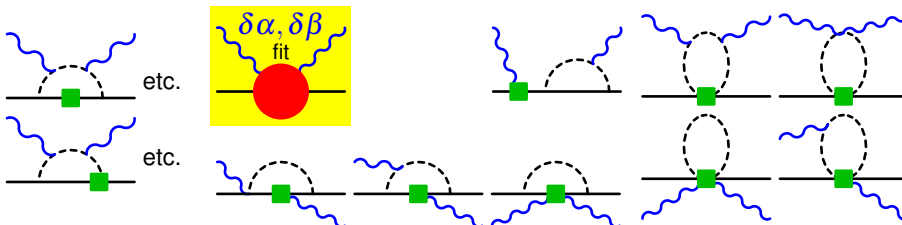
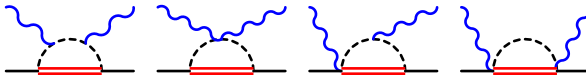
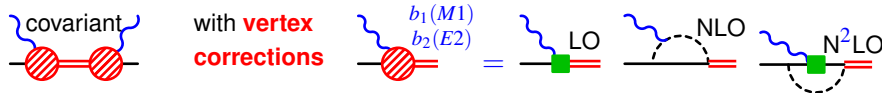
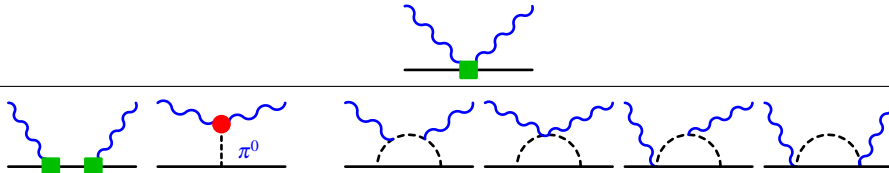
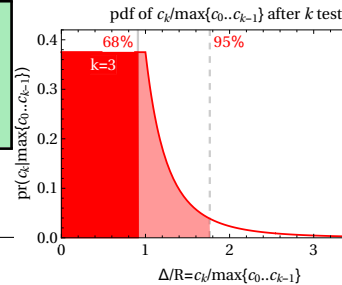
**Effective Field THEORY: Finite accuracy with “known” residual theory uncertainties: non-Gaussian pdfs.**

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

**Unified Amplitude: accuracy decreases with  $\omega$ :**

in low régime  $\omega \lesssim m_\pi$  at least  $N^4\text{LO}$  ( $e^2\delta^4$ ): accuracy  $\delta^5 \lesssim 2\%$ ;

or in high régime  $\omega \sim M_\Delta - M_N$  at least NLO ( $e^2\delta^0$ ): accuracy  $\delta^2 \lesssim 20\%$ .



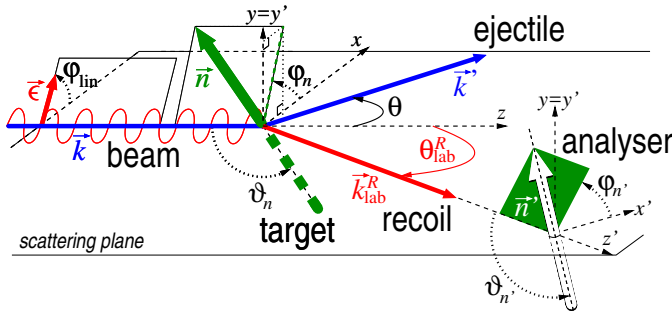
### 3. A Plethora of Observables To Determine 6 Parameters $\alpha_{E1}, \beta_{M1}, \gamma_i$

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/ $^3\text{He}$  (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



$$\frac{d\sigma}{d\Omega} \Big|_{\text{unpol}} \times \left[ 1 + \Sigma^{\text{lin}}(\omega, \theta) P_{\text{lin}}^{(\gamma)} \cos 2\phi_{\text{lin}} + \sum_{\substack{J=1, \dots, 2S \\ 0 \leq M \leq J}} T_{JM}(\omega, \theta) P_J^{(d)} d_{M0}^J(\theta) \cos[M\phi - \frac{\pi}{2} \delta_{J\text{odd}}] + \sum_{\substack{J=1, \dots, 2S \\ 0 \leq M \leq J}} T_{JM}^{\text{circ}}(\omega, \theta) P_{\text{circ}}^{(\gamma)} P_J^{(d)} d_{M0}^J(\theta) \sin[M\phi + \frac{\pi}{2} \delta_{J\text{odd}}] + \sum_{\substack{J=1, \dots, 2S \\ -J \leq M \leq J}} T_{JM}^{\text{lin}}(\omega, \theta) P_{\text{lin}}^{(\gamma)} P_J^{(d)} d_{M0}^J(\theta) \cos[M\phi - 2\phi_{\text{lin}} - \frac{\pi}{2} \delta_{J\text{odd}}] \right]$$

6 p & n polarisabilities + constraints on  $\alpha_{E1} + \beta_{M1}, \gamma_0, \dots$ ; experiment: detector settings, feasibilities,...

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

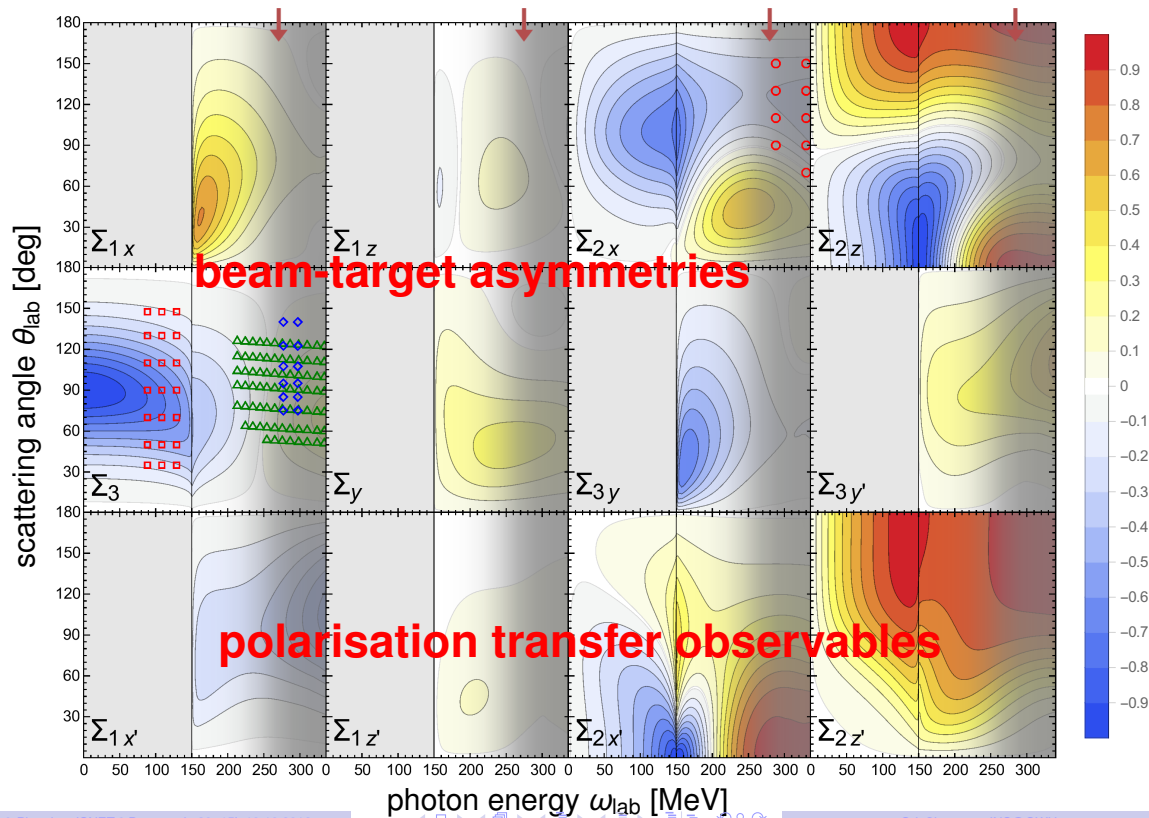
No single measurement to provide definitive answers: multi-parameter extractions, systematics, validation.

⇒ 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

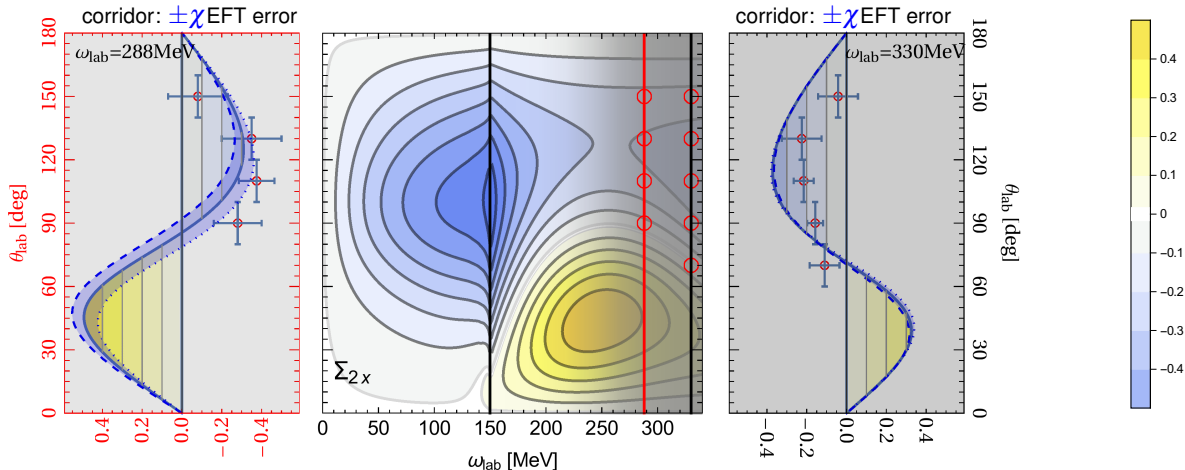
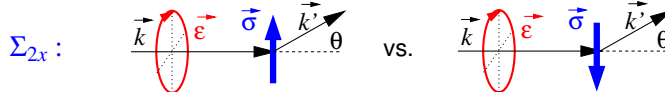
Fading Colours for  $\omega \gtrsim 250$  MeV indicate breakdown of  $\chi$ EFT expansion.



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



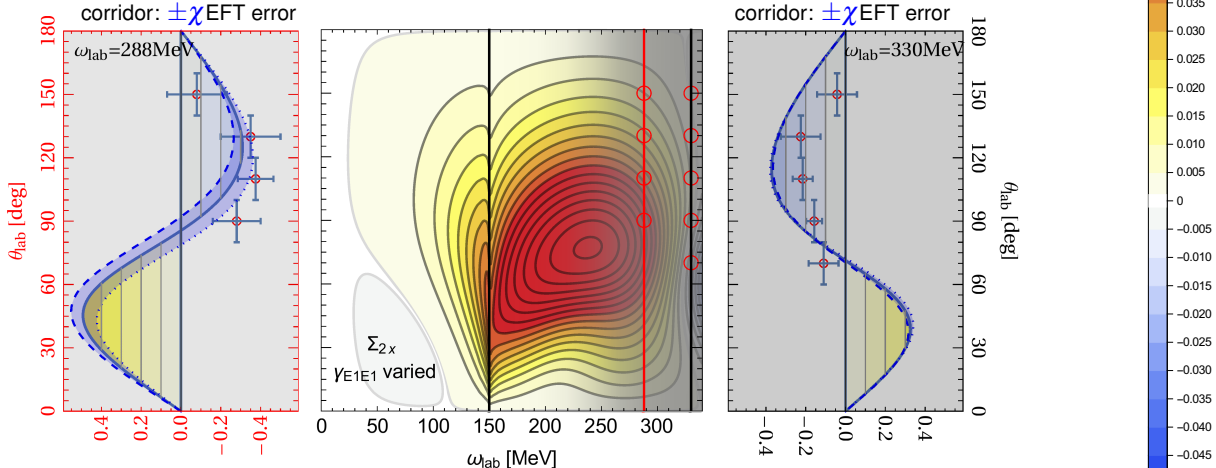
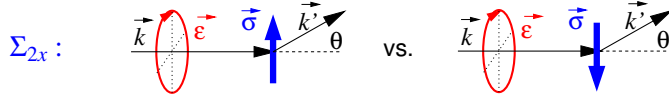
$\mathcal{O}(e^2\delta^4)$   $\chi$ EFT prediction hg/McGovern/Phillips 2014 vs. MAMI extraction Martel/... 2014

| static [ $10^{-4} \text{ fm}^4$ ]  | $\gamma_{E1E1}$            | $\gamma_{M1M1}$                                 | $\gamma_{E1M2}$            | $\gamma_{M1E2}$           |
|------------------------------------|----------------------------|-------------------------------------------------|----------------------------|---------------------------|
| MAMI 2014 proton                   | $-3.5 \pm 1.2$             | $3.2 \pm 0.9$                                   | $-0.7 \pm 1.2$             | $2.0 \pm 0.3$             |
| $\chi$ EFT proton <b>predicted</b> | $-1.1 \pm 1.9_{\text{th}}$ | $2.2 \pm 0.5_{\text{stat}} \pm 0.6_{\text{th}}$ | $-0.4 \pm 0.6_{\text{th}}$ | $1.9 \pm 0.5_{\text{th}}$ |

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

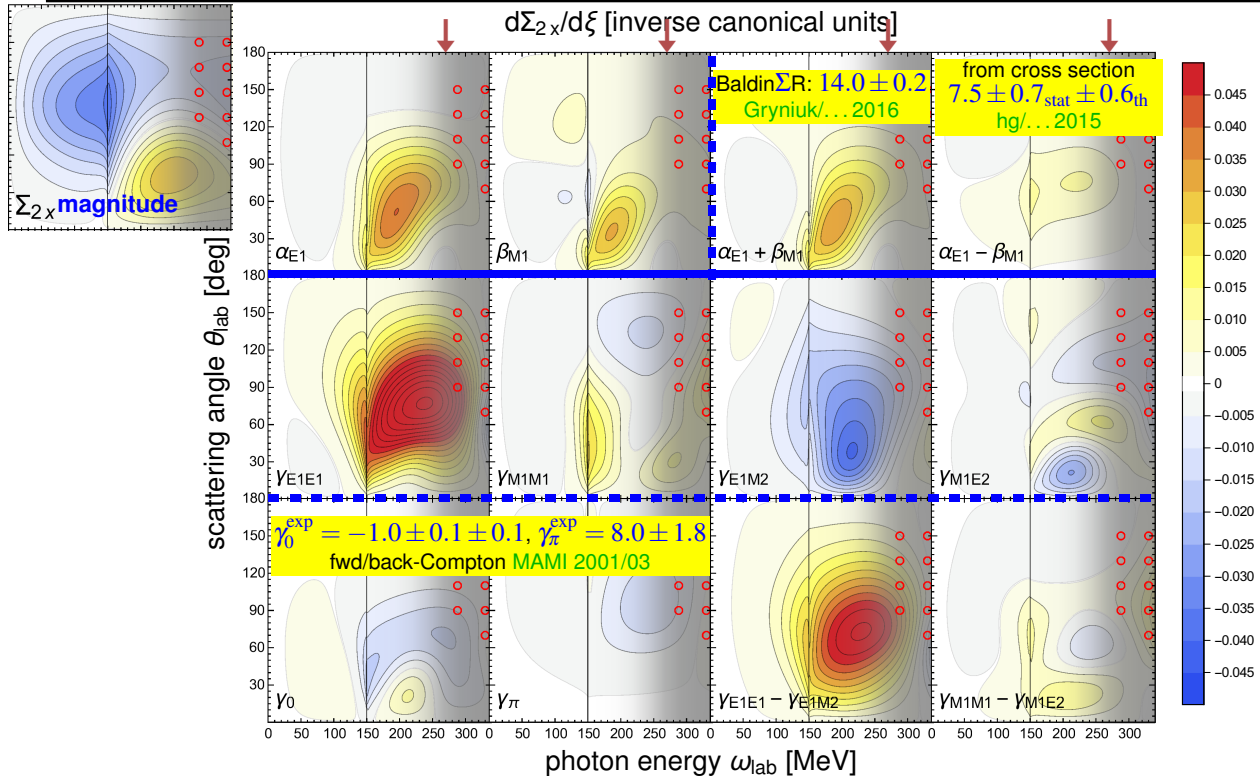
**Experiment:** magnitudes determine beamtime – sensitivities & efficiencies determine success.

# (c) Proton: Sensitivity of $\Sigma_{2x}$ (Circpol Beam on Linpol<sub>x</sub> Target)

JMcG/hg/DRP  
1711.11546

Fading Colours for  $\omega \gtrsim 250$  MeV: breakdown of  $\chi$ EFT expansion  $\Rightarrow$  prefer data below.

6 parameters, constraints on  $\alpha_{E1} \pm \beta_{M1}$ ,  $\gamma_0$ ,  $\gamma_\pi, \dots \Rightarrow$  Sensitivities to linear combinations – validation!

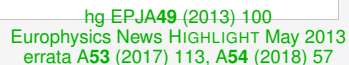


Instead of optimising a set of observables to a linear combination of polarisabilities, optimise 9 continuous parameters (kinematics & polarisations) to one polarisability!?

Cross section difference of configurations:

$$\Delta \frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega} \Big|_{\text{unpol}} \left[ (0 + 0.78 \tau_{1,-}^{\text{in}} - 0.55 \tau_{1,0}^{\text{circ}} - 0.78 \tau_{1,1} + 0.78 \tau_{1,1}^{\text{in}} - 0.32 \tau_{2,-}^{\text{in}} + 0.8 \tau_{2,0} - 0.8 \tau_{2,0}^{\text{in}} + 0.32 \tau_{2,2} - 0.32 \tau_{2,2}^{\text{in}}) \right]$$

Cross section sum of configurations:

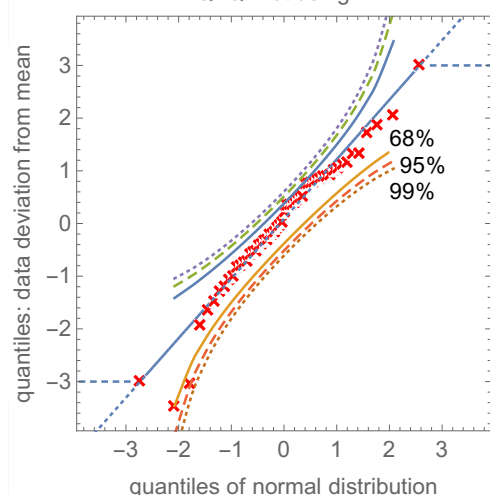
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# (e) Curating: The Good, The Bad, and The Ugly Data

Illinois 1994 ●, Lund 2003 ▲, Saskatoon 2000 ◆, Lund 2014 ×

—  $N\pi + \Delta$  + stat. error, Baldin constrained

Q-Q Plot using R



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.

$\omega_{\text{lab}}=86.2\text{MeV}$

$\omega_{\text{lab}}=94.5\text{MeV}$

$\omega_{\text{lab}}=104\text{MeV}$

$\omega_{\text{lab}}=112.5\text{MeV}$



## 4. 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  $\Rightarrow$  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.  $\Rightarrow$  Curate!**

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

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Often under-/over-estimated.  $\Rightarrow$  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  $\Rightarrow$  short runs, high statistics — theory less accurate

**Low energy:** low count rates  $\Rightarrow$  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,...**



# 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  $Q = \frac{\text{typ. low scale } p_{\text{typ}}}{\text{typ. high scale } \bar{\Lambda}_{\text{EFT}}}$*

*Does Nuclear Structure emerge from QCD?  
Beyond-Standard-Model Physics from Supernovae?*

Religion

Science: Degree of Belief

Thou Shalt Believe!

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?

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

**Observable as series:**  $\mathcal{O} = c_0 + c_1 \delta^1 + c_2 \delta^2 + \text{unknown} \times \delta^3$   
 Assuming  $\delta \simeq 0.4$ :  $11.2 - 9.1 \delta^1 - 0.6 \delta^2 + \text{unknown} \times \delta^3$

⇒ Estimate next term “most conservatively” as  $|\text{unknown } c_3| \lesssim \max\{|c_0|; |c_1|; |c_2|\}$ .

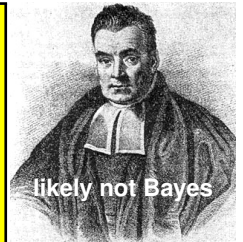
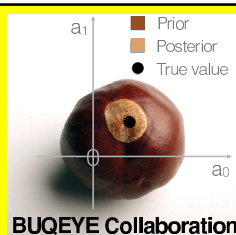
**Call upon the Reverend Bayes for probabilistic interpretation!**

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

**New information increases level of confidence.**

⇒ **Smaller corrections, more reliable uncertainties.**

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



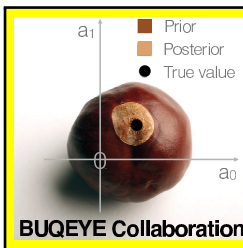
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BUQEYE 1506.01343  
hg/JMcG/DRP 1511.01952

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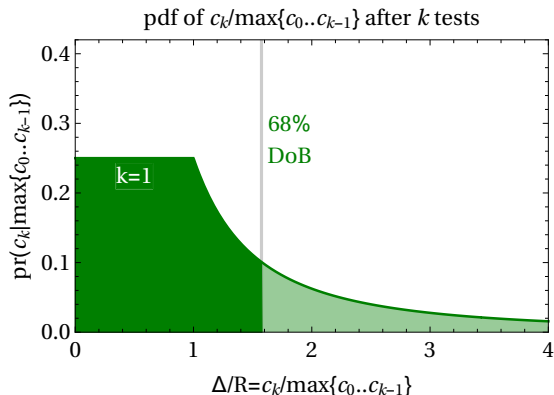
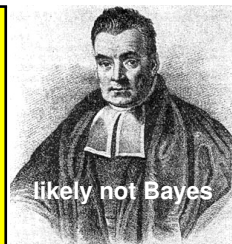
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**Priors: all  $c_n$  “equally likely”, “any upper bound”  $\bar{c}$ .**

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

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

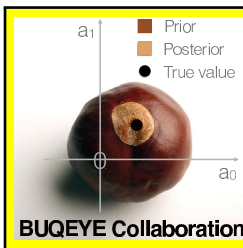
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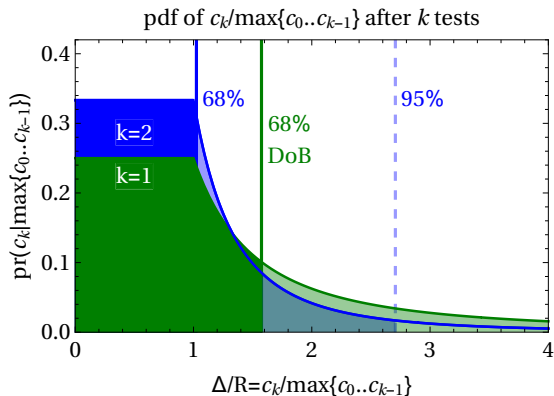
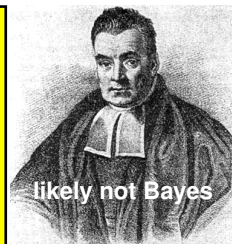
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|-------|------------------------|----------------|---------------------|
| LO    | $\frac{1}{2} = 50\%$   | 1.6 R          | 11R = 7 $\sigma$    |
| NLO   | $\frac{2}{3} = 66.7\%$ | 1.0 R          | 2.7R = 2.6 $\sigma$ |
| Gauß  | 68.27%                 | 1.0 R          | 2.0 $\sigma$        |

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

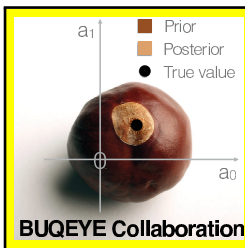
## (b) What Does “Conservative” Theory Uncertainty Mean?

BUQEYE 1506.01343  
hg/JMcG/DRP 1511.01952

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

**Observable as series:**  $\mathcal{O} = c_0 + c_1 \delta^1 + c_2 \delta^2 + \text{unknown} \times \delta^3$   
 Assuming  $\delta \approx 0.4$ :  $11.2 - 9.1 \delta^1 - 0.6 \delta^2 \pm (11.2 \times \delta^3 \approx 0.7??)$

⇒ Estimate next term “most conservatively” as  $|\text{unknown } c_3| \lesssim \max\{|c_0|; |c_1|; |c_2|\}$ .



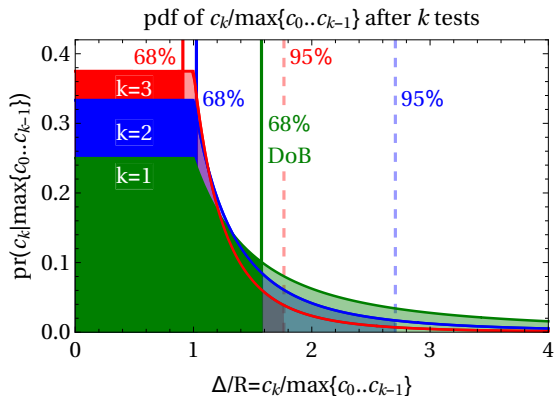
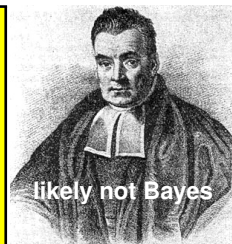
**Call upon the Reverend Bayes for probabilistic interpretation!**

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

**New information increases level of confidence.**

⇒ **Smaller corrections, more reliable uncertainties.**

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



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

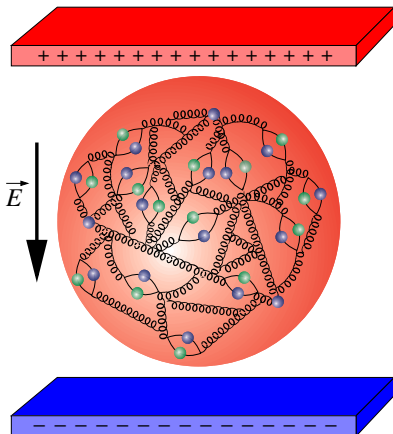
| order                 | DOB in $\pm R$         | $\sigma$ : 68%                    | $\Delta$ (95%)     |
|-----------------------|------------------------|-----------------------------------|--------------------|
| LO                    | $\frac{1}{2} = 50\%$   | $1.6 R$                          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

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

Towards comparable uncertainties in experiment,  $\chi$ EFT and lattice QCD.

$\chi$ EFT: reliable error estimate for  $\frac{m_\pi}{\Lambda_\chi}$  extrapolation.

$\Rightarrow$  *Fading corridors beyond  $\sim 250$  MeV.*

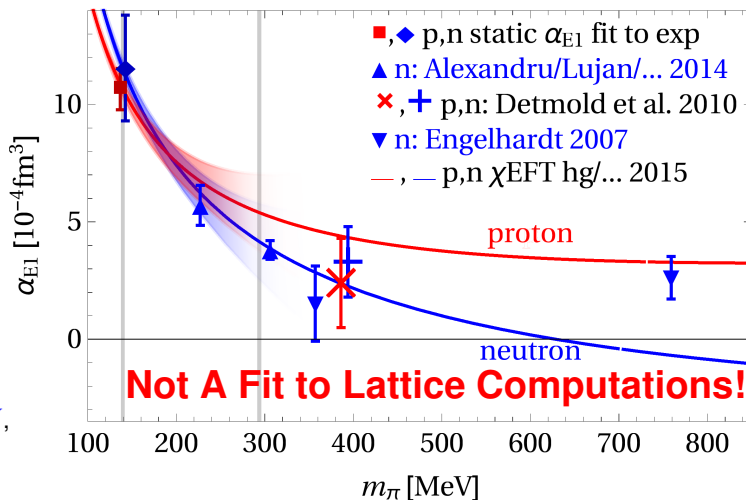


**Ongoing:** charged sea,  $m_\pi \searrow 200$  MeV,  
larger volumes, more statistics,...

**Active lattice groups:**

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

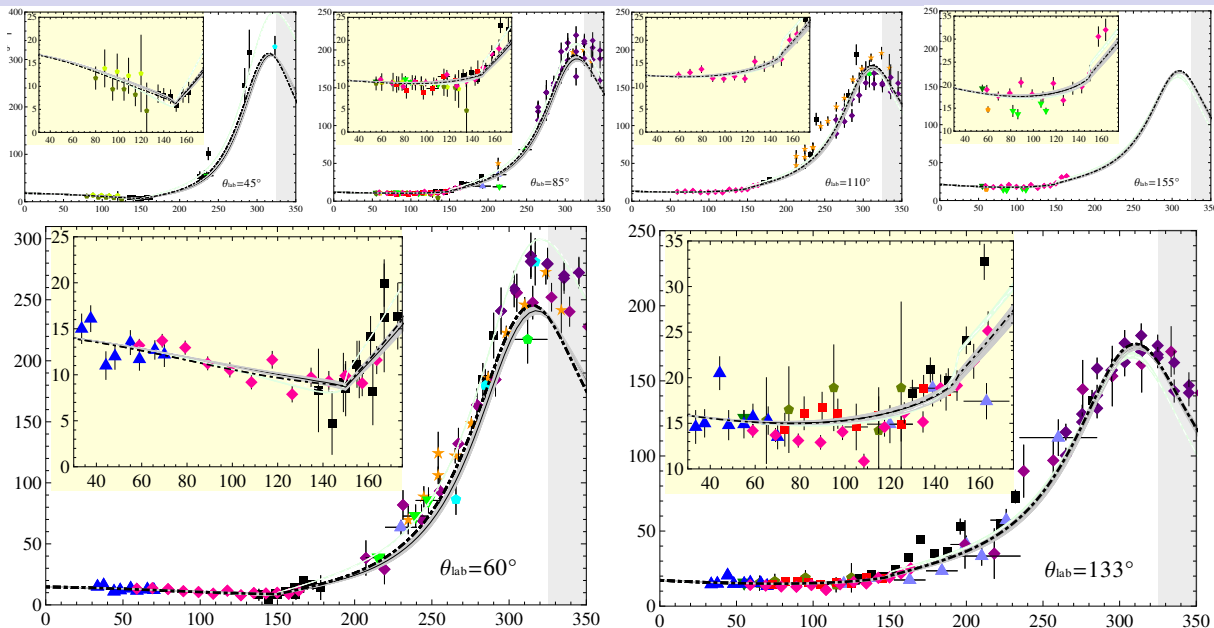
Example: static electric polarisability  $\alpha_{E1}$





# (d) Nucleon Polarisabilities from a Consistent Database

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

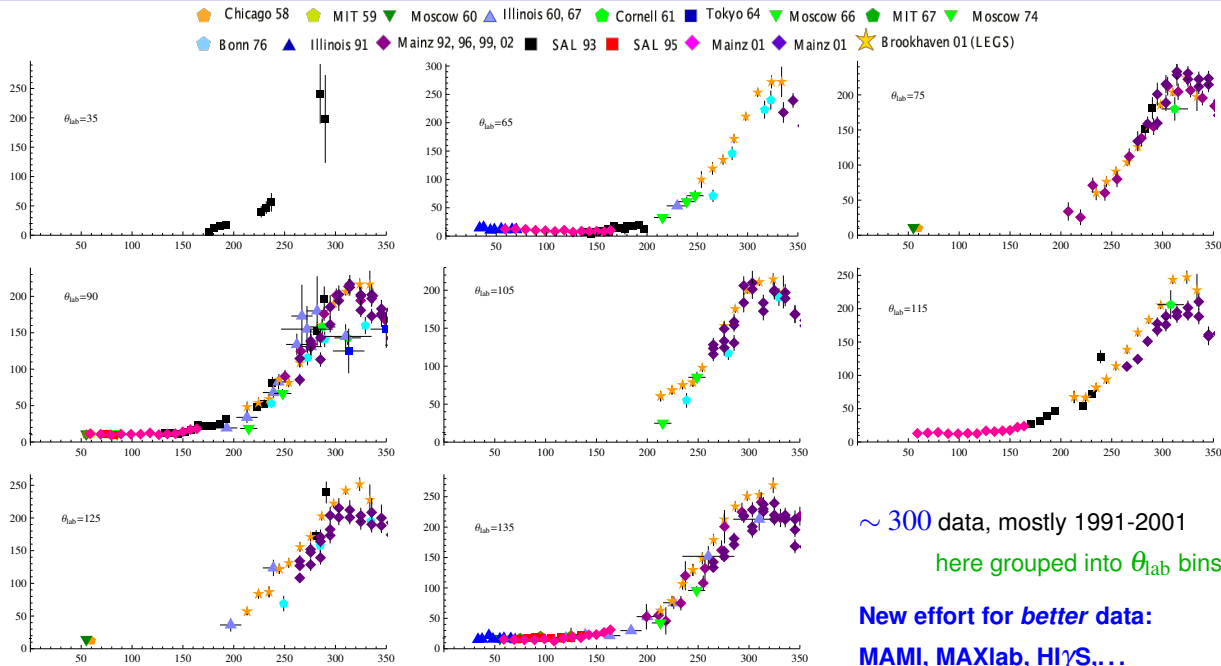


Noisy database, partially conflicting  $\Rightarrow$  reproducible trimming necessary.

Fit focuses on different Physics in different regions:  
 $> 200 \text{ MeV}$ :  $\Delta(1232)$  fit  $b_1 = 3.61 \pm 0.02 \iff < 170 \text{ MeV}$ : polarisabilities

# (e) Creating a Consistent Proton Compton Database

hg/McGovern/Phillips/Feldman PNP 2012



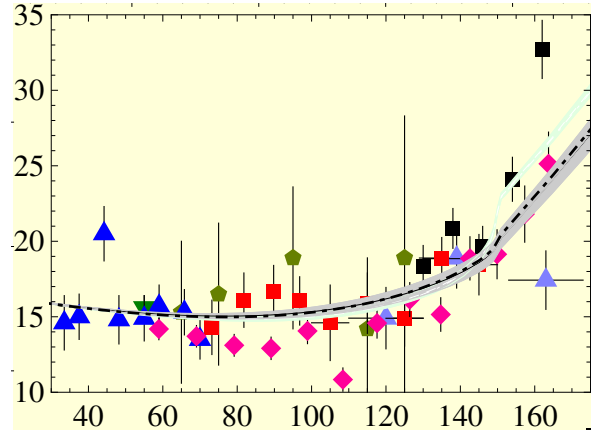
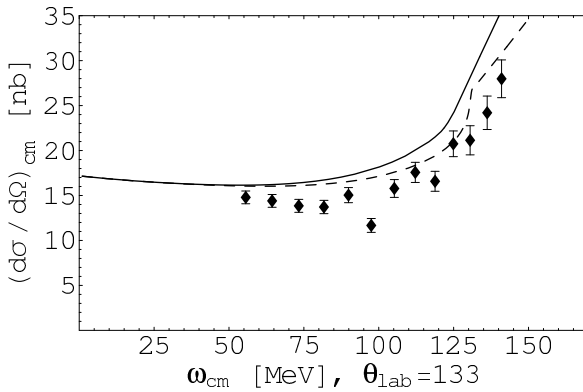
Quoted stat+sys too small for quoted fluctuations; tensions MAMI vs. LEGS; etc.

$$\Rightarrow \frac{\chi^2}{\text{d.o.f.}} \approx 1 \text{ needs pruning.}$$

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

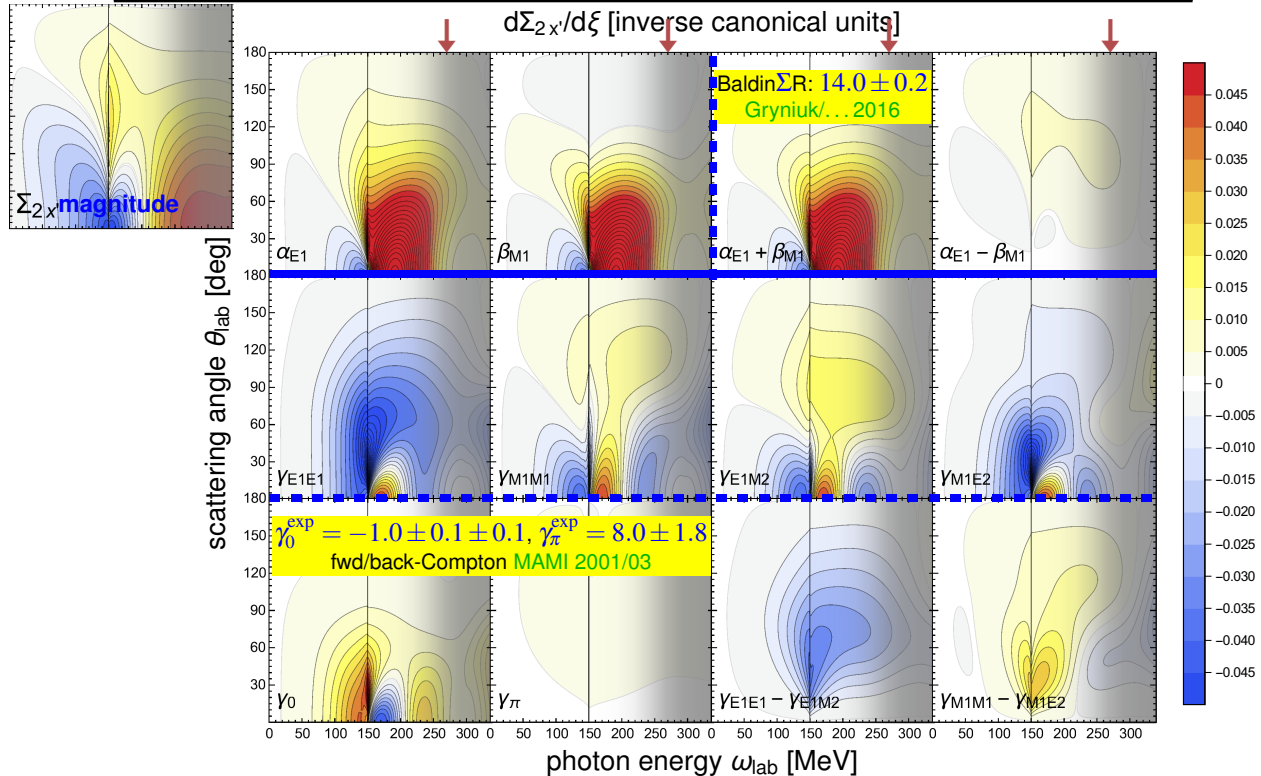
## (f) The Good, The Bad and the Ugly Data

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

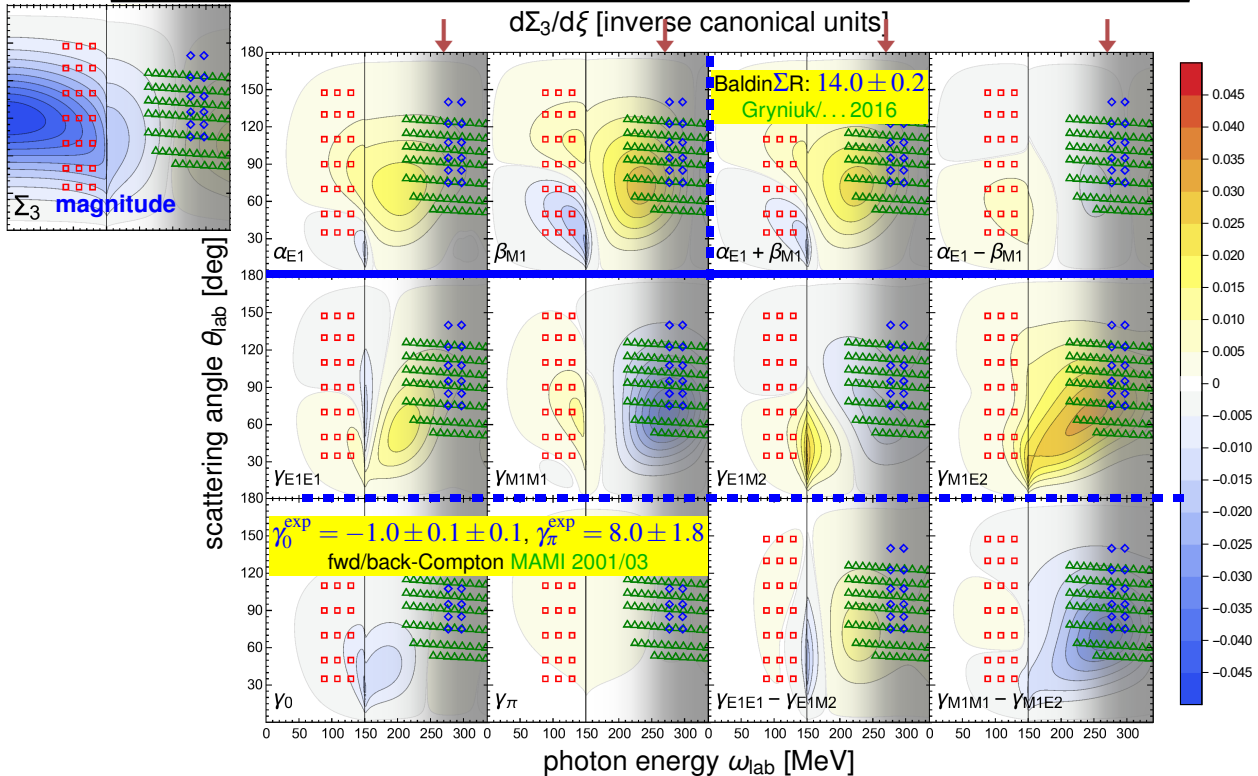


JMcG/hg/DRP  
1711.11546

Fading Colours for  $\omega \gtrsim 250$  MeV: breakdown of  $\chi$ EFT expansion  $\Rightarrow$  prefer data below.  
6 parameters, constraints on  $\alpha_{E1} + \beta_{M1}$ ,  $\gamma_0$ ,  $\gamma_\pi$ , ...  $\Rightarrow$  Sensitivities to linear combinations.

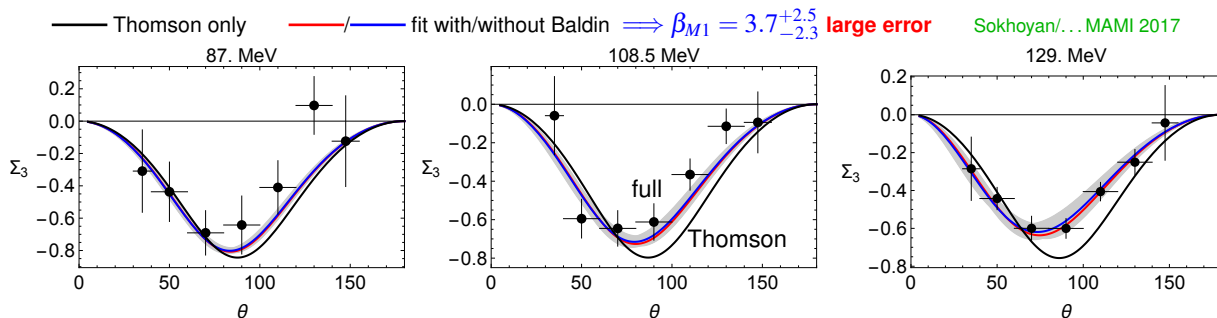


Fading Colours for  $\omega \gtrsim 250$  MeV: breakdown of  $\chi$ EFT expansion  $\Rightarrow$  prefer data below.  
 6 parameters, constraints on  $\alpha_{E1} + \beta_{M1}$ ,  $\gamma_0$ ,  $\gamma_\pi$ , ...  $\Rightarrow$  Sensitivities to linear combinations.



$\Sigma_3$  for  $\omega \lesssim 200$  MeV dominated by Thomson.  $\Rightarrow$  Theory check; polarisabilities need high accuracy.

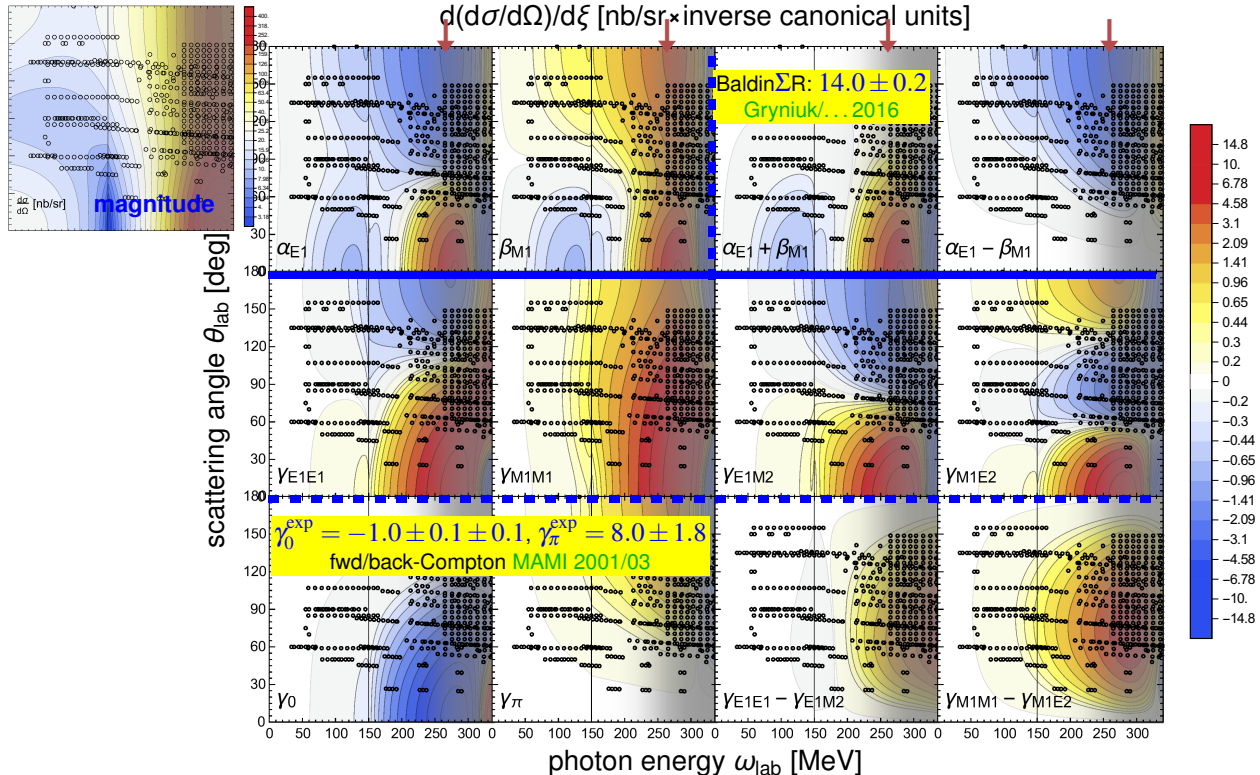
**Rule of Thumb: Thomson dominates large asymmetries. Polarisabilities dominate small ones.**



# (j) Proton: Sensitivity of Unpolarised Cross Section

JMcG/hg/DRP  
1711.11546

Fading Colours for  $\omega \gtrsim 250$  MeV: breakdown of  $\chi$ EFT expansion  $\Rightarrow$  prefer data below.  
6 parameters, constraints on  $\alpha_{E1} + \beta_{M1}$ ,  $\gamma_0$ ,  $\gamma_\pi$ ...  $\Rightarrow$  Sensitivities to linear combinations.





# (j) Proton: Sensitivity of Unpolarised Cross Section

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6 parameters, constraints on  $\alpha_{E1} + \beta_{M1}$ ,  $\gamma_0$ ,  $\gamma_\pi$ ...  $\Rightarrow$  Sensitivities to linear combinations.

