The A4 experiment

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PAVI 11
From parity violation to hadronic structure and more…

Rome, Italy
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Outline

- The A4 experiment at MAMI
- A4-II
  Backward, hydrogen
  Backward, deuterium
- A4-III
  Forward, Q^2=0.62 GeV^2
- A4-IV
  Backward, Q^2=0.11 GeV^2

A4: The early years

Participants of the Workshop on Parity Violation in Electron Scattering at Caltech, February 1990.

A4: The early years

D. v. Harrach: *Proposal for an Experiment „Measurement of Parity Violating Electron Scattering on Hydrogen“, MAMI Exp. Nr. A4/1-93*

- **E= 855 MeV, Θ=35°, H_2**

A4: The early years

D. v. Harrach: *Proposal for an Experiment „Measurement of Parity Violating Electron Scattering on Hydrogen“, MAMI Exp. Nr. A4/1-93*

Proposal: 1993

- **E= 855 MeV, Θ=35°, H_2**

Measurement carried out: 2001 - 2003

A4: Many years

~ 20 measurements, ~6.000 h data taking, 84219 runs

	Longitudinal	Transverse
Forward angle	➢ E= 855 MeV, Θ=35°, H_2 ➢ E= 570 MeV, Θ=35°, H_2 ➢ E=1508 MeV, Θ=35°, H_2	➢ E= 855 MeV, Θ=35°, H_2 ➢ E= 570 MeV, Θ=35°, H_2 ➢ E=1508 MeV, Θ=35°, H_2 ➢ E= 510 MeV, Θ=35°, H_2 ➢ E= 420 MeV, Θ=35°, H_2 ➢ E= 315 MeV, Θ=35°, H_2
Backward angle	➢ E= 315 MeV, Θ=35°, H_2 ➢ E= 315 MeV, Θ=35°, D_2 ➢ E= 210 MeV, Θ=35°, H_2 ➢ E= 210 MeV, Θ=35°, D_2	➢ E= 315 MeV, Θ=35°, H_2 ➢ E= 315 MeV, Θ=35°, D_2 ➢ E= 420 MeV, Θ=35°, H_2 ➢ E= 420 MeV, Θ=35°, D_2 ➢ E= 210 MeV, Θ=35°, H_2 ➢ E= 210 MeV, Θ=35°, D_2

Extraction of form factors

Parity violating asymmetry (proton target):

$$A^{PV} = A_V + A_A + A_S$$

$$A_V = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left((1-4\sin^2\Theta_w) - \frac{\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right)$$

Standard model calculation

$$A_A = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(- \frac{(1-4\sin^2\Theta_w)\sqrt{1-\varepsilon^2}\sqrt{\tau(1+\tau)}\,G_M^p G_A^p}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right)$$

Axial form factor

$$A_S = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(- \frac{\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right)$$

Strange form factors

Measurement of strange form factors

Three quantities to measure: G_E^s, G_M^s, G_A

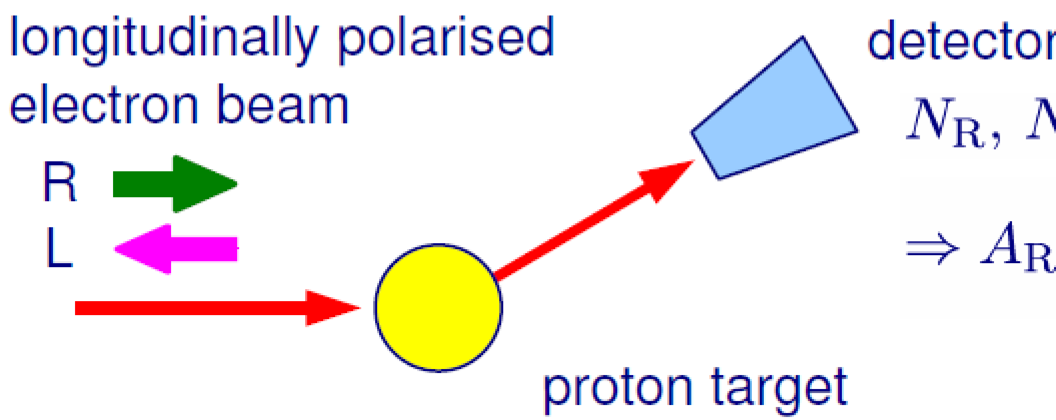
Strangeness contribution (G_E^s, G_M^s)

Large electroweak corrections
Nuclear anapole moment (G_A)

For a specific momentum transfer Q^2: At least three measurements

Scattering experiment	sensitive to
• e + p (elastic), forward angles:	G_E^s and G_M^s
• e + p (elastic), backward angles:	G_M^s and G_A
• e + ^{4}He (elastic), forward angles:	G_E^s
• e + d (quasi-elastic), backward angles:	G_M^s and G_A

A4 experimental principle



$N_\mathrm{R}, N_\mathrm{L}$

$$\Rightarrow A_\mathrm{RL} = \frac{N_\mathrm{R} - N_\mathrm{L}}{N_\mathrm{R} + N_\mathrm{L}}$$

- Statistical uncertainty

  for a counting experiment:

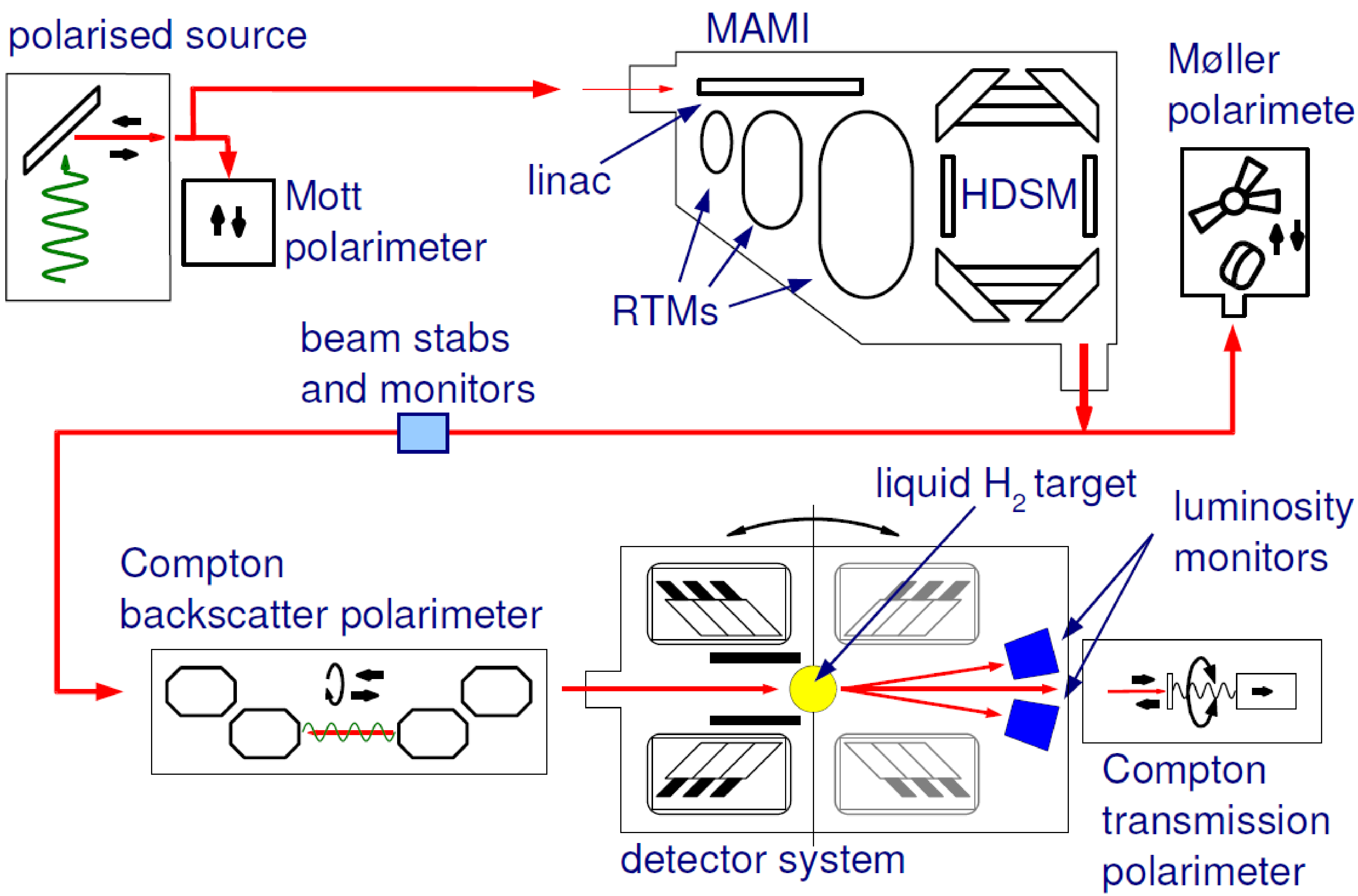
$$A = 10^{-6}$$
$$\delta A = \frac{1}{\sqrt{N}} \simeq 10^{-7}$$
$$\Rightarrow N \simeq 10^{14}$$

1000 hours $\Rightarrow$ ~10 MHz

- high luminosity
- large acceptance
- fast detector

- Systematic uncertainty
  - helicity correlated fluctuations
  - polarisation measurement

A4 Experiment at MAMI

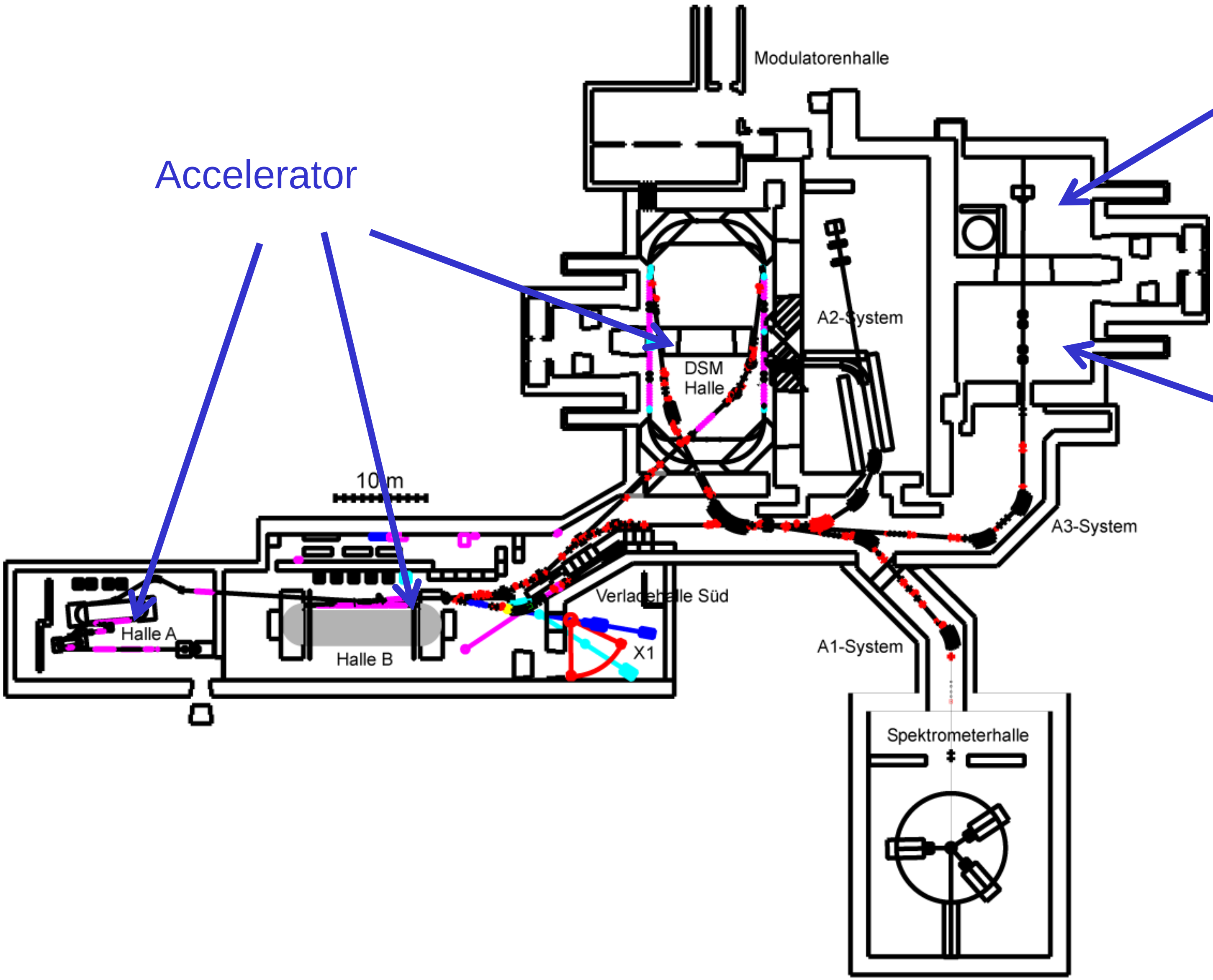


MAMI facility

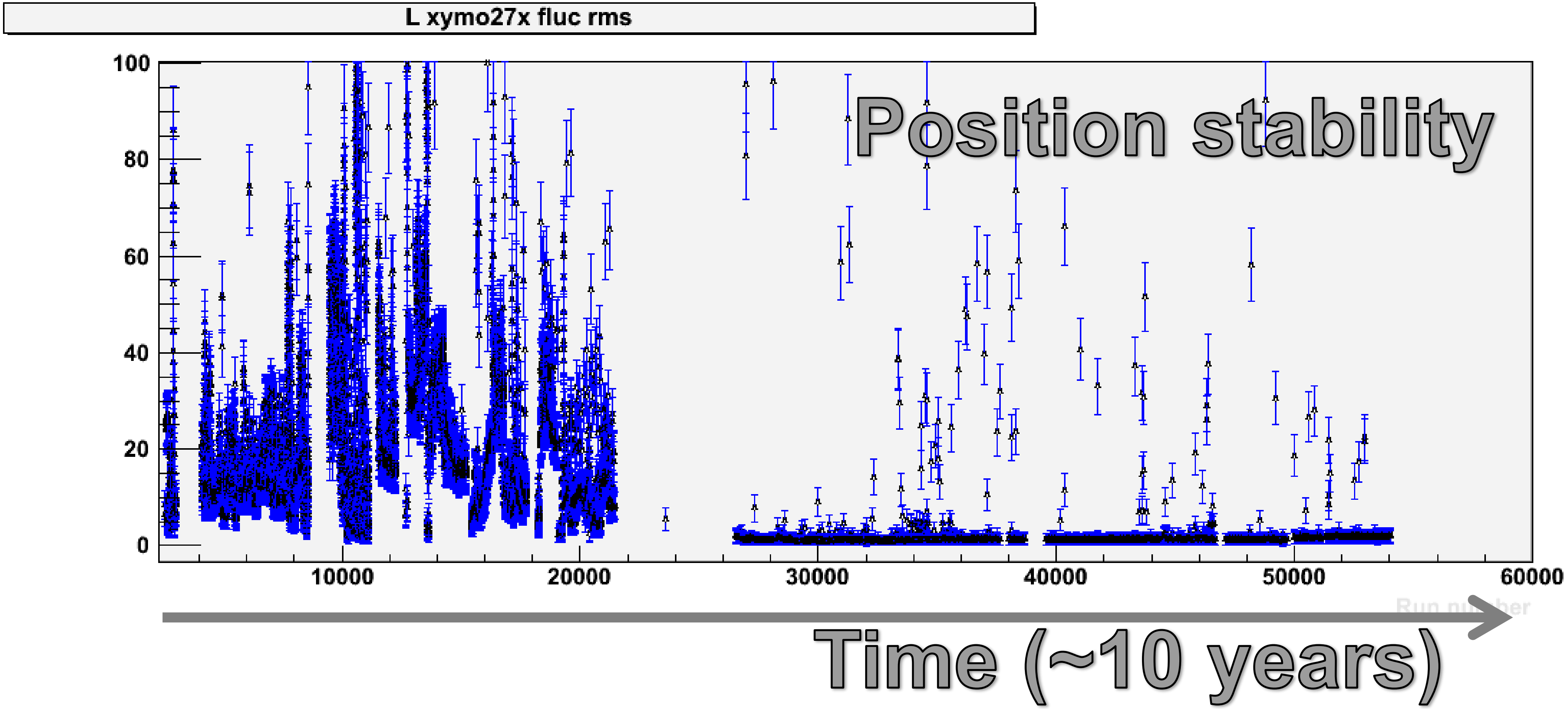
Accelerator

A4 Hall
PbF_2 calorimeter

A3 Hall
Compton backscatter polarimeter

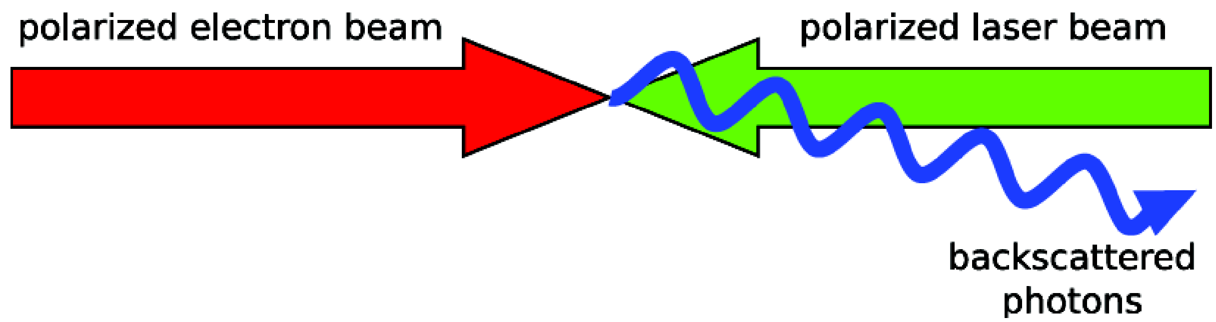


MAMI: Control of beam parameters



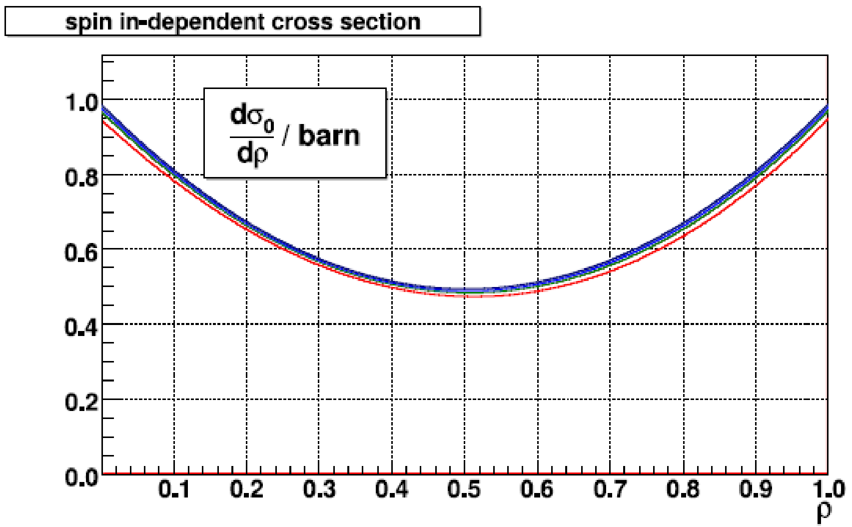
- Average helicity correlated position differences < 100 nm
- Average helicity correlated angle differences < 10 nrad

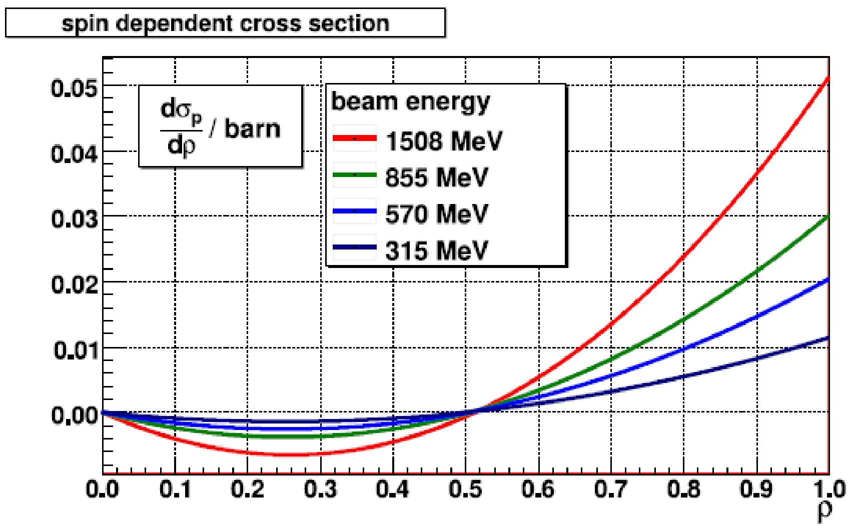
Compton Backscatter Polarimeter



$$\sigma = \sigma_0 \mp P_e P_\gamma \sigma_p$$

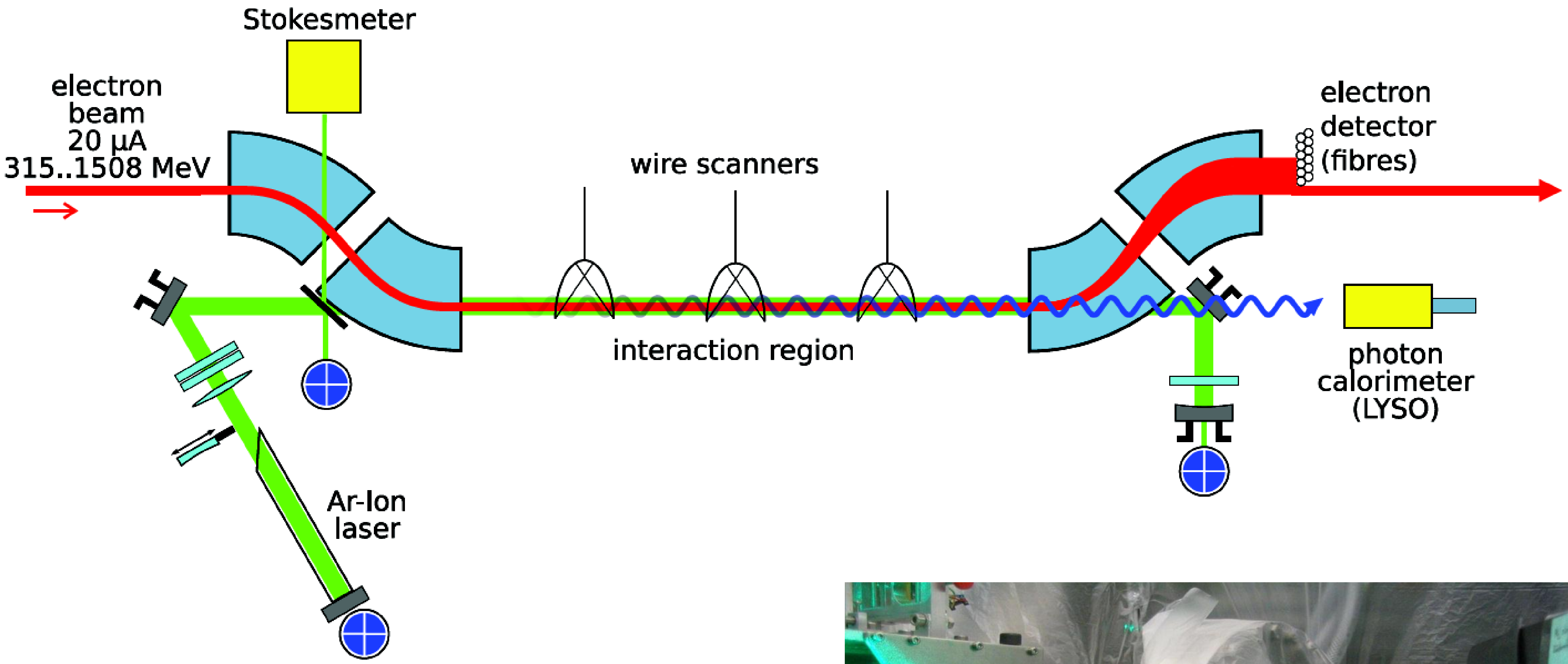
$$\rho = k/k_{max}$$



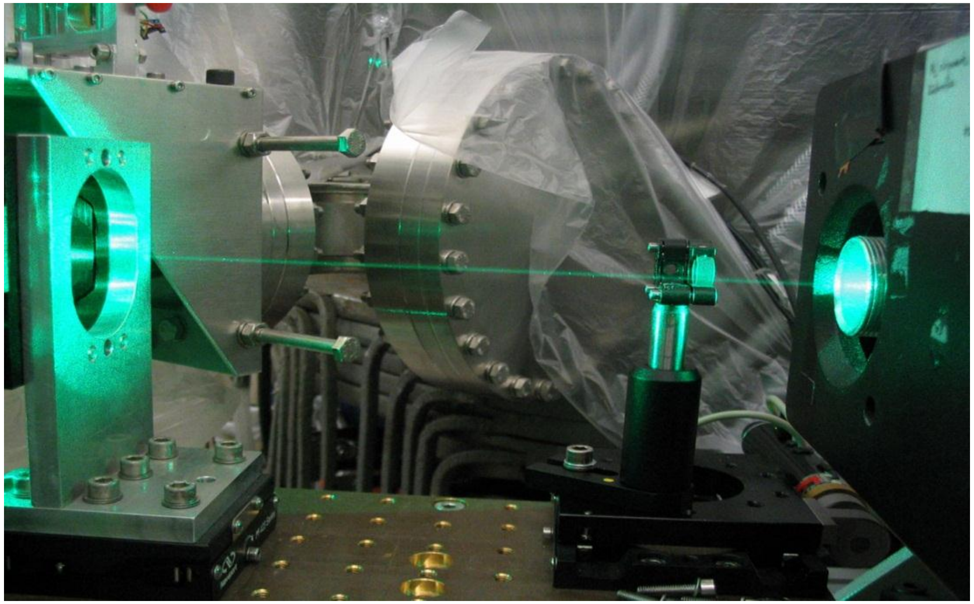


514.5 nm Argon-Ion laser light

Compton Backscatter Polarimeter



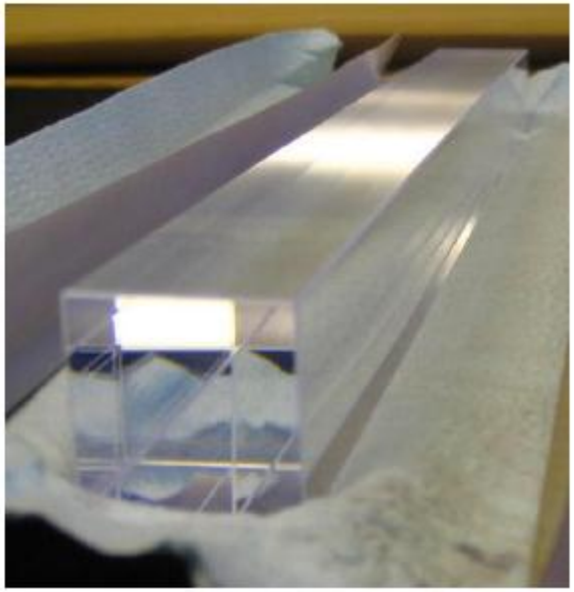
- Ar-Ion Laser, 514.5 nm
- 7.8 m internal cavity
- Zero crossing angle

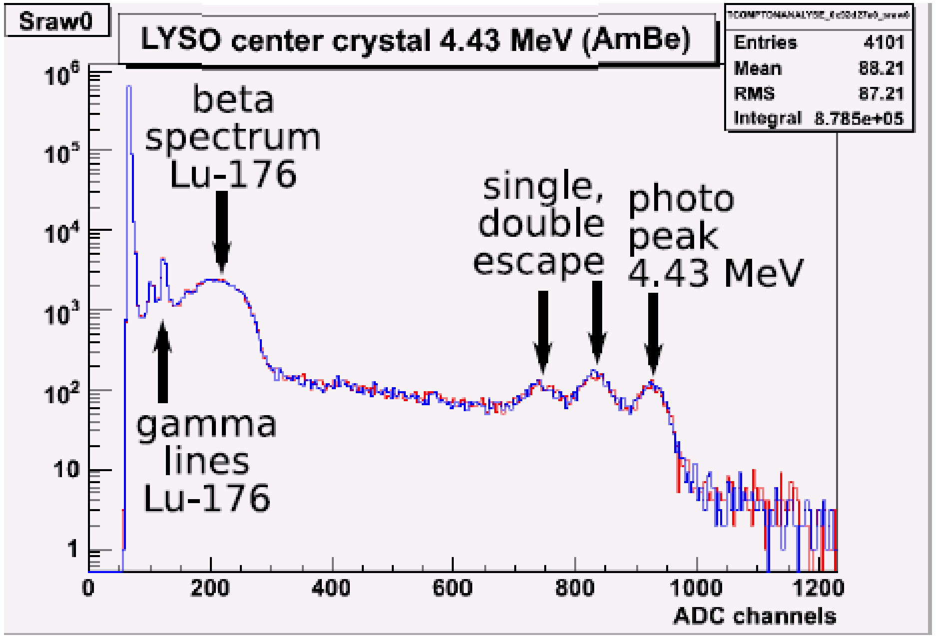


Compton Backscatter Photon Detector

LYSO ($Lu_{1.8}Y_{0.2}SiO_5$),
PreLude420 from Saint Gobain

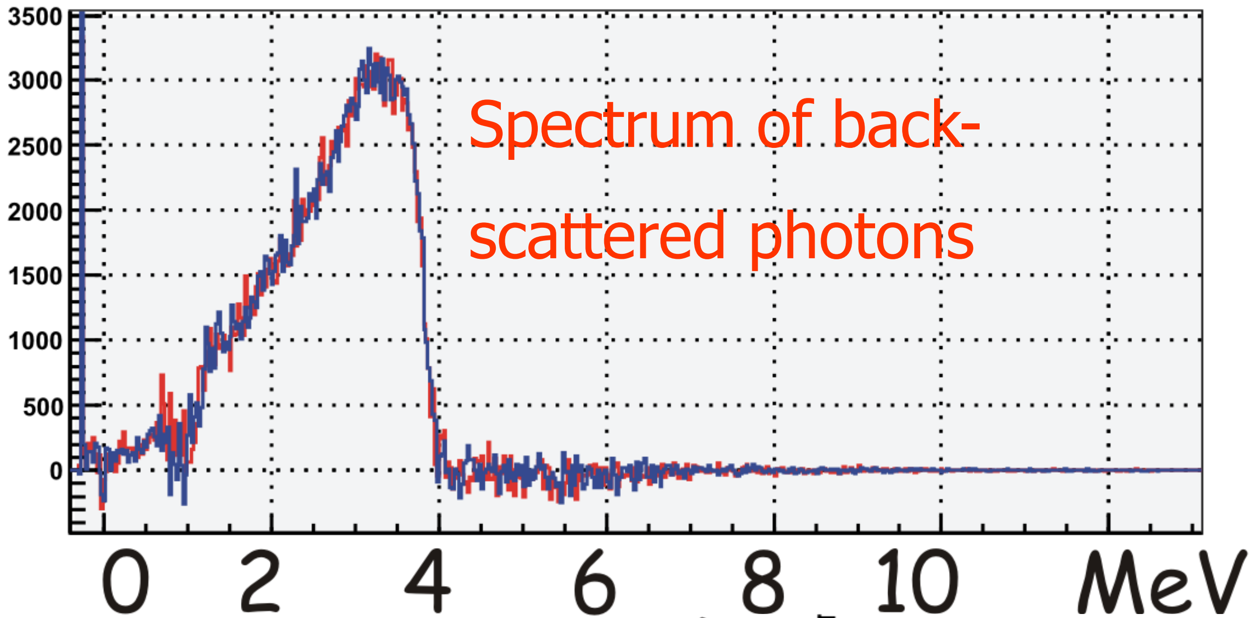
- density: 7.1 g/cm^3
- rad. length: 12 mm
- decay time: 41 ns
- light yield: 32 photons/keV, i.e. ≈75% of NaI(Tl)





- 3x3 crystals of 20x20x200 mm³
- **Fast, compact calorimeter for 1.5 ... 100 MeV photons**

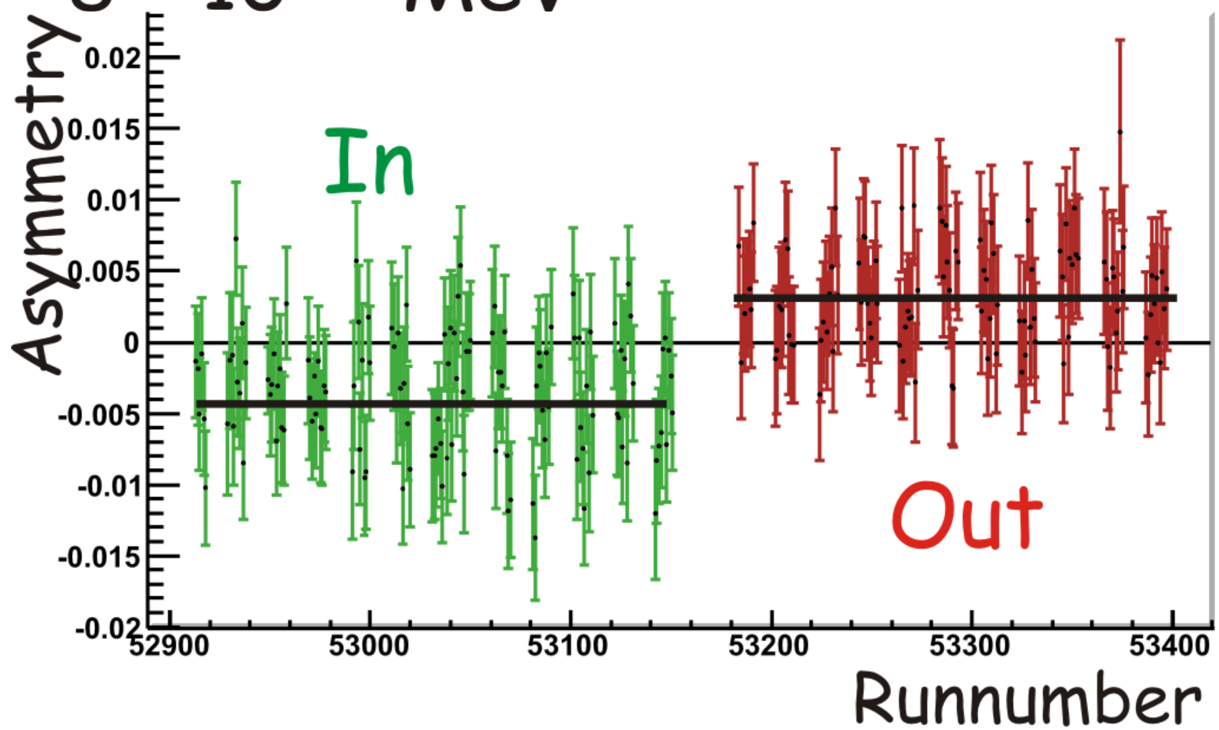
Compton Backscatter Measurements



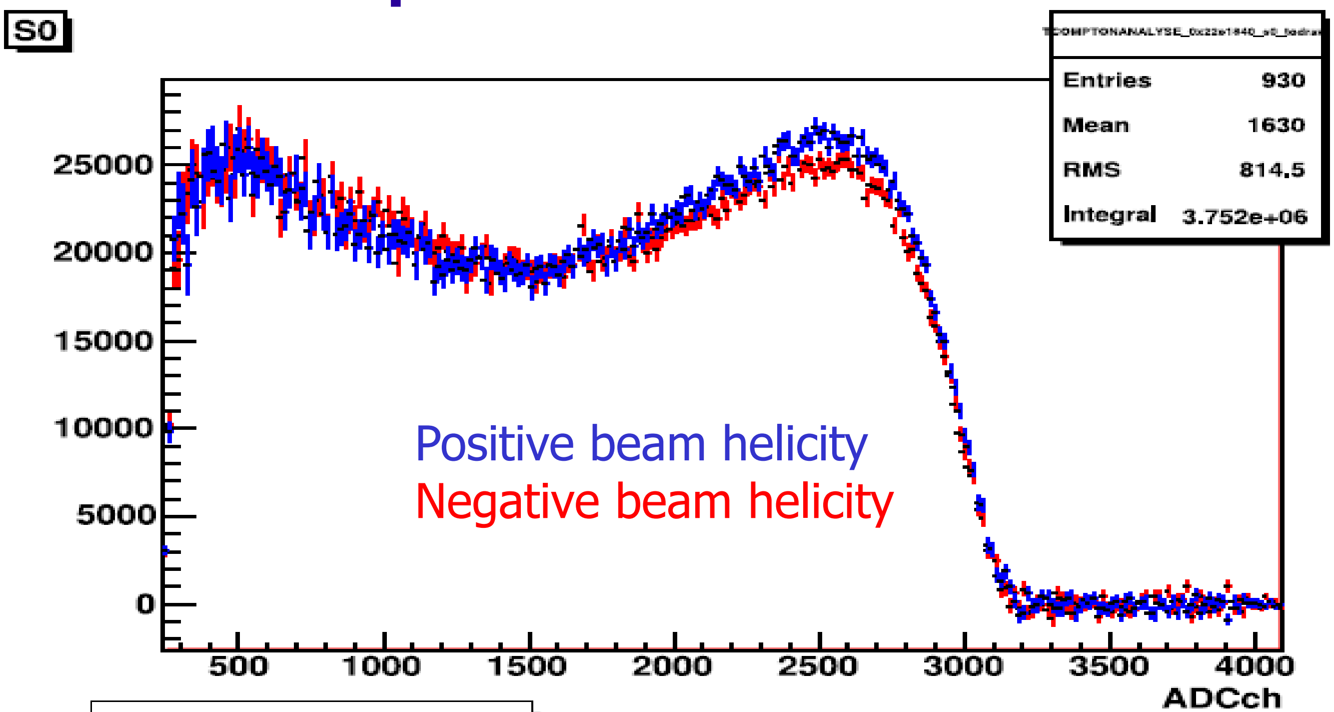
Low beam energy:

$\mathbf{E_{beam}=315\ MeV}$!

$A_{compton} \sim P_{laser} \times P_{beam}$



Compton Backscatter Measurements

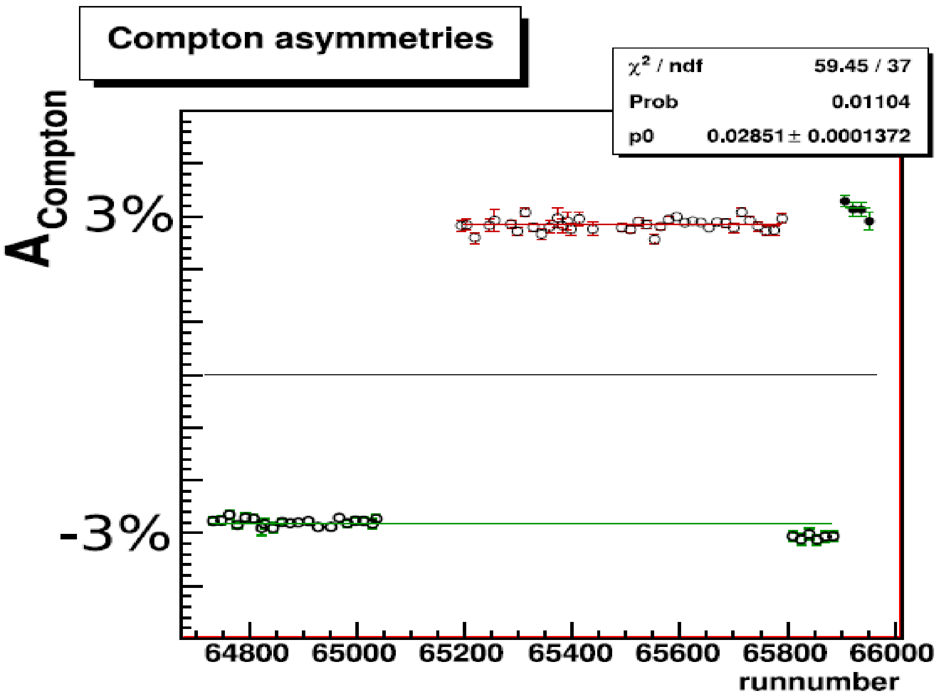


Beam energy:

E_{beam}= 1508 MeV

=> Asymmetry can be seen in 5min run!

(Red riding hood/blue riding hood)



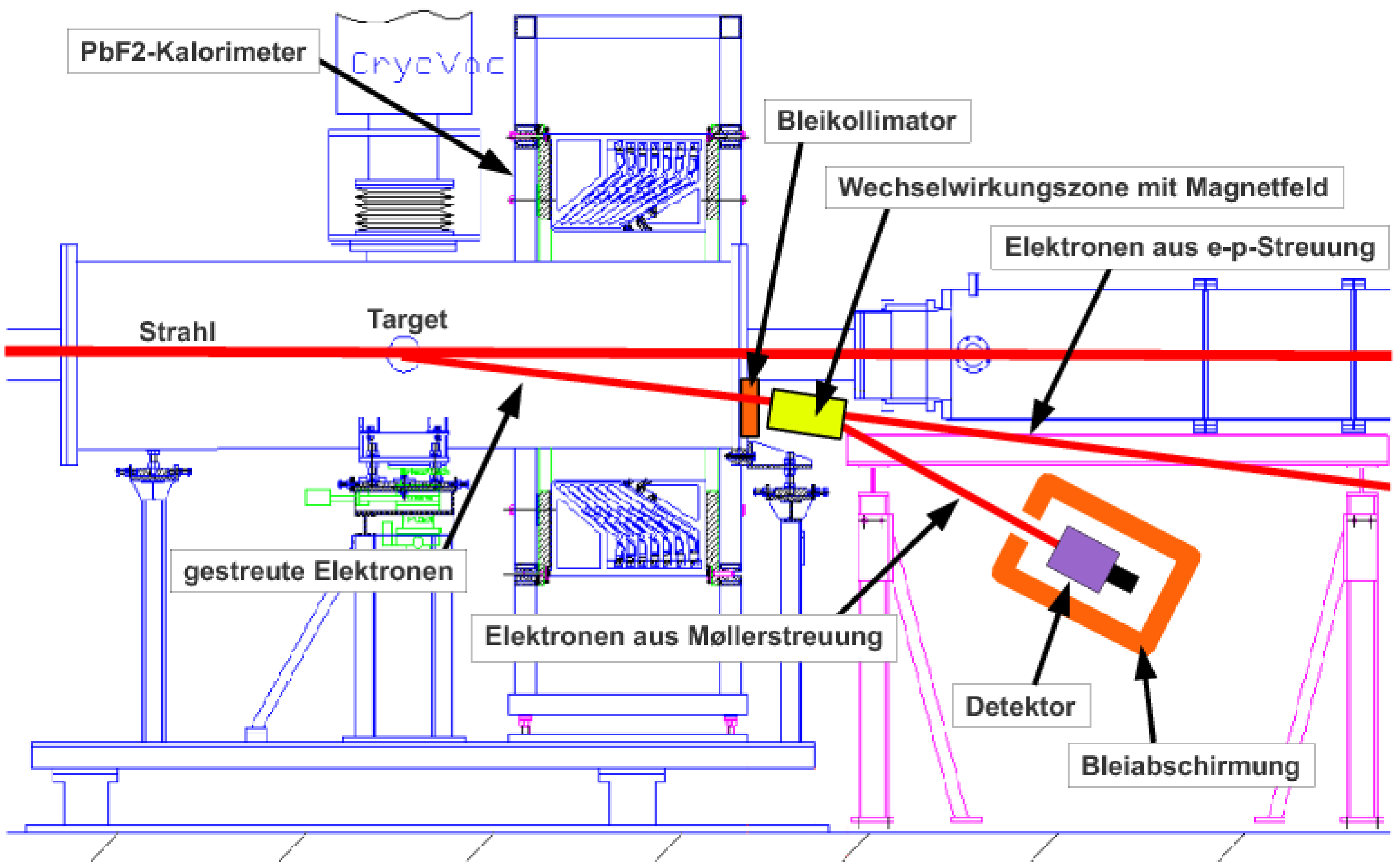
- Routine operation during beamtimes
- Statistical precision:
  ~ 1% within 24 h for 855 MeV

  < 1% within 12 h for 1508 MeV

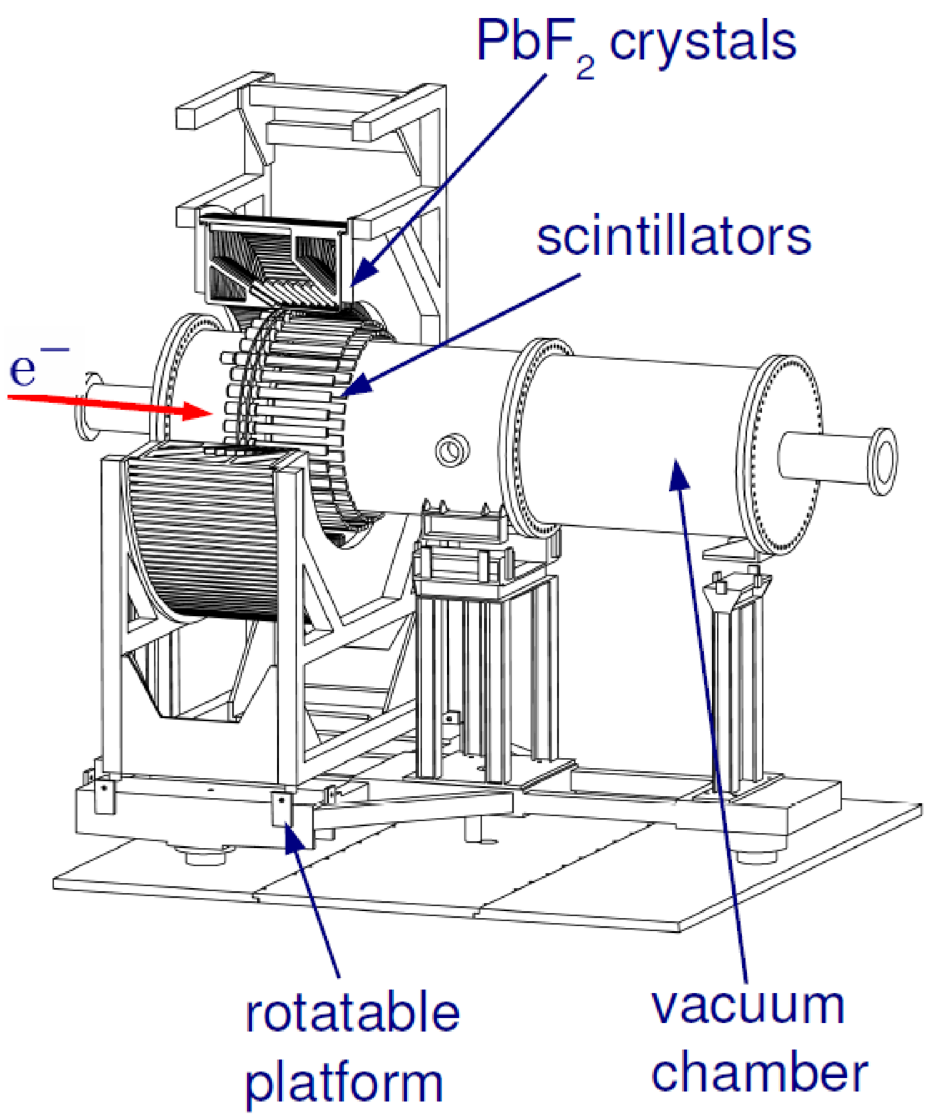
S.A.M.S. - Measurement of transverse beam polarization

- Two-Photon exchange in Moller scattering

- Clean QED process



A4 Lead fluoride calorimeter



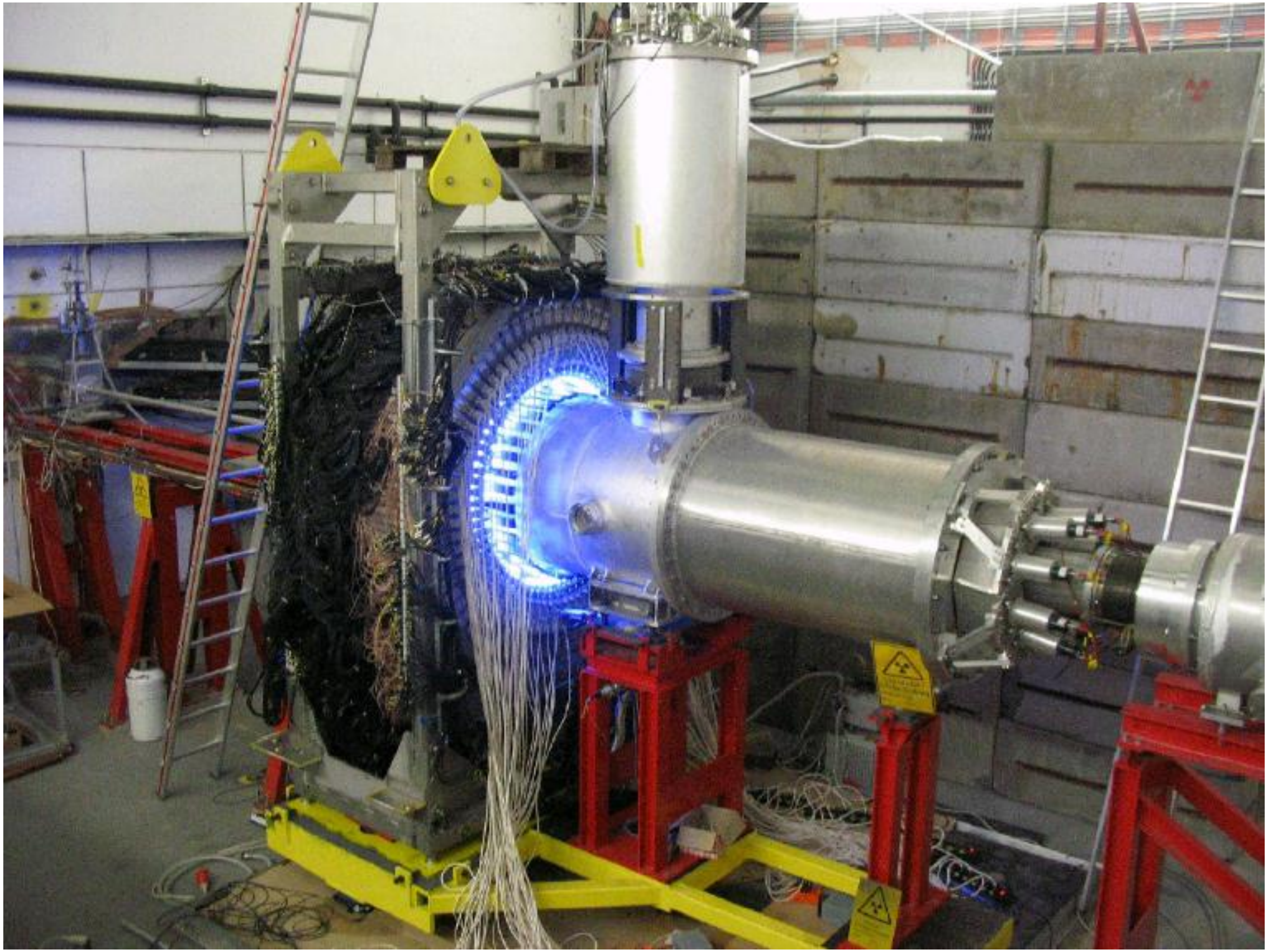
PbF_2 calorimeter:

- pure Cherenkov radiator
- count rate: 100 MHz
- acceptance: 0.6 sr
  (30° to 40° or 140° to 150°)
- 1022 crystals in 7 rings
- fully absorbing

Electron tagger (backward):

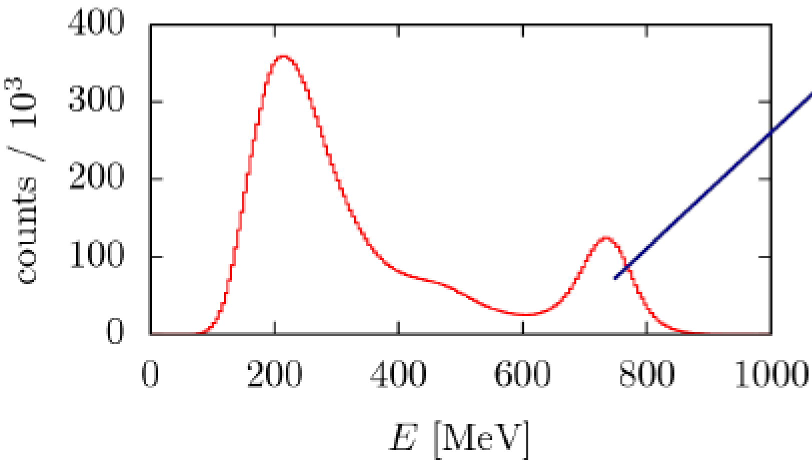
- 72 plastic scintillators

A4 Lead fluoride calorimeter



Data analysis

855 MeV forward



- 2044 spectra every 5 min.
- Extraction of elastic events

N_R, N_L

- Target density normalisation:

$$A_{\text{meas}} = \frac{N_R/\rho_R - N_L/\rho_L}{N_R/\rho_R + N_L/\rho_L}$$

- Correction for false asymmetries and polarisation:

$$A_{\text{meas}} = P A_{\text{RL}} + \sum a_i X_i$$

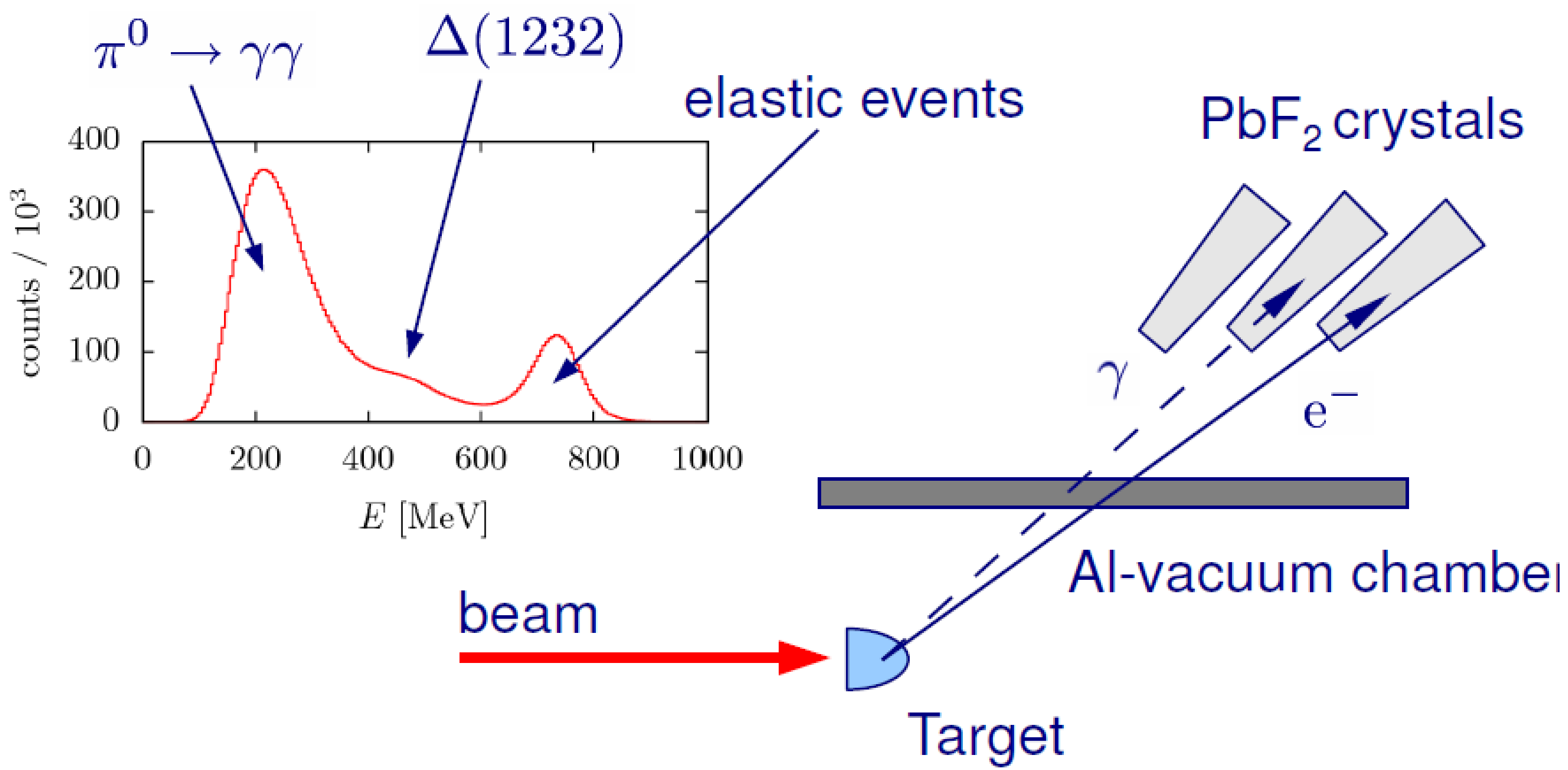
Data analyis

6000 hours of asymmetry data (2001 - 2010):

Beam parameter $\overline{X_i}$ (helicity correlated)		False Asymmetry $a_i\overline{X_i}$ (Estimation)
Intensity Asymmetry A_I	0.05 ppm	0.05 ppm
Horizontal position diff. ΔX	10.2 nm	0.01 ppm
Vertical position diff. ΔY	51.9 nm	0.35 ppm
Horizontal angle diff. $\Delta X'$	6.8 nrad	0.07 ppm
Vertical angle diff. $\Delta Y'$	4-2 nrad	+0.12 ppm
Energy diff. ΔE	0.05 eV	0.02 ppm

Background

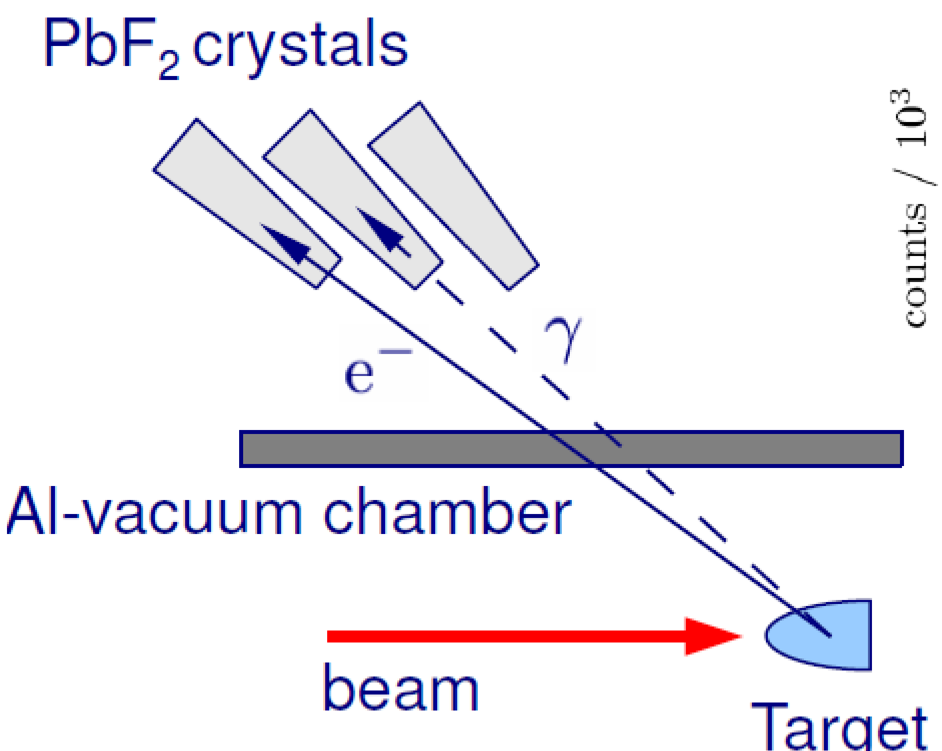
- Forward angle (855 MeV):

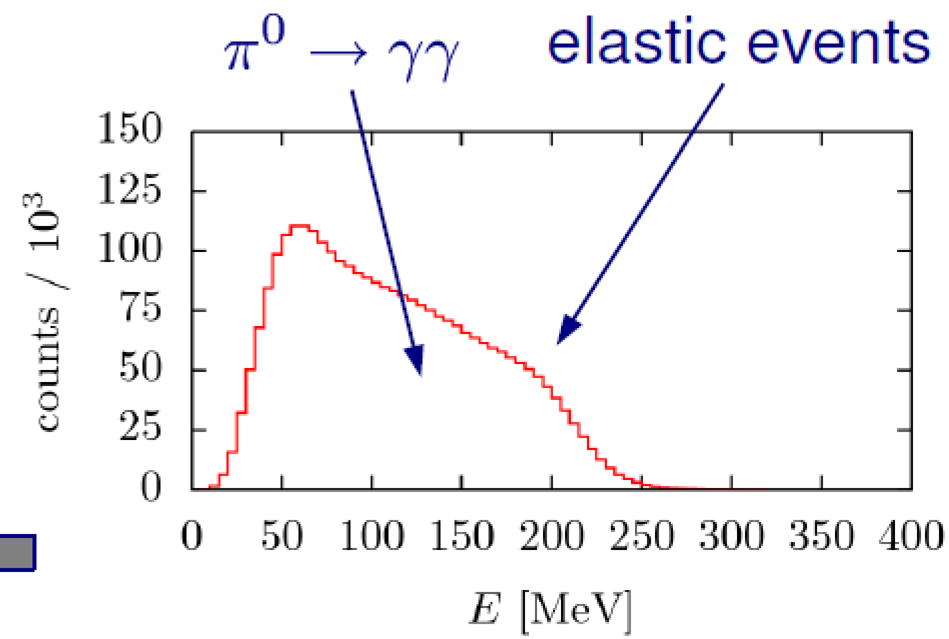


=> Separation by energy of elastic from inelastic events

Background

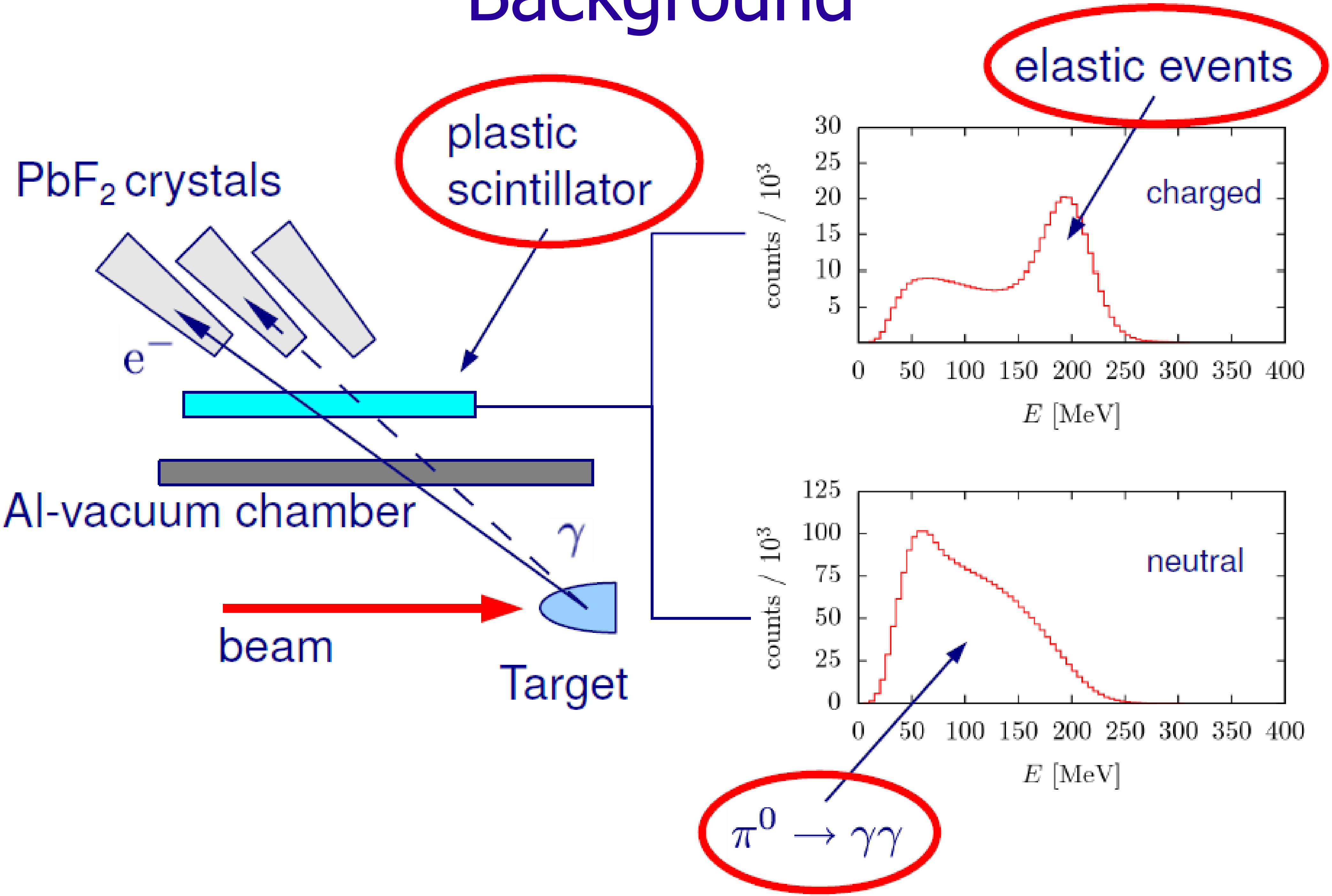
- Backward angle (315 MeV):





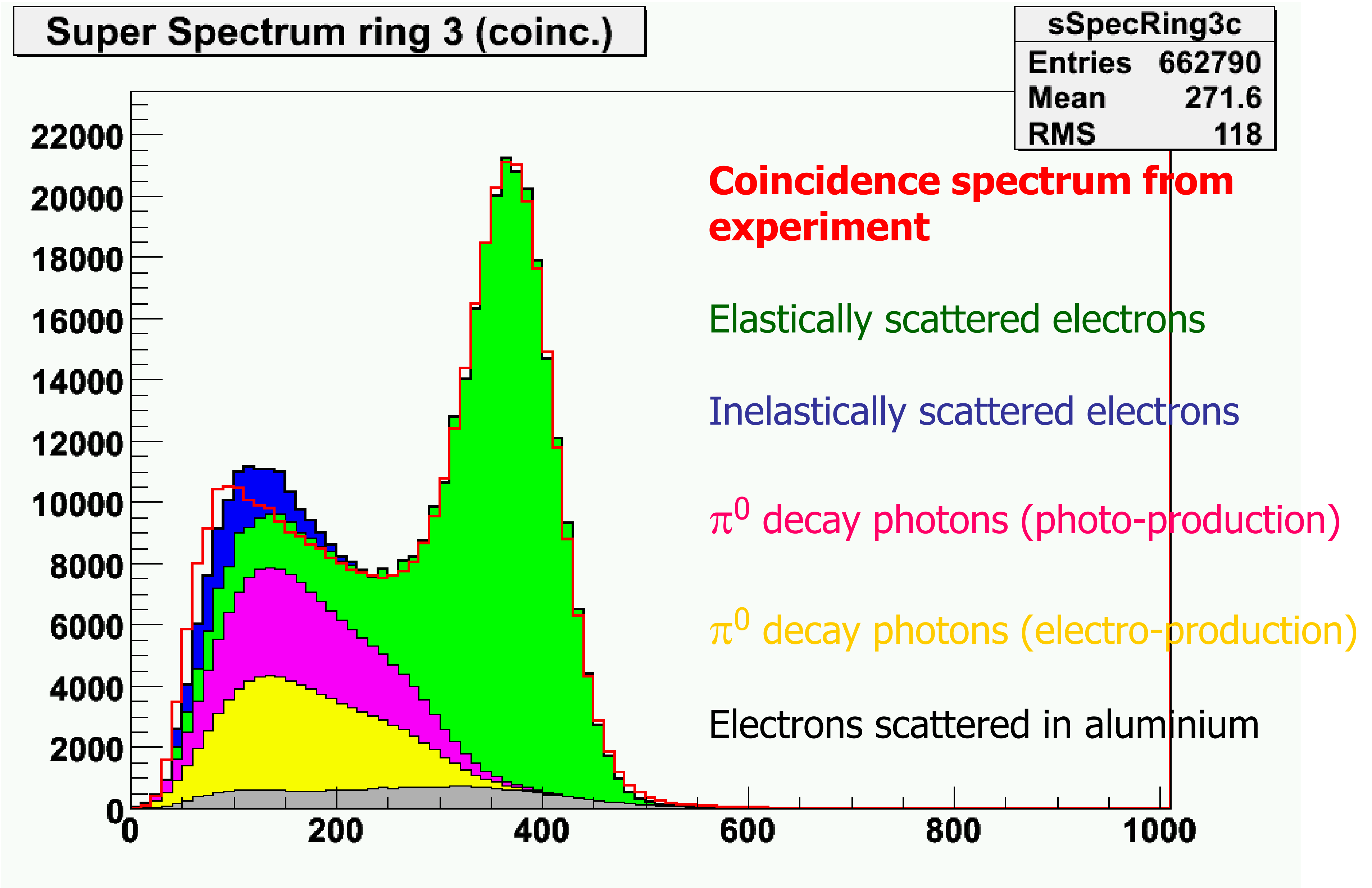
No energy separation at backward angle

Background

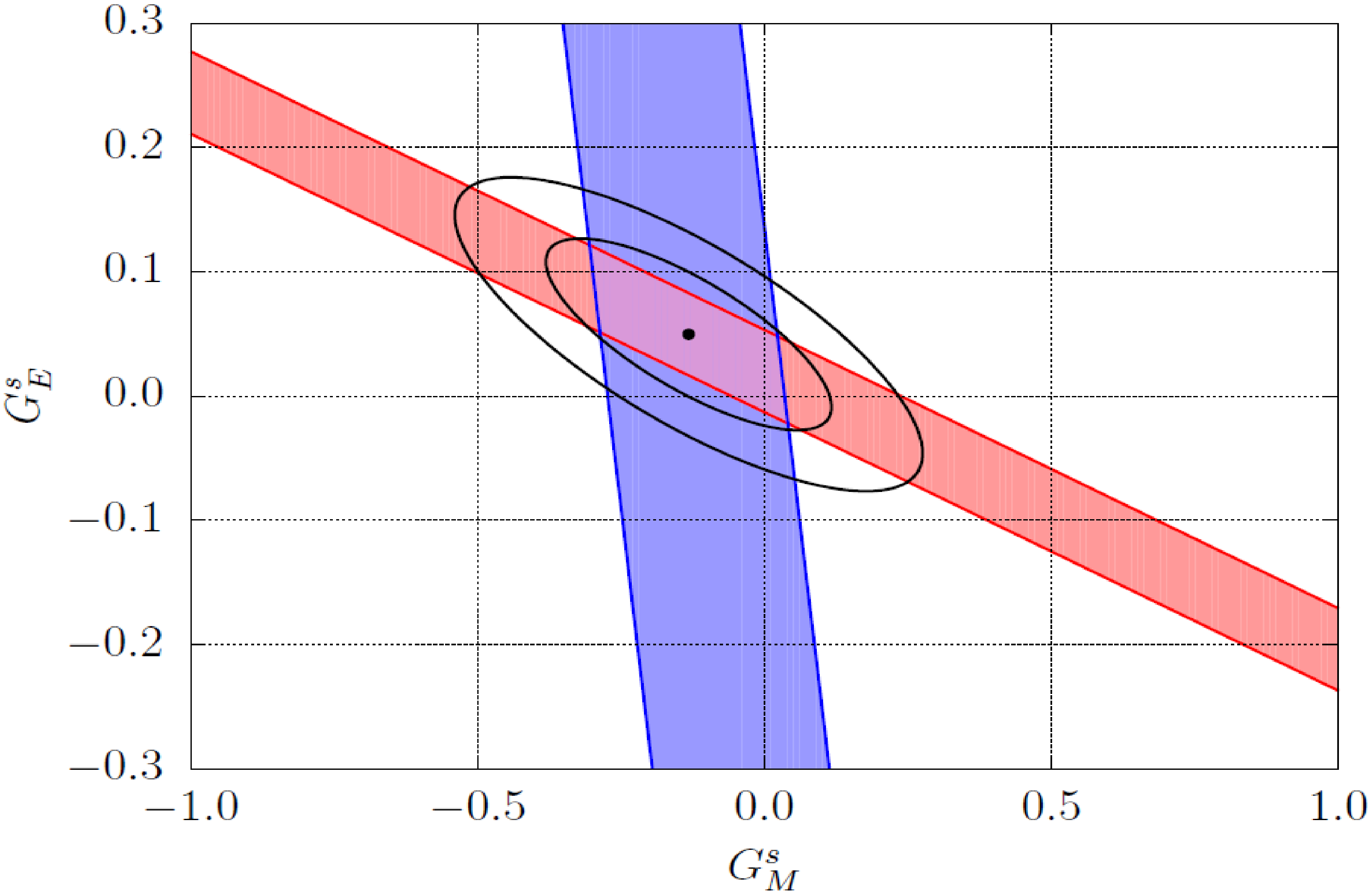


elastic events
plastic scintillator
PbF_2 crystals
e^-
γ
Al-vacuum chamber
beam
Target
charged
counts / 10^3
30
25
20
15
10
5
0
50
100
150
200
250
300
350
400
E [MeV]
neutral
counts / 10^3
125
100
75
50
25
0
0
50
100
150
200
250
300
350
400
E [MeV]
$\pi^0 \to \gamma\gamma$

Full MC simulation results



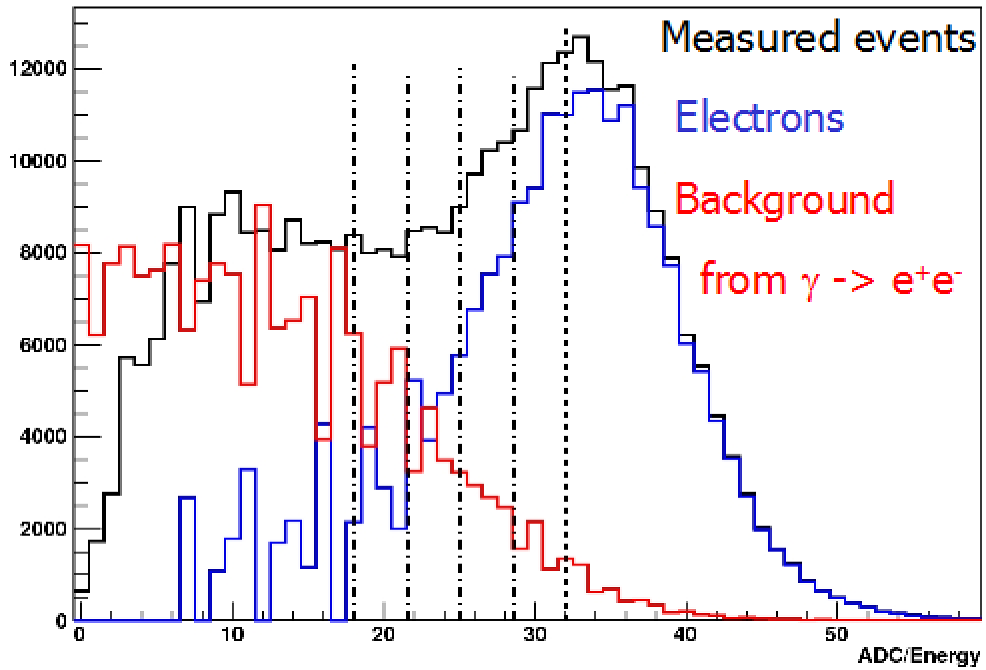
A4: Strange FF at Q^2=0.23 GeV^2



G_E^s = 0.050 ± 0.042 (± 0.038_{exp} ± 0.019_{FF})

G_M^s = -0.14 ± 0.16 (± 0.11_{exp} ± 0.11_{FF})

A4 Deuterium measurements

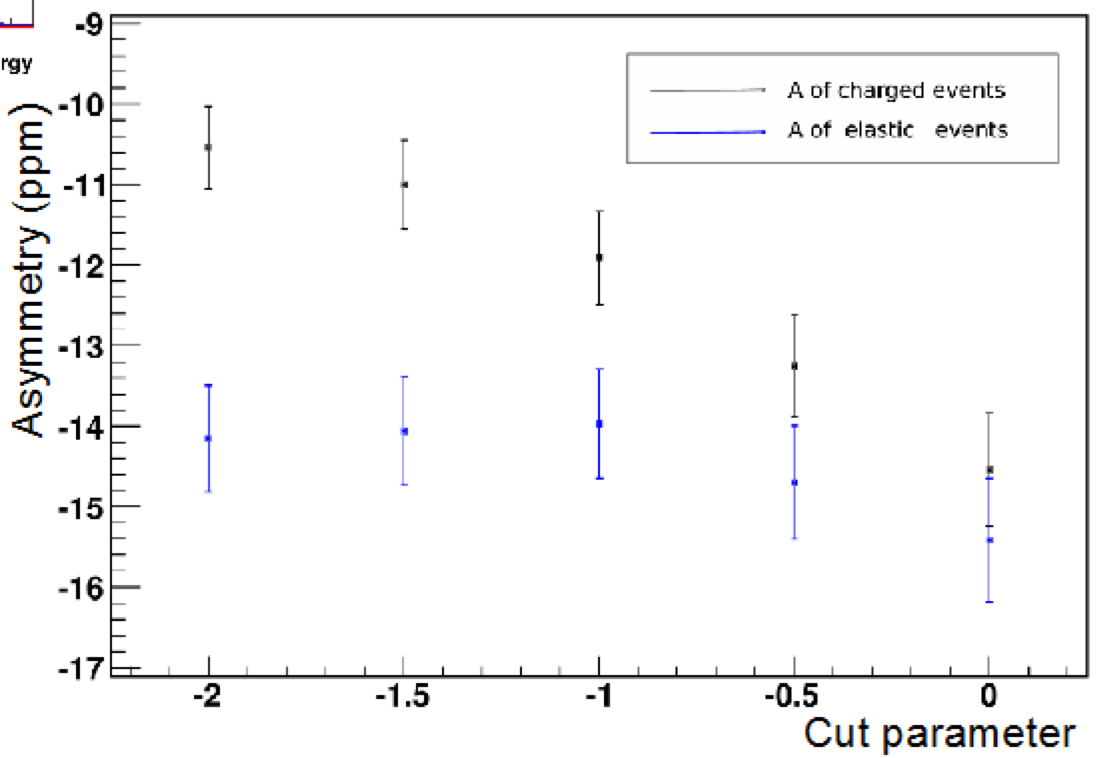


- 1100 h of asymmetry data at $Q^2=0.23$ GeV^2
- Different linear combination of G_M^s and G_A
- So far: G_A as input from Zhu *et al.*
- Aim: Determination of G_A from the measuremen

Analysis compared to H_2:

- Peak broader due to Fermi motion
- Rate of charged particles increases by a factor of ~1.5, rate of neutral particles increases by factor ~2

=> Careful study of background subtraction data necessary!

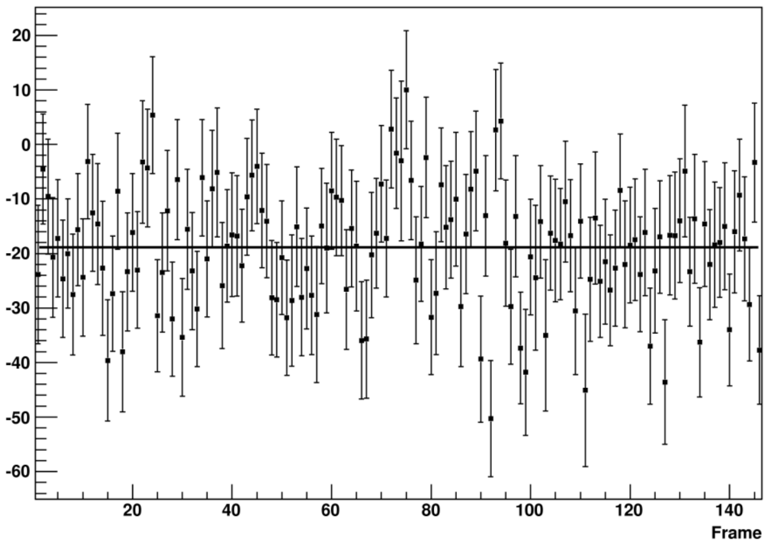


A4 Backward angle: D_2, Q^2=0.23 GeV^2

	Scaling factor	Error(ppm)
Polarization	0.74	0.89
	Correction(ppm)	Error(ppm)
Dilution of γ backgr.	-4.02	0.44
ϵ, δ parameters	–	0.43
Helicity corr. beam diff.	-0.33	0.10
Non-helicity corr. beam fluc.	–	0.42
Al windows	0.50	0.05
Random coinc. events	-1.55	0.10
Luminosity	-0.87	0.26
Nonlinearity of L	–	–
spin angle deviation	1.73	0.35
Sum syst. errors		1.25

$$A_\perp = (-20.02 \pm 0.84 \pm 1.25) \text{ ppm}$$

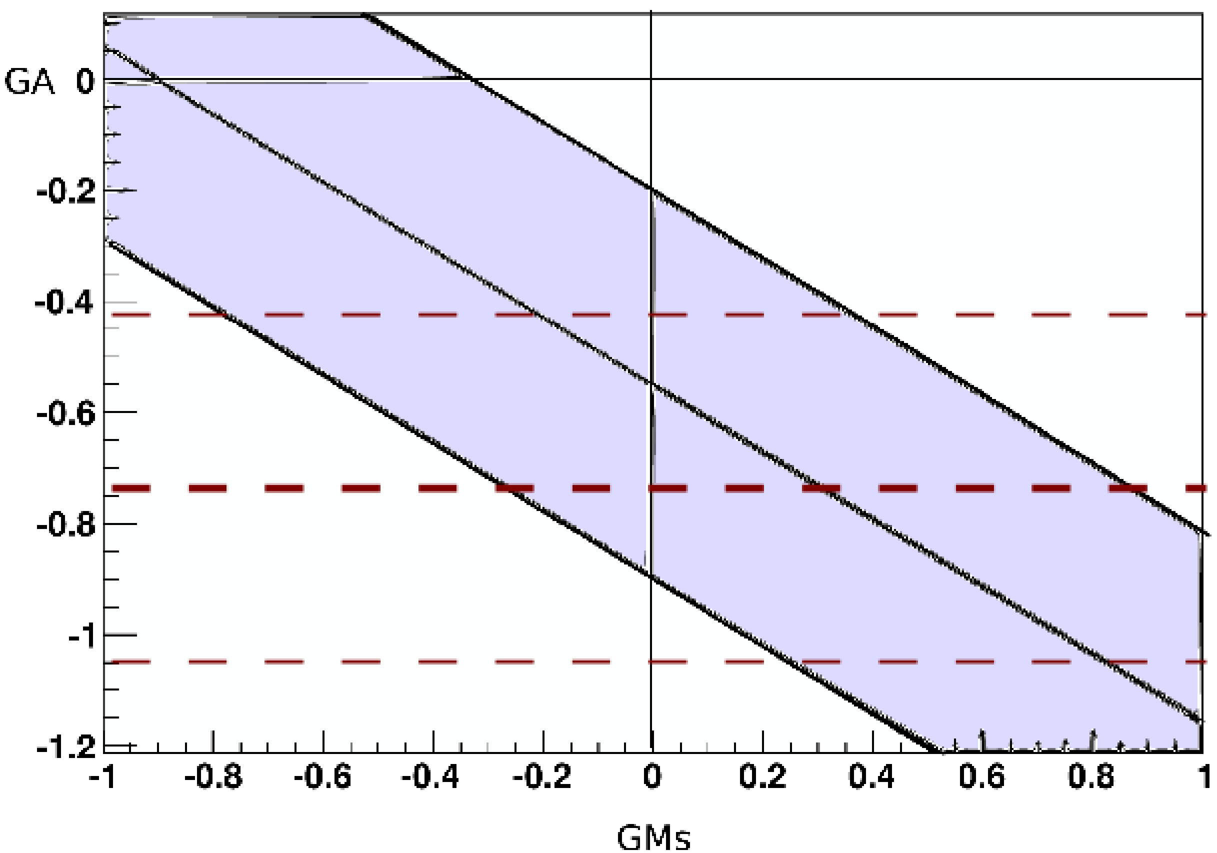
A4 Backward angle: Deuterium



Asymmetry in quasielastic *ed* scattering:

A= (-20.02 +- 0.84$_{stat}$ +. 1.25$_{syst}$) ppm

(all corrections included)



Preliminary result:

$G_A + 0.61{*}G_M^s = -0.55 \pm 0.35$

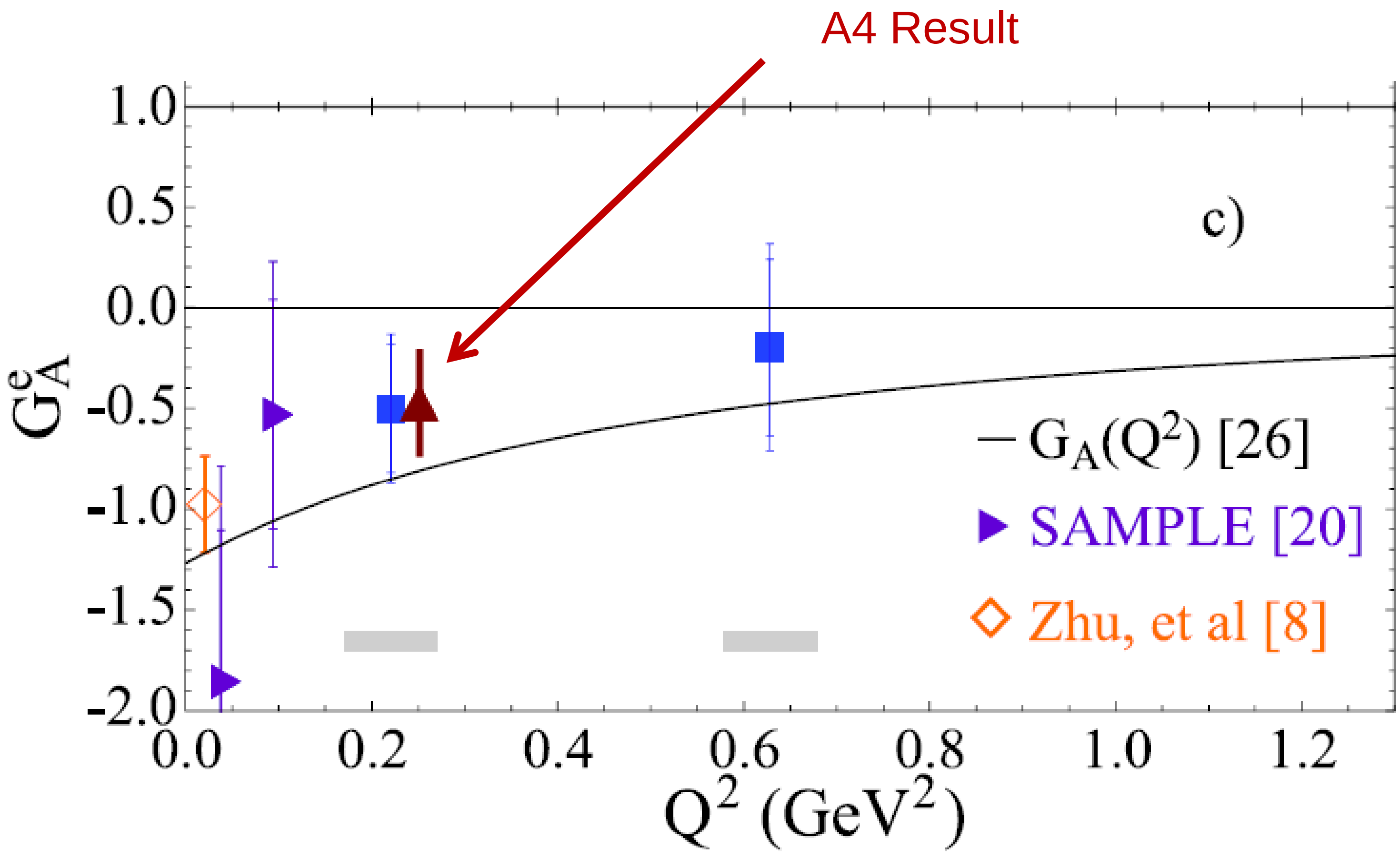
(all errors added in quadrature)

Experiment: G_A=-0.47 +- 0.31

Zhu *et al.*: G_A=-0.77 +- 0.35

A4 Backward angle: Deuterium

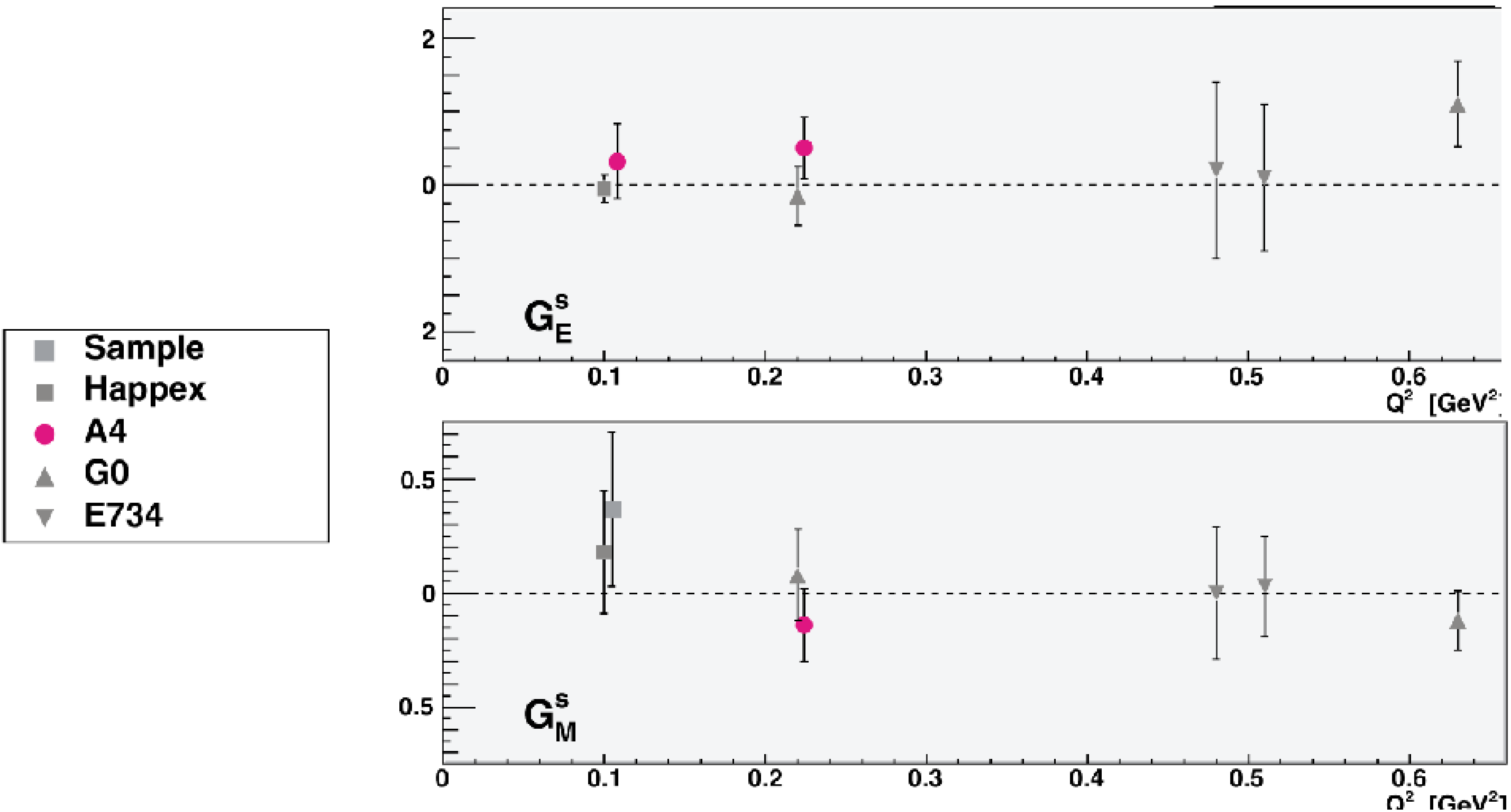
Comparison with G0 backward angle measurement (*same momentum transfer*):



Phys.Rev.Lett. 104 (2010) 012001

“A4-III”

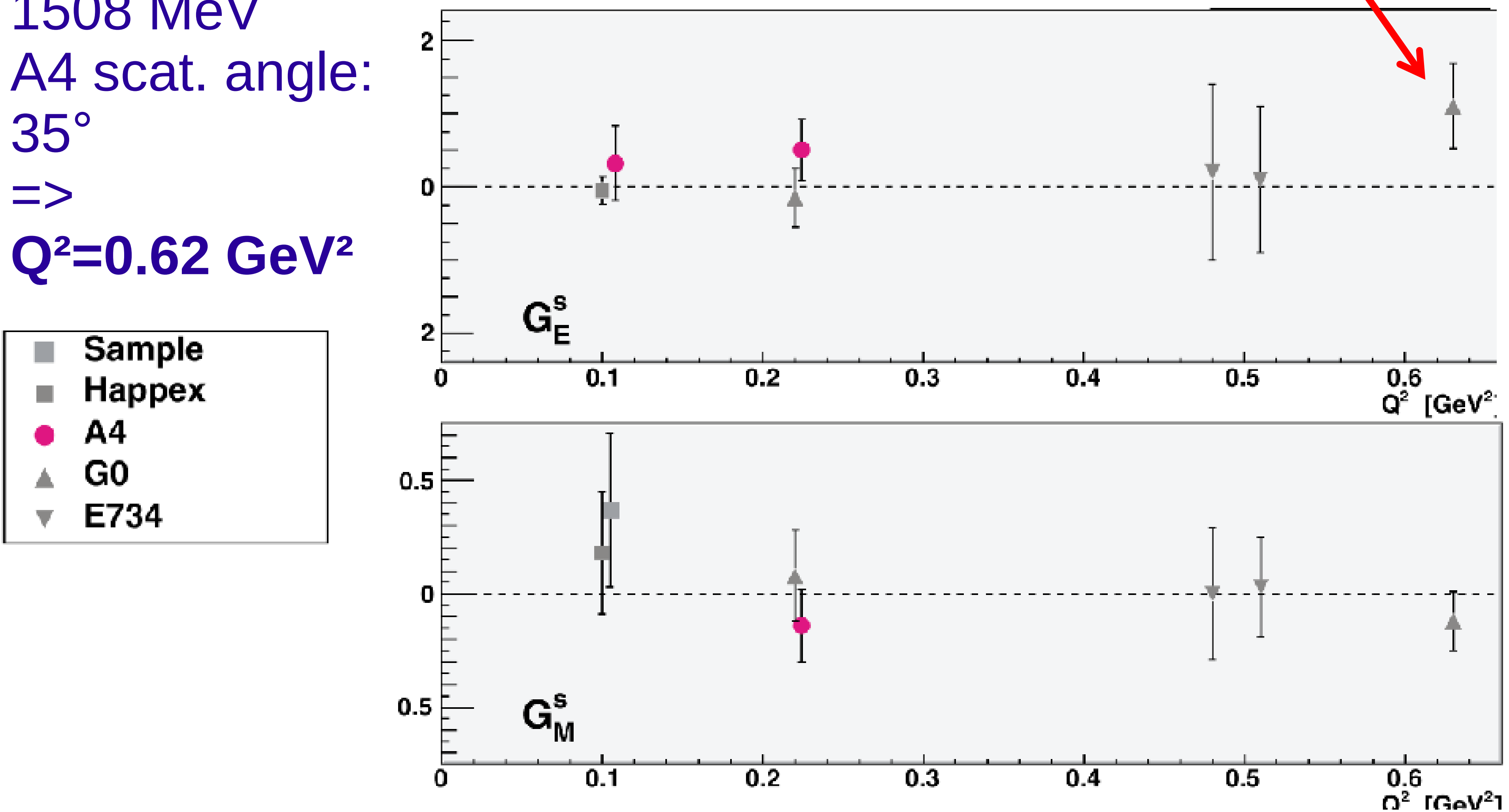
Disentangling of strange electric and magnetic form factors with data from different experiments:



"A4-III"

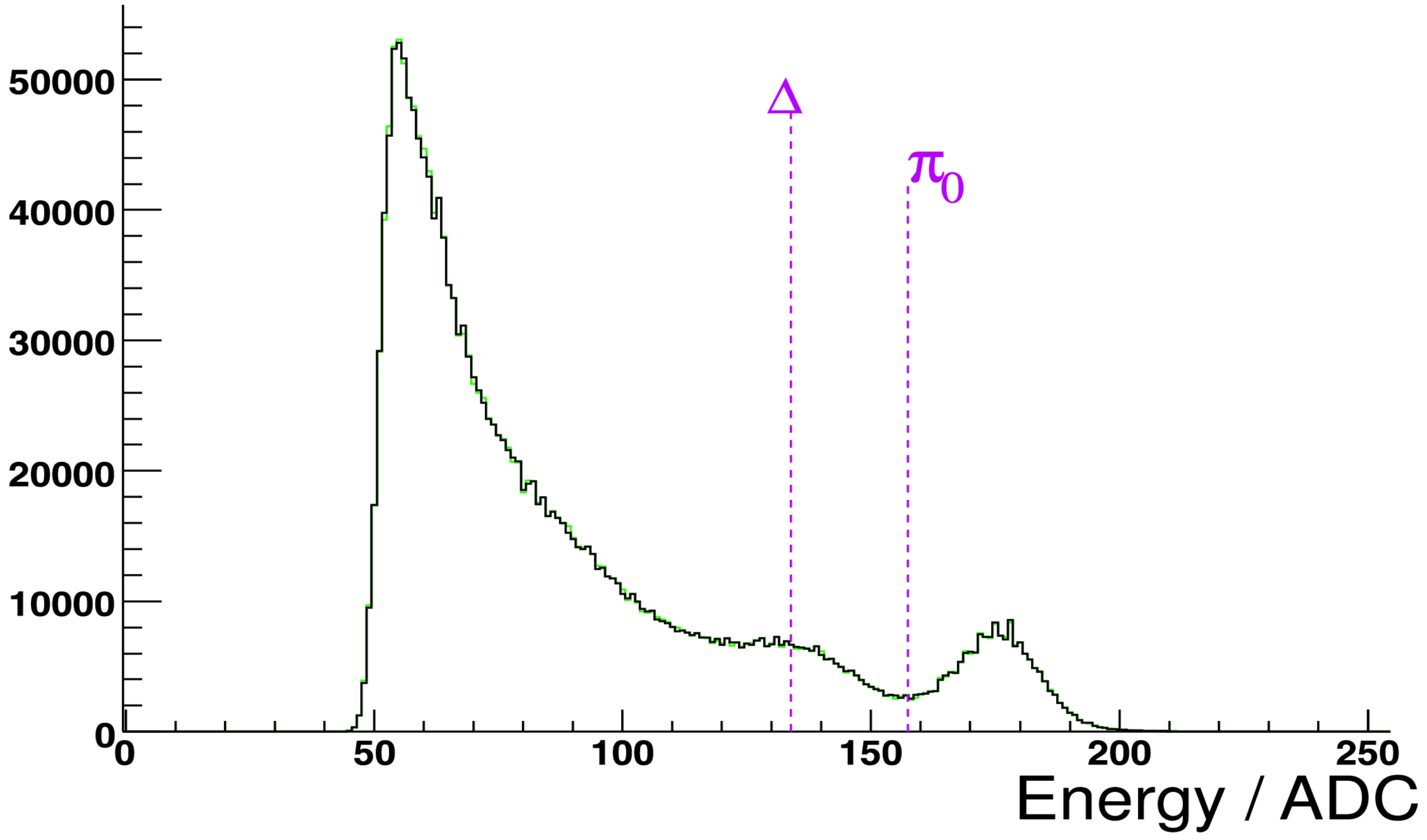
Looks interesting…

MAMI C energy:
1508 MeV
A4 scat. angle:
35°
=>
Q^2=0.62 GeV²



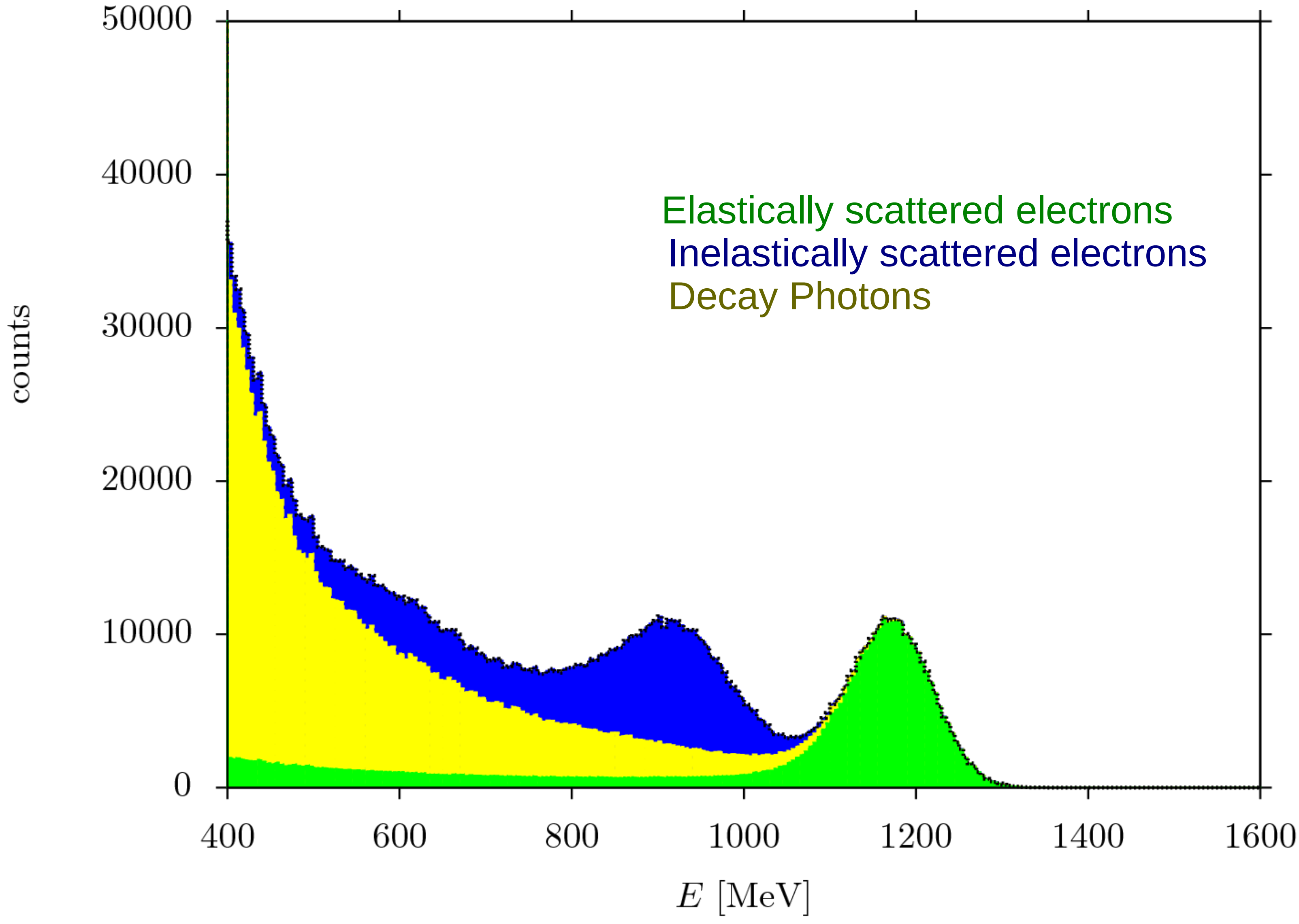
“A4-III”

PbF$_2$ energy spectrum



"A4-III"

Energy spectra: MC Study



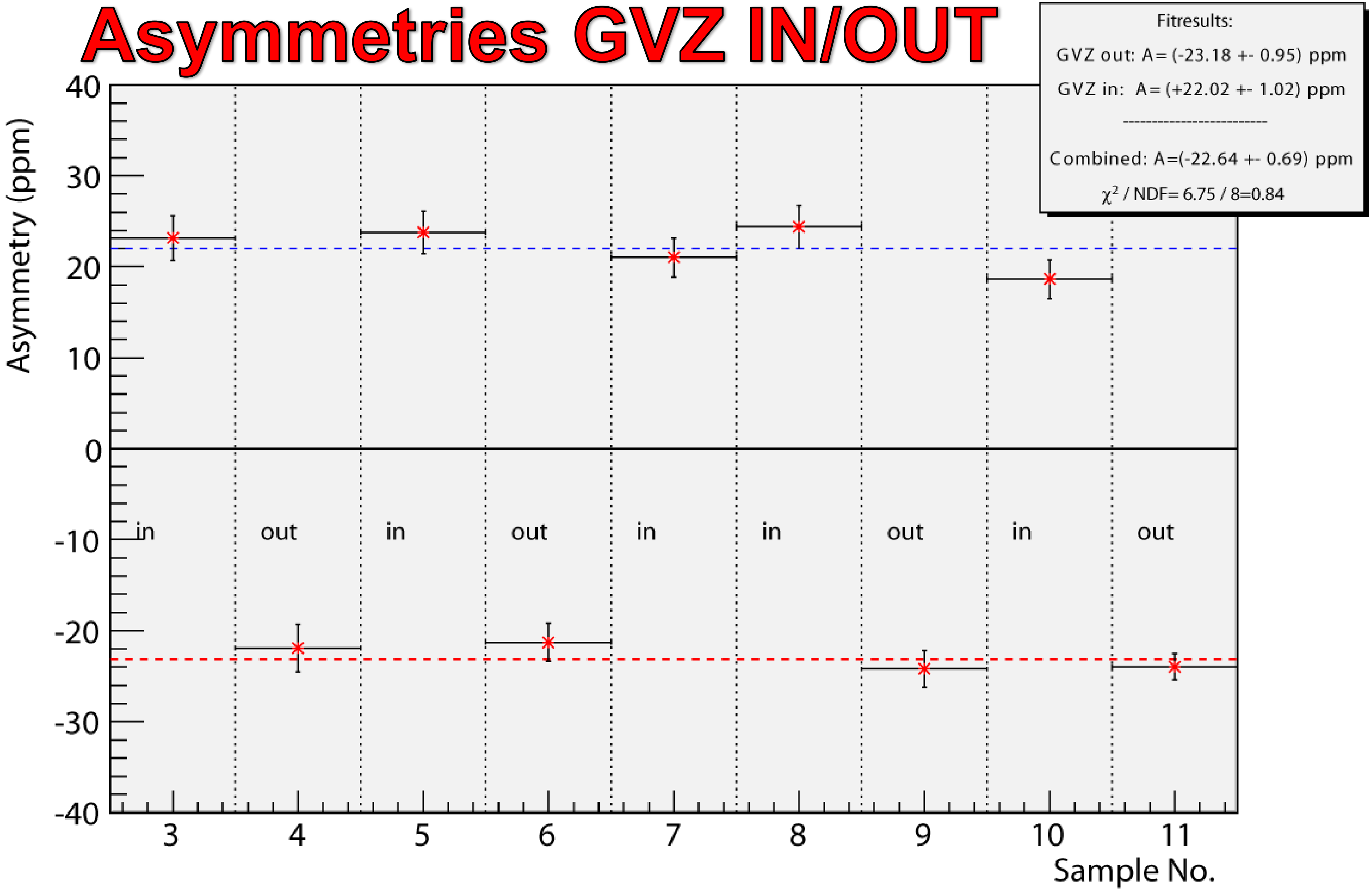
“A4-III”

Data taking:

- 600 hours of asymmetry data on disk
- Average beam polarization of 85%
- N=12.8 x 10^{12} elastically scattered electrons
- 👎A/A ~ 0.05
- Asymmetry analysis nearly finished

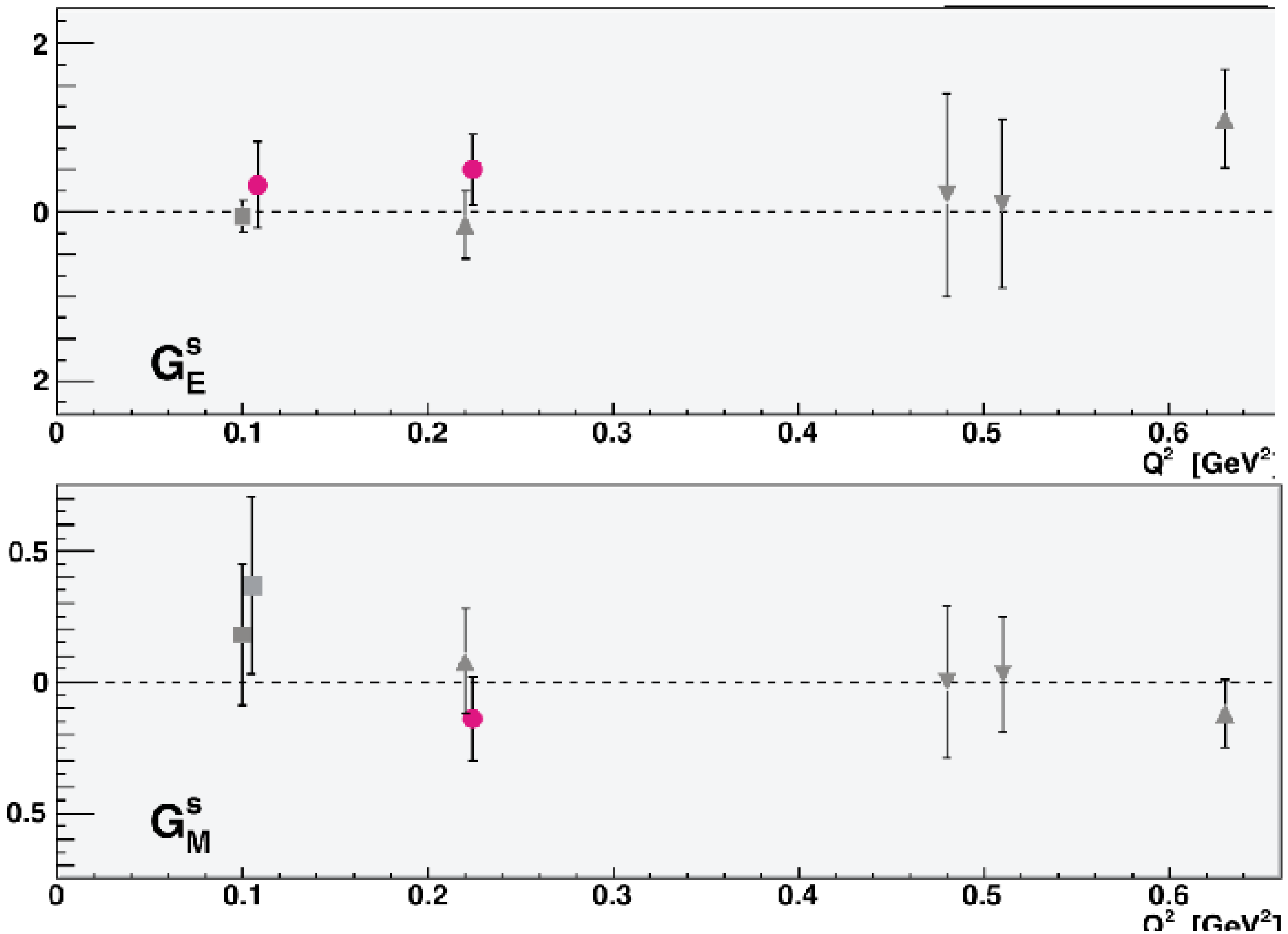
"A4-III"

Asymmetries GVZ IN/OUT



"A4-III"

Preliminary result: $G_E^s + 0.628 * G_M^s = 0.067 \pm 0.030$ *(all errors added in quadrature)*



"A4-III"

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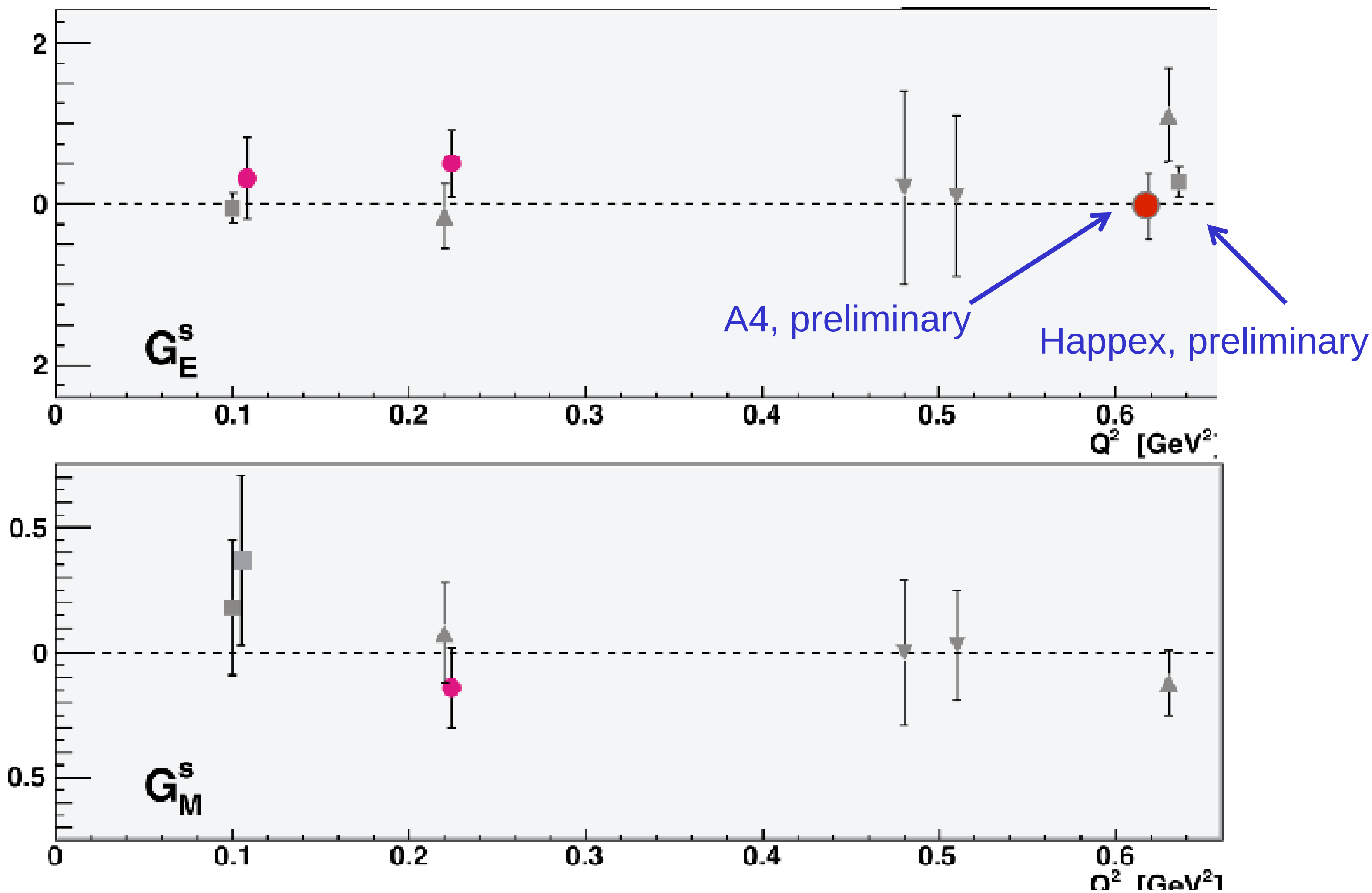
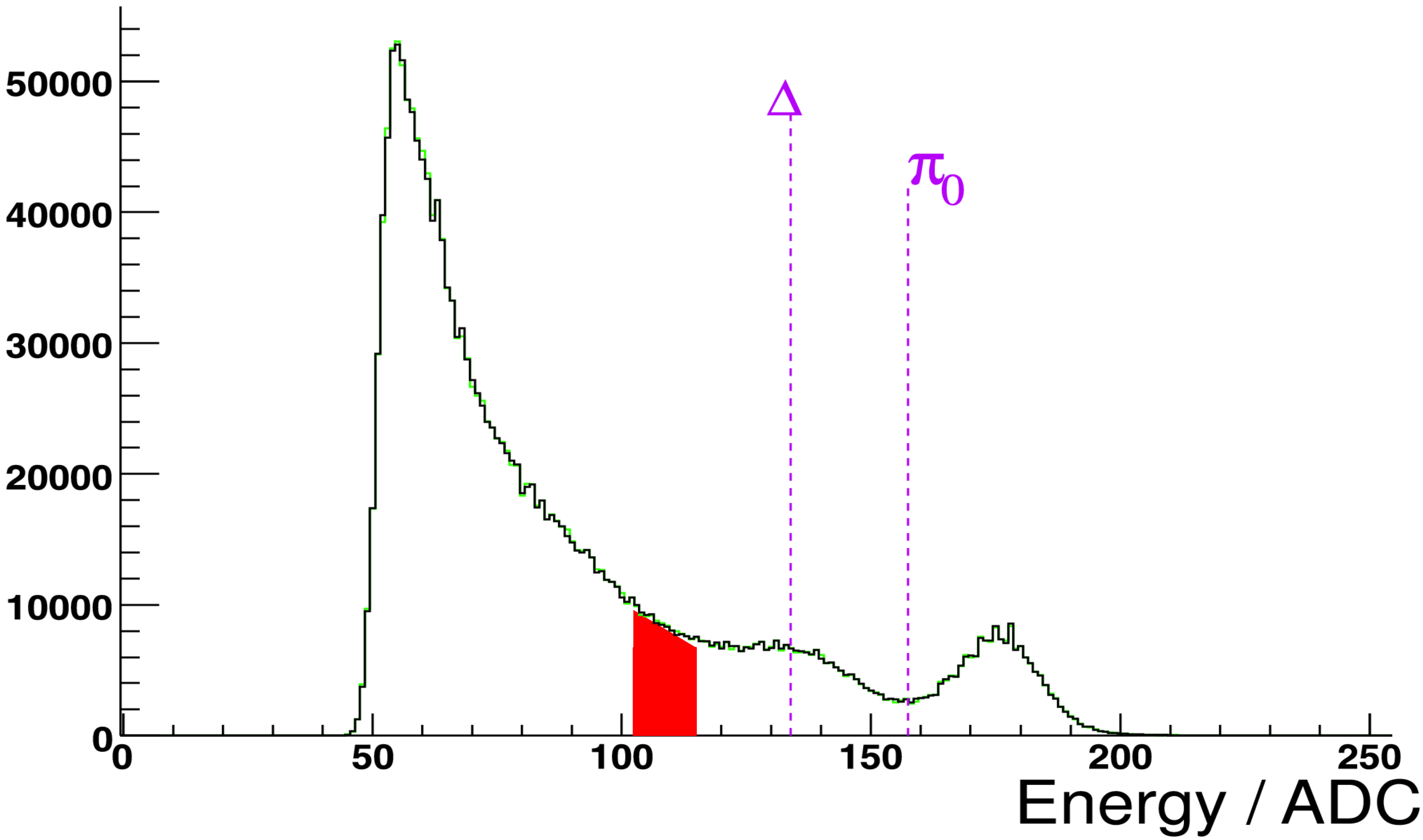


“A4-III”

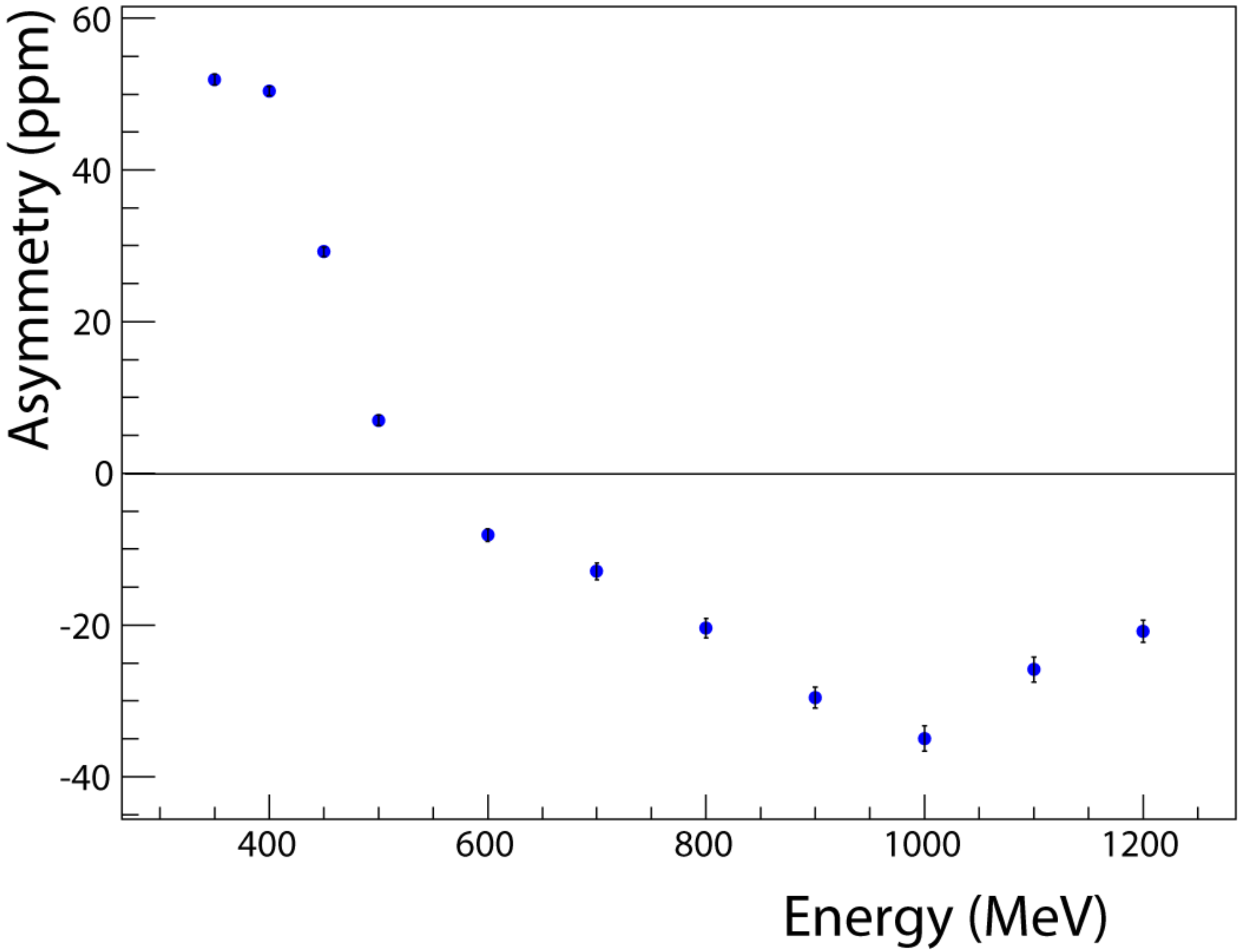
Asymmetry as a function of the energy of the scattered particles:



"A4-III"

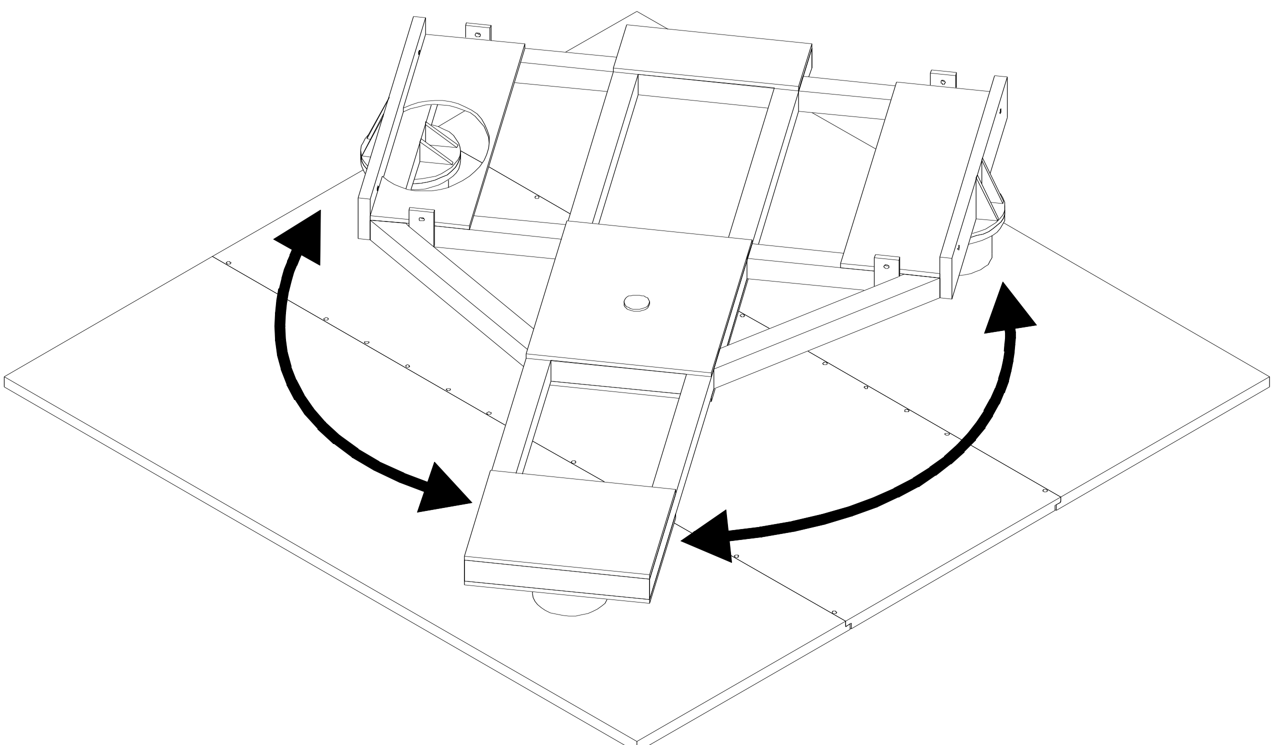
Asymmetry as a function of the energy of the scattered particles:

- Apply cuts with +- 50 MeV



“A4-IV”

- Turn calorimeter to backward angles
- Beam energy of 210 MeV (Q^2=0.11 GeV^2)
- Targets: H_2, D_2 (~ 1000 hours each)
- Aim: Reduce existing error by factor of 2
- Time scale: 2011 - 2012

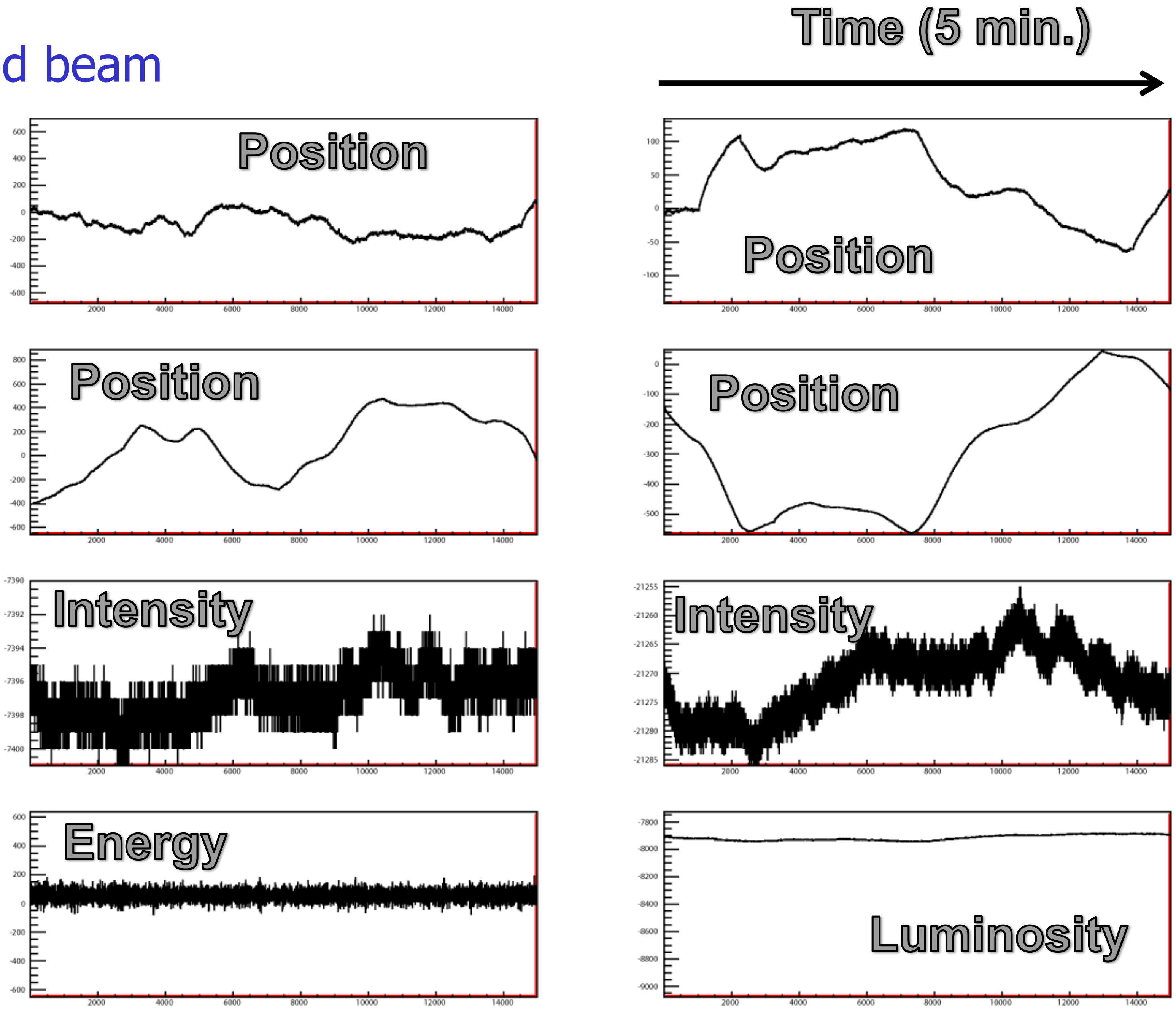


“A4-IV”

- Calorimeter rearrangement: **May-July 2011**
- Cavity installation at MAMI-B for energy measurement and stabilization: **July 2011**
- First 210 MeV beam with H_2: **August 2 – August 22, 2011**
- First check / analysis of data: **August 24 – September 3, 2011**

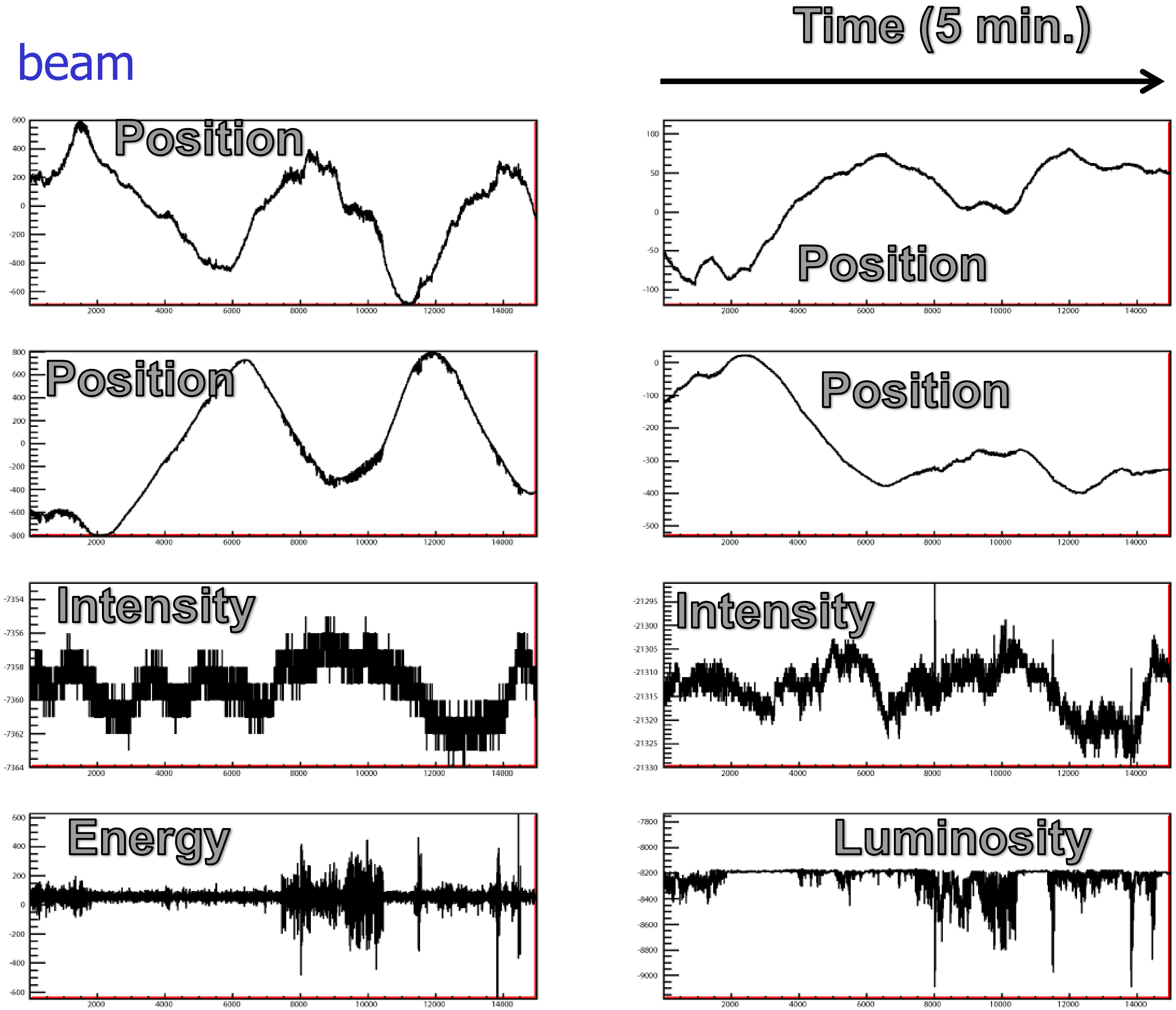
“A4-IV”

- Good beam



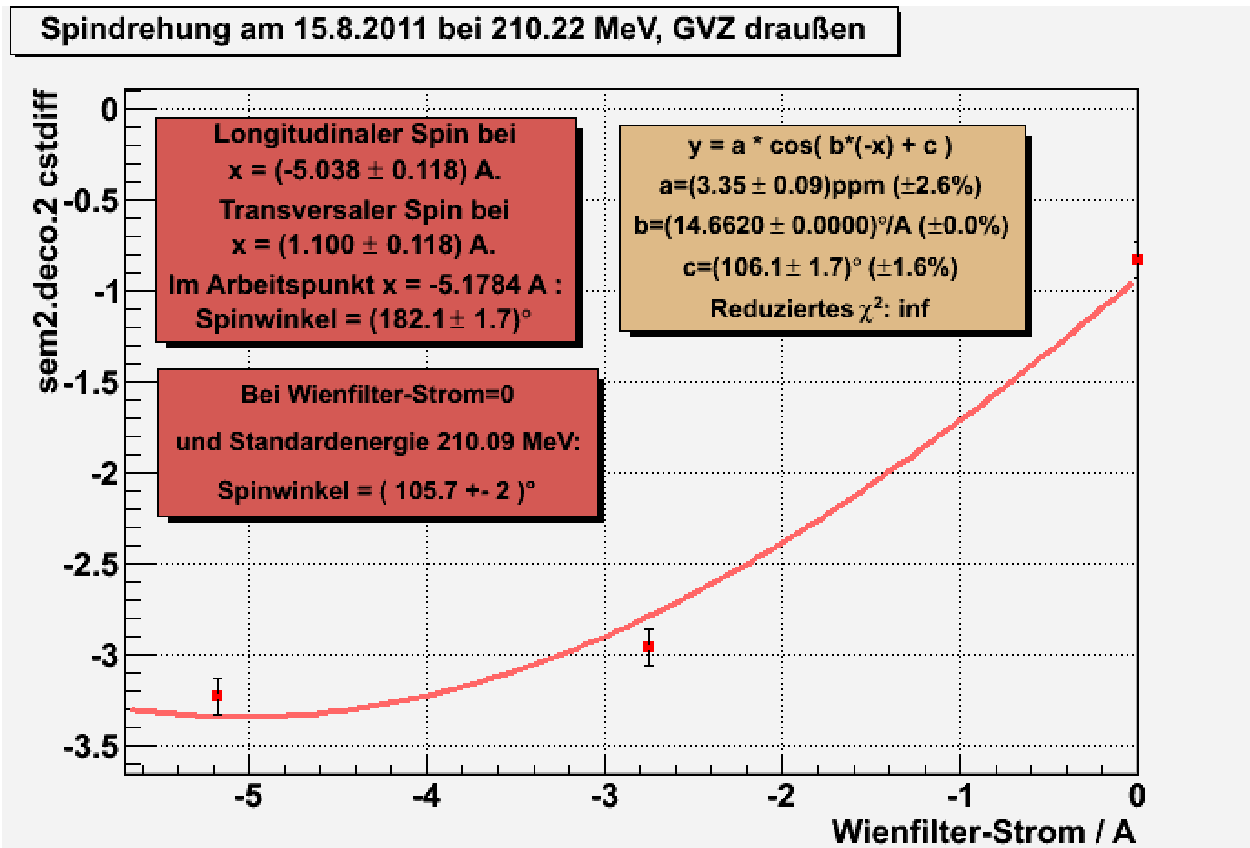
"A4-IV"

- Bad beam



"A4-IV"

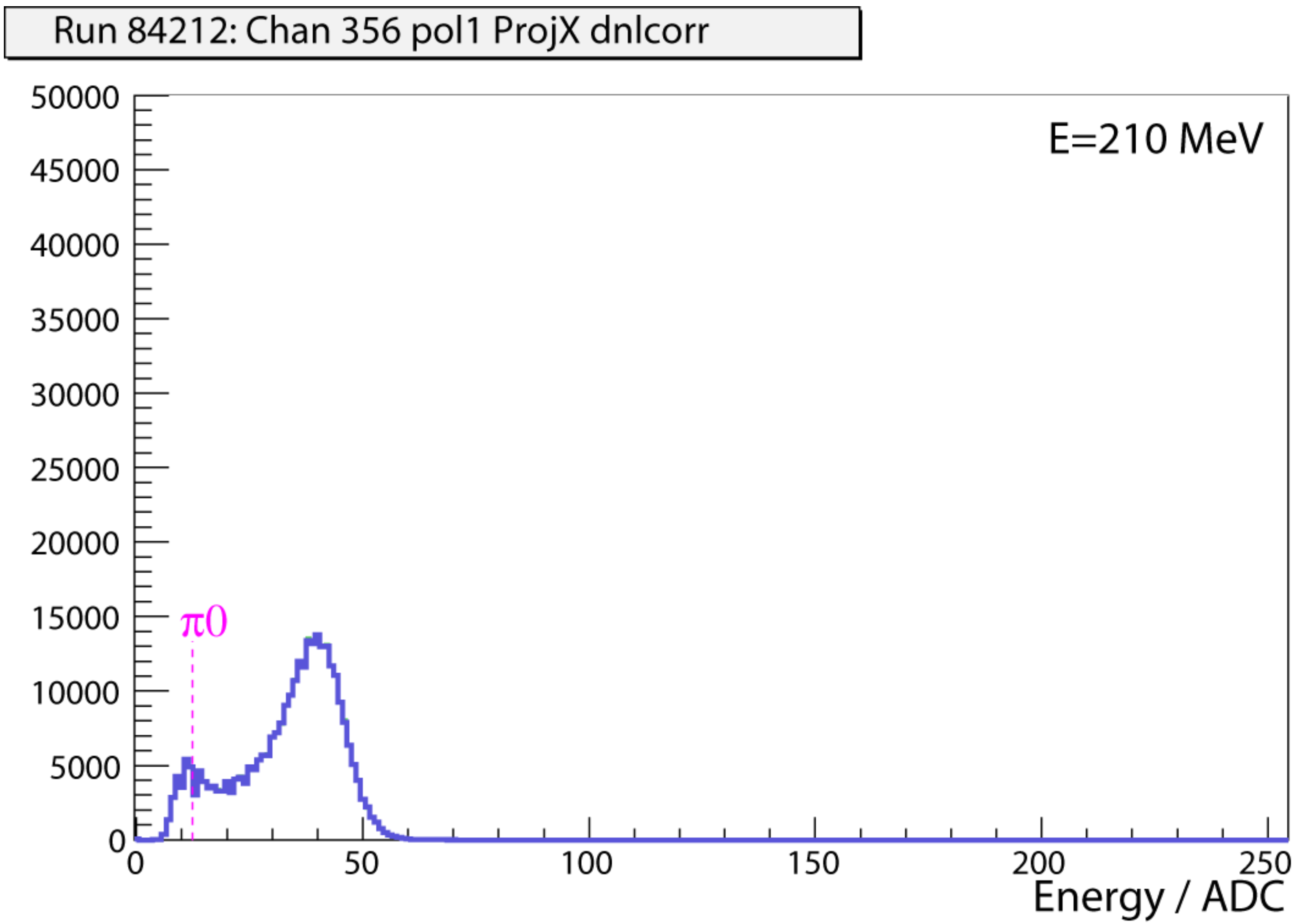
- Determination of spin angle: **Spin rotation**



- **Spin longitudinal within uncertainty of +-2°**

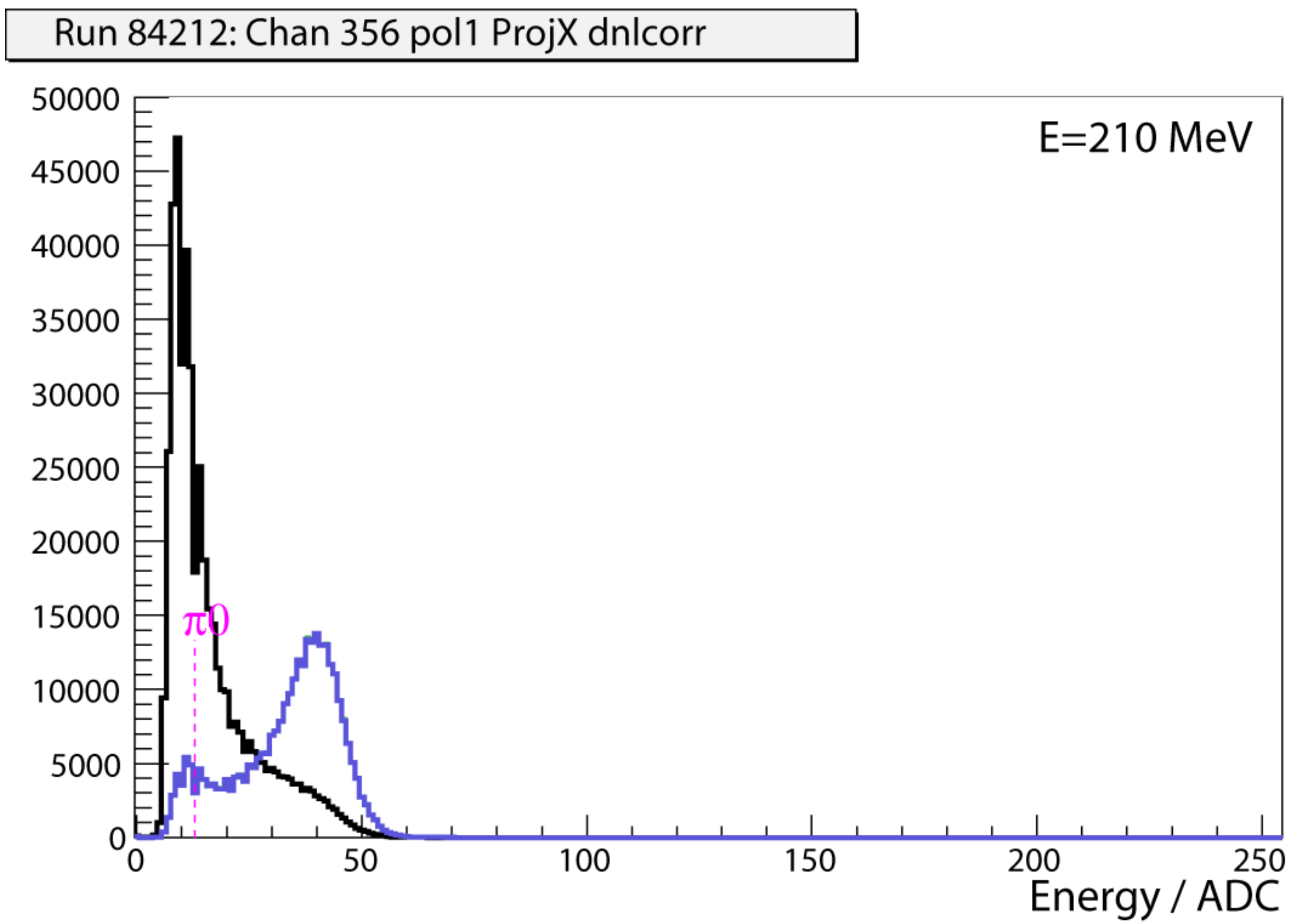
"A4-IV"

- **PbF2 energy spectrum** for E=210 MeV
- Elastic peak and pion threshold visible



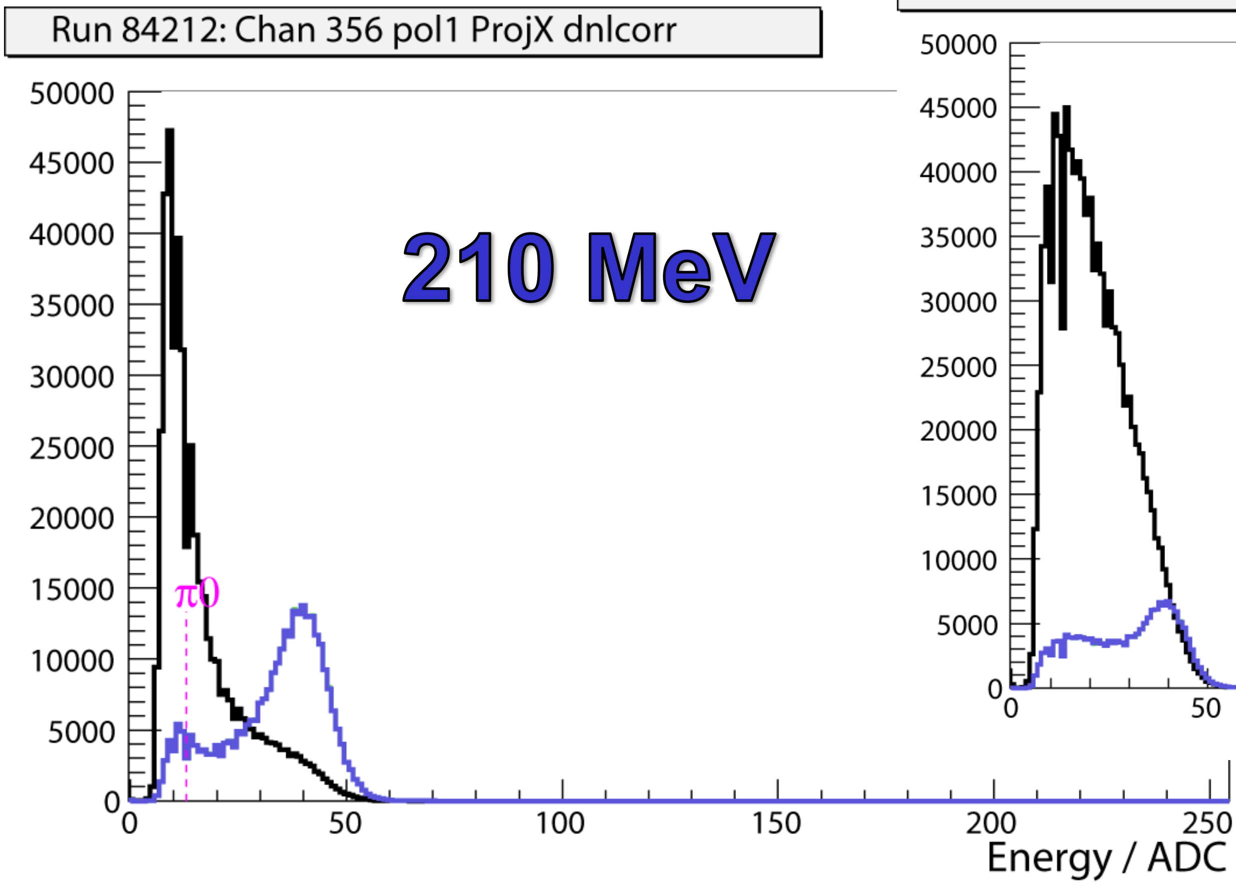
“A4-IV”

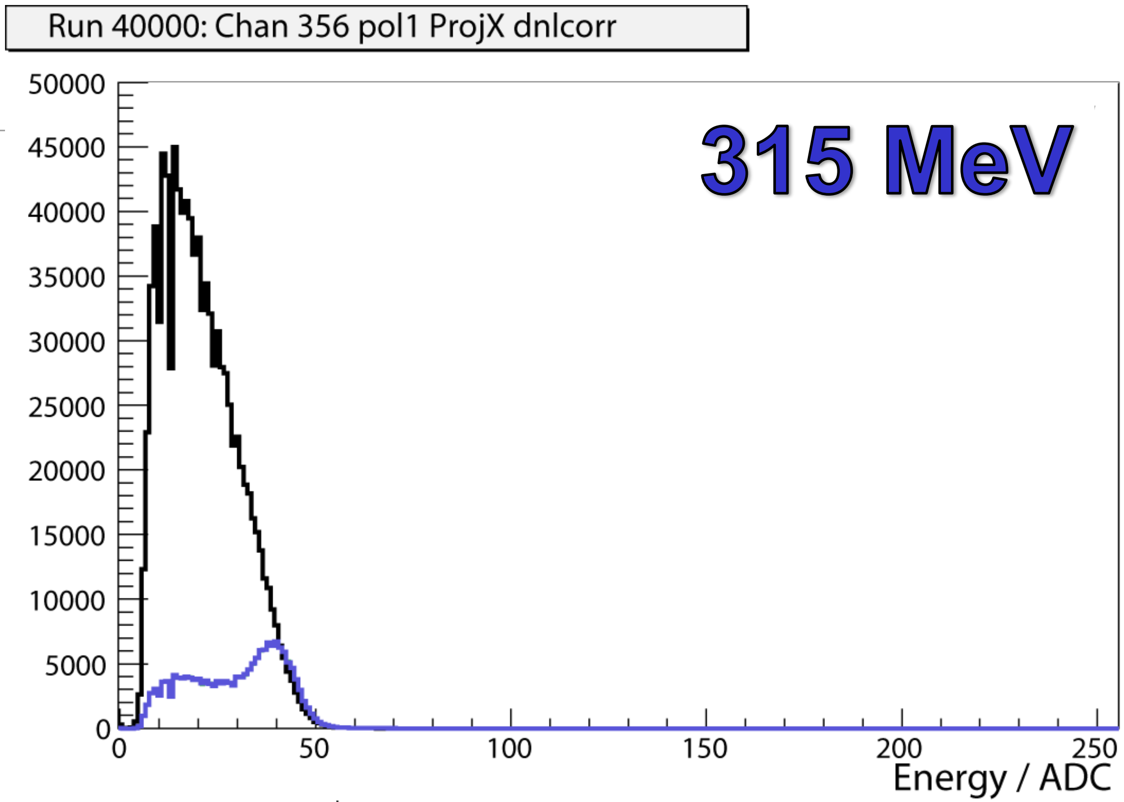
- Measurement with scintillators:
- **Coincidence (*charged particles*)**
- **Non-coincidence (*neutral particles*)**



"A4-IV"

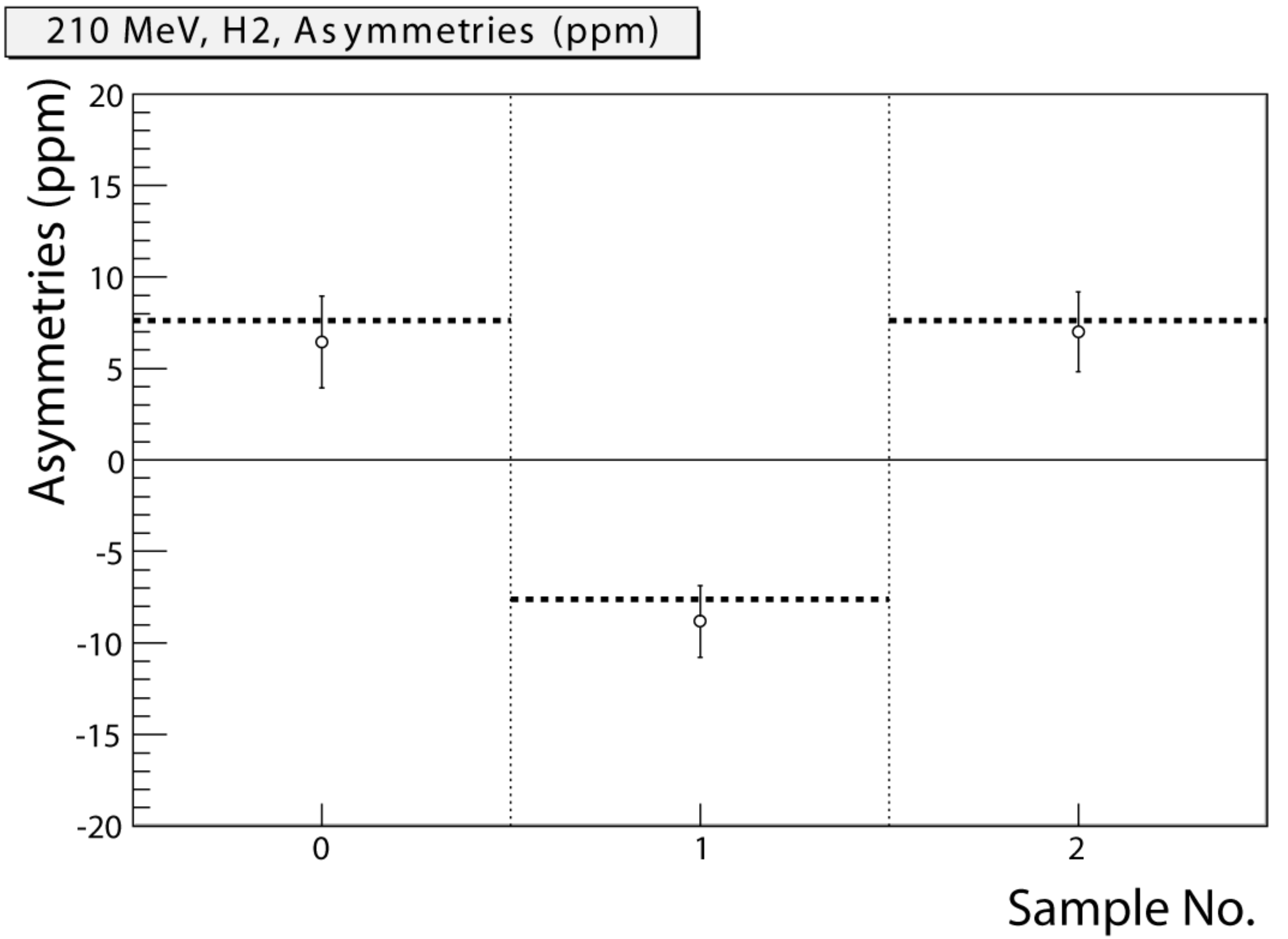
- Less background contamination than in 315 MeV measurement!





"A4-IV"

- ~ 250 hours of data, halfwave plate IN / OUT
- **Rough analysis** yields**:**



“A4-IV”

- Error estimation, based on data from this beamtime:

$G_M s$ (Q^2=0.1 GeV^2) = xxx +- 0.36 *(G_A taken from calculation)*

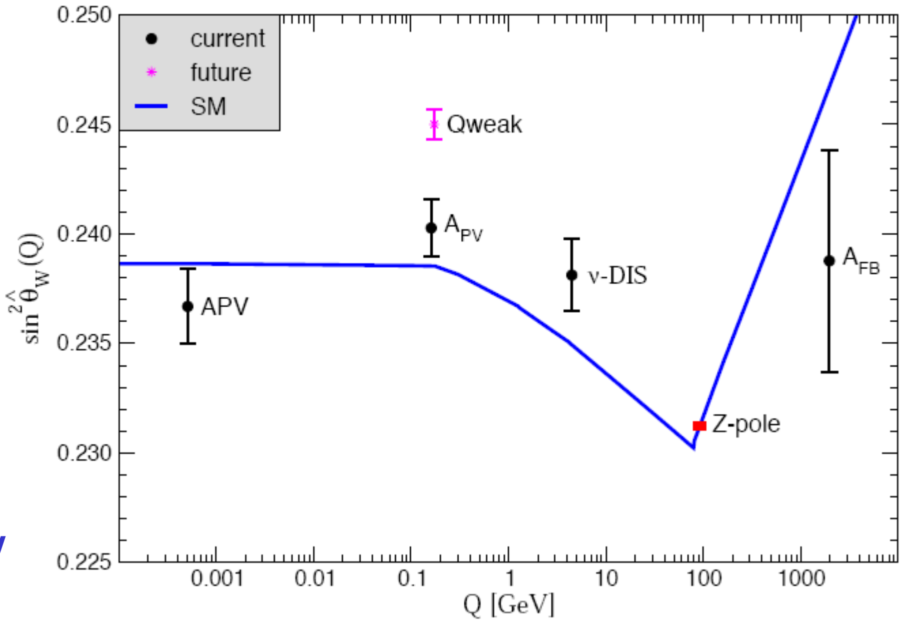
- Comparison with SAMPLE result *(D.T. Spayde et al., Phys Lett. B583 (2004))*

$G_M s$ (Q^2=0.1 GeV^2) = 0.37 +- 0.33 *(G_A taken from calculation)*

Next beamtimes will reduce the uncertainty.

Beyond A4...

- Measurement of the weak charge of the proton at low $Q^2 \sim 0.05\ GeV^2$
- New detector
- Enhanced polarimetry (*Brute force Moller, Double Mott => Mainz 0.5*)
- Beam energy 137 MeV (*low theoretical uncertainties due to two-boson-exchange*)
- Precision goal: $\Delta \sin^2\Theta_W = 0.00037$
- Time scale: 2015 - 2020



Summary

A4 experiment:

- 10 years of parity violating electron scattering at MAMI
- Five kinematical points covering momentum transfers between 0.1 GeV^2 and 0.6 GeV^2
- Side product: Exploration of the Two-Photon Exchange Amplitude

What have we learnt?

- Strangeness contributions to the electromagnetic form factors are small
- Since they are small, it is hard to measure a non-zero with signifance.

What can we do at MAMI in the future?

- Precision measurement at low Q^2=0.1 GeV^2 (G_M^s and G_A)
- High precision measurement: The weak charge of the proton ($\sin^2\Theta_W$)

Strangeness contribution to the nucleon form factors

Flavour Decomposition of form factors:

$$G^{p}_{E,M} = \frac{2}{3} G^{p,u}_{E,M} - \frac{1}{3} G^{p,d}_{E,M} - \frac{1}{3} G^{p,s}_{E,M}$$

$$G^{n}_{E,M} = \frac{2}{3} G^{n,u}_{E,M} - \frac{1}{3} G^{n,d}_{E,M} - \frac{1}{3} G^{n,s}_{E,M}$$

4 equations, 12 unknown quantities…

Charge Symmetry

Proton and neutron form an isospin dublett with
T=1/2 and T_3=+1/2 (p) and T_3=-1/2 (n)

$$G_{E,M}^{p,u} = G_{E,M}^{n,d}$$

$$G_{E,M}^{p,d} = G_{E,M}^{n,u}$$

$$G_{E,M}^{p,s} = G_{E,M}^{n,s}$$

Strangeness in the Nucleon

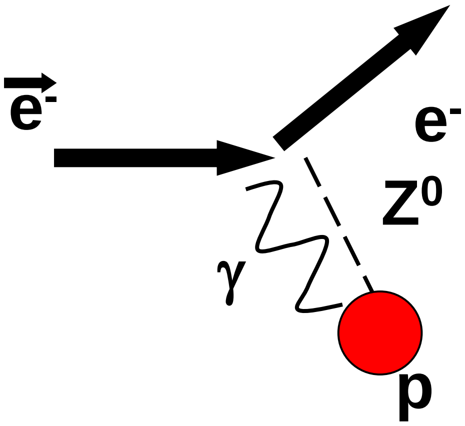
Charge symmetry:

$$G^{p}_{E,M} = \frac{2}{3} G^{u}_{E,M} - \frac{1}{3} G^{d}_{E,M} - \frac{1}{3} G^{s}_{E,M}$$

$$G^{n}_{E,M} = \frac{2}{3} G^{d}_{E,M} - \frac{1}{3} G^{u}_{E,M} - \frac{1}{3} G^{s}_{E,M}$$

4 equations, 6 unknown quantities…

Weak interaction



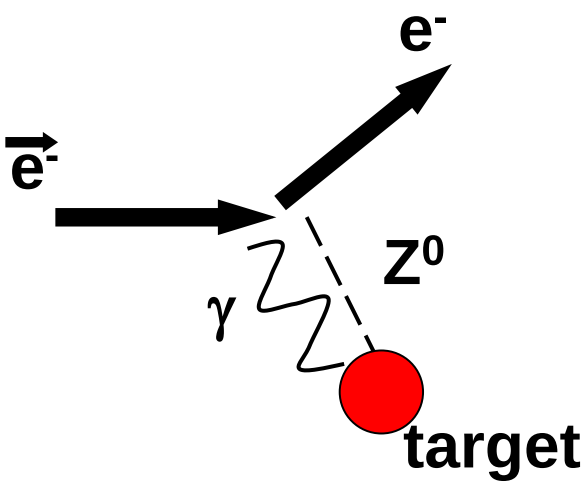
Exchange of photon and Z^0

Universality of quark distribution

$$G_{E,M}^{p,Z} = \left(\frac{1}{4} - \frac{2}{3}\sin^2\Theta_W\right) G_{E,M}^{u} - \left(\frac{1}{4} - \frac{1}{3}\sin^2\Theta_W\right) G_{E,M}^{d} - \left(\frac{1}{4} - \frac{1}{3}\sin^2\Theta_W\right) G_{E,M}^{s}$$

Two more equations => Problem in principle solved

Parity violating electron scattering



- Polarised electron beam
- Unpolarised target

$$\sigma \propto |M^{EM} + M^{NC}|^2 \approx 1 \square 10^{-6} \square 10^{-12}$$

Direct measurement not possible

=> Asymmetry measurement

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M^{NC}|}{|M^{EM}|} \sim \frac{Q^2}{\square M_Z \square^2} \approx 10^{-6}$$

A4 backward results (H_2 / D_2)