

A project to measure quantum spin correlations of relativistic electron pairs in Møller scattering

Jacek Ciborowski

P. Caban, M. Dragowski, J. Enders,
Y. Fritzsch, A. Poliszczuk,
J. Rembieliński, M. Włodarczyk

University of Warsaw, University
of Łódź, Technische Universität
Darmstadt



Motivation

- 1935 paradox EPR Einstein, Podolsky, Rosen
- 1950 Bohm's idea of spin correlations
- 1963 Bell's inequalities
- 1969 CHSH inequality Clauser, Horne, Shimony, Holt
- 1982-> violation established (pairs of photons)
Aspect et al. (numerous subsequent expts)
- violation established for non-relativistic proton pairs
(massive fermions)
- 2000-ties theory startup on **spin correlations**
of relativistic massive particles:
new physics topics

Physics issues

- Spin
- Localisation
- Non-locality vs. Lorentz symmetry
- Beyond the Einstein's relativity

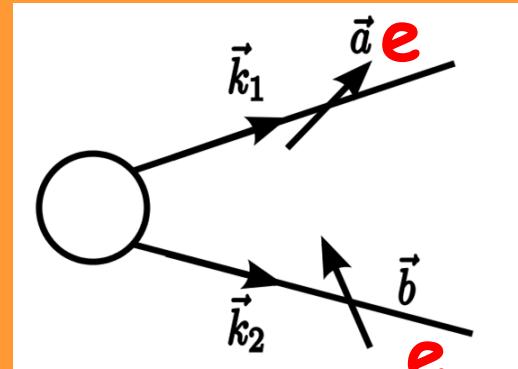
M. Czachor	Phys. Rev. A 55 (1997) 72
J. Rembieliński + co-workers	Phys. Rev. A 66 (2002) 052114 Phys. Rev. A 68 (2003) 042107
For various bipartite pure states	Phys. Rev. A 72 (2005) 052103 Phys. Rev. A 73 (2006) 042103 Phys. Rev. A 77 (2008) 012103 Phys. Rev. A 79 (2009) 014102

No measurements until now

fermions, bosons
singlet, triplet

Aim of the project

- relativistic Møller scattering:
(semi-polarised) $e^-e^- \rightarrow e^-e^-$
- spin projections e^-, e^-
at chosen directions:
+ or - : Mott polarimetry
- measure CORRELATIONS: probabilities P_{ij}
 $C = P_{++} + P_{--} - P_{-+} - P_{+-}$: correlation function
- Testing spin observables
(not a Bell test)



Predictions

- For C and probabilities P
- Obtained by us using the Newton-Wigner spin operator ("best choice") - S

$$C(\vec{a}, \vec{b}) = Tr[\rho(\hat{\vec{a}S} \otimes \hat{\vec{b}S})]$$

ρ - spin density matrix

- Expect a relativistic term in C

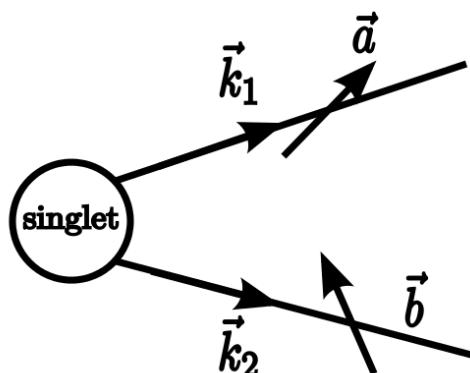
What is the relativistic term?

Simple case: singlet

singlet $\rightarrow k_1 k_2$

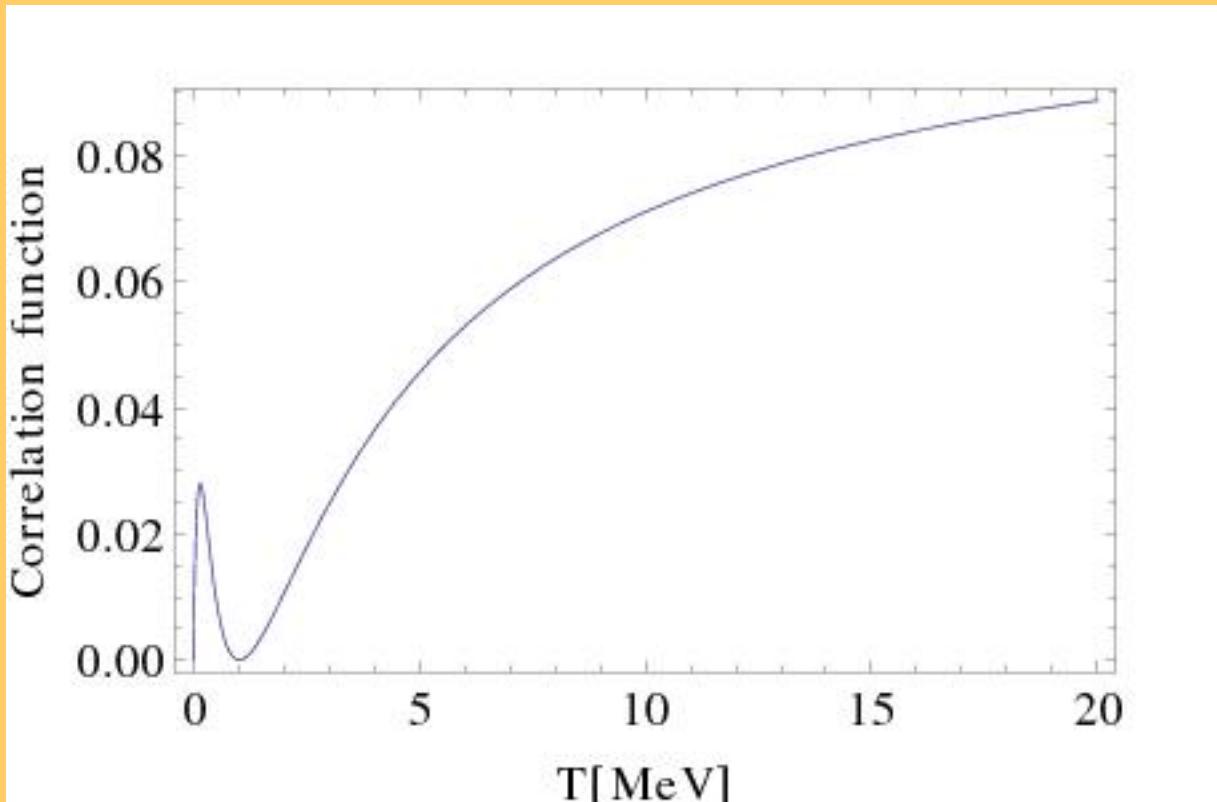
$$\mathcal{C}(\vec{a}, \vec{b}) = -\vec{a} \cdot \vec{b} +$$

$$+ \underbrace{\frac{\vec{k}_1 \times \vec{k}_2}{m^2 + k_1 k_2} \left[\vec{a} \times \vec{b} + \frac{(\vec{a} \cdot \vec{k}_1)(\vec{b} \times \vec{k}_2) - (\vec{b} \cdot \vec{k}_2)(\vec{a} \times \vec{k}_1)}{(k_1^0 + m)(k_2^0 + m)} \right]}_{\text{relativistic correction}}$$



Relativistic term depends on outgoing momenta

Correlation function Møller



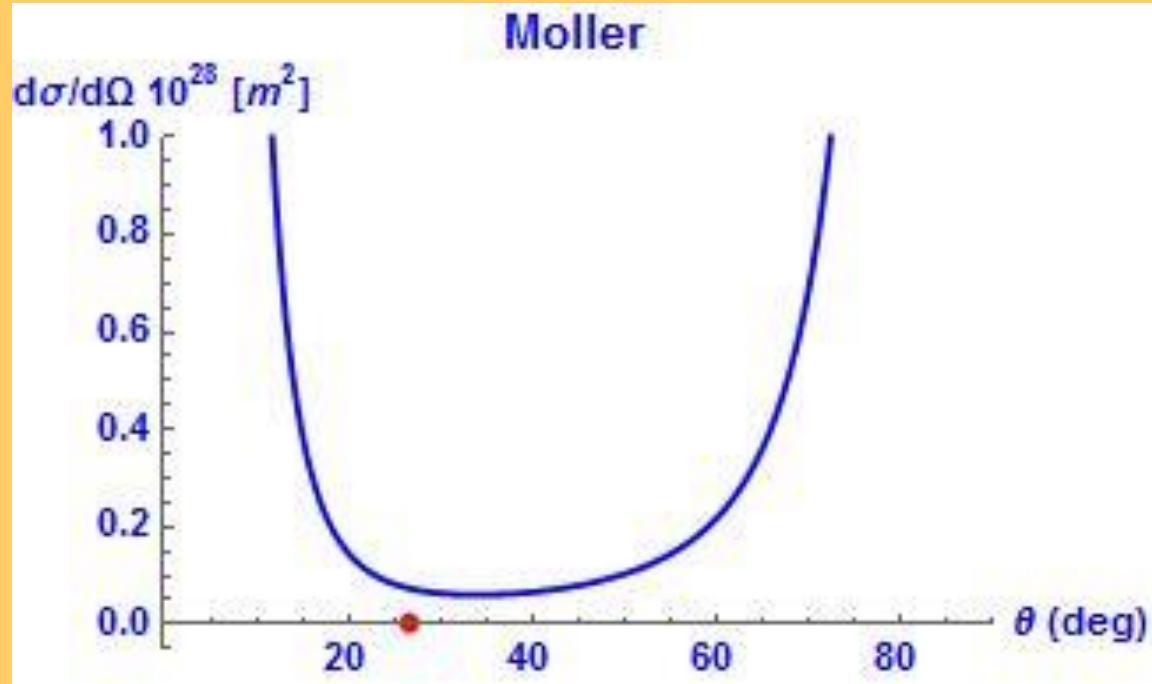
J. Rembieliński,
P. Caban, M.
Włodarczyk,
Phys. Rev. A 88
(2013) 032116;

Phys. Rev. A 88
(2013) 022119;



T- beam energy, symmetric scattering, projection directions
a,b in the scattering plane

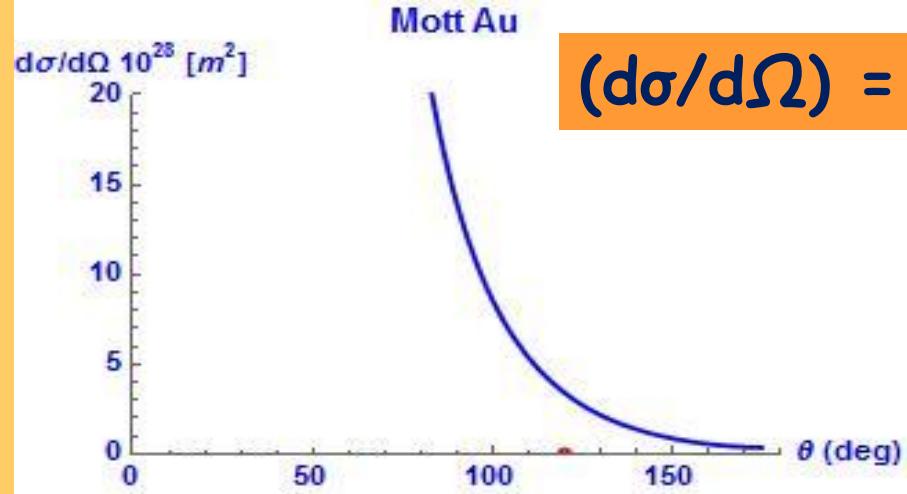
(1) Møller scattering



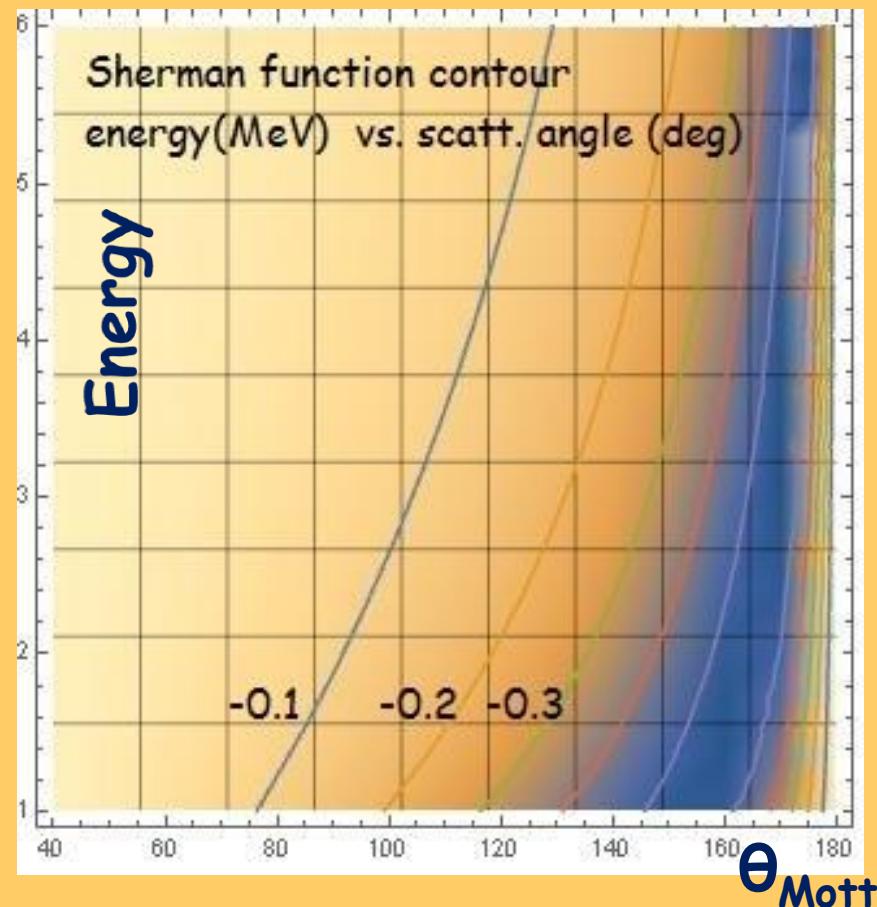
- 3 MeV polarised e^- beam
- 25 μm Be target (unpolarised)
- scattering on atomic electrons
- e^- -Be Mott bgd

Max correlation for symmetric scattering: $\theta=26.75^\circ$

(2) Mott scattering

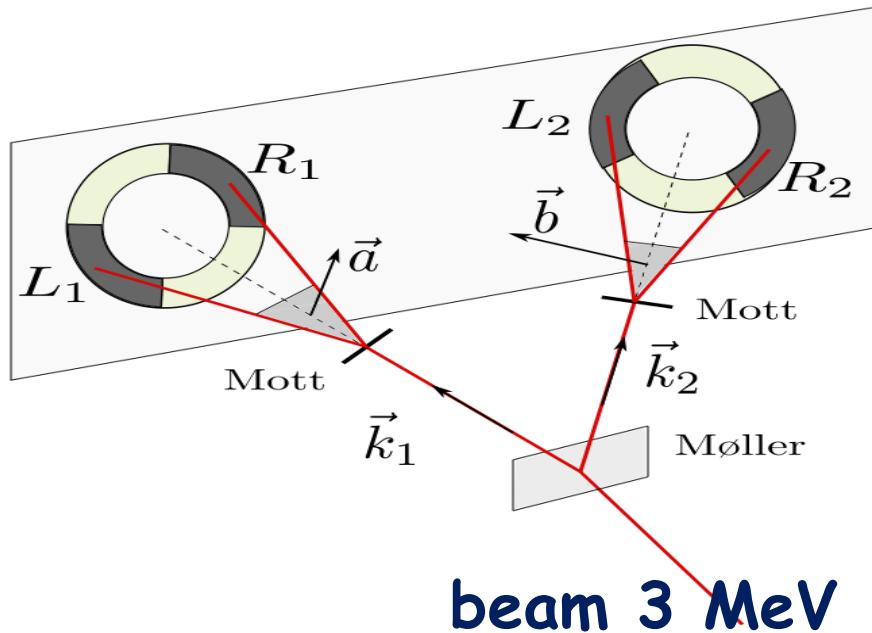


$$(d\sigma/d\Omega) = (d\sigma/d\Omega)_{\text{unpol}} [1 + S(\theta) P \cdot n]$$



- $E \approx 1.5 \text{ MeV } e^-$
- $S(\theta)$ - Sherman function
- $P \cdot n$ - spin projection -
= AsymLR / $S(\theta)$

Double Mott polarimetry



$$\text{Mott: } \vec{a} \perp \vec{k}_1 \quad \vec{b} \perp \vec{k}_2$$

Need a
dedicated
double
polarimeter

(4 counters)

Counting coincidences:

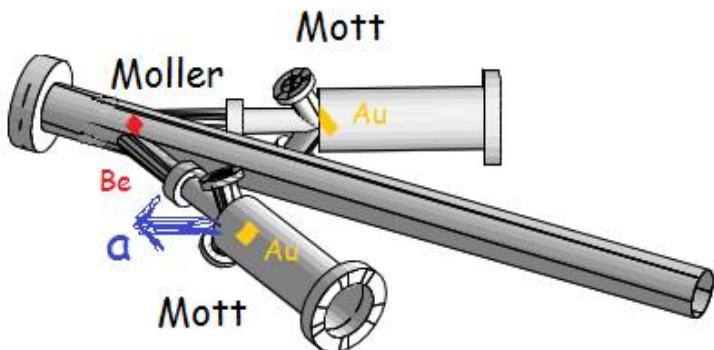
$L_1 L_2$, $R_1 R_2$, $L_1 R_2$, $R_1 L_2$

4 numbers

(3) Deriving results

- $L_1 L_2, R_1 R_2, L_1 R_2, R_1 L_2 \rightarrow$ procedure Θ
 $\rightarrow P_{++}, P_{--}, P_{-+}, P_{+-}$ 4 probabilities
- Θ critically depends on $S_{\text{eff}}(\theta)$ (given target)
- scarce available data on $S_{\text{eff}}(\theta)$
 - dedicated measurement of Sherman function at $E=1.5$ MeV
 - simulations (in progress)

(4) The double polarimeter



Prototype under construction:



Angular acceptances:

- Møller $\approx 3 \cdot 10^{-4} \text{ sr}$ 3 MeV
- Mott $\approx 7 \cdot 10^{-3} \text{ sr}$ 1.5 MeV

$$\theta_{\text{Mott}} \approx 110^\circ$$

No tracking

Møller target $\approx 25 \mu\text{m}$ Be

2 Mott targets $\approx 10 \mu\text{m}$ Au

Precise mechanical symmetry

Event rate:

order of $10^{-16}/\text{beam e}$

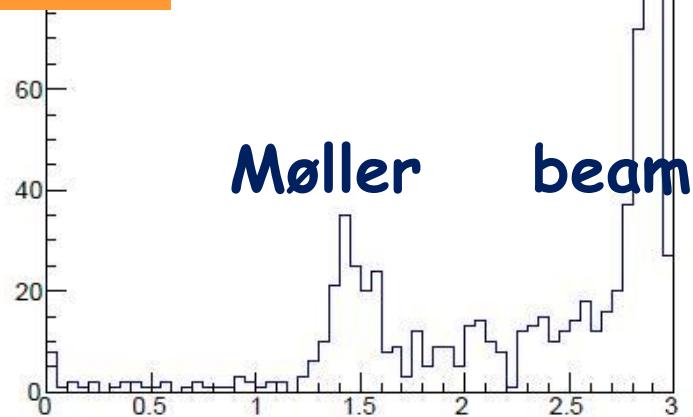


(5) Detector simulations

energy deposit sum in all counters

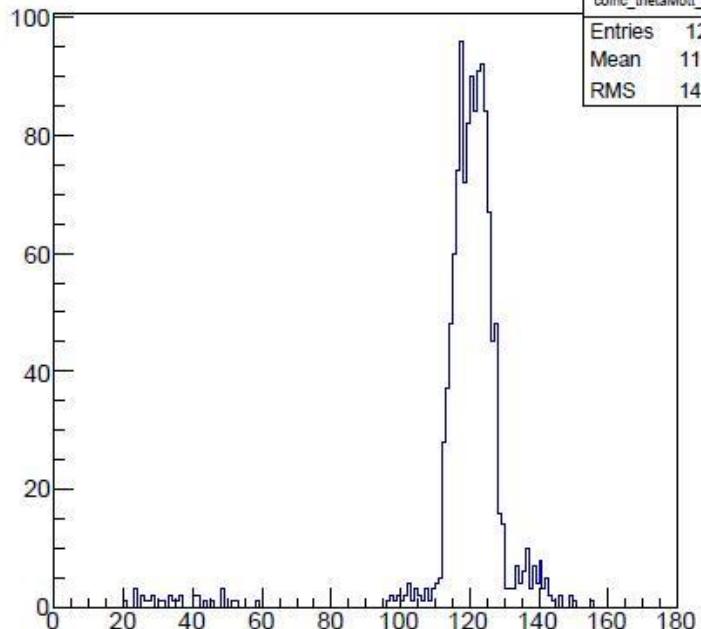
coinc_totEDep
Entries 786
Mean 2.305
RMS 0.6991

Geant4



mott theta, moller moller events

coinc_thetaMott_min
Entries 1269
Mean 119.3
RMS 14.55



Energy (MeV)

Mott θ (deg)

Background reduction owing to coincidences and energy cuts

(6) Beam

S-DALINAC



- Institut fuer Kernphysik
Technische Universitaet
Darmstadt
- 3 MeV extraction
(pre-accelerating stage)
- polarisation 0.35 - 0.85,
L & T
- beam $\approx 10^{14}$ e⁻/s (20 μ A)
- $10^2 \div 10^3$ events/day
- polarised e⁻ source under
construction

Summary

- First attempt ever to measure relativistic quantum spin correlations (Møller pairs)
- Testing spin observables in rQM
- Predictions different than for photons !!!
- Prototype of a dedicated double Mott polarimeter under construction
- Lab tests using a β -source under way
- Future: 3 MeV 0.35-0.85 % L,T polarised e^- beam at S-DALINAC (Darmstadt)
- Prototype operation by 2017 (proof)

Backup

A glance at the spin in rQM

In unitary, non-reducible representation of the Poincaré group, the square of the spin is defined:

$$\hat{W}^\mu \hat{W}_\mu |k, \lambda\rangle = -m^2 s(s+1) |k, \lambda\rangle$$

where \hat{W}^μ is the Pauli-Lubanski vector.

There exists no covariant position operator in rQM, Q, needed to define the spin operator according to decomposition:

$$\hat{S} = \hat{\vec{J}} - \hat{\vec{Q}} \times \hat{\vec{P}}$$

where $\hat{\vec{J}}$ is the total angular momentum (generator of rotations)

Many position operators proposed, none fulfills all the requirements:

- 1. Hermiticity**
- 2. Commuting components**
- 3. Canonical commutation relations with momentum operators**
- 4. Covariance w.r.t. rotations and Lorentz boosts**
- 5. Covariant eigenvectors**

**The best choice: Newton-Wigner position operator
for which one obtains the following spin operator:**

$$\hat{\vec{S}}_{NW} = \frac{1}{m} \left(\hat{\vec{W}} - \hat{W}^0 \frac{\hat{\vec{P}}}{\hat{P}^0 + m} \right)$$

- 1. Linear function of components of the Pauli-Lubanski four-vector**
- 2. Components fulfill standard commutation relations for spin operators**
- 3. Reduces to the Pauli-Lubanski four-vector in the rest frame**
- 4. However not Lorentz covariant**

Used by M. Czachor:

$$\hat{\vec{S}}_{MC} = \frac{\vec{a} \hat{\vec{W}}}{\sqrt{m^2 + (\vec{a} \vec{P})^2}}$$