Testing Locality via Bell's Inequality at Colliders?

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ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

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(*Received* 4 *November* 1964)

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly non-local structure. This is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions.

II. Formulation

With the example advocated by Bohm and Aharonov [6], the EPR argument is the following. Consider a pair of spin one-half particles formed somehow in the singlet spin state and moving freely in opposite directions. Measurements can be made, say by Stern-Gerlach magnets, on selected components of the spins $\vec{\sigma}_1$ and $\vec{\sigma}_2$. If measurement of the component $\vec{\sigma}_1 \cdot \vec{a}$, where $\vec{a}$ is some unit vector, yields the value

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I completed my PhD there 25 years later

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My b'day, I was exactly 2 yrs old

60th anniversary coming up

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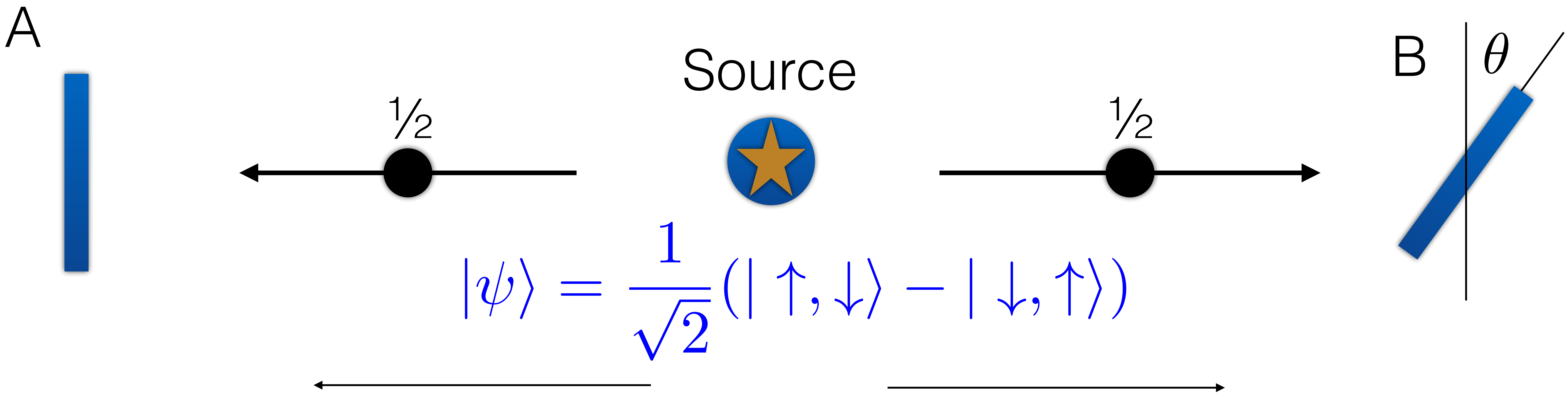
What did Bell say?

$$A(\vec{a}, \lambda) = \pm 1 \qquad\qquad B(\vec{b}, \lambda) = \pm 1$$

- Consider two spin-½ particles flying apart, spins anti-correlated

QM: $$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow, \downarrow\rangle - |\downarrow, \uparrow\rangle\right)$$

- QM measurement of component: $\vec{\sigma}_A \cdot \vec{a}, \quad \pm 1 \overset{\vec{b} = \vec{a}}{\Longrightarrow} \vec{\sigma}_B \cdot \vec{a}, \quad \mp 1$



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle)$$

QM Expectation

$$|\vec{a}| = |\vec{b}| = 1$$

- QM expectation value: $\langle \vec{\sigma}_1 \cdot \vec{a} \;\; \vec{\sigma}_2 \cdot \vec{b} \rangle = -\vec{a} \cdot \vec{b} = -\cos\theta$

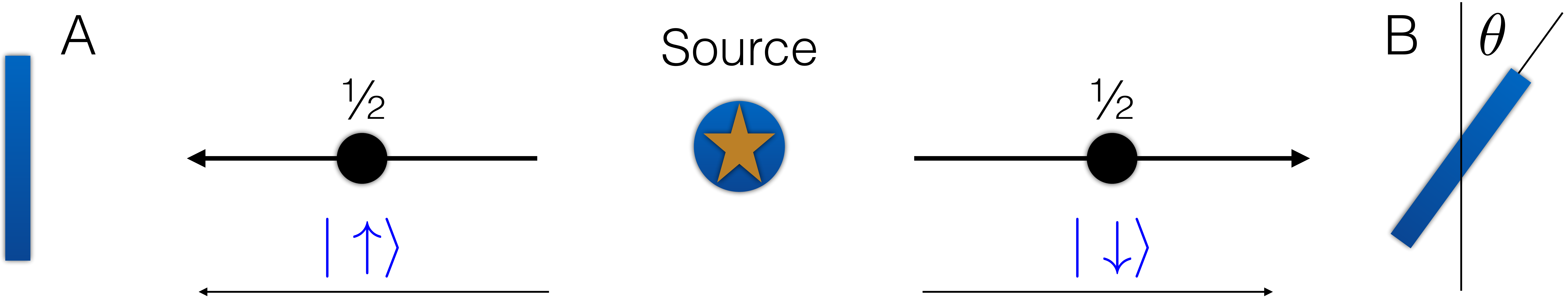
- States are **entangled** — information connected despite separation

- State on the left is only determined AFTER measurement on the right (assuming measurement on the right is first)

What was Bell interested in?

$$\mathrm{A}(\vec{a}, \lambda) = \pm 1 \qquad \mathrm{B}(\vec{b}, \lambda) = \pm 1$$

- Can this be described by a local hidden variable theory (LHVT)?
- What is a LHVT? — “Common sense”
- Measurements at A and B are independent of each other
- And the results as well



- Emitted at source with **definite** spin, just spins are anti-correlated
- If results are independent: a person or a machine can sit at source and toss out the pairs
- Definite result is achieved through additional, unknown, hidden variables

$\lambda_i \to \lambda,$ $\rho(\lambda)$ prob. dist.

- LHVT expectation value

$$P(\vec{a},\vec{b}) = \int d\lambda\, \rho(\lambda)\, A(\vec{a},\lambda) B(\vec{b},\lambda)$$

$$\int d\lambda\, \rho(\lambda) = 1$$

- No problem for LHVT to reproduce several special cases

1) Spin measurement on a single particle $\vec{\sigma} \cdot \vec{a} \longrightarrow \mathrm{sign}(\vec{\lambda} \cdot \vec{a}')$

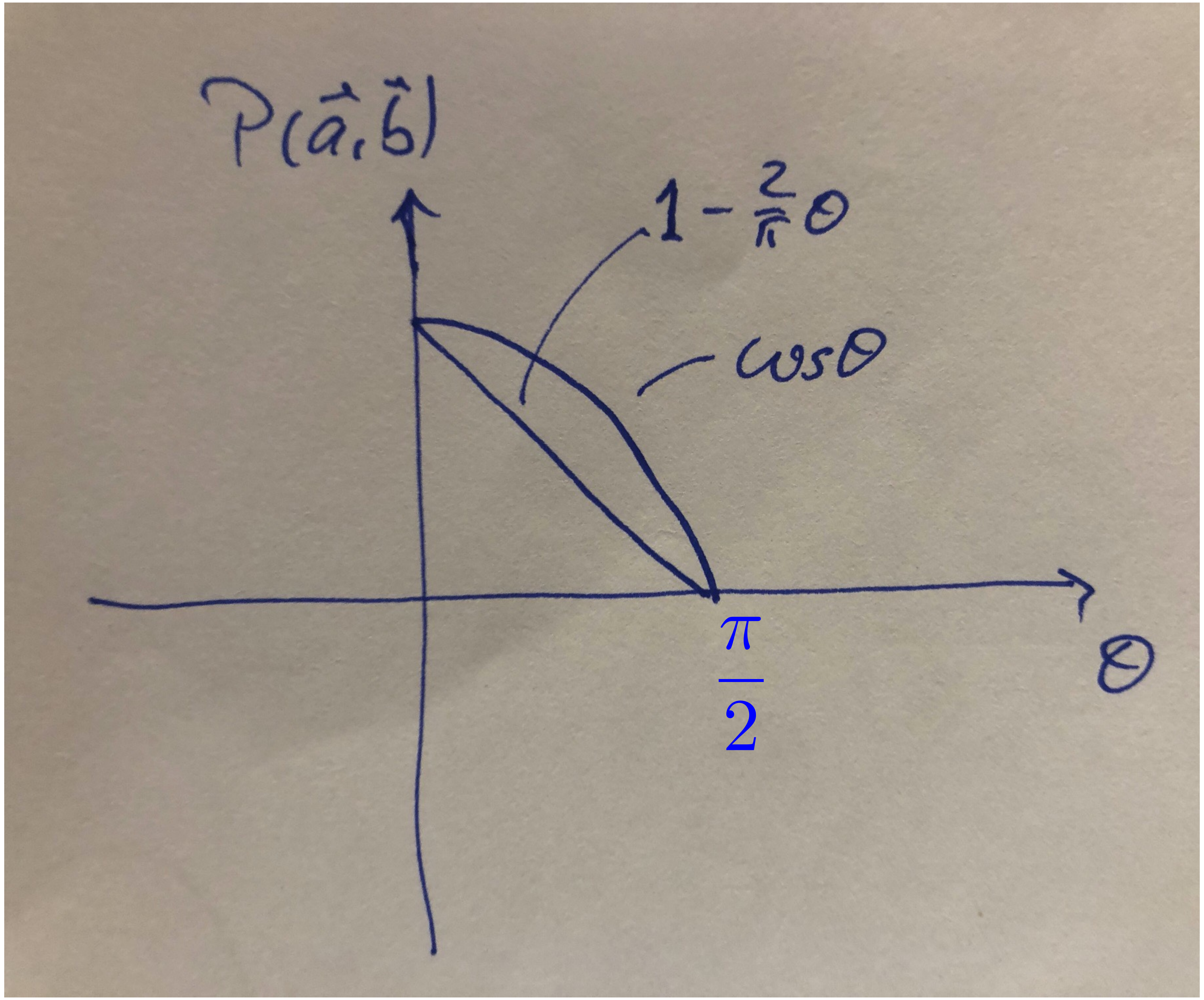
2) Using this in $P(\vec{a}, \vec{b})$ can easily reproduce simple cases

$$P(\vec{a}, \vec{a}) = -P(\vec{a}, -\vec{a}) = -1$$

$$P(\vec{a}, \vec{b}) = 0, \quad \text{if} \quad \vec{a} \cdot \vec{b} = 0$$

3) The most general case results in

$$P(\vec{a}, \vec{b}) = -1 + \frac{2}{\pi}\theta$$



- You need 3 measurements to distinguish the 2 curves

Bell's Inequality

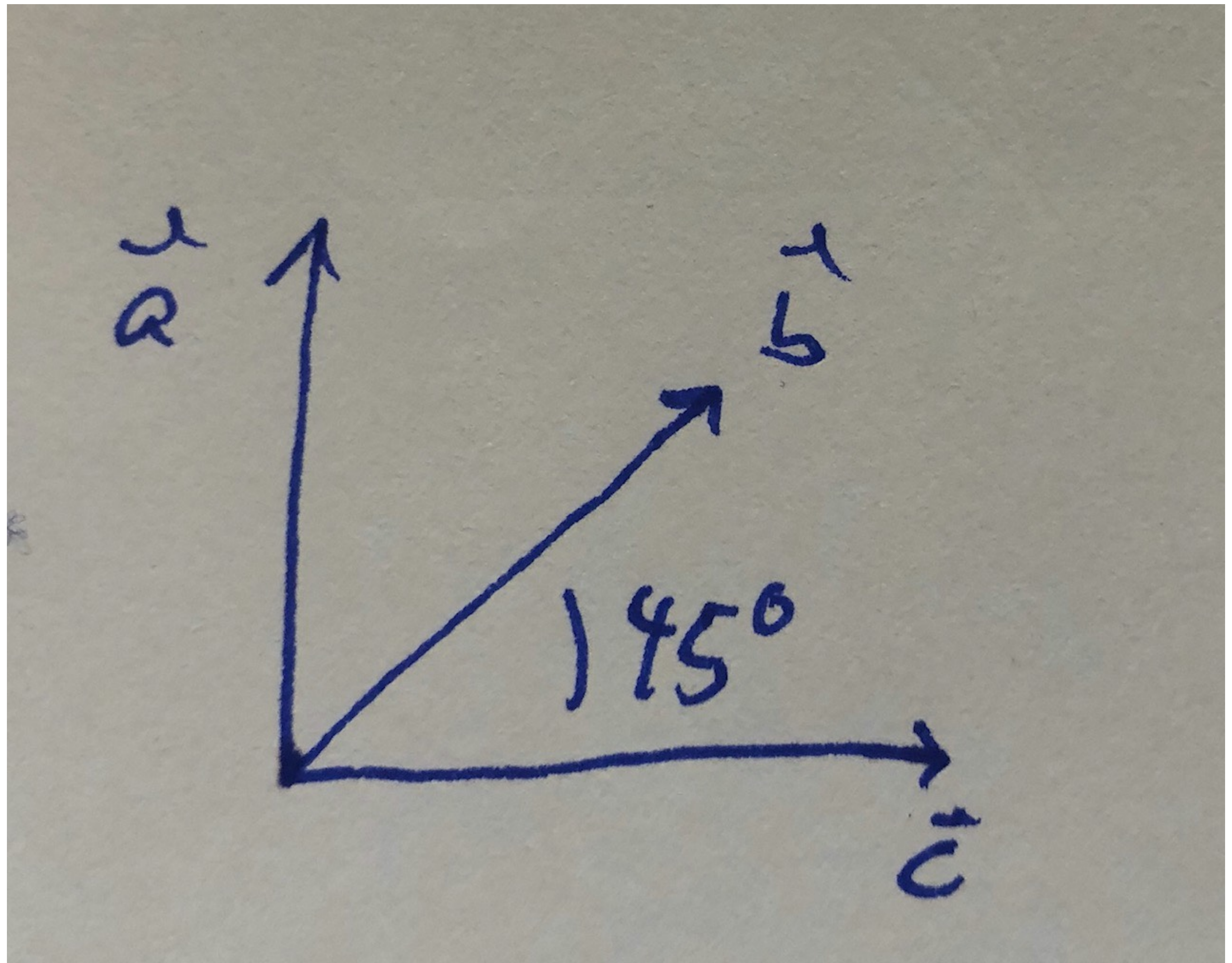
- Bell proved for all LHVT's

$$1 + P(\vec{b}, \vec{c}) \geq |P(\vec{a}, \vec{b}) - P(\vec{a}, \vec{c})|$$

- Note you need 3 settings

- QM expectation value violates this!

$$1 - \frac{1}{\sqrt{2}} \geq \frac{1}{\sqrt{2}}$$



Bell's Inequality

- All experimental tests of locality via Bell's inequality are with photons

- Measure 3 settings related to 2 independent spin components using polarimeters (Alain Aspect)

$$S_x , \quad S_y$$

- Would like to test this idea also at high energy and/or with fermions

Physics Letters B 280 (1992) 304–312
North-Holland

PHYSICS LETTERS B

Testing locality at colliders via Bell's inequality?

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(1992)

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We consider a measurement of correlated spins at LEP and show that it does *not* constitute a *general* test of local-realistic theories via Bell's inequality. The central point of the argument is that such tests, where the spins of two particles are inferred from a scattering distribution, can be described by a local hidden variable theory. We conclude that with present experimental techniques it is not possible to test locality via Bell's inequality at a collider experiment. Finally we suggest an improved fixed-target experiment as a viable test of Bell's inequality.

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How to find a Higgs boson with a mass between 155 and 180 GeV at the CERN LHC

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(1996)

(Received 13 August 1996)

We reconsider the signature of events with two charged leptons and missing energy as a signal for the detection of the standard model Higgs boson in the mass region $M(\mathrm{Higgs})=155$–180 GeV. It is shown that a few simple experimental criteria allow us to distinguish events originating from the Higgs boson decaying to $H \to W^+W^-$ from the nonresonant production of W^+W^-X at the CERN LHC. With this set of cuts, signal to background ratios of about one to one are obtained, allowing a 5–10σ detection with about 5 fb^{-1} of luminosity. This corresponds to less than one year of running at the initial lower luminosity $\mathcal{L}=10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. This is significantly better than for the hitherto considered Higgs boson detection mode $H \to Z^0Z^{0*} \to 2\ell^+2\ell^-$, where in this mass range about 100 fb^{-1} of integrated luminosity are required for a 5σ signal. [S0556-2821(97)02701-X]

PACS number(s): 14.80.Bn, 13.85.−t

Abel, Dittmar and Dreiner (1992)

- Our idea: at LEP use the decay

$$Z^0 \longrightarrow \tau^+ + \tau^- \longrightarrow (\pi^+ + \bar{\nu}_\tau) + (\pi^- + \nu_\tau)$$

tau-spins are correlated

weak decay of tau,
pion momentum correlated
with tau spin

- Consider: $P(\hat{p}_{\pi^-}, \hat{p}_{\pi^+})$; $\quad \hat{p}_{\pi^\pm}$ unit $\pi^\pm$ momenta in $\tau^\pm$ rest frame avg over Z-pol's

- Compute in SM:

$$\frac{d\sigma}{d\cos\theta_{\pi\pi}}(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau) = A(1 - \frac{1}{3}\cos\theta_{\pi\pi})$$

$$P_{\rm QM}(\cos\theta_{\pi\pi}) = \frac{d\sigma/d\cos\theta_{\pi\pi}(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau)}{\sigma(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau)}$$

$$= \frac{1}{2}(1 - \frac{1}{3}\cos\theta_{\pi\pi})$$

- Insert into Bell's inequality: satisfies it for all angles!!!

Recall the Logic

- All LHVT's satisfy Bell's inequality

LHVT —> Bell's inequality

- QM can or can not satisfy Bell's inequality

- The art is to find a setup where QM violates Bell's inequality

non(Bell's inequality) —> non(LHVT)

Why does it fail as a test of locality, despite anti-correlated spins?

- Simple answer: in decay $\tau^- \to \pi^- + \nu_\tau$ only measure τ-helicity

- This is just one component of spin: $(\vec{S}_\tau)_z$

$$P(S_z^+ = \uparrow, S_z^- = \uparrow) \ \text{parallel}$$

$$P(S_z^+ = \uparrow, S_z^- = \downarrow) \ \text{anti-parallel}$$

- According to Bell analysis should be able to reproduce experiment with LHVT

- That is in fact the case!

- Consider

SM diff. X-Section

$$\frac{d\sigma}{d\cos\theta_{\pi\pi}}(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau) = f(\hat{p}_{\pi^+}, \hat{p}_{\pi^-})$$

- Now let the hidden variables for each τ be a set of unit vectors

$$\hat{\lambda}_e, \hat{\lambda}_\mu, \hat{\lambda}_\pi, \hat{\lambda}_\rho, \ldots$$

- If tau decays as $\tau^- \to \pi^- + \nu_\tau$ then $\hat{\lambda}_\pi$ tells it to decay such that

$$\hat{p}_\pi = \hat{\lambda}_\pi$$

- Let $F(\hat{\lambda}_{\pi^+}, \hat{\lambda}_{\pi^-})$ be original prob. distribution of hidden variables

- Identify $F(\hat{\lambda}_{\pi^+}, \hat{\lambda}_{\pi^-}) = f(\hat{\lambda}_{\pi^+}, \hat{\lambda}_{\pi^-})$ $\quad (= \dfrac{d\sigma}{d\Omega_+ d\Omega_-})$

- Have an LHVT which **exactly** reproduces **all** experimental results

- Essential that

$$[(\hat{p}_{\pi^+})_i, (\hat{p}_{\pi^-})_j] = 0$$

$$[(\hat{p}_{\pi^\pm})_i, (\hat{p}_{\pi^\pm})_j] = 0$$

$$\forall i, j$$

- Only then does QM provide the function $f(\hat{\lambda}_{\pi^+}, \hat{\lambda}_{\pi^-})$

- For non-commuting spins (2 photon case), QM does **not** provide function $f(S_x^i, S_y^i, \ldots)$

Main Statement — Theorem

For all experiments where the correlated observables **commute** we can construct an LHVT using the QM function, which exactly reproduces the data.

In collider experiments we measure 4-momenta. These all commute. Ergo: all results can be reproduced by an LHVT.

Examples at the LHC from the Recent Literature

$$gg \to H^0 \to W^+W^- \,, \quad W^+ \to \ell^+ + \nu_\ell$$

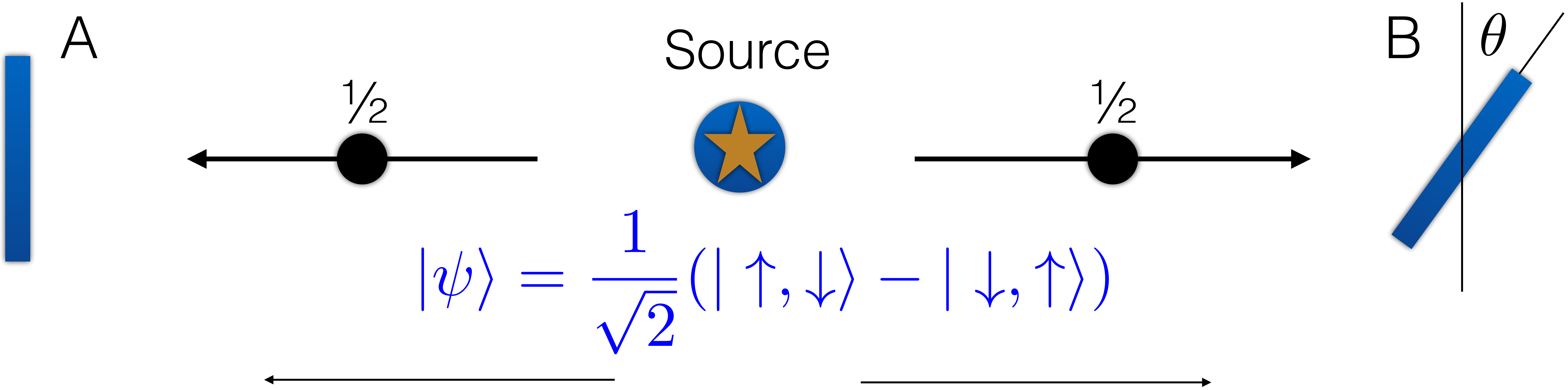
$$gg \to H^0 \to Z^0 Z^0 \,, \quad Z^0 \to \ell^+ + \ell^-$$

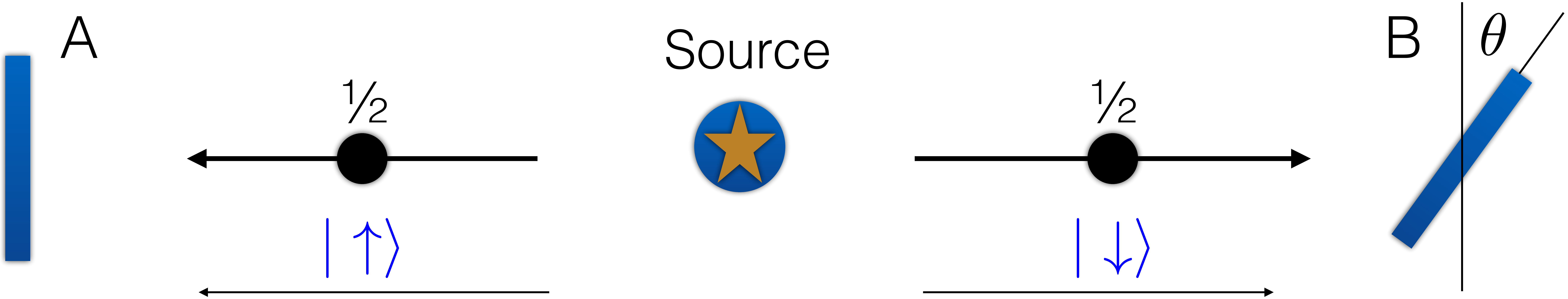
$$gg,\, q\bar{q} \to t\bar{t} \,, \quad t \to W^+ + b$$

$$gg,\, q\bar{q} \to \tau^+\tau^- \,, \quad \tau^\pm \to \pi^\pm + \nu_\tau$$

- In all cases measure final state momenta, i.e. can write an LHVT reproducing the data using the SM diff. X-section.

A Word on Logic: entanglement vs local realism





- You can describe the data exactly with an LHVT, i.e. with a **non-entangled** state!

- Thus you have simply chosen a poor set-up to test locality.

- So: you are NOT testing locality, at all!

Where our Paper was purposely(?) misunderstood

- Can show on general symmetry grounds that **QM expectation value** must have form (s-wave plus p-wave)

$$P_{\pi\pi}(\theta) = c_1 + c_2 \langle (\hat{p}_{\pi^+} \cdot \sigma_{\tau^+})(\hat{p}_{\pi^-} \cdot \sigma_{\tau^-}) \rangle_{\rm QM}$$

QM expectation value to observe to τ^+ spin in the $\hat{p}_{\pi^+}$ direction **and** the τ^- spin in the $\hat{p}_{\pi^-}$ direction

$$P_{\sigma^\tau \sigma^\tau}(\theta) = \langle (\vec{a} \cdot \sigma_{\tau^+})(\vec{b} \cdot \sigma_{\tau^-}) \rangle_{\rm QM}$$

(★) $$P_{\sigma^\tau \sigma^\tau}(\theta) = \frac{P_{\pi\pi}(\theta) - c_1}{c_2} = -\cos\theta$$

math. construction which violates Bell's inequality

but: SO WHAT?!?!

- In deriving Eq.(★) I have made blatant use of QM. Thus I am assuming QM … to “test” QM? - No, I am not even testing QM. I am not testing anything.

- It is a meaningless function which happens to mathematically violate Bell’s inequality. It makes **NO statement about LOCALITY**.

- Yes, you are testing an **unknown** subclass of LHVT’s, but you are doing this also if you drop 2 watermelons from the tower of Pisa.

- In our paper the computation of Eq.(★) was just to illustrate what people were doing.

- In our paper, we conclude by saying: “It is the second cornerstone in our claim that **it is not possible to test the completeness of QM in a collider experiment**.”

- The first cornerstone was the direct proof that Bell’s inequality is NOT violated.

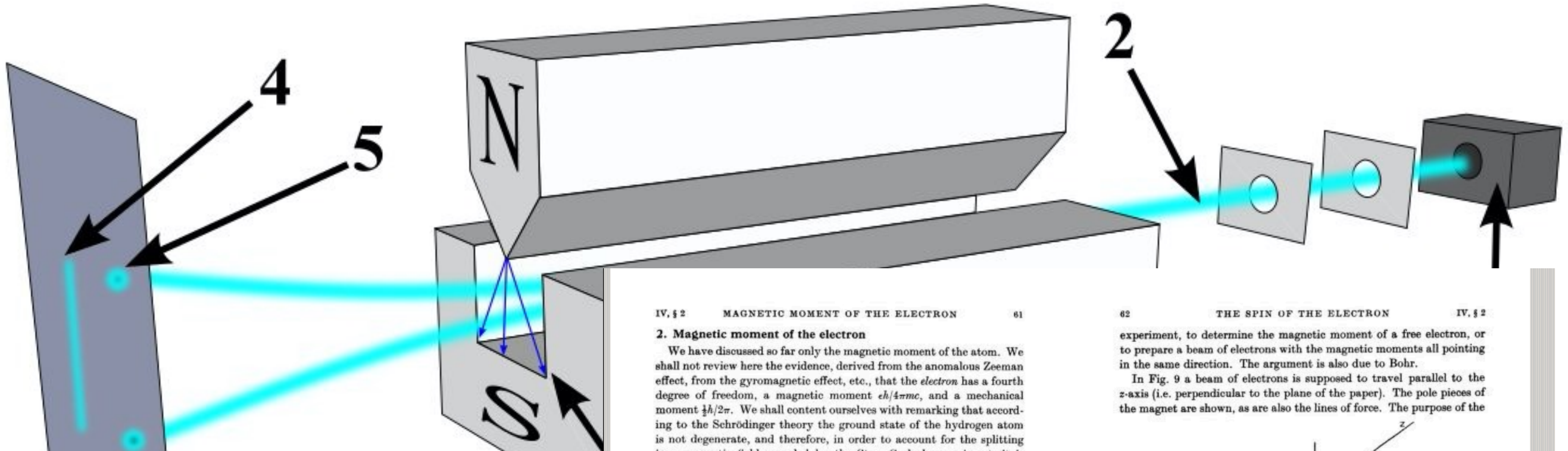
- The statement: “this is not a general test of locality via Bell’s inequality” is logically true but highly misleading as it is NO test of locality. The data is described by a local theory!

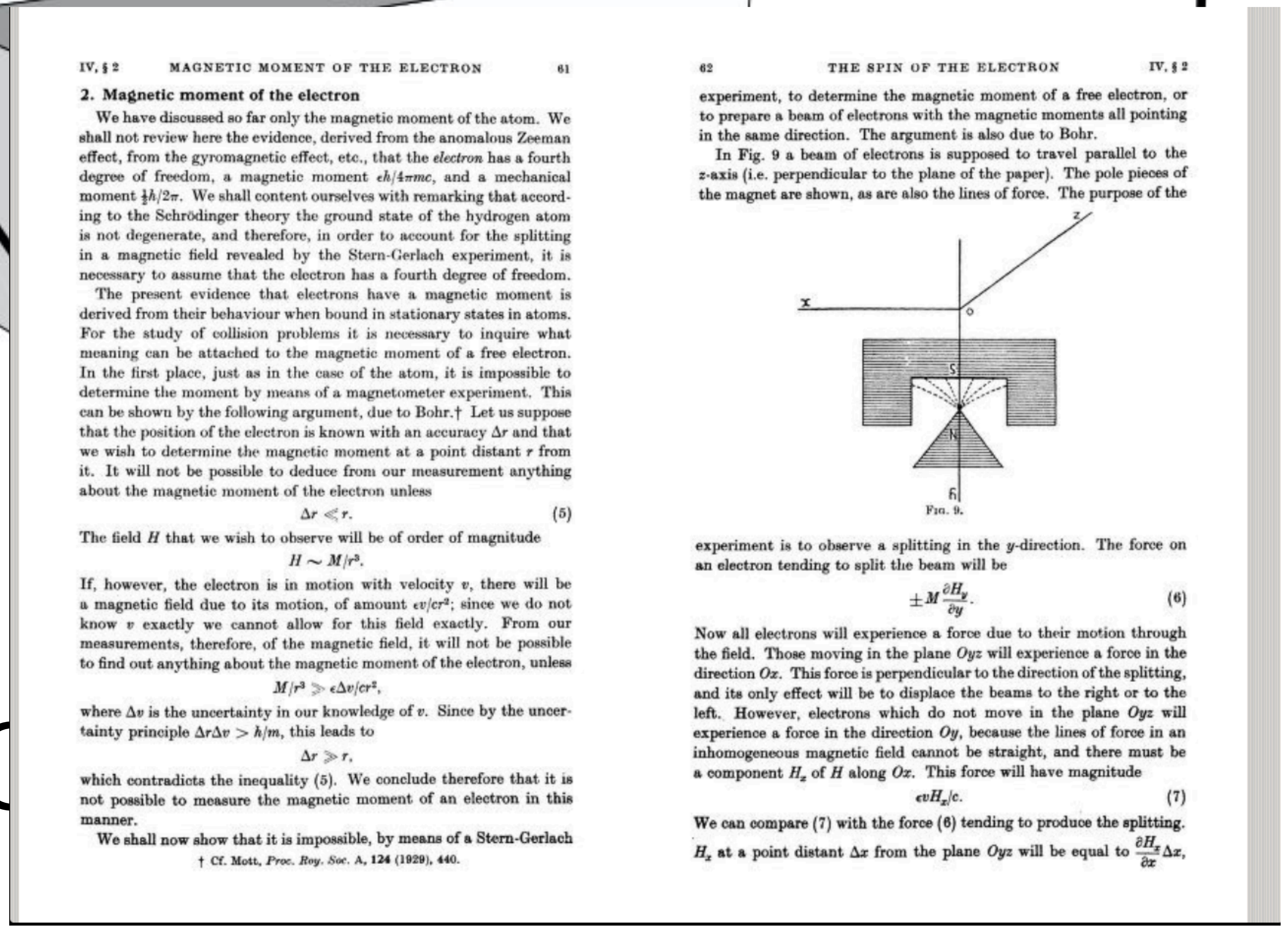
- The data is described by a non-entangled state. You are **NOT** testing entanglement

Bell's Inequality

- Bell showed for the first time you can distinguish **experimentally** between entangled state and local realistic state

- Problems with this





IV, § 2 MAGNETIC MOMENT OF THE ELECTRON 61

2. Magnetic moment of the electron

We have discussed so far only the magnetic moment of the atom. We shall not review here the evidence, derived from the anomalous Zeeman effect, from the gyromagnetic effect, etc., that the *electron* has a fourth degree of freedom, a magnetic moment $\epsilon h/4\pi mc$, and a mechanical moment $\frac{1}{2}h/2\pi$. We shall content ourselves with remarking that according to the Schrödinger theory the ground state of the hydrogen atom is not degenerate, and therefore, in order to account for the splitting in a magnetic field revealed by the Stern-Gerlach experiment, it is necessary to assume that the electron has a fourth degree of freedom.

The present evidence that electrons have a magnetic moment is derived from their behaviour when bound in stationary states in atoms. For the study of collision problems it is necessary to inquire what meaning can be attached to the magnetic moment of a free electron. In the first place, just as in the case of the atom, it is impossible to determine the moment by means of a magnetometer experiment. This can be shown by the following argument, due to Bohr.† Let us suppose that the position of the electron is known with an accuracy Δr and that we wish to determine the magnetic moment at a point distant r from it. It will not be possible to deduce from our measurement anything about the magnetic moment of the electron unless

$$\Delta r \ll r. \tag{5}$$

The field H that we wish to observe will be of order of magnitude

$$H \sim M/r^3.$$

If, however, the electron is in motion with velocity v, there will be a magnetic field due to its motion, of amount $\epsilon v/cr^2$; since we do not know v exactly we cannot allow for this field exactly. From our measurements, therefore, of the magnetic field, it will not be possible to find out anything about the magnetic moment of the electron, unless

$$M/r^3 \gg \epsilon\Delta v/cr^2,$$

where Δv is the uncertainty in our knowledge of v. Since by the uncertainty principle $\Delta r \Delta v > h/m$, this leads to

$$\Delta r \gg r,$$

which contradicts the inequality (5). We conclude therefore that it is not possible to measure the magnetic moment of an electron in this manner.

We shall now show that it is impossible, by means of a Stern-Gerlach

† Cf. Mott, *Proc. Roy. Soc.* A, **124** (1929), 440.

62 THE SPIN OF THE ELECTRON IV, § 2

experiment, to determine the magnetic moment of a free electron, or to prepare a beam of electrons with the magnetic moments all pointing in the same direction. The argument is also due to Bohr.

In Fig. 9 a beam of electrons is supposed to travel parallel to the z-axis (i.e. perpendicular to the plane of the paper). The pole pieces of the magnet are shown, as are also the lines of force. The purpose of the

FIG. 9.

experiment is to observe a splitting in the y-direction. The force on an electron tending to split the beam will be

$$\pm M\frac{\partial H_y}{\partial y}. \tag{6}$$

Now all electrons will experience a force due to their motion through the field. Those moving in the plane Oyz will experience a force in the direction Ox. This force is perpendicular to the direction of the splitting, and its only effect will be to displace the beams to the right or to the left. However, electrons which do not move in the plane Oyz will experience a force in the direction Oy, because the lines of force in an inhomogeneous magnetic field cannot be straight, and there must be a component H_x of H along Ox. This force will have magnitude

$$\epsilon v H_x/c. \tag{7}$$

We can compare (7) with the force (6) tending to produce the splitting. H_x at a point distant Δx from the plane Oyz will be equal to $\frac{\partial H_x}{\partial x}\Delta x$,

- Impossible to measure spin-½ with Stern-G particles, i.e. electrons (or taus)

Mott, Theory of Atomic Collisions

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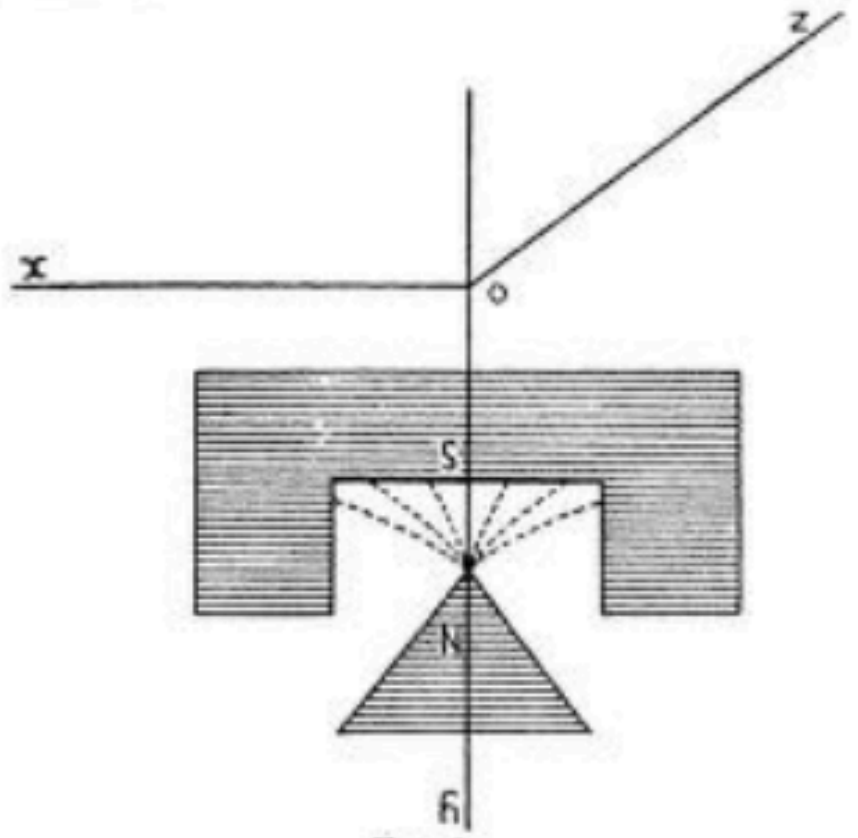

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We can compare (7) with the force (6) tending to produce the splitting. H_x at a point distant Δx from the plane Oyz will be equal to $\frac{\partial H_x}{\partial x}\Delta x$, and since div H vanishes, this is equal to $-\frac{\partial H_y}{\partial y}\Delta x$. The quantities (6) and (7) therefore stand in the ratio

$$\frac{\epsilon h}{4\pi mc}\frac{\partial H_y}{\partial y}:\frac{\epsilon v}{c}\frac{\partial H_y}{\partial y}\Delta x.$$

Dividing through by common factors this becomes

$$1:4\pi\Delta x/\lambda, \tag{7.1}$$

where λ is the wave-length h/mv of the waves that represent the electrons. Suppose now that $\pm\Delta x$ is the distance from the plane Oyz of the two extremities of the beam. Since Δx must be greater than λ, it is clear that the two extremities of the beam will be deflected in opposite directions through angles greater than the angle of splitting, which we hope to observe.

To see now that it is impossible to observe any splitting, let us consider the trace that the beam would make on a photographic plate. Suppose that it were possible to use finer beams than is allowed by the uncertainty principle, so that the thickness Δy of the beam in the y-direction would be infinitely small. Before passing through the magnetic field, the cross-section of the beam would be as in Fig. 10(a). Afterwards, it would be as in Fig. 10(b), which shows the trace produced on a photographic plate. The tilting of the traces is produced by the Lorentz forces discussed above. If ABC, $A'B'$ are two lines parallel to Oy and distant λ apart, then by (7.1) we see that the tilting is so great that $AB > BC$. If $A\beta\gamma$ is drawn perpendicular to the traces, it follows that $A\beta > \beta\gamma$. But $A\beta < \lambda$, and hence $\beta\gamma$, the distance between the traces, is less than λ. Thus the maximum separation that can be produced is λ. But actually we cannot obtain a trace of breadth comparable with λ. Therefore it is impossible to observe any splitting.

From these arguments we must conclude that it is meaningless to assign to the free electron a magnetic moment. It is a property of the electron that when it is bound in an S state in an atom, the atom has a magnetic moment. When we consider the relativistic treatment of the electron due to Dirac, we shall see that this magnetic moment is not in general equal to $\epsilon h/4\pi mc$, unless the velocities of the electron within the atom are small compared with that of light (§ 3.3). A single electron bound in its lowest state in the field of a nucleus of charge $Z\epsilon$ gives, according to Dirac's theory, a magnetic moment†

$$\tfrac{1}{3}[1+2\sqrt{(1-\gamma^2)}]\epsilon h/4\pi mc \quad (\gamma = 2\pi Z\epsilon^2/hc). \tag{8}$$

† This formula is due to Breit, *Nature*, **122** (1928), 649. Cf. § 3.3 of this chapter.

The statement that a free electron has four degrees of freedom is on a different footing, for it is hardly conceivable that an electron in an atom should have four degrees of freedom, and a free electron three. It is interesting to inquire, therefore, whether there is any conceivable experiment by which this fourth degree of freedom could be detected.

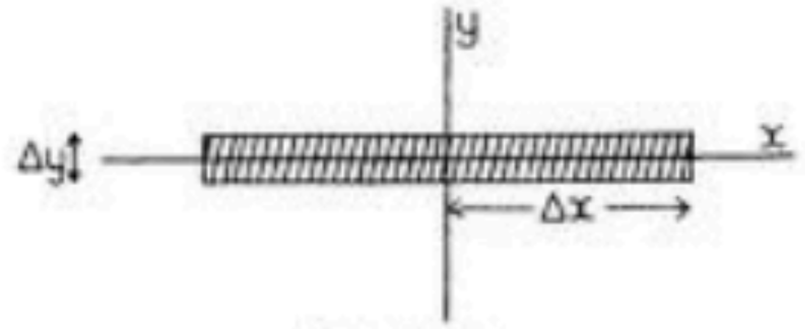

Fig. 10(a).

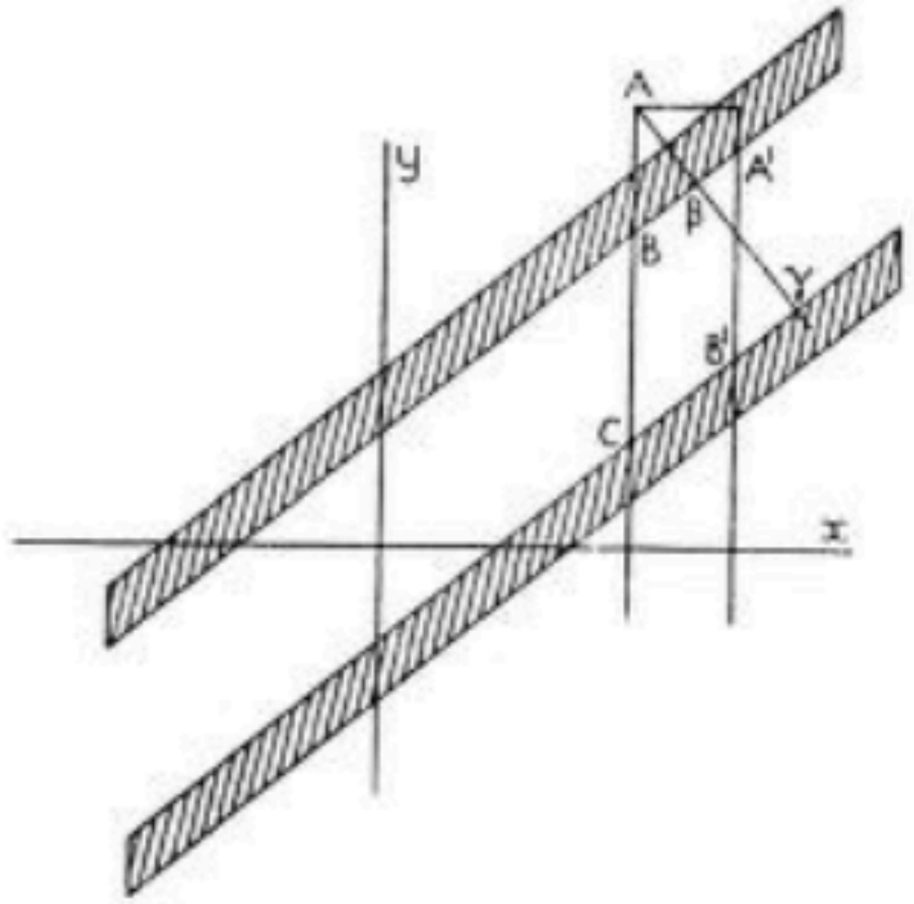

Fig. 10(b).

We wish to know whether it is possible to prepare a beam of electrons that is in some sense 'polarized', and whether it would be possible to detect this polarization.

There is at present no certain experimental evidence on this point; theoretical considerations show, however, that it is possible, in principle, both to prepare a polarized beam and to detect the polarization. Let us consider the following experiment.† A beam of atoms is prepared, by means of a Stern-Gerlach experiment, with their axes all pointing in the same direction, say along the z-axis. Electrons are ejected from

† This method of preparing a polarized beam of electrons was first suggested by Fues and Hellmann, *Phys. Zeits.* **31** (1930), 465.

Particle Physics Show & Play
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"What's (the) Matter?", A Show on Elementary Particle Physics with 28 Demonstration Experiments

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We present the screenplay of a physics show on particle physics, by the Physikshow of Bonn University. The show is addressed at non-physicists aged 14+ and communicates basic concepts of elementary particle physics including the discovery of the Higgs boson in an entertaining fashion. It is also demonstrates a successful outreach activity heavily relying on the university physics students. This paper is addressed at anybody interested in particle physics and/or show physics. This paper is also addressed at fellow physicists working in outreach, maybe the experiments and our choice of simple explanations will be helpful. Furthermore, we are very interested in related activities elsewhere, in particular also demonstration experiments relevant to particle physics, as often little of this work is published. Our show involves 28 live demonstration experiments. These are presented in an extensive appendix, including photos and technical details. The show is set up as a quest, where 2 students from Bonn with the aid of a caretaker travel back in time to understand the fundamental nature of matter. They visit Rutherford and Geiger in

The End

$$1 + P(\cos\theta_{ac}) \geq |P(\cos\theta_{ab}) - P(\cos\theta_{bc})|$$

$$1 + \frac{1}{2}(1 - \frac{1}{3}\cos\theta_{ac}) \geq | -\frac{1}{6}\cos\theta_{ab} + \frac{1}{6}\cos\theta_{bc}|$$

$$9 - \frac{1}{3}\cos\theta_{ac} \geq |\cos\theta_{ab} - \cos\theta_{bc}|$$