On the relevance of spin in High Energy Physics: An introduction for pedestrians

Jacques Soffer

Department of Physics, Temple University, Philadelphia, PA 19122-6082, USA

Outline

- Some practical and technical issues
- Spin in e^+e^- collisions
- Spin in ep collisions
- Spin in hadronic collisions
- Conclusions

List of references

- Spin in particle physics
  Elliot Leader,
  Cambridge University press,(2001)
- Polarization phenomena in hadronic reactions
  Claude Bourrely, Elliot Leader, Jacques Soffer,
  Physics Reports 59, 95 (1980)
- Spin effects at supercollider energies
  Claude Bourrely, Fernand Renard, Jacques Soffer, Pierre Taxil
  Physics Reports 59, 95 (1989)
- Prospects for spin physics at RHIC
  Gerry Bunce, Naohito Saito, Jacques Soffer, Werner Vogelsang
  Ann. Rev. Nucl. Part. Sci. 50, 525 (2000)
- Spin observables and spin structure functions: inequalities and dynamics
  Xavier Artru, Mokhtar Elchikh, Jean-Marc Richard, Jacques Soffer, Oleg Teryaev
  Physics Reports 470, 1 (2009)

Some general remarks

- Spin is a fundamental quantum number which was first discovered 90 years ago. It allowed to formulate the famous Pauli exclusion principle according to which two electrons cannot be in the same state

  Nov. 24, 1925 Heisenberg wrote to Pauli: It would of course be simpler if the electron possessed only charge and mass, but no angular momentum; in principle one cannot argue against the angular momentum, but the idea that the electron has a structure (in particular that several types of electrons exist) appears to me to be detestable

- Spin of elementary particles determines their symmetry properties under space-time transformation
- Spin is a very good tool to understand the inner structure of composite objects

Some general remarks

- Spin is a fundamental quantum number which was first discovered 90 years ago. It allowed to formulate the famous Pauli exclusion principle according to which two electrons cannot be in the same state

  Nov. 24, 1925 Heisenberg wrote to Pauli: It would of course be simpler if the electron possessed only charge and mass, but no angular momentum; in principle one cannot argue against the angular momentum, but the idea that the electron has a structure (in particular that several types of electrons exist) appears to me to be detestable

- Spin of elementary particles determines their symmetry properties under space-time transformation
- Spin is a very good tool to understand the inner structure of composite objects
- Spin is therefore an essential property of any new elementary particle which must be determined, most of the time from its decaying processes
- Spin dependence of reactions is probing very deeply the underlying theoretical structure
- Spin is a powerful tool to confirm or invalidate a theory

Spin in relativistic theory

- Spin in classical mechanics
  It characterizes the behavior of a system under rotations and it is related to the concept of intrinsic angular momentum
- Spin in relativistic theory emerges automatically with the beautiful Dirac equation
- The fundamental operators are the 10 generators of the inhomogeneous Lorentz group, P^μ for the translations and $J^{\mu\nu}$ for the pure rotations and the boosts

Spin in relativistic theory

- Spin in classical mechanics
  It characterizes the behavior of a system under rotations and it is related to the concept of intrinsic angular momentum
- Spin in relativistic theory emerges automatically with the beautiful Dirac equation
- The fundamental operators are the 10 generators of the inhomogeneous Lorentz group, P^μ for the translations and $J^{\mu\nu}$ for the pure rotations and the boosts
- For the quantum relativistic description of angular momentum, one introduces the PAULI-LUBANSKI pseudovector $W_\mu = 1/2\epsilon_{\mu\nu\rho\sigma}J^{\nu\rho}P^\sigma$
  Clearly $P^\mu W_\mu = 0$, $[P^\mu, W_\nu] = 0$ and $[W_\mu, W_\nu] = -i\epsilon_{\mu\nu\rho\sigma}W^\rho P^\sigma$
  The scalar $W_\mu W^\mu$ is a Lorentz invariant operator and commutes with the four momentum.
- To label the irreducible representations of the Lorentz group, in addition to the label $P_\mu P^\mu = m^2$ for the mass, it can serve as the label for the spin.
  One has $W_\mu W^\mu = -m^2 s(s+1)$, where s, which can take the values 0,1/2,1,.. is the spin quantum number of the particle of mass m.

Some practical and technical issues

- Hundreds of scientists are involved and they form
  a world wide SPIN PHYSICS COMMUNAUTY
- Several very active labs are dedicated to high energy spin physics
- Many spin physics meetings around the world
- How to make polarized beams and targets?

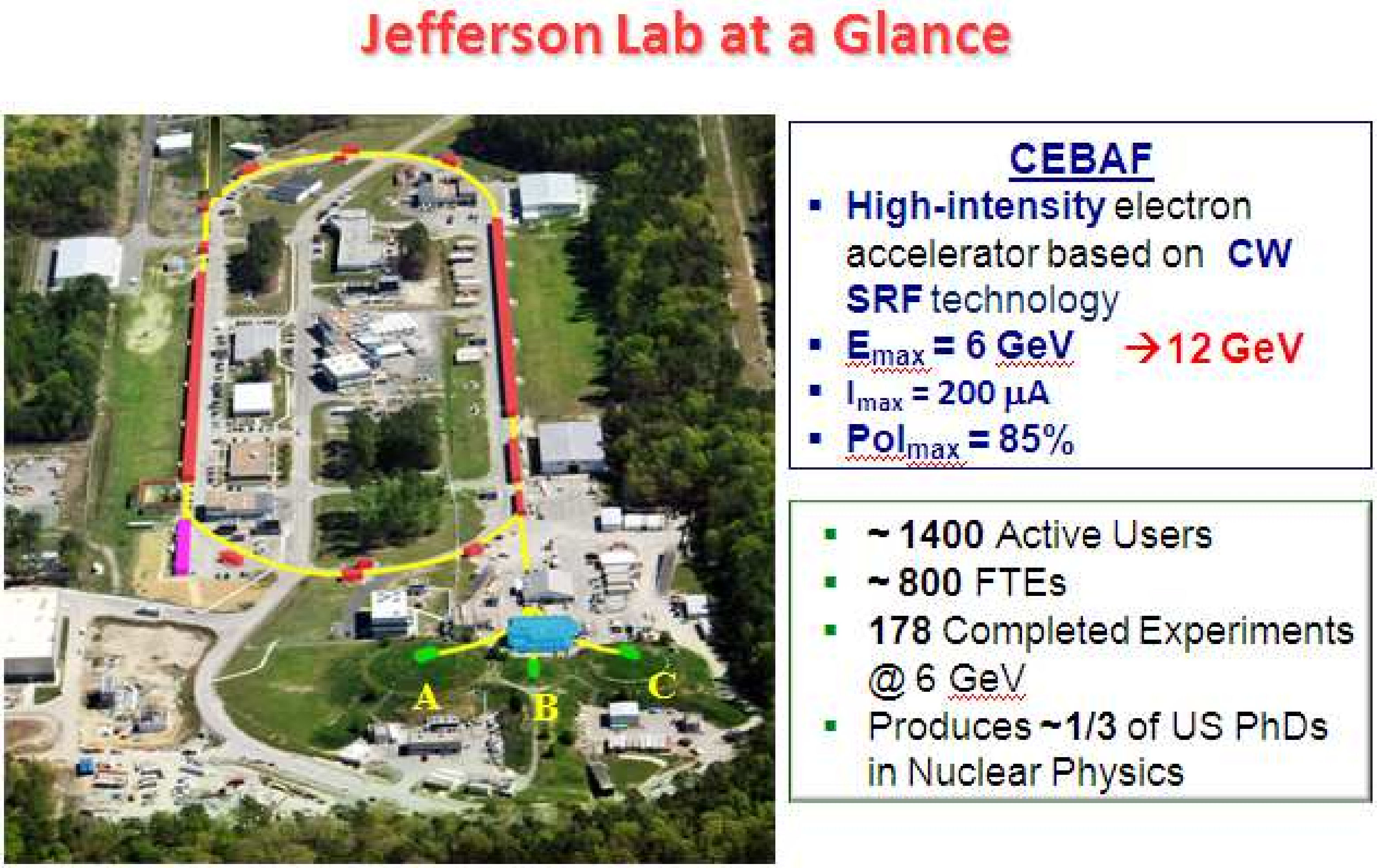
A world picture

The Spin Community And The World

- HERMES has been the pioneering collaboration in TMD and GPD fields
- still very important player in the field of nucleon (spin) structure
  - polarized $e^{+/-}$ beams
  - pure gas target
  - good particle identification
  - recoil detector

DSPIN 2011

One dedicated lab.: JLab



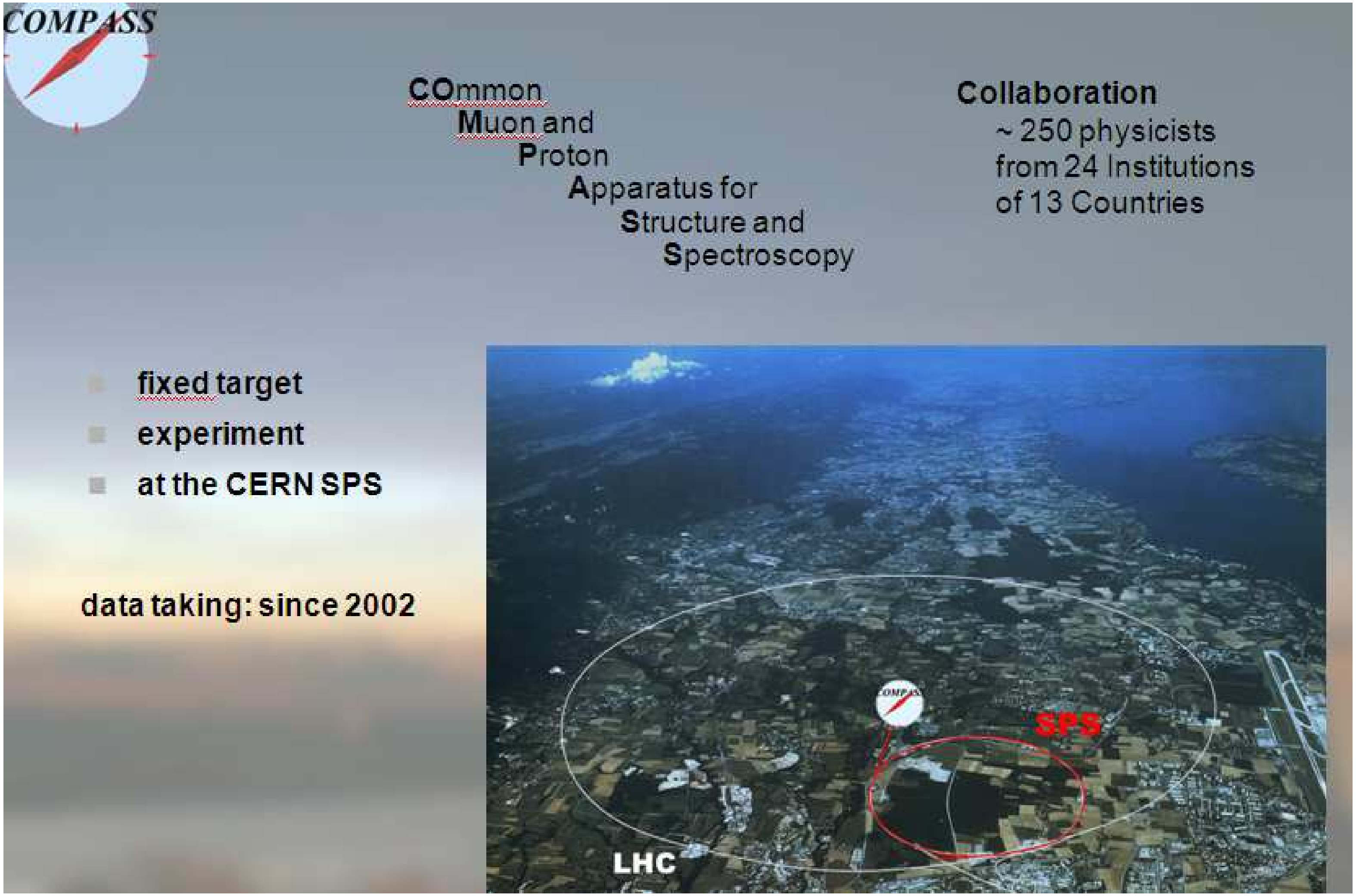
Jefferson Lab at a Glance

CEBAF

- **High-intensity** electron accelerator based on **CW SRF** technology
- **E_{max} = 6 GeV** → 12 GeV
- **I_{max} = 200 μA**
- **Pol_{max} = 85%**

- ~ 1400 Active Users
- ~ 800 FTEs
- 178 Completed Experiments @ 6 GeV
- Produces ~1/3 of US PhDs in Nuclear Physics

One dedicated fixed target experiment: COMPASS at CERN



COMPASS

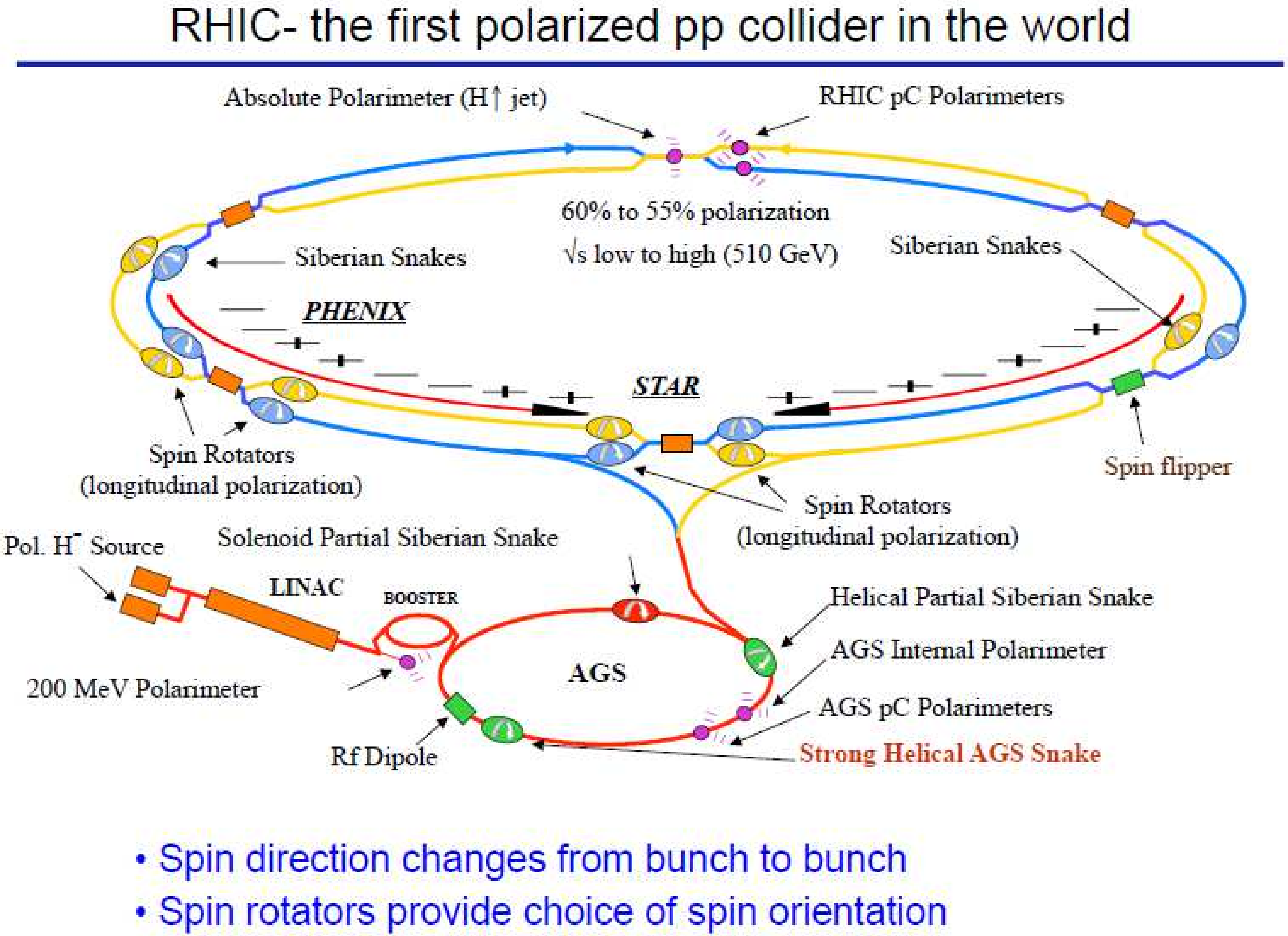
COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration
~ 250 physicists
from 24 Institutions
of 13 Countries

- fixed target
- experiment
- at the CERN SPS

data taking: since 2002

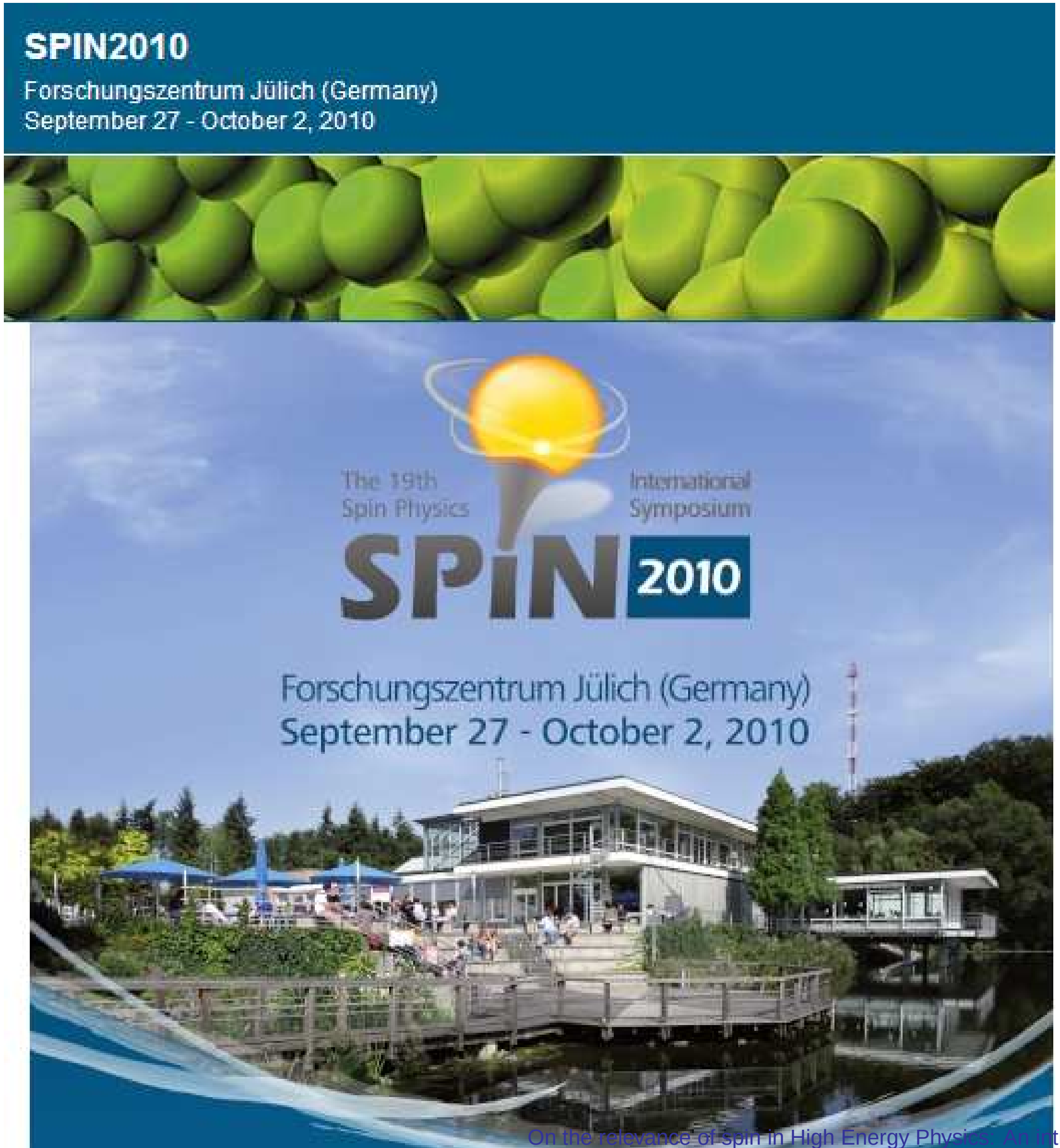
One dedicated polarized pp collider: RHIC at BNL



RHIC- the first polarized pp collider in the world

- Spin direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation

Spin physics meetings



SPIN2010

Forschungszentrum Jülich (Germany)
September 27 - October 2, 2010

The 19th Spin Physics International Symposium

SPIN 2010

Forschungszentrum Jülich (Germany)
September 27 - October 2, 2010

Spin physics meetings

8th Circum-Pan-Pacific Symposium on High Energy Spin Physics: PacSPIN2011

Workshop hosted by the

Special Research Centre for the Subatomic Structure of Matter,

June 20-24, 2011 in Cairns, QLD, Australia

Spin physics meetings

XV WORKSHOP ON HIGH ENERGY SPIN PHYSICS

DSPIN-13

Dubna, Russia, October 8 - 12, 2013

Spin physics meetings

Transversity 2014

Fourth International Workshop on

Transverse Polarization Phenomena in Hard Processes

9 - 13 June, Chia, Cagliari

WEBPAGE UNDER CONSTRUCTION

COME BACK SOON

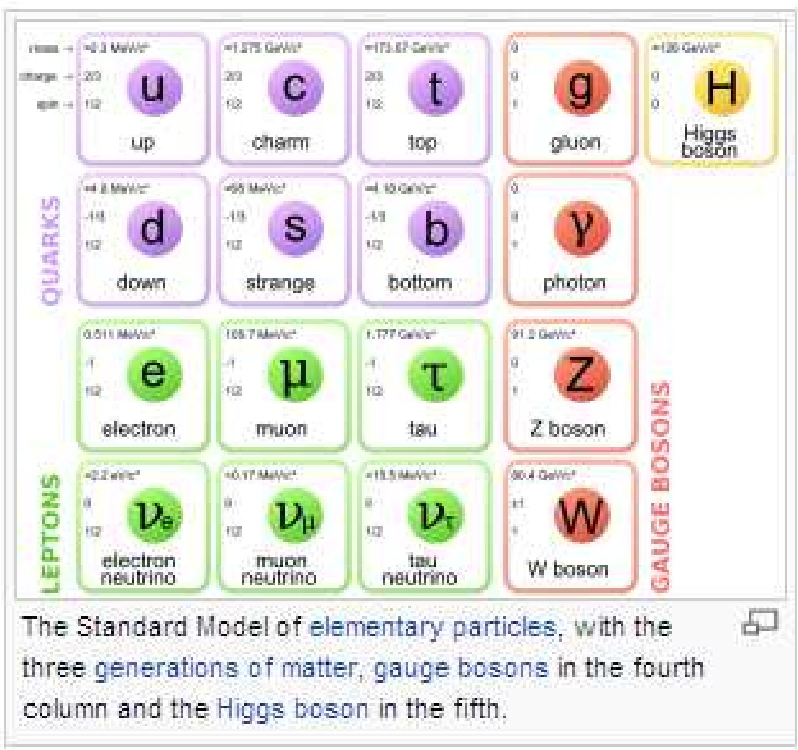
Polarized targets and high energy polarized beams

- Frozen targets which allow to obtain a high intensity polarized protons
  Need materials resistant to radiation damage (e.g. Amonia). Dilution problem
- Gas-jet targets using hydrogen atoms. Low density but no dilution
- High-density gaseous polarized ^{3}He(ppn), which is to a good approximation a polarized neutron target, since the spin of the two protons are in opposite direction

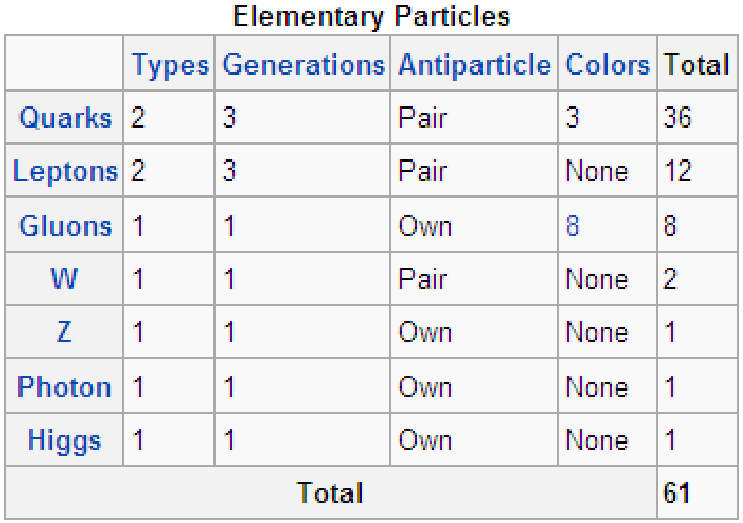
Polarized targets and high energy polarized beams

- Frozen targets which allow to obtain a high intensity polarized protons
  Need materials resistant to radiation damage (e.g. Amonia). Dilution problem
- Gas-jet targets using hydrogen atoms. Low density but no dilution
- High-density gaseous polarized ^{3}He(ppn), which is to a good approximation a polarized neutron target, since the spin of the two protons are in opposite direction
- High energy polarized proton beams can be obtained in a circular machine by acceleration
  Difficulties is to prevent depolarization and need to be able to measure the degree of polarization after acceleration (Importance of polarimetry)
- Low intensity polarized proton beam can be obtained from an extracted high energy Λ beam which decays into $p\pi^-$, where the proton is polarized.
- The only polarized antiproton beam has been obtained at Fermi Lab from a $\bar{\Lambda}$ beam
- Polarized beams can be obtained from a pion beam since in the dominant decay mode $\pi \to \mu\nu$ the muon is polarized.

The Standard Model (SM) of elementary particles : 61 objects !



The Standard Model of elementary particles, with the three generations of matter, gauge bosons in the fourth column and the Higgs boson in the fifth.



Elementary Particles

	Types	Generations	Antiparticle	Colors	Total
Quarks	2	3	Pair	3	36
Leptons	2	3	Pair	None	12
Gluons	1	1	Own	8	8
W	1	1	Pair	None	2
Z	1	1	Own	None	1
Photon	1	1	Own	None	1
Higgs	1	1	Own	None	1
Total					61

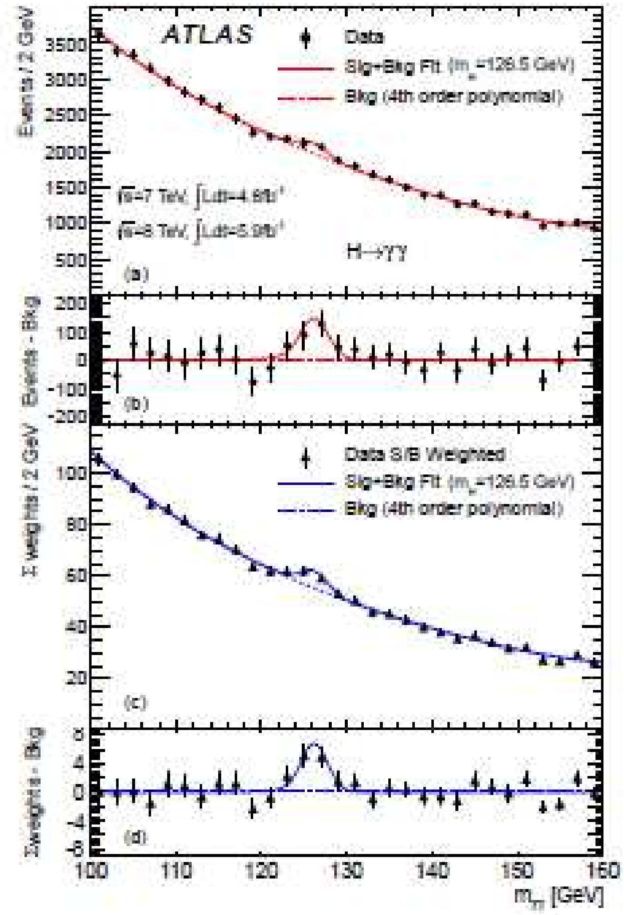
Quarks and Leptons are spin-1/2, Gauge bosons spin-1, Higgs spin-0

July, 4th 2012

A major discovery at CERN

First observation of a new particle at LHC in the 2γ spectrum

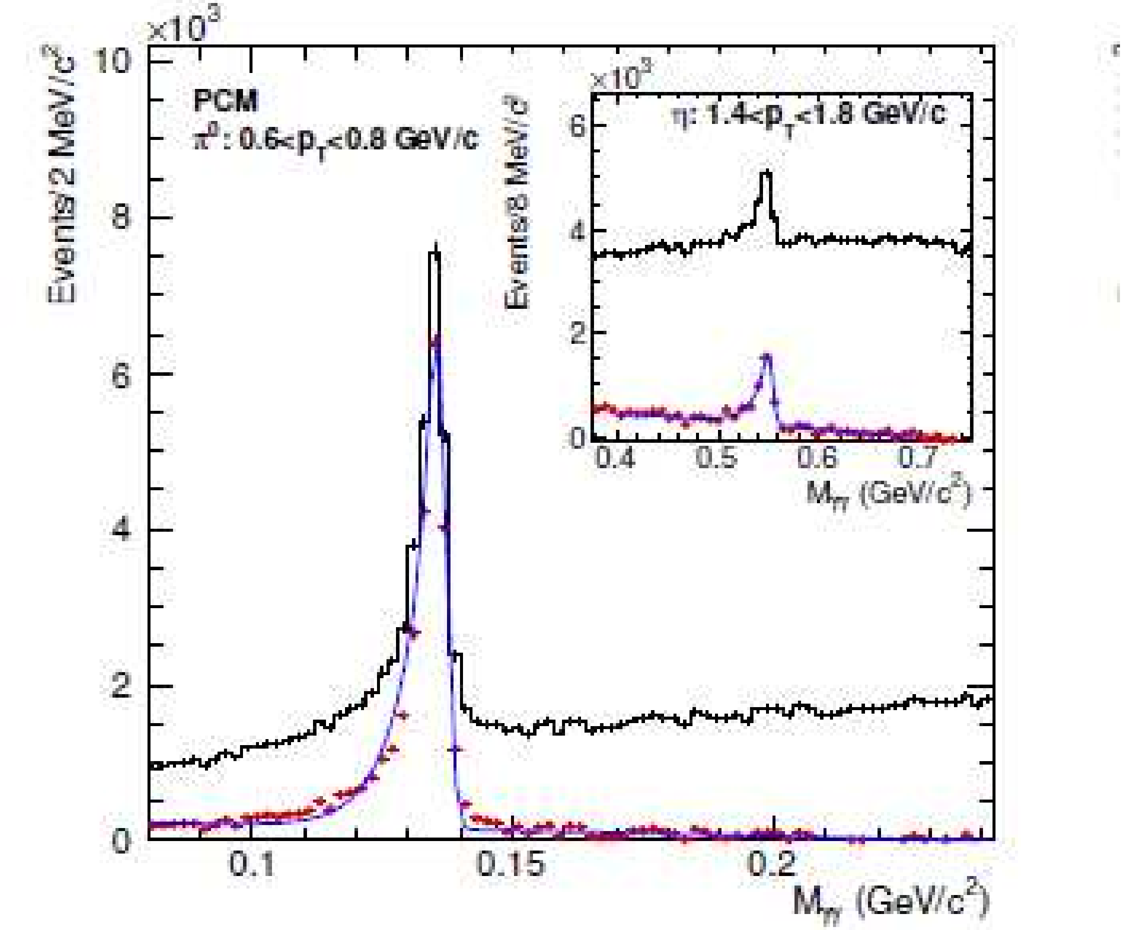
G. Aad et al. (ATLAS Coll.) PLB 716 (2012) 1



Its mass is $(126.0 \pm 0.4(stat.) \pm 0.4(sys.))$GeV

π^0 and η production at LHC

ALICE Coll. arXiv: 1205.5724



Clearly seen in the 2γ spectrum at 135 MeV and 548 MeV

Why they cannot have spin-1 ?

L.D. Landau, D.A.N.S.F. 60, 207 (1948), C.N. Yang, Phys. Rev. 77, 242 (1950)

A final state wave function in momentum space for the 2γ must be constructed from the polarization vectors $\vec{e}_1$ and $\vec{e}_2$ and their relative momentum vector $\vec{k}$. It must be linear in $\vec{e}_1$ and $\vec{e}_2$ and, if the initial particle has spin-1, it must transform like a vector under rotations. Moreover one must obey Bose-Einstein statistics because photons are bosons. There are three independent combinations of $\vec{e}_1$, $\vec{e}_2$ and $\vec{k}$ that are linear in $\vec{e}_1$ and $\vec{e}_2$ and transform like vectors:

Why they cannot have spin-1 ?

L.D. Landau, D.A.N.S.F. 60, 207 (1948), C.N. Yang, Phys. Rev. 77, 242 (1950)

A final state wave function in momentum space for the 2γ must be constructed from the polarization vectors $\vec{e}_1$ and $\vec{e}_2$ and their relative momentum vector $\vec{k}$. It must be linear in $\vec{e}_1$ and $\vec{e}_2$ and, if the initial particle has spin-1, it must transform like a vector under rotations. Moreover one must obey Bose-Einstein statistics because photons are bosons. There are three independent combinations of $\vec{e}_1$, $\vec{e}_2$ and $\vec{k}$ that are linear in $\vec{e}_1$ and $\vec{e}_2$ and transform like vectors:

- $\vec{e}_1 \times \vec{e}_2$
  not satisfactory because it is antisymmetric under interchange of the two photons
- $(\vec{e}_1 \cdot \vec{e}_2)\vec{k}$
  not satisfactory either for the same reason ($\vec{k} \to -\vec{k}$ under interchange)
- $(\vec{e}_1 \times \vec{e}_2) \times \vec{k}$
  it satisfies Bose-Einstein statistics, but it is identically zero because $\vec{k} \cdot \vec{e} = 0$ by the transversality condition.

Therefore they cannot have spin-1

How to distinguish spin-0^+ and spin-0^- ?

Knowing it is a spin zero object which decays into two photons, the final state wave function in momentum space for the 2γ must be constructed from the polarization vectors $\vec{e}_1$ and $\vec{e}_2$ and their relative momentum vector $\vec{k}$. There are two independent combinations of $\vec{e}_1$, $\vec{e}_2$ and $\vec{k}$ that are linear in $\vec{e}_1$ and $\vec{e}_2$:

- $\vec{e}_1 \cdot \vec{e}_2$ even parity
- $(\vec{e}_1 \times \vec{e}_2) \cdot \vec{k}$ odd parity

How to distinguish spin-0^+ and spin-0^- ?

Knowing it is a spin zero object which decays into two photons, the final state wave function in momentum space for the 2γ must be constructed from the polarization vectors $\vec{e}_1$ and $\vec{e}_2$ and their relative momentum vector $\vec{k}$. There are two independent combinations of $\vec{e}_1$, $\vec{e}_2$ and $\vec{k}$ that are linear in $\vec{e}_1$ and $\vec{e}_2$:

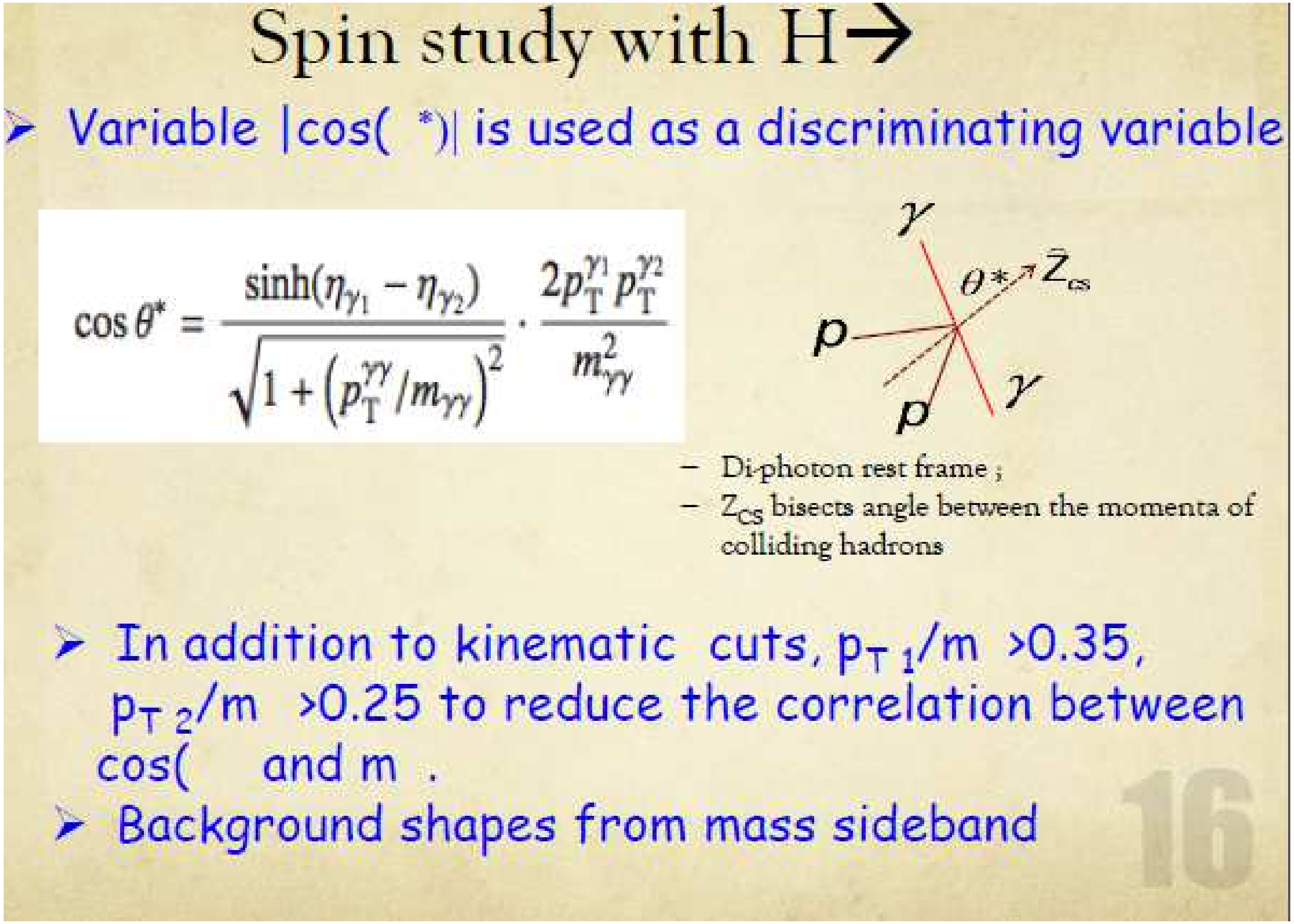
- $\vec{e}_1 \cdot \vec{e}_2$ even parity
- $(\vec{e}_1 \times \vec{e}_2) \cdot \vec{k}$ odd parity

For a pseudoscalar object, $\vec{e}_1$ cannot have any component in the direction of $\vec{e}_2$. This was done for π^0 by studying the relative orientation of the two e^+e^- production planes.

However not practical for the Higgs. Use $H \to ZZ^*$ (see below)

Evidence for spin-0^+ from $\gamma\gamma$ channel (supplemented by ZZ^* and WW^*)

G. Aad et al. (ATLAS Coll.) PLB 726 (2013) 120



Spin study with H→

- Variable |cos(*)| is used as a discriminating variable

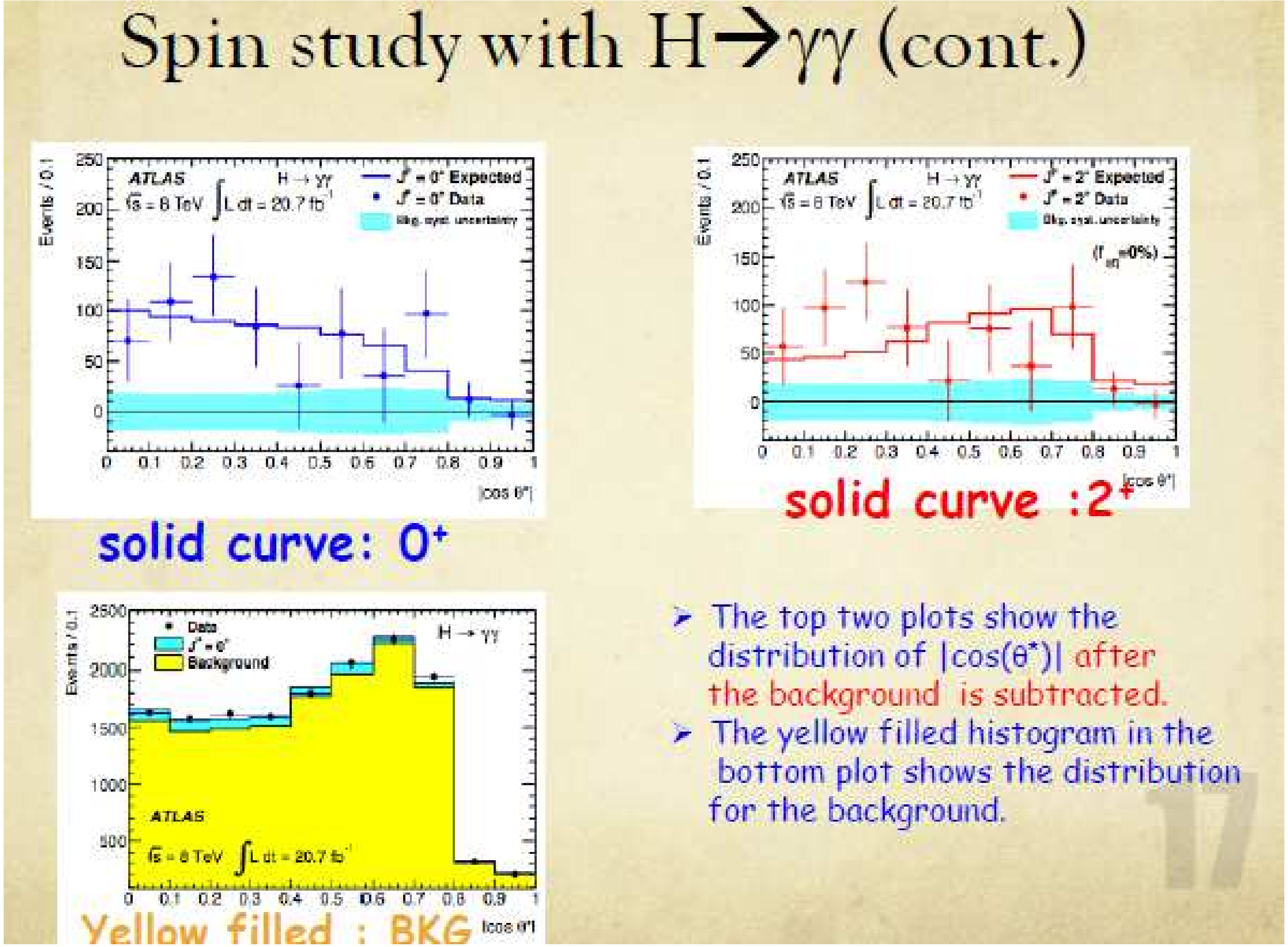
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1}-\eta_{\gamma_2})}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

- Di-photon rest frame ;
- Z_{CS} bisects angle between the momenta of colliding hadrons

- In addition to kinematic cuts, $p_{T\,1}/m$ >0.35, $p_{T\,2}/m$ >0.25 to reduce the correlation between cos(and m .
- Background shapes from mass sideband

Evidence for spin-0^+ from $\gamma\gamma$ channel (supplemented by ZZ^* and WW^*)

G. Aad et al. (ATLAS Coll.) PLB 726 (2013) 120



Spin study with H→γγ (cont.)

solid curve: 0⁺

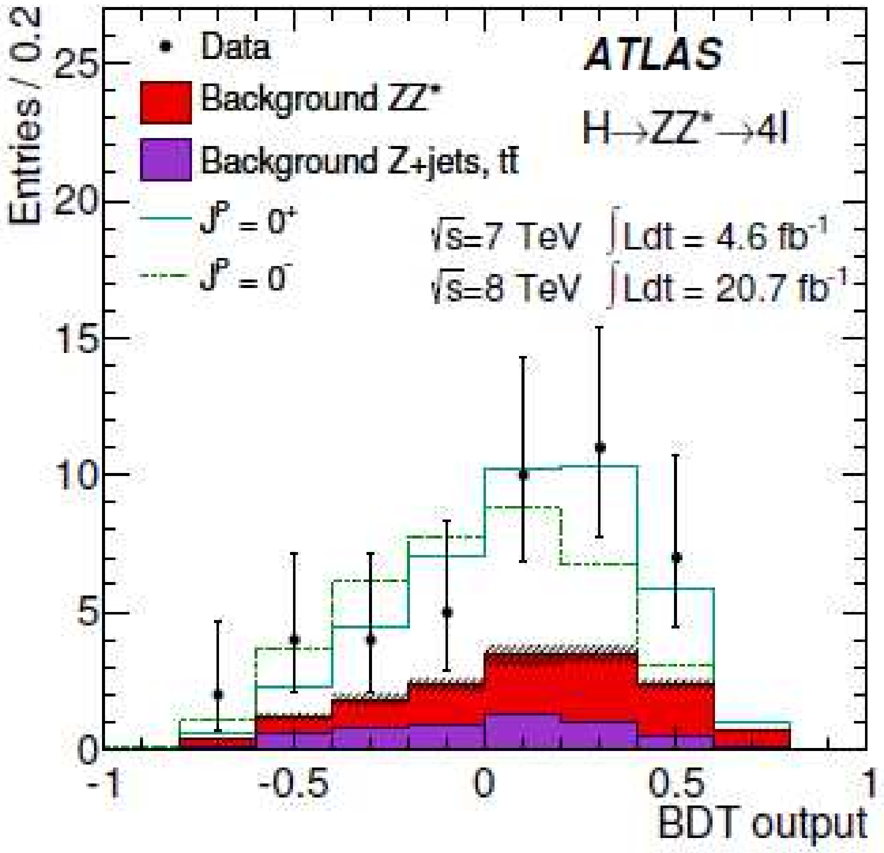
solid curve :2⁺

- The top two plots show the distribution of |cos(θ*)| after the background is subtracted.
- The yellow filled histogram in the bottom plot shows the distribution for the background.

Yellow filled : BKG

Evidence for spin-0^+ from $\gamma\gamma$ channel (supplemented by ZZ^* and WW^*)

G. Aad et al. (ATLAS Coll.) PLB 726 (2013) 120



Spin in e^+e^- collisions

- Spin of the quarks
- Electroweak quark couplings
- Signature for SUSY particles
- Gluon spin

Spin of the quarks *Effect Sokolov-Ternov*

In e^+e^- storage rings, radiative effects generate a natural transverse beam polarization, along the direction of the magnetic field, $P_T(e^+) = -P_T(e^-) = P$, with a maximum value of 92%(=8$\sqrt{3}$/15). The existence of this beam polarization has been observed at SPEAR (SLAC) and PETRA (DESY) up to $\sqrt{s}$= 30GeV and also later at LEP (CERN).

It leads to a specific azimuthal distribution which is used :

* To determine the degree of polarization

* To check directly that quarks are spin 1/2 objects

Spin of the quarks *Effect Sokolov-Ternov*

In e^+e^- storage rings, radiative effects generate a natural transverse beam polarization, along the direction of the magnetic field, $P_T(e^+) = -P_T(e^-) = P$, with a maximum value of 92%(=8$\sqrt{3}$/15). The existence of this beam polarization has been observed at SPEAR (SLAC) and PETRA (DESY) up to $\sqrt{s}$= 30GeV and also later at LEP (CERN).

It leads to a specific azimuthal distribution which is used :

* To determine the degree of polarization

* To check directly that quarks are spin 1/2 objects

Let us consider the inclusive process $e^+e^- \to hX$, where the hadron h is a fragmentation product of the quark (or antiquark) in $e^+e^- \to \gamma^* \to q\bar{q}$.

The angular distribution of h is

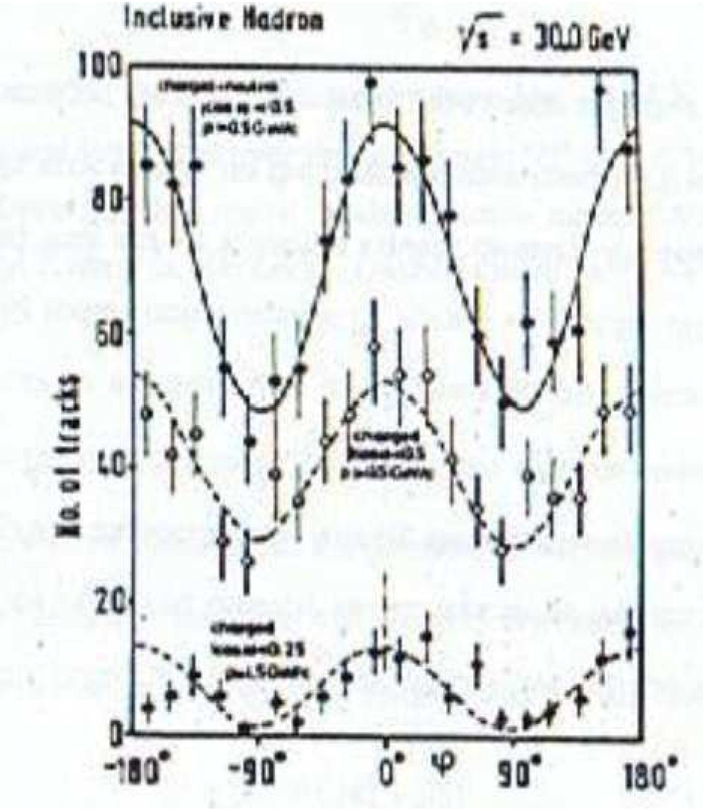
$$d\sigma/d\Omega = \sigma_0(1 + \alpha\cos^2\theta + P^2\alpha\sin^2\theta\cos 2\phi) \ ,$$

where θ and ϕ are the polar angles in the frame where Oz is the electron beam direction and Oy is that of the magnetic guide field. We have $\alpha = (\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$, σ_L and σ_T denote the cross sections where the virtual photon γ^μ is purely longitudinal respectively purely transverse.

For spin 1/2 quarks $\sigma_L = 0$, i.e. $\alpha = +1$, whereas for spin 0 quarks $\sigma_T = 0$, i.e. $\alpha = -1$.

Spin of the quarks (R.F. Schwitters et al., Phys. Rev. Lett. 35, 1320 (1975))

The ϕ distribution, with various cuts, has minima for $\phi = \pm\pi/2$, therefore quarks have indeed spin 1/2



A crucial test at SLAC

Electroweak quark couplings

Among the tests of the SM, one should measure the electroweak quark couplings which are predicted unambigously. For the Z° interaction $-e\gamma^\mu(a_q - b_q\gamma^5)$ one has

$$a_q = 1 - 8/3\sin^2\theta_W \quad , \quad b_q = 1 \quad for\ \ q = u, c, t$$

$$a_q = -1 + 4/3\sin^2\theta_W \quad , \quad b_q = -1 \quad for\ \ q = d, s, b$$

Due to the axial couplings of the Z° to the quark, it generates a non-zero *longitudinal* polarization $P_q = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where $\sigma_\pm$ are the cross sections for $e^+e^- \to q_h\bar{q}$, with the quark helicity $h = \pm$.

Electroweak quark couplings

Among the tests of the SM, one should measure the electroweak quark couplings which are predicted unambigously. For the Z° interaction $-e\gamma^\mu(a_q - b_q\gamma^5)$ one has

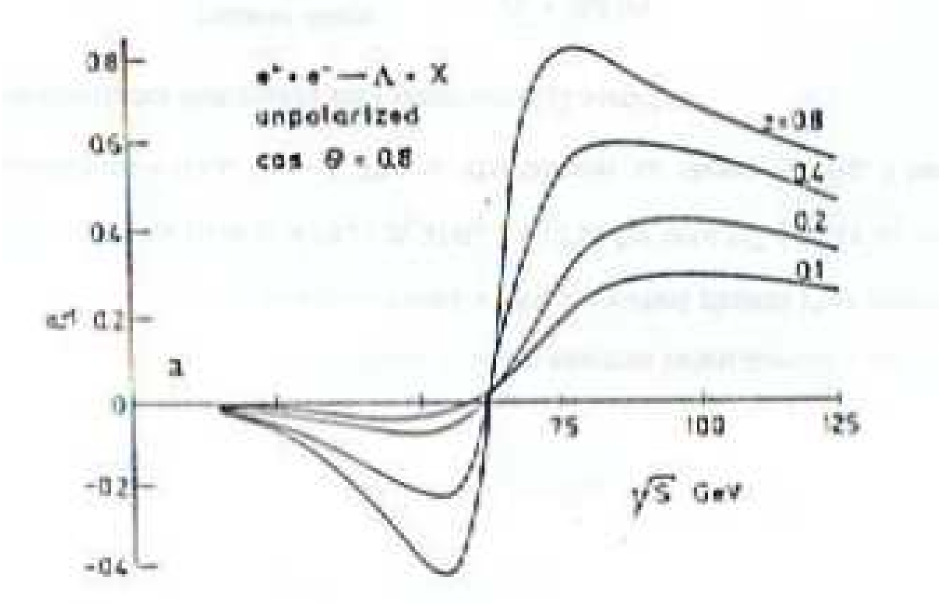
$$a_q = 1 - 8/3\sin^2\theta_W \quad , \quad b_q = 1 \quad for\ \ q = u, c, t$$

$$a_q = -1 + 4/3\sin^2\theta_W \quad , \quad b_q = -1 \quad for\ \ q = d, s, b$$

Due to the axial couplings of the Z° to the quark, it generates a non-zero *longitudinal* polarization $P_q = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where $\sigma_\pm$ are the cross sections for $e^+e^- \to q_h\bar{q}$, with the quark helicity $h = \pm$.
At the Z° pole one finds $P_q = 2a_qb_q/(a_q^2 + b_q^2)$, which reaches a value close to 100% for the down-type quarks, because $\sin^2\theta_W = 0.23$. Of course since the quarks are confined this effect cannot be observed directly and it must be transmitted to the outgoing hadron produced by the quark fragmentation.
Among them, the hyperon $\Lambda(uds)$ is certainly favoured because, first in the $SU(6)$ limit, the Λ polarization P_Λ is that of the s quark contained in it, and second the Λ polarization is relatively easy to measure due to its characteristic decay angular distribution.

Λ Polarization in $e^+e^- \to \Lambda + X$

The predicted Λ polarization at high $z = E_\Lambda/\sqrt{s}/2$ is large and reflects that of a s quark directly coupled to the Z°



A practical test

(Could also consider $e^+e^- \to \Lambda + \bar{\Lambda}$ but smaller cross section)

Signature for Susy particles

One possible way to go beyond the SM is to appeal to supersymmetric (SUSY) theories which relate particles of *different* spin, by conjecturing a symmetry between fermions and bosons which are put together in the same SUSY multiplet. 6Therefore the most exciting prediction of SUSY is that every know particle of the SM with spin s is expected to have a supersymmetric partner with spin $s \pm 1/2$ and with identical mass in case of EXACT supersymmetry. However none of these particles have been observed so far, therefore we must assume that supersymmetry is badly broken, leaving a great uncertainty on the the mass spectrum of the SUSY particles.

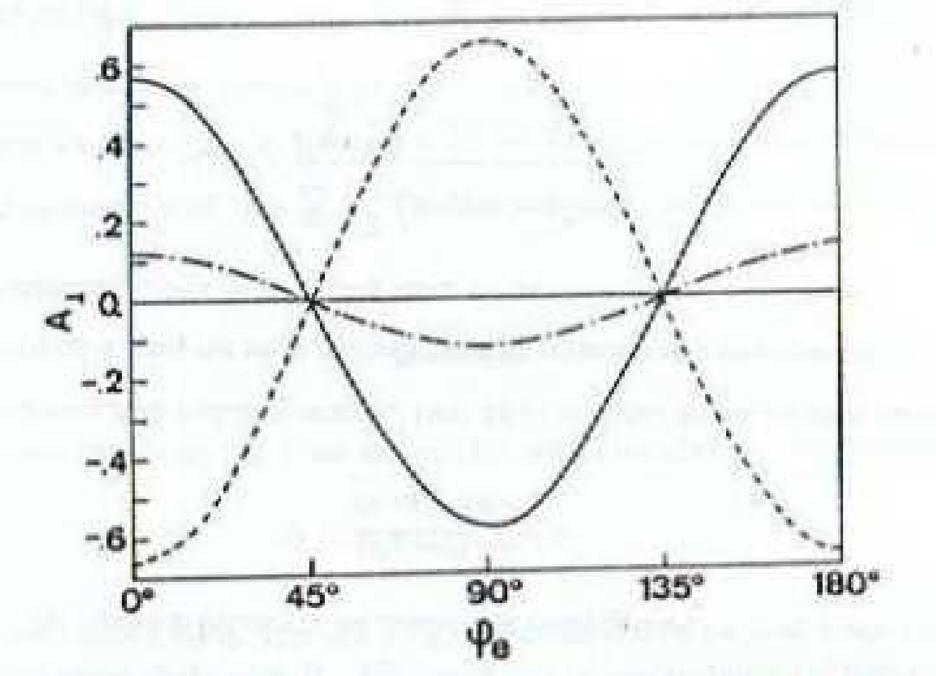
Signature for Susy particles

One possible way to go beyond the SM is to appeal to supersymmetric (SUSY) theories which relate particles of *different* spin, by conjecturing a symmetry between fermions and bosons which are put together in the same SUSY multiplet. 6Therefore the most exciting prediction of SUSY is that every know particle of the SM with spin s is expected to have a supersymmetric partner with spin $s \pm 1/2$ and with identical mass in case of EXACT supersymmetry. However none of these particles have been observed so far, therefore we must assume that supersymmetry is badly broken, leaving a great uncertainty on the the mass spectrum of the SUSY particles.

However the spin properties associated to these new objects are an essential tool to be used for detecting them in experimental searches with polarized beams, thanks to the characteristic features of spin asymmetries.
As an example we denote $\tilde{e}^+$, the SUSY spin-0 partner of e^+ and similarly $\tilde{e}^-$ for e^-.
In e^+e^- collisions, provided the c.m. energy allows it, the SUSY partners could be pair produced in $e^+e^- \to \tilde{e}^+\tilde{e}^-$, followed by the decay $\tilde{e}^\pm \to e^\pm\tilde{\gamma}$, where $\tilde{\gamma}$ is the photino, the spin-1/2 partner of the photon. Assuming that both initial beams have their natural transverse polarization in a collider ring, we can consider the transverse asymmetry defined as $A_\perp = (\sigma(\uparrow\downarrow) - \sigma(\uparrow\uparrow))/(\sigma(\uparrow\downarrow) + \sigma(\uparrow\uparrow))$

Transverse asymmetry $A_\perp$ for SUSY particles production in $e^+e^- \to \tilde{e}^+\tilde{e}^-$

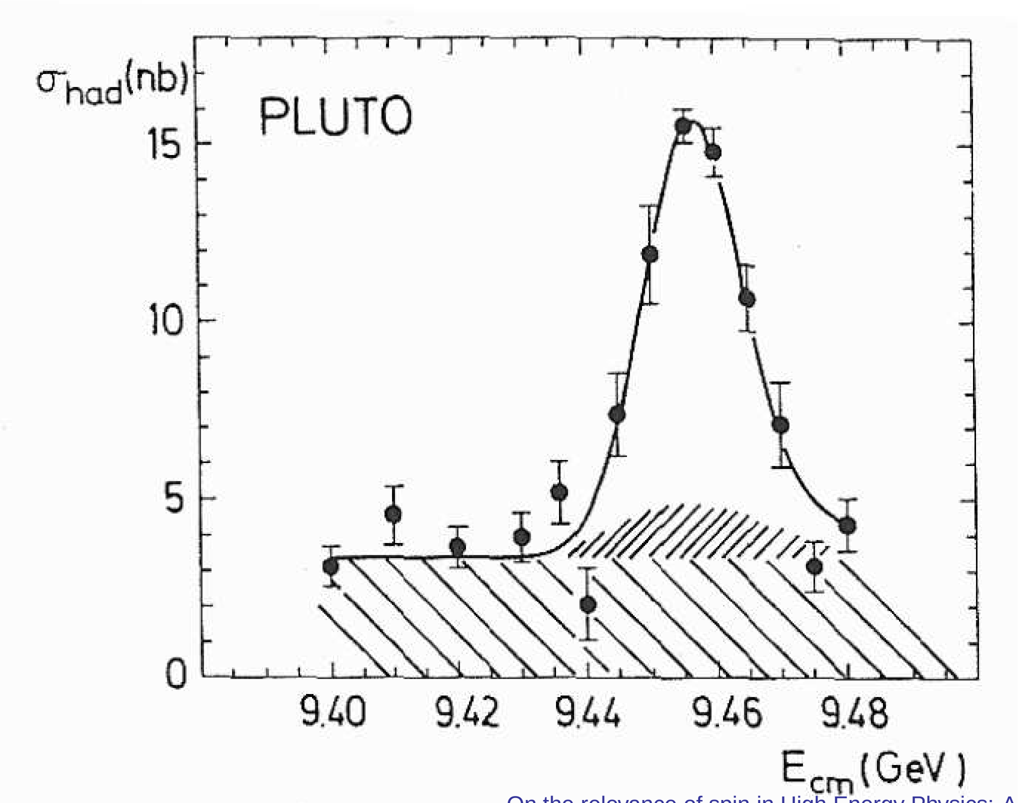
The ϕ dependence of $A_\perp$, integrated over the polar angle θ, at the Z° pole. Solid curve scalar electron of mass 20GeV. Dotted-dashed scalar electron of mass of 40GeV. Dashed curve $e^+e^- \to e^+e^-$ for comparison



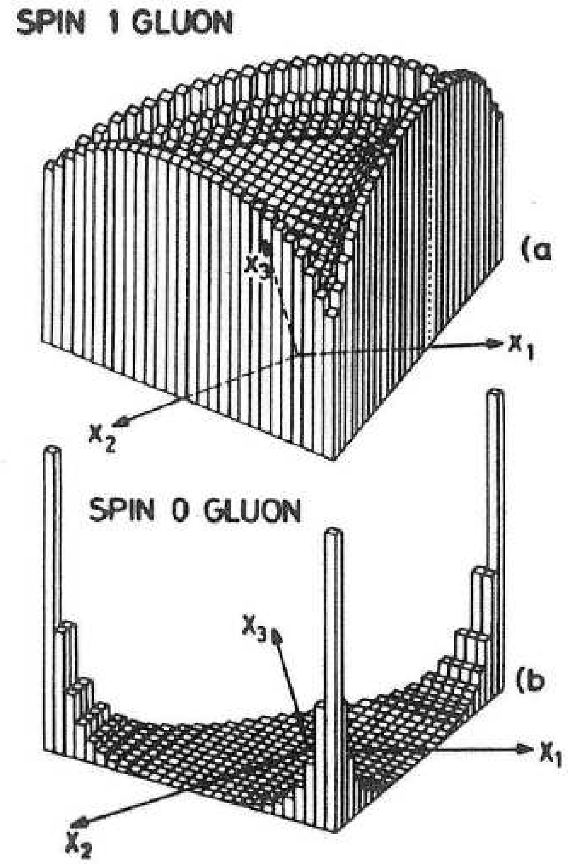
The sign change is a spectacular signature for SUSY particles

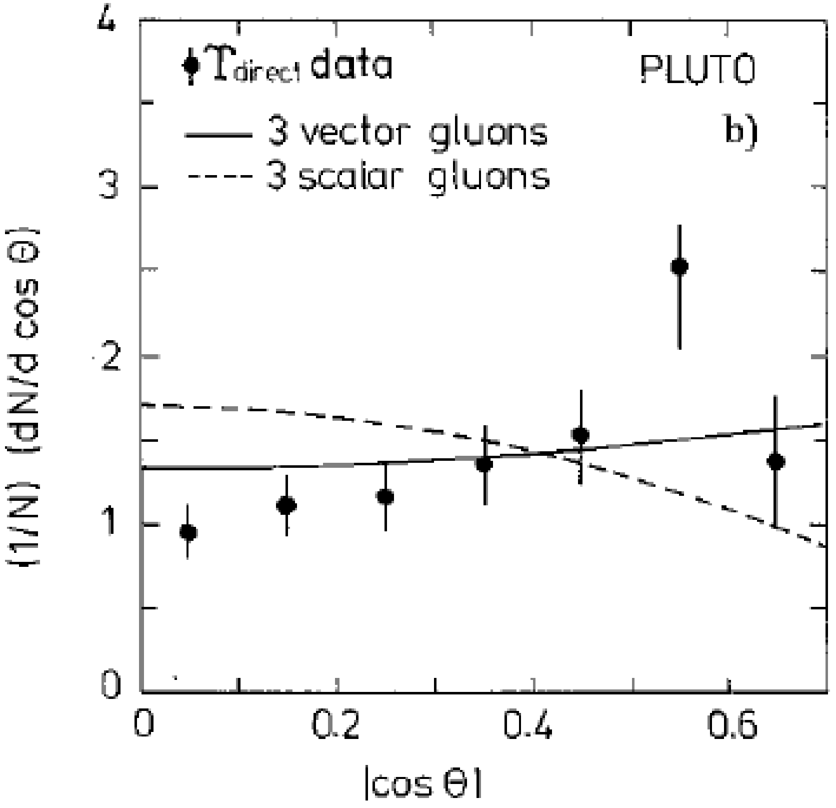
Gluon spin from $\Upsilon(9.46)$ production in e^+e^- collisions

In 1978 the PLUTO detector at DESY demonstrated that the main decay of the $b\bar{b}$ resonance, $\Upsilon(9.46)$, was mediated by 3 gluons.
The kinematics of the $\Upsilon \to$ 3-gluon decay is fixed by the 3 gluon scaled momenta x_1, x_2, x_3 and the momentum distribution of the gluons is very different for spin-1 and for spin-0 gluons



Gluon spin from $\Upsilon(9.46)$ production in e^+e^- collisions



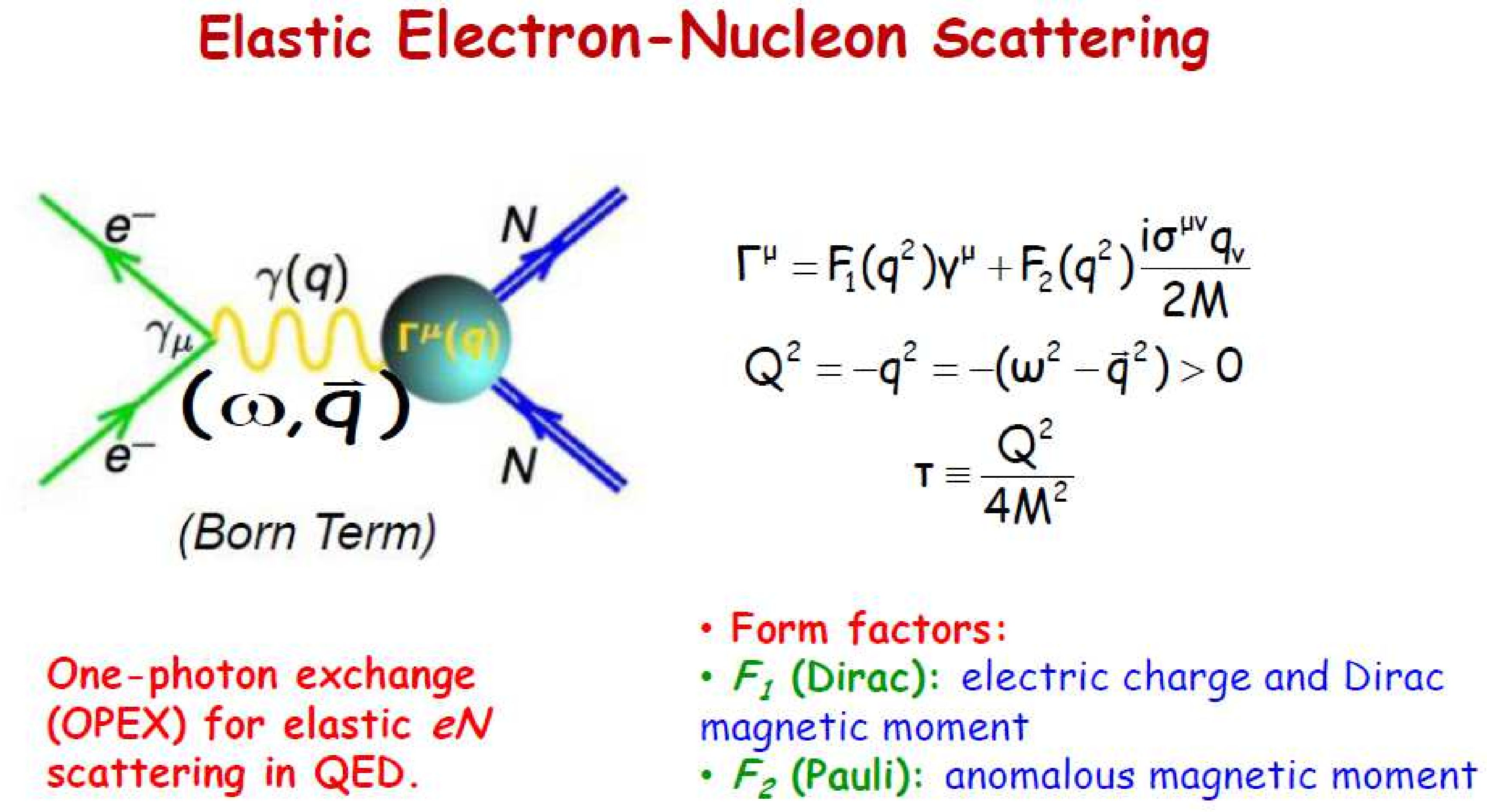


Spin-1 was clearly established

Spin in ep collisions

- Elastic proton form factors
- Weak interactions issues
- Issues beyond the Standard Model
- The nucleon spin structure

Spin in ep collisions: Proton elastic form factors



Elastic Electron-Nucleon Scattering

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

$$Q^2 = -q^2 = -(\omega^2 - \vec{q}^{\,2}) > 0$$

$$\tau \equiv \frac{Q^2}{4M^2}$$

One-photon exchange (OPEX) for elastic *eN* scattering in QED.

- Form factors:
- *F_1* (Dirac): electric charge and Dirac magnetic moment
- *F_2* (Pauli): anomalous magnetic moment

Spin in ep collisions: Proton elastic form factors

It is preferable to introduce the Sachs form factors $G_E = F_1 - \tau F_2$ and $G_M = F_1 + F_2$
Question: How to know the Q^2 behavior of G_E and G_M?
Rosenbluth separation method with unpolarized cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}$$

$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

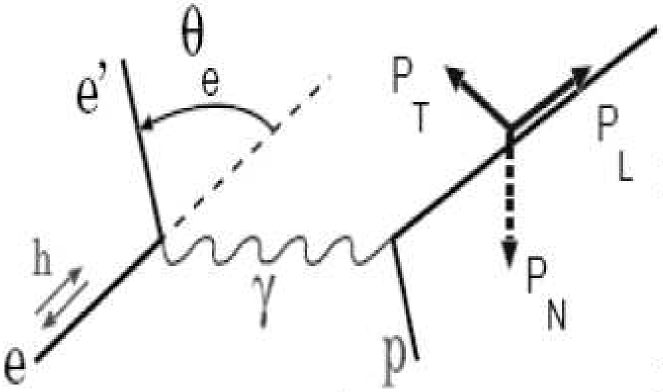
$$\sigma_R \equiv \epsilon(1+\tau)\frac{\sigma}{\sigma_{Mott}} = \epsilon G_E^2 + \tau G_M^2$$

- *Measure angular dependence of cross section at fixed Q^2*

With a bad precision it leads to $\mu G_E/G_M \sim 1$!

Spin in ep collisions: Proton elastic form factors

Polarization Transfer Method in Born Approximation



$H(\vec{e},e'\vec{p})$

$$P_t = -2hP_e\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}\frac{G_{Ep}G_{Mp}}{I_0} = -hP_e\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\,\frac{r}{1+\frac{\varepsilon}{\tau}r^2}$$

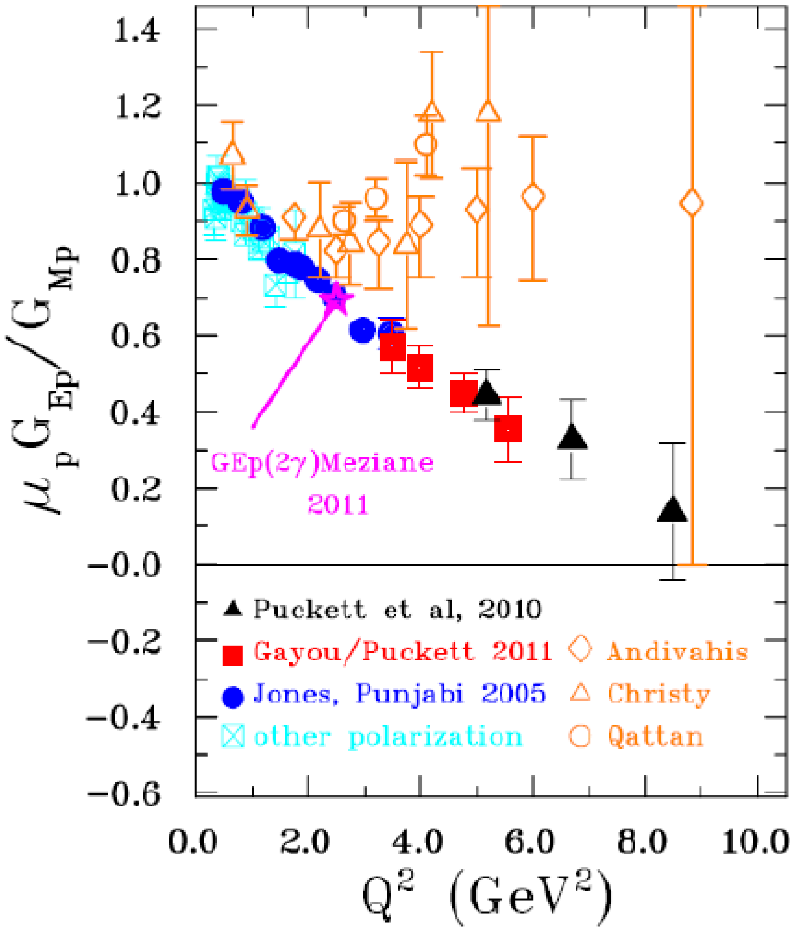
$$P_\ell = hP_e\frac{(E_{beam}-E_e')\sqrt{\tau(1+\tau)}}{M_p}\tan^2\frac{\theta_e}{2}\frac{G_{Mp}^{\ 2}}{I_0} = hP_e\sqrt{1-\varepsilon^2}\,\frac{1}{1+\frac{\varepsilon}{\tau}r^2}$$

$$I_0 = G_{Ep}^2 + \frac{\tau}{\varepsilon}G_{Mp}^2, \qquad r = \frac{G_{Ep}}{G_{Mp}} = \frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}$$

$h=\pm1$ beam helicity, P_e beam polarization

Pioneering theoretical work by: Akhiezer, Rosentweig,Shmushkevich (1958), Akhiezer, Rekalo (1968, 1974), Dombey (1969), Arnold, Carlson and Gross (1981).

Spin in ep collisions: Proton elastic form factors



$\mu_p G_{Ep}/G_{Mp}$ from all double Polarization Experiments

Recent Rosenbluth data including:
L. Andivahis et al., Phys. Rev. D 50, 5491 (1994).
Christy et al., Phys. Rev. C 70, 015206 (2004).
Qattan et al. Qattan I.~A. et al., Phys. Rev. Lett. 94, 142301 (2005).

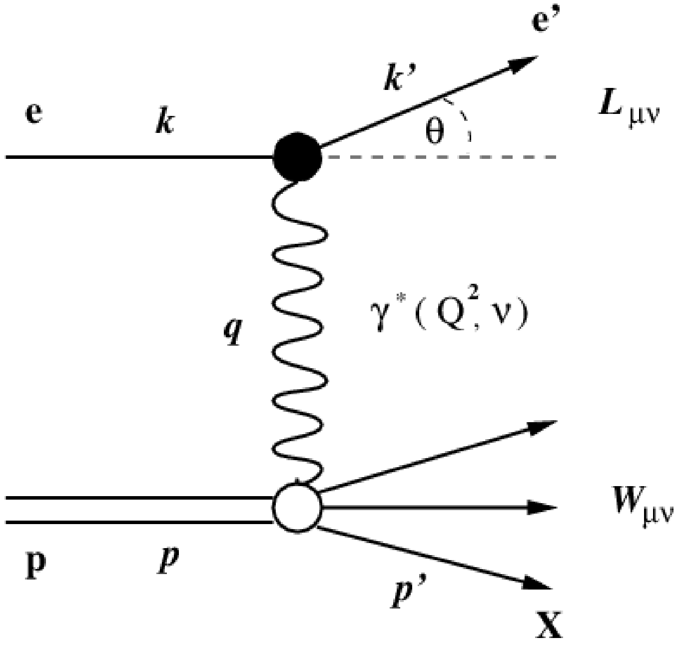
Other polarization results (cyan, or aqua marine), including recoil polarization and beam-target asymmetry results.

Reveals an unexpected behavior

Spin in ep collisions: Deep inelastic scattering

Deep inelastic scattering (DIS) has played a major role in the development of our understanding of the substructure of elementary particles, i.e. the discovery of Bjorken scaling in the late 1960s and the invention of the parton model, in the reaction $l + N \to l' + X$.

Bjorken variable $x = Q^2/p \cdot q = Q^2/2M\nu$ and $y = p \cdot q/p \cdot k = \nu/E$



Can generalize this diagram with the exchange of electroweak bosons Z^0 and $W^\pm$

Spin in ep collisions: weak interactions issues

For the photon exchange one has $1/Q^2$ and for the Z^0 boson, $1/(Q^2 + M_Z^2)$ with both vector and axial couplings

So with a longitudinally polarized electron beam, one can generate a single helicity asymmetry $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$.

For a deuterium target $e + D \to e + X$, one has

$$A_L/Q^2 = \frac{3G_F}{5\sqrt{2}\pi\alpha_{em}}[(C_{1u} - C_{1d}/2) + (C_{2u} - C_{2d}/2)\frac{1-(1-y)^2}{1+(1-y)^2}]$$

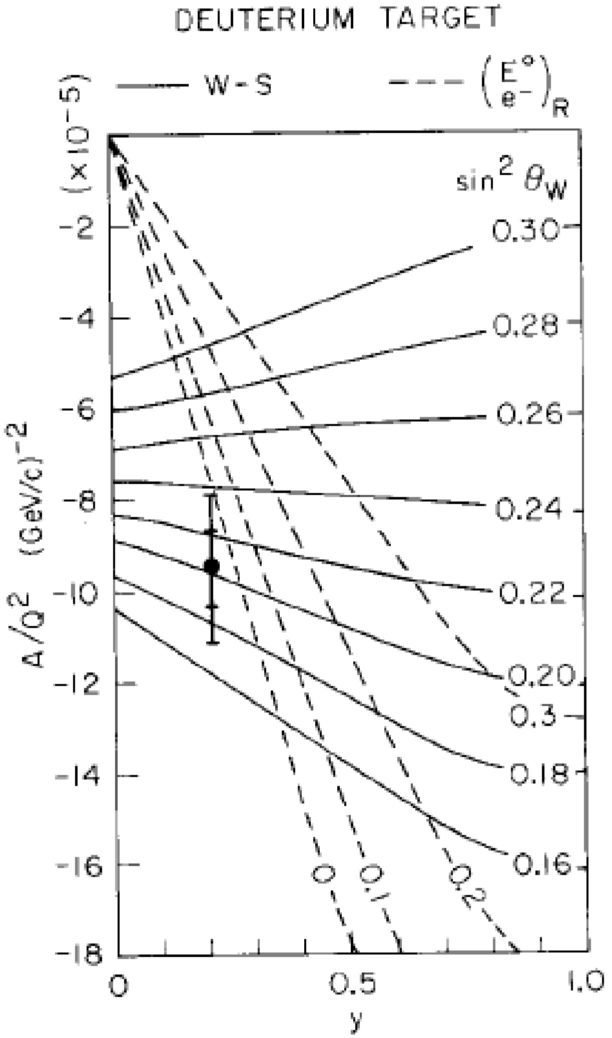
The famous SLAC experiment with an electron beam of definite helicity, found a non zero A_L

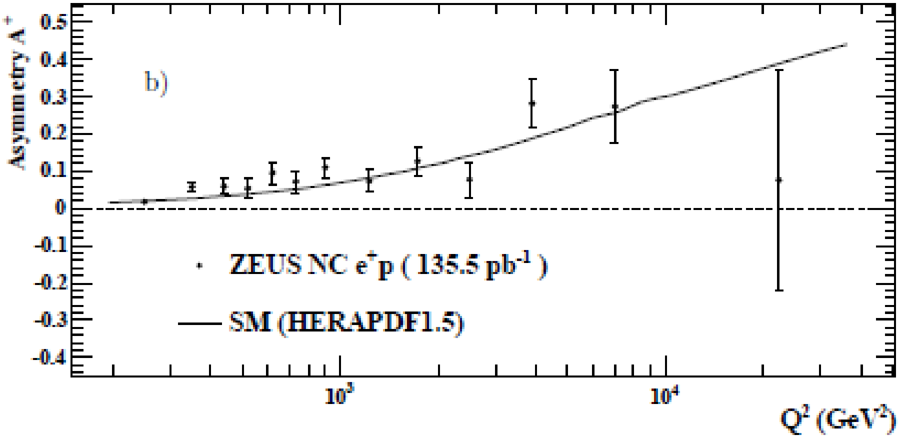
(Ch. Prescott et al. Phys. Lett. B77 (1978) 347)

$A_L/Q^2 = (-9.5 \pm 1.6)10^{-5}$GeV^{-2}, for Q^2 = 1.6 GeV^2 and $y = 0.21$

This heroic measurement provided the confirmation of the existence of the Z^0 boson and led to the first determination of $\sin\theta_w^2$.

Spin in ep collisions: weak interactions issues

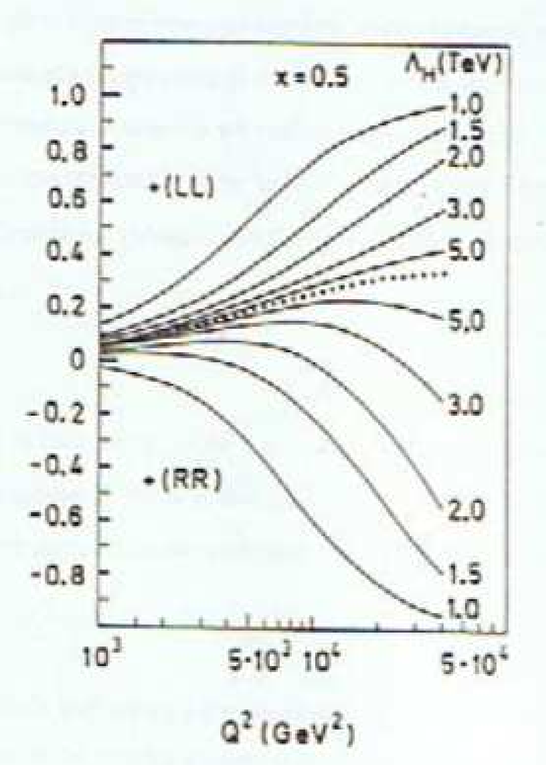




Zeus Coll. arXiv: 1208.6138

Spin in ep collisions: issues beyond the SM

The SM asymmetry is well predicted at the HERA collider at the energy $\sqrt{s}$ = 314 GeV and it grows up to 30% or so. However if quarks and leptons have a substructure, compositeness effects in eq interactions can be treated by considering aa effective Lagrangian $L_{eff} = \eta_{ab} 4\pi/\Lambda_H(\bar{e}_a\gamma^\mu e_a)(\bar{q}_b\gamma_\mu q_b)$, where $\eta = \pm$, a,b = L,R and Λ_H is the compositeness scale.



R. Ruckl, Nucl. Phys. B234, 91 (1984)

Spin in ep collisions: the nucleon spin structure

We want to understand the role of the partons in the proton spin so let'us go back to DIS and the parton model.
The cross section has the following expression

$$\frac{d^2\sigma}{dE' d\Omega_e} = \frac{4\alpha^2}{Q^4}\frac{E'}{E} L^{(e)}_{\mu\nu} W^{\mu\nu} ,$$

where $\alpha = 1/137.036$ and $L^{(e)}_{\mu\nu} = L^{(S)}_{\mu\nu} + L^{(A)}_{\mu\nu}$ is the leptonic tensor

$$L^{(S)}_{\mu\nu} = 2[k'_\mu k_\nu + k_\mu k'_\nu + (m_e^2 - k.k')g_{\mu\nu}] \ , \quad L^{(A)}_{\mu\nu} = -2i\varepsilon_{\mu\nu\alpha\beta} s_e^\alpha q^\beta \ ,$$

where s_e is the lepton spin vector.$W_{\mu\nu}$ is the hadronic tensor defined as $W^{(S)}_{\mu\nu} + W^{(A)}_{\mu\nu}$. $W^{(A)}_{\mu\nu}$ is antisymmetric and contains the proton spin vector s_p.
Because the electromagnetic current J_μ is conserved, namely $\partial_\mu J_\mu = 0$, we have $q_\mu W^{(S)}_{\mu\nu} = q_\nu W^{(S)}_{\mu\nu} = 0$, and by using parity conservation and T invariance, one shows that $W^{(S)}_{\mu\nu}$ can be expressed in terms of two real *structure functions* $W_1(\nu, Q^2)$ and $W_2(\nu, Q^2)$.
Similarly for $W^{(A)}_{\mu\nu}$ which can be expressed in terms of $G_1(\nu, Q^2)$ and $G_2(\nu, Q^2)$.

Spin in ep collisions: the nucleon spin structure

From the 1968 SLAC experiment, it was observed that at a fixed value of W^2, the invariant square mass of X, when Q^2 is large enough, both MW_1 and νW_2 vanish, like in the elastic case. However in the *scaling limit*, that is when both ν and Q^2 are large, with $x = Q^2/2M\nu$ fixed, this is no longer the case and according to Bjorken, one expects for $Q^2 \to \infty$

$$MW_1(\nu, Q^2) \to F_1(x) \; , \qquad \nu W_2(\nu, Q^2) \to F_2(x) \; ,$$

where $F_{1,2}(x)$ are two scaling functions independent of Q^2. Therefore the SLAC experiment has shown that the DIS cross section is much larger than expected and obeys scaling as predicted by Bjorken.
In the scaling limit one also expects

$$\nu M^2 G_1(\nu, Q^2) \to g_1(x), \quad \nu^2 M G_2(\nu, Q^2) \to g_2(x) \; ,$$

where $g_{1,2}(x)$ are two scaling functions independent of Q^2.

Spin in ep collisions: the nucleon spin structure

According to the interpretation in the parton model one has

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)\ ,$$

where $q_i(x) = q_{i+}(x) + q_{i-}(x)$. Clearly $q_i(x)$, which is called the *unpolarized* quark distribution function, contains the sum over two quark spin directions and the average over the quark intrinsic transverse momentum k_T.
One also has the Callan-Gross relation $2xF_1(x) = F_2(x)$, which reflects the fact that partons are spin-1/2 objects.
Similarly for the spin-dependent structure functions one has

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x) \quad and \quad g_2(x) = 0\ ,$$

where $\Delta q_i(x) = q_{i+}(x) - q_{i-}(x)$ is called the *polarized (or helicity)* quark distribution.

Spin in ep collisions: the nucleon spin structure

In the case of longitudinal beam and target polarization along the beam direction (*i.e.* $s_e = \frac{1}{m_e}(|\vec{k}|, E\vec{k}/|\vec{k}|)$ and *idem* for s_p), the EMC Collaboration has measured the double helicity asymmetry

$$A_{\|} = \frac{d^2\sigma^{\uparrow\downarrow} - d^2\sigma^{\uparrow\uparrow}}{d^2\sigma^{\uparrow\downarrow} + d^2\sigma^{\uparrow\uparrow}} \ ,$$

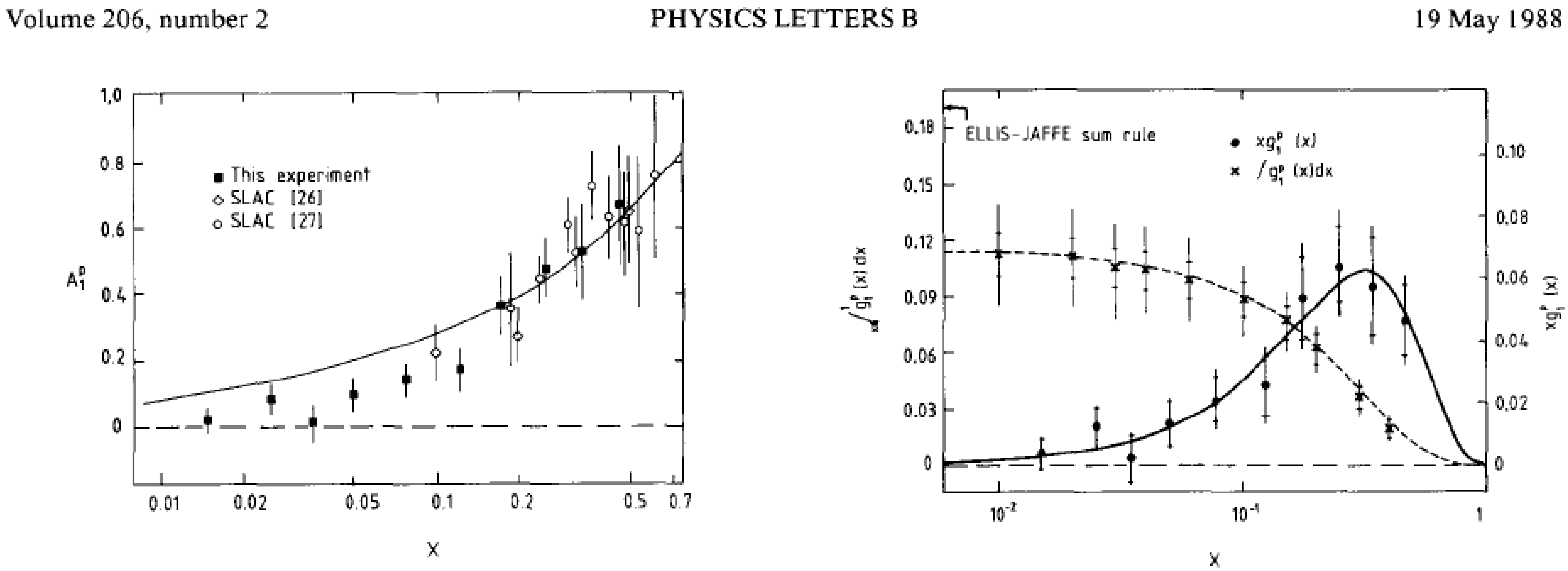
which leads, in the scaling limit ($Q^2 \to \infty$), the extraction of the quantity

$$A_1(x) = g_1(x)/F_1(x) \tag{1}$$

It supplemented the earlier SLAC-Yale experiment and allowed to explore for the first time the low x-region of g_1^p.

Spin in ep collisions: the nucleon spin structure

EMC Collaboration, Phys. Lett. B206, 364 (1988) (1700 citations)



Volume 206, number 2 PHYSICS LETTERS B 19 May 1988

A Tsunami (Spin Crisis) reported at the EPS 1987 Conference, Uppsala (Sweden)

The quarks carry only 1$\%$ of the proton spin

It has strongly boosted the field, both on theory and experiment

Spin in ep collisions: the nucleon spin structure

Before going to the theoretical interpretation of the data let us recall the important constraints. The total amount of the proton spin carried by quarks (and antiquarks) is

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

with $\Delta q_i = \int_0^1 [\Delta q_i(x) + \Delta \bar{q}_i(x)] dx$. We have the spin sum rule

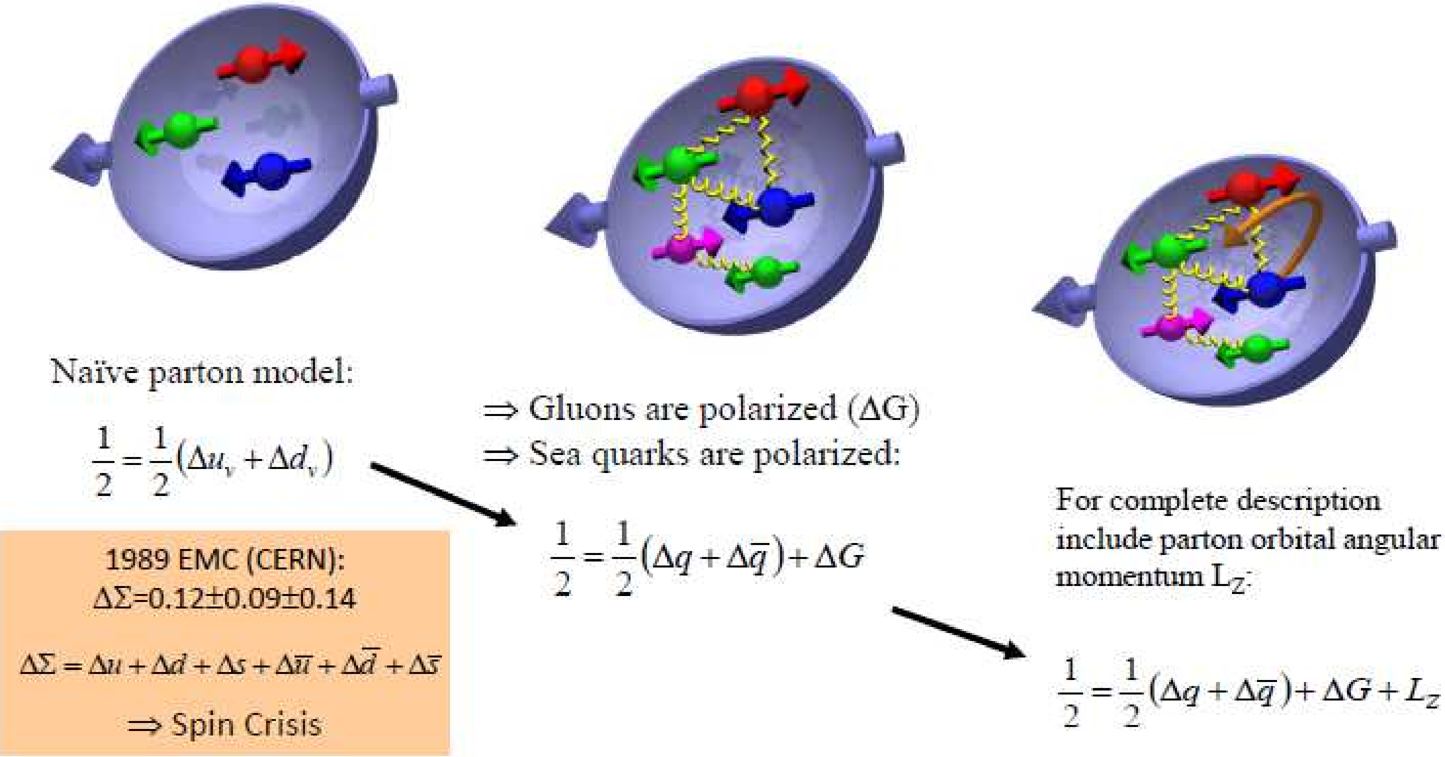
$$1/2 = 1/2 \Delta\Sigma + \Delta G + < L_z >$$

and the *Ellis-Jaffe sum rules* which read

$$\Gamma_1^p = \int_0^1 dx g_1^p(x) = \frac{1}{18}(9F - D + 6\Delta s) \text{ and } \Gamma_1^n = \int_0^1 dx g_1^n(x) = \frac{1}{18}(6F - 4D + 6\Delta s) \, ,$$

where $F = 0.459 \pm 0.008$ and $D = 0.798 \pm 0.008$ are the β-decay axial coupling constants of the baryon octet. One obtains the famous Bjorken sum rule by taking the difference because $F + D = g_A/g_V$. In their original work, Ellis and Jaffe made the critical assumption that $\Delta s = 0$, which allows to make definite predictions for Γ_1^p and Γ_1^n. Find $\Gamma_1^p = \int_0^1 dx g_1^p(x) = 0.114 \pm 0.012 \pm 0.026$

Spin in ep collisions: the nucleon spin structure



Naïve parton model:

$$\frac{1}{2}=\frac{1}{2}(\Delta u_v+\Delta d_v)$$

1989 EMC (CERN):
ΔΣ=0.12±0.09±0.14

$$\Delta\Sigma=\Delta u+\Delta d+\Delta s+\Delta\bar{u}+\Delta\bar{d}+\Delta\bar{s}$$

⇒ Spin Crisis

⇒ Gluons are polarized (ΔG)
⇒ Sea quarks are polarized:

$$\frac{1}{2}=\frac{1}{2}(\Delta q+\Delta\bar{q})+\Delta G$$

For complete description include parton orbital angular momentum L_Z:

$$\frac{1}{2}=\frac{1}{2}(\Delta q+\Delta\bar{q})+\Delta G+L_Z$$

Is the riddle of the proton spin solved ?

Spin in ep collisions: the nucleon spin structure

Where do we stand after 25 years?

- Many higher orders QCD calculations have been done
- Many models for the proton spin have been proposed
- New experimental facilities have been built
- The fundamental Bjorken sum rule has been tested to a few percents accuracy
- Quarks carry only 30$\%$ of the proton spin
- Need to go beyond a simple picture

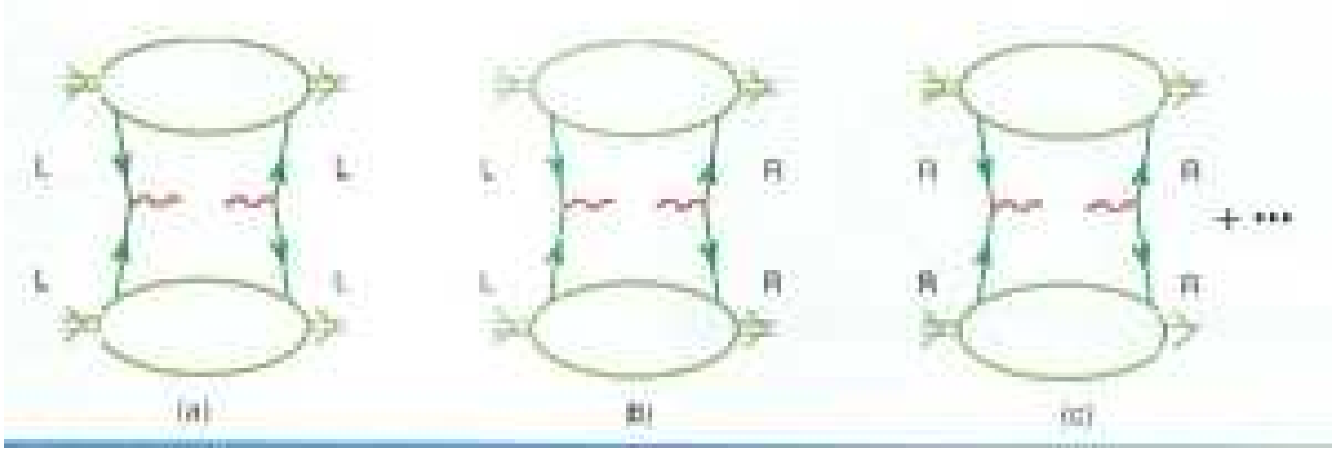
Spin in hadronic collisions

- The quark transversity distribution
- Positivity for two-body reactions
- The RHIC spin program

Quark Transversity Distribution $\delta q(x, Q^2)$

It was first mentioned by Ralston and Soper in 1979, in $pp \to \mu^+\mu^- X$ with transversely polarized protons, but forgotten until 1990, where it was realized that it completes the description of the quark distribution in a nucleon as a density matrix

$$\mathcal{Q}(x, Q^2) = q(x, Q^2) I \otimes I + \color{red}{\Delta q(x, Q^2)} \color{black}{\sigma_3 \otimes \sigma_3} + \color{blue}{\delta q(x, Q^2)} \color{black}{(\sigma_+ \otimes \sigma_- + \sigma_- \otimes \sigma_+)}$$

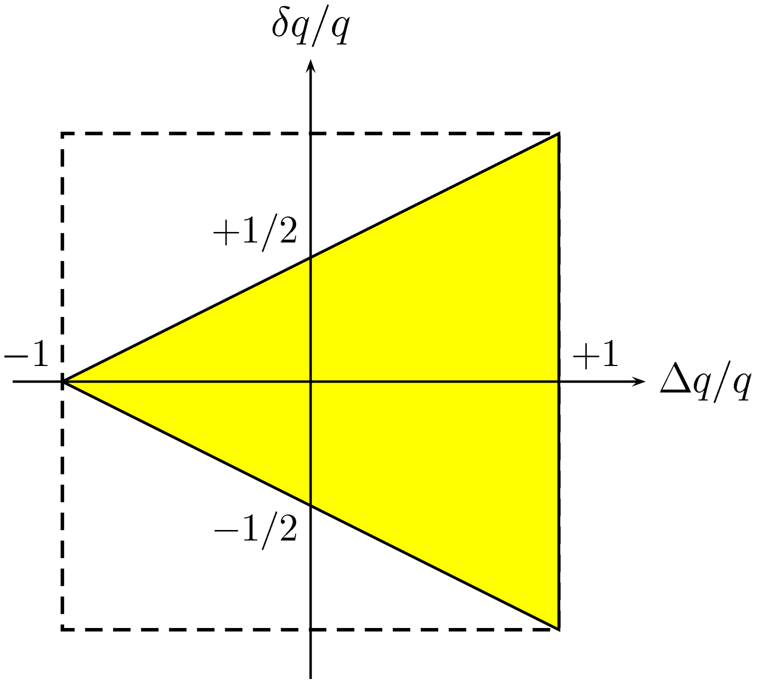


This new distribution function $\delta q(x, Q^2)$ (also denoted h_q or Δ_T^q) is chiral odd, leading twist and decouples from DIS.

Quark Transversity Distribution $\delta q(x, Q^2)$

There is a positivity bound (J.S., PRL 74,1292,1995) survives up to NLO corrections

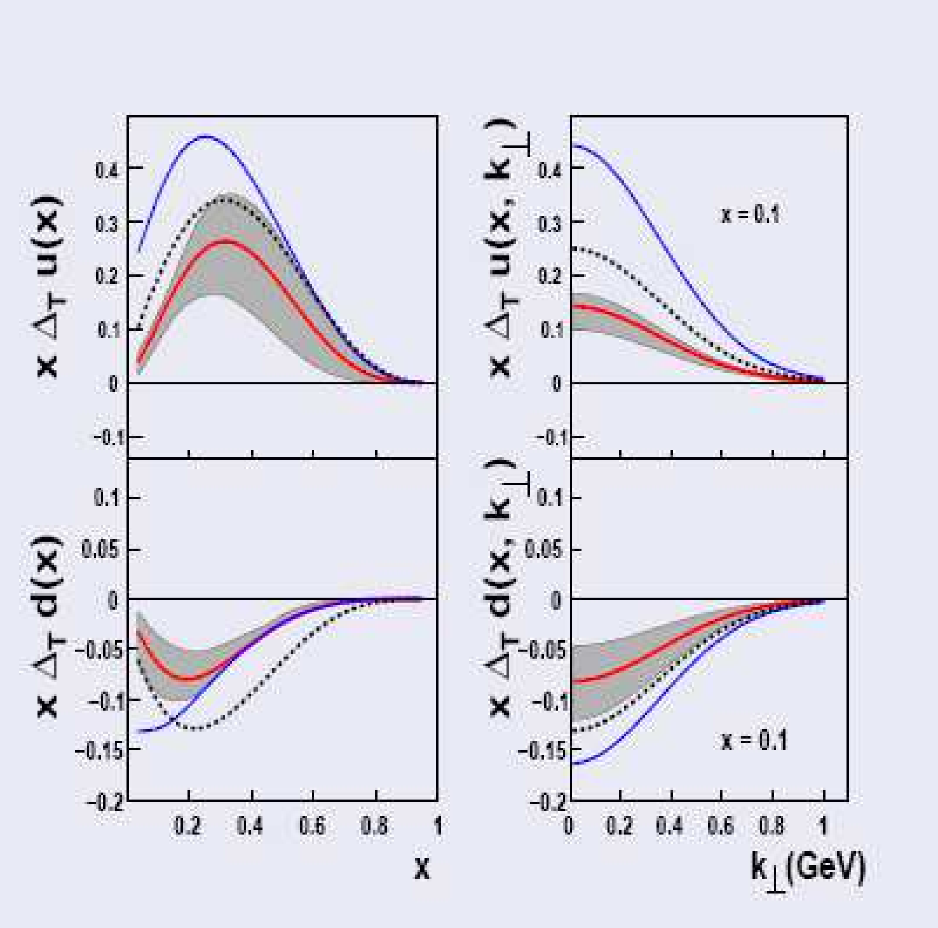
$$q(x, Q^2) + \Delta q(x, Q^2) \geq 2|\delta q(x, Q^2)|$$



Only half of the domain is allowed

Recently, it has been extracted indirectly, for the first time.

First determination of $\delta q(x, Q^2)$



Saturation (or possible violation) for d-quark in the high x region.

Positivity for two-body reactions

- If X, Y, Z are spin observables with standard normalization $-1 \leq X \leq +1$
- the domain for the pair of observables (X,Y) is often smaller than the square $[-1,+1]^2$
- the domain for the triple of observables (X,Y,Z) is often smaller than the cube $[-1,+1]^3$

Positivity for two-body reactions

- If X, Y, Z are spin observables with standard normalization $-1 \leq X \leq +1$
- the domain for the pair of observables (X,Y) is often smaller than the square $[-1, +1]^2$
- the domain for the triple of observables (X,Y,Z) is often smaller than the cube $[-1, +1]^3$
- Explicit inequalities are obtained, relating two or three spin observables, for instance $X^2 + Y^2 \leq 1$ (disk) or $X^2 + Y^2 + Z^2 \leq 1$ (sphere)
- Also triangles, tetrahedrons, etc...(See below)

πN scattering

A scattering process involving spinning particles and described by n *complex* amplitudes is fully determined by $(2n-1)$ *real* functions, up to an over-all phase. Since there are n^2 possible measurements for this reaction, we must have $(n-1)^2$ independent quadratic relations between the n^2 observables.

πN scattering

A scattering process involving spinning particles and described by n *complex* amplitudes is fully determined by $(2n-1)$ *real* functions, up to an over-all phase. Since there are n^2 possible measurements for this reaction, we must have $(n-1)^2$ independent quadratic relations between the n^2 observables.

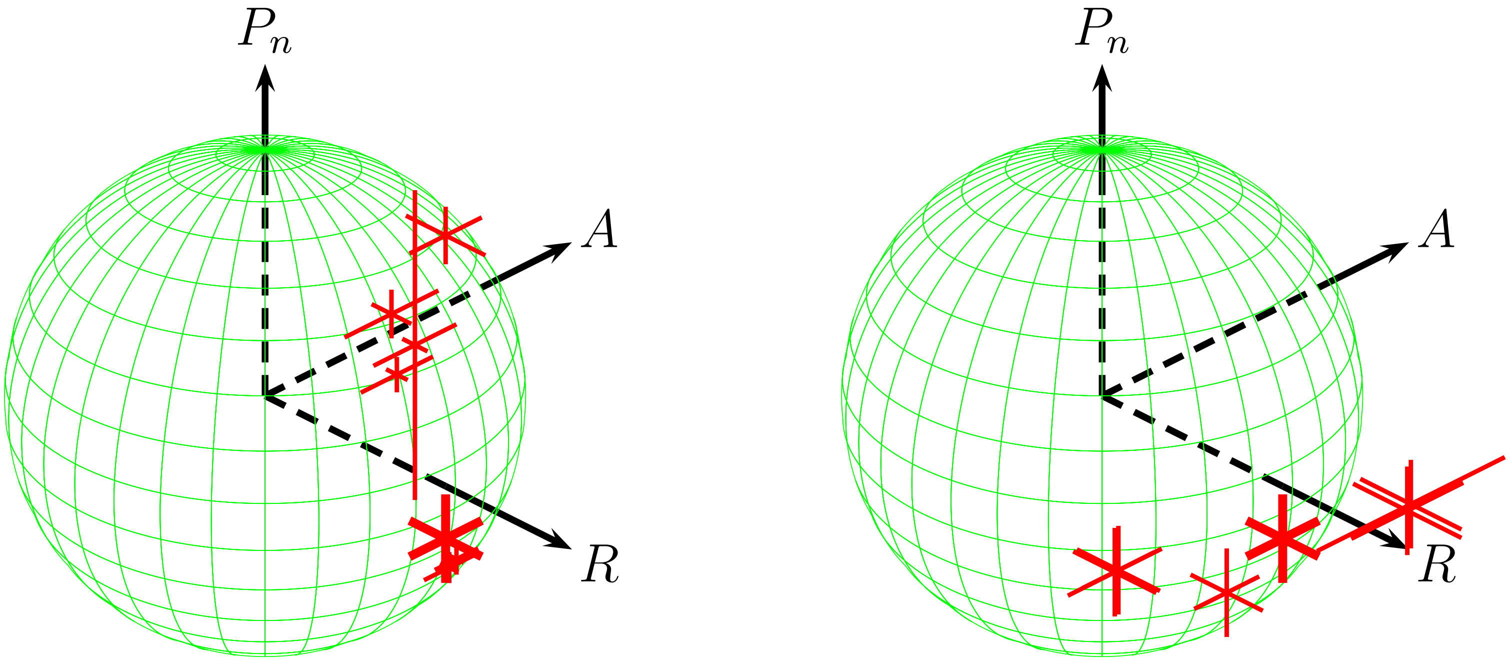
First consider the simplest case of an exclusive two-body reaction with a spin-0 and a spin-1/2 particle, namely $0+1/2 \to 0+1/2$. As an example $\pi N \to \pi N$ is described in terms of 2 amplitudes , the non-flip and the flip amplitudes,

$$M(s,t) = a(s,t) + i\vec{\sigma}\cdot\vec{n}\, b(s,t) \quad where \;\; \vec{n} = \vec{k_i} \times \vec{k_f} \;,$$

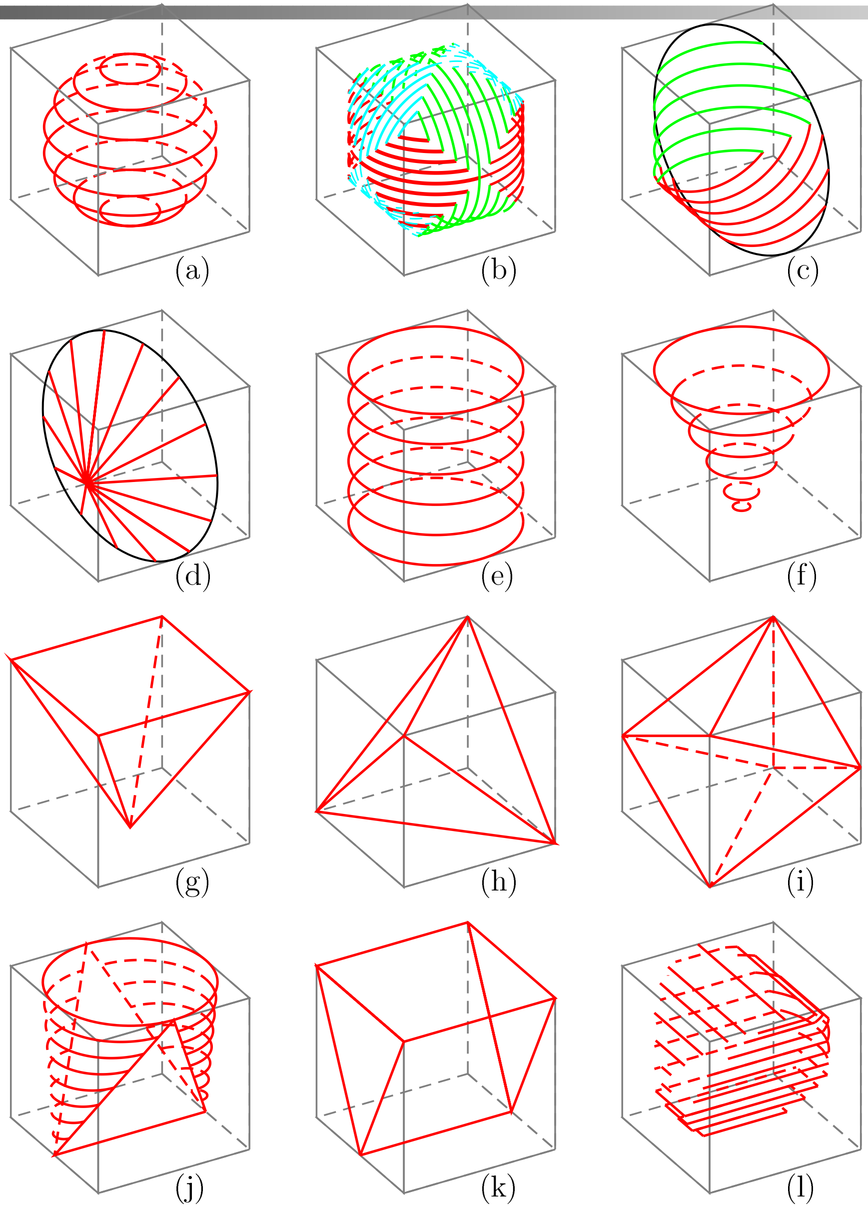
so we have 4 observables, the cross section $d\sigma/dt$, the polarization P_n and two rotation parameters R and A. There is one well known quadratic relation, that is
$P_n^2 + A^2 + R^2 = 1$.
If all three are measured they should be on the surface of the unit sphere

πN scattering

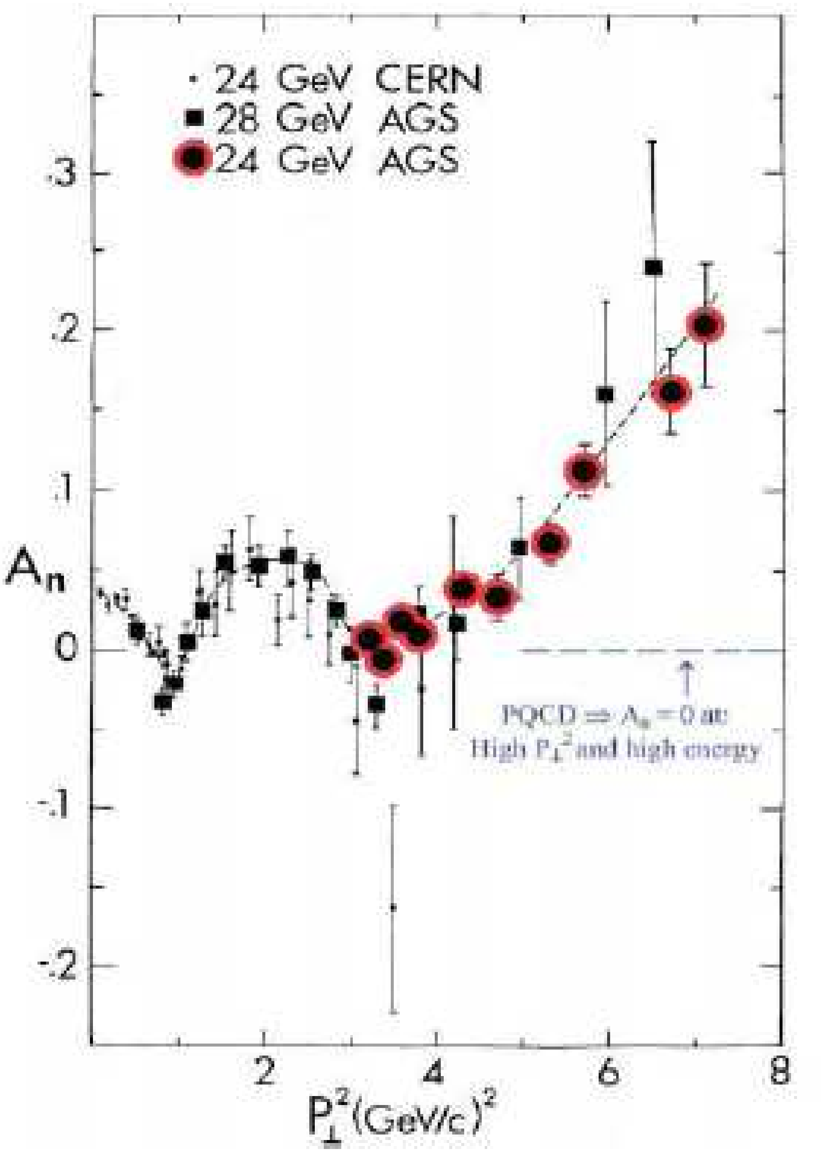
Spin observables for $\pi^{\pm}p$ el. scatt. in axes (R, A, P_n) must lie on the surface



Case of three observables for $\bar{p}p \to \bar{\Lambda}\Lambda$



A remarkable old effect in pp elastic scattering



The RHIC spin program

Spin sector of pQCD and polarized parton distributions functions

- The RHIC polarized pp collider, a unique facility, has certainly the required energy for testing, for the first time, the SPIN SECTOR of pQCD. Several predictions for spin asymmetries exist at the NLO level and are waiting for confrontation with future data.
- Our knowledge on the polarized PDF comes mainly from DIS (far poorer than for unpolarized PDF), but obviously hadron colliders can also be used to improve it. A few examples:
  - Δq and $\Delta\bar{q}$ flavor separation from $W^\pm$ production
  - ΔG from $pp \to \gamma X$, $pp \to jetX$ and $pp \to \pi^0 X$.

Conclusions

C.N. Yang (High Energy Spin Physics - 1982 BNL):

The concept of spin is both an intriguing and extremely difficult one

Have we heard the final word about spin?

I do not believe so

Conclusions

C.N. Yang (High Energy Spin Physics - 1982 BNL):

The concept of spin is both an intriguing and extremely difficult one

Have we heard the final word about spin?

I do not believe so

****

****

I hope you have enjoyed these lectures and that I have convinced you to join

THE SPIN PHYSICS COMMUNAUTY