# 40 Years DIS Experiments at M2 - still going STRONG

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a tale of

- **two** "crises" (may be only narcisstic insults) with profound consequences
- **two** very different views (and communities) of **strong interactions**

The **"EMC effect"** brought me to CERN and EMC in 1984,
the **"spin crisis"** kept **M2** and myself busy (NMC, SMC, COMPASS) for the last 35 years

# Mission of SPS and the NA Experiments in late 70'

- Completion and test of the 3-family Standard Model

- precise handling of the difficult QCD sector, needs unifying the **two** views:
  - massive, extended hadrons as **initial** and **final** scattering states
  - hard scattering processes with quarks and gluons in PQCD
    (point like object, assymptotic freedom)

**Quark Parton Model** quantiative prediction hard scattering X-sections

• **separation of transverse scales**: hadron size $r_h$ and resolution $\frac{1}{Q^2}$
• **factorizing** "soft" confinement pysics from "hard" scattering physics
- **structure functions** $F_q^h(x_{Bj})$, and parton distribution functions
- **fragmentation functions** $D_{q'}^{h'}(z)$ :embedding a parton $q'$ in $h'$ $(z, x_F)$
100-300 GeV **M2** $\mu^{\pm}$: **wide dynamical range** $x_{bj}$ **and** $Q^2 > 1\,GeV^2$ **in logarithmic scaling region**

# NA4, NA2/NA9: Scaling and Factorisation at quest

$\mu$-**DIS NA4 (BCDMS)** optimized for luminosity and acceptance at high $Q^2$ and high $x$

- established logarithmic **scaling** and evolution of $F_2^{p,d}(x, Q^2)$ and its limitations(twist-4)
- derived $\alpha_s(M_Z^2) = 0.118(0.005)$ from scale dependence in the valence region

$\mu$-**DIS NA2(EMC)** open dipole spectrometer with tracking

-$F_2^{p,n}$ in the sea region better $Q^2, x$ resolution and acceptance at low $x$

- evolution analysis with $g(x)$, Gottfried Sumrule from proton neutron difference:

$\mu$-**SIDIS NA9(EMC)** two dipoles, difficult hybrid (low rate) streamer ch.,PID

- forward current and backward target fragmentation
- **factorisation** generally applicable, significantly broken in certain regions, due to correlations
- measured fragmentation functions $D_{u,d}^{\pi,K}(z)$

# The first crisis: The EMC-effect

**Nuclear targets** at NA2 (Fe) and NA4 (C/Be) for increased luminosity

- for logarithmic scaling

surprise:

- SF ratio $\frac{F_2^{Fe}}{F_2^D} = r(x, Q^2)$ different from 1 and complex x-dependence: three sign changes of $r - 1)$

Structure of **bound nucleon** different **free nucleon !**

explanations

$\Rightarrow$**longitudina an transvers scale changes**

• shadowing, "swelling" of nucleons

**NMC** (nuclear or new muon collaboration, hadron and nuclear physics community

• precision measurements of $2 \leq A \leq 208$ dependence structure function ratios

• nuclear radius dependence nuclear shadowing, "cold hadronic matter" in ion physics

# Polarized Sum Rules - the Spin Crisis

**M2** "bonus": (long.)**polarized beam** $\vec{\mu}$ and a (long.) **polarized** $\vec{p}$ **EMC target**

- measurement of polarized structure function $g_1^p(x, Q^2)$ and parton distributions $\Delta q_i(x)$
- proton spin sumrule

$$\Gamma_1^p = \int_{x=0}^{x=1} g_1(x, Q_0)\, dx$$

(integration limits, extrapolations to common $Q_0$)

comparison (model dependent) prediction; Ellis-Jaffe sumrule.

"fundamental" Bjorken sumrule also requires neuton $\Gamma_1^n$ (measured and confirmed later by SMC)

$$\Gamma_1^p - \Gamma_1^n = \int_0^1 [g_1^p(x, Q_0) - g_1^n(x, Q_0)]\, dx = \frac{1}{6} G_A$$

- EMC found the E-J sumrule **significantly violated**:

: $\Gamma_1^p = 0.126 \pm 0.01 \pm 0.015$ instead of $0.185(5)$

# Where is the spin?

spin(helicity) contribution of quarks to total angular momentum of the nucleon flavour **singlet axial charge** expected: $\Delta\Sigma^p = \sum \Delta q_i \approx 0.6$ , EMC deduced

$$\Delta\Sigma^p = \sum \int (\Delta q_i^p(x) + \Delta \bar{q}_i^p(x))dx = 0.10 \pm 0.12$$

The spin of the nucleon **is not carrried by quarks**
Conservation of angular momentum requires

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_g + L_q$$

the other components $(\Delta G, L_g, L_q)$ must carry a **significant** fraction of $\frac{1}{2}$
- axial anomaly suggests large $\Delta G$ (and a cancellation $L_{q,g}$)
- $L_q$ has to exist to explain anomalous magnetic moments in the extended p,n
- transverse spin quark distribution must exist $\delta q_i(x)$ and also a Twist2 SF $h_1(x)$

# $\mu$–COMPASS: $\Delta G$ and Transversity $h_1(x)$

(polarized) gluons $g(x, Q^2)$ and $\Delta g(x, Q^2)$

• scaling violations in DIS ($\rightarrow$HERA small $x$, missed $\vec{e}\vec{p}$ and $\vec{e}\vec{d}$)

• in SIDIS: singling out the hard process $\vec{\gamma}^* + \vec{g} \rightarrow q\bar{q}$ with high $M_q$ or $p_T$

• double longitudinal polarisation asymmetry $\vec{\mu}$,$\vec{Li}_6$

• charmed meson production, high $p_T$ hadron(pairs)

COMPASS found a small gluon polarisation $-0.1 < \frac{\Delta g}{g} < 0.2$ at $x \approx 0.1$

ruling out the anomaly szenario but not a "democratic" scenario with $\Delta G \approx \frac{1}{3}$

Transversity SF is $h_1$ is chirally odd

• can be measured in SIDIS on a transversly polarized nucleon

• needs a chirally odd FF $D^{coll}(z, p_T)$ to produce the Collins azimuthal asym.

• there are other (but distinguishable) transvers asymmetries $\rightarrow$ TMD

Rich pattern of charged hadron asymmetries observed

showed existence of $D^{coll}$, derived $\delta u(x) > 0$ and $\delta d(x) < 0$ in the nucleon

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# Transversely Resolved Structure Functions and DVCS

hadrons have form factors and finite radii

$\rightarrow$transversely extended objects with transverse (parton) density profile

Idea of **transversely resolved structure functions** lead

• GPDs generalized structure functions , accessibel in **exclusive** DIS

Relevant to the spin problem: Ji's sumrule relates to the quark angular momentum

DVCS=deeply virtual compton scattering at COMPASS (also at Jefferson Lab, 12GeV $\vec{p}$)

•There are operators in GPDs with quantum numbers of the graviton ...?

# Is spin the universal language of quantum gravity ?

- spin considered as the quantum bit
-“it from bit” (Wheeler), universe as a (quantum) information problem
leads immediately to
dark energy density $\frac{3}{4} \iff$ if universe is a singlet with $J = 0$
- 3+1 dimensions and 3 families and other symmetries follow

My conclusion:
go “strong” to understand size, mass and angular momentum of hadrons **and the universe**