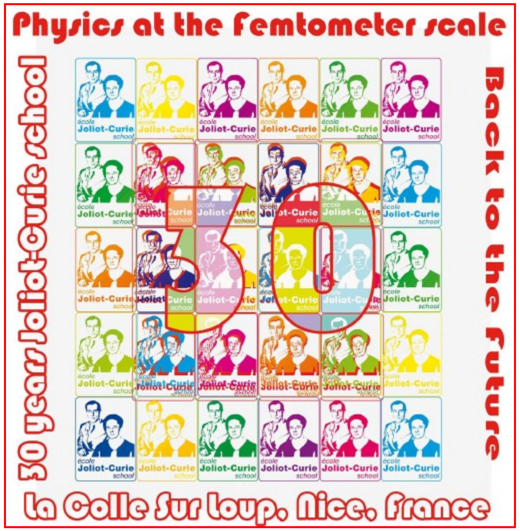
Probing the nucleon structure

What have we learnt during the last 30 years?

Nicole d'Hose, Irfu – CEA Saclay
La Colle sur Loup, Sept 16, 2011



Probing the nucleon structure

A brief story of the nucleon

Proton and neutron are the basic building blocks of *the visible matter of the universe*

Nucleon Identity card (PDG):

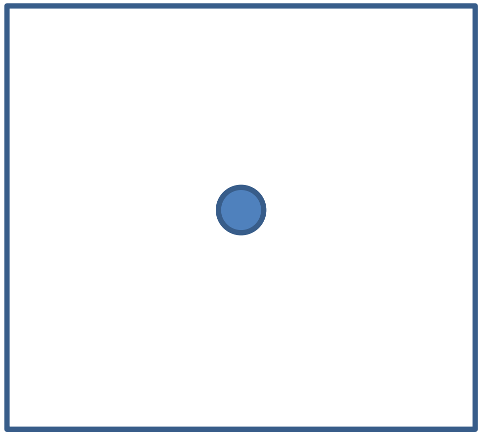
Proton	Neutron
$Q=+e$	$Q=0$
$M_p=938.27$ MeV	$M_n=939.57$ MeV
$S=\frac{1}{2}$	$S=\frac{1}{2}$
$\mu_p=2.79\ \mu_N$ ($\kappa_p=1.79$)	$\mu_n=-1.91\ \mu_N$ ($\kappa_n=-1.91$)

Probing the nucleon structure

A brief story of the nucleon

Identified in 1919 (proton) and 1932 (neutron)

Until 1933: they were thougth as
a point-like particle, like electron

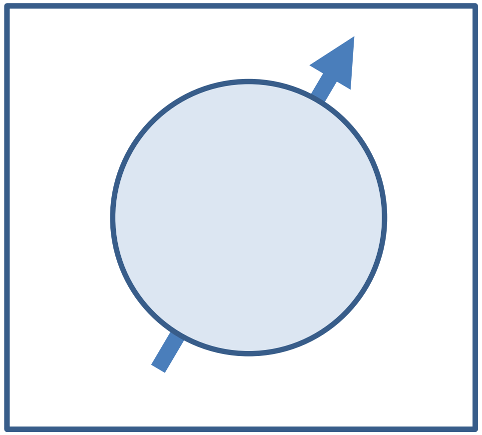


Probing the nucleon structure

A brief story of the nucleon

1933-1960: extented object

1933: *Stern (NP 1943)* measured
the anomalous magnetic moment
1rst evidence the proton is not point -like

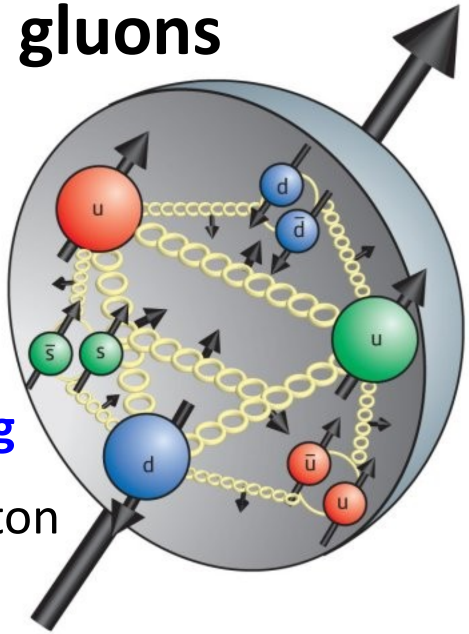


1955: Stanford : e^- beam of 1 GeV → **elastic scattering**
Hofstadter (NP 1961) measured the charge radius of the proton $\approx$ 0.8fm

Probing the nucleon structure

A brief story of the nucleon

1960-1980: nucleon composed of **quarks and gluons**



1964: *Gell-Mann* and *Zweig (NP 1969)* postulated that
there are 3 quarks in the proton: u u d
-> hadron spectroscopy and classification

1969: Stanford: e^- beam of 20 GeV → **deep inelastic scattering**

Friedman, Kendall, Taylor (NP 1990) found quarks in the proton

Feynman, Bjorken *Gross, Politzer, Wilczek (NP 2004)*

Quantum ChromoDynamics (QCD)

✓**Asymptotic Freedom**
✓**Confinement**

Probing the nucleon structure

In 1980:

We know a lot and we know little

Proton is made of 2 up quarks (e=2/3) + 1 down quark (e=-1/3)
+ any number of quark-antiquarks
+ any number of gluons

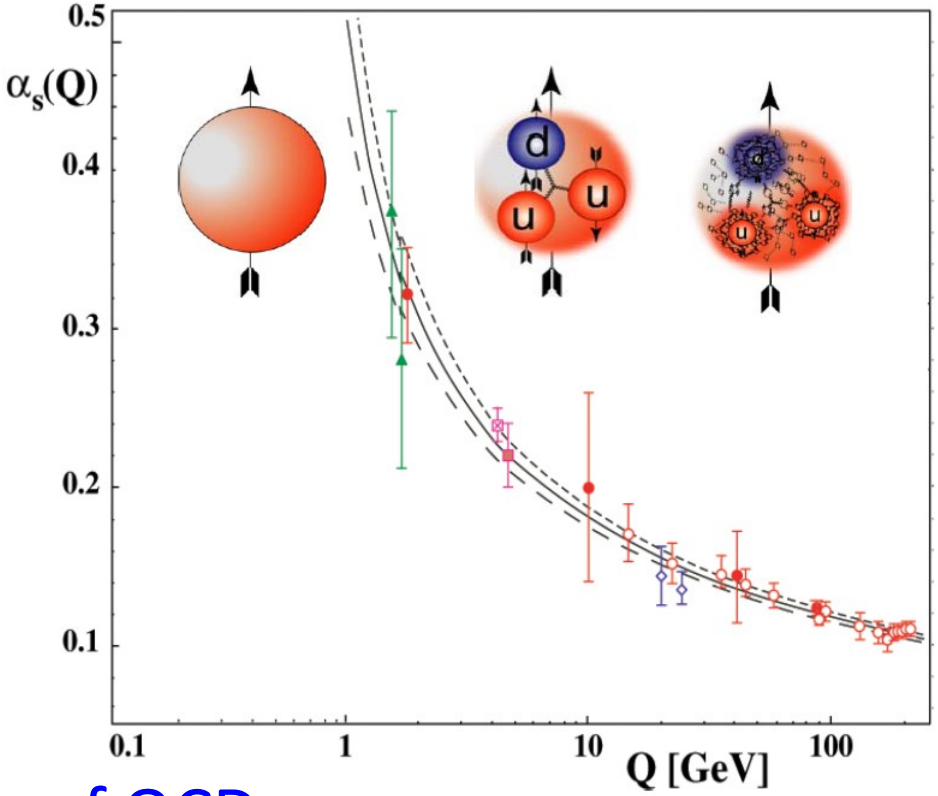
Still fundamental questions ?

Origin of mass?
$M_p \approx 2000 \times M_{e-}$
~10% from Higgs interaction
~90% comes from the motion of quarks and gluons

Proton spin crisis 1987: the valence quarks contribute very little to the proton spin

QCD: still unsolved in non-perturbative region

Gross, Politzer, Wilczek (NP 2004)
Asymptotic freedom



Non perturbative regime of QCD
One of the top 10 challenges for physics
Nucleon structure provides much insight about how QCD works in the confinement regime

Understanding the nucleon structure

Solving QCD

- ✓ Numerically simulation, lattice calculations continue to make advances in techniques and computing power
- ✓ Effective field theories (chiral physics, large Nc, …)
- ✓ (Phenomenological models, fits of structure functions…)

Experimental probes

- ✓ Require clean reaction mechanisms with photons, electrons
- ✓ through low and high-energy scattering off the nucleon

Probing the nucleon structure

What has been done during the last 30 years?

Old Chinese compass

Exploration

Probing the nucleon structure

What has been done during the last 30 years?

Hand-held compass

Consolidation

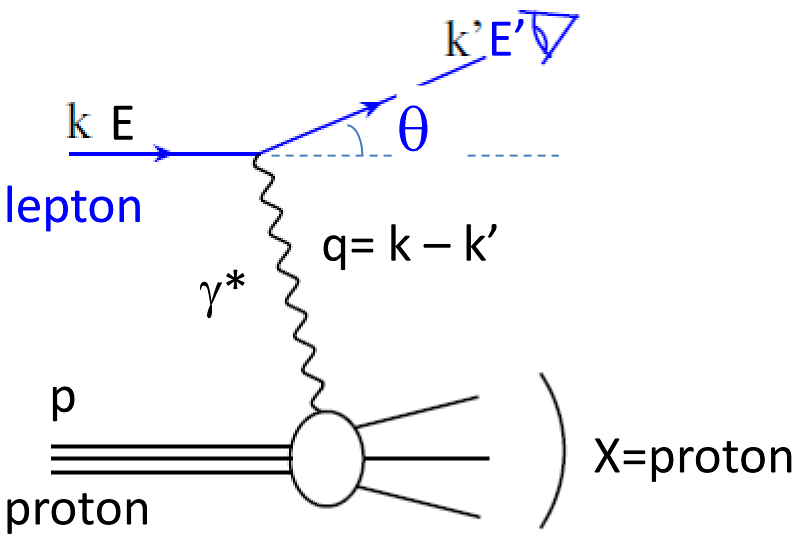
Probing the nucleon structure

What has been done during the last 30 years?

GPS compass

Precision

Probing: Lepton-nucleon scattering



Hypotheses:

- ✓One photon exchanged
- ✓M_{e-} <<

$$Q^2 = -q^2 = 4\,E\,E'\,\sin^2\theta/2 \;> 0$$

$$x_B = Q^2/(2p.q) = Q^2/(2M_p(E-E'))$$

in lab.

for fixed target

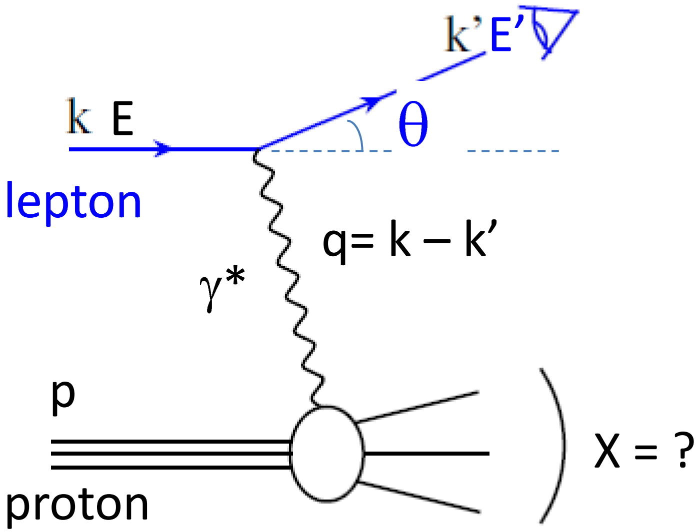
Elastic Scattering: X=proton

$$s = (p+q)^2 = M_p^2 - Q^2 + 2p.q = M_p^2 \quad \Rightarrow \quad x_B = 1$$

at fixed beam energy E, only one variable Q^2 (E' and θ are not independent)

- Form Factors (Q^2) => Consolidation and Exploration at higher Q^2
- Nucleon radius (from $Q^2 \rightarrow 0$) => High Precision, but also need of Consolidation

Probing: Lepton-nucleon scattering



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$$x_B = Q^2/(2p.q) = Q^2/(2M_p(E-E'))$$

in lab.
for fixed target

Deep Inelastic Scattering (DIS): the proton is broken in many debris X

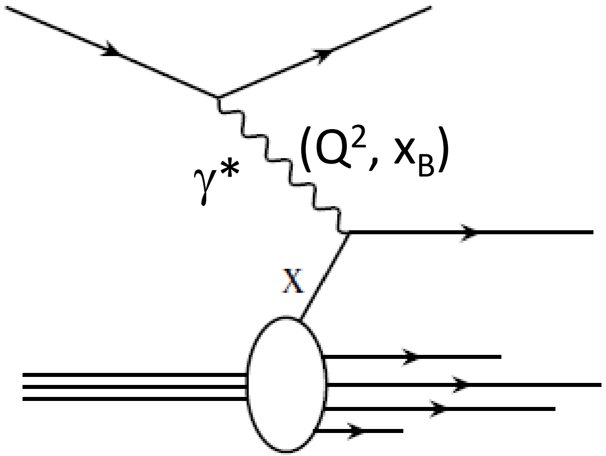
$s = (p+q)^2 = M_p^2 - Q^2 + 2p.q \;>\; M_p^2 \quad \Rightarrow \quad 0 < x_B < 1$

at fixed beam energy E, 2 variables (E', θ) or (Q^2, x_B)

We learnt that : $\sigma_{DIS}(ep \to e\,X) \;=\; \Sigma_q \;\; \sigma_{elastic}(eq \to eq)$

incoherent

Probing: Lepton-nucleon scattering



longitudinal size contracted
time dilatation
$\text{time}_{\text{hadronization}} \gg \text{time}_{\gamma^* q\ \text{interaction}}$

Deep Inelastic Scattering (DIS):

$$\sigma_{DIS}(ep \rightarrow e\,X) = \sum_q \sigma_{elastic}(eq \rightarrow eq)$$

incoherent

Quark parton model (QPM)

- Point-like, non-interacting partons
- Collinear to the nucleon movement in photon-nucleon collision (longitudinal direction)
- Each parton carries a fraction x of the nucleon momentum and for the struck parton: $x = x_B$
- Scaling: observables function of x_B (at first order)

Parton Distribution Functions (PDF (x))

unpolarized => High precision

polarized => Nucleon Spin Crisis Consolidation

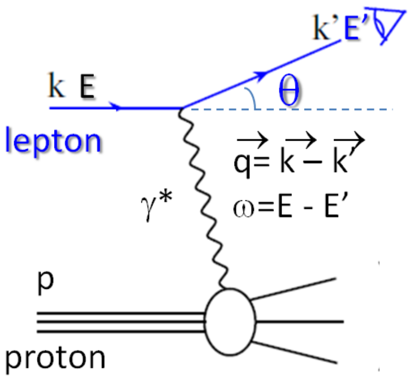
More on transverse information

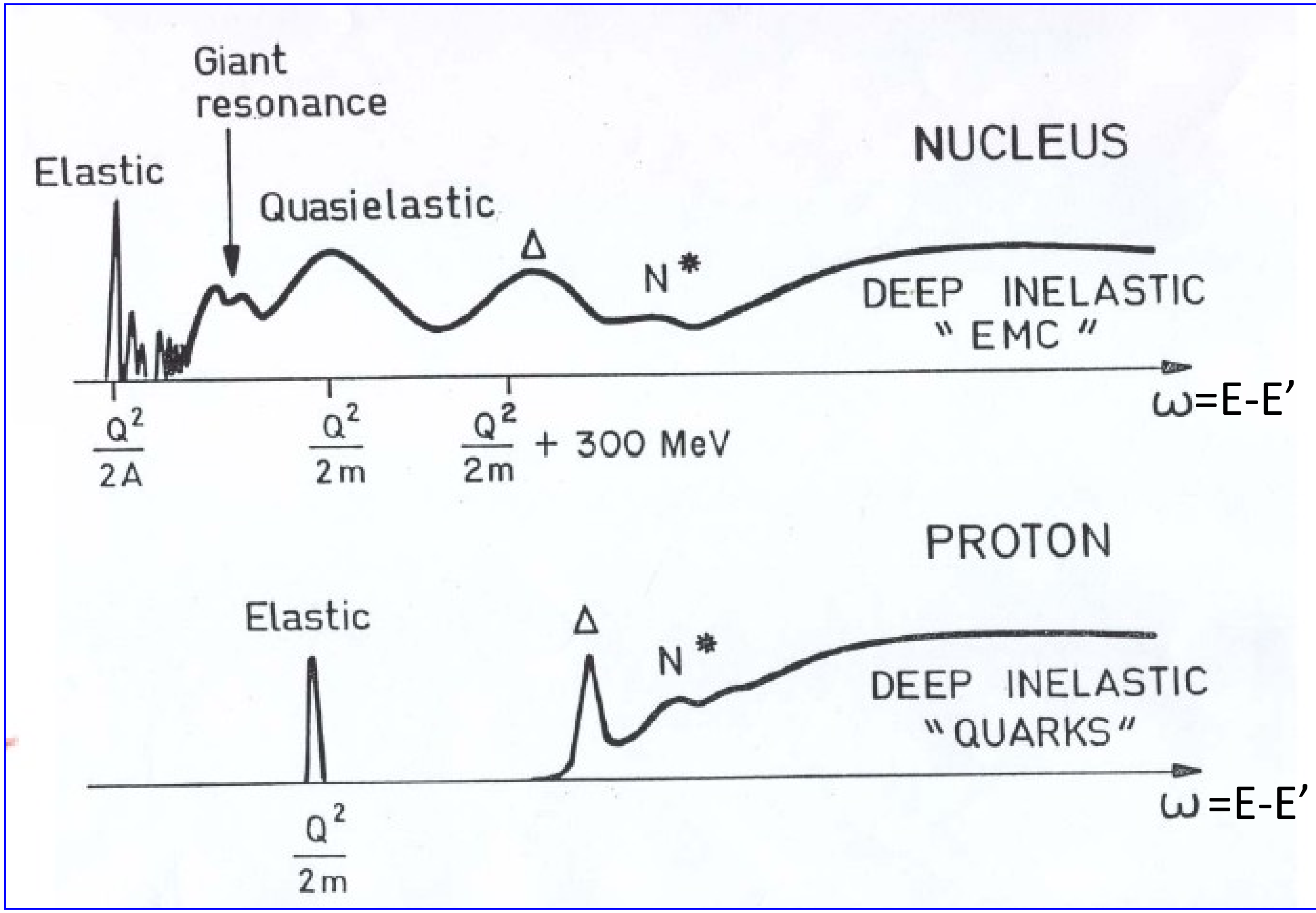
momentum: Transverse Momentum Dependent PDF

position: Generalized Parton Distributions (GPD)

=> Exploration in 3D

Lepton nucleon or nucleus scattering



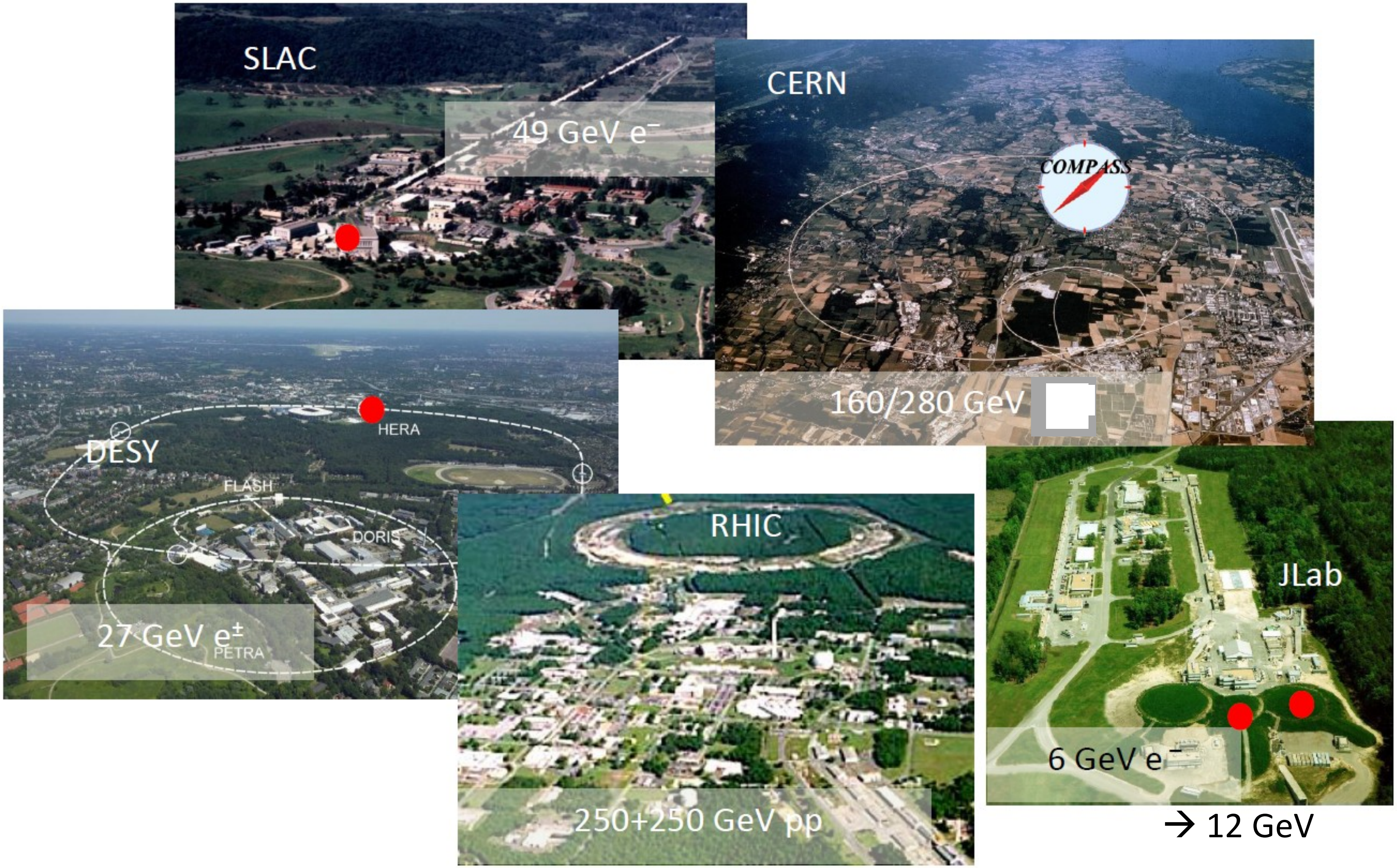


Elastic: $\Delta x = \hbar c / |\vec{q}|$ exploration of distance of 1fm with 200 MeV

Deep Inelastic: q and ω varie independently

$\Delta t = \hbar c / \omega$ instantaneous picture to observe free proton

The main facilities in the world (1980-2015)

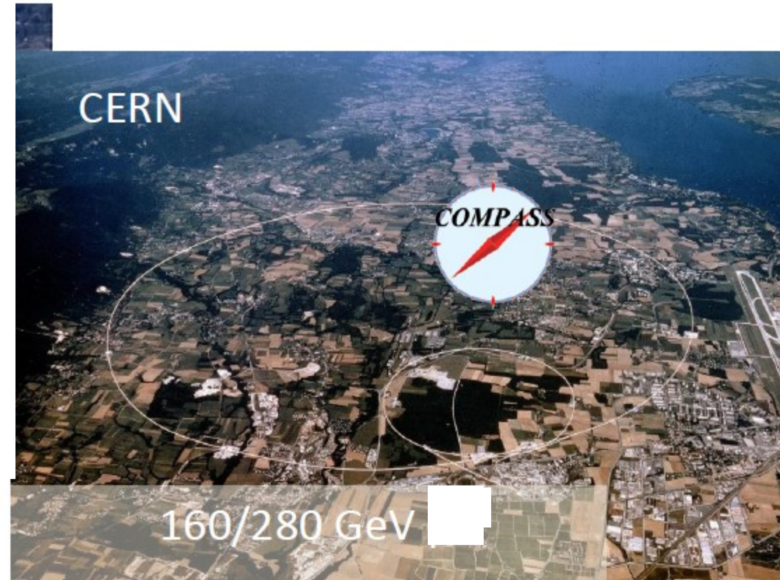


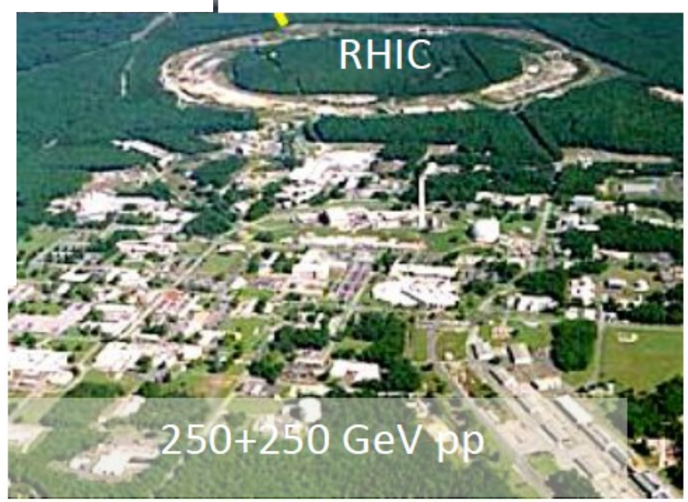
→ 12 GeV

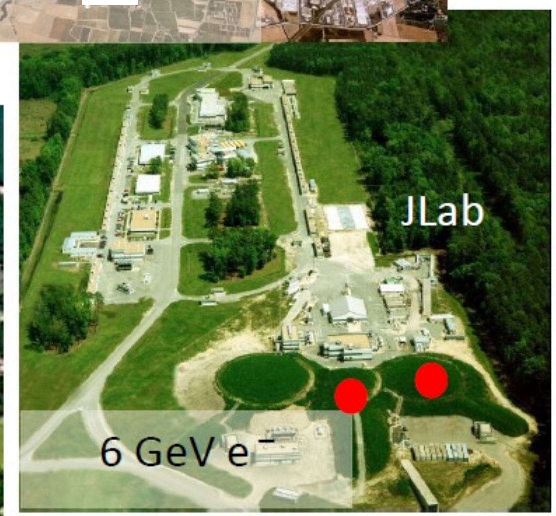
+KEK 6 GeV $e^{\pm}$ (Belle)

+ MAMI (Mainz Microtron) 1.5 GeV e-

The main facilities in the world (1980-2015)







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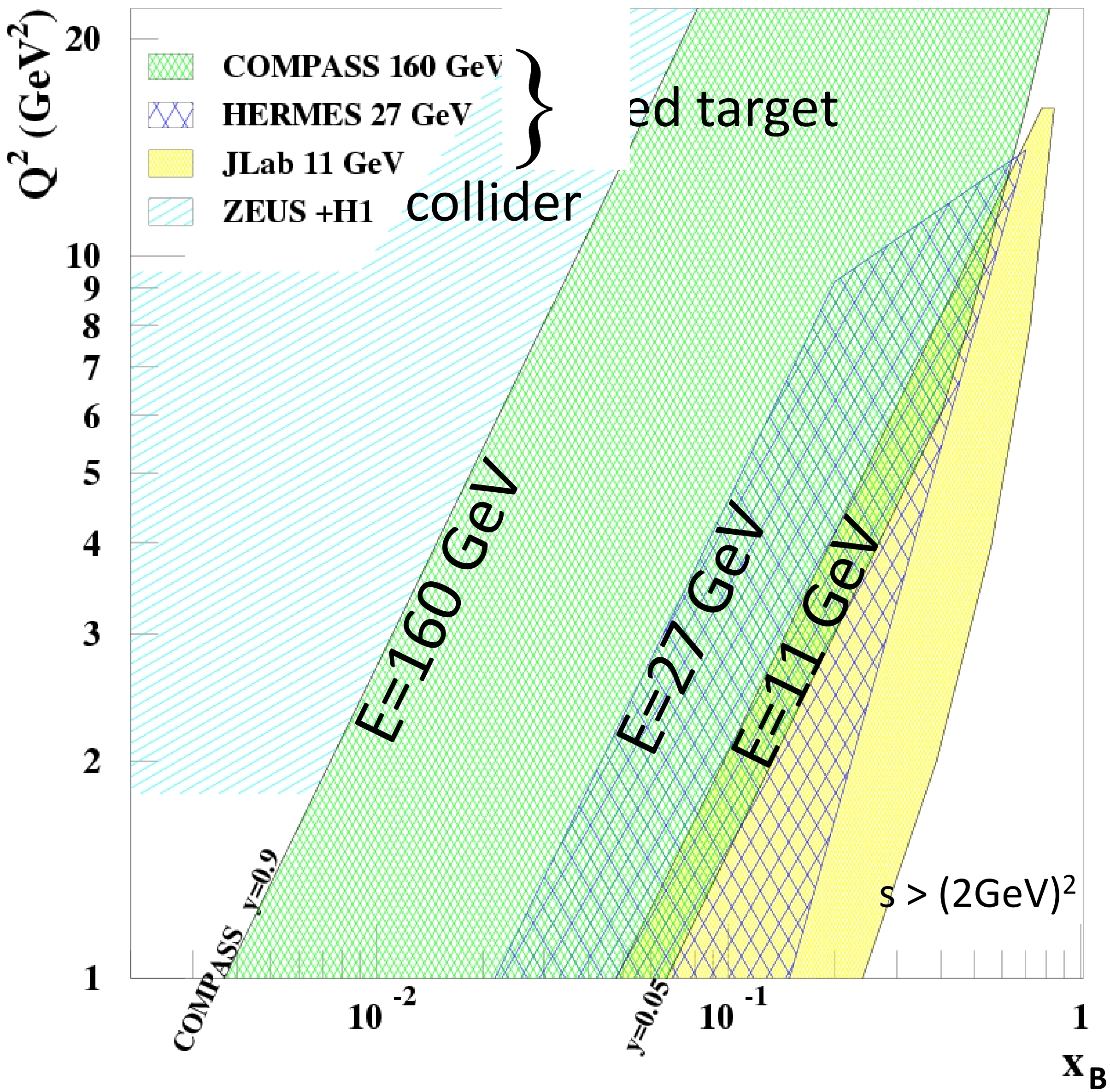
Kinematic domain (Q^2, x_B) for DIS



Elastic Scattering

- Form Factors (Q^2) => Consolidation and Exploration at higher Q^2
- nucleon radius (from $Q^2 \rightarrow 0$) => Very High Precision and Consolidation

Elastic Scattering

Spin-less point-like electron in a the static Coulomb field given by a charge Z of infinite mass

$$\frac{d\sigma}{d\Omega} = |f(\vec{q})|^2 = \left(\frac{Z\alpha}{2k}\right)^2 \frac{1}{\sin^4\theta/2} |F(\vec{q})|^2$$

$$= \sigma_{Rutherford} \quad |F(\vec{q})|^2$$

$$F(\vec{q}) = \int \rho(\vec{r}) e^{i\vec{q}\vec{r}} d^3\vec{r}$$

Relativistic calculation for a spin ½ electron in the EM field given by a charge +e and finite mass

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \frac{E'}{E_{recoil}} \times |F(\vec{q})|^2 \text{ with } \sigma_{Mott} = \frac{\alpha^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)}.$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{point} \times |F(\vec{q})|^2$$

The Form Factor measures the deviations from a structure less particle

- Point particle : $\rho(\vec{r}) = \delta(\vec{r}) \qquad F(\vec{q}) = 1$
- Spherical distribution: $\rho(\vec{r}) = \rho(r) \qquad F(\vec{q}) = \frac{4\pi}{q} \int_0^\infty \rho(r) \sin(qr) r\, dr$

$$= 1 - \frac{\vec{q}^{\,2}}{6}\langle r^2 \rangle + \frac{\vec{q}^{\,2}}{120}\langle r^4 \rangle + \ldots$$

Taylor expans.

$$\langle r^2 \rangle = -6 \frac{\partial F}{\partial \vec{q}^{\,2}}\Big|_{\vec{q}^{\,2}=0}$$

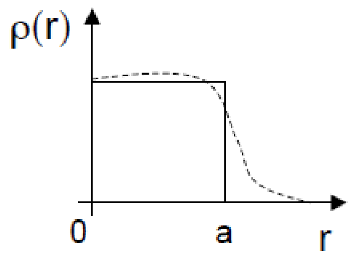
Quadratic mean charge radius of the nucleon

Form Factors for sphere or nucleus

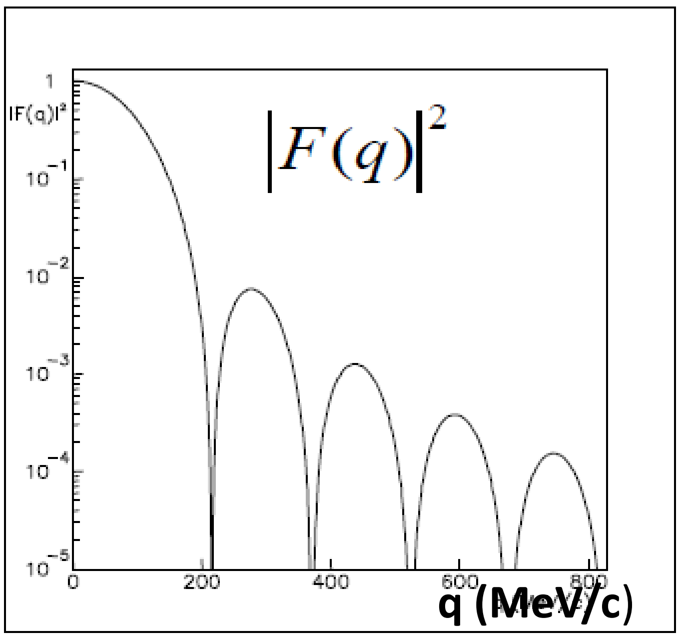
Sphère uniforme :

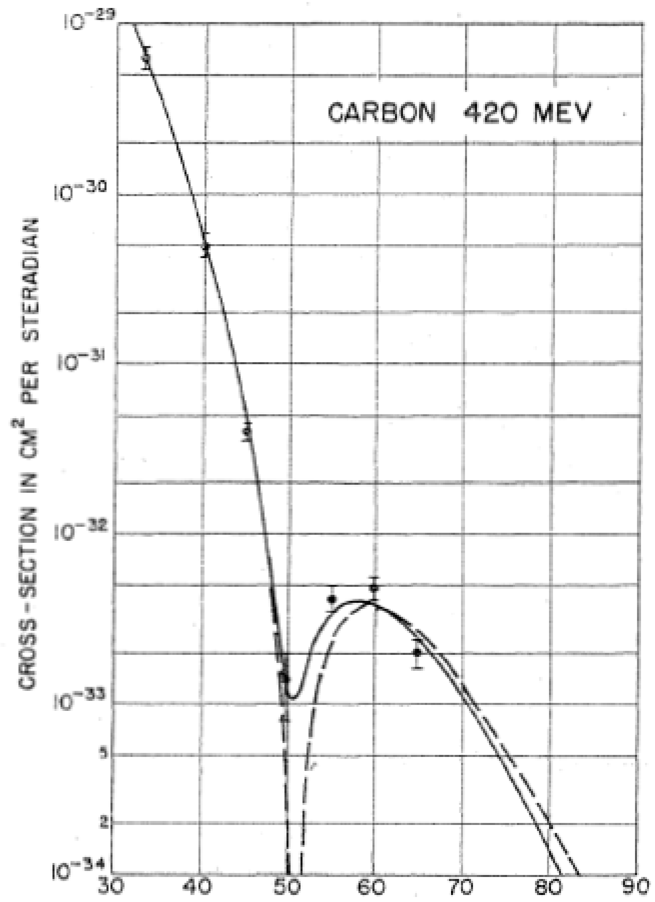
$\rho(r)=\rho_0$ pour r<a

0 pour r>a



$\rightarrow F(q) = 3(\sin x - x \cos x)/x^3 \quad (x=qa)$





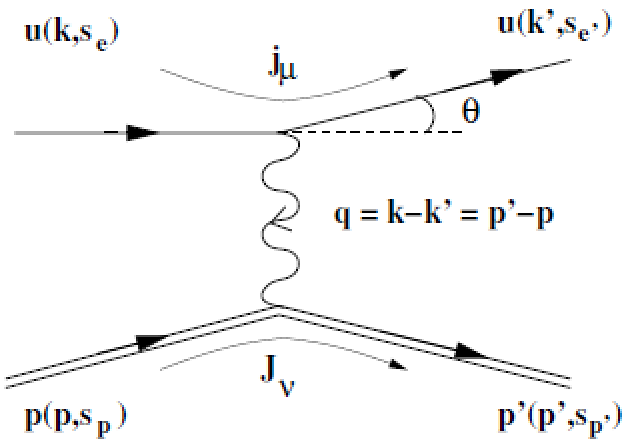
Scattering angle θ in degrees

Minima due to the discontinuity of ρ(r)

Real nucleus without discontinuity

=> Diffractive minimum partly filled

Scattering on a spin ½ particle: ep → ep



$$-iM^{(ep)} = -j^{\mu} \frac{-ig_{\mu\nu}}{q^2} J^{\nu}$$

$$\left|\mathcal{M}^{(e,p)}\right|^2 \Longrightarrow \frac{1}{4} \sum_{s_e, s_{e'} s_p, s_{p'}} \left|\mathcal{M}^{(e,p)}\right|^2$$

General expression for the hadronic current according symmetries of the interaction

$$J_{\mu} = (-ie)\, \bar{u}(p') \left[F_1(q^2)\, \gamma_{\mu} + F_2(q^2)\, \frac{i}{2M}\, \sigma_{\mu\nu}\, q^{\nu} \right] u(p)$$

Dirac and Pauli Form Factors

With Gordon identity

$$J_{\mu} = \frac{-ie}{2Mp}\, \bar{u}(p') \left[\underbrace{F_1(q^2)}_{charge\, Q} P_{\mu} + i\sigma_{\mu\nu}\, q^{\nu} \underbrace{(F_1(q^2) + F_2(q^2))}_{moment\, magn.\mu} \right] u(p)$$

$$Q^2 = -q^2 > 0$$

$$F_1(0) = Q$$
$$F_2(0) = \kappa$$

$$\frac{\mu}{\mu_N} = Q + \kappa$$

Scattering on a spin ½ particle: ep → ep

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \sigma_{Mott}\frac{E'}{E}\left[F_1^2 + \tau F_2^2 + \tau(F_1 + F_2)^2 \tan^2\frac{\theta}{2}\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \sigma_{Mott}\frac{E'}{E}\left[\frac{G_E^2+\tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right]$$

characterize the magnetic interaction with a particle of spin 1/2

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \sigma_{Mott}\frac{E'}{E}\left[\frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}\right]$$

$$\epsilon = [1 + 2(\vec{q}^{\,2}/Q^2)\tan^2(\theta/2)]^{-1}$$

$$\tau = \frac{Q^2}{4M_p^2}$$

→ **Electric and Magnetic Sachs Form Factors** (Fourier Transform (TF) of the charge and magnetization distribution in the breit frame or brick-wall frame)

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \qquad G_E(0) = Q$$

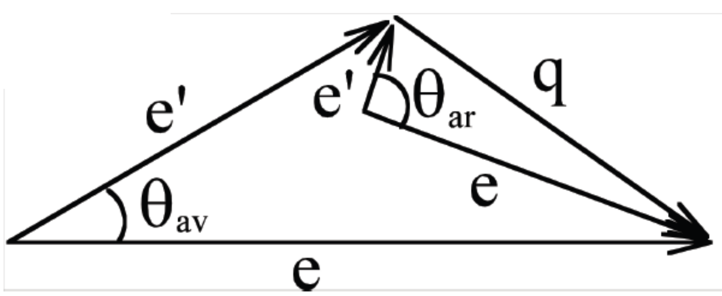
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \qquad G_M(0) = \mu_N$$

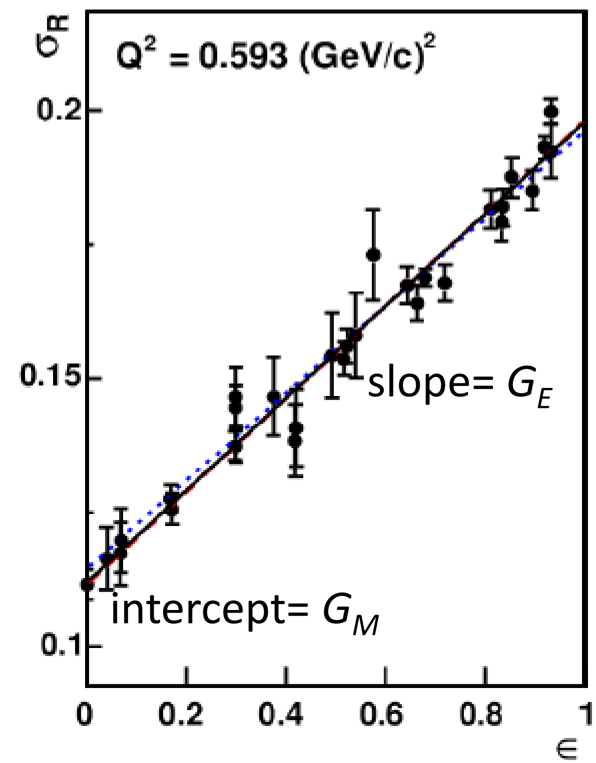
Measurement of Form Factors (Q^2)

Rosenbluth separation:

We plot $\sigma_R = \epsilon(1+\tau)\frac{d\sigma}{d\Omega}\frac{E}{E'}\frac{1}{\sigma_{Mott}} = \epsilon G_E^2 + \tau G_M^2$

Fixed Q^2 ➔ use of different beam energies to get different ε

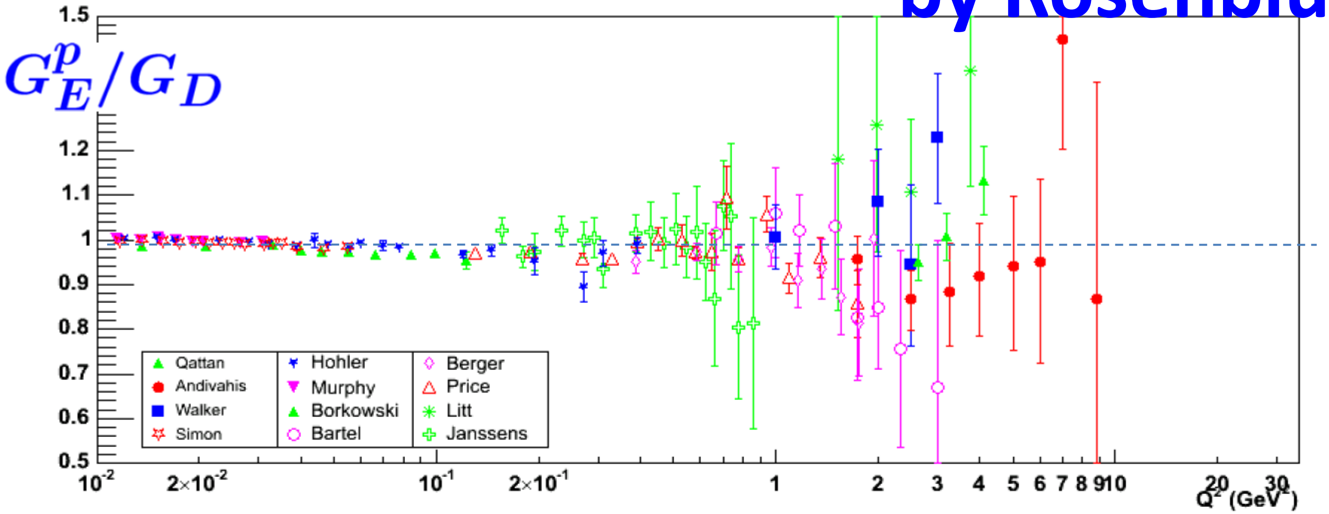




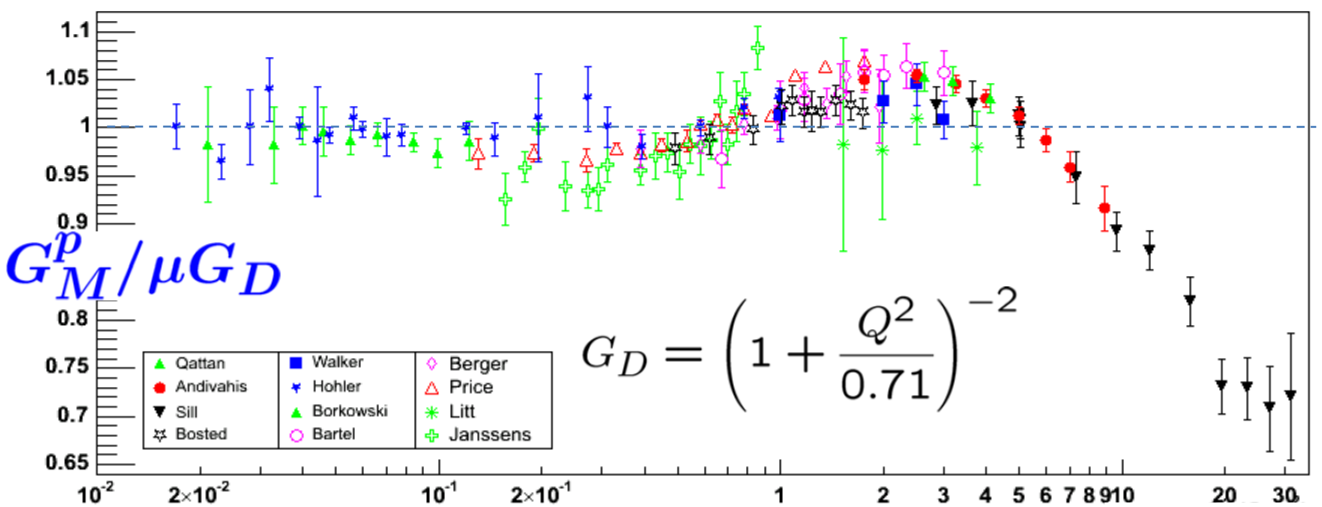
- Different scattering angles
  ➔ large systematic effects on the slope = G_E
- At large Q^2 $G_E^2 \ll \tau G_M^2$
  ➔ Method to determine G_M

Measurement of proton Form Factors (Q^2)

by Rosenbluth separation



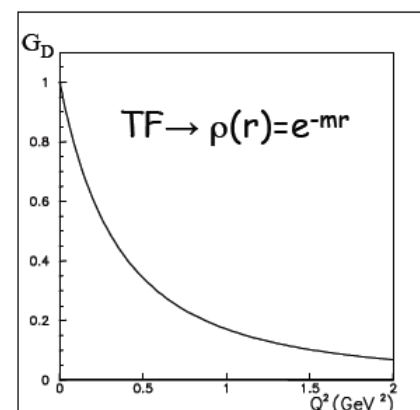
≈ 1



$$G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

Q^2 (GeV^2)

deviation from the dipolar approximation



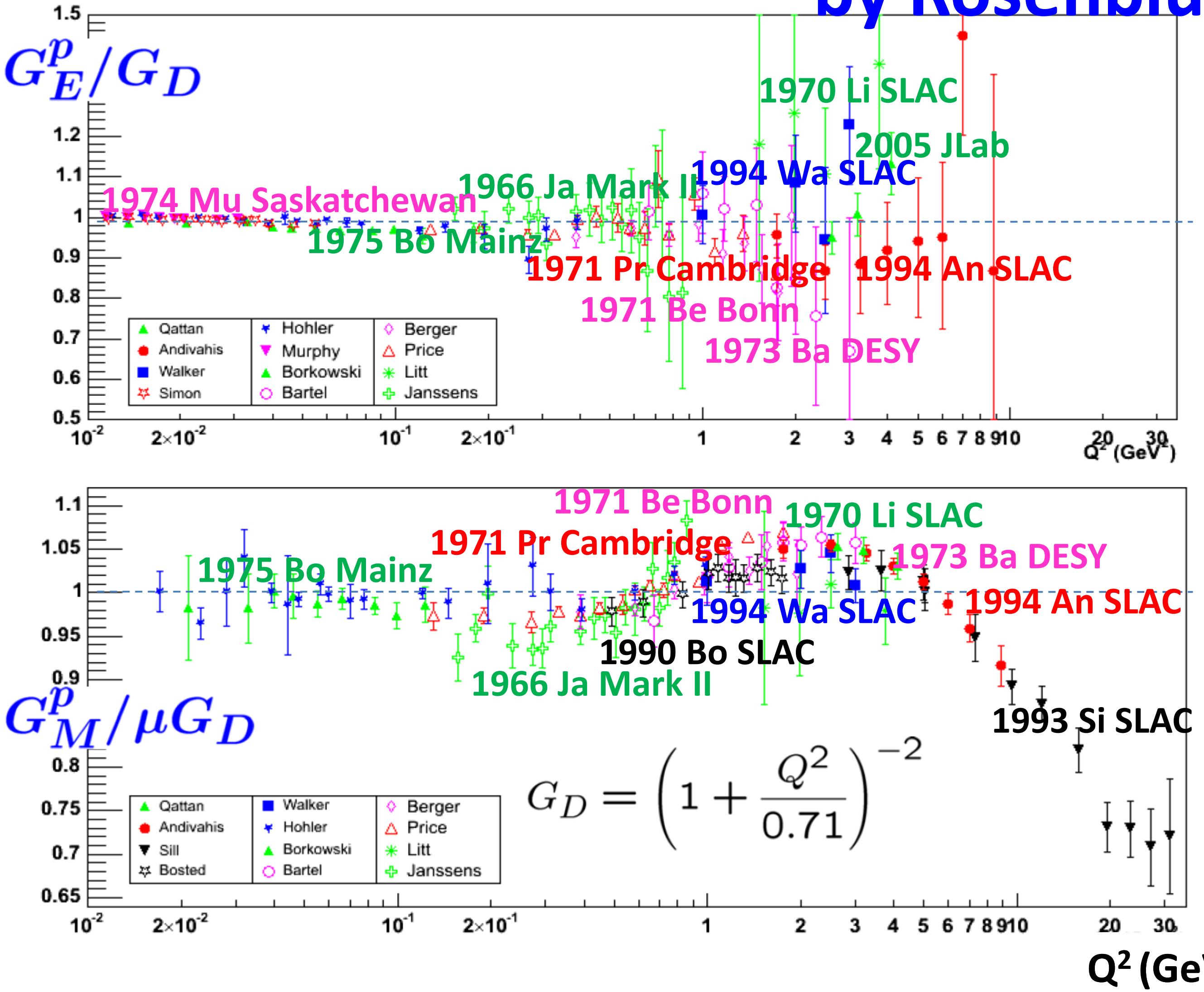
Dipolar approximation with G_D:

Contribution of an effective double pole in the time-like region

FT -> exponential distribution ρ(r) =exp(-0.84 r) non physical

Measurement of proton Form Factors (Q^2)

by Rosenbluth separation



$$G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

deviation from the dipolar approximation

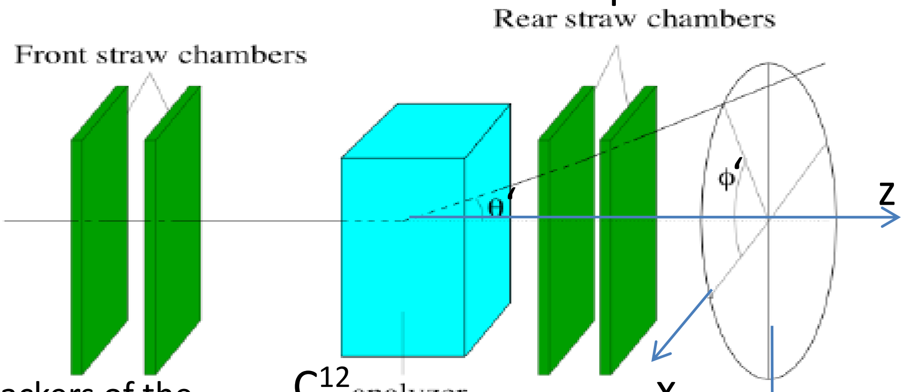
Measurement of Form Factors (Q^2)

New Double Polarization technique:

polarized e- beam + unpolarized target

→ recoil proton analyzed in a magnetic spectrometer and a polarimeter

Detectors in the focal plane



trackers of the charged particule analyzed in the spectrometer

polarimeter

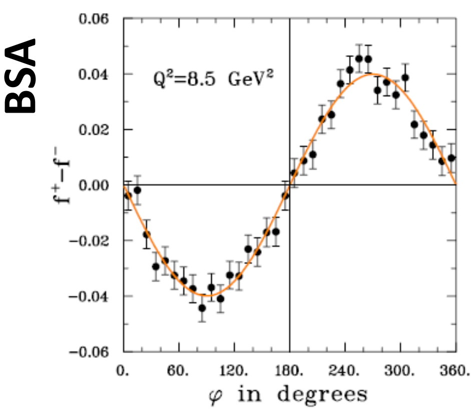
$$\sigma = \sigma_0 \left[1 + P_e P_x A_y(\theta') \sin\phi' + P_e P_z \sin\chi A_y(\theta') \cos\phi'\right]$$

Beam polarization (P_e), Spin precession ($\sin\chi$), Analyzing power (A_y)

$$P_x = \frac{-\sqrt{\tau}\sqrt{2\epsilon(1-\epsilon)}G_E G_M}{\epsilon G_E^2 + \tau G_M^2}$$

$$P_z = \frac{\tau\sqrt{1-\epsilon}G_M^2}{\epsilon G_E^2 + \tau G_M^2}$$

Proposed in 1967 Akhiezer Rekalo but only experimentally possible since high duty cycle facilities advent



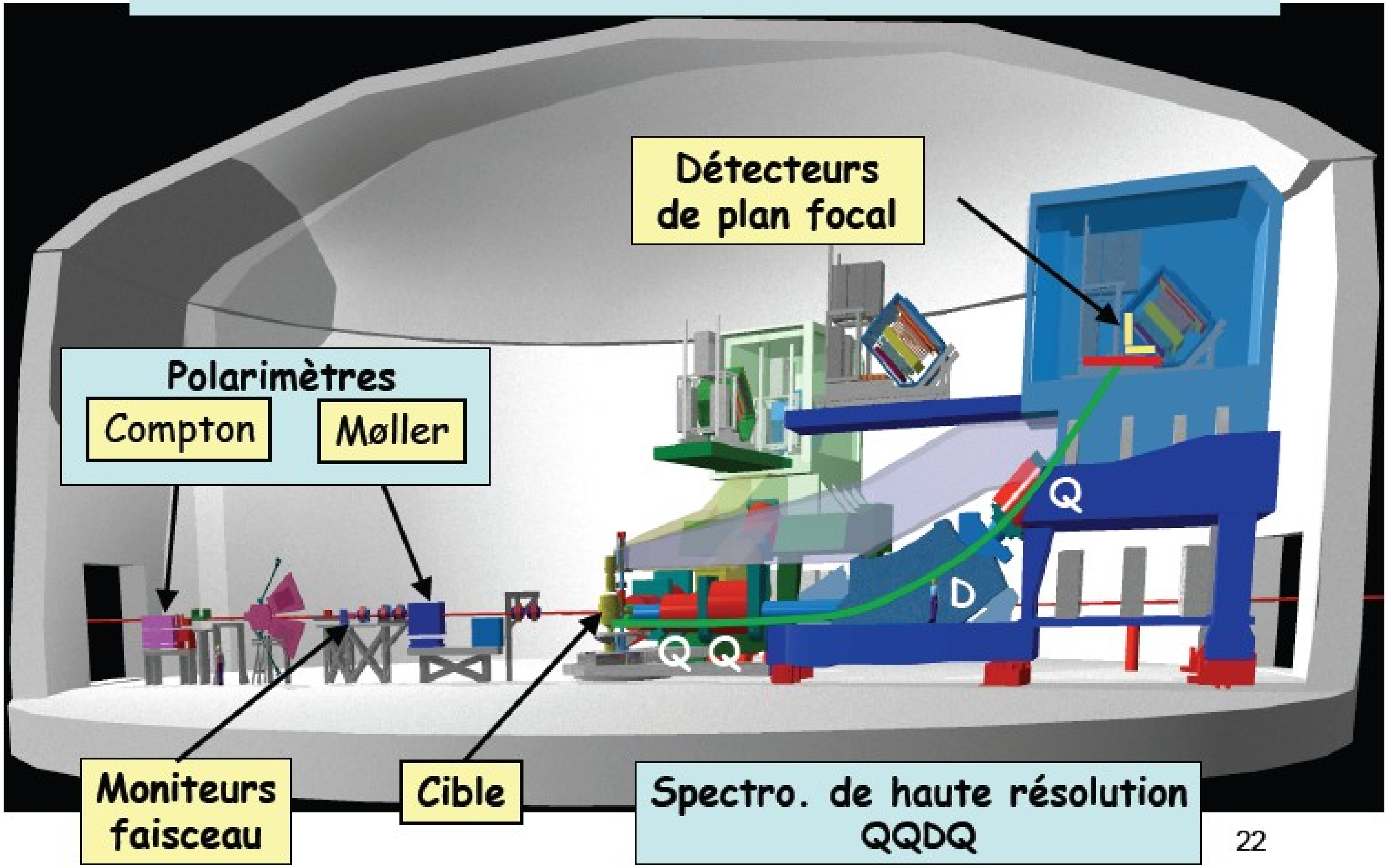
Beam spin asymmetry

$$BSA = \frac{N^+ - N^-}{N^+ + N^-} = a \sin\phi' + b \cos\phi'$$

$$\frac{a}{b} = \frac{P_x}{P_z \sin\chi} = \frac{G_E}{G_M}$$

No systematic effects due to Beam polar and analyzing power as they cancel out in the ratio

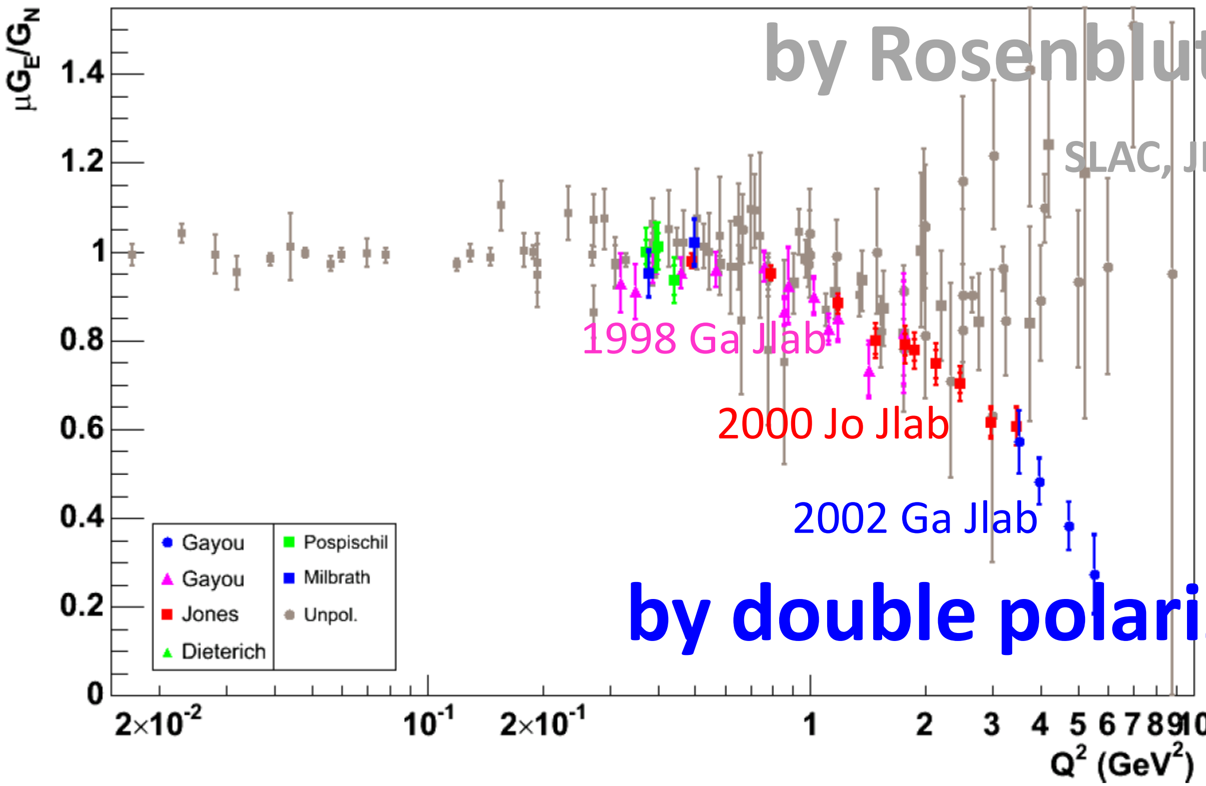
JLab - Hall A



Détecteurs
de plan focal
Polarimètres
Compton
Møller
Q
D
Q Q
Moniteurs
faisceau
Cible
Spectro. de haute résolution
QQDQ

Measurement of proton Form Factors (Q^2)

$$\mu_p G_{Ep} / G_{Mp}$$

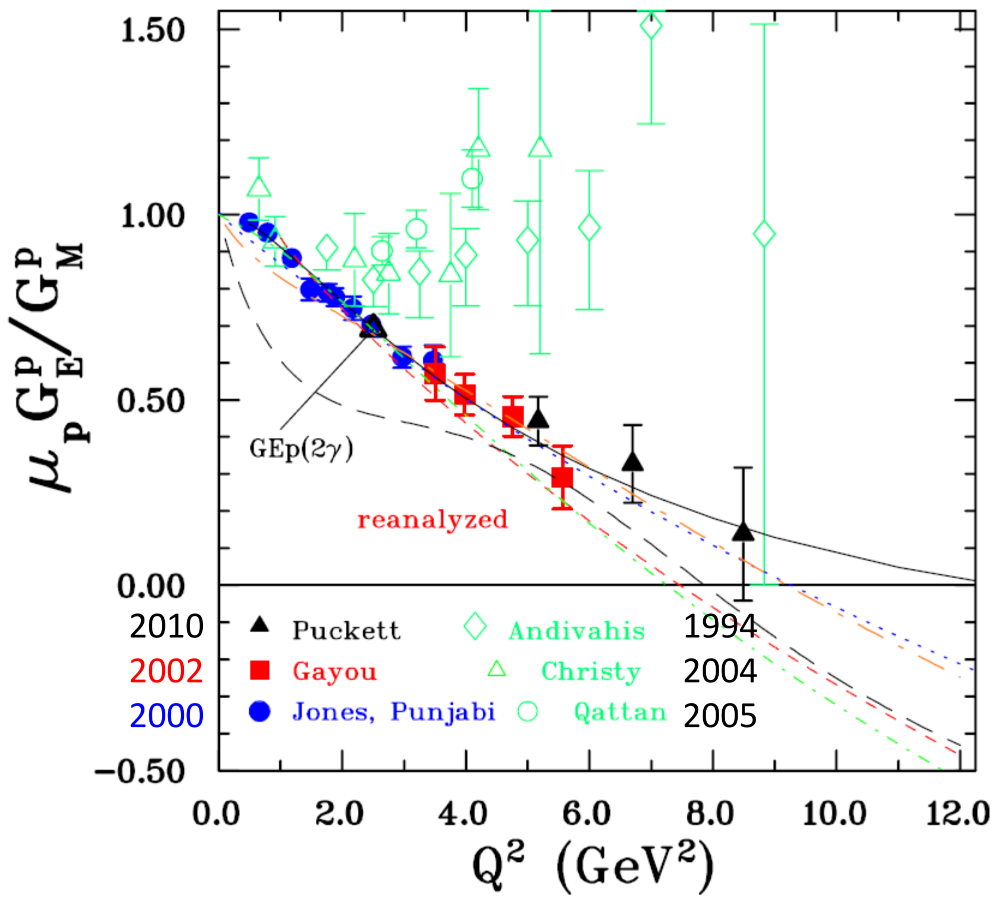


by Rosenbluth separation

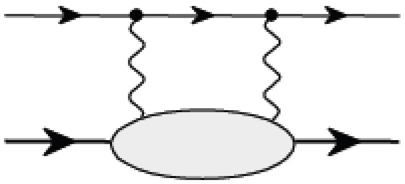
SURPRISE !!!

by double polarization technique

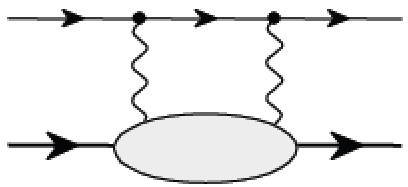
Difference persists between two techniques



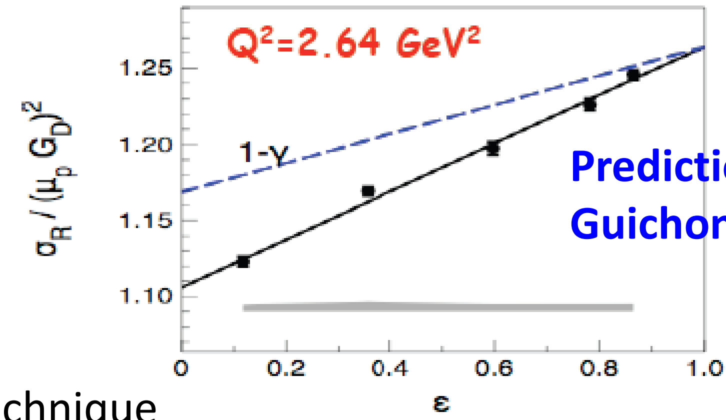
- Jlab Rosenbluth separation data confirm earlier data and global analysis
- No evidence for experimental errors for either of the experimental techniques
- Two photon exchange (TPE) amplitudes can explain a significant part of the discrepancy
- Intensive theoretical and experimental effort on adressing the TPD effect



2 photon exchange proposed as an explanation

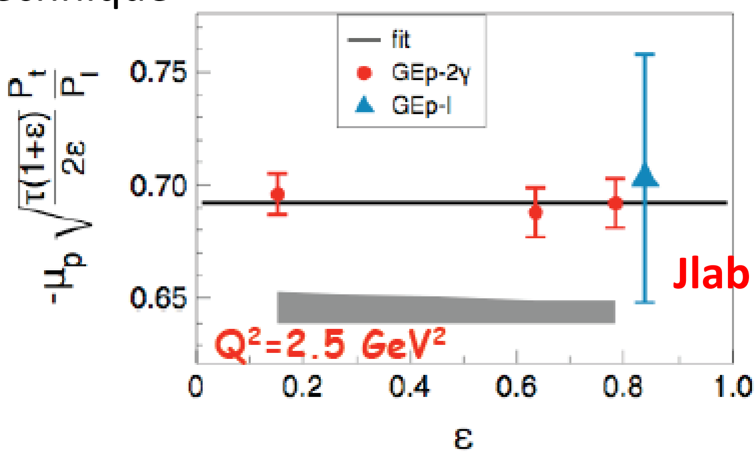


Rosenbluth separation



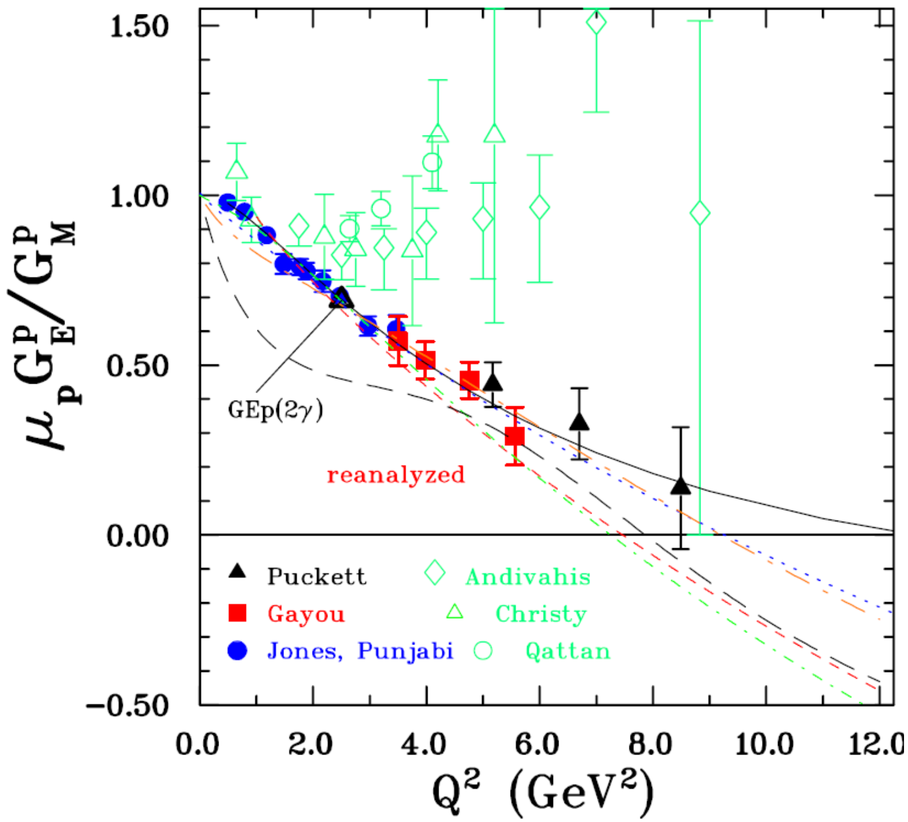
Prediction wih two photon exchange
Guichon, Vanderhaeghen 2003

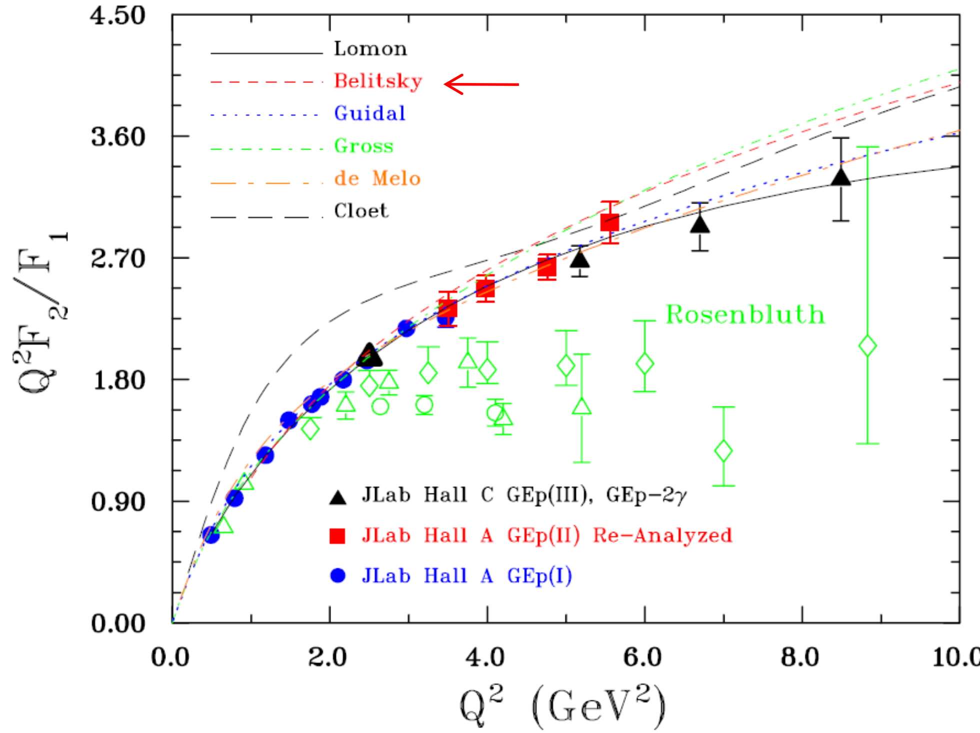
Polarization technique



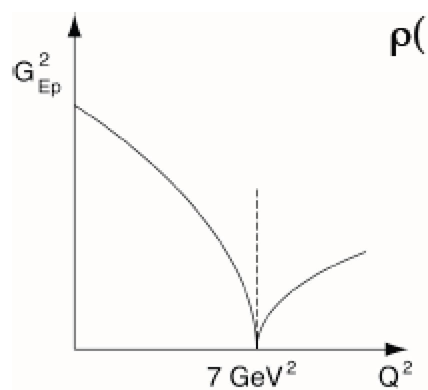
Jlab data Meziane 2011

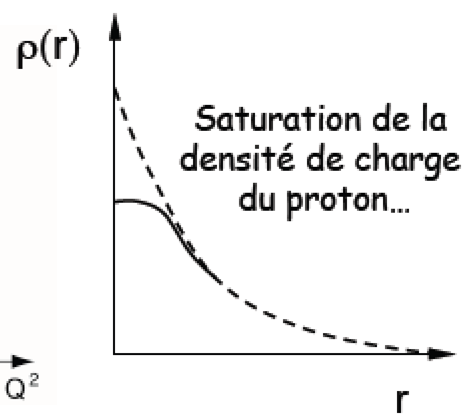
What we learnt from the Q^2 Evolution?





Many models: rQCM, VDM, pQCD

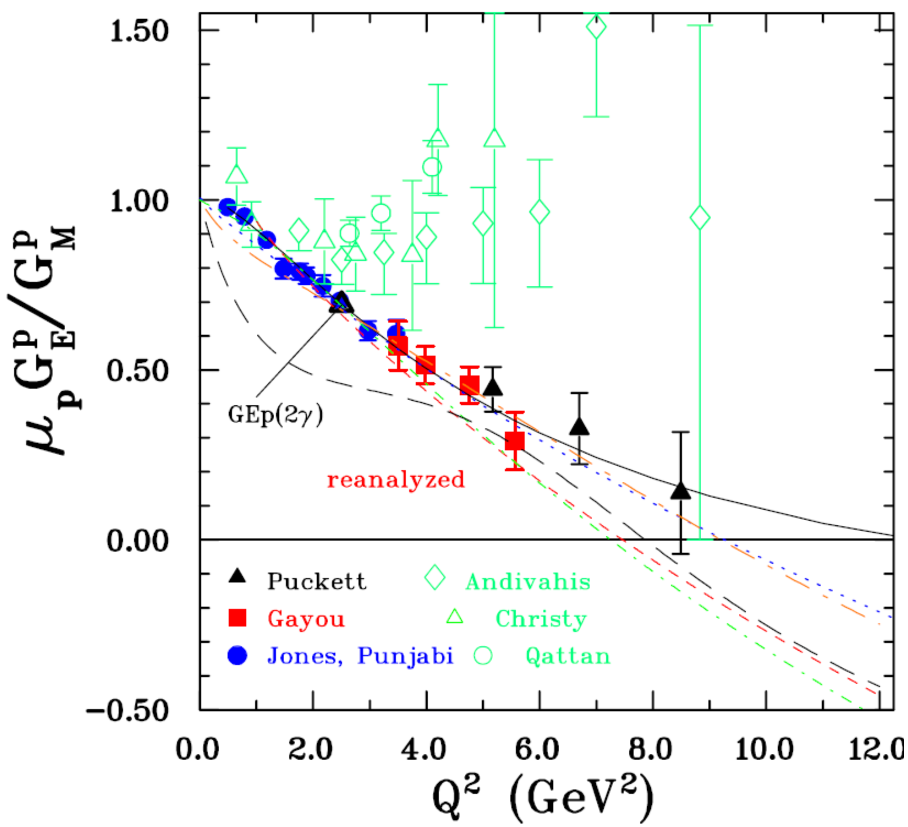


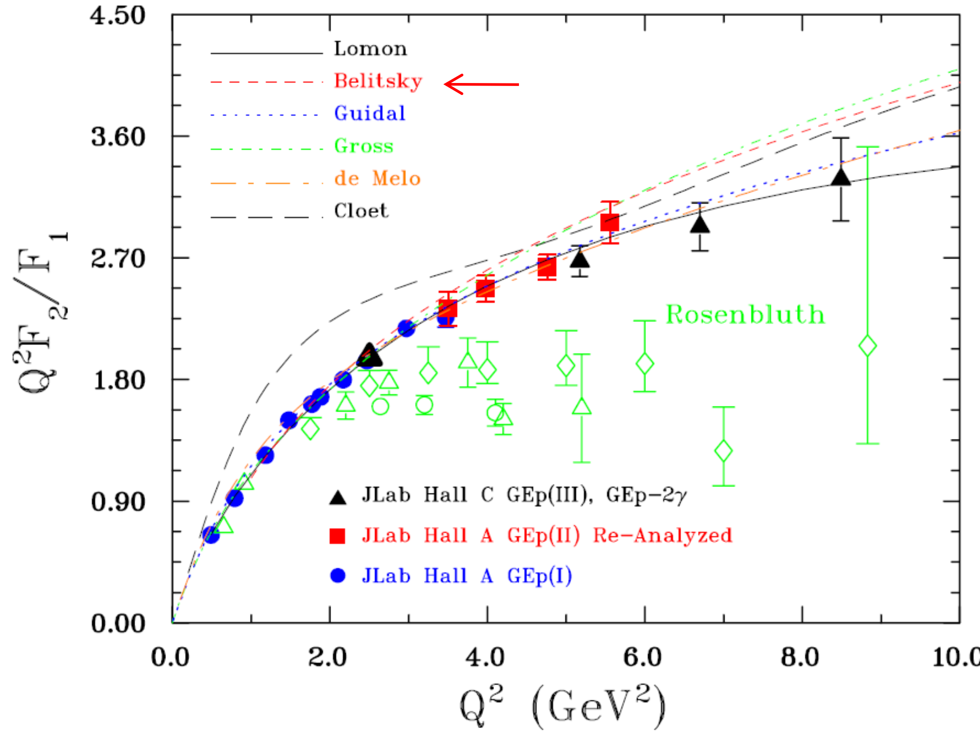


$\mu_p G_{Ep}/G_{Mp}$ **crossing 0 at Q^2=?**

saturation of charge density

What we learnt from the Q^2 Evolution?





- Far from the scaling regime even at Q^2 =10 GeV^2
- No early scaling as in DIS

pQCD scaling : Q^2F_2/F1 should be constant

$$F_1(Q^2) \simeq \frac{1}{Q^4}$$

$$F_2(Q^2) \simeq \frac{1}{Q^6}$$

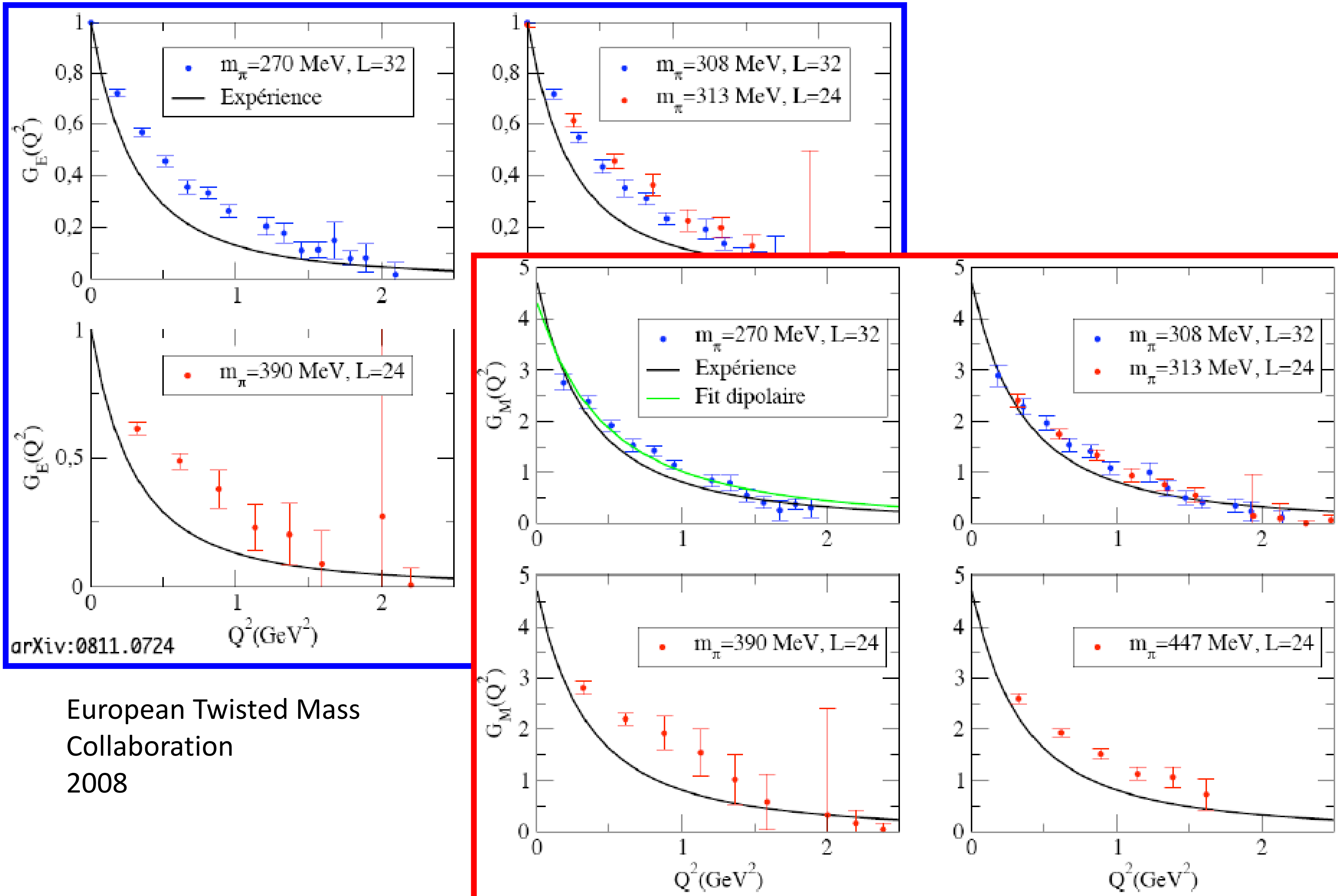
$$G_E \sim G_M \sim \frac{1}{Q^4}$$

Belitsky, Ji, Yuan (2003)

$$Q^2 F_2/F_1 \to \ln^2(Q^2/\Lambda^2)$$

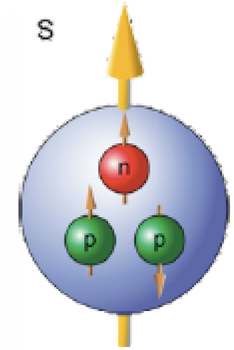
related to quark OAM

Lattice QCD calculations



European Twisted Mass
Collaboration
2008

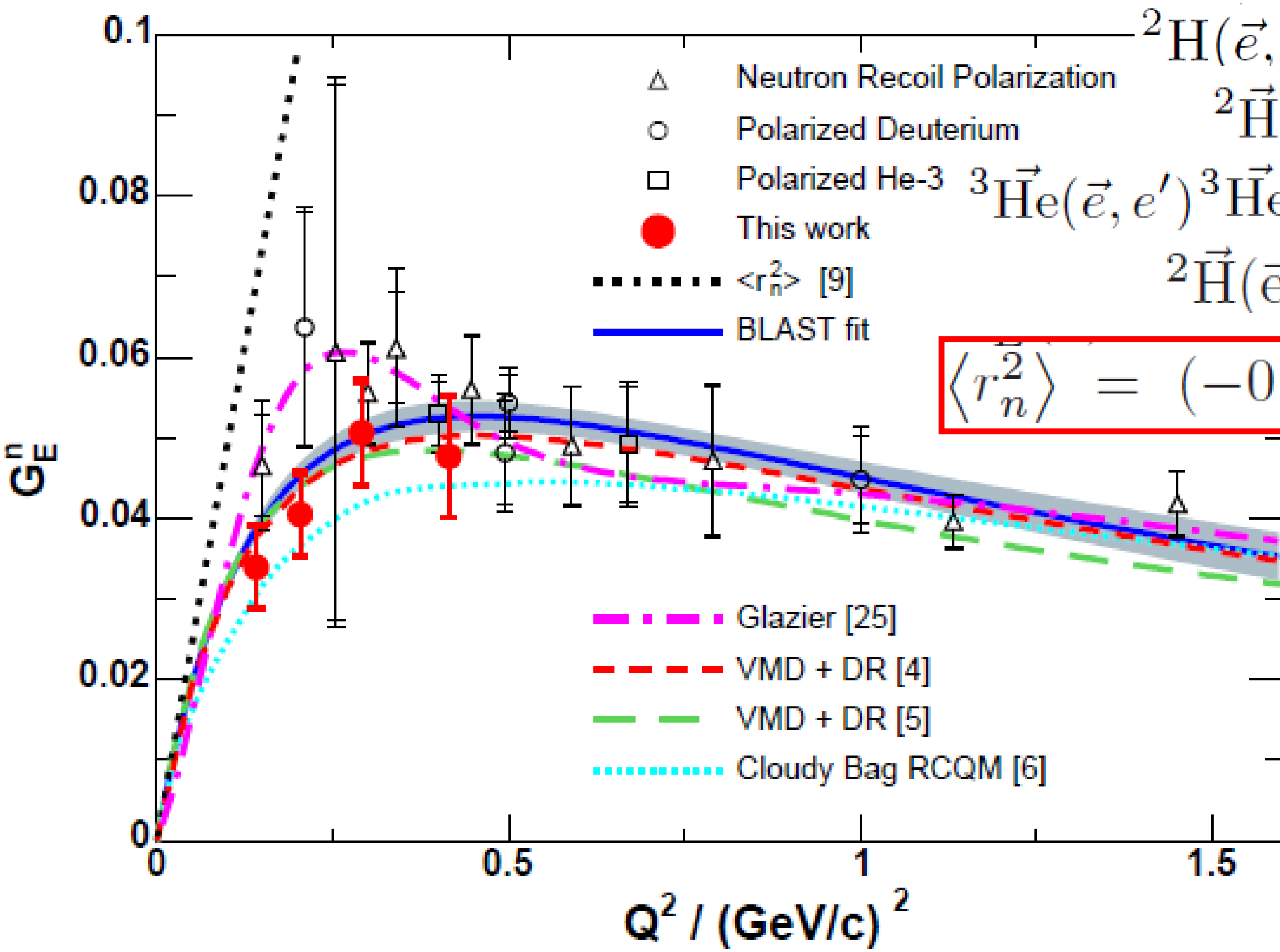
Neutron Form Factor as a function of Q^2



~90%

No stable free neutron target

Neutron form factors measured using quasi-elastic electron scattering from deuteron target (p+n) or polarized ^3H_e target



$^2H(\vec{e}, e'\vec{n})^1H$ 2005-6 MAMI –MIT

$^2\vec{H}(\vec{e}, e'n)$ 2001 Jlab4

$^3\vec{He}(\vec{e}, e')\,^3\vec{He}(\vec{e}, e'n)$ 2003 MAMI -Jlab

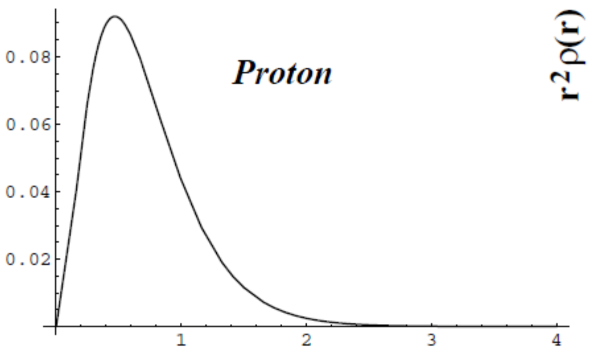
$^2\vec{H}(\vec{e}, e'p)n$ 2008 Blast MIT

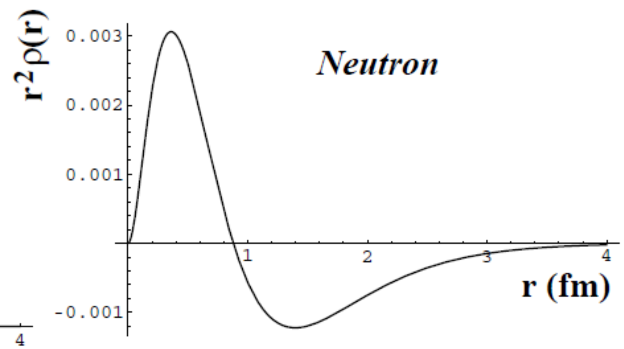
$$\langle r_n^2 \rangle = (-0.1148 \pm 0.0035)\ \mathrm{fm}^2$$

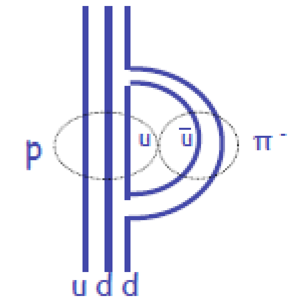
$$\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

Meaning of G_e^p and G_E^n

The proton and neutron charge distributions obtained from Fourier Transform of G_e^P and G_E^n







neutron=proton+ π cloud

$$Q = \int \rho(r)\, 4\pi r^2 dr = 0$$

$$\langle r^2_n \rangle = \int r^2 \rho(r)\, 4\pi r^2 dr < 0$$

$$\langle r_n^2 \rangle = (-0.1148 \pm 0.0035)\ \text{fm}^2$$

2008 Blast MIT

What is the real size of the proton ?

The Muonic hydrogen Lamb shift gives the most precise measurement of the proton charge radius with an unprecedented precision of 0.1%

This value is much smaller (5 standard deviations) than the other measurements using e-p scattering and standard Lamb shift.

UNEXPECTED !

Publication: 8 July 2010
and quickly spread on all the media

Then:

- ✓16 theoretical papers in 2 months
- ✓several planned experiments

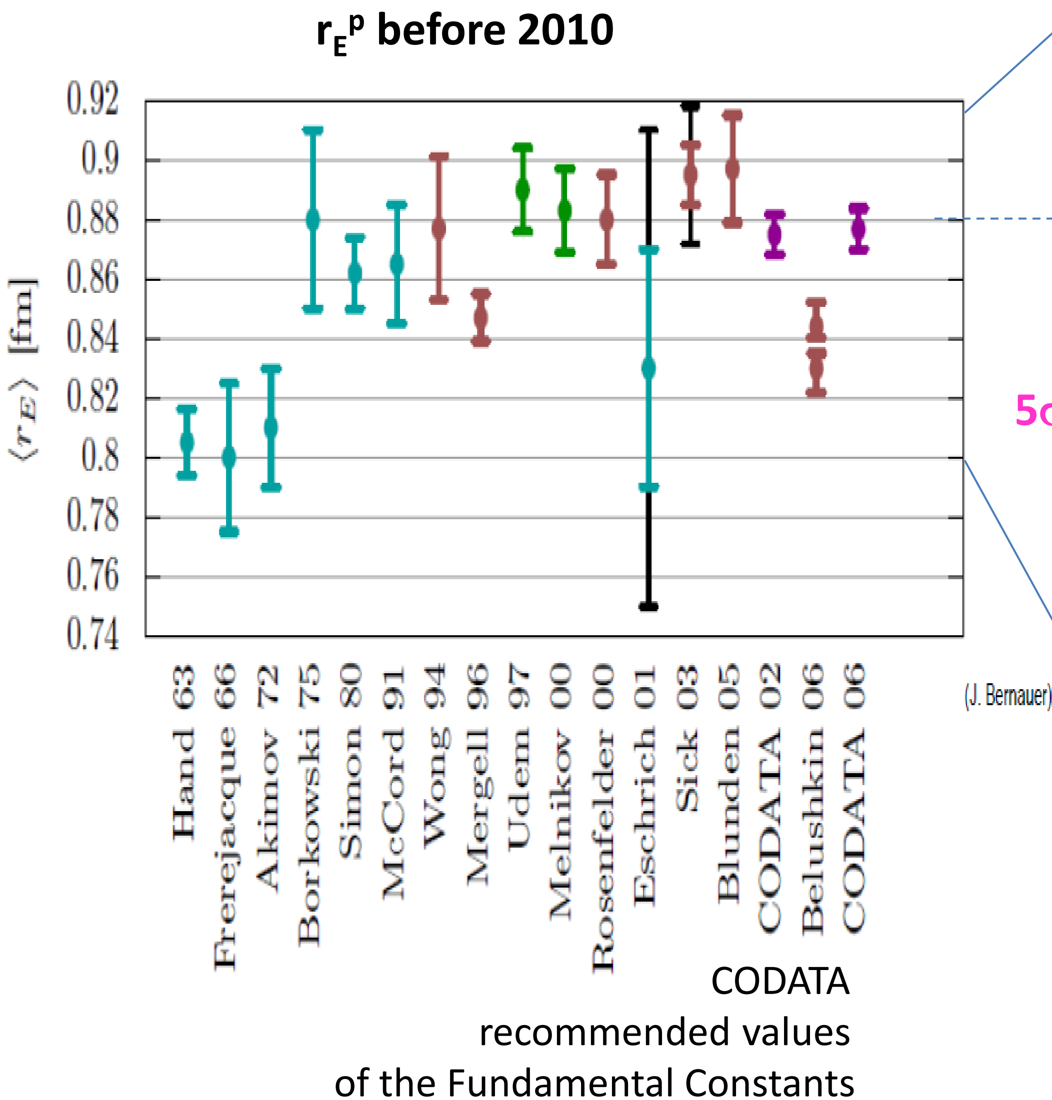
Proton Form Factor

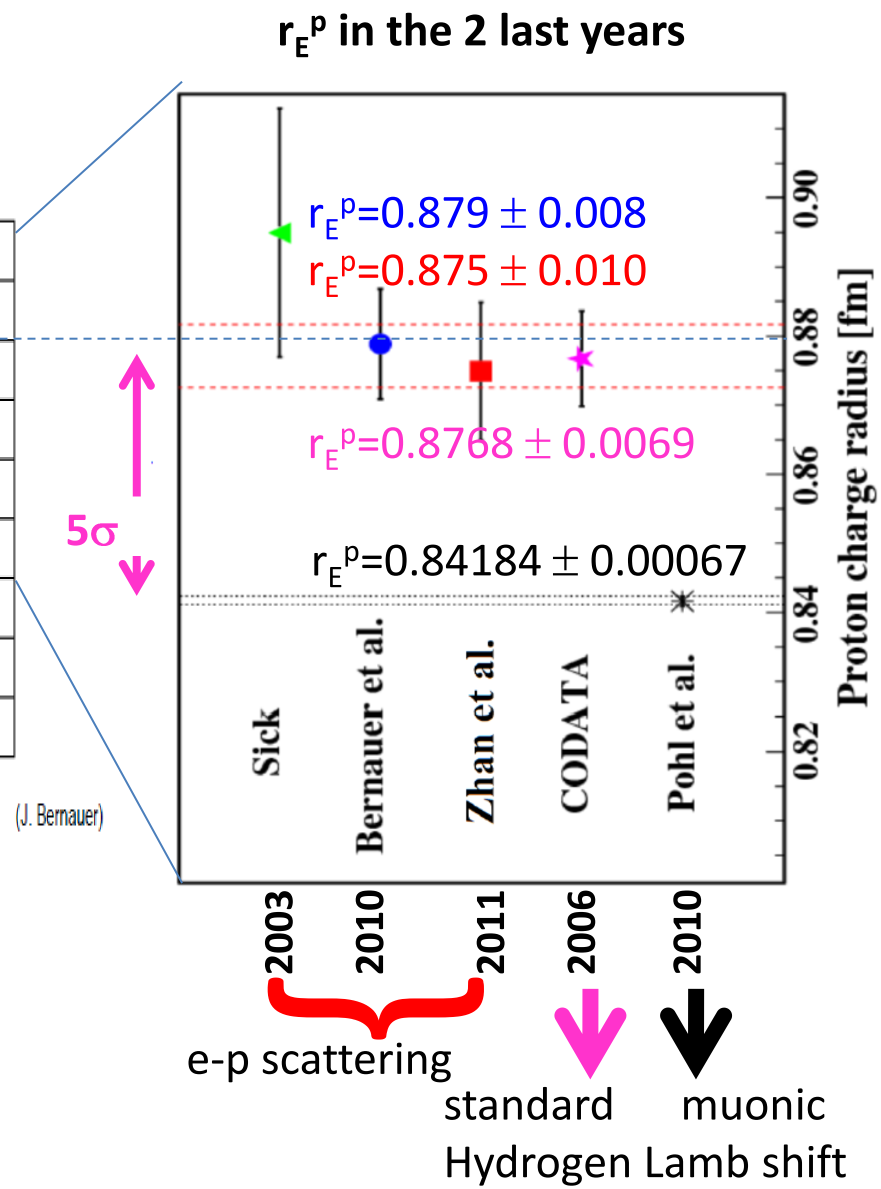
Focus on measurements at large Q^2

but what is the situation at low and very low Q^2 ?

- 2010 *(PRL105 MAMI Bernauer et al.)* :
  The lowest Q^2 is 4×10^{-3} GeV^2 , super Rosenbluth separation
- 2011 *(Jlab Zhan et al.)* :
  $Q^2 \in [0.3 : 0.7] GeV^2$, Polarization technique
- Planned experiment Q^2 $[2\times10^{-4} : 2\times10^{-2}] GeV^2$ in the future at JLab

Results for the proton charge radius

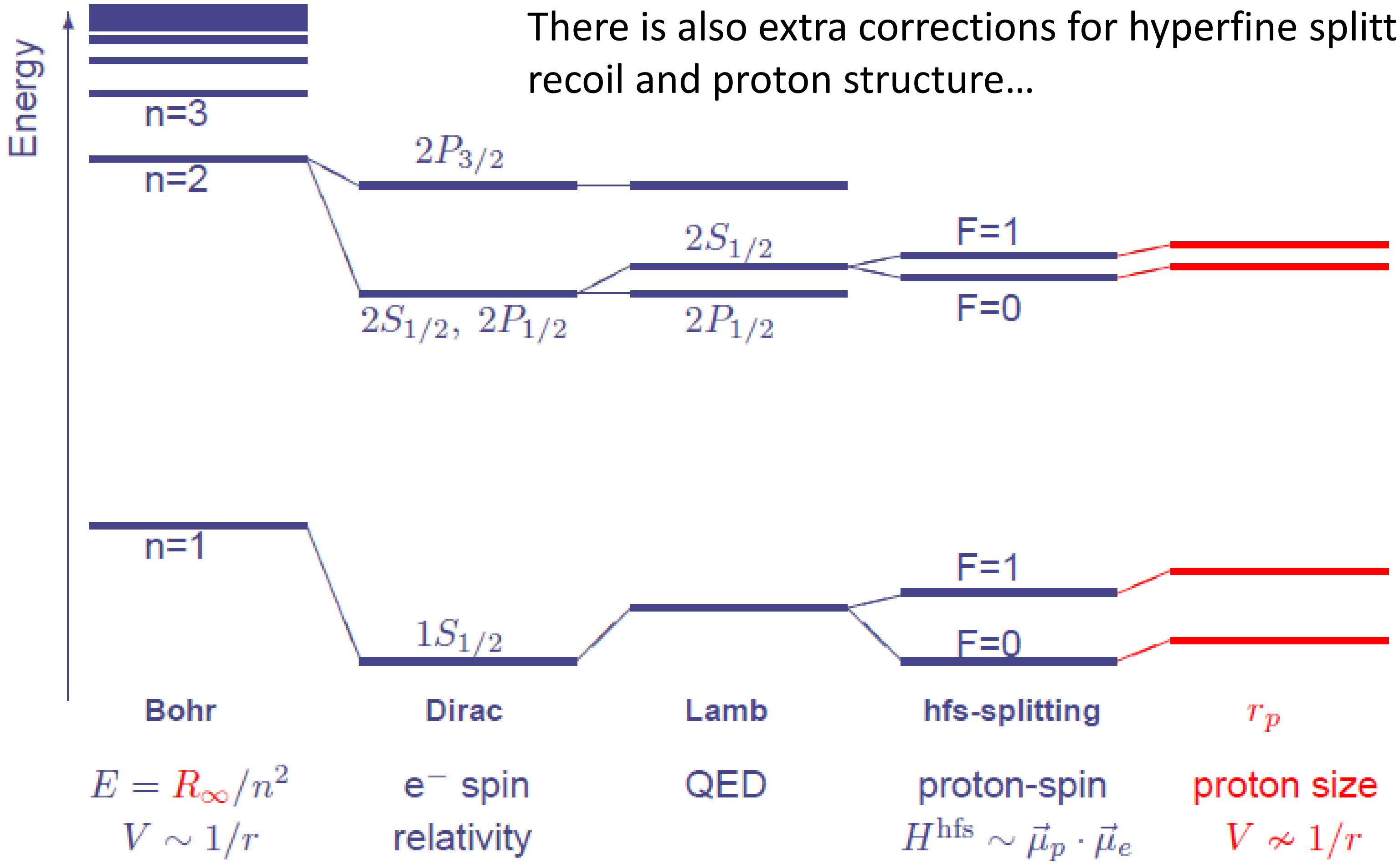




Lamb shift

(1947) subtle difference between the binding energies of the $2S_{1/2}$ and $2P_{1/2}$ (pure radiative QED effects such as 'self energy' and 'vacuum polarization')

There is also extra corrections for hyperfine splitting, recoil and proton structure…

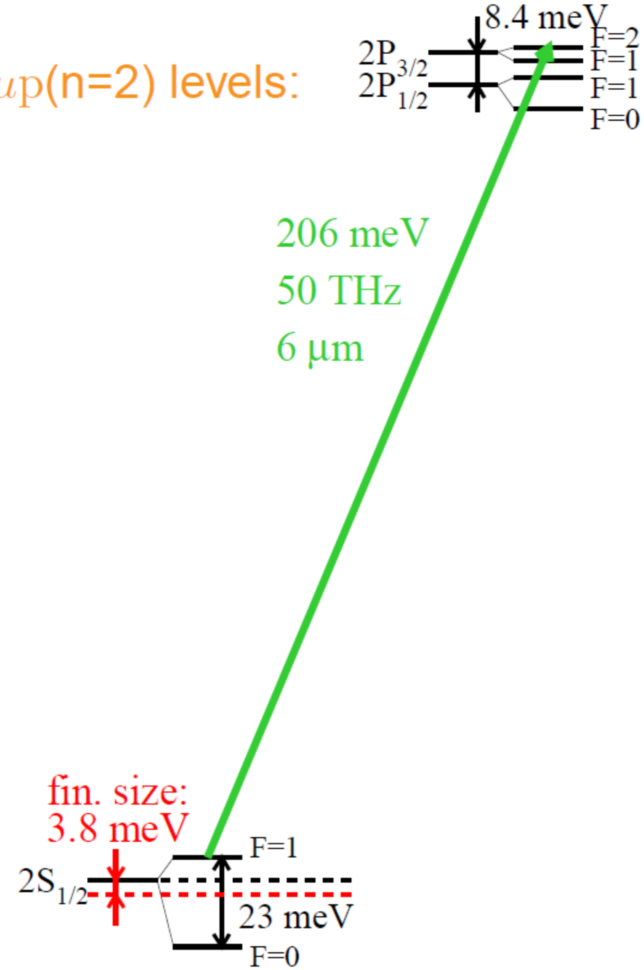


Muonic hydrogen Lamb shift and proton radius

muonic hydrogen = $\mu^- p$ mass m_μ = 207 m_e

$$\Delta E_{\text{finite size}}(nl) = \frac{2(Z\alpha)^4 c^4}{3\hbar^2 n^3} m_r^3 \, r_p^2 \, \delta_{l0}$$

μp(n=2) levels:



Lamb shift in μp: $\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1})$ =

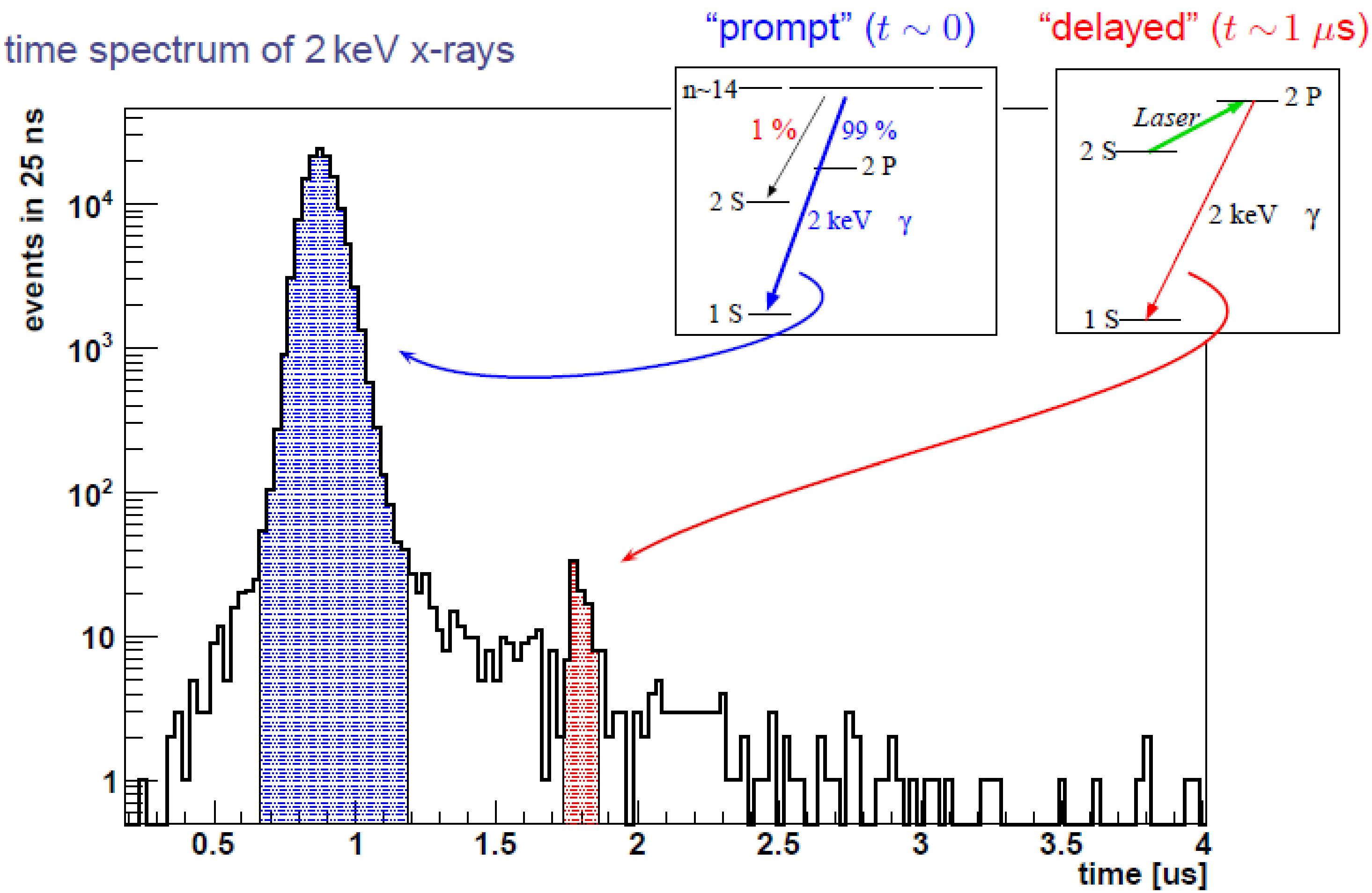
$$209.9779(49) - 5.2262 \, r_p^2 + 0.0347 \, r_p^3 \quad \text{[meV]}$$

finite size contribution is 2% of the μp Lamb shift

μp Lamb shift experiment: principle

New 5keV muon beam line at PSI

Muons stopped in H_2 gas at low pressure ➔ excited μp atoms (n=14) are formed



Laser tunable around λ=6nm 50THz 206mEV

μp Lamb shift experiment: principle

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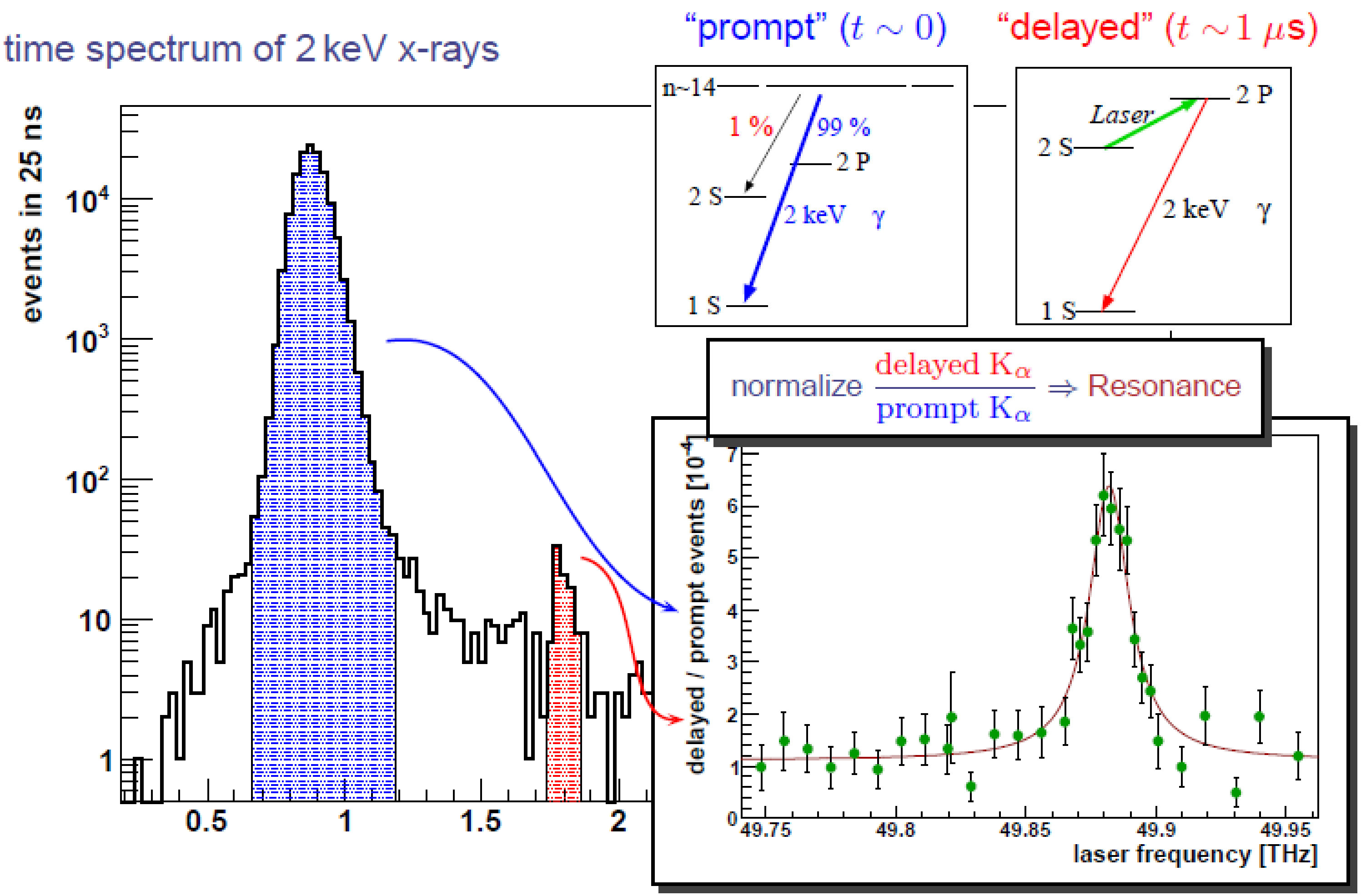
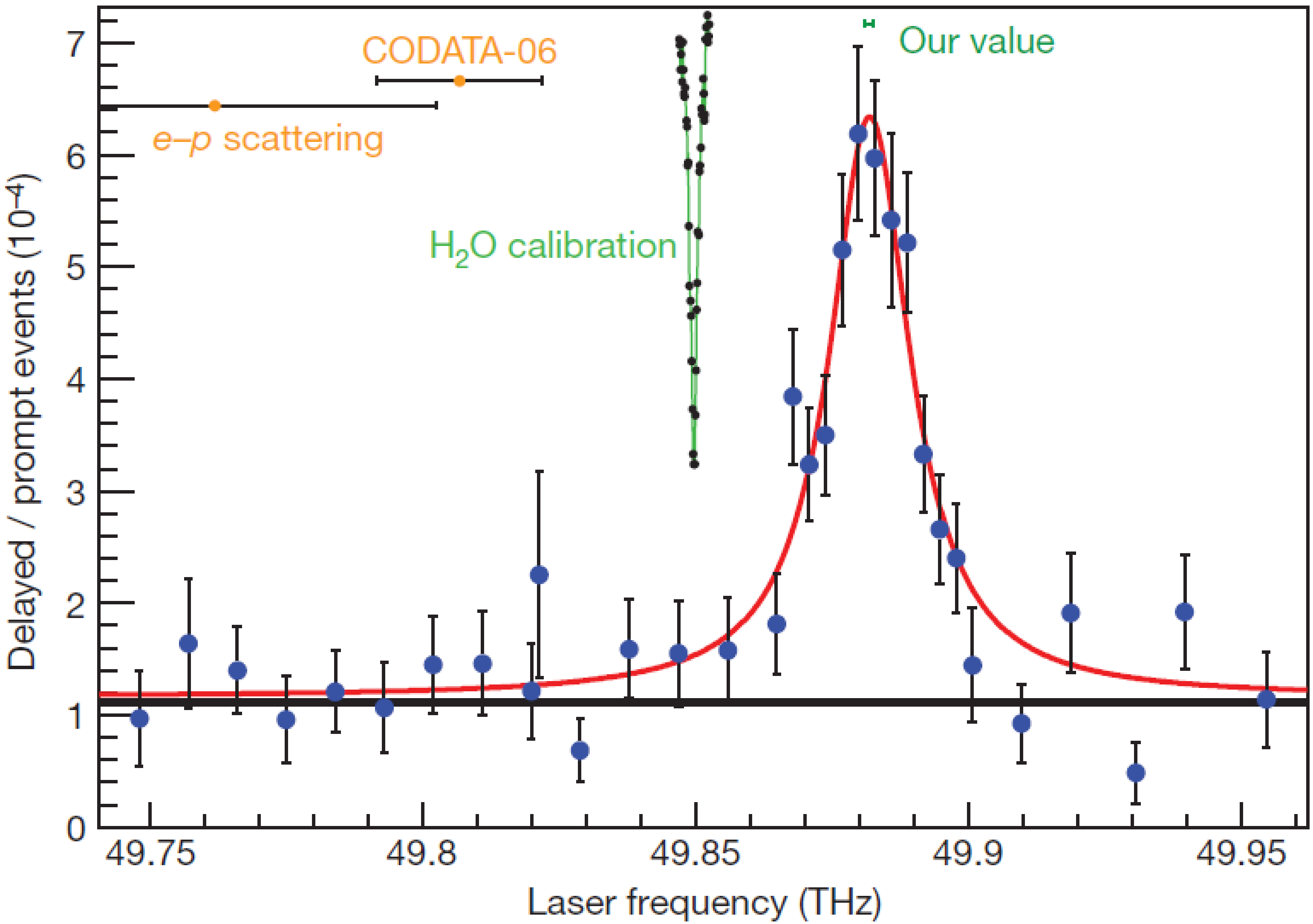


Laser tunable around λ=6nm 50THz 206mEV

μp Lamb shift result



UNEXPECTED ! Skrinking the proton

Conclusion: what is wrong ?

- Spectroscopy: Missing element in the QED corrections
in the bound μp system…
- Lepton Scattering: Need of very precise and very low Q2 data…
- …

The proton, already an old-fashioned objet,
but still embedded in exciting challenges

Deep Inelastic Scattering

Parton Distribution Functions (PDF (x))

unpolarized => High precision

polarized => Nucleon Spin Crisis Consolidation

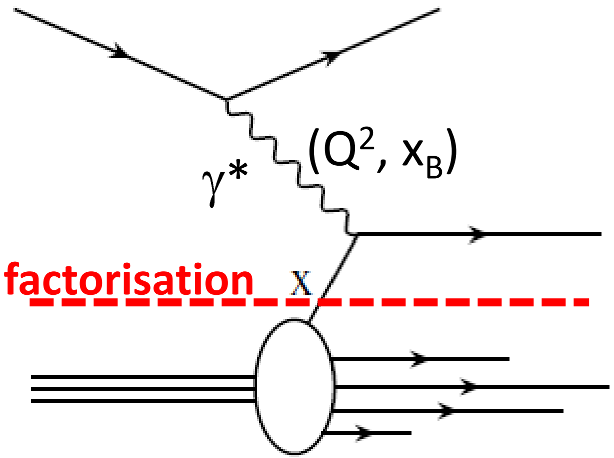
More on transverse information

momentum: Transverse Momentum Dependent PDF

position: Generalized Parton Distributions (GPD)

=> Exploration in 3D

Probing: Lepton-nucleon scattering



longitudinal size contracted
time dilatation
$\text{time}_{\text{hadronization}} \gg \text{time}_{\gamma^* q \text{ interaction}}$

Deep Inelastic Scattering:

$\sigma_{DIS}(ep \rightarrow e X) = \Sigma_q \; \sigma_{elastic}(eq \rightarrow eq)$
incoherent

Quark parton model (QPM)

- Point-like, non-interacting partons
- Collinear to the nucleon movement in photon-nucleon collision (longitudinal direction)
- Each parton carries a fraction x of the nucleon momentum and for the struck parton: $x = x_B$
- Scaling: observables function of x (at first order)

The inclusive cross section is described by 4 structure functions:

unpolarized

F1(x), F2(x),

$$F_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 q(x) = \frac{F_2(x)}{2x}$$

$$q(x) = q^+(x) + q^-(x)$$

probablity of finding a quark with a fraction x of the nucleon longitudinal momentum

polarized

g1(x), g2(x)

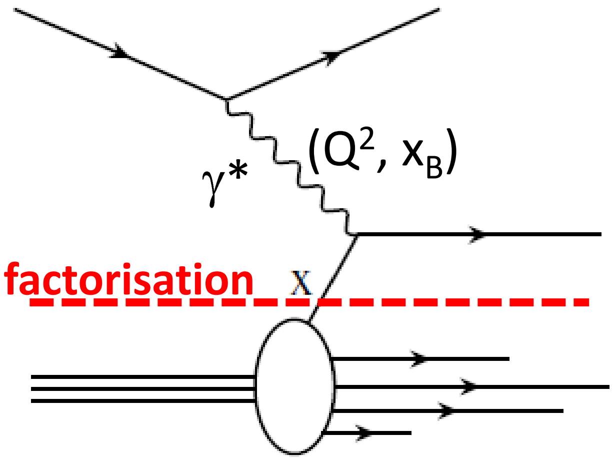
$$g_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x)$$

$$g_2(x) = 0$$

$$\Delta q(x) = q^+(x) - q^-(x)$$

probablity of finding a quark with a momentum fraction x and spin // to that of the nucleon

Probing: Lepton-nucleon scattering



longitudinal size contracted
time dilatation
$\text{time}_{\text{hadronization}} >> \text{time}_{\gamma^* q \text{ interaction}}$

Deep Inelastic Scattering:

$$\sigma_{DIS}(ep \rightarrow e\,X) \underset{\text{incoherent}}{=} \sum_q \sigma_{elastic}(eq \rightarrow eq)$$

Quark parton model (QPM)

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probablity of finding a quark with a fraction x of the nucleon longitudinal momentum

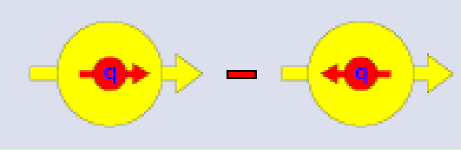
polarized

g1(x), g2(x)

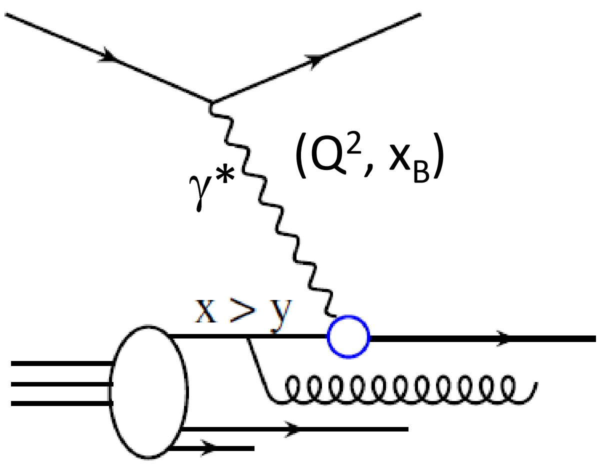
$$g_1(x) = \frac{1}{2}\sum_{q=u,d,s} e_q^2 \Delta q(x)$$

$$g_2(x) = 0$$

$$\Delta q(x) = q^+(x) - q^-(x)$$



Probing: Lepton-nucleon scattering



Deep Inelastic Scattering:

$\sigma_{DIS}(ep \rightarrow e\,X) = \Sigma_q \; \sigma_{elastic}(eq \rightarrow eq)$

incoherent

QCD improved parton model

- at finite Q^2, partons interact
  - ➔ PDFs and structure functions depend on Q^2
  - ➔ gluons are visible (in the Q^2 evolution)

The inclusive cross section is described by 4 structure functions:

unpolarized	**polarized**
$F1(x, Q^2)$, $F2(x, Q^2)$,	$g1(x, Q^2)$, $g2(x, Q^2)$

$$F_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 q(x) = \frac{F_2(x)}{2x}$$

$$q(x) = q^+(x) + q^-(x)$$

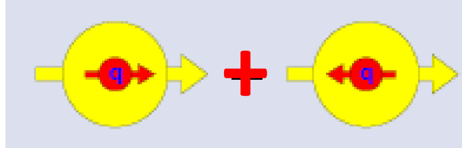
$$g_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x) \qquad g_2(x) = 0$$

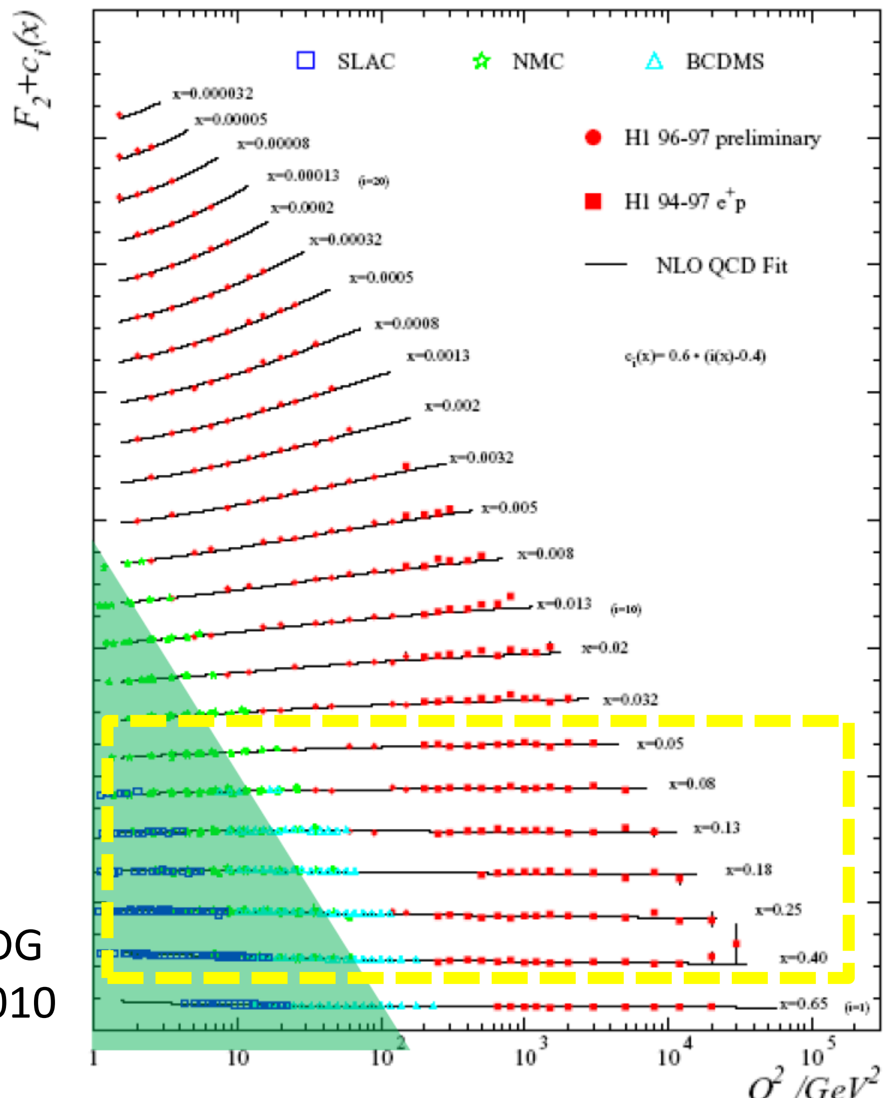
$$\Delta q(x) = q^+(x) - q^-(x)$$

➔ quark PDF $q(x,Q^2)$ — $\Delta q(x,Q^2)$

and gluon PDF $G(x,Q^2)$ from F_1 evolution — $\Delta G(x,Q^2)$ from g_1 evolution

$F_2(x,Q^2)$



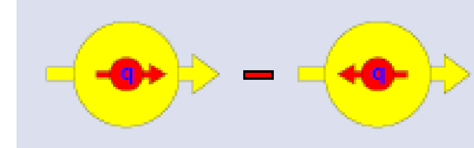


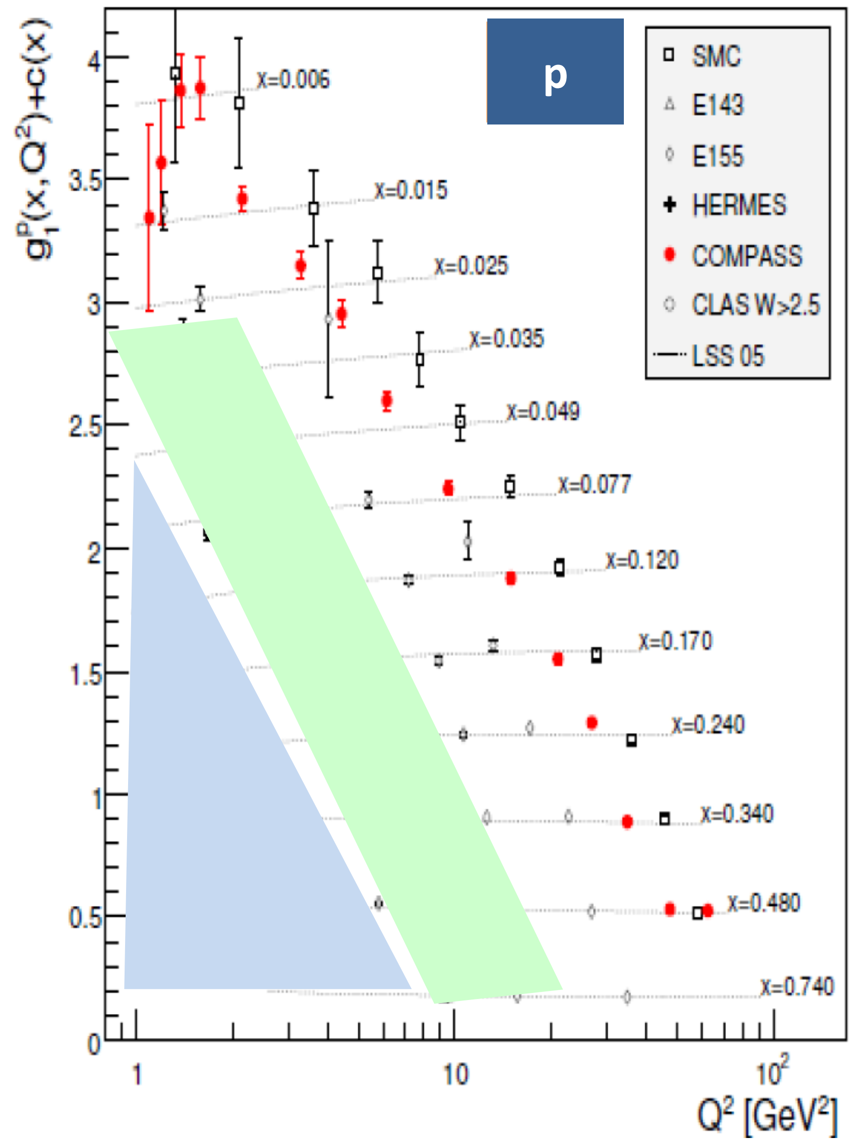
PDG 2010

Very gentle QCD evolution

Factorisation scale Q^2 few GeV^2

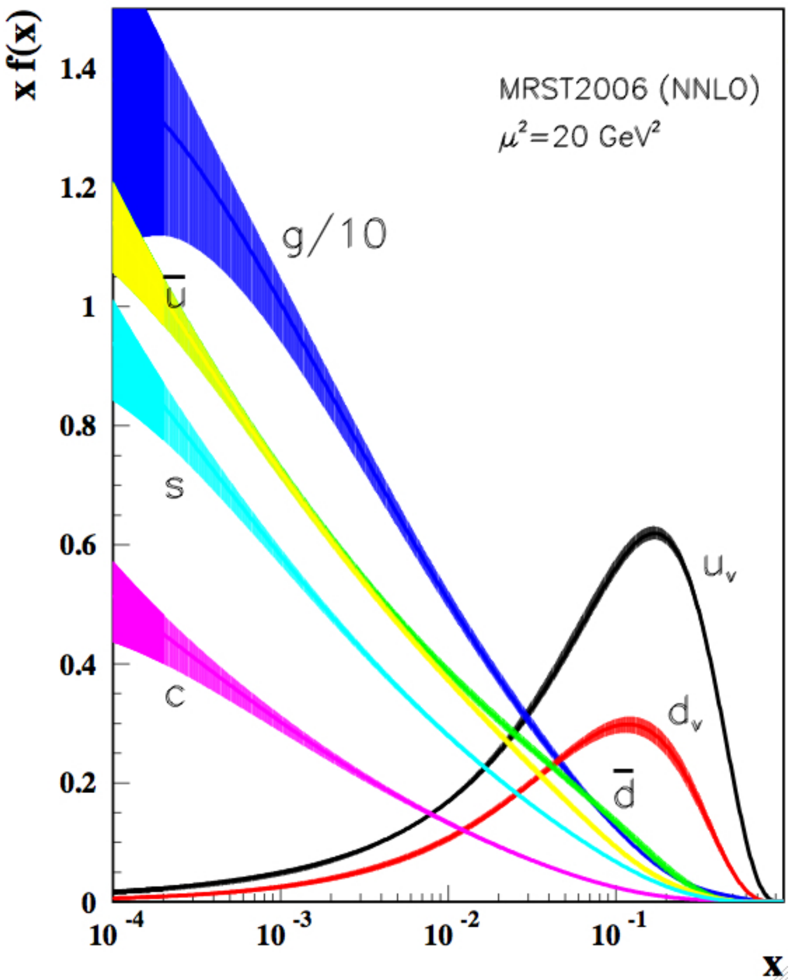
$g_1(x,Q^2)$





Still not so well known

Unpolarized quark and gluon PDF

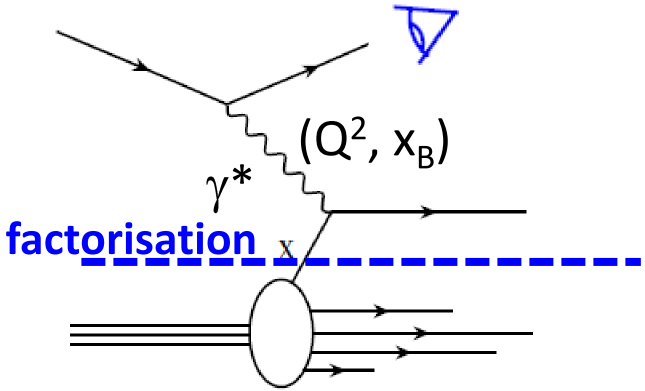


Global fit
on the world data

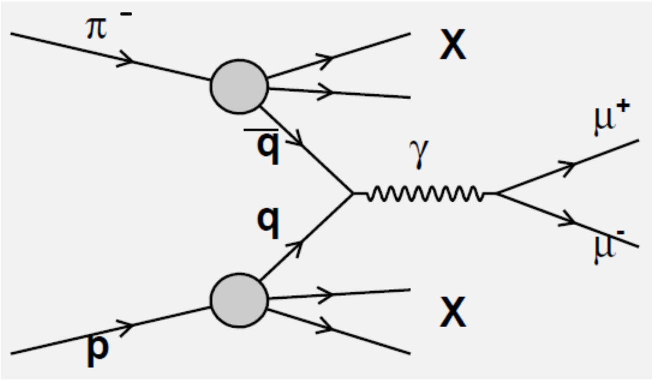
Universality of PDF

Physical cross section = cross section for partonic process ($\gamma^* q \rightarrow q$ or $q\bar{q} \rightarrow \gamma^*$) × **PDF**

Deep Inelastic Scattering (DIS) $\ell p \rightarrow \ell' X$



Drell Yan (DY) $\pi p \rightarrow \ell^+ \ell^- X$



Factorisation: scheme dependent!

nucleon spin crisis

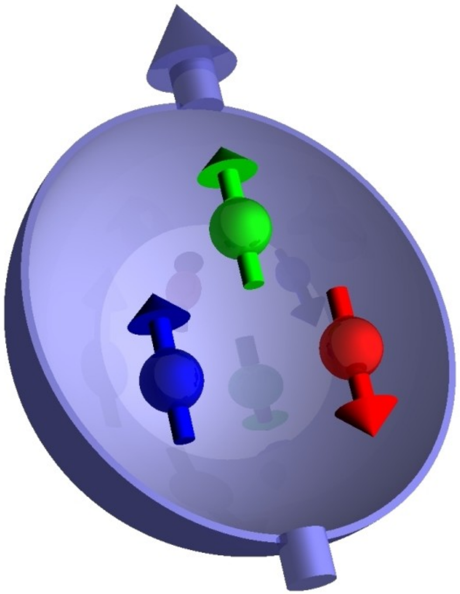
$\Delta q(x)$ and $\Delta q = \int_0^1 \Delta q(x)dx$

$\Delta G(x)$ and $\Delta G = \int_0^1 \Delta G(x)dx$

Need of longitudinally polarized beam

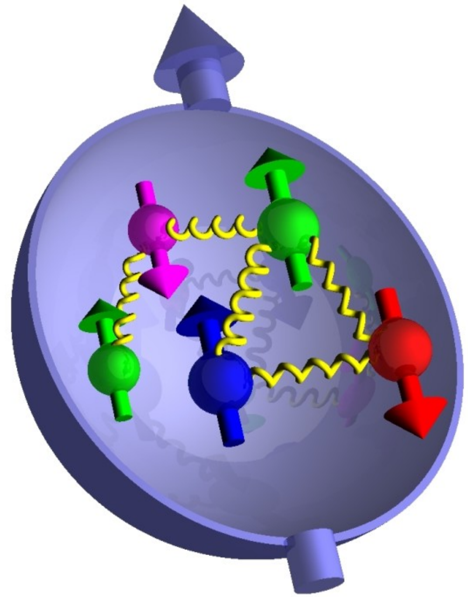
and longitudinally polarized target

The spin of the nucleon

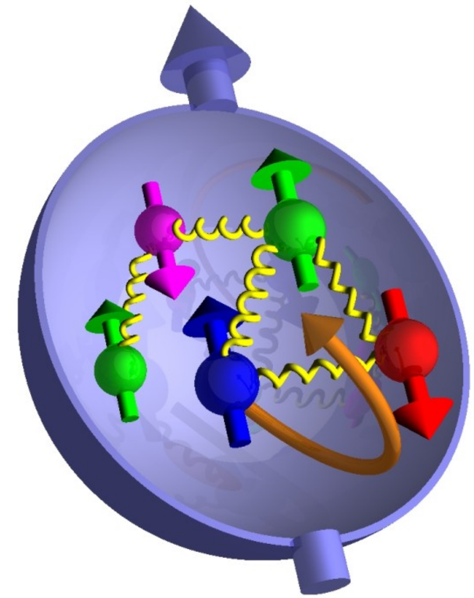


Naive quark parton model
$\Delta\Sigma = \Delta u_v + \Delta d_v = 1$

Note Δ means $\int_0^1 dx$



QCD: sea quarks and gluons
Δq_s, ΔG



Orbital angular momentum
L_z^q, L_z^g

$$\tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

$\Delta\Sigma = \Delta u + \Delta d + \Delta s$ ~ 0.6 QCD with $\Delta s = 0$ (Ellis-Jaffe)

~ 0.12 ± 0.17 EMC (1987) surprise!

The structure function g_1 and its first moment

$$\mathbf{g_1(x)} = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x) \qquad \Gamma_1 = \int_0^1 \mathbf{g_1(x)}\, dx$$

In naive QPM + SU(3)

$$\Gamma_1^p = \frac{1}{2}\left\{\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right\} \quad \text{with} \quad \Delta q = \int \Delta q(x) dx$$

$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{\sqrt{3}a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

General sum rule (OPE)

$$\Gamma_1^{p,n} = \frac{1}{12}\left(\pm a_3 + \frac{1}{\sqrt{3}} a_8\right) + \frac{1}{9} a_0$$

Neutron decay
$g_A/g_V \rightarrow a_3$

hyperon decay
3F-D $\rightarrow a_8$

? $Q^2 \neq \infty$

$a_0 = \Delta u + \Delta d + \Delta s \equiv \Delta\Sigma$

measured first
by EMC in 1987

$a_0 = 0.12 \pm 0.17$ surprise!

The structure function g_1 and its first moment

$$\mathbf{g_1(x)} = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x) \qquad \Gamma_1 = \int_0^1 \mathbf{g_1(x)}\, \mathrm{d}x$$

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$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{\sqrt{3}a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

General sum rule (OPE)

$$\Gamma_1^{p,n} = \frac{1}{12}\left(\pm a_3 + \frac{1}{\sqrt{3}}a_8\right) + \frac{1}{9}a_0$$

measured first by EMC in 1987

A crisis in the parton model: where, oh where is the proton's spin?

E. Leader[1] and M. Anselmino[2]

Birkbeck College, University of London, London, UK
Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy

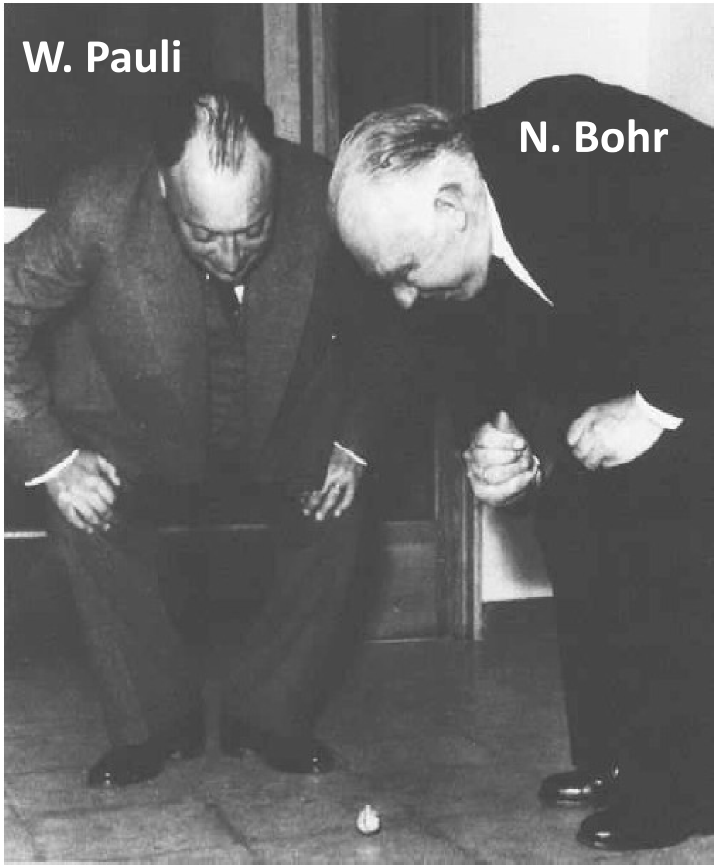
Received 18 March 1988

? $Q^2 \neq \infty$

$a_0 = \Delta u + \Delta d + \Delta s \equiv \Delta\Sigma$

$a_0 = 0.12 \pm 0.17$ surprise!

How to solve the spin crisis?



Pauli and Bohr wondering about a tip top toy (1955)

In polarised DIS, one measures a_0 flavor singlet axial matrix element at $Q^2 \neq \infty$

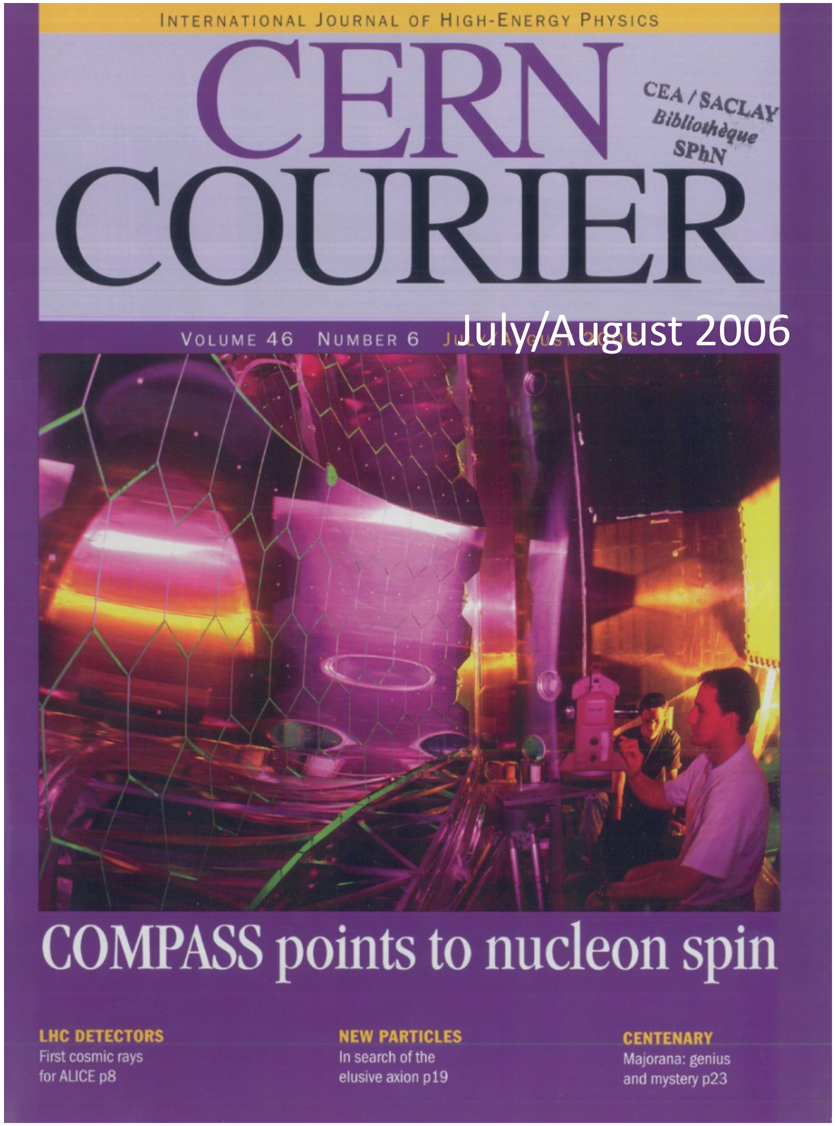
- ✓ In the MS renormalisation scheme

$$a_0 = \Delta\Sigma$$

- ✓ While in the Adler-Bardeen and JET schemes (axial anomaly)

$$a_0 = \Delta\Sigma - (\alpha_s/2\pi) n_f \Delta G$$

So a large positive value of ΔG (~3 at Q^2=3 GeV^2) might resolve the spin crisis ?



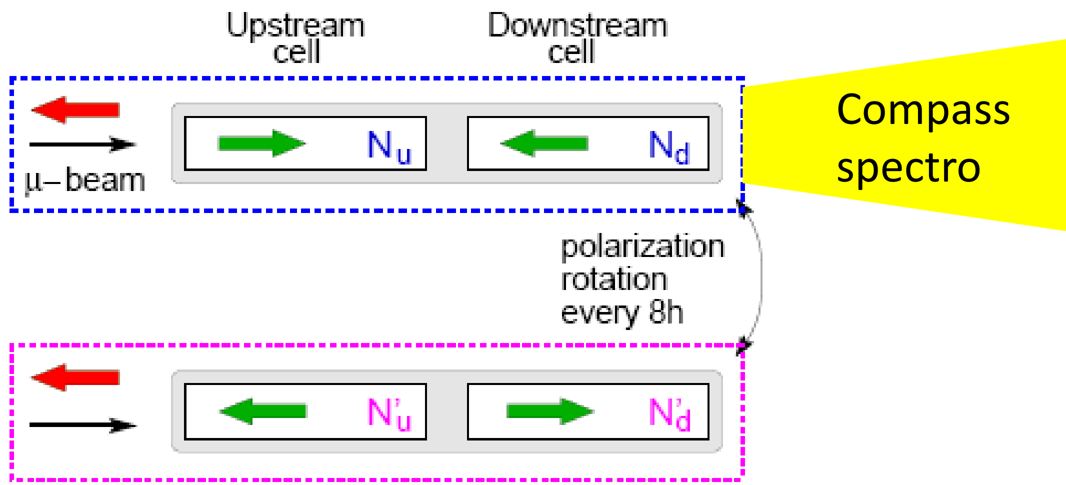
Huge effort during
the past 20 years
Today: COMPASS, HERMES, RHIC

- new measurements of g1, Δq
- first measurements of ΔG

Polarized Beam + Polarized Target ^{6}LiD(d) and NH_3(p)

- **to be measured:**

$$A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$



- **flux normalization:**

$$A_{\mathrm{exp}} = \frac{N_u - N_d}{N_u + N_d}$$

- **acceptance difference:**
  Polarisation rotation

- **take average asymmetry:**

$$\Rightarrow A_{\mathrm{exp}} = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

$\Rightarrow$ minimization of bias

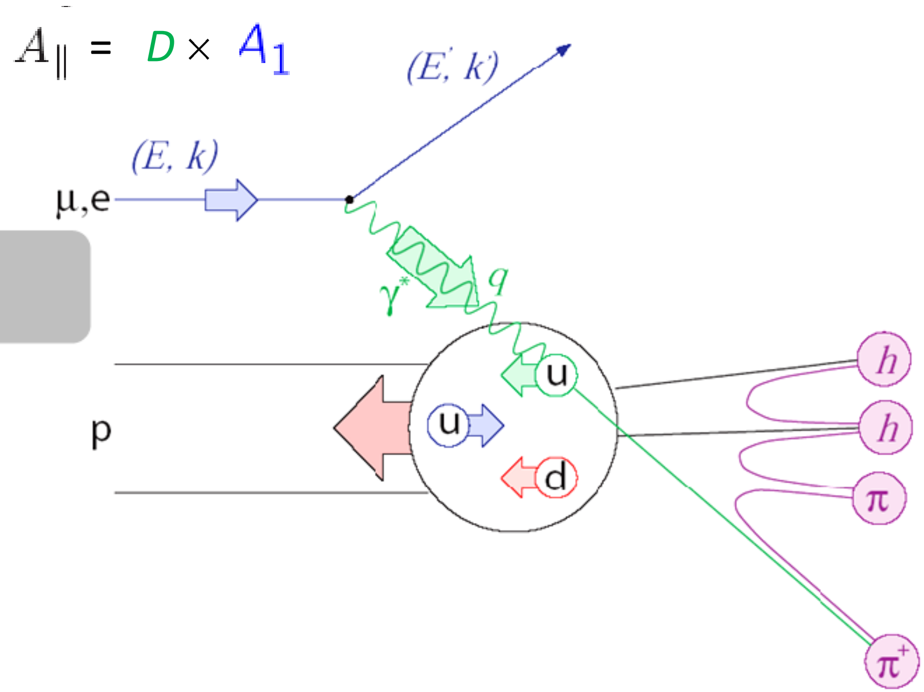
elegant and efficient strategy

Asymmetry measurement

$$\frac{A_{exp}}{f\ P_{\mu}\ P_T\ D} \simeq A_1$$

- Inclusive scattering

$$A_1 = \frac{\sum_q e_q^2 g_1^q(x, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2)}$$



D depolarization factor
P_{μ} target polarization
P_T target polarization
f dilution factor

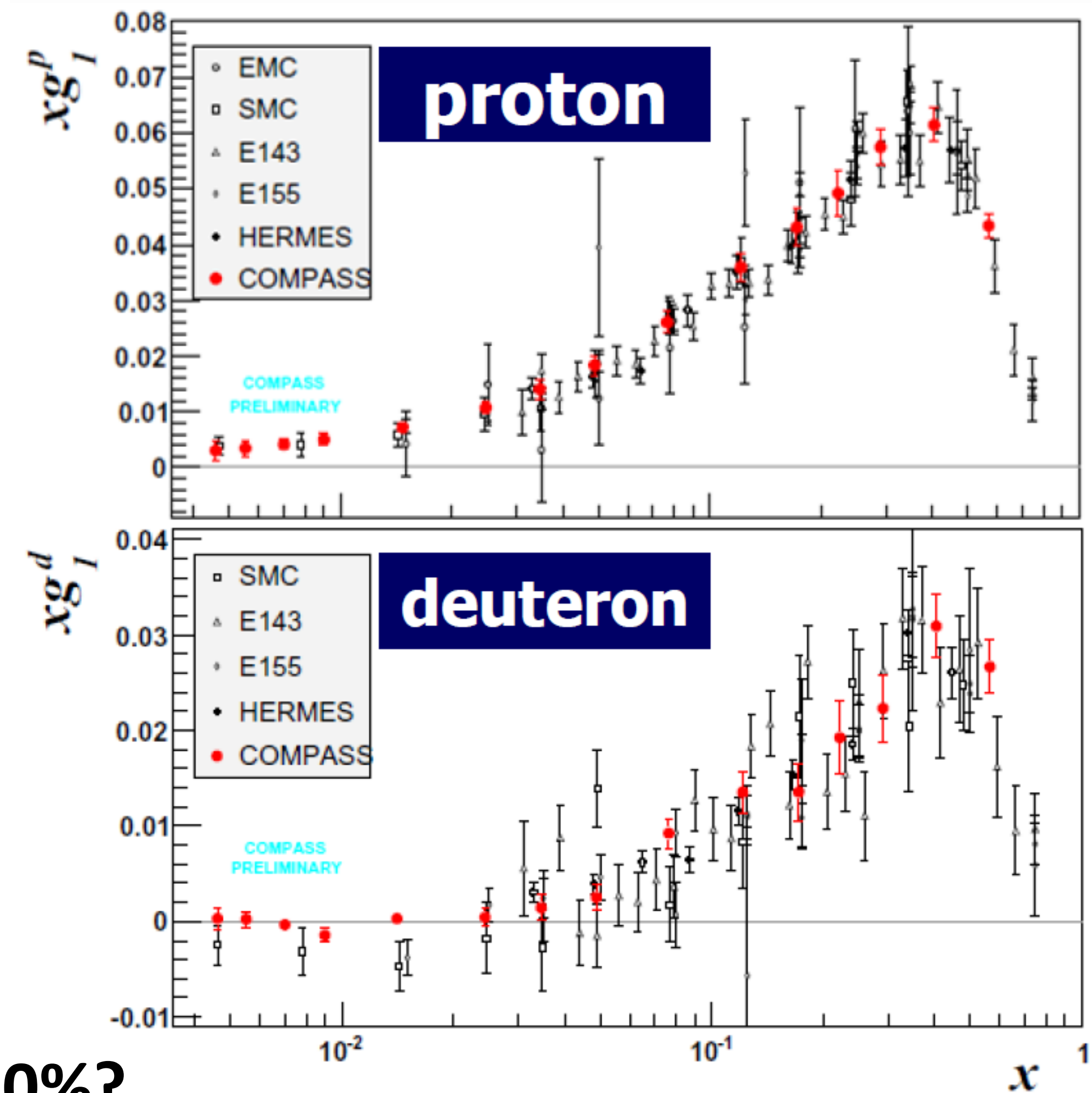
Spin Structure Function $g_1(x,Q^2)$

Using inclusive data

$$g_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x)$$

- Very precise data
- Only COMPASS for x<0.01 (Q2>1)
- COMPASS Deuteron data from Γ1 @ Q2 → ∞

a0= Δ Σ= 0.33 ± 0.03 ± 0.05
Δs+ Δs=1/3 (a0-a8)
= - 0.08 ± 0.01 ± 0.02



What makes up the missing 70%?

Direct Access to the Gluon polarisation (SIDIS)

ℓp→ ℓ' h X

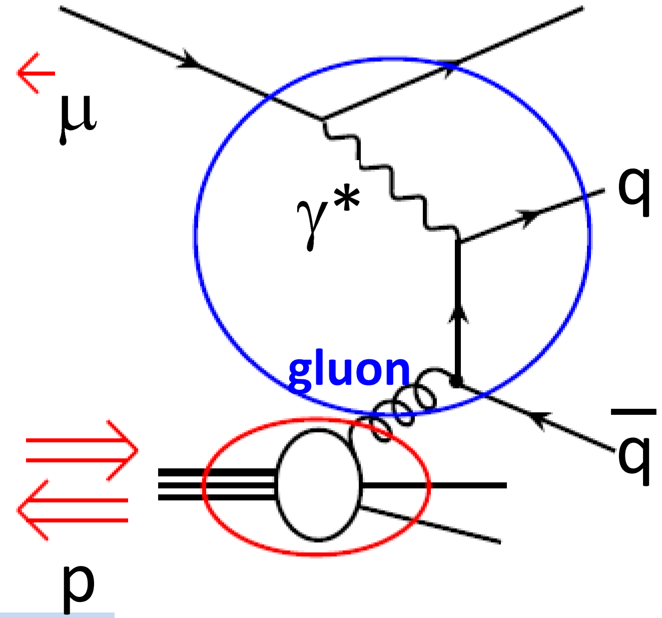
Measured in photon-gluon fusion (PGF)

$$A_{||} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} + A_{bdf}$$

Fraction of process (R_{pgf})

Analyzing power calculable at LO and NLO ($\hat{a}_{pgf}$)

Background (A_{bdf})

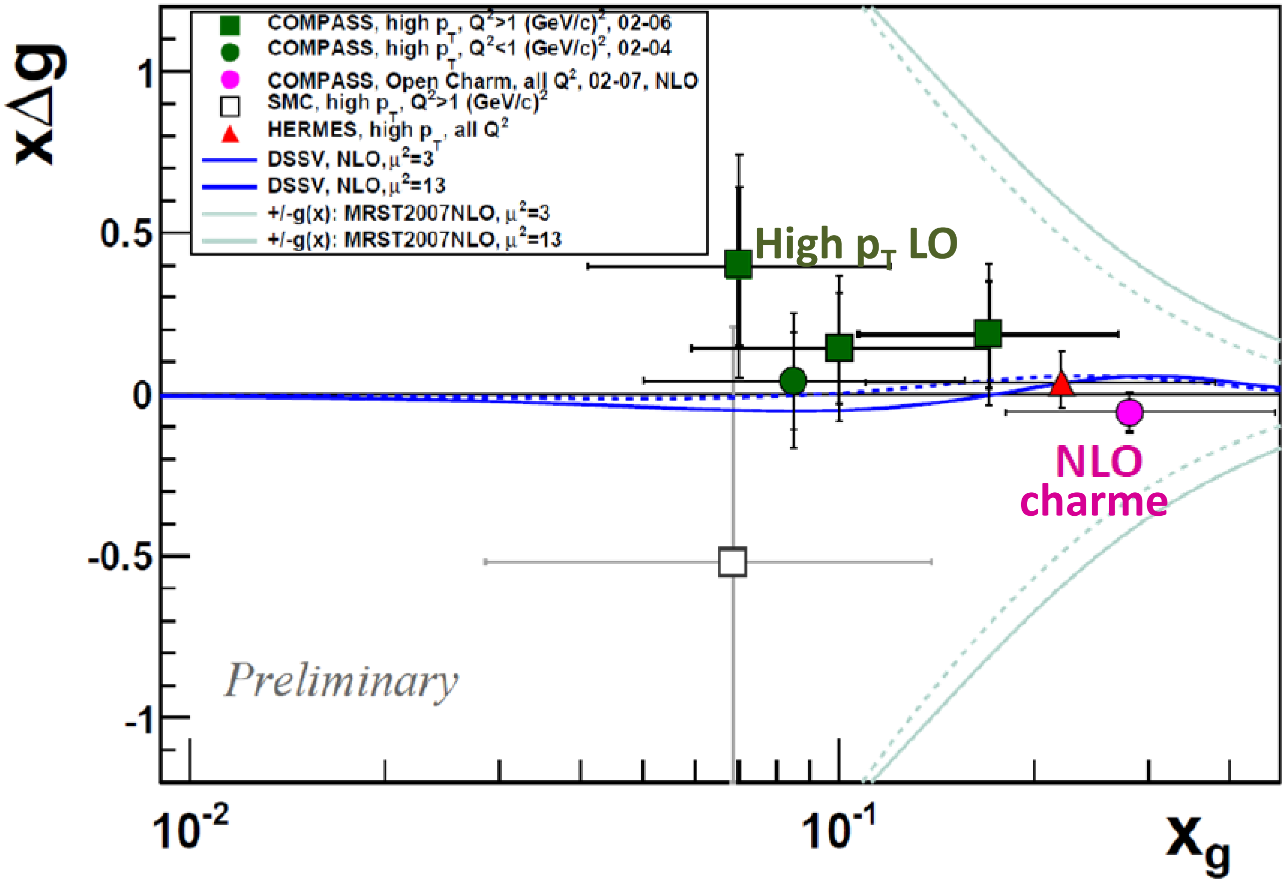


2 signatures to suppress the background:

- q=c and charm hadronization in meson D^0 ($c\bar{u}$) → K π
  Detection of D^0 *mesons*
  Very clean signal but limited statistics

- soit q=u,d,s and q $\bar{q}$ → hadron1 + hadron2
  Detection of a high p_T *hadron pair*
  Physical background, better described at high Q^2

Gluon Polarization: from LO to NLO



x_g =fraction d'impulsion du gluon dans le nucléon

- All results compatible with avec 0 ! (a0= Δ Σ)
- Confirmed by RHIC results in pp

Let's go to measure L_z!

So far the partons were consider collinear to the nucleon movement
in photon-nucleon collision (longitudinal direction),
but what else about the transverse information?

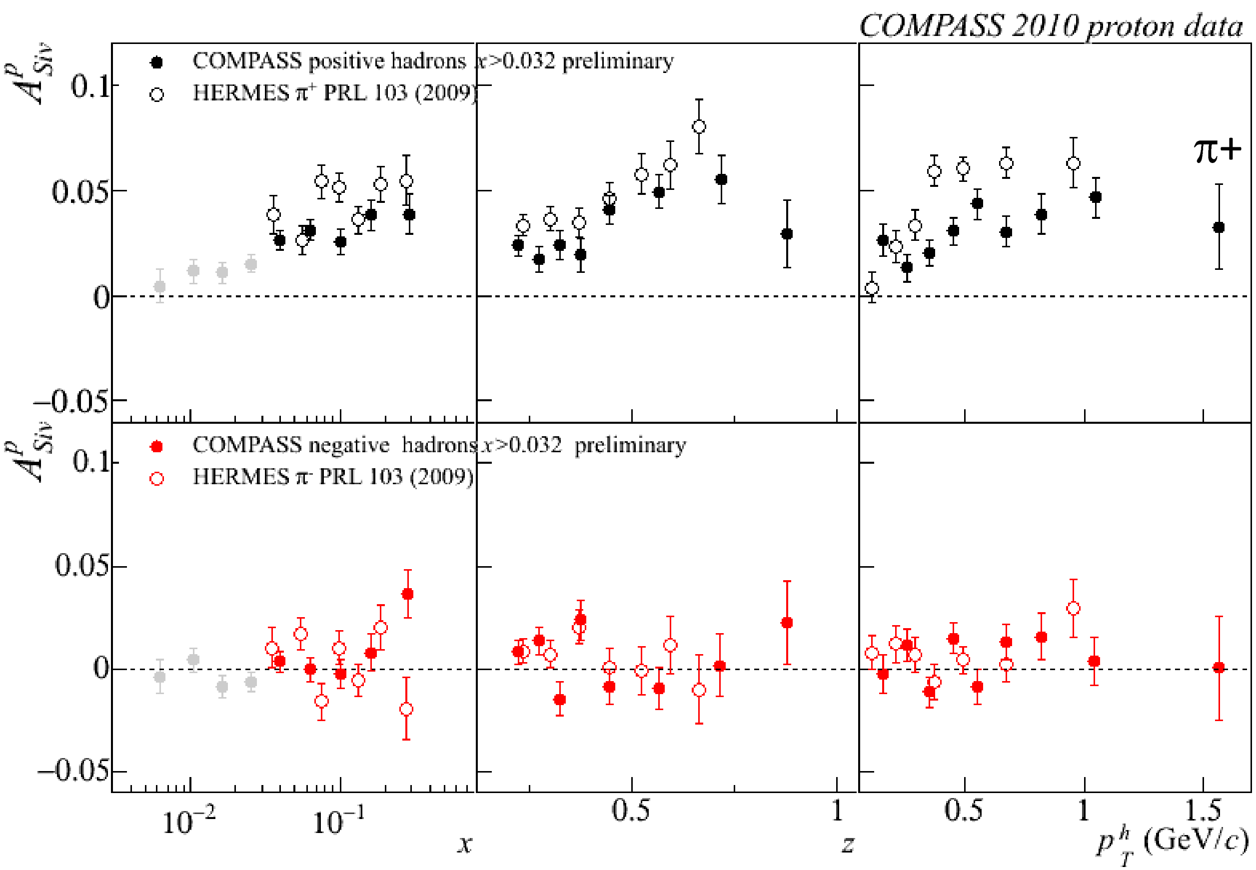
Transverse spin
and transverse momentum

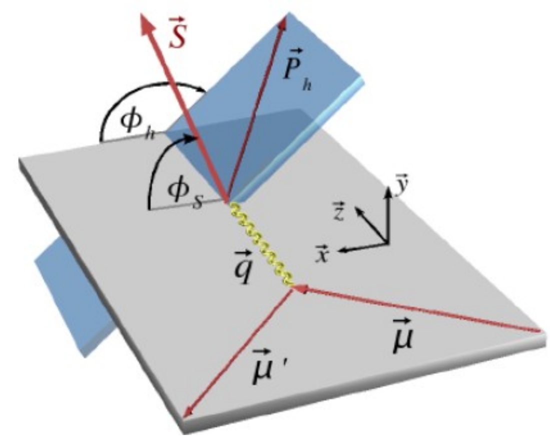
Proton Sivers effect in tranv. pol. SIDIS: ℓp↑→ ℓ' h X

Azimuthal cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin \Phi_S$$

$$\Phi_S = \phi_h - \phi_S$$



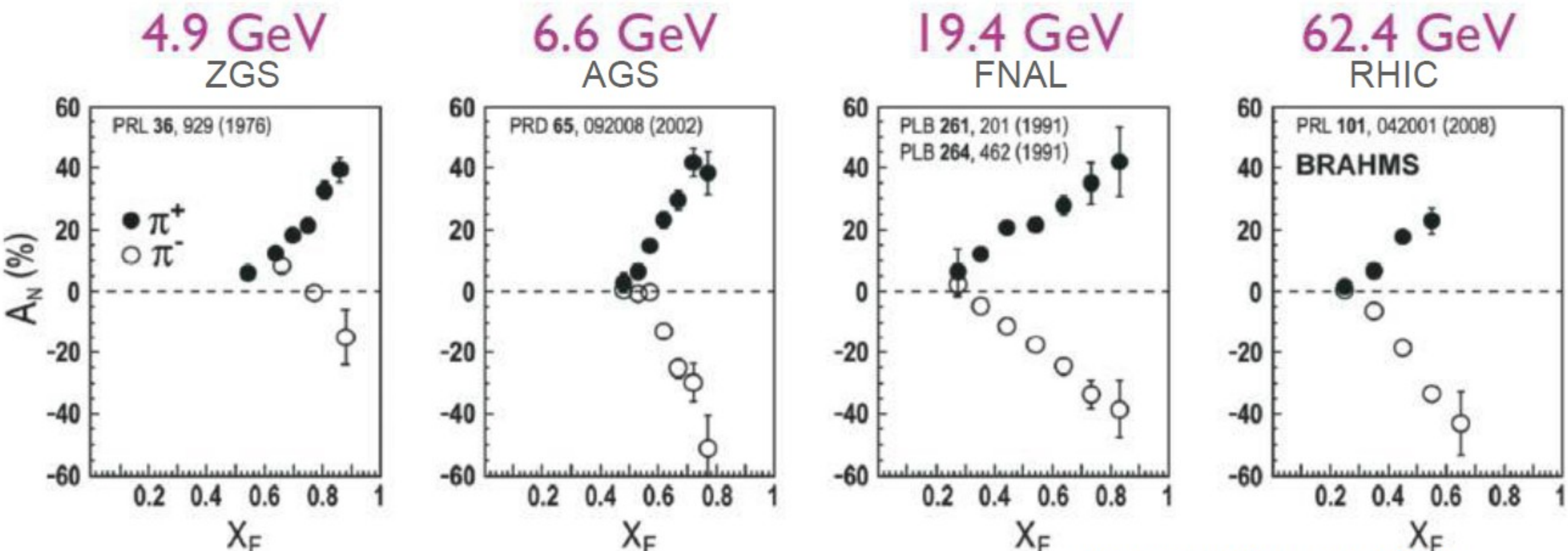


After a long debate this effect is actually observed

Observation of large transverse single spin asymmetries

$p\,p\uparrow \rightarrow \pi^{+/-/0} + X$

persisting at large energy



from Christine Aidala, Spin 2008 and Don Crabb & Alan Krisch in then Spin 2008 Summary, CERN Courier, 6-2009

CERN Courier, June 2009

and what’s next

Focus on transverse structure of the nucleon

- Transverse Momentum Dependent TMD PDF →
  - → Study of SIDIS and DY

- Transverse size and orbital angular momentum : Generalized Parton Distributions (GPDs) →
  - → Study of Exclusive reactions

Coming from the general Wigner phase-space-distributions

- COMPASS-II programme (2012-2016)
- Jlab 11 GeV (start in 2014)
- RHIC
- JPARC

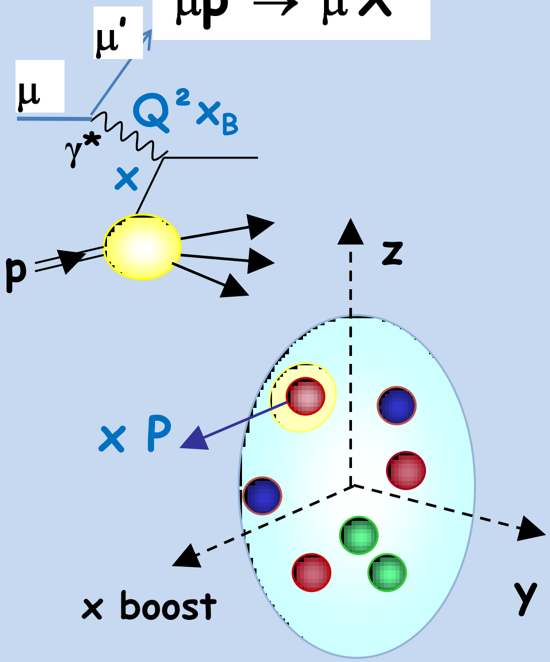
- and more future ENC, eRHIC/ELIC, NICA

from inclusive reactions

to exclusive reactions

Deep Inelastic Scattering

$\mu p \to \mu' X$

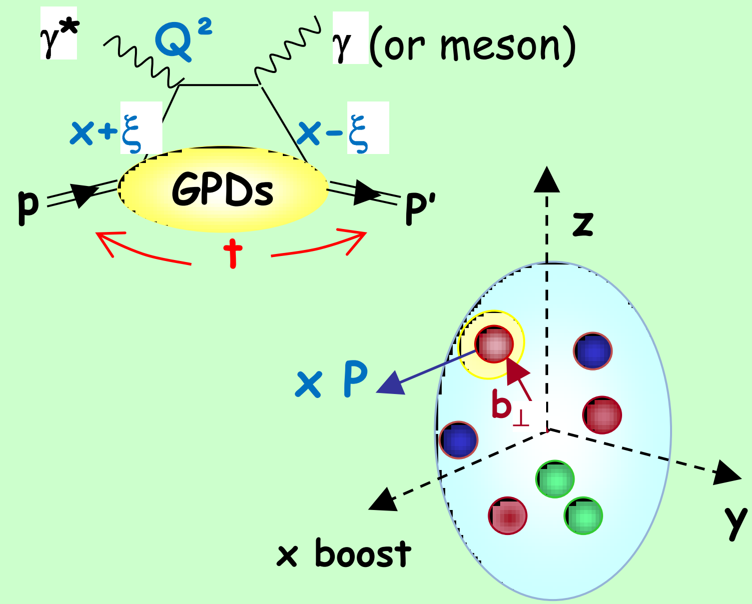


Parton Distribution q (x)

P_x

Deeply Virtual Compton Scattering

$\mu p \to \mu' p' \gamma$



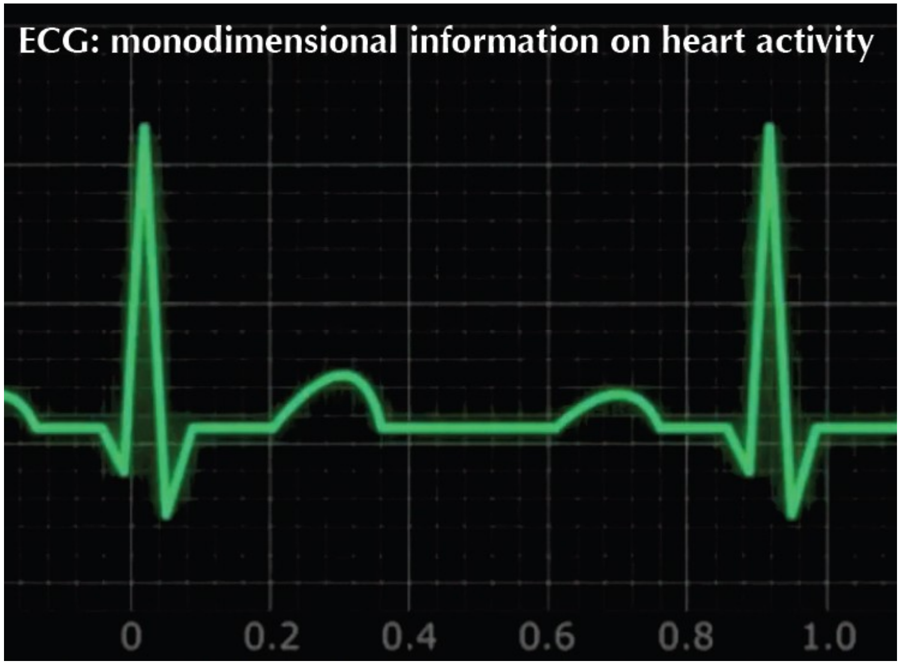
Generalized Partons Distrib. $H(x, \xi, t)$

$(P_x, b_\perp)$

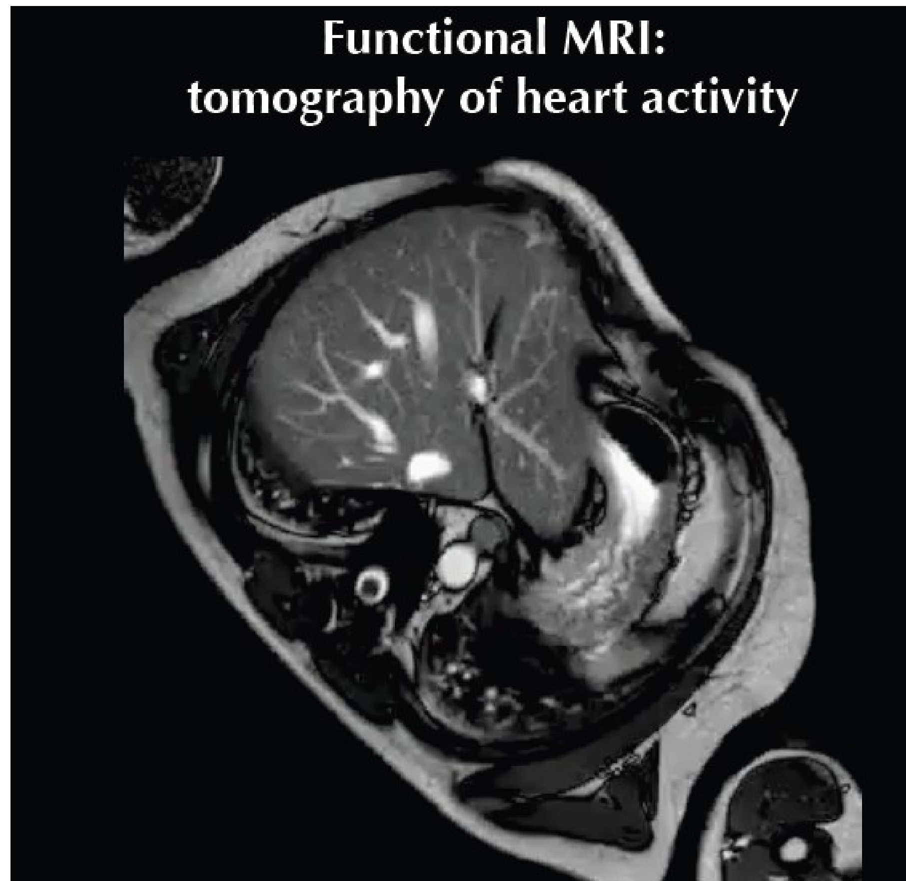
Observation of the Nucleon Structure

in 1 dimension | **in 1+2 dimensions**

From 1D

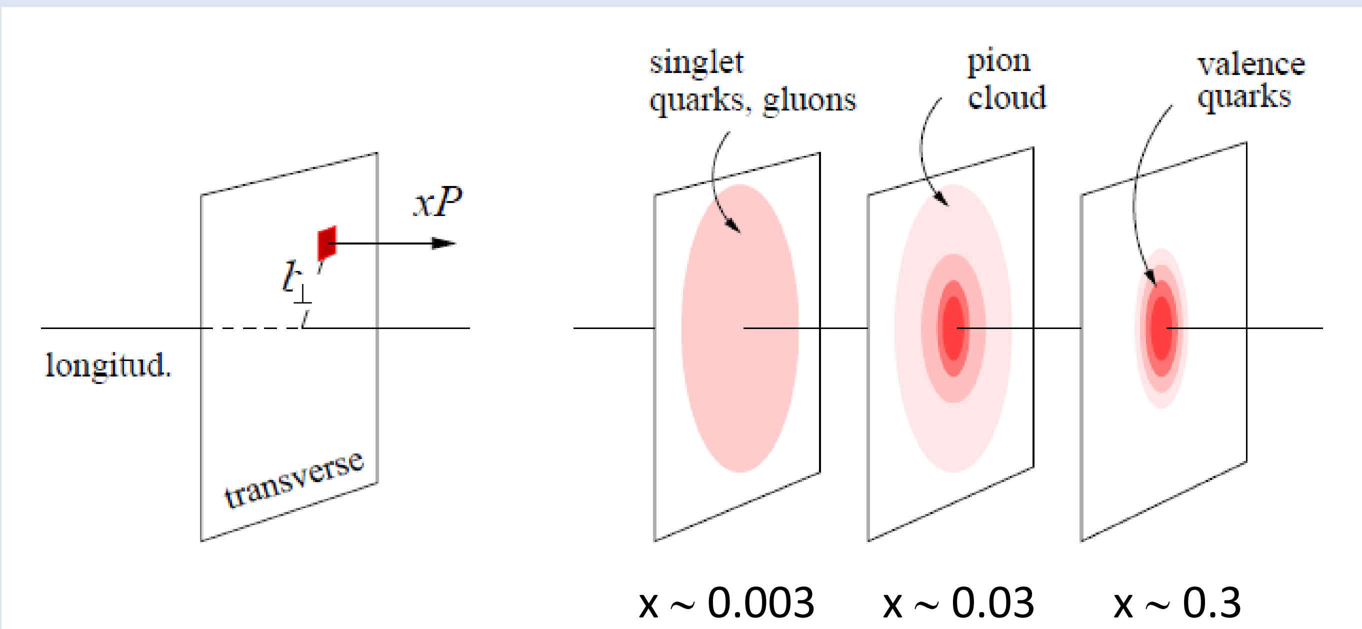

ECG: monodimensional information on heart activity
0
0.2
0.4
0.6
0.8
1.0

to 3D


Functional MRI:
tomography of heart activity

Generalized Partons Distributions (H,E,…)

- Allow for a unified description of form factors and parton distributions
- Allow for transverse imaging (nucleon tomography) and give access to the quark angular momentum (through E)

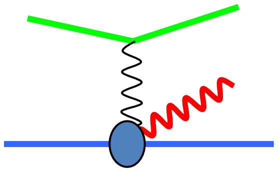


Impact parameter $b_\perp$

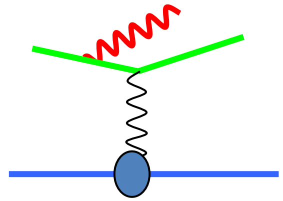
Longitudinal momentum fraction x

Tomographic parton images of the nucleon

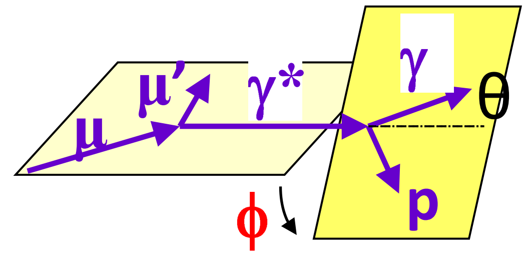
Contributions of DVCS and BH at E 160 GeV



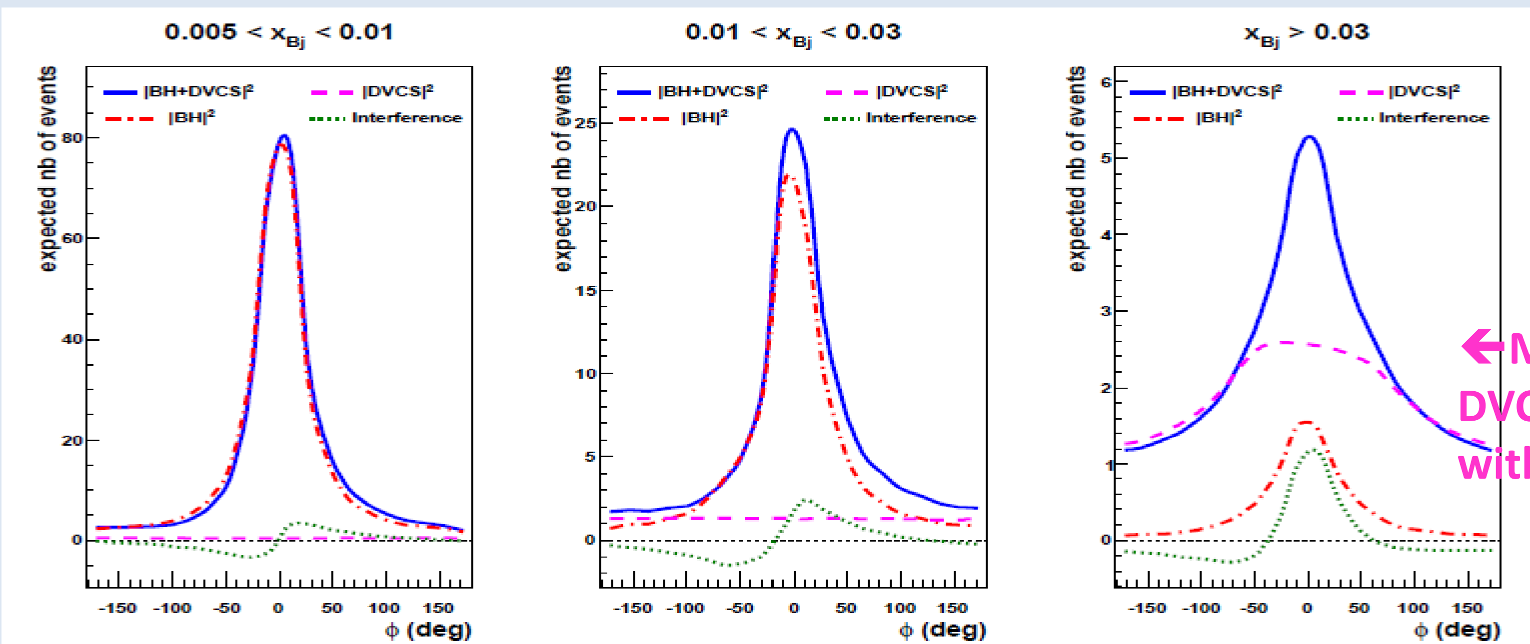
Deep VCS



Bethe-Heitler



$d\sigma \; \alpha \; |T^{DVCS}|^2 + |T^{BH}|^2$ + Interference Term



Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

← Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

→ Re T^{DVCS}

or Im T^{DVCS}

DVCS dominates

study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

Transverse imaging at COMPASS

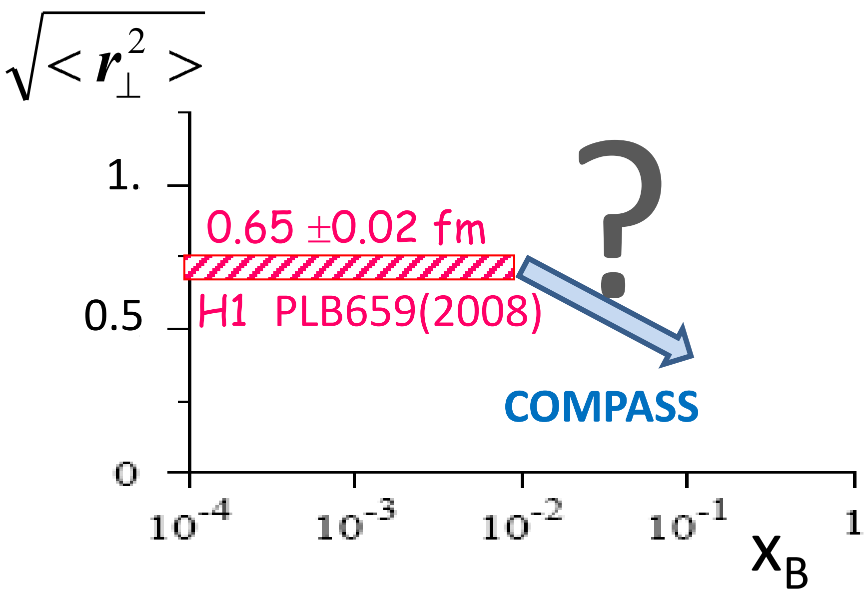
d VCS /dt ~ exp(-B|t|)

$B(x_B) = ½ < r_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by H(x, ξ=x, t)



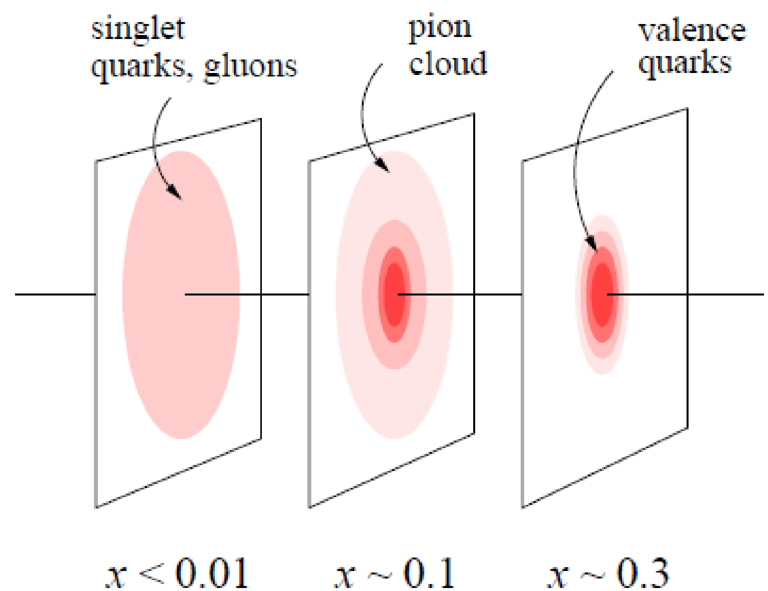
$0.65 = \sqrt{2/3}\ 0.8$

related to $½ < b_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of the nucleon

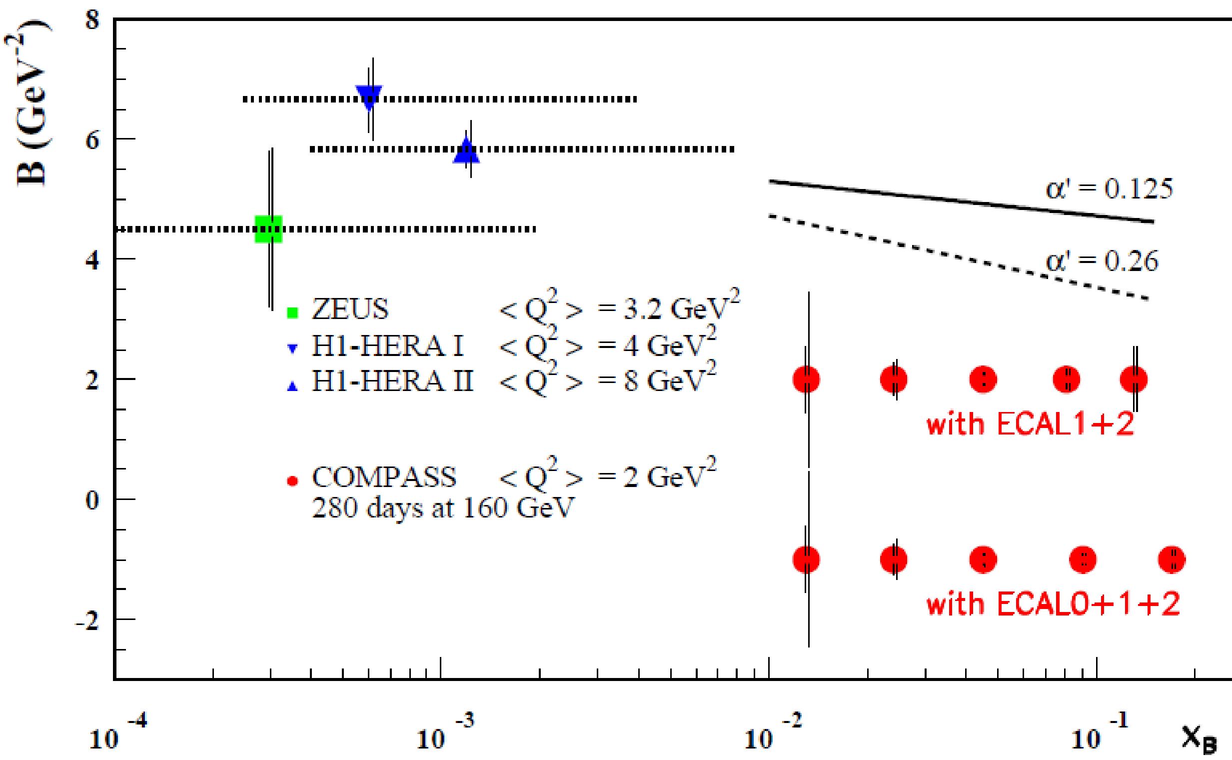
Impact Parameter Representation

$q(x, b_\perp) \leftrightarrow$ H(x, ξ=0, t)



Transverse imaging at COMPASS

d ^{VCS} /dt ~ exp(-B|t|)



2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

ansatz at small x_B
inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

α' slope of Regge traject

without any model we can extract $B(x_B)$

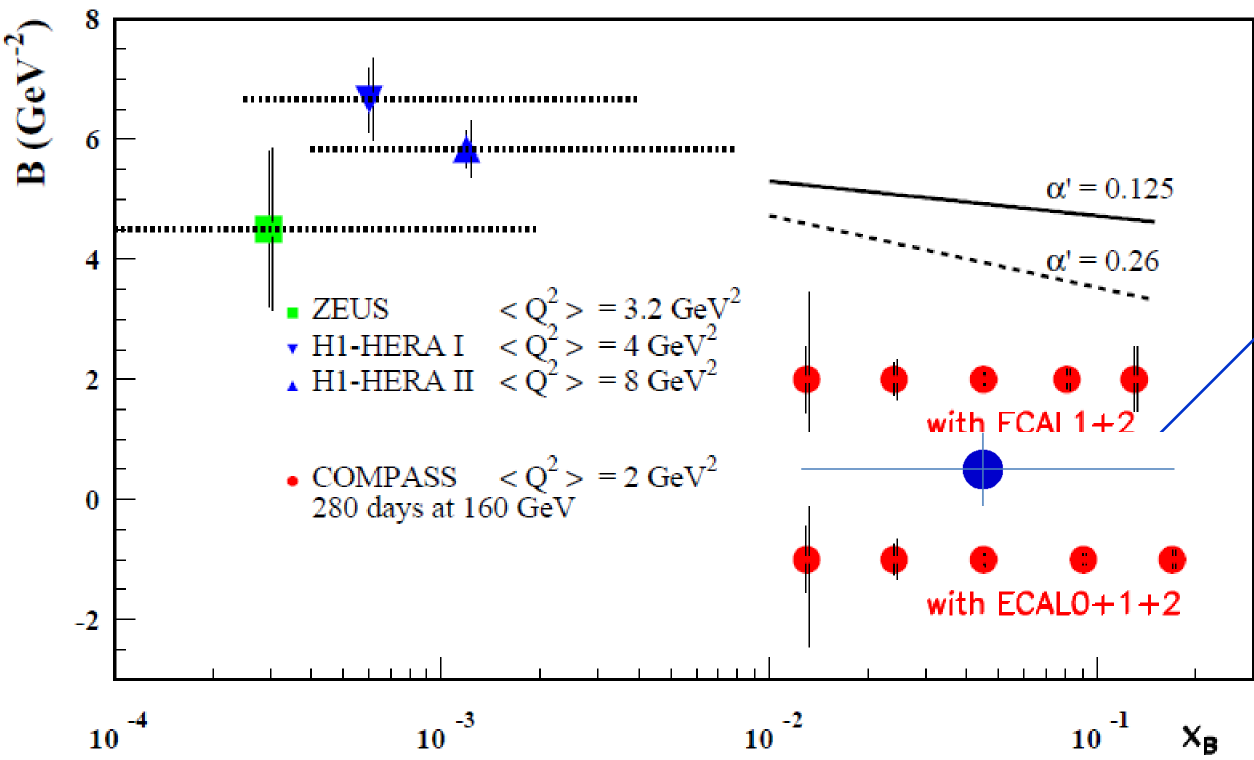
$B(x_B) = \frac{1}{2} < r_\perp^{\,2}(x_B) >$

$r_\perp$ is the transverse size of the nucleon

Accuracy > 2.5 f α' = 0.125 and full ECALS

Transverse imaging at COMPASS

d ^{VCS} /dt ~ exp(-B|t|)



DVCS test in 2012

With 1 week
Using the 4m long RPD
+ the 2.5m long LH2 target

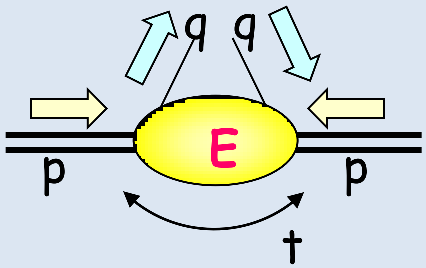
1/40 of the complete statistics

2012: we can determine one mean value of B in the COMPASS kinematic range

The GPD E is the 'Holy-Grail' of the GPD quest

the GPD E allows nucleon helicity flip

so it is related to the angular momentum



Ji sum rule: $2J_q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

Constrains on the GPD E

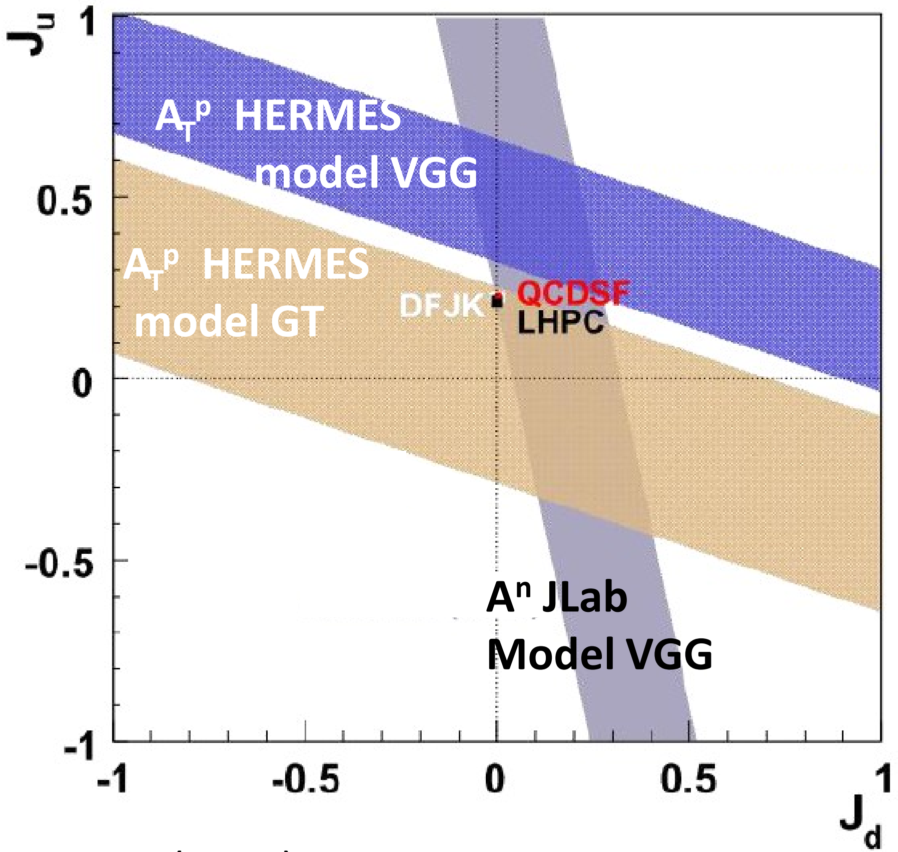
-Using a neutron target $A^n \propto F_1(t)\cdot \mathrm{H} - \frac{t}{4M^2} F_2(t)\cdot \mathrm{E})$

-Using a transversely polarized protontarget

$$A_T^p \propto F_2(t)\cdot \mathrm{H} - F_1(t)\cdot \mathrm{E})$$

Potential of these experiments

A model-dependent case-study



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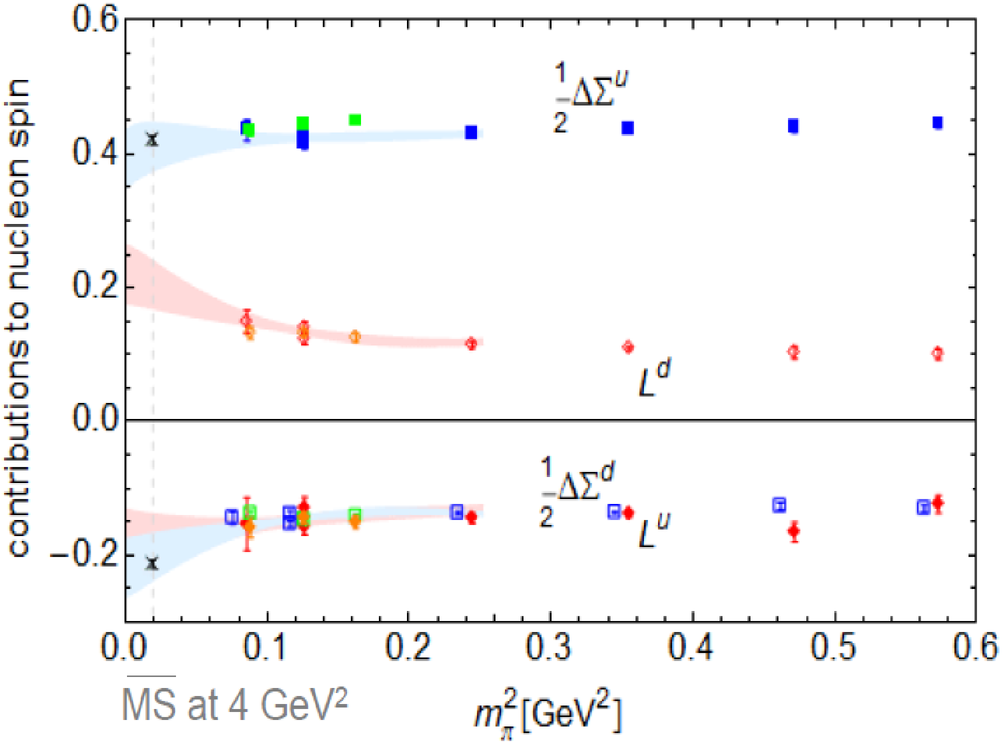
In the near future

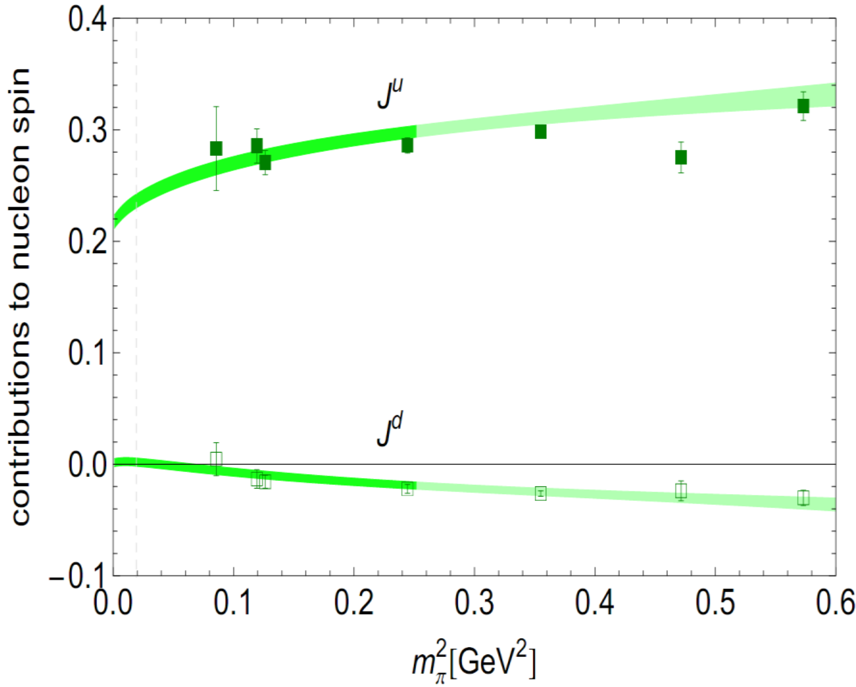
Two main actors

- COMPASS (sea quarks and gluons)
- Jlab (valence domain,
  with a huge luminosity

An important activity
For global fits on the world data
(Mueller, Guidal, Moutarde, …)

Lattice QCD calculations





Ph. Haegler, 2010

Nucleon Spin is fun!

Still a long
and exciting trip