Detectors in hadronic physics

- **Introduction: QCD and Hadronic Physics**
- **Polarizing target & beam**
- **One example: ‘COMPASS Unchained’,**
  a visit to a fixed target experiment

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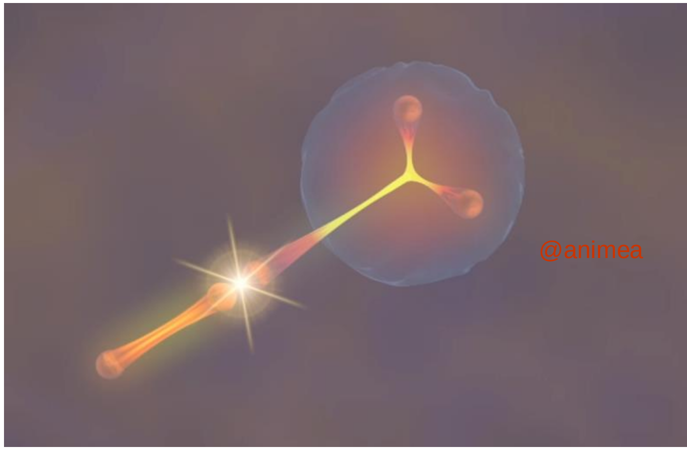

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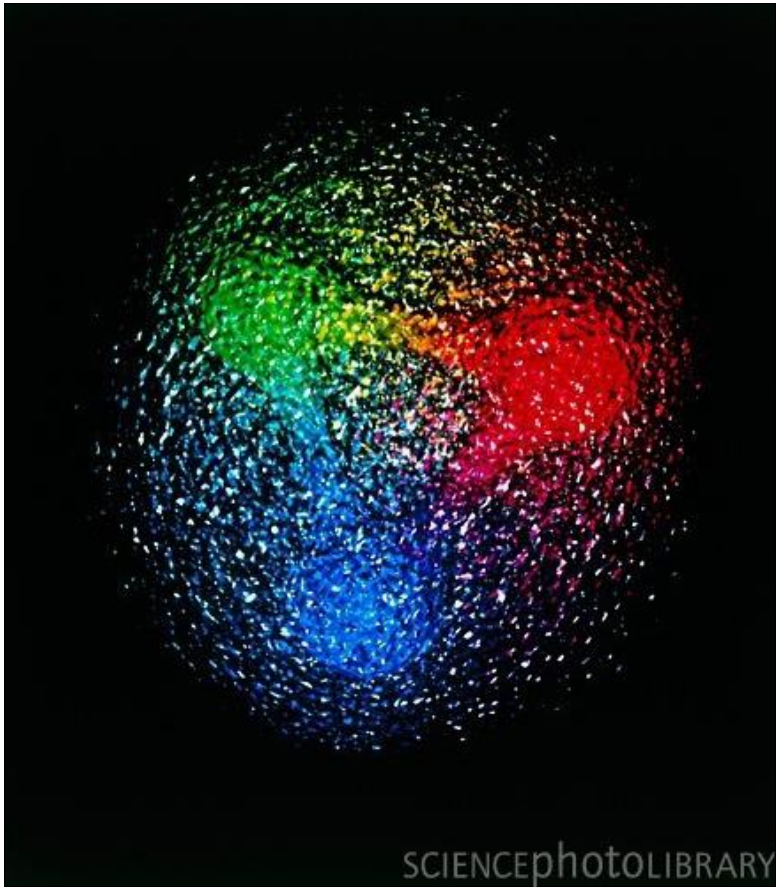
Part I - Introduction

- Questions in hadronic physics
- A few reminders on QCD
- Methods: Some physics processes used

Questions in hadronic physics



- How hadrons are formed and interact from QCD degrees of freedom ?

→ Lattice QCD calculations

- How does the proton spin originates at the microscopic level ?

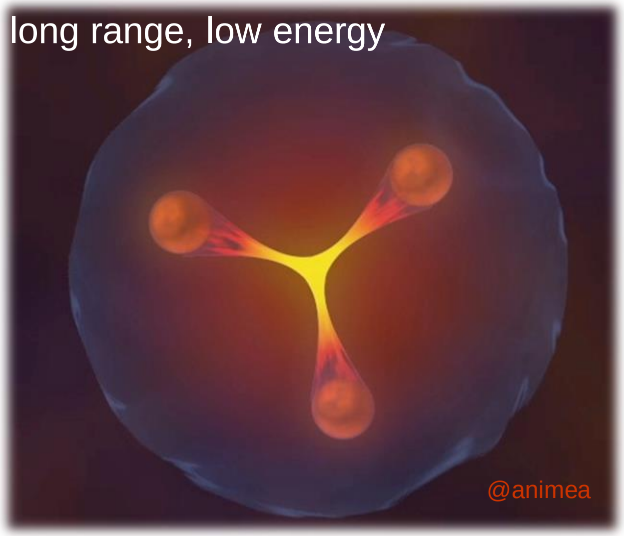
→ Measuring pertinent spin sum rules

- How does confinement manifests itself in the structure of hadrons ?

→ Space and momentum distributions of quarks and gluons

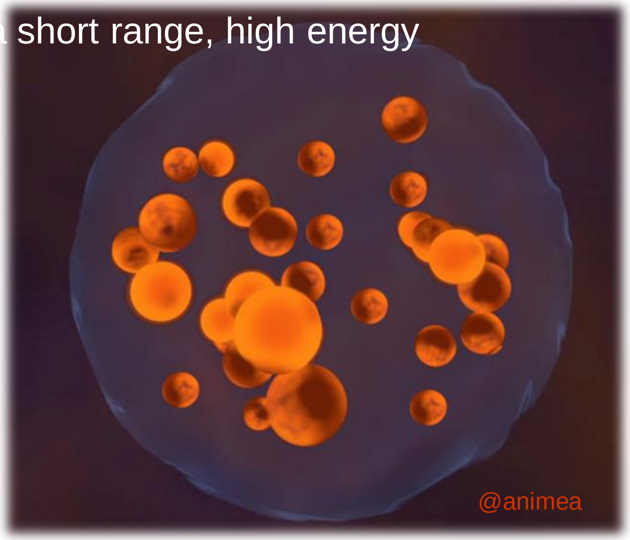
- **PDFs,** Parton Distribution Functions and **FFs,** Quark Fragmentation Functions,
  DIS *Deep Inelastic Scattering*, ***SIDIS***
- **GPDs,** Generalized Parton Distributions
  DVCS *Deep Virtual Compton Scattering*
- **TMDs,** Transverse Momentum Dependent distributions. ***SIDIS*** *or* ***Polarized Drell-Yan.***

Confinement, asymtotic freedom, factorization



Bound states: hadrons

A unique laboratory for the study of QCD



Degrees of freedom: quarks and gluons

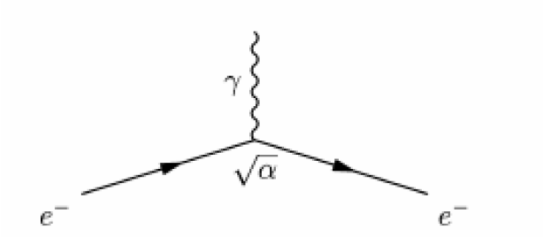
Perturbation theory

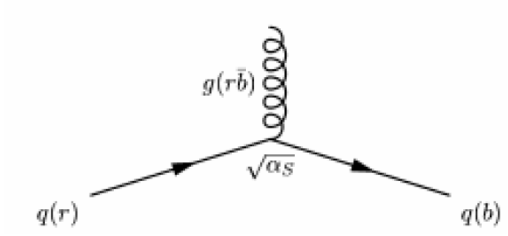
The observed states are not the degrees of freedom of the theory, but …

… factorization allows us to relate the observed states to the degrees of freedom in some ”hard” processes.

Analogies QED QCD

	QED	**QCD**
Quantum field theory of:	Electromagnetic interactions	**Strong interactions**
Mediated by exchange of:	photon	**gluon**
Which couples to:	charge e	**colour charge of quark**
Coupling strength:	$\propto e \quad \propto \sqrt{\alpha}$	$\propto \sqrt{\alpha_s}$





$\alpha = e^2/4\pi \approx 1/137$

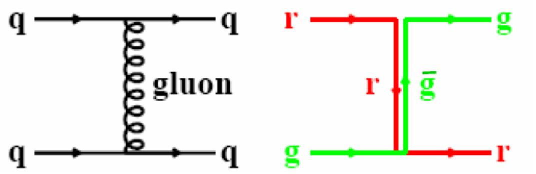
$\alpha_S = g_S{}^2/4\pi \sim 1$

QCD coupling constant >> QED

Higher probability of interaction

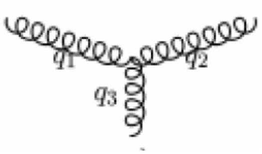
Gluons, quarks, Interactions

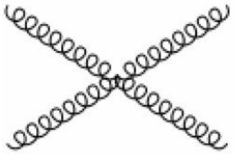
- Gluon are massless spin1 bosons (like γ)
- QCD propagator $1/q^2$
- Emission or absorption of gluons by quarks changes colour of quarks
- Colour is conserved



BUT, gluons carry colour charge themselves

→ Gluons interact with each other (3-gluon or 4-gluon vertex)





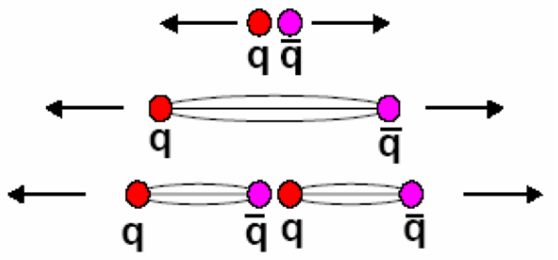
Makes a very big difference between QCD and QED

Fragmentation and hadronization

- Because of gluon self-interaction,
  - colur force lines between quarks are pulled together
  - particles with colour (quarks and gluons):
    - . are **confined** inside QCD potential
    - . combine into hadrons (zero net colour)

- No free quarks are observed, only hadrons.

- **Fragmentation:** When string between q-qbar breaks, further q-qbar pairs are formed.



- **Hadronization**

Pictures from F.Muheim

Study :

- Quark and gluon distributions in the gluon
- Nucleon spin structure
- Correlations between parton spin and parton momenum,
- Correlations between parton transverse position/ momentum
- Quark hadronization

Methods?

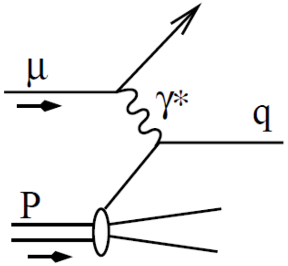
Methods -1. Quark and gluon spin distributions

A- Probe quarks or gluons in nucleon using e.g. lepton beam

Chose adequate process:

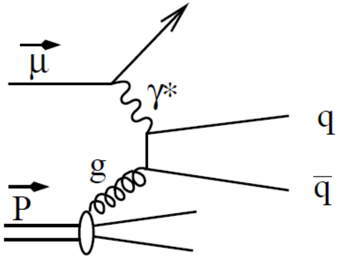
quarks

Deep inelastic scattering



gluons

Photon-gluon fusion: $\gamma g \rightarrow qq$



x : nucleon momentum fraction carried by quark
Q^2 : 4-momentum transfered (resolution ~ 1/Q)

B - Measure spin asymmetry of cross sections, using polarized beam and target

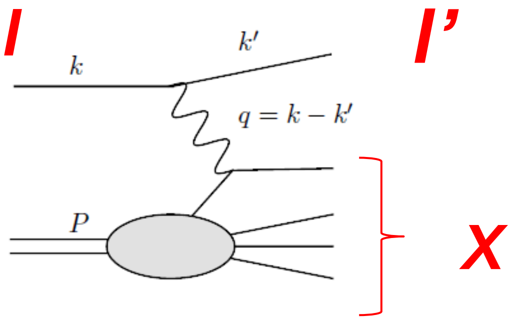
$\Delta q = \overset{\rightrightarrows}{q} - \overset{\rightleftarrows}{q}$ access quark polarization in the nucleon

$\Delta\Sigma$: sum over u, d, s quark flavours

ΔG

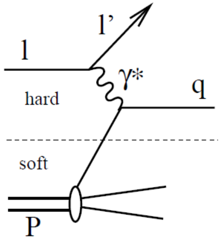
- **Access quark and gluon spin contribution to the nucleon**
- **Compare to lattice QCD**

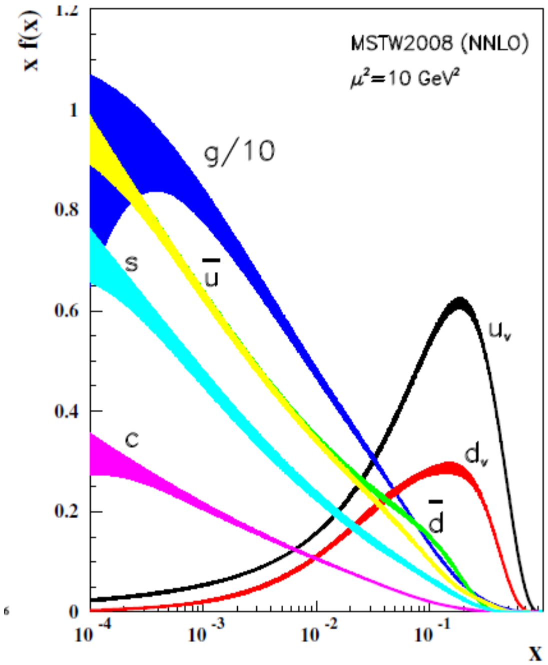
DIS Deep Inelastic Scattering



$l\,p \rightarrow l'\,X$

Factorization in hard and soft parts





x=fraction of momentum

Parton Distribution Functions vs x, from global QCD analysis of world data, from several processes

One goal of present experiments with polarized beam and target is to obtain similar distributions for spin dependent distributions.

Probing polarized quarks in the nucleon

Polarized photon probing a polarized quark inside a polarized nucleon

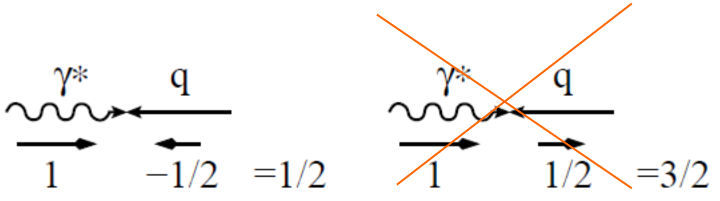


Figure 13: Spin projections in the Breit frame. The absorption of the photon by a quark is only possible on the left when the total projection is 1/2 but not on the right when the total projection is 3/2.

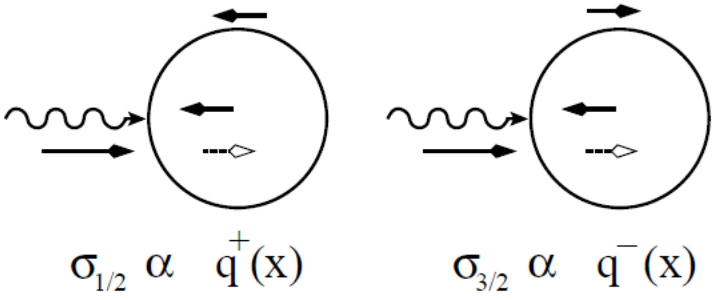


Figure 14: Absorption of the photon by a polarized nucleon.

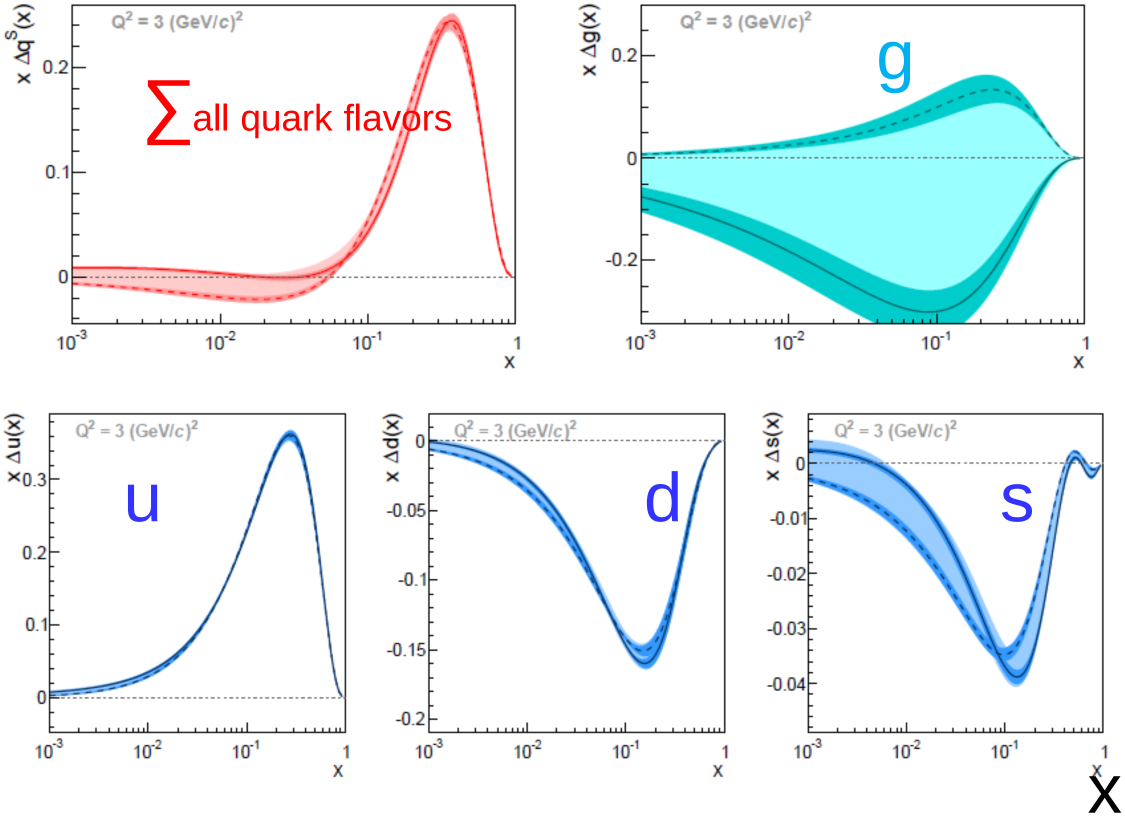
Measure $\Delta q = q^{+} - q^{-}$

for all quark flavors

Polarized DIS… results

Spin-dependent Parton Distribution Functions vs x, obtained from global QCD analysis of polarized DIS world data

World data are spin asymmetries in DIS, with polarized beam and target



u quarks polarized up dir.

d quarks: opposite

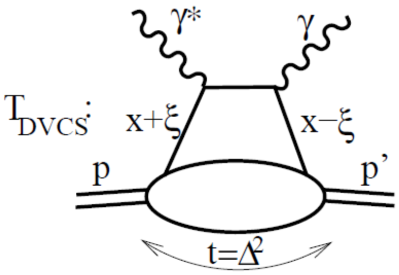
s quarks: very small polar.

ubar, dbar small also

Integrals in agreement with lattice QCD calculation which have progressed a lot in the recent years. A big step in spin physics.

Methods - 2. Generalized Parton Distributions

For the first time, study **correlation** between longitudinal quark **momentum** and quark transverse **position** in nucleon: ‘3D picture of the nucleon’



x, ξ : quark momentum fraction

t : transfer to proton

$H(x,\xi,t)$: Gen. Parton distribution

process :**Deep virtual Compton scattering (DVCS)**

$\mu\, p \rightarrow \mu\, p'\gamma$

Production of a real photon

‘Exclusive’ process :all products are detected

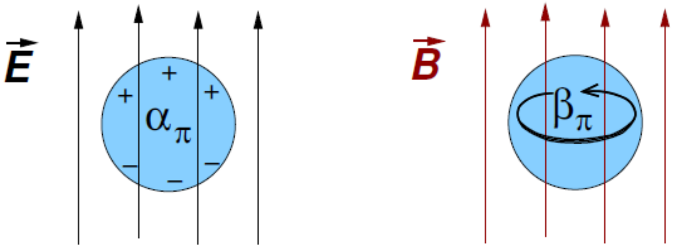
(a process which interferes with Bethe-Heitler)

Compare first moments to lattice QCD

- Theoretical concept: 1996
- First dedicated experiment 2004 JLab
- One of the major goals of future programmes:
  - e^- 12 GeV Jlab upgrade in US
  - μ 200 GeV, COMPASS at CERN,
  - future US electron-ion collider EIC …

Method 3- Pion polarisability- low energy QCD

Polarisabilities: measure deviation from pointlike particle
= deformation in an electric (α) and magnetic (β) field



Predictions for the values exist from Chiral Perturbation theory (Ch PT)

- **Pion** : the simplest and lightest bound state of QCD (quark - anti quark)

- Testing properties and interactions of the pion

→ Testing if ChPT is a correct representation of QCD at low energy

Previous experiments to measure α_π since 1980: not conclusive

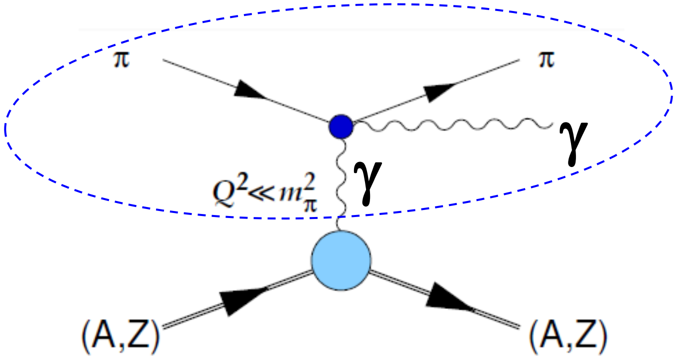
The measurement… embedded in a nucleus

- Compton cross-section $\gamma\pi \rightarrow \gamma\pi$ proportional to $\alpha_\pi - \beta_\pi$ (LO)

  Difficulty : no pion target

Measure $\pi\gamma \rightarrow \pi\gamma$

via $\pi Z \rightarrow \pi Z \gamma$

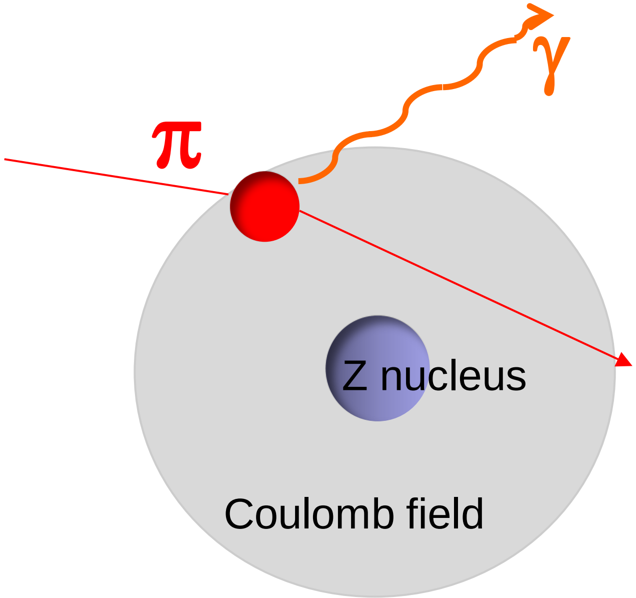


- The charged **pion**, diameter ~0.6 fm, crosses the **electric field** of a nucleus

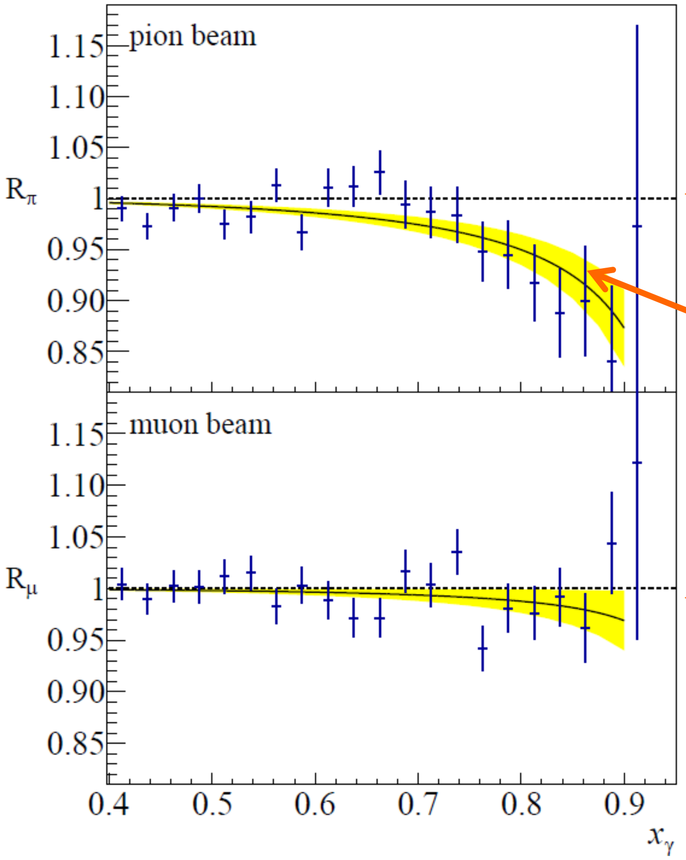
  Typical field at r=5 R_{Ni} : **E ~ 300 kV/fm**

- Bremsstrahlung emission:

- Polarisability effect: reduction of cross section



Pion polarizability - result



Ratio of measured cross section to cross section for pointlike particle
2009 data, ~ 2 weeks, 63000 pions

COMPASS: 190 GeV π beam, Nickel target

Expected value for point like particle (Monte-Carlo simulation)

pion measurement: reduction of cross section due to polarizability

α_π = (2 ± 0.6 ± 0.7) x 10^{-4} fm^3 (**$\alpha_\pi+\beta_\pi$ =0**)

muon control measurement

Phys. Rev. Lett. 114 (2015)

CERN press release, Feb.2015

→ Need precise Monte-Carlo simulation of setup

Methods – summary

Some methods (lepton beam, $l = e, \mu$...):

- Deep Inelastic scattering: parton distribution functions in the nucleon
  ‘inclusive’ $l\,p \rightarrow l\,X$
  $l\,p \rightarrow l\,X\,h$
- Deep Virtual Compton Scattering:’exclusive γ’ $l\,p \rightarrow l\,p\,\gamma$

… (or exclusive Meson) $l\,p \rightarrow l\,p\,\pi^0$

Other methods (hadron beam):

- Drell-Yan reaction also for parton distribution functions in the nucleon
  q qbar → l l’
- Pion properties (polarisability) via Compton scattering in a nucleus(next)
- Spectroscopy of mesons and baryons via (exotic) resonance formation
- *p-p* reactions … ***qq, gg, qg,…***

All accesssible in existing fixed target experiments like COMPASS at CERN, or some in experiments at Jlab or RHIC in US.

Methods – comments

Polarized beams and targets to study nucleon spin (e.g. Polarized DIS):
Measure **Spin Asymmetry** of cross sections, rather than cross-sections

Advantages:

- Do not need absolute normalisation
- Experimental effects cancel:
  like acceptance, efficiency variation in time

Difficulties:

- Need polarized beams
- Need polarized targets
- Need much much more statistics

Other methods to study hadron specctroscopy, etc…(hadron beam):

- Spectroscopy of light mesons: measure differential cross-sections
  Need high developped analysis for extraction of resonances
  (Partial Wave Pnalysis with physics model)

- Pion polarisability: absolute cross-section
  Need highly controlled apparatus, and excellent Monte-Carlo description

End of part I – Introduction/Methods

Part II : Polarized target and
Dynamic Nuclear Polarization

Part III : ‘Compass Unchained’

Polarized proton target

Goal: nucleon target with nucleon spins aligned

- Figure of merit of the setup
  - Importance of a high Pt value
  - Chosing a material (dilution factor)
- Dynamical Nuclear Polarization

The Figure of Merit in Asymmetry Experiments

- transverse target asymmetry in the case of spin-1/2 -

Measured counting rate asymmetry: $\varepsilon = \dfrac{N\uparrow - N\downarrow}{N_{tot}}$

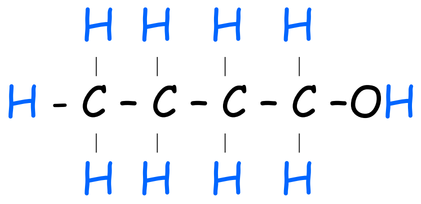
Physics asymmetry for a pure target: $A = \dfrac{1}{P_t} \cdot \varepsilon$

<u>Dilution factor:</u>

$$f = \frac{f_A \sigma}{(1 - f_A)\sigma_0 + f_A \sigma} \approx f_A$$

= fraction of polarizable nucleons

<u>H-Butanol:</u>



$$\begin{array}{c} \;\;\;\;\mathrm{H}\;\;\mathrm{H}\;\;\mathrm{H}\;\;\mathrm{H} \\ \;\;\;\;|\;\;\;\;|\;\;\;\;|\;\;\;\;| \\ \mathrm{H-C-C-C-C-OH} \\ \;\;\;\;|\;\;\;\;|\;\;\;\;|\;\;\;\;| \\ \;\;\;\;\mathrm{H}\;\;\mathrm{H}\;\;\mathrm{H}\;\;\mathrm{H} \end{array}$$

f=10/74~13.5%

Physics asymmetry for a dilute target: $A = \dfrac{1}{f} \dfrac{1}{P_t} \cdot \varepsilon$

<u>Absolute error of *A*:</u>

$$\frac{1}{\sqrt{N_{tot}}}$$

$$\Delta A = \sqrt{\left(\frac{1}{f}\frac{1}{P_t} \cdot \Delta\varepsilon\right)^2 + \underbrace{\left(A\frac{\Delta P_t}{P_t}\right)^2 + \left(A\frac{\Delta f}{f}\right)^2}_{\text{small}}} \approx \frac{1}{f}\frac{1}{P_t} \cdot \Delta\varepsilon = \frac{1}{f}\frac{1}{P_t}\boxed{\frac{1}{\sqrt{T \cdot L}}}$$

slide from S.Goertz

Measuring time for ΔA = const :

$$T = \frac{1}{f^2 \cdot P_t^2 \cdot L \cdot (\Delta A)^2} =: \frac{1}{FoM_t \cdot I \cdot (\Delta A)^2}$$

Target Figure of Merit:

$$\boxed{FoM_t = f^2 \cdot P_t^2 \cdot n_t} \qquad n_t = \text{target thickness } [1/cm^2]$$

Typical FoM's (continuous polarization at B = 2.5 T, COMPASS like dilution fridge)

increasing radiation hardness

Material	f_A[%]	P[%]	ρ[g/cm^3]	κ (pack.f.)	$f_A^2 \cdot P_t^2 \cdot \rho \cdot \kappa$
H-Butanol	13.5	90	0.985	0.62	1
$^{14}NH_3$	17.6	90	0.853	0.58	1.37
^{7}LiH	1/8+0.59/8	90 + 70 (?)	0.80	0.55	1.32
D-Butanol	23.8	45 / 90 (!)	1.12	0.62	1 / 4
$^{14}ND_3$	30	30 - 40	1.00	0.58	0.6 – 1.05
^{6}LiD	50	55	0.82	0.55	4.3

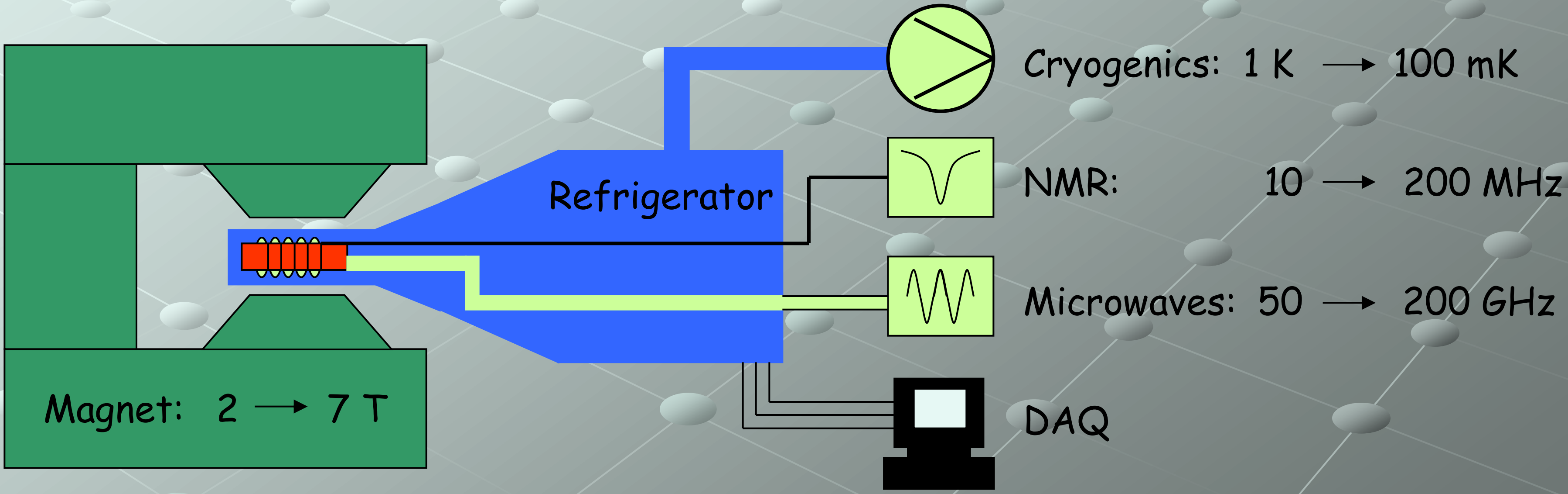
slide from S.Goertz

The basic concept of Dynamic Nuclear Polarization (DNP)

Doping and transfer of polarization

$$P \sim \frac{\mu B}{kT}$$

B / T	P_p[%]	P_d [%]	P_e [%]
2.5 T / 1 K	0.25	0.05	93
15 T / 10mK	91	30	100



Cryogenics: 1 K ⟶ 100 mK

NMR: 10 ⟶ 200 MHz

Microwaves: 50 ⟶ 200 GHz

DAQ

Magnet: 2 ⟶ 7 T

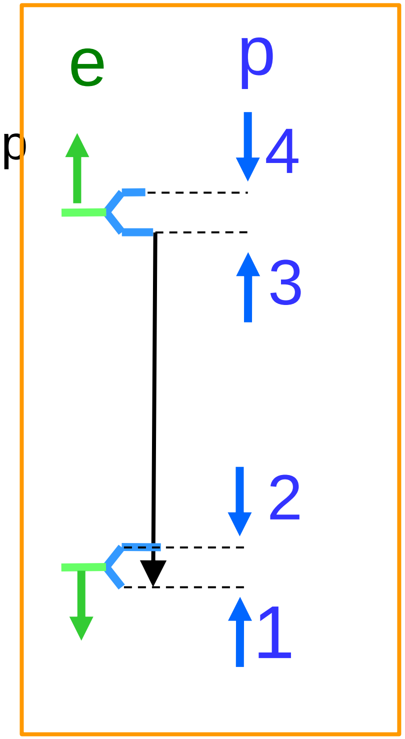
slide from S.Goertz

Dynamical Nuclear Polarization

- Brute polarization at TE is small for protons 0.2%
- **DNP idea:** transmit high e polarisation ~100 % to proton
- Use a target material where e and p can interact

Dynamical Nuclear Polarization

Two ½ spin system : e and p
The material must contain the two types, to be polarizable
Dipolar interaction permits high polarization transfers from e to p



High magnetic field B.
Zeemann effect: degeneration of energy levels

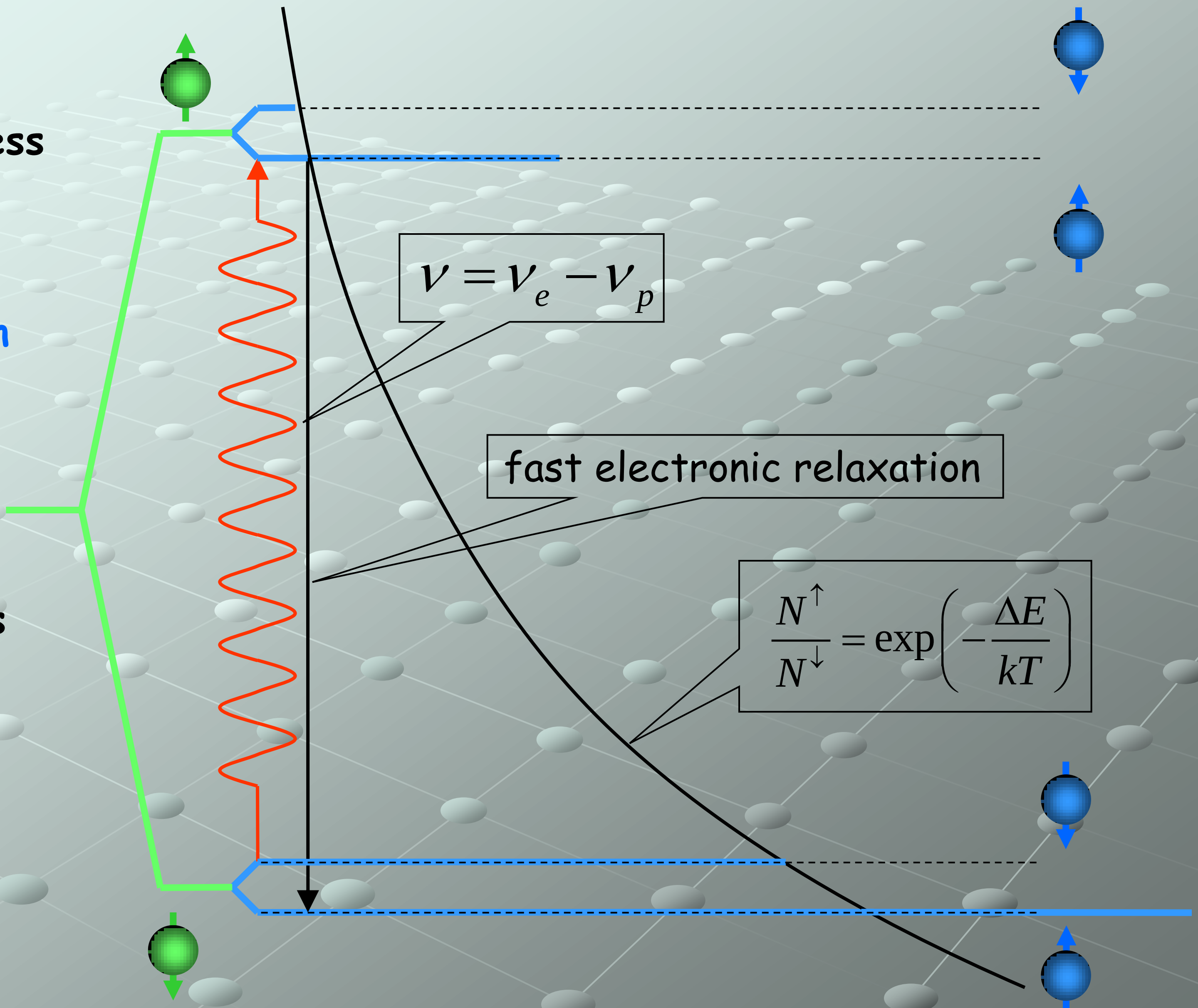
$\Delta E = hv_e$, with **v_e = 70 GHz** at B= 2.5 Tesla
$\delta E = hv_p$, on each electronic level, with **v_p = 106 MHz**
Ratio v_e / v_p ~ **1000**

Polarisation $p_e = N^+ - N^- / N^+ + N^-$
and similarly for the proton

At Boltzmann Thermodynamical Equilibrium (**TE**)
$N^+ / N^- = \exp(- E / kT)$

At TE, with B=2.5 T and T=1K: **$p_e \approx 90\ \%$ and $p_p = 0.2\ \%$**

The DNP process via the Solid State Effect (SSE)



The DNP process

uses the high

TE-polarization
of electrons

by

transferring it
to the nucleons

via

off-resonance
microwave
transitions

$$\nu = \nu_e - \nu_p$$

fast electronic relaxation

$$\frac{N^{\uparrow}}{N^{\downarrow}} = \exp\left(-\frac{\Delta E}{kT}\right)$$

slide from S.Goertz

Dynamical Nuclear Polarization, the steps

Apply magnetic field B.
The energy levels 1 to 4 are populated following **$N^+ / N^- = \exp(-E / kT)$**
→ Larger difference of population between 1-2 and 3-4
than between 1 and 2 (or 3 and 4)
Obtain **$p_e \approx 100\%$ and $p_p = 0.3\%$**

Inject microwave **$v_e - v_p$**
Force a level transition 2 to 3 (off equilibrium)

Relaxation
System relaxes towards equilibrium.
But **electron relaxion time (ms) << proton r.t. (seconds)**
e go to level 1, while p still on 3

Propagation via dipolar interaction between nuclear spins

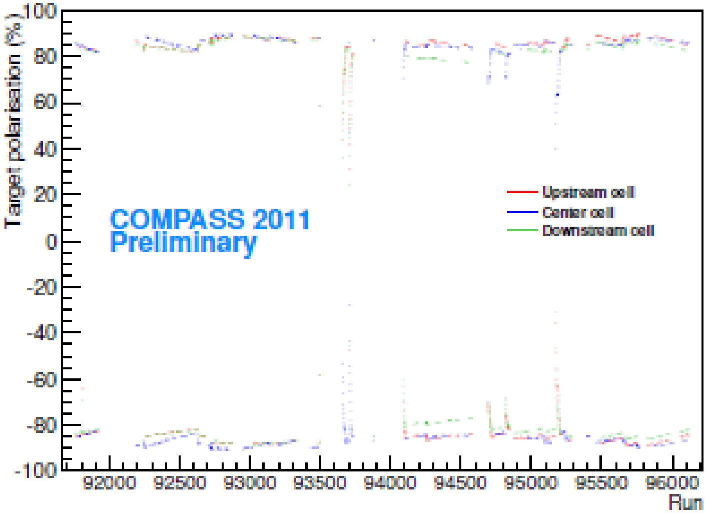
Repeat microwave untill p_p increases close to maximum

Target polarization measurement

At TE, the small brut polarization obtained can be calculated from: **$N^+ / N^- = \exp(-E / kT)$**
In addition a RMN signal is measured as reference (calibration)

With DNP process, the polarization is enhanced by microwaves + relaxation process and spin transfers.
The final polarization cannot be calculated.

→ Measure RMN signal and normalize to reference signal measured at TE



Example of measured values from 8 RMN probes along a 3-cell target, vs time (several months)

The direction of polarization is regularly changed by adiabatic rotation in a magnetic field

Polarized target, main features

Hardware

- High magnetic field B
- Low temperature (a few 10 mK)
- Microwaves

Choice of target material :

- Dilution factor (% of polarizable nucleons)
- doped/irradiated with free electron
- Relaxation time: important to keep p polarition high for a long time (days or weeks).

Polarized beam - Muons

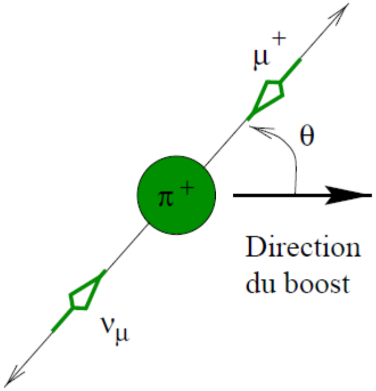
The muon beam is a tertiary beam:

400 GeV p on Be target → π 280 GeV

Followed by π decay to μ → 100- 200 GeV

$$\pi^+ \to \mu^+ \nu_\mu$$

$$J = 0$$



Weak interaction produces **left** neutrinos (negative helicity)

Outgoing μ has negative helicity (spin)

→ The μ beam is naturally polarized

θ depends on energy of μ and parent π, so does the final polarization

→ The μ beam polarization is calculated from a MC simulation of the setup

End of Part II

on polarized target/beam