PROBING THE QUARKS AND GLUONS IN THE PROTON

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MATTER IS MADE OF .....

Atoms. Inside atoms , there's the nucleus

Nucleus : made of protons and neutrons

Protons and neutrons are made of quarks and antiquarks, they interact with each other through the exchange of gluons

Quarks and antiquarks are spin 1/2 particles. There are six different types of quarks u,d,s,c,b,t

The interaction of quarks and gluons is called strong or color interaction (QCD) ; this interaction has rather unusual properties

As quarks are close to each other the interaction strength is very small interaction becomes stronger as they move apart

There are many things to be understood yet about it ! This is our goal

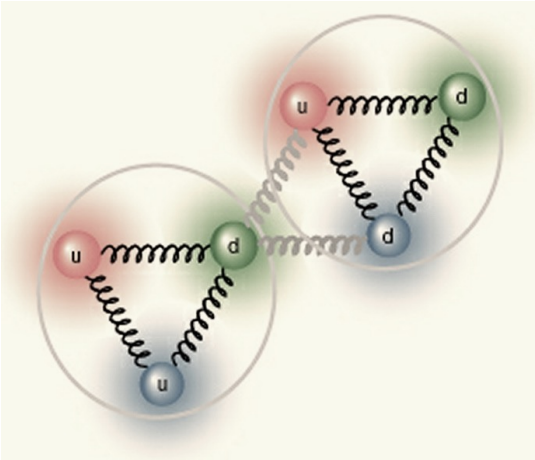
QCD : QUANTUM CHROMODYNAMICS

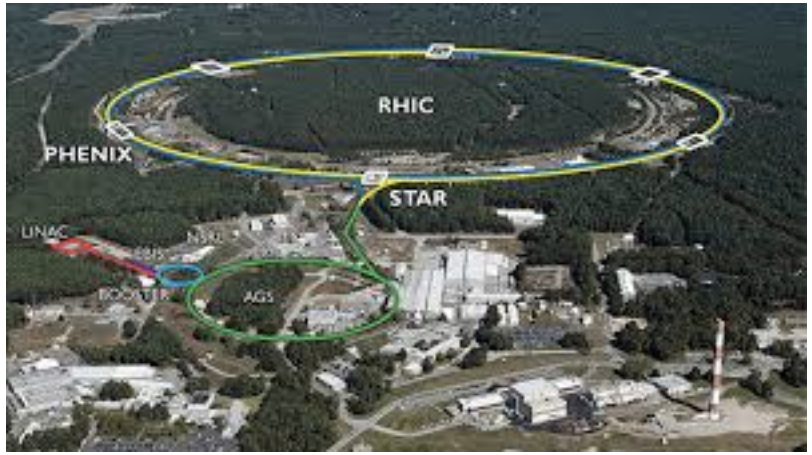
How strong is the 'strong' interaction ?? Particles decay within 10^{-23} seconds through strong interaction, whereas the lifetime of particles decaying through electromagnetic interaction is about 10^{-16} sec

In high energy colliders, for example at RHIC or LHC; highly energetic proton beams are collided with each other , proton breaks up and the final particles are detected to understand the structure of the protons and interaction of fundamental particles. There are fixed target experiments like in Jefferson lab as well

Energies of these colliders are of the order of a few hundreds or thousands of GeV

$1\ eV = 1.6 \times 10^{-19}\ J$





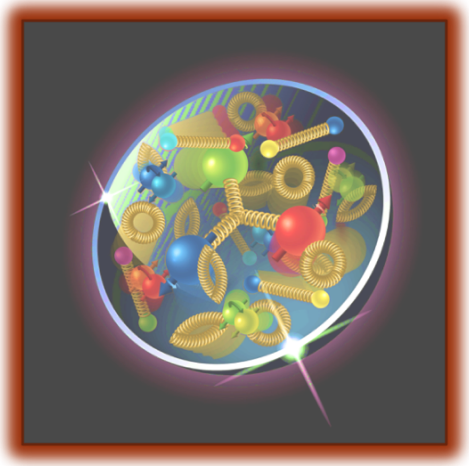
HIGH ENERGY PP SCATTERING PROCESS

High energy scattering of AB → CD is measured in terms of the cross section

Cross section $d\sigma = W_{fi}$ (number of final states)/Initial flux

W_{fi} : transition rate per unit volume from initial state to final state

Cross section may be thought of an effective area over which particle A and B interact to produce C and D



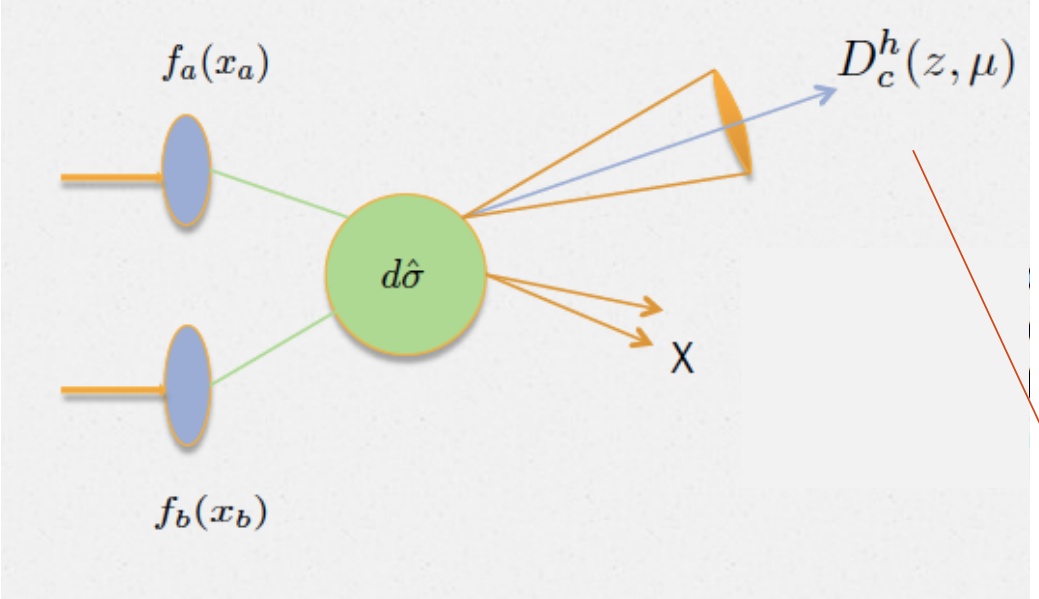
Proton : bound state of quarks, antiquarks and gluons

At high energy, proton does not interact as a single particle, rather interacts through the many quarks and gluons with which it is made of

Probability to find a particular quark/gluon inside the proton with a definite momentum fraction x is called parton distribution f_i (x)

FACTORIZATION

Collins, Soper, Sterman, 1983



At high energy, pp scattering cross section can be factored into several parts

The quark-gluon interaction part can be calculated using perturbation theory in an expansion of the coupling strength of QCD ; this is called the 'hard' part

After interaction the quarks and gluons again combine to form a bound state (hadron), through fragmentation function

Fragmentation function is similar to the distribution function in the sense that it gives the probability that a quark/gluon forms a hadron with momentum fraction z

Parton distribution and fragmentation functions are non-perturbative objects, to be obtained from experimental data, as QCD has not been solved non-perturbatively

DISTRIBUTION AND FRAGMENTATION FUNCTIONS

Other than the momentum fraction, pdfs and ffs depend on the momentum scale in which they are probed , this momentum scale is related to the energy of the experiment

As the momentum scale is changed, the pdfs and ff also change (evolve)

This evolution can be calculated perturbatively. But at a low scale, pdfs and ffs have to be fitted by the data

Key point of factorization theorem : pdfs and ffs are process independent (universal). Only the hard perturbative part depends on the specific scattering process

This gives the theoretical predictive power; once the pdfs and ffs are obtained from one process, they can be used to predict the cross section for another process. We have to calculate only the hard part perturbatively

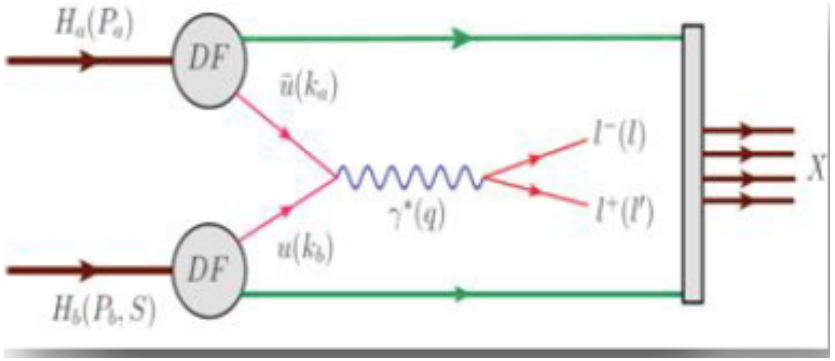
Factorization has been found to hold for a large number of high energy scattering processes

TMDS (TRANSVERSE MOMENTUM DISTRIBUTIONS)

Ordinary pdfs do not probe the intrinsic transverse momentum of the quarks and gluons, they depend on the longitudinal momentum fraction x

However by measuring certain observables in high energy scattering experiments, one can gain insight into the transverse momentum distributions of quarks and gluons; these are called TMD pdfs and TMD FFs

Fig : A Kotzinian



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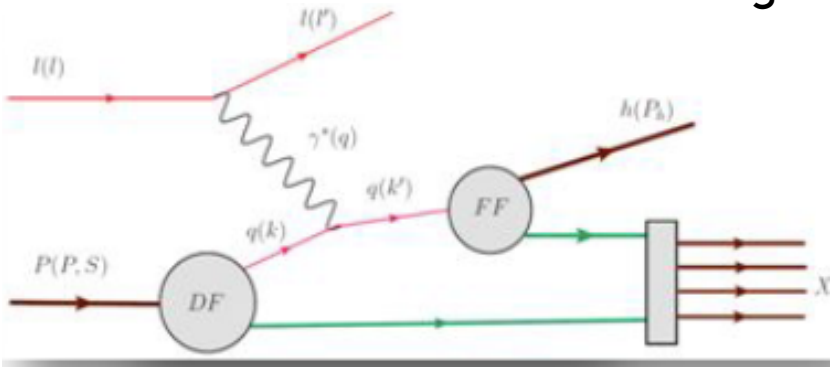
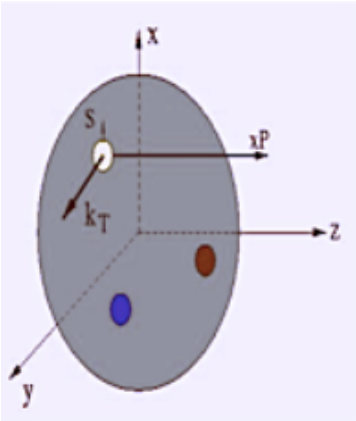


SIDIS

For example angular distribution of the lepton pair produced in Drell-Yan process or the azimuthal angle dependence of the hadron produced in semi-inclusive deep inelastic scattering

TMDS

TMD pdfs : probability to find a quark/gluon (parton) in the proton with longitudinal momentum fraction x and transverse momentum k_T

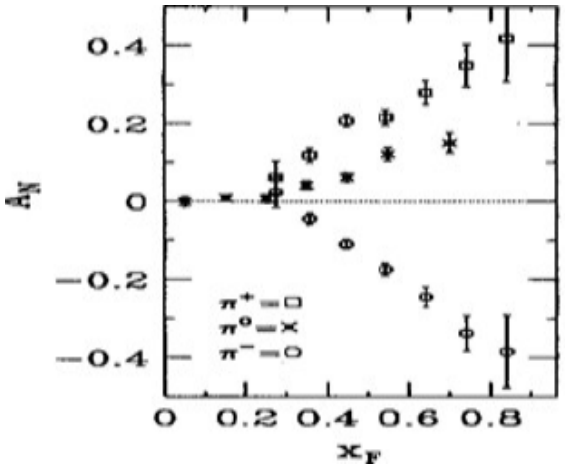


Similarly TMD fragmentation functions

Thus TMDs give a 3 D picture of the nucleon in momentum space

In addition to the transverse momentum, TMDs carry information on interesting spin correlations of the quarks/gluons as well as spin and transverse momentum correlations

When one of the proton beams is transversely polarized, experiments have measured an asymmetry called single spin asymmetry, such asymmetry can be explained in terms of TMDs



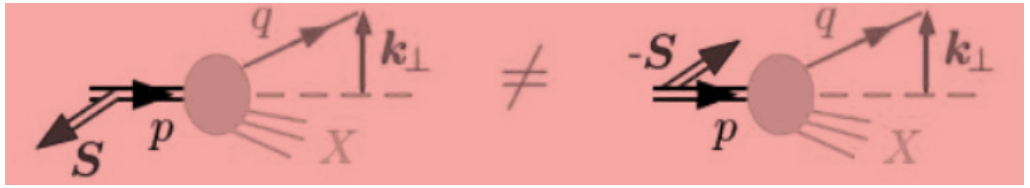
$$p^{\uparrow} + p \rightarrow \pi + X, A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$\sqrt{s} = 20\ GeV$$

E704 Collaboration, FermiLab, 1991

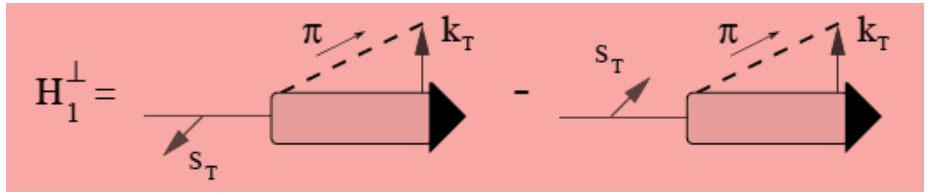
TMDS : WHY INTERESTING ?

Different TMDs give different information about the quarks and gluons inside the proton !



Distribution of quarks and gluons in a transversely polarized proton is not left-right symmetric with respect to the plane formed by its transverse momentum and spin directions : this asymmetry is described by a TMD called Sivers function

This results in an asymmetry in the azimuthal angle distribution of the hadron produced in SIDIS or in the lepton pair in DY : related to the orbital angular momentum of the quarks and gluons



Collins fragmentation function describes the fragmentation of a transversely polarized quark into an unpolarized hadron in the final state : results in a modulation of the azimuthal angle distribution of the produced hadron : this is called Collins effect

Both these effects are experimentally observed

THEORETICAL CHALLENGES

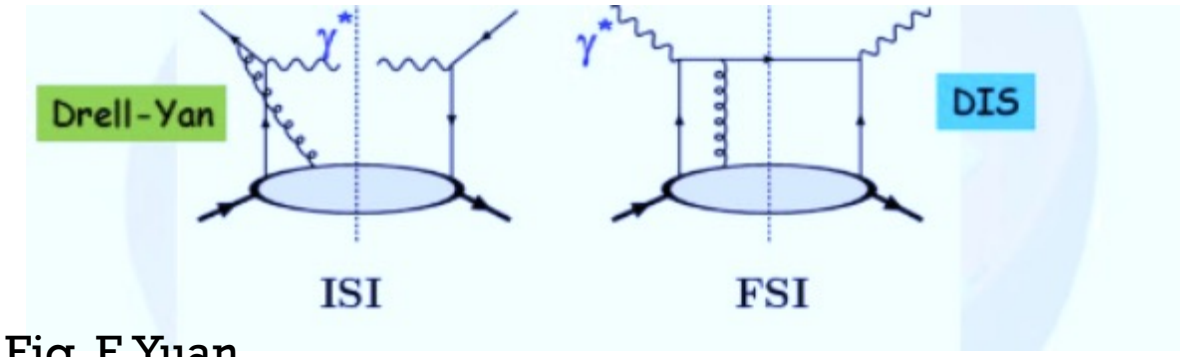


Fig. F. Yuan

Factorization allows to separate the cross section into a soft (nonperturbative) part and hard (perturbative) part

There can be soft gluon exchanges between the soft and hard part

These exchanges may violate factorization. It has been shown that for SIDIS and DY, such gluon exchanges to all perturbative order can be theoretically taken into account (resummed) into a calculable factor in the TMDs

In fact, these give leading contributions to observables that are sensitive to time-reversal odd TMDs like Sivers and Collins function.

These resummed contributions give the so-called gauge link or Wilson line. This is needed for the color gauge invariance of QCD, which is a fundamental symmetry of the theory

THEORETICAL CHALLENGES (CONTD.)

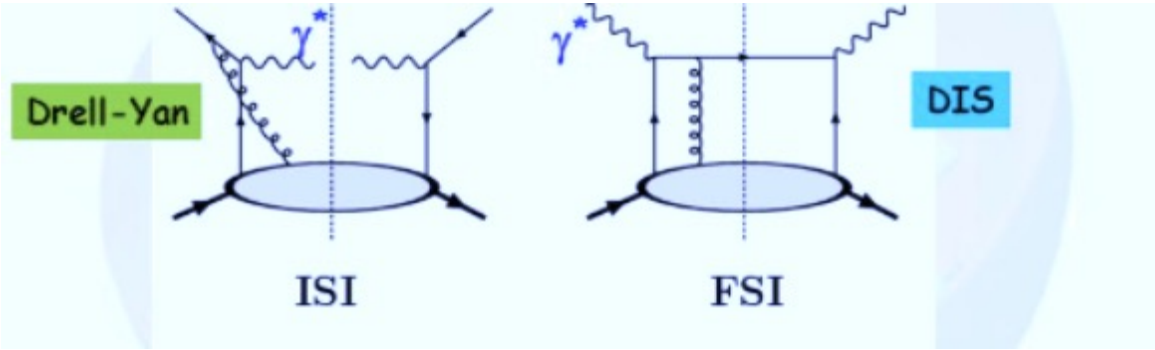


Fig. F. Yuan

Soft gluon exchanges depend of the process

For SIDIS, it is the final state interaction whereas for DY , it is initial state interaction

Gauge link depends on the process

For SIDIS, gauge link is future pointing [+], for DY it is past pointing [-]

More complex processes have more complicated gauge links

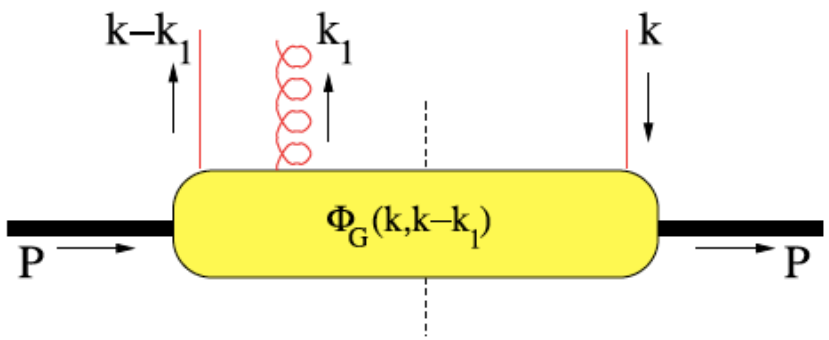
TMDs are process dependent (not universal) unlike ordinary pdfs : affects the basic spirit of factorization

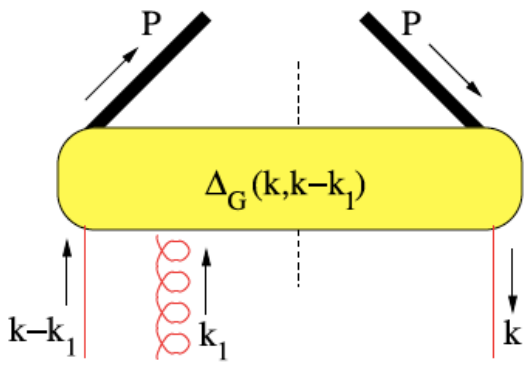
Different experiments probe different Collins function ??

NON-UNIVERSALITY OF TMDS

Gamberg, Mukherjee, Mulders, Phys. Rev. D 77, 114026 (2008)

Idea developed in Workshop on High Energy Physics Phenomenology (WHEPP), IMSC, Chennai, January 2008



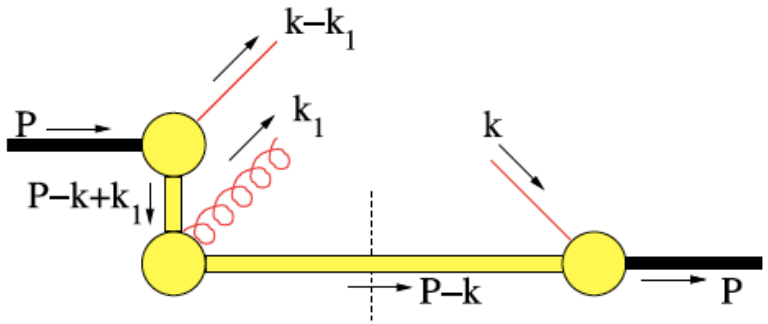


Studied TMDs in terms of quark-quark gluon correlators in the limit of soft gluon, $k_1 \to 0$

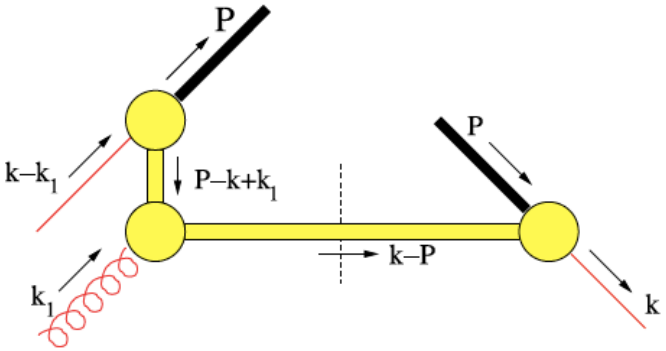
(these are called gluonic poles)

Correlators are matrix elements of non-local operators of quark gluon fields between hadron states

NON-UNIVERSALITY OF TMDS



Distribution fn.



Fragmentation fn.

Modeled the proton in a simple way : an active quark and a 'spectator', may be a diquark

Calculated the effects of the TMD distribution and fragmentation functions to observables in this model

These can be separated into two parts : process independent part and process dependent part coming from gauge link

$$\Phi_\partial = \tilde{\Phi}_\partial + \pi\Phi_G(k_1 = 0),$$

$$\Delta_\partial = \tilde{\Delta}_\partial + \pi\Delta_G(k_1 = 0),$$

UNIVERSALITY OF FRAGMENTATION FUNCTION

Distribution

$$\Phi_\partial = \tilde{\Phi}_\partial + \pi\Phi_G(k_1 = 0),$$

Process independent

Process dependent gluonic pole

Fragmentation

$$\Delta_\partial = \tilde{\Delta}_\partial + \pi\Delta_G(k_1 = 0),$$

Process independent

Process dependent gluonic pole

Operator structure of $\tilde{\Phi}_\partial$ and $\tilde{\Delta}_\partial$ are T-even. These are not contributions from gauge link

Operator structure of the other two parts are T odd, and these are process dependent

We showed that $\Delta_G(k_1 = 0)$, gluonic pole contribution to the fragmentation fn vanishes. But a T –odd part comes in Δ_∂ from the final state, this kind of T –odd part is absent in $\tilde{\Phi}_\partial$

CONCLUSION

T-odd part of the distribution function comes only from the gauge link part which is process dependent. So T odd TMDs like the Sivers function will be process dependent

However, the gauge link gluonic pole contribution of the fragmentation function vanishes. So The T-odd fragmentation function like Collins function will be process independent or universal

Obtained the same conclusion in a model independent way in

Gamberg, Mukherjee, Mulders, Phys. Rev. D 83 (2011), 071503

Major step to theoretically understand the experimental results of single spin asymmetries.