Guidance from QGP to Hadron Physics

RIKEN/RBRC
Itaru Nakagawa

〇月〇日(金)

Question 1: Solve following equation for $y = 0$

$$y = x^2 - 5x + 6$$

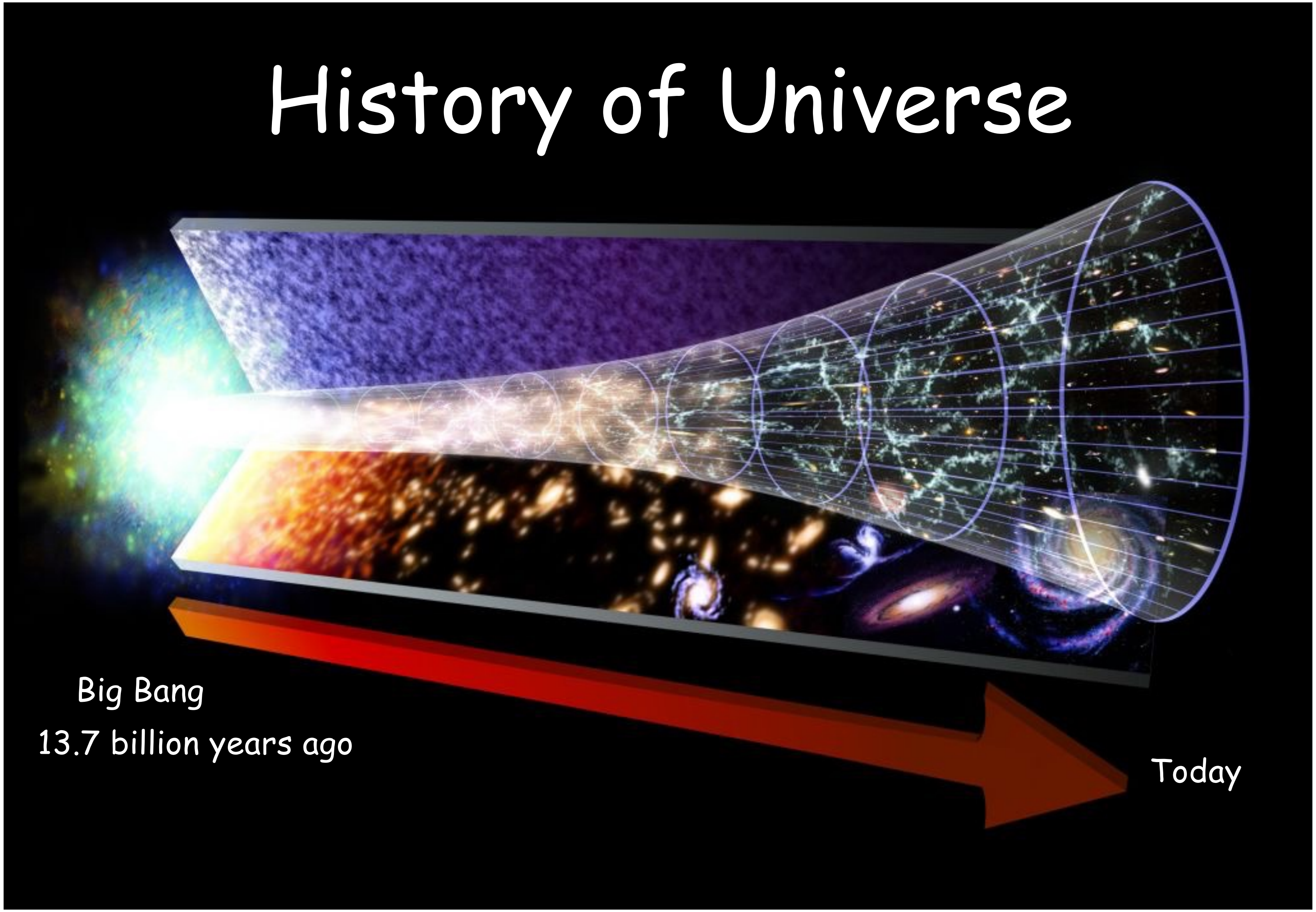
Factorization (因数分解)

〇月〇日(金)

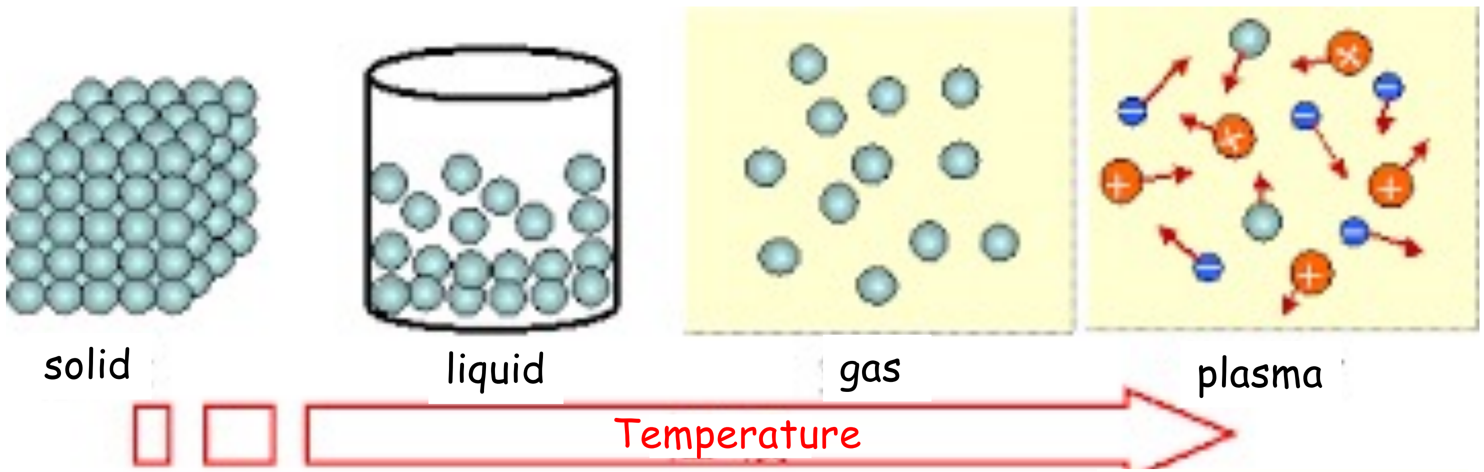
Question 1: Solve following equation for $y = 0$

$$y = x^2 - 5x + 6$$
$$= (x-2)(x-3)$$

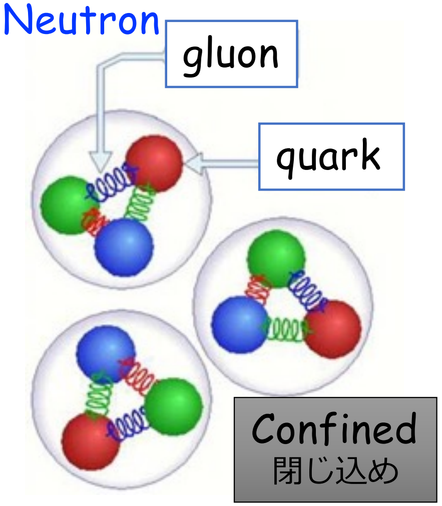
$$x = 2, 3$$


History of Universe
Big Bang
13.7 billion years ago
Today

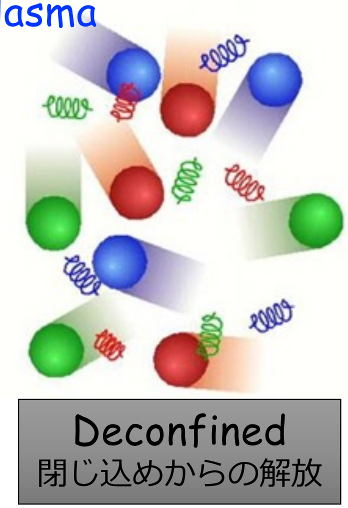
State of Matters



Proton, Neutron



Quark-Gluon Plasma



http://kakudan.rcnp.osaka-u.ac.jp/jp/overview/world/QGP.html

Confined Status

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Quark-Gluon Plasma

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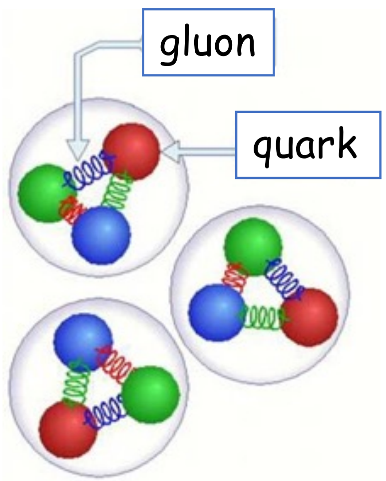
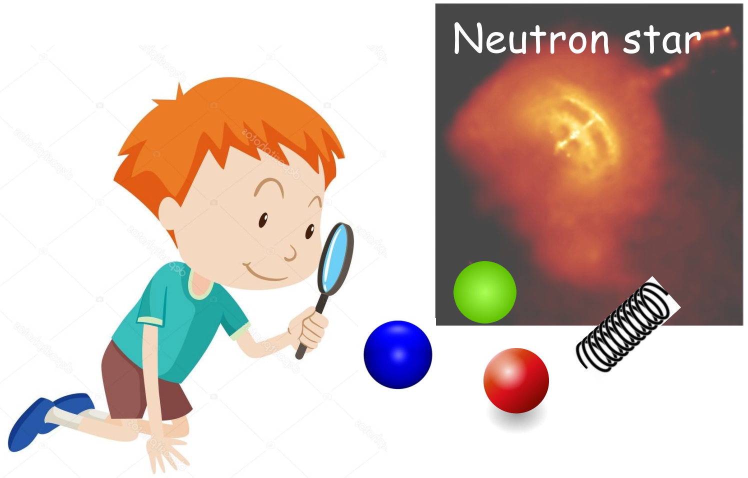
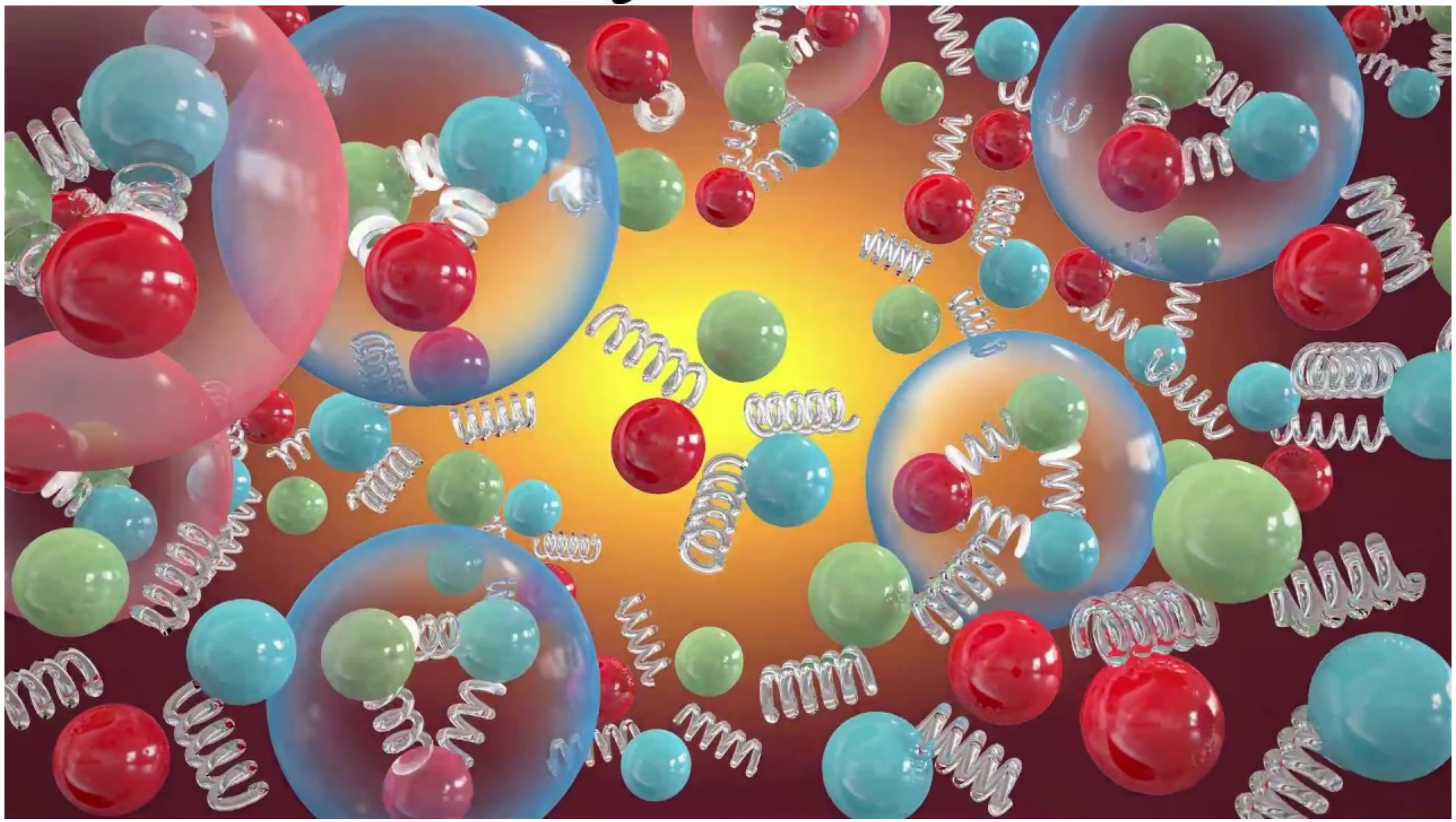
Default in Nature

Not Trivial Observable

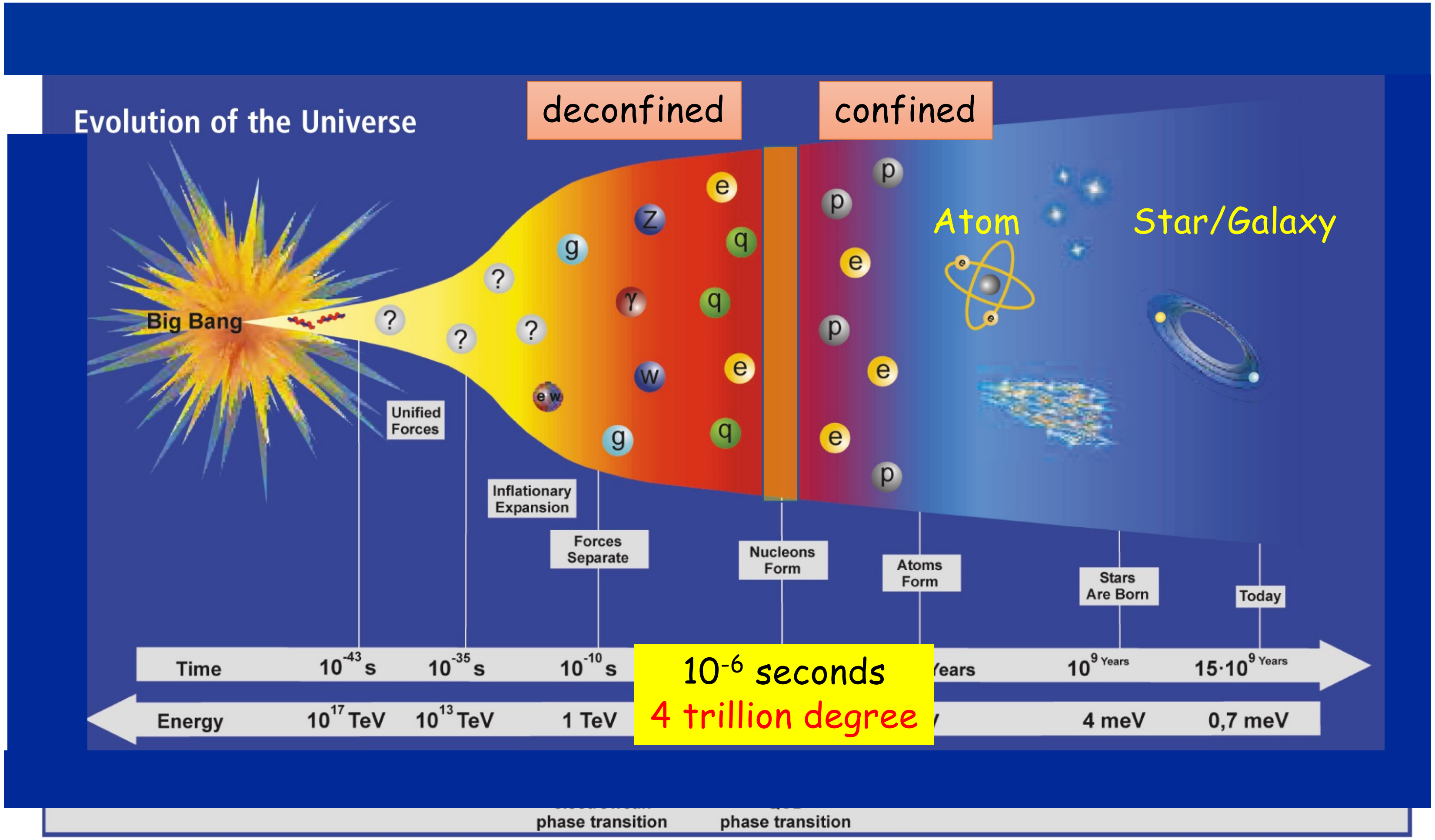






Quark-Gluon Plasma is mysterious object !!

History of the Universe



QGP

hadron

Heavy Ion physicist

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Hadron physicist

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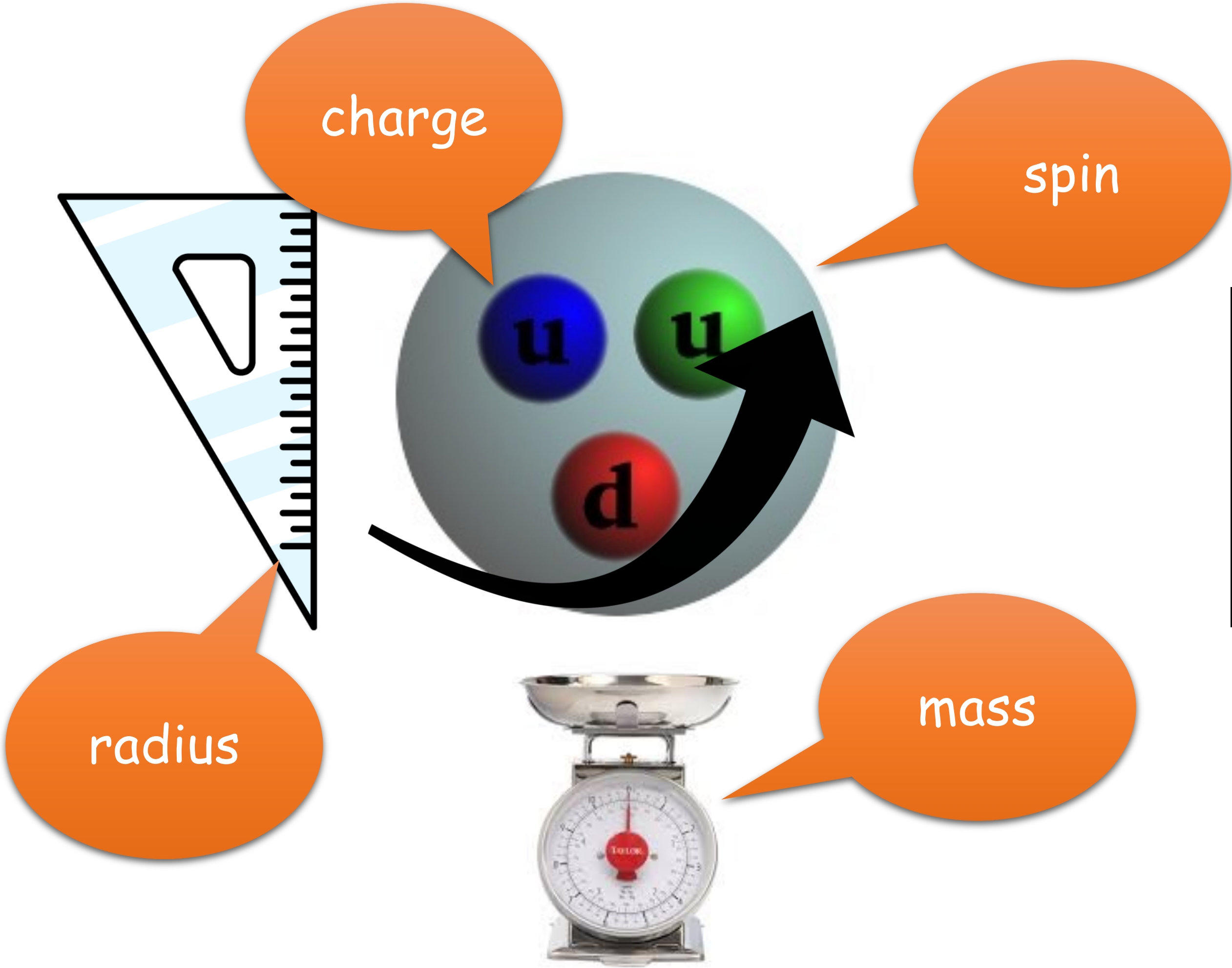
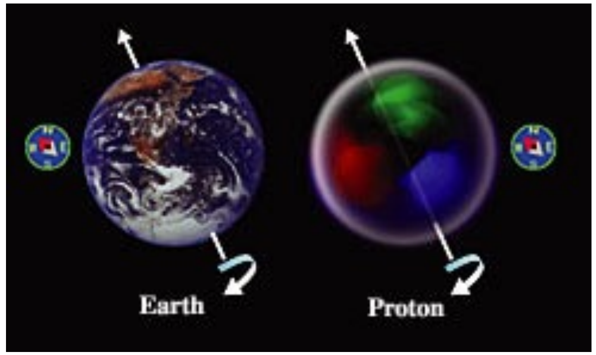
Introduction to Hadron Physics

Static Properties of Proton





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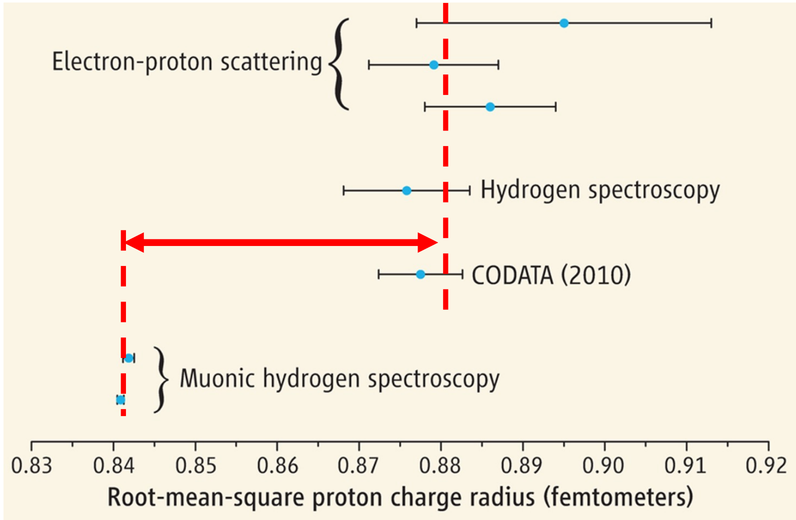
Breaking News of Proton Radius



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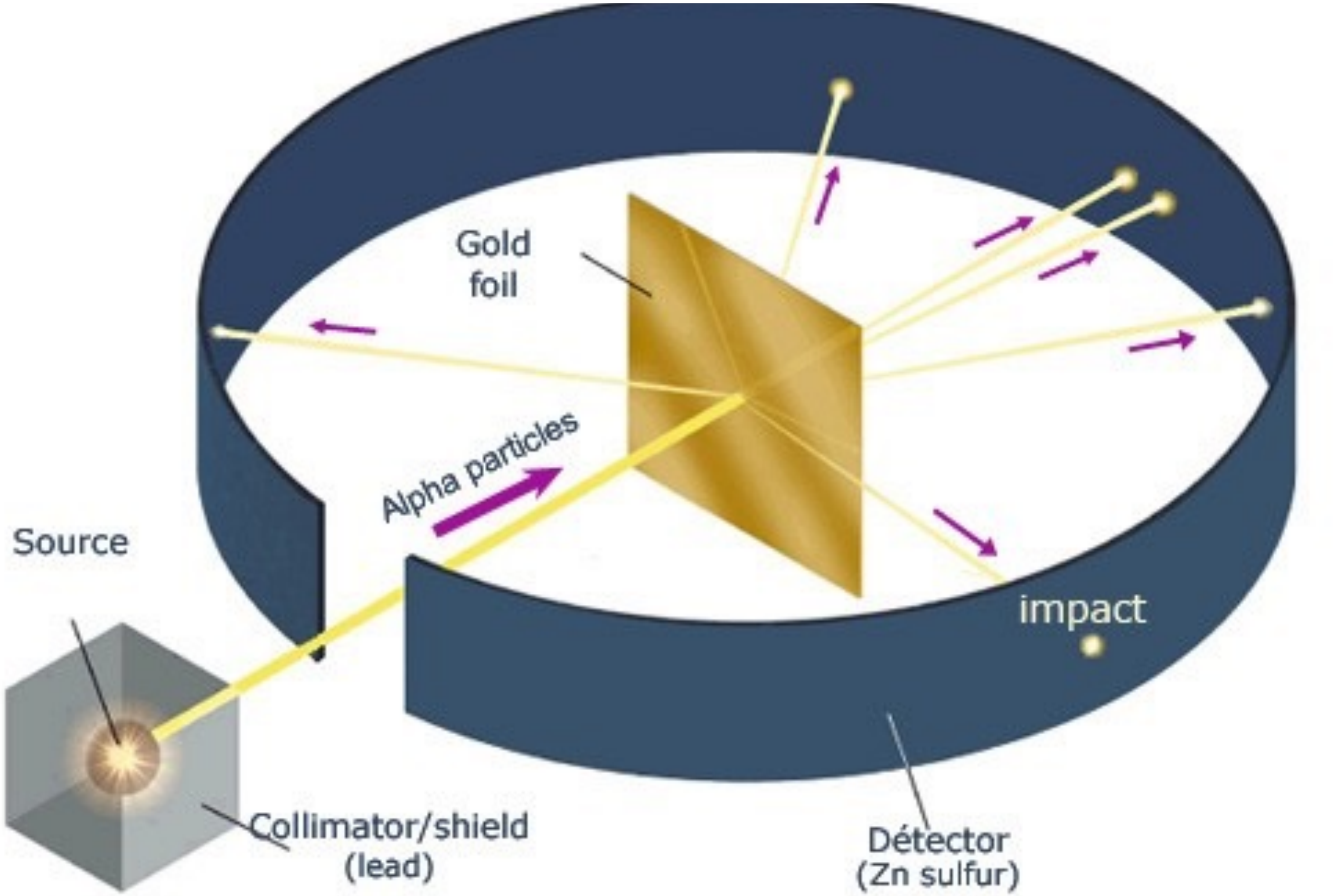
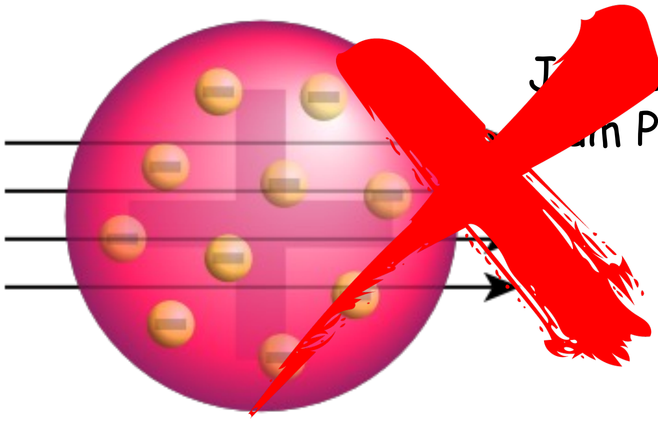
How do we measure proton radius?



Ratherford's Experiment

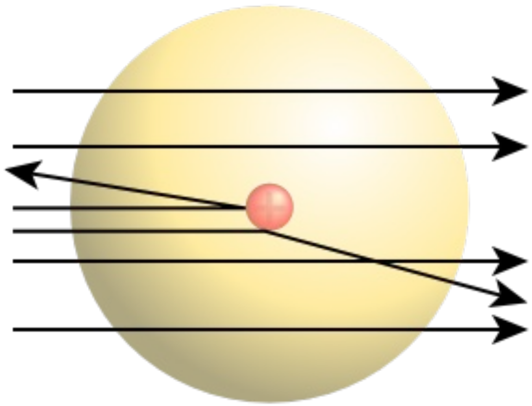
Description of Atom

ratherford scattering experiment



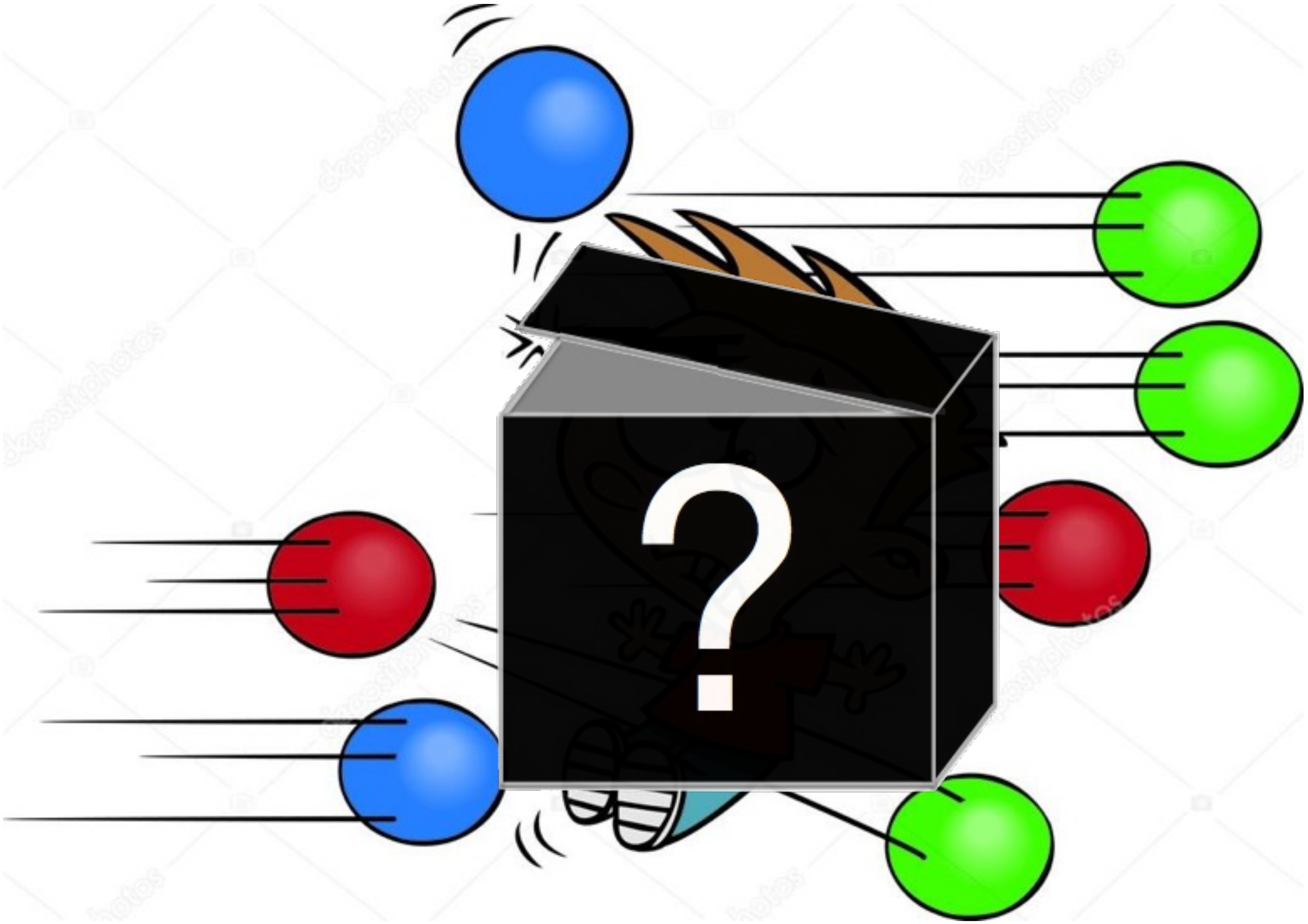
J omson
m Pudding Model

a-Ray



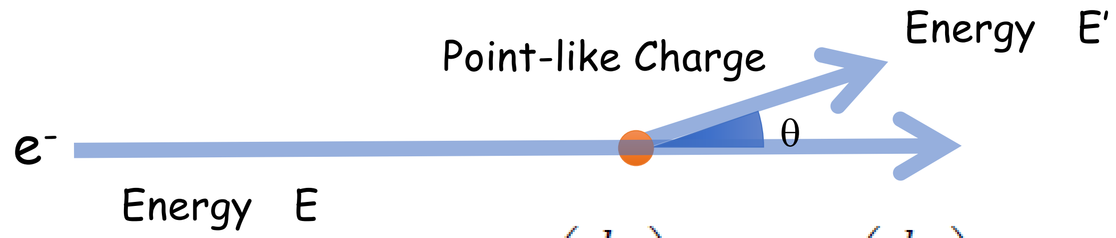
Cross Section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} = \frac{Z^2\alpha^2}{4E^2\sin^4\theta/2}$$

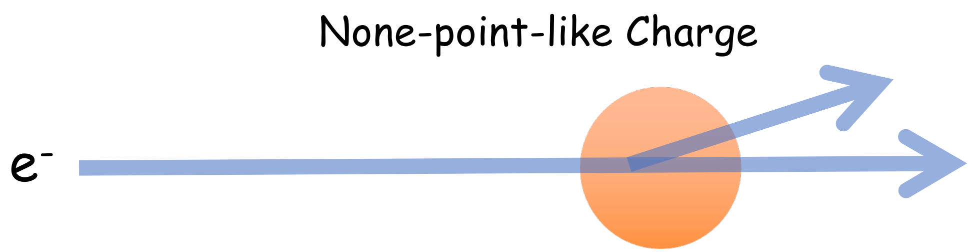


We can possibly know the feature of target object by observing scattering pattern

Electron Scattering

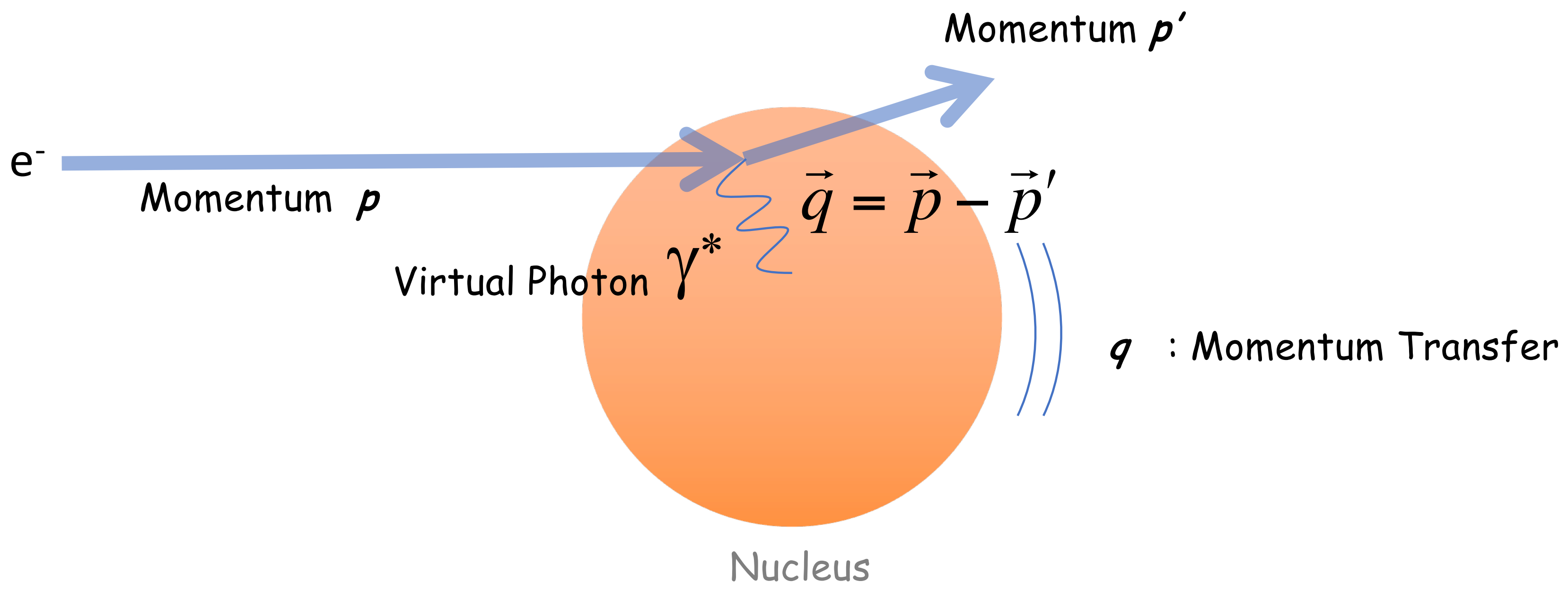


$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} \cdot \cos^2\frac{\theta}{2} \cdot \frac{E'}{E}$$

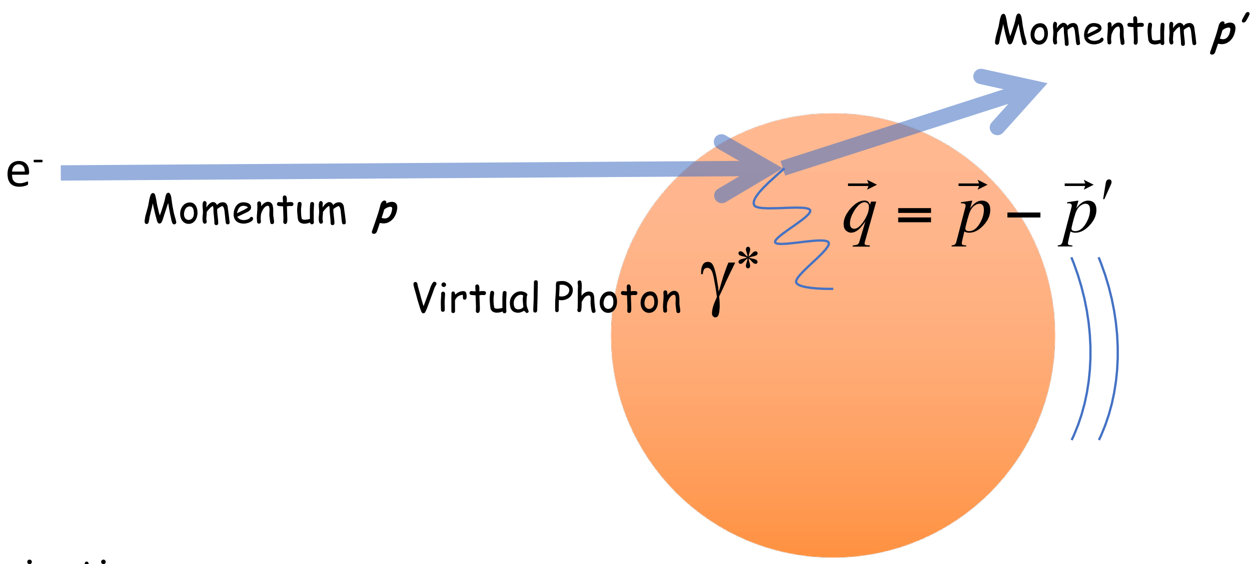


$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} \neq \left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

Elastic Scattering



Form Factor of Nucleus



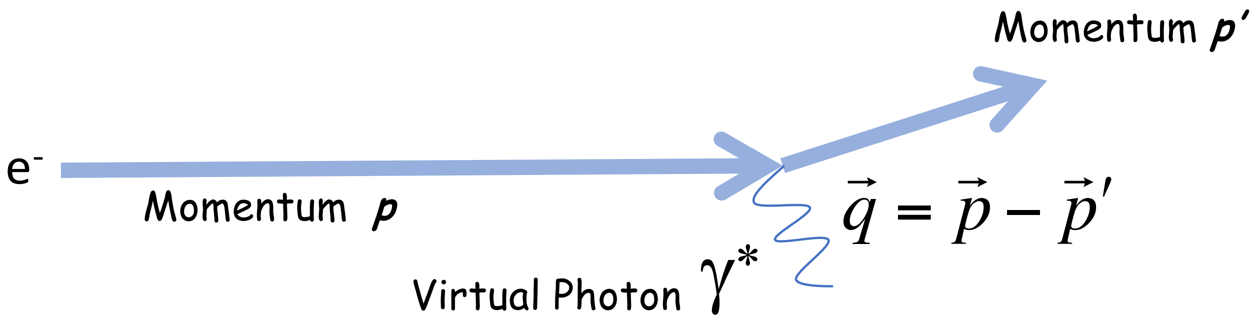
Factorization

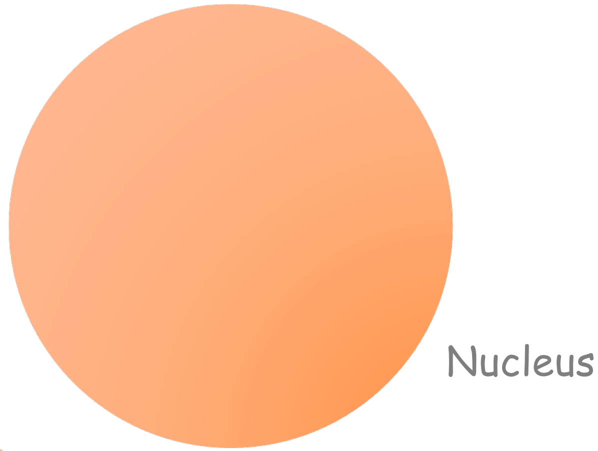
$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \bullet \left|F(q^2)\right|^2$$

Electric Form Factor

q : Momentum Transfer

Form Factor of Nucleus





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Factorization

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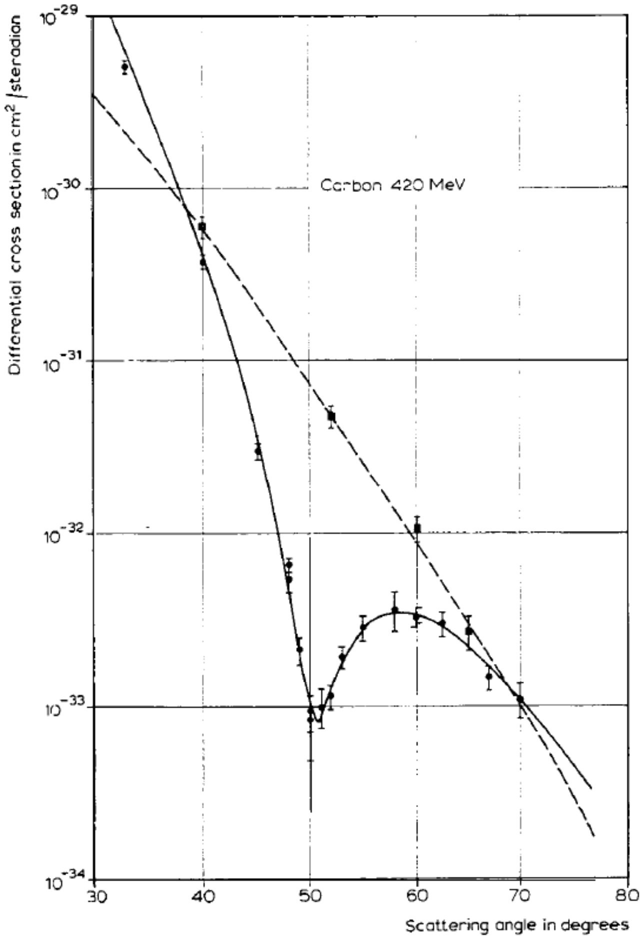
Electric Form Factor

Coulomb Distribution of Nucleus

Differential Cross Section

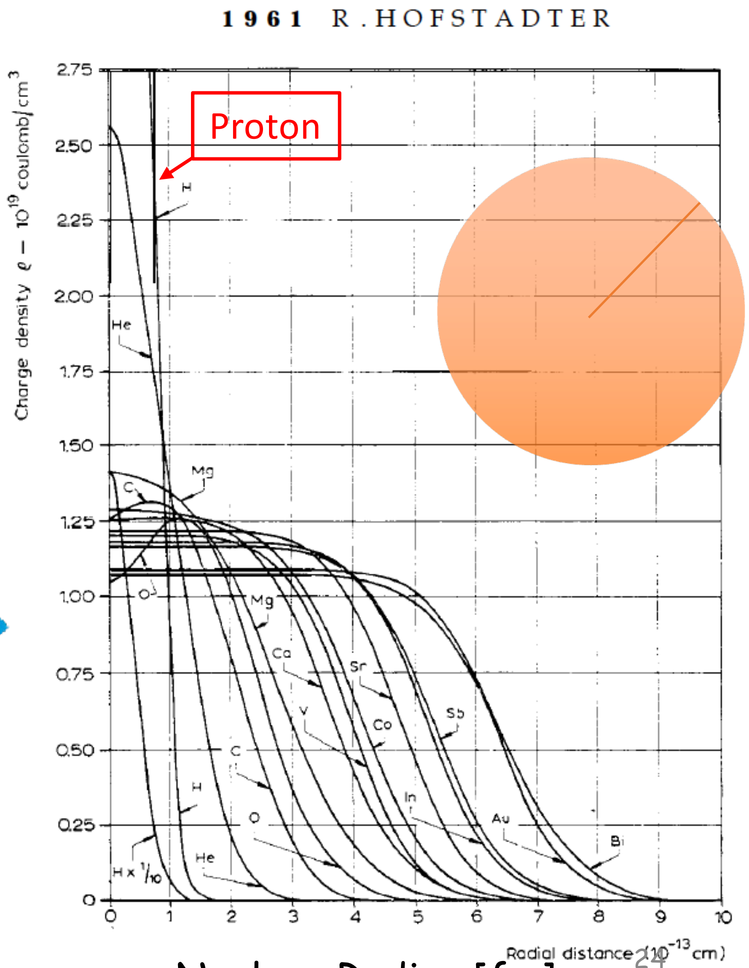


Scattering Angle ∝ Momentum transfer

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \bullet \left|F(q^2)\right|^2$$

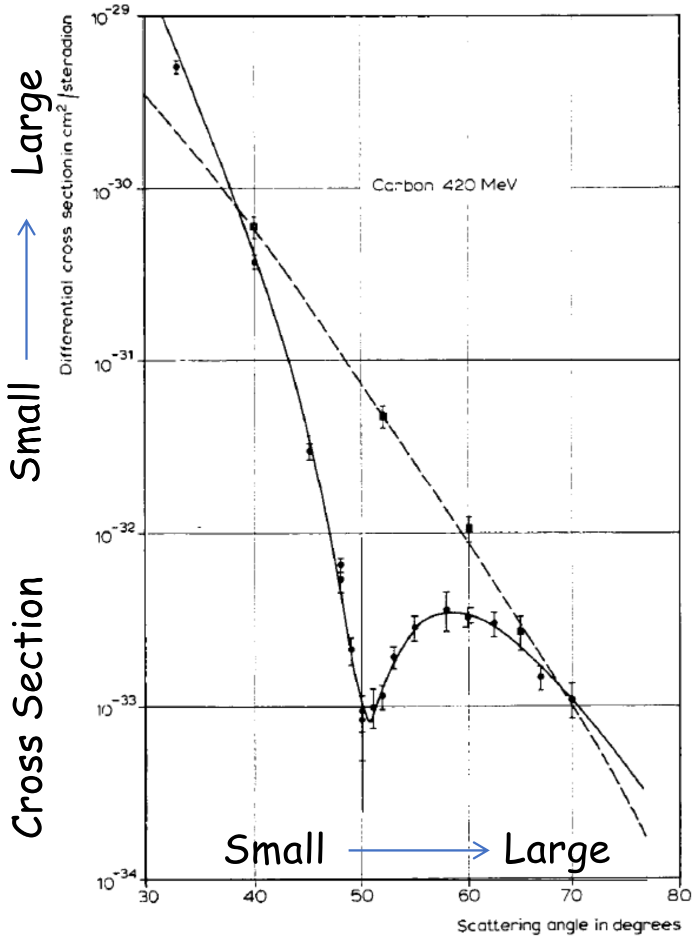
$$F(q^2) = \int_{-\infty}^{+\infty} \rho(\vec{r}) e^{i\vec{q}\vec{r}} dr^3$$

Fourier Transform



Nuclear Radius [fm]

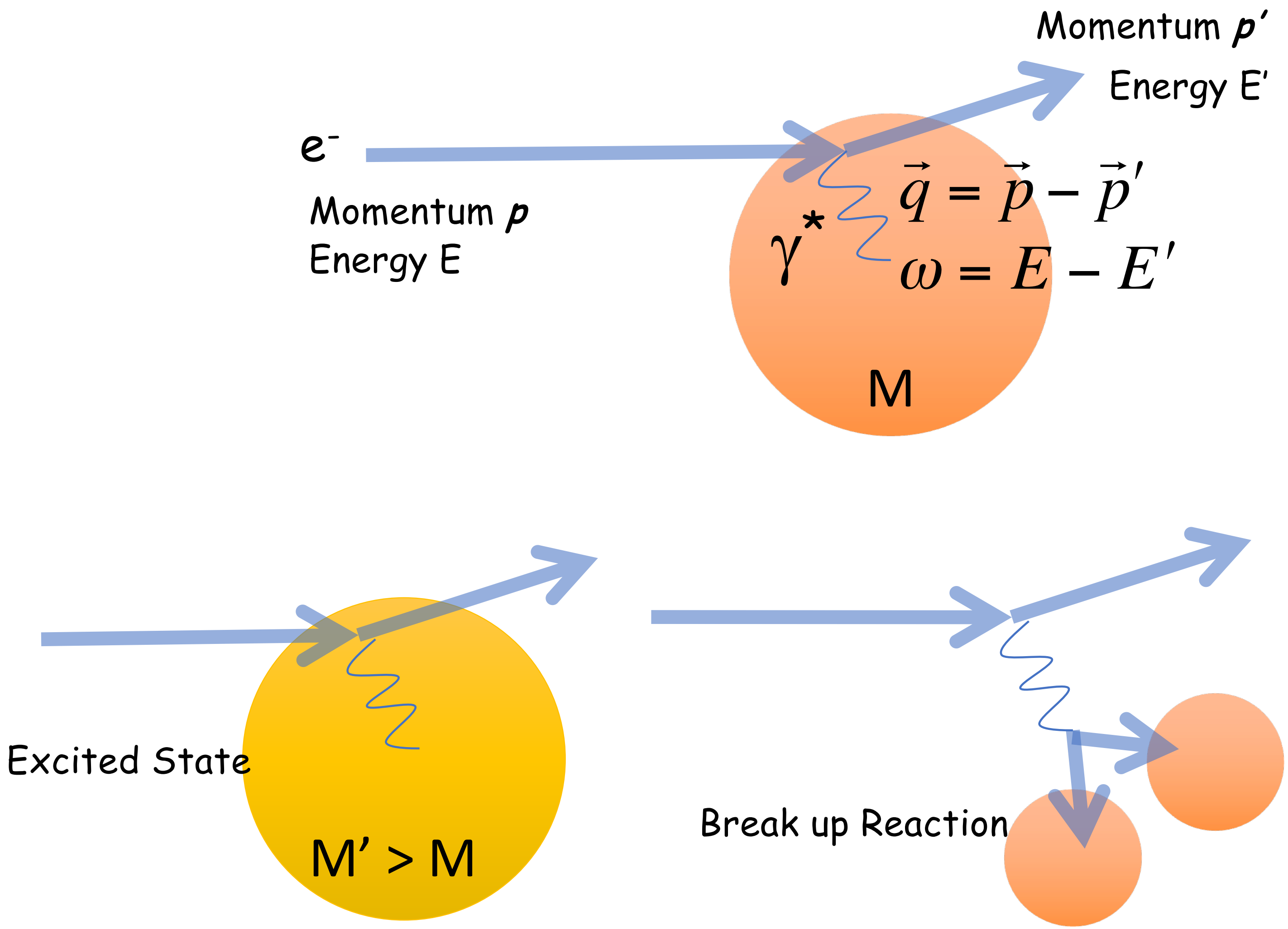
High Momentum Transfer



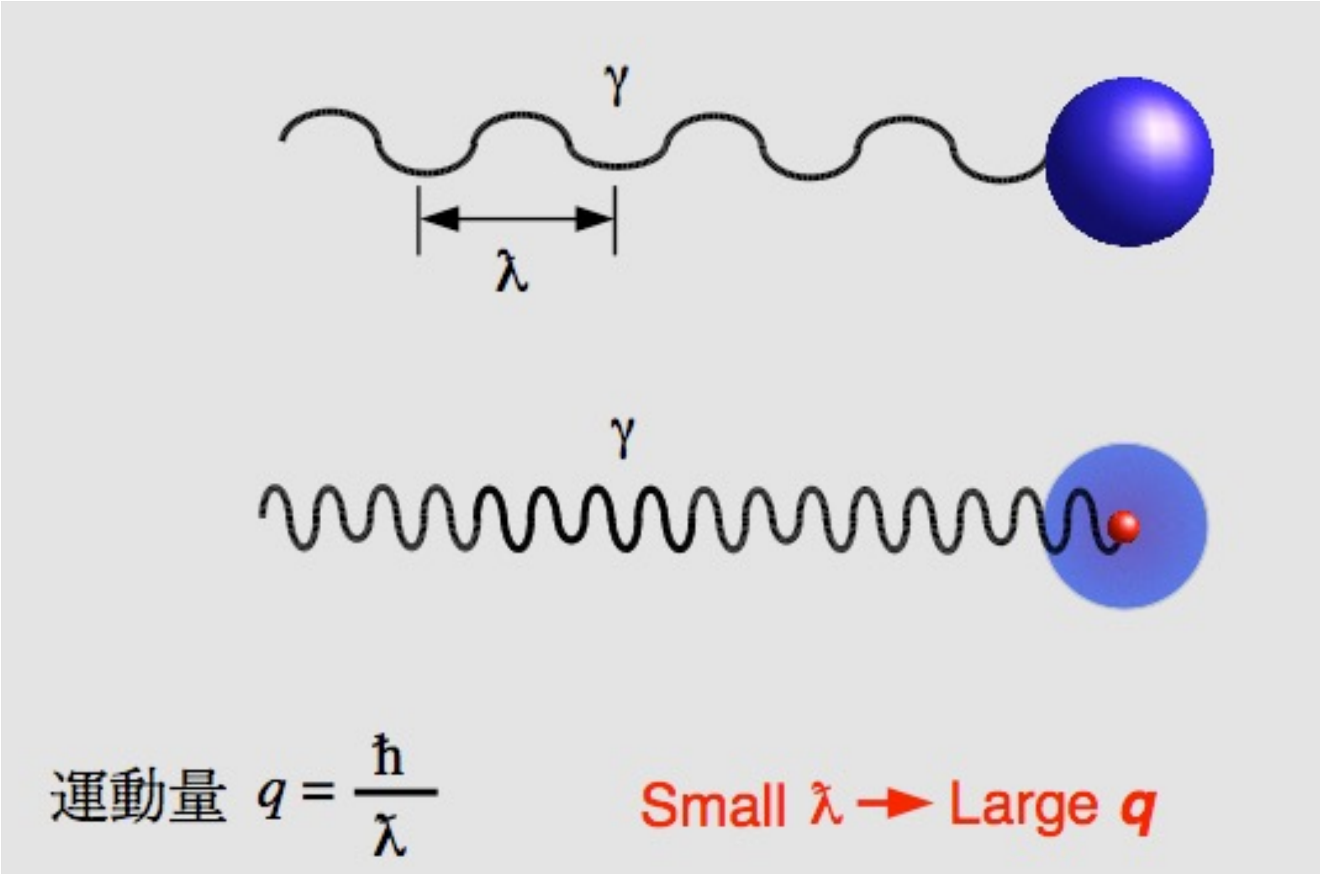
Scattering Angle ∝ Momentum transfer

Large Momentum Transfer
→ Large Impact

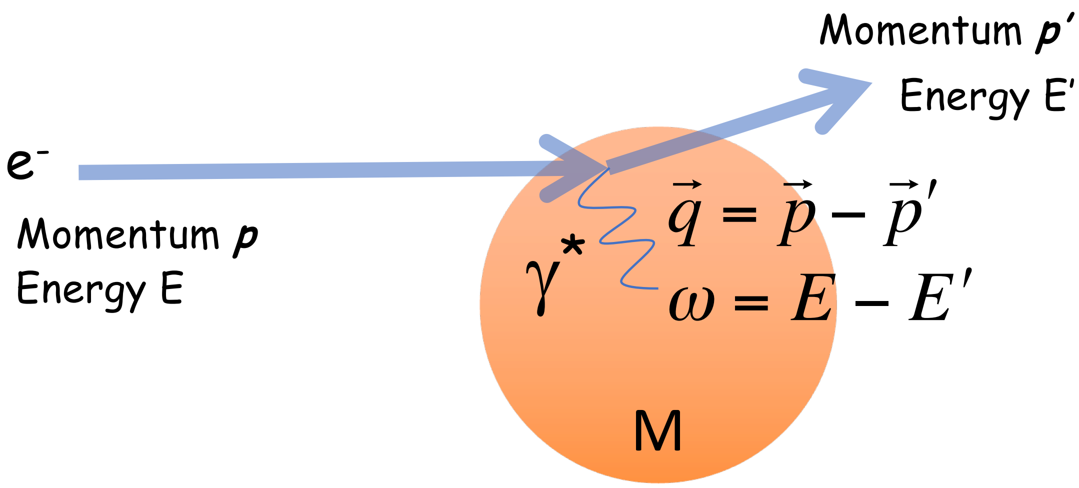
Inelastic Scattering

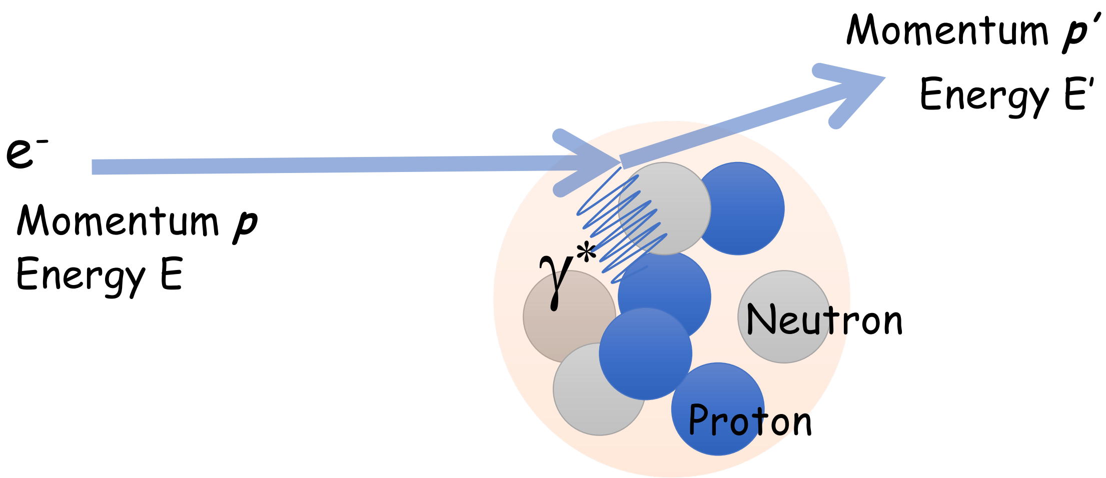


Wave Length and Resolution



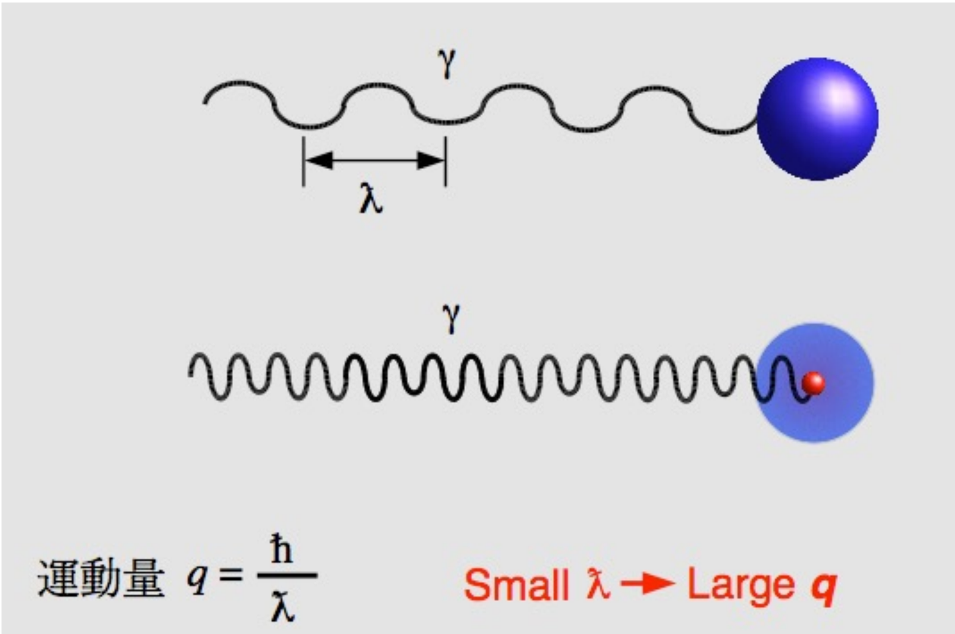
High Momentum Transfer





Interacting with a proton/neutron in nucleus

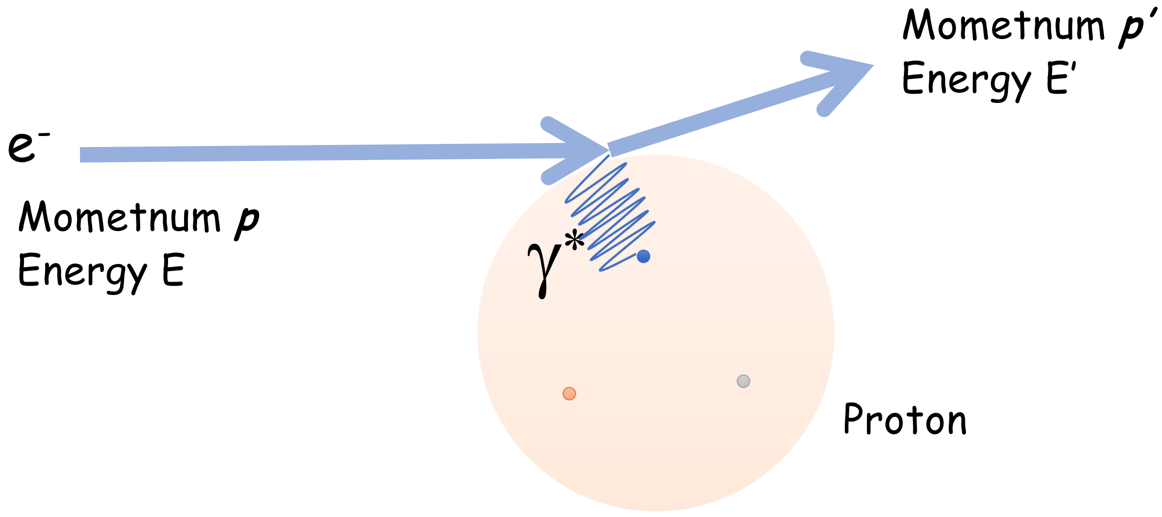
Wave Length and Resolution

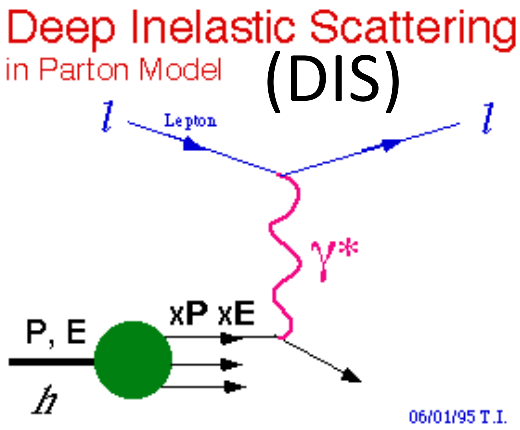


proton

proton

Even Higher Momentum Transfer





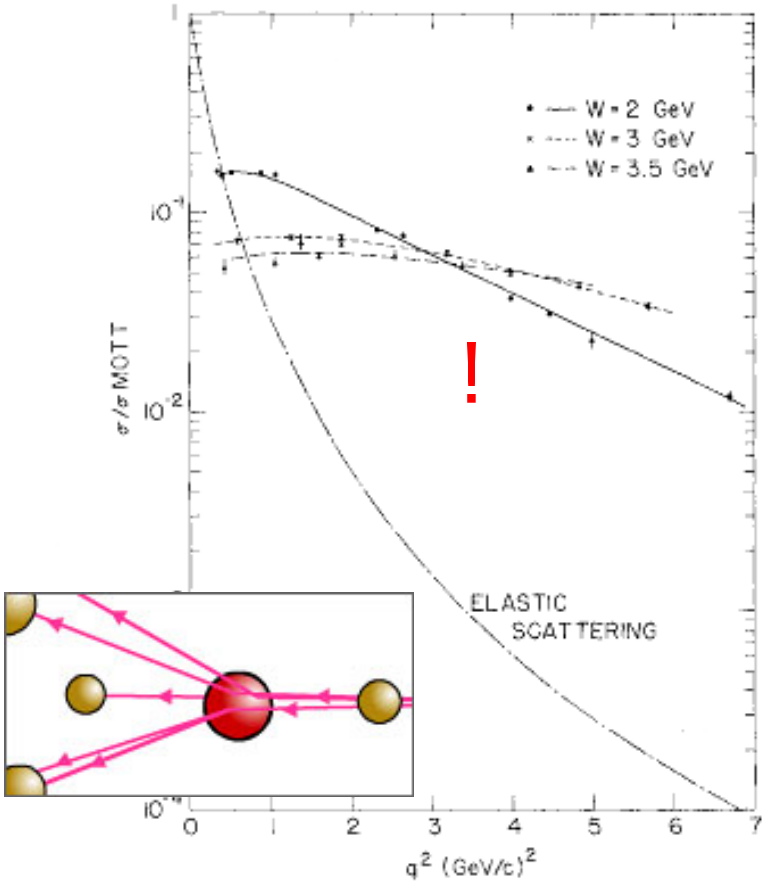
ep→eX

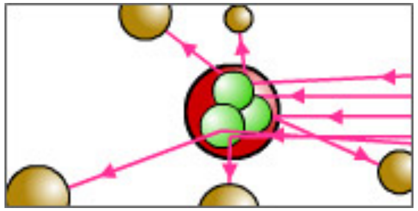
$$\frac{d^2\sigma}{dE'\,d\Omega} = \sigma_{Mott}\left[\frac{2}{M_N}F_1(Q^2,\nu)\tan^2\frac{\theta_e}{2} + \frac{F_2(Q^2,\nu)}{\nu} \pm \quad \ldots \right]$$

Point-like Scattering

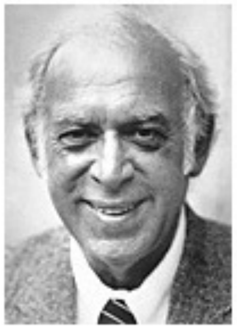
Structure Functions

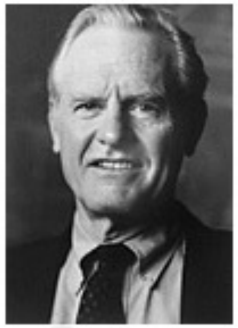
Discovery of Quark



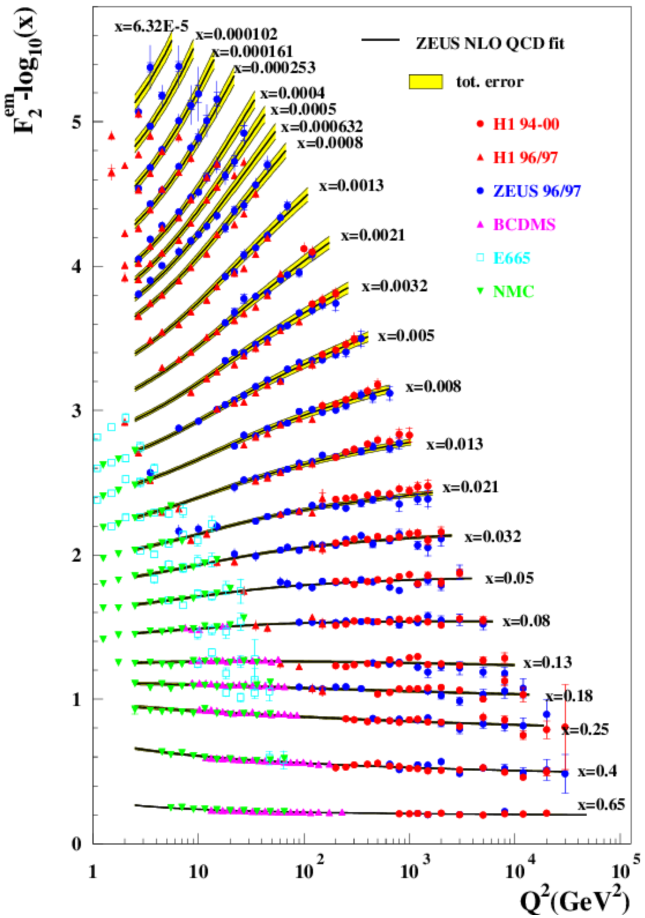


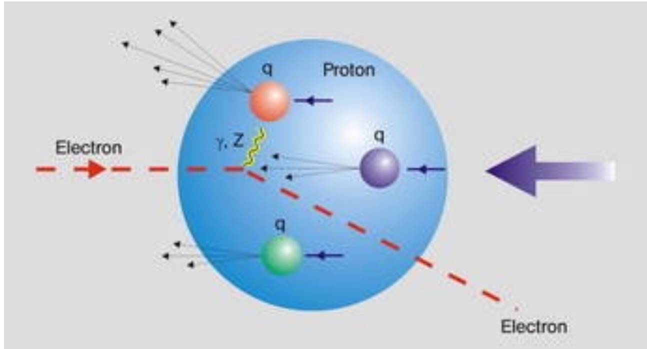
Novel Prize in 1990

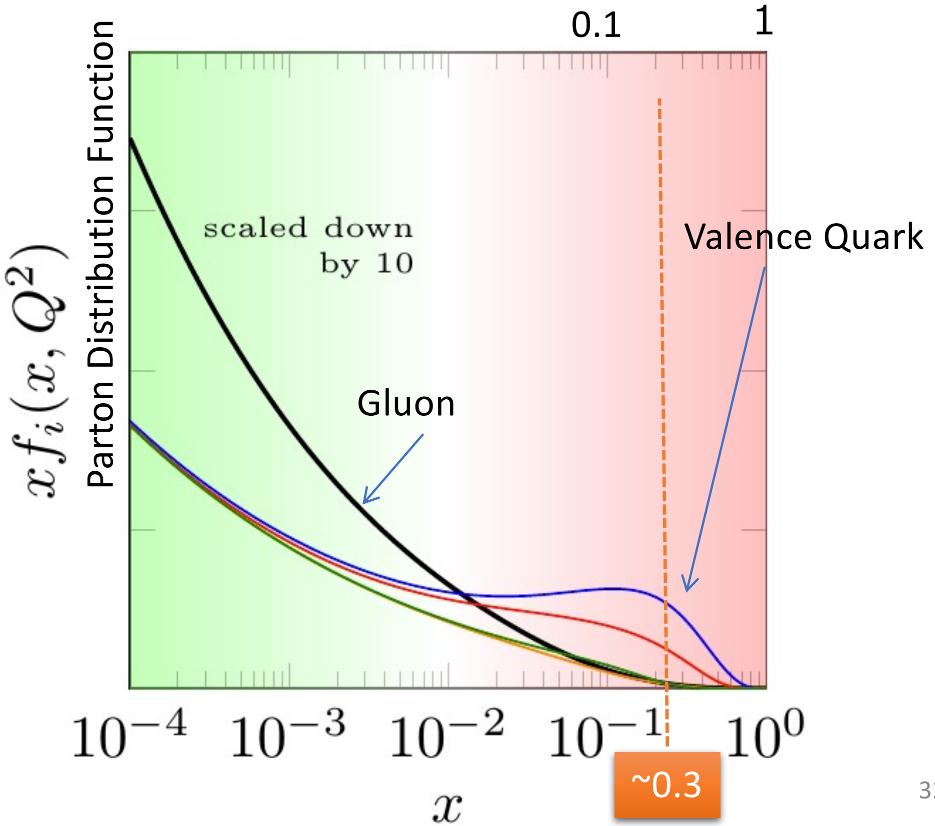




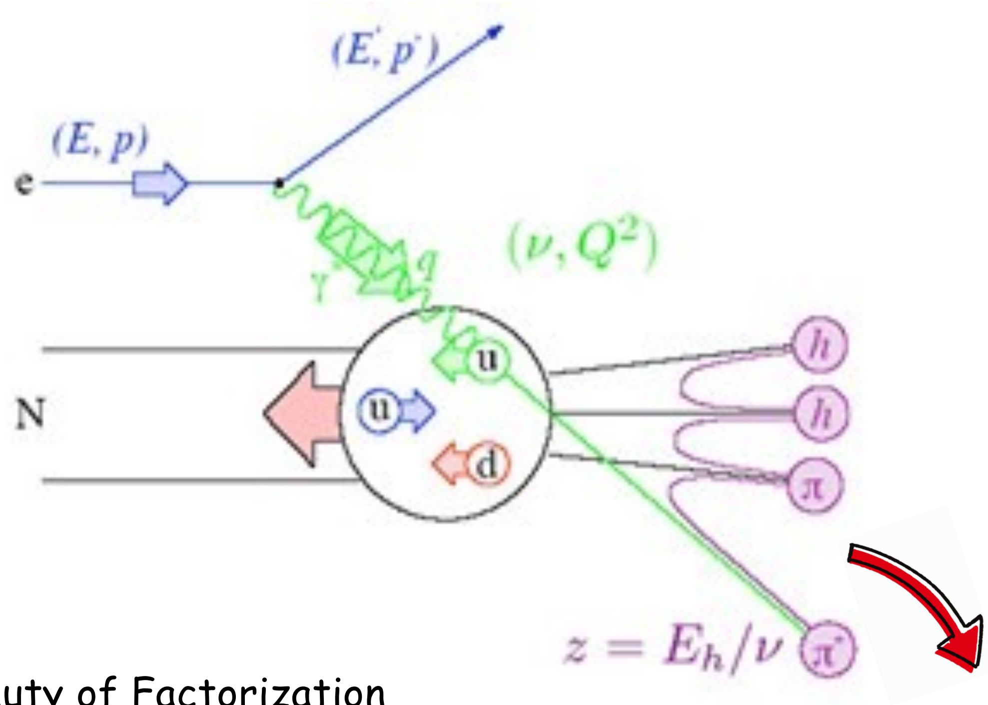
Structure Functions







Semi Inclusive DIS

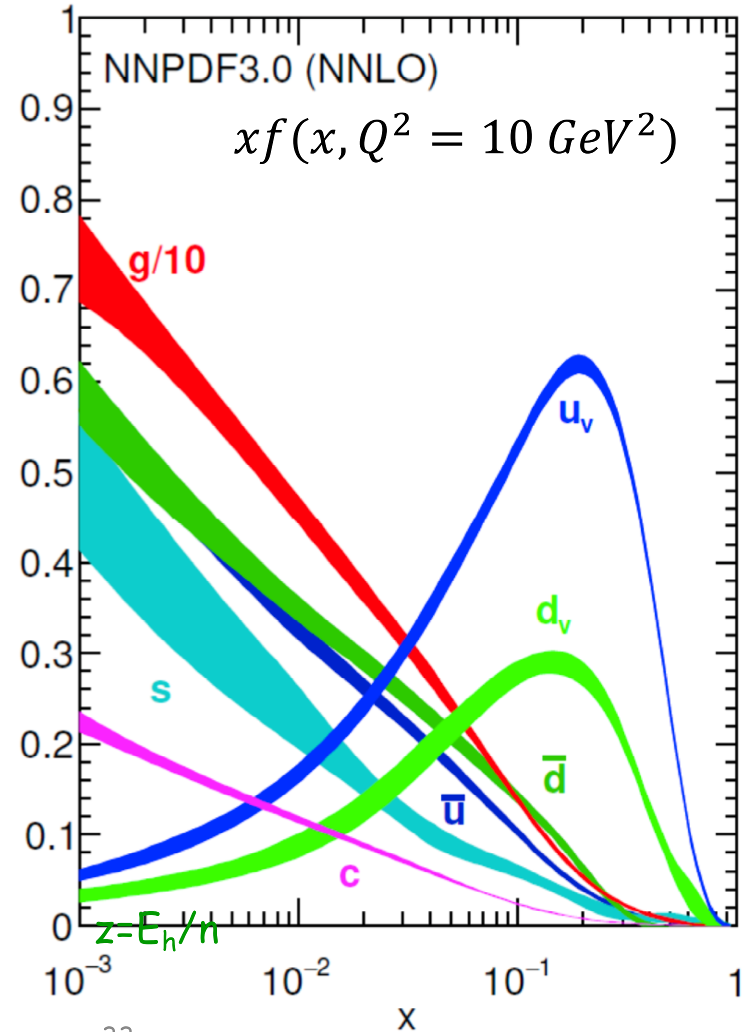


Beauty of Factorization

$$d\sigma^{lp\to lhX} = \sum_q f_q(x, Q^2) \otimes d\sigma^{lq\to lq} \otimes D_q^h(z, Q^2)$$

Fragmentation Function

Flavor deptendent parton distribution functions



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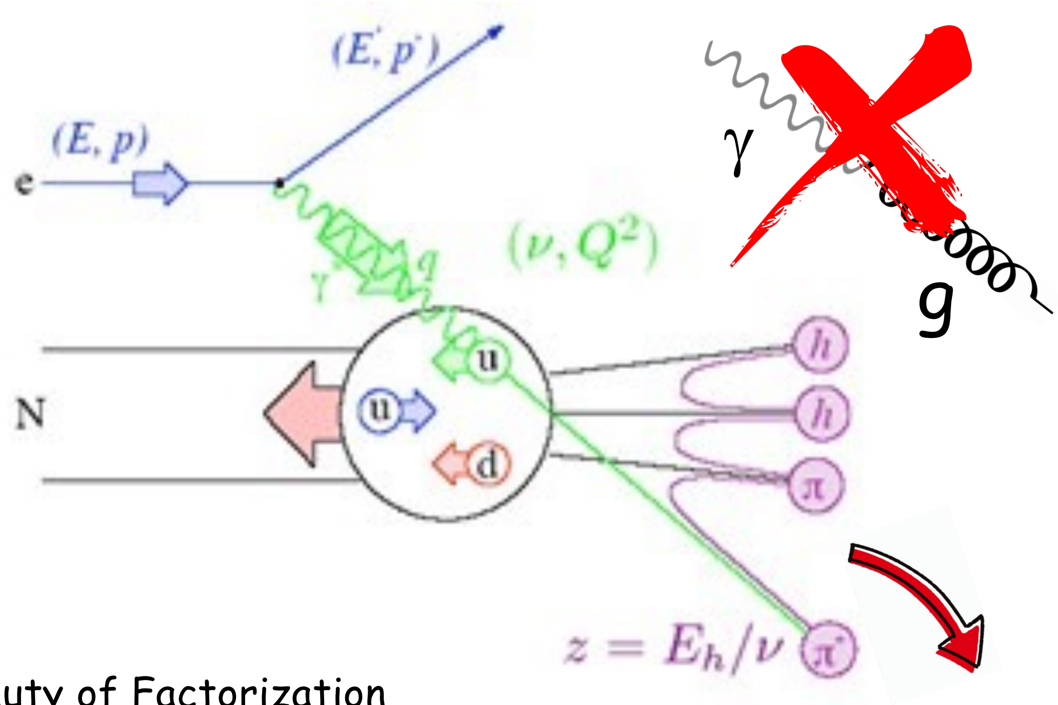
Semi Inclusive DIS



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Fragmentation Function

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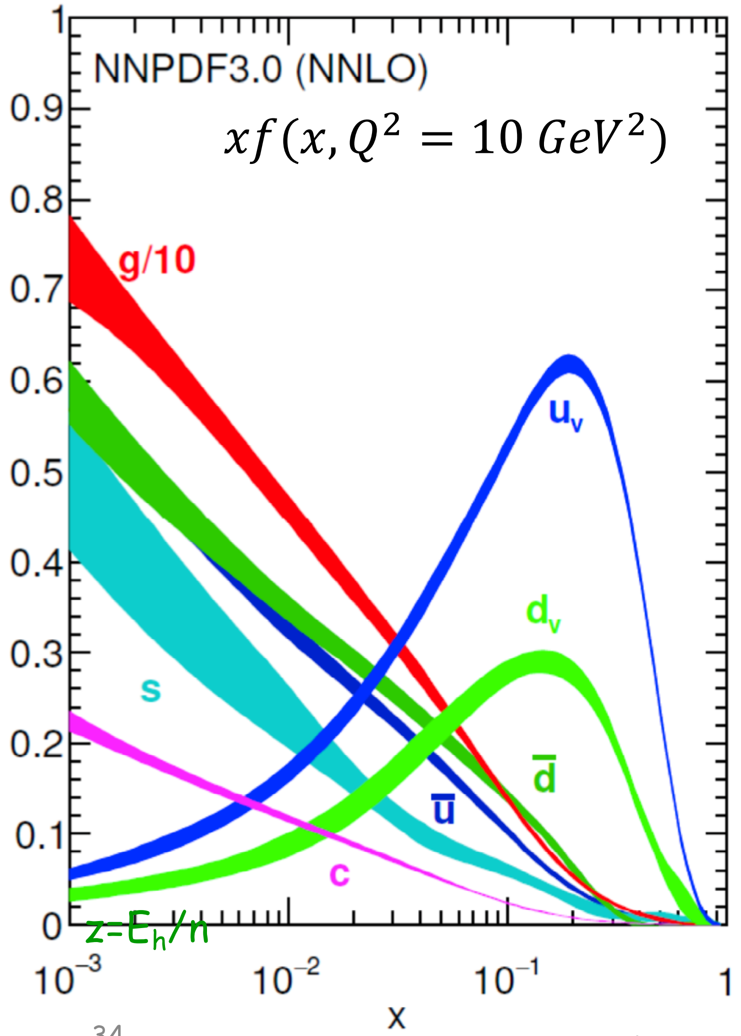

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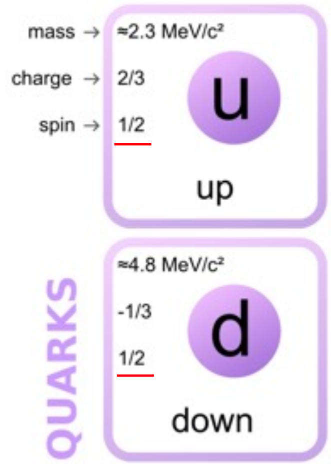
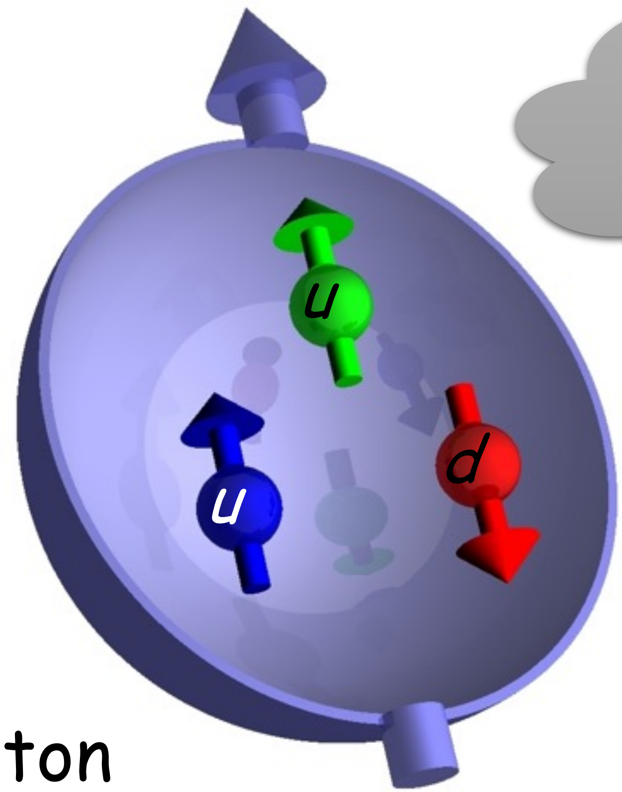
Naïve Proton Spin Model





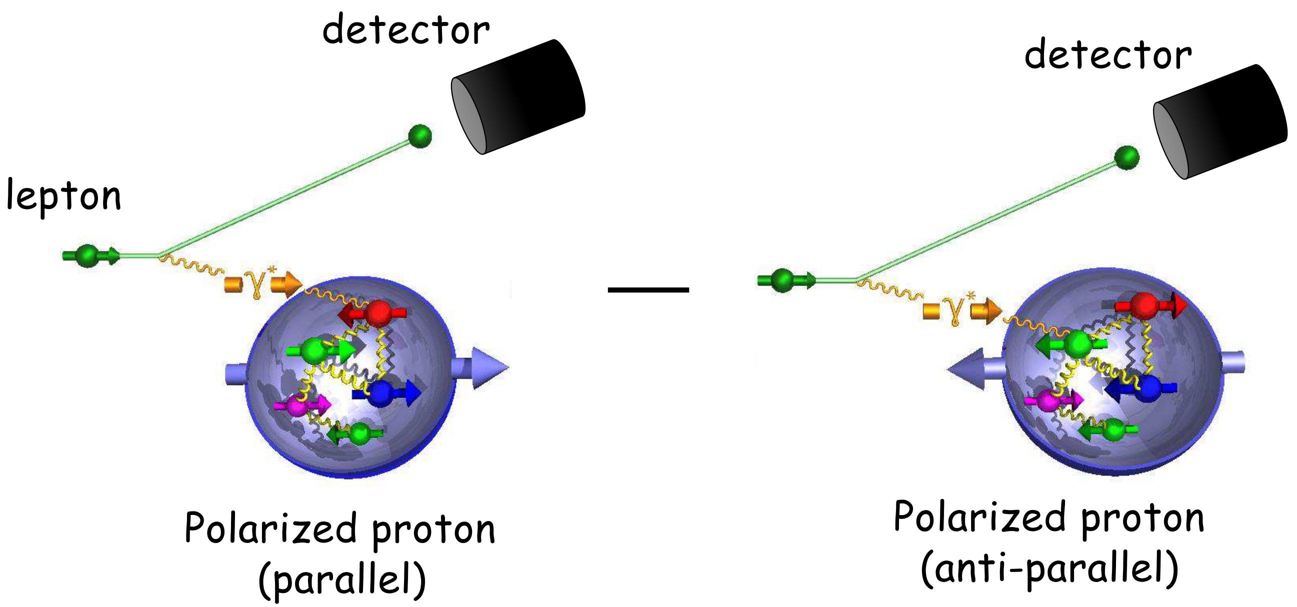
Proton

Proton Spin
= Quark + Quark + Quark

$$\frac{1}{2} = \frac{1}{2} + \frac{1}{2} + \left(-\frac{1}{2}\right)$$

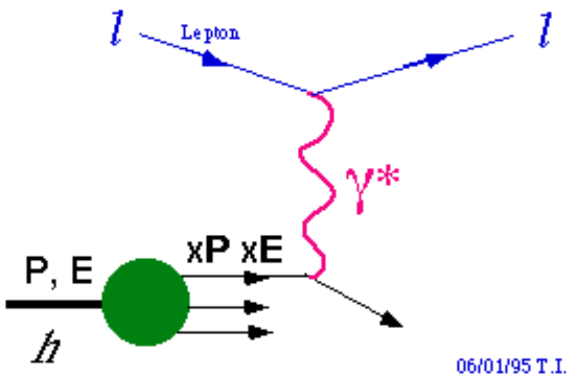
Polarized Deep Inelastic Scattering

Asymmetry

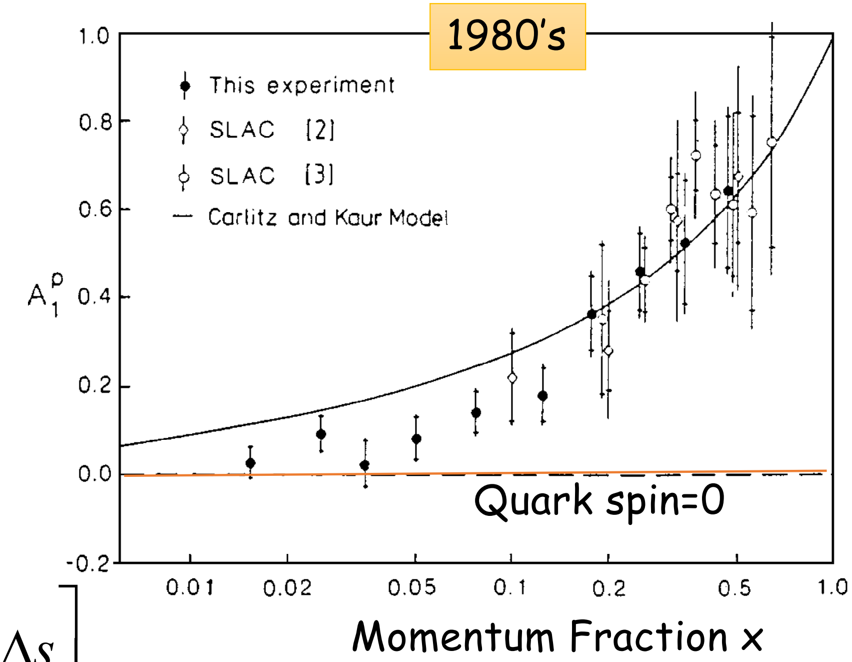


Quark Spin Component of Proton Spin

Deep Inelastic Scattering
in Parton Model



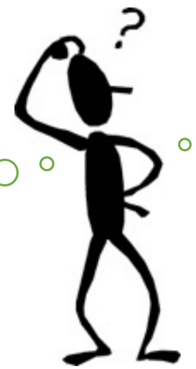
Momentum fraction x



$$\int_0^1 dx g_1^p(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

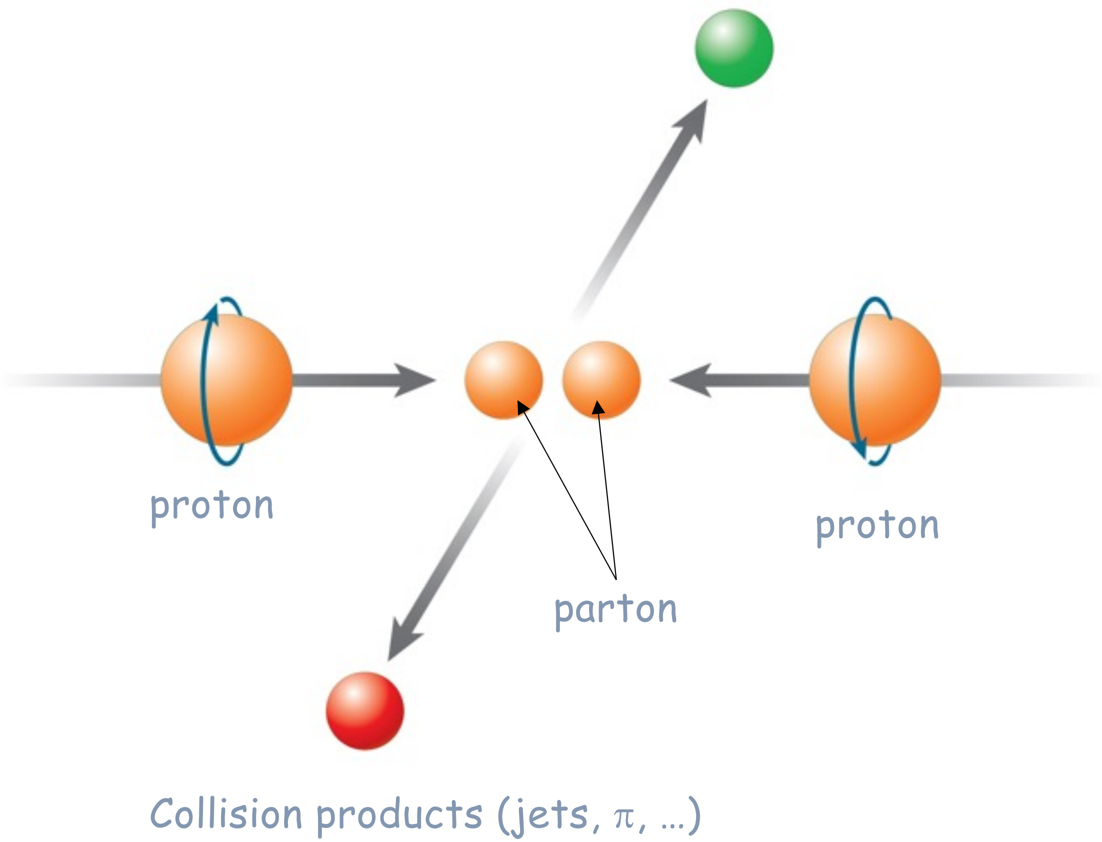
$$= 0.123 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$$

Only 25% is carried by quarks of proton spin ½

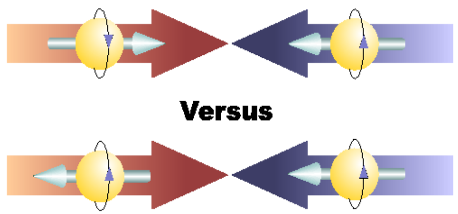


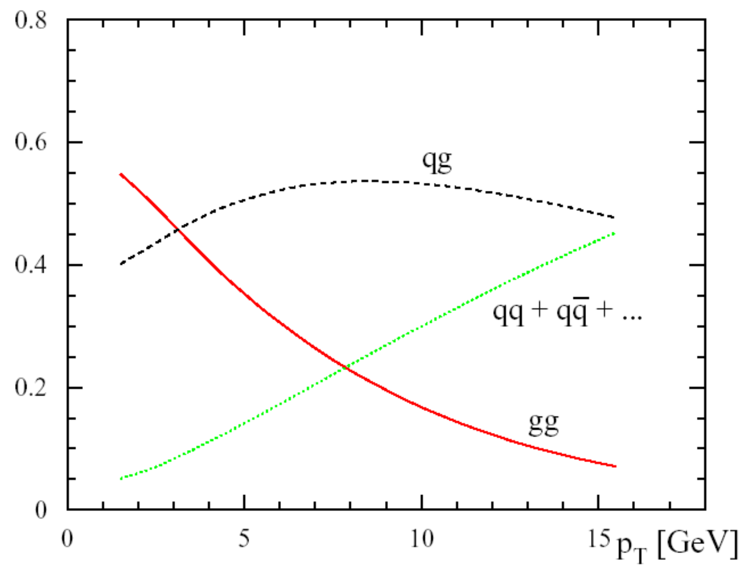
Where is the rest then?

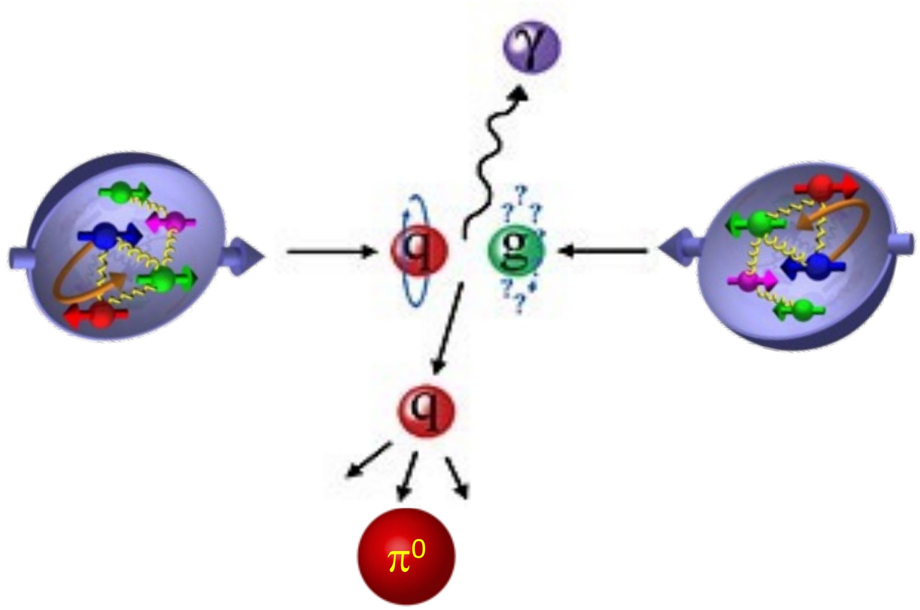
Longitudinally Polarized Proton + Proton Collision



Gluon Spin Component of Proton Spin







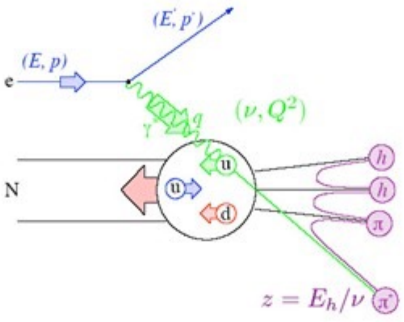
$$A_{LL}=\frac{d\sigma^{++}-d\sigma^{+-}}{d\sigma^{++}+d\sigma^{+-}}=\frac{\sum_{a,b}\Delta f_a\otimes\Delta f_b\otimes d\hat{\sigma}^{f_af_b\to fX}\cdot\hat{a}_{LL}^{f_af_b\to fX}\otimes D_f^h}{\sum_{a,b}f_a\otimes f_b\otimes d\hat{\sigma}^{f_af_b\to fX}\otimes D_f^h}$$

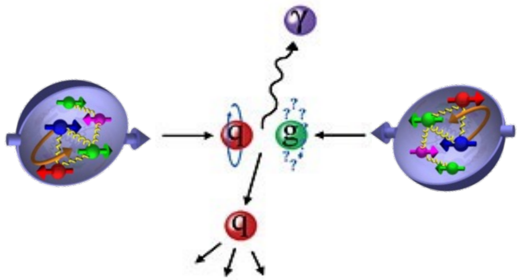
More details were discussed in Yuji's talk

Summary

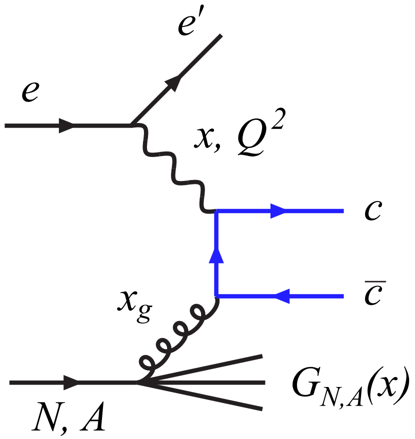
$$y = x^2 - 5x + 6$$
$$= (x-2)(x-3)$$
$$x = 2, 3$$

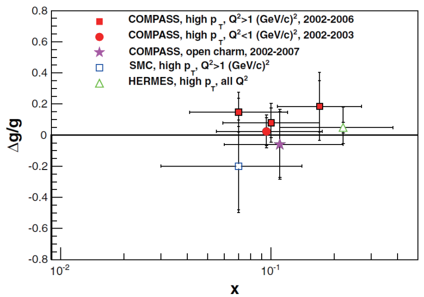
- Hadron physics aims to explore internal structure of hadron using well established factorization scheme to interpret observed cross section.
- By increasing resolution (= higher Q^2) of the probe, the fine structure of hadron can be observed like partons
- Lepton scattering and proton-proton reactions compensate each other to explore quarks or gluons by taking advantage of each sensitivities.



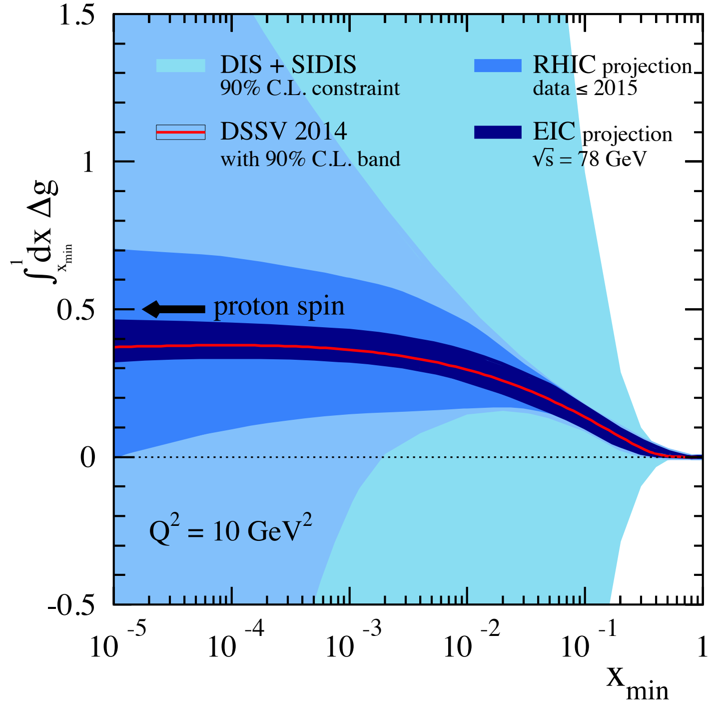


Role of EIC in Gluon Spin

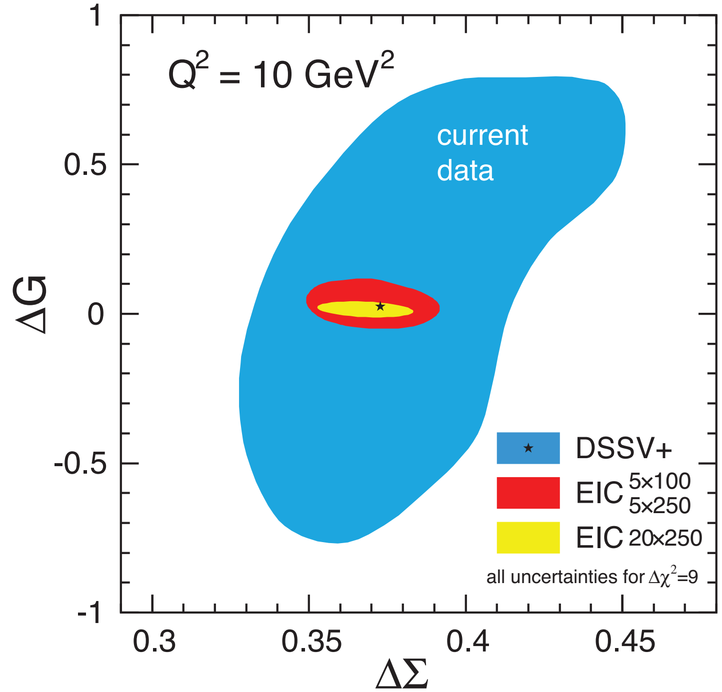




Polarized Gluon Distribution

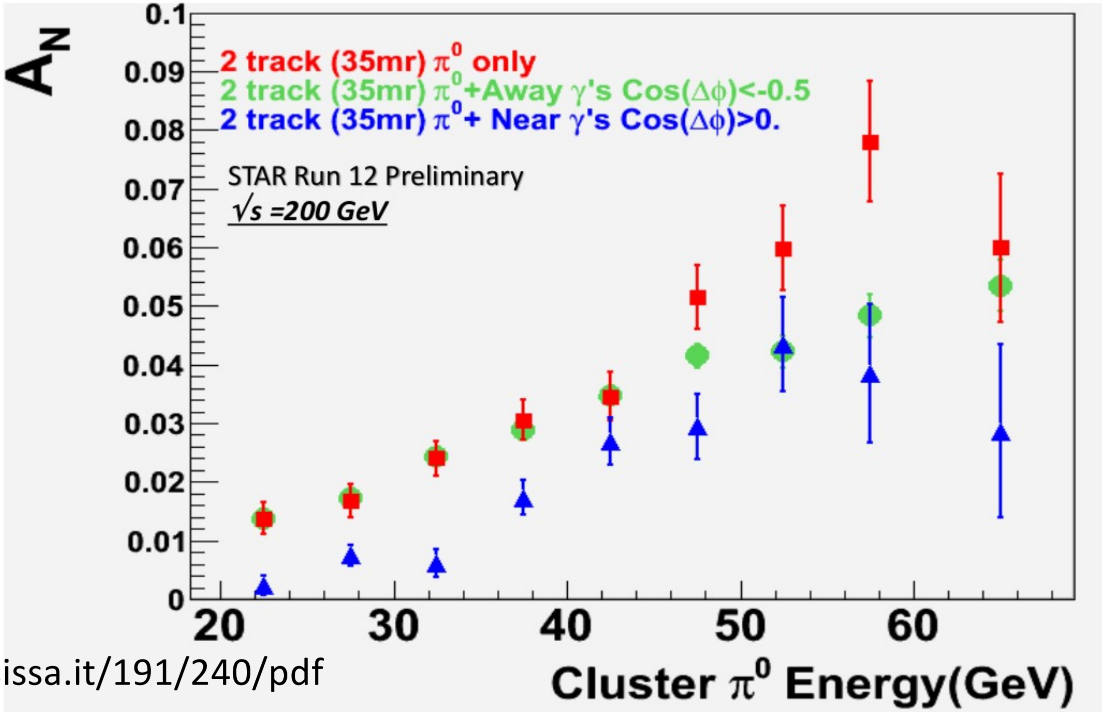


Integrated Gluon vs. Quark Spin

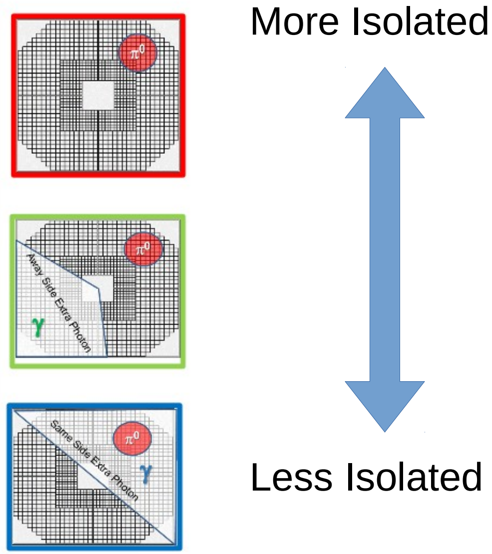


Thanks to the high luminosity of EIC, DG precision can be further improved!

Next Generation Measurement
~Activities around π^0 ~



https://pos.sissa.it/191/240/pdf

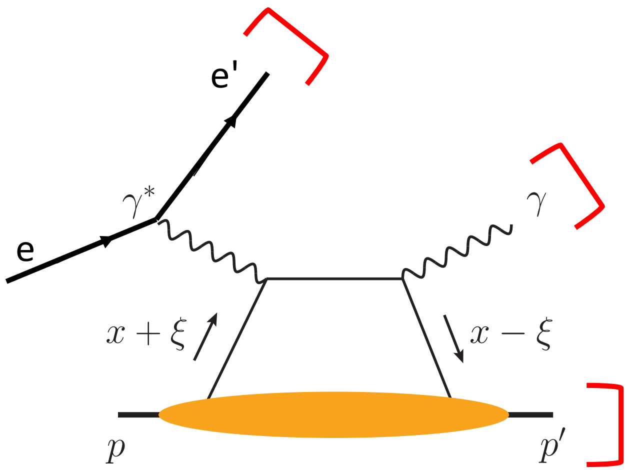


The more isolated π^0, the larger the A_N.
Smaller A_N for jet-like events?

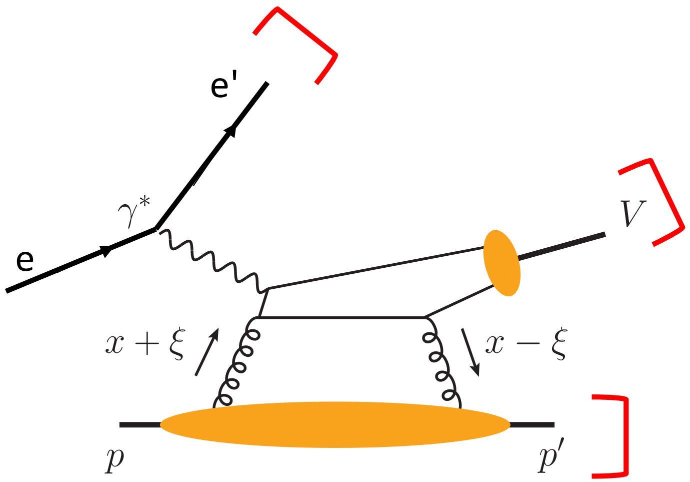
Collins Effect or Even Diffractive Nature A_N?

What EIC can do for Orbital Angular Momentum?

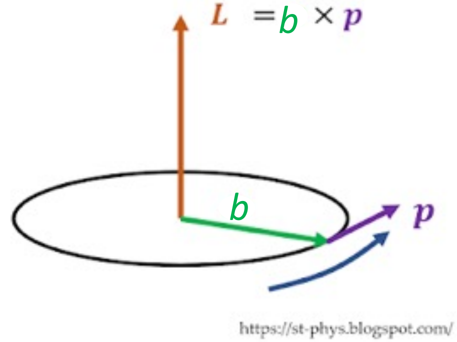
Exclusive Process



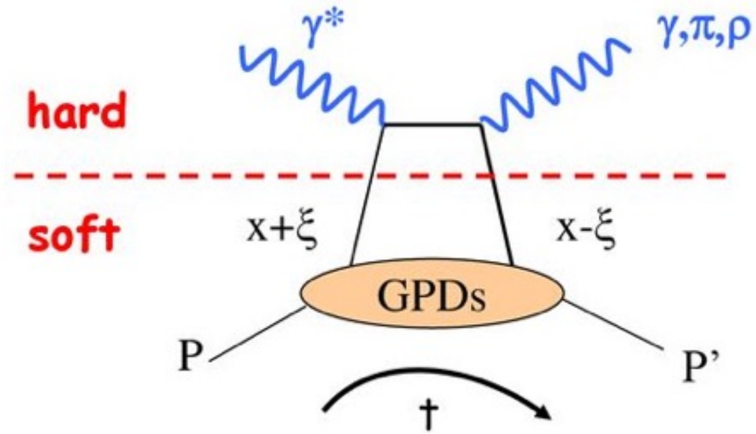
Deeply Virtual Compton Scattering
(DVCS)



Deeply Virtual Meson Production
(DVMP)



Generalized Parton Distribution (GPD)



Factorisation:
Q^2 large, $-t < 1$ GeV^2

Generalized Parton Distributions

for quarks :
4 functions $H, E, \tilde{H}, \tilde{E}(x,\xi,t)$

contains pdf
$H(x,0,0) = q(x)$
measured in DIS

contains form factors
$\int dx H(x,\xi,t) =$ F(t)
measured in elastic scattering

contains information on the nucleon spin :
Ji's sum rule : $\int x(H(x,\xi,t=0) + E(x,\xi,t=0))dx = J_z$
and $1/2 = 1/2\ \Delta\Sigma + L_z + \Delta G = J_z + \Delta G$

Probing Gluons by EC