QCD structure of the nucleon and spin physics
Lecture 1: overview

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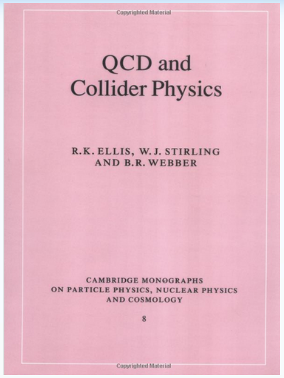
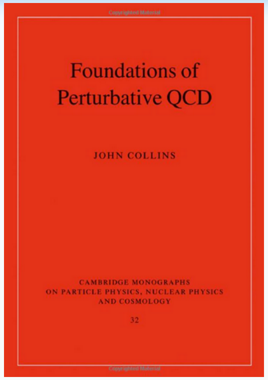
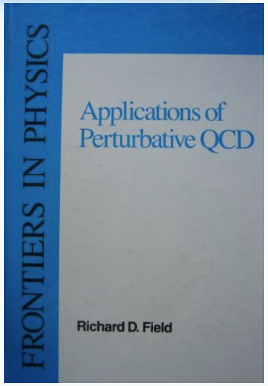
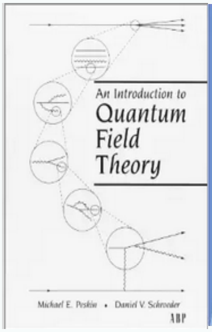
Selected references on QCD

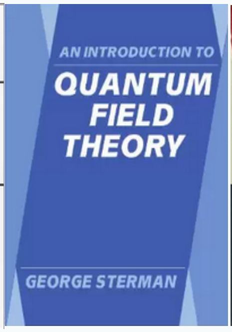
- Textbooks on QCD
  - QCD and Collider Physics – Ellis, Stirling, Webber
  - Foundations of Perturbative QCD: J. Collins
  - Applications of Perturbative QCD: R. Field
- Textbooks on Quantum Field Theory
  - An Introduction to Quantum Field Theory: Peksin & Schroeder, as well as Sterman
  - Quantum Field Theory and the Standard Model: M. Schwartz
  - Quantum Field Theory in a Nutshell: A. Zee
- The structure of the Nucleon: Thomas & Weise
- CTEQ collaboration http://www.phys.psu.edu/~cteq
- QCD Resource Letter: arXiv: 1002.5032 – Kronfeld-Quigg

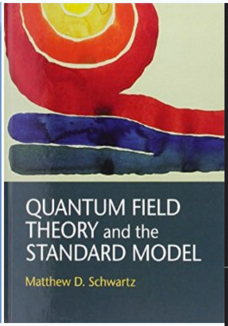


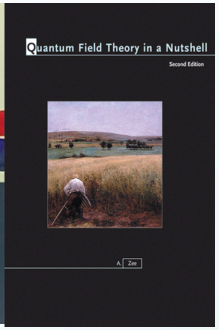


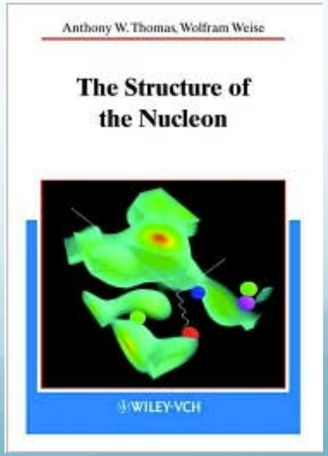










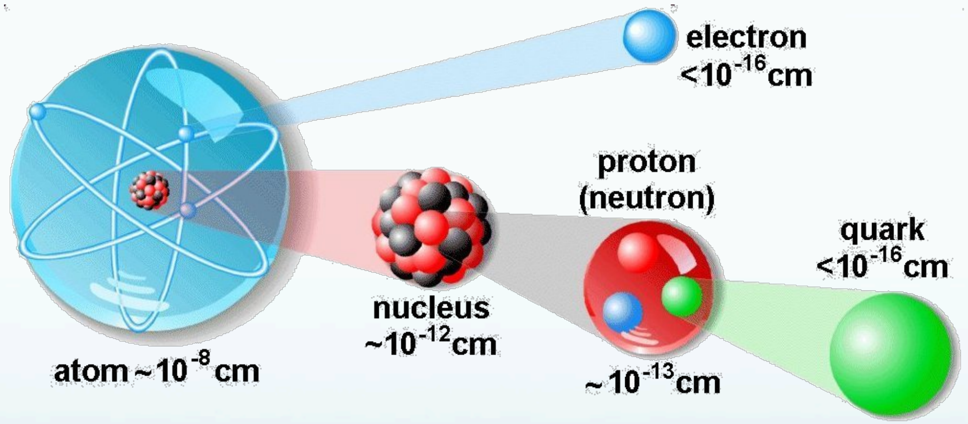


Tentative plans

- Lecture 1: Introduction and overview
- Lecture 2 & 3: QCD collinear factorization and evolution
- Lecture 4 & 5: Operator analysis & TMD factorization
- Lecture 6: Phenomenology

The structure of matter

- The exploration on the structure of matter has a really long history
  - Dalton 1803 (atom)
  - Rutherford 1911 (nucleus)
  - Chadwick 1932 (neutron)
  - Gell-Mann and Zweig 1964 (quark model)
  - Feynman 1969 (parton model), ...

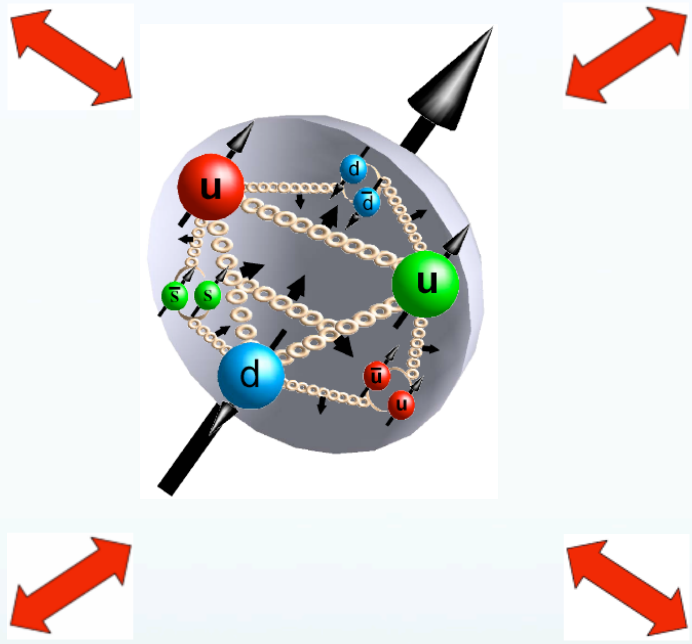


- Central goal of nuclear science
  - **To discover, explore, and understand all forms of nuclear matter and the associated dynamics**

Exploring the nucleon: fundamental importance in science

Know what we are made of:
Most abundant particles around us
Building blocks of all elements

Fundamental properties:
Proton mass, spin, magnetic moment, understand them in terms of the internal degrees of freedom



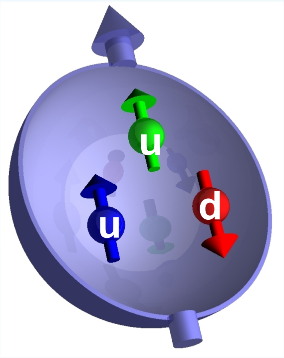
Tool for discovery:
Colliding high energy nucleons
New Physics beyond SM
LHC, Tevatron,
RHIC, HERA, ...

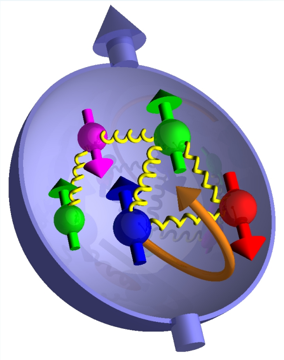
Exploring QCD and strong interaction:
Confinement,
Lattice QCD,
Asymptotic freedom,
perturbative QCD, ...

The proton in QCD

- Proton is made of
  - 2 up quarks + 1 down quarks ➡ valence
  - + any number of quark-antiquark pairs ➡ sea
  - + any number of gluons

Infinite many …





- Fundamental questions for proton structure (what is the internal landscape of the nucleons?)
  - What are the momentum distributions of quarks, antiquarks, and gluons?
  - How are quarks and gluons distributed spatially?
  - How do partons carry the proton spin-1/2? (spin and orbital angular momentum)
  - How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction?

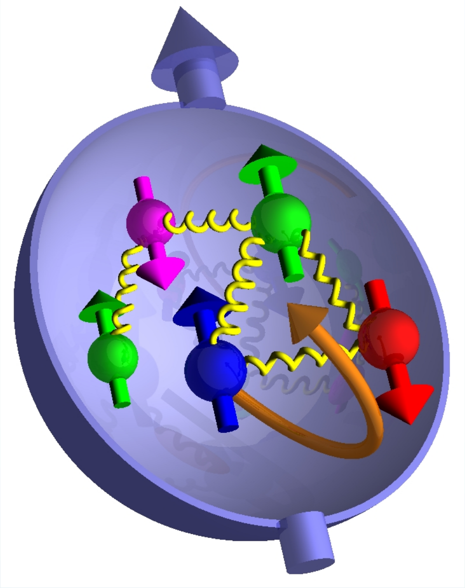
2007 nuclear physics long range plan
EIC white paper

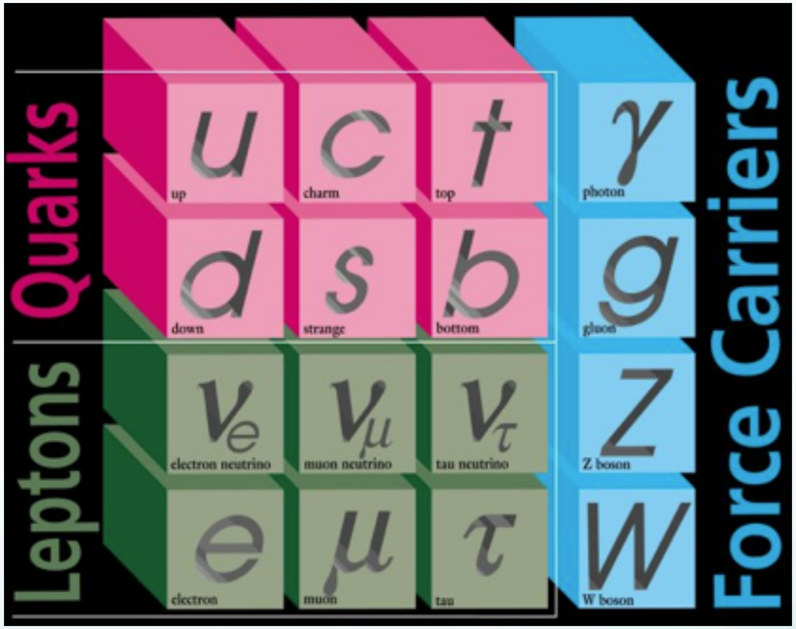
Parton distribution functions (PDFs), Transverse momentum dependent distributions (TMDs), …

Quantum Chromodynamics (QCD)

- Quarks and gluons carry a new degree of freedom called "color" (color charge), their interaction is described by QCD

- QCD: the underlying theory of the strong interaction

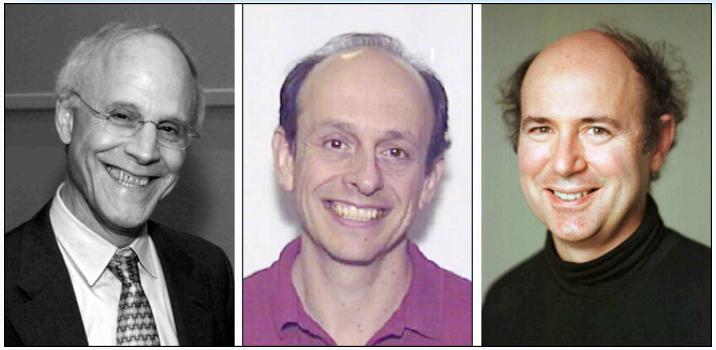




- Tools:

  Lattice QCD, DSE method, perturbative QCD, models, …

Asymptotic freedom and confinement



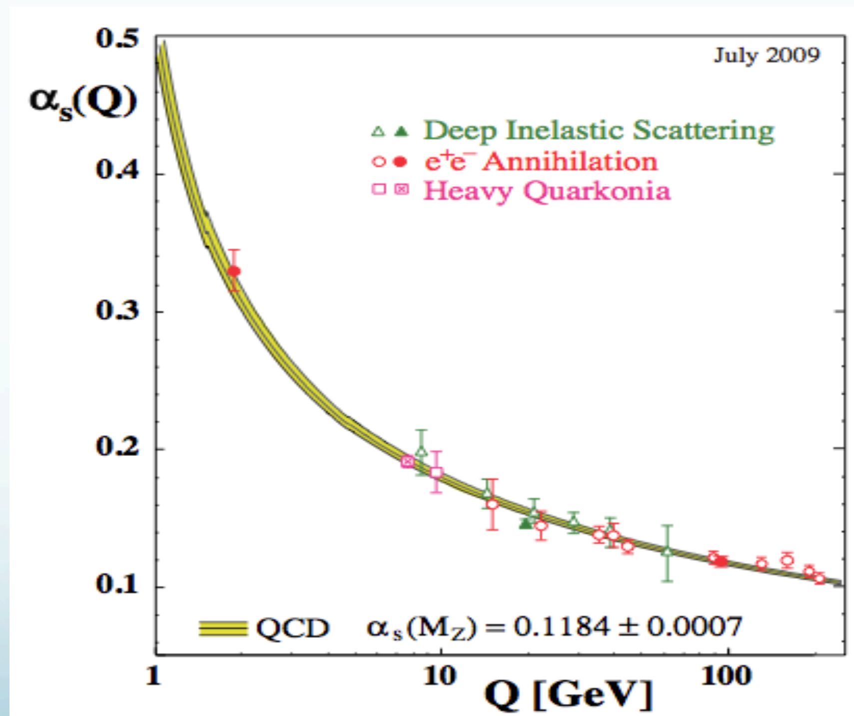
D. Gross H.D. Politzer F. Wilczek

2004 Nobel Prize

Asymptotic freedom: at high energy, the interaction between quarks and gluons are weak, thus one could use perturbation theory (expansion in α_s) - perturbative QCD (pQCD)

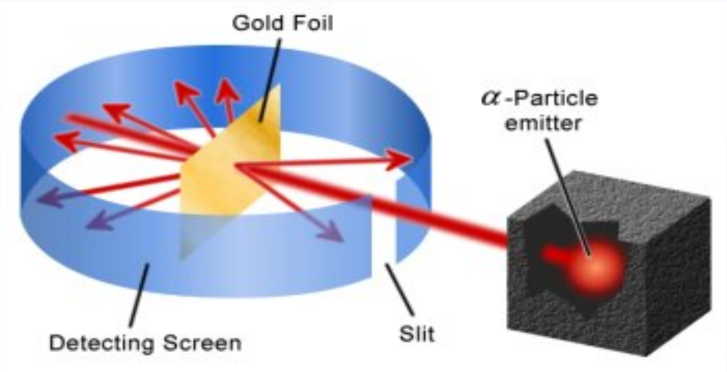
However

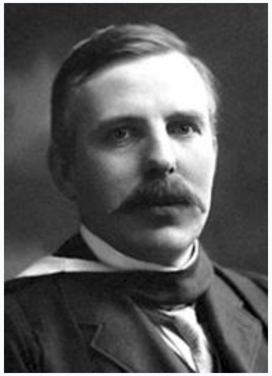
Confinement: Quark and gluons are confined inside the hadron, quarks and gluons can never be observed



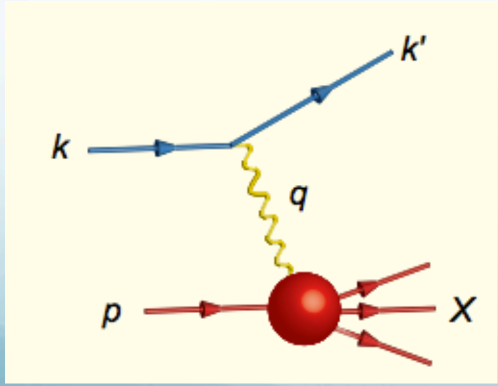
Experimental tool

- High energy scattering: one way to study the structure of matter
  - Originated from Rutherford's experiment (1911)

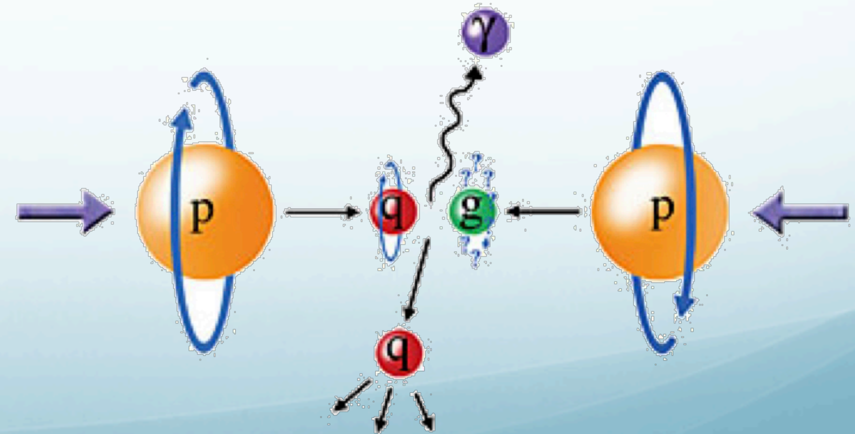




- To extract information on the nucleon structure, we send in a probe and study the outcome of the collisions



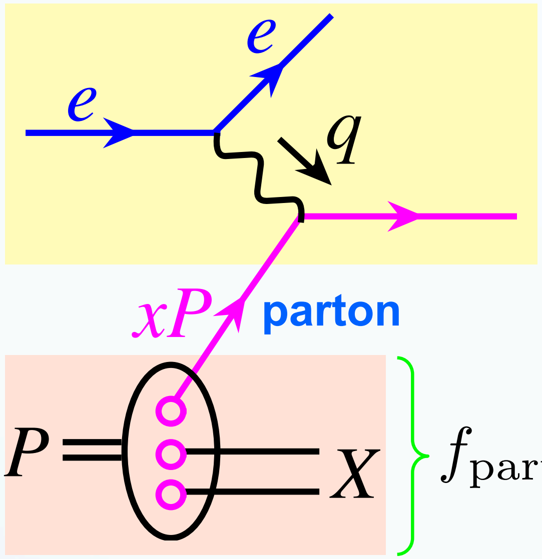
Deep Inelastic Scattering (DIS)



Proton-Proton collisions

The paradigm of perturbative QCD

- The common wisdom: to trace back what's inside the proton from the outcome of the collisions, we rely on QCD factorization



$\hat{\sigma}_{\text{parton}}$

$f_{\text{parton}}(x)$

Parton Distribution Functions (PDFs):
Probability density for finding a parton in a proton with momentum fraction x

$$\sigma_{\text{proton}}(Q) = f_{\text{parton}}(x) \otimes \hat{\sigma}_{\text{parton}}(Q)$$

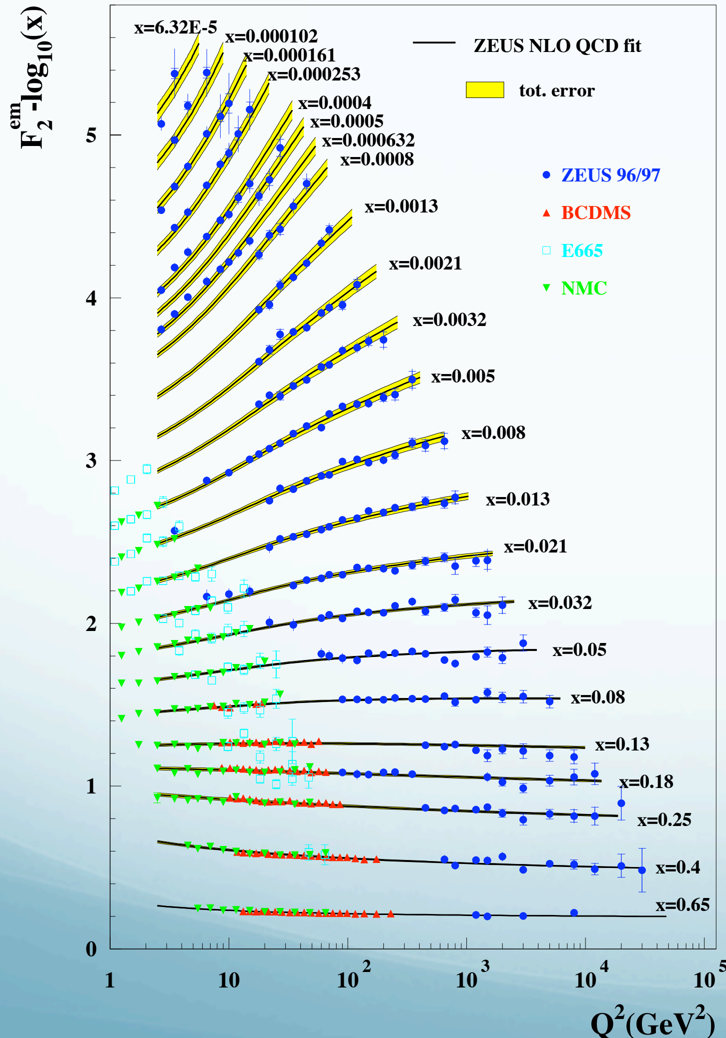
Universal (measured) **calculable**

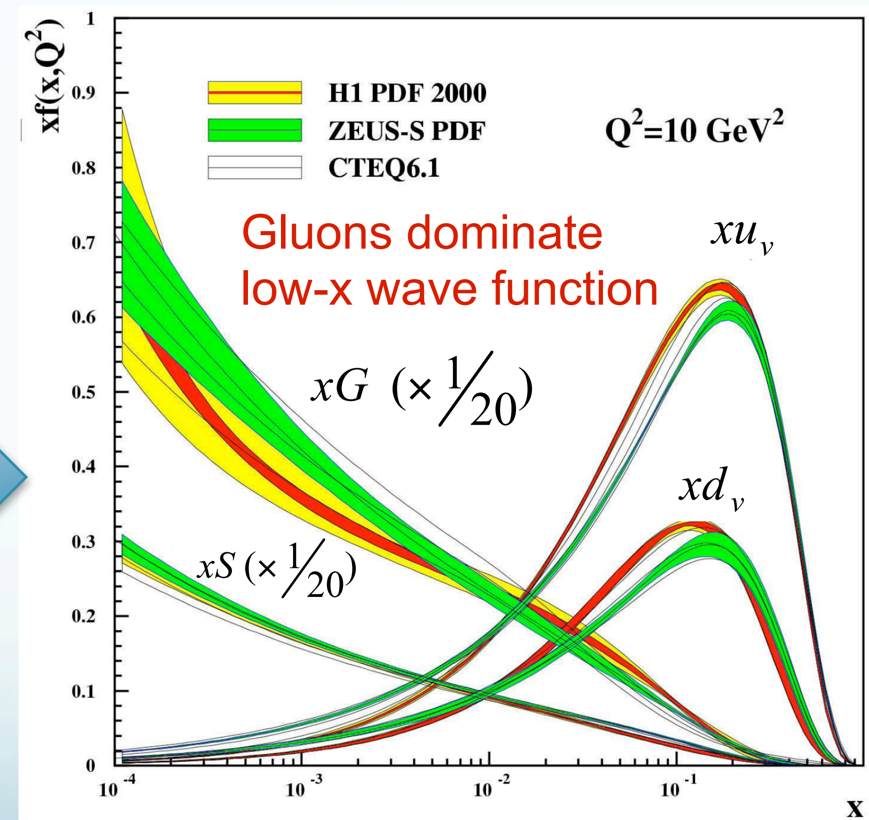
- Hadron structure: encoded in PDFs
- QCD dynamics at short-distance: partonic cross section, perturbatively calculable

Universality of PDFs: extraction from DIS

$$\sigma_{\text{proton}}(Q) = f_{\text{parton}}(x) \otimes \hat{\sigma}_{\text{parton}}(Q)$$

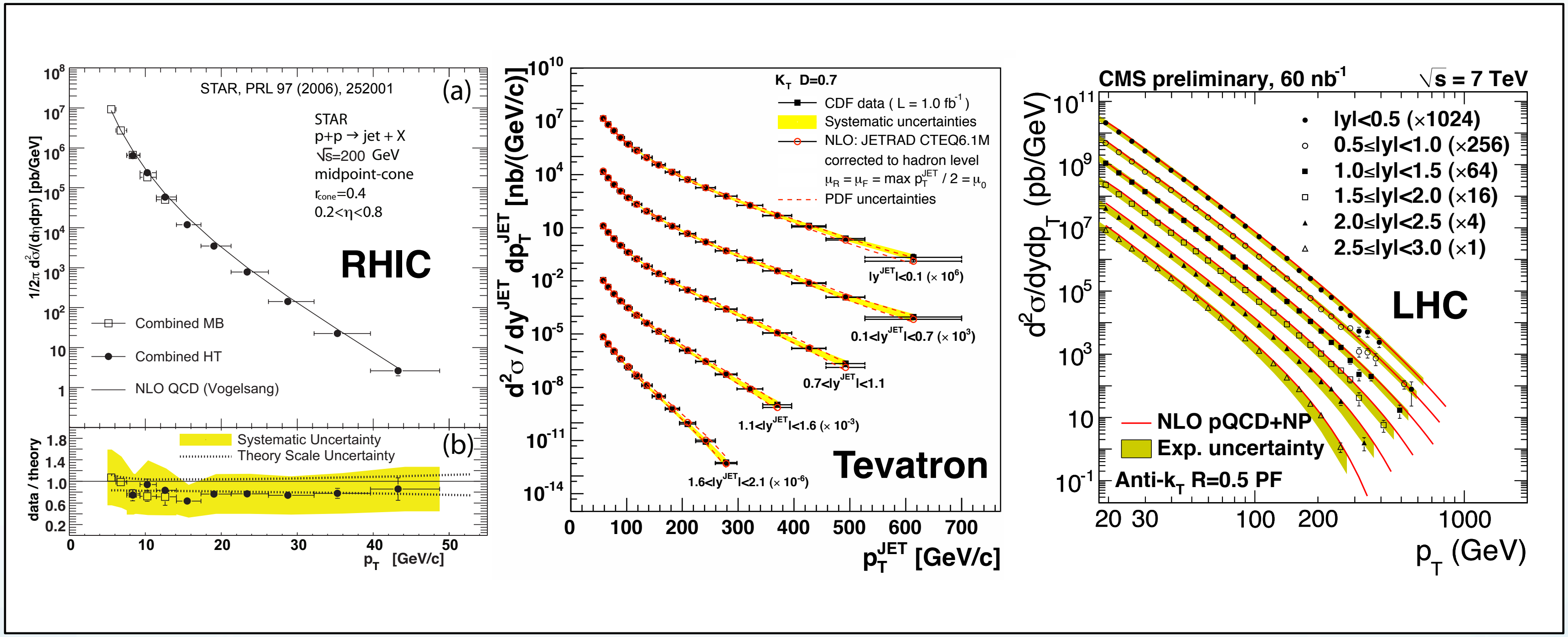
Universal (measured) **calculable**





Success of QCD factorization

- Use the same set of PDFs, one could describe other physics processes: jet cross section (p+p→jet+X)

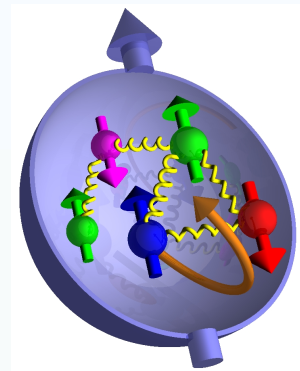


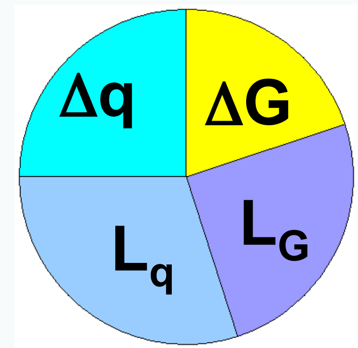
- Emerged around 1980s, this picture has been very successful
  - **Higher order for short-distance**
  - Essential for physics beyond standard model

Spin structure of the proton

- Proton is spin-1/2 particle, where does the spin of the proton come from?

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





- $\Delta\Sigma$: quark spin
- ΔG : gluon spin
- L : orbital angular momentum

- How one might obtain these contributions through QCD factorization and perturbative computations?
  - Quark helicity distribution

$$\Delta q(x) =$$

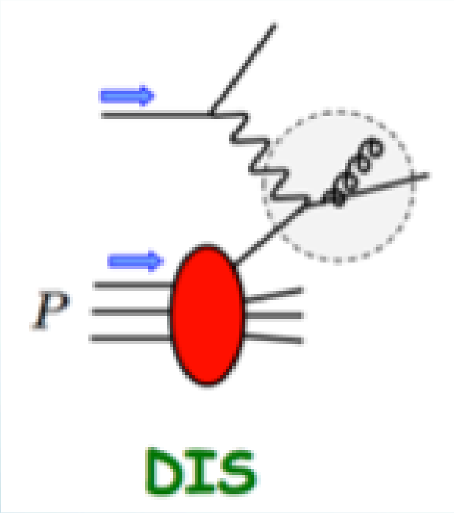
  - Quark spin contribution

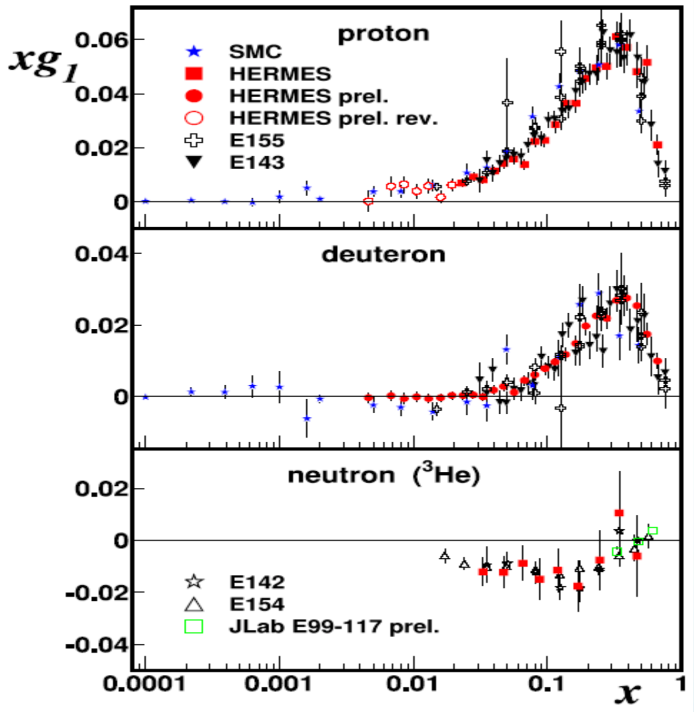
$$\Delta\Sigma = \int_0^1 dx\left[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + s(x) + \bar{s}(x)\right]$$

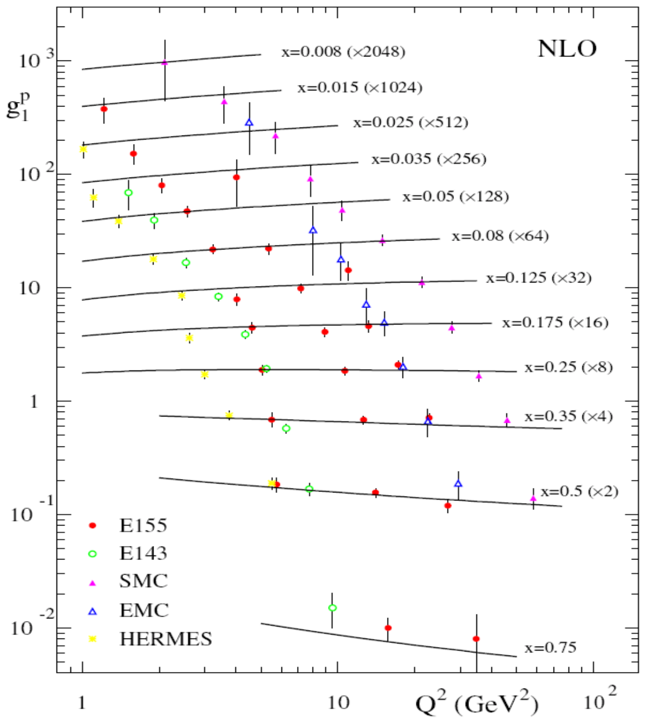
DIS with longitudinal polarized beam and target

- Longitudinal polarized DIS scattering

$$\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}} \propto g_1(x,Q^2) = \sum_q e_q^2 \left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

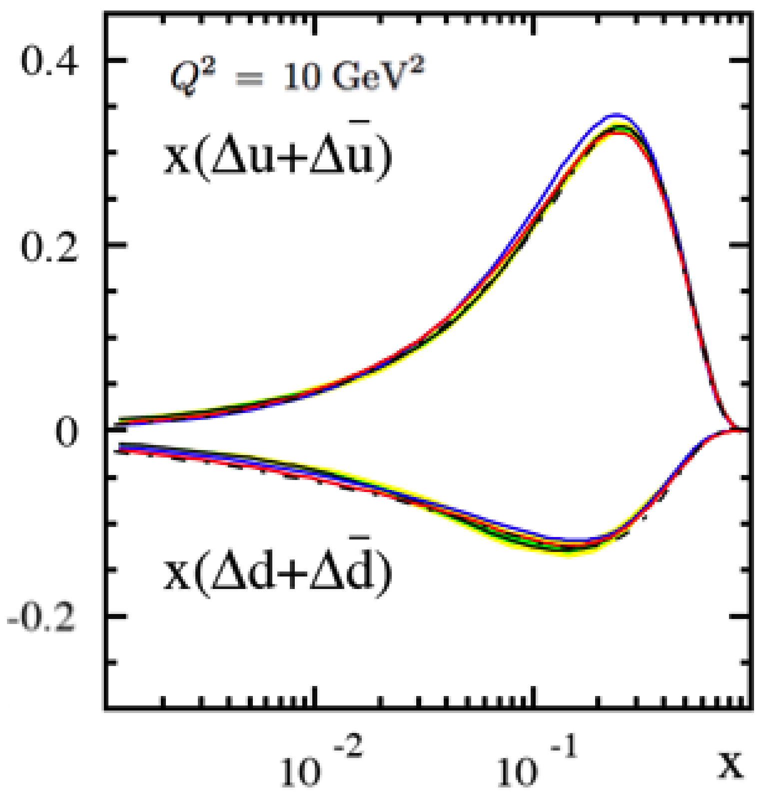






Best determined quark helicity distributions

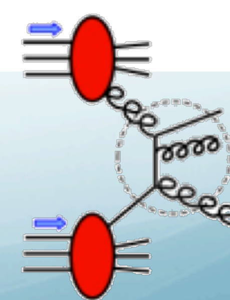
- Best determined: $\Delta u+\Delta\bar{u}$, $\Delta d+\Delta\bar{d}$



Comparison with:
DNS de Florian,Navarro,Sassot
GRSV Glück, Reya, Stratmann, WV

Similar results:
Leader, Stamenov, Sidorov
Blümlein, Böttcher; & HERMES
Hirai, Kumano, Saito (AAC)
COMPASS

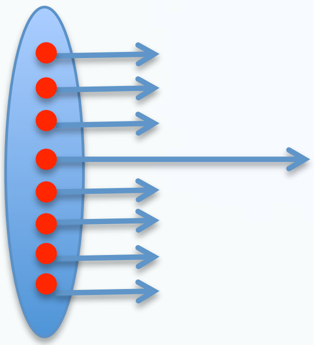
- Similar idea for gluon at pp scattering



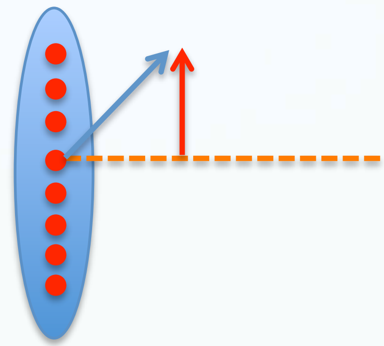
pp (RHIC)

Going beyond collinear – 3D structure of the proton

- So far only collinear/longitudinal momentum information are studied, what about transverse motion?

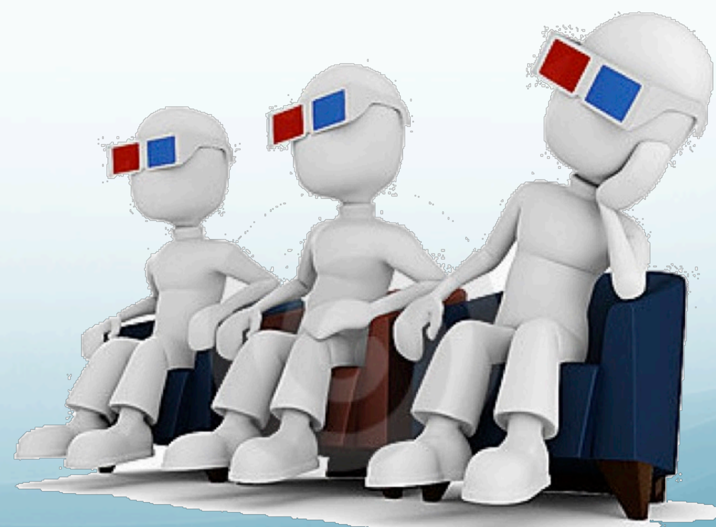


$$p = x\,P$$



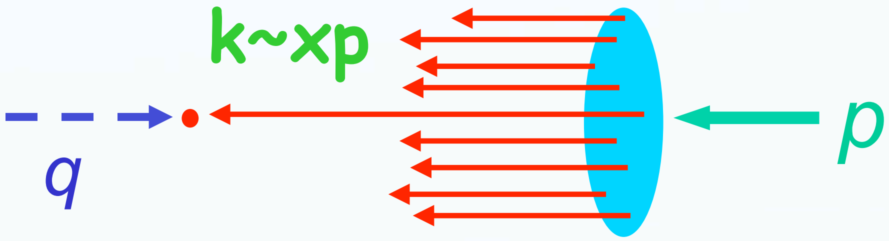
$$p = x\,P + k_\perp$$

- With both longitudinal and transverse information, one can construct a 3D picture of the real nucleon in momentum space



Parton's transverse motion

- Parton's transverse momentum is usually smaller than the longitudinal component in the proton, which moves very fast in the longitudinal direction, how do we probe the parton's transverse motion?

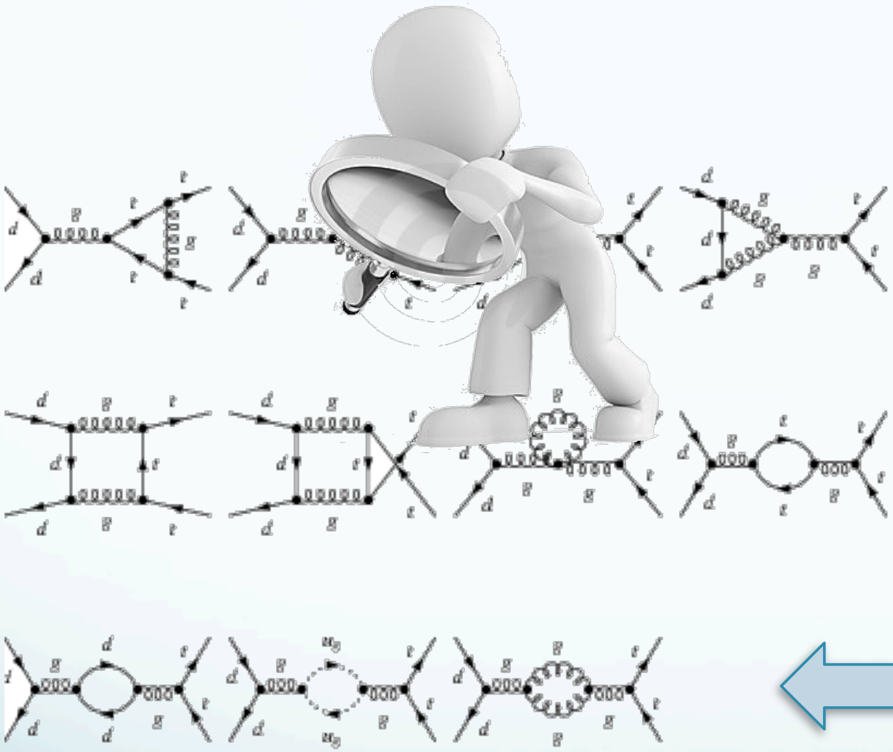


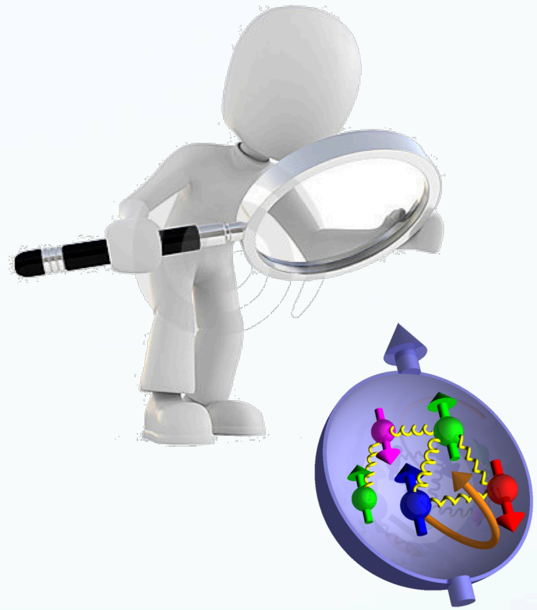
- Use transverse spin as a probe: transverse-spin dependent observables are sensitive probes of the partons transverse momentum as they can correlate with each other

Transverse spin physics

Spin physics: excellent laboratory for QCD

- We are looking into both the partonic dynamics at the short distance, as well as the nucleon structure at long distance

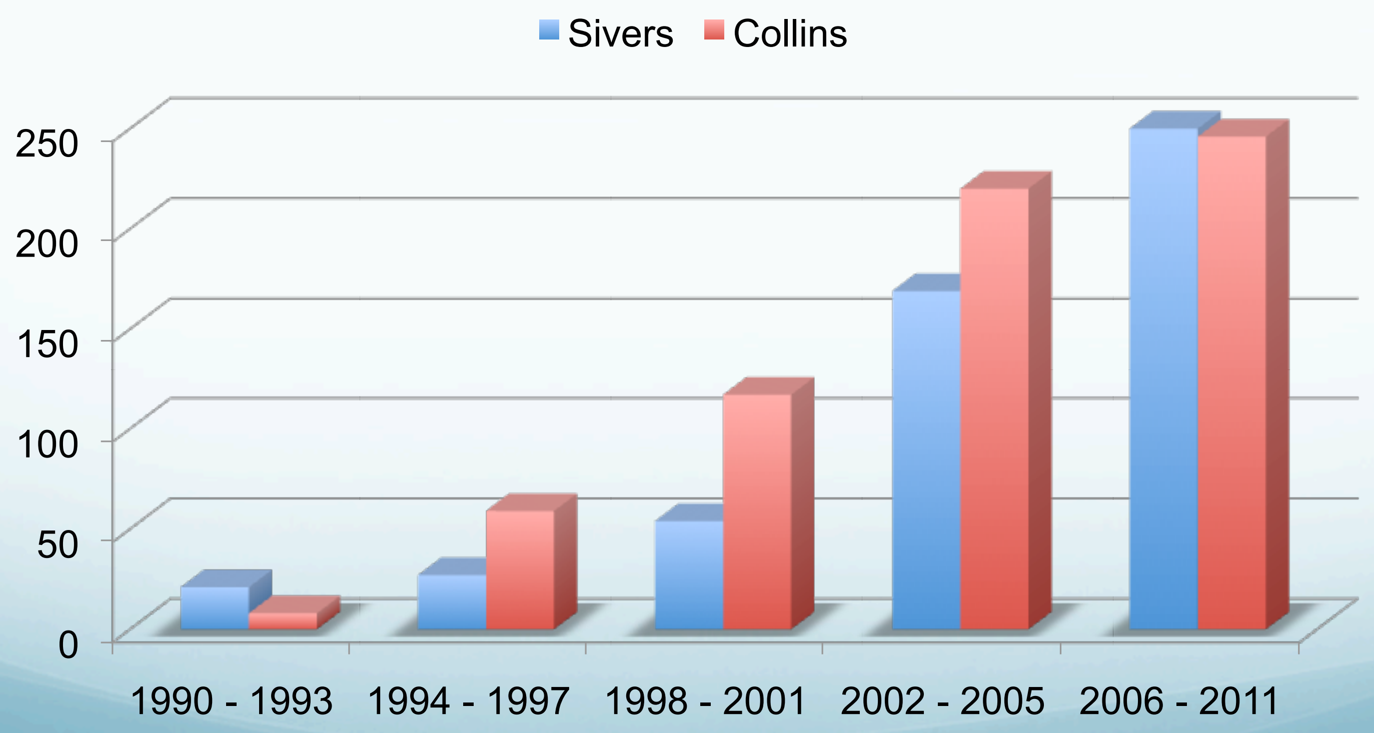




QCD Factorization

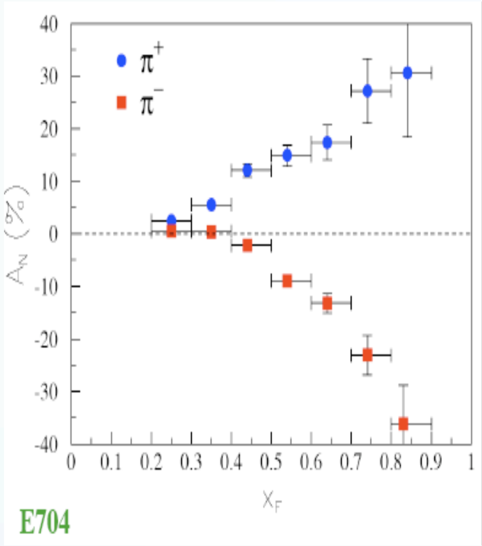
Transverse spin physics: birth and growth

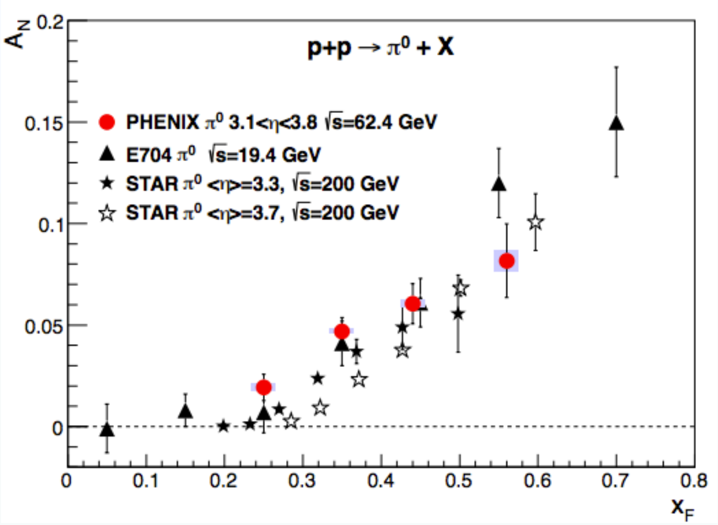
- Remarkable development of this field
  - From the sidelines in strong interaction physics
  - To center stage in our efforts to figure out QCD
- Numerous exciting new developments over recent years
  - Differential citation grows exponentially as a function of time

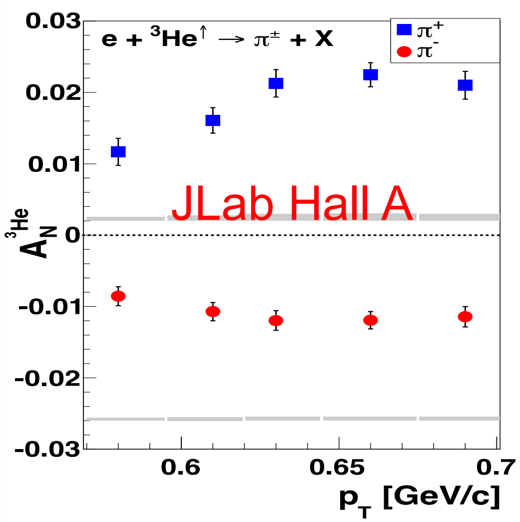


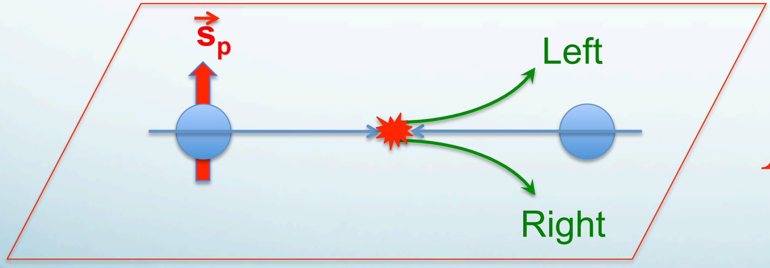
Example: experimental observable

- Consider a transversely polarized proton scattering with an unpolarized proton or lepton









$$A_N \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$

SSA vanishes with collinear momentum only

- If one assumes partons are purely collinear

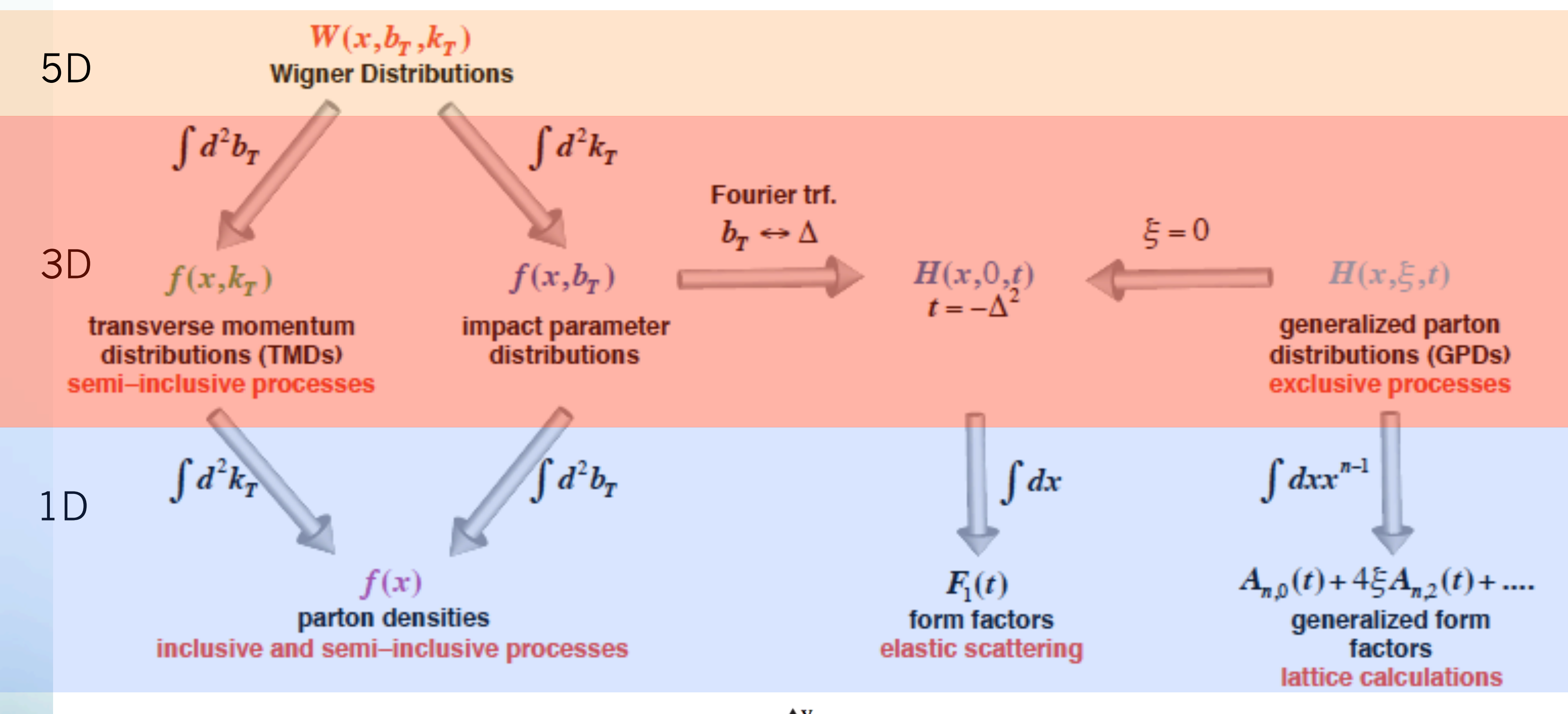
Kane-Pumplin-Repko, 1978

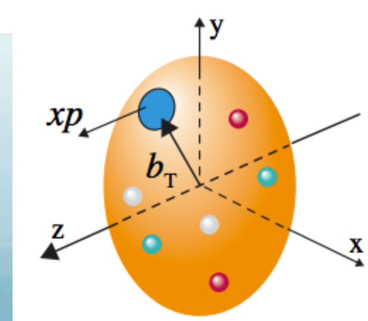
$$A_N \sim \alpha_s \frac{m_q}{\sqrt{s}} \to 0$$

- $A_N \neq 0$: result of parton's transverse motion
- A new window: much richer QCD dynamics

Unified view of nucleon structure

- Wigner distributions





TMDs: rich quantum correlations