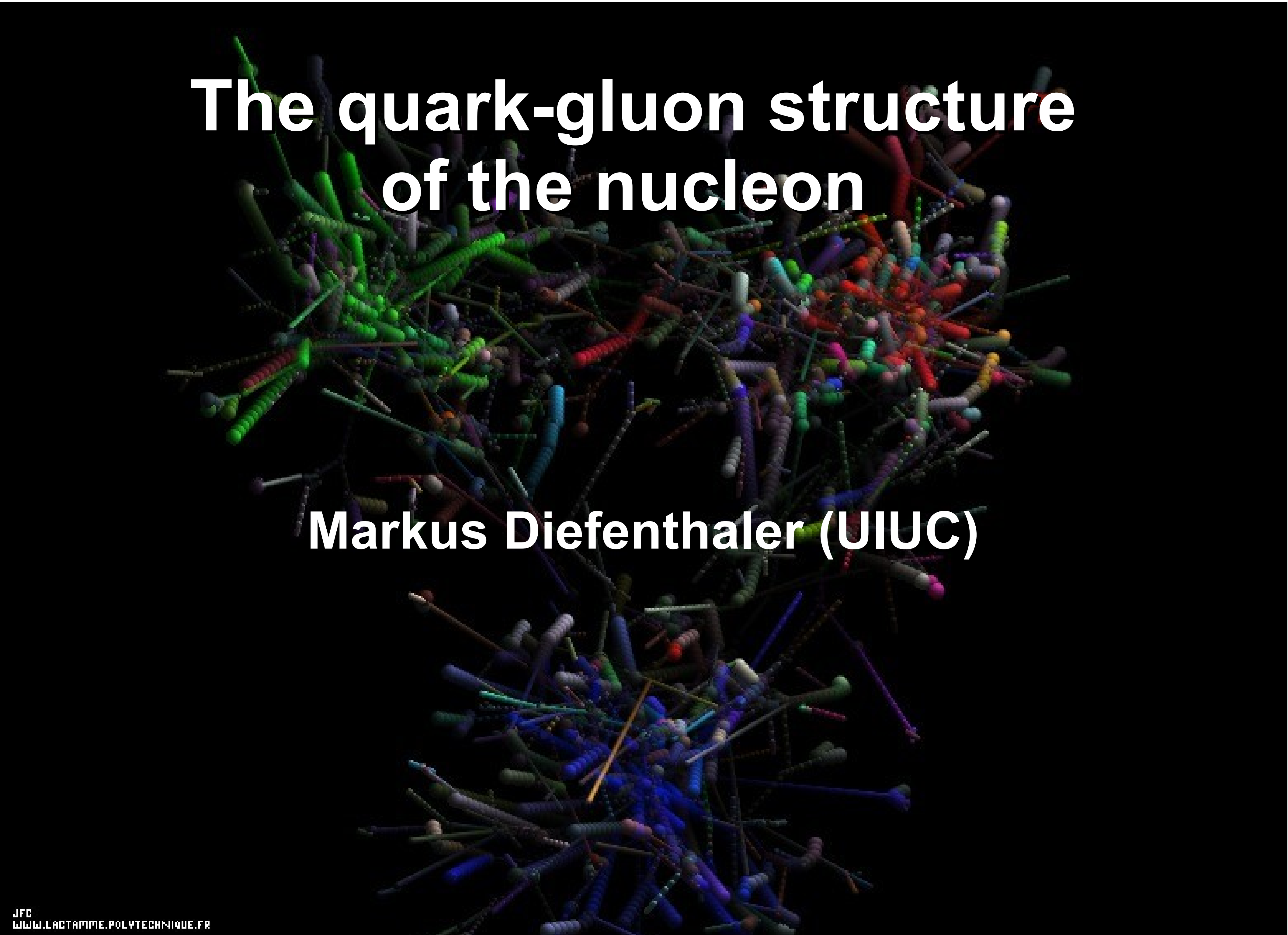
The quark-gluon structure of the nucleon

Markus Diefenthaler (UIUC)



QCD in a nutshell

Quantum Chromodynamics (QCD)

- established theory of the **strong interaction**
- self-consistent **relativistic quantum field theory**
  - two types of fields:

    1) **quark fields** → basic constituents of hadrons

    2) **gluon fields** → binding energy between quarks
  - non-abelian gauge theory (Yang-Mills theory)
- unlike electroweak interactions, no direct calculations of many QCD phenomena by weak-coupling perturbation theory

  → QED first principle prediction of spectacular accuracy

  → many phenomena, e.g., the pion and proton bound states, are **non-perturbative** and **highly non-trivial**
- QCD is of utmost importance, e.g., most of the mass of ordinary matter is due to the strong interaction

Key features of QCD

- **Confinement:**
  - QED: electrons and photons exist in isolated single-particle states
  - QCD: no states for isolated quarks and gluons
- **Asymptotic Freedom:**
  - breakdown of electroweak theory (ultra-violet divergences)
  - effective QCD coupling goes to zero at zero distance

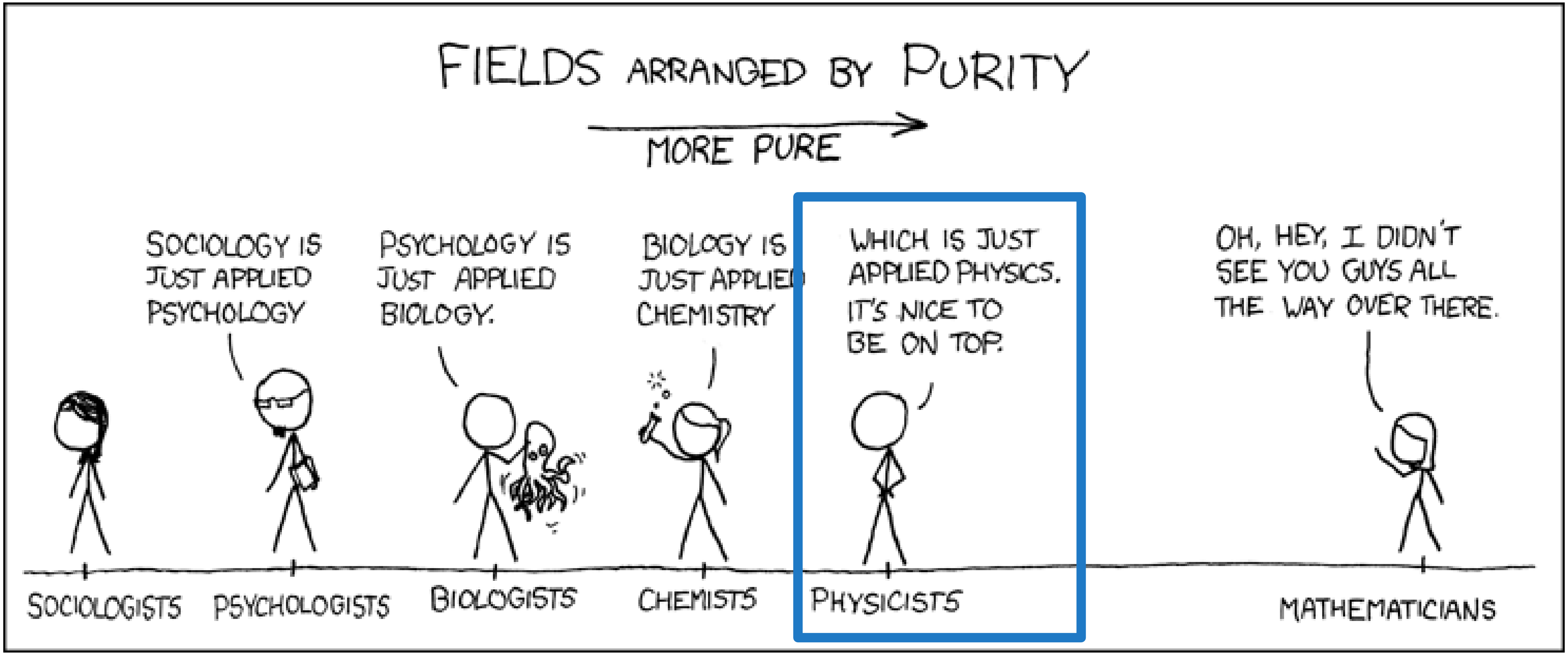
    $\longrightarrow$ short-distance processes yield to perturbation theory

    $\longrightarrow$ correct renormalization of ultra-violet divergencies

    $\longrightarrow$ no breakdown of the theory

More is different

The Reductionist Ideal



The Theory of Everything

For experts we write

$$i\hbar \frac{\partial}{\partial t} |\Psi > \; = \mathcal{H} |\Psi > \qquad \textbf{[1]}$$

where

$$\mathcal{H} = -\sum_{j}^{N_e} \frac{\hbar^2}{2m} \nabla_j^2 - \sum_{\alpha}^{N_i} \frac{\hbar^2}{2M_\alpha} \nabla_\alpha^2$$

$$-\sum_{j}^{N_e} \sum_{\alpha}^{N_i} \frac{Z_\alpha e^2}{|\vec{r}_j - \vec{R}_\alpha|} + \sum_{j \ll k}^{N_e} \frac{e^2}{|\vec{r}_j - \vec{r}_k|} + \sum_{\alpha \ll \beta}^{N_j} \frac{Z_\alpha Z_\beta e^2}{|\vec{R}_\alpha - \vec{r}_\beta|}. \qquad \textbf{[2]}$$

The symbols $Z\alpha$ and $M\alpha$ are the atomic number and mass of the α^{th} nucleus, $R\alpha$ is the location of this nucleus, e and m are the electron charge and mass, r_j is the location of the j^{th} electron, and $\hbar$ is Planck's constant.

Higher organizing principles - **Continuous Symmetry Breaking**

REVIEWS OF
MODERN PHYSICS

VOLUME 41, NUMBER 3 JULY 1969

Determination of e/h, Using Macroscopic Quantum Phase Coherence in Superconductors: Implications for Quantum Electrodynamics and the Fundamental Physical Constants

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Higher organizing principles - **Localization**

VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

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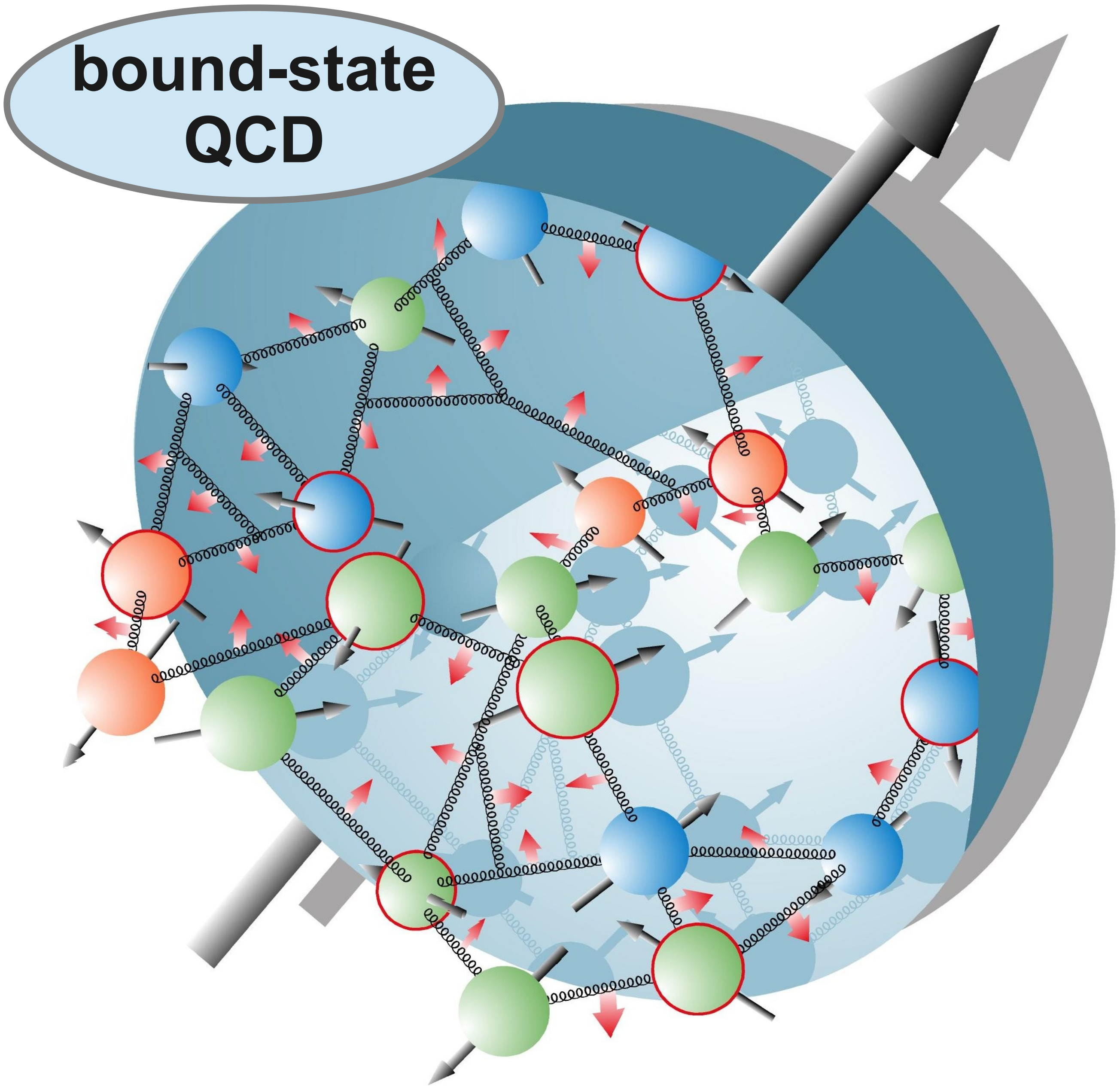
(Received 30 May 1980)

Measurements of the Hall voltage of a two-dimensional electron gas, realized with a silicon metal-oxide-semiconductor field-effect transistor, show that the Hall resistance at particular, experimentally well-defined surface carrier concentrations has fixed values which depend only on the fine-structure constant and speed of light, and is insensitive to the geometry of the device. Preliminary data are reported.

Hierarchical Structure of Science

- Symmetry is of great importance in physics.
- Internal structure of matter needs not be symmetrical even if the total state of this is.
- The state of a really big system does not at all have the symmetry of the laws which govern it; it usually has less symmetry.
- Theory of things - emerging from its parent and involving into into its children as the energy is lowered.

The inner structure of the nucleon



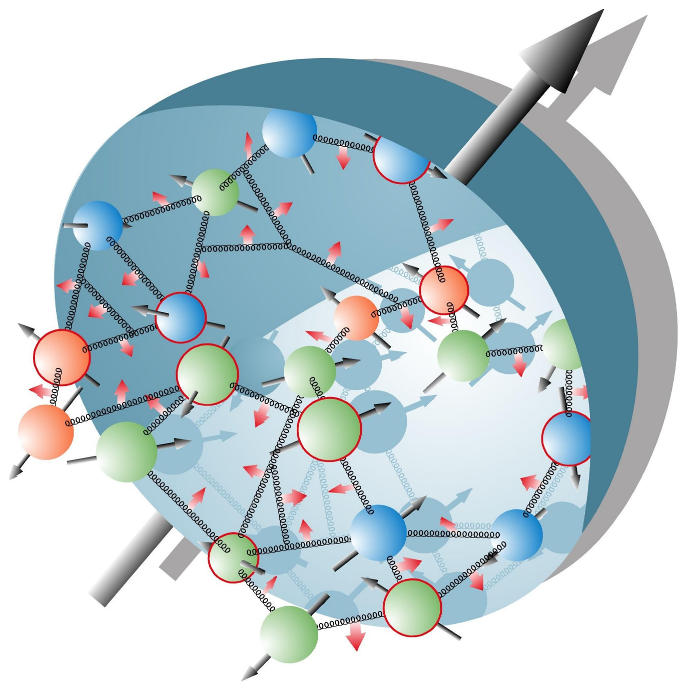
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

The inner structure of the nucleon

- Mathematical proof of confinement included among the seven Millennium Prize Problems in Mathematics.
- **Exploring the nonperturbative regime:**
  - **Lattice QCD:** *“Through difficult calculations of merciless precision that call upon the full power of modern computer technology, […] they have demonstrated the origin of the proton's mass [...]I believe this is one of the greatest scientific achievements of all time.”* (Frank Wilczek)
  - Intense **experimental studies** of deep-inelastic scattering, electron-positron annihilation and proton-proton collisions (including **Drell-Yan scattering**).

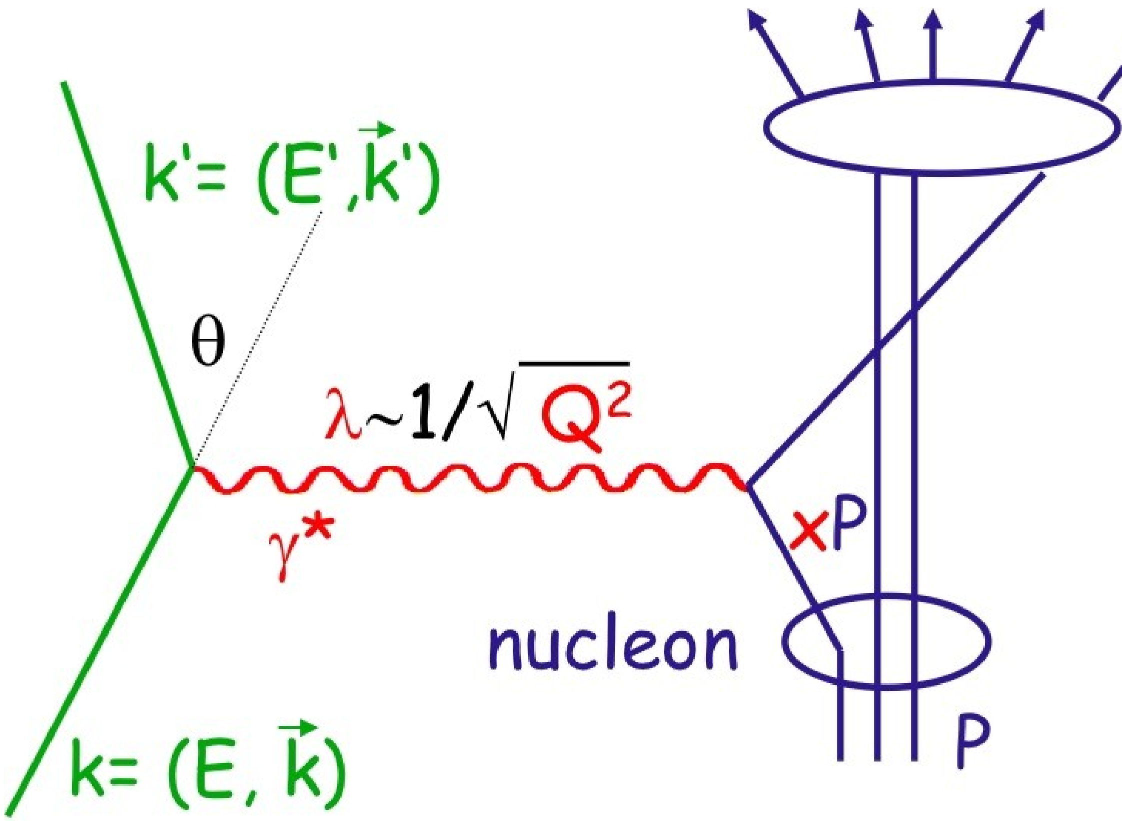
Properties of the nucleon



property	quarks	gluons
momentum	~50%	~50%
mass	~5%	~95%
charge	valence quarks |p> = |uud> |n> = |ddu>	-
spin	30%	~0%

PDF

Deep-inelastic lepton-nucleon scattering



$Q^2 = -(k-k')^2 = 2EE'(1-\cos\theta)$

$\nu = E - E', y = \nu/E$

$x = Q^2/(2M\nu)$ = fraction of nucleon's momentum P, carried by struck quark

Probing the inner structure

cross-section measurements

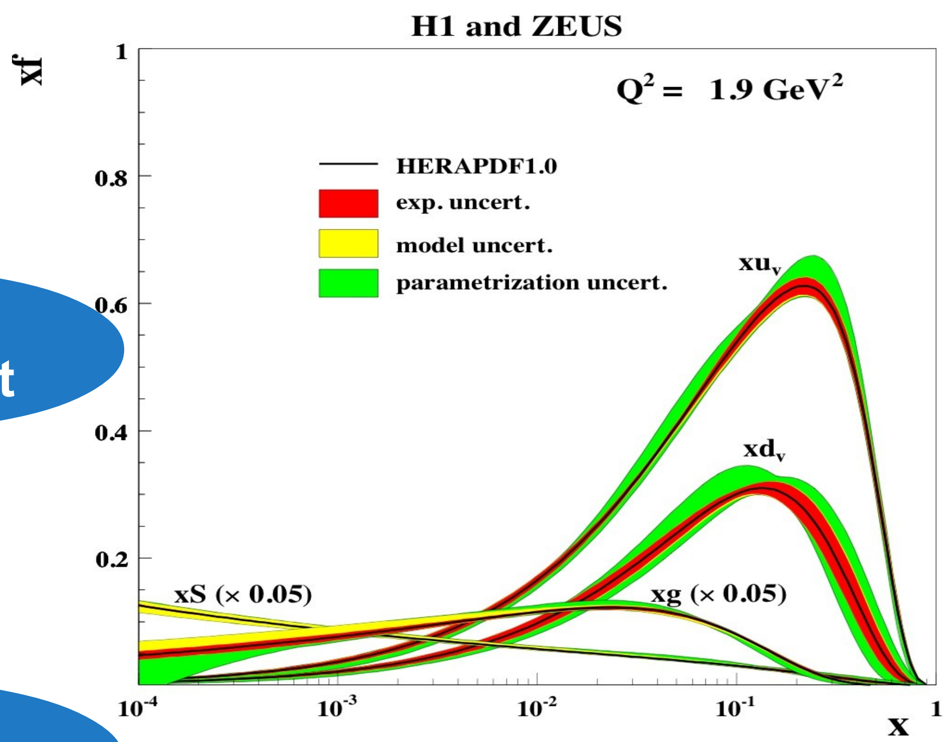
decomposed ↓

structure functions — process dependent

interpreted ↓

Parton Distribution Functions — universal

$$F_1(x,Q^2) = \sum_q e_q^2 \left(f_1^q(x,Q^2) + f_1^{\bar{q}}(x,Q^2) \right)$$

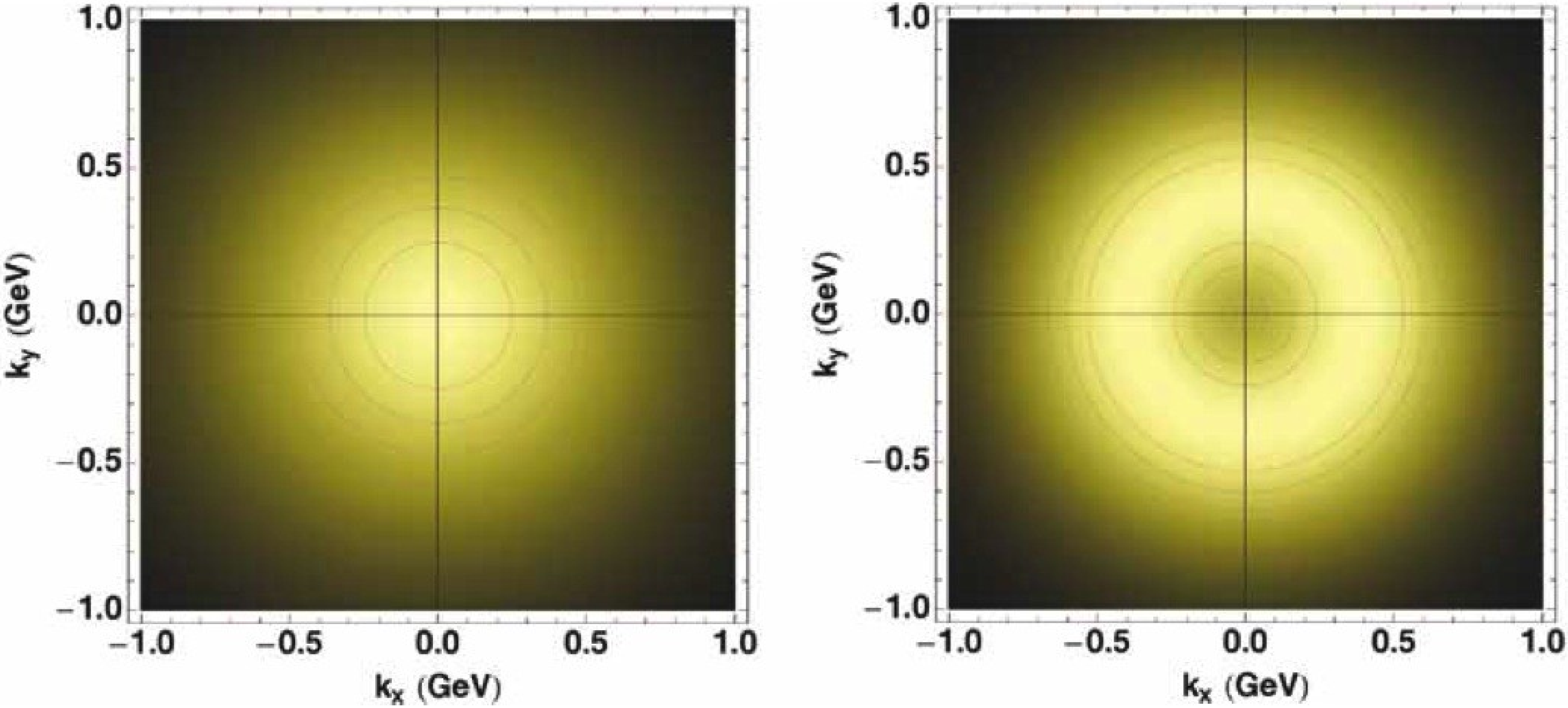


TMD

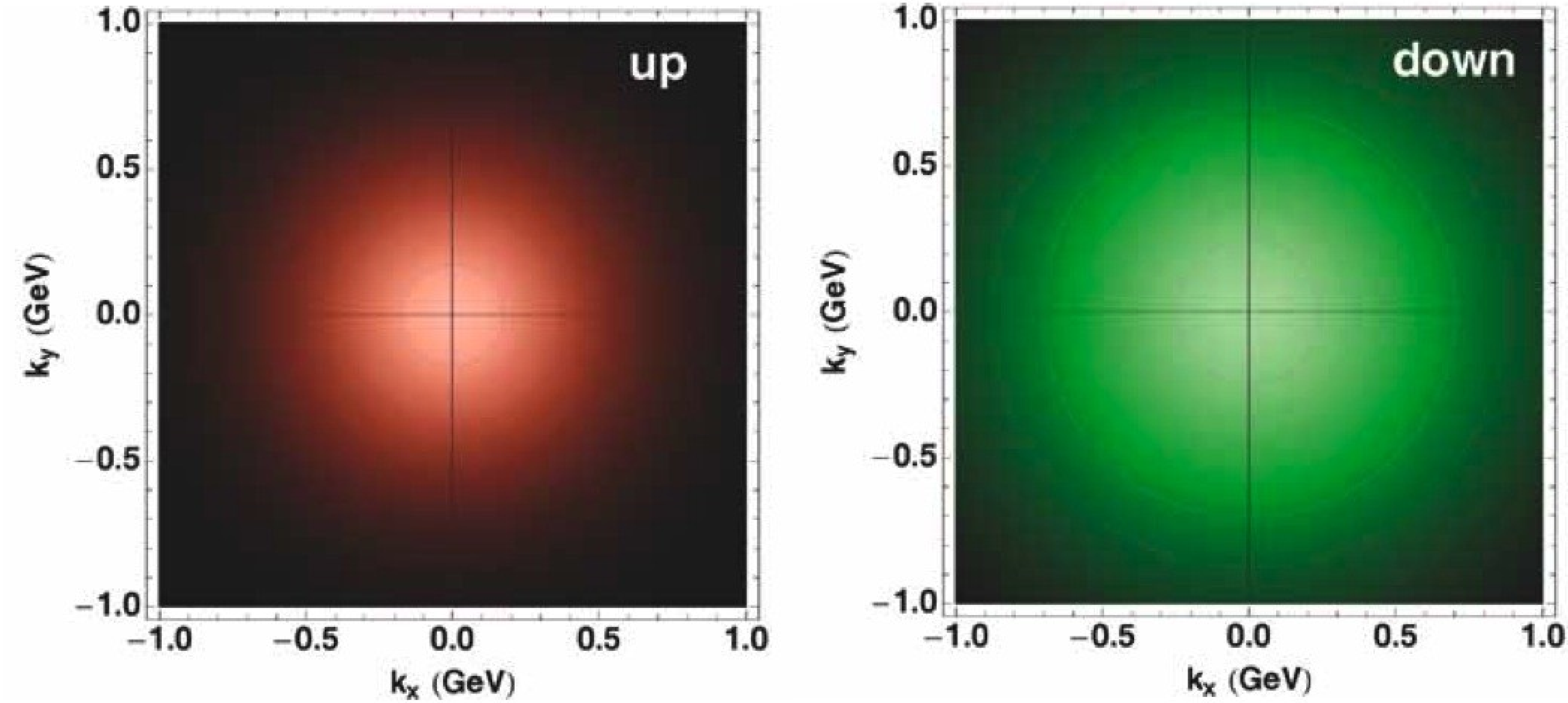
Images of the proton

- **partons within the nucleon:**
  - three position coordinates
  - three momentum coordinates
  - hard probe → longitudinal direction → transverse plane
- their state can be described by **Wigner distributions:**
  - quantum phase space distribution
  - quasi-probability density (uncertainty principle, not positive definite)
  - equivalent to **parton's complete wave function**
- **projections of Wigner distributions: PDF, TMD, GPD** have probabilistic interpretation

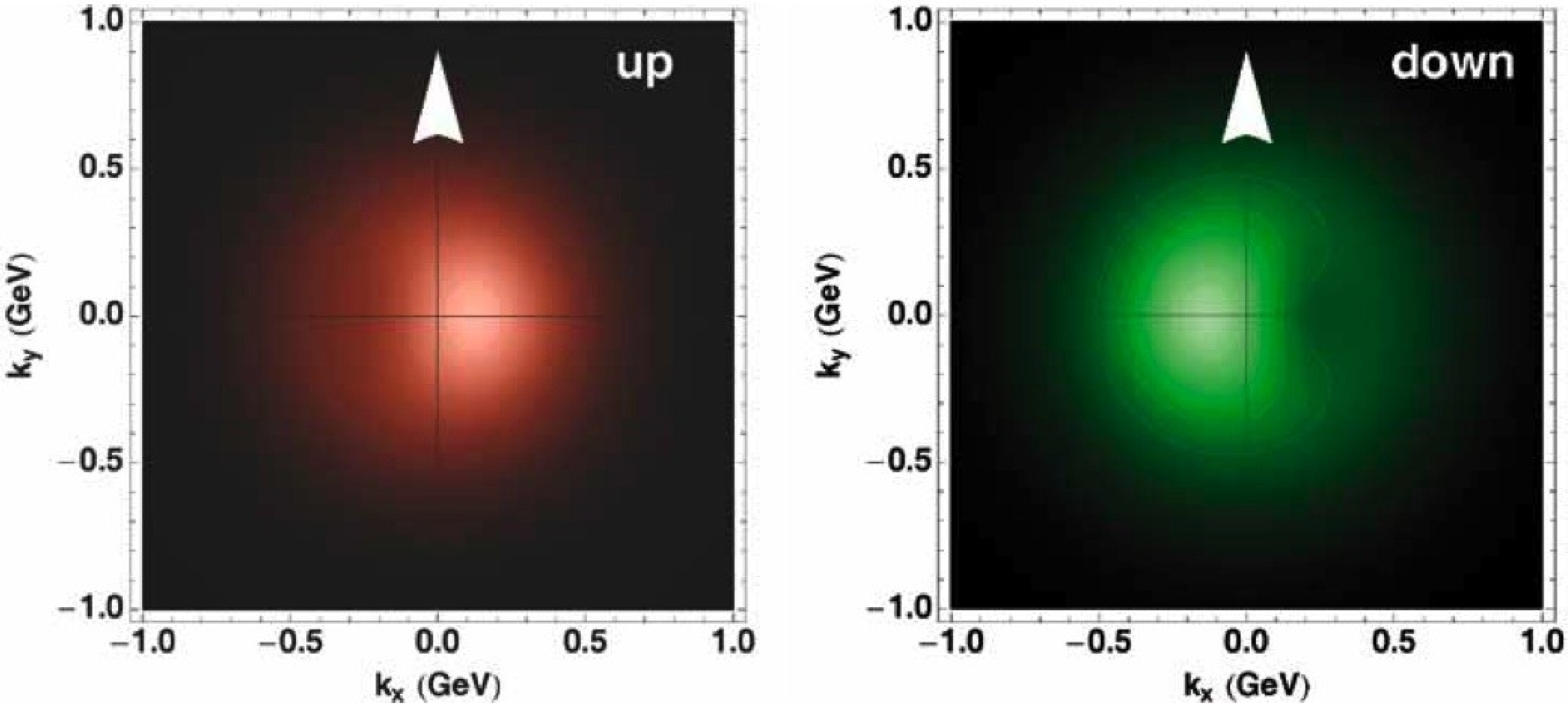
Distributions in momentum space



Flavor-dependence of TMD



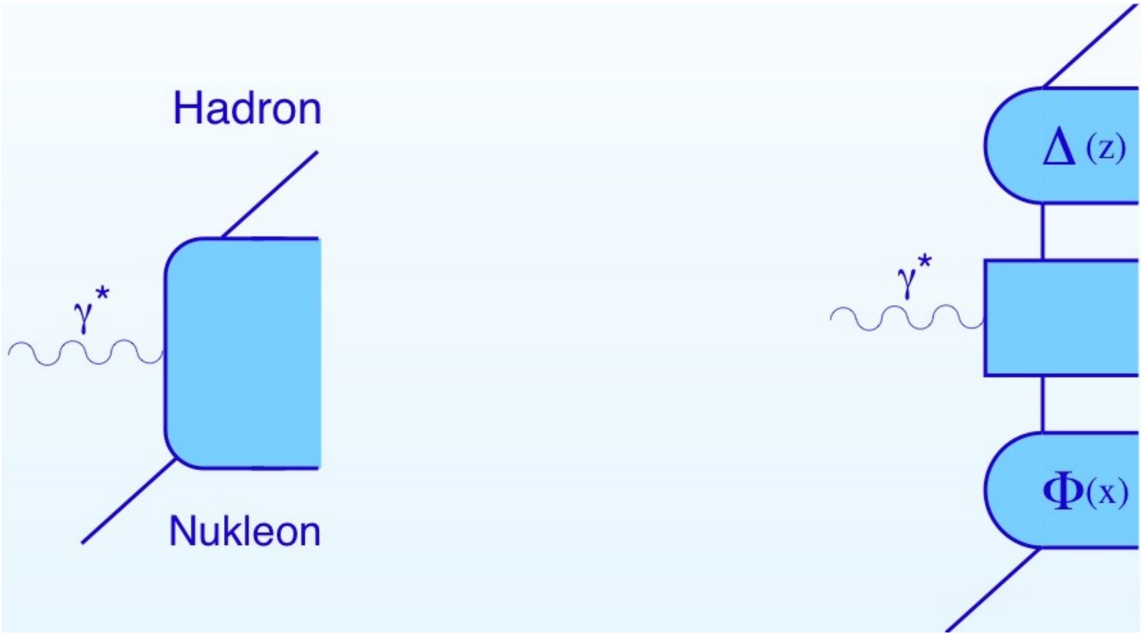
Distortion of distributions



TMD factorization

The inner structure of the nucleon

Measurement: | **QCD analysis:**



fragmentation

confinement

cross section

cross-section asymmetries

factorization theorem

Leading-twist representation of the nucleon structure

- description of the nucleon structure **including** p_T:

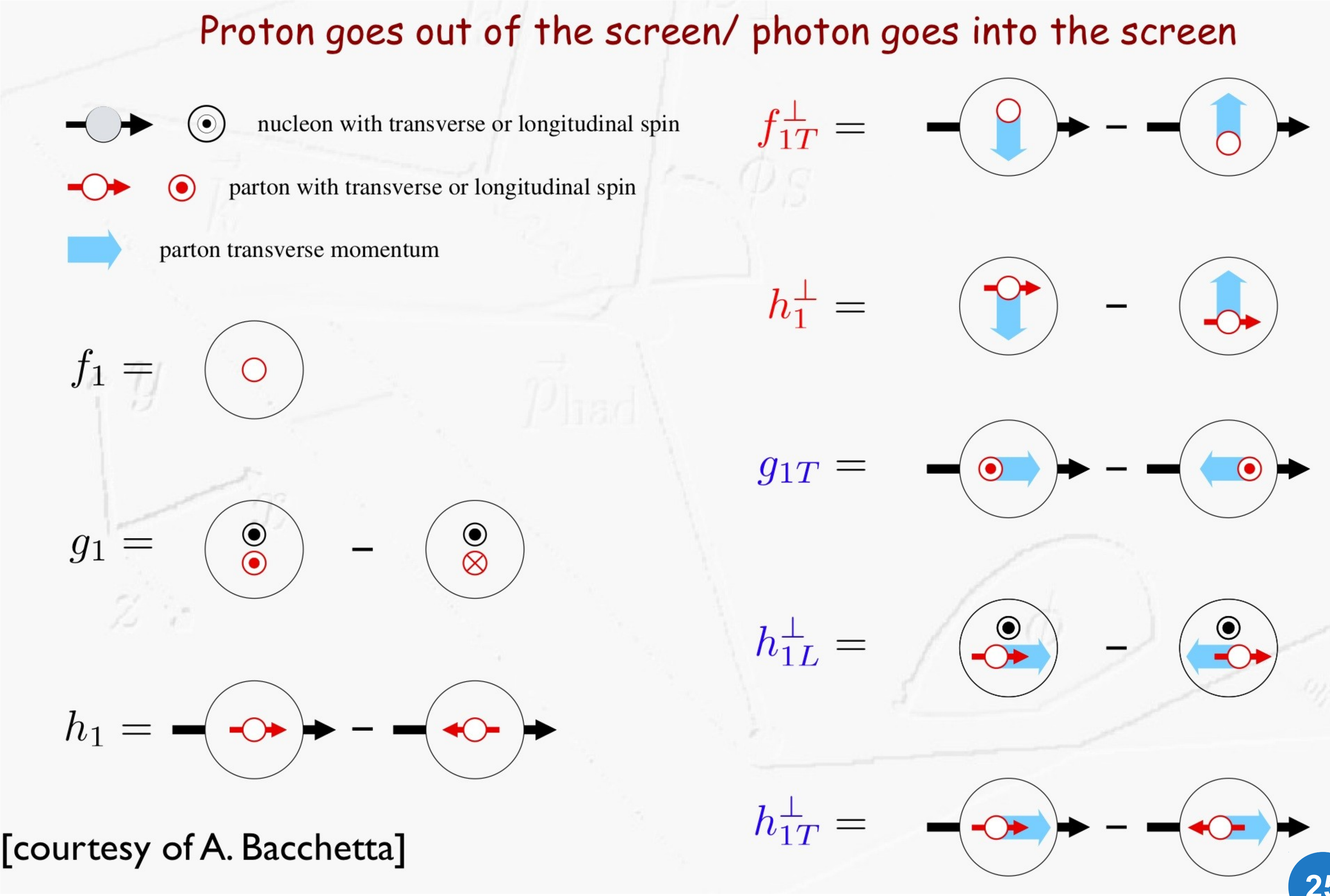
$$\frac{1}{2}\,\mathrm{Tr}\left[\left(\gamma^+ + \lambda\gamma^+\gamma_5\right)\Phi\right] = \frac{1}{2}\left[f_1^q + S_T^i\epsilon^{ij}p_T^j\frac{1}{M}\,f_{1T}^{\perp,q} + \lambda\Lambda\,g_1^q + \lambda S_T^i p_T^i\frac{1}{M}\,g_{1T}^{\perp,q}\right],$$

$$\frac{1}{2}\,\mathrm{Tr}\left[\left(\gamma^+ - s_T^j i\sigma^{+j}\gamma_5\right)\Phi\right] = \frac{1}{2}\left[f_1^q + S_T^i\epsilon^{ij}p_T^j\frac{1}{M}\,f_{1T}^{\perp,q} + s_T^i\epsilon^{ij}p_T^j\frac{1}{M}\,h_1^{\perp,q} + s_T^i S_T^i\,h_1^q + s_T^i\left(2p_T^i p_T^j - \boldsymbol{p}_T^2\delta^{ij}\right)S_T^j\frac{1}{2M^2}\,h_{1T}^{\perp,q} + \Lambda s_T^i p_T^i\frac{1}{M}\,h_{1L}^{\perp,q}\right],$$

quark λ and nucleon helicity Λ, transverse spins $\boldsymbol{s}_T$ and $\boldsymbol{S}_T$ of quarks and nucleons

- **transverse-momentum-dependent PDF**
  ➥ related to **spin-orbit correlations**
  ➥ constraints on orbital angular momentum (contributions)?
- **naive-T-odd** Sivers $f_{1T}^{\perp,q}$ and Boer–Mulders $h_1^{\perp,q}$ functions
  ➥ initial- or final-state interactions / **transverse SSA**
  ➥ profound consequences on factorisation and universality

Leading-twist TMD

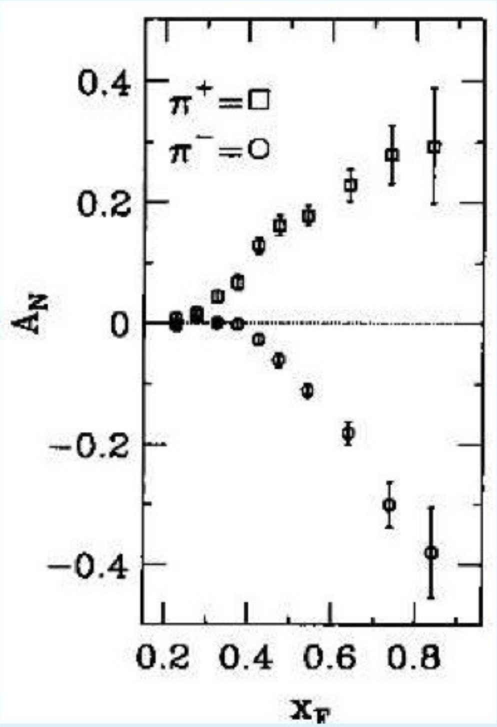


Transverse SSA

Transverse Single-spin Asymmetries

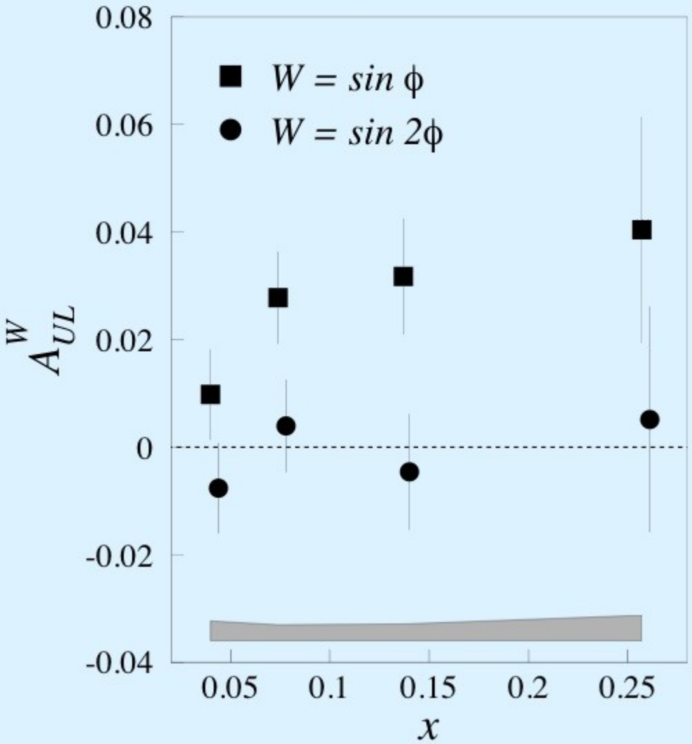
- **Observation of single-spin asymmetries**:

E581/E704 ($p^{\Uparrow}p \to hX$) :



PL**B261**, 201–206, 1991

HERMES ($lp^{\Rightarrow} \to l'hX$) :



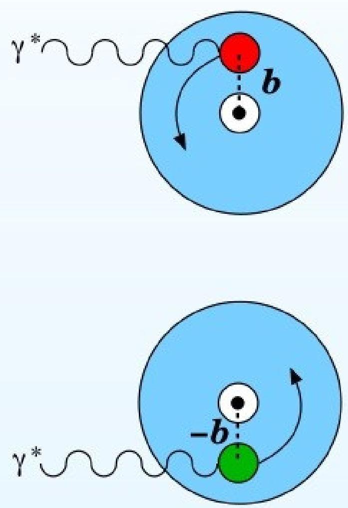
PRL**84**, 4047–4051, 2000

- Global analysis of:

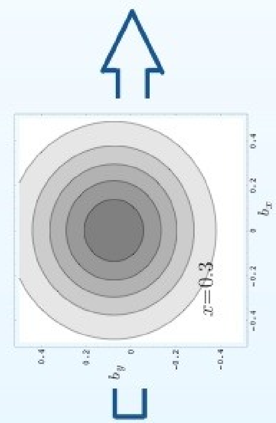
transverse-momentum-dependent PDF

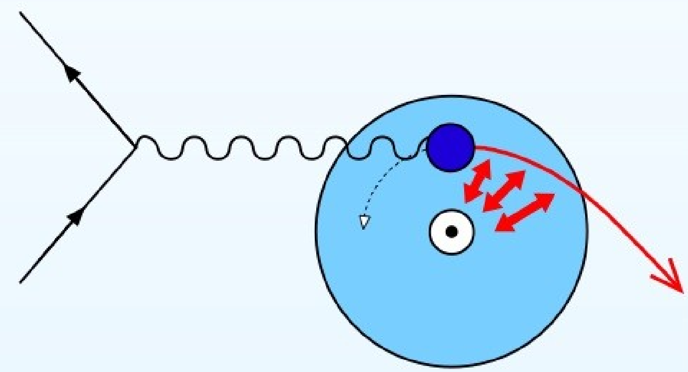
The Sivers mechanism

- **Sivers function** $f_{1T}^{\perp}\left(x, \boldsymbol{p_T}^2\right)$: $N^{\Uparrow} q^{\uparrow} \rightarrow N^{\Downarrow} q^{\uparrow}$
- **orbital angular momentum of quarks:**



$u_X\left(x, \boldsymbol{b}_\perp\right)$:





- **final-state interaction:**

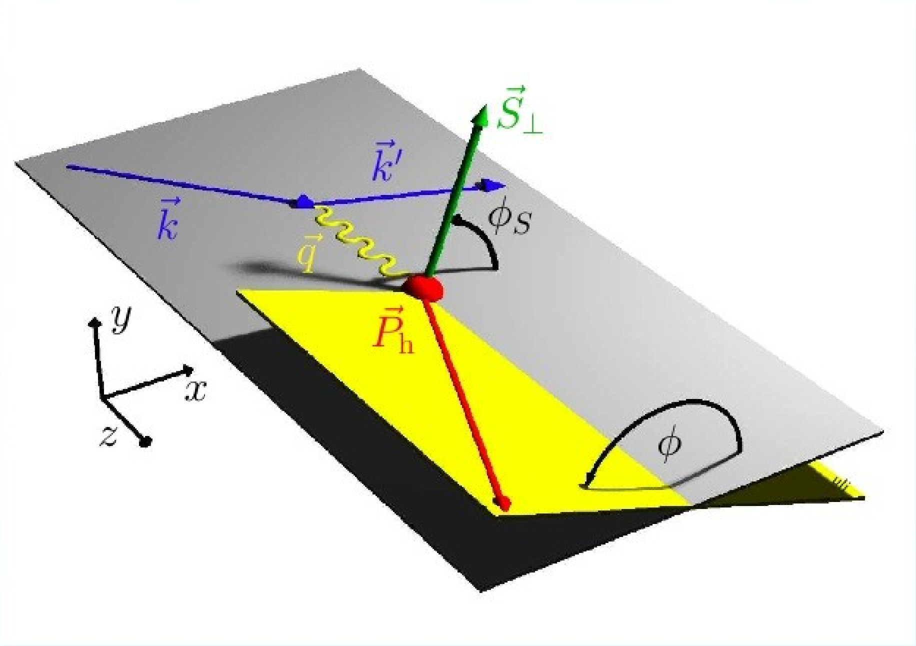
  left-right asymmetry of quark distribution

  ➥ left-right-asymmetry of momentum distribution of hadrons

- **structure function**: $F_{UT,T} = -\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M} f_{1T}^{\perp}\left(x, \boldsymbol{p_T}^2\right) D_1\left(z, z^2\boldsymbol{k_T}^2\right)\right]$

Fourier decomposition of TSSA

Measurement of **azimuthal single-spin asymetries** $A_{\mathrm{UT}}(\phi,\phi_S)$:



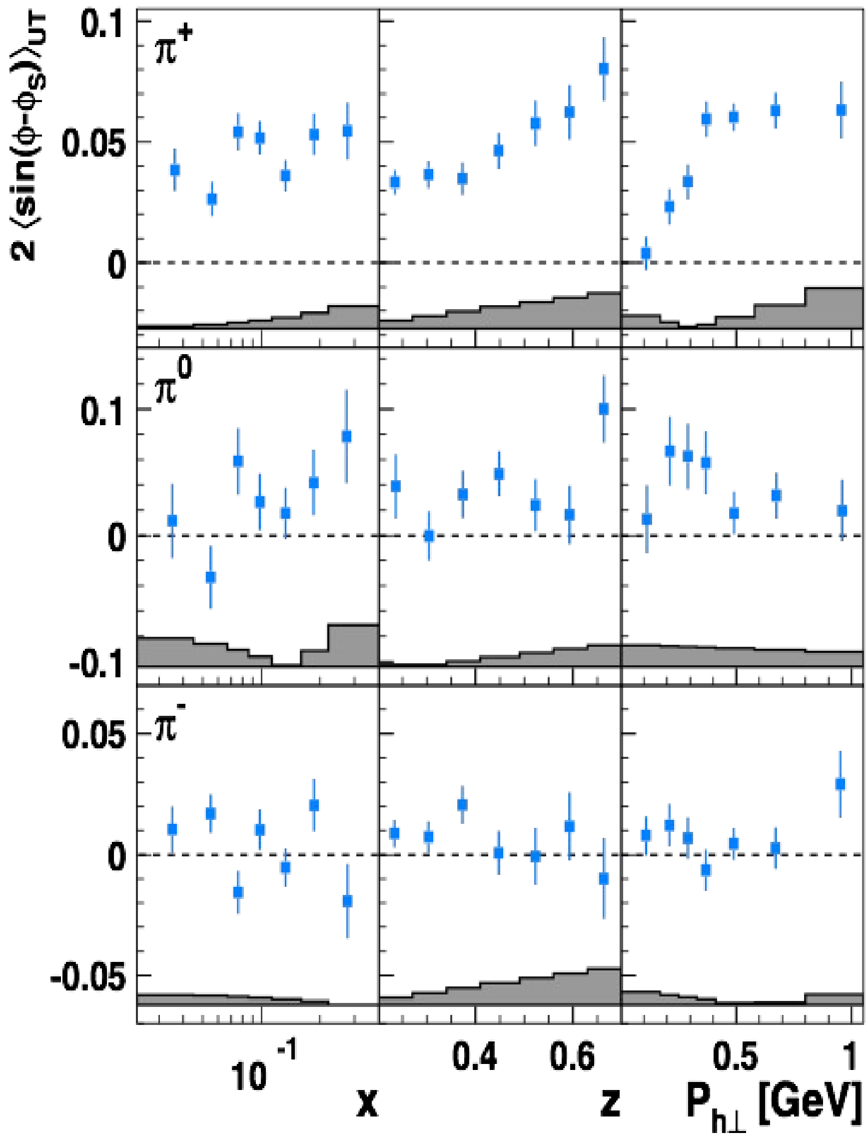
$$\boldsymbol{P}_{h\perp} = z(\boldsymbol{p}_T - \boldsymbol{k}_T)$$

$$\frac{d\sigma^h}{dx\, dy\, d\phi_S\, dz\, d\phi\, d\boldsymbol{P}_{h\perp}^2} \propto \ldots \sin(\phi - \phi_S)\, F_{UT,T}^{\sin(\phi-\phi_S)} + \sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} \ldots$$

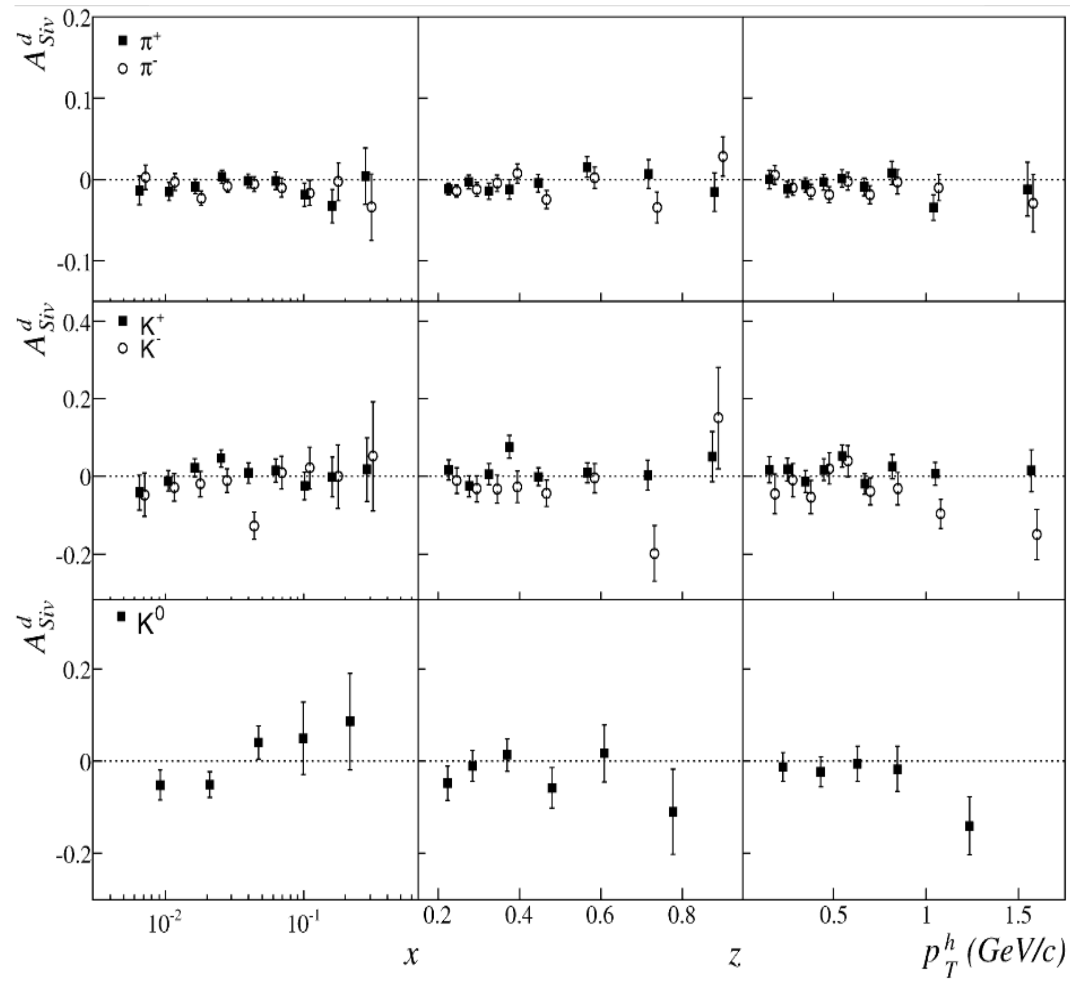
Sivers mechanism:	$\sin(\phi - \phi_S)$
Collins mechanism:	$\sin(\phi + \phi_S)$

Sivers SSA for from $H^{\uparrow}$ & $D^{\uparrow}$

HERMES final $H^{\uparrow}$



COMPASS final 2003-04 $D^{\uparrow}$

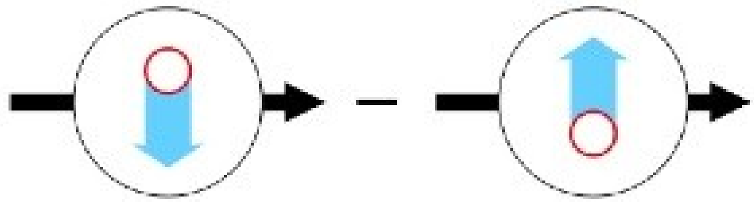


$$f_{1T}^{\perp}(x,k_T)\otimes D_1^{\perp}(z)$$

The Sivers TMD

The Sivers function

- **transverse-momentum dependent PDF:**

$f_{1\mathrm{T}}^{\perp,q}(x, \mathbf{p}_T^2)$  $S_T^i \varepsilon^{ij} p_T^j$

- rather exotic in being **naïve-time-reversal-odd**

  $\leftrightarrow$ initial (Drell-Yan) and final state (SIDIS) interactions

  $\rightarrow$ **single-spin asymmetries:**

$$A_N^{\mathrm{DY}} \sim f_{1T}^{\perp,q}(x_b) \otimes f_1^{\bar{q}}(x_t), \quad A_{UT} \sim f_{1T}^{\perp,q}(x) \otimes D_1(z)$$

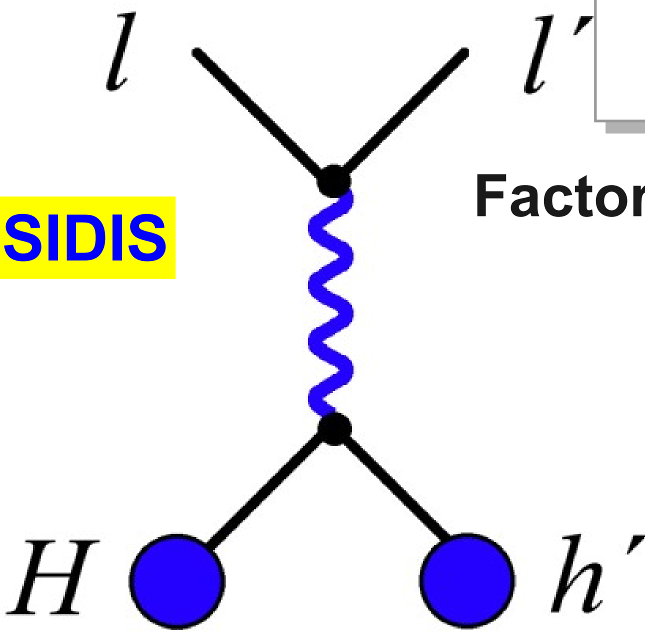
- close **relationship to quark orbital angular momentum**
- challenging the concept of factorization and universality
  - **fundamental QCD prediction:** $f_{1T}^{\perp,\mathrm{DIS}} = -f_{1T}^{\perp,\mathrm{DY}}$
  - remains to be experimentally tested
  - **polarized Drell-Yan measurement required**

T-even and naïve T-odd

- **T** and **naïve-T** are defined as operators on certain objects, e.g. a Lagrangian density or a scattering amplitude.
- T invariance means that the QCD Lagrangian density is invariant under a **T** operator. This implies that the scattering amplitude(A -> BC) is equal to the scattering amplitude(B'C' -> A'). Here, the ' refers to an reversal of spin and momentum directions.
- The **naïve-T** operator reverses the spin and momentum directions of particles. Thus, you read in the literature that T-odd is T without interchange of initial and final states. Naive-T-odd implies that the scattering amplitude(A -> BC) is minus equal the scattering ampltidude(A' -> B'C').
- **naïve-T-odd** cross-section contributions are build from **T-even** scattering amplitudes requiring either an interference between two amplitudes where at least one of them has an imaginary part or involves a spin flip.
- The concept of **naïve-T-odd** is used to mark functions with the property to explain **SSA** in hard scattering processes.
- **naïve-T-odd** is not related to a symmetry (like **T**) of QCD or another theory.

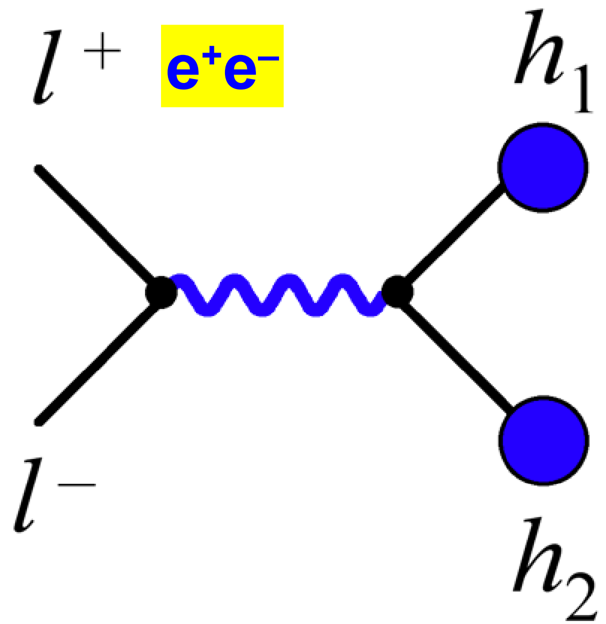
Global analysis of the Sivers TMD

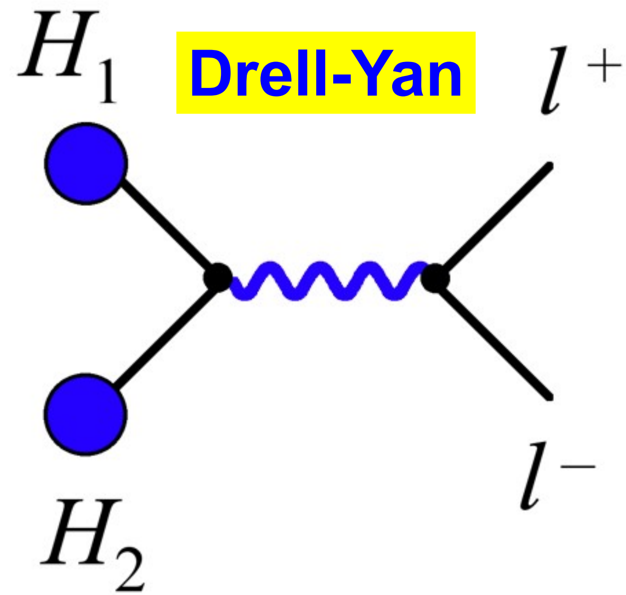
Fundamental processes



Factorization: $d\sigma \sim \sum_q e_q^2 \; \mathbf{f_q^{(H)}}(x) \; \mathbf{D_q^{h'}}(z)$

- *Disentangle **distribution** (f) and **fragmentation** (D) functions → measure **all process***
- *Disentangle **quark flavours** q → measure as many **hadron species** H,h as possible*



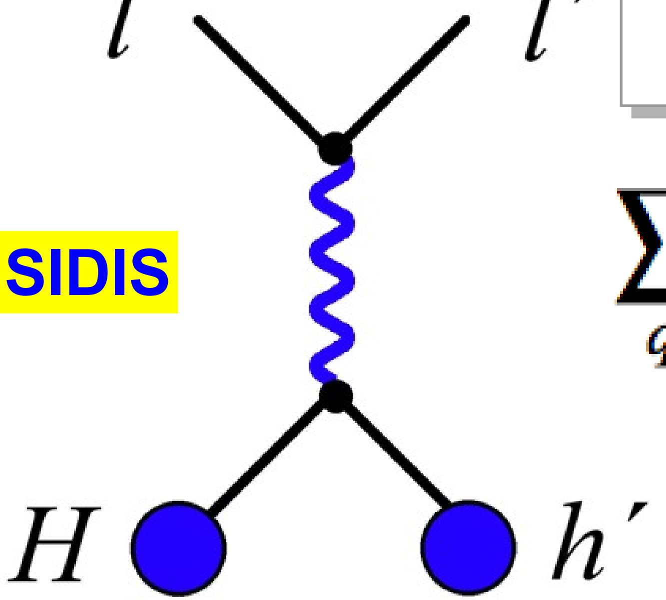


$$\sum_q e_q^2 \; \mathbf{D_q^{h_1}}(z_1) \; \mathbf{D_{\bar{q}}^{h_2}}(z_2)$$

$$\sum_q e_q^2 \; \mathbf{f_q^{(H_1)}}(x_1) \; \mathbf{f_{\bar{q}}^{(H_2)}}(x_2)$$

Fundamental processes

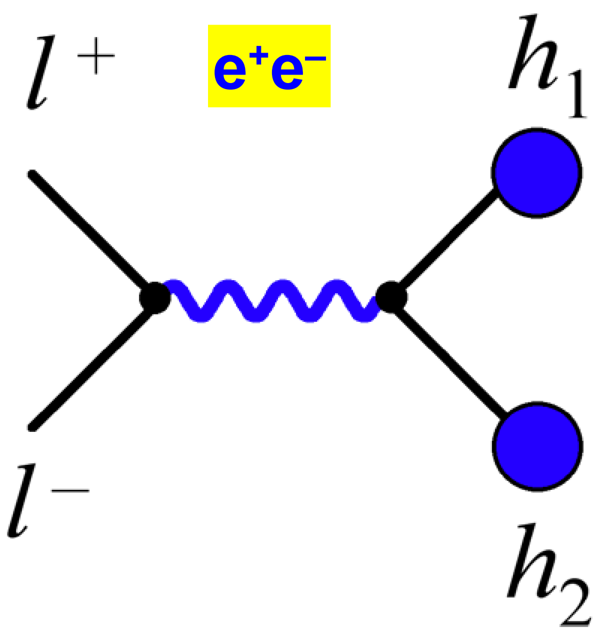
SIDIS



$$\sum_q e_q^2 \, \mathbf{f}_{\mathbf{q}}^{(\mathbf{H})}(x) \, \mathbf{D}_{\mathbf{q}}^{\mathbf{h}'}(z)$$

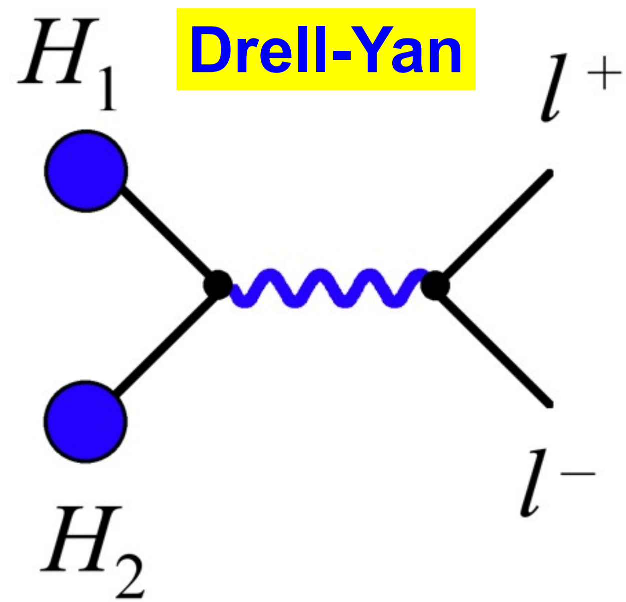
Spin Programs

e⁺e⁻

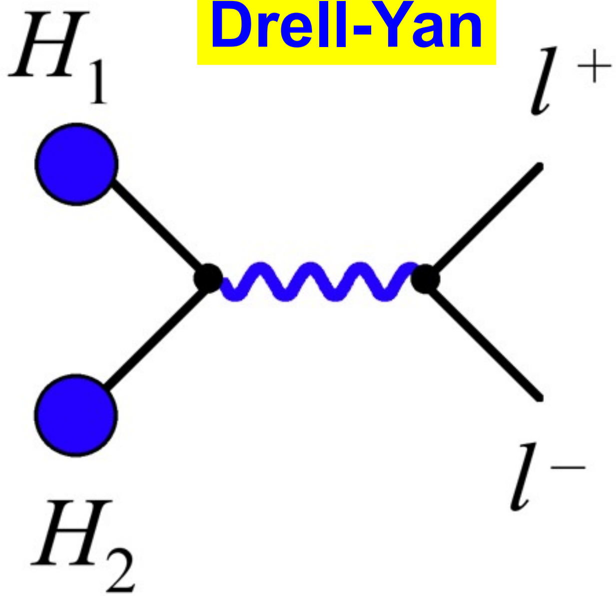


$$\sum_q e_q^2 \, \mathbf{D}_{\mathbf{q}}^{\mathbf{h_1}}(z_1) \, \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h_2}}(z_2)$$

Drell-Yan

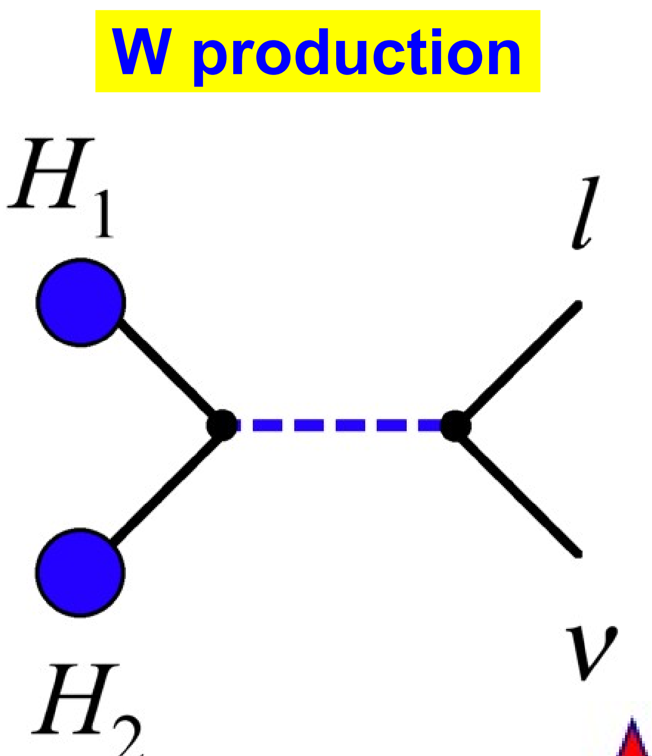


$$\sum_q e_q^2 \, \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \, \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$



The Missing Spin Program

$$\sum_q e_q^2\; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1)\; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$



- Clean access to **sea quarks**
  e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC
- Crucial test of **TMD formalism**
  → sign change of T-odd functions
- A **complete** spin program requires multiple hadron species
  → **nucleon & meson beams**

Global interest in polarized DY

experiment		particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	[11]	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17.4$ GeV	$x_2 = 0.2 - 0.3$	$1 \times 10^{32}\ cm^{-2}s^{-1}$	2014
PAX (GSI)	[12]	$p^{\uparrow} + \overline{p}$	collider $\sqrt{s} = 14$ GeV	$x_1 = 0.1 - 0.9$	$2 \times 10^{30}\ cm^{-2}s^{-1}$	>2017
PANDA (GSI)	[13]	$\overline{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$ GeV	$x_2 = 0.2 - 0.4$	$2 \times 10^{32}\ cm^{-2}s^{-1}$	>2016
NICA (JINR)	[14]	$p^{\uparrow} + p$	collider $\sqrt{s} = 20$ GeV	$x_1 = 0.1 - 0.8$	$1 \times 10^{30}\ cm^{-2}s^{-1}$	>2014
RHIC AnDY (BNL (IP-2))	[15]	$p^{\uparrow} + p$	collider $\sqrt{s} = 500$ GeV	$x_1 = 0.1 - 0.3$	$2 \times 10^{32}\ cm^{-2}s^{-1}$	2013
PHENIX (BNL)	[16]	$p^{\uparrow} + p$	collider $\sqrt{s} = 200$ GeV	$x_1 = 0.05 - 0.1$	$2 \times 10^{32}\ cm^{-2}s^{-1}$	>2018
RHIC internal target phase-1	[17]	$p^{\uparrow} + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_1 = 0.25 - 0.4$	$2 \times 10^{33}\ cm^{-2}s^{-1}$	>2015
RHIC internal target phase-2	[17]	$p^{\uparrow} + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_1 = 0.25 - 0.4$	$3 \times 10^{34}\ cm^{-2}s^{-1}$	>2018
SeaQuest (FNAL)	[1]	$p + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_1 = 0.3 - 0.9$ $x_2 = 0.1 - 0.45$	$2.0 \times 10^{35}\ cm^{-2}s^{-1}$	2011
pol. SeaQuest (FNAL)		$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_1 = 0.3 - 0.9$	$1 \times 10^{36}\ cm^{-2}s^{-1}$	>2014

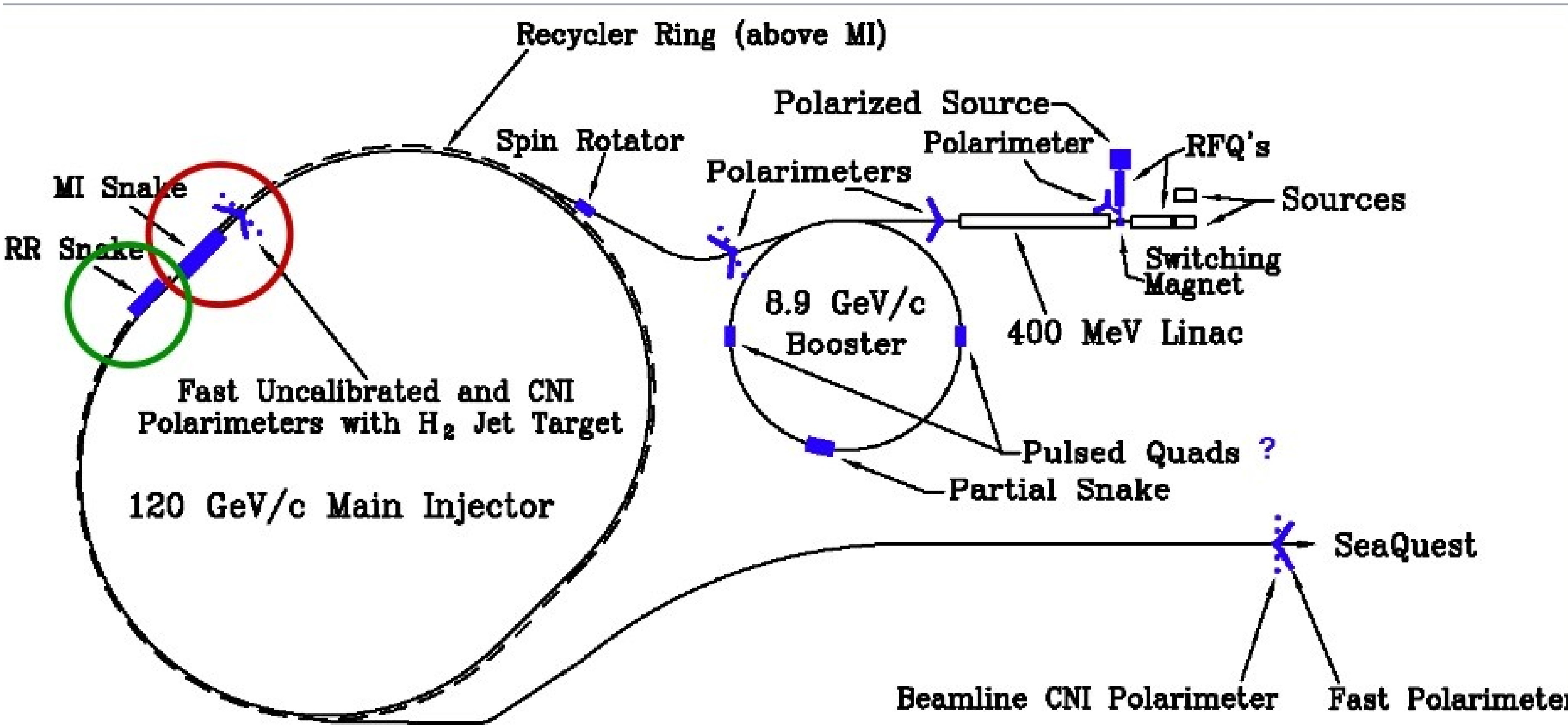
E-906/SeaQuest at Fermilab

- fixed-target Drell-Yan experiment
- target: unique access to sea quarks at high-x
- 120 GeV proton beam from Main Injector

- 2013 – 2015: well-understood experiment by 2015
- **E-1027 - upgrade with polarized beam**
- sensitive to beam valence quarks at high-x

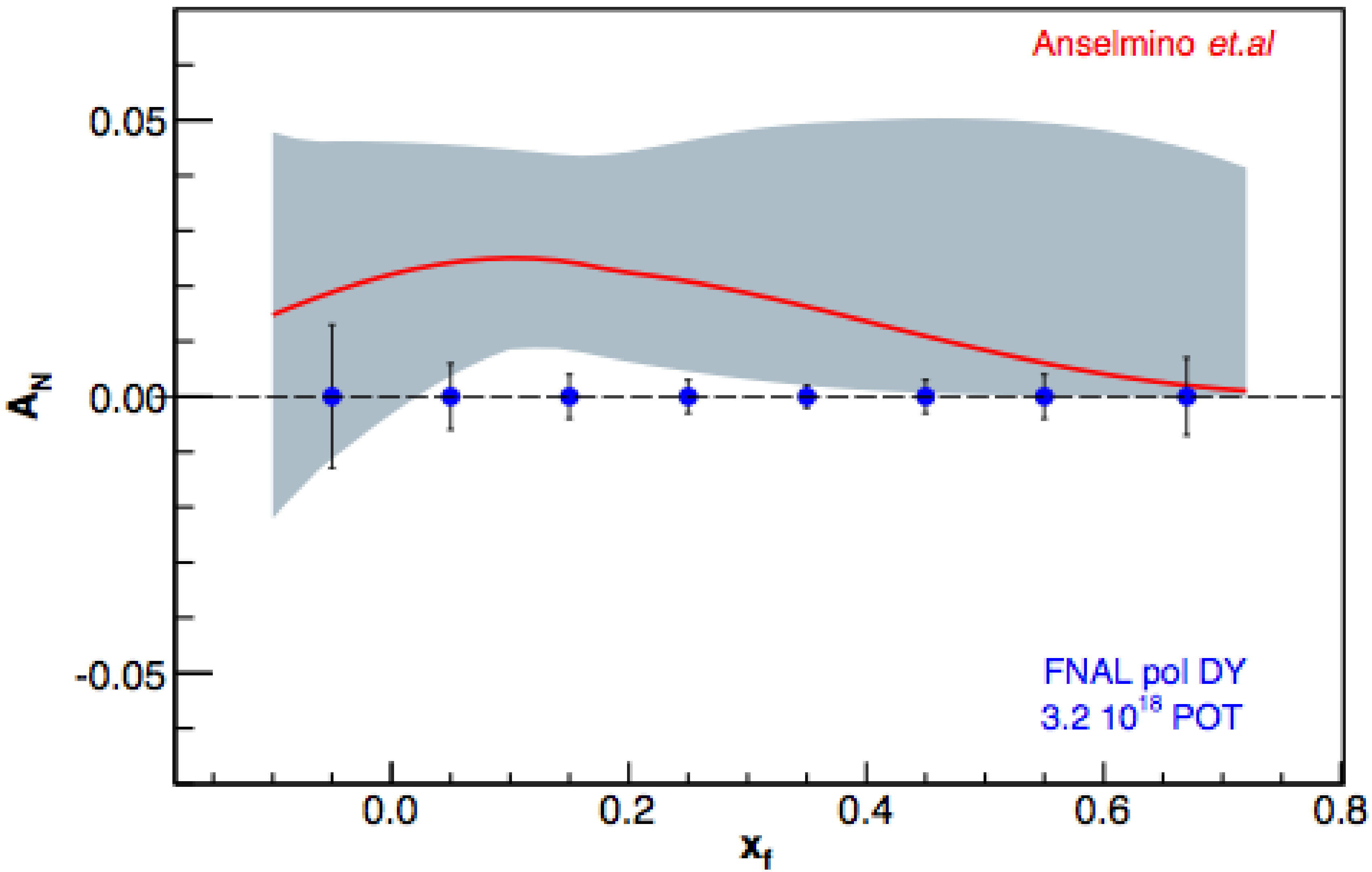
  → large effects → size / shape of Sivers TMD

Reestablishing spin at Fermilab



75% polarization

P-1027 - Predictions



The global investigation of the nucleon's quark-gluon structure is an interesting field of perturbative QCD.

TMDs challenge the concepts of universality and factorization.

Polarized Drell-Yan measurements are the missing component in the global TMD analysis.

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WWW.LACTAMME.POLYTECHNIQUE.FR