Nuclear Physics in Four Quadrants

QCD

1 Hadron Structure

2 Heavy Ions

4 Fundamental Symmetries

incl. ***neutrinos***

3 Nuclear Structure

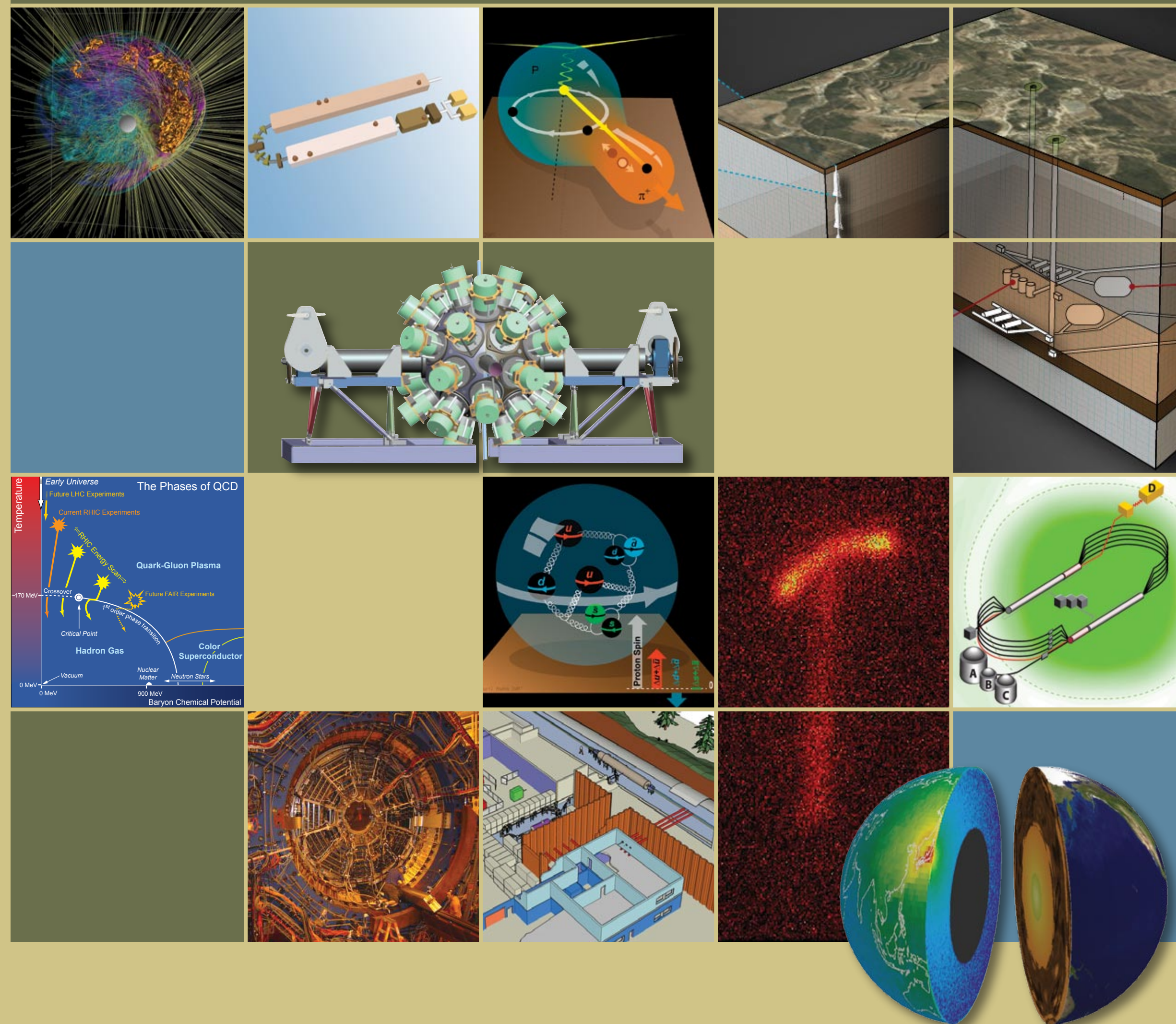
High Energy

Astro

The Frontiers of Nuclear Science

December 2007

Long Range Plan 2007

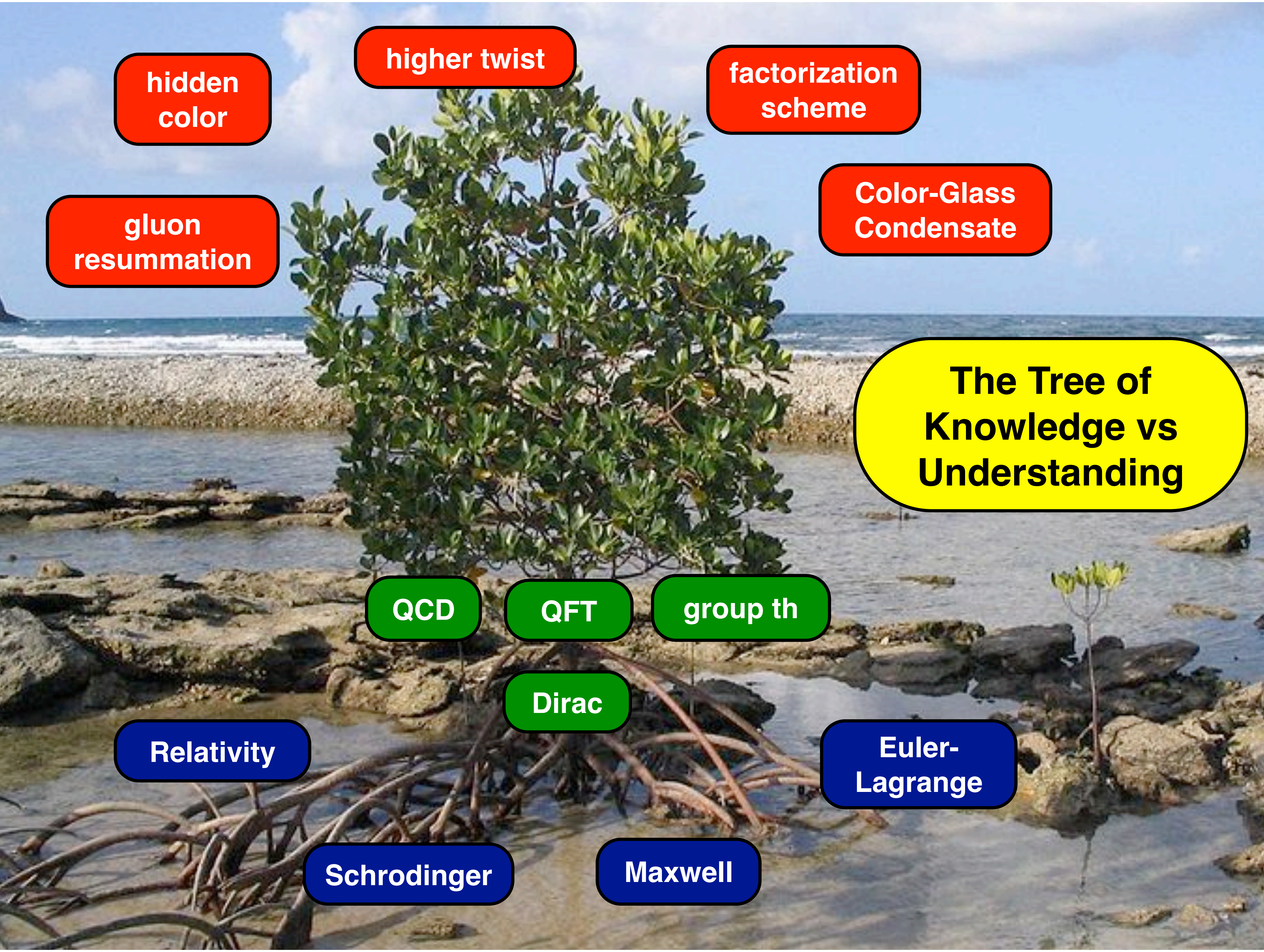


The Frontiers of Nuclear Science

A LONG RANGE PLAN

December 2007

The DOE/NSF Nuclear Science Advisory Committee
U.S. Department of Energy • Office of Science • Office of Nuclear Physics
National Science Foundation • Division of Physics • Nuclear Physics Program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higher twist
factorization scheme
Color-Glass Condensate
gluon resummation
The Tree of Knowledge vs Understanding
QCD
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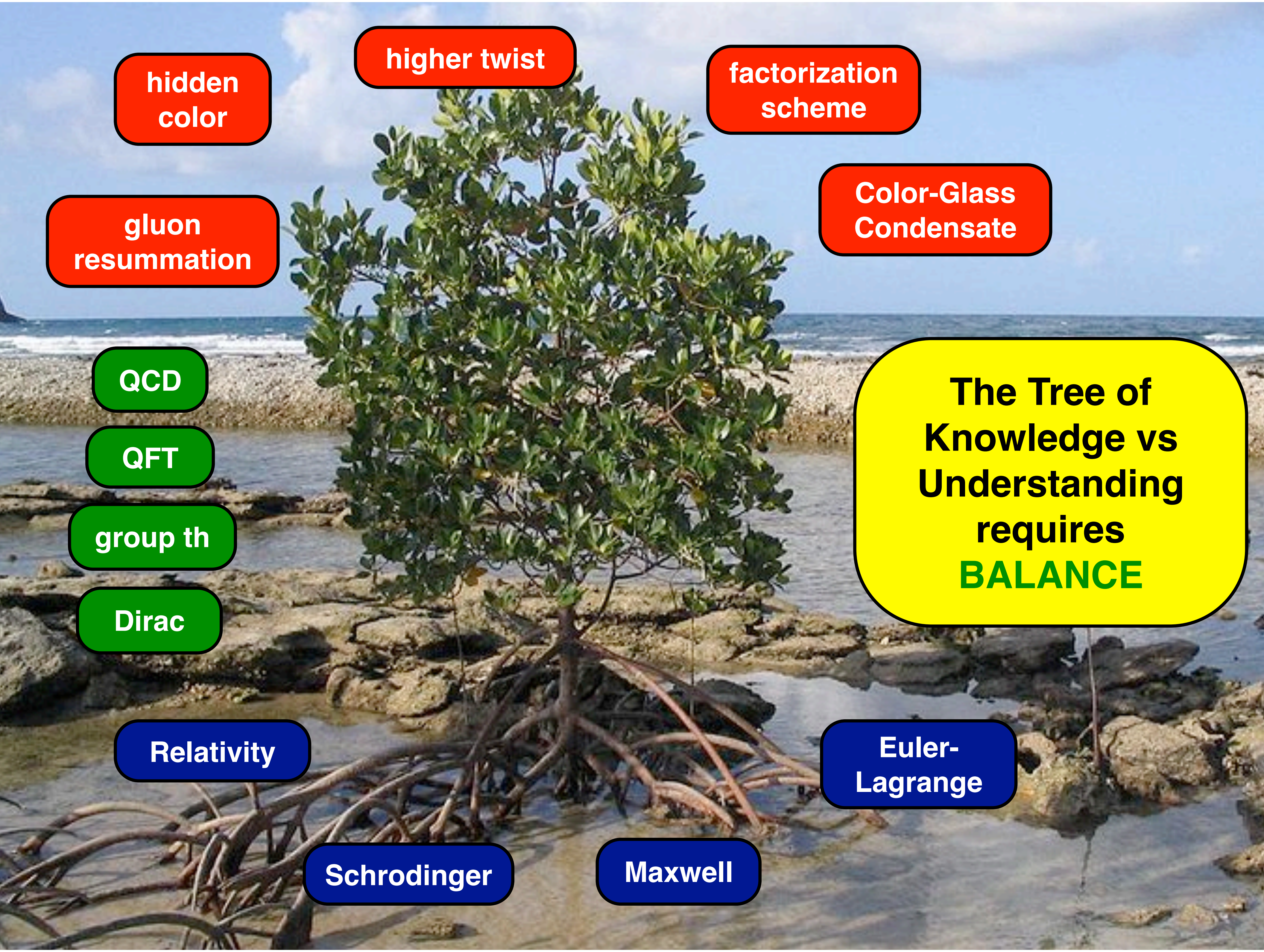
Dirac
Relativity
Euler-Lagrange
Schrodinger
Maxwell


JARGON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The Tree of Knowledge vs Understanding requires BALANCE
Relativity
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Maxwell

"Classification" Categories to be Used for the Assignment of Scientific Priority to the 12 GeV Experiments → *a la Larry Cardman, JLab PAC*

* Fragmentation

1. **The Hadron spectra as probes of QCD**
   (GluEx and heavy baryon and meson spectroscopy)

   Spectroscopy

2. **The transverse structure of the hadrons**
   (Elastic and transition Form Factors)

   Form Factors

3. **The longitudinal structure of the hadrons**
   (Unpolarized and polarized parton distribution functions)

   PDFs

4. **The 3D structure of the hadrons**
   (Generalized Parton and Transverse Momentum Distributions)

   GPDs & TMDs

5. **Hadrons and cold nuclear matter** *
   (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body expts)

   Nuclear Effects

6. **Low-energy tests of the Standard Model and Fundamental Symmetries**
   (Møller, PVDIS, PRIMEX, …..)

   SM / FS

Crash Intro to Hadron Structure

The Quark Model

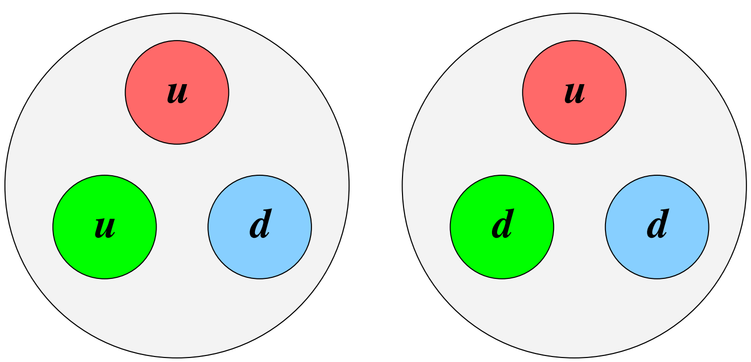
Hadrons are composed of **quarks** with :

❶ **flavor**: u,c,t (charge +2/3) d,s,b (charge -1/3) ❷ **color**: R,G,B ❸ **spin**: 1/2

Each hadron observed in nature is **white** ("color singlet")

➢ **Baryons** 3-quark systems, with colors RGB

➢ **Mesons** quark + antiquark with colors CC̄



proton **neutron**

The ***spectrum*** *of observed hadrons is (roughly) explained:*

Mesons: Spin 0

π^+	$u\bar{d}$
π^-	$d\bar{u}$
π^0	$u\bar{u} \oplus d\bar{d}$
K^+	$u\bar{s}$
K^-	$s\bar{u}$
K^0	$d\bar{s}$
$\overline{K^0}$	$s\bar{d}$
η	$u\bar{u} \oplus d\bar{d} \oplus s\bar{s}$
η'	$u\bar{u} \oplus d\bar{d} \oplus s\bar{s}$

Mesons: Spin 1

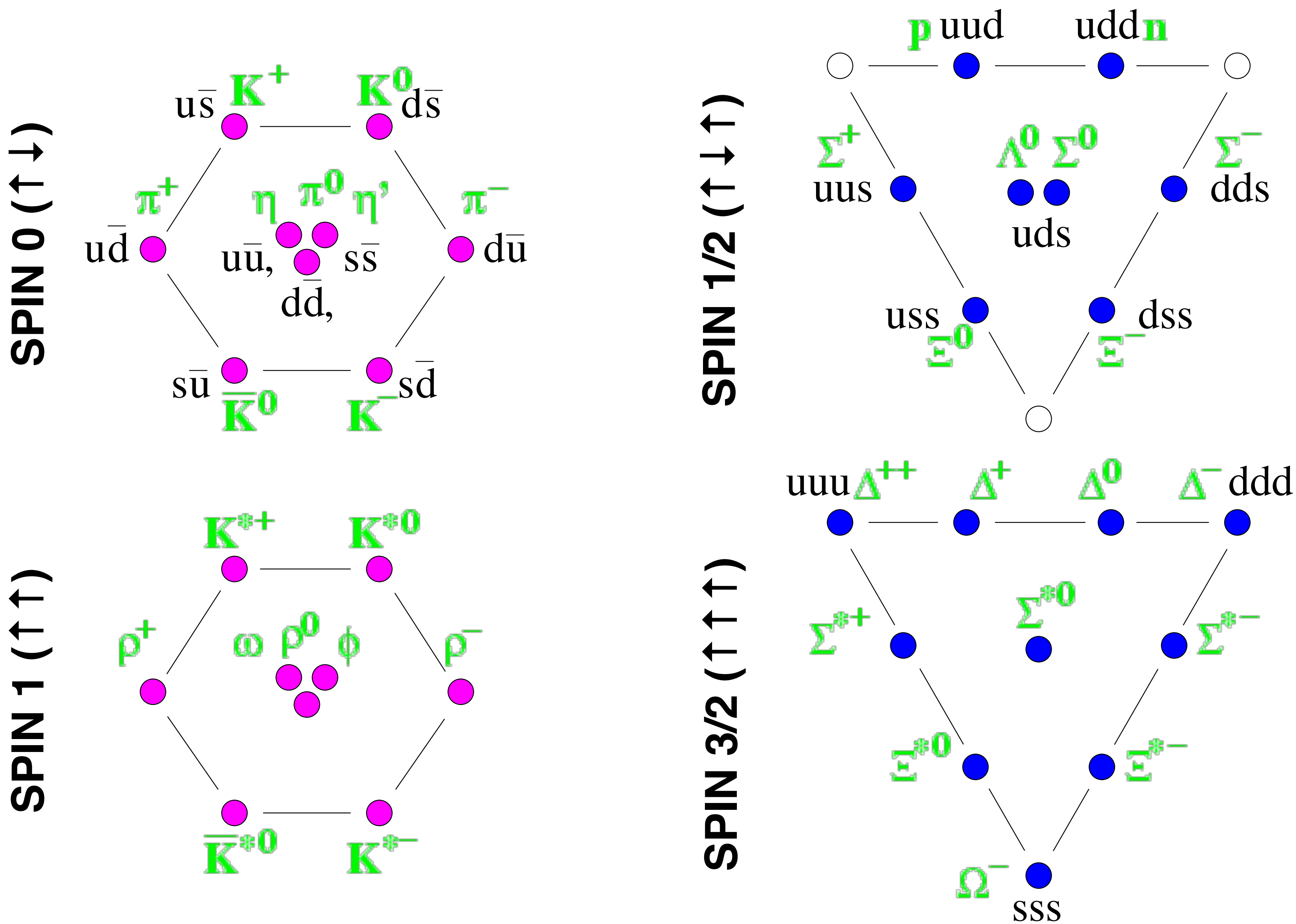
ρ^+	$u\bar{d}$
ρ^-	$d\bar{u}$
ρ^0	$u\bar{u} \oplus d\bar{d}$
K^{*+}	$u\bar{s}$
K^{*-}	$s\bar{u}$
K^{*0}	$d\bar{s}$
$\overline{K^{*0}}$	$s\bar{d}$
ϕ	$s\bar{s}$
ω	$u\bar{u} \oplus d\bar{d} \oplus s\bar{s}$

Baryons: Spin 1/2

p	uud
n	udd
Σ^+	uus
Σ^0	uds
Σ^-	dds
Λ	uds
Ξ^0	uss
Ξ^-	dss

Hadronic Multiplets

- **MESONS =** $q\bar{q}$
- **BARYONS =** qqq or $\overline{qqq}$

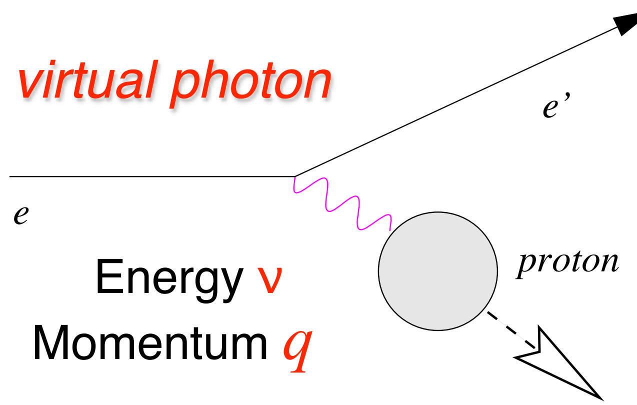


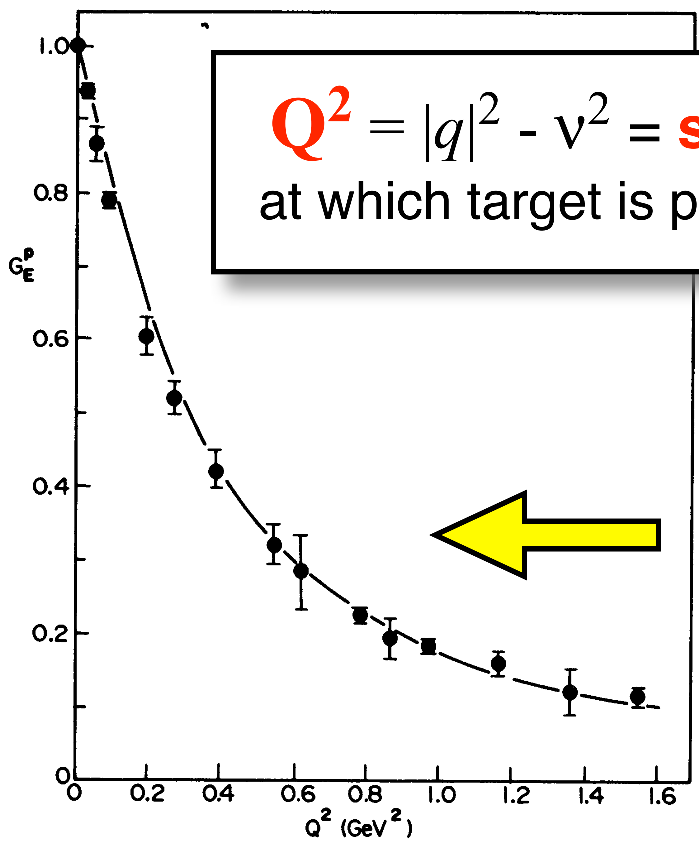
Murray Gell-Mann, 1964:

"A search for stable quarks ... at the highest energy accelerators would help to reassure us of the non-existence of real quarks."

Electron Scattering and Scaling

Elastic scattering from the proton:





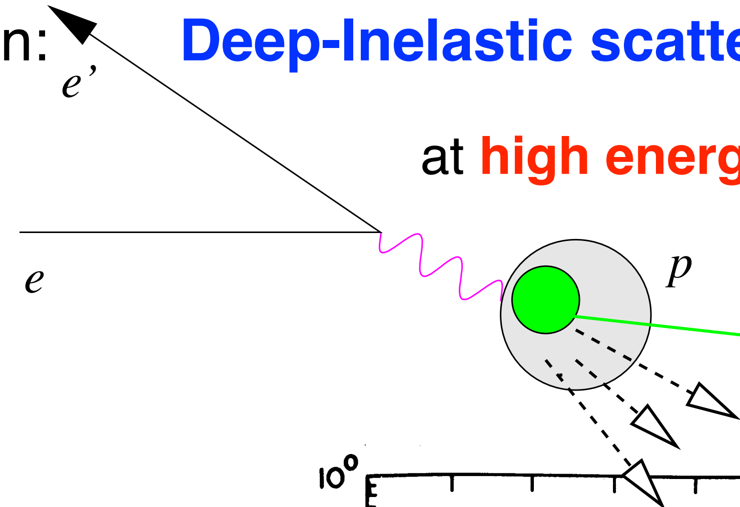
$Q^2 = |q|^2 - \nu^2$ = **scale**

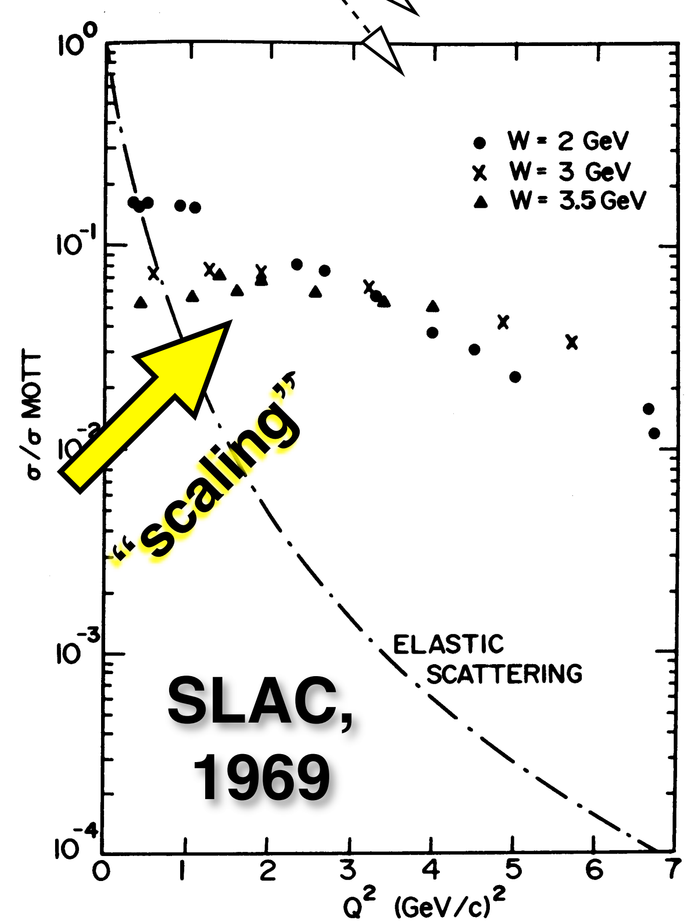
at which target is probed

$$\frac{\sigma(Q^2)}{\sigma_{point}(Q^2)}$$

Deep-Inelastic scattering (DIS):

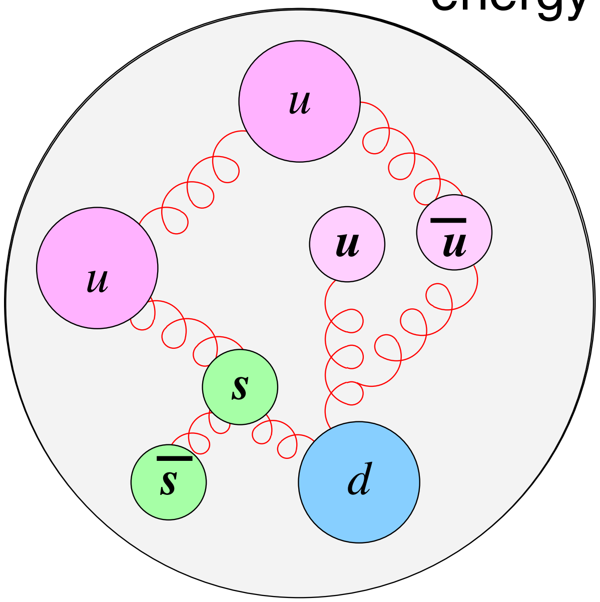
at **high energies** you see ...





Parton Distribution Functions

Let's look ***inside*** the proton: **Deep-Inelastic Scattering** (DIS) with high energy beams ⇒ a rich substructure is revealed!



sea quarks : virtual quark-antiquark pairs that fluctuate in and out of the vacuum!

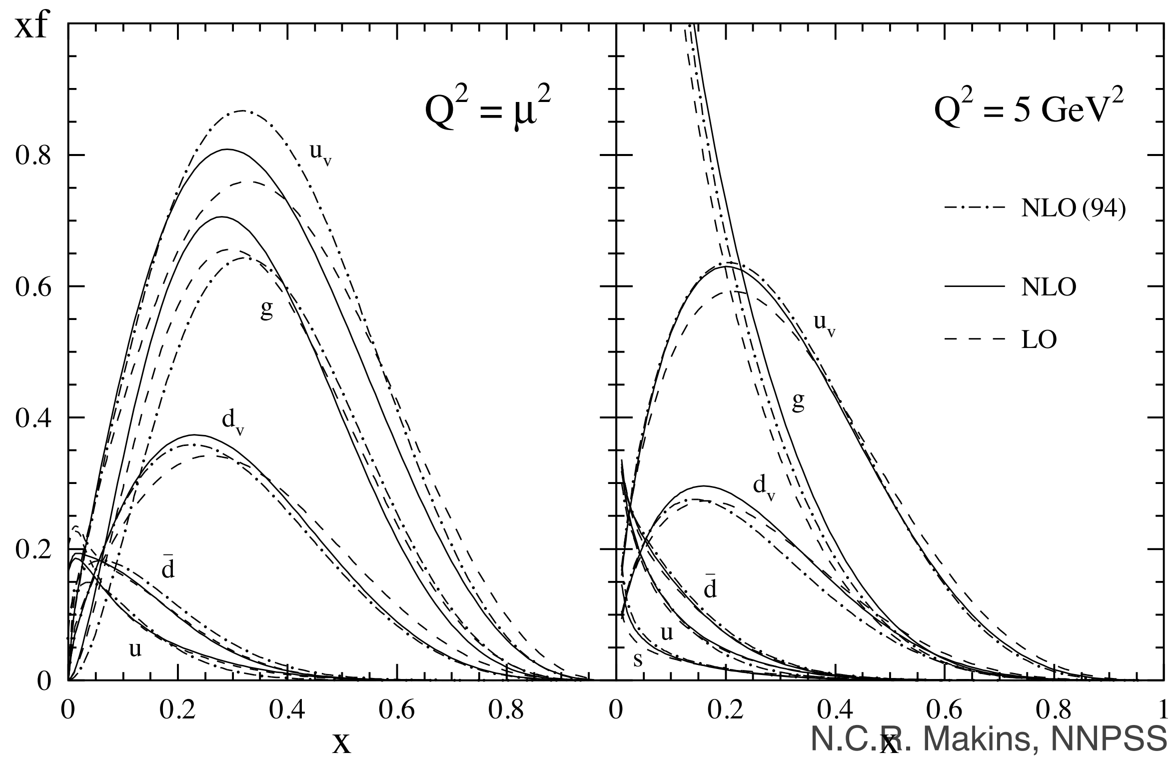
gluons : carriers of the strong force

x fraction of proton momentum carried by struck quark

$q(x)$ parton distribution funcⁿ
(number density for quark flavor q)

3 **constituent quarks**
of mass ≈ 350 MeV

∞ many **current quarks**
with bare masses ≈ 5 MeV



N.C.R. Makins, NNPSS 2015

Quantum Chromodynamics

The Theory of the Strong Interaction

$$\mathcal{L}_{\rm QCD} = -\Psi \left\{ \gamma_\mu [\partial_\mu - \frac{i}{2} g \lambda^a A^a_\mu(x)] + M \right\} \Psi - \frac{1}{4} \mathcal{F}^a_{\mu\nu} \mathcal{F}^a_{\mu\nu}$$

The End.

Bound States in QED and QCD

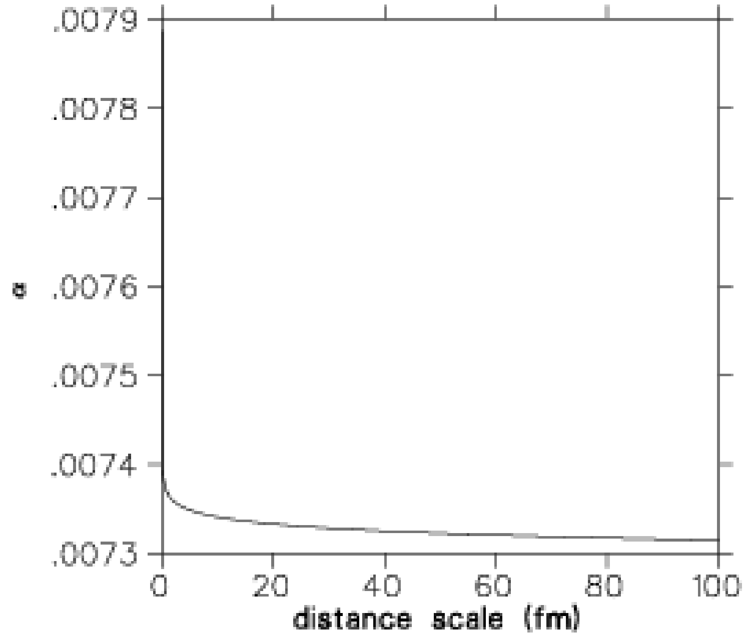
QED

Coupling α = 1/137 is weak at relevant scales

✔ **Perturbation theory** works very well

✔ **Non-relativistic** quantum mechanics ok

e.g. Hydrogen: binding E = 13.6 eV << M_{elec} = 511 keV



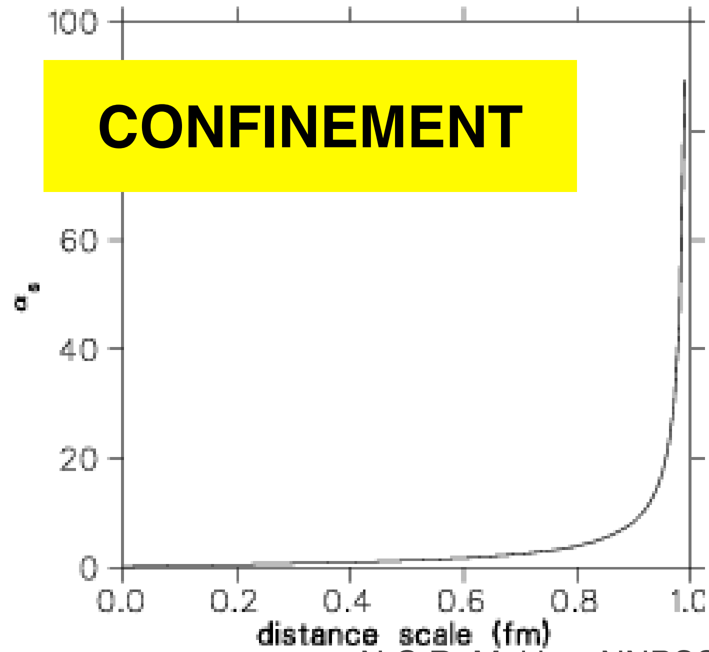
QCD

Coupling α_s ***blows up*** at relevant scales !

✘ **Perturbation** theory **impossible**

✘ Bound systems inherently **relativistic**

e.g. Proton: Mass = 938 MeV >>
bare m_{quark} = 5 MeV !



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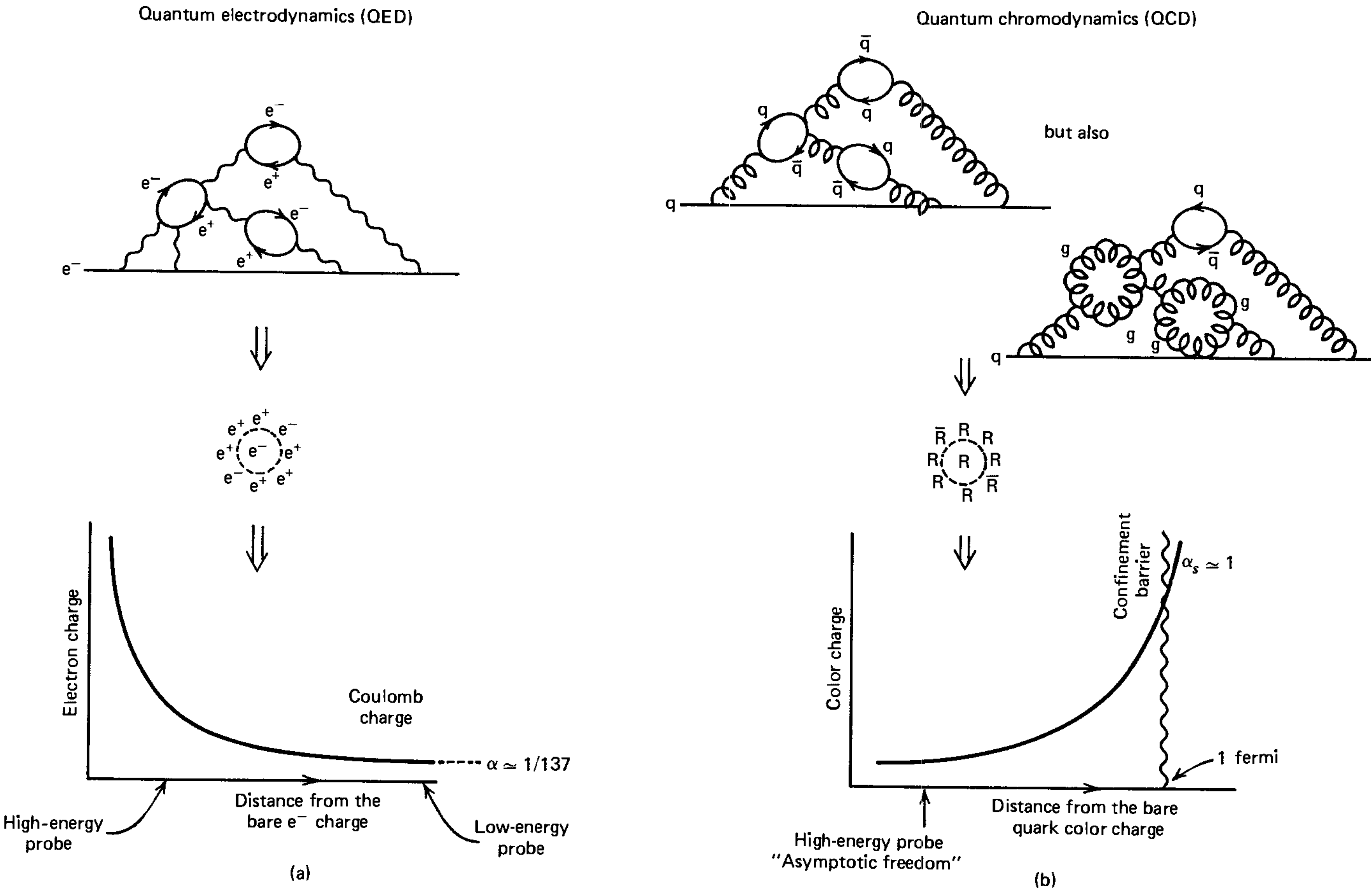
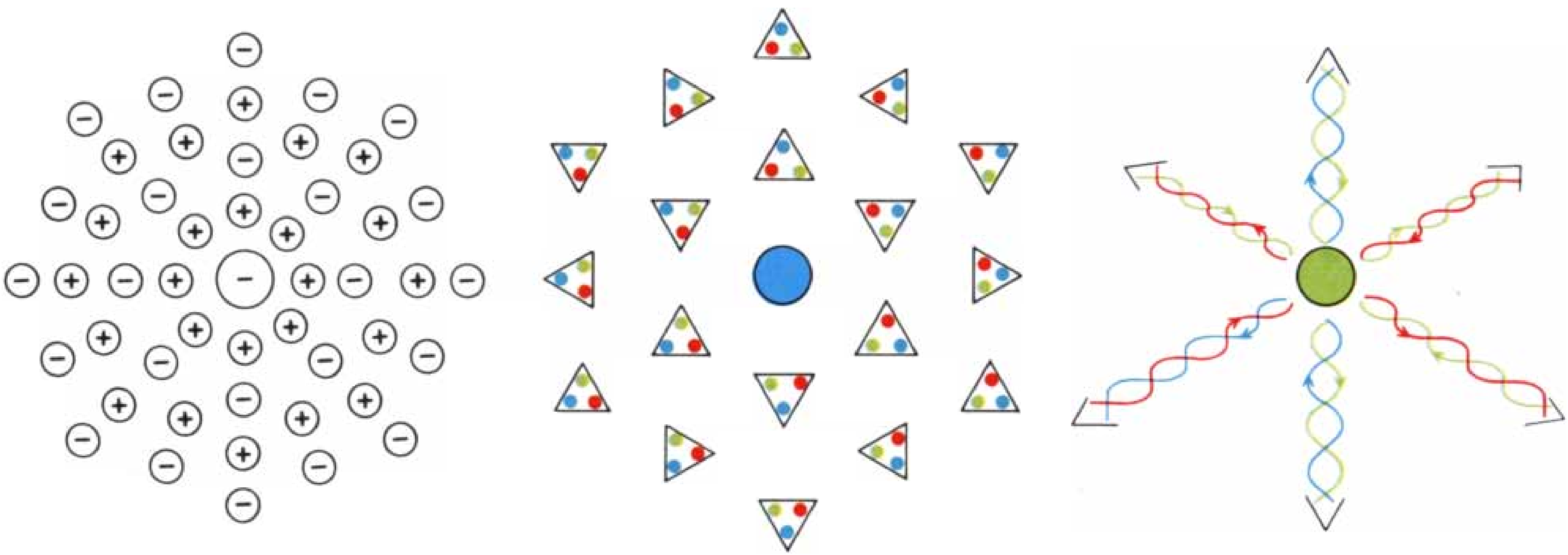
Color Anti-Screening



Color Anti-Screening: C.Quigg, Sci. Am. April 1985

found in a footnote from Griffiths, "Elementary Particles"



SCREENING AND CAMOUFLAGE EFFECTS modify the behavior of fundamental forces over distance. The left panel shows an electron in a vacuum; it is surrounded by short-lived pairs of virtual electrons and positrons, which in quantum theory populate the vacuum. The electron attracts the virtual positrons and repels the virtual electrons, thereby screening itself in positive charge. The farther from the electron a real charge is, the thicker the intervening screen of virtual positive charges is and the smaller the electron's effective charge will be. The color force is subject to the same screening effect (*center*). Virtual color charges (mostly quark-antiquark pairs) fill the vacuum; a colored quark attracts contrasting colors, thereby surrounding itself with a screen that acts to reduce its effective charge at increasing distances. An effect called camouflage counteracts screening, however. A quark continuously radiates and reabsorbs gluons that carry its color charge to considerable distances and change its color, in this case from blue to green (*right*). A charge's full magnitude can be felt only outside the space it occupies. Therefore camouflage acts to increase the force felt by an actual quark as it moves away from the first quark, toward the edge of the color-charged region. The net result of screening and camouflage is that at close range the strong interaction, which is based on the color charge, is weaker, whereas at longer ranges it is stronger.

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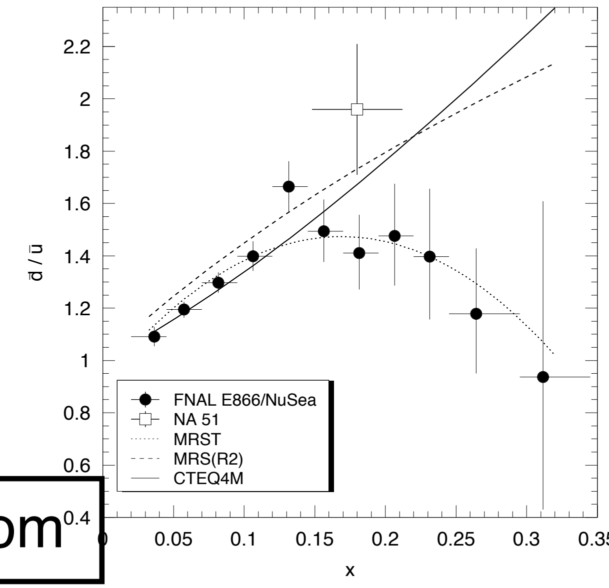
Flavor Structure of the Proton

E866: $\bar{d}/\bar{u} > 1$



Constituent Quark Model

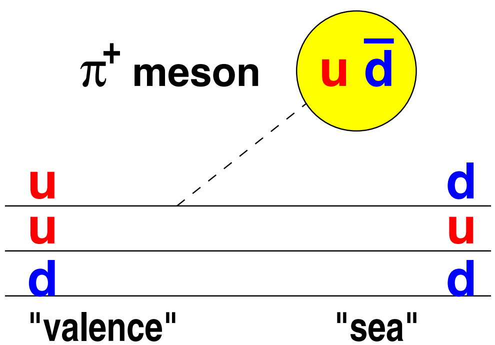
Pure valence description: proton = $2u + d$

Perturbative Sea

Sea quark pairs from $g \to q\bar{q}$ should be flavor symmetric: $\bar{u} = \bar{d}$

Non-perturbative models: alternate deg's of freedom

Meson Cloud Models

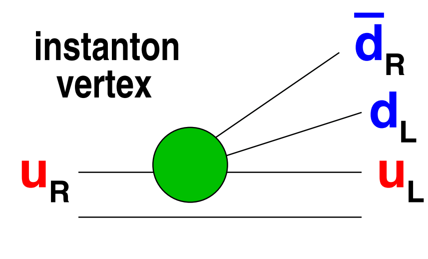


Quark sea from cloud of 0⁻ mesons: $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model

- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$

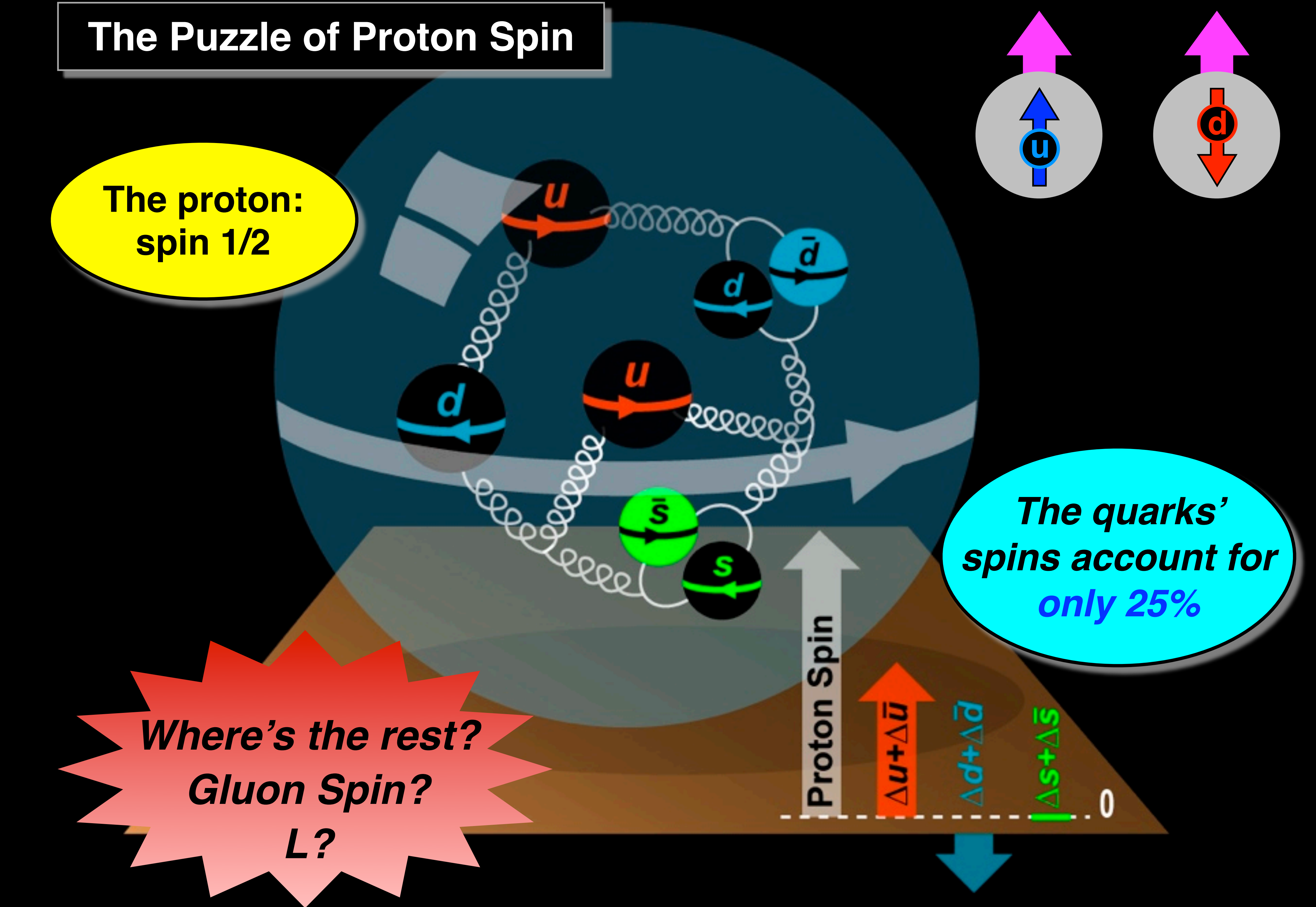
$\bar{d} > \bar{u}$



'tHooft instanton vertex

$\sim \bar{u}_R u_L \bar{d}_R d_L$

The Puzzle of Proton Spin



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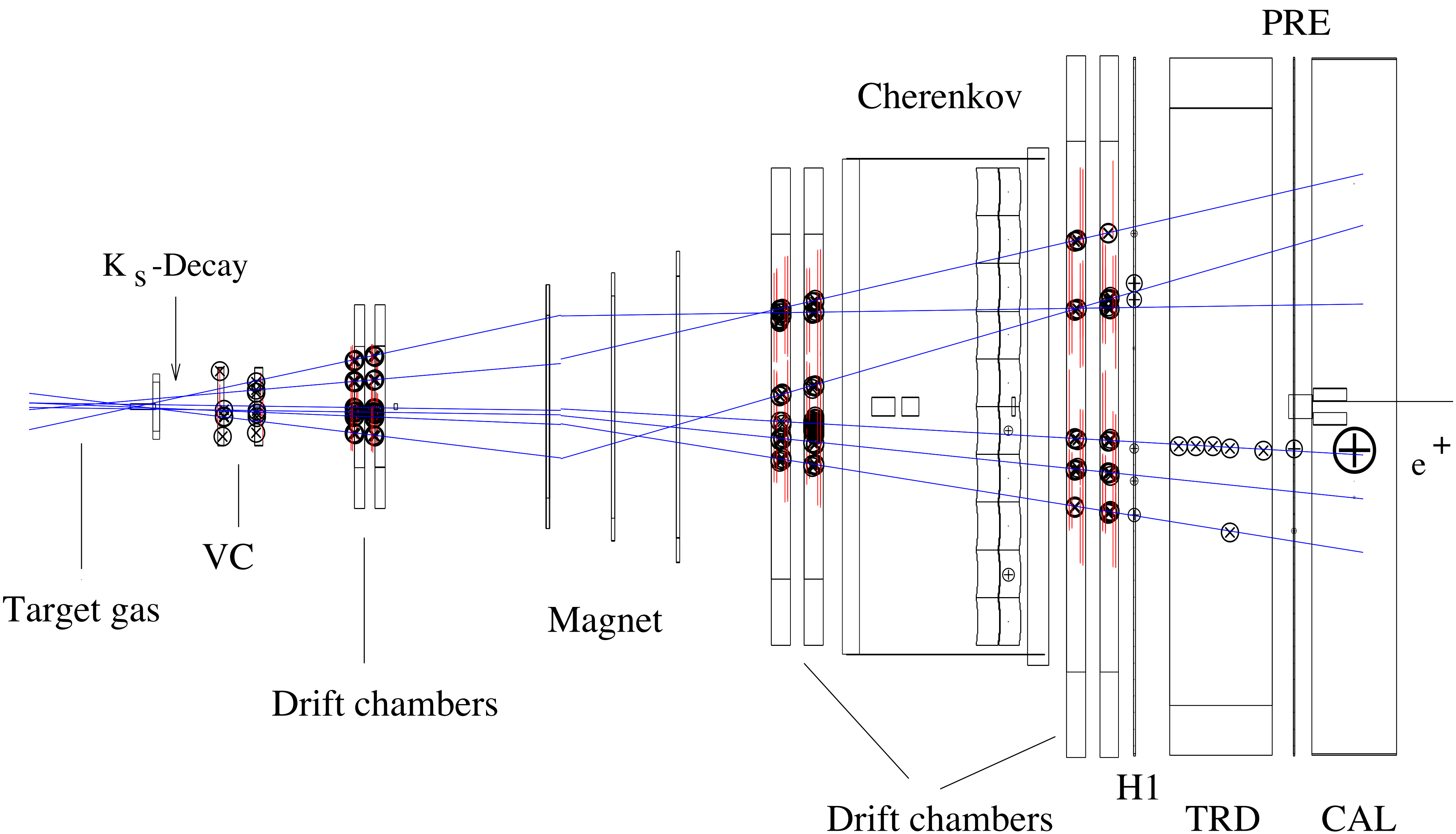
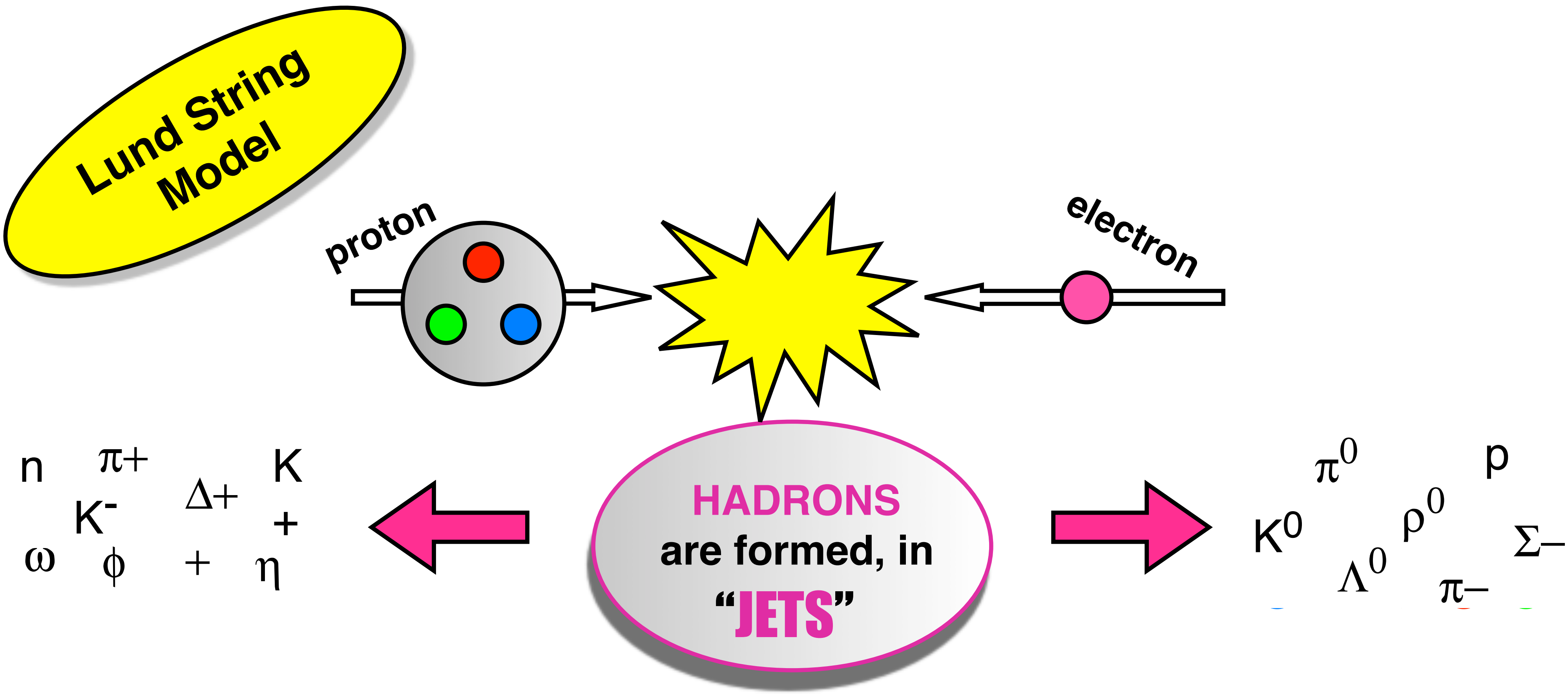
What the Detector Sees in a High-Energy Collision ...



What Happens in a High Energy Collision



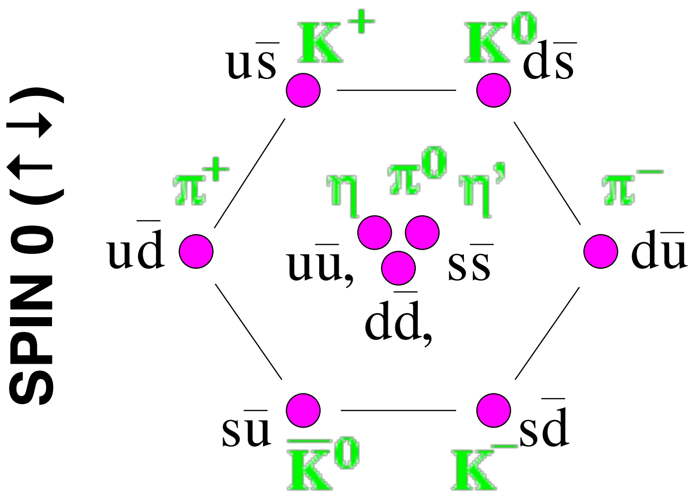
Confinement at Work !

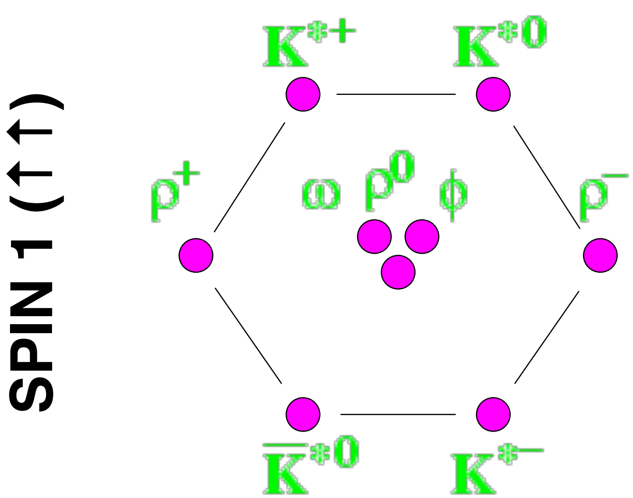
Creation of **hadrons** from **struck quark**: Fragmentation

Our Friends, the Hadrons

Particles you need to know!

*The **only** particles that can **make tracks** in typical detectors : must be **charged** and must **live long enough***





- **Pions**: $\pi^+ = u\bar{d}, \quad \pi^- = d\bar{u}, \quad m_{\pi^\pm} = 140$ MeV

  lightest and most common of **mesons**
- **Kaons**: $K^+ = u\bar{s}, \quad K^- = s\bar{u}, \quad m_{K^\pm} = 494$ MeV

  lightest mesons with **strange quarks**
- **Protons** and **antiprotons**:

  $p = uud, \quad \bar{p} = \bar{u}\bar{u}\bar{d}, \quad m_p = 938$ MeV

  the ***only*** truly **stable hadrons** in nature

- **Electrons** and **positrons**: $e^\pm, \; m_e = 0.5$ MeV

  lightest charged leptons, also stable
- **Muons**: $\mu^\pm, \; m_\mu = 107$ MeV

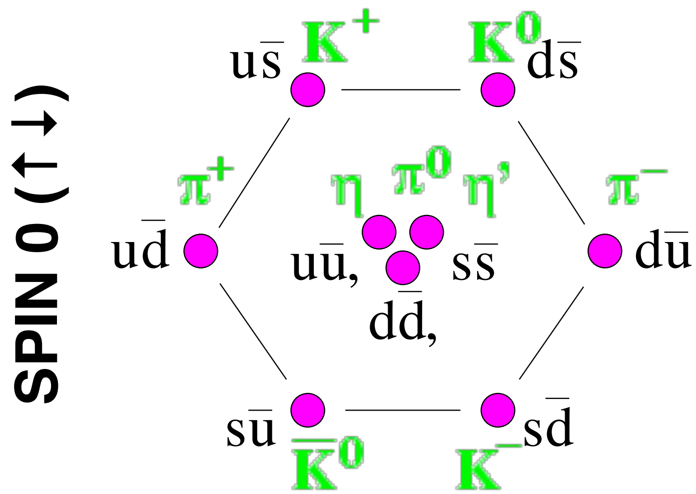
  heavy electrons → don't radiate much,

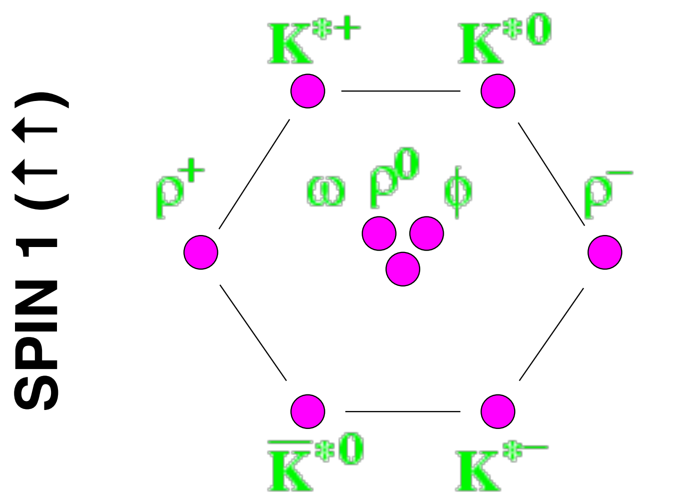
  ∴ easily pass through materials

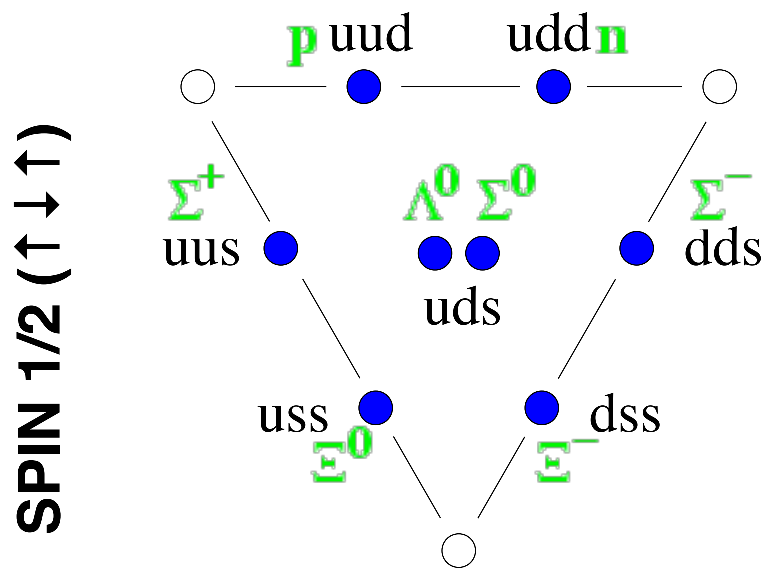
*Other hadrons are observed via their **decays**, e.g. $\rho^0 \to \pi^+\pi^-$*

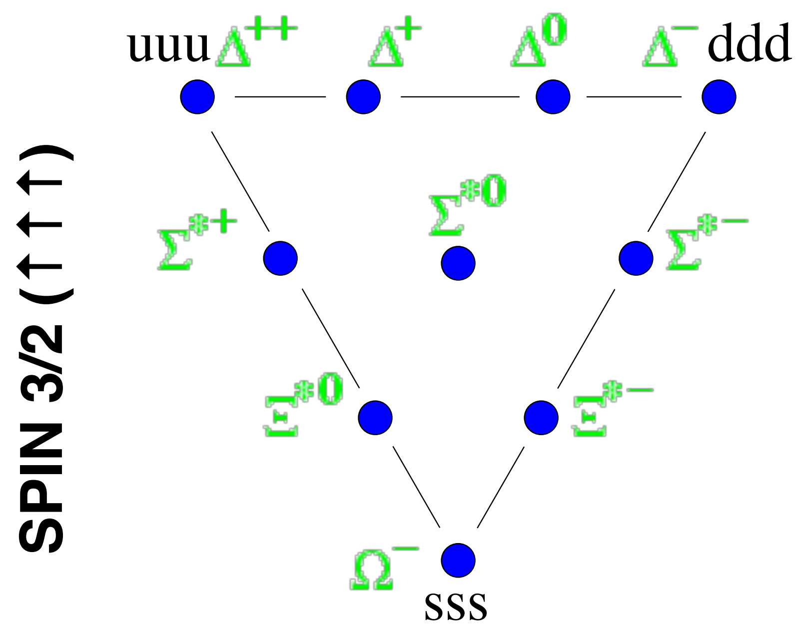
Hadronic Multiplets

- **MESONS =** $q\bar{q}$
- **BARYONS =** qqq or $\overline{qqq}$









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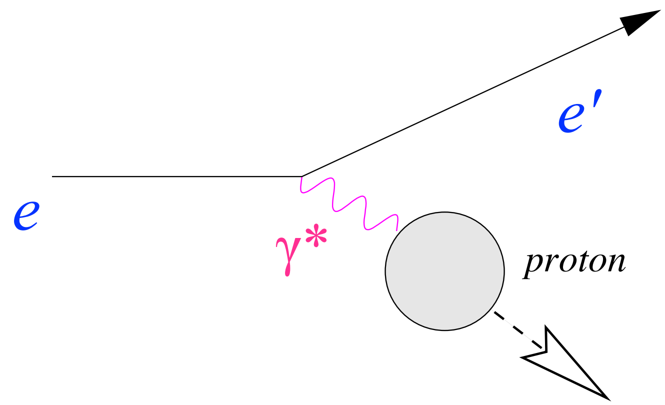
A Wee Bit O' Jargon-Busting

- baryon jargon: **N*s**, **hyperons**, and **cascades**
- meson classes: **pseudoscalar**, **vector**, **scalar**, ...
  - quantum numbers **J^P = 0^-** (π), **1^-** (ρ), **0^+** (f_0)
  - why do pions have negative parity? (S=0, L=0)
    ∵ quarks & antiquarks have **opposite intrinsic parity**
- **isovector** vs **isoscalar**: mesons and PDF combinations
  - isovector (I=1): π, ρ ... $u(x) - d(x)$
  - isoscalar (I=0): η, ω ... $u(x) + d(x)$

Deep-Inelastic Scattering & friends : Key Processes

The virtual photon and Q^2



In relativistic quantum mechanics = **quantum field theory**, scattering due to a force between particles (e.g. E&M) is treated as if a **virtual particle** were **exchanged** between beam and target

force	carrier
E & M	photon γ
strong	gluon g
weak	W, Z

The **virtual photon** γ^* is just a combination of E and B fields ... "**virtual**" → *short-lived*

<u>**Kinematic variables**</u> of electron scattering

electron beam e $\quad k = [E, \vec{k}] = [E, 0, 0, k]$

scattered electron e' $\quad k' = [E', \vec{k}']$ $\quad m_e^2 = k \cdot k = k' \cdot k'$

virtual photon γ^* $\quad q = [\nu, \vec{q}] \equiv k - k' = [E - E', \vec{k} - \vec{k}']$

$$Q^2 \equiv -q \cdot q = |\vec{q}|^2 - \nu^2 > 0!$$

→ *Virtual photon has* ***imaginary mass****, unlike a real photon*

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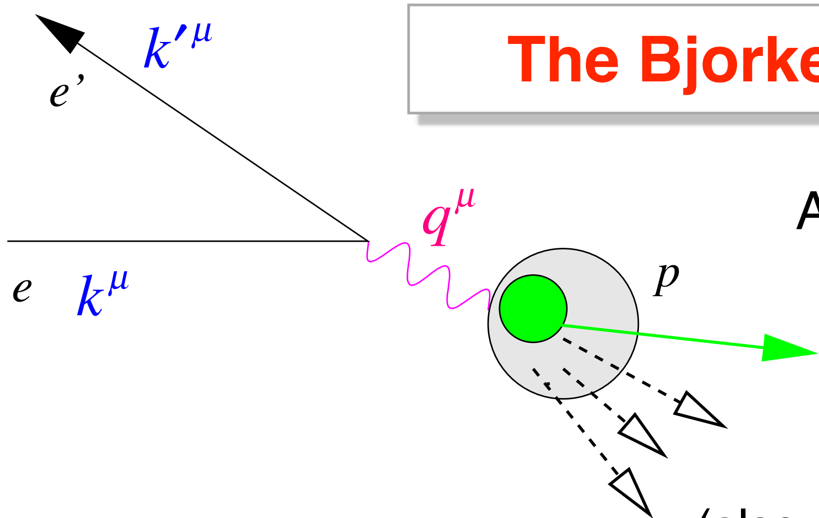
The Bjorken scaling variable x



At fixed beam energy, electron scattering xsecs depend on **two variables**: Q^2 and ν of the γ^*

... or E' and θ of the scattered beam:

$$Q^2 = 4EE'\sin^2(\theta/2)$$
$$\nu = E - E'$$

(also define $y \equiv \nu/E$ = fractional energy of γ^*, range 0 → 1)

At high enough Q^2 and W^2 we scatter not from the whole proton, but from a collection of **pointlike, nearly-massless quarks**

Elastic electron-quark scattering:

$$k + p_q = k' + p'_q \quad \rightarrow \quad p'_q = q + p_q$$

$$(p'_q)^2 = \cancel{m_q}^2 = (q+p_q)^2 = q^2 + \cancel{p_q}^2 + 2q\cdot p_q \quad \rightarrow \quad 2q\cdot p_q = -q^2 = Q^2$$

Suppose the **struck quark** carries a **fraction x** of the target **proton's 4-momentum** P

$$\boldsymbol{p_q = xP}$$

$\rightarrow\ p_q = xP\ = [xM_p, 0]$ in lab frame

$\rightarrow\ Q^2 = 2q\cdot p_q = 2q\cdot P\,x = 2\nu M_p\, x$

$$x = \frac{-q\cdot q}{2P\cdot q} = \frac{Q^2}{2M_p\nu}$$

DIS experiments measure this for every event

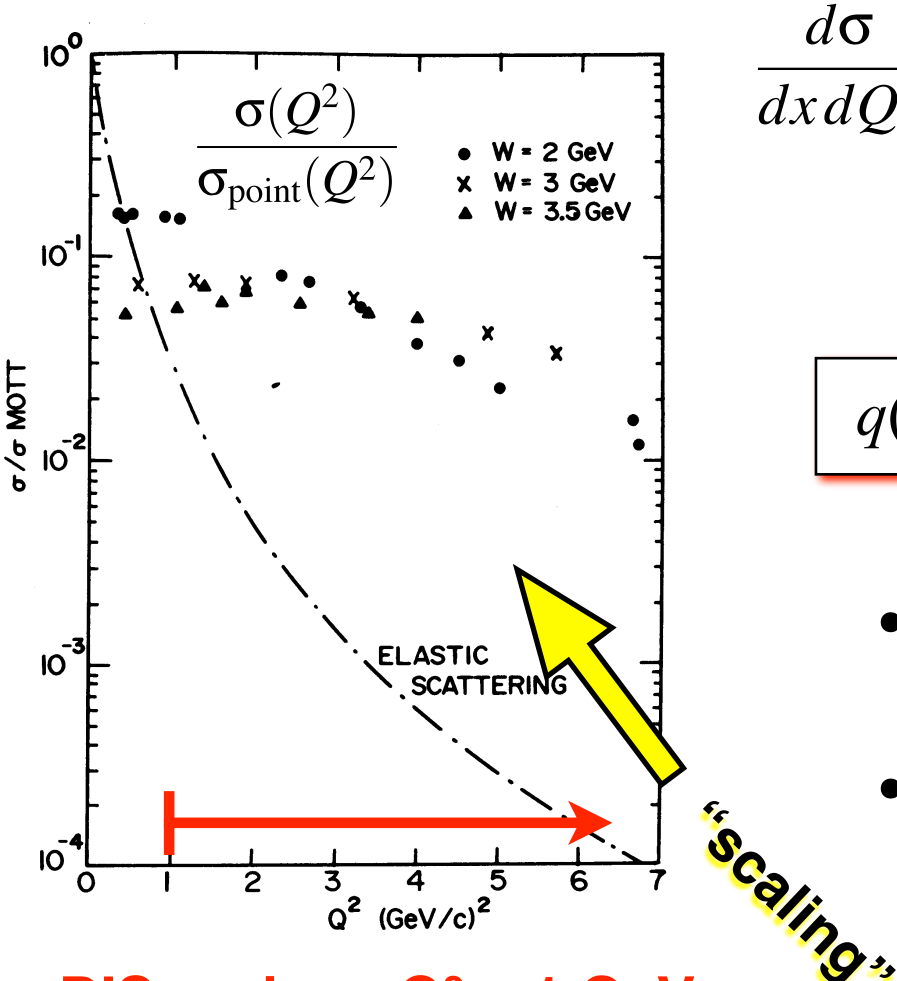
Deep-inelastic scattering : PDFs and Q²

$p_q = xP$

$$x = \frac{Q^2}{2M_p\nu}$$

When we are scattering from individual pointlike quarks within the target, we are in the regime of **deep-inelastic scattering**

$$\frac{d\sigma}{dx\,dQ^2} = \left(\frac{d\sigma}{dx\,dQ^2}\right)_{\text{point}(\text{eq}\rightarrow\text{eq})} \cdot \sum_{q=u,d,s,\bar{u},\bar{d},\bar{s}} e_q^2\, q(x,Q^2)$$



DIS regime: Q² > 1 GeV

$$q(x,Q^2)$$

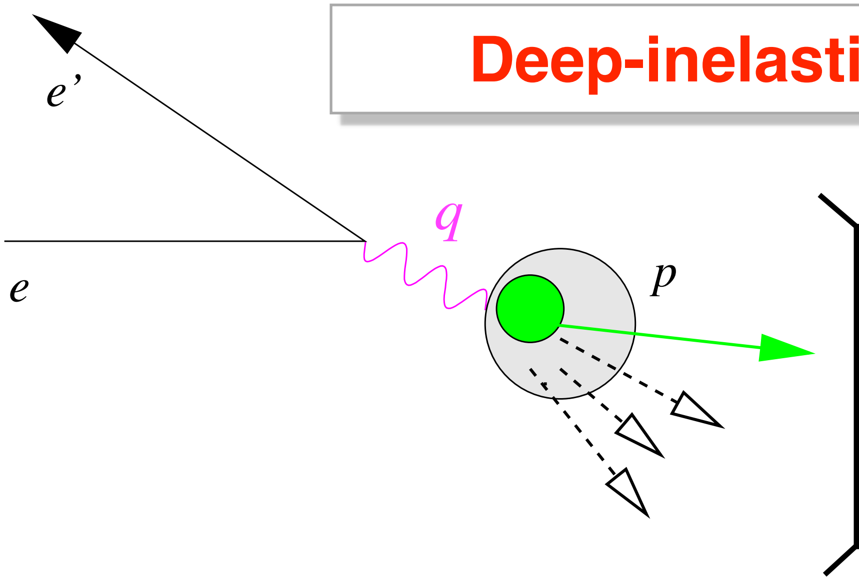
The interesting, **proton substructure** part of the xsec is described by **parton distribution functions** $q(x)$

- PDFs describe **number density** of quarks at different momentum-fractions ***x***
- one PDF per **quark flavour**

$$\{q(x)\} = u(x), d(x), s(x), \bar{u}(x), \bar{d}(x), \bar{s}(x)$$

- PDFs depend only very **weakly on Q^2**

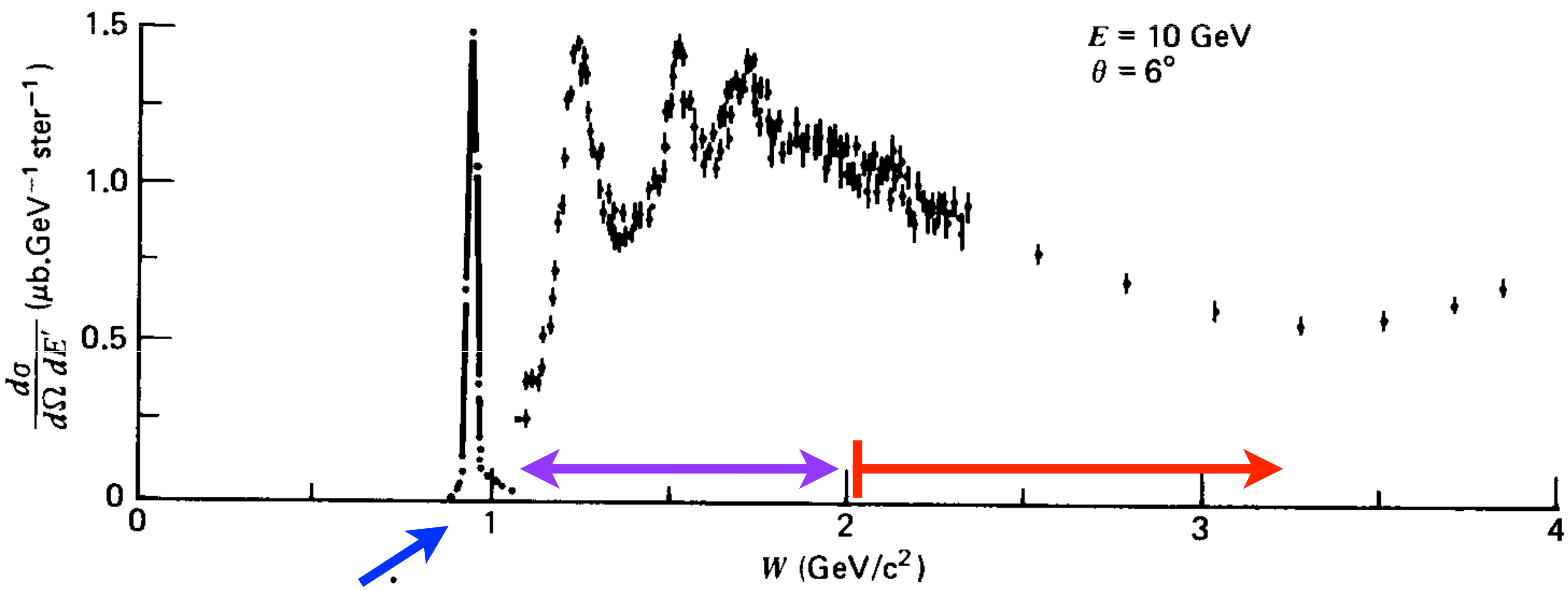
Deep-inelastic scattering and W^2



In DIS, the proton **breaks up** into many hadrons → fragmentation

hadronic final state: total **invariant-mass** W

$$W^2 = (q+P)^2 = (\nu+M_p)^2 - |q|^2$$
$$= M_p^2 - Q^2 + 2\, M_p\, \nu$$



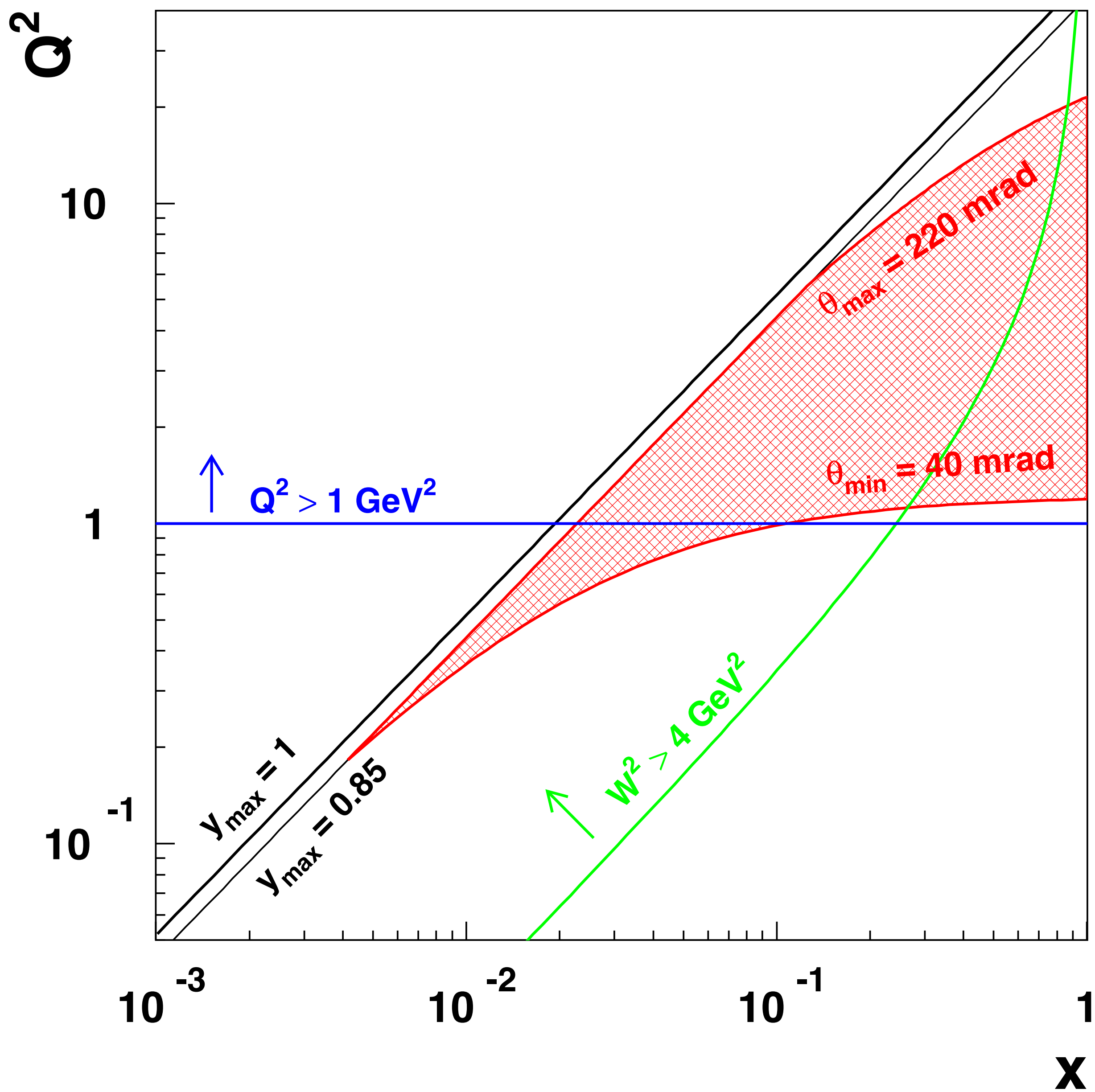
elastic scattering
ep → ep

resonance region
ep → eΔ, eN*, ...

DIS regime: W > 2 GeV
ep → e(X = many hadrons)

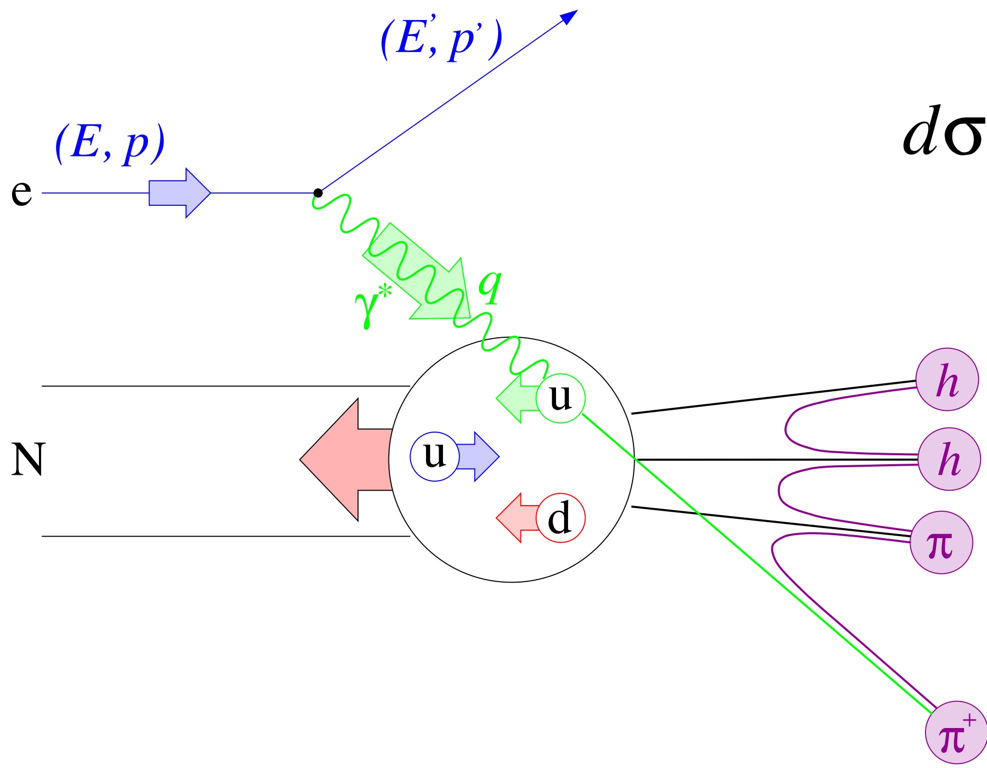
Example kinematics : HERMES

e+/e– beam of energy 27.6 GeV –on– fixed targets



Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

In SIDIS, a ***hadron h*** *is detected in* ***coincidence*** *with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2 \, q(x) \cdot \hat{\sigma} \cdot D^{q\rightarrow h}(z)$$

The perturbative part

Cross-section for elementary photon-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q*** within their proton bound state

➡ **lattice QCD** progressing steadily

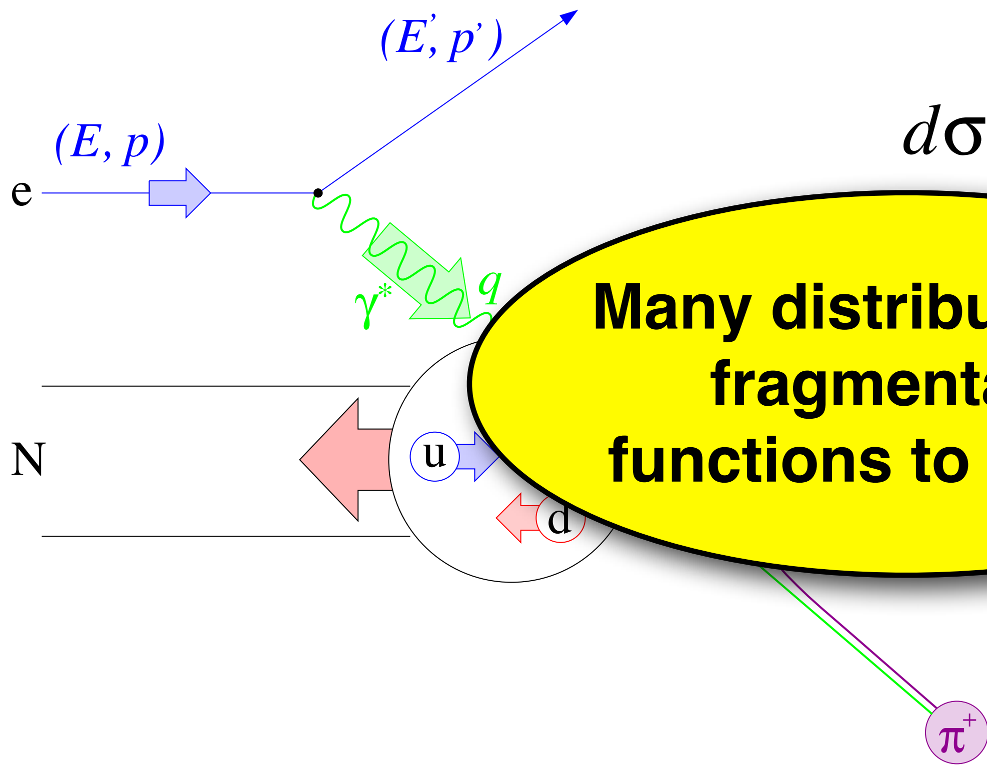
The Fragmentation Function

momentum ***distribution of hadrons h*** formed from quark *q*

➡ not even lattice can help ...

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

*In SIDIS, a **hadron h** is detected in **coincidence** with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2 \, q(x) \cdot \hat{\sigma} \cdot D^{q\to h}(z)$$

Many distribution and fragmentation functions to explore!

perturbative part

-section for elementary
hoton-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q***
within their proton bound state

➡ **lattice QCD** progressing steadily

The Fragmentation Function

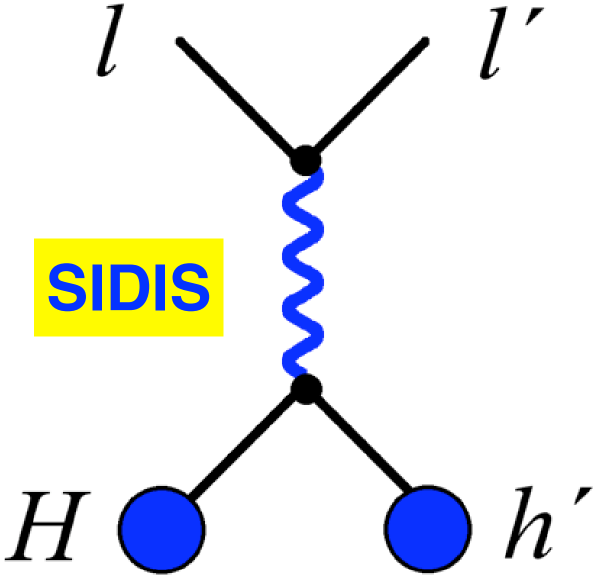
momentum ***distribution of hadrons h***
formed from quark *q*

➡ not even lattice can help ...

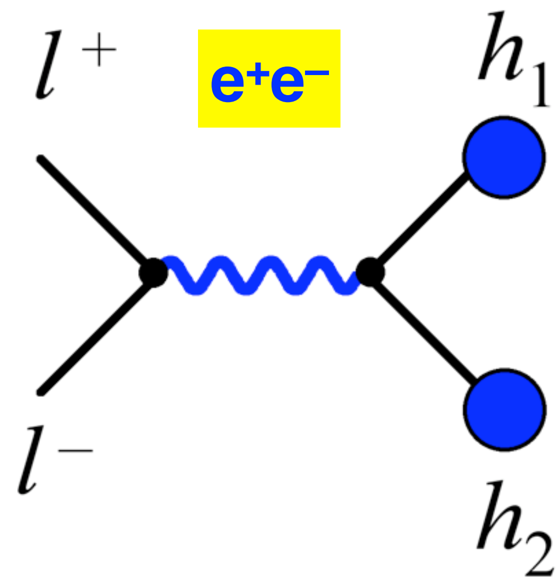
Leptons: clean, surgical tools

The Big Three

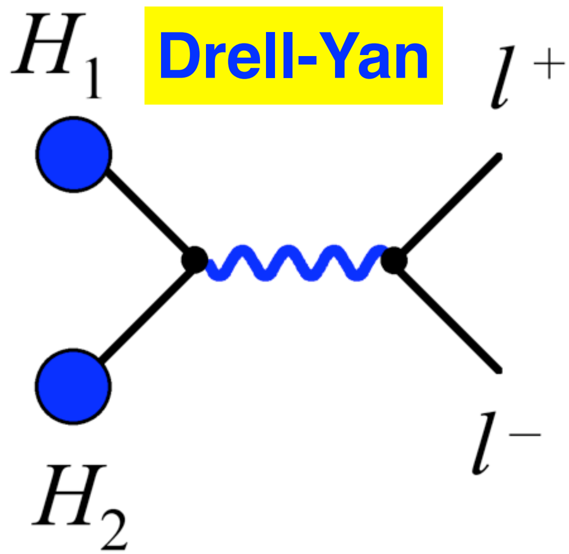
Disentangle **distribution** (f) and **fragmentation** (D) functions → ideally measure **all processes**



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

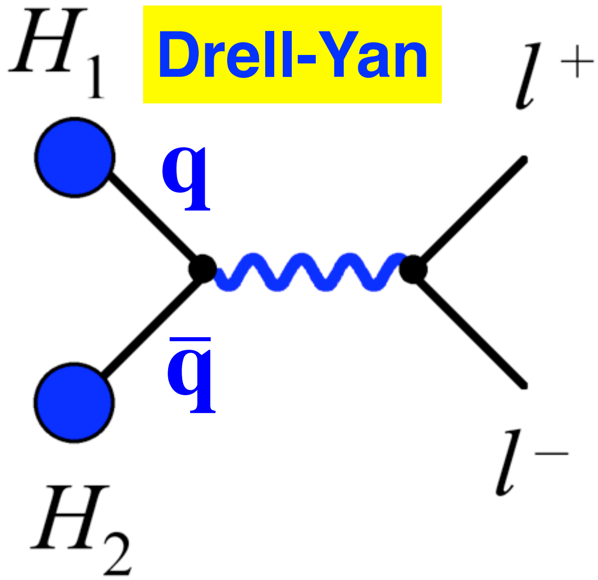


$$\sum_q e_q^2 \, \mathbf{D}_\mathbf{q}^{\mathbf{h}_1}(z_1) \, \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h}_2}(z_2)$$



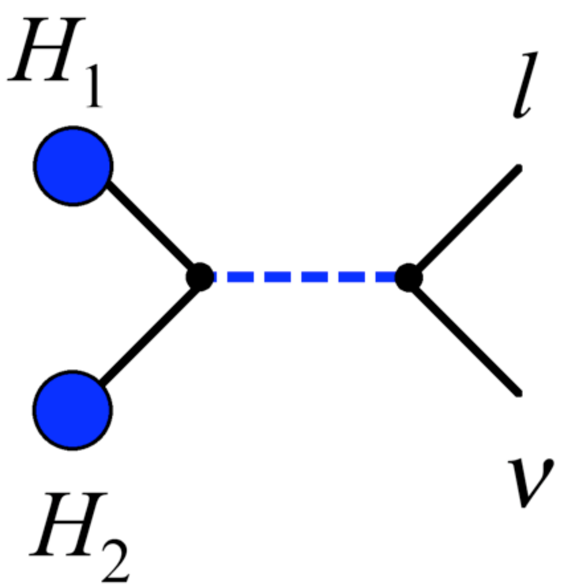
$$\sum_q e_q^2 \, \mathbf{f}_\mathbf{q}^{(\mathbf{H}_1)}(x_1) \, \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H}_2)}(x_2)$$

*These are the **only** processes where TMD factorization is proven*



W production

"Drell-Yan 2.0"



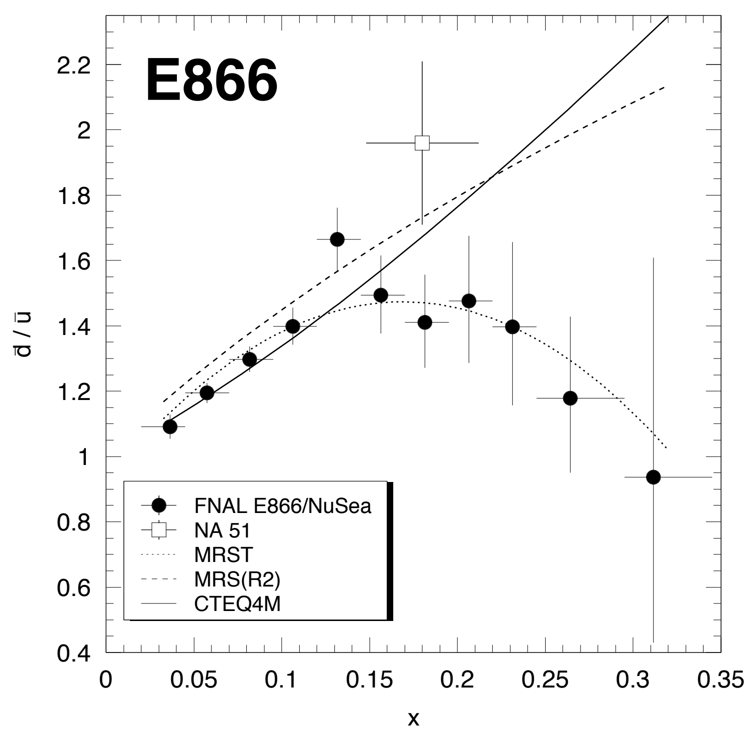
Hadron-Hadron → Leptons

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

- Cleanest access to **sea quarks**

e.g. $\bar{d}(x)/\bar{u}(x)$ @Fermilab

e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ @RHIC



N.C.R. Makins, NNPSS 2015

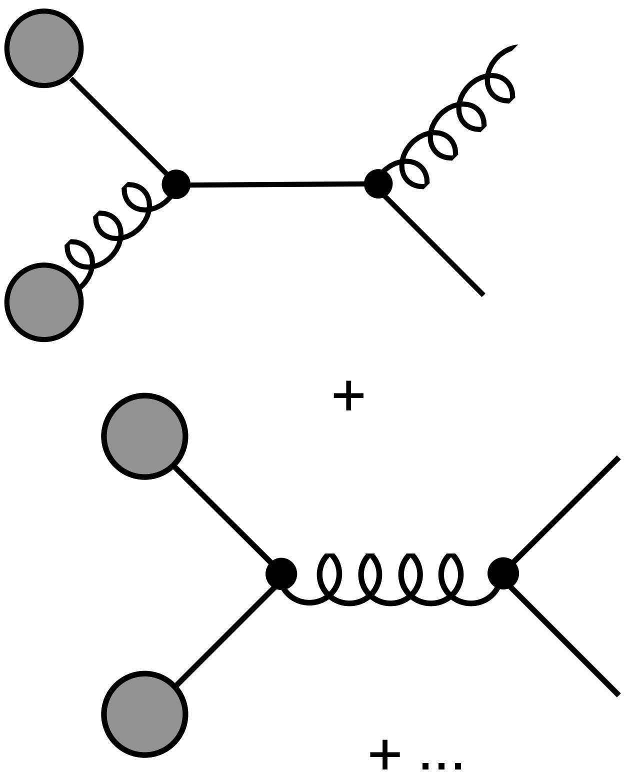
Hadron-Hadron → Hadrons

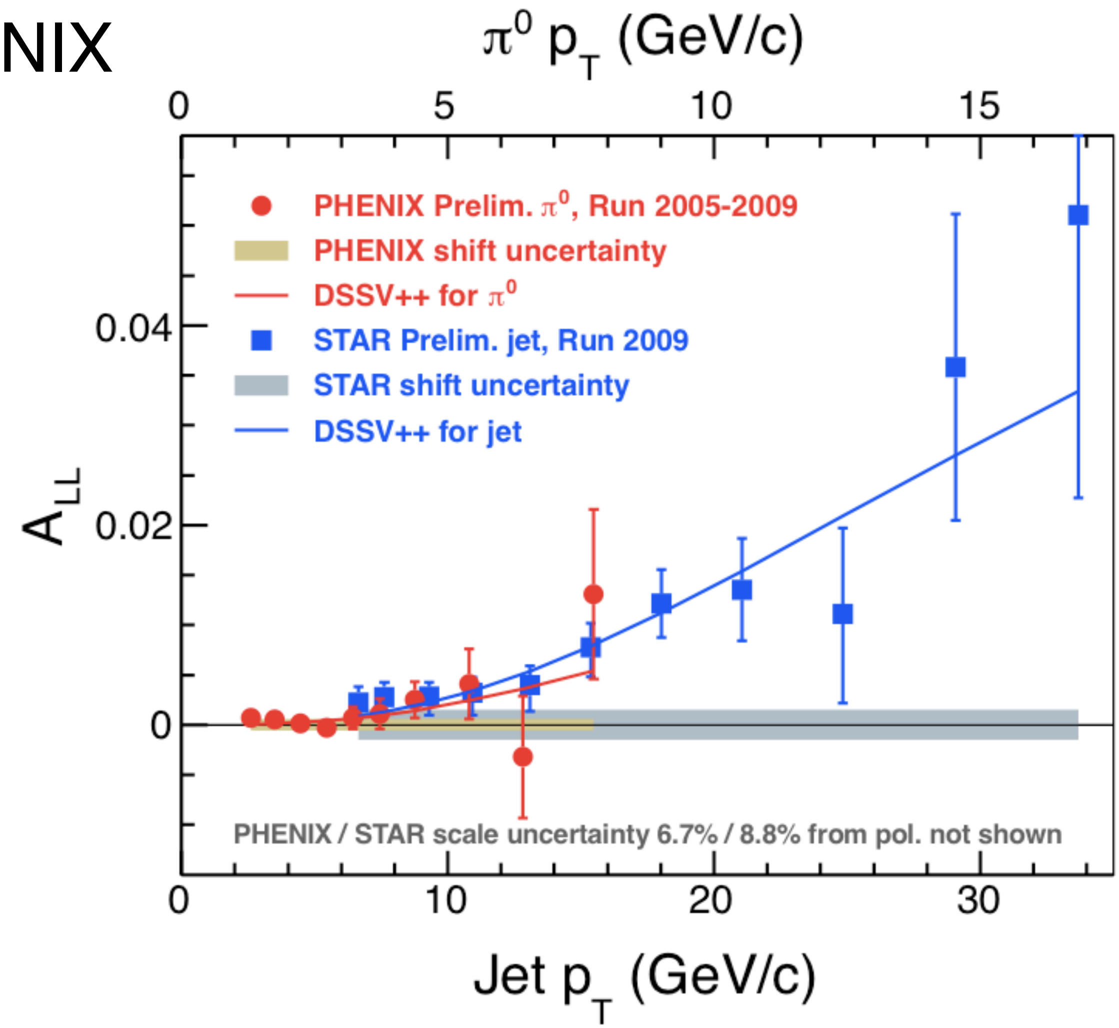
- Powerful + large cross-sections but more complex

e.g. Δg "workhorse" processes at RHIC :

A_{LL}→ π^0 + X @ PHENIX

A_{LL}→ jet + X @ STAR





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More Jargon-Busting

- **u-quark dominance**
- **off-shell** vs **on-shell** and **poles** in xsecs/amplitudes
- **longitudinal** vs **transverse photons**
- **helicity conservation**
- **Vector Meson Dominance** (VMD) ... any more ?

Helicity Conservation & L,T Photons

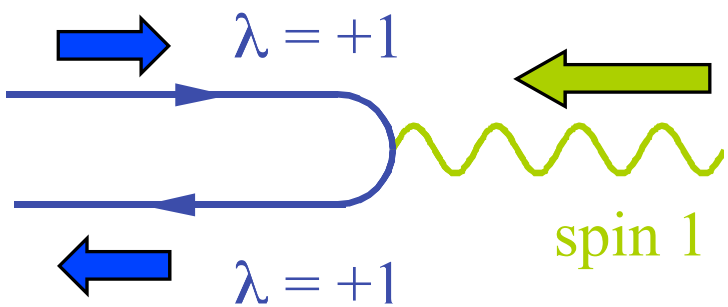
Write DIS xsec to reveal contributions from L and T photons:

$$\frac{d\sigma}{dE'd\Omega} \sim \sigma_L + \sigma_T \left(1 + \frac{2|\vec{q}|^2}{Q^2}\tan^2\frac{\theta}{2}\right)$$

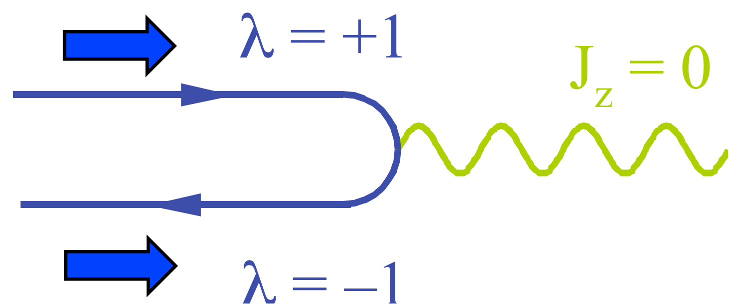
$$F_1 \sim \sigma_T$$

$$F_2 \sim (\sigma_L + \sigma_T)\,2x/(1+\tfrac{Q^2}{\nu^2})$$

Fact : **Fermions with $E >> m$ conserve helicity** in any EM interaction, which requires Transv = Spin 1 photons ... *unless transv momentum significant*



TRANSVERSE PHOTON



LONGITUDINAL PHOTON

- $R = \frac{\sigma_L}{\sigma_T} \rightarrow 0$ as $Q^2 \rightarrow \infty$ = key evidence that quark is spin 1/2 !
- $R \approx 0 \rightarrow$ Callan-Gross relation: (only one structure function) $\sum_q e_q^2\, x\, q(x) = F_2(x) \approx 2x F_1(x)$

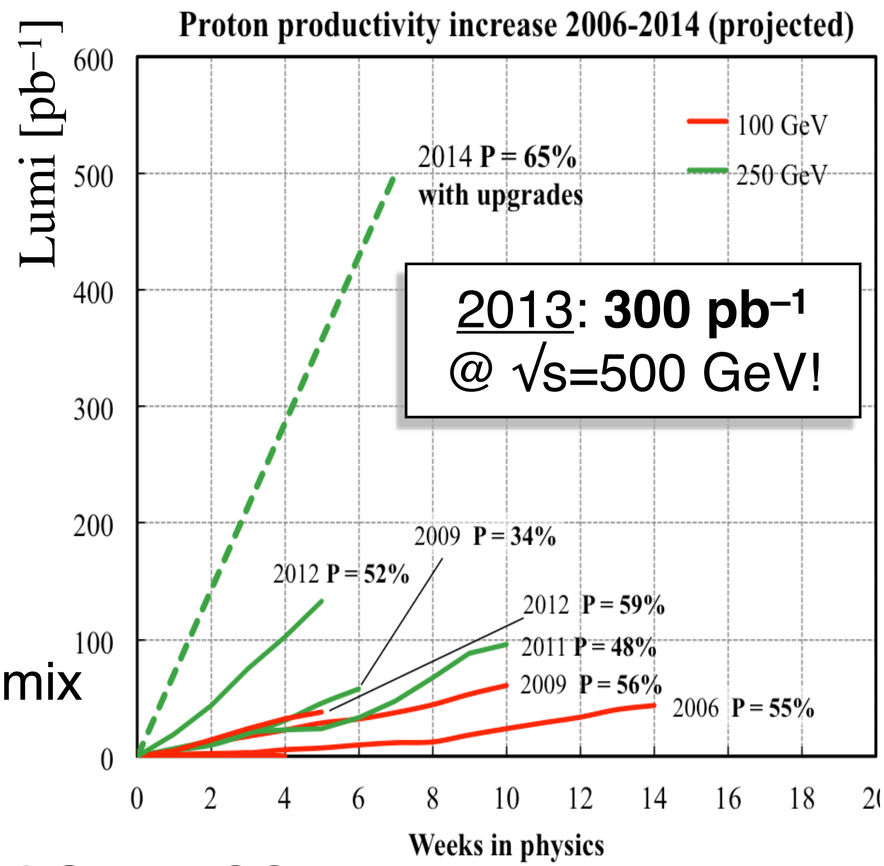
The Hadron Physics Landscape :

Next 10 Years

The Facilities : Today

Jefferson Lab

- **12 GeV** polarized e : first beam 2013, commission^{g} 2014, produc^{n} 2015
- Complementary capabilities in 4 Halls
  → **broad physics program**



STAR PHENIX

- Transv (T) & Longit (L) polarized p beams colliding at $\sqrt{s}$ = 200 GeV or 500 GeV
- L core : $A_{LL}^{\pi 0}$ (PHENIX) & A_{LL}^{jet} (STAR) → **Δg(x)**
  : $A_L^{W\pm}$ at $\sqrt{s}$ = 500 GeV → **Δqbar(x)**
- T core : A_N $^{\pi 0, \eta, jet, ...}$ → Sivers/Collins/Twist-3 mix

E906 SeaQuest

- 120 GeV p from Main Injector on p,d,A targets → **high-x Drell-Yan**
- Production running declared Mar'14

COMPASS-II

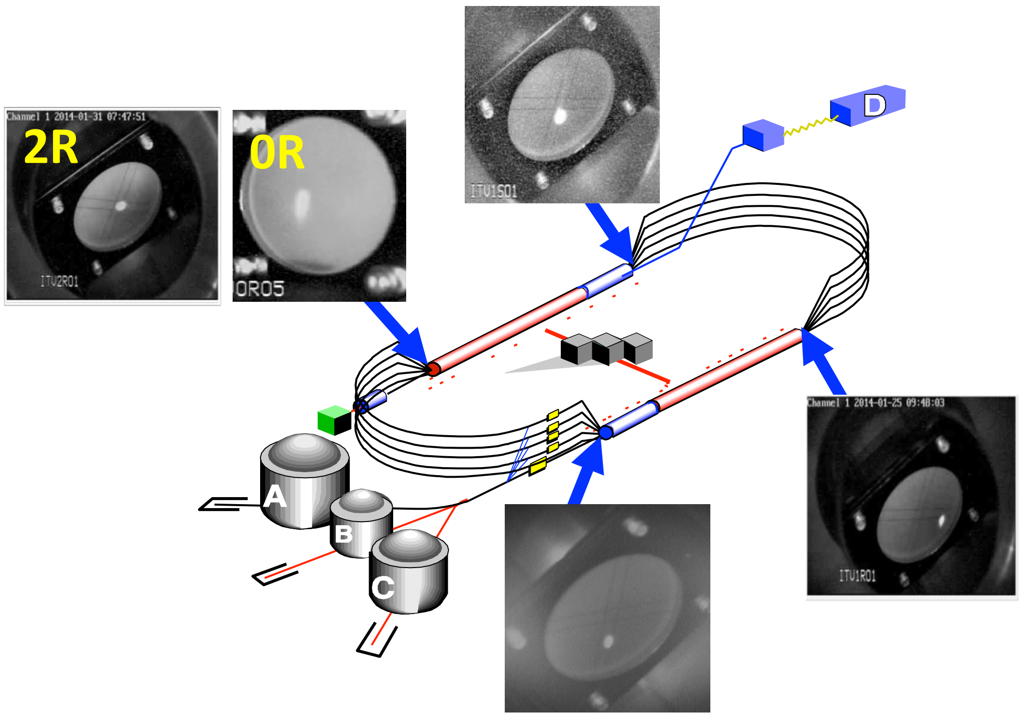
- 190 GeV π^- beam on T-polarized H target → **polarized Drell-Yan**
- First beam expected end of 2014

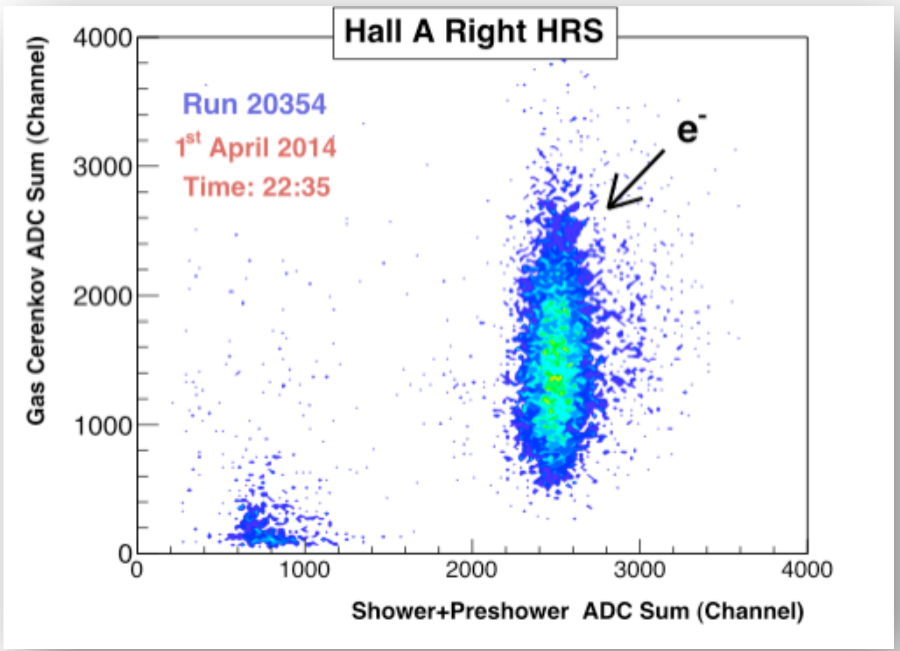
Beam Commissioning to Hall A

Jefferson Lab in Newport News hits major milestone in accelerator upgrade

April 30, 2014|By Tamara Dietrich, tdietrich@dailypress.com | Daily Press

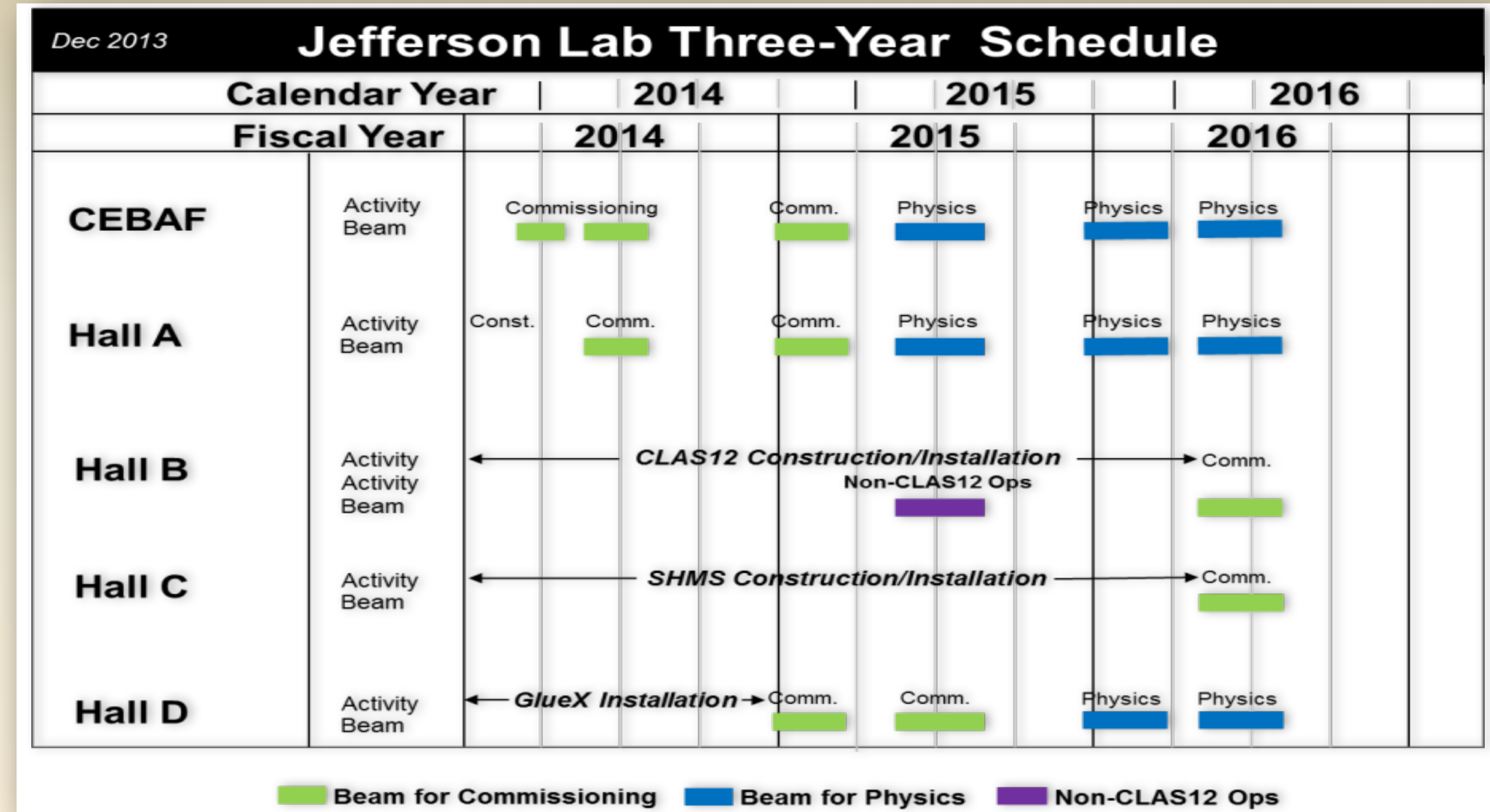
Jefferson Lab in Newport News has reached a "major milestone" in its drive to double the energy of its electron accelerator and become the only facility in the world capable of answering key questions about quarks, the building blocks of matter.





Beam on carbon target in Hall A ; E_{beam} = 6.1 GeV

12 GeV CEBAF: Three Year Schedule



Pushing to Physics

The Facilities : 2020+

we hope ...

✚ **SOLID** detector in Hall A → large acceptance & high rate for **parity violation** (PVDIS) & **polarized SIDIS** programs

Forward! Forward! → *higher η = higher x_{beam}, lower x_{target}*

✚ **STAR Forward Calorimeter System** = EMCal + HCal
→ forward **jets** & e/h separaton for **Drell-Yan**

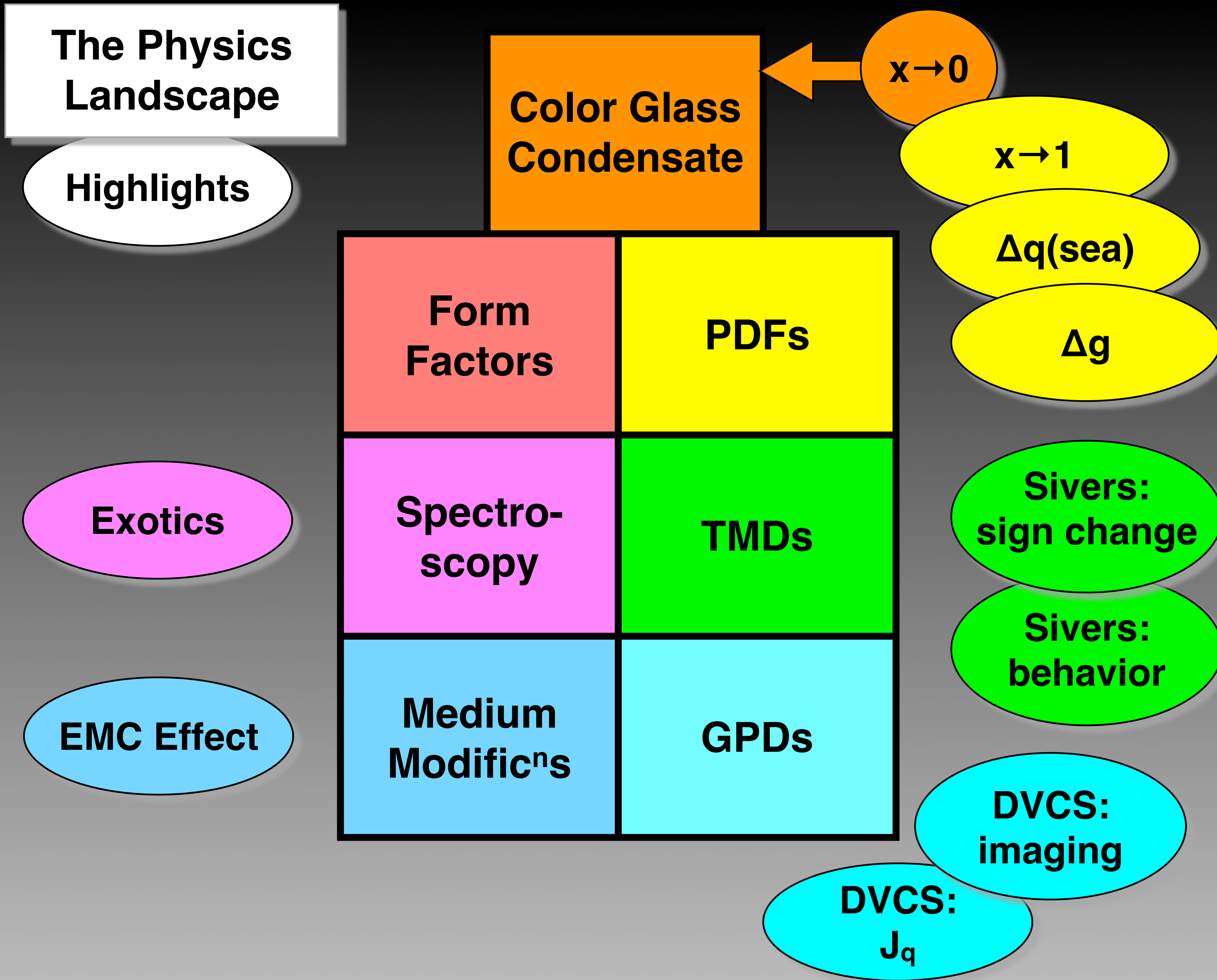
✚ **fsPHENIX** = forward spectrom w EMCal, HCal, RICH, tracking
→ forward **jets** + **identified hadrons** and **Drell-Yan**

Polarized Beam and/or Target w SeaQuest detector

*A **high-luminosity** facility for **polarized Drell-Yan***

✚ **E-1027** MI p↑ beam w polarized source + 1 Siberian Snake

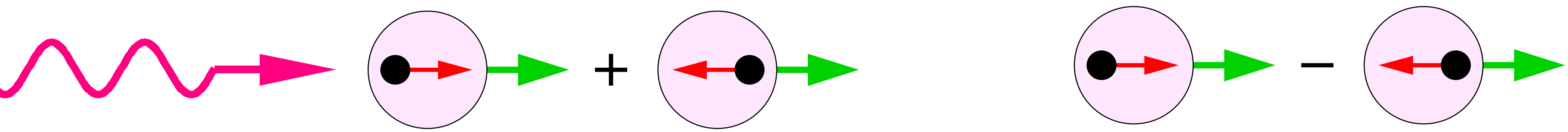
✚ **E-1039** SeaQuest with polarized p↑ target


The Physics Landscape
Highlights
Color Glass Condensate
x→0
x→1
Δq(sea)
Δg
Form Factors
PDFs
Spectro-scopy
TMDs
Medium Modific^{ns}
GPDs
Exotics
EMC Effect
Sivers: sign change
Sivers: behavior
DVCS: imaging
DVCS: J_q

The Proton Spin Puzzle: Quark and Gluon Polarization

The Pieces of the Spin Puzzle

$$q(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x) \qquad \Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$$



only three possibilities ⇒ $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

❶ Quark polarization

$$\Delta\Sigma \equiv \int dx\,(\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x))$$ ≈ 25% only

❷ Gluon polarization

$$\Delta G \equiv \int dx\,\Delta g(x)$$ small…?

❸ Orbital angular momentum

$$L_z \equiv L_q + L_g$$

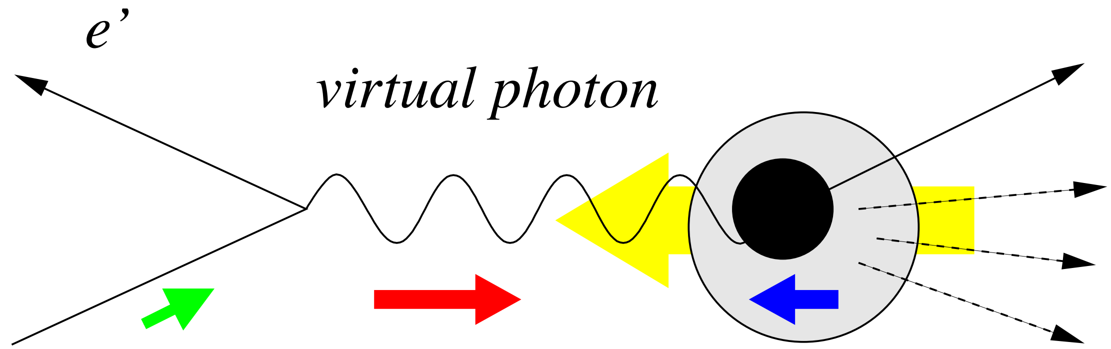
State of the art: DSSV global fit to Δq and ΔG

full next-to-leading order QCD

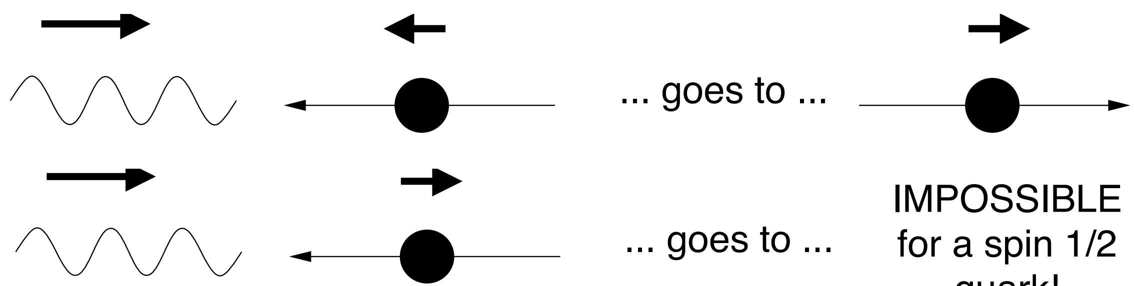
DeFlorian, Sassot, Stratmann, Vogelsang, PRL 101 (2008) and PRD 80 (2009)

World Data: polarized **eN** and **pp** scattering

Spin-Dependent Deep Inelastic Scattering (DIS)



The polarized photon selects certain quark polarizations :



Double spin asymmetries are measured :

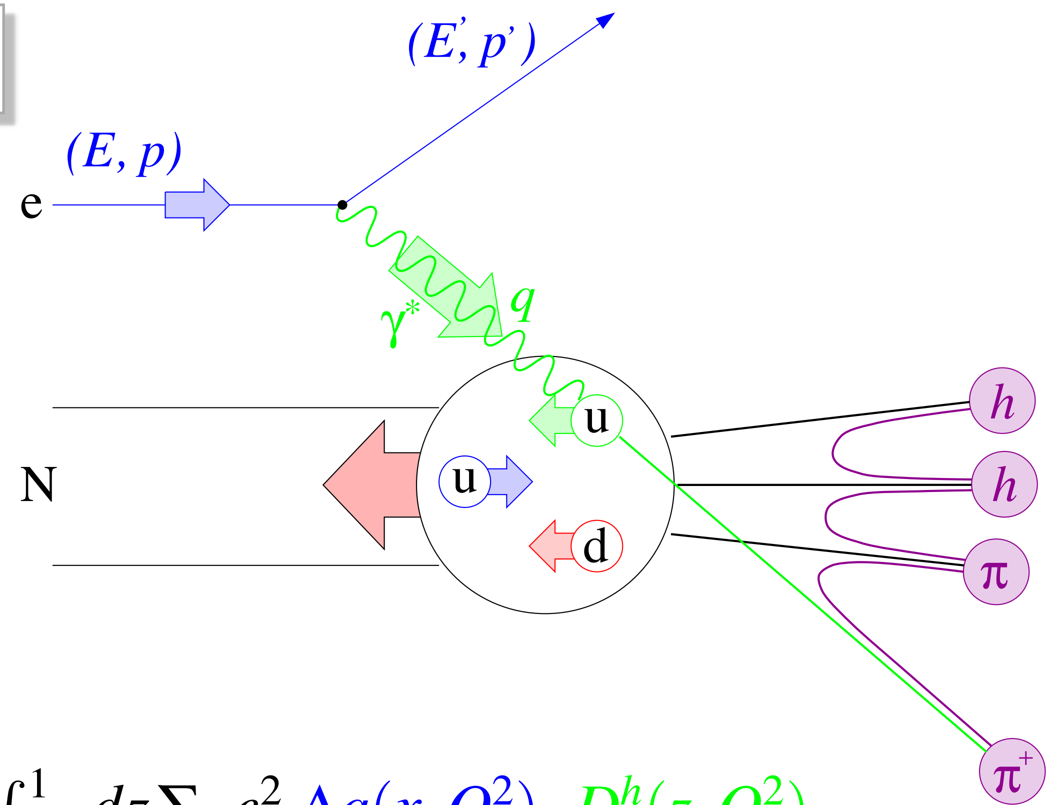
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1} = \frac{\sum_q e_q^2 \, \Delta q(x, Q^2)}{\sum_q e_q^2 \, q(x, Q^2)}$$

The story so far ... from inclusive measurements of $g_1(x,Q^2)$

- $\Delta\Sigma$ is around 20-30 %
- some indication that Δs may be negative ... (-10% ??)
- some indication that ΔG may be positive ... ?

Semi-Inclusive DIS (SIDIS)

*In SIDIS, a <u>**hadron**</u> **h** is detected **in coincidence** with the scattered lepton*



Flavor Tagging in LO QCD:

$$A_1^h(x,Q^2) = \frac{\int_{z_{min}}^1 dz \sum_q e_q^2 \, \Delta q(x,Q^2) \cdot D_q^h(z,Q^2)}{\int_{z_{min}}^1 dz \sum_q e_q^2 \, q(x,Q^2) \cdot D_q^h(z,Q^2)}$$

$D_q^h(z,Q^2)$ **: Fragmentation function**

Measures probability for struck quark q to produce a hadron h with

Energy fraction

$$z \equiv \frac{E_h}{\nu}$$

N.C.R. Makins, NNPSS 2015

The Proton Spin Puzzle:
What results might we expect?

Constituent Quarks

Spin from the SU(6) Proton Wave Function

The 3 quarks are **identical fermions** ⇒ ψ **antisymmetric** under exchange

$$\psi = \psi(\text{color}) * \psi(\text{space}) * \psi(\text{spin}) * \psi(\text{flavor})$$

❶ **Color**: All hadrons are color singlets = **antisymmetric**

$$\psi(\text{color}) = 1/\sqrt{6}\,(RGB - RBG + BRG - BGR + GBR - GRB)$$

❷ **Space**: proton has $l = l' = 0 \rightarrow \psi(\text{space})$ = **symmetric**

❸ **Spin**: $2 \otimes 2 \otimes 2 = (\,3_S \oplus 1_A\,) \otimes 2 = 4_S \oplus 2_{MS} \oplus 2_{MA}$

- 4_S symmetric states have spin 3/2, e.g. $\left|\frac{3}{2},+\frac{3}{2}\right\rangle = \uparrow\uparrow\uparrow$
- 2_{MS} and 2_{MA} have spin 1/2 and **mixed symmetry**: S or A under exchange of *first 2* quarks only. For proton:

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MS} = (\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)/\sqrt{6} \qquad \left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MA} = (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{2}$$

❹ **Flavor**: symmetry groups SU(2)-spin and SU(3)-color are exact ...

- strong force is ***flavor blind***
- constituent q masses ***similar***: $m_u, m_d \approx$ 350 MeV, $m_s \approx$ 500 MeV

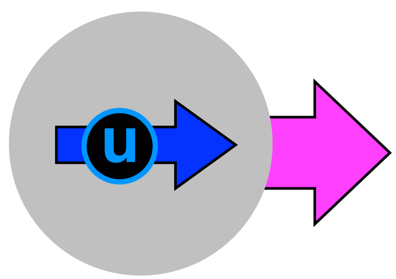
➡ SU(3)-flavor is ***approximate*** for u, d, s

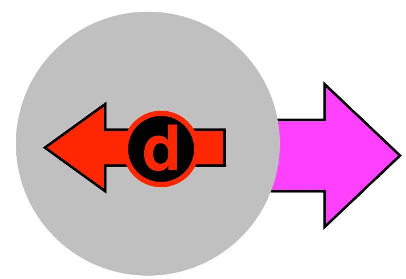
SU(3)-flavor gives $3 \otimes 3 \otimes 3 = 10_S \oplus 8_{MS} \oplus 8_{MA} \oplus 1_A$

➤ **Proton**: $\psi(s=1/2)$ from spin $2_{MS}, 2_{MA}$ $\otimes$ $\psi(uud)$ from flavor $8_{MS}, 8_{MA}$

$$|p^\uparrow\rangle = (u^\uparrow u^\downarrow d^\uparrow + u^\downarrow u^\uparrow d^\uparrow - 2u^\uparrow u^\uparrow d^\downarrow + \text{ 2 permutations})/\sqrt{18}$$

➤ Count the number of quarks with spin up and spin down:





➤ Quark contributions to proton spin are:

$$\Delta u = N(u^\uparrow) - N(u^\downarrow) = +\frac{4}{3} \qquad \Delta d = N(d^\uparrow) - N(d^\downarrow) = -\frac{1}{3}$$

$$\Rightarrow \Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$$

All spin present & accounted for!

Proton Spin Structure: the Sea

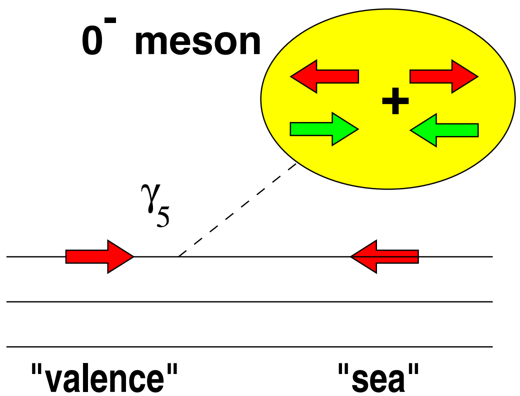
Constituent Quark Model

$$\Delta u = +\frac{4}{3}, \quad \Delta d = -\frac{1}{3}$$

$\Delta q \equiv N^{\uparrow} - N^{\downarrow}$

Meson Cloud Models

Li, Cheng, hep-ph/9709293



➡ $\Delta q_{\text{valence}} > 0$

➡ $\Delta q_{\text{sea}} < 0$

➡ $\Delta \bar{q} = 0$

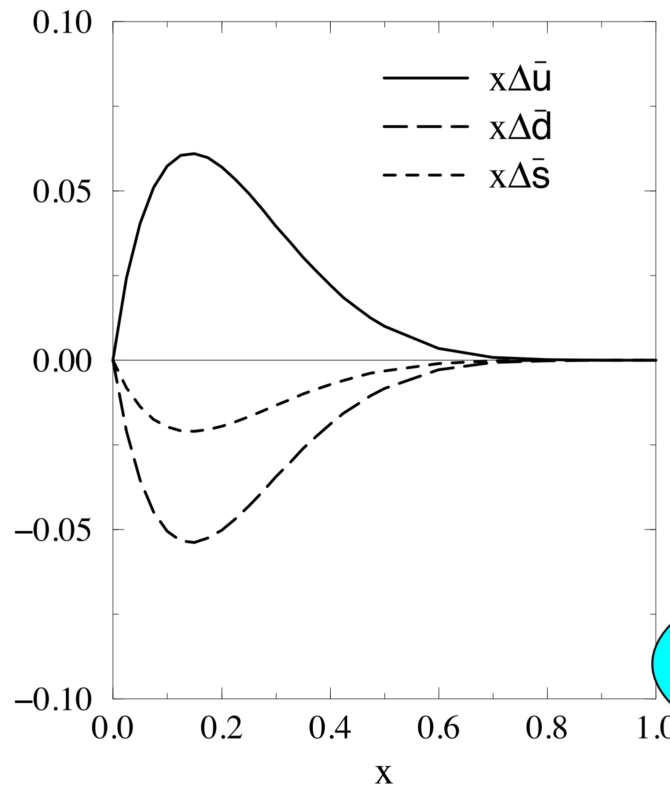
"Higher-order" cloud of vector mesons can generate a small polarization.

Chiral-Quark Soliton Model

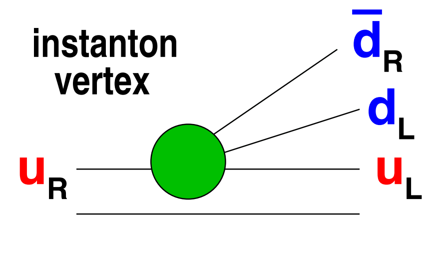
Goeke et al, hep-ph/0003324

Light sea quarks polarized:

$$\Delta \bar{u} \simeq -\Delta \bar{d} > 0$$



Instanton Mechanism



'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$ transfers helicity from valence u quarks to $d\bar{d}$ pairs

No gluons in these models

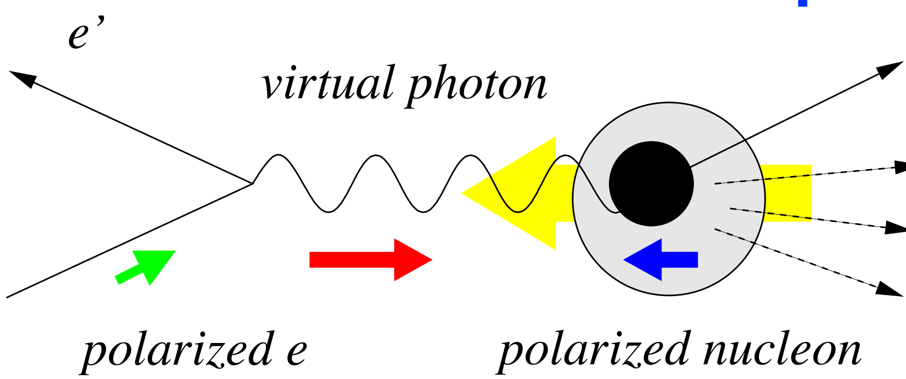
What results do we get?

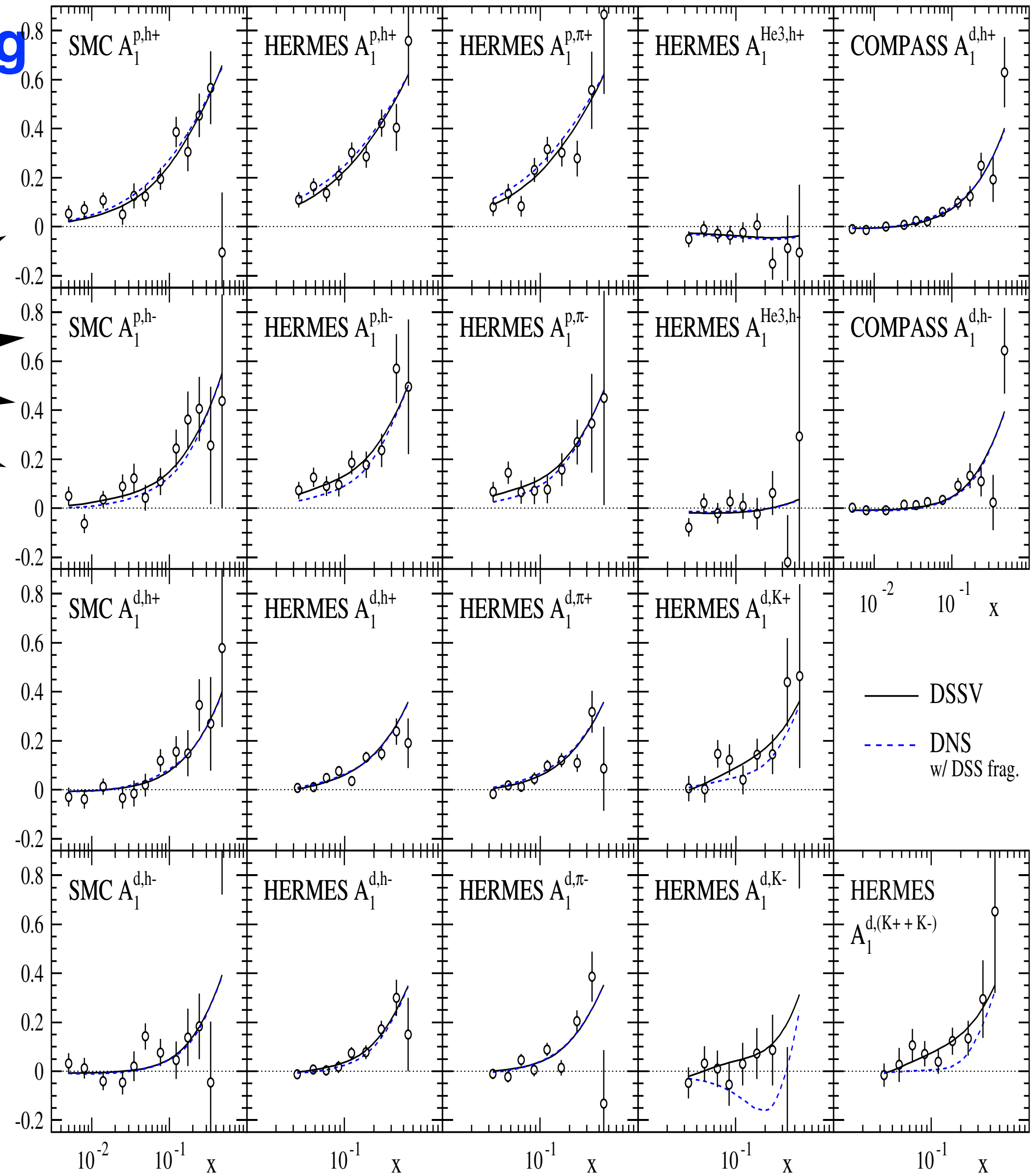
A Wealth of Spin Data

a sample ...

Polarized Deep-Inelastic Scattering

electron / muon beams → **Δq**





hermes

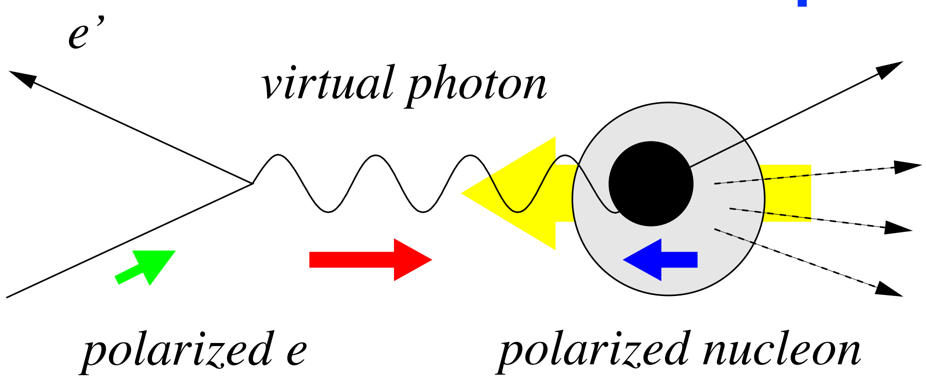
COMPASS

Jefferson Lab
Exploring the Nature of Matter

A Wealth of Spin Data

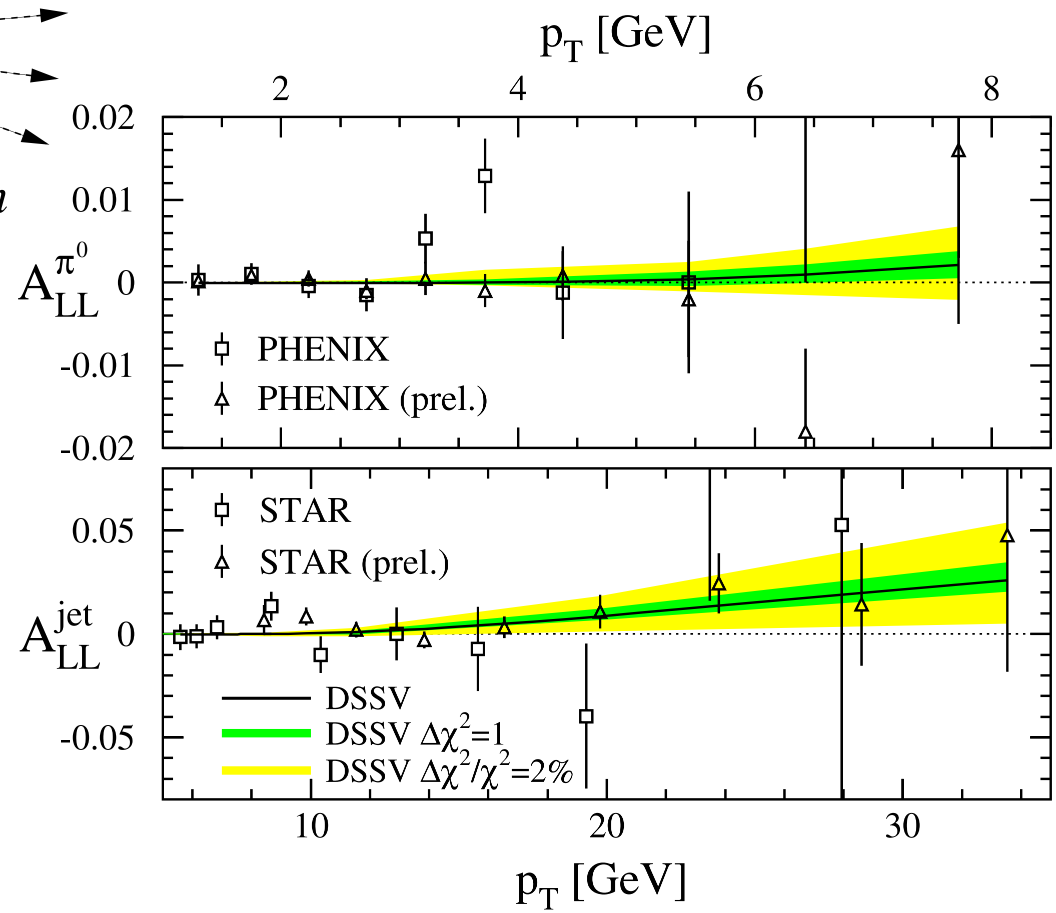
Polarized Deep-Inelastic Scattering

electron / muon beams → **Δq**



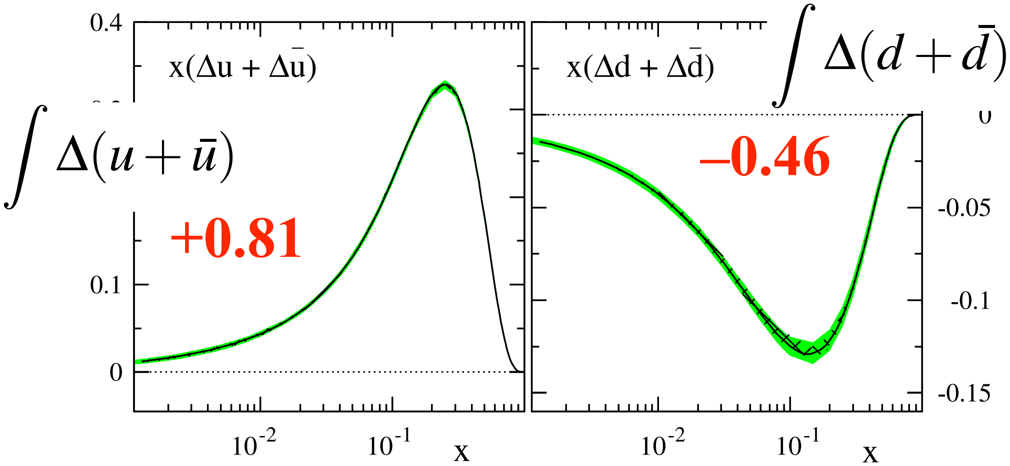
Polarized p-p Scattering

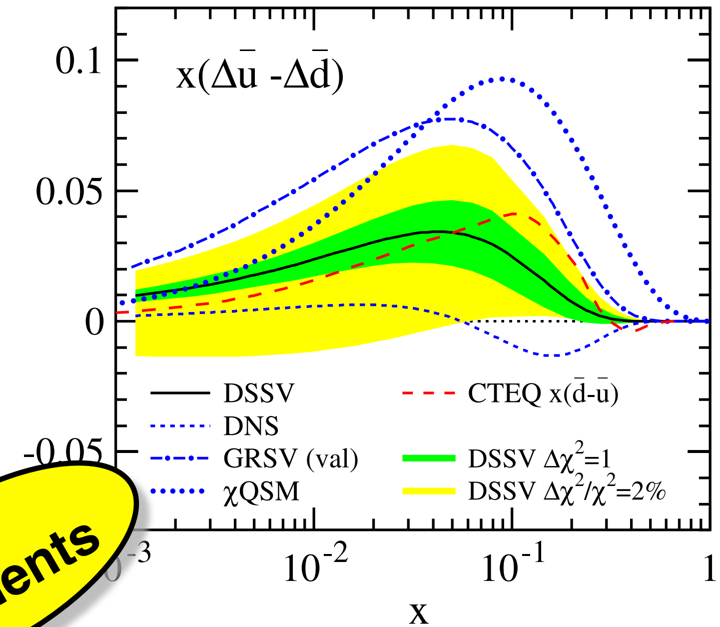
at RHIC → **ΔG**

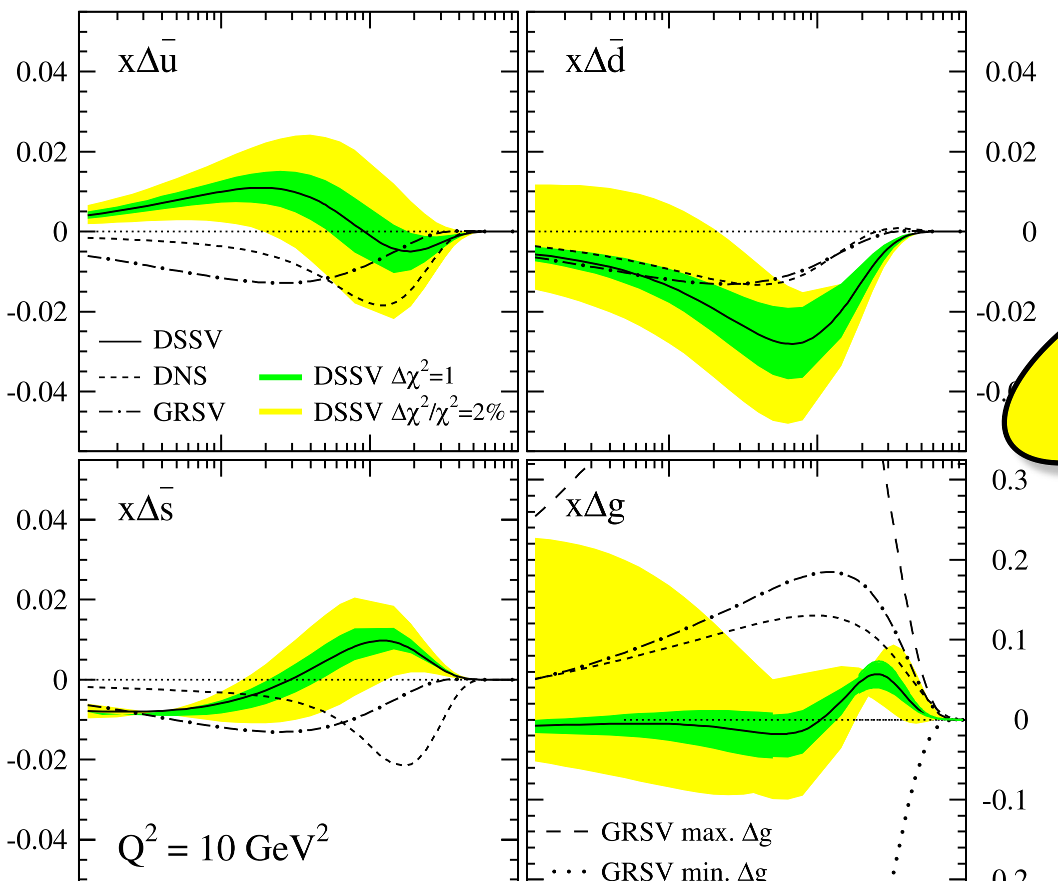


DSSV NLO global fit: Δq & Δg

DeFlorian, Sassot, Stratmann, Vogelsang,
PRL 101 (2008) 071001, PRD 80 (2009) 034030







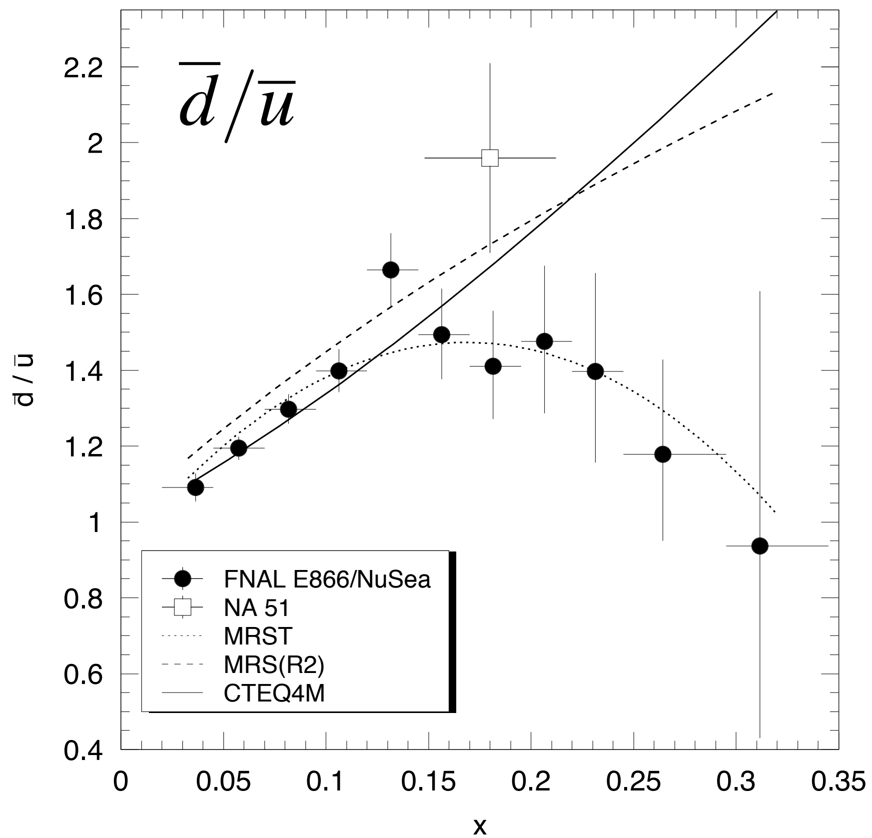
1st moments

	meas: x > .001	extrap: all x	error
ΔΣ	0.37	**0.24**	+0.04 –0.06
$\Delta\bar{u}$	0.03	0.04	±0.06
$\Delta\bar{d}$	–0.09	–0.12	±0.09
Δs	–0.01	–0.06	±0.03
ΔG	0.01	–0.08	+0.7 –0.3

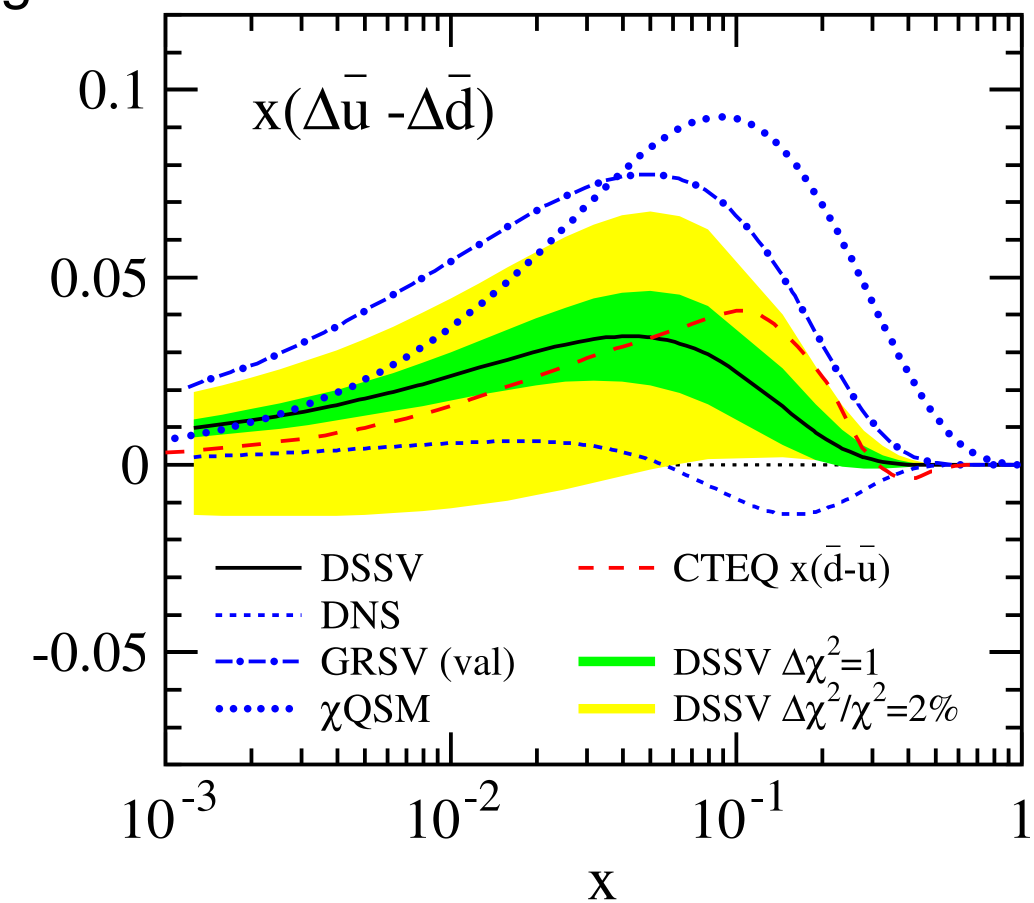
gluons & sea: spin-polarizations
all negative-ish ***zeros***

Flavour Symmetry of the Light Sea

Unpolarized PDF's for $\bar{u}$ and $\bar{d}$:
Strong isospin-symmetry breaking



Polarized PDF's for $\bar{u}$ and $\bar{d}$ ...



Weak isospin-asymmetry observed in the light sea polarization

➡ ***results between meson cloud & chiral-quark soliton models***

... more data coming from RHIC

N.C.R. Makins, NNPSS 2015

Longitudinal Data

	√s	L* (pb⁻¹)
2006	200	7
2009	200	**25**
“	500	10
2011	500	12
2012	500	82
2013	500	**300**

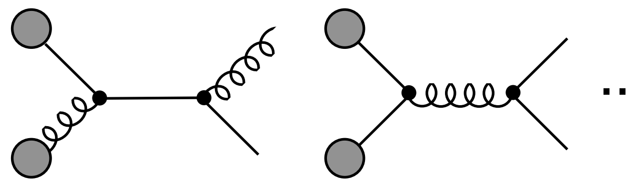
L* recorded at STAR

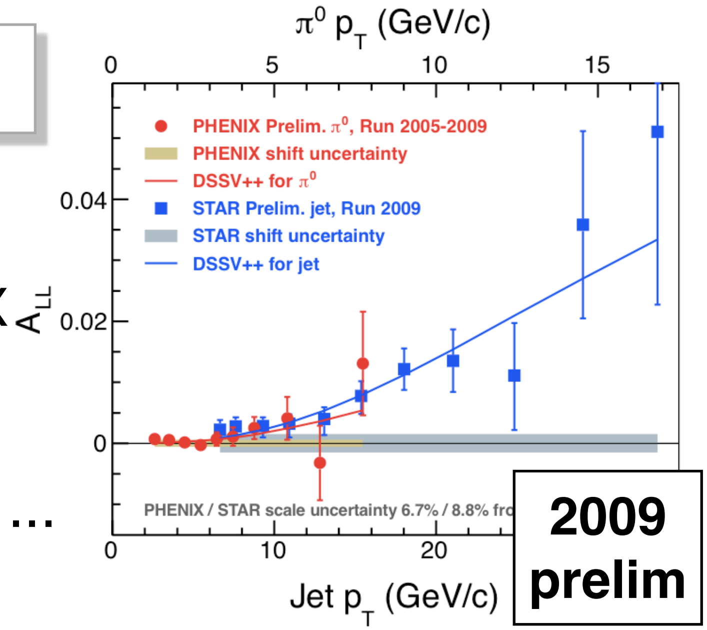
Δg at RHIC → 2020

(1) Δg workhorses:

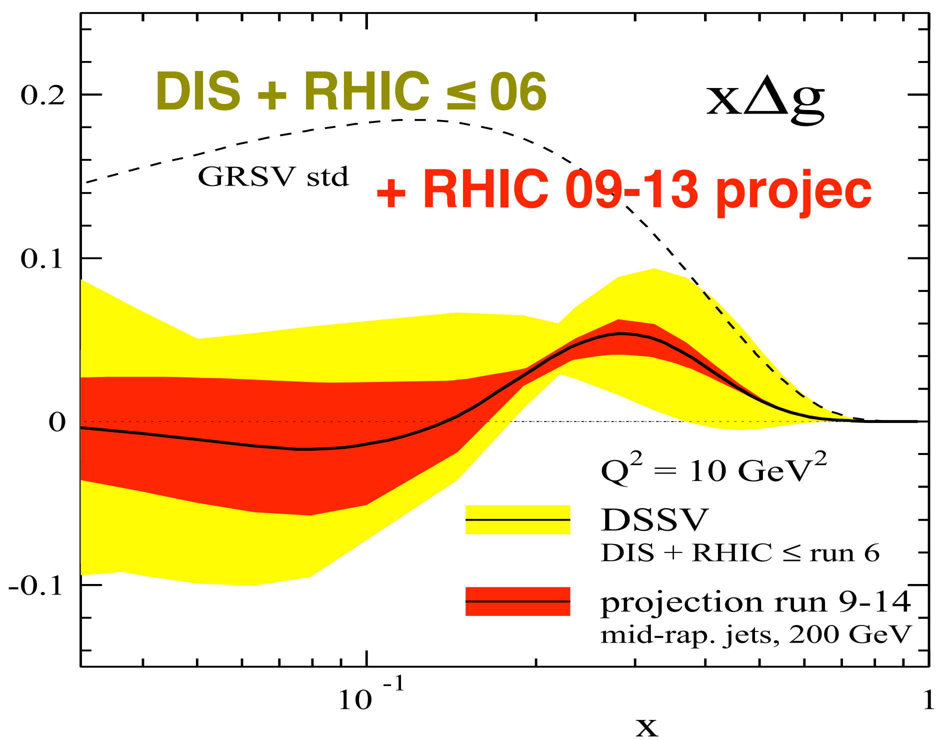
A_{LL} → π^0 + X @ PHENIX

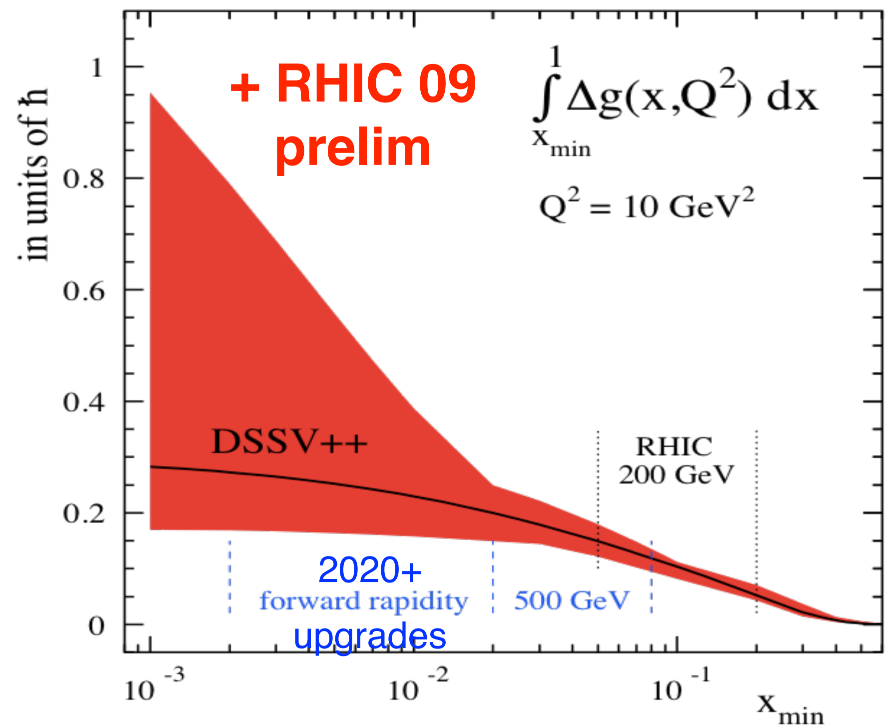
A_{LL} → jet + X @ STAR

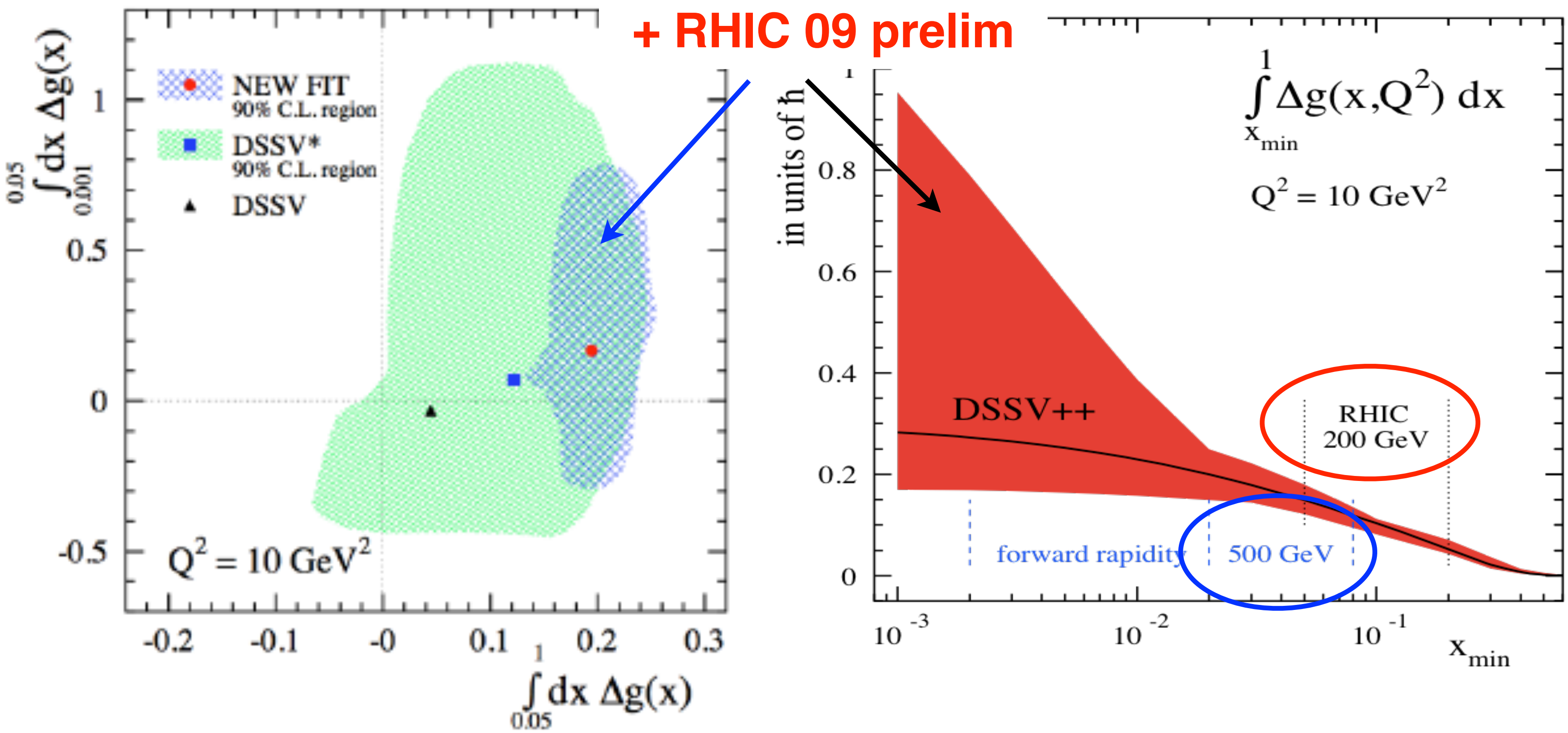




pQCD Fits :







(2) reduce x_{min} from **0.05** → **0.02** via √s = 500 GeV &

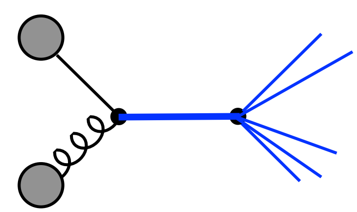
new/near-term forward detectors (e.g. PHENIX MPC)

(3) constrain **x-dependence** of Δg(x) via ≈**exclusive final states**

→ **dijets** at STAR & **di-π^0** at PHENIX

→ reconstruct initial-state **parton kinematics**

dijets



Δg 2020+

(4) forward upgrades : **reduce x_{min}** → **0.001**

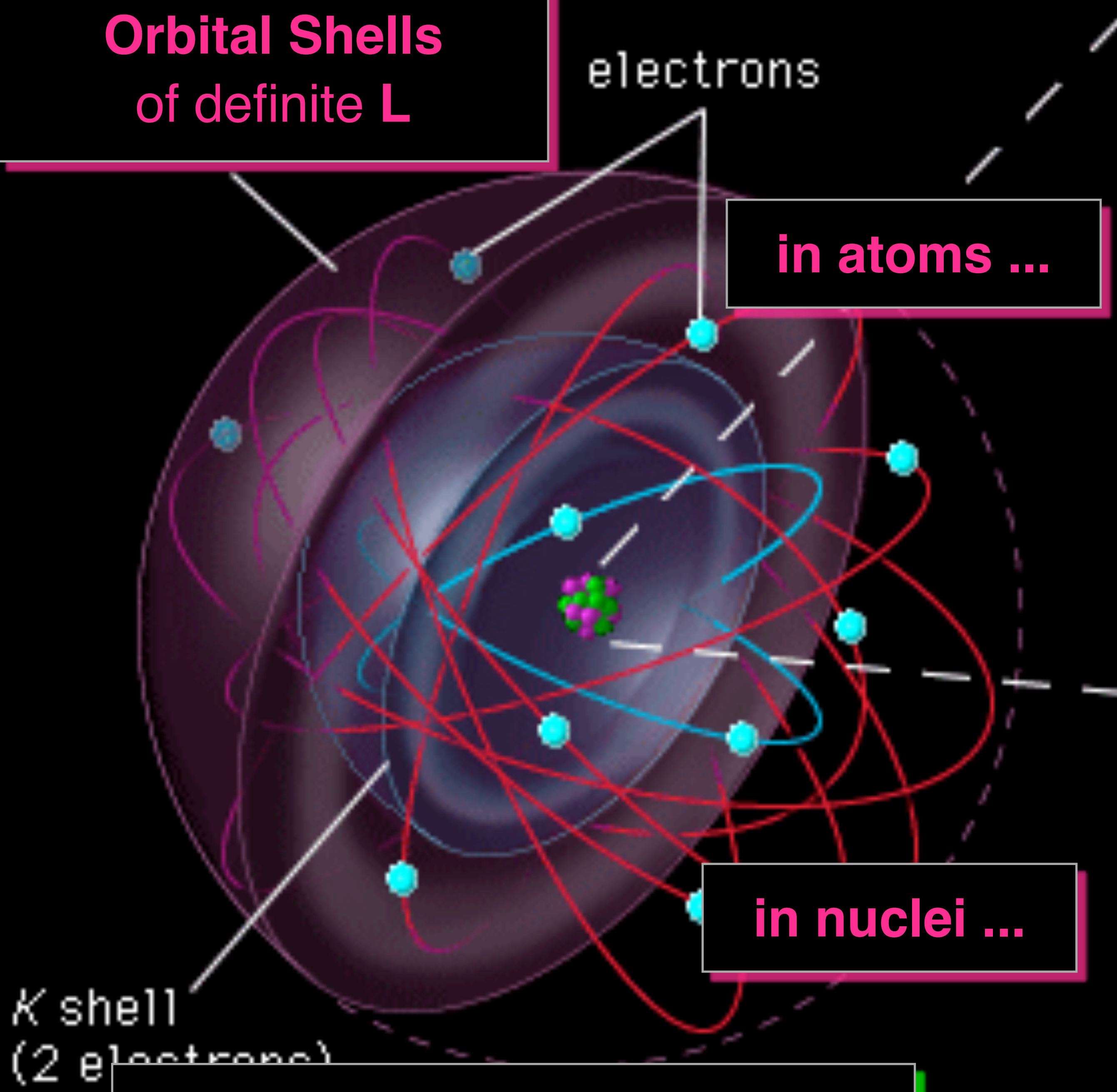
What's left?

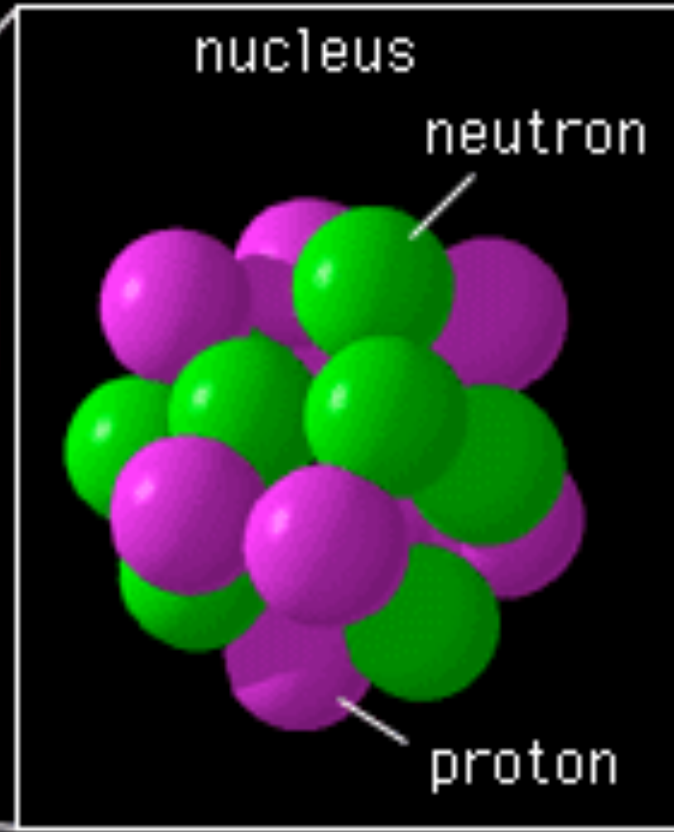
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathbf{L_q} + \mathbf{L_g}$$

L + Relativity = Weirdness

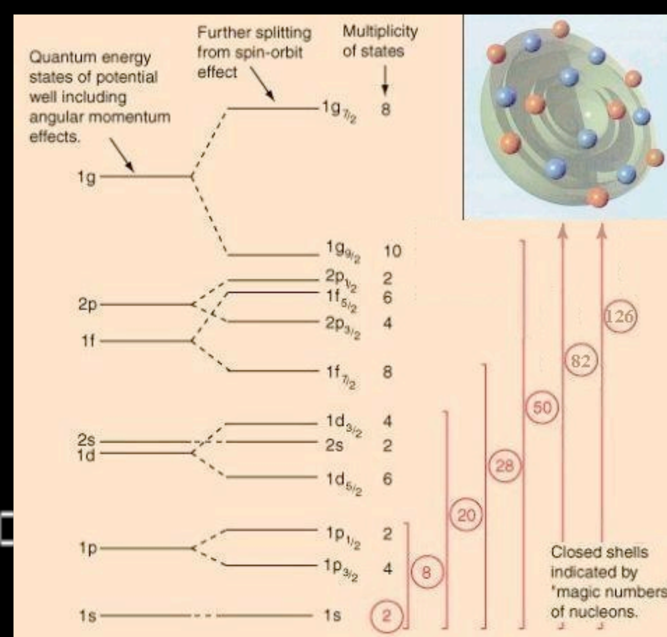
Orbital Shells
of definite **L**

in atoms ...





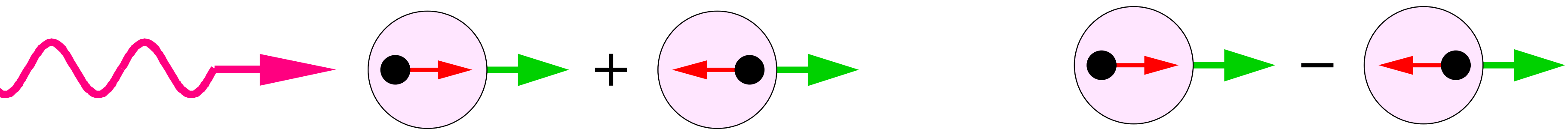
in nuclei ...



... and within the proton? ...

The Pieces of the Spin Puzzle

$$q(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x) \qquad \Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$$



only three possibilities ⟹

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

❶ Quark polarization

$$\Delta\Sigma \equiv \int dx\,(\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)) \approx 30\% \text{ only}$$

❷ Gluon polarization

$$\Delta G \equiv \int dx\,\Delta g(x) \quad \text{small...?}$$

❸ Orbital angular momentum

$$L_z \equiv L_q + L_g$$

?

In friendly, **non-relativistic** bound states like atoms & nuclei (& constituent quark model), particles are in ***eigenstates of L***

<u>Not so</u> for bound, ***<u>relativistic</u> Dirac particles*** ...
Noble *L* is ***<u>not a good quantum number</u>***

Dirac free plane-wave particle with spin $\boldsymbol{S_z = +1}$

Boosting a Dirac Spinor

and Σ isn't a 4-vector, oy

at rest $\vec{p} = 0$

$$\psi = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} e^{-imt}$$

BOOST
in **–x direc**$^{\mathbf{n}}$ with

$$\beta = p'/E' = \tanh\phi$$

$$\hat{B}(\hat{x},\phi) = e^{\frac{\phi}{2}\vec{\alpha}\cdot\hat{x}} = \cosh\frac{\phi}{2}\,\mathbf{1} + \sinh\frac{\phi}{2}\,\boldsymbol{\alpha}_x$$

$\vec{p}\,' = p'\,\hat{x}$

$$\psi' = N \begin{pmatrix} 1 \\ 0 \\ 0 \\ \dfrac{p'}{E'+m} \end{pmatrix} e^{i(p'x'-E't')}$$

What's its spin?

$$\frac{\psi^\dagger \vec{\Sigma}\,\psi}{\psi^\dagger \psi} = \hat{z}$$

$$\vec{\Sigma} = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$$\vec{\sigma} = \begin{pmatrix} \hat{z} & \hat{x} - i\hat{y} \\ \hat{x} + i\hat{y} & -\hat{z} \end{pmatrix}$$

$$\frac{\psi'^\dagger \vec{\Sigma}\,\psi'}{\psi'^\dagger \psi'} = \hat{z}\left[1 - \left(\frac{p'}{E'+m}\right)^2\right]$$

$$\approx \hat{z}\,\frac{1}{\gamma^2} \quad \text{for } \gamma \gg 1$$

Why there are no transversely polarized electron machines

Spin, L, and the free Dirac Hamiltonian

$$\mathbf{H} = \boldsymbol{\alpha}\cdot\vec{p} + \boldsymbol{\beta} m = \begin{pmatrix} m\mathbf{1} & -i\vec{\boldsymbol{\sigma}}\cdot\vec{\nabla} \\ -i\vec{\boldsymbol{\sigma}}\cdot\vec{\nabla} & m\mathbf{1} \end{pmatrix}$$

$$\vec{\mathbf{L}}(\vec{x}) = 1\ \vec{x}\times\vec{p} = -1\, i\,\vec{x}\times\vec{\nabla}$$

➡ **L** position-dependent, doesn't commute w ∂_i in **H**

$$[\ \mathbf{H}, \vec{\mathbf{L}}(x_i)\ ] = -\vec{\boldsymbol{\alpha}}\times\vec{\nabla}$$

L NOT CONSERVED

no shells!

$$\vec{\boldsymbol{\Sigma}} = \begin{pmatrix} \vec{\boldsymbol{\sigma}} & 0 \\ 0 & \vec{\boldsymbol{\sigma}} \end{pmatrix}$$

➡ Pauli matrices in **Σ** and **H** don't commute

$$[\ \mathbf{H}, \vec{\boldsymbol{\Sigma}}\ ] = 2\vec{\boldsymbol{\alpha}}\times\vec{\nabla}$$

$$[\ \boldsymbol{\sigma}_i, \boldsymbol{\sigma}_j\ ] = 2i\,\varepsilon_{ijk}\,\boldsymbol{\sigma}_k$$

SPIN NOT CONSERVED

intuition?

➡ $$\left[\ \mathbf{H}, \vec{\mathbf{L}} + \tfrac{1}{2}\vec{\boldsymbol{\Sigma}}\ \right] = \left[\ \mathbf{H}, \vec{\mathbf{J}}\ \right] = 0$$

J CONSERVED

Liang, Meng, ZPA 344 (1992)

Dirac particle in a central potential

We denote the solution of the above-mentioned equation by the Dirac four-spinor ψ and/or its upper- and lower-component, the corresponding two-spinors φ and χ. The stationary states are characterized by the following set of quantum numbers ε, j, m and P which are respectively the eigenvalues of the operators $\hat{H}$ (the Hamiltonian), $\hat{\mathbf{j}}^2$, $\hat{j}_z$ (total angular momentum and its z-component) and $\hat{P}$ (the parity). Since every eigenstate of the valence quark characterized by ε, j, m and P corresponds to two different orbital angular momenta l and $l'=l\pm 1$, (see Appendix A), it is clear that *orbital motion is involved in every stationary state*. This is true *also when the valence quark is in its ground state* ($\psi_{\varepsilon jmP}$ where $\varepsilon=\varepsilon_0$, $j=1/2$, $m=\pm 1/2$, $P=+$[2]). This state can be expressed as follows:

$$\psi_{\varepsilon 0 1/2\ m+}(r,\theta,\phi)=\begin{pmatrix} f_0(r)\,\Omega_0^{1/2\ m}(\theta,\phi) \\ g_1(r)\,\Omega_1^{1/2\ m}(\theta,\phi)\end{pmatrix}. \qquad (2.1)$$

The angular part of the two-spinors can be written in terms of spherical functions $Y_{ll_z}(\theta,\phi)$ and (non-relativistic) spin-eigenfunctions which are nothing else but the Pauli-spinors $\xi(\pm 1/2)$:

$$\Omega_0^{1/2\ m}(\theta,\phi)=Y_{00}(\theta,\phi)\,\xi(m),$$

The spherical solutions of a Dirac particle in a central potential are discussed in some of the text books (see, for example, Landau, L.D., Lifshitz, E.M.: Course of theoretical physics. Vol. 4: Relativistic quantum theory. New York: Pergamon 1971). The notations and conventions we use here are slightly different. In order to avoid possible misunderstanding, we list the general form of some of the key formulae in the following:

In terms of spherical variables, a state with given ε, j, m and P can be written as:

$$\psi_{\varepsilon jmP}(r,\theta,\phi) = \begin{pmatrix} f_{\varepsilon l}(r)\,\Omega_l^{jm}(\theta,\phi) \\ (-1)^{(l-l'+1)/2} g_{\varepsilon l'}(r)\,\Omega_{l'}^{jm}(\theta,\phi)\end{pmatrix}. \qquad (A1)$$

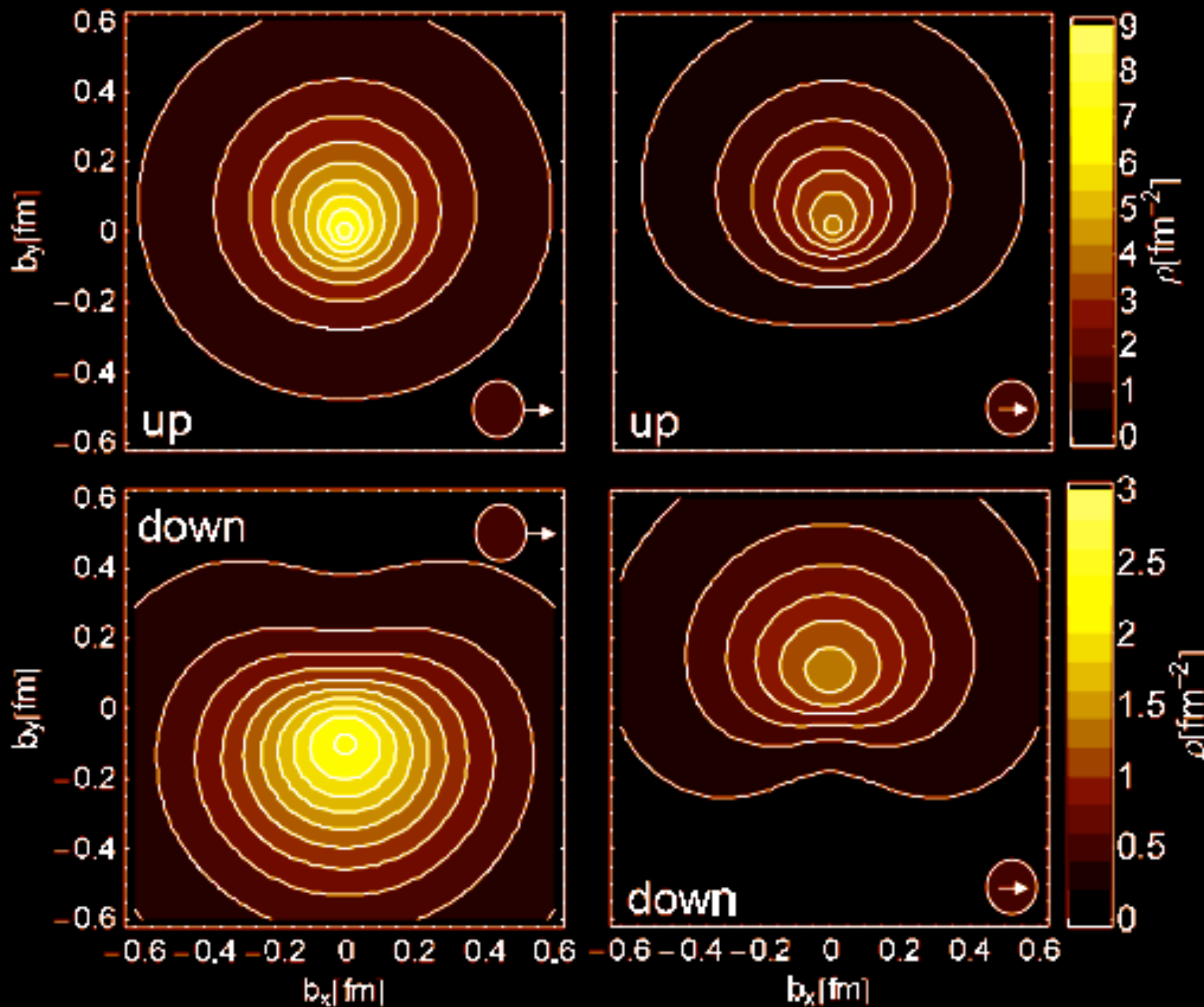
Here $l=j\pm 1/2$, $l'=2j-l$ and $P=(-1)^l$; Ω_l^{jm} and $\Omega_{l'}^{jm}$ are two-spinors which, for the possible values of l, are given by:

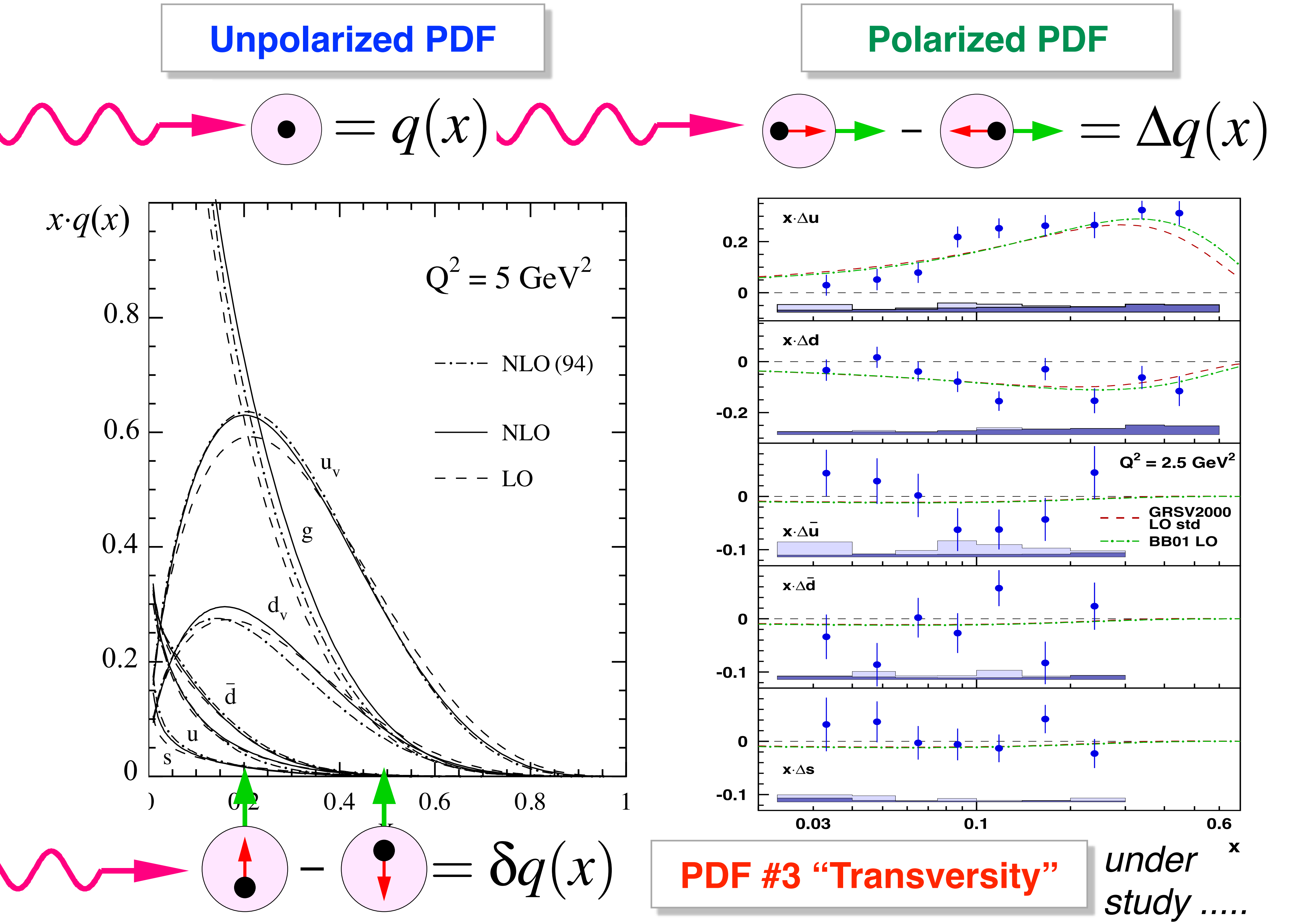
$$\Omega_{l=j-1/2}^{jm}(\theta,\phi) = \sqrt{\frac{j+m}{2j}}\,Y_{l l_z=m-1/2}(\theta,\phi)\,\xi(1/2) + \sqrt{\frac{j-m}{2j}}\,Y_{l l_z=m+1/2}(\theta,\phi)\,\xi(-1/2), \qquad (A2)$$

$$\Omega_{l=j+1/2}^{jm}(\theta,\phi) = -\sqrt{\frac{j-m+1}{2j+2}}\,Y_{l l_z=m-1/2}(\theta,\phi)\,\xi(1/2) + \sqrt{\frac{j+m+1}{2j+2}}\,Y_{l l_z=m+1/2}(\theta,\phi)\,\xi(-1/2). \qquad (A3)$$

Here, $\xi(\pm 1/2)$ stand for the eigenfunctions for the spin-operator $\hat{\sigma}_z$ with eigenvalues ± 1, and $Y_{ll_z}(\theta,\phi)$ for the spherical harmonics which form a standard basis for the orbital angular momentum operators $(\hat{\mathbf{l}}^2, \hat{l}_z)$. The function $f_{\varepsilon l}(r)$ and $g_{\varepsilon l'}(r)$ are solutions of the coupled differential equations:

TMDs, GPDs, and the Meaning of Life

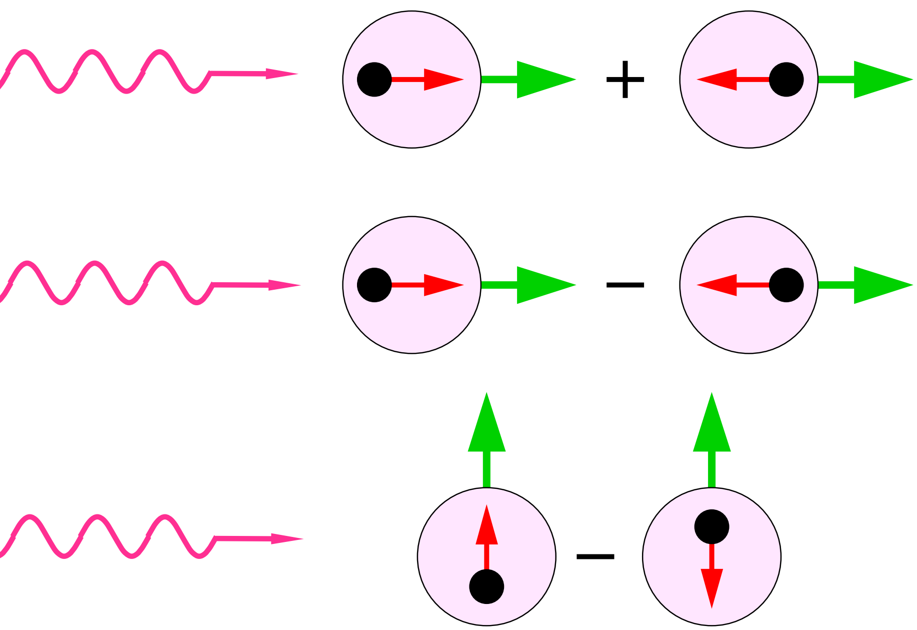




Unpolarized PDF
Polarized PDF
$= q(x)$
$= \Delta q(x)$
$x \cdot q(x)$
$Q^2 = 5$ GeV^2
NLO (94)
NLO
LO
u_v
g
d_v
$\bar{d}$
u
s
0.8
0.6
0.4
0.2
0
0.4
0.6
0.8
1
$x \cdot \Delta u$
$x \cdot \Delta d$
$x \cdot \Delta \bar{u}$
$x \cdot \Delta \bar{d}$
$x \cdot \Delta s$
$Q^2 = 2.5$ GeV^2
GRSV2000 LO std
BB01 LO
0.2
0
-0.2
-0.1
0.03
0.1
0.6
x
$= \delta q(x)$
PDF #3 “Transversity”
under study .....

3 Classes of Parton Distribution Functions

❶ Traditional PDFs



$$f_{1,q}(x) = \overrightarrow{q}(x) + \overleftarrow{q}(x)$$

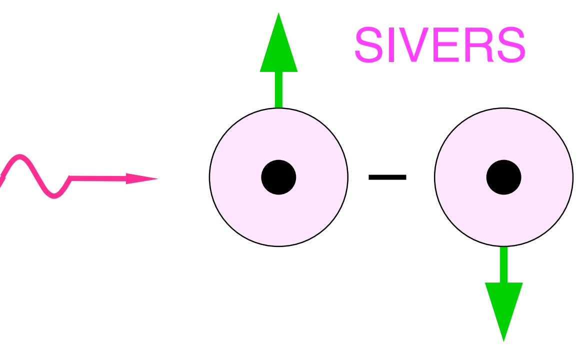
$$g_{1,q}(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$$

$$h_{1,q}(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$

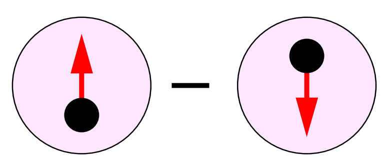
TRANSVERSITY

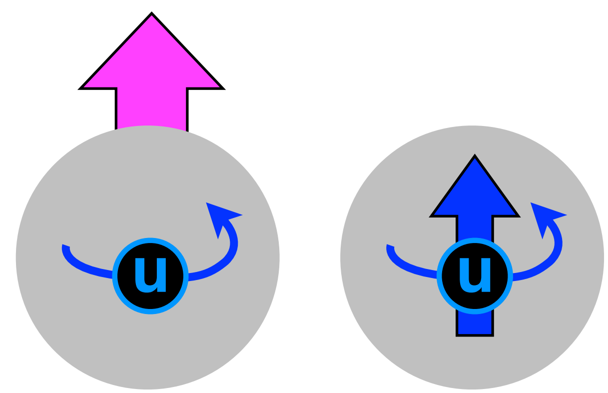
❷ **TMDs**: Transverse Momentum Dependent PDFs

SIVERS



BOER-MULDERS





$$f_{1T,q}^{\perp}(x, k_T) \sim \vec{L}_q \cdot \vec{S}_p \qquad h_{1,q}^{\perp}(x, k_T) \sim \vec{L}_q \cdot \vec{S}_q$$

N.C.R. Makins, NNPSS 2015

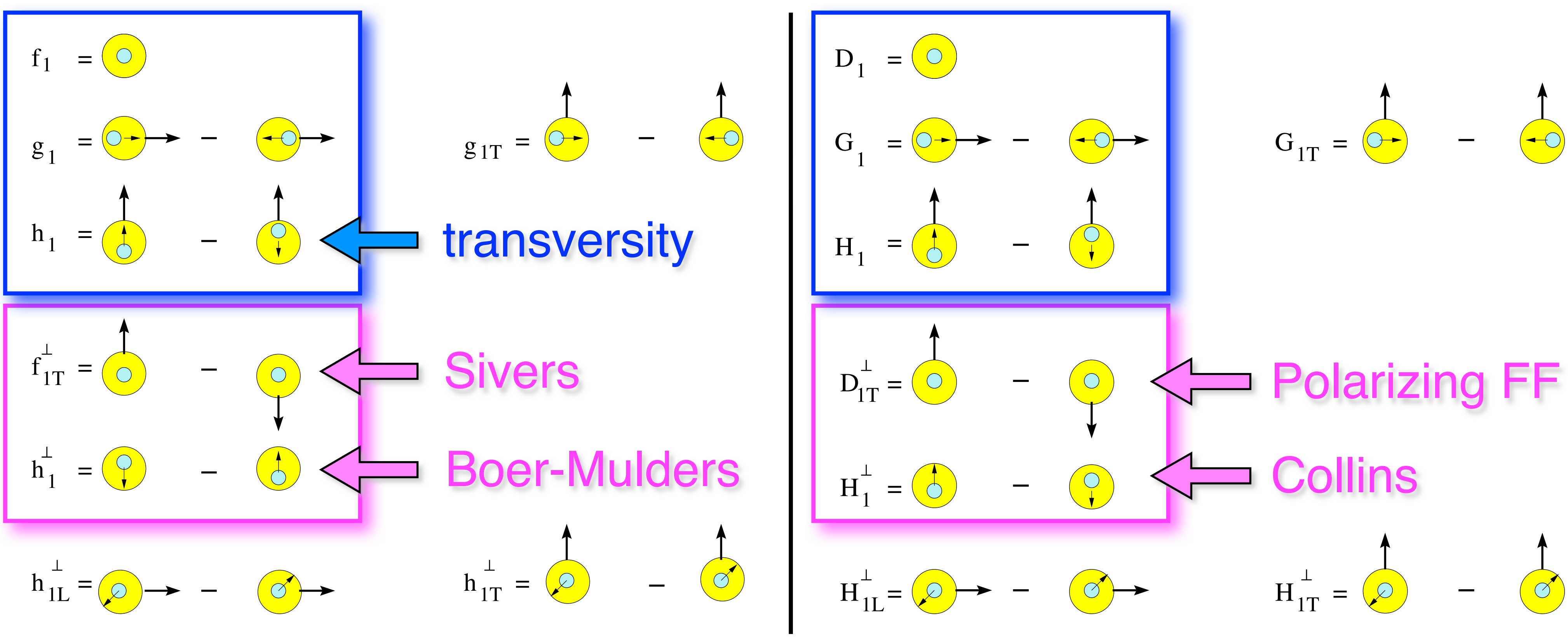
Blue boxes: Functions surviving on integration over transverse momentum

The others are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions

Fragmentation Functions



One ***T-odd function*** required to produce ***single-spin asymmetries*** in SIDIS

Measuring: Azimuthal Asymmetries

beam pol$^{\underline{n}}$ **target pol$^{\underline{n}}$**

SIDIS, at leading twist

UU	1	$\otimes\, f_1 =$	$\otimes\, D_1 =$
	$\cos(2\phi_h^l)$	$\otimes\, h_1^\perp =$	$\otimes\, H_1^\perp =$
UL	$\sin(2\phi_h^l)$	$\otimes\, h_{1L}^\perp =$	$\otimes\, H_1^\perp =$
UT	$\sin(\phi_h^l + \phi_S^l)$	$\otimes\, h_1 =$	$\otimes\, H_1^\perp =$
	$\sin(\phi_h^l - \phi_S^l)$	$\otimes\, f_{1T}^\perp =$	$\otimes\, D_1 =$
	$\sin(3\phi_h^l - \phi_S^l)$	$\otimes\, h_{1T}^\perp =$	$\otimes\, H_1^\perp =$
LL	1	$\otimes\, g_1 =$	$\otimes\, D_1 =$
LT	$\cos(\phi_h^l - \phi_S^l)$	$\otimes\, g_{1T} =$	$\otimes\, D_1 =$

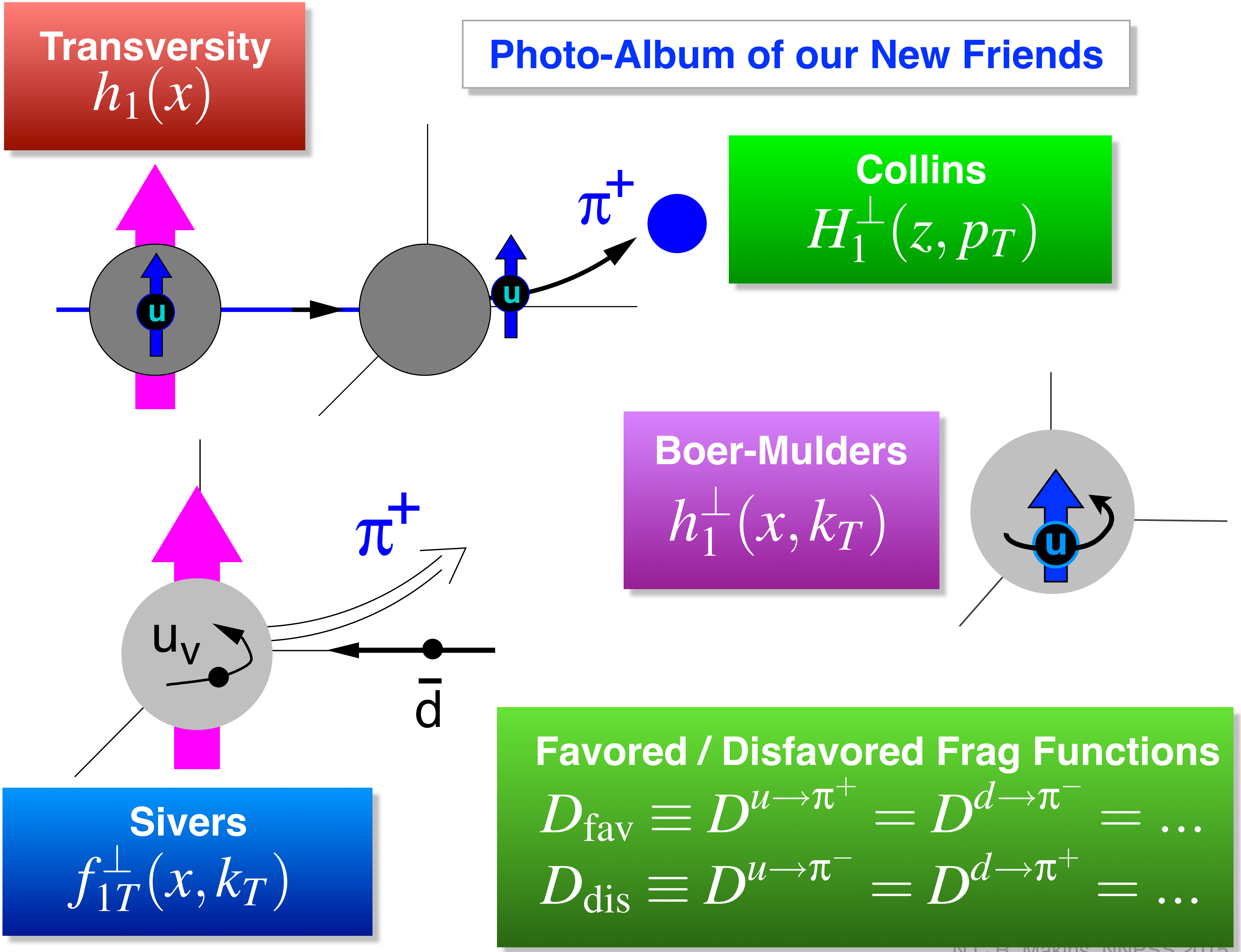


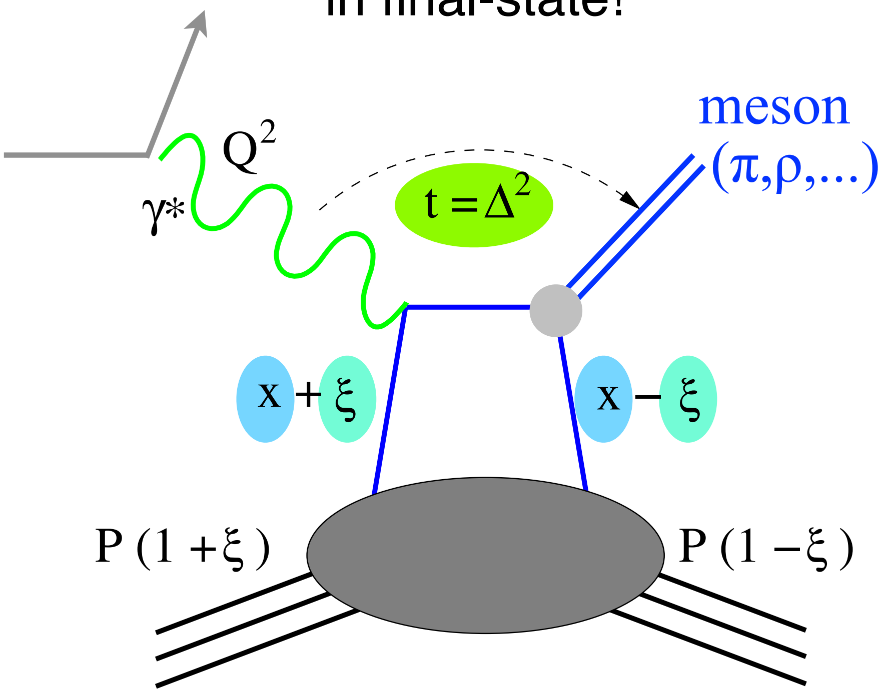
Photo-Album of our New Friends
Transversity
$h_1(x)$
u
π^+
u
Collins
$H_1^\perp(z, p_T)$
Boer-Mulders
$h_1^\perp(x, k_T)$
u
π^+
u_v
$\bar{d}$
Sivers
$f_{1T}^\perp(x, k_T)$
Favored / Disfavored Frag Functions
$D_{\text{fav}} \equiv D^{u\to\pi^+} = D^{d\to\pi^-} = \ldots$
$D_{\text{dis}} \equiv D^{u\to\pi^-} = D^{d\to\pi^+} = \ldots$
N.C.R. Makins, NNPSS 2015

❸ Generalized Parton Distributions

The Other Road to L

Analysis of ***hard exclusive processes*** leads to a new class of parton distributions

Scattering at high Q^2 and W^2
... but ***create only one particle***
in final-state!



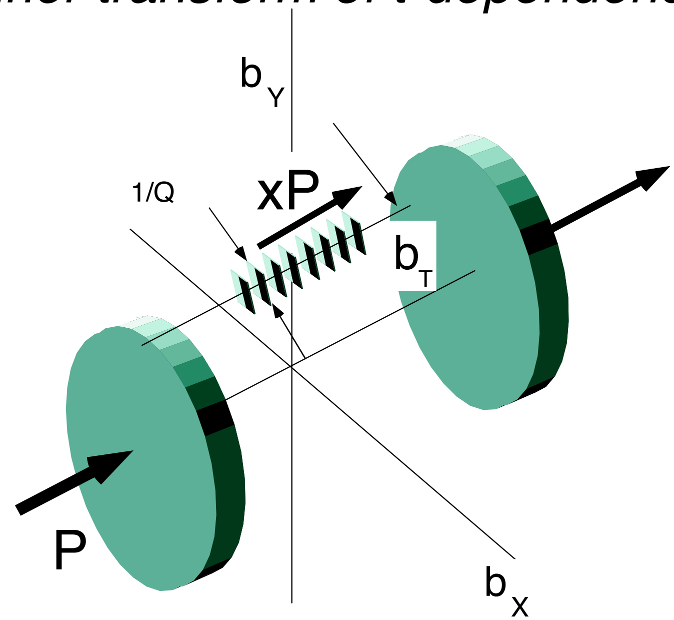
Four new distributions = "GPDs"

helicity conserving $\longrightarrow$ $H(x,\xi,t), E(x,\xi,t)$

helicity flip $\longrightarrow$ $\tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

"Femto-photography" of the proton

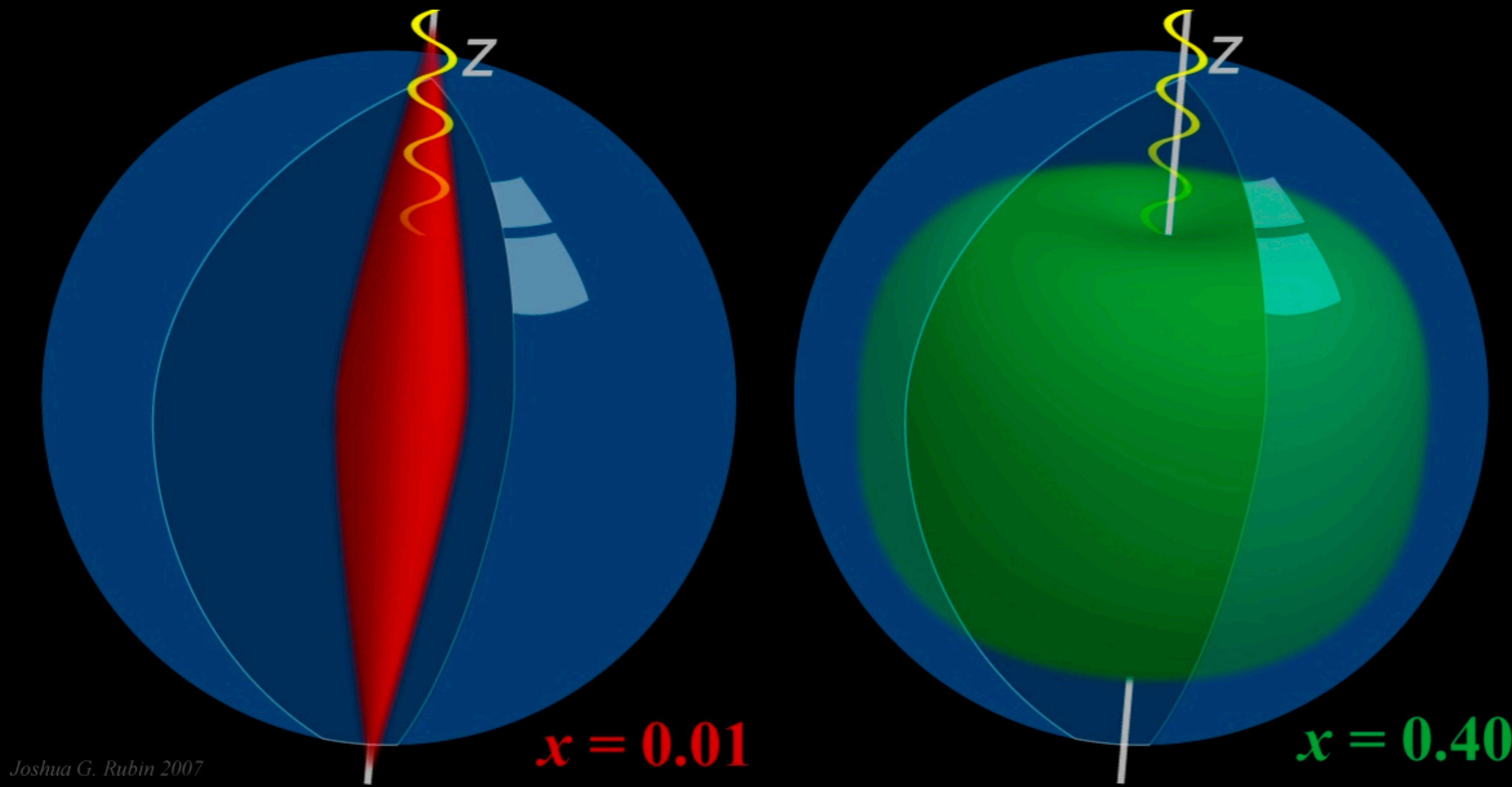
Fourier transform of t-dependence ...



- x: average quark momentum fracⁿ
- ξ: "skewing parameter" = $x_1 - x_2$
- t: 4-momentum transfer² to target

➡ ***spatial distribution*** of partons !

N.C.R. Makins, NNPSS 2015


z
z
x = 0.01
x = 0.40
Joshua G. Rubin 2007

- **DIS structure func's**: forward limit ($\xi = 0$, $t = 0$)

$$q(x) = H^q(x, \xi = 0, t = 0)$$
$$\Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

Connection to many observables

- **Elastic form factors**: first moments in x

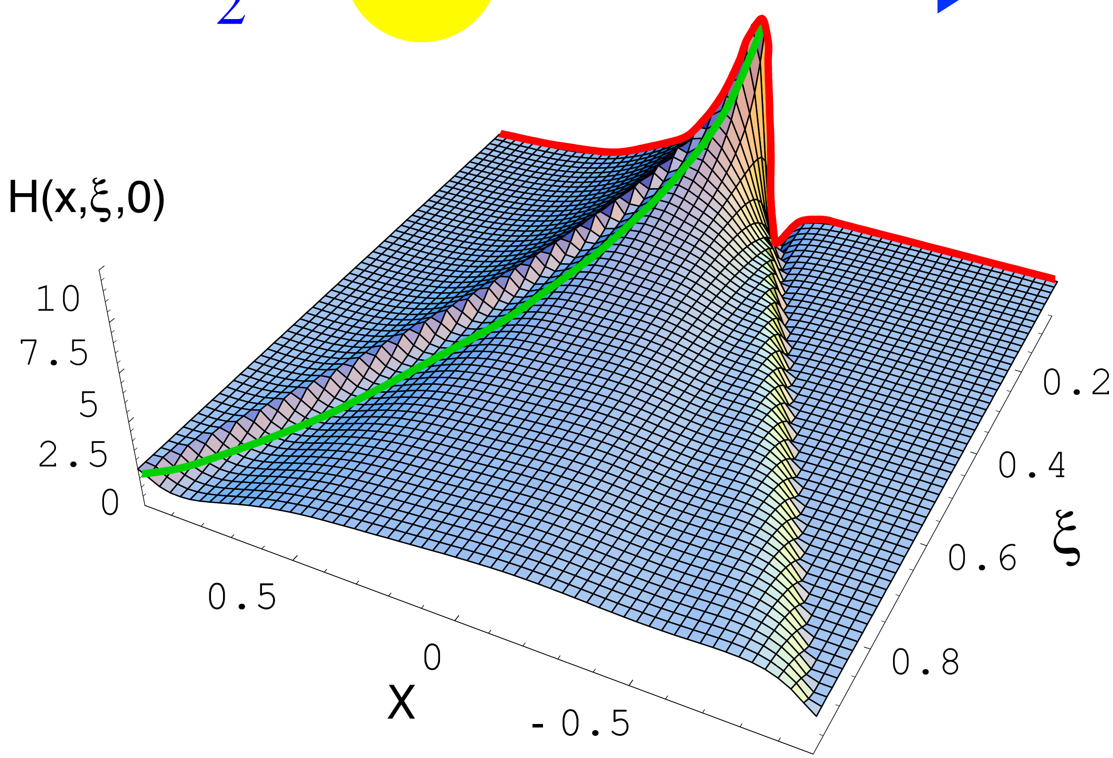
$$F_1^q(t) = \int_{-1}^{1} dx\, H^q(x, \xi, t) \qquad F_2^q(t) = \int_{-1}^{1} dx\, E^q(x, \xi, t)$$

- **Ji sum rule**:

$$J^q = \frac{1}{2}\int_{-1}^{1} x\, dx\, [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)]$$

$$J^q = \frac{1}{2}\Delta\Sigma + L^q$$

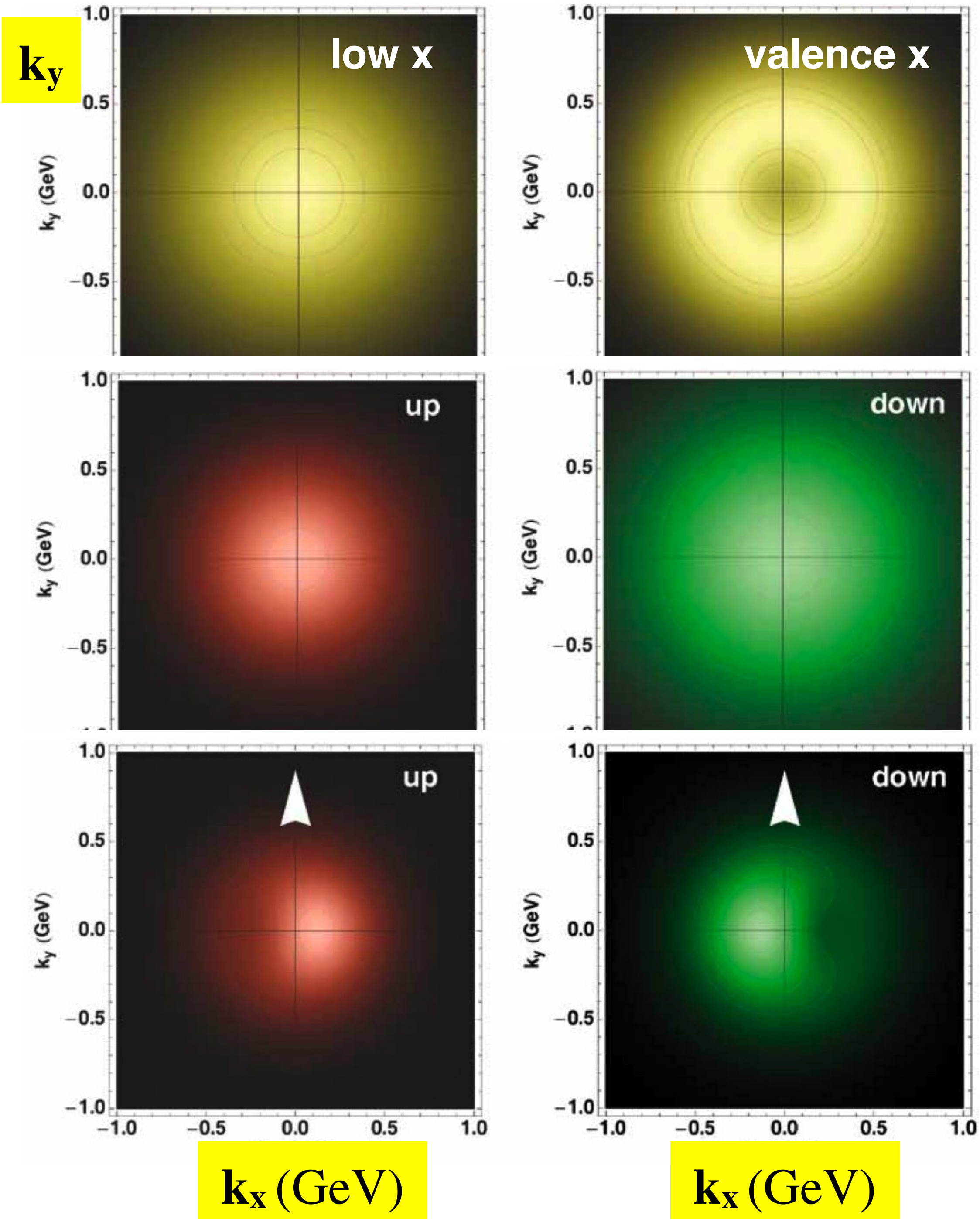
→ ***model-independent* access to *L* !**



Note connection of *H*, *E* to Dirac, Pauli form factors ... and their connection to nucleon *magnetic moment:*

$$F_1^N(0) + F_2^N(0) = \mu_N$$

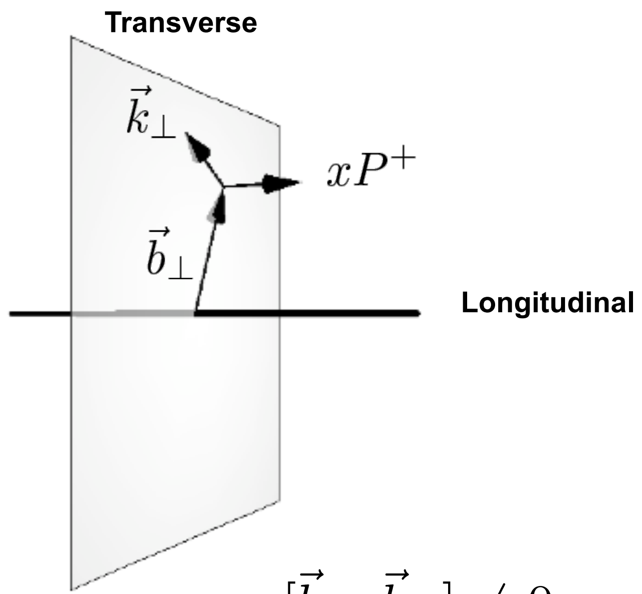
Transverse-momentum dependent PDFs (TMDs)



- **3D-densities in momentum space** : (x, k_{Tx}, k_{Ty})
- Gaussian distributions with a width of ~ 0.6 GeV in k_T
- **flavor dependence**: d-quark TMDs are larger than u-quark TMDs
- **transversely polarized nucleon**:
  - u-quarks (d-quarks) moving preferentially to the right (left)
  - TMDs are distorted in opposite ways for u and d-quarks

slide: M. Diefenthaler

Wigner Distributions



[Wigner (1932)] QM
[Belitsky, Ji, Yuan (04)] QFT (Breit frame)
[Lorce', BP (11)] QFT (light cone)

$$\vec{b}_\perp = \frac{\vec{r}_{f\perp}+\vec{r}_{i\perp}}{2} \quad \xleftrightarrow{\text{Fourier conjugate}} \quad \vec{\Delta}_\perp = \vec{k}_{f\perp} - \vec{k}_{i\perp}$$

$$\vec{z}_\perp = \vec{r}_{i\perp} - \vec{r}_{f\perp} \quad \xleftrightarrow{\text{Fourier conjugate}} \quad \vec{k}_\perp = \frac{\vec{k}_{f\perp}+\vec{k}_{i\perp}}{2}$$

$[\vec{b}_\perp, \vec{k}_\perp] \neq 0$ Heisenberg's uncertainty relations → Quasi-probabilistic

TMDs → $\rho(x, k_x, k_y)$

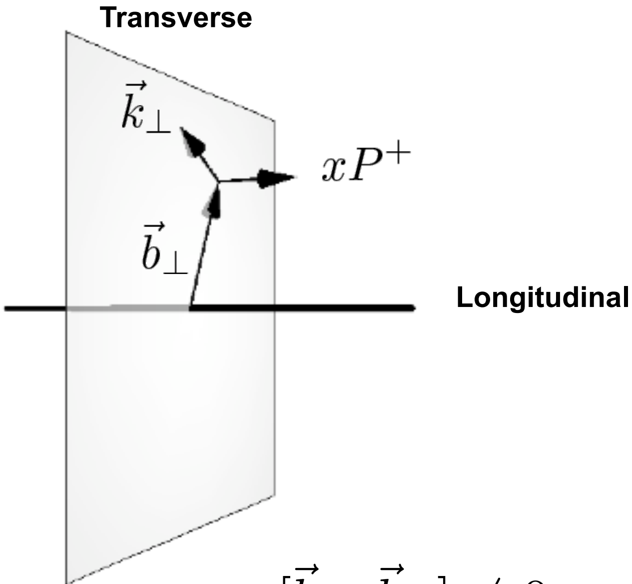
GPDs → $\rho(x, b_x, b_y)$

- **x**: longitudinal momentum
- **k_T**: transverse momentum
- **b_T**: transverse position

Impact-parameter picture of GPDs:** correlation between **transverse <u>position</u>** and **longitudinal momentum** → **<u>r</u> x p!

Barbara Pasquini, IWHSS'12

Wigner Distributions



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$$\vec{b}_\perp = \frac{\vec{r}_{f\perp} + \vec{r}_{i\perp}}{2} \quad \xleftrightarrow{\text{Fourier conjugate}} \quad \vec{\Delta}_\perp = \vec{k}_{f\perp} - \vec{k}_{i\perp}$$

$$\vec{z}_\perp = \vec{r}_{i\perp} - \vec{r}_{f\perp} \quad \xleftrightarrow{\text{Fourier conjugate}} \quad \vec{k}_\perp = \frac{\vec{k}_{f\perp} + \vec{k}_{i\perp}}{2}$$

$[\vec{b}_\perp, \vec{k}_\perp] \neq 0$ Heisenberg's uncertainty relations → Quasi-probabilistic

GPDs → $\rho(x, b_x, b_y)$

TMDs → $\rho(x, k_x, k_y)$

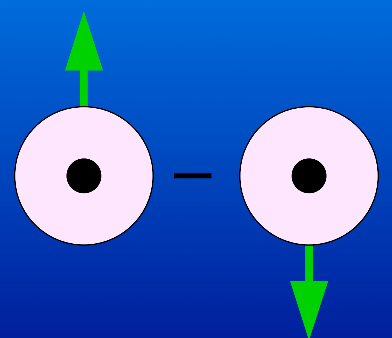
GTMDs → $\rho(x, b_x, k_y)$ Third 3D picture with probabilistic interpretation !

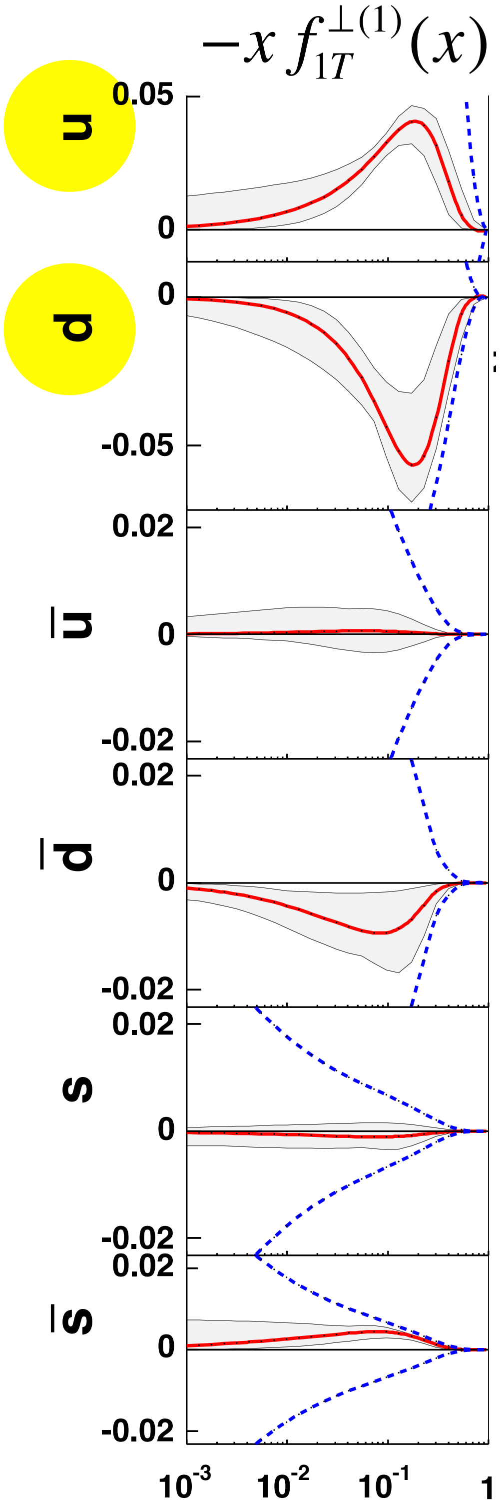
No restrictions from Heisenberg's uncertainty relations

Barbara Pasquini, IWHSS'12

L so far : the Sivers Function

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





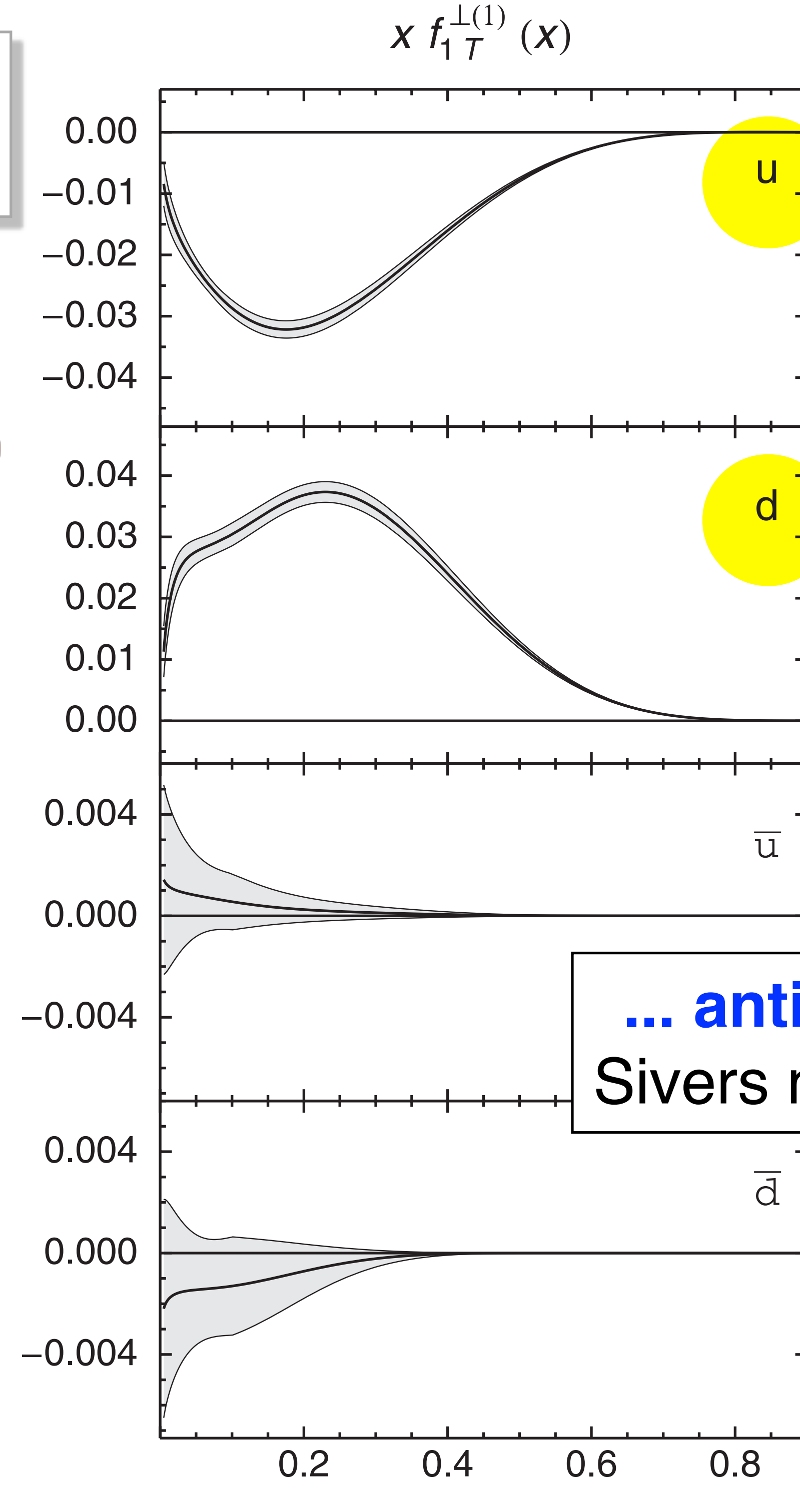
Global Fits to SIDIS data

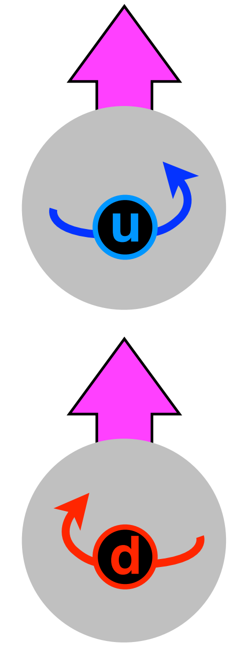
← *Anselmino et al, EPJA 39 (**2009**)*

final data

*Bacchetta & Radici, PRL 107 (**2011**)*

antiquark
orbital L ≠ 0
favoured





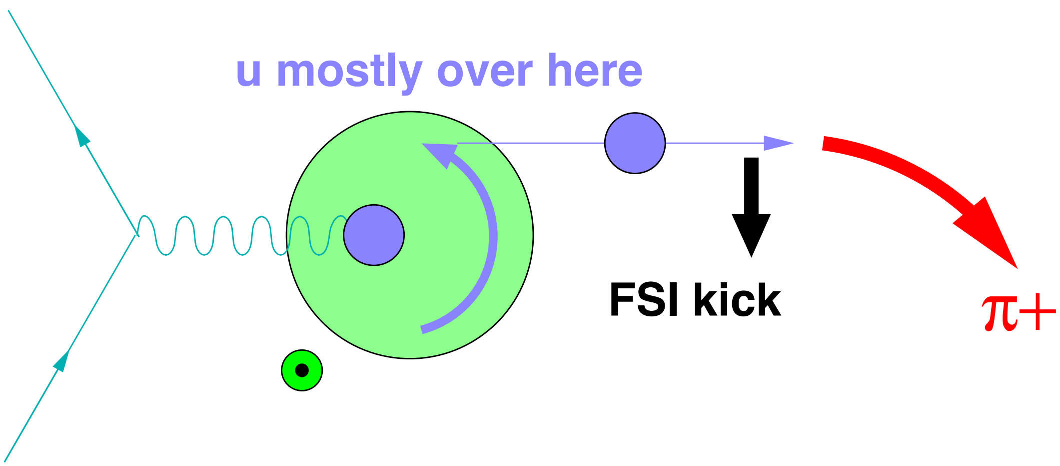
... antiquark
Sivers now ≈ 0

Phenomenology: The SIGN of L

Nearly all models predict $\mathbf{L_u > 0}$ ...

M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ ***stronger for oncoming quarks***



We observe $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{UT}^{\pi^+} > 0$

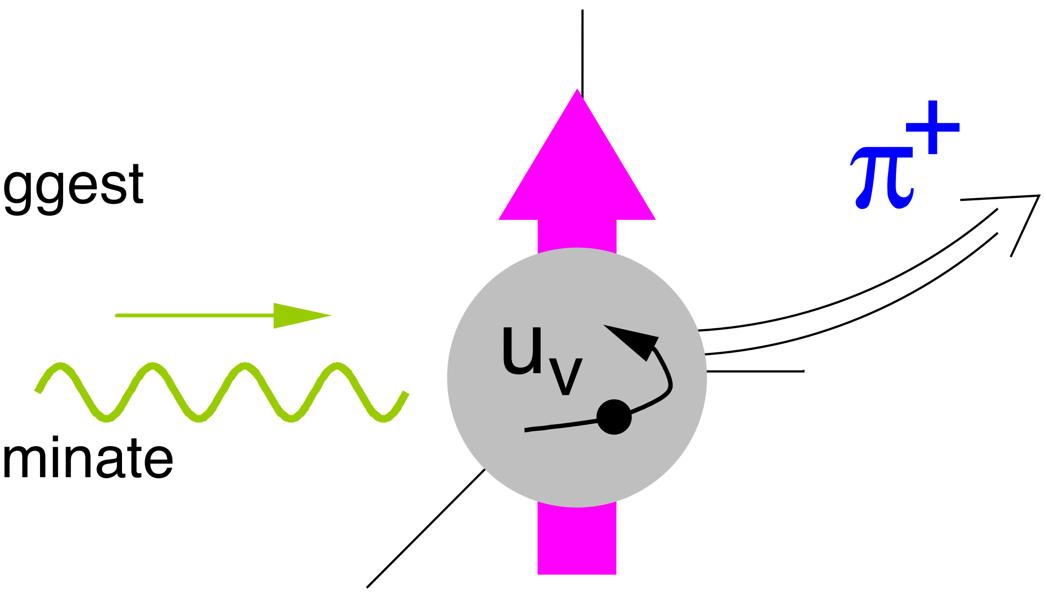
(and opposite for π^-)

$\therefore$ for $\phi_S^l = 0,\ \phi_h^l = \pi/2$ preferred

Model agrees!

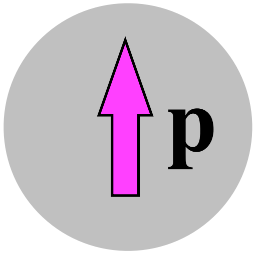
D. Sivers: Jet Shadowing

Parton energy loss considerations suggest ***quenching of jets*** from ***"near" surface of target***



➡ quarks from "far" surface should dominate

Opposite sign to data ...



Meson Cloud on an Envelope → It ORBITS

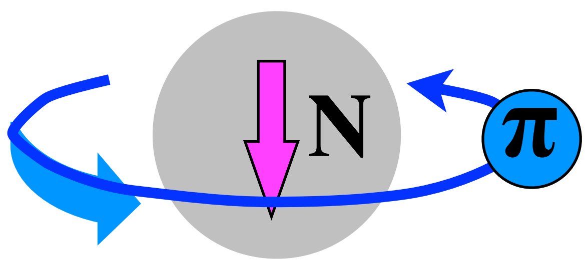
Pions have $J^P = 0^-$ = **negative parity** ...

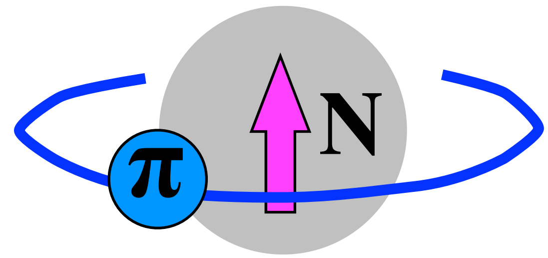
→ ***need L = 1*** to get proton's $J^P = ½^+$

$|p\rangle = p + N\pi + \Delta\pi + \ldots$

Nπ cloud:

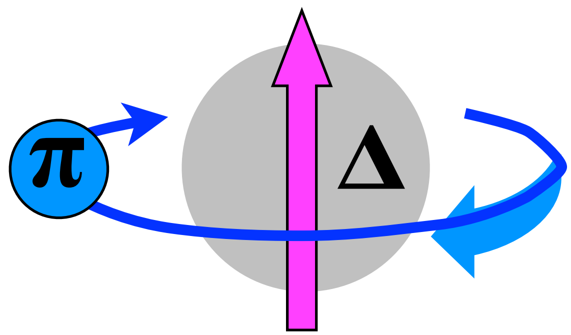
2/3	**$n\,\pi^+$**	$\otimes$	**2/3** $L_z = +1$	1/3 $L_z = 0$
1/3	$p\,\pi^0$			





Δπ cloud:

1/2	**$\Delta^{++}\,\pi^-$**		
1/3	$\Delta^+\ \pi^0$	$\otimes$	1/3 $L_z = 0$
1/6	$\Delta^0\ \pi^+$		1/6 $L_z = +1$



1/2 $L_z = -1$

*L is in the **SEA***

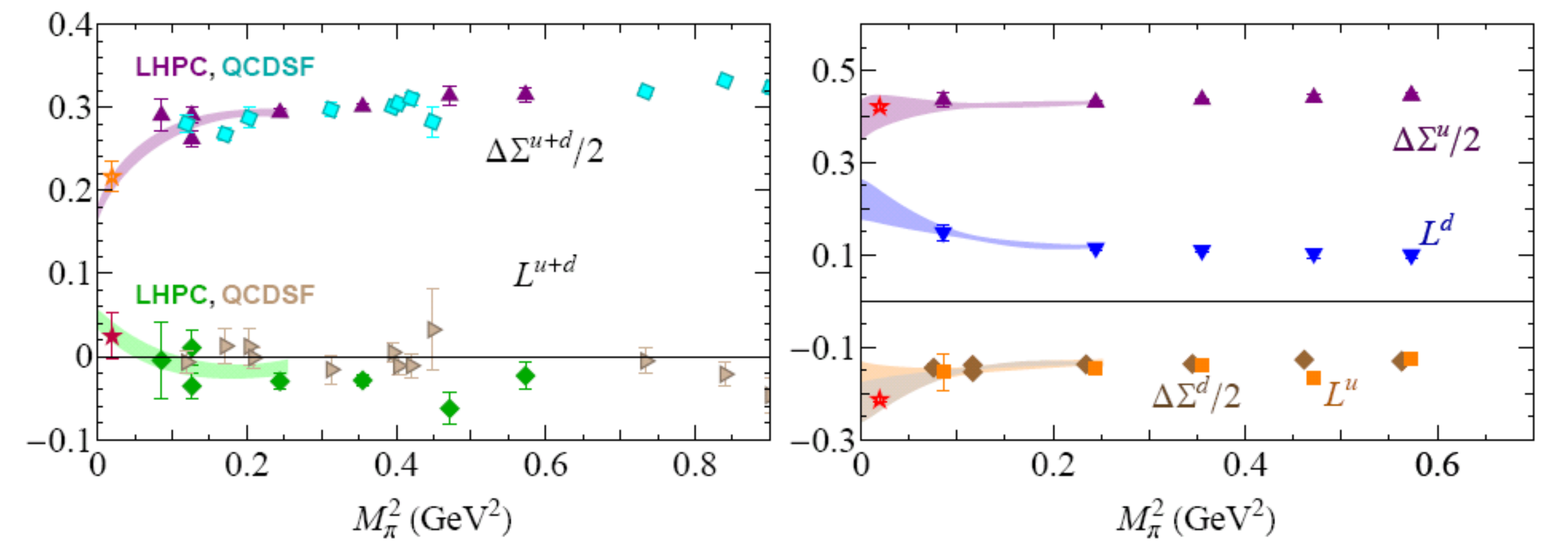
Dominant source of:

u, dbar sea = $n\,\pi^+$ with $L_z(\pi^+) > 0$

d, ubar sea = $\Delta^{++}\,\pi^-$ with $L_z(\pi^-) < 0$

Quark Orbital Angular Momentum (connected insertion)

Lattice calculations : L(u+ubar) *negative* ?



LHPC, S. Syritsyn et al., [111.0718]
QCDSF, A. Sternbeck et al, [1203.6579]

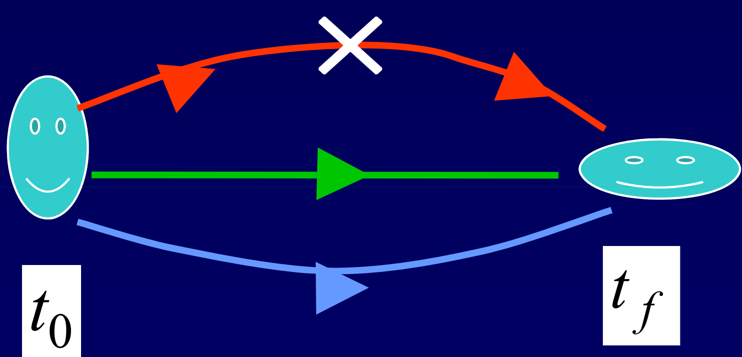
Keh-Feh Liu
@ SPIN 2014

Flavor-singlet g_A

KehFeh Liu,
INT Workshop, Feb 2012

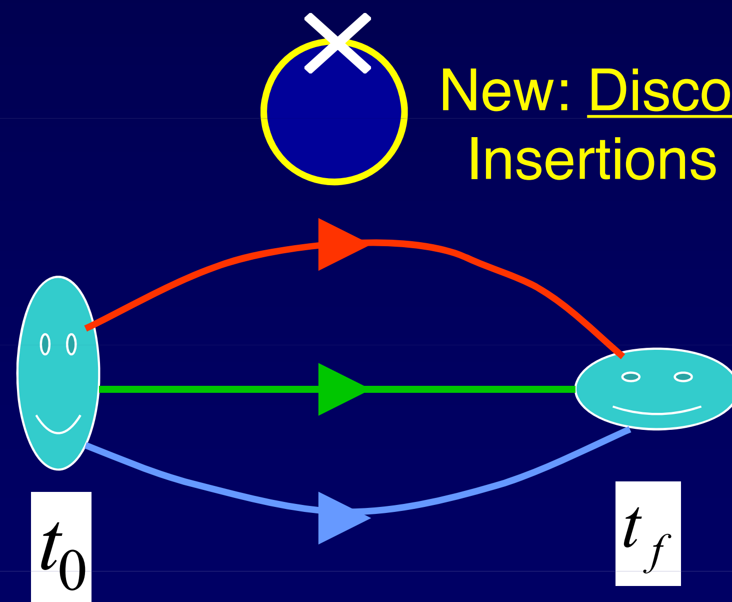
- Quark spin puzzle (dubbed `proton spin crisis')
  - $$g_A^0 = \Delta u + \Delta d + \Delta s = \begin{cases} 1 & \text{NRQM} \\ 0.75 & \text{RQM} \end{cases}$$
  - Experimentally (EMC, SMC, … $\Delta\Sigma = g_A^0 \sim 0.2 - 0.3$

$$(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)(t)$$



$$g^0_{A,con} = (\Delta u + \Delta d)_{con}$$

$$\overline{\Psi}\gamma_\mu\gamma_5\Psi(t)(u,d,s)$$

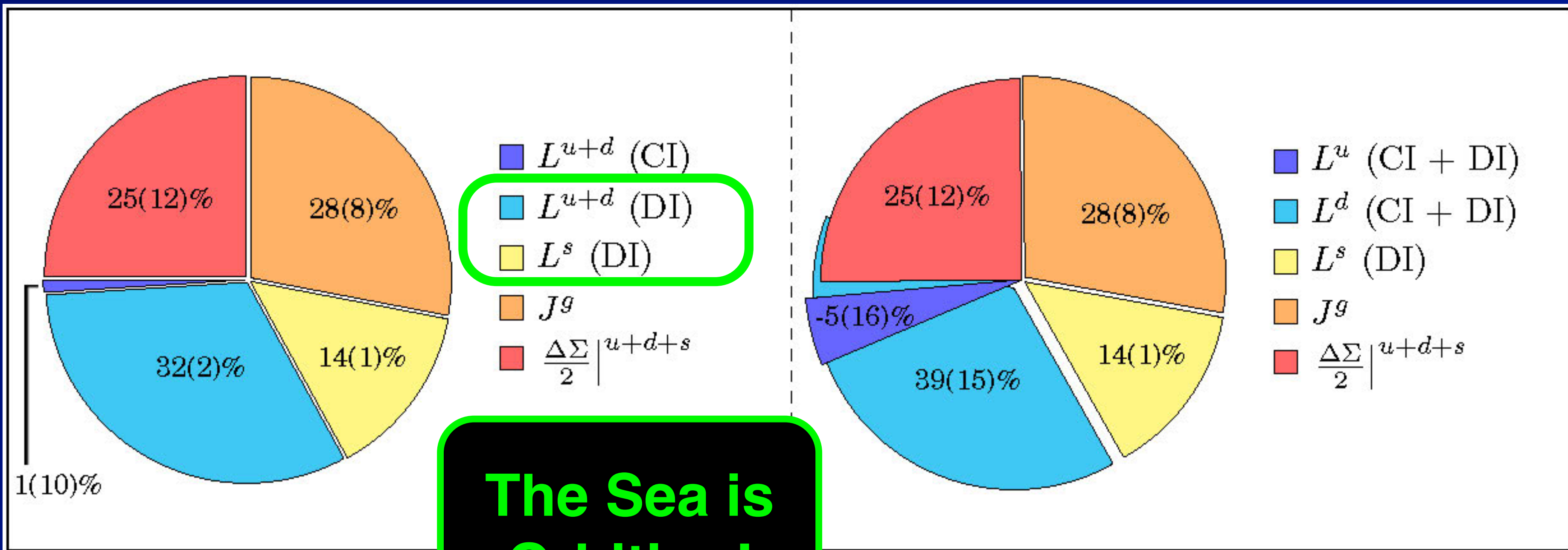


$$g^0_{A,dis} = (\Delta u + \Delta d + \Delta s)_{dis}$$

Quark Spin, Orbital Angular Momentum, and Gule Angular Momentum (M. Deka *et al*, 1312.4816)

add Disconnected Insertions → Pure Sea

pizza cinque stagioni



The Sea is Orbiting!

$$\Delta q \approx 0.25;$$

$$2\,L_q \approx 0.47\ (0.01(\mathrm{CI})+0.46(\mathrm{DI}));$$

$$2\,\mathrm{J}_g \approx 0.28$$

Access → **Drell-Yan** with p or π^+ beam & **polarized target**

These are quenched results so far.