# QCD and Baryon Polarization

## Lecture 1:

## Nucleon structure in terms of collinear and transverse-momentum-dependent parton distribution functions

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Università degli Studi di Milano
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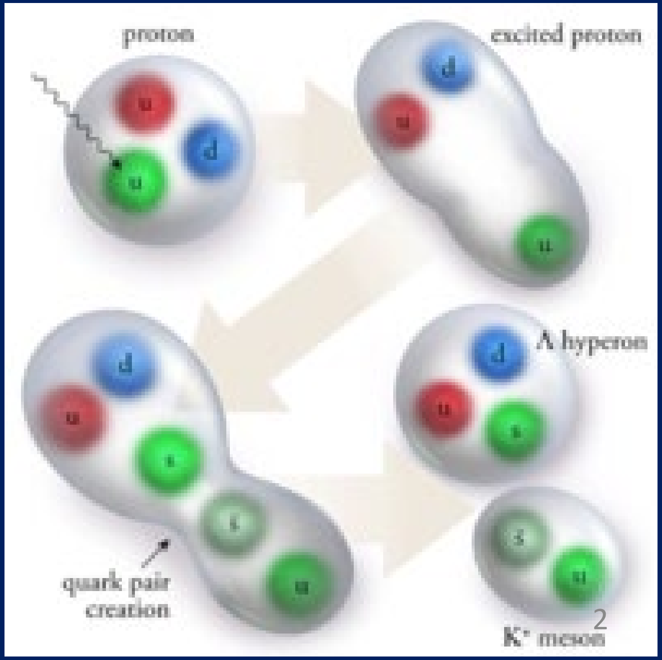
# *Theory of strong nuclear interactions: Quantum Chromodynamics*

- Fundamental field theory in hand since the early 1970s—BUT . . .
- Quark and gluon degrees of freedom in the theory cannot be observed or manipulated directly in experiment!

Color *confinement*—quarks and gluons are confined to color-neutral bound states



CLAS, PRL 113, 152004 (2014)

***How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?***

***How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?***

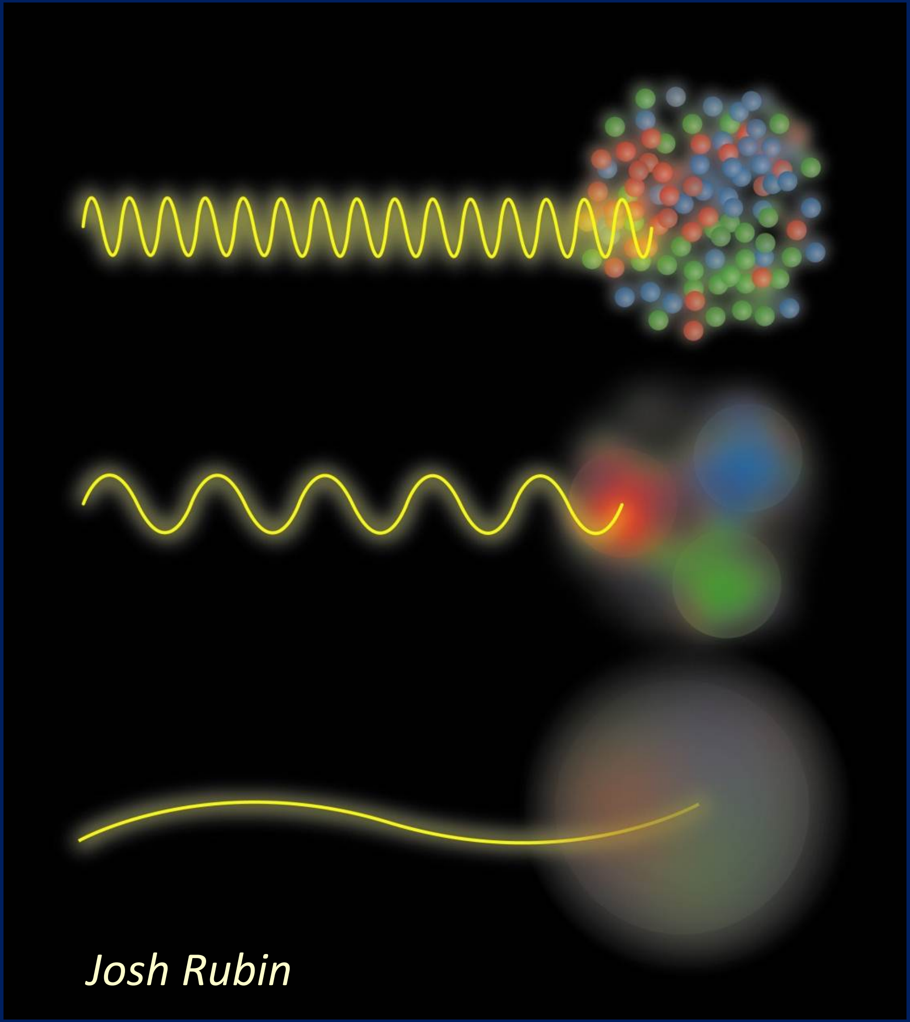
# *Outline of lectures*

1. Introduction; collinear and TMD nucleon structure
2. Spin-momentum correlations in the nucleon in terms of TMD PDFs and collinear twist-3 multiparton correlations
3. Hadronization: collinear and TMD fragmentation functions, collinear twist-3 correlations; dihadron FFs; different hadronization mechanisms/pictures
4. Hadron structure and hadronization: Sea quarks/non-valence quarks
5. Hyperon and heavy flavor baryon polarization I
6. Hyperon and heavy flavor baryon polarization II

# *The proton as a "laboratory" for studying QCD*

- Proton: simplest stable QCD bound state

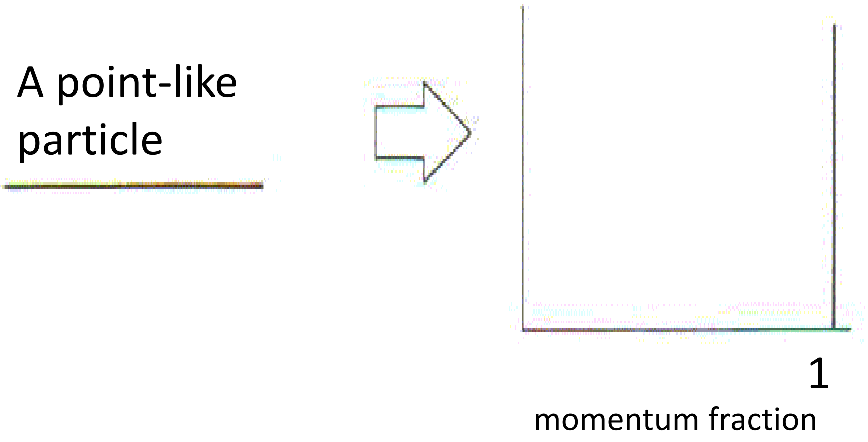
- Different energy scales offer information on different aspects of proton internal structure



*Josh Rubin*

# *Quark distribution functions inside the proton: The language we've developed (so far!)*

What momentum fraction would the scattering particle carry if the proton were made of …



Halzen and Martin, "Quarks and Leptons", p. 201

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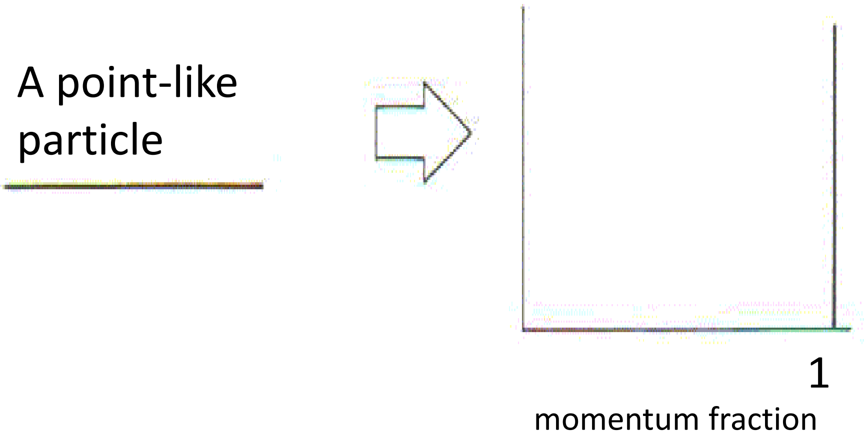
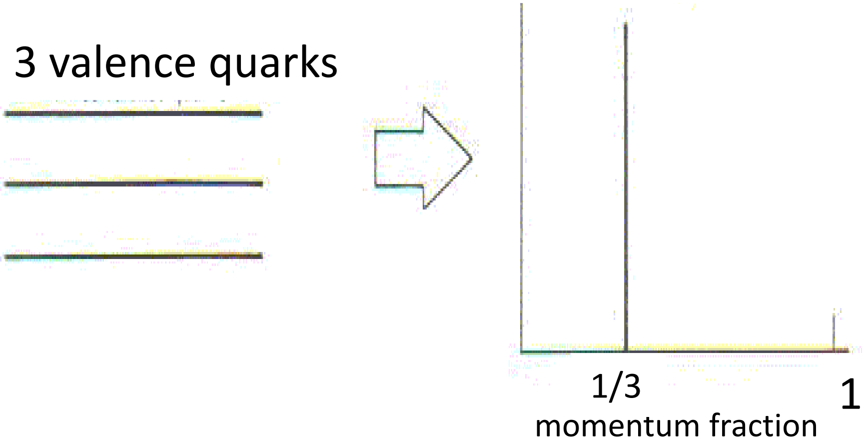

A point-like particle


3 valence quarks

Halzen and Martin, "Quarks and Leptons", p. 201

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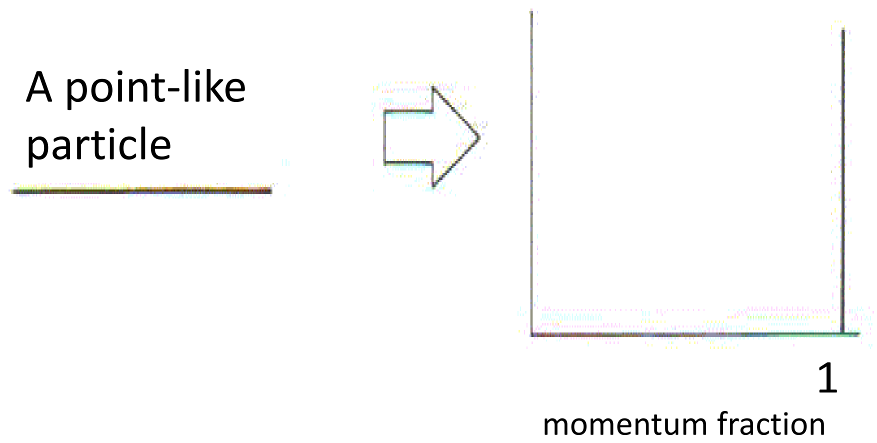

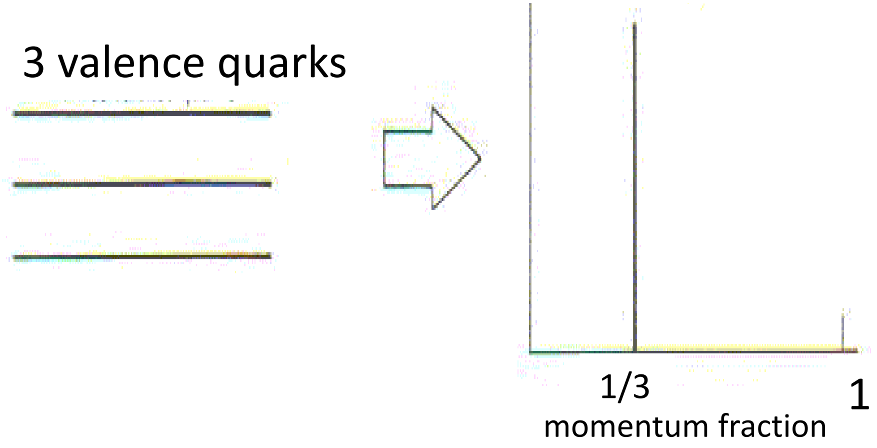

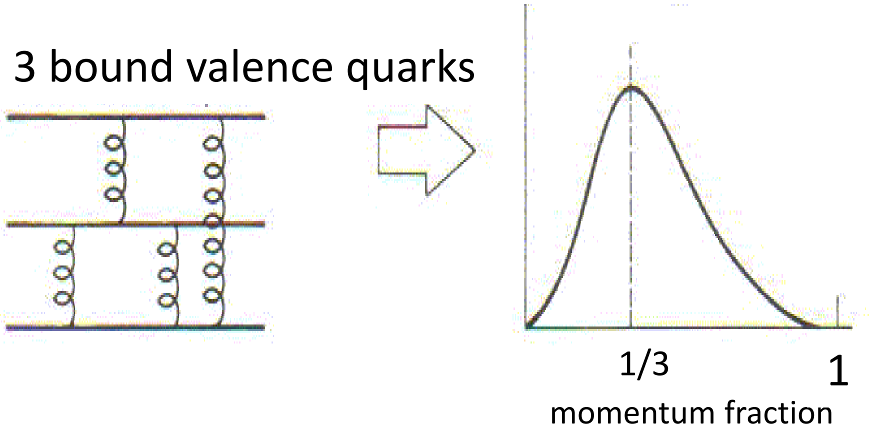

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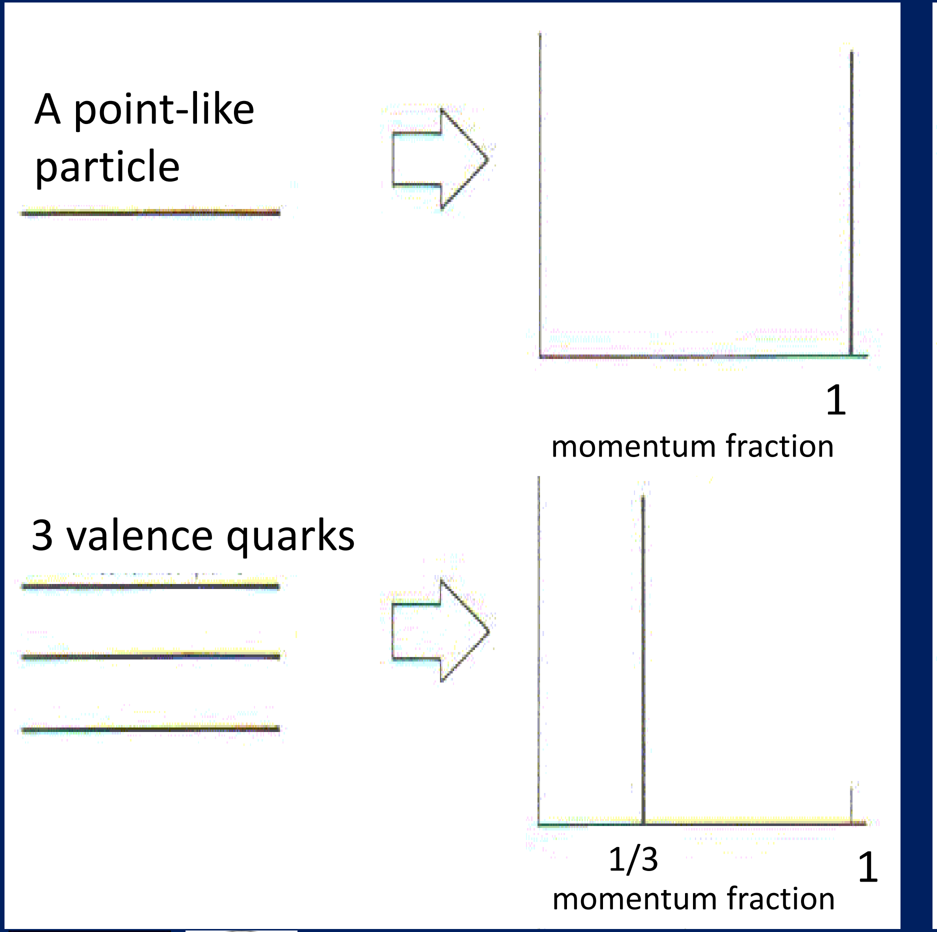
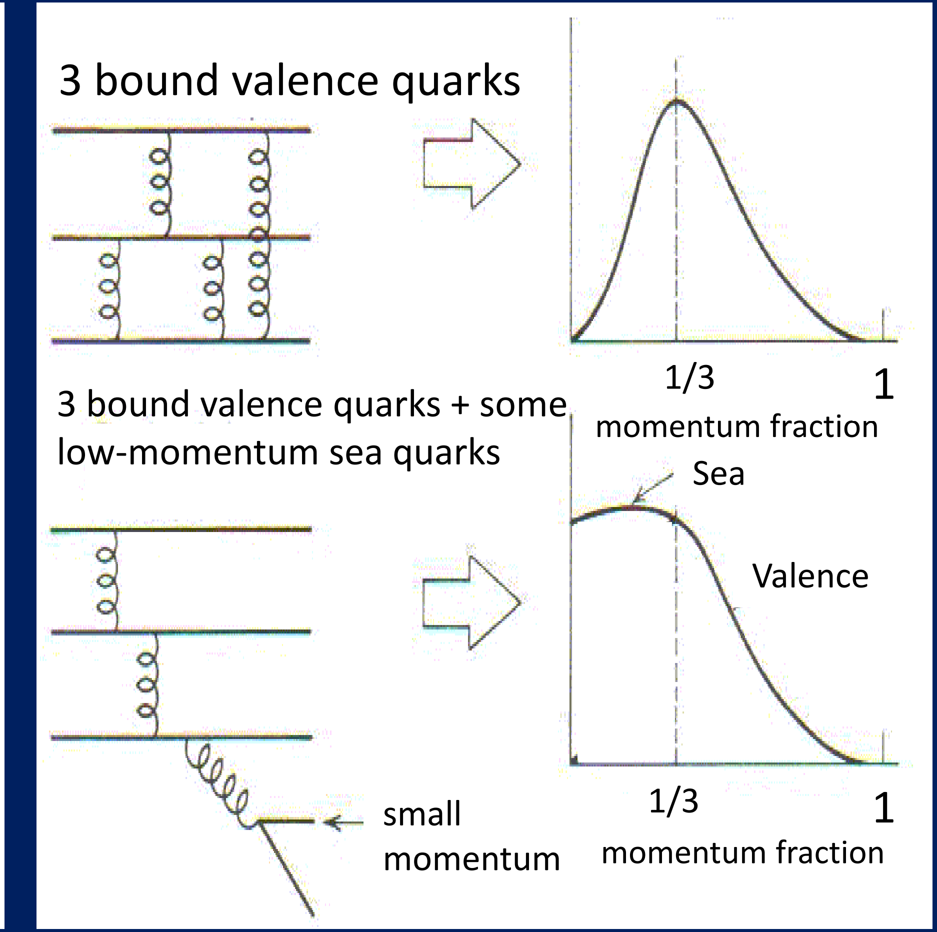
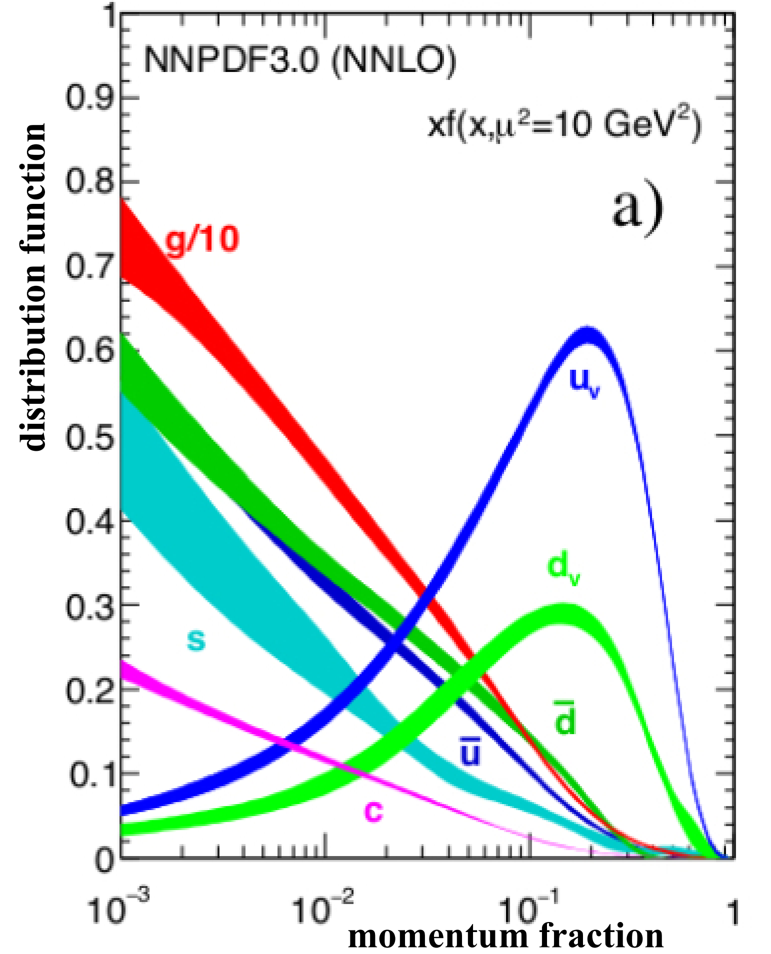




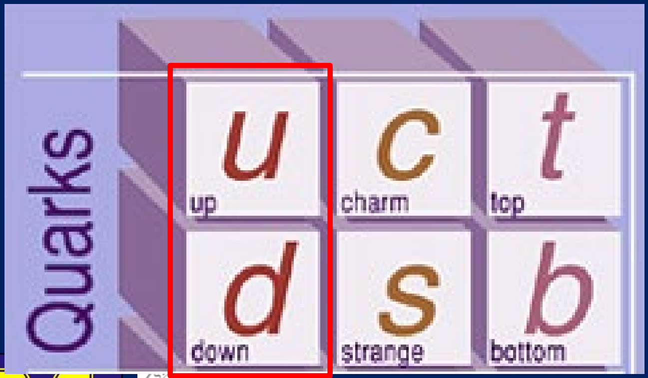
Halzen and Martin, "Quarks and Leptons", p. 201

# *What have we learned in terms of this picture by now? (Preview)*

- Up and down quark "valence" distributions peaked ~1/3
- Lots of sea quark-antiquark pairs and even more gluons!

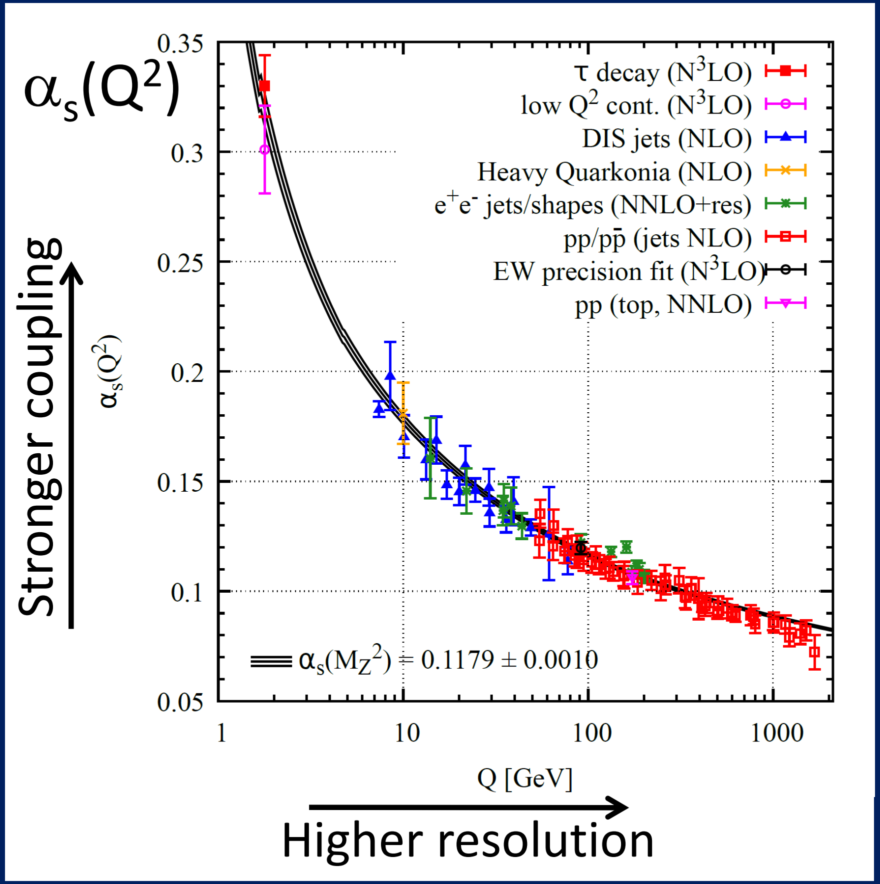


EPJ C76, 647 (2016)



# *Perturbative QCD*

- Take advantage of running of strong coupling constant with energy (*asymptotic freedom*)—weak coupling at high energies (short distances)
- Perturbative expansion as in quantum electrodynamics (but many more diagrams due to gluon self-coupling…)



Particle Data Group, 2019

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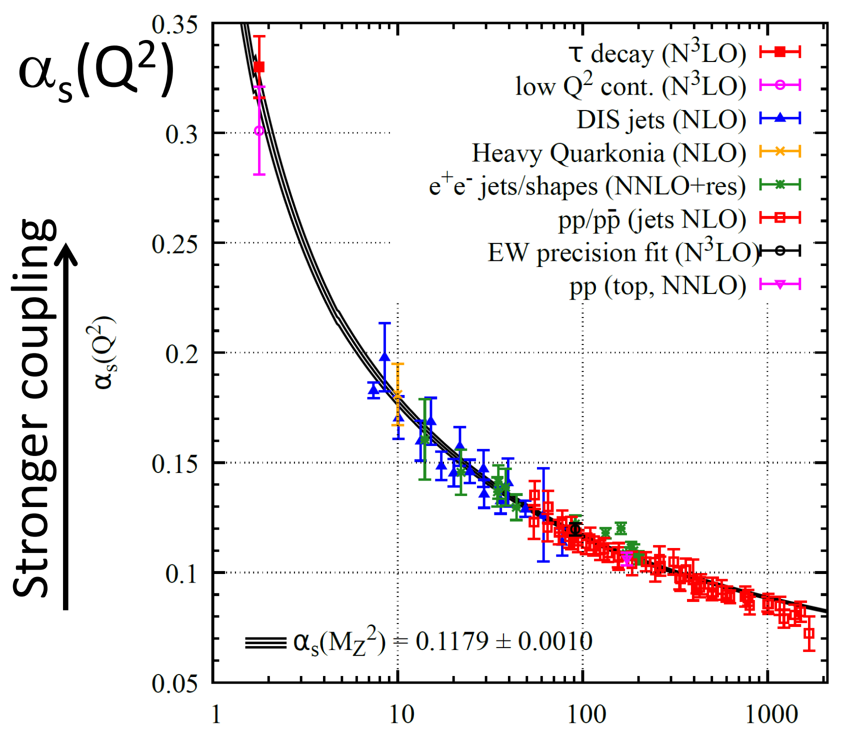

*Importantly: Perturbative QCD provides one rigorous way of relating the fundamental field theory—in terms of* ***quarks and gluons****—to a variety of physical observables—in terms of* ***hadrons***

# *Factorization and universality in perturbative QCD*

- Systematically *factorize* short- and long-distance physics
  - Observable physical QCD processes always involve at least one "long-distance" scale of ~$10^{-15}$ m describing bound-state structure (confinement)!
- Long-distance (i.e. not perturbatively calculable) functions describing structure need to be *universal*
  - Physically meaningful descriptions
  - Portable across calculations for many processes

# *Factorization and universality in perturbative QCD*

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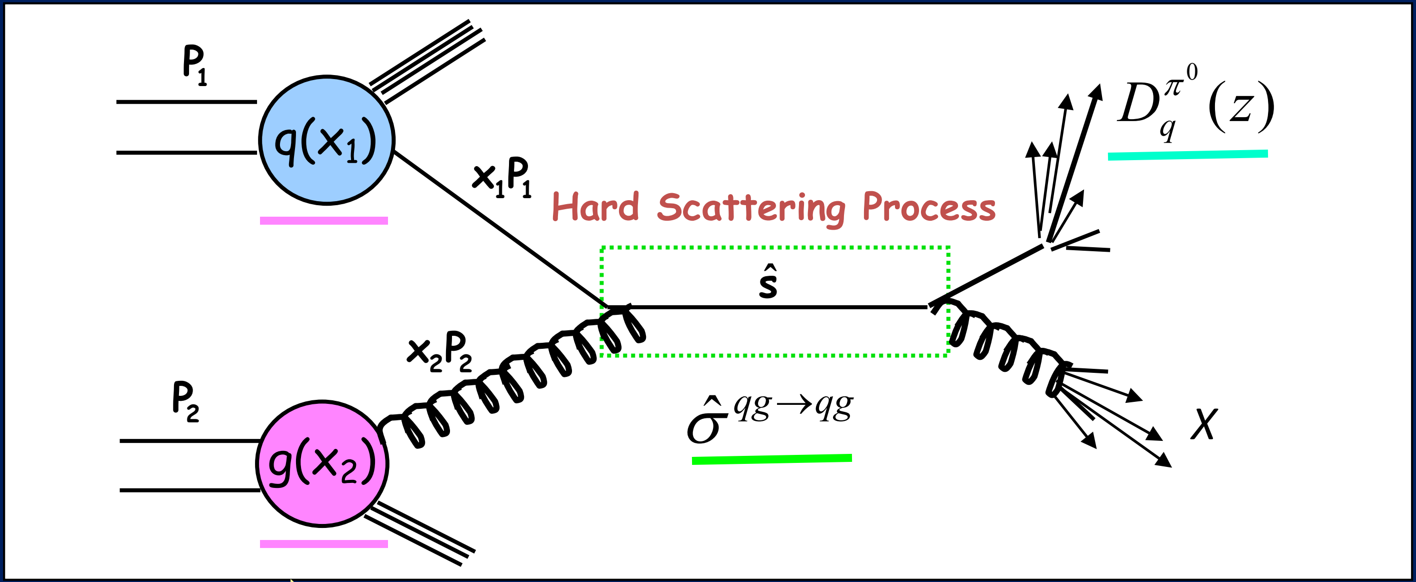
Constrain functions describing proton structure by measuring scattering cross sections in many colliding systems over wide kinematic range and performing *simultaneous fits to world data*

# Factorized pQCD calculations of observables

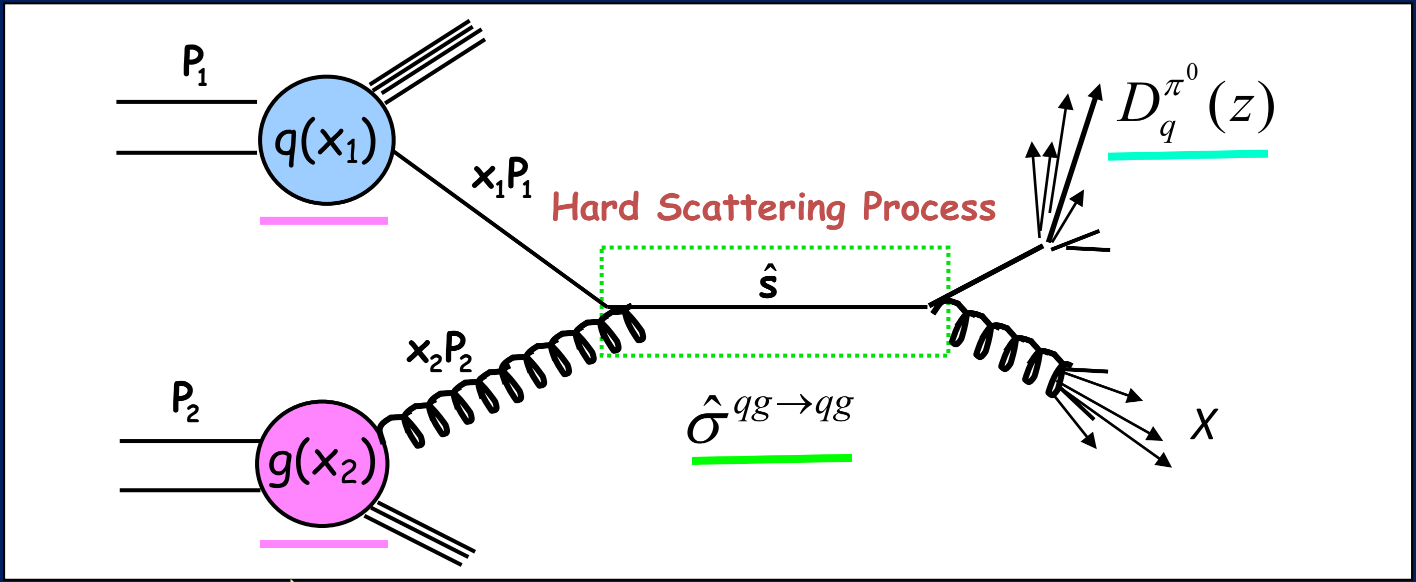


$$\sigma\left(pp\to\pi^0X\right)\propto \underline{q(x_1)\otimes g(x_2)}\otimes\underline{\hat{\sigma}^{qg\to qg}(\hat{s})}\otimes\underline{D_q^{\pi^0}(z)}$$

High-energy processes have predictable rates given:

- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (experiment )
- Fragmentation functions (experiment )

# *Factorized pQCD calculations of observables*



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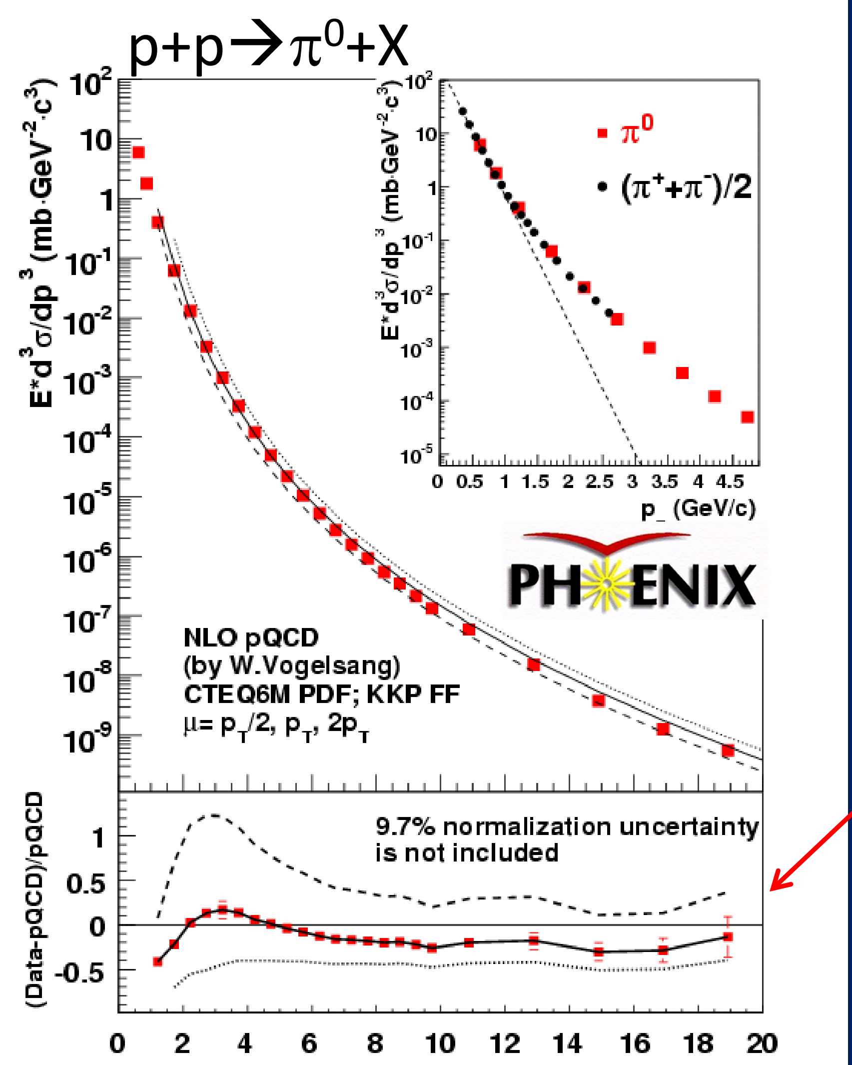
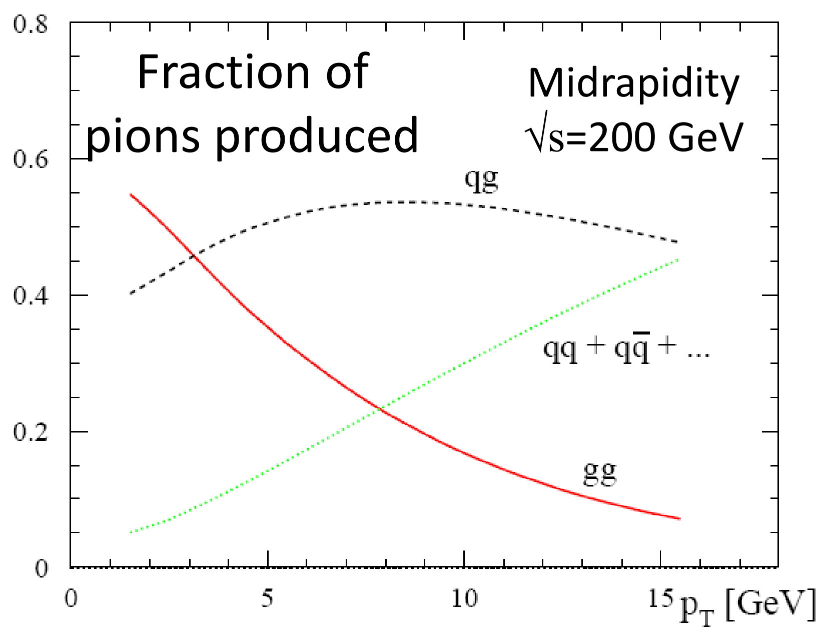
} **Universal non-perturbative factors**

# *Example NLO pQCD calculation for $p+p \rightarrow \pi^0+X$ at $\sqrt{s}=200$ GeV*



PRD76, 051106 (2007)



Systematic uncertainty on calculation due to factorization, renormalization, and fragmentation scale dependence. All three scales taken as equal and varied from $p_T/2$ to $2p_T$.
Cross section prediction varies by tens of percent here.

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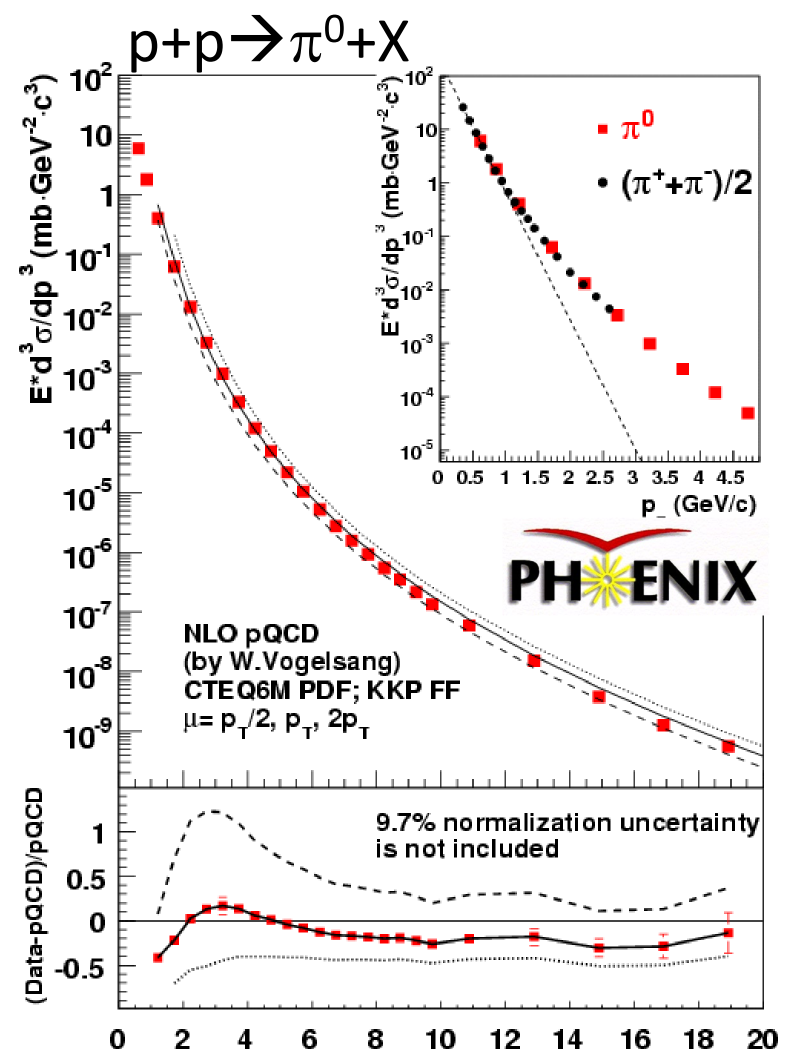
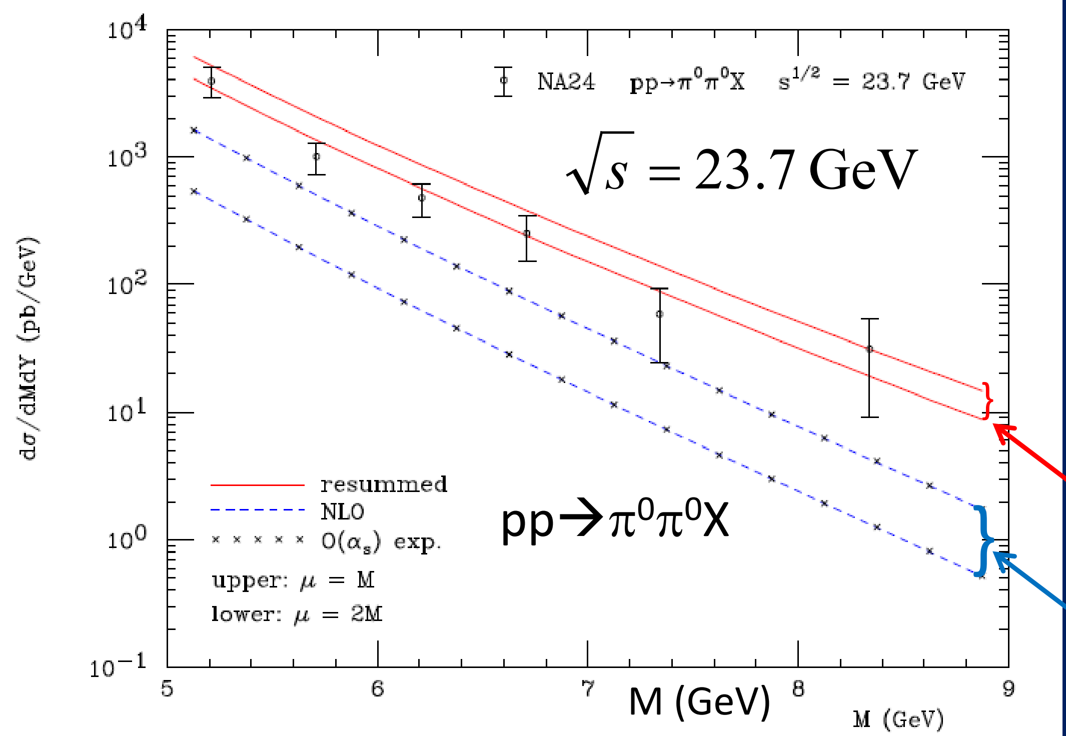


PRD76, 051106 (2007)

- Can reduce theoretical uncertainties due to the choice of factorization, renormalization, and fragmentation scales by
  - going to higher orders in $\alpha_s$
  - and/or using resummation techniques
- Both approaches allow you to include more terms in your perturbative expansion

# *Example: "Threshold resummation" Extending perturbative calculations to lower energies*



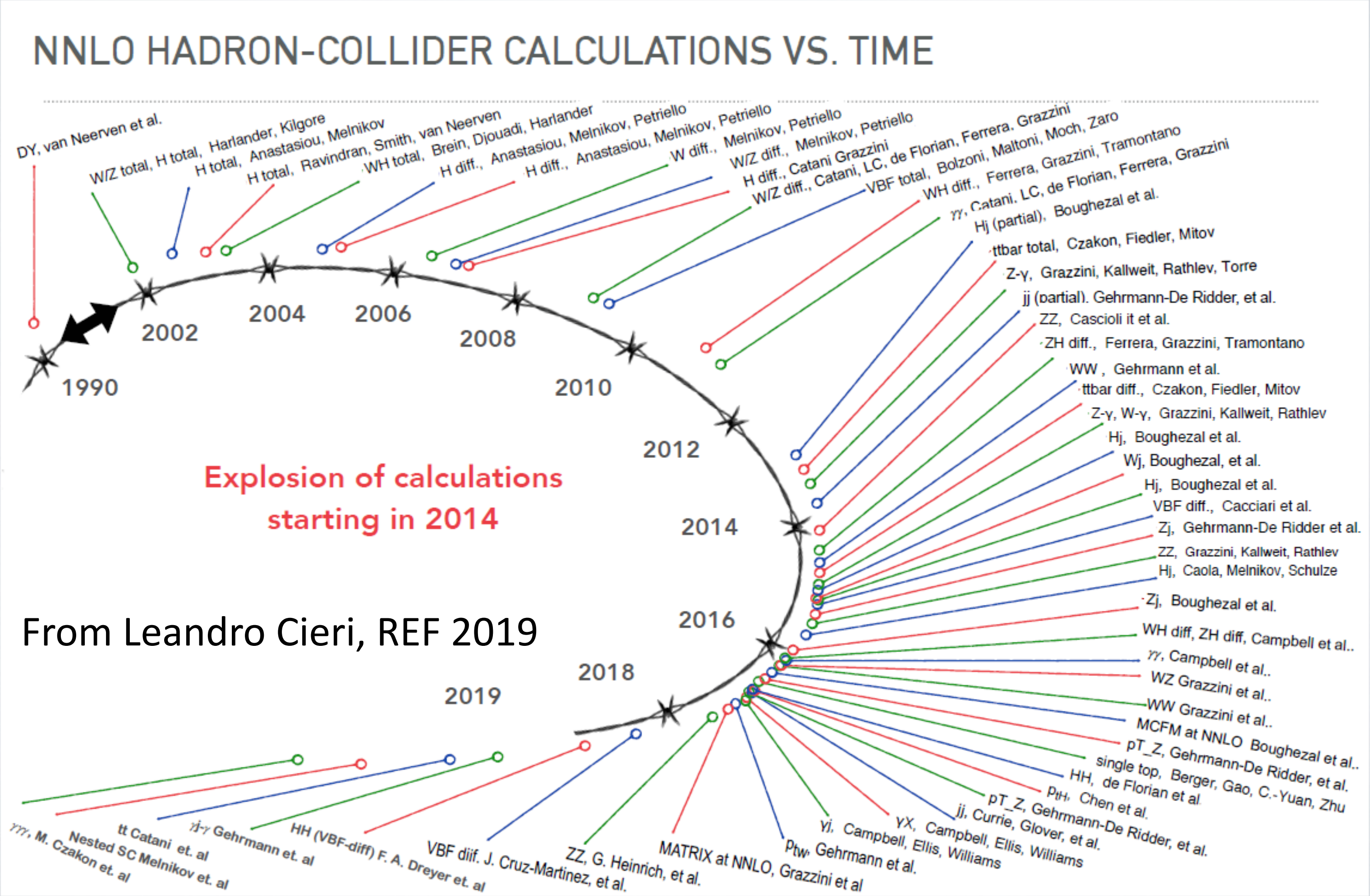
For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

Next-to-leading-order in $\alpha_s$ + resum.

Next-to-leading-order in $\alpha_s$

Almeida, Sterman, Vogelsang PRD80, 074016 (2009)

# THE NNLO STANDARD



From Leandro Cieri, REF 2019

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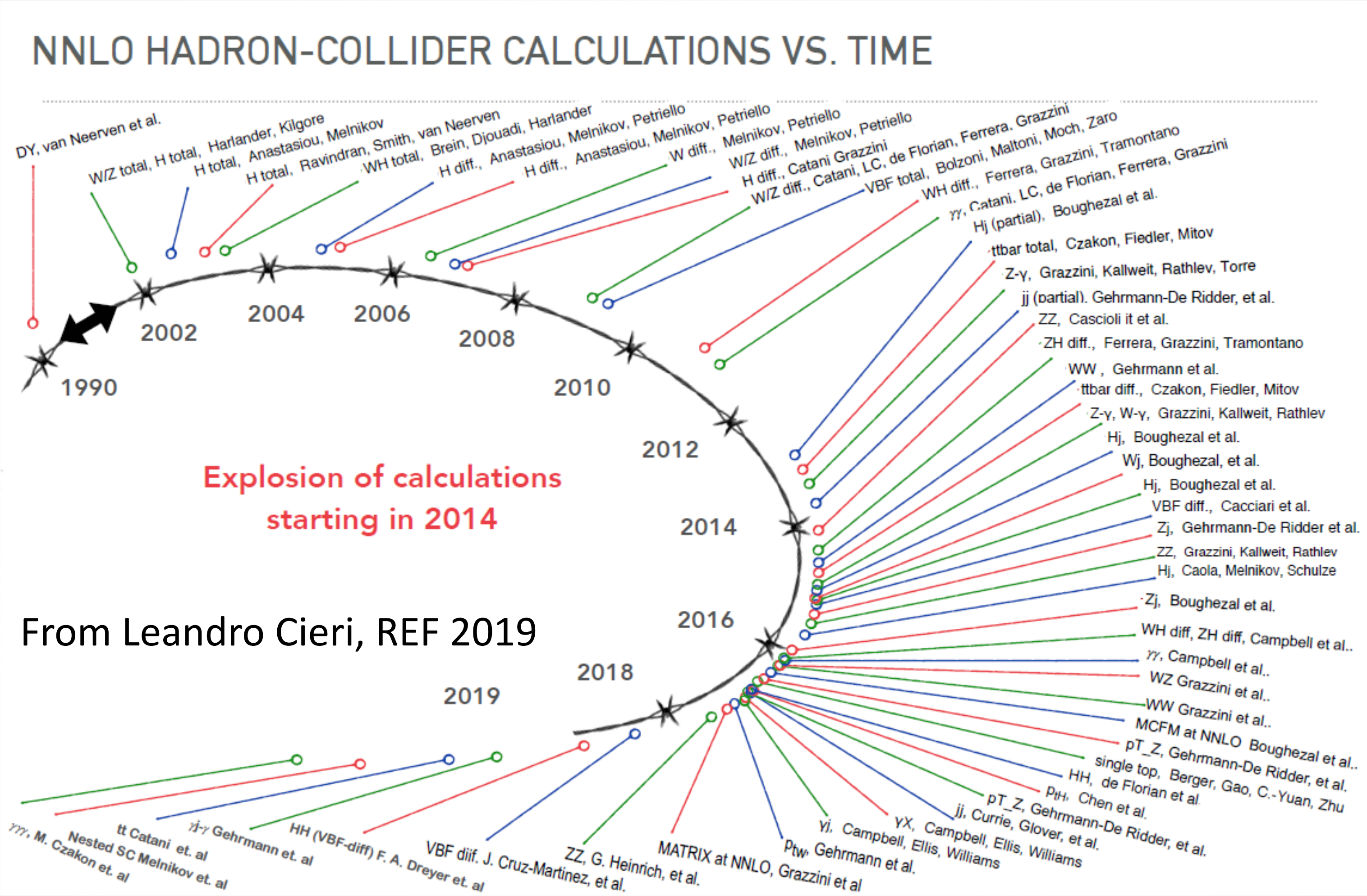

NNLO HADRON-COLLIDER CALCULATIONS VS. TIME

From Leandro Cieri, REF 2019

But note that these calculations are not for hadrons in the final state, only EW bosons, Higgs, and jets. More difficult when fragmentation functions involved!

# Complementary scattering systems

- Learn from p+p results in conjunction with information from simpler systems
  - Many subprocesses contribute to (e.g.) inclusive hadron production in p+p collisions—couldn't disentangle them with p+p data alone
  - (A few processes are simpler, e.g. Drell-Yan process of qqbar to leptons)

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- Note that Drell-Yan, DIS, and e+e- are all *QED* processes involving hadrons
- Once you have reasonably constrained PDFs and/or FFs, can use p+p data to further refine those constraints
  - Hadronic collisions have been especially important in constraining *gluons*—interact at leading order. E.g. pion production cross section measurements shown previously have improved constraints on gluon → pion FFs

# *Comparisons*

Beam on fixed target vs. colliding beams

- Colliding beams → higher energies
  - Production of new probes
  - Wide range of perturbatively calculable observables
- Fixed-target → higher luminosities
- Fixed-target → higher x

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Lepton-nucleon scattering vs. hadronic collisions

- Leptonic processes → access to full parton kinematics
- Hadronic collisions → leading-order access to gluons
- Color annihilation in hadronic collisions→ cleanly tag antiquarks

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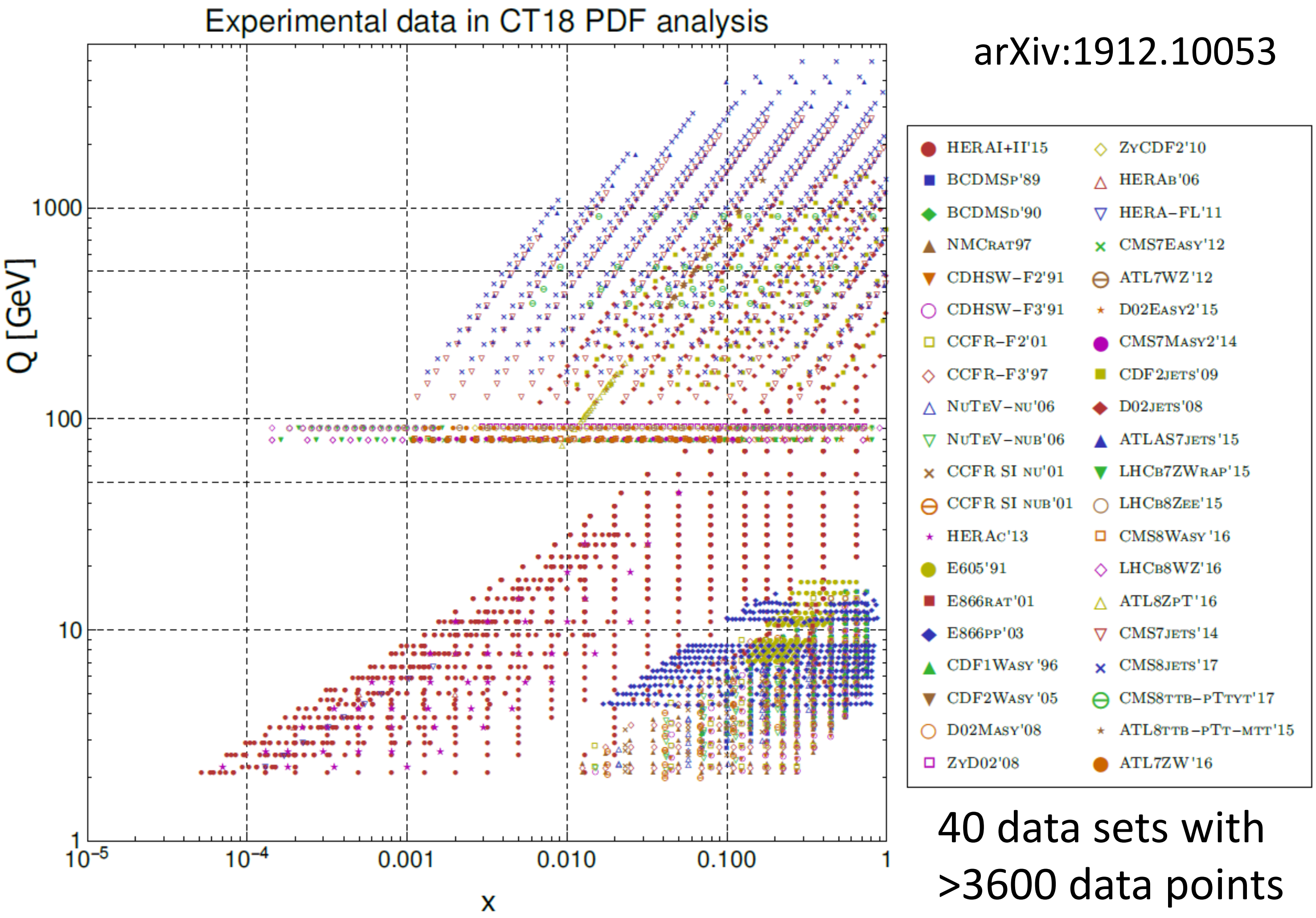
Recall: Constrain functions describing proton structure by measuring scattering cross sections in many colliding systems over wide kinematic range and performing *simultaneous fits to world data*

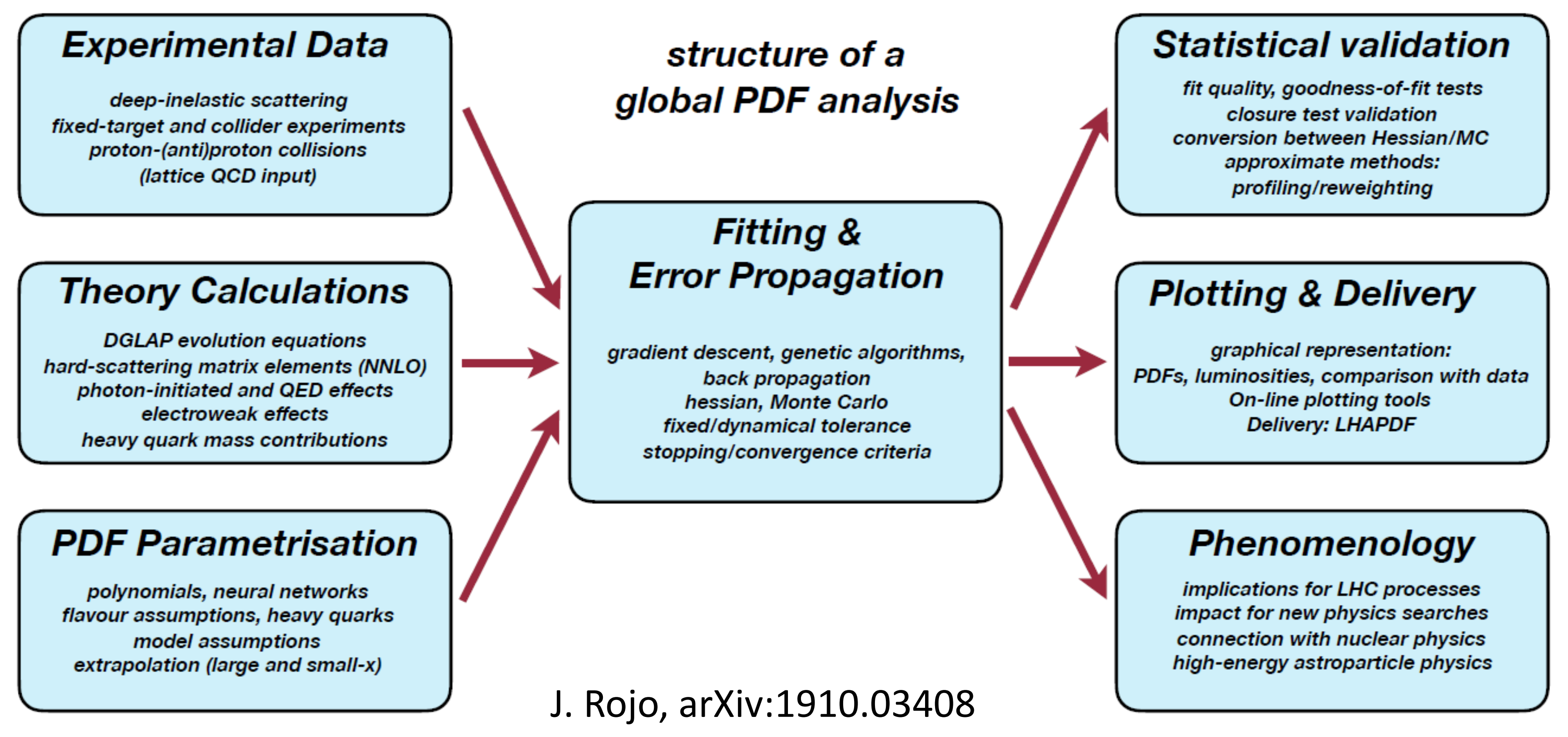
# *Data from many different experiments over wide kinematic range*



arXiv:1912.10053

40 data sets with >3600 data points

# *Global fits of parton distribution functions*



**structure of a global PDF analysis**

**Experimental Data**

*deep-inelastic scattering*
*fixed-target and collider experiments*
*proton-(anti)proton collisions*
*(lattice QCD input)*

**Theory Calculations**

*DGLAP evolution equations*
*hard-scattering matrix elements (NNLO)*
*photon-initiated and QED effects*
*electroweak effects*
*heavy quark mass contributions*

**PDF Parametrisation**

*polynomials, neural networks*
*flavour assumptions, heavy quarks*
*model assumptions*
*extrapolation (large and small-x)*

**Fitting & Error Propagation**

*gradient descent, genetic algorithms,*
*back propagation*
*hessian, Monte Carlo*
*fixed/dynamical tolerance*
*stopping/convergence criteria*

**Statistical validation**

*fit quality, goodness-of-fit tests*
*closure test validation*
*conversion between Hessian/MC*
*approximate methods:*
*profiling/reweighting*

**Plotting & Delivery**

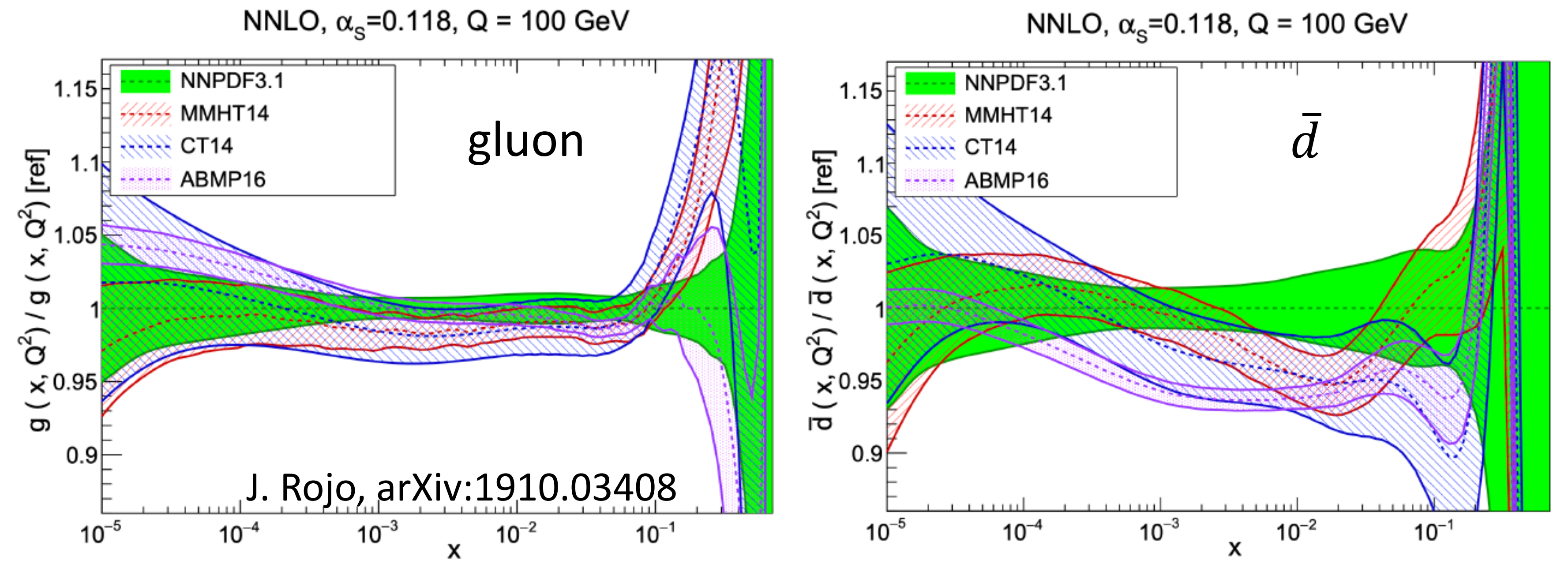
*graphical representation:*
*PDFs, luminosities, comparison with data*
*On-line plotting tools*
*Delivery: LHAPDF*

**Phenomenology**

*implications for LHC processes*
*impact for new physics searches*
*connection with nuclear physics*
*high-energy astroparticle physics*

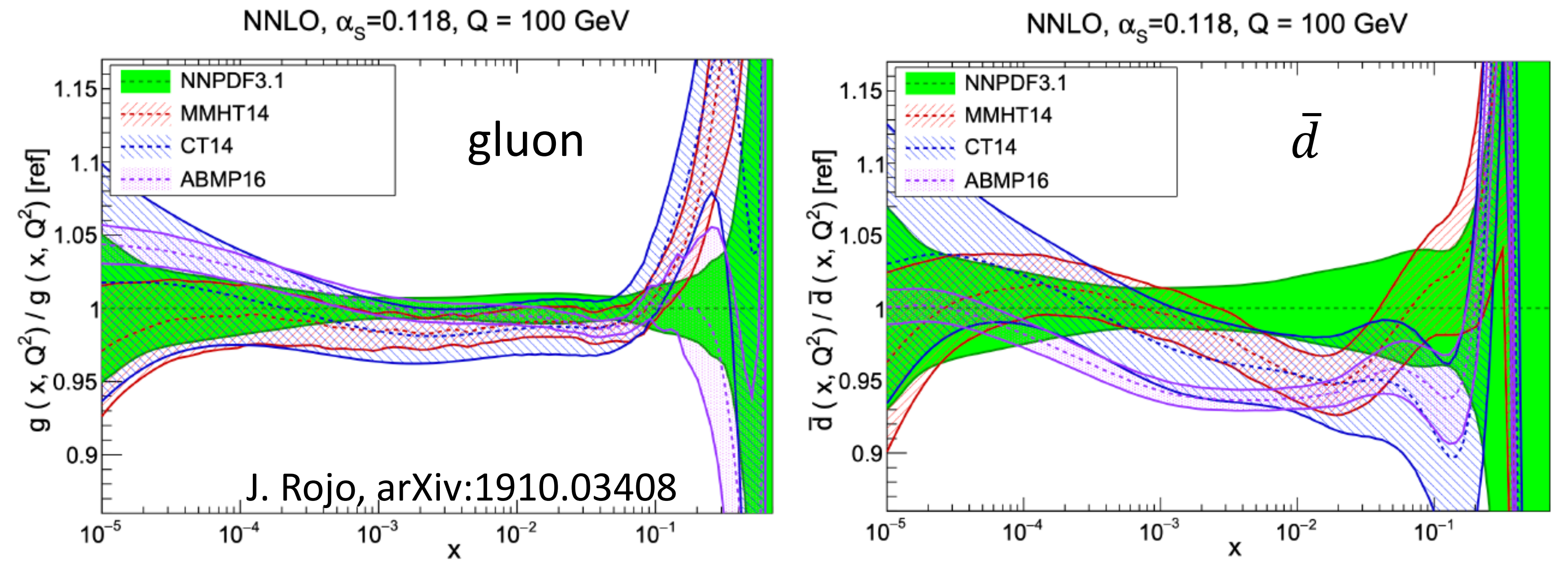
J. Rojo, arXiv:1910.03408

# *Comparison of PDF fits by different groups*



- Can compare and cross-check effects of different choices made by various groups

# Comparison of PDF fits by different groups



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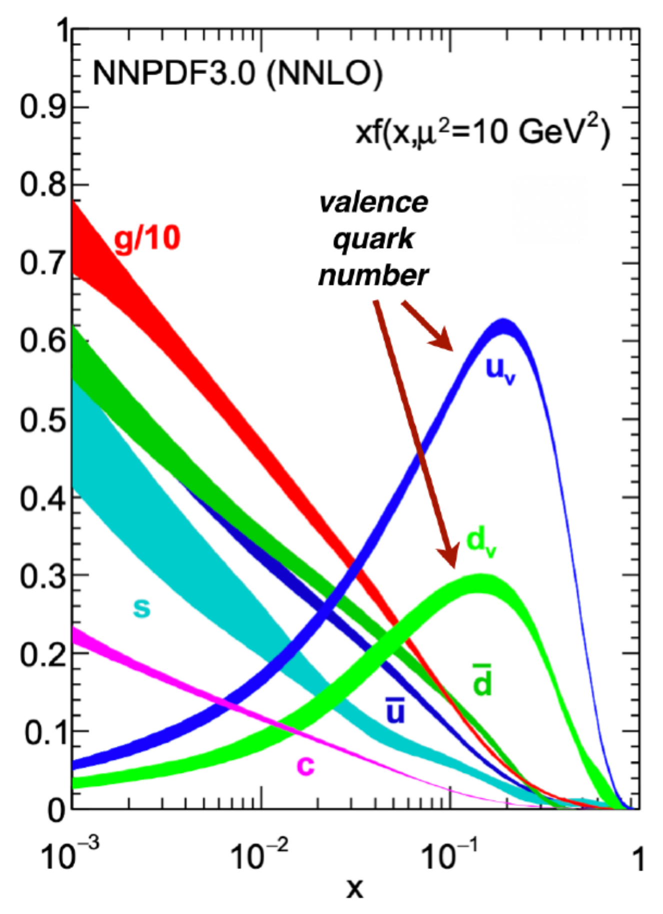
- Can compare and cross-check effects of different choices made by various groups
- Group of Stefano Forte / NNPDF has been a leader in robust determination of uncertainties on PDFs
  - Pioneered use of neural network techniques to eliminate systematic uncertainties due to choice of functional form of parameterization—see e.g. Nucl. Phys. B809, 1 (2009)
  - See also recent paper on handling missing higher-order theory uncertainties, EPJ C79, 11 (2019)

# *Resulting PDF fits*

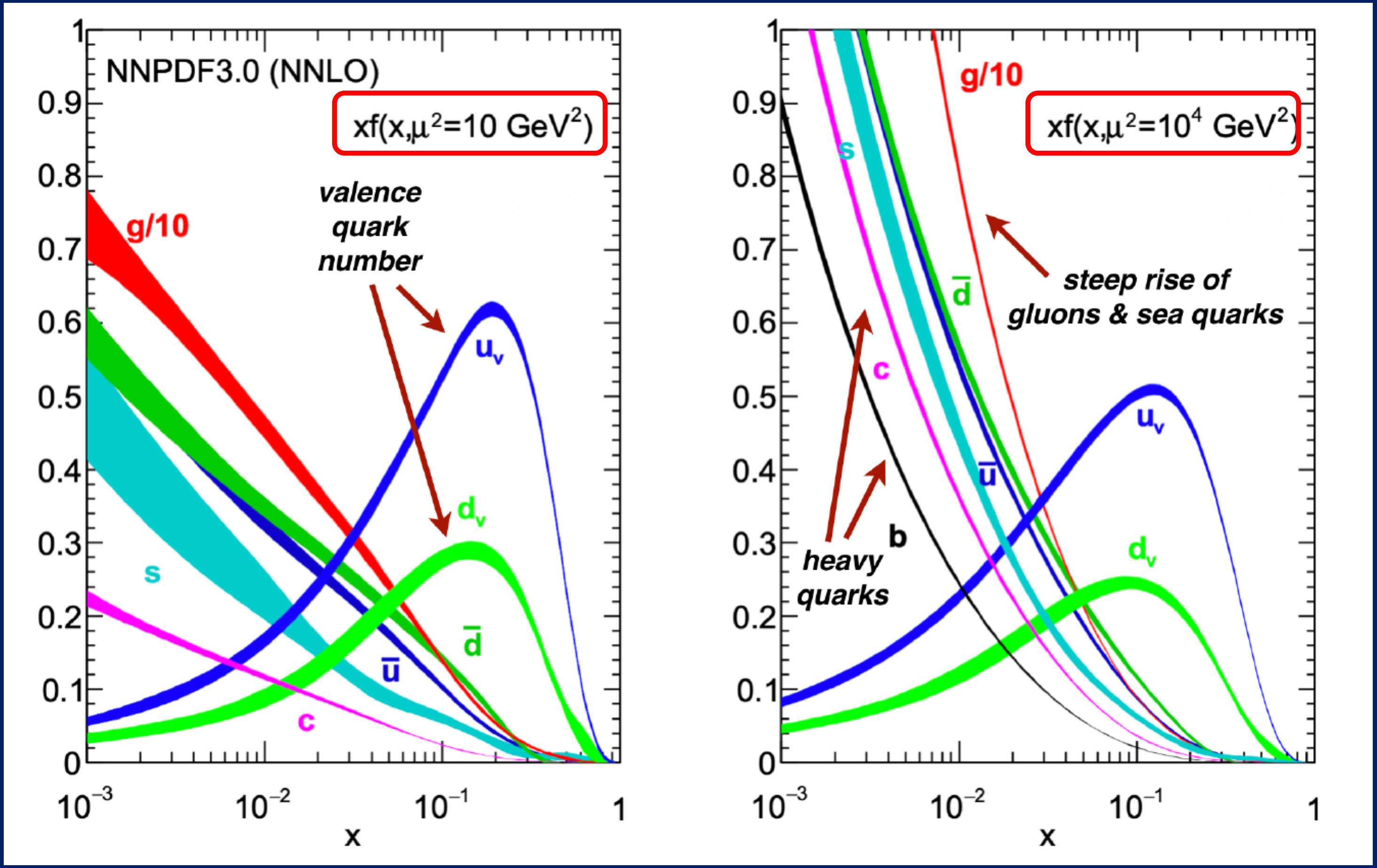
J. Rojo, arXiv:1910.03408



- Different observables give sensitivity to different partonic flavors
- Note gluon scaled down by factor of 10!
- PDFs are energy scale dependent

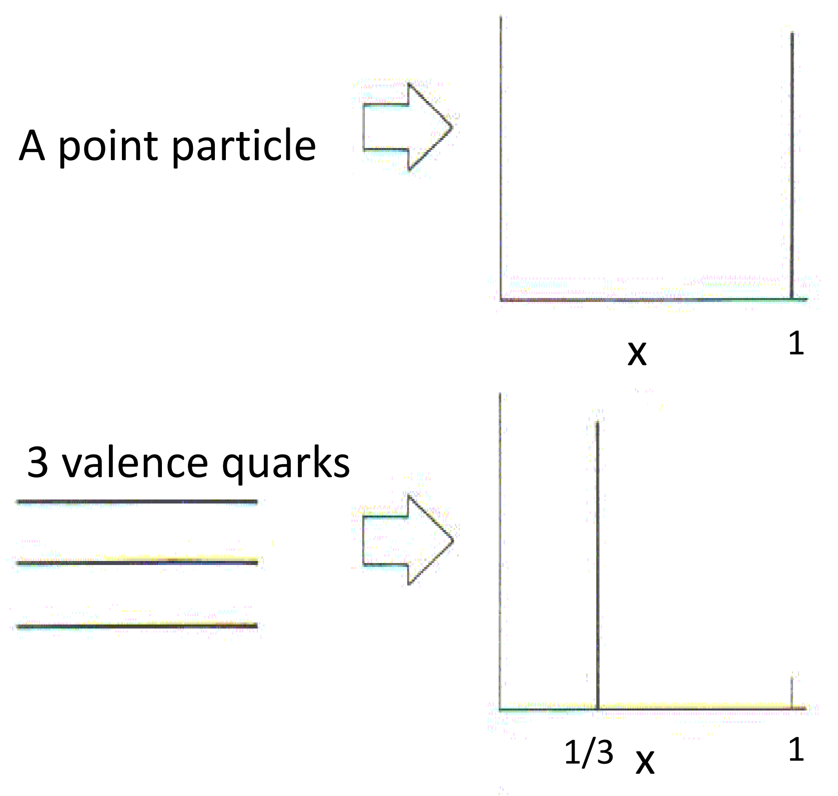
# *Resulting PDF fits*

J. Rojo, arXiv:1910.03408

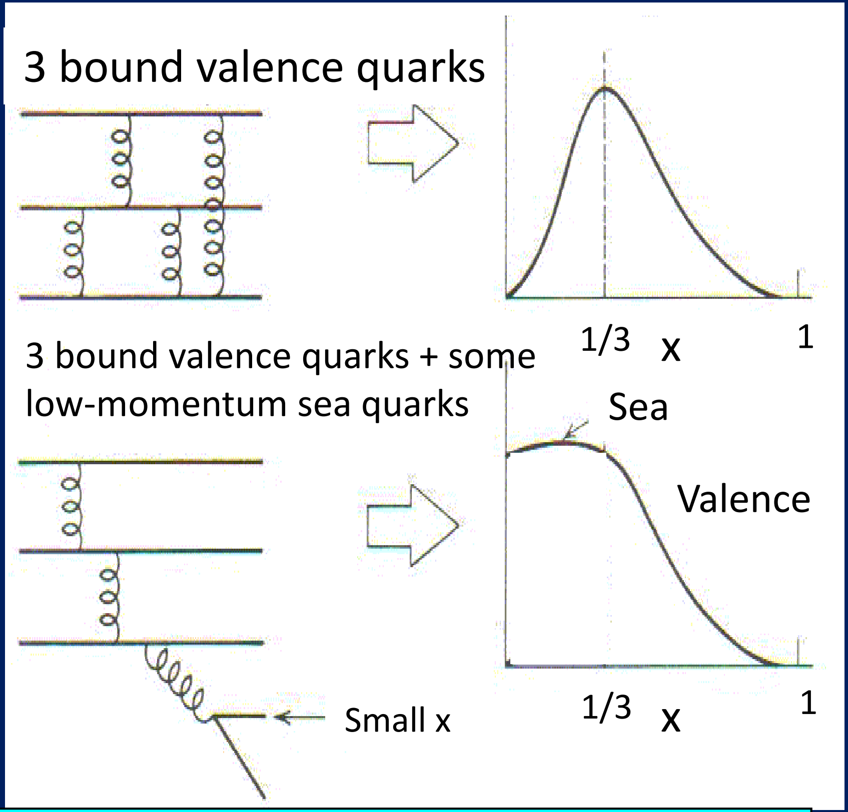


# *Ways to describe proton structure:* ***Unpolarized, collinear** PDFs*

What momentum fraction would the scattering particle carry if the proton were made of …


A point particle

3 valence quarks


3 bound valence quarks

3 bound valence quarks + some low-momentum sea quarks

- Don’t take into account polarization of proton or parton
- Integrate over partonic transverse momentum within proton

# *Mapping out the quark-gluon structure of the proton*

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

Vast majority of past five decades focused on *1-dimensional* momentum structure. Since 1990s starting to consider transverse components . . .

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Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well understood!

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Good measurements of flavor distributions in valence region. Flavor structure for sea quarks still yielding surprises.

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Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past ~decade.

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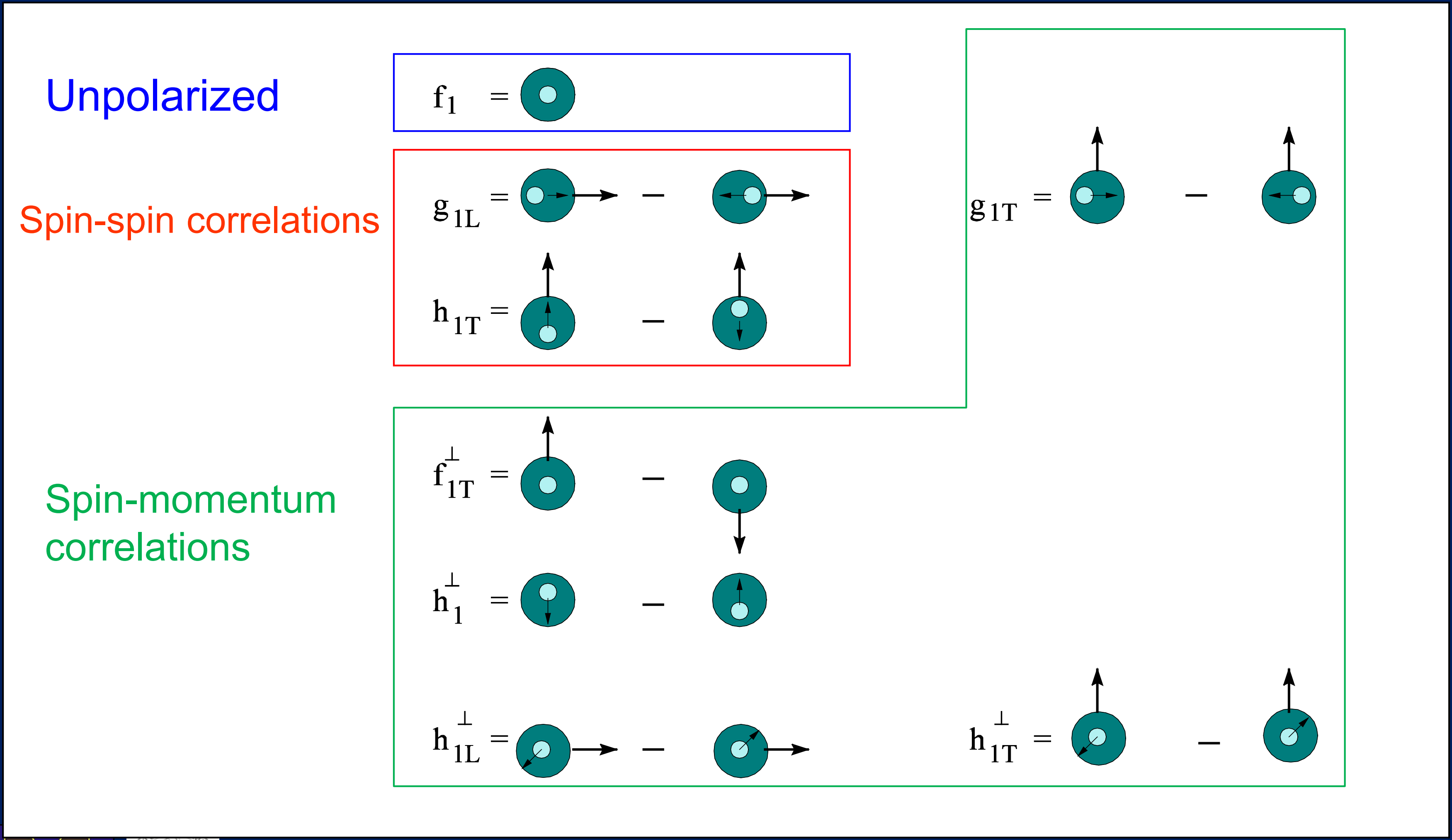
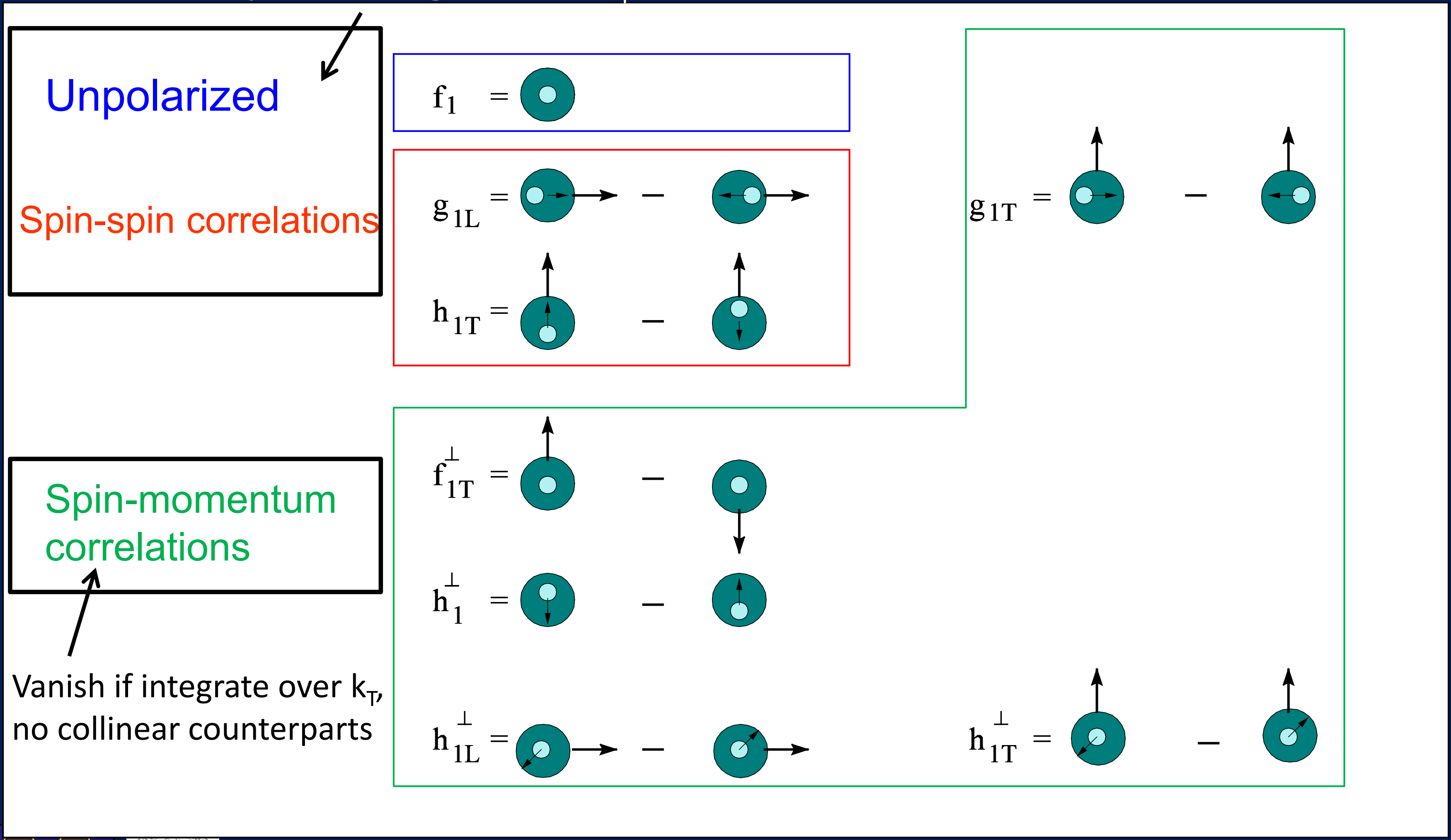
Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color flow have come to forefront in last decade . . .

# *Beyond unpolarized, collinear PDFs: Spin-spin and spin-momentum correlations in QCD bound states*



# *Transverse-momentum-dependent PDFs*

Can keep transverse momentum dependence (more info than collinear), but survive if you do integrate over $k_T$



Unpolarized

Spin-spin correlations

Spin-momentum correlations

Vanish if integrate over $k_T$, no collinear counterparts

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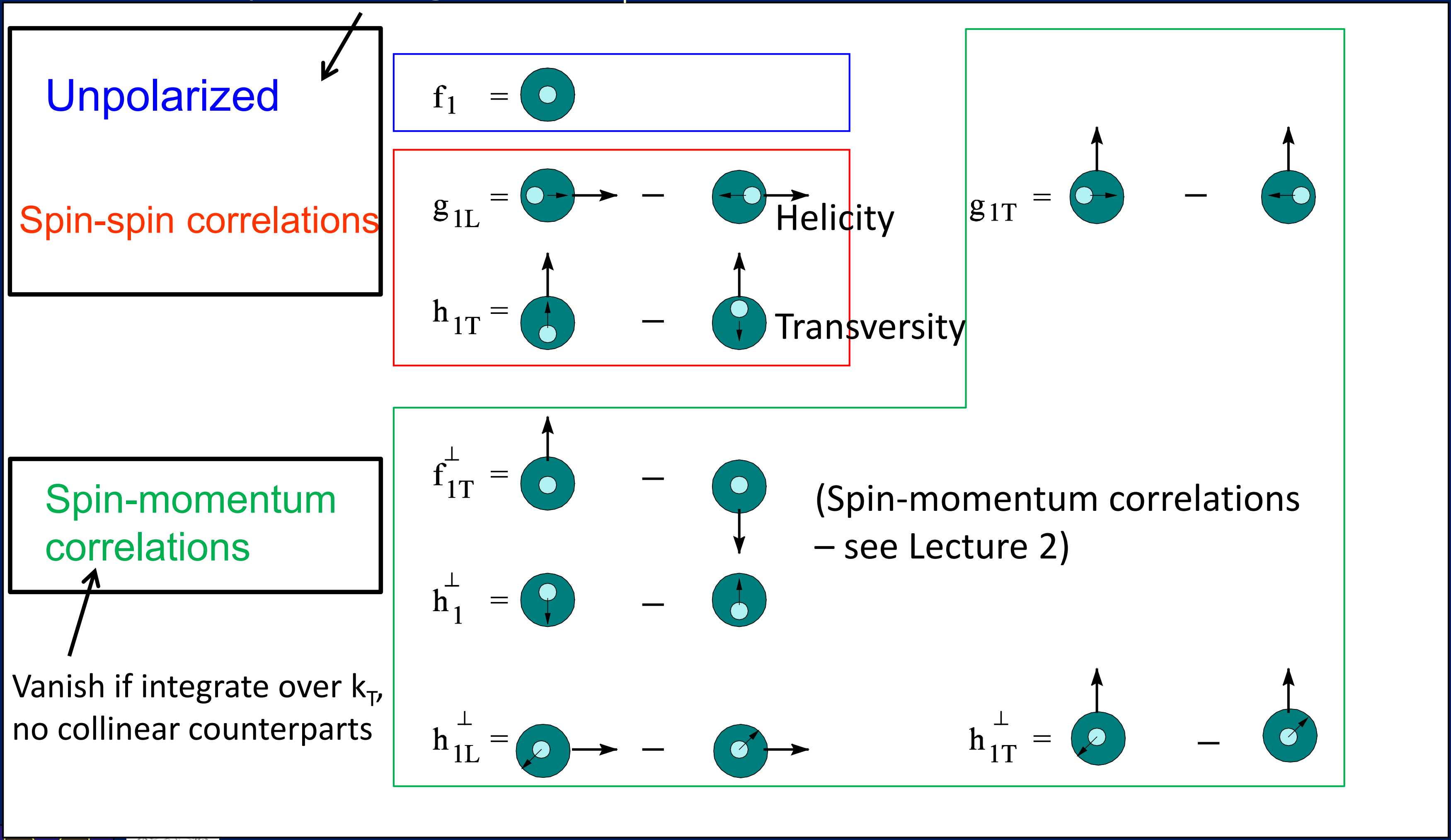


Unpolarized

Spin-spin correlations

Helicity

Transversity

Spin-momentum correlations

(Spin-momentum correlations – see Lecture 2)

Vanish if integrate over $k_T$, no collinear counterparts

# *Spin-spin correlations in terms of helicity*

## Elastic proton-quark scattering

(related to inelastic scattering through optical theorem)

Three independent PDFs corresponding to following helicity states in scattering:

$$\begin{array}{ccccc}
\frac{1}{2} & \frac{1}{2} & \longrightarrow & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & \frac{1}{2} & -\frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & -\frac{1}{2} & \frac{1}{2}
\end{array}$$

Take linear combinations to form familiar collinear PDFs:

$$\begin{array}{lcl}
q & \longleftrightarrow & \left(\frac{1}{2} \quad \frac{1}{2} \quad \rightarrow \quad \frac{1}{2} \quad \frac{1}{2}\right) + \left(\frac{1}{2} \quad -\frac{1}{2} \quad \rightarrow \quad \frac{1}{2} \quad -\frac{1}{2}\right) \\
\Delta q & \longleftrightarrow & \left(\frac{1}{2} \quad \frac{1}{2} \quad \rightarrow \quad \frac{1}{2} \quad \frac{1}{2}\right) - \left(\frac{1}{2} \quad -\frac{1}{2} \quad \rightarrow \quad \frac{1}{2} \quad -\frac{1}{2}\right) \\
\delta q & \longleftrightarrow & \left(\frac{1}{2} \quad -\frac{1}{2} \quad \rightarrow \quad -\frac{1}{2} \quad \frac{1}{2}\right)
\end{array}$$

Helicity average
(unpolarized PDF)

Helicity difference
(helicity PDF)

Helicity flip
(transversity PDF)

# *Spin-spin correlations in terms of helicity*

## Elastic proton-quark scattering

(related to inelastic scattering through optical theorem)

Three independent PDFs corresponding to following helicity states in scattering:

$$\begin{array}{ccccc} \frac{1}{2} & \frac{1}{2} & \longrightarrow & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \longrightarrow & \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \longrightarrow & -\frac{1}{2} & \frac{1}{2} \end{array}$$

Helicity basis not "natural" for transversity

Can think of as difference in probability of scattering off of transversely polarized quark within transversely polarized proton with quark spin parallel vs. antiparallel to proton's

Take linear combinations to form familiar collinear PDFs:

$$q \longleftrightarrow \left(\frac{1}{2}\ \frac{1}{2} \rightarrow \frac{1}{2}\ \frac{1}{2}\right) + \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow \frac{1}{2}\ -\frac{1}{2}\right)$$

Helicity average (unpolarized PDF)

$$\Delta q \longleftrightarrow \left(\frac{1}{2}\ \frac{1}{2} \rightarrow \frac{1}{2}\ \frac{1}{2}\right) - \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow \frac{1}{2}\ -\frac{1}{2}\right)$$

Helicity difference (helicity PDF)

$$\boxed{\delta q \longleftrightarrow \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow -\frac{1}{2}\ \frac{1}{2}\right)}$$

Helicity flip (transversity PDF)

# *Spin-spin correlations (collinear or TMD): Helicity vs. transverse spin structure*

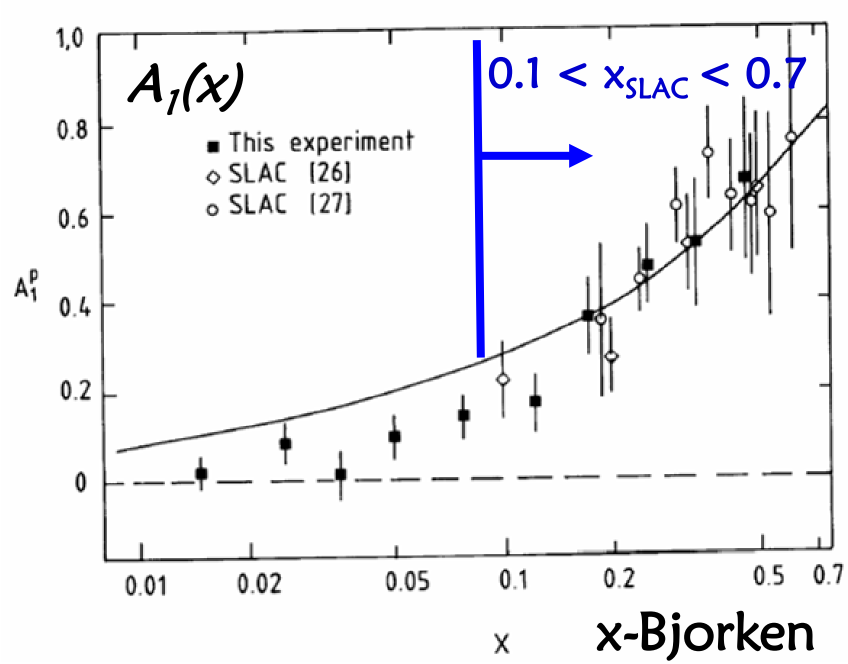
- Transverse spin structure of the proton cannot be deduced from helicity structure
  - Spatial rotations and Lorentz boosts don't commute
  - Relationship between longitudinal and transverse structure provides information on the relativistic nature of partons in the proton
  - Even collinear transverse spin structure (transversity) should thus be linked to parton $k_T$
    - I haven't dug into this yet myself to try to understand it better . . .

# *Spin-spin correlations: Proton "spin crisis"*

SLAC: *0.10 < x <0.7*

$$\frac{1}{2}=\frac{1}{2}\cdot\Delta\Sigma + \Delta G + L_{G+q}$$

| Total spin of quarks and antiquarks | Total spin of gluons | Orbital ang. momentum |
|---|---|---|



$\Delta\Sigma_{SLAC} \sim 0.6$ Quark–Parton Model expectation

E130, Phys.Rev.Lett.51:1135 (1983)

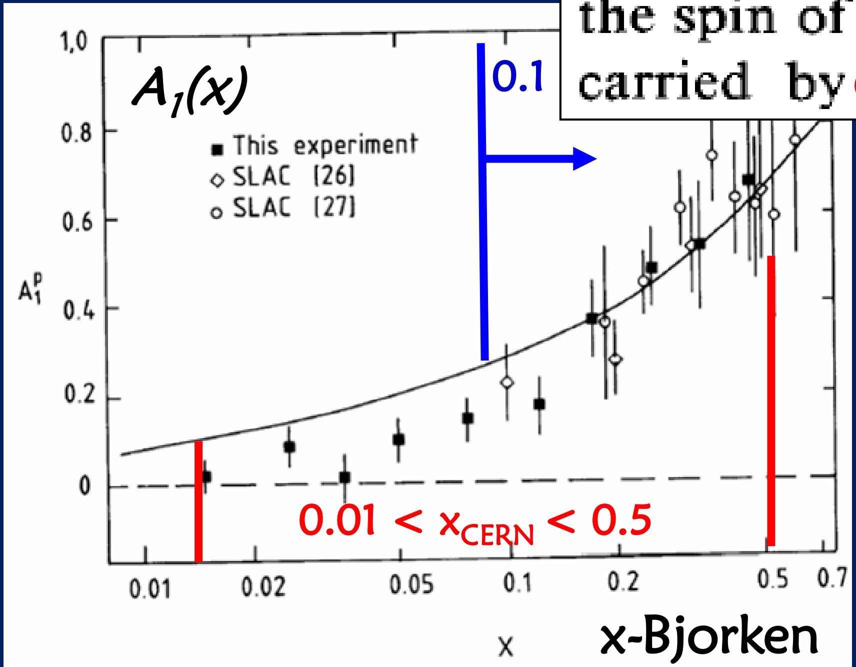
# *Spin-spin correlations: Proton "spin crisis"*

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$

SLAC: *$0.10 < x < 0.7$*

CERN: *$0.01 < x < 0.5$*

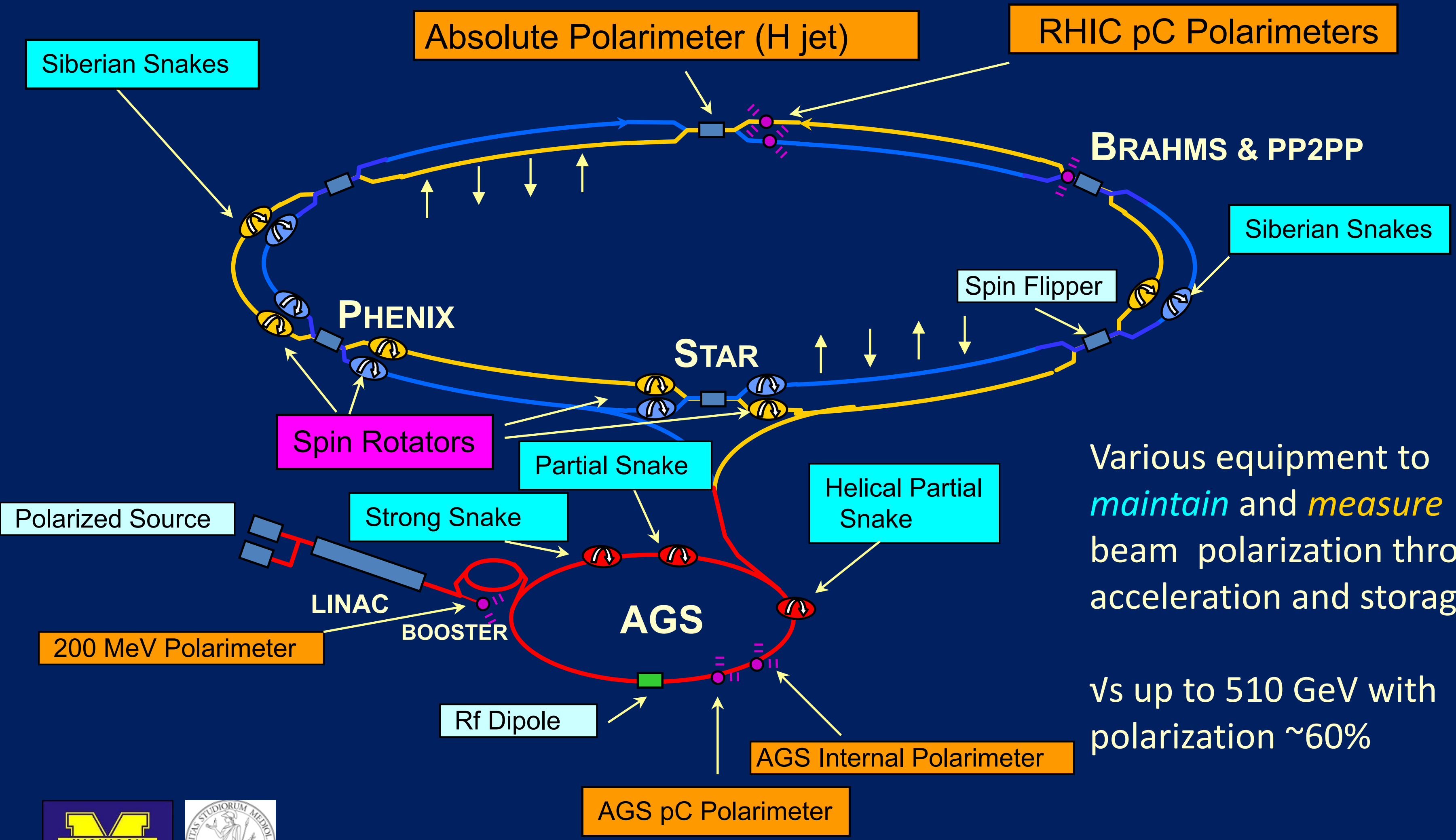
Hence ( 14 ± 9 ± 21 )% of the proton spin is carried by the spin of the quarks. The remaining spin must be carried by gluons or orbital angular momentum



EMC (CERN), Phys.Lett.B206:364 (1988)
2136 citations…

"Proton spin crisis"

# *The Relativistic Heavy Ion Collider:*
# *A **polarized** p+p collider*



Absolute Polarimeter (H jet)

RHIC pC Polarimeters

Siberian Snakes

**BRAHMS & PP2PP**

Siberian Snakes

Spin Flipper

**PHENIX**

**STAR**

Spin Rotators

Partial Snake

Helical Partial Snake

Polarized Source

Strong Snake

**LINAC**

**BOOSTER**

**AGS**

200 MeV Polarimeter

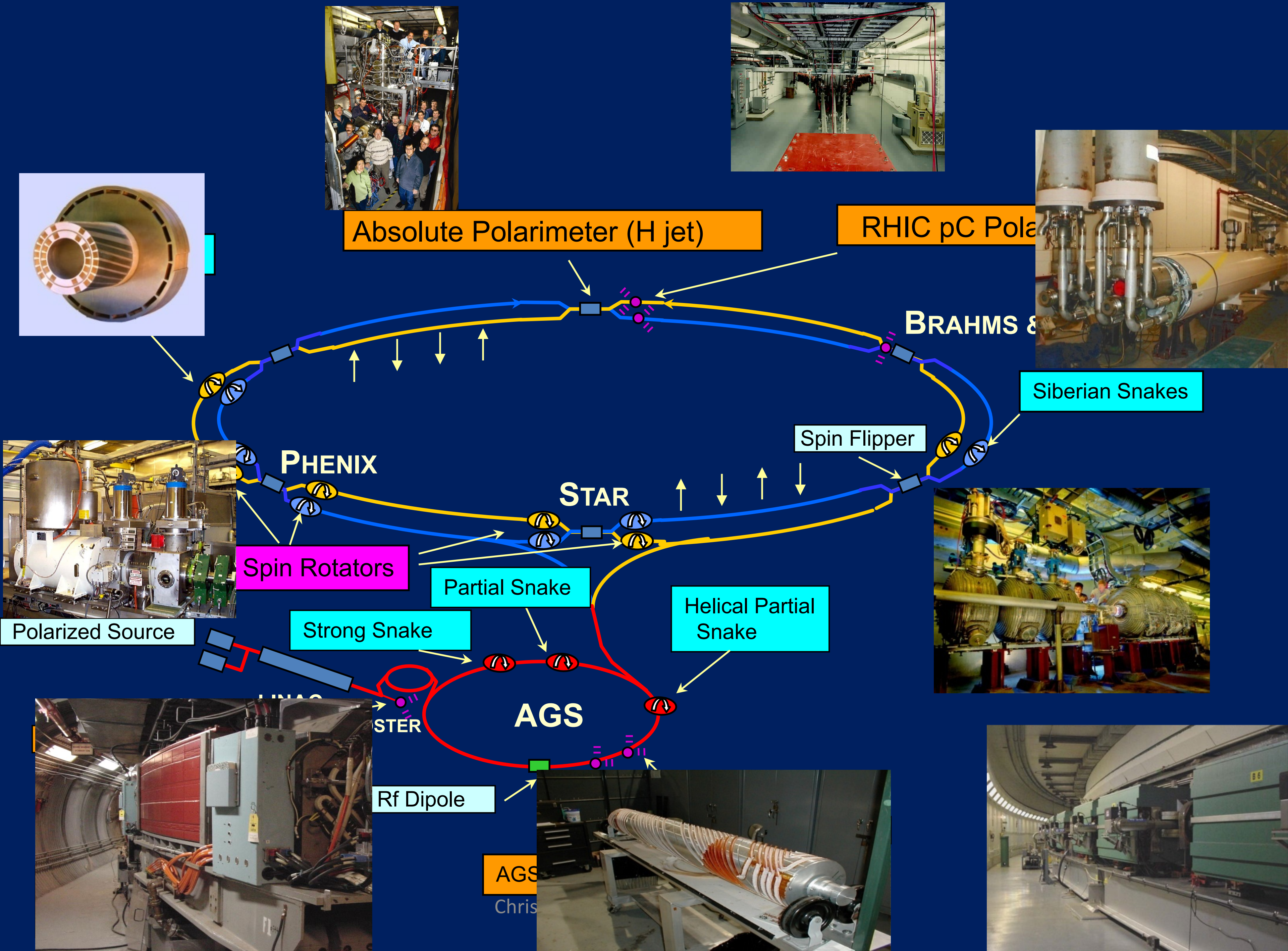
Rf Dipole

AGS Internal Polarimeter

AGS pC Polarimeter

Various equipment to *maintain* and *measure* beam polarization through acceleration and storage.

√s up to 510 GeV with polarization ~60%



Absolute Polarimeter (H jet)

RHIC pC Pola

BRAHMS &

Siberian Snakes

Spin Flipper

PHENIX

STAR

Spin Rotators

Partial Snake

Helical Partial Snake

Strong Snake

Polarized Source

STER

AGS

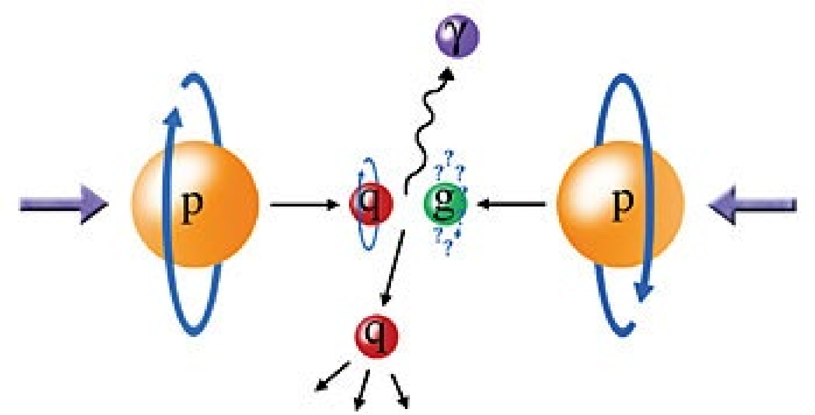
Rf Dipole

AGS

Chris

# *Accessing gluon spin with polarized p+p collisions*

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$



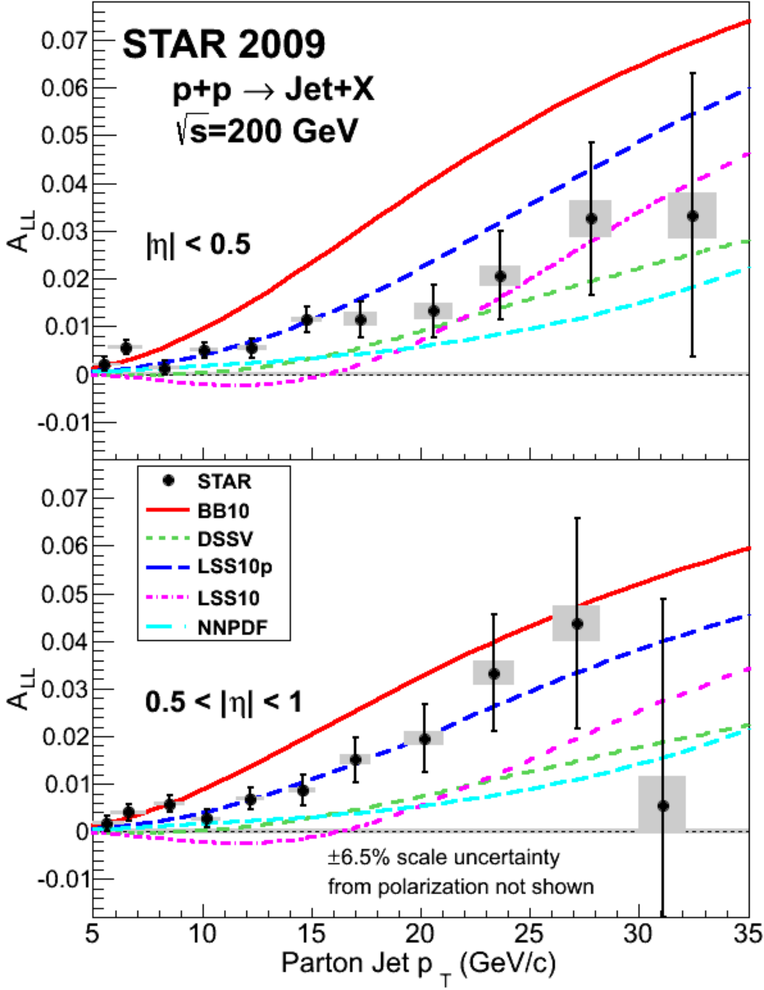
Study difference in particle production rates for same-helicity vs. opposite-helicity proton collisions

$$\Delta\sigma(pp \to \pi^0 X) \propto \underbrace{\Delta q(x_1)}_{\text{DIS}} \otimes \underbrace{\Delta g(x_2)}_{?} \otimes \underbrace{\Delta\hat{\sigma}^{qg\to qg}(\hat{s})}_{\text{pQCD}} \otimes \underbrace{D_q^{\pi^0}(z)}_{\text{e+e-}}$$

Leading-order access to gluons

# *RHIC measurements sensitive to gluon spin*

PRD86, 032006; PRL 115, 092002

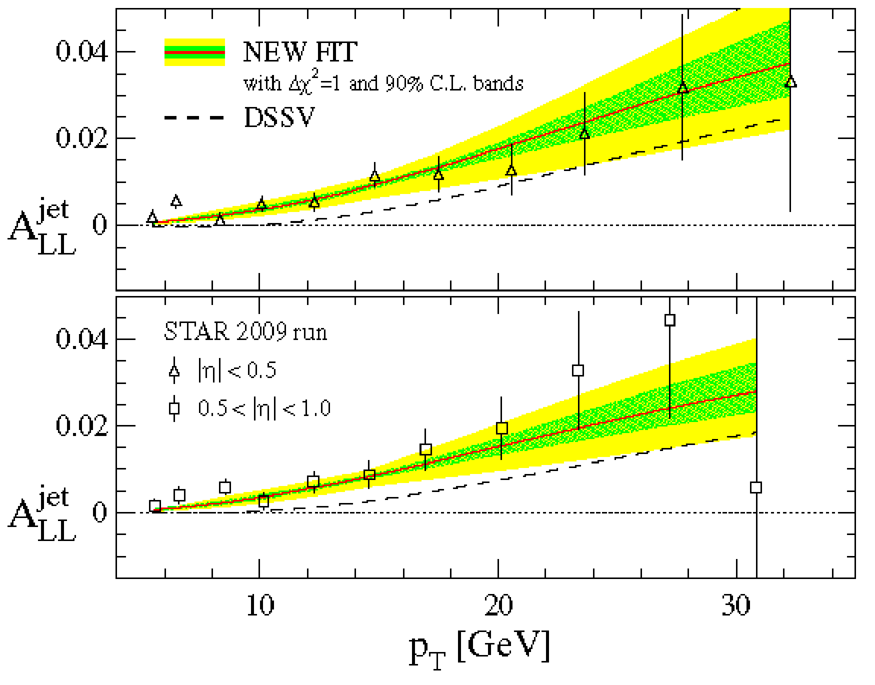


- Clear nonzero asymmetry seen in STAR jet measurements
- PHENIX $\pi^0$ data consistent (PRD90, 012007)

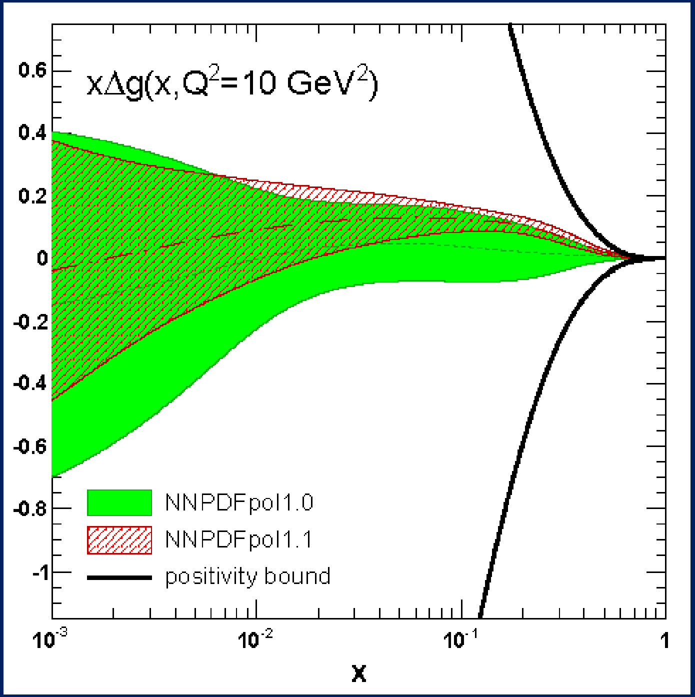
$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1P_2|}\frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

# *Gluon spin from two subsequent global fits*

**DSSV, PRL 113, 012001 (2014)**



**NNPDF, NPB 887, 276 (2014)**



- Can extract helicity PDFs using global fits of world data on longitudinally polarized protons (but much less data available than unpolarized)
- Fits by DSSV and NNPDF including RHIC data consistently found evidence for small but positive gluon polarization in the region x > 0.05

July 2014

# Proton Spin Mystery Gains a New Clue

Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

By Clara Moskowitz | July 21, 2014

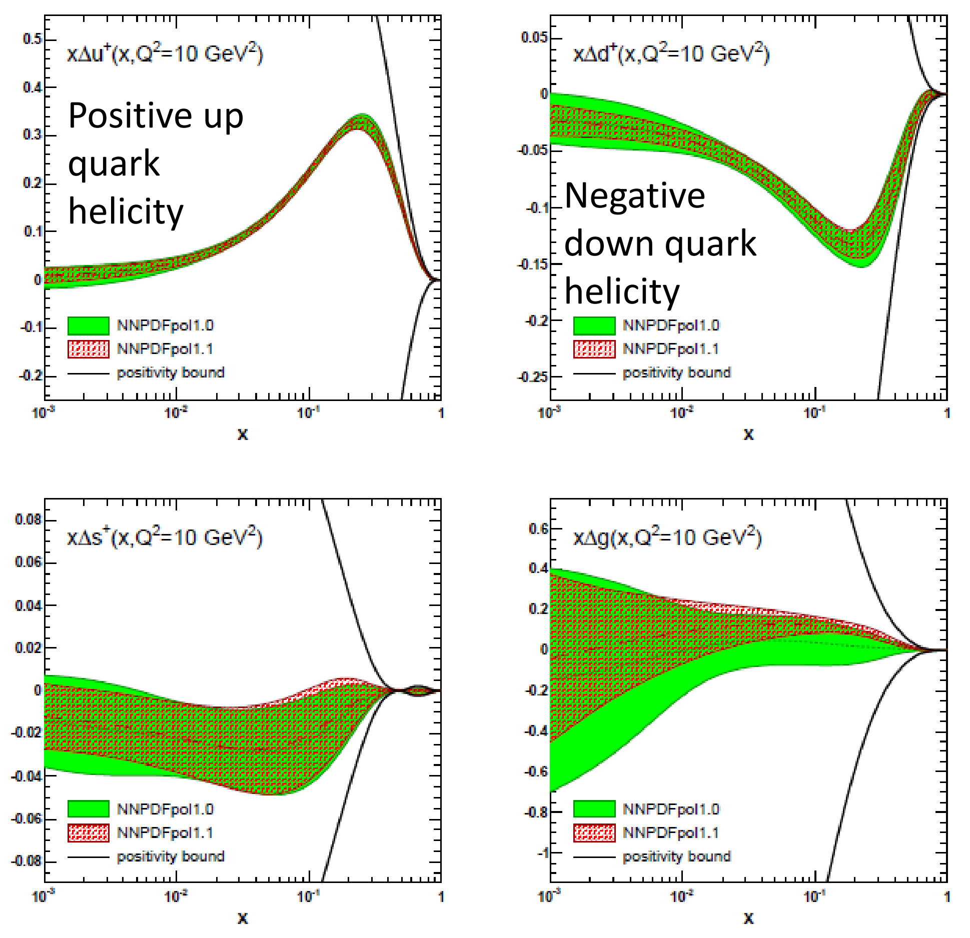
*Brookhaven National Laboratory*

Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987 experiment showed that quarks can account for only a small portion of a proton's spin, raising the question of where the rest arises. The quarks inside a proton are held together by gluons, so scientists suggested perhaps they contribute spin. That idea now has support from a pair of studies analyzing the results of proton collisions inside the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, N.Y.

# *Parton helicity distributions*

- First NNPDF polarized fits: Ph.D. thesis of Emanuele Nocera, UniMi

- Nocera et al., Nucl. Phys. B887, 276 (2014)


Positive up quark helicity

Negative down quark helicity

# *Parton helicity distributions*

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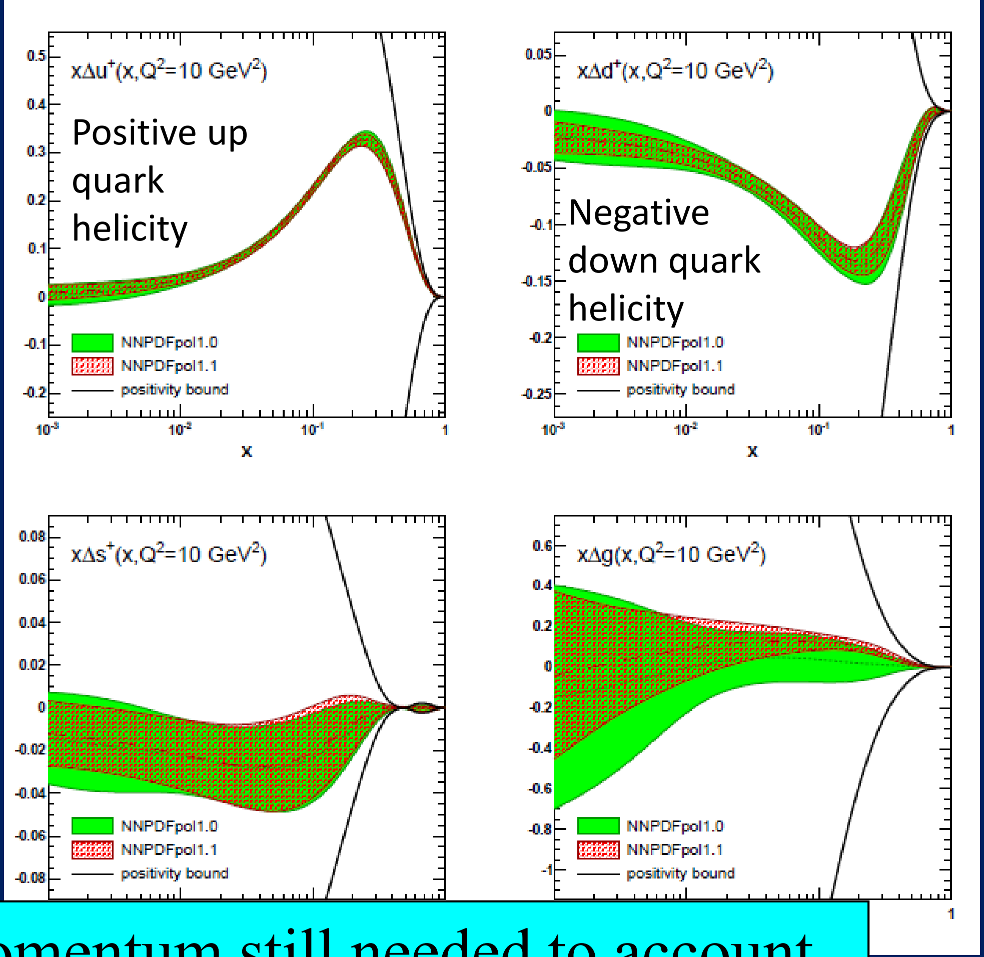
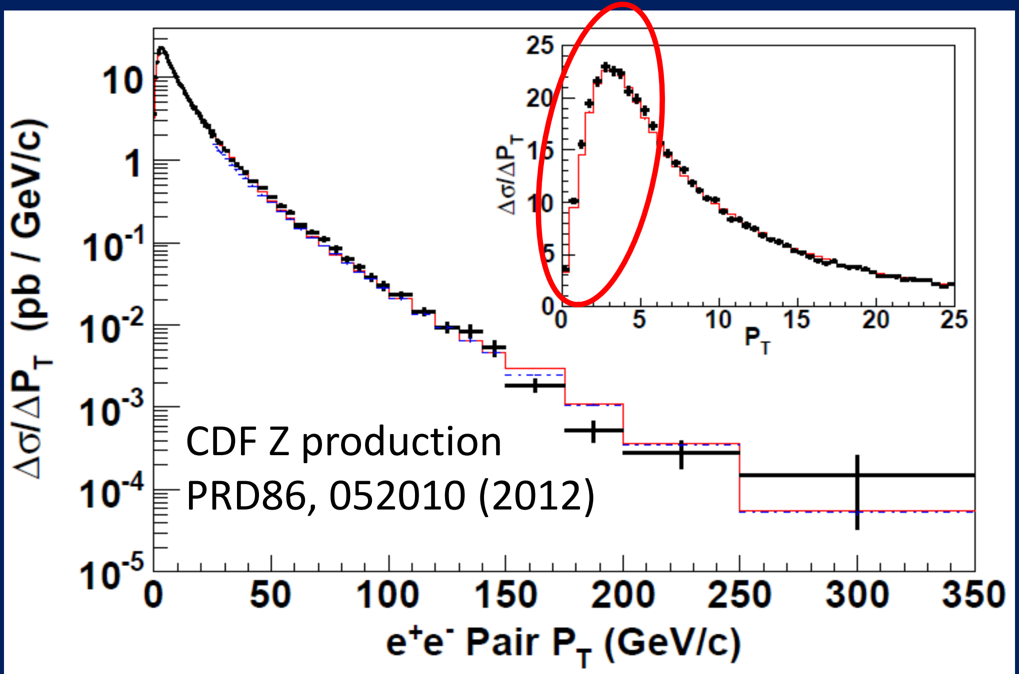
- Nocera et al., Nucl. Phys. B887, 276 (2014)



Orbital angular momentum still needed to account for total proton spin → parton *dynamics* important

# *Parton dynamics: Transverse-momentum-dependent PDFs*

- Don't integrate over partonic transverse momentum ($k_T$): explicitly keep information on parton *dynamics* within the proton
  - $f(x, k_T, Q^2)$
- Framework of TMD-factorization goes back to 1980s (Collins, Soper, Sterman)
- Observables need sensitivity to two scales, $q_T << Q^2$
  - E.g. Z transverse momentum for $p_T << M_Z$
  - Higher $p_T$ generated by hard (perturbative) radiation

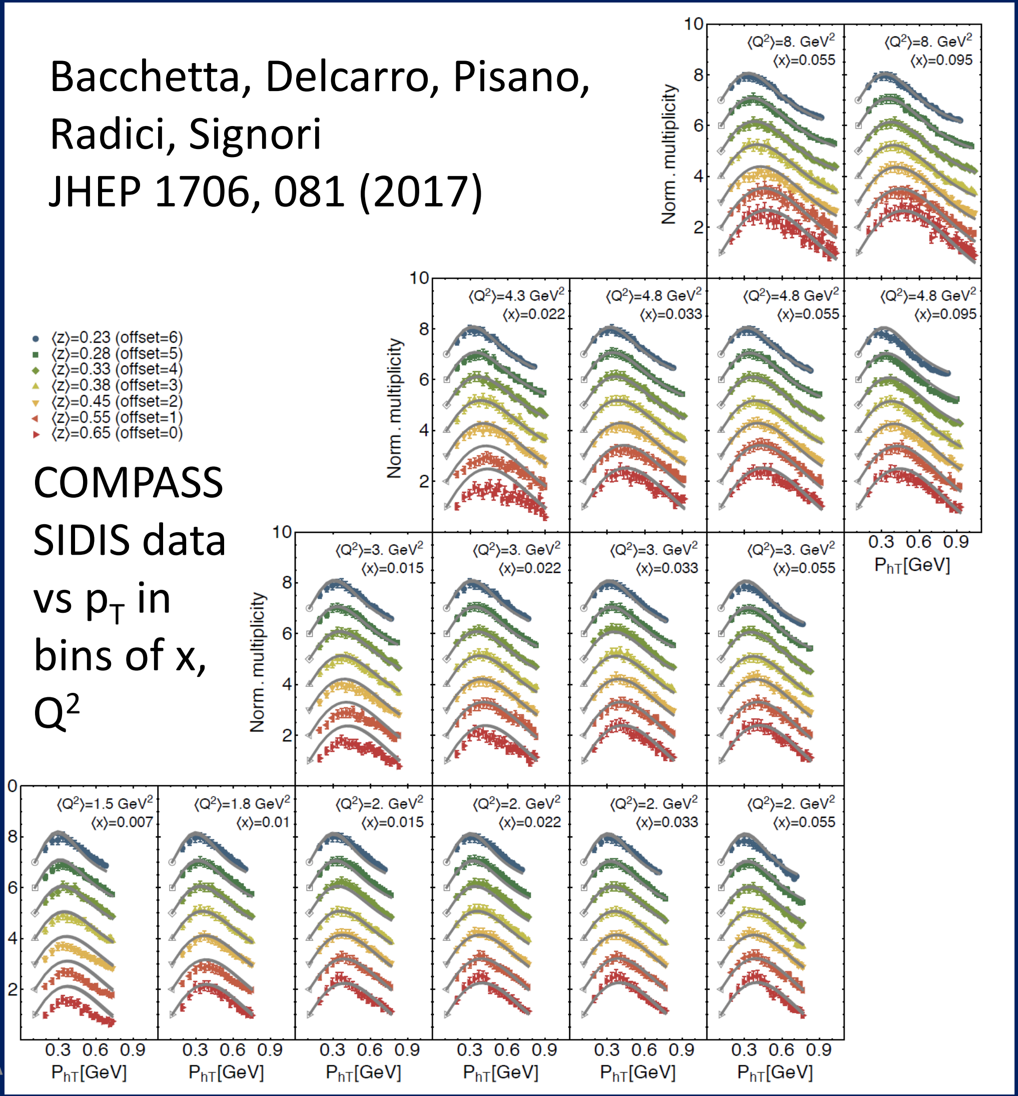


CDF Z production
PRD86, 052010 (2012)

At leading order, $p_T$ of Z boson at low $p_T$ due to sum of $k_T$ of annihilating quark and antiquark

# *Example: Fits of transverse-momentum-dependent PDFs*

- First global fit of unpolarized TMD PDFs, including semi-inclusive deep-inelastic scattering, Drell-Yan, and Z boson data



Bacchetta, Delcarro, Pisano, Radici, Signori
JHEP 1706, 081 (2017)

COMPASS SIDIS data vs $p_T$ in bins of x, $Q^2$

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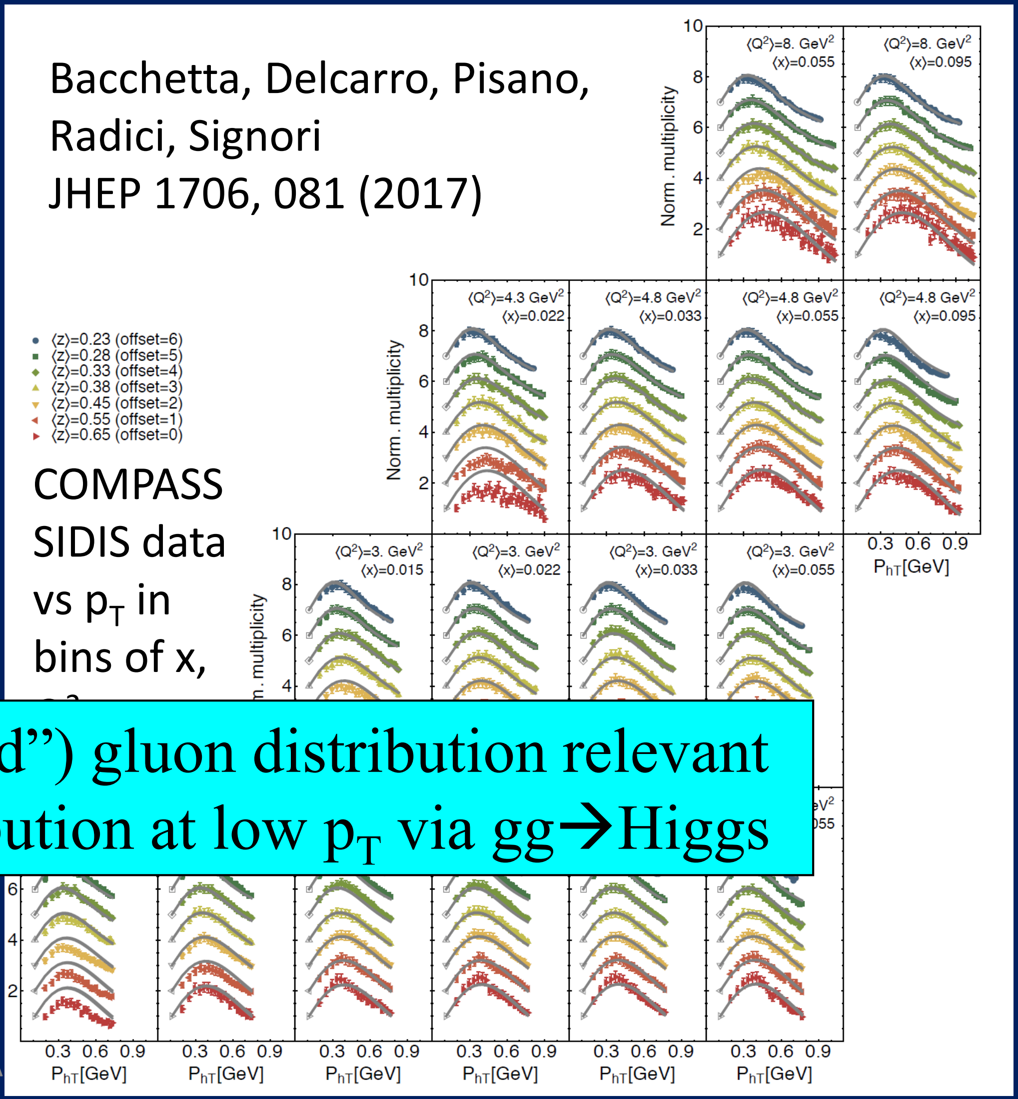
- First global fit of unpolarized TMD PDFs, including semi-inclusive deep-inelastic scattering, Drell-Y

data



Bacchetta, Delcarro, Pisano, Radici, Signori
JHEP 1706, 081 (2017)

COMPASS SIDIS data vs $p_T$ in bins of x,

TMD ("unintegrated") gluon distribution relevant e.g. to Higgs distribution at low $p_T$ via gg→Higgs

# *Example: Fits of transverse-momentum-dependent PDFs*

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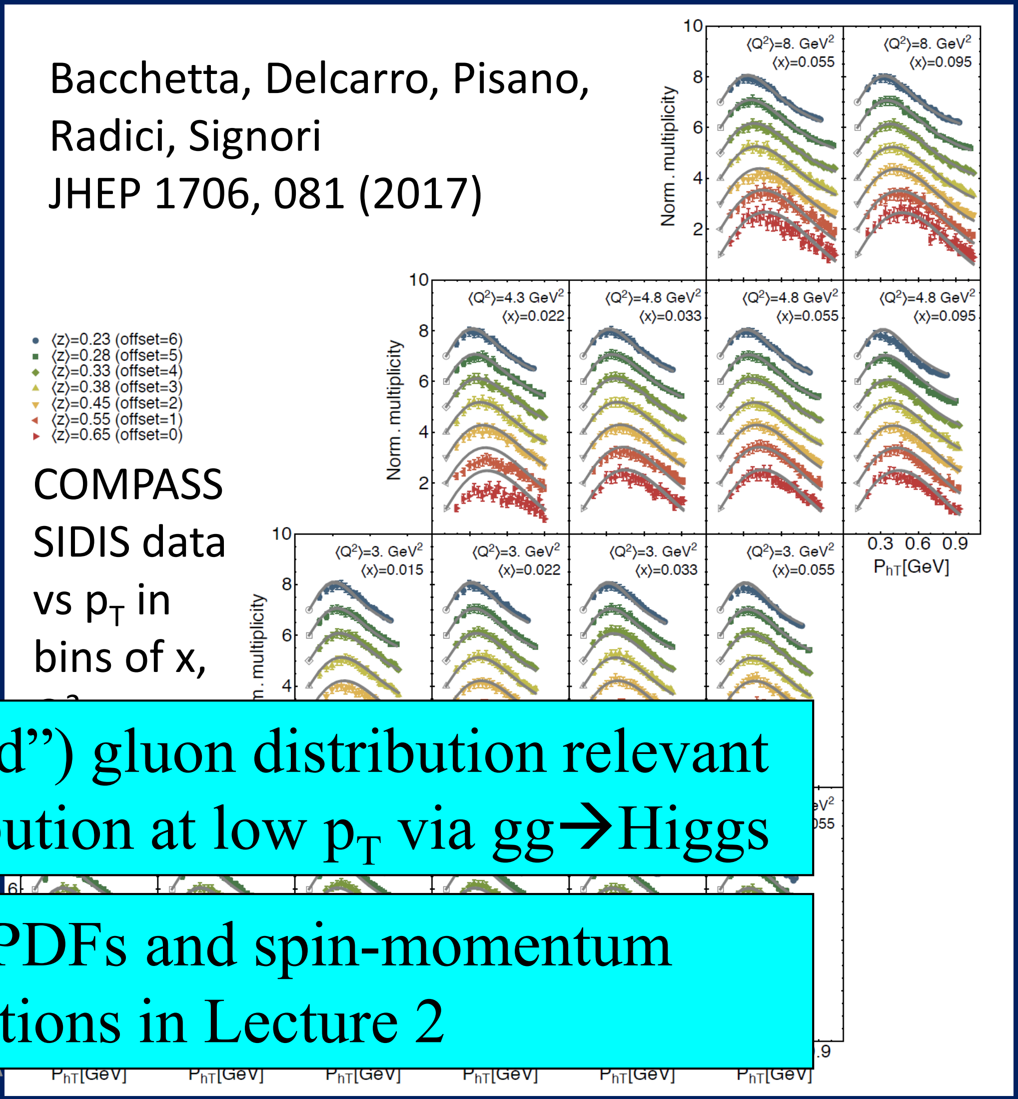

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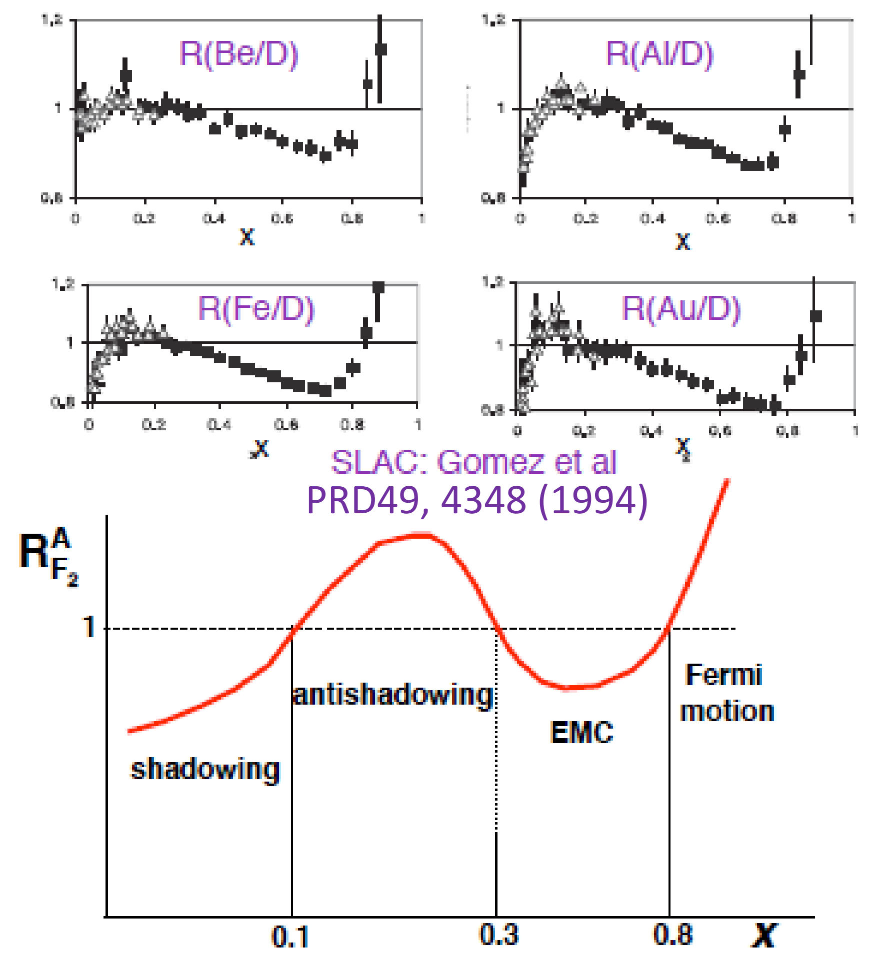
JHEP 1706, 081 (2017)

COMPASS SIDIS data vs $p_T$ in bins of x,

TMD ("unintegrated") gluon distribution relevant e.g. to Higgs distribution at low $p_T$ via gg→Higgs

More on TMD PDFs and spin-momentum correlations in Lecture 2

# *A few words on nuclei: Not just superposed protons and neutrons*



SLAC: Gomez et al
PRD49, 4348 (1994)

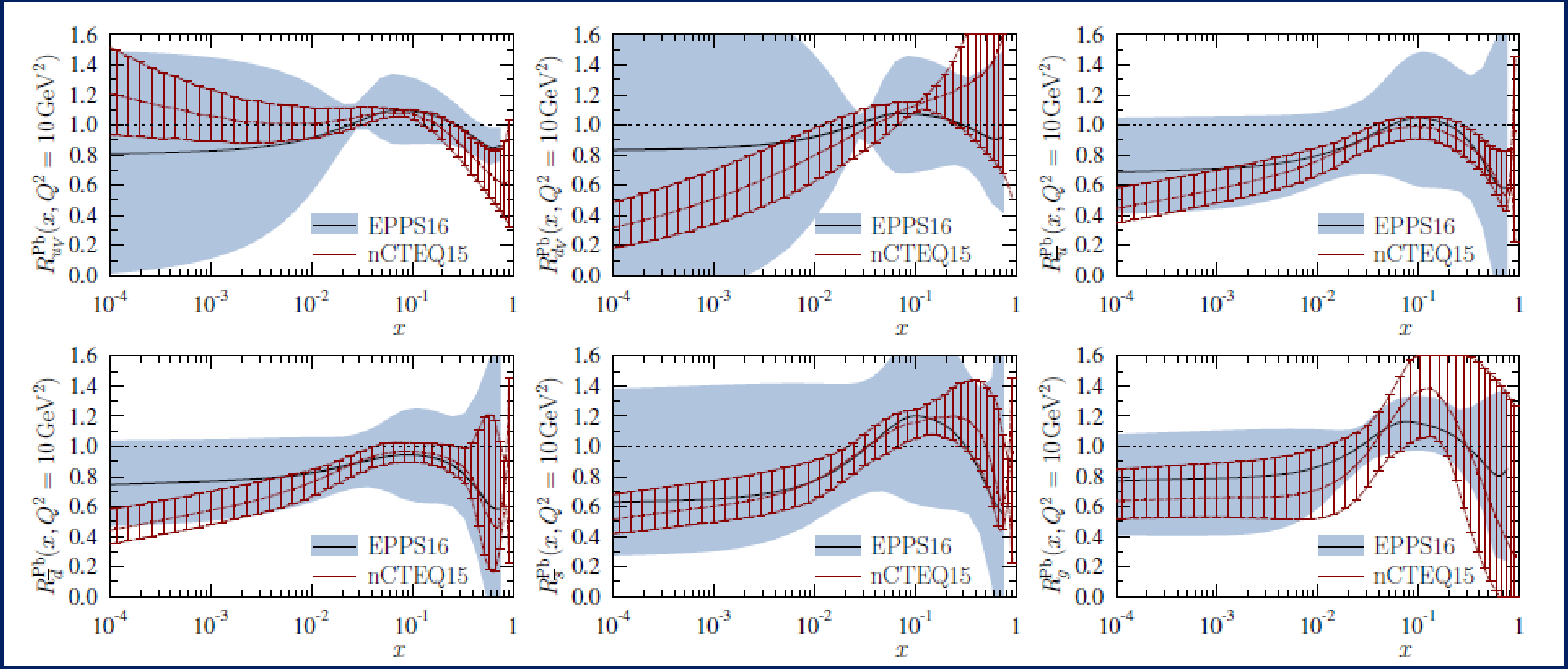
$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction $x$
- Regions of both enhancement and depletion

# *Partonic momentum structure of nuclei: Nuclear parton distribution functions*

(Traditional collinear, unpolarized) Nuclear PDFs:

Ratio of nuclear PDFs in lead with respect to deuterium



EPPS16 – EPJ C77, 163 (2017)

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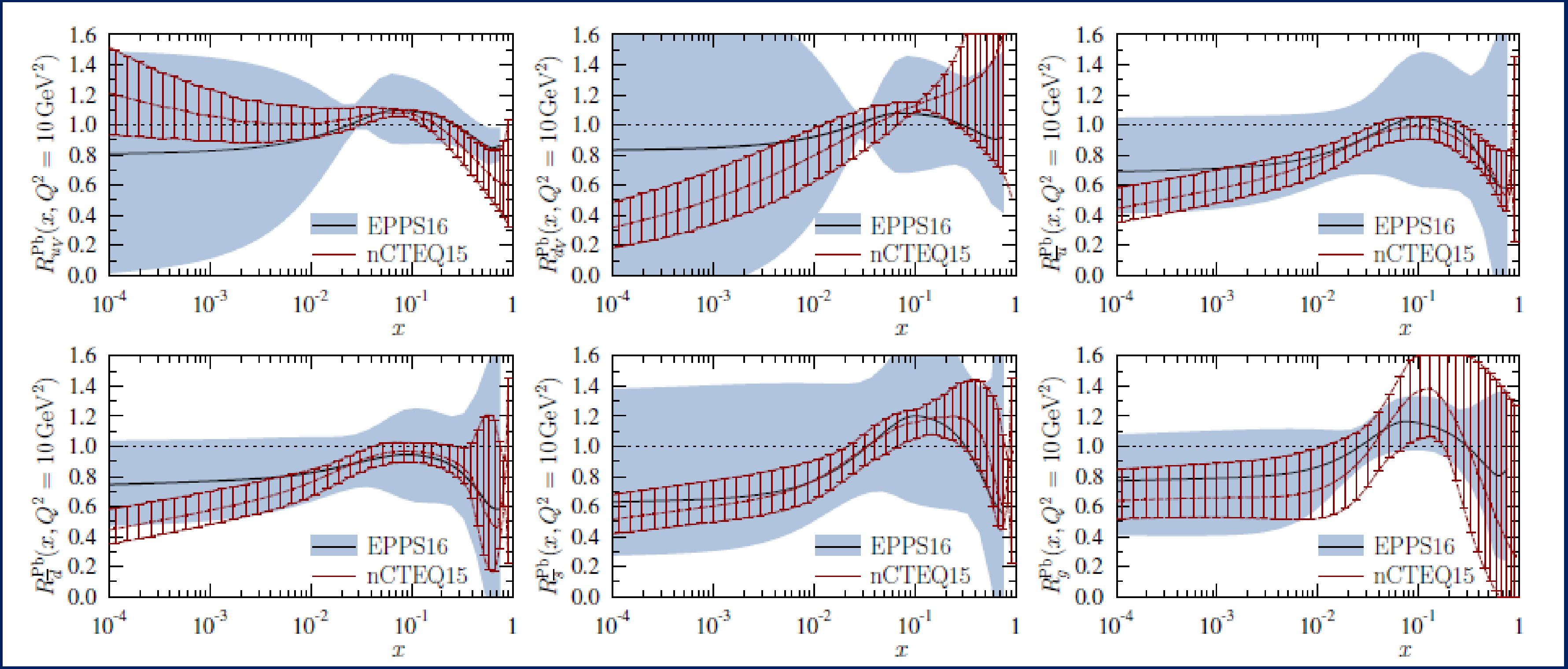


EPPS16 – EPJ C77, 163 (2017)

*Still lots to learn about partonic structure of nuclei!*

# *Summary: Lecture 1*

- Parton distribution functions have proven to be a very useful language to describe the quark-gluon structure of hadrons
  - Understanding proton structure
  - Making analytical cross section predictions within the framework of perturbative QCD
  - Input to Monte Carlo event generators
- Beyond collinear, unpolarized PDFs in the proton
  - spin-spin correlations in a polarized proton can be described by the helicity and transversity PDFs
  - transverse-momentum-dependent PDFs encode information on parton dynamics within the proton
  - nuclear PDFs describe modification of PDFs in nuclei with respect to free nucleons

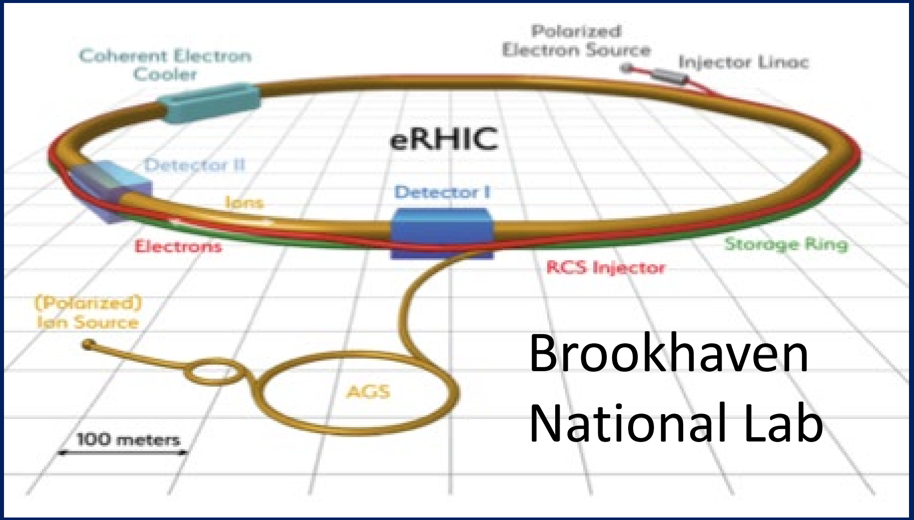
# *Extra*

# *Next-generation QCD facility: The Electron-Ion Collider*

Key science questions:

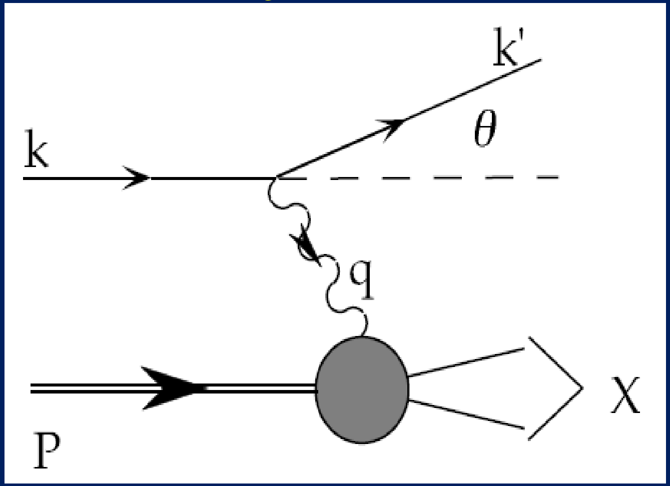
- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*

Project approval (“Critical Decision 0”) and site selection at Brookhaven National Lab announced Jan 9, 2020!



Brookhaven National Lab

# *Deep-inelastic lepton-nucleon scattering: A tool of the trade*



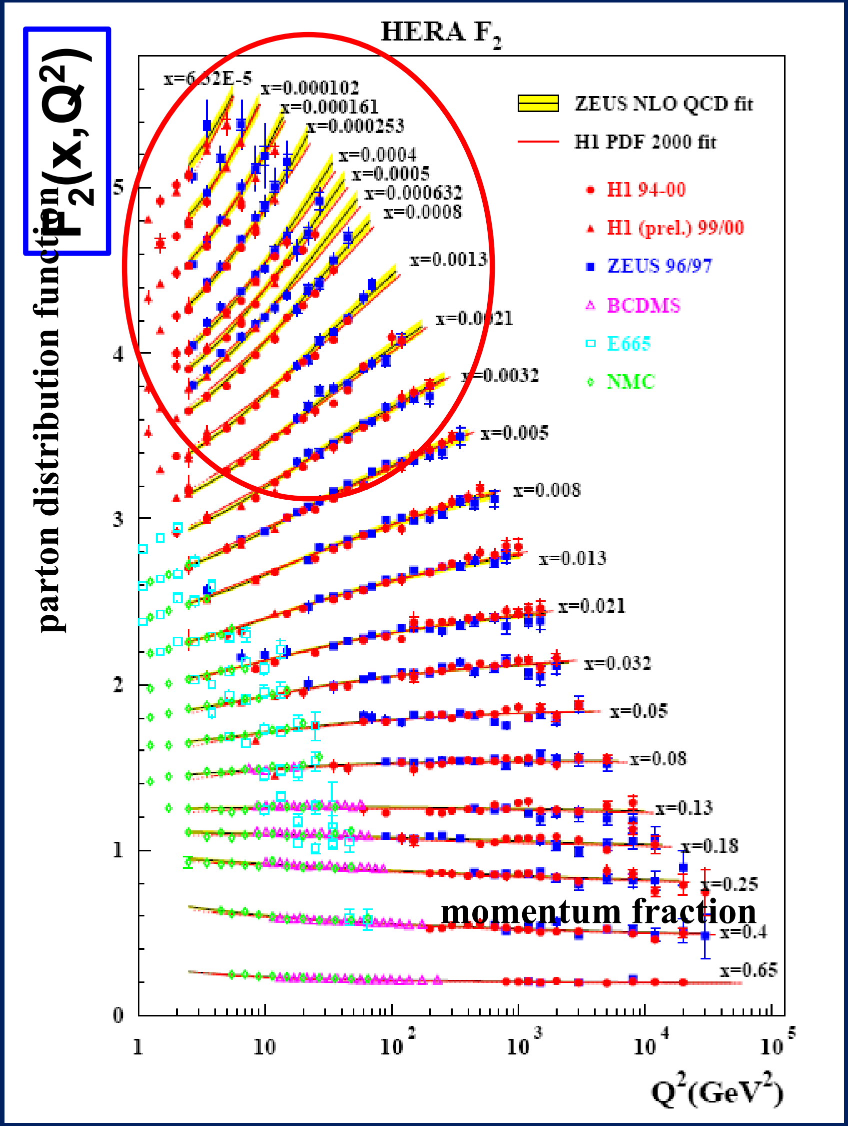
- Probe nucleon with an electron or muon beam
- Interacts electromagnetically with (charged) quarks and antiquarks
- "Clean" process theoretically—quantum electrodynamics well understood and easy to calculate!

# *Decades of DIS data: What have we learned?*

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\Bigg[\Bigg[\left(1-y+\frac{y^2}{2}\right)\boxed{F_2(x,Q^2)}-\frac{y^2}{2}F_L(x,Q^2)\Bigg]$$

- Wealth of data largely thanks to proton-electron collider, HERA, in Hamburg (1992-2007)

- Rich structure at low *x*
- Half proton's momentum carried by gluons!



$F_2(x,Q^2)$

parton distribution function

momentum fraction

# *What have we learned in terms of this picture by now?*

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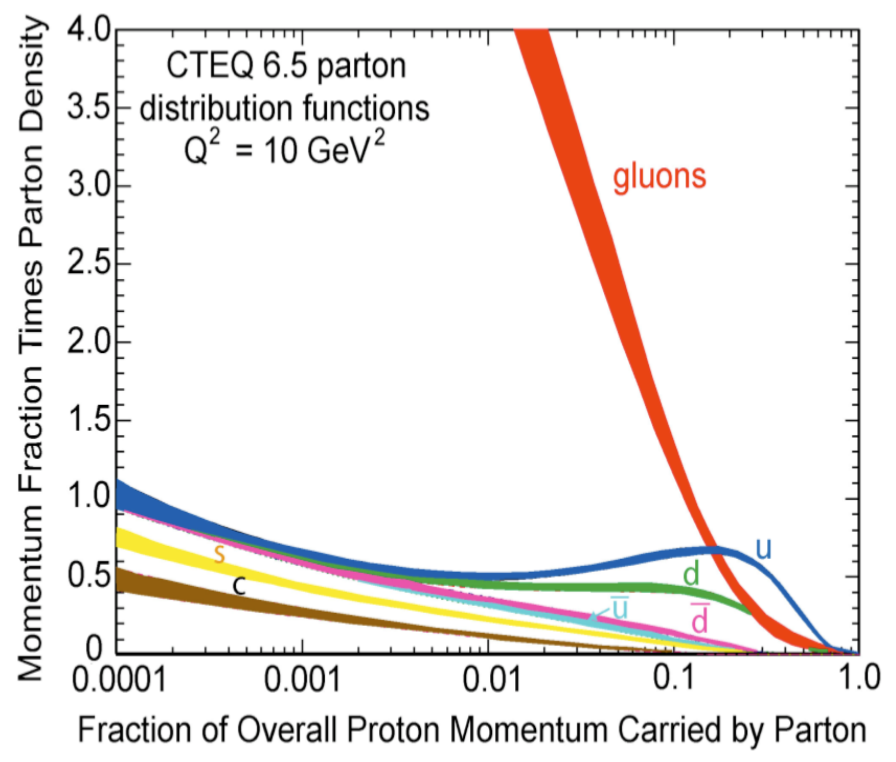
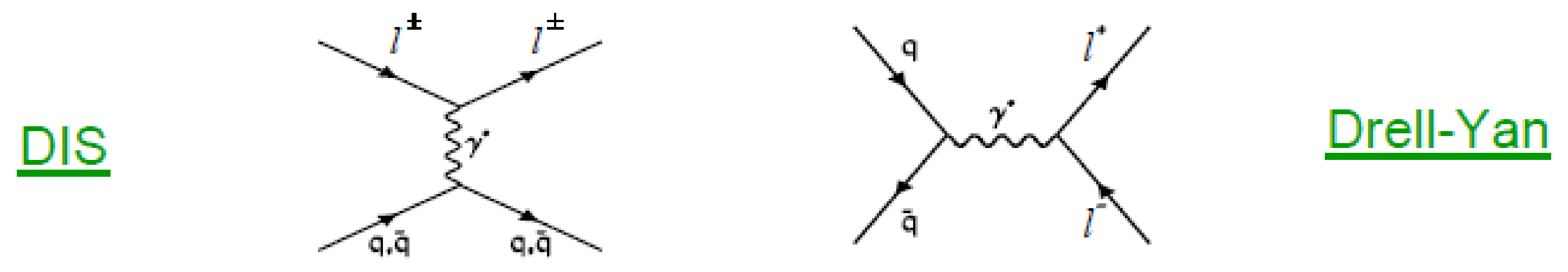
- Half proton's momentum carried by gluons!



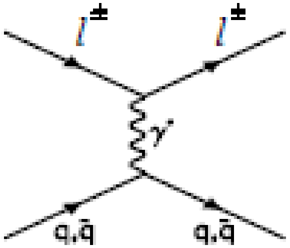
# *Complementarity of Drell-Yan and DIS*

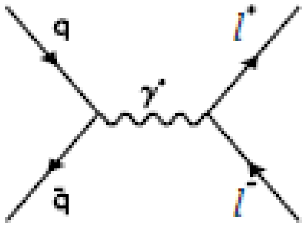


- Both deep-inelastic lepton-nucleon scattering (DIS) and quark-antiquark annihilation to leptons (Drell-Yan process) are tools to probe the quark and antiquark structure of hadrons

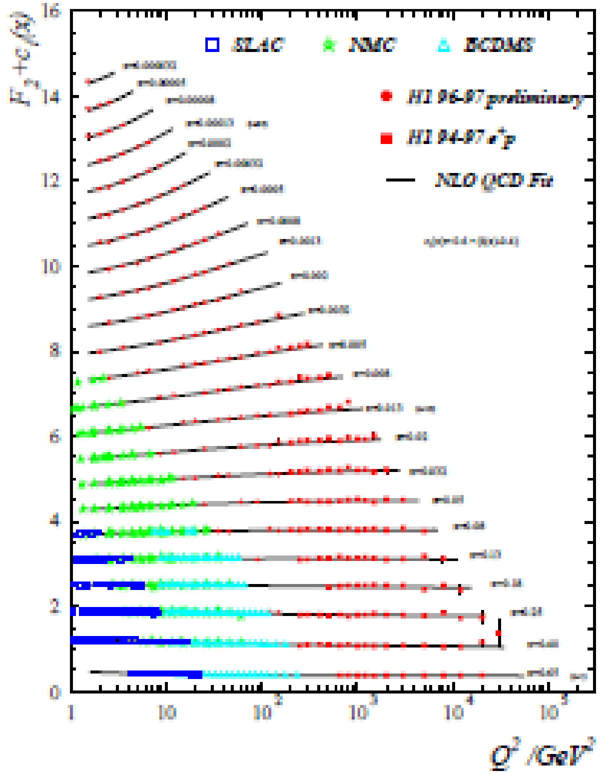
# *Drell-Yan complementary to DIS*

DIS

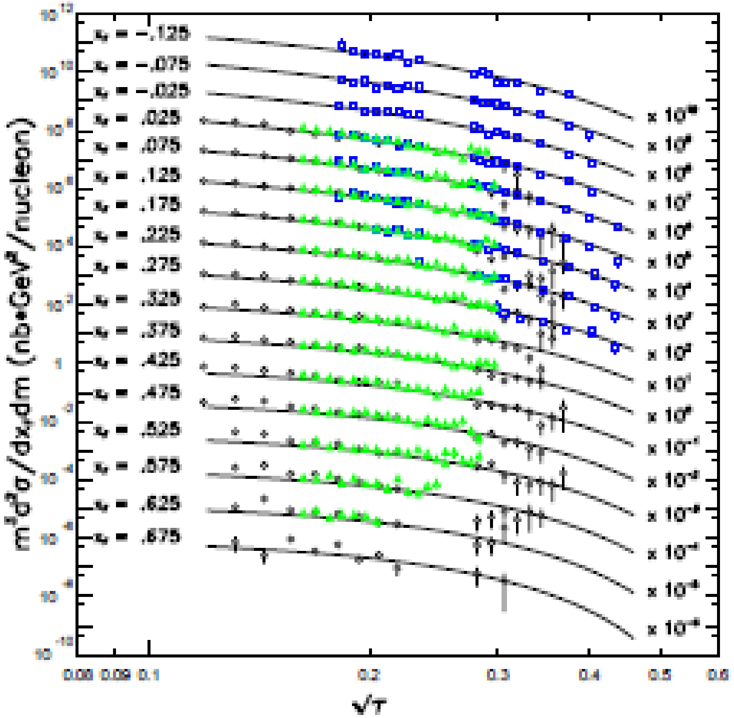




Drell-Yan



p A → $\mu^+\mu^-$ X

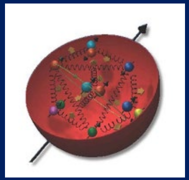


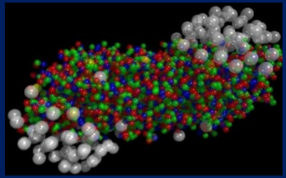
McGaughey, Moss, JCP,

Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

# *The Relativistic Heavy Ion Collider at Brookhaven National Laboratory*

- A great place to be to study QCD
- A collider-based program, but not designed to be at the energy (or intensity) frontier. More closely analogous to many areas of condensed matter research—create a system and study its properties
- What systems are we studying?
  - "Simple" QCD bound states—the proton is the simplest stable bound state in QCD (and conveniently, nature has already created it for us!)
  - Collections of QCD bound states (nuclei, also available out of the box!)
  - QCD deconfined! (quark-gluon plasma, some assembly required!)





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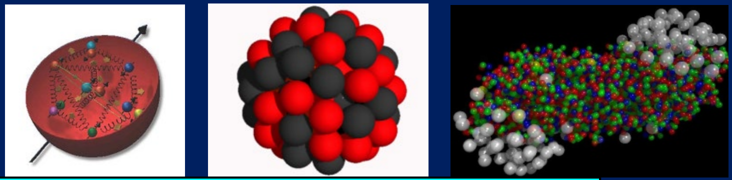
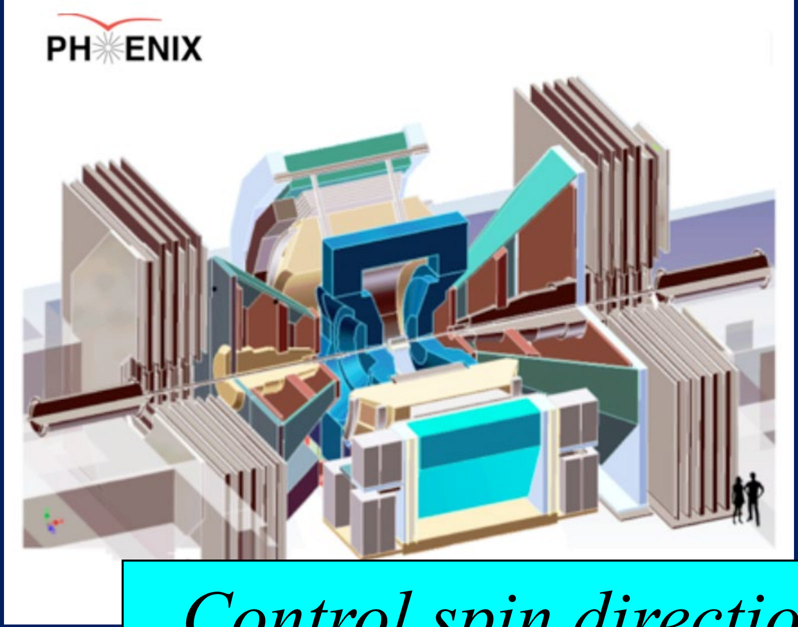


  - able

***Polarized** proton beams colliding at center-of-mass energies 62-510 GeV. Running 2001-present*

  - t of
  - QCD deconfined! (quark-gluon plasma, some assembly required!)

# *RHIC's current main experiments*



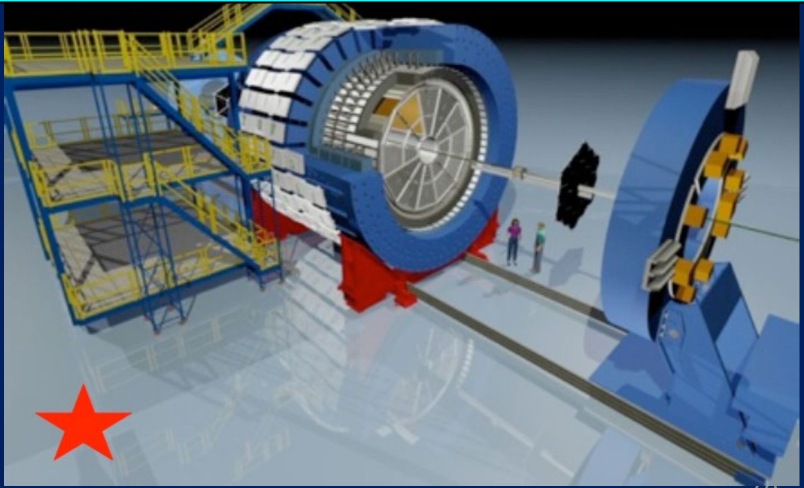
PHENIX:

- High resolution; high rate capabilities for rare probes
- Central arms $|\eta|<0.35$, $\Delta\phi\sim2\pi$ with key strength measuring EM probes
- Muon arms $1.2<|\eta|<2.4$
- Forward EM calorimetry

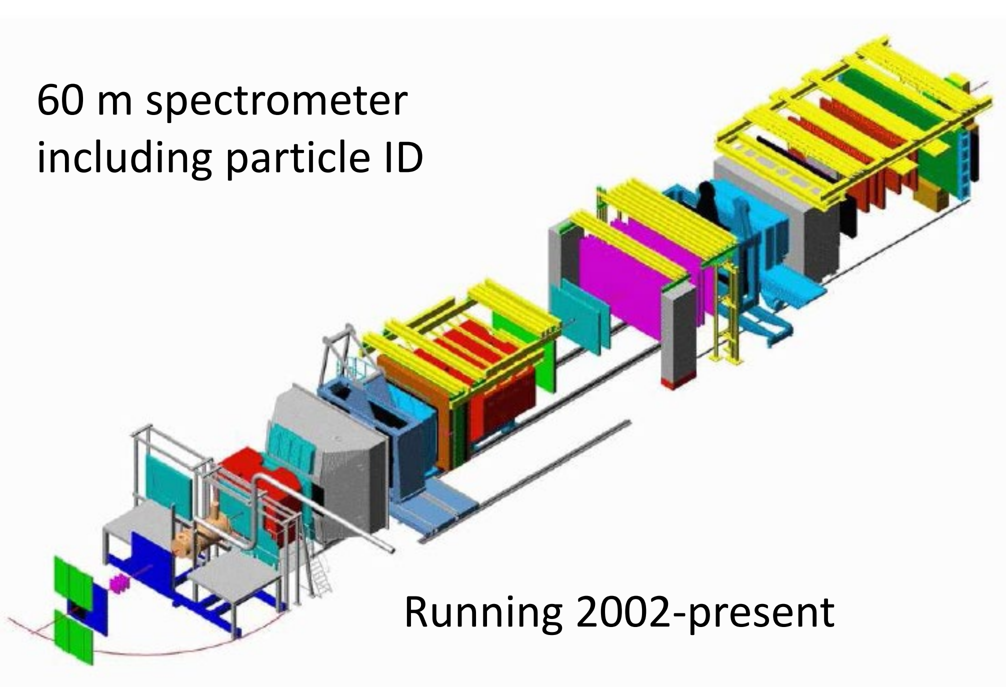
*Control spin direction of proton beams independently*

STAR:

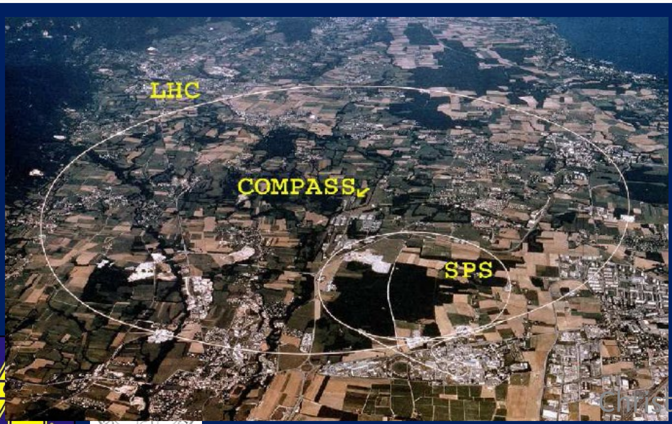
- Key strengths jets + correlations
- Full acceptance including PID for $|\eta|< 1$, $\Delta\phi\sim2\pi$
- Forward EM calorimetry



# *COMPASS at CERN:*
# *Muon/Pion scattering off of fixed targets*

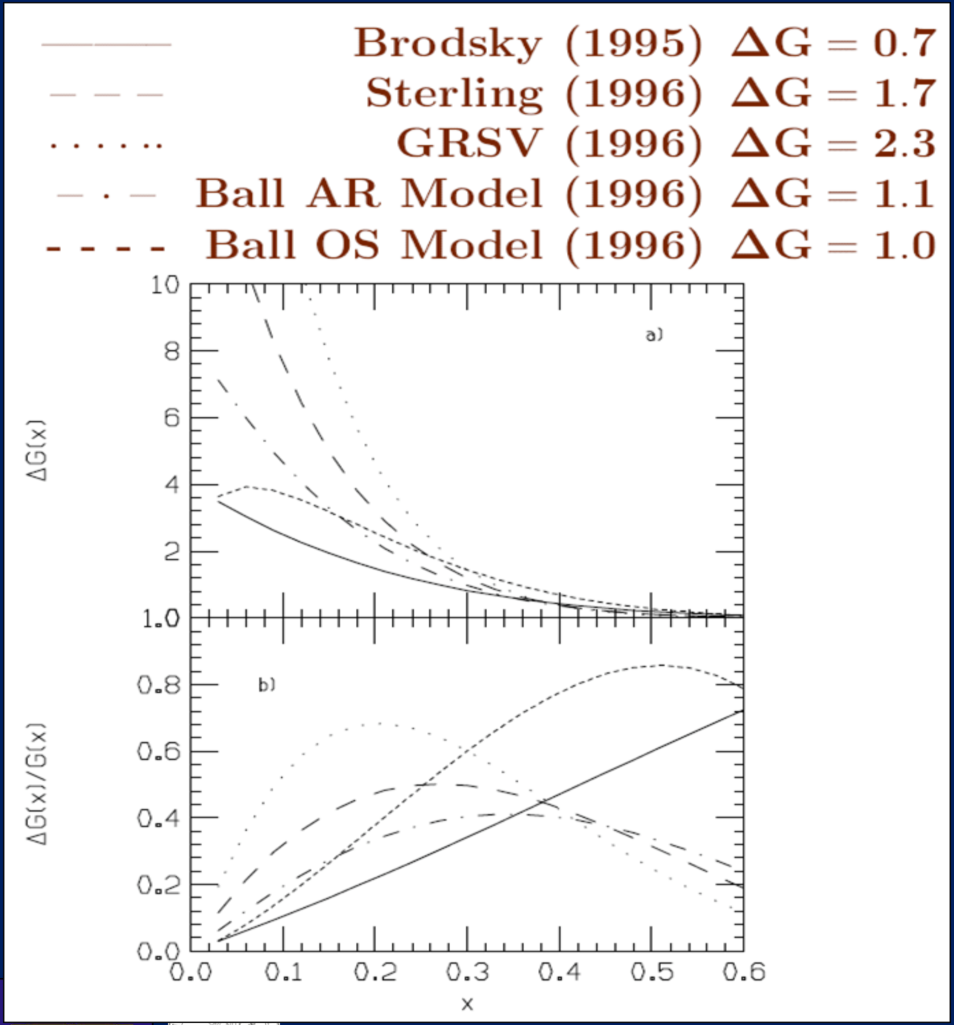

60 m spectrometer
including particle ID

Running 2002-present



- Nucleon structure and hadron spectroscopy
- Polarized muon beam, unpolarized negative pion beam, 160-200 GeV/c
- Polarized $^6$LiD and NH$_3$ targets (polarized deuterons and protons)

# *Quest for ΔG, gluon spin contribution to spin of proton*

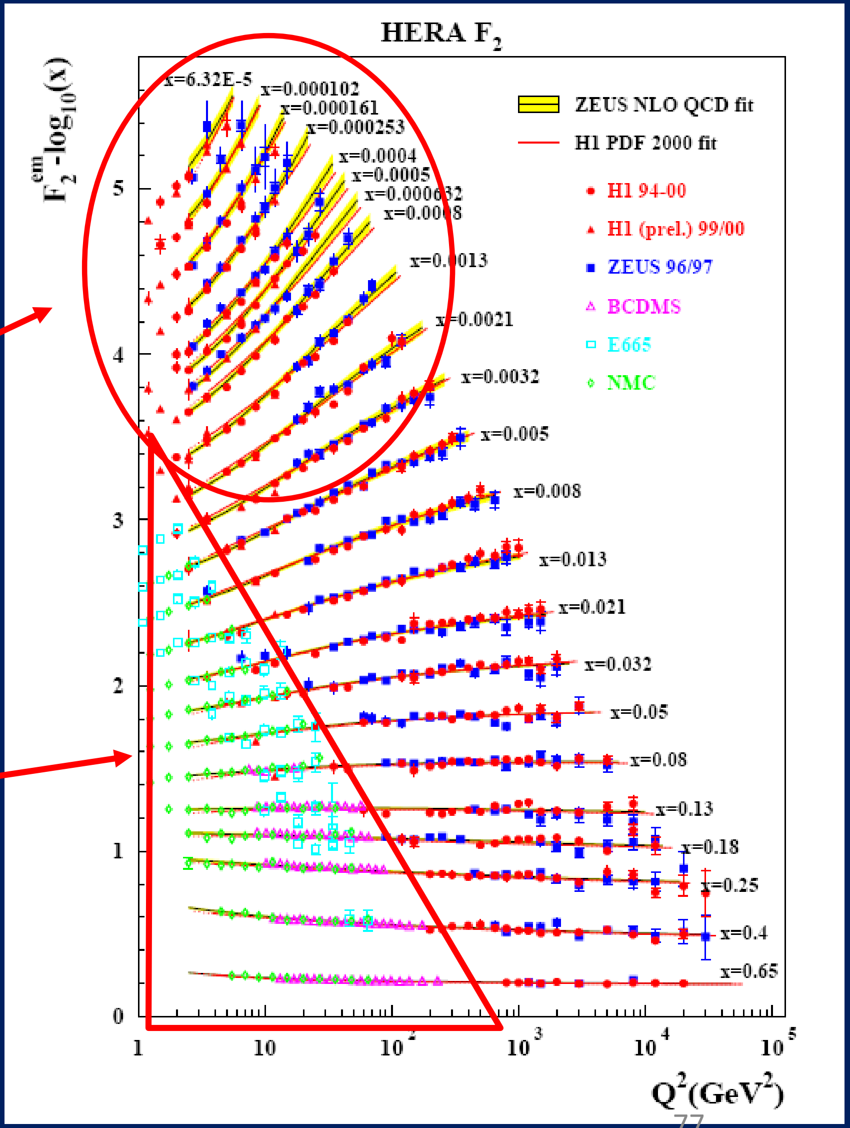


- In mid-1990s predictions for the integrated gluon spin contribution to proton spin ranged from 0.7 – 2.3!
  - Many models hypothesized large gluon spin contributions to screen the quark spin, but these would then require large orbital angular momentum in the opposite direction

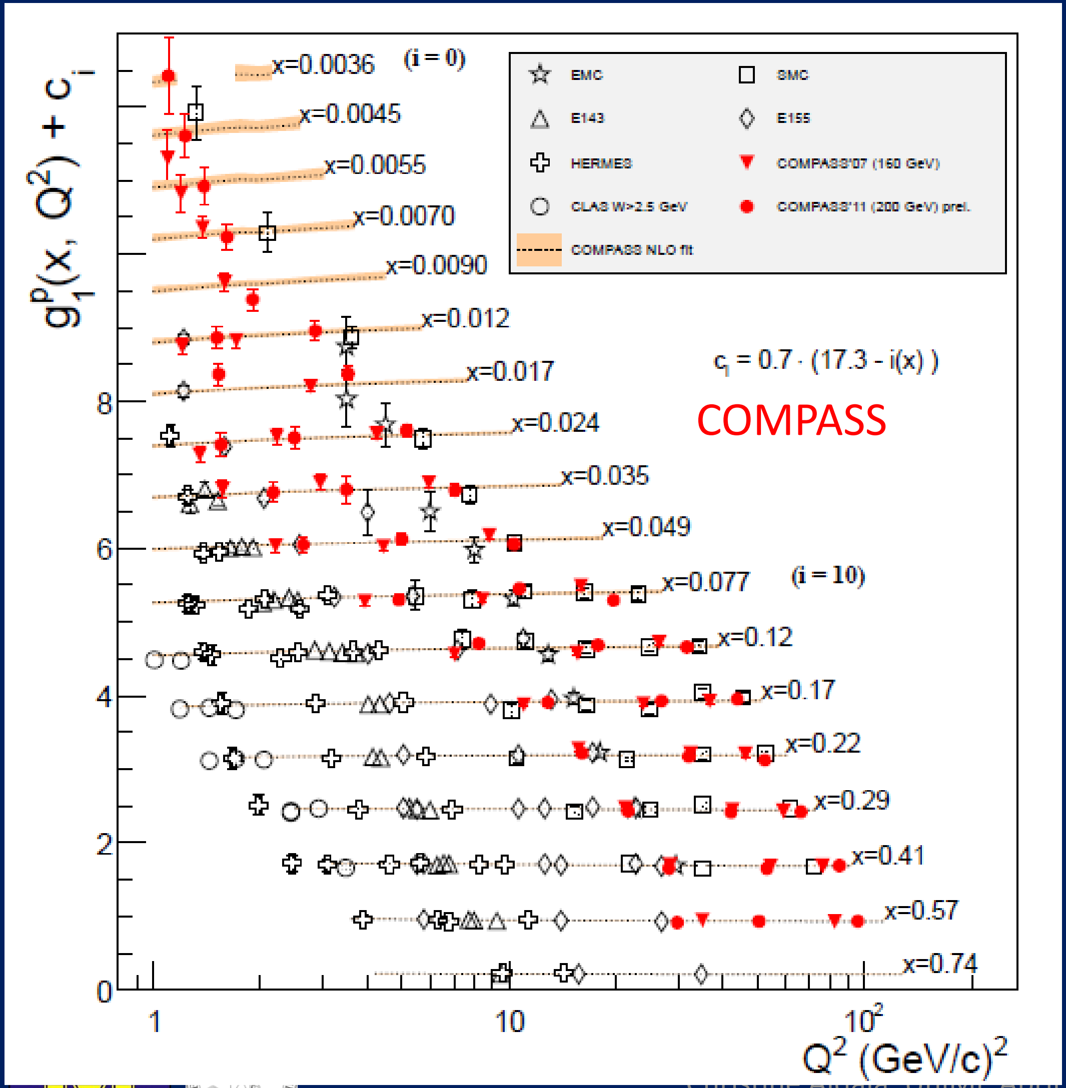
# *Unpolarized proton structure from deep-inelastic lepton-proton scattering*

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$

- Wealth of data largely from HERA e+p collider
- Rich structure at low *x*
- Half proton’s linear momentum carried by gluons!
- Kinematic coverage of polarized experiments much smaller



# *World data on longitudinally polarized proton structure function*



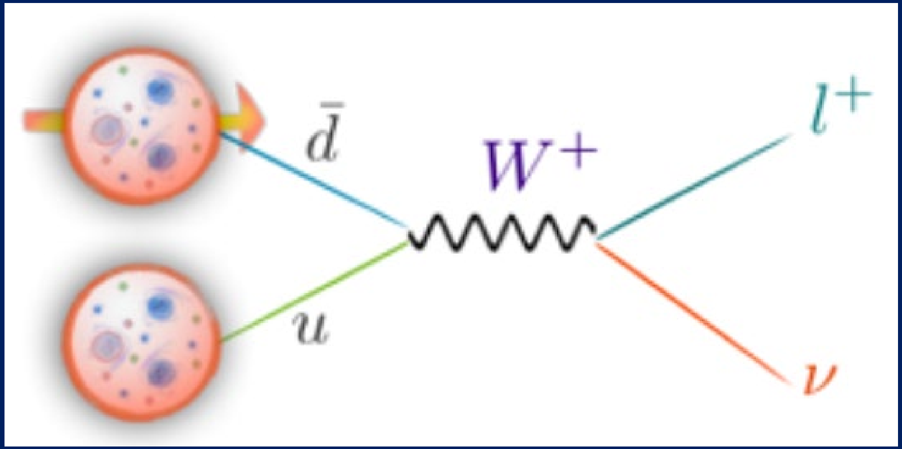
$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \boxed{\Delta G} + \boxed{L_{G+q}}$$

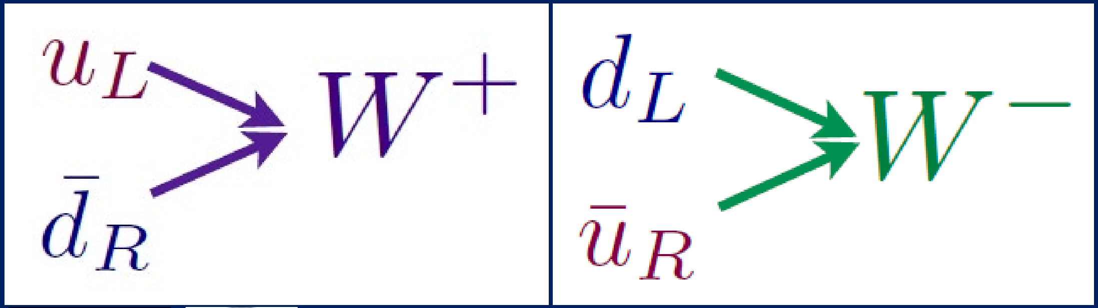
# Flavor-separated sea quark helicities through W production

$$\Delta q(x), \Delta\bar{q}(x)$$

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)}$$





Parity violation of weak interaction + control over proton spin orientation gives access to *flavor*-spin structure of proton

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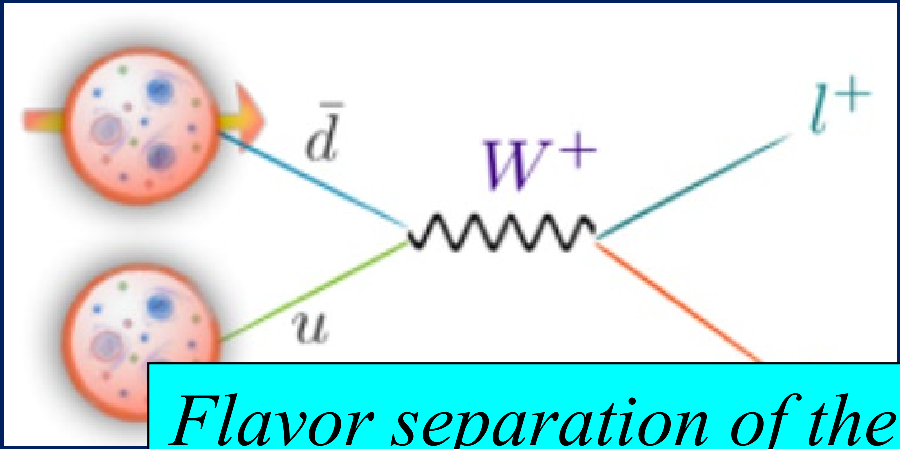

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Parity violation of weak
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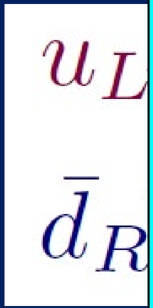
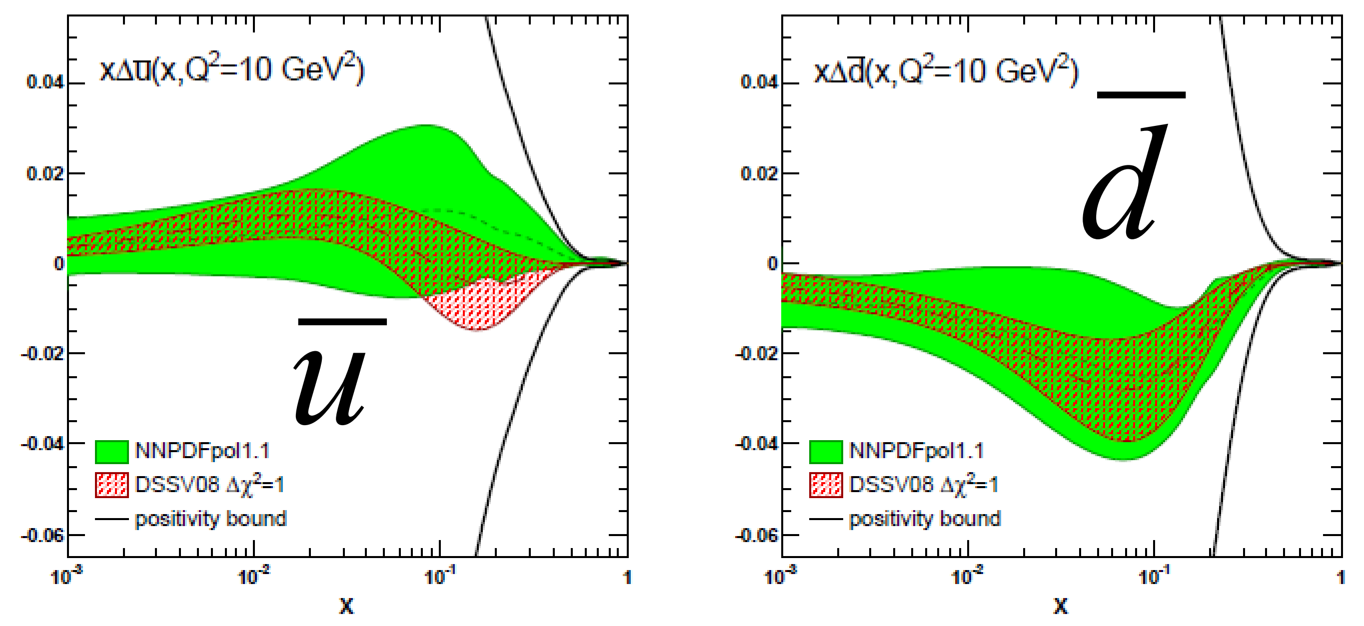


*Flavor separation of the polarized sea quarks with* ***no reliance on fragmentation functions,*** *and at* ***much higher scale*** *than previous fixed-target experiments.*

***Complementary*** *to semi-inclusive DIS measurements.*

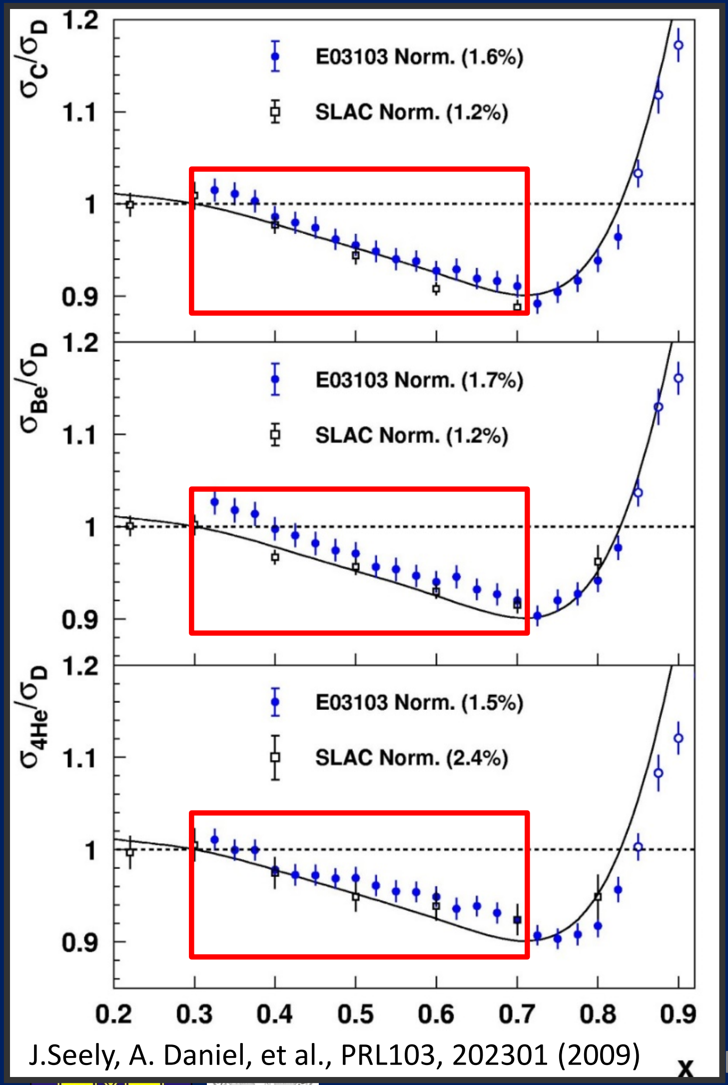
# *Flavor-separated sea quark helicities through W production*

**NNPDF, NPB 887, 276 (2014)**



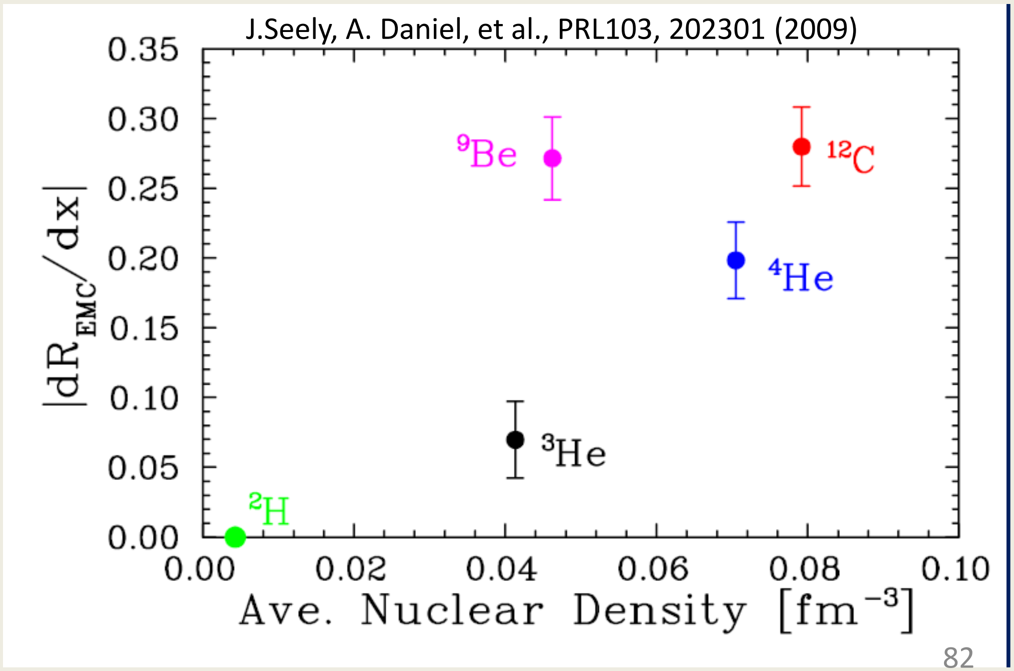
Includes RHIC W boson data:
Indication of SU(3) breaking in polarized quark sea (as in unpolarized sea)

# *Partonic momentum structure of nuclei: EMC effect and local density*



J.Seely, A. Daniel, et al., PRL103, 202301 (2009)

- Fit slope of ratios for $0.3<x<0.7$; compare across nuclei
- EMC slope doesn’t scale with A or with avg nuclear density…



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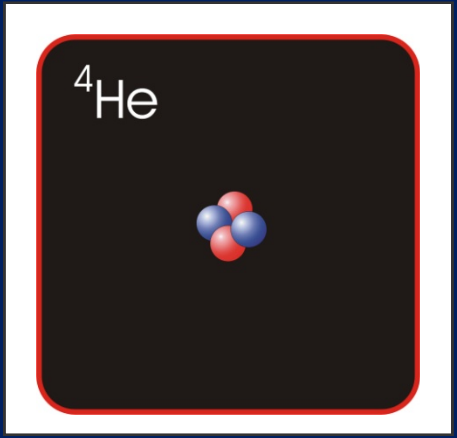
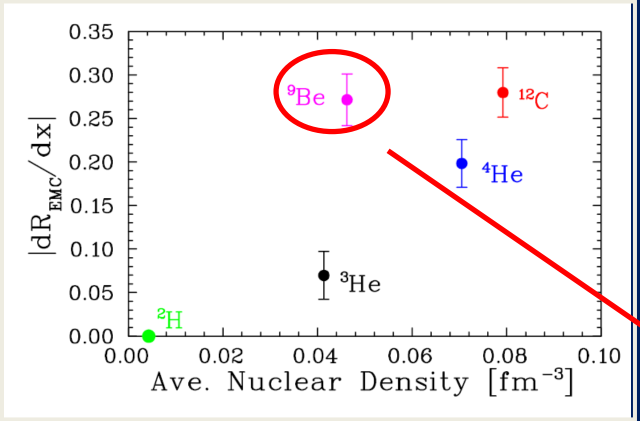
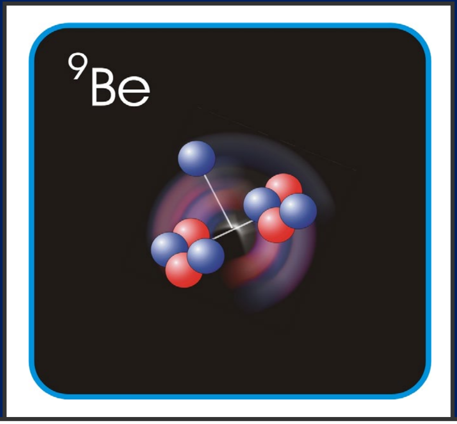


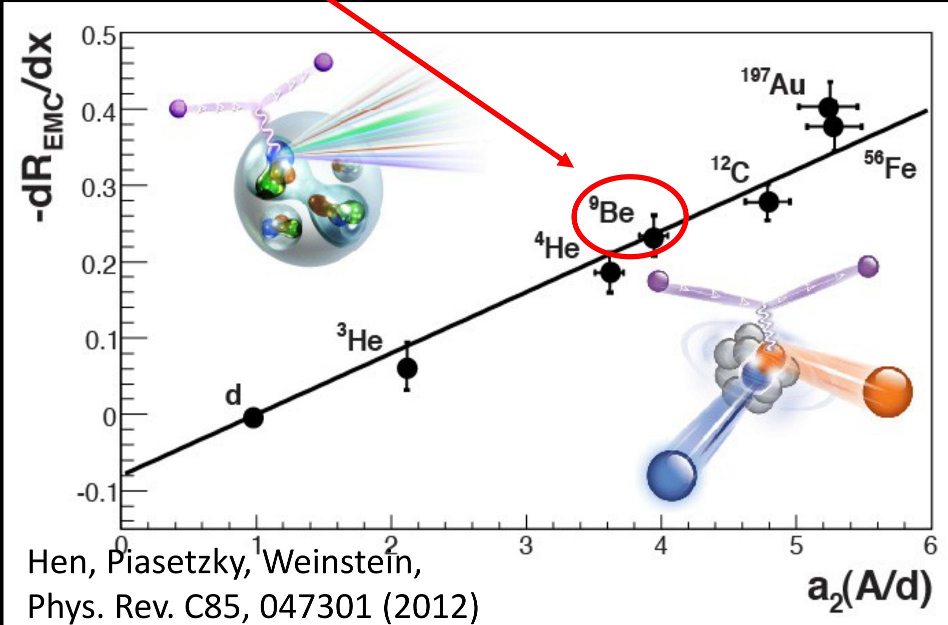


But appears to scale with local density!



Density determined from *ab initio* few-body calculation

*S.C. Pieper and R.B. Wiringa,*
*Ann. Rev. Nucl. Part. Sci 51, 53 (2001)*



Hen, Piasetzky, Weinstein,
Phys. Rev. C85, 047301 (2012)

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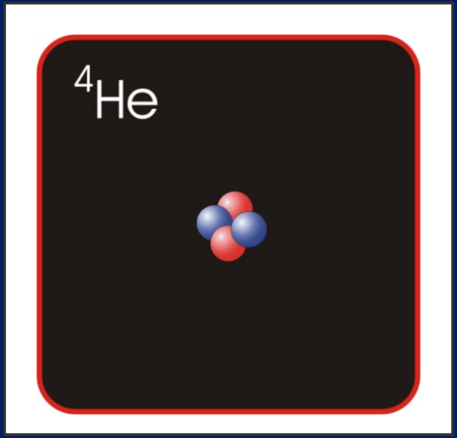

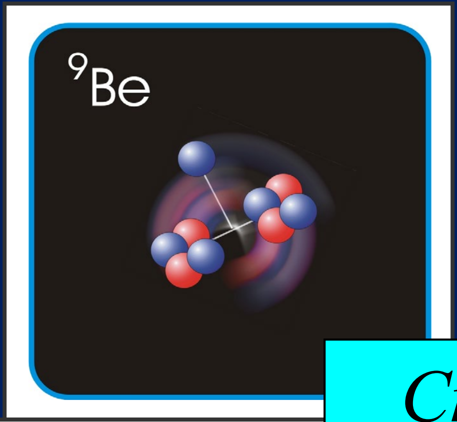

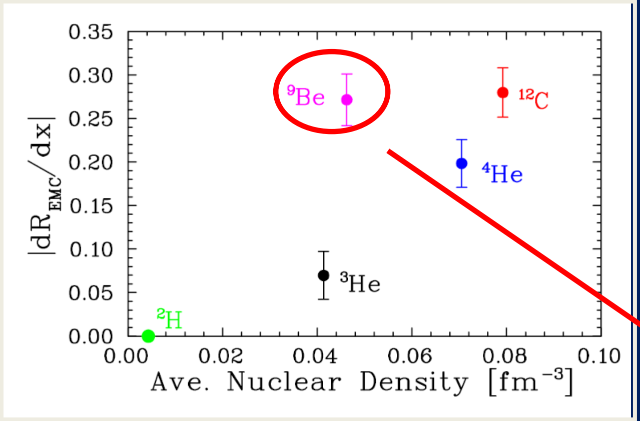

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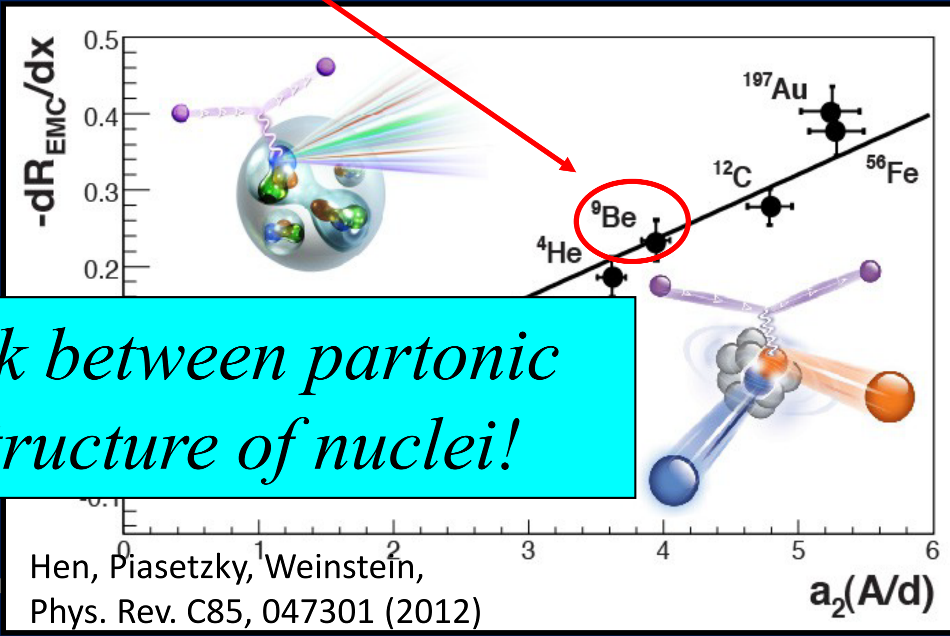

Hen, Piasetzky, Weinstein,
Phys. Rev. C85, 047301 (2012)

*Critical direct link between partonic and nucleonic structure of nuclei!*

Density determine
body calculation
*S.C. Pieper and R.B. Wiringa,*
*Ann. Rev. Nucl. Part. Sci 51, 53 (2001)*