Slide 1:

* Introduction

Slide 2:

* Before the late 20th century proton was a fundamental spin-1/2 fermion
* No experiment had high enough power to interact with quark substructure directly

Slide 3:

* Earlier in the course we saw development of quark model of hadrons to describe big sea of new particles being discovered
  + Bjorken, Drell, Gell-Mann, Feynman develop parton model of proton to describe baryonic and particularly nucleonic matter
* At SLAC in late 1960s, crank up energy to increase spatial resolution and interact directly with quarks to confirm their existence
* At this point, the picture of the proton is slightly messier, but if it’s in its S-wave state then all its spin its attributable the valence quark spin
  + Proton is defined to be this state (no real physics here: just packaging the characteristics of a particle into one definition)

Slide 4:

* Modern accelerators and colliders: crank up the energy and observe a chaotic soup of quarks and gluons
* This is a messy picture now
* Nontrivial spin problem: how do we always stay on the spin-1/2 budget in every reference frame, all scales with valence quarks, gluons, and sea quark-antiquark pairs
  + And so begins the proton spin crisis

Slide 5:

* Deep-inelastic scattering: separate leptonic and hadronic parts
  + Leptonic part: worked out spin average but full expression not too bad to generalize
  + Hadronic part: inclusive – sum over unobserved final states and parameterize ignorance using current conservation, symmetry arguments, and Lorentz covariance
    - Have unpolarized and polarized structure functions (g1 is the “longitudinal” scaling spin structure function – observe by assuming proton is longitudinally polarized so S = lambda P)

Slide 6:

* Factorization formalism at high energy so that in specific reference frame we can write momentum fraction probability distributions that weight the partonic matrix elements with how likely it is that a parton with momentum xi interacts with photon
  + Polarized PDFs are a little more nuanced: helicity dependent distributions (asymmetry between right and left handed polarizations)
* Some unpolarized PDFs are shown

Slide 7:

* There are some facts that have to be recovered – properties of the proton (total momentum, valence quarks, charge, etc.)

Slide 8:

* There are some more subtle sum rules a bit complicated to work out
  + Note: these are model-dependent and subtle because they are dependent on physical quantities in more complex ways than the previous ones
* But some very smart people have done so: one of the most well-known is the Ellis-Jaffe sum rule
  + Related to total polarization of up and down quarks inside proton
  + Related to nucleon axial couplings which are scale-independent and determined through beta/hyperon decays
  + Original expression from EJ did not depend on strong coupling
    - These are first order QCD corrections
  + Plugging in the couplings we obtain a value for the integral over the g1 structure function in the naïve parton model (only valence contributes significantly)

Slide 9:

* In the 1970s-80s, European Muon Collaboration did deep inelastic scattering experiments with muons at CERN
* At end of ‘80s, did polarized DIS experiments for muon proton scattering and set out to test quark model
  + Had ability to polarize beam and targets so measured double longitudinal spin asymmetry which is related to g1 (unpolarized structure functions already known)
  + Once asymmetry known can extract g1

Slide 10:

* Essential findings: the naïve parton model fails miserably to describe why the proton has spin-1/2
  + The EJ sum rule with its corrections is wrong – the predicted quark spin contribution is consistent with 1 but the experimentally determined quark spin contribution is consistent with zero
  + Furthermore, found that the strange sea is sizably and negatively polarized (EJ assumed that the strange sea is unpolarized)
  + Do we even understand the proton? Well apparently not!

Slide 11:

* Later experiments by other collaborations at different facilities internationally find the same thing: the quark spin contribution is a lot smaller than we originally expected
  + Large kinematic phase space (the sum rule fails at all scales)
  + Also did it with neutrons (which are isospin conjugate to the proton) and found same violation of sum rule
  + Establishment of the proton spin crisis

Slide 12:

* How do we go forward?
* At this point: the quark spin contribution is precisely known
  + Only about 30% of the total proton spin
  + The decomposition into up, down, and strange is still in question (especially the strange polarization question – how sizable and with what sign?)
* This also means that the gluons spin and quark/gluon orbital angular momentum makes up the rest of the spin
  + We expect that the gluons hold most of this just because we expect that there is not much angular momentum in the proton system (from the definition of the proton)
* The gluon spin contribution is determined from the gluon helicity distribution function
* The angular momentum contribution is determined from generalized parton distribution functions – but these are still not very well understood and are mostly in their infancy

Slide 13:

* There is a lot of work being done to pin down the size of the gluon spin contribution
* Calculations on the lattice tell us that the gluon spin contribution is quite sizable: roughly 50% of the total proton spin – that would leave only 20% for orbital angular momentum
* Perturbative work has hit a bit of a roadblock though
  + Recent global QCD analyses have found that two gluon pPDFs are compatible with existing polarized scattering data
    - What does this mean: we don’t have a good theoretical value in perturbative regions for the gluon spin contribution?
    - Also: we need data that has sensitivity to the sign of the gluon helicity

Slide 14:

* Looking forward there is a lot of reason to be excited though about gluon polarization
* At JLab, there is talk of upgrading the energy of the electron beam
* And at brookhaven, the construction of the EIC will give unprecedented access to studying polarized scattering processes and elucidating nucleonic structure including the spin structure
  + Figure shows kinematic phase space access

Slide 15:

* Recap
* Questions, comments