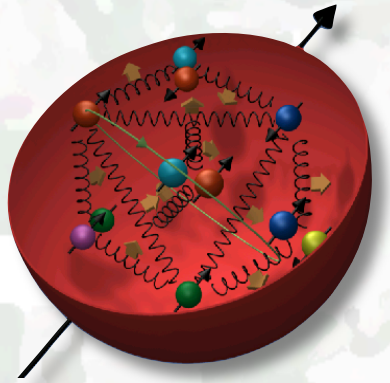
Fundamental measurements of the proton's sub-structure using high-energy polarized p-p collisions

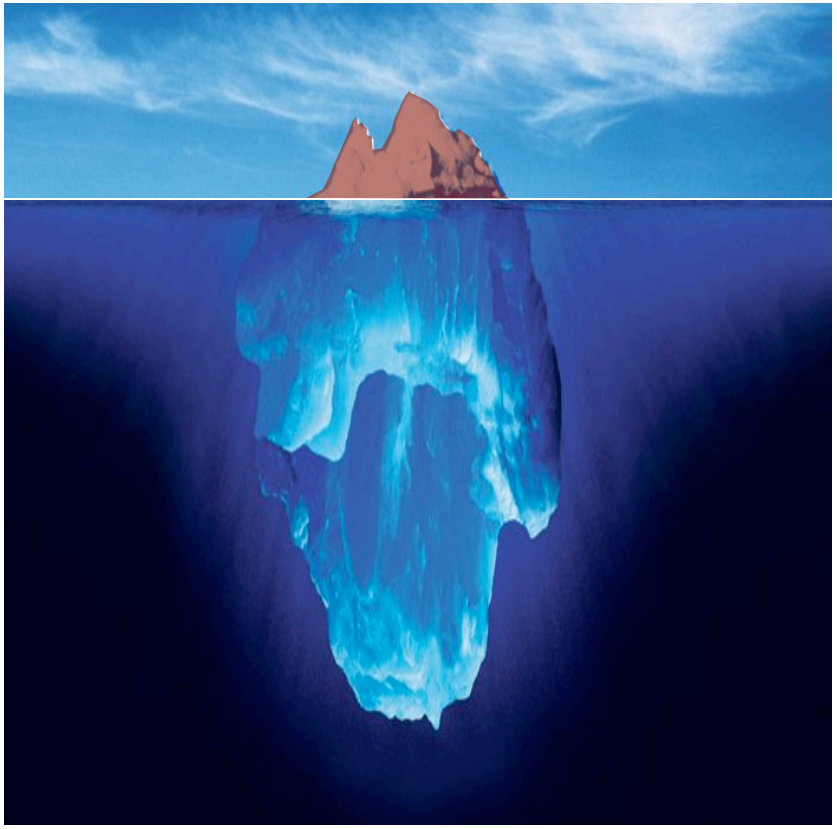
Bernd Surrow

TEMPLE UNIVERSITY

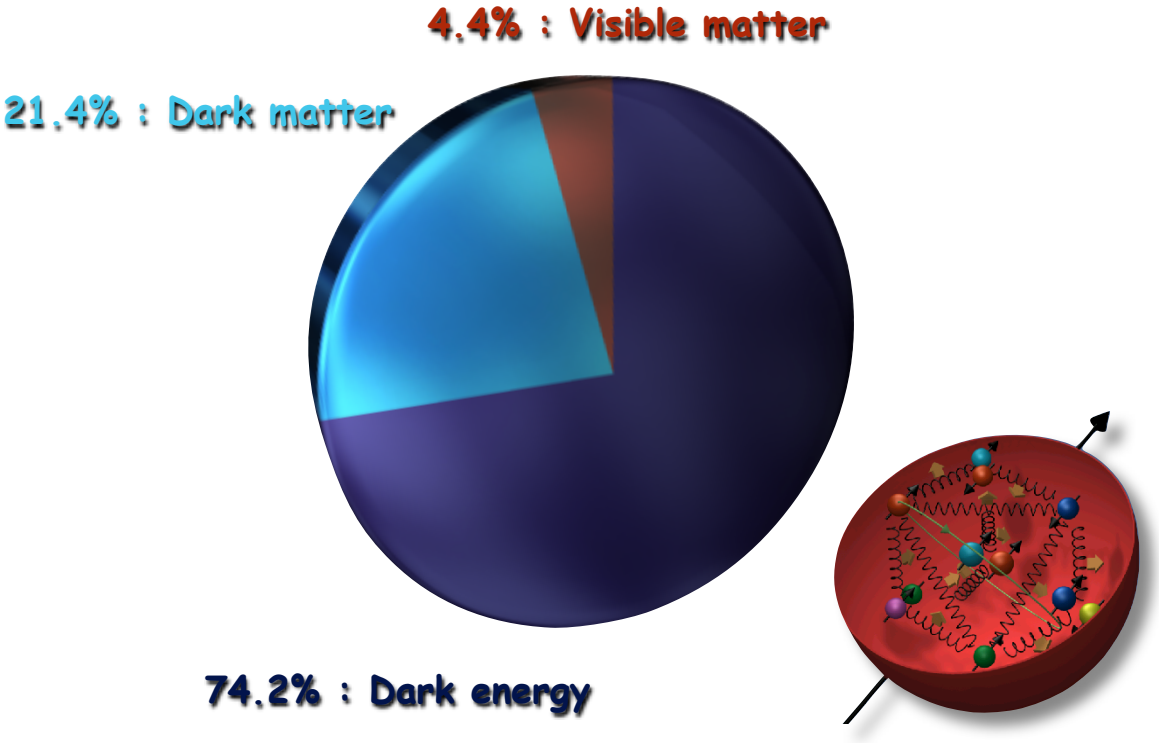


Introduction

- What makes up the world around us?

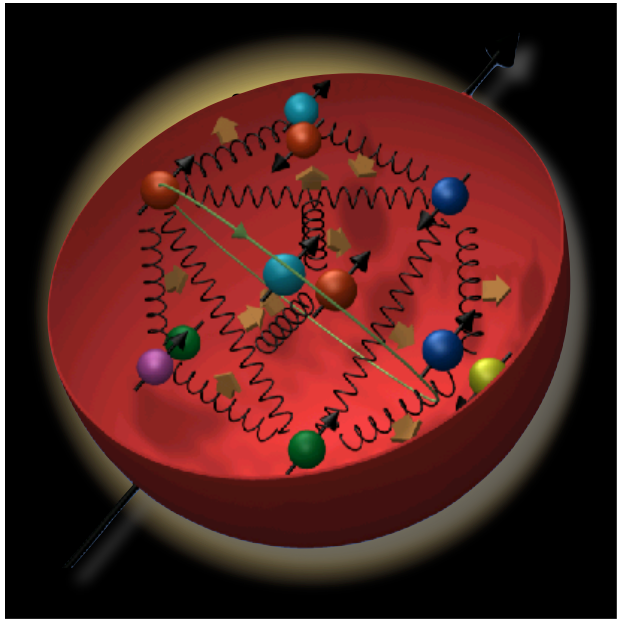


Data from Wilkinson Microwave Anisotropy Probe (**WMAP**) satellite - Full-sky observation of cosmic microwave background (**CMB**): D.N. Spergel et al., Astrophys. J. Suppl. 170 (2007) 377.



Introduction

- Force carriers (Fields) and matter constituents within the Standard Model



BOSONS — force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

FERMIONS — matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

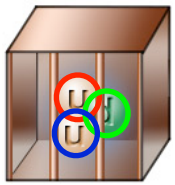
Proton mass: ~ 1GeV

- m_u ~ 3MeV
- m_d ~ 6MeV
- m_g = 0
- Proton mass arises predominantly from interactions / energy

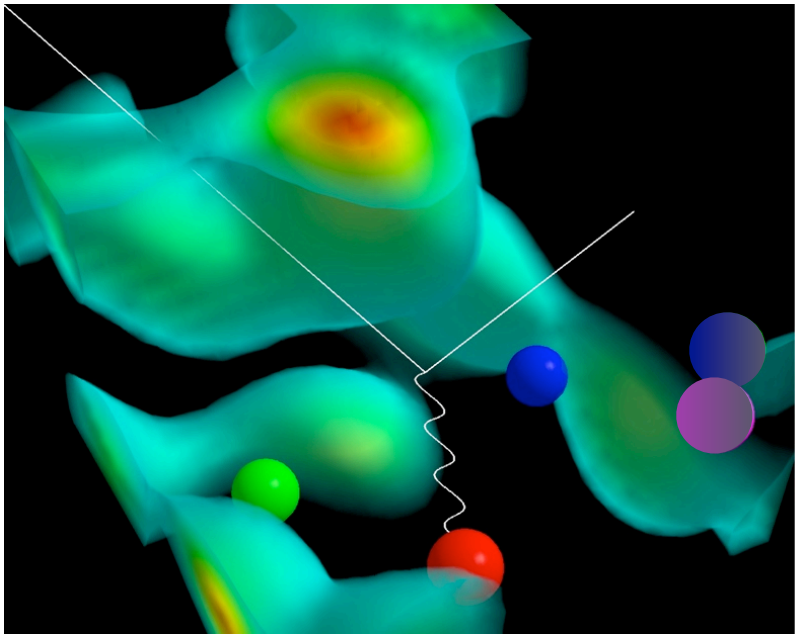
Proton spin: 1/2

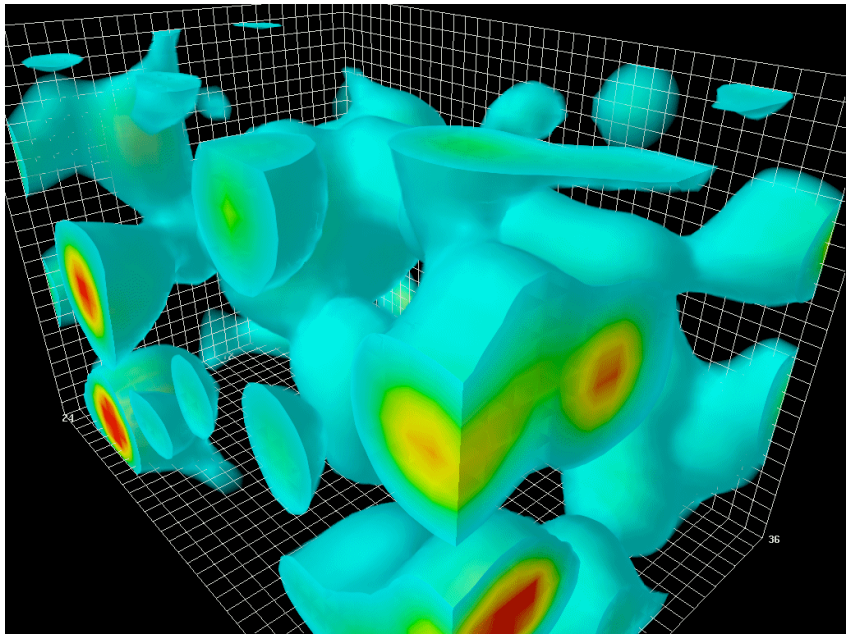
Introduction

- Strong Interactions



Proton=uud

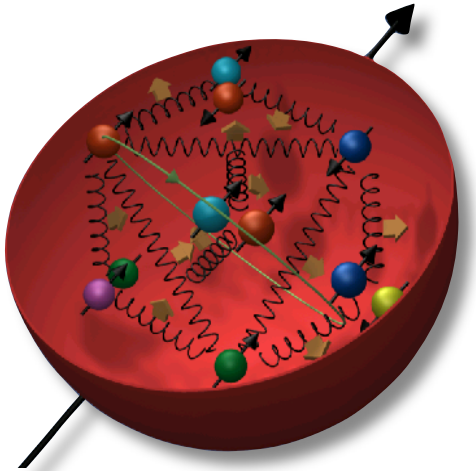




(D. Leinweber: Action (~energy) density fluctuations of gluon-fields in QCD vacuum)

Visible Universe

Consists of….:



Protons & **Neutrons**

3 valence quarks +…

Silent Partners:

Virtual quark-antiquark pairs (QCD sea) ($\Delta E\, \Delta t \sim h$)

Gluons!

Introduction

- Mass in QCD
  - Quote from Nobel prize lecture in physics, 2004, given by Frank Wilczek:

Stated as $m=E/c^2$: Possibility of explaining mass in terms of energy.

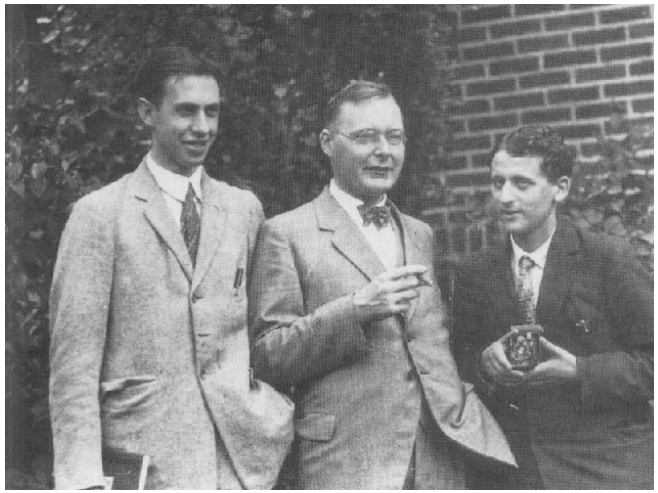
Einstein's original paper does not contain the equation $E=mc^2$, but rather $m=E/c^2$:

"Does the Inertia of a Body Depend Upon its Energy Content? "(A. Einstein, Annalen der Physik, 18 (1905) 639.)"

Modern QCD answers Einstein's question with a resounding "Yes!". Indeed, the mass of ordinary matter derives almost entirely from energy - the energy of massless gluons and nearly massless quarks, which are the ingredients from which protons, neutrons, and atomic nuclei are made.

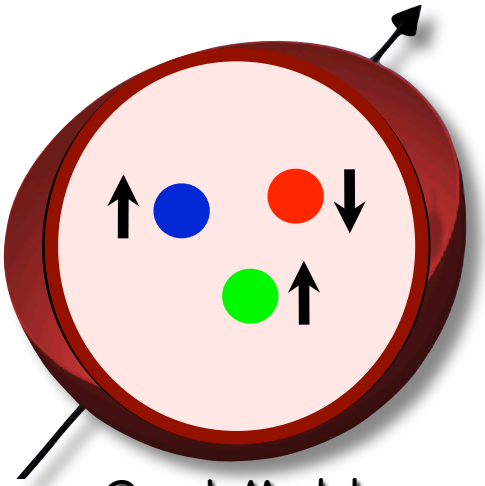
Introduction

Spin in QCD

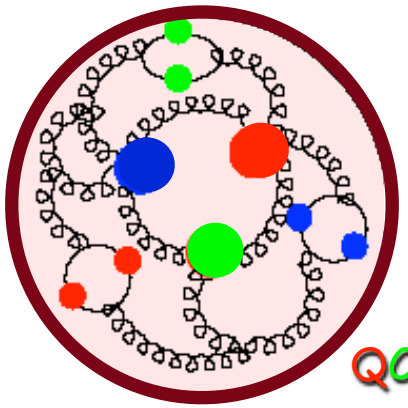


- Traditional way to introduce spin in QM textbooks: Stern-Gerlach experiment (1922)
- Concept of spin: Long and tedious battle to understand splitting patterns and separations in line spectra
- Anomalous magnetic moment of proton by Stern et al. (1933)

Proposal of self-rotating electron by Uhlenbeck and Goudsmit (1925)



Quark Model



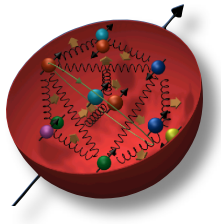
QCD (Spin... and Orbital motion)

Introduction

- Spin in everyday life

Paul C. Lauterbur

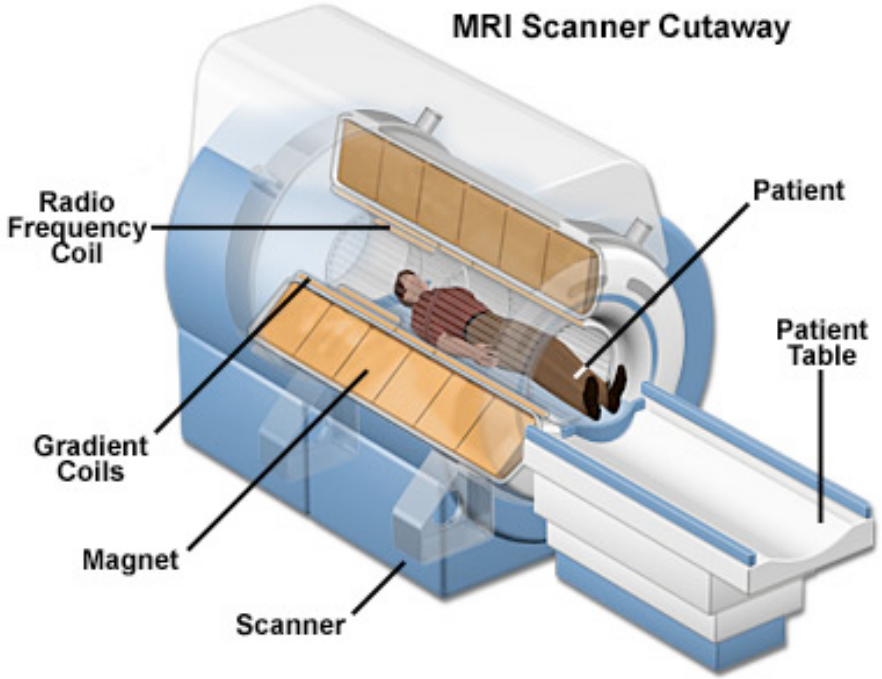
Sir Peter Mansfield

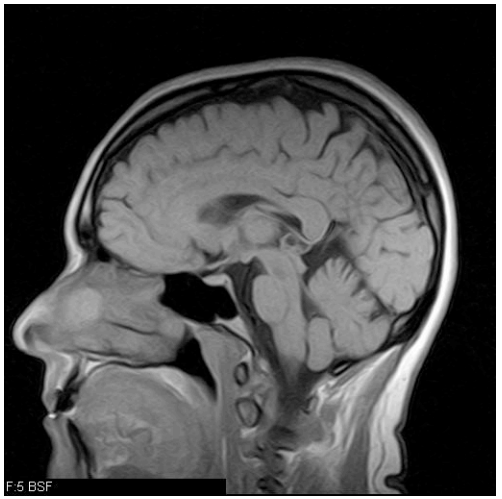


Proton spins are used to image the structure and function of the human body using the technique of Magnetic Resonance Imaging (MRI)

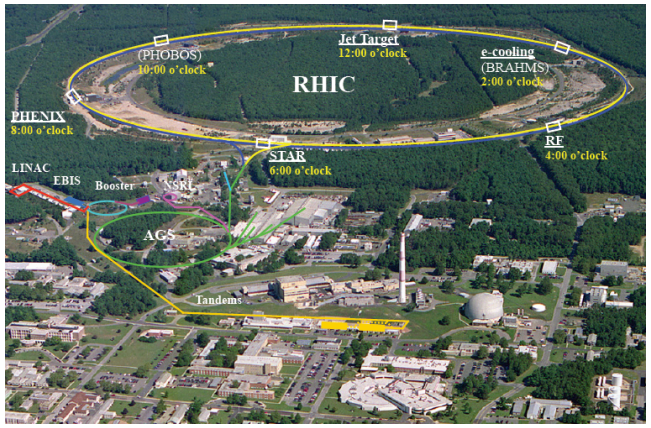
Nobel Prize Medicine 2003:

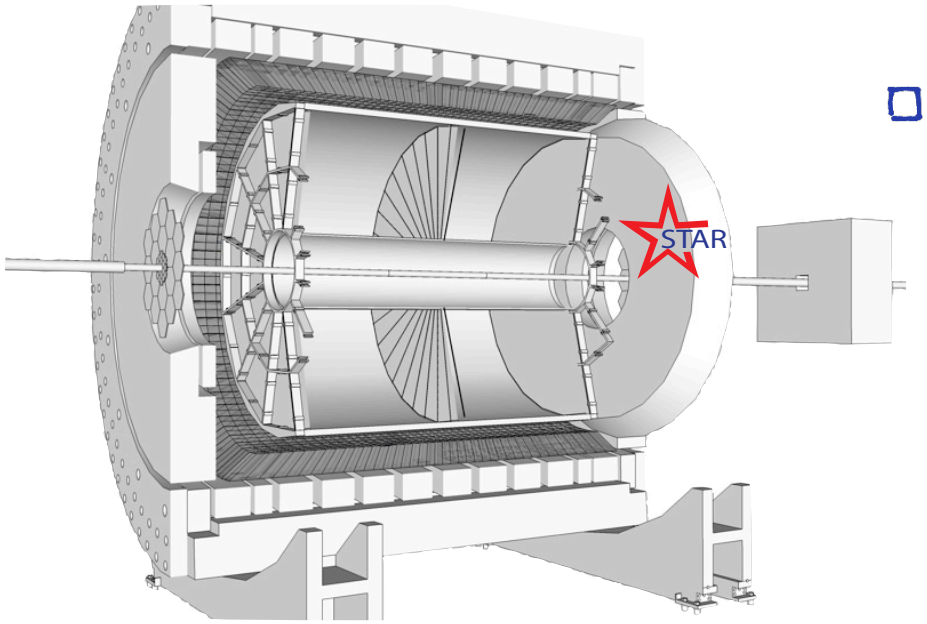
"for their discoveries concerning Magnetic Resonance Imaging"



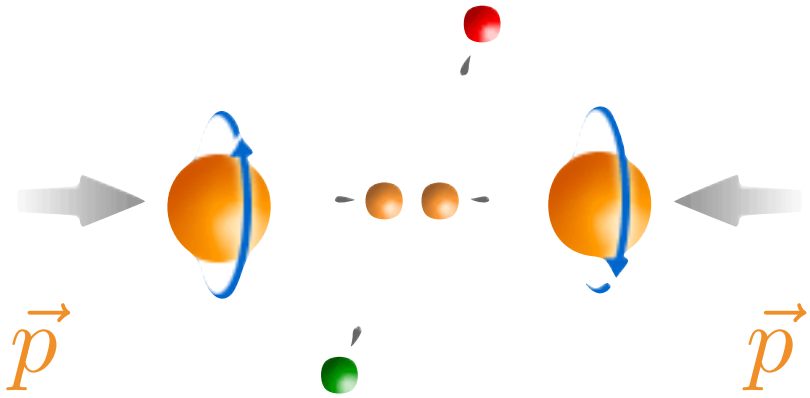


Outline

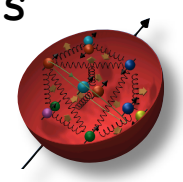




- Experimental aspects: RHIC / STAR
- Theoretical foundation



- Results

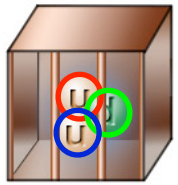


  - Gluon polarization
  - Quark polarization
- Summary and Outlook

Theoretical foundation

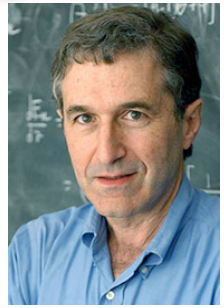
Quantum Chromodynamics - Basics

- Interactions arise from fundamental symmetry principles: $SU(3)_c$
- Visible universe (e.g. proton): Emergent through complex structure of the vacuum (e.g formation of hadrons from quarks/gluons)



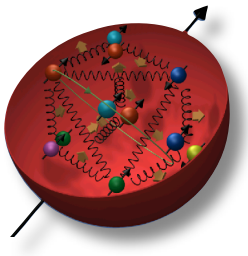
$$\mathcal{L}_{QCD} = \bar{q}\left(iD_\mu\gamma^\mu + m\right)q - \frac{1}{4}TrF_{\mu\nu}F^{\mu\nu}$$

- Atoms, molecules,...:
  - Interactions decrease at longer distances
  - Constituents can be removed
  - Most of mass from fermion constituents
- Nucleons:
  - Interactions decrease at shorter distances (Asymptotic freedom)
  - Quarks are confined (Confinement)
  - Most of mass generated by interactions (~99%)



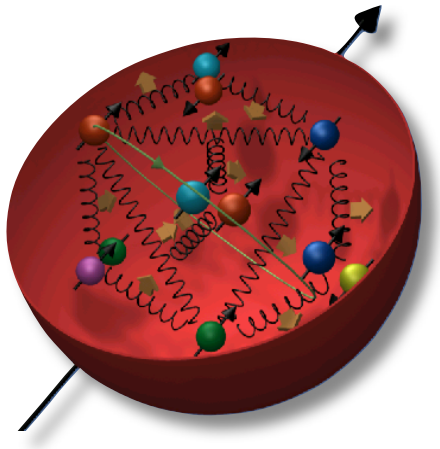
Bob Jaffe

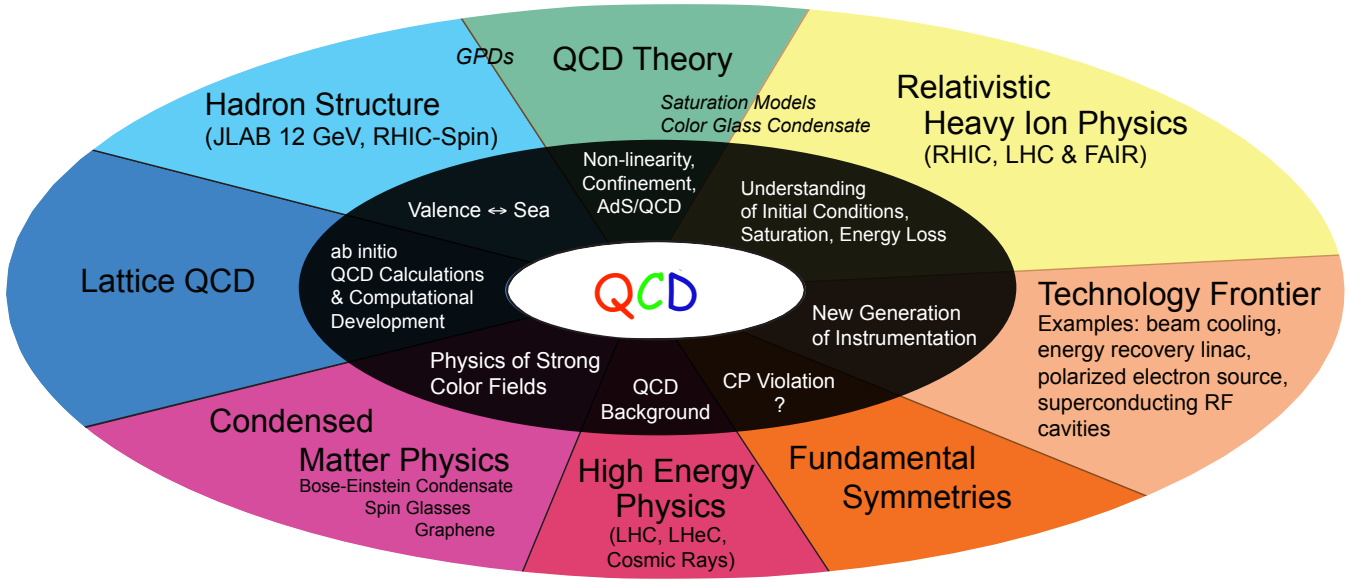
"The decomposition of the proton spin into contributions from spin and orbital motion of quarks and gluons is well defined and probes interesting features of confinement - It is a world-class problem!"



Theoretical foundation

- Exploring the proton spin structure and dynamics





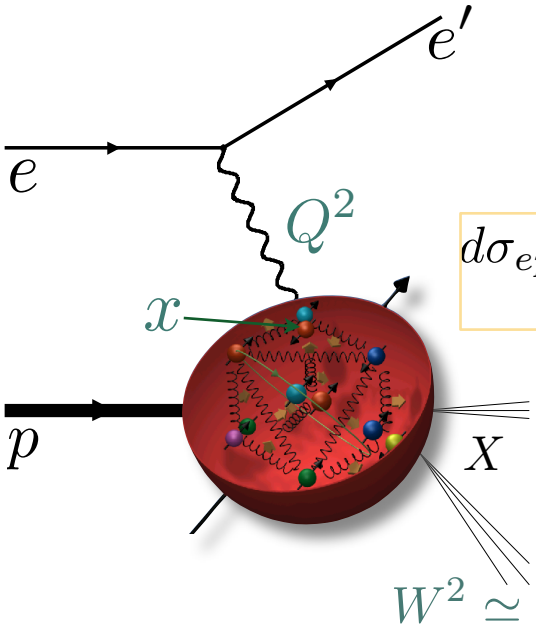
Structure and dynamics of proton (**mass**) (→ visible universe) originates from QCD-interactions!

What about **spin** as another fundamental quantum number?

Synergy of experimental progress and theory (Lattice QCD / Phenomenology incl. phenomenological fits / Modeling) is critical!

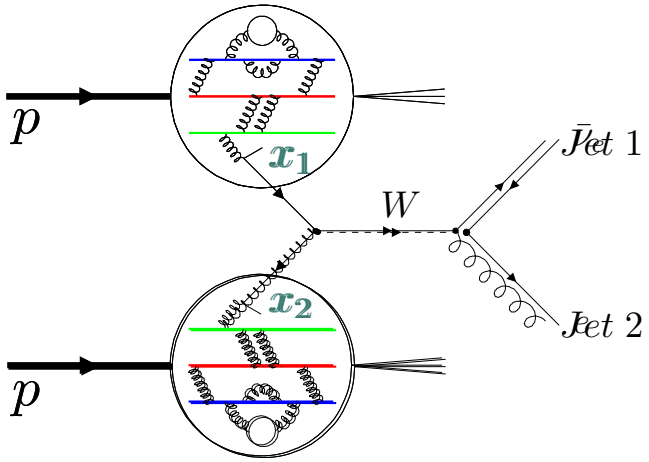
Theoretical foundation

- How do we probe the structure and dynamics of matter in ep / pp scattering?



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

Universality



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$ Factorization

Momentum contribution

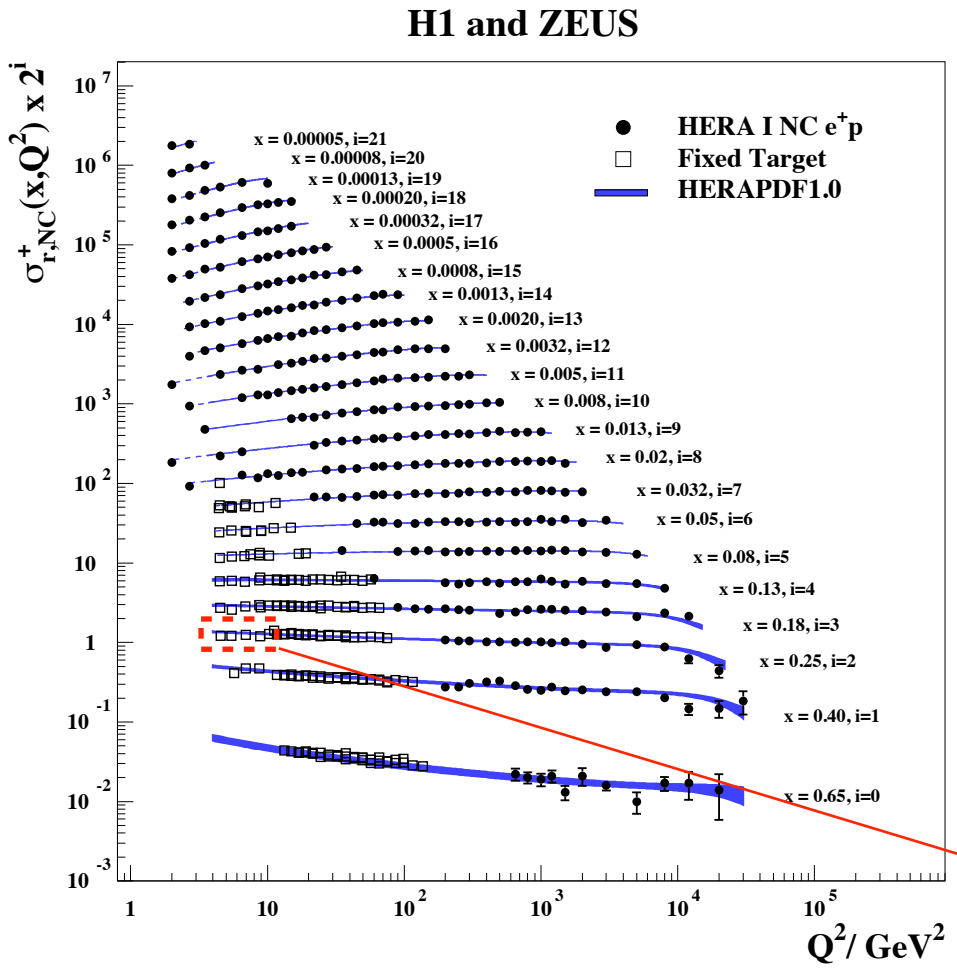
$$f(x) = f^+(x) + f^-(x)$$

$$\Delta f(x) = f^+(x) - f^-(x)$$

Spin contribution

Theoretical foundation

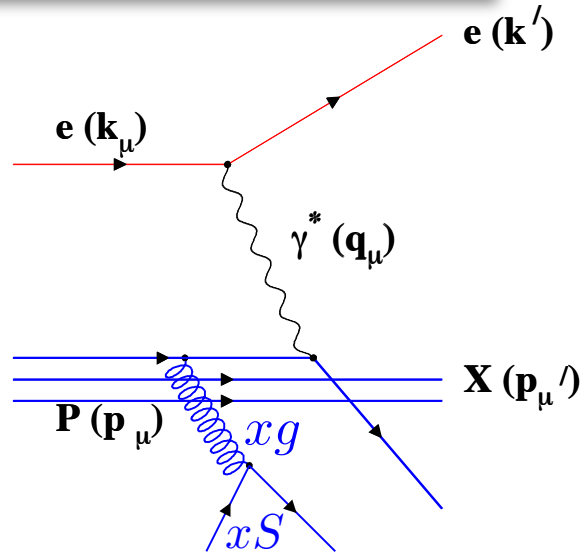
- Picture of the proton from unpolarized ep scattering

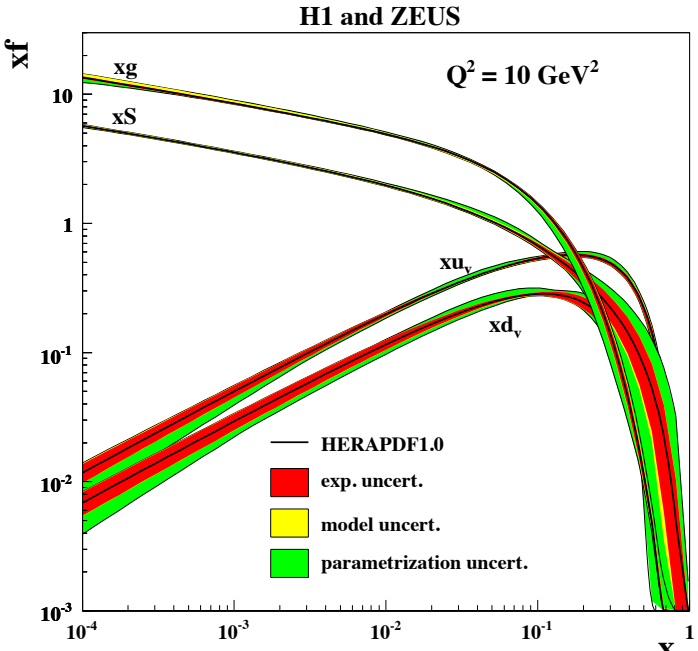


Strong violation of scaling at low x and high Q^2

In contrast to:

Low Q^2 high x!

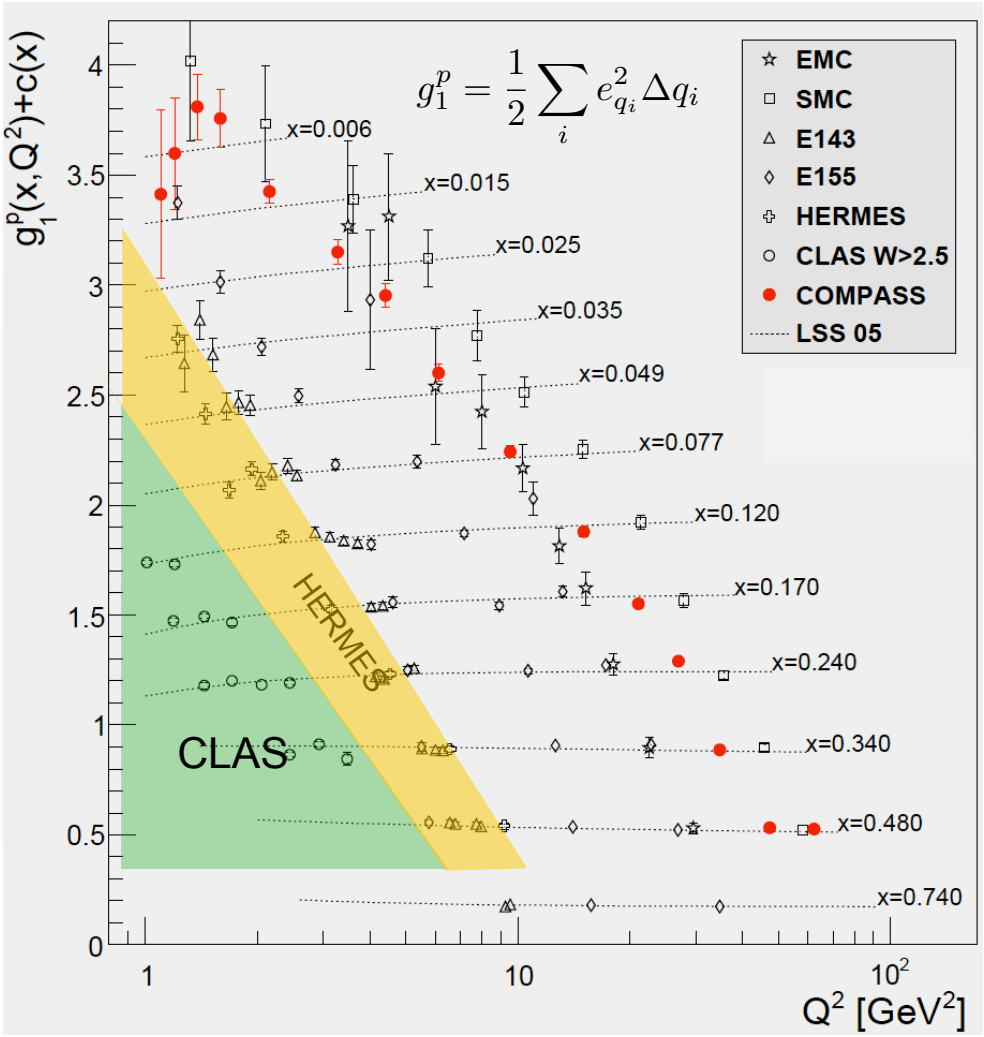




- Huge gluon and QCD sea contribution!

Theoretical foundation

- Picture of the proton from polarized ep scattering



- Spin sum rule:

$$\underbrace{\frac{1}{2}\Delta\Sigma}_{} = \frac{1}{2} = \langle S_q \rangle + \underbrace{\langle S_g \rangle}_{\Delta G} + \langle L_q \rangle + \langle L_g \rangle$$

(R.L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990))

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x,Q^2)dx \qquad \Delta G(Q^2) = \int_0^1 \Delta g(x,Q^2)dx$$

- Current status:
  - Data only from fixed-target experiments (Limited reach in x and Q^2) mostly at lower energy
  - Quark spin contribution is small (~25%):

$$\Delta\Sigma = 0.242 \; (Q^2 = 10\,\mathrm{GeV}^2)$$

(D. deFlorian et al., Phys. Rev. D80, 034030 (2009))

  - Gluon spin contribution unconstrained so far!

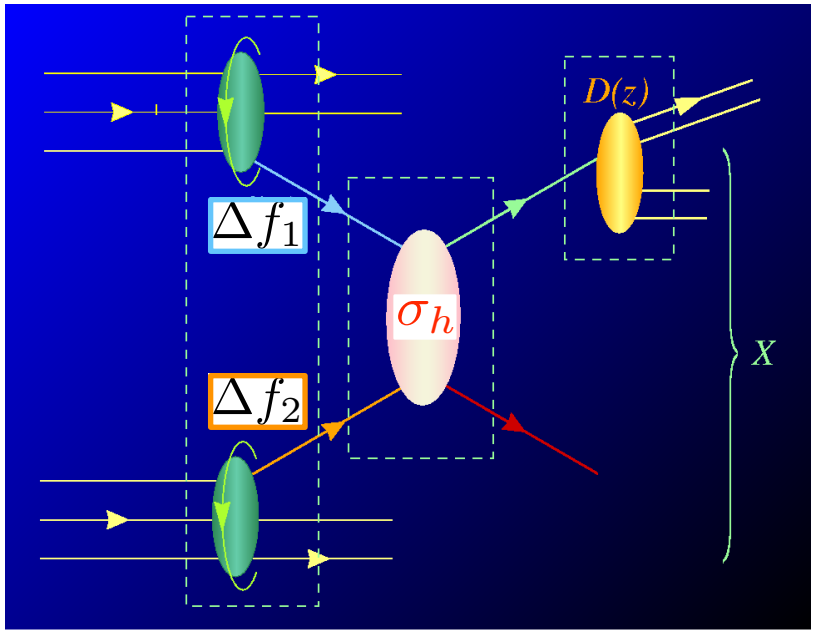
Theoretical foundation

- New scheme to explore proton spin structure: High-energy polarized p+p collisions

- Observable: Quark/Anti-quark polarization (W production)
  - Longitudinal single-spin asymmetry A_L

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

  - Parity (Spatial inversion) violating for W production!



- Observable: Gluon polarization (Jet/Hadron production)
  - Double longitudinal single-spin asymmetry A_{LL}

long-range short-range long-range

$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$

Input

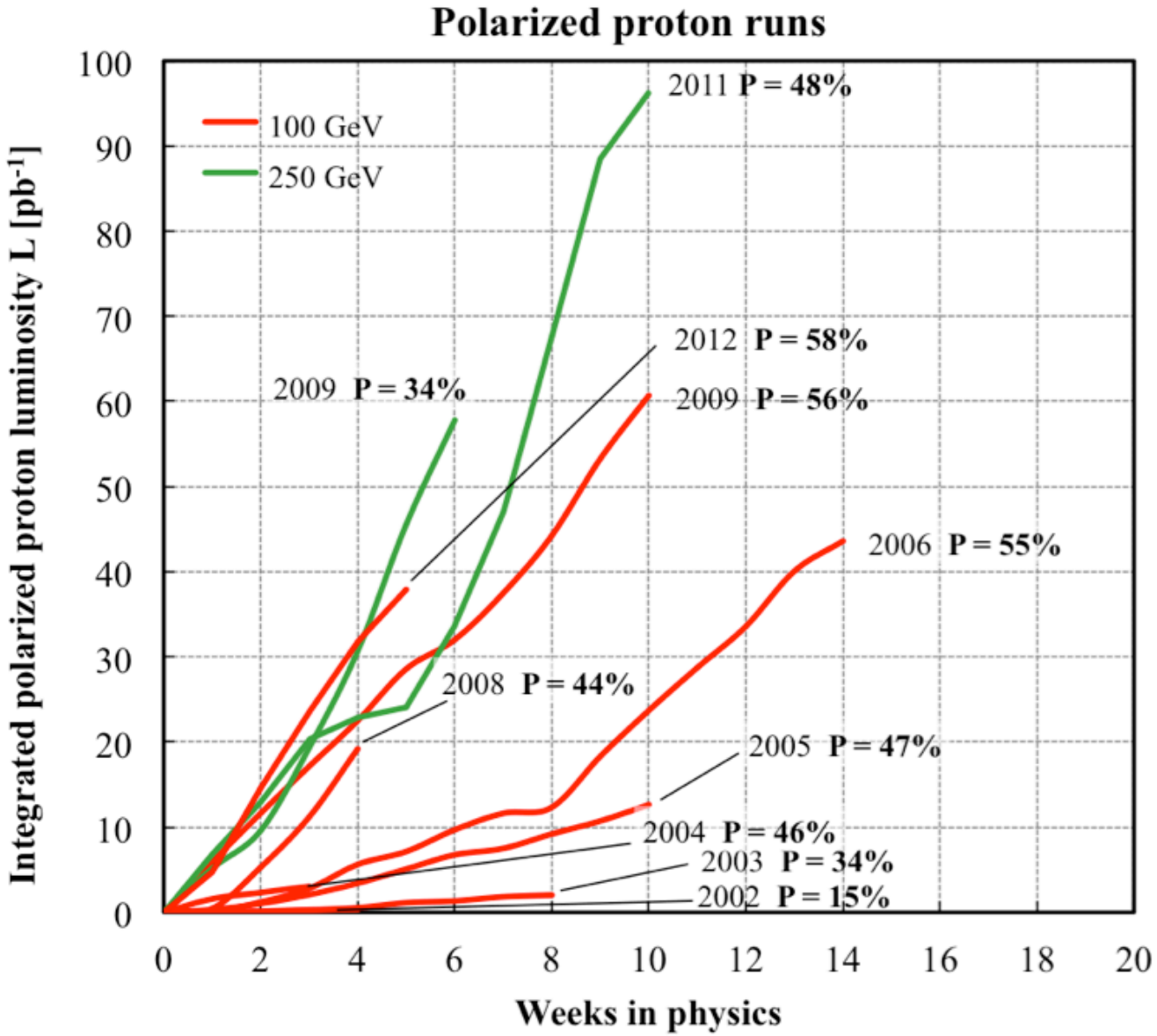
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

Experimental aspects - RHIC

- The world's first polarized proton-proton collider

Experimental aspects - RHIC

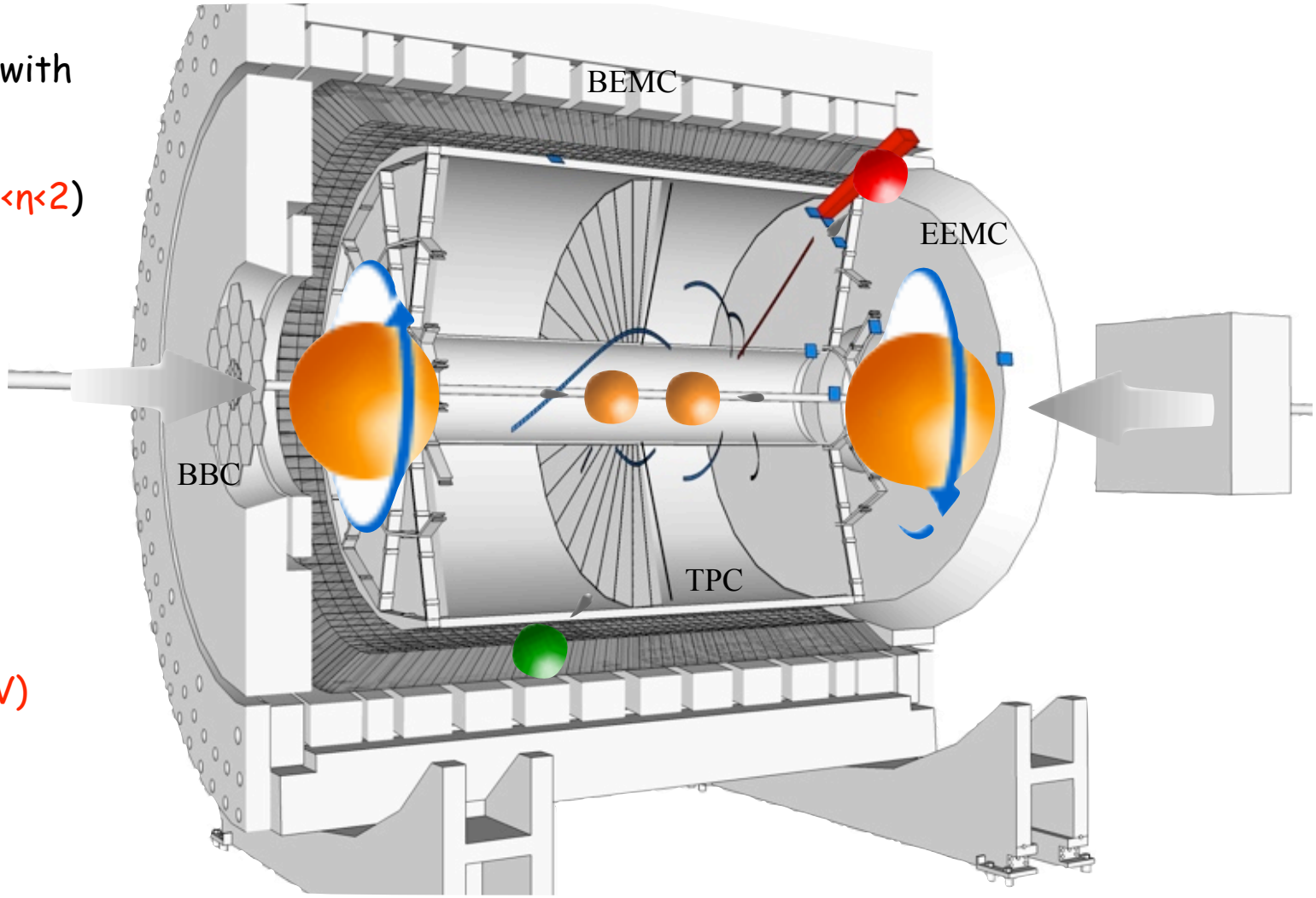
- Polarized p-p collisions
  - Long production runs at $\sqrt{s}$=200GeV (long. polarization) in 2005, 2006 and 2009: Jet and Hadron production (Gluon polarization)
  - First collisions of polarized proton beams at $\sqrt{s}$=500GeV (long. polarization) in 2009: W production (Quark polarization)



Experimental aspects - STAR

Overview

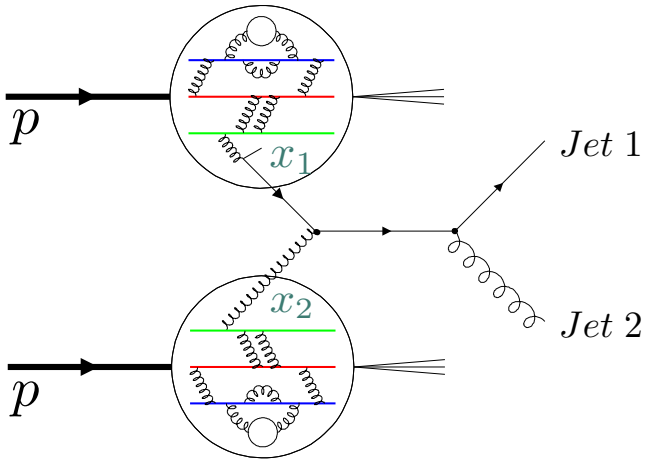
- Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
- TPC: Tracking and particle ID
- ZDC: Relative luminosity and local polarimetry (500GeV)
- BBC: Relative luminosity and Minimum bias trigger



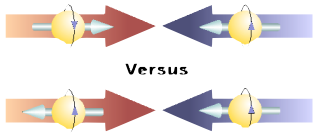
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Experimental aspects

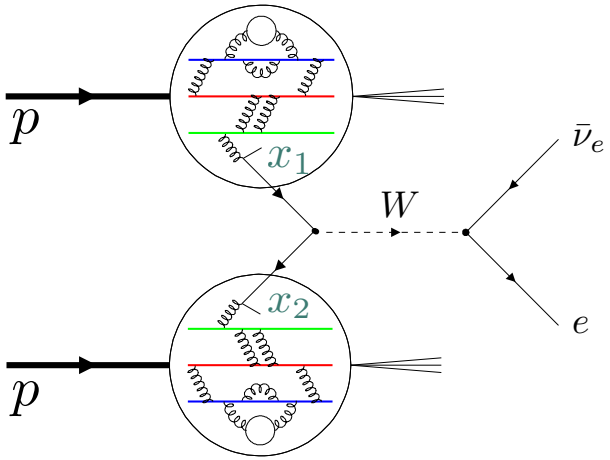
- Asymmetry measurement



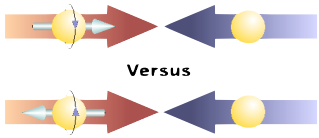
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$



- Require concurrent measurements:
  - Longitudinal beam polarization $P_{1(2)}$ at STAR IR
  - Direction of polarization vector
  - Relative luminosity R of bunch crossings with different spin directions
  - Spin dependent yields of process of interest N_{ij}

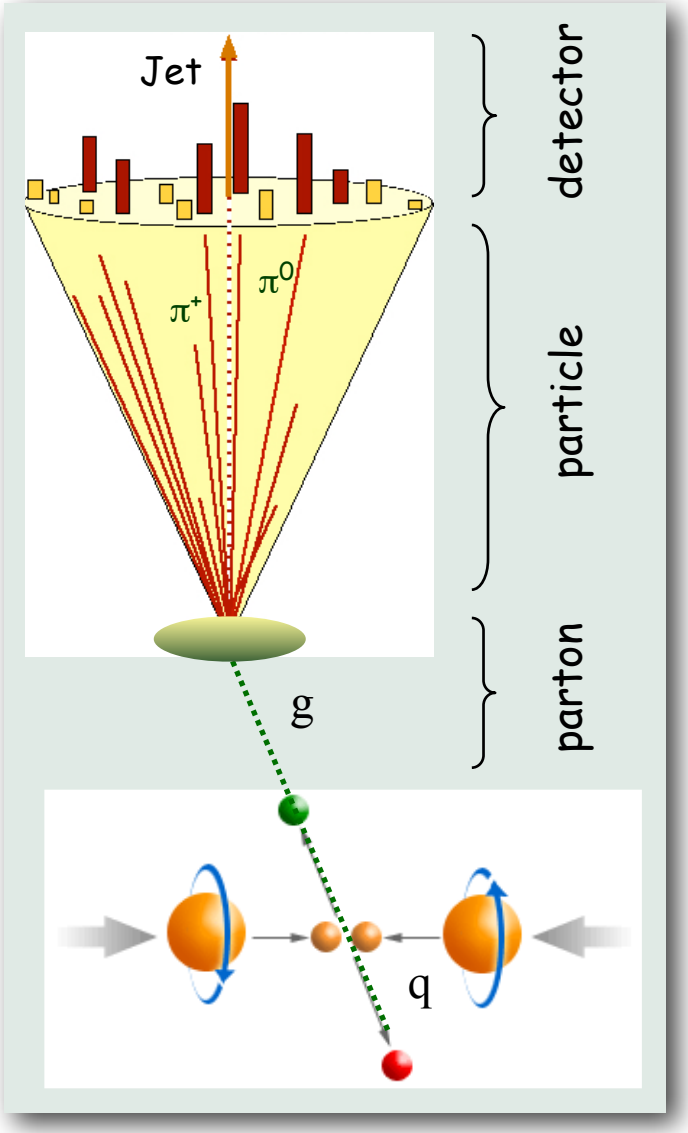


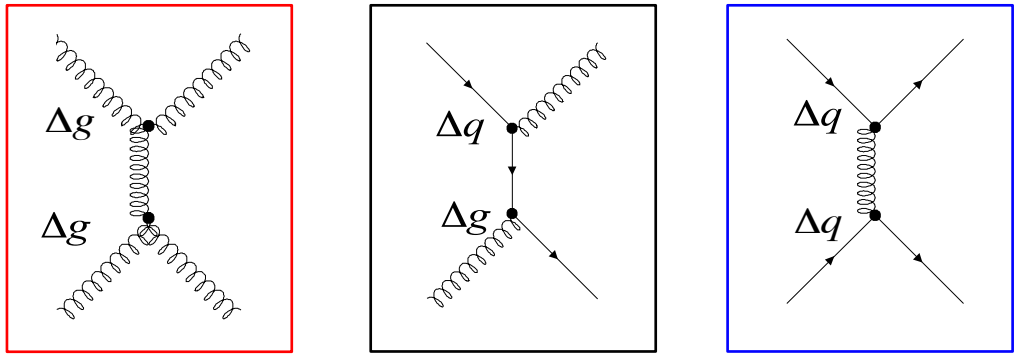
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P} \frac{N_+ - R N_-}{N_+ + R N_-}$$



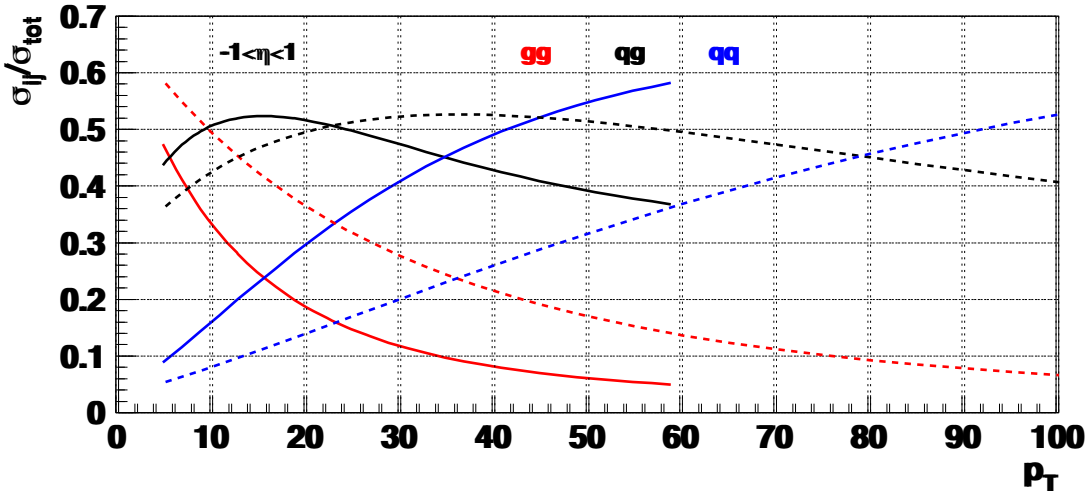
Gluon measurements: Jet/Hadron production

- RHIC Gluon polarization: Inclusive measurements





Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)



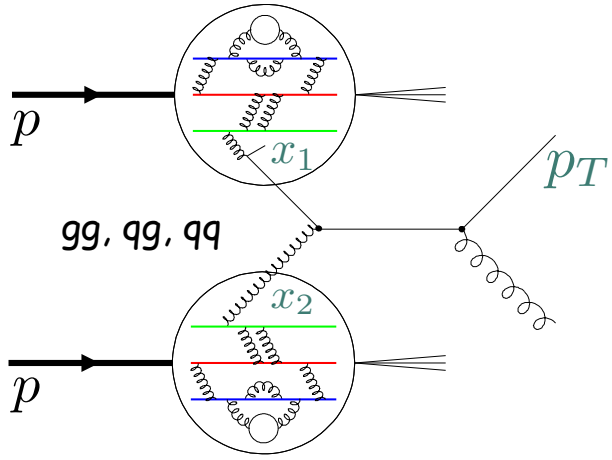
Gluon measurements: Jet/Hadron production

RHIC Gluon polarization - Correlation Measurements

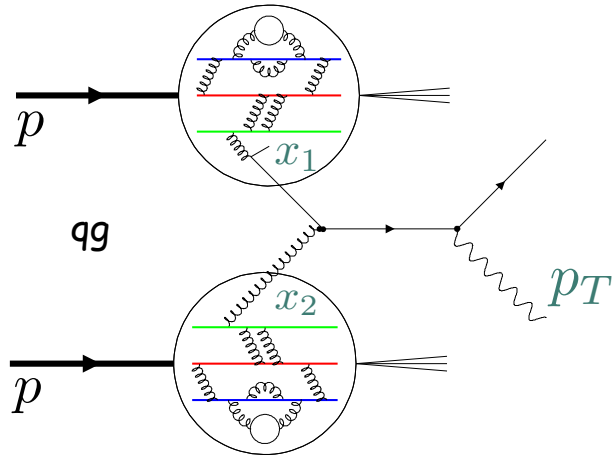
- Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:

$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)}\right)$$

- Di-Jet production / Photon-Jet production
  - Di-Jets: All three (LO) QCD-type processes contribute: gg, qg and qq
  - Photon-Jet: One dominant underlying (LO) process
  - Larger cross-section for di-jet production compared to photon related measurements
  - Photon reconstruction more challenging than jet reconstruction
  - Full NLO framework exists ⇒ Input to Global QCD analysis



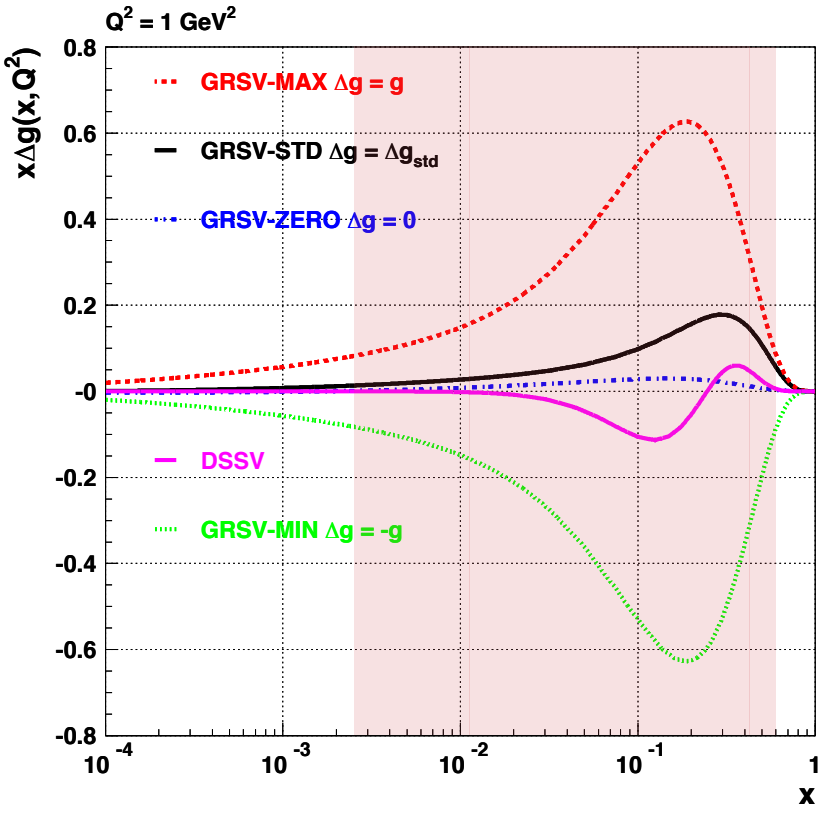
Di-Jet production



Photon-Jet production

Gluon measurements: Jet/Hadron production

- Measurement: Connection of Δg and A_{LL}

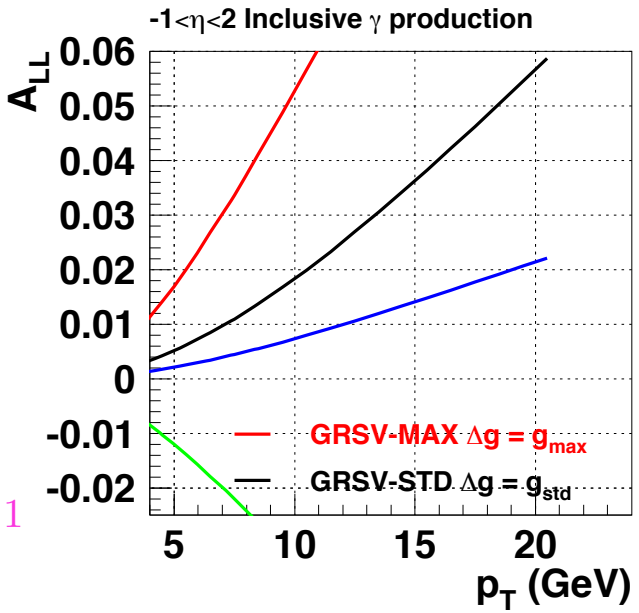


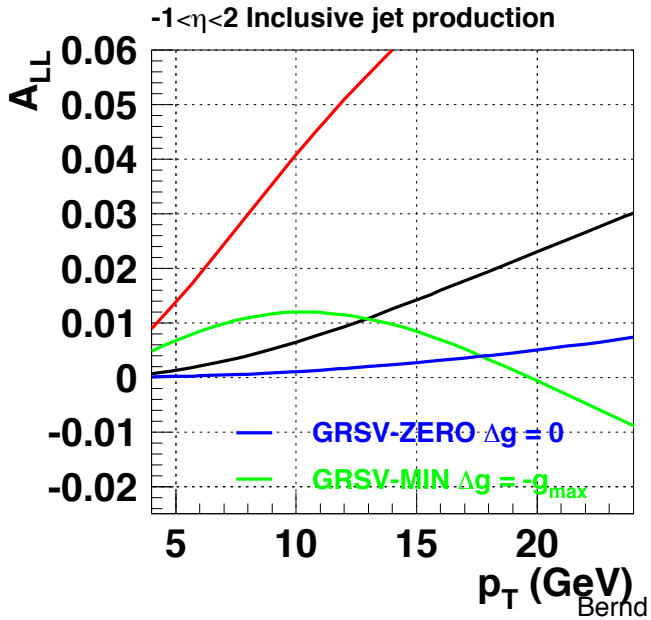
$$\Delta G(Q^2 = 1GeV^2) \approx 1.8$$

$$\Delta G(Q^2 = 1GeV^2) \approx 0.4$$

$$\Delta G(Q^2 = 1GeV^2) \approx 0.1$$

$$\Delta G(Q^2 = 1GeV^2) \approx -0.1$$





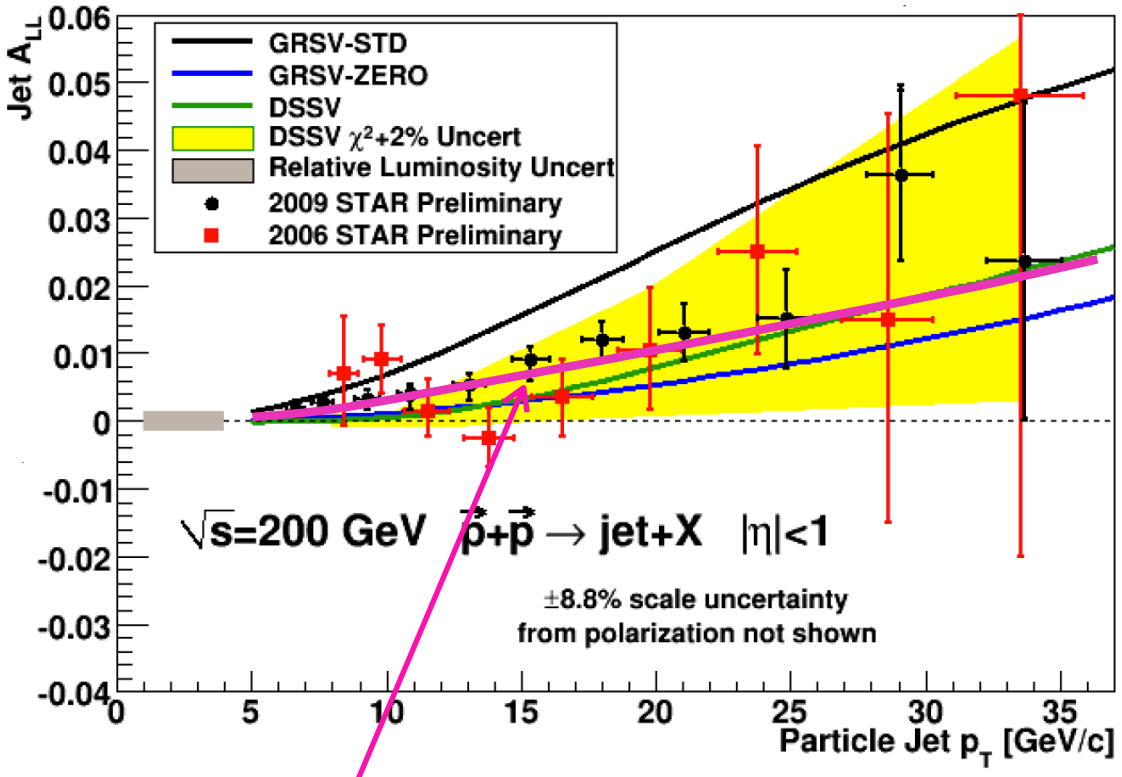
- Examine wide range in Δg: $-g < \Delta g < +g$
- GRSV-STD: Global QCD analysis of polarized DIS experiments only!

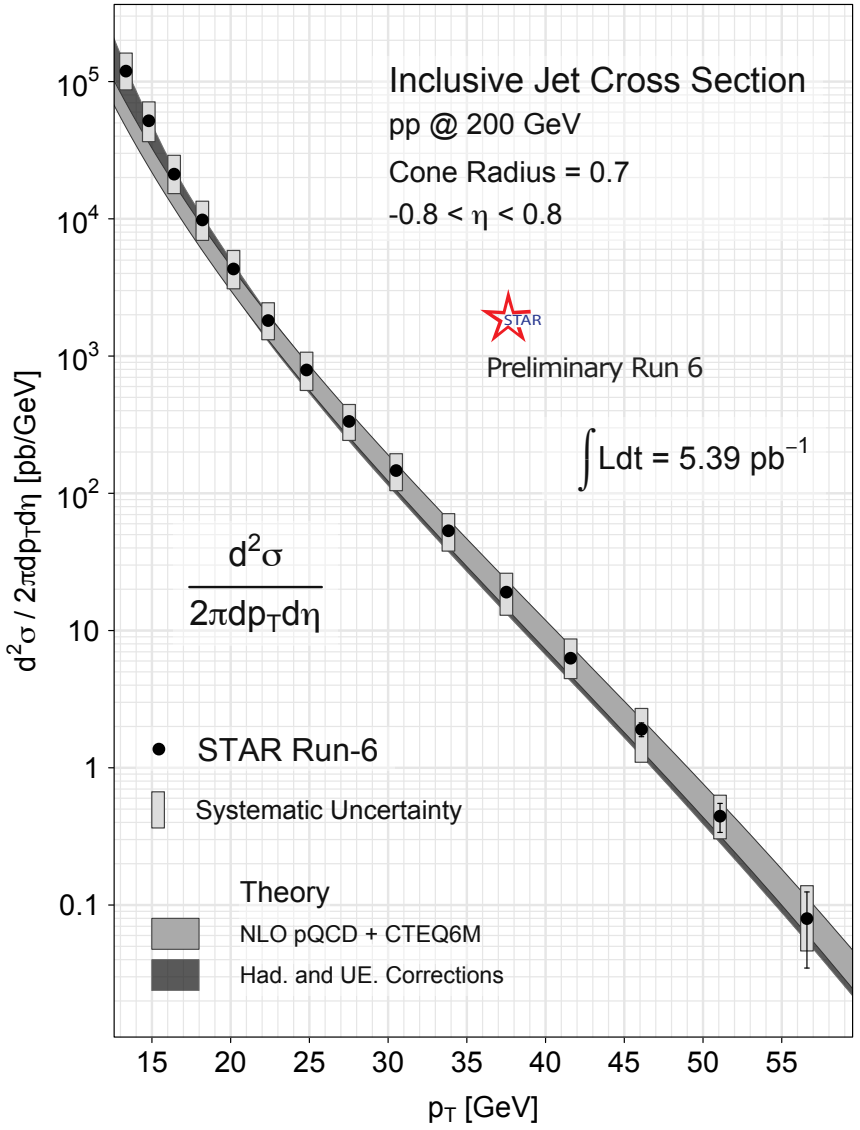
M. Gluck et al. PRD 63 (2001) 094005.

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

Recent results - Gluon polarization program

- STAR: Mid-rapidity Inclusive Jet A_{LL} measurement





- Data are well described by NLO pQCD plus hadronization c

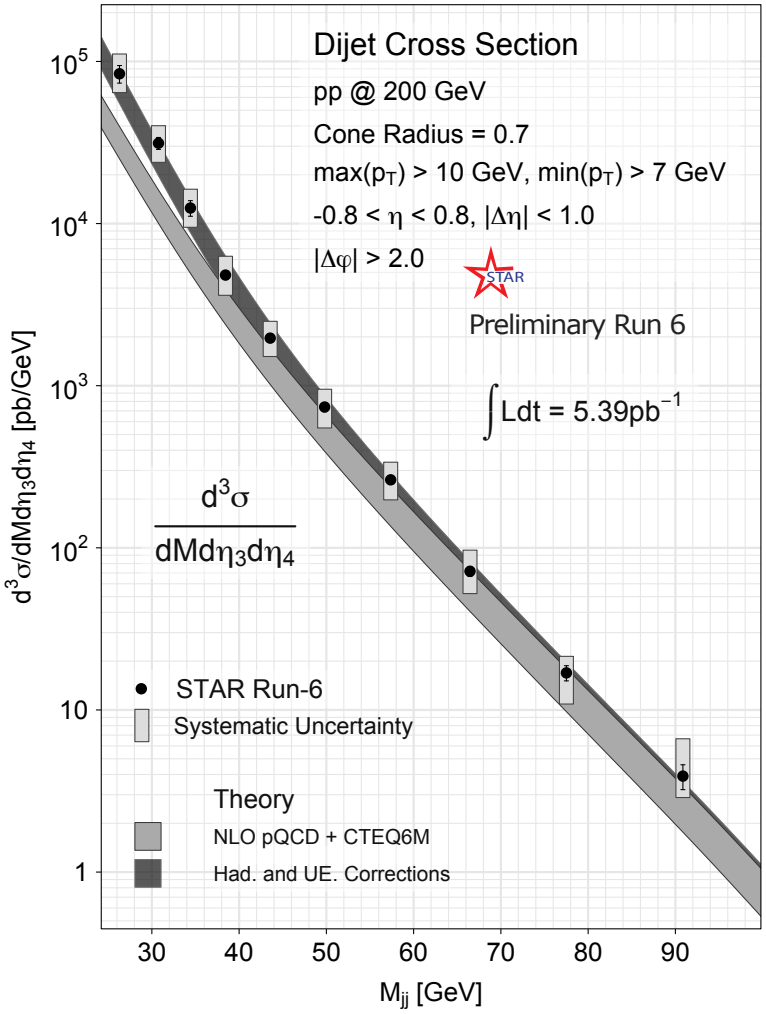
$$\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$$ ections

- Run 9 A_{LL} measurement between GRSV-STD and GRSV-ZE
- Run 9 A_{LL} measurement between GRSV-STD and DSSV

W. Vogelsang, DIS 2012

Recent results - Gluon polarization program

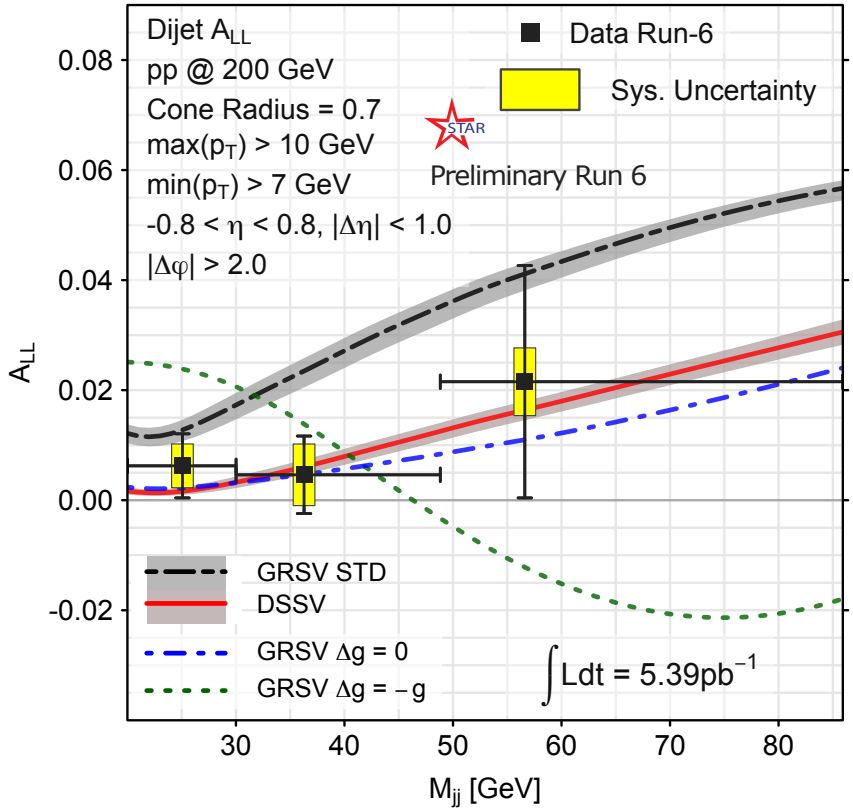
First STAR Di-Jet A_{LL} measurement



- Data are well described by NLO pQCD plus hadronization and underlying event corrections

$$M = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

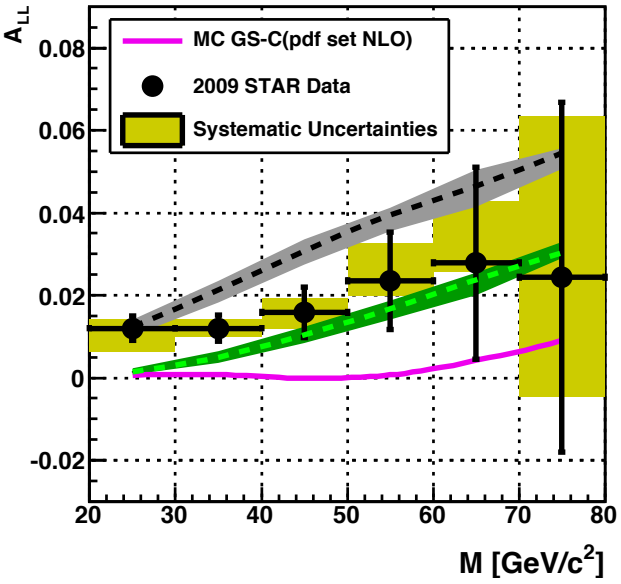


- First Di-Jet A_{LL} measurement in agreement with Δg constrained by previous inclusive jet result, i.e. small gluon polarization preferred!

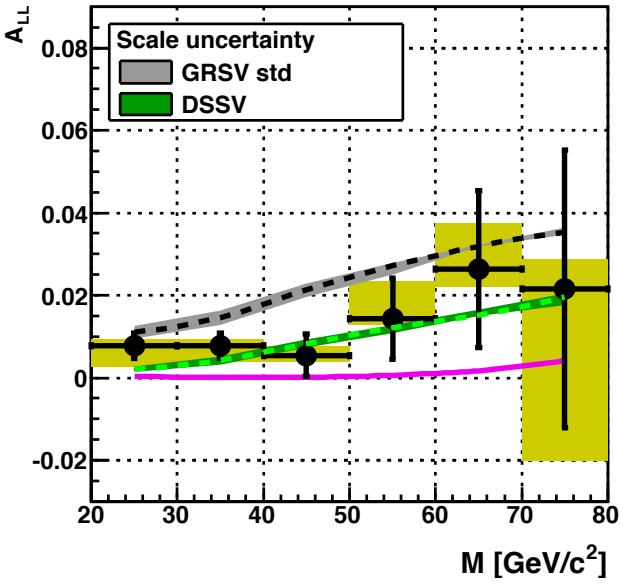
Recent results - Gluon polarization program

First STAR Di-Jet A_{LL} measurement

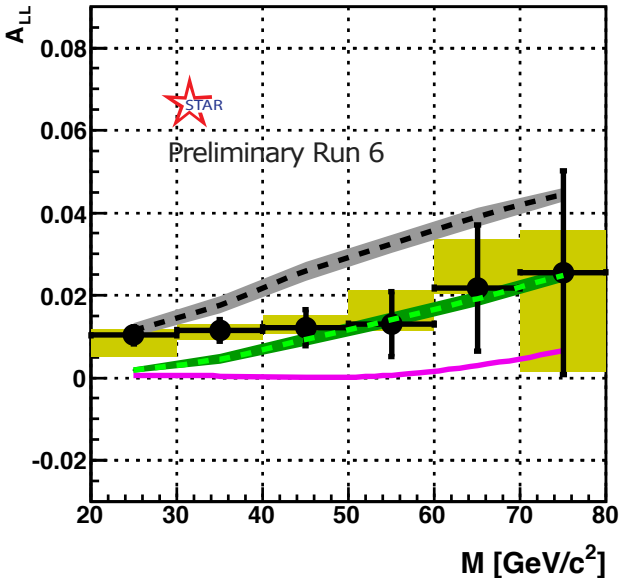
East - East and West - West Barrel

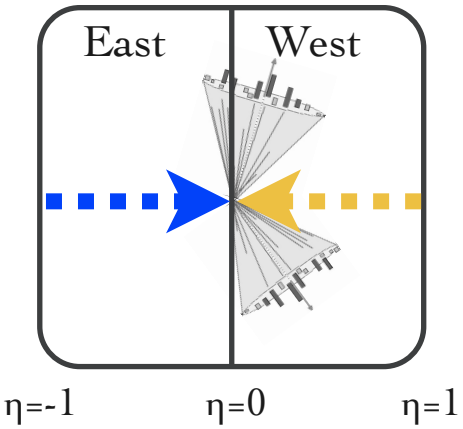


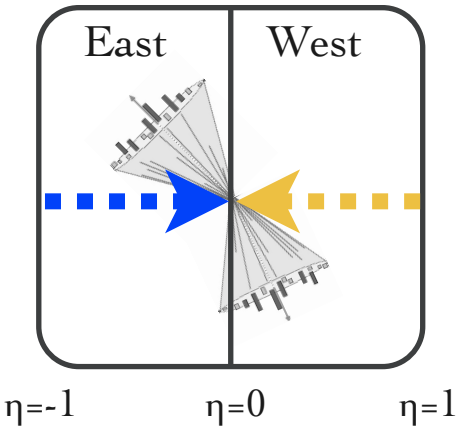
East Barrel - West Barrel



Full Acceptance







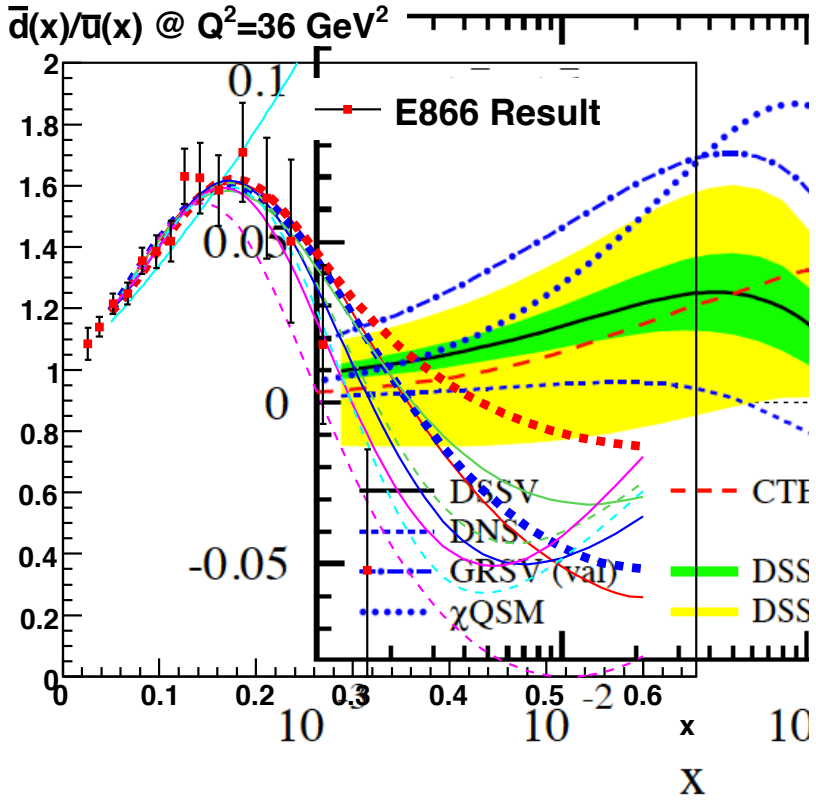
$$M = \sqrt{x_1 x_2 s} \qquad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

- ALL measurements tend to fall in-between GRSV-STD and DSSV
- Run 9 data: First rapidity dependent di-jet measurement

  ⇒ Constrain x dependence!

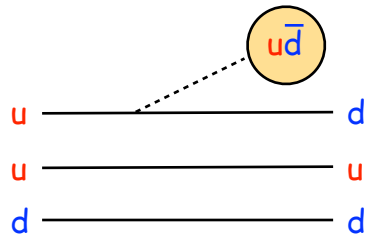
Quark measurement: W production

- Motivation
  - What mechanism allows to account for the generation of the QCD sea, i.e. quark / anti-quark pairs?
  - Pure perturbative QCD sea: Flavor symmetric, i.e $\bar{u} = \bar{d}$
  - Non-perturbative models important invoking alternative degrees of freedom:



MRST2001
MRST2002
MRST2004
MRTW2008
CTEQ4m
CTEQ5m
CTEQ6m
CTEQ6.1
CTEQ6.5
CTEQ6.6

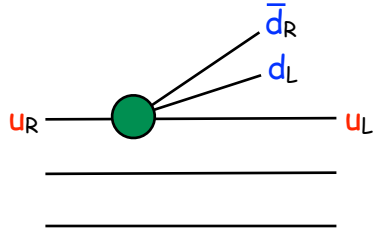
- Meson-Cloud model:



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

Quark sea from cloud of mesons!

- Chiral-Quark Soliton model:



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

Quark degrees of freedom in a pion mean-field

Quark measurement: W production

- Probing the quark flavor structure using W boson production: Unique new probe

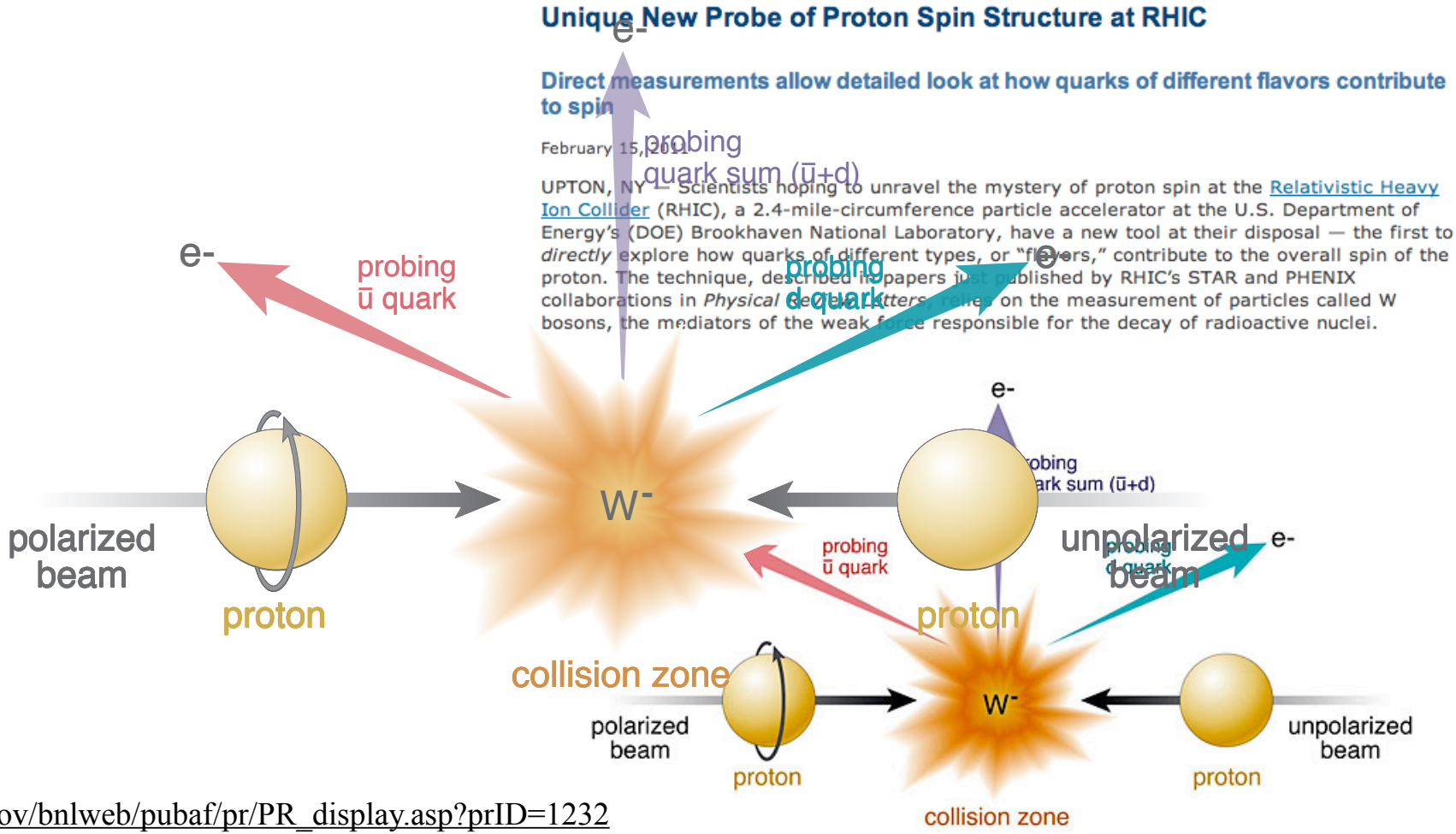


Illustration of a new measurement using W boson production in polarized proton collisions at RHIC. Collisions of polarized protons (beam entering from left) and unpolarized protons (right) result in the production of W bosons (in this case, W-). RHIC's detectors identify the particles emitted as the W bosons decay (in this case, electrons, e-) and the angles at which they emerge. The colored arrows represent different possible directions, which probe how different quark flavors (e.g., "anti-up," ū; and "down," d) contribute to the proton spin. + ENLARGE

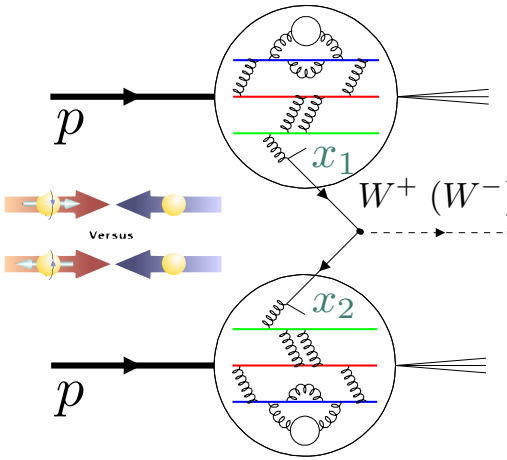
News Release:

http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=1232

Recent results - Quark / Anti-quark pol. program

- Probing the quark flavor structure using W boson production

$\Delta d + \bar{u} \rightarrow W^-$
$\Delta \bar{u} + d \rightarrow W^-$



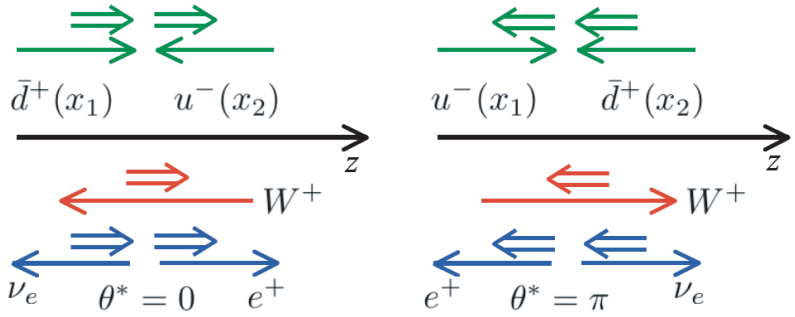
$W^+ \ (W^-)$

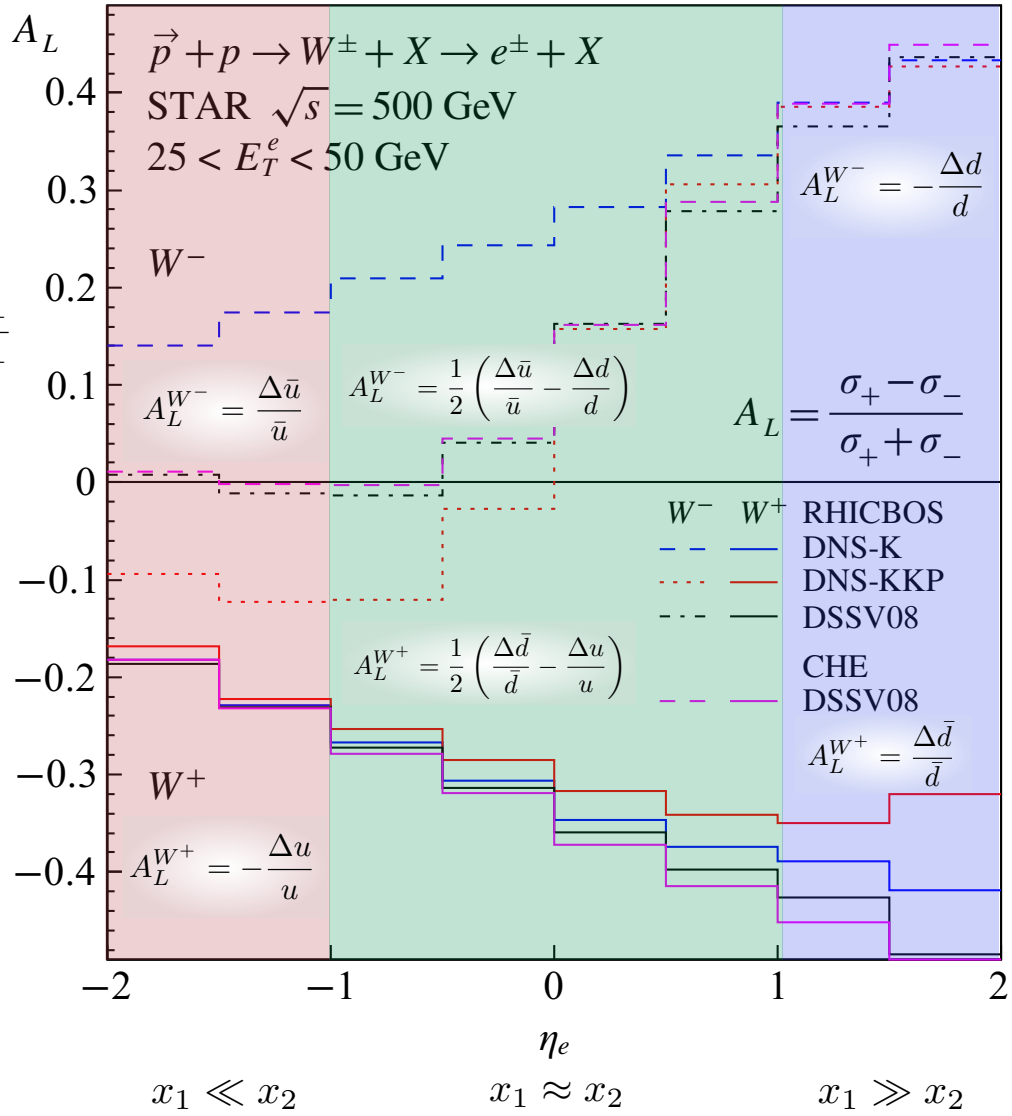
$\nu_e \ (\bar{\nu}_e)$

$e^+ \ (e^-)$

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

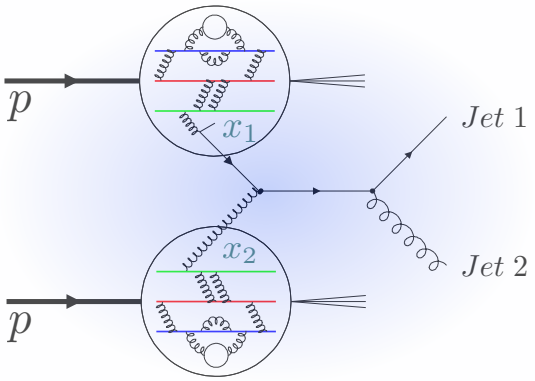
$\Delta \bar{d} + u \rightarrow W^+$
$\Delta u + \bar{d} \rightarrow W^+$





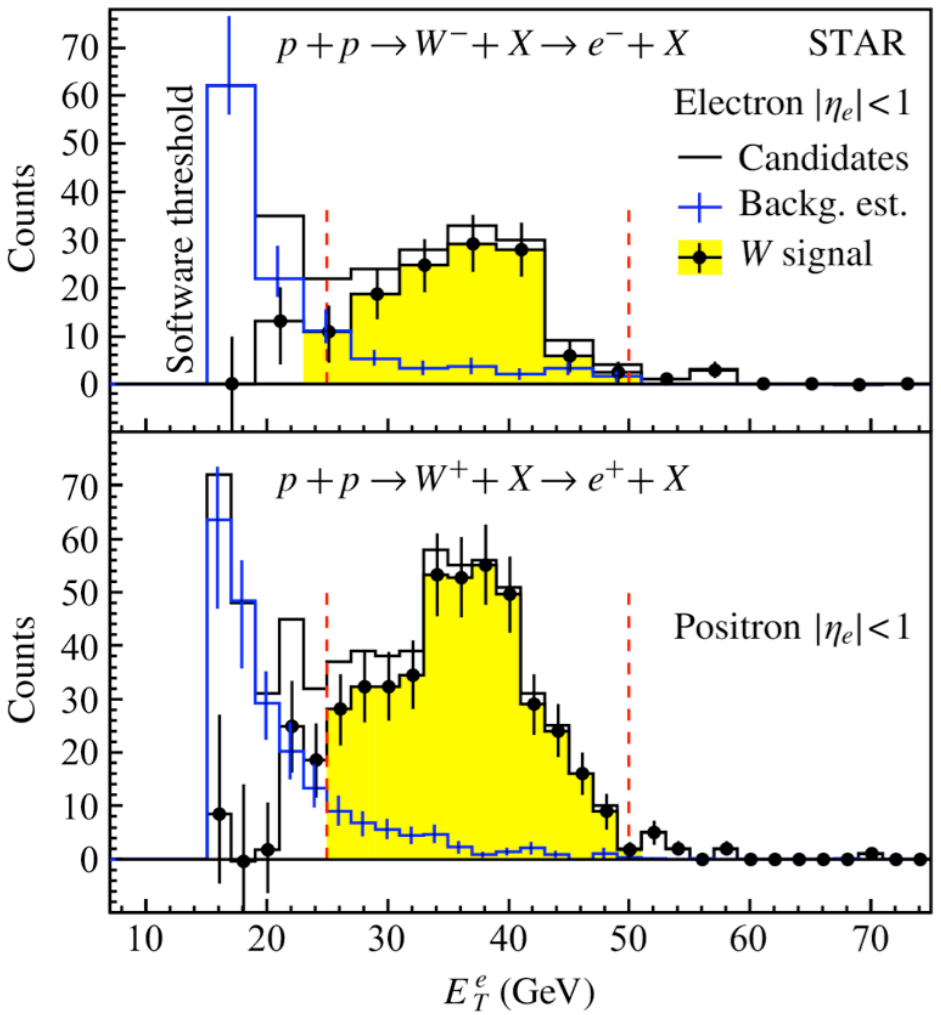
Quark flavor measurements: W production

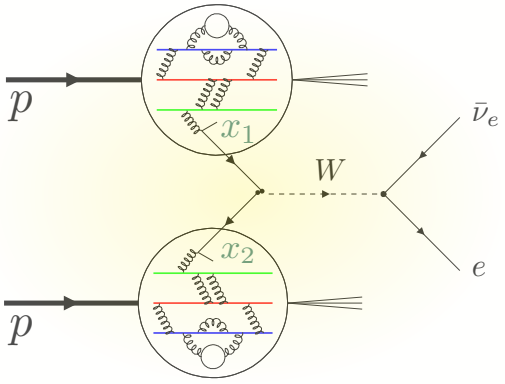
- Measurement: Background treatment / Signal distribution



- Background dominated by QCD background (Data driven estimate) with smaller fractions from W boson induced τ decays and Z^0 boson events (MC estimate)

- Total background (B):
  - e^+: 39 ± 9
  - e^-: 23 ± 6



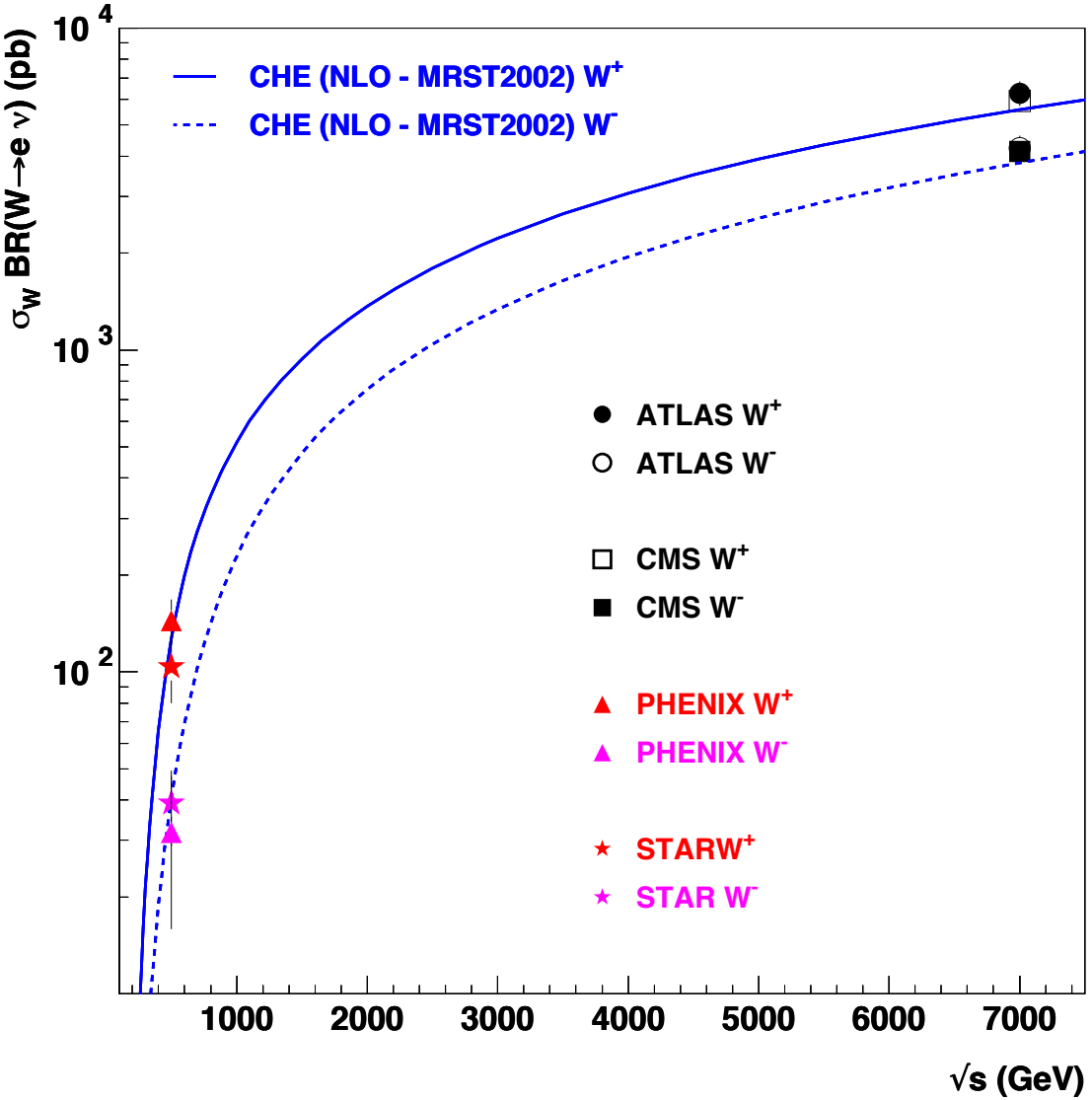


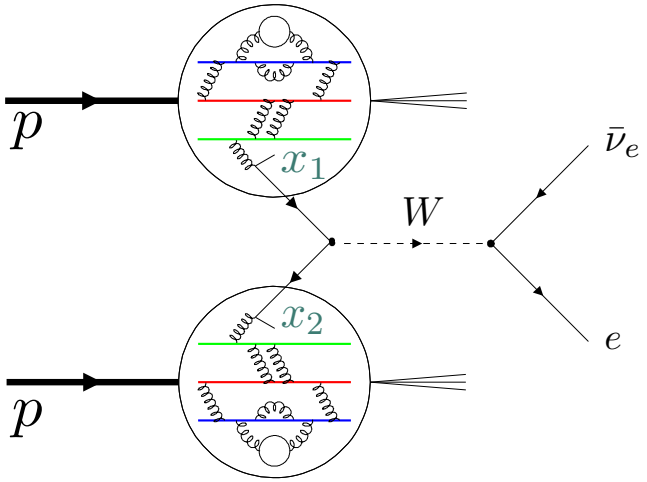
- Total e^+/e^- cand. events (S+B):
  - e^+: 462
  - e^-: 139

STAR Collaboration, hep-ex/1009.0326, submitted to PRL.

Quark flavor measurements: W production

- First STAR W^+ / W^- cross section measurement in pp collisions



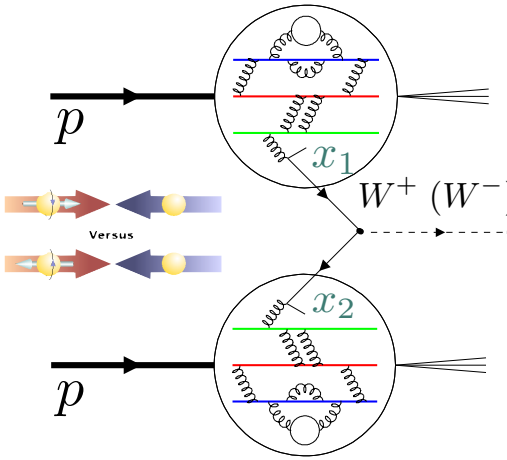


- Measured and theory evaluated cross-sections agree within uncertainties
- Theory calculations: Full NLO framework

Quark flavor measurements: W production

- First STAR A_L result (1)

$\Delta d + \bar{u} \rightarrow W^-$
$\Delta \bar{u} + d \rightarrow W^-$



$W^+ \ (W^-)$

$\nu_e \ (\bar{\nu}_e)$

$e^+ \ (e^-)$

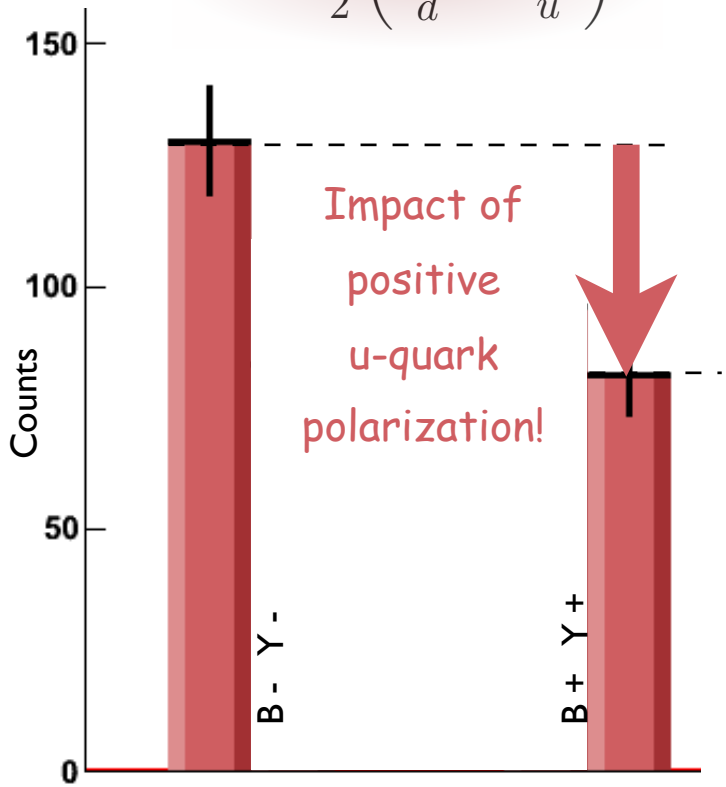
$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

$\Delta \bar{d} + u \rightarrow W^+$
$\Delta u + \bar{d} \rightarrow W^+$

- First measurement of parity-violation in polarized proton-proton collisions at RHIC

- W^+: Observe directly u quark polarization!

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta \bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right)$$



Quark flavor measurements: W production

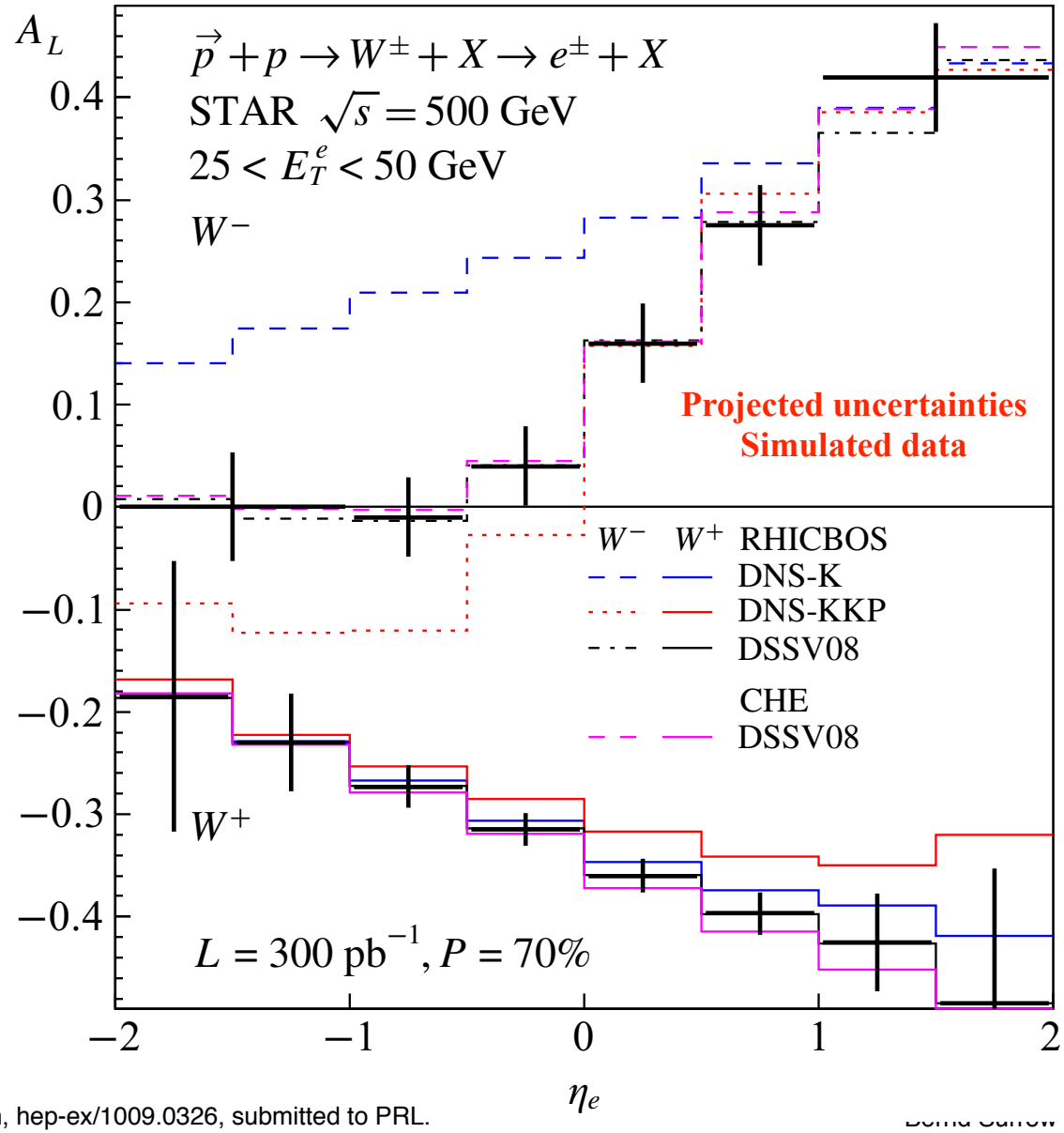
- First STAR A_L result (2)

$$A_L^{W^-} = 0.14 \pm 0.19\ (\text{stat.}) \pm 0.02\ (\text{syst.}) \pm 0.01\ (\text{norm.})$$

$$A_L^{W^+} = -0.27 \pm 0.10\ (\text{stat.}) \pm 0.02\ (\text{syst.}) \pm 0.03\ (\text{norm.})$$

- $A_L(W^+)$ negative with a significance of ~3σ
- $A_L(W^-)$ central value positive
- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data

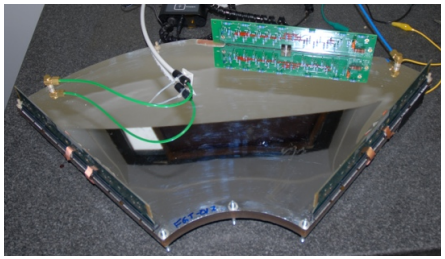
  ⇒ Universality of helicity distr. functions!



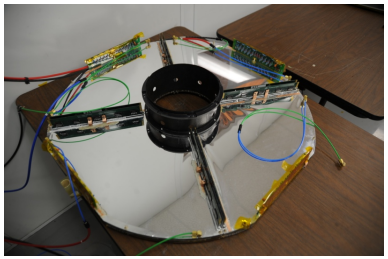
STAR Collaboration, hep-ex/1009.0326, submitted to PRL.

Future - Quark / Anti-quark pol. program

Forward GEM Tracker - Layout

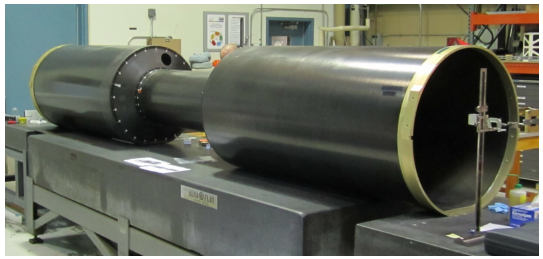


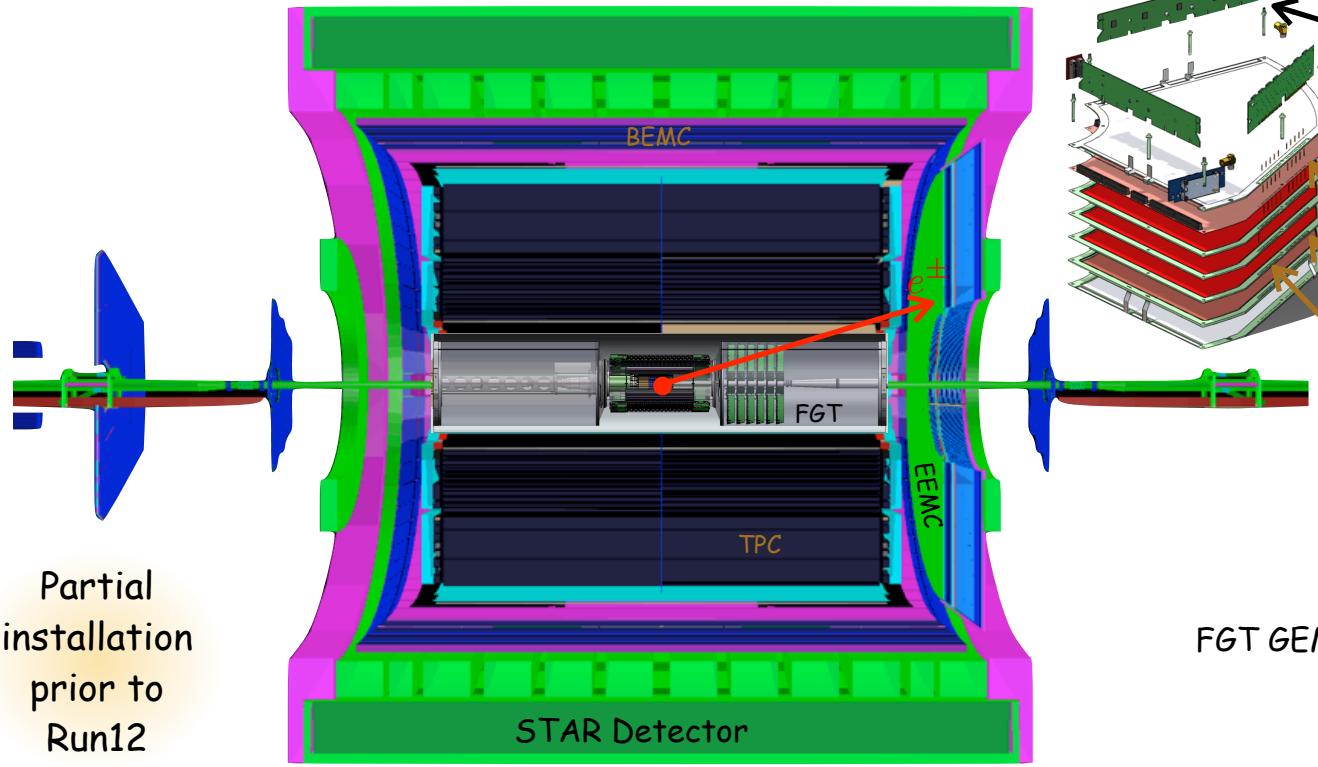
Quarter section



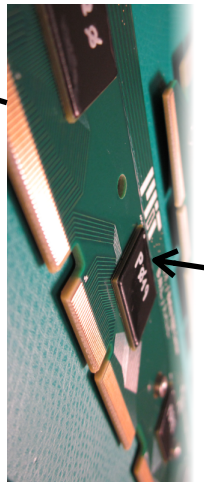
Disk

Quarter section





Partial installation prior to Run12



APV module

Packaged APV chip

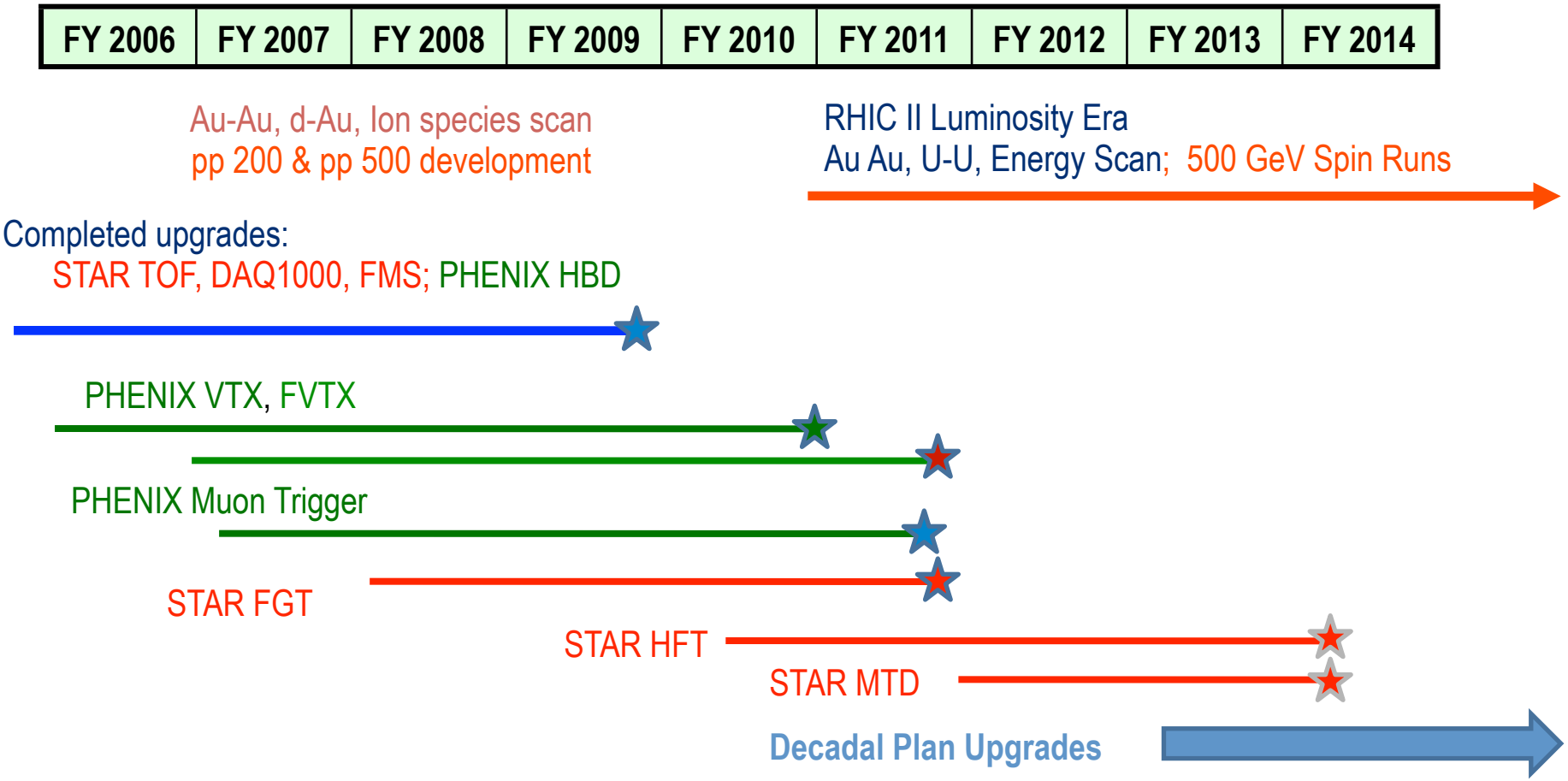
FGT GEM foil

Summary

- Gluon polarization program
  - Several final states (Hadron / Jet) have been measured all pointing to the same conclusion that the gluon polarization is small, much smaller than the proton spin itself, in contrast to earlier theoretical - controversial - speculations
  - Run 9 results: Precise A_{LL} measurement above DSSV fit suggesting $\Delta G \sim 0.1 > 0$
- W boson program
  - First measurement of W boson production in polarized p+p collisions at RHIC in 2009
  - Installation of FGT extends W boson measurement in 2009 to forward direction
- Run 12 and future
  - Run 12: Successful trans. 200GeV (~20pb^{-1} rec.) run and ongoing long. 500GeV run (~40pb^{-1} rec.) for another two weeks!
  - Future: Expect and need several long 500GeV production runs beyond Run 12

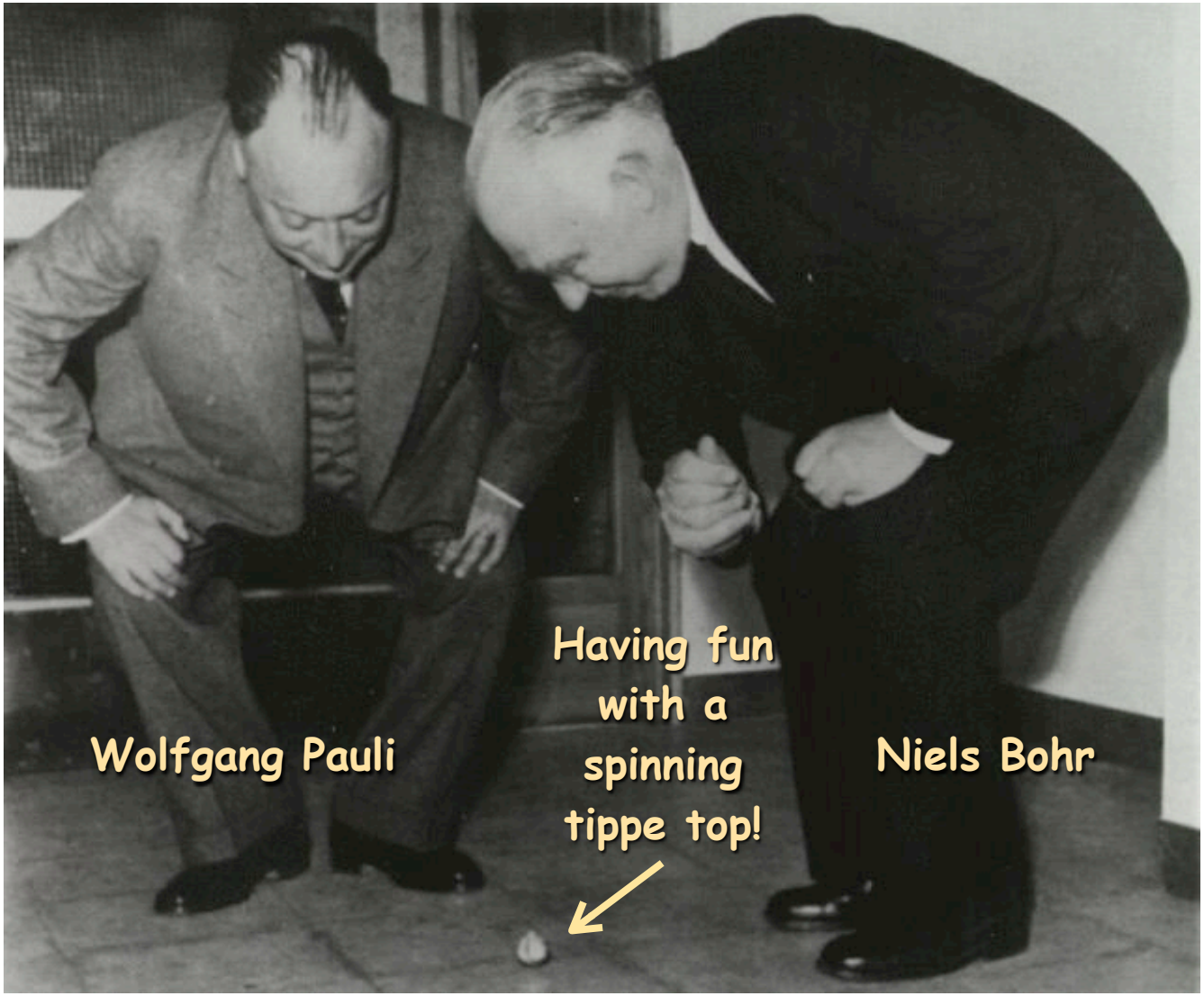
Outlook

- Timeline of RHIC program



- Long-term: Establish a new collider facility at BNL/JLAB - Electron-Ion Collider!

Fun with SPIN

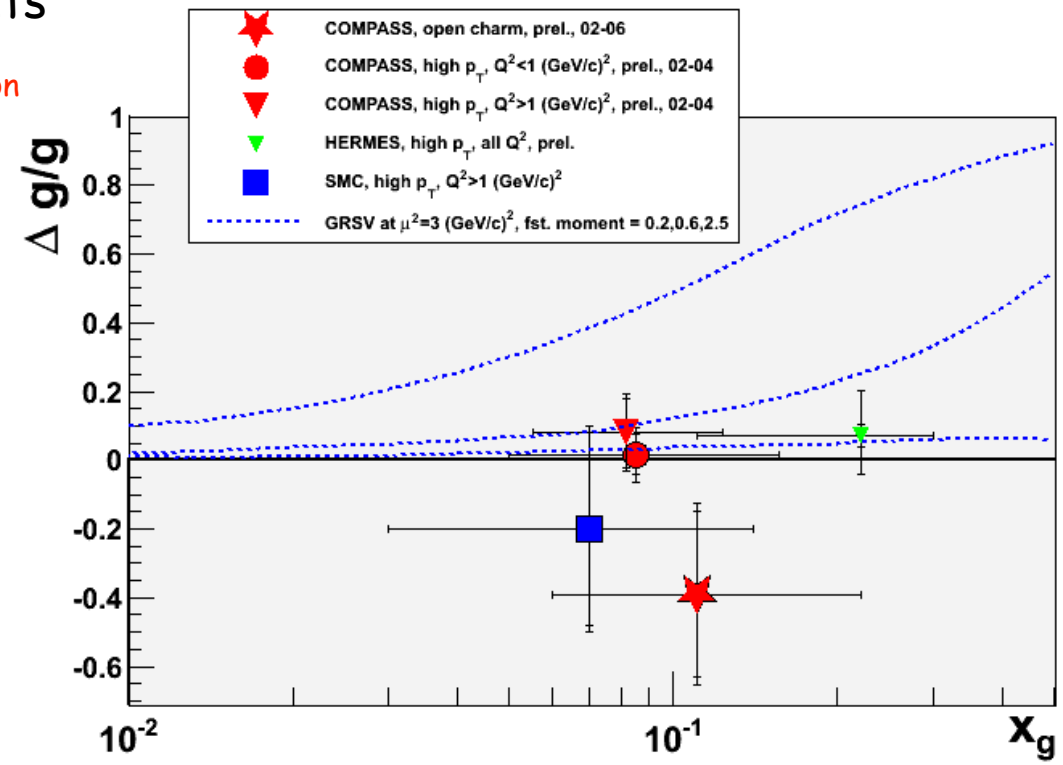


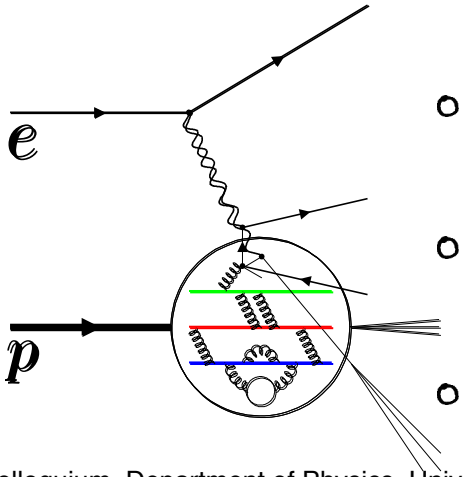
Opening of the new institute of physics at the University of Lund, Sweden, May 31, 1951

Backup

Motivation and previous measurements

- Gluons play a crucial role to account for the proton mass
- Following first EMC results (Small quark spin contribution), a scenario - theoretically very controversial - has been discussed with a large gluon spin contribution, much larger than the proton spin itself!
- Gluon spin contribution unstrained in previous inclusive polarized fixed-target scattering experiments

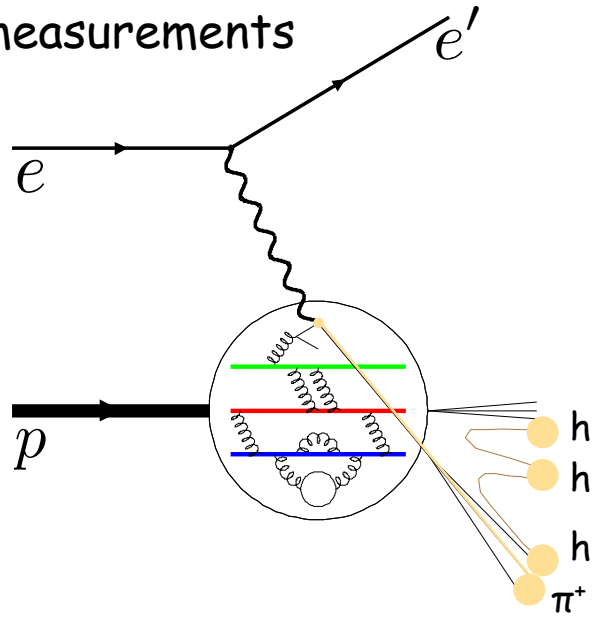


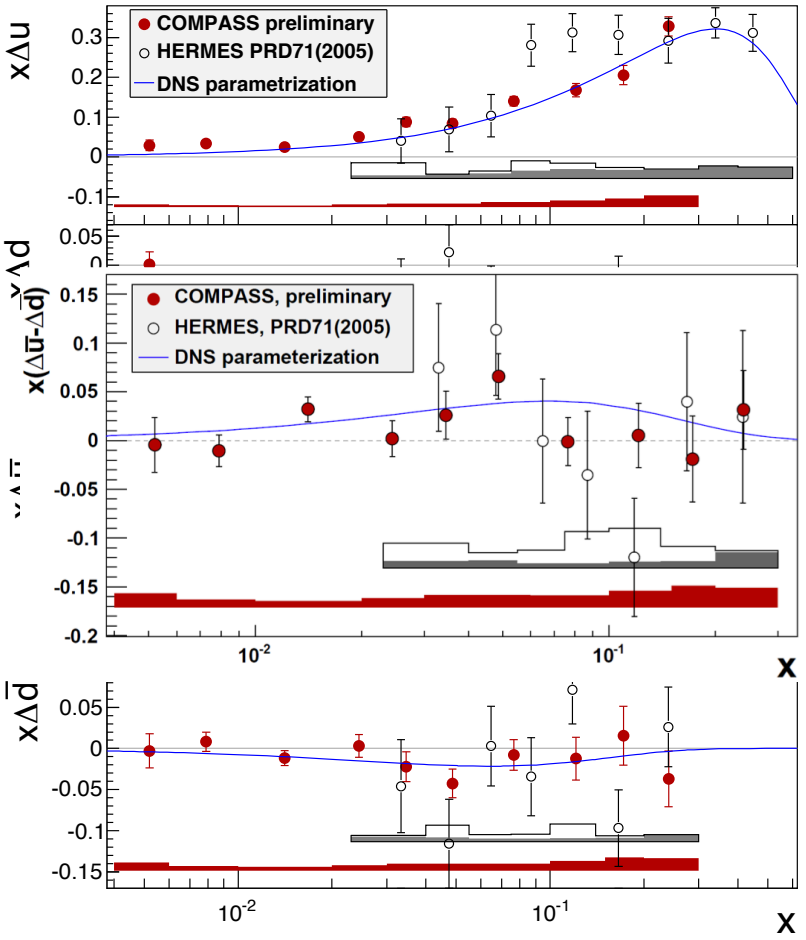


- Photon-gluon fusion process employing hadron pair production and charm production (So far, no theory framework to include in global QCD analysis)
- Leading order (LO), model dependent analysis by SMD, COMPASS and HERMES point to small $\Delta g/g$ around x=0.1
- Great value of independent probe at large momentum scales to be used in full NLO global analysis

Backup

- Previous measurements





- Semi-inclusive DIS: Correlation of flavor content of hadron with flavor of quark / antiquark probed
- Good agreement of COMPASS and HERMES LO analysis
- Good agreement with global fit analysis / Sea quark distributions compatible with zero
- Great value of independent probe at large momentum scales without hadronic fragmentation