Selected topics in High-energy QCD physics

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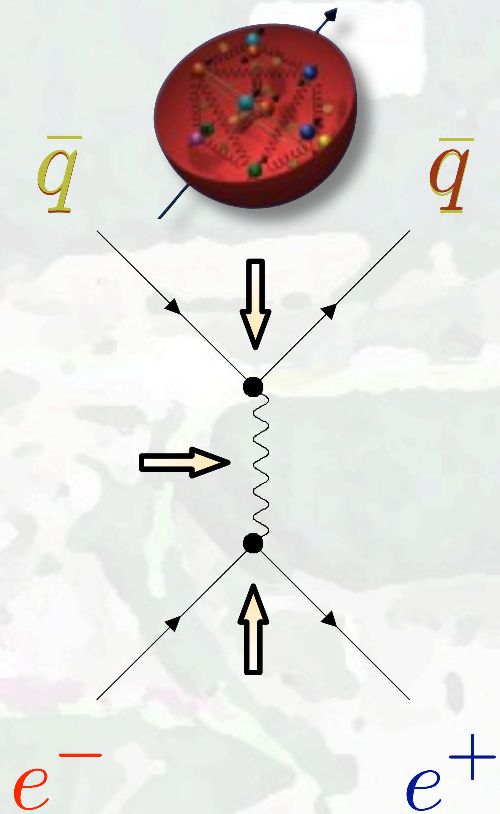
Outline

- Recent results in high-energy QCD physics



- QCD - Theoretical Foundation
- QCD Features
- Summary and Outlook

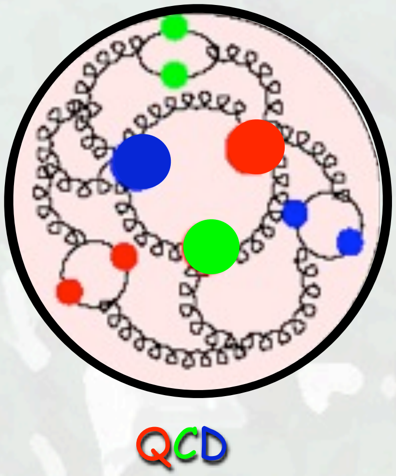
QCD Features

QCD - Features

$$\mathcal{L}_{QCD} = \bar{\psi}\left[i\gamma^{\mu}\partial_{\mu} - m\right]\psi - g_s\bar{\psi}\gamma^{\mu}G^a_{\mu}\frac{\lambda_a}{2}\psi - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_{\mu}G^a_{\nu} - \partial_{\nu}G^a_{\mu} - g_s f^a_{bc}G^b_{\mu}G^c_{\nu}$$

- Interactions arise from fundamental symmetry principles: $SU(3)_c$
- Visible phenomena (e.g. proton) emerge through complex structure of the vacuum (e.g formation of Hadrons from quarks/gluons)
- Fundamental differences to QED:
  - Self-interacting: highly nonlinear
  - Interaction increases at large distances: Confinement
  - Interaction decreases at small distances: Asymptotic freedom
  - Strong coupling: $\alpha_s \gg \alpha_{em}$
  - Topological excitations



QCD Features

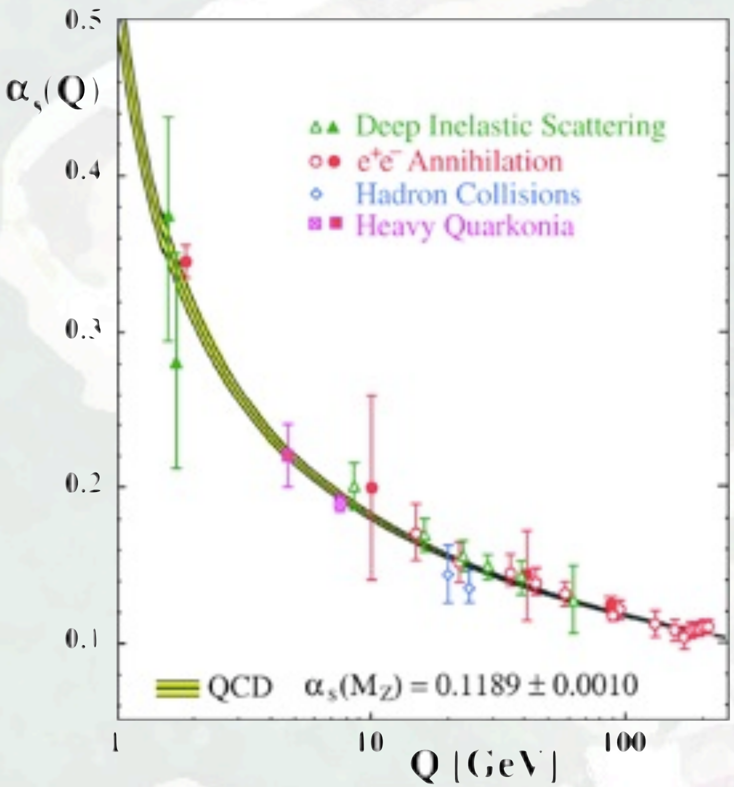
- QCD - Profound differences between hadrons and other many-body systems
  - Atoms, molecules, nuclei,...:
    - Constituents can be removed
    - Exchanged boson generating interaction may be subsumed into static potential (e.g. photon into Coulomb potential)
    - Most of mass from fermion constituents
  - Nucleons:
    - Quarks are confined
    - Gluons are essential degrees of freedom
    - Most of mass generated by interactions (~99%)
  - Exploration of QCD: Analytical (e.g. perturbative) / non-perturbative (e.g. Lattice QCD - Numerical solution on space-time lattice) methods in comparison to experimental results

Force-dominated matter

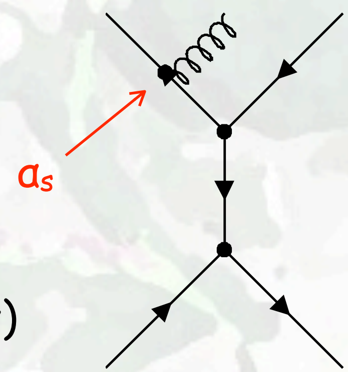
matters

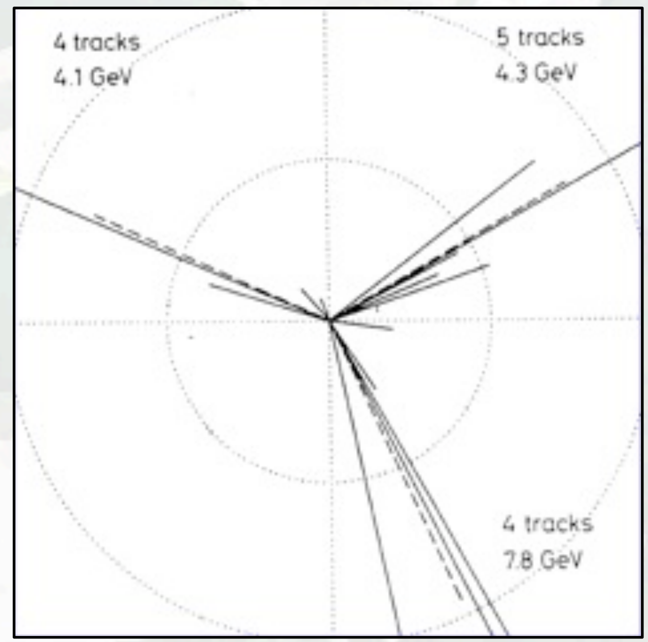
QCD Features

QCD - Perturbative Side



Discovery of asymptotic freedom in the theory of strong interaction (Quantum Chromo Dynamics): Nobel prize in physics 2004



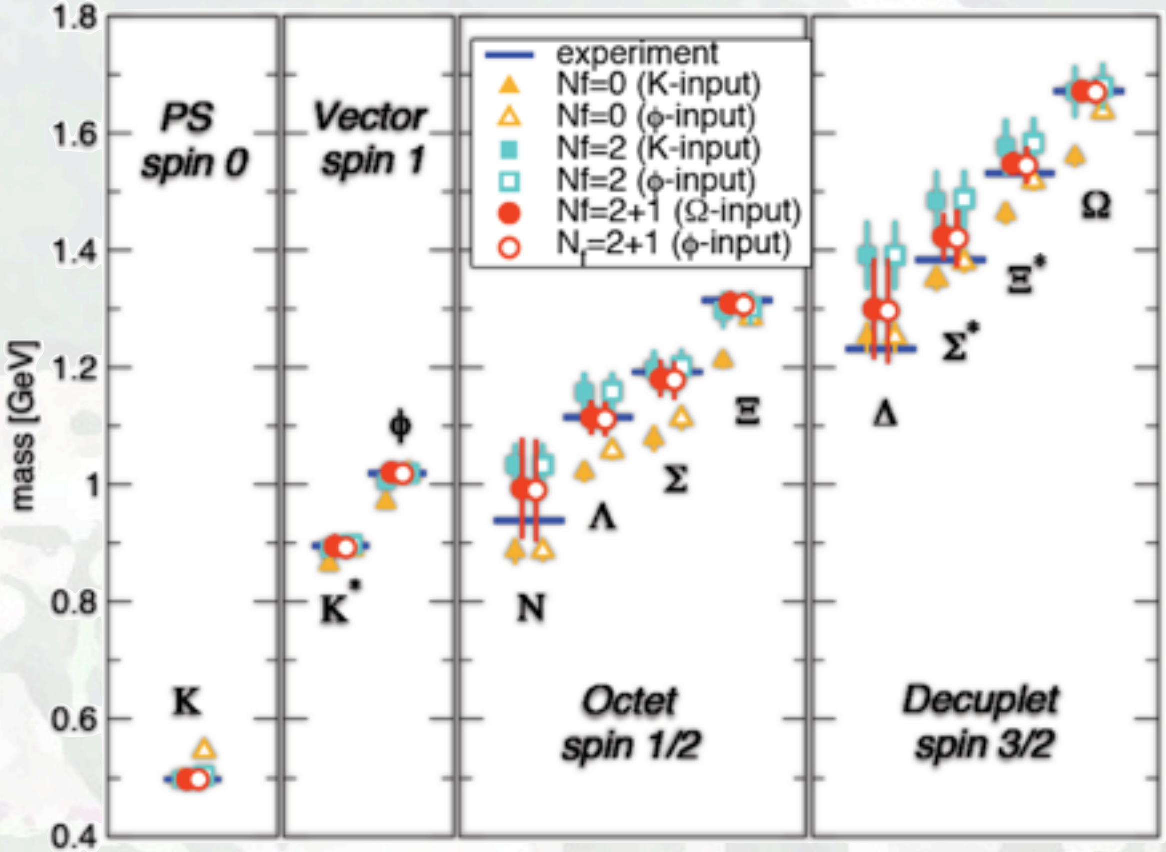


TASSO Collaboration, R. Brandelik et al., Phys. Lett. B 86 (1979) 243.

- α_s large at large distances (low energy)
- α_s small at small distances (high energy)

QCD Features

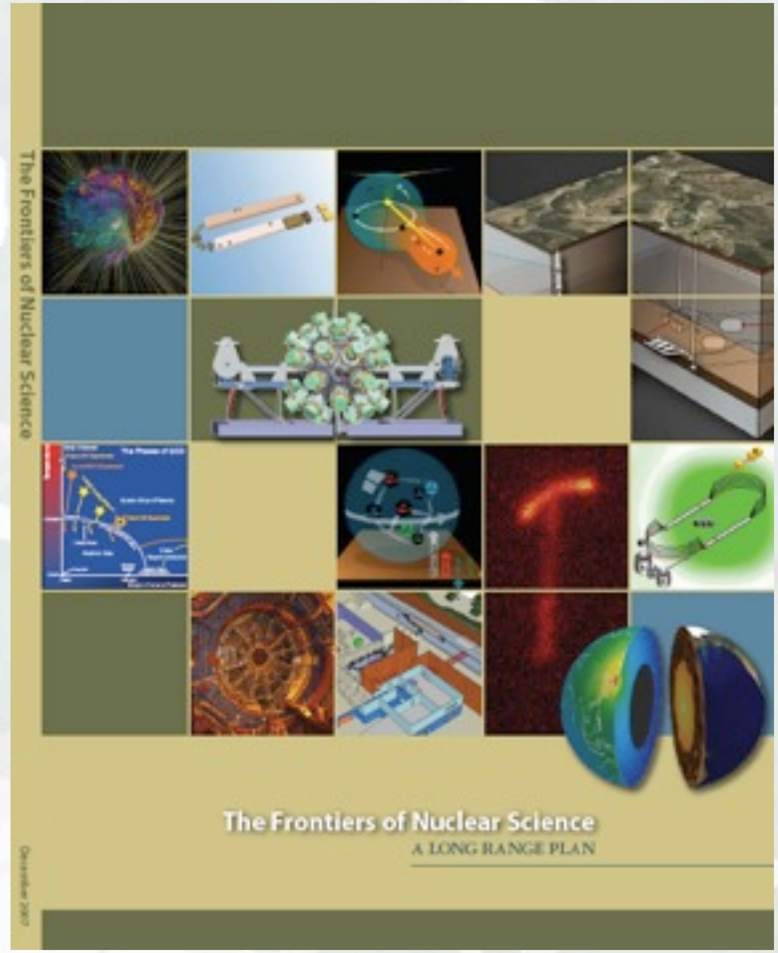
- QCD - Non-Perturbative Side
  - Lattice QCD: Numerical solution of path integrals on space-time lattice
  - Successful description of various hadron properties (e.g. mass spectrum in the context of lattice QCD calculations)
  - For a large class of problems (e.g. hadron formation from quarks), phenomenological methods and modeling are indispensable



Y. Kuramashi, Lattice 2007, PACS-CS Collaboration

QCD Features

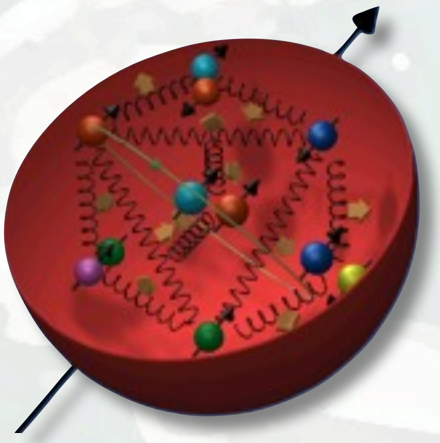
- QCD - Questions (The Frontiers of Nuclear Science - Long Range Plane 2007)
  - What is the internal landscape of the nucleons?
  - What does QCD predict for the properties of strongly interacting matter?
  - What governs the transition of quarks and gluons into hadrons?
  - What is the role of gluons and gluon self-interactions in nucleons and nuclei?
  - What are the phases of strongly interacting matter?
  - What determines the key features of QCD?

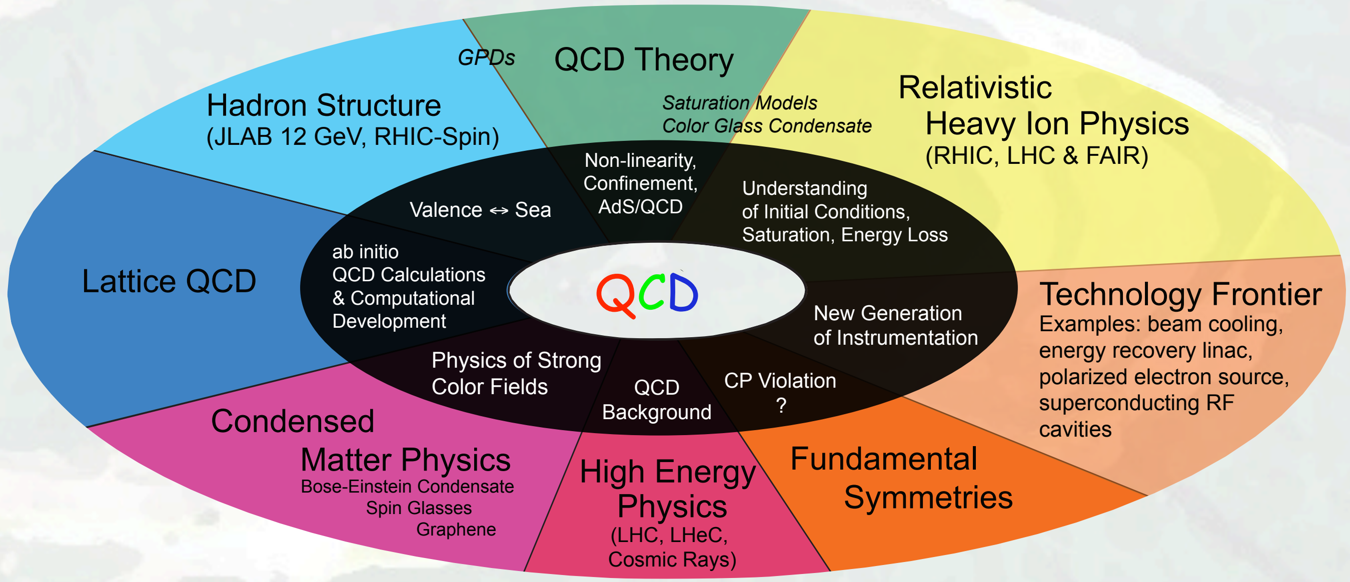


http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

QCD Features

- Exploring the proton 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) critical!

QCD Features

- Mass in QCD

Quote from Nobel prize lecture in physics, 2004, given by Professor Frank Wilczek (MIT):

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.)"

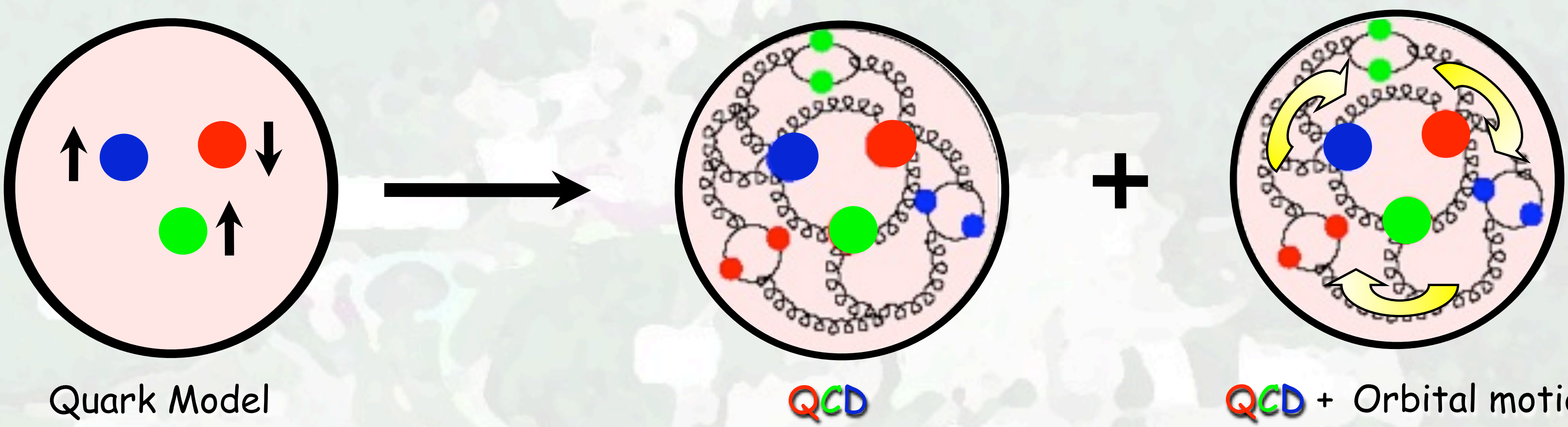
Modern QCD: Mass of ordinary matter derives almost entirely from energy - the energy of massless gluons and nearly massless quarks, which are the ingredients from which protons, neutrons, and atomic nuclei are made.

QCD Features

Spin in QCD

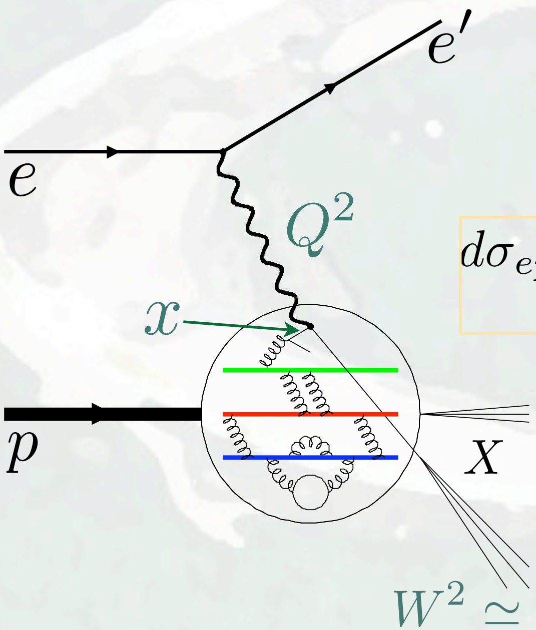
- Traditional way to introduce spin in QM textbooks: Stern-Gerlach experiment (1922)
- Concept of spin: Long and tedious battle to understand splitting patters and separations in line spectra
- Anomalous magnetic moment of proton by Stern et al. (1933)

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

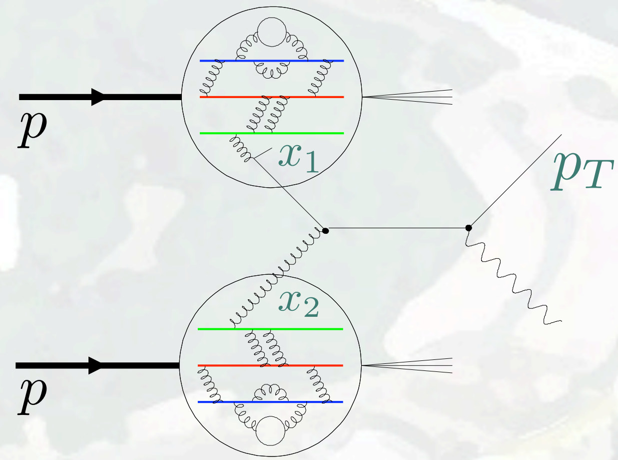


QCD - Theoretical foundation

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



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

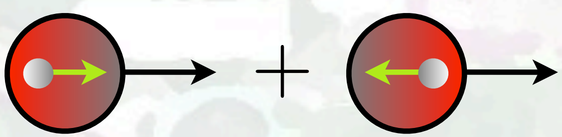


Universality

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

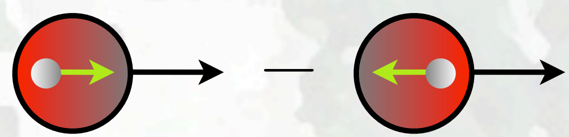
Momentum contribution

$f(x) =$



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

$\Delta f(x) =$



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

Spin contribution

QCD - Theoretical foundation

- Fundamental QCD ingredients

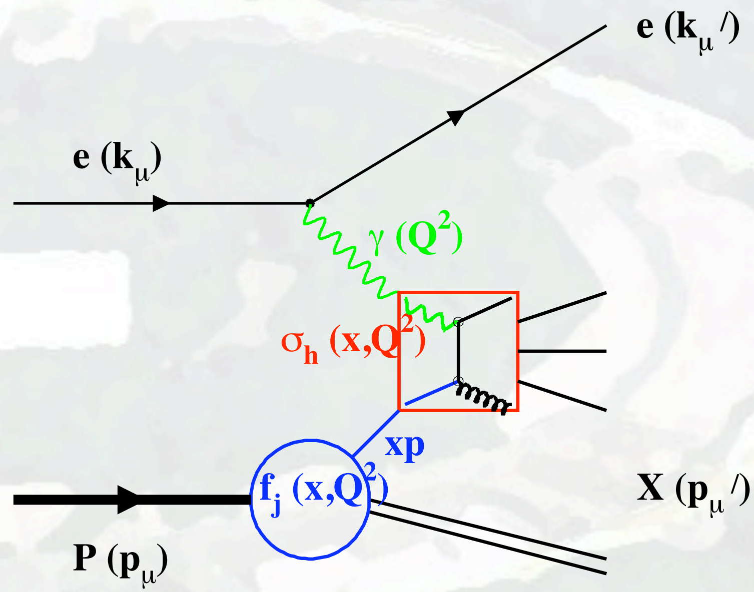
  - Asymptotic freedom:

    $\alpha_s \rightarrow 0$ at short distances:

    $\Rightarrow$ perturbative QCD

    α_s large at long distances:

    $\Rightarrow$ non-perturbative QCD



  - Factorization: hard scale Q^2, m_c, m_b

$$\sigma^{ep} = \gamma(x, Q^2) \otimes f_j(x, Q^2) \otimes \hat{\sigma}(x, Q^2)$$

non-perturbative part

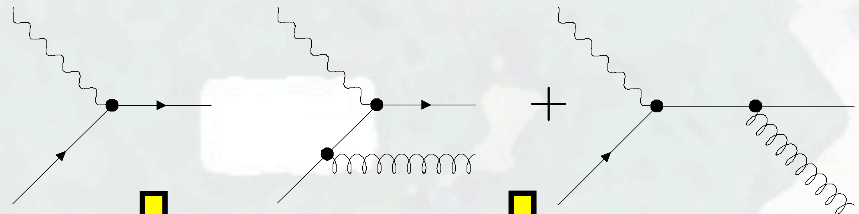
  - Evolution:
    - Beyond Quark-Parton model, Parton densities become functions of Q^2
    - Predict Q^2 dependence of parton distribution functions (DGLAP evolution equations)

QCD - Theoretical foundation

- Evolution
  - The presence of QCD related diagrams leads to a modification of F_2

$$F_2 = \nu W_2$$

$$\nu = \frac{p \cdot q}{m_p}$$



$$\frac{F_2(x,Q^2)}{x} = \sum_i Q_i^2 \int_0^1 \left(\frac{dy}{y}\right) q(y) \left(\delta\left(1-\frac{x}{y}\right) + \left(\frac{\alpha_s}{2\pi}\right) P_{qq}\left(\frac{x}{y}\right) \log\frac{Q^2}{\mu^2} \right)$$

Parton model: $\delta\left(1-\frac{x}{y}\right)$

Gluon radiation: $\left(\frac{\alpha_s}{2\pi}\right) P_{qq}\left(\frac{x}{y}\right) \log\frac{Q^2}{\mu^2}$

Logarithmic violation of scaling: $\log\frac{Q^2}{\mu^2}$

Splitting function: $P_{qq}\left(\frac{x}{y}\right)$

$$q(y) \equiv f_q(y)$$

$$\frac{F_2(x,Q^2)}{x} = \sum_i Q_i^2 \int_0^1 \left(\frac{dy}{y}\right) \left(q(y) + \Delta q(y,Q^2)\right) \delta\left(1-\frac{x}{y}\right) =$$

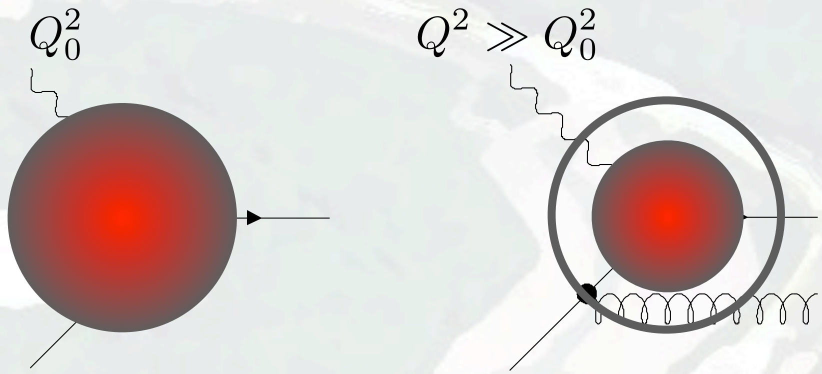
$$\sum_i Q_i^2 \left(q(x) + \Delta q(x,Q^2)\right)$$

Quark densities depend on x and Q^2: →

$$\Delta q(x,Q^2) = \left(\frac{\alpha_s}{2\pi}\right) \log\left(\frac{Q^2}{\mu^2}\right) \int_x^1 \left(\frac{dy}{y}\right) q(y) P_{qq}\left(\frac{x}{y}\right)$$

QCD - Theoretical foundation

- Evolution of parton distribution functions (1)
  - Consider the change of the quark density $\Delta q(x,Q^2)$ over an interval of $\Delta \log Q^2$
  - General including other types of splitting functions:



$$\frac{d}{d\log Q^2} q(x,Q^2) = \left(\frac{\alpha_s}{2\pi}\right)\int_0^1 \left(\frac{dy}{y}\right) q(y,Q^2) P_{qq}\left(\frac{x}{y}\right)$$

Probability of finding a parton of type i with momentum fraction x which originated from parton j having momentum fraction y!

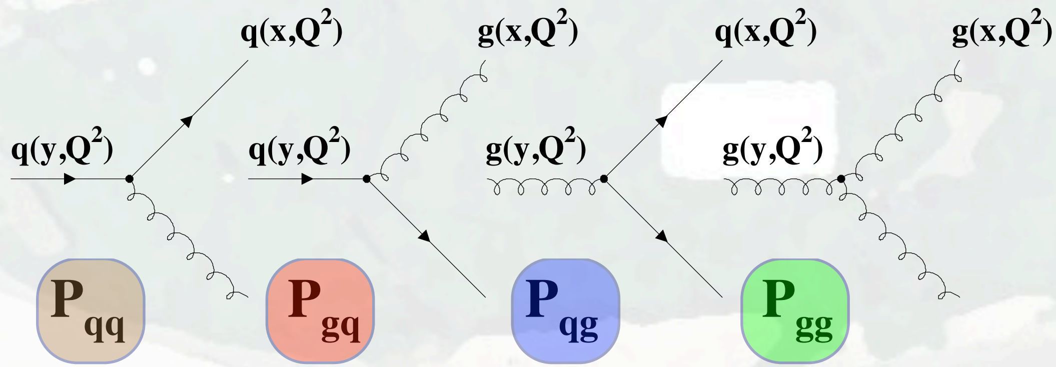
Singlet distribution $$\Sigma(x,Q^2) = \sum_{i=1}^{n_f}\left[q_i(x,Q^2) + \bar{q}_i(x,Q^2)\right]$$

Gluon distribution $$g(x,Q^2)$$

$$P_{ij}\left(\frac{x}{y}\right)$$

QCD - Theoretical foundation

- Evolution of parton distribution functions (2)
  - Types of splitting functions



Probability of finding a parton of type i with momentum fraction x which originated from parton j having momentum fraction y!

$$P_{ij}\left(\frac{x}{y}\right)$$

$$\frac{d\Sigma(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{qq}\left(\frac{x}{z}\right)\Sigma(z,Q^2) + P_{qg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{gq}\left(\frac{x}{z}\right)\Sigma(z,Q^2) + P_{gg}\left(\frac{x}{z}\right)g(z,Q^2)\right]$$

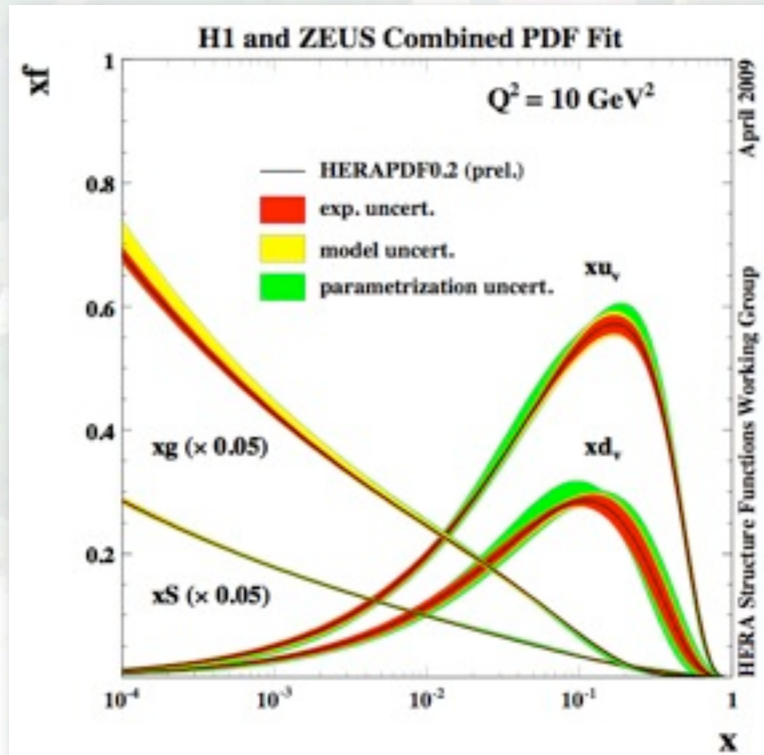
DGLAP evolution equations:

G. Altarelli and G. Parisi, Nucl. Phys. B 126 (1977) 298; V. Gribov and L.N. Lipatov, Soc. J. Nucl. Phys. 15 (1972) 438; L.N. Lipatov, Soc. J. Nucl. Phys. 20 (1975) 96; Y.L. Dokshitzer, Soc. Phys. JETP 46 (1977) 641.

QCD - Theoretical foundation

- Global fits
  - Determine F_2^{QCD} in terms of parton distribution functions
  - Evolve F_2^{QCD} through parton distribution functions based on evolution equations
  - Minimize χ^2 in terms of F_2^{QCD} and F_2^{data} by adjusting parameters in $xf_i(x,Q^2)$
  - Net result: QCD prediction for $xf_i(x,Q^2)$ and therefore $F_2(x,Q^2)$
  - Various global pdf analysis:
    - GRV
    - CTEQ
    - MRST

$$xf_i(x,Q_0^2) = A_i x^{-\lambda_i}(1-x)^{\eta_i}F(x)$$

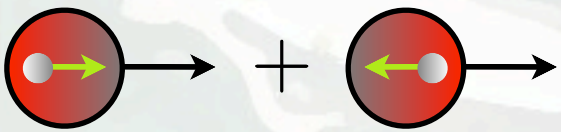


Low x: λ_i High x: η_i

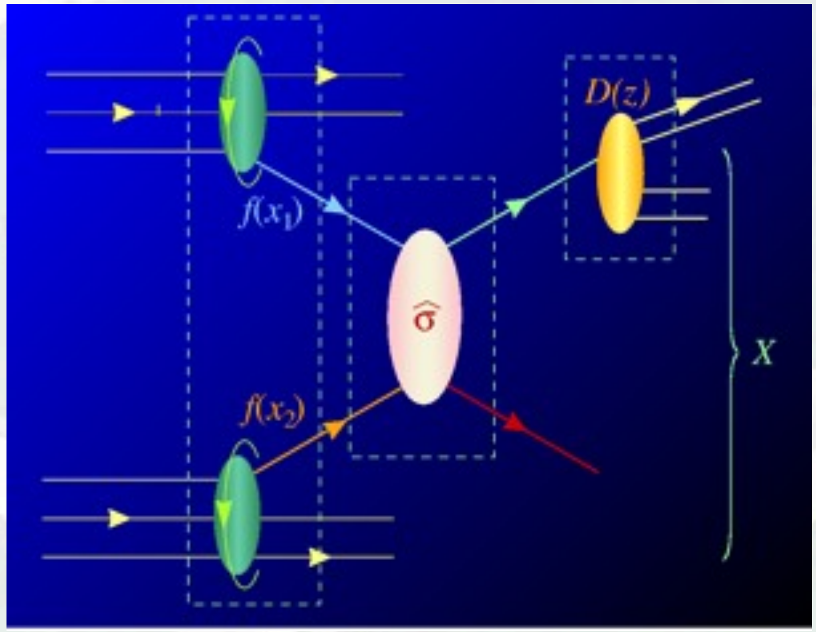
QCD - Theoretical foundation

- Factorization
  - Unpolarized proton structure:

$$f(x) =$$



$$f^{+}(x) + f^{-}(x)$$



long-range | short-range | long-range

$$\sigma_{pp\rightarrow\pi X} = \sum_{f_1,f_2} f_1 \otimes f_2 \otimes \hat{\sigma} \otimes D_f^{\pi}$$

- Three step process:
  - Partons (quarks/gluons) in initial state: Long distance (non-perturbative QCD domain)

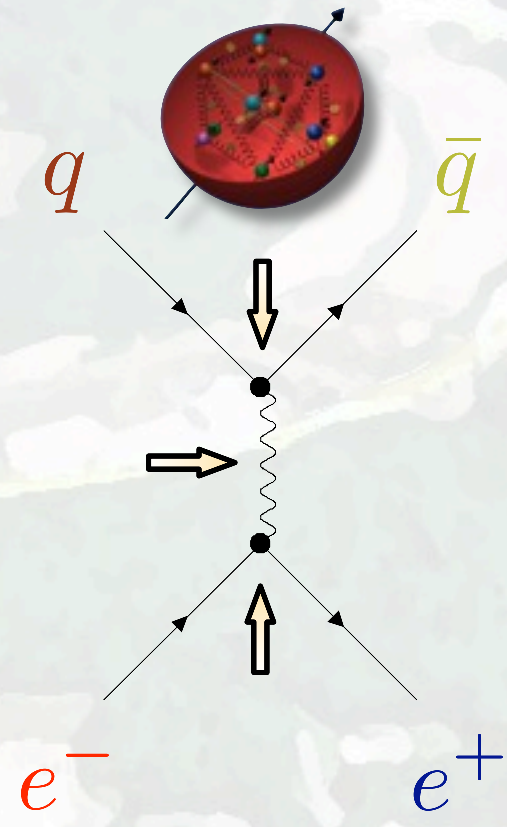
    ⇒ Parton (quarks/gluons) distribution functions
  - Hard interaction: Small distances (high energies) (perturbative QCD domain)

    ⇒ Cross-section prediction (LO,NLO,NNLO)
  - Quarks in final state: Long distance (non-perturbative QCD domain):

    ⇒ Quarks fragment into observable hadrons described by fragmentation functions

Recent results in high-energy QCD physics

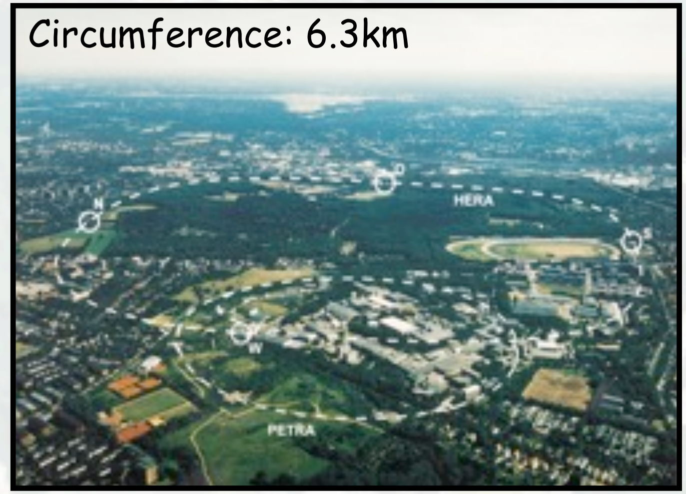
- Overview
  - Collider programs:
    - Hadron-Hadron: Tevatron/ RHIC
    - Electron-Hadron: HERA
    - Electron/Positron: LEP
  - QCD topics
    - QCD factorization
    - Parton-distribution functions / Fragmentation functions
    - Strong-coupling constant
    - Jet algorithms
    - QCD matrix elements in LO, NLO, NNLO
    - Multi-leg final states
    - Low-x physics
    - Soft processes: Underlying event / Hadronization / Diffraction



Recent results in high-energy QCD physics

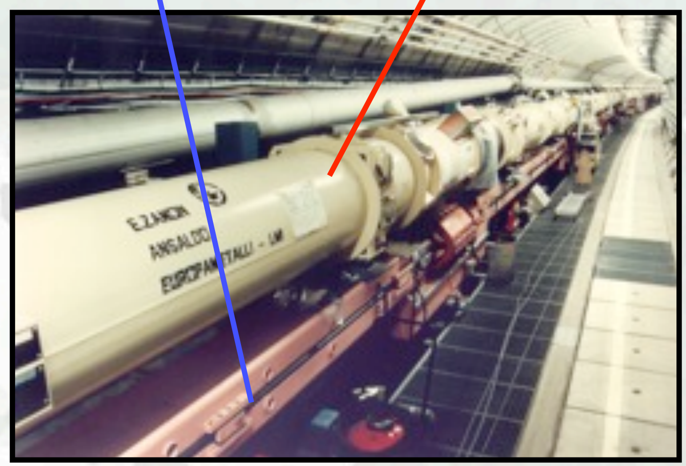
- Experimental QCD tests in ep
  - Measurement of α_s
  - Fragmentation functions
  - Extraction of parton distribution functions
  - Color/spin dynamics
  - Quark-Gluon jet properties
  - Event shape variables (Sphericity, thrust, ...)
  - Diffraction

DESY



E_e = 27.5 GeV

E_p = 920 GeV



Recent results in high-energy QCD physics

- Experimental QCD tests in ee
  - Measurement of α_s
  - Fragmentation functions
  - Color/spin dynamics
  - Quark-Gluon jet properties
  - Event shape variables (Sphericity, thrust, ...)

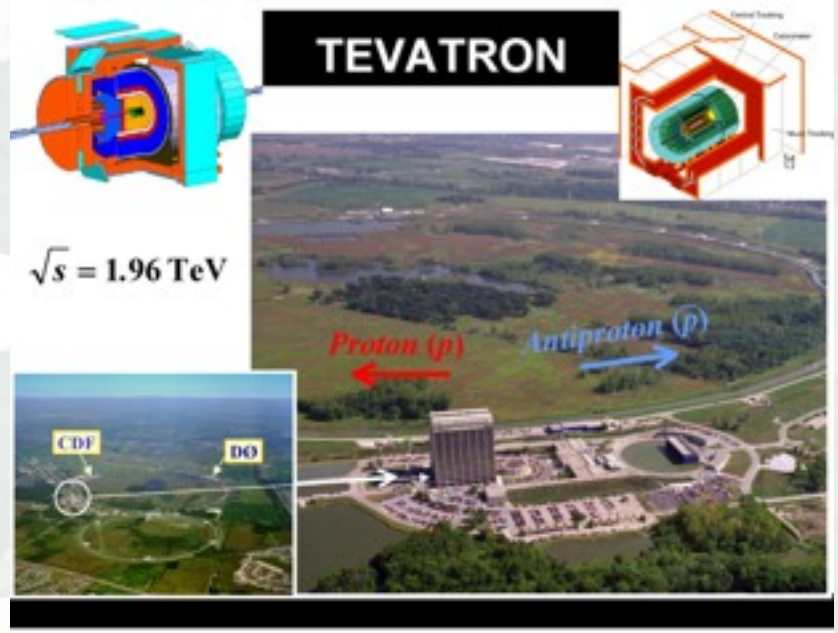
CERN

LEP: Centre-of-mass energy (e^+e^-) up to 205GeV

Recent results in high-energy QCD physics

- Experimental QCD tests in pp
  - Measurement of α_s
  - Fragmentation functions
  - Extraction of parton distribution functions
  - Color/spin dynamics
  - Quark-Gluon jet properties
  - Event shape variables (Sphericity, thrust, …)
  - Diffraction

FNAL

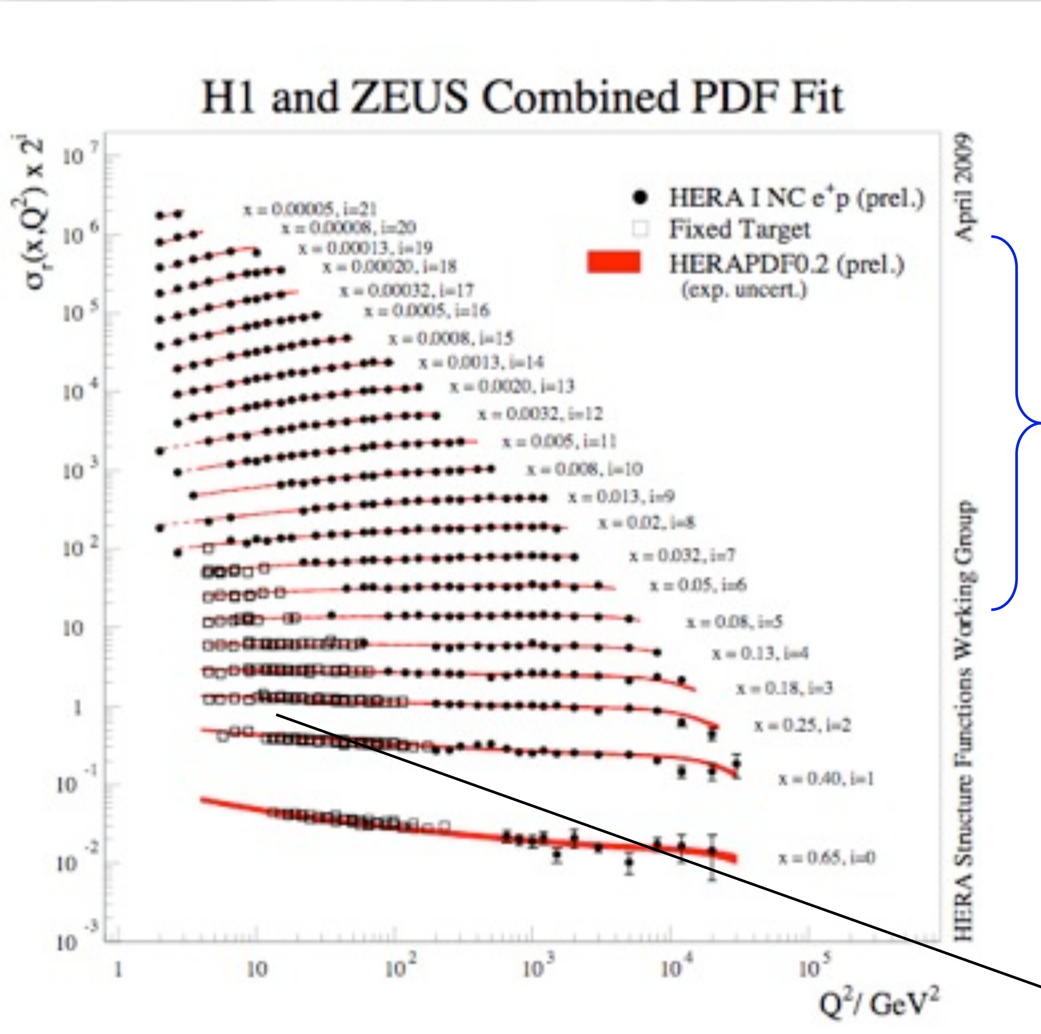


BNL

RHIC: Centre-of-mass energy 200-500GeV (polarized protons)

Recent results in high-energy QCD physics

- Precision measurements (e.g. F_2) ⇒ Precision on quark/gluon structure

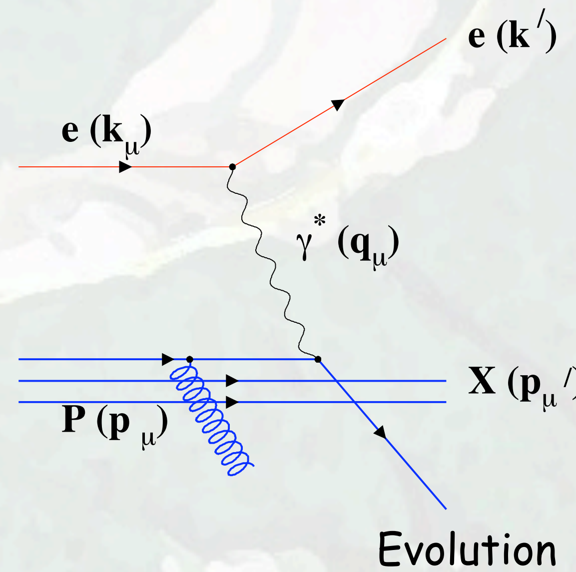


Strong violation of scaling at low x and high Q^2

$$xg \propto \left(\frac{dF_2}{d\ln Q^2}\right)$$

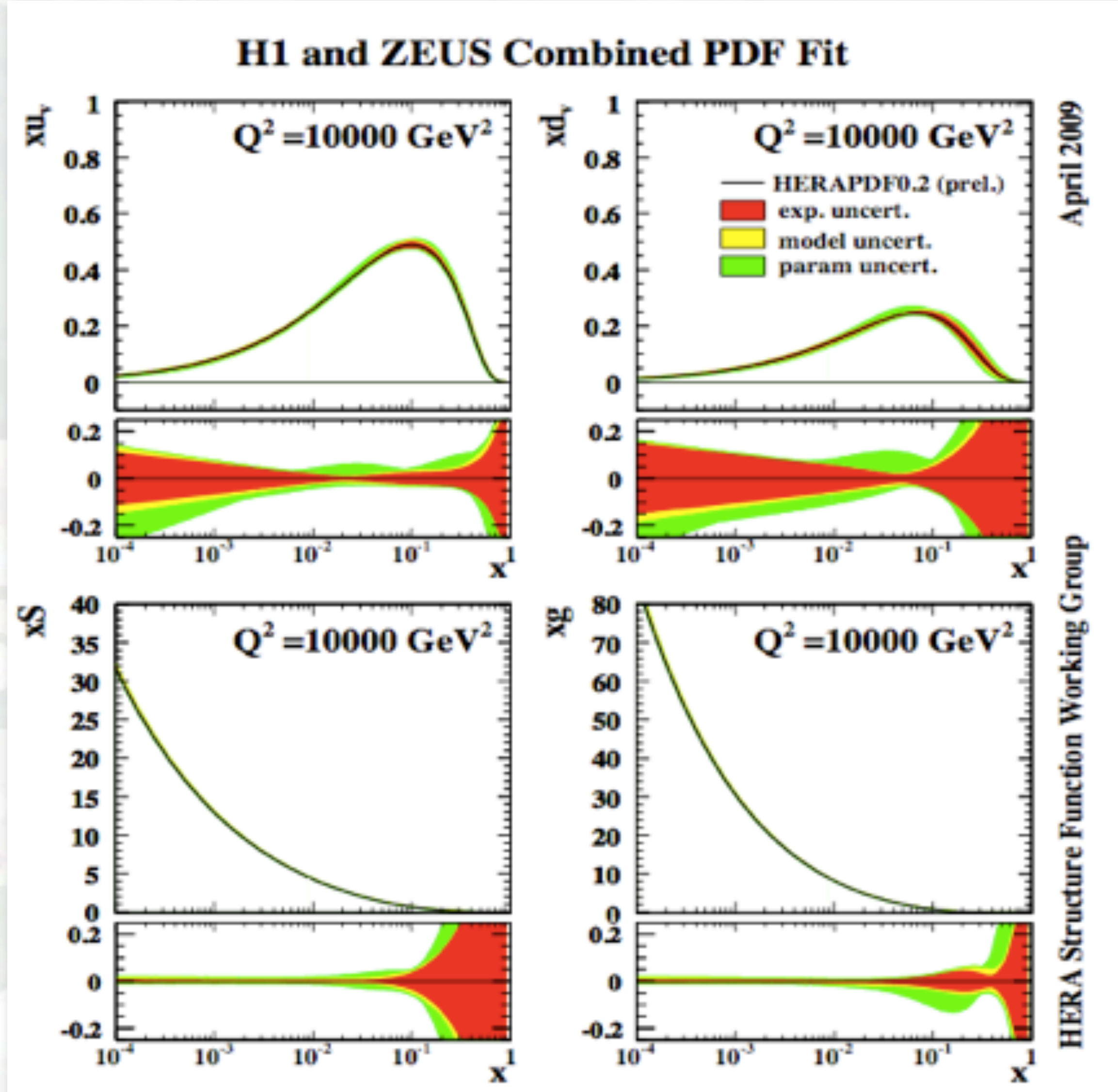
In contrast to:

Low Q^2 high x!



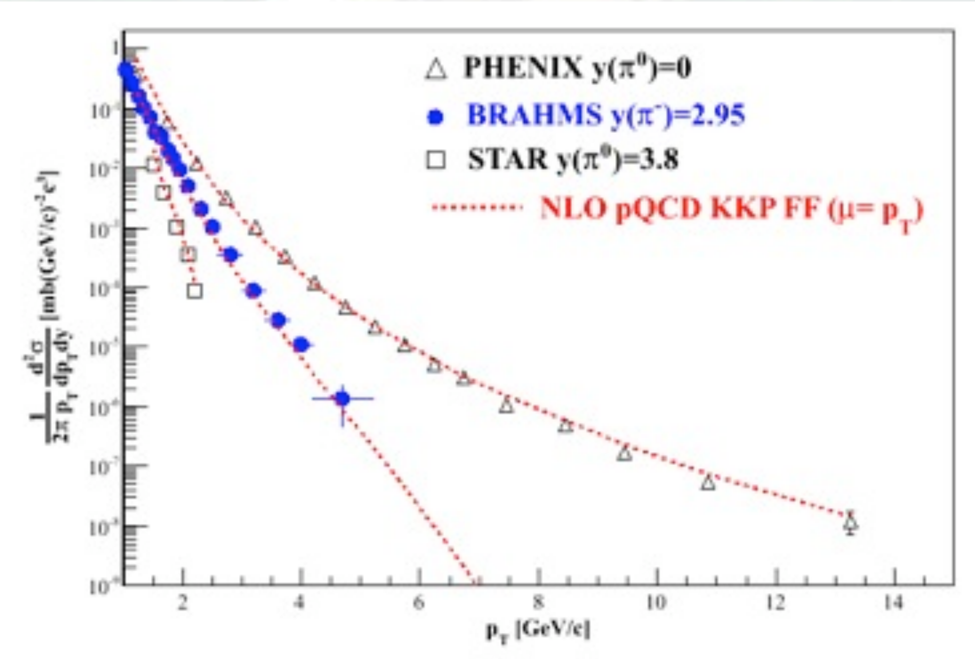
Recent results in high-energy QCD physics

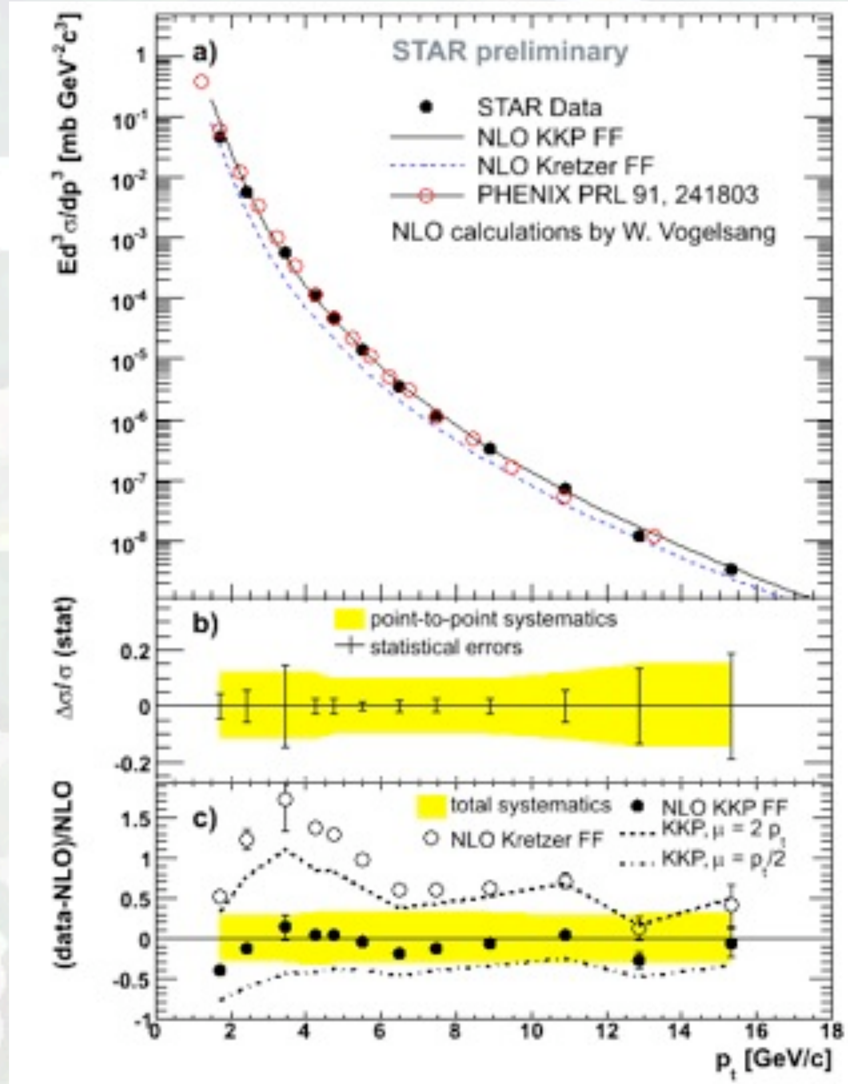
- Precision on quark/gluon structure
  - Enormous precision reached over a wide kinematic region
  - Large uncertainties for all distribution functions at large momentum fractions:
    - Impact of W/Z program at LHC
    - Impact of high-E_T jet production



Recent results in high-energy QCD physics

- Cross Section Results - RHIC (Hadrons)

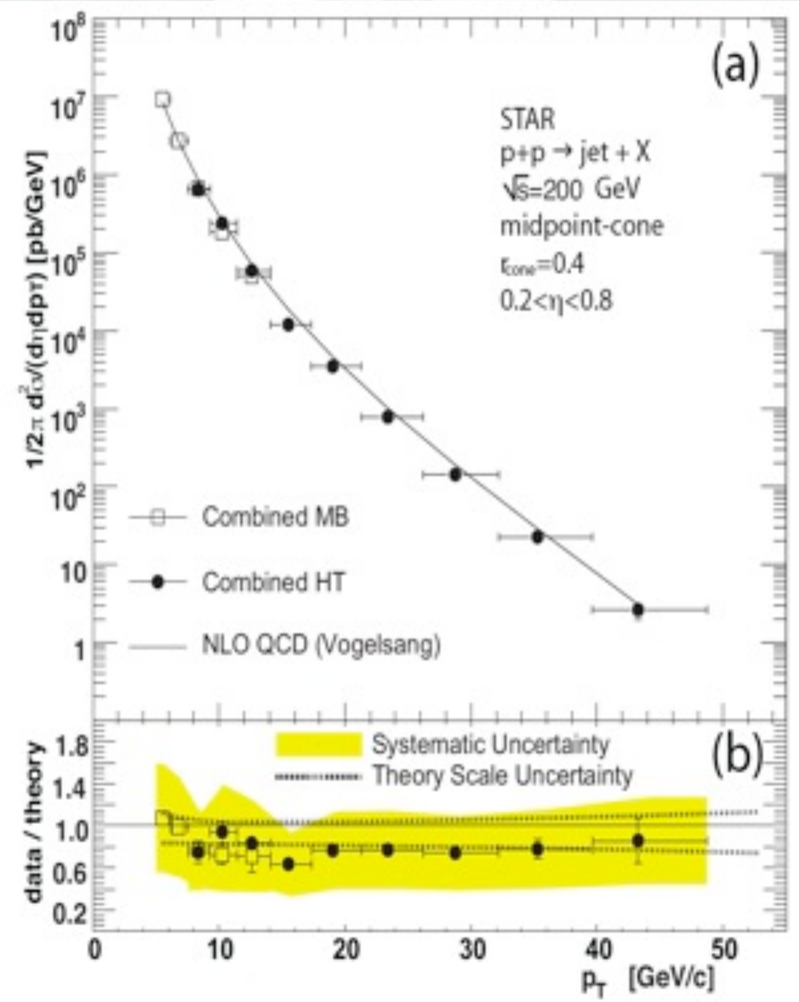


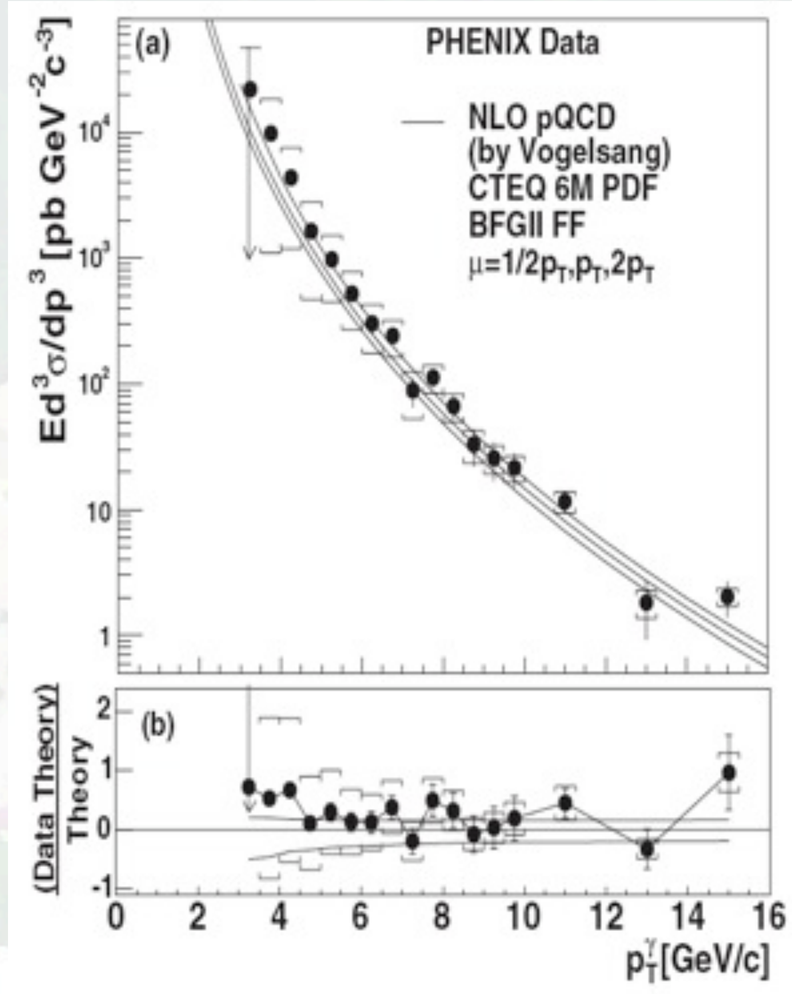


- Good agreement between data and NLO calculations for neutral pion production at forward and central rapidity

Recent results in high-energy QCD physics

- Cross Section Results - RHIC (Jets / Photons)





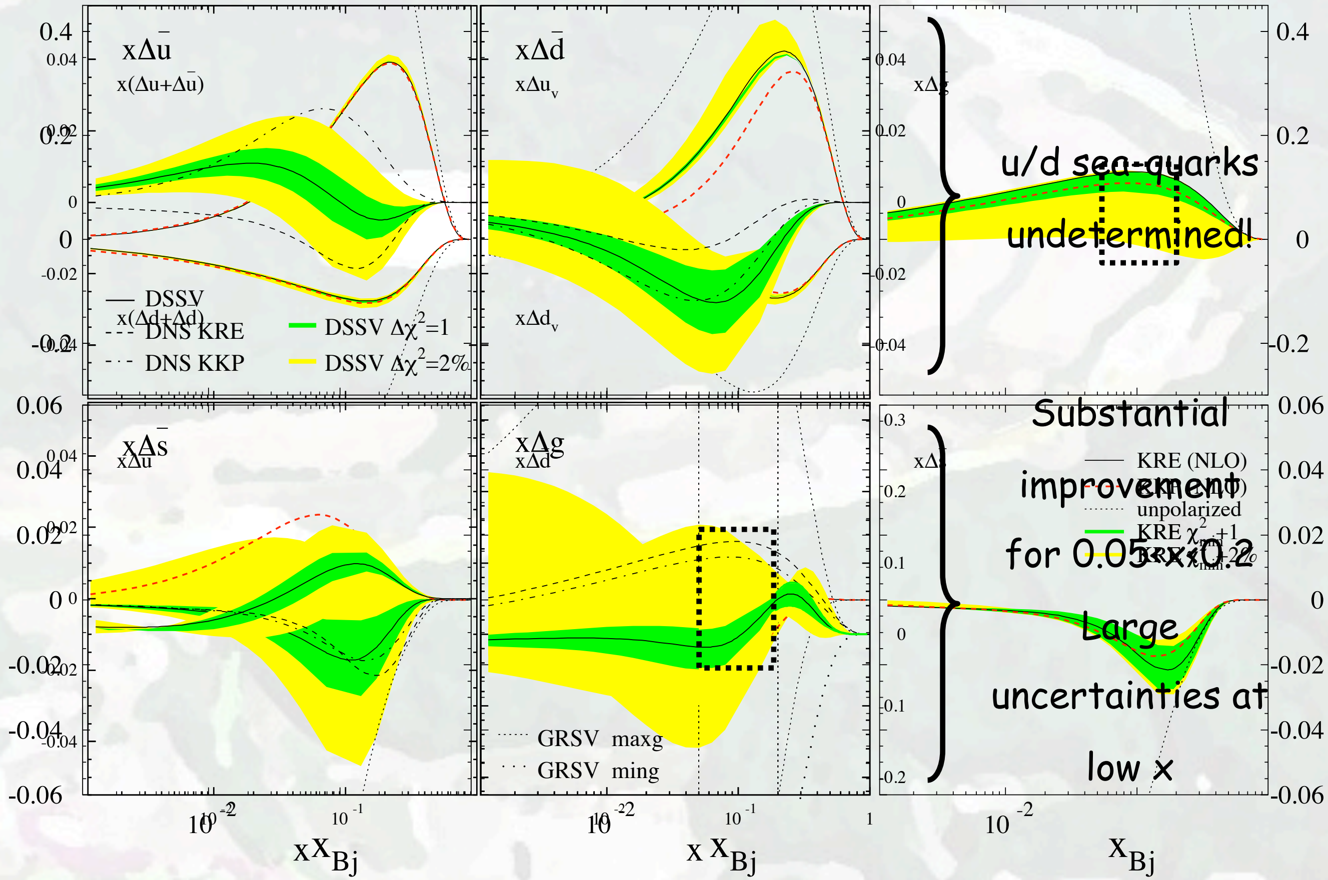
- Good agreement between data and NLO calculations for jet production and prompt photon production at central rapidity

Recent results in high-energy QCD physics

- What do we know about the polarized quark and gluon distributions?
  - Spin carried by quarks is very small ($\Delta\Sigma \sim 0.4$)!

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

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



D. de Florian et al., Phys. Rev. D 71, 094018 (2005).

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

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

Recent results in high-energy QCD physics

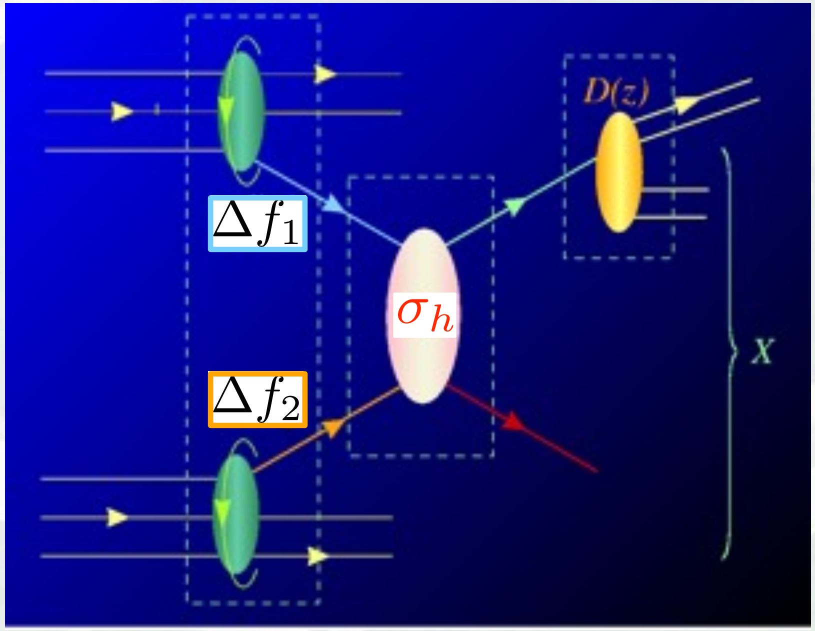
- Gluon polarization - Extraction

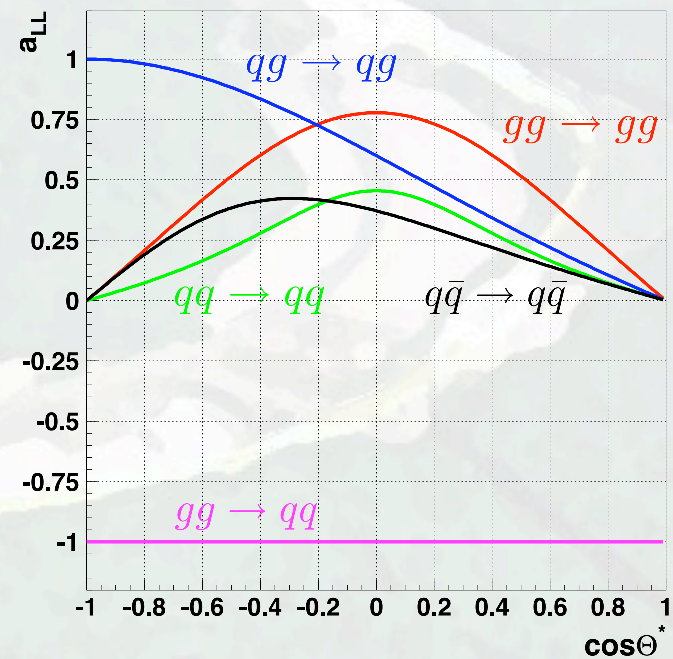
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

Extract $\Delta g(x,Q^2)$ through

Global Fit (Higher Order

QCD analysis)!





long-range short-range long-range

Δf_1 Δf_2

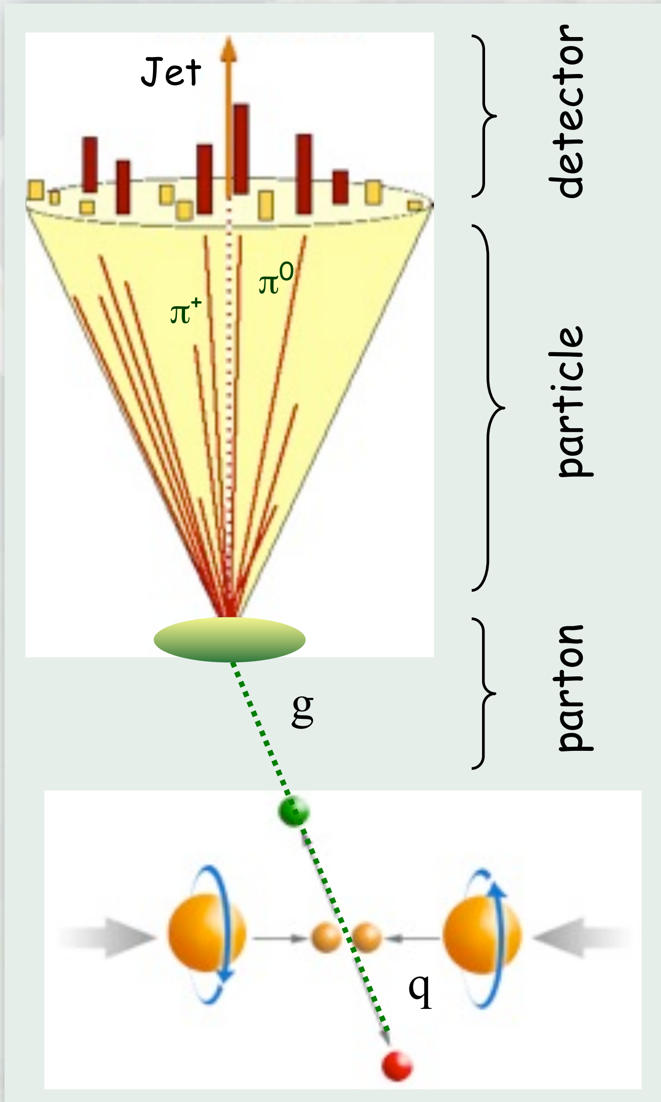
$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$ Input

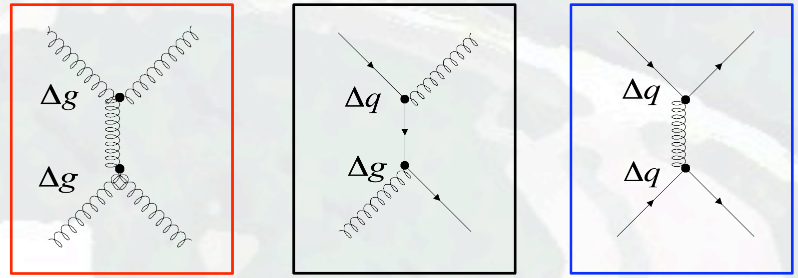
$$A_{LL} = \frac{d\Delta\sigma}{d\sigma}$$

$$\propto \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

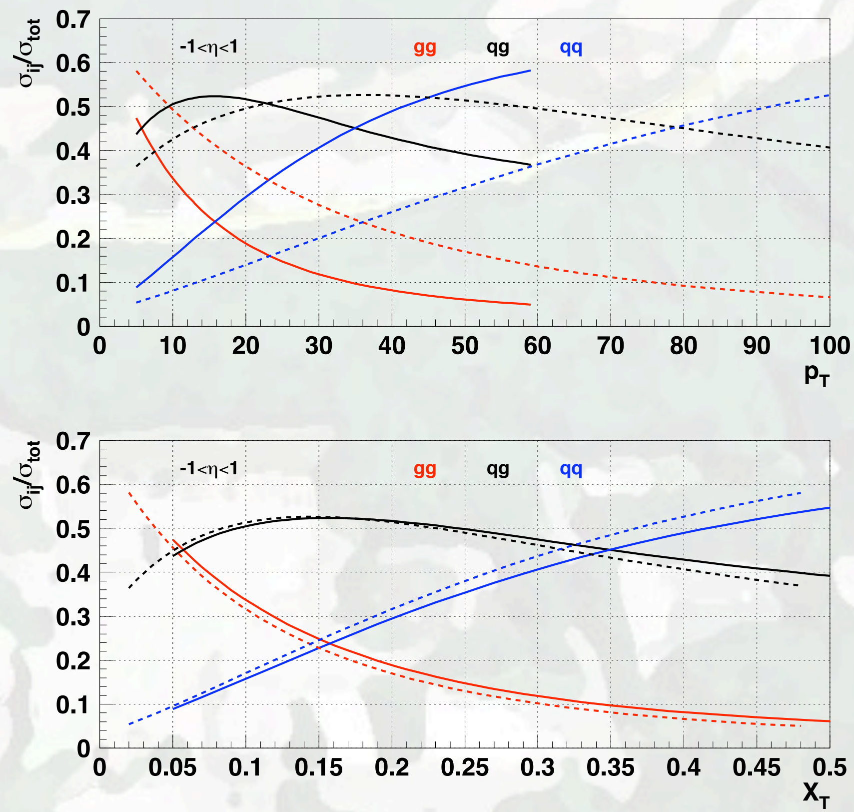
Recent results in high-energy QCD physics

Gluon polarization - Inclusive Measurements





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



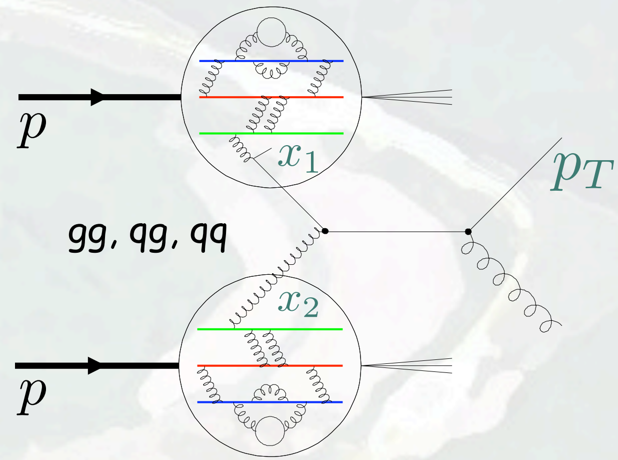
$$x_T = 2p_T/\sqrt{s}$$

Recent results in high-energy QCD physics

Gluon polarization - Correlation Measurements

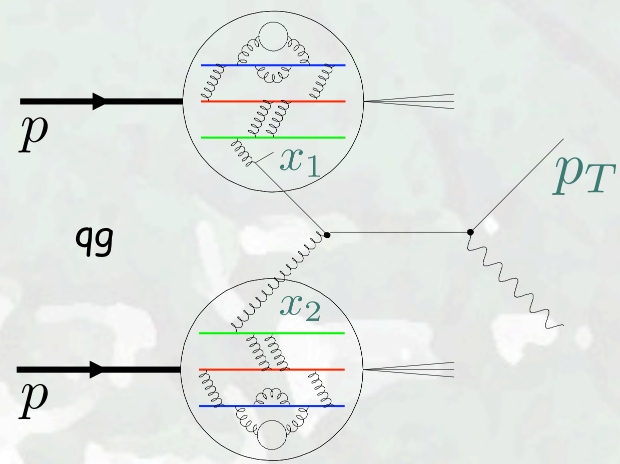
- Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production

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



Di-Jet production

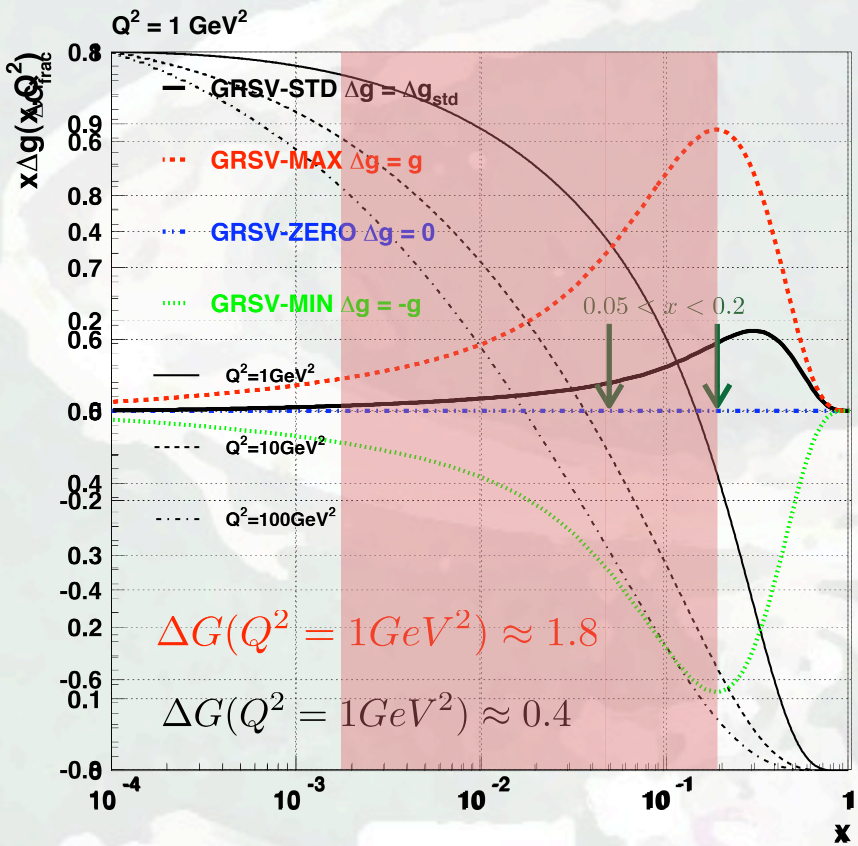
- Di-Jet production / Photon-Jet production
  - Di-Jets: All three (LO) QCD-type processes contribute: gg, qg and qq with relative contribution dependent on topological coverage
  - Photon-Jet: One dominant underlying (LO) process with large partonic a_{LL} at forward rapidity
  - Larger cross-section for di-jet production compared to photon related measurements
  - Photon reconstruction more challenging than jet reconstruction
  - Full NLO framework exists ⇒ Input to Global analysis

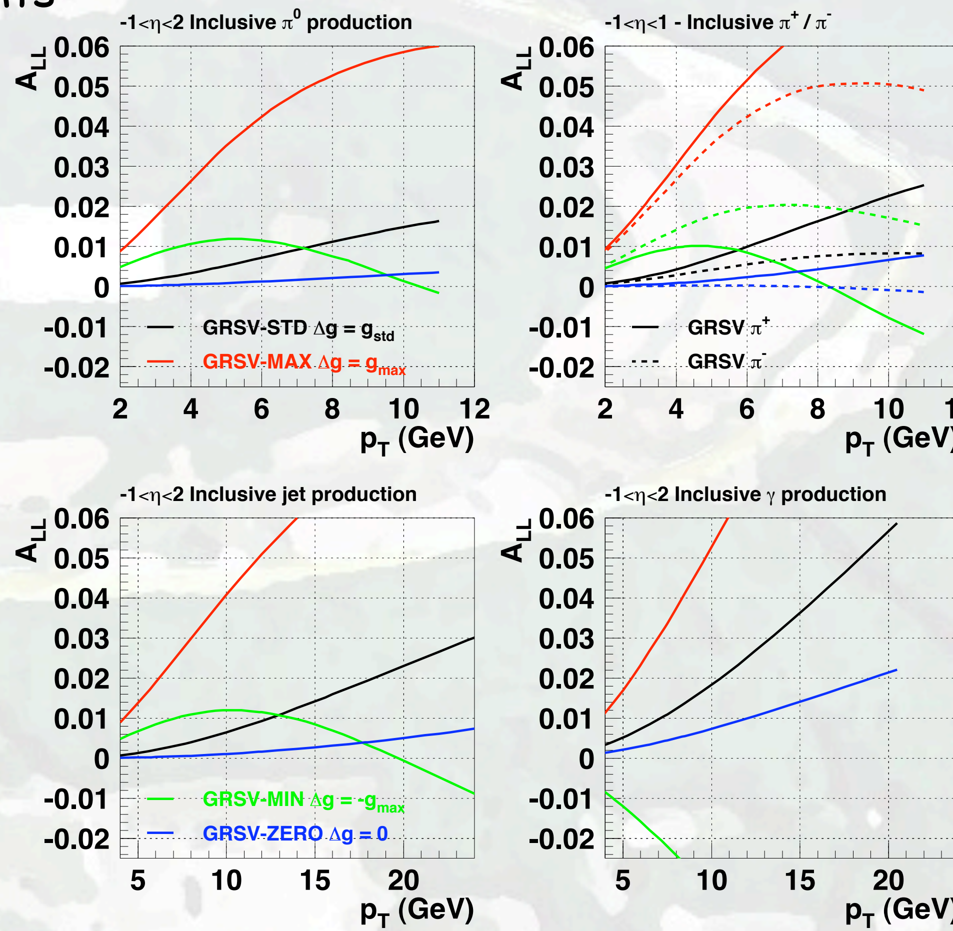


Photon-Jet production

Recent results in high-energy QCD physics

Gluon polarization - Inclusive Measurements





- Examine wide range in Δg: $-g < \Delta g < +g$

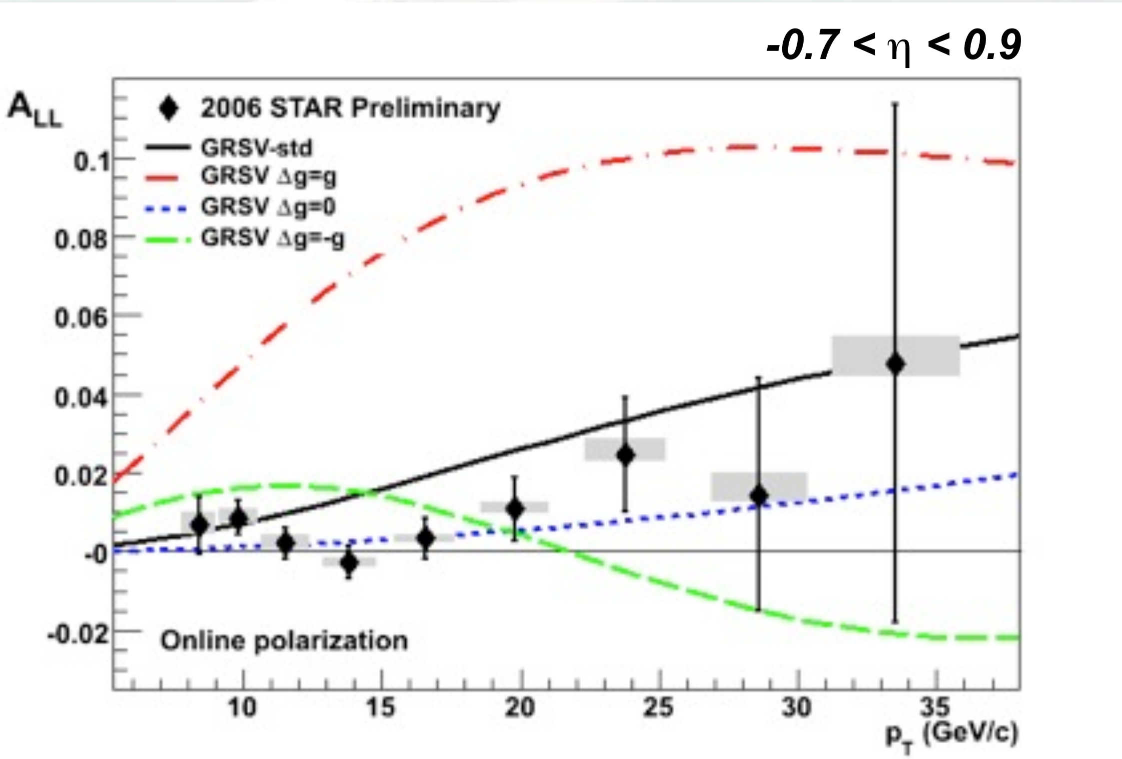
$$x_{\text{parton}} \simeq 2p_T/\sqrt{s}$$

- GRSV-STD: Higher order QCD analysis of polarized DIS experiments!

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

Recent results in high-energy QCD physics

- STAR Inclusive Jet production - RUN 6: A_{LL} ⇨ Gluon spin contribution

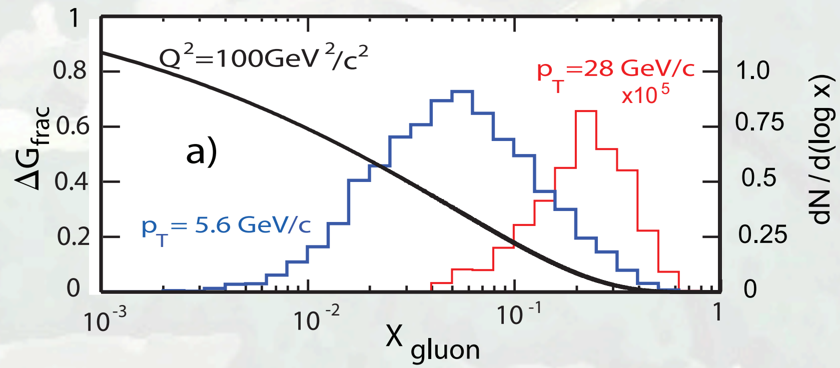


$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

$$\Delta G(Q^2 = 1\,\mathrm{GeV}^2) \approx 1.8$$

$$\Delta G(Q^2 = 1\,\mathrm{GeV}^2) \approx 0.4$$

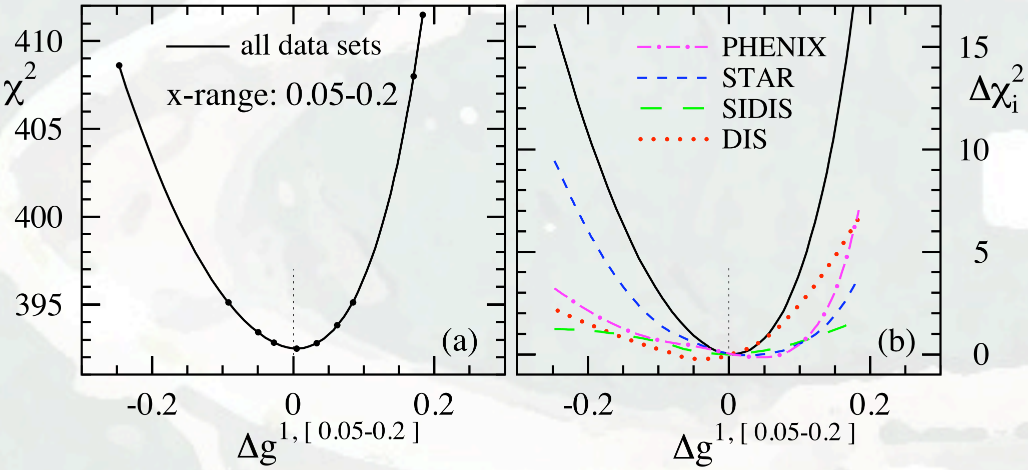
$$x_{\mathrm{parton}} \simeq 2p_T/\sqrt{s}$$



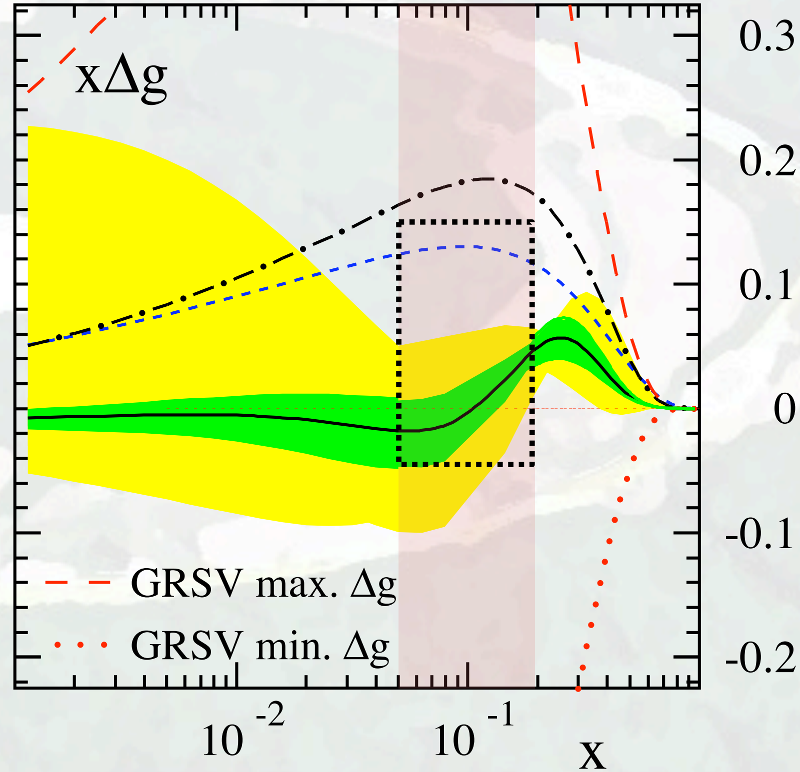
- RUN 6 results: GRSV-MAX / GRSV-MIN ruled out - A_{LL} result favor a gluon polarization in the measured x-region which falls in-between GRSV-STD and GRSV-ZERO
- Consistent with RUN 5 result (Factor 3-4 improved statistical precision for p_T>13GeV/c)

Recent results in high-energy QCD physics

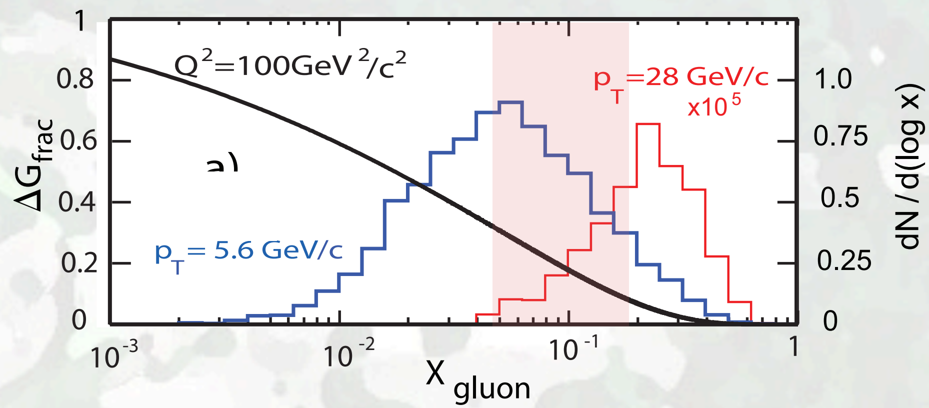
- Global analysis incl. RHIC pp data



D. de Florian et al. PRL 101 (2008) 072001.



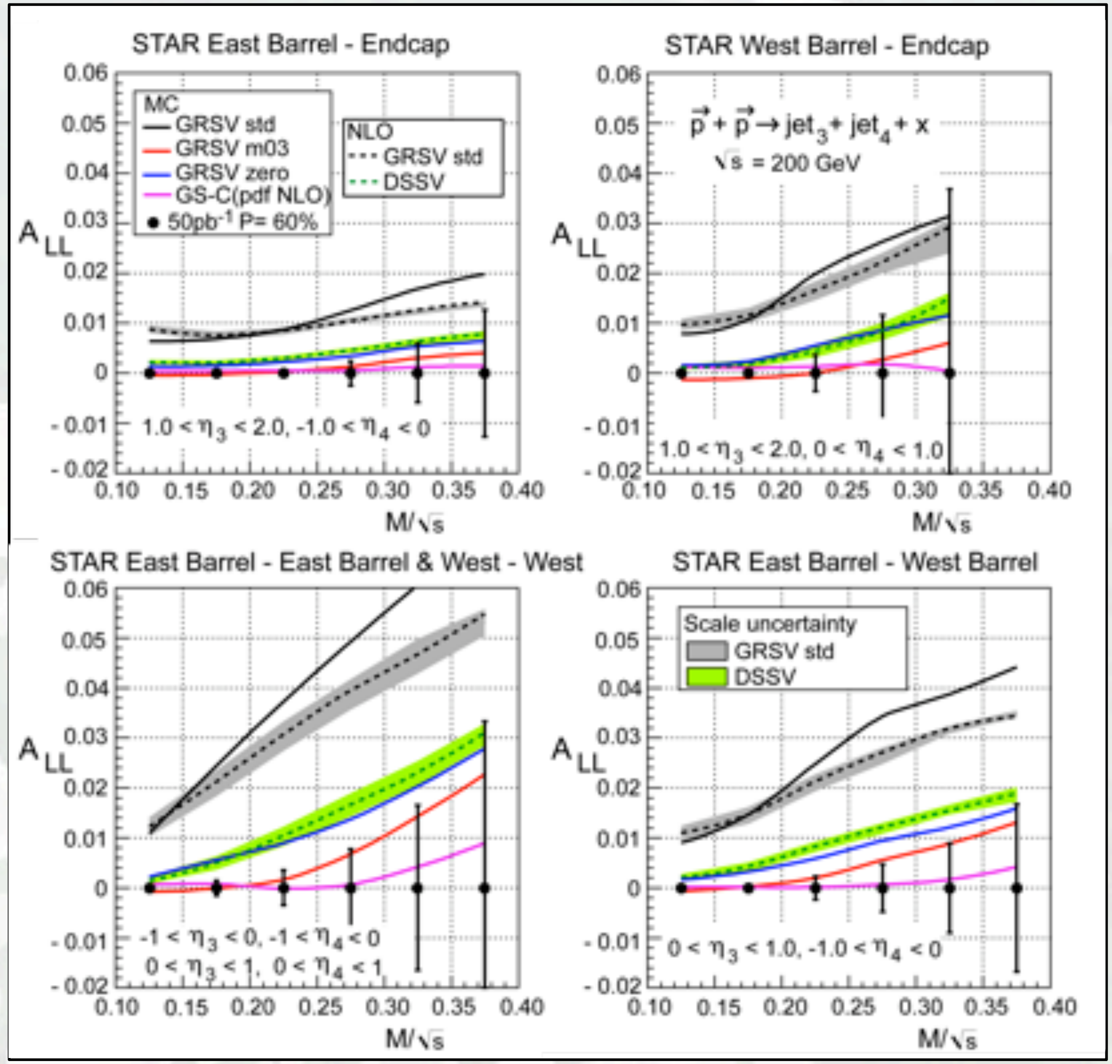
- Strong constraint on the size of Δg from RHIC data for 0.05<x<0.2
- Evidence for a small gluon polarization over a limited region of momentum fraction
- Important: Mapping of x-dependence and extension of x-coverage needed!



STAR Collaboration, PRL 100 (2008) 232003.

Recent results in high-energy QCD physics

- Run 9 STAR Beam-Use Request: Di-Jet projections
  - Substantial improvement in from Di-Jet production: 50pb^{-1} and 60% beam polarization
  - Good agreement between LO MC evaluation and full NLO calculations

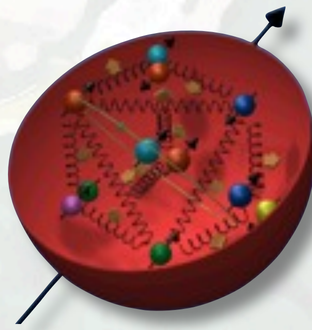


$$M = \sqrt{x_1 x_2 s} \qquad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

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

Summary and Outlook

- Summary
  - Enormous precision reached for unpolarized distribution functions - Large uncertainties remain at larger momentum fractions - Impact for LHC program
  - Higher-order QCD calculations needed (Beyond NLO) for precision pdf extraction and α_s
  - Generally large uncertainties and model dependence on soft processes such as underlying event and hadronization
  - Evidence for a small gluon polarization ⇒ Renaissance of constituent quark model!



- Outlook
  - Electron-Ion Collider: Precision measurement of polarized ep and eA scattering