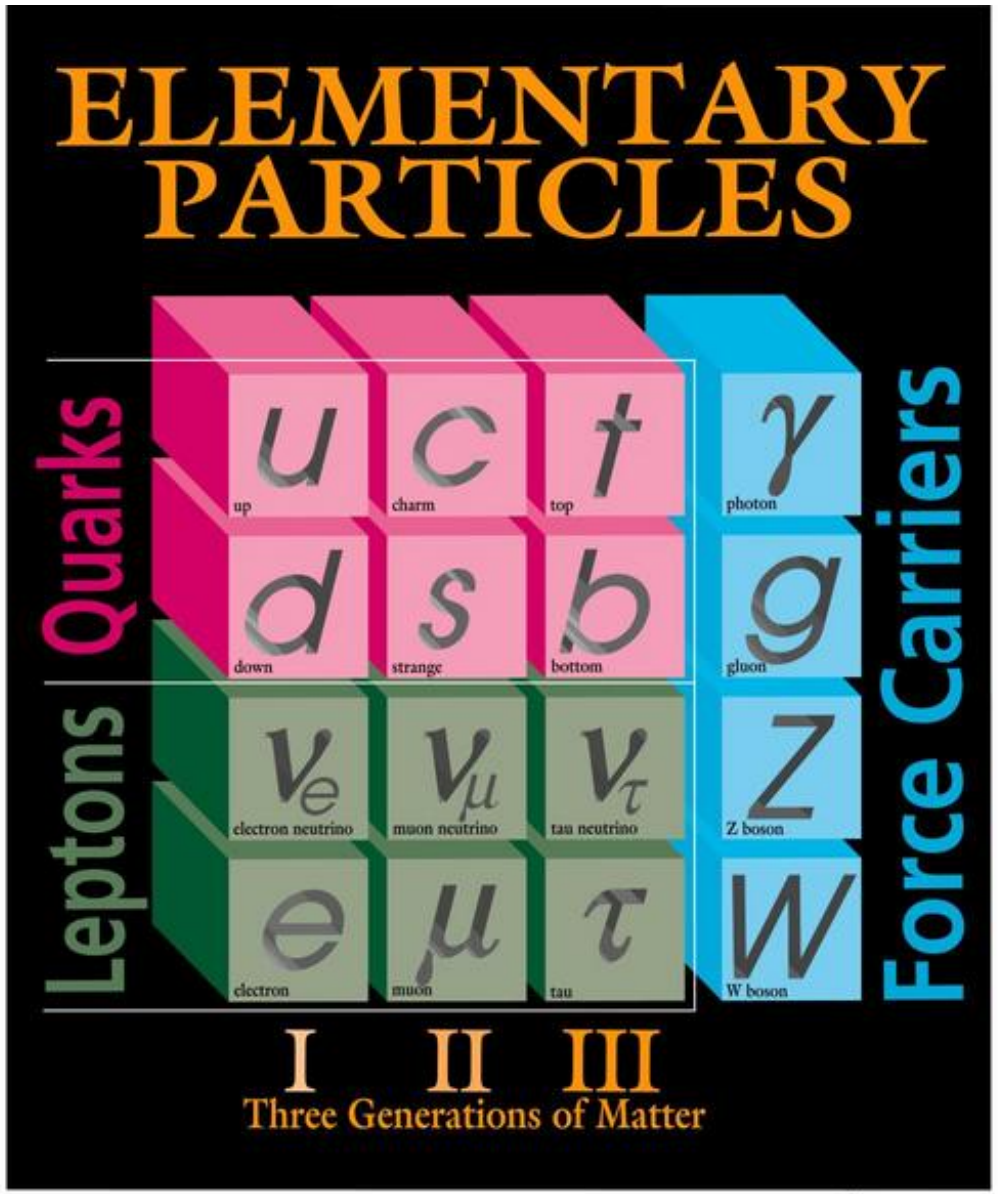
Exploring the Proton's Spin

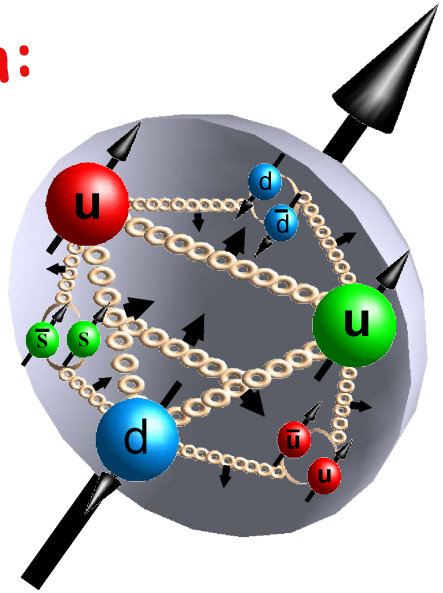
Werner Vogelsang
Universität Tübingen
Colloquium, PSI, 02.12.2010

Spin 1/2



Spin 1

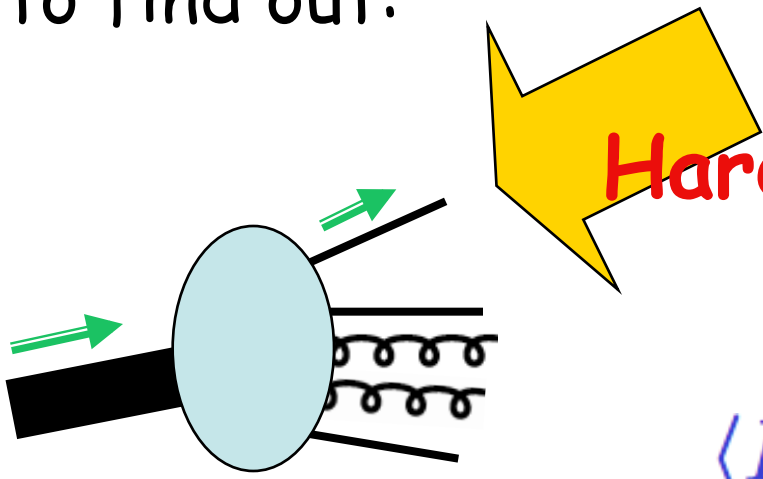
The nucleon, a composite particle with spin:



Goal: understand the spin structure of the nucleon in terms of quarks and gluons

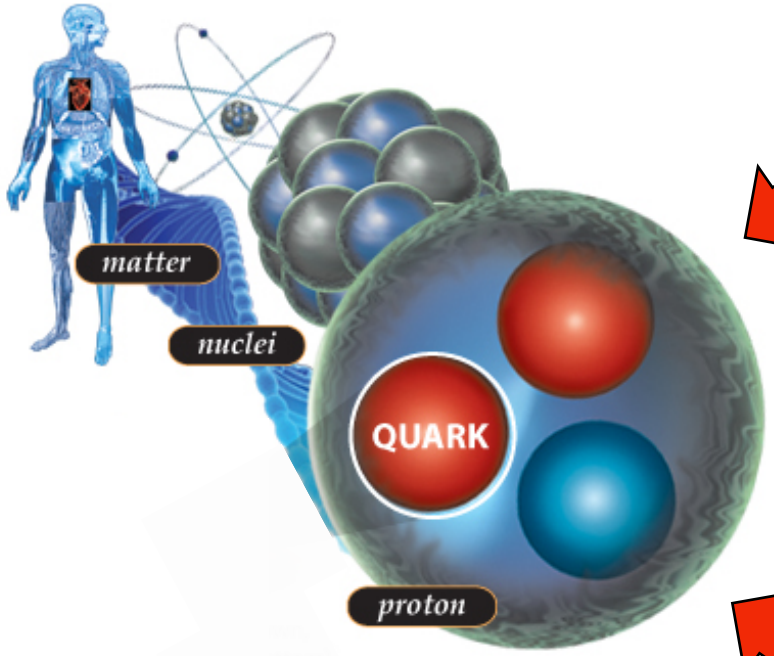
- **How do quarks and gluons carry the proton spin ?**

The way to find out:



$$\langle P,s\,|\,\mathcal{O}_{q,g}\,|\,P,s\rangle$$

Exploring the nucleon: a fundamental quest



Know what we are made of !

Understand the strong force: "QCD"

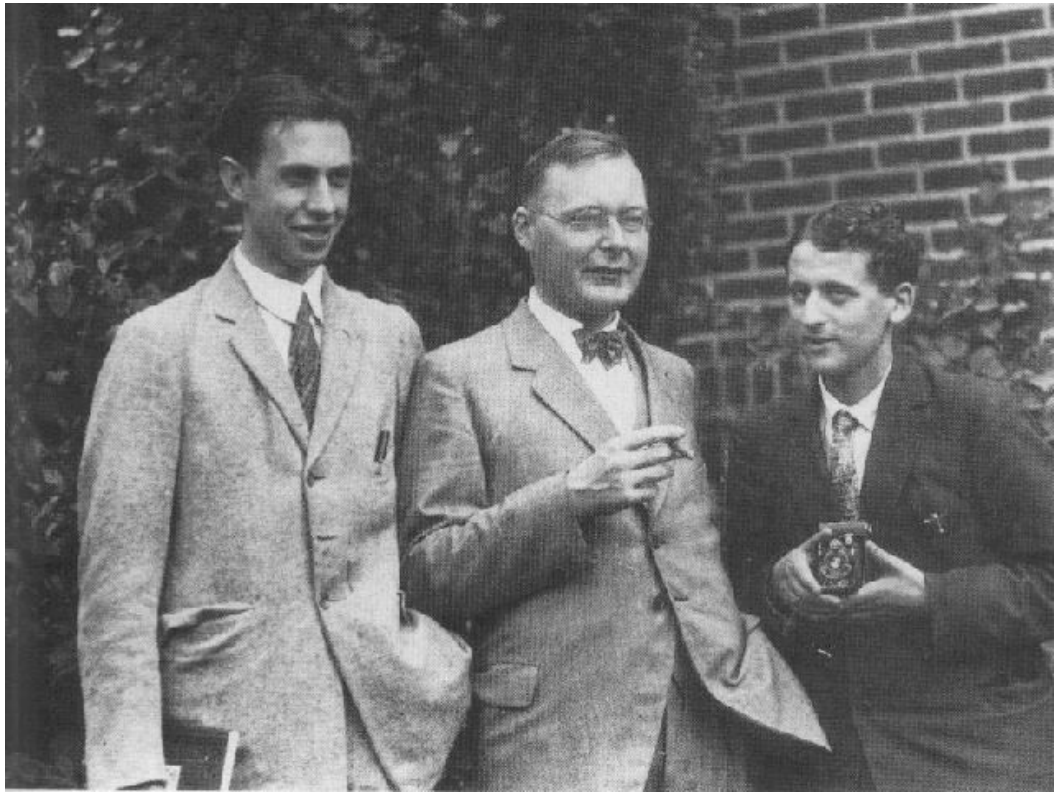
Use protons as tool for discovery (e.g. LHC)

Outline:

- Brief history of spin & nucleon structure
- The "proton spin crisis"
- Current questions in spin physics
- Recent results and present knowledge
- Conclusions

Brief history of spin and nucleon structure

Goudsmit & Uhlenbeck 1925: "self-rotating" electron



"This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not lose anything by making a stupid mistake." (Ehrenfest)

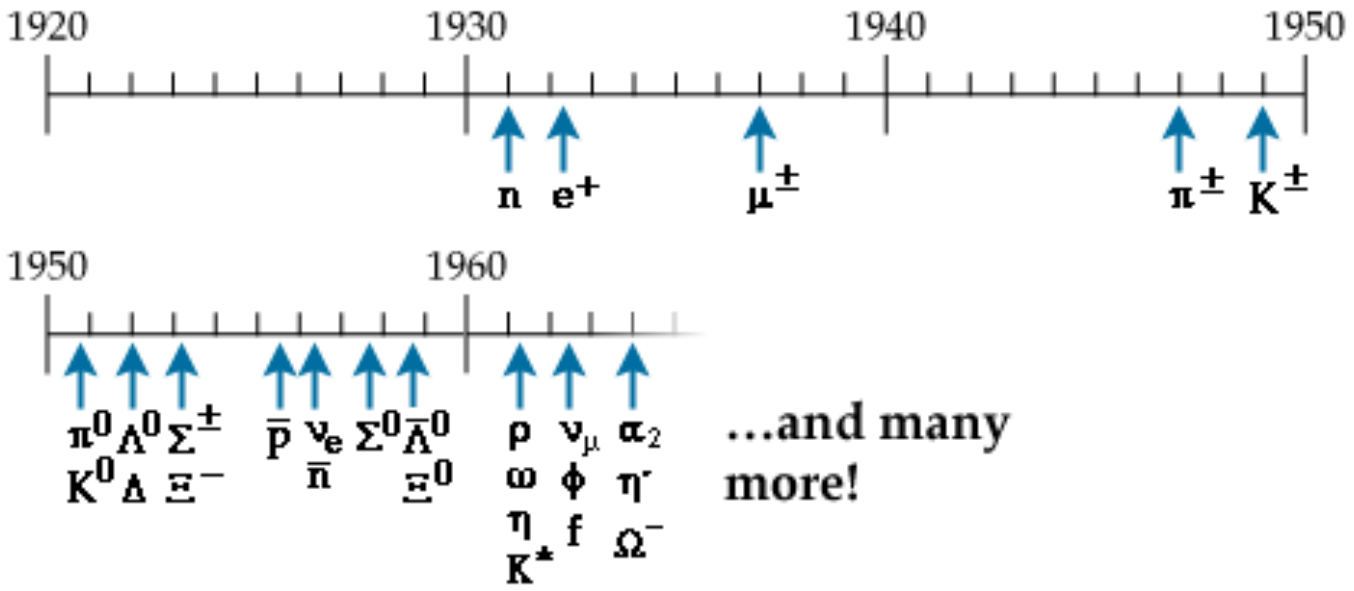
I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig believed in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth.

Thomas to Goudsmit '26

1927: the proton has spin 1/2 Dennison / Heisenberg

1933: the magnetic moment of the proton Stern

The proton must have internal structure !



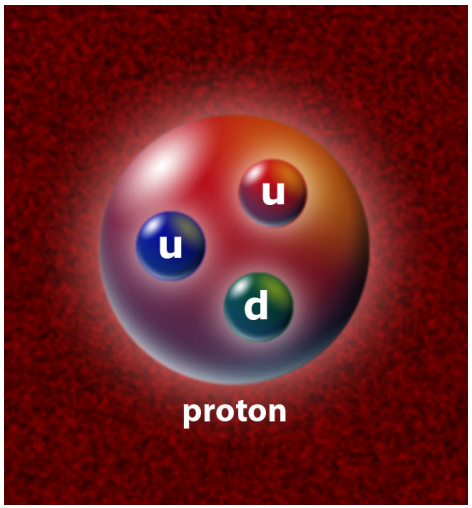
. . . neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons . . . . . the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a \$10,000 fine!

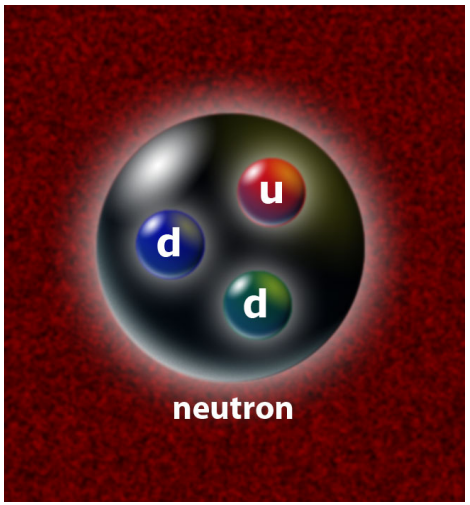
Lamb, Nobel Lecture 1955

u d s quarks

Gell-Mann; Zweig

$$|\text{baryon}\rangle = |qqq\rangle \qquad |\text{meson}\rangle = |q\bar{q}\rangle$$



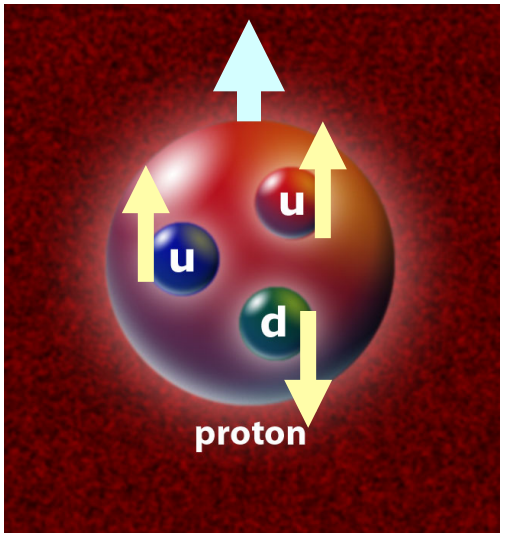


A SCHEMATIC MODEL OF BARYONS AND MESONS *

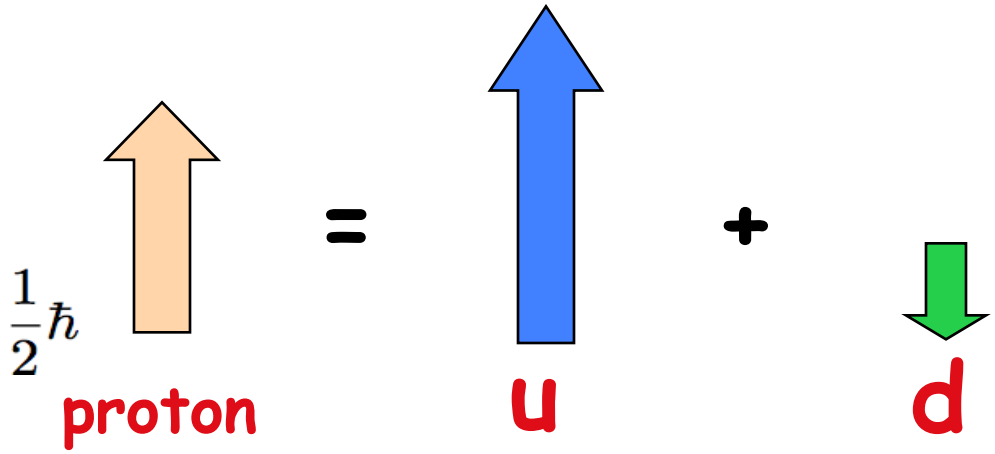
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

It is fun to speculate about the way quarks would behave if they were physical particles of finite mass instead of purely mathematical entities



- predict: quarks carry the proton spin



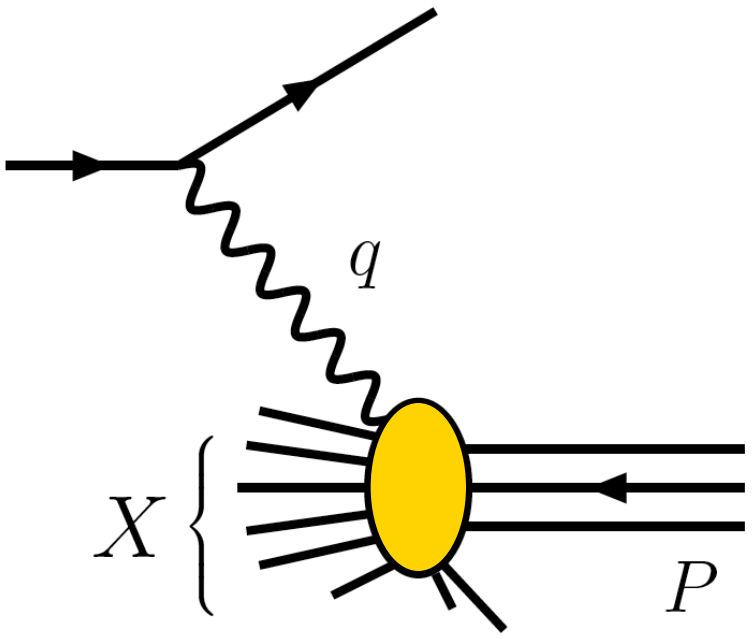
- expect higher Fock states :

$$|\,u,u,d\,\rangle \;+\; |\,u,u,d,(u\bar{u})\,\rangle \;+\; |\,u,u,d,(s\bar{s})\,\rangle \;+\; \ldots$$

- model expectation: ~ 70% of proton spin due to quark and anti-quark spins

Measure in deeply-inelastic processes!

Deeply-inelastic scattering ep → e X :

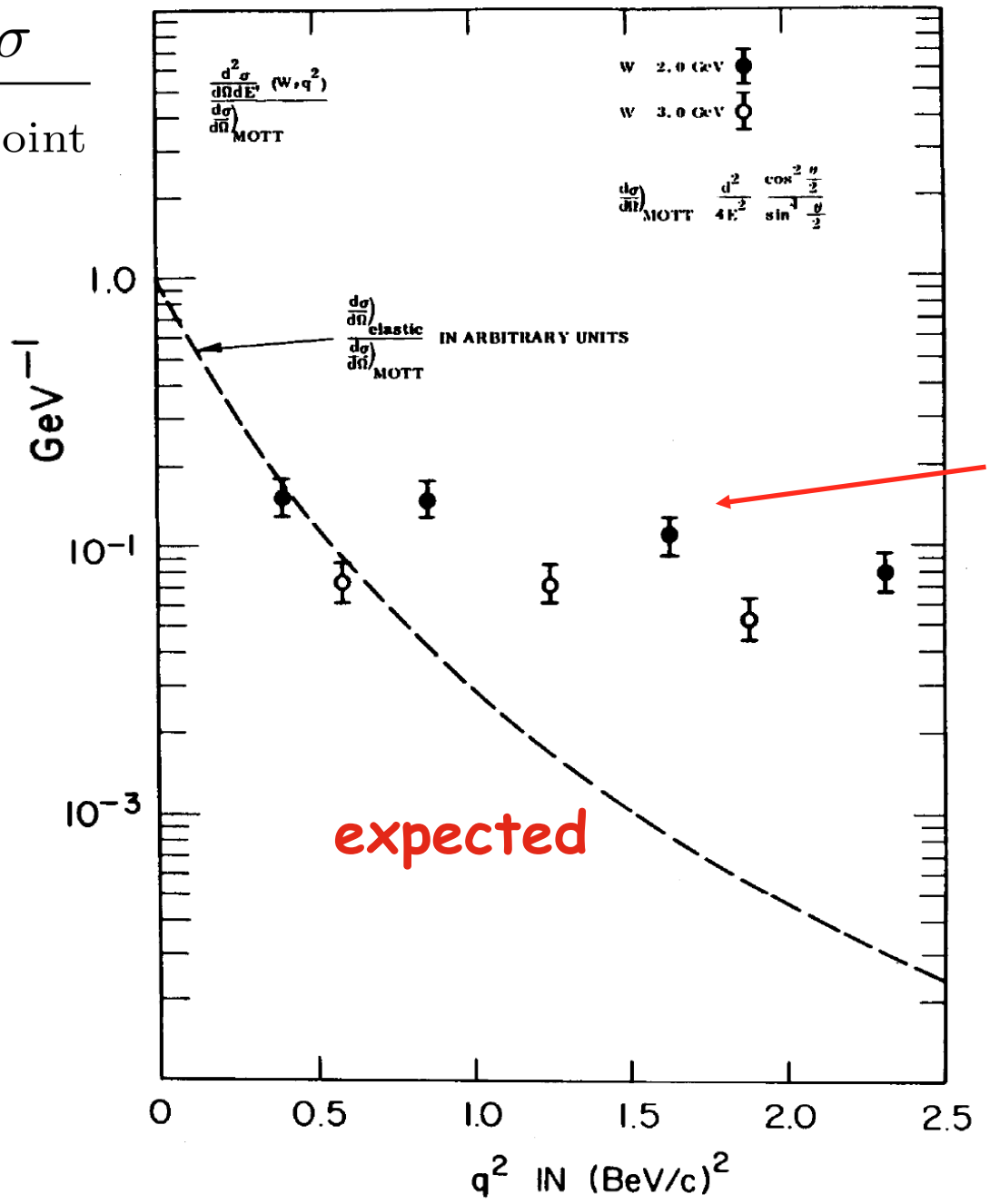


$$Q^2 = -q^2$$

$$x \equiv \frac{Q^2}{2P \cdot q}$$

Bjorken variable

$\frac{\sigma}{\sigma_{\text{point}}}$



Friedman, Kendall, Taylor

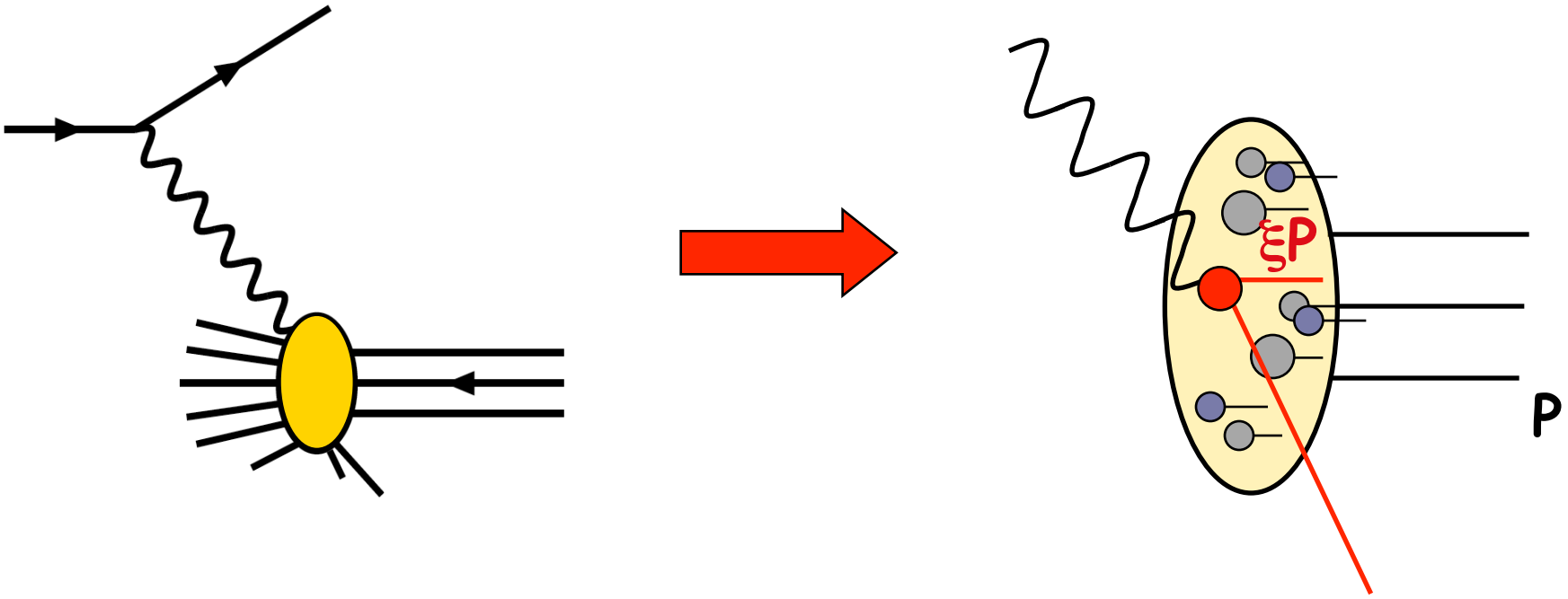
seen !

expected

The modern rendition of Rutherford's experiment !

Parton Model :

Feynman; Bjorken, Paschos



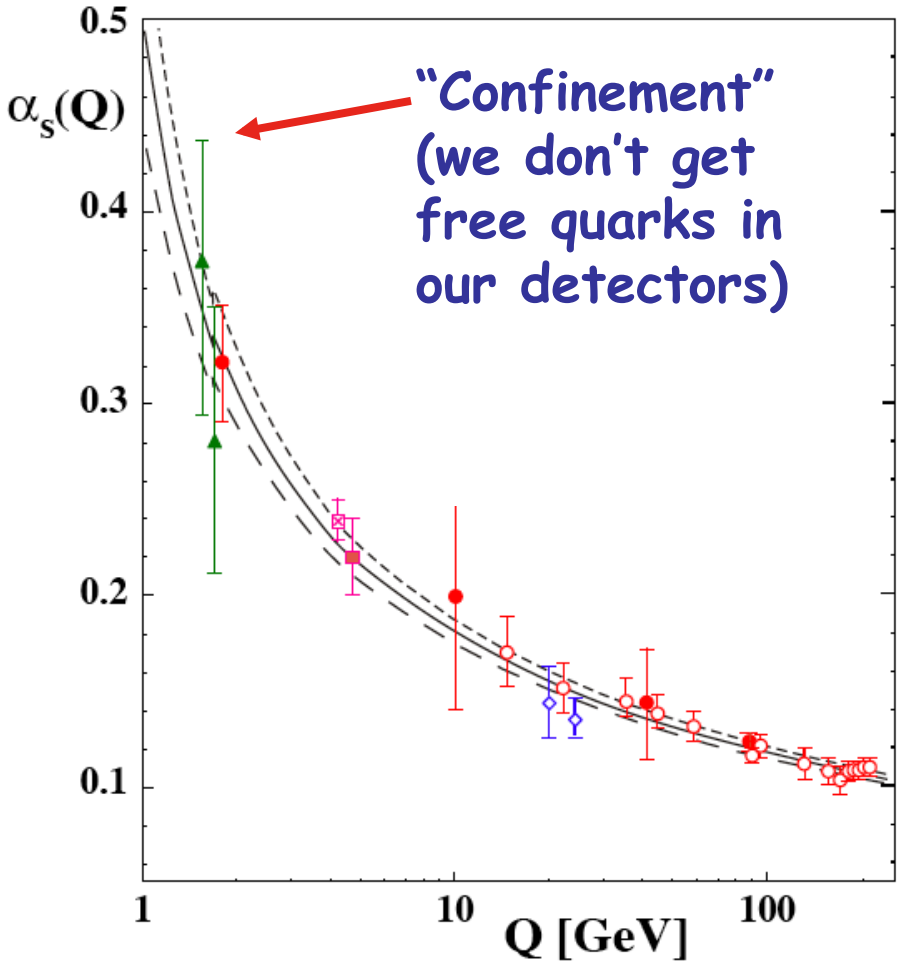
Assume: parton carries momentum ξ P

Find: $\xi \equiv x$

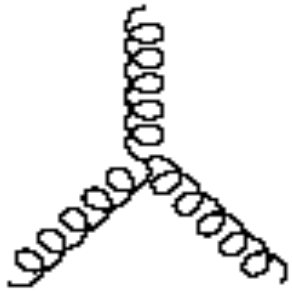
$$\sigma \sim \sum_q e_q^2 \left[q(x) + \bar{q}(x) \right] = 2F_1(x)$$

quark and anti-quark distributions

"Running strong charge"



"Confinement" (we don't get free quarks in our detectors)



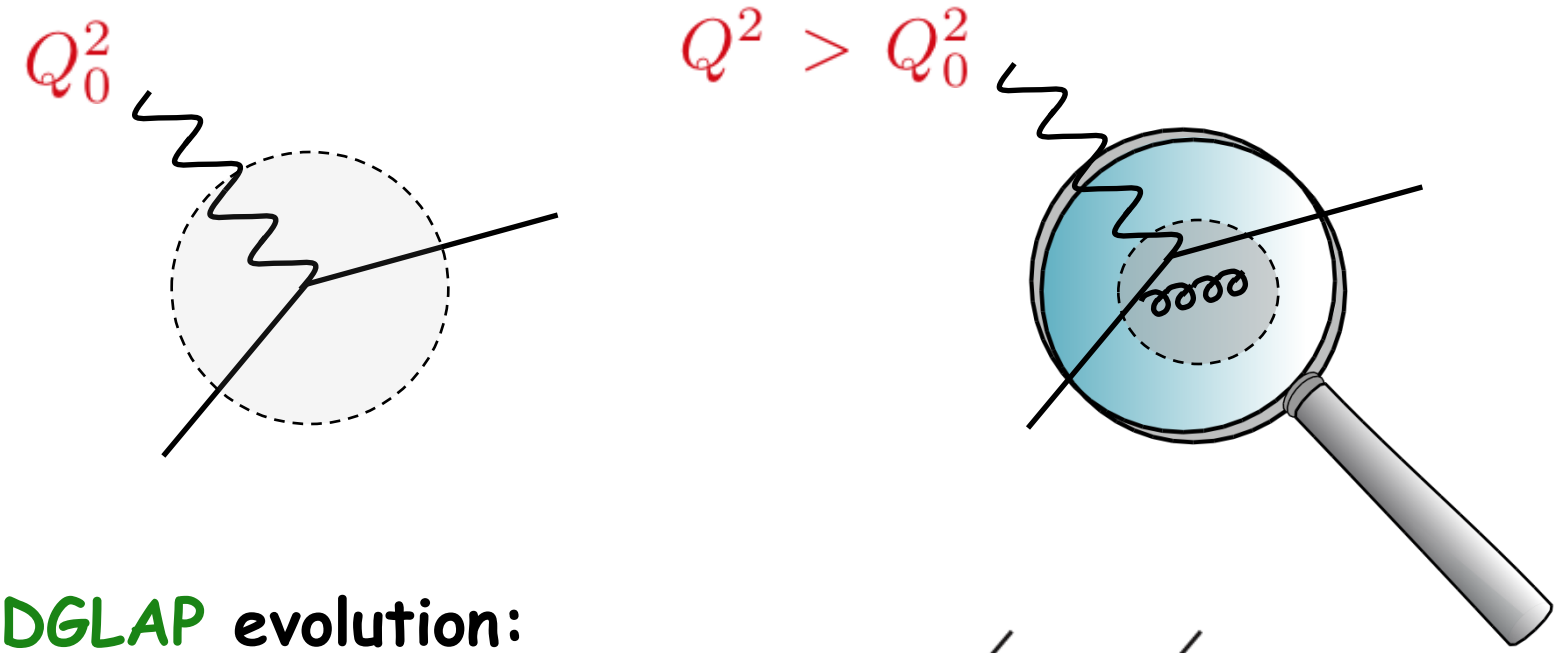
"Asymptotic Freedom"

Gross, Wilczek; Politzer

- crucial success for QCD :

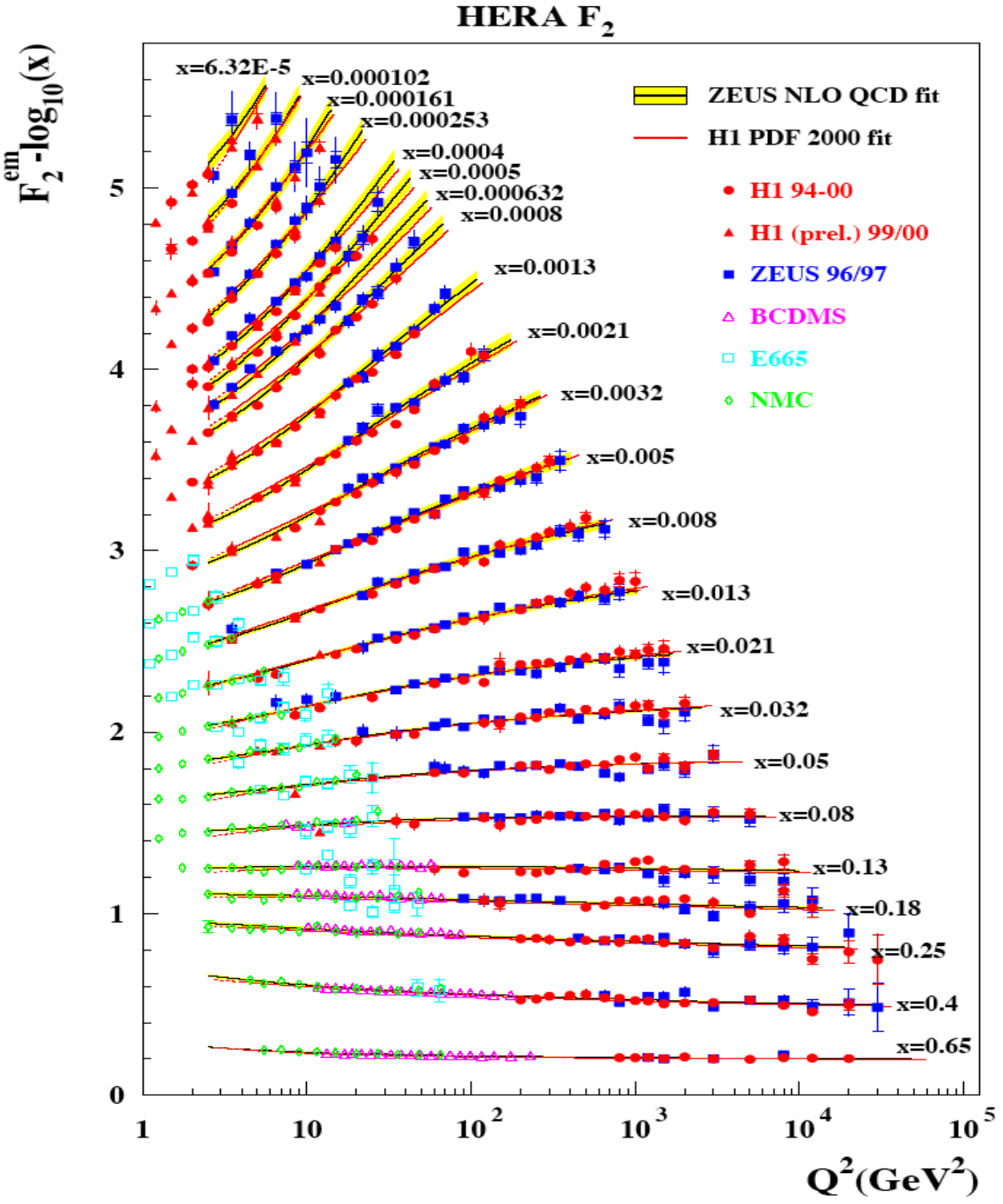
  quantitative prediction of scaling violations in DIS

  Christ,Hasslacher,Mueller; Georgi,Politzer; DGLAP



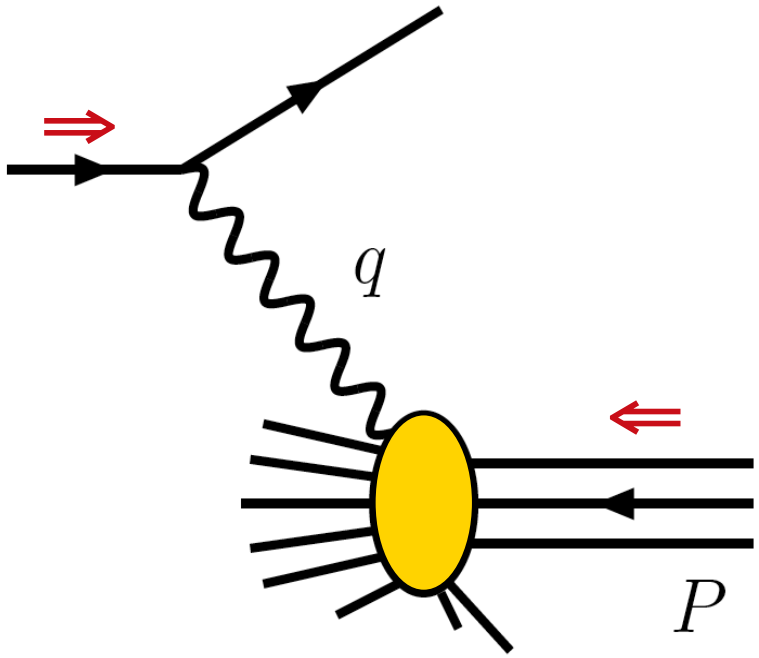
- **DGLAP evolution:**

$$Q^2 \frac{\mathrm{d}}{\mathrm{d}Q^2} \begin{pmatrix} q(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \mathcal{P}_{qq} & \mathcal{P}_{qg} \\ \mathcal{P}_{gq} & \mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} q \\ g \end{pmatrix} \left(\frac{x}{z}, Q^2\right)$$

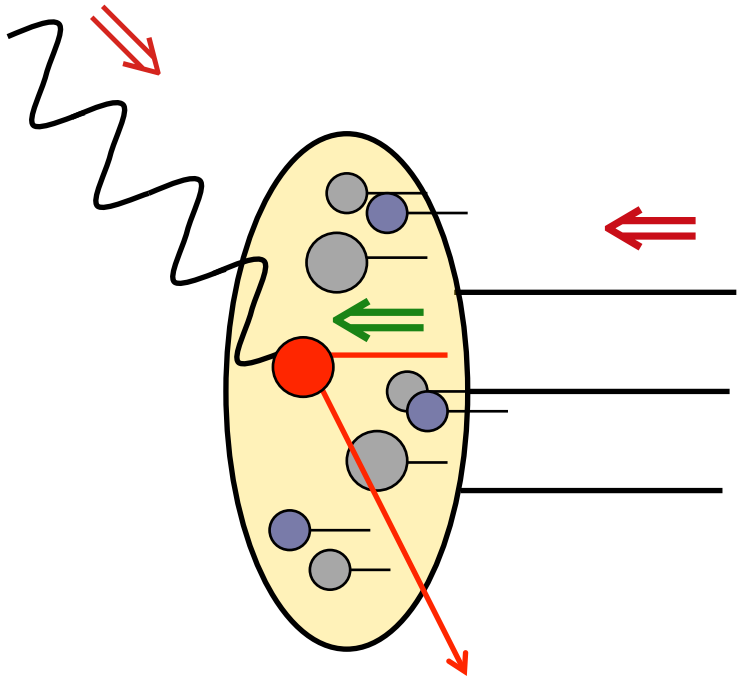

HERA F_2
F_2^{em}-log$_{10}$(x)
Q^2(GeV^2)
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 94-00
H1 (prel.) 99/00
ZEUS 96/97
BCDMS
E665
NMC
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65

The proton "spin crisis"

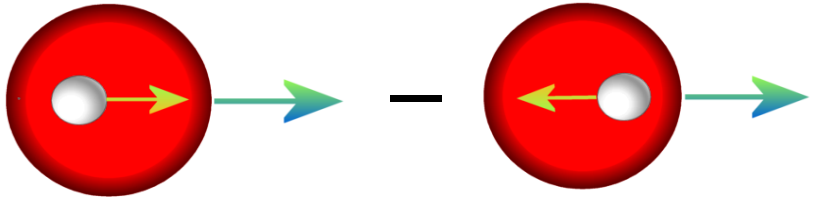
Starting from mid '70s: "Polarized DIS"



Parton Model :



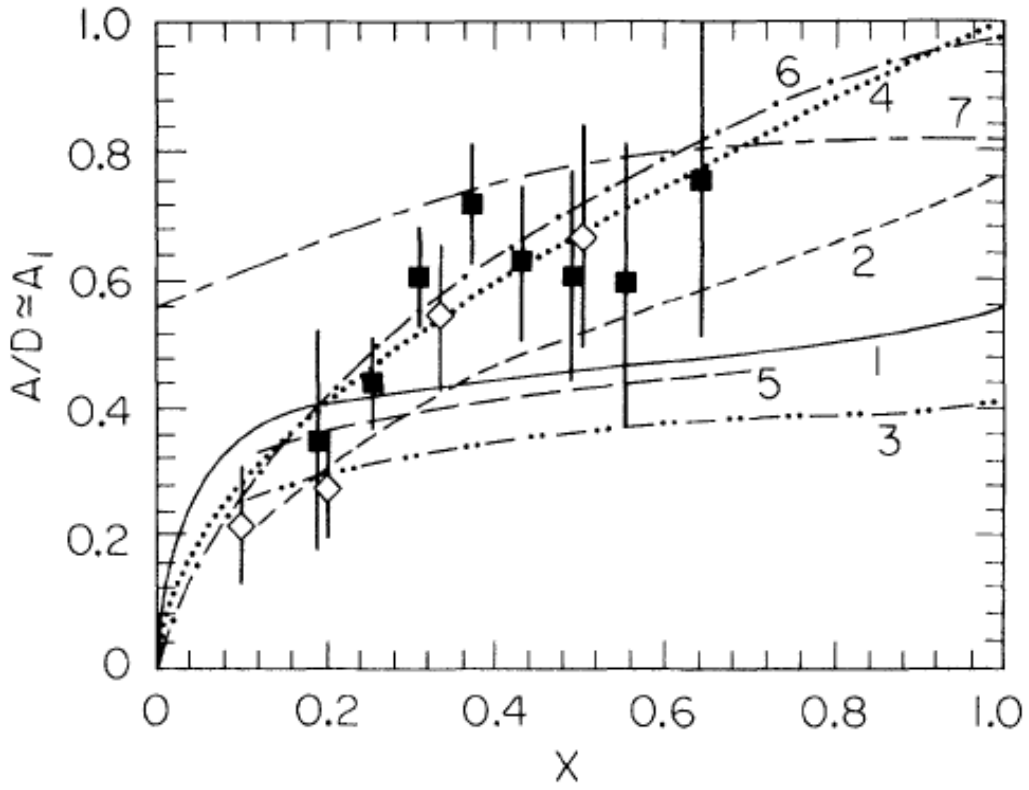
$$\sigma(\Rightarrow\Rightarrow) - \sigma(\Rightarrow\Leftarrow) \sim \sum_q e_q^2 \left[\, \Delta q(x) + \Delta\bar{q}(x) \,\right] = 2g_1(x)$$

$$\Delta q(x) \;=$$  $$-$$

$$\Delta\, q(x) \;=\; \frac{1}{4\pi} \int dy^- \, \mathrm{e}^{-iy^- x P^+} \, \langle\, P,S \,|\, \bar{\psi}\left(0, y^-, \mathbf{0}_\perp\right) \gamma^+ \gamma_5 \, \psi(0) \,|\, P,S \,\rangle$$

All was well … initially…

$$\frac{g_1^p}{F_1^p} =$$



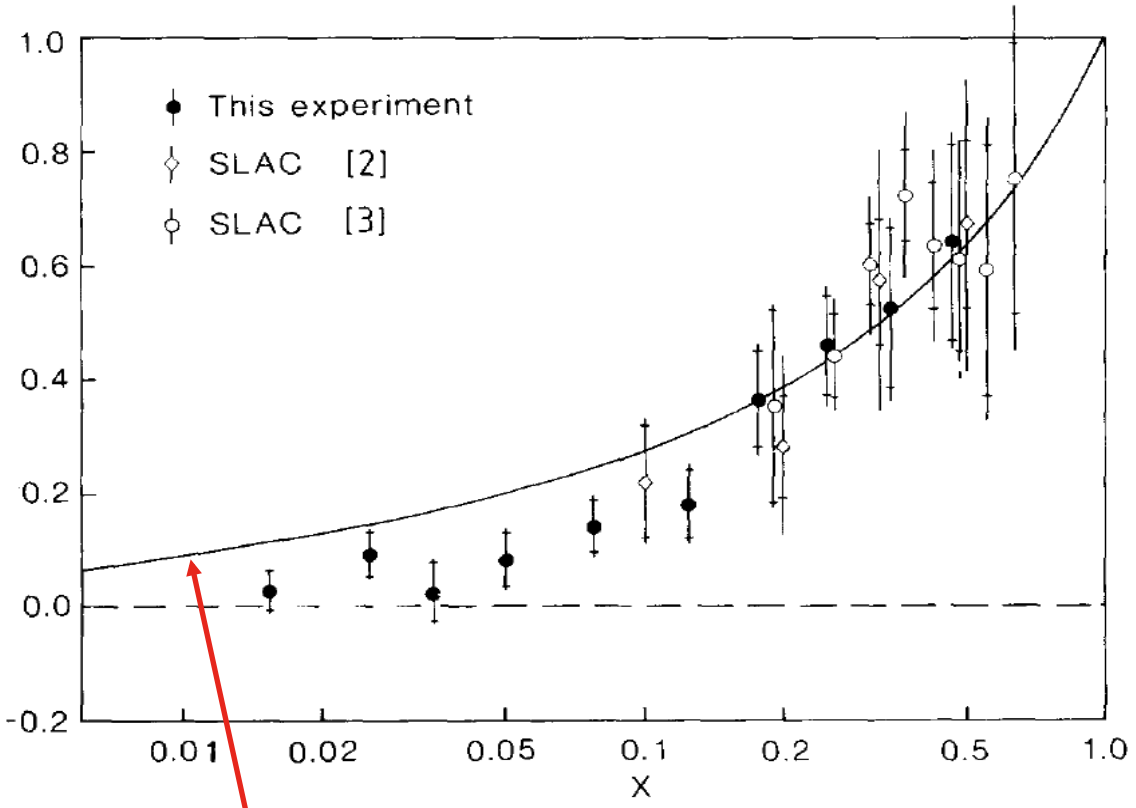
SLAC-E80, E130

(1976-83)

But then:

EMC (1987)

$$\frac{g_1^p}{F_1^p} = A_1^p$$



If quarks and anti-quarks carried ~70% of the proton spin…

$$2\int_0^1 dx\, g_1(x,Q^2) = \frac{4}{9}\Delta\Sigma_u + \frac{1}{9}\Delta\Sigma_d + \frac{1}{9}\Delta\Sigma_s$$

$$\Delta\Sigma_q \equiv \int_0^1 dx\,(\Delta q + \Delta\bar{q})\,(x,Q^2) \;\propto\; \langle\, P,s \,|\, \bar{\psi}_q\, \gamma^\mu\gamma_5\, \psi_q \,|\, P,s \,\rangle$$

(axial charges)

use SU(3) to obtain *non-singlet* combinations from baryon decays:

Bjorken;
Ellis, Jaffe;
Karliner, Lipkin;
Ratcliffe;…

$$\Delta\Sigma_u - \Delta\Sigma_d = g_A = 1.257 \pm \ldots$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s = 3F - D = 0.58 \pm 0.03$$

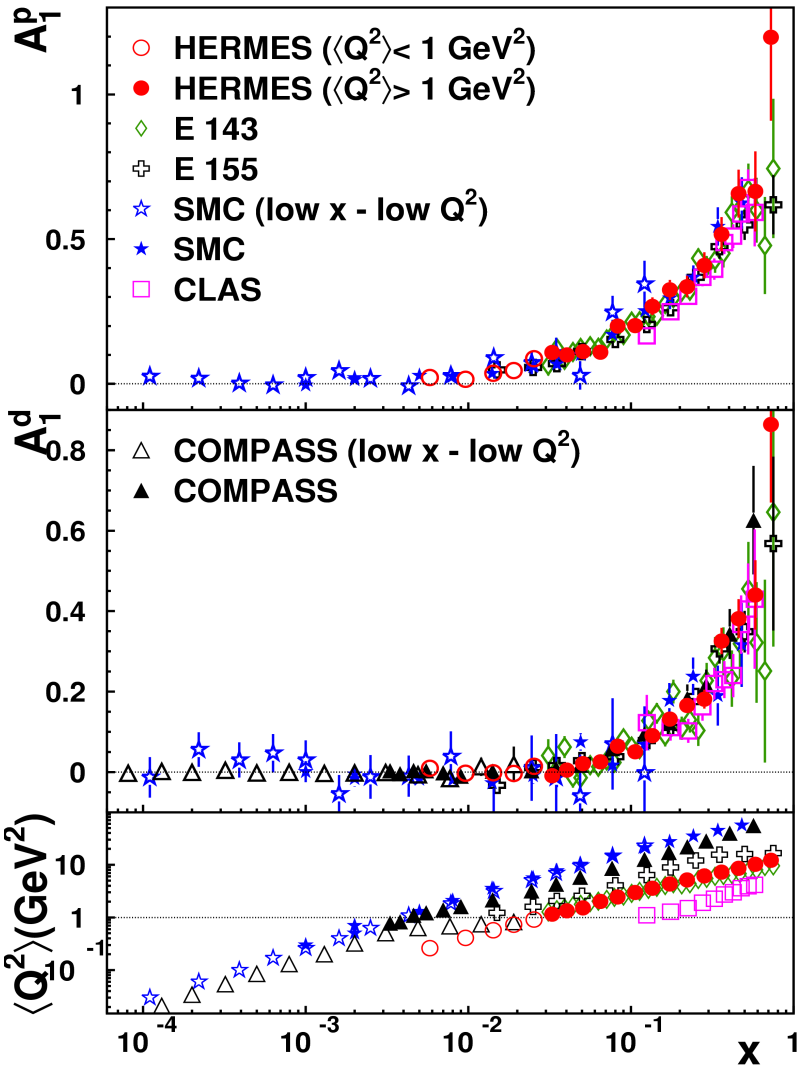
$$\Delta\Sigma = \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s = 0.12 \pm 0.17$$

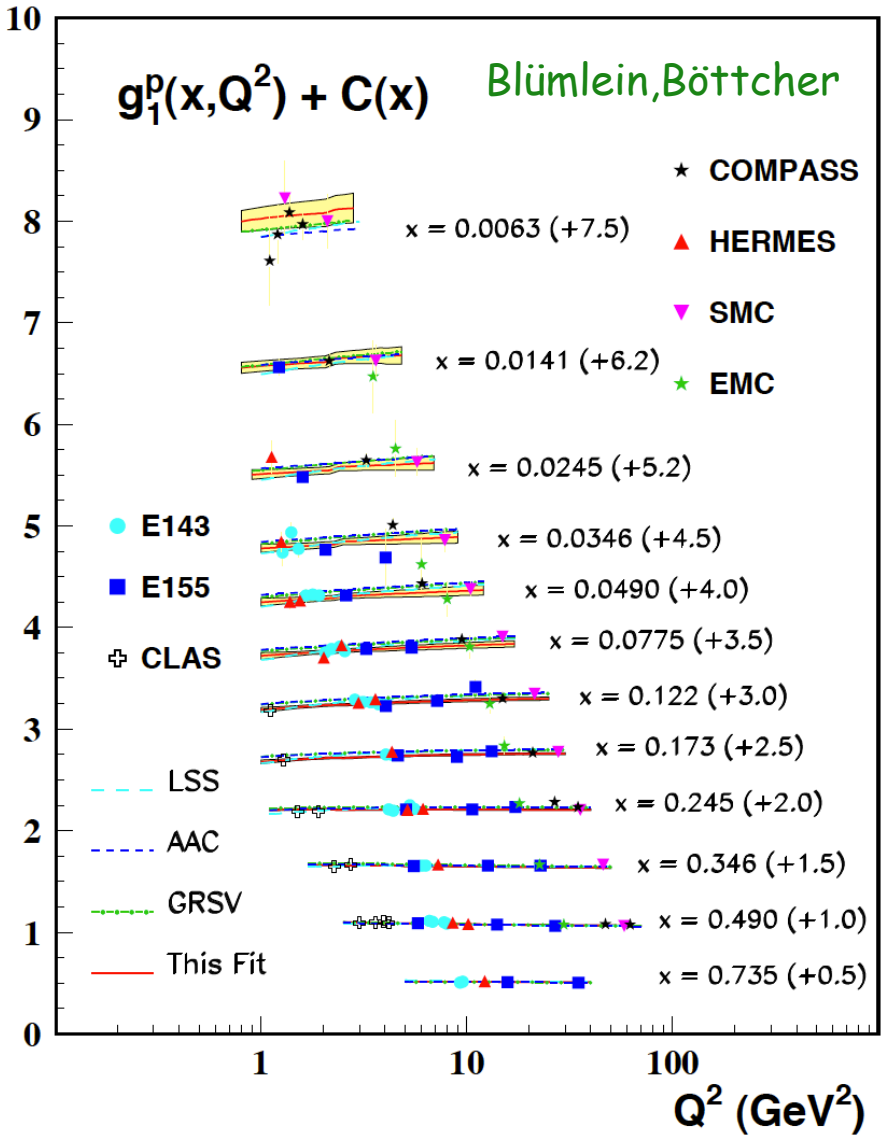
EMC '89

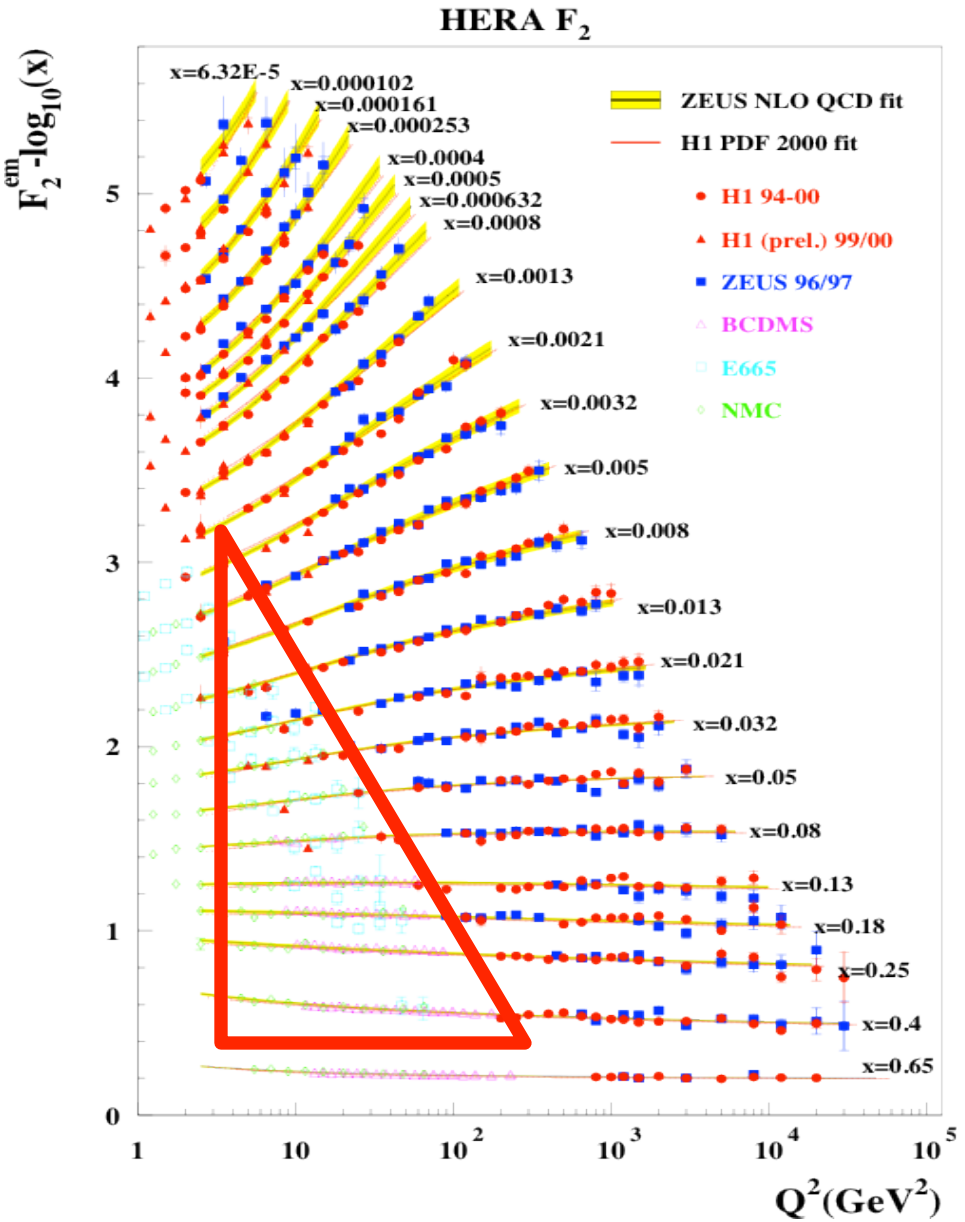
- Note,

$$\Delta\Sigma = \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s = 3F - D + 3\Delta\Sigma_s$$

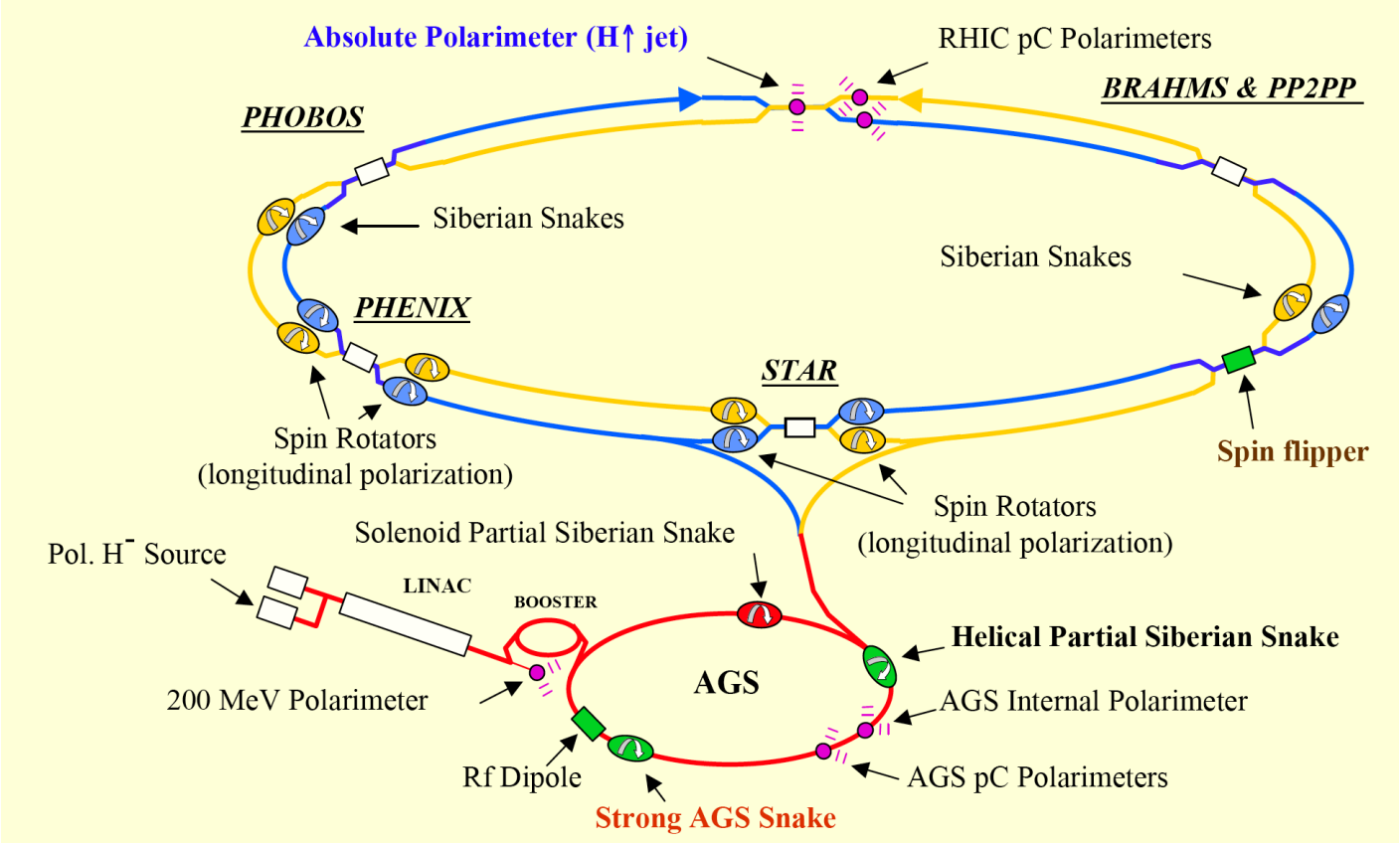
Today:


A_1^p
HERMES ($\langle Q^2\rangle$< 1 GeV^2)
HERMES ($\langle Q^2\rangle$> 1 GeV^2)
E 143
E 155
SMC (low x - low Q^2)
SMC
CLAS
A_1^d
COMPASS (low x - low Q^2)
COMPASS
$\langle Q^2\rangle$(GeV^2)
x


$g_1^p(x,Q^2) + C(x)$
Blümlein,Böttcher
COMPASS
HERMES
SMC
EMC
E143
E155
CLAS
LSS
AAC
GRSV
This Fit
x = 0.0063 (+7.5)
x = 0.0141 (+6.2)
x = 0.0245 (+5.2)
x = 0.0346 (+4.5)
x = 0.0490 (+4.0)
x = 0.0775 (+3.5)
x = 0.122 (+3.0)
x = 0.173 (+2.5)
x = 0.245 (+2.0)
x = 0.346 (+1.5)
x = 0.490 (+1.0)
x = 0.735 (+0.5)
Q^2 (GeV^2)

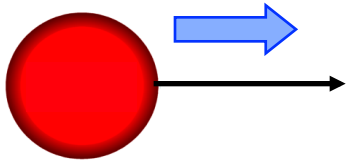

HERA F_2
F_2^{em}-log$_{10}$(x)
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 94-00
H1 (prel.) 99/00
ZEUS 96/97
BCDMS
E665
NMC
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
Q^2(GeV^2)

Plus: polarized pp at RHIC !



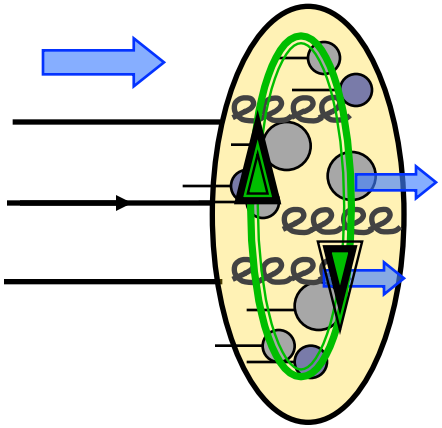
Current questions in spin physics

- **How do quarks and gluons carry the proton spin ?**



$$\frac{1}{2} = \langle P, \frac{1}{2} | \hat{J}_z | P, \frac{1}{2} \rangle$$

$$\hat{J}_z = \int d^3x \left[\frac{1}{2} \bar{\psi} \gamma_z \gamma_5 \psi - i\psi^\dagger \left(\vec{x} \times \vec{\nabla} \right)_z \psi + \left(\vec{E} \times \vec{A} \right)_z + E_i \left(\vec{x} \times \vec{\nabla} \right)_z A_i \right]$$



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

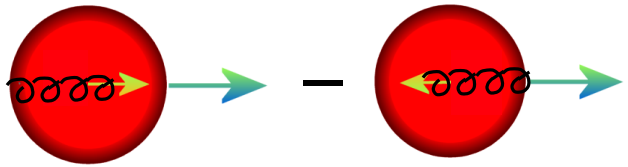
Jaffe, Manohar; Jaffe, Bashinsky; Brodsky; Chen et al.; Wakamatsu

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

- it is known how to access the q and g spin contributions:

$$\Delta\Sigma = \int_0^1 dx \Big[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\Big](x)$$

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

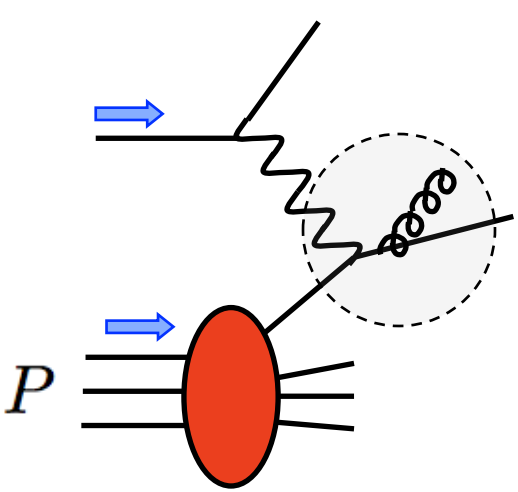


- Polarized gluon distribution ?
- Polarized sea quarks ? Strangeness ?
  Flavor asymmetries ?
- Parton orbital angular momenta ?
- Transverse-spin phenomena ?
- Parton spatial distributions ?

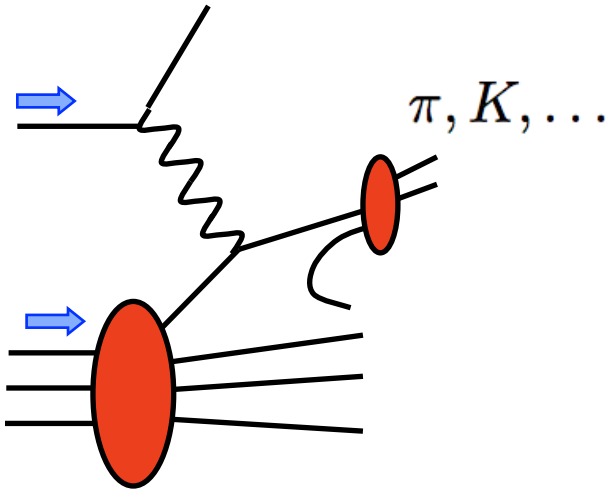
  •
  •
  •

Recent results and present knowledge

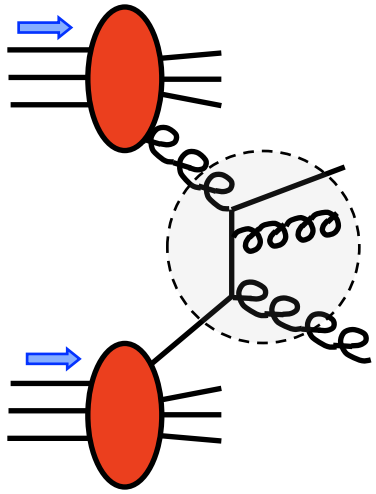
The probes of nucleon helicity structure :



DIS



SIDIS



pp (RHIC)

DIS $$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \Delta f(x,Q^2)\, \Delta\hat{\sigma}^f(xP,\alpha_s(Q^2)) + \ldots$$

pp $$\Delta\sigma = \sum_{a,b=q,\bar{q},g} \int dx_a\, \Delta f_a(x_a,p_\perp^2) \int dx_b\, \Delta f_b(x_b,p_\perp^2) \Delta\hat{\sigma}^{ab}(x_aP, x_bP', \alpha_s(p_\perp^2)) + \ldots$$

$$\Delta\hat{\sigma} = \Delta\hat{\sigma}_{\rm LO} + \alpha_s \Delta\hat{\sigma}_{\rm NLO} + \ldots$$

A lot of theory work:

- **DGLAP evolution:**

$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} \begin{pmatrix} \Delta q(x,\mu^2) \\ \Delta g(x,\mu^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} \left(\frac{x}{z},\mu^2\right)$$

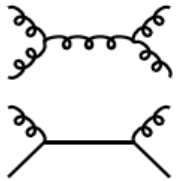
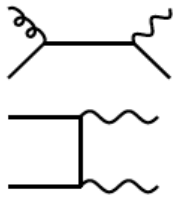
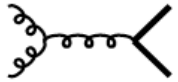
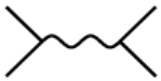
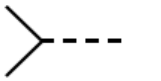
$$\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta\mathcal{P}_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta\mathcal{P}_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta\mathcal{P}_{ij}^{\mathrm{NNLO}} + \ldots$$

Ahmed,Ross Altarelli,Parisi,…

Mertig, van Neerven WV

Moch, Rogal, Vermaseren, Vogt (ij = qq,qg)

Polarized pp (RHIC) :

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $q\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\,\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\,\vec{\bar{q}} \to Z^0,\ \vec{q}'\,\vec{\bar{q}} \to W^\pm$ $\vec{q}'\,\bar{q} \to W^\pm,\ q'\,\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

NLO:

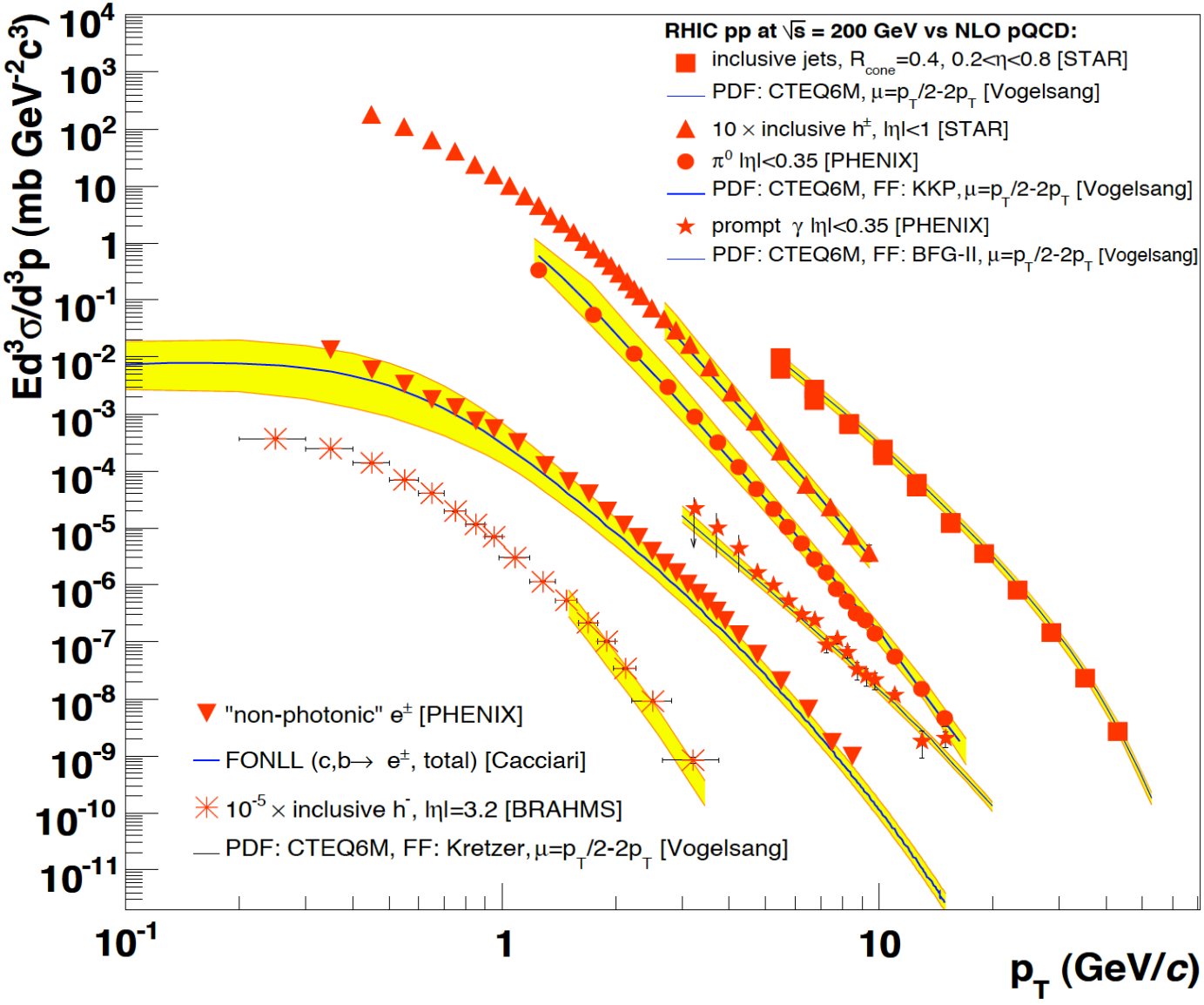
Jäger, Schäfer, Stratmann, WV

Jäger,Stratmann, WV; Signer et al.

Gordon, WV; Contogouris et al.; Gordon, Coriano; Frixione. WV

Stratmann, Bojak

Weber; Gehrmann; Kamal; Smith, van Neerven, Ravindran; Nadolsky, Yuan; de Florian, WV


RHIC pp at √s = 200 GeV vs NLO pQCD:
inclusive jets, R_cone=0.4, 0.2<η<0.8 [STAR]
PDF: CTEQ6M, μ=p_T/2-2p_T [Vogelsang]
10 × inclusive h±, |η|<1 [STAR]
π0 |η|<0.35 [PHENIX]
PDF: CTEQ6M, FF: KKP, μ=p_T/2-2p_T [Vogelsang]
prompt γ |η|<0.35 [PHENIX]
PDF: CTEQ6M, FF: BFG-II, μ=p_T/2-2p_T [Vogelsang]
"non-photonic" e± [PHENIX]
FONLL (c,b→ e±, total) [Cacciari]
10-5 × inclusive h-, |η|=3.2 [BRAHMS]
PDF: CTEQ6M, FF: Kretzer, μ=p_T/2-2p_T [Vogelsang]
Ed3σ/d3p (mb GeV-2c3)
pT (GeV/c)
10-1
1
10

Long history of NLO QCD analyses of helicity parton distributions in DIS:

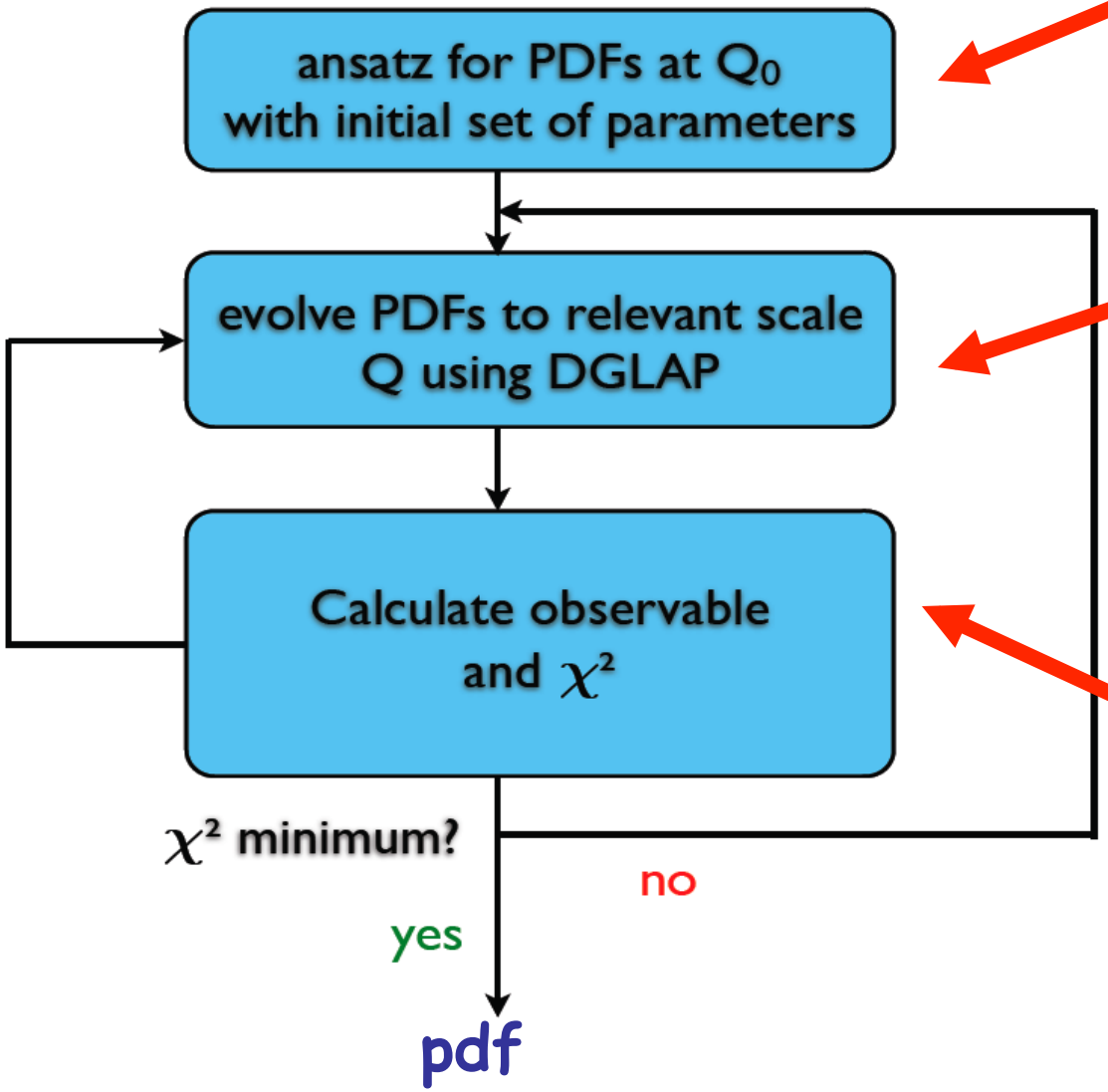
GRSV Glück, Reya, Stratmann, WV
ABFR Altarelli, Ball, Forte, Ridolfi
GS Gehrmann, Stirling
BB Blümlein, Böttcher
BBS Bourrely, Buccella, Soffer
LSS Leader, Sidorov, Stamenov
AAC Hirai, Kumano, Saito
DNS de Florian,Navarro,Sassot

...

For the first time, NLO ($\overline{\text{MS}}$) "Global analysis" of all DIS, SIDIS, RHIC data sets:

DSSV de Florian, Sassot, Stratmann, WV PRL 101, 2008
PRD 80, 2009

"Global pdf analysis"



$$\Delta q(x, Q_0^2),\ \Delta g(x, Q_0^2)$$

$$\propto N x^{\alpha}(1-x)^{\beta}\,(1+\gamma x+\ldots)$$

$$\Delta q(x, Q^2),\ \Delta g(x, Q^2)$$

need ~1000s of times!

Issue: complexity of NLO for pp (unpol. case: K factor method)

Mellin method for pp scattering :

Stratmann, WV

$$\Delta\sigma = \sum_{abc} \int dx_a \int dx_b \;\; \Delta f_a(x_a)\, \Delta f_b(x_b)\, \Delta\hat{\sigma}_{ab\to cX}$$

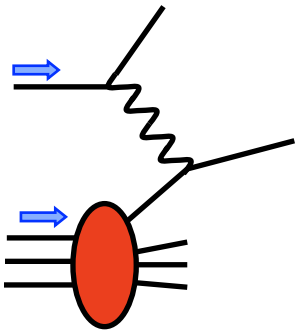
$$\frac{1}{2\pi i}\int_C dn\, x_a^{-n}\, \Delta f_a^n \qquad\qquad \frac{1}{2\pi i}\int_{C_m} dm\, x_b^{-m}\, \Delta f_b^m$$

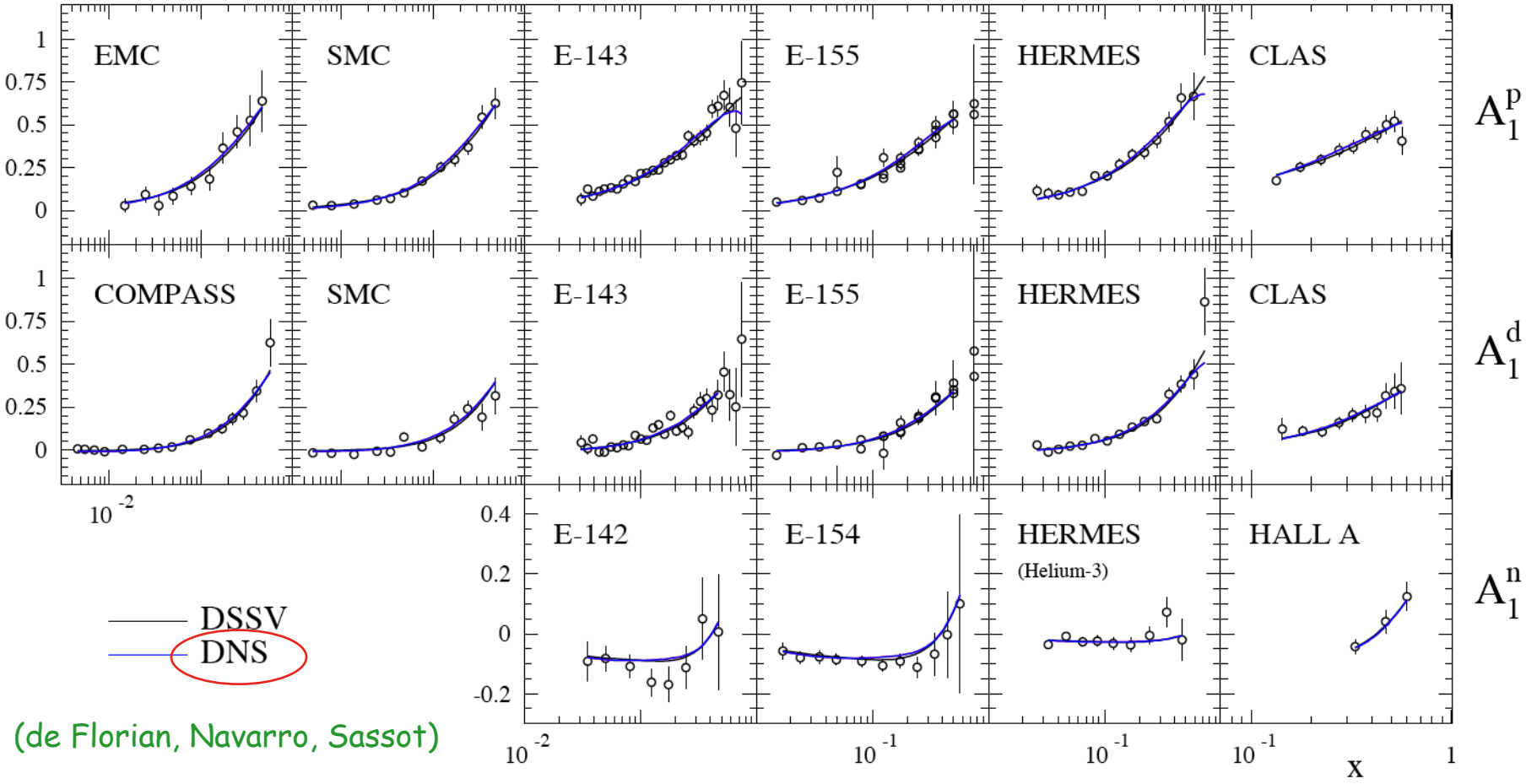
$$= \frac{1}{(2\pi i)^2}\sum_{abc}\int_{C_n} dn \int_{C_m} dm \; \Delta f_a^n\, \Delta f_b^m \; \int dx_a \int dx_b \;\; x_a^{-n}\, x_b^{-m}\, \Delta\hat{\sigma}_{ab\to cX}$$

Contain all dependence on fit parameters

Completely independent of pdfs. Can be "pre-calculated" prior to analysis

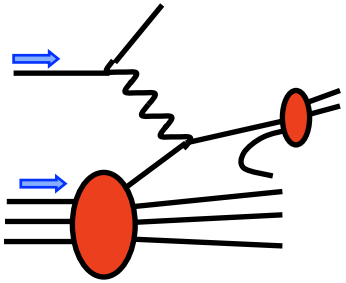
Spin asymmetries in inclusive DIS:

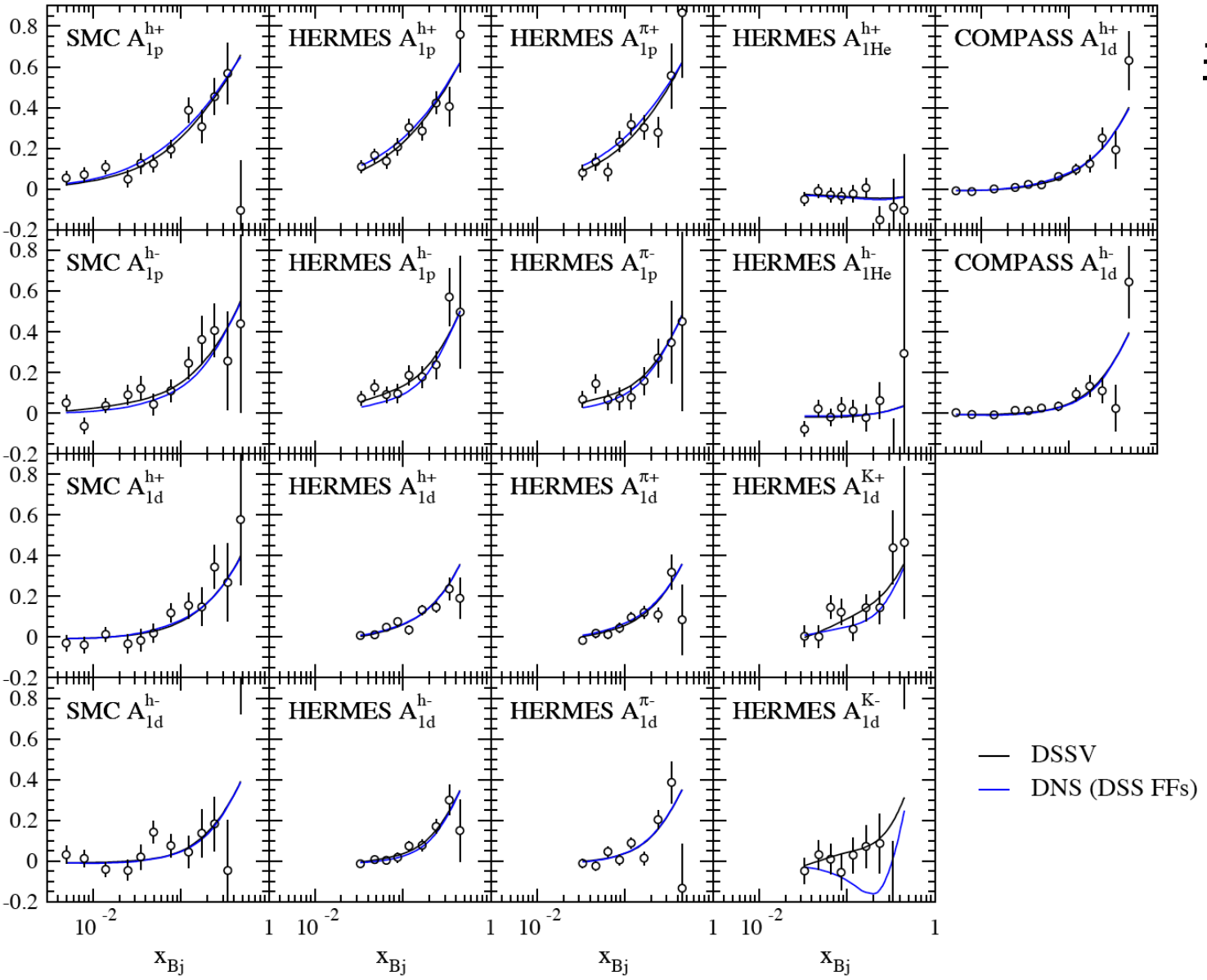




(de Florian, Navarro, Sassot)

Spin asymmetries in semi-inclusive DIS:

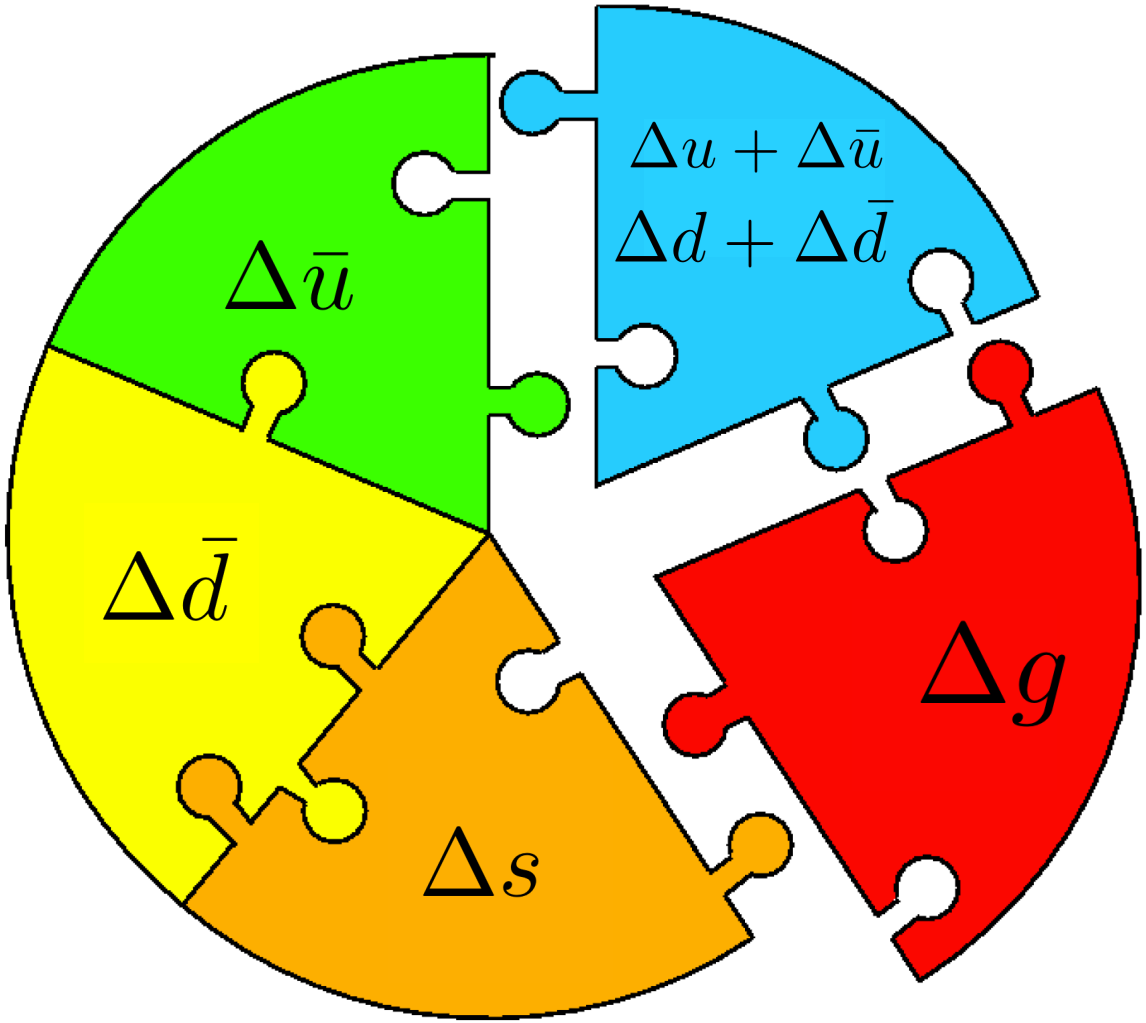




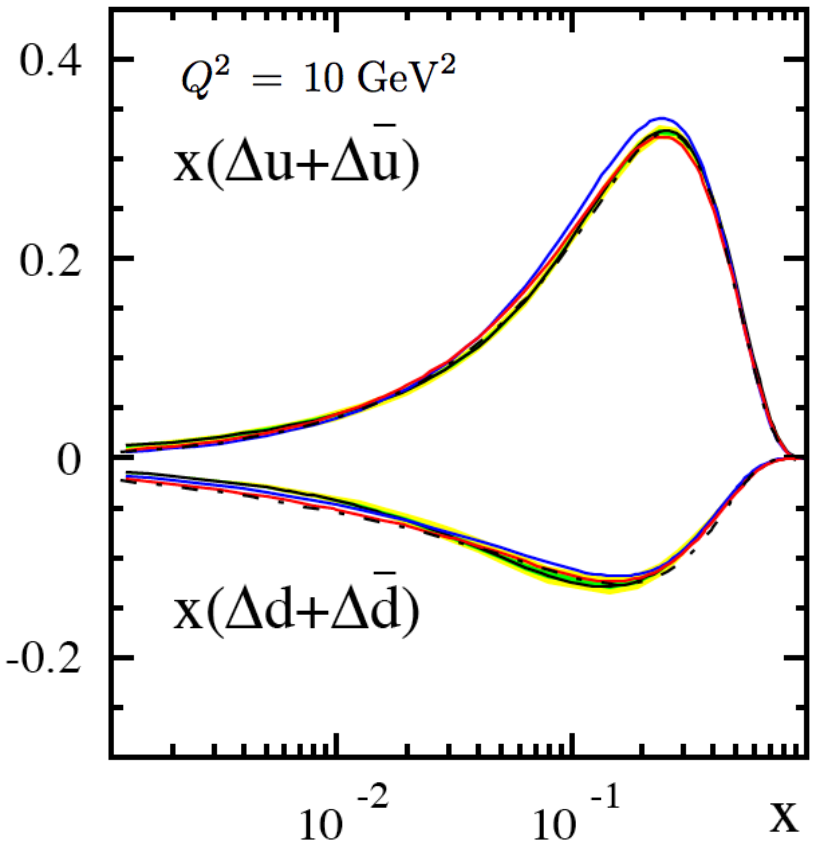
DSSV

DNS (DSS FFs)

What's the emerging picture ?



- best determined: $\Delta u + \Delta\bar{u}$, $\Delta d + \Delta\bar{d}$

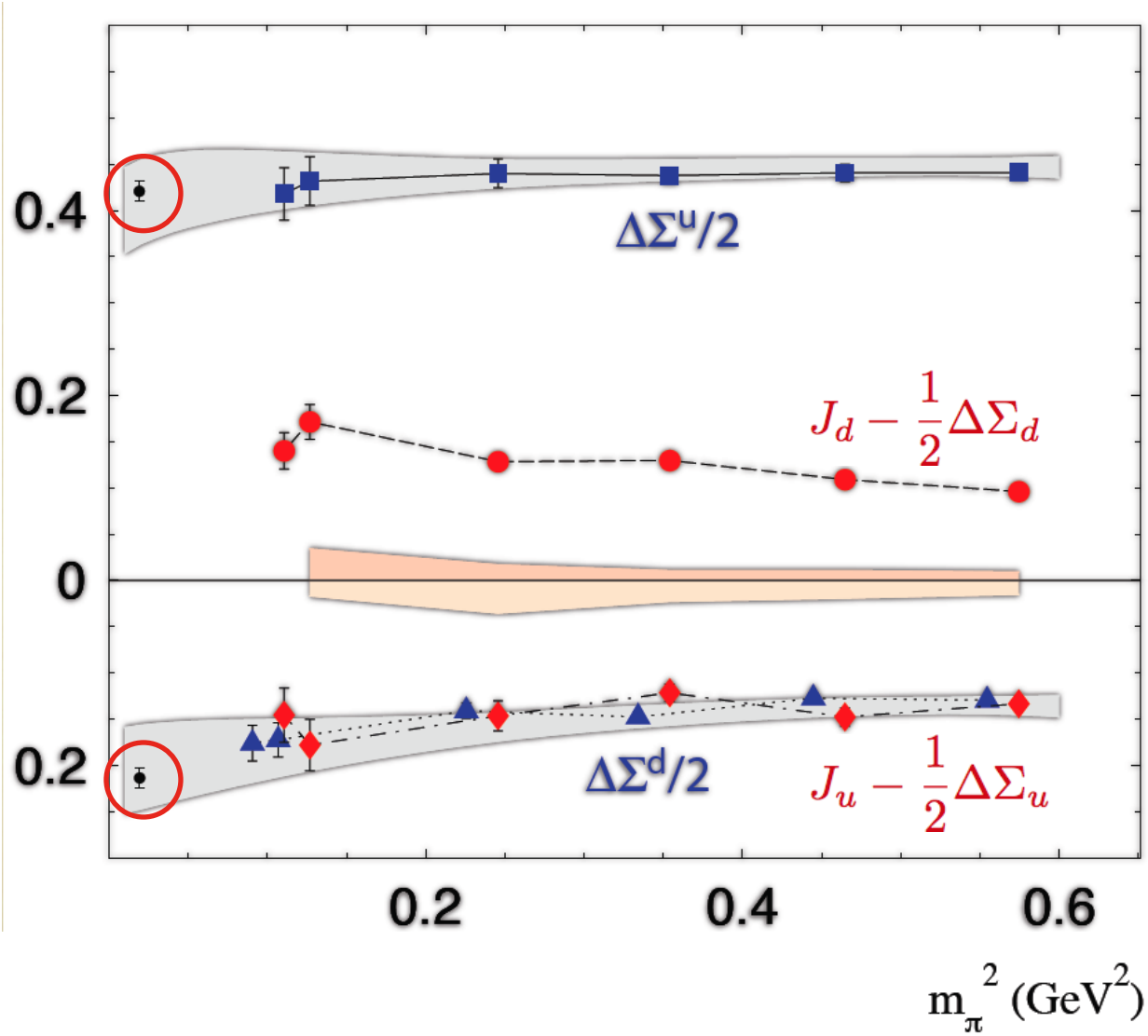


Comparison with:
DNS de Florian,Navarro,Sassot
GRSV Glück, Reya, Stratmann, WV

Similar results:
Leader, Stamenov, Sidorov
Blümlein, Böttcher; & HERMES
Hirai, Kumano, Saito (AAC)
COMPASS

- on the lattice :

LHPC Collab., P. Hägler et al.



disconnected diagrams not yet included

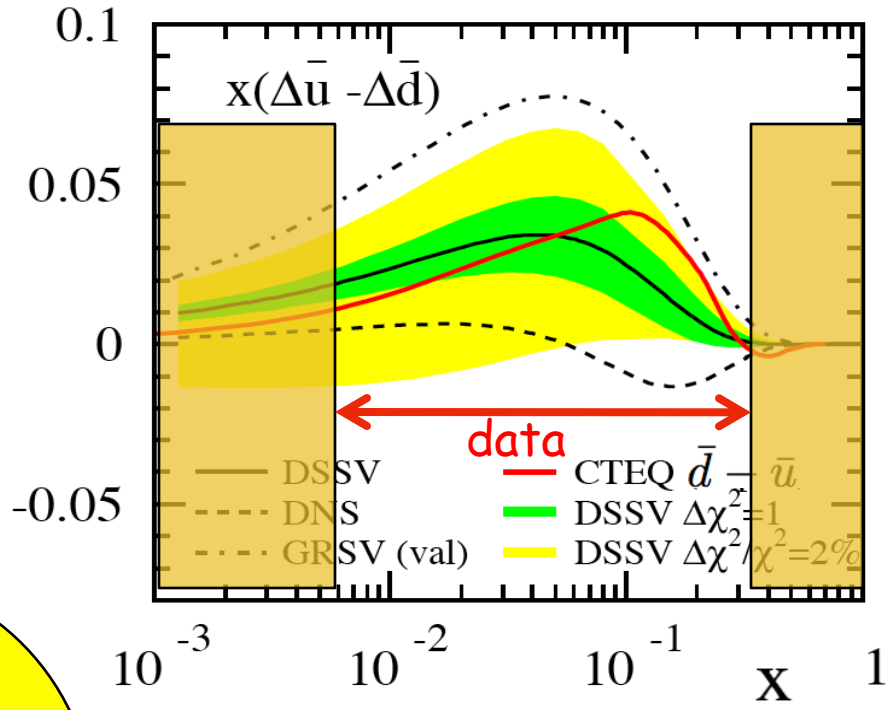
- gives confidence in small-x extrapolations

- light flavor sea :

driven by SIDIS

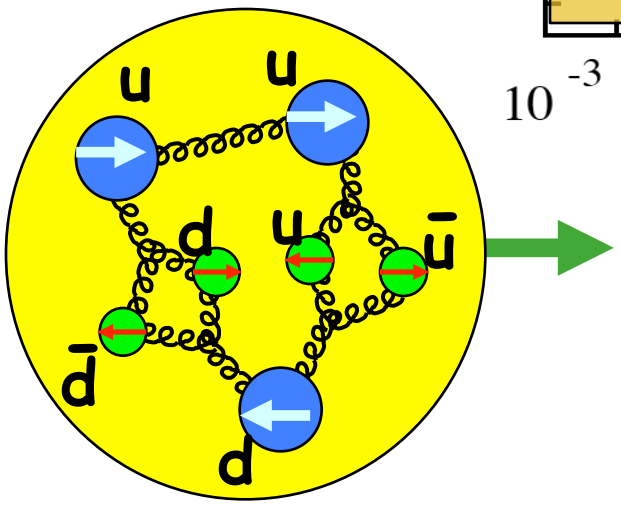
$$\Delta\bar{u} > 0$$

$$\Delta\bar{d} < 0$$



- qualitatively:

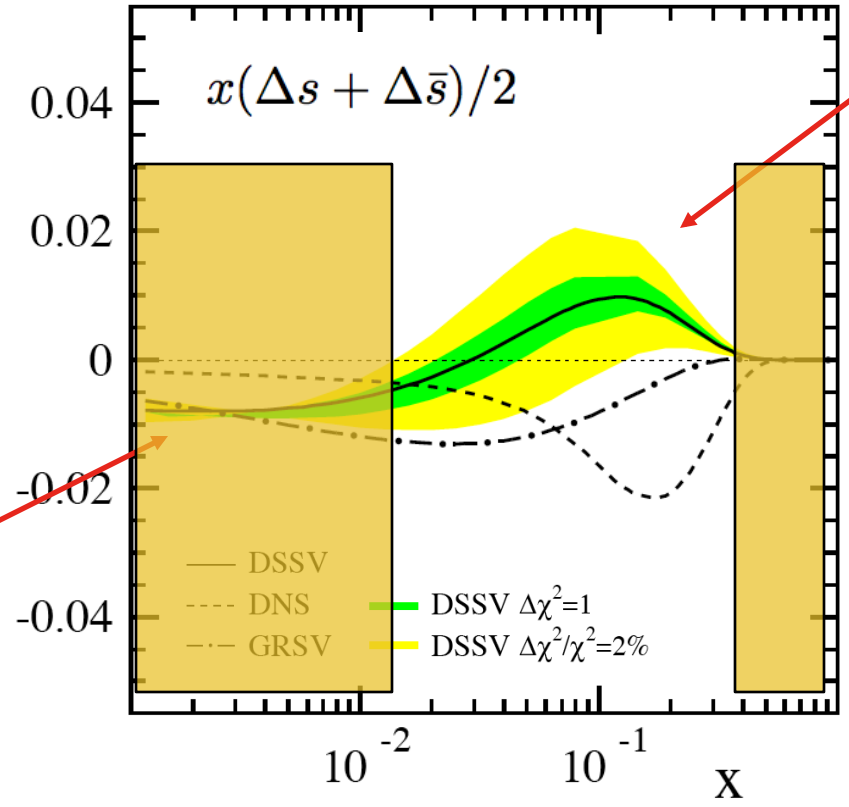
Glück,Reya;…



- large-N_c, chiral quark models, meson cloud

Thomas,Signal,Cao; Holtmann,Speth,Fässler; Diakonov,Polyakov,Weiss; Schäfer,Fries; Kumano; Wakamatsu; Bourrely, Soffer …

- strangeness :



driven by SIDIS (kaons … fragm. fcts.?)

driven by SU(3) (3F-D)

$$\int_{0.001}^{1} dx\, \Delta s(x) = -0.006 \pm 0.01 \qquad (\Delta\chi^2 = 1)$$

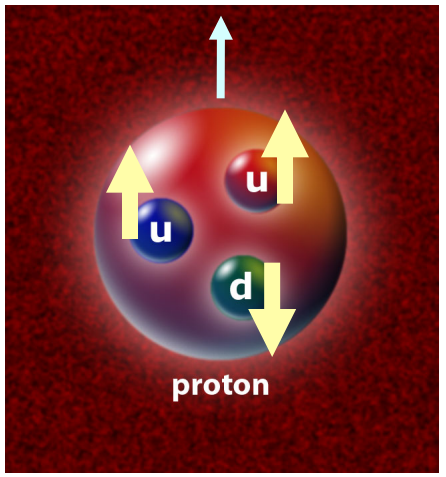
$$\int_{0}^{1} dx\, \Delta s(x) = -0.057 \pm ? \qquad \text{using F,D and SU(3)}$$

- total quark and anti-quark spin contribution :

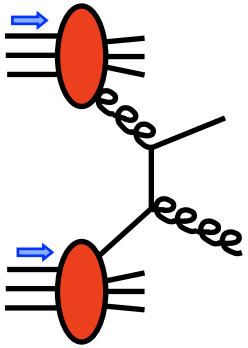
$$\int_{0.001}^{1} dx\Delta\Sigma = 0.366 \pm 0.016 \qquad (\Delta\chi^2 = 1)$$

$$\int_{0}^{1} dx\Delta\Sigma = 0.242 \pm ?$$

- in any case, $\Delta\Sigma \ll 1$



- polarized glue ?

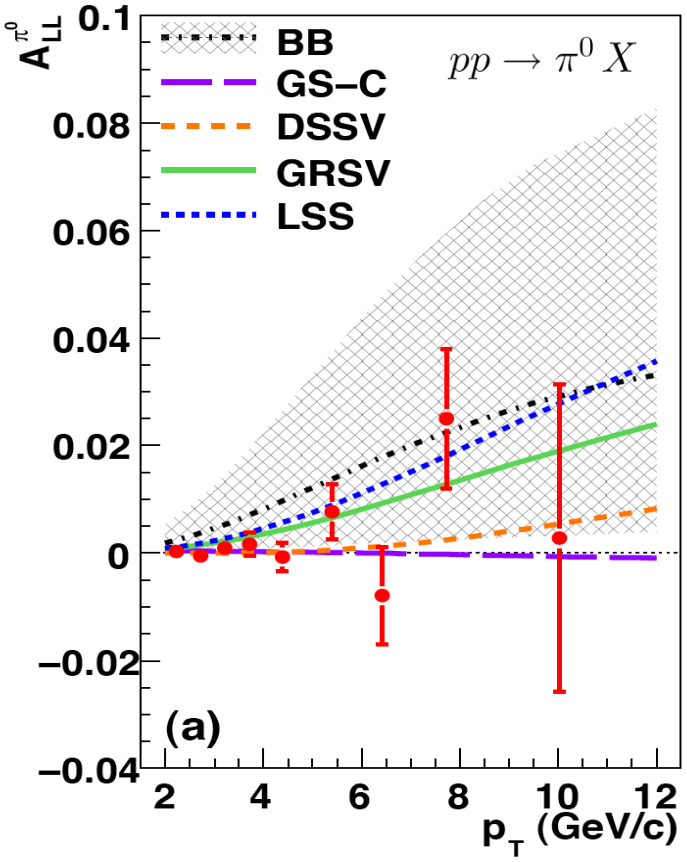


$\Delta G \approx 1.8$

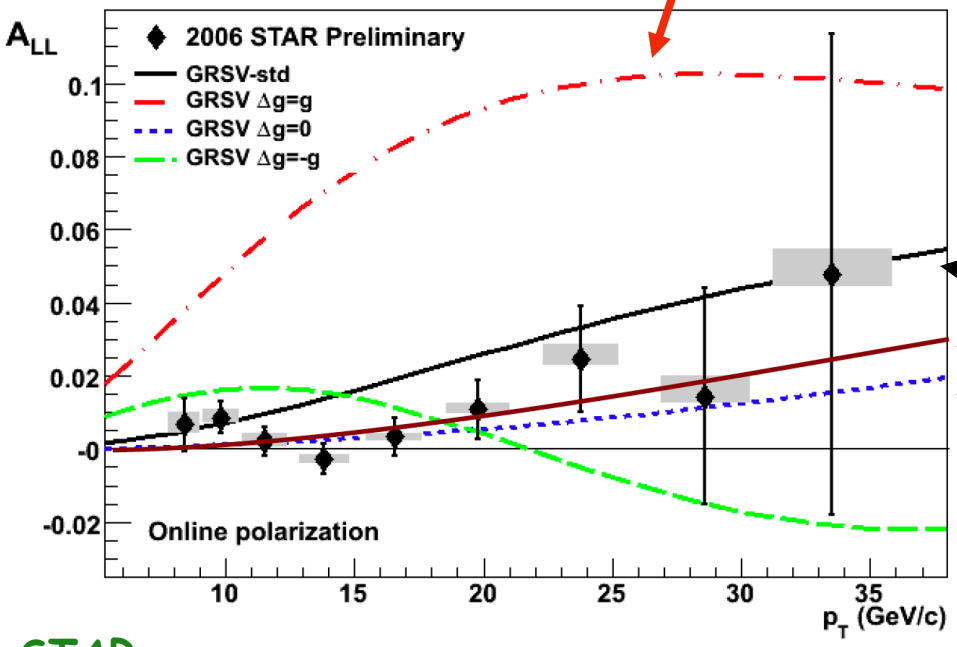
"axial anomaly" Altarelli et al.

$$\Delta\Sigma \rightarrow \Delta\Sigma - n_f \frac{\alpha_s(Q^2)}{2\pi}\Delta G(Q^2)$$

PHENIX



$pp \rightarrow \text{jet}\, X$

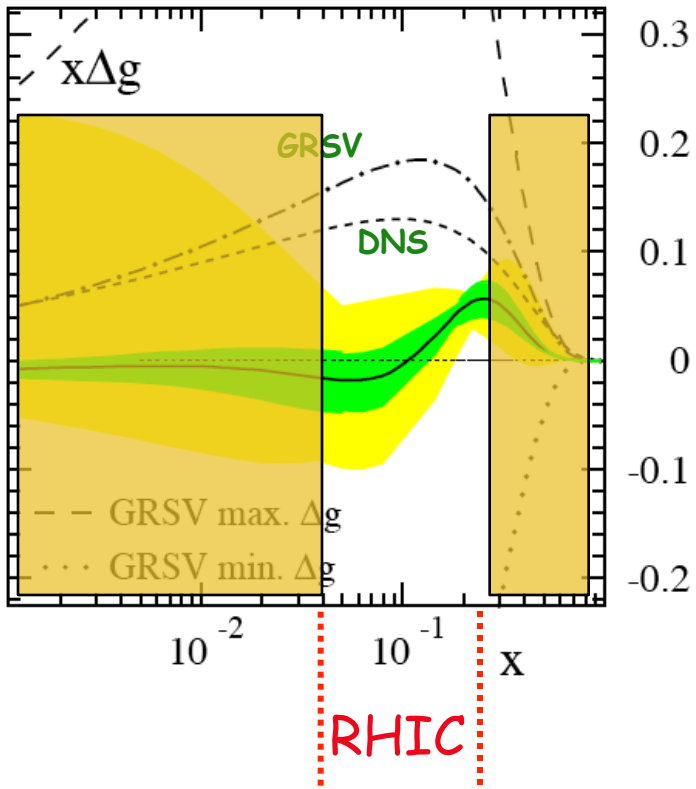


$\Delta G \approx 0.4 \quad (Q^2 = 1\,\text{GeV}^2)$

DSSV

$\Delta G = 0$

STAR

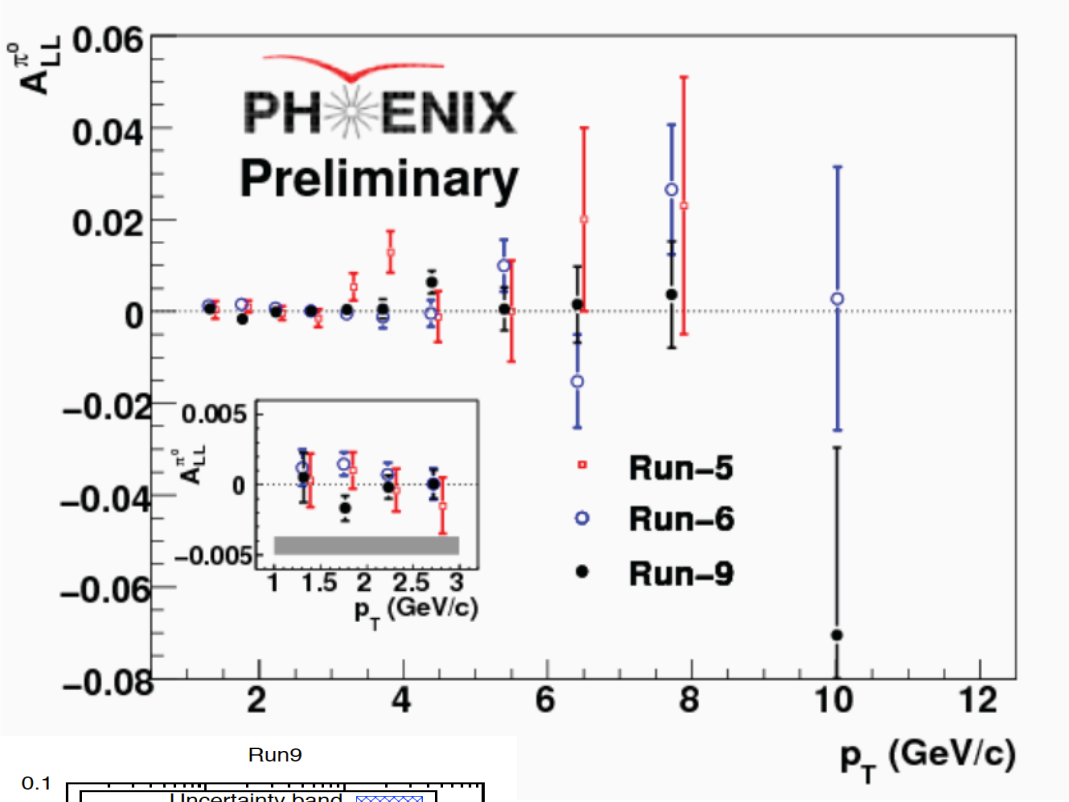


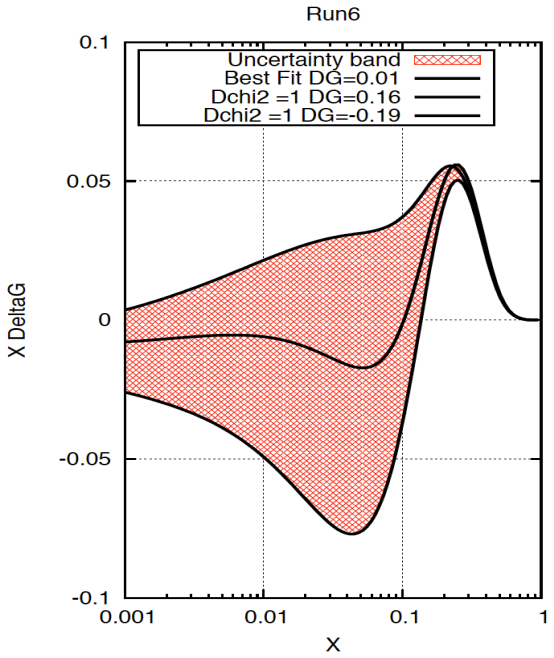
$$\int_{0.05}^{0.2} dx\,\Delta g \;=\; 0.006 \pm 0.06 \qquad (\Delta\chi^2 = 1)$$

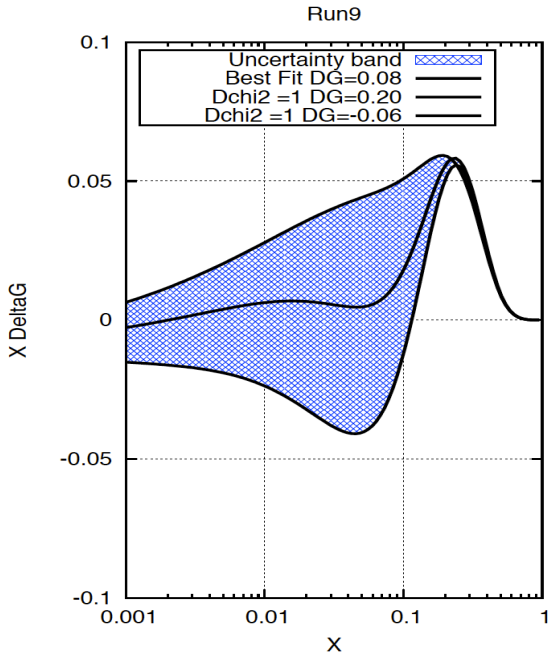
$$\int_{0}^{1} dx\,\Delta g \;=\; -0.084 \pm ?$$

- there could still be significant contribution to proton spin
- constraints become better with new data from RHIC

Most recent data:

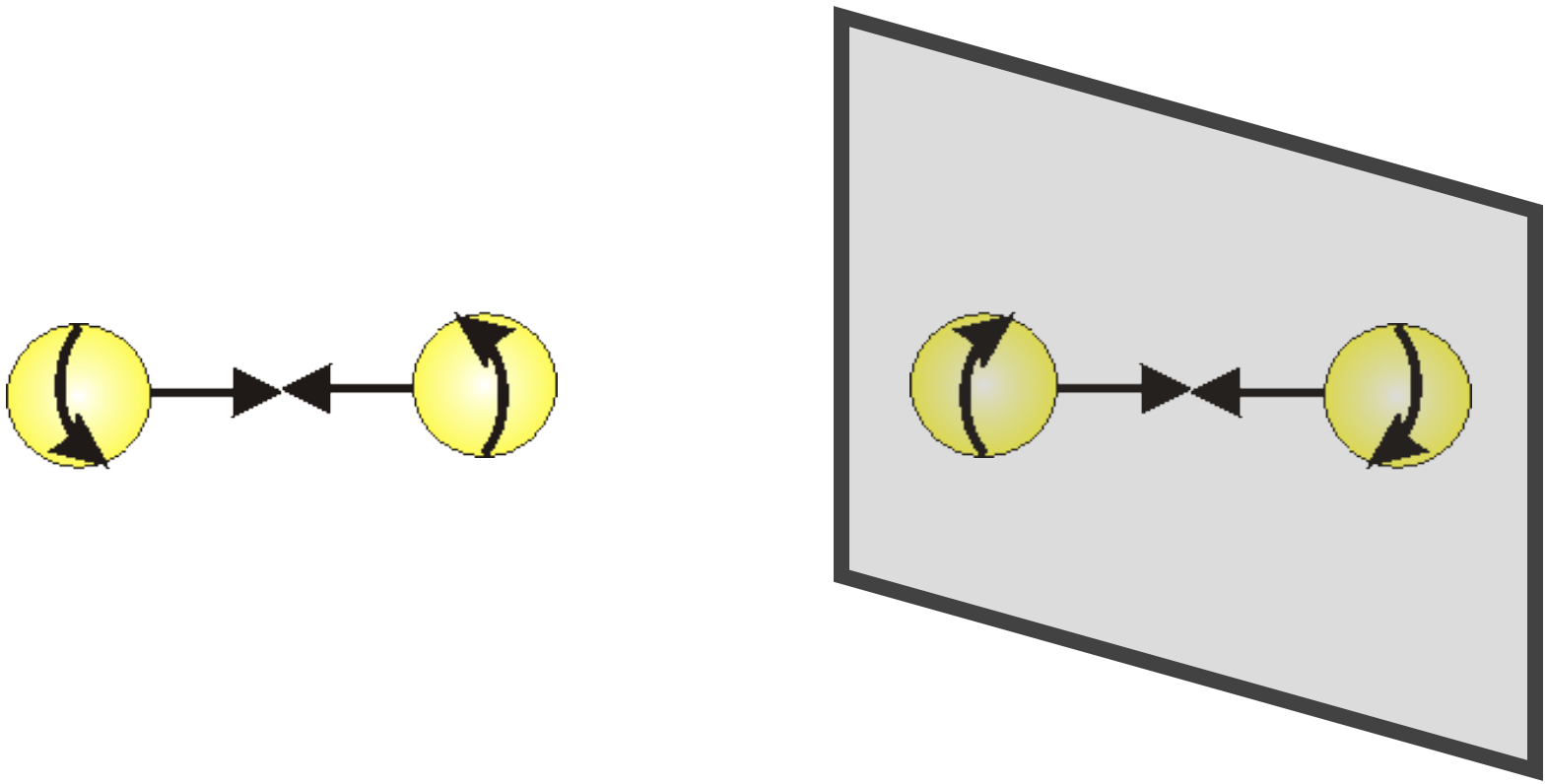






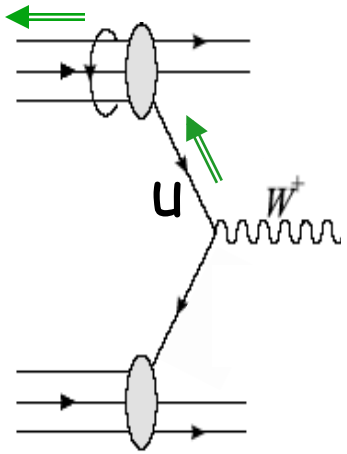
S.Taneja

The latest:
W-boson production at RHIC



Parity violation: can have

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$



unpol.

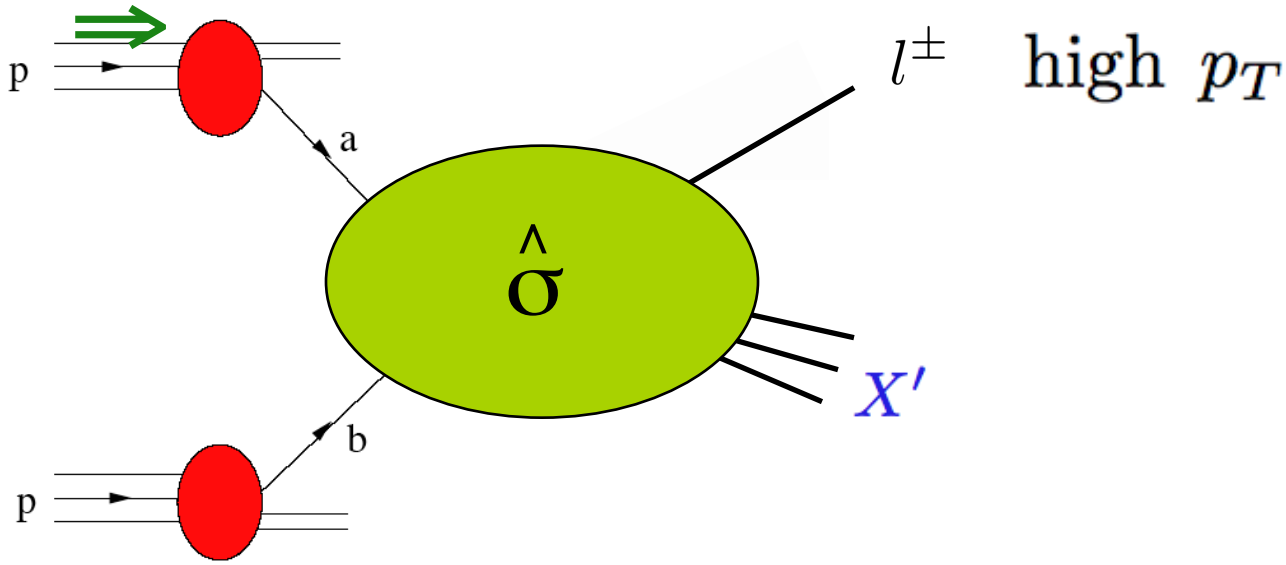
$$\sqrt{s} = 500 \text{ GeV}$$

- large scale Q~M_W: pQCD
- large Parity Violation effect:

$$A_L^{W^+} \approx - \frac{\Delta u(x_1)\, \bar{d}(x_2) - \Delta \bar{d}(x_1)\, u(x_2)}{u(x_1)\, \bar{d}(x_2) + \bar{d}(x_1)\, u(x_2)} \qquad x_{1,2} = \frac{M_W}{\sqrt{S}}\, \mathrm{e}^{\pm y_W}$$

- complementary to SIDIS, but cleaner
- NLO corrections known Ratcliffe, Gehrmann, Kamal, de Florian, WV

In practice:



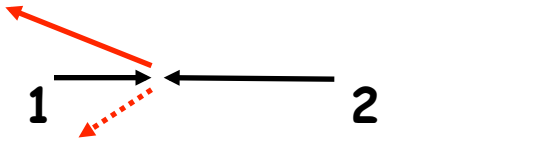
$$d\sigma^+ - d\sigma^- = \sum_{a,b} \int dx_a dx_b \, \Delta f_a(x_a,\mu) \, f_b(x_b,\mu) \, \left[d\hat{\sigma}^+ - d\hat{\sigma}^- \right]_{ab\to W\to l} + \text{power corr.}$$

perturbative QCD

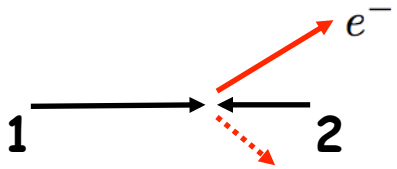
$$\hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_s \, \hat{\sigma}^{(1)} + \ldots$$

W^- :

$$\sigma^{W^-} \propto \bar{u}(x_1)\, d(x_2)\, (1-\cos\theta)^2 + d(x_1)\, \bar{u}(x_2)\, (1+\cos\theta)^2$$

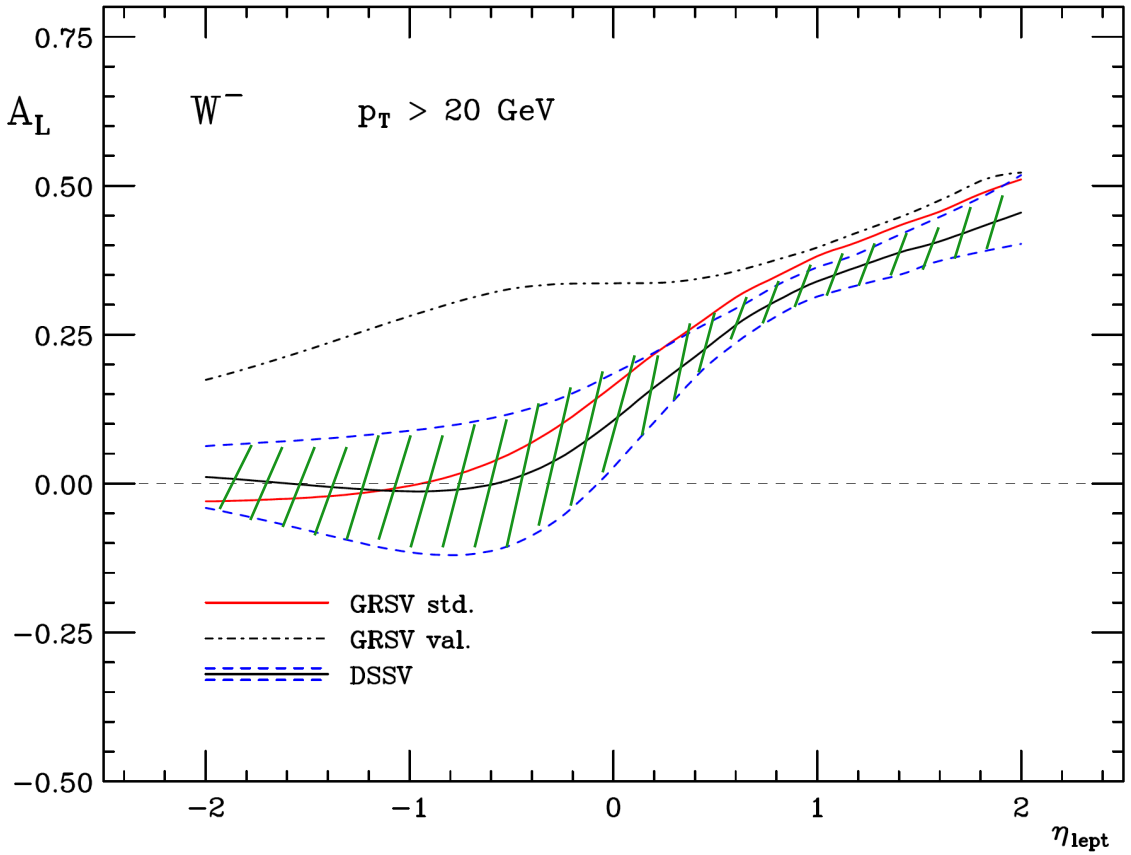


$\bar{u}(x_1)\, d(x_2)$

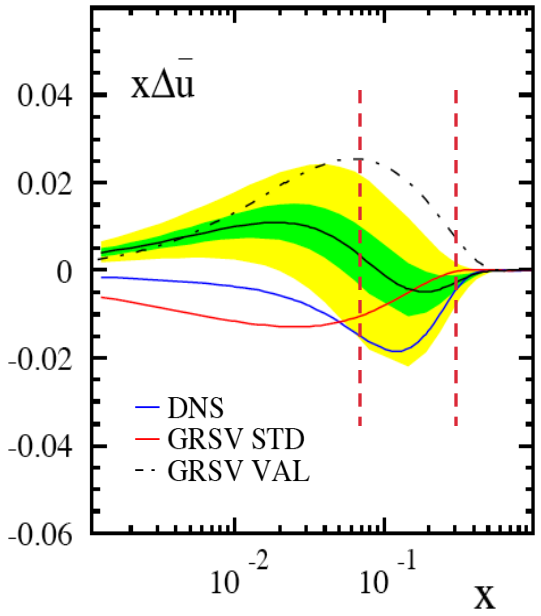


$d(x_1)\, \bar{u}(x_2)$

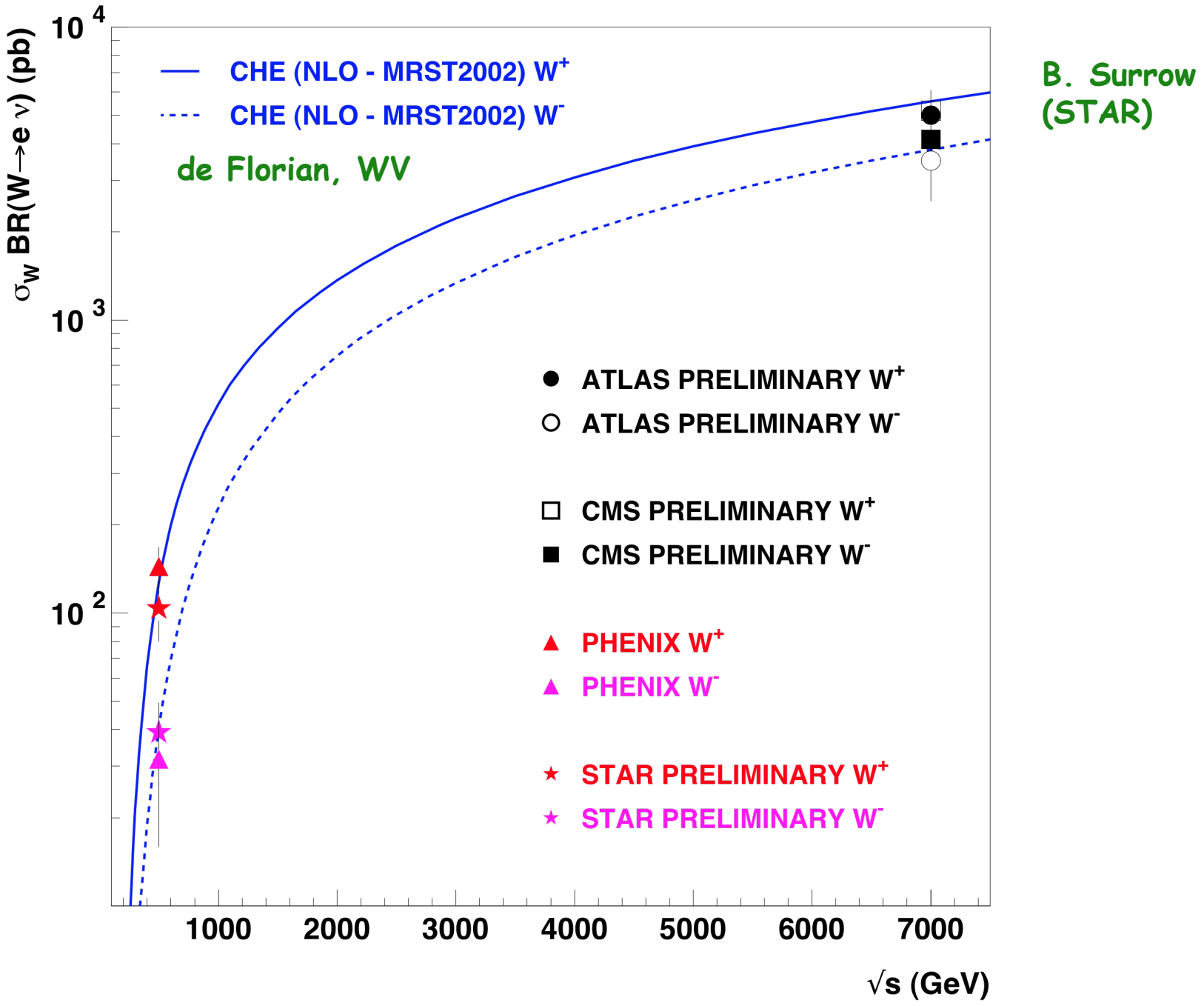
$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$



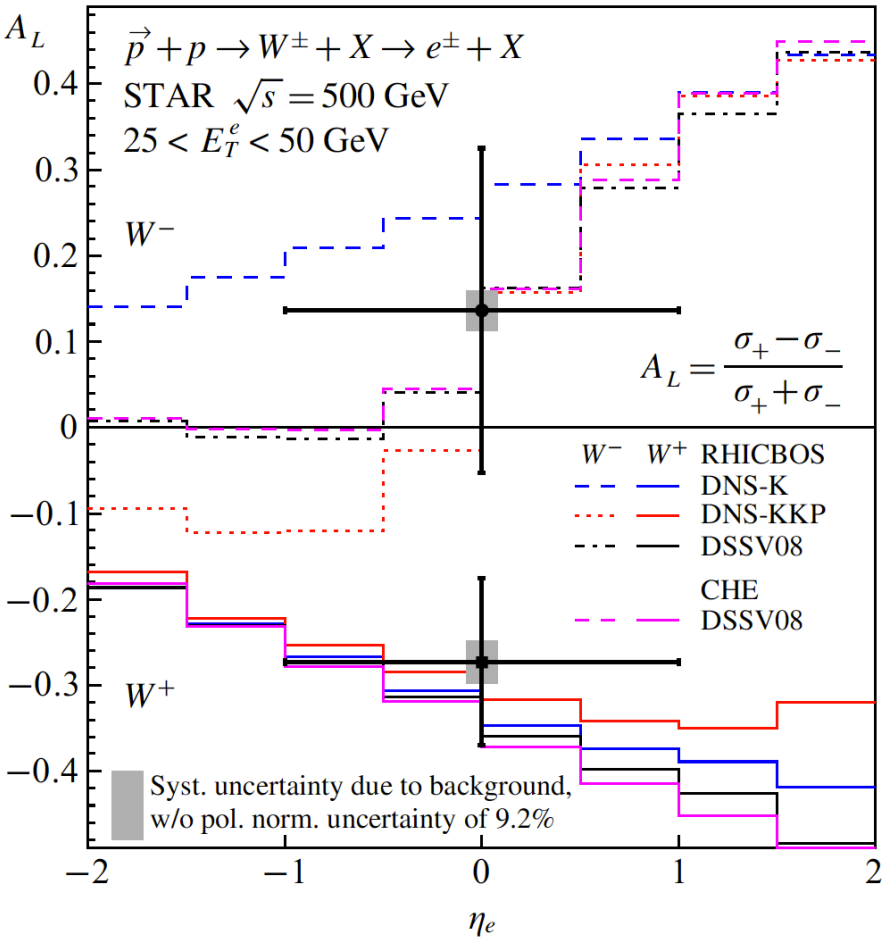
$\theta > \frac{\pi}{2}$ $\theta < \frac{\pi}{2}$

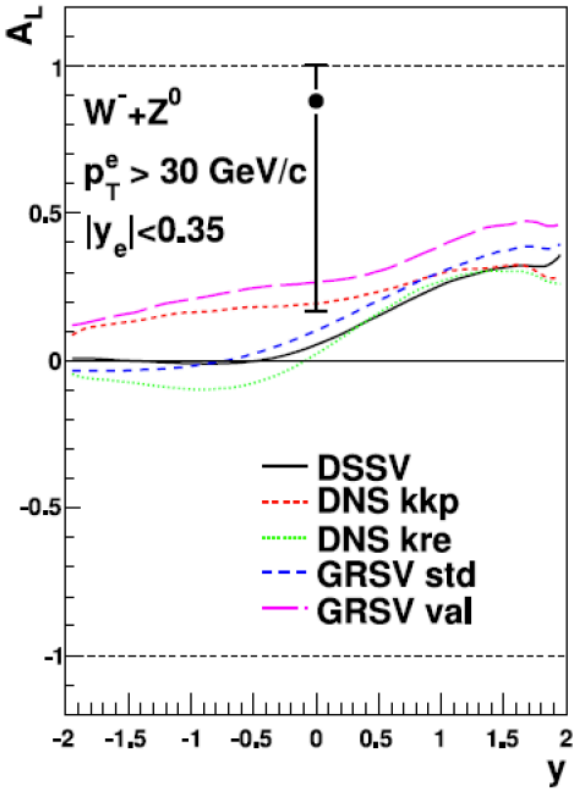


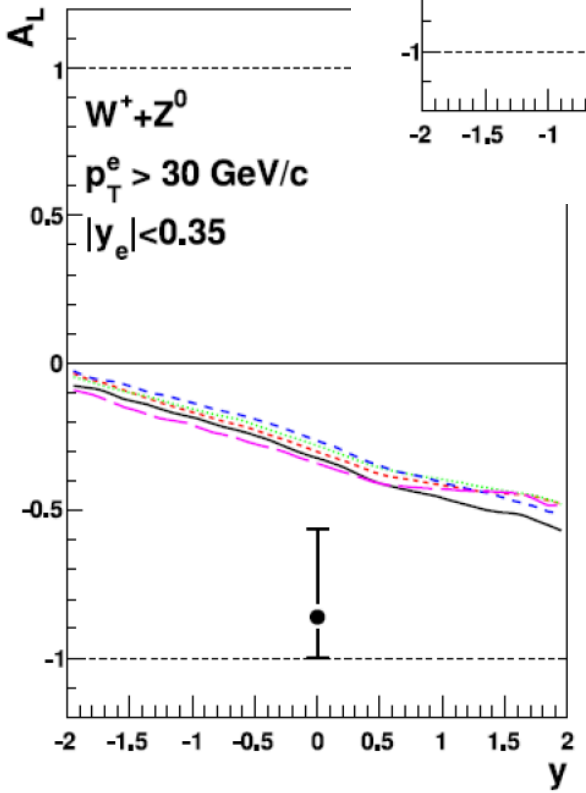
- **NLO:**
  de Florian, WV


σ_W BR(W→e ν) (pb)
10 4
10 3
10 2
CHE (NLO - MRST2002) W+
CHE (NLO - MRST2002) W-
de Florian, WV
B. Surrow (STAR)
ATLAS PRELIMINARY W+
ATLAS PRELIMINARY W-
CMS PRELIMINARY W+
CMS PRELIMINARY W-
PHENIX W+
PHENIX W-
STAR PRELIMINARY W+
STAR PRELIMINARY W-
1000
2000
3000
4000
5000
6000
7000
√s (GeV)

STAR


A_L
$\vec{p}+p \to W^{\pm}+X \to e^{\pm}+X$
STAR $\sqrt{s}=500$ GeV
$25 < E_T^e < 50$ GeV
W^-
W^+
$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
W^- W^+ RHICBOS
DNS-K
DNS-KKP
DSSV08
CHE
DSSV08
Syst. uncertainty due to background,
w/o pol. norm. uncertainty of 9.2%
η_e

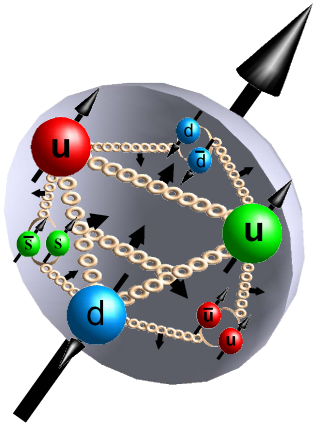

A_L
W^-+Z^0
$p_T^e > 30$ GeV/c
$|y_e|<0.35$
DSSV
DNS kkp
DNS kre
GRSV std
GRSV val
y


A_L
$W^+ + Z^0$
$p_T^e > 30$ GeV/c
$|y_e|<0.35$
y

Phenix

Conclusions:

- spin structure of the proton in QCD has turned out to be more complex than expected !



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

≈ 25% small ? ?

- field carried by tremendous experimental efforts: RHIC, HERMES, COMPASS, Jlab, …
- and by theory advances
- synergy of lepton-nucleon and proton-proton scattering

  Electron-Ion Collider (EIC) ?