The Sea quark helicities
and how to get to them

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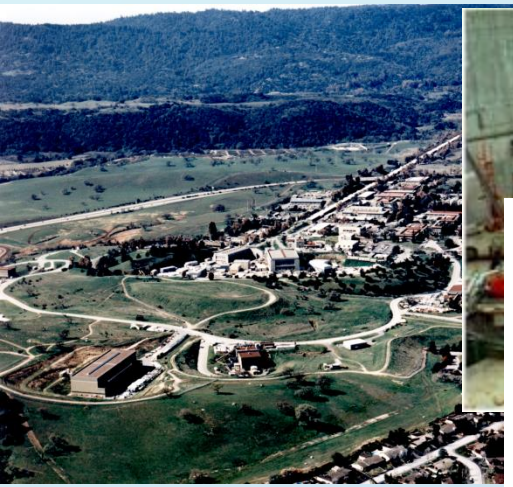
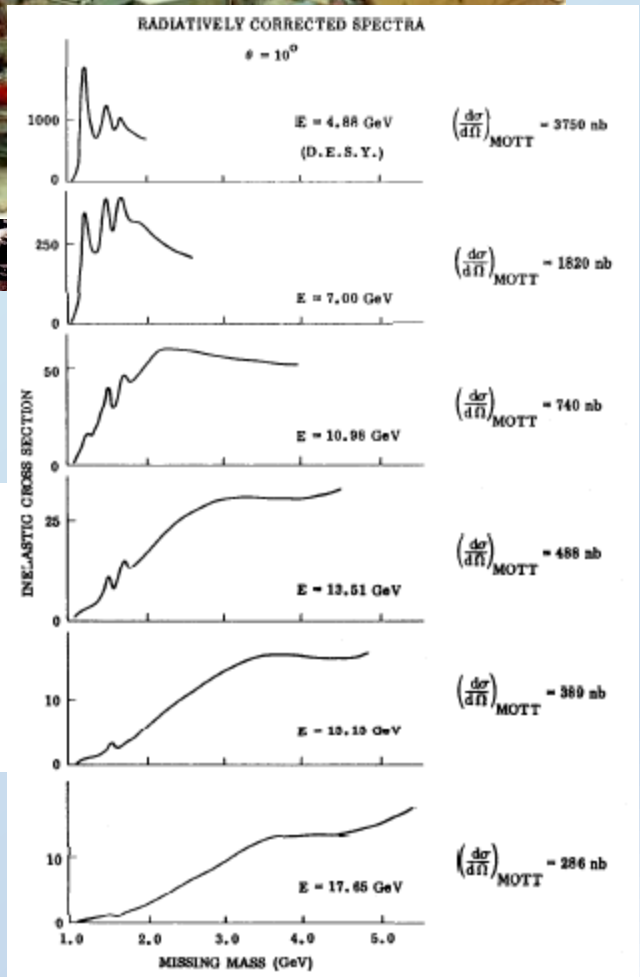
Outline

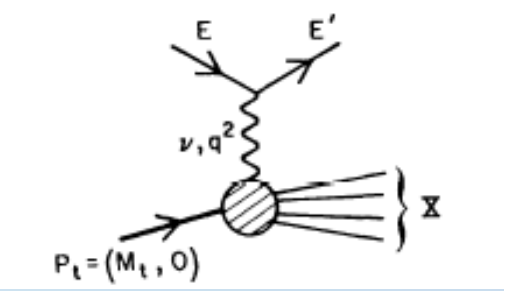
- DIS/QCD history
  - Scattering as tool to probe substructure: Kendall/Friedmann→Deep Inelastic Scattering DIS
- Access to (spin dependent) parton distribution functions via deep inelastic scattering
  - DIS process
  - SIDIS (+ a little Fragmentation functions)
  - Experiments and results
- RHIC access to sea quarks
  - The weak interaction
  - W kinematics
  - Inclusive lepton asymmetries
- The Future: EIC – a polarized e – p(d,He,A) collider

Kendall, Friedman and Taylor

1972, Nobel Price 1990

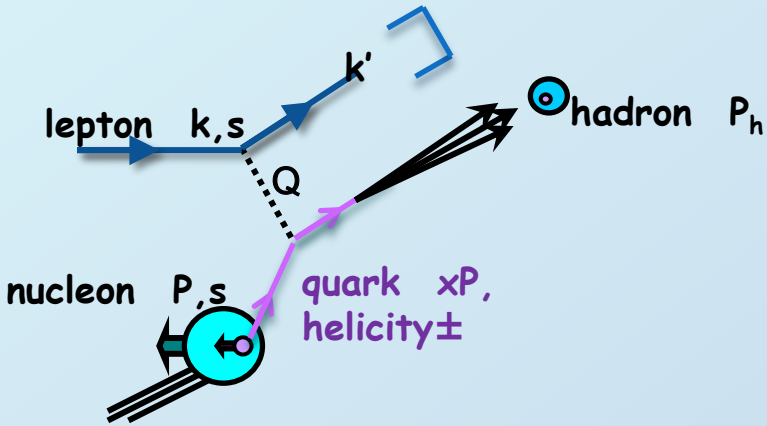


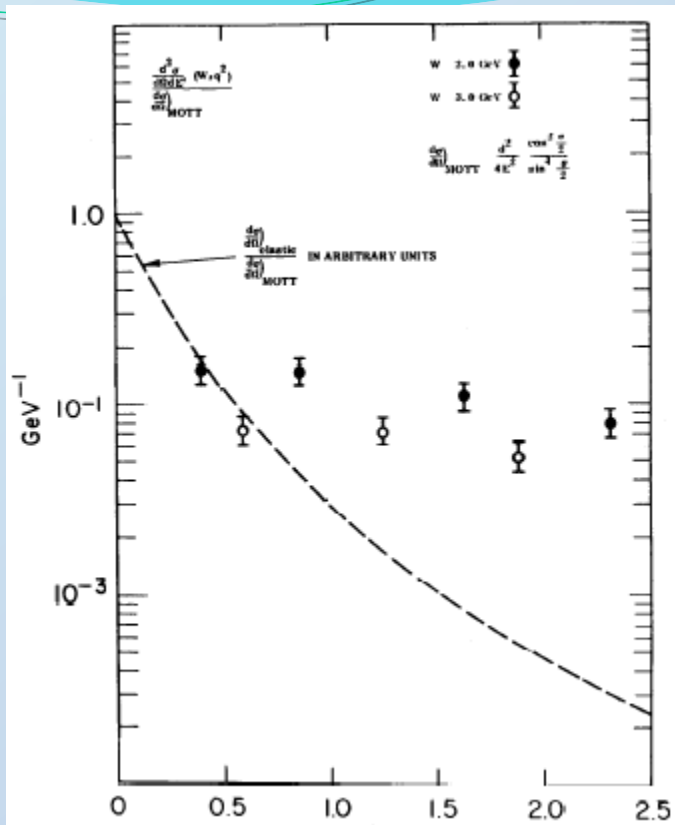




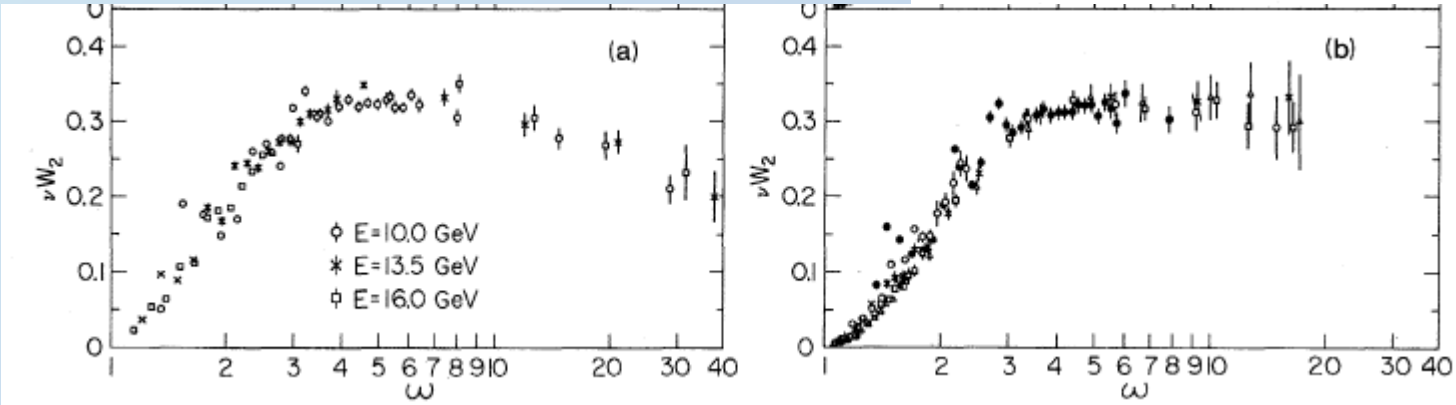
- Deep inelastic scattering (DIS):
  - Use high enough energies to break up the proton → produce new particles: hadrons
  - Can also be viewed as elastic scattering on point-like constituents called quarks partons

Kendall, Friedman and Taylor, continued

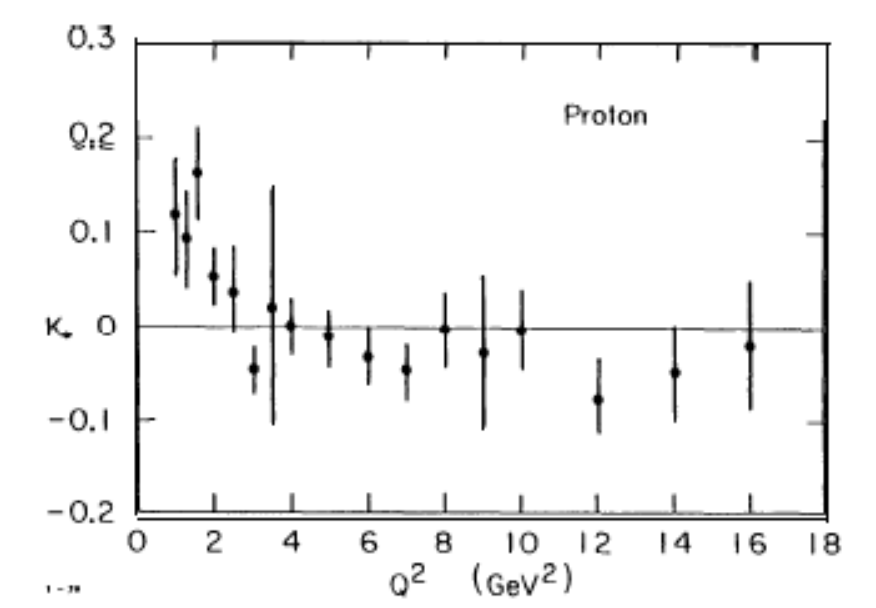




- Scaling
- x dependence

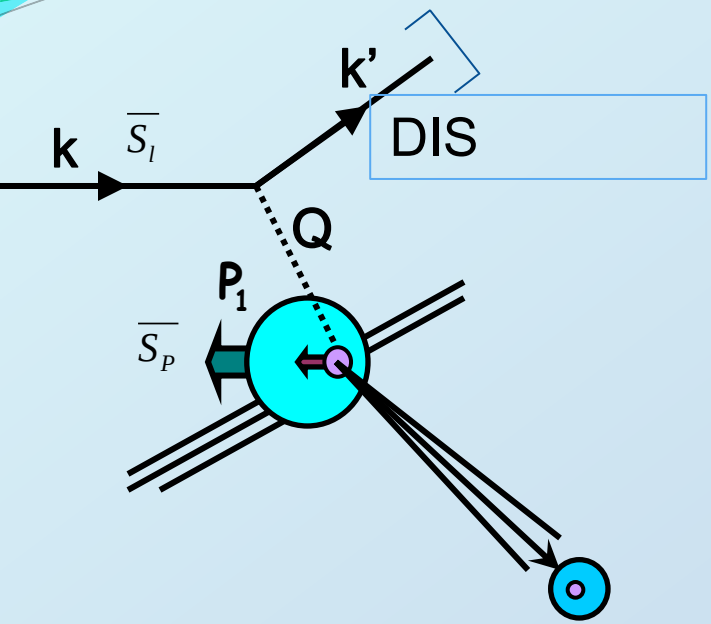


Callan-Gross relation



- $2xF_1(x,Q^2) = F_2(x,Q^2)$
- Spin of quarks inside nucleon: ½

DIS Kinematics



$$\frac{d\sigma}{dQ^2} = f_q(x_1) \otimes \tilde{\sigma}$$

Quark distribution functions: quark q in nucleon

$$Q^2 = -q^2 = -(k-k')^2$$

- Squared Momentum transfer of photon/Z

$$x_B = \frac{Q^2}{2Pq}$$

- Bjorken scaling variable, at high Q^2 momentum fraction of quark

$$k^+ = xP^+$$

$$y = \frac{qP}{kP}$$

- Inelasticity (sometimes called depolarization factor)

$$W^2 = (P+q)^2$$

- Mass of hadronic final state

- Hard scales: $Q^2 >> 1\ \mathrm{GeV}^2$ otherwise photo-production
- Photo-production usable is at least on hadron pt >1GeV

Unpolarized proton structure

$$\frac{d^2\sigma^i}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\eta^i\left[Y_+F_2^i \pm Y_-xF_3^i - y^2F_L^i\right]$$

$$F_L^i = F_2^i - 2xF_1^i$$

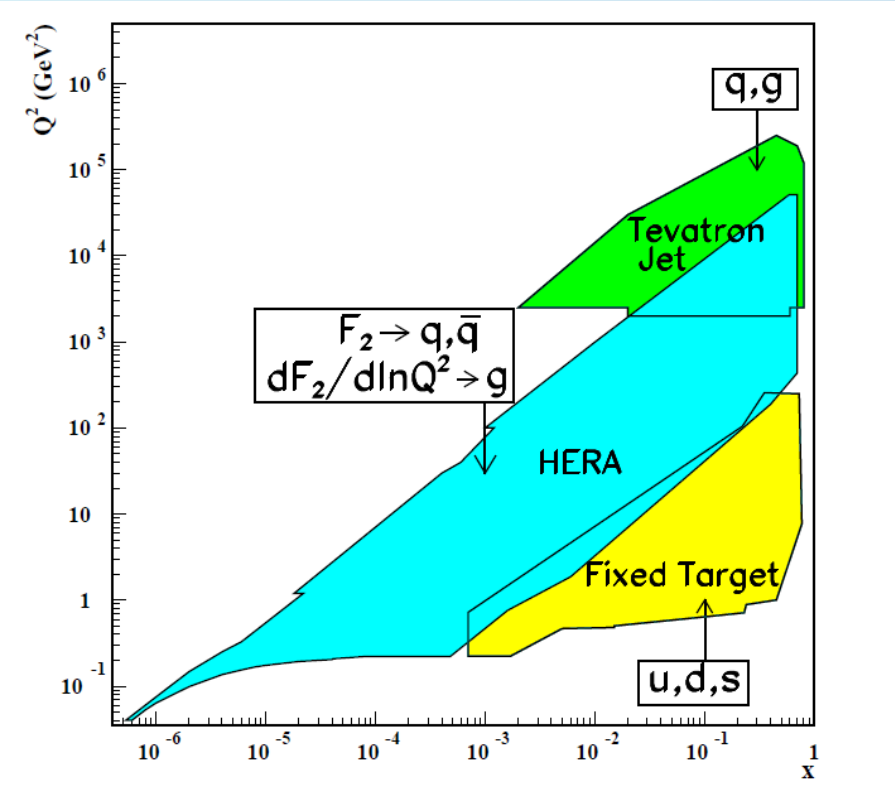
$$Y_\pm = 1 \pm (1-y)^2$$

$$F_2^\gamma = x\sum_q e_q^2(q+\bar{q})$$

Neutral current

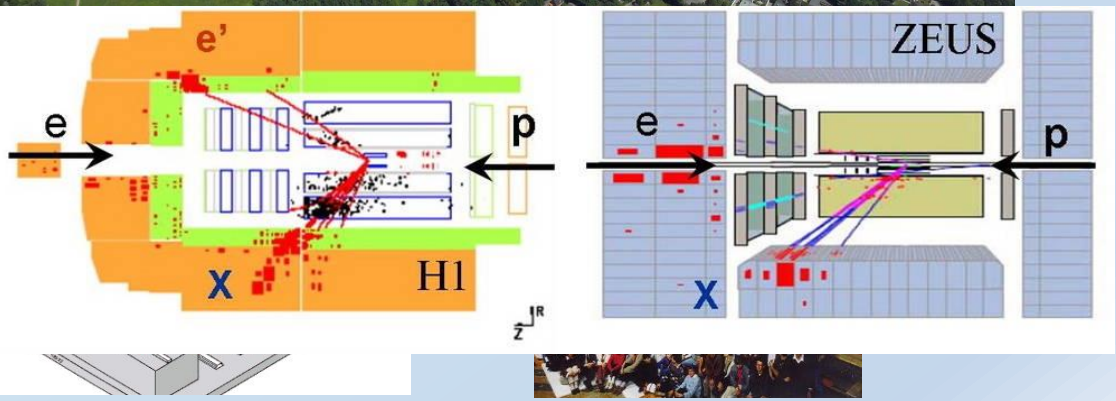
- F_2 (and F_1) measure the sum of quark and antiquark distribution in the nucleon or nucleii
- The majority of our knowledge on the unpolarized PDFs is coming from F_2 measurements

DIS kinematics



- Collider geometry → larger access in x and Q2 than fixed target
- Inclusive DIS gives access to valence quarks, in particular u quarks:
  - 4/9 u + 1/9 d + 1/9 s
- DGLAP evolution allows access to gluons

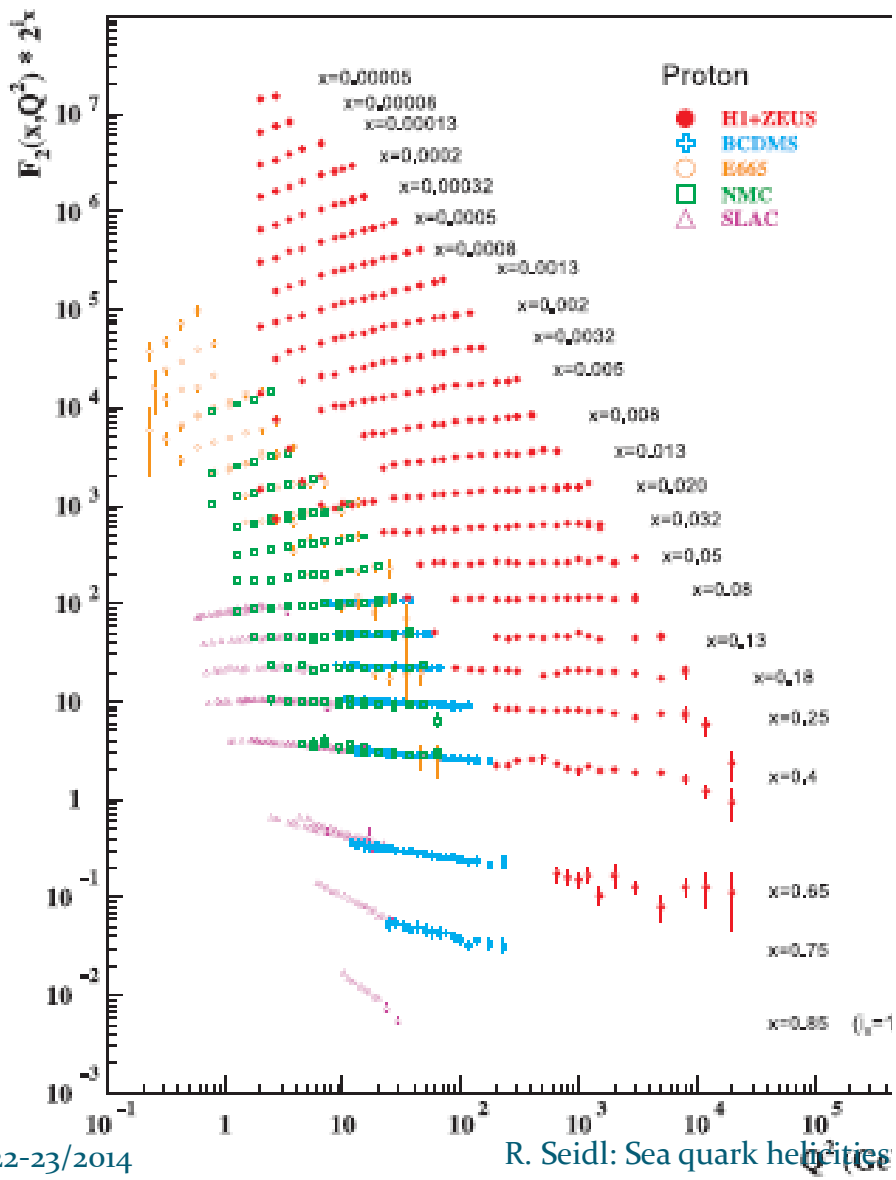
Modern day DIS

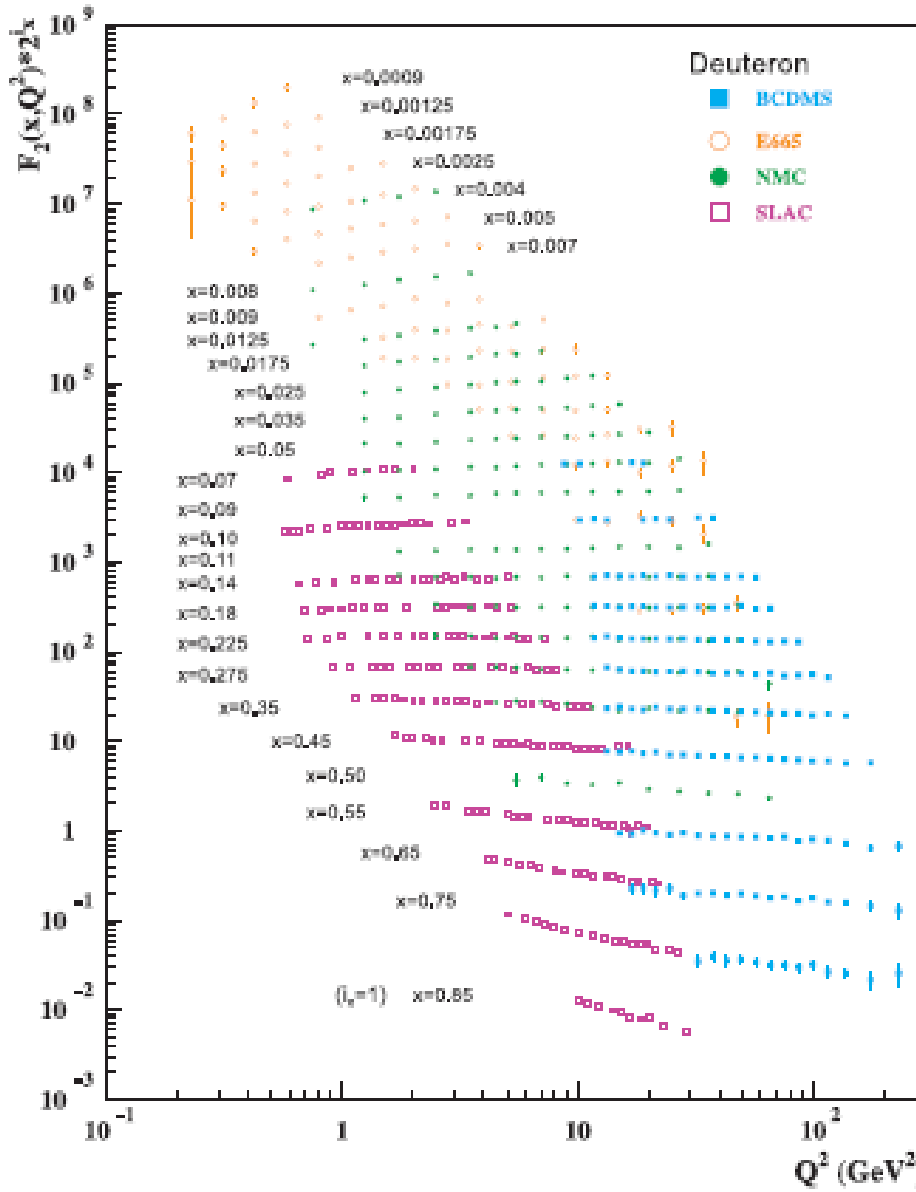


- At Slac Fixed target with electron energies of up to ~20 GeV
- HERA @DESY in Hamburg Germany:
  - First e-proton collider with 920 GeV Protons on 27 GeV (polarized) electons
  - About 2 orders of magnitude better resolution: 10^{-17}m

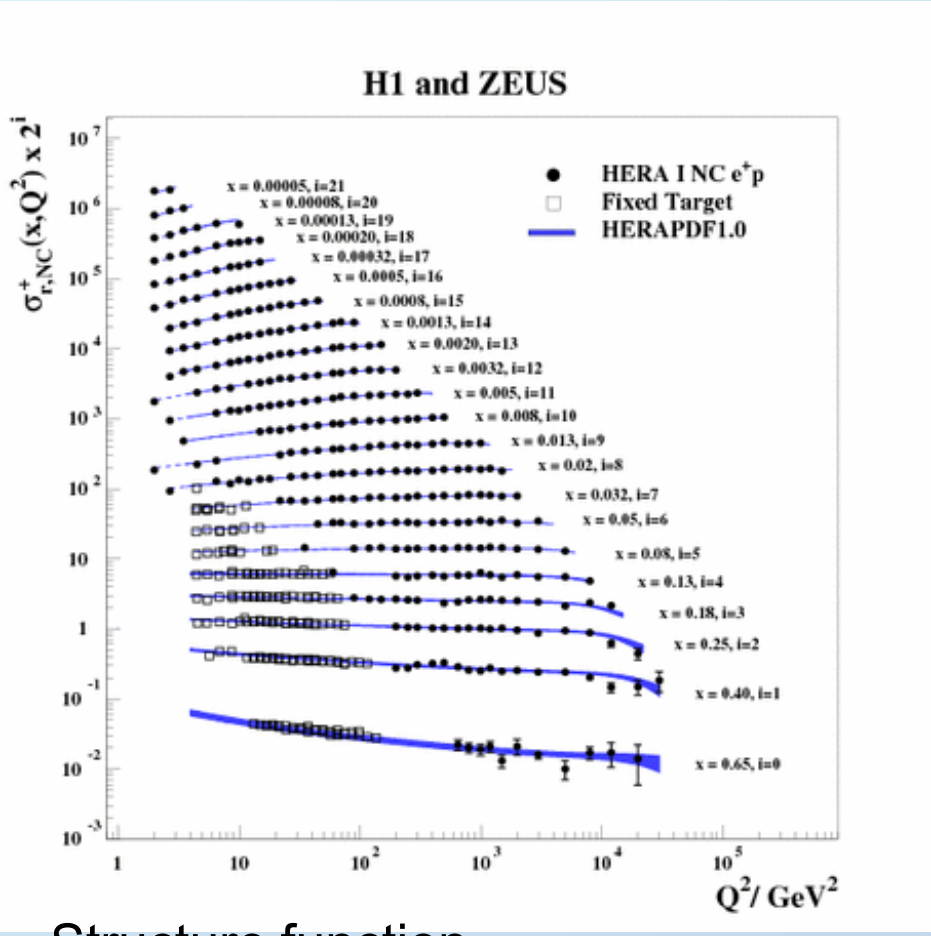
    …and partons at very low momentum fraction

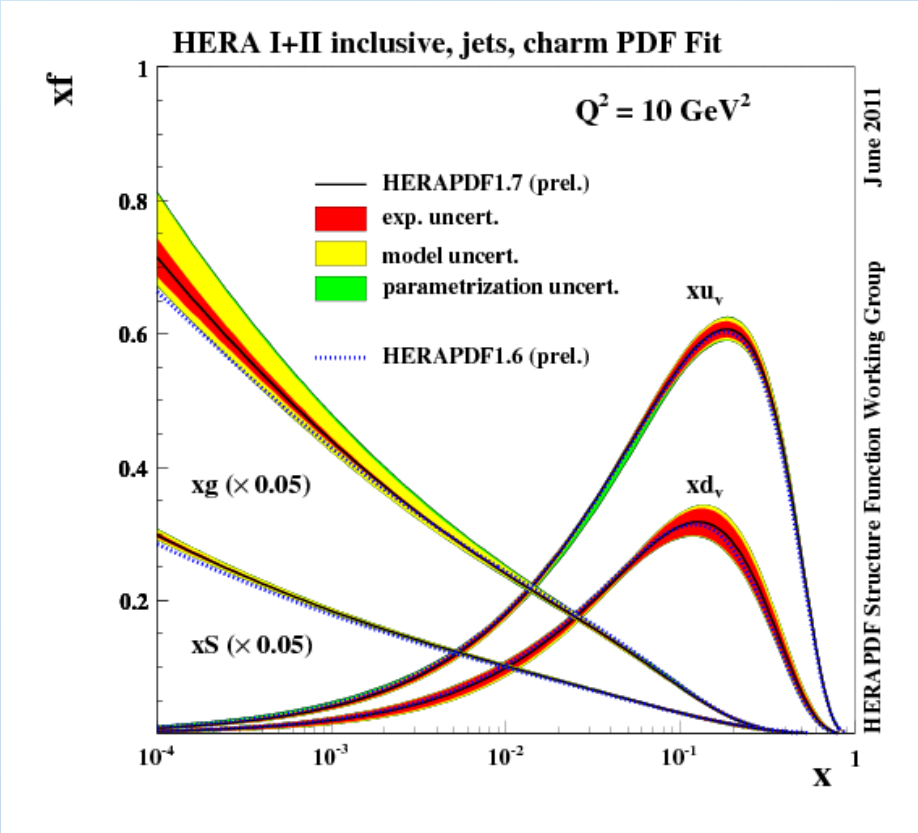
Proton and Deuteron F_2 data





Current unpolarized structure and distribution functions from DIS





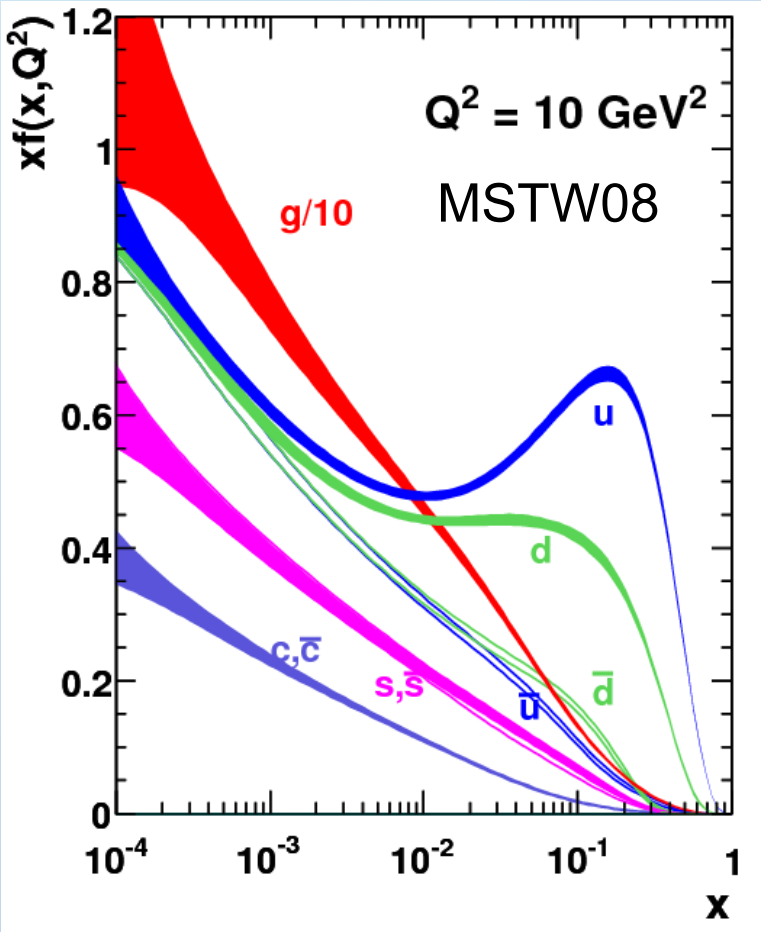
Structure function

$$F_2(x) = x \sum_q e_q^2 \left(q(x) + \bar{q}(x)\right)$$

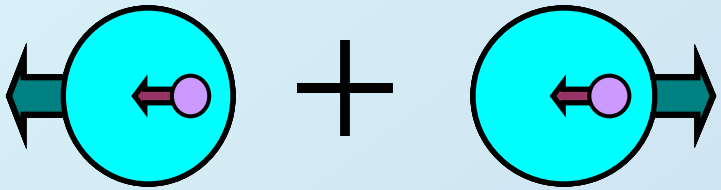
Large lever arm of data+DGLAP evolution allows for a good determination of pdfs

Global fits

- Regular DIS data
- Neutrino DIS data
- HERA charged current data
- Hadron collider
  - Jet cross sections
  - W, Z cross sections
  - Drell-Yan process



Quark distributions



$q(x), G(x)$

Unpolarized distribution function q(x)

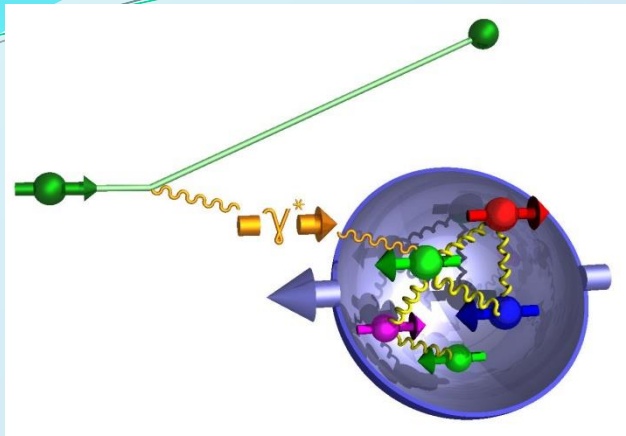
$\Delta q(x), \Delta G(x)$

Helicity distribution function $\Delta q(x)$

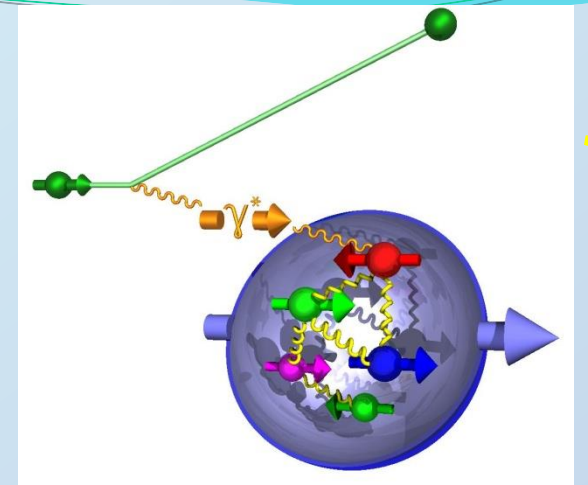
$\delta q(x)$

Transversity distribution function $\delta q(x)$

Polarized inclusive DIS



$$\vec{S}_{\gamma^*} + \vec{S}_N = 1/2$$
$$\vec{S}_N = \vec{S}_q$$
$$\sigma_{1/2} \sim q^+(x)$$



$$\vec{S}_{\gamma^*} + \vec{S}_N = 3/2$$
$$\vec{S}_N = -\vec{S}_q$$
$$\sigma_{3/2} \sim q^-(x)$$

- Virtual photon γ^* can only couple to quarks of opposite helicity
- Select $q^+(x)$ or $q^-(x)$ by changing the orientation of target nucleon spin or helicity of incident lepton beam

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

Asymmetry definition:

beam target

$$A_1(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \overset{\text{L.O.}}{\cong} \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)} = \frac{g_1(x)}{F_1(x)}$$

inclusive DIS: only e' info used

polarized proton structure

$$\frac{d^2\Delta\sigma^i}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\eta^i\left[Y_+ 2g_5^i - g_L^i \mp Y_- 2xg_1^i + y^2 g_L^i\right]$$

$$g_L^i = g_4^i - 2xg_5^i$$

$$Y_\pm = 1 \pm (1-y)^2$$

$$\boxed{g_1^\gamma = x\sum_q e_q^2(\Delta q + \Delta\bar{q})}$$

$$g_1^{\gamma Z} = x\sum_q 2e_q g_V^q(\Delta q + \Delta\bar{q})$$

$$g_1^Z = x\sum_q ({g_V^q}^2 + {g_A^q}^2)(\Delta q + \Delta\bar{q})$$

$$g_5^{\gamma Z} = \sum_q 2e_q^2 g_A^q(\Delta q - \Delta\bar{q})$$

$$g_5^Z = \sum_q 2g_V^q g_A^q(\Delta q - \Delta\bar{q})$$

- g_1 measures the total quark spin contribution to the nucleon
- Flavor information from γZ interference, Z exchange and in particular charged curent (W exchange) interactions

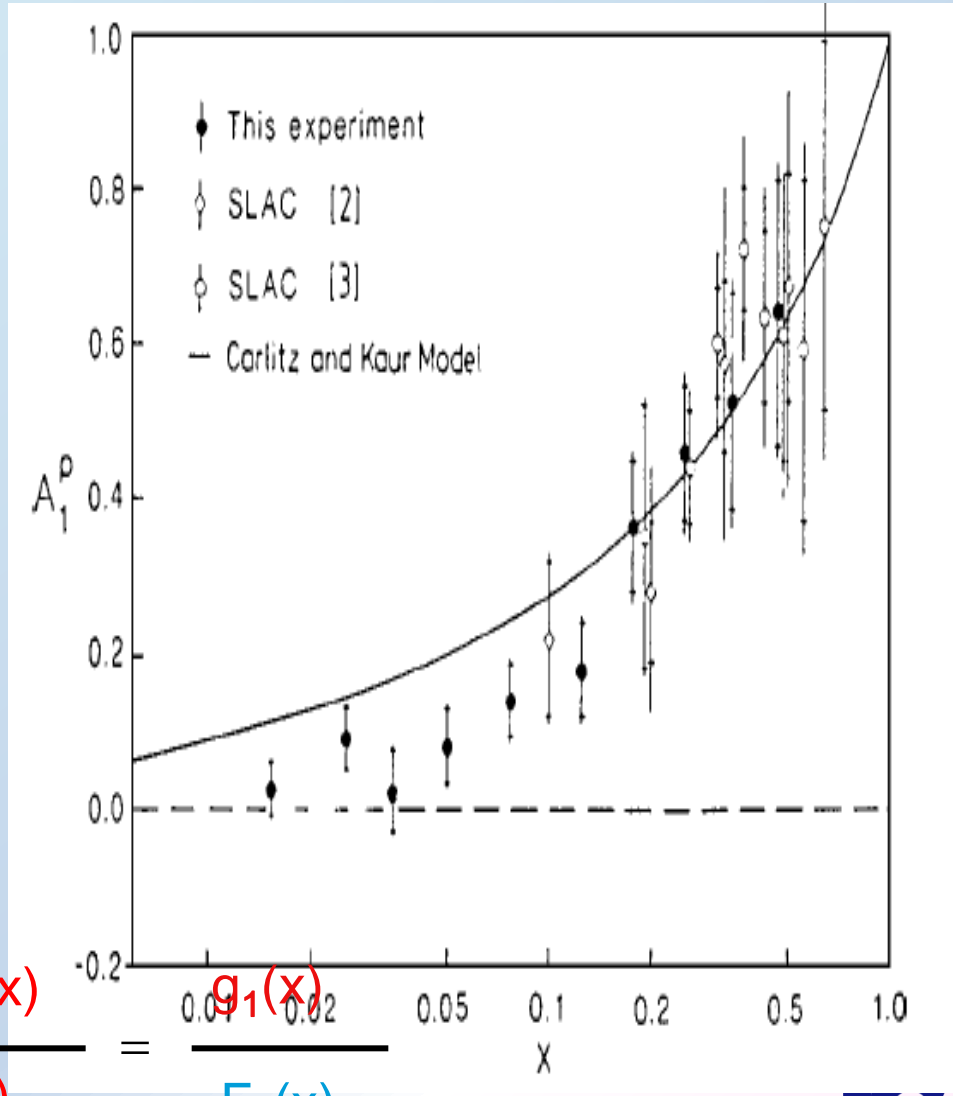
$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c \ldots)$$

$$g_5^{W^-} = (\Delta u - \Delta\bar{d} - \Delta\bar{s} + \Delta c \ldots)$$

$$W^+ : u \to d \ldots$$

First polarized DIS measurements and spin crisis

- First SLAC measurements consistent with naïve quark model (valence quarks make up proton spin)
- EMC finds quark contribution of only ~12%
  - Anomaly: huge gluon and orbital angular momentum contribution?
- 20 years later $\Delta\Sigma$ around 0.3

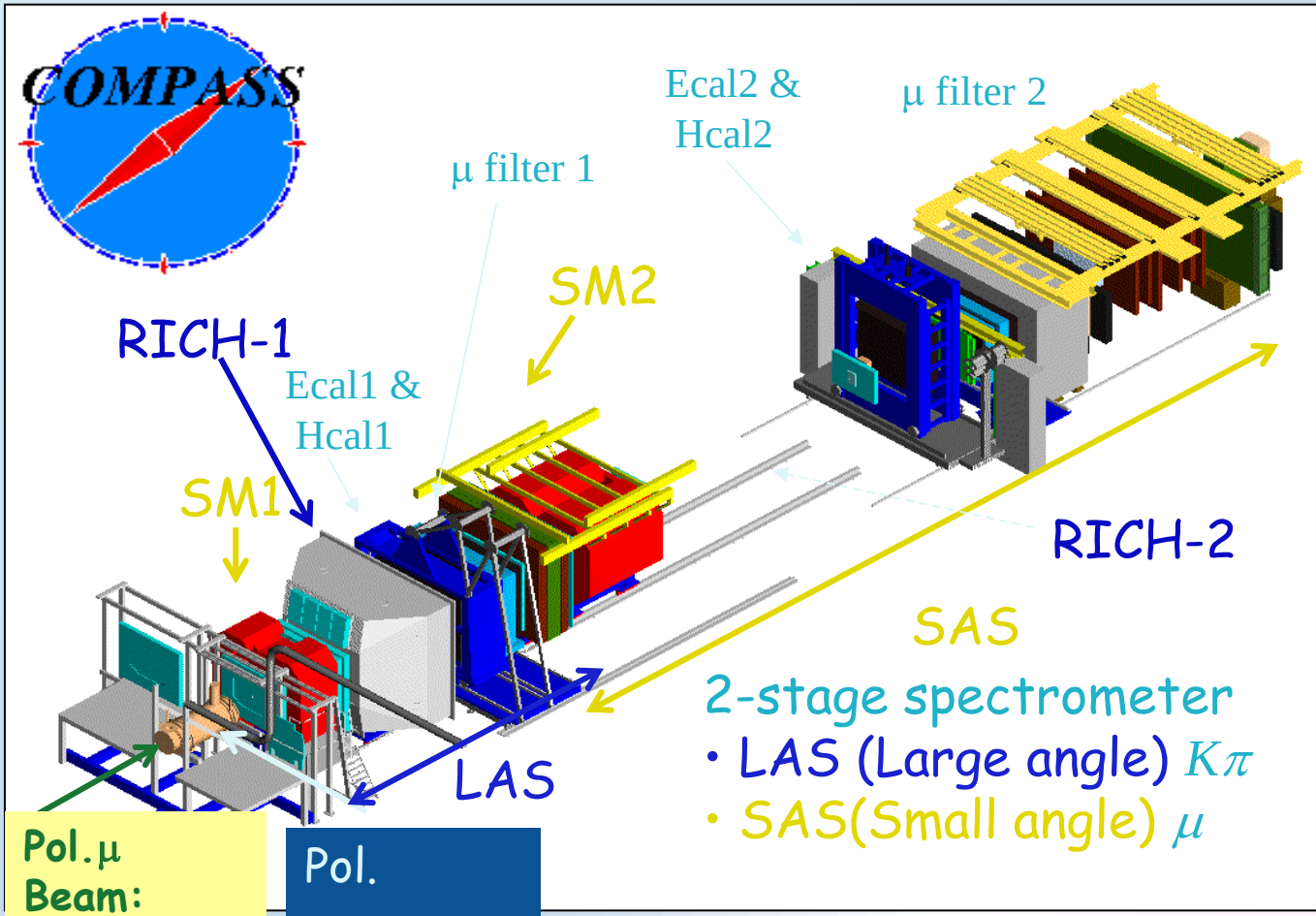


beam target

$$A_1(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \overset{\text{L.O.}}{\cong} \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)} = \frac{g_1(x)}{F_1(x)}$$

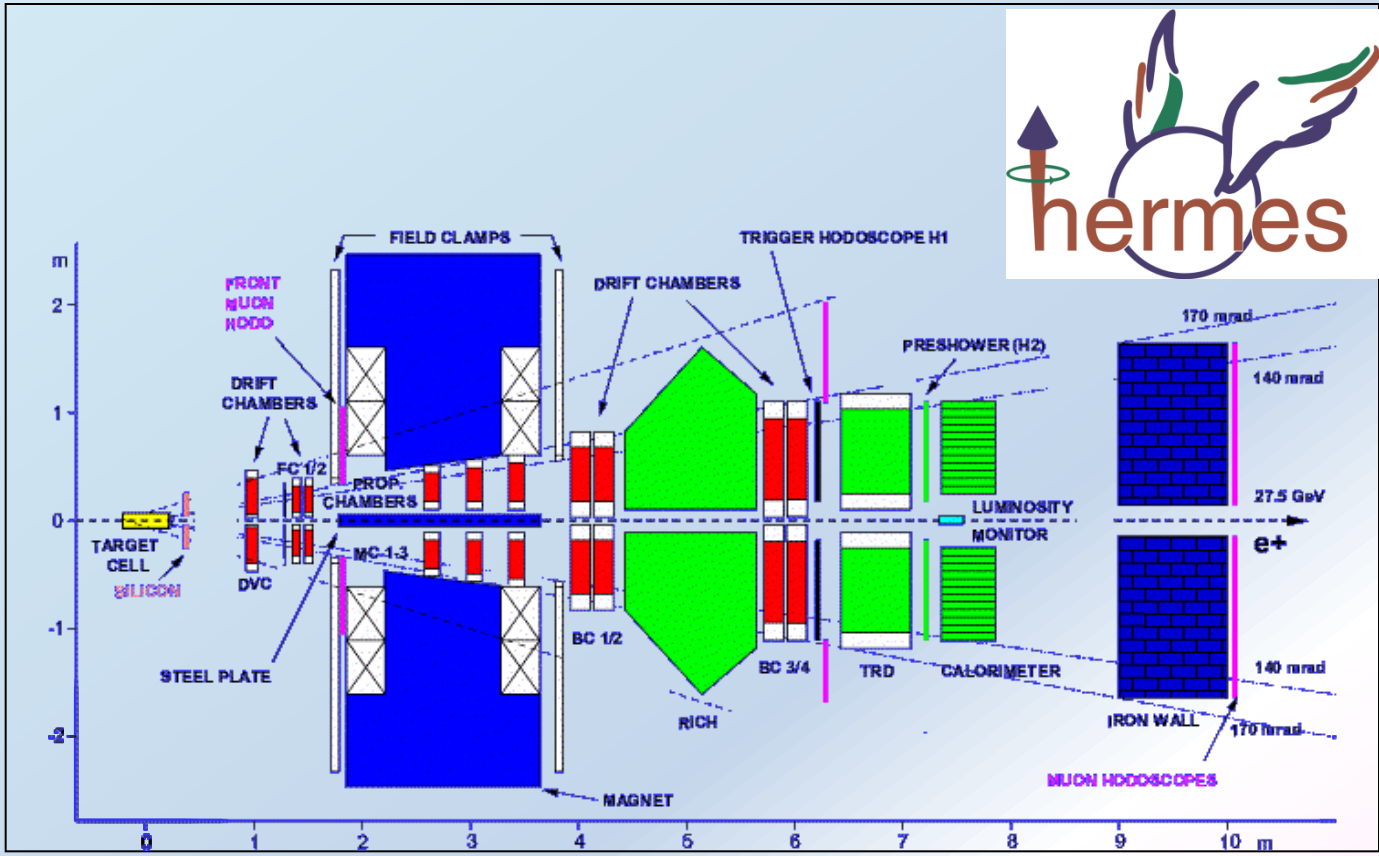
Polarized DIS Experiments

- EMC/NMC/SMC/COMPASS
  - Pol.μ from π decay (why polarized?)
  - Energy 160-200 GeV
  - Solid state targets (NH_3,LiD), longitudinal, transverse



Polarized DIS Experiments

- HERMES
  - Pol.$e^{\pm}$ from Sokolov Ternov effect
  - 27.5 GeV
  - Pure transversely, longitudinally polarized H, D, He3, many unpolarized gases



Flavor information from DIS

- g_1 is charge weighted sum of quark helicities:

  $4/9\ (\Delta u + \Delta \bar{u}) + 1/9\ (\Delta d + \Delta \bar{d}) + 1/9\ (\Delta s + \Delta \bar{s})$
- Necessary for spin sum rule :

  $\Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$
- Decompose $\Gamma_1 = \int g_1 dx$ into singlet and nonsinglet $SU(3)_f$ contributions:

$$\int_0^1 dx g_1^{p(n)}(x, Q^2) = C^{ns}(1, a_s(Q^2))(\pm\frac{1}{12}|g_A| + \frac{1}{36}a_8) + C^s(1, a_s(Q^2)) \exp\left(\int_{a_s(\mu^2)}^{a_s(Q^2)} da'_s \frac{\gamma^s(a'_s)}{\beta(a'_s)}\right) \frac{1}{9}a_0(\mu^2)$$

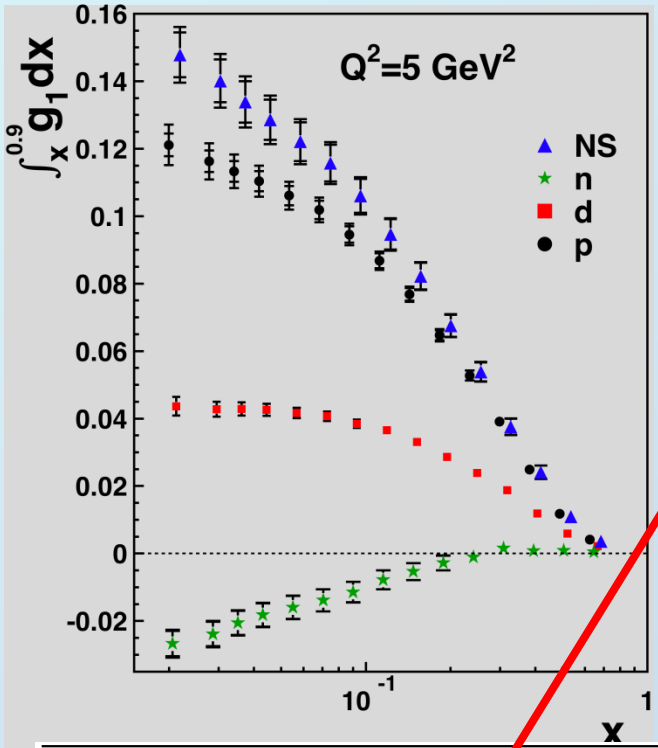
$g_A \approx a_3 \approx (\Delta u + \Delta \bar{u}) - (\Delta d + \Delta \bar{d})$

$a_8 \approx (\Delta u + \Delta \bar{u}) + (\Delta d + \Delta \bar{d}) - 2\,(\Delta s + \Delta \bar{s})$

LO: $a_0 = \Delta \Sigma$ NLO: $a_0 = \Delta \Sigma - 3\,\alpha_s/2\pi\,\Delta g$

Example: Hermes g_1 Integrals

$$\int_{0.021}^{0.9} dx g_1^d = 0.0436 \pm 0.0012(stat) \pm 0.0018(syst) \pm 0.0008(par) \pm 0.0026(evol)$$



Saturation in deuteron integral is assumed

- use only deuterium

$$a_0 = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{(1-\frac{3}{2}w_D)} - \frac{1}{4}a_8 \Delta C_{NS}\right]$$

From hyperon beta decay
a_8=0.586±0.031

From neutron beta decay
a_3=1.269±0.003

$$\Delta u + \Delta\bar{u} = \frac{1}{6}[2a_0 + a_8 + 3a_3]$$

$$\Delta d + \Delta\bar{d} = \frac{1}{6}[2a_0 + a_8 - 3a_3]$$

$$\Delta s + \Delta\bar{s} = \frac{1}{3}[a_0 - a_8]$$

	central value	uncertainties theor.	exp.	evol.
a_0	0.330	0.011	0.025	0.028
$\Delta u + \Delta\bar{u}$	0.842	0.004	0.008	0.009
$\Delta d + \Delta\bar{d}$	-0.427	0.004	0.008	0.009
$\Delta s + \Delta\bar{s}$	-0.085	0.013	0.008	0.009

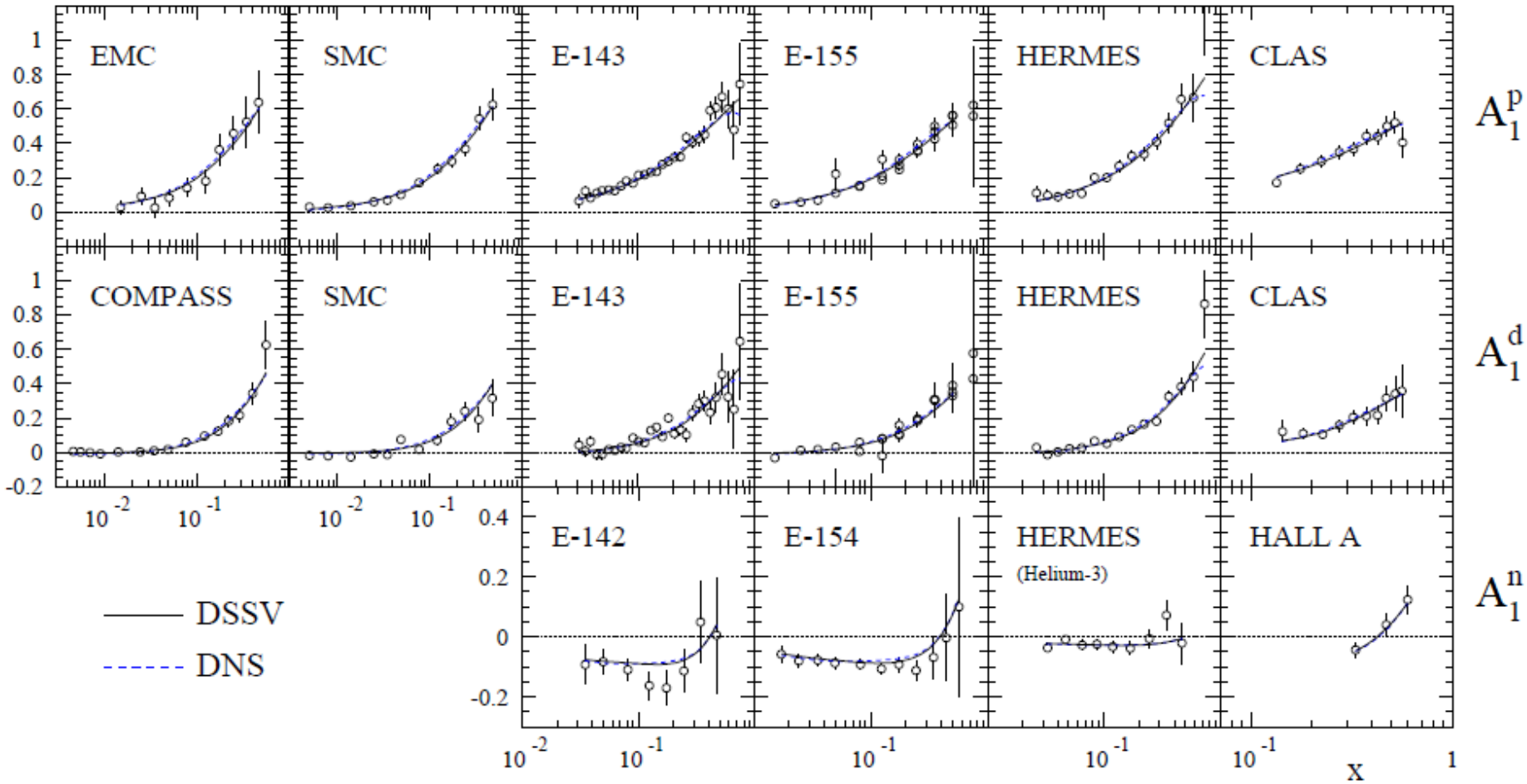
Q^2=5 GeV^2, NNLO in $\overline{MS}$ scheme

- COMPASS:

$$a_0 = 0.33 \pm 0.03 \pm 0.05$$

$$\Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02$$

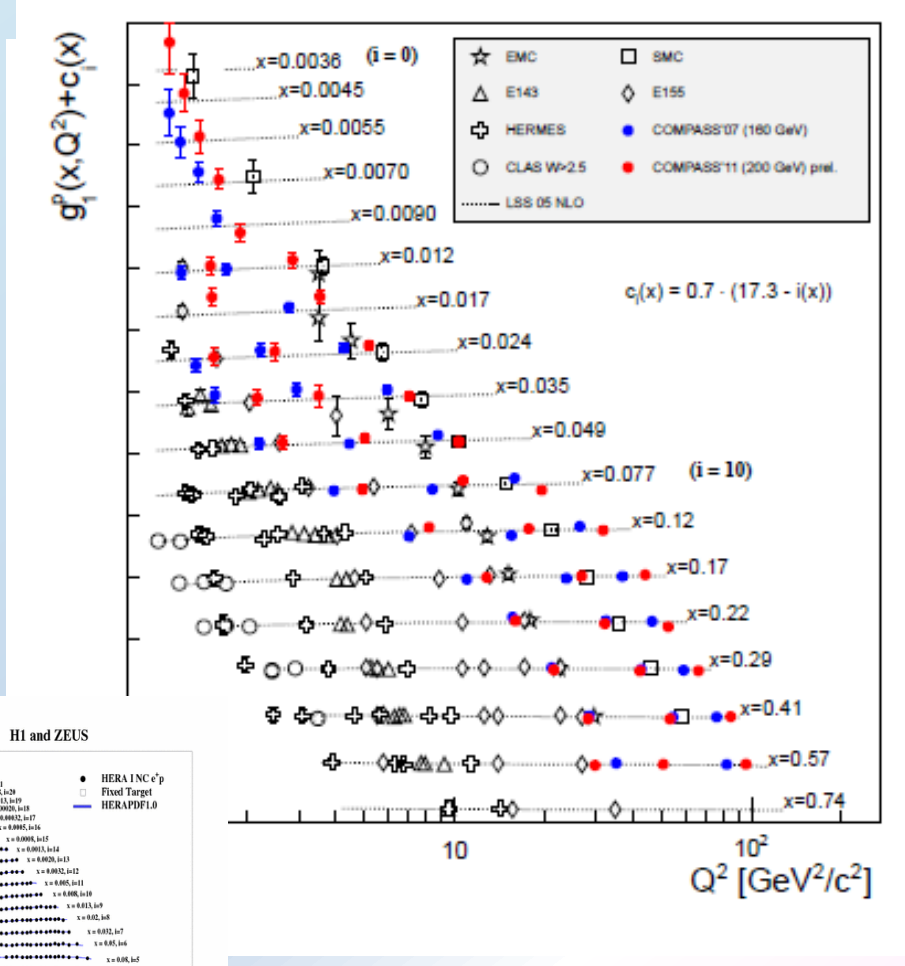
Polarized DIS world data

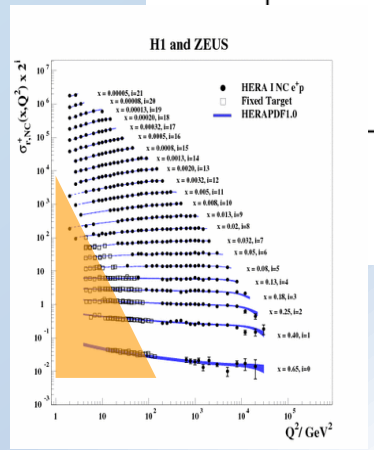


Polarized Global inclusive analysis

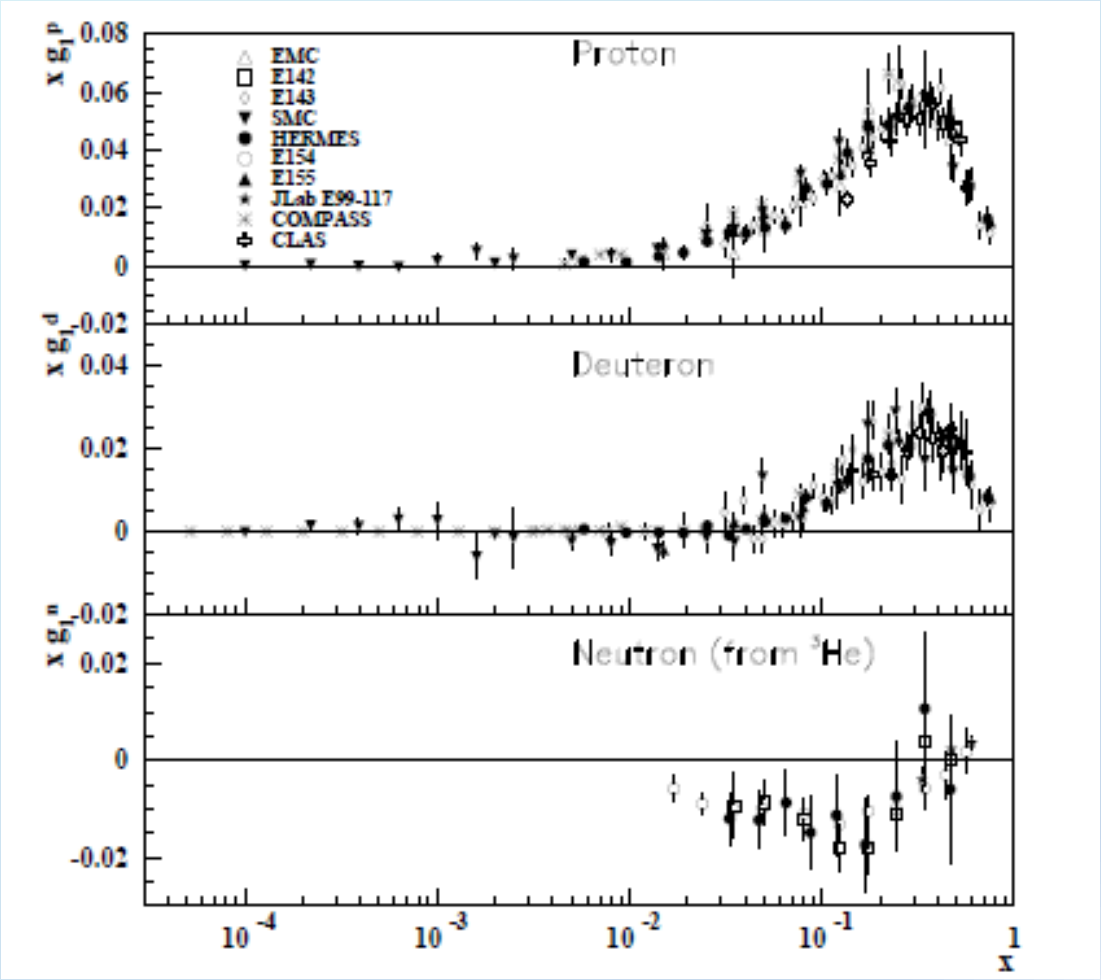
- Using only inclusive data is rarely performed with the wealth of semi-inclusive and pp data
- Most recent: Bluemlein Boettcher 2011
- Valence quarks relatively well determined
- Gluons in DIS only accessible over QCD evolution:

$g_1(x,Q_o) \rightarrow g_1(x,Q>Q_o)$

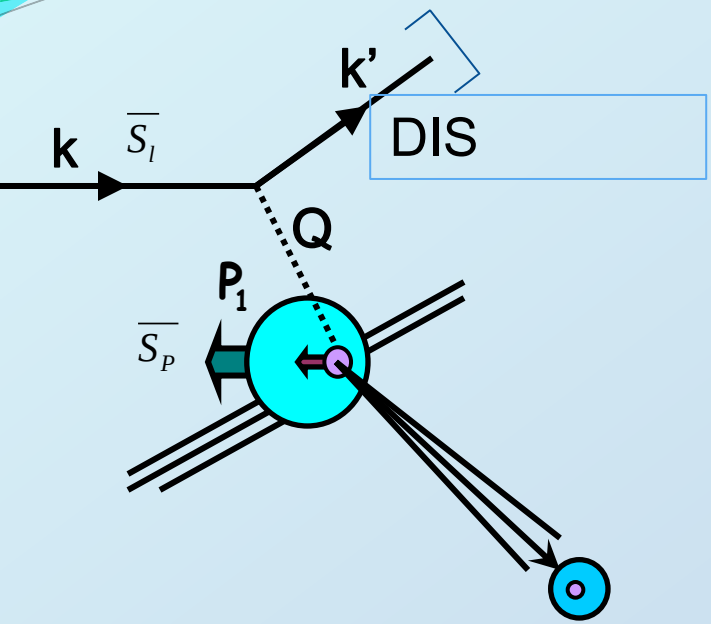




g_1 world data



DIS Kinematics



$$\frac{d\sigma}{dQ^2} = f_q(x_1) \otimes \tilde{\sigma}$$

Quark distribution functions: quark q in nucleon

$$Q^2 = -q^2 = -(k-k')^2$$

- Squared Momentum transfer of photon/Z

$$x_B = \frac{Q^2}{2Pq}$$

- Bjorken scaling variable, at high Q^2 momentum fraction of quark

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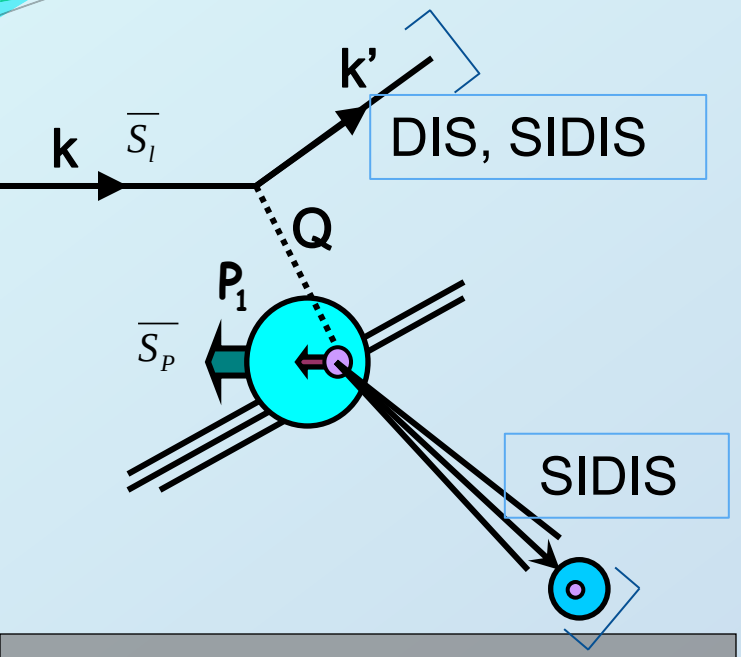
- Inelasticity (sometimes called depolarization factor)

$$W^2 = (P+q)^2$$

- Mass of hadronic final state

- Hard scales: $Q^2 >> 1\ \mathrm{GeV}^2$ otherwise photo-production
- Photo-production usable is at least on hadron pt >1GeV

SIDIS Kinematics



$$\frac{d\sigma}{dQ^2} = f_q(x_1) \otimes \tilde{\sigma} \otimes D^h(z)$$

Quark distribution functions: quark q in nucleon

Fragmentation functions functions: quark q →hadron h

Q^2	$=$	$-q^2$	• Squared Momentum transfer of photon/Z
	$=$	$-(k-k')^2$	
x_B	$=$	$\frac{Q^2}{2Pq}$	• Bjorken scaling variable, at high Q^2 momentum fraction of quark
k^+	$=$	xP^+	
y	$=$	$\frac{qP}{kP}$	• Inelasticity (sometimes called depolarization factor)
W^2	$=$	$(P+q)^2$	• Mass of hadronic final state
P_h^-	$=$	zk^-	• Fractional hadron momentum

•Hard scales: Q^2>>1 GeV^2 otherwise photoproduction

Factorization and Universality

- Physics processes can be factorized into small distance large distance behaviour:
  - Small distance: asymptotic freedom →perturpative QCD calculation
  - Large distance: confinement, need to be measured!
- Nonperturbative functions universal (same in ep, pp or e^+e^-)

Hard scattering cross section from pQCD or EM

Fragmentation function measured in e^+e^-

quark distribution functions Known from DIS

$$d\sigma_{ep} \approx f_1^a(x_a) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_1(z_c, M_c^2)$$

$$d\sigma_{pp} \approx f_1^a(x_a) f_1^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_1(z_c, M_c^2)$$

Excursion: What are fragmentation functions (FF)?

$$D_i^h(z,\mu)$$

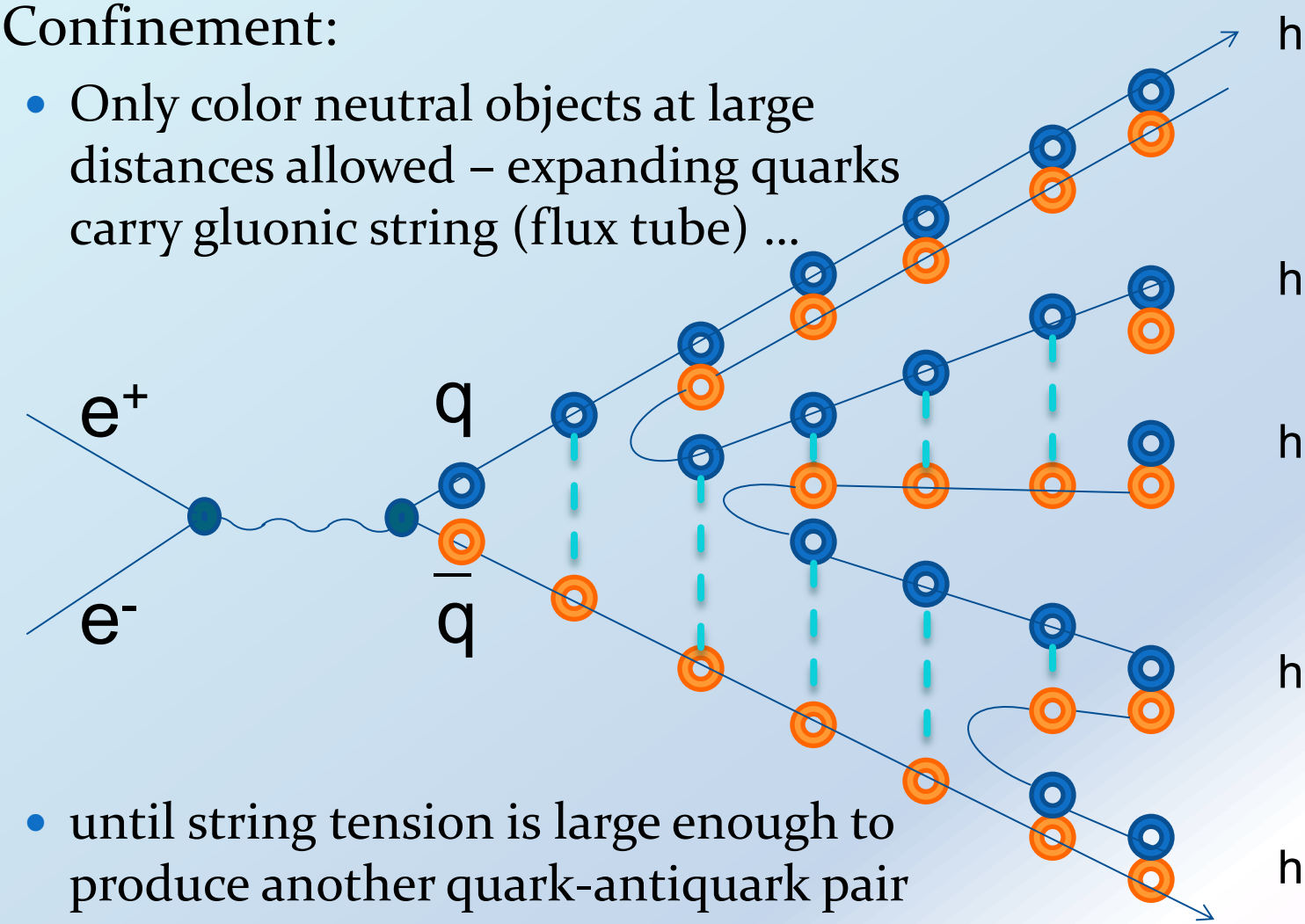
- Fragmentation of a parton i (quarks, antiquarks, gluons) with energy E_i into a hadron h with a fractional energy $z=E_h/E_i$.
- Similar to parton distribution functions (PDFs) in the nucleon, but only one sum rule:

$$\sum_h \int_0^1 dz\; z D_i^h(z,\mu) = 1$$

- Later: extension to spin dependent and transverse momentum dependent fragmentation functions

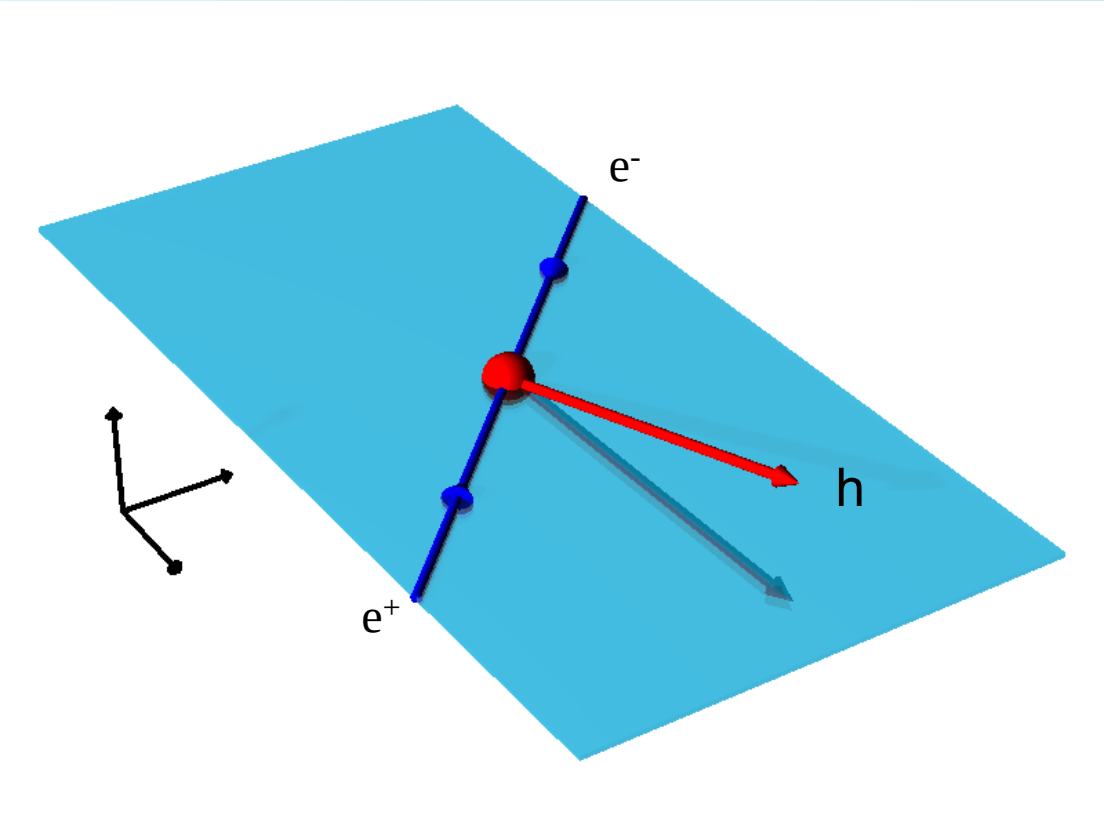
The (string) fragmentation process

- Confinement:
  - Only color neutral objects at large distances allowed – expanding quarks carry gluonic string (flux tube) …



  - until string tension is large enough to produce another quark-antiquark pair

Fragmentation functions in e^+e^- annihilation



$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\,\mathbf{GeV}$$

- Process:

  $e^+ e^- \rightarrow hX$
- At leading order sum of unpolarized fragmentation functions from quark and anti-quark side

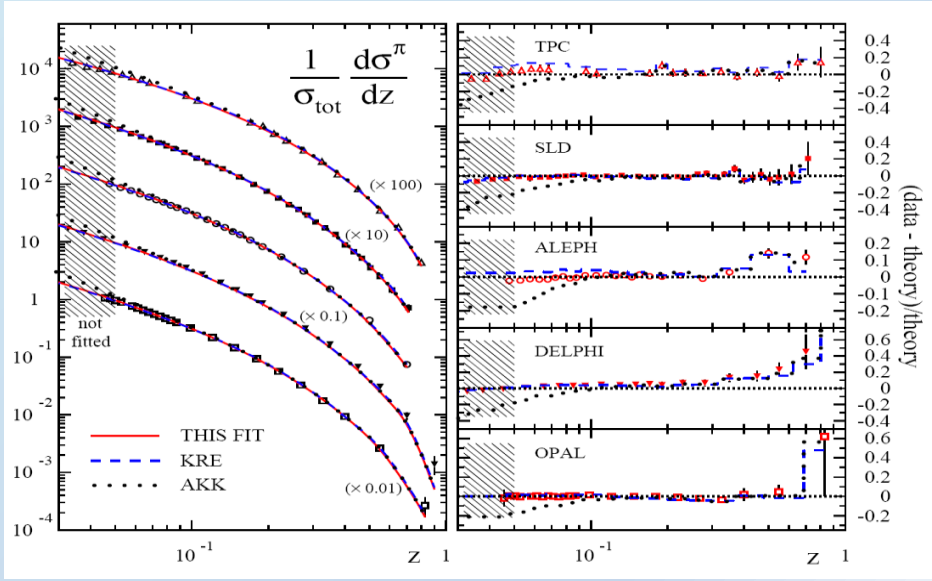
LO $$F^h(z,s) = \frac{\sum_q e_q^2 [D_q^h(z) + D_{\bar{q}}^h(z)]}{\sum_q e_q^2}$$

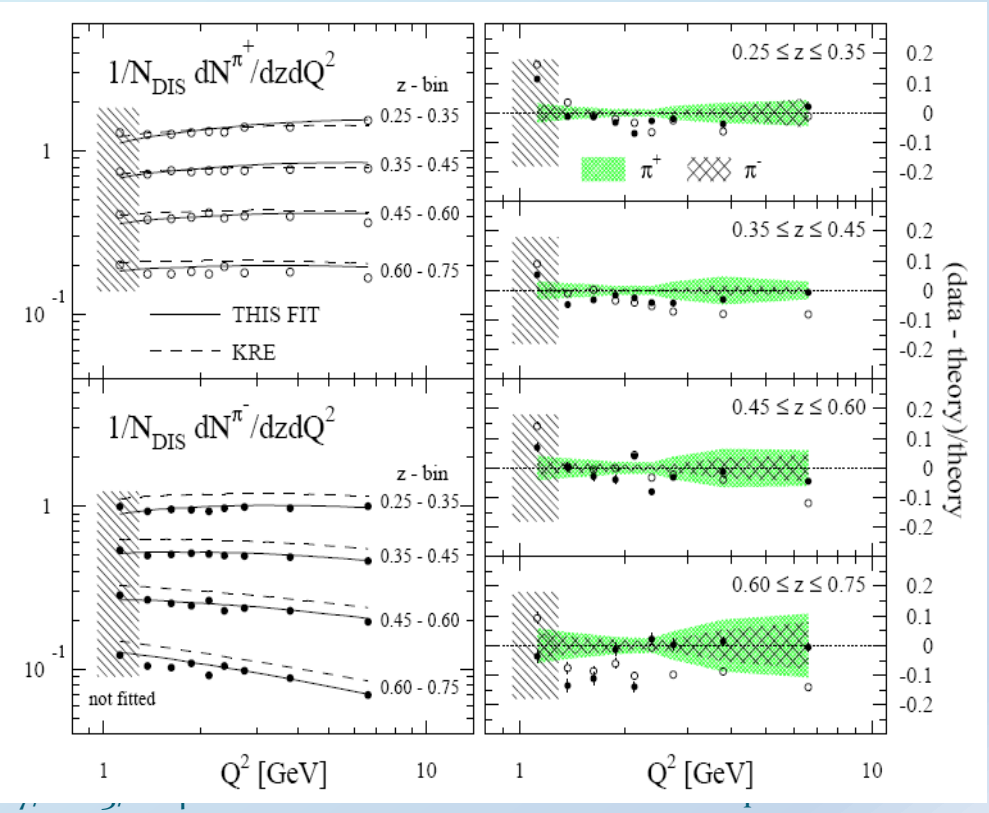
NLO $$F^h(z,s) = \sum_i \int_z^1 \frac{dz'}{z'} C_i(s; z'\alpha_s) D_q^h(z)$$

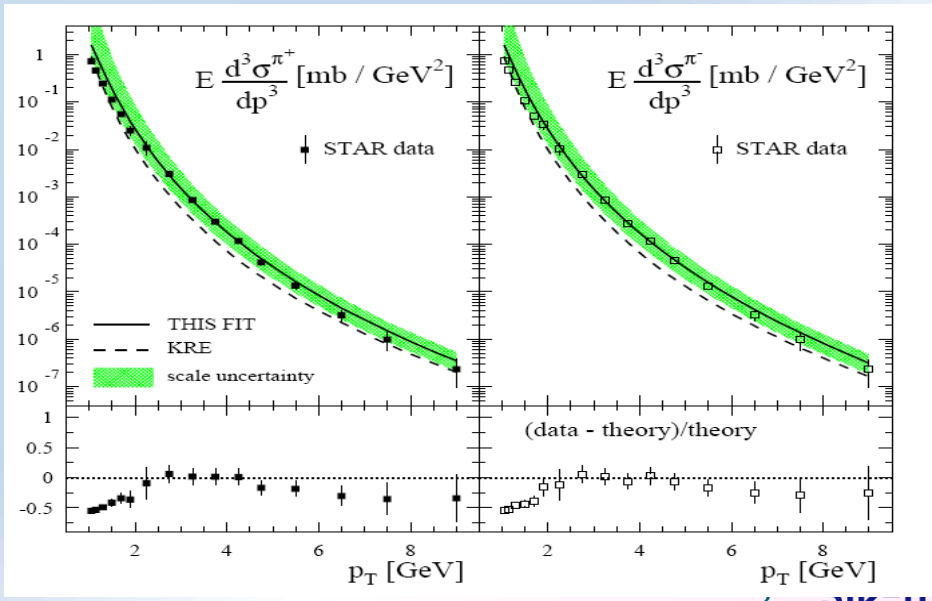
Fragmentation functions

de Florian, Sassot, Stratmann

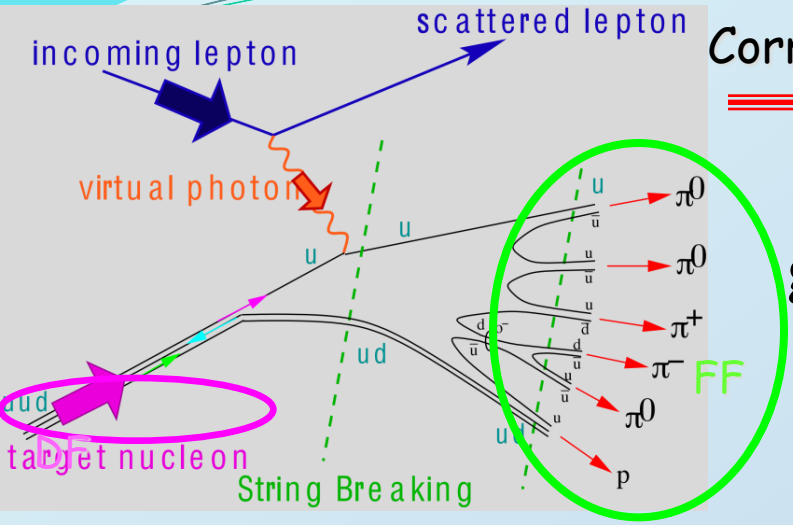
- results for $\pi^{\pm}$, $K^{\pm}$, chg. hadrons
- full flavor separation for $D_i^H(z)$ and D_g^H
- fits to all LEP, HERMES, SMC, RHIC, … data
- supersede old fits based only on e^+e^- data
- B-factory data not yet included







SIDIS: access to individual quark polarizations



Correlation between detected hadron and struck q_f

⟹ "Flavor - Separation"

Inclusive DIS:

$$g_1 = 4/9(\Delta u + \Delta \bar{u}) + 1/9(\Delta d + \Delta \bar{d}) + 1/9(\Delta s + \Delta \bar{s})$$

Semi-inclusive DIS:

$$(\Delta u,\ \Delta \bar{u},\ \Delta d,\ \Delta \bar{d},\ \Delta s,\ \Delta \bar{s})$$

$$A_1^h(x,Q^2,z) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \sim C\,\frac{\sum_q e_q^2\ q(x,Q^2)D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2 q'(x,Q^2)D_{q'}^h(z,Q^2)}\,\frac{\Delta q(x,Q^2)}{q(x,Q^2)}$$

Extract Δq by solving:

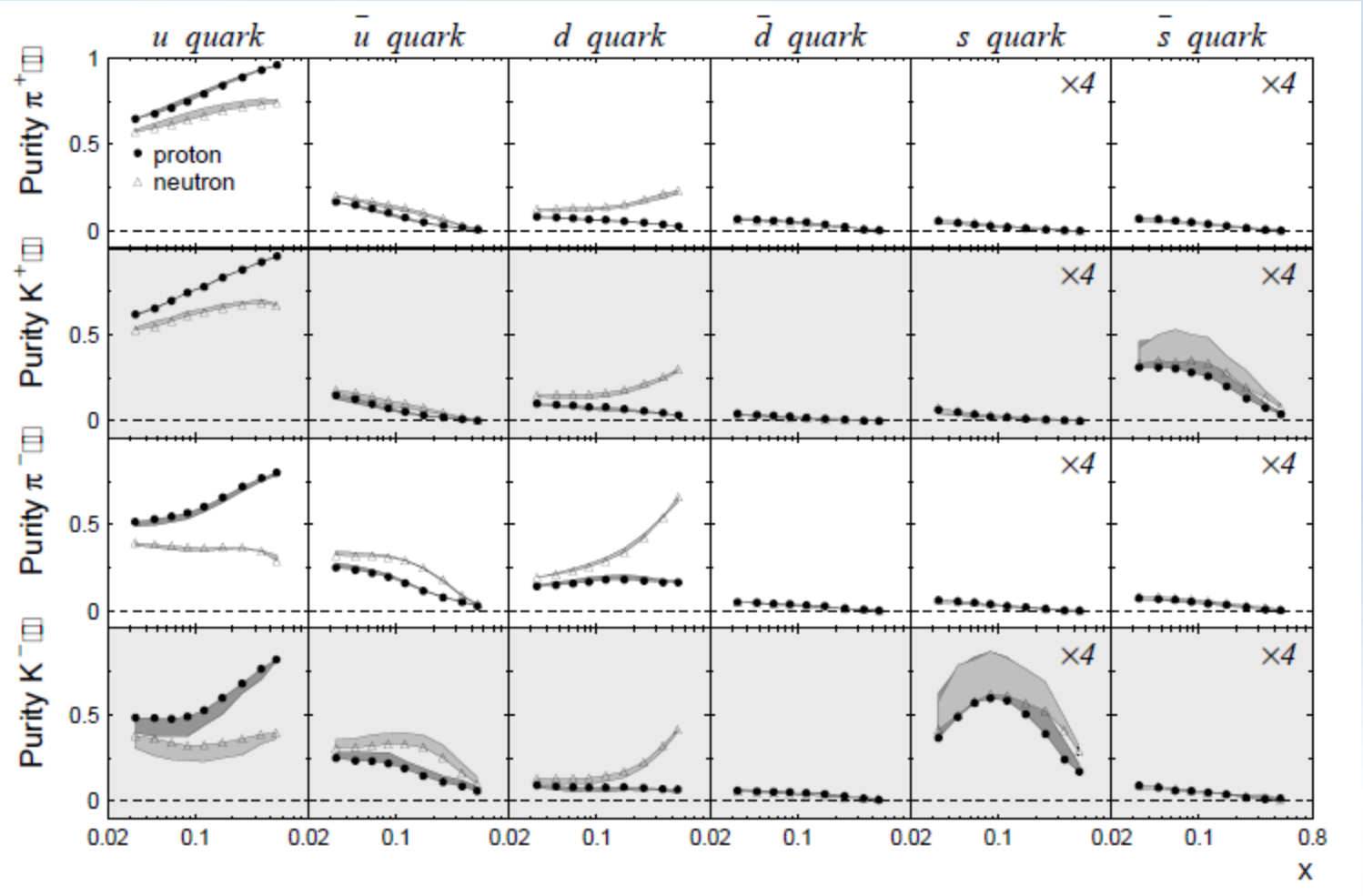
$P_q^h(x,Q^2,z)$ ⟸ *MC or DSSxPDF*

$$\vec{A} = P\,\vec{Q}$$

$$\vec{A} = (A_{1,p}(x), A_{1,p}^{\pi\pm}(x), A_{1,d}(x), A_{1,d}^{\pi\pm}(x), A_{1,d}^{K\pm}(x)) \qquad \vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s}{s}, \frac{\Delta \bar{s}}{\bar{s}} = 0\right)$$

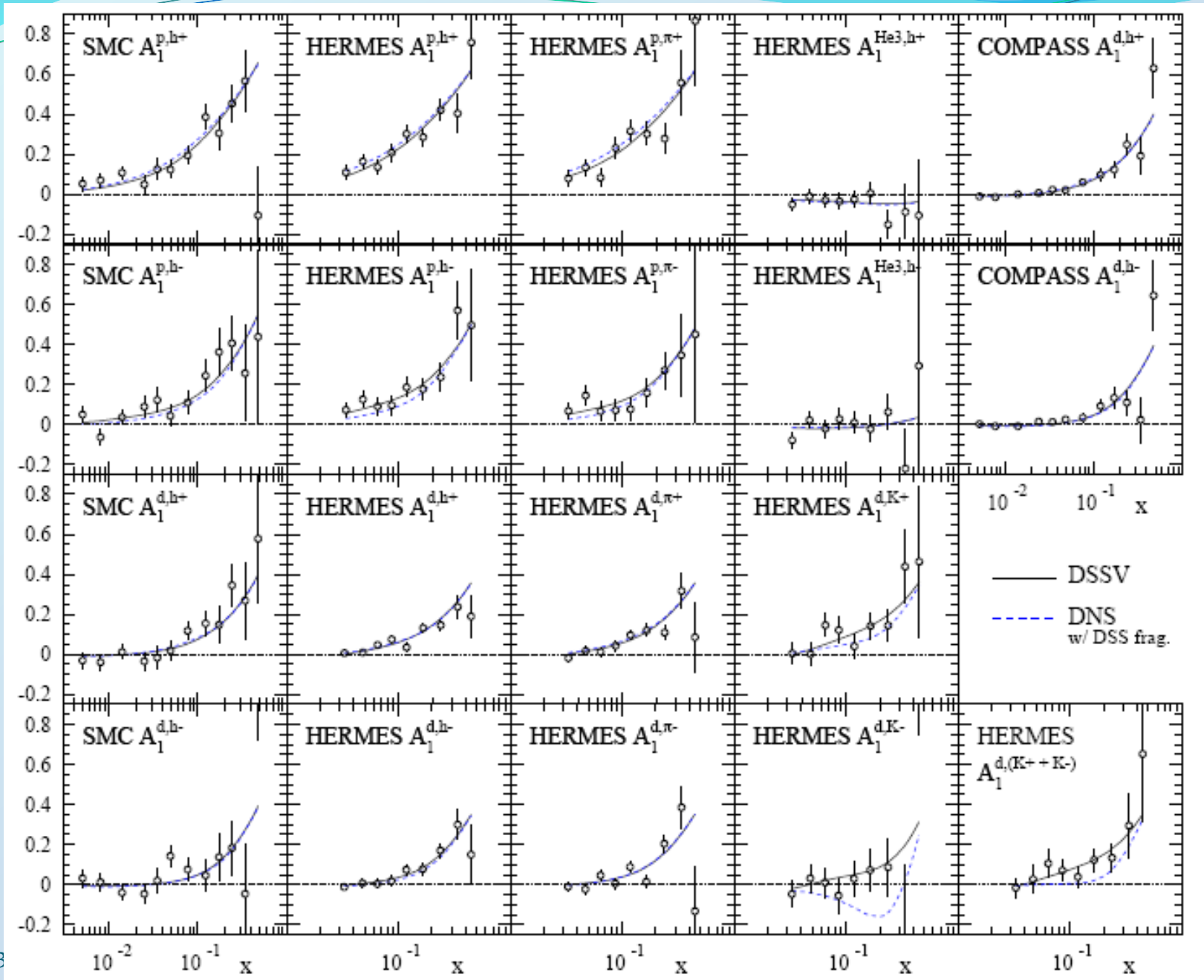
Phys.Rev. D71 (2005) 012003

HERMES purities at 27.6 GeV fixed target ep,ed SIDIS

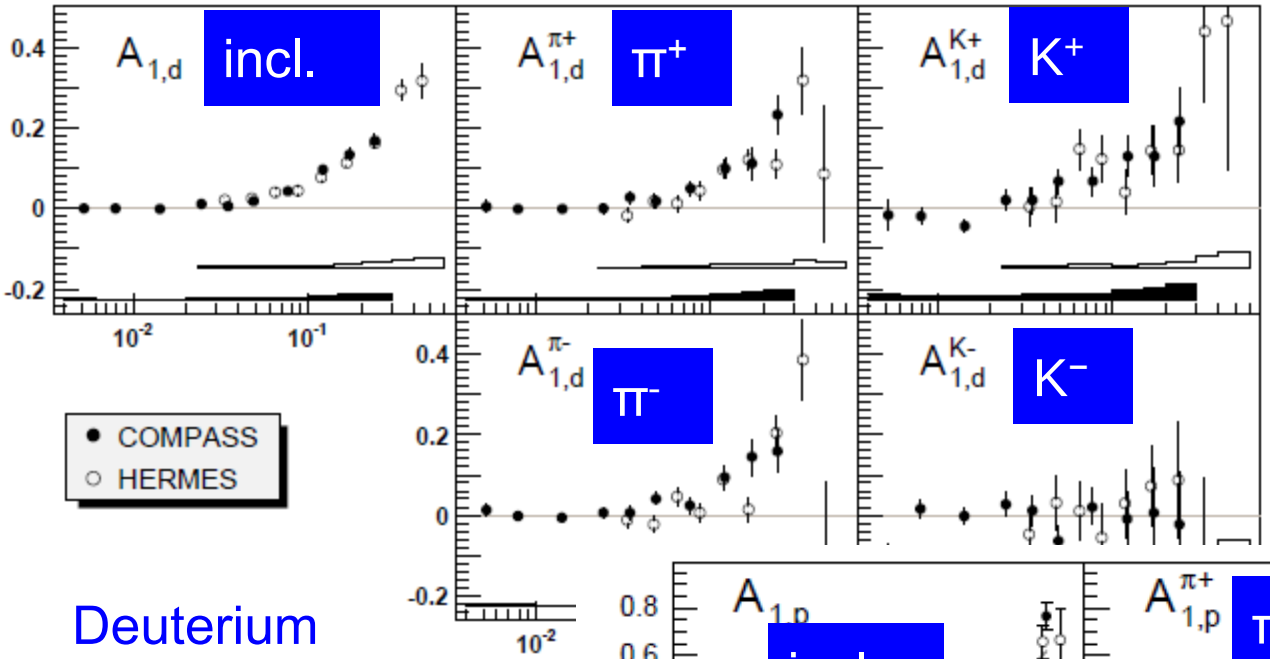


- SIDIS on proton: u-quark dominance: Factor 4 by charge and factor 2 by valence content

Semi-inclusive World data

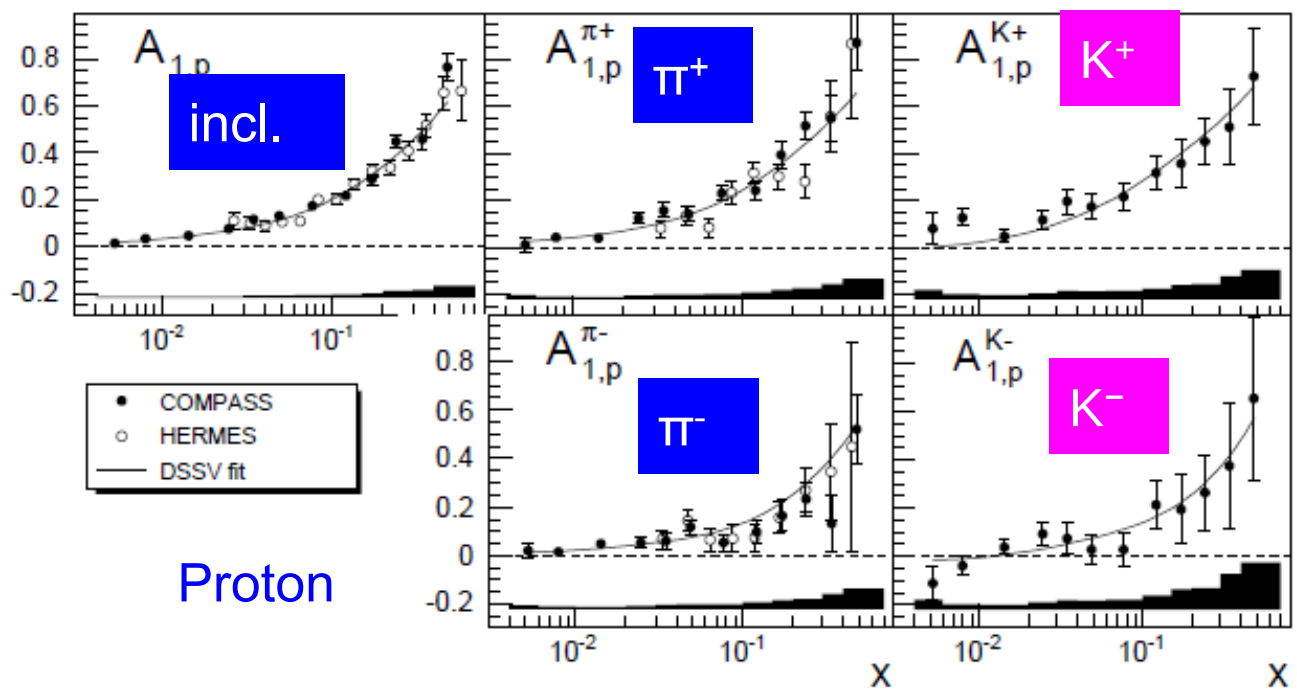


+recent COMPASS results



Deuterium

Phys.Lett. B680 (2009) 217-224

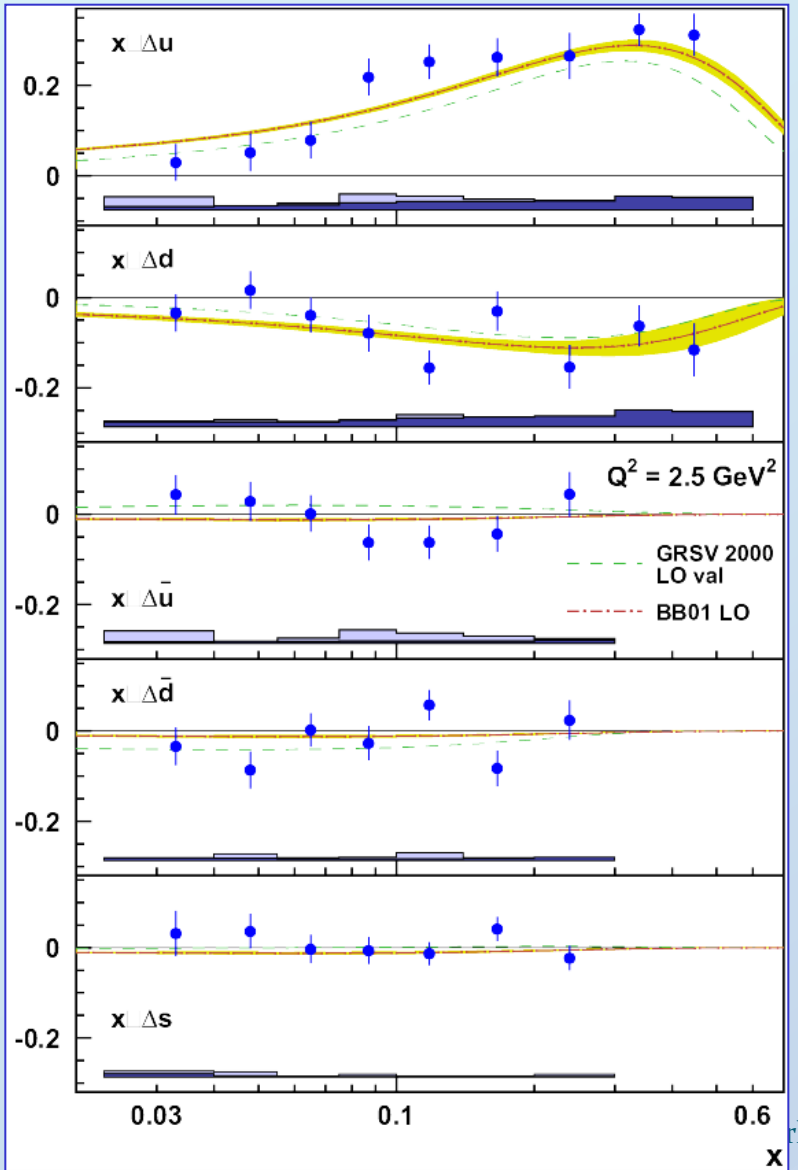


Proton

Phys.Lett. B690 (2010) 466-472

SIDIS results

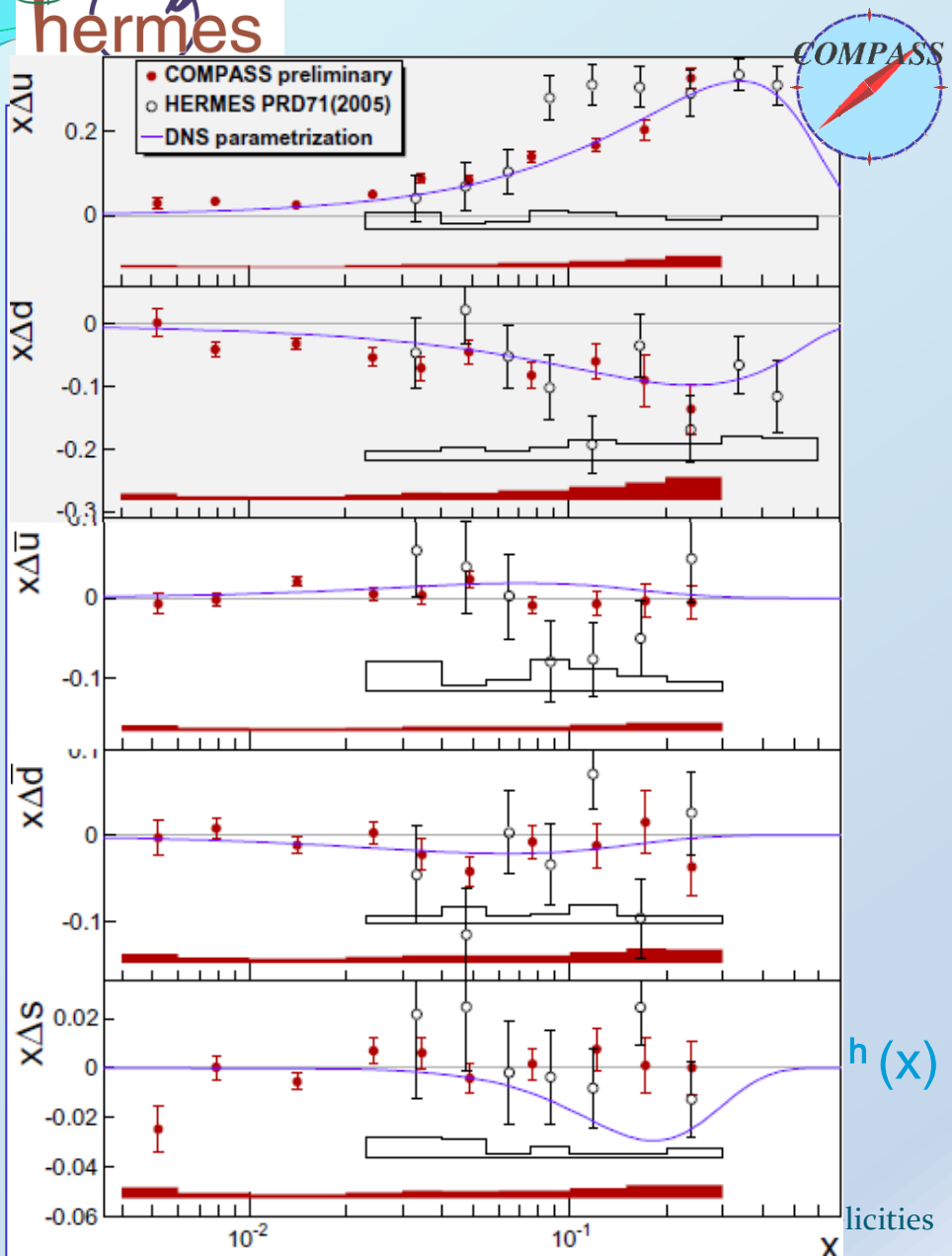
HERMES, PRL 92 (2004) 012005, PRD 71 (2005) 012003



- HERMES semi-inclusive extraction of quark helicities from p and d targets

$$A_1^h(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \overset{L.O.}{\cong} \frac{\int \sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\int \sum_q e_q^2 q(x)\, D_q^h(z)}$$

SIDIS results

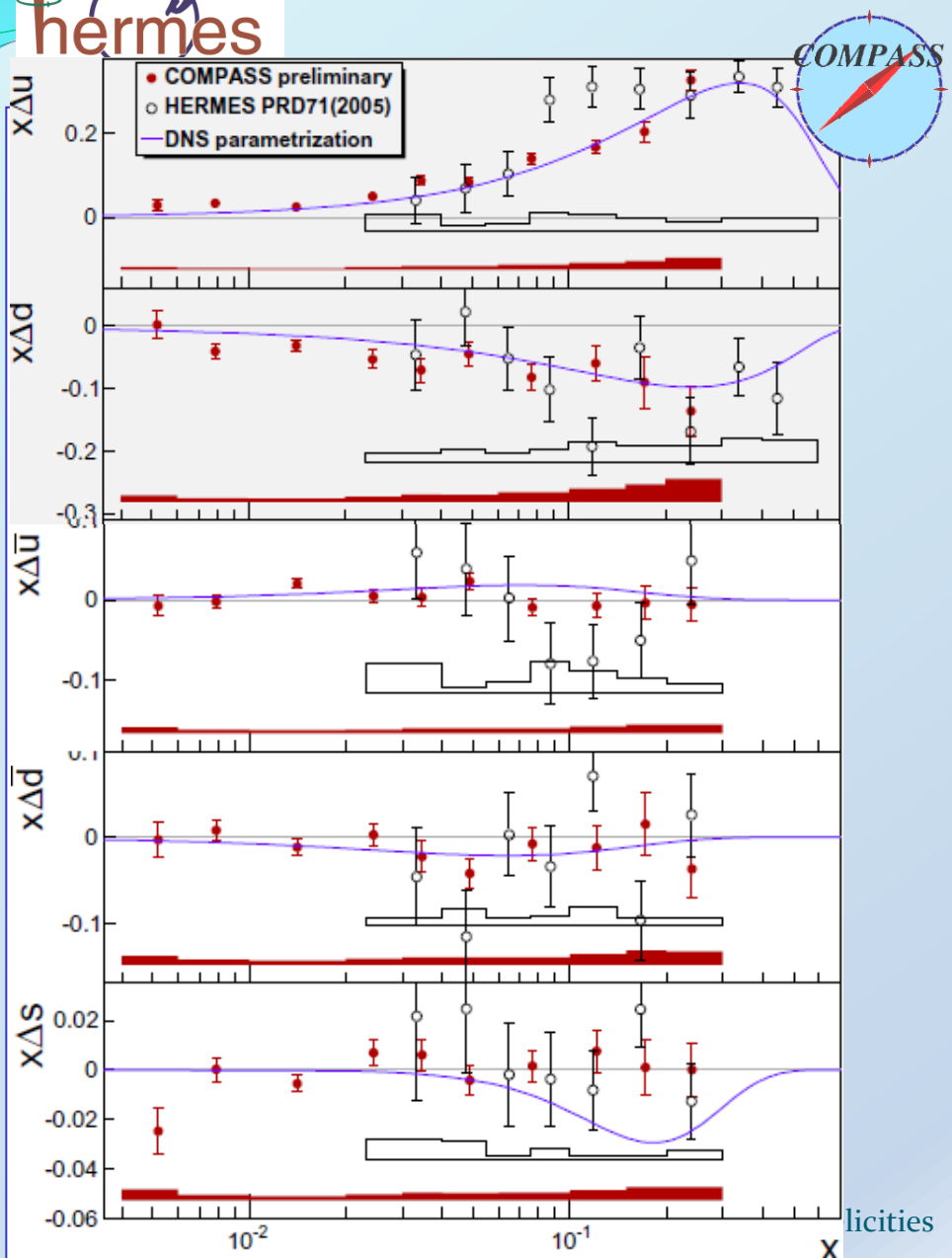


- HERMES semi-inclusive extraction of quark helicities from p and d targets
- semi-inclusive results from COMPASS, asymmetries consistent

$$^{h}(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \overset{L.O.}{\cong} \frac{\int \sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\int \sum_q e_q^2 q(x)\, D_q^h(z)}$$

licities

SIDIS results

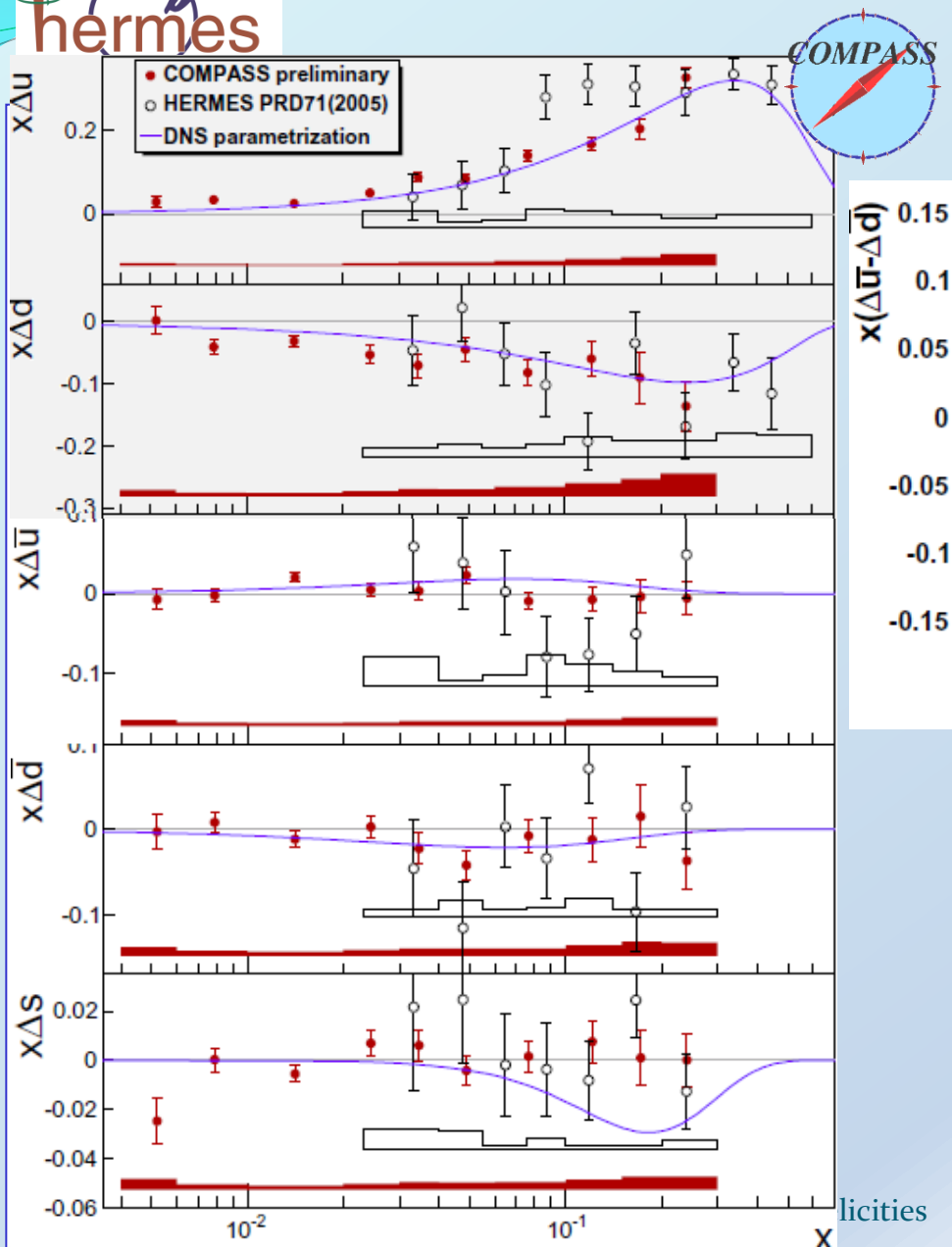


- HERMES semi-inclusive extraction of quark helicities from p and d targets
- semi-inclusive results from COMPASS, asymmetries consistent
- Small strangeness seen in measured range in both experiments

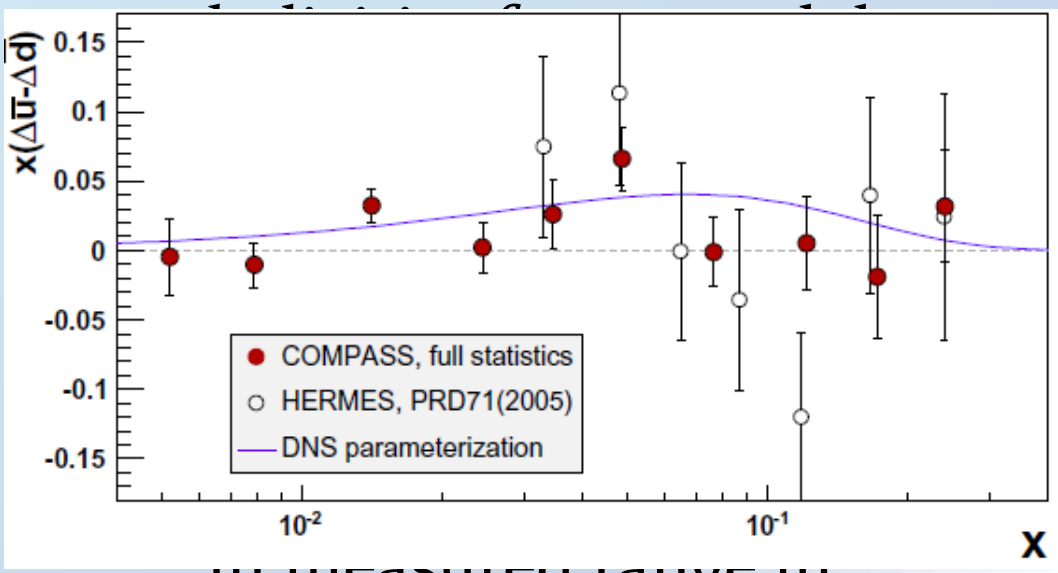
L.O. $$\frac{\int \sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\int \sum_q e_q^2 q(x)\, D_q^h(z)}$$

licities

SIDIS results



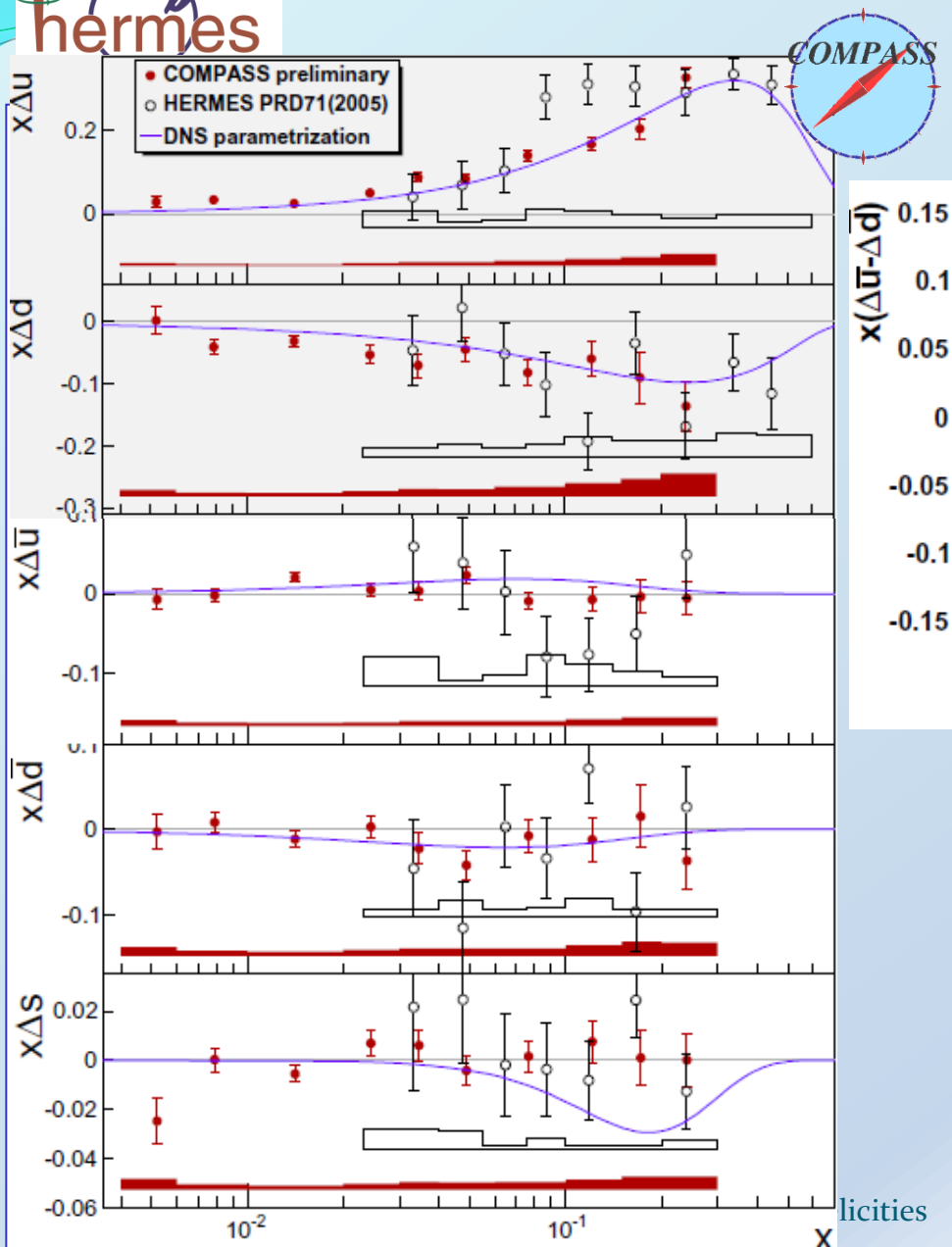
- HERMES semi-inclusive extraction of quark



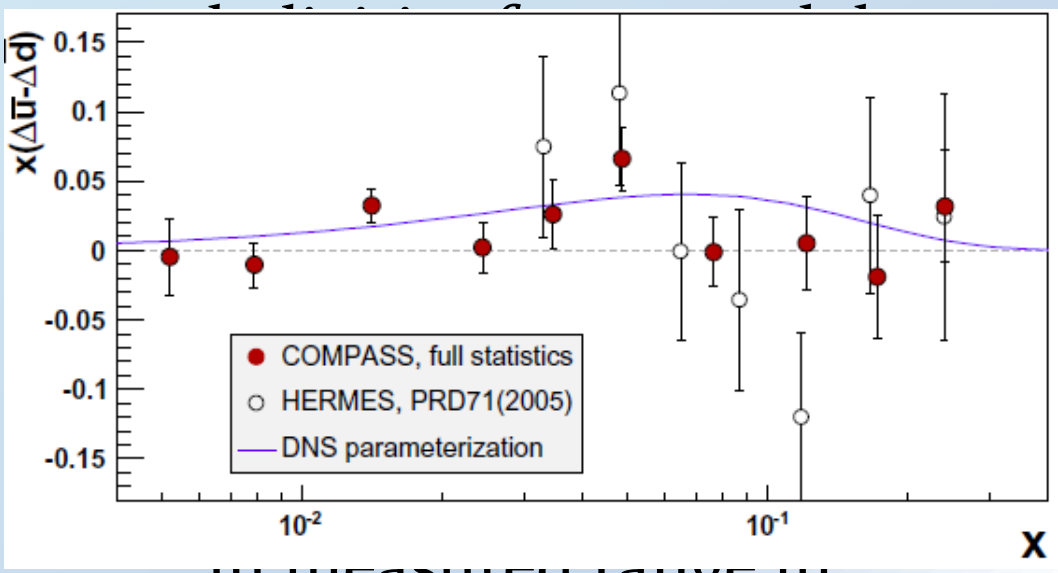
in measured range in both experiments

L.O. $\frac{\int \sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\int \sum_q e_q^2 q(x)\, D_q^h(z)}$

SIDIS results



- HERMES semi-inclusive extraction of quark



in measured range in both experiments

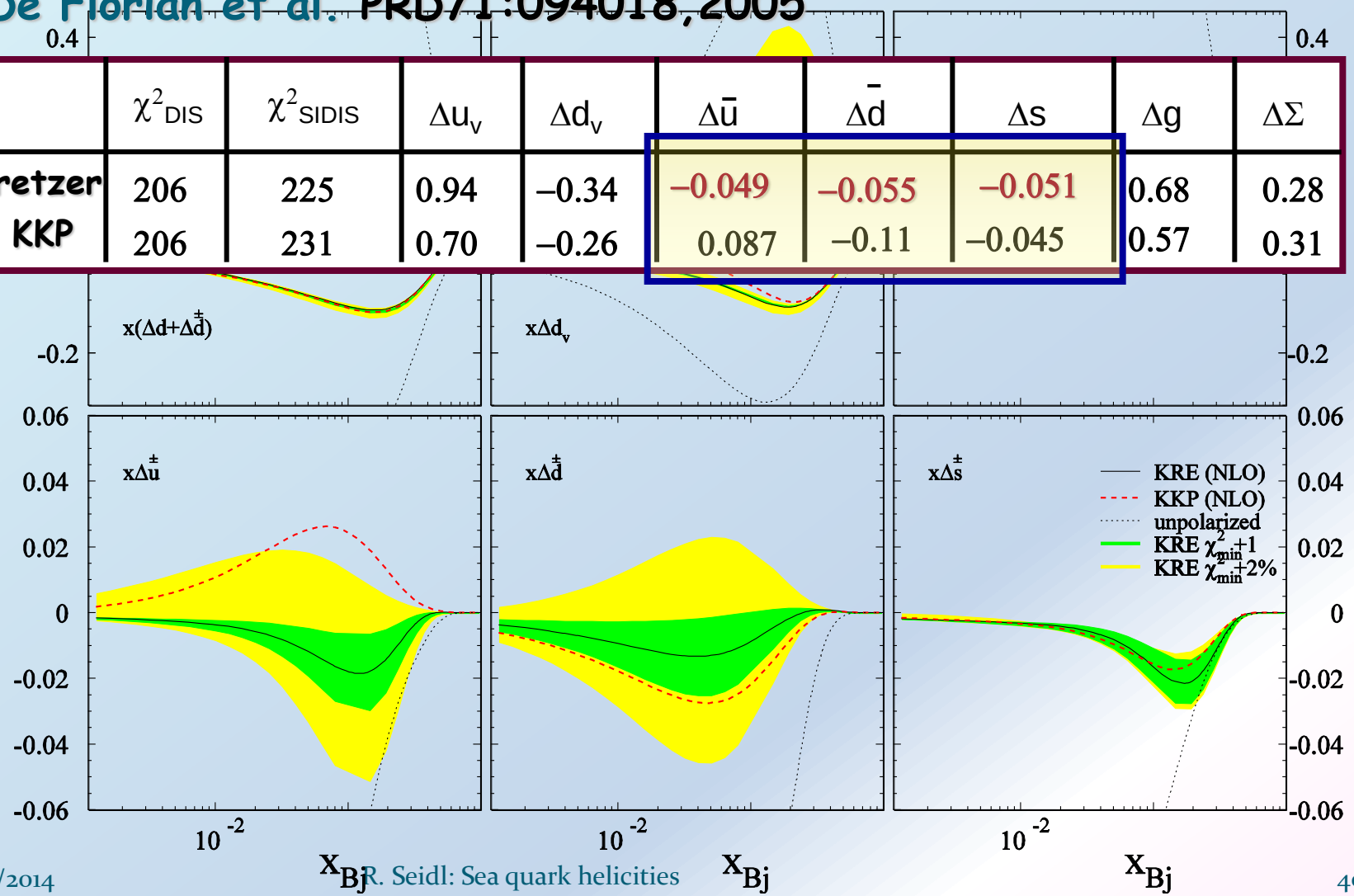
- Symmetric light sea

L.O. $\frac{\int \sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\int \sum_q e_q^2 q(x)\, D_q^h(z)}$

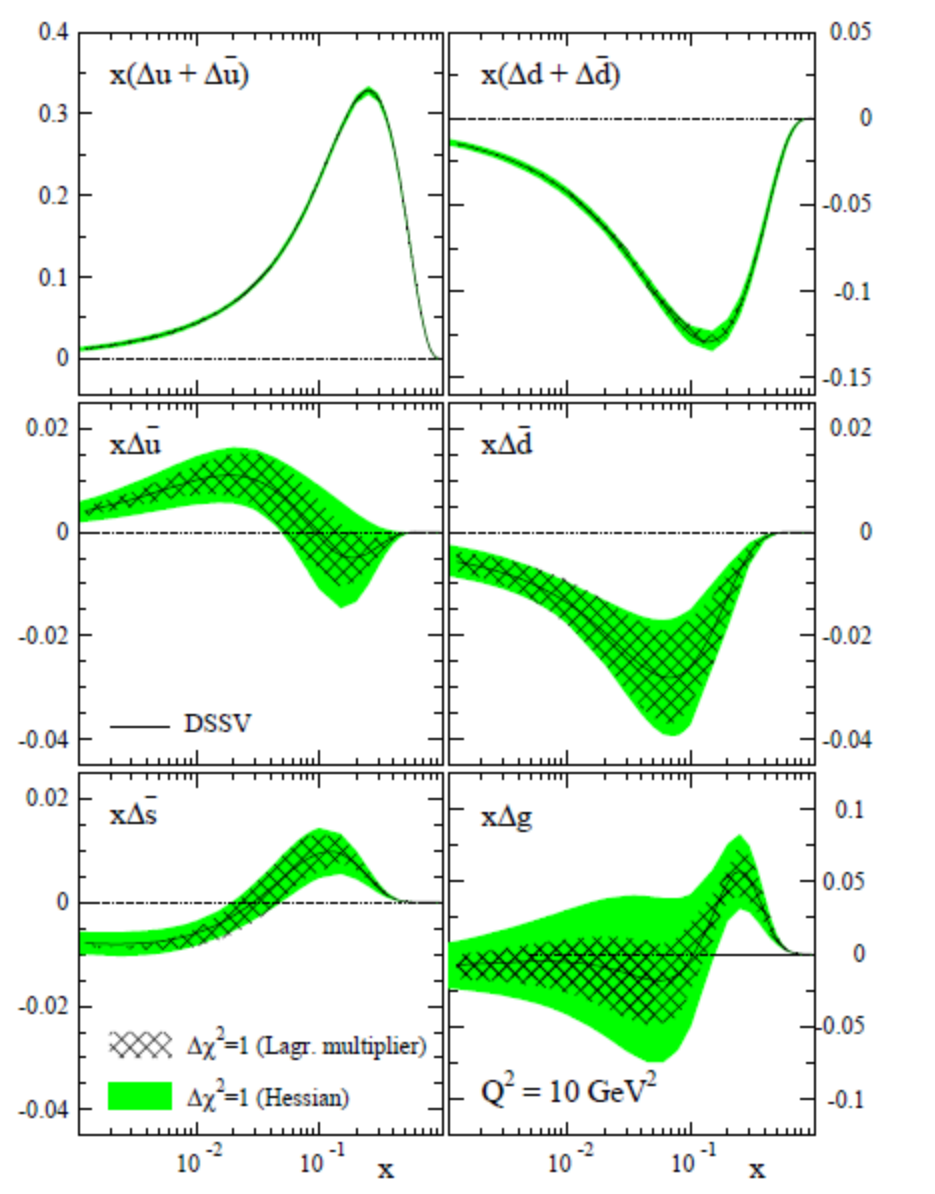
However, be sure you understand all your input

D. De Florian et al. PRD71:094018,2005

	χ^2_{DIS}	χ^2_{SIDIS}	Δu_v	Δd_v	$\Delta\bar{u}$	$\Delta\bar{d}$	Δs	Δg	$\Delta\Sigma$
Kretzer	206	225	0.94	–0.34	–0.049	–0.055	–0.051	0.68	0.28
KKP	206	231	0.70	–0.26	0.087	–0.11	–0.045	0.57	0.31

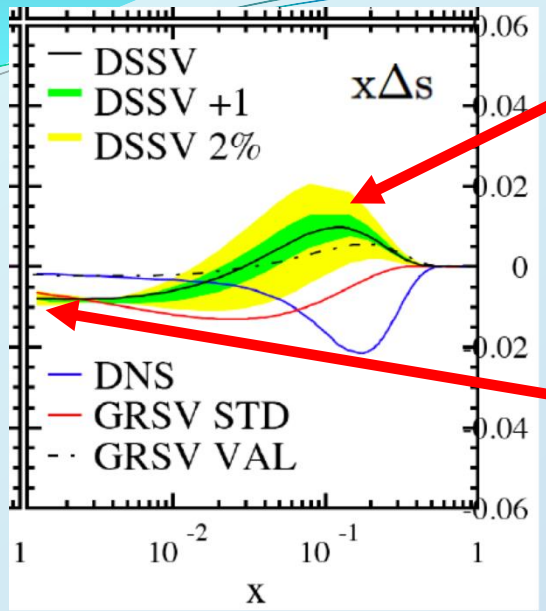


DSSV



Phys.Rev. D80 (2009) 034030
Phys.Rev.Lett. 101 (2008) 072001

Polarized Strangeness



Driven by SIDIS
K-Asymmetries
K-FF
dominated by hermes

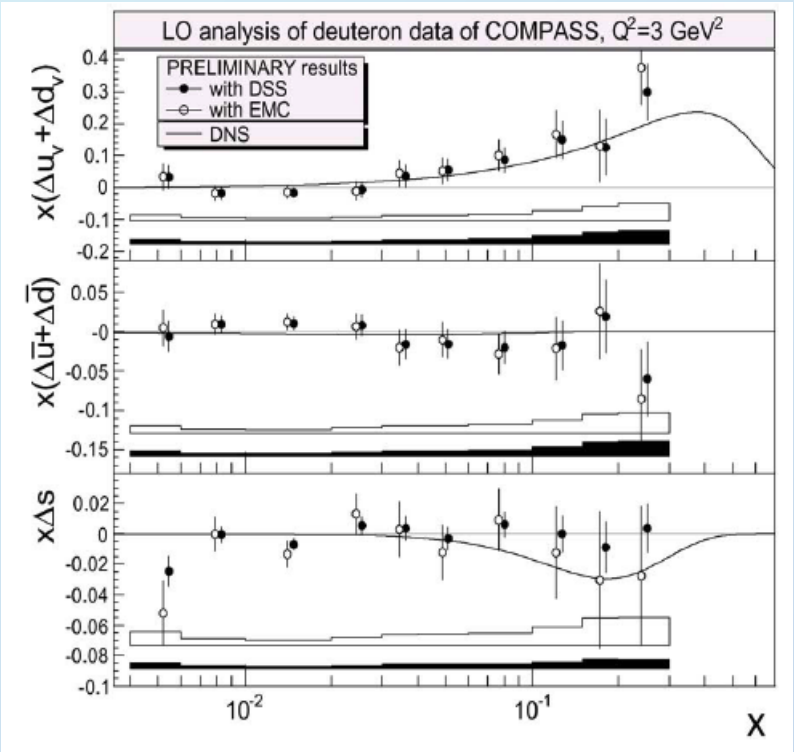
Driven by
SU(3); (3F-D)

Polarized Strangeness

New Results from COMPASS

- isoscaler method A^{K++K-} & A^{incl}
- "Purity" Method using FF

Input **:** $A_{1,d}, A_{1,d}^{\pi^+}, A_{1,d}^{\pi^-}, A_{1,d}^{K^+}, A_{1,d}^{K^-}$

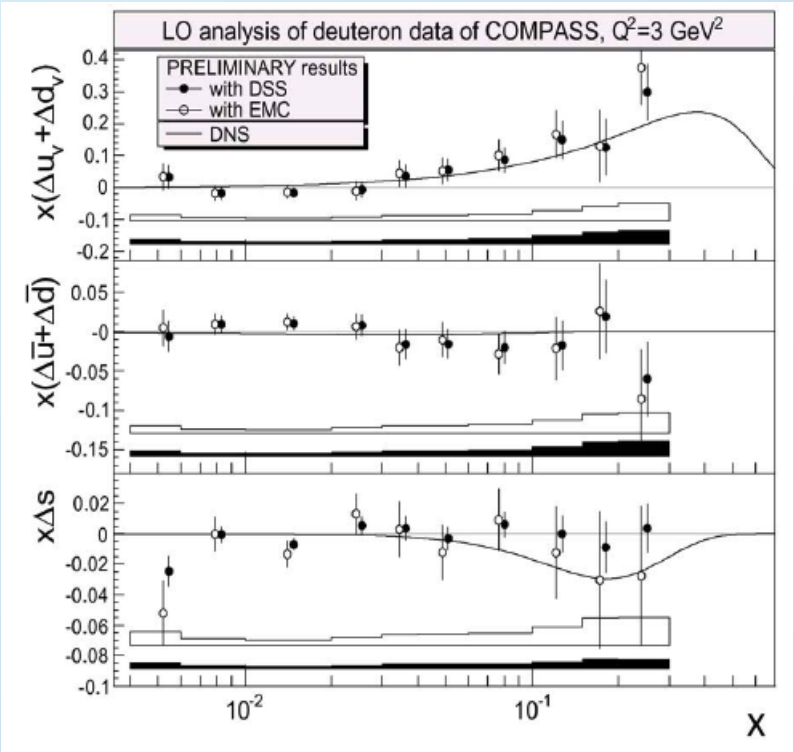


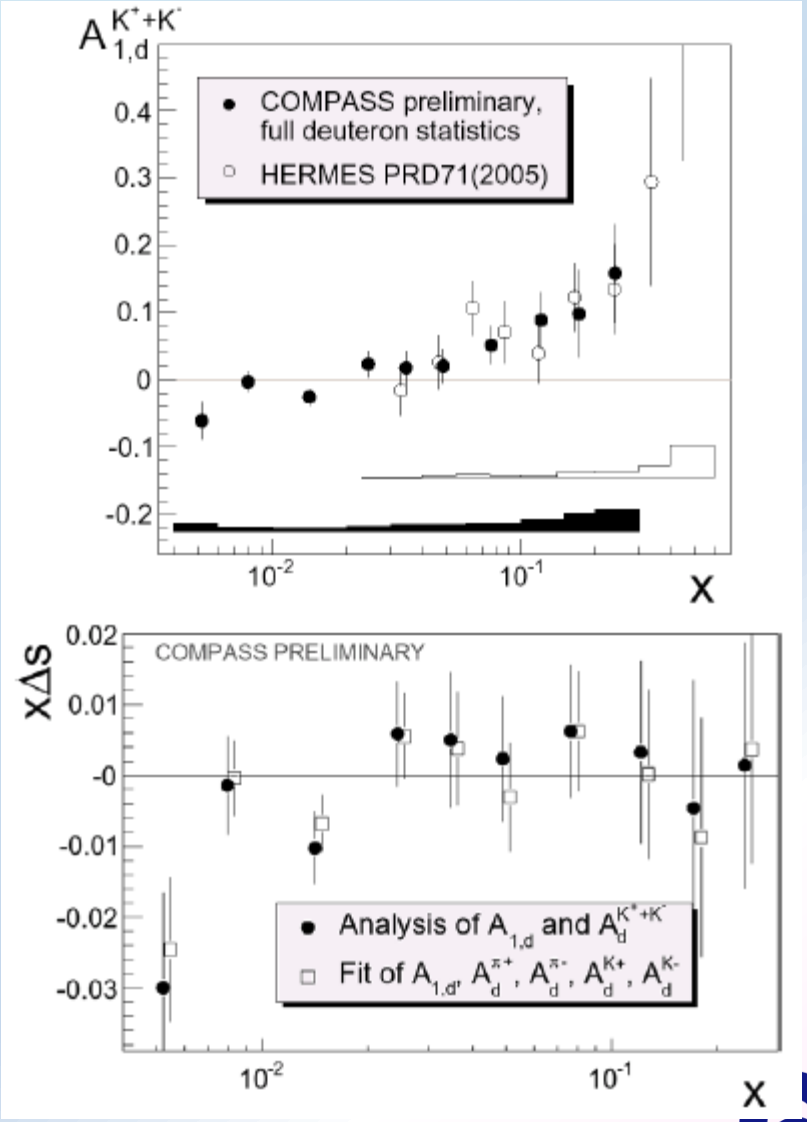
Polarized Strangeness

New Results from COMPASS

- isoscaler method A^{K++K-} & A^{incl}
- "Purity" Method using FF

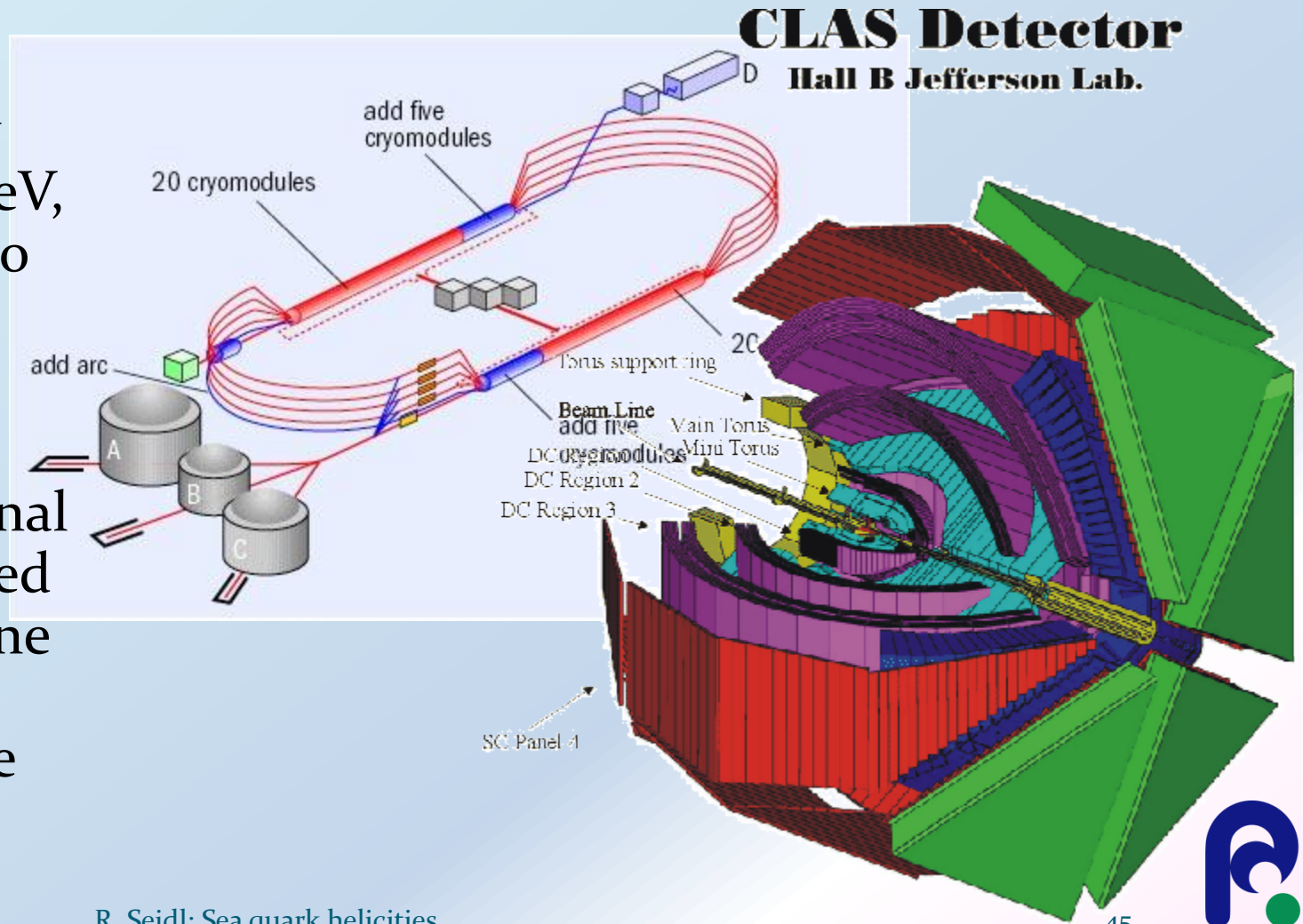
Input **:** $A_{1,d}, A_{1,d}^{\pi^+}, A_{1,d}^{\pi^-}, A_{1,d}^{K^+}, A_{1,d}^{K^-}$





Near term SIDIS additions for quark helicities: JLAB11

- JLab Exp's
  - Pol.e-
  - Currently up to 6 GeV, upgrade to 11 GeV ongoing
  - Mostly longitudinally polarized targets, one He3 transverse target

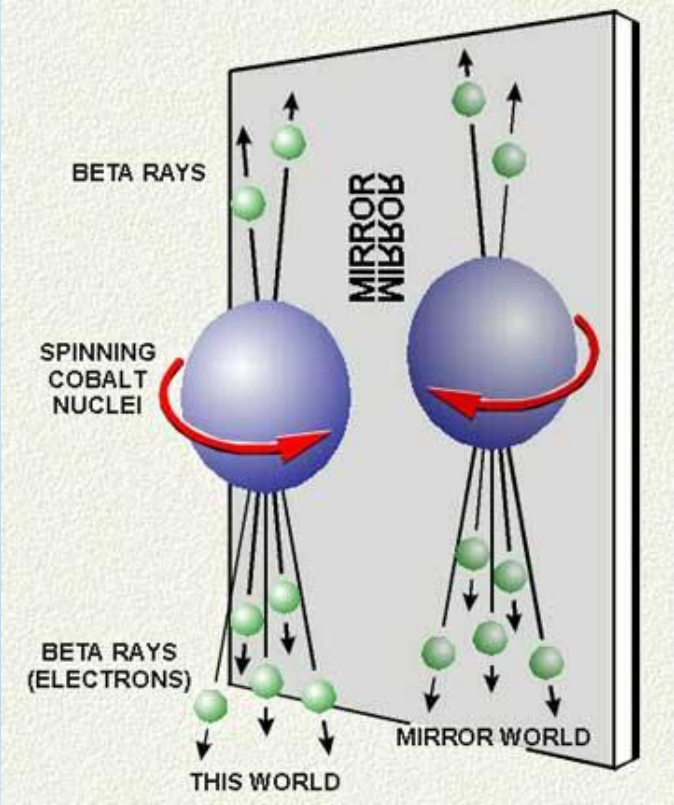


W production
in polarized pp collisions

Parity

- The symmetry of a system under transformation from x → -x
- Helicity is odd under parity
- The strong interaction and the EM interaction conserve parity, assumed to be true also for the weak interaction (Feynman bet $50 on it)
- TD Lee and CN Yang suggested P violation in weak interaction and exp to measure it

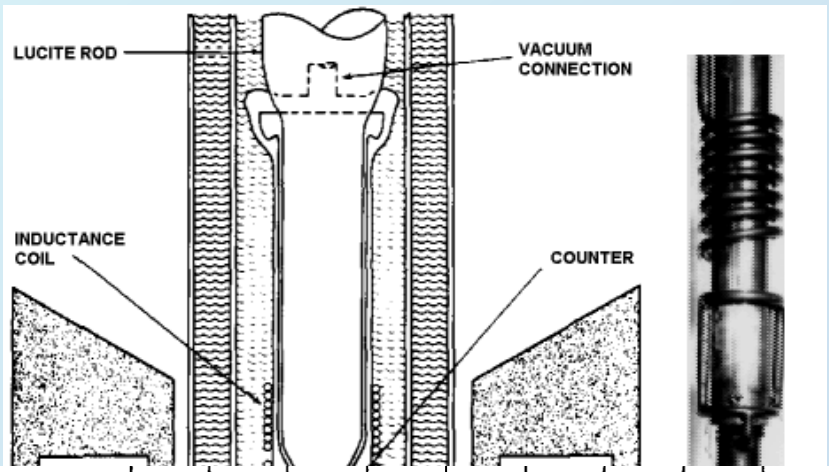
$$h = \frac{\mathbf{p}\cdot\mathbf{s}}{|\mathbf{p}||\mathbf{s}|}$$



$$h' = \frac{-\mathbf{p}\cdot\mathbf{s}}{|-\mathbf{p}||\mathbf{s}|}$$

The discovery of parity violation

Phys. Rev 105 (1957) 1413



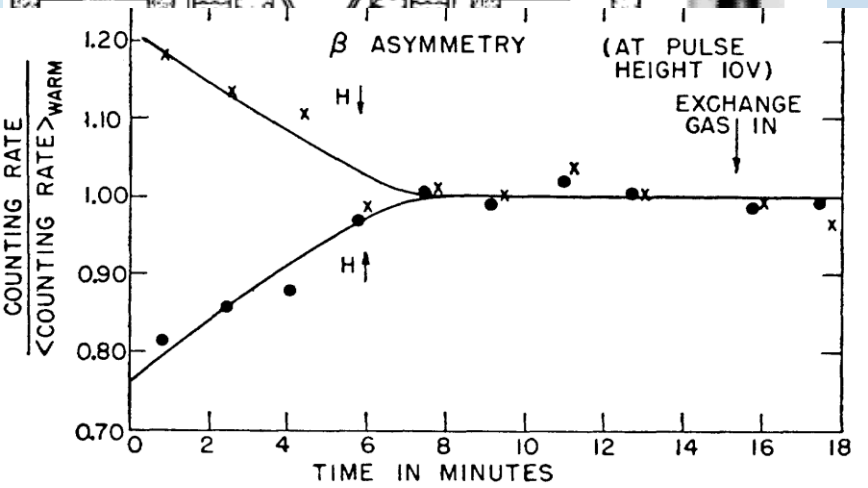


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

- C. S. Wu et al. (1957)
  - Polarized Co^{60} at very low temperatures: β emission preferably against polarization axis
  - Later also tested opposite effect with Co^{58} (β^+ emitter)
- The weak interaction only couples to left-handed particles and right-handed antiparticles, maximally parity violating

Pion decay measurement

Phys. Rev 105 (1957) 1415

- Nearly at same time (back-to-back in Physics Review) Garwin, Lederman and Weinrich confirmation in pion decay @Nevis Cyclotron:
  - Decay muons polarized (being used in [E,N,S]MC/COMPASS)
  - Parity is not conserved under weak interacton
  - Charge conjugation is not conserved

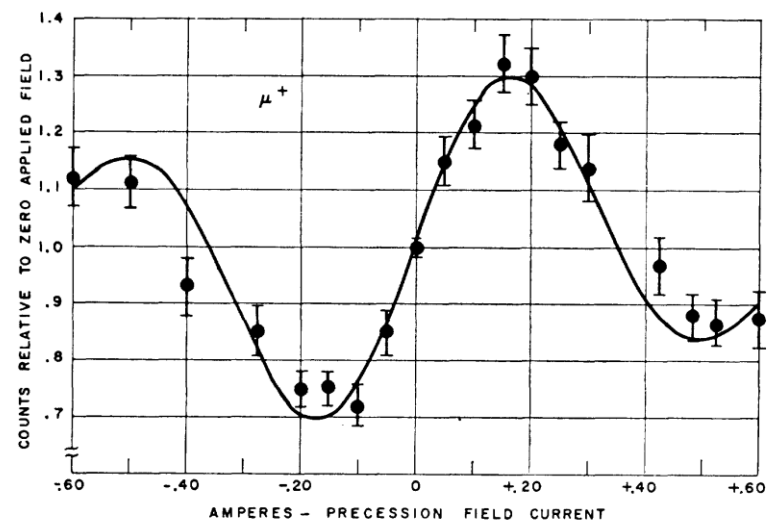
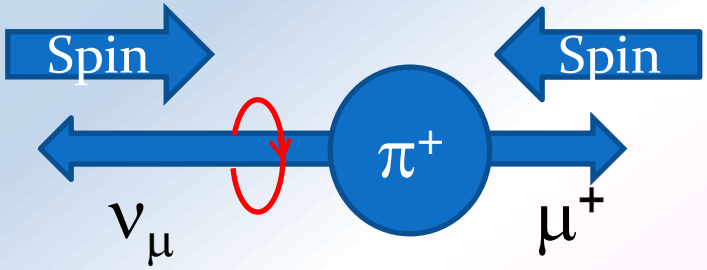
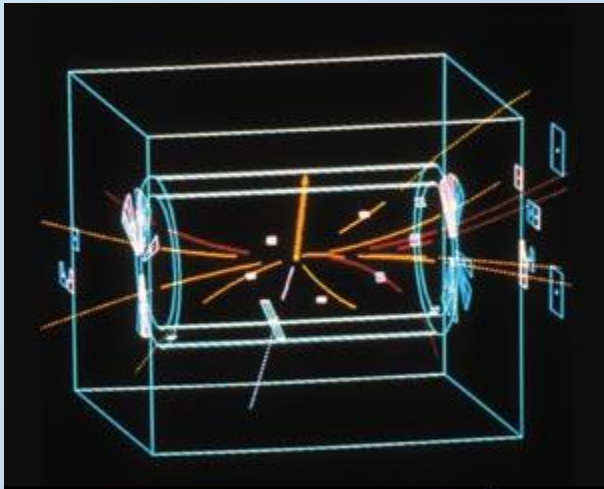


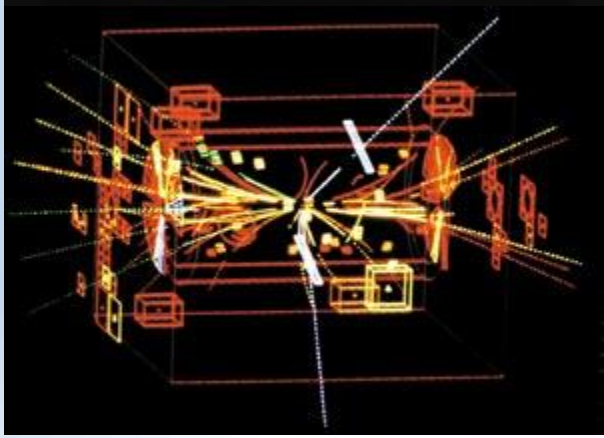
FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.



Discovery of W and Z bosons

- Electroweak unification Sheldon Lee Glashow, Abdus Salam, Steven Weinberg : W and Z bosons
- "Discovery" at the SPS by UA1 and UA2
- '84: Carlo Rubbia, Simon van der Meer





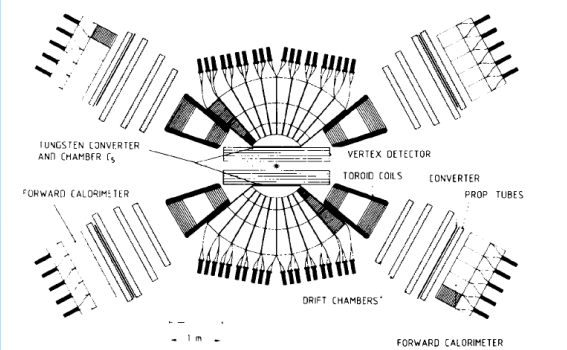


Fig. 1. The UA2 detector: Schematic cross section in the vertical plane containing the beam.

W discovery: UA1 **Phys.Lett. B122 (1983) 103-116**
UA2 **Phys.Lett. B122 (1983) 476-485**

Z discovery: UA1 **Phys.Lett. B126 (1983) 398-410**

W and Z bosons

- W Bosons
  - Mass: 80.39 GeV
  - Spin: 1
  - Decay modes:
    - $l\nu$ 10.80% (e,μ,τ)
    - $q\,\bar{q}$ 10.80% (u,c)*3
- Z Boson
  - Mass: 91.18 GeV
  - Spin: 1
  - Decay modes:
    - $\nu\bar{\nu}$ 6.8 % (e,μ,τ)
    - l^+l^- 3.4 % (e,μ,τ)
    - $q\,\bar{q}$ 15.2% (d,s,b)
      11.8 % (u,c)

Real W production: need to have enough energy to produce W: $x_1 x_2 \sqrt{s} > m_W$; general feature of DY like processes

With full W kinematics known LO extraction of x_1 and x_2 possible

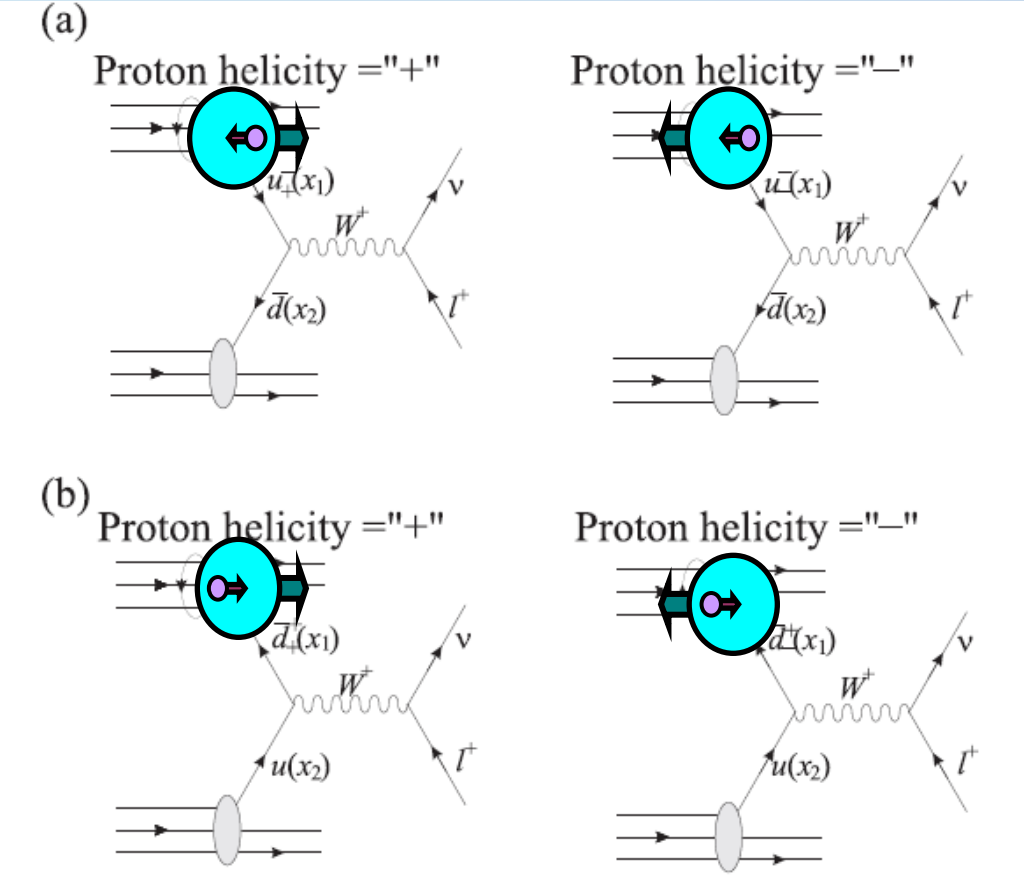
Real W production as access to quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:

➔Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

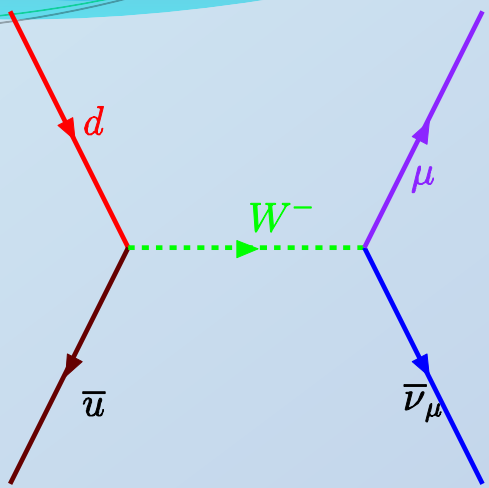
➔Difference of the cross sections gives quark helicities $\Delta q(x)$

- No Fragmentation function required
- Very high scale defined by W mass



Bourrely , Soffer
Nucl.Phys. B423 (1994) 329-348

Quark and antiquark helicities probed in W production



- Building single spin asymmetries of decay lepton

$$A_L = \frac{1}{P}\frac{\vec{N}-\overleftarrow{N}}{\vec{N}+\overleftarrow{N}}$$

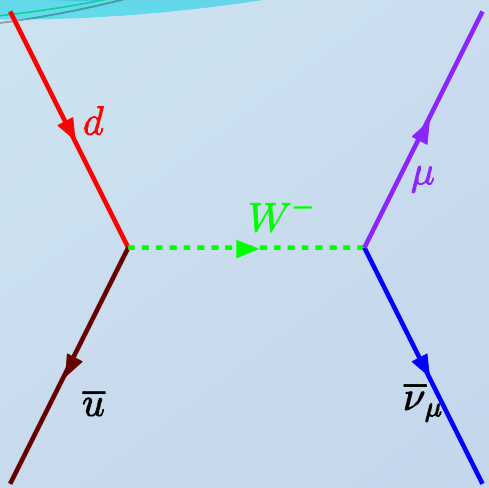
- Positive lepton asymmetries sensitive to $\Delta u\,(x)$ and $\Delta\,\bar{d}\,(x)$

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

- Negativ lepton asymmetries sensitive to $\Delta d\,(x)$ and $\Delta\,\bar{u}\,(x)$

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

Quark and antiquark helicities probed in W production



- Building single spin asymmetries of decay lepton

$$A_L = \frac{1}{P}\frac{\vec{N}-\overleftarrow{N}}{\vec{N}+\overleftarrow{N}}$$

But unfortunately we don't have a 4π detector,
Need to find the Ws inclusively via their decay leptons

- Positive le
asymmetr
Δu (x) and

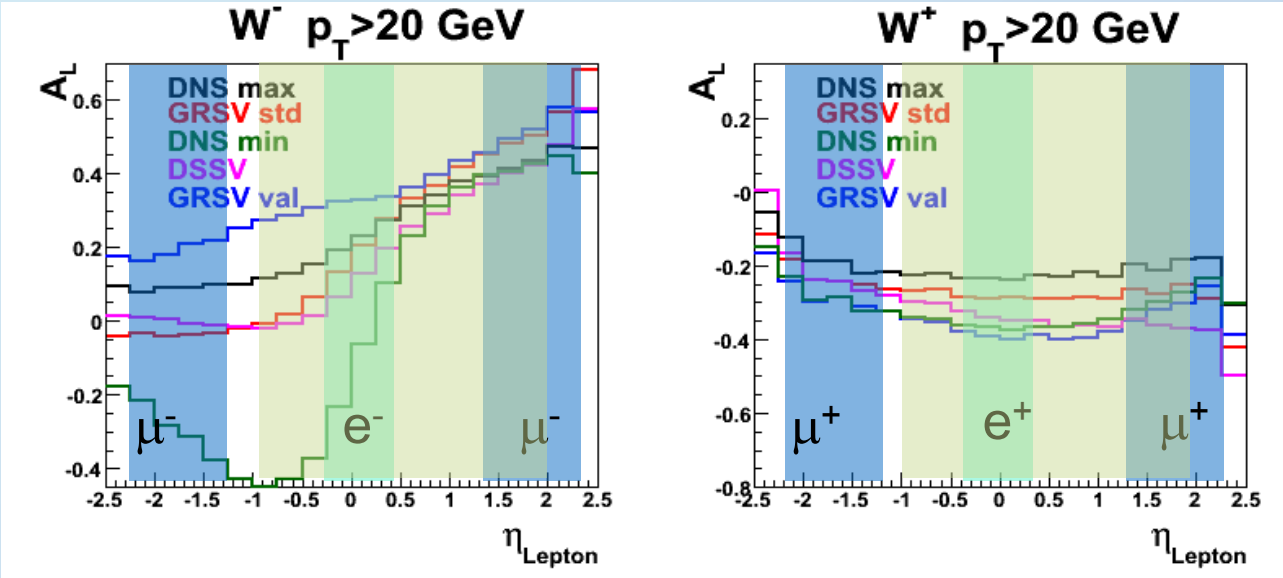
$$\frac{\bar{d}(x_2)-\Delta\bar{d}(x_1)u(x_2)}{\bar{d}(x_2)-\bar{d}(x_1)u(x_2)}$$

- Negativ lepton asymmetries sensitive to Δd (x) and Δ $\bar{u}$ (x)

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

Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics

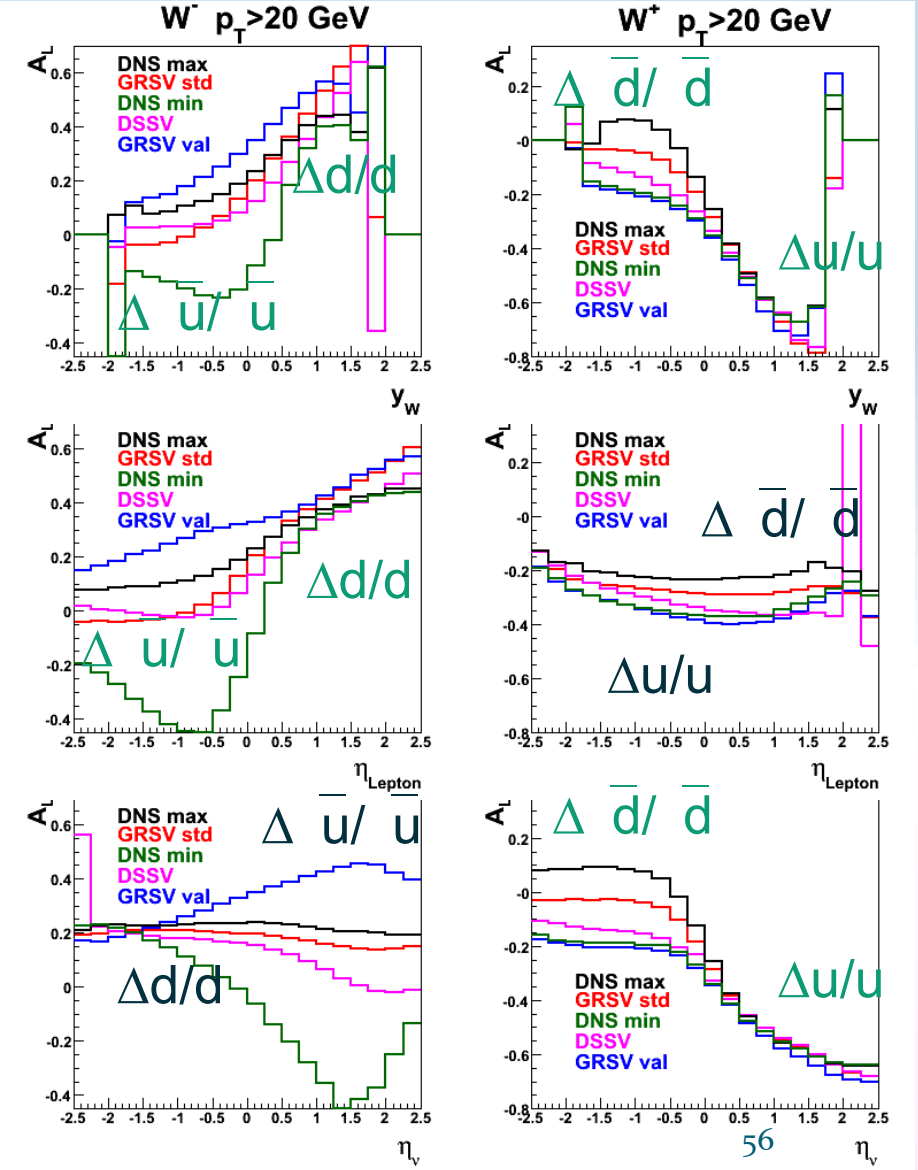


$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2}{u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \bar{d}(x_1)u(x_2)(1+\cos\theta)^2}$$

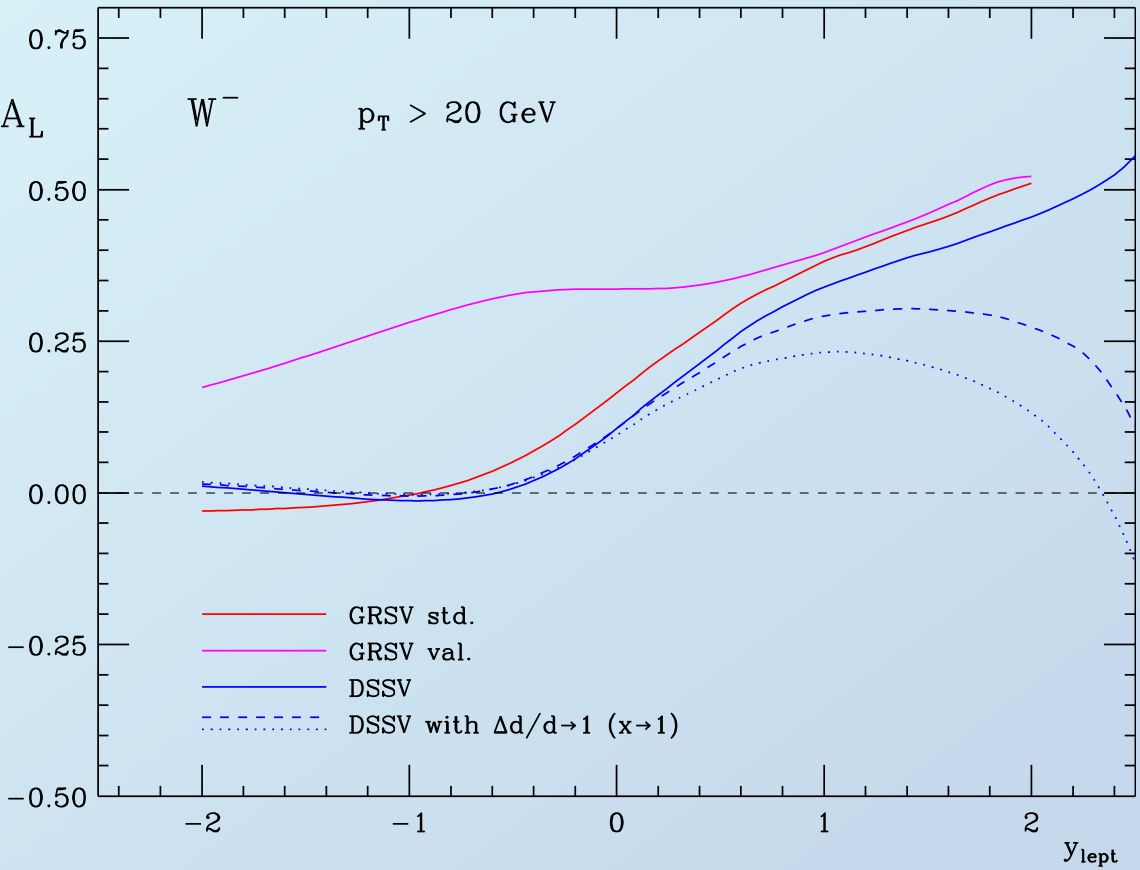
$$A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2}{d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \bar{u}(x_1)d(x_2)(1-\cos\theta)^2}$$

W vs lepton asymmetries

- Clear correlation for W: valence quark polarization→forward sea quark → backward
- However, not for decay muon/electron: enhanced for W^-, mixed for W^+
- reversed effect for neutrino asymmetry
- neutron target reverses that due to isospin asymmetry →run He3 colisions eventully?
- x is not affected by this; still forward is larger x, backward smaller x

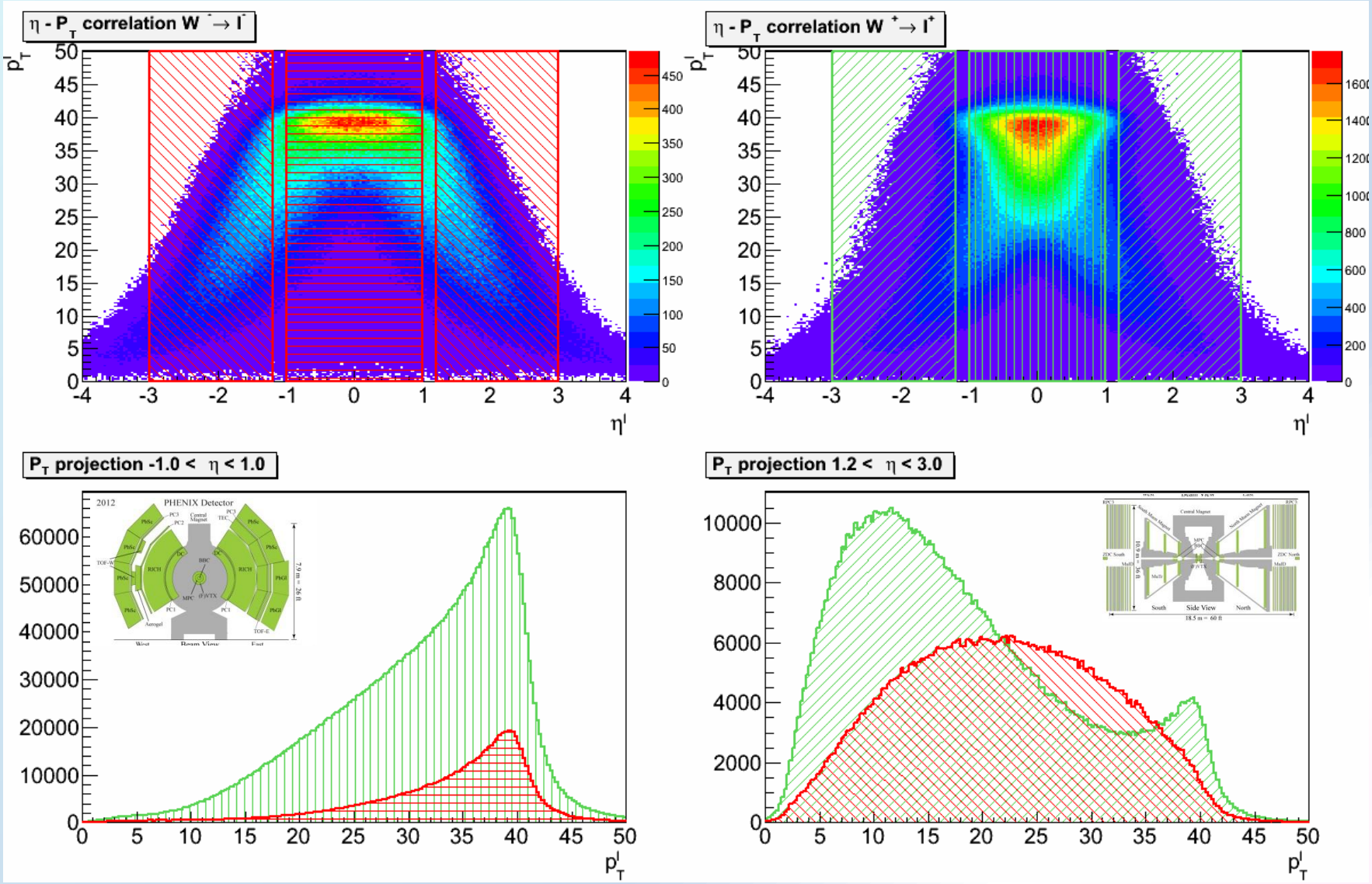


High x behavior of d helicity



- Power counting suggests that d polarization has to become 1 at x→1
- turnaround visible in future JLAB data
- In forward μ^- production visible

W kinematics

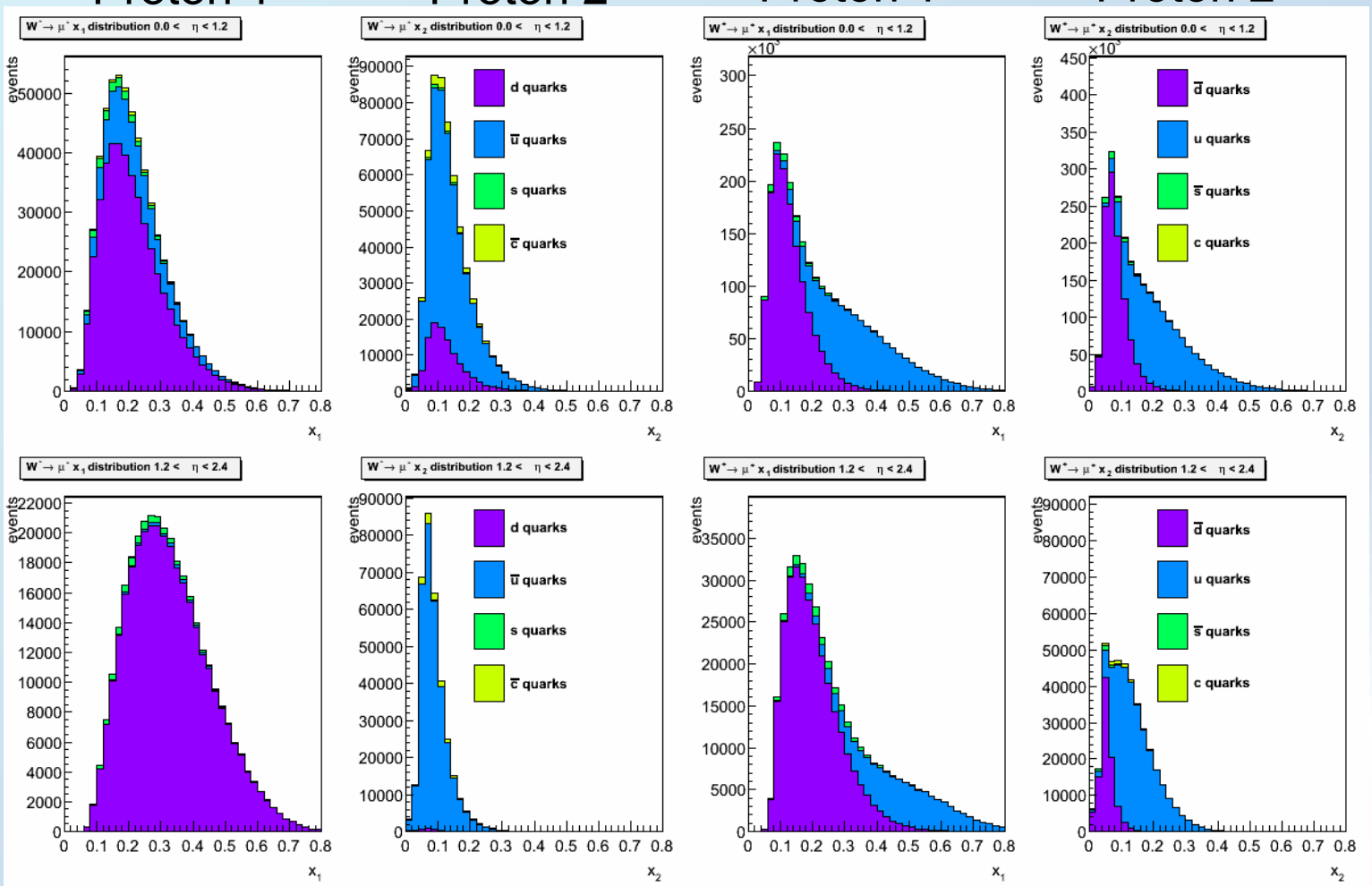


Pythia: quark flavors and x ranges

Proton 1 | Proton 2 | Proton 1 | Proton 2

Central

Forward

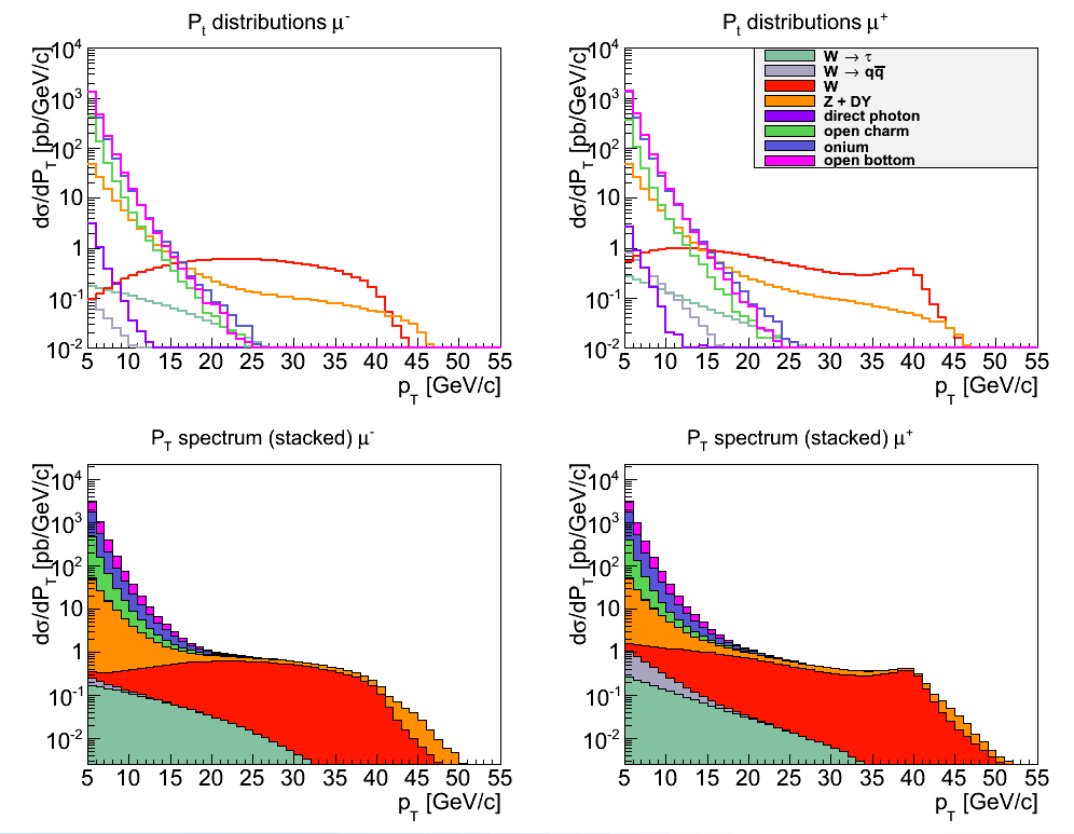


$W^- \rightarrow \mu$ case: almost entirely forward d quarks and backwards $\bar{u}$

$W^+ \rightarrow \mu$ case: predominantly forward $\bar{d}$ quarks and backwards u

Forward W analysis

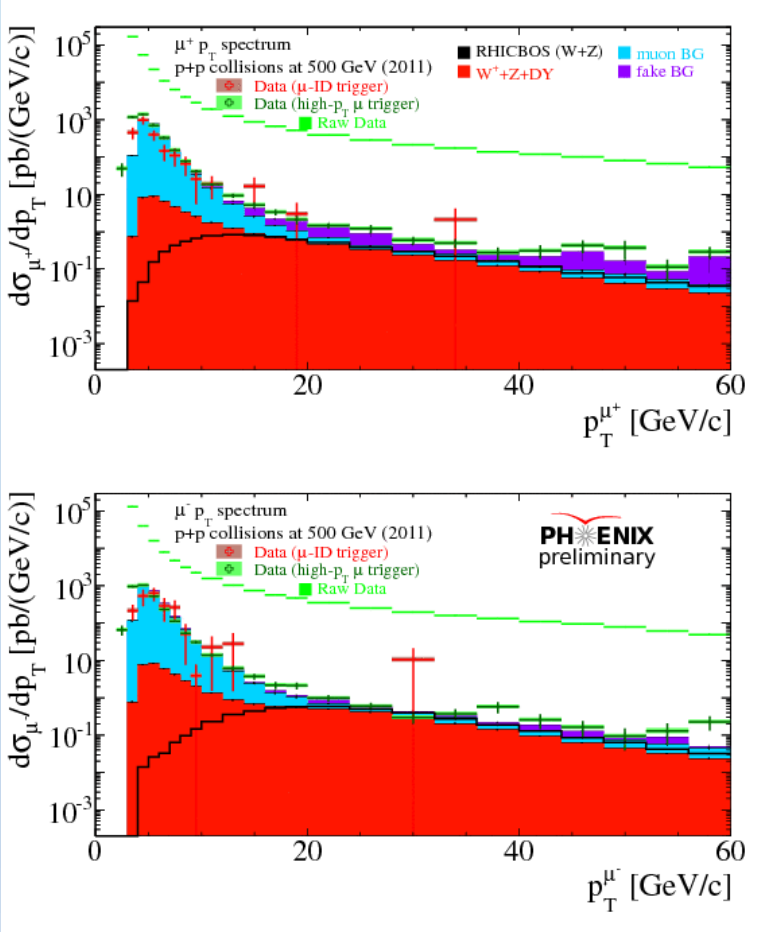
- W momentum cannot be ignored
- Jacobian peak only visible for forward moving W^+ decaying at close to 90 degrees
- Need to understand and suppress backgrounds lacking distinct signal signature



Pythia 6.4, muons in rapidities 1.2 – 2.4

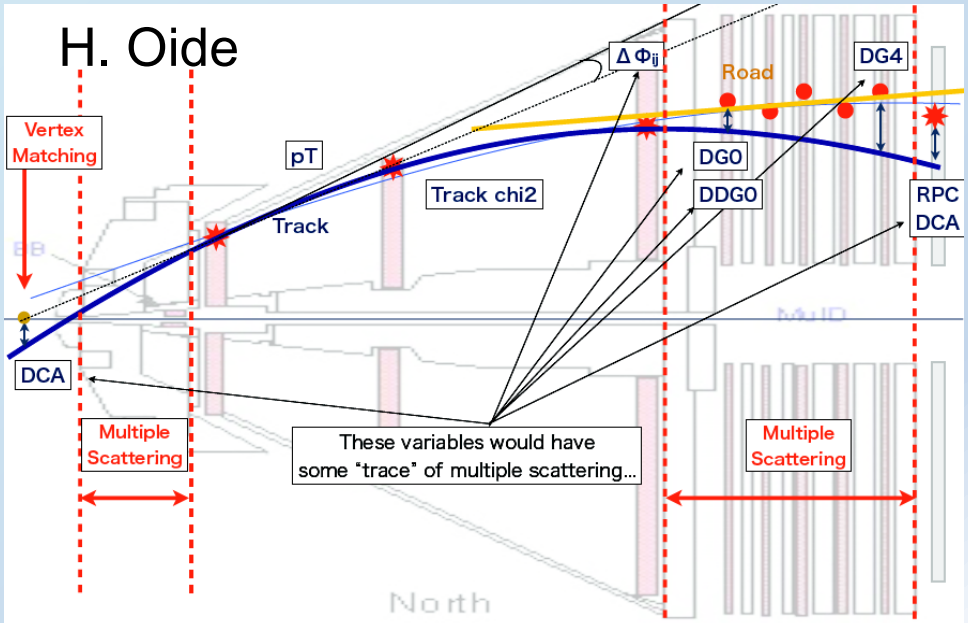
Forward Muon Backgrounds

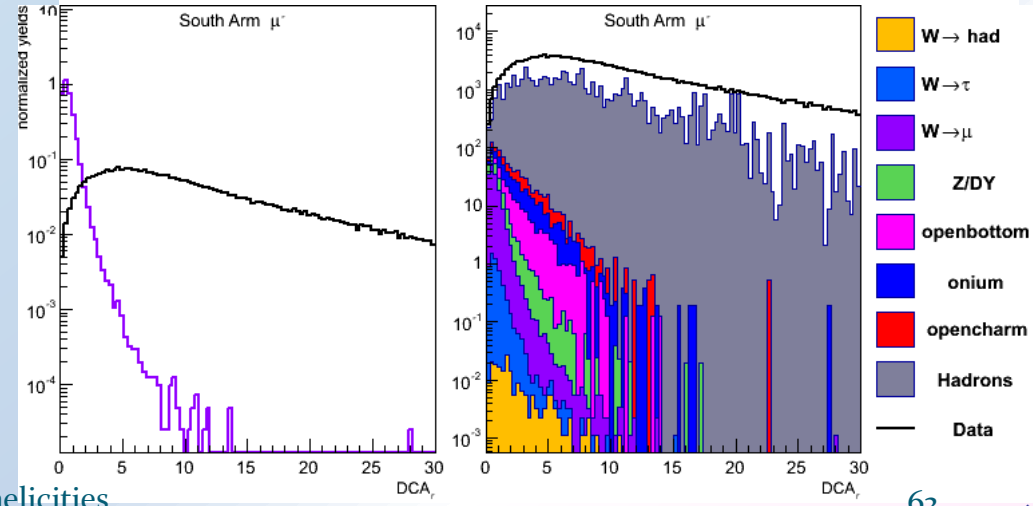
- Real muons from heavy flavor and DY decays get smeared to higher transverse momenta
- Low energetic hadrons (huge cross section) decay within the muon tracker, mimicking a straight track
- Raw yields 3 orders above signal



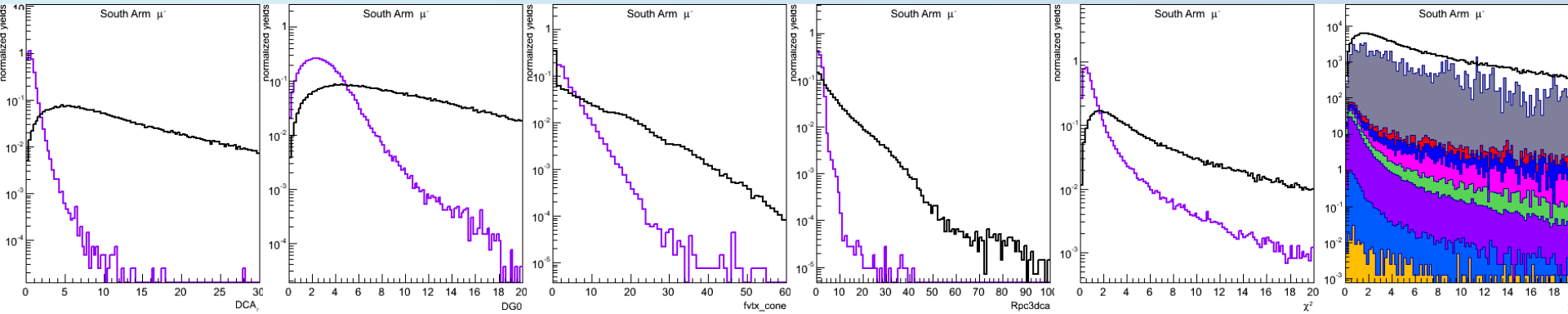
Reducing the background components

- Apply sensitivity to multiple scattering to reduce hadronic backgrounds
- Initially (2011) cut based removal of backgrounds
- Improved by using likelihood based pre-selection and unbinned max likelihood fit

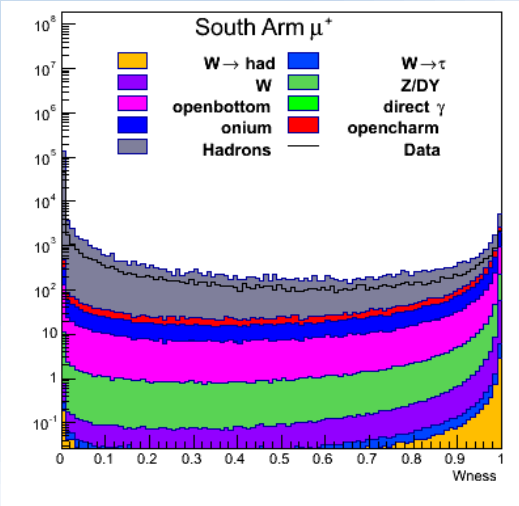




Multivariate analysis



- Define Wness likelihood using 5-9 kinematic variables based on signal MC and data (= mostly BG)

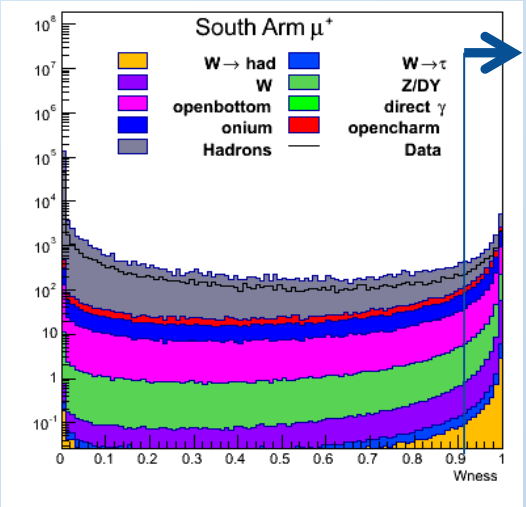


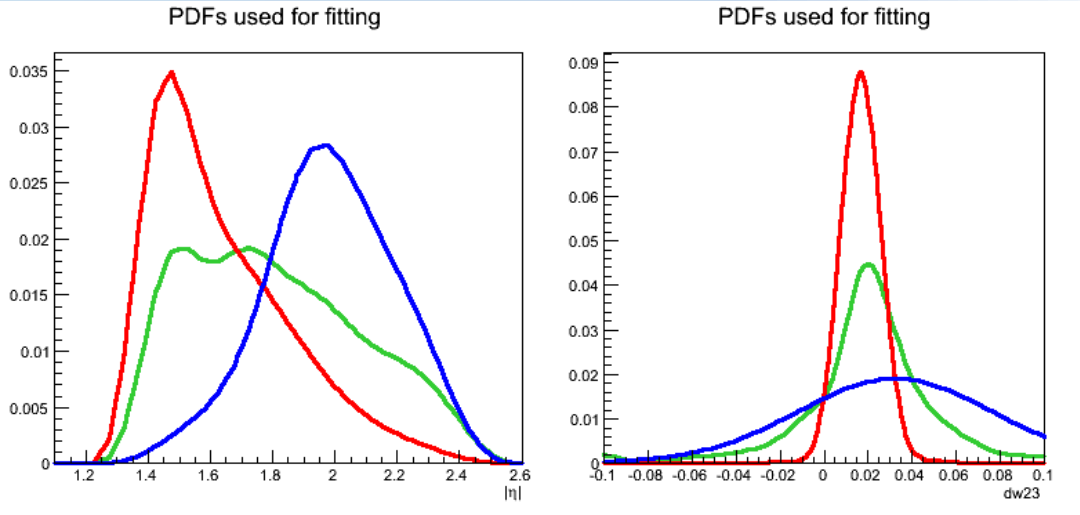
$$Wness = \frac{\lambda_{(SIG)}}{\lambda_{SIG} + \lambda_{BG}}$$

$$\lambda = [p(DG0, DDG0), p(DCA_r), p(\chi^2), p(RPC1,3_DCA), p(FVTX_Match), p(FVTX_Cone)]$$

W signal fit

- After preselecting W like events (>0.92) perform unbinned max likelihood fit in independent variables rapidity and effective bending angle
- Shapes for fit are extracted from:
  - Hadron Background: extrapolation from lower wness data
  - Muon from MC (fixed)
  - Signal MC





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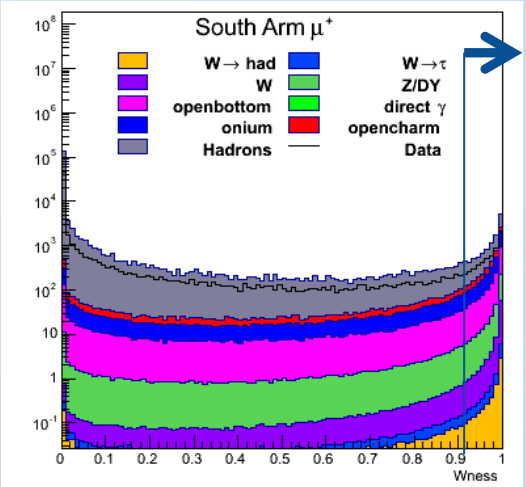
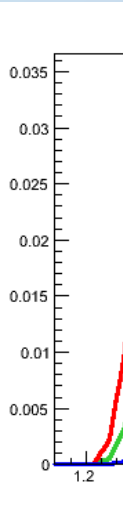
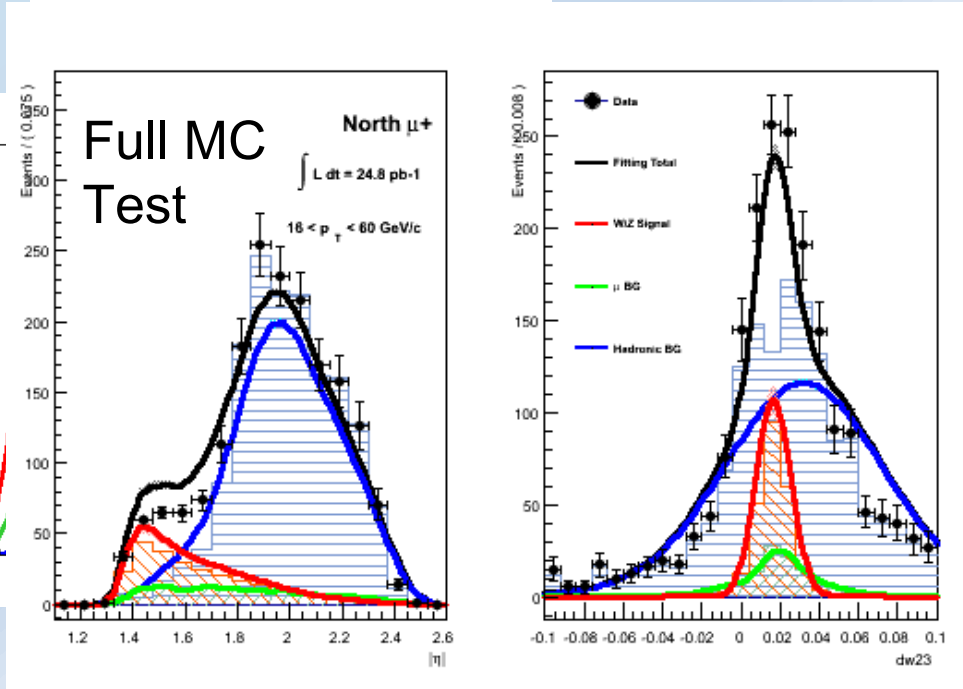
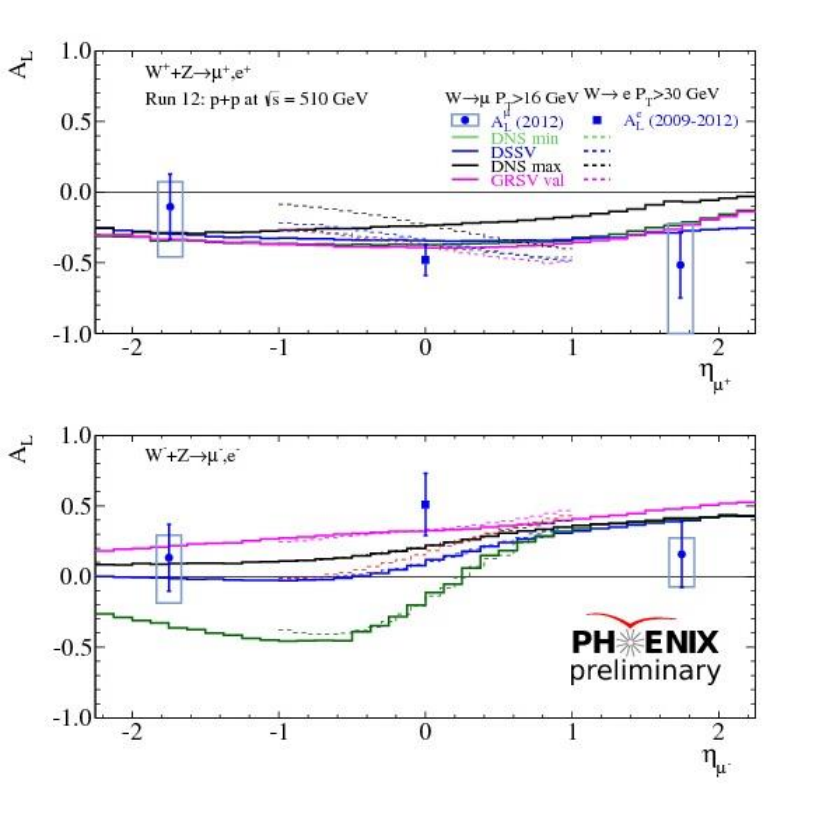






Forward W asymmetries

- After extracting S/BG ratios (in 2012 preliminary data ~0.3) extract asymmetries and correct for BG (BG asymmetries are consistent with zero)
- Inclusion of FVTX information will improve BG rejection (isolation, multiple scattering)
- 2011 and 2012 Analysis will be finalized soon
- 2013 data analysis is ongoing



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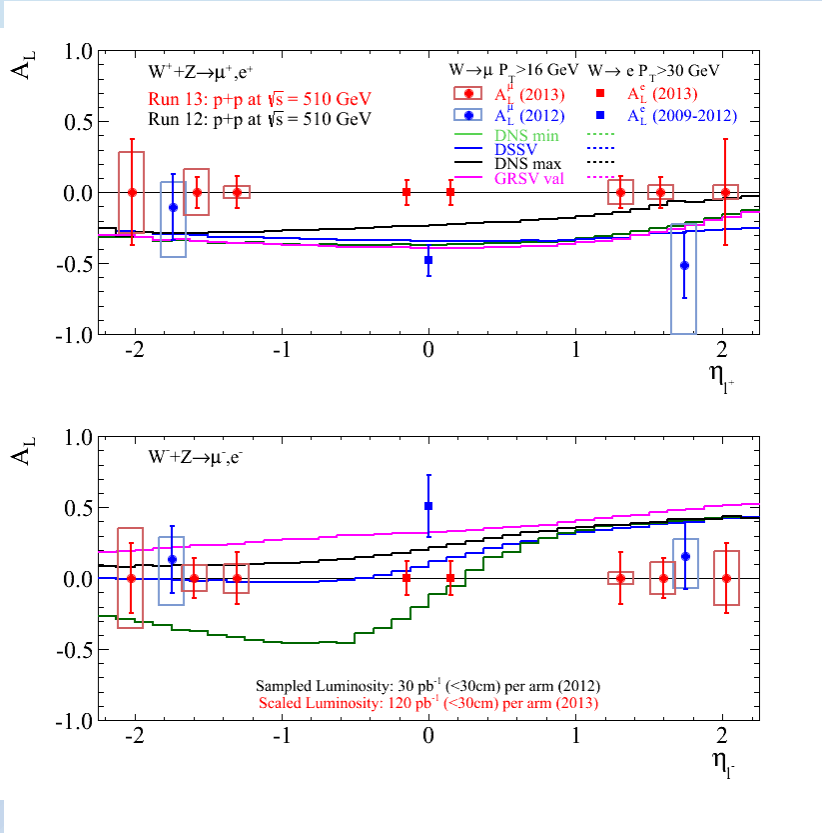
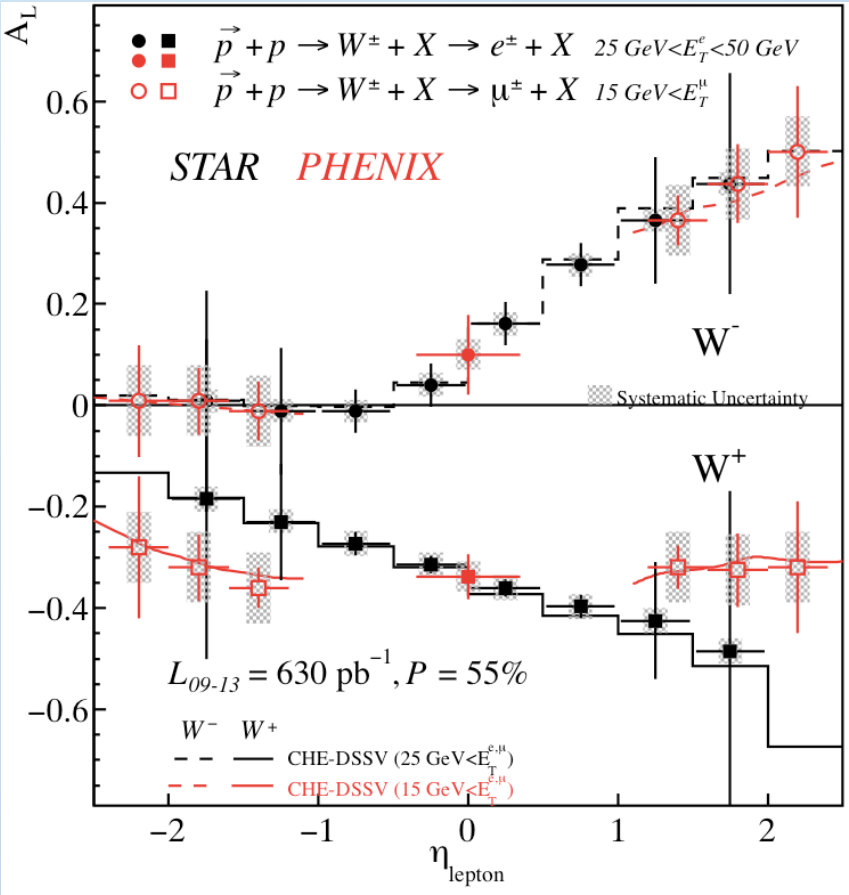


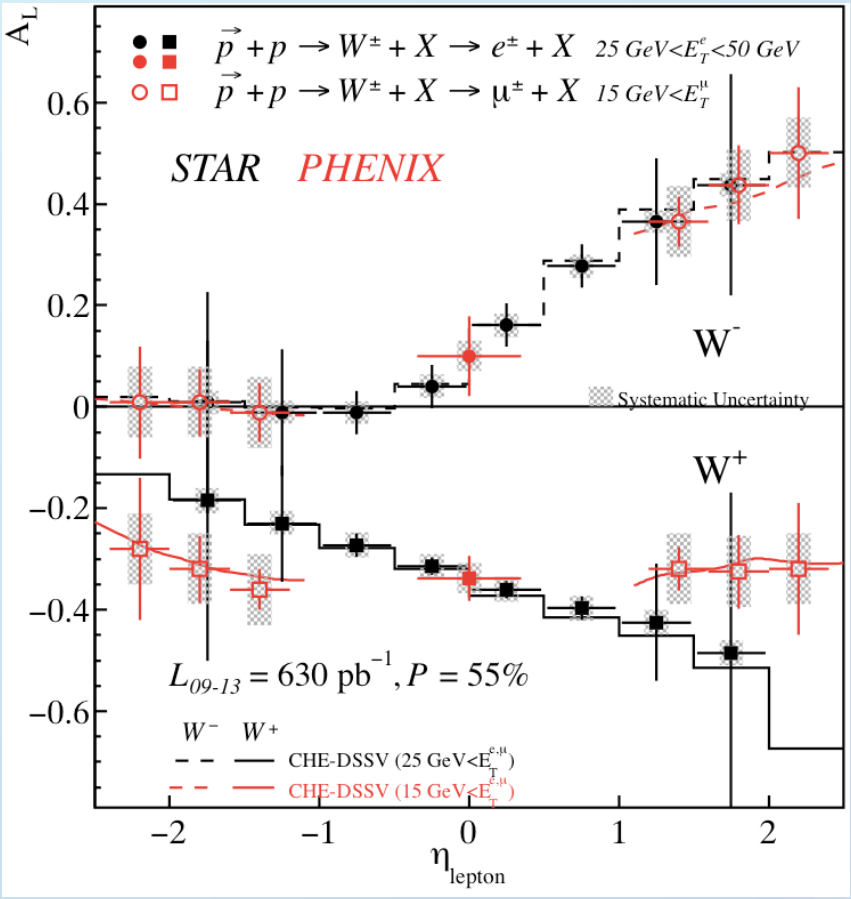
Outlook for full RHIC W data

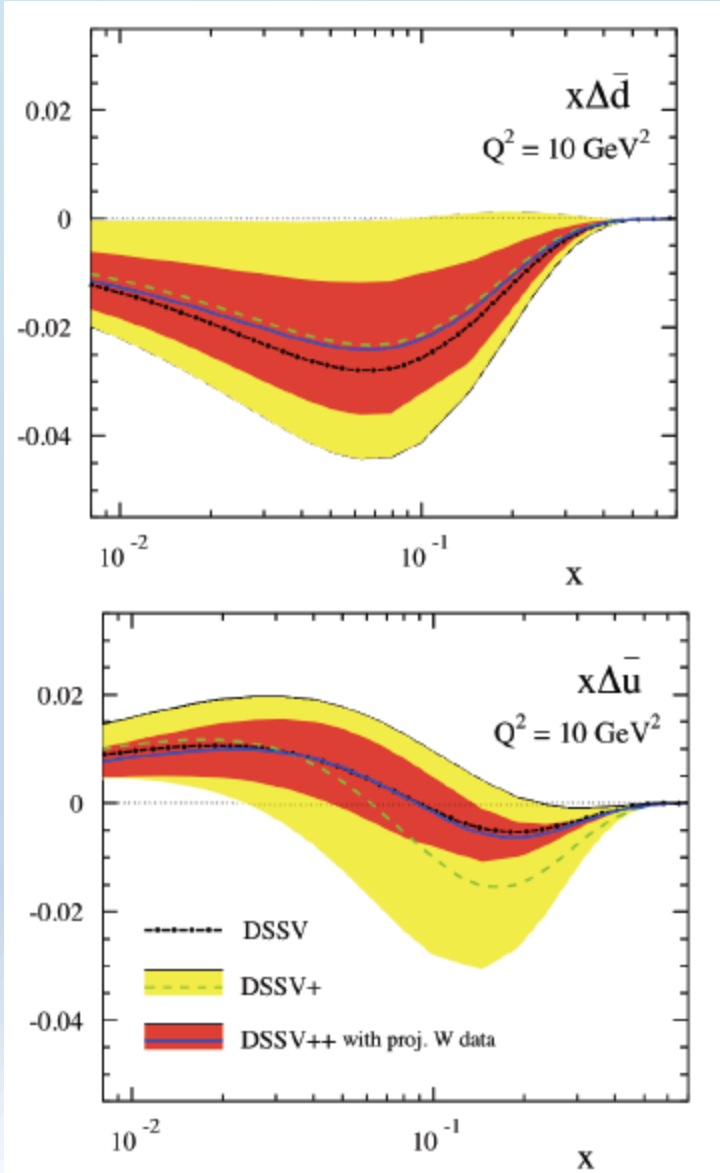
RHIC Spin NSAC write-up:
Aschenauer et. al: arXiv:1304.0079

- Real W boson production as clean access to sea quark helicities
- RHIC has delivered 510 GeV polarized pp collisions from 2009-2013
- Run 13 analysis will significantly improve sea quark helicity knowledge



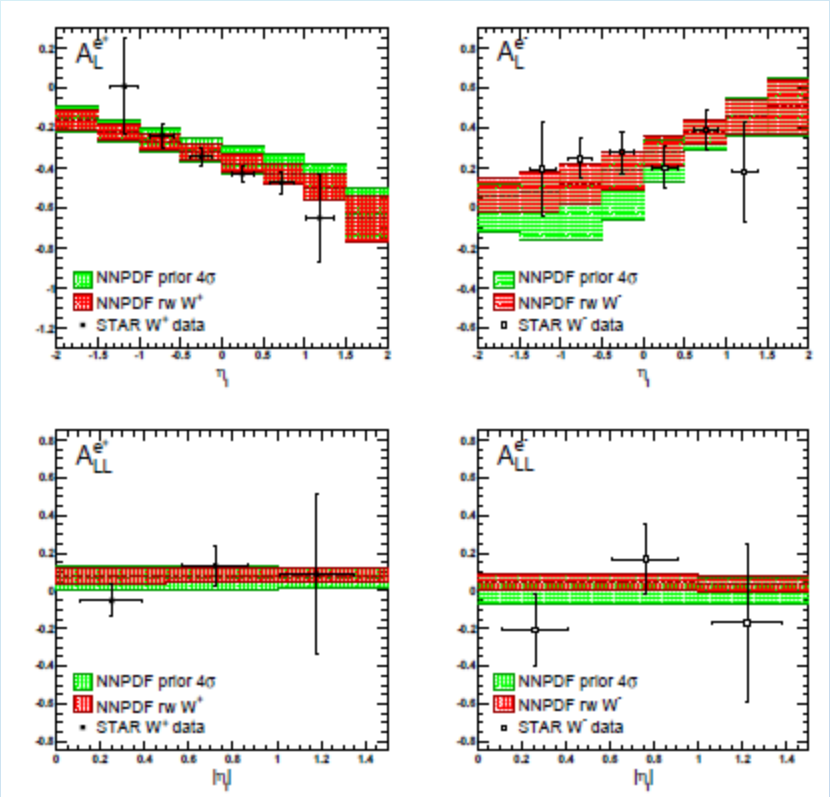
Expected total RHIC uncertainties

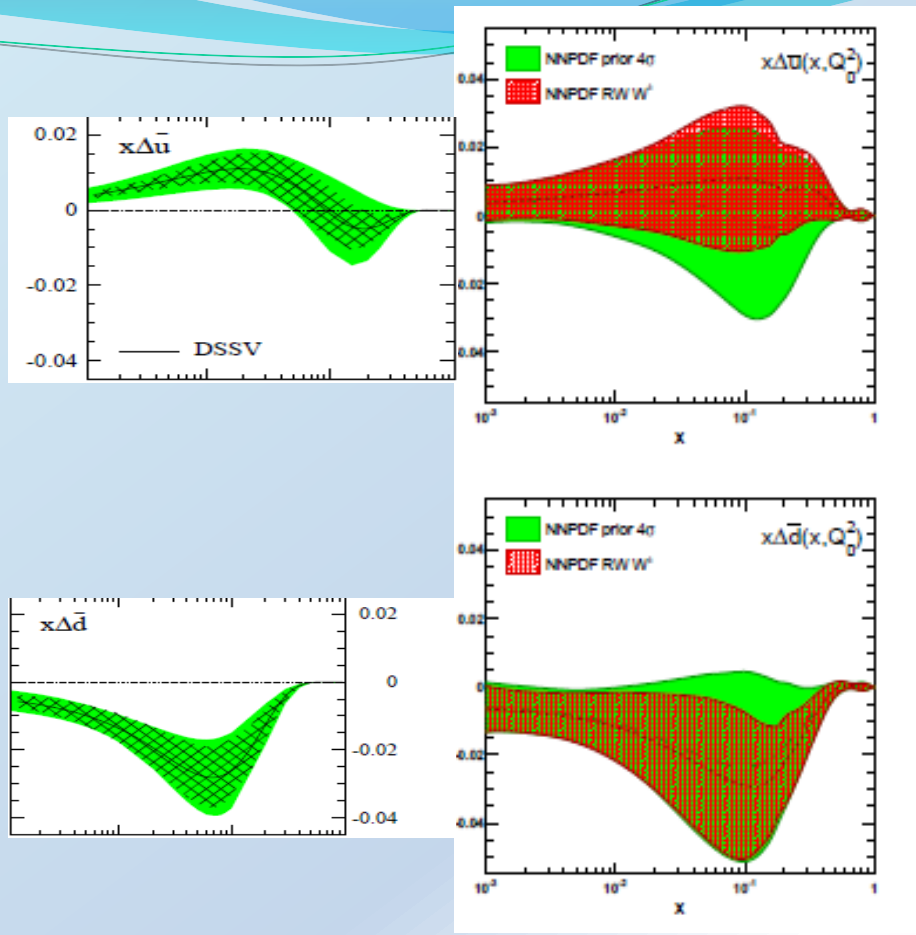




hep-ph:1406.5539

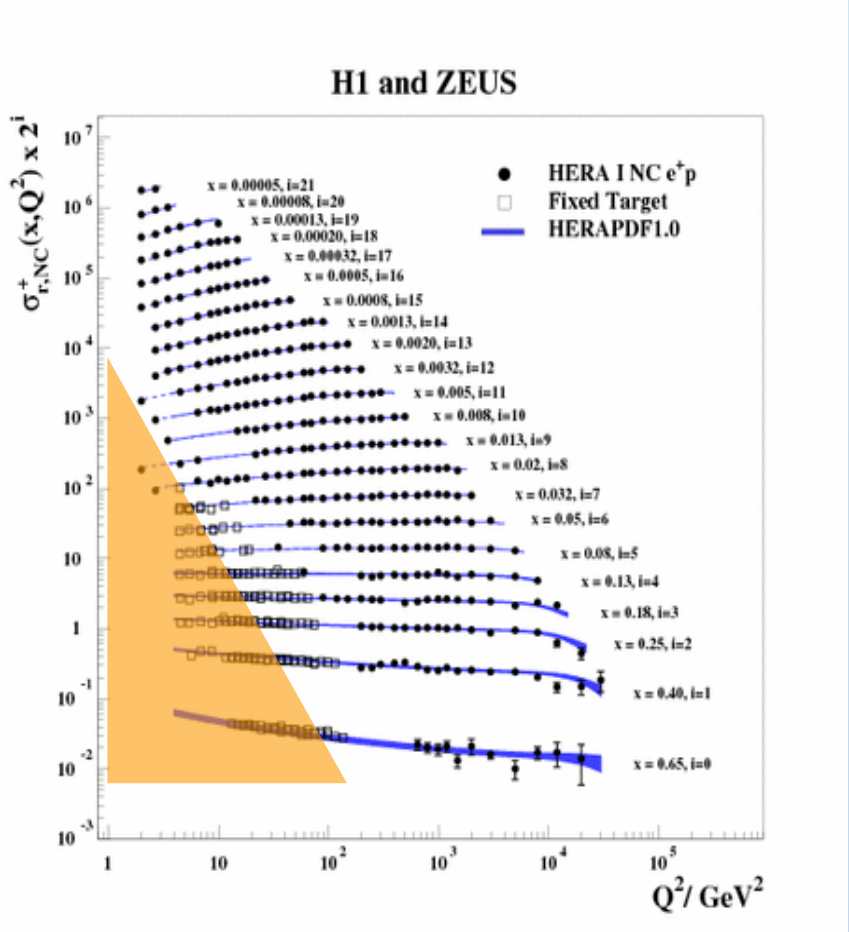
NNPDFpol1.1





- Uncertainties naturally larger as SIDIS data is not included
- However, caution necessary about uncertainties in un-covered regions

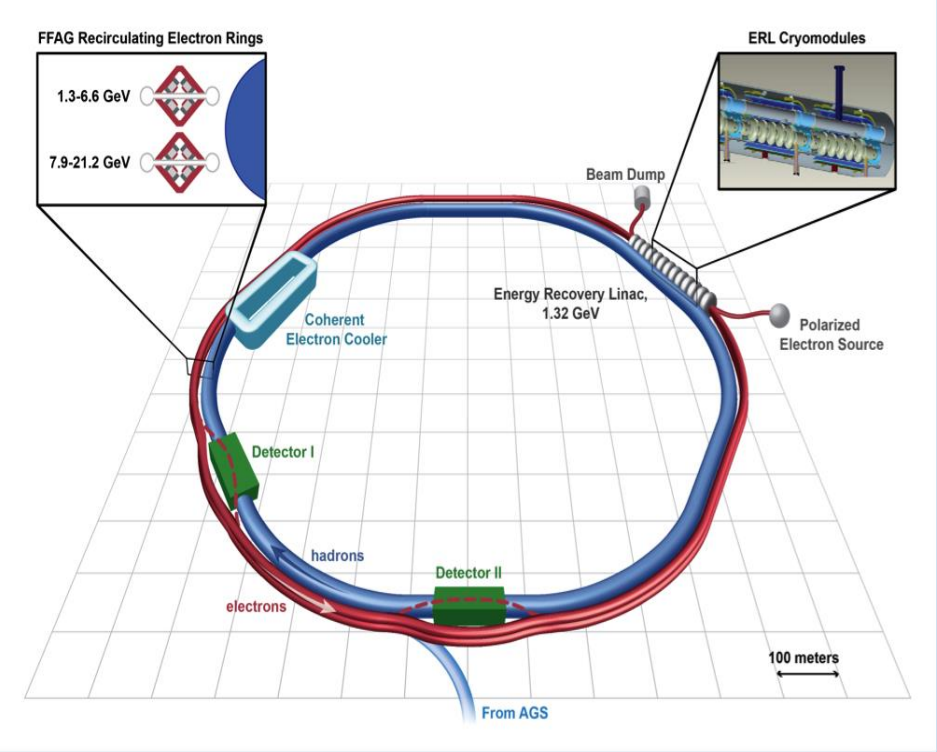
What comes after RHIC? EIC

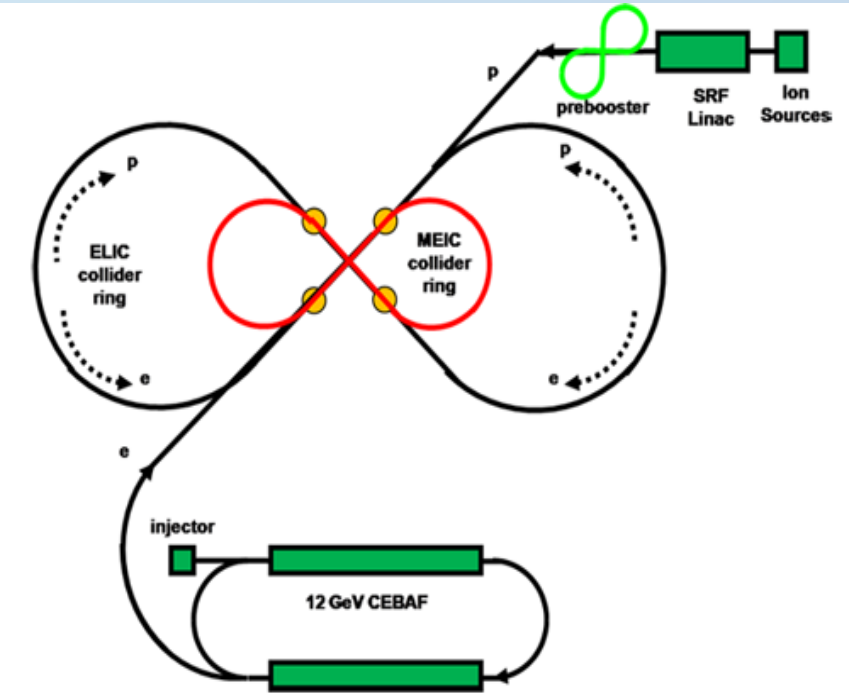


- Build the first polarized electron-Ion collider
  → collider geometry allows larger reach in Q^2 and smaller x
- Gluon polarization to lowest x values
- Study the 3D structure of the nucleon through transverse momentum dependent functions
- Study saturation effects at the lowest x

The Future: EIC

Two proposals: eRHIC (at BNL) and ELIC (at JLAB)



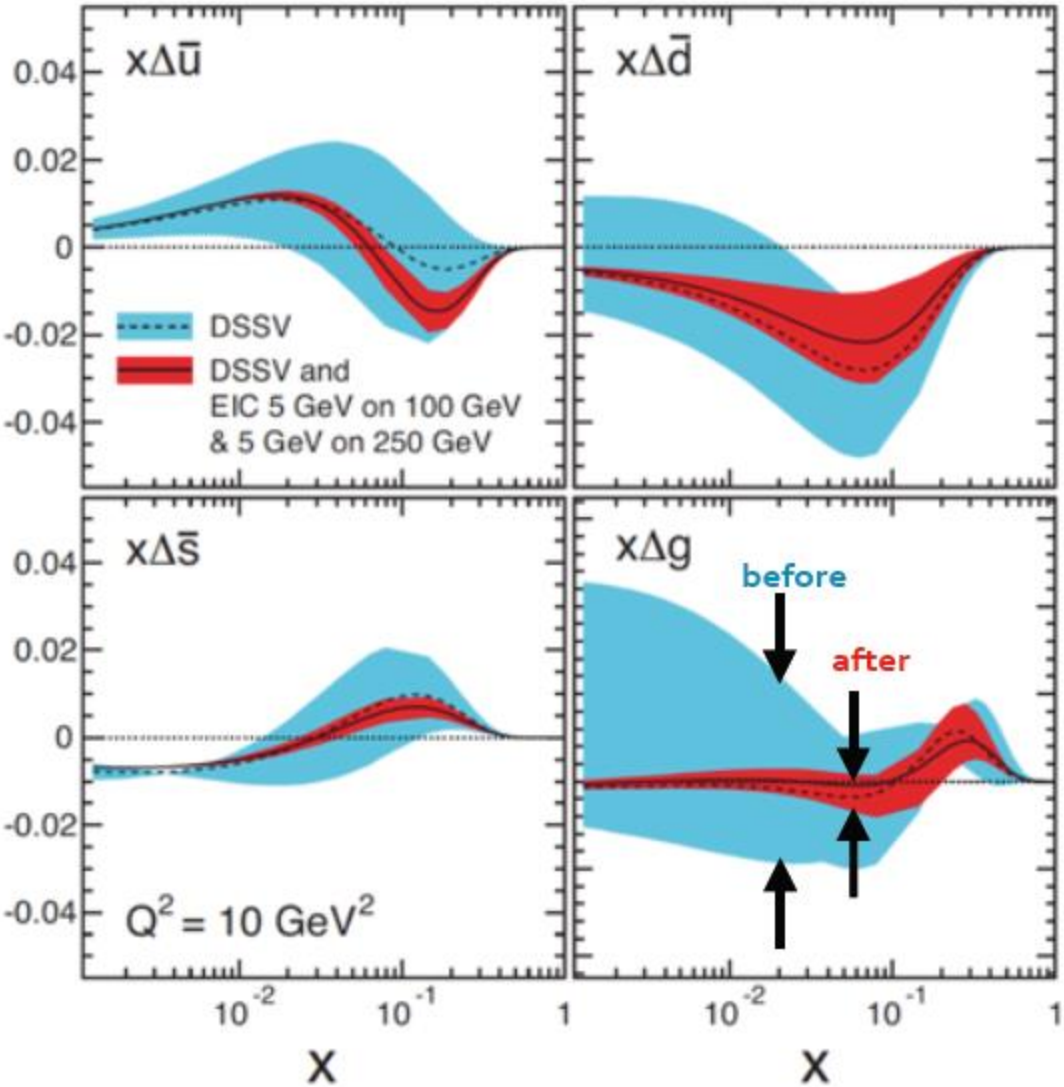


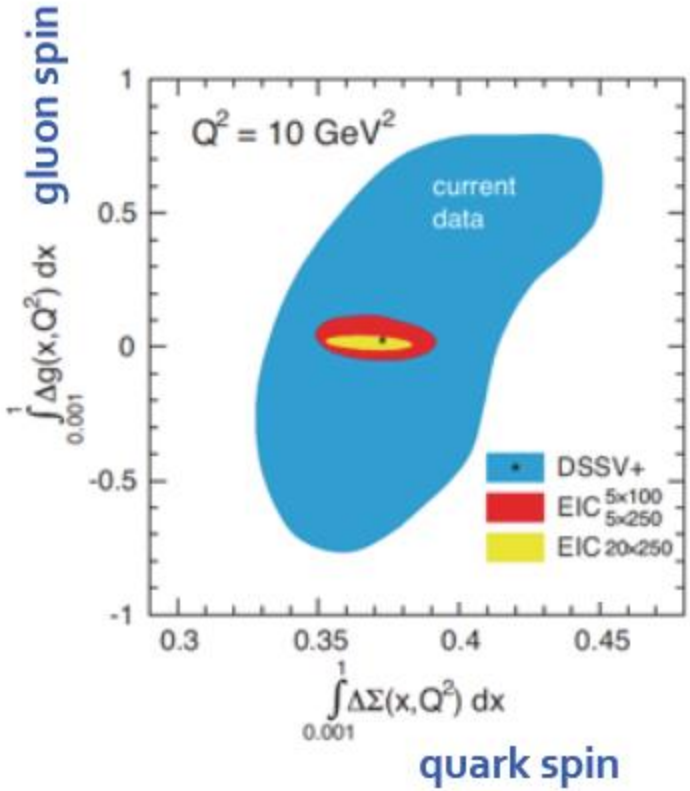
Staged approach first: 5 GeV x 50 GeV until 20x250

expectations for helicity PDFs

only uses DIS + SIDIS data up to $\sqrt{S} \simeq 70$ GeV and $Q^2 > 2$ GeV^2

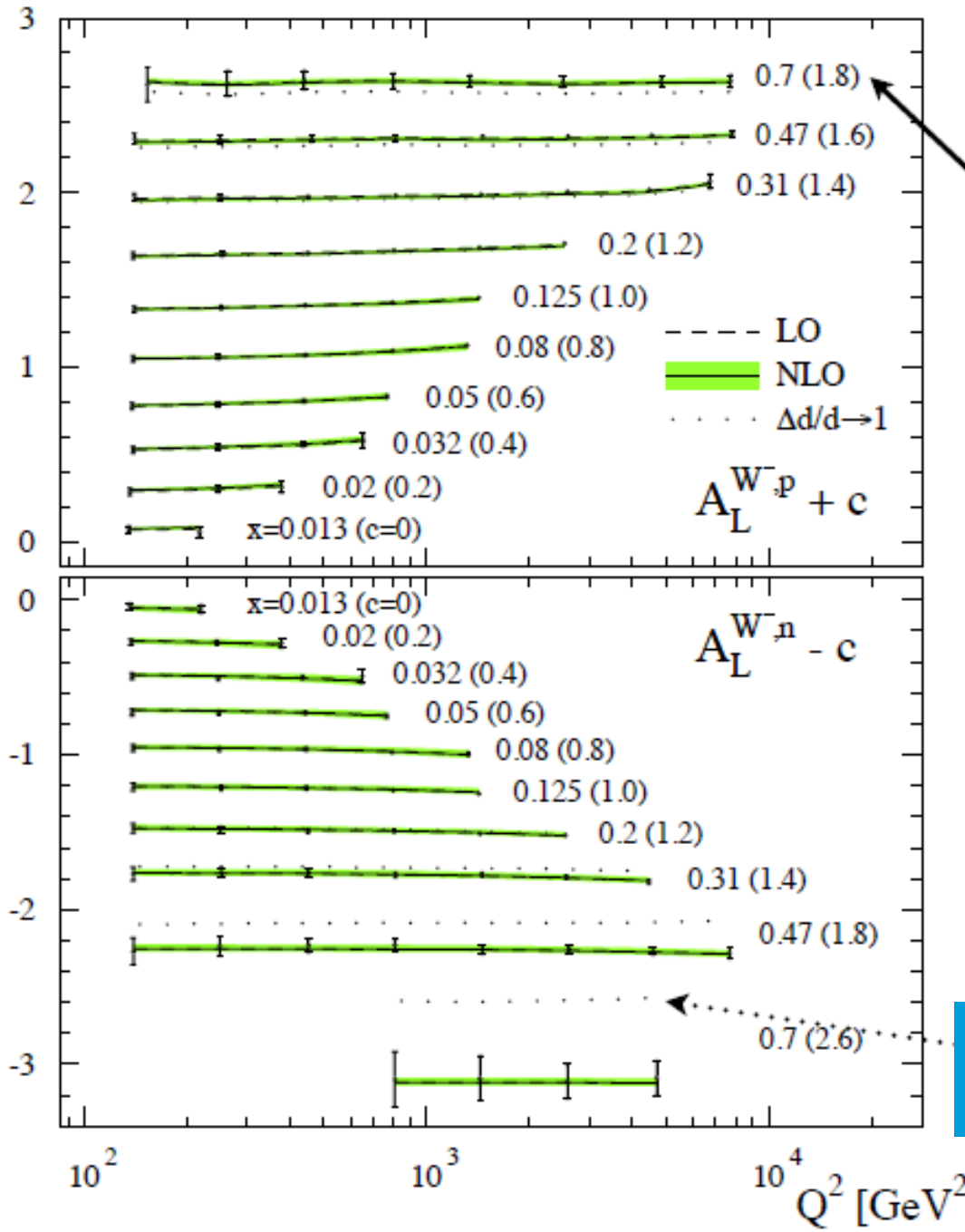
Aschenauer, Sassot, MS 1209.3240





only relative improvement
of uncertainties matters

A_L^W results

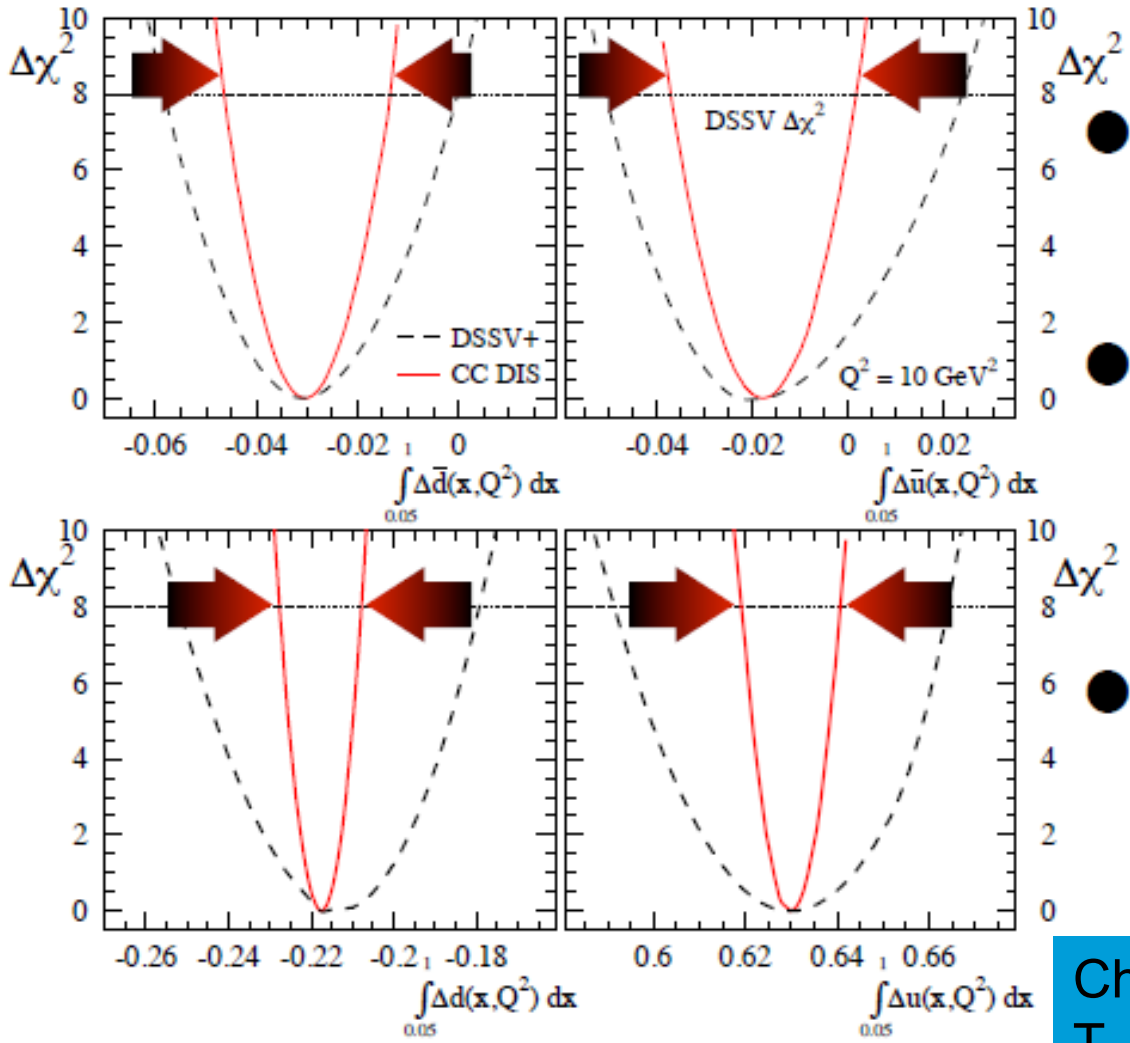


- Large A_L^W at large x ~80%
- NLO effects small
- $\sigma(A_L^W)/A_L^W$ small
  - <~5% for **p**
  - <~8% for **n**
  - ~25% at x limits

Charged current DIS at an EIC; T. Burton at DIS2014

helicity retention

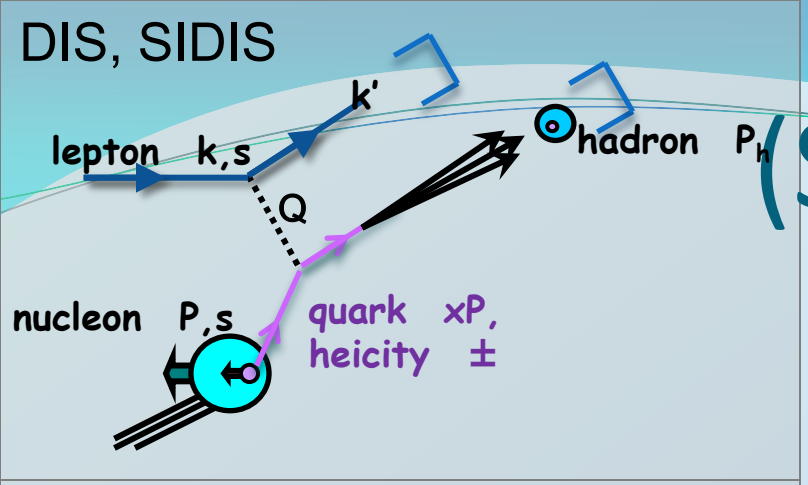
Impact on global analyses

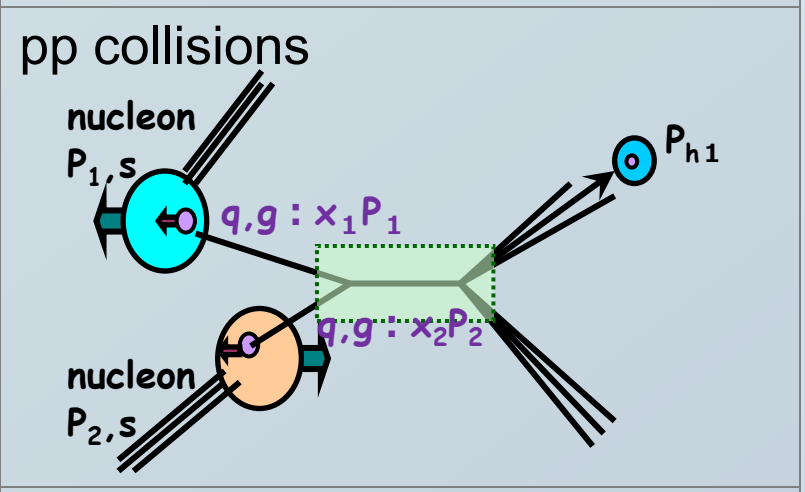


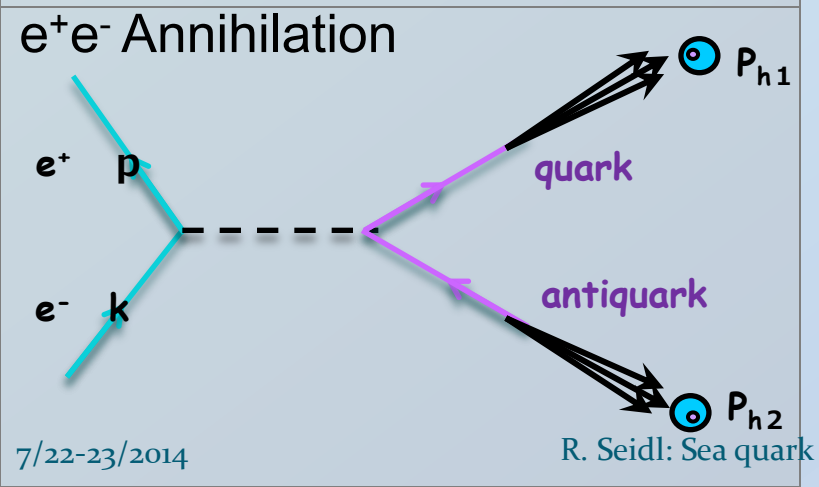
- Constrain **u**, **d** & **anti-q** helicities
- Flavour constraint independent of **fragmentation**
- Important cross check on **SIDIS**
  - low Q^2, higher

Charged current DIS at an EIC; T. Burton at DIS2014

(SI)DIS, e^+e^- and pp







	PDF 1	PDF 2	FF 1	FF 2
el. Charge	$q(x)$, $[g(x)]$	-	$D_{q,g}^h(z)$	-
Strong charge	$g(x_1)$, $q(x_1)$, $\bar{q}(x_1)$	$g(x_2)$, $q(x_2)$, $\bar{q}(x_2)$	$D_{q,g}^h(z)$	-
Weak charge V – A	$q_L(x_1)$, $q_R(x_1)$	$q_L(x_2)$, $q_R(x_2)$	-	-
el/weak charge	-	-	$D_{q,g}^h(z_1)$	$D_{q,g}^h(z_2)$

Summary

- DIS accesses charge square weighted sum of flavors, both unpolarized and polarized
- Hadrons allow you to tag certain flavors to some extend as long as unpol distribution and fragmentation functions are well enough known
- W (and Z,DY) production access certain flavor combinations without fragmentation
- Together a good understanding of the sea quark helicities becomes available at intermediate x
- Future: SIDIS at EIC to lower x