INT Seattle, February 6th, 2012

Global Analysis of Helicity PDFs

present status & future avenues

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outline

Anatomy of a
Global QCD Analysis

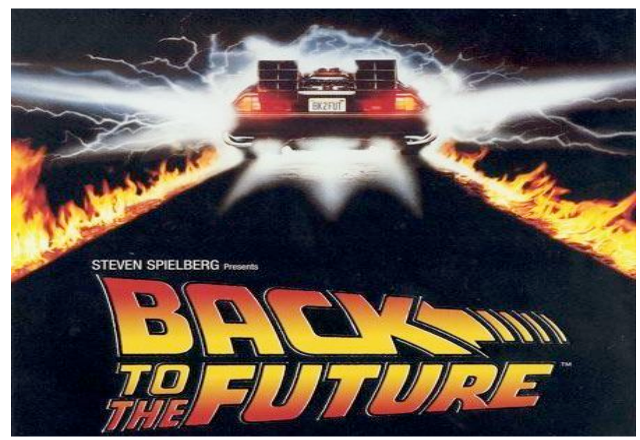
Brief Outline

Longitudinal Spin Structure

Current Status, Latest Developments, OAM

Interlude: Fragmentation

Quick Overview



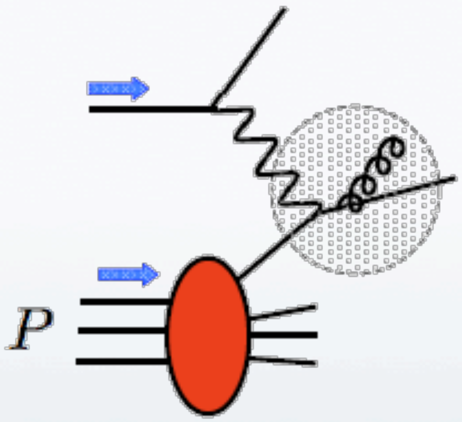
Future Avenues

RHIC & Opportunities At An EIC

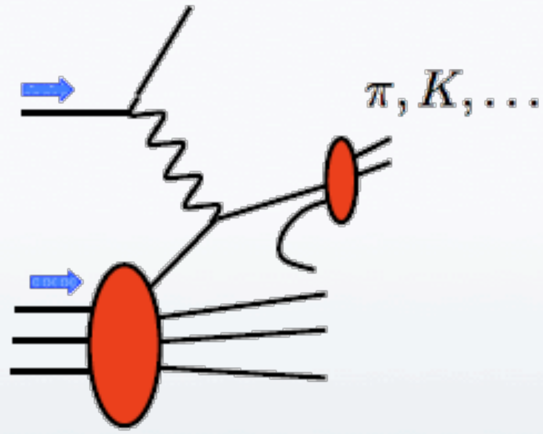
Anatomy of a Global QCD Analysis

how to determine PDFs (and FFs) from data?

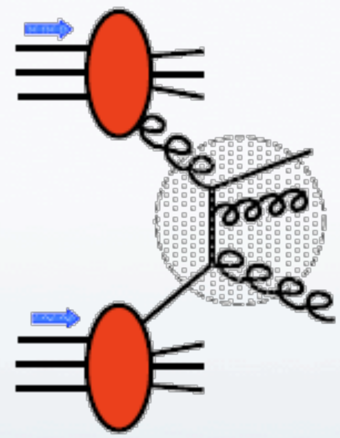
information on nucleon (spin) structure available from



DIS



SIDIS



hadron-hadron

task: extract reliable PDFs (or FFs) not just compare some curves to data

- all processes tied together: universality of pdfs & Q^2 - evolution
- each reaction provides insights into *different* aspects and kinematics
- need at least NLO for quantitative analyses; PDFs are not observables!
- information on PDFs "hidden" inside complicated (multi-)convolutions

a **"global QCD analysis"** is required

prerequisite: a reliable theoretical framework

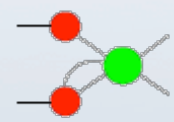
guiding principle: factorization

long-distance physics
μ-dep. predicted by pQCD

$$\frac{d\sigma^{pp\to\pi X}}{dp_T d\eta} = \sum_{abc} \int dx_a\, dx_b\, dz_c\, f_a(x_a, \mu_f)\, f_b(x_b, \mu_f)\, D_c^{\pi}(z_c, \mu'_f)$$
$$\times \frac{d\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu'_f, \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

short-distance physics
calculable in pQCD as series in α_s

power corrections
usually safely neglected

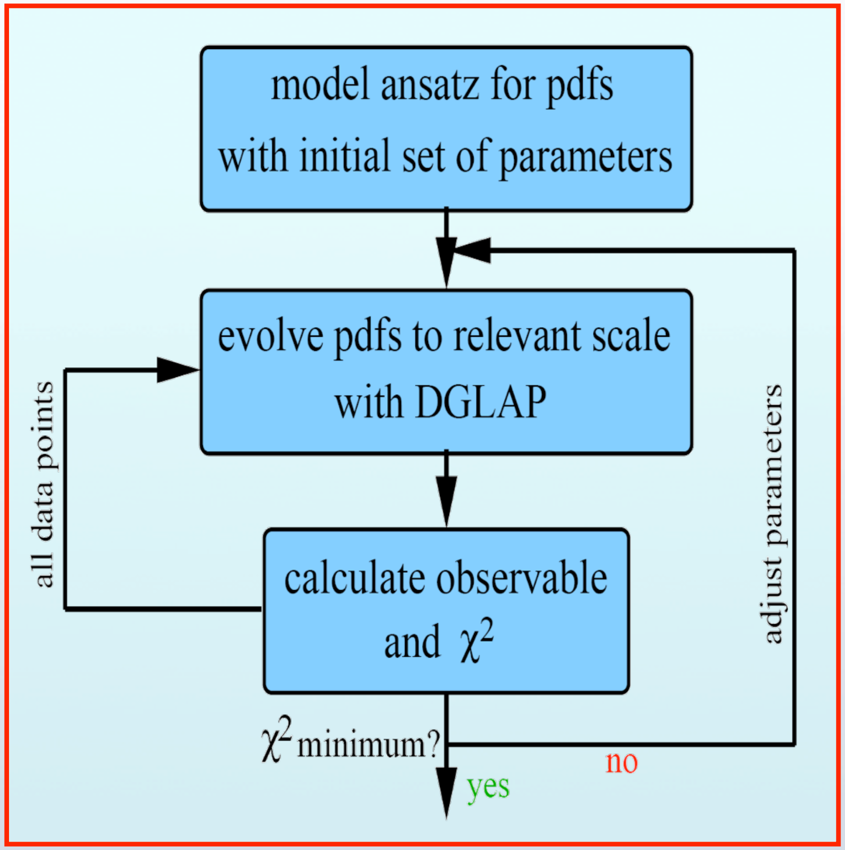


factorization …

- … separates physics happening at different time/distance scales
- … introduces unphysical scales $\mu_{f,r}$ (leads to powerful RGE like DGLAP)
- … requires presence of a hard scale (like Q in DIS or p_T in pp collisions)
- … is an approximation – corrections are power suppressed
- … leads to a successful quantitative description of many hard scattering proc's

outline of a global QCD analysis

start: choose fact. scheme ($\overline{MS}$,...) & pert. order (NLO, ...), select data sets, cuts, ...



flexible functional form to parametrize PDFs

$$f(x,\mu_0) = N x^\alpha (1-x)^\beta \left[1 + \kappa\sqrt{x} + \gamma x\right]$$

at some initial scale μ_0 (of order 1 GeV)

obtain PDFs at any $x, \mu > \mu_o$ relevant for comparing with data by solving evolution eqs.

compute DIS, pp, ... cross sections at NLO

judge goodness of current fit

$$\chi^2 = \sum_i \frac{(T_i - E_i)^2}{\delta E_i^2}$$

optimum set of parameters **$\{\alpha_i, \beta_i, ...\}$**

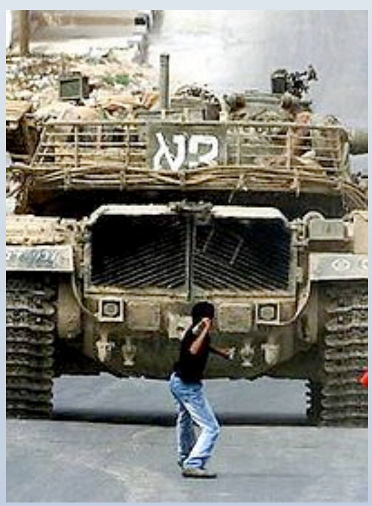
recent achievement: also **quantify PDF uncertainties** and properly propagate them to any observable of interest

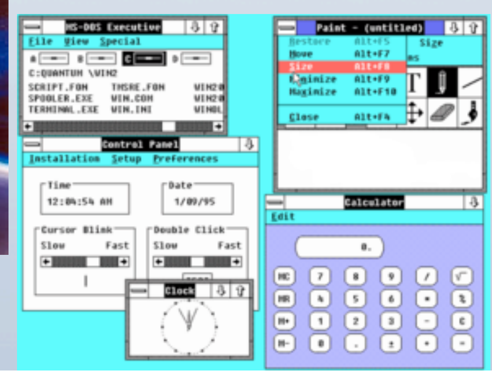
Helicity PDFs

(I) Basics & DSSV Global Analysis

things that shook the World in Dec. 1987

- Dec 1st: construction of Channel tunnel initiated
- Dec 1st: NASA awards contracts to build Space Station Freedom
- Dec 8th: first Intifada begins in Gaza strip
- Dec 8th: INF treaty signed in Washington, D.C.
- Dec 9th: Windows 2 released
- Dec 18th: Perl created by Larry Wall
- Dec 24th: Japanese band BOØWY declares breakup





… meanwhile in Physics

The total cross section for the production of heavy quarks in hadronic collisions

P. Nason and S. Dawson
Brookhaven National Laboratory
Upton, LI, New York 11973

R. K. Ellis
Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, Illinois 60510

December 23, 1987

Abstract

We present the results of a full calculation of the QCD $O(\alpha_s^3)$ radiative corrections to the total cross section for the production of a heavy quark pair. We find large contributions for parton sub-energies near threshold and well above threshold. The implications for the production of top and bottom quarks at collider energies are discussed.

NPB303 (1988) 607
1218 citations

on the very same day …

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-230
December 23rd, 1987

A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON-PROTON SCATTERING

The European Muon Collaboration

ABSTRACT

The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large x range (.01 < x < 0.7). The spin dependent structure function $g_1(x)$ for the proton has been determined and its integral over x found to be 0.114 ± 0.012 ± 0.026, in disagreement with the Ellis-Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of g_1 for the neutron. These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

PLB206 (1988) 364 1533 citations

tremendous exp. efforts in the past 25+ years

SLAC

E142, E143,
E154, E155

CERN

EMC, SMC,
COMPASS

DESY

HERMES

JLab

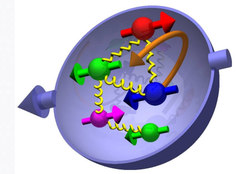
Hall A, CLAS

BNL

PHENIX, STAR

pp collisions at
200 & 500 GeV

helicity PDFs and proton spin sum

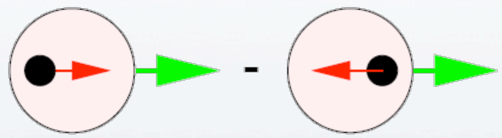


need a reliable extraction of helicity PDFs from data

momentum fraction

$$\Delta f(x) \equiv f_{+}^{N_+}(x) - f_{-}^{N_+}(x)$$

helicity parton densities



x-moment $\int_0^1 dx$ → **total spin polarizations S_q and S_g**

DGLAP scale evolution "only" known up to NLO yet **Mertig, van Neerven; Vogelsang**

but NNLO emerging **Moch, Rogal, Vermaseren, Vogt**

issue: limited x-range of data → extrapolation to x→0 and 1, how reliable?

helicity sum rule (A^+=0 gauge "incarnation") **Jaffe, Manohar; Ji; …**

$$\frac{1}{2}\hbar = \langle P,\frac{1}{2}|J^z_{\rm QCD}|P,\frac{1}{2}\rangle = \sum_q \frac{1}{2}S^z_q + S^z_g + \sum_q L^z_q + L^z_g$$

total u+d+s quark spin | gluon spin | orbital angular momentum

other decompositions / OAM to be discussed during the workshop

"quotable" properties of the nucleon

helicity parton densities

defined as matrix elements of *bi-local operators* on the light-cone, e.g.:

Collins, Soper; ...

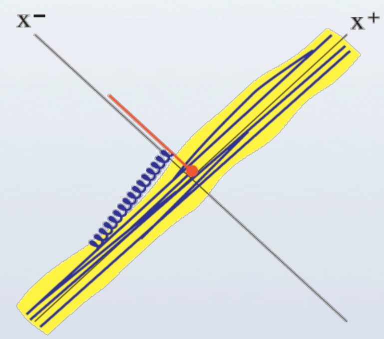
$$\Delta q(x) = \frac{1}{4\pi}\int dy^- e^{iy^- xP^+} \langle P,S|\overline{\Psi}_q(0,y^-,\vec{0})\gamma^+\gamma_5\,\mathcal{F}\,\Psi_q(0)|P,S\rangle$$

Fourier transform such that quark carries x P^+

recreates quark at $x^+=0$ and $x^-=y^-$

annihilates quark at $x^\mu=0$

we need a "**gauge link**" for a gauge invariant definition:



$$\mathcal{F} = \mathcal{P}\exp\left(-ig\int_0^{y^-} dz^- A_a^+(0,z^-,\vec{0})T_a\right)$$

("irrelevant" here, but plays a major role for transverse polarization)

$$\Delta g(x) = \frac{1}{4\pi x P^+}\int dy^- e^{iy^- xP^+} \langle P,S|F_a^{+j}(0,y^-,\vec{0})\mathcal{F}\tilde{F}_{+j}(0)|P,S\rangle$$

complicates connection with S_g

(local operator only in $A^+=0$ gauge)

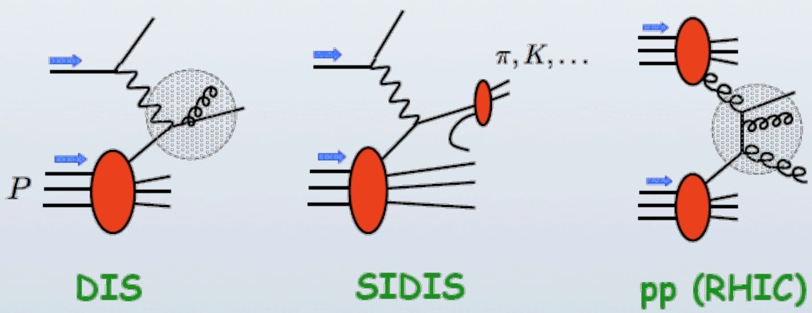
DSSV analysis – overview

DSSV: de Florian, Sassot, MS, Vogelsang; PRL101 (2008) 072001; PRD80 (2009) 034030

- **1st global QCD analysis of polarized PDFs**; consistently performed at NLO
- flexible functional form $x\Delta f_j(x, 1\,\mathrm{GeV}) = N_j\, x^{\alpha_j}\,(1-x)^{\beta_j}\left[1+\kappa_j\sqrt{x}+\gamma_j x\right]$ (possible nodes)

  assumptions on parameter space avoided as much as possible

  fit respects, however, constraints on 1st moments
  $$\Delta u_{\mathrm{tot}} - \Delta d_{\mathrm{tot}} = (F+D)[1+\varepsilon_{\mathrm{SU(2)}}]$$
  $$\Delta u_{\mathrm{tot}} + \Delta d_{\mathrm{tot}} - 2\Delta s_{\mathrm{tot}} = (3F-D)[1+\varepsilon_{\mathrm{SU(3)}}]$$
  small
- excellent description of world data



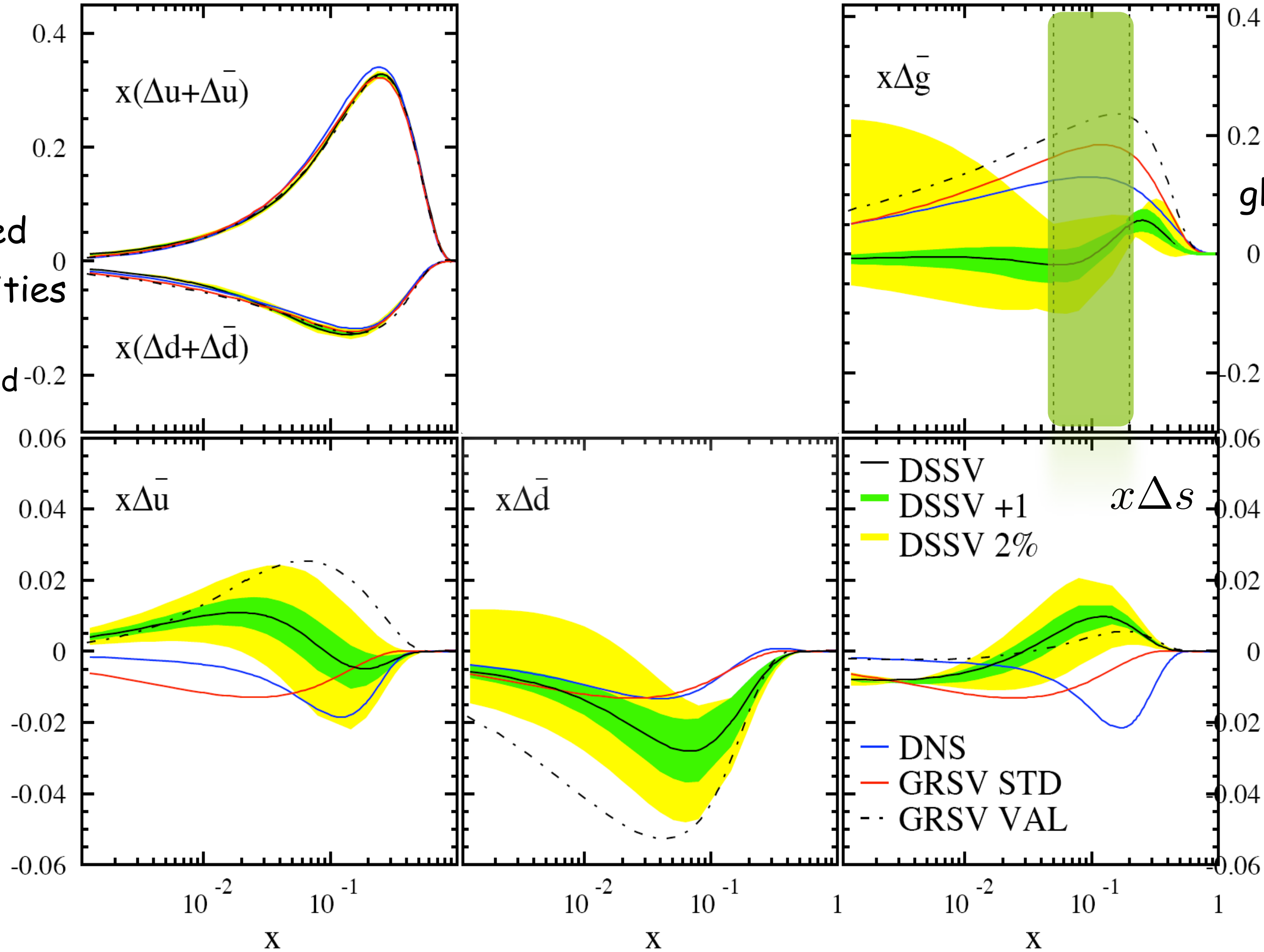
(χ^2 / d.o.f. $\simeq 0.88$)

- estimates of PDF uncertainties with Lagrange multipliers & Hessian method
- other recent fits: LSS (Leader, Sidorov, Stamenov); BB (Blumlein, Bottcher); NNPDF (Neural Network PDF Collaboration, R.D. Ball et al.)

results will be shown along the way

emerging picture from DSSV analysis in 2008/09

well constrained
total quark densities
x -> 1 behavior
to be determined



gluon small (node?)
in x-region
constrained by
RHIC data

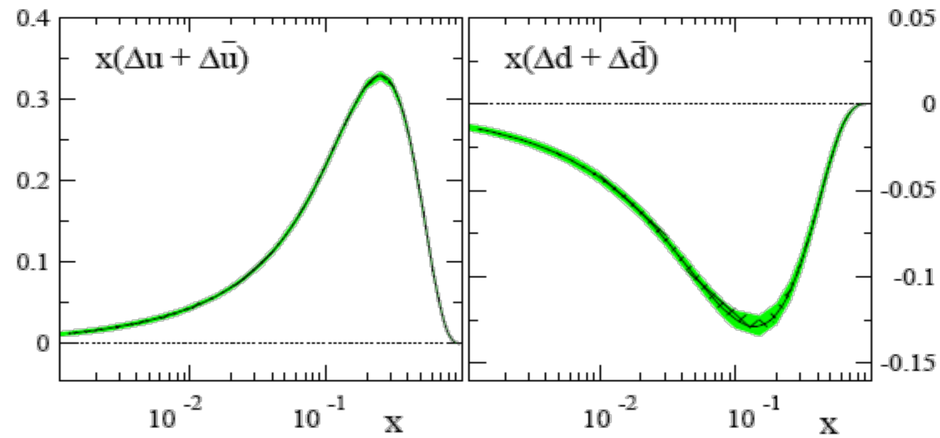
indications for non-trivial sea quark polarizations $\Delta\bar{u} > 0$ $\Delta\bar{d} < 0$

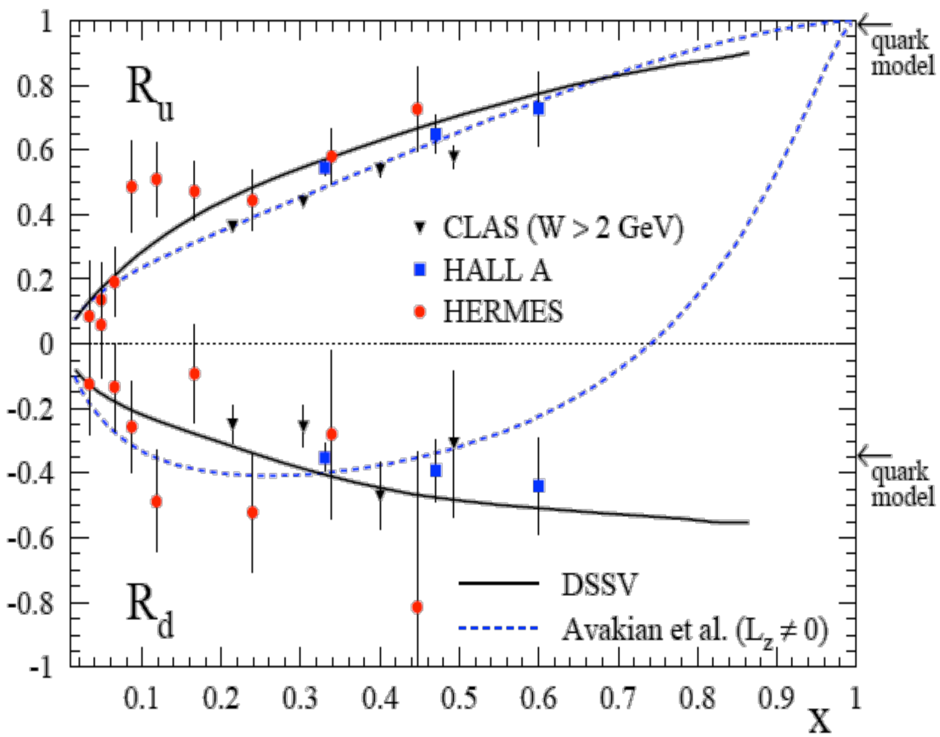
surprising strangeness polarization
sizable SU(3) breaking?
requires reliable kaon fragmentation fcts.

lattice: Bali et al., 0811.0807; 0911.2407; 1011.2194

a closer look: valence quark PDFs

- **determined best**
  - uncertainty bands very narrow
  - agrees well with previous "DIS-only" fits
    GRSV, BB, LSS, AAC, DNS, …





- **large-x frontier** (→ JLab 12 GeV)

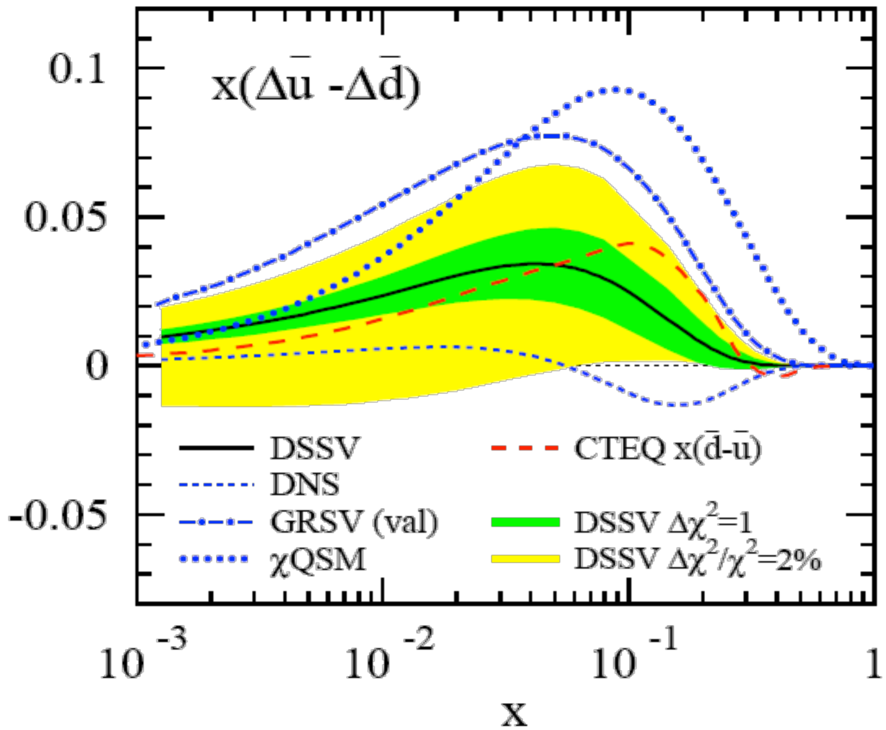
$$R_q(x) \equiv \frac{\Delta q(x) + \Delta \bar{q}(x)}{q(x) + \bar{q}(x)}$$

- R_u (x→ 1) → 1 as expected
- R_d (x→ 1) remains negative
- counting rules + helicity retention + nonzero OAM: expect R_d (x→ 1) → 1
  Avakian, Brodsky, Deur, Yuan

Q: what happens as x → 1 ?

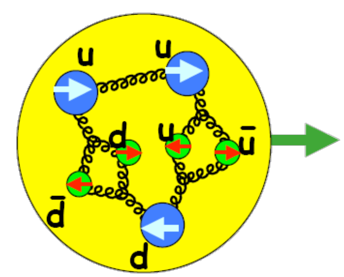
1^{st} hints at non-trivial sea polarizations

- indications for an SU(2) breaking of light polarized u,d sea



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

- similar size than in unpol. case
- driven by SIDIS $h^{\pm}$, $\pi^{\pm}$ data
- still large uncertainties



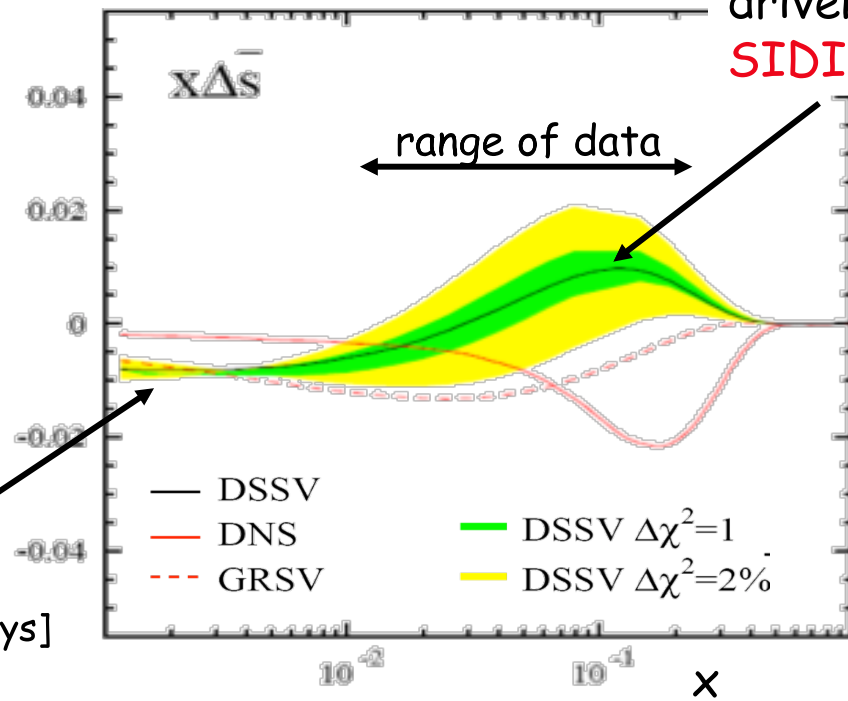
- many models give comparable results

large-N_C, chiral quark models, meson cloud, Pauli blocking, …

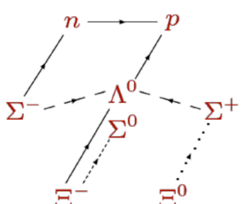
Thomas, Signal, Cao; Holtmann, Speth, Fassler; Diakonov, Polyakov, Weiss; Schafer, Fries; Kumano; Wakamatsu; Gluck, Reya; Bourrely, Soffer, …

strangeness conundrum

- $\Delta s(x)$ always thought to be negative from DIS data, but …



driven by
SIDIS $K^{\pm}$



driven by
SU(3) constraint
on $\int_0^1 \Delta s(x)\, dx$

[F,D values from hyperon decays]

striking result, but relies on

- kaon fragmentation – **Q: how reliable ?**
  more data available soon (BELLE, COMPASS, HERMES)
- unpolarized PDFs – **Q: how well do we know s(x) ?**
  HERMES result for s(x) does not agree well with CTEQ
- SU(3) breaking uncertainties – **Q: sizable ?**

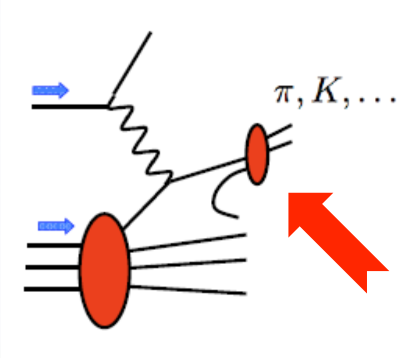
Lipkin; Zhu, Puglia, Ramsey-Musolf; Savage, Walden; …

needs further studies exp. & theory !

aside: Δs also small in lattice computations
Bali, Collins, …

Interlude: Fragmentation

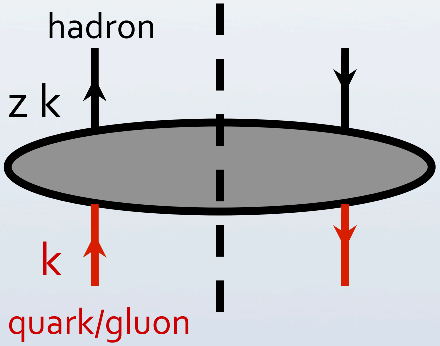
fragmentation functions: overview



crucial for pQCD interpretation (factorization)
of all data with detected (identified) hadrons, e.g.,
SIDIS (HERMES, COMPASS), pp -> πX (PHENIX, ALICE, ...)

observation: all FFs based only on e^+e^- (LEP) data do a bad job here

some properties of $D_i^h(z,\mu)$ [very similar to PDFs]:



- non-perturbative but universal; pQCD predicts μ-dep.
- describe the *collinear* transition of a parton "i" into a massless hadron "h" carrying fractional momentum z
- bi-local operator: $D(z) \simeq \int dy^- e^{iP^+/zy^-} \mathrm{Tr}\gamma^+ \langle 0|\, \psi(y^-) |hX\rangle \langle hX| \overline{\psi}(0)\, |0\rangle$

  Collins, Soper '81, '83

no inclusive final-state
no local OPE --> no lattice formulation

also: power corrections are much less developed and entwined with mass effects unlike for pdfs

DSS analysis: overview

D. de Florian, R. Sassot, MS
PRD 75 (2007) 114010
76 (2007) 074033

goal: provide NLO (LO) sets for pions, kaons, protons, charged hadrons from a **global fit** to e^+e^-, ep, and pp data on 1-hadron production

- requires a flexible functional form

$$D_i^h(z, 1\,\mathrm{GeV}) = N_i z^{\alpha_i}(1-z)^{\beta_i}\left[1+\gamma_i(1-z)^{\delta_i}\right]$$

- try to avoid assumptions on paramater space if possible

SU(2), SU(3) breaking: $D_{d+\bar{d}}^{\pi^+} = N D_{u+\bar{u}}^{\pi^+}$ $\quad D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = N' D_{\bar{u}}^{\pi^+}$

only normalization shifts can be fitted

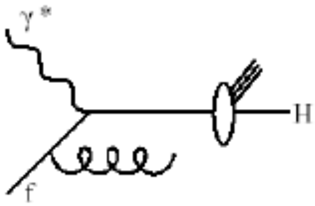
but data do not discriminate between other unfavored FFs:

$$D_{\bar{u}}^{\pi^+} = D_d^{\pi^+}$$

$$D_{\bar{u}}^{K^+} = D_s^{K^+} = D_d^{K^+} = D_{\bar{d}}^{K^+}$$

- like in PDF fits we allow for
  - relative normalizations/shifts of data sets
  - cuts: z > 0.05 pions, z > 0.1 otherwise
  - extra "TH errors": scale uncertainty (pp); flavor tag; bin size, …

good description of SIDIS multiplicities



HERMES data (not yet final)
A. Hillenbrand (thesis)

π^+

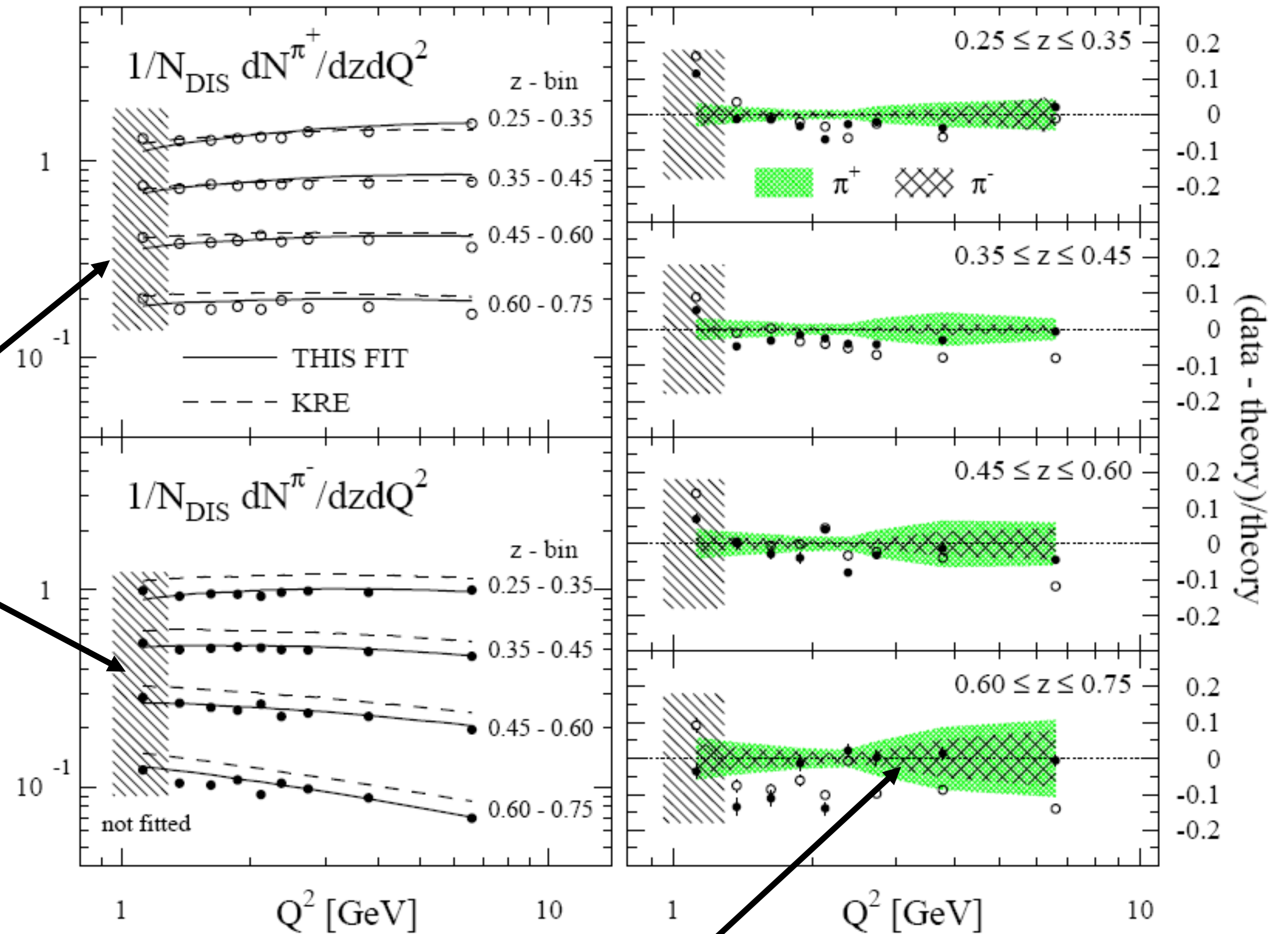
π^-

Kretzer's assumption

$D_d^{\pi^+} \simeq (1-z) D_u^{\pi^+}$

works for π^+

but not for π^-



x,Q^2 range can be significantly extended at a future EIC

shaded bands: our estimate of "Q^2-binning effects"

other recent fits of NLO FFs

table from arXiv:0804.2021 (ECT* FF workshop)

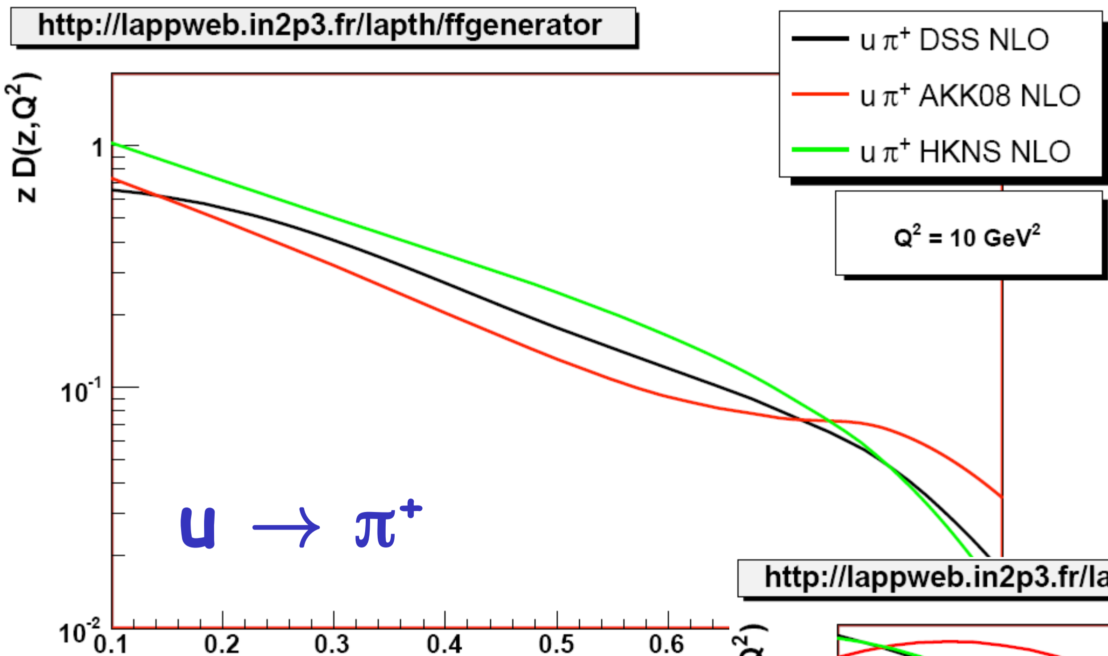
Name	Ref.	Species	Error	z_{min}	Q^2 (GeV^2)
AKK	[4]	$\pi^{\pm}, K^{\pm}, K_s^0, p, \bar{p}\,\Lambda, \bar{\Lambda}$	no	0.1	$2-4\cdot10^4$
AKK08	[5]	$\pi^{\pm}, K^{\pm}, K_s^0, p, \bar{p}\,\Lambda, \bar{\Lambda}$	yes	0.05	$2-4\cdot10^4$
BKK	[6]	$\pi^+ + \pi^-, \pi^0, K^+ + K^-, K^0 + \bar{K}^0, h^+ + h^-$	no	0.05	$2-200$
BFG	[7]	γ	no	10^{-3}	$2-1.2\cdot10^4$
BFGW	[8]	$h^{\pm}$	yes[1]	10^{-3}	$2-1.2\cdot10^4$
CGRW	[9]	π^0	no	10^{-3}	$2-1.2\cdot10^4$
DSS	[10, 11]	$\pi^{\pm}, K^{\pm}, p, \bar{p}, h^{\pm}$	yes[2]	0.05-0.1	$1-10^5$
DSV	[12]	polarized and unpolarized Λ	no	0.05	$1-10^4$
GRV	[13]	γ	no	0.05	≥ 1
HKNS	[14]	$\pi^{\pm}, \pi^0, K^{\pm}, K^0 + \bar{K}^0, n, p + \bar{p}$	yes	$0.01-1$	$1-10^8$
KKP	[15]	$\pi^+ + \pi^-, \pi^0, K^+ + K^-, K^0 + \bar{K}^0, p + \bar{p}, n + \bar{n}, h^+ + h^-$	no	0.1	$1-10^4$
Kretzer	[16]	$\pi^{\pm}, K^{\pm}, h^+ + h^-$	no	0.01	$0.8-10^6$

AKK08: Albino, Kniehl, Kramer || HKNS: Hirai, Kumano, Nagai, Sudoh

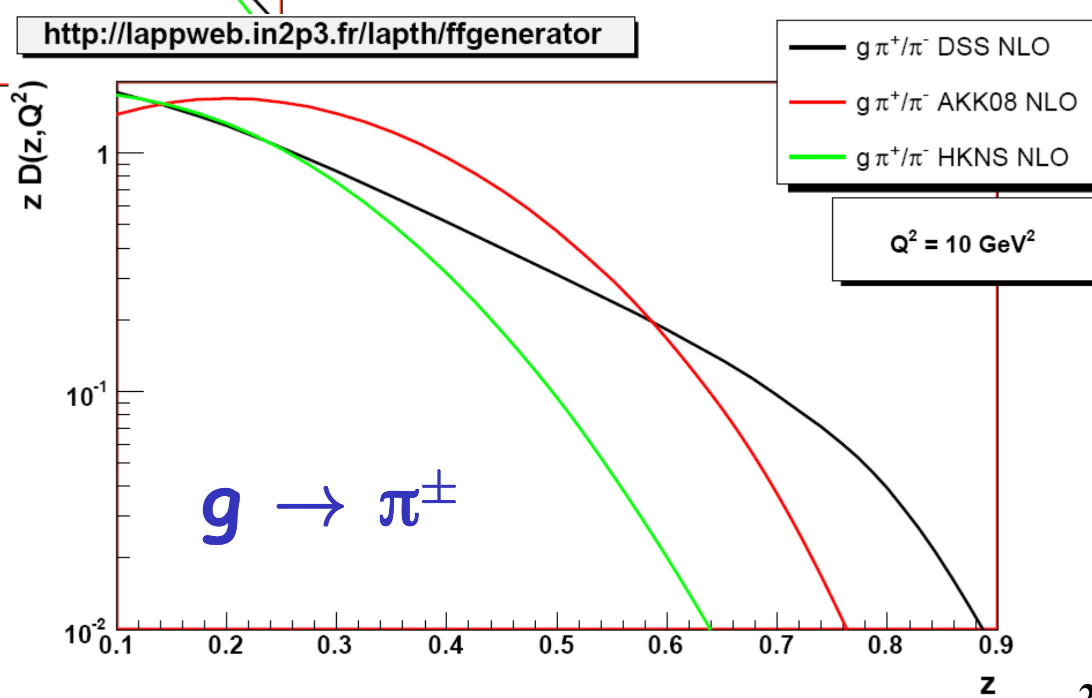
AKK08:
- e^+e^- & pp data
- impose isospin sym. for pions
- Hessian method for uncertainties
- fit hadron masses
- large-z resummations
- mass corrections (ad hoc for pp)

HKNS:
- e^+e^- data only
- impose isospin sym. for pions
- Hessian method for uncertainties

comparison of pion FFs



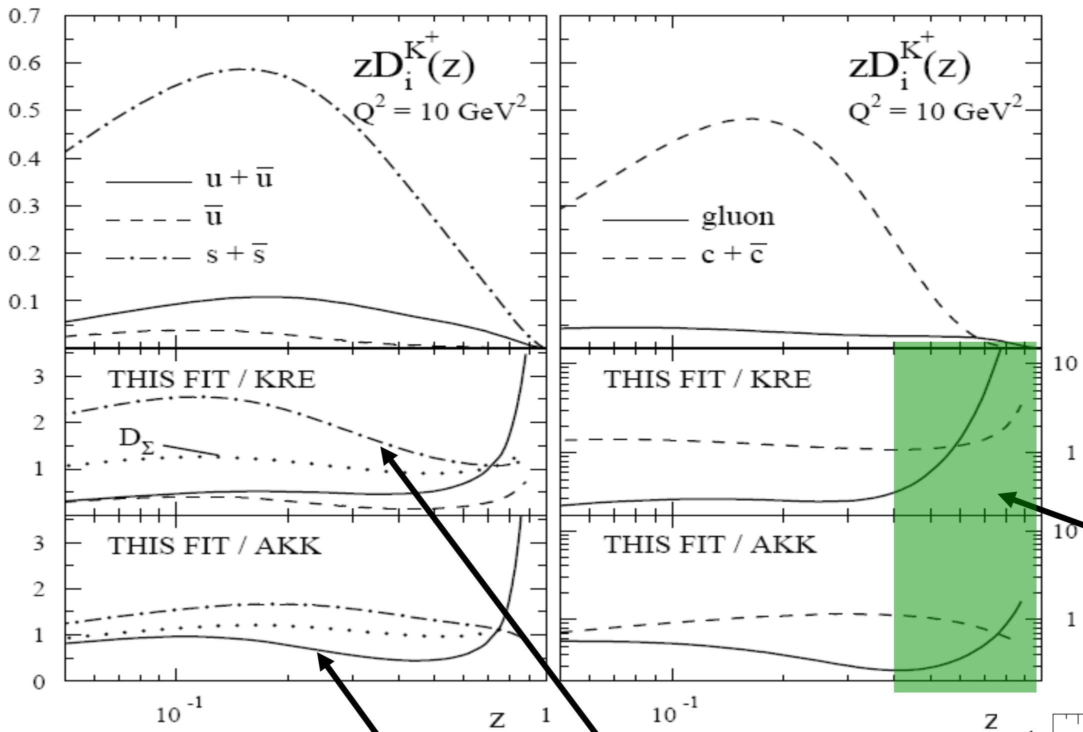
making use of nice
online-plotting tool
for fragmentation fcts
F. Arleo, J.Ph. Guillet, M. Werlen

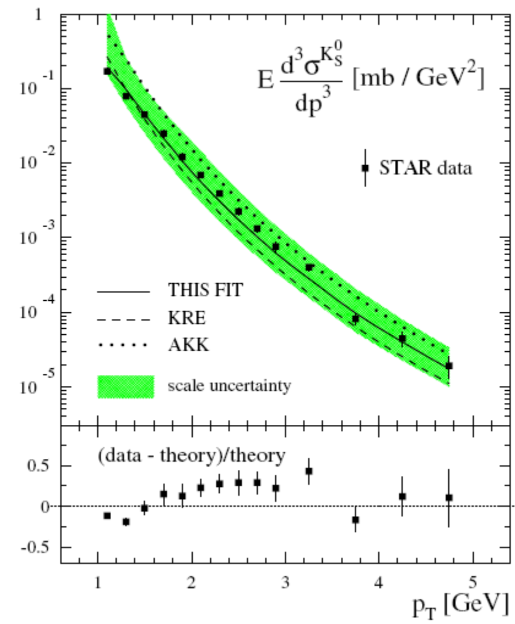


faithful measure of uncertainties of FFs ?

recall: DSS, AKK08, HKNS
are based on different data sets
and assumptions

meet the $D_i(z)$'s for kaons

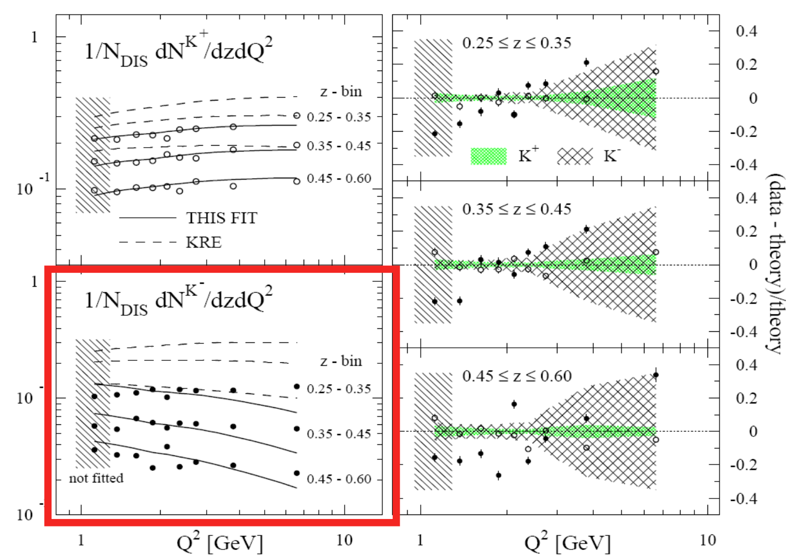




RHIC pp data
explain different D_g

smaller u & larger s-frag.
required by SIDIS data

impact on PDF fits: Δs



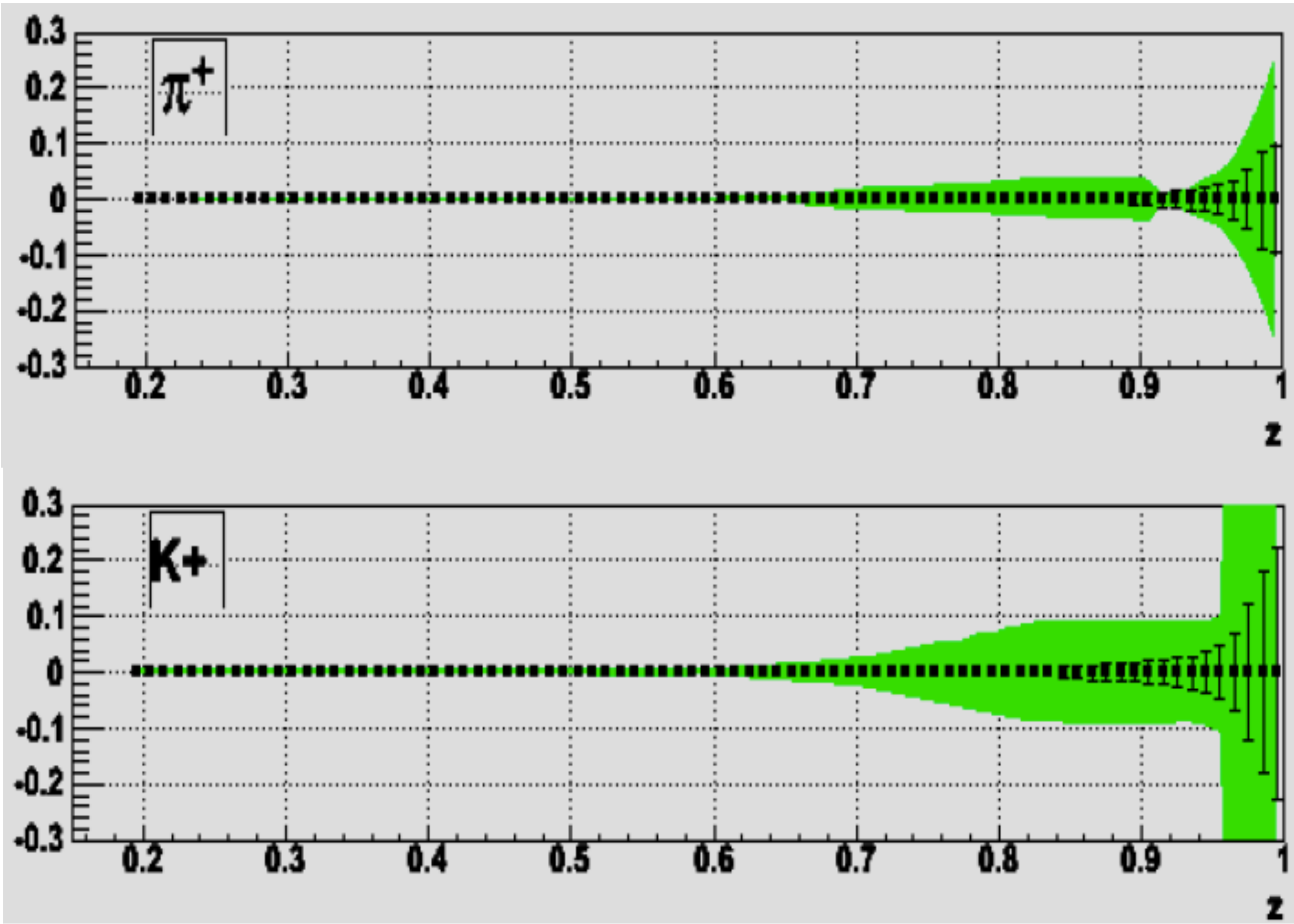
note: some issues with K^- data (slope!)

final HERMES multiplicities will
be used in upcoming DSS 2.0

upcoming precision e^+e^- data from B factories

BELLE: projected relative stat. and sys. uncertainties

M. Leitgab @ DIS 2010



$$e^+e^- \to HX$$

$$Q^2 \simeq 100\,\mathrm{GeV}$$

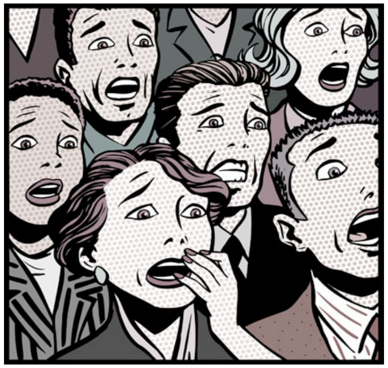
- data will allow for precision studies of scaling violations -> D_g
- unique access to FFs at large z

also part of upcoming DSS 2.0 update
(plus new RHIC & LHC results)

Helicity PDFs

(II) Some Recent Developments

meanwhile, new data became available ...



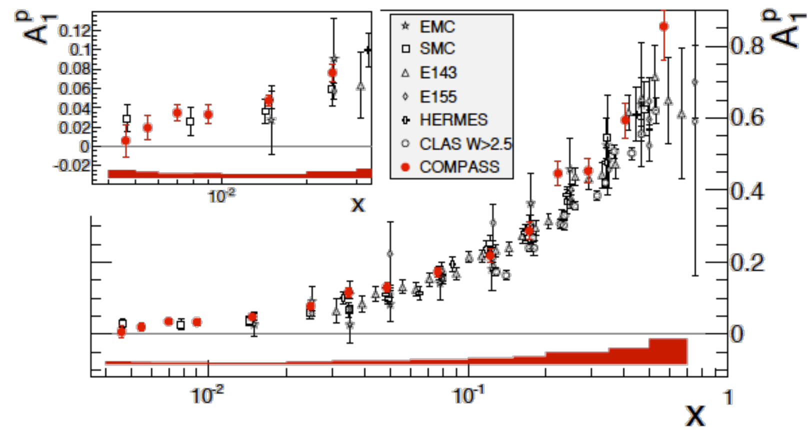
- how well are we doing ?
- refit/new analysis necessary ?
- impact on uncertainties ?

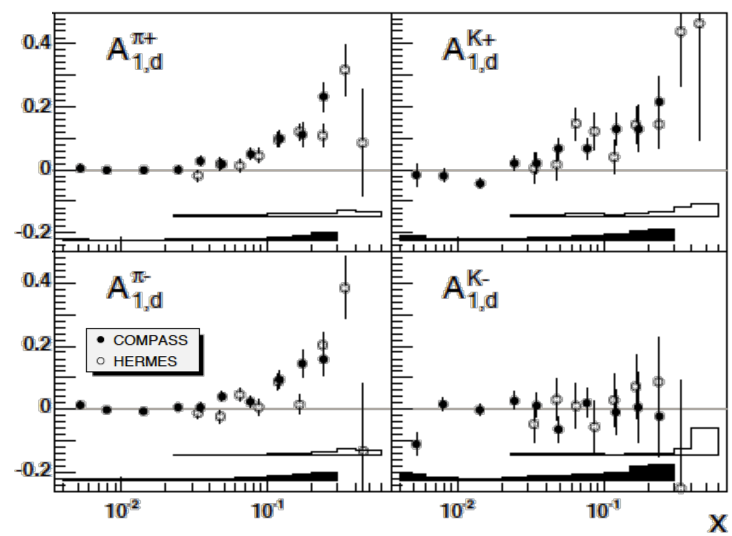
- **DIS:** A_1^p from COMPASS
  arXiv:1001.4654

- **SIDIS:** $A_{1,d}^{\pi,K}$ from COMPASS
  arXiv:0905.2828

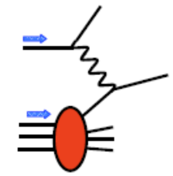
- **SIDIS:** $A_{1,p}^{\pi,K}$ from COMPASS
  arXiv:1007.4061

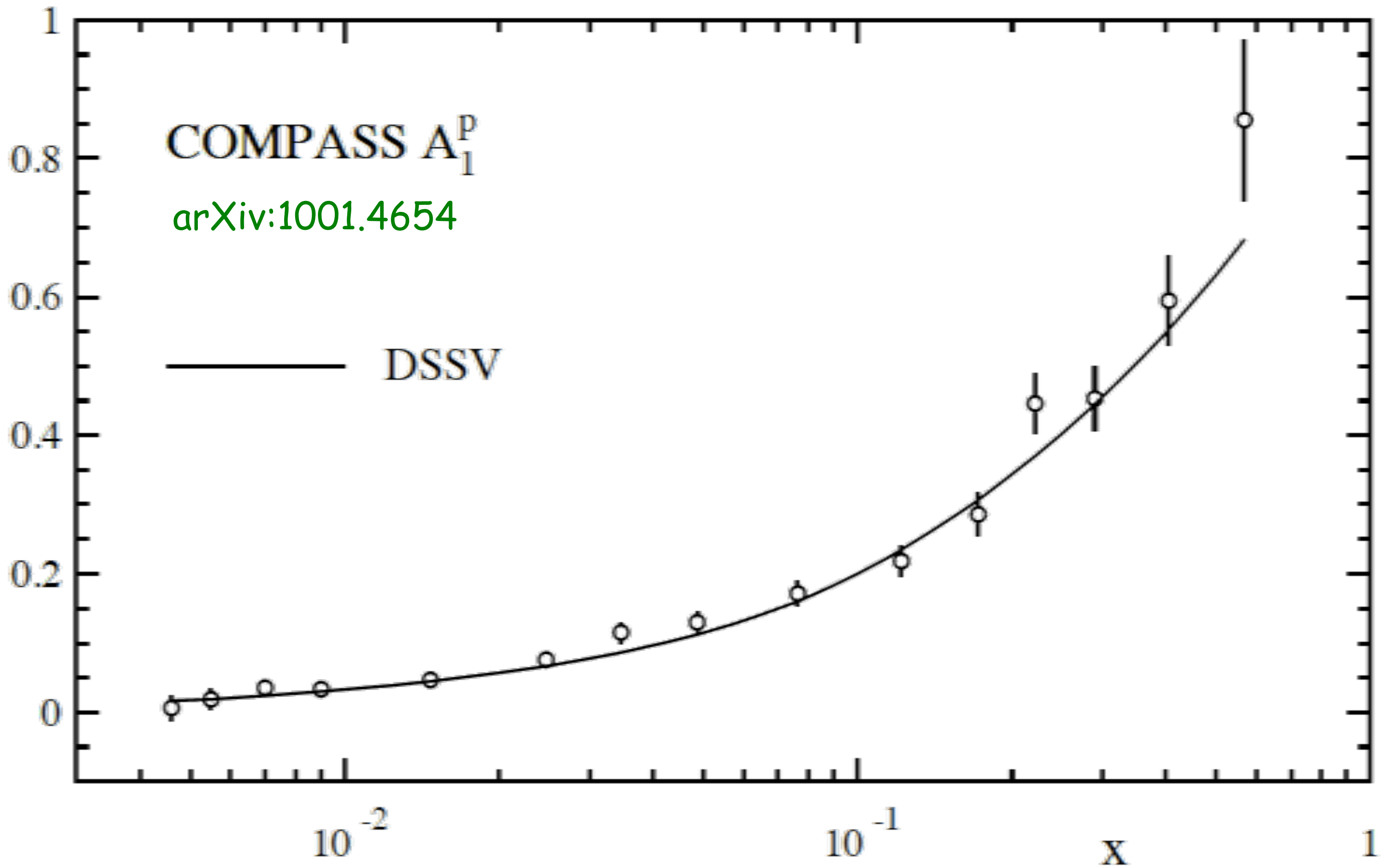
extended x coverage w.r.t. HERMES





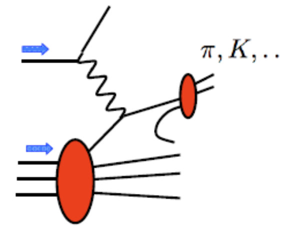
coping with new data: DIS A_1^p

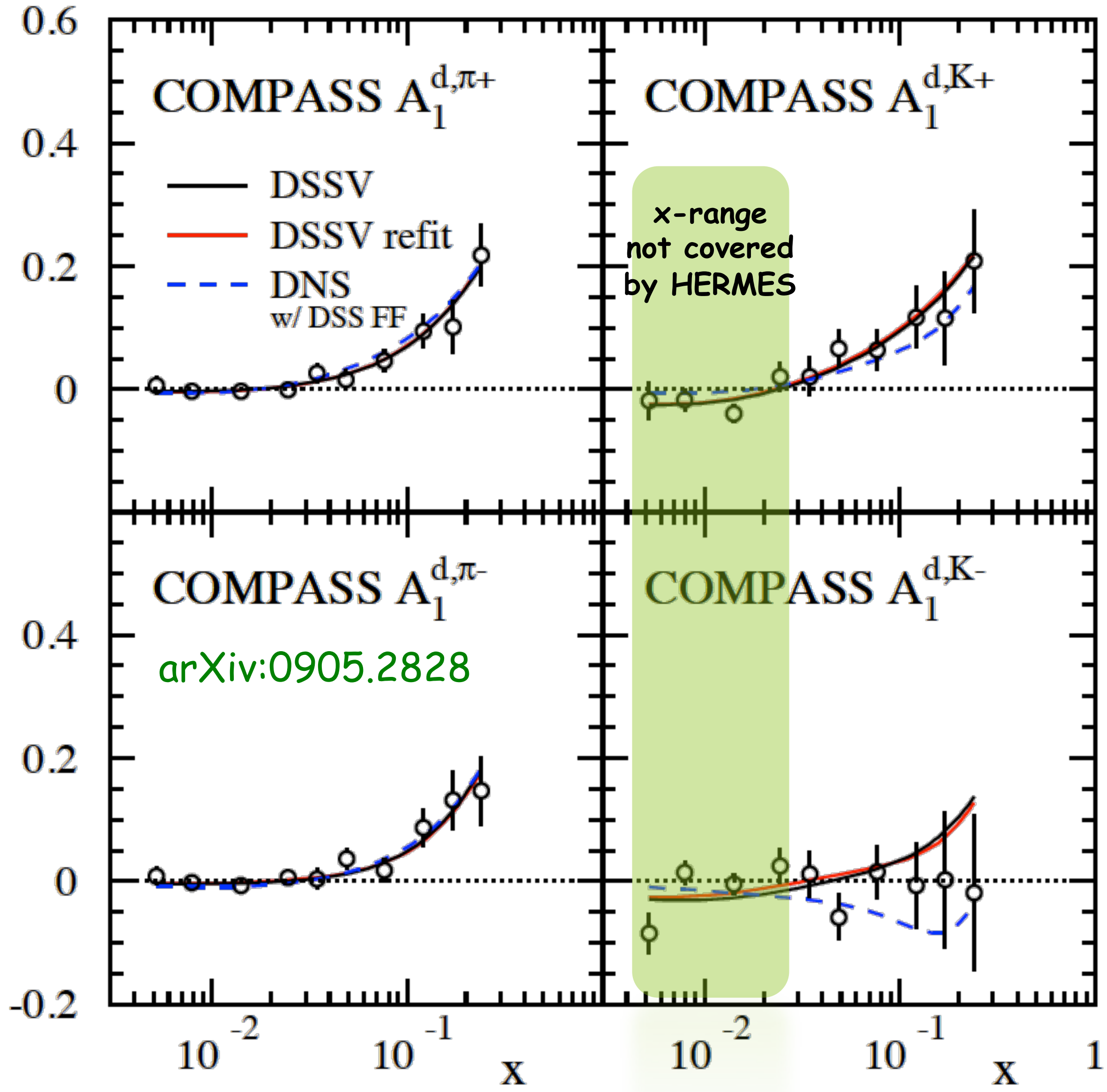




✓ DSSV does a very good job: 15 points, χ^2 = **14.2**

coping with new data: SIDIS $A_1^{d,\pi,K}$





✓ DSSV works well:

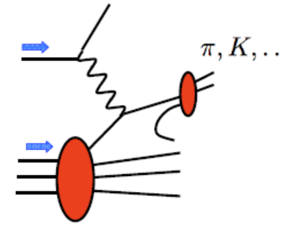
no surprises at small x

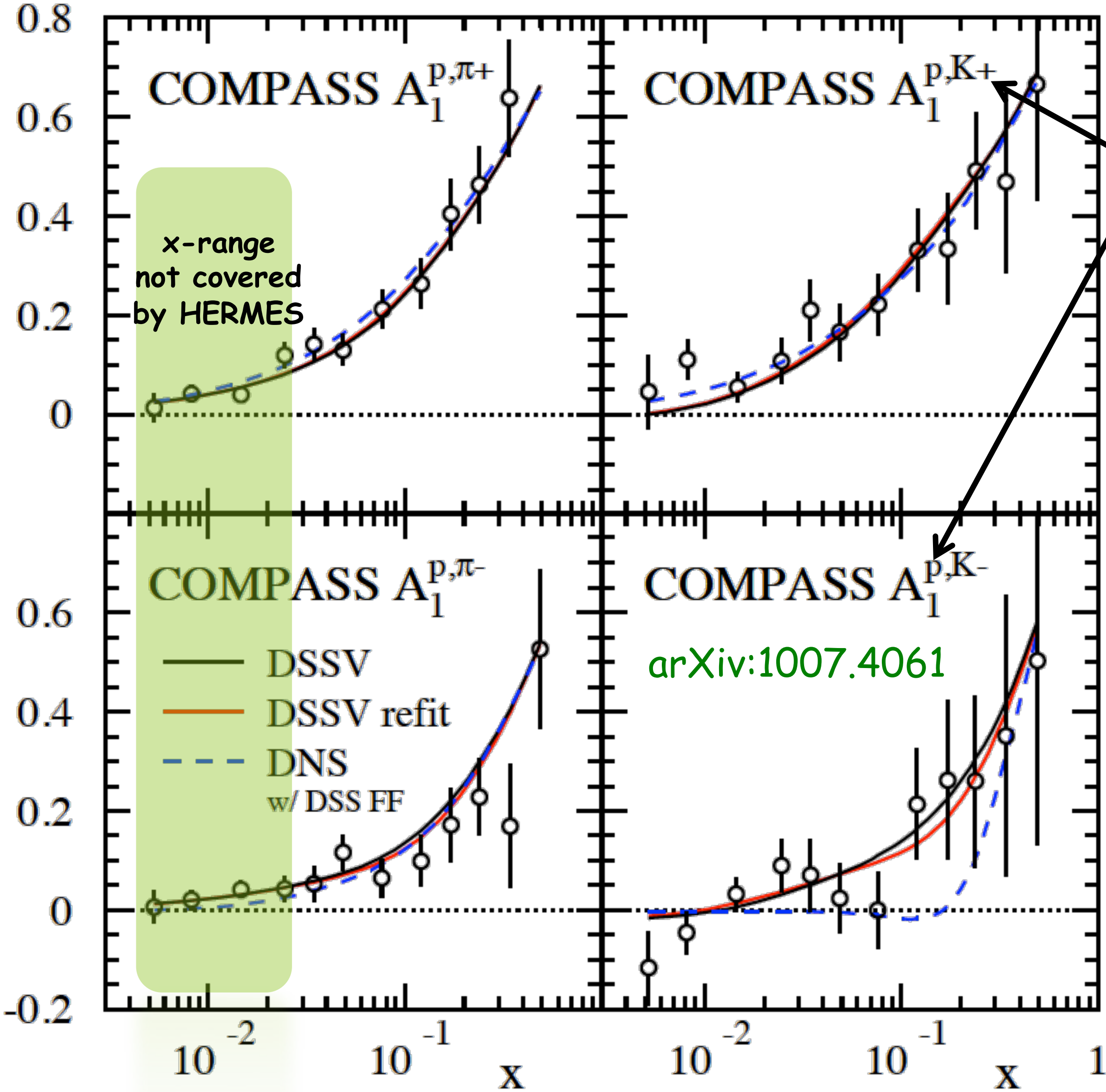
χ^2 numerology♮:

	DSSV 08 data sets	with $A_1^{d,\pi,K}$
DSSV 08	392.5	420.8
DSSV+		418.9

♮ the branch of knowledge that deals with the occult significance of numbers

coping with new data: SIDIS $A_1^{p,\pi,K}$





1st kaon data on p-target
(not available from HERMES)

χ^2 numerology:

	DSSV 08 data sets	with $A_1^{p\&d,\pi,K}$
DSSV 08	392.5	456.4
DSSV+		453.0

✓ **no refit required**

($\Delta\chi^2=1$ does not reflect faithful PDF uncertainties)

- trend for somewhat less polarization of sea quarks; $\Delta\bar{u}-\Delta\bar{d}\neq 0$ less significant

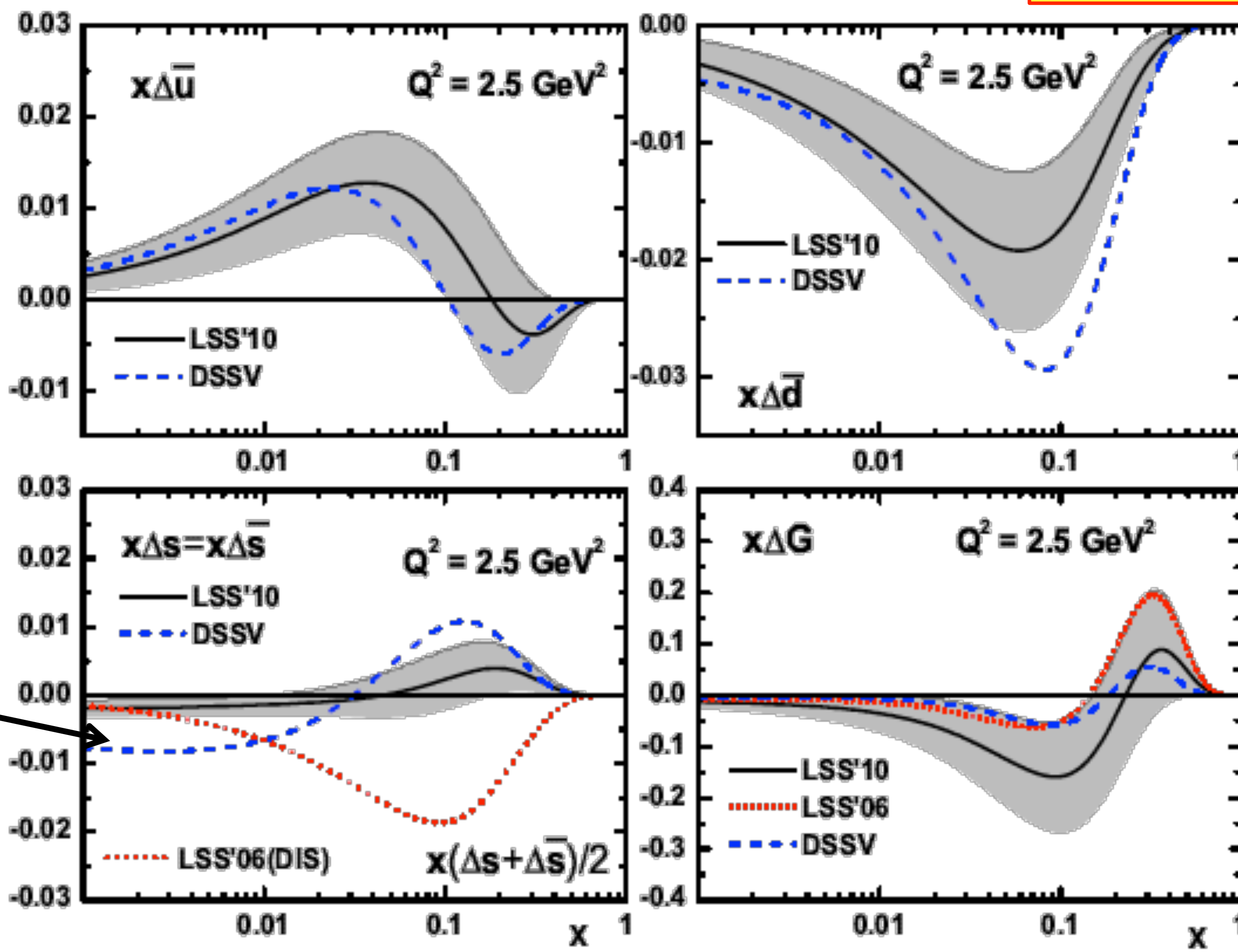
LSS Leader, Sidorov, Stamenov analysis

arXiv:1010:0574

fit uses latest DIS and SIDIS data (except COMPASS $A_1^{p,\pi,K}$)

functional form: $\Delta f(x) = N x^{\alpha}(1-x)^{\beta}(1+\delta\sqrt{x}+\gamma x)$

outcome very similar to DSSV analysis within uncertainties



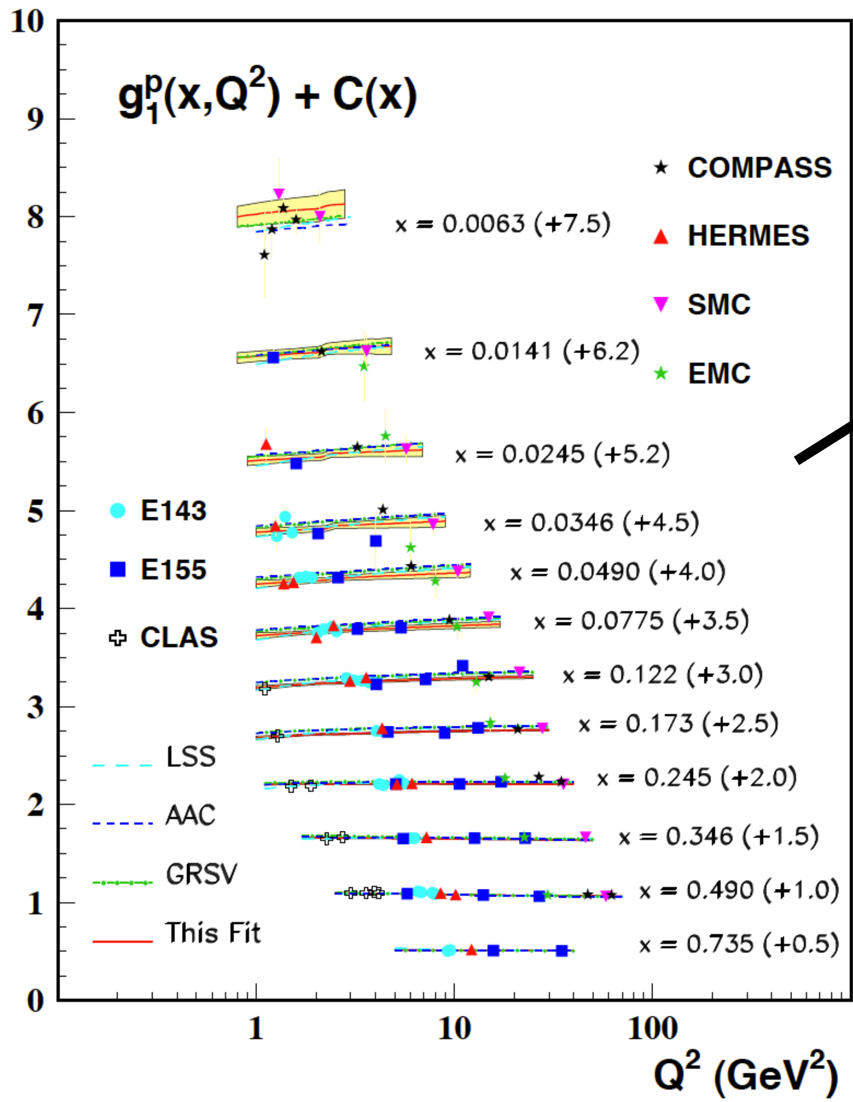
recall:
DSSV fit has no COMPASS kaon data

BB Blumlein/Bottcher analysis

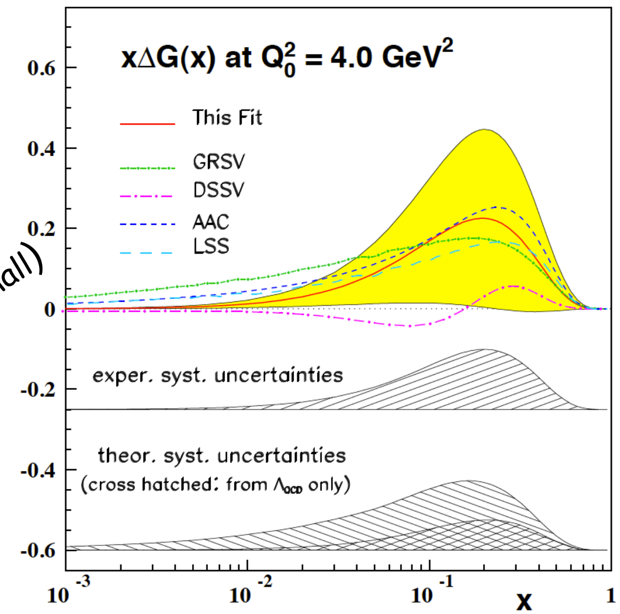
arXiv:1005:3113

fit uses latest DIS data only

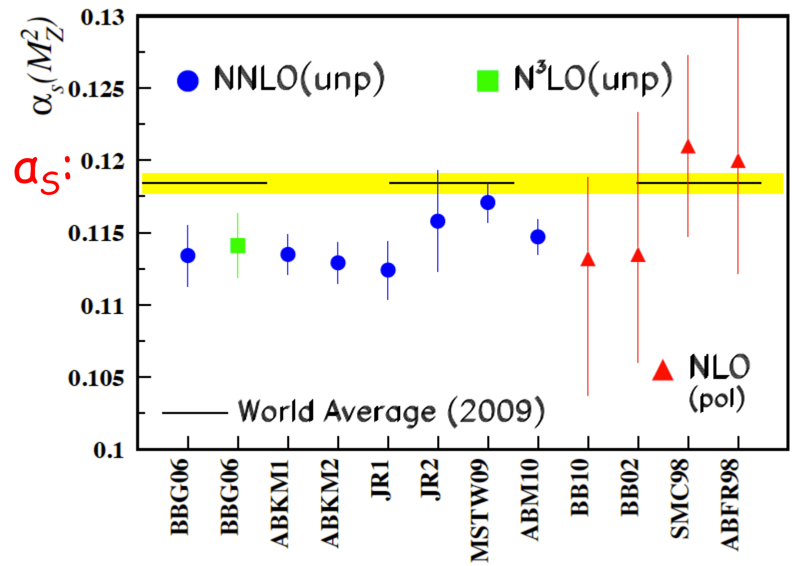
functional form: $\Delta f(x) = Nx^{\alpha}(1-x)^{\beta}(1+\gamma x)$



Δg solely from DIS scaling violations (small)

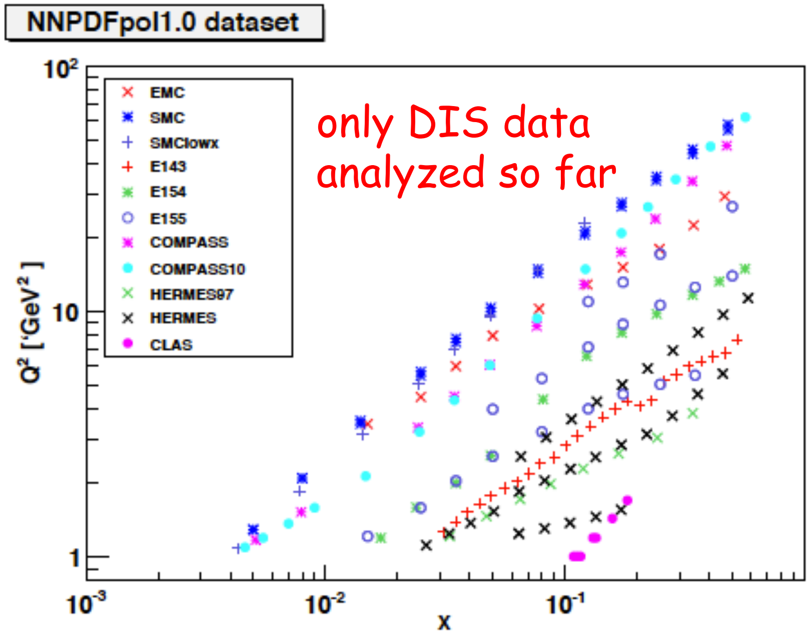


BB fit α_S:



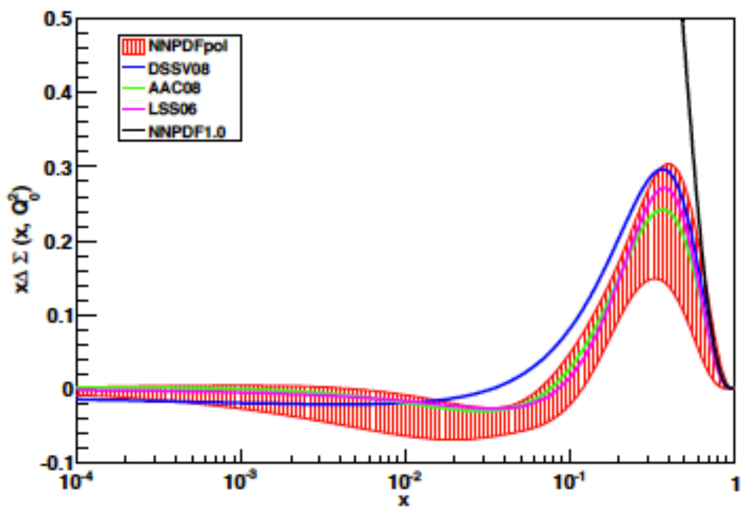
NNPDF Neural Network PDF Collaboration analyses

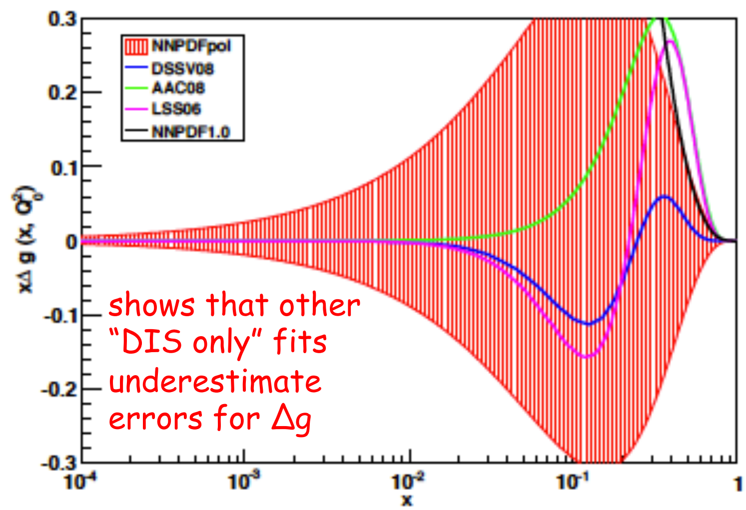
arXiv:1007:0351



- novel way to estimate PDF uncertainties
- successfully applied to unpolarized PDFs
- statistical approach based on large number of replicas -> clear way to "define" errors
- "issues": over-learning (?); no central fit, need average over 100-1000 replicas

a full polarized PDF analysis is work in progress

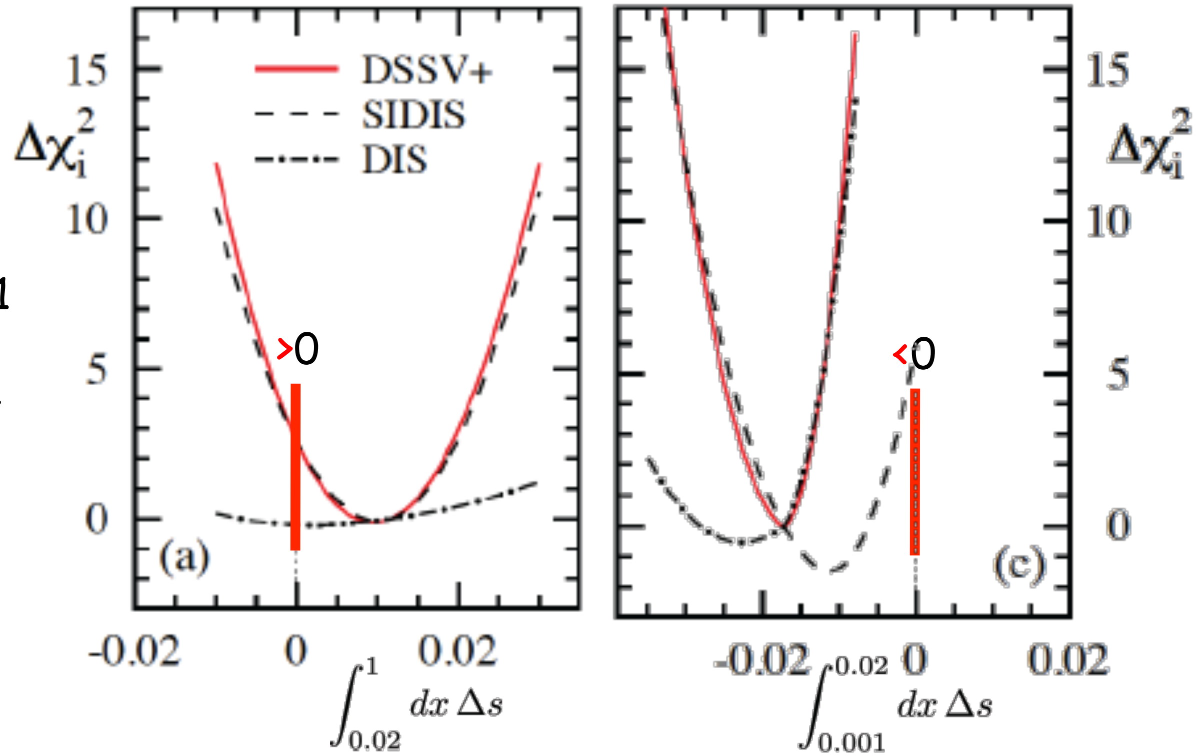




Δs revisited: impact of COMPASS data

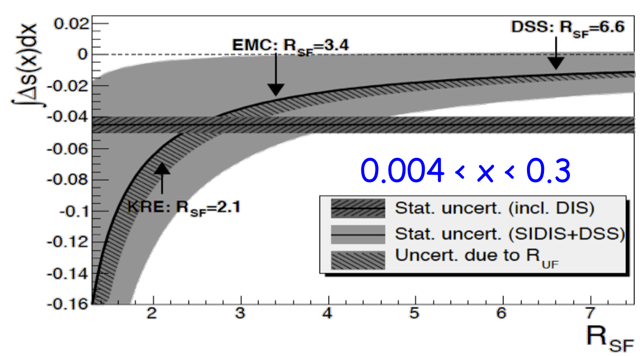
current value for ΔΣ strongly depends on assumptions on low-x behavior of Δs

- new COMPASS data support small/positive Δs(x) at x > 0.01
- they also prefer a sign change at around x=0.01



- but large negative 1st moment entirely driven by assumptions on SU(3) [F,D values]
- caveat: dependence on FFs

$$R_{SF} \equiv \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$$



COMPASS

Δs: can we blame it on the fragmentation fcts ?

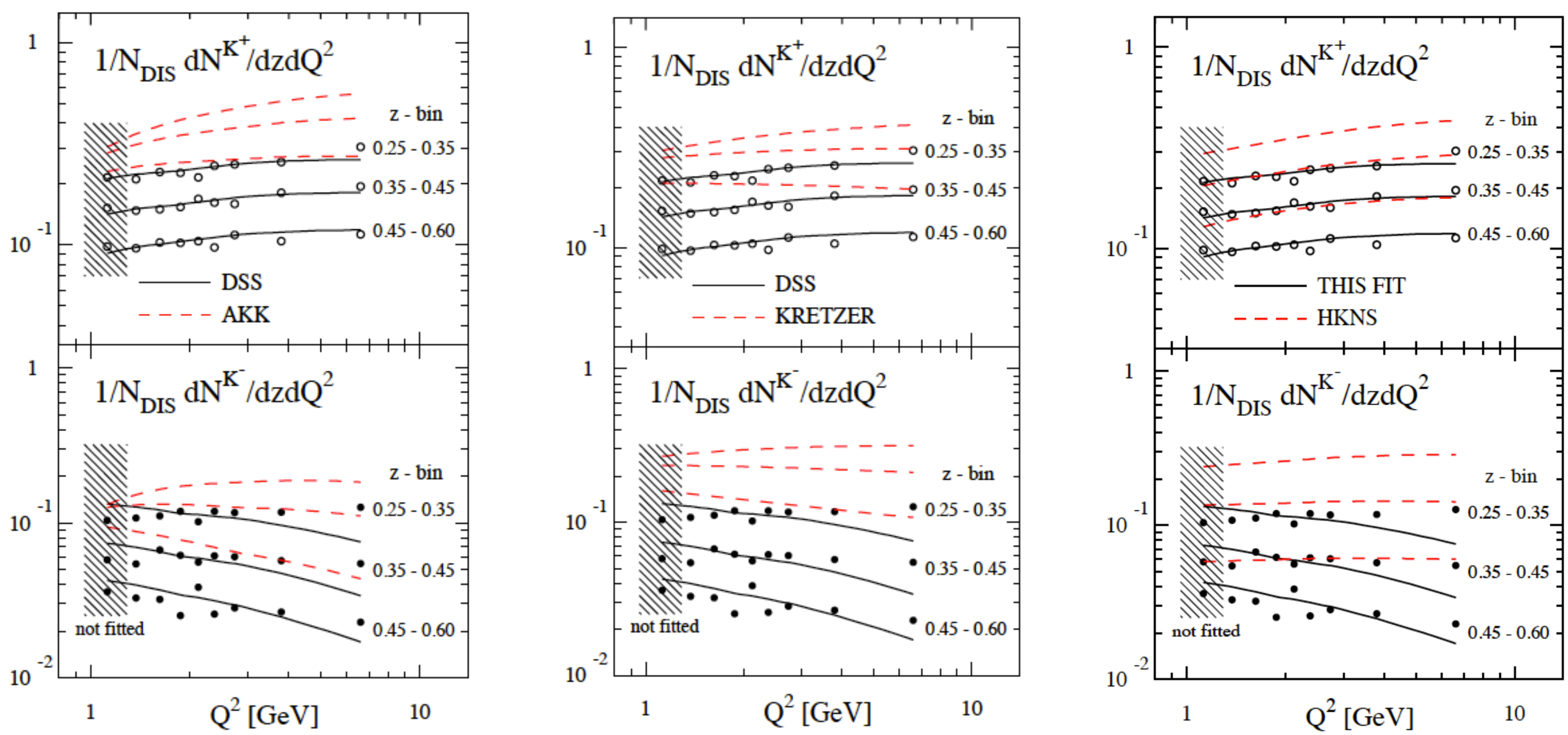
recently proposed as a "solution" to the "strange quark puzzle": Leader, Sidorov, Stamenov arXiv:1103.5979

indeed, flavor decomposition strongly depends on fragmentation functions

different FFs → different results but wrong FFs → misleading results

find: only DSS FFs describe underlying unpol. cross sections in the relevant kinematics

of course, this does not guarantee that we extracted the right Δs: more data are needed



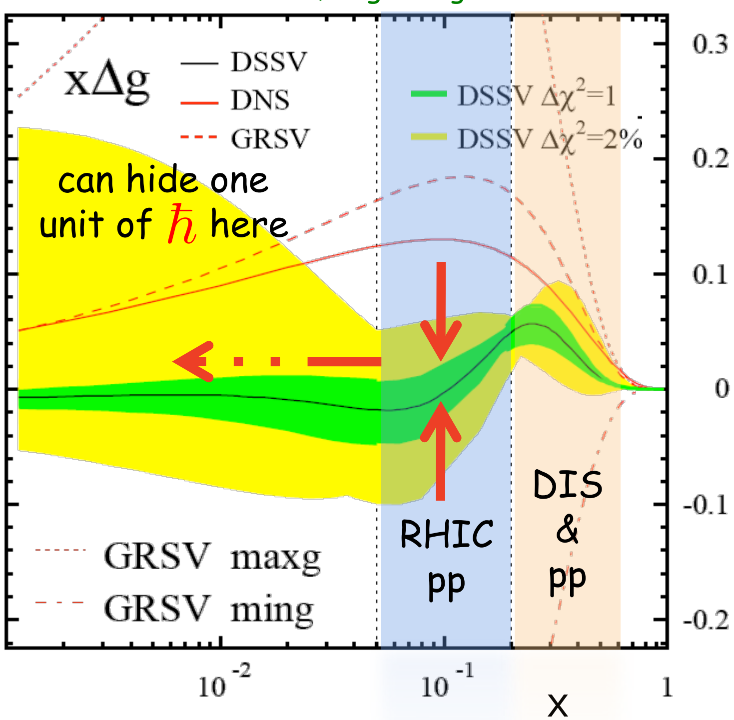
Δg : where are we now - what to expect

- inclusive pions & jets remain to be the bread & butter probes
- jet/hadron correlations essential to cover smaller x

straightforward to analyze in global fits

current status:

DSSV global fit
de Florian, Sassot, MS, Vogelsang



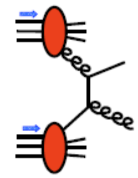
DSSV includes "only" RHIC run6 data

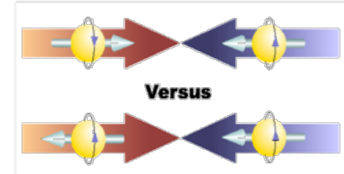
"soon" we expect to have:

- DSSV 2.0 global analysis based on new world data
- reduced uncertainties on Δg in current x range
- possibility of a node further scrutinized
  "evidence" may become statistically significant or not
- extend x-range towards somewhat lower x
  500 GeV running & particle correlations

full 1st moment (proton spin sum) will have smaller but still significant uncertainties from unmeasured small x region

Δg – latest results from RHIC





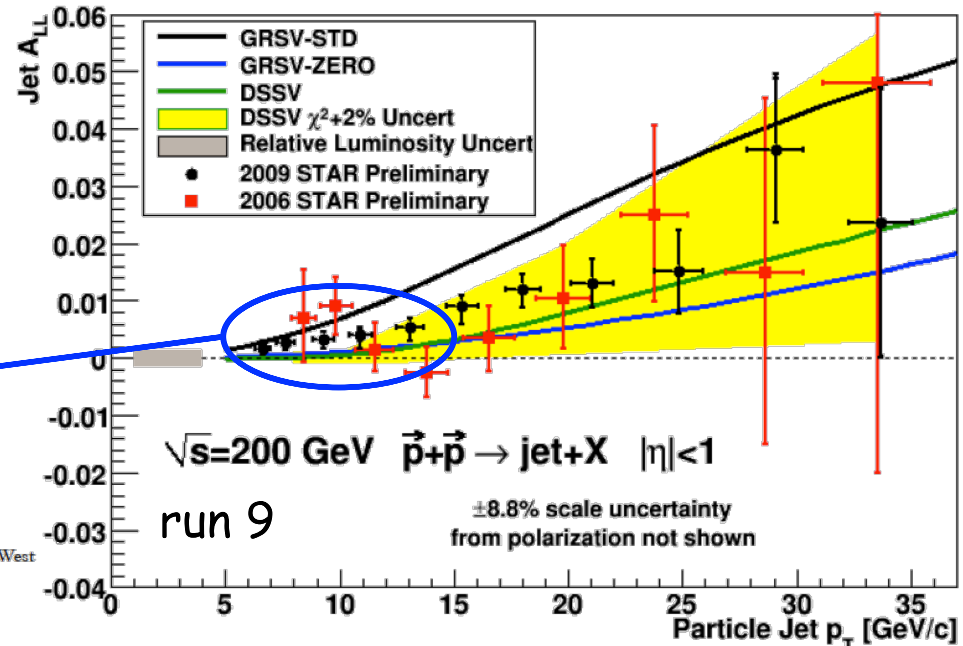
we continuously make progress on Δg: interesting trends in preliminary run-9 data

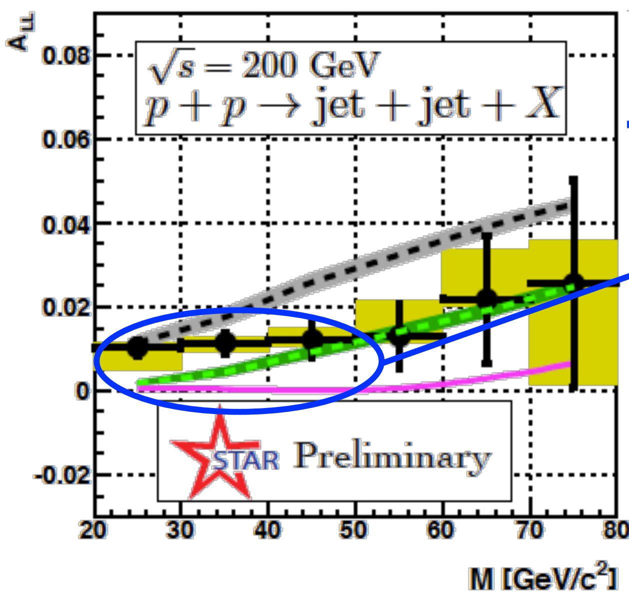
- run 9 data: smaller uncertainties

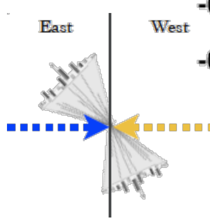
  better constraint on Δg

  node in Δg might go away ?

  slightly larger polarization ?
  as compared to DSSV best fit
  but within uncertainties







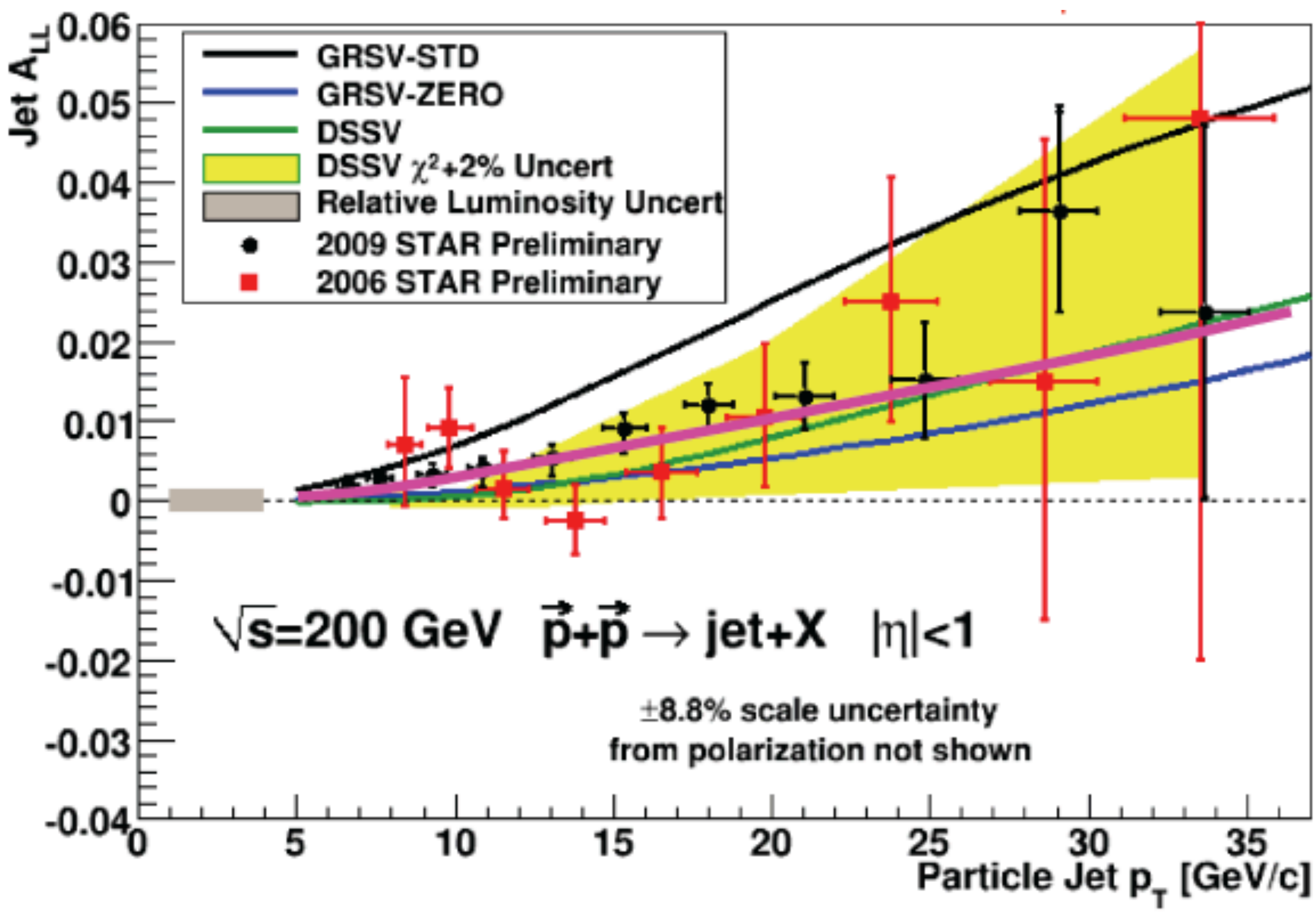
similar trend in di-jets

$$x_{1,2} = \frac{p_T}{\sqrt{S}}(e^{\pm\eta_3} + e^{\pm\eta_4})$$

$$M^2/S = x_1 x_2$$

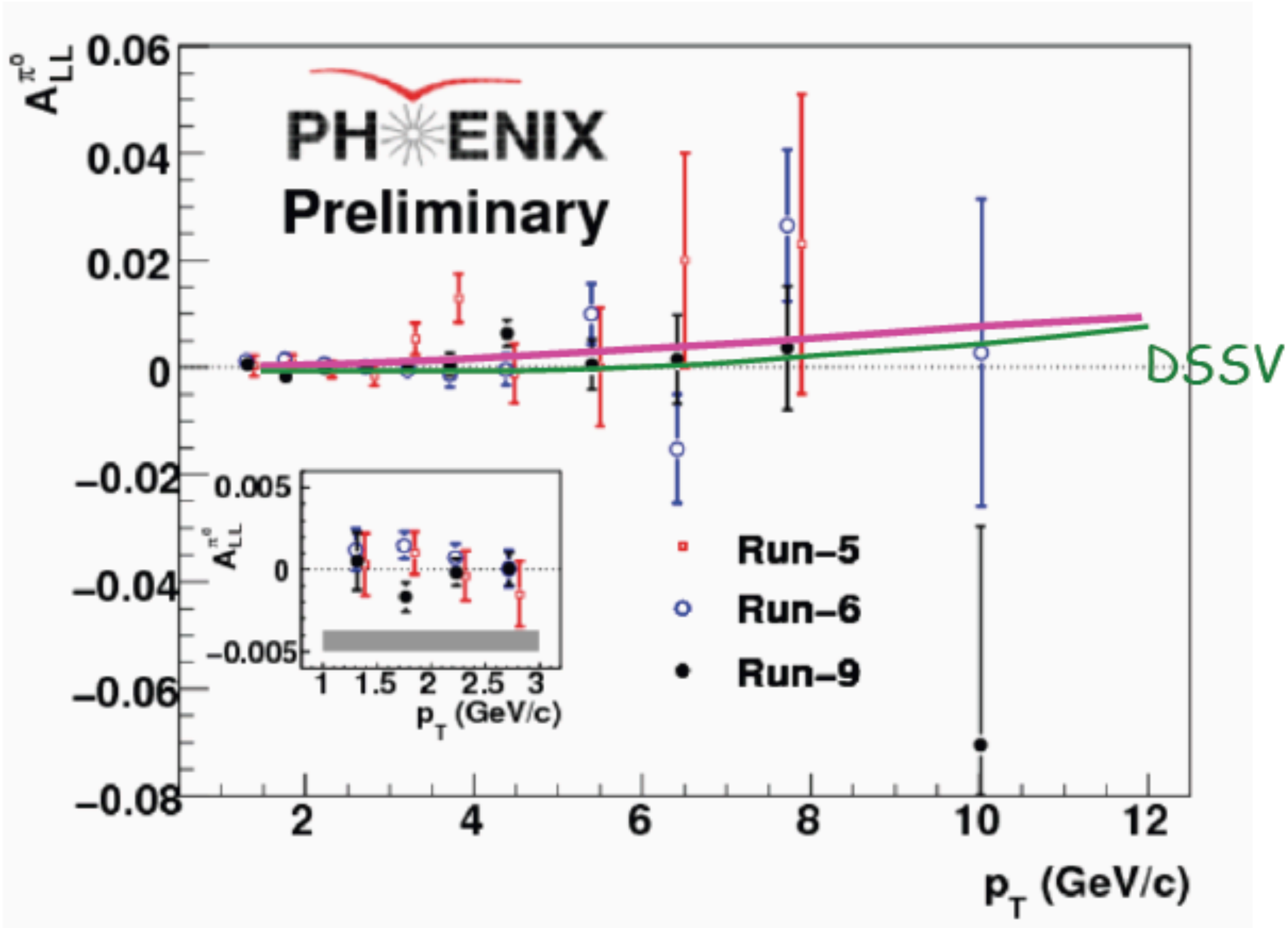
new data ready to go into
DSSV global analysis once available
(to quantify their impact)

Δg – possible impact of STAR run 9 data



gluon with $\int_{0.05}^{0.2} \Delta g(x) dx \simeq 0.1$ fits well (upper edge of DSSV unc. band)

Δg – PHENIX run 9 data



still zero A_{LL} but compatible with STAR (PHENIX probes somewhat lower values of x)

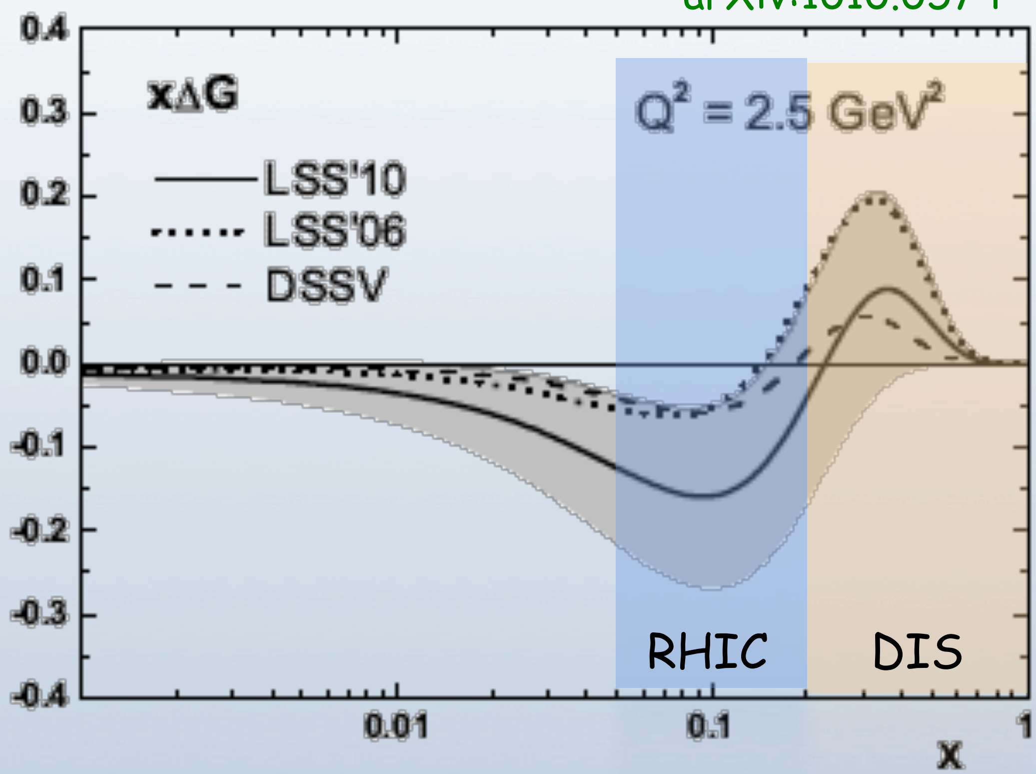
comparison: DSSV vs. LSS'10 gluon

Leader, Sidorov, Stamenov

- LSS fit based on latest DIS/SIDIS data only
- resulting quark PDFs largely a carbon-copy of DSSV
- **striking**: also gluon very similar (node!) but *w/o* using any RHIC pp data

arXiv:1010.0574

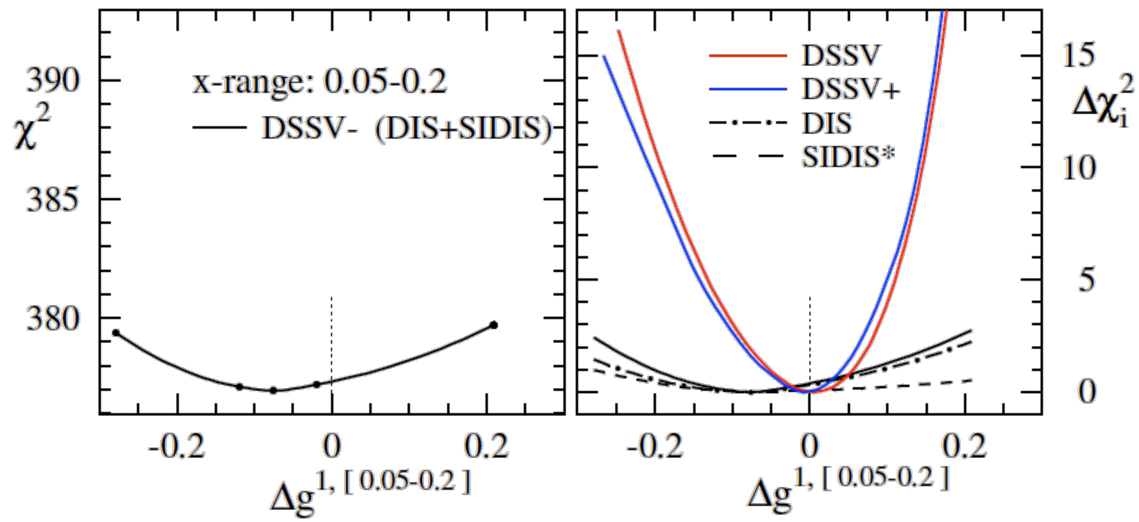
why?



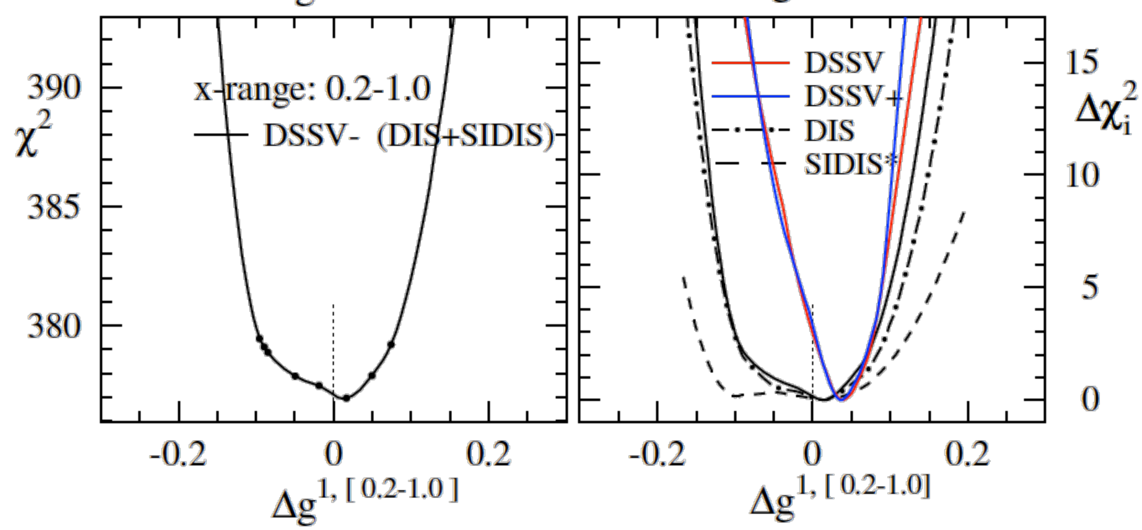
look into χ^2 profiles with LM

Δg and the relevance of RHIC data

truncated moment
("RHIC pp region")



truncated moment
("high x")



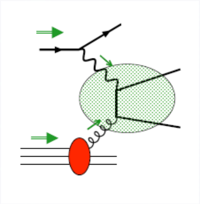
bottom line

- RHIC pp data clearly needed (current DIS+SIDIS data alone do not really constrain Δg)
- new (SI)DIS data do not change much for Δg
- trend for positive Δg at large x (as before)

Δg from fixed target experiments

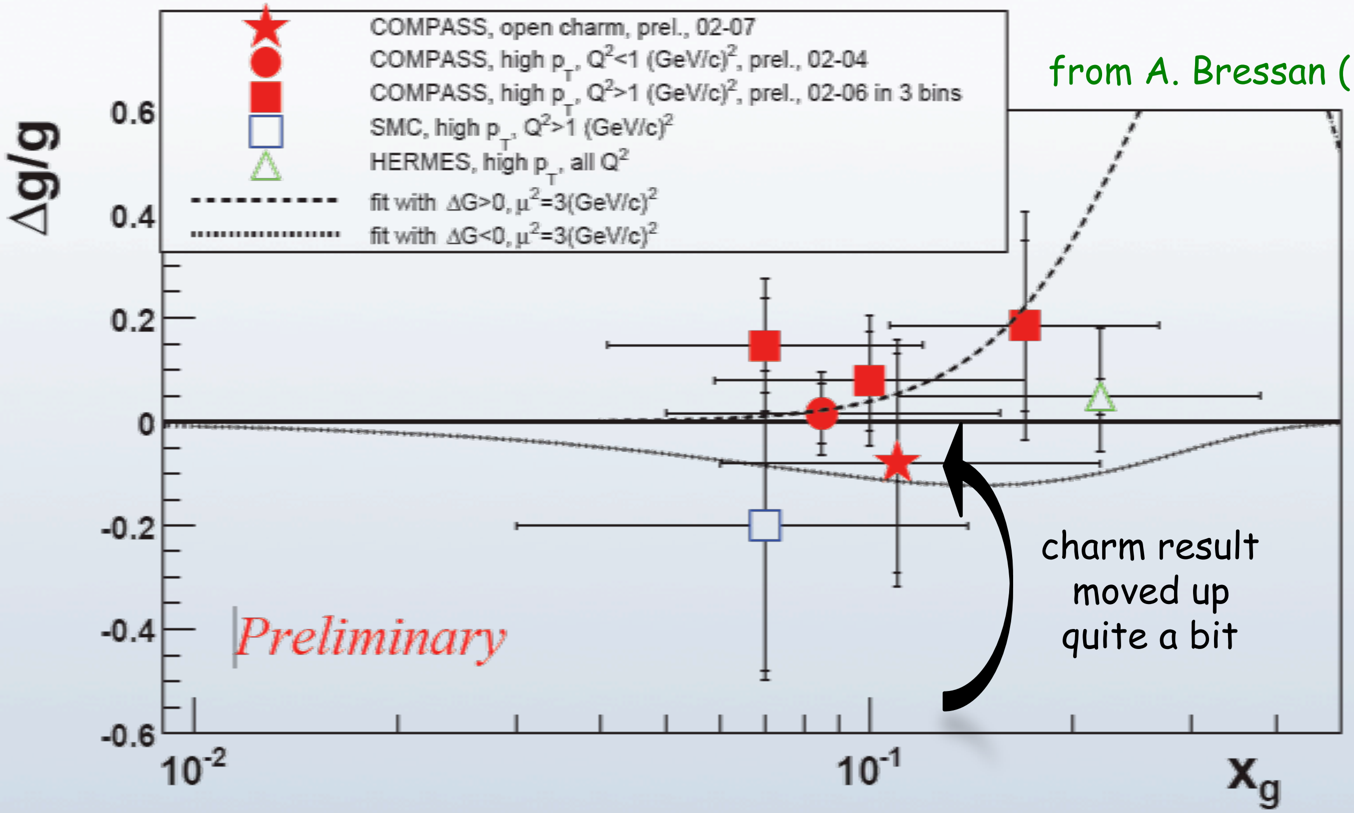
idea: study processes sensitive to **photon-gluon-fusion**

data available for one/two hadron production, charm



COMPASS, HERMES, SMC, E155

from A. Bressan (DIS '10)

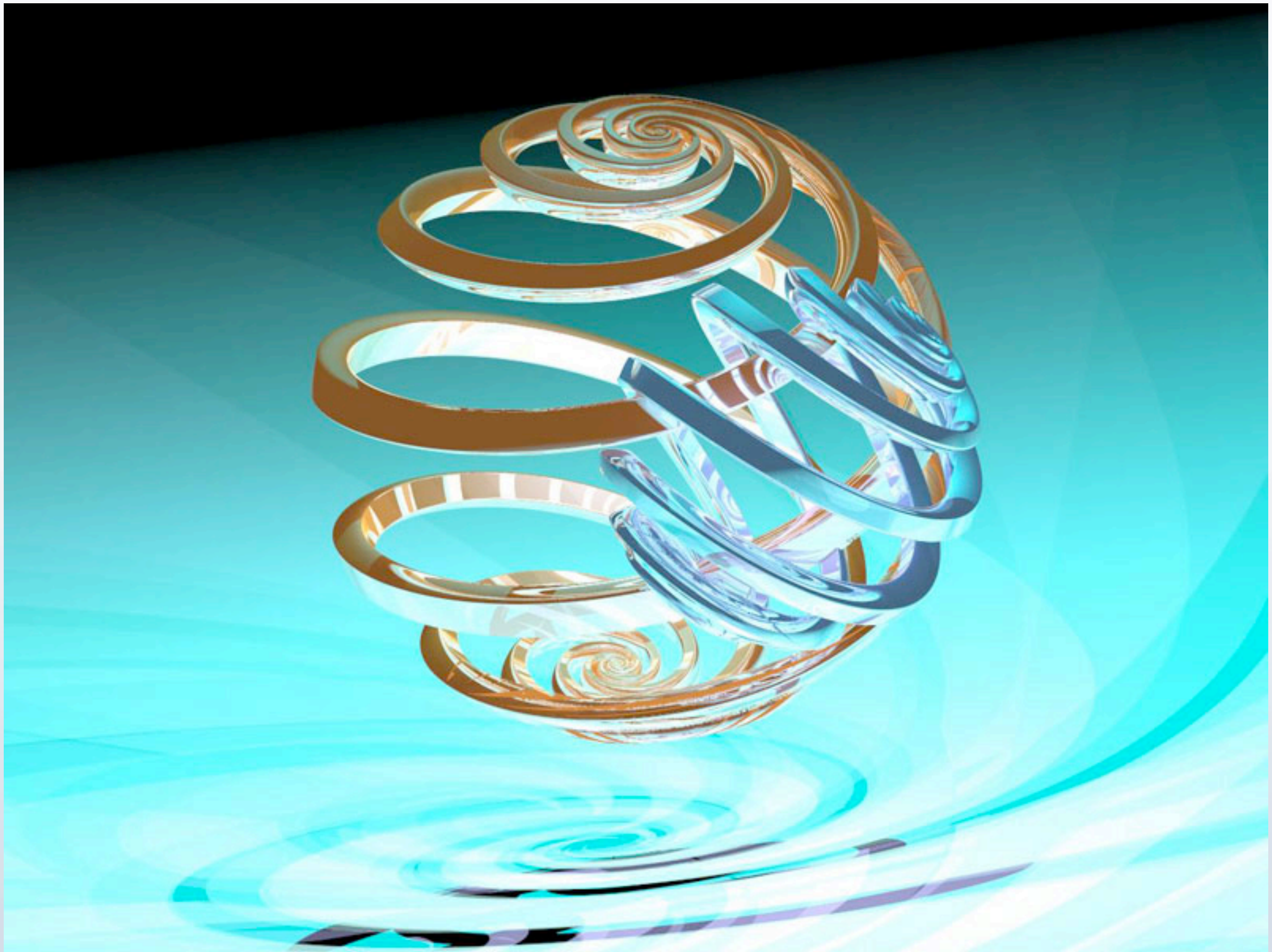


agrees well with DSSV

NLO results just emerging: [but nothing available for $Q^2 \neq 0$ yet]

Jäger,MS,Vogelsang; Bojak, MS; Riedl, Schäfer, MS; Hendlmeier, Schäfer, MS

data will be included in DSSV analysis once NLO results become available



Helicity PDFs and OAM

helicity sum rule revisited

the decomposition of the nucleon spin also depends on the resolution:

$$S_z^p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu^2) + \Delta g(\mu^2) + L_q(\mu^2) + L_g(\mu^2)$$

where the flavor singlet $\Delta\Sigma$ sums up all quark spin contributions

$$\Delta\Sigma(\mu^2) \equiv \int_0^1 [\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}](x,\mu^2)$$

scale evolution of 1st moments $\Delta\Sigma$ and Δg predicted by DGLAP:

at LO $$\frac{d}{d\ln(\mu^2)}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}0 & 0 \\ \frac{3}{2}C_F & \frac{1}{2}\beta_0\end{pmatrix}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix}$$

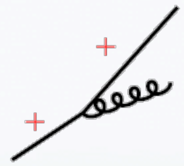
- the quark spin contribution is scale independent at lowest order
- the gluon evolves logarithmically; find: $\alpha_s(\mu^2)\Delta g(\mu^2) \to \text{const as } \mu^2 \to \infty$

helicity sum rule revisited

why $\Delta\Sigma(\mu^2)$ = const at LO ?

helicity conservation:

$\Delta P_{qq} = P_{qq}$ only



→ no net helicity change

at NLO however:

($\overline{MS}$ scheme)

→ net helicity change possible

find $$\Delta\Sigma(\mu^2) = \left(1 + \frac{6N_f}{(33-2N_f)\pi}[\alpha_s(\mu^2) - \alpha_s(\mu_0^2)]\right)\Delta\Sigma(\mu_0^2)$$

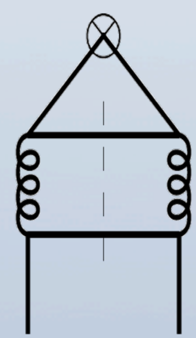
→ very moderate decrease for $\mu > \mu_0$

Jaffe

related to so called axial anomaly

singlet axial current $j_0^\mu = \Psi\,\gamma^\mu\gamma_5\,\Psi$ associated with $\Delta\Sigma$ gets renormalized

Kodaira, ...



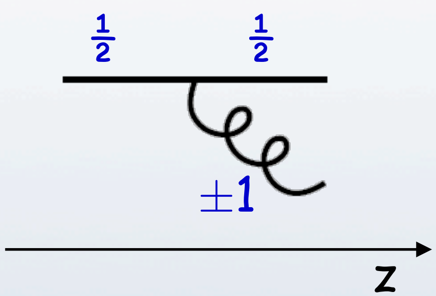
scale evolution of angular momentum

what about the scale dependence of orbital angular momentum?

total angular momentum conservation in parton-parton splittings necessarily *implies* presence of orbital angular momentum (OAM):

Ratcliffe

e.g.



$$\frac{1}{2} = \frac{1}{2} \underbrace{\pm 1}_{\Delta g} \underbrace{\mp 1}_{L_z}$$

- used to derive evolution equations for OAM at LO — Ji, Tang, Hoodbhoy
- LO asymptotic behavior of $J_{q,g}$

find Ji

$$J_q = L_q + \frac{1}{2}\Delta\Sigma \xrightarrow{\mu\to\infty} \frac{1}{2}\frac{3N_f}{16+3N_f}$$

$$J_g = L_g + \Delta g \xrightarrow{\mu\to\infty} \frac{1}{2}\frac{16}{16+3N_f}$$

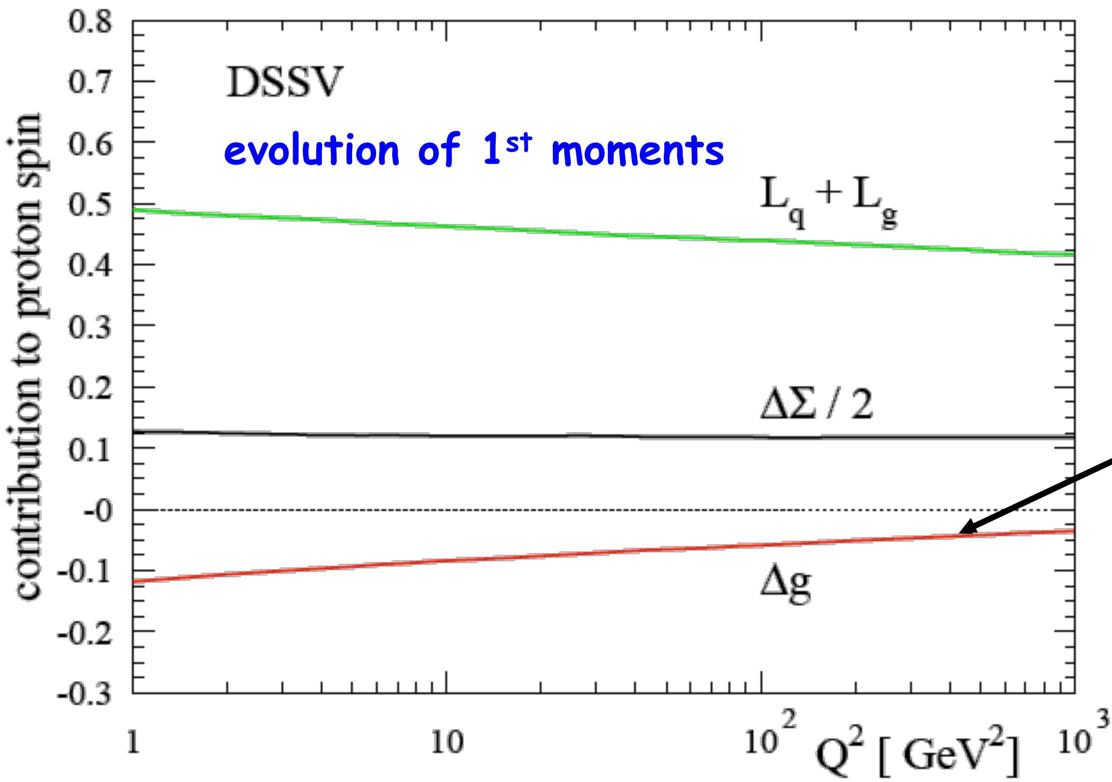
share of nucleon spin between quarks and gluons same as for nucleon momentum

an observation about the spin sum rule in DSSV fit

DSSV **best fit** has the property that proton spin is almost entirely OAM for all Q^2

recall (at LO) $$\frac{d}{d\ln(\mu^2)}\begin{pmatrix}\Delta\Sigma\\ \Delta g\end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix}0 & 0\\ \frac{3}{2}C_F & \frac{1}{2}\beta_0\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta g\end{pmatrix}$$

in general, Δg evolves logarithmically but there is a "static solution" (in LO)



DSSV Δg is close to
"static solution"
$\Delta g \simeq -0.15$
where $d\Delta g/d\ln\mu = 0$

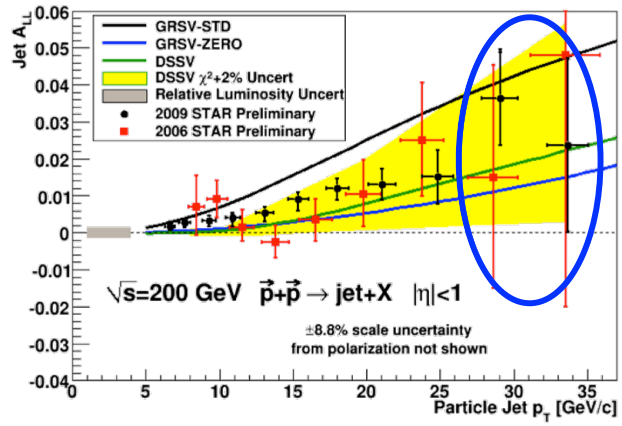
beware: run 9 RHIC data

Future Avenues

RHIC & Opportunities at an EIC

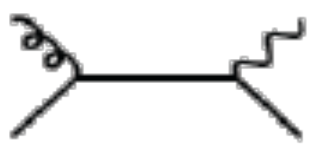
Δg – further improvements from RHIC ?

- important to measure A_{LL} precisely
  also at large p_T (where gg scattering is small)
  - qg scattering -> sign of Δg at large x
  - expect rise a large p_T due to large $\Delta q/q$ at large x (as extracted from DIS)



- current determinations of Δg from pions and jets is based on the ***same*** partonic hard scattering processes
  - with sufficient luminosity we can probe Δg in other, *independent* channels

prompt photons



heavy flavors

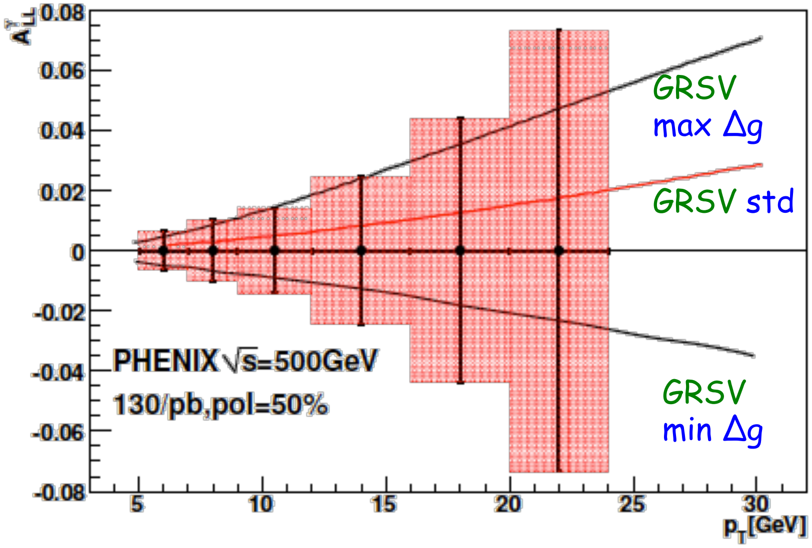
rare probes

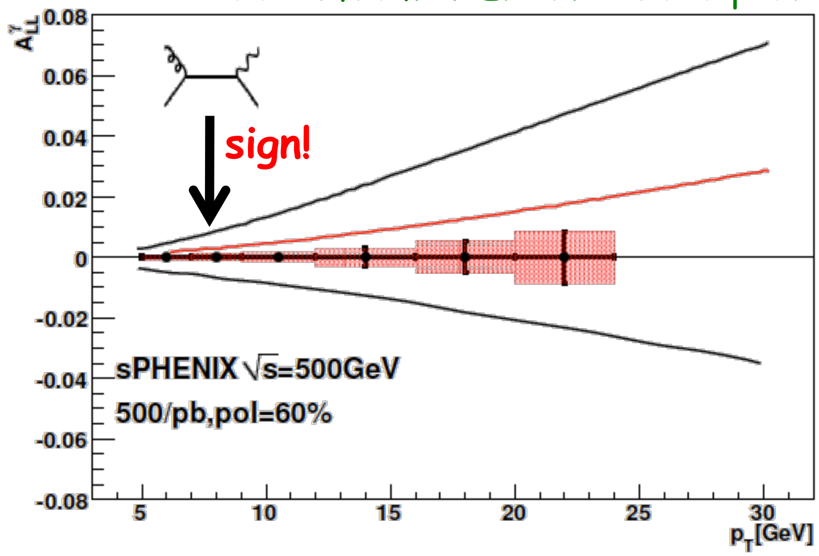
✓ much smaller number of subprocesses
✓ photons sensitive to sign of Δg
✓ different hard scattering dynamics

crucial in understanding
spin-dep. QCD hard scattering
test idea of factorization
and universality

Δg from prompt photons ?

taken from PHENIX decadal plan

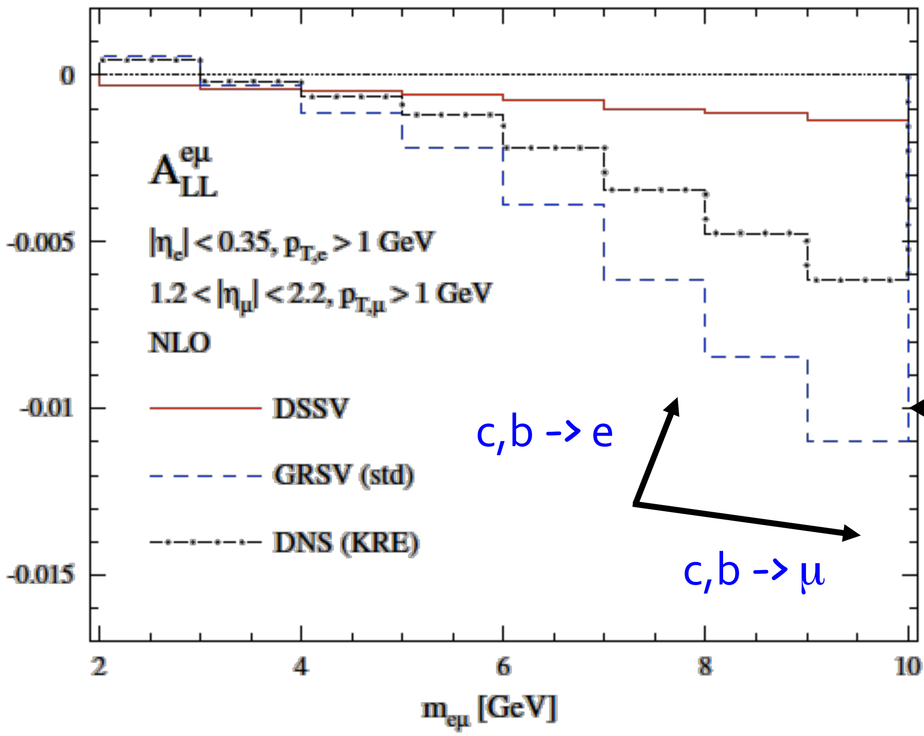




still *the* golden channel for Δg in pp
measurement should be done

- only probe in pp which provides sensitivity to sign of Δg at small p_T (i.e. small x!)
- requires a significant integrated luminosity **(0.5 ÷ 1 fb^{-1})** to make an impact
- straightforward to include in global QCD analysis; NLO corrections known
- γ-jet correlations would allow for detailed mapping of x dependence

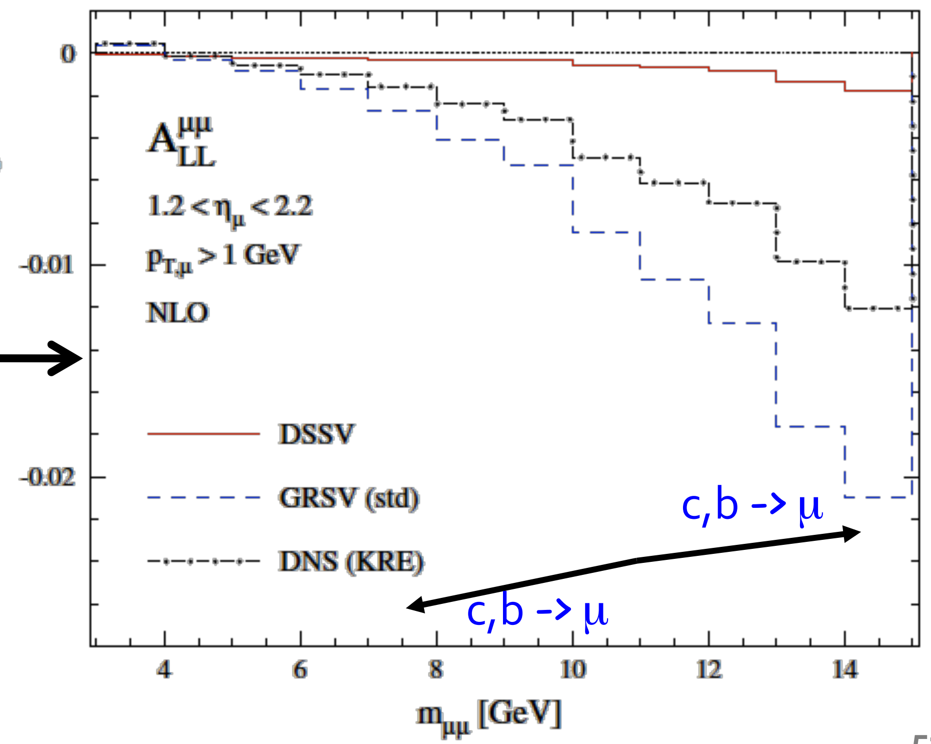
Δg from heavy flavors ?



- correlations most promising
  (recent NLO calculation Riedl, Schafer, MS)
- correlation between A_{LL} and Δg at large enough invariant mass (= larger x)

forward-central e-μ coincidences

forward-backward μ-μ coincidences

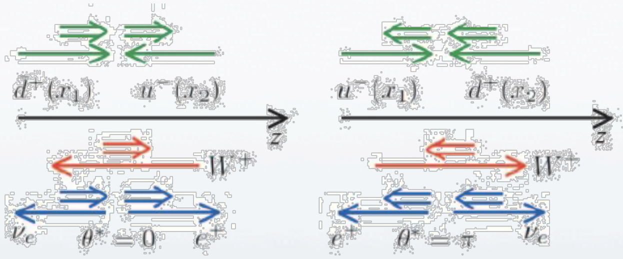


luminosities of a **few hundred pb^{-1}** are required for meaningful measurements at $m_{e\mu,\mu\mu}$ up to 10 ÷ 12 GeV
(less compelling than prompt photons)

u,d quarks from W boson production

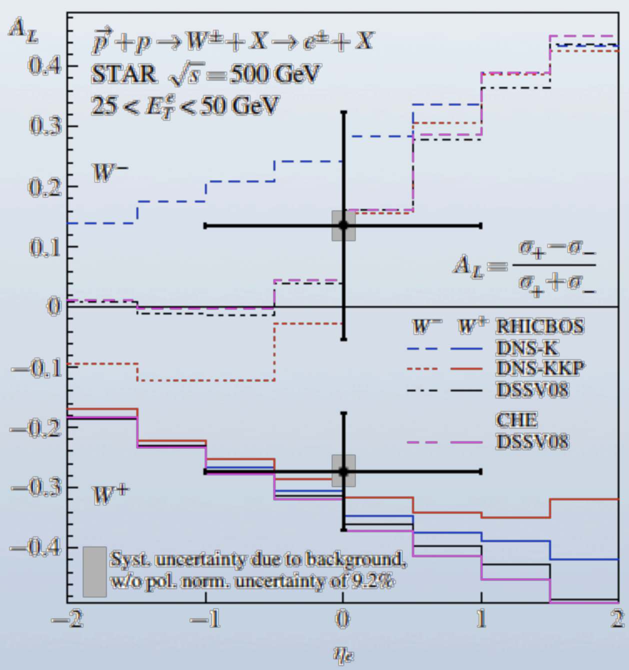
key measurement at RHIC

- based on parity violation: W's couple only to one parton helicity



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

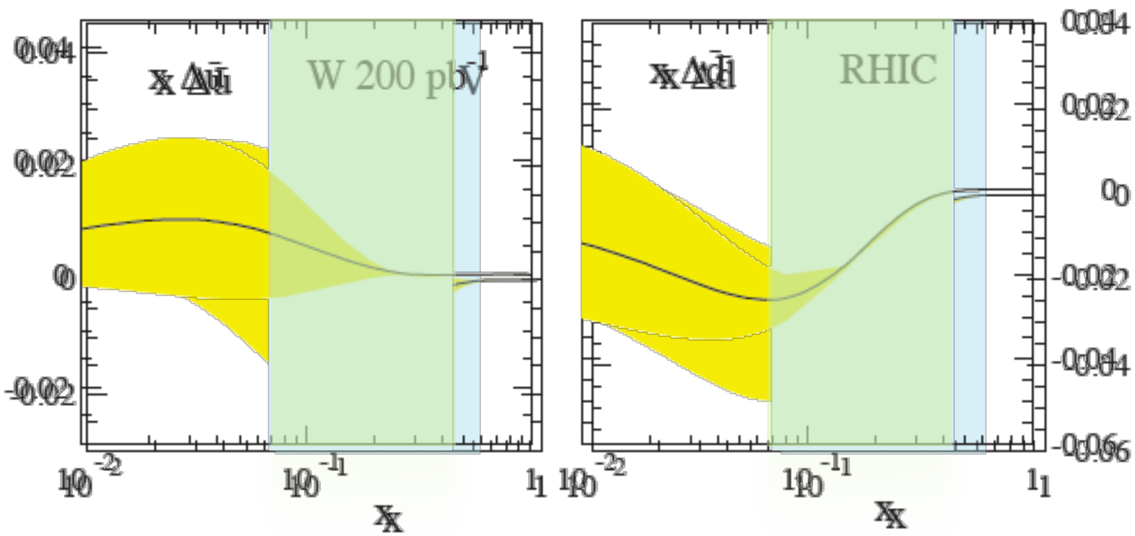
- 500 GeV program started in 2009 – 1st W bosons seen at RHIC !



STAR arXiv:1009.0326
PHENIX arXiv:1009.0505

- no impact on fits yet
  "proof of principle"

Δq's – what do we expect to learn ?



simulated impact of RHIC / current uncertainties DSSV
W boson data on global fit

de Florian, Vogelsang

✓ reduction of uncertainties for 0.07 < x < 0.4

✓ can test consistency of low Q^2 SIDIS data in that x regime

complication:

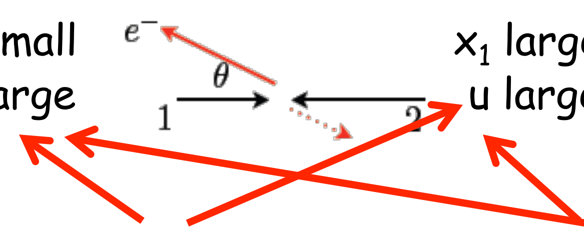
angular and PDF x dependence for decay lepton not always work hand-in-hand

$\hat{t}^2 \simeq (1+\cos\theta)^2$ $\qquad$ $\hat{u}^2 \simeq (1-\cos\theta)^2$

backward $\qquad$ forward

x_1 small $\qquad$ x_1 large

t large $\qquad$ u large



$\Delta\bar{u}(x_1)d(x_2)(\hat{t}^2) + \Delta d(x_1)\bar{u}(x_2)(\hat{u}^2)$

$\Delta\bar{d}(x_1)u(x_2)(\hat{u}^2) + \Delta u(x_1)\bar{d}(x_2)(\hat{t}^2)$

strong sensitivity to $\Delta\bar{u}$ / limited sensitivity to $\Delta\bar{d}$

can we flip u <-> d around?

running with polarized ^{3}He (= neutron target) would be an option

Δs from spin transfer to Λ baryons

idea:
- study helicity transfer to Λ in $\vec{p}p \to \vec{\Lambda}X$ (preferably at forward η where x_1 is large)
- use self-analyzing decay of Λ to determine its polarization
- quark model: Λ spin predominantly carried by s --> **sensitivity to Δs**

s-dominance perhaps as naïve
as proton spin in quark model

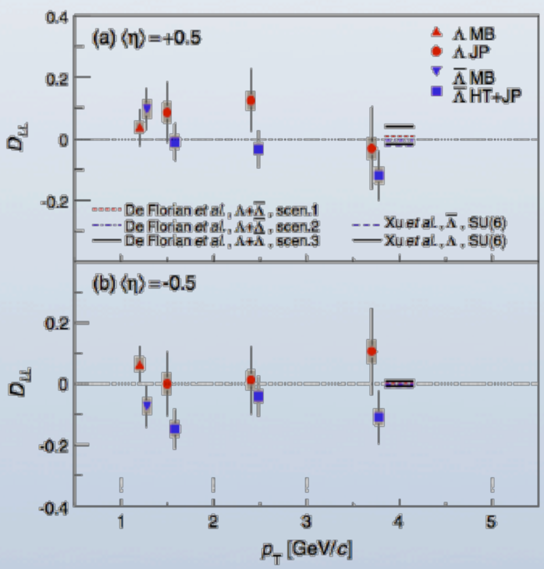
theory prerequisites:
- reliable NLO sets of D_i^Λ *and* ΔD_i^Λ FFs

DSV: de Florian, MS, Vogelsang

AKK: Albino et al.

updates needed
don't describe STAR data

DSV: de Florian, MS, Vogelsang
sparse data; updates desirable
3 models for ΔD_i considered



- feed-down from hyperon weak decays; effect on polarization?
- compute helicity-transfer subprocesses at NLO
  difficult – many more processes than pion production; work in progress

the good news: "proof of principle" by STAR

best shot at Δs at RHIC
needs also some theoretical work though

opportunities for spin physics studies at an EIC

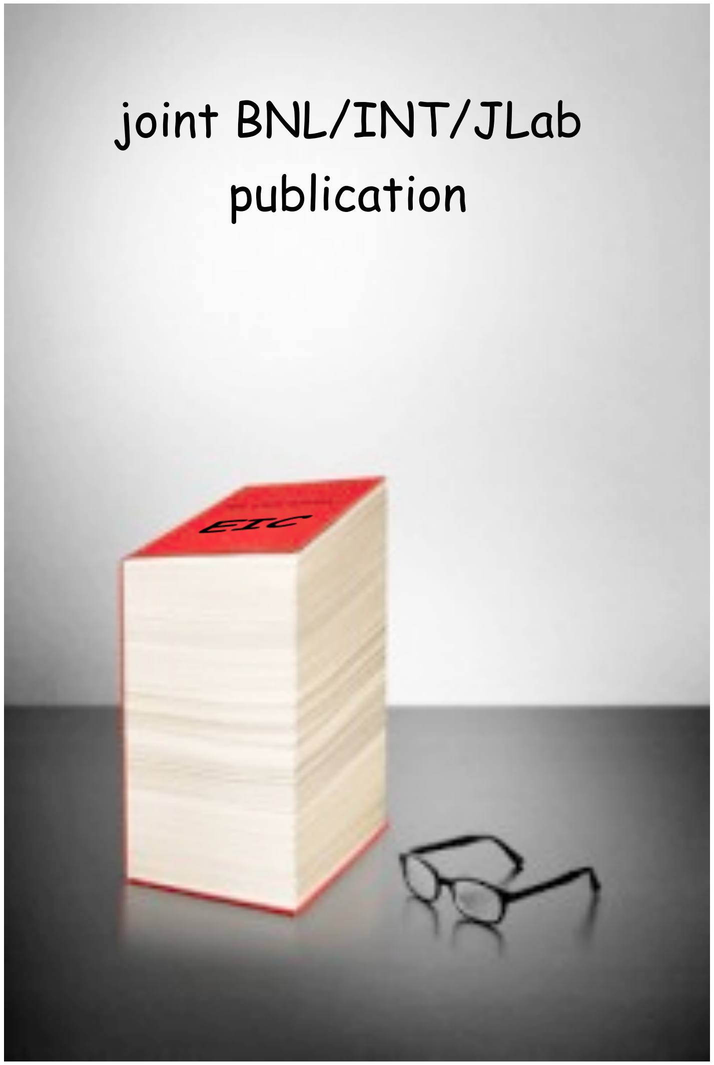
so far, our knowledge on polarized (SI)DIS is based on fixed target experiments

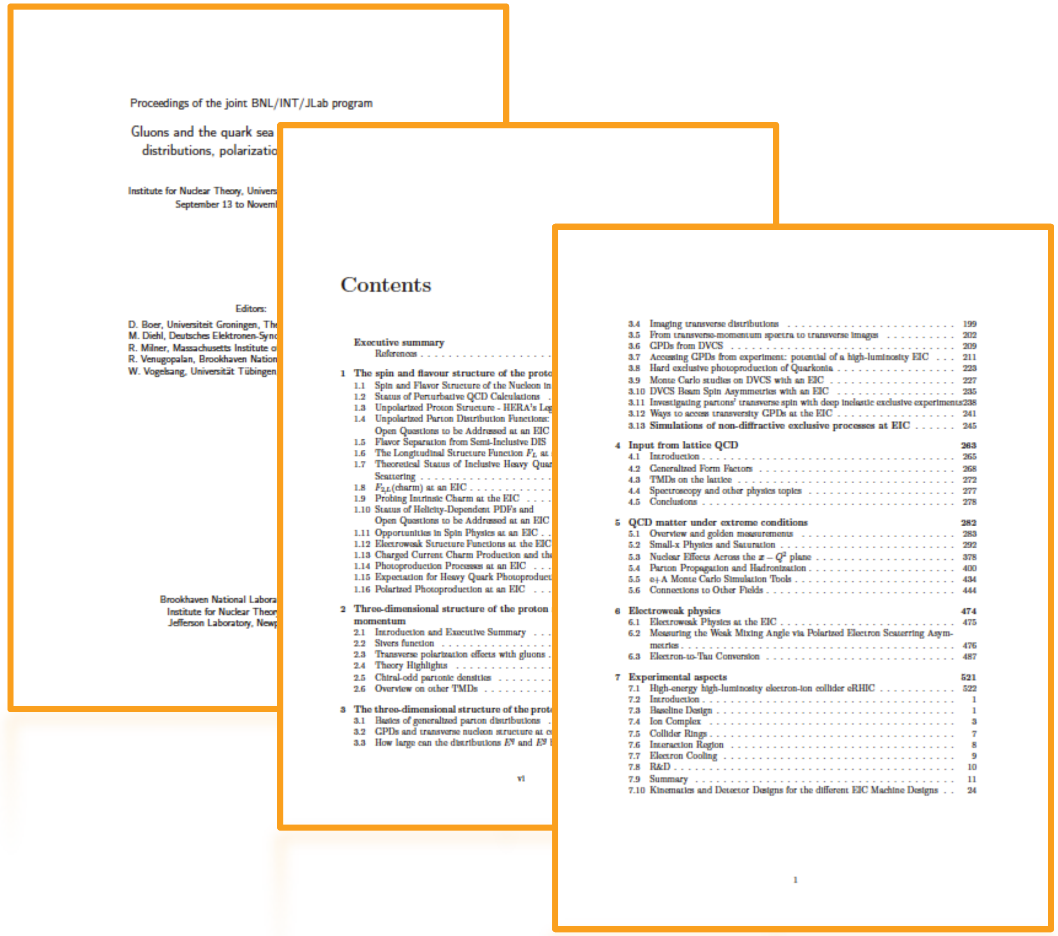
many "weak spots" & room for new "spin surprises":

- small x region: crucial for all sum rules ("proton spin", "Bjorken", …) **unknown**
- flavor separation: SU(2), SU(3) breaking, strangeness **largely unknown**
- electroweak effects/structure fcts. **never measured**
- full understanding of transverse spin phenomena **still in early stages**
- issues with factorization for Sivers fct. **intriguing**
- role of orbital angular momentum **largely unknown**
- plus: spin phenomena in diffraction, photoproduction, hadronization, …

repeat full HERA program in polarized high energy ep scattering with good particle ID & ability to measure exclusive processes

detailed 500+ pages write-up on EIC Science available **arXiv:1108.1713**

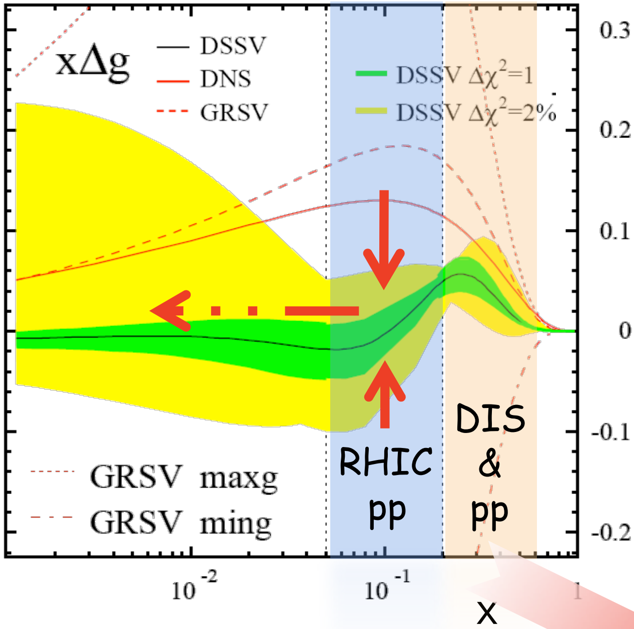




Δg at small x from QCD scaling violations

current status:

DSSV global fit

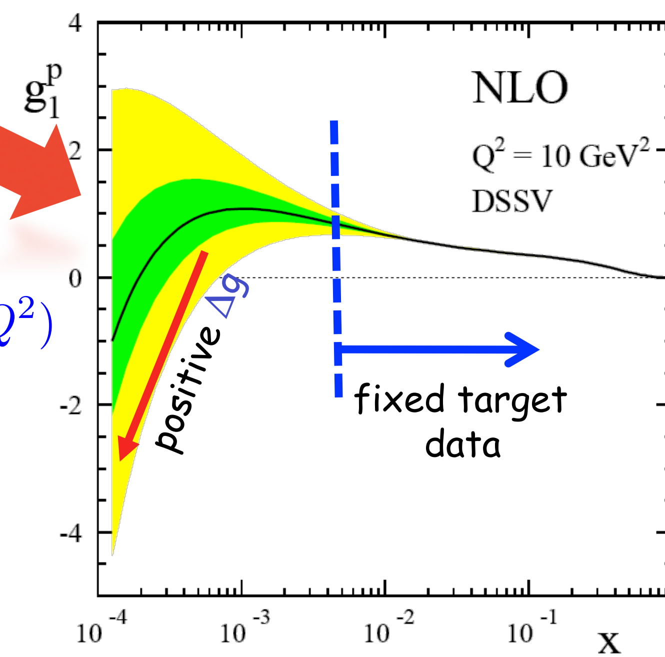


- low x behavior unconstrained
  significant polarization still possible
- no reliable error estimate
  for 1st moment $\int_0^1 dx\, \Delta g(x, Q^2)$
  (enters spin sum rule)
- RHIC will continue to improve
  our knowledge at medium x

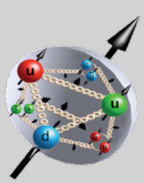
best probe for small x gluons

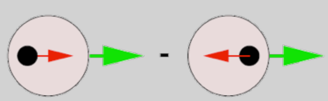
pQCD scaling violations

$$\frac{dg_1(x,Q^2)}{d\ln Q^2} \propto -\Delta g(x,Q^2)$$



$$\Delta f(x) \equiv f_+^{N_+}(x) - f_-^{N_+}(x)$$

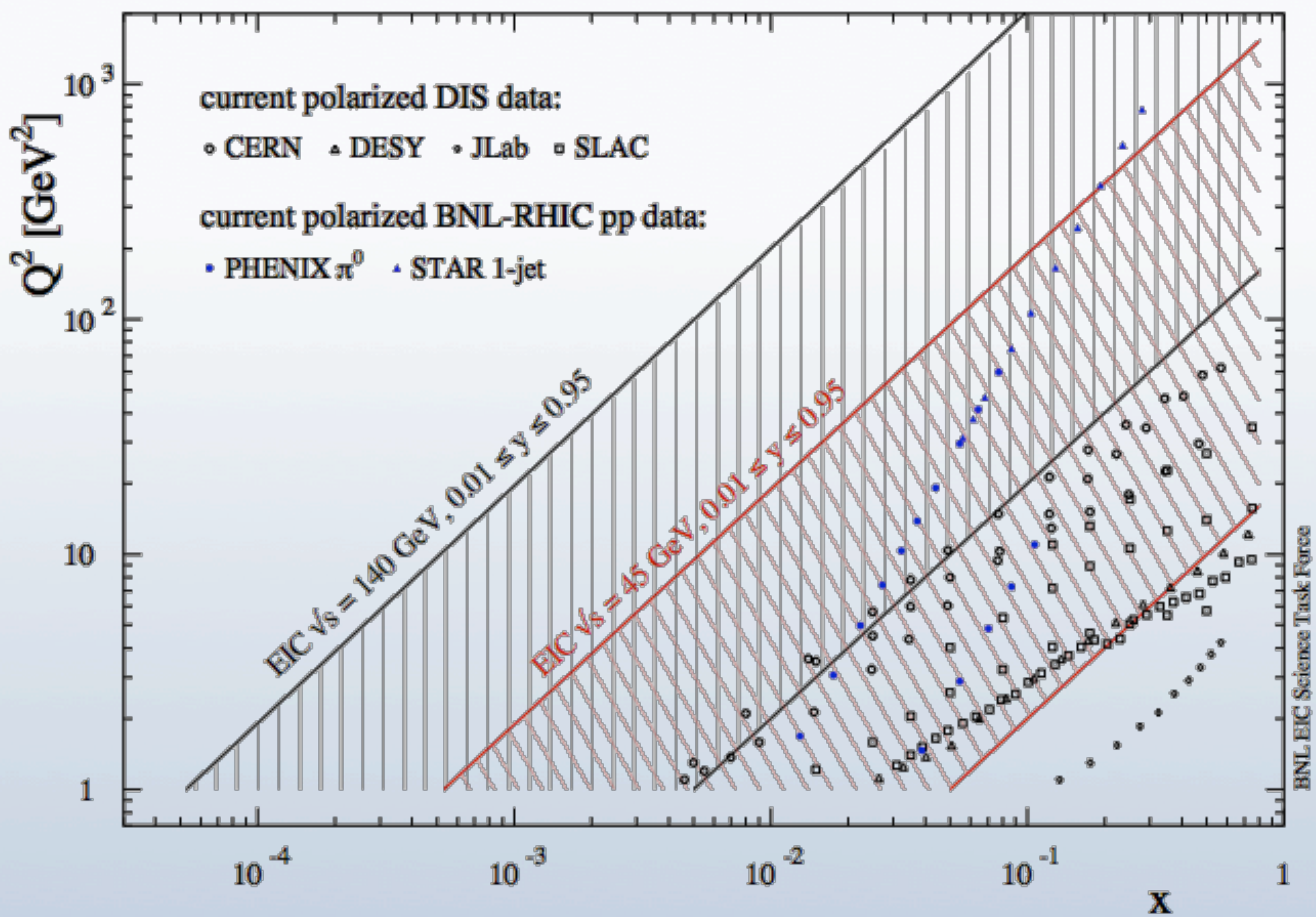




$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta g + L_{q,g}$$

quarks gluons OAM

kinematic reach of an EIC

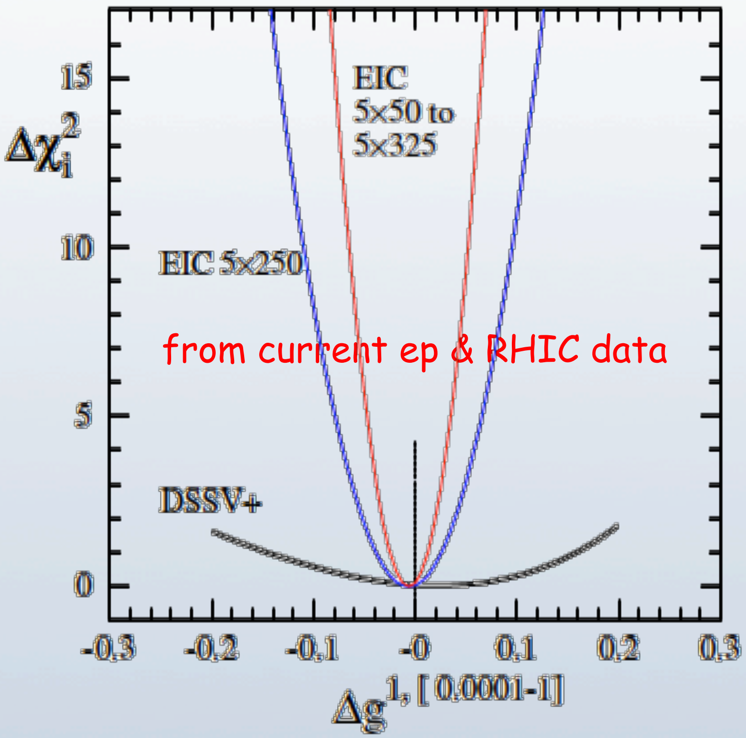


what can be achieved for Δg ?

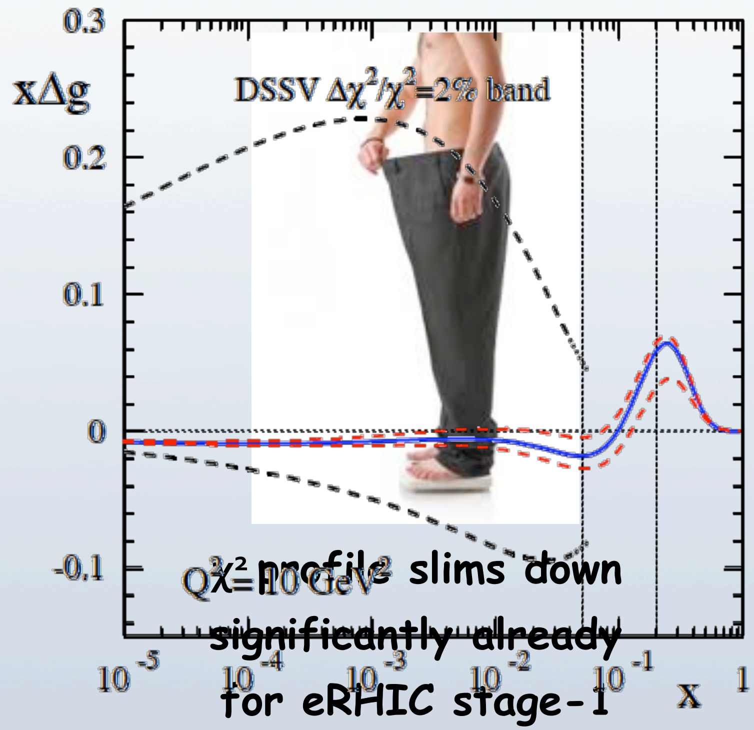
how effective are scaling violations ? Sassot, MS

quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, **100**, **250**, 325) GeV

χ^2 profile for $\int_{10^{-4}}^{1} \Delta g(x,Q^2)\,dx$



uncertainties on the x-shape of $\Delta g(x,Q^2)$



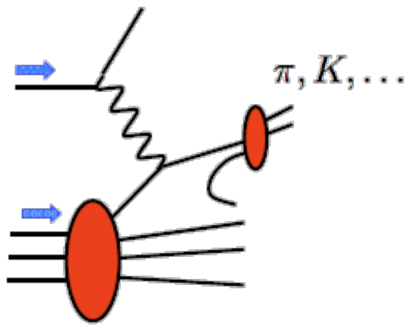
χ^2 profile slims down significantly already for eRHIC stage-1

expect to determine $\int_0^1 dx\,\Delta g(x,Q^2)$ at about 10% level (more detailed studies under way)

kinematic reach down to $x = 10^{-4}$ essential to determine integral reliably

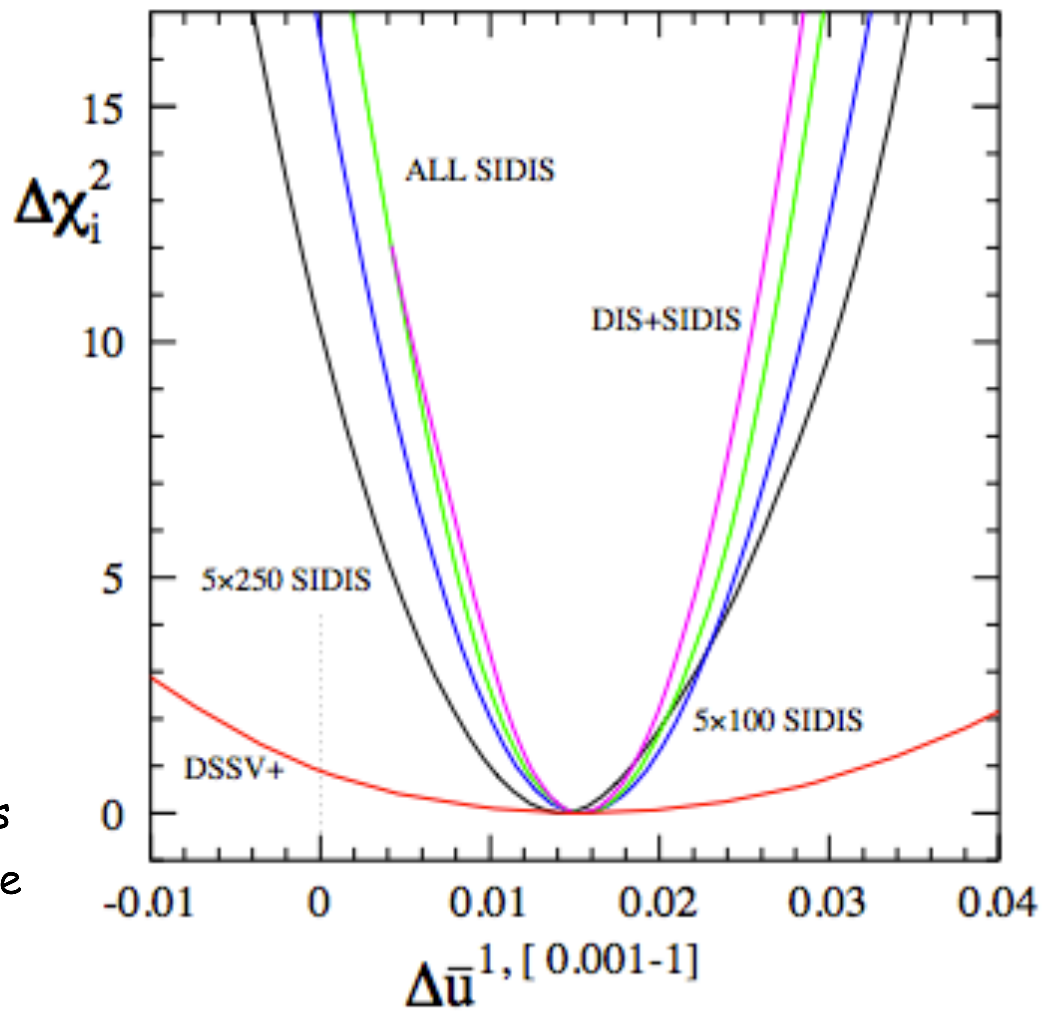
similar improvements expected for u,d,s sea quarks

key: precision SIDIS data



1^{st} quantitative study
with realistic exp. cuts

Aschenauer, Sassot, MS



- very encouraging
- similar results for d and s quarks
- need to study also 0.0001-1 range
- need to translate profiles into errors on x-shape

large Q²: novel electroweak probes for Δq's

aneja, Vogelsang

vant

nce)

robe

nge

plings

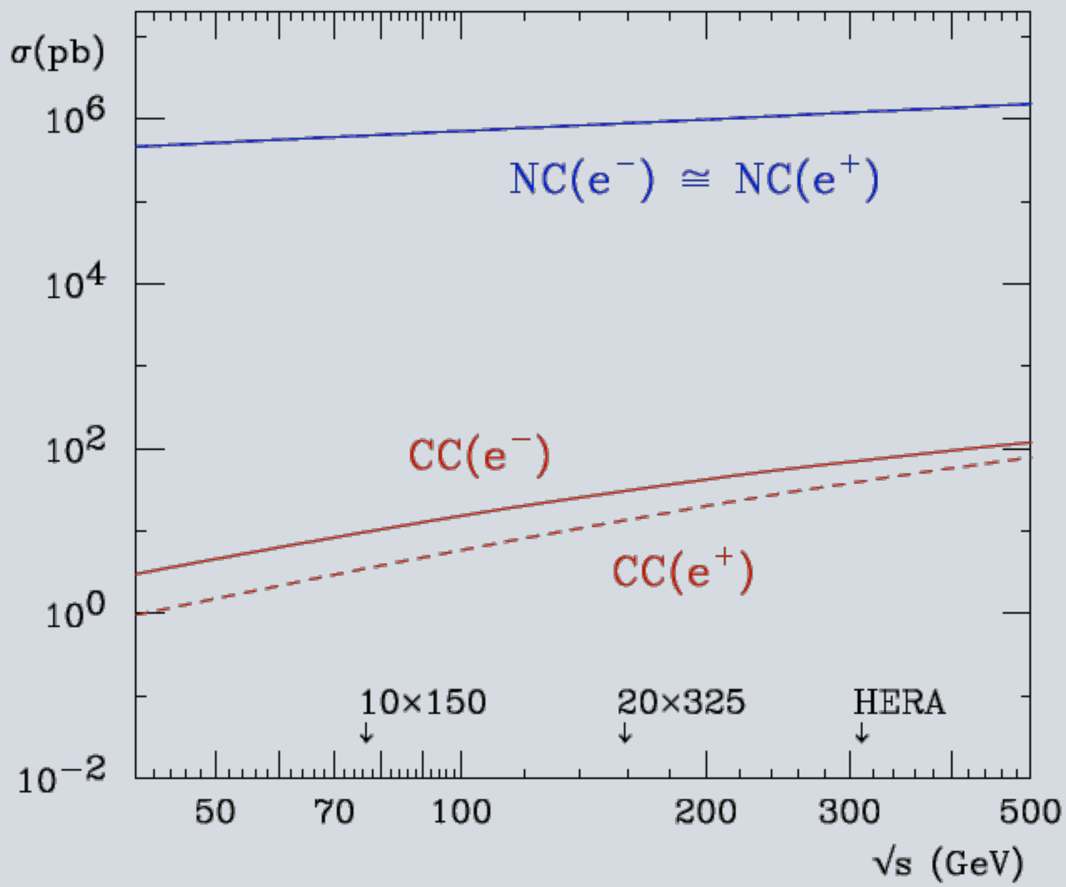
hadron-s

hadron-s

Vogelsang;
nowski;
ano, Ridolfi; ...

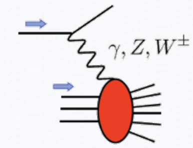
key for e-w measurements at eRHIC:

drop in cross section more than compensated by luminosity increase



unexplored so far – unique opportunity for the EIC

electroweak effects – cont'd



most promising at an EIC: charged current str. fcts.

details: INT EIC report

CC:

also related by **isospin rotation** (no positron beam required)

$$g_1^{W^-} = (\Delta u + \Delta \bar{d} + \Delta \bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta \bar{u} + \Delta d + \Delta s + \Delta \bar{c})$$
$$g_5^{W^+} = (\Delta \bar{u} - \Delta d - \Delta s + \Delta \bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta \bar{d} + \Delta \bar{s} - \Delta c)$$

require a positron beam
not necessarily polarized

- NLO QCD corrections all available
- can be easily put into global QCD analysis
- enough combinations for a flavor separation at $Q \approx M_W$ (no fragmentation) but kinematically limited to medium-to-large x region

de Florian, Sassot; MS, Vogelsang, Weber; van Neerven, Zijlstra; Moch, Vermaseren, Vogt

novel Bj – type sum rules: MS, Vogelsang, Weber

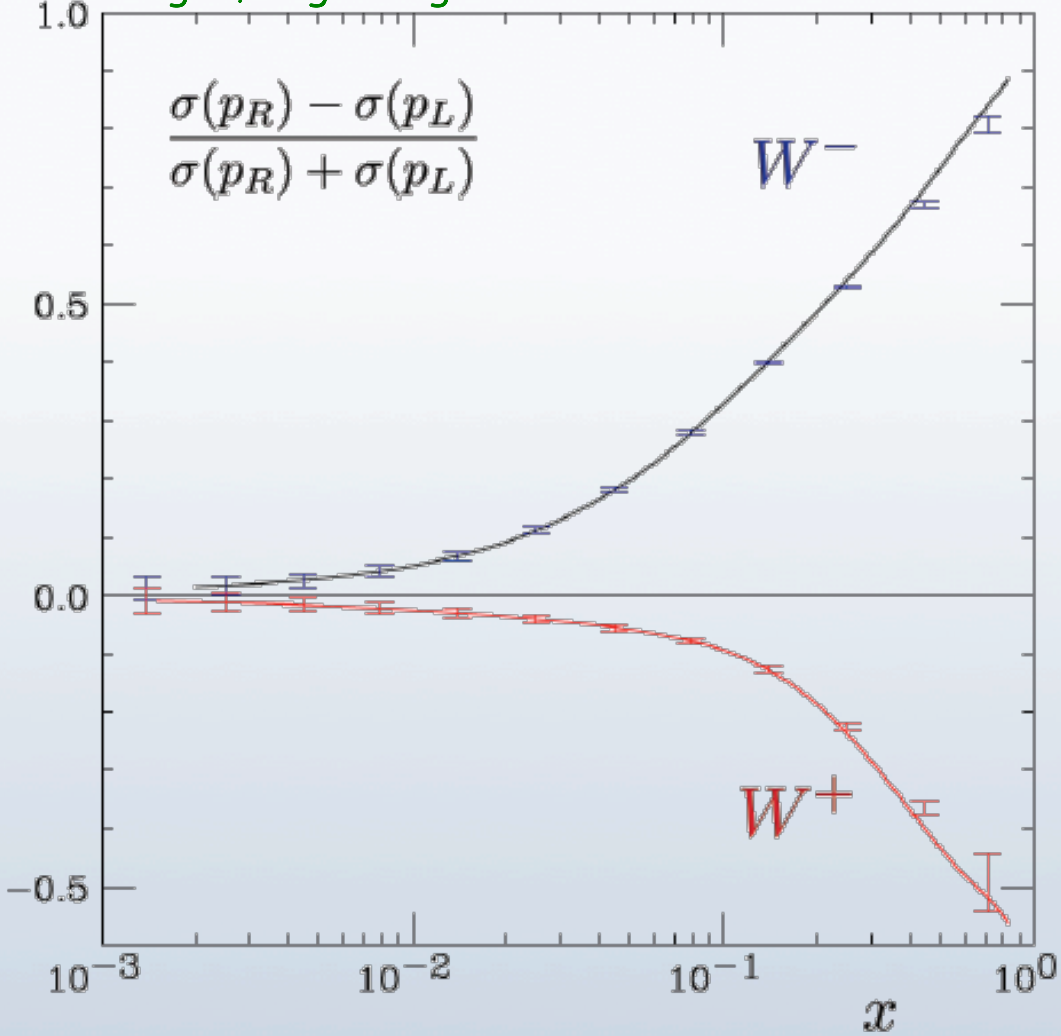
details: PRD53 (1996) 138

e.g. $$g_5^{W^-,p} - g_5^{W^+,n} = \left(1 - \frac{2\alpha_s}{3\pi}\right) g_A$$

- probes again Δq_3
- reach to small x limited
  extrapolation uncertainties?

feasibility - 1st exploratory studies

Ringer, Vogelsang



20 × 250 GeV

$Q^2 > 1\ GeV^2$

$0.1 < y < 0.9$

10 fb^{-1}

DSSV PDFs

very promising!

even doable with
5x250 GeV

need to be able to reconstruct
x, Q^2 from hadronic final-state

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u+c) + (1-y)^2(\bar{d} + \bar{s})} \quad A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta \bar{u} + \Delta \bar{c})}{(1-y)^2(d+s) + (\bar{u} + \bar{c})}$$

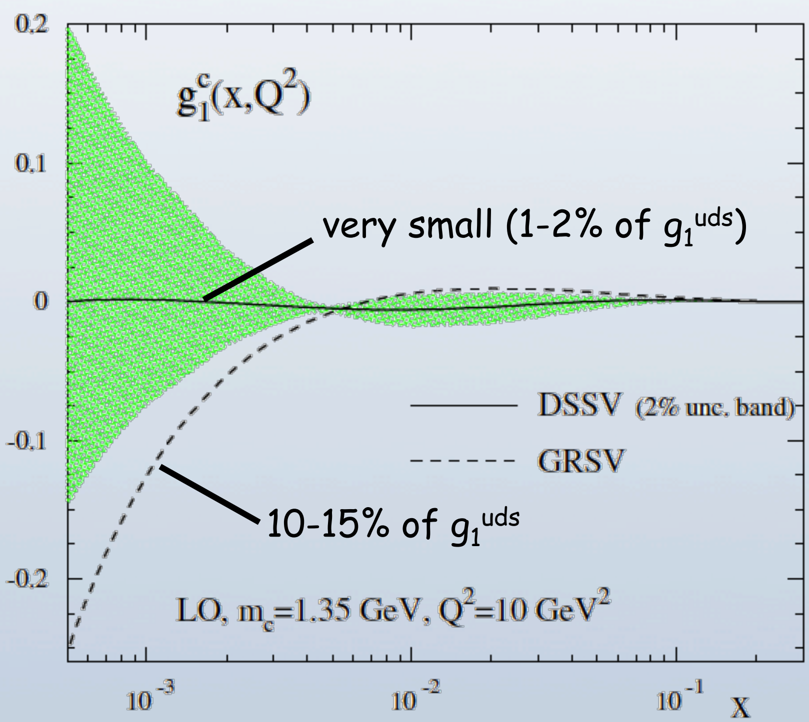
Cabibbo suppressed contributions neglected

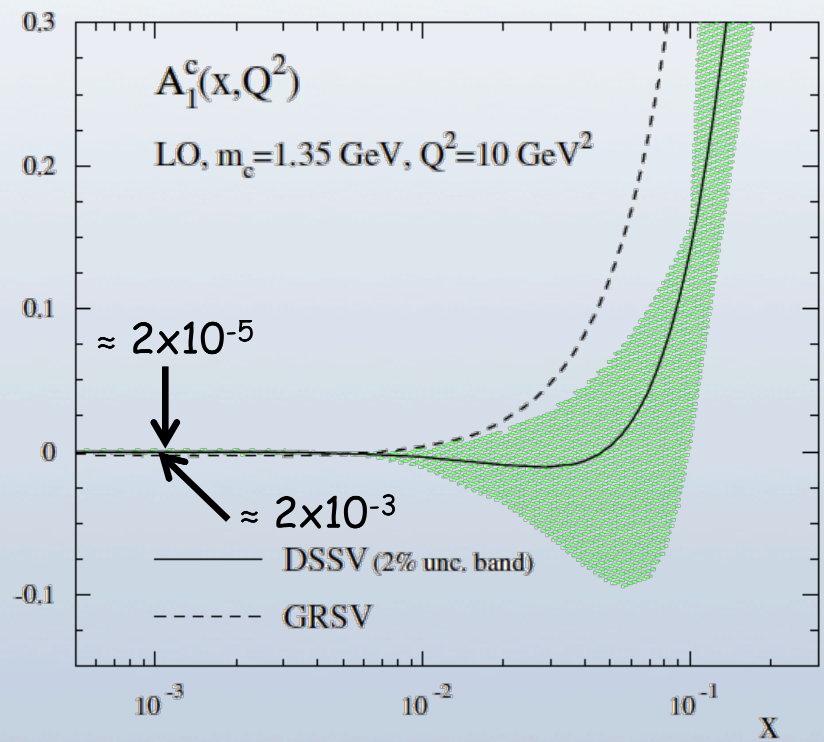
charm contribution to pol. DIS: g_1^c

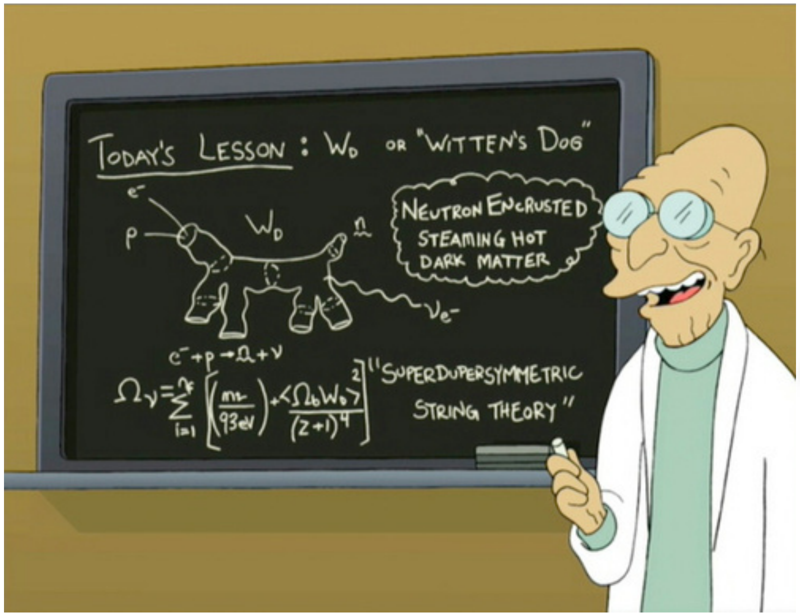
- so far safely ignored: « 1% to existing g_1 fixed-target data
- numerical relevance at an EIC depends strongly on size of Δg
- need massive Wilson coefficients (charm not massless for most of EIC kinematics) so far only known to LO (NLO is work in progress Kang, MS)

aside:
CC charm production probes strangeness PDF

some expectations: (need to be studied in more detail)







summary & outlook

- DSSV analysis of 2008 still in good shape
  - no official update imminent
  - need to update DSS fragmentation functions first
  - COMPASS SIDIS data nicely described
  - new RHIC run9 data may prefer somewhat larger Δg
- ready to include di-jet, W boson data, … at NLO as they become available
- for the time being, flavor separation depends largely on SIDIS data
  - important to further improve fragmentation functions; DSS global analysis efforts ongoing
- to address outstanding questions access to small x is required
  - **having an EIC in the future is essential** (the sooner the better)
  - its c.m.s energy must be sufficiently large to reach $x \approx 10^{-4}$
  - we will need to control systematic uncertainties with unprecedented accuracy