Jefferson Lab
Exploring the Nature of Matter

Theory Seminar, 02/14/11

Fragmentation Functions and Spin-Dependent PDFs

Status & Prospects

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outline

Anatomy of a
Global QCD Analysis

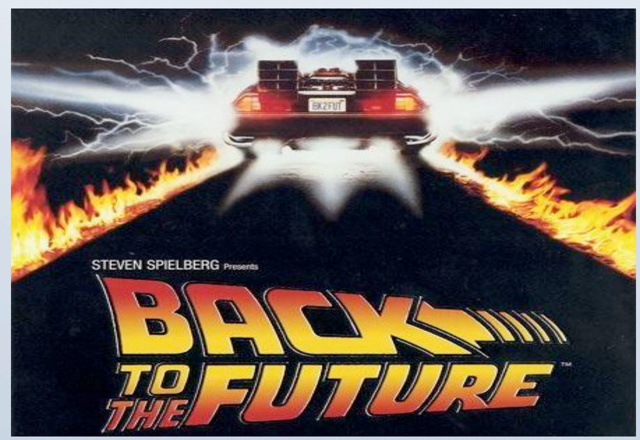
Brief Outline

Longitudinal Spin Structure

Status, DSSV+, New Data

Fragmentation

Status, New Results, New Data



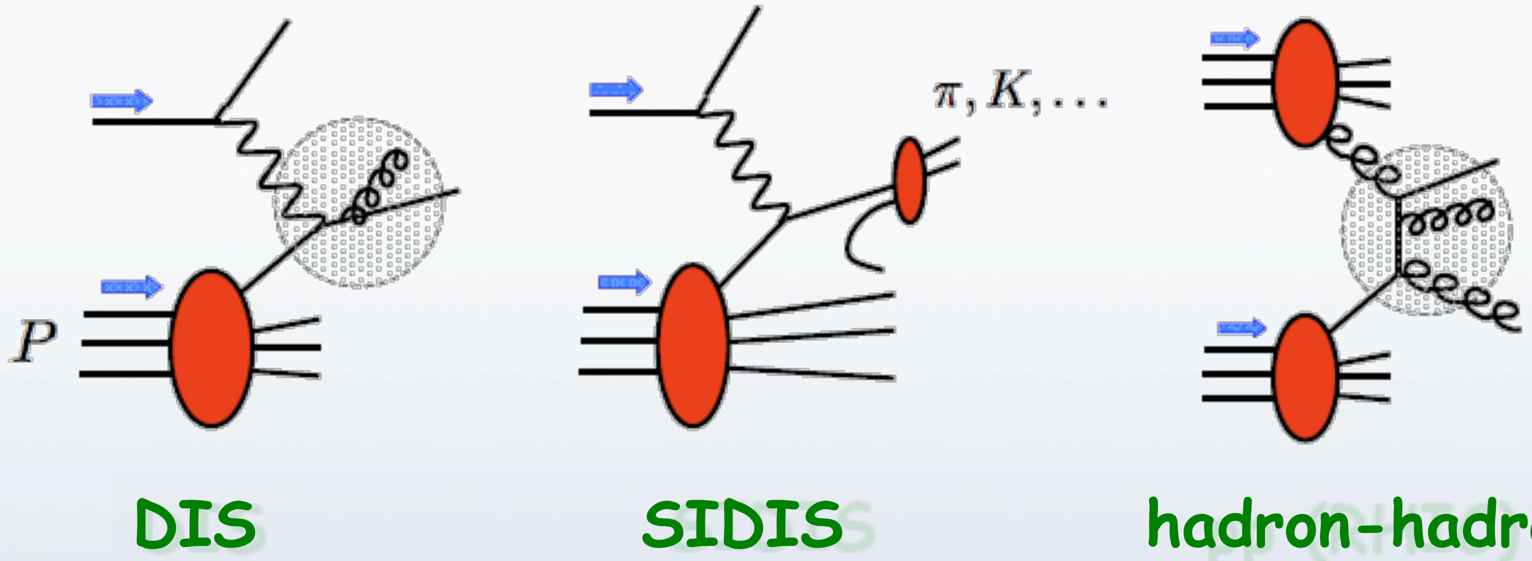
Future Avenues

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



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

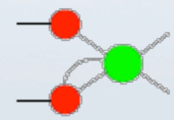
guiding principle: factorization

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

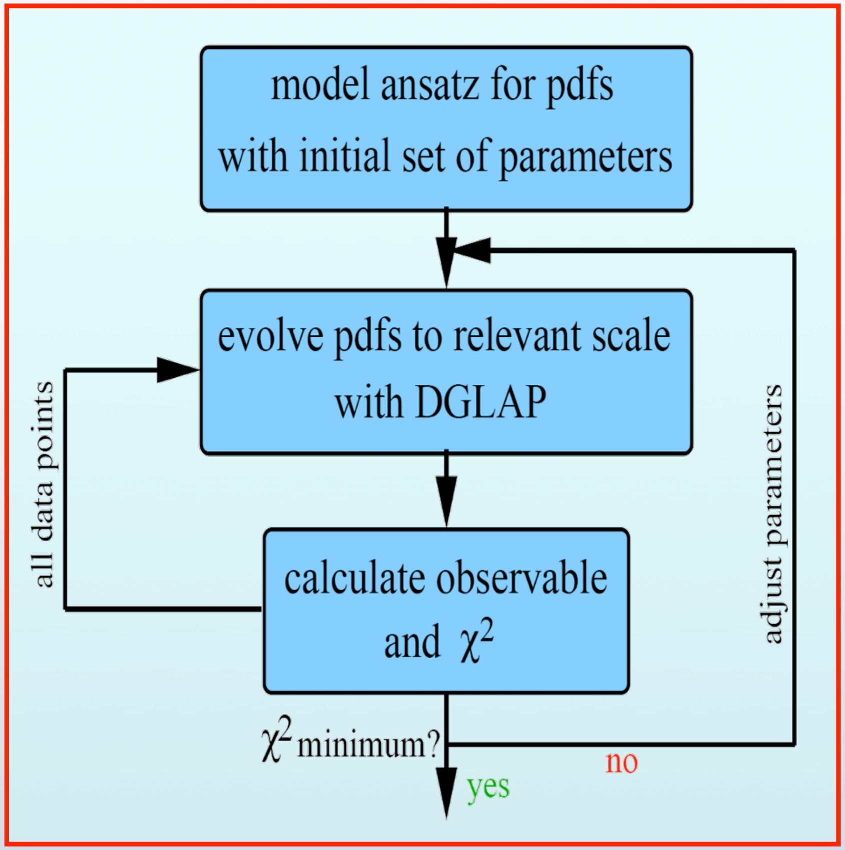


factorization …

- … 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, $\mu > \mu_0$ relevant for comparing with data by solving evolution eqs.

compute DIS, pp, … cross sections at NLO

judge goodness of current fit

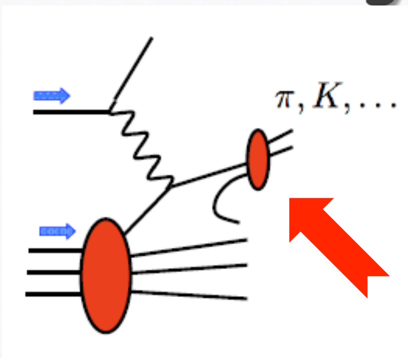
$$\chi^2 = \sum_i \frac{(T_i - E_i)^2}{\delta E_i^2}$$

optimum set of parameters $\{\alpha_i, \beta_i, \ldots\}$

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

Fragmentation

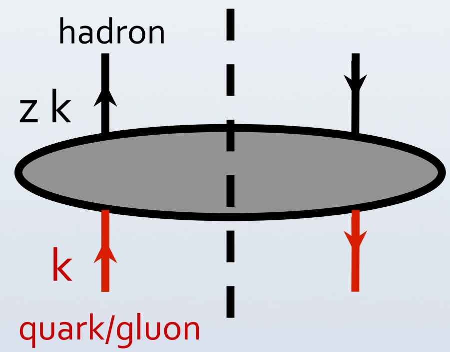
fragmentation functions: overview



crucial for pQCD interpretation (factorization) of all data with detected (identified) hadrons, e.g., SIDIS (HERMES, COMPASS), pp$\rightarrow\pi$X (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

timelike scale evolution of FFs

DGLAP $$\frac{dD_i^h(z,\mu^2)}{d\ln\mu^2} = \int_z^1 \frac{dy}{y} P_{ji}^T(z,\alpha_s) D_j^h\left(\frac{z}{y},\mu^2\right)$$

$$P_{ji}^T(z,\alpha_s) = \frac{\alpha_s}{4\pi} P_{ji}^{(0)T} + \left(\frac{\alpha_s}{4\pi}\right)^2 P_{ji}^{(1)T} + \left(\frac{\alpha_s}{4\pi}\right)^3 P_{ji}^{(2)T} + \ldots$$

same as space-like PDF evolution
Gribov-Lipatov relation

related to $P_{ij}^{(1)S}$ by analytic continuation
Curci, Furmanski, Petronzio; Floratos et al.; MS, Vogelsang

$P_{qq}^{(2)T}$, $P_{gg}^{(2)T}$ known
naïve AC fails: π^2 terms
Moch, Vogt

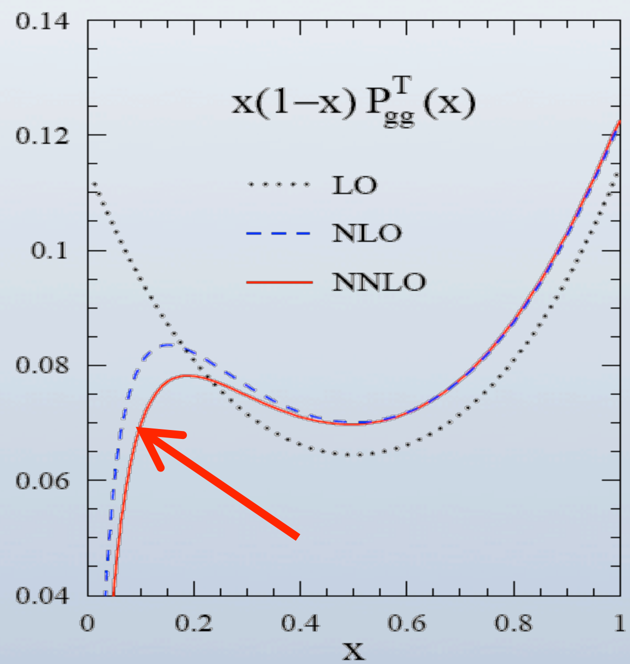
find

small-z behavior markedly different from space-like case: much more singular

$$zP_{gg}^{(n)T} \propto \alpha_s^n \ln^{2n} z$$

has impact already at $z \simeq 0.1$

resummations ?



limitations for the use of FFs

- however, small z region completely spoiled by "mass effects"

  [problem: hadron energy can be even smaller than its (neglected) mass]

  → need to introduce a cut on z, typically **$z \gtrsim 0.05 \div 0.1$**

- implies that sum rules are of limited practical use in fits of FFs

  "energy-momentum conservation": $\sum_h \int_0^1 z D_i^h(z,\mu) = 1$

  (a parton fragments with 100% probability into *something* preserving its momentum)

- FFs are - by definition - inclusive quantities

  → can compute *inclusive distributions* of hadrons with momentum fractions z but *not* a cross section for a "leading hadron"

  (under certain kin. conditions it might be a good approximation though)

- fragmentation is assumed to be independent of other colored particles

  → need a hard scale to be a valid approximation

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

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

- try to avoid assumptions on paramater space if possible

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

only normalization shifts can be fitted

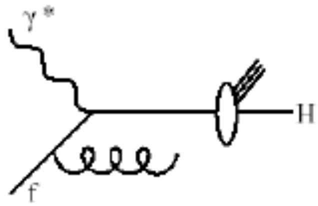
but data do not discriminate between other unfavored FFs:

$$D^{\pi^+}_{\bar{u}} = D^{\pi^+}_{d}$$

$$D^{K^+}_{\bar{u}} = D^{K^+}_{s} = D^{K^+}_{d} = D^{K^+}_{\bar{d}}$$

- 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^+

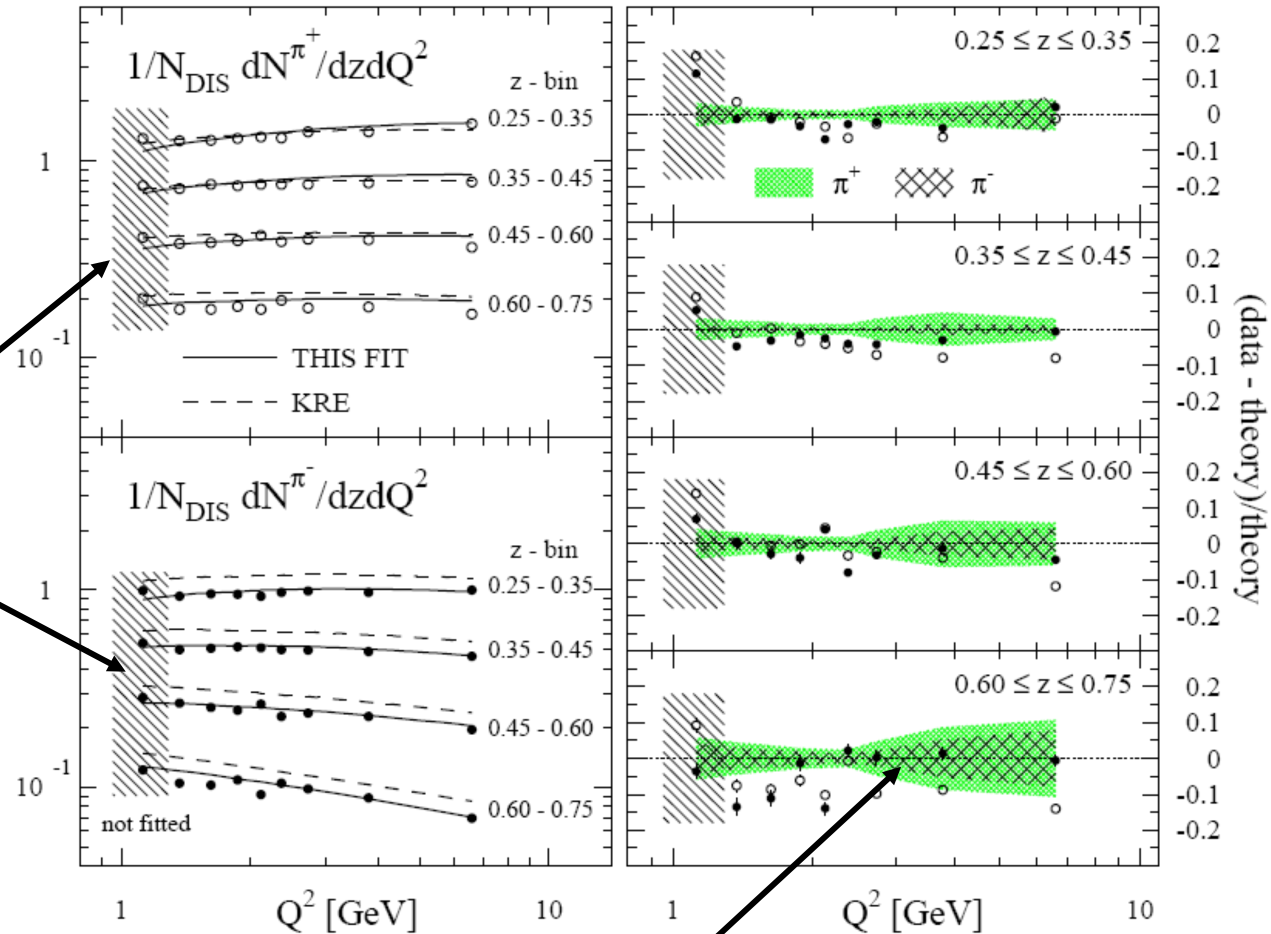
Kretzer's assumption

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

works for π^+

but not for π^-

π^-

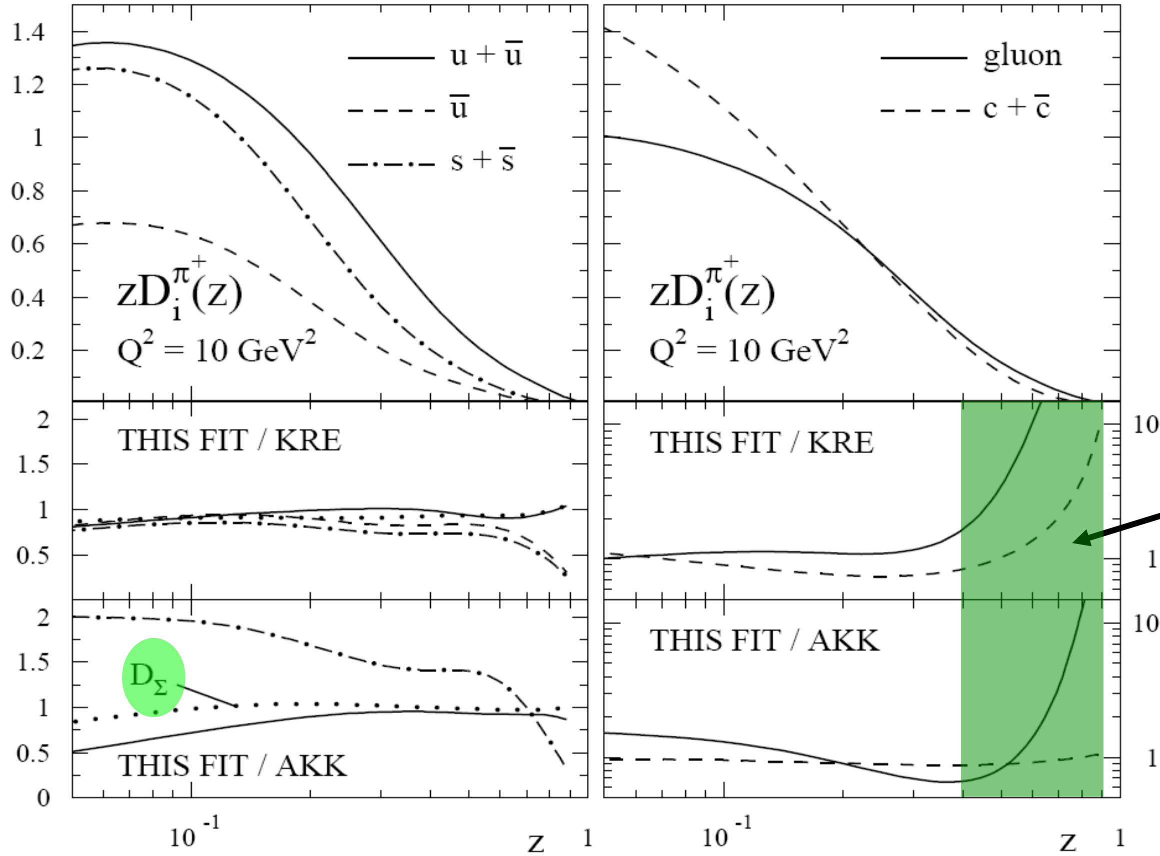


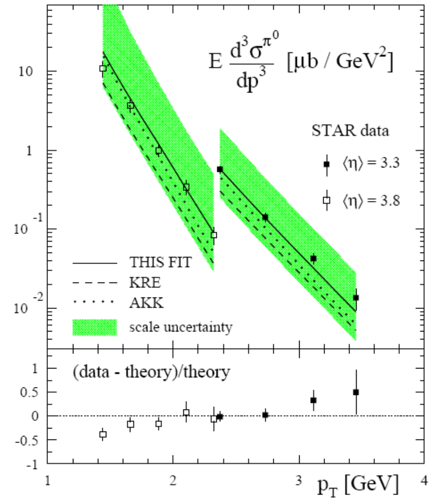
x,Q^2 range can be significantly extended at an EIC

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

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

$\langle z \rangle \gtrsim 0.6$





z-range of RHIC pp data explains differences in D_g

- singlet fragmentation D_Σ very similar (fixed by SIA at M_Z)
- u-frag. smaller than in AKK (due to SIDIS) ; compensated by larger D_s in SIA
- find: SU(2) violation < 10%; SU(3) violation $\simeq$ 17% (with large uncertainties)

charge symmetry violation ?

fit prefers a $\approx 9\%$ breaking (within large uncertainties!) driven by $\pi^{\pm}$ multiplicities

small, large, or just about right?

puzzling - need precision data to settle this

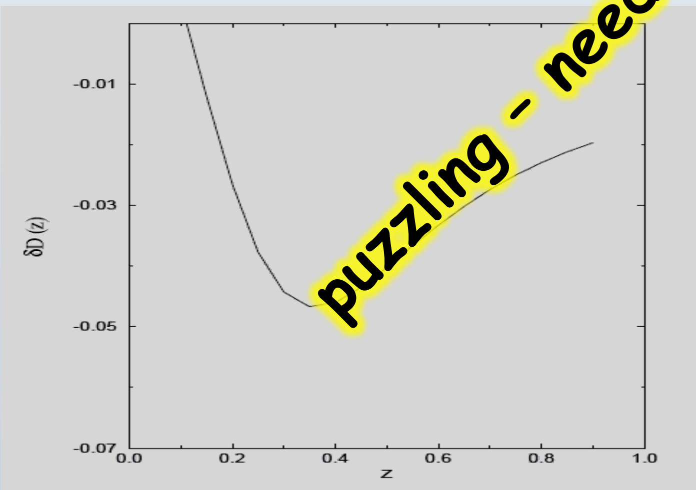
estimate magnitude in a simple model

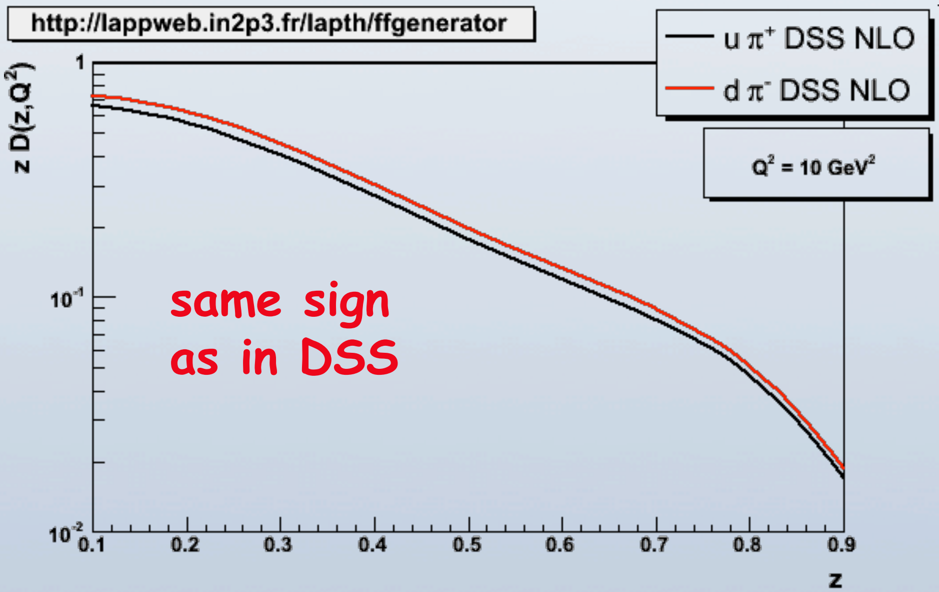
Londergan, Pang, Thomas
PRD54 (1996) 3154

define charge-symmetry breaking as

$$\delta D(z) = \frac{D_u^{\pi^+} - D_d^{\pi^-}}{D_u^{\pi^+}}$$

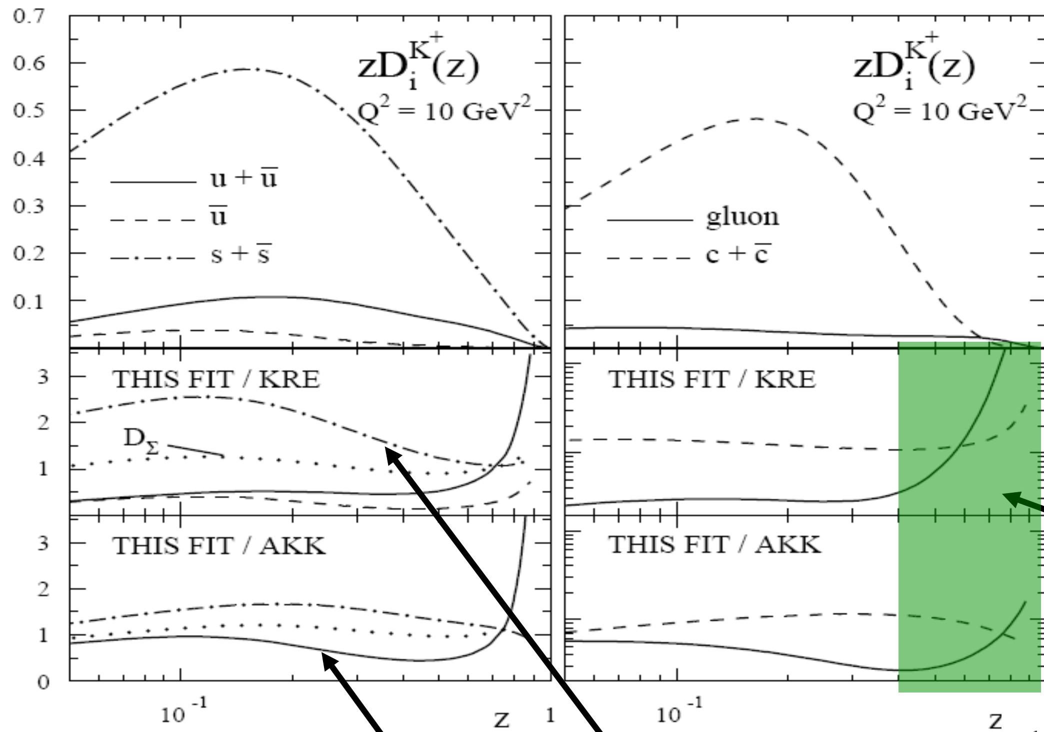
find $\delta D(z) < 0$ and O(few percent)

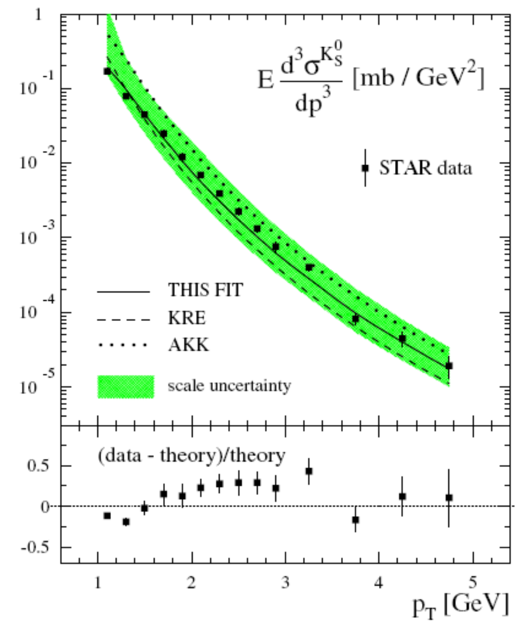




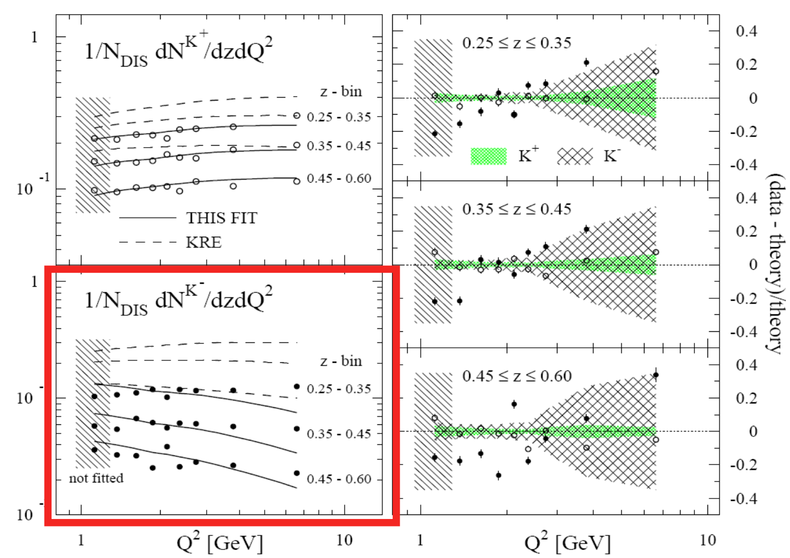
same sign
as in DSS

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





again, 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!)

await final HERMES data

other recent fits of NLO FFs

table from arXiv:0804.2021 (ECT* FF workshop)

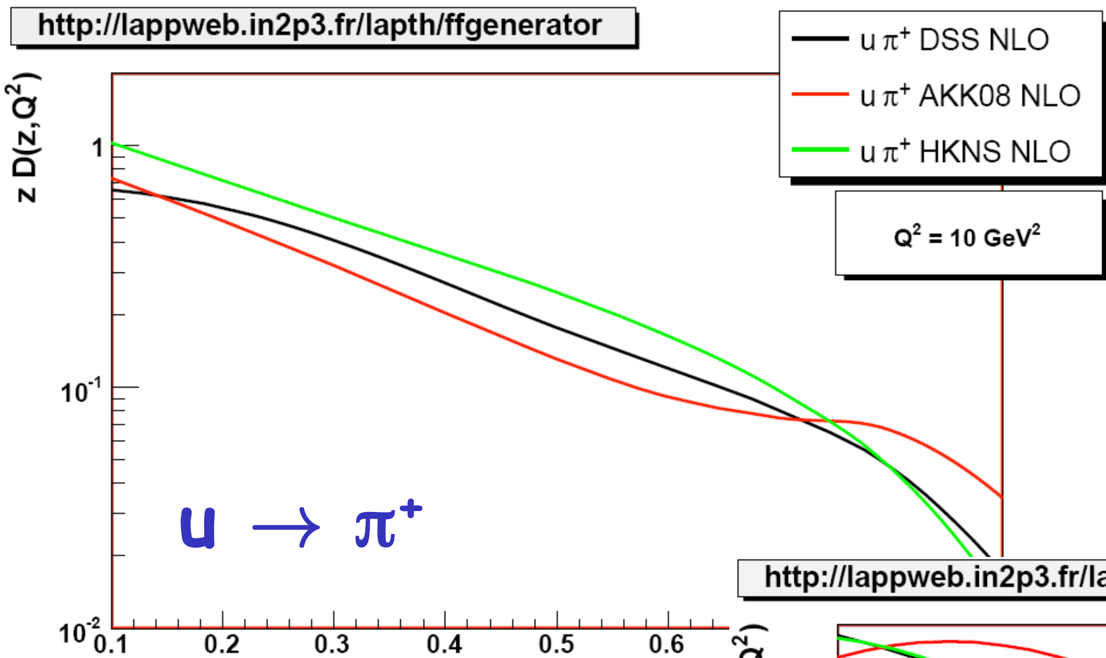
Name	Ref.	Species	Error	$z_{\min}$	Q^2 (GeV^2)
AKK	[4]	$\pi^\pm, K^\pm, K_s^0, p, \bar{p}\,\Lambda, \bar{\Lambda}$	no	0.1	$2-4\cdot 10^4$
AKK08	[5]	$\pi^\pm, K^\pm, K_s^0, p, \bar{p}\,\Lambda, \bar{\Lambda}$	yes	0.05	$2-4\cdot 10^4$
BKK	[6]	$\pi^+ + \pi^-, \pi^0, K^+ + K^-, K^0 + \bar{K}^0, h^+ + h^-$	no	0.05	$2-200$
BFG	[7]	γ	no	10^{-3}	$2-1.2\cdot 10^4$
BFGW	[8]	$h^\pm$	yes[1]	10^{-3}	$2-1.2\cdot 10^4$
CGRW	[9]	π^0	no	10^{-3}	$2-1.2\cdot 10^4$
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

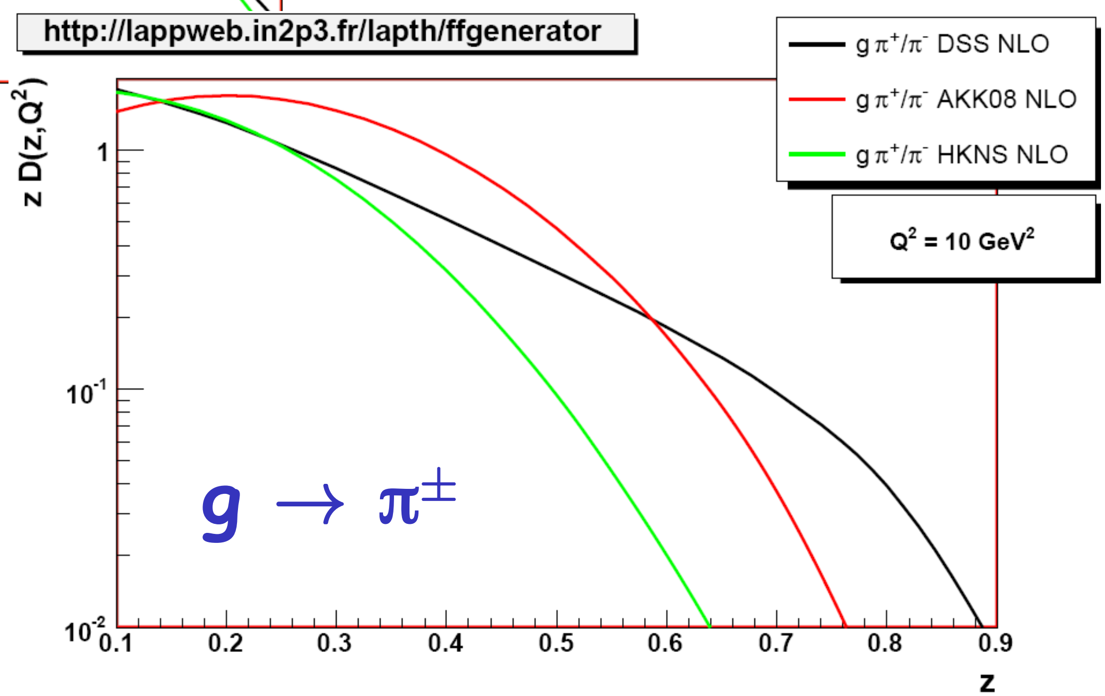
AKK08:
- e^+e^- & pp data
- impose isospin sym. for pions
- Hessian method for uncertainties
- fit hadron masses
- large-z resummations
- mass corrections (look ad hoc for pp)

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

comparison with other 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 ?

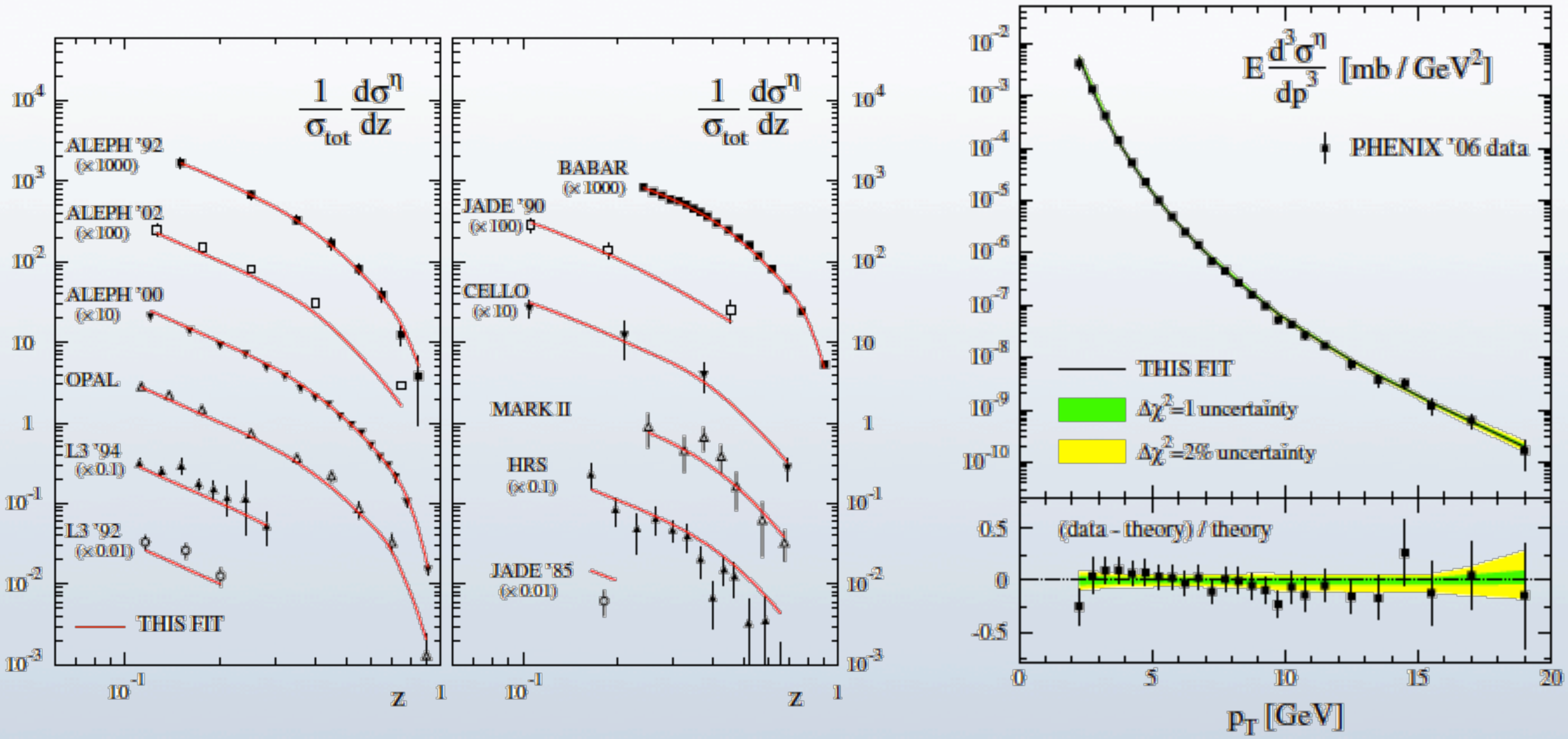
recall: DSS, AKK08, HKNS
are based on different data sets
and assumptions

latest addition to suite of FFs: eta

C. Aidala, F. Ellinghaus,
J. Seele, R. Sassot, MS
PR D83 (2011) 034002

all light quark & antiquarks in wavefunction

$$|\eta\rangle \simeq |u\bar{u} + d\bar{d} - 2s\bar{s}\rangle$$



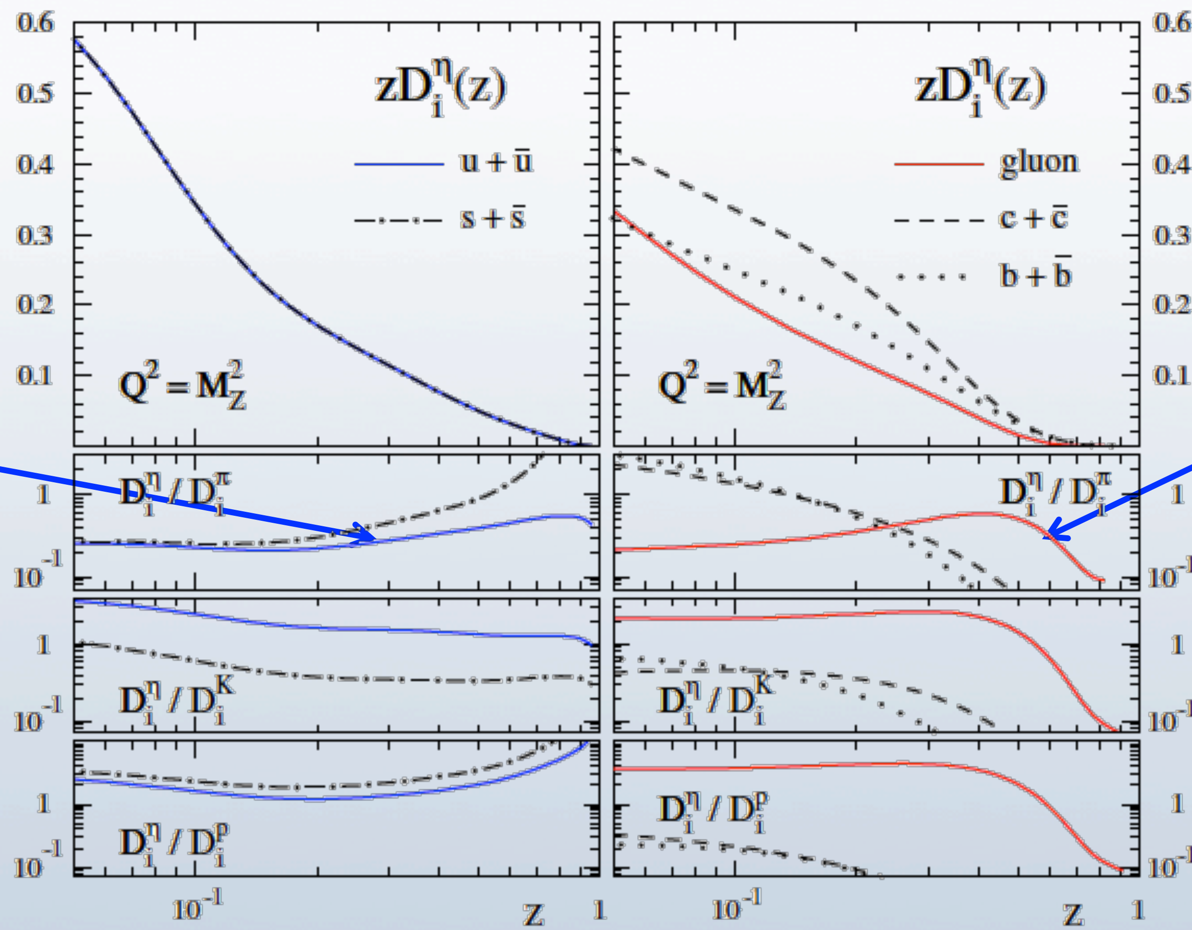
complication: no c, b tagged e^+e^- data; no SIDIS data --> η FF less well constrained

eta fragmentation functions

forced to assume (lack of data): $D_u^\eta = D_{\bar{u}}^\eta = \ldots = D_{\bar{s}}^\eta$

reflects z-dep. of η/π ratio in e^+e^- collisions

(probes mainly D_q)



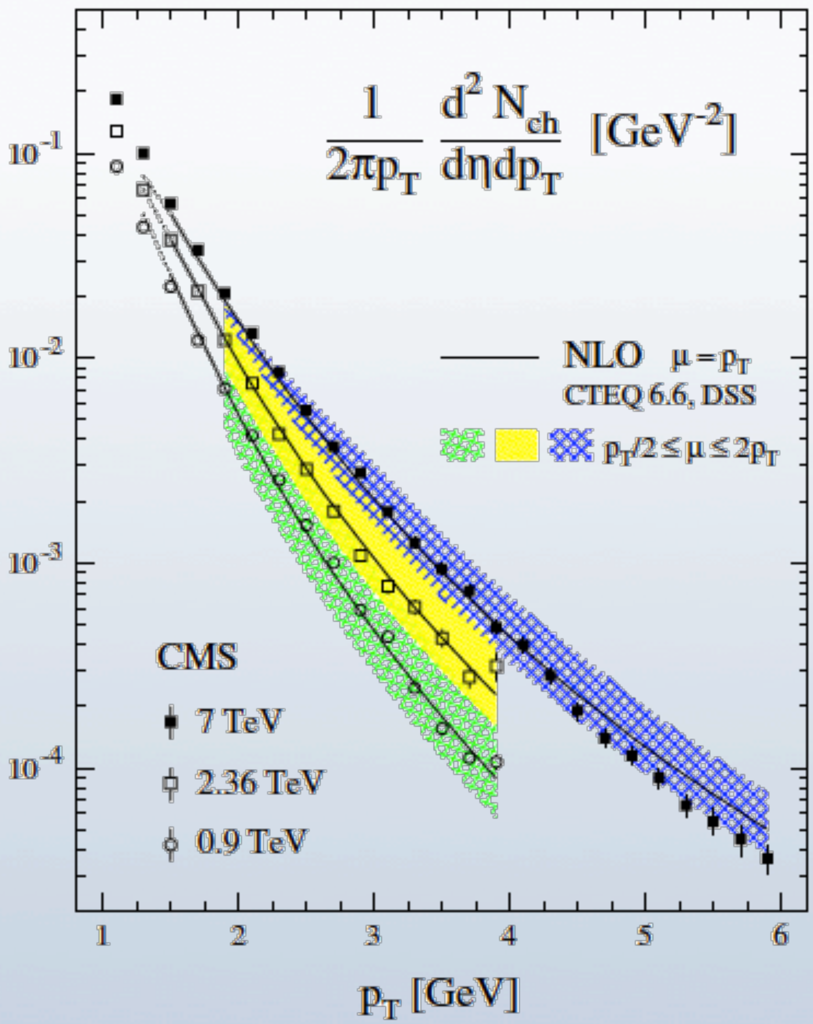
η/π ratio in pp roughly $\frac{1}{2}$

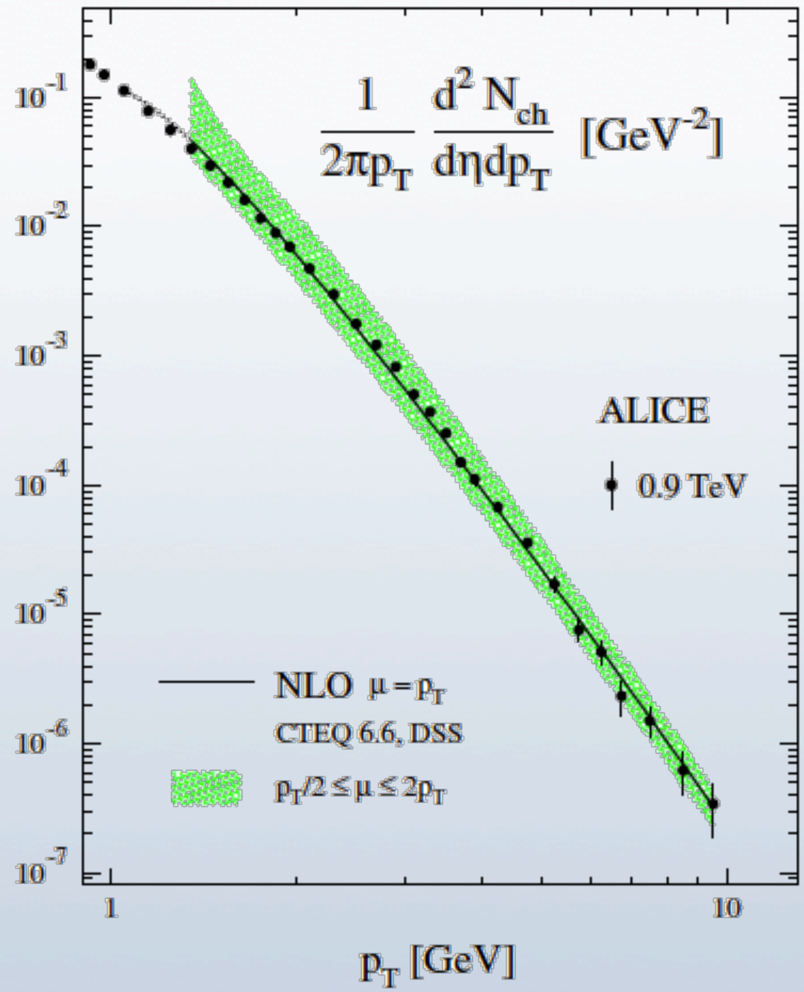
(probes mainly D_g at large z)

towards DSS 2 : new data sets

- DSS doing well for 1st charged hadron spectra from the LHC

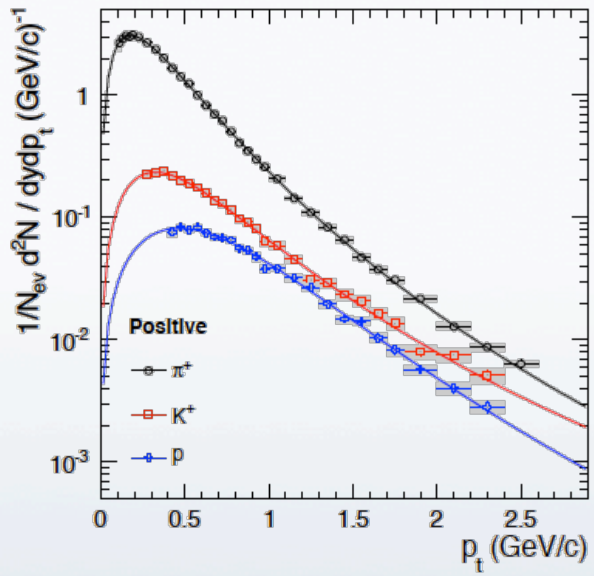
R. Sassot, MS, P. Zurita

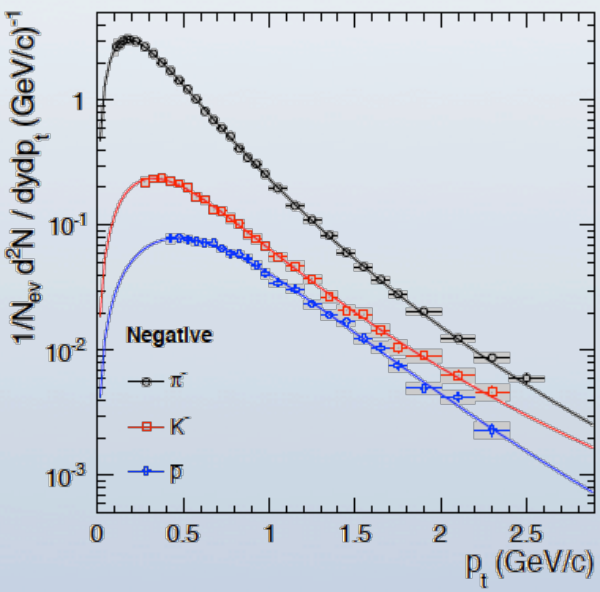




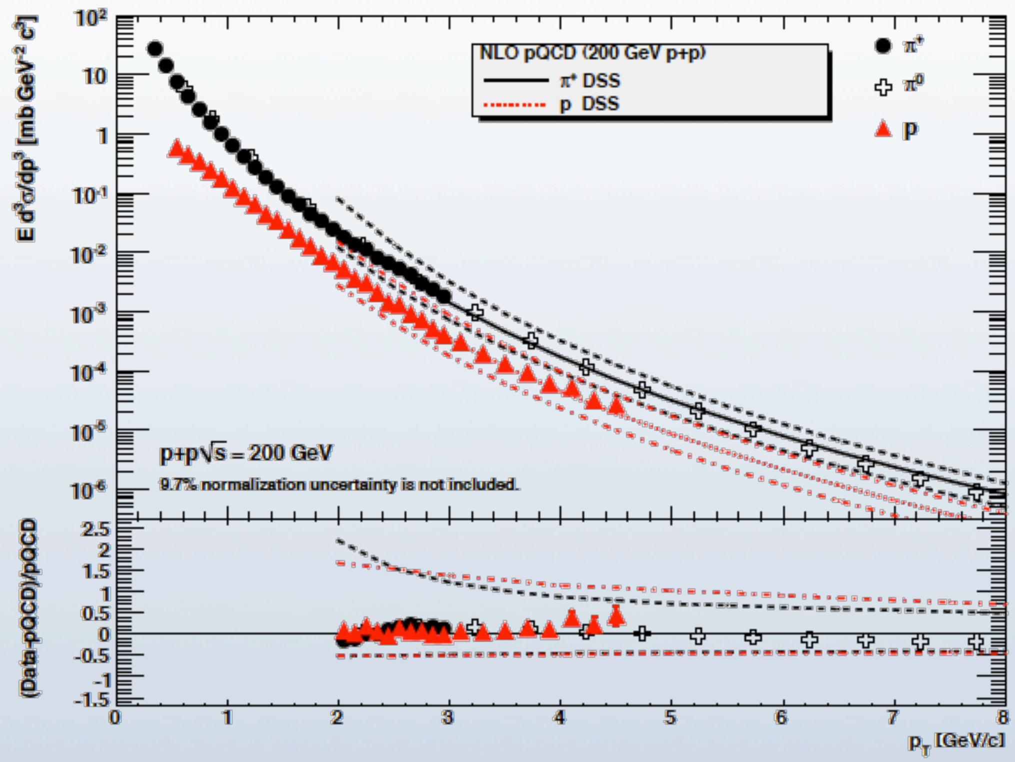
new identified hadron spectra

ALICE: 900 GeV pp, arXiv:1101.4110





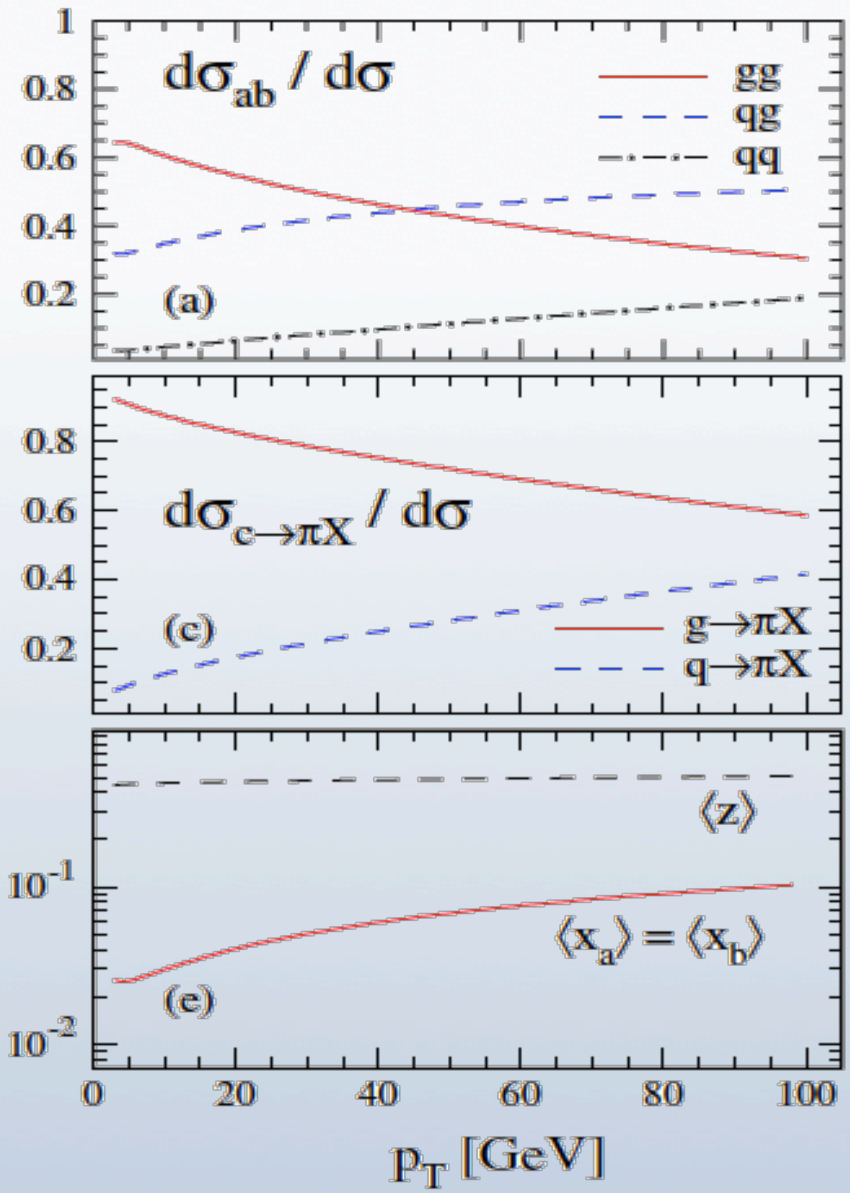
PHENIX: 200 & 62.4 GeV pp, arXiv:1102.0753

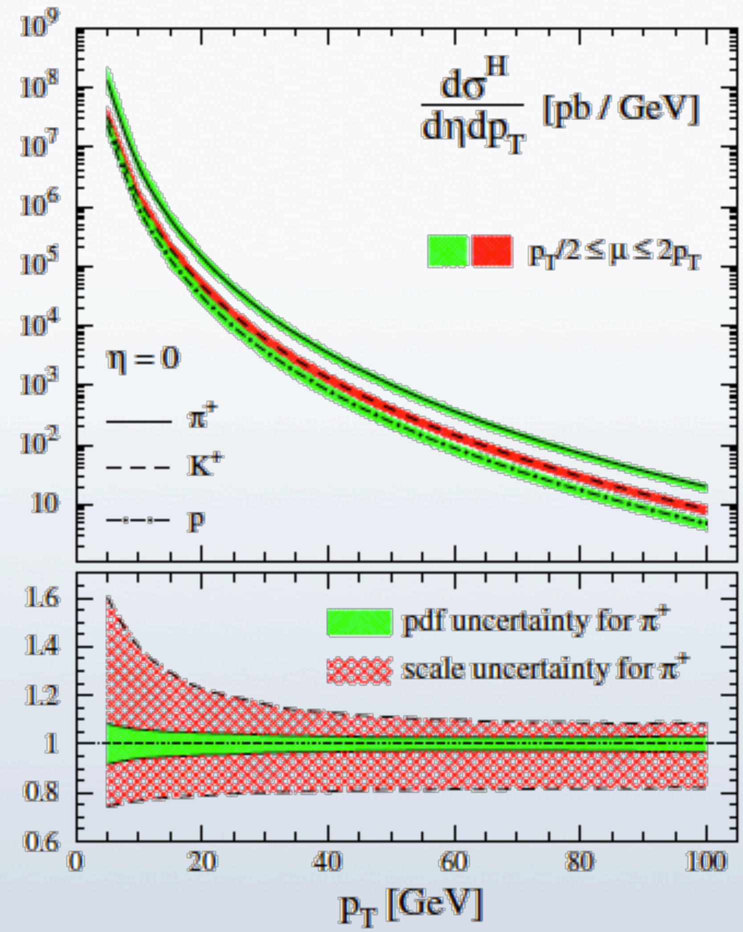


much more to come from the LHC

FFs from pp data

R. Sassot, MS, P. Zurita



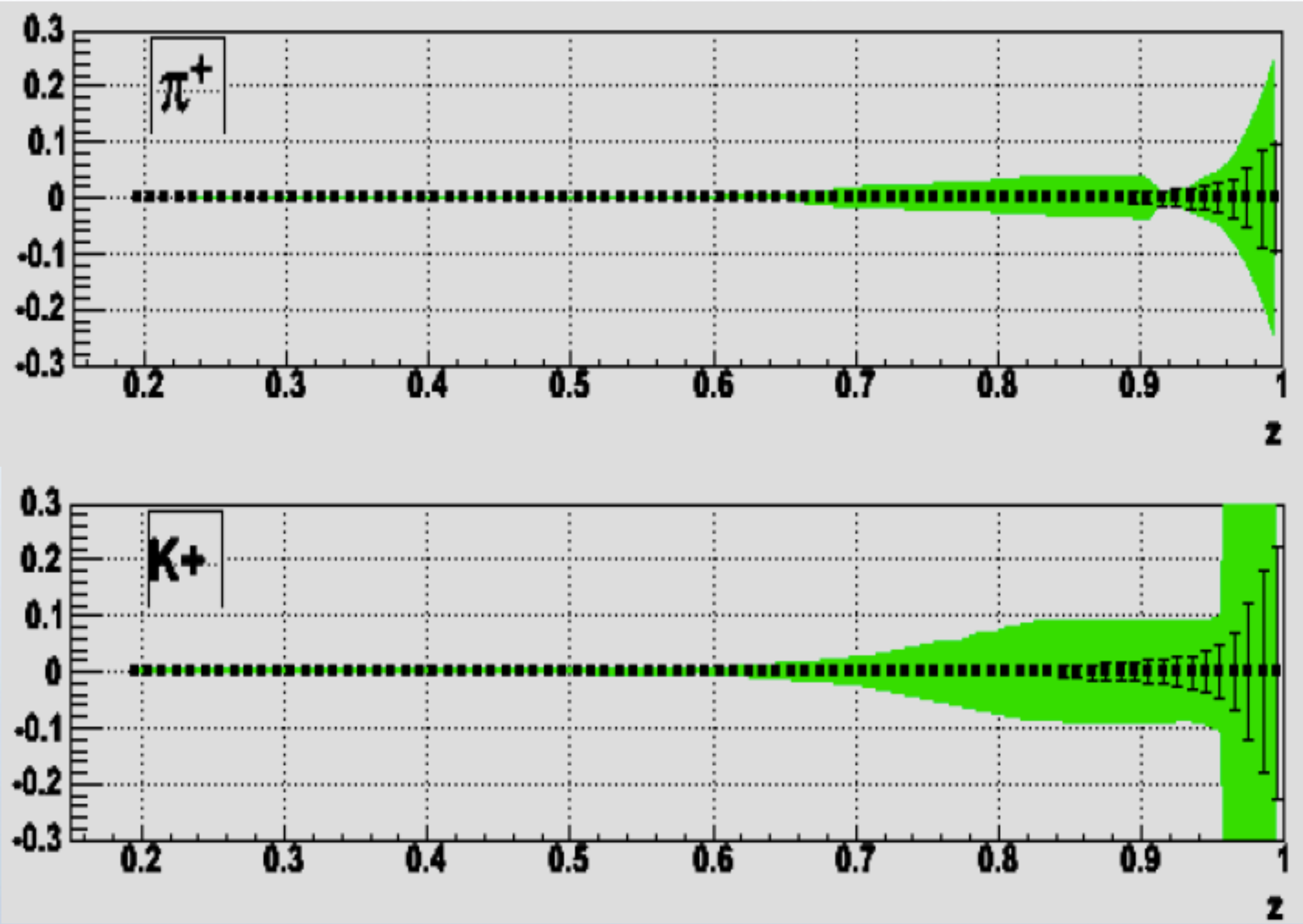


- dominated by gluons up to fairly large p_T
- probes mainly z values around 0.4 ÷ 0.5
- scale uncertainties larger than PDF unc.

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

BELLE: projected relative stat. and sys. uncertainties

M. Leitgab @ DIS 2010



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

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

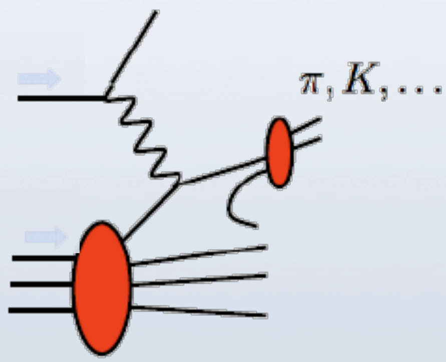
- data will allow for precision studies of scaling violations -> D_g
- unique access to FFs at large z

hadronization in a nuclear medium

- increasing number of data available: clear indication of non-trivial A dependence
  - SIDIS off nuclei (HERMES) show strong "hadron attenuation" (R < 1)
  - dAu data (BRAHMS, PHENIX, STAR) show both R < 1 and R > 1 ("Cronin effect")

Q: how far can one push factorization & universality

R. Sassot, MS, P. Zurita
PRD81 (2010) 054001



$f_{i/p}(x, Q^2)$	$\rightarrow$	$f_{i/A}(x, Q^2)$
vacuum/nucleon		nuclei
$D^H_{i/p}(z, Q^2)$	$\rightarrow$	$D^H_{i/A}(z, Q^2)$

complication:

- no straightforward probe (= e^+e^-) for nFFs – always entangled with nPDFs

  use "known" nDS (EPS) nPDFs to isolate medium effects in the initial state

medium modified pion FFs

R. Sassot, MS, P. Zurita
PRD81 (2010) 054001

choose a "**convolutional approach**"

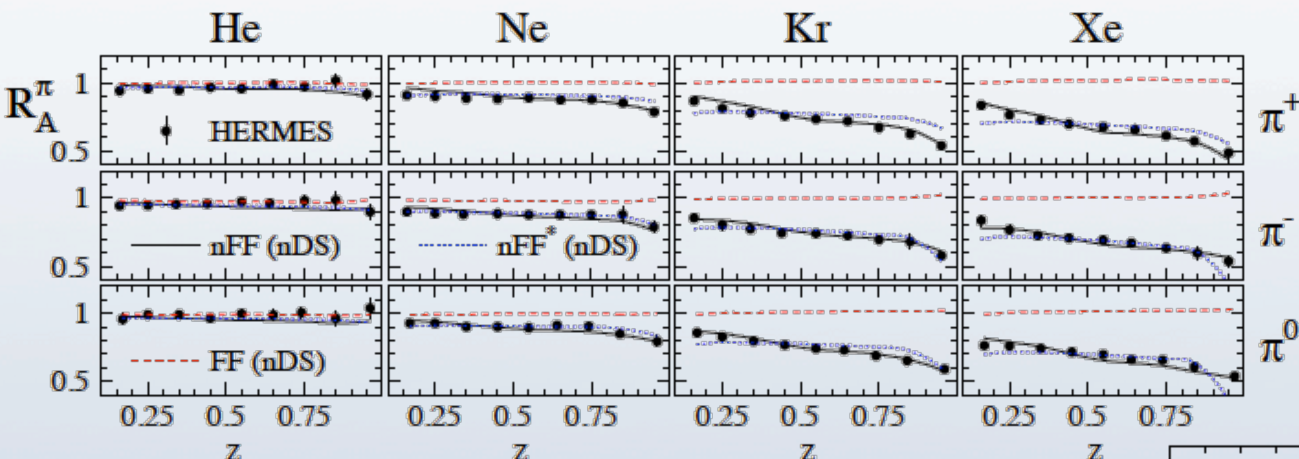
$$D^{H}_{i/A}(z,Q_0^2) \equiv \int_z^1 dy\, W_i(y,A)\, D^{H}_{i/p}(\frac{z}{y},Q_0^2)$$

"weight fct" to be fitted

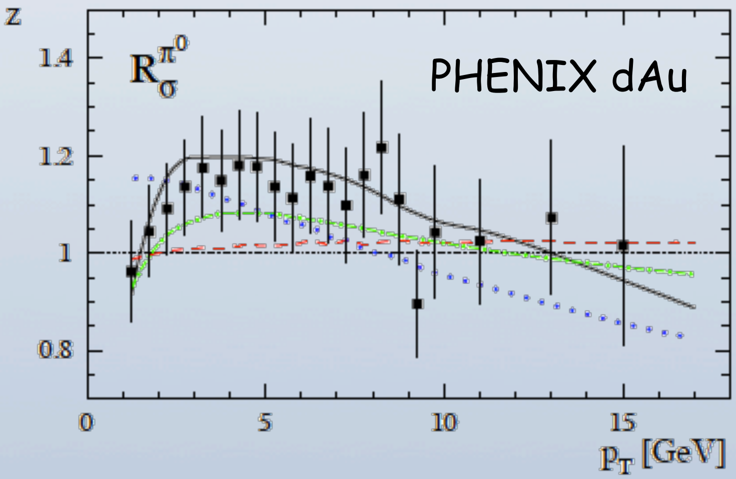
from DSS global analysis

find:

- $D_{q/A}$: suppression incr. with A
- $D_{g/A}$: enhanced around $z \approx 0.5$

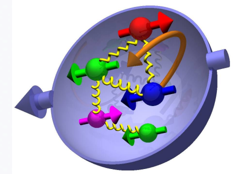


- only nPDFs does not work well (dashed lines)
- medium effect in initial & final-state (solid lines) works very well



Longitudinal Spin Structure of the Nucleon

special interest in polarized PDFs



holy grail: proton spin sum - a key measurement at an EIC ?

A^+=0 gauge version

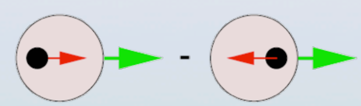
Jaffe, Manohar; Ji; …

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

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

"quotable" properties of the nucleon

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



- requires good knowledge of $\Delta g(x)$ and $\Delta\Sigma(x)$ for a given Q^2
  not to mention orbital angular momentum (OAM)
- low x needed to capture most of the 1st moment integrals, e.g. $S_g = \int_0^1 \Delta g(x) dx$
- however, should not focus too much on one moment; want to know full x-dep. !
- picture emerging from present data still rather fuzzy and inconclusive

DSSV analysis – highlights

- 1st global QCD analysis of polarized PDFs; consistently performed at NLO

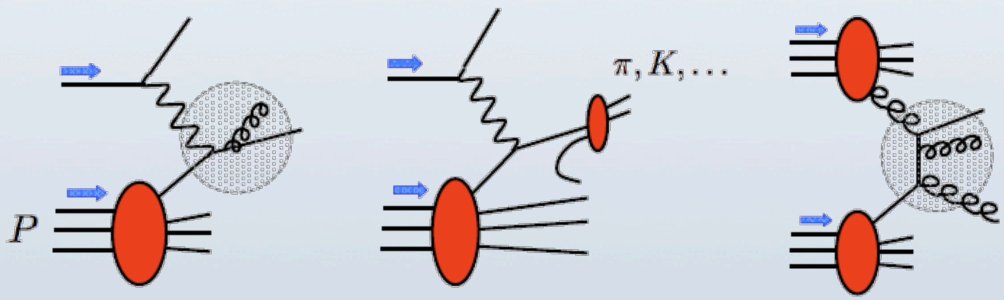
- flexible functional form $x\Delta f_j(x, 1\,\text{GeV}) = N_j\, x^{\alpha_j}\,(1-x)^{\beta_j}\left[1 + \kappa_j\sqrt{x} + \gamma_j x\right]$

  possible nodes

  assumptions on parameter space avoided as much as possible

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

- excellent description of world data



DIS SIDIS pp (RHIC)

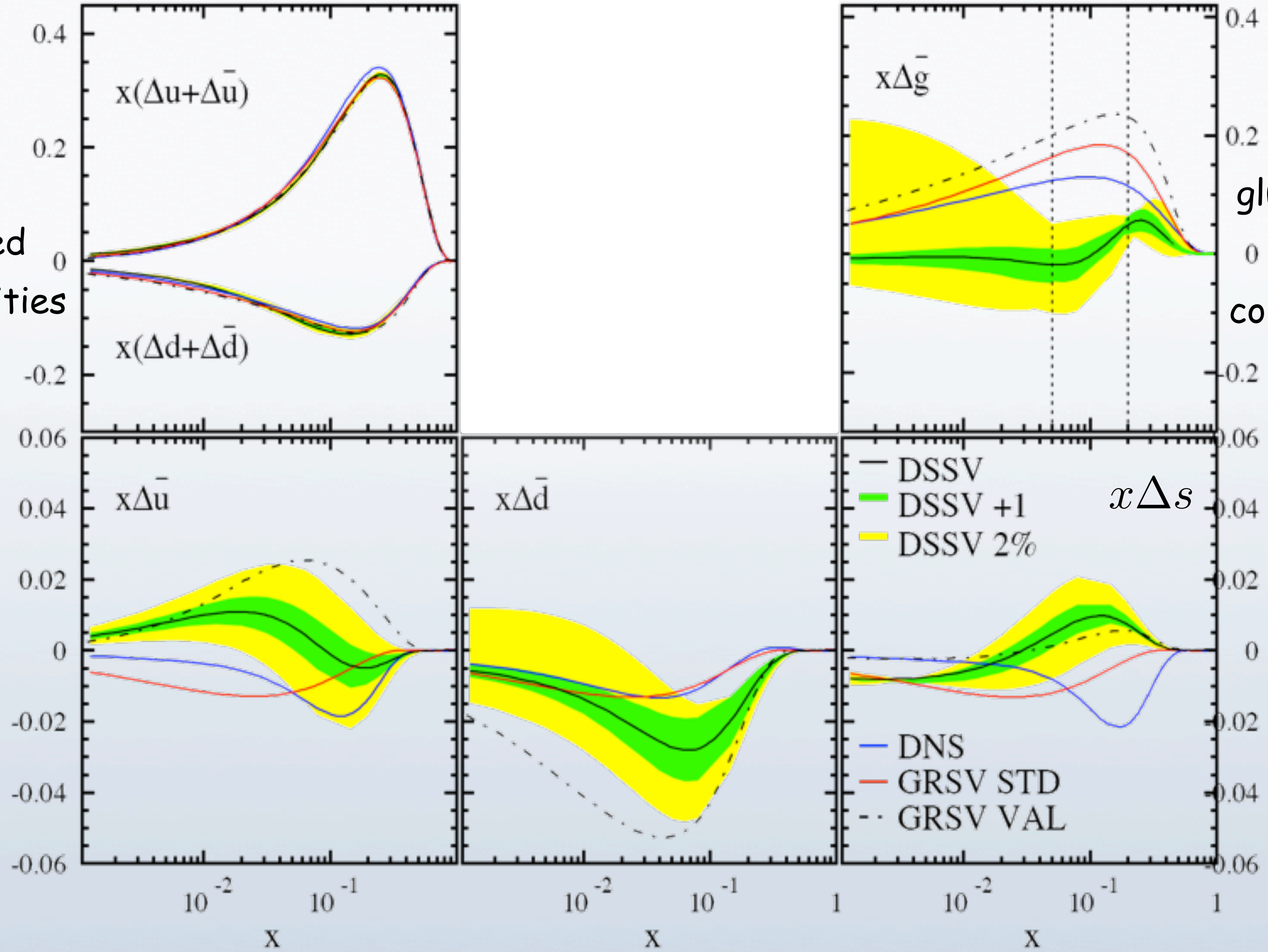
(χ^2 / d.o.f. $\simeq 0.88$)

- estimates of PDF uncertainties with Lagrange multipliers & Hessian method

DSSV: de Florian, Sassot, MS, Vogelsang; PRL 101 (2008) 072001; PRD 80 (2009) 034030

DSSV analysis – emerging picture

well determined
total quark densities



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

indications for non-trivial
sea quark polarizations

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

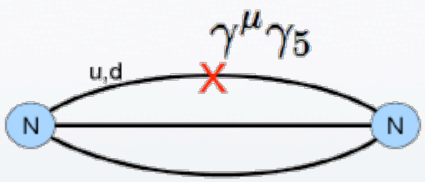
surprising strangeness polarization
(also found in lattice QCD; sizable SU(3) breaking?)
Bali et al., 0811.0807; 0911.2407

flavor separation only from SIDIS; depends on fragmentation functions (global NLO fit by DSS)
de Florian, Sassot, MS

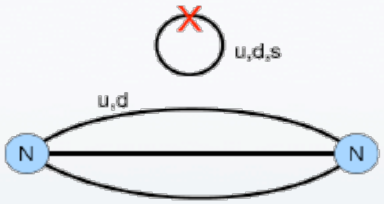
strangeness conundrum

1st attempts to compute disconnected (sea) contributions on the lattice

Bali, Collins, Schafer, arXiv:0811.0807v2; 0911.2407



connected

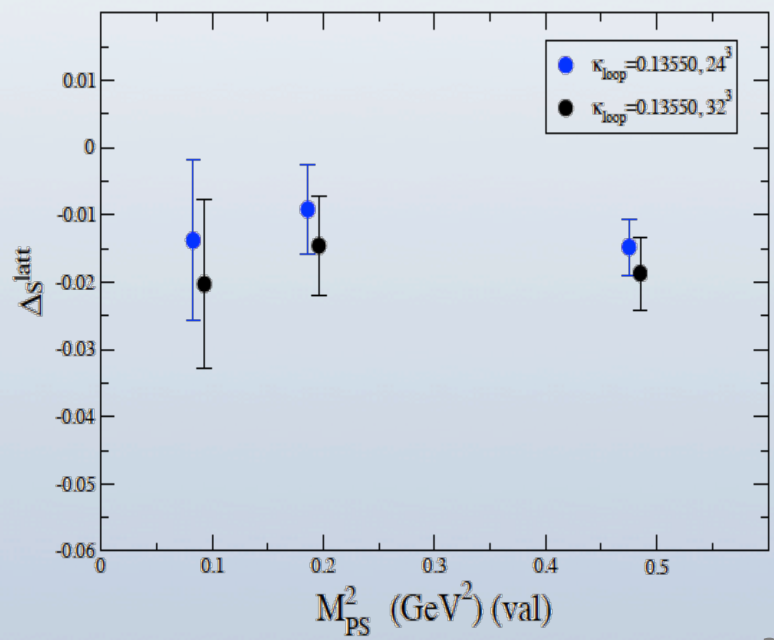


disconnected

find: $\frac{1}{2}\int_0^1[\Delta s+\Delta\bar{s}](x)\,dx = -0.01 \pm 0.007$

[DSSV w/ SU(3): -0.06 !!]

issues: not renormalized yet, continuum extrapolation, ...



SU(3) strongly broken ?

perhaps $\Delta s = -\Delta\bar{s}$?

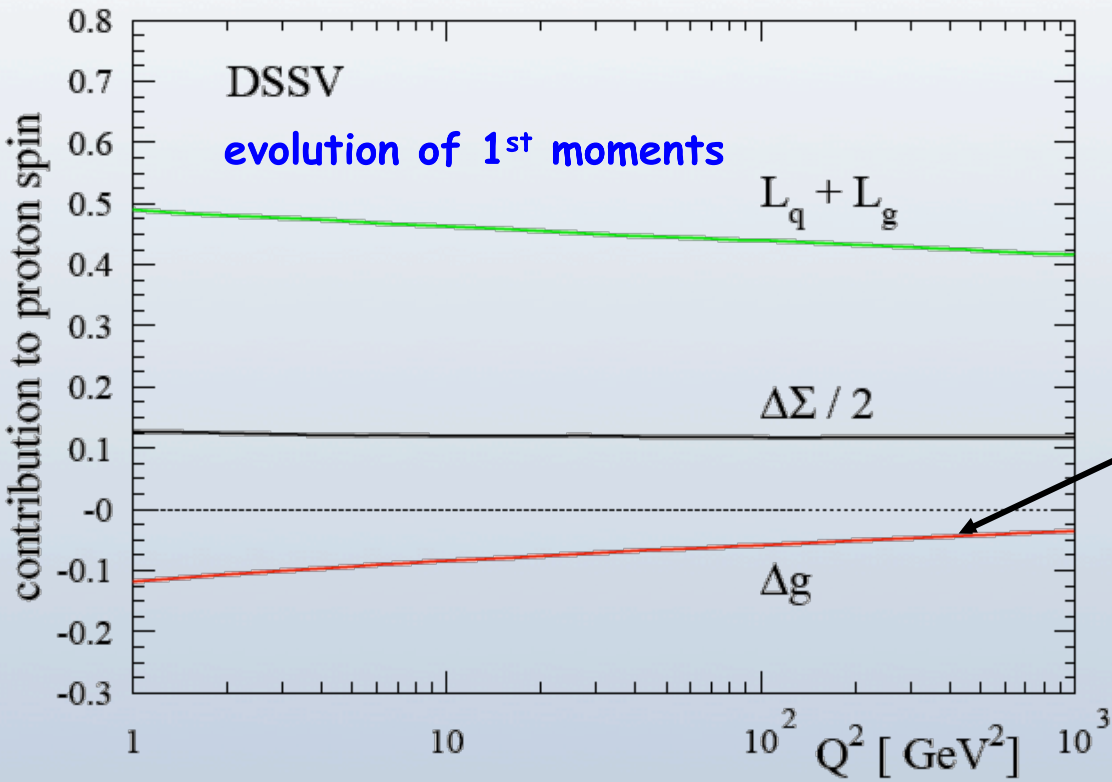
assumed SU(3) symmetry certainly debatable
at 20÷30 % level M. Savage @ INT 10-3

an observation about the spin sum rule

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

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

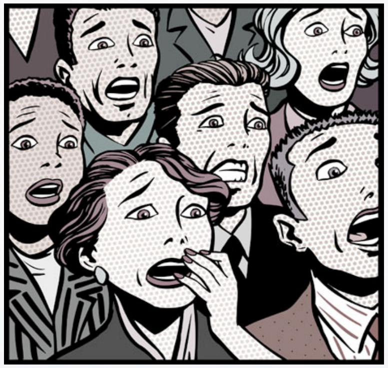
in general, Δg evolves logarithmically but there is a "static solution" (in LO)



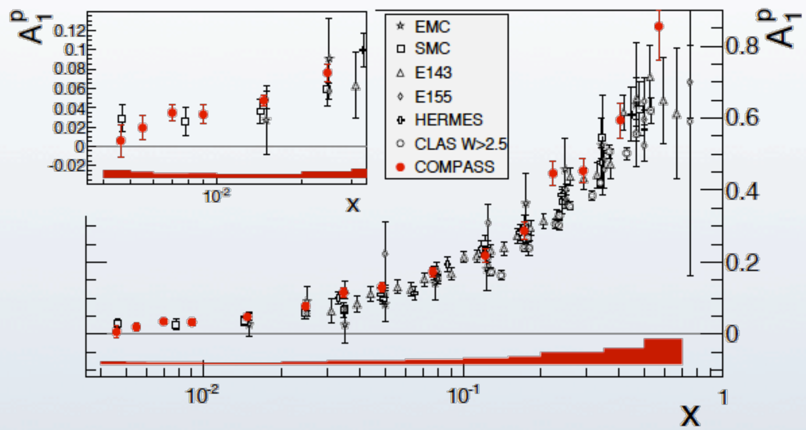
DSSV Δg is close to **"static solution"** $\Delta g \simeq -0.15$ where $d\Delta g/d\ln\mu = 0$

any deeper reason for that ?

meanwhile, new data became available …

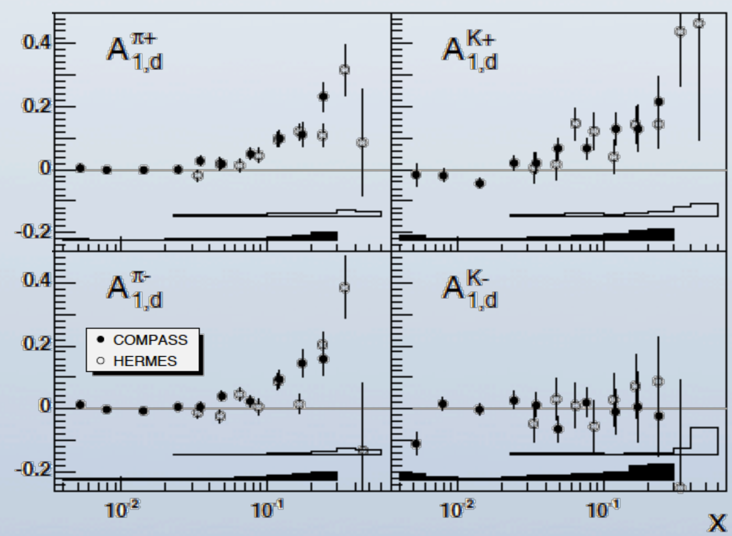


- how well are we doing ?
- refit/new analysis necessary ?
- impact on uncertainties ?



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

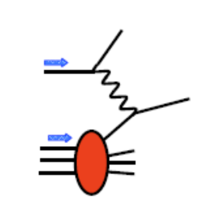
- **SIDIS:** $A_{1,d}^{\pi,K}$ from COMPASS
  arXiv:0905.2828

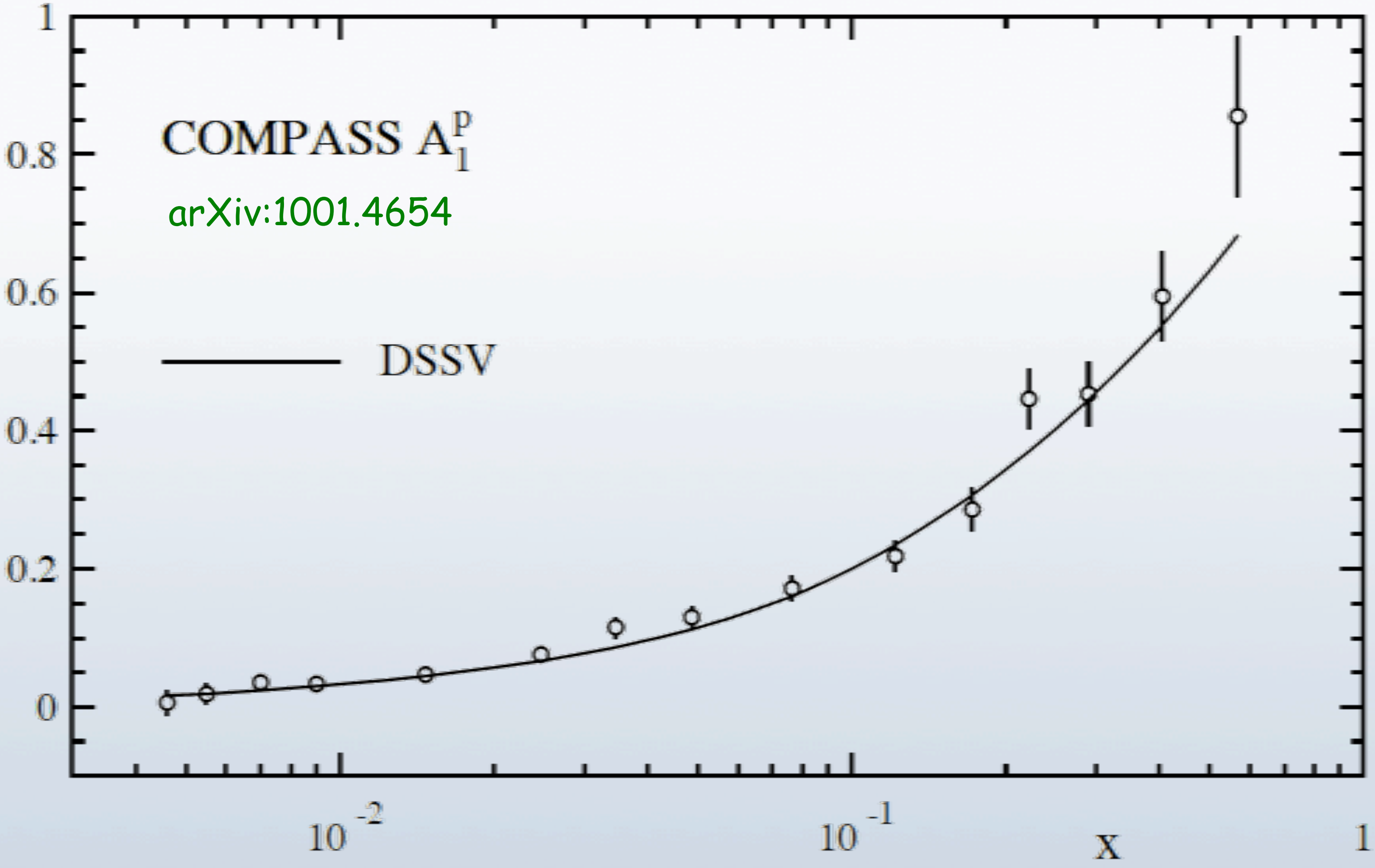


- **SIDIS:** $A_{1,p}^{\pi,K}$ from COMPASS
  arXiv:1007.4061

extended x coverage w.r.t. HERMES

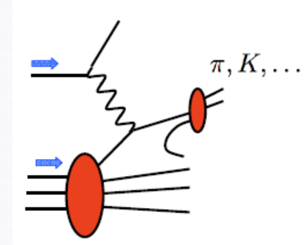
coping with new data: DIS A_1^p

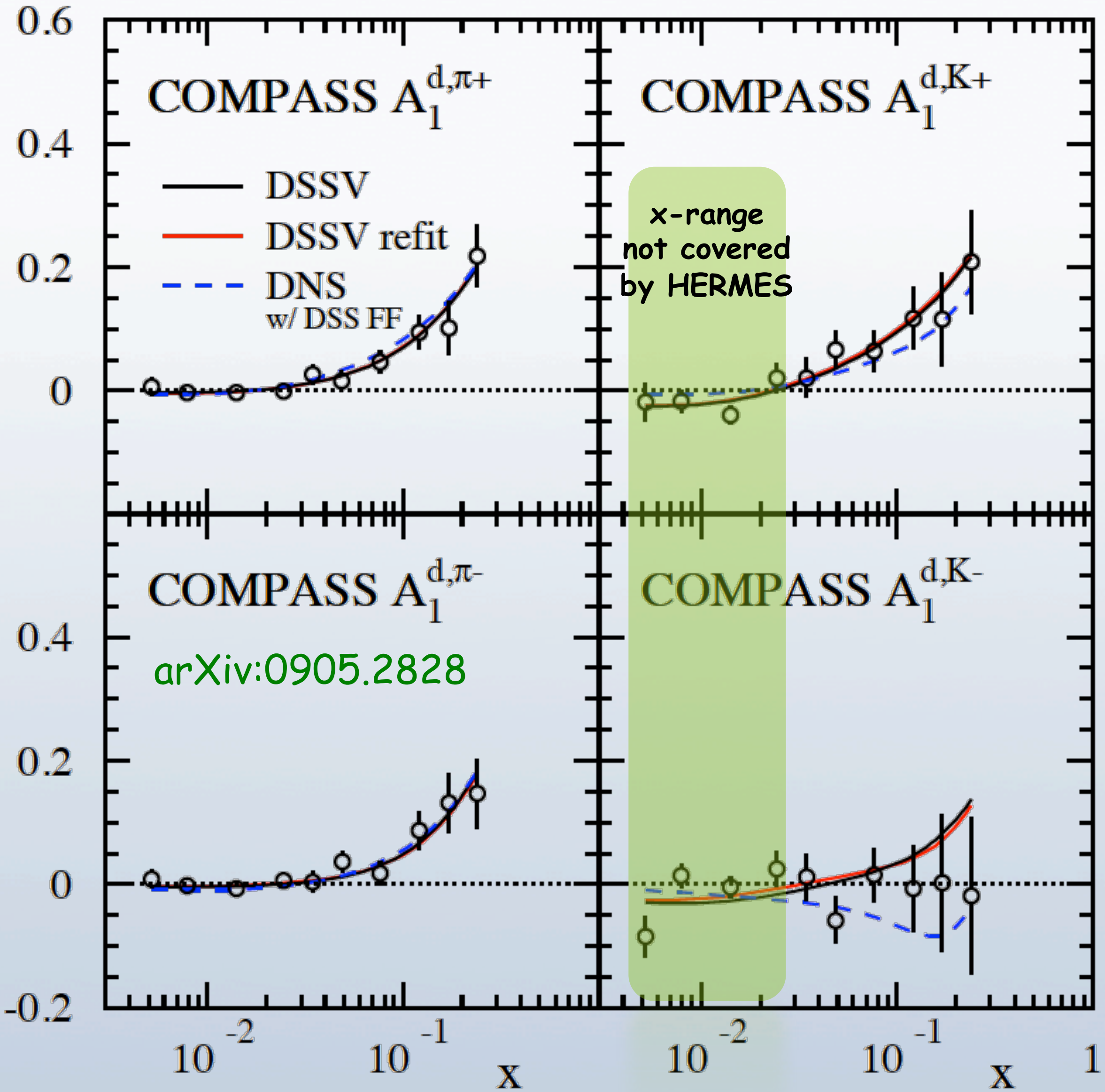




✓ DSSV does a very good job: 15 points, χ^2 = **14.2**

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





✓ DSSV works well:

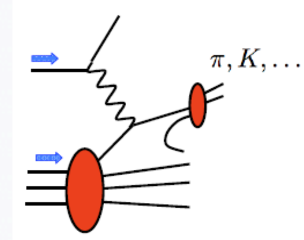
no surprises at small x

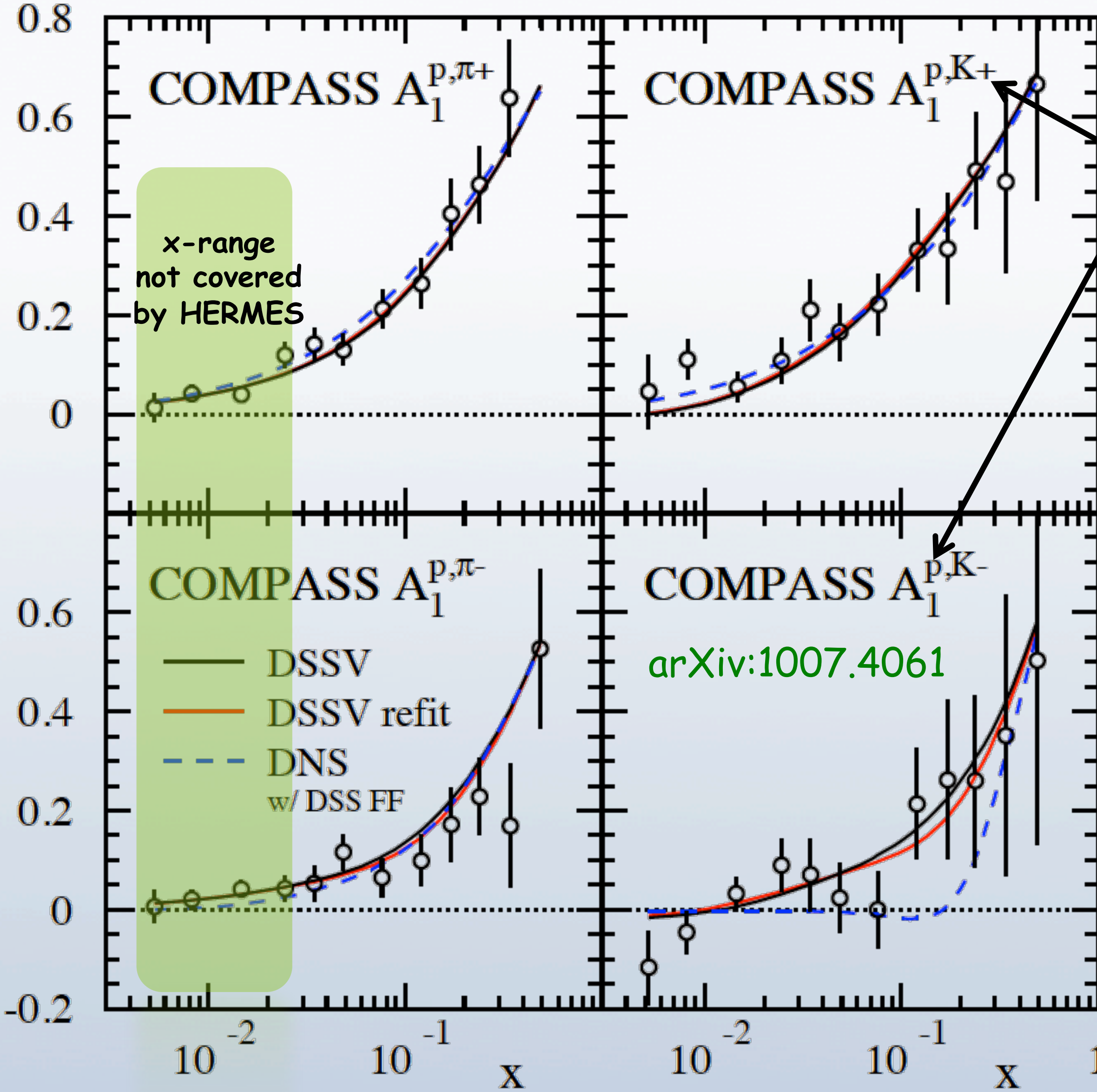
χ^2 **numerology**♮:

	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**

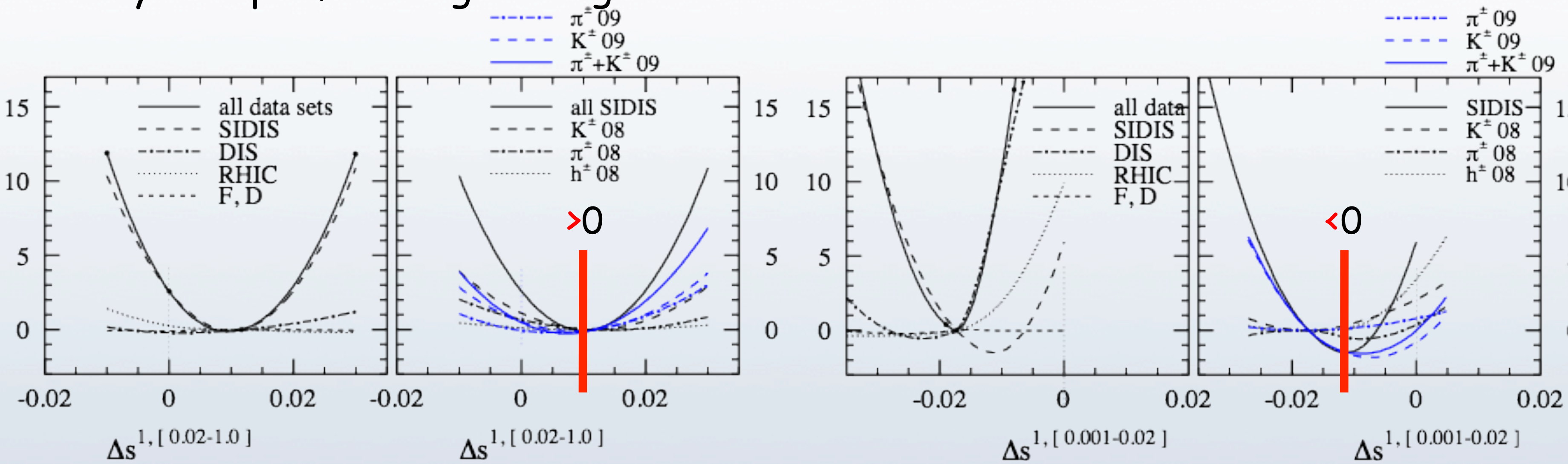
($\Delta\chi^2=1$ does not reflect faithful PDF uncertainties)

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

Δs revisited: impact of COMPASS data

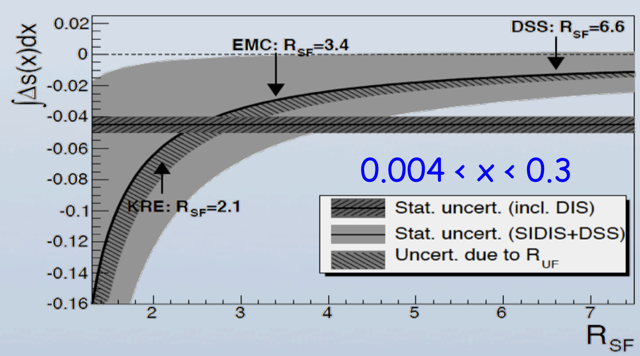
current value for $\Delta\Sigma$ strongly depends on assumptions on low-x behavior of Δs

- new COMPASS data support small/positive $\Delta s(x)$ 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)
- caveat: dependence on FFs

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



COMPASS

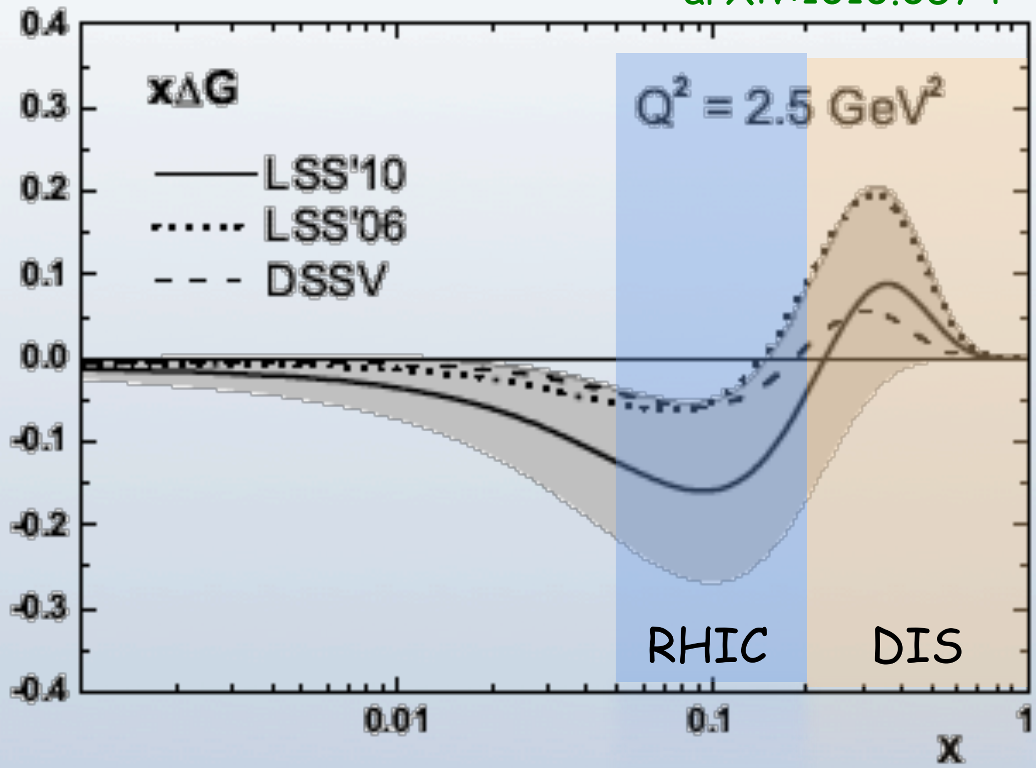
comparison with latest LSS'10 analysis

Leader, Sidorov, Stamenov

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

arXiv:1010.0574

why?

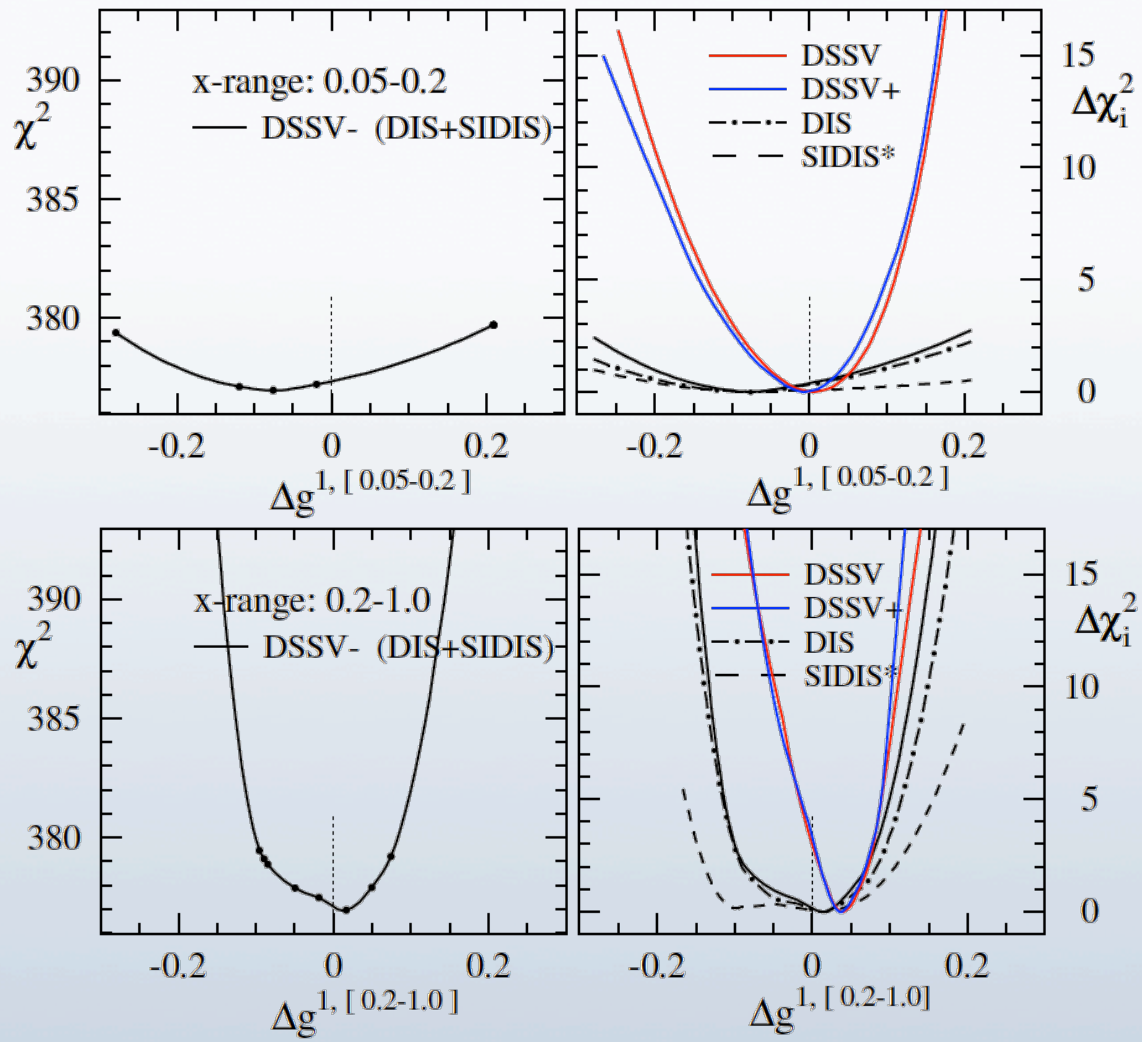


look into χ^2 profiles with LM

Δg and RHIC data

truncated moment
("RHIC pp region")

truncated moment
("high x")



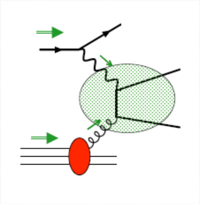
bottom line

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

Δg from fixed target experiments

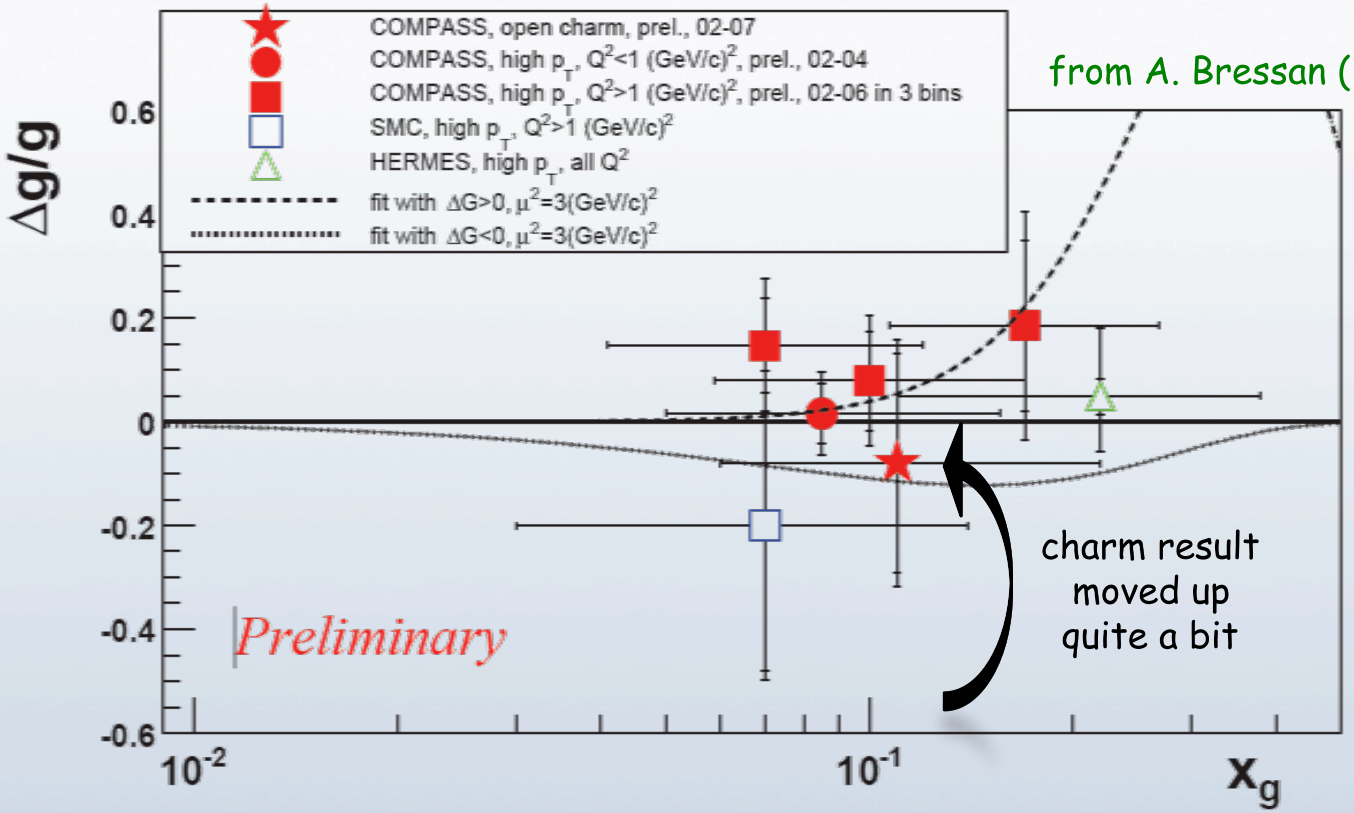
idea: study processes sensitive to **photon-gluon-fusion**

data available for one/two hadron production, charm



COMPASS, HERMES, SMC, E155

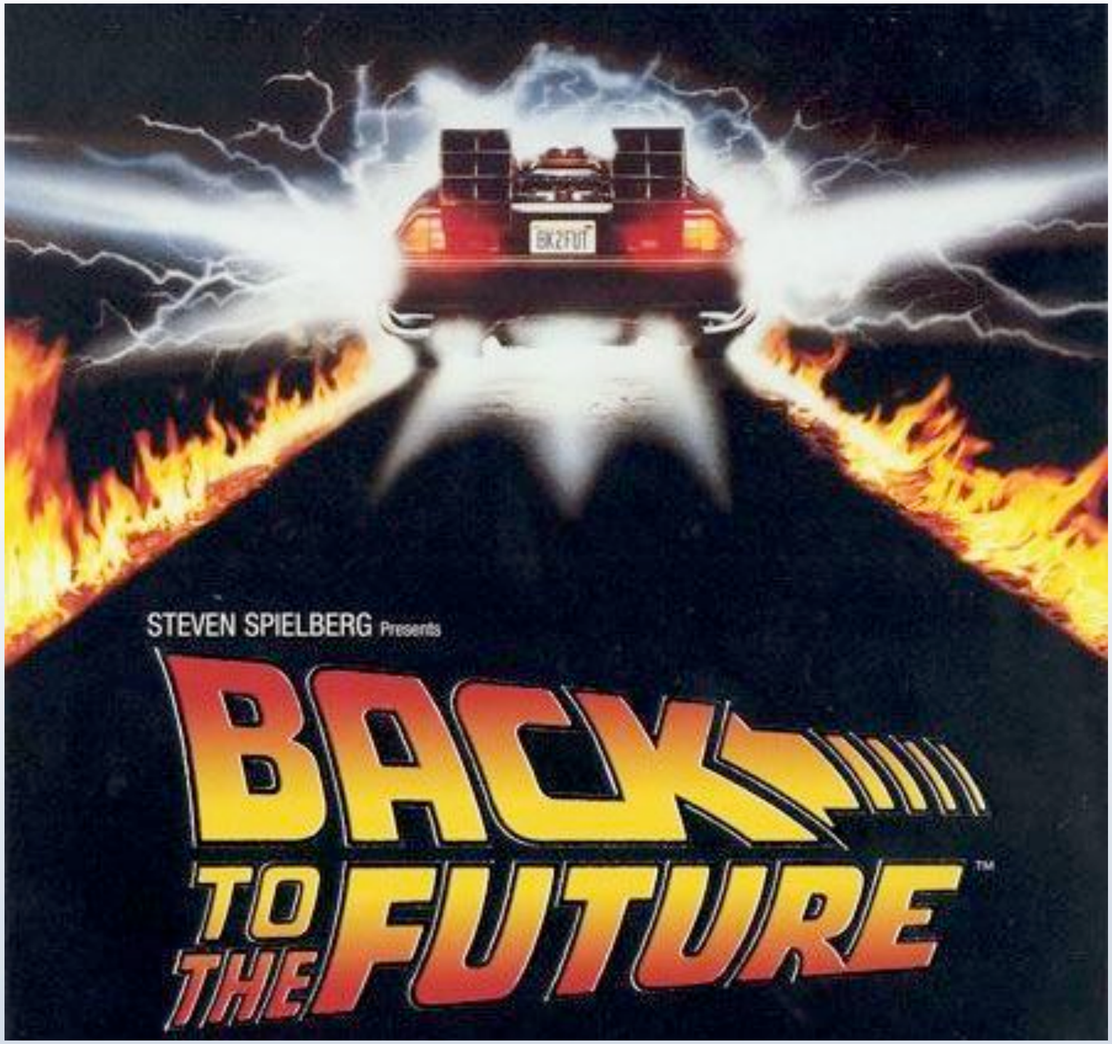
from A. Bressan (DIS '10)



agrees well with DSSV

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

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

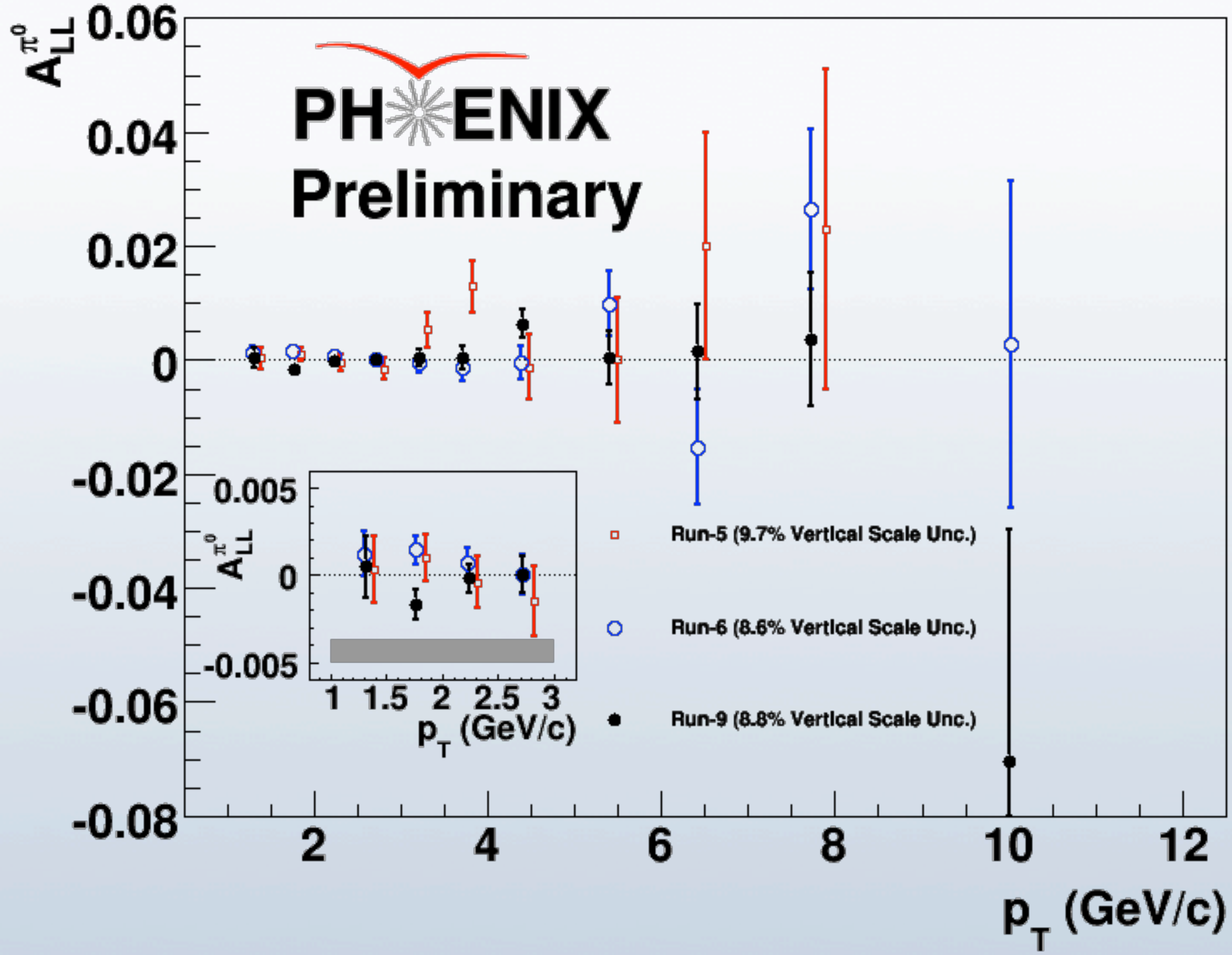


Future Avenues

RHIC & Beyond

RHIC: improved single-inclusive observables

as presented at DIS'10



- A_{LL} for π^0 from "run 9" even closer to zero than before

Δg from jet-jet correlations

as presented at DNP'10

- particle correlations allow for a more precise mapping of x dependence

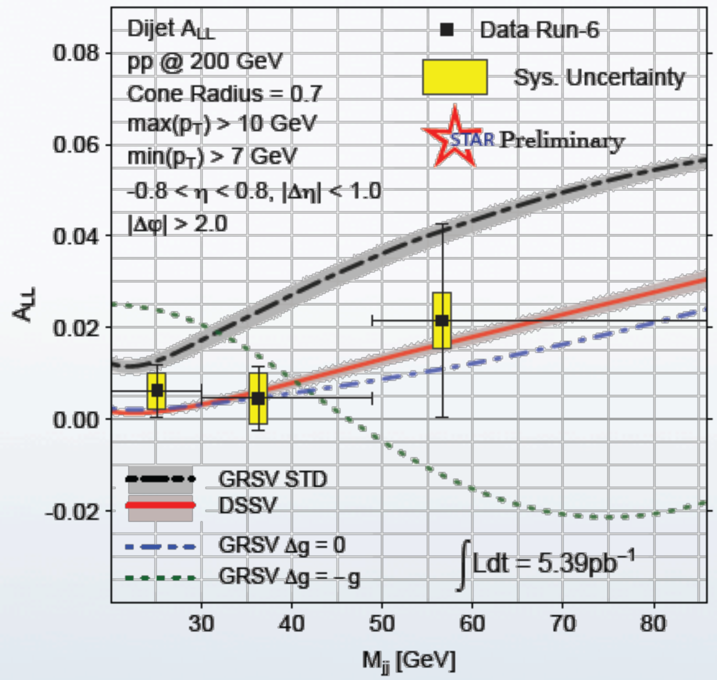
$$x_{1,2} = \frac{p_T}{\sqrt{S}}(e^{\pm\eta_3} + e^{\pm\eta_4})$$

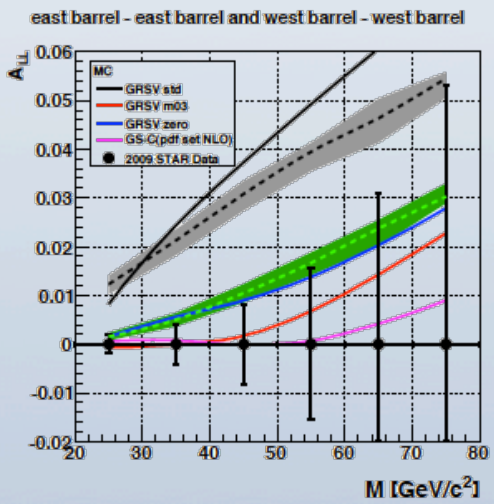
$$M^2/S = x_1 x_2$$

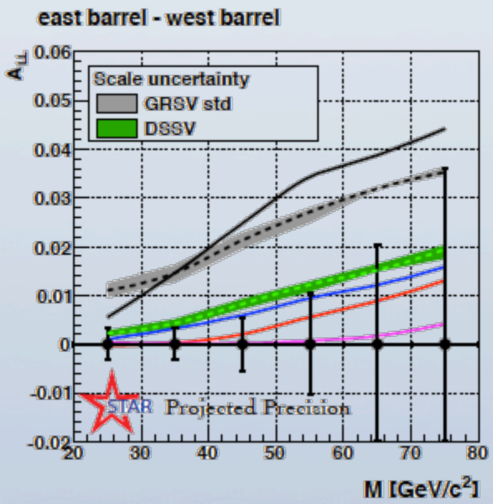
- NLO corrections available for dijets

de Florian, Frixione, Signer, Vogelsang

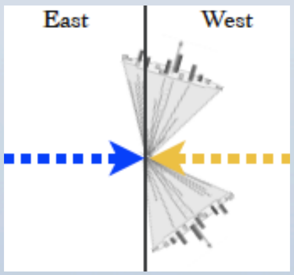
- Mellin technique in place to include upcoming data in DSSV analysis

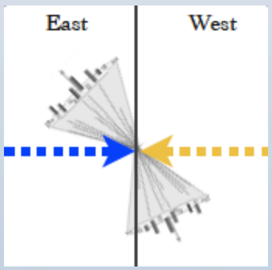






- projections for run 9

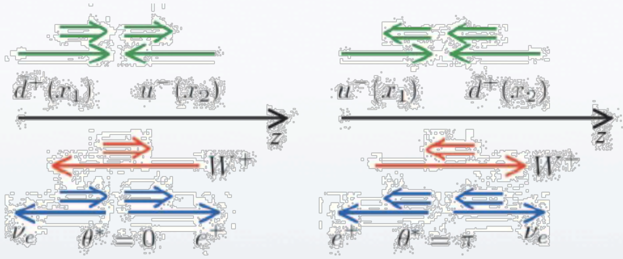




u,d quarks from W boson production

key measurement at RHIC

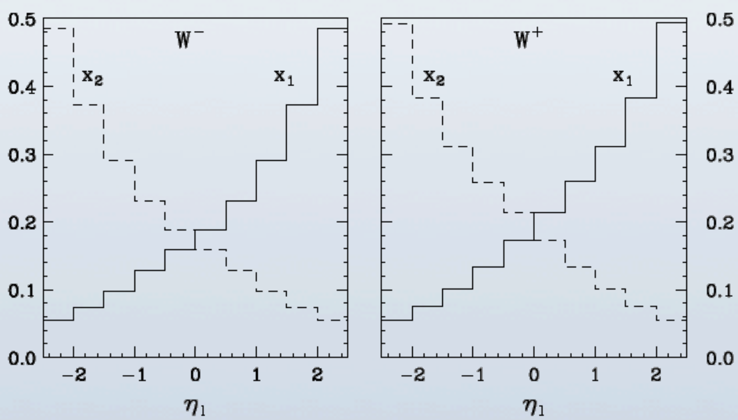
- based on parity violation: W's couple only to one parton helicity



study single spin asymmetries

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

- RHIC: can detect only decay leptons; lepton rapidity most suited observable



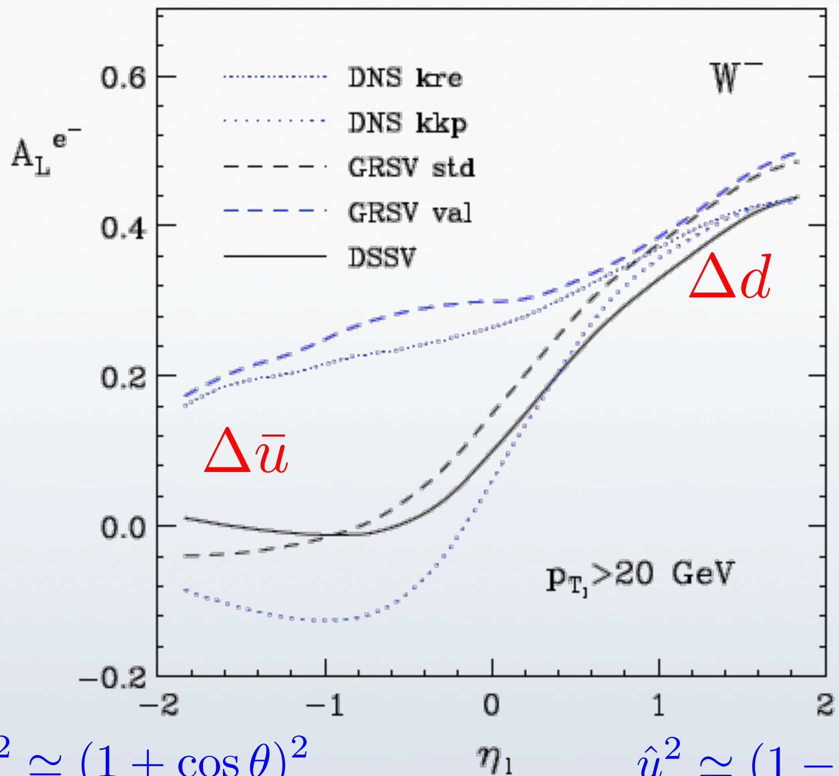
- strong correlation with $x_{1,2}$
- allows for flavor separation for $x > 0.07$
- new versatile NLO MC code "CHE" available

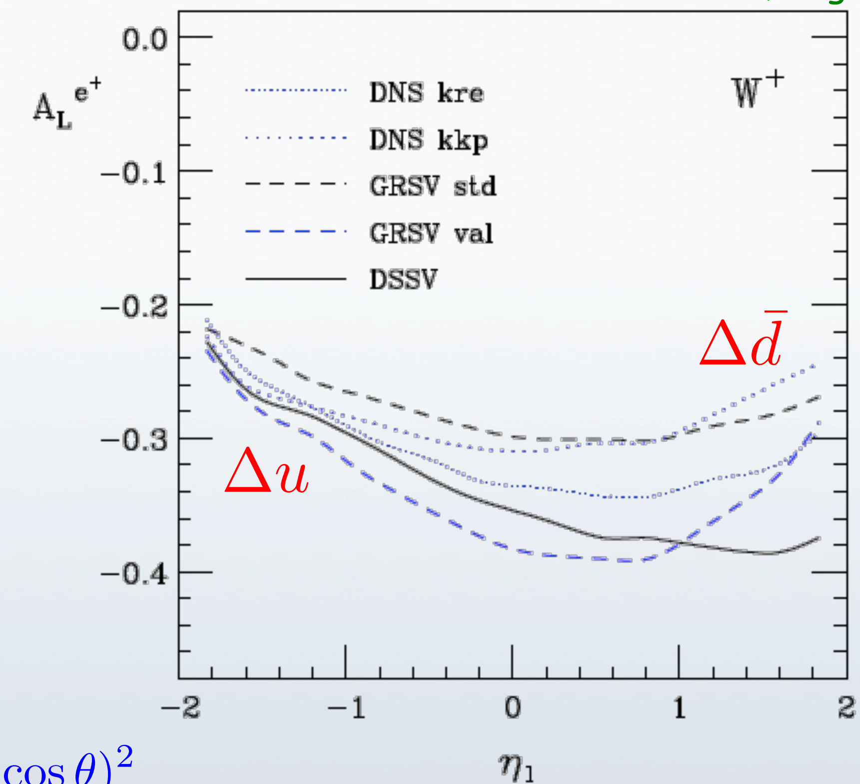
de Florian, Vogelsang, arXiv:1003.4533

- 500 GeV program at RHIC started in 2009 – 1st results ("proof of principle")

expectations for A_L^e

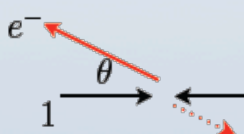
de Florian, Vogelsang





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

t large u large



t large u large

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

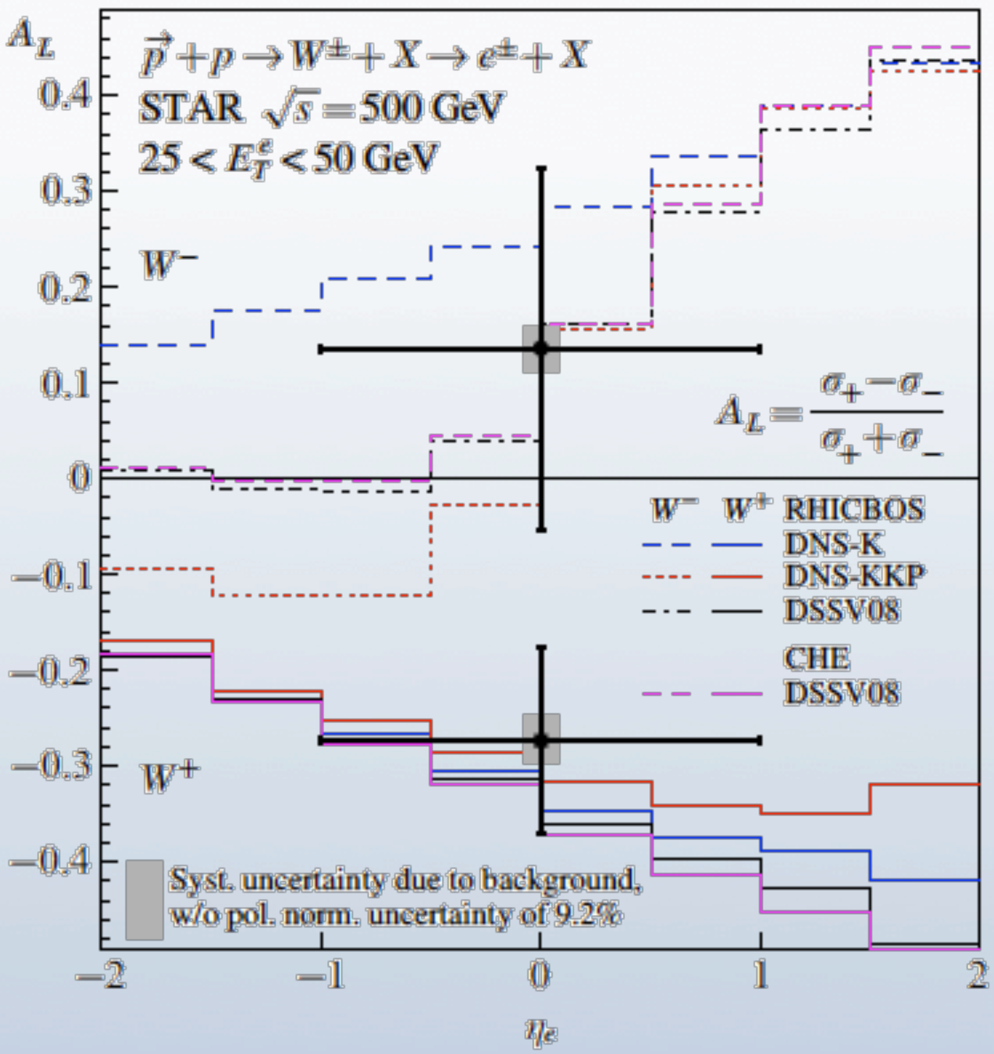
$\boldsymbol{\Delta}\bar{d}(x_1)u(x_2)(\hat{u}^2) + \Delta u(x_1)\bar{d}(x_2)(-\hat{t}^2)$

strong sensitivity to $\boldsymbol{\Delta}\bar{u}$

limited sensitivity to $\boldsymbol{\Delta}\bar{d}$

1st results from PHENIX and STAR

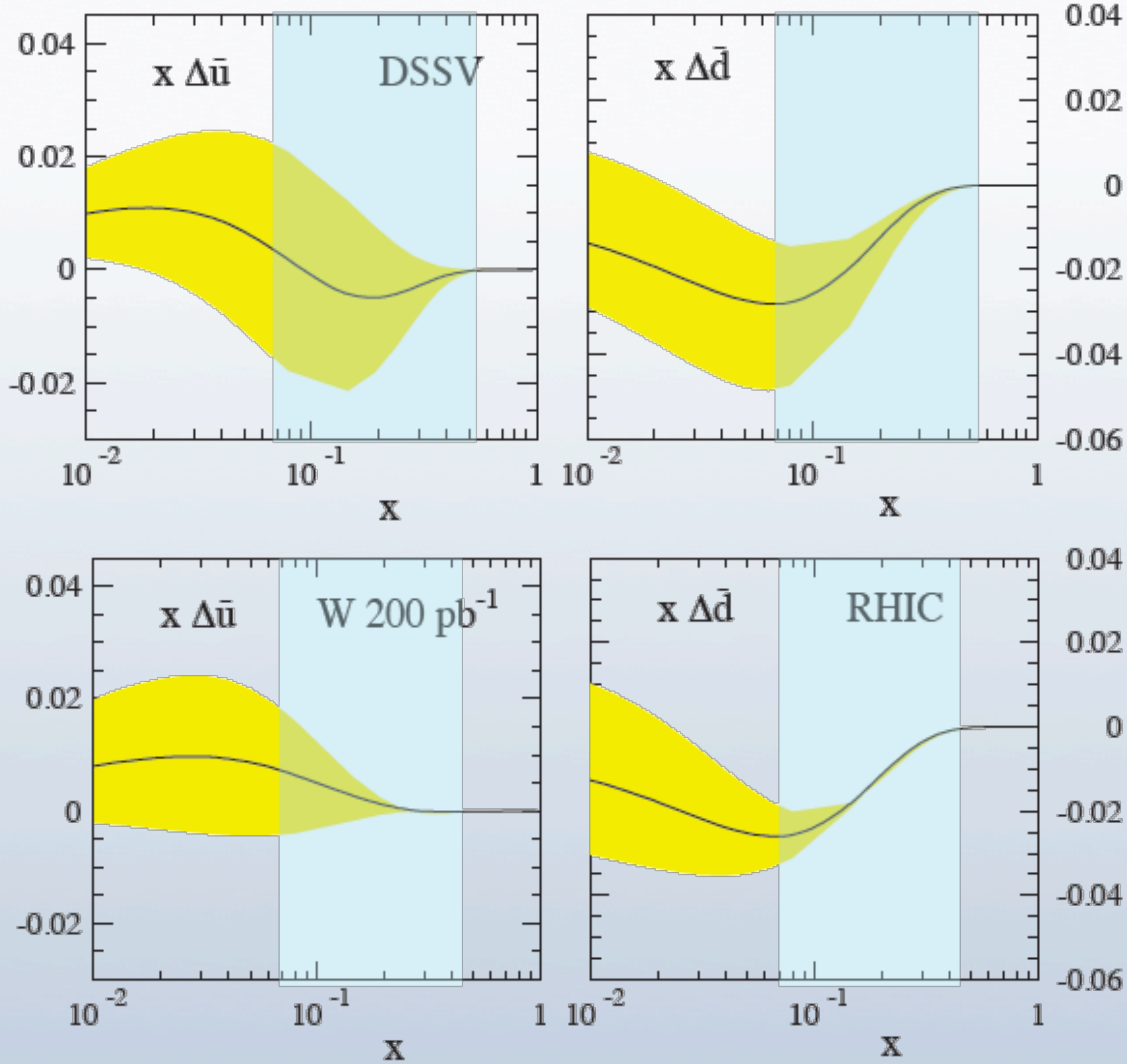
arXiv:1009.0505 arXiv:1009.0326



- no impact on fits yet
  "proof of principle"

W program @ RHIC: what can we learn?

✓ "CHE" integrates nicely into DSSV global analysis code based on Mellin moments



$\Delta\chi^2 = 2\%$ uncertainty bands of DSSV analysis

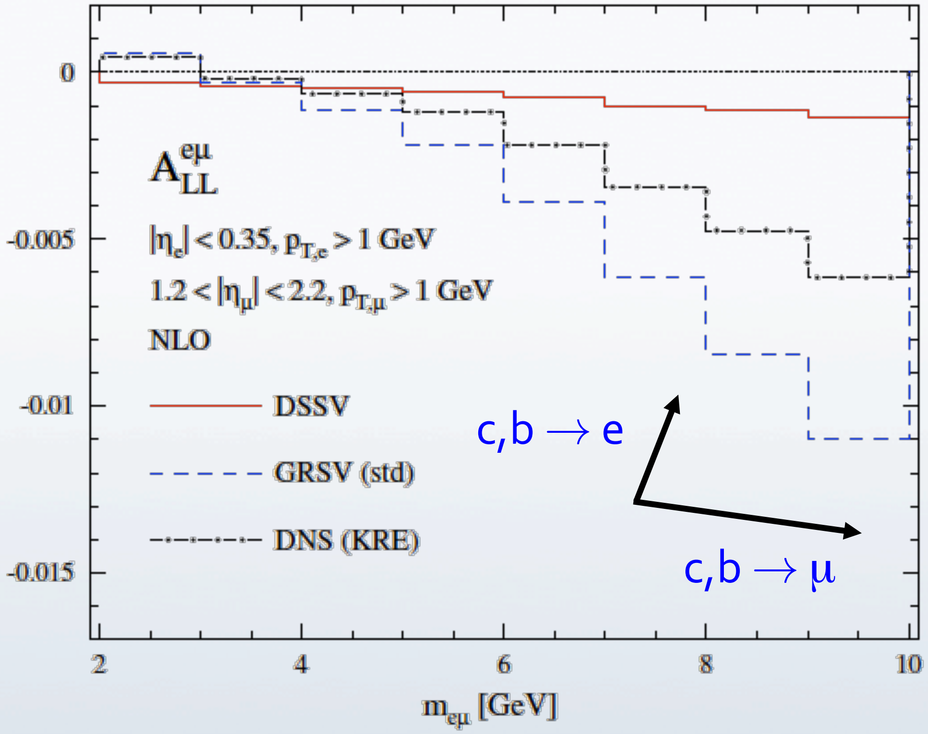
simulated impact of RHIC W boson data on global fit

✓ reduction of uncertainties for $0.07 < x < 0.4$

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

de Florian, Vogelsang

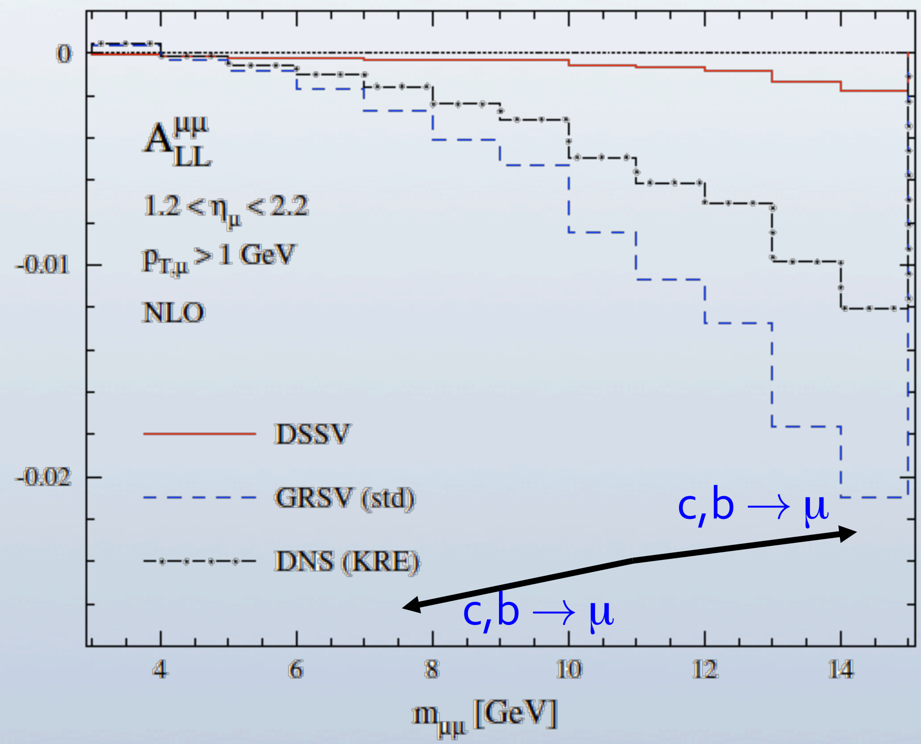
future: heavy quark correlations



forward-central e-μ coincidences

- best suited heavy flavor observables to explore nucleon spin structure
- different hard scatt. dynamics than jets
- clear correlation between A_{LL} and Δg
- full NLO MC available Riedl, Schafer, MS

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 10-15 GeV

opportunities for spin physics studies at an EIC

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

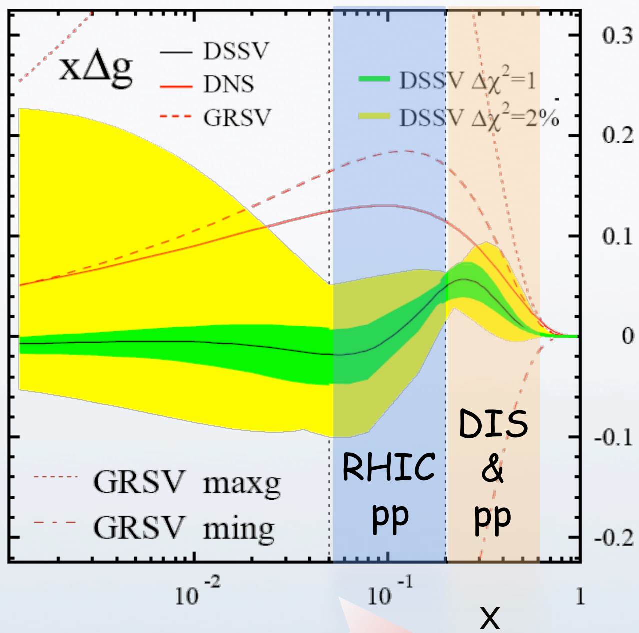
many “weak spots” & room for new “spin surprises”:

- small x region: crucial for all sum rules (“proton spin”, “Bjorken”, …) **unknown**
- flavor separation: SU(2) breaking, strangeness **largely unknown**
- electro-weak 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

teaser I: what can be achieved for Δg?

recall:

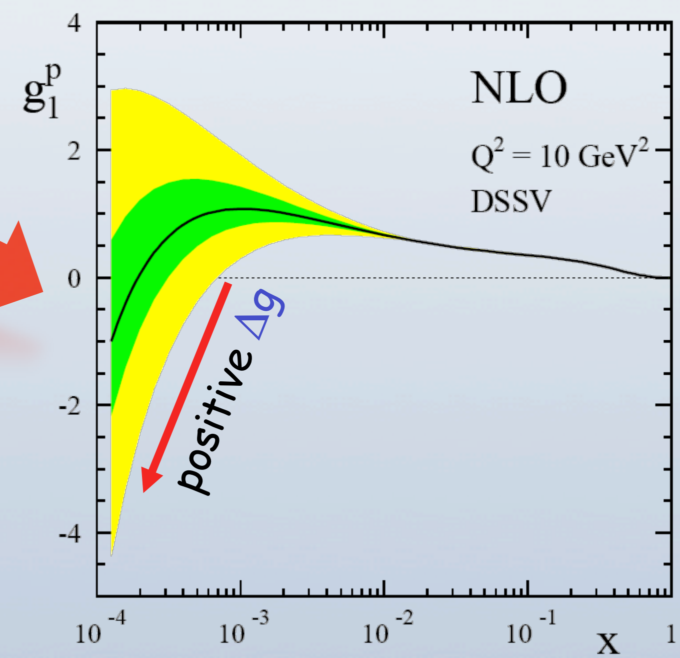


DSSV global fit
de Florian, Sassot,
MS, Vogelsang

- low x behavior unconstrained
- no reliable error estimate for 1st moment $\int_0^1 dx\, \Delta g(x, Q^2)$ (entering spin sum rule)
- find $\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2) \approx 0$

pQCD scaling violations

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



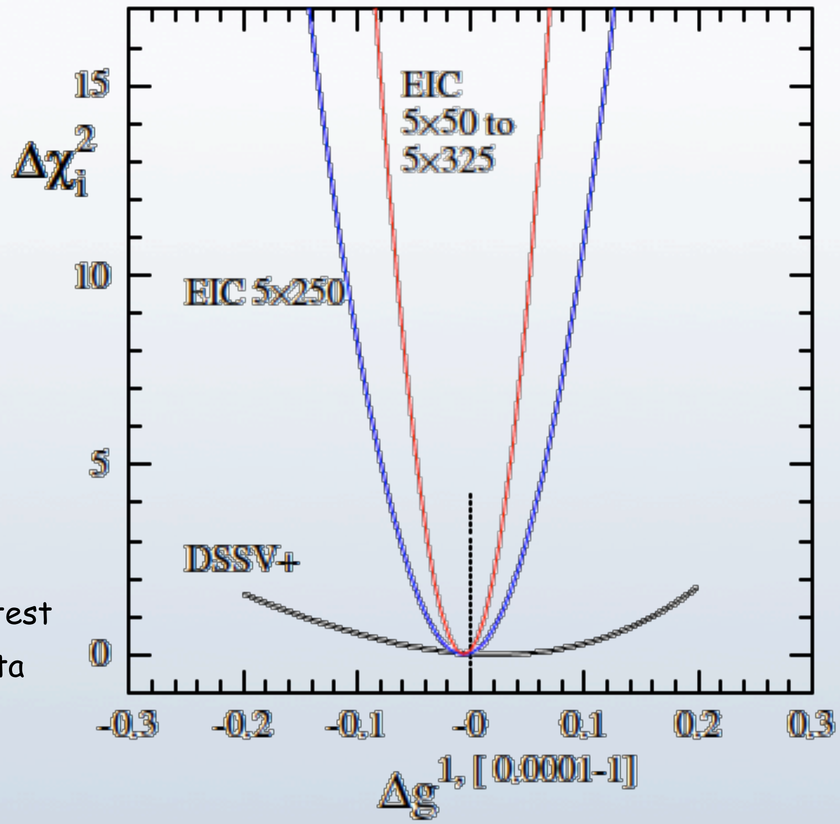
what can be achieved for Δg? – cont'd

how effective are scaling violations at the EIC…

(studies based on simulated data for stage-1 [5x50, 5x100, 5x250, 5x325])

Sassot, MS

DSSV+ includes also latest COMPASS (SI)DIS data (no impact on DSSV Δg)



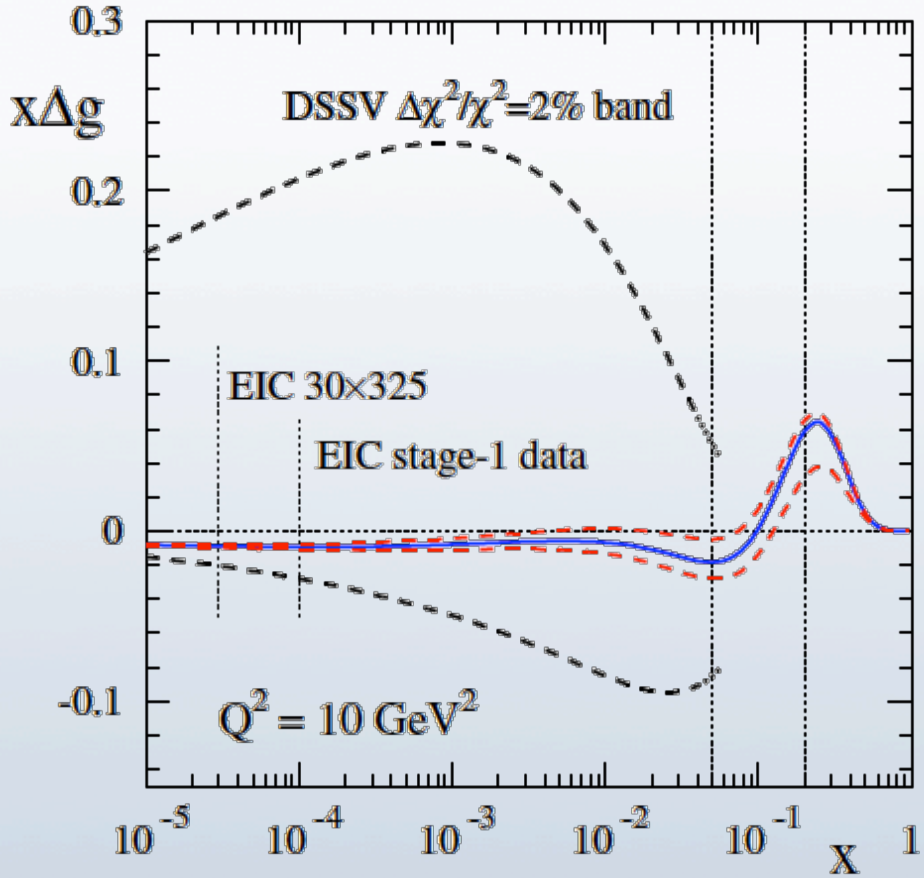
χ^2 profile slims down significantly already for EIC stage-1 (one month of running)

- with 30x325 one can reach down to $x \approx 3{\times}10^{-5}$ (impact needs to be studied)

what can be achieved for Δg? – cont'd

what about the uncertainties on the x-shape …

Sassot, MS



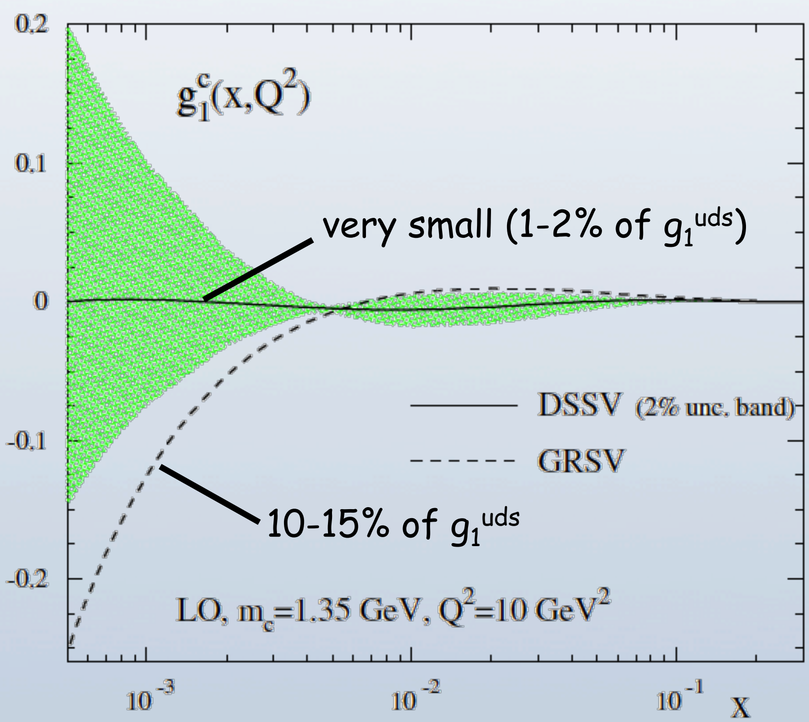
… wow – cool!

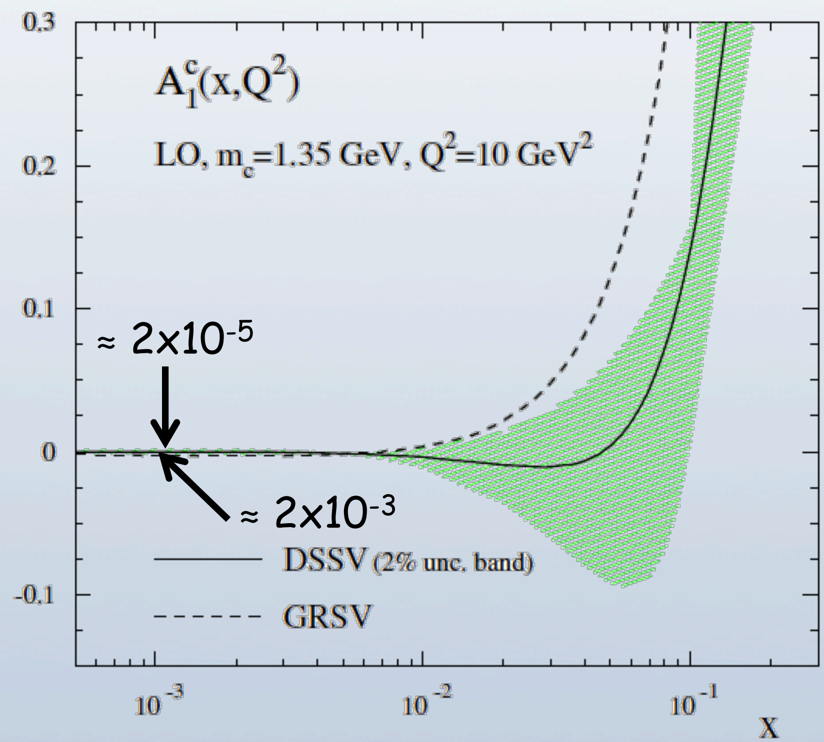
- even with flexible DSSV x-shape we can now determine $\int_0^1 dx\, \Delta g(x, Q^2)$ up to ± 0.07
- work in progress: try weird x-shapes below x = 10^{-4} to improve/check error estimate

issue: charm contribution to g_1

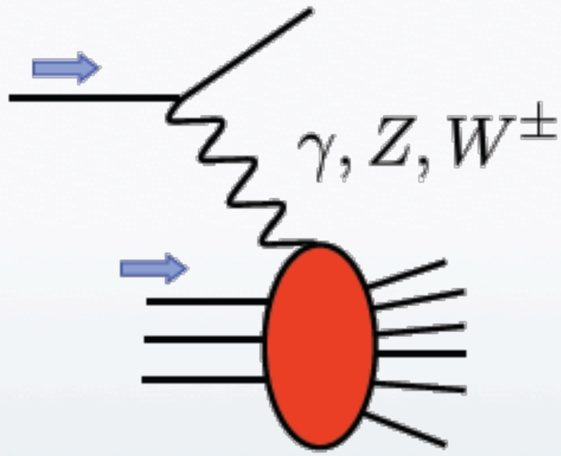
- so far safely ignored: << 1% to existing g_1 fixed-target data
- relevance at an EIC depends strongly on size of Δg
- need massive Wilson coefficients (charm not massless for most of EIC kinematics)
  so far only known to LO (NLO is work in progress Kang, MS)

some expectations: (needs to be studied in detail)





teaser II: electroweak effects at high Q^2



at high enough Q^2 electroweak probes become relevant

- **neutral currents** (γ, Z exchange, γZ interference)
- **charged currents** (W exchange)

parameterized by new structure functions which probe combinations of PDFs different from photon exchange
--> **flavor decomposition without SIDIS, e-w couplings**

hadron-spin averaged case: studied to some extent at HERA (limited statistics)

hadron-spin difference:

Wray; Derman; Weber, MS, Vogelsang; Anselmino, Gambino, Kalinowski; Blumlein, Kochelev; Forte, Mangano, Ridolfi; ...

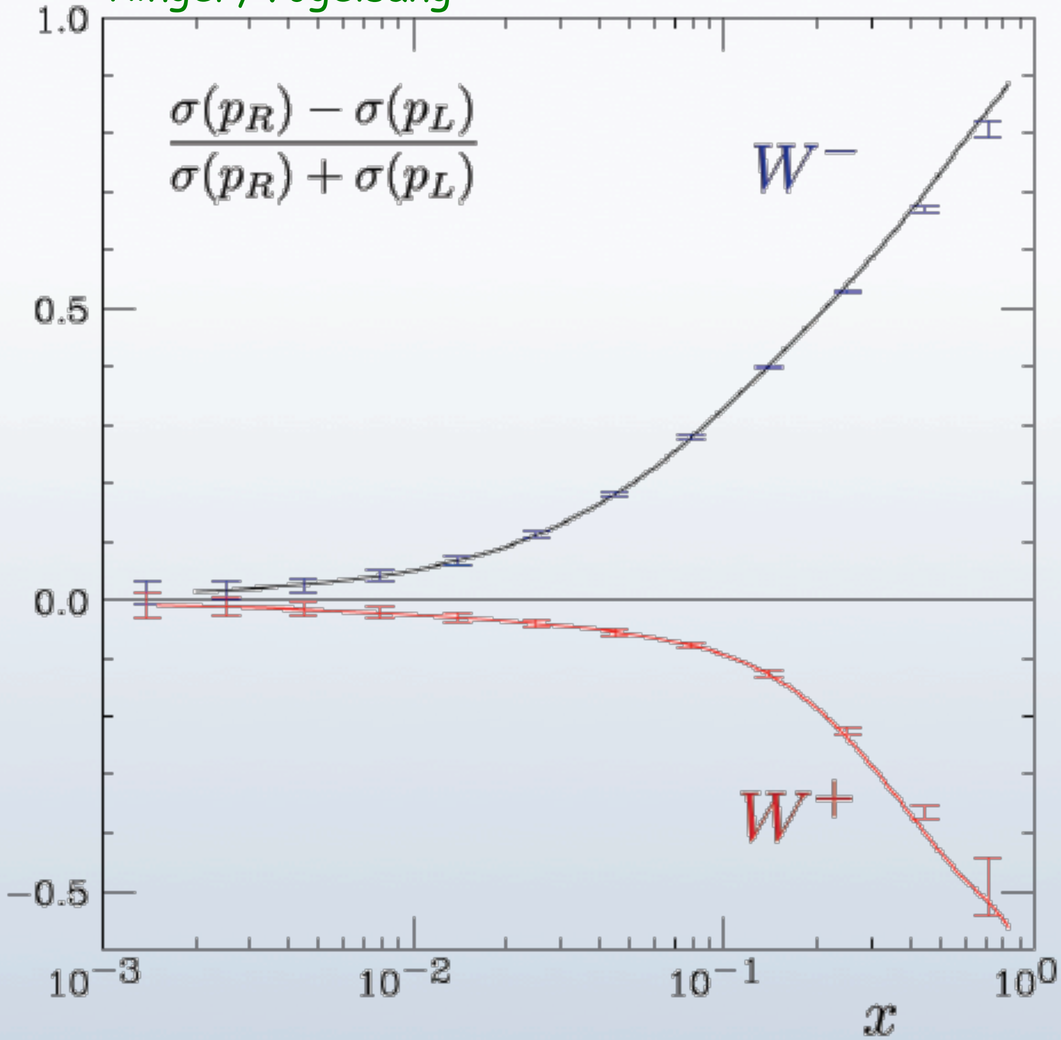
contains
e-w propagators
and couplings

$$\frac{d\Delta\sigma^{e^{\mp},i}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-y)x\hat{g}_1^i - (1-y)\hat{g}_4^i - y^2 x\hat{g}_5^i\right] \quad \mathrm{i} = \mathrm{NC}, \mathrm{CC}$$

unexplored so far – unique opportunity for an EIC

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

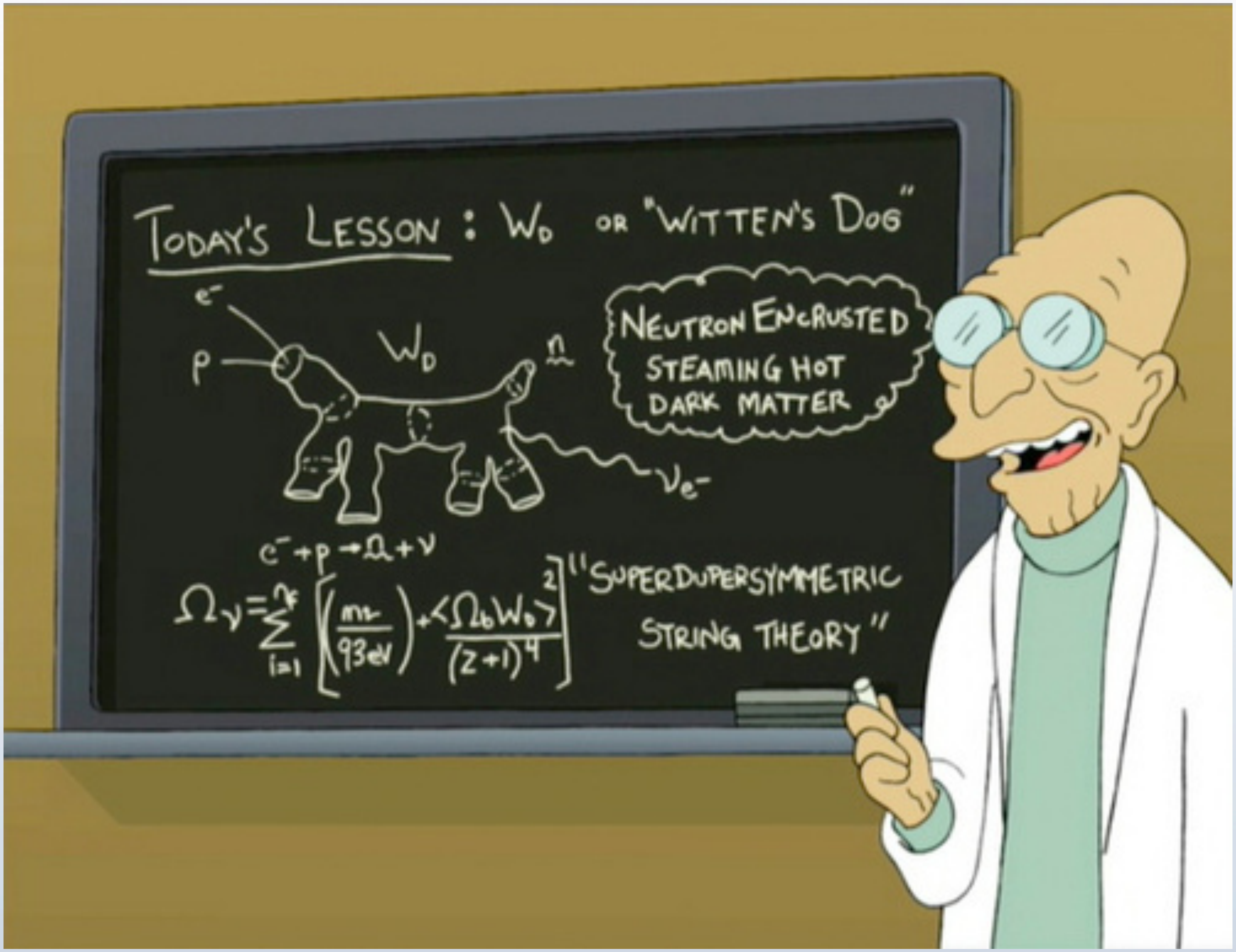
$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta\bar{d} + \Delta\bar{s})}{(u+c) + (1-y)^2(\bar{d}+\bar{s})} \quad A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta\bar{u} + \Delta\bar{c})}{(1-y)^2(d+s) + (\bar{u}+\bar{c})}$$

other opportunities in polarized DIS

- in 10+ years the NNLO corrections will be available (needed to match precision of data) — Moch, Vogt, …
- watch out for surprises at small-x = deviations from DGLAP (expected to set in earlier than in unpol. DIS; showing up as tension in global fit (?)) — Bartels, Ermolaev, Ryskin; Greco, Troyan; …
- strong coupling from scaling violations (needs to be worked out / quantified)
- Bjorken sum rule: $\int_0^1 dx\,[g_1^p(x,Q^2) - g_1^n(x,Q^2)] = \frac{1}{6} C_{\mathrm{Bj}}\,[\alpha_s(Q^2)]\;g_A$
  - C_{Bj} known to $O(\alpha_s^4)$ — Kodaira; Gorishny, Larin; Larin, Vermaseren; Baikov, Chetyrkin, Kühn, …
  - but not a tool to determine α_s (1% change in α_s translates in 0.08% change of Bj sum)
  - experimental challenge: effective neutron beam (^{3}He), very precise polarimetry, …
  - theor. motivation for precision measurement: **Crewther relation**

    non-trivial relation of two seemingly unrelated quantities

$$\text{Adler function } D(Q^2) \text{ in } e^+e^- \xleftrightarrow[\text{deviation from exact conformal symmetry}]{\sim 1 + \frac{\beta(\alpha_s)}{\alpha_s} K(\alpha_s)} \text{Bj sum } C_{Bj}(Q^2) \text{ in DIS}$$


TODAY'S LESSON : W_D OR "WITTEN'S DOG"
NEUTRON ENCRUSTED STEAMING HOT DARK MATTER
e^-
p
W_D
Ω
ν_{e^-}
$e^- + p \to \Omega + \nu$
"SUPERDUPERSYMMETRIC STRING THEORY"

SUMMARY

final remarks

- **FFs are in good shape** – many new data sets available/upcoming
  watch out for updated DSS sets & more detailed uncertainty studies

- **DSSV describes all new polarized data sets well** – no refit needed
  still many open questions: strangeness, flavor separation, 1st moments, …

- **global QCD analyses are an ongoing effort**:
  more data sets/processes; further improvements (e.g. on uncertainties)

- **many opportunities at a future EIC**:
  small x behavior of Δg, electro-weak effects, …