October 20th, 2009

INT, Seattle

Status of Helicity-Dependent PDF's

or the quest for small x

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plan of the talk

I. current status of global analyses

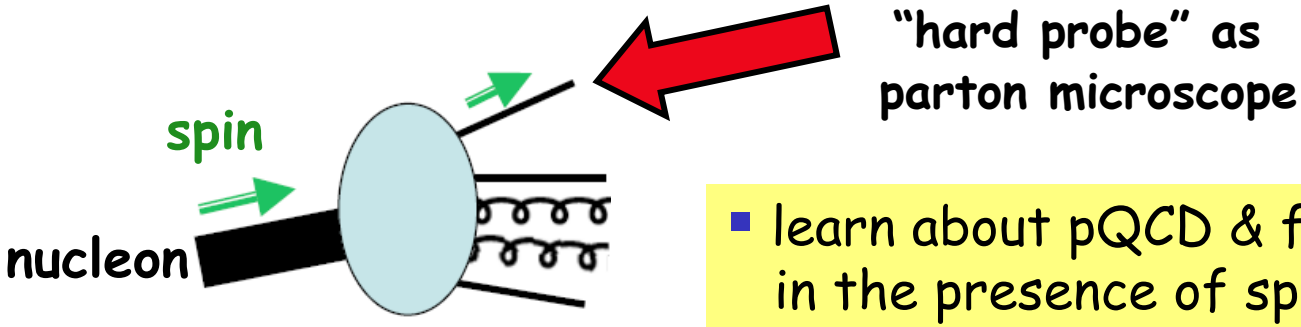
- *how do quarks and gluons carry the proton spin:*
  present knowledge of helicity PDFs, spin sum rule, …
- *questions emerging:*
  strangeness, gluons @ small-x, flavor decomposition, …

II. future avenues with RHIC & beyond

- *taking on the status quo – near term:*
  1-inclusive, jet correlations, W bosons, rare probes, …
- *taking on the status quo – long term:*
  (SI)DIS @ small x, Bjorken sum, electroweak str. fcts., photoproduction, …

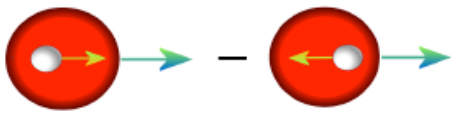
roadmap of what we want to achieve

(1) study polarized scattering processes quantitatively



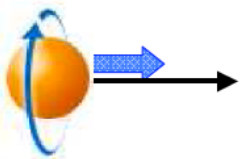
- learn about pQCD & factorization in the presence of spin

(2) extract nucleon helicity structure

$\Delta f \equiv$  $\langle P, \frac{1}{2} | \mathcal{O}_{q,\bar{q},g} | P, \frac{1}{2} \rangle$

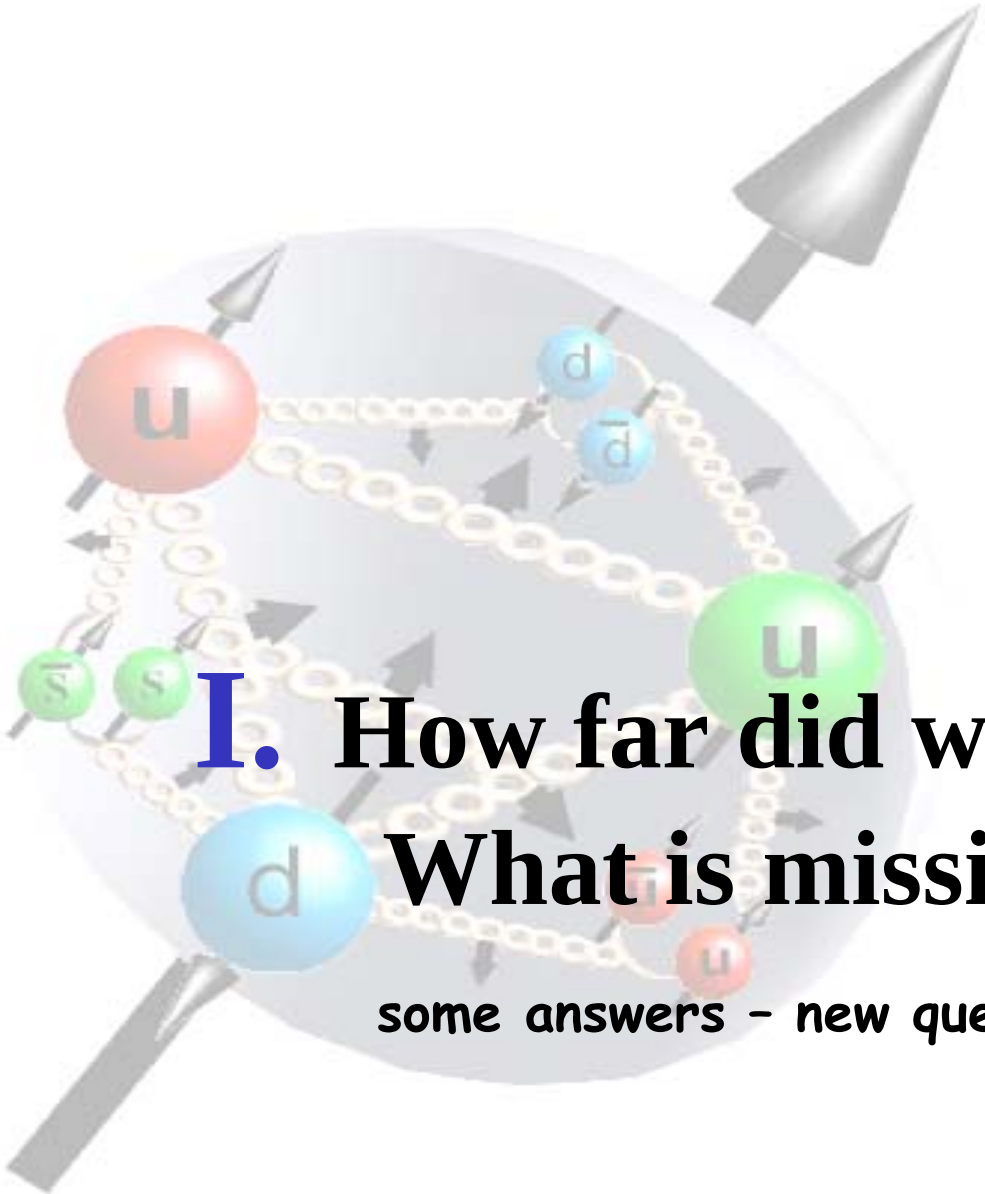
- develop global analysis tools, propagate & quantify uncertainties
- compare with low-energy models/non-pert. lattice calculations

(3) learn about proton spin in terms of quarks and gluons



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

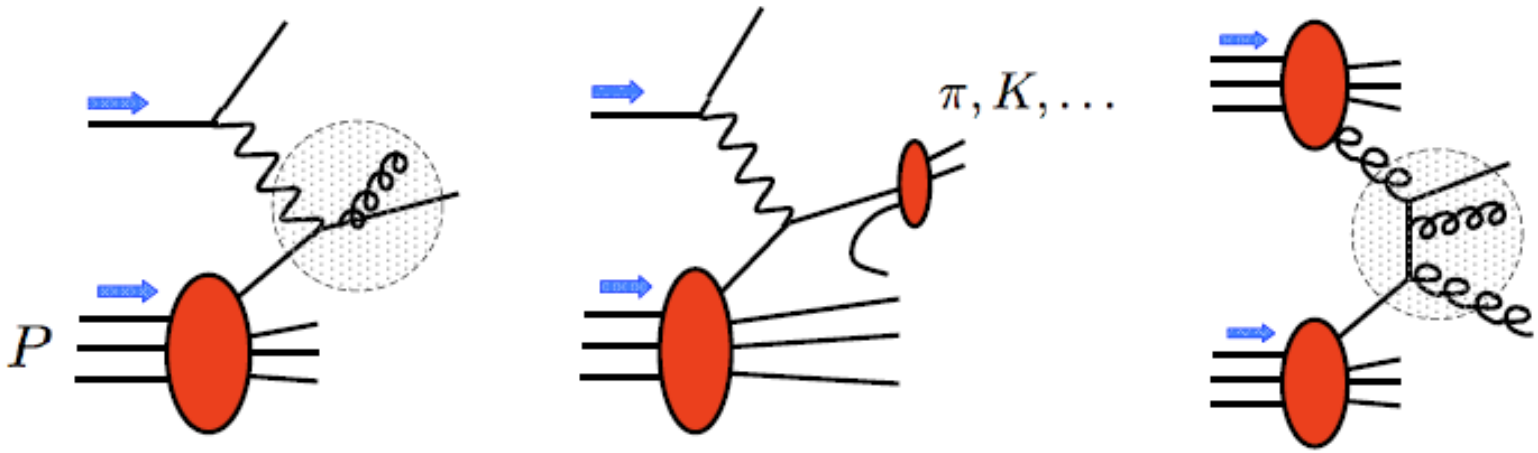
- what is the role of orbital angular momentum



I. How far did we get? What is missing?

some answers – new questions

probes of nucleon (spin) structure



DIS **SIDIS** **hadron-hadron**

- each reaction provides insights into *different* aspects and kinematics

$\Delta q + \Delta\bar{q}$ $\Delta q,\ \Delta\bar{q}$ Δg

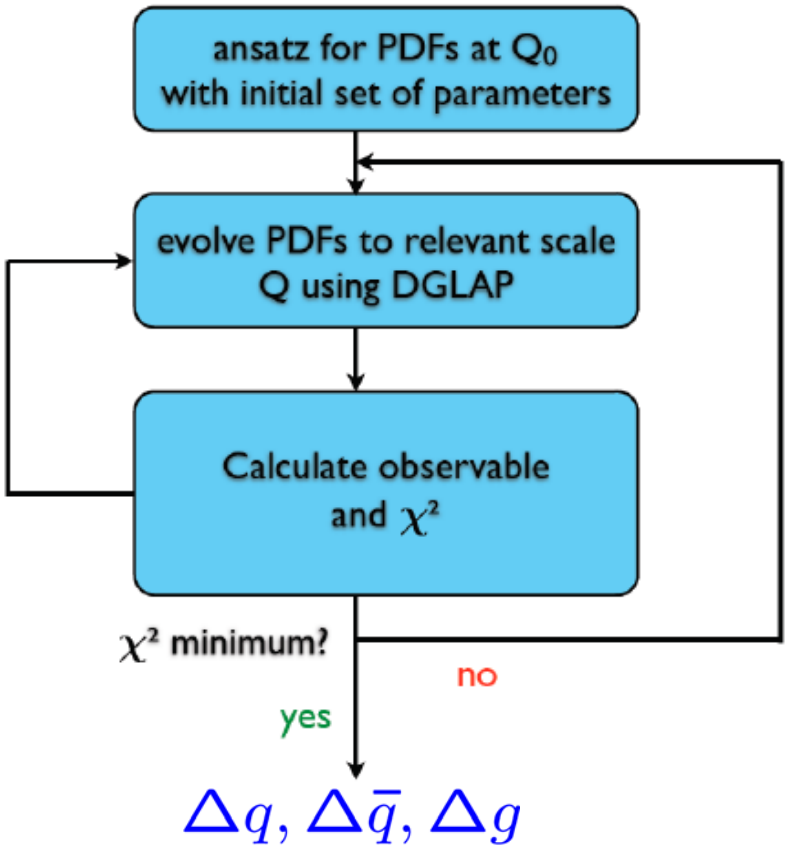
- all processes tied together: universality of pdfs & scale evolution

- information on PDFs "hidden" inside complicated (multi-)convolutions, e.g.,

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

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

global analysis: a computational challenge



- long history of NLO χ^2 fits to DIS data
  GRSV, GS, BB, LSS, AAC, …
  not really sufficient in view of new probes
- O(500) data pts. from many processes
  $\approx$ 10% from RHIC & much more to come
- fit O(20) parameters describing PDFs
  issues: func. form, possible nodes, …
- NLO expressions often very complicated
  need sophisticated techniques, e.g., based on Mellin moments Kosower; Vogt; Vogelsang, MS
- need to quantify PDF uncertainties

recently: 1st global NLO analysis based on all probes: DIS, SIDIS, RHIC pp

DSSV de Florian, Sassot, MS, Vogelsang

PRL 101 (2008) 072001; PRD 80 (2009) 034030

prerequisite: a reliable theoretical framework

- knowledge of at least NLO QCD corrections for all processes analyzed
  - ✓ DIS, SIDIS, most of the processes in pp relevant for RHIC
  - ✗ not much known for finite Q^2 processes in ep, e.g., g_1^{charm} !!

quite some work to be done for the EIC

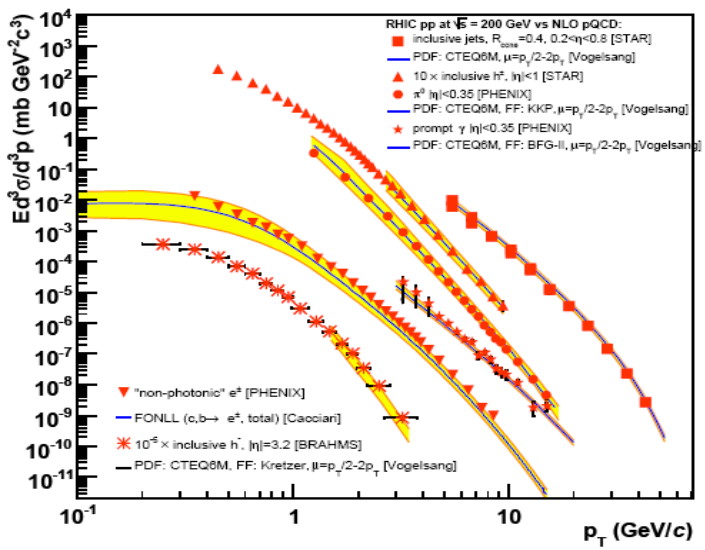
- successful quantitative description of unpolarized "reference" processes

  at RHIC π, jets, γ, charm yields nicely agree with pQCD @ NLO

  compilation by D.d'Enterria

  should work out at the EIC as well

  lesson from HERA



- flexible enough/unbiased functional form to accommodate all data

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

large x — possible nodes

input scale μ_0 — small x

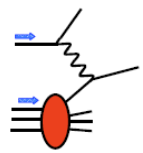
new: ≈ bias free approach based on neural networks

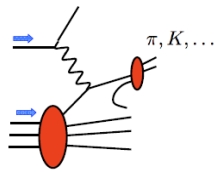
Del Debbio, Guffanti, Piccione; …

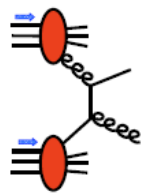
DSSV fit: excellent global description of data

no significant tension
among different data sets

experiment	process	$N_{\rm data}$	χ^2
EMC [2]	DIS (p)	10	3.9
SMC [3]	DIS (p)	12	3.4
SMC [3]	DIS (d)	12	18.4
COMPASS [4]	DIS (d)	15	8.1
E142 [5]	DIS (n)	8	5.6
E143 [6]	DIS (p)	28	19.3
E143 [6]	DIS (d)	28	40.8
E154 [7]	DIS (n)	11	4.5
E155 [8]	DIS (p)	24	22.6
E155 [9]	DIS (d)	24	17.1
HERMES [10]	DIS (He)	9	6.3
HERMES [11]	DIS (p)	15	10.5
HERMES [11]	DIS (d)	15	16.9
HALL-A [12]	DIS (n)	3	0.2
CLAS [13]	DIS (p)	10	5.9
CLAS [13]	DIS (d)	10	2.5
SMC [14]	SIDIS (p, h^+)	12	18.7
SMC [14]	SIDIS (p, h^-)	12	10.6
SMC [14]	SIDIS (d, h^+)	12	7.3
SMC [14]	SIDIS (d, h^-)	12	14.1
HERMES [15]	SIDIS (p, h^+)	9	6.4
HERMES [15]	SIDIS (p, h^-)	9	4.9
HERMES [15]	SIDIS (d, h^+)	9	11.4
HERMES [15]	SIDIS (d, h^-)	9	4.5
HERMES [10]	SIDIS (He, h^+)	9	4.7
HERMES [10]	SIDIS (He, h^-)	9	6.9
HERMES [15]	SIDIS (p, π^+)	9	9.6
HERMES [15]	SIDIS (p, π^-)	9	4.9
HERMES [15]	SIDIS (d, π^+)	9	9.4
HERMES [15]	SIDIS (d, π^-)	9	19.5
HERMES [15]	SIDIS (d, K^+)	9	6.2
HERMES [15]	SIDIS (d, K^-)	9	5.8
HERMES [15]	SIDIS (d, $K^+ + K^-$)	9	3.4
COMPASS [16]	SIDIS (d, h^+)	12	6.2
COMPASS [16]	SIDIS (d, h^-)	12	12.0
PHENIX [22]	pp (200 GeV, π^0)	10	14.2
PHENIX [23]	pp (200 GeV, π^0)	10	7.1 [13.8] [a]
PHENIX [24]	pp (62 GeV, π^0)	5	3.1 [2.8] [a]
STAR [25]	pp (200 GeV, jet)	10	8.8
STAR (prel.) [26]	pp (200 GeV, jet)	9	6.9
TOTAL:		467	392.6







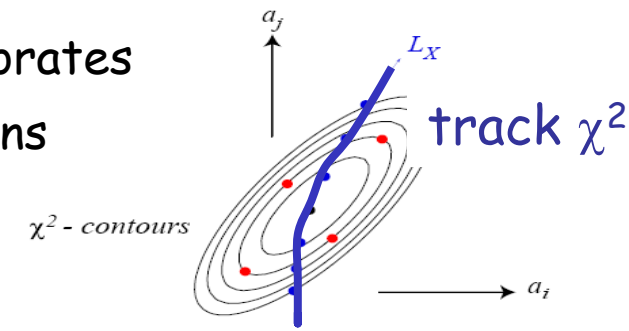
χ^2/d.o.f. $\simeq$ 0.88

note: for the time being, stat. and syst. errors are added in quadrature
room for improvement!

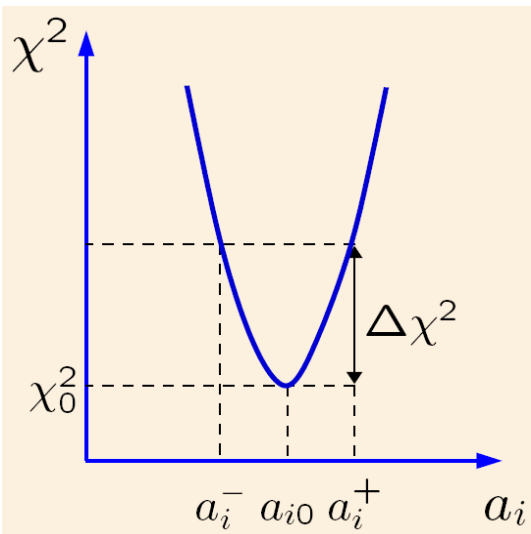
estimating PDF uncertainties

mainly two methods in use: [reshaped for PDF analyses by J. Pumplin and CTEQ]

- **Hessian method:** classic tool, explores vicinity of χ^2-minimum in quadratic approx.; often unstable for multi-parameter PDF analyses
- **Lagrange multiplier:** track how the fit deteriorates when PDFs are forced to give different predictions for selected observables; explores the full paramater space indep. of approximations

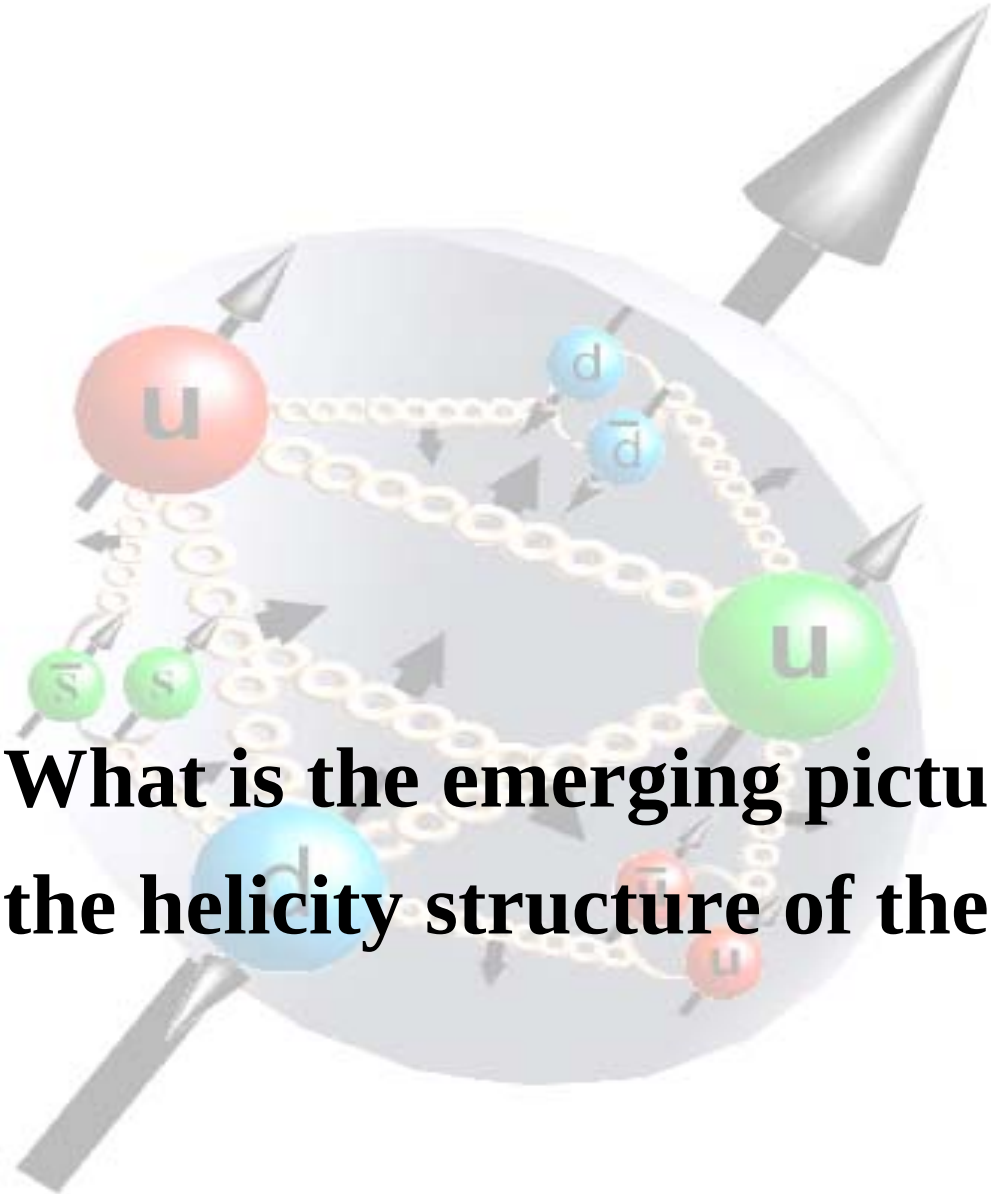


issue: what value of $\Delta\chi^2$ (tolerance) defines a 1-σ error?



- non Gaussian errors, χ^2 "landscape" not parabolic
- uncertainties with diverse characteristics
- theor. errors correlated and poorly known
- data sets often marginally consistent for $\Delta\chi^2=1$

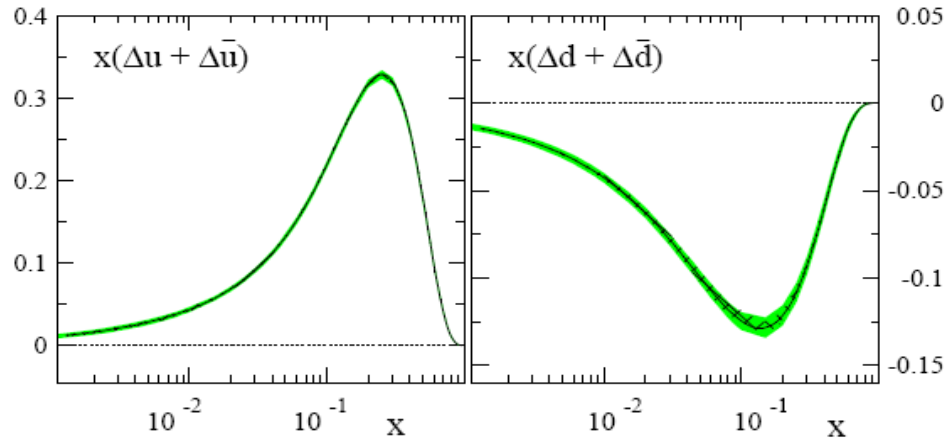
we present uncertainties bands for both $\Delta\chi^2$ = 1 and a more pragmatic 2% increase in χ^2

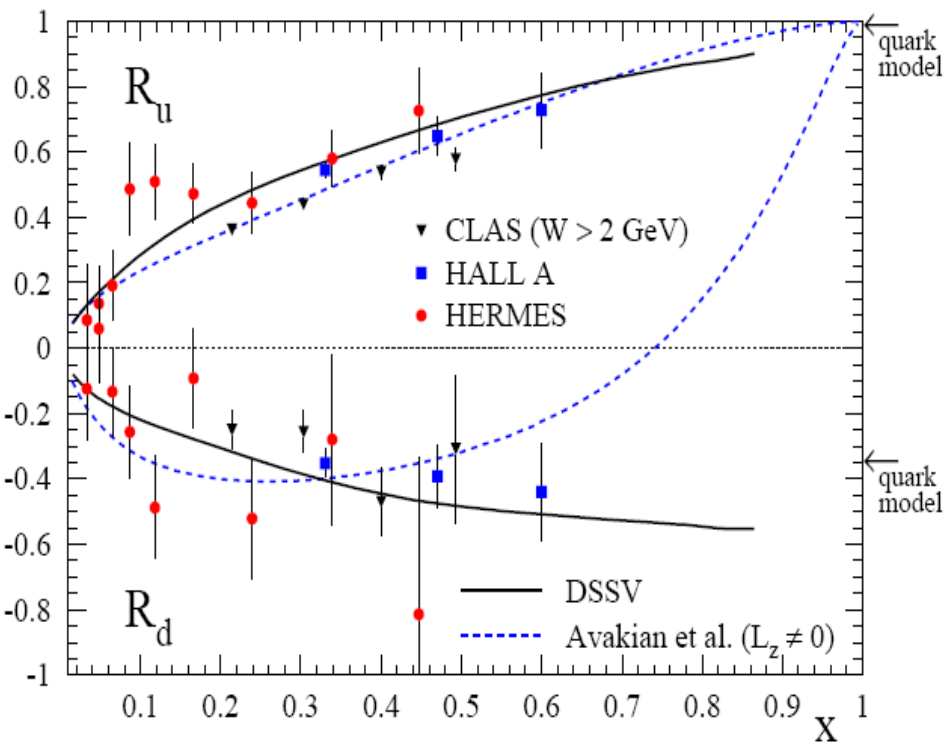


What is the emerging picture for the helicity structure of the nucleon ?

DSSV valence quark polarizations

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





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

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

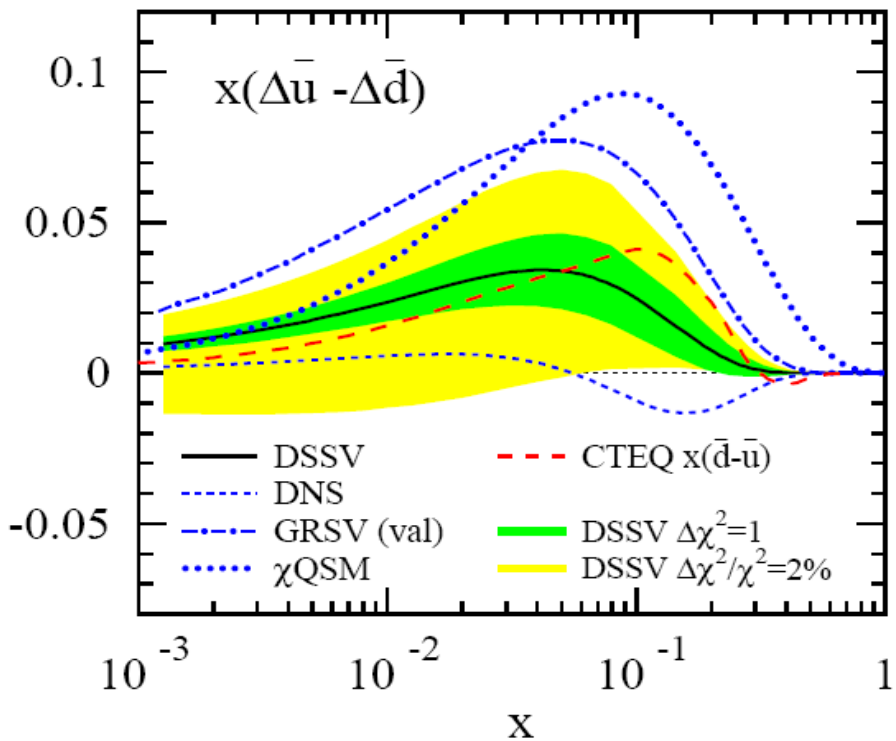
- $R_u(x \to 1) \to 1$ as expected
- $R_d(x \to 1)$ remains negative
- counting rules + helicity retention + nonzero OAM: expect $R_d(x \to 1) \to 1$

  Avakian, Brodsky, Deur, Yuan

what happens as $x \to 1$?

DSSV: tantalizing hints at non-trivial sea polarizations

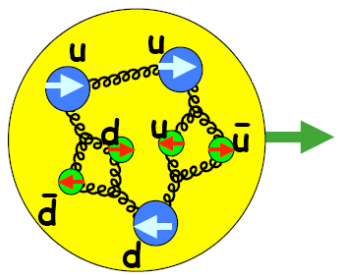
- **indications for an SU(2) breaking of light polarized u,d sea**



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

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

pattern confirmed by future probes?



- many models give comparable results

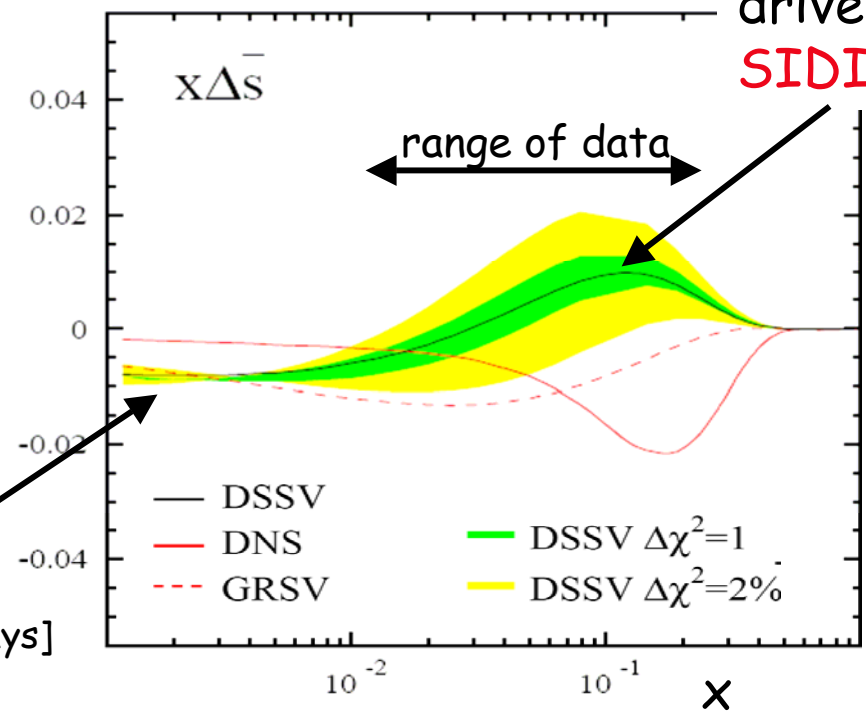
  large-N_C, chiral quark models, meson cloud, Pauli blocking, …

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

DSSV sea polarizations – cont'd

- **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]

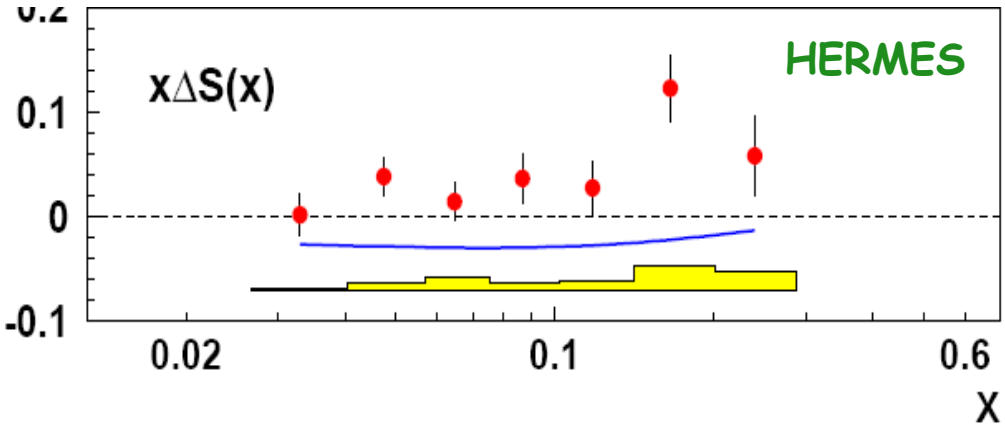
striking result, but relies on

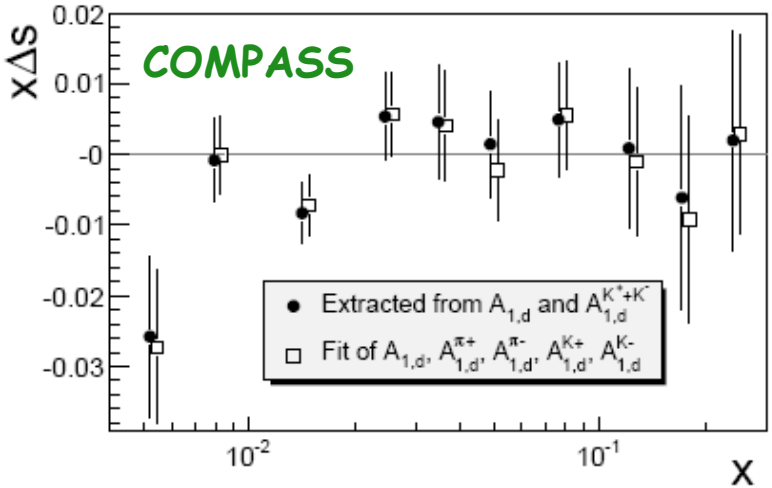
- kaon fragmentation – **how reliable ?**
  more data available soon (BELLE, …)
- unpolarized PDFs – **how well do we know s(x) ?**
  HERMES result for s(x) does not agree well with CTEQ
- SU(3) breaking uncertainties – **sizable ?**
  Lipkin; Zhu, Puglia, Ramsey-Musolf; …

needs further studies exp. & theory !

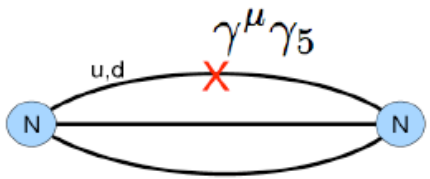
strangeness conundrum – cont'd

- **LO extractions** by HERMES & COMPASS agree well with DSSV

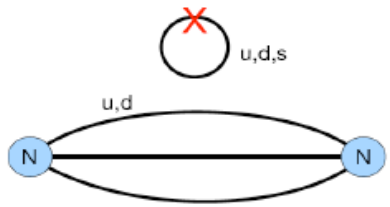




- **lattice QCD result:** Bali, Collins, Schafer, arXiv:0811.0807v2



connected



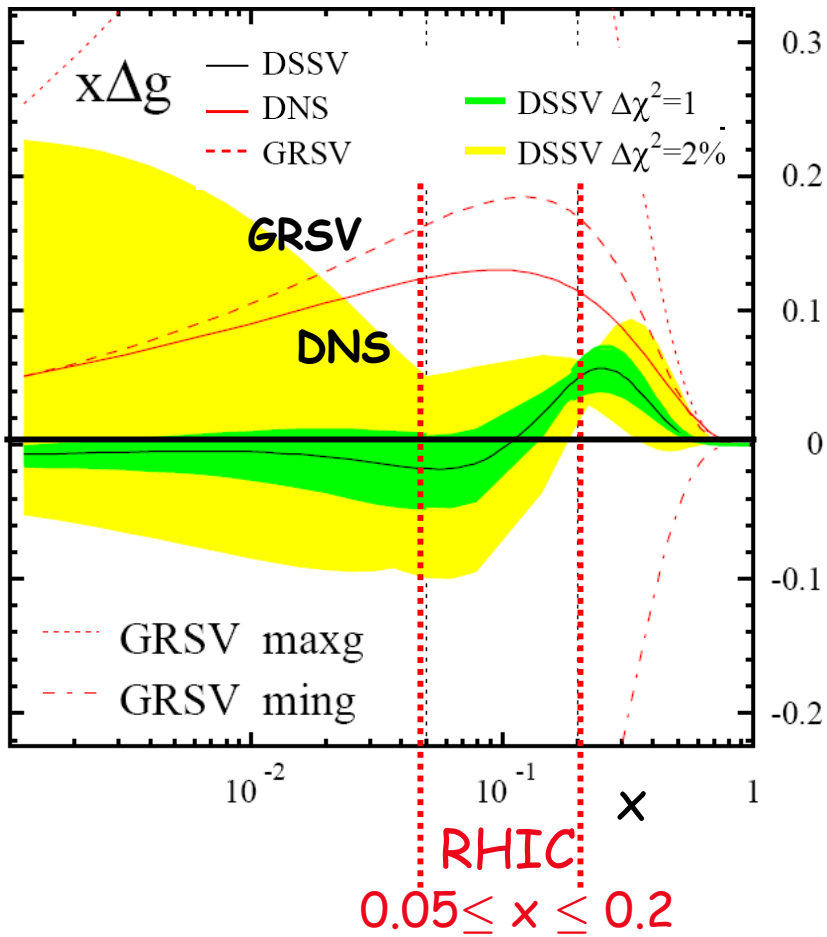
disconnected

find: $\frac{1}{2}\int_0^1[\Delta s+\Delta\bar{s}](x)\,dx = -0.01 \ldots 0.01$ (95%CL) [DSSV w/ SU(3): -0.06 !!]

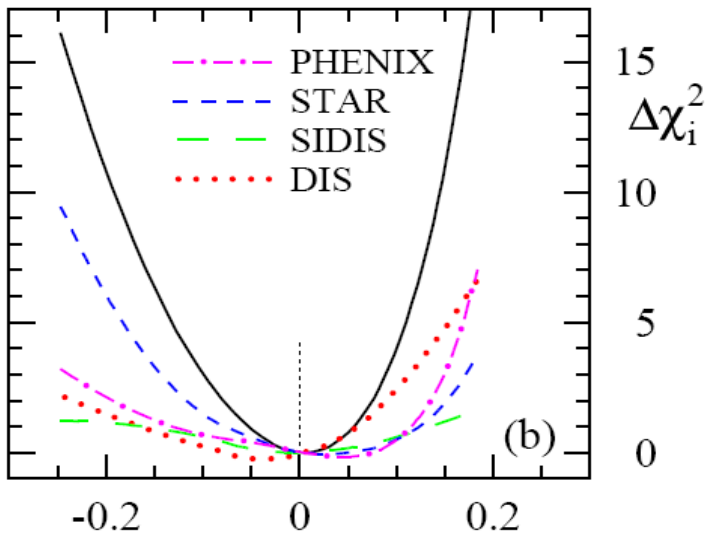
issues: not renormalized yet, continuum extrapolation, …

very small value → **SU(3) strongly broken ? perhaps $\Delta s = -\Delta\bar{s}$?**

DSSV gluon polarization



- best fit has a node at $x \simeq 0.1$
- $\Delta g(x)$ very small at medium x
  (vanishing integral)



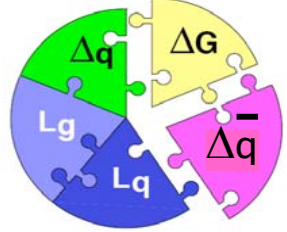
$$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10\,\mathrm{GeV}^2)\,dx$$

- huge uncertainties at small x
  a significant polarization is still possible, even opposite to the nucleon spin

could the gluons be paired to spin-0 at around μ = 1 GeV ?

Kharzeev, Levin, Tuchin hep-ph:0809.3794

spin audit: 1st moments & the spin of the proton



"helicity sum rule"

Jaffe, Manohar; Ji; ...

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

$A^+ = 0$ gauge, IMF
partonic interpretation

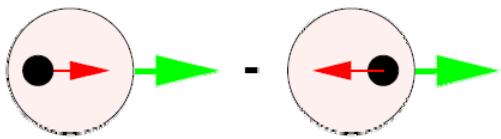
total u+d+s quark spin | gluon spin | orbital angular momentum

"quotable" properties of the nucleon !

momentum fraction

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

helicity parton densities



x-moment $\xrightarrow{\int_0^1 dx}$ **total spin polarizations S_q and S_g !**

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

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

numerical results (DSSV)

$Q^2 = 10\ GeV^2$

$$\Delta f^{1,[x_{\min},1]} \equiv \int_{x_{\min}}^{1} \Delta f(x)dx$$

	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

- Δs, $\Delta\Sigma$ receive large negative contribution at small x
- Δg: huge uncertainties

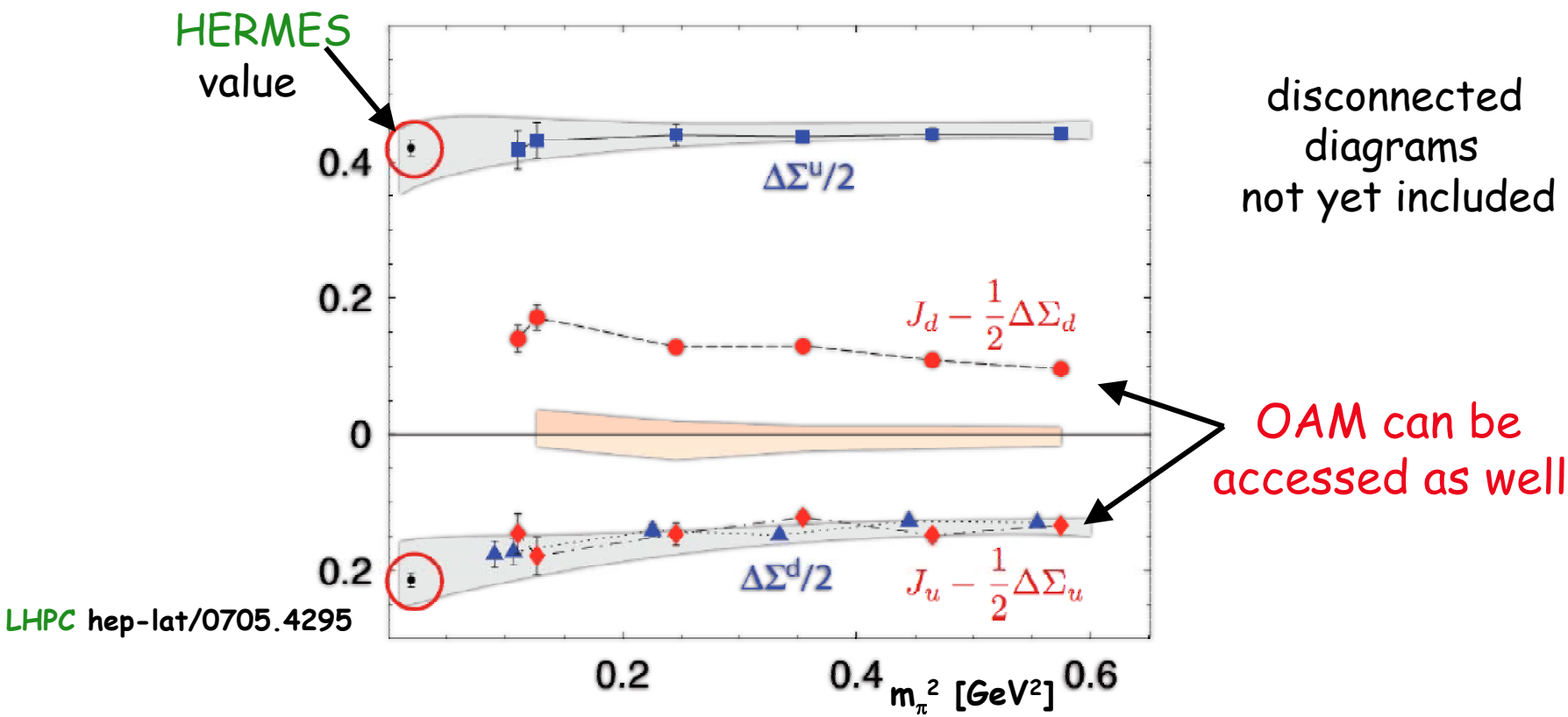
very difficult to give reliable estimates for full moments

issues:

- small x extrapolation
- validity of SU(3) "constraints"

http://www.sciencecartoonsplus.com/index.htm

1st moments can be computed on the lattice …



find: $\Delta u > 0$ and $L_u < 0$; $\Delta d < 0$ and $L_d > 0$ but in any quark model $L_u > 0$, $L_d < 0$

sign due to strong scale evolution of L_q ? Myhrer, Thomas

$L_u + L_d \simeq 0$ contribution from disconnected diagrams?

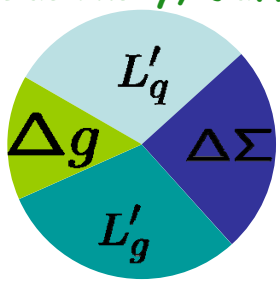
if $\Delta g \simeq 0$, does this leave us with gluon OAM as culprit in spin audit?

note: using AdS/CFT nucleon spin comes entirely from OAM Hatta, Ueda, Xiao arXiv:0905.2493

complication: "different" spin sum rules

ambiguities arise when decomposing proton spin in gauge theories

Jaffe, Manohar;
Bashinsky, Jaffe

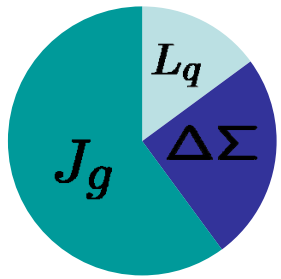


reshuffling of ang. momentum

between matter and gauge degrees

only $\Delta\Sigma$ unchanged

Ji



intuitive; partonic interpretation

Δg, $L'_{q,g}$ local only in $A^+ = 0$ gauge

how to determine $L'_{q,g}$ experimentally ?

manifest gauge invariant local operators

contain interactions $\rightarrow$ interpretation ?

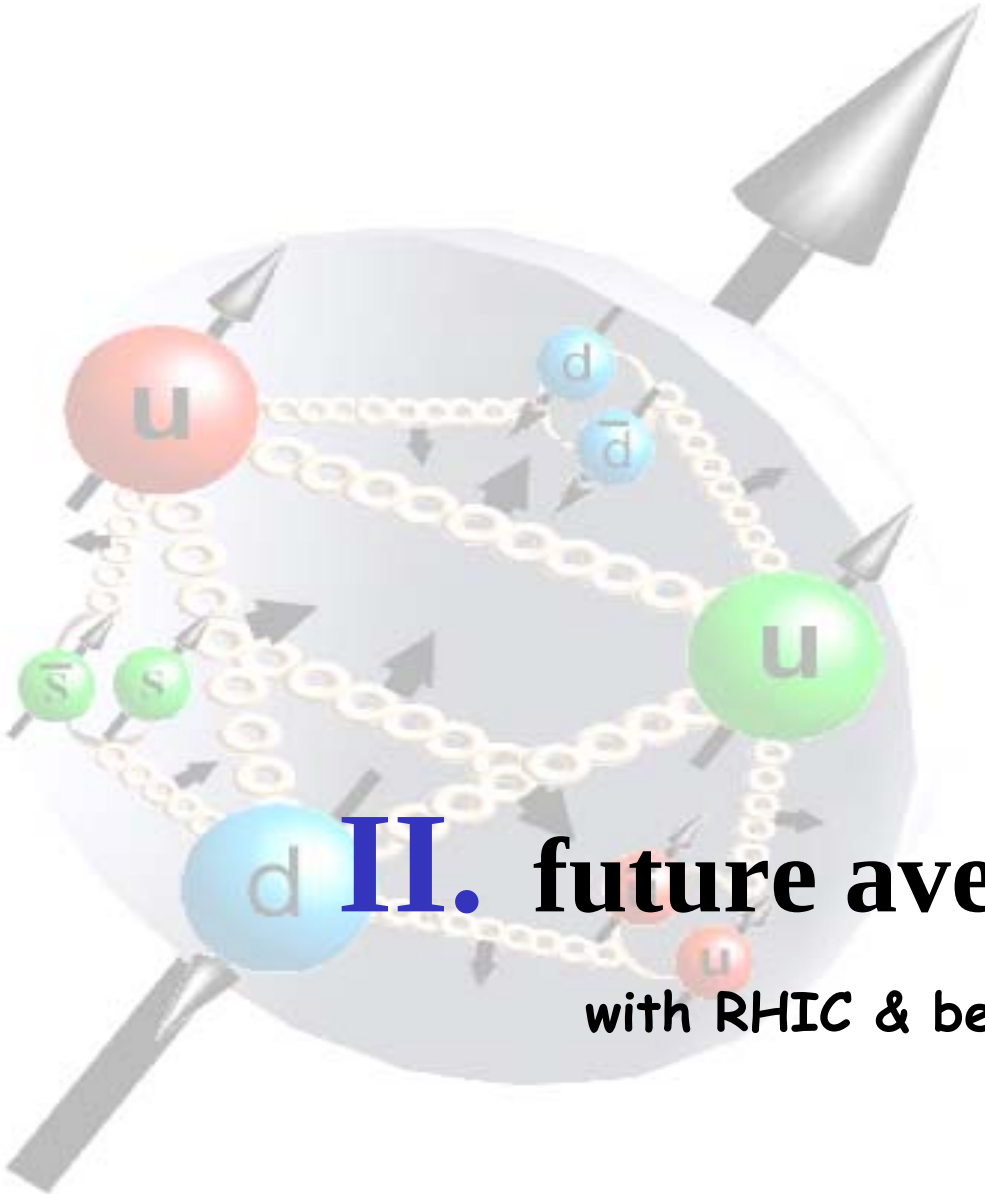
$L_q + \Delta q/2$, $J_g \leftrightarrow$ GPDs (DVCS)

- lattice results for L_q are for Ji's sum rule and cannot be mixed with Δg
- num. difference between L_q and L_q' can be sizable Burkardt, BC arXiv:0812.1605

latest twist: Chen, Lu, Sun, Wang, Goldman arXiv:0806.3166; 0904.0321

3rd decomposition: like Jaffe, Manohar but w/ manifest gauge inv. operators

physical interpretation? requires new def. of PDFs – relation to experiment?



II. future avenues

with RHIC & beyond

- **single-inclusive measurements = bread & butter probes**

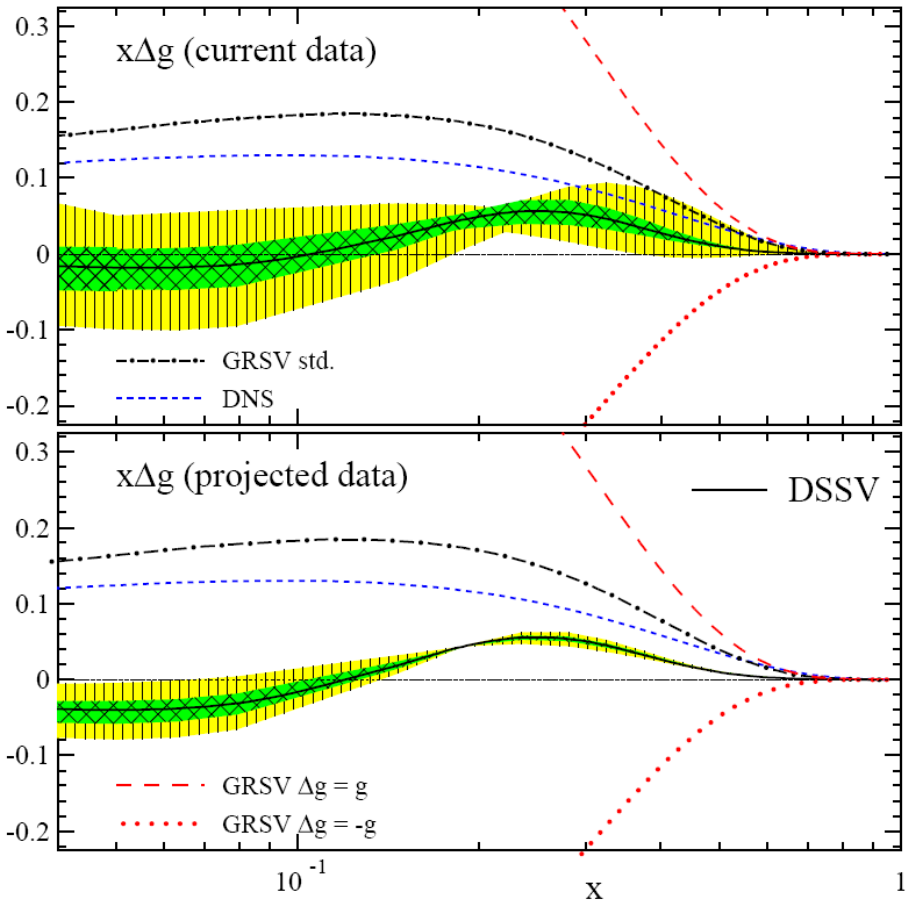
- hope for O(50pb^{-1}) with 60% pol. @ 200 GeV
- significant 500 GeV running

expect:

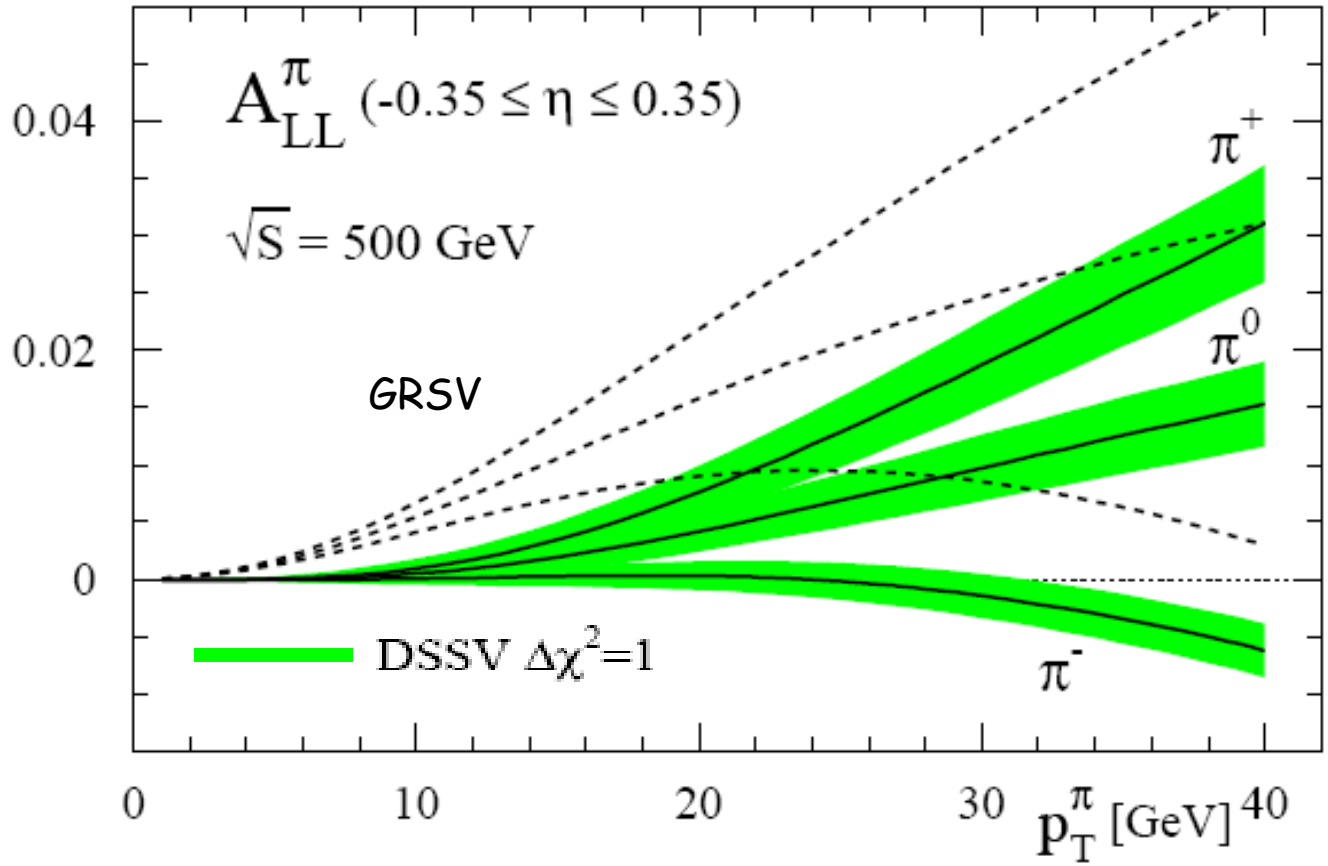
o significant improvement of inclusive jet & π^0 data sample

exercise: global fit w/ 4× the statistics of current STAR jet data

from 2008 Spin Plan



o compare charged pion production with theory predictions



$p_T \gtrsim$ 10 GeV: driven by qg scattering

$$[\Delta u \otimes D_u^{\pi} + \Delta\bar{u} \otimes D_{\bar{u}}^{\pi} + \Delta d \otimes D_d^{\pi} + \Delta\bar{d} \otimes D_{\bar{d}}^{\pi}] \otimes \Delta g$$

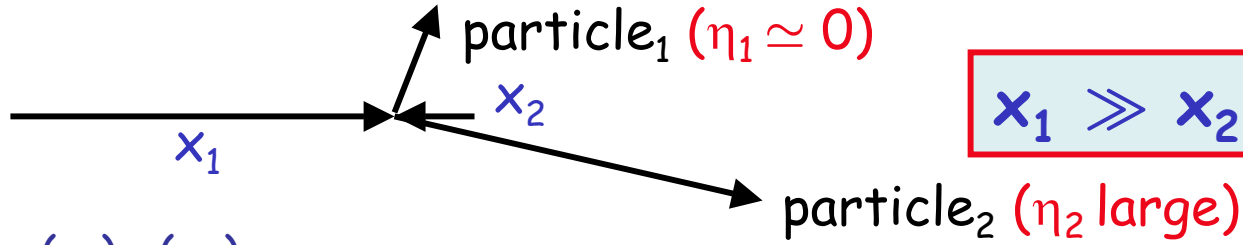
properties of FFs → expect

$A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-)$

going beyond 1-inclusive: particle correlations

idea:

forward-central correlations



$$x_1 \gg x_2$$

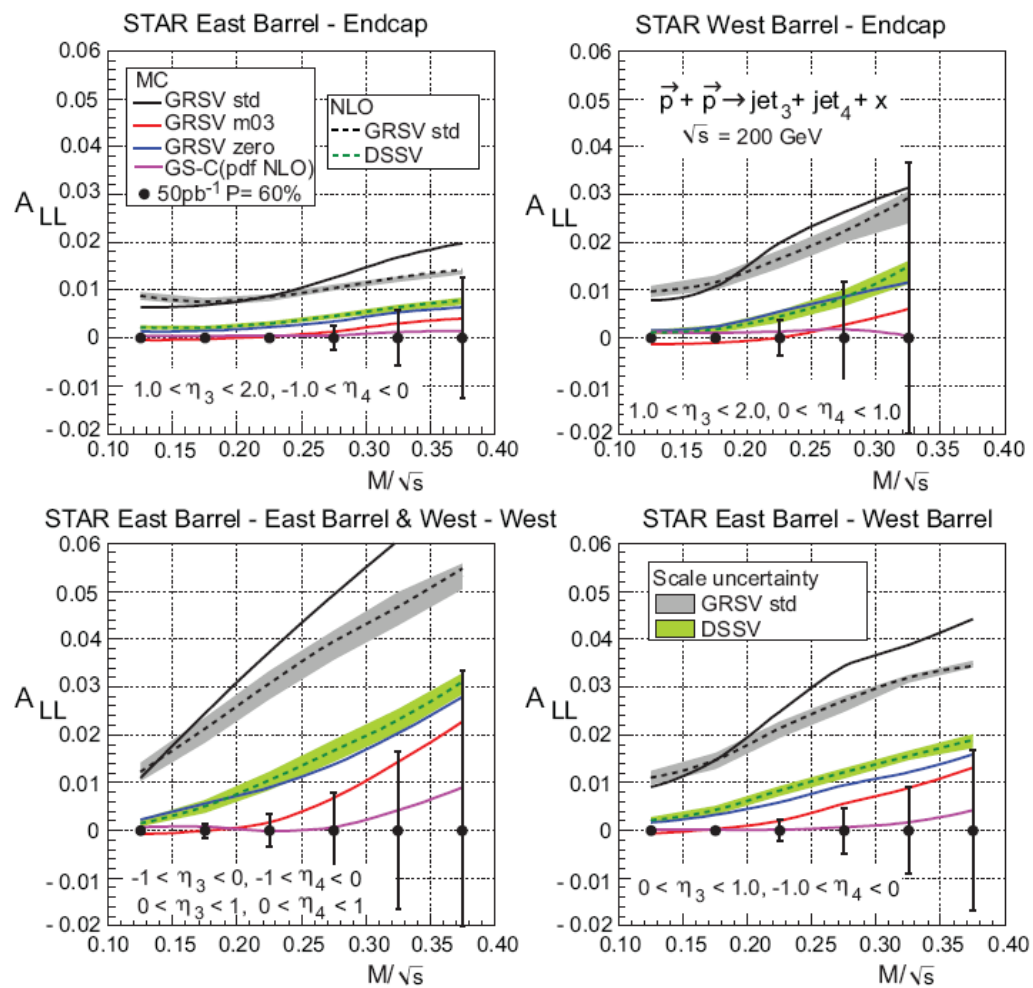
→ mainly qg-scatt.: $q(x_1)\, g(x_2)$

di-jet simulation from STAR

→ more precise mapping of $\Delta g(x)$

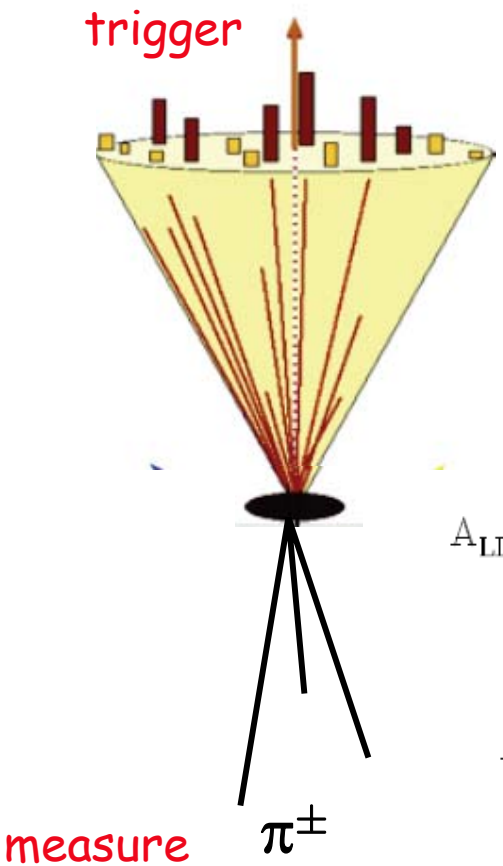
$$x_{1,2} = \frac{p_T}{\sqrt{S}}(e^{\pm\eta_3} + e^{\pm\eta_4})$$
$$M^2/S = x_1 x_2$$

✓ NLO & Mellin technique is basically in place to analyze also particle correlations



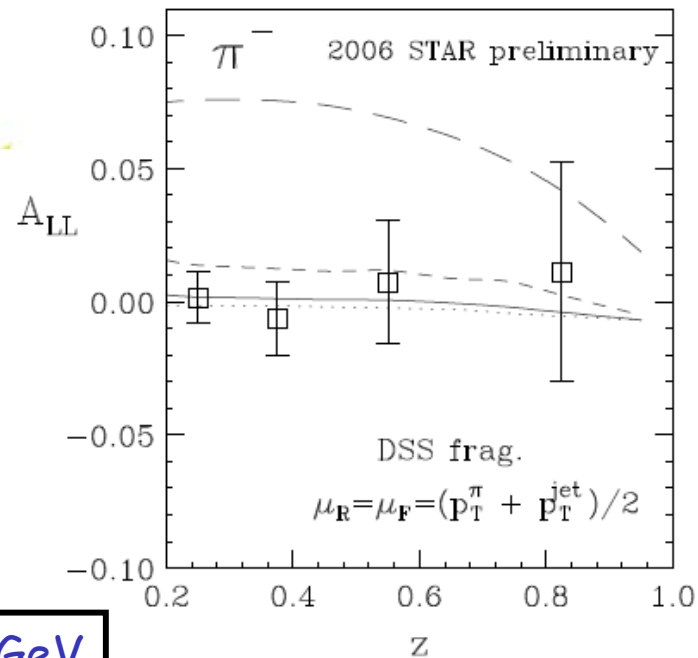
taken from 2008 RHIC spin plan

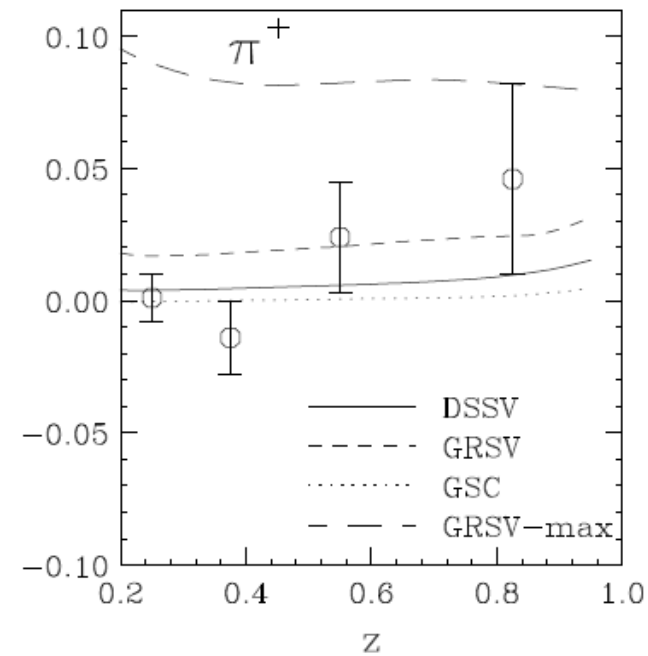
o 1st promising result from STAR: mid-rapidity $\pi^{\pm}$ w/ jet patch trigger



data compare well with a recent NLO calculation using DSS FFs & DSSV PDFs

de Florian, arXiv:0904.4402





$|\eta| \leq 1$; $p_T^{\pi} > 2$ GeV
$25 > p_T^{jet} > 10$ GeV

$z \simeq p_T^{\pi}/p_T^{jet}$

role of "rare" probes: prompt photons & heavy flavors

often hear statements like

"statistically not as significant as jets $\rightarrow$ don't bother"

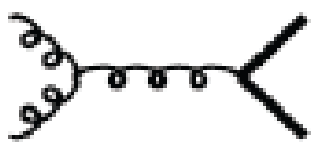
cannot disagree more !

probe rather different hard scattering dynamics than jets and hadrons

(plus: much smaller number of contributing subprocesses here)

prompt photons

heavy flavors

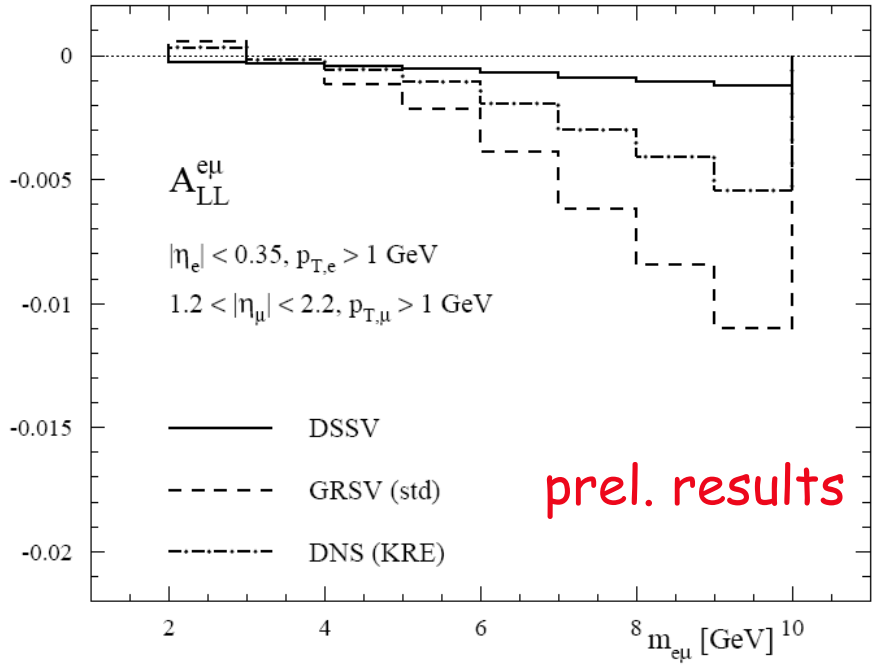


crucial in understanding spin-dep. QCD hard scattering
test universality and factorization

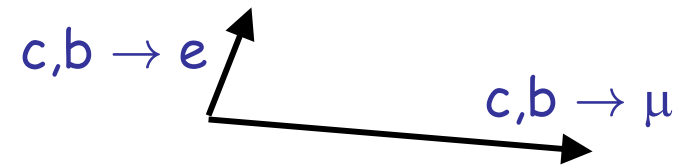
o expectations for heavy flavor correlations

Riedl, Schafer, MS

obtained with new flexible NLO MC code; includes hadronization and leptonic decays

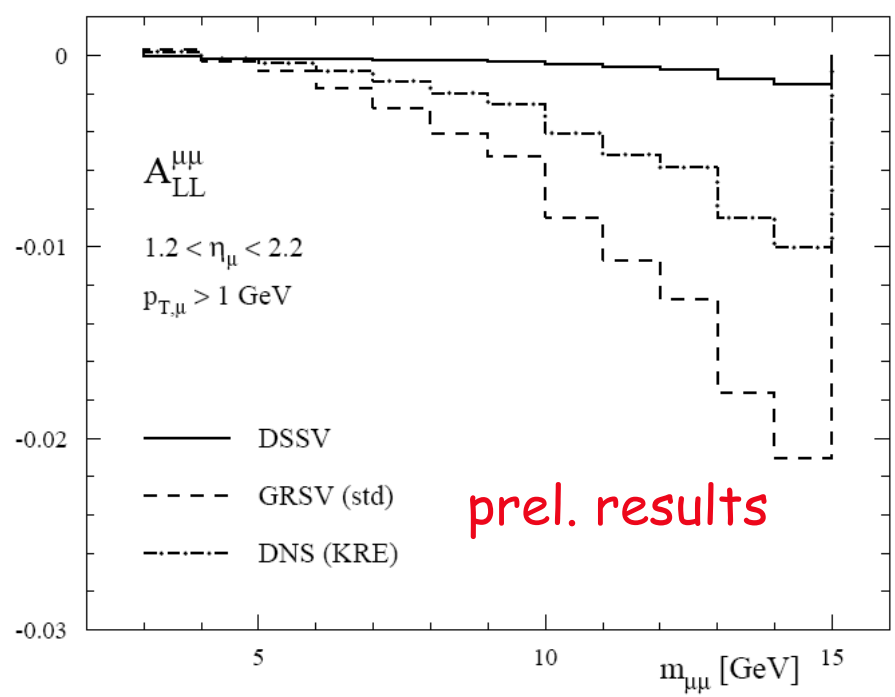


forward-central e-μ coincidences



note: single-e & single-μ have tiny A_{LL}'s

forward-backward μ-μ coincidences

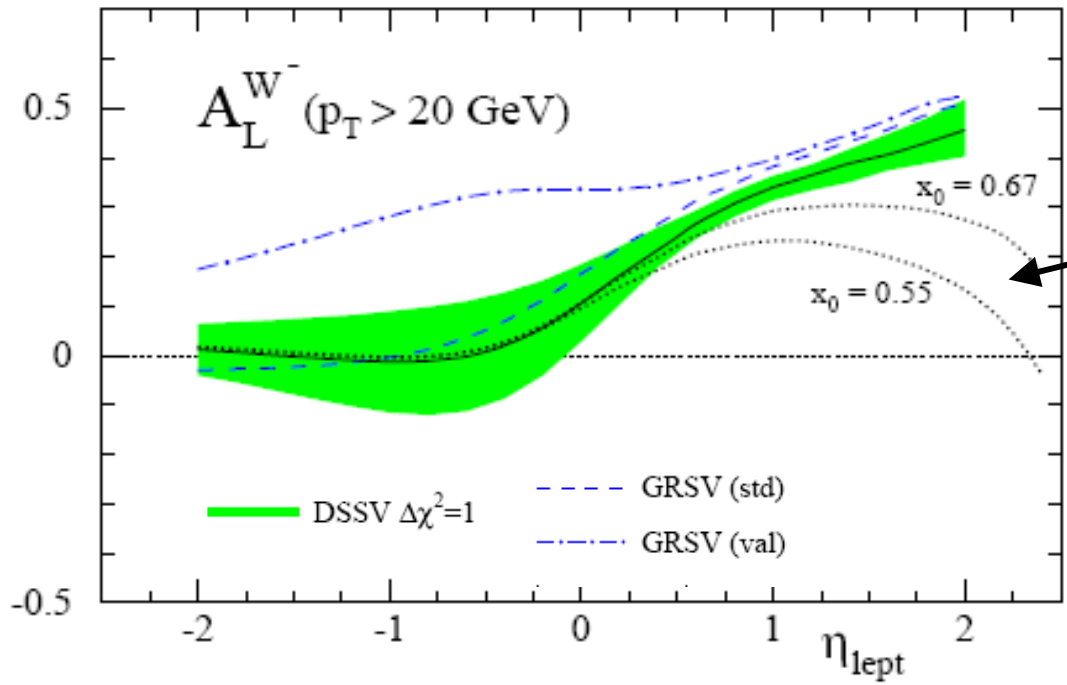


detailled paper soon on the arXiv

key measurement at 500 GeV: W boson production

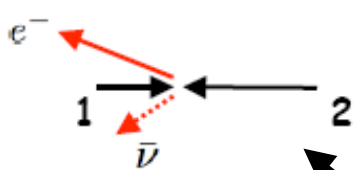
flavor separation from parity-viol. single-spin asymmetry $A_L \equiv \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

example: A_L for W^-



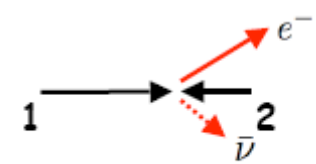
two "DSSV" sets enforcing $\Delta d/d \to 1$ as $x \to 1$

$\frac{\Delta\bar{u}}{\bar{u}}$



$\theta \to \pi$
$x_2 \gg x_1$

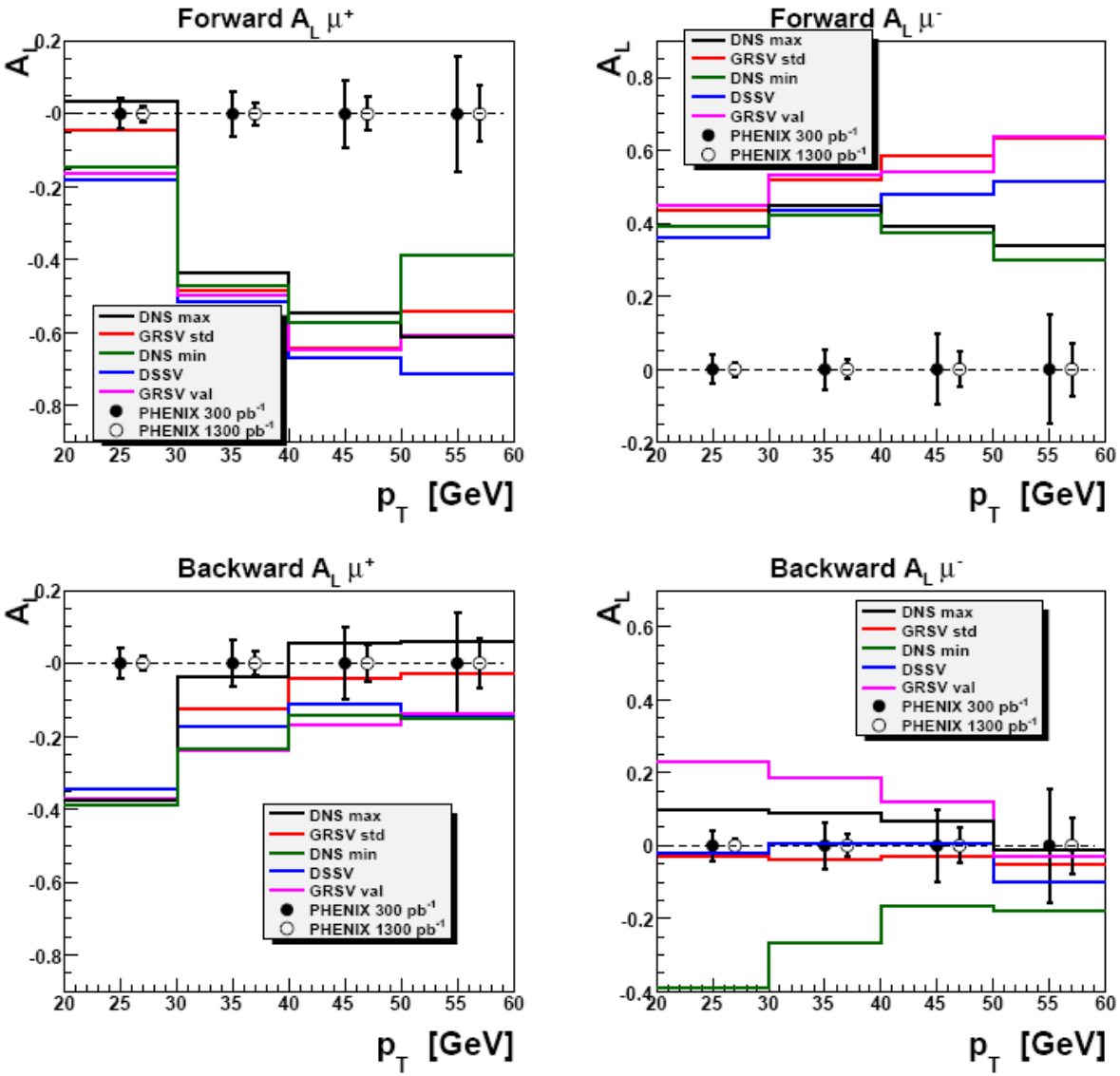
$\theta \to 0$
$x_1 \gg x_2$



$\frac{\Delta d}{d}$

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

o example: PHENIX simulation w/ detector & background



taken from 2008 RHIC spin plan

complementary to SIDIS
(which has better statistics)

- scale $Q \sim M_W$
  $\rightarrow$ tests evolution
- no fragmentation
- should look also into hadronic decays

Berger, Nadolsky; ...

urgent task:
run global fit with projected data

prospects on Δs

- final HERMES data sets for SIDIS & DIS multiplicities; more from COMPASS; can we distinguish Δs and $\Delta\bar{s}$ in the future?

- notoriously difficult in pp:
  two channels: W+charm (extremely rare probe)
  polarized Λ production $\rightarrow$ **STAR**

  1st paper recently
  arXiv:0910.1428 [hep-ex]

important issues to be addressed for Λ production:

- reliable NLO sets of D_i^Λ *and* ΔD_i^Λ

  DSV: de Florian, MS, Vogelsang, PRD 57 (1998) 5811
  updated global analysis required, D_g too small (STAR data)

  AKK: Albino et al., arXiv:0803.2768v2

  DSV: de Florian, MS, Vogelsang, PRD 57 (1998) 5811
  sparse data; 3 models considered; update desirable

- feed-down from hyperon weak decays; effect on polarization?

- compute helicity-transfer subprocesses at NLO (work in progress)

Jager, MS

expect significant progress from ongoing RHIC program

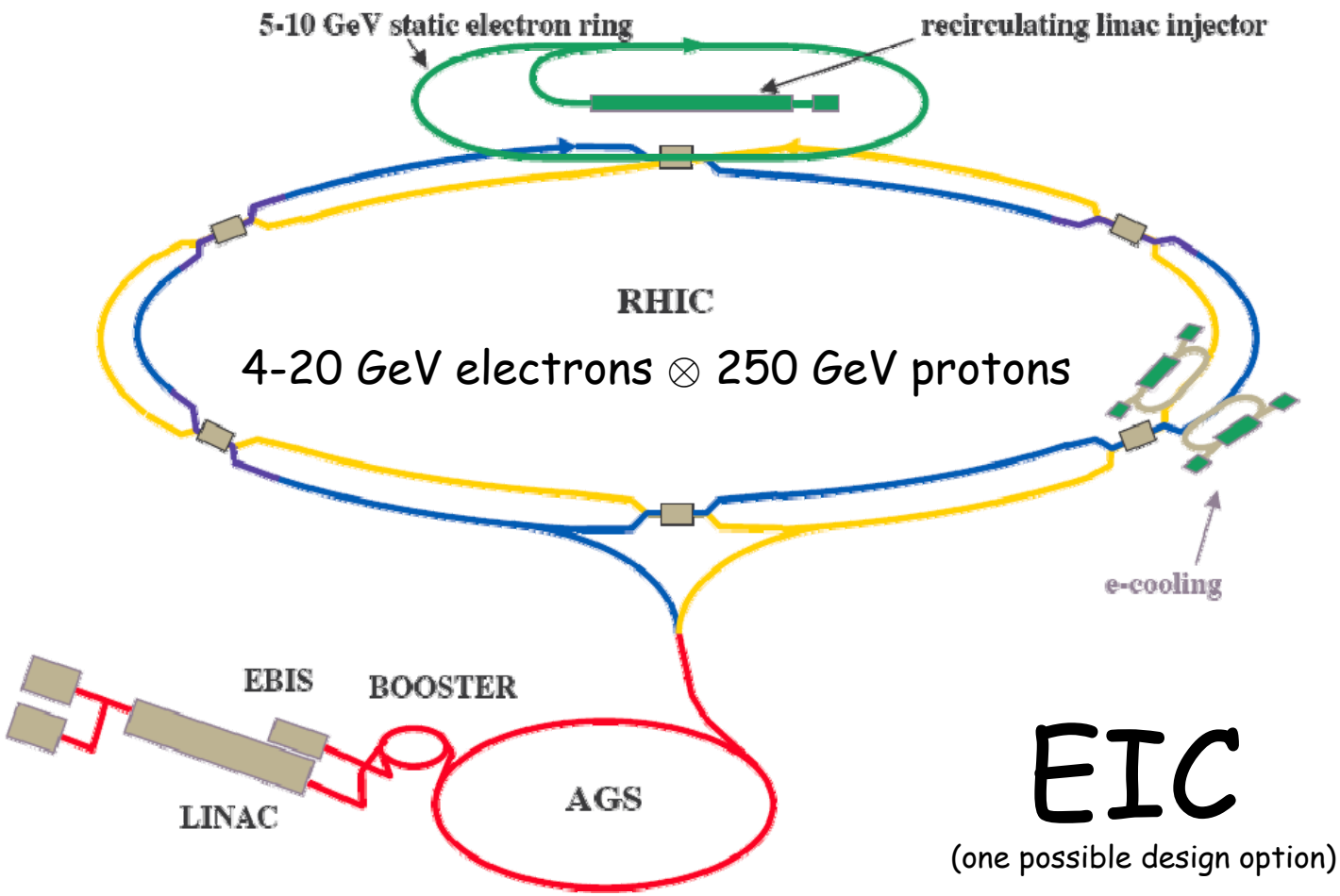
but crucial questions will remain at the small-x frontier

history (DESY-HERA) suggests that extrapolations towards small-x are notoriously unreliable

we need to measure at small x to settle this issue

$\rightarrow$ case for a high-energy polarized ep-collider

further into the future … small x



for PDF studies energy matters much more than luminosity

taking up HERA's legacy

repeat the successful HERA program w/ spin (and w/ heavy ions)

suite of key measurements with longitudinal polarization, e.g.:

- **deep-inelastic scattering**

  scaling violations in g_1 to extract Δg at small x $\rightarrow$ reliable $\int \Delta g(x)\, dx$
  charm (bottom) contribution
  electroweak effects at high Q^2 $\rightarrow$ quark flavor structure
  semi-inclusive a la HERMES, COMPASS $\rightarrow$ flavor separation, Δs at small x
  precision test of Bjorken sum rule $\rightarrow$ α_s
  diffractive phenomena w/ spin?

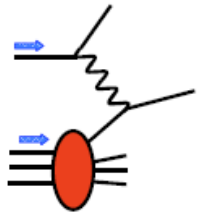
- **photoproduction regime**

  HERA established non-perturbative structure of the photon in
  hadron, jet, heavy quark production $\rightarrow$ helicity structure of photons

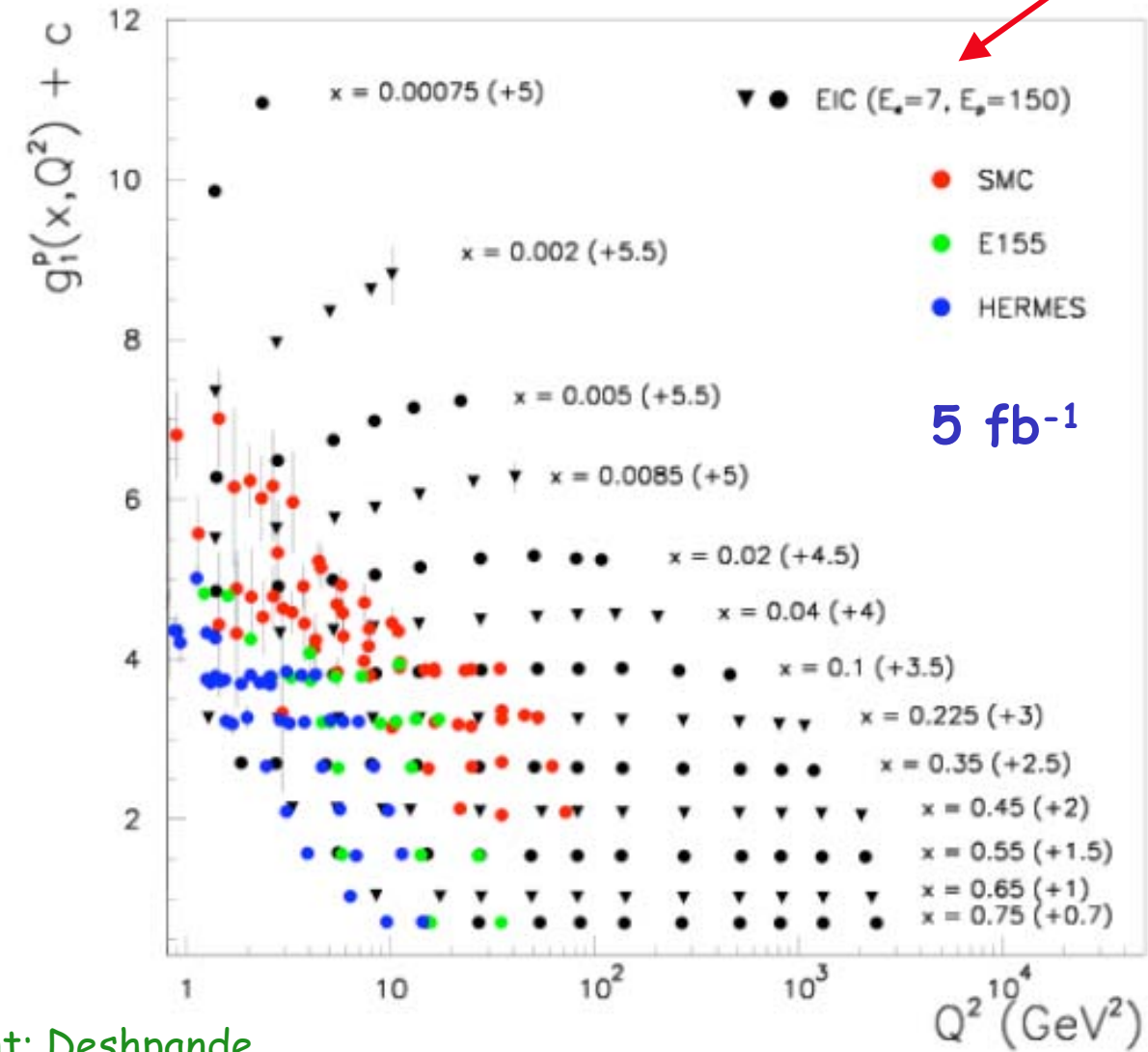
we need to perform quantitative studies well before the next LRP

scaling violations in DIS

projections available (2007 EIC White Paper)



$\simeq 4 \times 250$ GeV

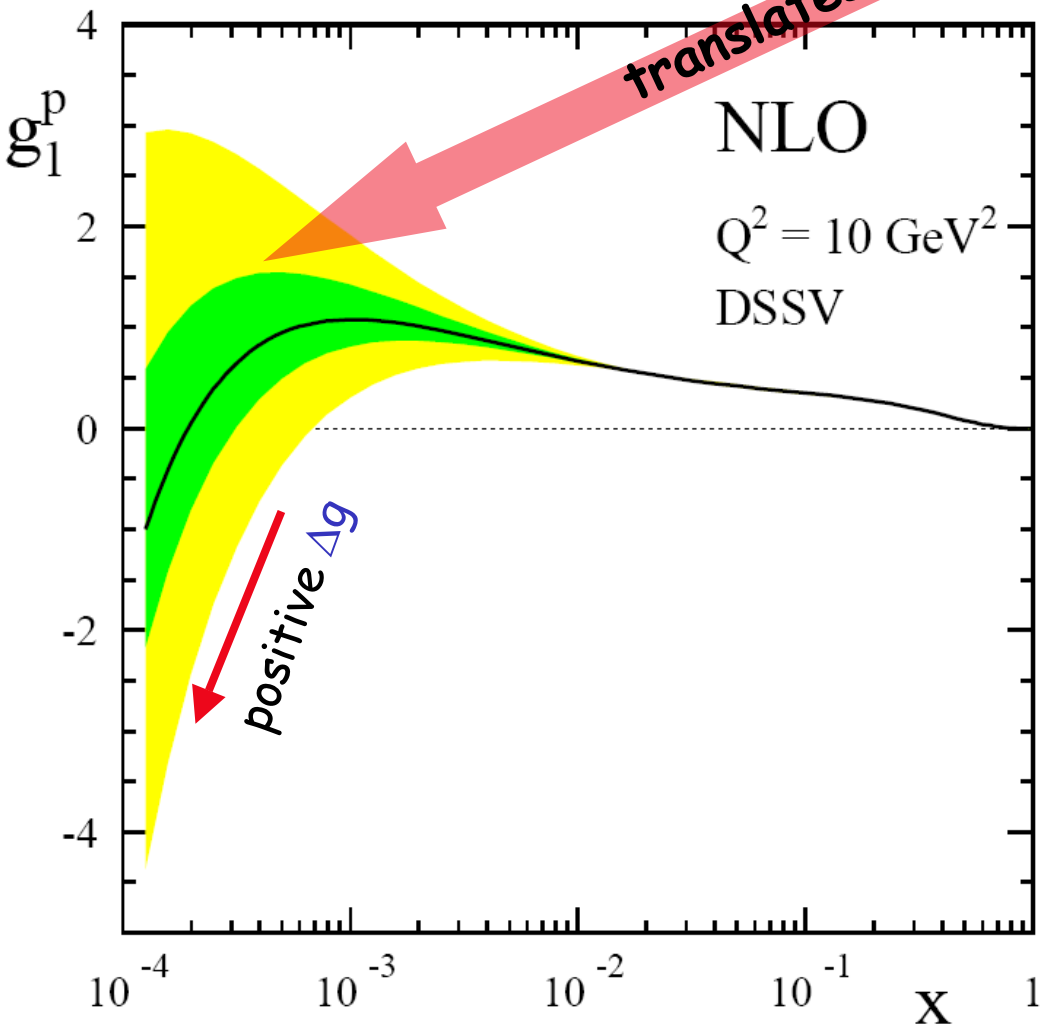


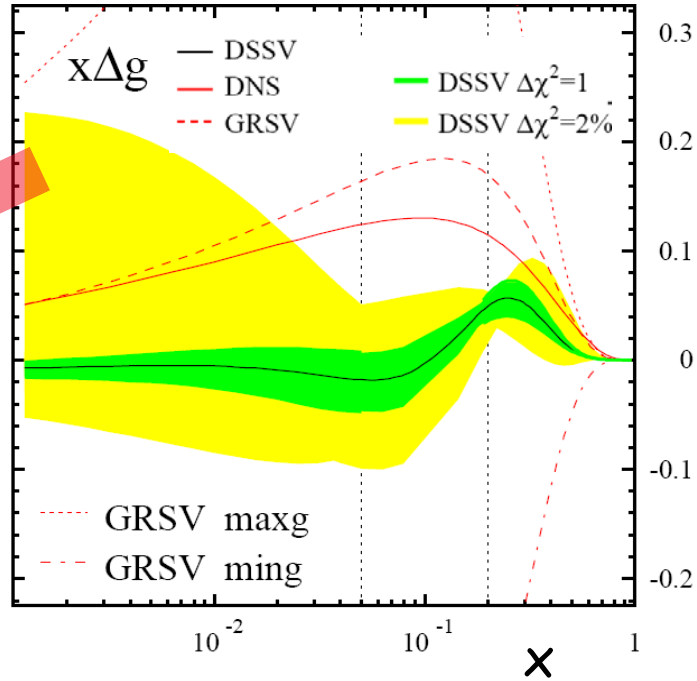
Bruell, Ent; Deshpande

o small x uncertainty from DSSV

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

translates into





QCD theory progress:

NNLO kernels on the horizon

Vogt, Moch, Rogal, Vermaseren

important exercise to be done:

global QCD fit with projected EIC data to quantify their impact

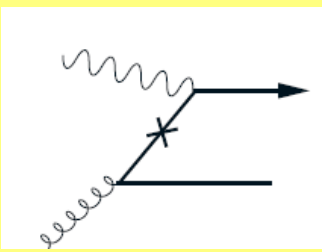
studies already under way

o one issue: massive charm contribution to g_1

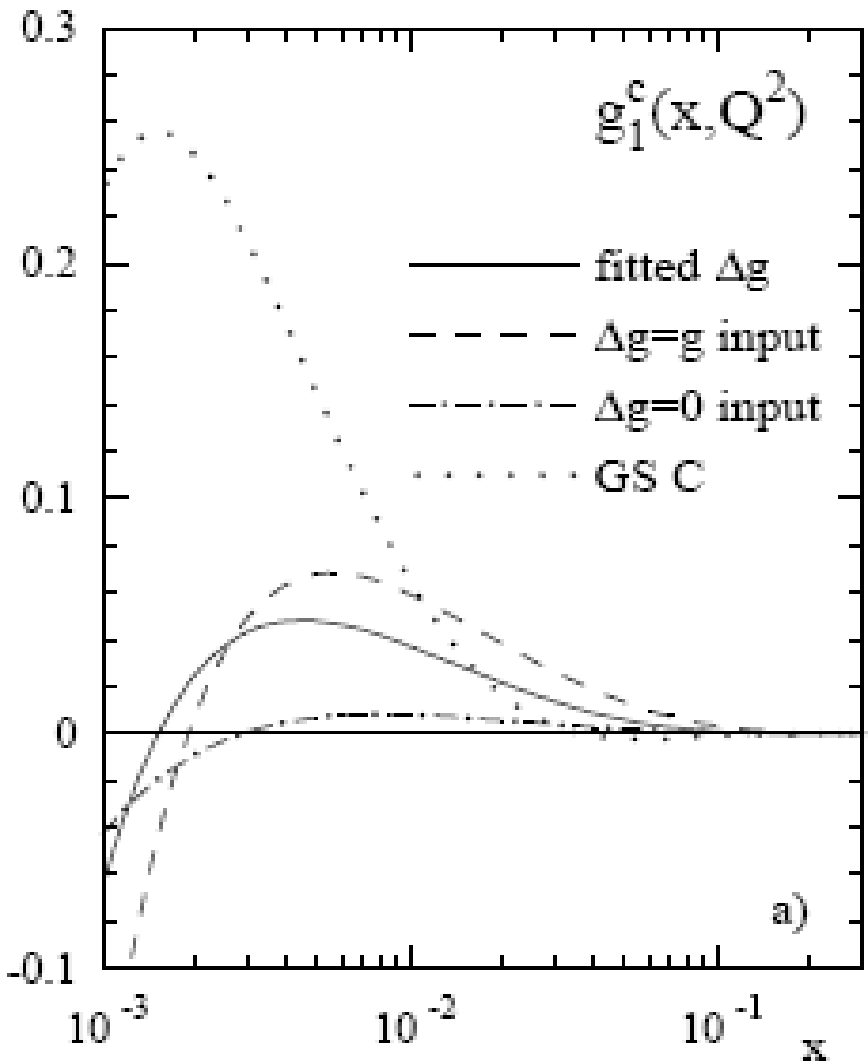
work to be done !

- so far safely ignored
  $\ll$ 1% to existing g_1 data
- $\simeq$ 20% contribution to F_2
  at small x seen at HERA
- expect g_1^{charm} of O(10%)
  at EIC depending on Δg

- **problem:** PGF $\gamma^*(Q^2)g \to c\bar{c}$
  only known to LO in pol. case
- no variable flavor scheme
  a la CTEQ, MRST developed yet

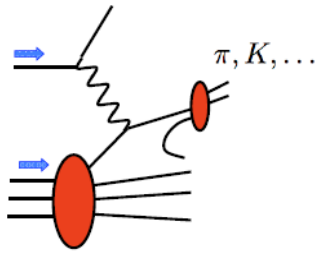


$\sim P_{cg} \ln [Q^2/m^2]$

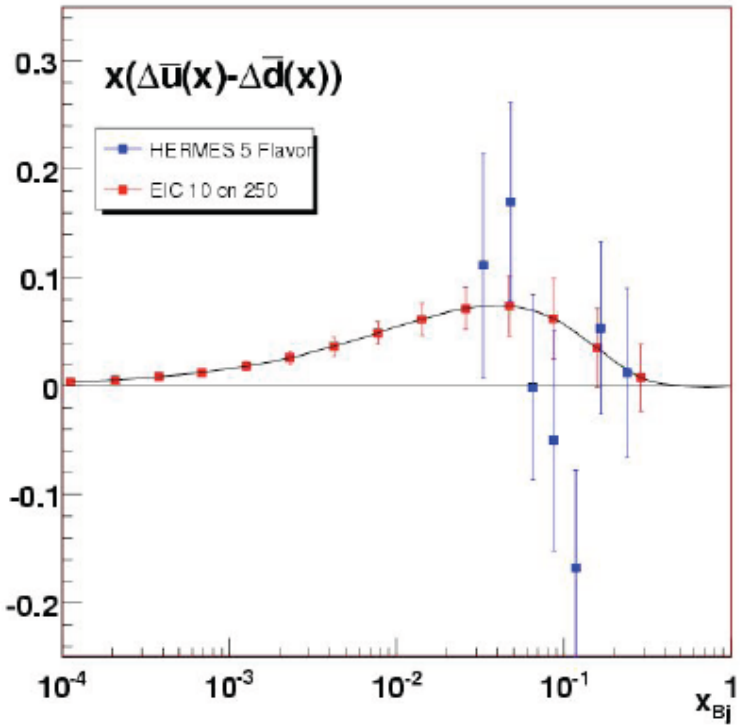


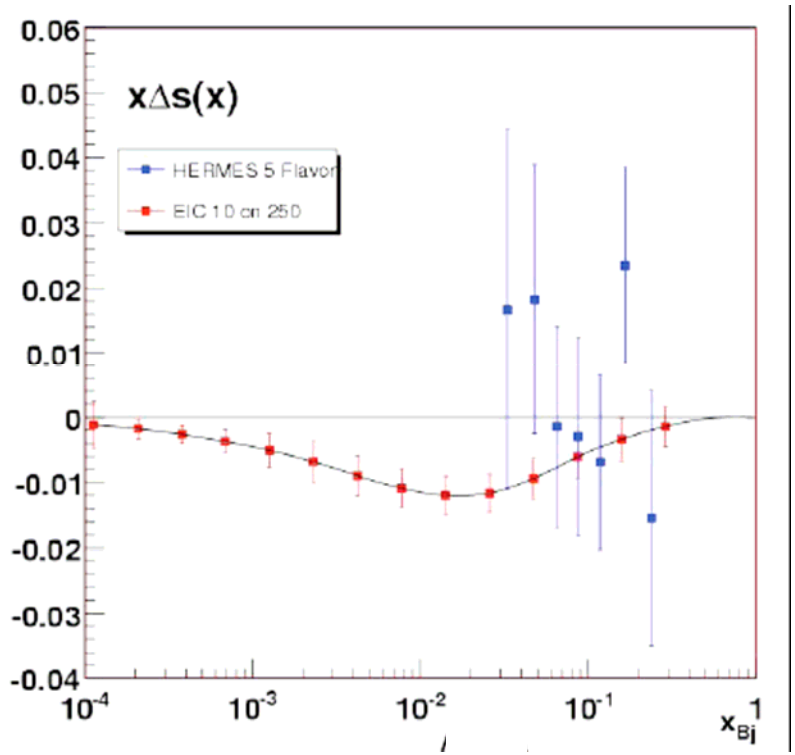
LO estimates from 1996 MS, Vogelsang

flavor decomposition from SIDIS



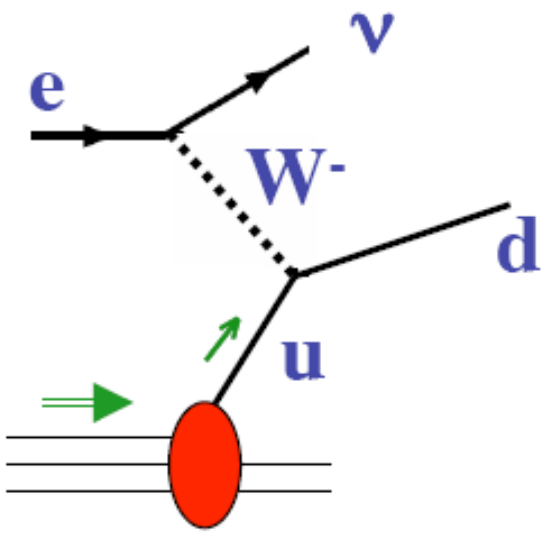
projections by J. Seele, E. Kinney



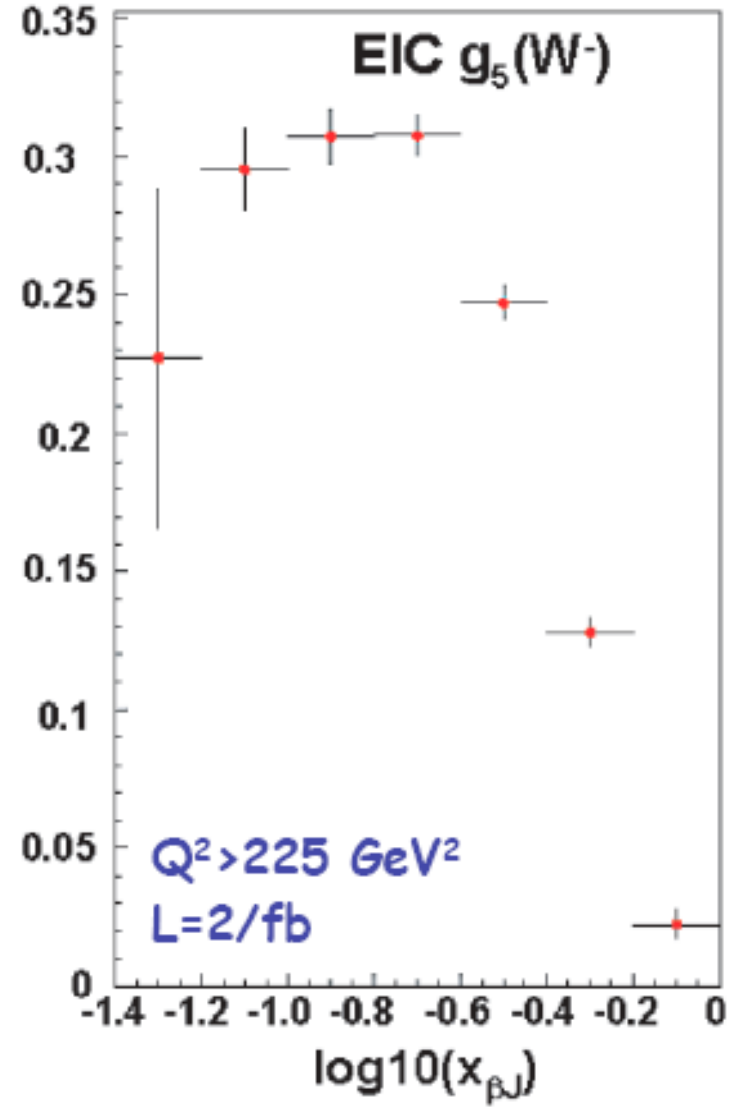


again, make use of projections and demonstrate their impact in a global QCD fit

electroweak effects in DIS at high Q^2



Contreras et al.



e.g., $g_5 \propto \Delta u - \Delta \bar{d} - \Delta \bar{s}$

→ flavor separation

extension to SIDIS ?

new sum rules, e.g.,

$$\int_0^1 dx [g_5^{W^+,p} - g_5^{W^-,n}] = -\left(1 - \frac{2\alpha_s}{3\pi}\right) g_A$$

MS, Vogelsang, Weber

precision test of Bjorken sum rule

- rare example of a well understood quantity in QCD, computed to $O(\alpha_s^3)$

Bj-sum: $$\int_0^1 dx \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] = \frac{1}{6} C_{\rm Bj}\left[\alpha_s(Q^2)\right]\ g_A$$

$$C_{\rm Bj}(\alpha_s) = 1 - \frac{\alpha_s}{\pi} - \left[\frac{55}{12} - \frac{n_f}{3}\right]\left(\frac{\alpha_s}{\pi}\right)^2$$

Kodaira; Gorishny, Larin;
Larin, Vermaseren

$$- \left[41.4 - 7.6\, n_f + \frac{115}{648}\, n_f^2\right]\left(\frac{\alpha_s}{\pi}\right)^3 \pm \ldots$$

- currently experimentally verified to about 10%
- needs (effective) neutron beams at EIC
- can turn into one of the best extractions of α_s

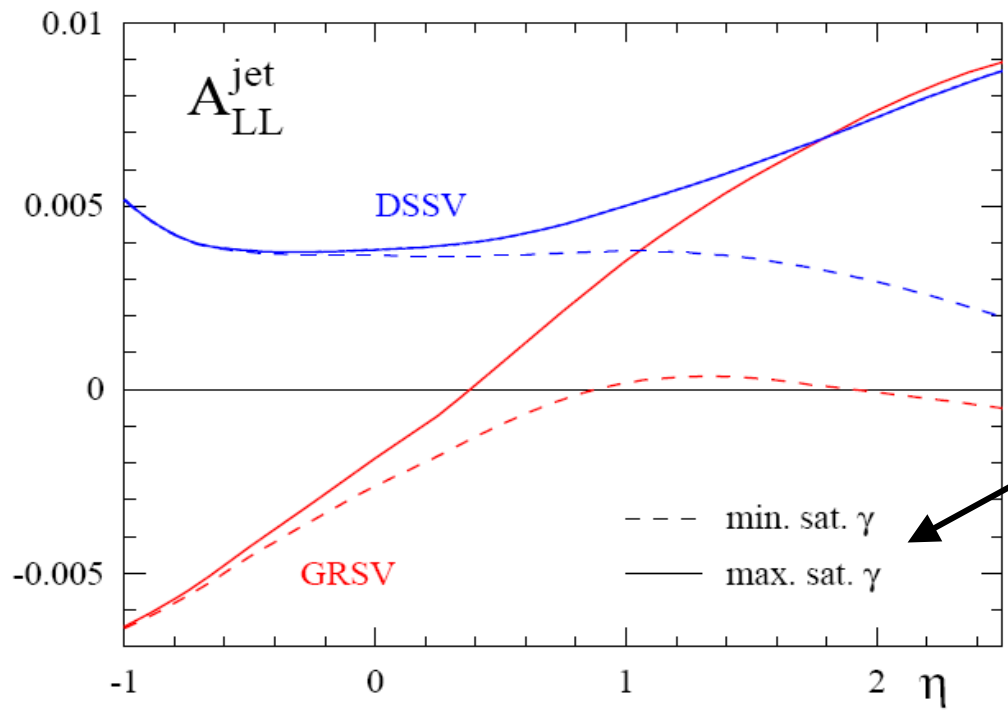
suite of measurements in photoproduction

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

- one of the highlights of the HERA program
- many studies available at NLO for EIC, e.g.

1-jet

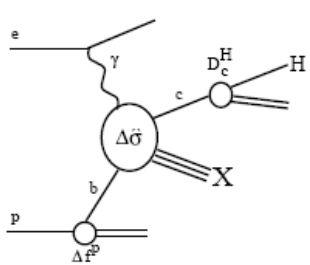
Jäger
arXiv:0807.0066

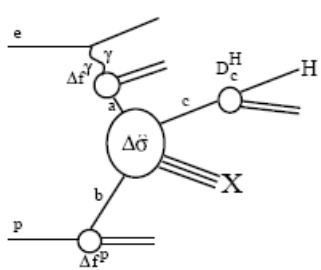


different assumptions about Δf^{γ}

lepton ← → **proton**

$x_\gamma \simeq 1$
probes proton PDFs





$x_\gamma \ll 1$
probes unknown photon PDFs

conclusions

- important progress in recent years

  first data from RHIC, NLO global analysis, …

- Δg and sea polarizations start to surface

  but contributions to spin sum rule still unclear

- RHIC continues to provide crucial input to global analyses

  but questions about small x behaviour of PDF's will remain

- only a polarized ep collider can address open questions

  energy matters more for PDF studies than luminosity

- lots of work to be done in preparation for ep physics

  crucial NLO results missing; need to demonstrate impact of EIC