2015 JLab Users Group Meeting
Newport News, VA

The Story of the Proton Spin

Status & Prospects

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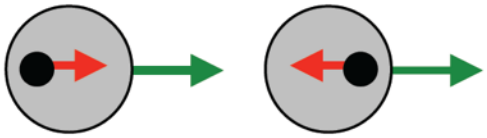
June 1st, 2015

the cookies we crumble: fundamental questions driving spin physics

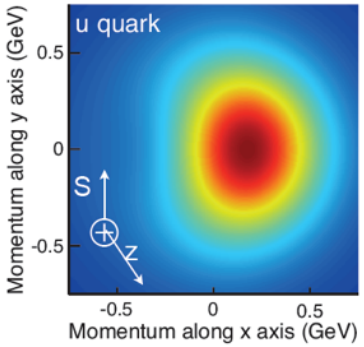
how do quarks and gluons carry the proton spin

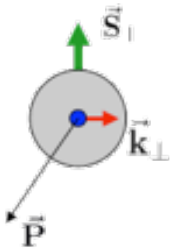


$$\Delta f(x) \equiv f_{\rightrightarrows}(x) - f_{\rightleftarrows}(x)$$

- what is the role of gluons and sea quarks
- what is the role of orbital angular momentum
- how does it compare to models/lattice QCD

reveal mechanisms behind transverse spin phenomena

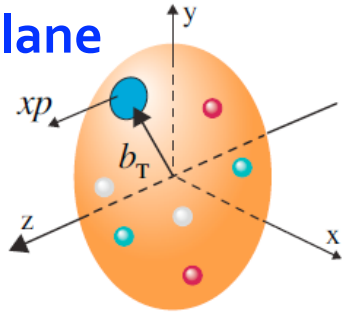




- further develop TMD framework / evolution
- role of multi-parton correlations & their matching to TMD's
- explore connections to unintegrated PDFs

what is the distribution of partons in the transverse plane

- physics of exclusive processes & generalized parton distributions
- possible access to **quark and gluon angular momentum**
- high-level connections of TMDs & GPDs to Wigner functions



the cookies we crumble: fundamental questions driving spin physics

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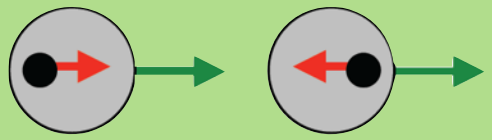

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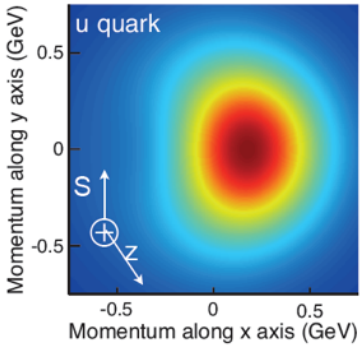
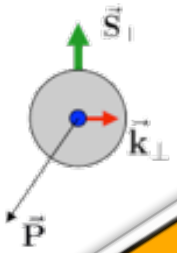
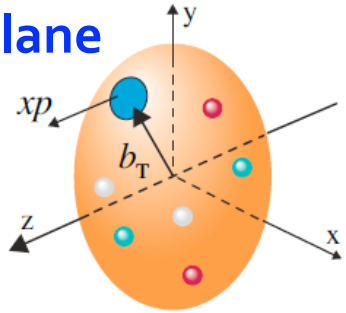




- further dev… rk / evolution
- role … & their matching to TMD's
- … integrated PDFs

what is the di… in the transverse plane

- physi… generalized parton distributions
- possibl… nd gluon angular momentum
- high-leve… ns of TMDs & GPDs to Wigner functions



see other talks in this meeting

topics to be covered

1

some helicity PDF and
global analysis basics

3

theoretical developments

2

global fits through the years
current status & issues

4

future avenues

1

some basics

helicity parton densities

$\Delta f(x) \equiv f_{\rightrightarrows}(x) - f_{\rightleftarrows}(x)$

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

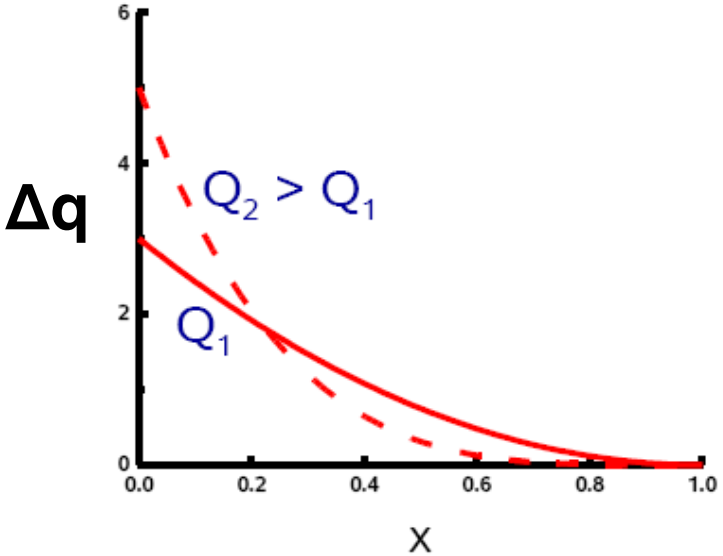
Collins, Soper; ...

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

- non-perturbative but universal objects (through factorization theorem)
- not measurable quantities —> need to be extracted from cross section data
- **scale dependence is key prediction of pQCD** (factorization again)

$$\frac{\mathbf{d}}{\mathbf{d}\ln \mathbf{Q^2}}\begin{pmatrix}\mathbf{\Delta q}\\ \mathbf{\Delta g}\end{pmatrix} = \underbrace{\mathbf{\Delta}\mathcal{P}[\alpha_s]}_{\text{calculable}} \otimes \begin{pmatrix}\mathbf{\Delta q}\\ \mathbf{\Delta g}\end{pmatrix}$$

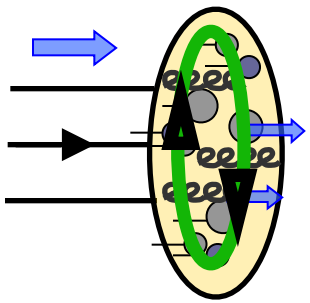
- PDF at (x,Q_2) "knows about" PDF values in range [x,1] at smaller scales $Q_1 < Q_2$ through evolution



why do we care?

- proton helicity sum rule

Jaffe, Manohar; Ji, Hoodbhoy, Lu; Brodsky; Ji, Yuan; Wakamatsu; Chen et al.; Burkardt; Leader et al.; Ji, Zhang, Zhao; Lorce; Hatta; ...

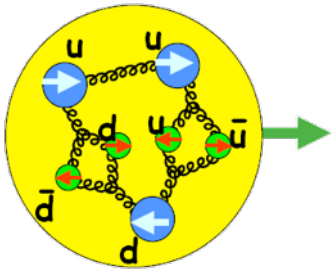


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- all quantities depend on scale Q & factorization scheme
- ignoring all the complications about choice of gauge, etc ...

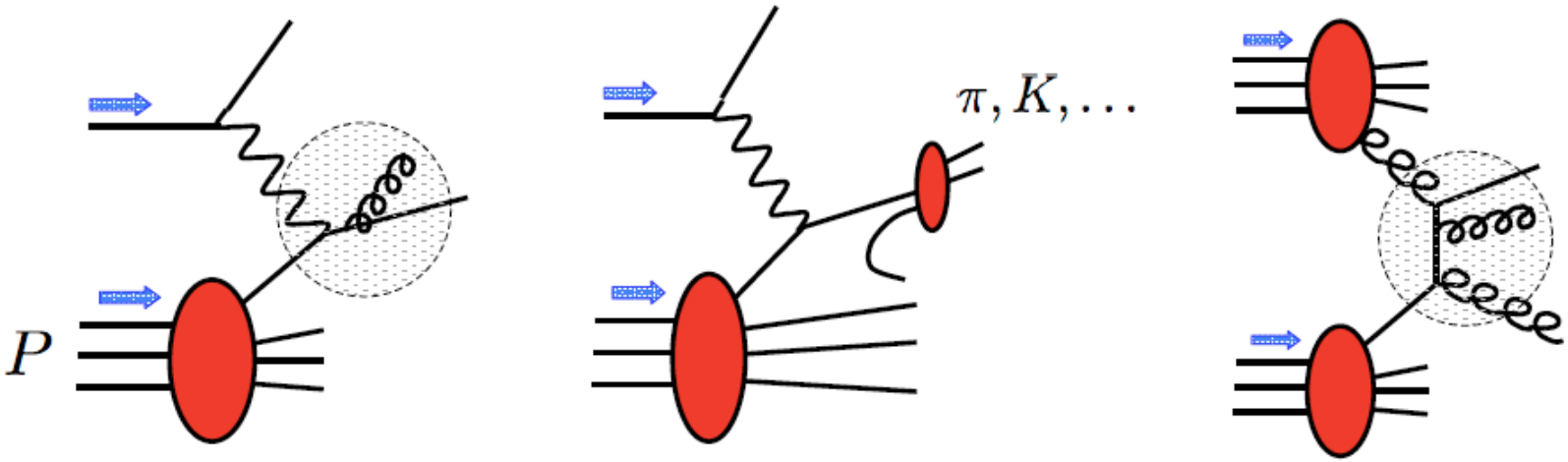
- indirect handle on net **OAM (Q^2)** once we know **$\Delta\Sigma$** and **Δg**
- **$\Delta f(x,Q^2)$** are fundamental building blocks of nucleon structure
- compare to attempts to model/compute nucleon structure theoretically
  - valence region and x —> 1 behavior
  - flavor structure, e.g., $\Delta\bar{u} - \Delta\bar{d}$ large-N_C, chiral quark model, meson cloud, ...
  - lattice QCD calculations
    - traditional: some lower moments
    - **quasi parton densities** : promising & very active field

Ji; Ma, Qiu; Lin et al.; Alexandrou et al.; Liu et al., ...



probes of nucleon helicity structure

$\Delta f(x) = f_{\rightleftarrows}(x) - f_{\rightleftarrows}(x)$



DIS

SIDIS

identified pions, kaons
charm, 2-hadrons

pp

1-jet, 1-hadron inclusive
$W^{+/-}$ bosons

guiding principle for theoretical description: **factorization**

e.g. **DIS**

$$d\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \underbrace{\Delta f(x,Q^2)}_{\text{universal PDF}}\, \overbrace{d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2))}^{\text{calculable in pQCD}}$$

essential: QCD corrections $d\Delta\hat{\sigma} = d\Delta\hat{\sigma}^{\rm LO} + \alpha_s\, d\Delta\hat{\sigma}^{\rm NLO} + \ldots$

to reduce theoretical uncertainties

tremendous exp. efforts in the past 30++ years

SLAC

..., E142, E143, E154, E155, ...

CERN

EMC, SMC, COMPASS

DESY

HERMES

JLab

Hall A, B, C

upcoming 12 GeV program

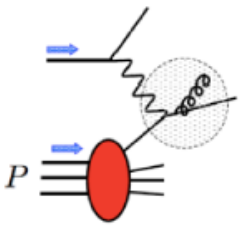
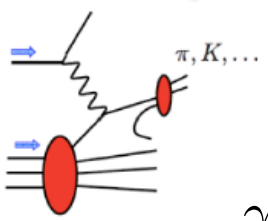
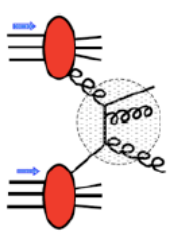
BNL

PHENIX, STAR

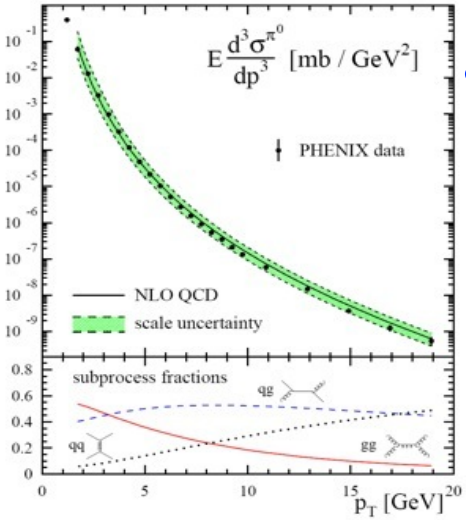
polarized pp collisions up to 510 GeV

How to make the most of it ?

global QCD analysis: synergy of all probes

probe	dominant LO process		PDF probed	x range	scale² [GeV²]	feature
 DIS	$\gamma^* q \to q$		$\Delta q + \Delta \bar{q}$	0.003 - 0.8	1- 70	only sum probed very clean
			Δg	0.003 - 0.8	1- 70	$dg_1/d\ln Q^2$ needs large Q^2 range at fixed x
 SIDIS	$\gamma^* q \to q$	pions	$\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}$	0.005 - 0.5	1- 60	pion FF
		kaons	Δs	0.005 - 0.5	1- 60	kaon FF
	$\gamma^* g \to q\bar{q}, c\bar{c}$		Δg	0.05 - 0.2	5- 20	statistics theo. unc.
 pp	$gg \to gg$	jets	Δg	0.05 - 0.3	40- 900	very clean
	$qg \to qg$	pions	Δg	0.02 - 0.2	4- 100	pion FF
	$u_L \bar{d}_R \to W^+$		$\Delta u, \Delta \bar{d}$	0.05 - 0.4	M_Z^2	very clean
	$d_L \bar{u}_R \to W^-$		$\Delta \bar{u}, \Delta d$			

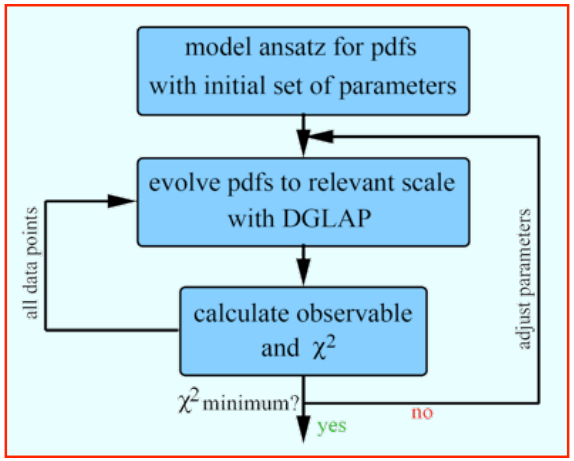
anatomy of a global QCD analysis



Jager, MS, Vogelsang; de Florian; Bojak, MS; Riedl, Schafer, MS; Gordon, Vogelsang; Signer et al.; Hendlmeier, Schafer, MS; Contogouris et al.; ....

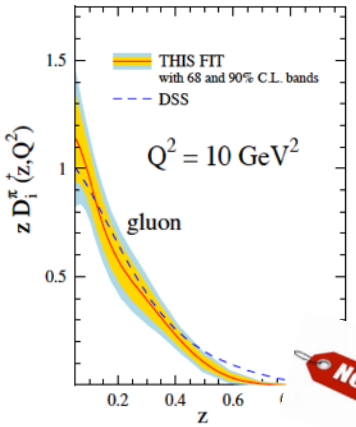
cross sections at NLO

obtain helicity PDFs through global χ^2 optimization



set of **optimum parameters** for *assumed* functional form

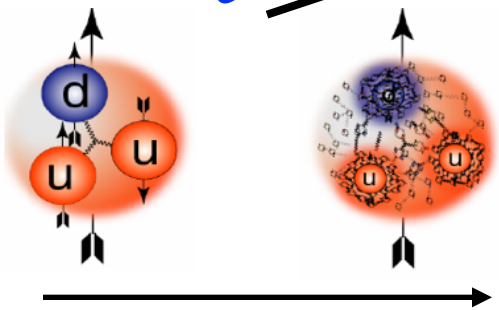
non-pert. inputs e.g. frag. fcts.



New

de Florian, Sassot, MS; ... ;
DSS14: arXiv:1410.6027

evolution kernels at NLO



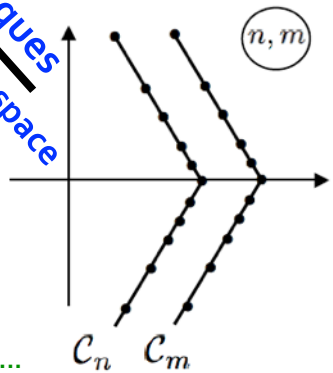
"resolution scale" μ

NLO: Mertig, van Neerven; Vogelsang; ... ;
NNLO: Moch, Vermaseren, Vogt 1409.5131

New

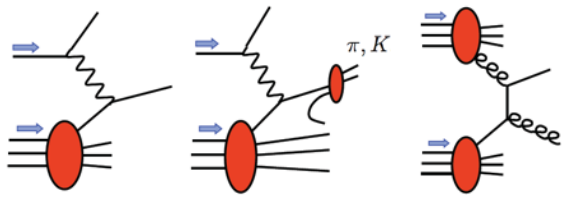
plus a prescription to estimate & propagate **uncertainties**

novel techniques e.g. in complex Mellin space



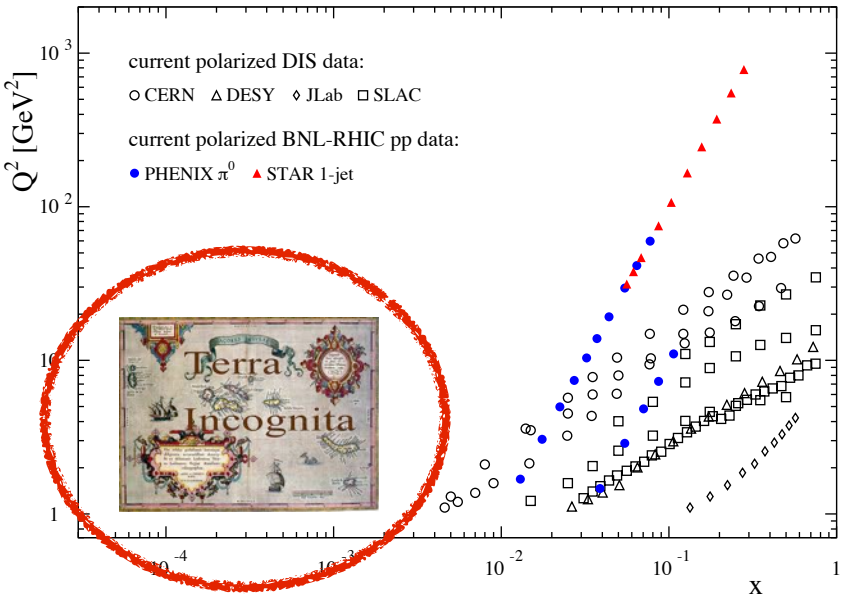
Vogt et al.;
MS, Vogelsang; ...

overview of recent helicity PDF fits @ NLO



	latest paper					uncertainties	features & focus
NNPDF Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	1406.5539	✓	✗	✓	jets, W's	100 MC replicas stat. approach	pp data w/ reweighing method
DSSV de Florian, Sassot, MS, Vogelsang	0904.3821 1404.4293	✓	✓	✓	jets, pions	Lagrange mult. (Hessian)	pp data fitted fast Mellin method
JAM Jimenez-Delgado, Accardi, Avakian, Melnitchouk, Sato, ...	1403.3355	✓	✗	✗		Hessian	large x / JLab region pp soon
LSS Leader, Sidorov, Stamenov	1010.0574	✓	✓	✗		Hessian	higher twist, Δs
BBS Bourrely, Buccella, Soffer	1502.02517 1408.7057	✓	✗	✗		Hessian	statistical approach unpol/pol simult. fit
BB Blumlein, Bottcher	1010.3113	✓	✗	✗		Hessian	α_s , higher twist
⋮			⋮				⋮
GRSV Gluck, Reya, MS, Vogelsang	9508347 0011215	✓	✗	✗		✗	1st NLO analysis 1995

extra challenges compared to unpolarized PDF fits



- **rather limited x-Q² coverage**
  - **difficult to get Δg from scaling violations**
    - need to rely on "direct probes" for Δg
  - **need to use data down to Q² = 1 GeV²**
    - applicability of pQCD ? higher twist ?

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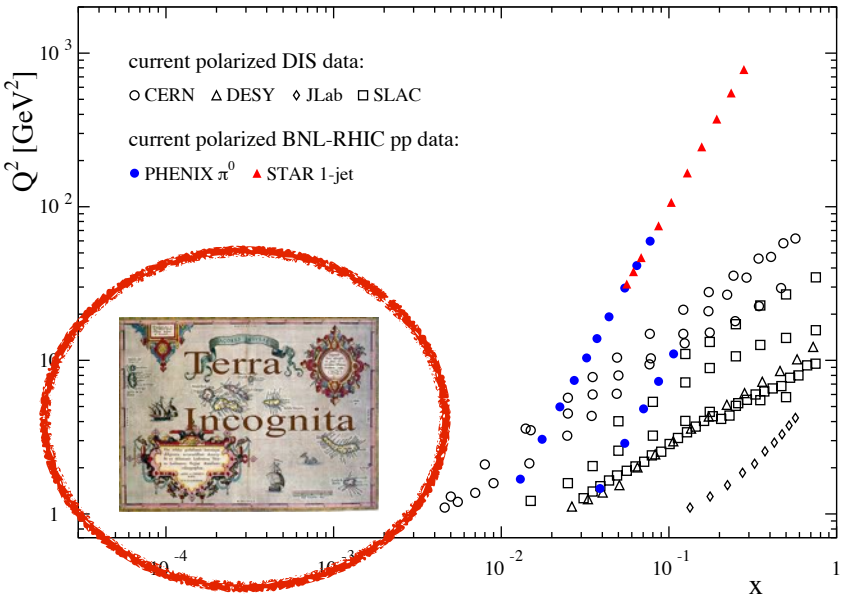

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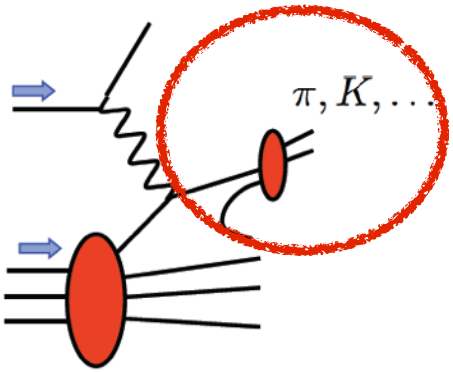
  - **no quark/anti-quark separation from DIS**
    - largely rely on SIDIS for flavor separation
    - need fragmentation functions to analyze data



extra source of uncertainties

new data on FFs:
ALICE, BABAR, BELLE, COMPASS, HERMES

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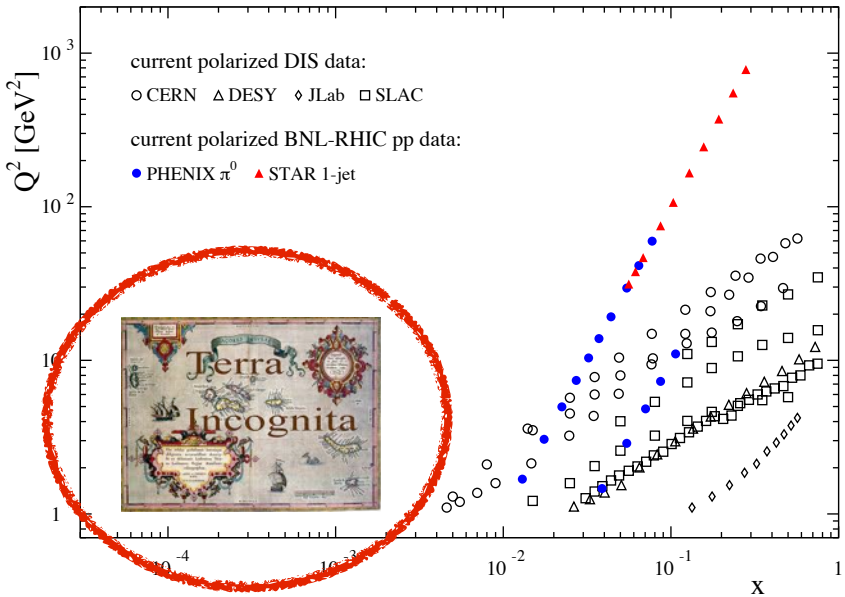

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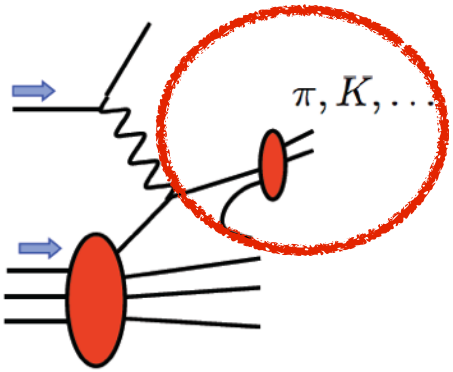

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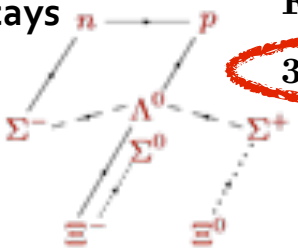
- **sum rules on shaky (?) grounds**
  - **1st moments of non-singlet combinations <-> hyperon decays**
    - constraint on unmeasured small-x behavior of Δs and ΔΣ
    - doubts, however, on applicability of SU(3) relation
      Savage, Walden; … ; Bali et al. 1112.3354 (lattice)



$$F + D = 1.2701 \pm 0.0025$$

$$3F - D = 0.585 \pm 0.025$$

$$\Delta s(x) \; ??$$

2

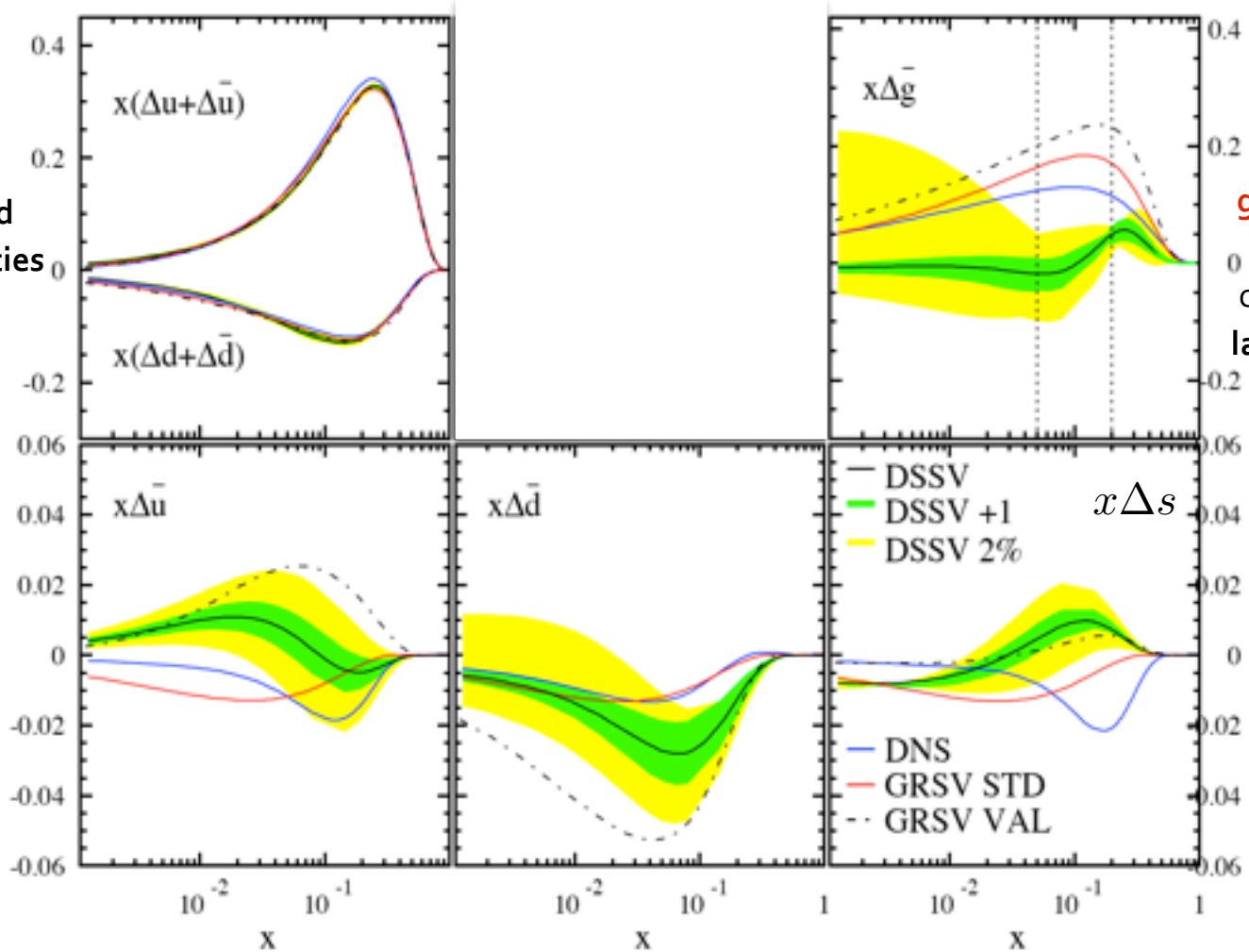
global fits through the years
current status & remaining issues

emerging picture from 1st global analysis back in '08

de Florian, Sassot, MS, Vogelsang; PRL 101 (2008) 072001; PR D80 (2009) 034030

well constrained total quark densities

x -> 1 behavior to be determined



gluon small (node?) in x-region constrained by data **large errors though!**

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

surprising strangeness polarization

sizable SU(3) breaking?

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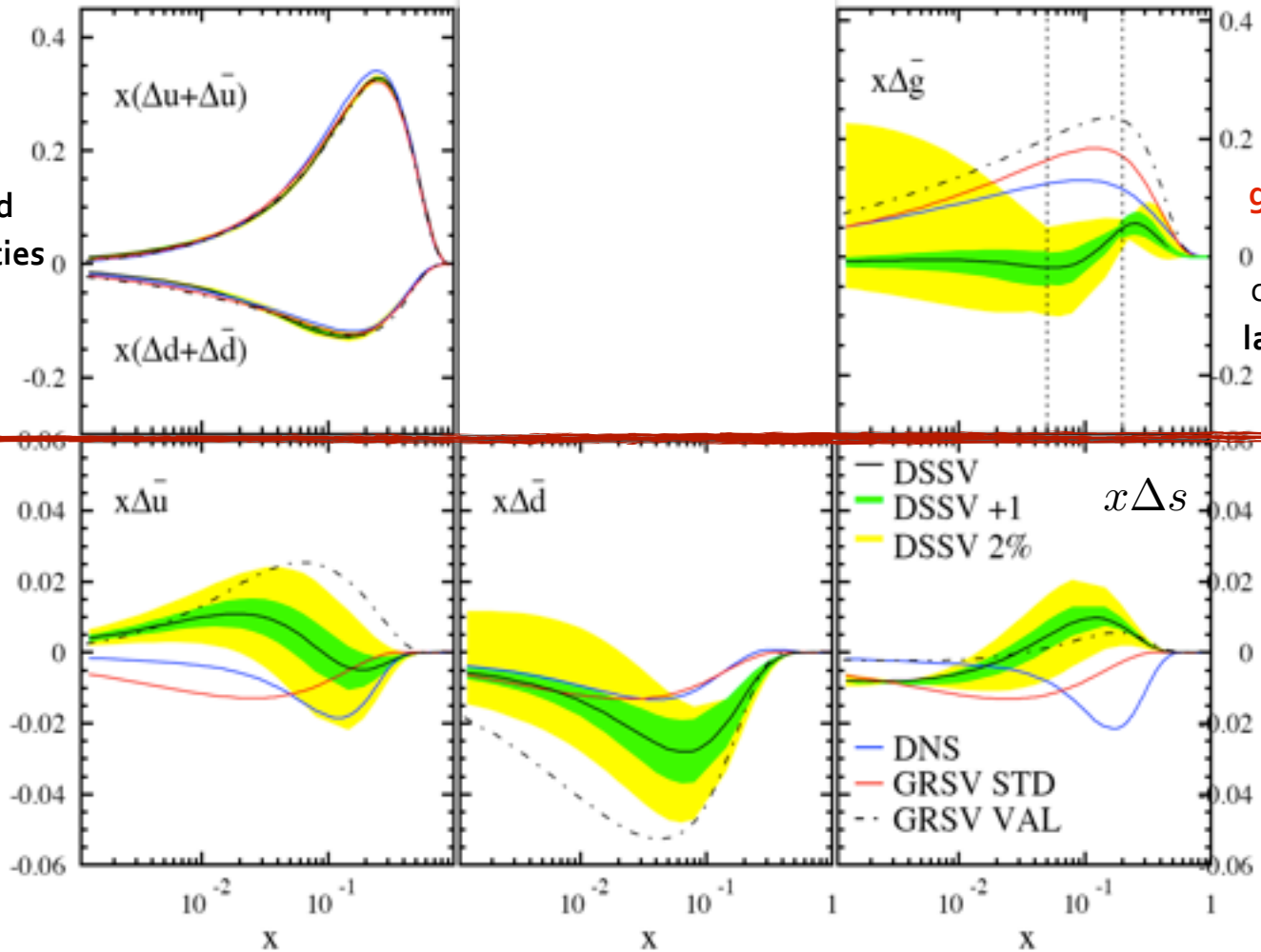

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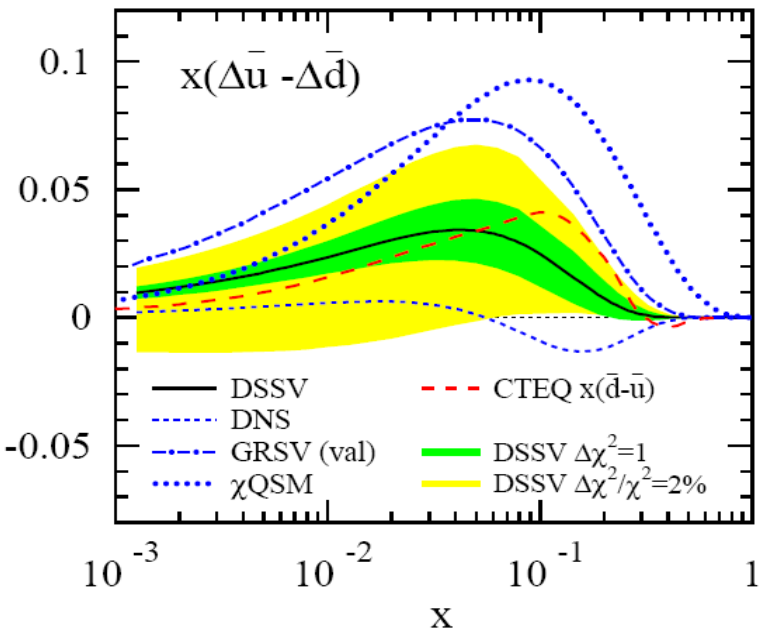
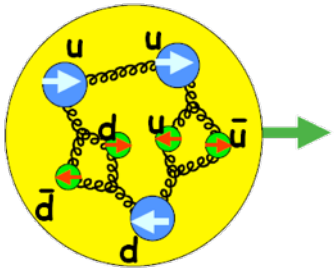
some hints at non-trivial sea polarizations



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

- similar size but opposite sign than in unp. fits
- uncertainties still large
- driven by SIDIS data on π^+ and π^-
- connection to model calculations

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



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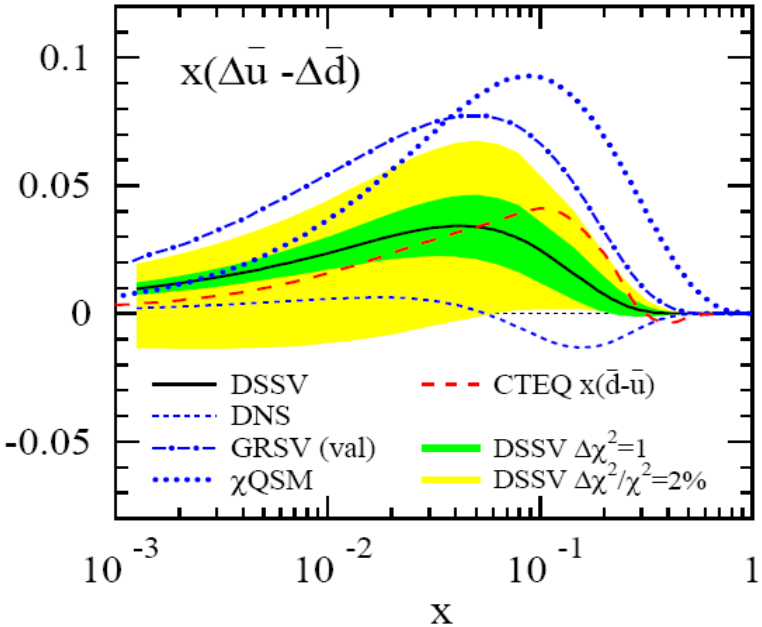

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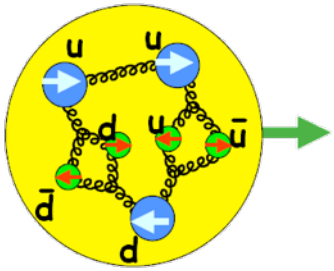
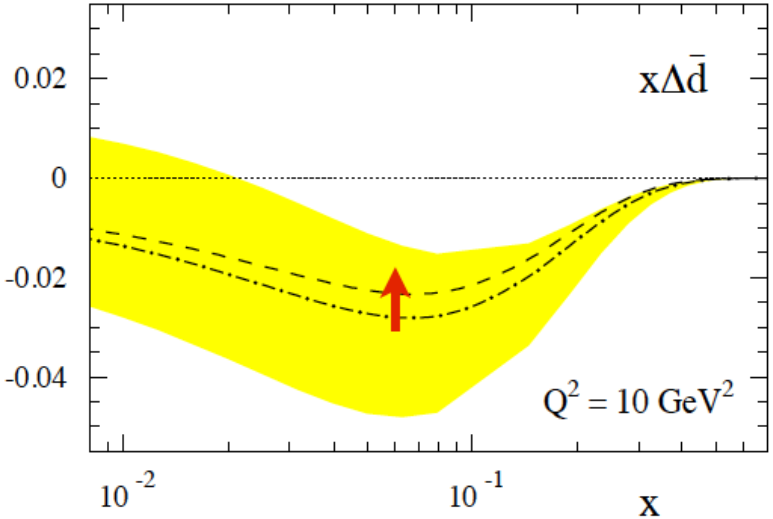


latest COMPASS data prefer smaller net sea polarizations though

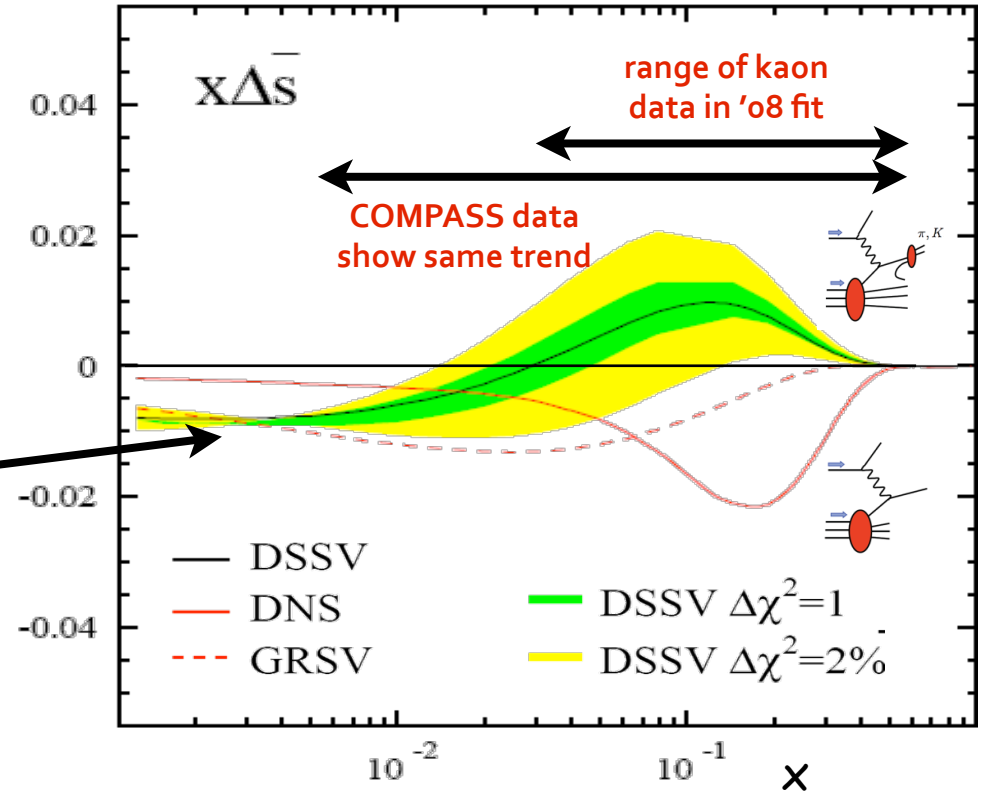
- changes well within uncertainties
- smaller $\Delta\bar{u}(x) - \Delta\bar{d}(x)$

—> later



strangeness conundrum

- **Δs always *assumed* to be negative in fits to DIS data ...**



sign change & small uncertainties entirely driven by

$$3F - D = 0.585 \pm 0.025$$

leads to $\int_0^1 dx[\Delta s + \Delta\bar{s}](x) \simeq -0.1$

- **new SIDIS data at smaller x compatible**

remarks/caveats:

- knowledge of parton-to-kaon FFs
- do we really now unpol. strangeness ?
- can we trust 3F-D constraint ?
  Lipkin; Zhu, Puglia, Ramsey-Musolf; Savage, Walden; ...

- lattice also finds smallish strangeness

$$\int_0^1 dx[\Delta s + \Delta\bar{s}](x) \simeq -0.020(10)(1)$$

Bali et al. 1112.3354

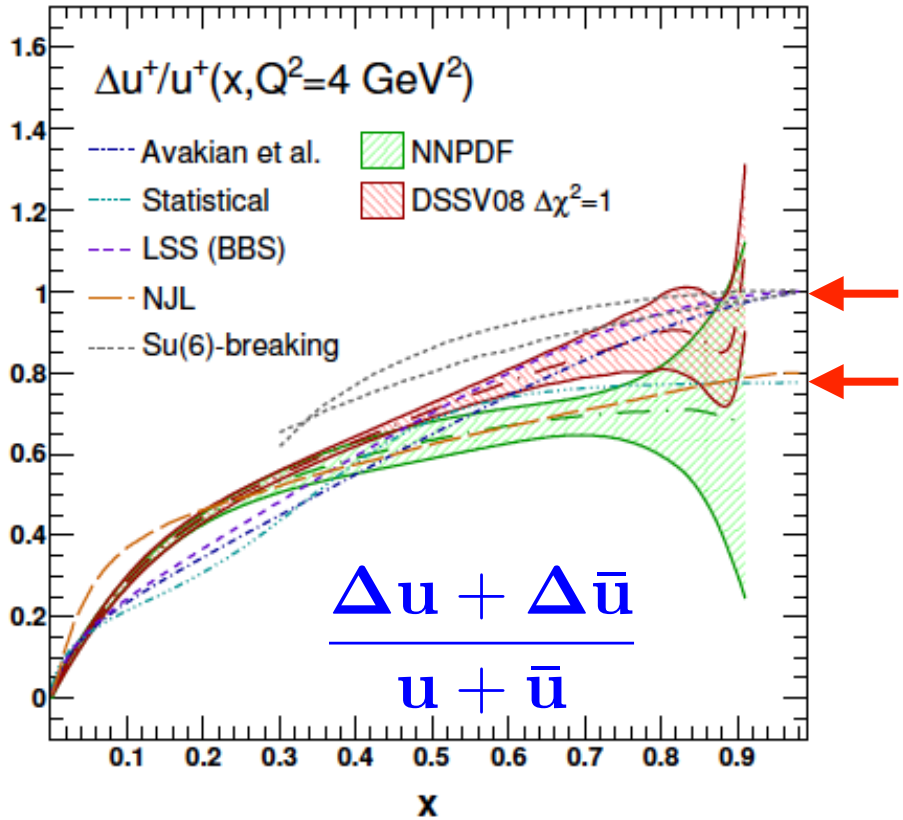
<-> large breaking of 3F-D relation

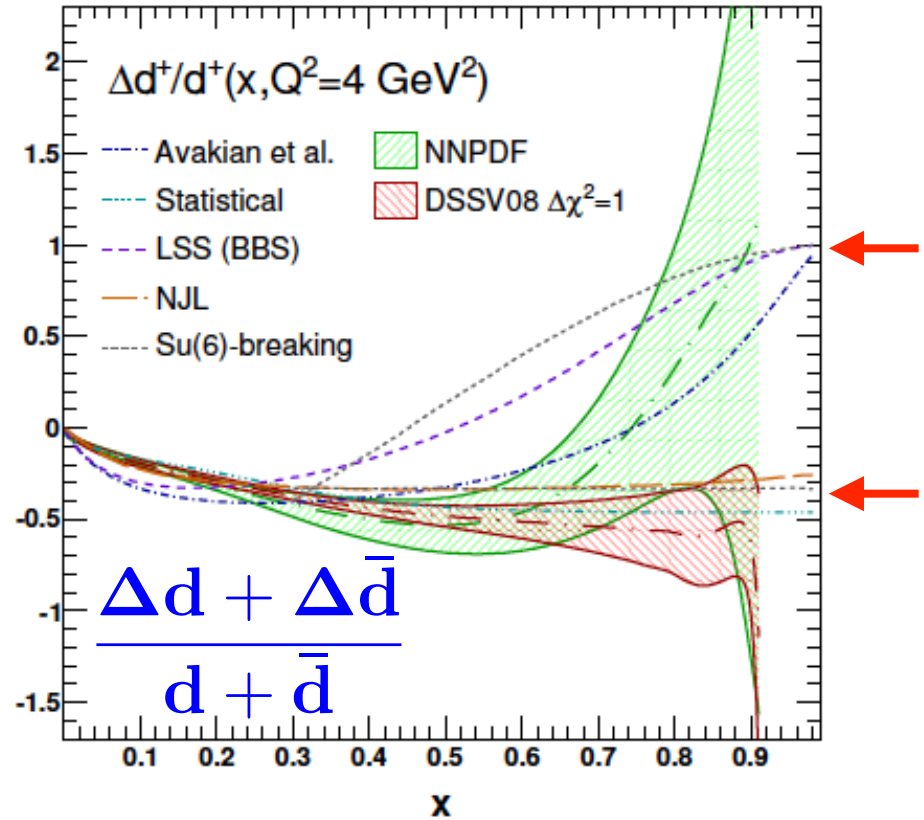
- recall old GRSV "valence scenario" with Δs = 0 !

large x behavior of helicity PDFs

several different theoretical expectations for x —> 1

Close; Isgur; Close, Melnitchouk; Cloet, Bentz, Thomas; Roberts, Holt, Schmidt; …

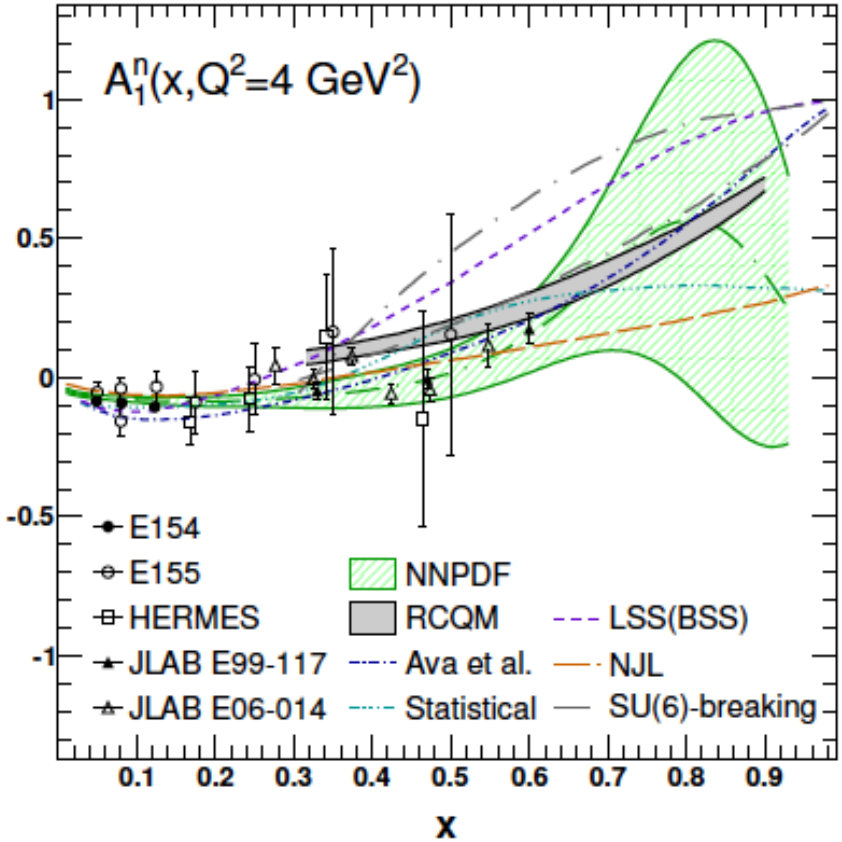


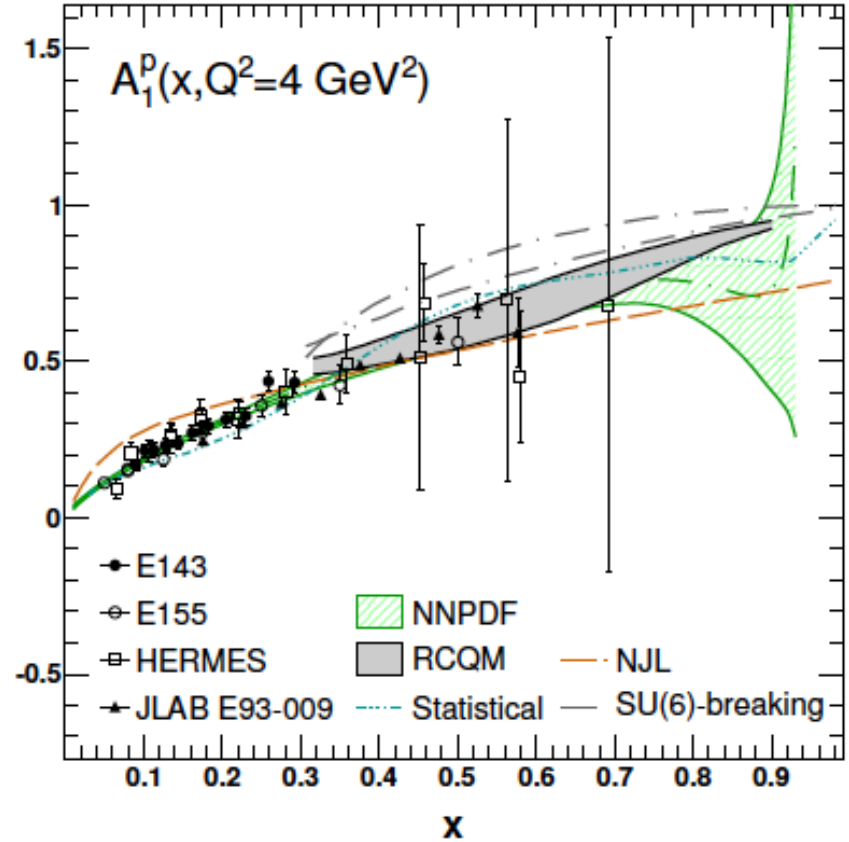


compilation by E. Nocera
arXiv:1410.7290

large x behavior - cont'd

to settle this, measure A_1^p & A_1^n at large x —> JLab-12 program





compilation by E. Nocera arXiv:1410.7290

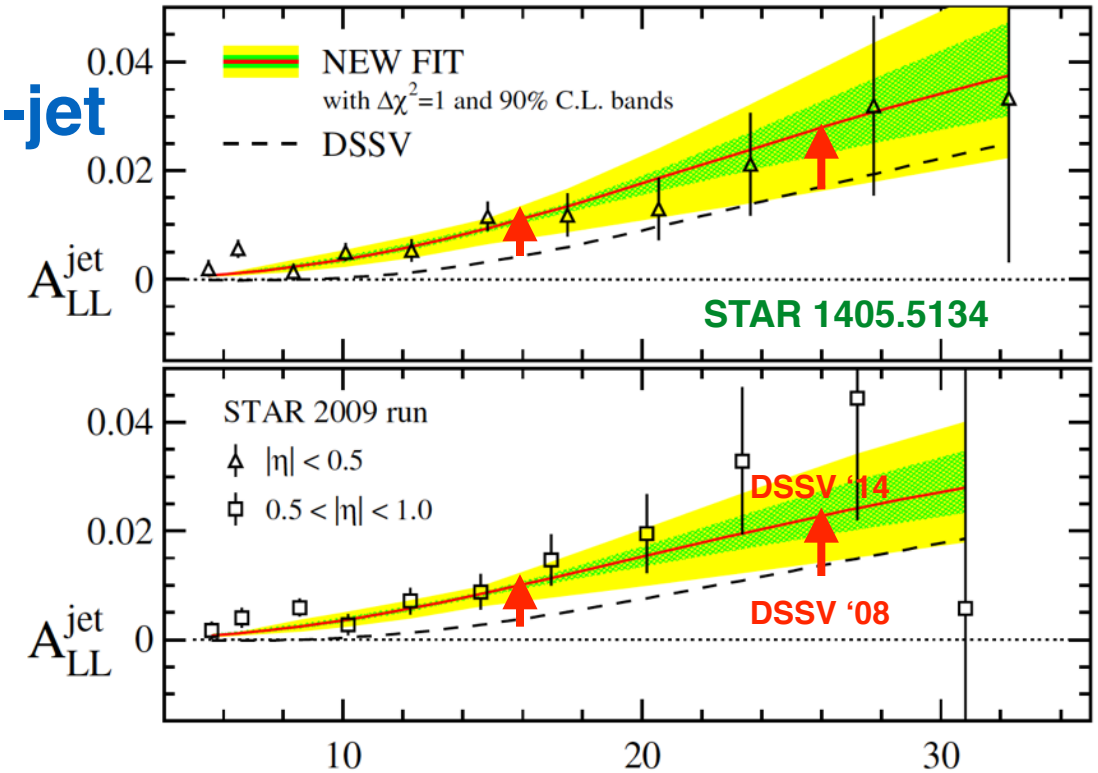
Model	A_1^n	A_1^p	Model	A_1^n	A_1^p
SU(6)	0	5/9	NJL	0.35	0.77
RCQM	1	1	DSE (*realistic*)	0.17	0.59
QHD ($\sigma_{1/2}$)	1	1	DSE (*contact*)	0.34	0.88
QHD (ψ_ρ)	1	1	pQCD	1	1
NNPDF ($x = 0.7$)	0.41 ± 0.31	0.75 ± 0.07	NNPDF ($x = 0.9$)	0.36 ± 0.61	0.74 ± 0.34


BREAKING NEWS
THE WORLDWIDE LEADER IN NEWS
BREAKING NEWS
RHIC sees first evidence for non zero Δg
LIVE
CNN
UPDATE
major contributor to proton spin - - - perhaps little room left for OAM
2:35 PM ET

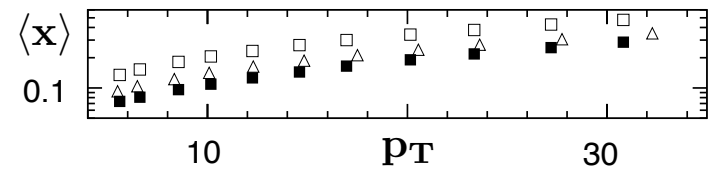
Δg: DSSV '14 adds latest RHIC jet and π^0 data

de Florian, Sassot, MS, Vogelsang; PRL 113 (2014) 012001

1-jet

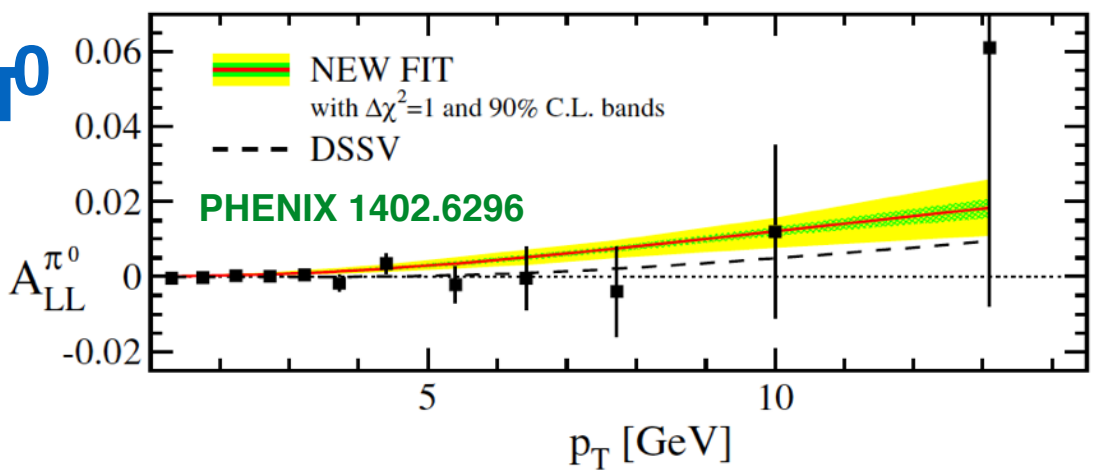


- jet data pull on Δg
- relevant x-range:

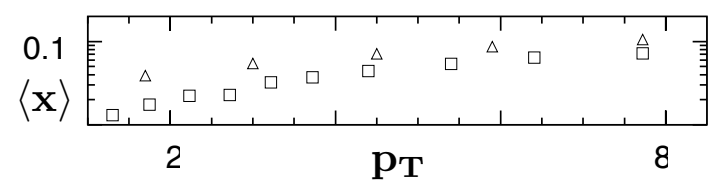


good combined fit of STAR & PHENIX data complementarity!

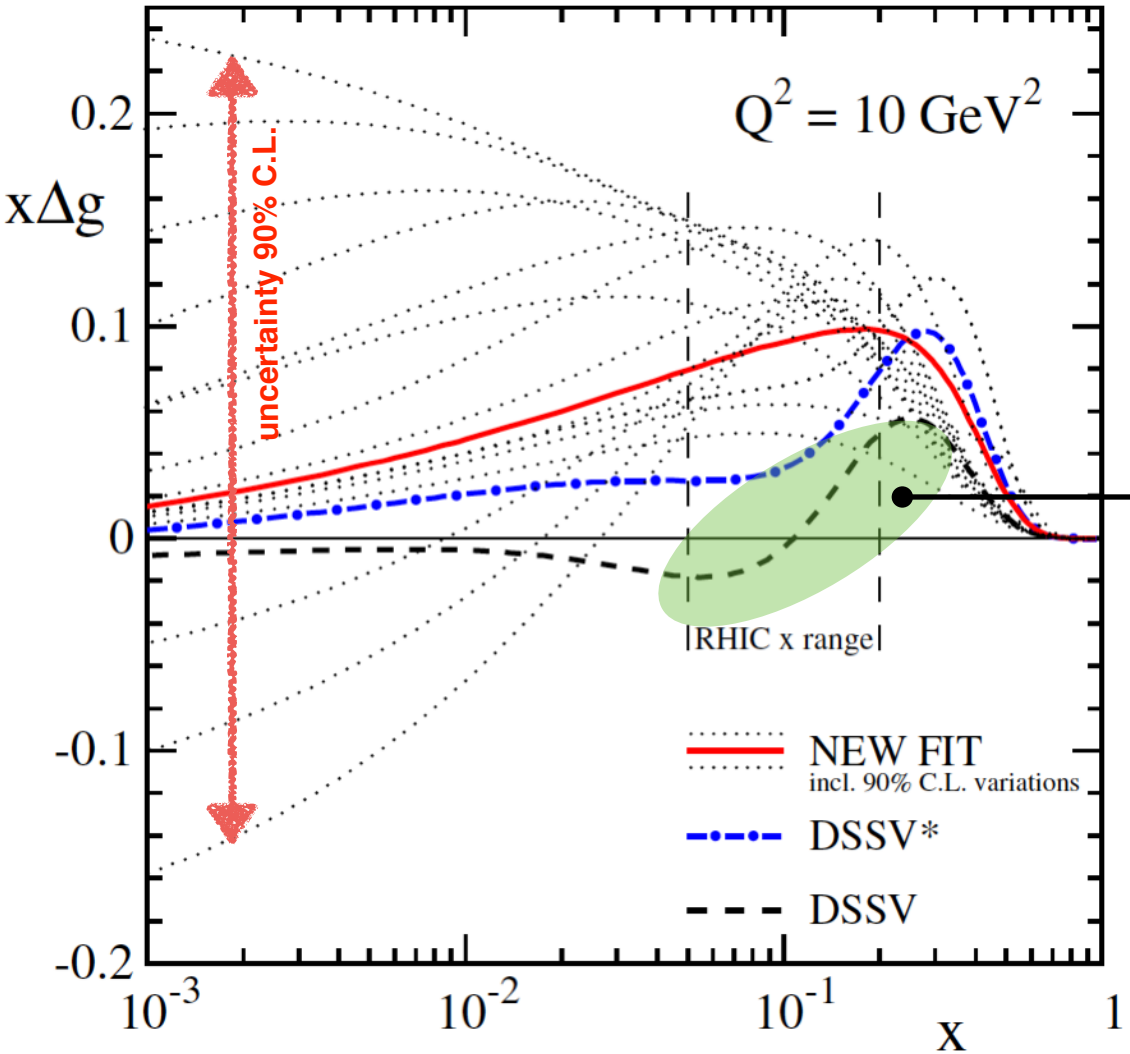
π^0



- π^0's well described by DSSV '08
- probes lower x values:



resulting DSSV '14 gluon



functional form in DSSV:

$$x\Delta g(x,\mu_0^2) = N_g\, x^{\alpha_g}(1-x)^{\beta_g}(1+\eta_g x^{\kappa_g})$$

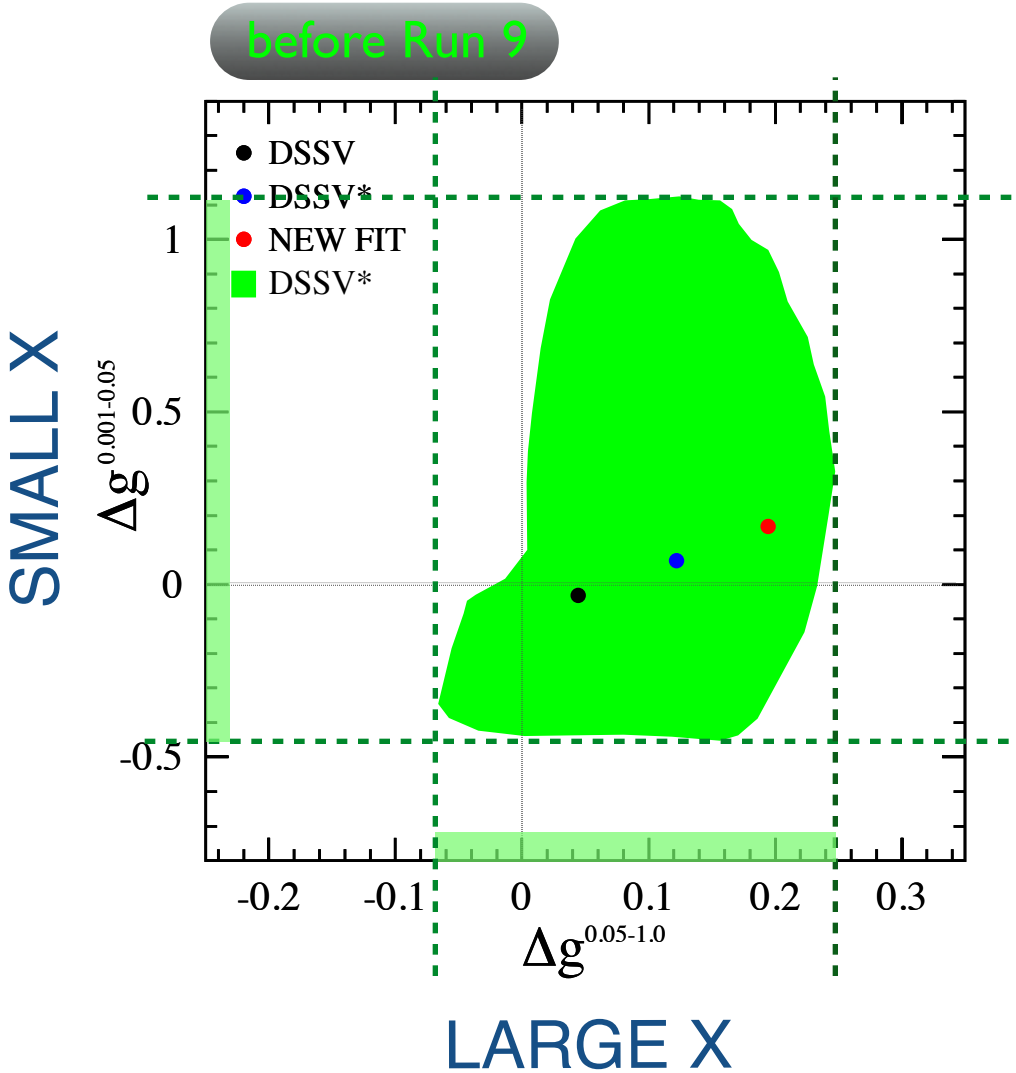
"famous" node in DSSV'08

η_g essential for good fit

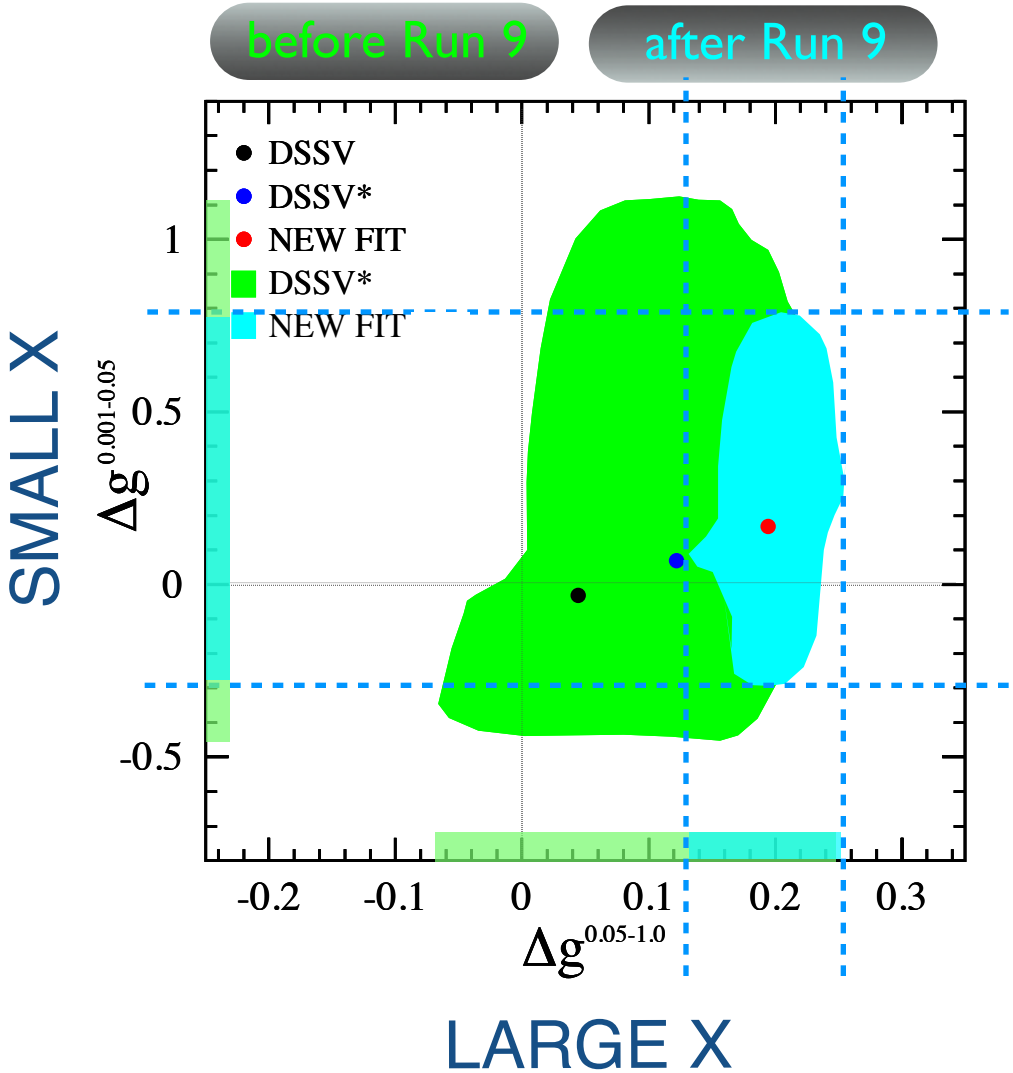
DSSV '14 Δg much larger and positive

η_g only to produce small x variations

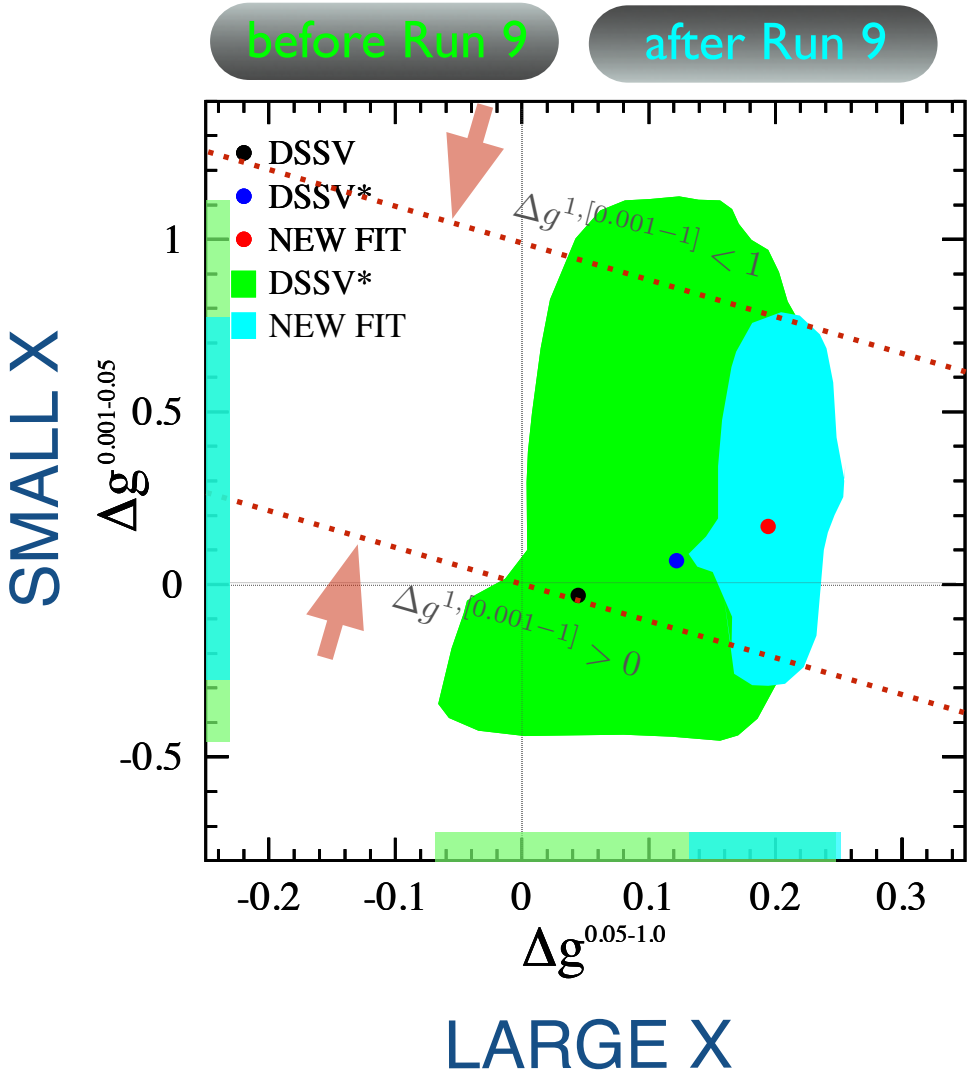
towards the first moment of Δg



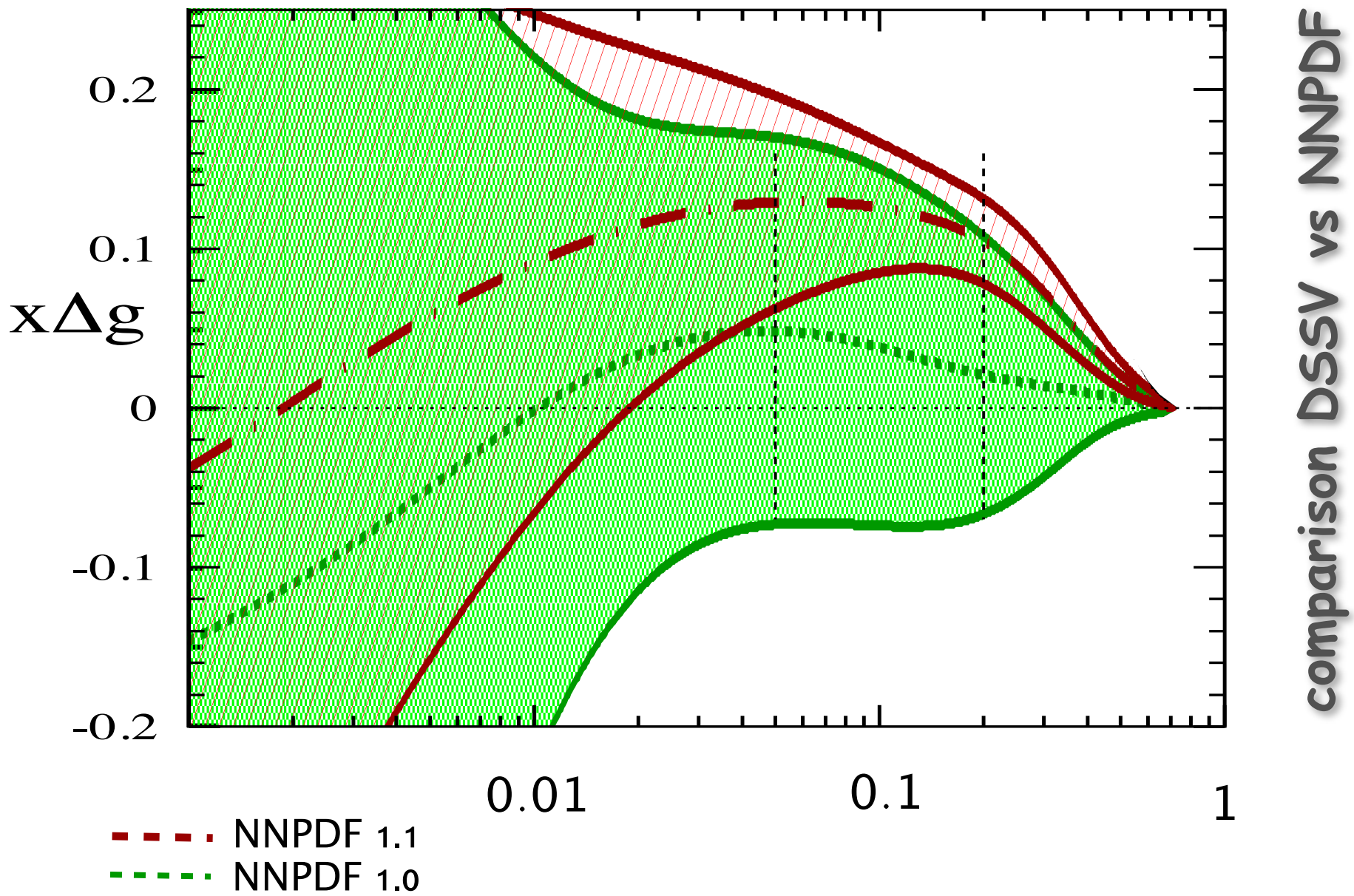
towards the first moment of Δg

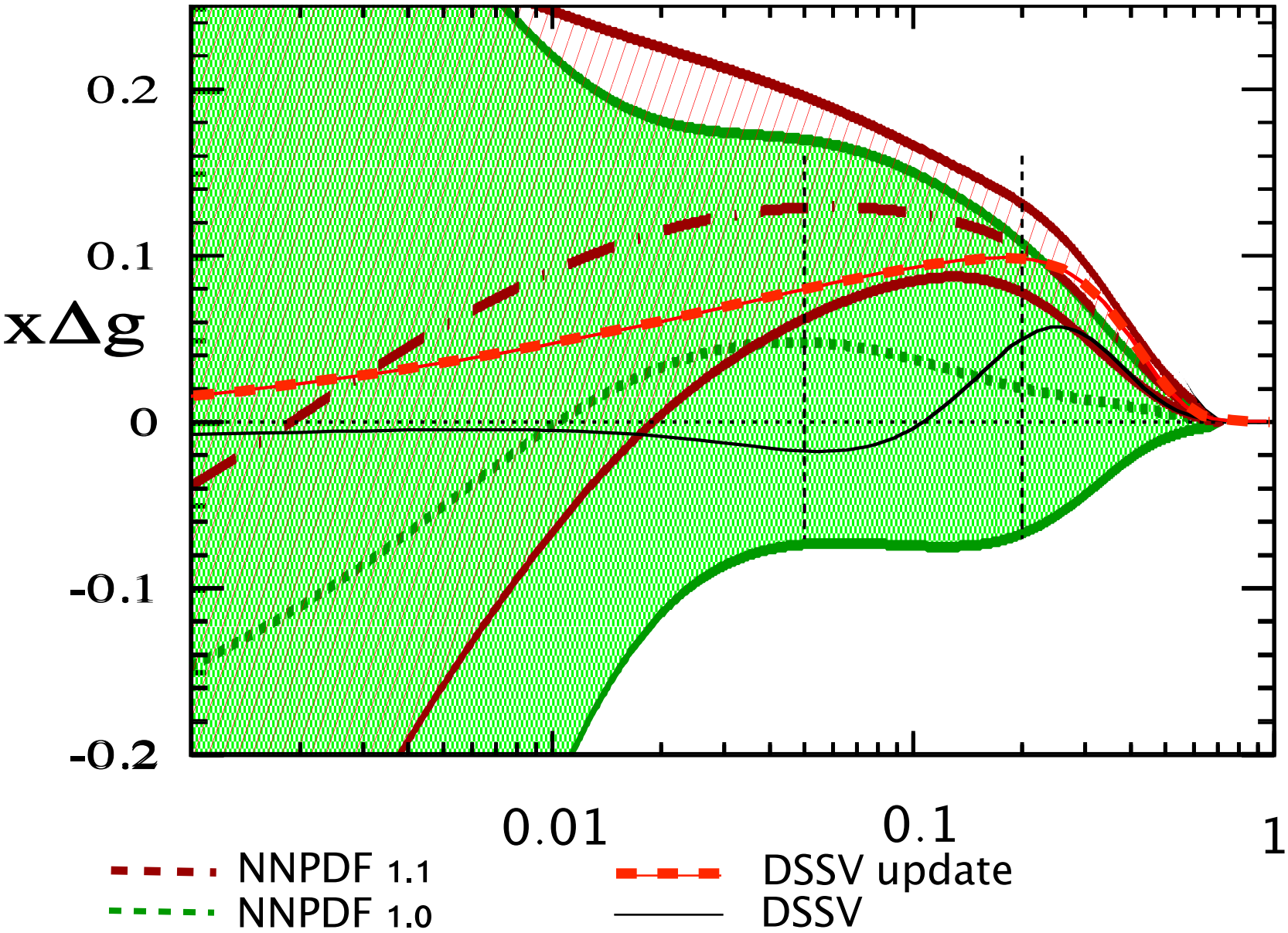


towards the first moment of Δg

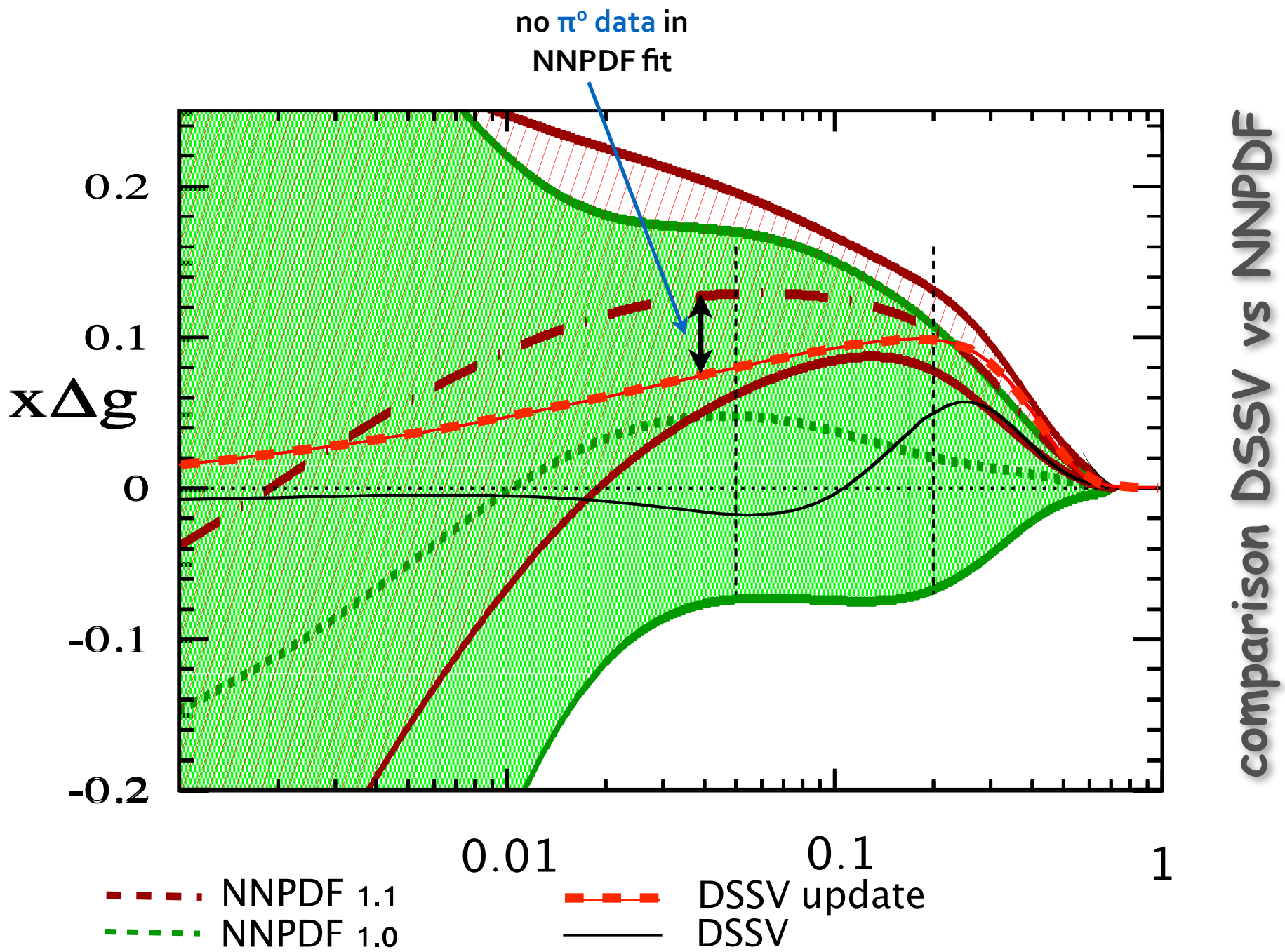


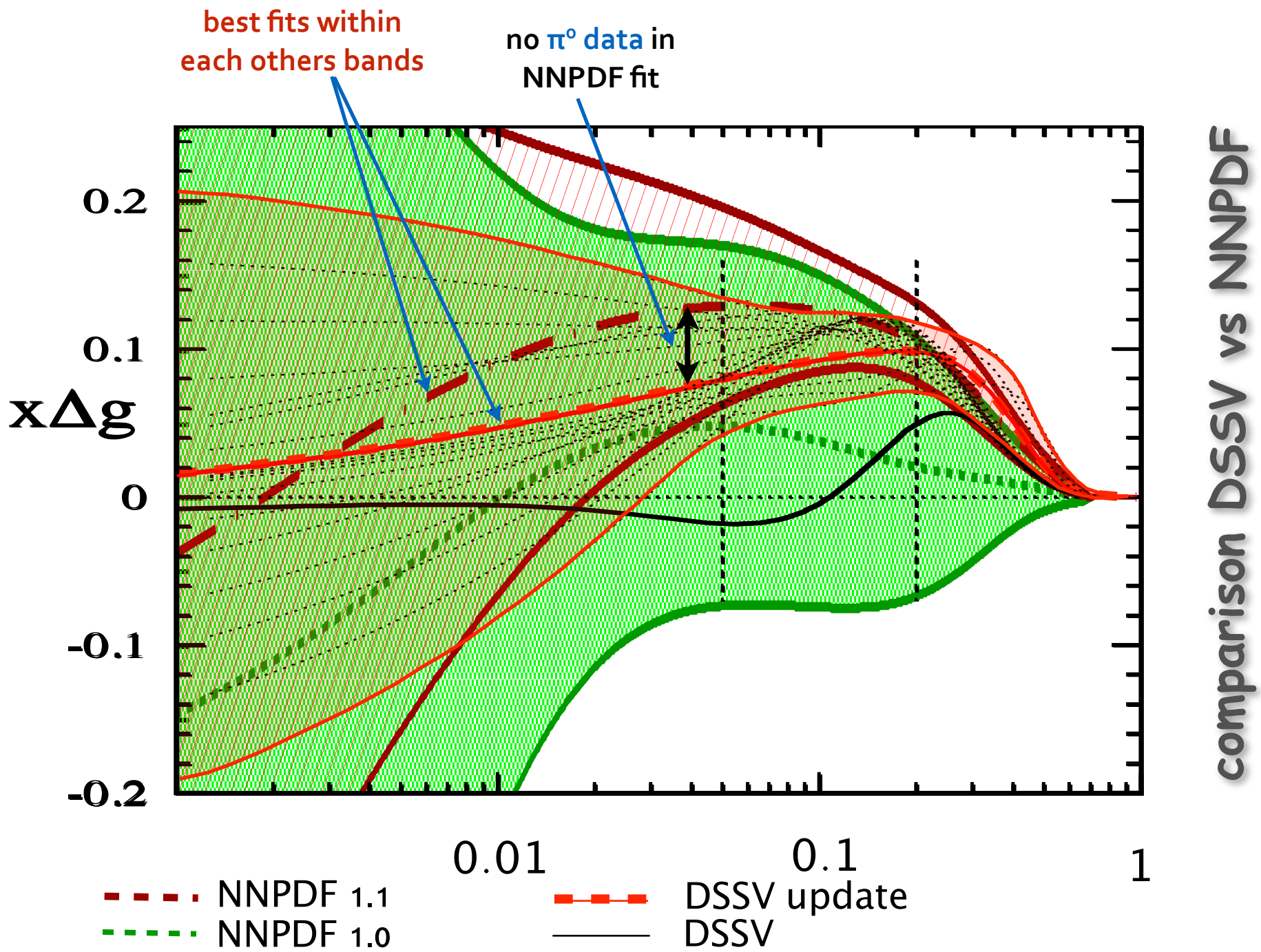
gluon contribution down to x ~10^{-3}
tends to be positive and smaller than 1

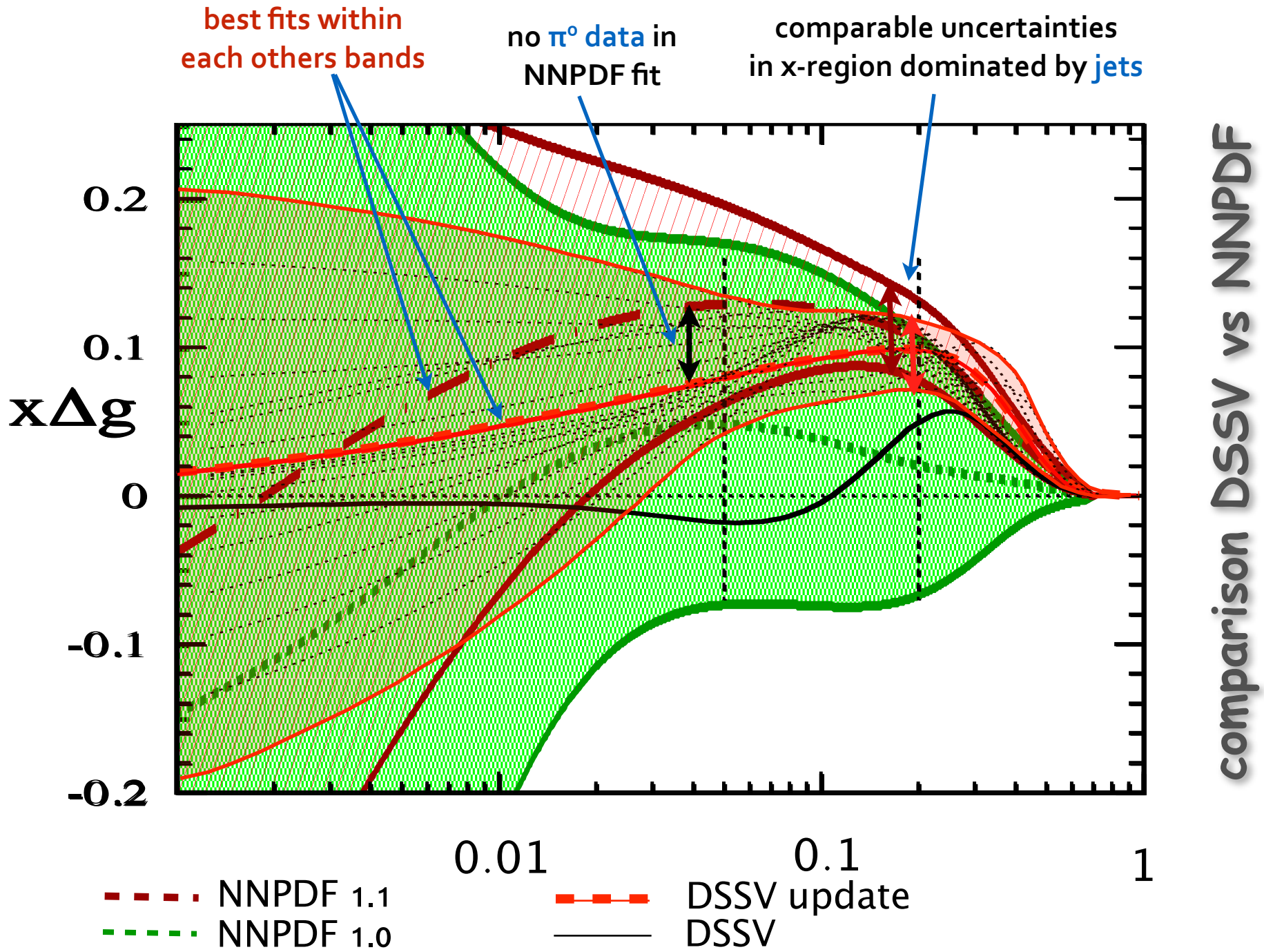

0.2
0.1
xΔg
0
-0.1
-0.2
0.01
0.1
1
NNPDF 1.1
NNPDF 1.0
comparison DSSV vs NNPDF

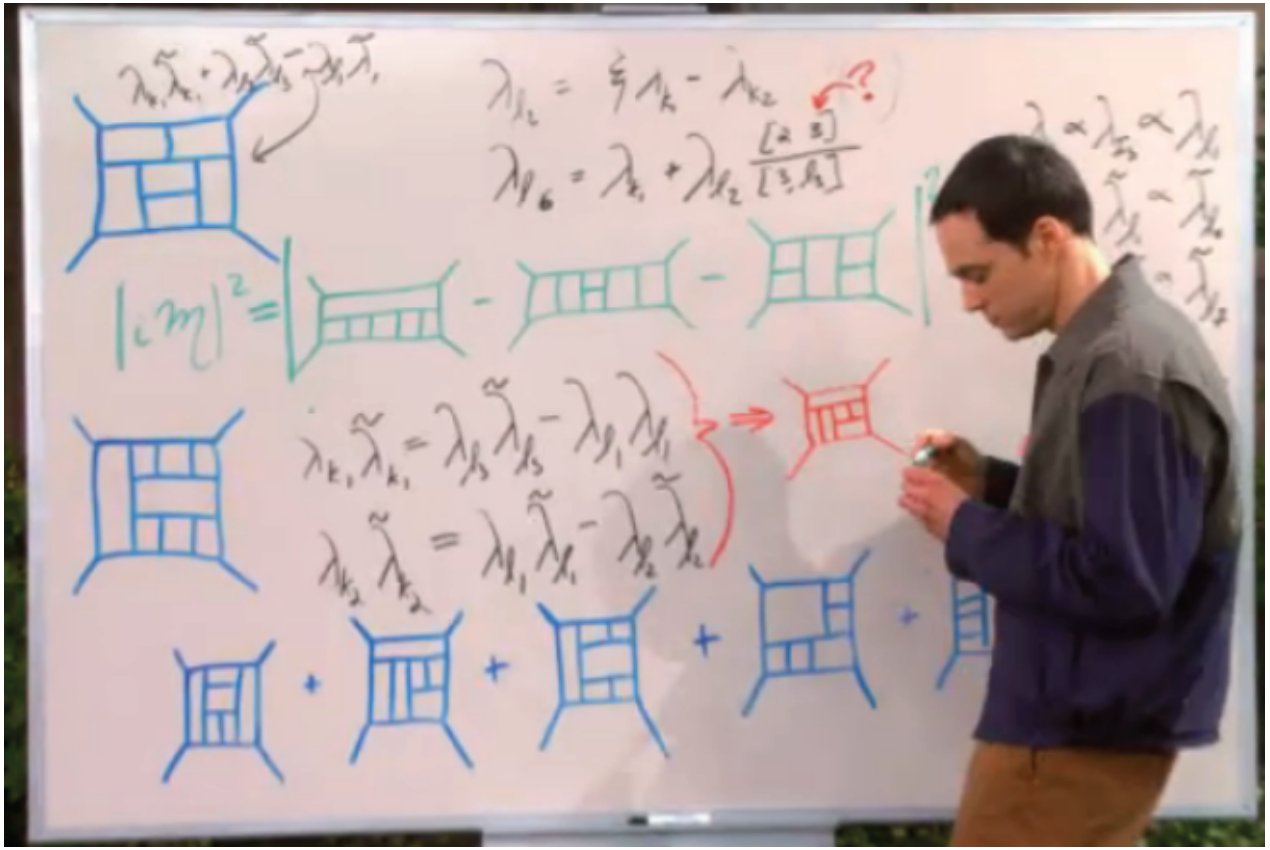


comparison DSSV vs NNPDF


no π° data in
NNPDF fit
0.2
0.1
0
-0.1
-0.2
xΔg
0.01
0.1
1
NNPDF 1.1
NNPDF 1.0
DSSV update
DSSV
comparison DSSV vs NNPDF


best fits within
each others bands
no π° data in
NNPDF fit
0.2
0.1
xΔg
0
-0.1
-0.2
0.01
0.1
1
NNPDF 1.1
NNPDF 1.0
DSSV update
DSSV
comparison DSSV vs NNPDF


best fits within
each others bands
no π° data in
NNPDF fit
comparable uncertainties
in x-region dominated by jets
comparison DSSV vs NNPDF
xΔg
0.2
0.1
0
-0.1
-0.2
0.01
0.1
1
NNPDF 1.1
NNPDF 1.0
DSSV update
DSSV



3

some recent theoretical developments

towards NNLO accuracy

- major achievement: Moch, Vermaseren, Vogt arXiv:1409.5131

2014

$$\Delta\mathcal{P}_{ij} = a_s \Delta P^{(0)}_{ij} + a_s^2 \Delta P^{(1)}_{ij} + a_s^3 \Delta P^{(2)}_{ij}$$

1977 — Ahmed, Ross; Altarelli, Parisi, ...

1995 — Mertig, van Neerven; Vogelsang

- obtained from calculating several fixed N moments in graviton-exchange DIS, e.g.:

$$\Delta P^{(2)}_{gq}(N=25) = -C_A^3 \frac{1890473255283802937678830745102921869938637}{2^3 19^4 17^4 13^5 11^4 7^4 5^{10} 3^5 2^{12}} + \ldots$$

- full N dependence reconstructed from fixed moments through some sophisticated math

- x space expressions from algebraic procedure:

  harmonic sums in N space <—> harmonic polylog's in x space

- requires extra care with γ_5 —> finite renormalization to avoid problems with non-singlet axial currents and Bjorken sum rule

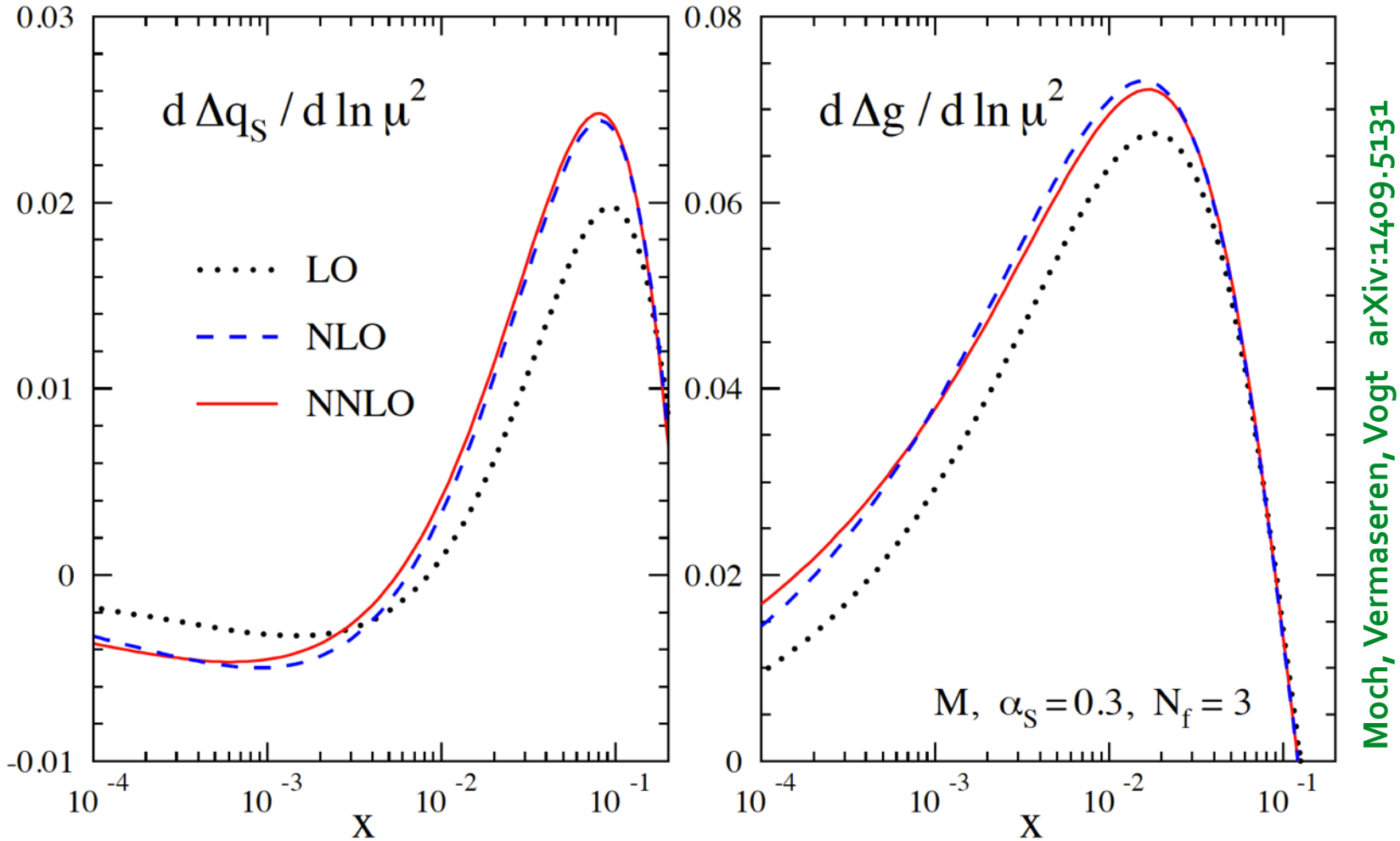
$$
\begin{aligned}
\Delta P_{gg}^{(2)}(x) \;=\; & 16 C_A^3 \Big(4\Delta p_{gg}(-x)\,(-11/8\,\zeta_2^2 + H_{-3,0} - 4H_{-2}\zeta_2 - 2H_{-2,-1,0} + 3H_{-2,2} \\
& + 9/2\,H_{-2,0,0} - 3H_{-1}\zeta_3 - 2H_{-1,-2,0} + 4H_{-1,-1}\zeta_2 - 6H_{-1,-1,0,0} - 4H_{-1,-1,2} \\
& - 9/2\,H_{-1,0}\zeta_2 + 4H_{-1,0,0,0} + H_{-1,2,0} + 4H_{-1,3} + 5/4\,H_0\zeta_3 + 2H_{0,0}\zeta_2 - H_{0,0,0,0} \\
& - 1/2\,H_2\zeta_2 - 1/2\,H_{3,0} - 2H_4 + 11/24\,H_0\zeta_2 + 67/36\,(\zeta_2 + 2H_{-1,0} - H_{0,0})) \\
& + 4\Delta p_{gg}(x)\,(245/96 - 3/40\,\zeta_2^2 - H_{-3,0} + 3/2\,H_{-2}\zeta_2 + H_{-2,-1,0} - H_{-2,0,0} - H_{-2,2} \\
& - 7/4\,H_0\zeta_3 - 2H_{0,0}\zeta_2 + H_{0,0,0,0} - 3/2\,H_1\zeta_3 - H_{1,-2,0} - 3/2\,H_{1,0}\zeta_2 + 2H_{1,0,0,0} \\
& + 2H_{1,1,0,0} + 2H_{1,2,0} + 2H_{1,3} - H_2\zeta_2 + 5/2\,H_{2,0,0} + 2H_{2,1,0} + 2H_{2,2} + 5/2\,H_{3,0} \\
& + 2H_{3,1} + 2H_4 + 11/12\,\zeta_3 + 11/12\,H_{-2,0} + 11/24\,H_{1,0,0} + 11/24\,H_3 \\
& - 67/36\,(\zeta_2 - H_{0,0} - 2H_{1,0} - 2H_2) + 1/24\,H_0) - 1/3\,(72 - 185x - 22x^2)\,H_0\zeta_2 \\
& - 1/3\,(32 - 161x - 11x^2)\,H_{-2,0} + 4\,(1-5x)\,H_{-3,0} - 1/6\,(312 - 393x - 55x^2)\,\zeta_3 \\
& + (1-x)\,(5579/18 + 4H_{-2}\zeta_2 + 8H_{-2,-1,0} + 12H_{-2,0,0} - 21/2\,H_1\zeta_2 + 37H_{1,0,0} \\
& + 1/18\,H_1 - 19/2\,H_{1,0}) - 1/5\,(43 + 33x)\,\zeta_2^2 - 8\,(1+3x)\,H_0\zeta_3 - 2\,(11 + 13x)\,H_{0,0}\zeta_2 \\
& + (1+x)\,(21H_{-1,-1,0} - 25/2\,H_{-1}\zeta_2 + 65H_{-1,0,0} + 23H_{-1,2} - 4H_2\zeta_2 + 10H_{2,0,0} \\
& + 16H_{3,0} + 26H_4 - 215/3\,H_{-1,0}) - 1/9\,(74 - 97x)\,H_2 + 1/3\,(77 - 115x)\,H_{2,0} \\
& + 1/3\,(40 - 185x - 11x^2)\,H_3 - 1/9\,(571 + 97x)\,\zeta_2 + 1/3\,(158 - 87x - 11x^2)\,H_{0,0,0} \\
& + 1/12\,(1019 - 1489x)\,H_{0,0} + 1/216\,(24625 + 40069x)\,H_0 - 11/6\,(x^{-1} - x^2)\,H_1\zeta_2 \\
& + 28H_{0,0,0,0} - 11/2\,(x^{-1} + x^2)\,(H_{-1}\zeta_2 + 2/3\,H_{-1,-1,0} - 2/3\,H_{-1,0,0} - 2/3\,H_{-1,2}) \\
& + \delta(1-x)\,(79/32 - 5\zeta_5 + 67/6\,\zeta_3 + 1/6\,\zeta_2 - \zeta_2\zeta_3 + 11/24\,\zeta_2^2)\Big) \\
& + 8 C_A^2 n_f \Big(2/3\,\Delta p_{gg}(x)\,(10/3\,\zeta_2 - 10/3\,H_{0,0} - 20/3\,H_{1,0} - 20/3\,H_2 - 209/36 - 8\zeta_3 \\
& - 2H_{-2,0} - H_{1,0,0} - H_3 - 1/2\,H_0) + 2/9\,\Delta p_{gg}(-x)\,(10H_{0,0} - 10\zeta_2 - 20H_{-1,0} \\
& - 3H_0\zeta_2) - 1/6\,(51 - 61x - 16x^2)\,H_0\zeta_2 - 1/18\,(146 + 227x + 36x^2)\,H_{0,0} \\
& - 1/3\,(23 + 43x - 4x^2)\,H_{-2,0} - 1/3\,(1 - 12x + 4x^2)\,H_{0,0,0} - 2\,(1-5x)\,H_{-3,0} \\
& + 2\,(1-x)\,(512/9 + 3H_{-2}\zeta_2 + 6H_{-2,-1,0} - 3H_{-2,0,0} - 11/2\,H_1\zeta_2 + 11/4\,H_{1,0,0} \\
& + 1087/72\,H_1 - 2H_{1,0}) + (1+x)\,(7H_{-1}\zeta_2 + 22H_{-1,-1,0} - 9H_{-1,0,0} + 4H_{-1,2} \\
& - 4/3\,H_{2,0} - 6H_2\zeta_2 + 3H_{2,0,0} + 3H_4 - 19H_{-1,0}) - 2/39\,(507 - 195x - 65x^2)\,\zeta_3 \\
& - 1/18\,(499 + 301x - 36x^2)\,\zeta_2 + 3/10\,(13 + 23x)\,\zeta_2^2 + 1/6\,(5 - 61x - 8x^2)\,H_3 \\
& - (5+3x)\,H_{0,0}\zeta_2 + 1/18\,(157 + 301x)\,H_2 + 1/108\,(2422 + 7609x)\,H_0 - 12H_0\zeta_3 \\
& - 2/3\,(x^{-1} - x^2)\,H_1\zeta_2 - 2\,(x^{-1} + x^2)\,(H_{-1}\zeta_2 + 2/3\,H_{-1,-1,0} - 2/3\,H_{-1,0,0} \\
& - 2/3\,H_{-1,2} - H_{-1,0}) + 2H_{0,0,0,0} - 1/3\,\delta(1-x)\,(233/48 + 10\zeta_3 + \zeta_2 + 1/2\,\zeta_2^2)\Big) \\
& + 8/3\,C_A C_F n_f \Big(4\Delta p_{gg}(x)\,(3\zeta_3 - 55/16) + 3\,(1-x)\,(8H_{-2,0,0} - 7507/27 - 16H_{-2}\zeta_2 \\
& - 32H_{-2,-1,0} + 30H_1\zeta_2 - 29H_{1,0,0} - 10H_{1,1,0} - 10H_{1,1,1} - 26/3\,H_{1,0} - 65/6\,H_{1,1} \\
& - 1127/18\,H_1) + 6\,(1+x)\,(61/6\,H_{-1,0} - 11H_{-1}\zeta_2 - 30H_{-1,-1,0} + 3H_{-1,0,0} \\
& - 4H_{-1,2} + 6H_{0,0}\zeta_2 + 8H_2\zeta_2 - 7H_{2,0,0} - 2H_{2,1,0} - 2H_{2,1,1} - 4H_{3,0} - H_{3,1} - 6H_4) \\
& + (125 + 38x - 20x^2)\,\zeta_3 + 1/6\,(848 + 341x - 108x^2)\,\zeta_2 - 1/18\,(8363 + 3362x)\,H_0 \\
& - (181 + 88x - 8x^2)\,H_{0,0,0} - 1/6\,(1723 - 692x - 108x^2)\,H_{0,0} - 3/5\,(43 + 83x)\,\zeta_2^2 \\
& - (32 - 43x - 8x^2)\,H_3 - 24\,(3 - 2x)\,H_{0,0,0,0} + 6\,(9-x)\,H_0\zeta_3 - (19 - 11x)\,H_{2,1} \\
& + 8\,(3 + 12x - x^2)\,H_{-2,0} + (56 - 43x - 16x^2)\,H_0\zeta_2 - 1/6\,(482 + 341x)\,H_2 \\
& - (38 - 37x)\,H_{2,0} + 4\,(x^{-1} - x^2)\,H_1\zeta_2 + 4\,(x^{-1} + x^2)\,(3H_{-1}\zeta_2 + 2H_{-1,-1,0} \\
& - 2H_{-1,0,0} - 2H_{-1,2} - 9/2\,H_{-1,0}) - 48xH_{-3,0} - 241/48\,\delta(1-x)\Big) \\
& + 8 C_F^2 n_f \Big(8\,(1-x)\,(H_{-2}\zeta_2 + 1 + 2H_{-2,-1,0} - H_{-2,0,0} - 2H_1\zeta_2 + 11/8\,H_{1,0,0} \\
& + 5/4\,(H_{1,1,0} + H_{1,1,1}) - 7/8\,H_{1,0} + 13/16\,H_{1,1} + 41/16\,H_1) + 4\,(1+x)\,(4H_{-1}\zeta_2 \\
& + 8H_{-1,-1,0} - 4H_{-1,0,0} + H_{0,0}\zeta_2 - H_{0,0,0,0} - 2H_2\zeta_2 + 3/2\,H_{2,0,0} + H_{2,1,0} + H_{2,1,1} \\
& + 1/2\,H_{3,1} - H_4 + 5/2\,H_{-1,0}) + (8 - 19/2x + 4x^2)\,\zeta_2 - (23 + 3/2x + 4x^2)\,H_{0,0} \\
& + (9 + 13x)\,\zeta_2^2 - 2\,(1 - 7x)\,H_0\zeta_3 + 2\,(2 - 3x)\,H_{2,1} + 2\,(4-x)\,(H_0\zeta_2 - H_3) \\
& - 2\,(3 + 4x)\,H_{2,0} + (2 + 19/2x)\,H_2 - 5/2\,(5 - 2x)\,H_0 - 2\,(7 - 3x)\,H_{0,0,0} \\
& - 2\,(5 + 21x)\,\zeta_3 + 4\,(x^{-1} + x^2)\,H_{-1,0} - 16x\,(2H_{-2,0} - H_{-3,0}) + 1/8\,\delta(1-x)\Big) \\
& + 2/27\,C_A n_f^2 \Big(-8\Delta p_{gg}(x) + 48\,(1+x)\,(\zeta_2 - 1/2\,H_{0,0} - H_2) - 3\,(1-x)\,(33 + 41H_1) \\
& - (56 - 67x)\,H_0 + 87/4\,\delta(1-x)\Big) \\
& + 2/27\,C_F n_f^2 \Big(-4\,(1-x)\,(146 + 90H_{1,0} + 45H_{1,1} + 78H_1) - 72\,(1+x)\,(\zeta_3 - 2H_0\zeta_2 \\
& + H_{0,0,0} + 2H_{2,0} + H_{2,1} + 2H_3) + 24\,(13 - 8x)\,(\zeta_2 - H_2) - 12\,(7 - 23x)\,H_{0,0} \\
& - 52\,(5-x)\,H_0 + 33/2\,\delta(1-x)\Big)\,.
\end{aligned}
$$

$$\Delta P_{gg}^{(2)}$$

Moch, Vermaseren, Vogt arXiv:1409.5131

phenomenological relevance

- **impact on evolution of helicity PDFs:**



crucial to match expected precision of future EIC DIS data

aside: large x feature @ NLO "fixed"

Moch, Vermaseren, Vogt, Rogal

- **at LO find:**

$$\mathbf{P_{ij}^{(0)} - \Delta P_{ij}^{(0)} \sim (1-x)^2 + \ldots}$$

in accordance with large x arguments by Brodsky, Burkardt, Schmidt

- **at NLO:** all fine and well, except for

$$\mathbf{P_{gq}^{(1)} - \Delta P_{gq}^{(1)}} \sim \log(\mathbf{1-x}) + \mathrm{const} + \ldots$$

- can be fixed by simple scheme transformation to yield

$$\mathbf{P_{gq}^{(1)} - \Delta P_{gq}^{(1)} \sim (1-x)^2 + \ldots}$$

- **phenomenological relevance for analysis of large x JLab-12 data ?**

- can be extended to NNLO

large x physics and all-order resummations

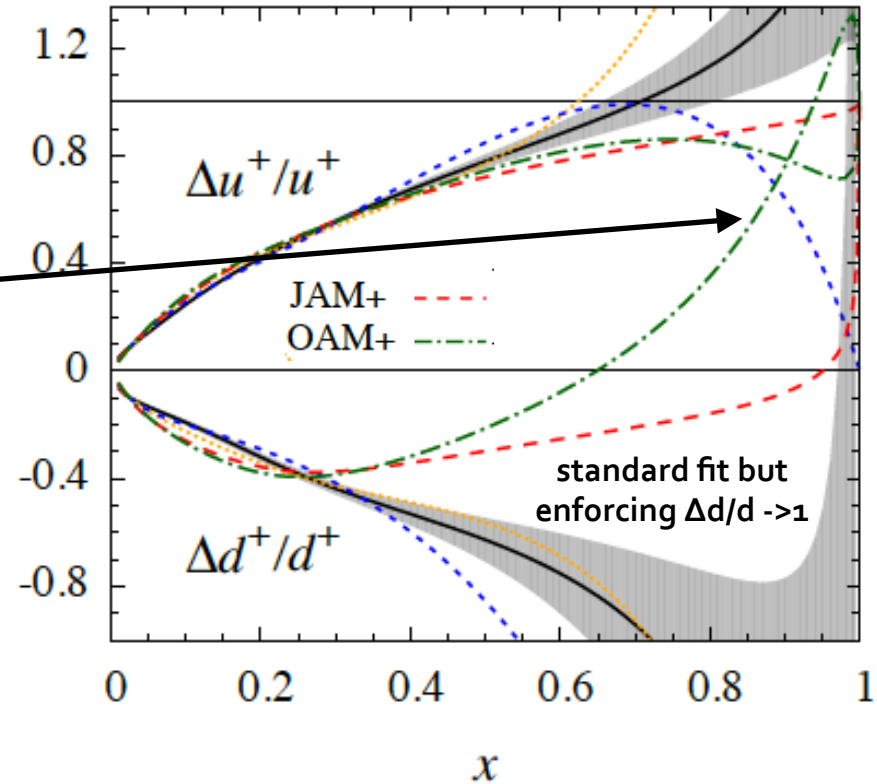
- **going back to Δq/q —> 1 :**

fit containing

$$\Delta d(x)/d(x) \sim (1-x)^{\beta} \log^2(1-x)$$

inspired by OAM arguments a la

Avakian, Brodsky, Deur, Yuan



Jimenez-Delgado, Melnitchouk
arXiv:1403.3355

- **however: pQCD develops same type of logarithms in each order**
  - can be systematically resummed to all orders
  - related to soft gluons —> log's the same in unpol. and pol. case

pQCD frontier: all-order resummations

- **main idea:** inhibited radiation near exclusive boundary; IR cancellation leaves large logs
  - example DIS: $C_q \sim e_q^2\left[\delta(1-x) + a_s C_F\left\{(1+x^2)\left(\frac{\ln(1-x)}{1-x}\right)_+ - \frac{3}{2}\frac{1}{(1-x)_+} + \ldots\right\}\right]$

    $\frac{1}{2}\log^2(1-x)\, q(x)$ in convolution with PDFs
  - well defined class of higher order corrections: $a_s^k L^{2k}, a_s L^{2k-1}, \ldots$ at kth order
- **terminology:** logs can be resummed to all orders (-> exponentiated)

Fixed Order

Resummation

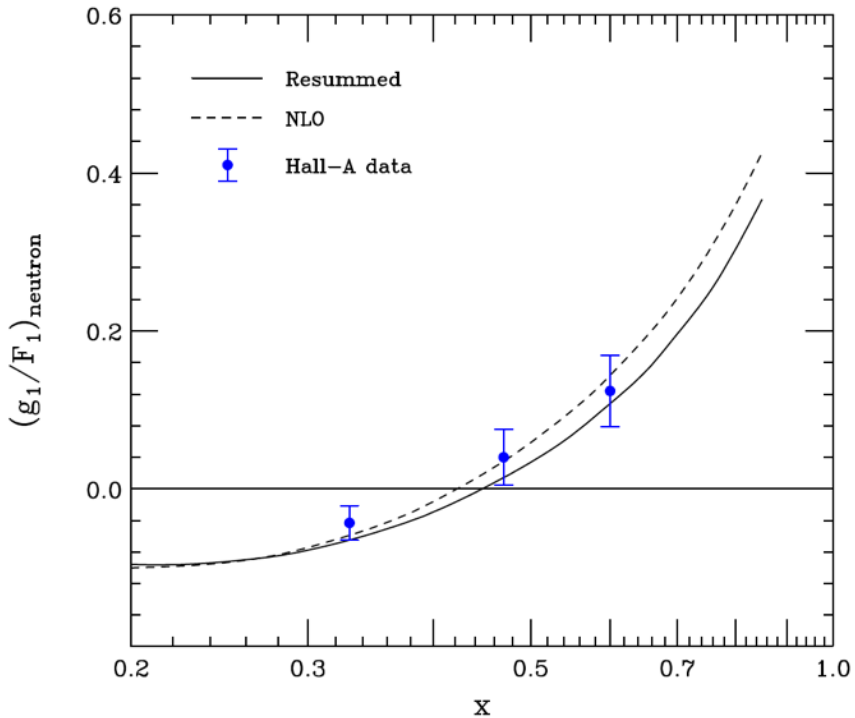
LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	...	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

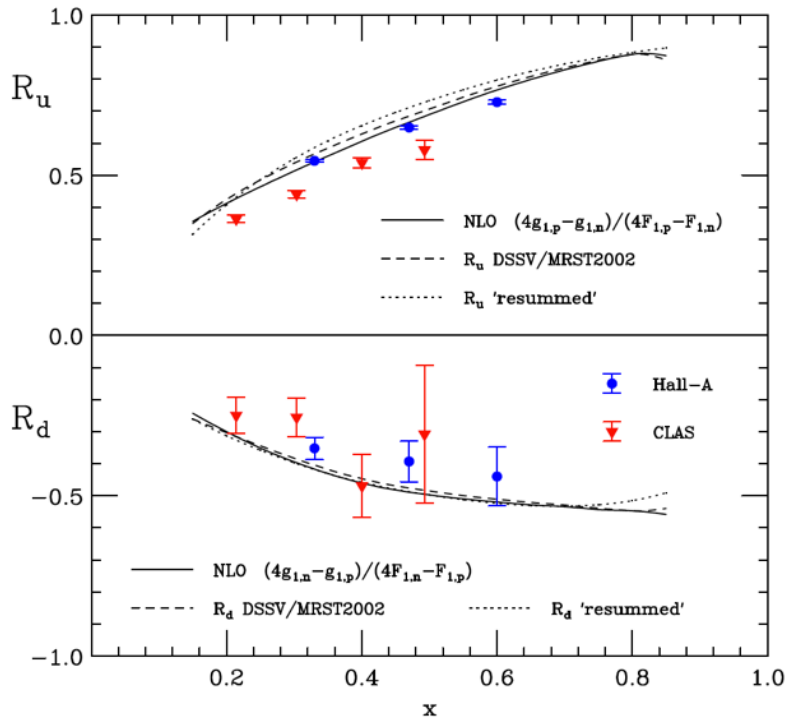
LL NLL NNLL

some phenomenological implications

- often relevant for pheno. studies (mostly at lower energies but also at colliders)
- **recent example**: resummation for (SI) DIS spin asymmetries

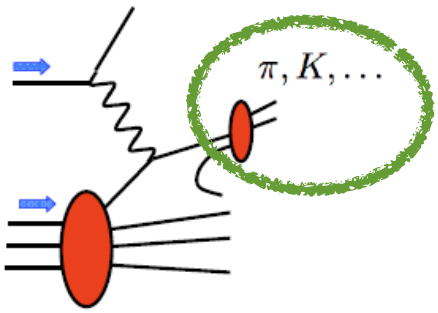
Anderle, Ringer, Vogelsang 1304.1373





resummations should be included in analyses of JLab-12 data

towards more precise fragmentation fct's



- **fragmentation functions** provide "***analyzing power***" for different quark flavors in **SIDIS** and **hadron production in pp**
- determine parton -> hadron FFs & uncertainties from **global fit** to π^+, π^-, K^+, K^- yields in e^+e^-, DIS multiplicities, and pp

—> DSSV uses DSS '07 FFs for SIDIS and RHIC π^0 data

DSS'07 in a nutshell: D. de Florian, R. Sassot, MS, PRD 75 (2007) 114010; 76 (2007) 074033

- ☑ good global description of all data sets
- ☑ only set of FFs which describes DIS multiplicities
- ☑ only set which constrains gluon FF through pp data

lots of new data *after* DSS'07 analysis:

e^+e^-: BaBar, Belle DIS: COMPASS, HERMES; pp: ALICE, STAR, PHENIX

—> DSS'14 update for pion FFs

kaon FF update in the making

arXiv:1410.6024


Parton-to-Pion Fragmentation Reloaded

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Universidad de Buenos Aires, Ciudad Universitaria, Pabellón 1 (1428) Buenos Aires, Argentina and
Instituto de Física Corpuscular, Universitat de València-Consejo Superior de Investigaciones Científicas,
Parc Científic, E-46980 Paterna, Valencia, Spain

Marco Stratmann¶
Institute for Theoretical Physics, University of Tübingen,
Auf der Morgenstelle 14, 72076 Tübingen, Germany

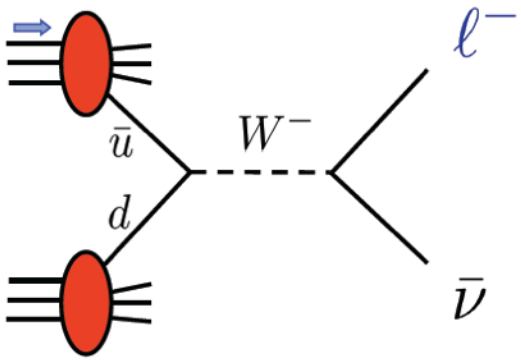
comprehensive global analysis of parton-to-pion fragmentation functions
racy in QCD. The obtained results are based on the latest experimen
pion production in electron-positron annihilation, lepton-nu
on-proton collisions. An excellent description of all data
ies in parton-to-pion fragmentation functions are est
parisons to the results from our previous global

4

future avenues
near and long term

exciting new result: W boson asymmetry

another key measurement at RHIC



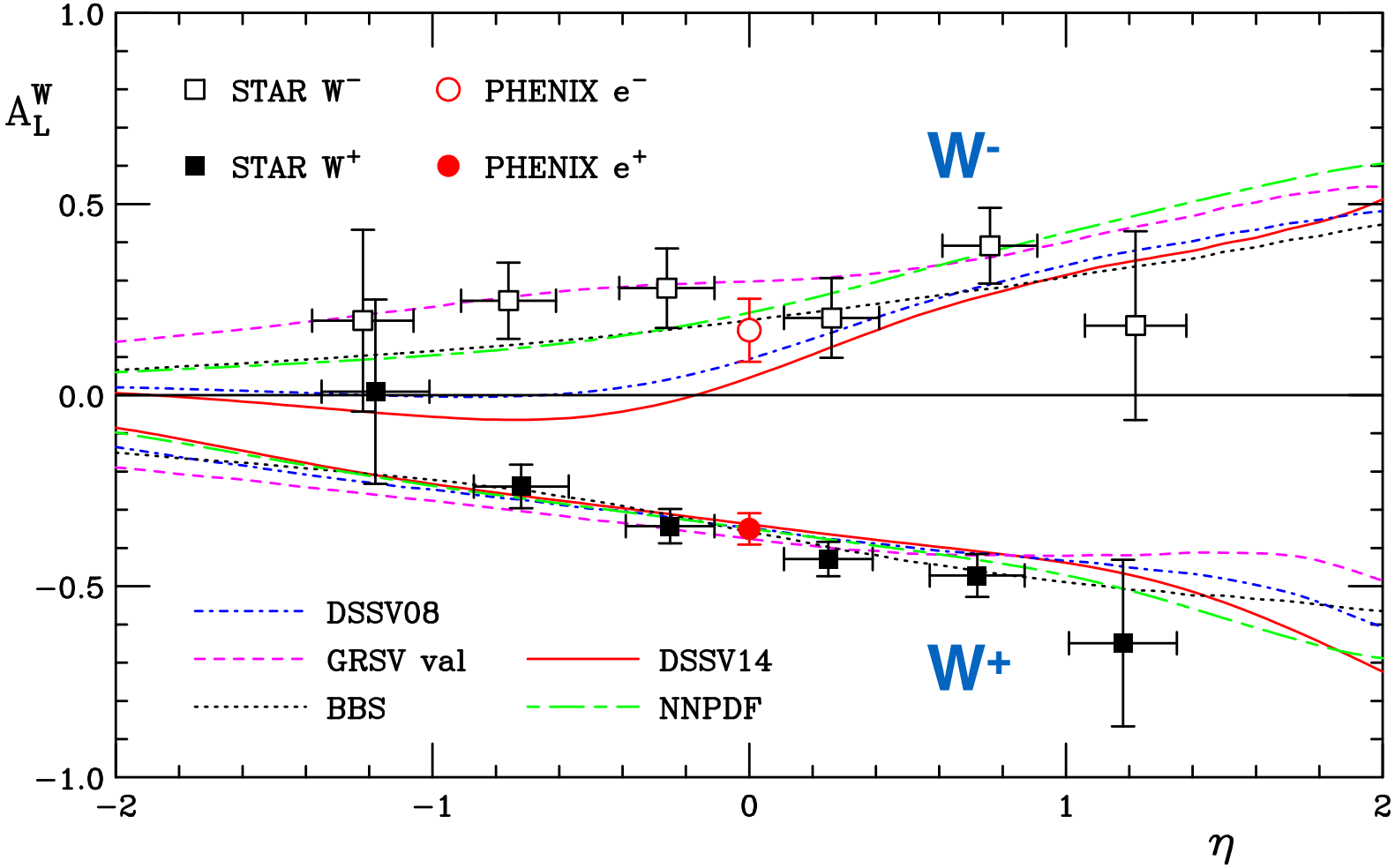
neat idea: measure parity-violating single-spin asymmetry

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

backward lepton rapidity forward lepton rapidity

- ☑ repeat for W^+ to get $\Delta u/u,\ \Delta\bar{d}/\bar{d}$
- ☑ leads to flavor separation at $Q = M_W$ **free of fragmentation uncertainties**
- ☑ accessible x-range at RHIC limited to $\langle x_{1,2}\rangle \simeq \frac{M_W}{\sqrt{S}} e^{\pm\eta_l/2} \simeq 0.04 \div 0.4$ **@ $Q=M_W$ evolution!**
- ☑ no access to strangeness (would require W+charm)

current situation



☑ uses new analytic NLO calculation for incl. lepton production **Ringer, Vogelsang arXiv:1503.07052**

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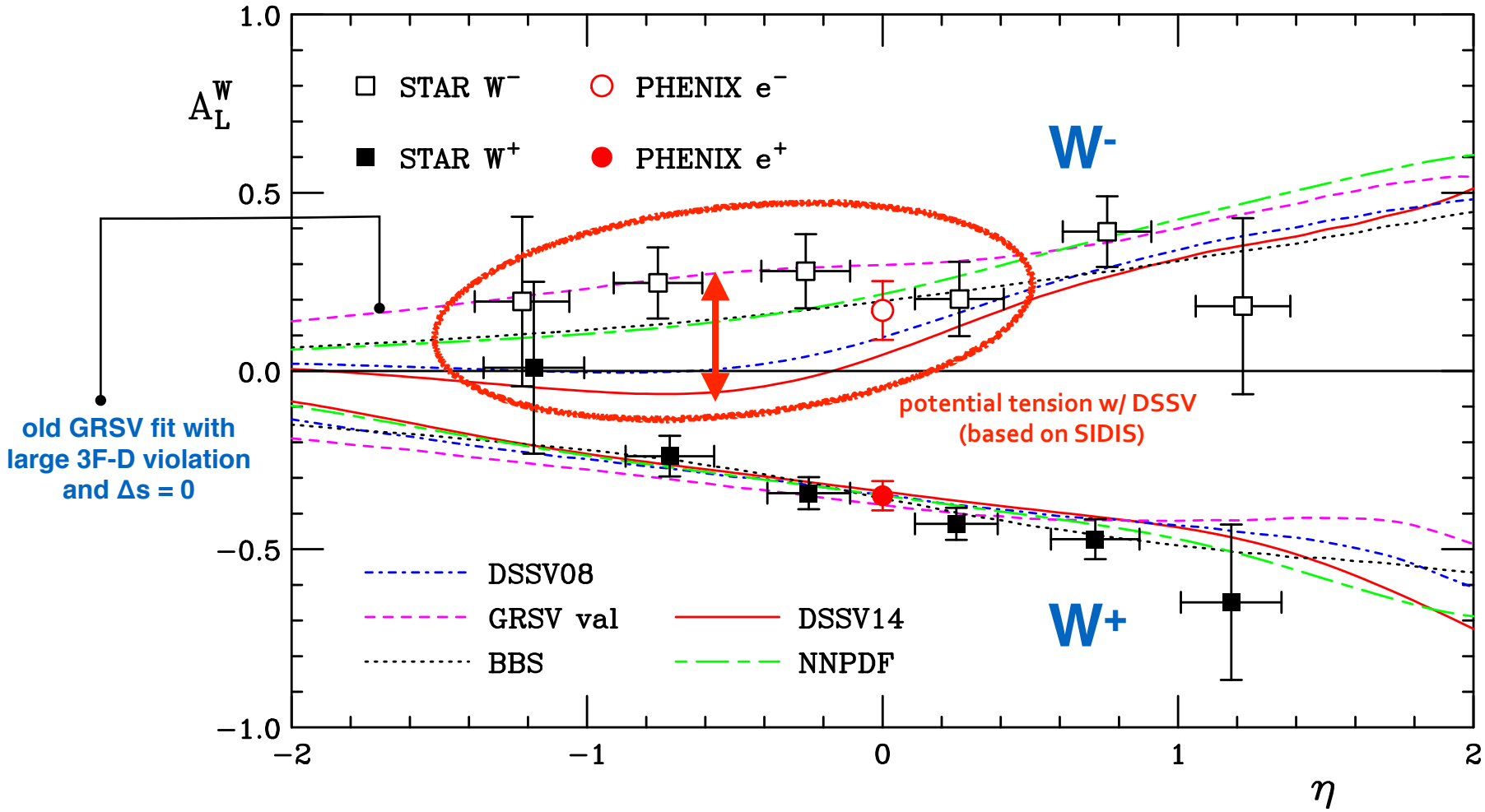

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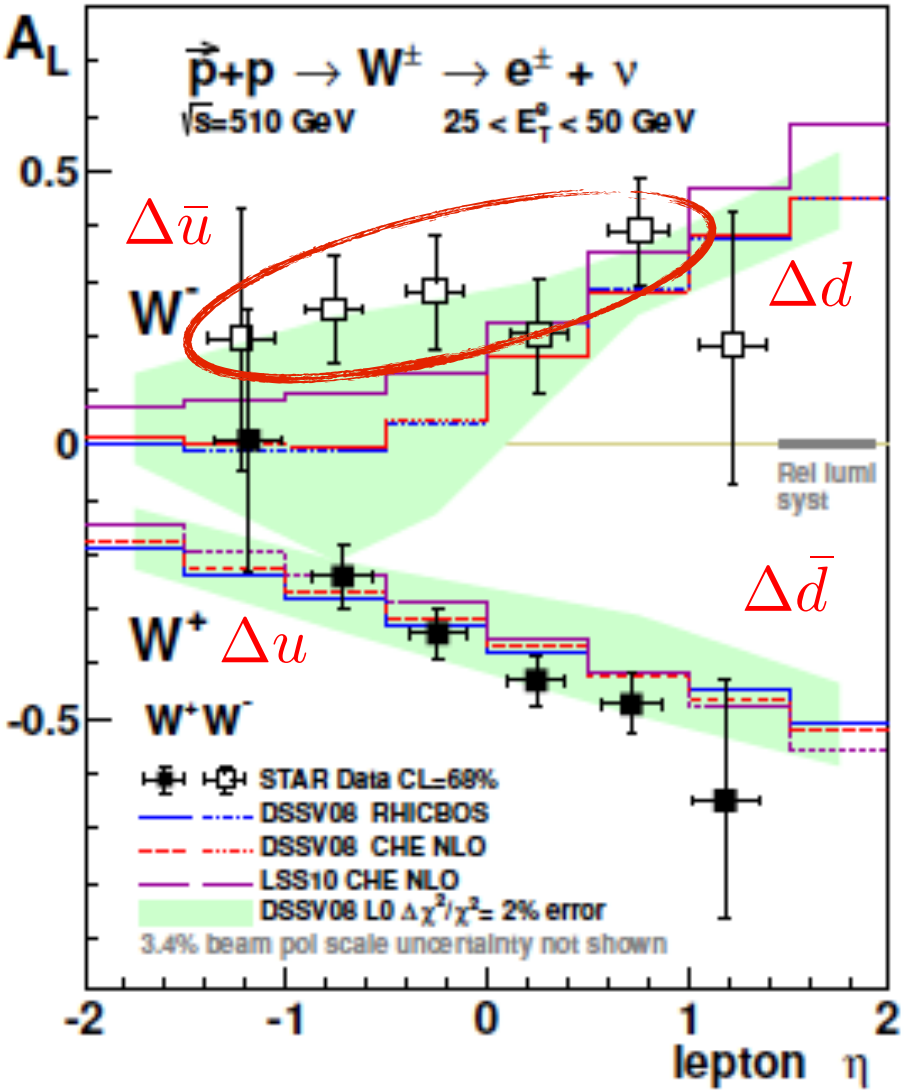
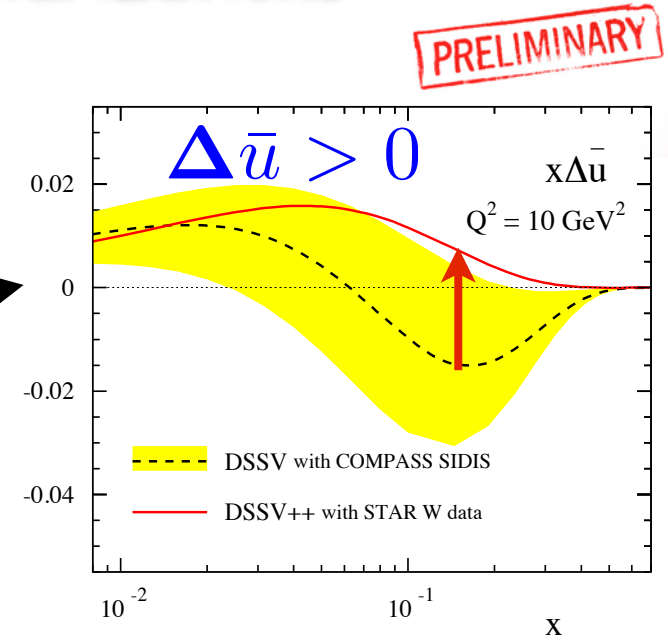
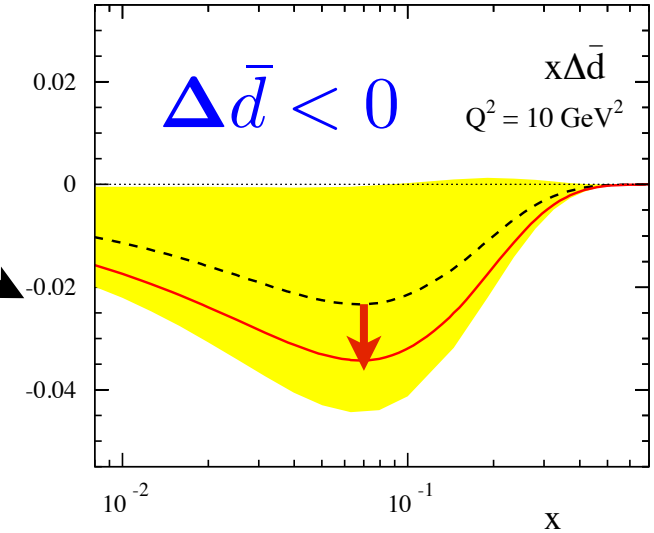
potential impact on sea polarizations

STAR arXiv:1404.6880



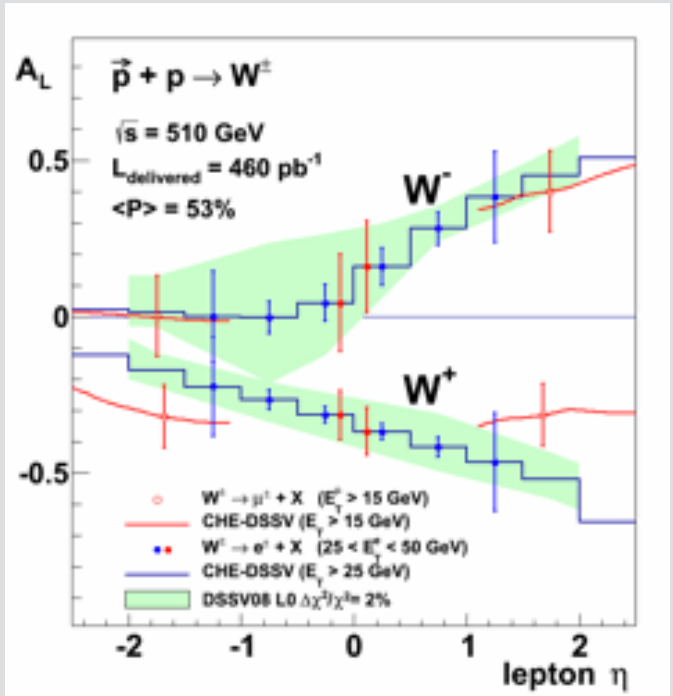
published data already have a significant impact

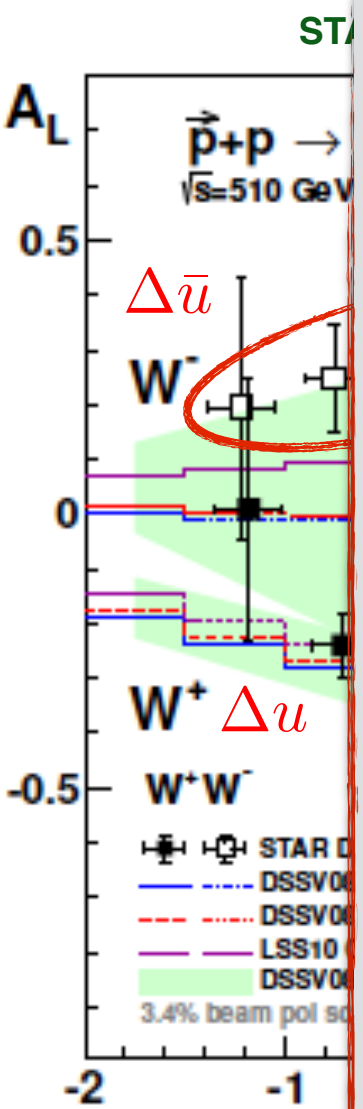


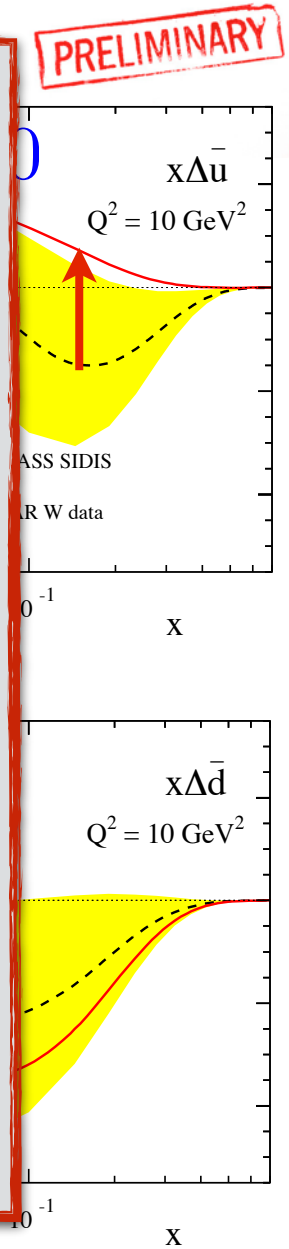


potential impact on sea polarizations

- points towards rather sizable positive $\Delta\bar{u}(x) - \Delta\bar{d}(x)$
- same trend seen by NNPDF, see 1406.5539
- starts to test of what we know from SIDIS
- 2013 STAR data soon: further reduce uncertainties by 2







Bj sum rule

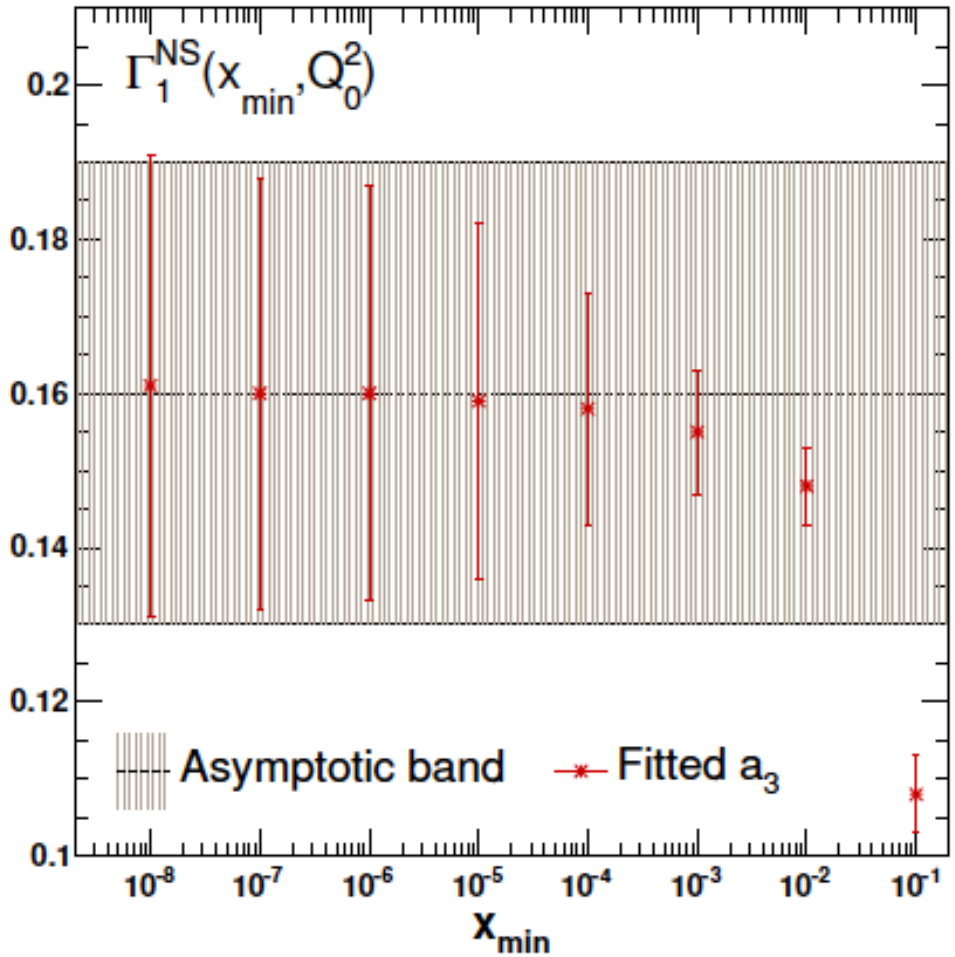
- rare example of a well understood quantity in pQCD

QCD corrections up to $O(\alpha_s^4)$

$$\Gamma_1^{p-n} = \frac{1}{6}\mathcal{C}_{Bj}[\alpha_s(Q^2)]\ \Delta q_3$$

Kodaira; Gorishny, Larin; Larin, Vermaseren; Baikov, Chetyrkin, Kuhn

NNPDF, arXiv:1303.7236



- probes conserved non-singlet Δq_3

$$\Delta q_3 \equiv \int_0^1 dx[\Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}](x, Q^2)$$

- all fits usually ***assume***

$$\begin{aligned}\Delta q_3 &= F + D \\ &= 1.2701 \pm 0.0025\end{aligned}$$

- significant uncertainties if fitted

NNPDF, arXiv:1303.7236

$$\Delta q_3 = 1.19 \pm 0.22$$

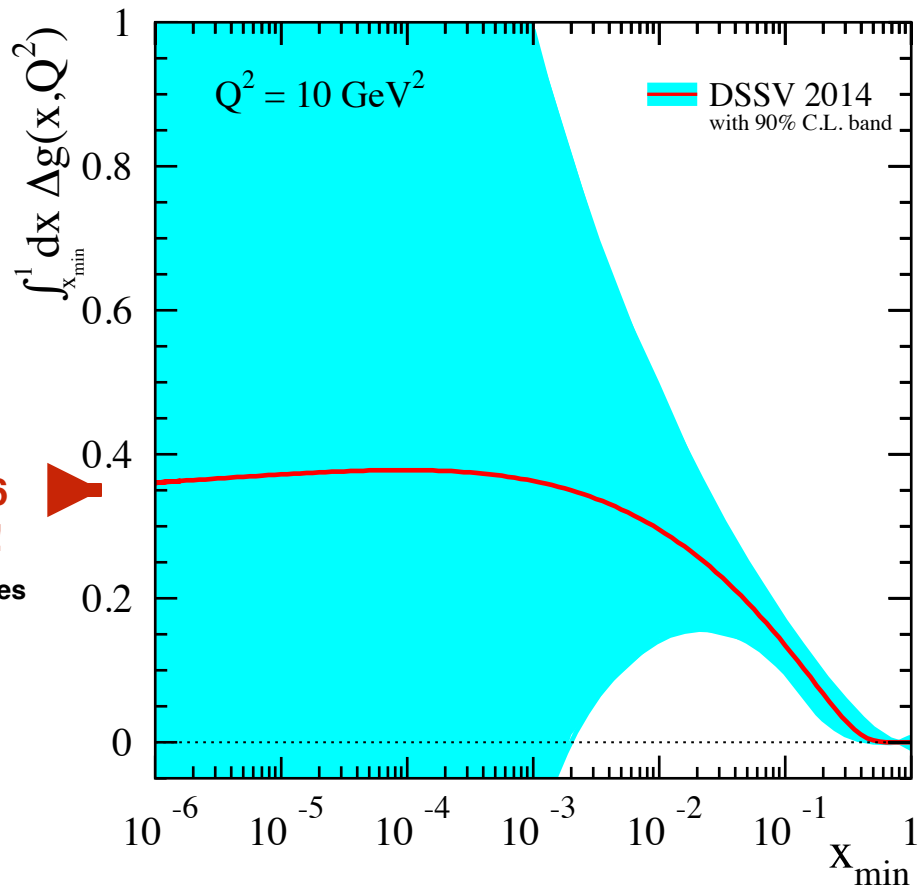
significantly worse than sometimes claimed !

- **needs an EIC to reduce uncertainty**

status & expectations for Δg

Aschenauer, Sassot, MS
to appear

status for "running integral" of Δg (—> spin sum rule) :



based on RHIC run9 jets and π^0

best fit prefers
Δg of about 0.36
70 - 75% of 1/2 !

but LARGE uncertainties

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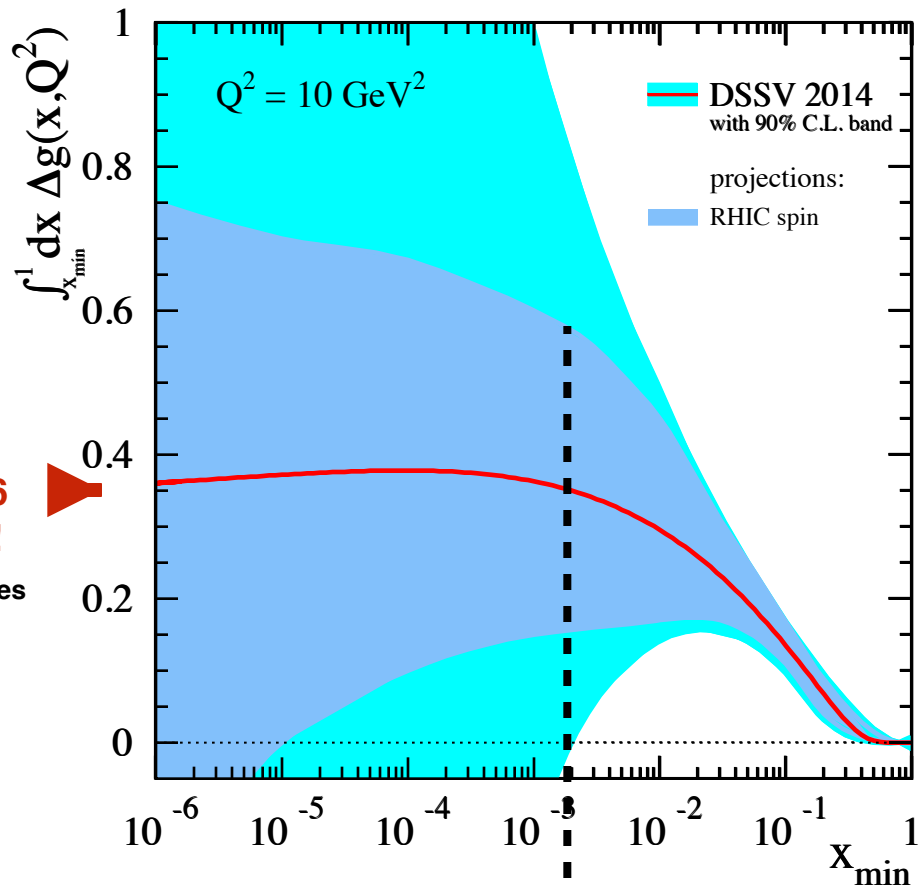

based on RHIC run9 jets and π^0

upcoming 200/510 GeV RHIC spin results

jets and π^0 @ central & forward η

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510 GeV forward rapidity data will have sensitivity down to **few x 10^{-3}**

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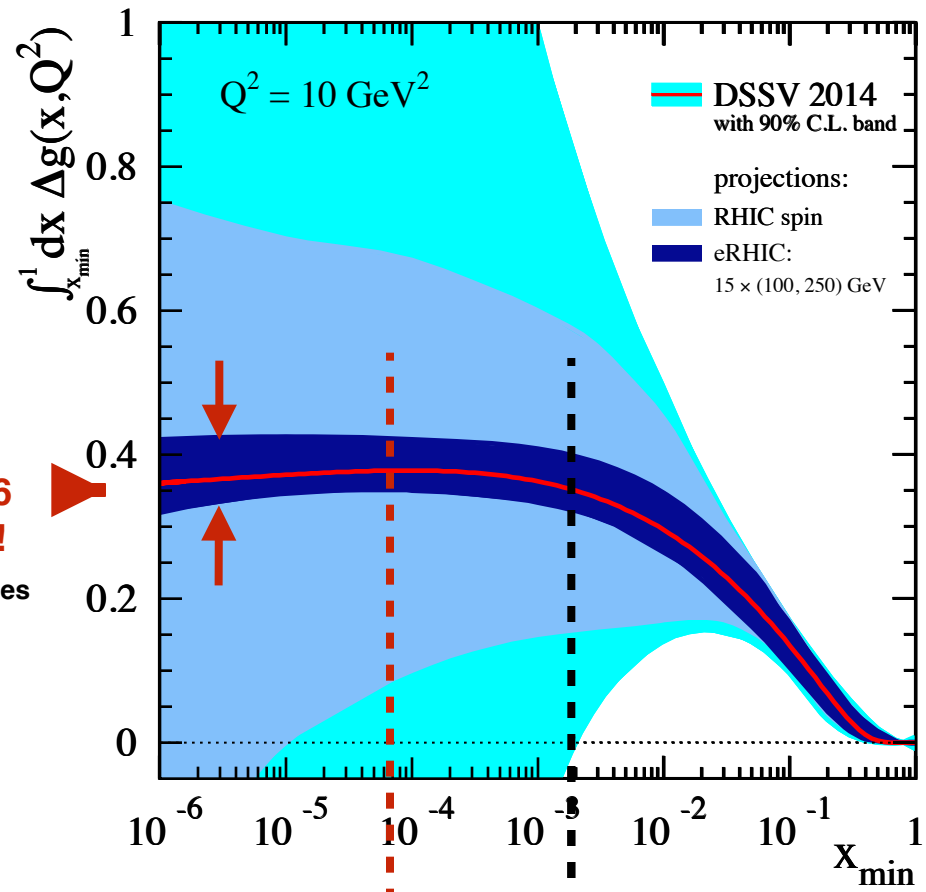

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sensitivity of 15x250 GeV

510 GeV forward rapidity data will have sensitivity down to **few x 10^{-3}**

based on RHIC run9 jets and π^0

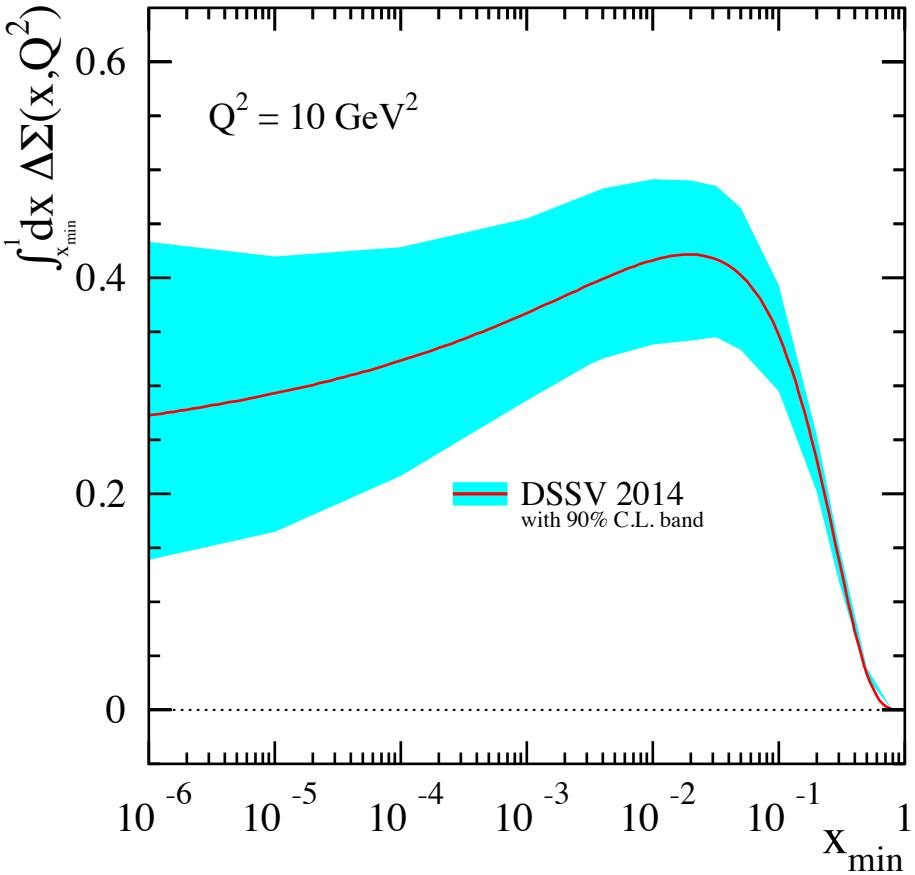
upcoming 200/510 GeV RHIC spin results
jets and π^0 @ central & forward η

ultimate goal: EIC ep collider
projection assumes modest luminosities

EIC can achieve 10% accuracy on Δg

what about ΔΣ and OAM ?

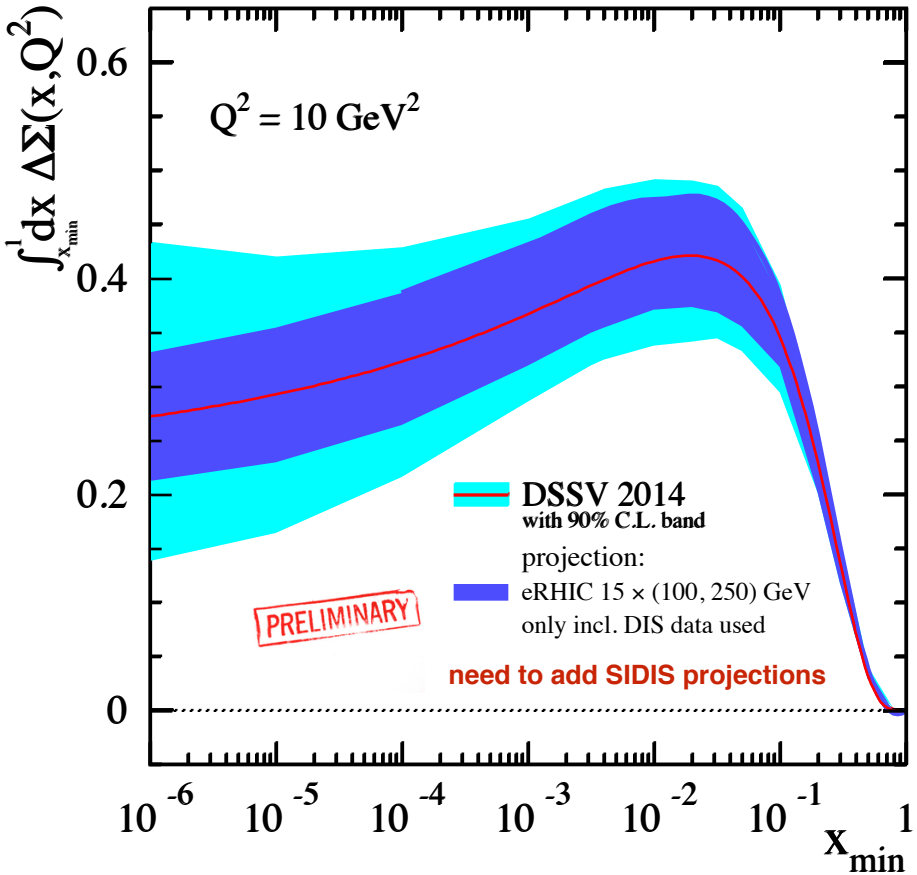
running integral for ΔΣ



- **we can't really say we "know" ΔΣ**
  likewise for the Bj sum rule !
- main culprit: small x behavior of Δs
  need to scrutinize 3F-D constraint

what about ΔΣ and OAM ?

running integral for ΔΣ



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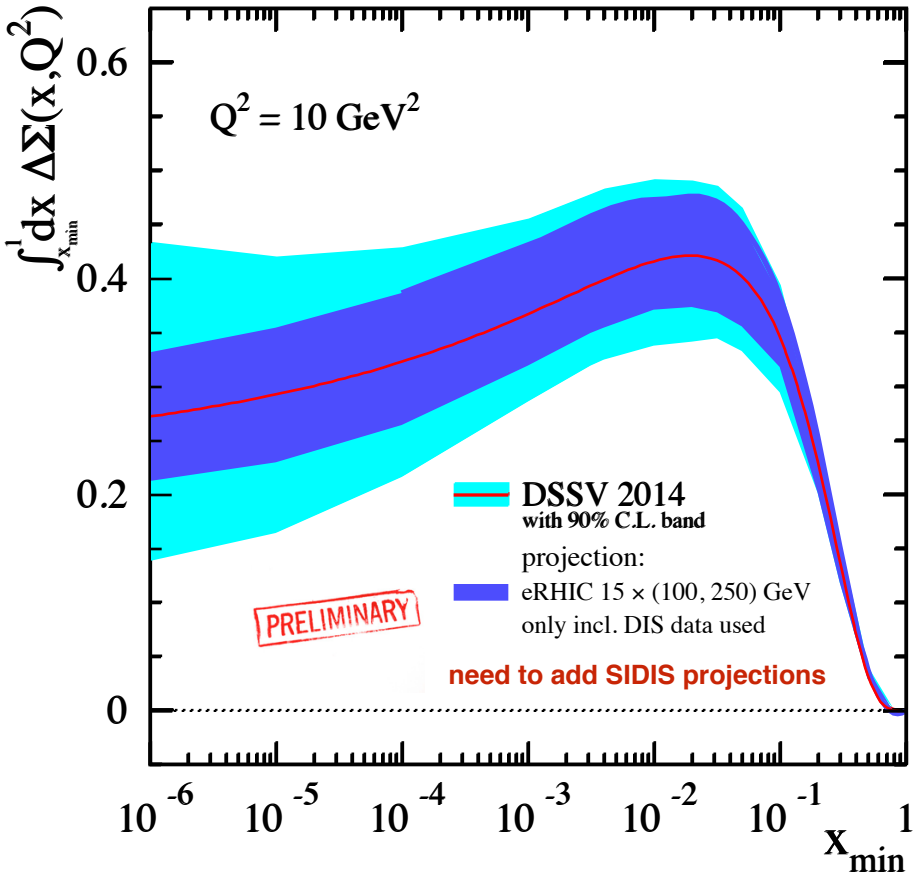

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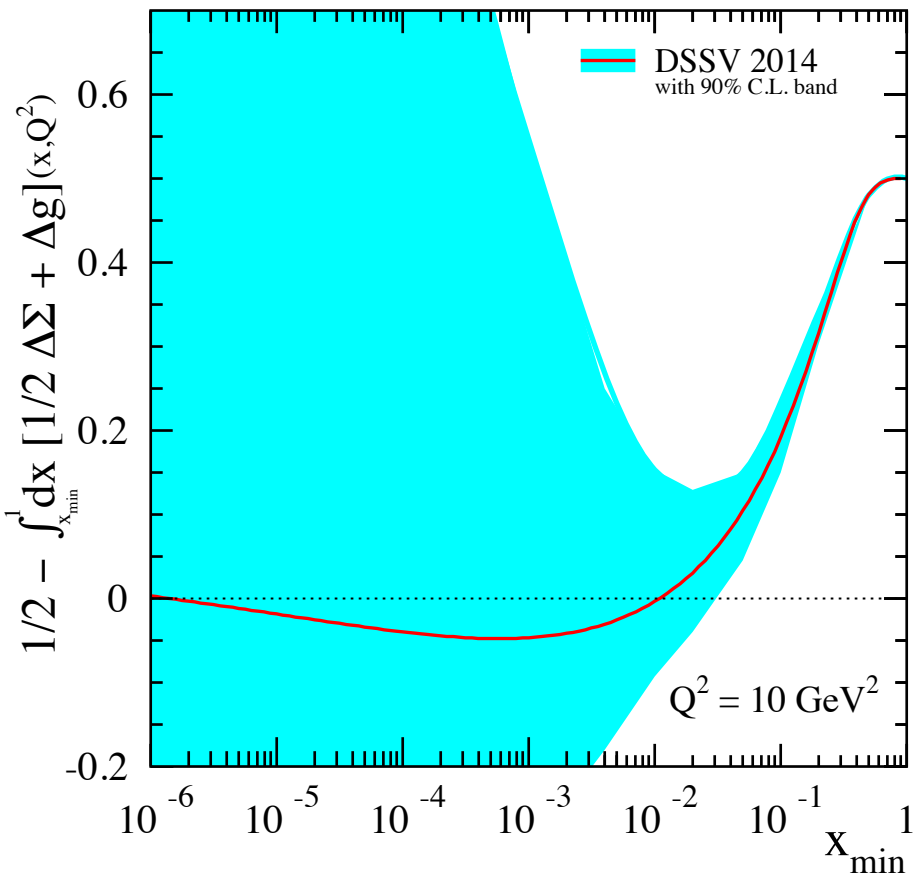
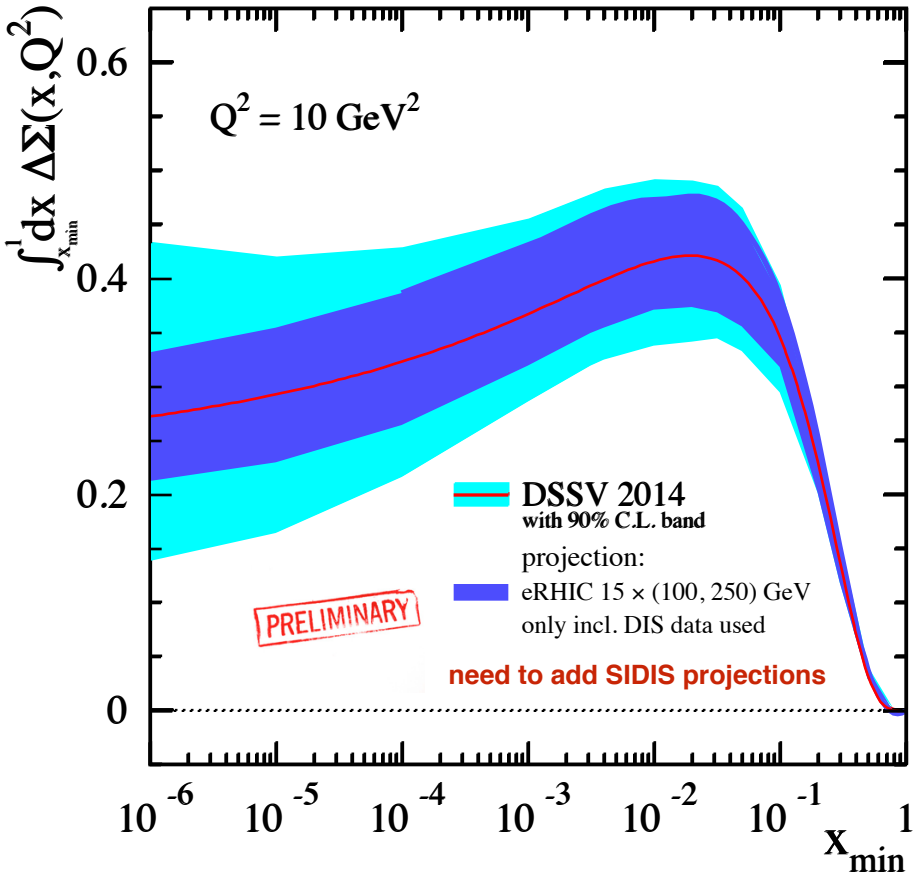
a little subtraction game



- **best fit has no OAM at 10 GeV²**

what about ΔΣ and OAM ?

running integral for ΔΣ



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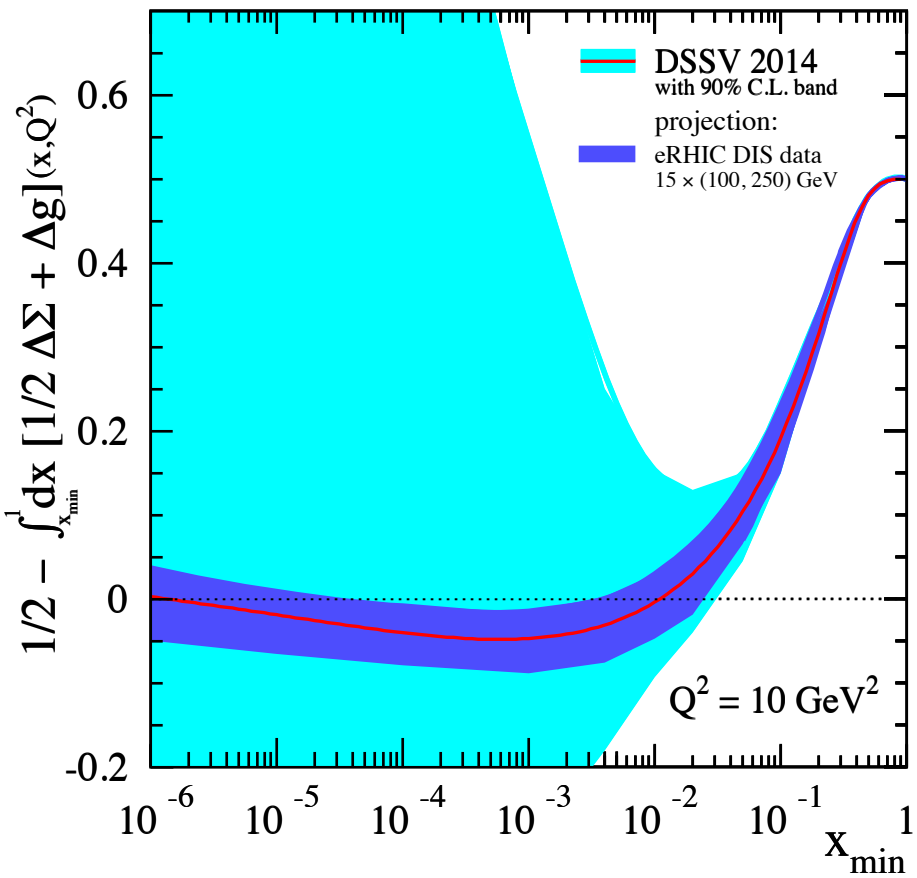

- **best fit has no OAM at 10 GeV²**
- EIC can make definitive statement
  presumably most precise (indirect) handle on OAM

take away message

spin experiments continue to produce high impact results

theory efforts & global QCD fits try to keep up

Δg has gained quite some weight in proton spin sum

RHIC spin and JLab-12 have many more results to come

to close the chapter on the proton spin

an EIC is the only option