Charlottesville, 04/19/02

Spin Physics @ RHIC – a Theoretical Overview

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(Regensburg)

- **Lessons from (un)polarized DIS**

- **Longitudinal polarization**:
  - Accessing Δg
  - Further information on Δq, $\Delta \bar{q}$
  - Status of NLO QCD calculations
  - Towards a "global" QCD analysis of upcoming data

- **Transverse polarization**:
  - Single spin asymmetries A_{N}
  - Accessing "transversity" via A_{TT}

- **"New physics"**

- **What remains to be discovered after RHIC?**

• Lessons from polarized DIS

20 years of beautiful data

– matched by theoretical efforts

What have we learned?

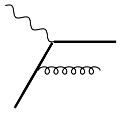
- ✓ NLO QCD fits describe data well
- ✓ Bjorken sum rule confirmed to $\sim 10\%$
- ✓ Gourdin-Ellis-Jaffe relation is violated
- ✓ quarks do *not* carry the proton spin

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\simeq 0} + \Delta g + L_{q,g}$$

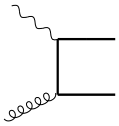
Still considerable *lack of knowledge* regarding

- × polarized gluon density $\Delta g(x,\mu)$
- × quark flavor separation Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, ...
- × reliability of leading-twist QCD analyses
- × spin effects with *transverse* polarization
- × orbital angular momentum $L_{q,g}$ of quarks and gluons

NLO QCD "picture" for polarized DIS:



$$g_1^{N={p \atop n}}(x,Q^2) \;=\; \left[\pm\frac{1}{12}\Delta q_3^{\rm NS}+\frac{1}{36}\Delta q_8^{\rm NS}+\frac{1}{9}\Delta\Sigma\right]\otimes\left(1+\frac{\alpha_s}{2\pi}\Delta C_q\right)$$
$$+\;\sum_q e_q^2\,\frac{\alpha_s}{2\pi}\Delta g\otimes\Delta C_g$$



from *perfect* data (+ *assuming* QCD) we would get:

Δq_3 from $g_1^p - g_1^n$

$\Delta q_8,\ \Delta\Sigma,\ \Delta g$ from $g_1^p + g_1^n$ due to different Q^2-evolution

$\swarrow$

$$\mu\frac{d}{d\mu}\begin{pmatrix}\Delta q(x,\mu)\\ \Delta g(x,\mu)\end{pmatrix}=\begin{pmatrix}\Delta P_{qq} & \Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix}(x,\mu)$$

NLO ΔP_{ij}: Mertig, van Neerven; Vogelsang

in '*real life*' we only get *some* information on

$$\Delta q_3,\ \Delta q_8,\ \Delta\Sigma \quad\leftrightarrow\quad \Delta q+\Delta\bar{q}\ \text{(q=u,d,s)}$$

[reason: · no lever-arm in Q^2 to *really* study scaling viol. $\leftrightarrow$ Δg

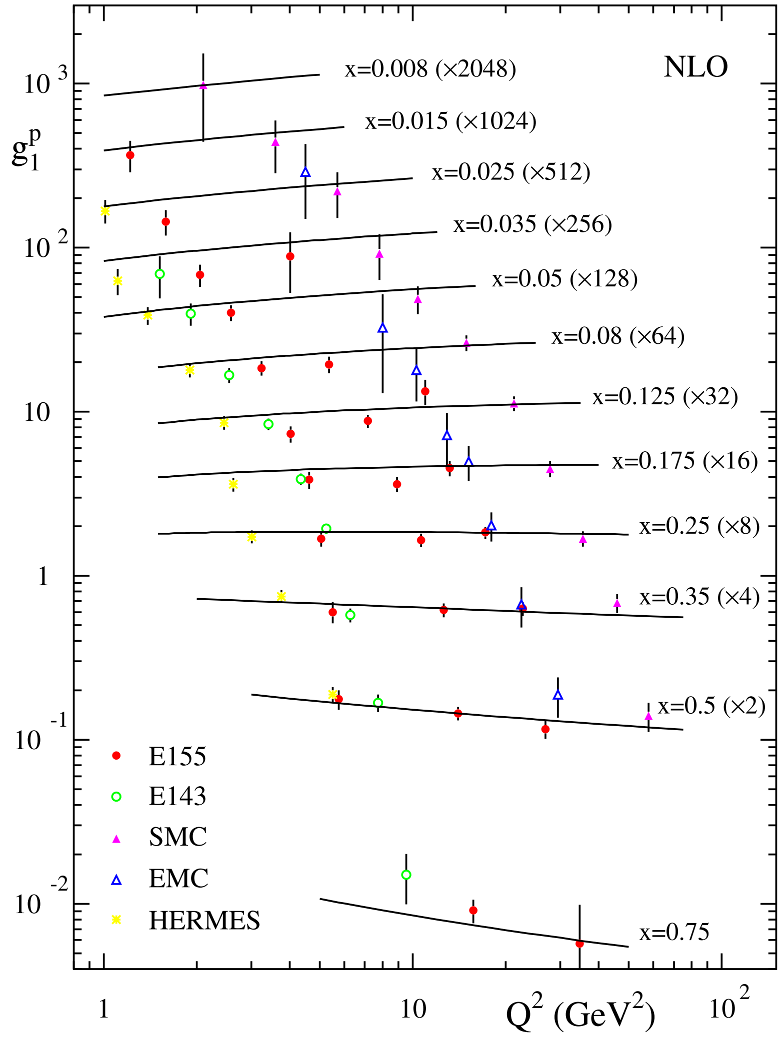
· kin. coverage of data much worse than in unpol. case]

$\Delta s+\Delta\bar{s}=\frac{1}{3}(\Delta\Sigma-\Delta q_8)$ is fixed by DIS data

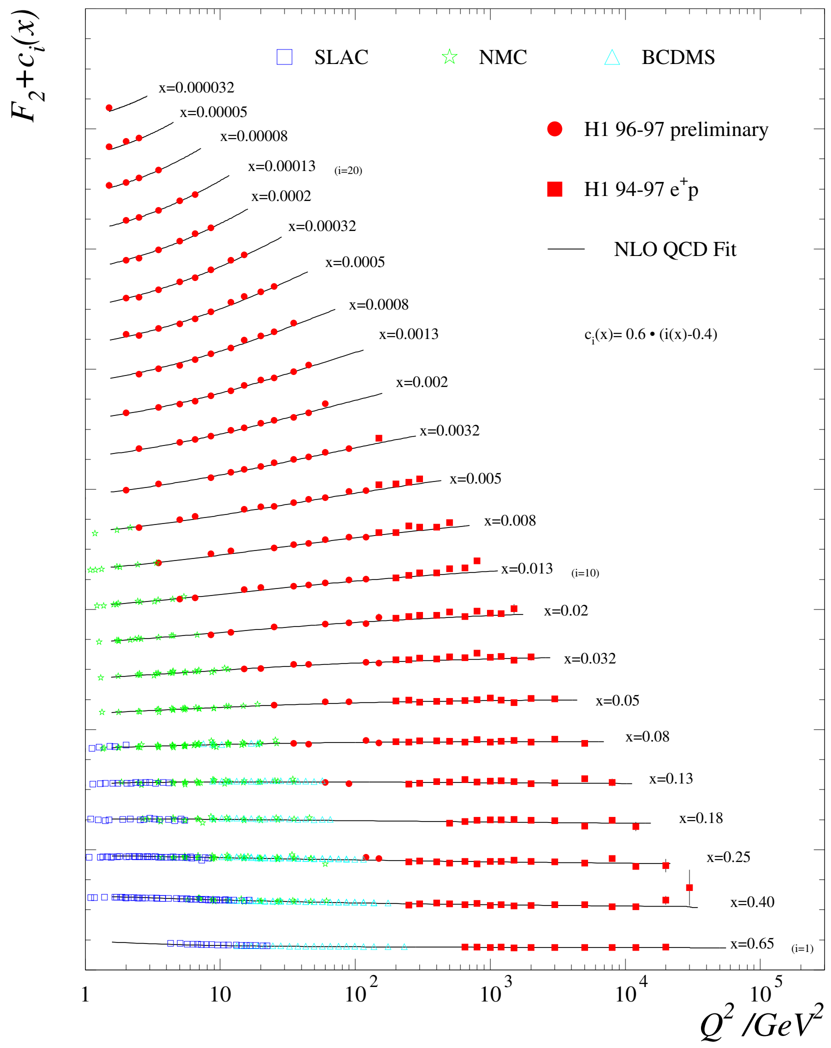
but we cannot decide if the sea is SU(2)/SU(3) or not

World data on pol. and unpol. deep-inelastic scattering

polarized



unpolarized



NLO QCD fit: Glück, Reya, Vogelsang, MS (2000 update)

Available analyses in NLO QCD:

- very active field, ever *growing* number of fits:

GRSV	Glück, Reya, Stratmann, Vogelsang
GS	Gehrmann, Stirling
ABFR	Altarelli, Ball, Forte, Ridolfi
DS(S)	De Florian, (Sampayo), Sassot
SMC	SM Collaboration
E155	E155 Collaboration
LSS	Leader, Sidorov, Stamenov
BBPSS	Bourrely, Buccella, Pisanti, Santorelli, Soffer
GGR	Gordon, Goshtasbpour, Ramsey
TBK	Tatur, Bartelski, Kurzela
GGI	Ghosh, Gupta, Indumathi
AAC	Asymmetry Analysis Collaboration
BB	Blümlein, Böttcher

(likely that I still have missed someone)

- analyses differ in *many* aspects (→ table)

  → gives *some* flavor of PDF uncertainties

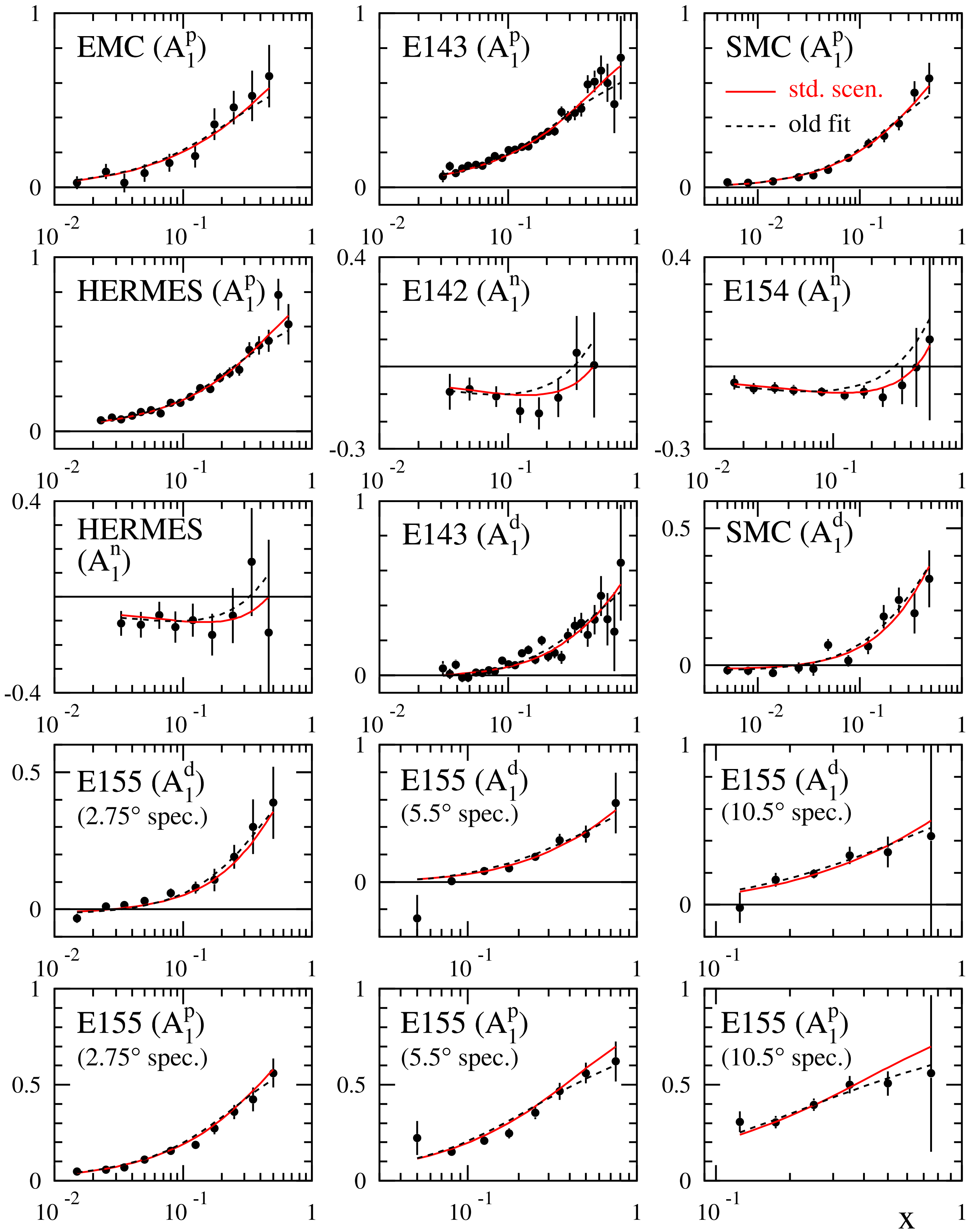
- several parametrizations available

- all groups use *different* methods to solve DGLAP eqs.

  → comparison of evolution codes should be done along similar lines as in unpol. case

NLO QCD analyses: overview & comparison

	GRSV	GS	ABFR	DS(S)	SMC	E155	LSS	BBPSS	GGR	TBK	GGI	AAC	BB
update	11/00	12/95	3/98	7/00	5/98	7/00	1/02	3/98	3/98	3/99	2/01	1/00	2/02
fit to	A_1	g_1	g_1	A_1	g_1	g_1	A_1	A_1	g_1	A_1	A_1	A_1	g_1
R/F_1	GRV	-	-	(EXP)	-	-	MRST	MRS	-	EXP	CTEQ	SLAC	-
data	new	old	mix	new	new	new	new	mix	mix	new	new	new	new
E155	✓	×	×	prel.	×	✓	✓	×	×	×	no p	no p	✓
LO	✓	✓	×	✓	×	×	✓	×	✓	×	✓	✓	✓
NLO scheme	$\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$	AB $\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$ AB	$\overline{\mathrm{MS}}$	JET $\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$ JET	$\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$	$\overline{\mathrm{MS}}$
# sets	2	3	4	3	1	1	1	7	3	1	2	2	2
Q_0^2	0.4	4	1	0.5	1	0.4	1	4	?	1	2.56	1	4
Λ_4	246	231	fit	246	300	246	300	326	?	344	280	246	fit
ansatz	GRV	MRS	free	free	free	GRV	MRST	free	SU(6)	free	free	GRV	free
g_A	✓	✓	fit	fit	fit	fit	✓	✓/fit	✓	fit	✓	✓	✓
$3F-D$	✓/×	✓	✓	fit	✓	fit	✓	✓/fit	?	✓	✓	✓	✓
sea	SU(3) $\bar{u}\neq\bar{d}$	SU(3)	-	$\bar{u}\neq\bar{d}$ fit	-	SU(3)	SU(3)	SU(3) zero	SU(2)	SU(2)	$\bar{u}, \bar{d}$ fit?!	SU(3)	SU(3)
$\lvert\Delta f\rvert \leq f$	✓	✓	×	✓	×	✓	✓	?	✓	✓	✓	✓	(✓)
parametr.	✓	✓	×	✓	×	×	✓	×	×	×	×	✓	✓
comments		LO with GRV	$\mu_{R,F}$ var.	SIDIS in fit	full error matrix				Q^2 evol. ??			$\Delta\Sigma$ $\leftrightarrow$ x^{sea}	errors on pdfs



(GRSV NLO QCD fit)

Remark on low-Q^2 fixed target data:

the measured x, Q^2 range is tricky . . .

lesson from *unpolarized* fits: CTEQ, GRV, MRST

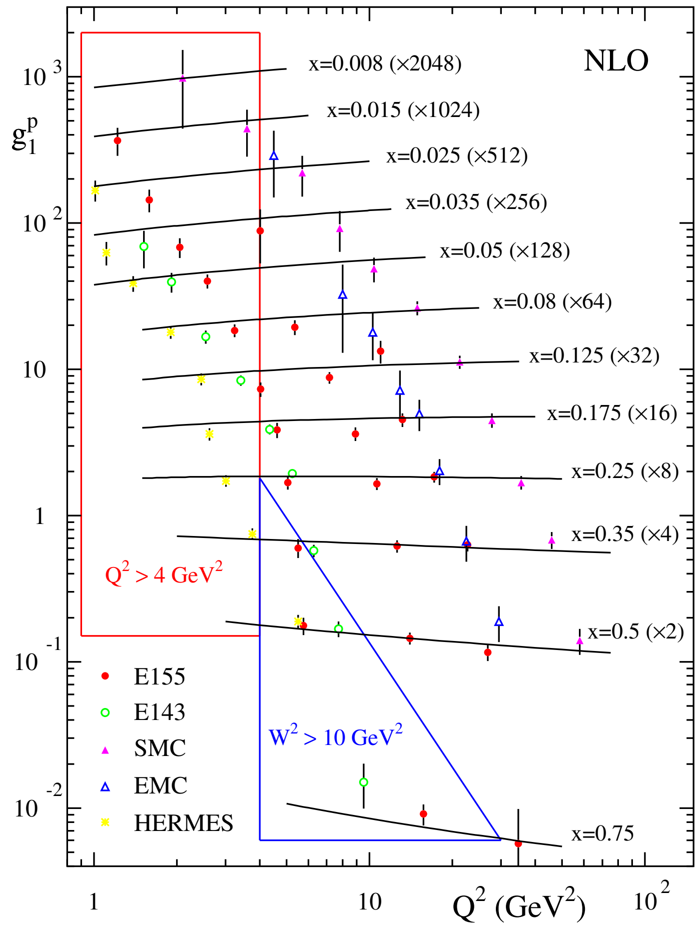
leading twist descr. of F_2 fails for low Q^2 and/or high x

$\rightarrow$ impose cuts ($Q^2 \gtrsim 4$, $W^2 \gtrsim 10\ \mathrm{GeV}^2$) to extract only the *universal* (twist-2) part of PDF's

we cannot afford similar cuts for g_1:

would loose most data

$\rightarrow$ usually only $Q^2 \gtrsim 1$, $W^2 \gtrsim 4\ \mathrm{GeV}^2$



$\rightarrow$ current PDF's may suffer from higher twist contrib.

[HT *may* partly cancel in g_1/F_1 but there is no proof for that]

$\rightarrow$ PDF's have to pass consistency check:

measurements at higher ('safer') scales $\leftrightarrow$ RHIC

Upshot: important questions remain unanswered

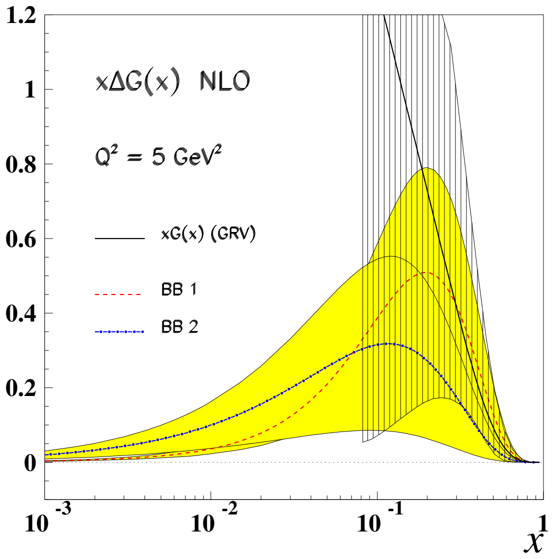
· $\Delta g(x, Q^2)$ completely unknown

new fit by Blümlein, Böttcher:

1st attempt: pol. pdfs with errors

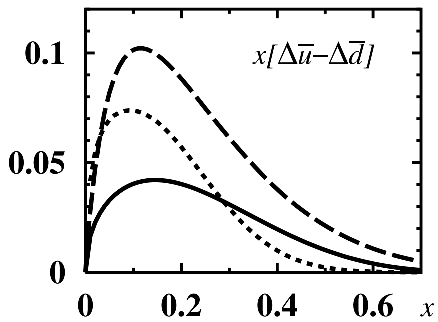
error-bands: only statistical!
huge theoretical errors
$\rightarrow$ Δg can be also negative

also g not known at large-x



· flavor separation of quark densities

in particular $\Delta\bar{u} - \Delta\bar{d}$ received much interest recently:



conv. consensus between models:
$\Delta\bar{u} - \Delta\bar{d}$ large & positive

solid: meson cloud+'$\pi\sigma$' Fries, ...
dashed: CQSM Diakonov, ...
dotted: 'Pauli' Glück, Reya

[HERMES is expected to make a first measurement here]

· angular momentum contribution to spin sum rule

· transverse polarization ['only' g_2 has been measured]

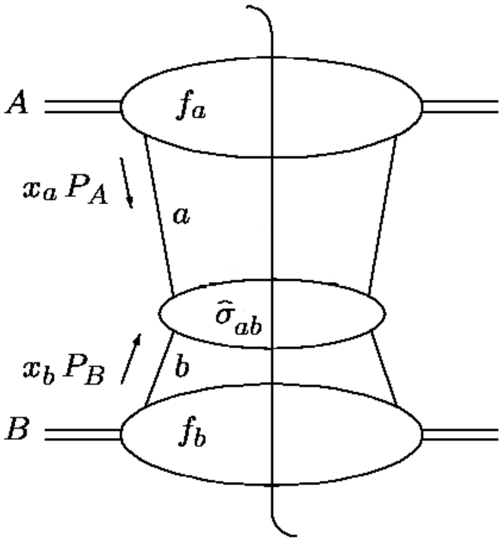
RHIC can address most of these open questions $\longrightarrow$

• Spin Physics at RHIC – Longitudinal Polarization

predictive power of pQCD follows from universality of pdfs

↔ factorization theorem [requires a hard scale, e.g., p_T]

Libby, Sterman; Ellis et al.; Collins et al.; ...



cross sections are convolutions:

$$\frac{d\sigma}{d\mathcal{P}} = \sum_{ab} \int dx_a dx_b f_a(x_a, \mu_f) f_b(x_b, \mu_f) \frac{d\hat{\sigma}}{d\mathcal{P}}(x_a P_A, x_b P_B, \mathcal{P}, \mu_f, \mu_r)$$

↑ ↑ long-distance: from exp.; μ-dep.: pQCD

↑ short-distance: pQCD, series in α_s

· $\mathcal{P}$: appropriate set of kin. variables $(p_T, y, \ldots)$

· arbitrary scale μ_f: separates long- and short-dist. physics

with longitudinally polarized beams measure

double-spin asymmetries: $A_{\mathrm{LL}} \equiv \dfrac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)}$

[similar for $\vec{S} \perp \vec{P}$ (↔ A_{TT}) and single-spin asymmetries (↔ $A_{\mathrm{L}}, A_{\mathrm{N}}$)]

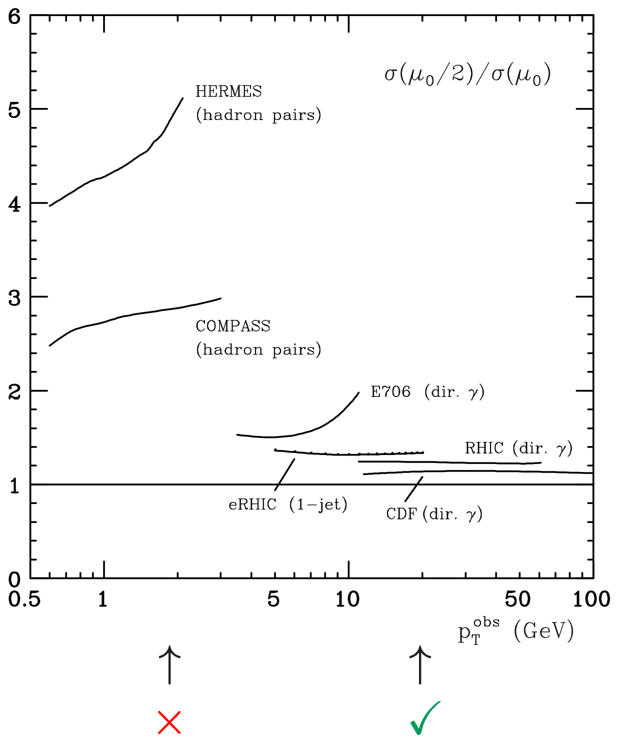
hunting down $\Delta g(x, Q^2)$ at RHIC:

$\Delta g(x, Q^2)$ can be probed in *various* processes
$\rightarrow$ good consistency check

candidates with a *dominant* gluon contribution in LO are:

- prompt photons (plus jets) $\vec{p}\vec{p} \rightarrow \gamma\, X$ ($\vec{p}\vec{p} \rightarrow \gamma + \text{jet}\, X$)
- jets/leading hadrons $\vec{p}\vec{p} \rightarrow \text{jet}\, X$
- heavy flavors $\vec{p}\vec{p} \rightarrow Q\bar{Q}\, X$

important advantage of RHIC:
large $\sqrt{S} \rightarrow$ can go to high-p_T where pQCD works



however, NLO QCD corrections are a must:

· reduced dependence on unphysical scales $\mu_{r,f}$
· corrections often sizable
· genuine NLO processes may dilute sensitivity to Δg
· more reliable ang./p_T distributions, jet definition, etc.

(I) prompt photon (plus jet) production at RHIC:

NLO: Gordon, Vogelsang, Contogouris et al., Frixione, Vogelsang

✓ $qg \to q\gamma$ dominant → *the* tool to pin down the gluon

✓ can be measured by PHENIX and STAR

✓ fragmentation contr. reduced if isolation is imposed
[isolation necessary to reduce $\pi^0 \to \gamma\gamma$ background]

✓ considerable theoretical efforts to go beyond NLO
[soft gluon/threshold (and k_T) resummations: Laenen et al.; Catani et al.; Li; Kidonakis Owens; Laenen, Sterman, Vogelsang]

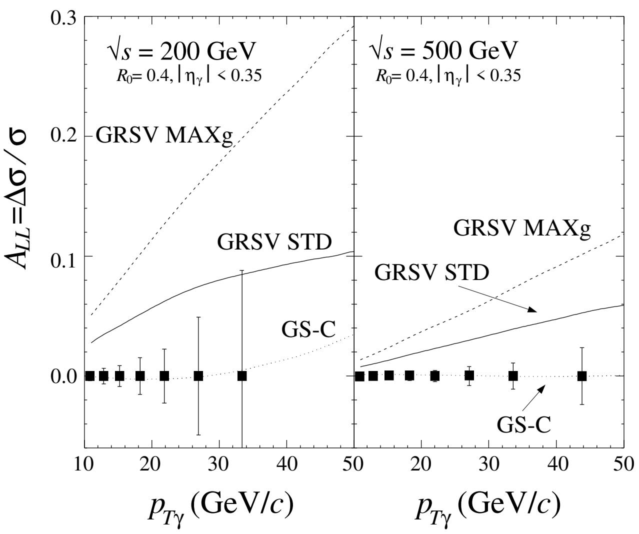
× some trouble with unpol. fixed target data; collider OK

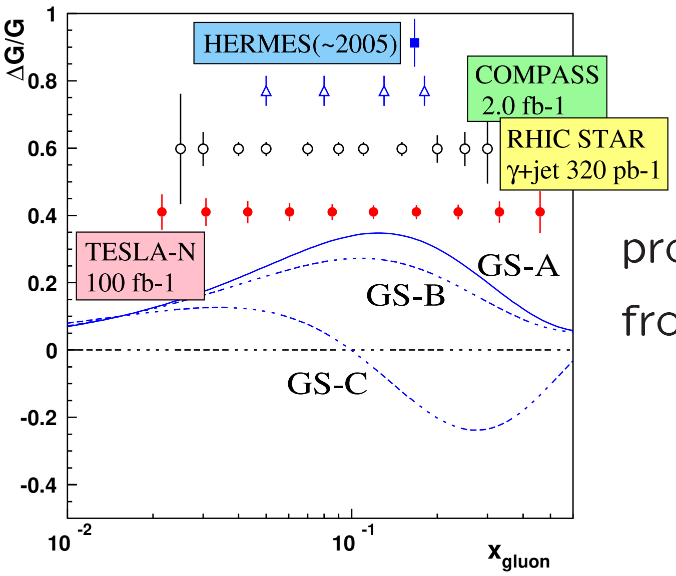
$A_{\rm LL}^{\gamma}(p_T)$ for PHENIX:
Frixione,Vogelsang

→ expected sensitivity to Δg

not shown:

· reduced scale dependence in NLO ✓



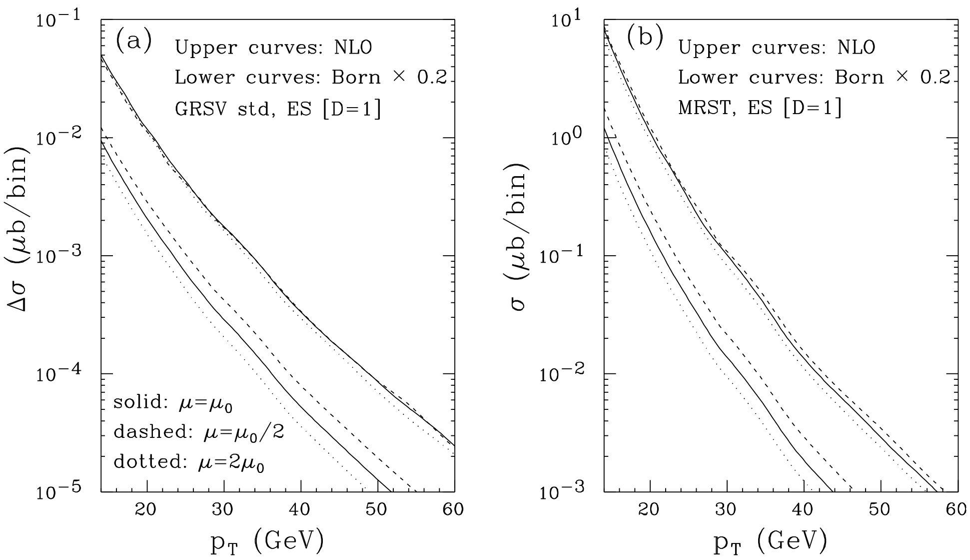


projected accuracy for $\Delta g/g$ from $\gamma + jet$ at STAR

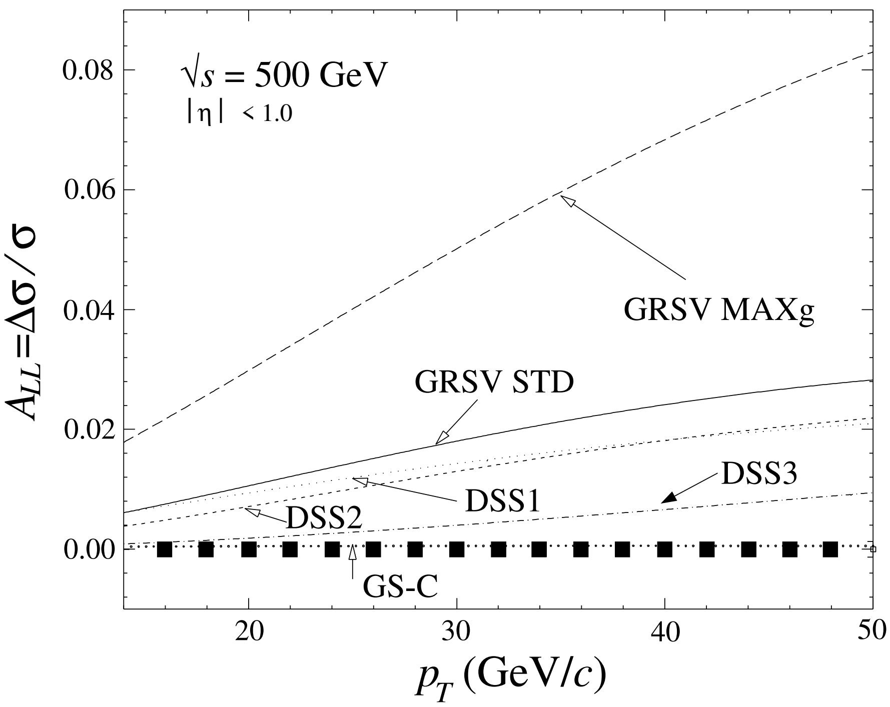
(II) high-p_T jet production at RHIC:

NLO: de Florian, Frixione, Signer, Vogelsang

- ✓ copiously produced at high energies → good statistics
- ✓ theoretically well understood in unpolarized case
- ✓ good sensitivity to Δg
- ✓ NLO essential for realistic jet description
- ✓ μ_f dependence strongly reduced in NLO:



expectations for A_{LL} for STAR:



(figures taken from de Florian et al.)

(III) leading pions as jet surrogates:

✓ also copiously produced

✓ don't have to see a jet → can go to lower p_T

✓ perhaps better suited than jets at $\sqrt{S} = 200\,\text{GeV}$

✓ recent LO studies promising — Vogelsang; Goto

× NLO QCD corrections not computed

work in progress: Vogelsang, MS

× knowledge of frag. fcts. not fully satisfactory

recent progress: Kretzer; Christova, Kretzer, Leader

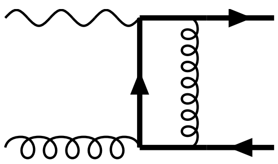
(IV) heavy flavor production at RHIC:

NLO: Bojak, MS

unpolarized calculations → NLO corrections mandatory

NLO: Smith et al., Nason et al.

two sources of large corrections:



• threshold: $\beta = \sqrt{1 - 4m^2/s} \to 0$

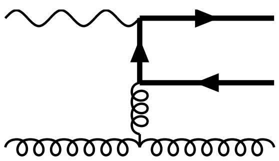
· 'Coulomb' singularity:

phase space $\sim \beta$

LO ME $\sim 1 \to 0$; NLO ME $\sim 1/\beta \to$ const

· 'soft gluons' $\sim \beta \ln^2 8\beta^2$ ← can be resummed

Kidonakis, Laenen, Moch, Vogt



• high energy: $\beta \to 1$

't-channel gluon exchange'

cancels in $\Delta\hat{\sigma}$

extra complications for heavy quarks:

- c, b not seen directly at RHIC
- c, b decays can have 'multi-body' kinematics
- c/b separation
- lepton detection is limited at PHENIX to

$$\begin{array}{lcr} e^{\pm} & : & |\eta_{e^{\pm}}| \leq 0.35 \\ \mu^{\pm} & : & 1.2 \leq |\eta_{\mu^{\pm}}| \leq 2.4 \end{array}$$

- non-trivial relation of exp. and theor. variables, e.g., p_T distr. of decay μ's vs. p_T^Q

→ *crucial* to include simulation of HQ-decay in all theory estimates for spin asymmetries

idea: supplement theory with *'efficiencies'* from PYTHIA

$$\varepsilon_{\text{eff}}^{c,b} \equiv \frac{\#[c, b \text{ in } (p_T, \eta)-\text{bin} \rightarrow e^{\pm} \text{ in 'acceptance'}]}{\#[c, b \text{ in } (p_T, \eta)-\text{bin}]}$$

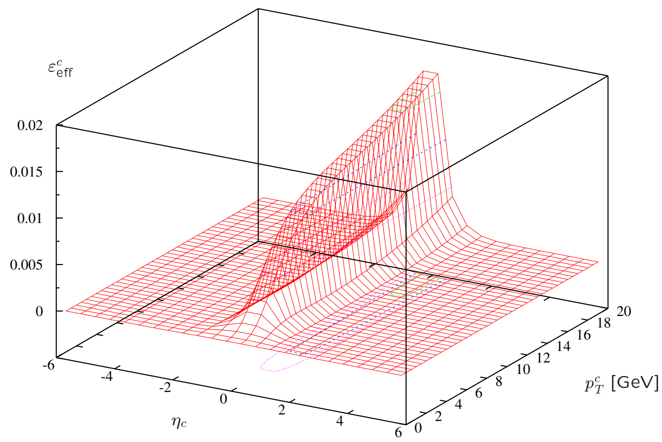
→ probabilities that c, b's in (p_T, η)-bin are seen in PHENIX

example:

Bojak, Grosse Perdekamp, MS

electron tag $c, b \rightarrow e + X$

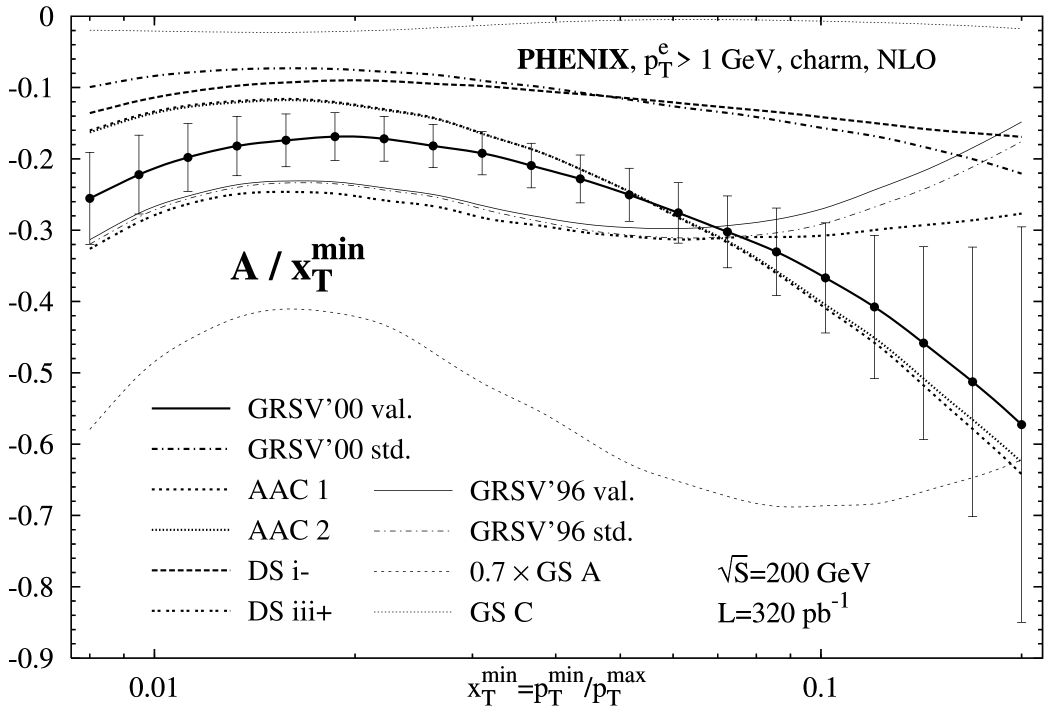
$p_T^e > 1$ GeV and $|\eta_e| \leq 0.35$



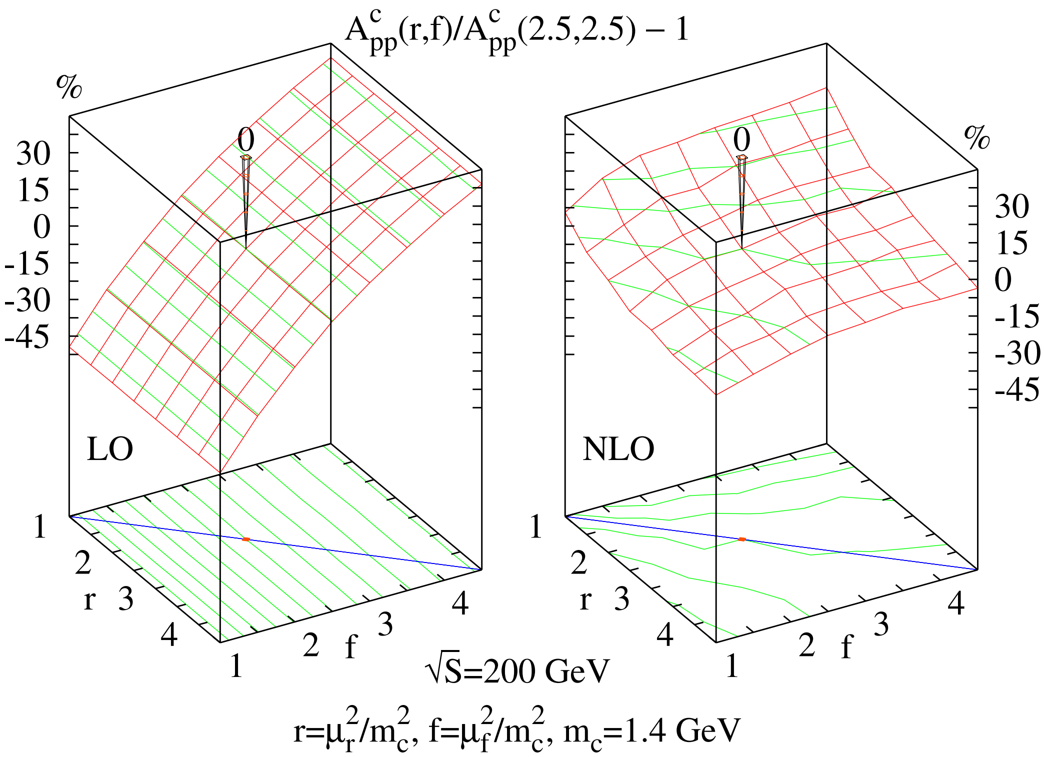
other HQ tags: $\mu\, e$ coincidences → better c/b separation
(more work needed here)

results for $A_{LL}^{\text{charm}}(p_T^{\min})$ via electron tag at PHENIX:

Bojak, MS



good news: scale dependence strongly reduced in NLO



further information on $\Delta \mathrm{q}$ and $\Delta \bar{\mathrm{q}}$:

remember: DIS provides only information on $\Delta q + \Delta \bar{q}$

$\rightarrow$ how can one achieve a *flavor separation*?

(1) semi-inclusive DIS $ep \rightarrow hX$ $\rightarrow$ HERMES

- ✓ data already start to roll in
- × fixed-target $\rightarrow$ low Q^2
- × involves knowledge of fragmentation functions $D_f^h(z, Q^2)$

(2) $W^{\pm}$ boson production at RHIC

- ✓ clean: $W^{\pm}$ selects parton helicity (max. parity viol.)
- × have to observe the $W^{\pm}$ via decay (needs 4π detector)

$\mathbf{W}^{\pm}$ boson production at RHIC:

idea: parity violating $\rightarrow$ single-spin asymmetry sufficient

in LO one has e.g. Leader, Sridhar; Bourrely, Soffer

$$A_{\mathrm{L}}^{W^+}(y) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} \quad \text{where} \quad x_{a,b} = \frac{M_W}{\sqrt{S}} e^{\pm y}$$

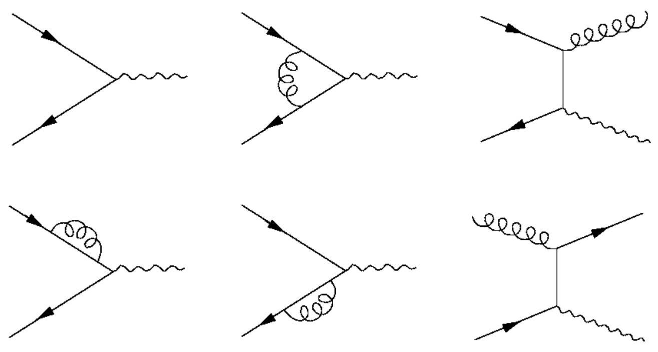
$$\rightarrow \text{y large \&} \left\{ \begin{array}{l} \text{positive } (x_a > x_b) \\ \text{negative } (x_a < x_b) \end{array} \right. : \; A_{\mathrm{L}}^{W^+} \simeq \left\{ \begin{array}{l} -\Delta u(x_a)/u(x_a) \\ \Delta \bar{d}(x_a)/\bar{d}(x_a) \end{array} \right.$$

in practice: Δu is probed for $x \gtrsim 0.2$ and $\Delta \bar{d}$ for $x \lesssim 0.12$

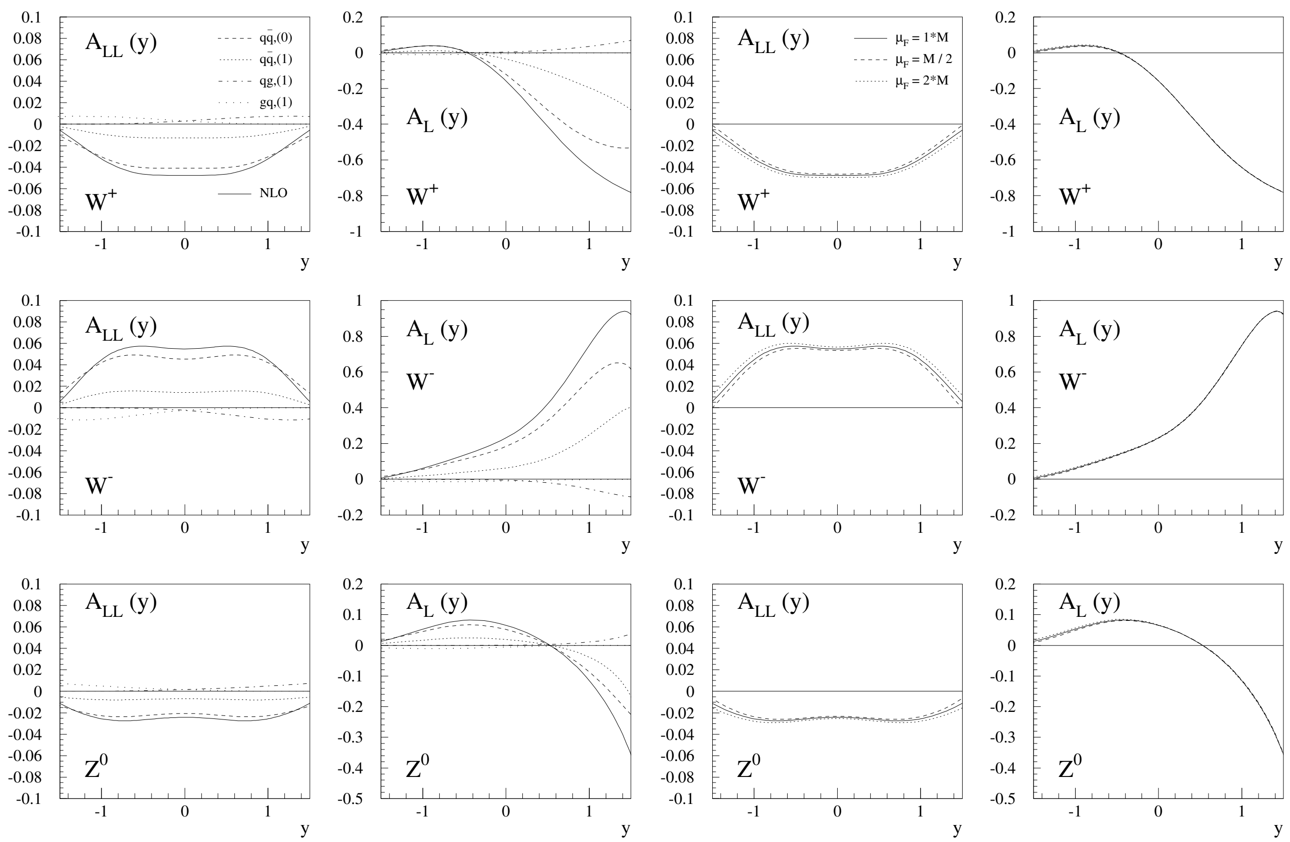
$A_{\mathrm{L}}^{W^-}(y)$: $u \leftrightarrow d$ $\rightarrow$ probes $\Delta d/d$ and $\Delta \bar{u}/\bar{u}$

complications:

(I) NLO corrections Weber; Kamal; Gehrmann



NLO corrections μ_F dependence



Gehrmann

✓ NLO corrections for A_L small

✓ μ_F dependence also small

not discussed: A_{LL} (probes other combinations of pdfs)

(II) detector issues

neither PHENIX nor STAR are hermetic

× missing E_T cannot be reconstructed

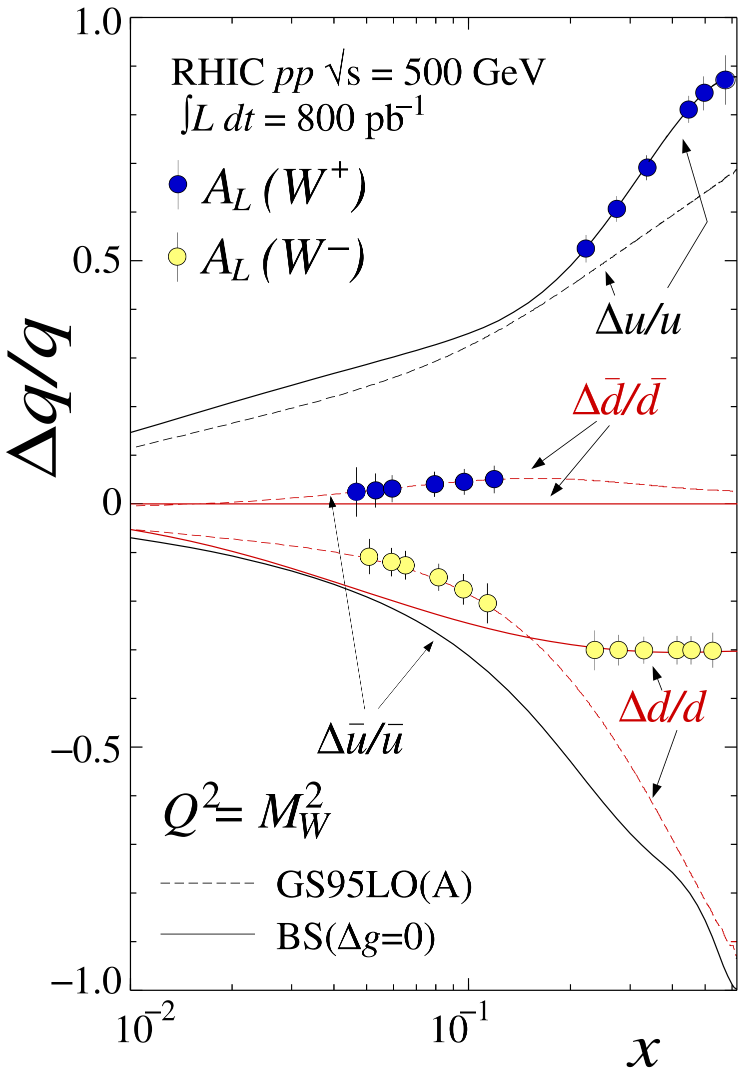
× reconstruction of $y(W)$ only from charged lepton

→ need full NLO *lepton-level* study of W boson production

Nadolsky, Yuan

- $A_{\mathrm{L}}(y)$ gets 'distorted'; LO not sufficient
- resummations of large logs for $p_T^W \to 0$ required
- all included in ResBos package

expected sensitivity on $\Delta q/q$ from $A_L^{W^\pm}(y)$ at RHIC:



towards a 'global' QCD analysis of upcoming data:

extraction of pdfs from data is art, science, and voodoo

non-trivial exercise since

· pdfs are *unphysical objects* beyond the LO
and reside inside complicated convolutions

$$d\sigma \;=\; \sum_{i,j} \int f_i \;\; \underbrace{f_j \;\; d\widehat{\sigma}_{ij}}_{\longleftrightarrow}$$

choice of scheme
reshuffling between $f_{i,j}$ and $d\widehat{\sigma}_{ij}$

→ not directly measurable

· large number of data & processes required to pin down *all* aspects of pdfs (→ table)
[e.g. in CTEQ-5: 15 sets from 11 exp. → 1295 pts.]

· not a priori clear which and where processes can be described by pQCD

· form of pdfs and # of param. not fixed by theory

· all processes should be analysed in NLO:

  · less dependent on unphysical scales μ_r and μ_f
  · NLO corrections are often sizable
  · NLO closer to experiment [jet definition, cuts, ...]

→ complicates & slows down the fits *considerably*

Process/ Experiment	Leading order subprocess	Parton behaviour probed
DIS $(\mu N \to \mu X)$ $F_2^{\mu p}, F_2^{\mu d}, F_2^{\mu n}/F_2^{\mu p}$ (SLAC*, BCDMS, NMC, E665)	$\gamma^* q \to q$	$u+\bar{u}$; $d+\bar{d}$; $\bar{u}+\bar{d}$; s ($s=\bar{s}$ assumed) plus
DIS $(\nu N \to \mu X)$ $F_2^{\nu N}, xF_3^{\nu N}$ (CCFR)	$W^* q \to q'$	$\int xg(x, 1\text{GeV})dx \simeq 0.35$ $\int(\bar{d}-\bar{u})dx \simeq 0.1$
DIS (small x**)** F_2^{ep} (H1, ZEUS)	$\gamma^*(Z^*)q \to q$	small x slopes of $\bar{q}$, g: $x\bar{q} \sim x^{-\lambda_{\bar{q}}}$, $xg \sim x^{-\lambda_g}$
DIS (F_L) (NMC, HERA)	$\gamma^* g \to q\bar{q}$	g
$\ell N \to c\bar{c}X$ F_2^c (EMC; H1, ZEUS)*	$\gamma^* c \to c$	c at $x \gtrsim 0.01$; $x \lesssim 0.01$
$\nu N \to \mu^+\mu^- X$ (CCFR)	$W^* s \to c$ $\hookrightarrow \mu^+$	$s \approx \frac{1}{4}(\bar{u}+\bar{d})$
$pN \to \gamma X$ (WA70*, UA6, E706)	$qg \to \gamma q$	g at $x \simeq 2p_T^\gamma/\sqrt{s}$ $\to x \approx 0.2 - 0.6$
$pN \to \mu^+\mu^- X$ (E605, E772*)	$q\bar{q} \to \gamma^*$	large x exponent of $\bar{q}$: $\bar{q} \sim (1-x)^{\beta_{\bar{q}}}$
$pp, pn \to \mu^+\mu^- X$ (E866, NA51)	$u\bar{u}, d\bar{d} \to \gamma^*$ $u\bar{d}, d\bar{u} \to \gamma^*$	$\bar{u}-\bar{d}$ $0.04 \lesssim x \lesssim 0.3$
$ep, en \to e\pi X$ (HERMES)	$\gamma^* q \to q$ with $q = u, d, \bar{u}, \bar{d}$	$\bar{u}-\bar{d}$ $0.04 \lesssim x \lesssim 0.2$
$p\bar{p} \to WX(ZX)$ (UA1, UA2; CDF, DØ) $\to \ell^\pm$ **asym** (CDF)	$ud \to W$	u, d at $x \simeq M_W/\sqrt{s}$ $\to x \approx 0.13$; 0.05 u/d slope at $x \approx 0.08$
$p\bar{p} \to Q\bar{Q}X$ (CDF, DØ)	$q\bar{q}, gg \to Q\bar{Q}$ with $Q = b, t$	q, g at $x \gtrsim 2m_Q/\sqrt{s}$
$p\bar{p} \to$ **jet** $+ X$ (CDF, DØ)*	$gg, qg, qq \to 2j$	q, g at $x \simeq 2E_T/\sqrt{s}$ $\to x \approx 0.05 - 0.5$

* (*) (not) in CTEQ-5 analysis (adapted from MRST)

extra complication in the polarized case:

scarce DIS data, no charged current DIS

$\rightarrow$ have to rely more on *non*-DIS processes than in unpol. case to pin down all aspects of polarized pdfs

$\rightarrow$ complicates analysis even further

apart from DIS/SIDIS data we expect to have:

$\times$	**photoproduction of two hadrons in lN**: HERMES NLO $\times$ $p_T \sim \mathcal{O}(1\,\text{GeV}) \leftrightarrow$ pert. theory applicable??
$\circ$	**photoproduction of charm in lN**: COMPASS probes Δg at $x \approx 0.15$ NLO ✓ [Bojak, MS; Contogouris et al.] $\Delta g/g$ at single $\langle x \rangle$ & large error $\leftrightarrow$ less useful
✓	**$\mathrm{W}^{\pm}$ bosons/Drell-Yan in pp**: RHIC probes mainly Δq, $\Delta \bar{q}$ at $x \gtrsim 0.06$ NLO ✓ [Weber; Gehrmann; Kamal; Chang et al.] for $q, \bar{q}$ separation (SIDIS data not precise enough)
✓	**jet production in pp**: RHIC probes Δg, Δq at $x \gtrsim 0.03$ NLO ✓ [De Florian, Frixione, Signer, Vogelsang] clean & clear; also used in unpol. fits
✓	**pion production in pp**: RHIC probes Δg, Δq at $x \gtrsim 0.03$ NLO $\times$ (work in progress: Vogelsang, MS) perhaps 1$^{\text{st}}$ RHIC measurement of Δg
✓	**prompt photon production in pp**: RHIC probes mainly Δg at $x \gtrsim 0.03$ NLO ✓ [Gordon, Vogelsang; Contogouris et al.] still trouble with unpol. fixed target data
$\circ$	**hadroproduction of heavy quarks in pp**: RHIC probes mainly Δg at $x \gtrsim 0.03$ NLO ✓ [Bojak, MS] tricky (c, b separ.); need MC for cuts and HQ decays

[✓: use in fit; $\circ$ use as cross-check; $\times$ don't use] how to handle NLO expressions in a 'global analysis' ?

$\checkmark$ modern evol. codes operate on grids $\rightarrow$ very fast

$\times$ NLO calc. of jets, prompt-γ, HQ, ... are based on multi-dim. MC's $\rightarrow$ *much too slow for global fitting*

$\Rightarrow$ need a *reliable* and *fast* work-around, e.g.:

- use LO with fudge K-factor (done in some unp. fits)
  $\times$ K-factor may crit. depend on unknown pdfs
  (pol. pdfs and $\Delta\hat{\sigma}$'s can oscillate!)

- *pre*-calculate major part of NLO cross sections ('grids')
  $\checkmark$ almost as fast as DIS fits

$$\Downarrow$$

'double Mellin transform' technique:

Kosower; Vogelsang, MS

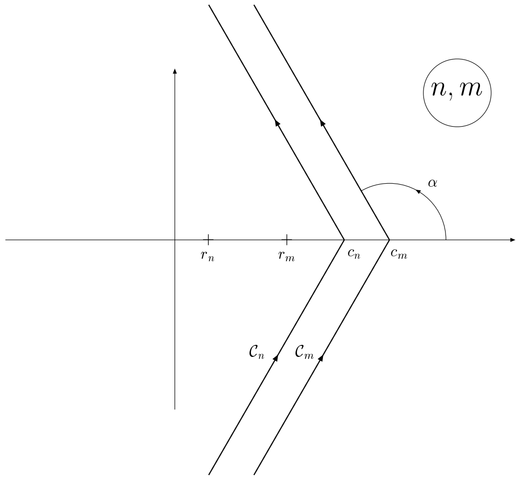
idea: get rid of slow 'double convolutions'

$$d\sigma \simeq \sum_{i,j} \int dx_1\, dx_2\, \underset{\textstyle \int_{\mathcal{C}_n} dn\, x_1^{-n}\, f_i^n}{\underset{\uparrow}{f_i(x_1)}}\ \underset{\textstyle \int_{\mathcal{C}_m} dm\, x_2^{-m}\, f_j^m}{\underset{\uparrow}{f_j(x_2)}}\ \hat{\sigma}_{ij}(x_1,x_2)$$

$$= \sum_{i,j} \int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm\ f_i^n\ f_j^m \left[\underbrace{\int dx_1\, dx_2\, x_1^{-n}\ x_2^{-m}\ \hat{\sigma}_{ij}(x_1,x_2)}_{\equiv\, \tilde{\sigma}_{ij}^{n,m}} \right]$$

then: pre-calculate $\tilde{\sigma}_{ij}^{n,m}$ on a suitable $n \times m$ grid for all subprocesses *and* data pts. *once* before the fit inverse transformation $\int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm$: done on $n \times m$ grids

$\mathcal{C}_n, \mathcal{C}_m$: contours in complex n, m plane to the right of all poles



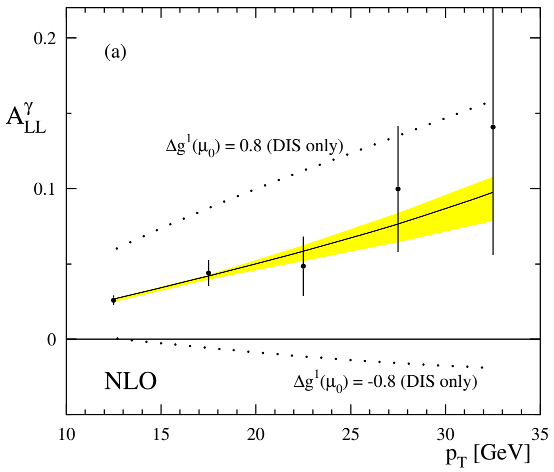
· no new poles beyond those already present in $f^{n,m}$

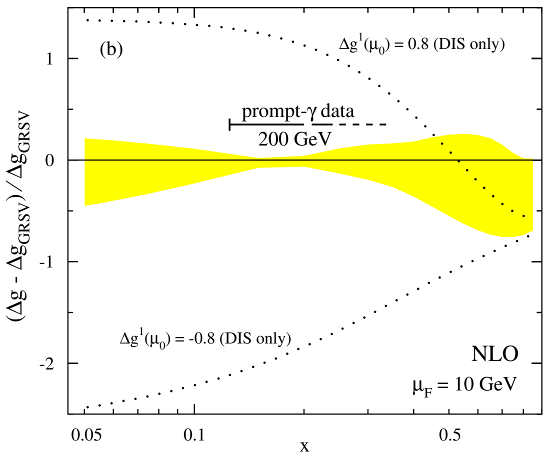
case study with projected prompt-γ data: Vogelsang, MS

· 64×64 grid gives excellent num. stability

· 1000 calc. of full NLO cross section take $10 \div 15$ sec.!

NLO fits (DIS+γ) with random start values for Δg give:
['data' pts. based on GRSV Δg and Gaussian 1σ-errors]





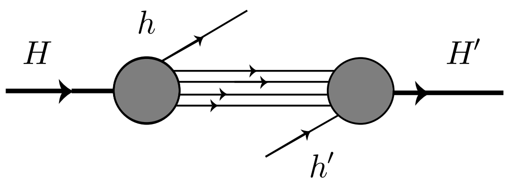
→ strong constraint on Δg around $x \simeq 0.15$

Mellin technique applicable to *all* NLO processes !

• Spin Physics at RHIC – Transverse Polarization

transversity density $\delta\mathbf{q}(\mathbf{x},\mathbf{Q}^2)$: (sometimes also called h_1)

view pdfs as imag. parts of quark-hadron fwd. scattering



label helicities as $\mathcal{A}(H,h;H',h')$:

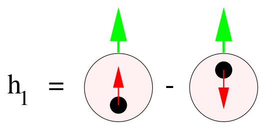
$$q \;\equiv\; \mathcal{A}(++;++)+\mathcal{A}(+-;+-)$$
$$\Delta q \;\equiv\; \mathcal{A}(++;++)-\mathcal{A}(+-;+-)$$

$\Rightarrow$ how about a *helicity-flip density* $\mathcal{A}(++;--)$?

helicity-flip amplitudes occur for *transverse* polarization:

$$|\perp\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle+|-\rangle\right) \text{ and } |\top\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle-|-\rangle\right)$$

$$\rightarrow \sigma_\perp - \sigma_\top \equiv \frac{1}{2}[\langle\perp|...|\perp\rangle - \langle\top|...|\top\rangle] \simeq \langle+|...|-\rangle + \langle-|...|+\rangle$$

features of transversity densities 

:

· 'as partonic as' q and Δq

Ralston, Soper; Artru, Mekhfi; Jaffe, Ji

· chiral-odd $\rightarrow$ difficult to measure (QCD helicity conserving)

· no gluon density for spin 1/2 targets possible

Jaffe, Ji; Artru, Mekhfi; Ji

$\rightarrow$ simple non-singlet type evolution eqs.

NLO δP_{qq}: Vogelsang; Kumano, Miyama; Koike et al.

· all moments $\int_0^1 x^{n-1}\delta q(x,Q^2)dx$ decrease $\rightarrow$ 'evolves away'

· no $g \rightarrow q\bar{q}$ splitting $\rightarrow$ $\delta\bar{q} = 0$ unless present at input

· δq could provide info on chiral-sym. breaking in QCD

Collins; Jaffe

accessing transversity densities $\delta\mathbf{q}$:

chirality has to be flipped *twice* to access δq

double-spin single-spin
asymmetries
A_{TT} A_{N}

$\mathbf{A}_{\mathrm{TT}}$: ✓ clean, involves only δq as 'unknowns' (but 'quadratic')

× small due to lack of gluons $\rightarrow$ exp. challenge

$\mathbf{A}_{\mathrm{N}}$: × requires *other unknown* chiral-odd fct. $\rightarrow$ involved

✓ $pp^{\uparrow} \rightarrow \pi X$ sizable at small $\sqrt{S}$ (E704)

modeling transversity densities $\delta\mathbf{q}$:

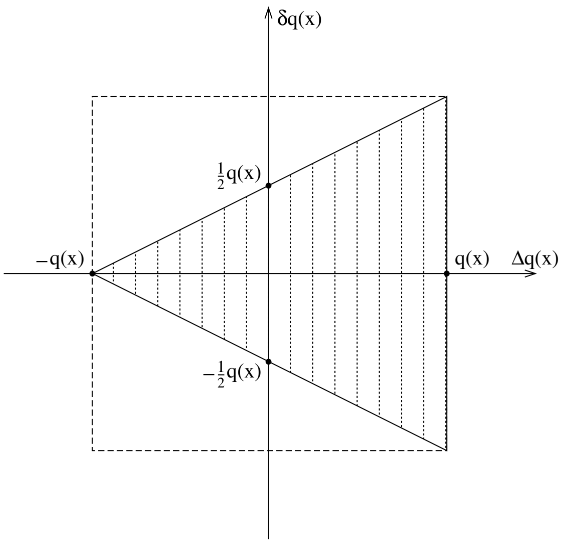
δq unmeasured $\rightarrow$ have to rely on theoretical prejudices to make predictions for RHIC

helpful constraint: Soffer inequality Soffer; Sivers

$$\underbrace{\left|\delta q(x,\mu^2)\right|}_{\text{unknown}} \leq \frac{1}{2}\left[\underbrace{q(x,\mu^2) + \Delta q(x,\mu^2)}_{\text{known (more or less)}}\right]$$

$\rightarrow$ *upper bounds* on δq and A_{TT}

- more restrictive than $|\delta q| \leq q$
- models based on $\delta q = \Delta q$ violate bound if $\Delta q \leq -\frac{1}{3}q$
- preserved in NLO ($\overline{\mathrm{MS}}$)
  Vogelsang; Martin et al.; Barone; Bourrely et al.



Double transverse spin asymmetries $\mathbf{A_{TT}}$:

several processes can be studied at RHIC:

Drell-Yan, jets or leading hadrons, prompt-photons

general problem: $\nexists$ 'transversity' gluons

$\rightarrow$ all asymmetries $A_{\text{TT}} = d\delta\sigma/d\sigma$ strongly diluted by gluon induced processes in $d\sigma$

$\rightarrow$ need process *w/o* gluon contribution in LO

only candidate: Drell-Yan process

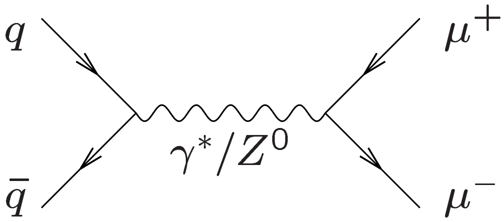
Ralston, Soper; Ji
Cortes, Pire, Ralston; Artru, Mekhfi; Jaffe, Ji

chirality flip ✓

M: dimuon mass

y: dimuon rapidity

ϕ: azimuth [$\phi = 0 \leftrightarrow \uparrow$ spin dir.]



$$\frac{d\delta\sigma}{dM\,dy\,d\phi} = \underbrace{\sum_q \tilde{e}_q^2}_{\text{electroweak effects}} \int dx_1 dx_2 \left[\delta q(x_1,\mu_f^2)\delta\bar{q}(x_2,\mu_f^2) + (1 \leftrightarrow 2)\right] \frac{d\delta\hat{\sigma}}{dM\,dy\,d\phi}$$

electroweak effects

$$\underset{\gamma}{e_q^2} + \underset{\gamma Z^0}{e_q G_F} \ldots + \underset{Z^0}{G_F^2} \ldots$$

defined as

$(d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow})/2$

all $d\delta\hat{\sigma}$ have non-trivial ϕ dependence:

$$d\delta\hat{\sigma} \simeq \cos(2\phi) \rightsquigarrow \int_0^{2\pi} d\phi\, d\delta\hat{\sigma} = 0$$

$\rightsquigarrow$ define $\left(\int_{-\pi/4}^{\pi/4} - \int_{\pi/4}^{3\pi/4} + \int_{3\pi/4}^{5\pi/4} - \int_{5\pi/4}^{7\pi/4}\right) d\phi$

Cortes, Pire, Ralston

best suited observables: $A_{\mathsf{TT}}(M, y)$ or $A_{\mathsf{TT}}(y)$

y dependence of A_{TT} $\leftrightarrow$ scan of $\delta q(x_1)\delta\bar{q}(x_2)$

$\leftrightarrow$ *shape* of δq

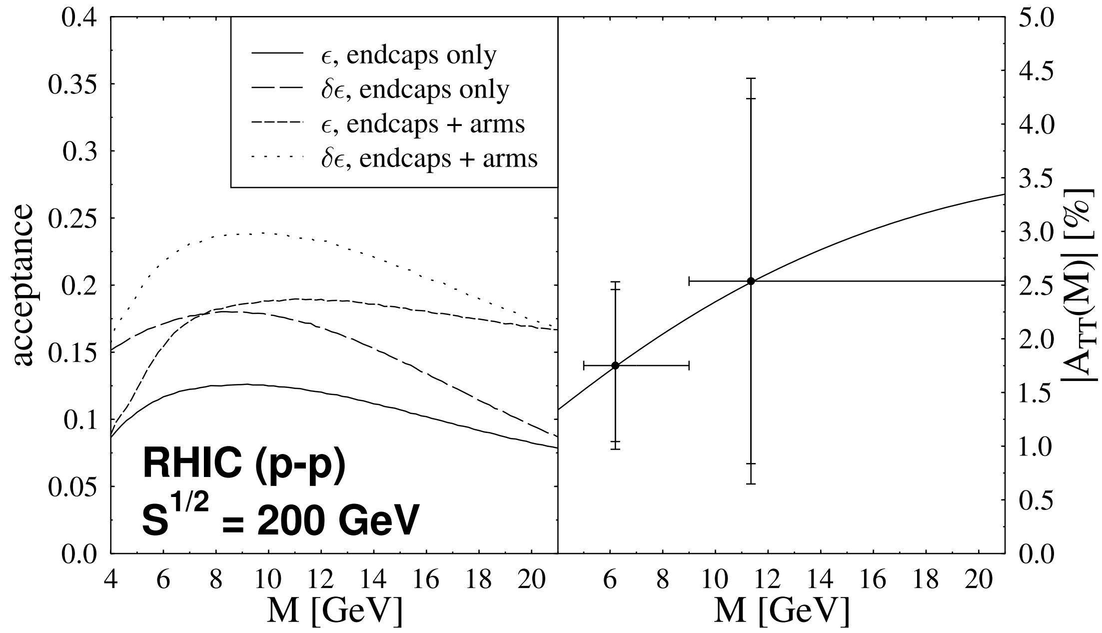
NLO $d\delta\hat{\sigma}$: Vogelsang, Weber; Contogouris et al.; Martin et al.

numerical study of upper bound for A_{TT} in NLO QCD:

Martin, Schäfer, MS, Vogelsang

- *saturate* Soffer bound at low scale $Q_0 \simeq 0.6$ GeV
- include crucial detector acceptance for PHENIX
  $1.2 \leq |y_{\mu^\pm}| \leq 2.4$; have to detect *both* muons

$\Rightarrow$ stat. errors too large for $A_{\mathsf{TT}}(y)$ but $A_{\mathsf{TT}}(M)$ still ✓



conclusion on DY: tough measurement; need more lumi

[keep in mind that this is a more or less realistic *upper* bound on A_{TT}]

single-inclusive high-p_T jet and prompt photon production:
Hidaka et al.; Artru, Mekhfi; Ji; Jaffe, Saito, Soffer, MS, Vogelsang

✓ jets (and photons) copiously produced at RHIC

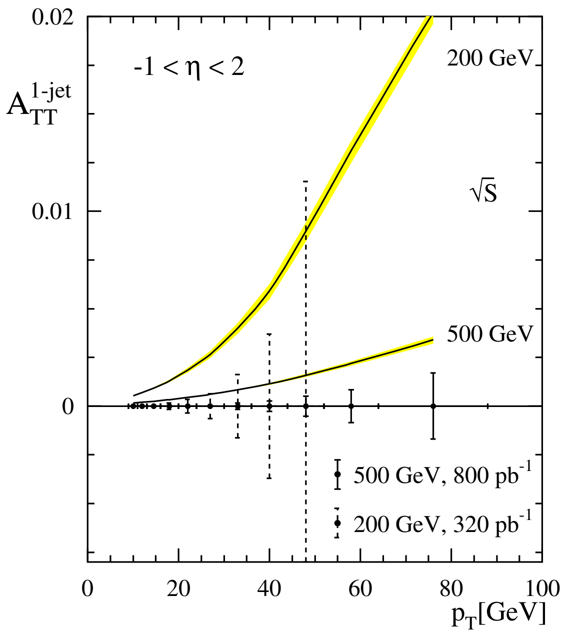
× cannot avoid dilution of A_{TT} by gluon-induced processes

× NLO QCD results not yet available

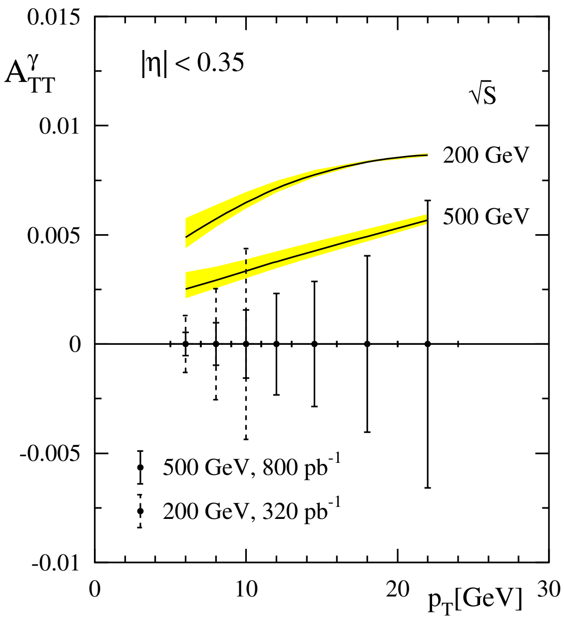
numerical study of upper bound for A_{TT} in LO QCD:
Soffer, MS, Vogelsang

· all details as for DY study above

1-jet
STAR



high-p_T photon
PHENIX



[yellow bands: μ_F dependence]

general conclusions on $\mathbf{A_{\mathrm{TT}}}$ at RHIC:

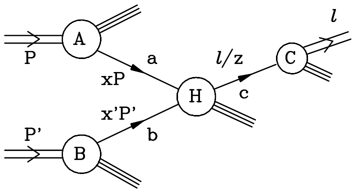
· difficult, albeit not impossible task

· requires great exp. efforts [in particular, small syst. errors]

· large A_{TT}'s would constitute a new 'spin surprise'

Single transverse spin asymmetries $\mathrm{A_N}$:

$A(p, \vec{s}_T) + B(p') \to C(l) + X$ with C '=' high-p_T π, γ, ...

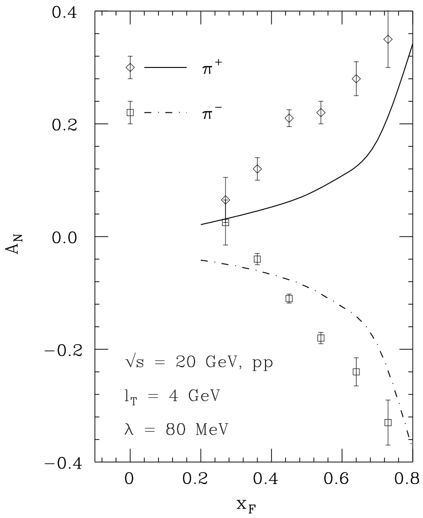


measure : $A_\mathrm{N} = \dfrac{\Delta_\mathrm{N}\sigma}{\sigma} \equiv \dfrac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$

'long-standing puzzle':

large A_N for π and Λ production e.g. E704 ($\sqrt{S} = 20\,\mathrm{GeV}$) $\longrightarrow$

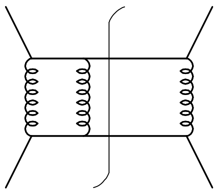
leading-twist pQCD: $A_\mathrm{N} = 0$



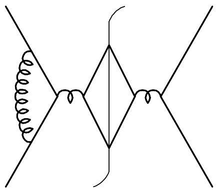
· A_N corresponds to T-odd product $\sim i\vec{s}_T \cdot (\vec{p} \times \vec{l})$

· $A_\mathrm{N} \neq 0$ requires: phase, spin flip, 'enough vectors'

A_N first analyzed in pQCD by Kane, Pumplin, Repko:



+ c.c.



+ c.c.

· imaginary part of loop $\to$ phase

· quark mass $\to$ spin flip

· $A_\mathrm{N} \simeq \frac{m_q}{l_T} \langle p, \vec{s}_T | \bar{\Psi} \Gamma \Psi | p, \vec{s}_T \rangle$

$\to$ twist-3 effect ($A_\mathrm{N} \simeq m_q$): too small to describe data but: QCD dynamics is much richer

twist-3 can arise from $\left\{ \begin{array}{l} \text{quark – gluon correlations} \\ \text{intrinsic } k_T \end{array} \right.$

generalized collinear factorization formula for $\Delta_{\mathrm{N}}\sigma$:

Qiu, Sterman

$\rightarrow$ provides *systematic way* to calc. A_{N} for *many* processes

$$\Delta_{\mathrm{N}}\sigma = \sum_{abc} T^{(3)}_{a/A} \otimes f_{b/B} \otimes \hat{\sigma}_{ab\to c} \otimes D_{c\to h}$$
$$+ \sum_{abc} \delta q_{a/A} \otimes \left[f_{b/B} \otimes \hat{\sigma}'_{ab\to c} \otimes D^{(3)}_{c\to h} + f^{(3)}_{b/B} \otimes \hat{\sigma}''_{ab\to c} \otimes D_{c\to h} \right]$$

features:

· introduces new twist-3 correlation functions

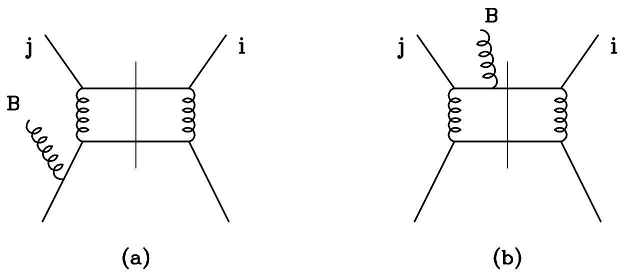
· $\hat{\sigma}$'s are perturbatively calculable

· chiral-odd $\delta q_{a/A} \rightarrow D^{(3)}_{c\to h}$ and $f^{(3)}_{b/B}$ chiral-odd

$\rightarrow$ 1st line $\simeq T^{(3)}_{a/A}$ dominant (chiral-even)

chiral-odd part studied by Kanazawa, Koike

· x_1 or x_2 in $T^{(3)}(x_1, x_2)$ is fixed by pole in partonic part



initial-state int. final-state int.

$\rightarrow$ soft-gluon pole gives the needed phase for A_{N}

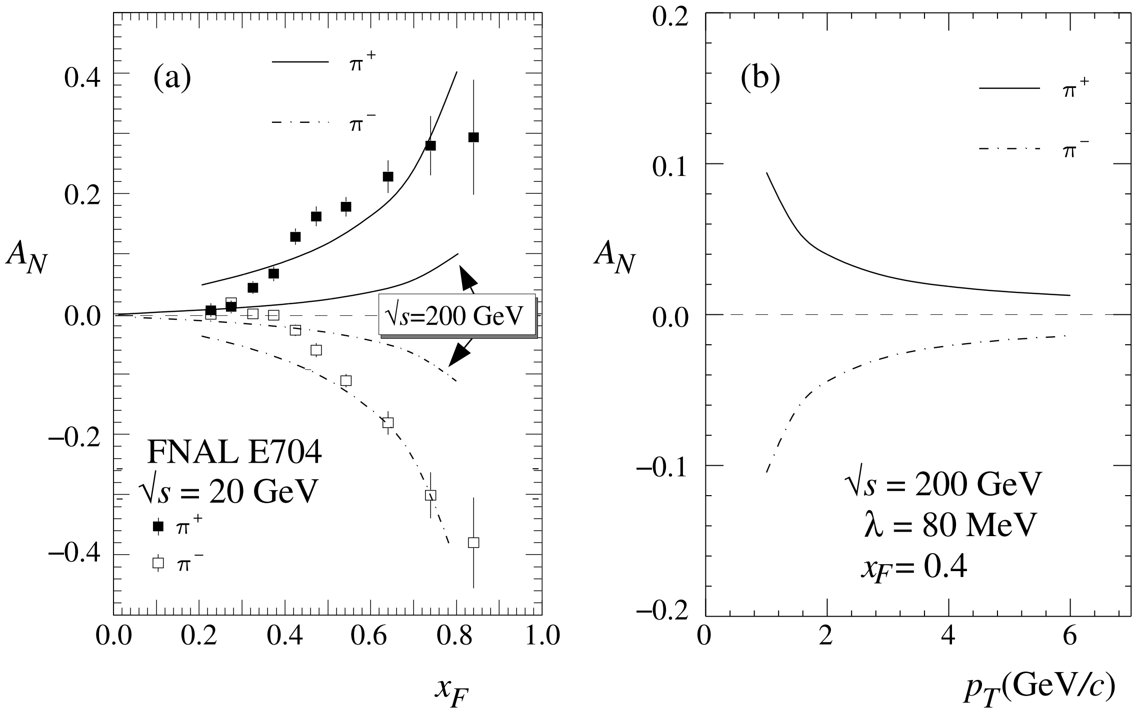
already observed by Efremov, Teryaev

e.g. $(x_2 - x_1 + i\varepsilon)^{-1} \rightarrow -i\pi\delta(x_2 - x_1) \rightarrow A_{\mathrm{N}} \simeq T^{(3)}(x, x)$

model calculation - minimal approach: Qiu, Sterman

- restrict to forward pion region $\leftrightarrow$ x_F large
- pol. 'partons' probed at large x, unpolarized at small x'
  $\rightarrow$ *valence quark - soft-gluon approximation*
- $T^{(3)}(x,x)$ and $\frac{d}{dx}T^{(3)}(x,x)$ contribute to $\Delta_{\mathrm{N}}\sigma$
  pdfs behave as $(1-x)^{\beta>0}$: $\frac{d}{dx}T^{(3)} \gg T^{(3)}$ as $x \to 1$
- naively $A_{\mathrm{N}}(l_T) \simeq \frac{\Lambda}{l_T}$ [Λ non-pert. scale $\mathcal{O}(100\,\mathrm{MeV})$]
  actually $A_{\mathrm{N}}(l_T) \simeq \left\{\frac{\Lambda l_T}{U} \simeq \frac{\Lambda l_T}{S}, \frac{\Lambda}{l_T}\right\}$ [and $\frac{1}{1-x_F}$ related to $\frac{d}{dx}T^{(3)}$]
  $\rightarrow$ mild l_T dep. for E704, more pronouced for RHIC

Qiu, Sterman



full LO calculation on the way Kouvaris, Qiu, Vogelsang

alternative approach to $\mathbf{A}_\mathrm{N}$:

introduce intrinsic k_T in pdfs and fragmentation functions

$\Rightarrow$ Pandora's box with many *new* & *unknown* functions !!

again three different types of contributions to A_N:

(1) $f_{1T}^{\perp}(x, k_T) = f_{q/p^\uparrow} - f_{q/p^\downarrow}$ Sivers

unpolarized quarks in transversely polarized hadron

T-odd; requires initial-state int.; $A_\mathrm{N} \simeq f_{1T}^{\perp} \otimes f \otimes D_\pi$

recently revived by Brodsky, Hwang, Schmidt; Collins

(2) $h_1^{\perp}(x, k_T) = f_{q^\uparrow/p} - f_{q^\downarrow/p}$ Boer

transversely polarized quarks in unpolarized hadron

T-odd; requires initial-state int.; $A_\mathrm{N} \simeq h_1^{\perp} \otimes \delta q \otimes D_\pi$

(3) $H_1^{\perp}(z, k_T) \simeq D_{\pi/q^\uparrow} - D_{\pi/q^\downarrow}$ Collins

transversely polarized quark fragmenting into unpolarized hadron

T-odd; requires final-state int.; $A_\mathrm{N} \simeq \delta q \otimes f \otimes H_1^{\perp}$

· each mechanism on its own can account for E704

Anselmino, Boglione, Murgia; Boer; Boglione, Leader; ...

$\rightarrow$ very difficult to disentangle all contributions

$\rightarrow$ RHIC can shed light on underlying mechanism for A_N

need also data from e^+e^- (BELLE)and ep (HERMES)

not discussed: $pp^\uparrow \rightarrow \pi^+\pi^- X$ via *interference frag.*

Jaffe, Jin, Tang; Ji; Collins, Heppelmann, Ladinsky

idea: phase from int. between s- and p-waves of $\pi\pi$-system

$A_\mathrm{N} \simeq \delta q \otimes f \otimes D_{\mathrm{int}}^{\pi\pi}$; $D_{\mathrm{int}}^{\pi\pi}$ from e^+e^- (?) $\rightarrow$ probes δq

• Spin Physics at RHIC – "New Physics"

RHIC is also a tool to uncover physics beyond the SM

(I) Parity-violating single-spin asymmetries:

single jet production : $A_L^{PV} \equiv \dfrac{(d\sigma/dE_T)_- - (d\sigma/dE_T)_+}{(d\sigma/dE_T)_- + (d\sigma/dE_T)_+}$

idea: only *small* SM-contr. from QCD$\otimes$EW interference

$\rightarrow$ new parity-viol. interactions can lead to sizable effects

Bourrely, Guillet, Soffer; Tannenbaum; Taxil, Virey

candidates: Taxil, Virey

· contact interactions:

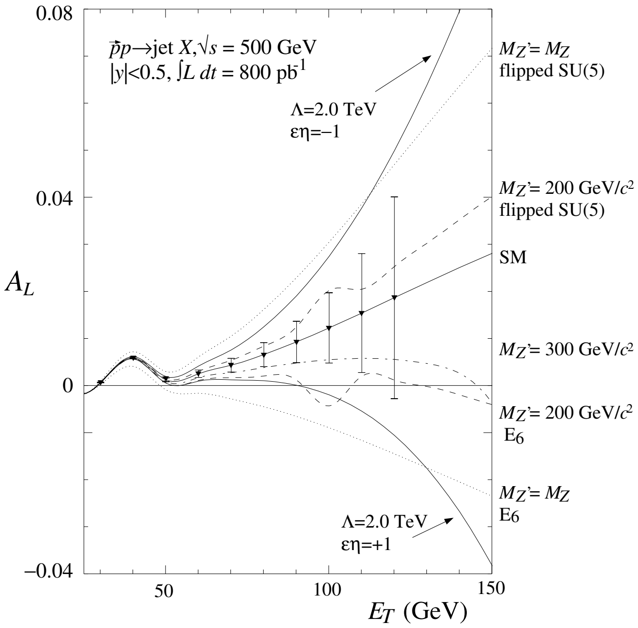
$\sim \frac{g^2}{\Lambda^2} \bar{\Psi}\Gamma_\mu \Psi \bar{\Psi}\Gamma_\mu \Psi$

'scale' $\Lambda > 2$ TeV

· leptophobic Z':

$M_Z \leq M_Z' \leq 1$ TeV

small mixing with SM Z



to be of any use need:

· $\sqrt{S} = 500$ GeV, high luminosity & precision

· knowledge of pol. pdfs & SM 'background' in NLO

Moretti, Ellis, Ross: EW 1-loop for $qg \rightarrow qg$, $q\bar{q} \rightarrow gg$, $gg \rightarrow q\bar{q}$

Vogelsang: LL-threshold resummations for $\log(1 - x_T^2)$

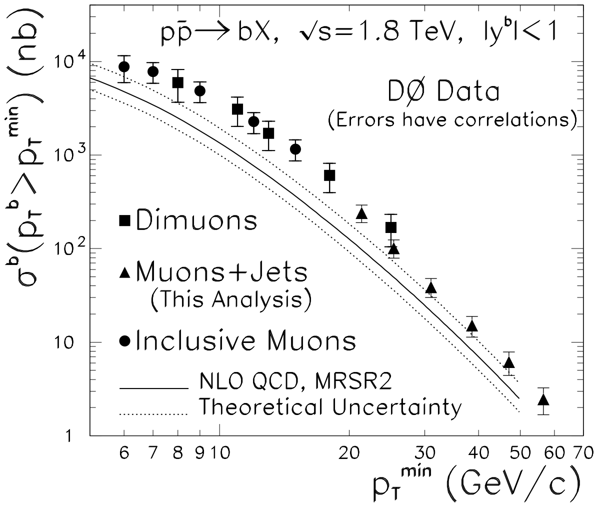
- RHIC can be competetive with Tevatron run II — Virey

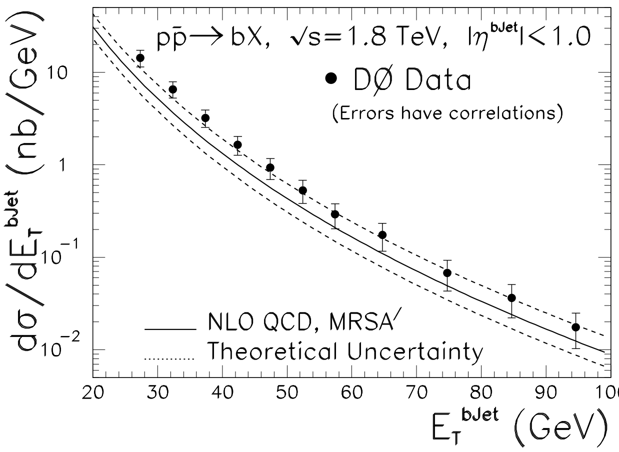
  (reduction of systematic errors in A_L^{PV})
- unique place to probe chiral structure of new interactions

(II) 'Bottom - puzzle':

incl. b-rate from QCD too small in $p\bar{p}$, ep, and $\gamma\gamma$?!?

latest DØ results: 'central' b's: $|y^b| < 1$, $p_T^b > p_T^{\min}$

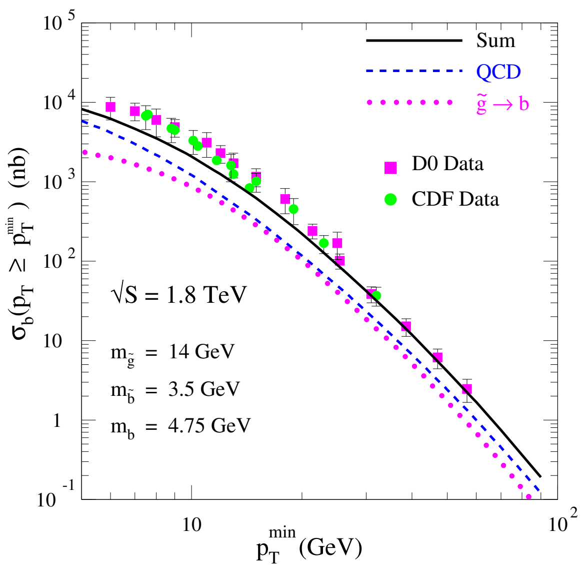




$\rightarrow$ b-jets $\approx$ ✓; otherwise data/theory $\approx 2 \div 2.5$

among other explanations: 'SUSY' effects ?

Berger, Harris, Kaplan, Sullivan, Tait, Wagner



- idea: $gg, q\bar{q} \to \tilde{g}\tilde{g}$, then $\tilde{g} \to b\tilde{b}$ ($\tilde{g}$, $\tilde{b}$ light)
- claim: consistent with all MSSM constraints
- tests: bb, $\overline{bb}$ pairs; slower running of α_s
- RHIC: spin effects? NLO $\vec{g}\vec{g} \to \tilde{g}\tilde{g}$ Bojak, MS

• What remains to be discovered after RHIC ?

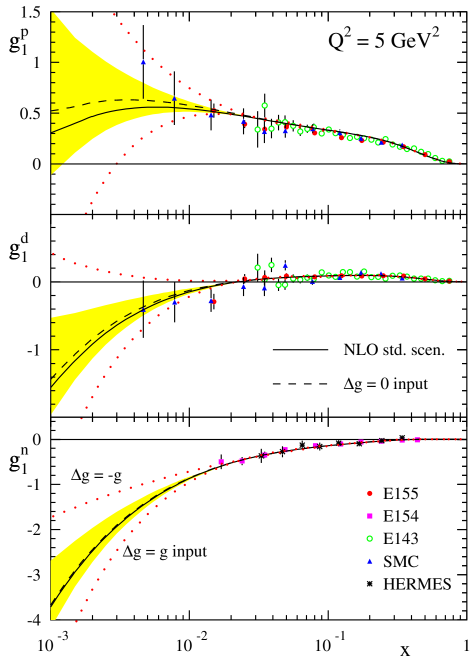
· important to see $g_1(x, Q^2)$ @ small-x → EIC, pol. HERA

with Δg from RHIC one can *predict* the small-x behaviour of $g_1(x, Q^2)$:

$$\Delta g \quad \rightleftarrows \quad \Rightarrow \quad g_1^p \quad \rightleftarrows$$

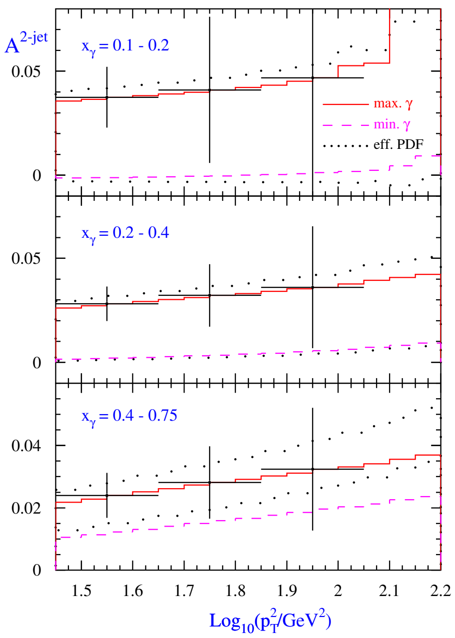
→ important cross-check

[keep in mind that DIS is the 'defining process' for pdfs]



· angular momentum contribution to spin sum rule

· parton content of polarized *photons* Vogelsang, MS



completely unknown so far !

accessible in $\vec{e}\vec{p}$ at large $\sqrt{S}$ via 'resolved-γ' contribution

best candidate:
di-jet production at the EIC

→ important QCD test

• Summary & Outlook

RHIC $\vec{p}\vec{p}$ started successfully

- first data hopefully start to roll in soon
- rich physics case

very exciting time ahead of us

- many open questions can be addressed
- many theoretical calculations in NLO QCD
- next 'spin surprise' is perhaps just round the corner
- already time to plan next steps: EIC