RBRC workshop on
"High p_T Physics at RHIC"

12/02/03

Spin Physics

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- **A Brief History of Spin**
- **Spin Physics at RHIC**
  - ▷ theoretical framework of perturbative QCD
  - ▷ accessing the gluon polarization
  - ▷ transverse spin phenomena
- **Summary & Outlook**

I. A Brief History of Spin

- *the* characteristic property of a particle besides mass
- determines whether the particle is a fermion or boson
- practical effects prevail the whole of science:
  - structure of composite objects
  - material properties like superconductivity
  - gateway to new physical phenomena like BEC

$$\Downarrow$$

A world without spin would be boring!

The story of the proton spin begins in 1927:

Hund: rot. part of specific heat of H_2 molecule

Hori: band spectrum of H_2

$\leftrightarrow$ proton's spin & statistics

Dennison: resolves discrepancy between their results

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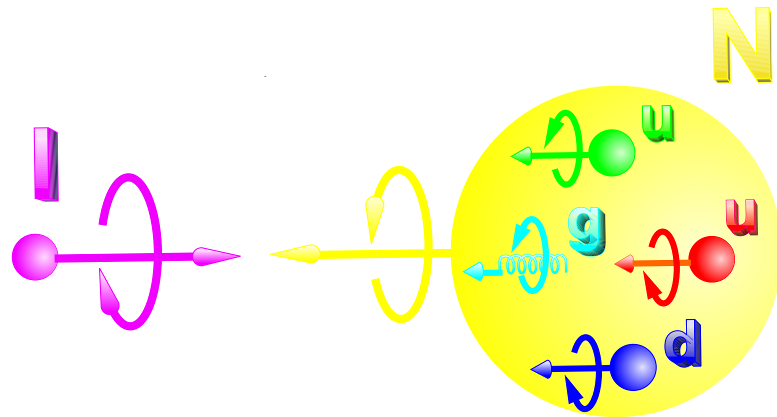
concludes (June 16th, 1927) proton is a fermion of spin $\frac{1}{2}$

Since then it is only getting much more complicated!

quark model/QCD: proton is a composite object

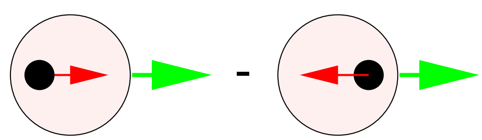


⇒ spin $\frac{1}{2}$ must be the result of a subtle interplay of quark & gluon spins and their angular momentum

quantitative description: parton densities

parton model definition of "helicity densities":

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

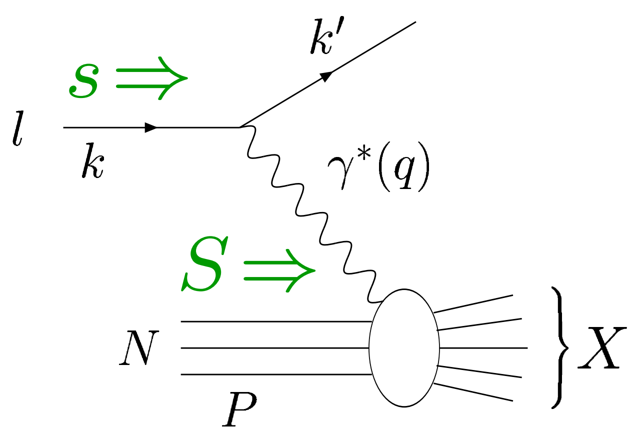


$f_{+(-)}^{N_+}$: "constituents" with same (opposite) helicity and momentum fraction x of the nucleon N

standard experiment: "DIS-lN-microscope"

$\tau_{\gamma^*} \ll$ time scale for parton-parton interactions

- lepton sees "snapshot" of nucleon
- lepton scatters off "free" quarks, incoherently



$$x = \frac{Q^2}{2\,P\cdot q}$$

$$y = \frac{P\cdot q}{P\cdot k}$$

$$s\cdot k = S\cdot P = 0$$

$$Q^2 = -q^2 \gg M_N^2$$

cross section: $d^2\sigma/dxdy \;\propto\; \underbrace{\mathcal{L}_{\mu\nu}(k,q,s)}_{\text{leptonic}} \cdot \underbrace{\mathcal{W}^{\mu\nu}(P,q,S)}_{\text{hadronic}}$

$\mathcal{L}_{\mu\nu}(k,q,s)$: fully calculable in QED

$\mathcal{W}^{\mu\nu}(P,q,S)$: parametrizes our ignorance of hadron structure in terms of structure functions

$$\Downarrow$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\,[\Delta q(x) + \Delta\bar{q}(x)]$$

for longitudinally polarized DIS

Naive parton model picture is modified in full QCD:

parton-parton interactions $\Rightarrow$ spin & parton content of the nucleon depends on "resolving power" of probe

e.g. DIS: "resolution scale" $R \simeq 1/\sqrt{Q^2}$

to explore scales $R \lesssim \frac{1}{5}$ fm $\Leftrightarrow$ $Q^2 \gtrsim 1 \div 2$ GeV^2

Main predictions of perturbative QCD

- applicable if hardness of probe is large ($\alpha_s(Q^2) \ll 1$)

- $\Delta f(x) \to \Delta f(x, Q^2)$; described by DGLAP eqs.:

$$\mu \frac{d}{d\mu} \begin{pmatrix} \Delta q(x,\mu) \\ \Delta g(x,\mu) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix}_{(z,\alpha_s(\mu))} \cdot \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} \left(\frac{x}{z}, \mu\right)$$

$\Delta\mathcal{P}_{ij}$: calculable spin-dep. $j \to i$ "splitting" functions:

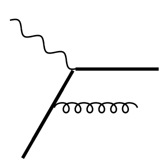
$$\Delta\mathcal{P}_{ij}(z,\alpha_s) = \frac{\alpha_s}{2\pi} \Delta P_{ij}^{(0)}(z) + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta P_{ij}^{(1)}(z) + \ldots$$

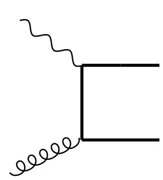
Ahmed, Ross
Altarelli, Parisi

Mertig, van Neerven
Vogelsang

- scaling violations in DIS: $g_1(x) \to g_1(x, Q^2)$

$$g_1(x,Q^2) = \frac{1}{2} \sum_q e_q^2 \left\{ \left[\Delta q + \Delta\bar{q}\right](x,Q^2) \right.$$

$+ \Big|$  $+ \ldots \Big|^2 \otimes \left[\Delta q + \Delta\bar{q}\right](x,Q^2) + \ldots$

$+ \Big|$  $+ \ldots \Big|^2 \otimes \Delta g(x,Q^2) + \ldots \Big\} + \mathcal{O}\left(\frac{1}{Q^n}\right)$

↑

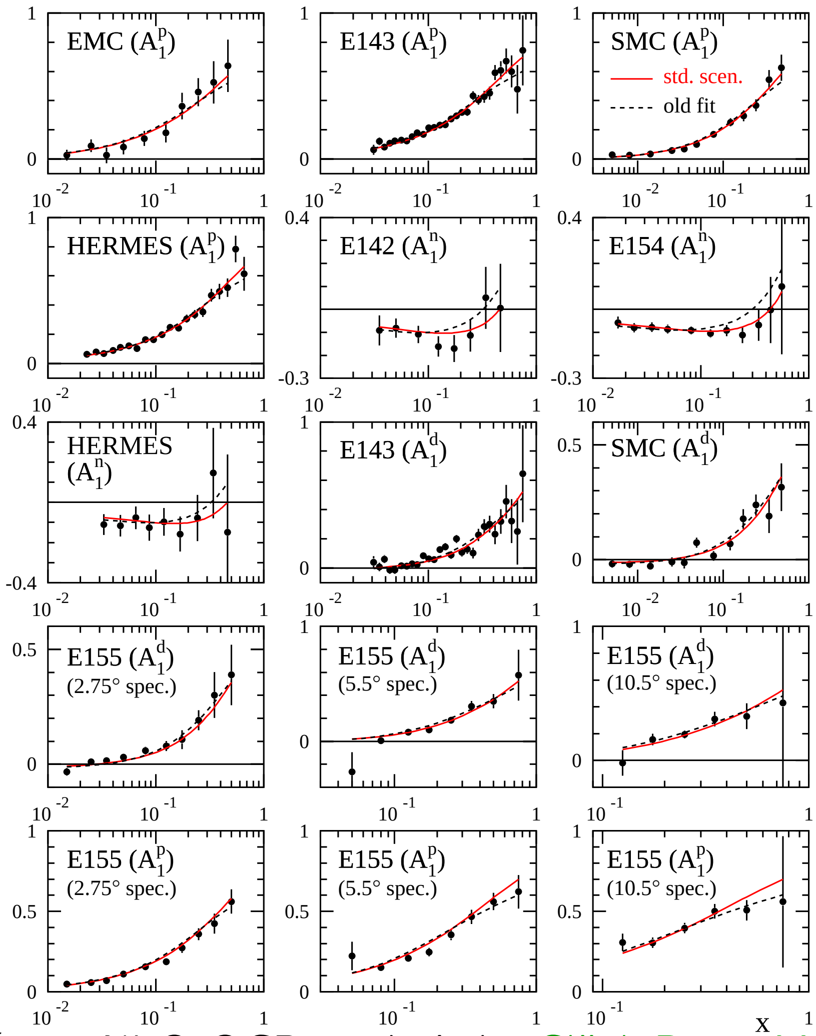
$\mathcal{O}(\alpha_s)$ QCD corrections ("coefficient functions" $\Delta C_{q,g}$)

Kodaira; Ratcliffe; Bodwin, Qiu; van Neerven, Zijlstra; ...

More than 20 years of beautiful data on polarized DIS

What have we learned so far?

- **NLO QCD fits work extremely well:**



(e.g., NLO QCD analysis by Glück, Reya, MS, Vogelsang)

- **nucleon spin-1/2 "sum rule":** Jaffe, Manohar; Ji

$$\frac{1}{2} = \underbrace{\frac{1}{2}\sum_q \int_0^1 [\Delta q + \Delta\bar{q}](x,Q^2)dx}_{\text{striking finding : } \simeq 0.1} + \underbrace{L_q(Q^2) + J_g(Q^2)}_{\text{unknown}}$$

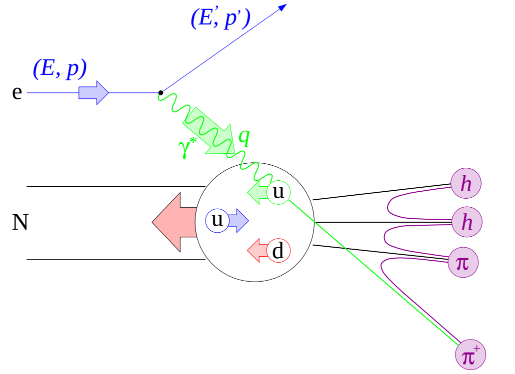
striking finding : $\simeq 0.1$
contrary to naive quark model

L_q: quark *orbital* angular momentum

J_g: gluon *total* angular momentum, contains $\int_0^1 \Delta g(x,Q^2)dx$

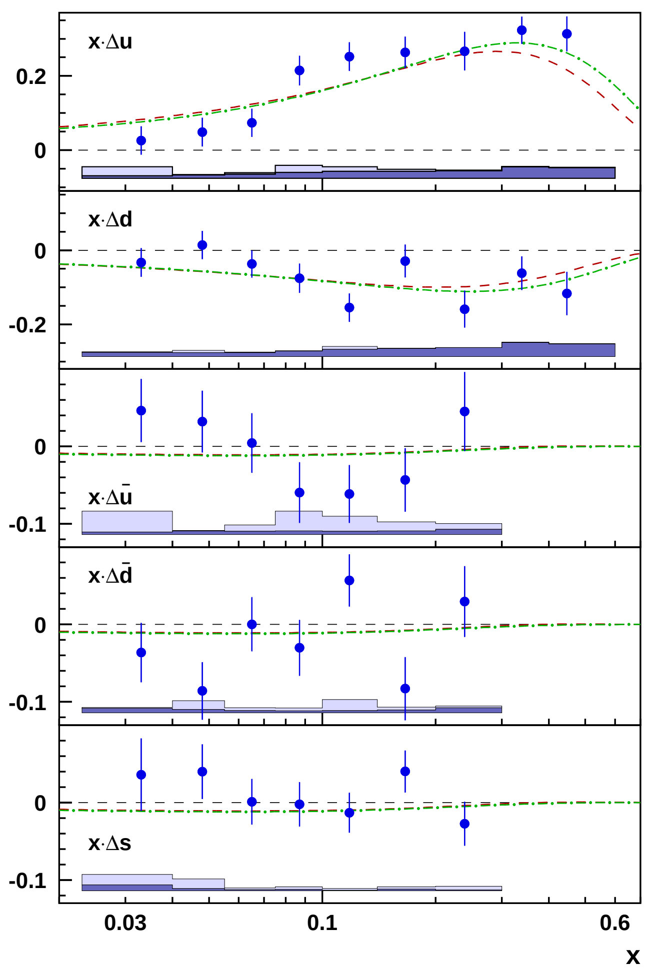
• recent exp. progress in semi-incl. DIS:

idea: flavor content of the observed hadron $\leftrightarrow$ flavor of the struck quark via frag. fcts. $D_q^h(z)$
$\Rightarrow$ $q/\bar{q}$ & flavor separation possible



LO spin asymmetry: (Q^2 dependence suppressed)

$$A_1^h(x,z) = \frac{g_1^h(x,z)}{F_1^h(x,z)} = \frac{\sum_q e_q^2 \left[\Delta q(x)\ D_q^h(z) + \Delta\bar{q}(x)\ D_{\bar{q}}^h(z)\right]}{\sum_q e_q^2 \left[q(x)\ D_q^h(z) + \bar{q}(x)\ D_{\bar{q}}^h(z)\right]}$$



considerable interest:

SU(2) breaking in sea
Diakonov et al.; Fries et al.; Kumano; Thomas et al.; . . .

strange polarization Δs
Brodsky et al.; Ellis et al.; . . .

points of discussion:

positive Δs?
Bass; Leader, Stamenov

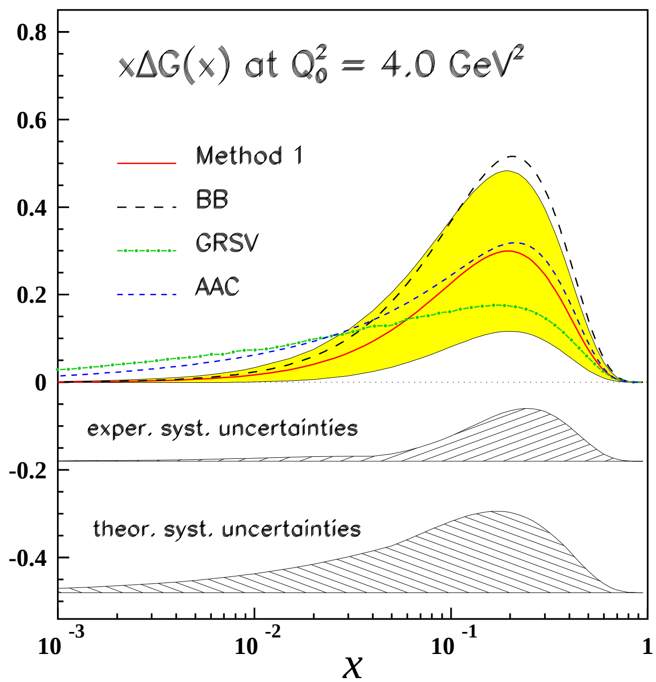
use of $D_q^h(z)$ at low Q^2?
Kretzer et al.; Kotzinian

higher twist?

But we are still not out of the woods -

the jury is still out on some **crucial questions**:

- need more information on Δq, $\Delta \bar{q}$ & flavor separation
- present data cover only small range in x and Q^2
  - DIS constrains Δg mainly through scaling violations
    $\rightarrow$ $\Delta g(x, Q^2)$ completely/largely unknown



taken from a recent fit by Böttcher, De Nardo

  - impossible to really verify predicted $\ln Q^2$ behavior

- still don't know very much about spin-$\frac{1}{2}$ "sum rule"
- haven't tested universality of polarized parton densities
- even worse: transverse polarization

$\Downarrow$

RHIC - Spin Program

II. Spin Physics at RHIC

starting point: universality of parton densities

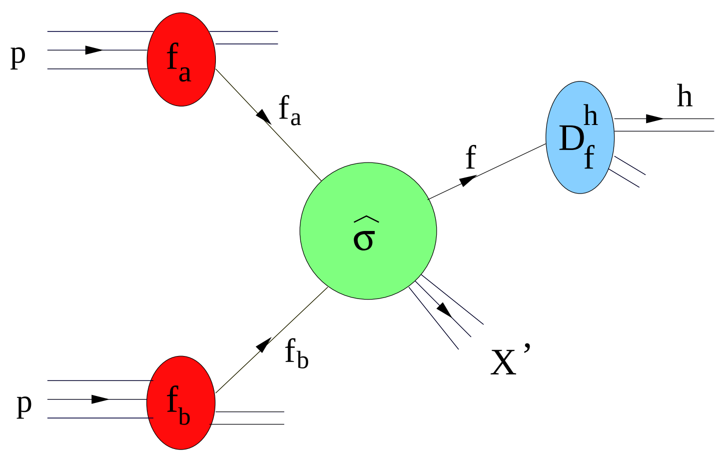
· foundation of predictive power of perturbative QCD

· makes notion of "nucleon structure" meaningful

factorization @ work: high-p_T processes

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

e.g., high-p_T single-inclusive hadron production



long-distance

from exp.; μ-dep.: $d\sigma/d\mu = 0$ (pQCD)

↓ ↓ ↓

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

↑ ↑

short-distance

calculable in pQCD: power series in α_s

power corr.

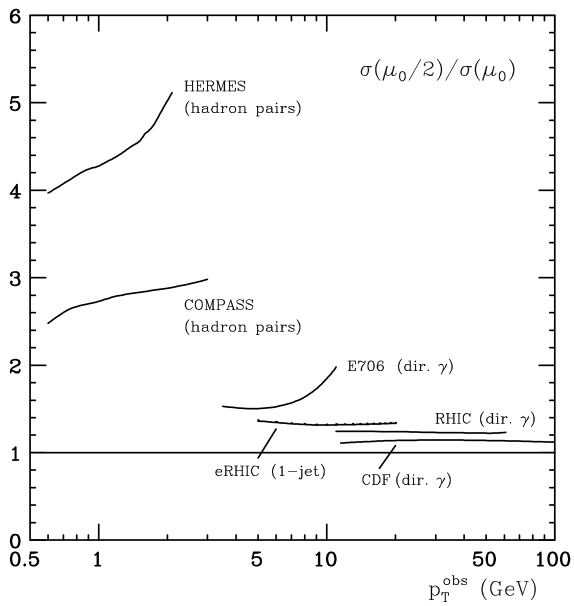
neglected

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

· arbitrary scales $\mu_{f,f',r}$: separate long- and short-dist. physics

QCD in a collider environment: many advantages ...

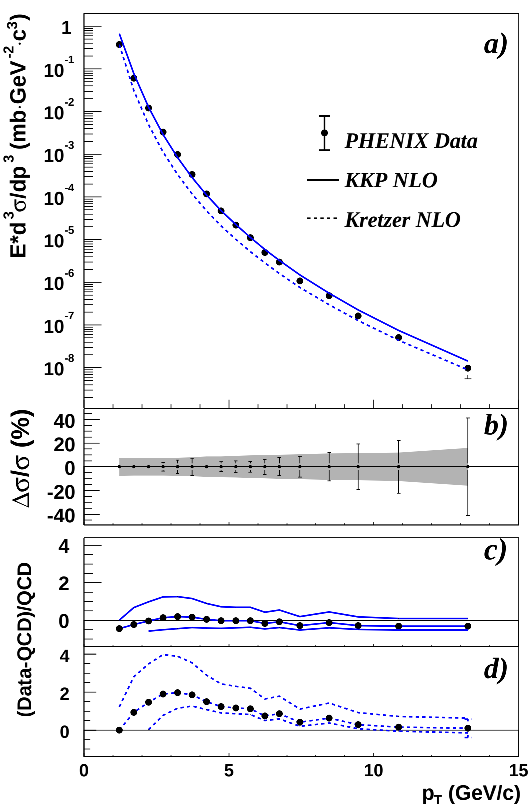
- large c.m.s. energy $\rightarrow$ high p_T accessible
  - · domain of perturbative QCD: $\alpha_s(\mu_r \simeq p_T) \ll 1$
  - · scale dependence $\leftrightarrow$ reliability of pQCD calc.:



ratios of "x-secs" for two choices of μ_f

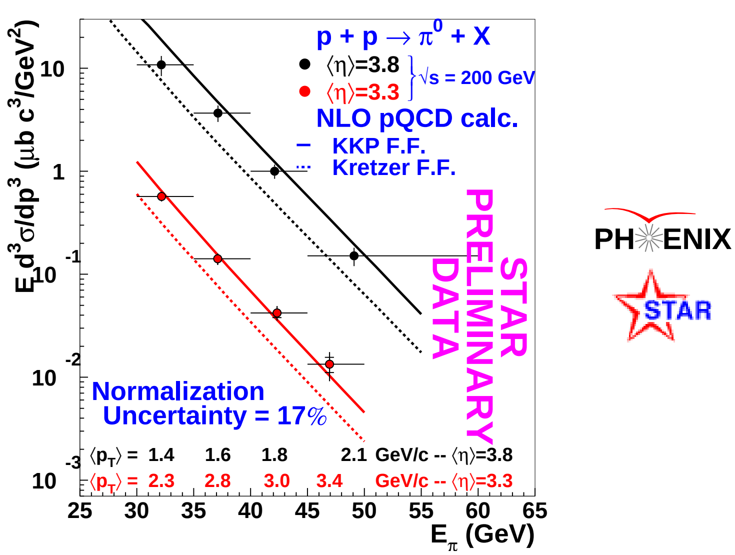
$\leftarrow$ should be $\simeq 1$

- a success story in describing *unpolarized* collisions



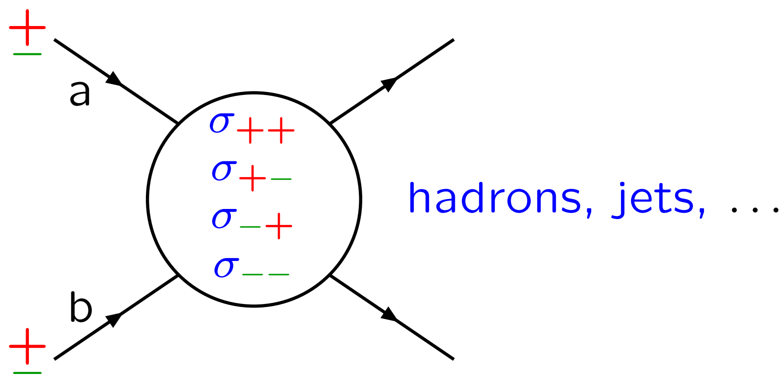
1st examples from RHIC:

high p_T pion production



agrees well with NLO pQCD

Longitudinal Polarization



$\rightarrow \frac{1}{2}(\sigma_{++} + \sigma_{+-}) \equiv \sigma$ (usual unpol. cross section)

$\frac{1}{2}(\sigma_{++} - \sigma_{+-}) \equiv \Delta\sigma = \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma}$

experimentally relevant: $A_{\rm LL} \equiv \frac{d\Delta\sigma/d\mathcal{P}}{d\sigma/d\mathcal{P}}$

ultimate goal:

pin down all aspects of helicity pdfs, in particular Δg

reaction	LO subprocesses	partons probed	x-range
$pp \rightarrow$ jets X	$q\bar{q}, qq, qg, gg \rightarrow$ jet X	Δq, Δg	$x \gtrsim 0.03$
$pp \rightarrow \pi X$	$q\bar{q}, qq, qg, gg \rightarrow \pi X$	Δq, Δg	$x \gtrsim 0.03$
$pp \rightarrow \gamma X$	$qg \rightarrow q\gamma$, $q\bar{q} \rightarrow g\gamma$	Δg	$x \gtrsim 0.03$
$pp \rightarrow Q\bar{Q}X$	$gg \rightarrow Q\bar{Q}$, $q\bar{q} \rightarrow Q\bar{Q}$	Δg	$x \gtrsim 0.01$
$pp \rightarrow W^{\pm}X$	$q\bar{q}' \rightarrow W^{\pm}$	Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$	$x \gtrsim 0.06$

$\Downarrow$

- test of fundamental QCD spin interactions
- verify universality of pdfs for the 1st time
- test predicted $\ln Q^2$ dependence of pdfs for the 1st time
- perhaps learn more about spin-1/2 "sum rule"

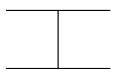
Complication: NLO QCD Corrections

Why NLO?

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

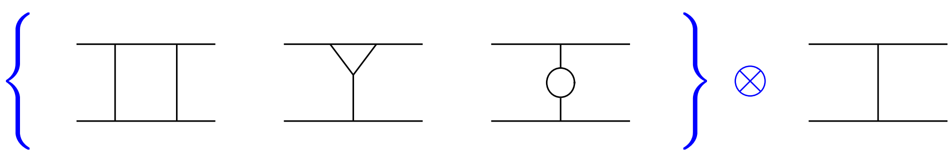
What are NLO QCD corrections all about?

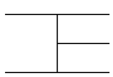
at $\mathcal{O}(\alpha_s^2)$ (LO) one has:

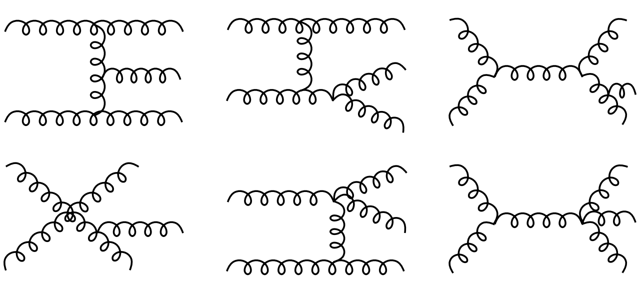
relevant $2 \rightarrow 2$  parton-parton scattering processes

at $\mathcal{O}(\alpha_s^3)$ (NLO) one has:

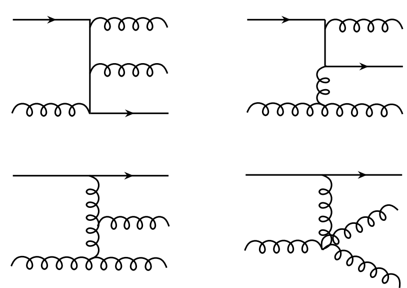
- interference of 1-loop and LO Born amplitudes:



- $2 \rightarrow 3$  parton-parton scattering processes, e.g.:



$gg \rightarrow ggg$



$qg \rightarrow qgg$

UV poles (loops): removed by *renormalization* $\rightarrow$ scale μ_r

IR poles: cancel in sum of virtual and $2 \rightarrow 3$ diagrams

collinear poles: removed by *factorization* $\rightarrow$ scales $\mu_{f,f'}$

good news: impressive progress recently

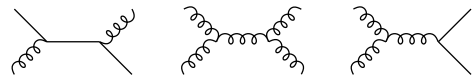
evol. kernels	ΔP_{ij} (spacelike)	NLO		Mertig, van Neerven;
				Vogelsang
	$\Delta P_{i\gamma}$ (photon)	NLO		Vogelsang, MS
	ΔP_{ij} (timelike)	NLO		Vogelsang, MS
DIS	$\vec{e}\vec{p} \to e'X$	NLO		Kodaira et al.;
				Ratcliffe; Bodwin, Qiu
		NNLO		van Neerven, Zijlstra
SIDIS	$\vec{e}\vec{p} \to e'H + X$	NLO		Chiappetta et al.;
				De Florian et al.
	$\vec{e}p \to e'\vec{H} + X$	NLO		De Florian et al.
	$e\vec{p} \to e'\vec{H} + X$	NLO		De Florian et al.
hadrons	$\vec{p}\vec{p} \to H + X$	NLO	•	De Florian; Jäger et al.
	$\vec{\gamma}\vec{p} \to H + X$	NLO		Jäger, MS, Vogelsang
	$p\vec{p} \to \vec{H} + X$	NLO		Jäger et al. (soon!)
jets	$\vec{p}\vec{p} \to$ jet(s) $+ X$	NLO	•	De Florian et al.;
				Jäger et al. (soon!)
	$\vec{\gamma}\vec{p} \to$ jet(s) $+ X$	NLO		De Florian, Frixione
	$\vec{e}\vec{p} \to$ jet(s) $+ X$	NLO		Mirkes, Willfahrt
prompt γ	$\vec{p}\vec{p} \to \gamma + X$	NLO	•	Gordon, Vogelsang;
				Contogouris et al.
	$\vec{p}\vec{p} \to \gamma\gamma + X$	NLO		Coriano, Gordon
	$\vec{e}\vec{p} \to \gamma + X$	NLO		Contogouris et al.
	$p\vec{p} \to \vec{\gamma} + X$	NLO		Vogelsang
γ **+ jet**	$\vec{p}\vec{p} \to \gamma +$ jet $+ X$	NLO		Gordon
	$\vec{\gamma}\vec{p} \to \gamma +$ jet $+ X$	NLO		Gordon
γ **+ charm**	$\vec{p}\vec{p} \to \gamma + c + X$	NLO		Berger et al. ($m_c = 0$)
heavy quarks	$\vec{p}\vec{p} \to Q\bar{Q}X$	NLO	•	Bojak, MS
	$\vec{\gamma}\vec{p} \to Q\bar{Q}X$	NLO		Bojak, MS;
				Contogouris et al.
Drell-Yan	$\vec{p}\vec{p} \to (\gamma^*)X$	NLO		Weber; Gehrmann;
		NNLO		Smith et al.
vector bosons	$\vec{p}\vec{p} \to (Z^0, W^\pm)X$	NLO		Weber; Gehrmann
	$p\vec{p} \to (Z^0, W^\pm)X$	NLO	•	Weber; Gehrmann

$\updownarrow$

details/results: $\longrightarrow$ next slides

Processes one-by-one

- **high-p_T hadrons**:



NLO: Jäger, MS, Schäfer, Vogelsang; de Florian

recall: · unpol. measurements agree well with pQCD

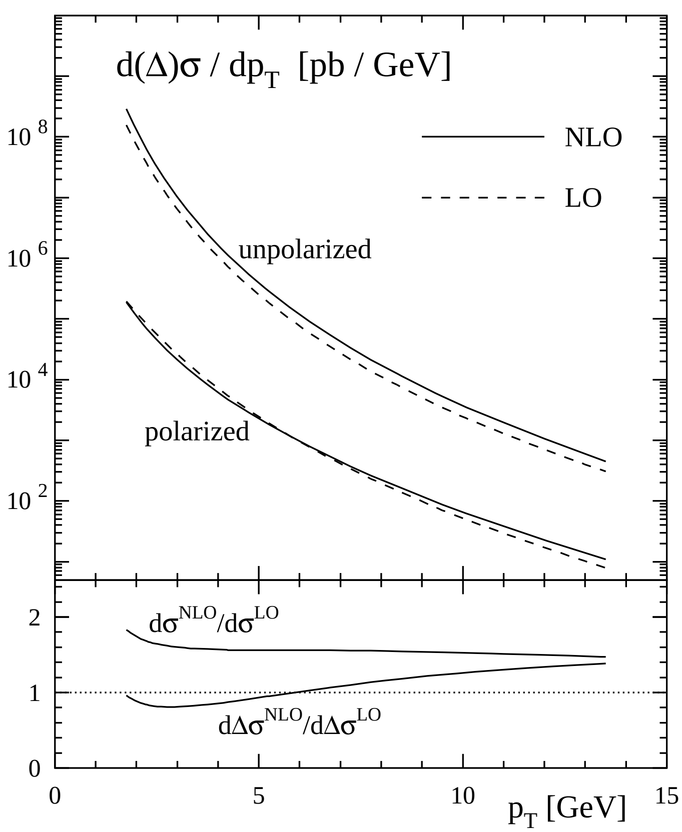
· $D^{\pi}(z)$ set of Kniehl, Kramer, Pötter favored

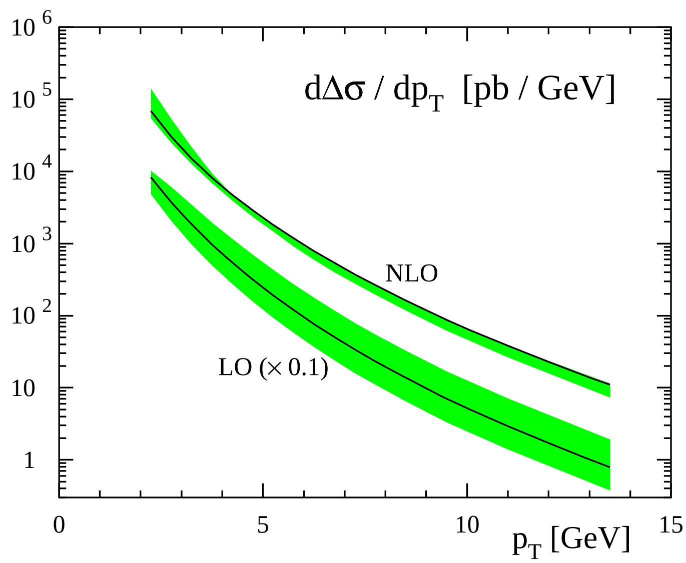
$\longrightarrow$ exciting prospects for polarized measurement

results: · $d(\Delta)\sigma^{\mathrm{NLO}}/d(\Delta)\sigma^{\mathrm{LO}}$ reasonably small

· theor. uncertainties much reduced in NLO

π^0-production, $\sqrt{S} = 200\,\mathrm{GeV}$, $|\eta| \leq 0.38$

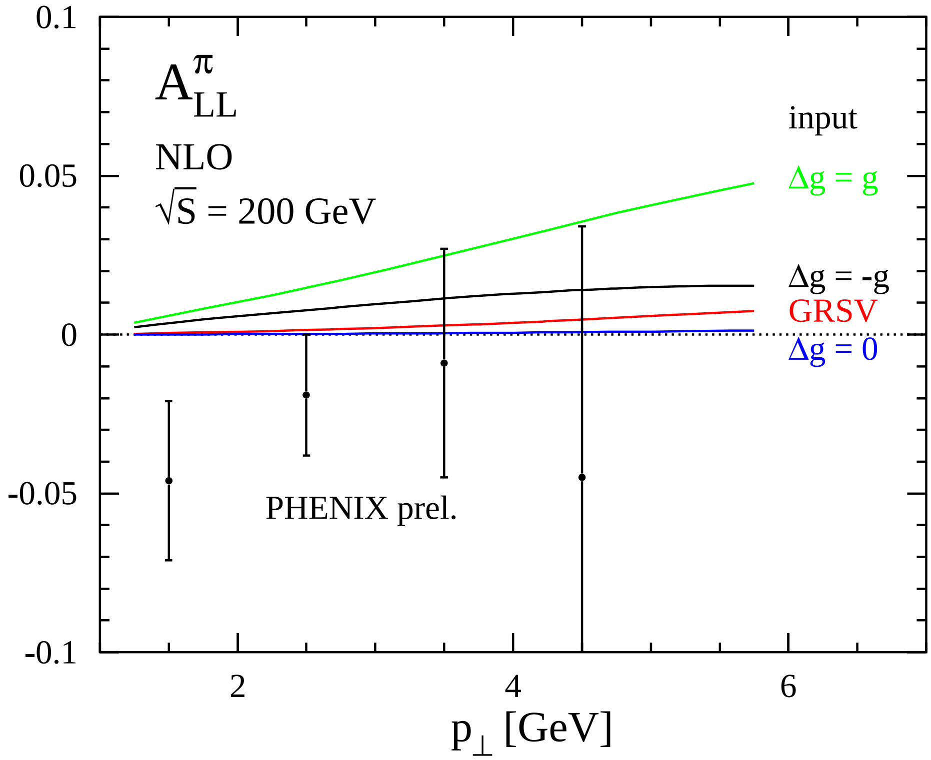




[figs. taken from Jäger et al.]

exciting development: first prel. results by PHENIX

[pol. scaling error ($\sim 30\%$) not included]



$\longleftarrow$ expectations for Δg inputs allowed by $|\Delta g| \leq g$

naive analysis:

partonic spin asymmetries:

$$gg \to gg \quad \hat{a}_{\rm LL} > 0$$
$$gg \to q\bar{q} \quad \hat{a}_{\rm LL} - 1$$
$$gq \to gq \quad \hat{a}_{\rm LL} > 0$$

$\langle z \rangle = 0.3 \div 0.4$ where $D_q^\pi > D_g^\pi$

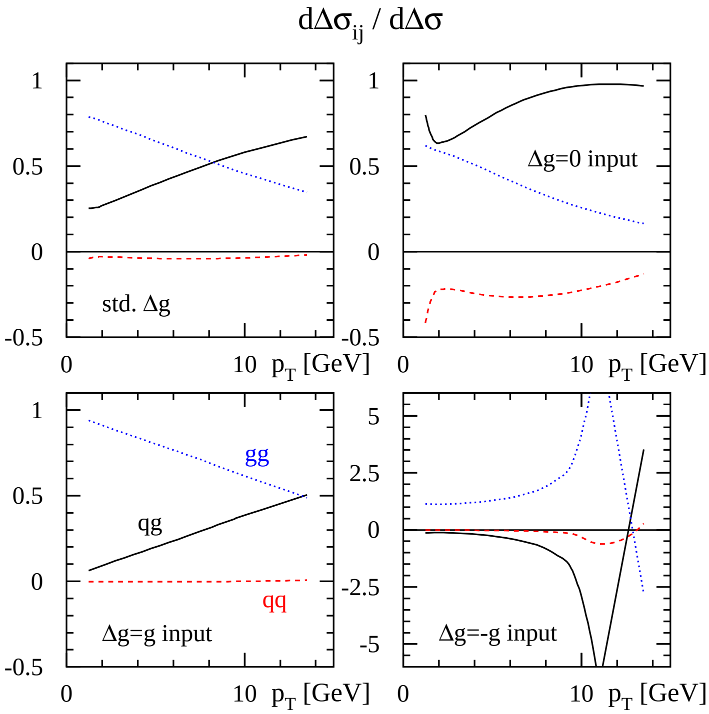
$\longrightarrow$ conclude: $gg \to q\bar{q}$ resp. for neg. $A_{\rm LL}^\pi$

but

$\Delta\hat{\sigma}_{gg\to gg} \simeq 160\, \Delta\hat{\sigma}_{gg\to q\bar{q}}$!! (for $\eta \simeq 0$)

a closer look: can $A_{\rm LL}^{\pi}$ be negative?

Jäger, Kretzer, MS, Vogelsang



subprocess contrib.:

gg process dominates for $p_T \lesssim 10\,\text{GeV}$

qg process takes over for $p_T \gtrsim 10\,\text{GeV}$

qq channel always small

take $x_T^2 \equiv 4p_T^2/S$ moments of η-integrated $d\Delta\sigma$:

$$\Delta\sigma^{\pi}(N) = \left(\Delta g^{N+1}\right)^2 \mathcal{A}^N + 2\Delta g^{N+1}\,\mathcal{B}^N + \mathcal{C}^N$$

$$\updownarrow \; gg \qquad \updownarrow \; qg \qquad \updownarrow \; qq$$

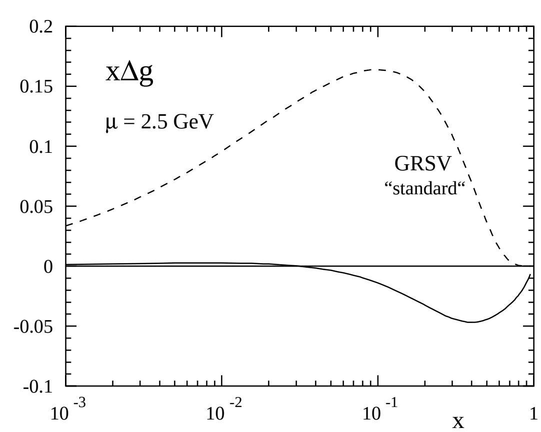
$$\text{minimize}: \quad \Delta\sigma^{\pi}(N)\Big|_{\rm min} = -\frac{\left(\mathcal{B}^N\right)^2}{\mathcal{A}^N} + \mathcal{C}^N$$

$\rightarrow$ negative, but tiny lower bound $A_{\rm LL}^{\pi}\Big|_{\rm min} \simeq \mathcal{O}(-10^{-3})$

resulting Δg:

node! $\rightarrow$ $\Delta g(x_a)\Delta g(x_b) < 0$

confirmed by full "global analysis"



prospects for STAR :

Kretzer, Vogelsang

recall: successful measurement of unpolarized cross section in forward region agrees with pQCD

$\longrightarrow$ A^{π}_{LL} measurement at large rapidities?

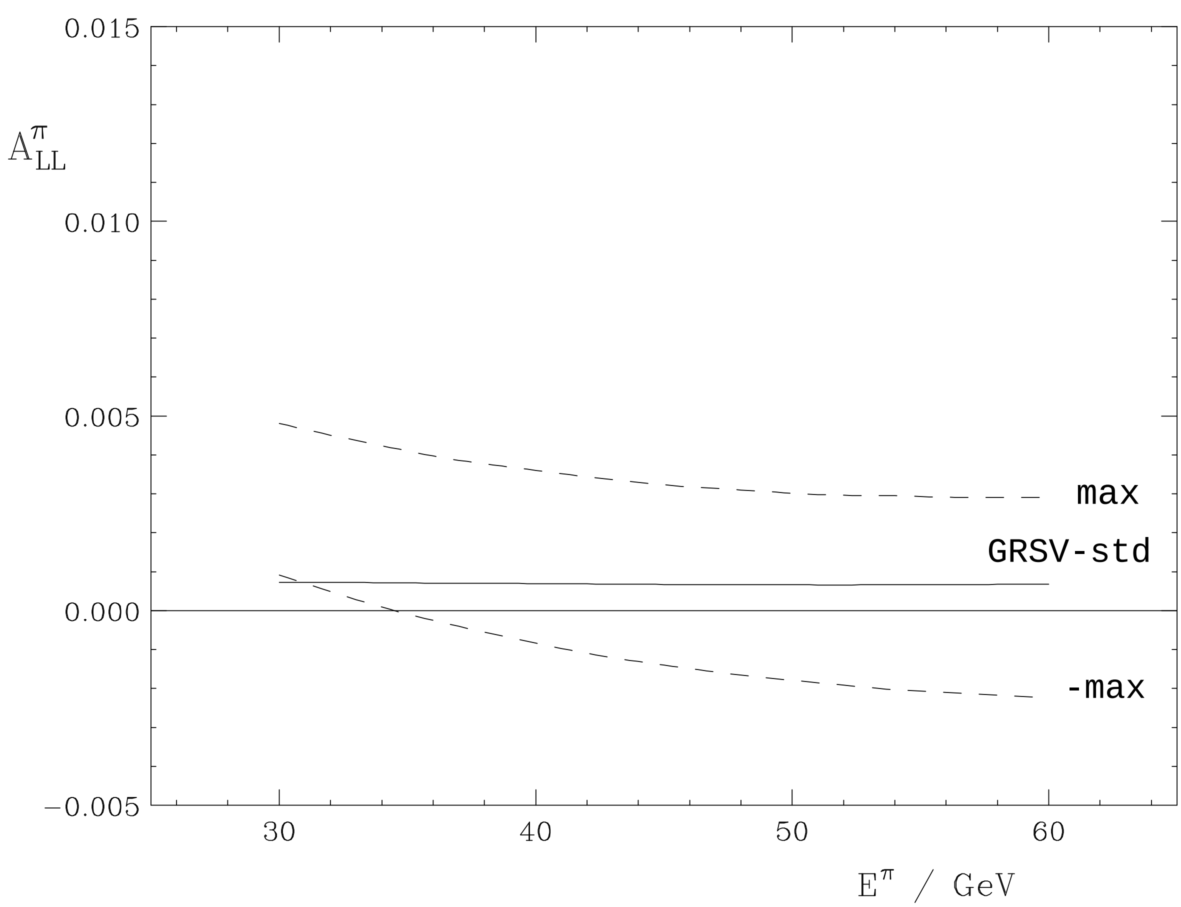
kinematics: $\langle\eta\rangle \simeq 3.5$; $\langle p_T\rangle \simeq 1.5 \div 3$ GeV; $\langle z\rangle \simeq 0.7 \div 0.8$

expect: dominance of qg subprocess sets in

$\longrightarrow$ sign/size of A^{π}_{LL} tied to sign/size of Δg

results:

$$\sqrt{S} = 200\,\mathrm{GeV},\ \eta = 3.3$$

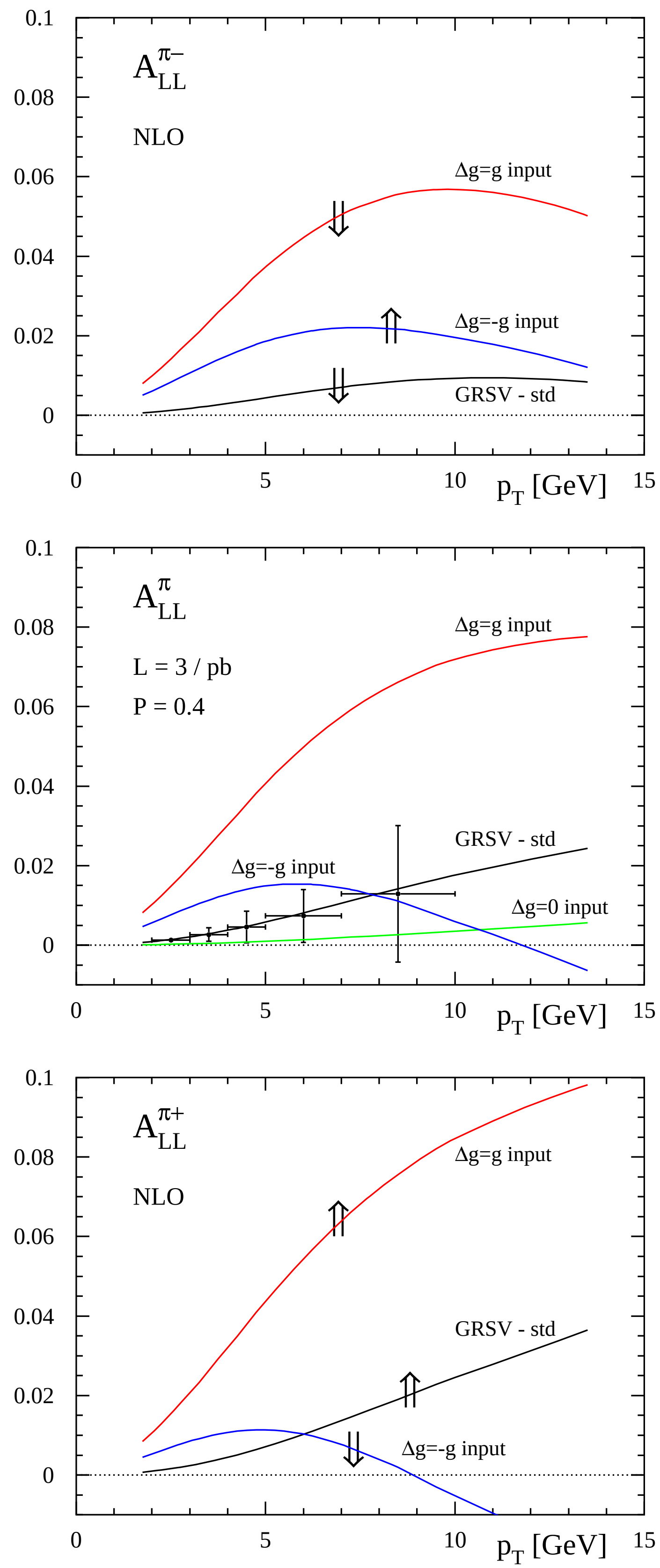


$\langle p_T\rangle =$ 2.3 2.8 3.0 3.4 GeV

long-term prospects on A_{LL}^{π} for PHENIX:

Jäger, MS, Vogelsang; Saito

compare $A_{LL}^{\pi^{\pm}}$ to $A_{LL}^{\pi^0}$



π^-

idea:

for $p_T \gtrsim 5$ GeV:

qg starts to dominate

and $D_u^{\pi^+} > D_u^{\pi^-}$, $D_g^{\pi^+} = D_g^{\pi^-}$

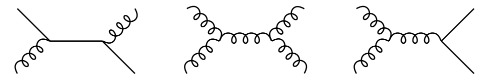
expect:

sensitivity to sign of Δg

e.g. pos. Δg: $A_{LL}^{\pi^+} > A_{LL}^{\pi^0}$

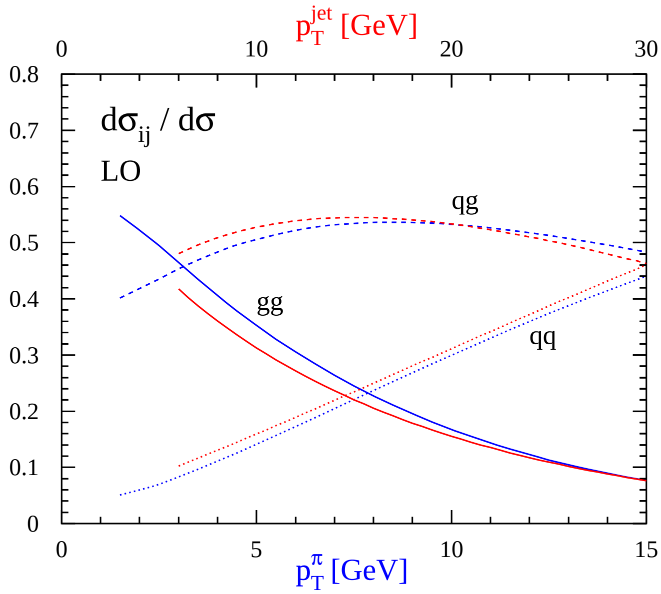
π^+

• high-p_T jets:



NLO: de Florian, Frixione, Signer, Vogelsang; Jäger, MS, Vogelsang

proceeds through the same subprocesses as π-production



π's have roughly $\langle z \rangle \simeq 0.5$:

π with $p_T \simeq$ jet with $2p_T$

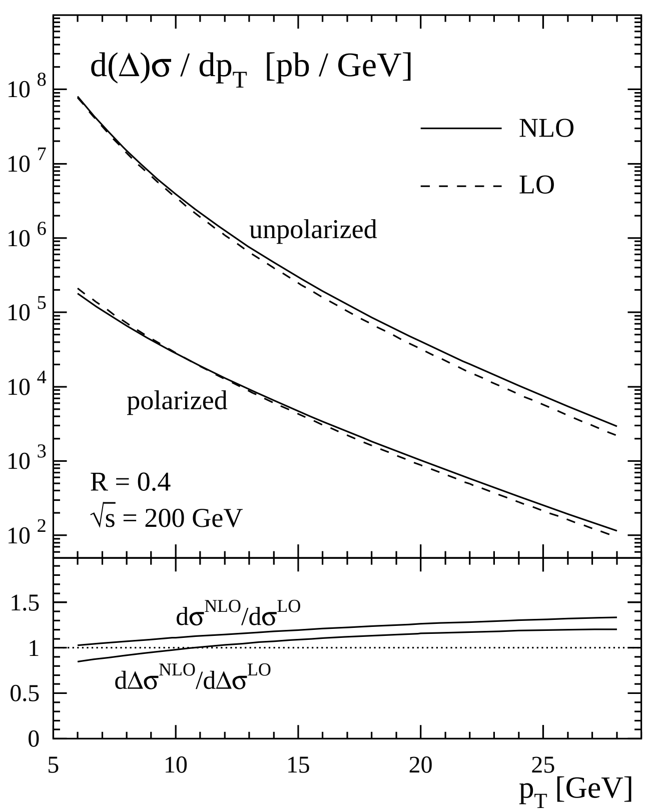
$\rightarrow$ jet and π results similar

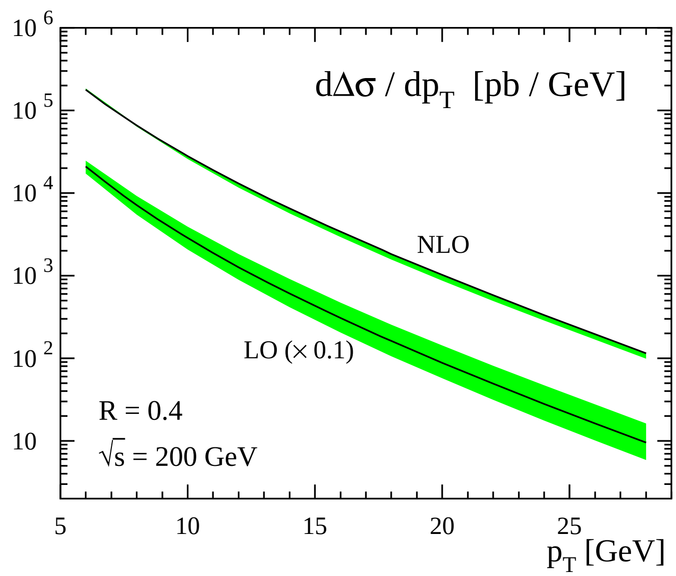
advantages of jets:

- much higher rates
- no uncertainties from $D(z)$

results: theor. uncertainties even smaller than for hadrons

$\sqrt{S} = 200$ GeV, $R_{\text{cone}} = 0.4$ (SCA), $|\eta| \leq 1$

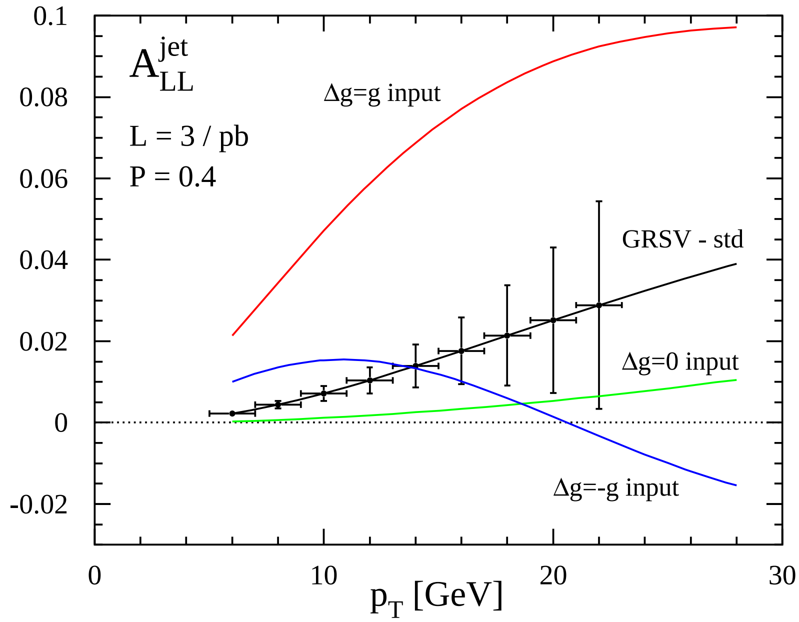




[figs. taken from Jäger, MS, Vogelsang]

expectations for STAR :

$\sqrt{S} = 200\,\text{GeV}$, $R_{\text{cone}} = 0.4$ (SCA), $0 \leq \eta \leq 1$



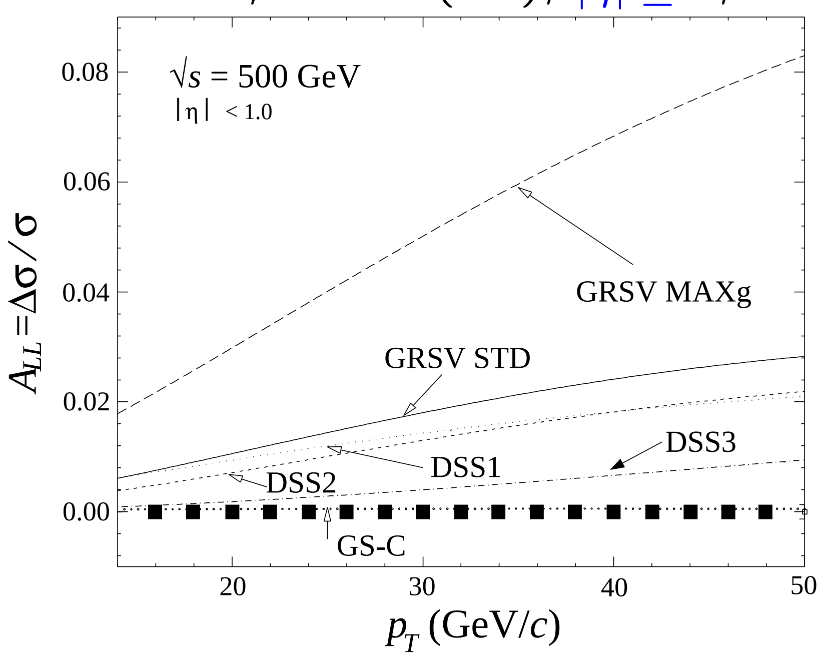
[fig. taken from Jäger, MS, Vogelsang]

estimate of statistical errors: $\delta A \simeq \frac{1}{P_1 P_2} \times \frac{1}{\sqrt{\mathcal{L}\sigma_{\text{bin}}}}$

[with $P_1 = P_2 = 0.4$ (beam pol.) and $\mathcal{L} = 3\ \text{pb}^{-1}$]

and in the long run:

$\sqrt{S} = 500\,\text{GeV}$, $D = 1$ (ES), $|\eta| \leq 1$, $\mathcal{L} = 800\ \text{pb}^{-1}$



[fig. taken from de Florian, Frixione, Signer, Vogelsang]

summary on inclusive jets and hadrons:

- excellent near-term prospects for a first determination of Δg

- important: unpolarized "benchmark x-secs" so far in perfect agreement with pQCD
  [even down to unexpectedly small p_T]

- first exciting results from PHENIX
  if large & negative A_{LL} persists:
  new spin surprise; effect due to intr. k_T or ?
  important to collect more data soon

long-term goals:

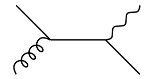
need much higher luminosities and/or $\sqrt{S} = 500\,\mathrm{GeV}$

- prompt photons: cross-check of Δg results

- heavy flavors: extend Δg to smaller x

- $W^{\pm}$ bosons: further information on $\Delta q, \Delta \bar{q}$

• **prompt photons (plus jets)**:



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

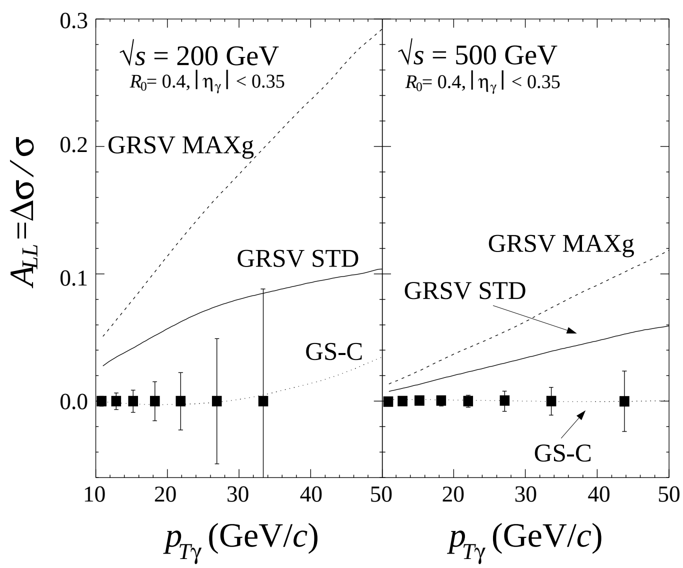
idea: $qg \to q\gamma$ dominant $\to$ clean signal for Δg

results: · some trouble with unpol. fixed target data but collider data O.K.

· theoretical efforts to go beyond NLO [soft gluon/threshold (and k_T) resummations]

Laenen et al.; Catani et al.; Li; Kidonakis Owens; ...

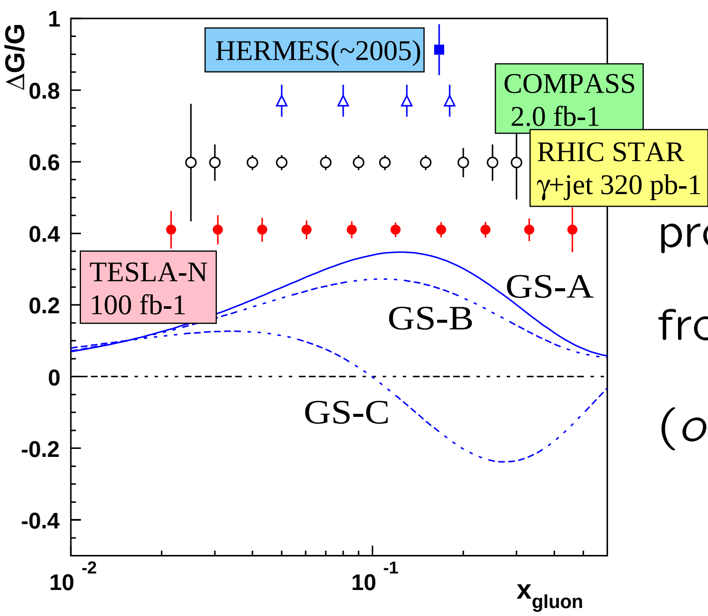
$A_{\rm LL}^{\gamma}(p_T)$ for PHENIX: Frixione,Vogelsang



$\to$ expected sensitivity to Δg

not shown:

· reduced scale dependence in NLO ✓

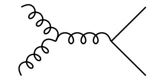


projected accuracy for $\Delta g/g$

from $\gamma +$ jet at STAR

(*only* for 200 GeV meas.)

• **heavy flavor production**:



NLO: Bojak, MS

idea: sensitivity to Δg through dominance of $gg \to Q\bar{Q}$

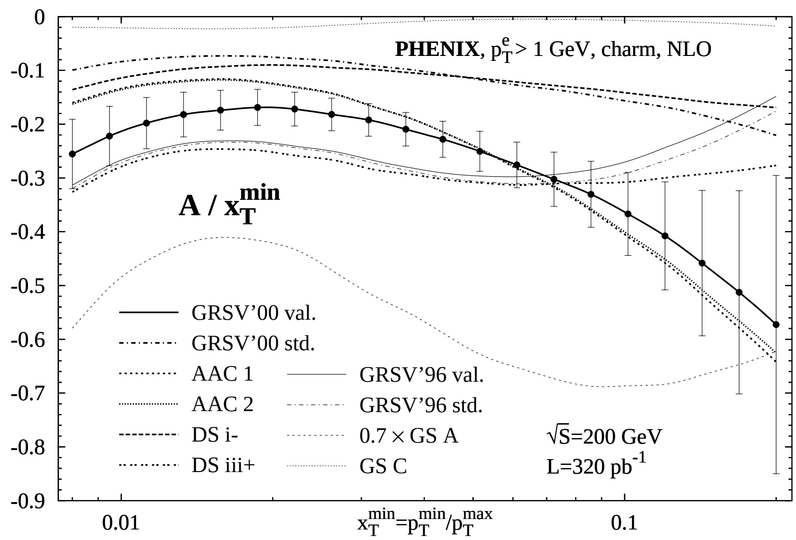
somewhat smaller x values accessible here

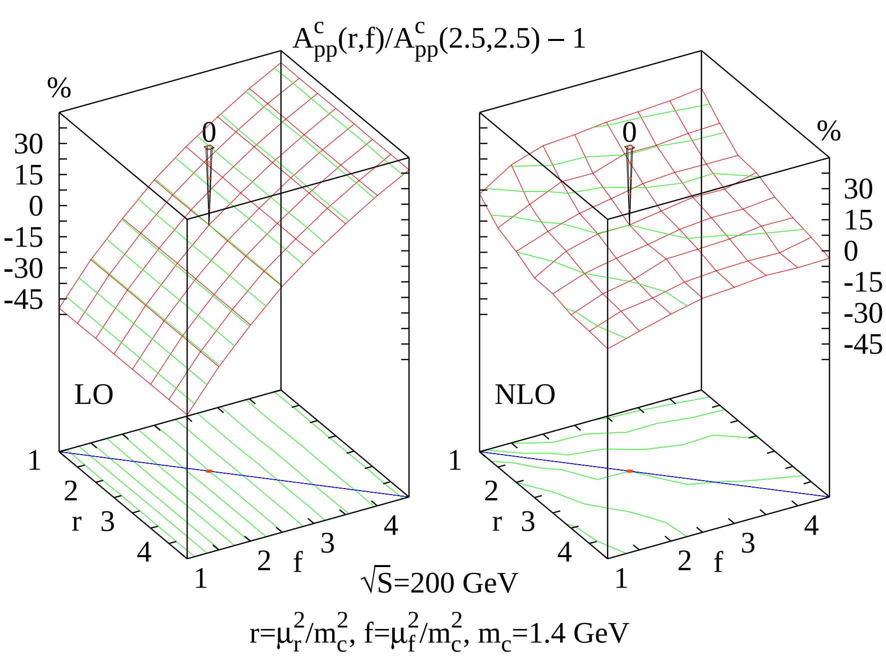
complication: c, b identified via their decay leptons

$\rightarrow$ have to simulate HQ-decays in estimates of A_{LL}^{Q}

$A_{\mathrm{LL}}^{c}(p_T^{\mathrm{min}})$ for PHENIX:

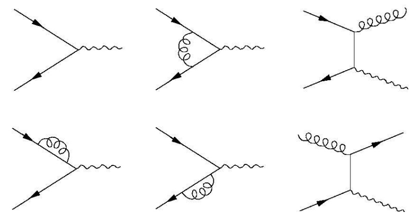
$\rightarrow$ sensitivity to Δg





$\mu_{r,f}$ dependence reduced in NLO

• $\mathbf{W^{\pm}}$ boson production:



NLO: Weber; Kamal; Gehrmann; Smith et al.

idea: parity violating → single-spin asymmetry sufficient

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

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

→ y large & $\begin{cases} \text{positive } (x_a > x_b) \\ \text{negative } (x_a < x_b) \end{cases}$: $A_L^{W^+} \simeq \begin{cases} -\Delta u(x_a)/u(x_a) \\ \Delta\bar{d}(x_a)/\bar{d}(x_a) \end{cases}$

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

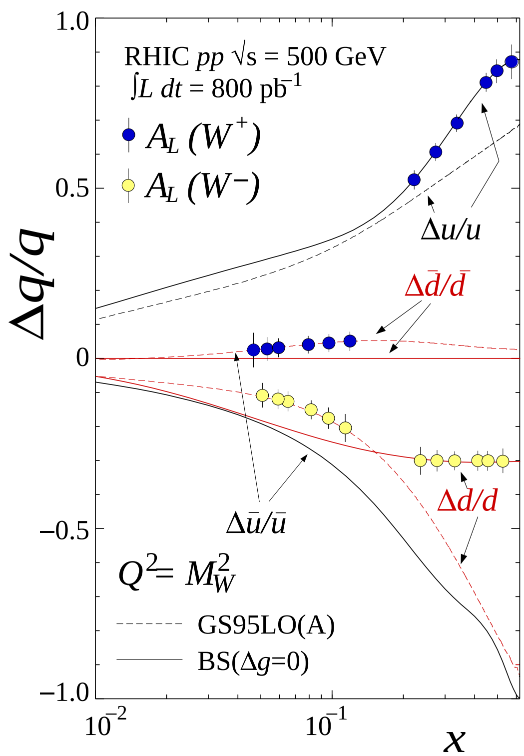
$A_L^{W^-}(y)$: $u \leftrightarrow d$ → probes $\Delta d/d$ and $\Delta\bar{u}/\bar{u}$

complication: have to observe $W^{\pm}$ via decay

but full NLO *lepton-level* MC is available

Nadolsky, Yuan

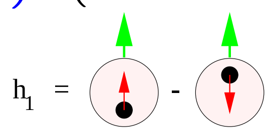
expected sensitivity on $\mathbf{\Delta q/q}$ from $\mathbf{A_L^{W^{\pm}}(y)}$:



Transverse Polarization

boosts and rotations do not commute $\longrightarrow$ new object

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

- "as partonic as" q and Δq: 

Ralston, Soper; Artru, Mekhfi; Jaffe, Ji

- reveals chiral-odd nature if described in helicity-basis

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

$\longrightarrow$ difficult to measure (fund. interactions preserve chirality)

$\longrightarrow$ no gluon density for spin 1/2 targets possible

Jaffe, Ji; Artru, Mekhfi; Ji

- simple non-singlet type evolution eqs.

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

- vanishes at large scales (all $\int_0^1 x^{n-1} \delta q(x, Q^2) dx$ decrease)
- constraint: Soffer; Sivers

$$\left|\delta q(x, \mu^2)\right| \leq \frac{1}{2}\left[q(x, \mu^2) + \Delta q(x, \mu^2)\right]$$

$\uparrow$ unknown $\qquad$ $\uparrow$ $\uparrow$ known (more or less)

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

Collins; Jaffe

- tensor charge $\sum_q \int_0^1 [\delta q - \delta \bar{q}](x, Q^2) dx \leftrightarrow$ neutron EDM

  Jaffe, Ji

accessing $\delta \mathbf{q}$ at RHIC:

chirality has to be flipped *twice* to access δq

$\swarrow \qquad \searrow$

double-spin **single-spin**

asymmetries

A_{TT} $\qquad$ 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 (E704, STAR)

(I) double transverse spin asymmetries $\mathbf{A}_{\mathrm{TT}}$:

on the menu: Drell-Yan, jets/hadrons, prompt-photons

general problem: $\nexists$ "transversity" gluons

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

- **Drell-Yan process** Ralston, Soper; Ji
  Cortes, Pire, Ralston; Artru, Mekhfi; Jaffe, Ji

✓ best candidate: $q\bar{q} \rightarrow \mu^{+}\mu^{-}$ $\rightarrow$ no gluons in LO

× numerical study in NLO QCD revealed:
Martin, Schäfer, MS, Vogelsang

measurement suffers from limited muon acceptance

of PHENIX: $1.2 \leq |y_{\mu^{\pm}}| \leq 2.4$; need *both* muons!

$\rightarrow$ conclusion on DY: tough, interesting with more lumi

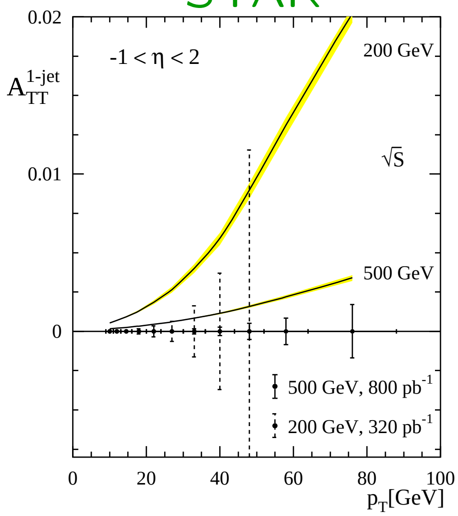
- **high-p_T jet and prompt photon production**

Hidaka et al.; Artru, Mekhfi; Ji; Jaffe, Saito; Soffer, MS, Vogelsang

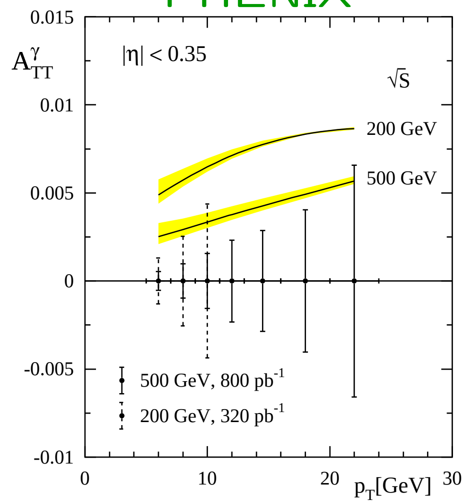
✓ jets (and photons) copiously produced at colliders

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

1-jet
STAR



high-p_T photon
PHENIX



[upper bounds for A_{TT} in LO QCD; bands: μ_F dependence]

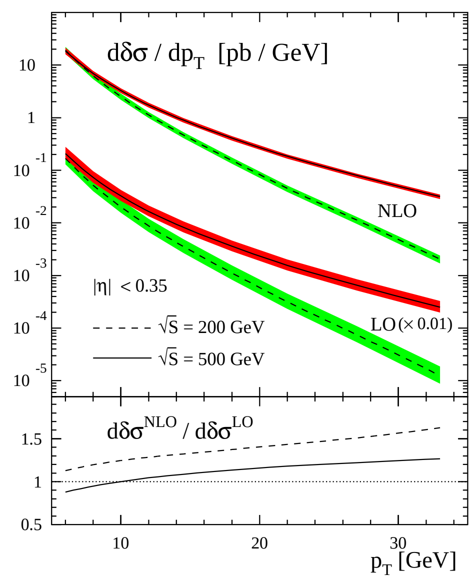
Soffer, MS, Vogelsang

very recently:

1st NLO computation of prompt photon production

Mukherjee, MS, Vogelsang

[more involved due to extra spatial direction]



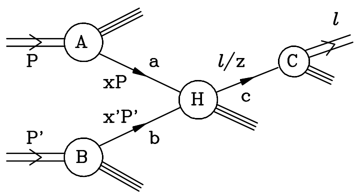
general conclusions on A_{TT} at RHIC:

- difficult, albeit not impossible task
- requires great exp. efforts [in particular, small syst. errors]
- large A_{TT}'s would constitute a new "spin surprise"

(II) single transverse spin asymmetries $\mathbf{A}_{\mathrm{N}}$:

exciting observable, goes back to the early days of spin

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

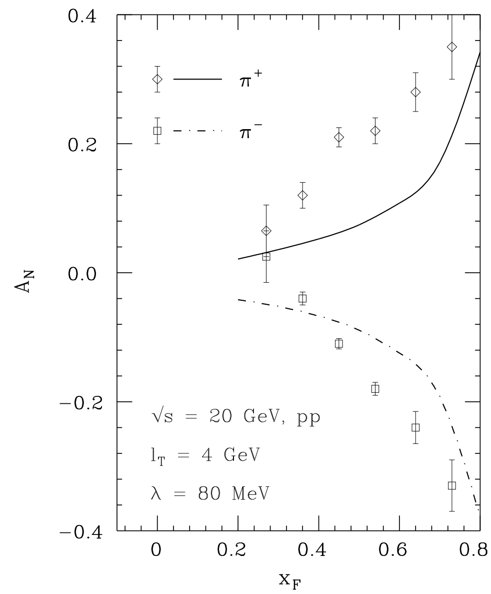


measure : $A_{\mathrm{N}} = \frac{\Delta_{\mathrm{N}}\sigma}{\sigma} \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$

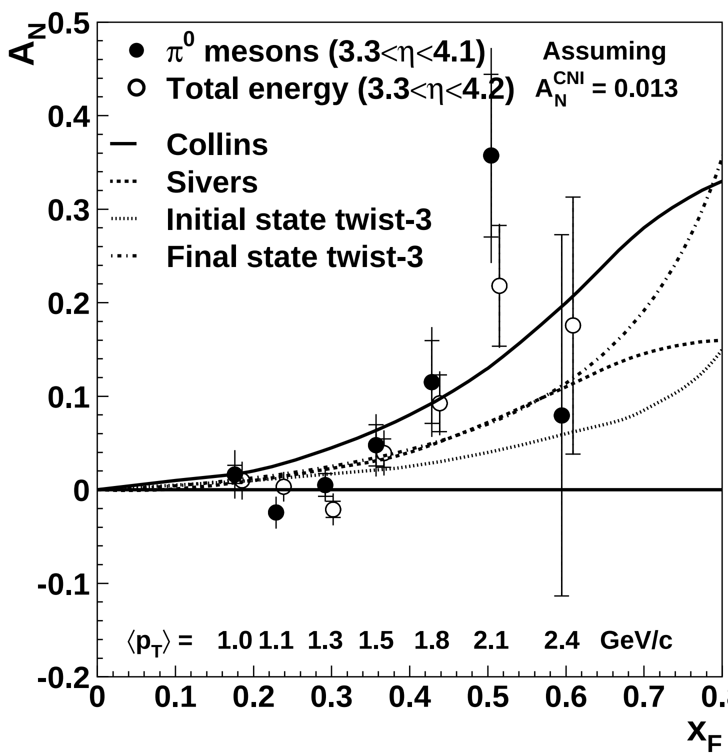
"long-standing puzzle" :

large A_{N} for π and Λ production

e.g. E704 ($\sqrt{S} = 20\,\mathrm{GeV}$) $\longrightarrow$



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



effect recently confirmed

also at $\sqrt{S} = 200\,\mathrm{GeV}$

by STAR

A_{N} opens a window to a new class of power-suppr. "pdfs"

"twist-3" can arise from

↙ ↘

quark-gluon correlations

Qiu, Sterman; Koike et al.; Teryaev et al.

pdfs/ffs with intrinsic $\mathbf{k_T}$

Sivers; Collins; Boer; Leader et al.; Anselmino et al.; Brodsky et al.; Bacchetta et al.; ...

problem:

very difficult to disentangle all these contributions

each mechanism on its own can account for E704 & STAR

⇓

progress requires combined efforts of

several experiments and theory

pp (RHIC), e^+e^- (BELLE), lp (HERMES, COMPASS)

intrinsic $\mathbf{k_T}$: a lot of theoretical activity recently

· mapping of all possible k_T distributions

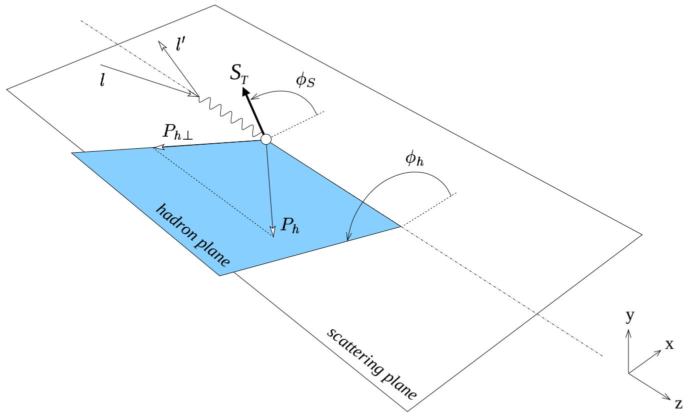
· importance of gauge links $\mathcal{P}\,\exp\left(ig\int_0^y dx^\mu A_\mu(x)\right)$

· universality of distributions

· evolution, NLO, ...

→ Morning Session on Thursday

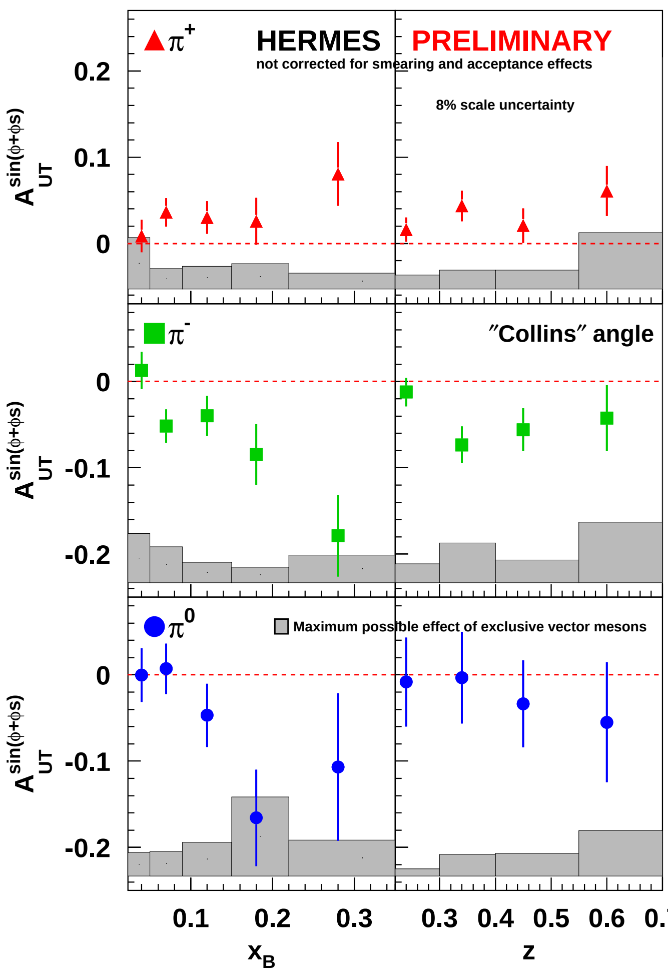
very recent results on $ep^{\uparrow} \rightarrow e\pi X$:



two leading contributions to A_{UT}:

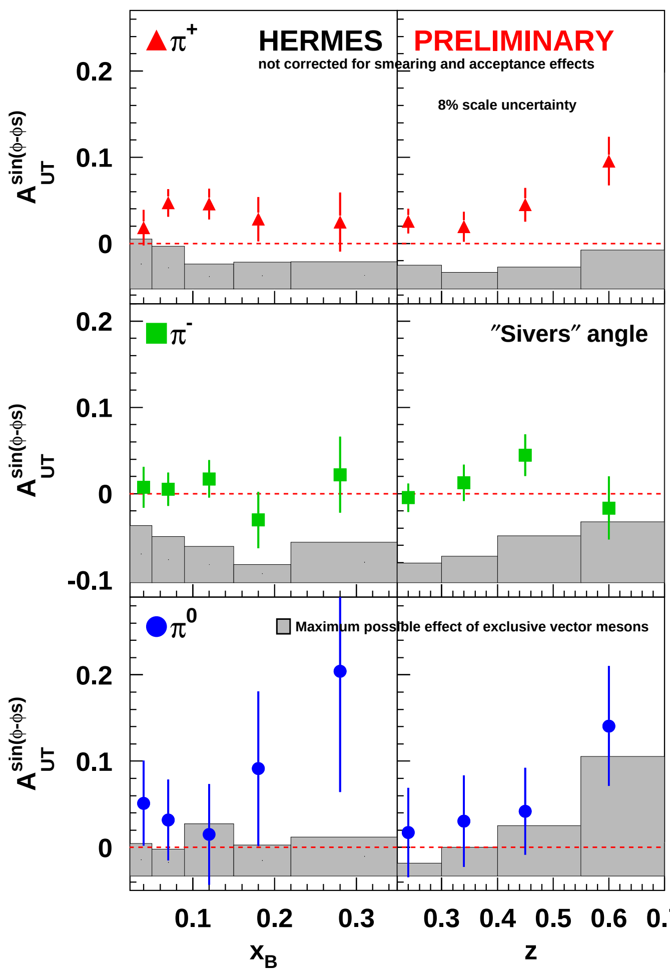
$\propto \sin(\phi_h + \phi_S)\delta q(x) H_1^{\perp,q}(z)$

"Collins"



$\propto \sin(\phi_h - \phi_S) f_{1T}^{\perp,q}(x) D_q(z)$

"Sivers"



Summary & Outlook

topics not touched: L_z, GPD's, lattice, . . .

RHIC is the ideal playground to
further test and learn much more
about QCD spin interactions

first exciting results:
QCD calculations will now be
challenged by experiment

for many years to come RHIC will be
the prime source of information on spin

next "spin surprise" is perhaps
just round the corner

very exciting times ahead of us