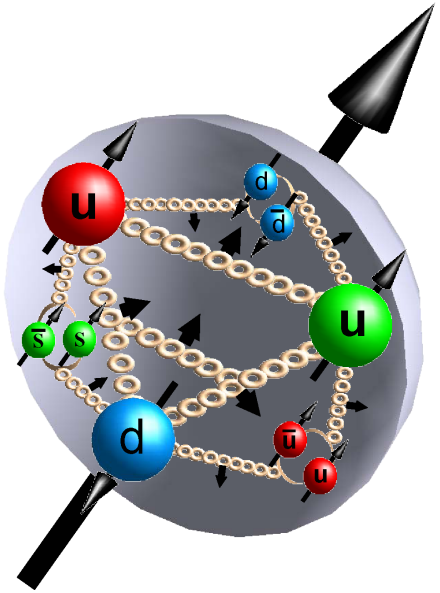
QCD Spin Physics: Partonic Spin Structure of the Nucleon

Werner Vogelsang
Univ. Tübingen

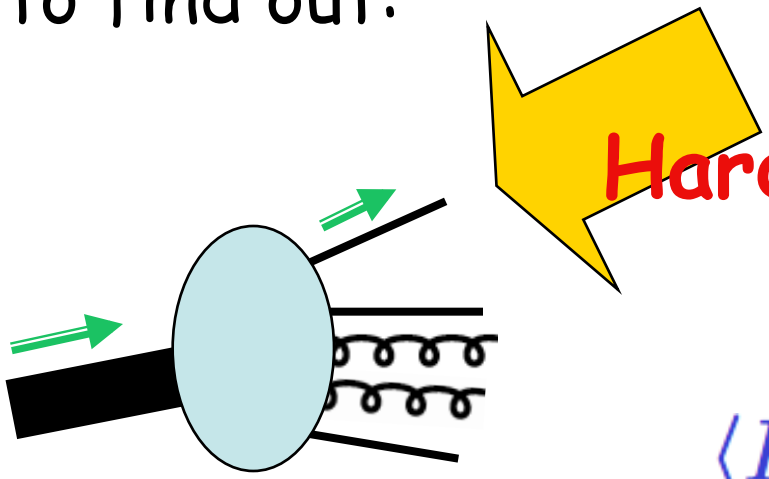
Erice, 17.09.2011

Goal: understand the spin structure of the nucleon in terms of quarks and gluons



- How do quarks and gluons carry the proton spin ?

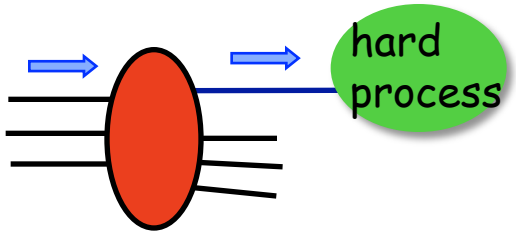
The way to find out:



$$\langle P,s|\mathcal{O}_{q,g}|P,s\rangle$$

Today: Helicity structure of the nucleon

- Helicity parton distributions and their physics
- Present knowledge
- Latest results and developments

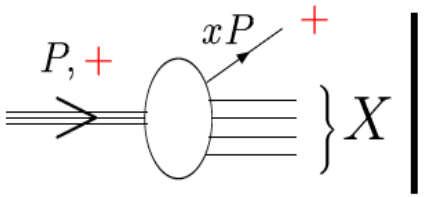


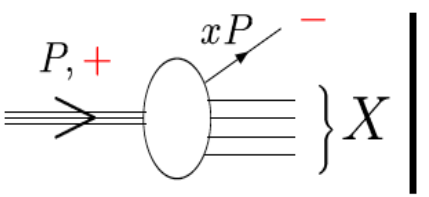
Note, there are many other exciting aspects:

- Transverse polarization
- Spatial & transverse momentum distributions of partons
- Orbital angular momenta
- Generalized Parton Distributions

see talks by
Burkardt
Schlegel
Kroll
Lyubovitskij
…

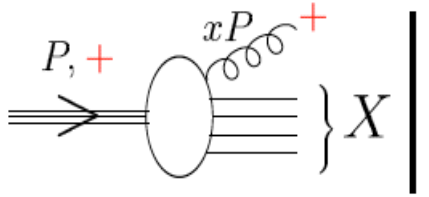
Helicity Parton Distributions

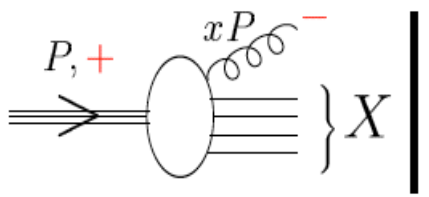
$$\Delta q(x) \;=\; \Big|$$ 

$$\Big|^2 \;-\; \Big|$$ 

$$\Big|^2$$

$$\Delta\, q(x) \;=\; \frac{1}{4\pi}\int dy^-\, \mathrm{e}^{-iy^-xP^+}\, \langle\, P,S\,|\,\bar{\psi}\,(0,y^-,\mathbf{0}_\perp)\;\gamma^+\gamma_5\,\psi(0)\,|\,P,S\,\rangle$$

$$\Delta g(x) \;=\; \Big|$$ 

$$\Big|^2 \;-\; \Big|$$ 

$$\Big|^2$$

$$\Delta g(x) \;=\; \frac{1}{4\pi x P^+}\int dy^-\, \mathrm{e}^{-iy^-xP^+}\, \langle\, P,S\,|\,F^{+\alpha}\,(0,y^-,\mathbf{0}_\perp)\;\tilde{F}_\alpha{}^{+}(0)\,|\,P,S\,\rangle$$

Collins, Soper; Manohar

Measured in numerous experiments:

SLAC

E142, E143,
E154, E155

CERN

EMC, SMC,
COMPASS

DESY

HERMES

JLab

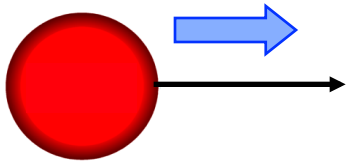
Hall A, CLAS

BNL

PHENIX, STAR

pp collisions at
200 & 500 GeV

(1) Δq, Δg and the proton spin



$$\frac{1}{2} = \langle P, \frac{1}{2} \,|\, J_{QCD} \,|\, P, \frac{1}{2} \rangle$$

$$\boldsymbol{J}_{QCD} \;=\; \boldsymbol{S}^q \;+\; \boldsymbol{L}^q \;+\; \boldsymbol{S}^g \;+\; \boldsymbol{L}^g$$

$$\boldsymbol{S}^q \;=\; \int \psi^\dagger \frac{1}{2} \boldsymbol{\Sigma}\, \psi \, d^3x,$$

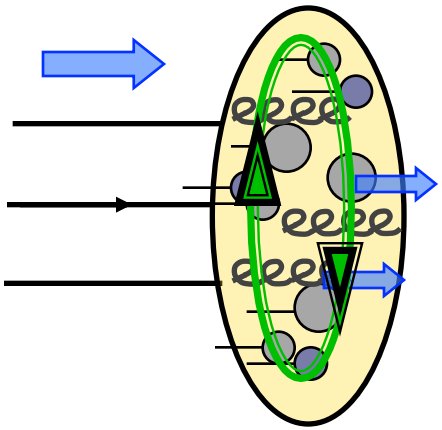
$$\boldsymbol{L}^q \;=\; \int \psi \, \boldsymbol{x} \times (\boldsymbol{p} - g\, \boldsymbol{A})\, \psi \, d^3x,$$

$$\boldsymbol{S}^g \;=\; \int \boldsymbol{E}^a \times \boldsymbol{A}^a_{phys} \, d^3x,$$

$$\boldsymbol{L}^g \;=\; \int E^{aj} \, (\boldsymbol{x} \times \nabla) \, A^{aj}_{phys} \, d^3x \;+\; g \int \psi^\dagger \, \boldsymbol{x} \times \boldsymbol{A}_{phys} \, \psi \, d^3x$$

Wakamatsu; Jaffe, Manohar; Jaffe, Bashinsky; Brodsky; Chen et al.

- gives rise to proton helicity ("spin") sum rule:



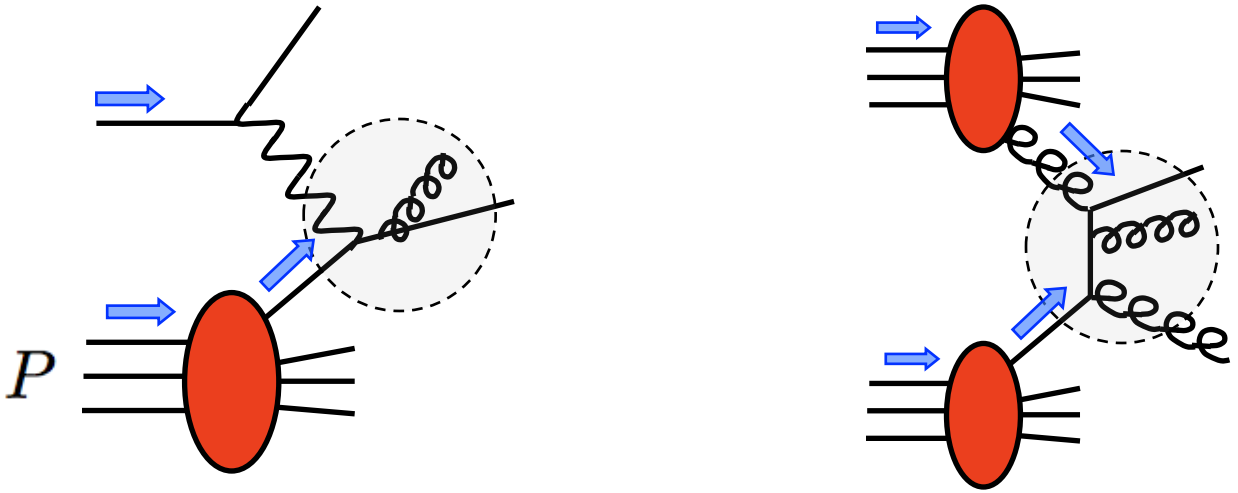
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$$\Delta\Sigma = \int_0^1 dx \Big[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\Big](x)$$

$$\Delta G = \int_0^1 dx\, \Delta g(x)$$

- known for past ~25 years: $\Delta\Sigma \sim 0.25 \ll 1$

(2) Δq, Δg and short-distance QCD



$$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx \, \Delta f(x,Q^2) \, \Delta\hat{\sigma}^f(xP, \alpha_s(Q^2)) + \ldots$$

universal !

$$\Delta\sigma = \sum_{a,b=q,\bar{q},g} \int dx_a \, \Delta f_a(x_a,p_\perp^2) \int dx_b \, \Delta f_b(x_b,p_\perp^2) \, \Delta\hat{\sigma}^{ab}(x_aP, x_bP', \alpha_s(p_\perp^2)) + \ldots$$

$$\Delta\hat{\sigma} = \Delta\hat{\sigma}_{\rm LO} + \alpha_s \Delta\hat{\sigma}_{\rm NLO} + \ldots$$

- Many higher-order calculations for polarized ep, pp:

  Jäger,Schäfer,Stratmann,WV; Signer et al.; Gordon, WV; Contogouris et al.; Stratmann,Bojak; Gehrmann; Kamal; Smith,van Neerven,Ravindran;Nadolsky, Yuan …

- DGLAP evolution:

$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} \begin{pmatrix} \Delta q(x,\mu^2) \\ \Delta g(x,\mu^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} \left(\frac{x}{z},\mu^2\right)$$

$$\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta\mathcal{P}_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta\mathcal{P}_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta\mathcal{P}_{ij}^{\mathrm{NNLO}} + \dots$$

Ahmed,Ross Altarelli,Parisi,… 1977

Mertig, van Neerven WV 1995

Moch, Rogal, Vogt, Vermaseren 2008 (ij = qq,qg)

- by now, complete NLO framework available

(3) Δq, Δg "beyond the proton spin sum rule"

Models of nucleon structure, e.g.:

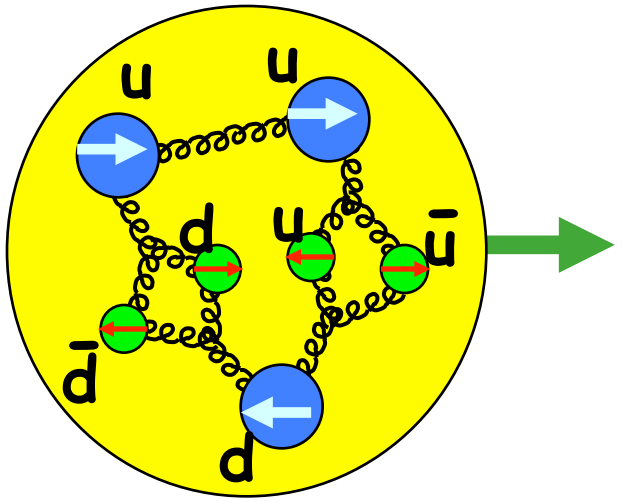
- valence region

$$\frac{\Delta d}{d} \xrightarrow{x \to 1} \begin{cases} 1 & \text{counting rules/pQCD} \\ -1/3 & \text{constituent quark model} \end{cases}$$

- flavor / sea structure

$$\Delta\bar{u} \text{ vs. } \Delta\bar{d}$$

large-N_c,
chiral quark models,
meson cloud,...



Lattice (see talks by Alexandrou,Bali, Ohta)

- connection to hyperon β decays, SU(3)

$$\Delta\Sigma_q \equiv \int_0^1 dx\,(\Delta q + \Delta\bar{q})\,(x,Q^2) \;\propto\; \langle\, P,s \,|\, \bar{\psi}_q\,\gamma^\mu\gamma_5\,\psi_q \,|\, P,s \,\rangle$$

(axial charges)

Bjorken;
Ellis, Jaffe;
Sehgal;
Karliner, Lipkin;
Ratcliffe;…

$$\Delta\Sigma_u - \Delta\Sigma_d \;=\; g_A = 1.257 \pm \ldots$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s \;=\; 3F - D \;=\; 0.58 \pm 0.03 \quad ?$$

Savage, Walden

- strangeness?

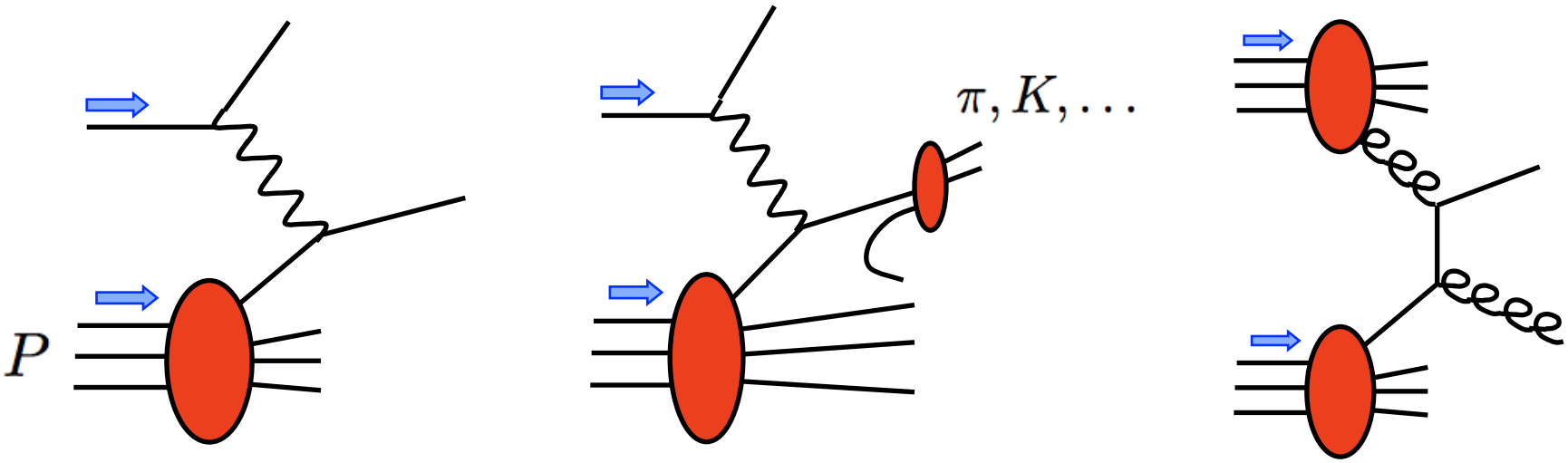
$$\Delta\Sigma \;=\; \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s \;=\; 3F - D + 3\Delta\Sigma_s$$

$\Delta q, \Delta g$: "Global analysis"

First NLO ($\overline{\text{MS}}$) "global analysis" of all DIS & RHIC data sets:

"DSSV" de Florian, Sassot, Stratmann, WV PRL 101, 2008

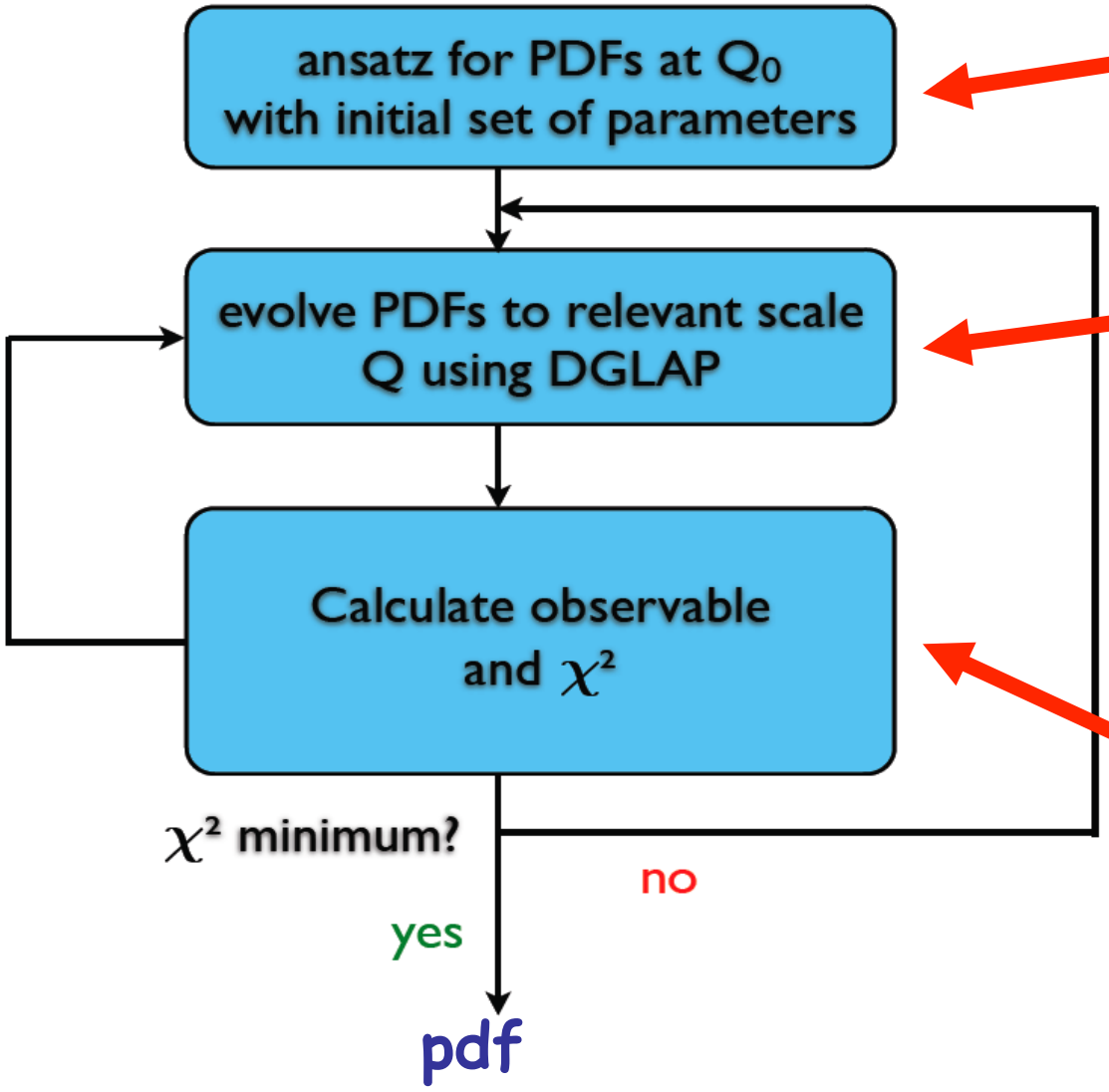
PRD 80, 2009



DIS **SIDIS** **pp**

- other recent analyses of DIS data :

  Blümlein, Böttcher; Leader, Stamenov, Sidorov; Forte et al. (NNPDFs)



$$\Delta q(x, Q_0^2),\ \Delta g(x, Q_0^2)$$

$$\propto N x^{\alpha}(1-x)^{\beta}\,(1+\gamma x+\ldots)$$

$$\Delta q(x, Q^2),\ \Delta g(x, Q^2)$$

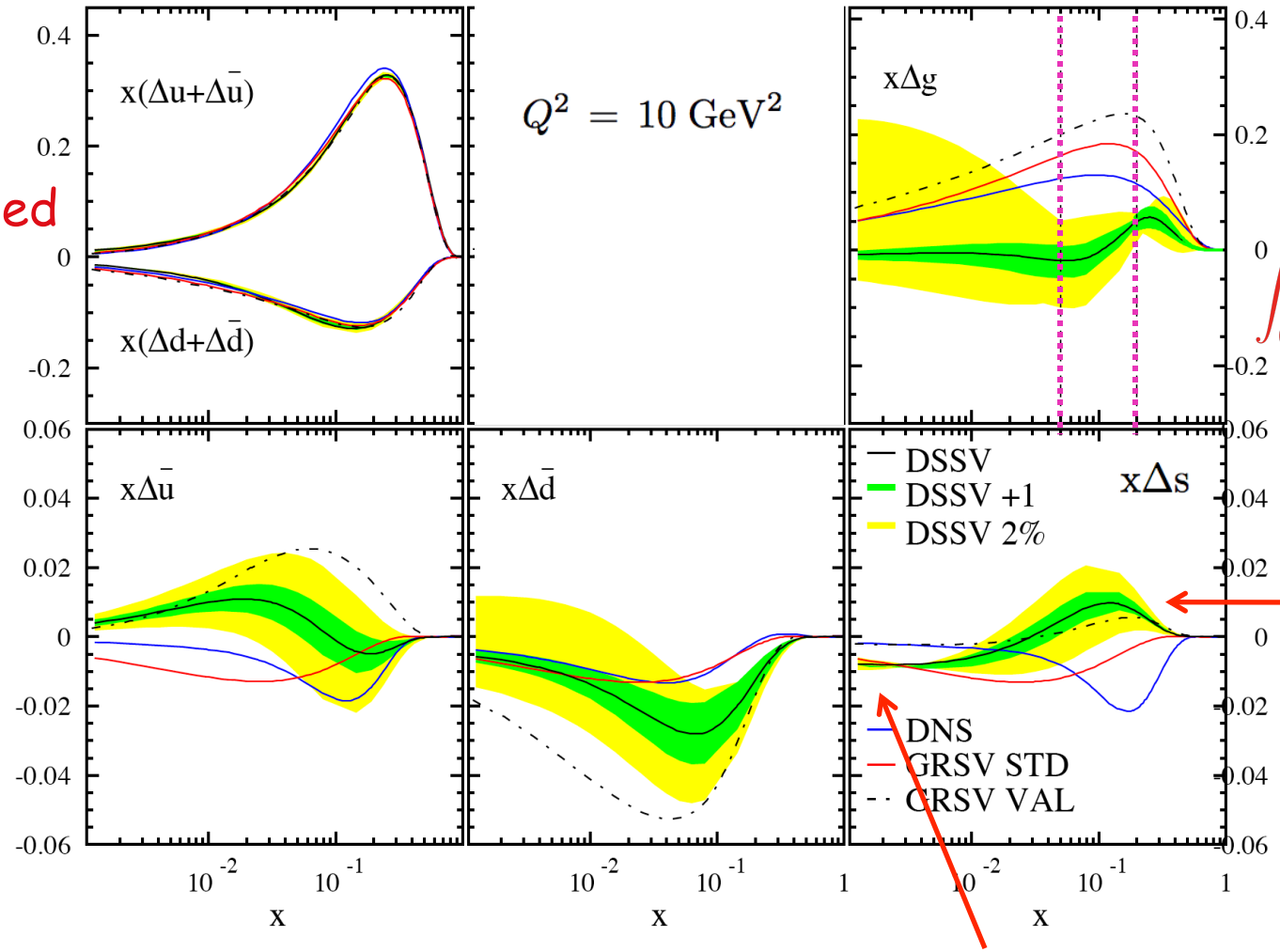
need ~1000s of Times!

-> a problem in computational physics

Status ~ 2009 :

best constrained

driven by SIDIS



small in measured regime !

$$\int_{0.05}^{0.2} dx\, \Delta g \approx 0$$

SIDIS

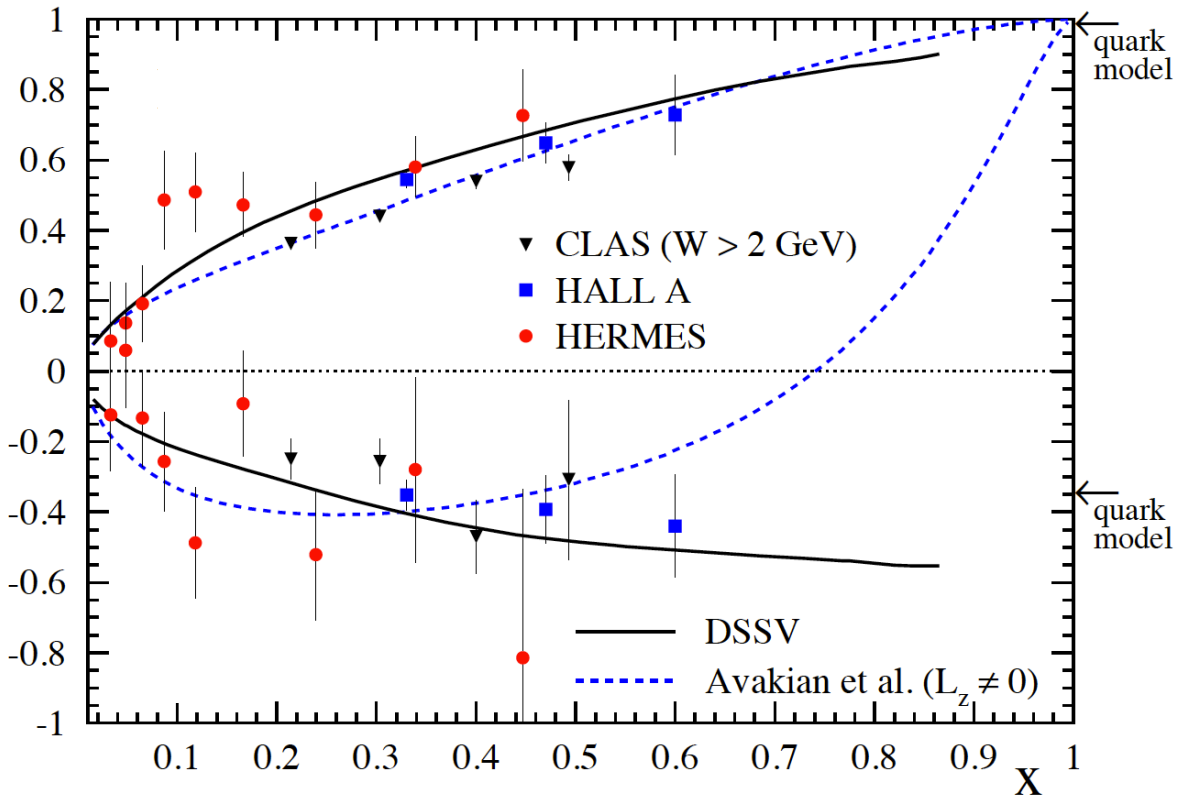
indications for $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

DIS + SU(3)

strangeness puzzle?

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

$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}}$$



Latest developments …

New data !

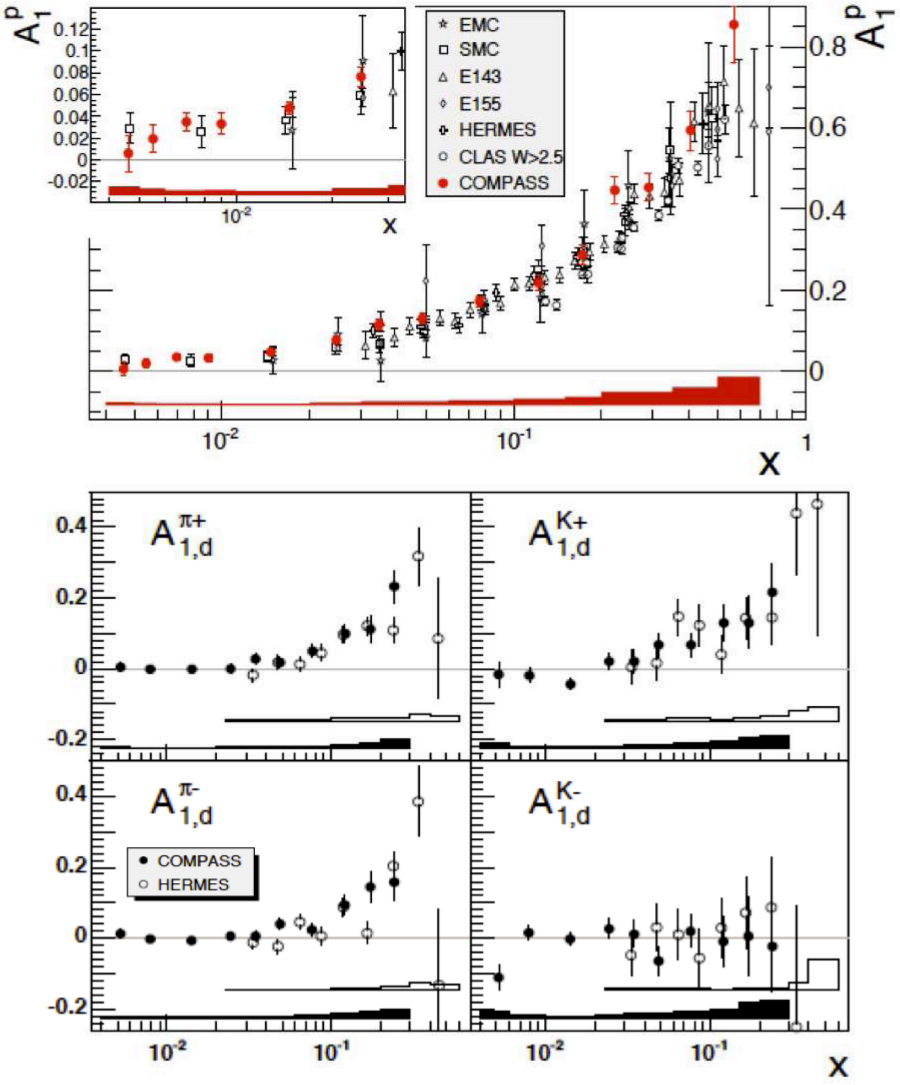
(1) Precise COMPASS DIS and SIDIS data:

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

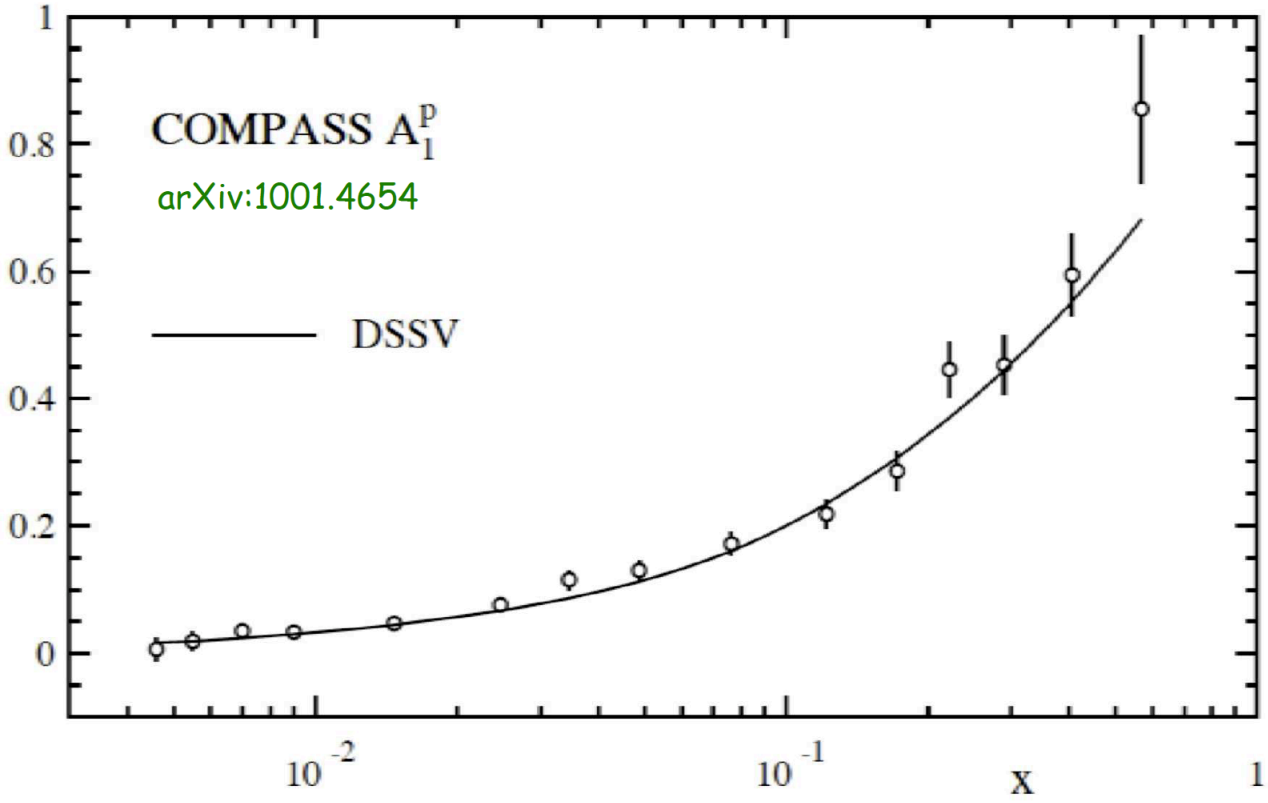
- **SIDIS:** $A_{1,d}^{\pi,K}$ from COMPASS
  arXiv:0905.2828

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

extended x coverage w.r.t. HERMES

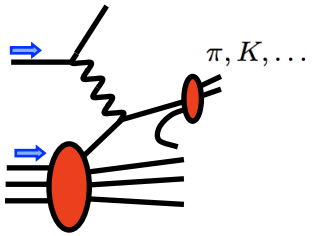


(M.Stratmann at DIS 2011)



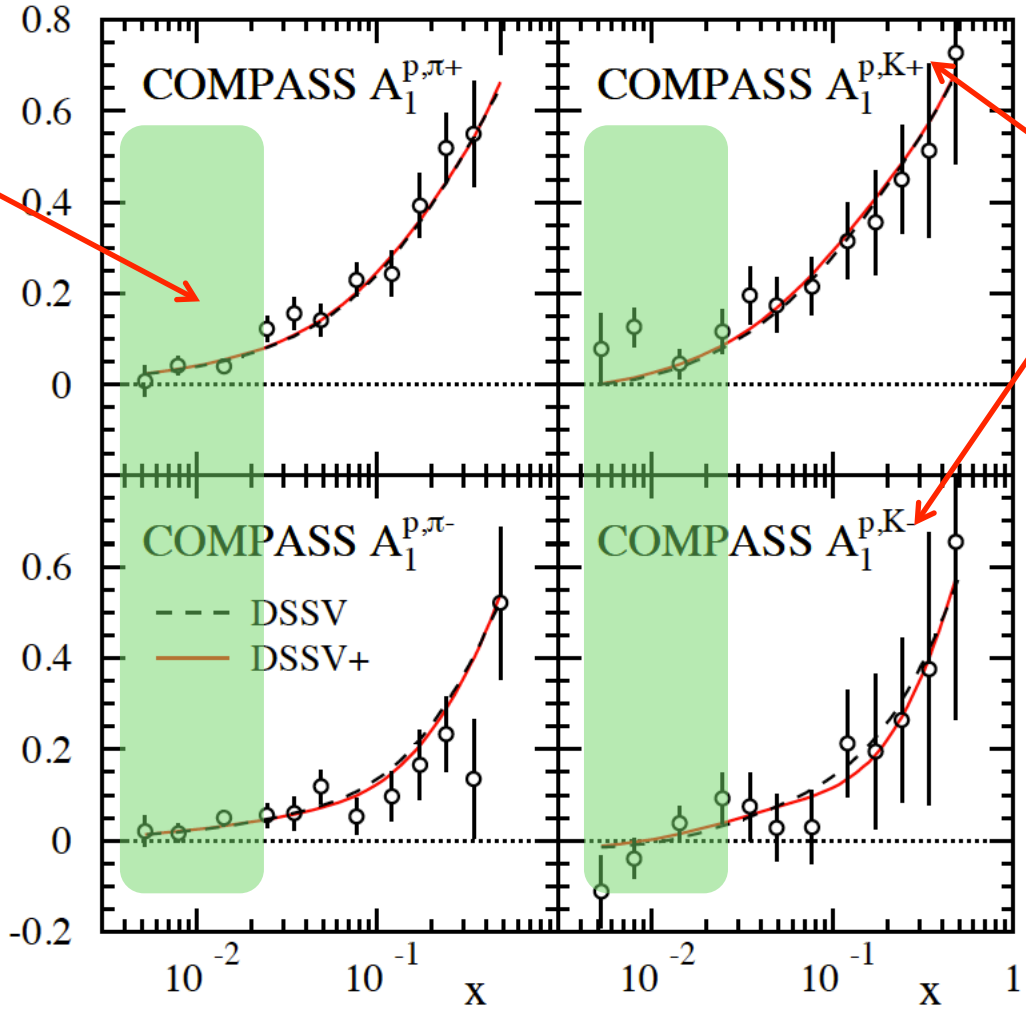
✔

- COMPASS semi-inclusive data:



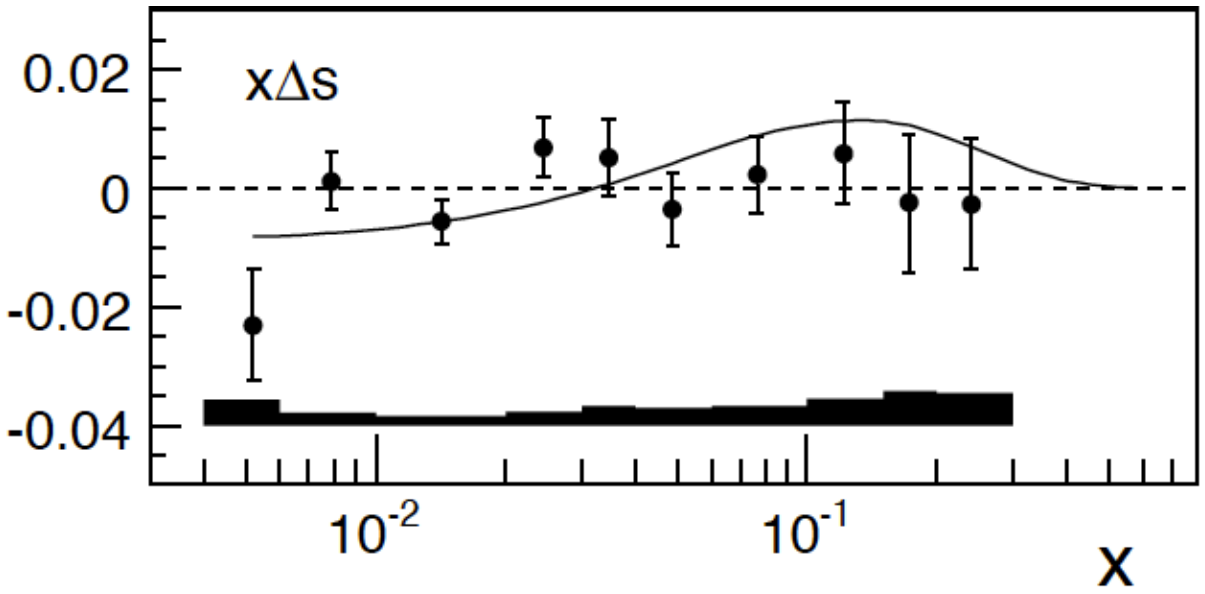
not covered by HERMES

not available from HERMES



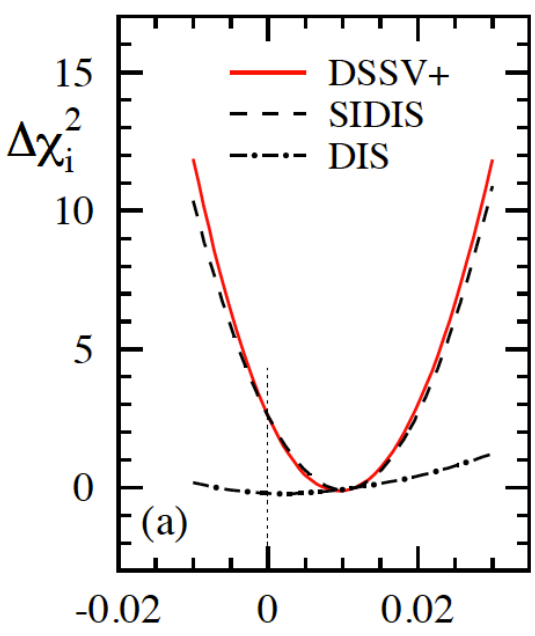
- refit: trend for $\Delta\bar{u} - \Delta\bar{d} \neq 0$ now less pronounced

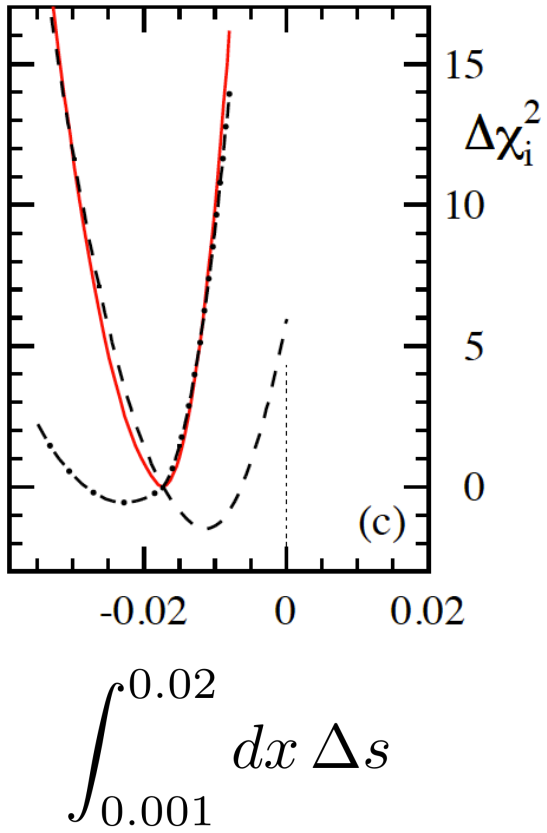
- implications for Δs ?



(COMPASS LO extraction,
see talk by E. Kabuss)

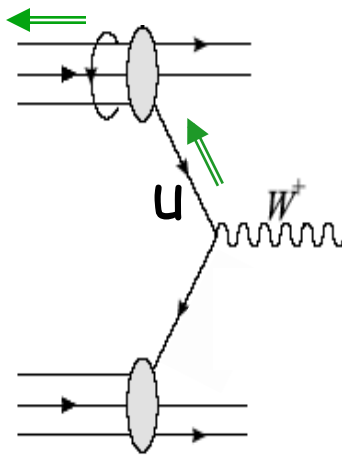
(M.Stratmann at DIS 2011)





- tendency toward negative low-x Δs also from SIDIS ?
- lattice ? (see talk by G. Bali)

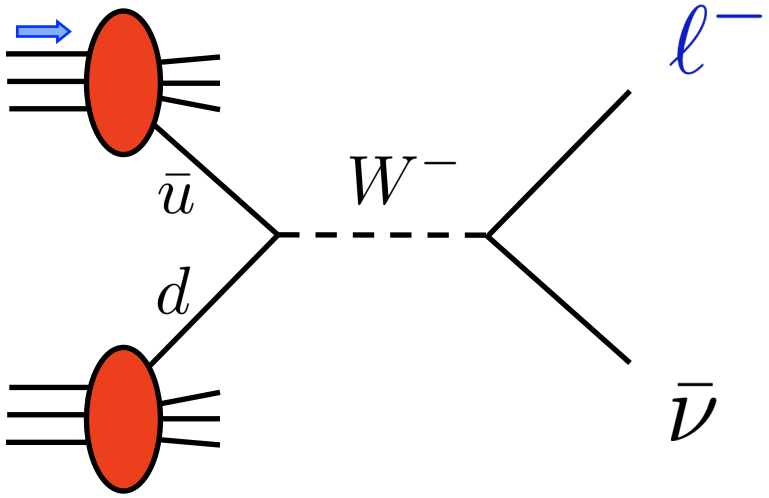
(2) RHIC sees W bosons !



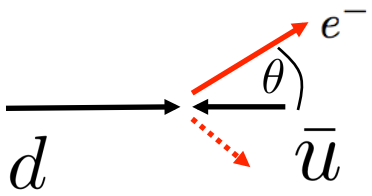
unpol.

$$\sqrt{s} = 500 \text{ GeV}$$

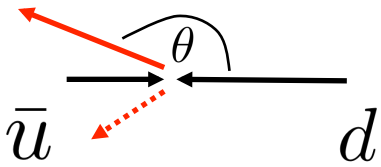
- large Parity Violation effect $A_L = \dfrac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$
- complementary to SIDIS – very "clean"
- new NLO for polarized case: de Florian, WV



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



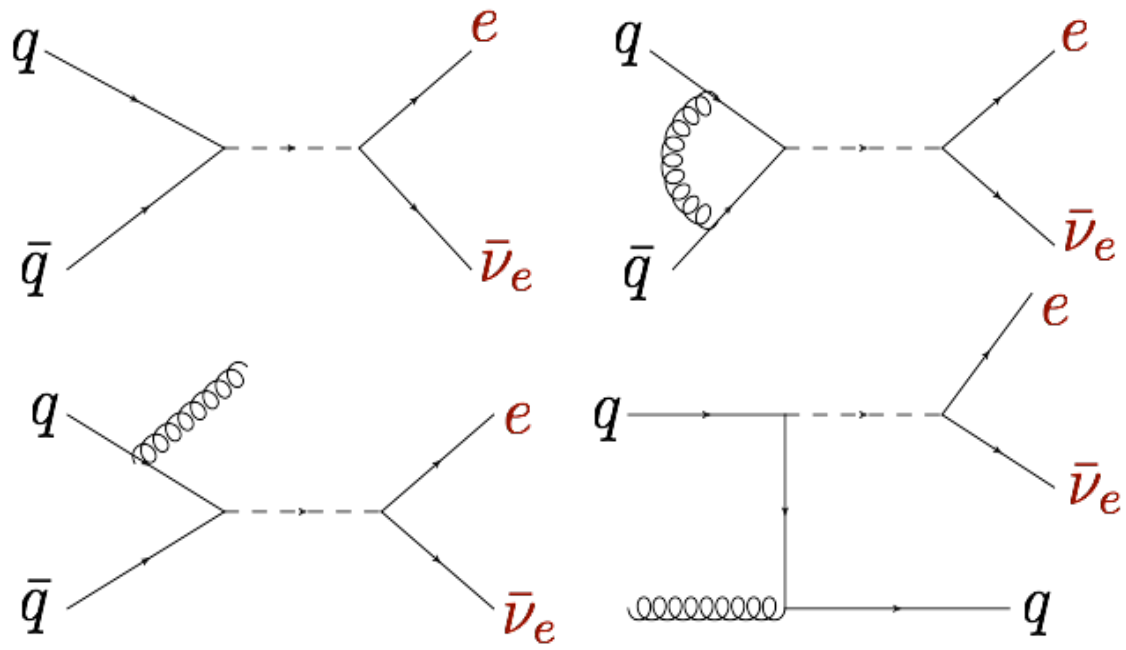
$$\sim (1+\cos\theta)^2$$



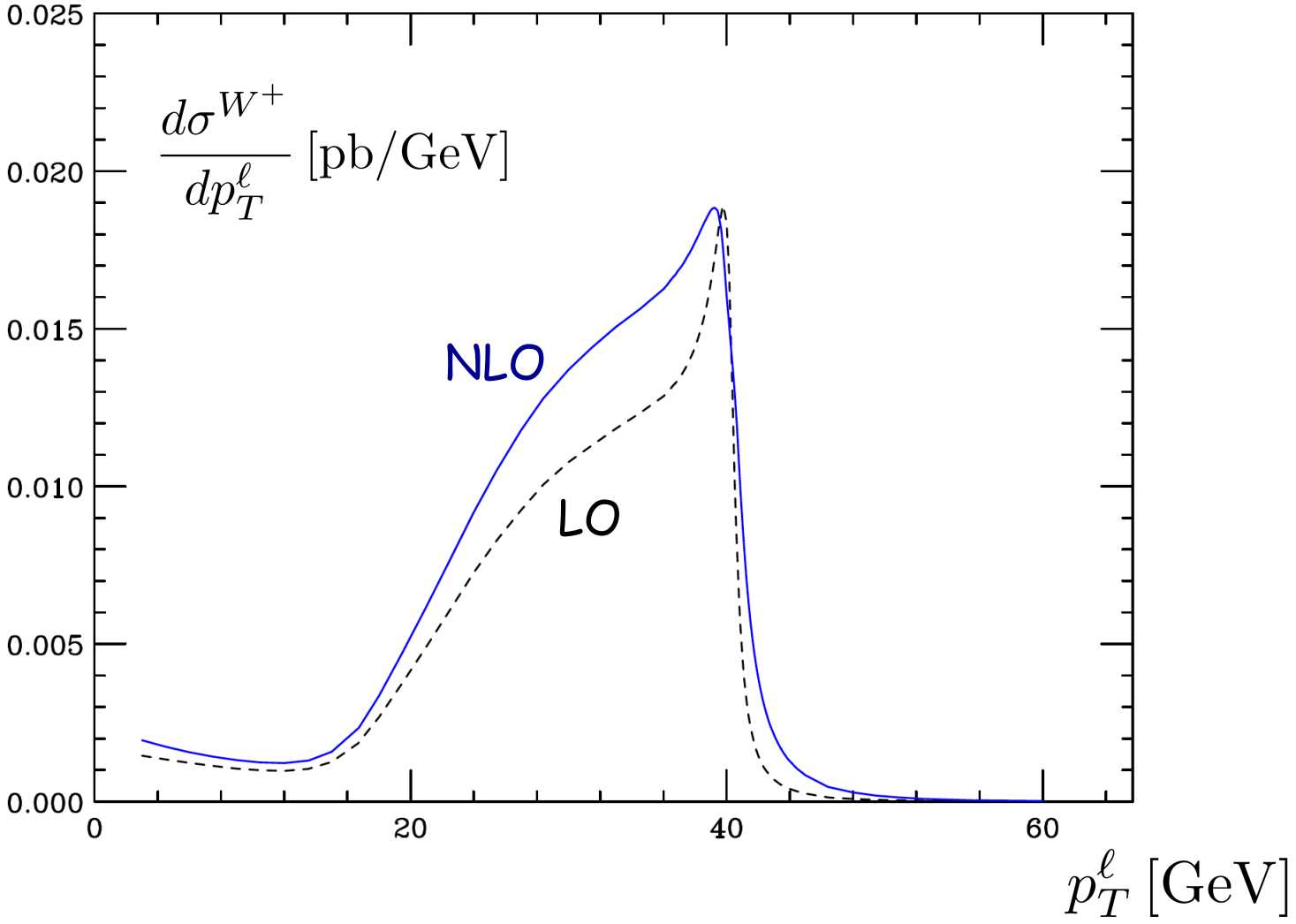
$$\sim (1-\cos\theta)^2$$

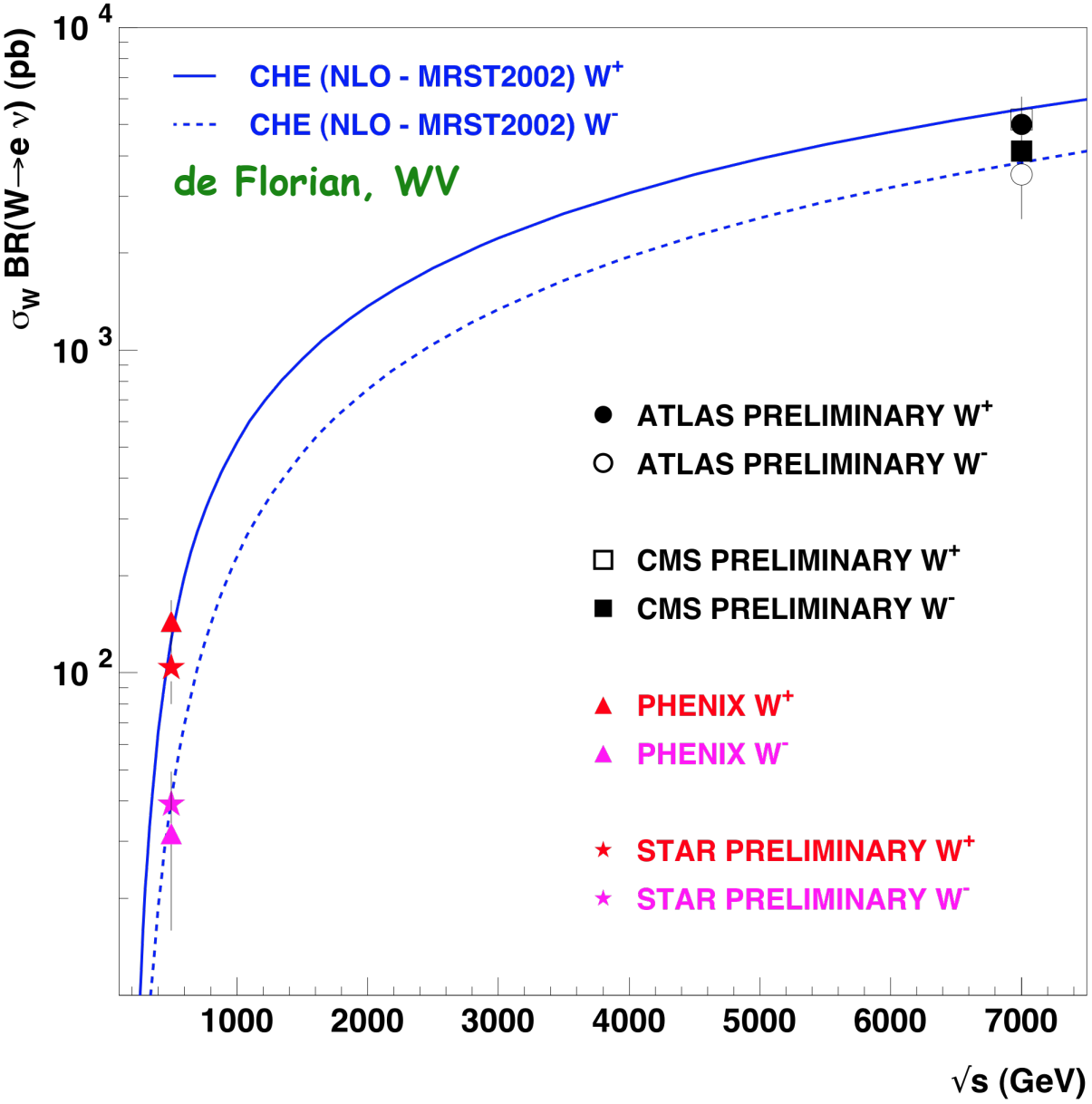
some NLO diagrams:

de Florian, WV



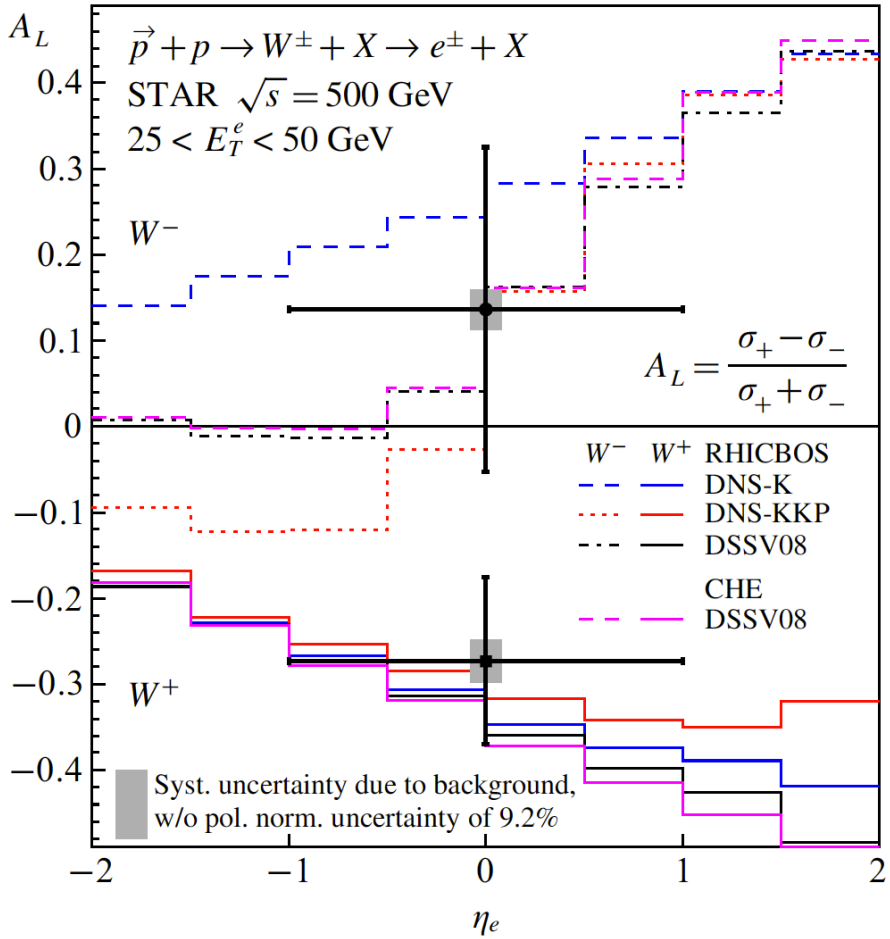
F. Ringer, WV


0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
$\frac{d\sigma^{W^+}}{dp_T^\ell}$ [pb/GeV]
NLO
LO
p_T^ℓ [GeV]

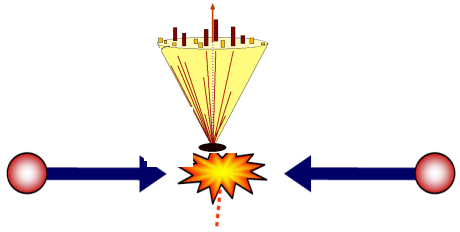


B. Surrow (STAR)

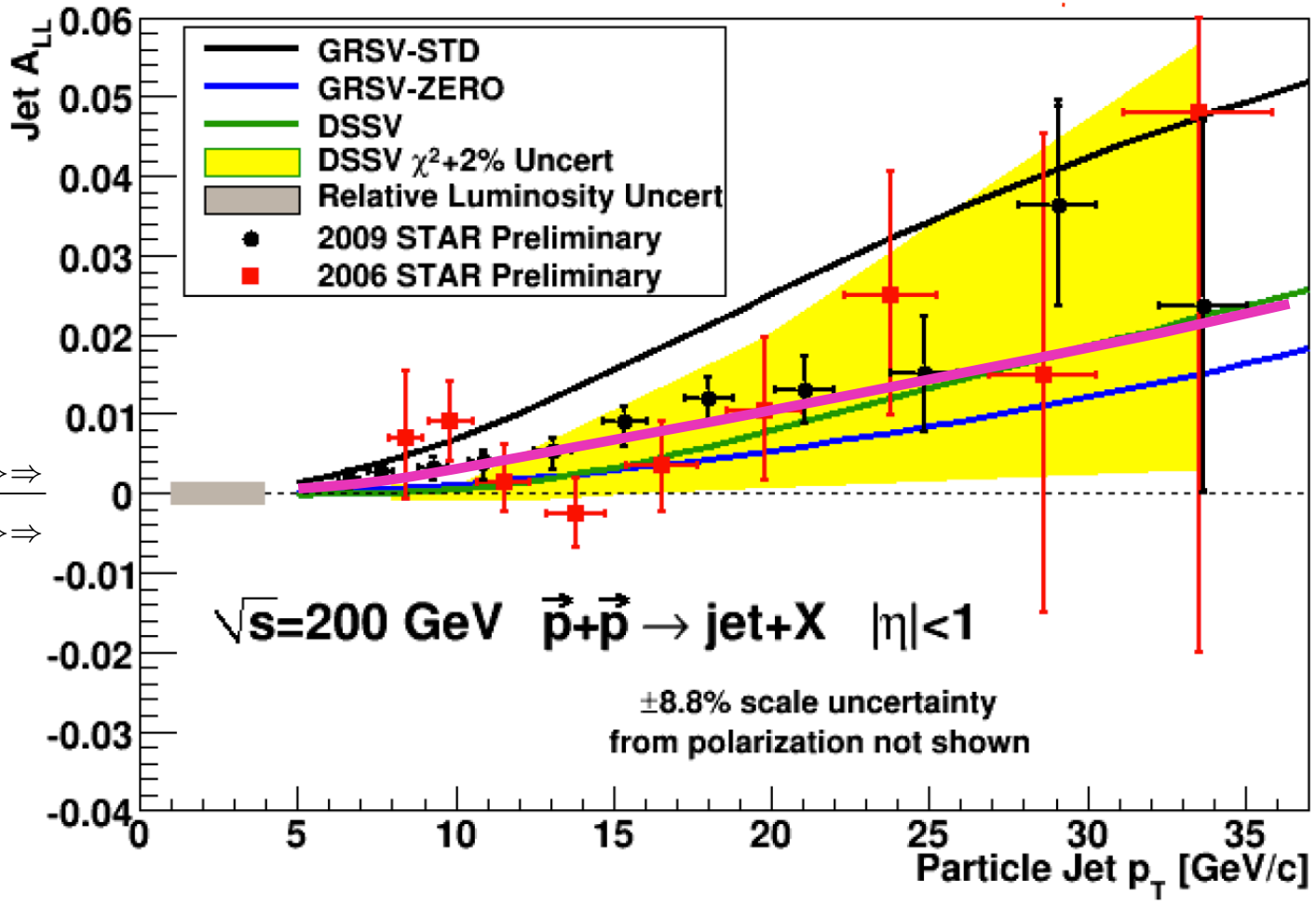
STAR (also Phenix)



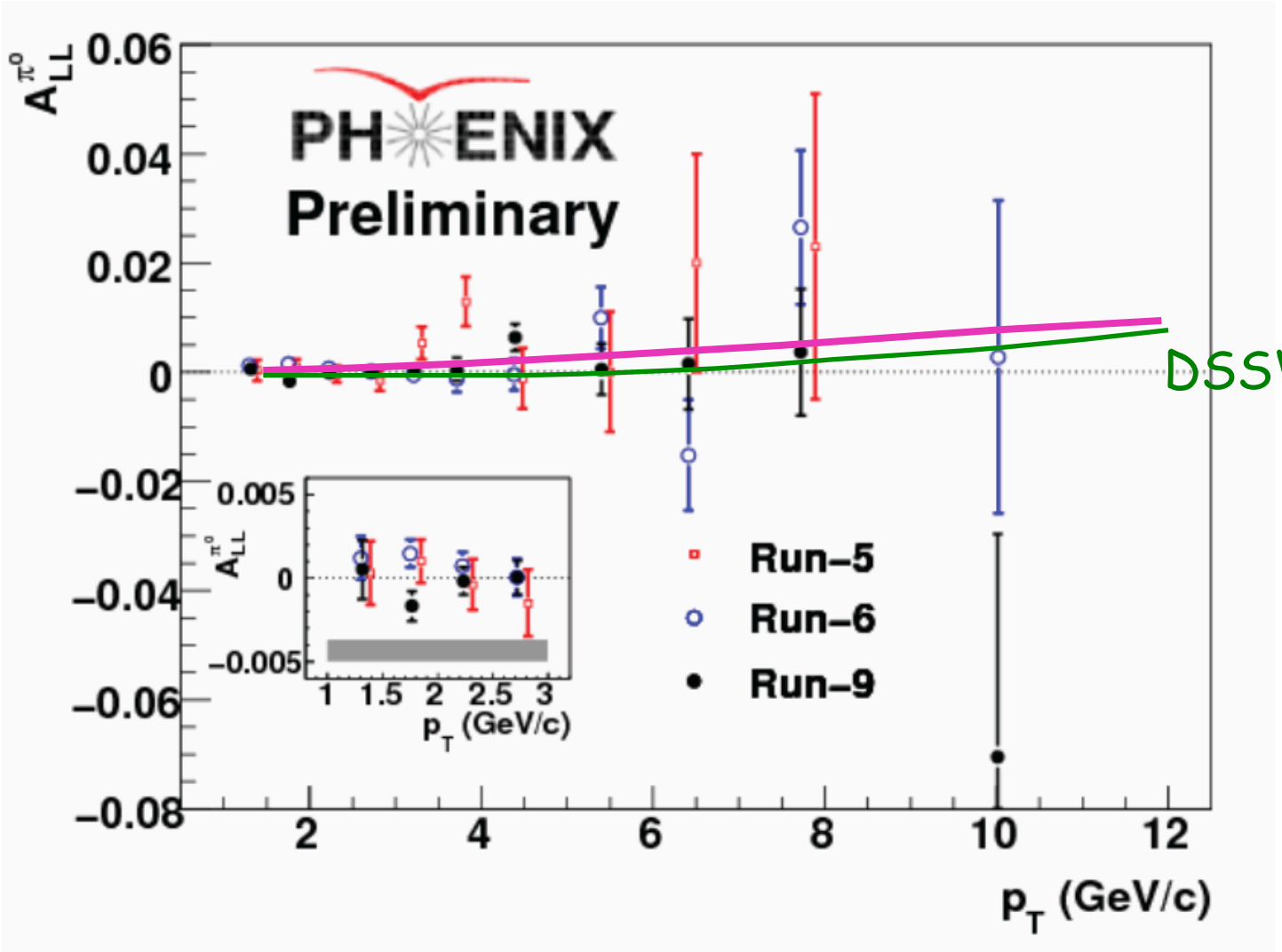
(3) New devlopments on Δg



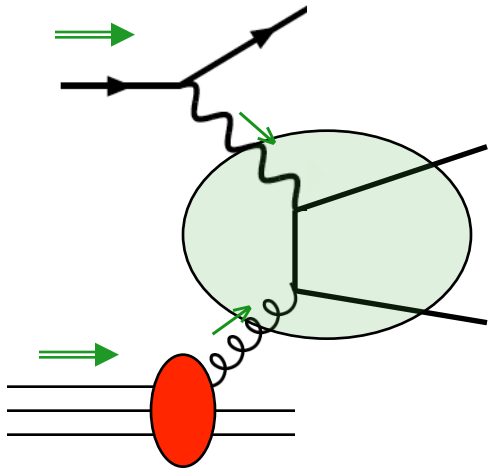
$$A_{LL} = \frac{\sigma_{\Rightarrow\Leftarrow} - \sigma_{\Rightarrow\Rightarrow}}{\sigma_{\Rightarrow\Leftarrow} + \sigma_{\Rightarrow\Rightarrow}}$$

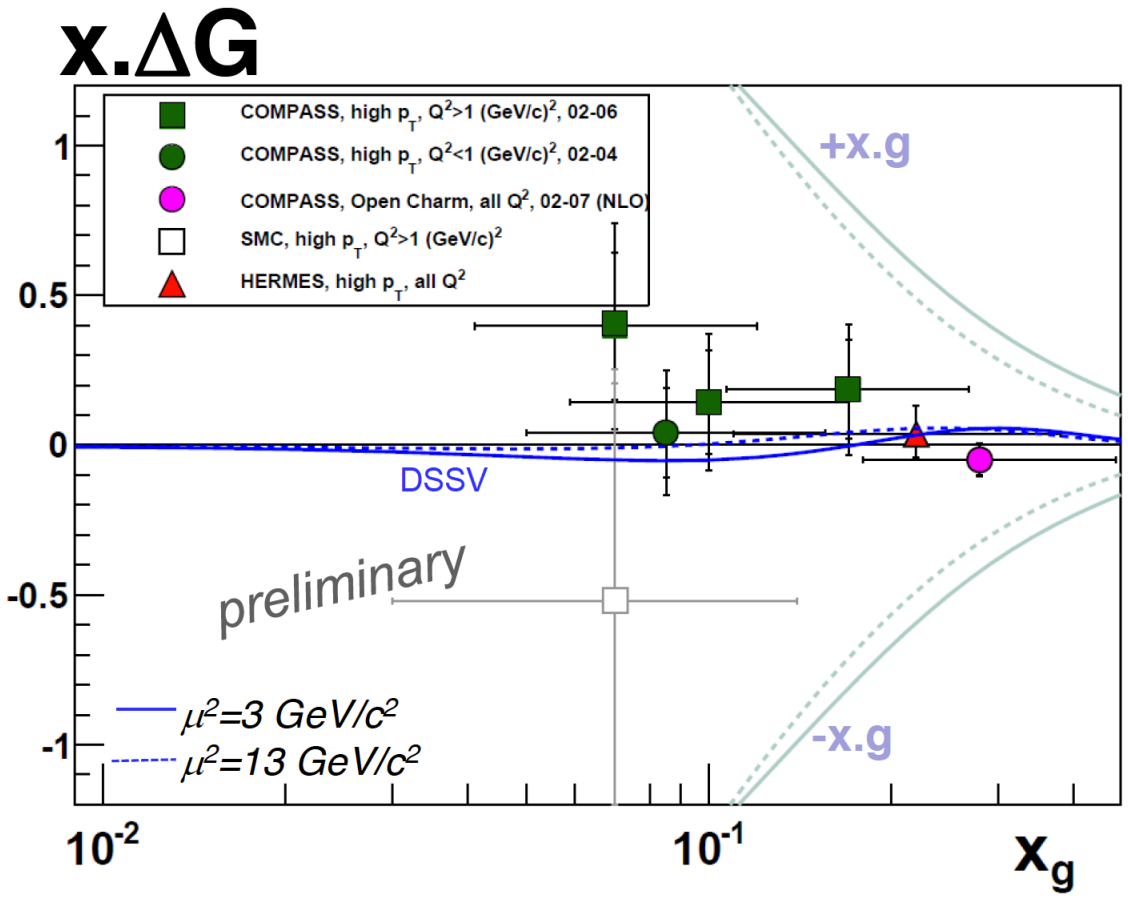


- gives gluon with $\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$


PHENIX
Preliminary
$A_{LL}^{\pi^0}$
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
2
4
6
8
10
12
p_T (GeV/c)
DSSV
Run−5
Run−6
Run−9
0.005
0
−0.005
1
1.5
2
2.5
3
p_T (GeV/c)

Most recent COMPASS data:





to be included in global analysis

Conclusions:

- ever-improving picture of nucleon's helicity distributions
- yet, many open questions remain:
  - are gluons polarized after all ?
  - are there flavor asymmetries in pol. sea ?
  - what exactly is the role of strangeness ?
  - AND:

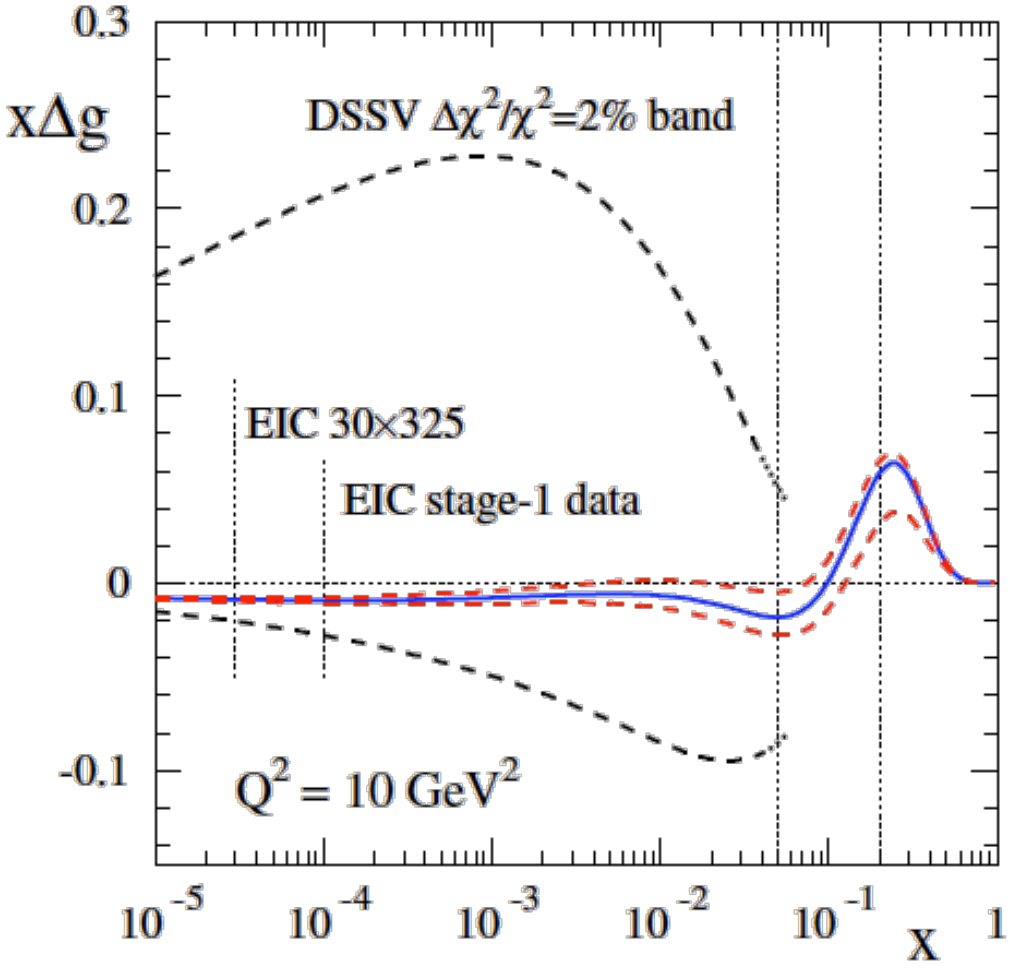
    What *is* the nucleons partonic spin budget ?

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

25-30% 20% ??

- have powerful experimental tools: COMPASS,RHIC,JLab

- the future: Electron-Ion Collider (EIC) ?



Sassot, Stratmann