Longitudinal Spin Effects
Present and Future

Marcin Stolarski, LIP-Lisboa

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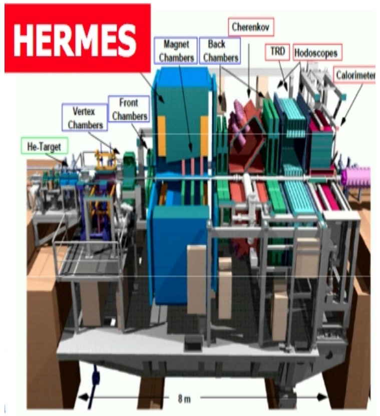
Disclaimer

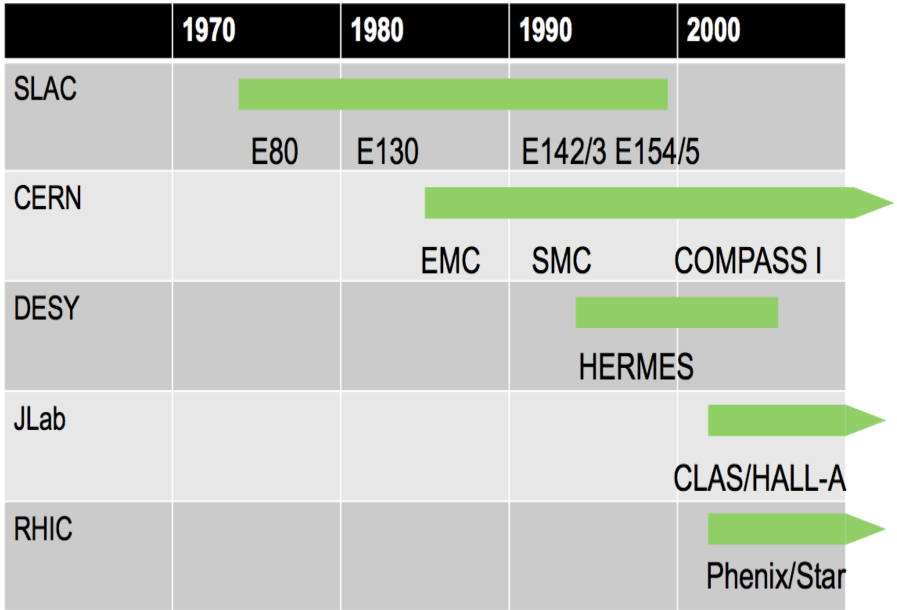
- unfortunately due to civil obligation Abhay Deshpande could not come to the Lisbon meeting
- I was asked to give the talk instead of him few days ago,
- I apologize for quality of some plots (I couldn't get better in due time)
- due to short notice I will give just a short review concentrated mostly on flavour separation and gluon polarization inside the nucleon
- I would like to thank Abhay for giving me access to some of his talks

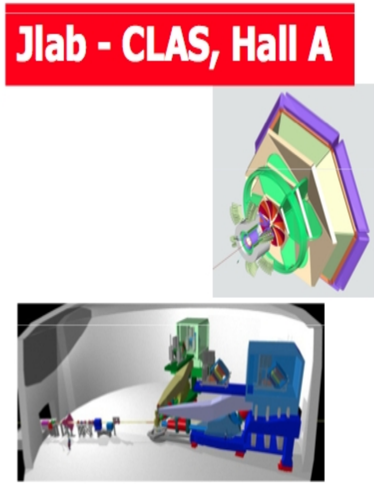
Spin of the Nucleon

- spin of the nucleon ($S_N = 1/2$) can be decomposed as:
  - $\Delta\Sigma$ - quark contribution to the nucleon spin
  - ΔG - gluon contribution
  - ΔL_q,ΔL_g - orbital momentum of quarks and gluons
- $S_N = 1/2 = 1/2\Delta\Sigma + \Delta G + \Delta L_q + \Delta L_g$
- in the simplest QPM model: $S_N = 1/2\Delta\Sigma$
- the direct measurement: $\Delta\Sigma \approx 0.3$
- how much is then ΔG?
- what are the contributions of different falvours to the nucleon spin?

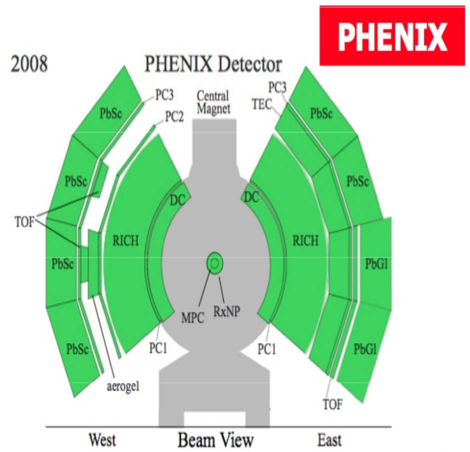
The experiments...

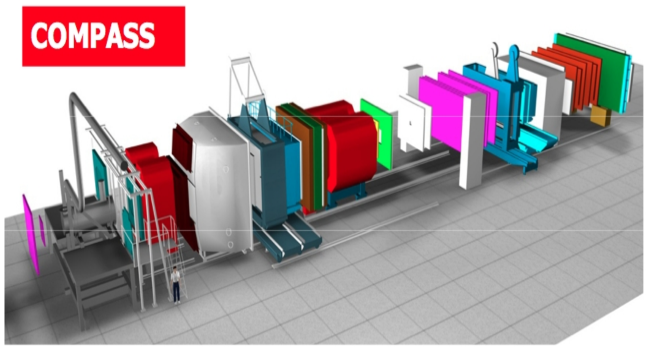


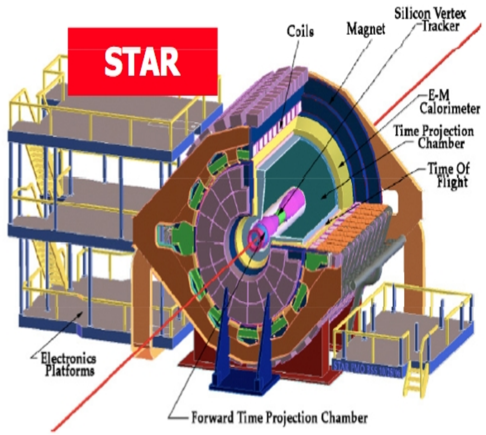




- A worldwide effort since decades

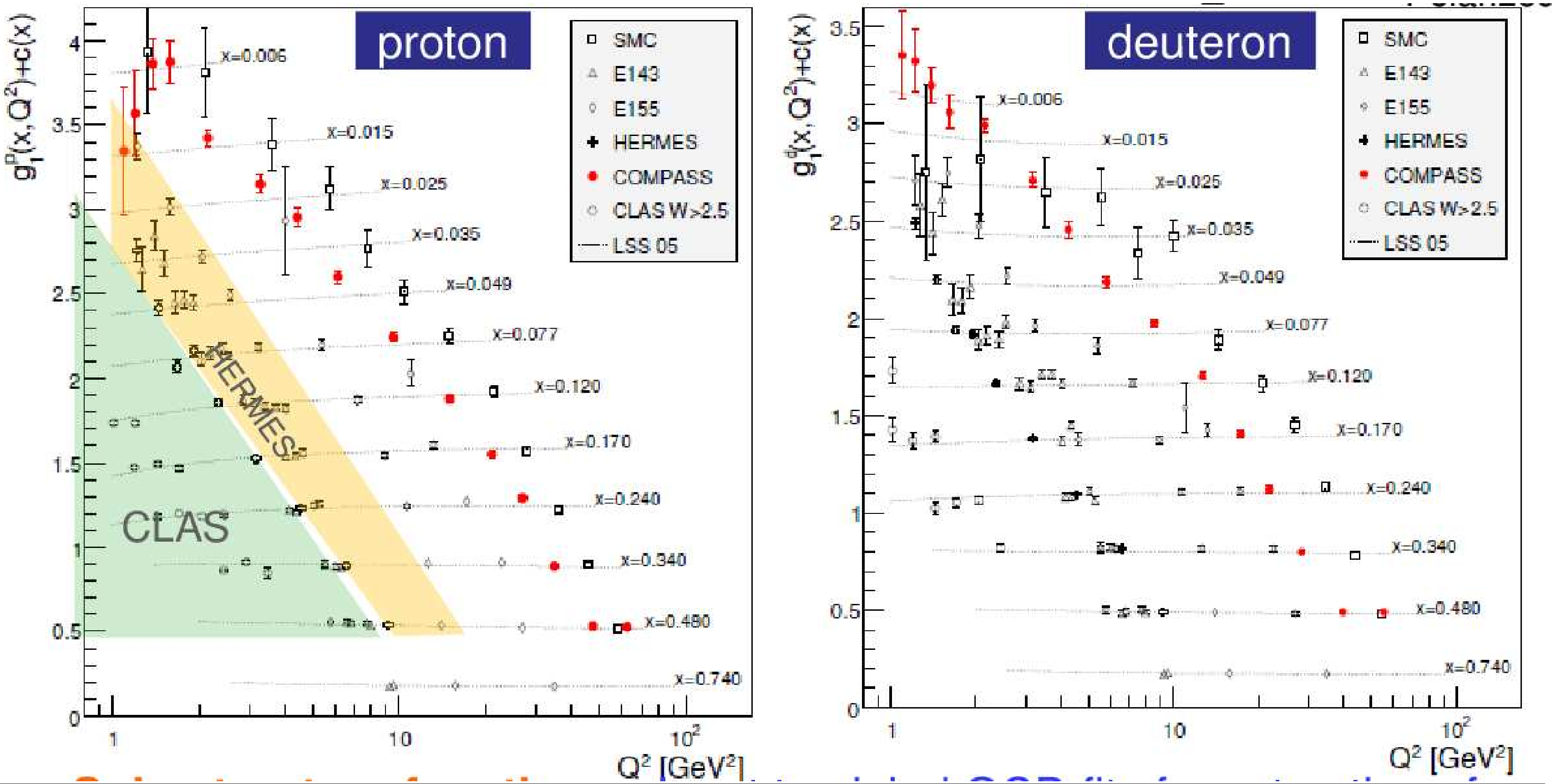






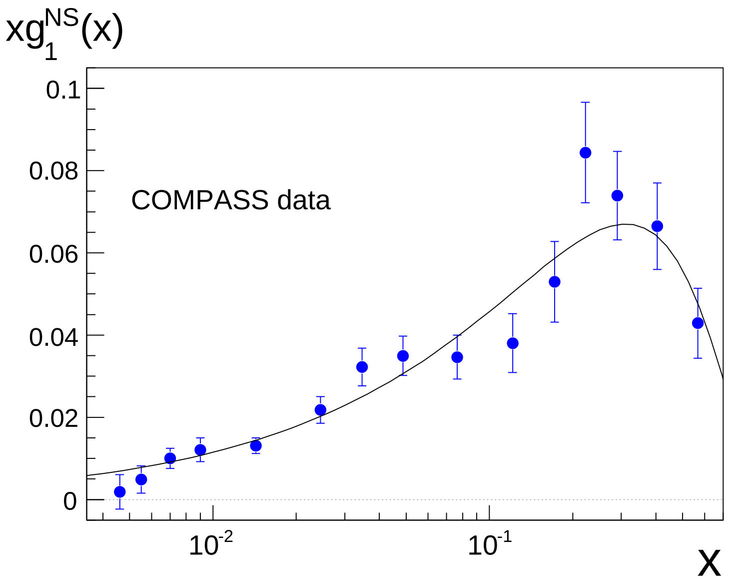
Spin Dependent Structure Function $g_1^{p,n}$

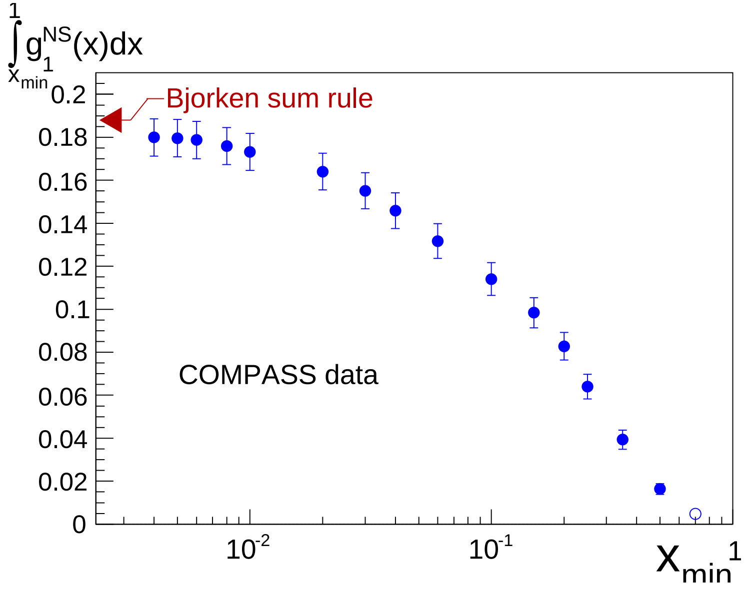
- $g_1 = 1/2 \sum_{q_i} e_i^2 \Delta q(x)$
- the knowledge of the spin dependent structure function g_1 is for the moment limited to fixed target experiments
- this leads to a limited Q^2 coverage at fixed x - low sensitivity to scaling violation *i.e.* gluon polarization



Test of the Bjorken Sum Rule

- $g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^d(x,Q^2)$
- $g_1^{NS}(x,Q^2)$ is interesting because its Q^2 dependence decouples from the singlet and gluon densities
- $\int_0^1 g_1^{NS}(x,Q^2) = \Gamma_1^{NS} = \frac{1}{6}\frac{g_A}{g_V}C_1^{NS}(Q^2)$,
  where $C_1^{NS}(Q^2)$ has been calculated in pQCD up to $\alpha_s^3(Q^2)$
- $\frac{g_A}{g_V}$ can be obtained from neutron beta decay: $\frac{g_A}{g_V} = 1.2694 \pm 0.0028$

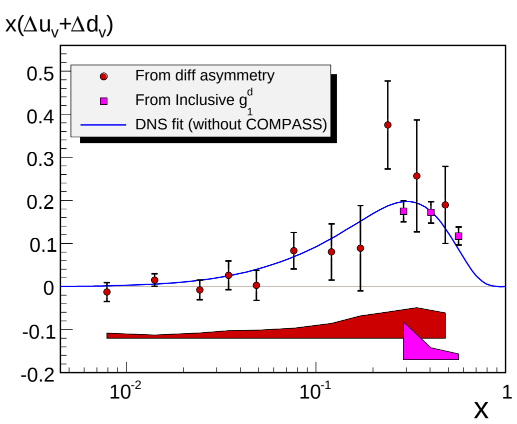


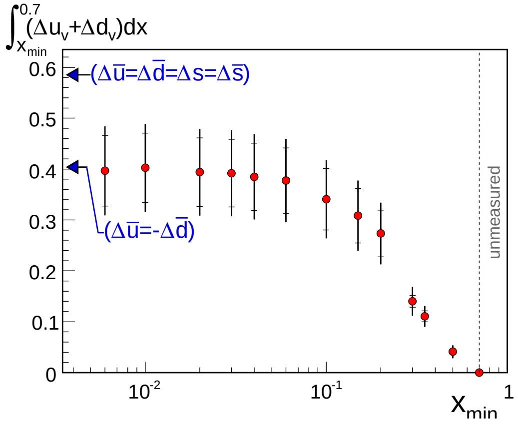


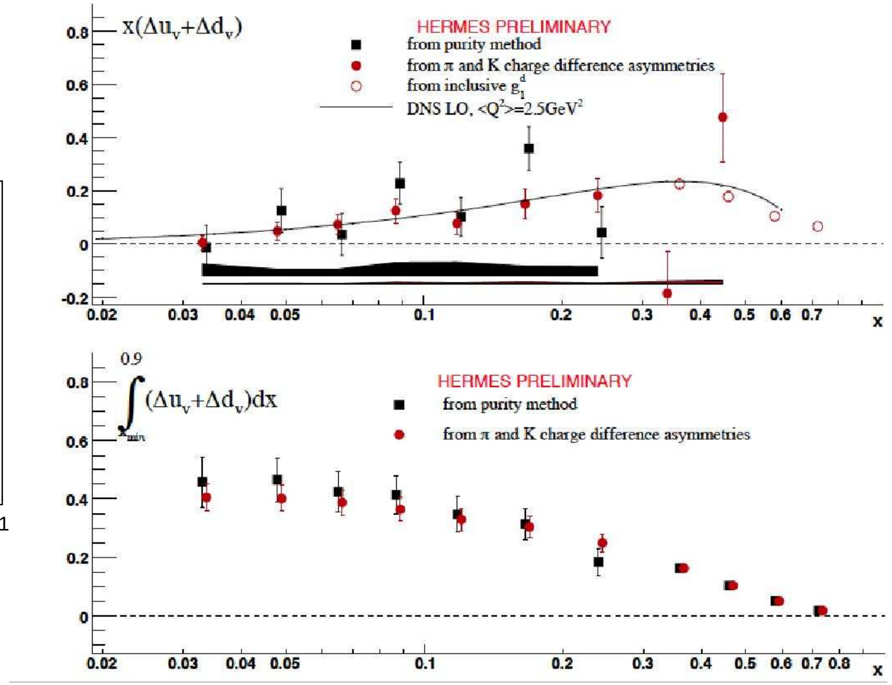
COMPASS result: $\frac{g_A}{g_V} = 1.28 \pm 0.07 \pm 0.10$

Semi-Inclusive asymmetries for non–identified hadrons

- assuming charge conjunction in the fragmentation process, one can write:
- $A_{1,d}^{h^+-h^-} = \frac{\Delta u_v(x) - \Delta d_v(x)}{u_v(x) + d_v(x)}$
- what is the contribution of valence quarks to the nucleon spin?
- Is the polarization of the sea flavour symmetric or not?

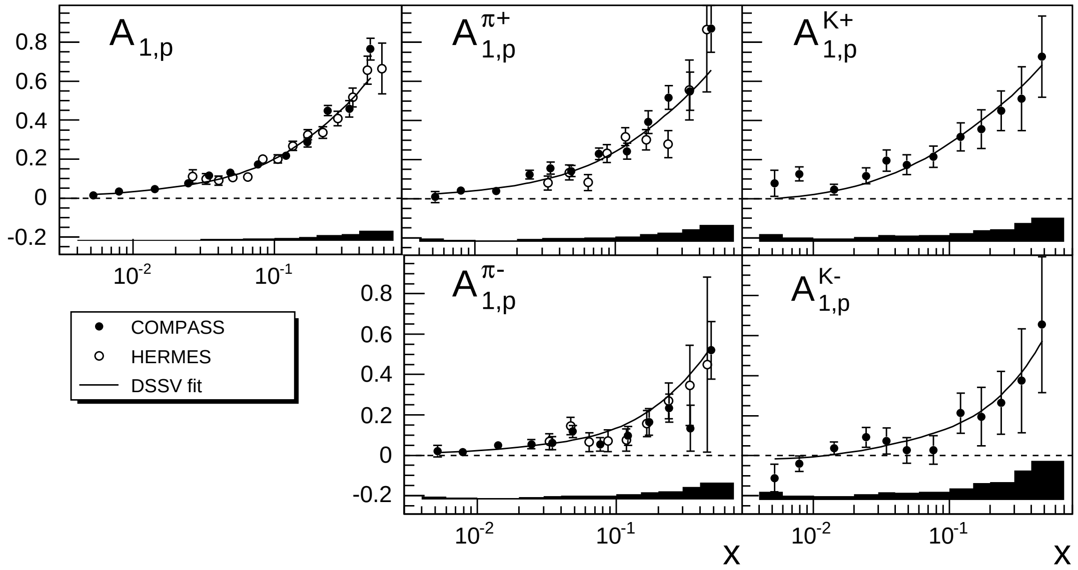






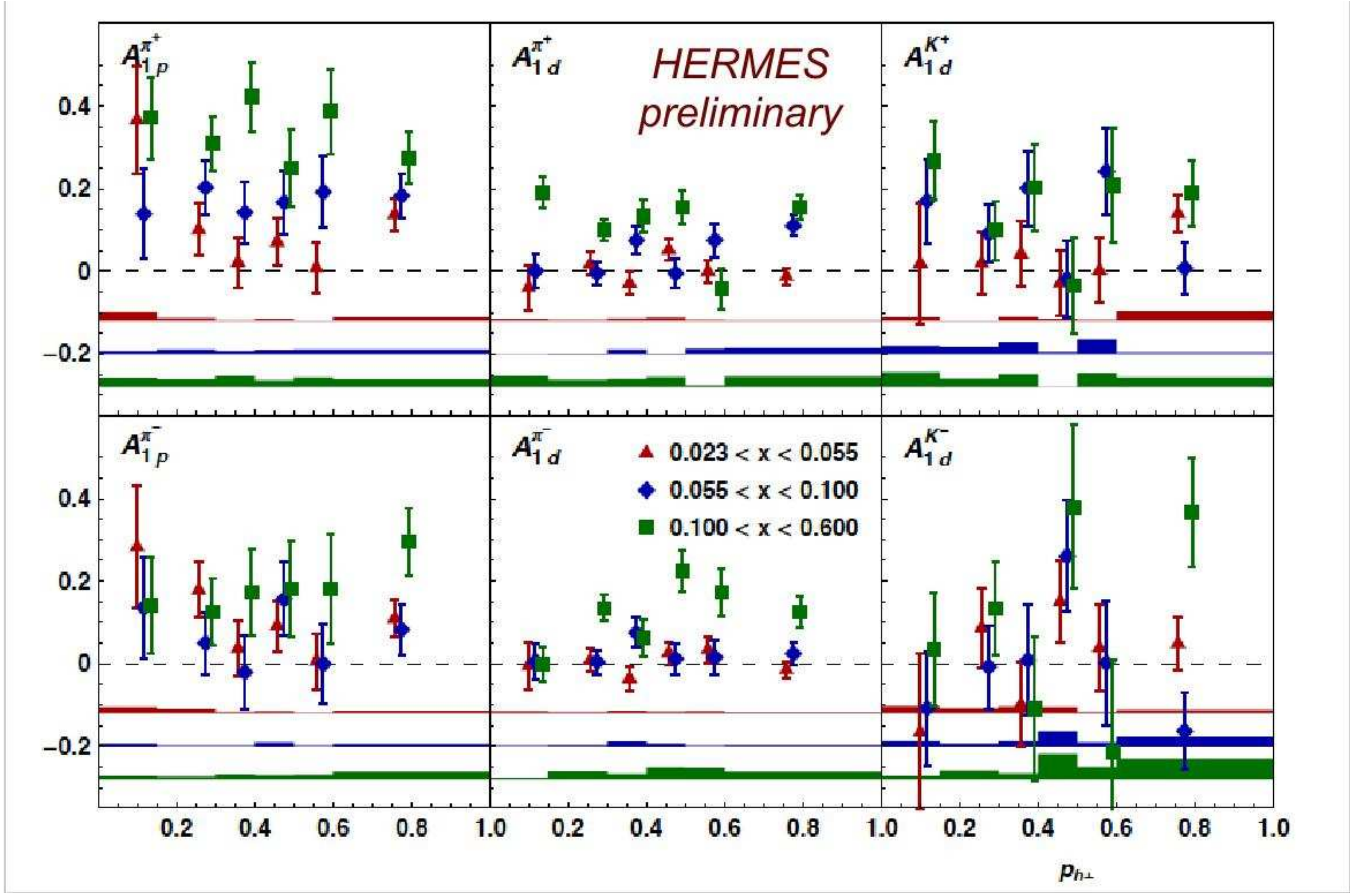
Semi-Inclusive Asymmetries

- semi-inclusive asymmetries were measured on both p and d targets in HERMES and COMPASS
- recently for the first time kaon asymmetries were measured on p target
- in LO approximation $A_1^h(x, Q^2, z) = \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q(z,Q^2)}$
- D_q^h is the fragmentation function of quark q into hadron h (FF)
- with 10 asymmetries ($A_{1p,d}^{incl}, A_{1p,d}^{\pi\pm}, A_{1p,d}^{K\pm}$) and 5 (6) unknown parameters ($\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s$) flavour separation is possible

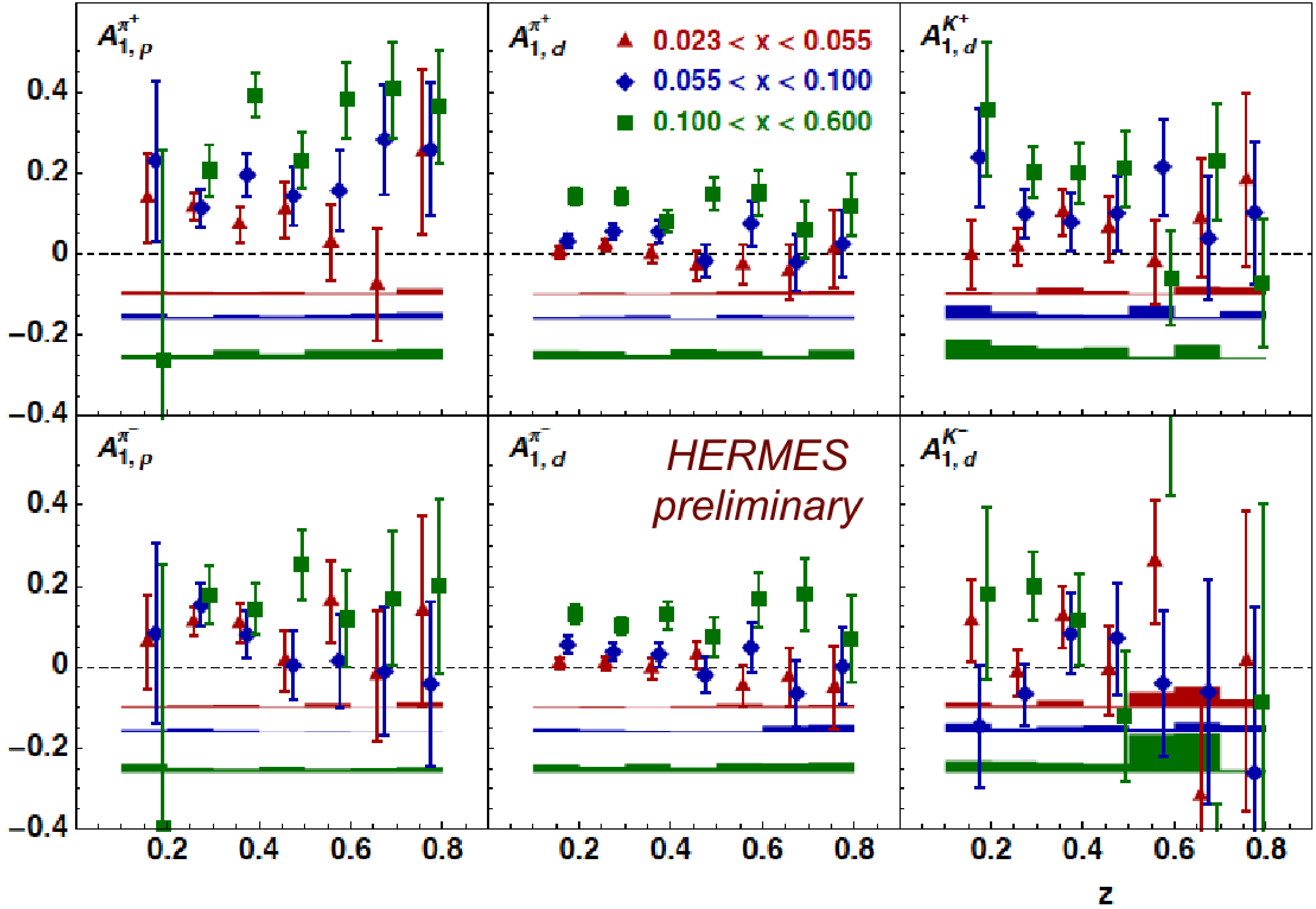


Semi-Inclusive Asymmetries cont.

- recently HERMES extracted semi-inclusive asymmetries in 3D phase-space of x,z and $p_\perp$
- main goal is to better understand hadron fragmentation

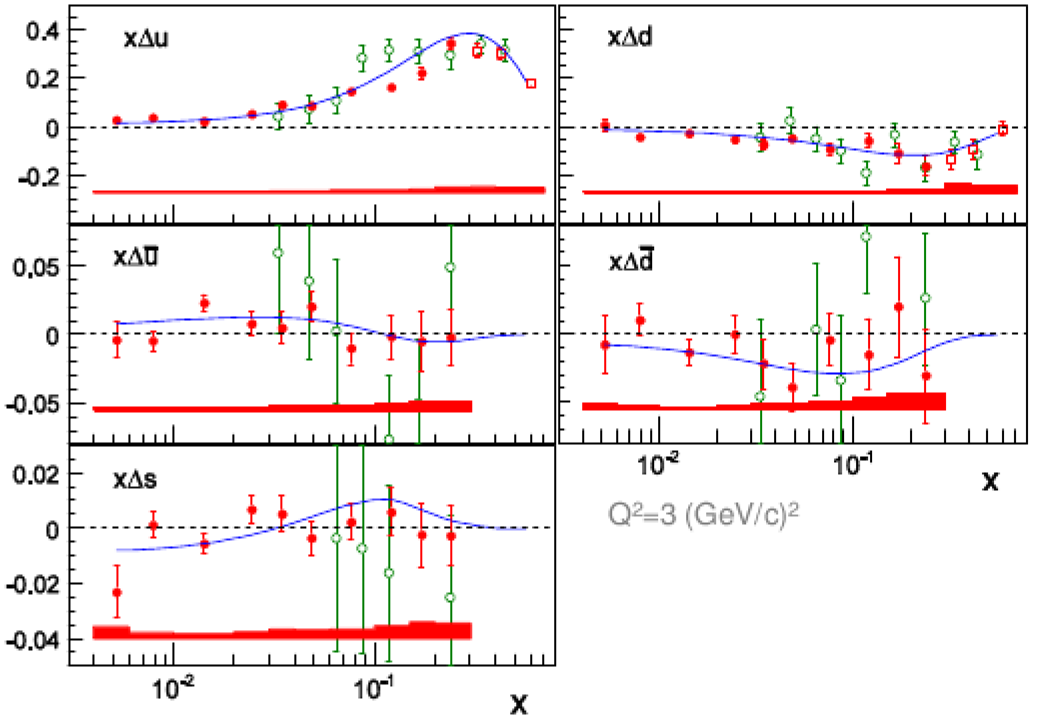


Semi-Inclusive Asymmetries cont.



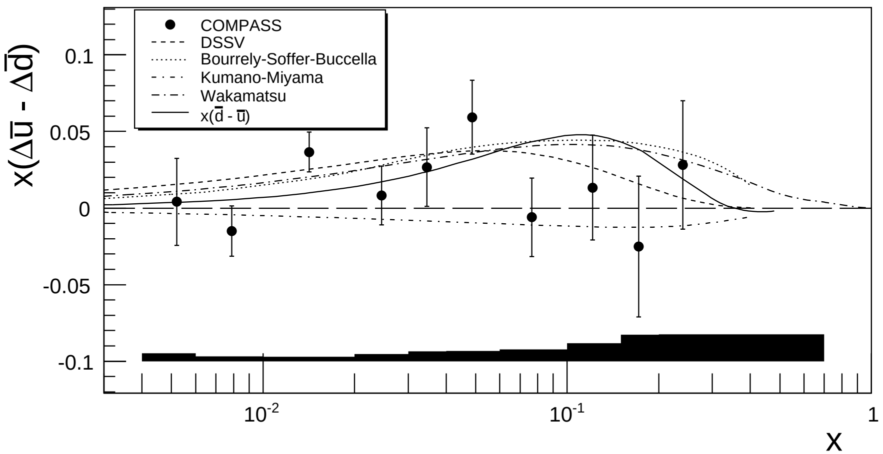
LO Flavour Separation

- HERMES results: PRD 71 (2005) 12003
- COMPASS results: PLB 693 (2010) 227
- curves are DSSV NLO parametrization Phys. Rev. Lett. 101 (2008) 072001; Phys. Rev. D80 (2009) 034030.
- good agreement between HERMES, COMPASS and DSSV parametrization (which includes HERMES data)

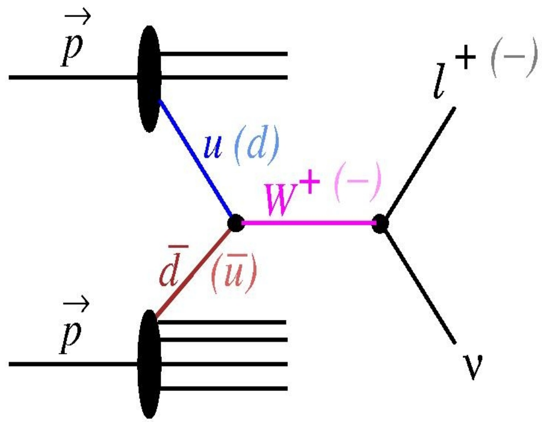


Flavour Asymmetry of the Sea

- the unpolarized sea ($\bar{u} - \bar{d}$) is flavour asymmetric
- it is interesting to measure this quantity in the polarized case

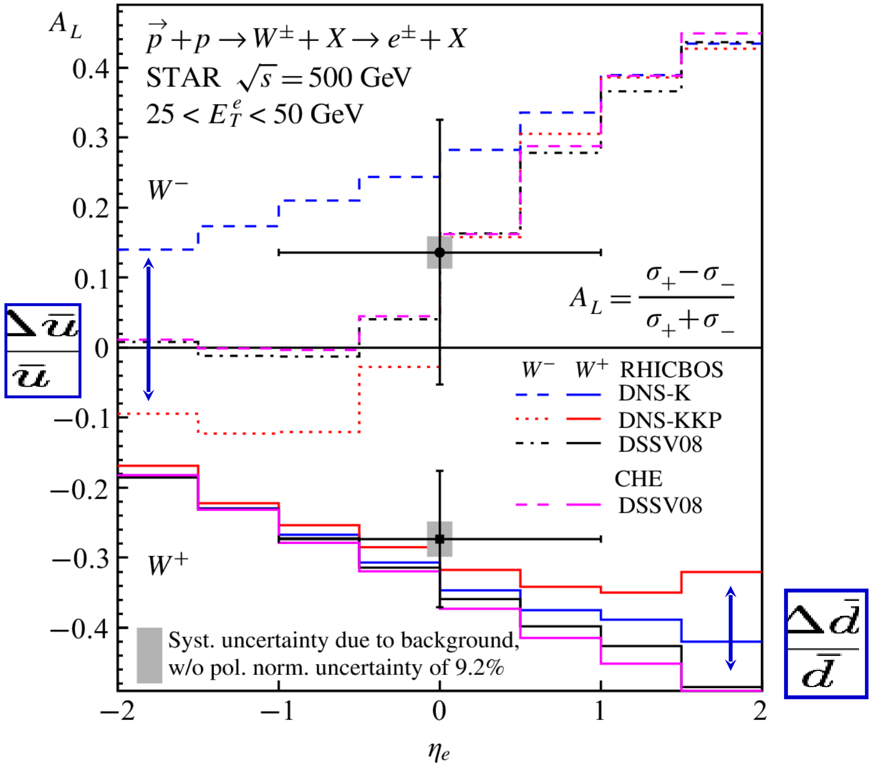


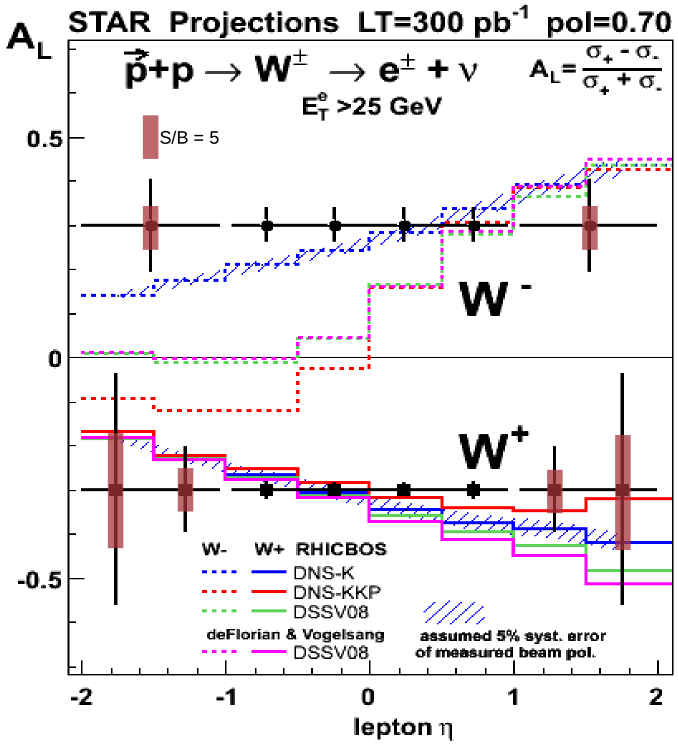
- recently new results from STAR
  - measurement of single spin asymmetries in W production
  - $u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$
  - $\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$
  - sensitivity to different flavours depends upon the rapidity of the outgoing lepton



Flavour asymmetry from STAR

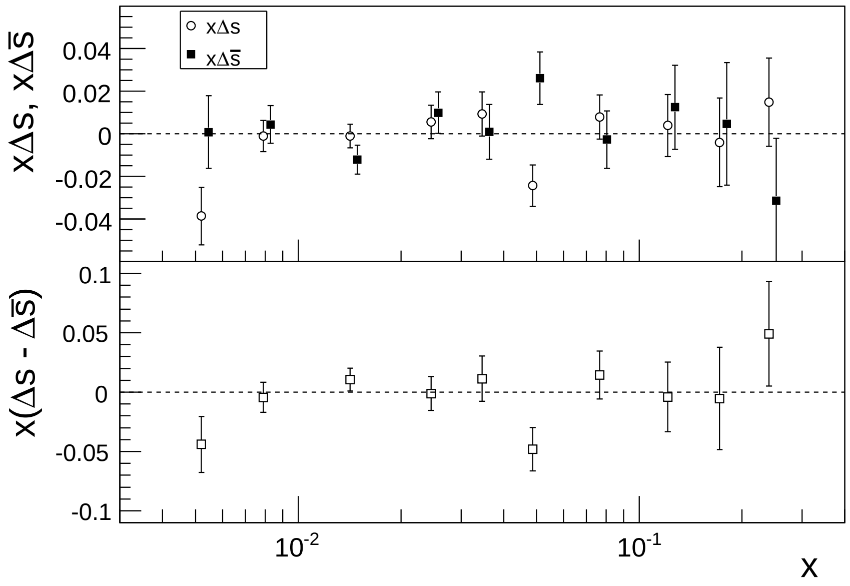
- first results have limited sensitivity (formally within 2σ the two results agree with each other)
- however very good prospects for the future!

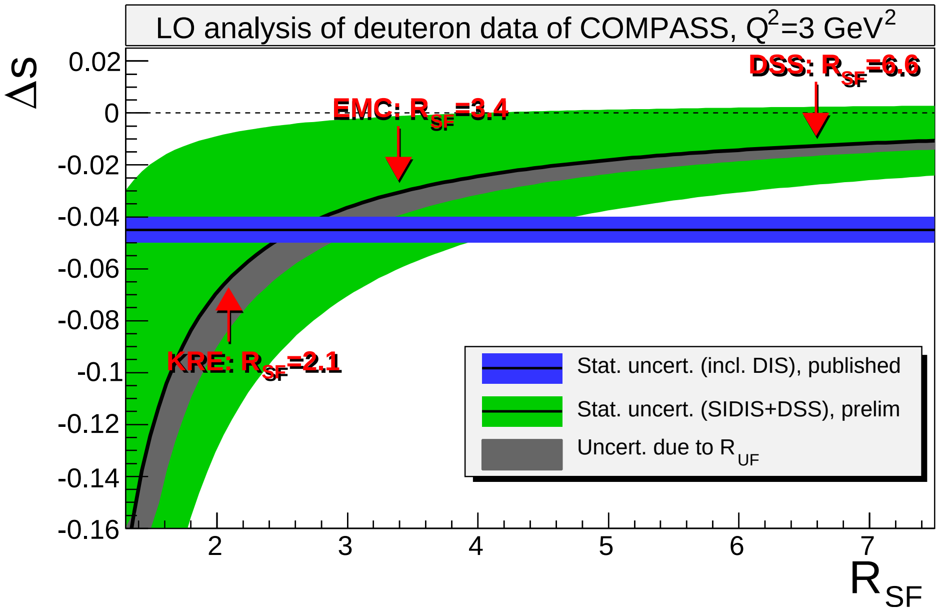




Strange Sea Polarization

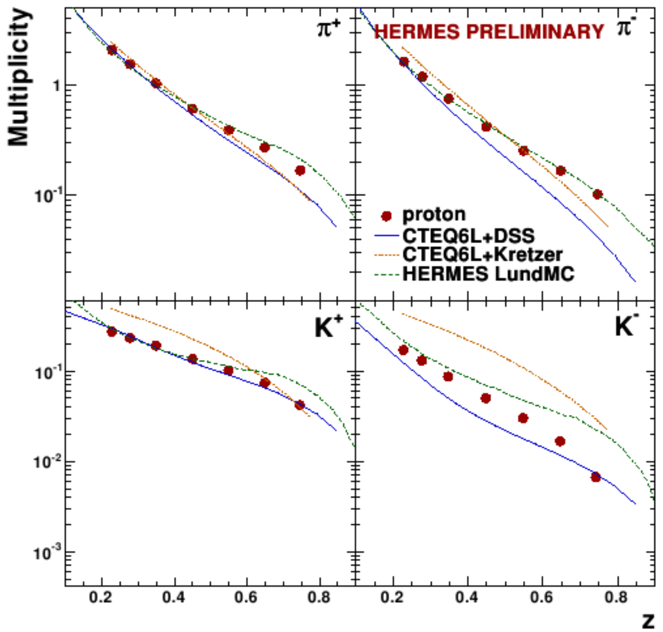
- $\int_0^1 \Delta s(x) + \Delta\bar{s}(x) = 2\Delta S$ is negative from inclusive asymmetries
  $2\Delta S = -0.09 \pm 0.01 \pm 0.02$
- HERMES SI: $\Delta s + \Delta\bar{s} = 0.037 \pm 0.019 \pm 0.027$ (PLB666 (2008) 466)
- ΔS obtained in semi-inclusive analysis strongly depends upon the choice of fragmentation functions
- ratio $\frac{D(s\to K^-)}{D(\bar{u}\to K^-)} = \frac{D(\bar{s}\to K^+)}{D(u\to K^+)}$, known as R_{SF} is especially important

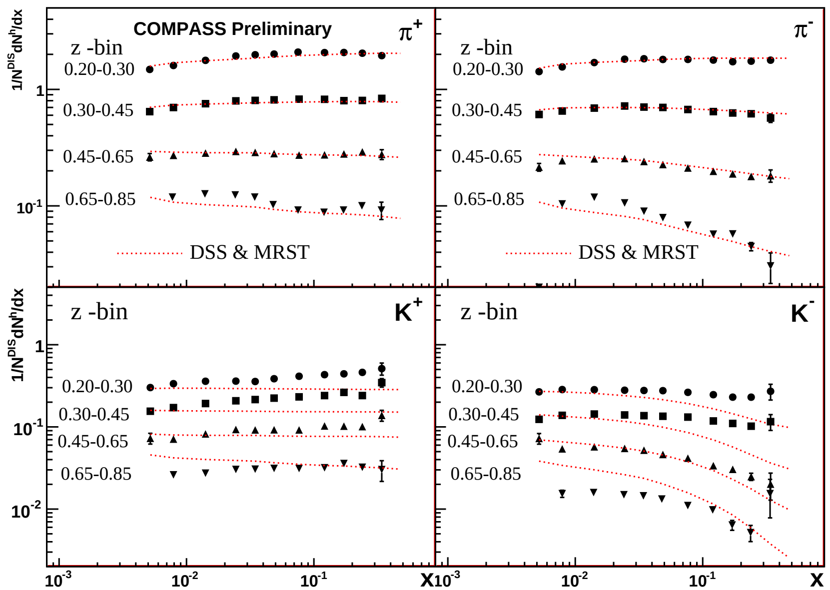




Hadron Multiplicities

- One way of extracting the fragmentation functions is to study hadron multiplicities *i.e.* number of hadrons produced per DIS event.
- various combinations of FF enter the $K^{\pm}$ multiplicities,
- mostly preliminary results released
- HERMES is extracting them in a multi-dimensional grid $x, z, Q^2 p_T$
- some problems visible between DSS and data





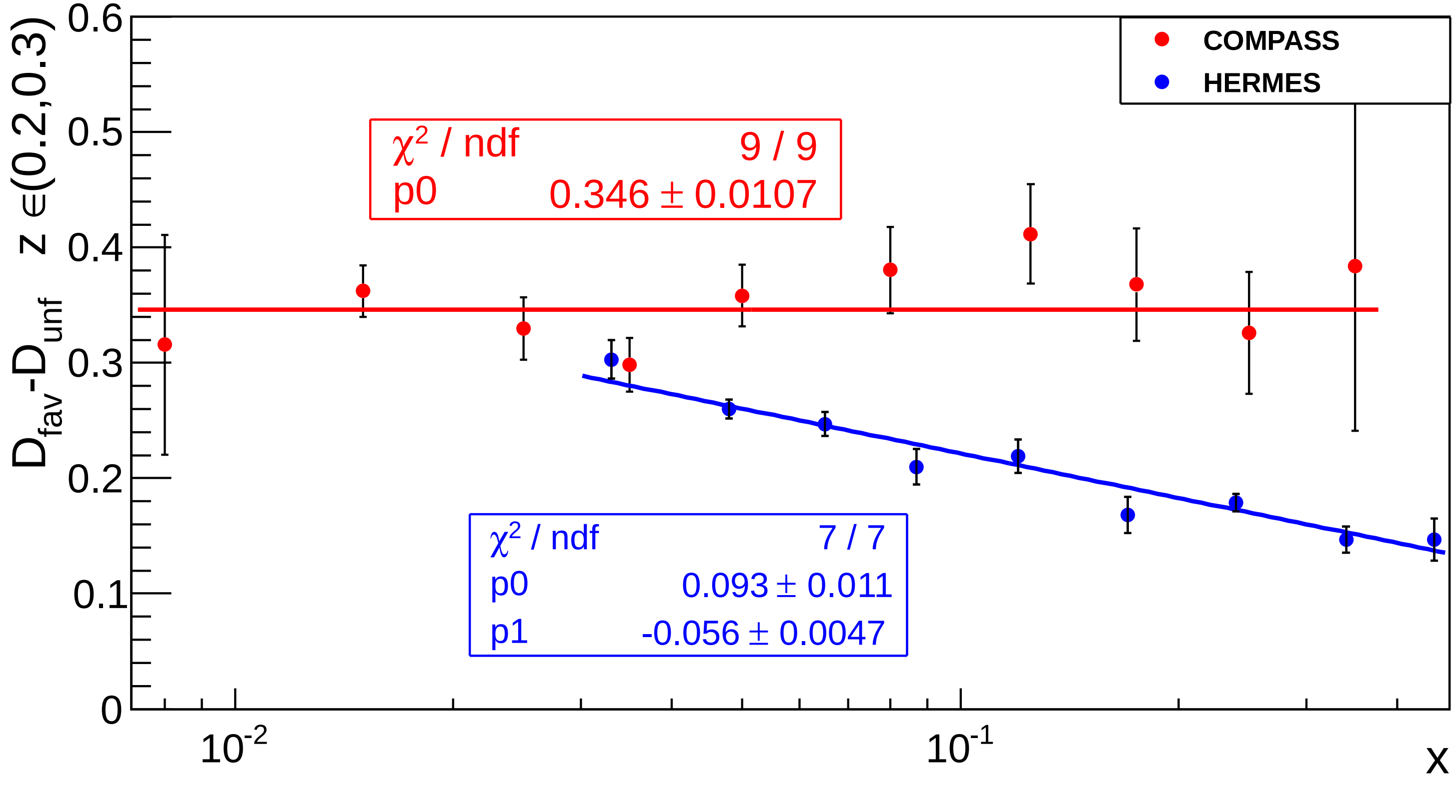
Hadron Multiplicities COMPASS vs HERMES

There are differences between COMPASS and HERMES results.
Instead of showing $K^\pm$ multiplicities for both experiments I will show the difference $K^+ - K^-$ as a function of x

- $K^+ - K^-$ is a non-singlet distribution, the contributions from gluons and strange quarks cancel
- in addition I divide $K^+ - K^-$ multiplicity by $4/9(u_v + d_v)(x)/\sum e_i^2 q_i(x)$
- this way the difference $D_{fav} - D_{unf}$ is obtained
- in the range of Q^2 1–30 GeV^2 in DSS parametrization $D_{fav} - D_{unf}$ is almost flat, changes by $\pm 1.5\%$ of its value
- in addition part of the experimental systematics cancels in $K^+ - K^-$ difference...
- since none of the experiments give covariance matrix (at this stage of the analyses) I have rescaled errors so that the χ^2/ndf =1 in the fit

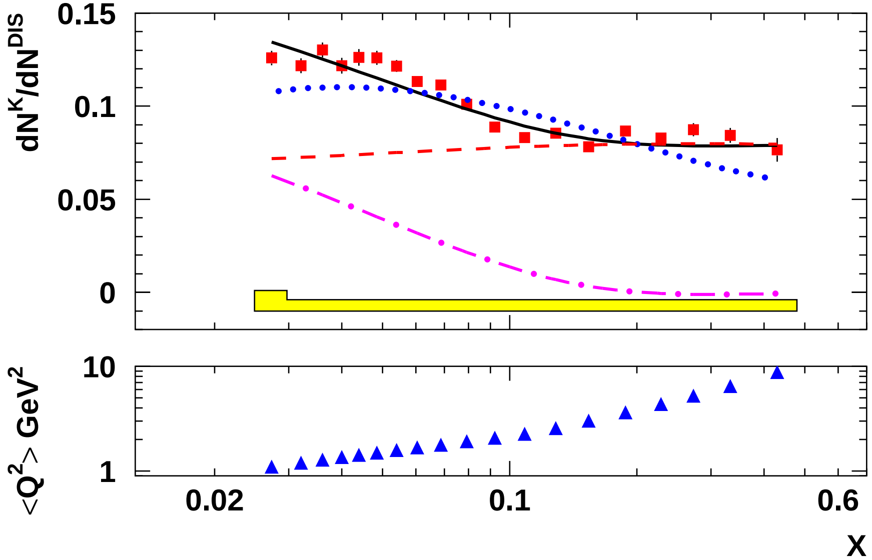
Hadron Multiplicities COMPASS vs HERMES cont.

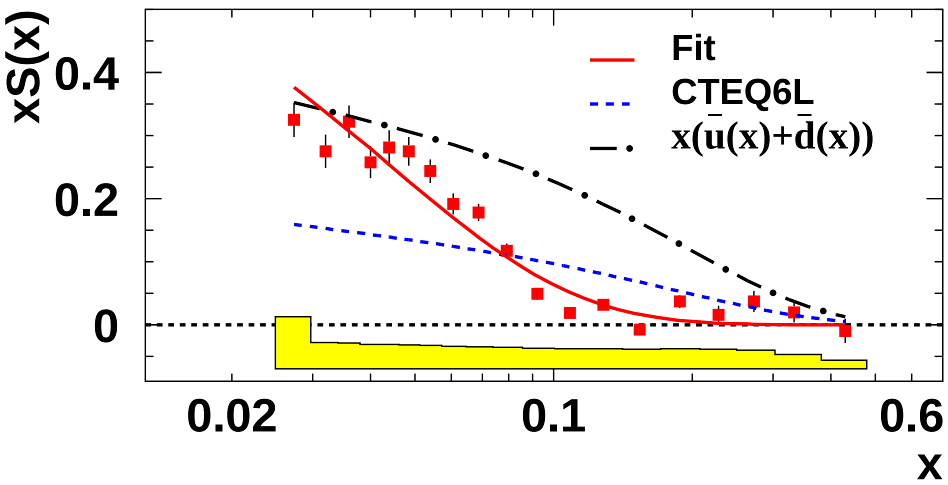
- a single bin $z \in (0.2, 0.3)$ is shown for the deuteron target
- HERMES preliminary $K^{\pm}$ multiplicities taken from DIS'11 presentation of Sylvester J. Joosten, page 15



Possible Implications

- in the paper PLB 666 (2008) 446, from $K^+ + K^-$ multiplicities contribution of non-strange quarks is extracted at high x. Assuming weak Q^2 dependence of FF the excess of $K^+ + K^-$ at low x is attributed to the strange quarks.
- impact on DSS fragmentation?
- impact on ΔS?





Gluon Polarization

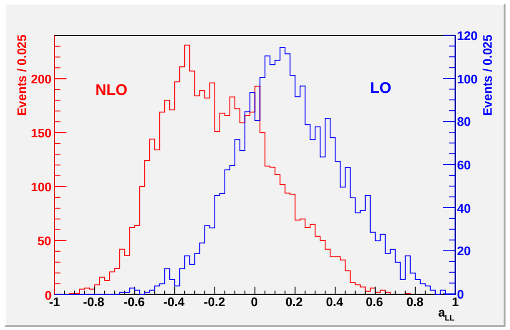
- after the onset of the "spin crisis" the natural candidate to carry the missing angular momentum was the gluon
  - gluons solved the puzzle of missing longitudinal momentum of the proton
  - in certain schemes due to the triangle anomaly $\Delta\Sigma = \Delta\Sigma_0 - n_f \frac{\alpha_s}{2\pi} \Delta G$
  - large $\Delta G \approx 2.5$ could then solve the spin crisis (but large $L_{q,g}$ is needed to compensate ΔG)
- we know that the gluon polarization is much smaller than the needed 2.5, however its exact value is still rather poorly known.
- $\Delta g/g$ measurements via photon-gluon fusion
  - open charm events
  - high p_T hadron(s) (fixed target, p-p)
  - high p_T jets in p-p collisions

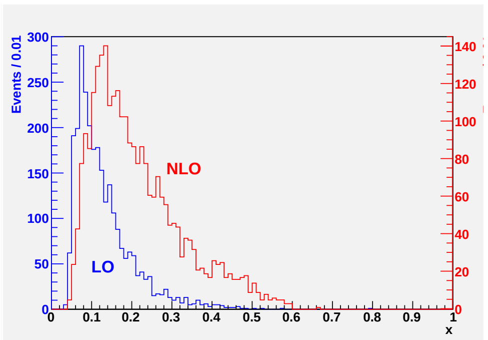
Open Charm Events

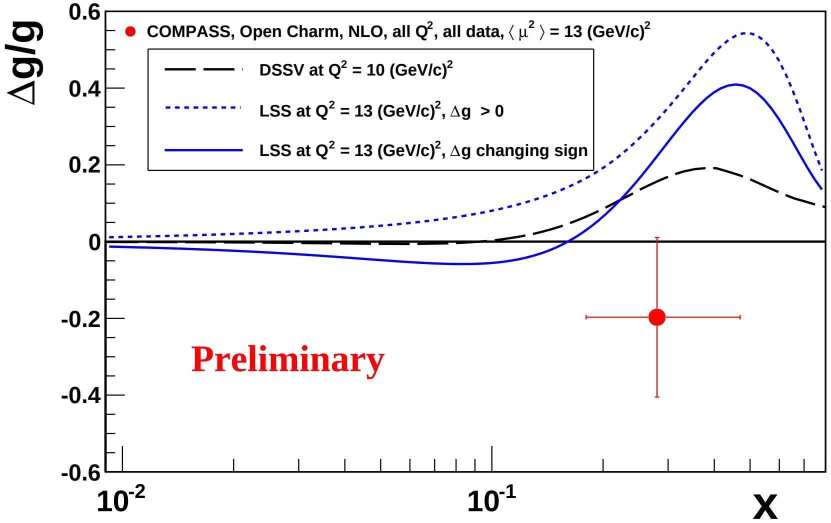
- open-charm is a clean source of PGF (in LO) but low statistics
- in LO simple relation between measured asymmetry and $\Delta g/g$:

$$\frac{\Delta g}{g} = \frac{1}{P_T P_b f a_{LL} \frac{S}{S+B}} A_{raw}$$

- COMPASS preliminary LO result: $\Delta g/g = -0.08 \pm 0.21 \pm 0.11$
- NLO analysis of open charm events was also performed
- significant changes of a_{LL} and x_g between LO and NLO are seen

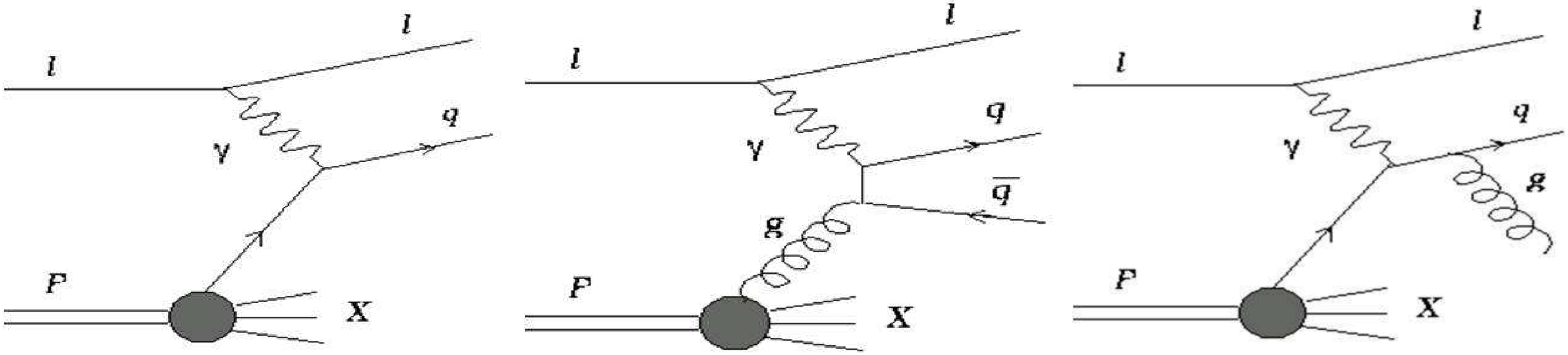






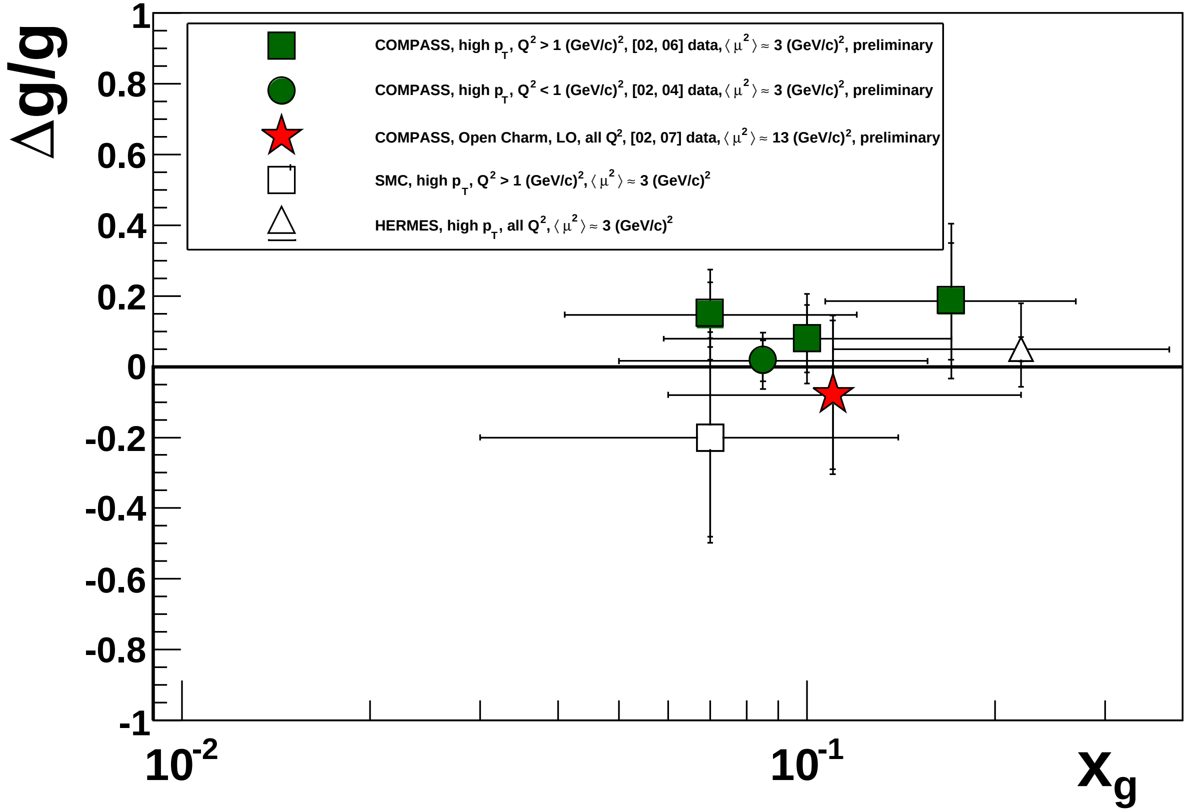
High-p_T Hadrons and $\Delta G/G$

- in LO three processes are contributing: LP, PGF and QCDC
- for low Q^2 there is additional contribution from resolved photons (>50% cross-section)
- the fraction of PGF in the sample has to be estimated based on MC
- in general, higher the p_T the larger is the fraction of PGF expected
- key point of the analysis is good agreement between data and MC
- much larger statistics than for open charm sample



LP PGF QCDC

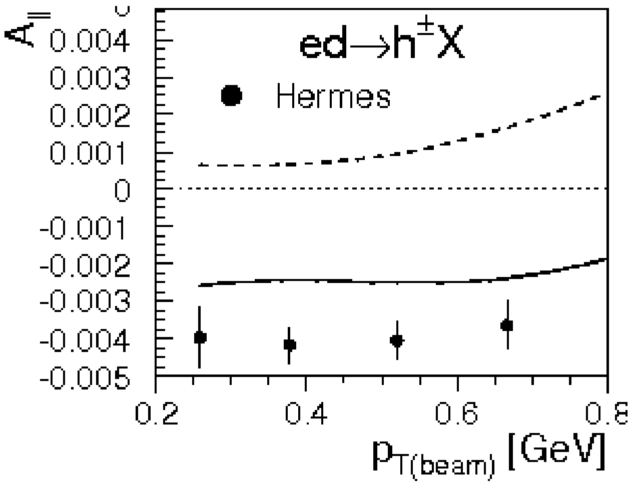
High-p_T Hadrons and $\Delta G/G$



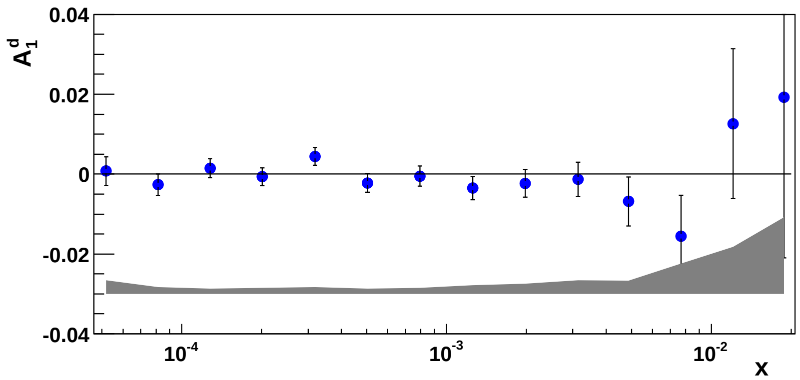
- SMC, PRD 70 (2004) 012002
- HERMES, JHEP 08 (2010) 130
- COMPASS, (hep-ex/1202.4064) subm. to PLB + some prel. res

small digression...

- part of $\Delta G/G$ results from HERMES is obtained from the so-called non-tagged sample *i.e.* only hadron is in the acceptance
- typical x of these events is 10^{-4}, and they have low Q^2
- HERMES measured $A_{LL}^{||} = DA_1^d$ from events with $p_T < 0.8$ GeV
- clear negative asymmetry is measured
- COMPASS measured A_1^d for $x > 3 \cdot 10^-5$,(PLB 647 (2007) 330)
- corresponding $A_d^{||} = -0.0002 \pm 0.0006 \pm 0.0004$ (4 lowest x points)
- discrepancy HERMES vs COMPASS $\approx 5\sigma$

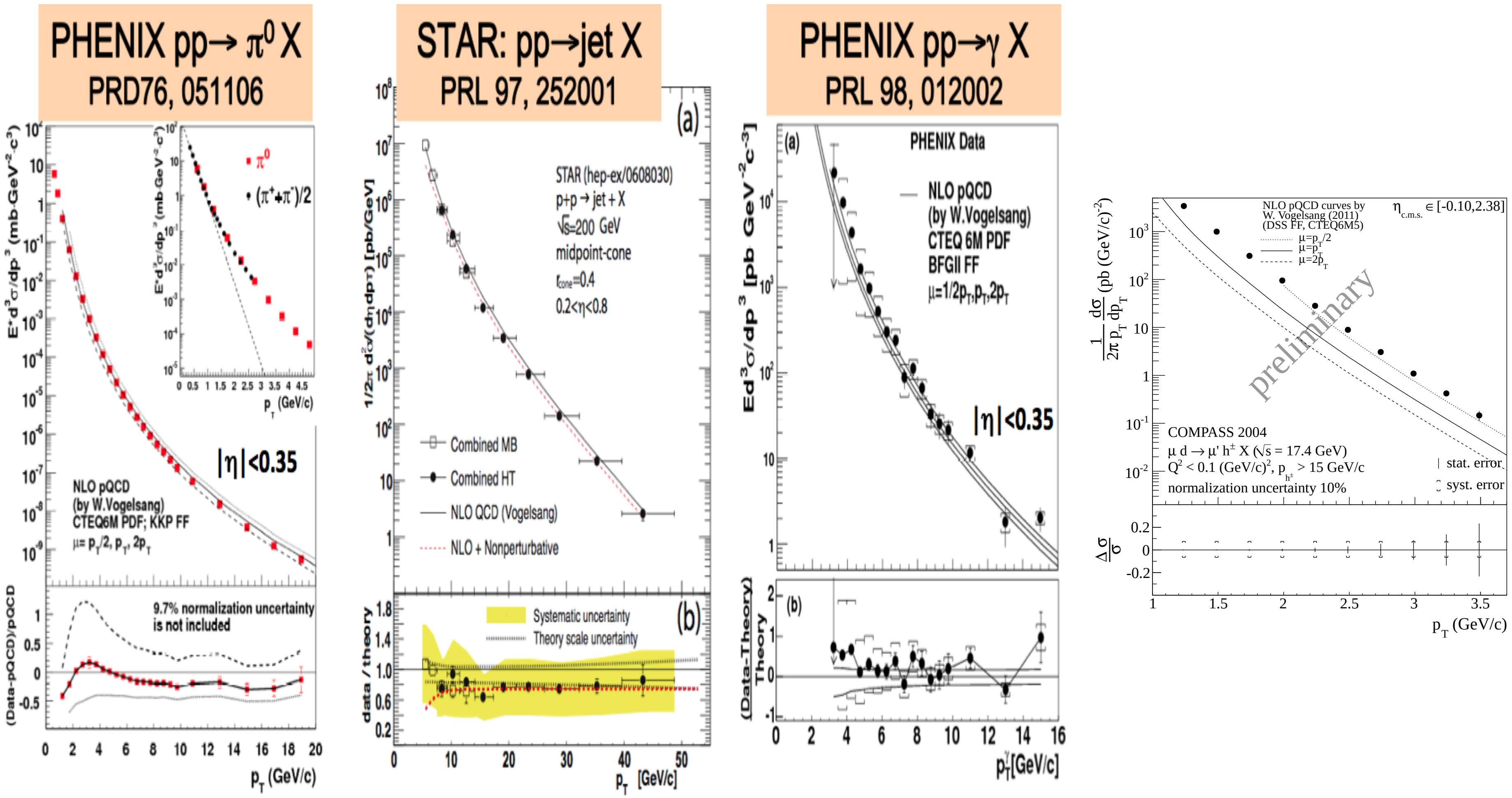


COMPASS



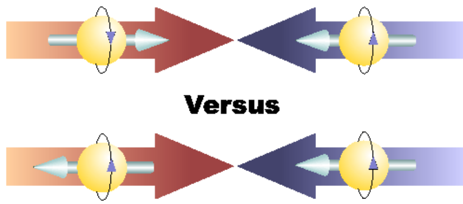
Towards $\Delta G/G$ at RHIC

- extraction of $\Delta G/G$ from $p-p$ collisions theoretically is more challenging, since two compound objects interact
- one has to use NLO QCD calculation

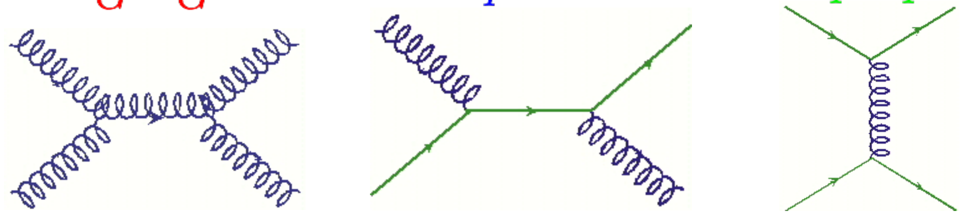


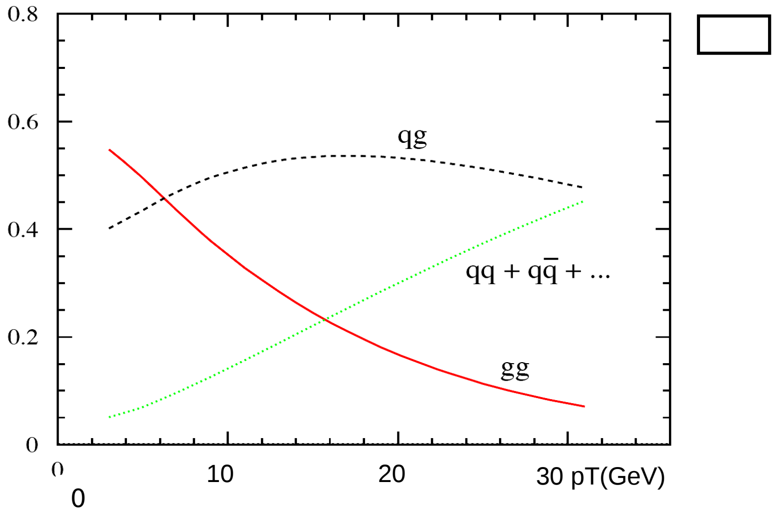
$\Delta G/G$ @ RHIC (slide from Justin Stevens)

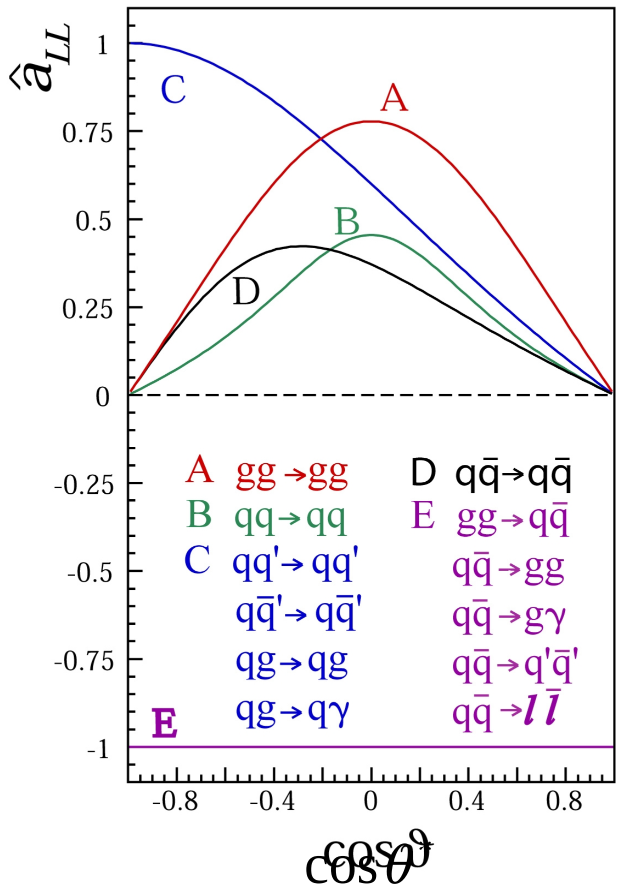
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$



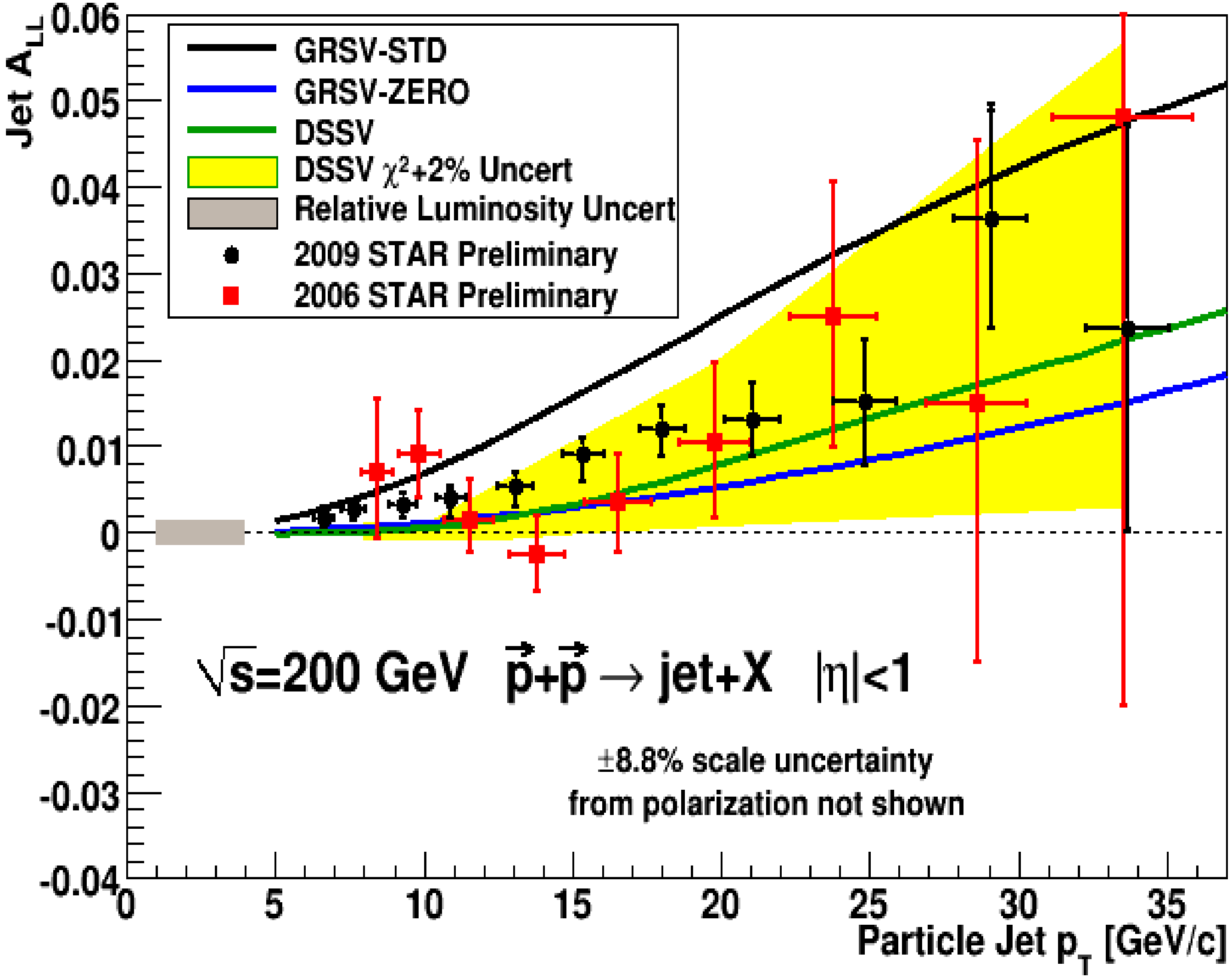
$\frac{\Delta G}{G}\frac{\Delta G}{G}$ $\qquad$ $\frac{\Delta q}{q}\frac{\Delta G}{G}$ $\qquad$ $\frac{\Delta q}{q}\frac{\Delta q}{q}$





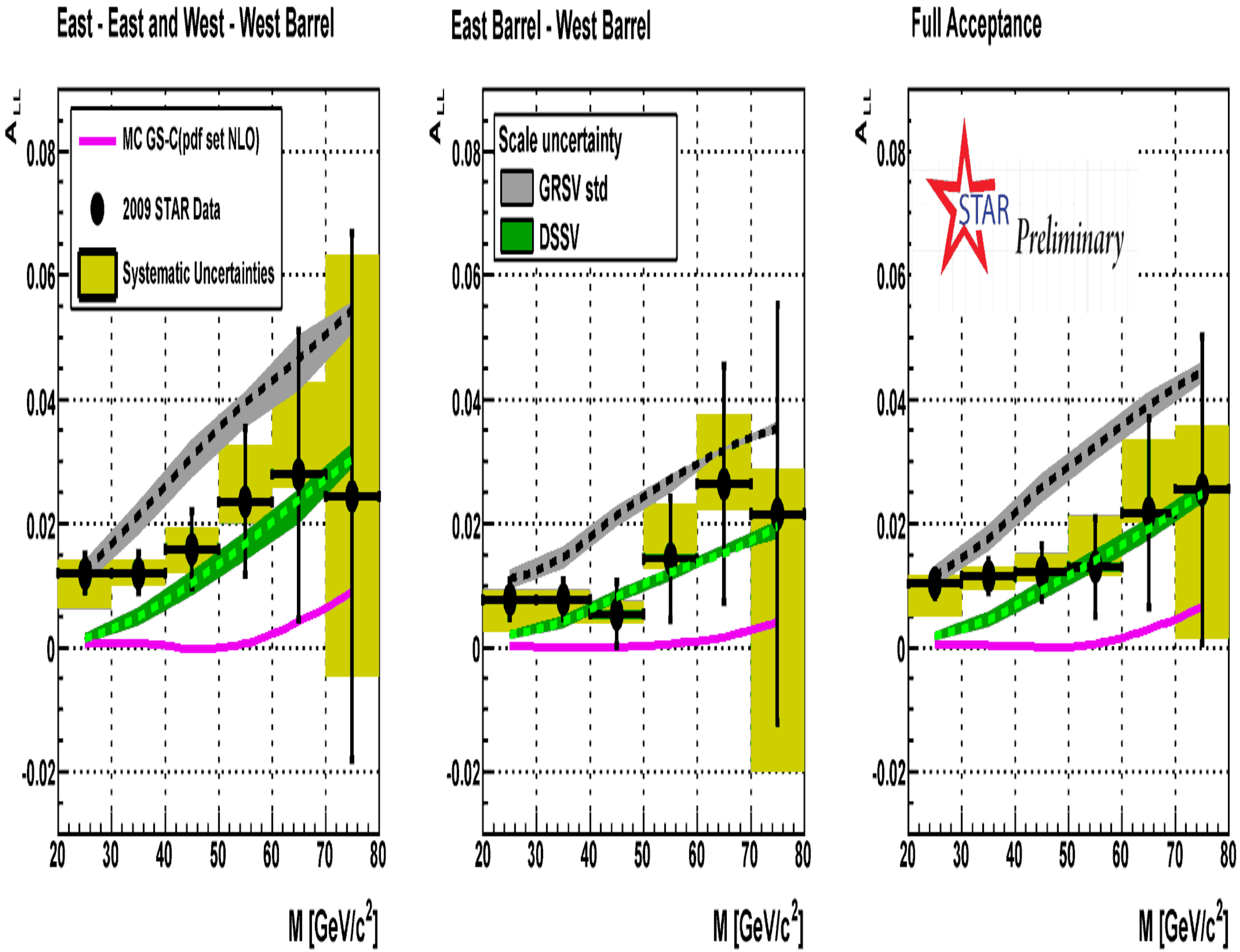


$\Delta G/G$ from Inclusive Jets at STAR



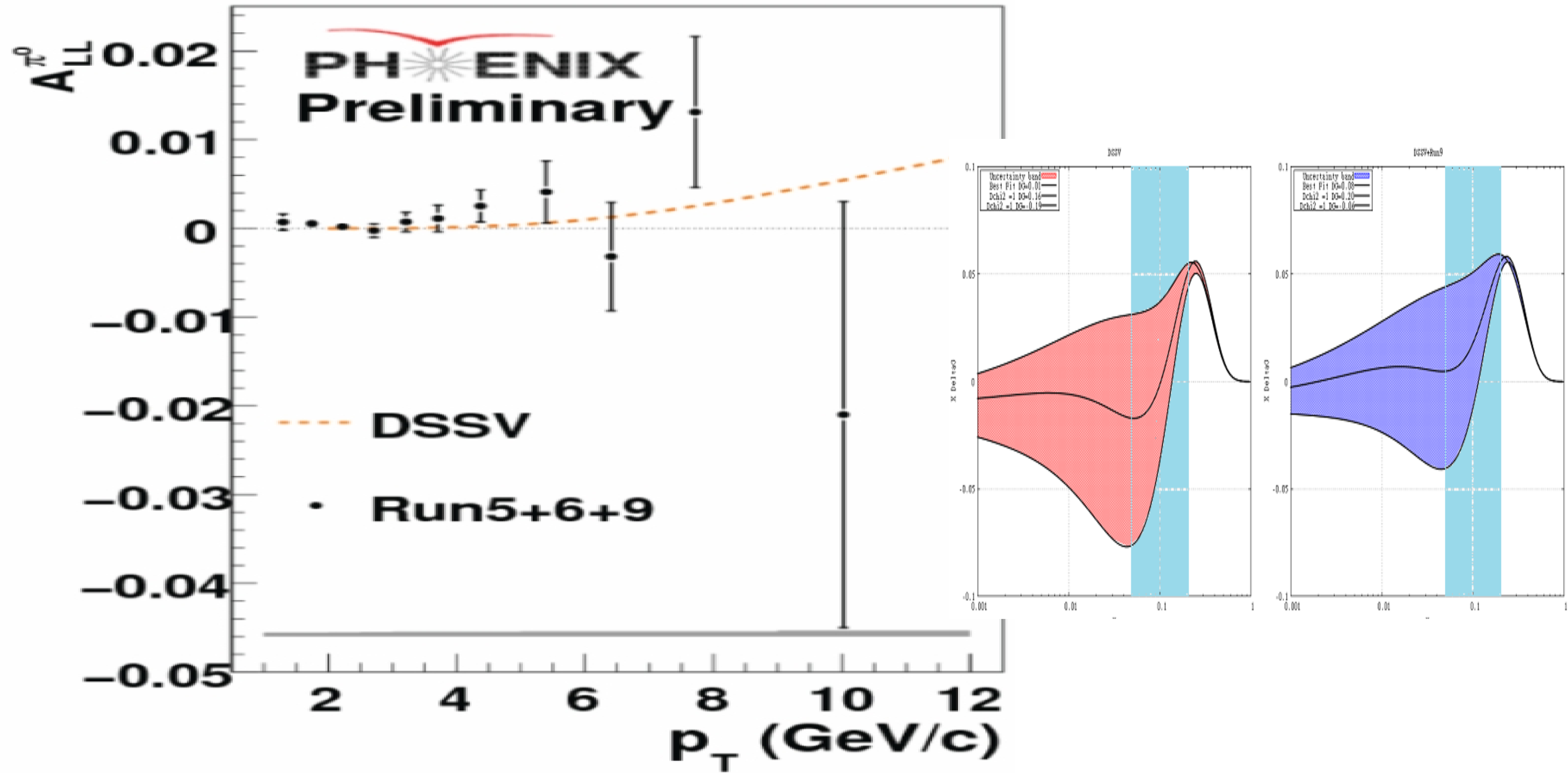
- the results fall between DSSV and STD GRVS

$\Delta G/G$ Di–Jets at RHIC



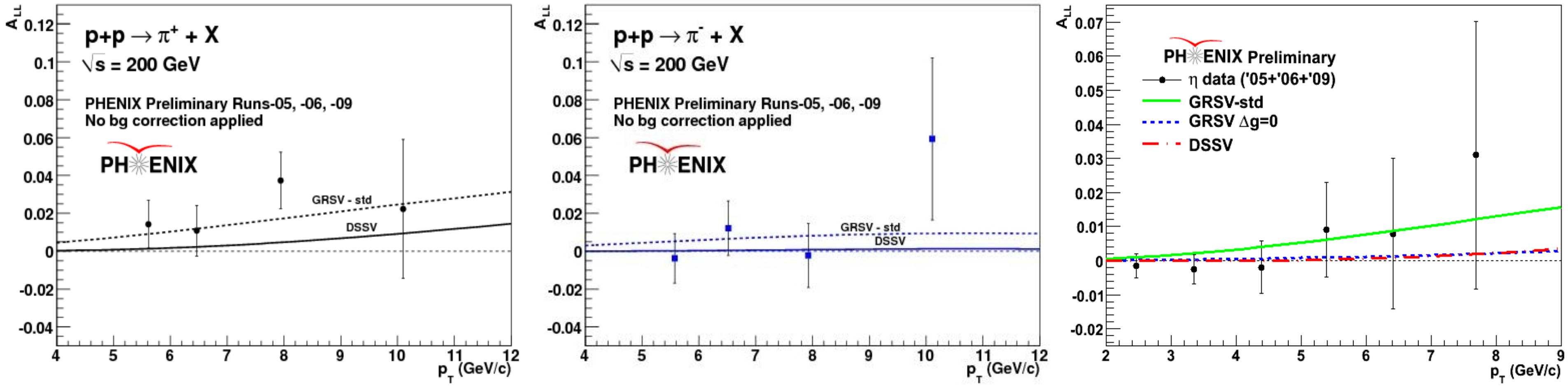
- again RUN9 data falls between DSSV and GRVS–std

$\Delta G/G$ from π^0 in PHENIX



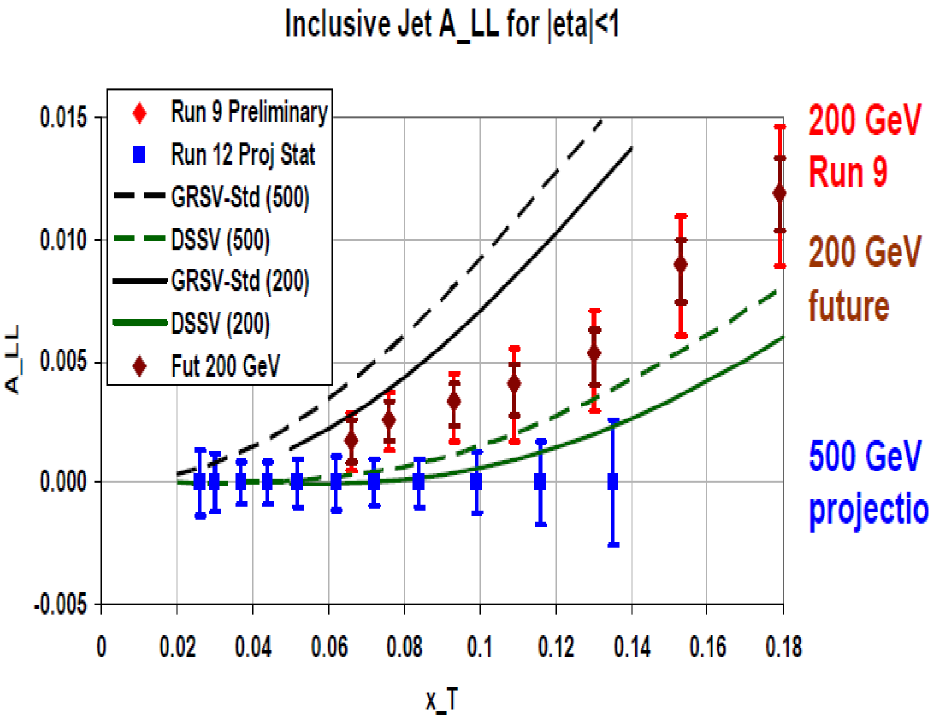
- adding new PHENIX data in the global DSSV fit disfavors the “node solution”, positive values of $\Delta g/g$ are preferred

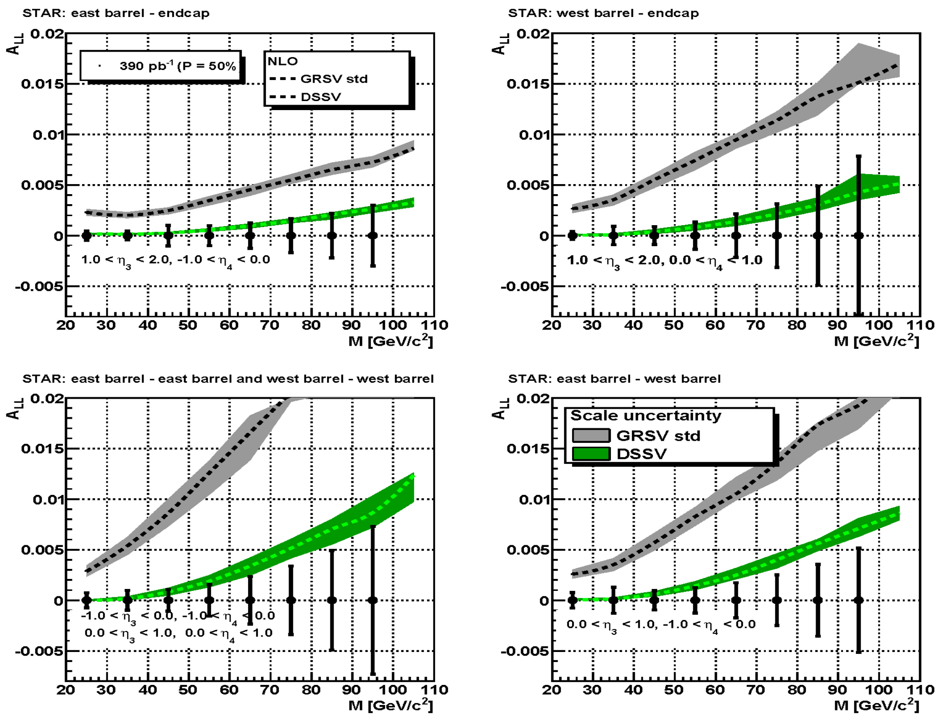
$\Delta G/G$ @ PHENIX



- charge hadrons sensitive to sign of ΔG
- $A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-) \Longrightarrow \Delta G > 0$
- $A_{LL}(\pi^+) < A_{LL}(\pi^0) < A_{LL}(\pi^-) \Longrightarrow \Delta G < 0$
- there are also η results

$\Delta G/G$ RHIC–Prospects

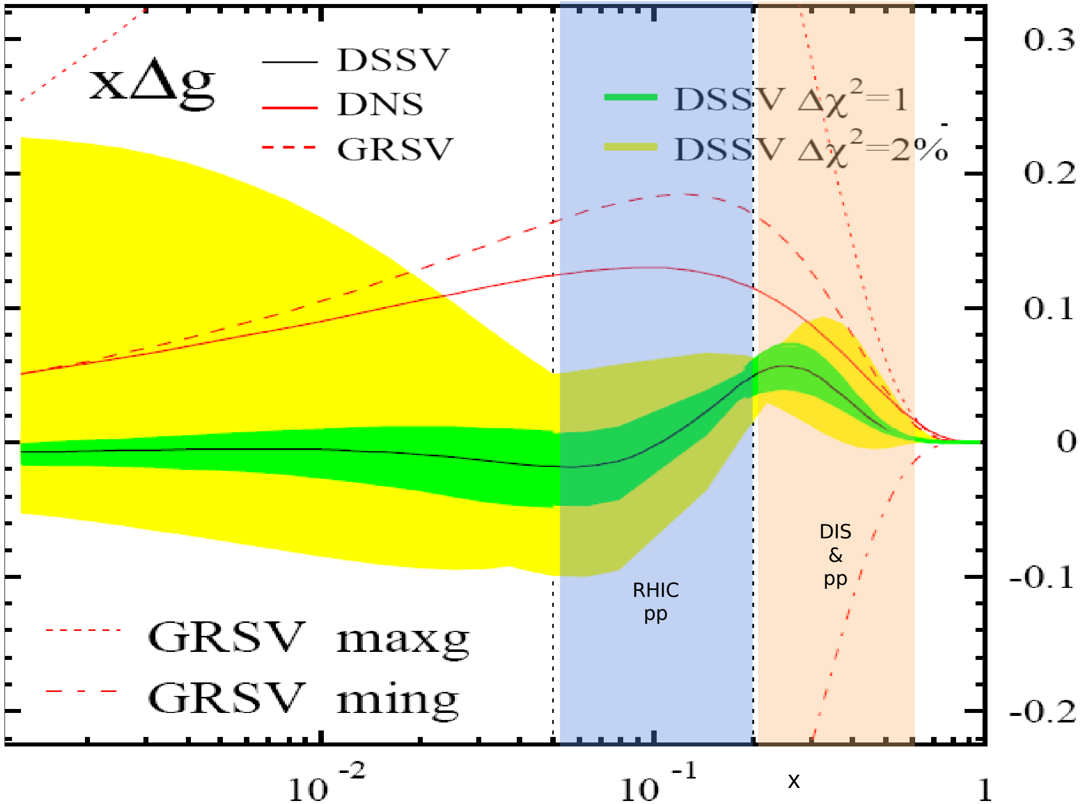




- examples of expected $\Delta g/g$ uncertainties from RUN12 and future 200 GeV run for STAR
- both experiments search new ways to access lower x_g region *e.g.* two π^0 production

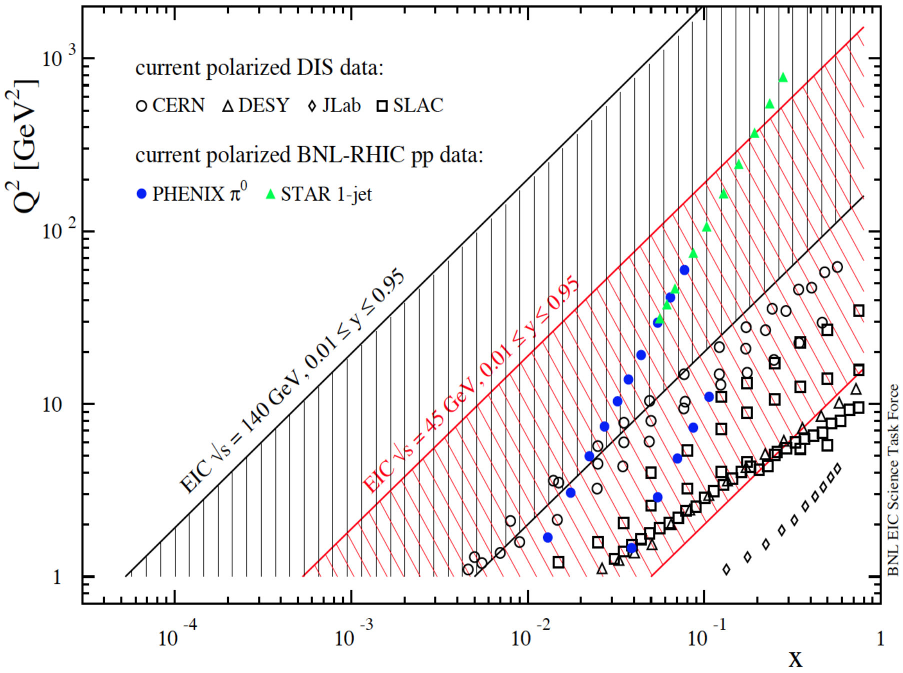
Limitations of the current experiments from the ΔG perspective

- effectively only a limited range in $x_g \in (0.05 - 0.30)$ is covered
- although ΔG is small in the measured region, still gluon polarization may be hidden at lower-x
- most figures from M. Stratmann presentation on DIS'12



Why Electron Ion Collider

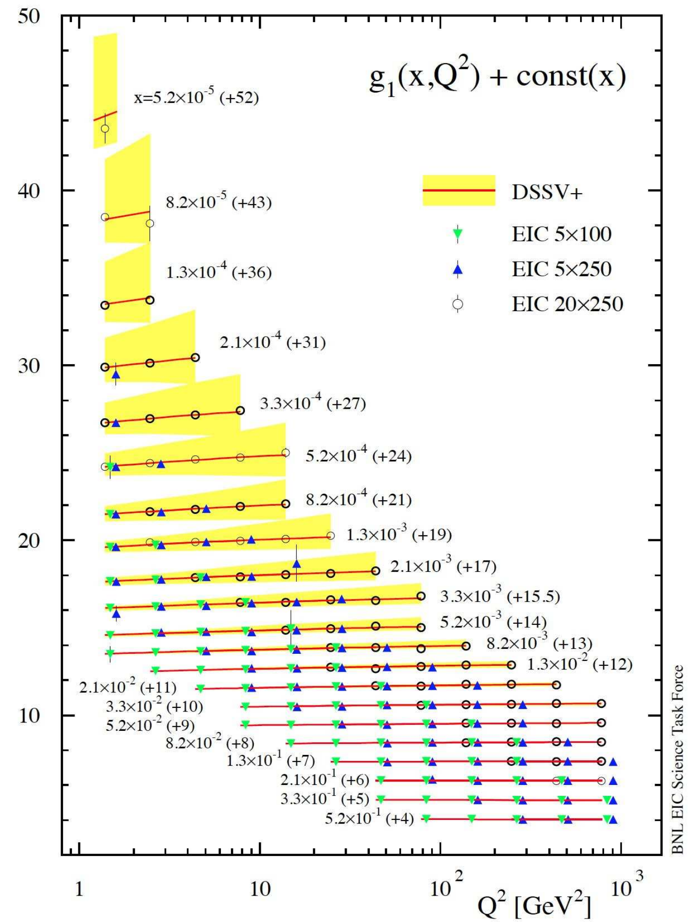
- access to small x for better $\Delta\Sigma$ and ΔG determination
- flavour separation in a broad range of x and Q^2 to study quark sea
- possibility to study electro-weak probes at high Q^2
- and many more...



WHERE: JLAB or RHIC, different possibilities being studied
WHEN: operational >2020

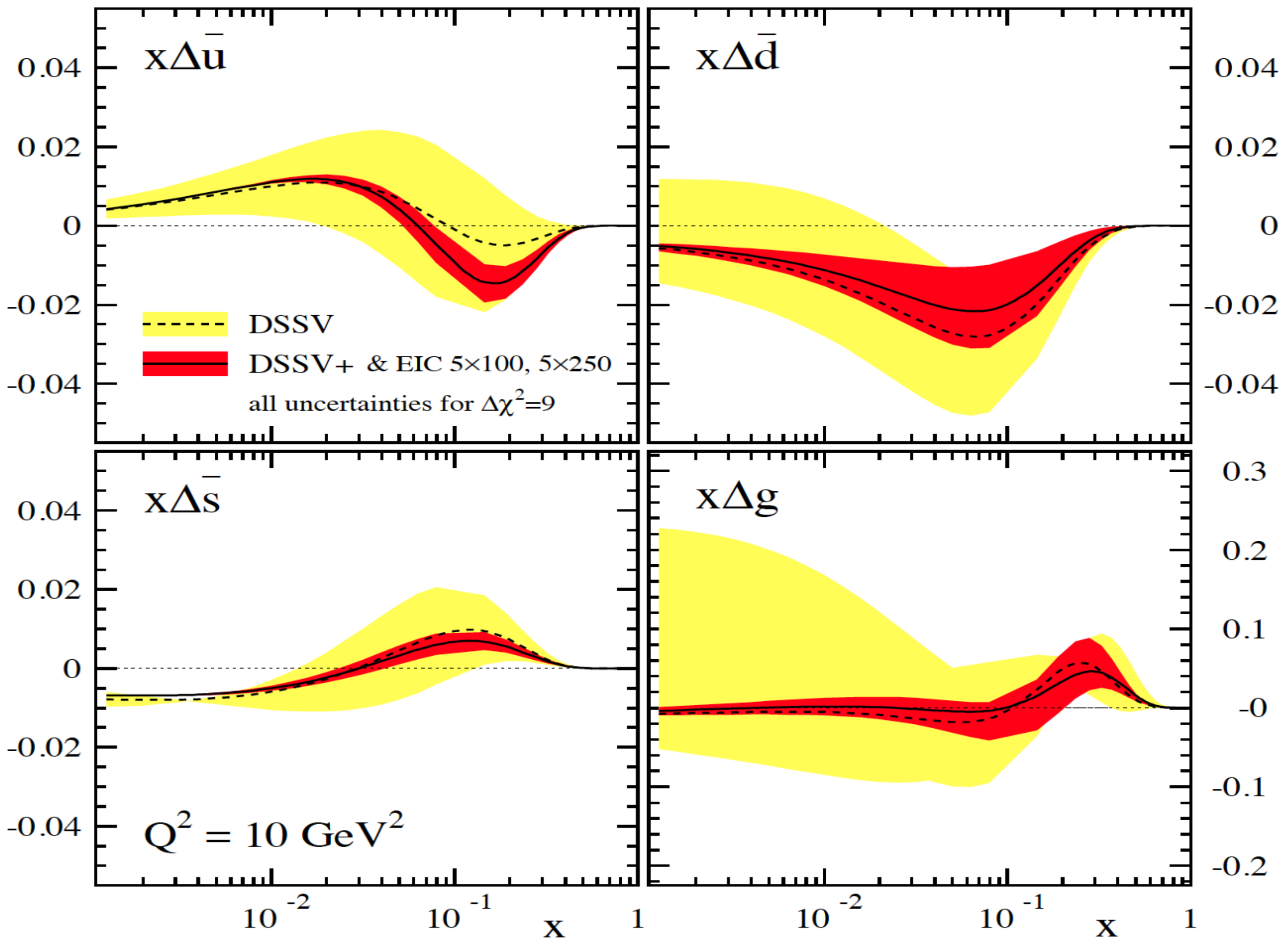
Electron Ion Collider and g_1^p

- large increase of phase space where g1p will be measured
- observe it will be possible to extract Δg from inclusive measurement!
- $\frac{dg1(x,Q^2)}{dlog(Q^2)} \sim -\Delta g(x, Q^2)$



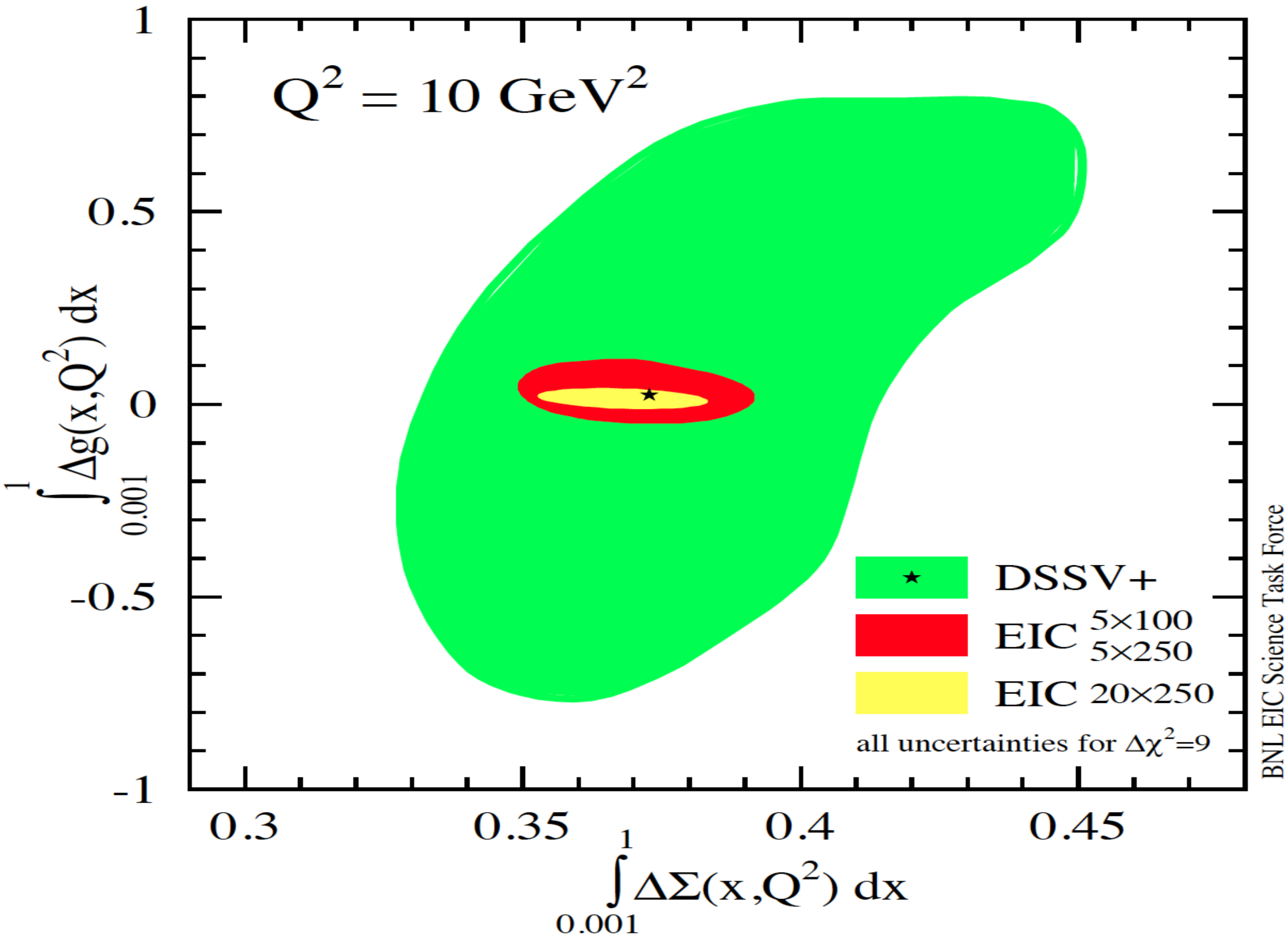
Electron Ion Collider and PDFs

- large reduction of statistical uncertainties of PDFs
- still the measurement will be challenging from systematic point of view *e.g.* one needs excellent control of luminosity



Electron Ion Collider cont.

- impact of EIC data for the $\Delta\Sigma$ and ΔG



Summary

- still a lot of interesting things happening in longitudinal spin physics
  - here and there discrepancies between experiments are visible
  - does strange quark puzzle exist?
  - ΔG is more and more constrained by the RHIC results, positive ΔG is preferred
- I really hope some EIC version will be built