Progress in spin and 3d nucleon structure

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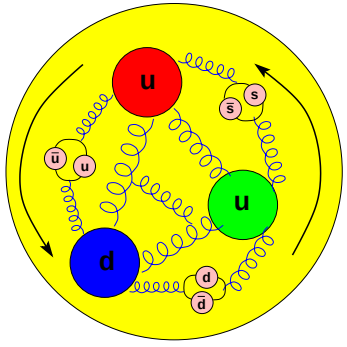
DIS 2017,
Birmingham, 3.-7. April 2017

bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

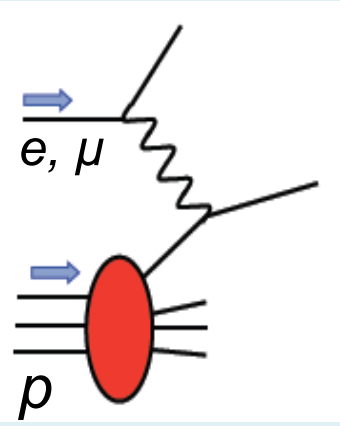
The spin of the nucleon

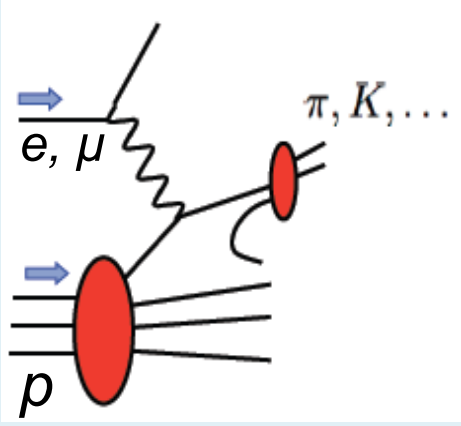


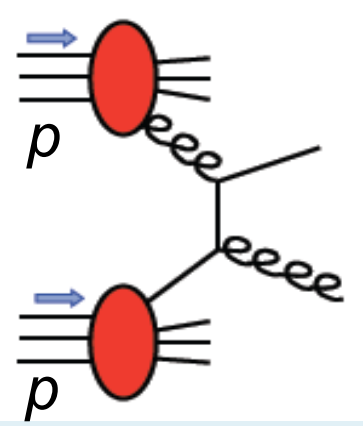
$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

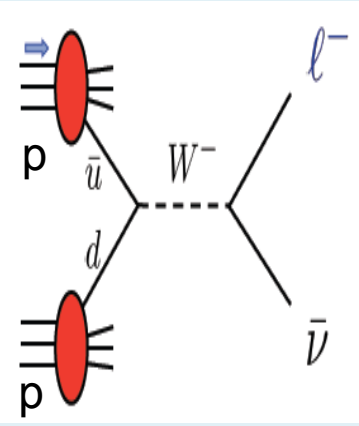
Main sources:	$\Delta\Sigma$, Δs	inclusive DIS
	ΔG	qg in pp, PGF in DIS
	Δu,Δd,Δs	Flavourseparation in SIDIS
		$W^{\pm}$ in pp
	L_q	GPD in DVCS, HEMP

Processes









DIS:

$\Delta q + \Delta \bar{q}$

Δg (From Q^2 evolution of g_1)

SIDIS:

$\Delta q, \Delta \bar{q}$

Δg

pp:

$\Delta q, \Delta \bar{q}$

Δg

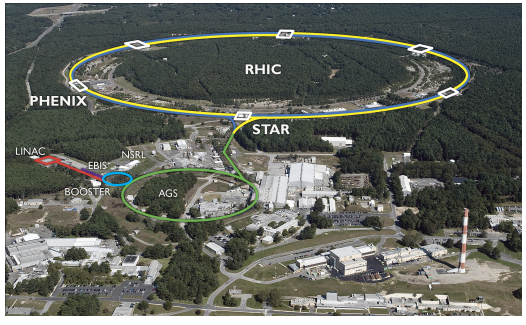
40 years of experimental effort

SLAC
E80-E155
$\vec{e}$ ($\leq$ 50 GeV)
p,d,^{3}He

HERA
HERMES
$\vec{e}$ (27.5 GeV)
p,d,^{3}He

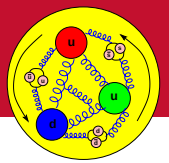
CERN
EMC,SMC
COMPASS
$\vec{\mu}$ ($\leq$ 200 GeV)
p,d

Jlab
Hall A,B,C
$\vec{e}$ ($\leq$ 6 GeV)
p,d,^{3}He



RHIC
PHENIX, STAR
$\vec{p}\vec{p}$ collider (200, 500 GeV)

Nucleon spin and helicity PDF

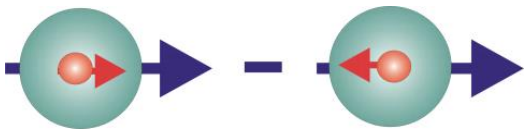


$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta\Sigma(Q^2) = \int_0^1 \mathrm{d}x[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}](x, Q^2)$$

$$\Delta G(Q^2) = \int_0^1 \mathrm{d}x \Delta g(x, Q^2)$$

Helicity PDFs: $\Delta q(x, Q^2) =$



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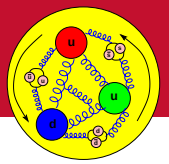

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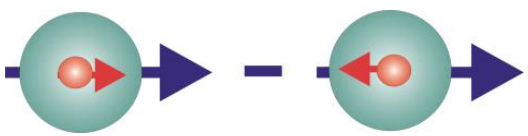
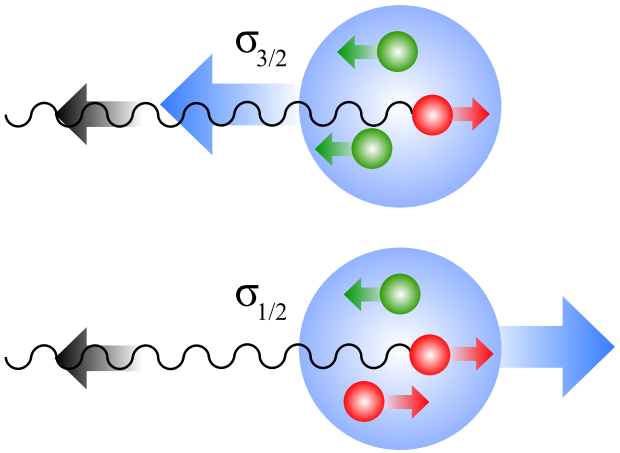
Helicity PDFs: $\Delta q(x, Q^2) =$ 

Polarised deep inelastic scattering



Absorption of polarised photons

$$\sigma_{1/2} \sim q^{+} \qquad q(x) = q(x)^{+} + q(x)^{-}$$

$$\sigma_{3/2} \sim q^{-} \qquad \Delta q(x) = q(x)^{+} - q(x)^{-}$$

- Photon nucleon asymmetries

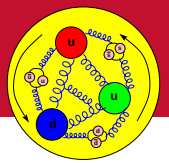
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{1}{F_1}(g_1 - \gamma^2 g_2) \overset{\gamma \text{ small}}{\approx} \frac{\sum_q e_q^2 \Delta q}{\sum_q e_q^2 q}$$

$$A_2 = \frac{\sigma_{LT}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\gamma}{F_1}(g_1 + g_2) \qquad \gamma = \frac{2Mx}{Q^2}$$

- Spin structure function g_1

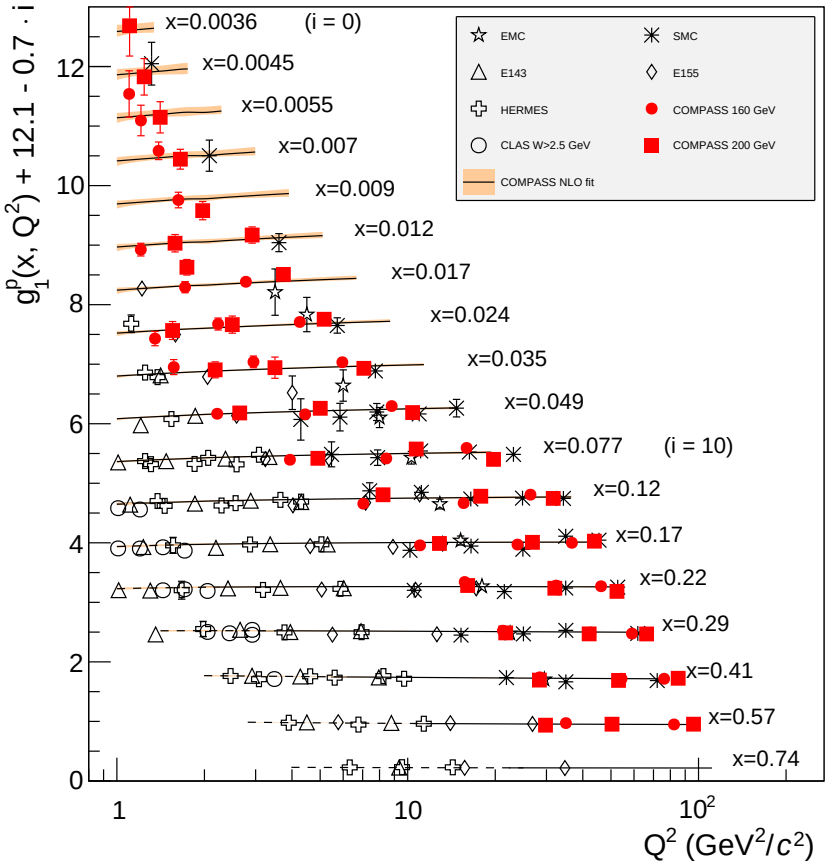
$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \Delta q(x) \approx A_1(x, Q^2) \cdot F_1(x, Q^2)$$

World data for spin structure function g_1



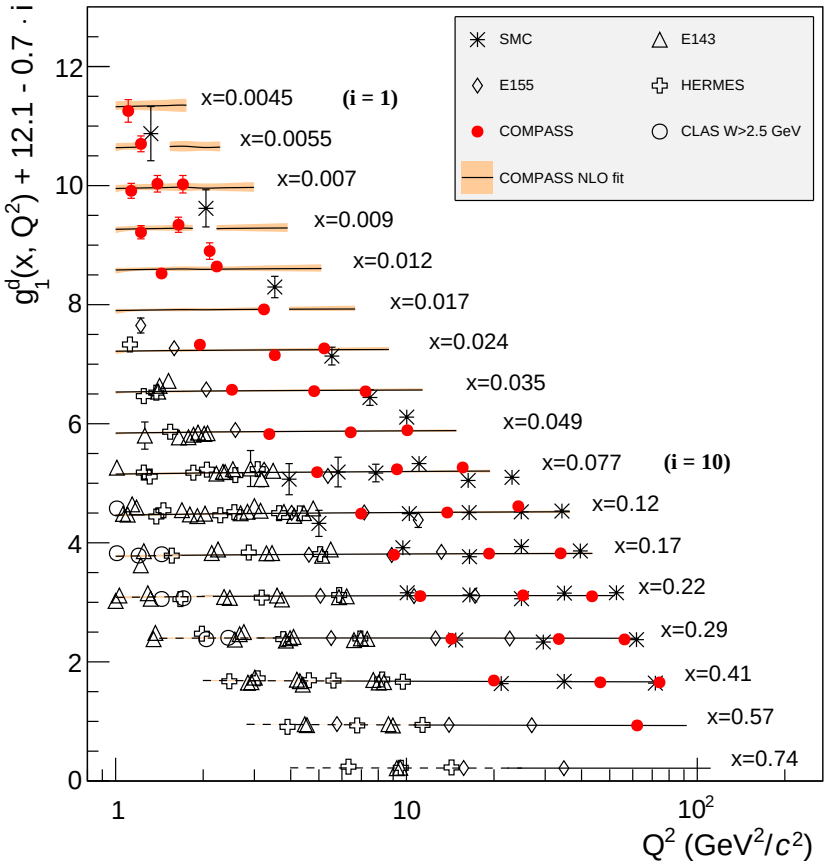
Proton

PLB 753 (2016) 18



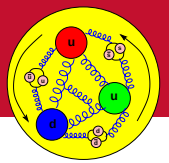
Deuteron

arXiv:1612.00620



- in addition: data for neutron using polarised ^{3}He
- new: final data set from COMPASS for deuteron

→Badelek
→Cosyn

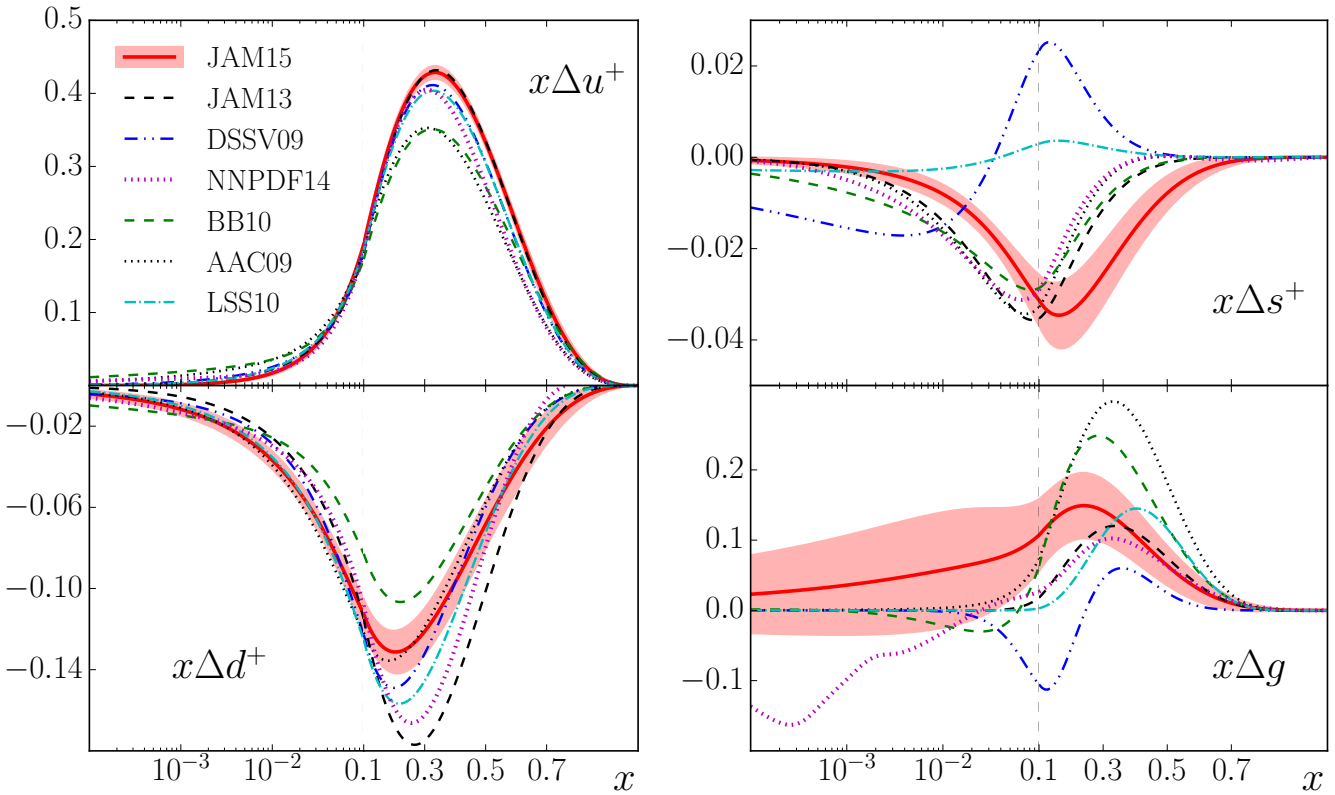


Recent determinations of polarized PDFs

E.Nocera SPIN2016

	DSSV	NNPDF	JAM	LSS
DIS	☑	☑	☑	☑
SIDIS	☑	☒	☒	☑
pp	☑ (jets, π^0)	☑ (jets, $W^{\pm}$)	☒	☒
statistical treatment	Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	Monte Carlo	Monte Carlo	Hessian $\Delta\chi^2 = 1$
parametrization	polynomial (23 pars)	neural network (259 pars)	polynomial (10 pars)	polynomial (20 pars)
features	global fit	minimally biased fit	large-x effects	higher-twist effects
latest update	PRL 113 (2014) 012001	NPB 887 (2014) 276	PRD 93 (2016) 074005	PRD 82 (2010) 114018

Polarised PDFs at $Q^2 = 1\,(\mathrm{GeV}/c)^2$



$$\Delta q^+ = \Delta q + \Delta \bar{q}$$

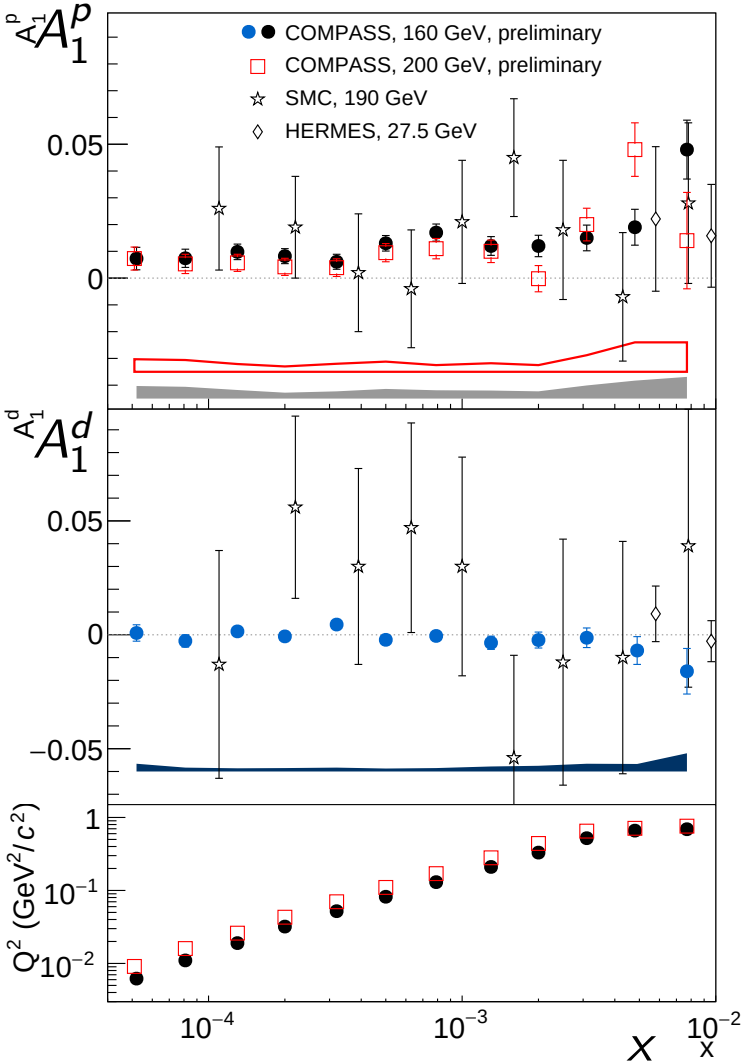
Jlab data with $W^2 > 4\mathrm{GeV}^2$ used

PRD93(2016)074005

- $\Delta\Sigma$ about 0.3 with 10–20% uncertainty
- Δu^+ and Δd^+ quite similar in different parametrisations
- Δs^+ small and negative (constraint from Δq_8)
- ΔG small, large uncertainty
- fit with TMC and HT, significant HT terms found

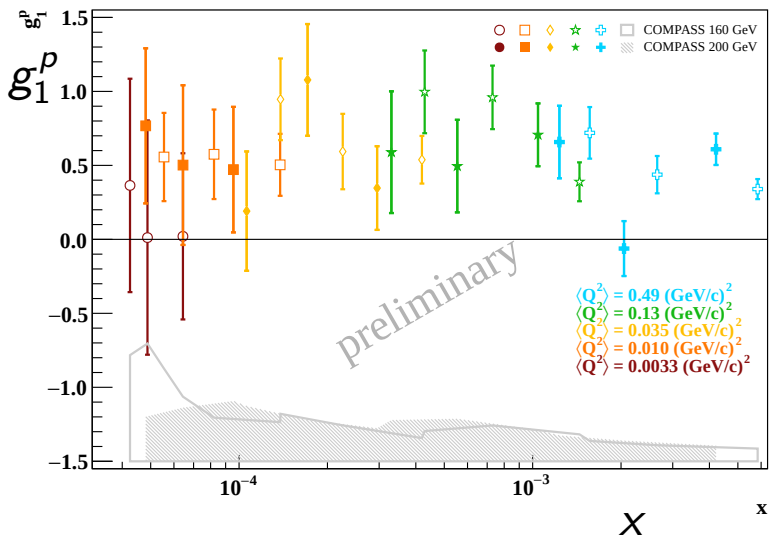
Measurements at small x (and small Q^2)

Final deuteron and proton results for $Q^2 < 1\,\mathrm{GeV}^2/c^2$ from COMPASS



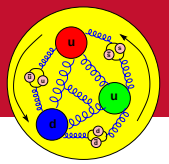
PLB 647 (2007) 330

- Improve previous data statistics by a factor ≥ 100
- A_1^d, g_1^d compatible with zero
- A_1^p about 1%
  significant spin effects at low x

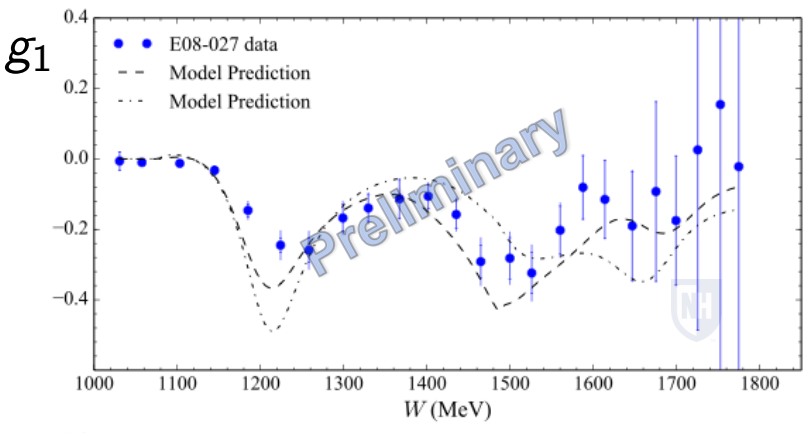


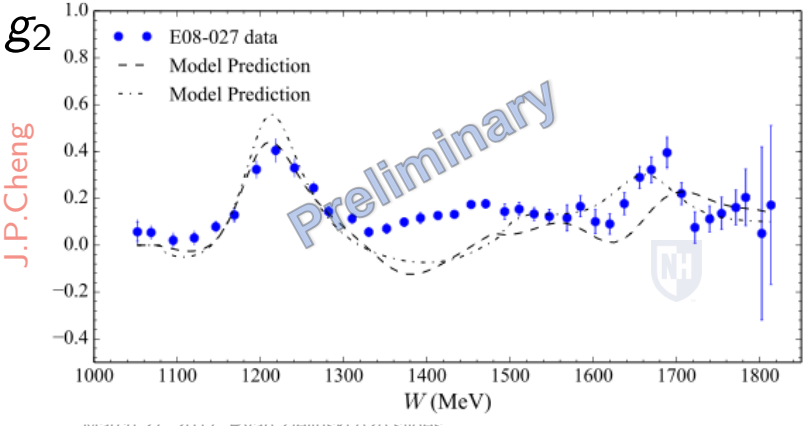
- g_1 models at low x, Q^2: extrapolation of partonic description combined with GVMD Ansatz

Measurements at large x



- domain of Jlab experiments: many high statistics results obtained, e.g. quark polarisation in valence region using $A_1^{p,d}$ at high x
- now focus on transition from perturbative to non-perturbative regime
- E08-027: transverse and longitudinal asymmetries on pol.^{3}He ($E = 2.254\,\text{GeV}$)





→ Melnitchouk

- for g_1: good agreement with CLAS in overlap region, extension towards lower Q^2
- for g_2: investigate HT contribution $\bar{g}_2$

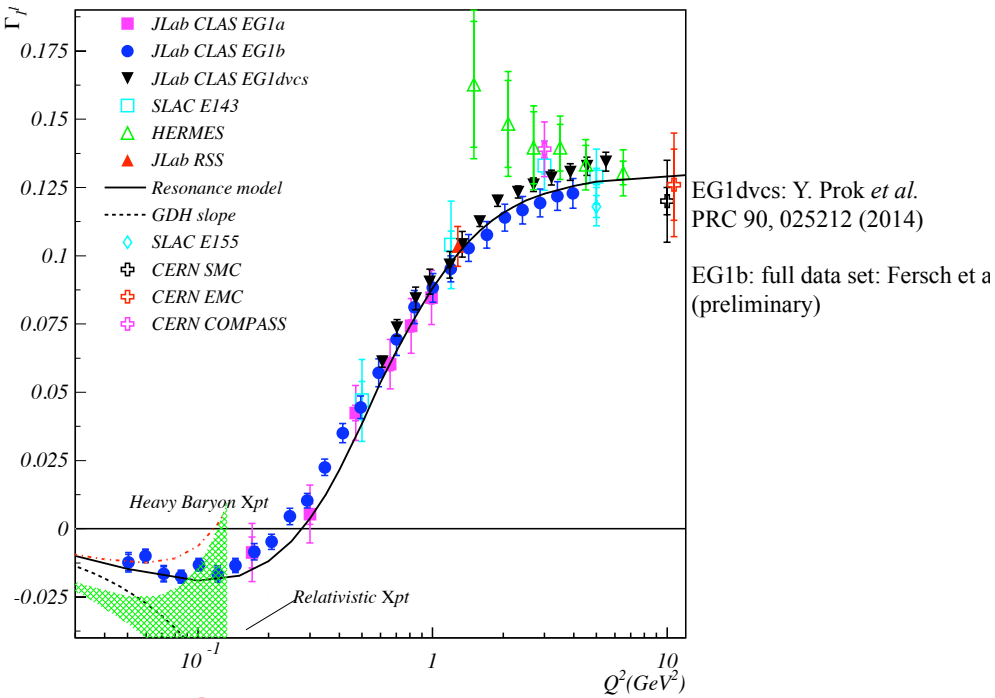
$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$

$$g_2^{WW} = -g_1(x, Q^2) + \int_x^1 \frac{\mathrm{d}y}{y} g_1(y, Q^2)$$

Sum rules

- **generalised GDH sum rule:** $I_{\mathrm{GDH}}(Q^2 \neq 0) = \dfrac{16\pi^2\alpha}{Q^2} \displaystyle\int_0^{x_{th}} g_1(x, Q^2)\,\mathrm{d}x$
- limits: $Q^2 = 0$ GDH sum rule
  $Q^2 \to \infty$ Bjorken sum rule

Γ_1^p

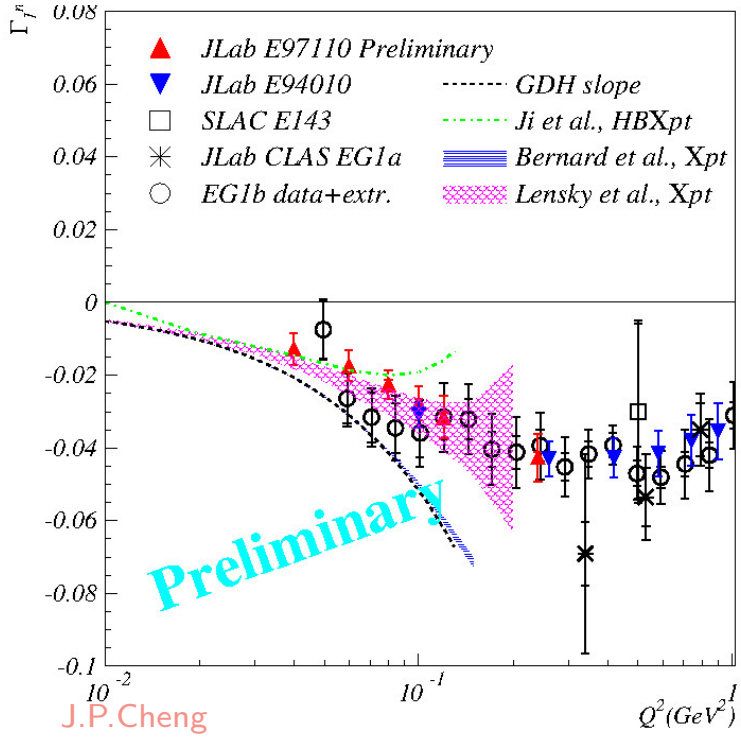


EG1dvcs: Y. Prok *et al.* PRC 90, 025212 (2014)

EG1b: full data set: Fersch et a (preliminary)

A.Deur, SPIN2016

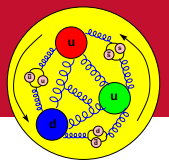
Γ_1^n



J.P.Cheng

- comparison with chiral perturbation theory at very low Q^2

Nucleon spin and helicity PDF



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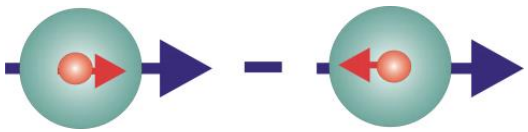
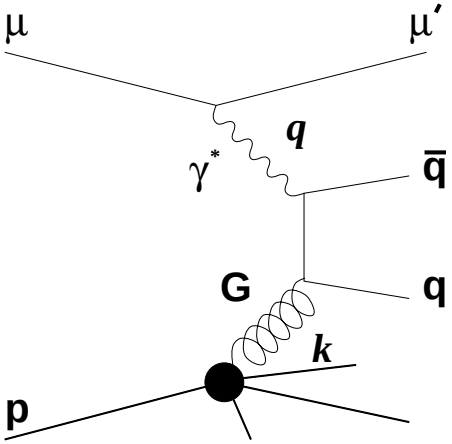


Direct measurements of gluon polarisation

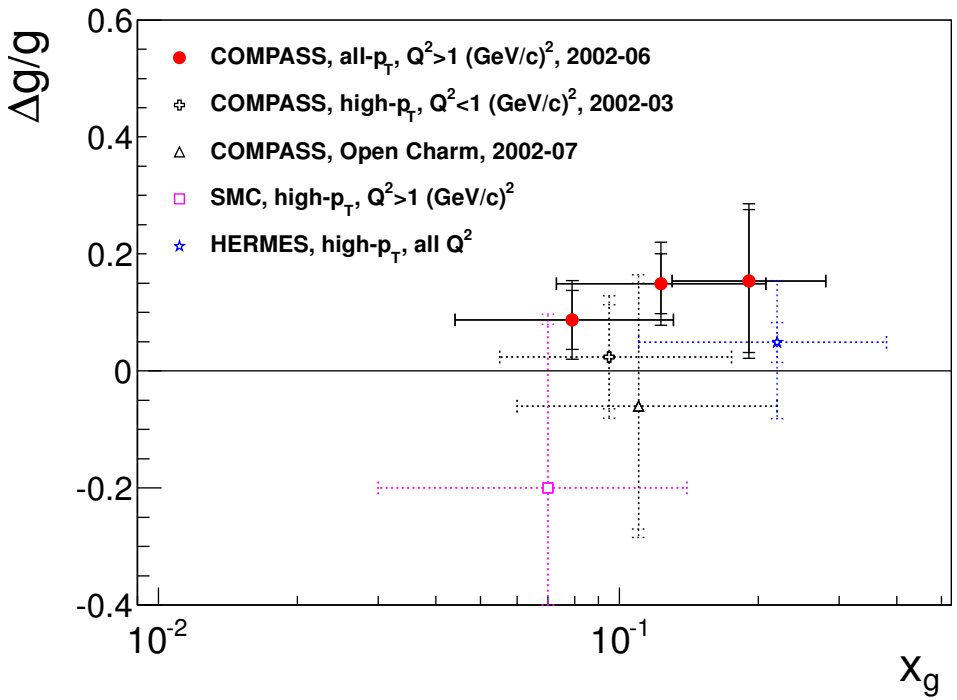
Photon gluon fusion



$$A_{\gamma N}^{PGF} \approx \langle a_{LL}^{PGF} \rangle \frac{\Delta g}{g}$$

$\langle a_{LL}^{PGF} \rangle$ analysing power

arXiv:1512.05053



- **Open charm production (LO,NLO)**

  $\gamma g \to c\bar{c} \to D^0, D^*$

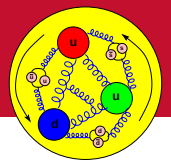
- **High p_T hadron pairs (LO)**

  $\gamma g \to q\bar{q} \to$ 2 jets or H^+H^-

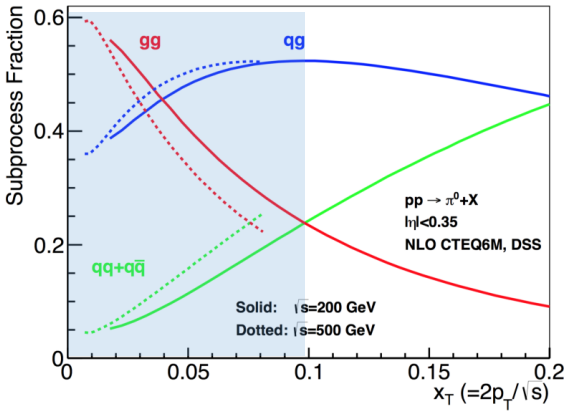
- **Clear indication of positive $\Delta g/g$ from new COMPASS result**

$$\Delta g/g^{LO} = 0.113 \pm 0.038_{stat} \pm 0.035_{syst}$$

Gluon polarisation from RHIC



arXiv1501.01220



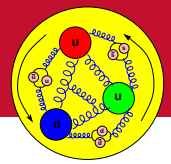
- measurement of A_{LL} sensitive to gluon polarisation ($+,-$ proton helicities)

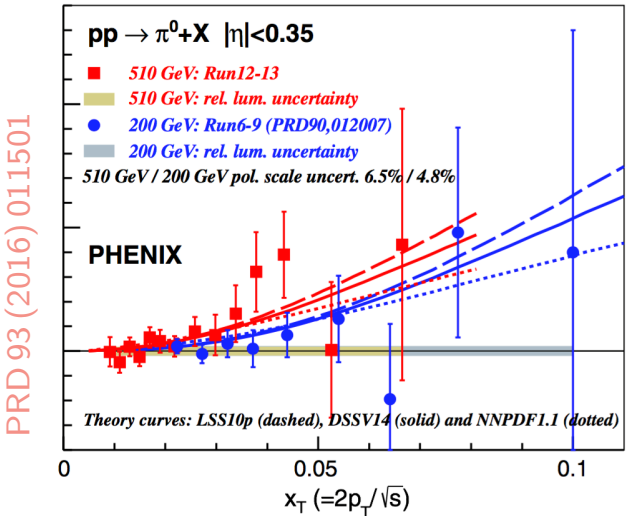
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

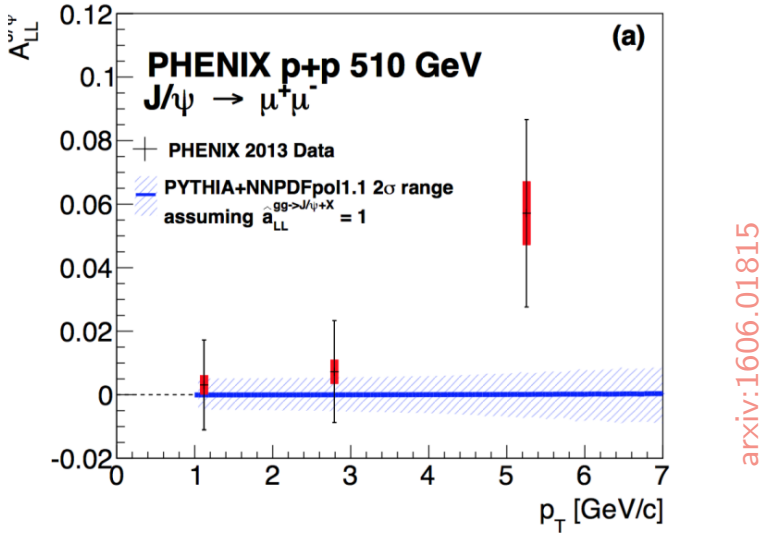
- wealth of new results from 2012/13 data at 500/510 GeV
  extend measurements to lower x_T
- many different channels investigated:
  inclusive jet, jet+jet, π^0,J/ψ
- many more analyses in pipeline

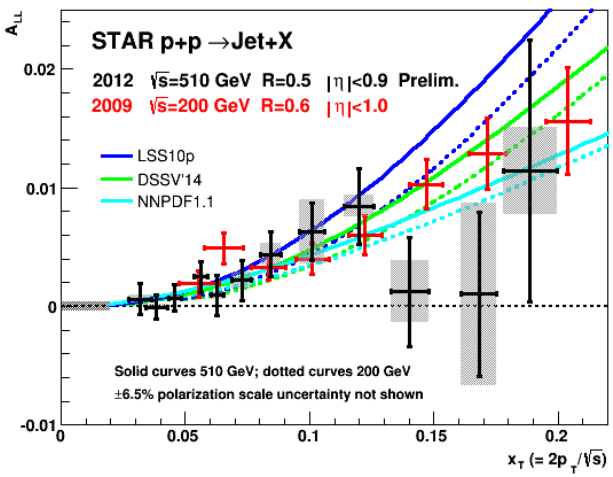
$\longrightarrow$ **Surrow**

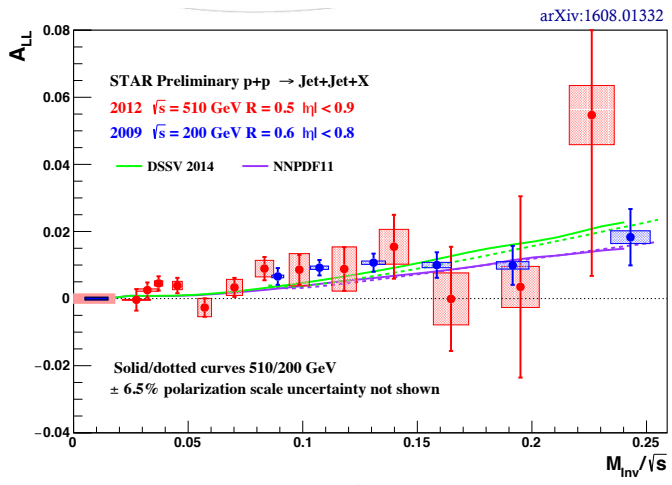
Gluon polarisation from RHIC





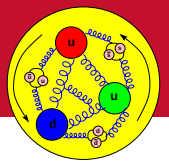






- good agreement with LSS10p, DSSV14 and NNPDF1.1
- all data point to $\int_{0.05}^{1} \Delta g(x)\mathrm{d}x \simeq 0.2$ (similar to COMPASS result)

Nucleon spin and helicity PDF



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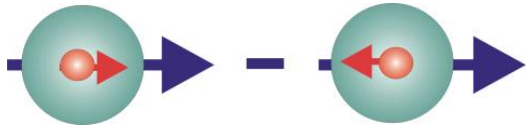
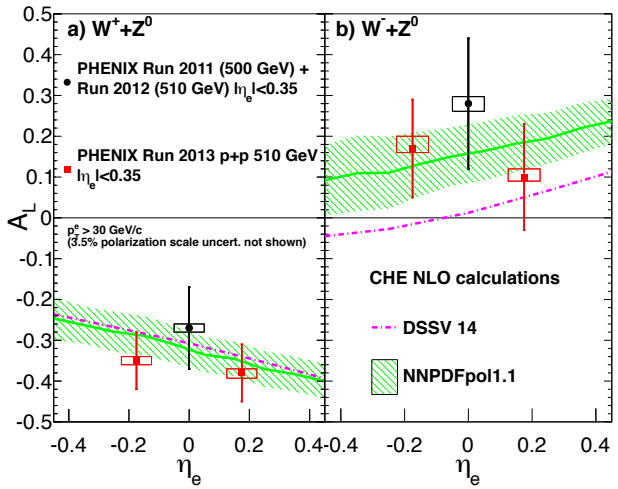
$$\Delta G(Q^2) = \int_0^1 \mathrm{d}x \Delta g(x, Q^2)$$

Quark helicity PDFs: $\Delta q(x, Q^2) =$

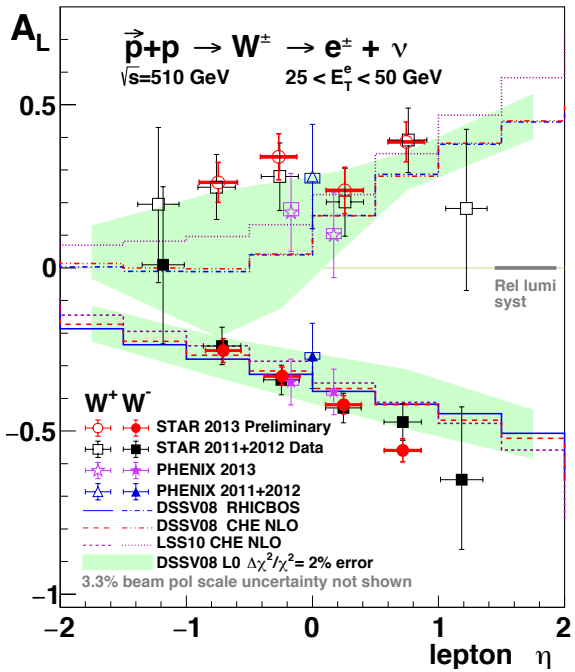


Seaquark polarisation from W production

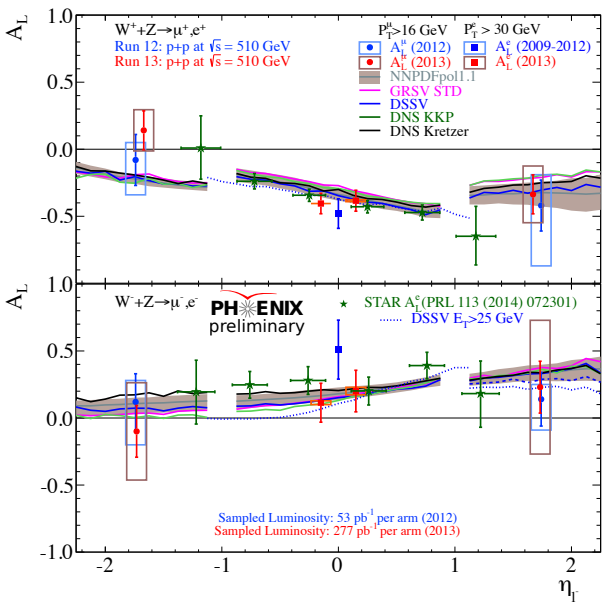
$$A_L^{\text{Corrected}} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}(1 + BG/Sig)$$



PRD 93 (2016) 051103



D.Gunarathne SPIN2016



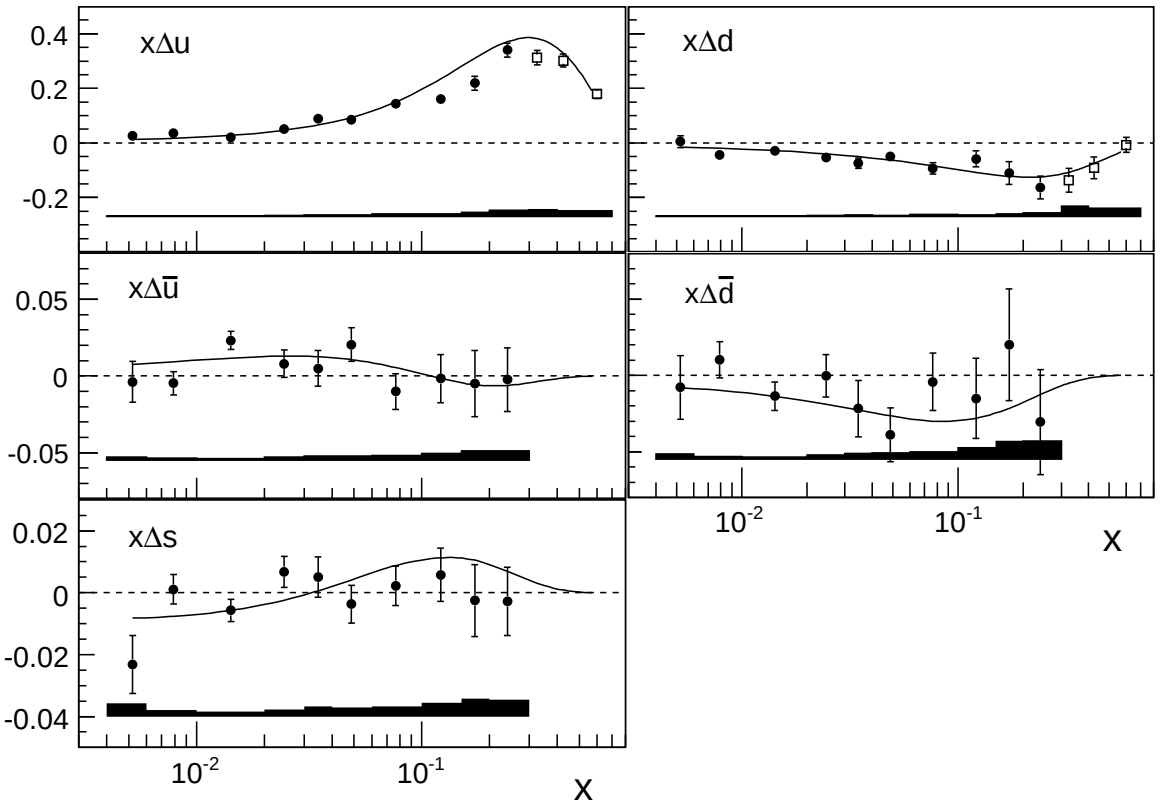
S.Park SPIN2016

- new precise STAR results from 2013
- good agreement with PHENIX
- data point to sizeable positive $\Delta\bar{u}$

→ Xu

Flavour separation using SIDIS data

$$A_1^h = \frac{\Sigma_q e_q^2 \Delta q(x) \int D_q^h(z) \mathrm{d}z}{\Sigma_q e_q^2 q(x) \int D_q^h(z) \mathrm{d}z}$$



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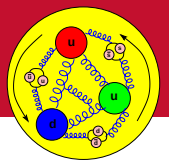
Basic concept

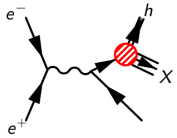
- measured:
  A_1^{d}, $A_{1\mathrm{d}}^{K^\pm}$, $A_{1\mathrm{d}}^{\pi^\pm}$,
  A_1^{p}, $A_{1\mathrm{p}}^{K^\pm}$, $A_{1\mathrm{p}}^{\pi^\pm}$
- determined:
  Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$,
  $\Delta s = \Delta \bar{s}$
- inputs:
  unpol. LO PDFs (MRST04)
  LO FFs (DSS)
- curves: DSSV param.
- results: $\Delta s \geq 0$??

$\longrightarrow$ Results for Δs depend very much on the strange quark FFs used

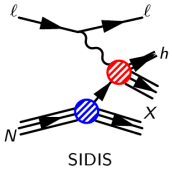
Fragmentation functions



Progress on global determinations of Fragmentation Functions

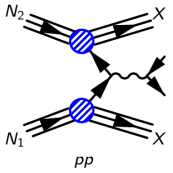


$e^+ + e^- \to h + X$
single-inclusive annihilation (SIA)



SIDIS

$\ell + N \to \ell' + h + X$
semi-inclusive deep-inelastic scattering (SIDIS)



pp

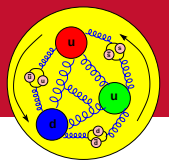
$N_1 + N_2 \to h + X$
high-p_T hadron production in pp collisions (PP)

Process	DSS	HKNS	JAM	NNPDF
SIA	☑	☑	☑	☑
SIDIS	☑	☒	☒	☒
PP	☑	☒	☒	☒
statistical treatment	Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	Hessian $\Delta\chi^2 = 15.94$	Monte Carlo	Monte Carlo
hadron species	$\pi^\pm$, $K^\pm$, $p/\bar{p}$, $h^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$	$\pi^\pm$, $K^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$
latest update	PRD 91 (2015) 014035	arXiv:1608.04067	arXiv:1609.00899	in progress

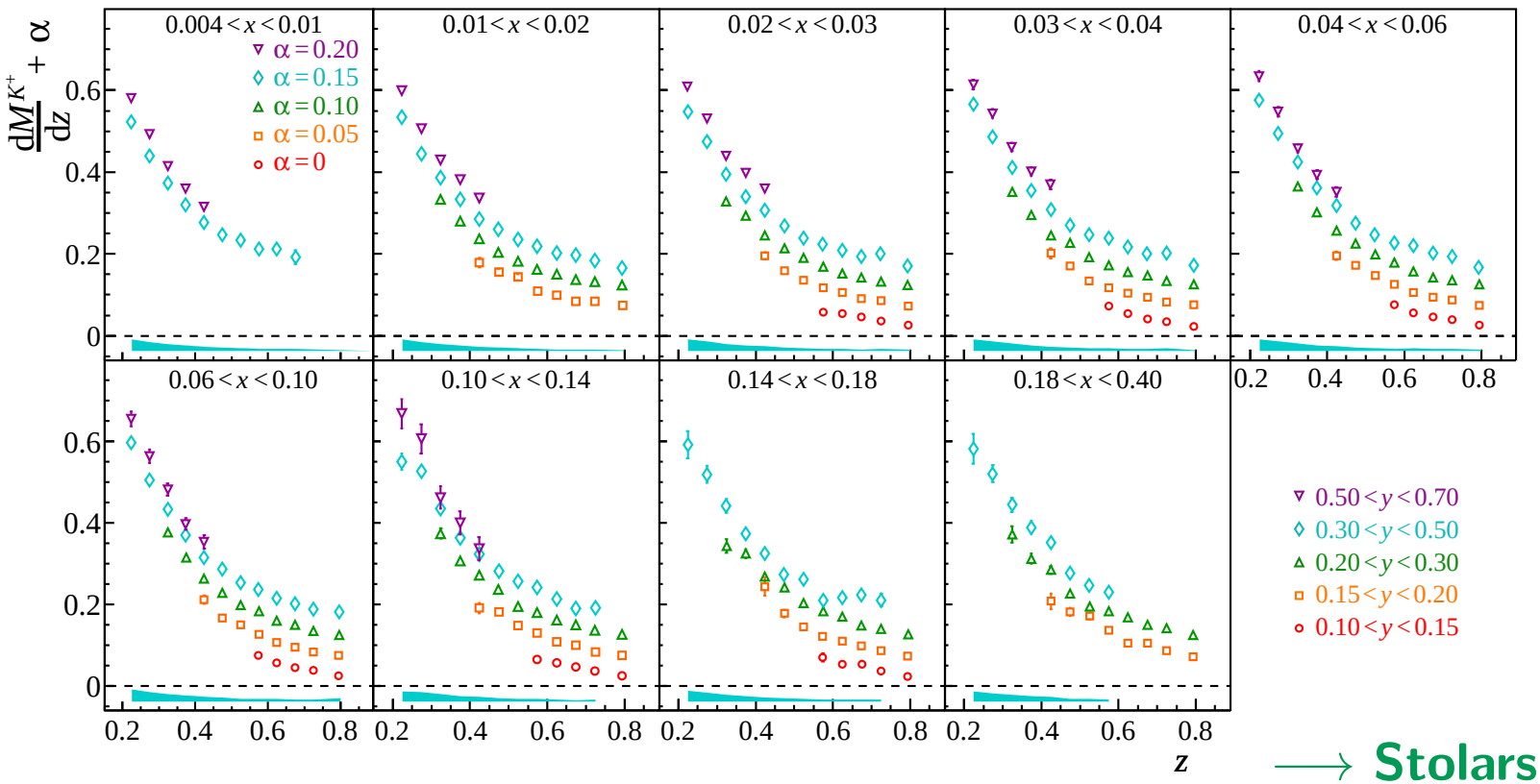
E. Nocera SPIN2016

$\longrightarrow$ **Nocera**
$\longrightarrow$ **Sato**
$\longrightarrow$ **Horn**

SIDIS data



- High precicion data from e^+e^- annihilation, but $q\bar{q}$ separation difficult
- SIDIS data allow for $q\bar{q}$ separation: high statistics π and K multiplicities from HERMES and COMPASS
- COMPASS multiplicities in 3 dim. bins of (x,y,z) from isoscalar ^{6}LiD



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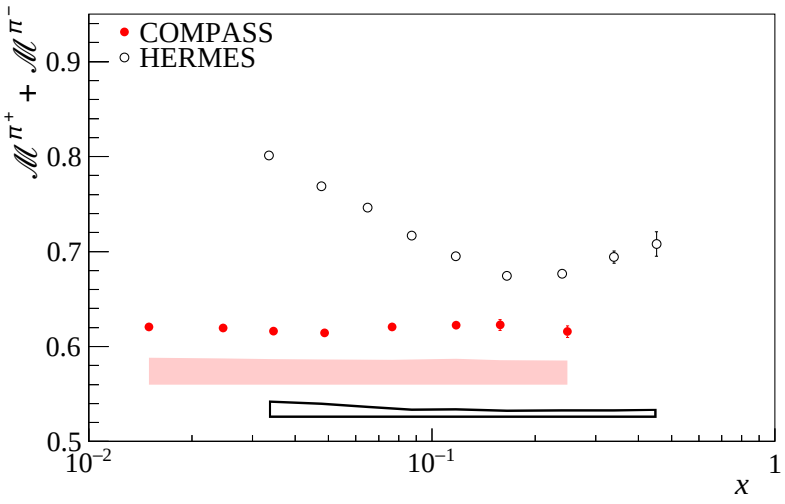
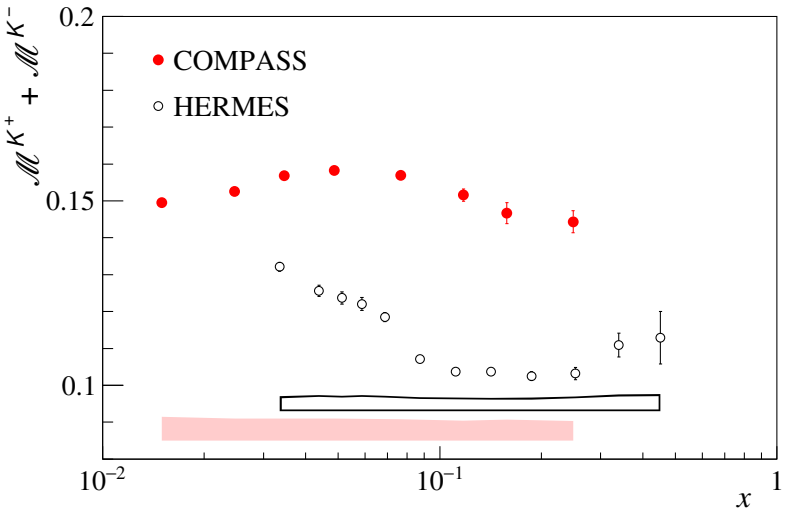
⟶ Stolarski

Pion and kaon multiplicities



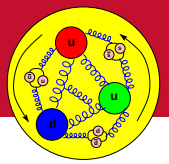


COMPASS K PLB 767 (2017) 133, π PLB 764 (2017) 1

HERMES K: PRD 89 (2014) 097101, π: PRD 87 (2013)074029

- LO FFs extracted from COMPASS pion data agree well with most NLO FFs parametrisations
- multiplicity sum: integrated over z (and y for COMPASS)
- simple interpretation in LO:
  π: almost no x dependence expected
  K: very simple relation to FFs
- clear discrepancies between COMPASS and HERMES being investigated
- kinematics is similar, but not identical
- multiplicity ratio: comparison ok for π^+/π^-, differs by 20% for K^+K^-

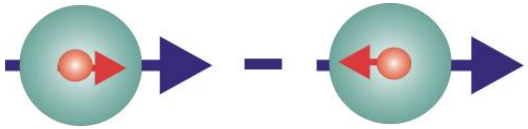
Nucleon spin and helicity PDF



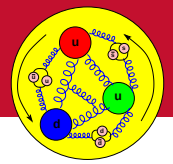
$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta\Sigma(Q^2) = \int_0^1 \mathrm{d}x[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}](x, Q^2)$$

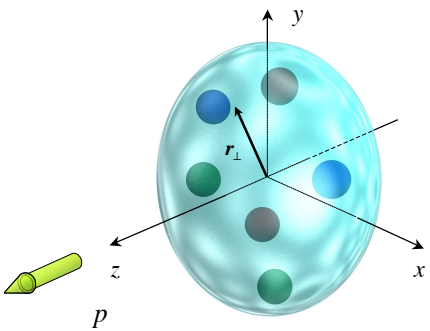
$$\Delta G(Q^2) = \int_0^1 \mathrm{d}x \Delta g(x, Q^2)$$

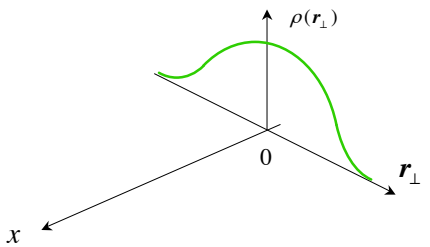
Helicity PDFs: $\Delta q(x, Q^2) =$ 

3D structure of the nucleon



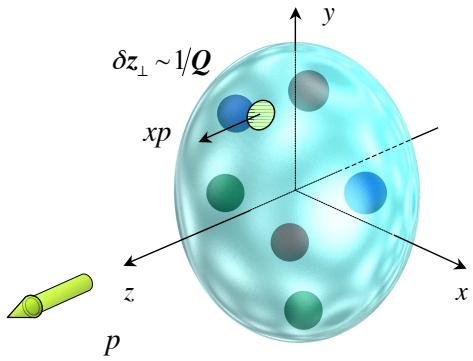
Elastic scattering

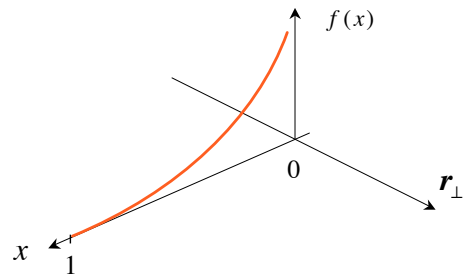




Form factors

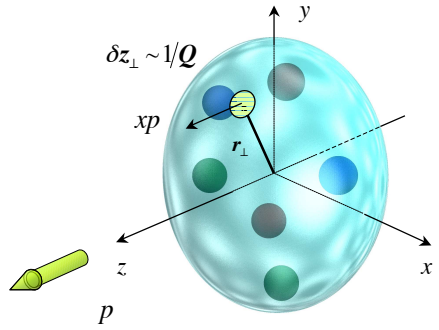
Deep inelastic scattering

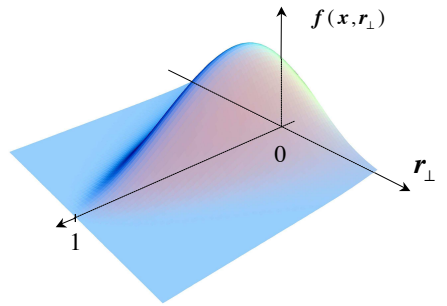




Parton distributions

Hard exclusive processes



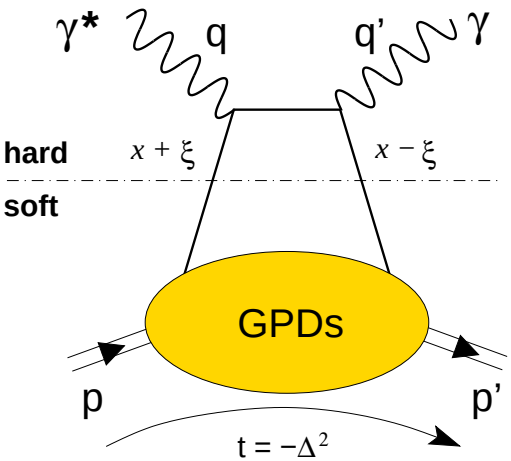


Generalized Parton Distributions (GPDs)

→ **Sokhan**
→ **Wagner**
→ **Kumano**

GPDs correlate transverse spatial size and longitudinal momentum

Generalised parton distributions



- accessible in exclusive reactions
- factorisation for Q^2 large, $|t| < 1$ GeV^2
- GPD for each quark flavour and for gluons
- depend on 3 variables: x, ξ, t with $\xi = \frac{x_B}{2-x_B}$

- 8 GPDs: $\mathrm{H}, \widetilde{\mathrm{H}}, \mathrm{H_T}, \widetilde{\mathrm{H}}_T$ conserve nucleon helicity
  $\mathrm{E}, \widetilde{\mathrm{E}}, \mathrm{E_T}, \widetilde{\mathrm{E}}_T$ flip nucleon helicity, T: flip quark helicity

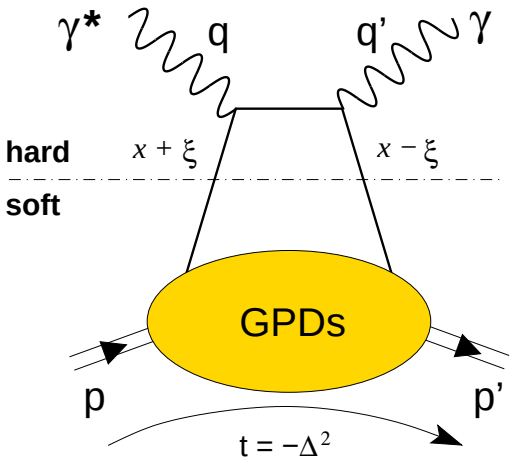
- **limits**: PDFs $q(x) = \mathrm{H}(x,0,0)$ and formfactors $F(t) = \int \mathrm{d}x\, \mathrm{H}(x,\xi,t)$

- **Ji's sumrule**

$$J^f = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} \mathrm{d}x\; x \left[\mathrm{H}^f(x,\xi,t) + \mathrm{E}^f(x,\xi,t)\right]$$

J^f: total angular momentum contribution of quark f

Deeply virtual Compton scattering



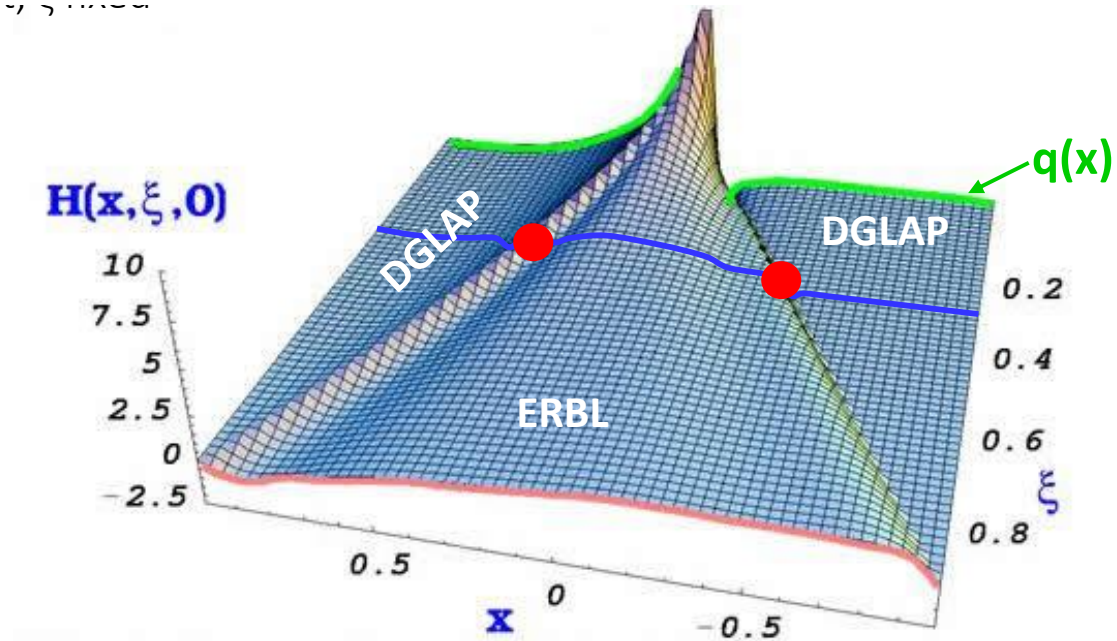
- mainly sensitive to GPDs H and E
- GPDs related to Compton form factors $\mathcal{H} = \Sigma e_f^2 \mathcal{H}^f$

$$\mathrm{Im}\,\mathcal{H}(\xi,t) \overset{\mathrm{LO}}{=} \mathrm{H}(\pm\xi,\xi,t)$$

$$\mathrm{Re}\,\mathcal{H}(\xi,t) \overset{\mathrm{LO}}{=} \mathcal{P}\int_{-1}^{1} \mathrm{d}x\; \mathrm{H}(x,\xi,t)\frac{1}{x-\xi}$$

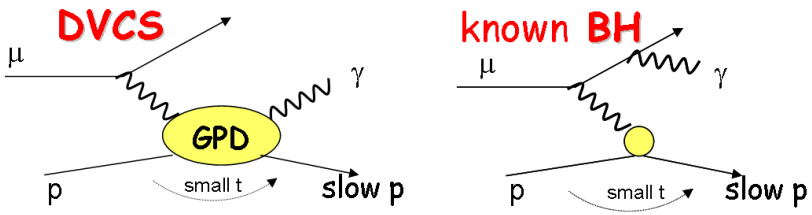
$\longrightarrow$ **Sznajder**

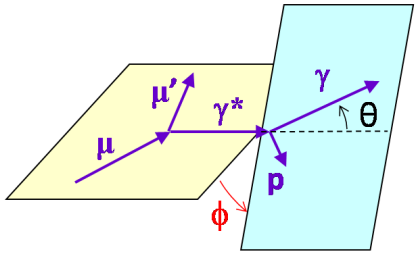
- Dependence on x cannot be measured $\rightarrow$ modelling very important



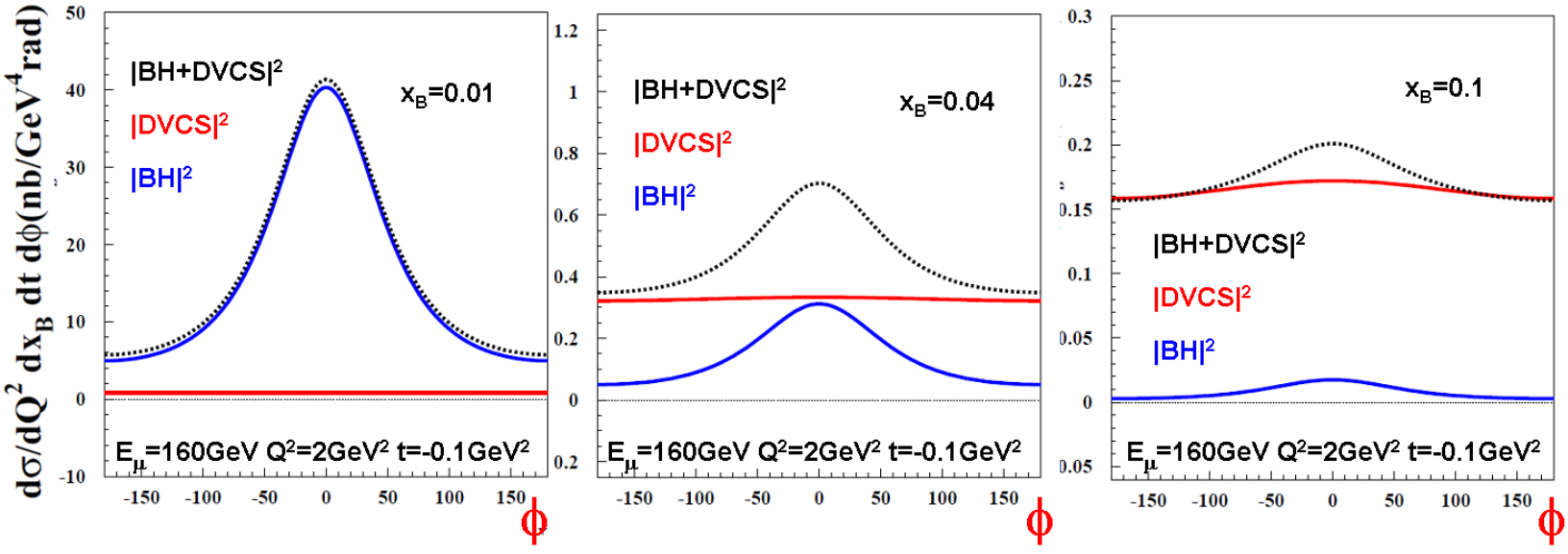
From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)

DVCS and Bethe-Heitler





$E = 160\,\text{GeV}$ $\quad d\sigma \sim |T^{BH}|^2 + \text{Interference Term} + |T^{DVCS}|^2$



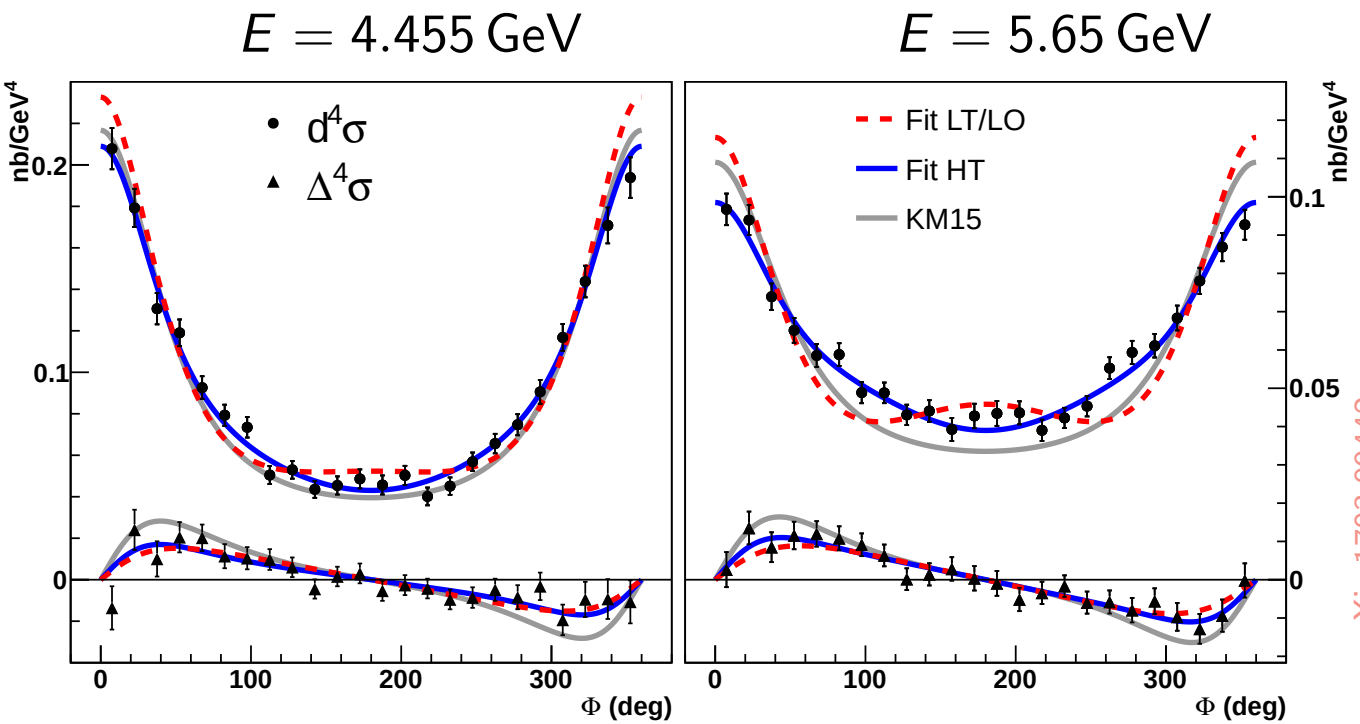
BH dominates, reference yield

DVCS amplitude via interference Jlab,HERMES,H1, COMPASS

DVCS dominates, study of $\mathrm{d}\sigma/\mathrm{d}|t|$, only for H1,ZEUS,COMPASS

DVCS: new results from HALL A E07-007

- new high statistics beam-spin and unpolarised cross section results (proton)



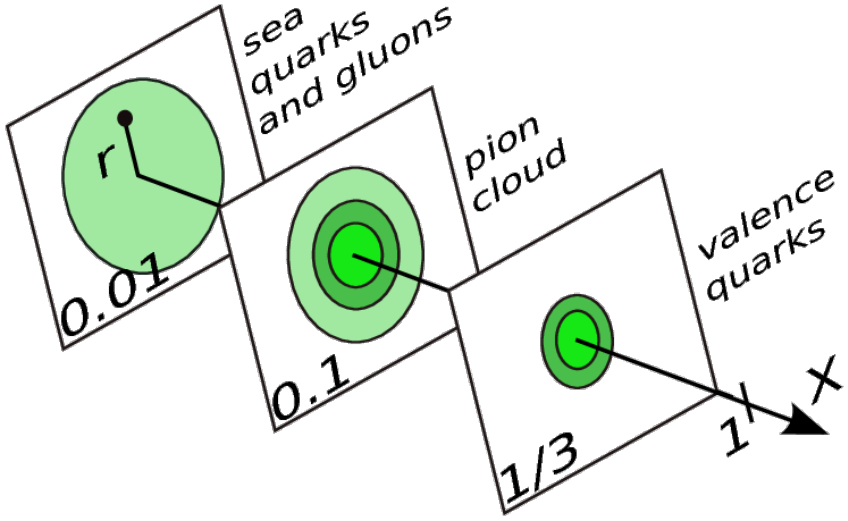
$Q^2 = 1.75\,\mathrm{GeV}^2/c^2$
$x_b = 0.36$
$t = -0.30\,\mathrm{GeV}^2/c^2$

arXiv:1703.09442

→ **Munoz**
→ **Hamilton**
→ **Boussarie**

- generalised Rosenbluth separation for DVCS and BH-DVCS interference term
- leading twist description not sufficient, twist 3 or/and higher order contributions neccessary

Transverse imaging



- t-slope of DVCS cross section $B(x_B)$

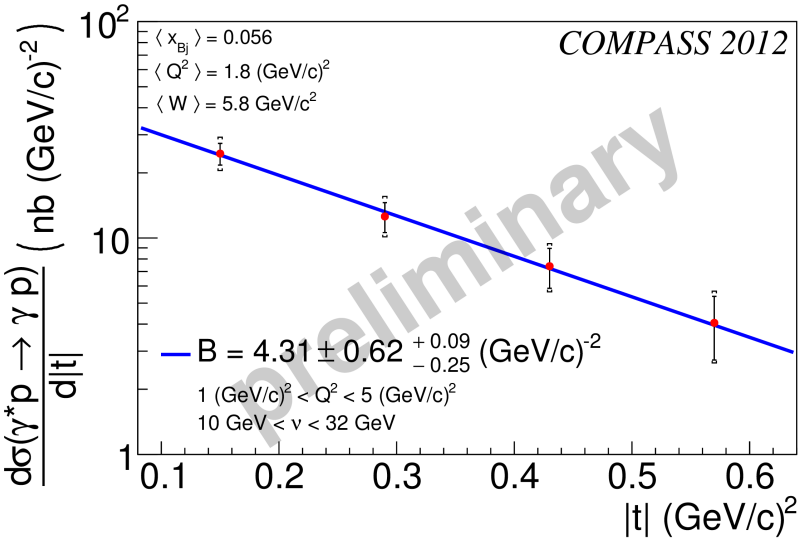
$$\mathrm{d}\sigma^{DVCS}/\mathrm{d}|t| \propto \exp(-B(x_B)|t|)$$

- related to distance $\langle r_\perp^2(x)\rangle$ between struck quark and spectator c.m.

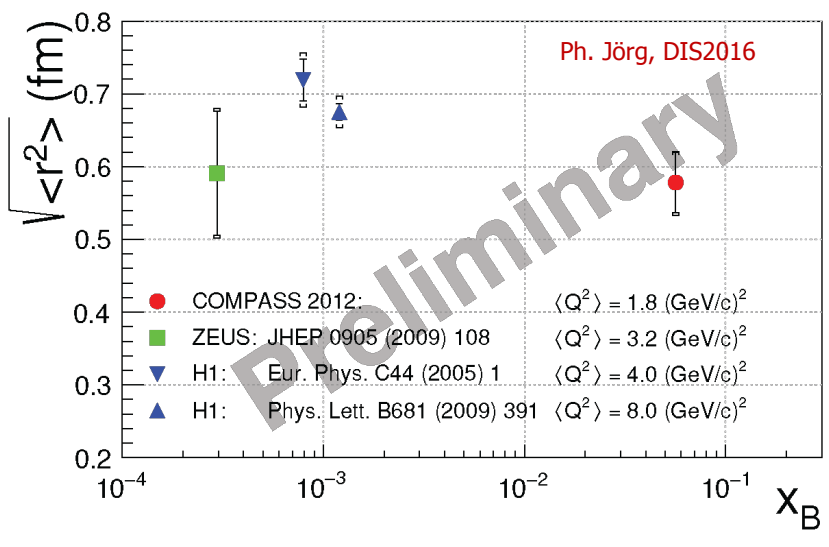
$$B(x_B) \sim 1/2\,\langle r_\perp^2(x_B)\rangle$$

⟶ **Ferrero**

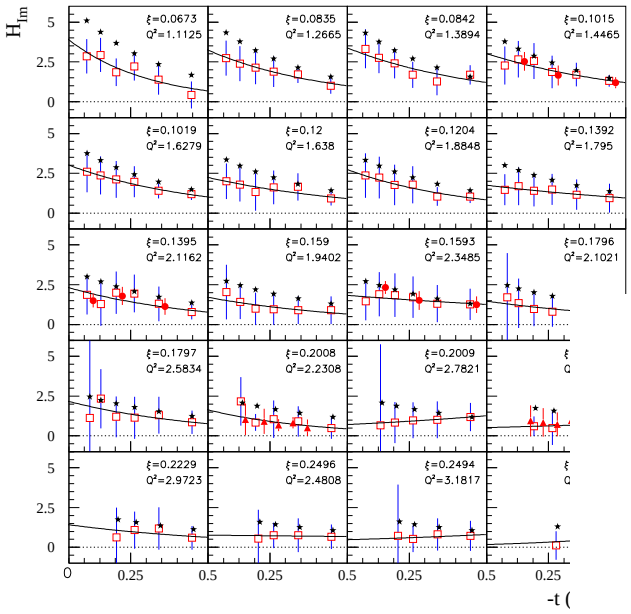
- model independent
- results from COMPASS 2012 pilot run



DIS2016

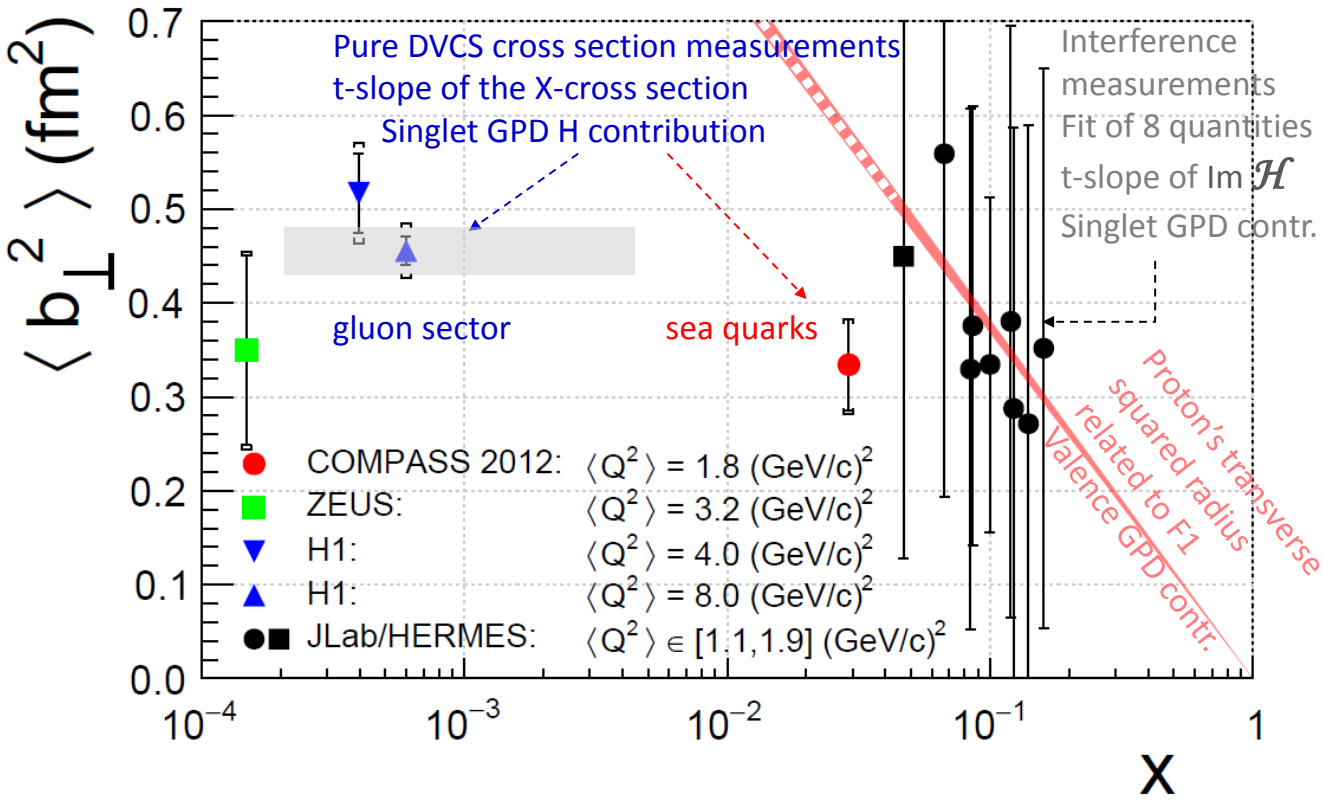


Transverse proton size from Jlab data

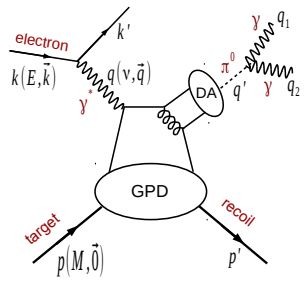


- analysis of CLAS and Hall A data: fit of 8 CFF at LO/LT

Dupre, Guidal, Vanderhaeghen PRD 95 (2017) 011501

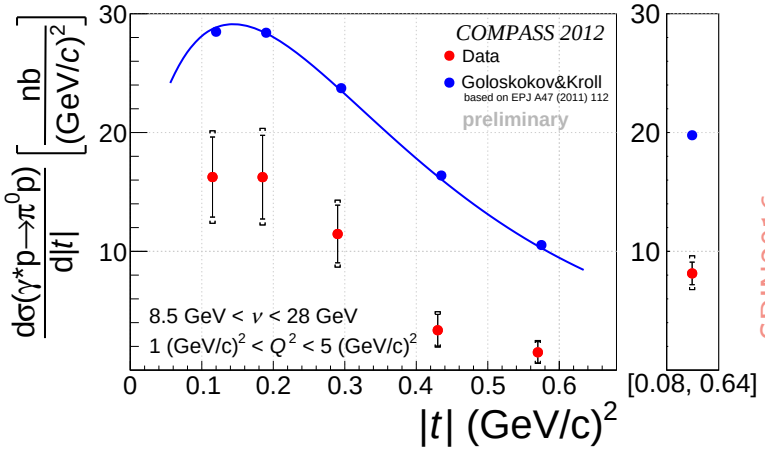


Hard exclusive meson production



$\longrightarrow$ **Sabatie**
$\longrightarrow$ **van Hulse**
$\longrightarrow$ **Tanaka**

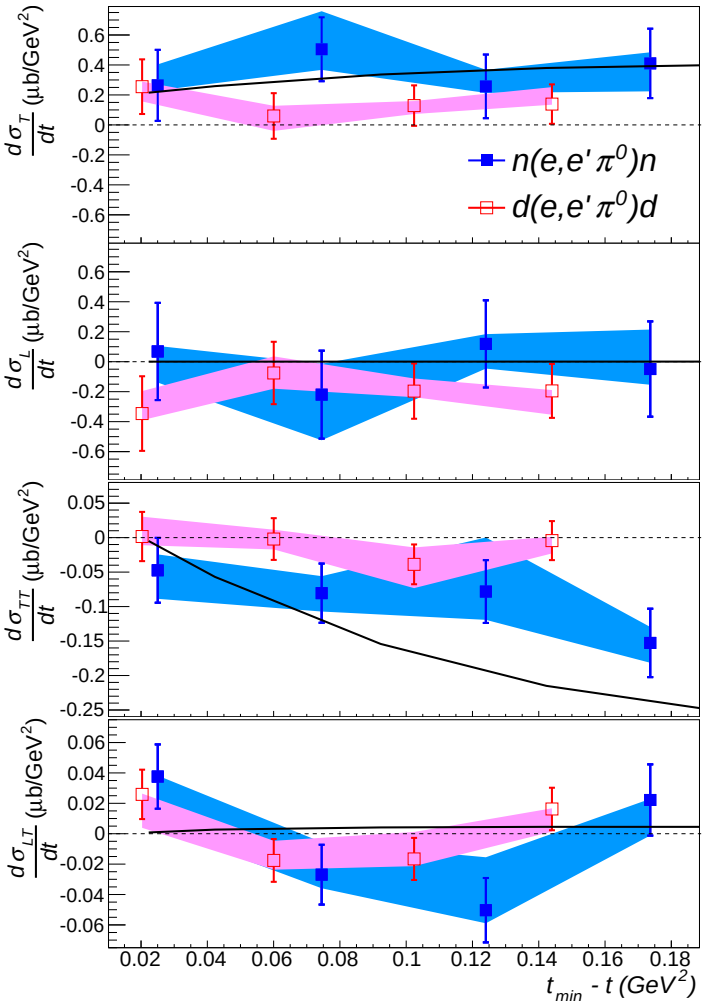
- many analyses for exclusive meson production: π^0, ρ, ω, ϕ



SPIN2016

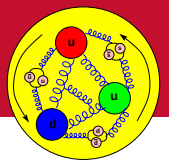
- new results from COMPASS on excl. π^0 from protons
- shape reproduced by model, but data factor 2 below model

- new Jlab Hall A results on exclusive π^0 from neutrons



arXiv:1702.00835

Summary and Outlook



Current knowledge

- Inclusive measurements yield $\Delta\Sigma \approx 30\%$ (NLO pQCD)
- Gluon polarisation small, but positive for $x \sim 0.1$
- Flavourseparation (SIDIS, W production)
- Discrepancy in strange quark polarisation from DIS and SIDIS measurements?
- New data for extraction of fragmentation functions

Future

- Data at large x from JLAB12 $\longrightarrow$ **Page**
- Hopefully data at low x from EIC $\longrightarrow$ **Zhao**
- Investigation of orbital angular momenta e.g. via deeply virtual Compton scattering