Recent experimental results on hadron structure, GPDs and TMDs

G.K. Mallot

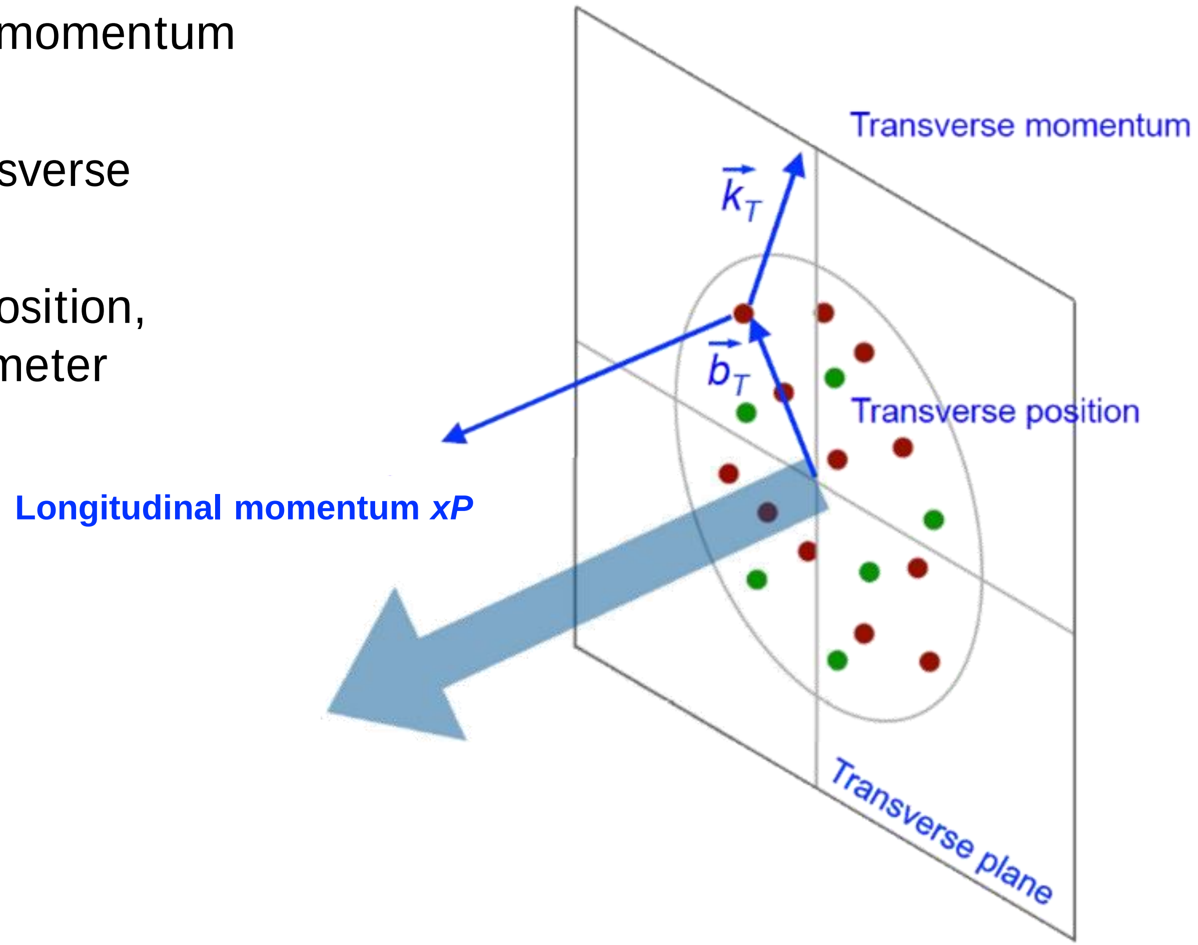
Outline

- Introduction
- spin-independent PDFs
- spin-dependent PDFs
  - inclusive DIS
  - semi-inclusive DIS
  - gluon polarisation
- TMDPDFs
- GPDs
- Outlook

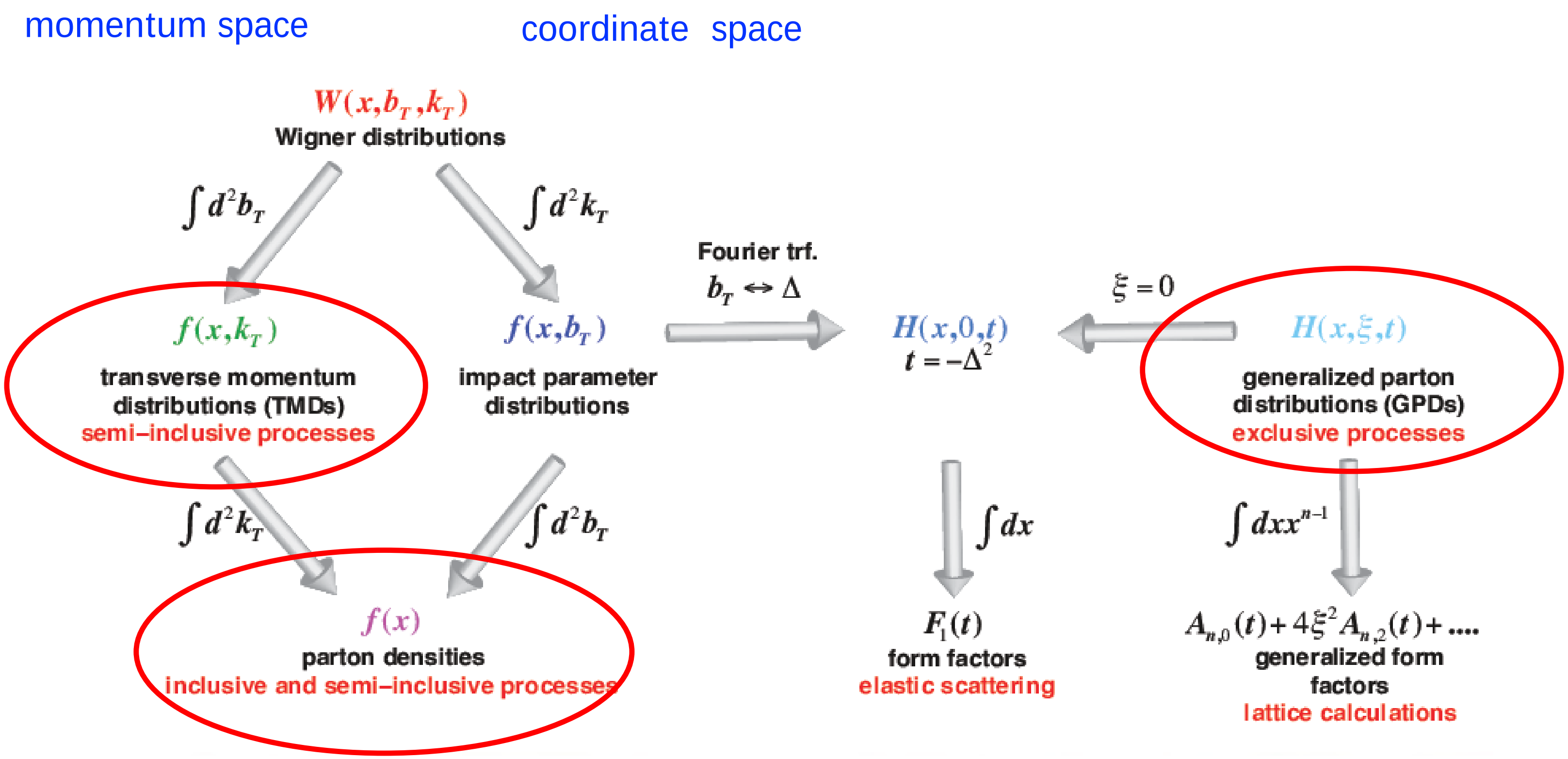
A parton in a hadron

Relative position and motion characterised by 5 dimensions

- x longitudinal momentum fraction
- $\vec{k}_T$ intrinsic transverse momentum
- $\vec{b}_T$ transverse position, impact parameter



Family tree of parton distributions



from EIC white paper arXiv:1212.1701

confined motion of a parton in a hadron needs 2 scales:

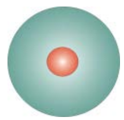
- soft scale k_T or t
- hard scale of the probe Q^2

k_T-integrated Parton Distribution Functions

Three twist-2 PDFs

q(x)

$f_1^q(x)$

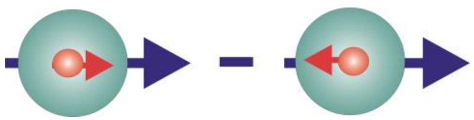


unpolarised PDF

quark/gluon with momentum xP in a nucleon

Δq(x)

$g_1^q(x)$

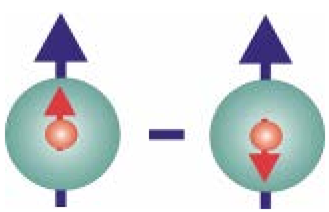


helicity PDF

quark/gluon with spin parallel to the nucleon spin in a longitudinally polarised nucleon

Δ_Tq(x)

$h_1^q(x)$

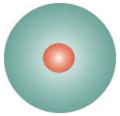


transversity PDF

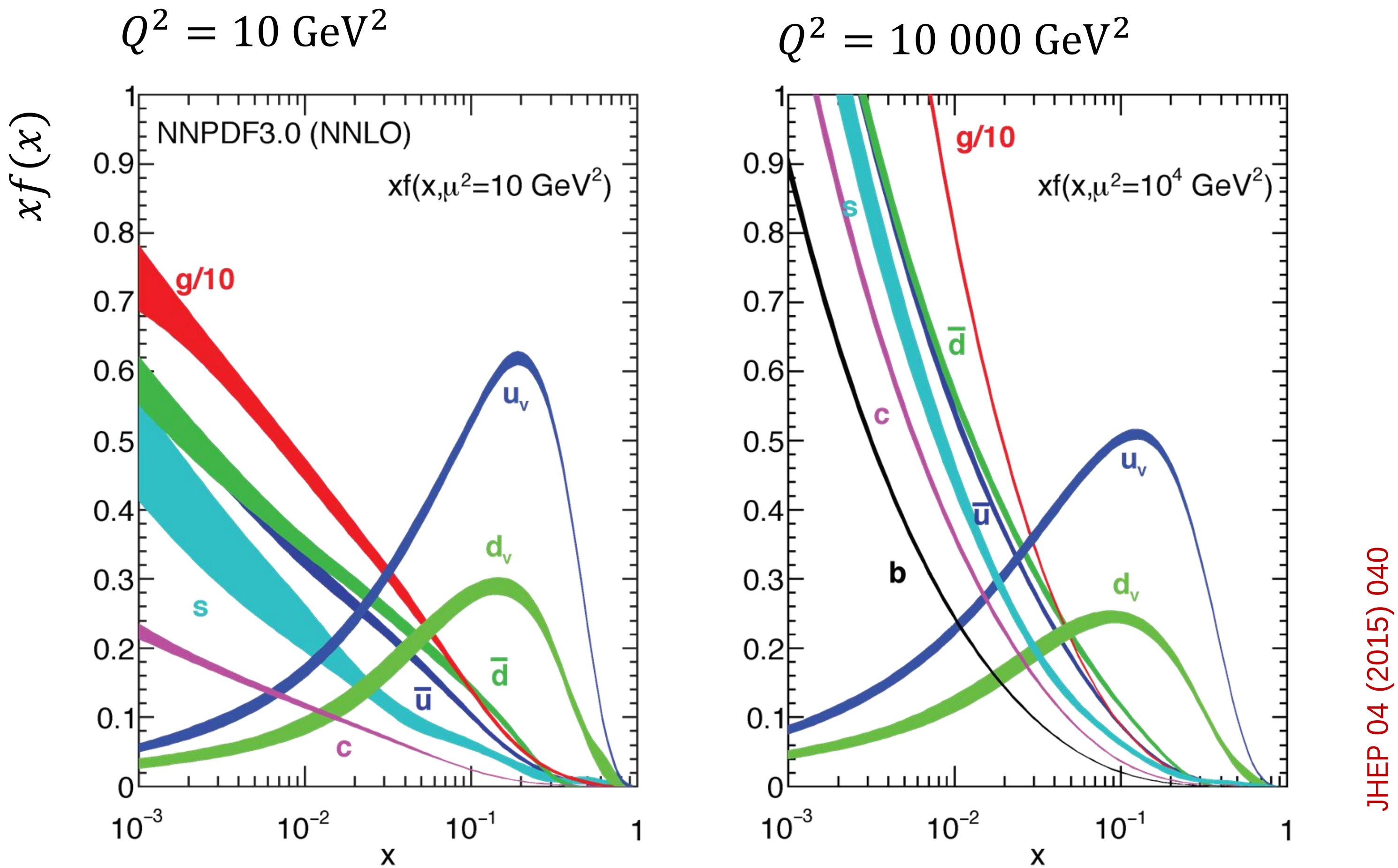
quark with spin parallel to the nucleon spin in a transversely polarised nucleon

unpolarized PDFs

$$q(x, Q^2) = \overrightarrow{q}(x, Q^2) + \overleftarrow{q}(x, Q^2)$$

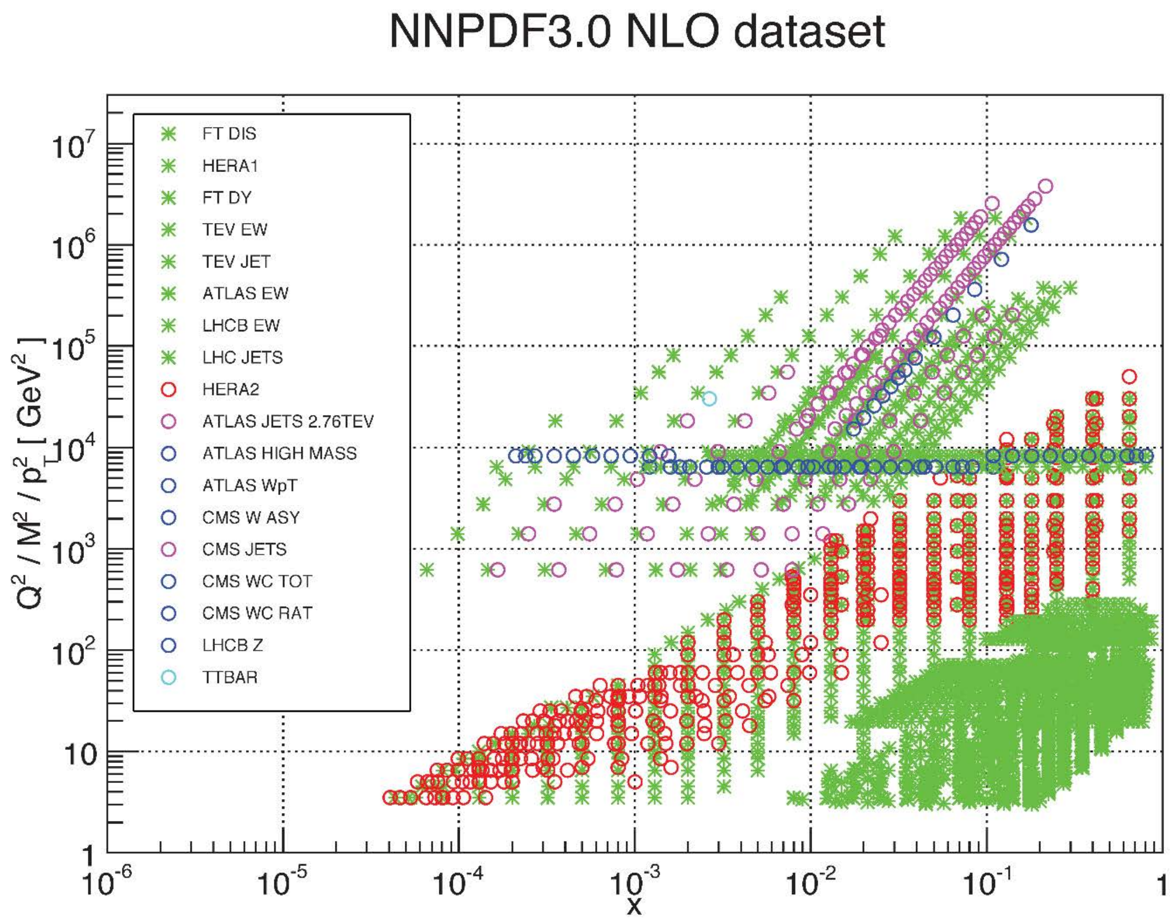


PDFs: Example NNPDF3.0



- Neural network approach NNLO (also LO, NLO)

Data used in NNPDF3.0



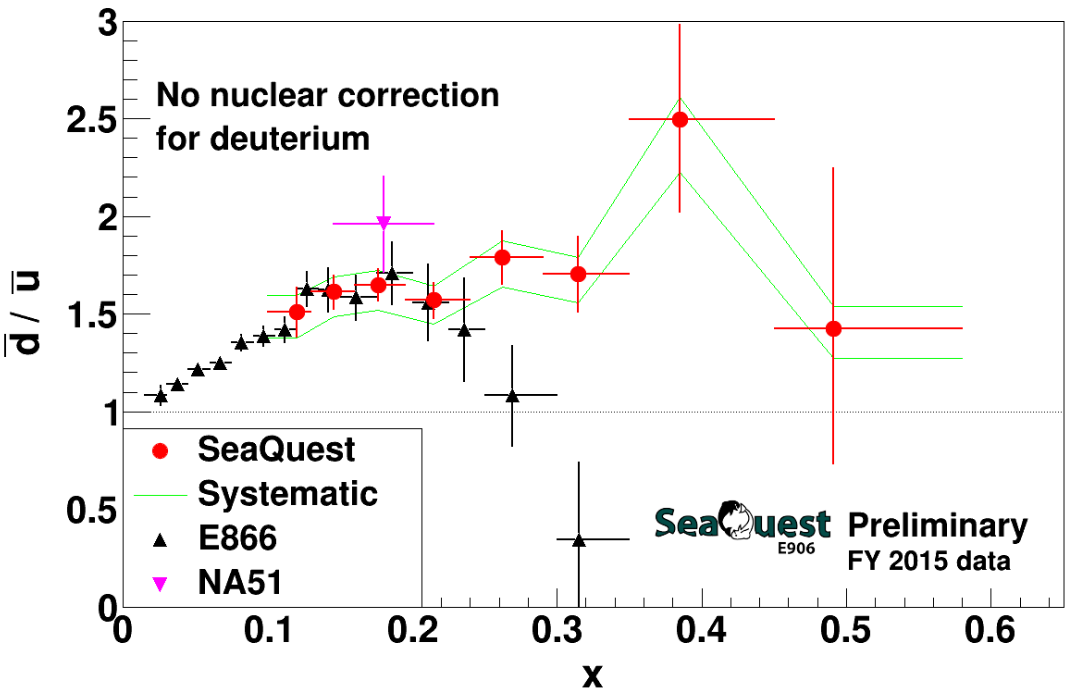
$W^2 \geq 12.5\mathrm{GeV}^2$
$Q^2 \geq 3.5\mathrm{GeV}^2$
no HT

exp. data:
NMC, SLAC, BCDMS, Chorus, NuTeV, Zeus, H1, DY E605/E866, CDF, D0, Atlas, CMS, LHCb

- other PDF sets: ABM12, CJ15, CT14, JR14, HERA-PDF2.0, MMHT14, JAM (→ W. Melnitchouk, Mon. 11:30)

Asymmetry of light quark sea $\bar{d}/\bar{u}$

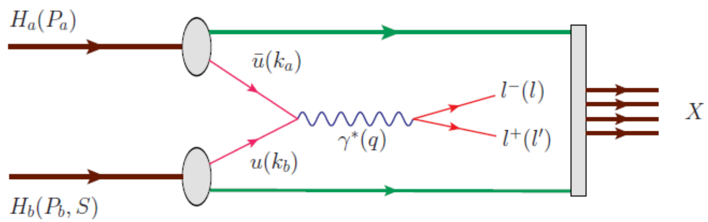
- first observed 1991 by NMC as violation of Gottfried sum rule
- NA51@CERN, E866@FNAL
- new preliminary results fron E906 SeaQuest @FNAL
- ~25% of anticipated data



W. Lorenzon QCD-N 2016

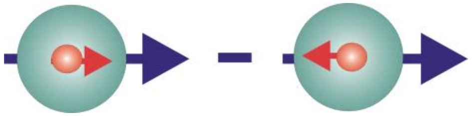
Drell-Yan: 120 GeV

$p \rightarrow LH_2$ / LD_2 / C / Fe / W

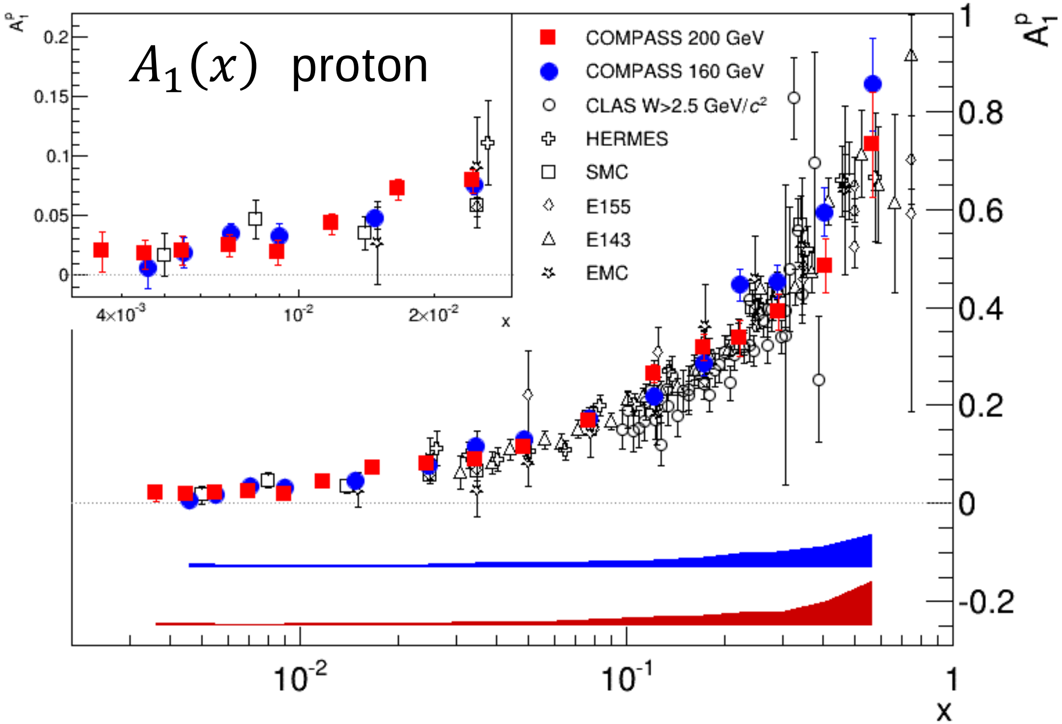


Helicity distributions

$$\Delta q(x, Q^2) = \overrightarrow{q}(x, Q^2) - \overleftarrow{q}(x, Q^2)$$



World data on proton A_1 spin asymmetry



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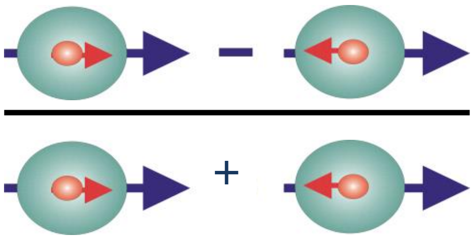
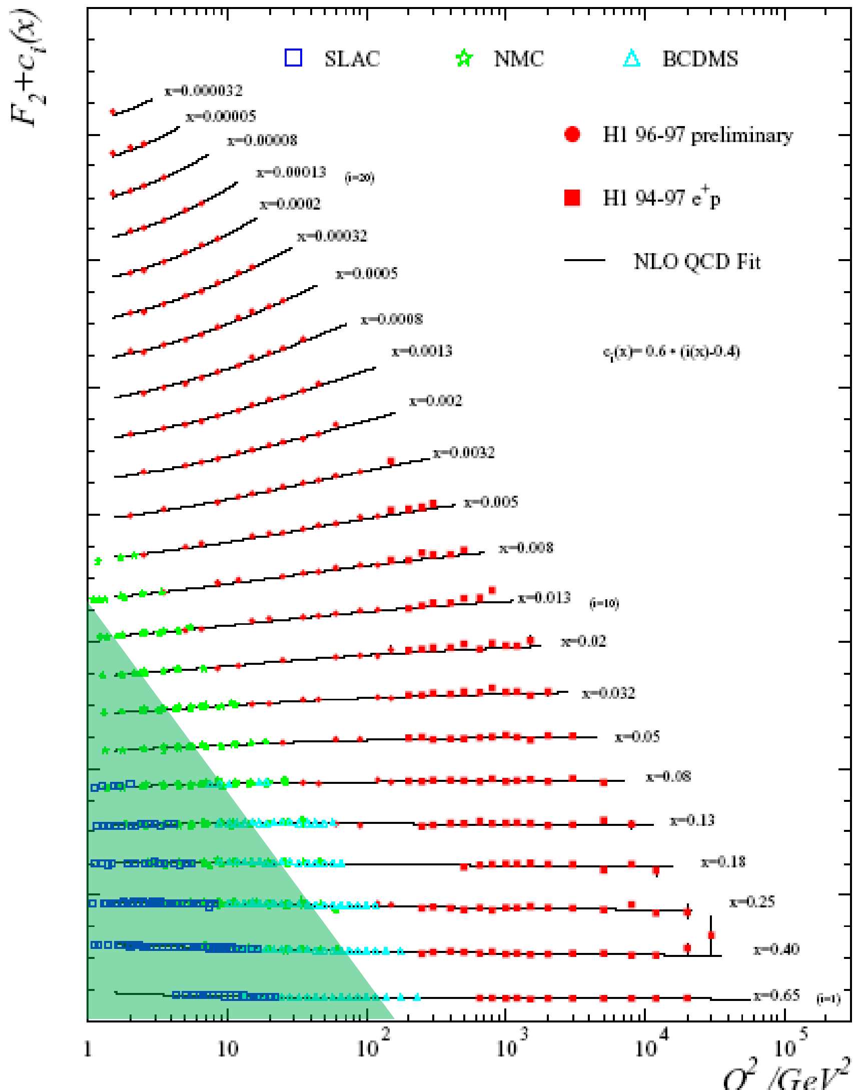
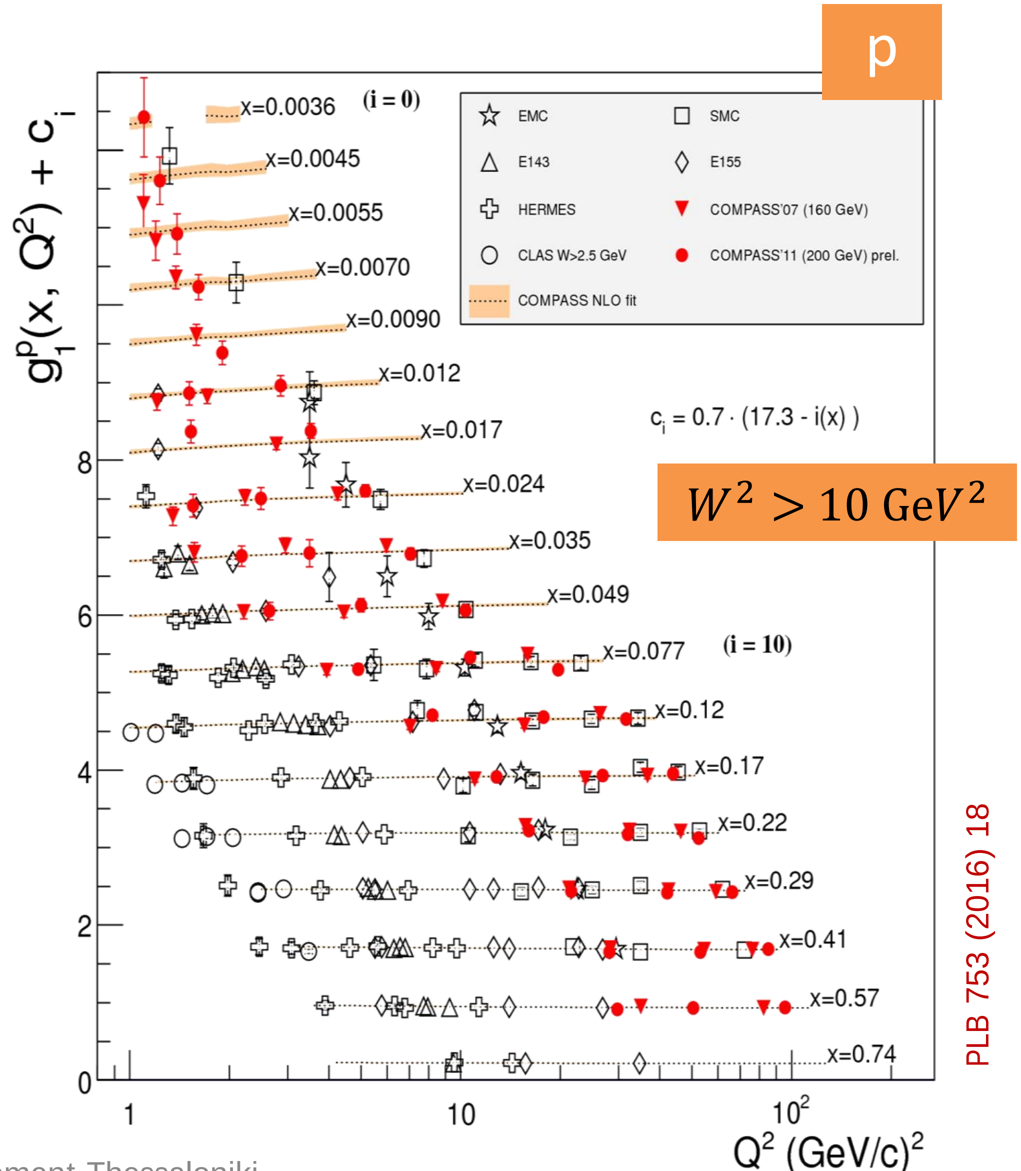


$$A_1(x,Q^2) = \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

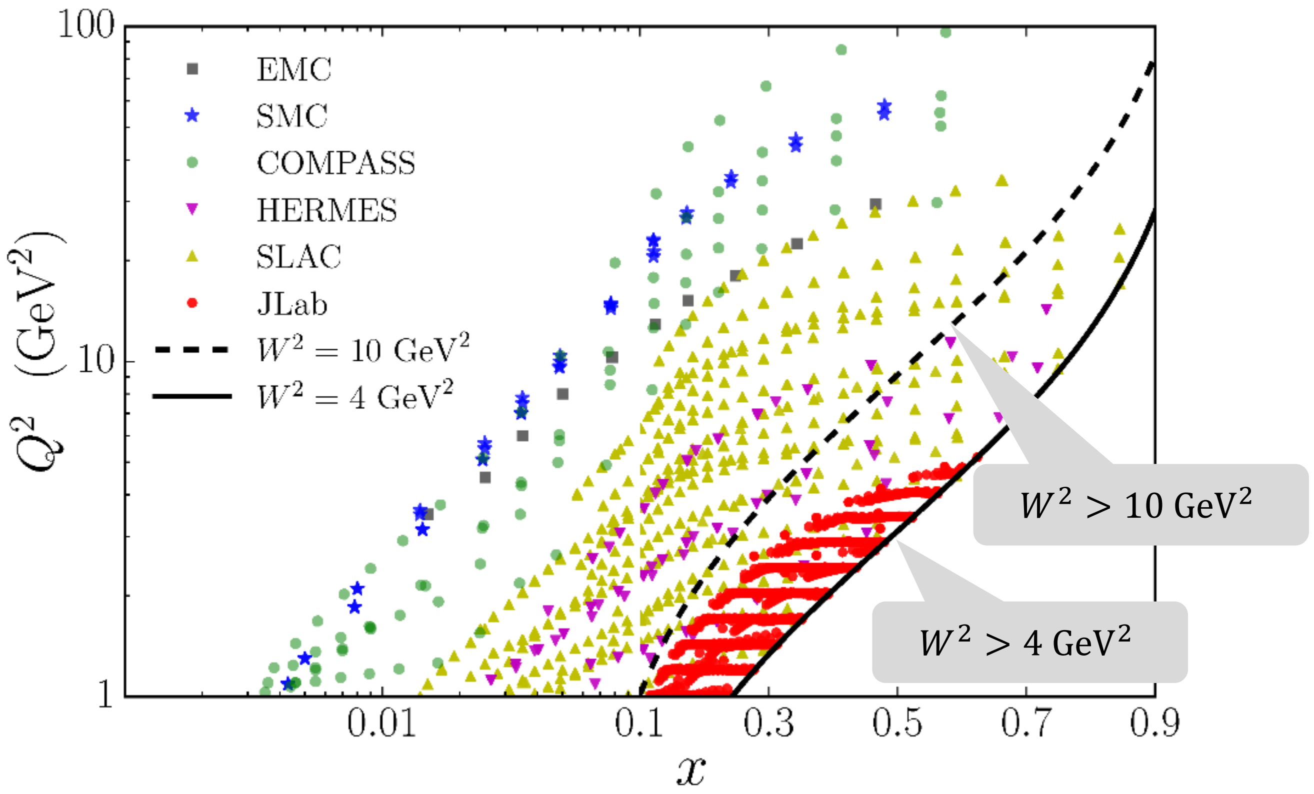
$F_2(x, Q^2)$ $\qquad$ $g_1(x, Q^2)$





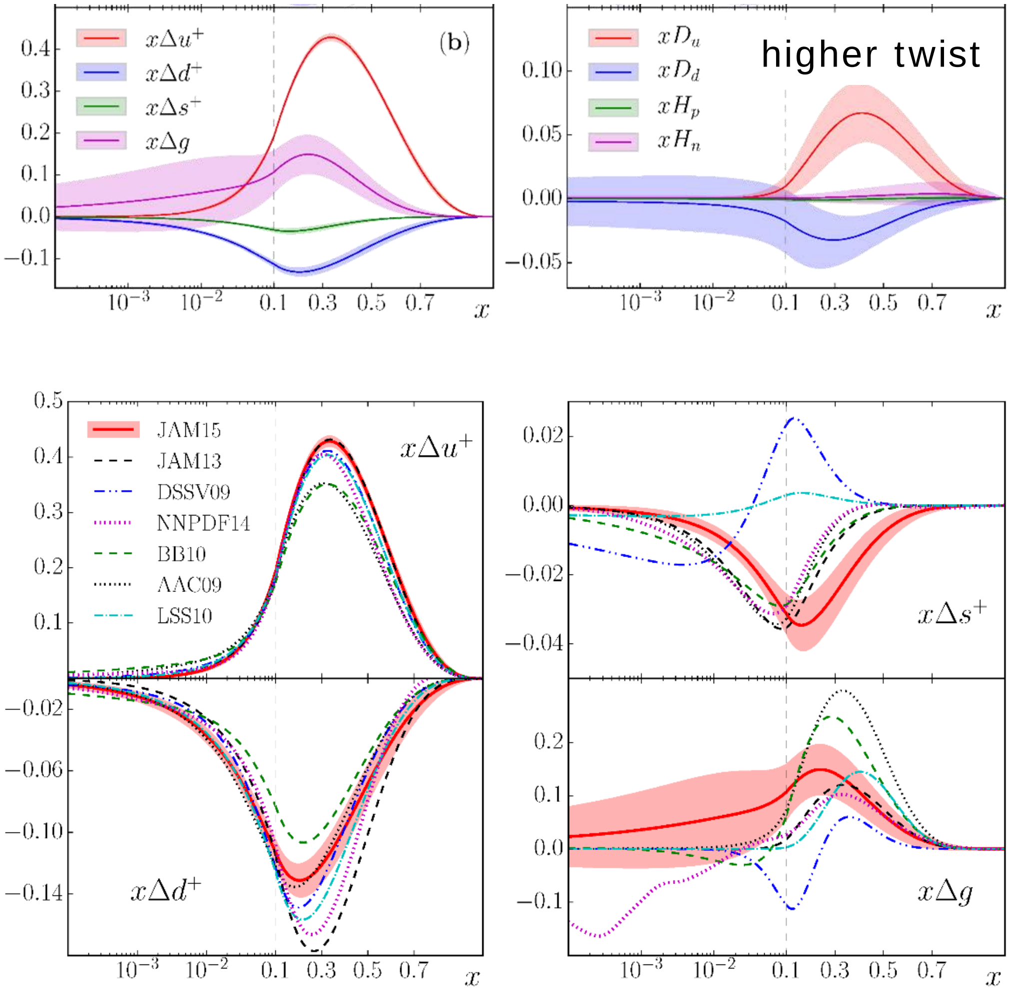
JAM15 – a new PDF fit to inclusive data

- includes precise low $W^2 > 4\ \mathrm{GeV}^2$ JLAB data
- only inclusive data, 2515 data points vs 854 for $W^2 > 10\ \mathrm{GeV}^2$



PRD 93 (2016) 074005

JAM15 – a new PDF fit to inclusive data



PRD 93 (2016) 074005

- $q^+ = q + \bar{q}$
- $Q^2 = 1\ \mathrm{GeV}^2$
- very significant higher twist terms
- improvements for strange quarks and gluon at large *x*

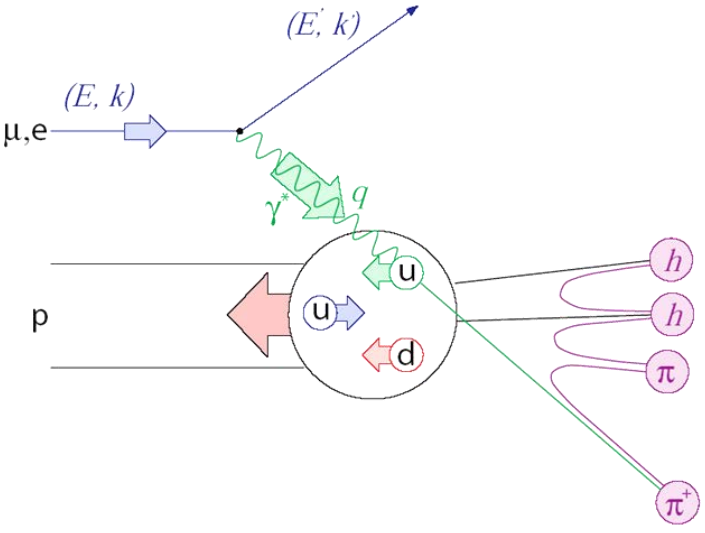
Beyond inclusive: Semi-inclusive DIS results

- additional hadron observed in FS

$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)}$$

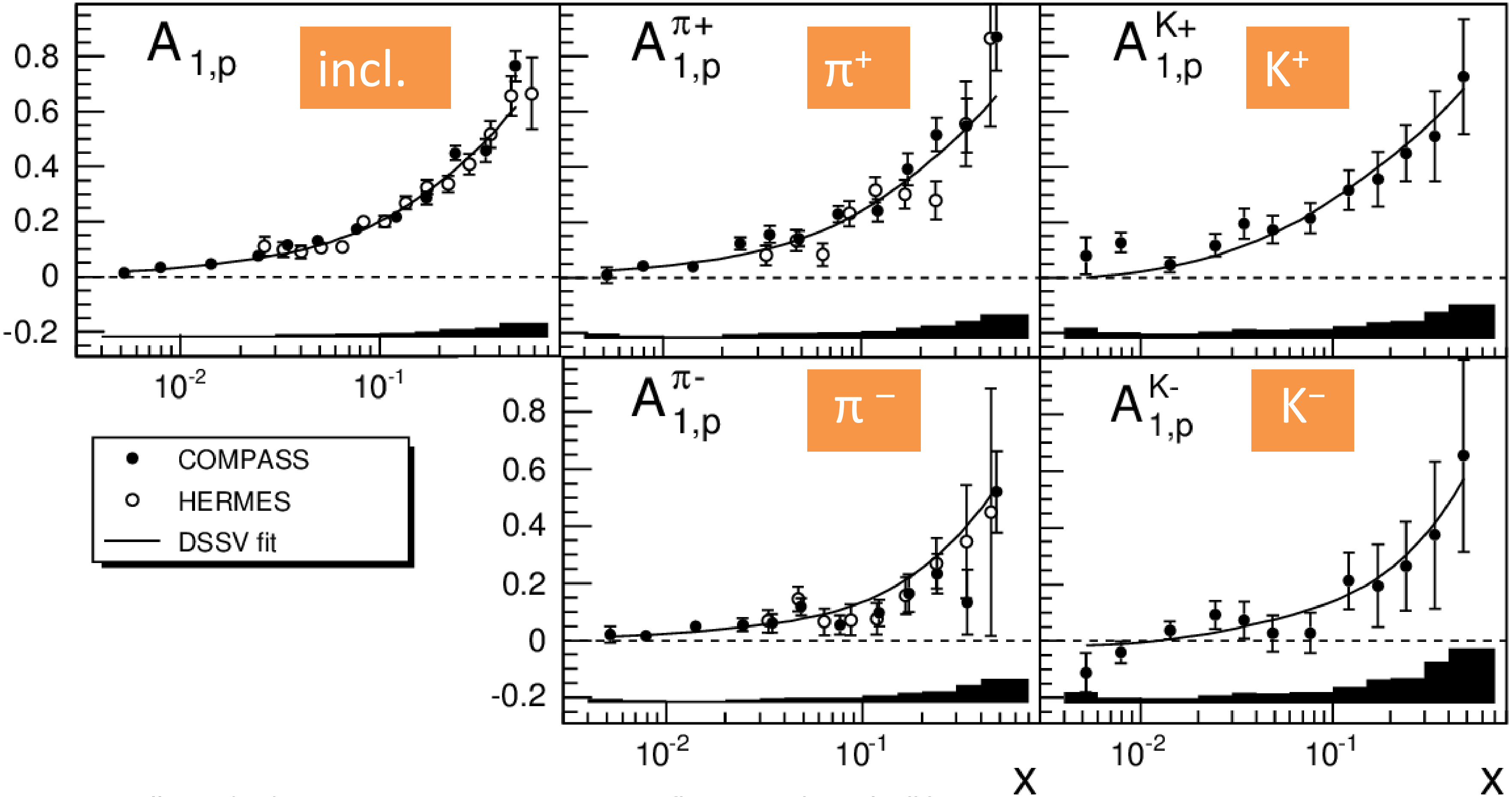
- gives access to flavour information via the fragmentation functions *D*

$z = E_h/\nu$



Incl. & semi-incl. A_1

- Compass and Hermes data for proton
- similar data for deuteron



PLB 693 (2010) 227

Hadron multiplicity data and FF

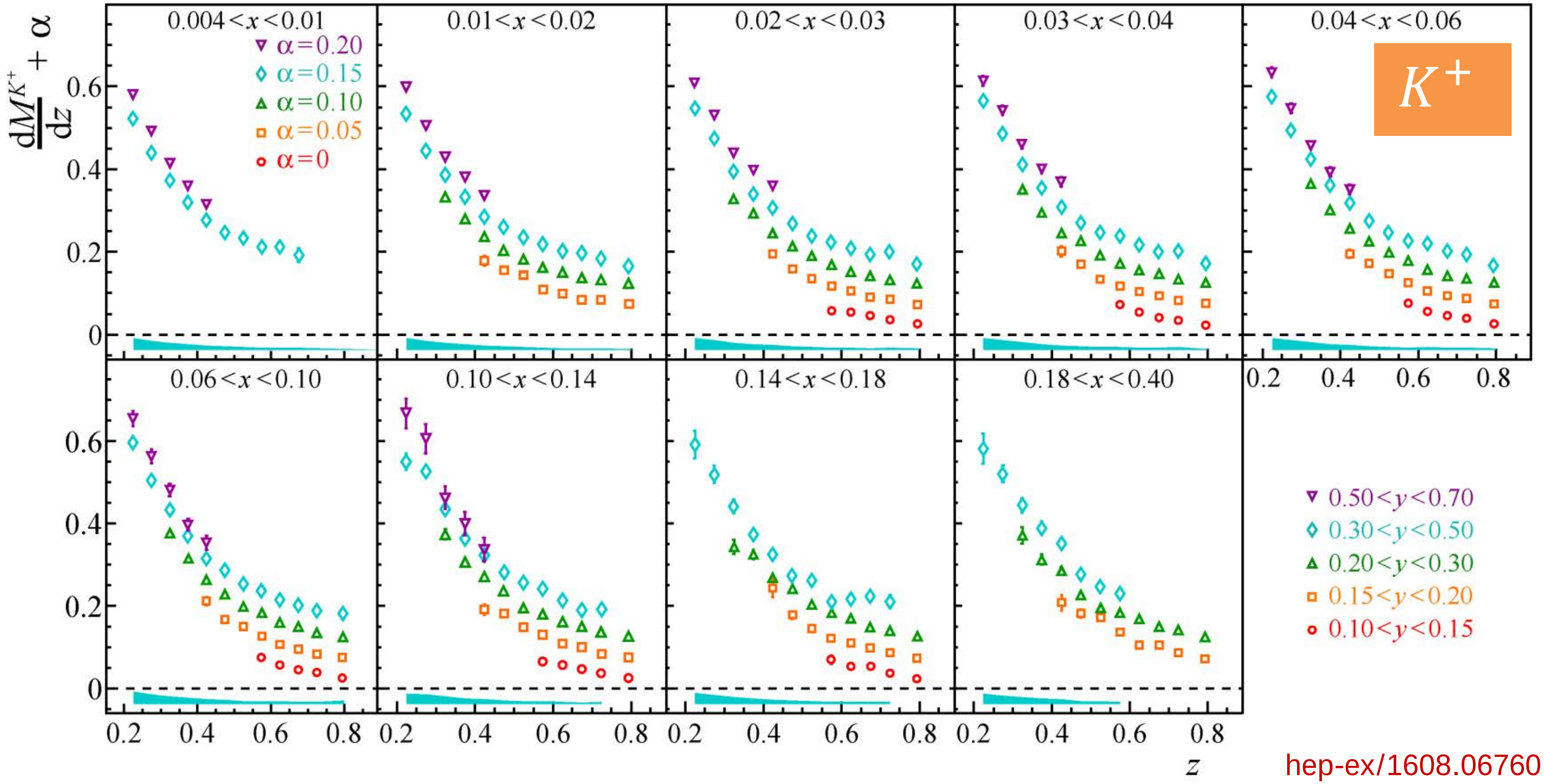
- Fragmentation functions not well enough known, in particular for the strange quark
- limit the determination of strange PDF
- new charged pion and kaon multiplicity data in 3-dimensional bins (x, y, z) from isoscalar target (^{6}LiD) by COMPASS

hep-ex/1604.02695
hep-ex/1608.06760

$$\frac{\mathrm{d}M^{\mathrm{K}}(x,y,z)}{\mathrm{d}z} = \frac{1}{N^{\mathrm{DIS}}(x,y)} \frac{\mathrm{d}N^{\mathrm{K}}(x,y,z)}{\mathrm{d}z} \frac{1}{A(x,y,z)}$$

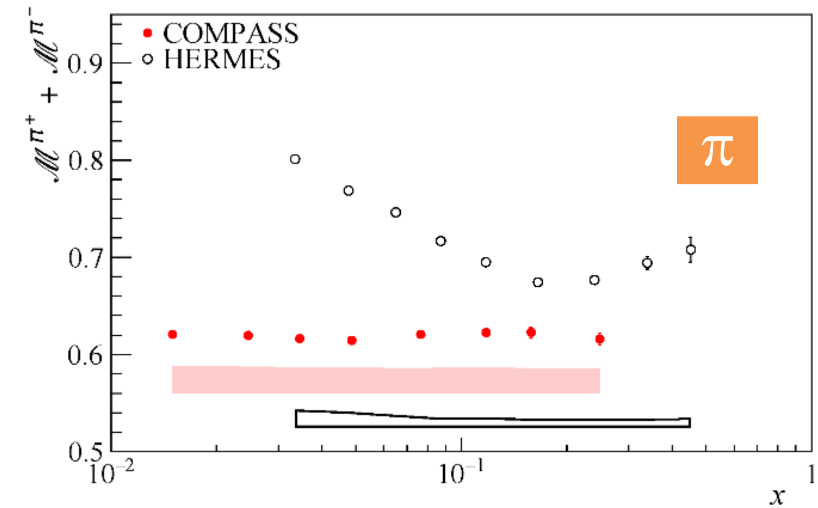
Charged kaon multiplicities

- data for positive and negative pion and kaons

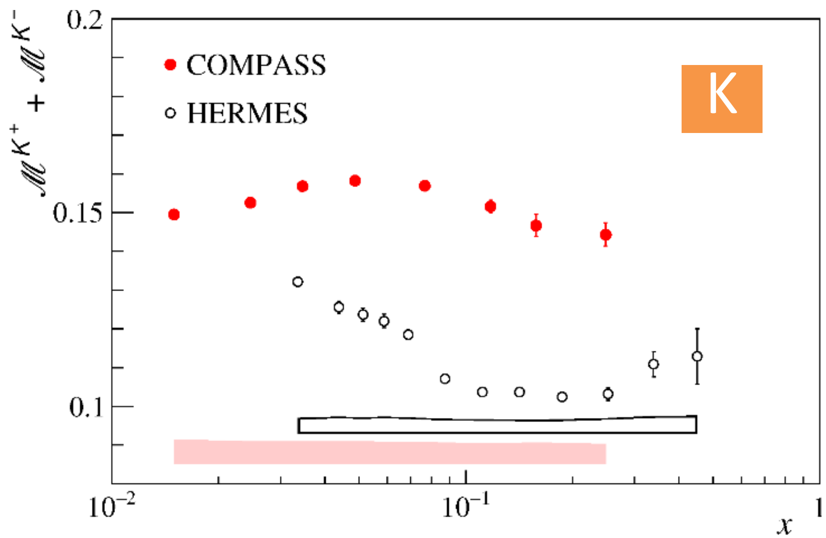


hep-ex/1608.06760

Pion and kaon multiplicities



hep-ex/1604.02695



hep-ex/1608.06760

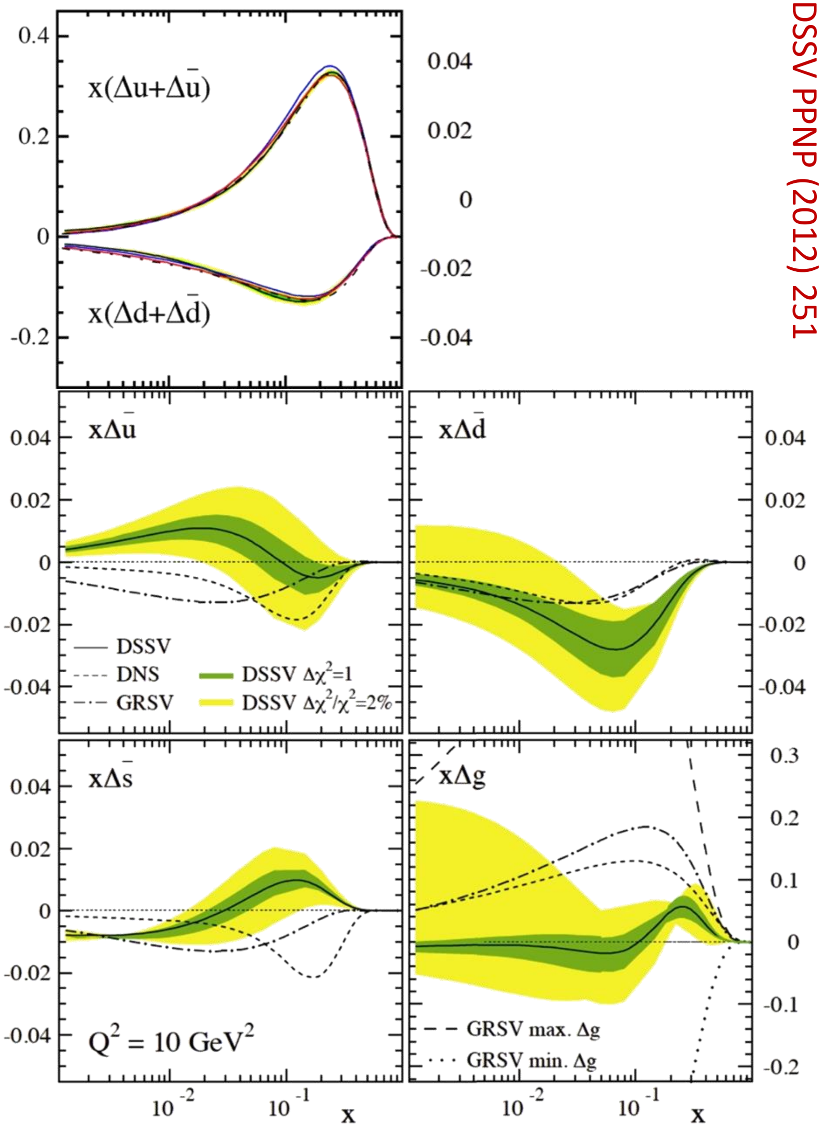
- isoscalar target, int. over z, p_T, Q^2
- discrepancies in multiplicities between Hermes and COMPASS
- similar, but not identical kinematics
- ratio π^+/π^- ok, K^+/K^- differs ~ 20%
- being investigated

- new data:
  impact on FF → strange PDF
  in next global fits

Hermes K: PRD 89 (2014) 097101; π: PRD 87 (2013) 074029

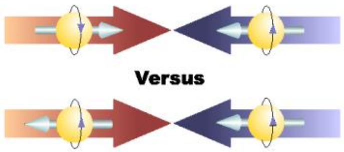
Status of PDFs: global analyses (e.g. DSSV)

- data: DIS, SIDIS, pp
- latest update DSSV14++ with STAR jet data
  PRL 113 (2014) 012001
- DSS fragmentation functions, new COMPASS data not yet included
- most uncertain: $\Delta g(x)$

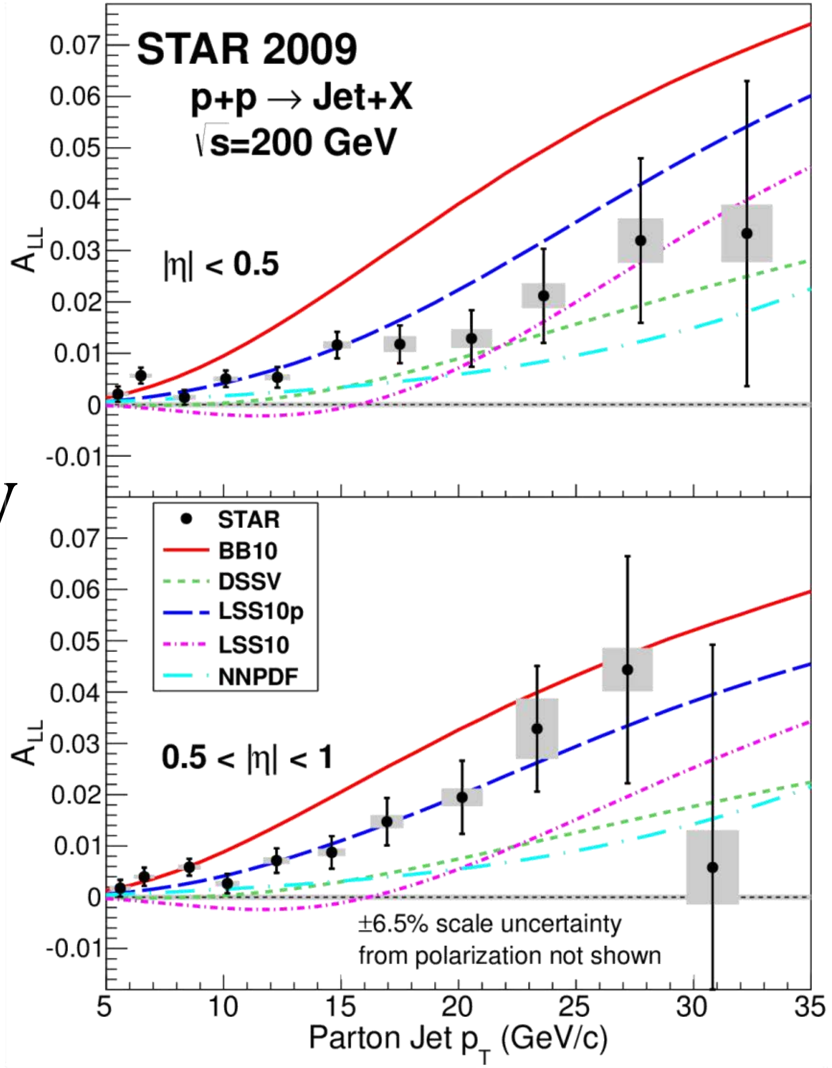


DSSV PPNP (2012) 251

STAR single jet asymmetry A_{LL}

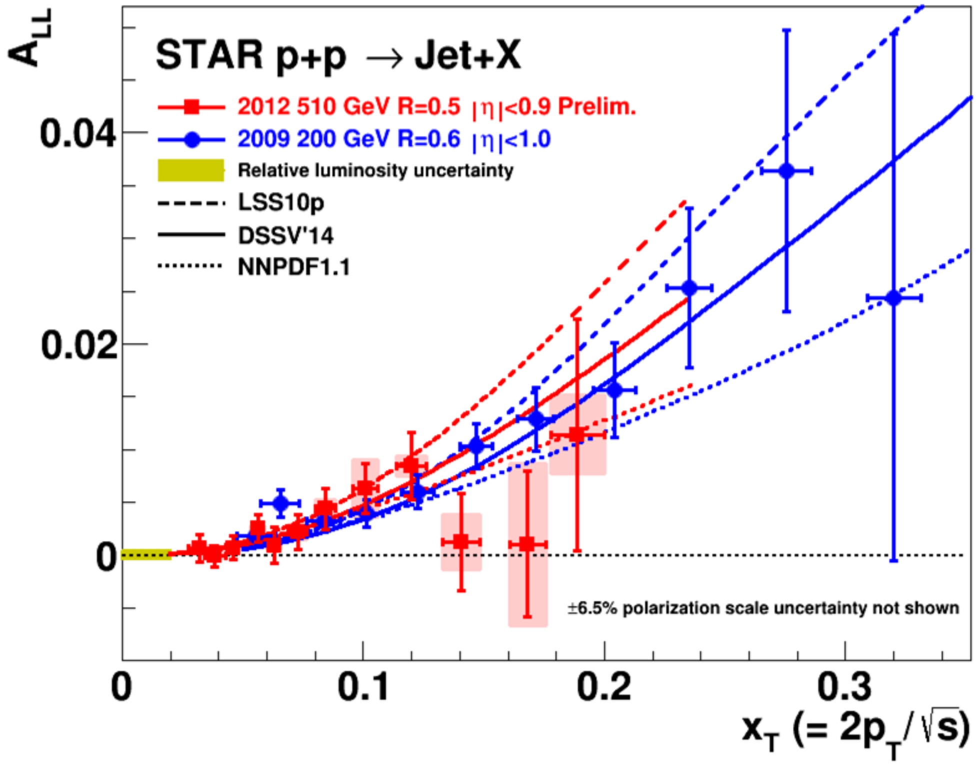


- $A_{\mathrm{LL}} \propto \Delta g$
- no fragmentation function
- $pp \to$ jet + X @ $\sqrt{s} = 200$ GeV
- 2009 data, mid rapidity
- A_{LL} in good agreement with LSS10p (pos. Δg)



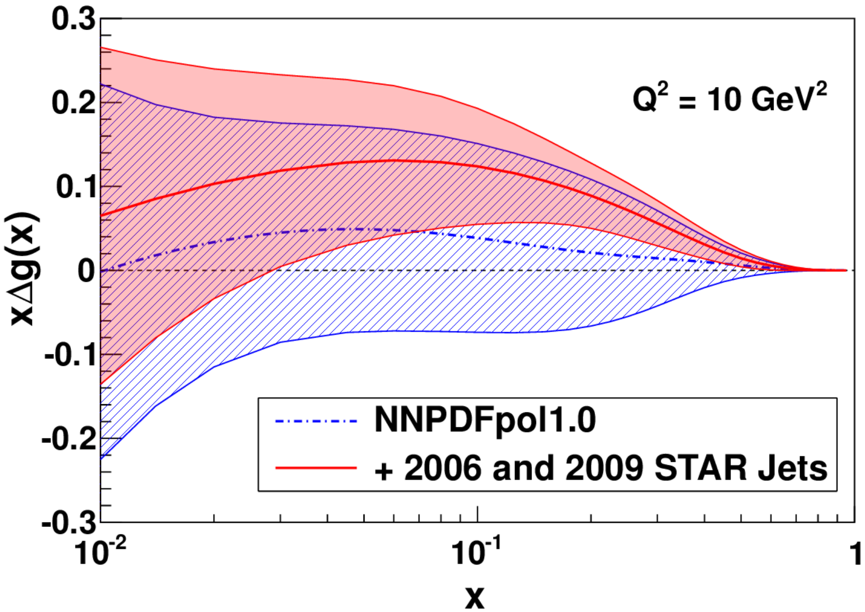
PRL 115 (2015) 092002

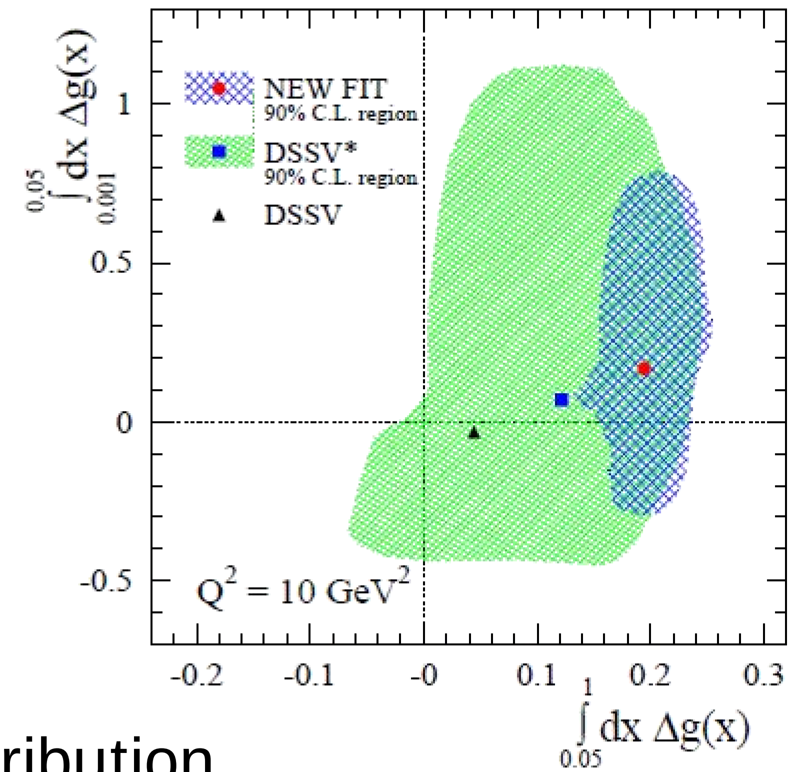
STAR single jet asymmetry A_{LL}



- prelim. 2012 data, $\sqrt{s} = 510\ \mathrm{GeV}$, lower x
- agree with 2009 data and LSS10p and DSSV14
- DSSV14 includes 2009 data

Impact of Star jet data





PRL 113 (2014) 012001

- big impact on pol. gluon distribution
- $\int_{0.05}^{1} \Delta g(x) \mathrm{d}x \simeq 0.20$
- need data at small *x*

$\Delta g/g$ from single hadron (NLO)

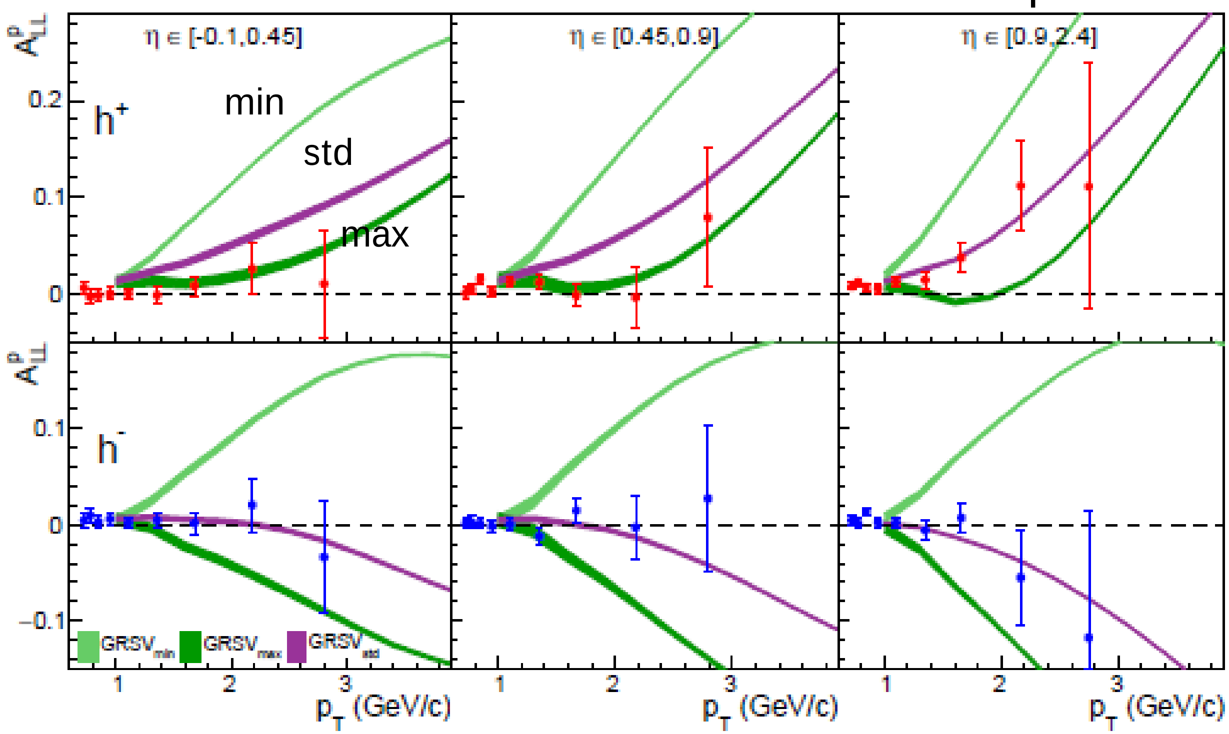
- quasi-real photoproduction of single hadrons, à la RHIC π^0 prod.
- calc. by group of Vogelsang, agreement for unpolarised case
- caveat: NNL resummation missing for polarised case

$$\eta_{cms} = -\ln\left(\tan\frac{\theta}{2}\right) - \frac{1}{2}\ln\left(\frac{2E}{M}\right)$$

- 3 bins of pseudorapidity η
- FF important, using DSS (2015), agree best with meas. multiplicities
- data prefer positive gluon polarisation as suggested by recent RHIC data
- same seen in LO analysis of $Q^2 > 1\ \mathrm{GeV}^2$

hep-ex/1512.05053

proton



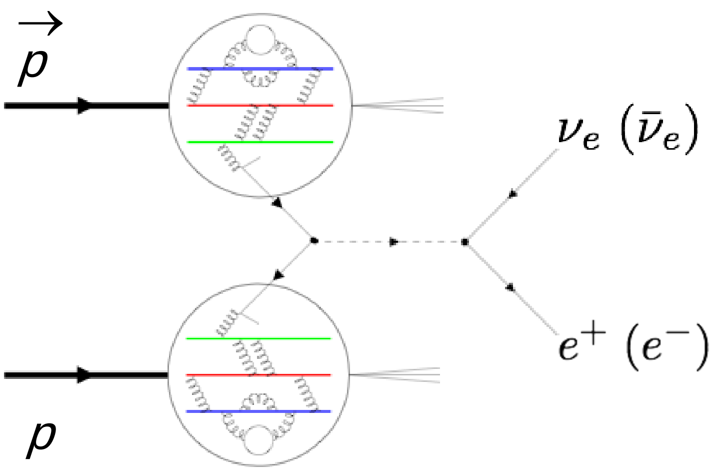
PLB 753 (2016) 573

W production & antiquark polarisation

- $\vec{p}p$ collisions at 250 GeV+ 250 GeV
- $u_L \bar{d}_R \rightarrow W^+$ and $\bar{u}_R d_L \rightarrow W^-$
- parity-violating long. SSA:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

- sensitive to antiquark polarisation



signature: high p_T lepton

$$\eta_e = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

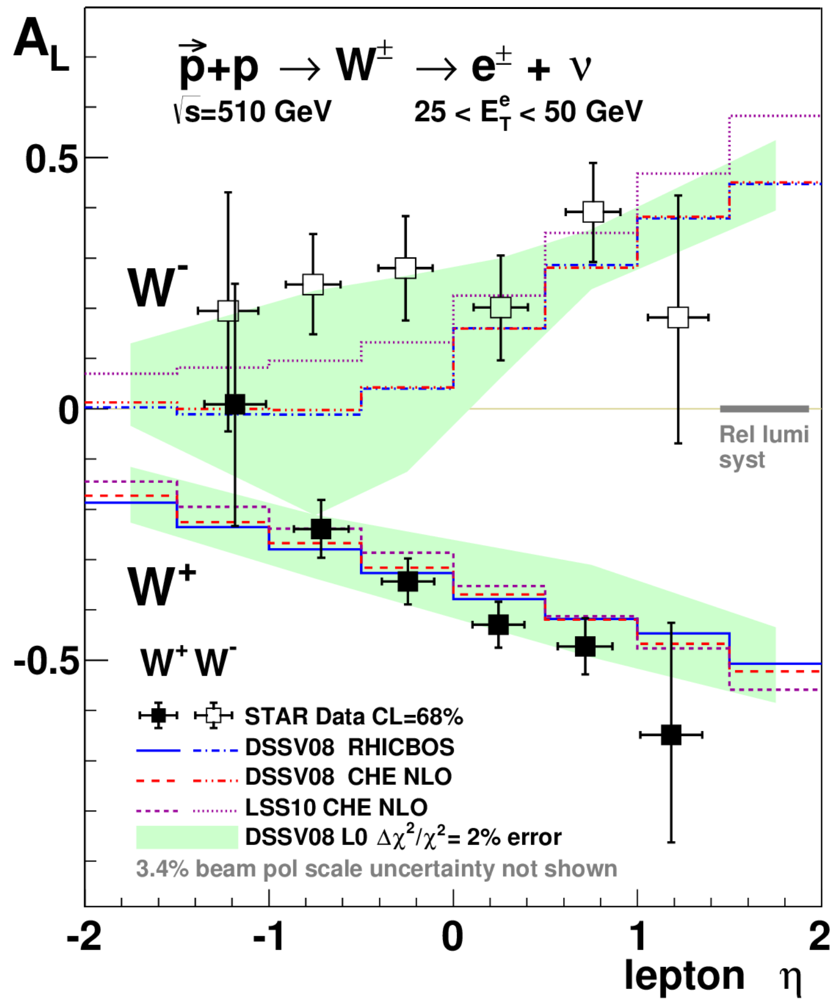
W production in *pp*

- run 11+12, $|\eta_e| < 1.2$
- A_L larger than expected for W^- @ η < 0
- indication for a sizable, positive up antiquark polarization
- 0.05 < x < 0.2

- New Phenix W data

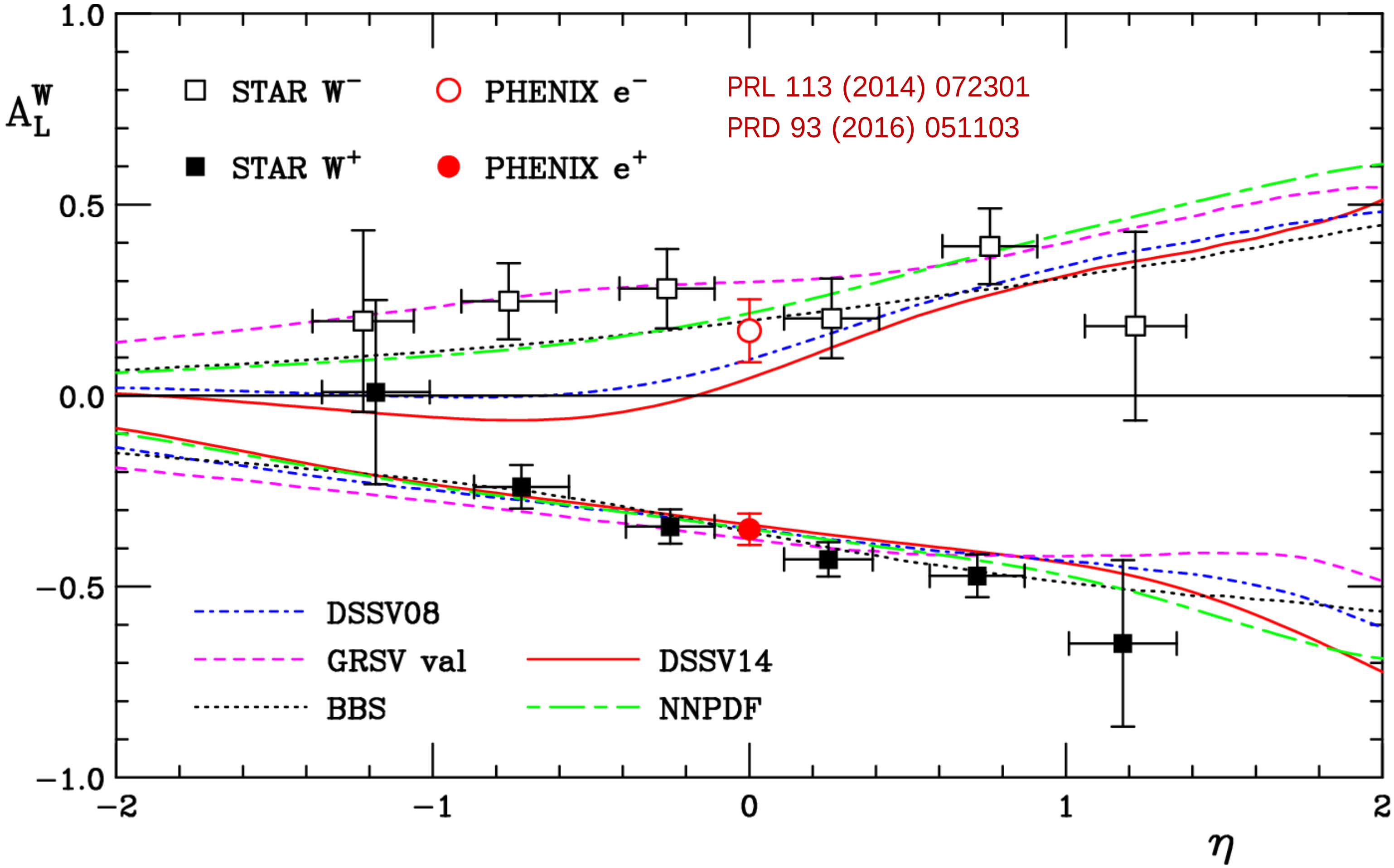
PRD 93 (2016) 051103

$$A_L^{W^-} = \frac{\Delta\bar{u}}{\bar{u}} \qquad \frac{1}{2}\left(\frac{\Delta\bar{u}}{\bar{u}} - \frac{\Delta d}{d}\right) \qquad -\frac{\Delta d}{d}$$



PRL 113 (2014) 072301

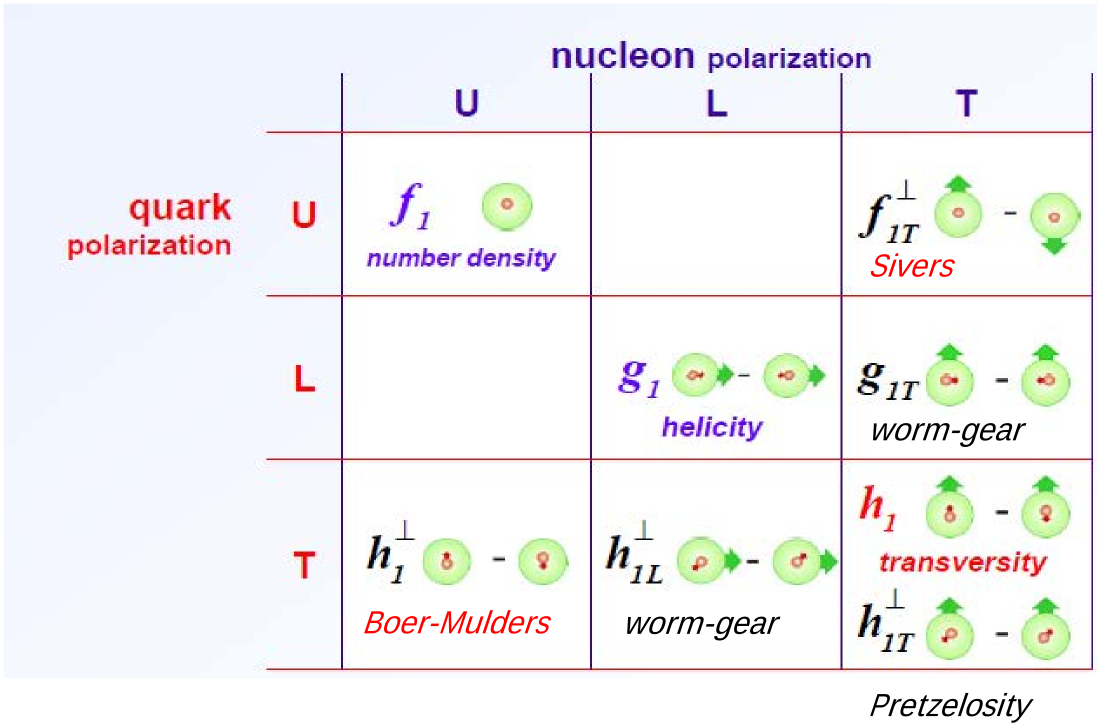
W production in *pp*



Ringer, Vogelsang: PRD 91 (2015) 094033

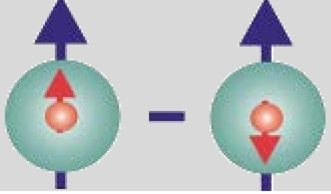
Best agreement for W^- with GRSV val
with sizable positive $\Delta\bar{u}$

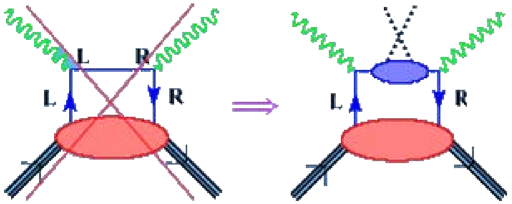
TMD distributions



- 8 TMD PDFs at leading twist
- 3 non-vanishing k_{T}-integrated PDFs: f_1, g_1, h_1
- Azim. asym. with different angular modulations in ϕ_h and ϕ_S
- TMDFF

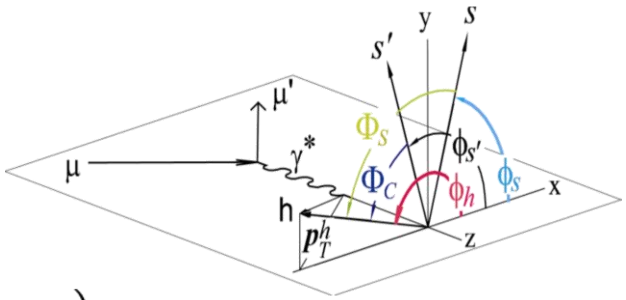
Transversity h_1





- chiral-odd → vanishes in DIS → SIDIS

- leads to azimuthal modulation in the Collins angle $\phi_C = \phi_h + \phi_S - \pi$
  ($-\pi$ used by COMPASS)



- amplitude

$$A^h_{\mathrm{Coll}} \propto \frac{\sum_q e_q^2 h_1^q(x) \otimes H_1^{\perp h/q}(z, p_T)}{\sum_q e_q^2 f_1^q(x) D^{h/q}(z)}$$

- Collins fragmentation function $H_1^{\perp}(z, p_T)$ from e^+e^-
- convolution ($\otimes$) over intrinsic transverse momentum k_T
- product for 2-hadron asymmetries coupled to IFF $H_1^{\sphericalangle}(z, M_h^2)$

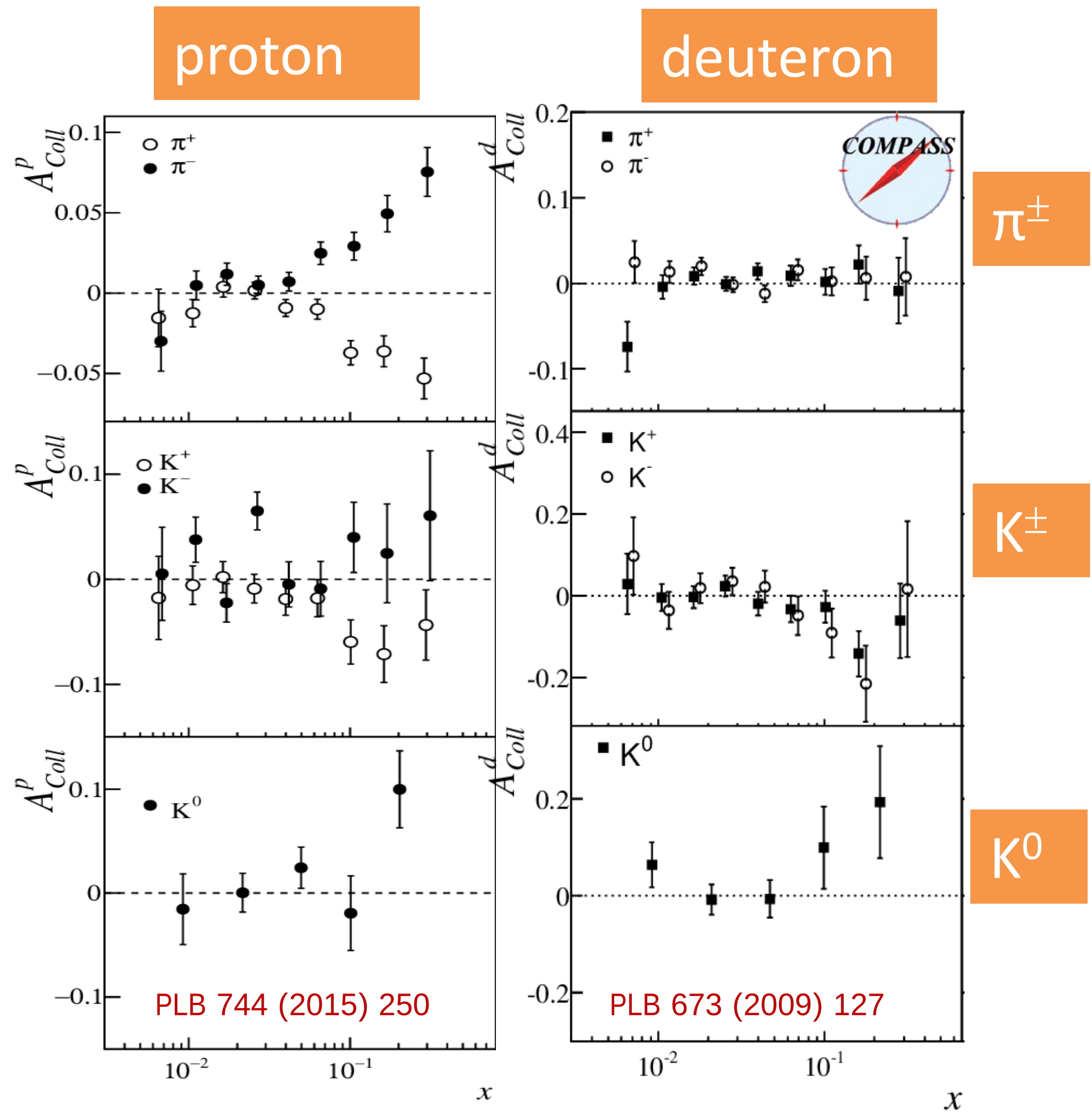
Collins asymmetry for proton & deuteron

- first proton data from Hermes

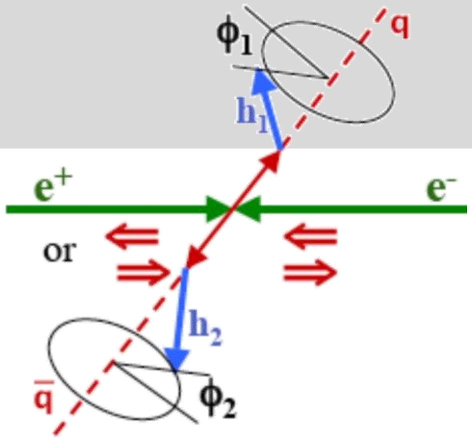
  PRL 94 (2005) 012002

- sizable for proton
- mirror symmetry π^+ and π^-
- small for deuteron
- di-hadron asym. are similar, collin. factorisation $h_1 \times H_1^{\sphericalangle}$

PLB 736 (2014) 124

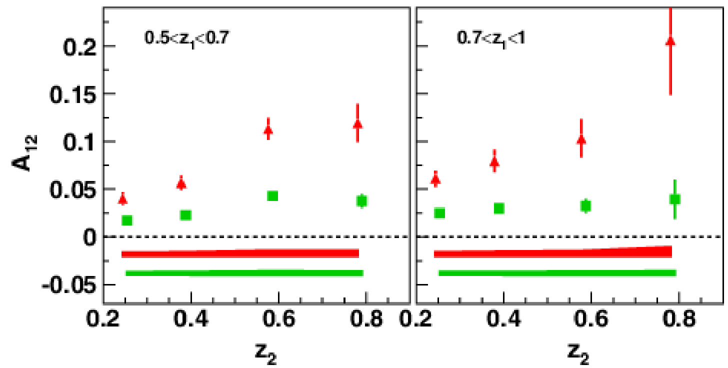


Collins FF from e^+e^-

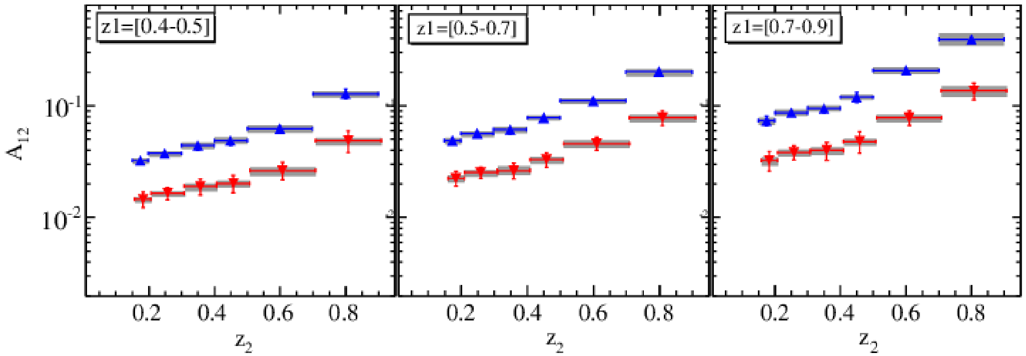


- $\propto H_1^{\perp} \otimes H_1^{\perp}$
- Belle, Barbar, BESIII

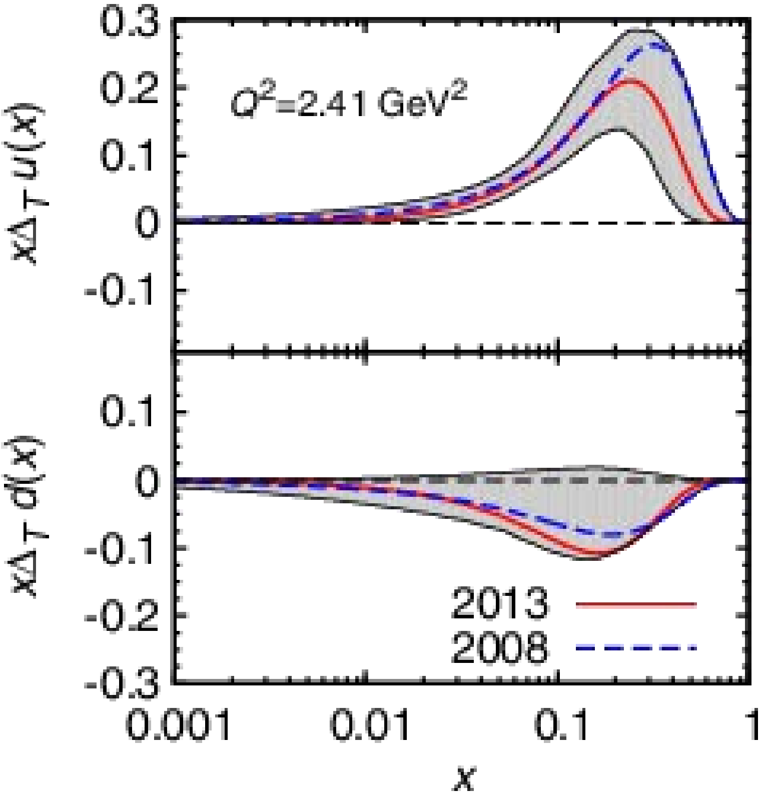
Belle: PRD 90 (2012) 052003
Babar: PRD 90 (2014) 052003
BESIII: PRL116 (2016) 042001



- clear signals



Determination of h_1 from SIDIS & e^+e^-



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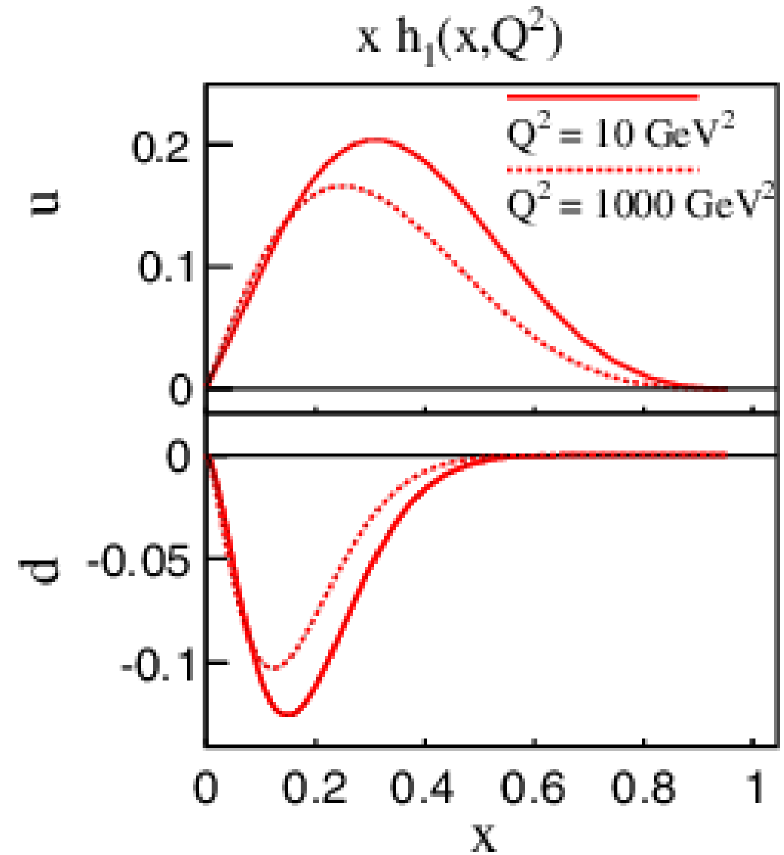
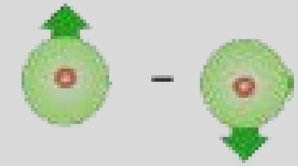


Anselmino et al.,
PRD 87 (2013) 094019

Kang et al.,
PRD 91 (2015) 071501(R)

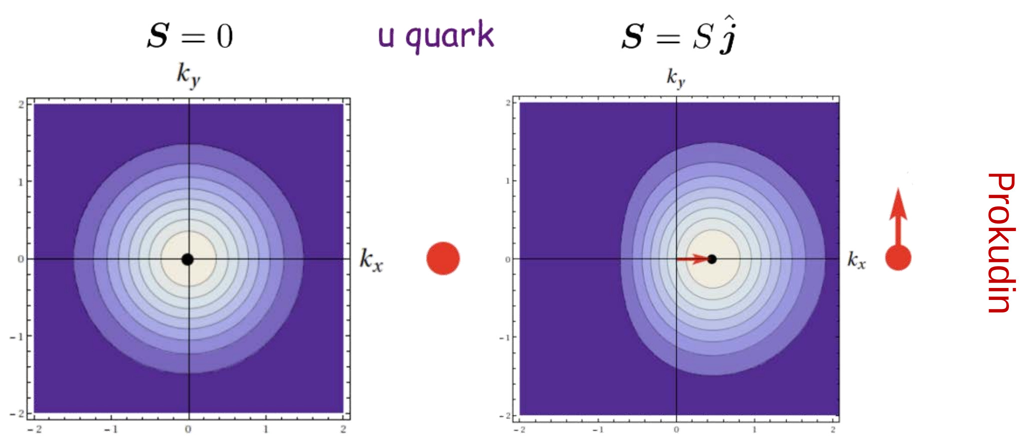
Sivers TMD $f_{1T}^{\perp}$



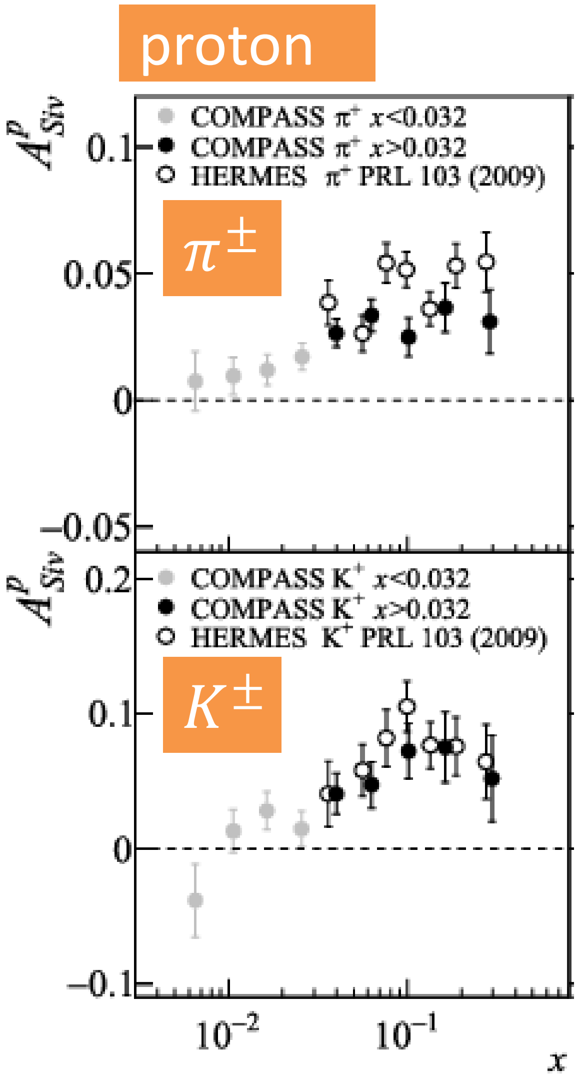
- azim. asym. in $\phi_{Siv} = \phi_h - \phi_S$

$$A_{\mathrm{Siv}}^{h} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,k_T) \otimes D_1^{h/q}(z,p_T)}{\sum_q e_q^2 f_1^{q}(x,k_T) \otimes D_1^{h/q}(z,p_T)}$$

- if non-zero $\rightarrow$ orbital angular momentum
- induces distortions in the PDF of polarized nucleons



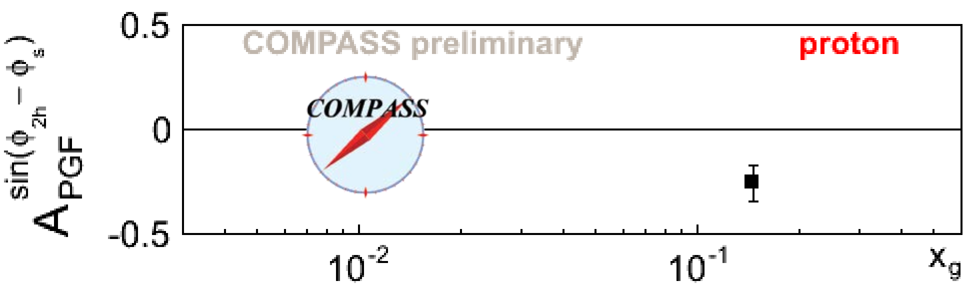
Sivers asymmetry



Hermes: PRL 103 (2009) 152002
COMPASS: PLB 744 (2015) 250

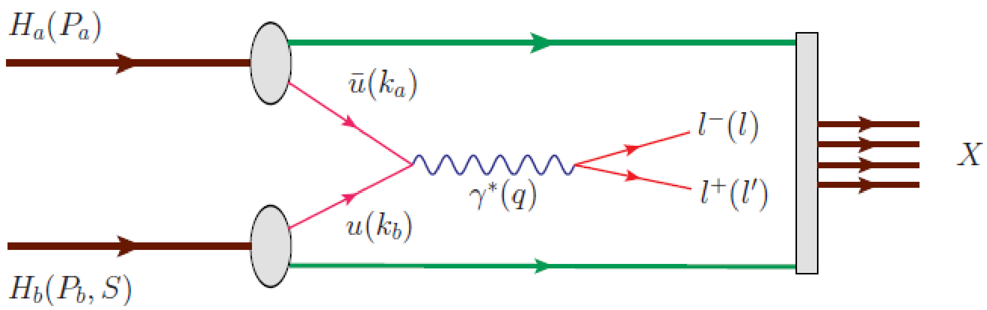
- sizable for proton
- Hermes vs Compass: some Q^2 evolution
- Sivers small for deuteron

- gluon: indication from 2h



A. Szabelski, DIS2016

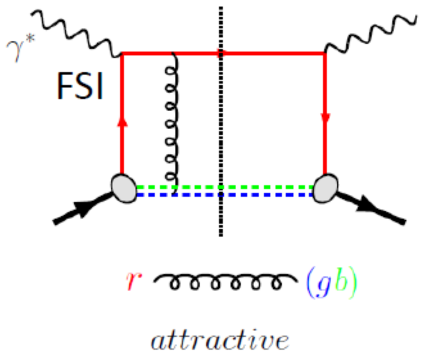
Restricted universality in SIDIS and pol. DY

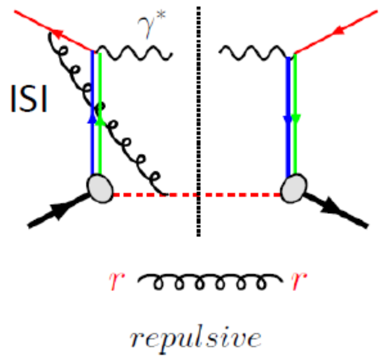


T-odd TMDs:

\`gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs

J.C. Collins, PLB536 (2002) 43





Compass measures SIDIS and DY with same spectrum.

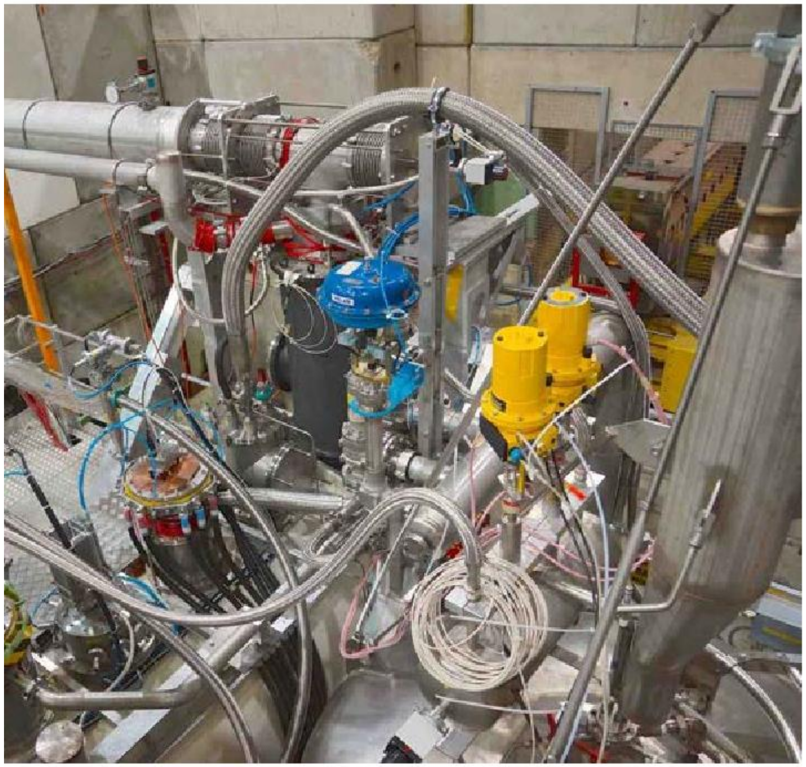
$$f_{1T}^{\perp}\Big|_{DIS} = - f_{1T}^{\perp}\Big|_{DY} \qquad h_1^{\perp}\Big|_{DY} = - h_1^{\perp}\Big|_{DIS}$$

Sivers — Boer-Mulders

- important prediction, needs to be verified: COMPASS, FNAL, RHIC?

COMPASS polarized DY

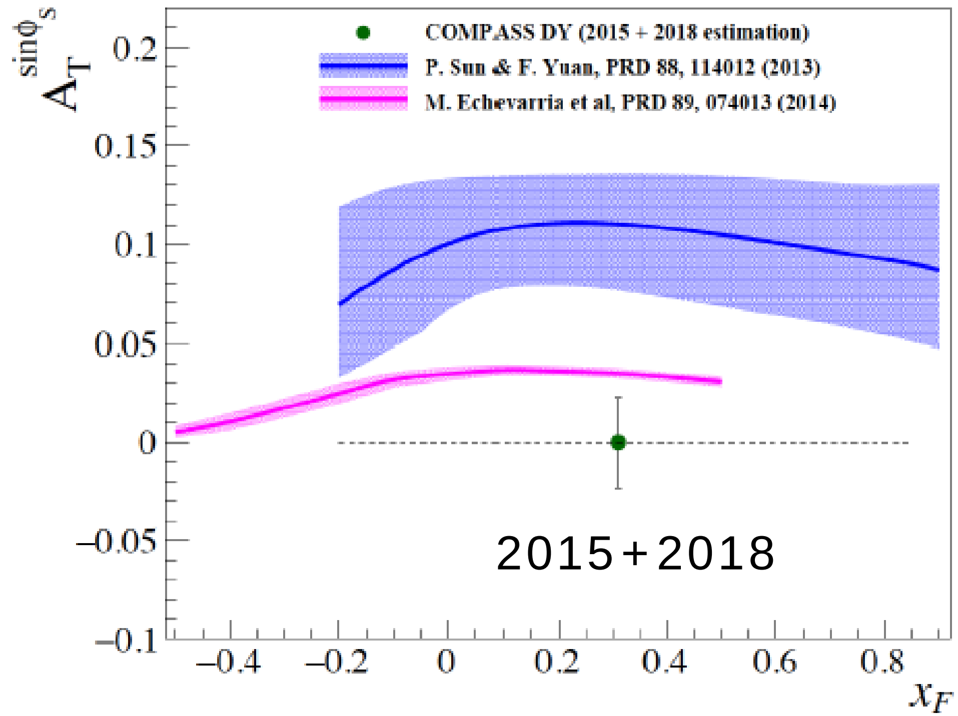
- first results at Spin2016



- Fermilab, RHIC, ...

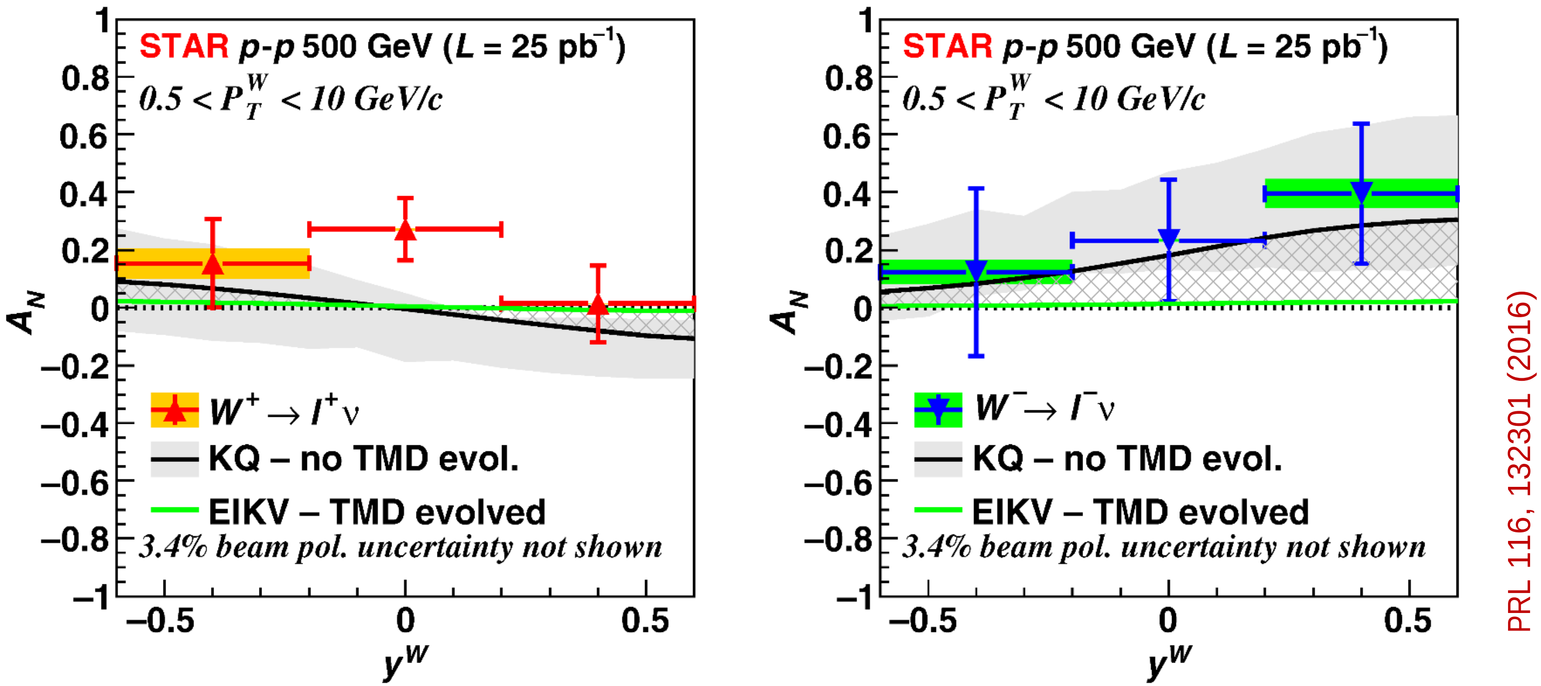
- Predictions vary strongly, due to different TMD evolution
- 2015: uncertainty ~0.04

→ Longo: Thu 17:30



$x_F = x_\pi - x_p$

Sivers in W production



PRL 116, 132301 (2016)

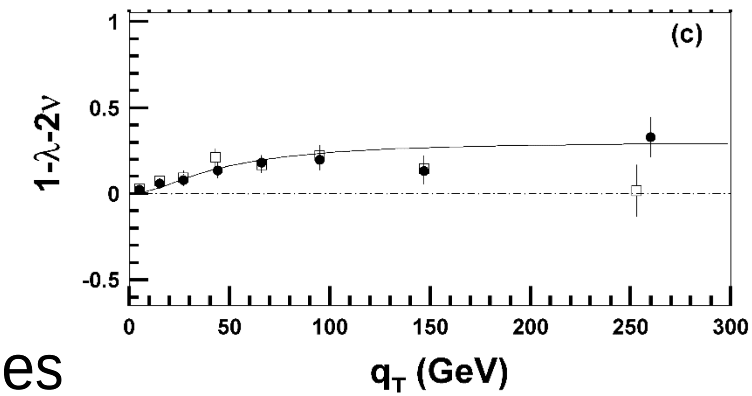
- 2011 data, 25 pb^{-1}
- no TMD evolution: clear preference for sign change!
- with EIKV TMD evolution: no sizable Sivers effect
- need more data

Boer-Mulders in Drell-Yan?

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

- Lam-Tung relation $1-\lambda-2\nu=0$
- new CMS data: $pp \to ZX \to \mu\bar{\mu}X$ violate Lam-Tung relation
- Boer-Mulders TMD $h_1^\perp$ contr. to $\cos 2\phi$ modulation?
- misalignment of $q\bar{q}$ and hadron planes do to gluon emission causes modification of Lam-Tung relation

CMS, PLB 750 (2015) 154



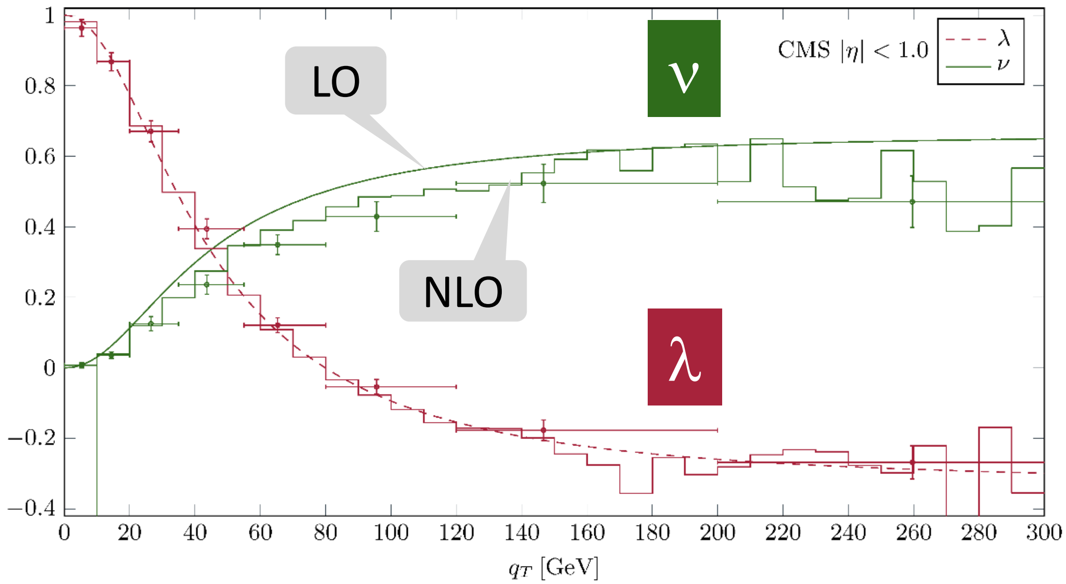
Peng et al., PLB 758 (2016) 384

Boer-Mulders in DY?

- NLO calculations describe DY data well!

Lambertsen, Vogelsang
PRD 93 (2016) 114013

CMS, PLB 750 (2015) 154



$\sqrt{s} = 8$ TeV
81 GeV $< Q <$ 101 GeV

- Need more data to establish a possible BM contribution
  → COMPASS, SeaQuest, LHC, RHIC?

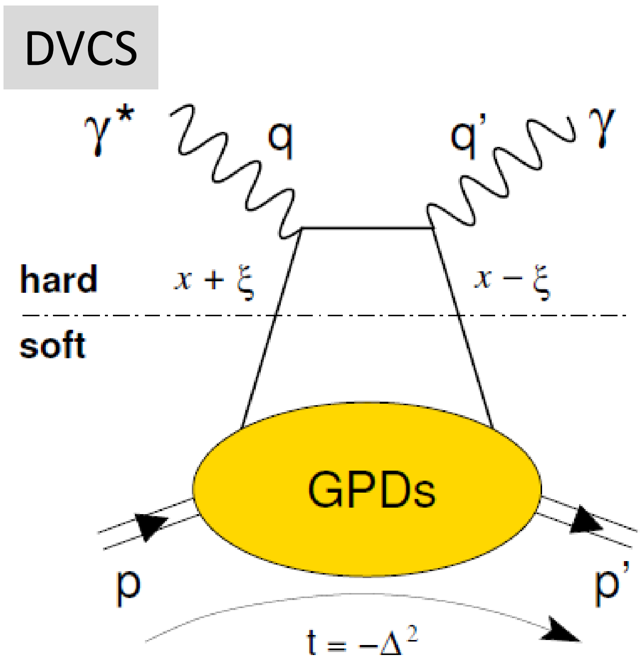
Generalised parton distributions

Generalized PDF's

- Correlating transverse spatial and longitudinal momentum degrees of freedom

$$H(x, \xi, t, Q^2); \quad Q^2 \text{ large, } t \text{ small}$$

- meas. 4 dim diff x-sect: x, Q^2, t, ϕ
- DVCS, hard exclusive meson prod.

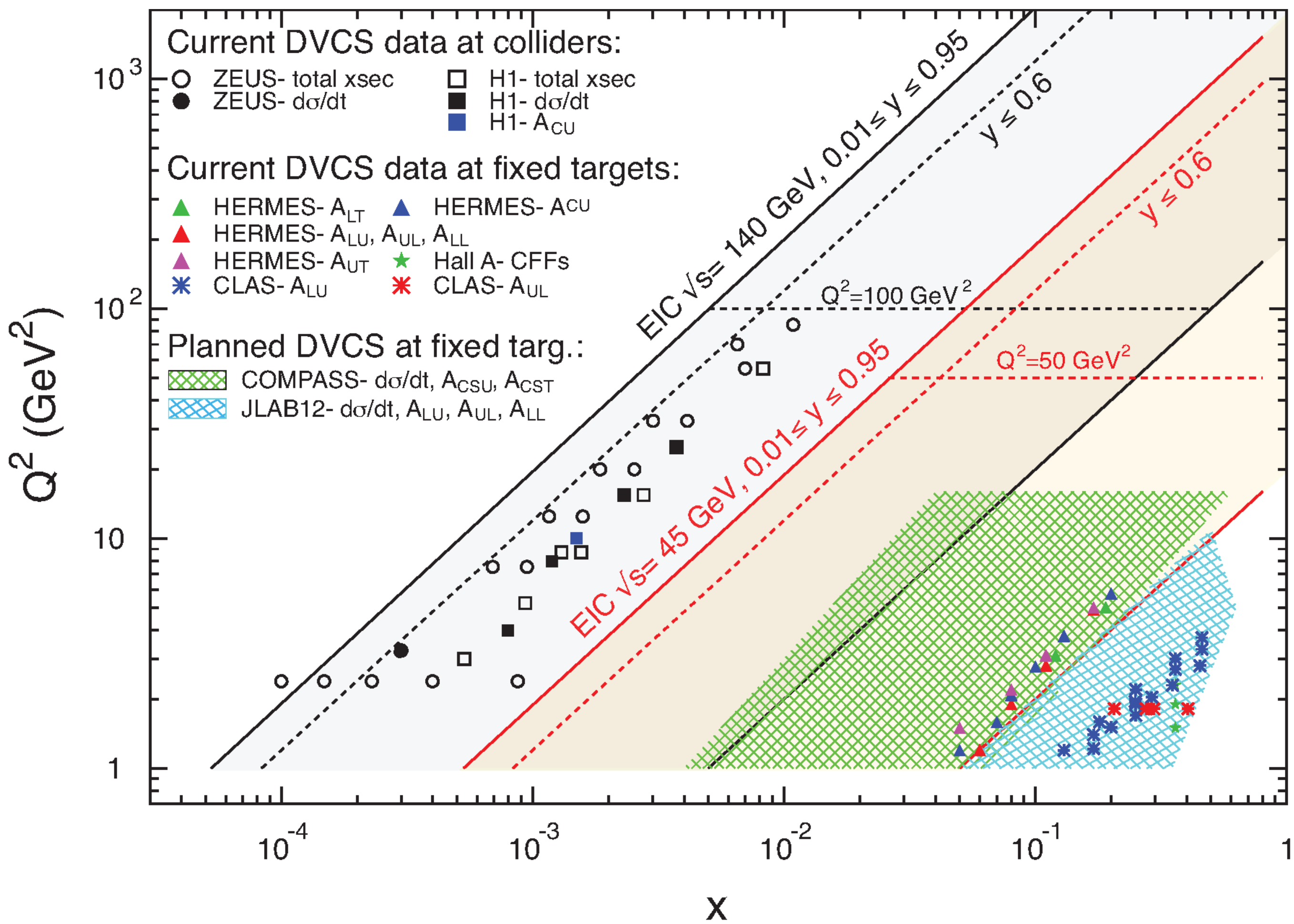


Ji's sum rule for total orbital momentum:

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

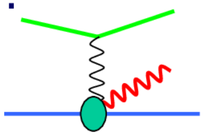
X.-D. Ji, PRL 78 (1997) 610

DVCS: experimental kinematic ranges

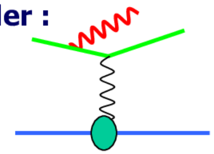


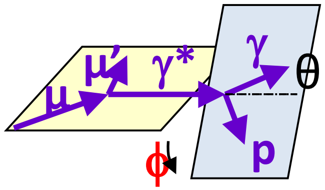
Deeply virtual Compton scattering

DVCS :



Bethe-Heitler :



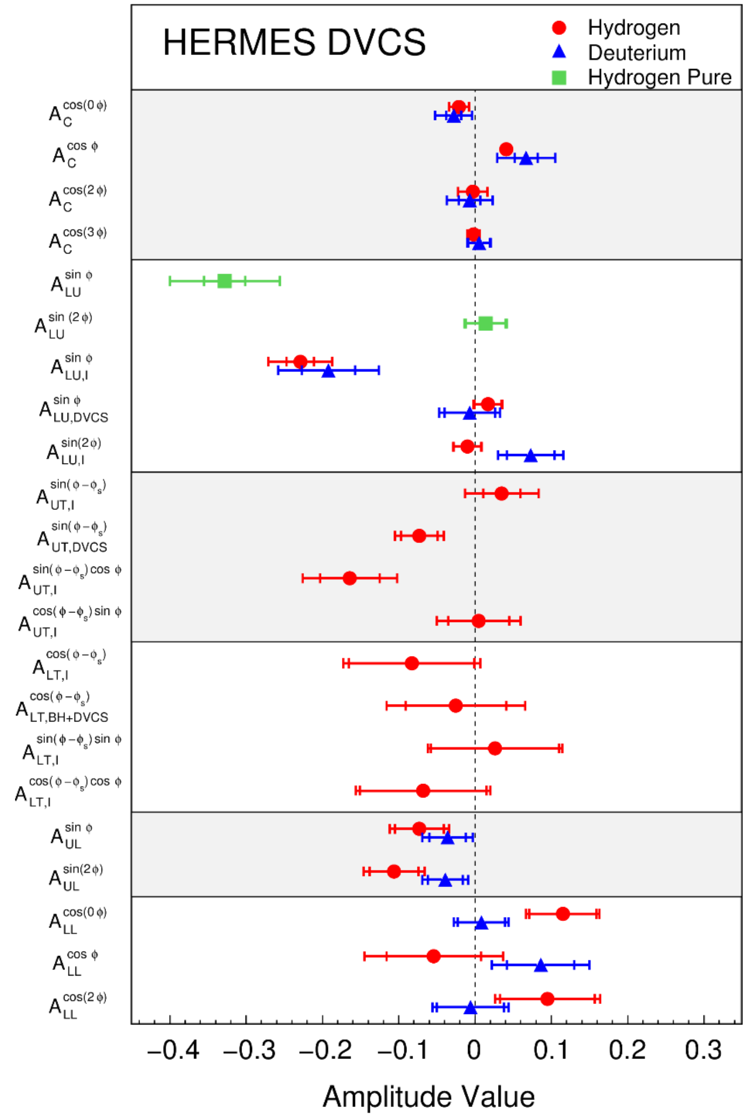


- cross-section depend on lepton charge e_ℓ and pol. P_ℓ, and on target pol. S
- contributions with different azimuthal dependence from:

BH interference DVCS

$$d\sigma(\ell p \to \ell \gamma p) \sim$$

$$\begin{array}{lll}
d\sigma_{UU}^{BH} & + e_\ell\, d\sigma_{UU}^{I} & + d\sigma_{UU}^{DVCS} \\
+ P_\ell S_L\, d\sigma_{LL}^{BH} & + e_\ell P_\ell S_L\, d\sigma_{LL}^{I} & + P_\ell S_L\, d\sigma_{LL}^{DVCS} \\
+ P_\ell S_T\, d\sigma_{LT}^{BH} & + e_\ell P_\ell S_T\, d\sigma_{LT}^{I} & + P_\ell S_T\, d\sigma_{LT}^{DVCS} \\
 & + e_\ell P_\ell\, d\sigma_{LU}^{I} & + P_\ell\, d\sigma_{LU}^{DVCS} \\
 & + e_\ell S_L\, d\sigma_{UL}^{I} & + S_L\, d\sigma_{UL}^{DVCS} \\
 & + e_\ell S_T\, d\sigma_{UT}^{I} & + S_T\, d\sigma_{UT}^{DVCS}
\end{array}$$

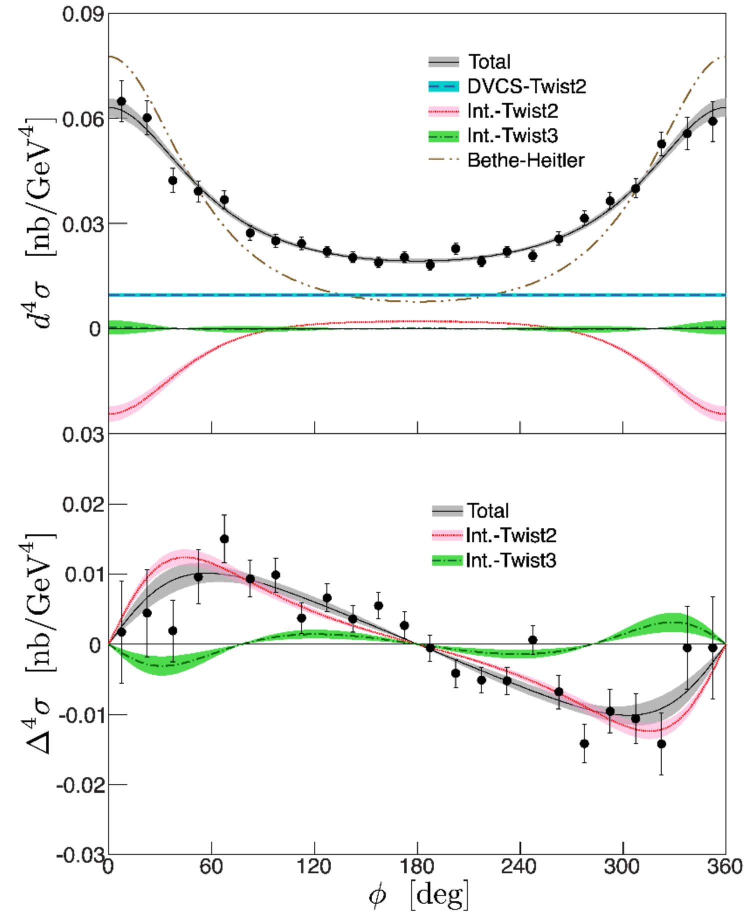


K. Rith DIS2014

DVCS @ Hall A E00-110

- final results of Hall-A E00-110
- unpol. x-sect and x-sect differences for beam pol.
- 588 bin $(x_B, Q^2, -t,\ \phi)$

- exp.:
  $-t$ = 0.32 GeV^2, x=0.36

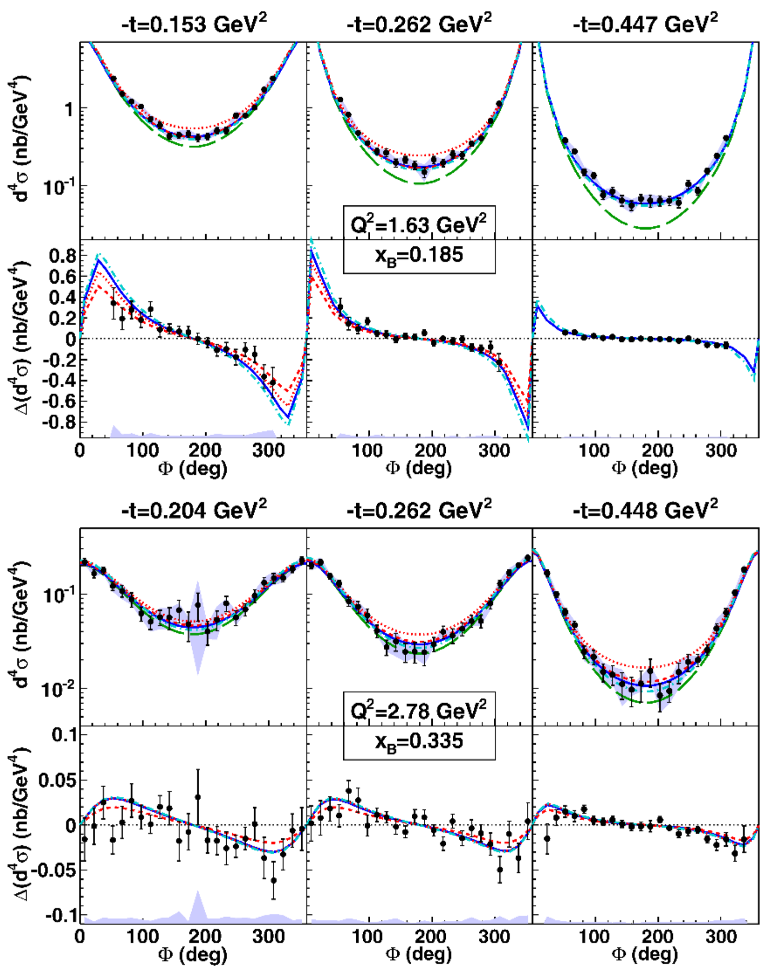


PRC 92 (2015) 055202

DVCS @ CLAS

Jefferson Lab

- pol. proton (NH_3) target
- x-sect, TSA, BSA, DSA
- 164 bins $(x_B, Q^2, -t,\ \phi)$
- $1.0 < Q^2 < 4.6\ \mathrm{GeV}^2$
- $0.10 < x_B < 0.58$
- $0.09 < -t < 0.52\ \mathrm{GeV}^2$



unpol.

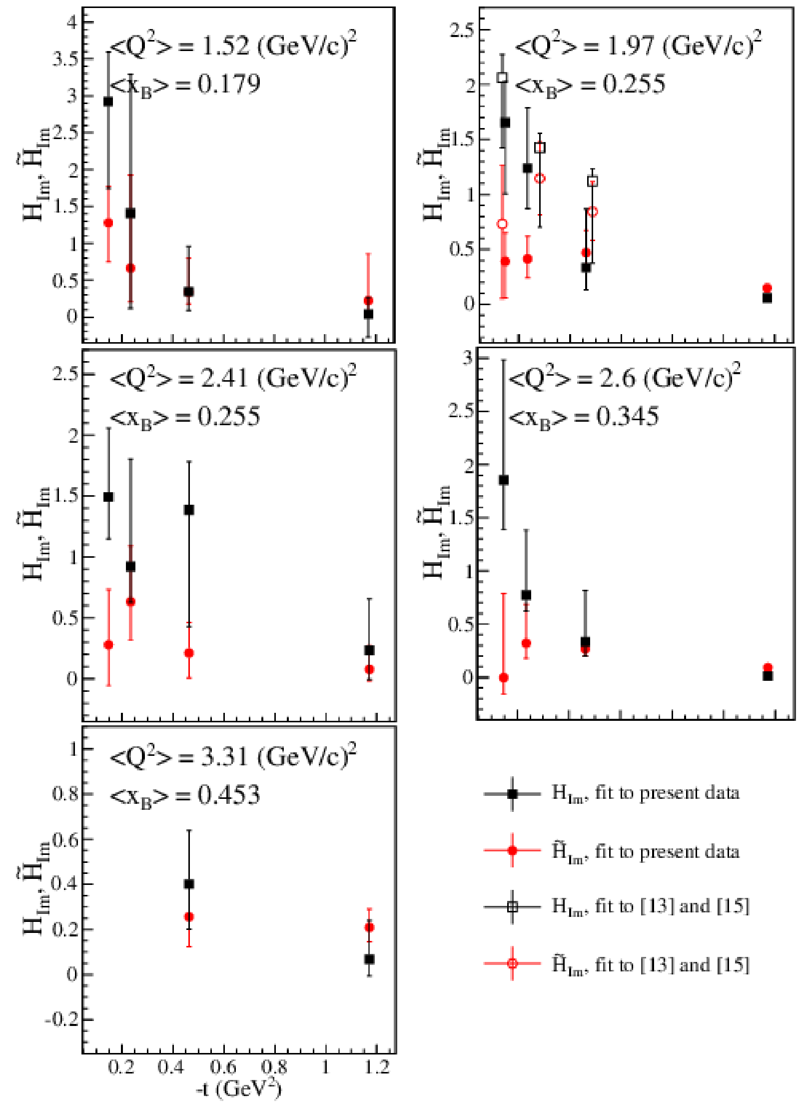
beam pol.

PRL 115 (2015) 212003
PRD 91 (2015) 052014

DVCS @ CLAS

- determine the imaginary part of CFF H_{Im} and $\widetilde{H}_{Im}$ of GPDs $\mathcal{H}$ and $\widetilde{\mathcal{H}}$
- most sensitive to $\widetilde{H}_{Im}$

$$F_{Im}(\xi,t) = -\frac{1}{\pi}\Im\mathrm{m}\mathcal{F}(\xi,t) = [F(\xi,\xi,t) \mp F(-\xi,\xi,t)]$$

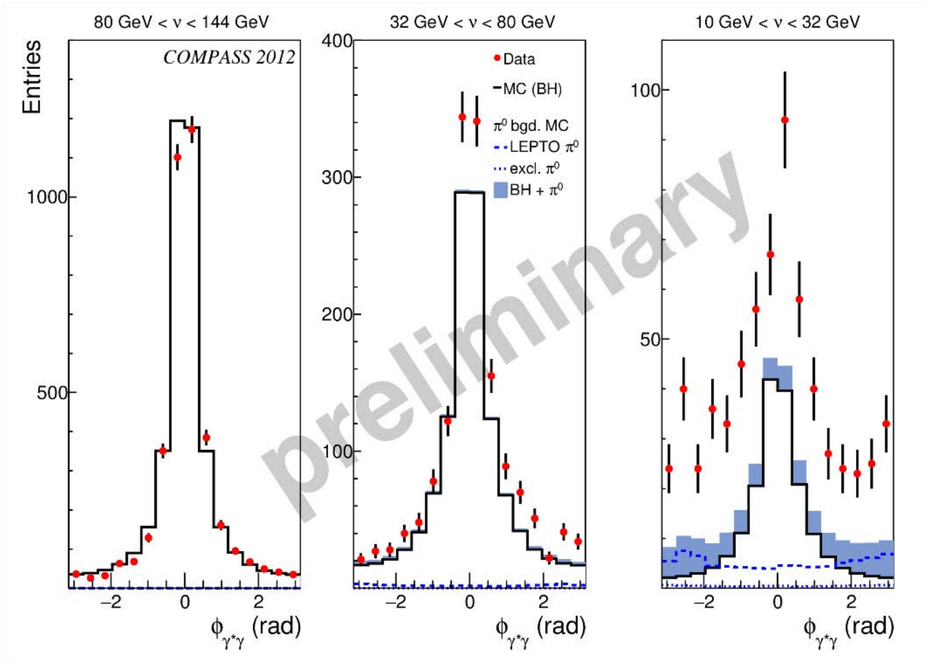


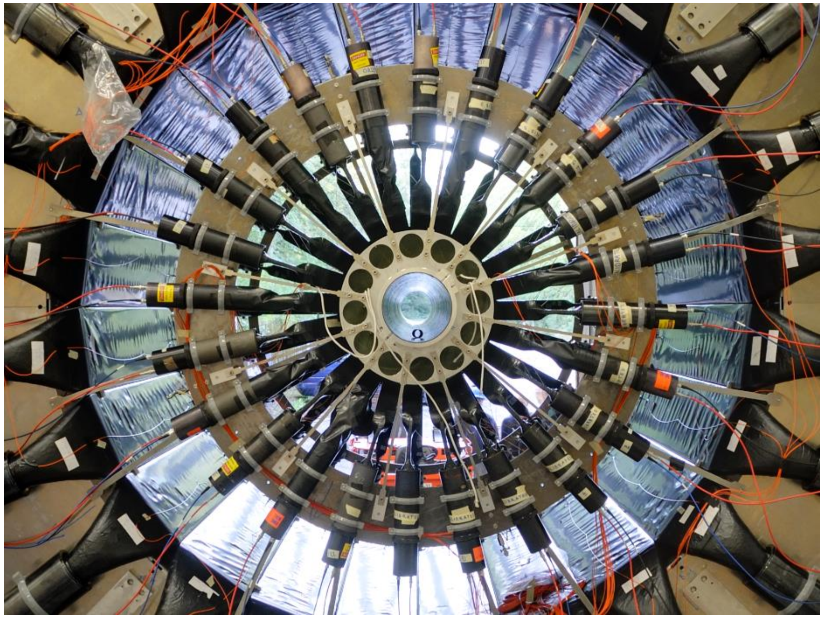
CLAS: PRD 91 (2015) 052014

COMPASS DVCS

- GPD data 2012 (pilot), 2016–2017
- liquid hydrogen target
- 3 bin in $\nu \sim {}^{1}/_{x}$

- 160 GeV muon beam
- CAMERA recoil detector

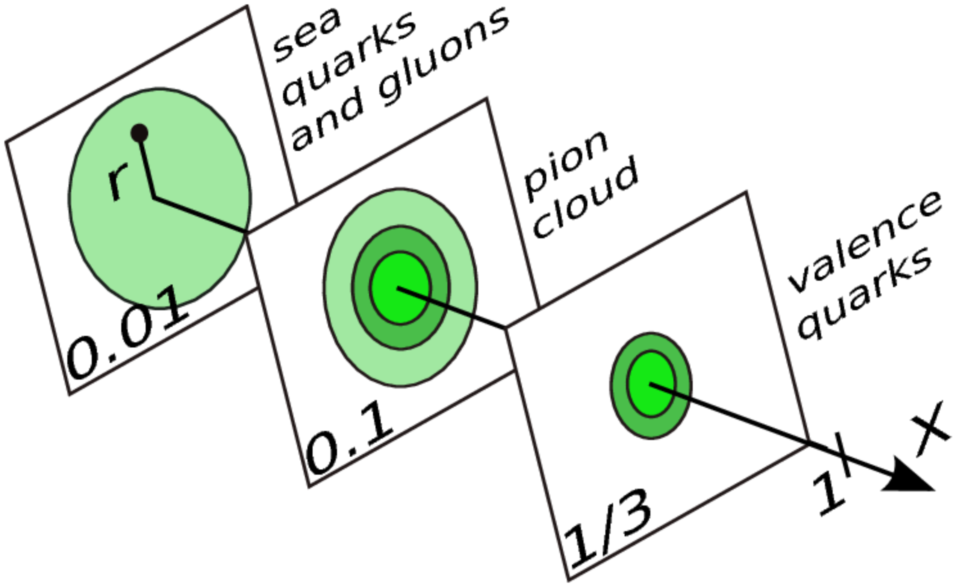




Transverse proton size

- The distance $\langle r_\perp^2 \rangle$ between struck quark and spectator c.m. given by *t*-slope of DVCS cross-section σ_0 (as function of x_B, LO)

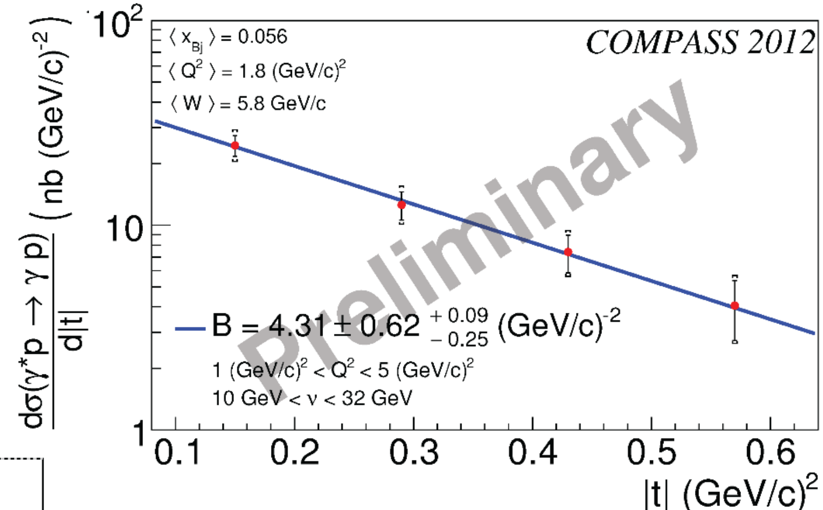
$$\frac{d\sigma_0^{DVCS}}{dt} \propto \exp(-B(x_B)|t|) \qquad \langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$

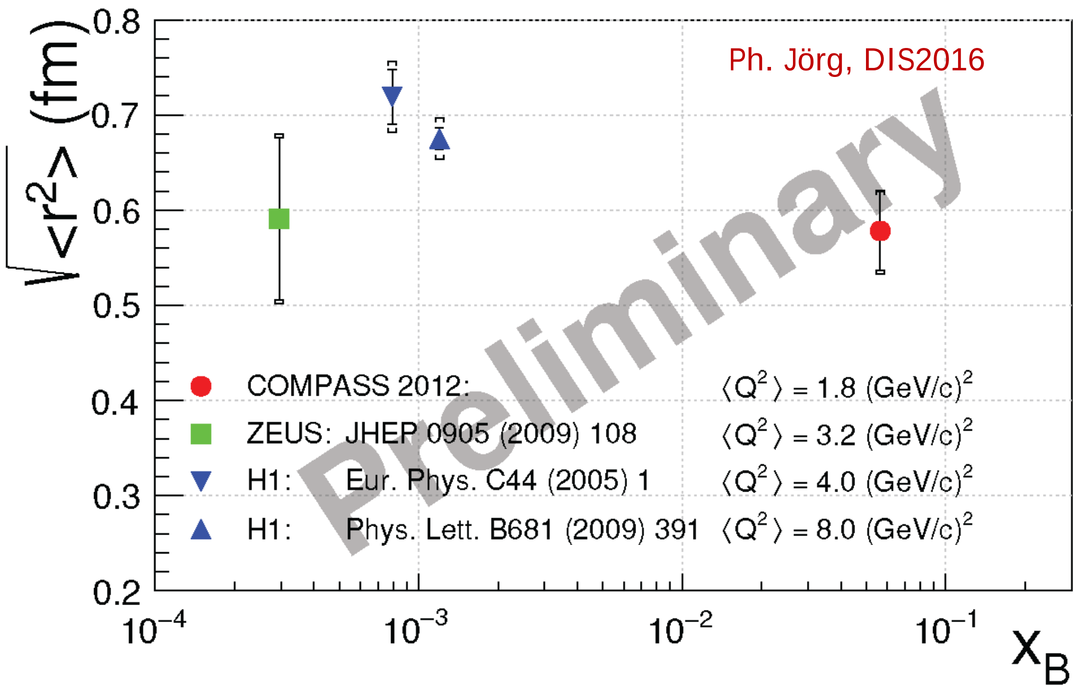


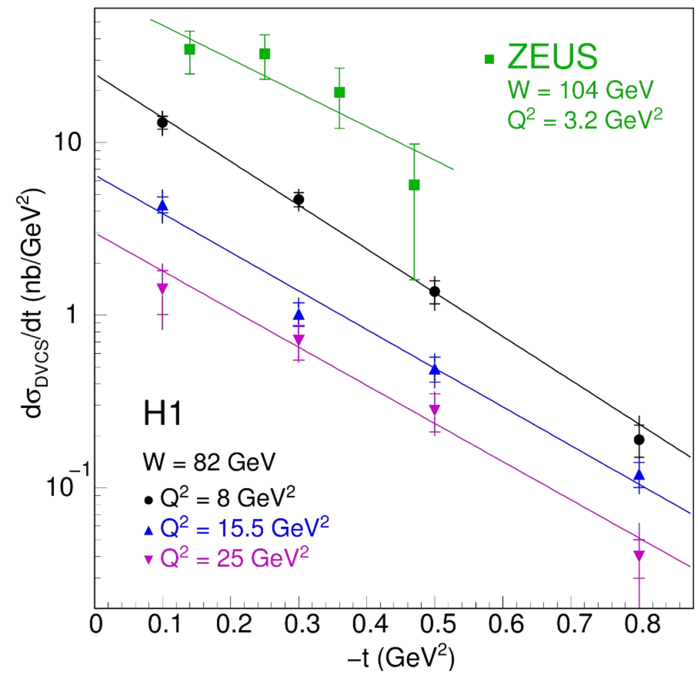
- Transverse size as function of x_B
- Expect log. dependence

t slope and transverse proton size

- model independent
- 2012 pilot run data only
- 2016/17 data: several x_B bins, higher precision







t slope and transverse proton size

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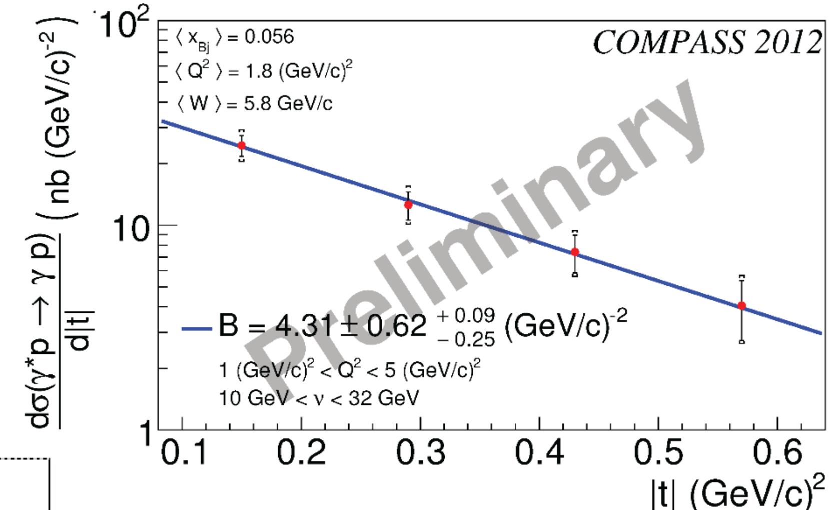

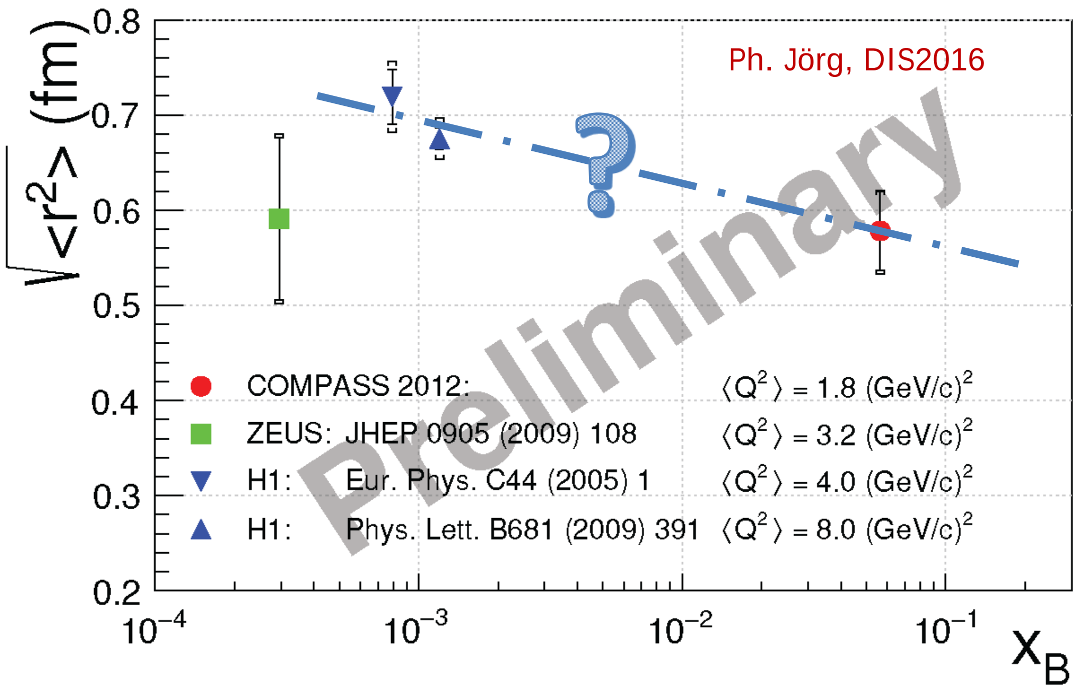

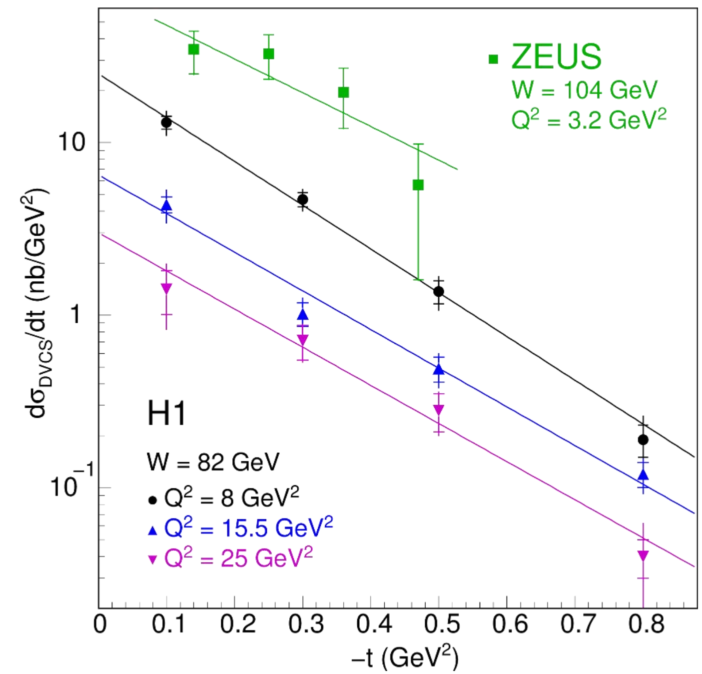

Outlook

- a wealth of new data
- gluon polarisation likely to be positive at $x \cong 0.2$, need low x_g data
- multilicities and FF to be clarified, in particular for kaons/strange quarks, impact PDF determination
- measure the sign change of T-odd TMDs in DY and SIDIS!
- new data coming up JLab 6/12, RHIC, COMPASS, JPARC and eventually EIC