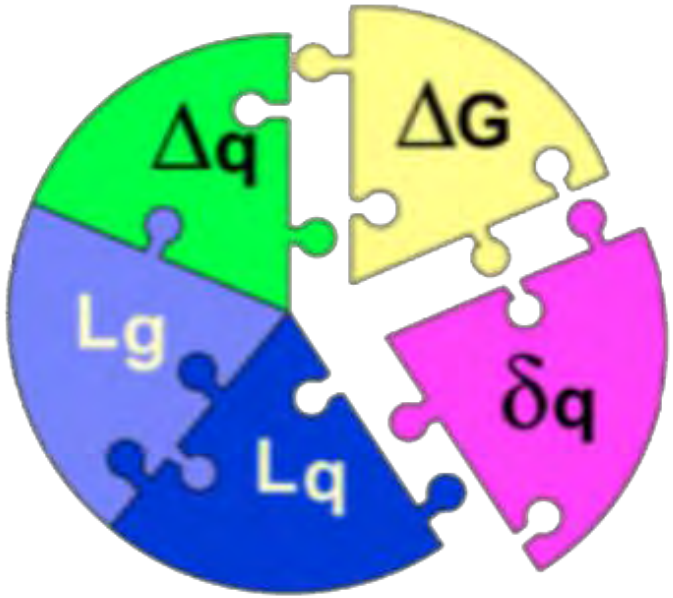
Spin of the nucleon: Experimental Overview

Gerhard K. Mallot /CERN-PH

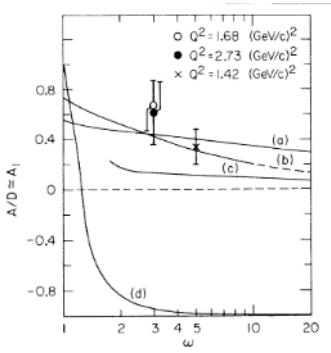
Outline

- Introduction
- DIS and SIDIS data
- TMDs
- GPDs
- Outlook



Introduction

- Nucleon spin structure measurements are not easy
- The start: 1971 approval of Yale-SLAC experiment E80, data 1976
- After more than 4 decades we learned a lot …
  … and new questions arose.
- From collinear to TMD and 3D structure of the nucleon



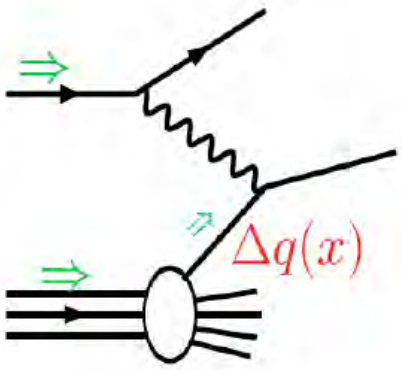
Vernon W. Hughes

Tools to study the partonic nucleon structure

Factorisation of hard interaction and nonperturbative nucleon structure/fragmentation:

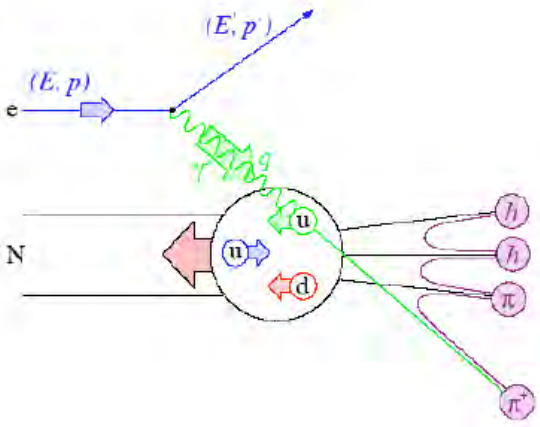
- PDF parton distribution functions
- FF fragmentation functions

DIS



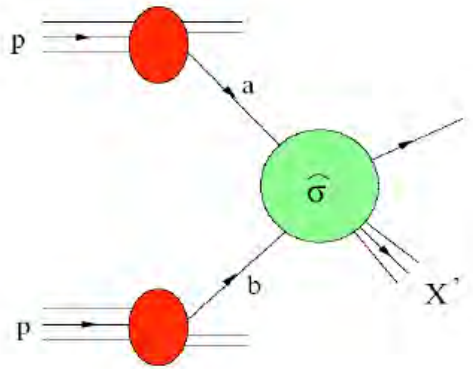
PDF

SIDIS



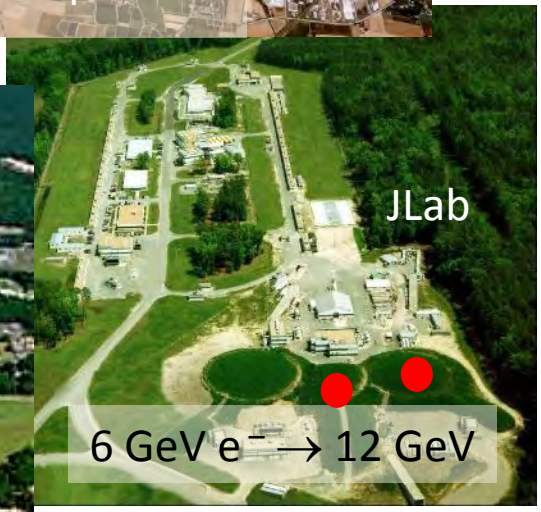
PDF⊗FF

pp

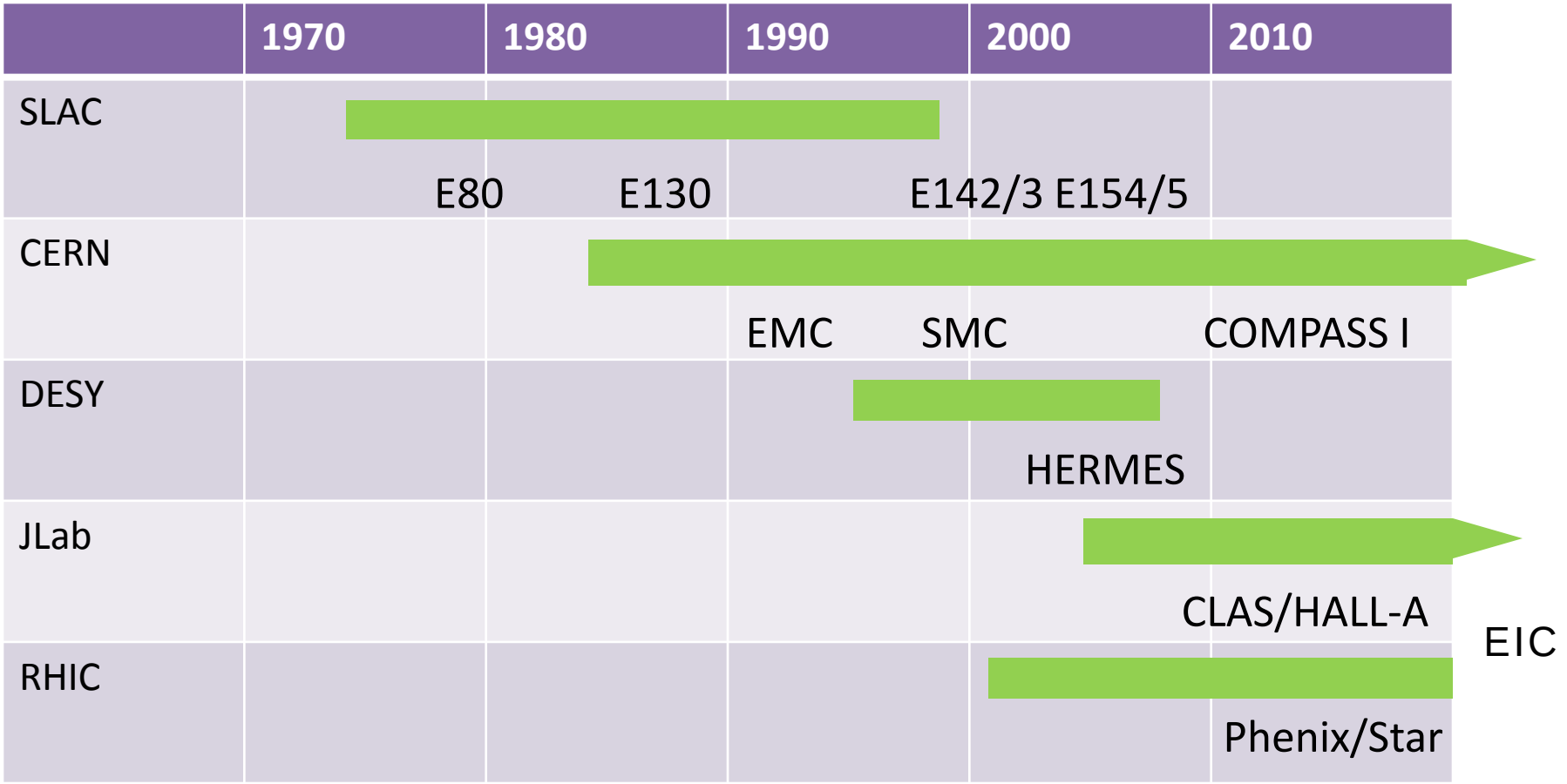


PDF⊗PDF

Laboratories



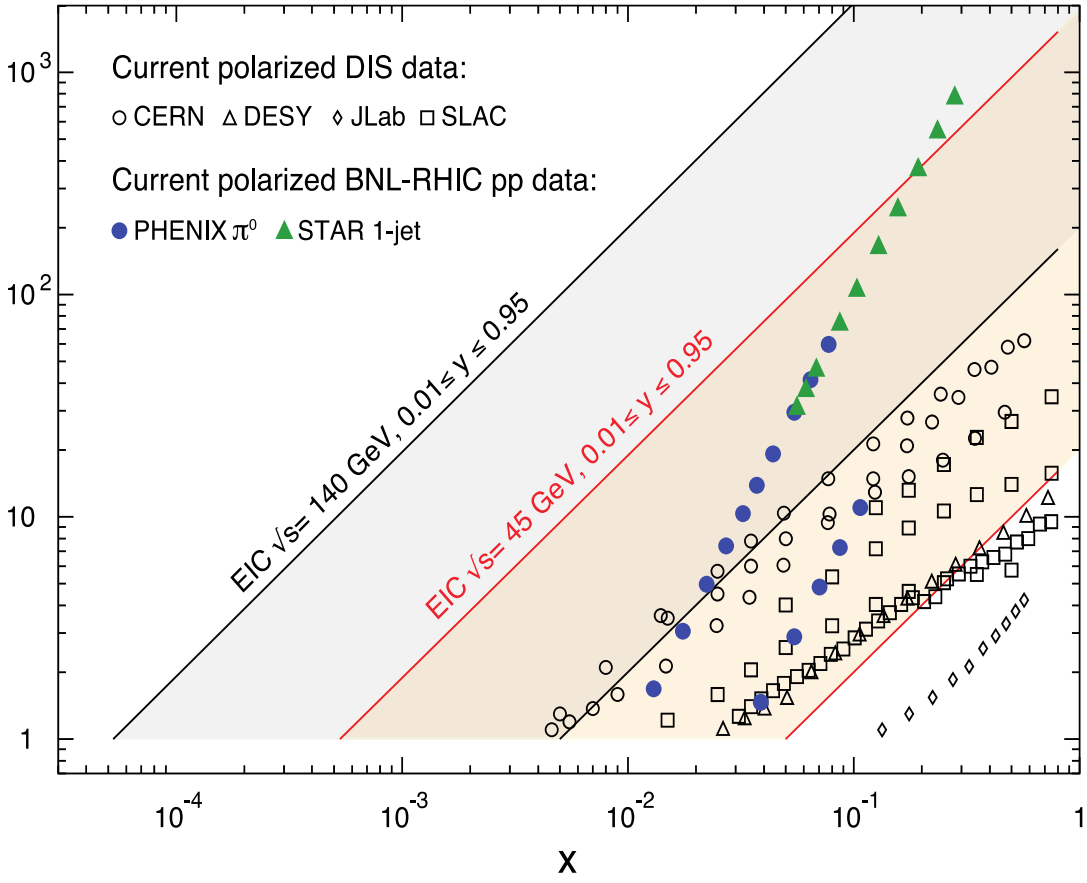
Global effort: Pol. DIS/pp

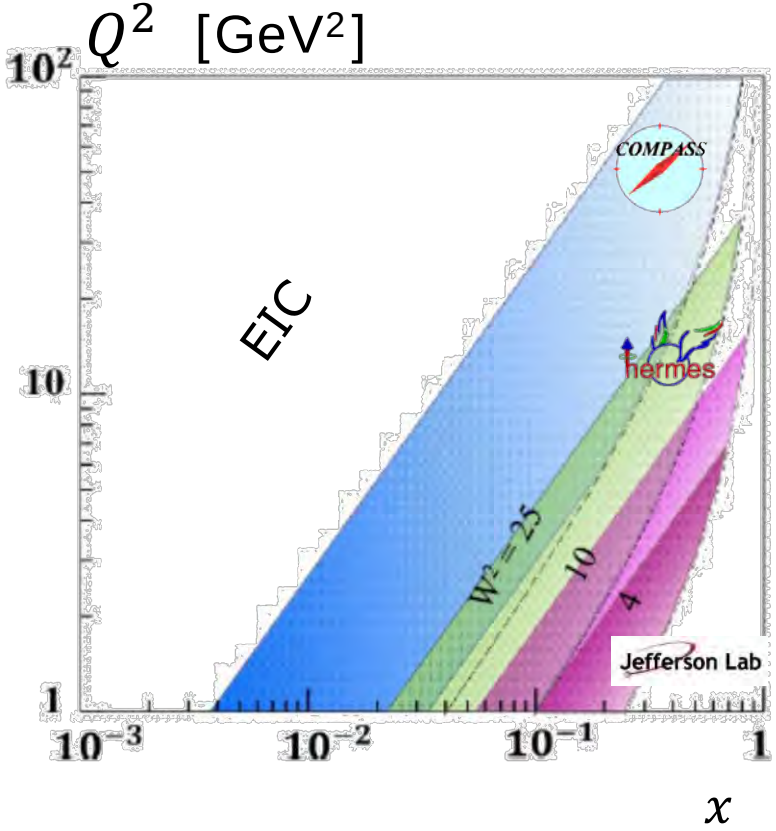


- A worldwide effort since decades

Kinematic reach

- similar *x* ranges as in DIS and *pp*
- much higher Q^2 in *pp* (RHIC: 250 + 250 GeV)

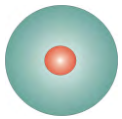




Structure: Parton Distribution Functions

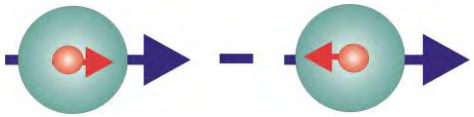
Three twist-2 PDFs

q(x)
$f_1^q(x)$



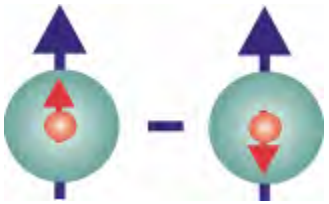
unpolarised PDF
quark/gluon with momentum *xP* in a nucleon

Δq(x)
$g_1^q(x)$



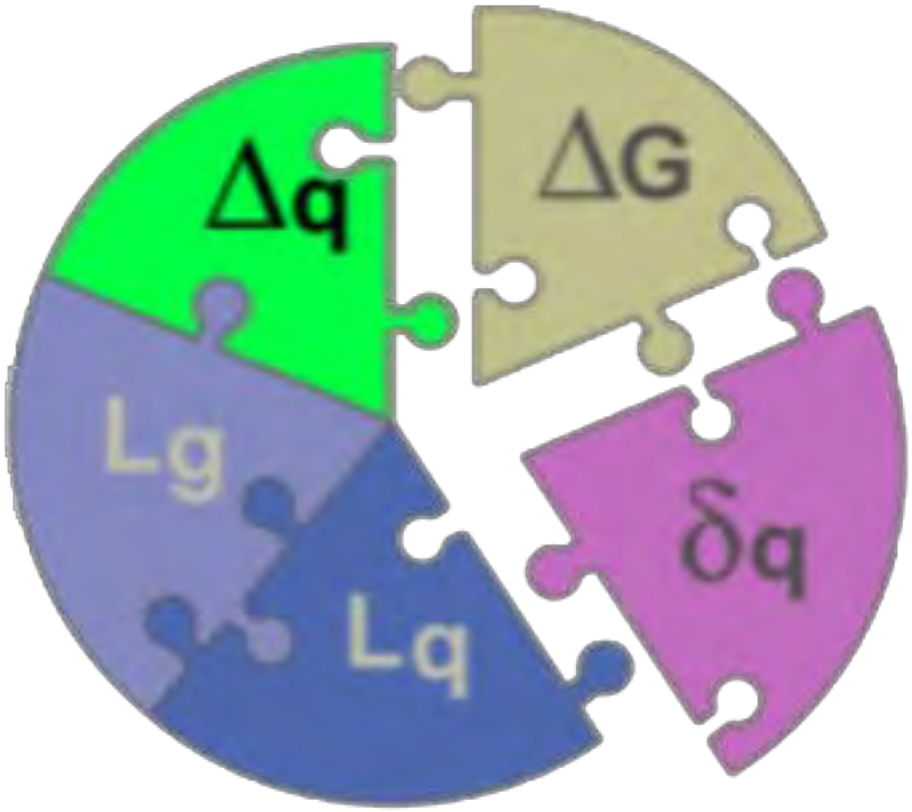
helicity PDF
quark/gluon with spin parallel to the nucleon spin in a longitudinally polarised nucleon

$\Delta_T q(x)$
$h_1^q(x)$

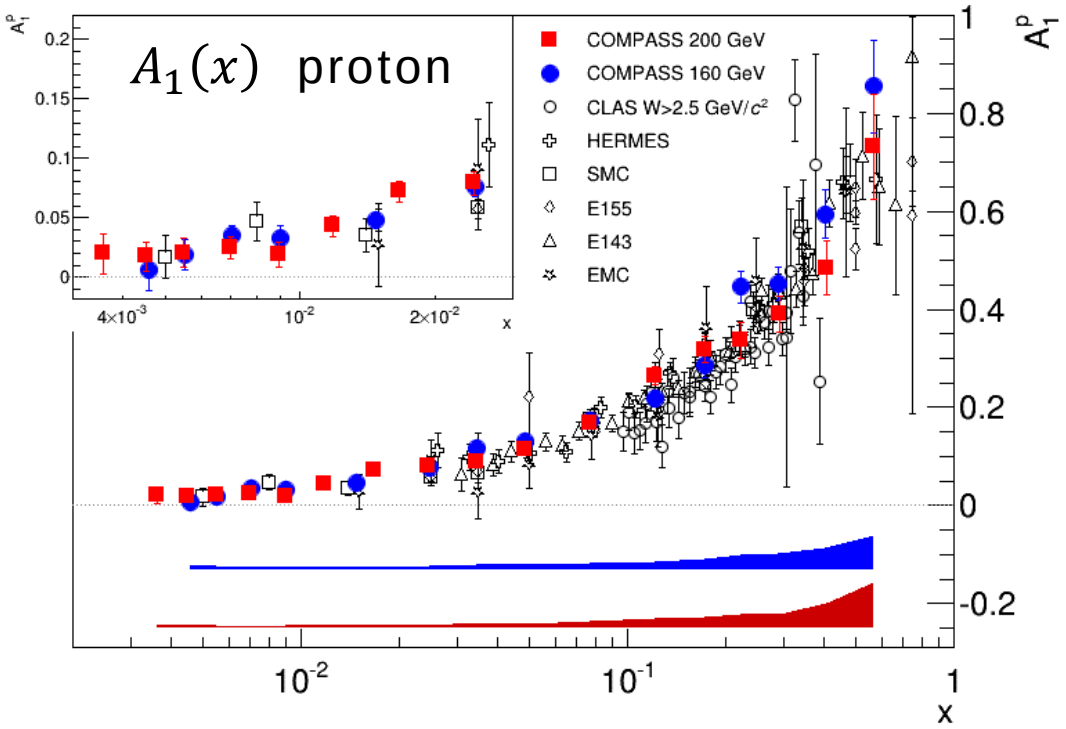


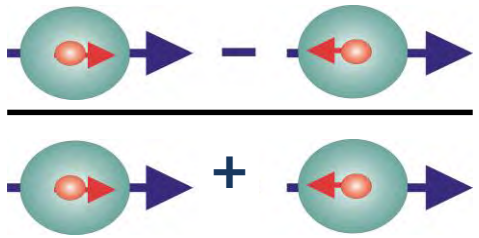
transversity PDF
quark with spin parallel to the nucleon spin in a transversely polarised nucleon

Quark polarisation



World data on proton A_1 spin asymmetry





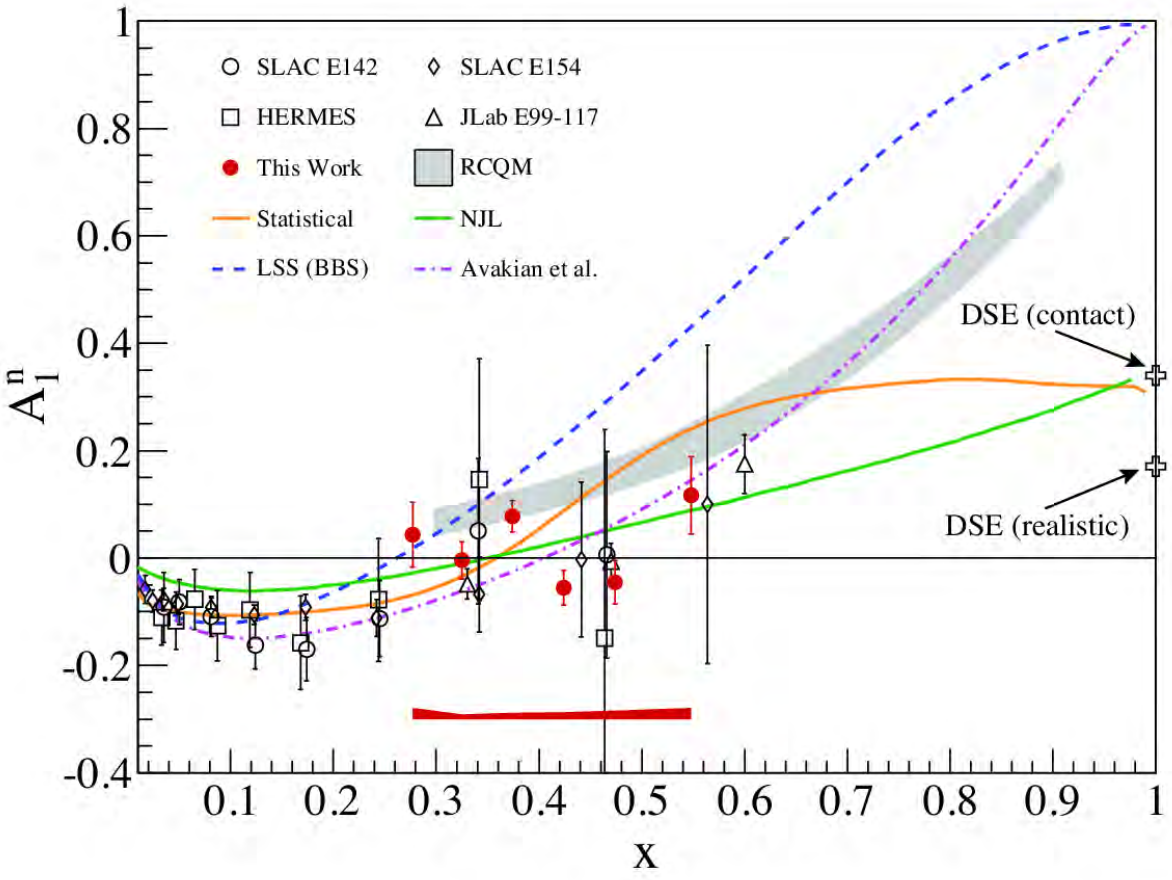
W > 2.5 GeV

arXiv:1503.08935

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

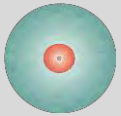
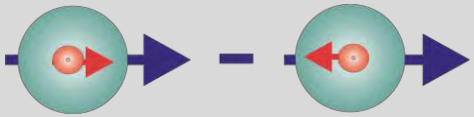
Hall A: precise A_1^n data

- Consistent with zero-crossing around x = 0.5

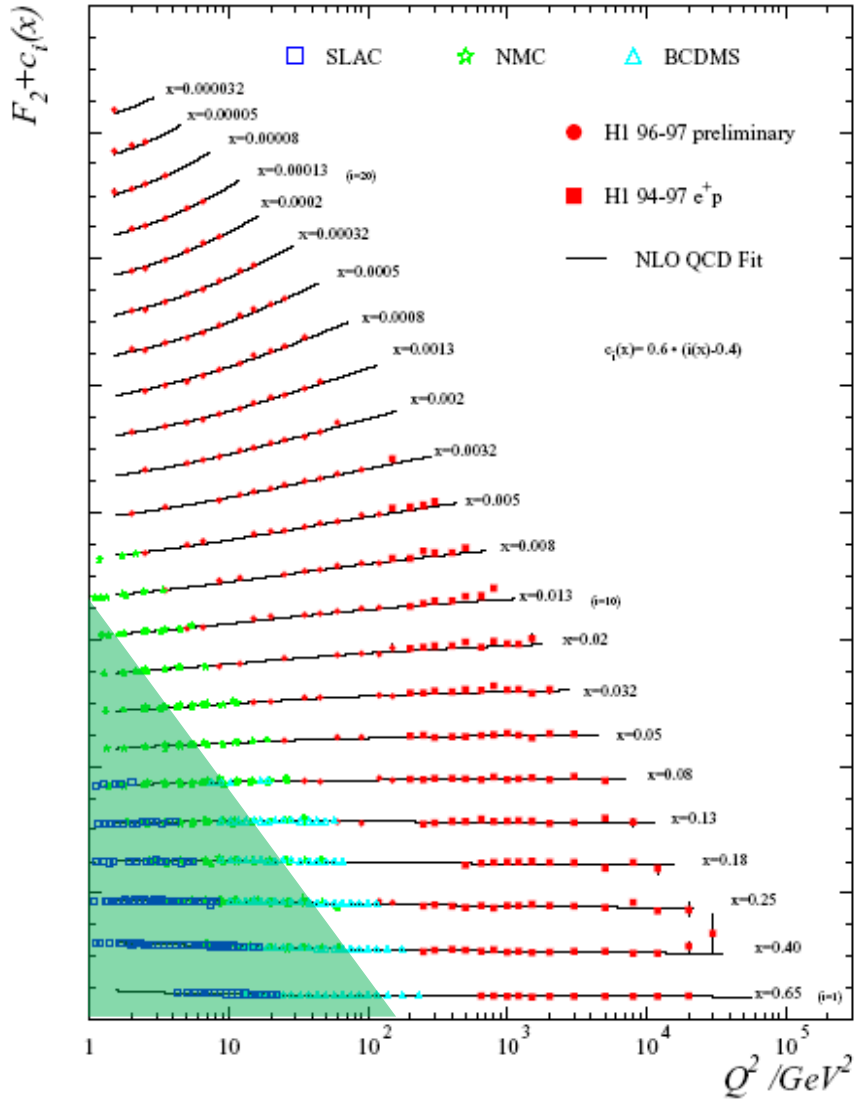


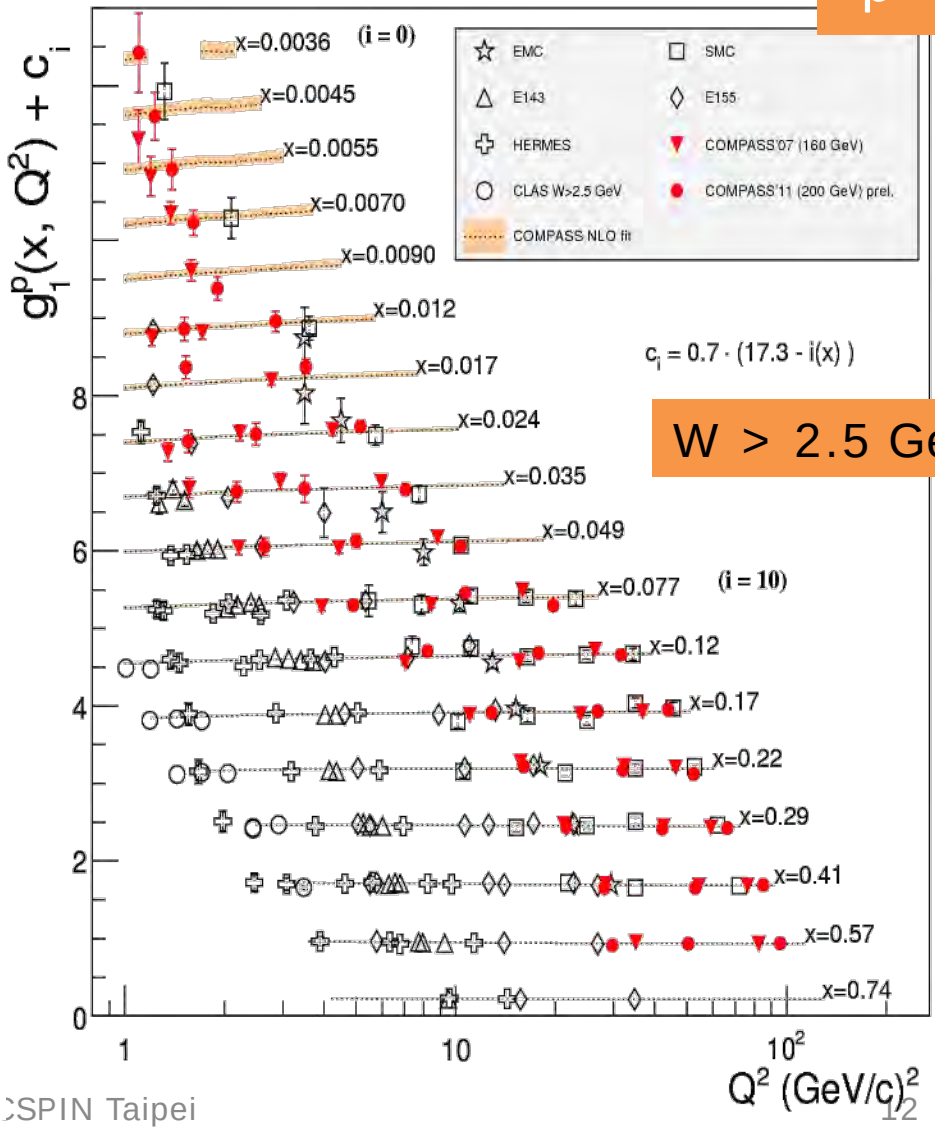
^{3}He gas target

PLB 744 (2015) 309–314

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

p





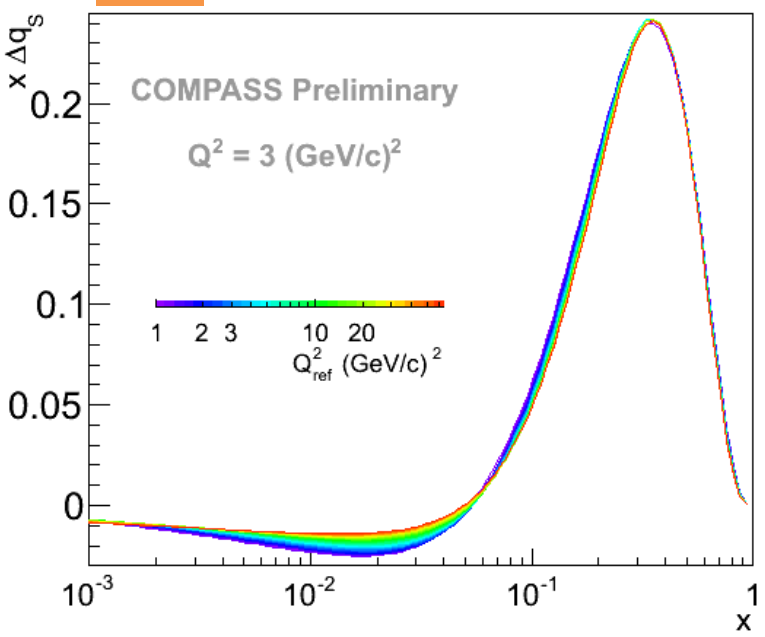
W > 2.5 GeV

arXiv:1503.08935

NLO QCD fit to world DIS data

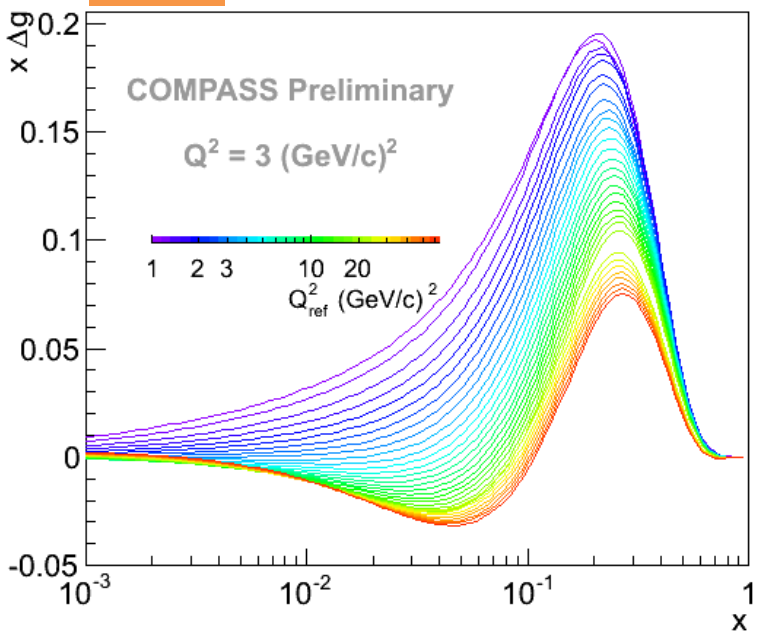
- study of PDF shapes, Q^2_{ref} dependence

$\Delta\Sigma$



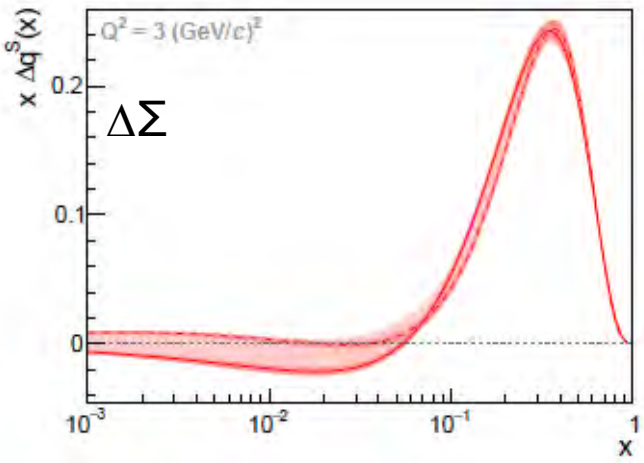
Δg

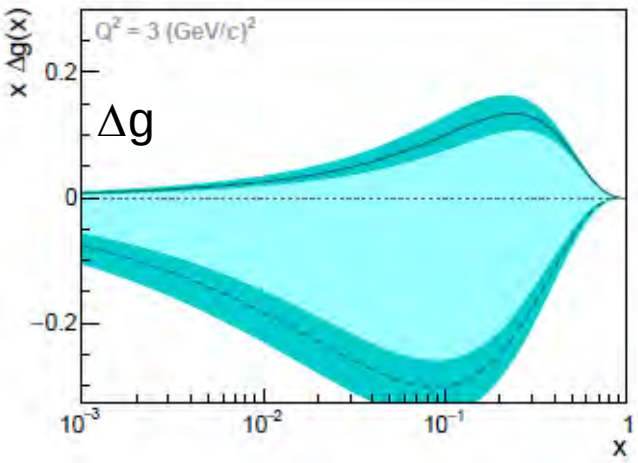
$Q^2 = 3\ \mathrm{GeV}^2$

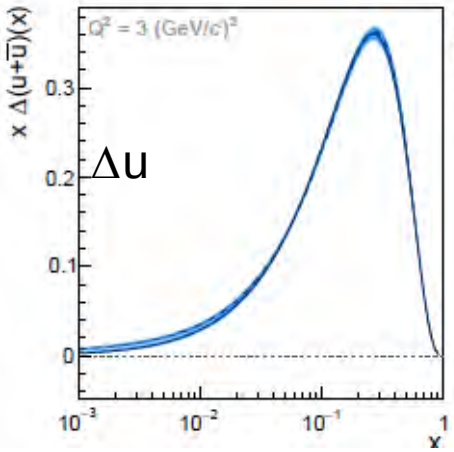


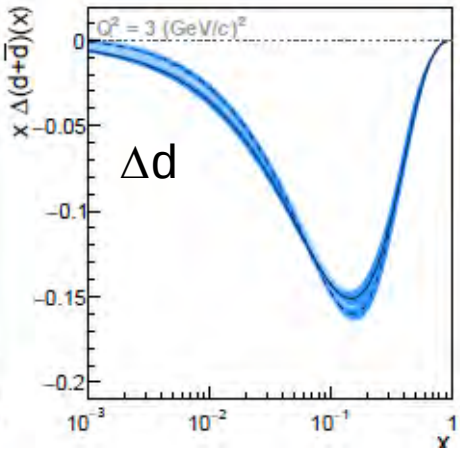
arXiv:1503.08935

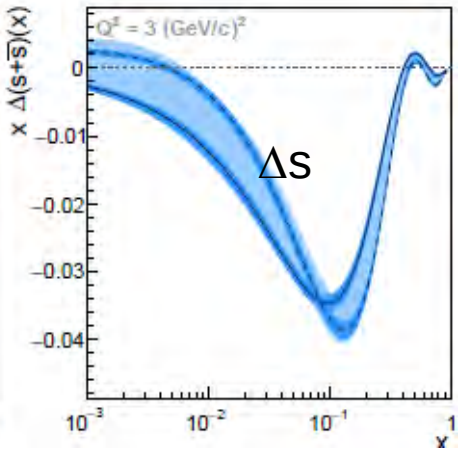
NLO QCD fit to world DIS data











$Q^2 = 3\ \mathrm{GeV}^2$

integrals:

$0.27 \leq \Delta\Sigma \leq 0.39$

$-1.6 \leq \Delta G \leq 0.5$

$0.82 \leq \Delta U \leq 0.85$

$-0.45 \leq \Delta D \leq -0.42$

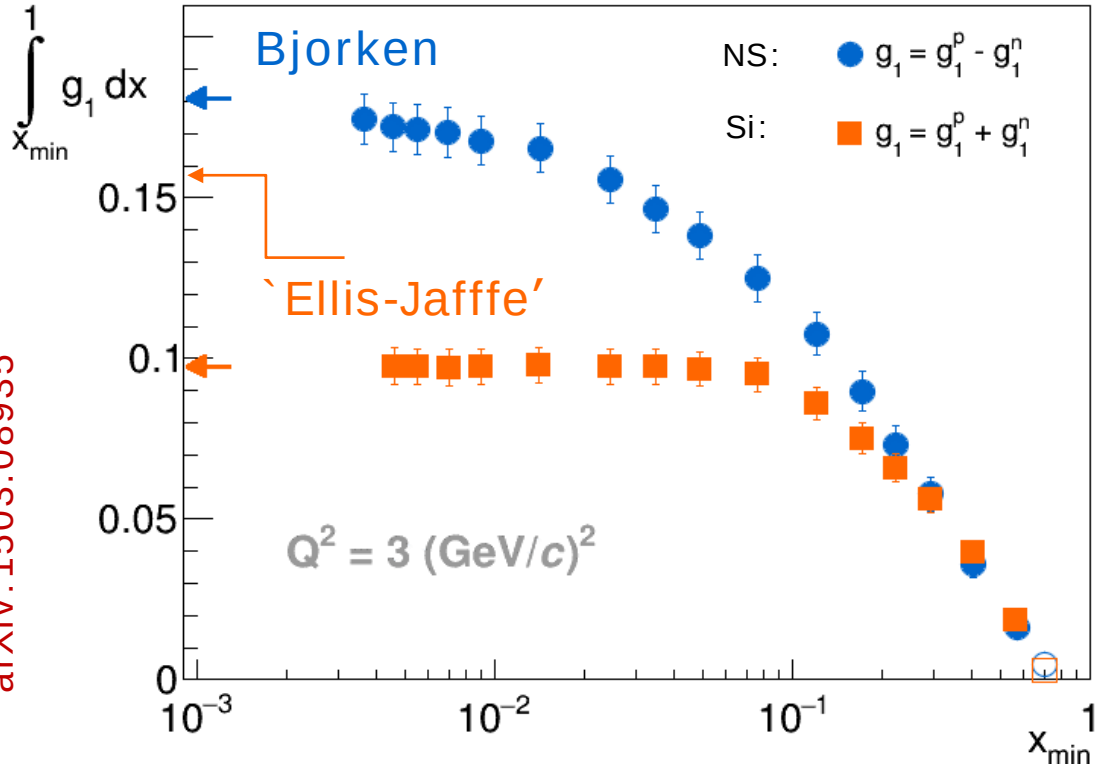
$-0.11 \leq \Delta S \leq -0.08$

using different functional shapes and Q_0^2

arXiv:1503.08935

- come back to World data fits incl. SIDIS and pp later

Sum rules



arXiv:1503.08935

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

Bjorken sum rule verified to 9%

- BJ SR major contribution from small *x*
- EJ SR no contribution at small *x*

COMPASS data only: $|g_A/g_V| = 1.22 \pm 0.05\ (\text{stat.}) \pm 0.10\ (\text{syst.})$

from neutron β decay: $|g_A/g_V| = 1.2723 \pm 0.0023$

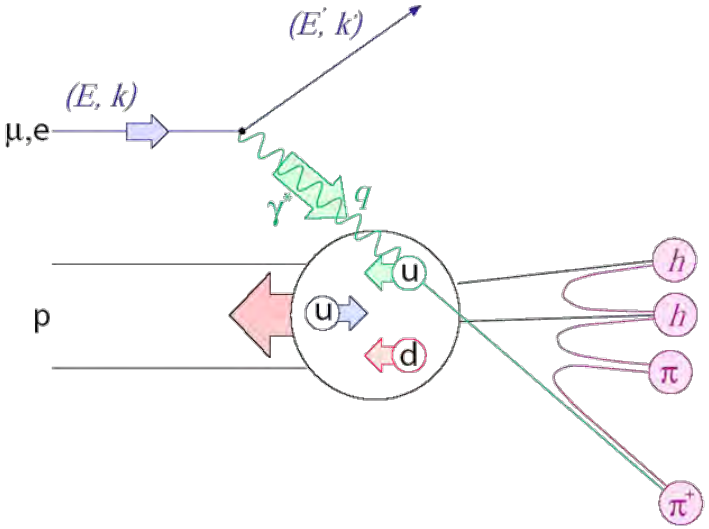
Semi-inclusive DIS results

- additional hadron observed in FS

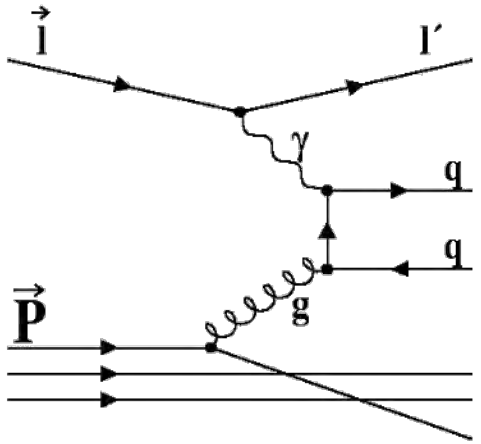
$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)}$$

- gives access to flavour information via the fragmentation functions D

$z = E_h/\nu$

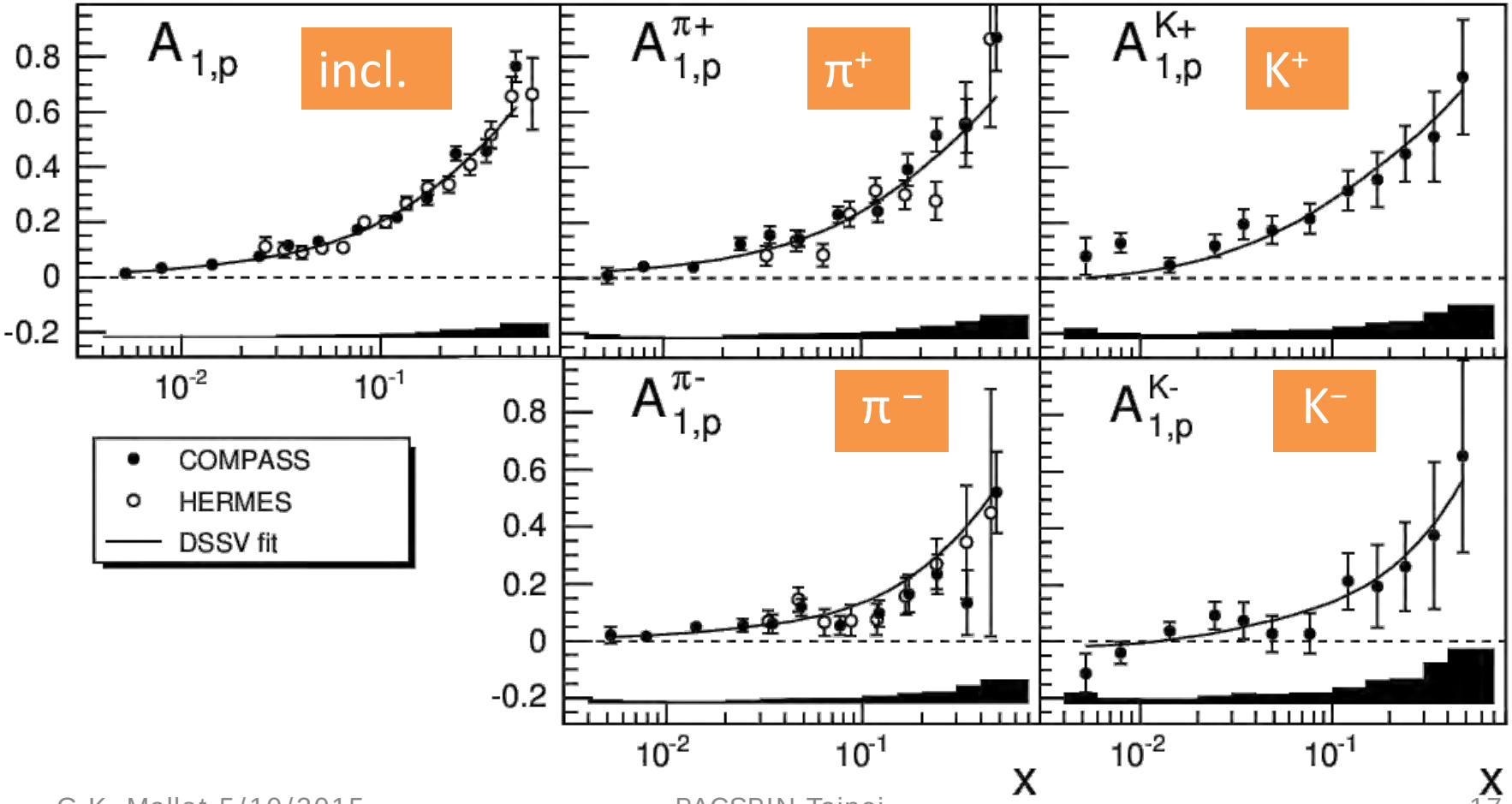


- photon–gluon fusion gives access to the gluon polarisation
- particularly interesting open charm production via $c\bar{c}$



Incl. & semi-incl. A_1

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

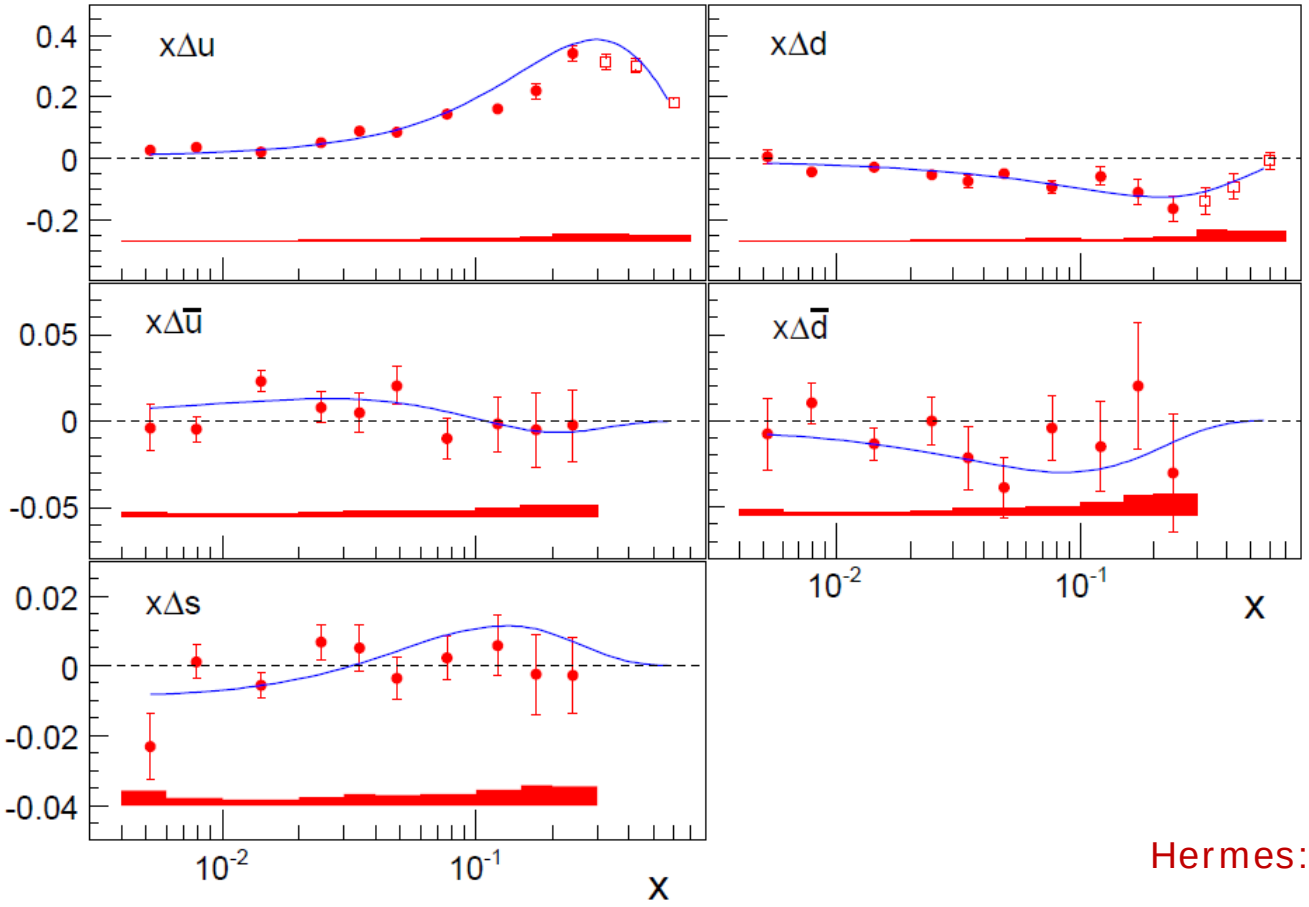


PLB 693 (2010) 227–235

The role of quark flavours

LO analysis of 5p+5d asymmetries, DSS FF
Line: NLO DSSV not including these data

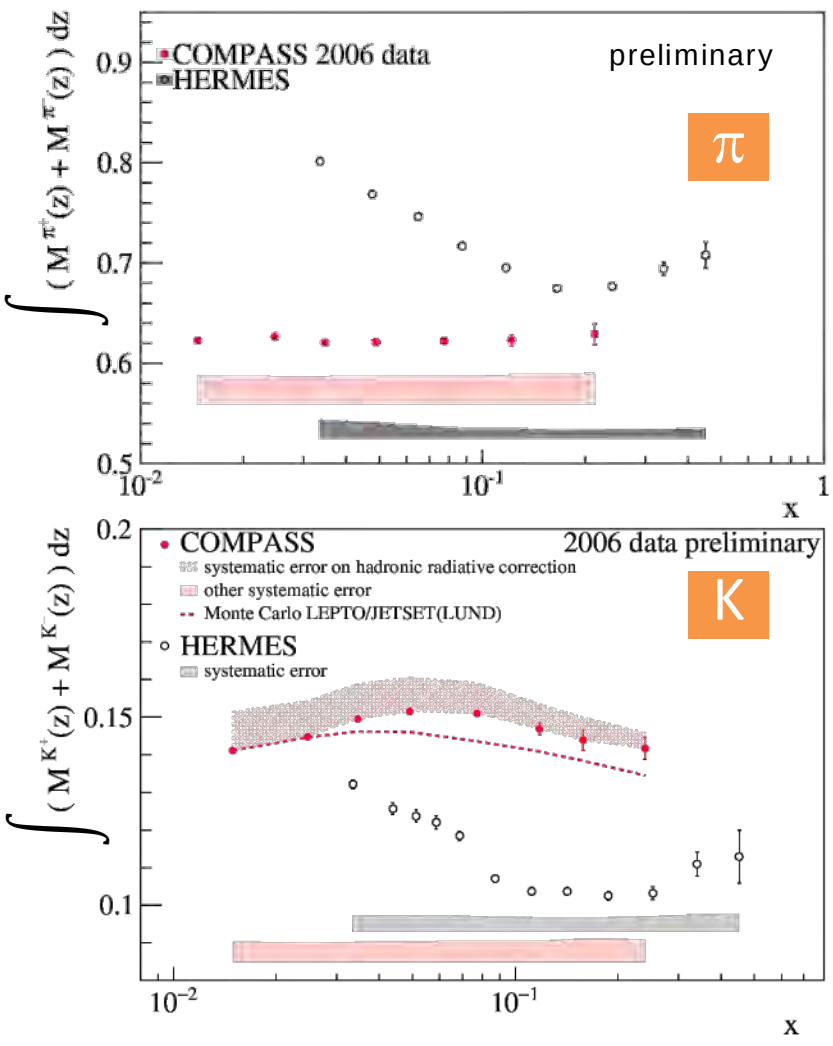
5-flavour fit,
assuming $\Delta s = \bar{\Delta} s$

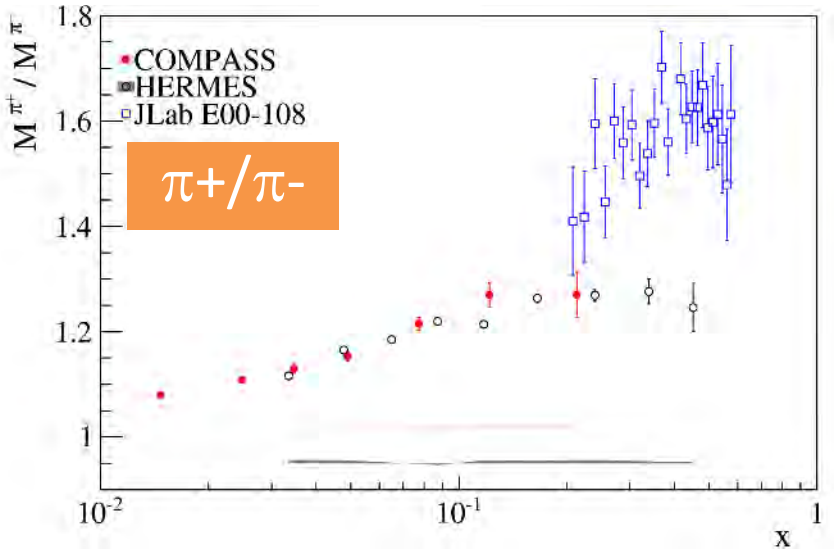


PLB693 (2010) 227

Hermes: PRD 71 (2005) 012003

pion and kaon multiplicities (unpol)



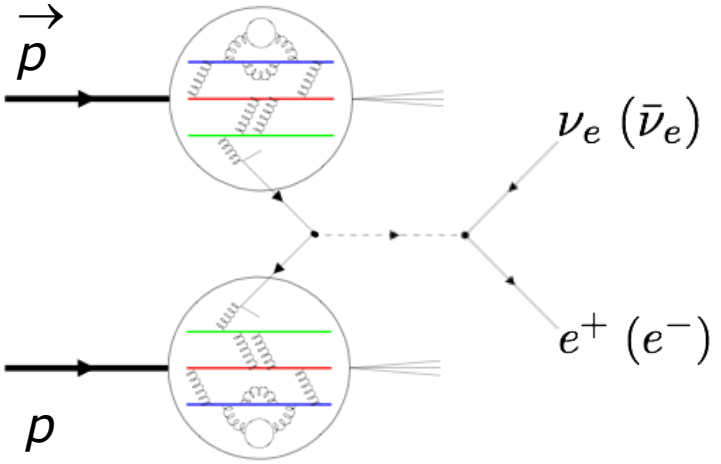


- $\frac{dM^h(x,y,z)}{dz} = \frac{1}{N^{DIS}(x,y)} \frac{dN^h(x,y,z)}{dz}$
- deuteron data, int. over z, p_T, Q^2
- large discrepancies in multiplicities
- ratio π^+/π^- ok, K^+/K^- differ ~ 20%
- Compass data being finalized
- impact on FF → strange quark PDF

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

W production & antiquark polarisation

- $\vec{p}p$ collisions at 250 GeV+ 250 GeV
- $u_L \overline{d}_R \to W^+$ and $\overline{u}_R d_L \to W^-$
- parity-violating long. SSA: $A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$
- sensitive to antiquark polarisation



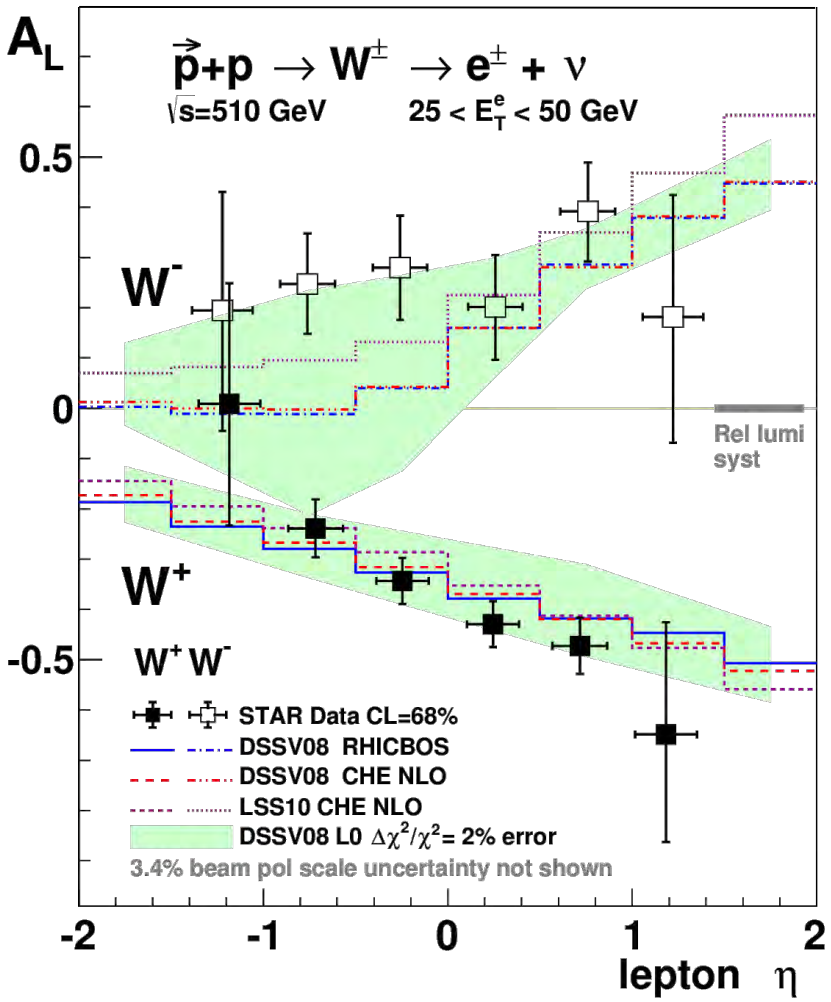
signature: high p_T lepton

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

W production in *pp*

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

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



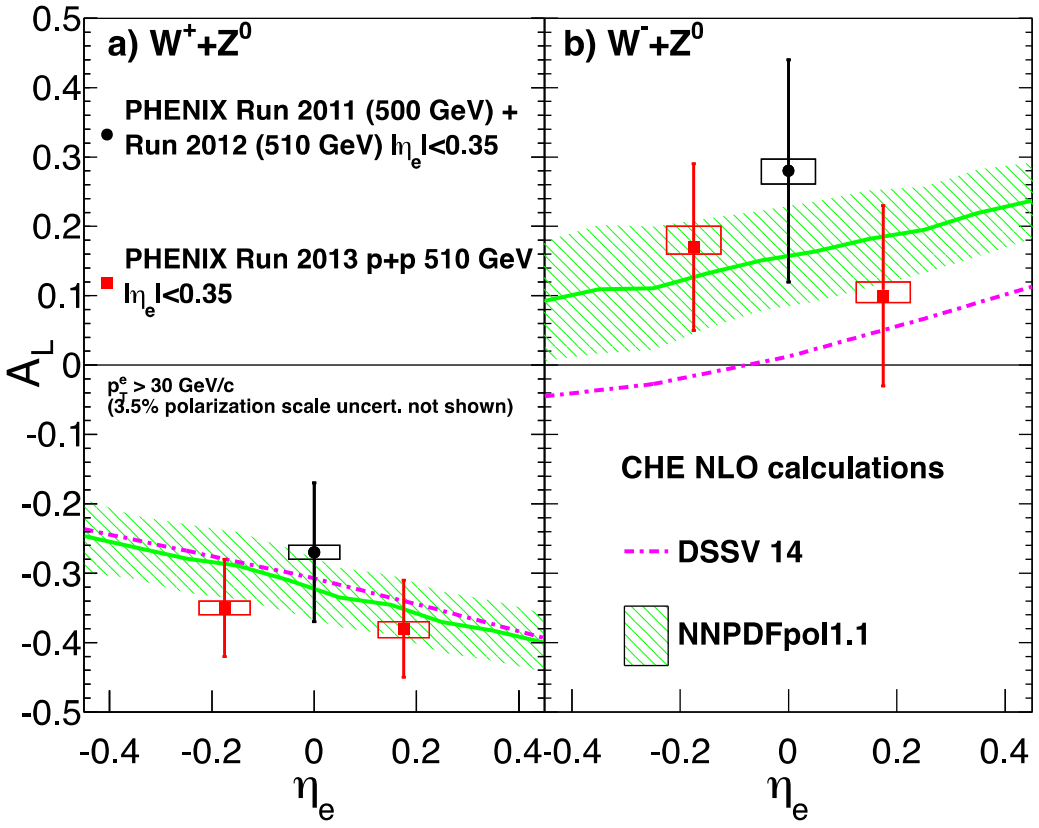
PRL 113 (2014) 072301

W production in *pp*

- Run 12+13, $|\eta| < 0.35$
- also larger A_L for W^- wrt to DSSV14
- recent NNPDF1.1 includes RHIC W data

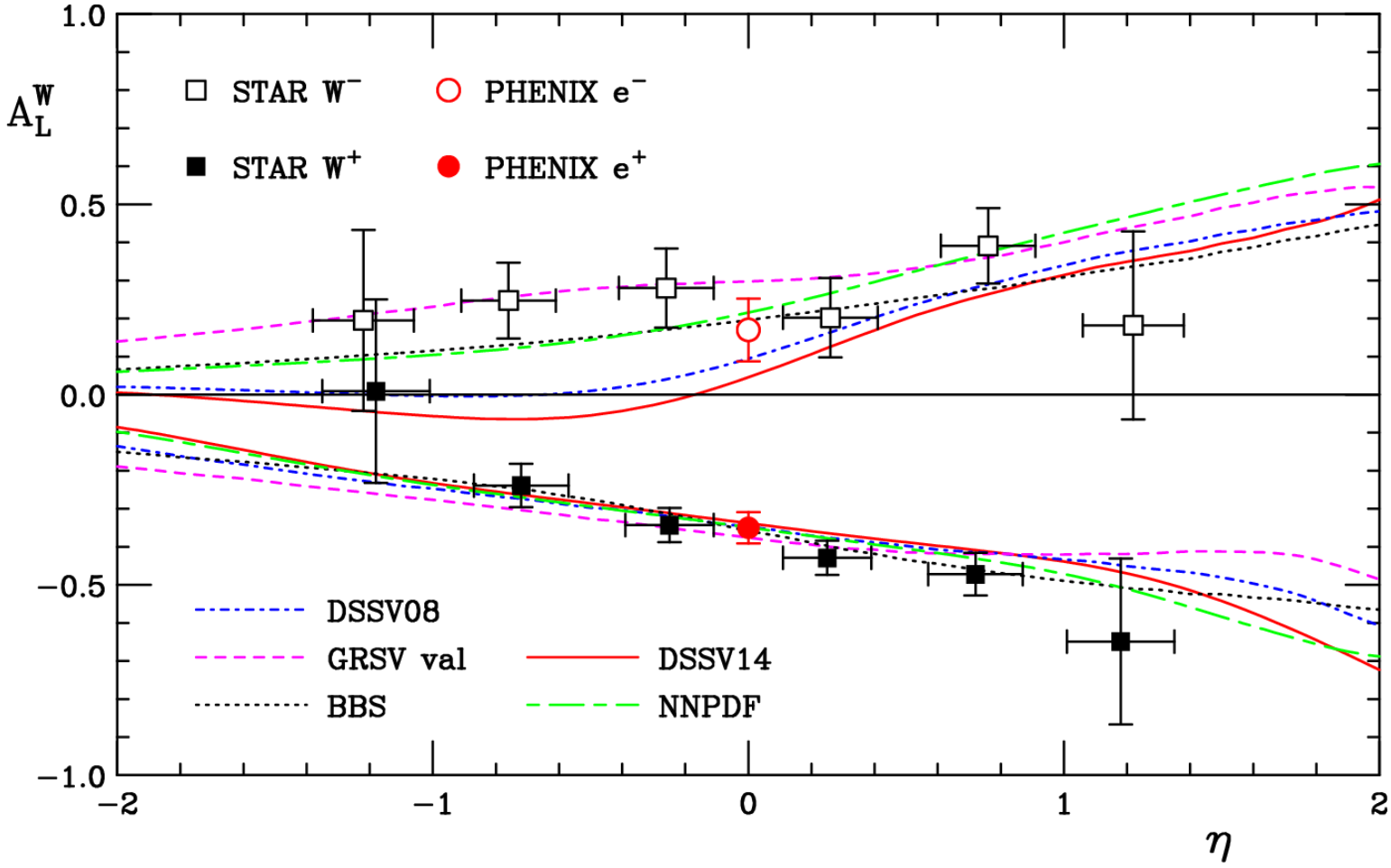
NNPDF: NPB 887 (2014) 276

arXiv:1504.07451

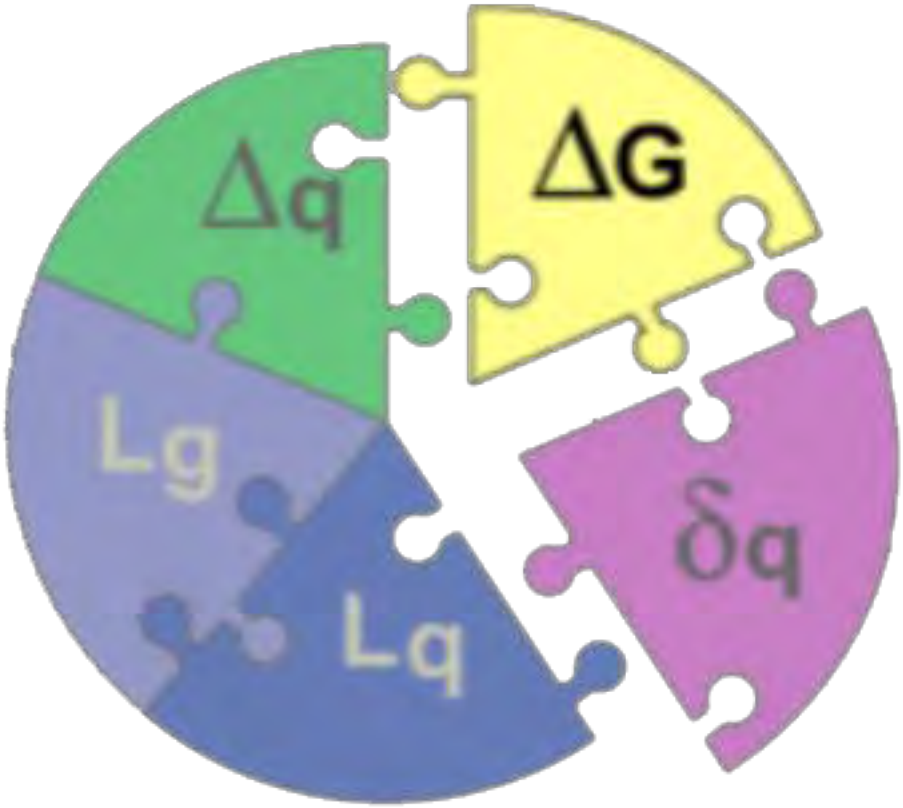


W production in *pp*

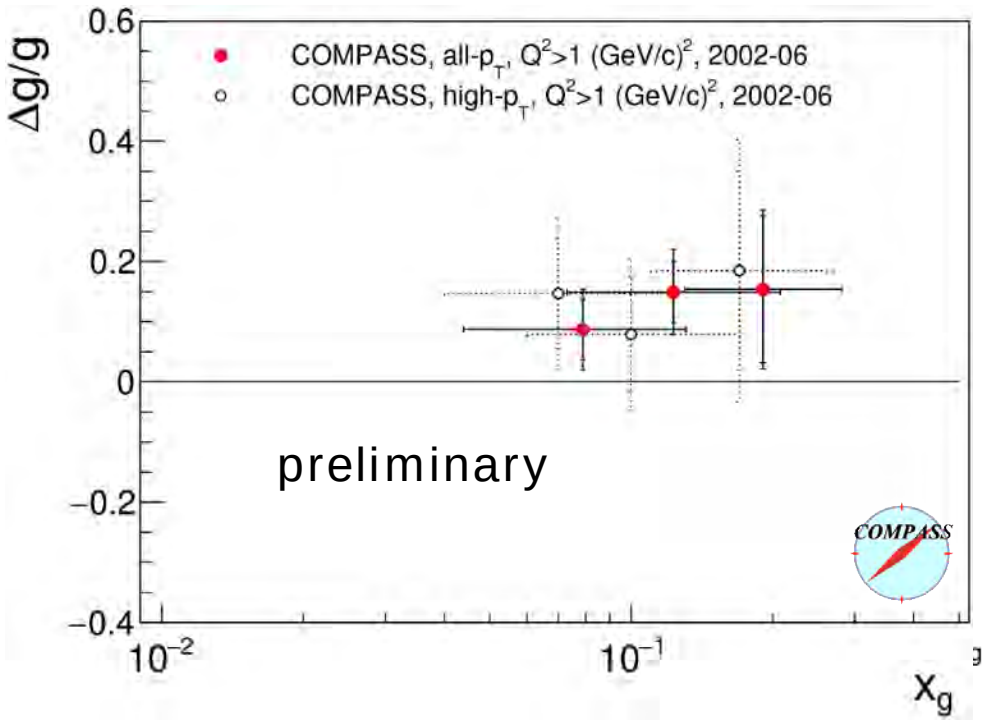
Ringer, Vogelsang: arXiv:1503.07052

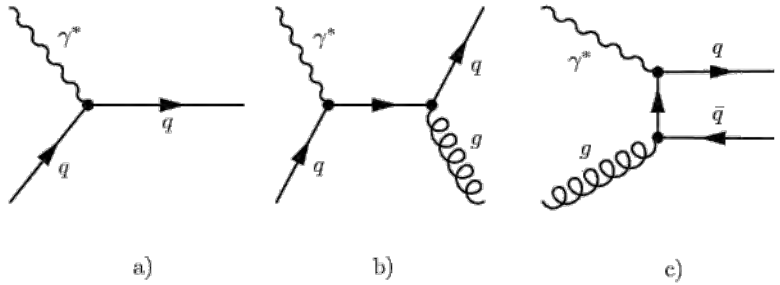


Gluon polarisation



$\Delta g/g$ from PGF (DIS, LO)





- $Q^2 > 1$ GeV^2

- $\Delta g(x)$ small, maybe positive around $x \cong 0.1$, caveat: LO
- no clear x dependence

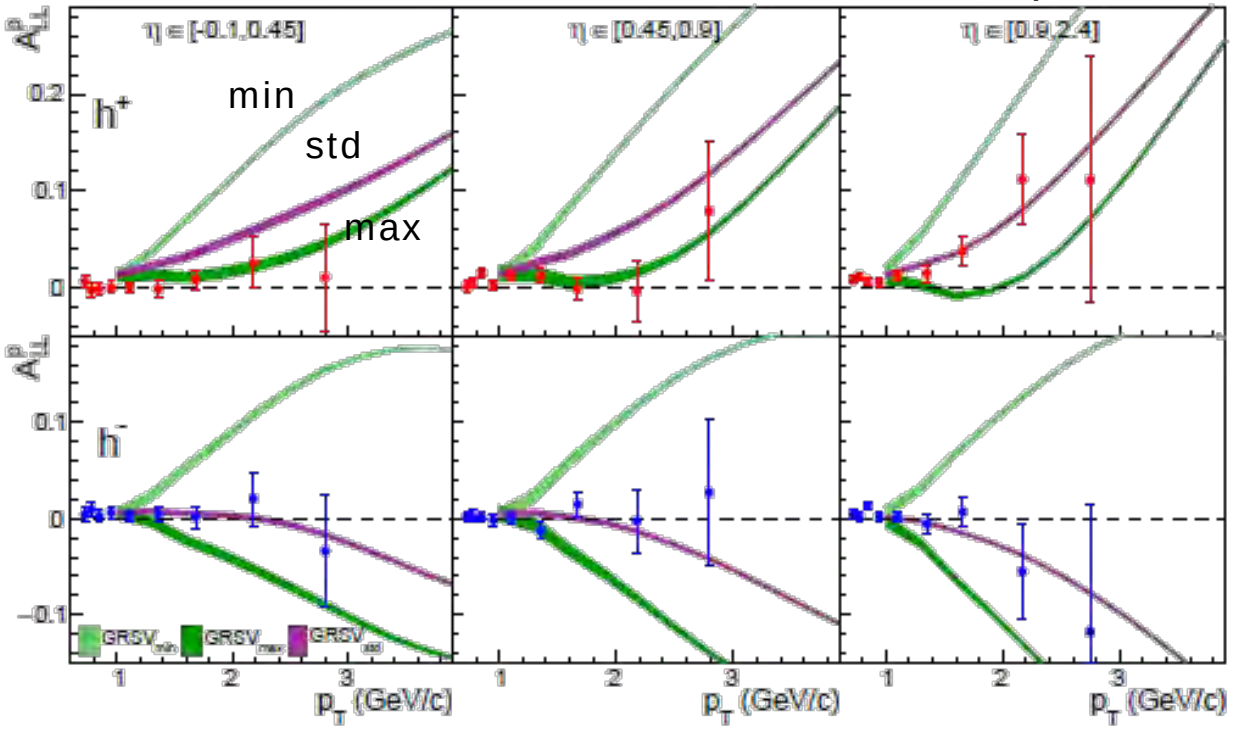
$\Delta g/g$ from single hadron (NLO)

- 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

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

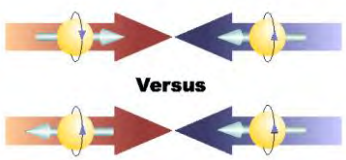
proton

- 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

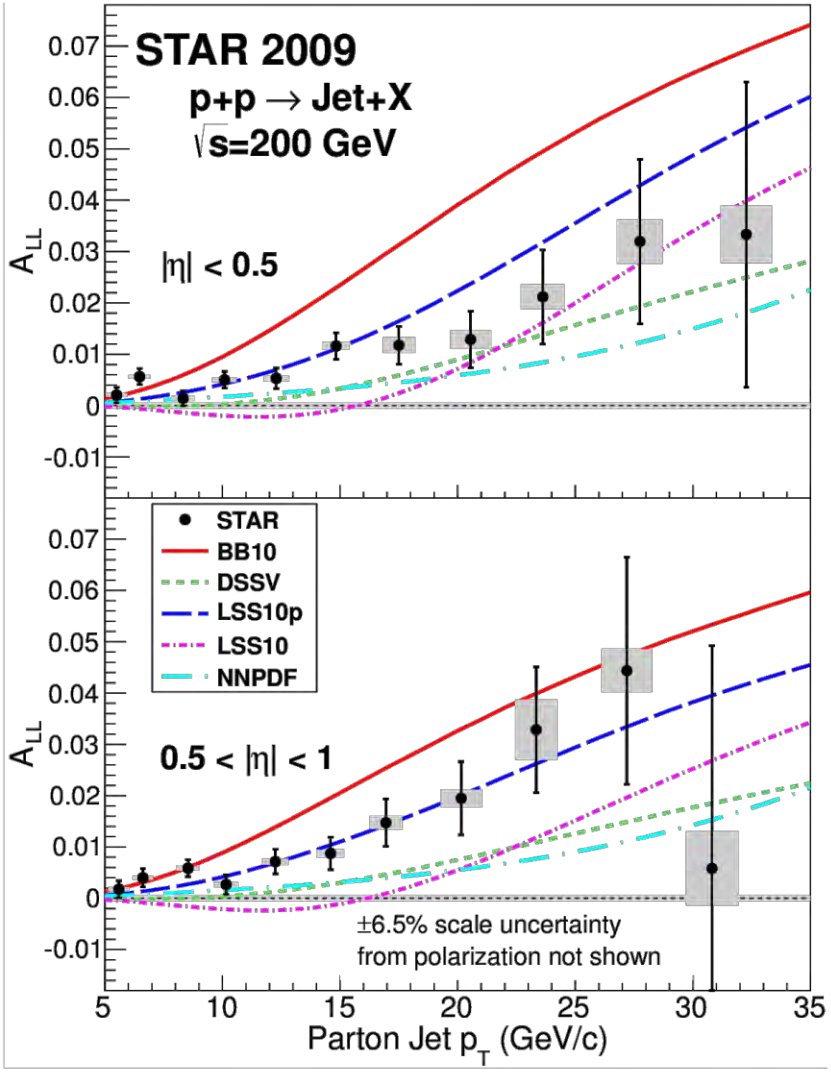


arXive:1509.03526

STAR single jet asymmetry A_{LL}

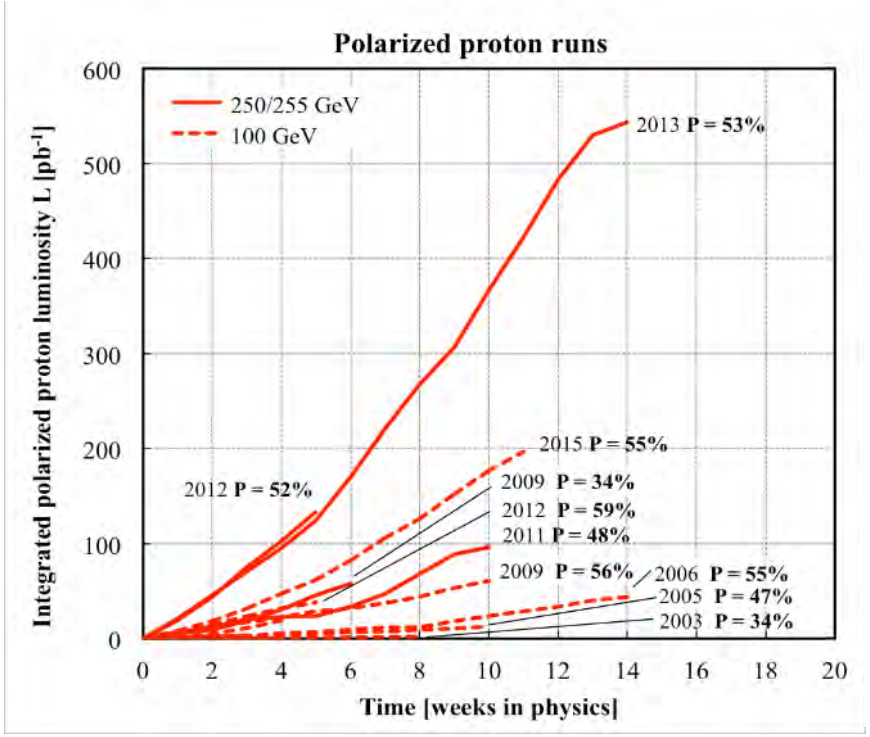


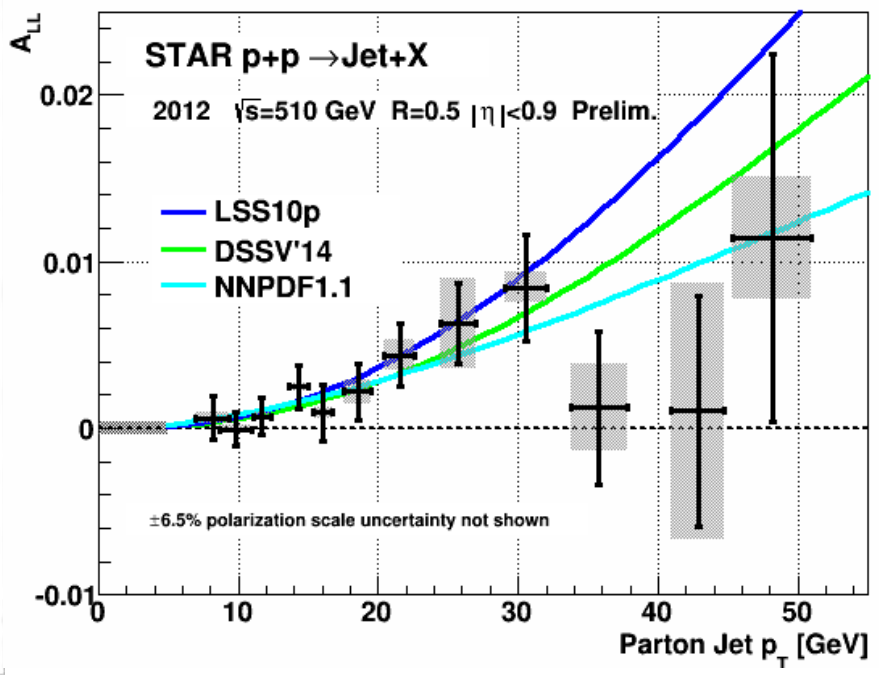
- $pp \rightarrow$ jet + X
- @ $\sqrt{s} = 200\,\mathrm{GeV}$
- 2009 data, mid rapidity
- $A_{LL} \propto \Delta g$
- A_{LL} in good agreement with LSSp (pos. Δg)



PRL 115 (2015) 092002

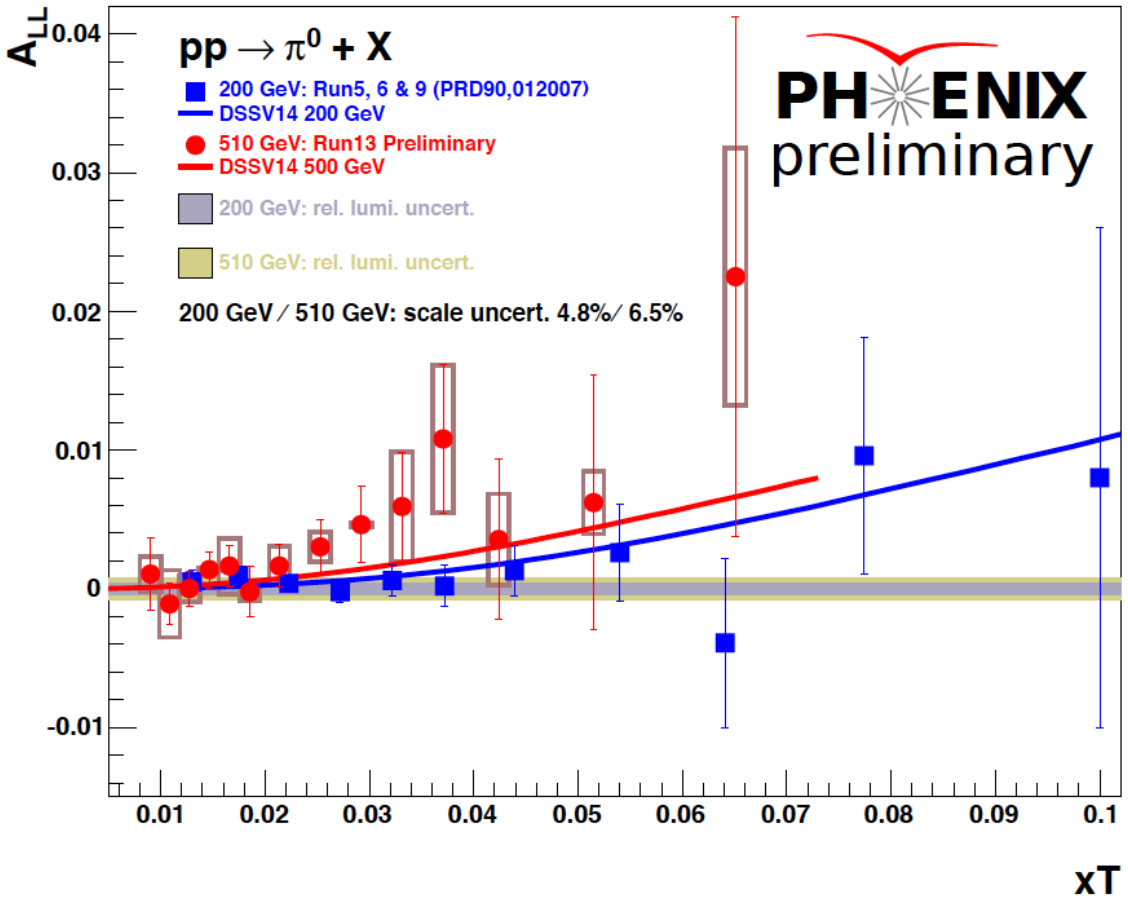
STAR single jet asymmetry A_{LL}





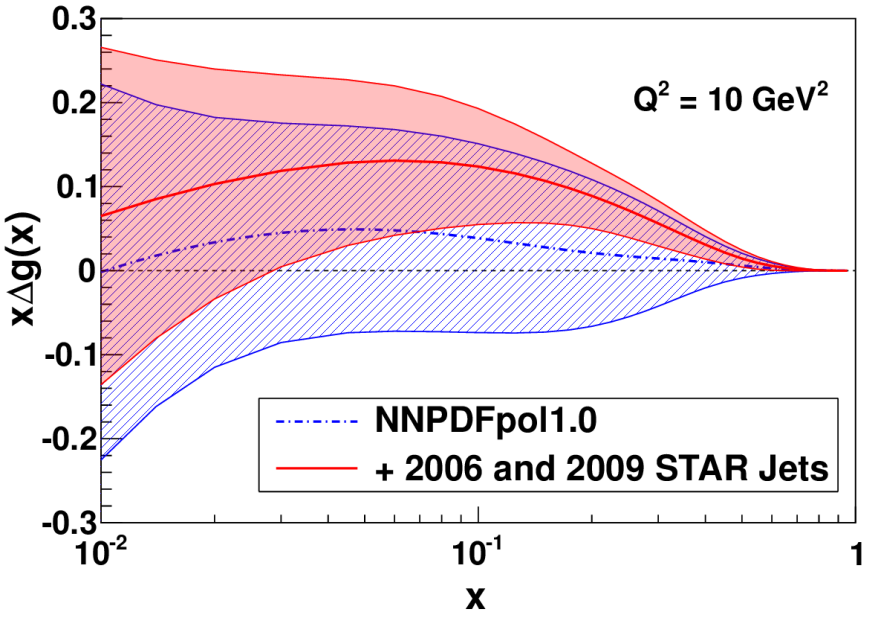
- prelim. 2012 data, $\sqrt{s} = 510\,\mathrm{GeV}$
- agree with 2009 data and LSS10p and DSSV14
- DSSV14 includes 2009 data

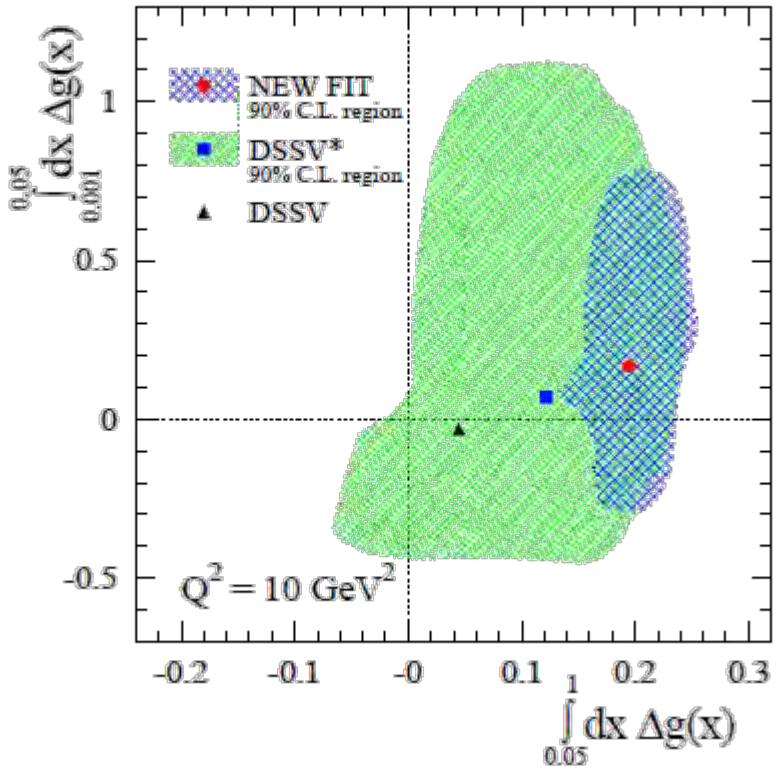
Inclusive neutral pion production



PRD 90 (2014) 012007

Impact of Star jet data

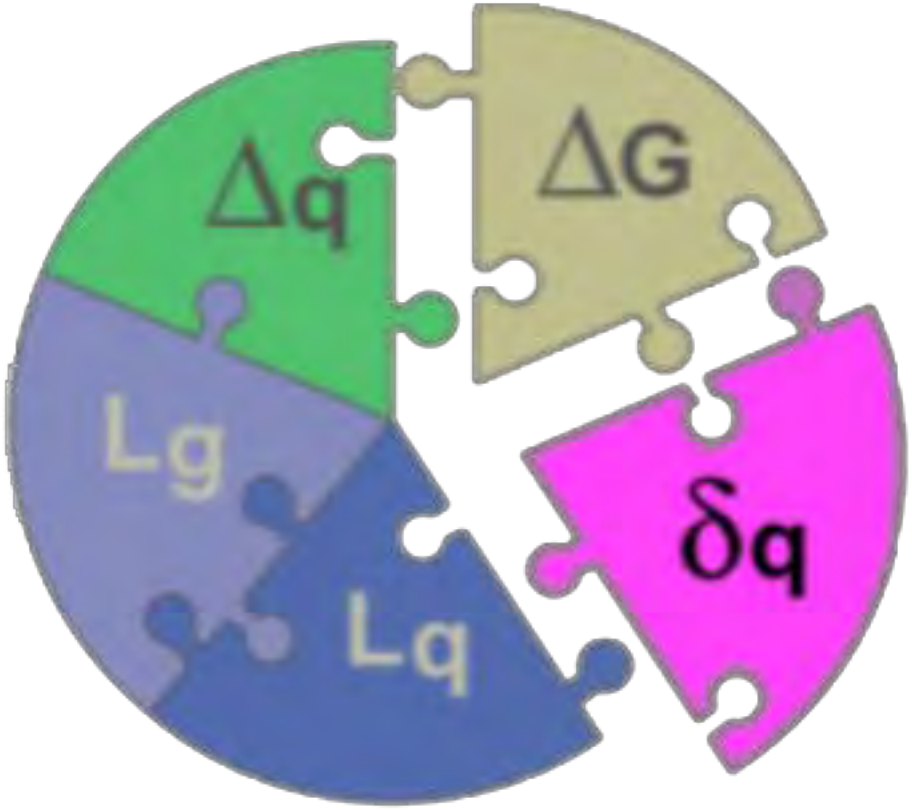




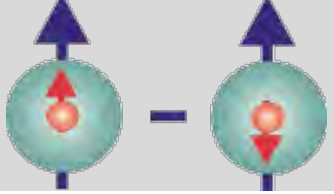
PRL 113 (2014) 012001

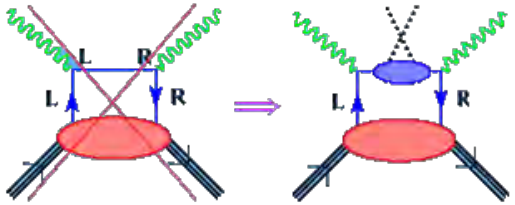
- big impact on pol. gluon distribution
- $\int_{0.05}^{1} \Delta g(x) \mathrm{d}x \simeq 0.20$
- need data at small *x*

Transversity



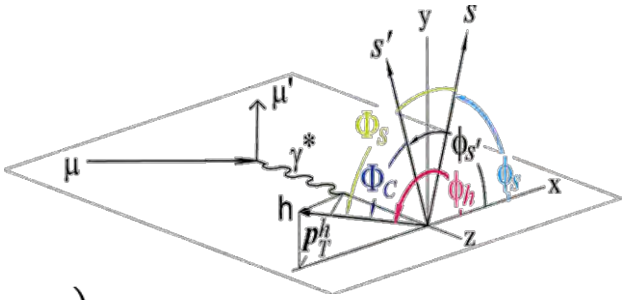
Transversity h_1





- 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)



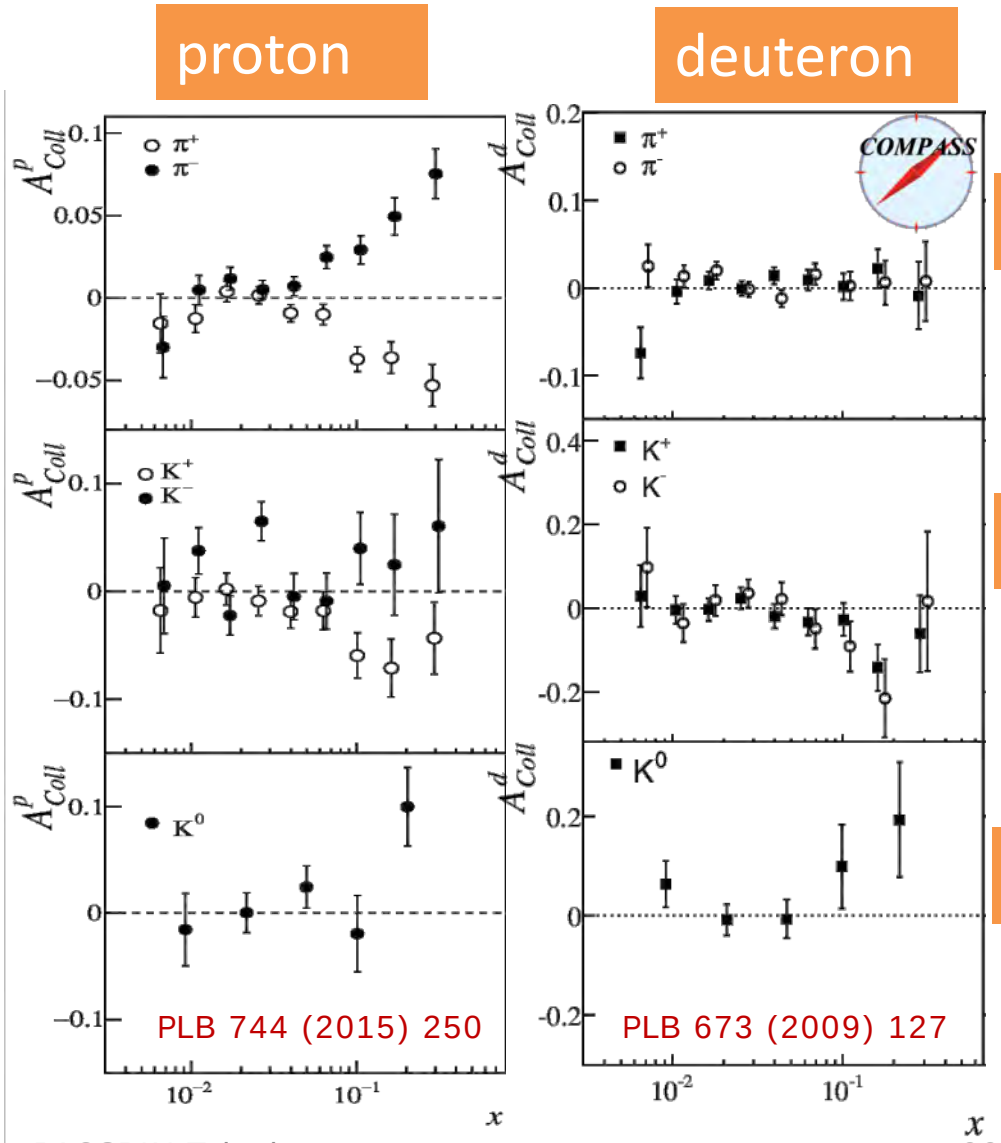
- amplitude

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

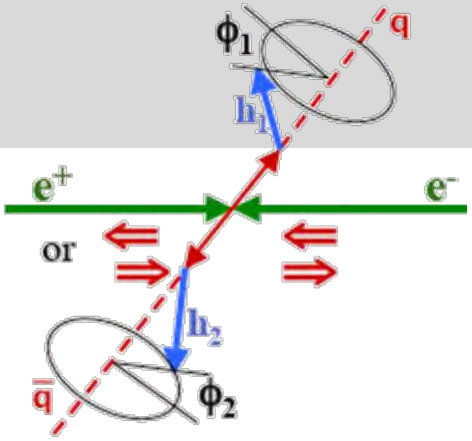
- Collins fragmentation function $H_1^{\perp}(z, p_T)$ from e^+e^-
- convolution ($\otimes$) over intrinsic transverse momentum k_T

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

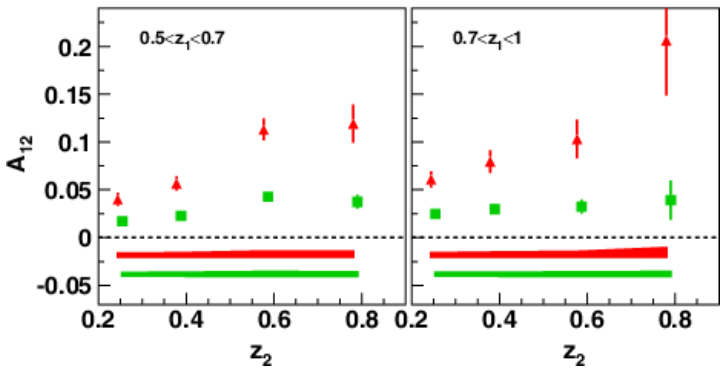


Collins FF from e^+e^-

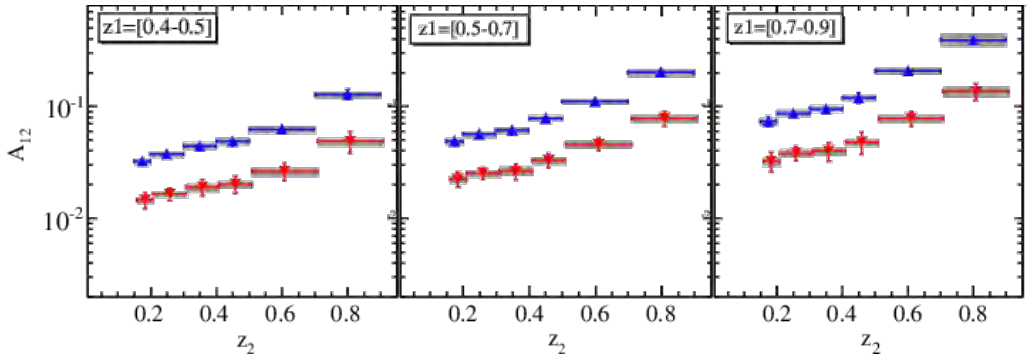


- $\propto H_1^\perp \otimes H_1^\perp$
- Belle, Barbar, BESIII

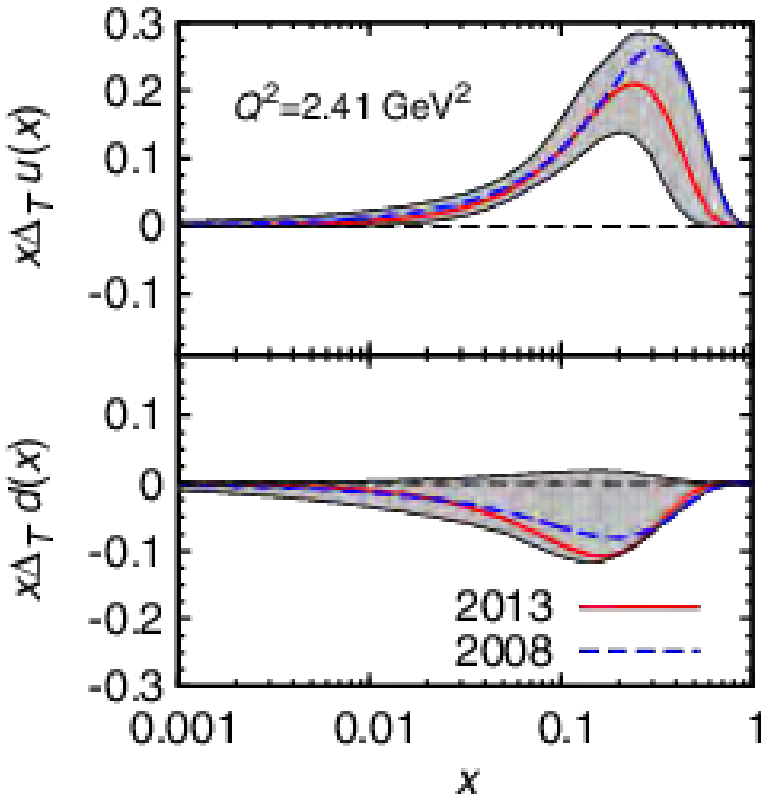
Belle: PRD 90 (2012) 052003
Babar: PRD 90 (2014) 052003
BESIII: arXiv:1507.06824



- clear signals



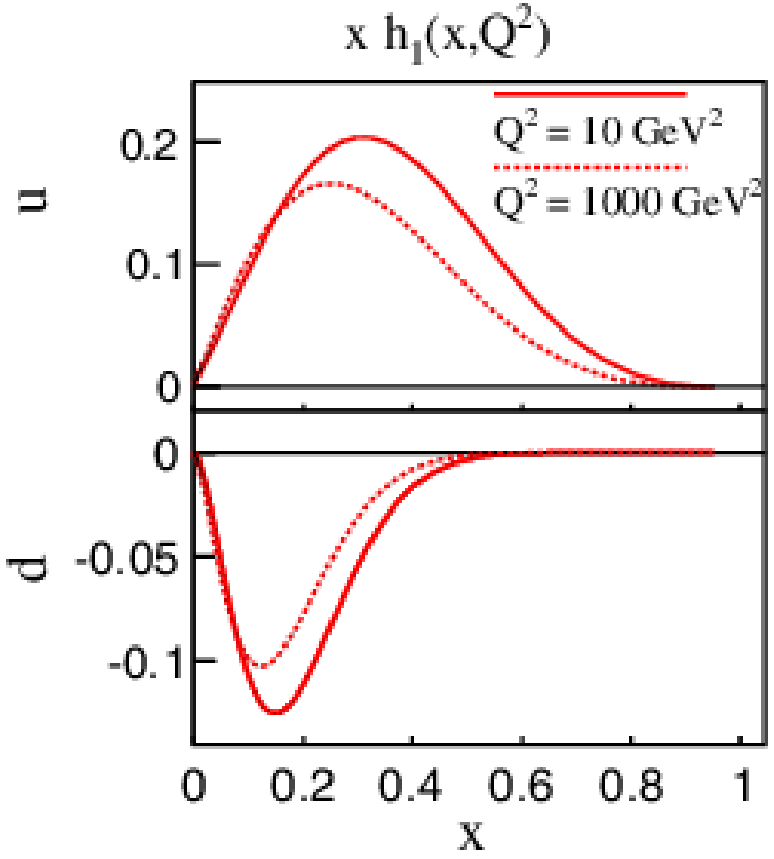
Determination of h_1 from SIDIS & e^+e^-



Anselmino et al.,
PRD 87 (2013) 094019

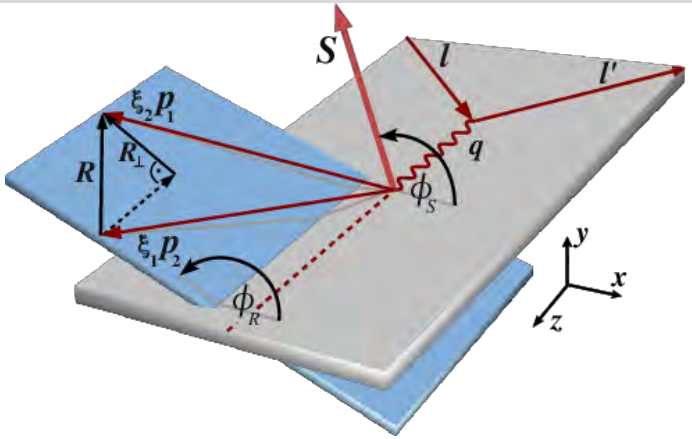
u

d



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

Transversity from dihadron asymmetries



- Transversity couples to IFF $H_1^{\sphericalangle}$
- leads to azimuthal modulation in the dihdron angle angle $\phi_{RS} = \phi_R + \phi_S - \pi$
- amplitude product of PDF and IFF, no convolution

$$A_{RS} \propto \frac{\sum_q e_q^2 h_1^q(x) H_1^{\sphericalangle}(z, M_h^2)}{\sum_q e_q^2 f_1^q(x) D^{h/q}(z, M_h^2)}$$

- IFF $H_1^{\sphericalangle}(z, M_h^2)$ from e^+e^- as for $H_1^{\perp}$

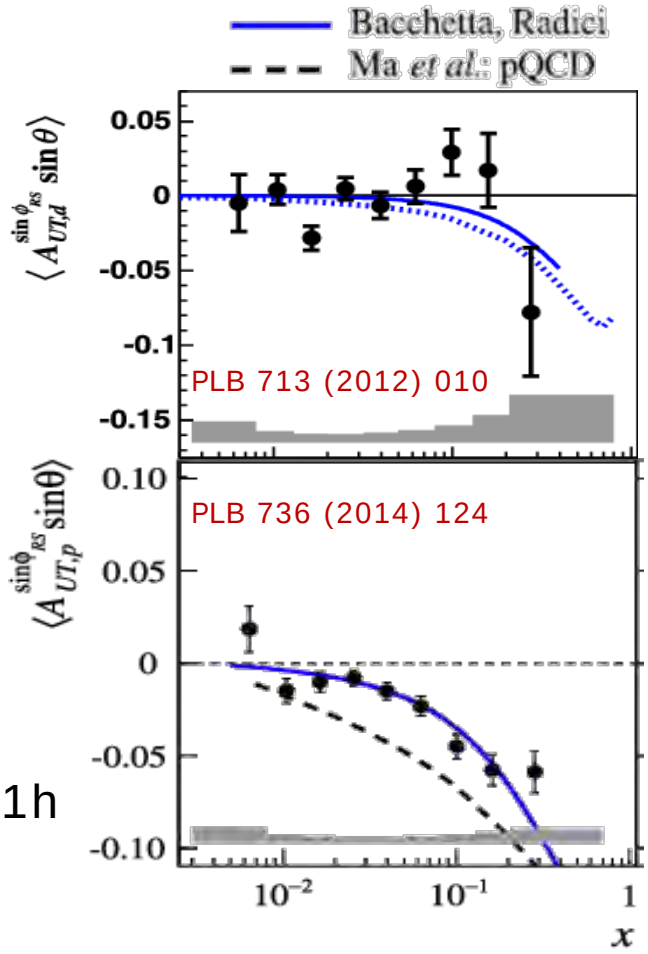
2h asymmetries

d

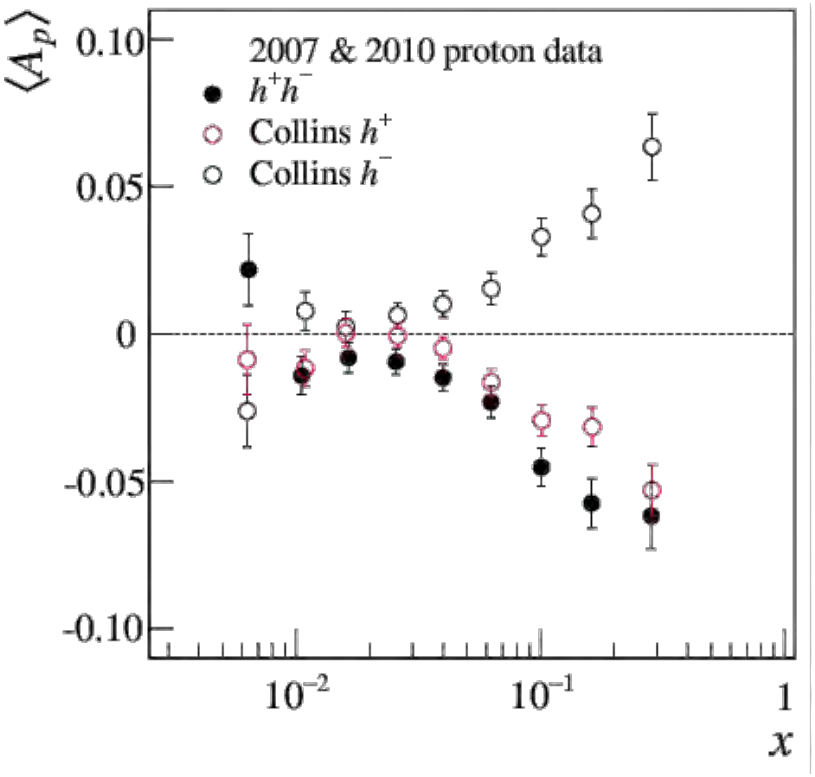
small

p

similar to 1h



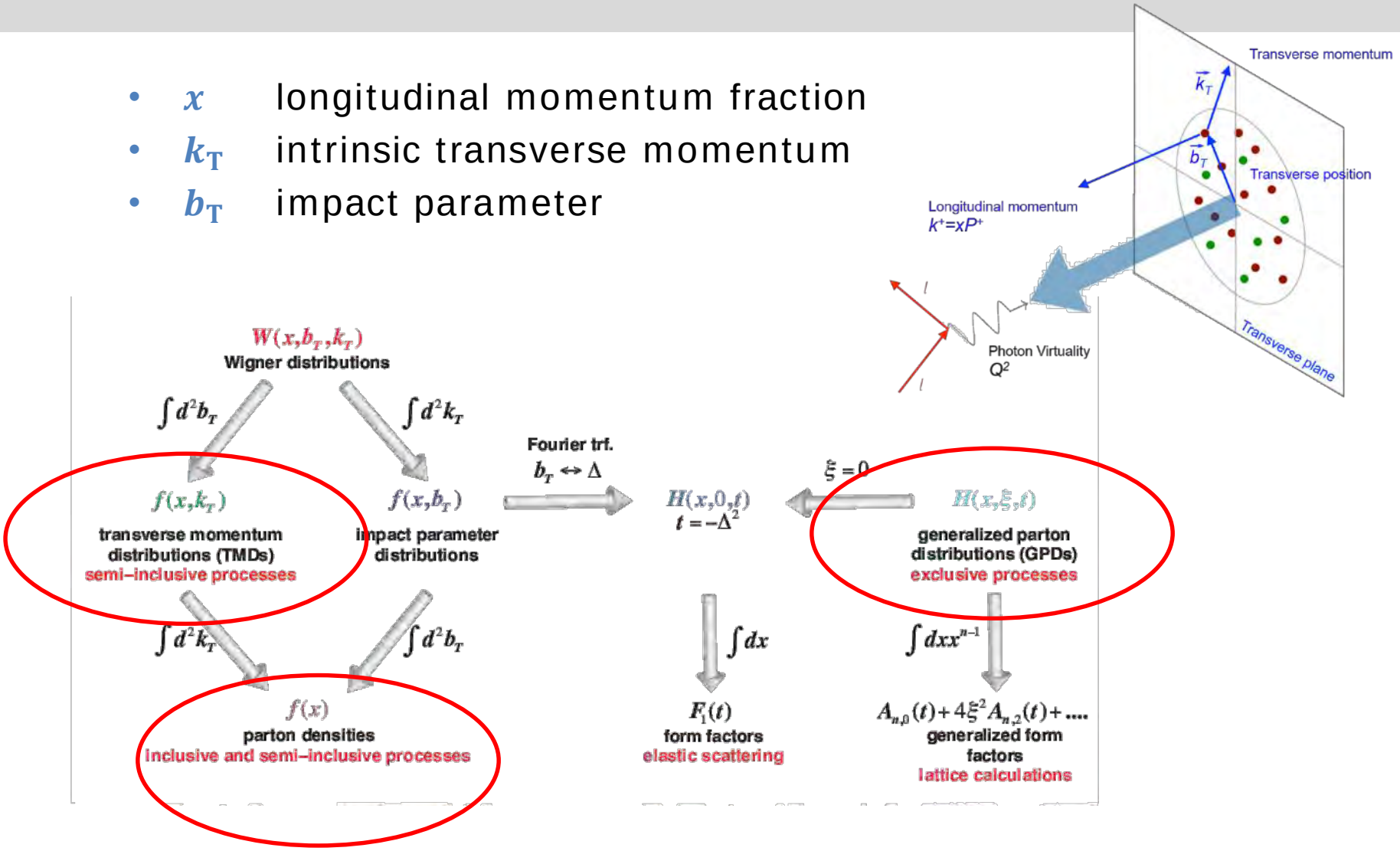
PLB 736 (2014) 124



- for a recent determ. of h_1 see e.g. Radici et al. JHEP 1505, 123
- common physics mechanism of 1h and 2h asym.?

Three dimensional structure of the nucleon

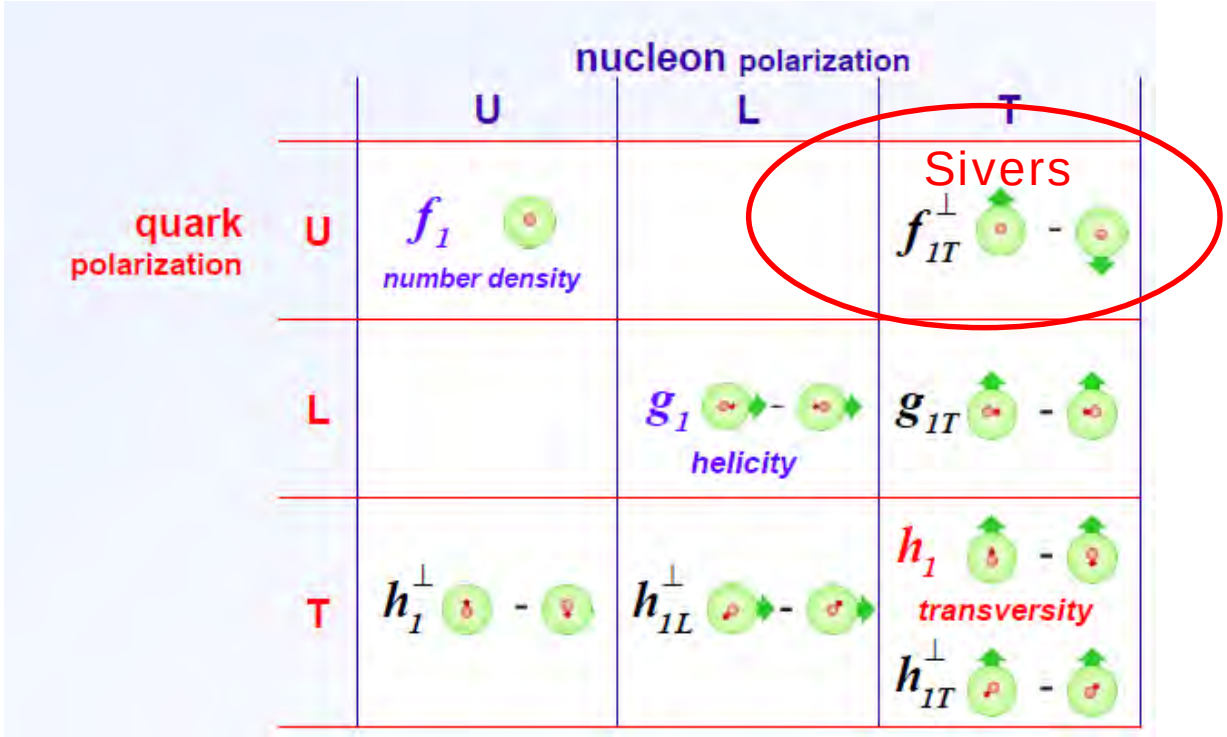
- x longitudinal momentum fraction
- k_T intrinsic transverse momentum
- b_T impact parameter



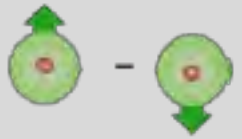
from EIC white paper arXiv:1212.1701

TMD parton distributions

- 8 k_T-integrated PDFs at twist-2
- 8 transverse momentum dependent PDFs at leading twist
- Azimuthal asymmetries with different angular modulations in Φ_h and Φ_s

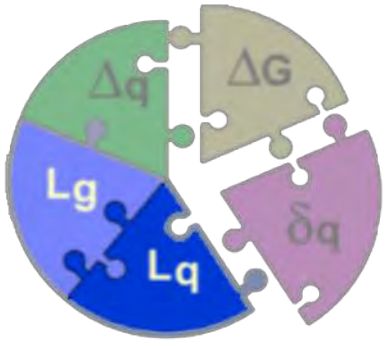


Sivers TMD

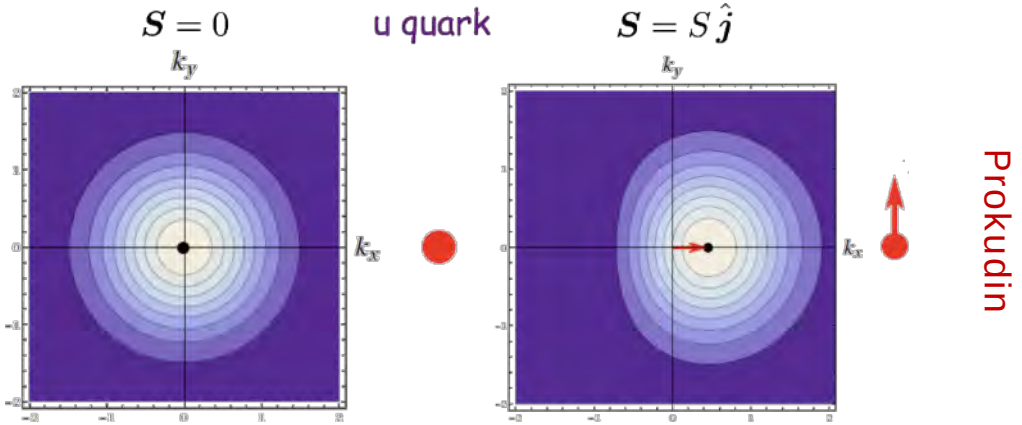


- azim. asym. in $\phi_{Siv} = \phi_h - \phi_S$

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

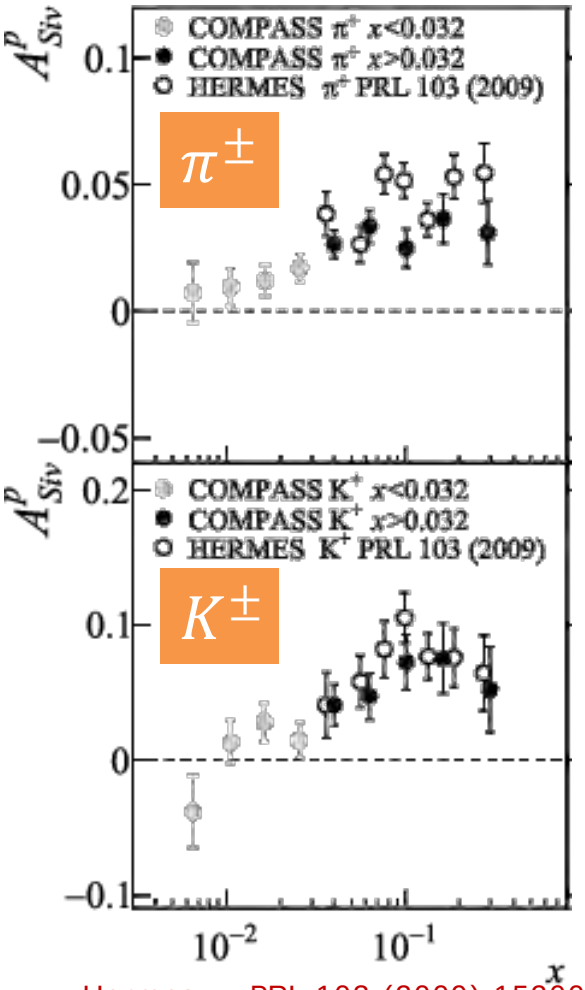


- if non-zero $\rightarrow$ orbital angular momentum
- induces distortions in the PDF of polarized nucleons



Sivers asymmetry

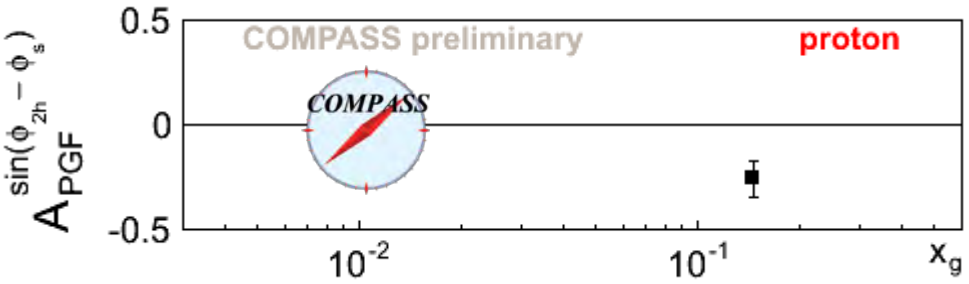
proton



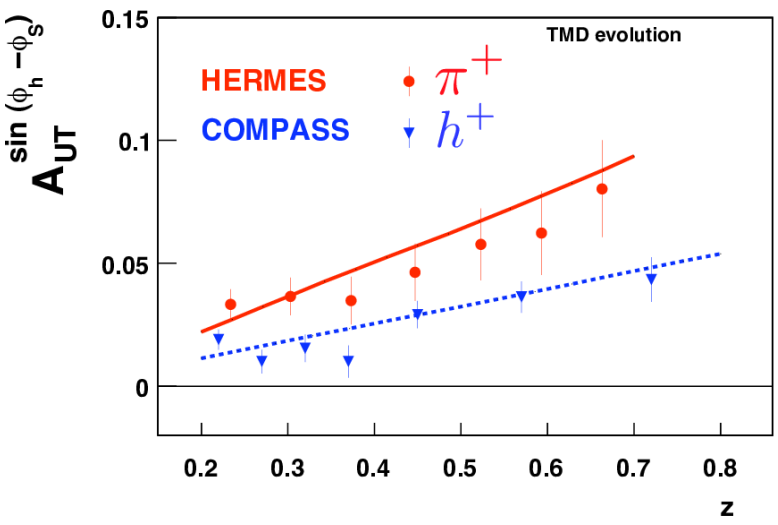
Hermes: PRL 103 (2009) 152002
COMPASS: PLB 744 (2015) 250

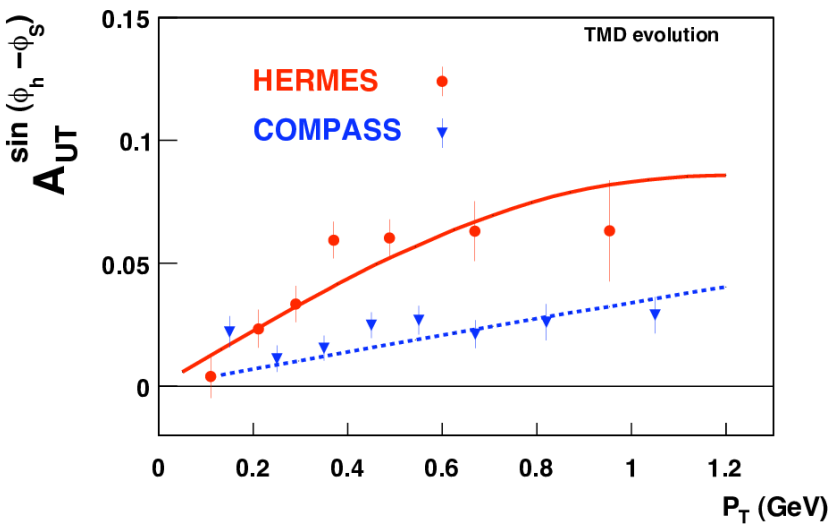
- sizable for proton
- Hermes vs Compass: some Q^2 evolution
- small for deuteron

- gluon: indication from 2h



TMD Q^2 evolution (Sivers proton)

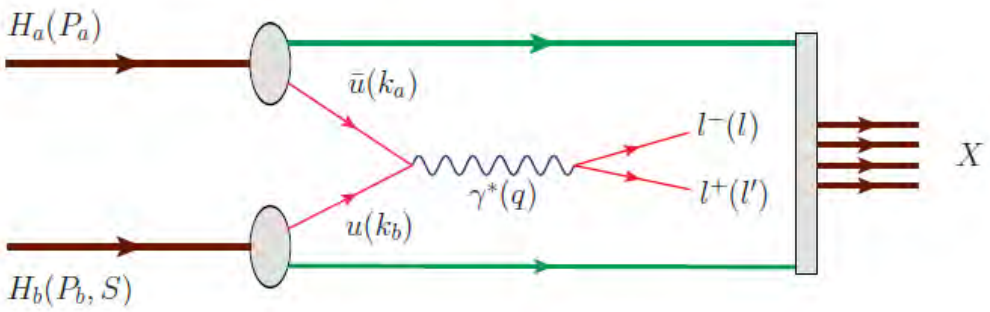




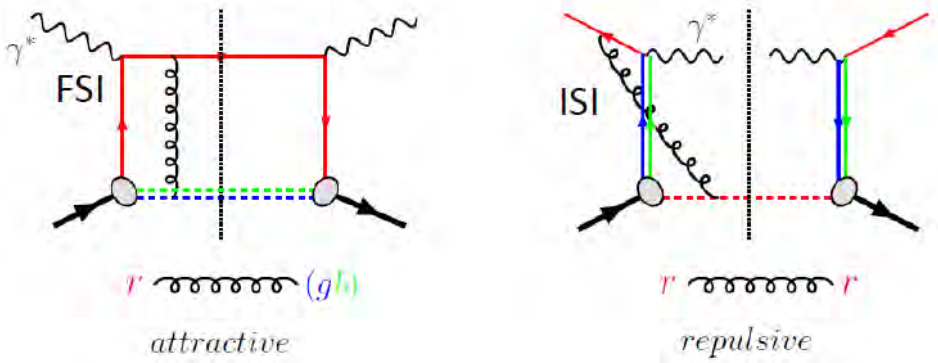
Aybat, Prokudin, Rogers, PRL 108 (2012) 242003

- Torino fit to Hermes data at $\langle Q^2 \rangle = 2.4$ GeV^2 evolved to $\langle Q^2 \rangle = 3.8$ GeV^2 of the Compass 2010 data
- Quite rapid decrease of asymmetry with Q^2

Restricted universality in SIDIS and pol. DY



T-odd TMD



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

J.C. Collins, PLB536 (2002) 43

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

Sivers

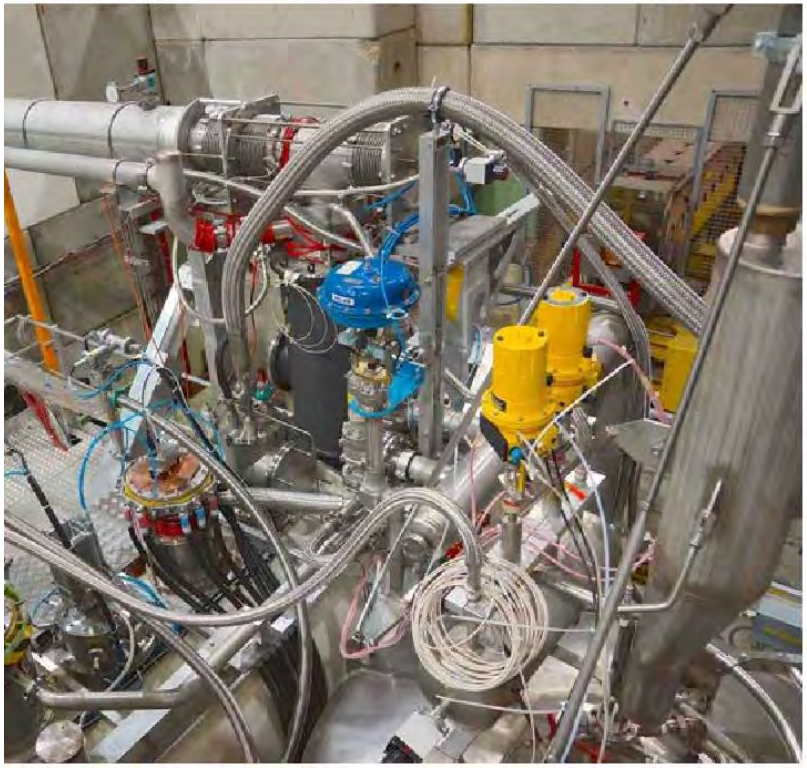
$$h_1^{\perp}\Big|_{\text{DY}} = - h_1^{\perp}\Big|_{\text{DIS}}$$

Boer-Mulders

- important prediction, needs to be verified

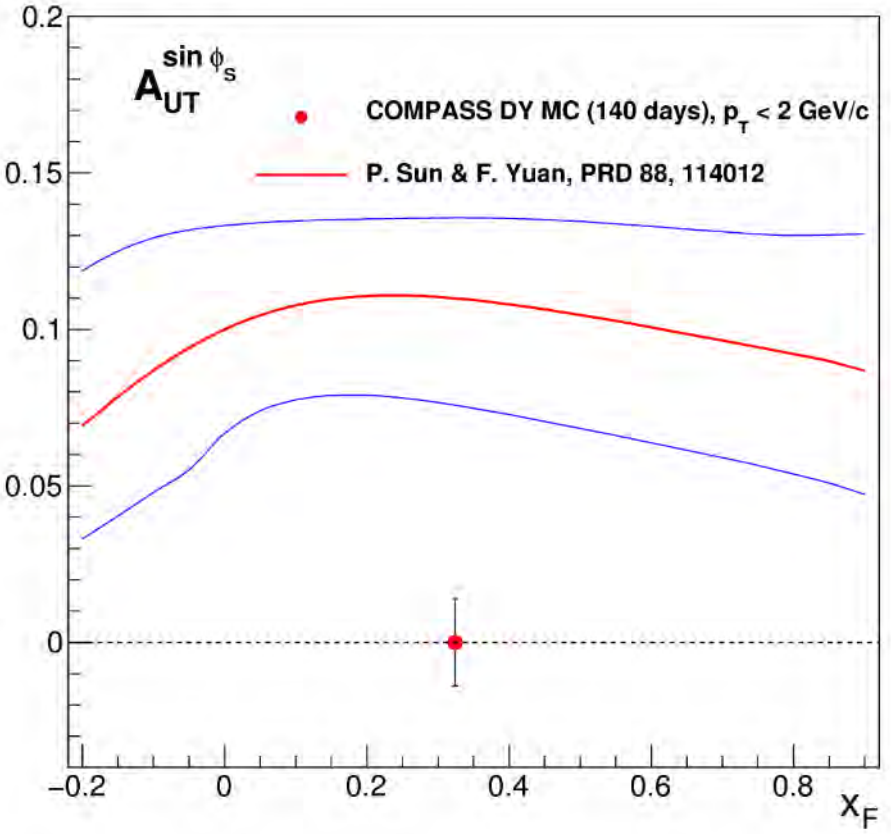
COMPASS polarized DY

- running now!



- Fermilab, RHIC, …

Predictions vary strongly, e.g.

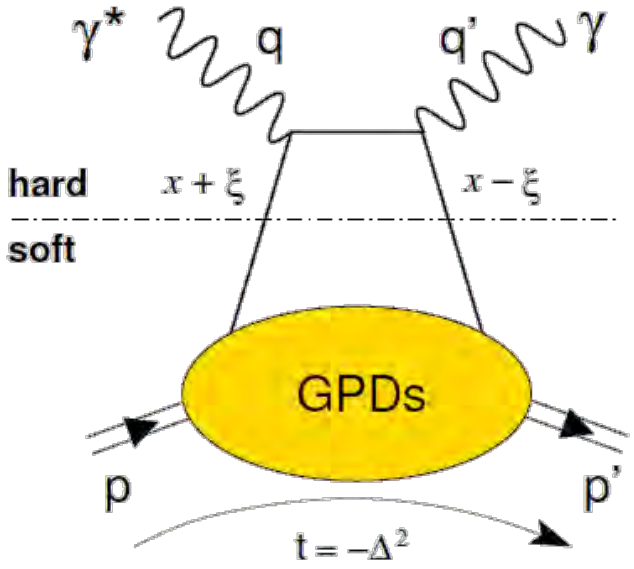


$x_F = x_\pi - x_p$

Generalized PDF's

- Correlating transverse spatial and longitudinal momentum degrees of freedom
- PDFs and elastic FF as limiting cases
- $H, \tilde{H} \to f_1, g_1$ for $\xi \to 0$;
- no such limiting cases for E, $\tilde{E}$
- *H (E)* for nucleon helicity (non)conservation

DVCS



$H(x, \xi, t, Q^2)$; Q^2 large, t small

H^f, E^f, $\tilde{H}^f$, $\tilde{E}^f$ with $f = q, g$

Ji's sum rule for total orbital momentum:

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

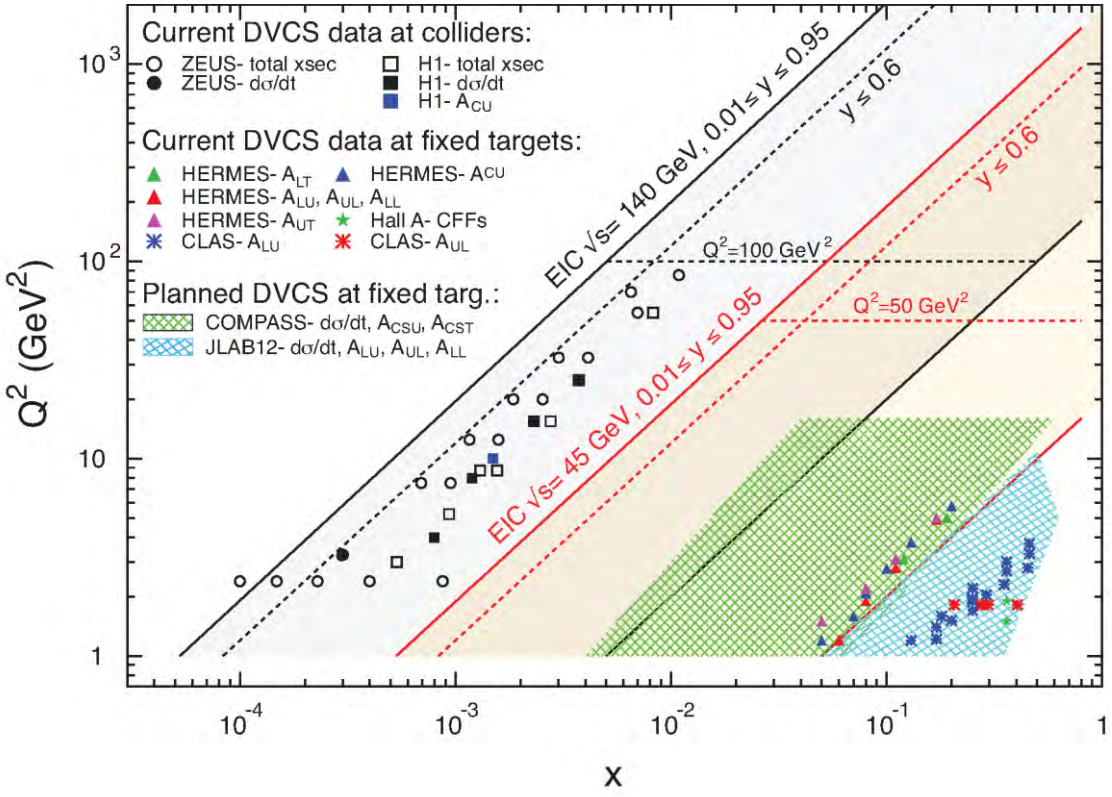
X.-D. Ji, PRL 78 (1997) 610

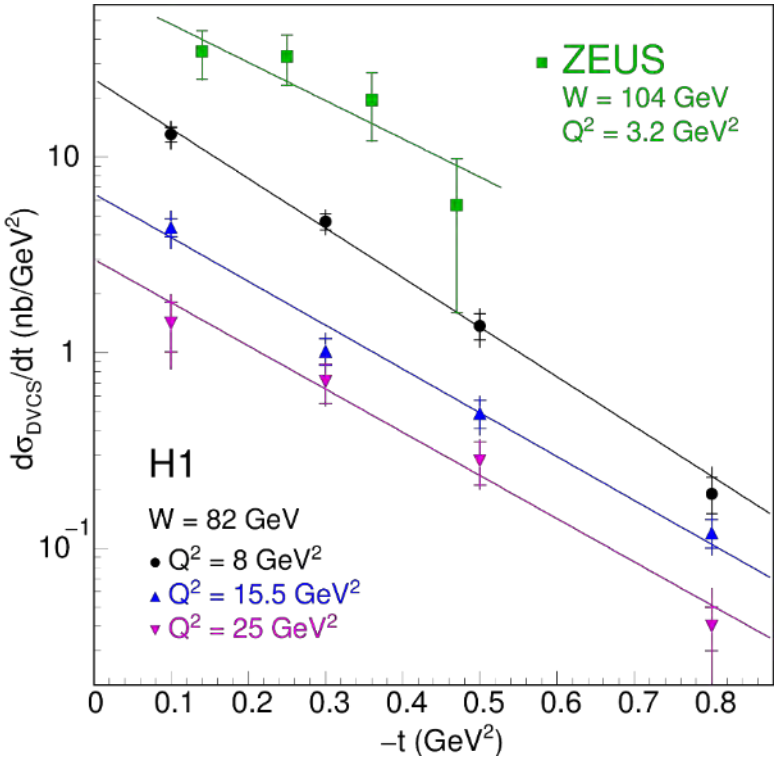
Generalized PDF's

- cannot be measured directly and not everywhere
- need global fits to many diff. measurements
- measure small excl. cross sections, much more difficult than incl./semi-incl.
- DVCS
  - cleanest interpretation
  - interference Bethe-Heitler
- HEMP (vect. & ps.scalar)
  - additional information on flavour and glue

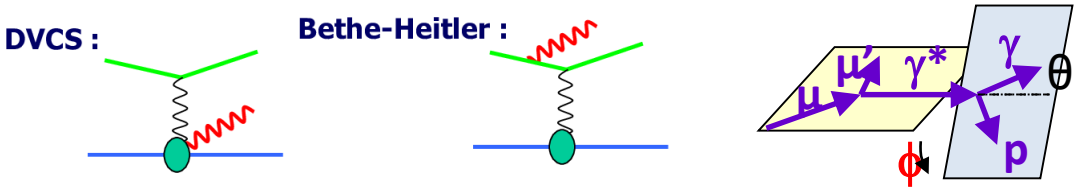
$$
\begin{aligned}
H_{\rho^0} &= \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u + \frac{1}{3}H^d + \frac{3}{8}H^g\right) \\
H_{\omega} &= \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u - \frac{1}{3}H^d + \frac{1}{8}H^g\right) \\
H_{\phi} &= -\frac{1}{3}H^s - \frac{1}{8}H^g
\end{aligned}
$$

DVCS: experimental kinematic ranges





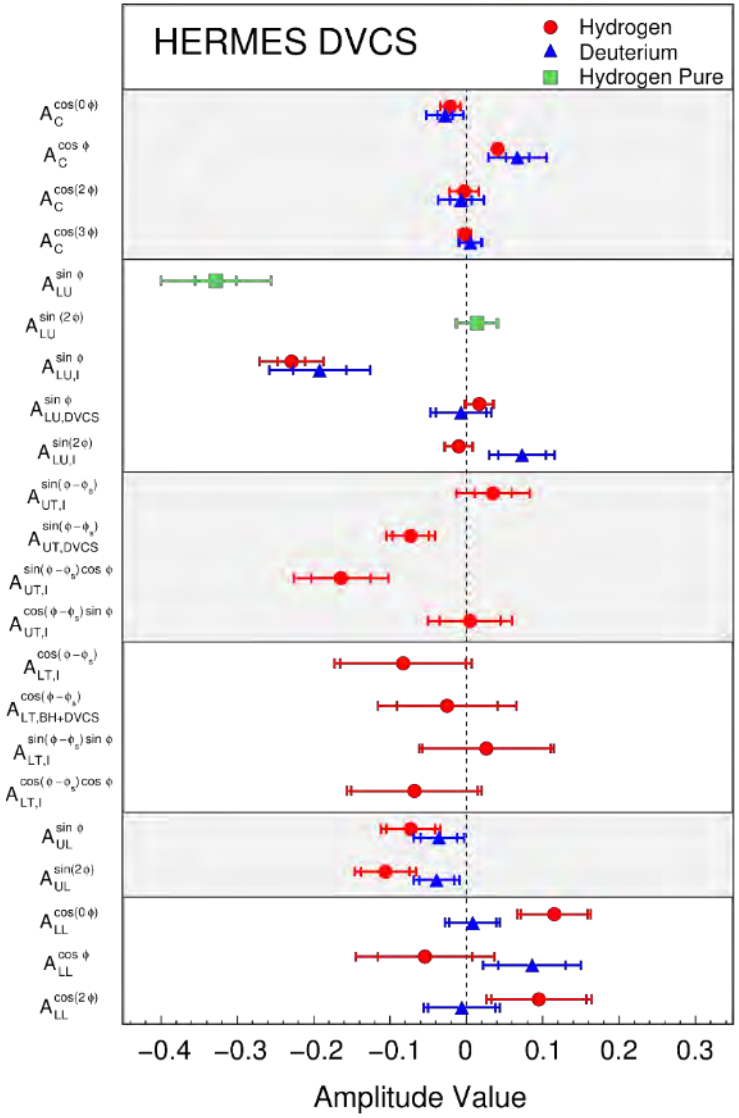
Deeply virtual Compton scattering



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

BH interference DVCS

$$
\begin{aligned}
d\sigma(\ell p \to \ell\gamma p) \sim\ & d\sigma_{UU}^{BH} + e_\ell\, d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} \\
& + P_\ell S_L\, d\sigma_{LL}^{BH} + e_\ell P_\ell S_L\, d\sigma_{LL}^{I} + P_\ell S_L\, d\sigma_{LL}^{DVCS} \\
& + P_\ell S_T\, d\sigma_{LT}^{BH} + e_\ell P_\ell S_T\, d\sigma_{LT}^{I} + P_\ell S_T\, d\sigma_{LT}^{DVCS} \\
& + e_\ell P_\ell\, d\sigma_{LU}^{I} + P_\ell\, d\sigma_{LU}^{DVCS} \\
& + e_\ell S_L\, d\sigma_{UL}^{I} + S_L\, d\sigma_{UL}^{DVCS} \\
& + e_\ell S_T\, d\sigma_{UT}^{I} + S_T\, d\sigma_{UT}^{DVCS}
\end{aligned}
$$

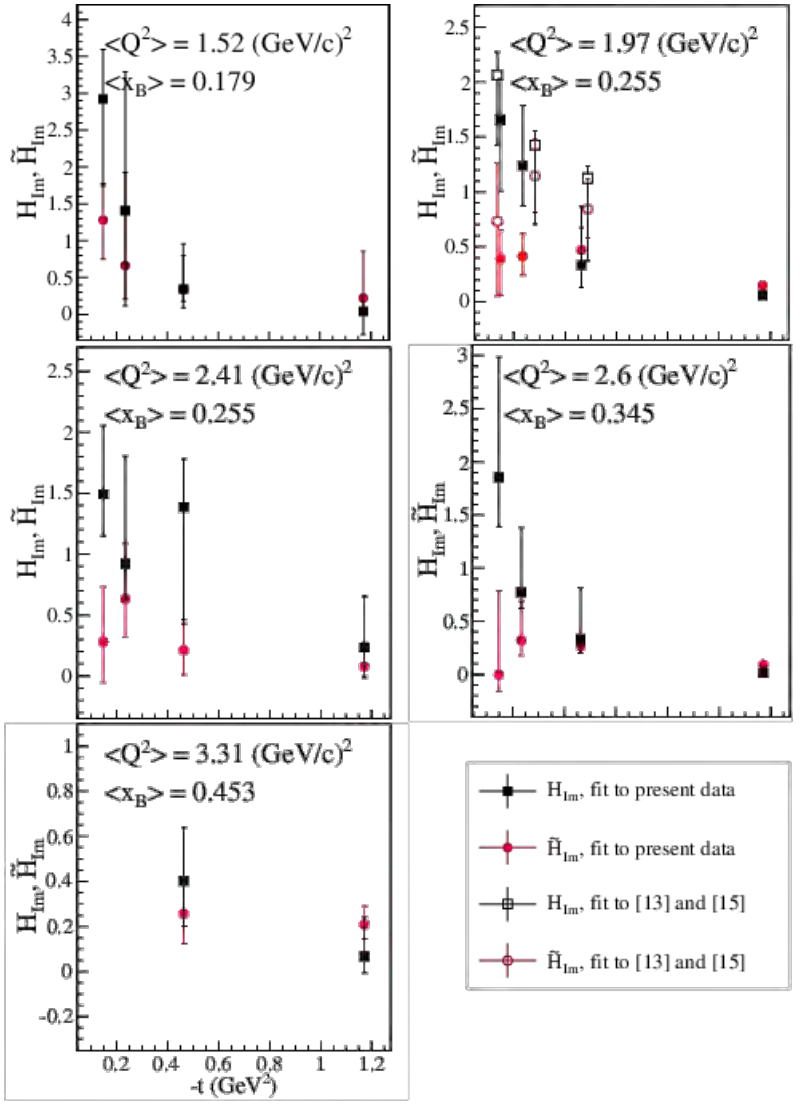


DVCS @ CLAS

- 2015 CLAS NH_3 proton data
- 164 four-dimensional bins in Q^2, x_B, $-t$, ϕ
- TSA, BSA, DSA
- determine the imaginary part of CFF H_{Im} and $\widetilde{H}_{Im}$ of GPDs $\mathcal{H}$ and $\widetilde{\mathcal{H}}$
- most sensitive to $\widetilde{H}_{Im}$

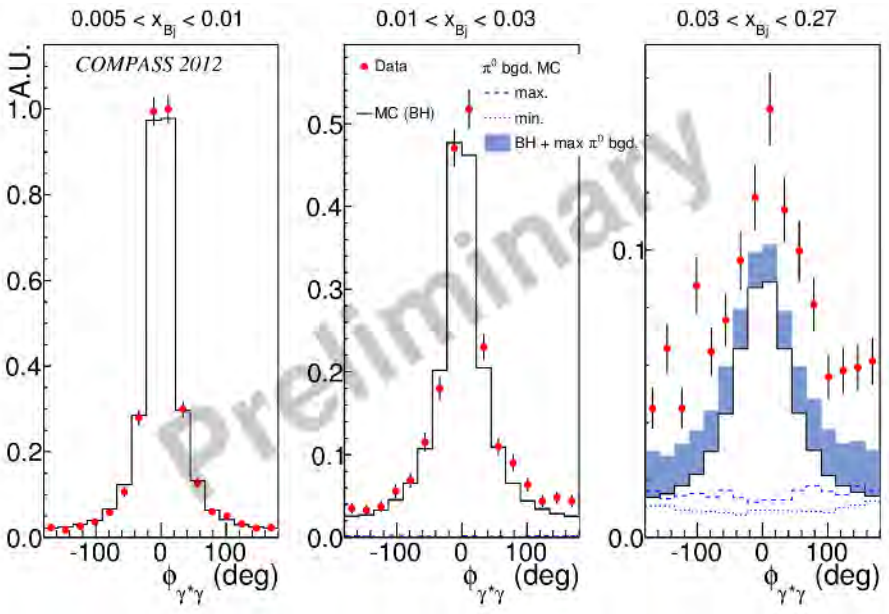
$$F_{Im}(\xi,t) = -\frac{1}{\pi}\Im\mathrm{m}\mathcal{F}(\xi,t) = [F(\xi,\xi,t) \mp F(-\xi,\xi,t)]$$

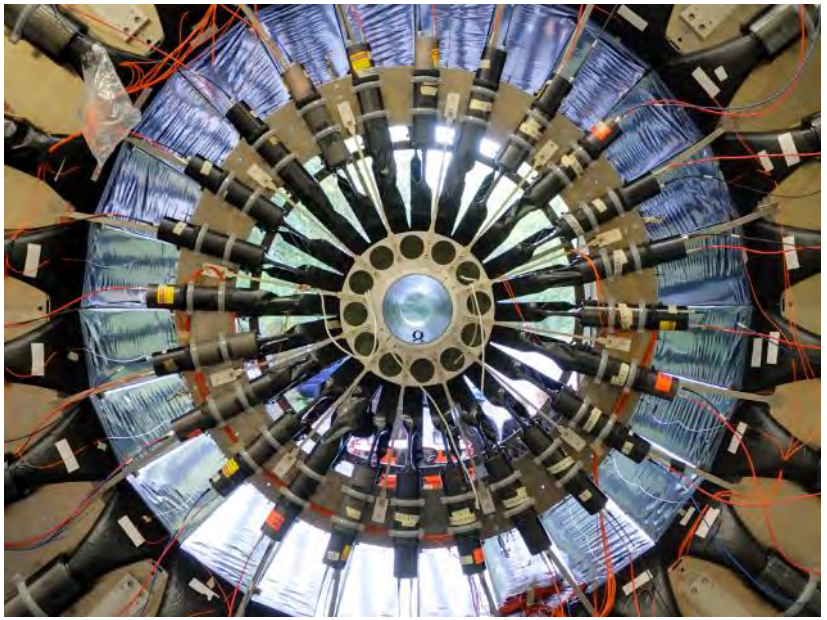
CLAS: PRD 91 (2015) 052014



COMPASS GPD, SIDIS

- GPD data 2016–2017
- liquid hydrogen target
- 160 GeV muon beam
- CAMERA recoil detecor



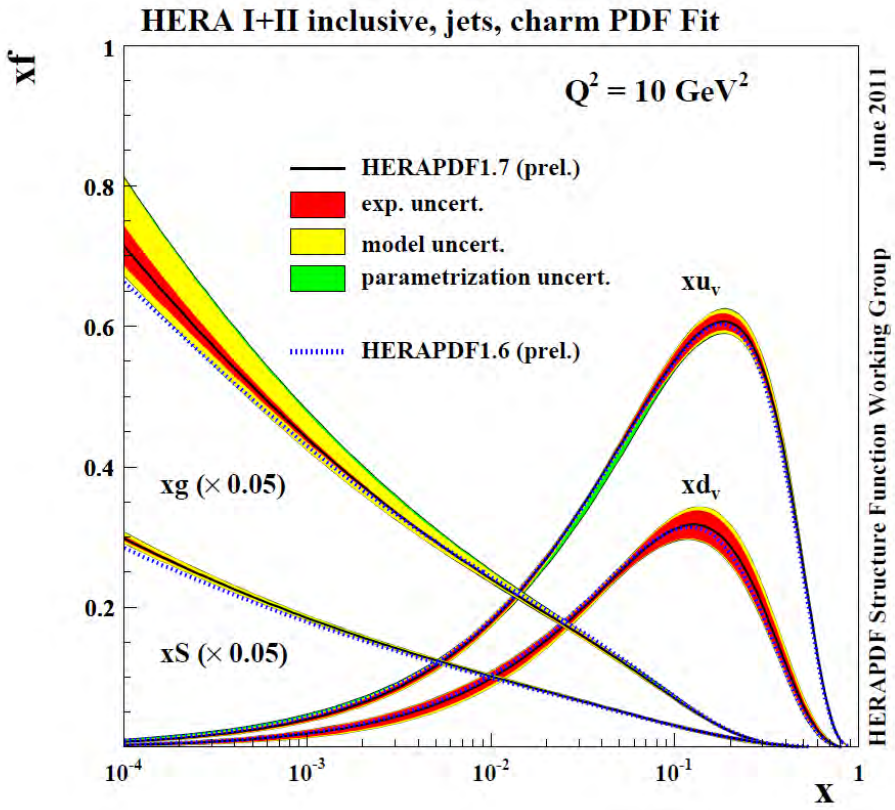


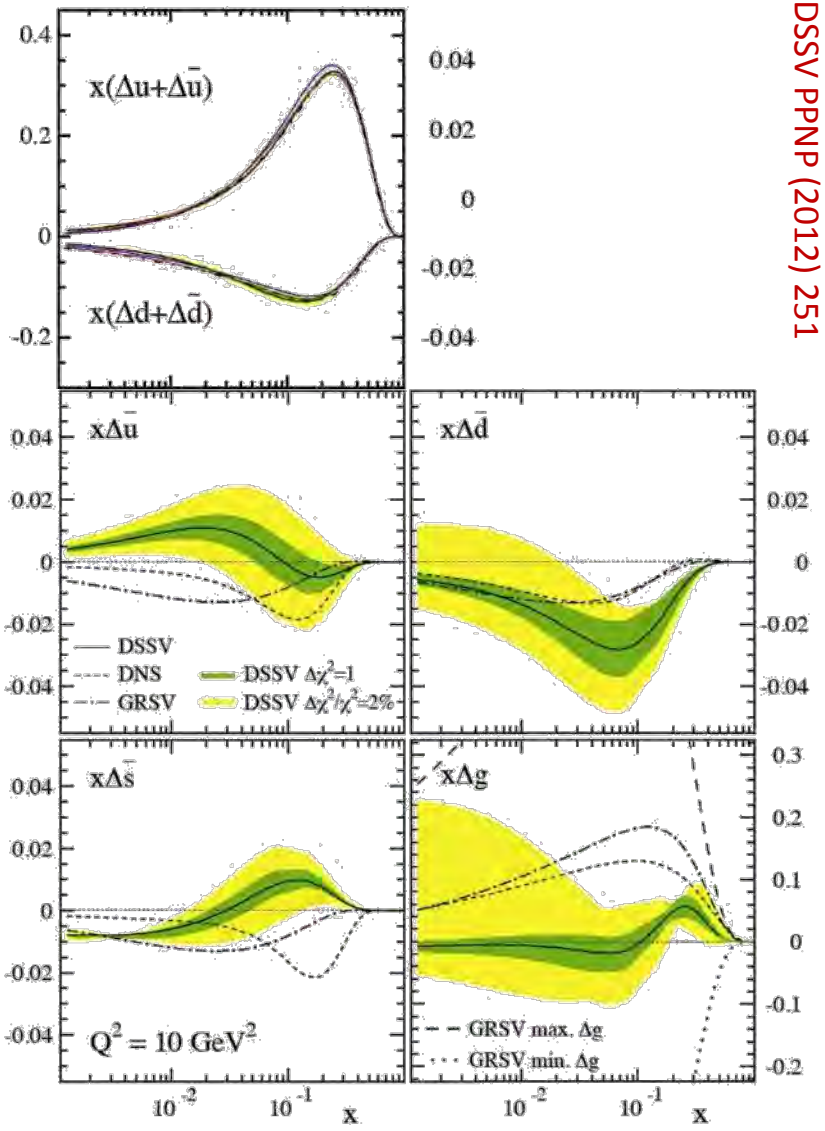
Outlook

- 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
- TMD show: there is orbital angular momentum
- measure the sign change of T-odd TMDs in DY!
- new data coming up JLab 6/12, COMPASS, JPARC and eventually EIC

Status of PDFs: global analyses (DSSV)

unpolarised





DSSV PPNP (2012) 251

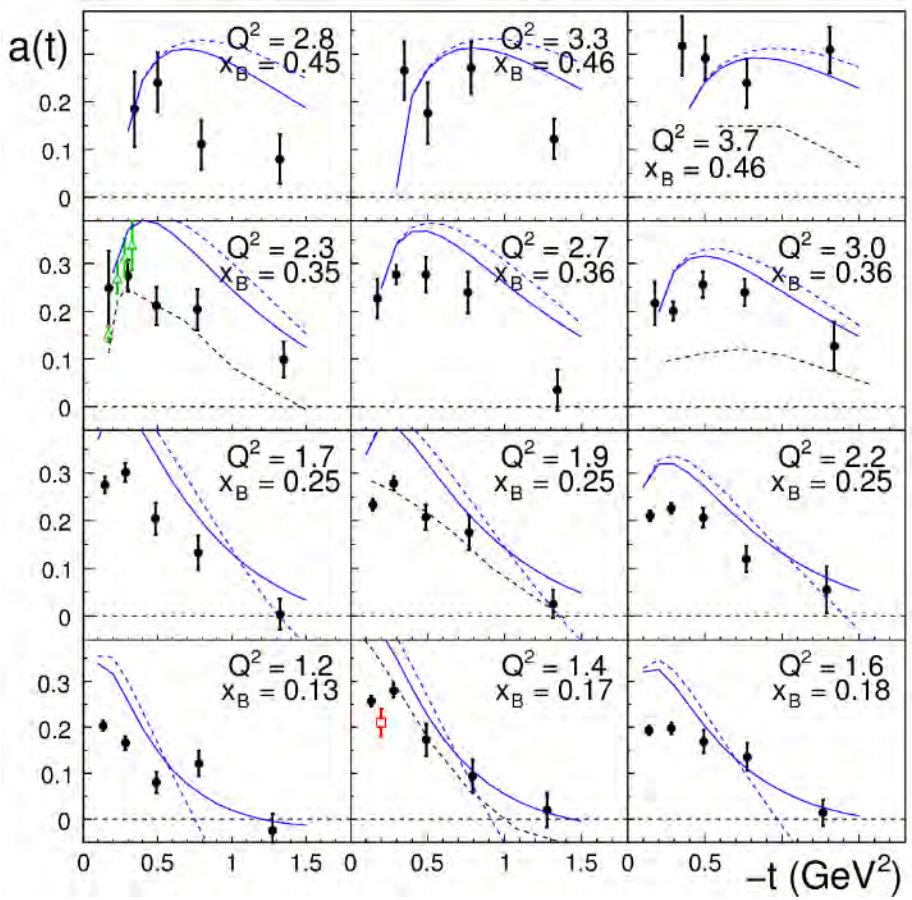
Deeply virtual Compton scattering

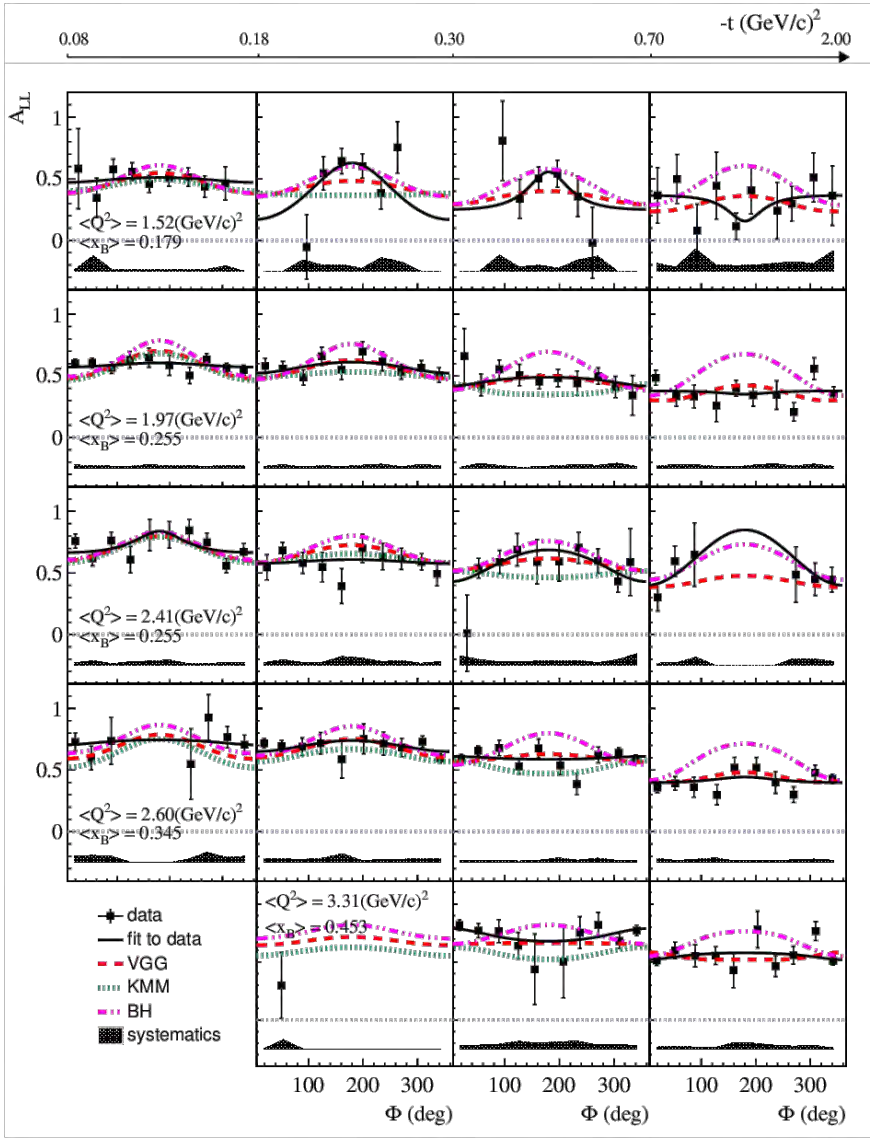
- leading lepton-spin asym. amplitude $A_{\mathrm{LU}}^{\sin\phi}$ differential in t, x, Q^2

CLAS

Jefferson Lab

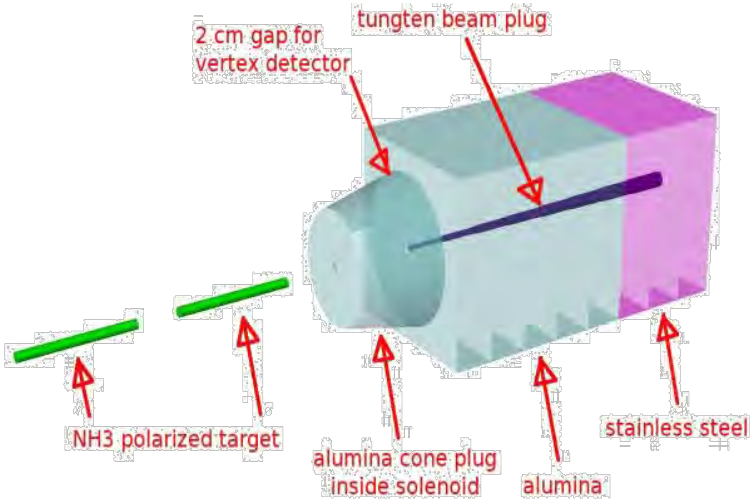
PRL 100 (2008) 162002

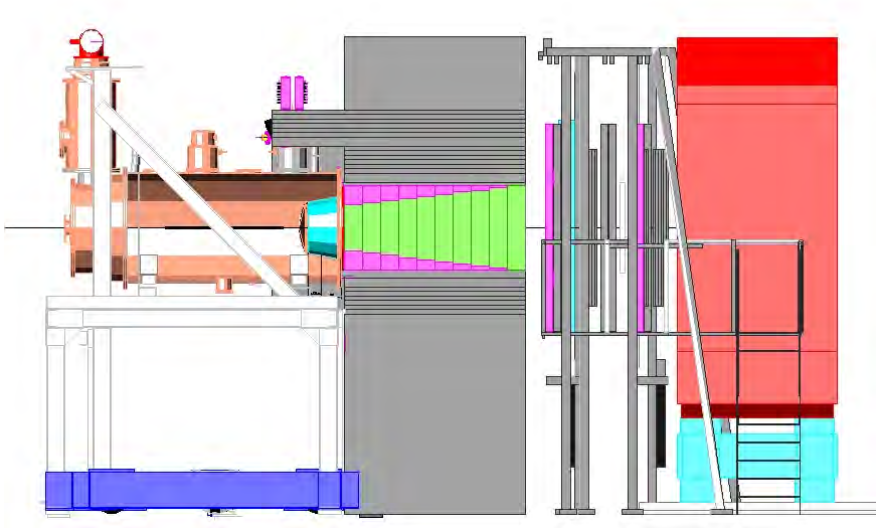



-t (GeV/c)^2
0.08
0.18
0.30
0.70
2.00
A_{LL}
$\langle Q^2 \rangle = 1.52(GeV/c)^2$
$\langle x_B \rangle = 0.179$
$\langle Q^2 \rangle = 1.97(GeV/c)^2$
$\langle x_B \rangle = 0.255$
$\langle Q^2 \rangle = 2.41(GeV/c)^2$
$\langle x_B \rangle = 0.255$
$\langle Q^2 \rangle = 2.60(GeV/c)^2$
$\langle x_B \rangle = 0.345$
$\langle Q^2 \rangle = 3.31(GeV/c)^2$
$\langle x_B \rangle = 0.453$
data
fit to data
VGG
KMM
BH
systematics
Φ (deg)

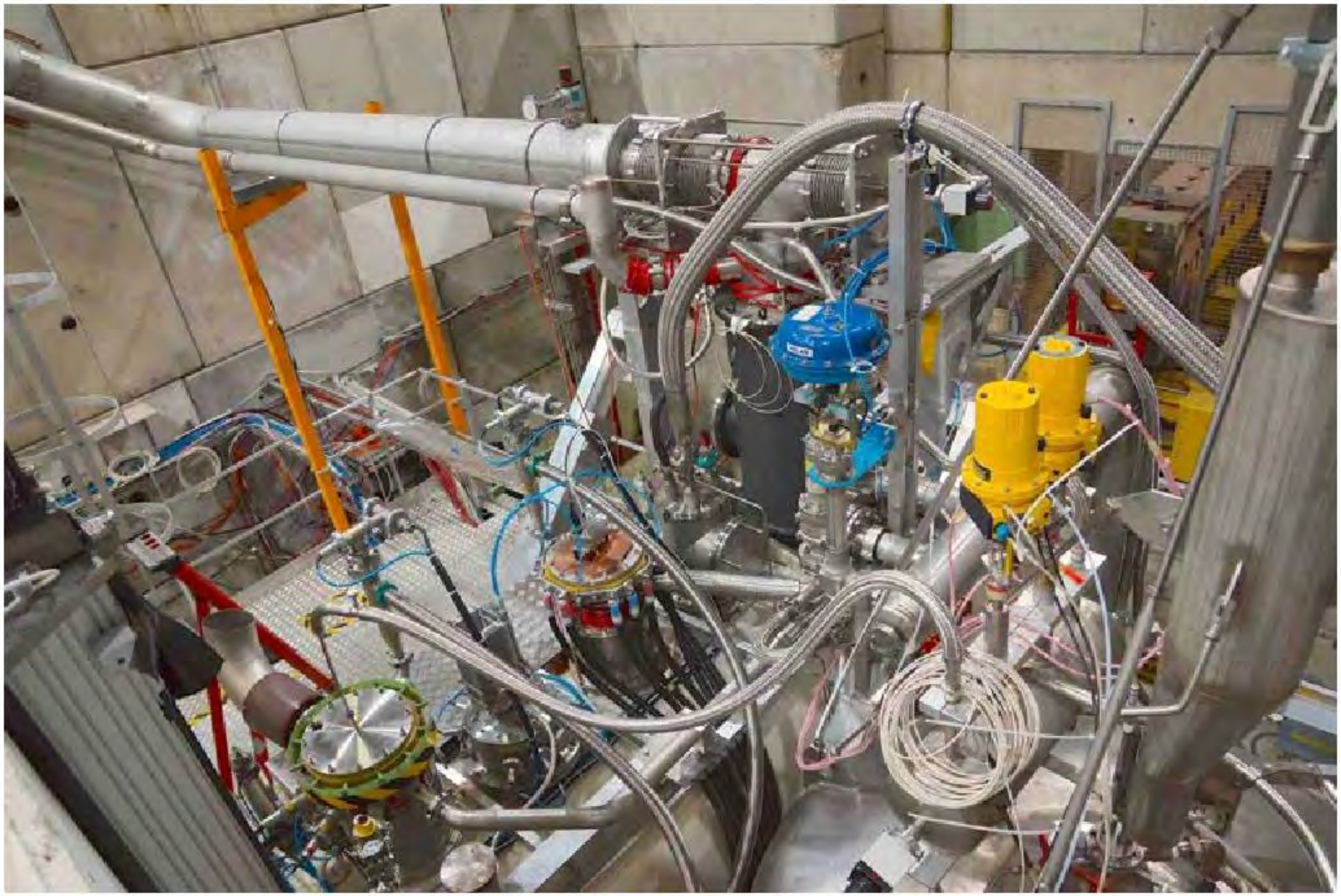
COMPASS-II Polarised Drell-Yan

- First ever polarized Drell–Yan experiment
- 190 GeV/c π^- beam on transv. pol. proton target
- Access to transversity , the T-odd Sivers and Boer–Mulders TMDs

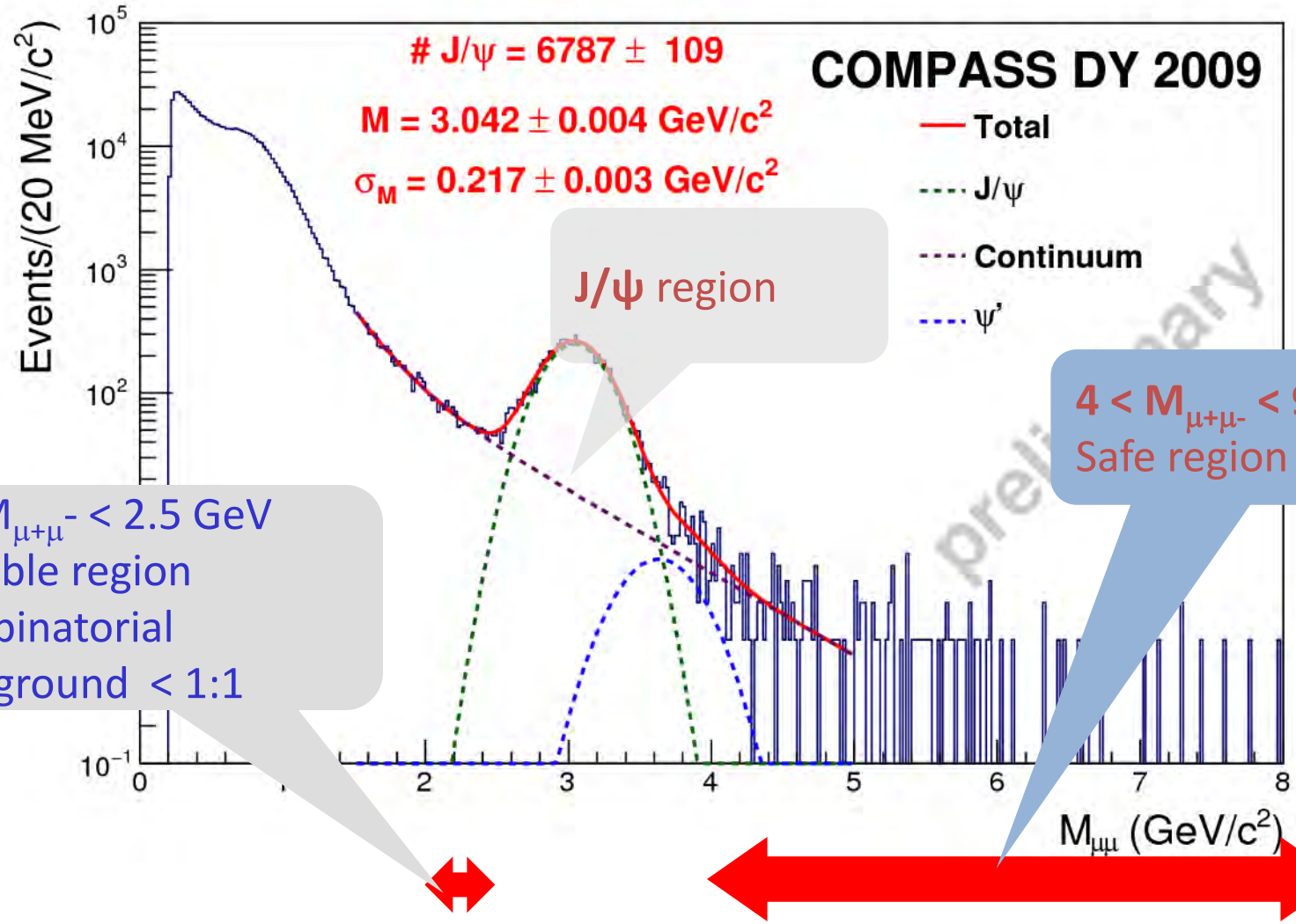




2015 run: polarised target

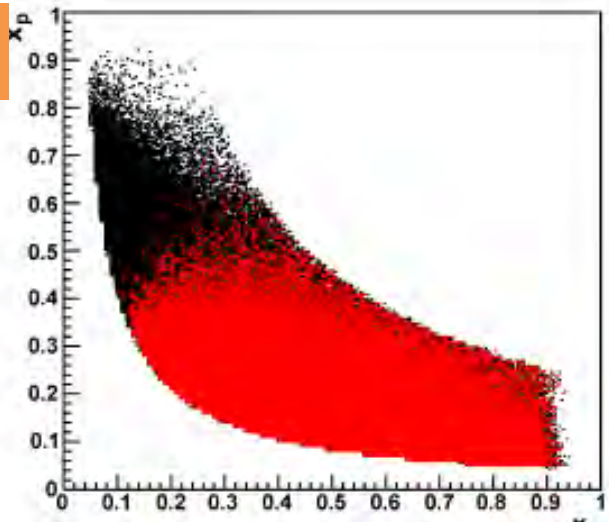
- 

Drell–Yan muon pair mass regions

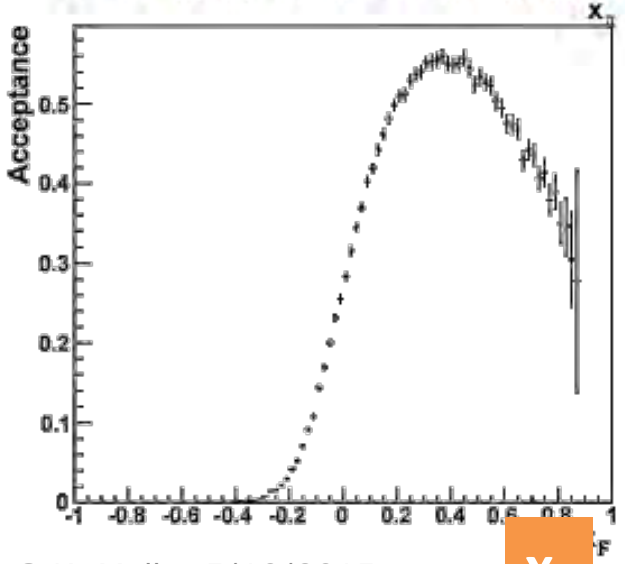


COMPASS polarized DY, projections HMR

x_p

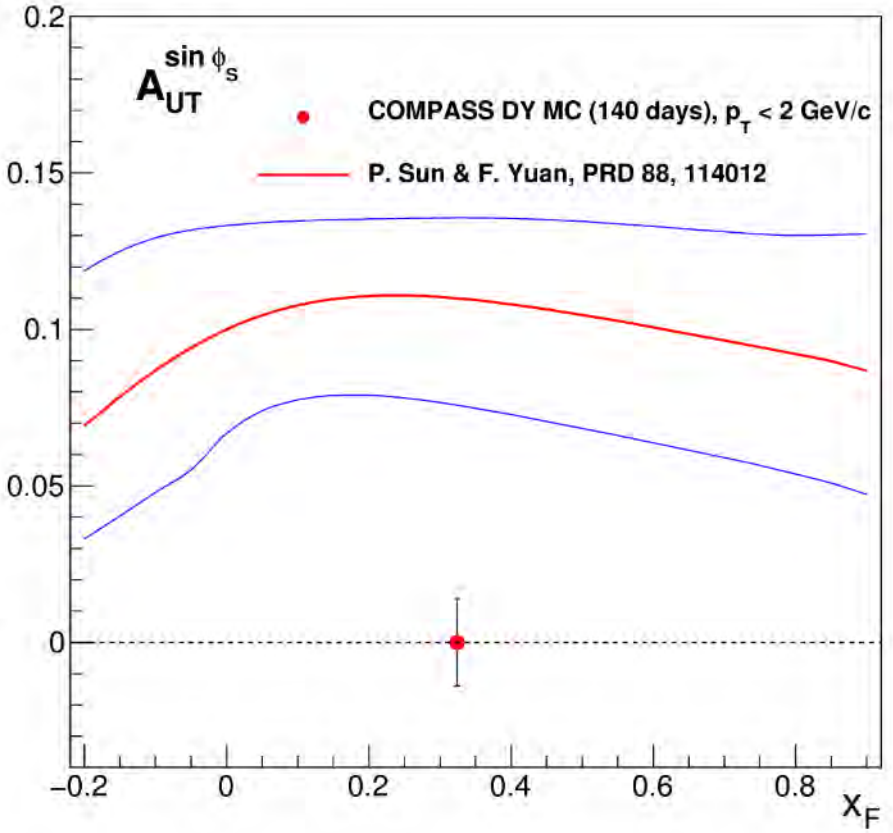


x_π



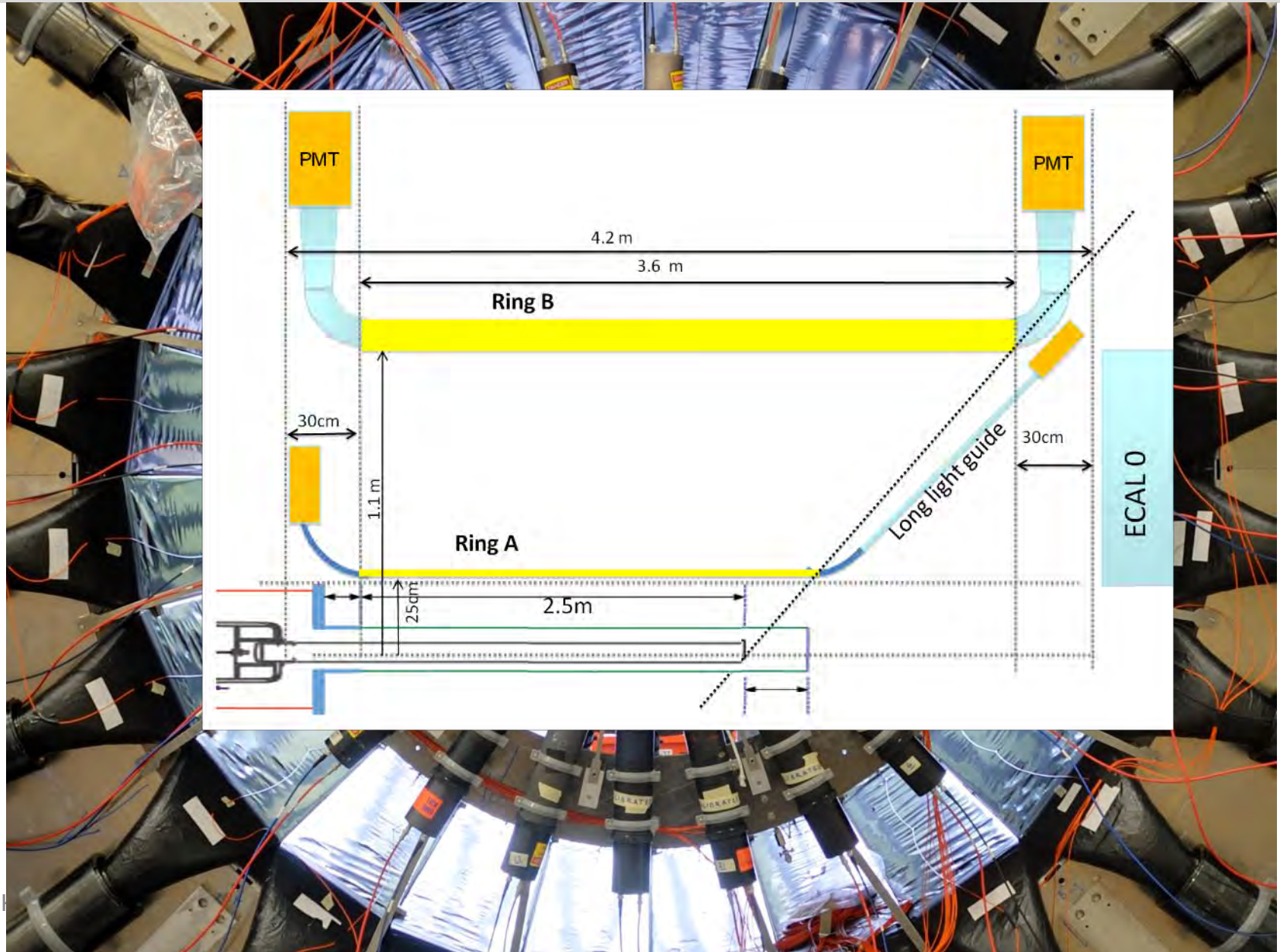
x_F

Predictions vary strongly, e.g.



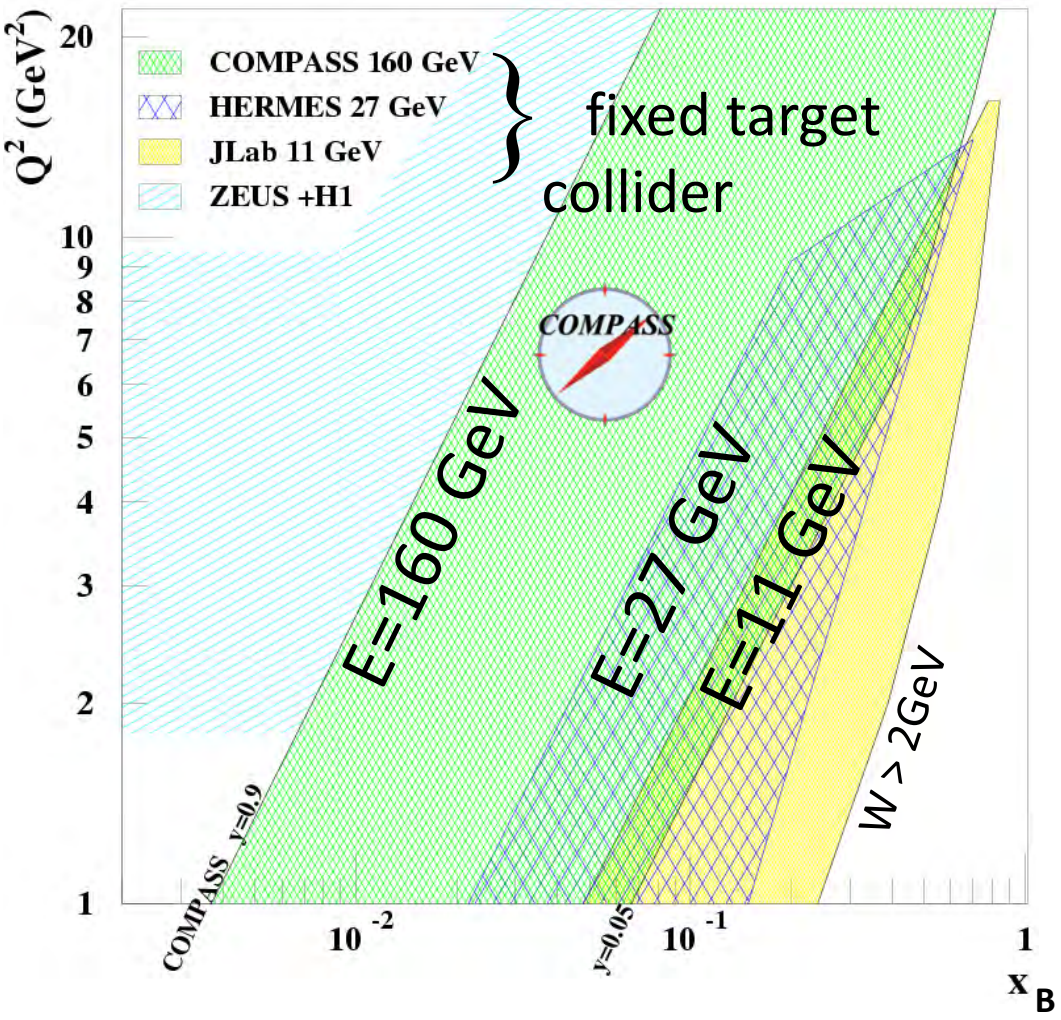
$x_F = x_\pi - x_p$

Camera detector for exclusivity



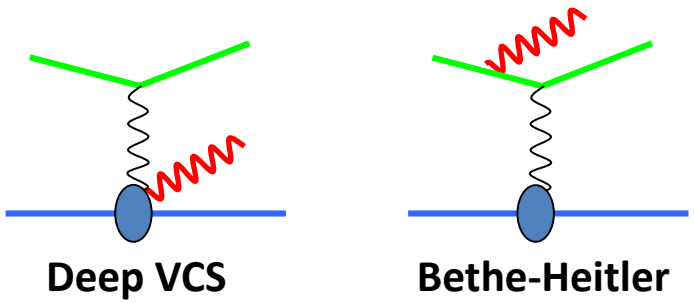
DVCS

- DVCS is the cleanest process to determine GPDs
- need a world-wide effort
- global analysis over large kinematic range mandatory
- COMPASS-II: bridges HERA to JLAB 11 GeV kinematics



DVCS–Bethe-Heitler interference *I*

- DVCS can be separated from BH and constrain the GPD *H* e.g. using different charge & spin (e_μ & P_μ) cross section combinations of the μ beam



- Note: $\mu^\pm$ beams have opposite polarisation at COMPASS

$$d\sigma^{\mu p\to\mu p\gamma} = d\sigma^{BH} + d\sigma_0^{DVCS} + P_\mu d\Delta\sigma^{DVCS} + e_\mu \mathrm{Re}\, I + P_\mu e_\mu \mathrm{Im}\, I$$

Charge & Spin sum and difference:

$$\mathcal{S} = d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2(d\sigma^{BH} + d\sigma_0^{DVCS} + \mathrm{Im}\, I)$$

$$\mathcal{D} = d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} = 2(d\sigma_0^{DVCS} + \mathrm{Re}\, I)$$

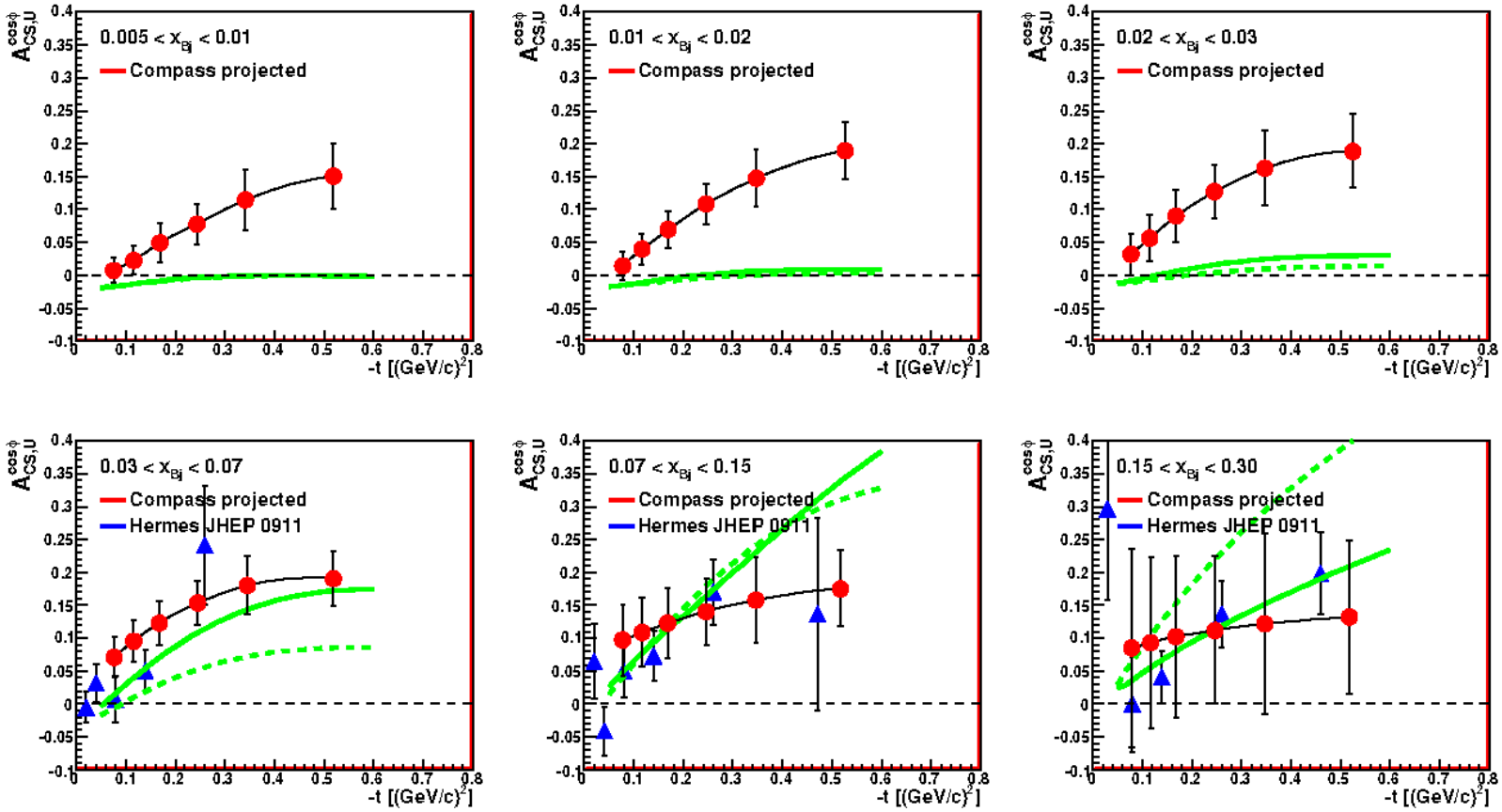
Im I and *Re I* related to

$$H(x=\xi,\xi,t)$$

$$\mathcal{P}\int dx\, H(x,\xi,t)/(x-\xi)$$

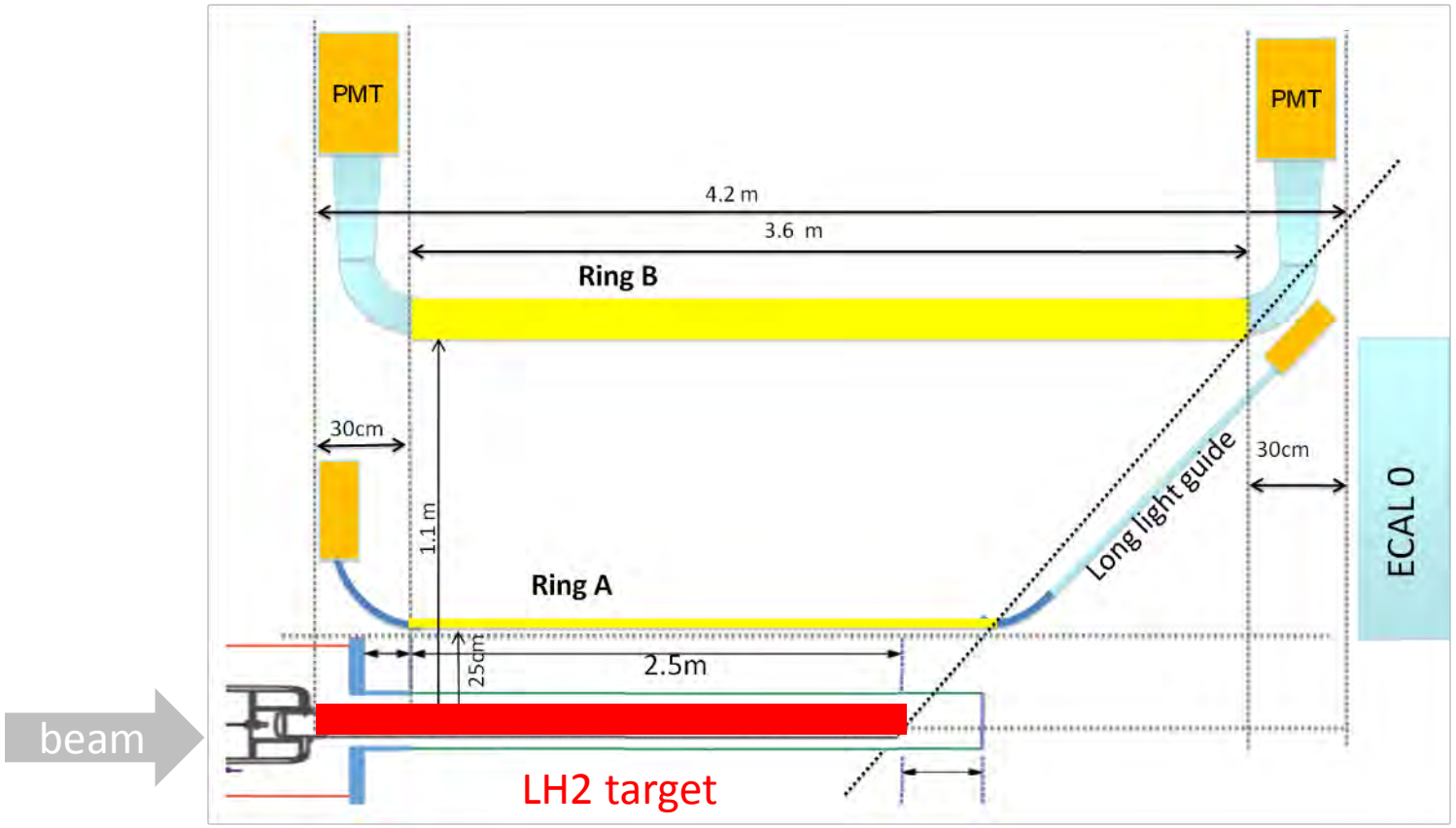
Projection for beam charge-and-spin asym.

Amplitude of cos ϕ modulation of $A_{CS,U} \equiv \frac{d\sigma^{\overleftarrow{+}} - d\sigma^{\overleftarrow{-}}}{d\sigma^{\overleftarrow{+}} + d\sigma^{\overleftarrow{-}}} = \frac{D_{CS,U}}{S_{CS,U}}$

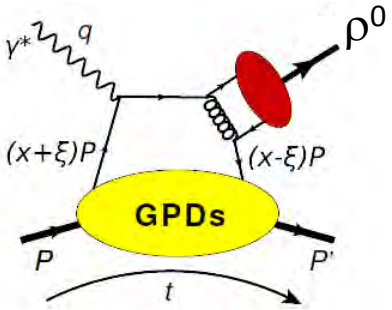


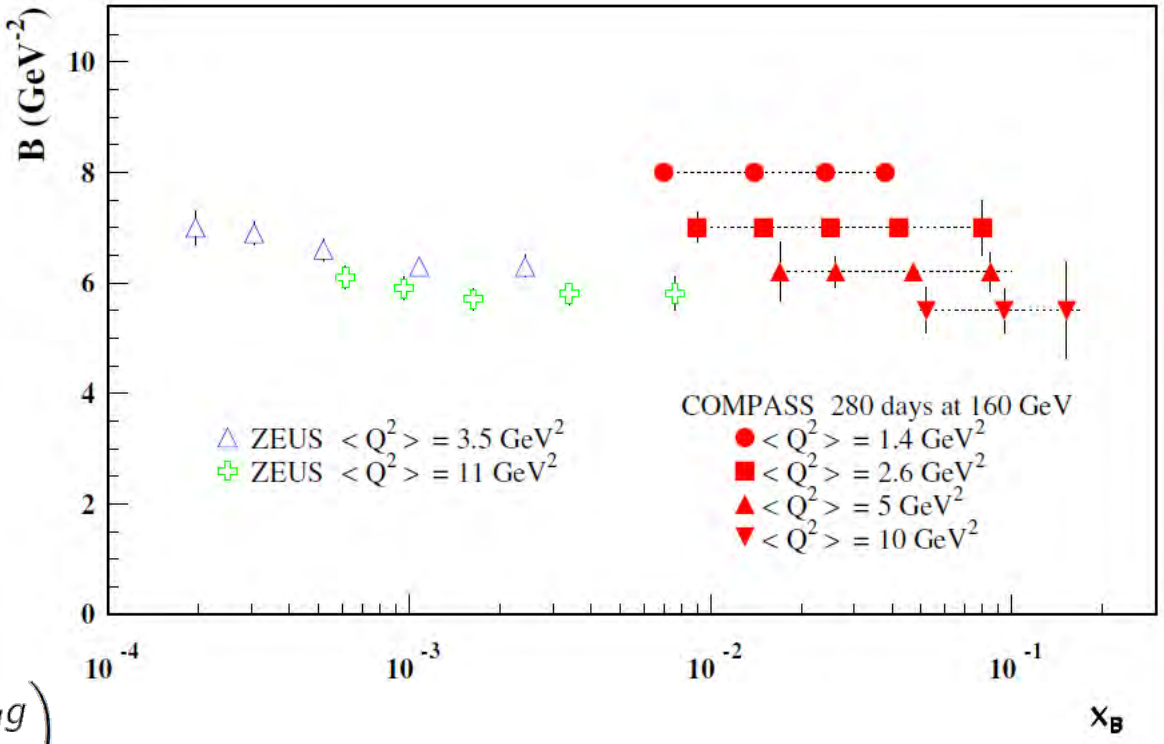
fits by Kumericki, Mueller

Geometry target region



t-slope for ρ^0 production





also ϕ, ω, ..

$$H_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u + \frac{1}{3}H^d + \frac{3}{8}H^g\right)$$

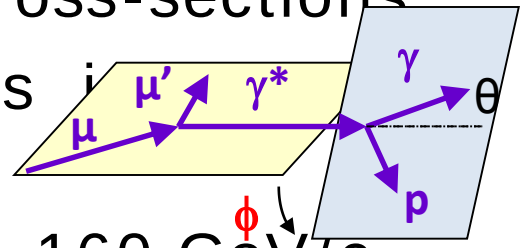
$$H_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u - \frac{1}{3}H^d + \frac{1}{8}H^g\right)$$

$$H_{\phi} = -\frac{1}{3}H^s - \frac{1}{8}H^g$$

COMPASS II proj. data

$$\mathcal{A} = \frac{d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}}{d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}}{\mathcal{S}}$$

- Example: Charge & spin asym
- Cancelation of several experimental uncertainties
- Easier to measure than absolute cross-sections
- Asymmetries, sums and differences i
  $6x_B \times 4\ Q^2$ bins as function of φ

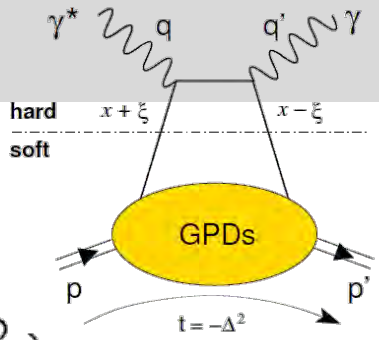


- Simulation for 2 years data taking, 160 GeV/c and a 2.5 m long liquid H_2 target
- LO:

$$\mathcal{S} : Im\, I, \quad \sin\phi \text{ dependence}, \quad H(x=\xi,\xi,t)$$

$$\mathcal{D} : Re\, I, \quad \cos\phi \text{ dependence}, \quad \mathcal{P}\int dx\, H(x,\xi,t)/(x-\xi)$$

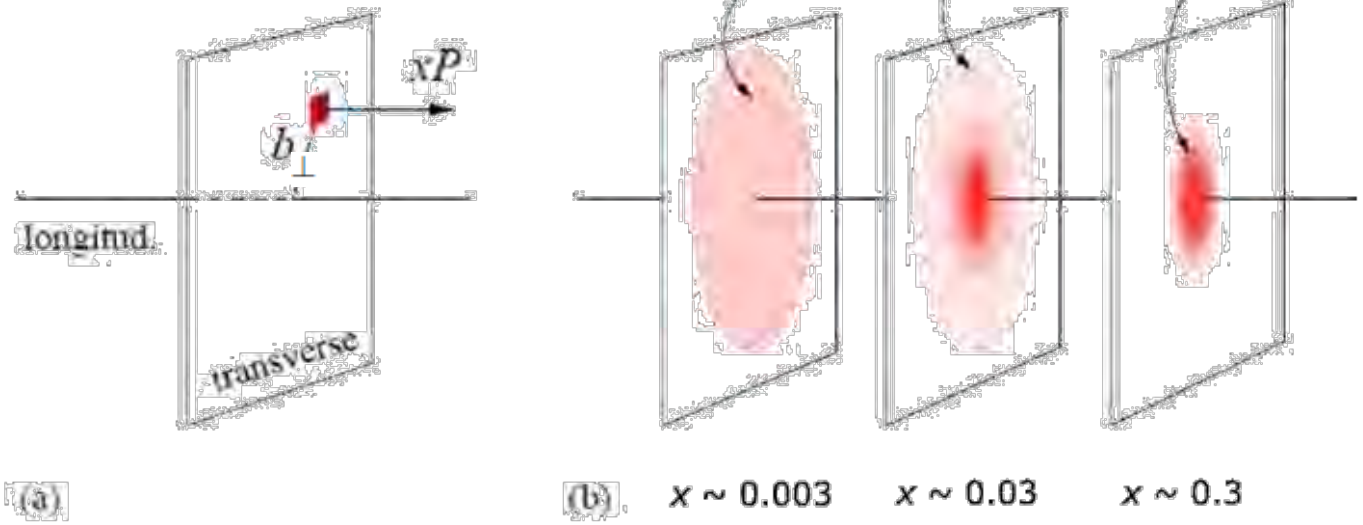
`Tomography'



- $\xi = 0 \rightarrow t = -\Delta_T^2$, no long. mom. transfer

$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{d^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} \exp(-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp) H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$$

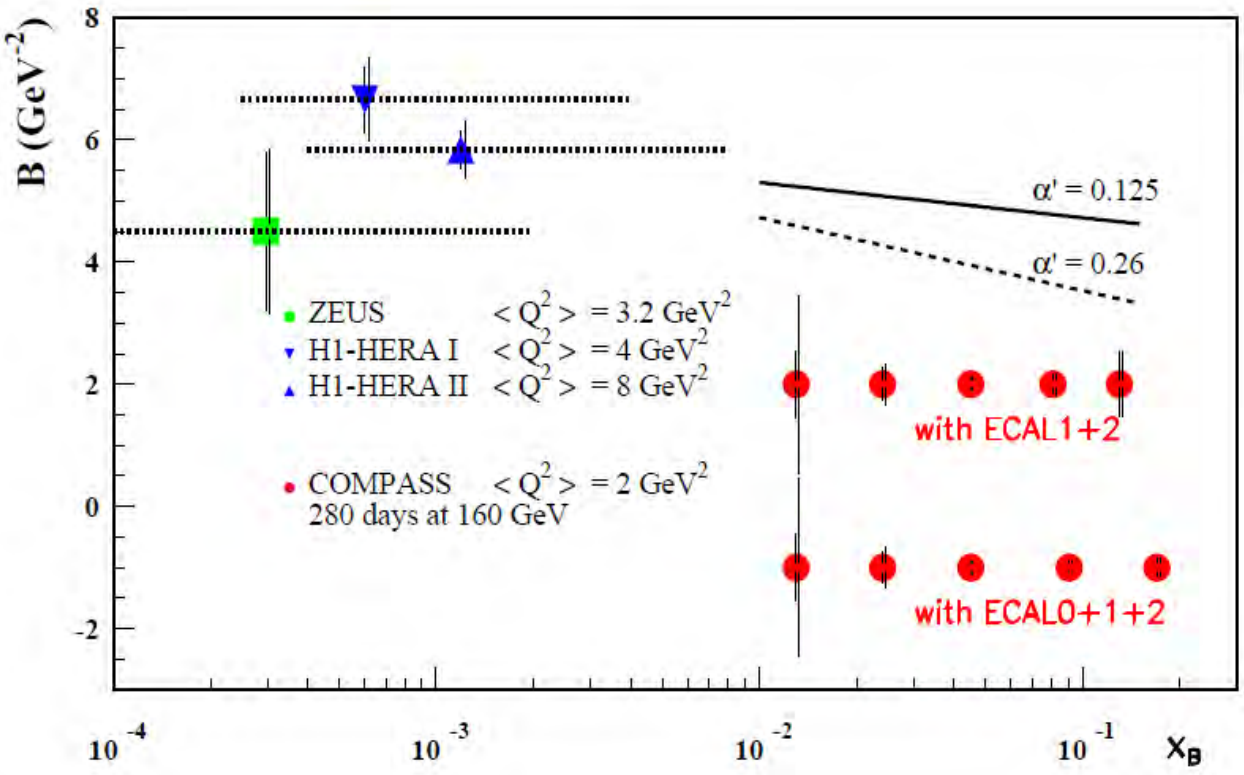
- Transverse size as function of longitudinal momentum fraction



adapted from JLAB 12 GeV CDR

projected *t*-slope

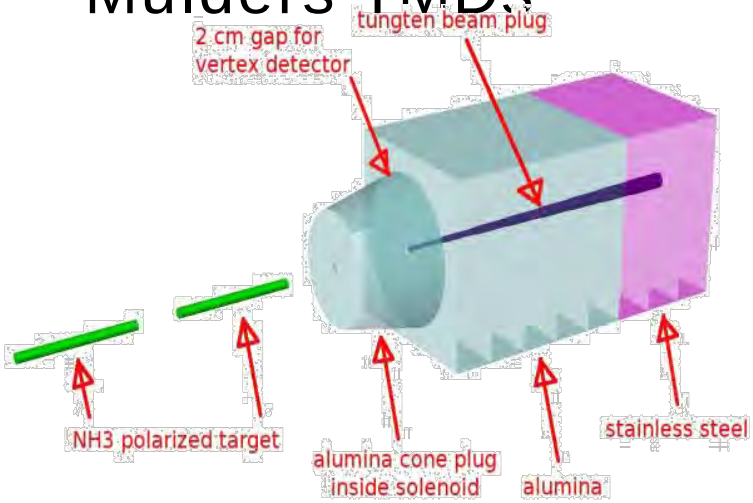
- COMPASS-II projection, 2 years of data taking ●
- x_B region unique to COMPASS
- transition from HERA → HERMES/JLab

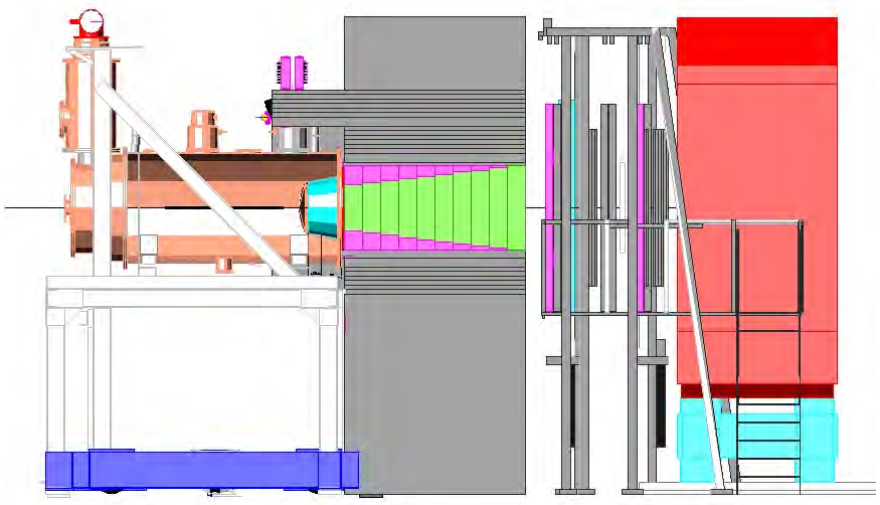


$$B(x_B) = B_0 + 2\alpha' \log \frac{x_0}{x_B}$$

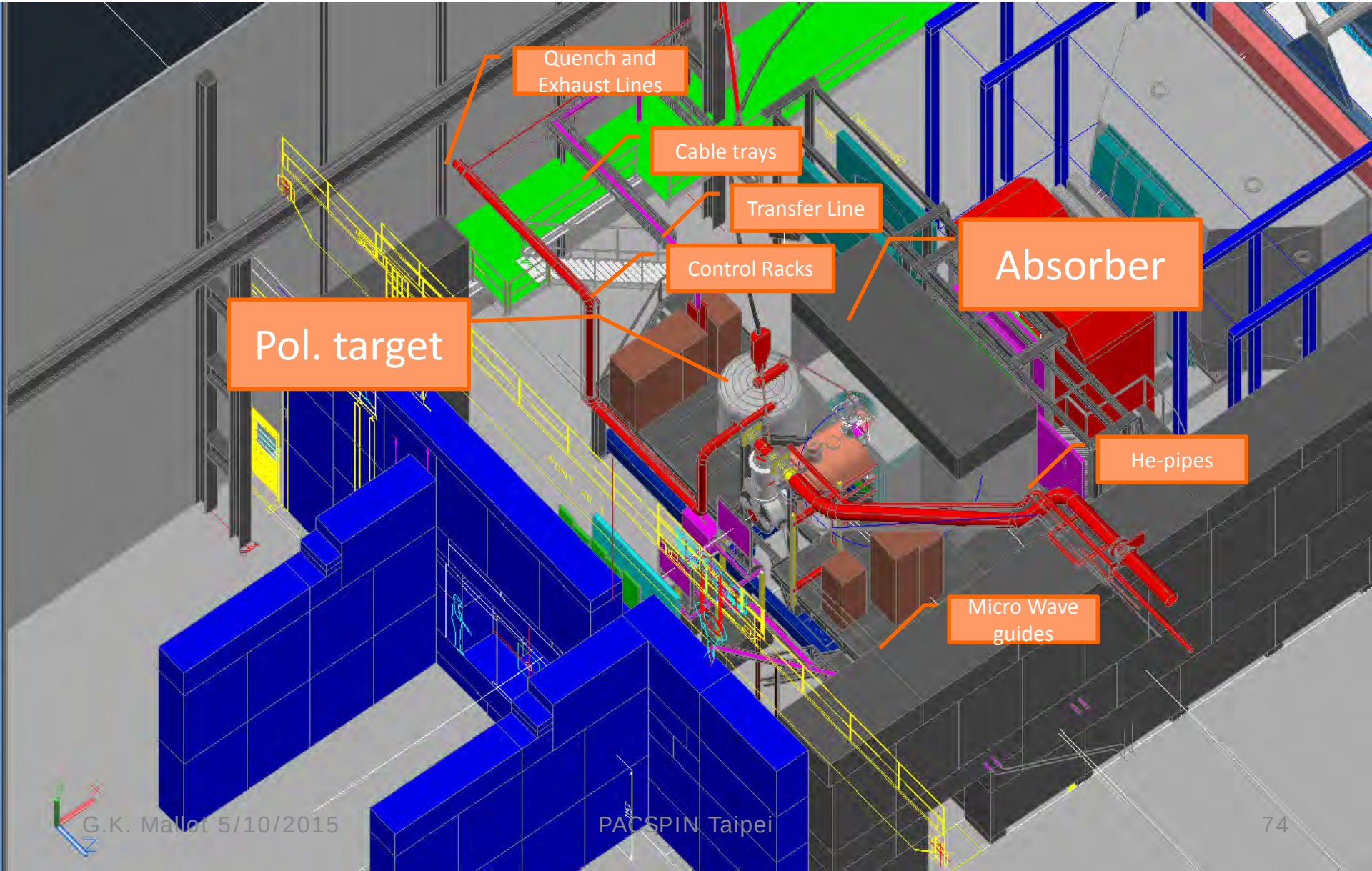
COMPASS-II Polarised Drell-Yan

- COMPASS-II: 190 GeV/c π^- beam on transversely pol. proton target
- π^- valence u-antiquark picks nucleon's u quark in valence region (u-quark dominance)
- Access to transversity , the T-odd Sivers and Boer-Mulders TMDs



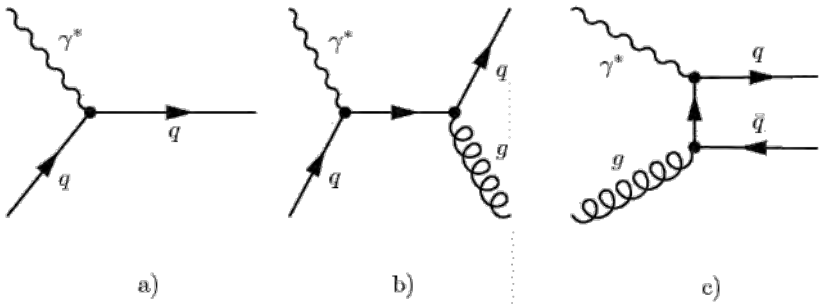


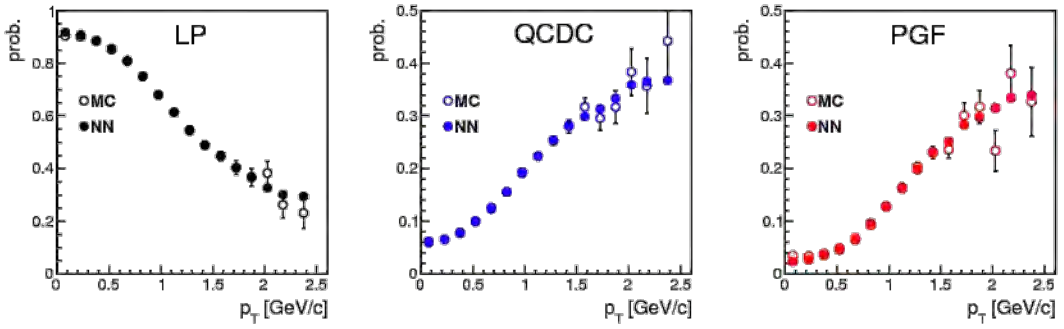
Target region for DY

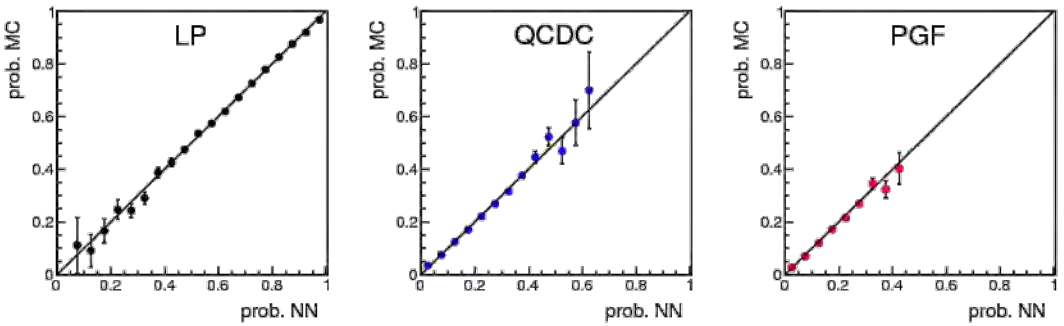


Gluon polarisation from PGF (LO)

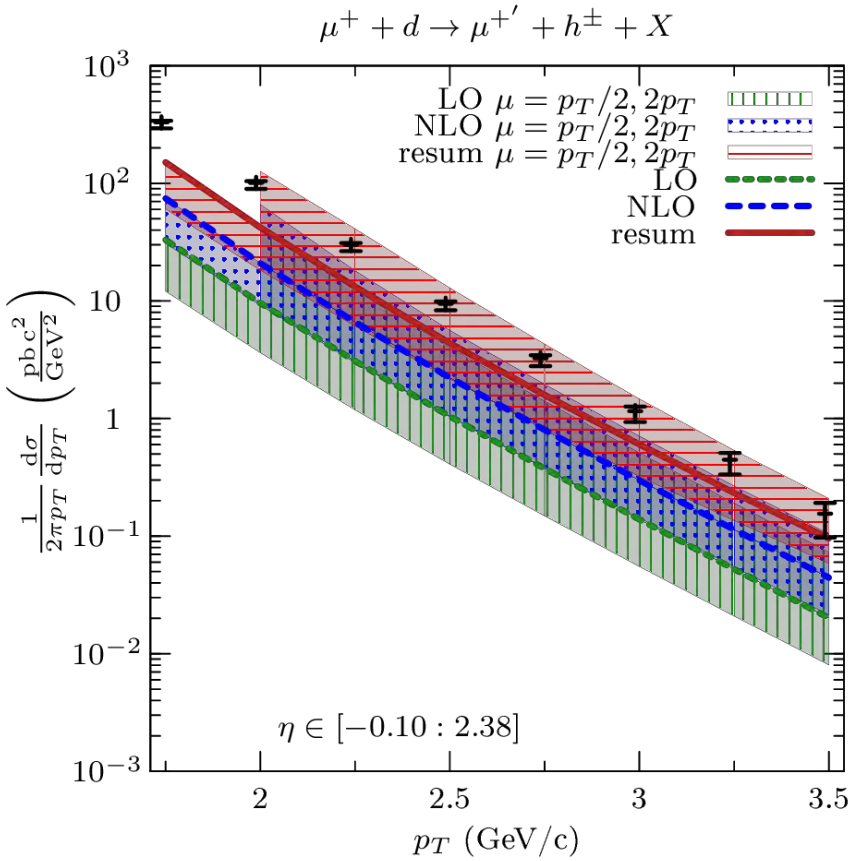
- LO reanalysis of 2002-2004, 2006 deuteron data
- $Q^2 > 1\ GeV^2$
- novel method using events with any p_T and NN weights
- simultaneous determ. of leading order asym. reduces syst. uncertainty
- determination of $\Delta g(x)$ in 3 x ranges







Spin independent cross-section



De Florian, Pfeuffer, Schaefer, Vogelsang, PRD 88 (2013) 014024

COMPASS, PRD 88 (2013) 091101

- semi-inclusive single hadron production
- COMPASS kinematics
- good agreement with NLL resummation

$\Rightarrow$ cross-section asymmetries can be used to determine the gluon polarisation

$\Rightarrow$ need NLL resummation for polarised case