highlights from HERMES

-- the nucleon structure: spin & 3D imaging --

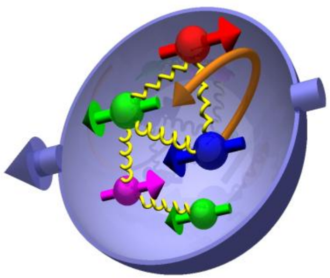
- polarised deep-inelastic lepton-nucleon scattering
- where is the spin of the nucleon ?
- towards a 3D imaging

Delia Hasch

hermes

HERa **ME**asurment of **S**pin

the mission



$$\frac{1}{2} = J_q + J_g$$

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

$$\Delta\Sigma = \Delta u_v + \Delta d_v + \Delta q_s$$

first measurements:

$$\Delta\Sigma \approx 0.05$$

spin puzzle

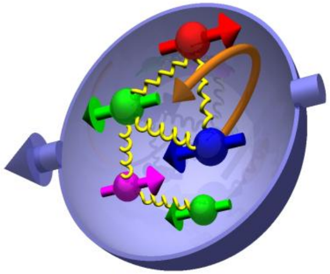
EMC @CERN [1988]

QPM: $\Delta\Sigma = 1$

relativistic QPM: $\Delta\Sigma \approx 0.7$

HERa MEasurment of Spin

the mission



$$\frac{1}{2} = J_q + J_g \quad = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$

spin puzzle

- hunting the orbital angular momentum

  → *towards a complete 3D description of the nucleon: beyond collinear approximation* hermes

HERa MEasurment of Spin

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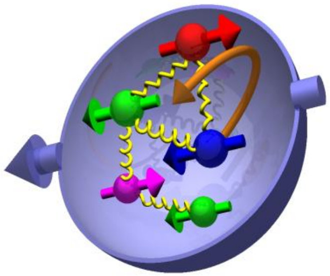

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spin puzzle

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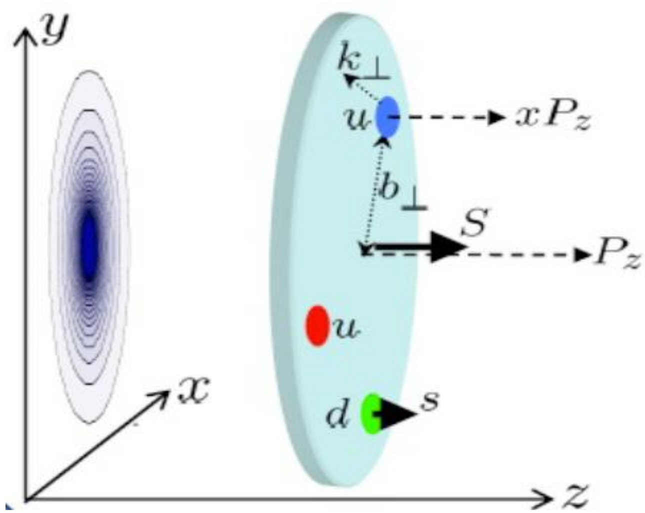
  → *towards a complete 3D description of the nucleon: beyond collinear approximation*



[plot: courtesy P. Haegler]

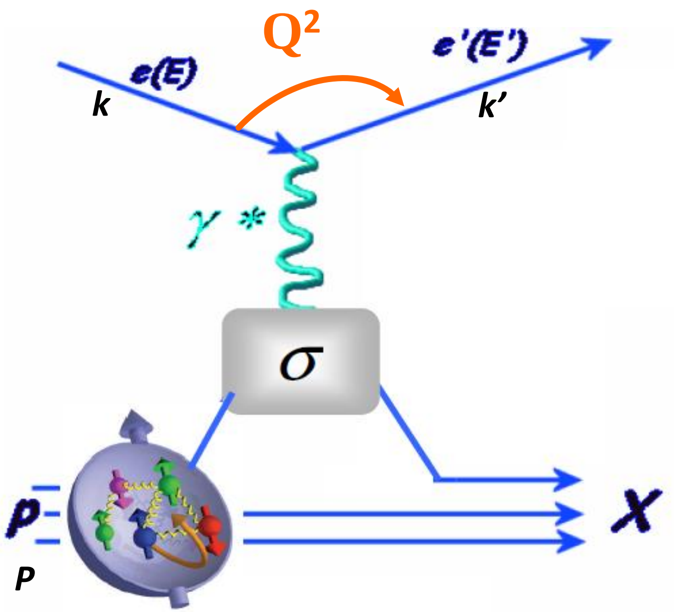
Wigner 'mother' distribution

$$W^{\vec{s}}(x, k_\perp, b_\perp, \vec{S})$$

probability of finding a quark
with certain spin projection,
position and momentum

[X. Ji, PRL 2003; A. Belitsky, X. Ji, F. Yuan, PRD 2004]
[Meissner, Metz, Schlegel, JHEP 0908:056, 2009]

the tool: deep inelastic scattering



$$Q^2 = -q^2 = (k - k')$$ (4-momentum)^2 of virtual photon

$$\lambda \sim 1/Q^2$$

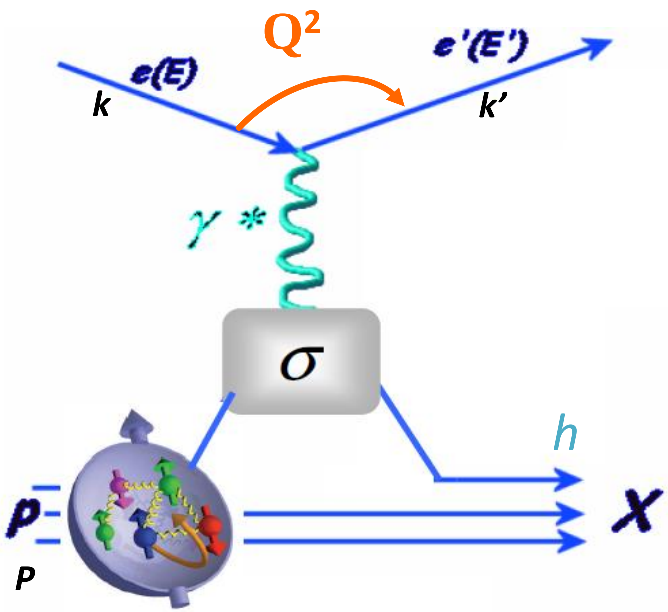
$$x = \frac{Q^2}{2P\cdot q}, \quad x \in [0,1]$$ fraction of proton momentum carried by the struck parton

pQCD factorisation:

$$\sigma_{DIS} \propto \sum_f \hat{\sigma}_{part} \otimes \boxed{pdf(x)}$$

parametrise the *structure* of nucleon

the tool: deep inelastic scattering



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$$z = \frac{P \cdot P_h}{P \cdot q}, \quad z \in [0,1]$$ energy fraction carried by produced hadron

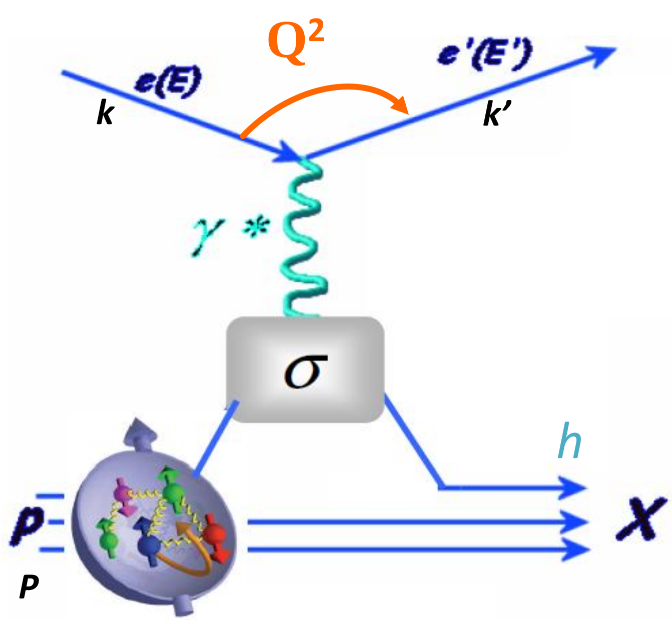
pQCD factorisation:

$$\sigma_{DIS} \propto \sum_f \hat{\sigma}_{part} \otimes \boxed{pdf(x)} \otimes \boxed{frag^{q,g \to h}(z)}$$

parametrise the *structure* of nucleon

parametrise fragmentation of parton in a hadron of type h

the tool: deep inelastic scattering



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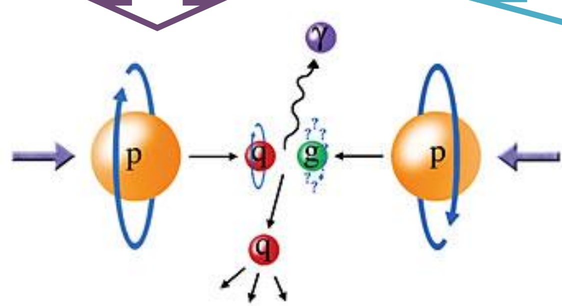
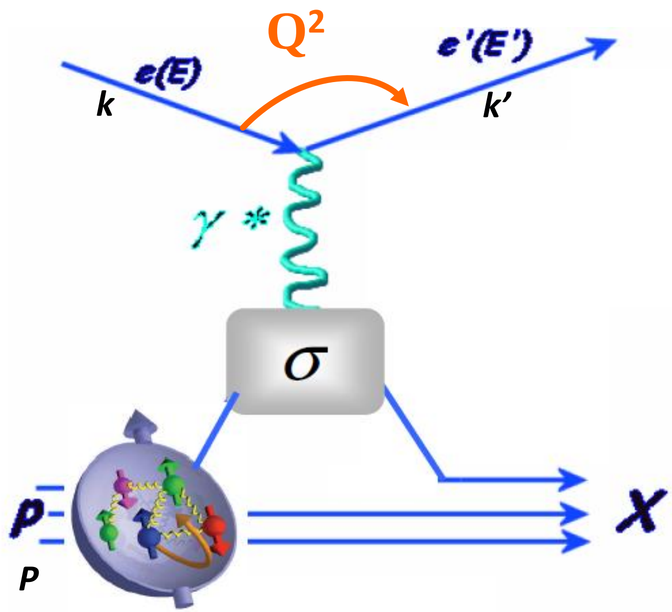


universal, same functions in, e.g., hadron reactions, DY, e+e-, …

the tool: deep inelastic scattering



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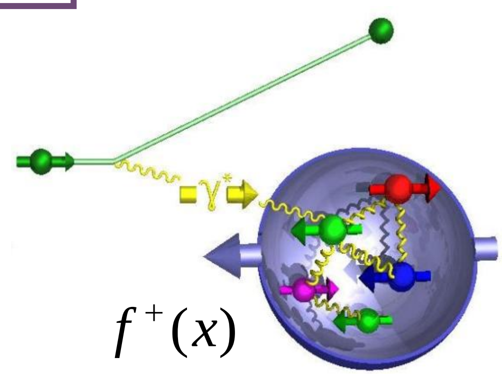
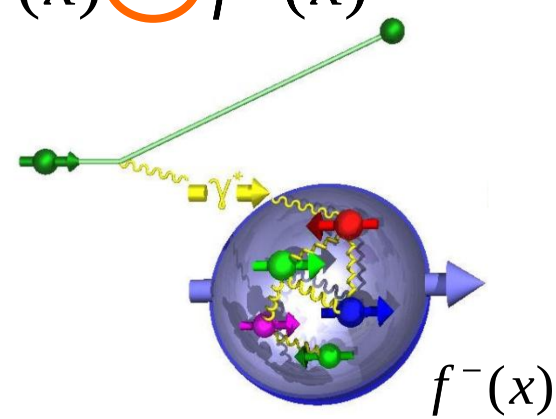
fraction of proton momentum carried by the struck parton

$$\sigma_{DIS} \propto \sum_f \hat{\sigma}_{part} \otimes \boxed{pdf(x)} \Rightarrow \Delta f(x) = f^+(x) - f^-(x)$$

→ *helicity distribution*

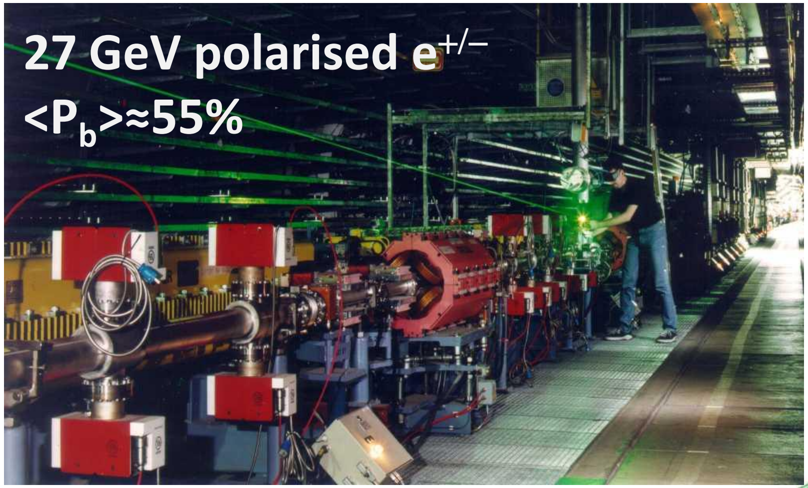
… probability to find a quark or gluon with momentum x *and spin* parallel to the proton spin

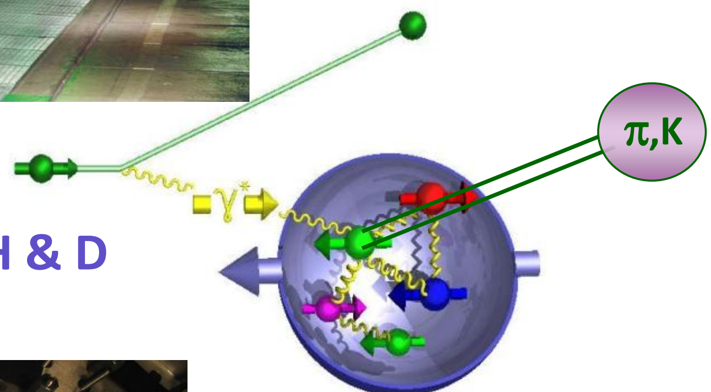




prerequisites

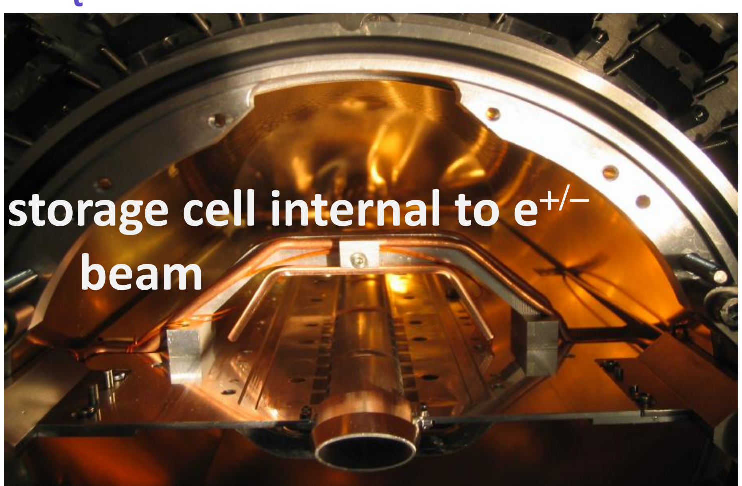
@HERA: 1995-2007





pure nuclear-polarised H & D

$\langle P_t \rangle \approx 80\%$

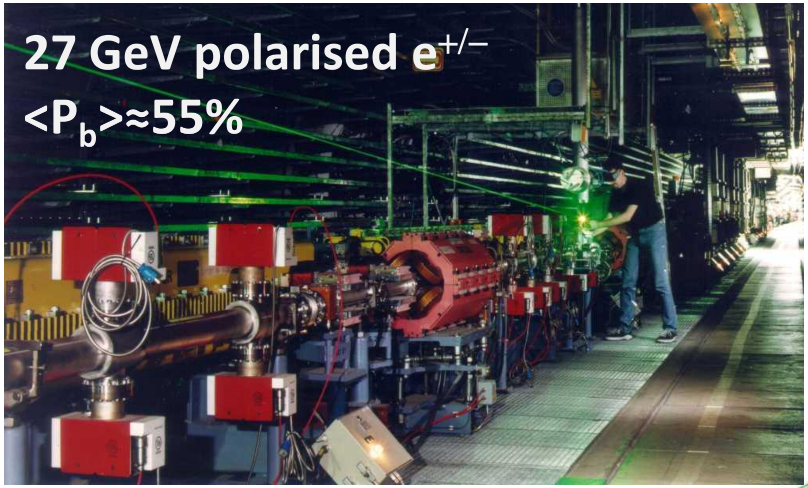


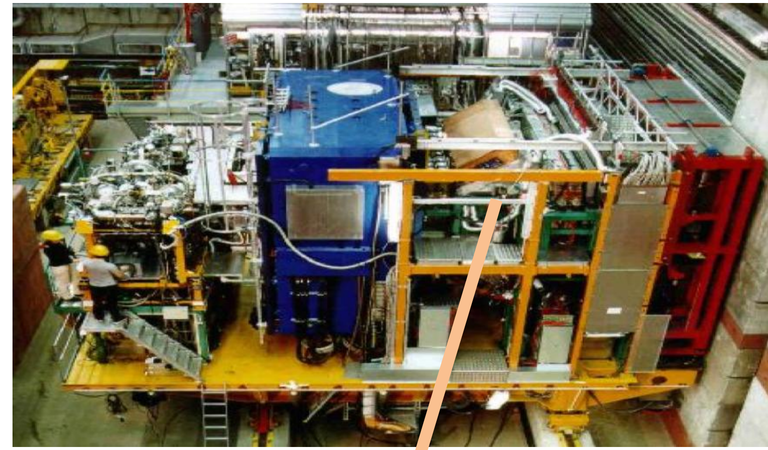
prerequisites

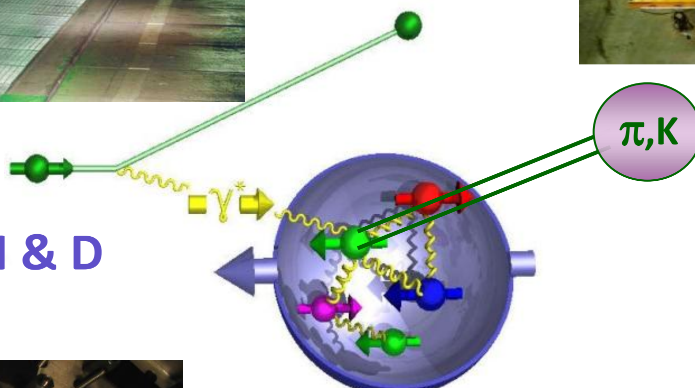
@HERA: 1995-2007

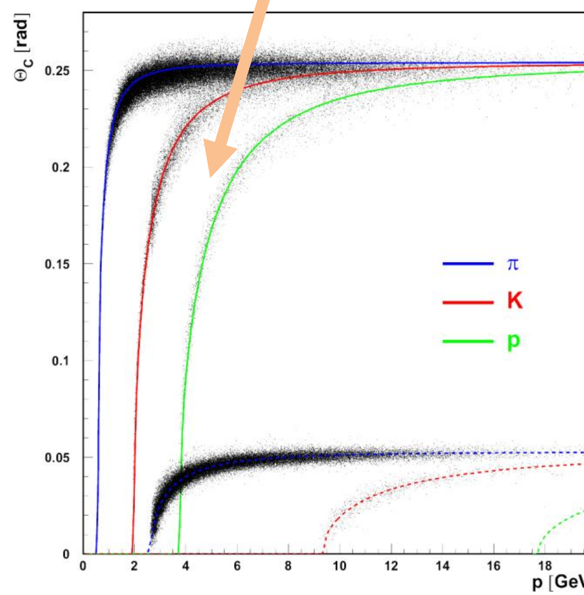
27 GeV polarised $e^{+/-}$

$\langle P_b \rangle \approx 55\%$









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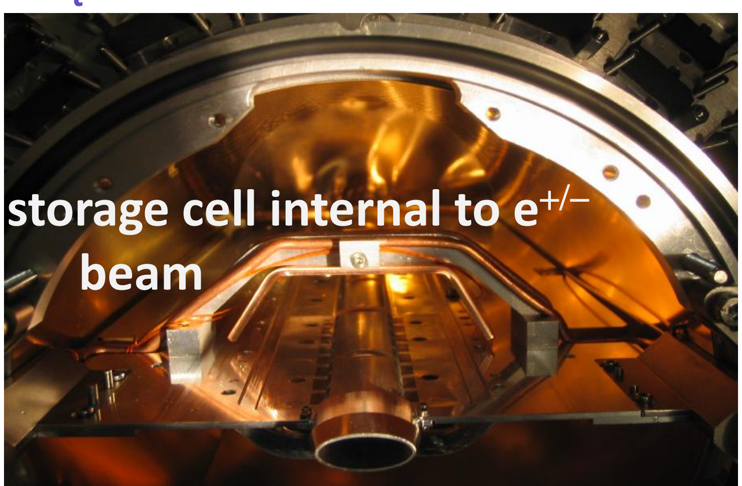
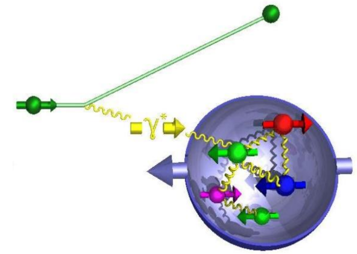


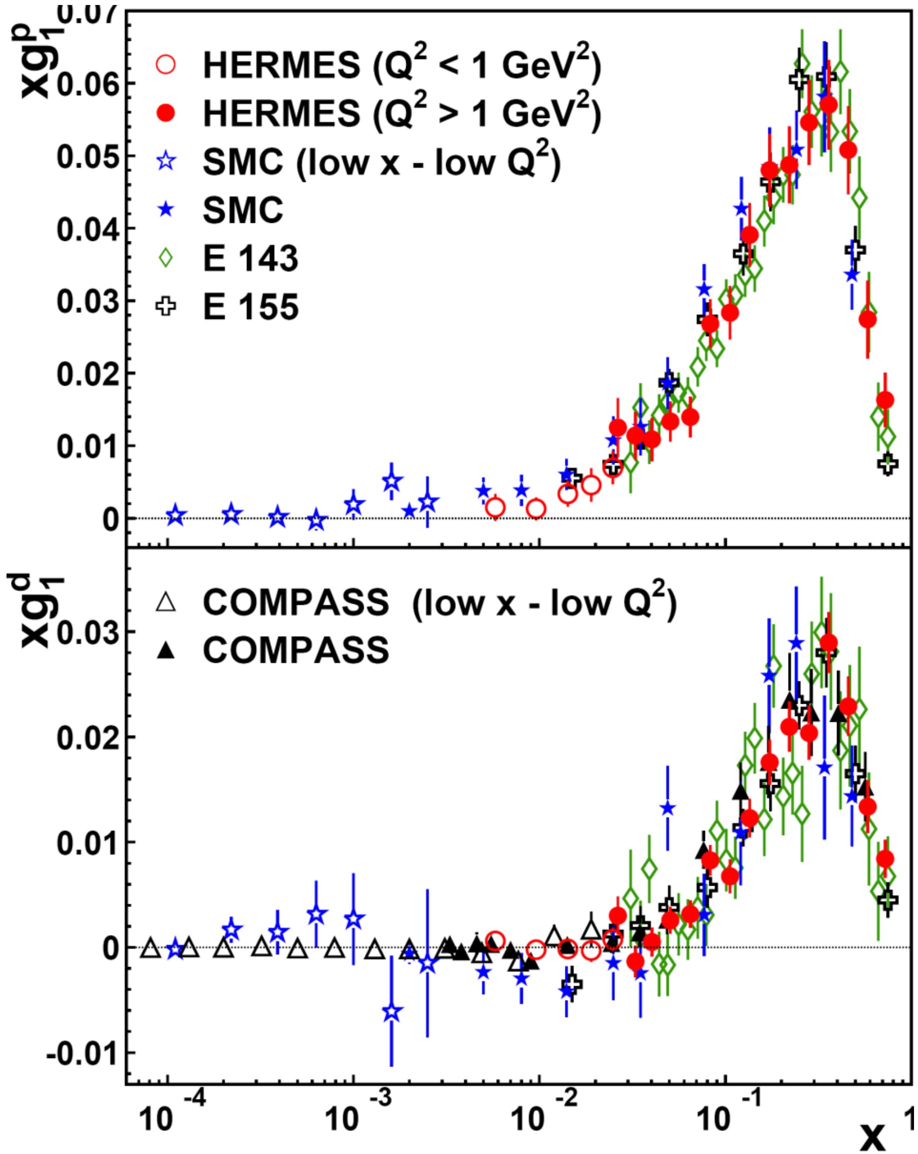
storage cell internal to $e^{+/-}$ beam

dual RICH: p / K / p separation over whole momentum range

inclusive DIS



[PRD75(2007), 012007]



polarised structure function:

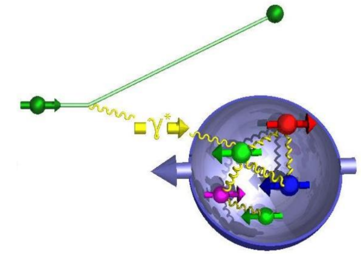
$$\sigma^{\overset{\rightarrow}{\Rightarrow}} - \sigma^{\overset{\leftarrow}{\Rightarrow}} \propto g_1(x)$$

$$g_1(x) \propto \frac{1}{2}\sum_q e_q^2(\Delta q(x) + \Delta\bar{q}(x))$$

... flavour summed contribution of quarks to nucleon spin

(...once integrated over all x...)

inclusive DIS



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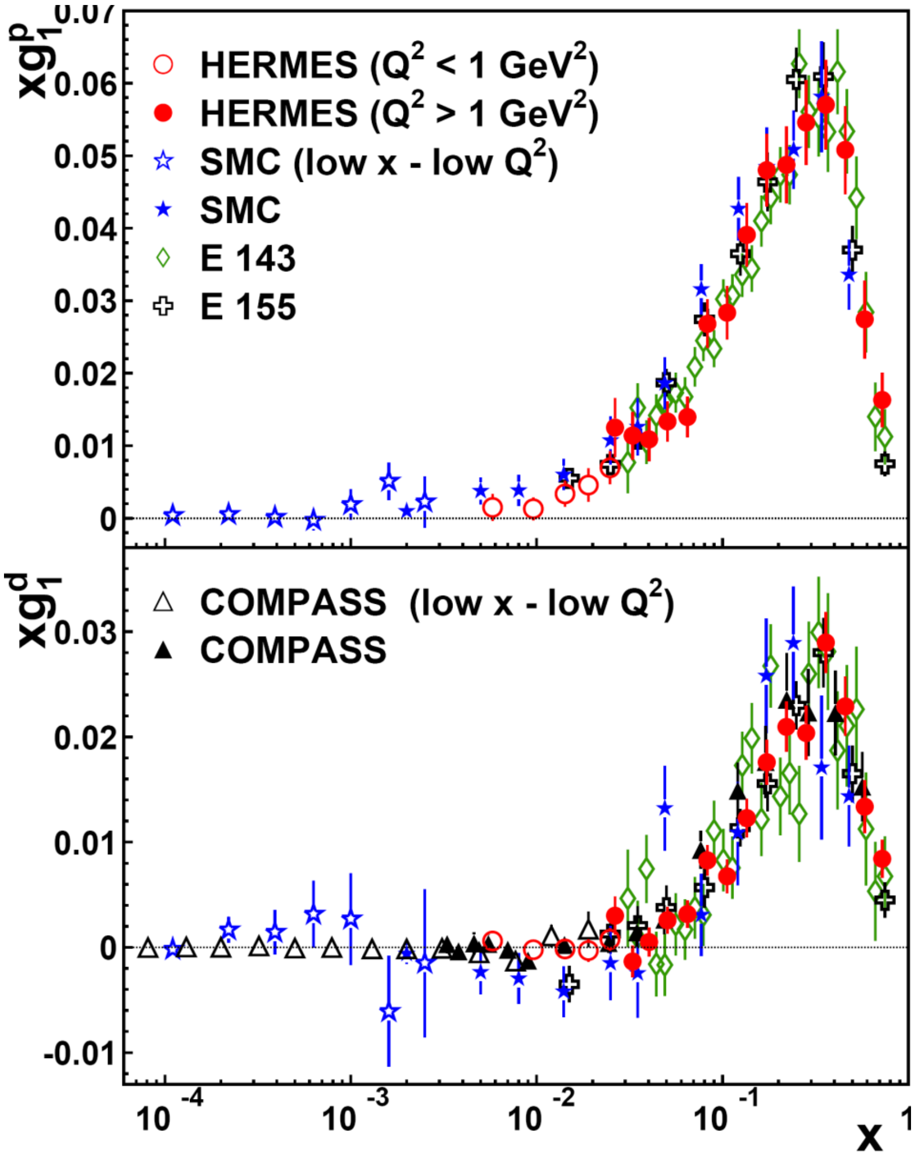

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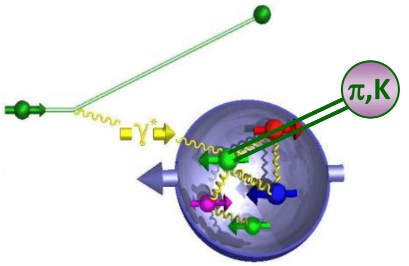
values from recent *NLO* analyses of world data:

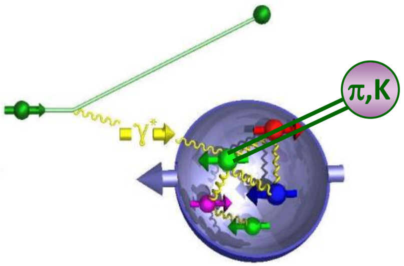
$$\int dx\, g_1(x) \rightarrow \boxed{\Delta\Sigma = 0.2 \div 0.35}$$

inclusive DIS & beyond

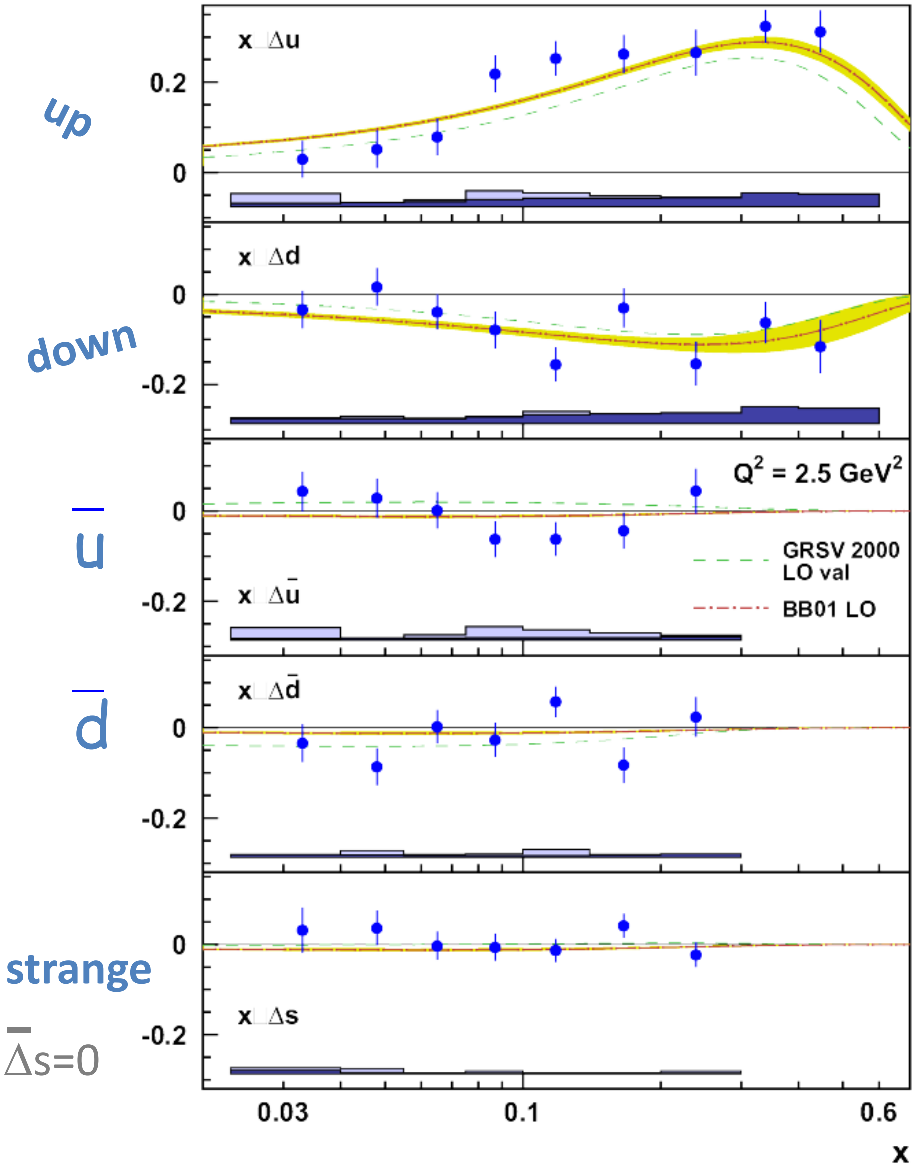


what about the individual quark contributions
&
gluons ?

inclusive DIS & beyond



[PRL92(2004),012004;PRD(2005)012003]



quark polarisations from flavour tagging

in short:

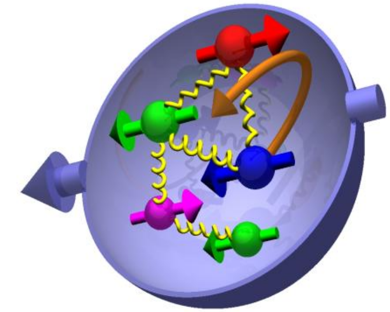
$$\Delta u(x) > 0 \quad \text{and large}$$

$$\Delta d(x) < 0 \quad \text{and smaller}$$

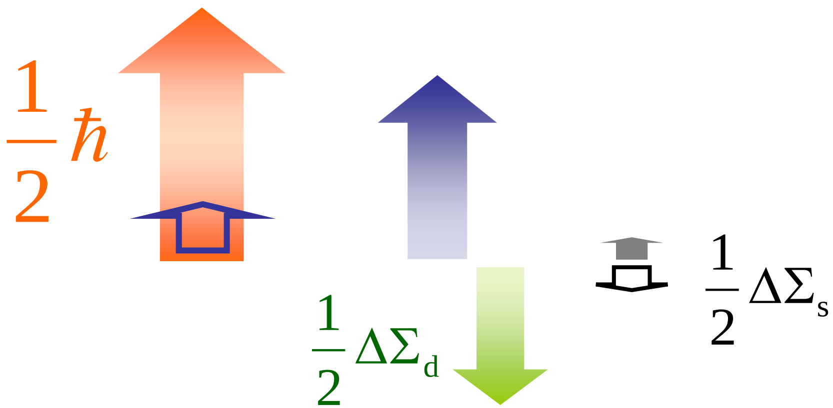
$$\Delta s(x) \approx 0$$

→ first *direct* 5-flavour separation of polarised pdfs

the spin budget

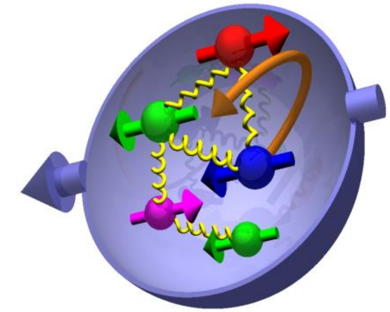


- contribution of quarks 25-35% :



- *gluon polarisation* surprisingly *small* in measured range ($0.05 < x_g < 0.2$) significant contributions of gluons and/or sea quarks @low x ?

the spin budget



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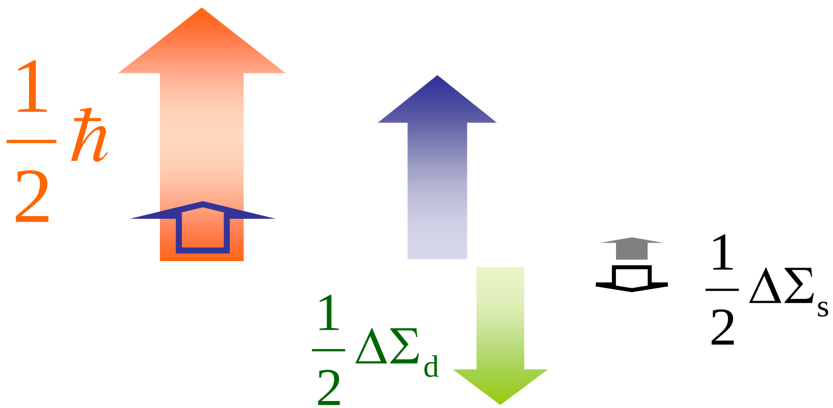


- ❑ *gluon polarisation* surprisingly *small* in measured range ($0.05 < x_g < 0.2$)
  significant contributions of gluons and/or sea quarks @low x ?

- ❑ *what about the orbital angular momentum ?*

→ **new concepts: GPDs & TMDs**

__G__eneralised __P__arton __D__istributions

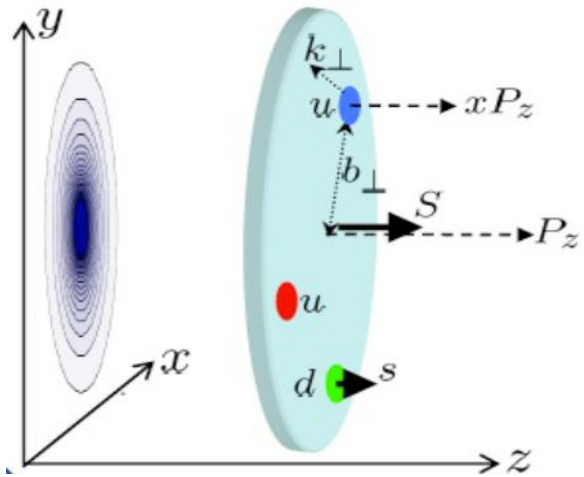
__T__ransverse __M__omentum __D__ependent functions

towards nucleon *tomography*

nucleon tomography

Wigner 'mother' distribution

$$W^{\vec{s}}(x, k_\perp, b_\perp, \vec{S})$$



cannot be measured... but its *projections* in coordinate or momentum space

nucleon tomography

$$W^{\vec{s}}(x, k_\perp, b_\perp, \vec{S})$$

cannot be measured... but its *projections* in coordinate or momentum space

transverse *coordinate* space

transverse *momentum* space

GPDs

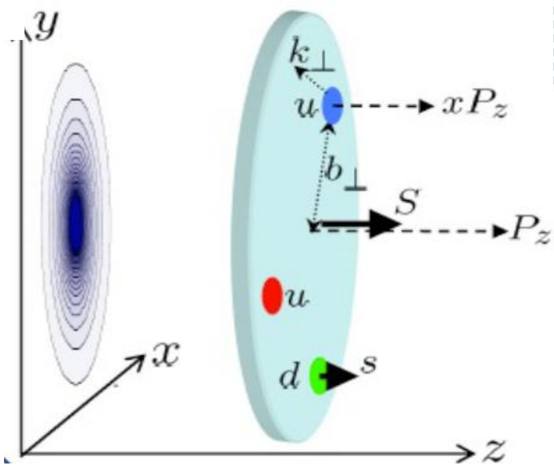
[*generalised* parton distributions]

TMDs

[*transverse momentum dependent* PDfs/FFs]

correlation between *longitudinal momentum* & *transverse position*

correlation between *spin* & *transverse momentum*



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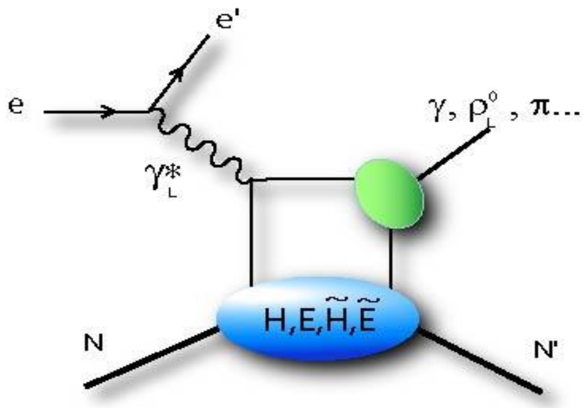
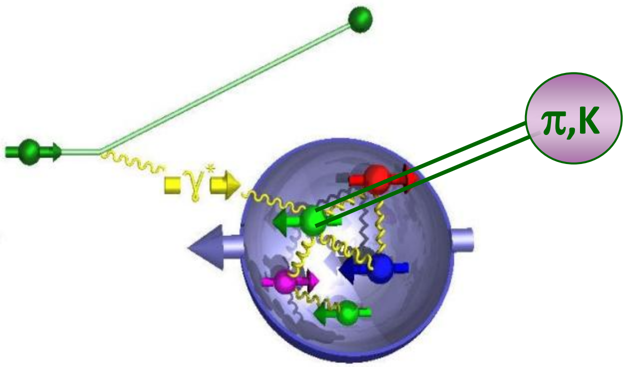


exclusive reactions

transverse *momentum* space

TMDs

[*transverse momentum dependent* PDFs/FFs]



fully differential semi-inclusive DIS

[... preferably with polarised beam and/or target ...]

nucleon tomography

$$W^{\vec{s}}(x, k_\perp, b_\perp, \vec{S})$$

cannot be measured... but its *projections* in coordinate or momentum space

transverse *coordinate* space

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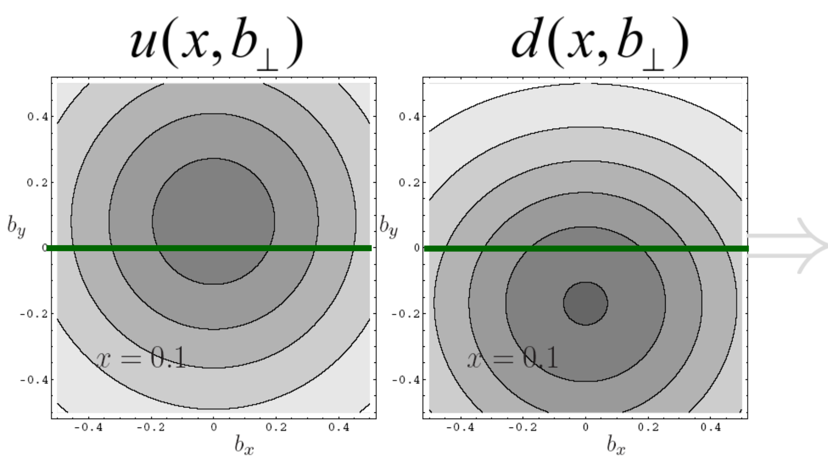
model calculations for a *transversely* polarised nucleon

GPD *E*



[model calculation by M. Burkardt]

nucleon tomography

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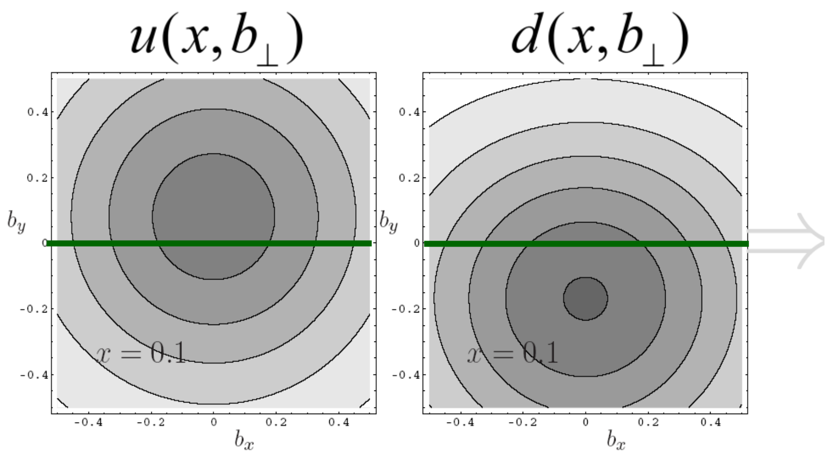

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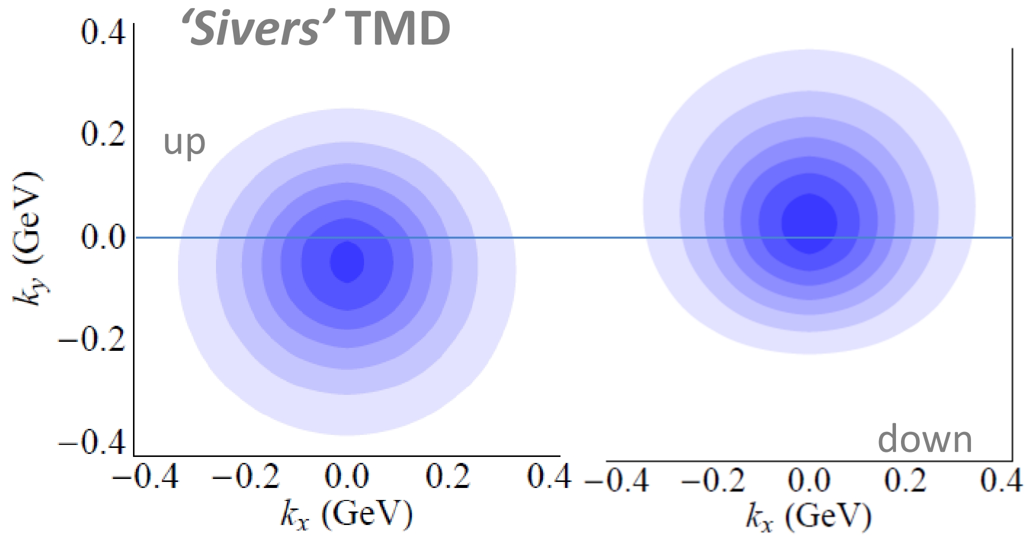

[model calculation by B. Pasquini, F. Yuan]

nucleon tomography

classification of TMDs

polarization of quark / (gluon)

nucleon

[plot: courtesy B. Musch]

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

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survive integration over intrinsic transverse momenta: *collinear approximation*

nucleon tomography

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'Boer-Mulders' fct.

'pretzelosity'

'Sivers' fct.

require interference of nucleon wave fct.s with *different units* **OAM** → *spin-orbit correlations*

nucleon tomography

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'Boer-Mulders' fct.

'pretzelosity'

'Sivers' fct.

all functions or related observables measured: select two TMDs

require interference of nucleon wave fct.s with *different units* **OAM** → *spin-orbit correlations*

nucleon tomography

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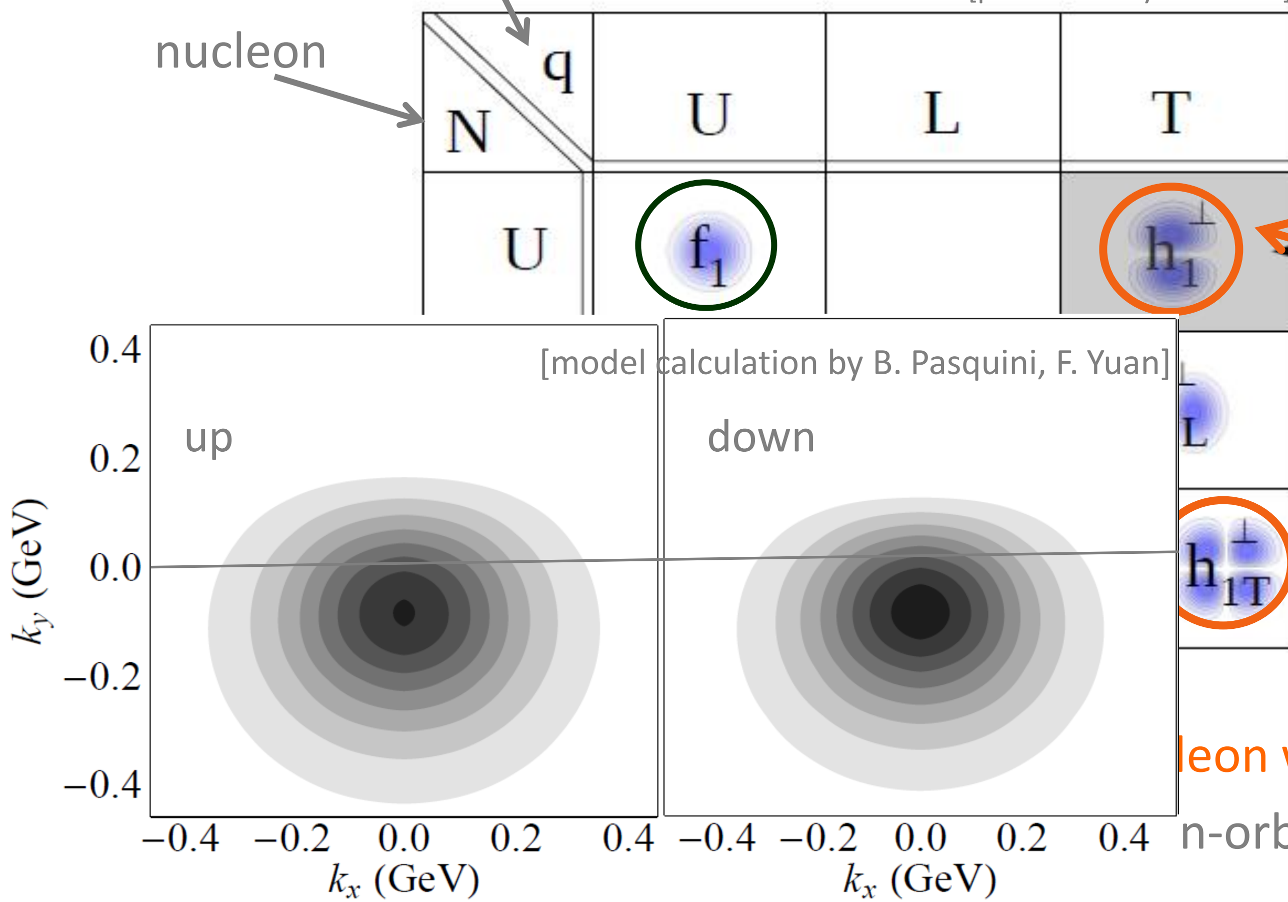
[plot: courtesy B. Musch]



'Boer-Mulders' fct.

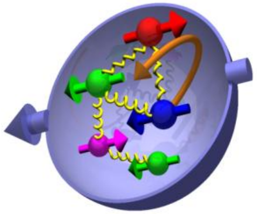
distortion of distribution even for *unpol* protons !
→ interpretation of HIC

'pretzelosity'

leon wave fct.s with

n-orbit correlation

relation to OAM



GPDs

TMDs

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L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$\Delta L=1$
'Boer-Mulders' fct.

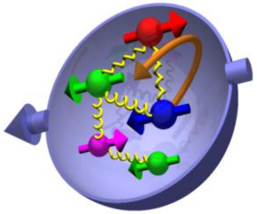
$\Delta L=1$
'Sivers' fct.

$\Delta L=2$
'pretzelosity'

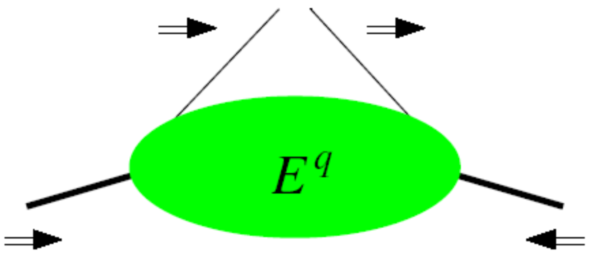
require interference of nucleon wave fct.s with different units OAM

→ spin-orbit correlation

relation to OAM



GPDs



proton helicity flipped but quark helicity conserved

$E^q \neq 0$ *requires* OAM

$$J^q = \Delta\Sigma + L^q = \frac{1}{2}\int x dx\ H^q + E^q$$

[X. Ji, PRL(1997)]

TMDs

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
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ΔL=1
'Boer-Mulders' fct.

ΔL=1
'Sivers' fct.

ΔL=2
'pretzelosity'

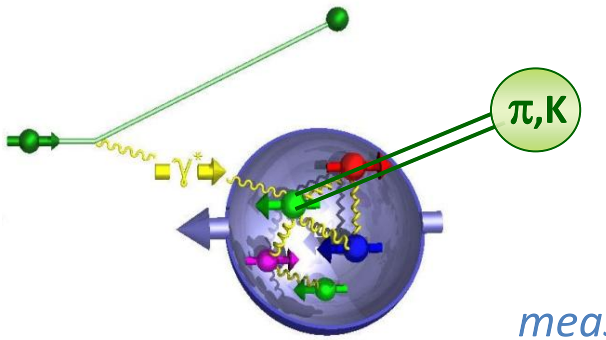
require interference of nucleon wave fct.s with different units OAM

→ spin-orbit correlation

observables of TMD

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

most successfully probed in semi-inclusive DIS:

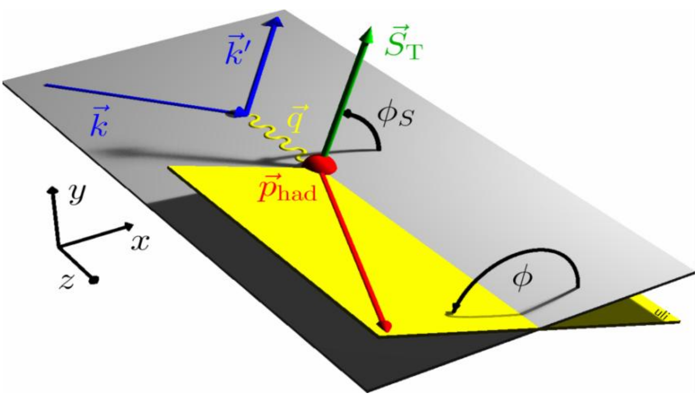


factorization for kinematic regime:

$$P_{hT} \cong k_\perp \cong \Lambda_{QCD} << Q^2$$

measure fully differential cross section:

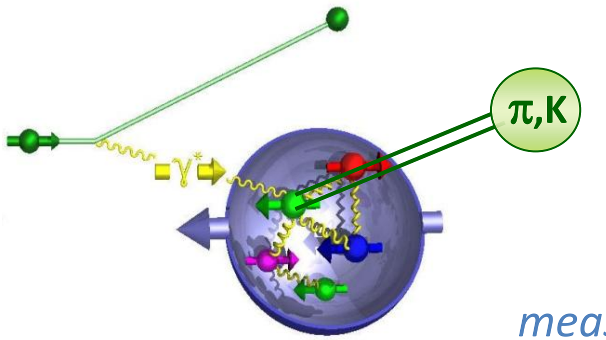
$$\frac{d\sigma}{dx_B\, dy\, d\phi_S\, dz_h\, d\phi_h\, dP_{hT}^2} \propto \Big\{ F_{UU,T} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + S_\parallel\, \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} + S_\parallel\, \lambda_\ell \sqrt{1-\varepsilon^2}\, F_{LL} + |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S)\, F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \Big] + |\boldsymbol{S}_\perp|\, \lambda_e \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots \Big\}.$$



observables of TMD

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

most successfully probed in semi-inclusive DIS:



factorization for kinematic regime:

$$P_{hT} \cong k_\perp \cong \Lambda_{QCD} << Q^2$$

measure fully differential cross section:

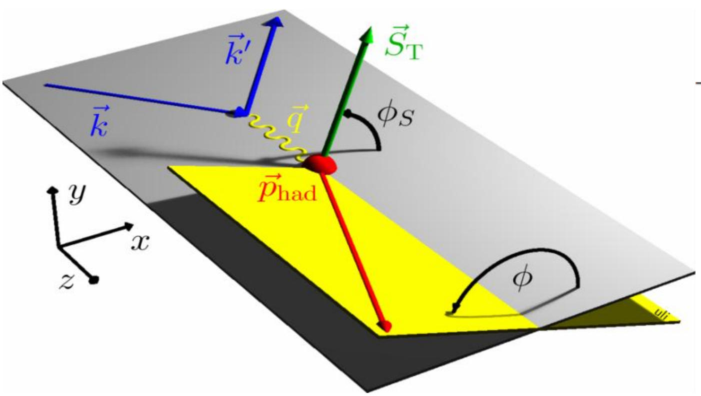
$$\frac{d\sigma}{dx_B\, dy\, d\phi_S\, dz_h\, d\phi_h\, dP_{hT}^2} \propto \Big\{ F_{UU,T} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h}$$

$$+ S_\parallel\, \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} + S_\parallel\, \lambda_e \sqrt{1-\varepsilon^2}\, F_{LL}$$

$$+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S)\, F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \Big]$$

$$+ |\boldsymbol{S}_\perp|\, \lambda_e \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots \Big\}.$$

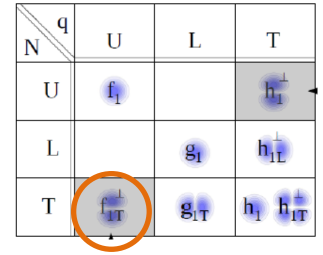


$$F_{UT}^{\sin(\phi-\phi_S)} \prec \sum_q e_q^2\ f_{1T}^{\perp q}(x, k_\perp) \otimes D_1^q(z, P_\perp)$$

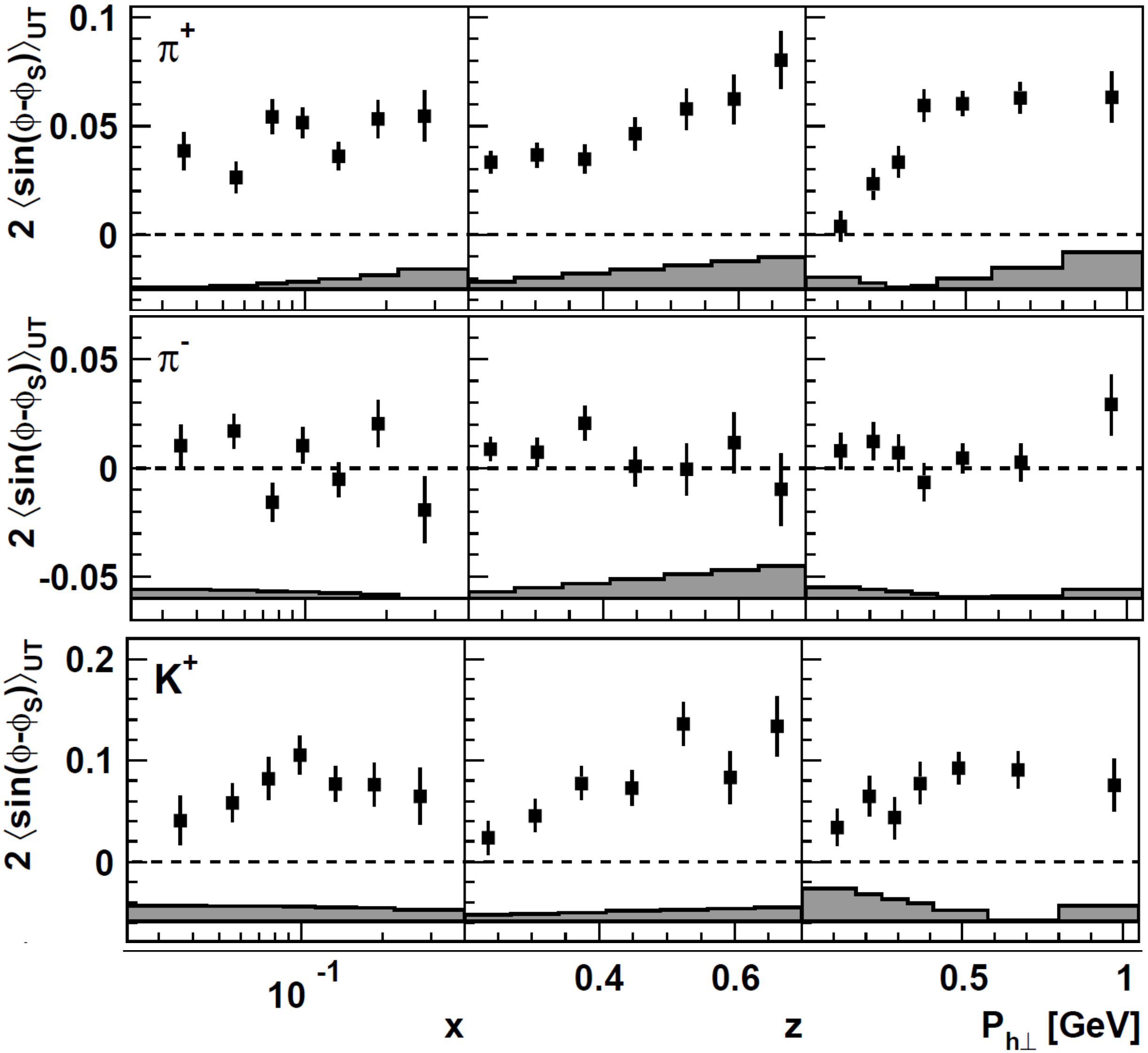
beam target polarisation

Sivers TMD

-- spin-orbit correlations & role of OAM --

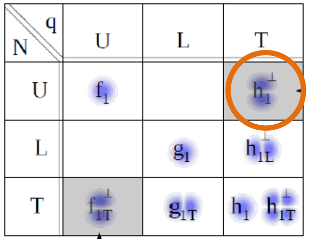


[PRL103(2009)152002]



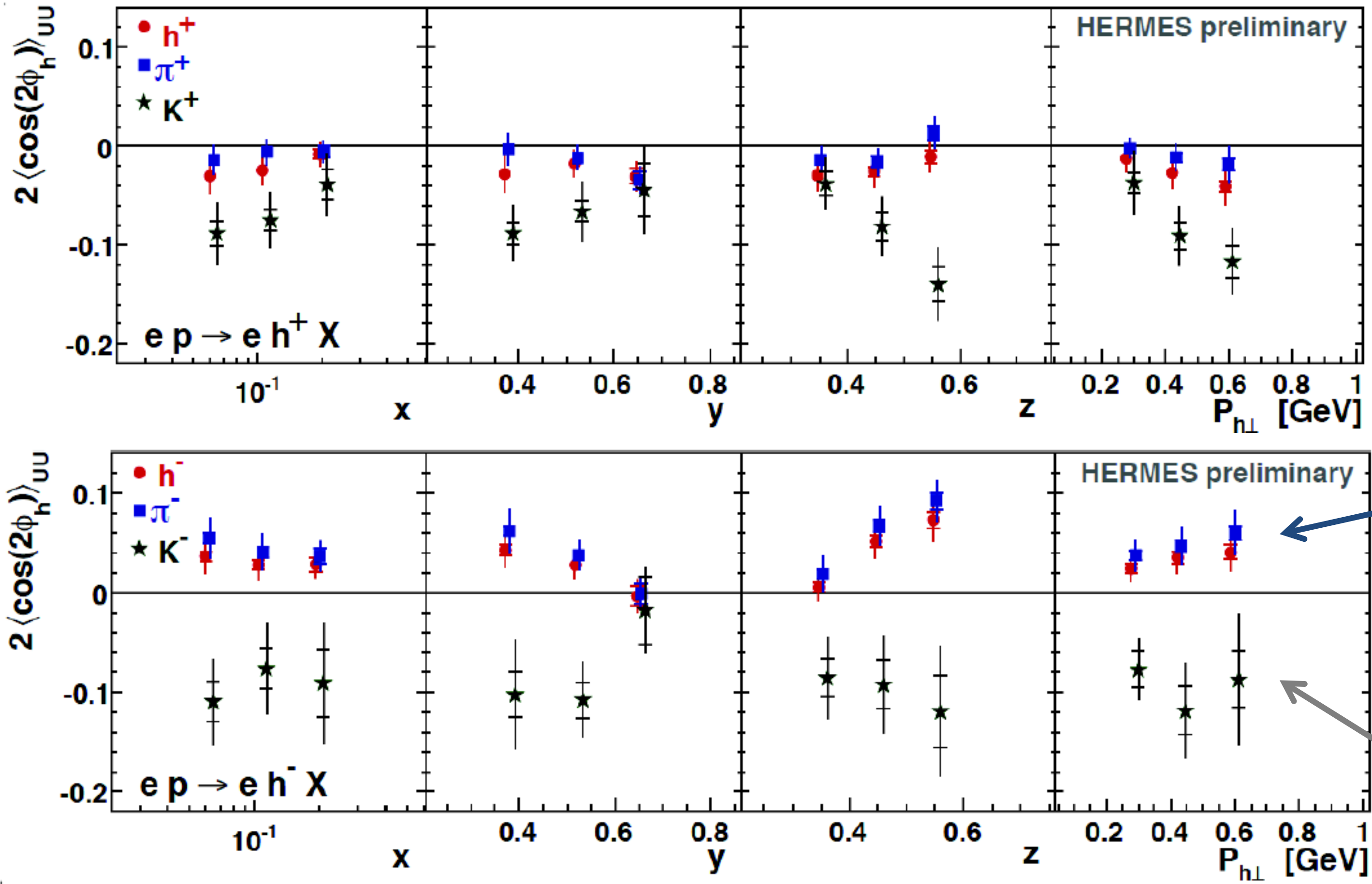
- first clear evidence for signficant role of OAM and effects of spin-orbit correlations
- cancellation of *u* and *d* quark contributions
- surprisingly large signal for K+ role of sea quarks ?

Boer-Mulders TMD



-- spin effects & spin-orbit correlations even in the *unpolarised proton* --

fully differential 5D information available, here only projections shown



➤ intriguing pattern for different hadron types

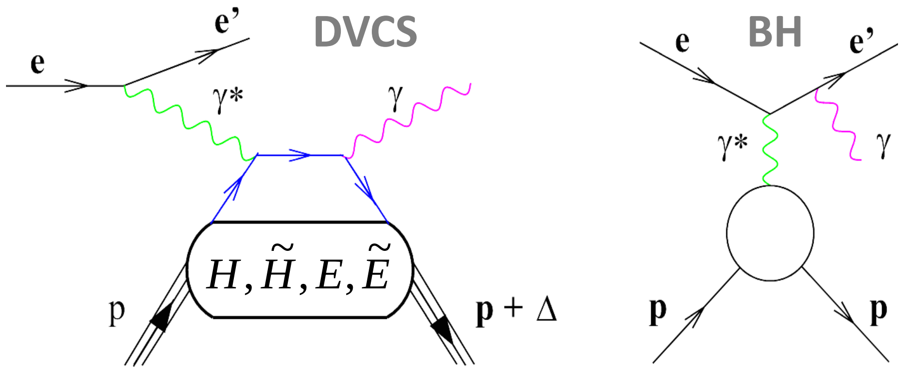
pions

kaons

[arXiv1204.4161, submitted to PRD]

observables of GPDs

golden channel : deeply virtual Compton scattering (DVCS)



$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

→ *linear* in GPDs

isolate interference term:

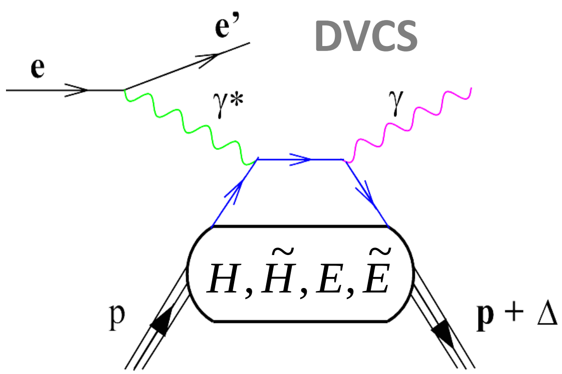
- different beam charges: e^+e^- only @HERA
- polarisation observables: $\Delta\sigma_{UT}(\phi, \phi_S, \ldots)$

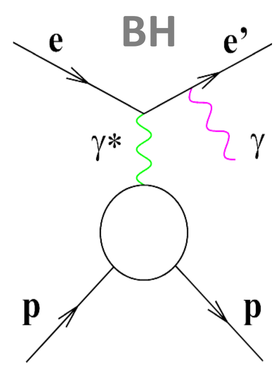
beam | target
U, L | U, L, T

Unpolarised, **L**ongitudinally, **T**ransversely polarised

observables of GPDs

golden channel : deeply virtual Compton scattering (DVCS)





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beam U, L

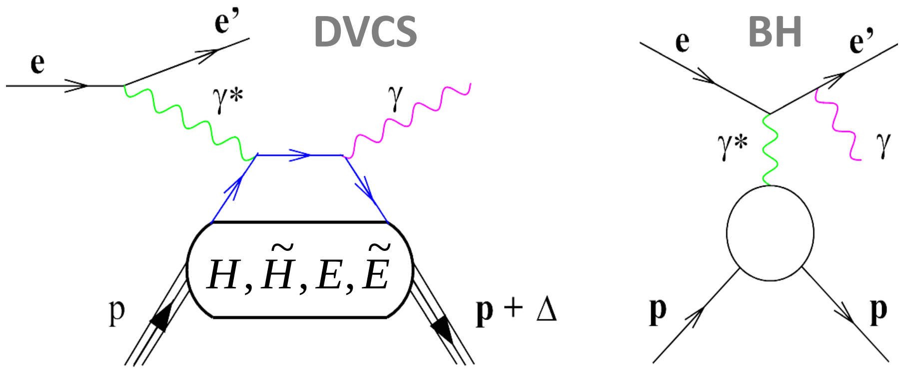
target U, L, T

$\Delta\sigma_C$, $\Delta\sigma_{LU}$	→ H_p, E_n
$\Delta\sigma_{UL}$	→ H, $\widetilde{H}$
$\Delta\sigma_{UT}$	→ H, E

@kinematics of current fixed target exp.

observables of GPDs

golden channel : deeply virtual Compton scattering (DVCS)



$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

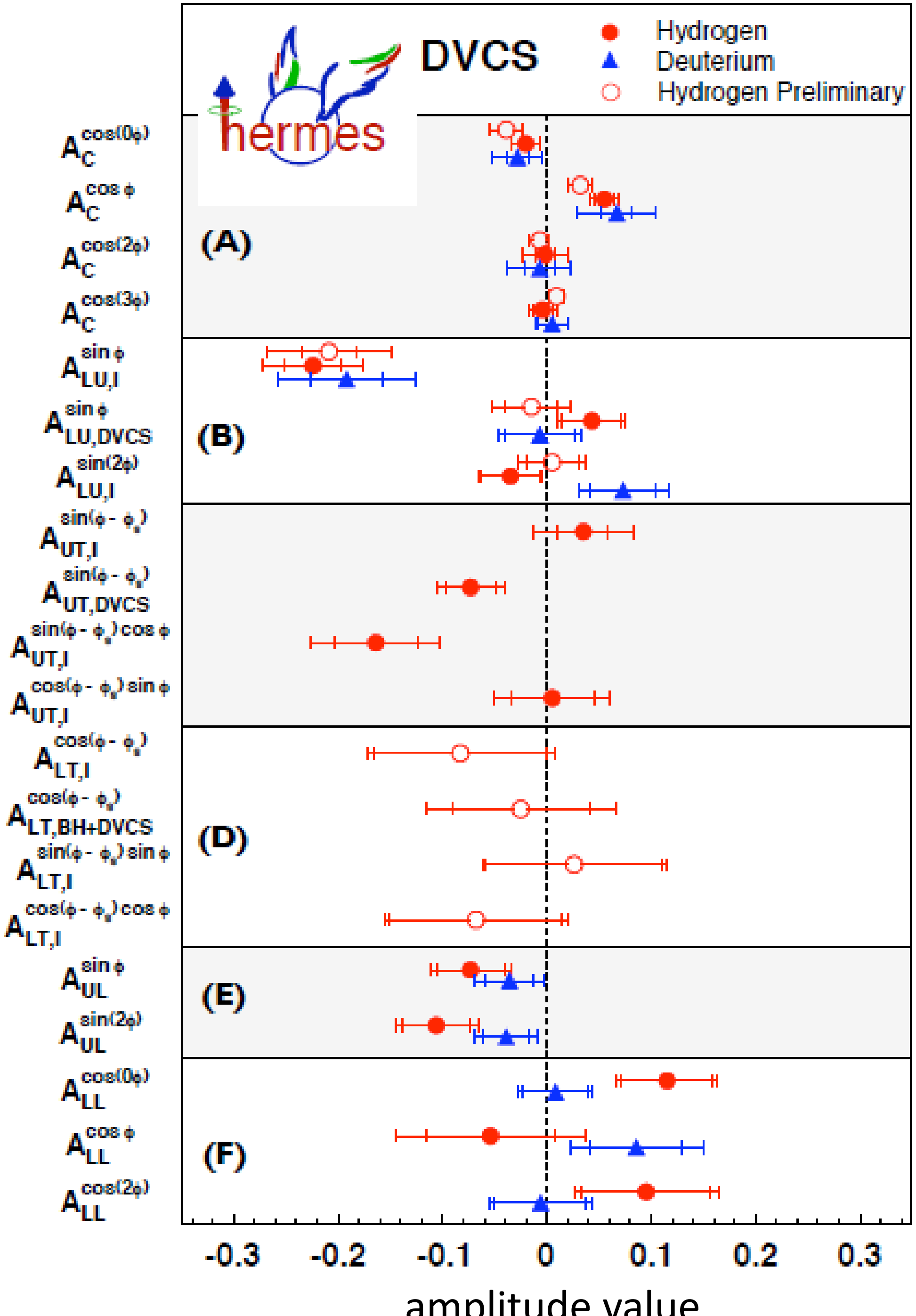
→ *linear* in GPDs

isolate interference term:

→ explore azimuthal dependence of cross section, *e.g.:*

$$\Delta\sigma_{XY} \propto \sum_{n=1}^{3} c^{\mathrm{I}}_{\mathrm{unp},n}\cos(n\phi) + \lambda\sum_{n=1}^{2} s^{\mathrm{I}}_{\mathrm{unp},n}\sin(n\phi)$$

... coefficients related to GPDs



unique data set

→charge asymmetry

Re (H)

→beam-spin asymmetry

Im (H)

→ transverse target spin asymmetry

Im (H-E)

→ transverse-target double-spin

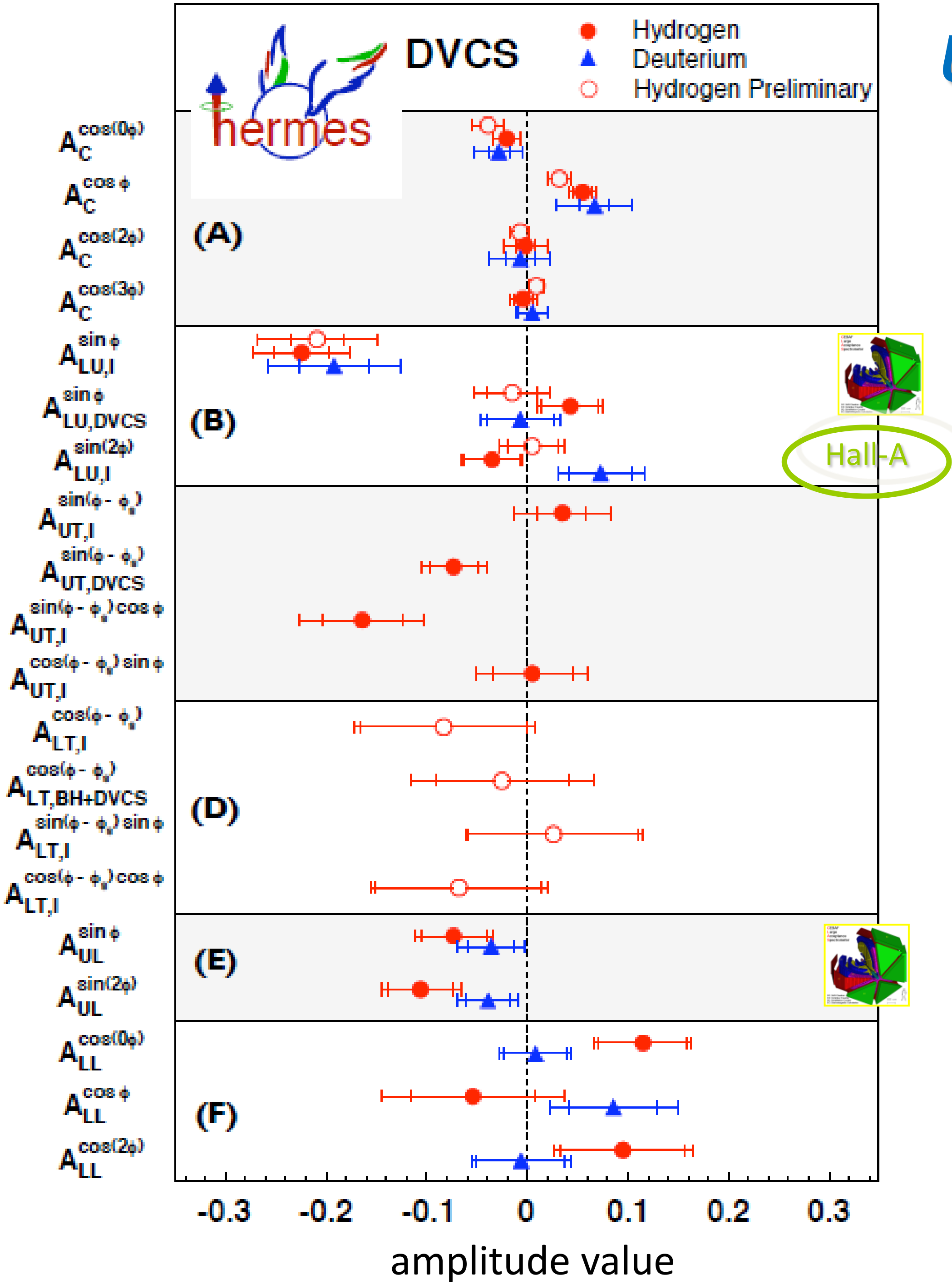
Re (H-E)

→ longitudinal target spin asymm.

Im $(\tilde{H})$

→ longitudinal-target double-spin

Re $(\tilde{H})$



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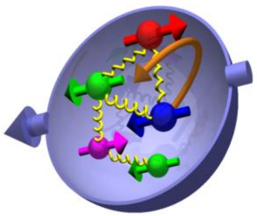
Re ($\tilde{H}$)

GPD *E* & OAM



$$J^q = \Delta\Sigma + L^q = \frac{1}{2}\int x dx\, H^q + E^q$$

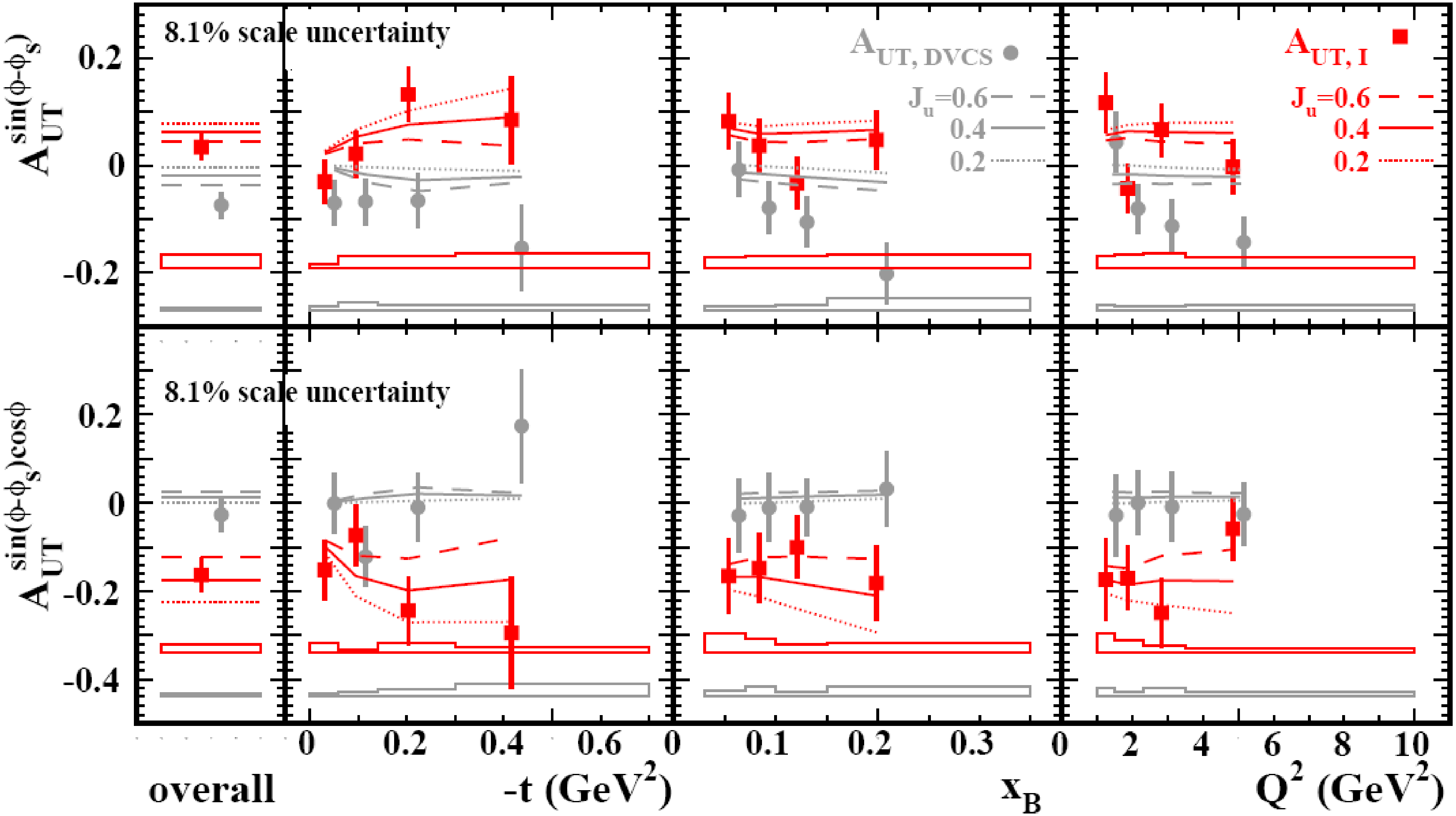
$\Delta\sigma_C$, $\Delta\sigma_{LU}$	→ H_p, E_n	Hall-A
$\Delta\sigma_{UL}$	→ H, $\tilde{H}$	
$\Delta\sigma_{UT}$	→ H, E	

@kinematics of current fixed target exp.

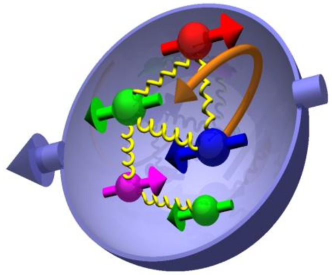
GPD *E* & OAM

$$J^q = \Delta\Sigma + L^q = \frac{1}{2}\int x dx\, H^q + E^q$$

→ GPD models: J^q free parameter in ansatz for E [JHEP06(2008)]



HERa MEasurment of Spin



summary

- ❑ 2nd generation *polarised* DIS experiment @HERA: polarised $e^{+/-}$ beam & novel target technology of storage cell with pure nuclear-polarised H or D

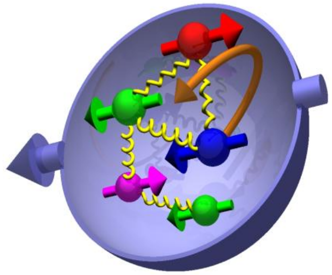
- ❑ ***mission:* exploring the nucleon structure *beyond* fully inclusive DIS**

many ***pioneering*** measurements:

→ first direct 5-flavour extraction of helicity distributions

→ quest for the orbital angular momentum:

HERa MEasurment of Spin



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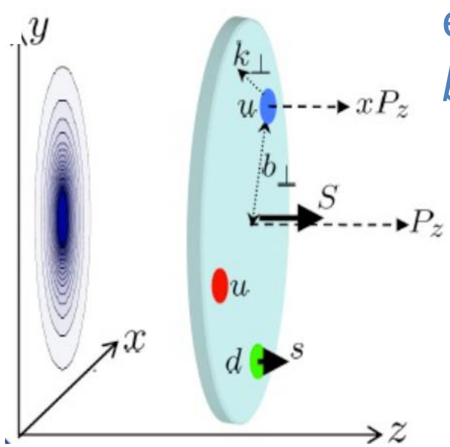


exploring novel distributions: **GPD**s & **TMD**s, wich go *beyond the collinear approximation* → nucleon tomography

from first signals of GPDs & TMDs
to the
most complete data set measured so far

for additional information, please have a look at the following pages...

Δq and ΔG from NLO QCD fits

@**N**ext-to-**L**eading **O**rder in α_s:

$$g_1^{NLO}(x, Q^2) = g_1^{LO} + \frac{1}{2}\langle e^2\rangle \sum_q e_q^2 [\underline{\Delta q(x, Q^2)} \otimes C_q + \underline{\Delta g(x, Q^2)} \otimes C_g]$$

$\Delta f(x)$ … to be measured (parametrised) !

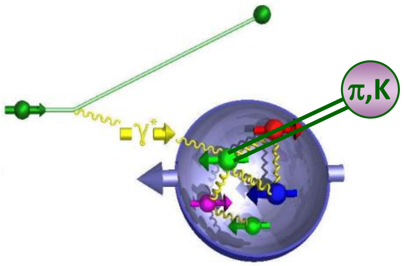
$\Delta f(x, \mathbf{Q^2})$ … fully calculable in QCD !
(splitting functions)

→ *different Q^2 evolution for different quark flavour and for gluons*

$$\chi^2 = \sum_{data} \frac{(g_1^{meas} - g_1^{calc})^2}{\sigma_{stat}^2}$$

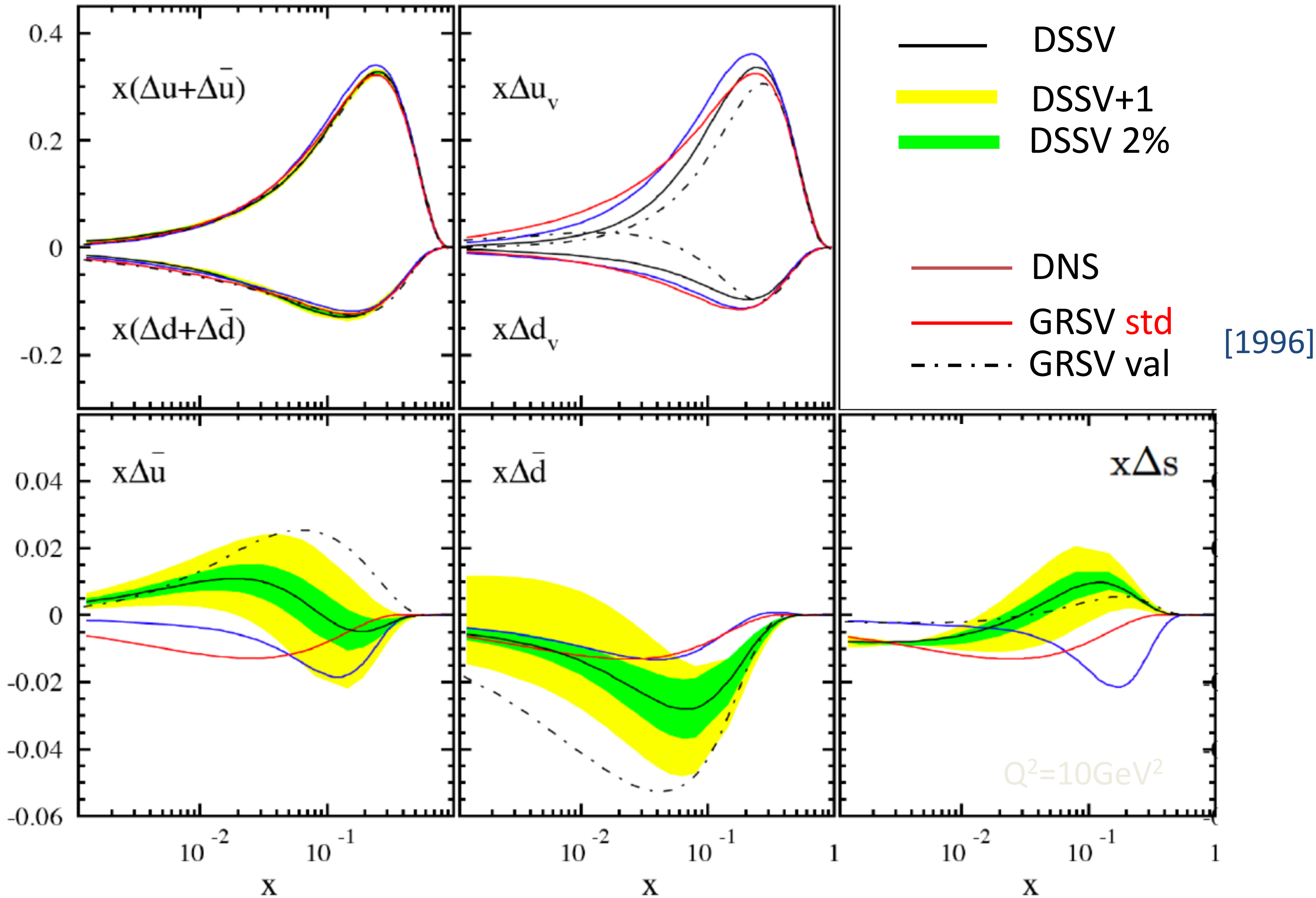
→ **requires** g_1 data in wide kinematic range in x and Q^2

polarised pdfs: Δq

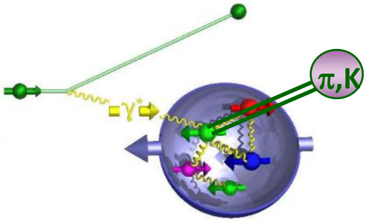


results driven by inclusive and *semi* -inclusive DIS

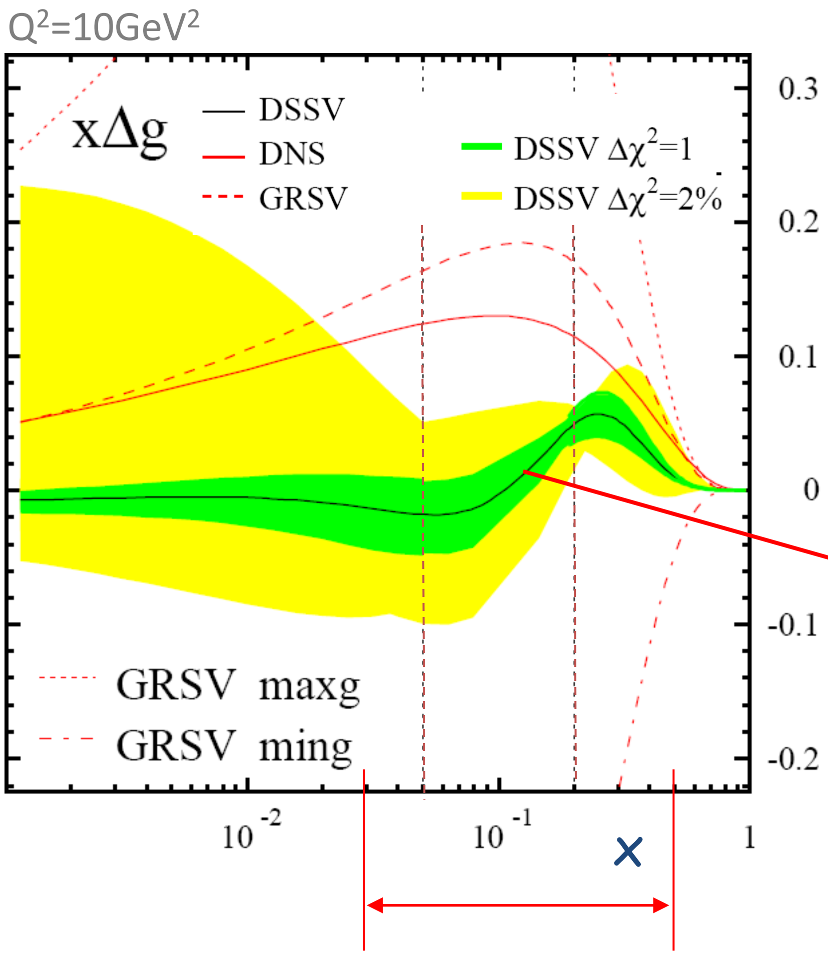
[DSSV, PRL101(2008), PRD(2009)]

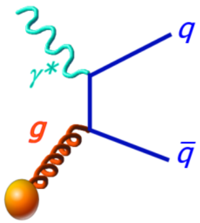


polarised pdfs: ΔG

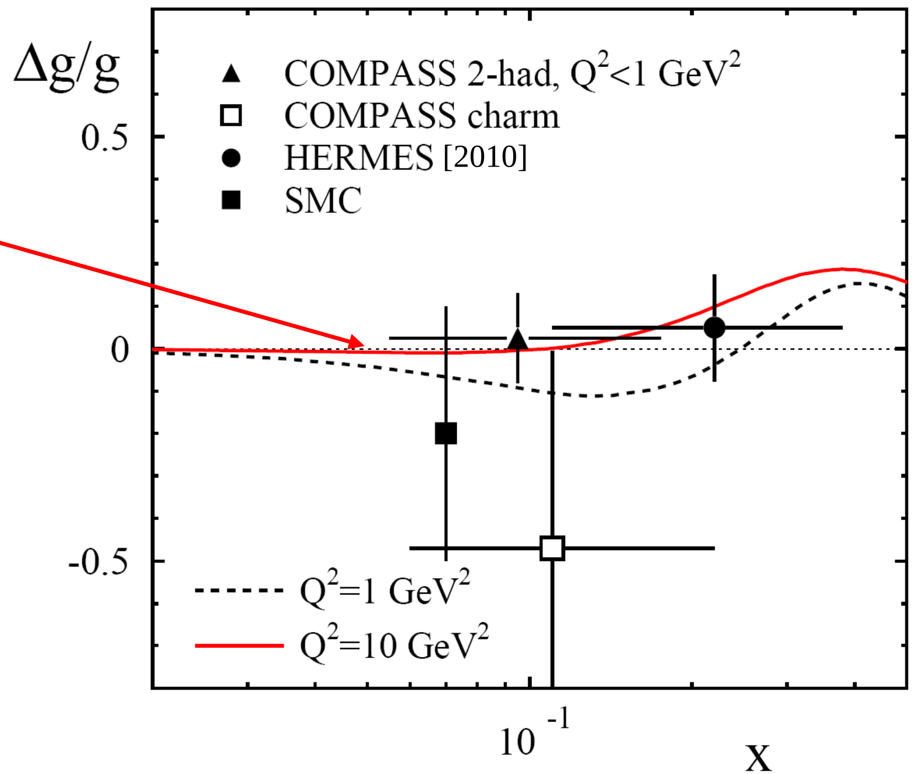


results driven by inclusive DIS & *pp-scattering data*

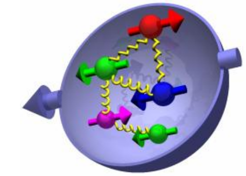




model dependent
LO analyses of **PGF**
process in DIS:



polarised pdfs: Δq & ΔG



global analysis of polarised DIS & pp-scattering data

contributions to nucleon spin:

$$\Delta f \equiv \int_{x_{\min}}^{1} dx\, \Delta f(x)$$

Q^2=10GeV^2

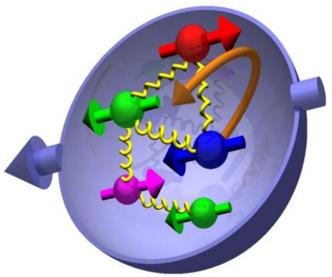
	$x_{\rm min} = 0$	$x_{\rm min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\boxed{\Delta\Sigma}$	$\boxed{0.242}$	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

[DSSV, PRL101(2008), PRD(2009)]

- **Δs** receives large negative contribution @small x
- **Δg:** hughe uncert. below $x \approx 0.01$ → 1st moment *undetermined*

call for new facilities: high energy polarised ep collider needed !

the quest for the orbital angular momentum



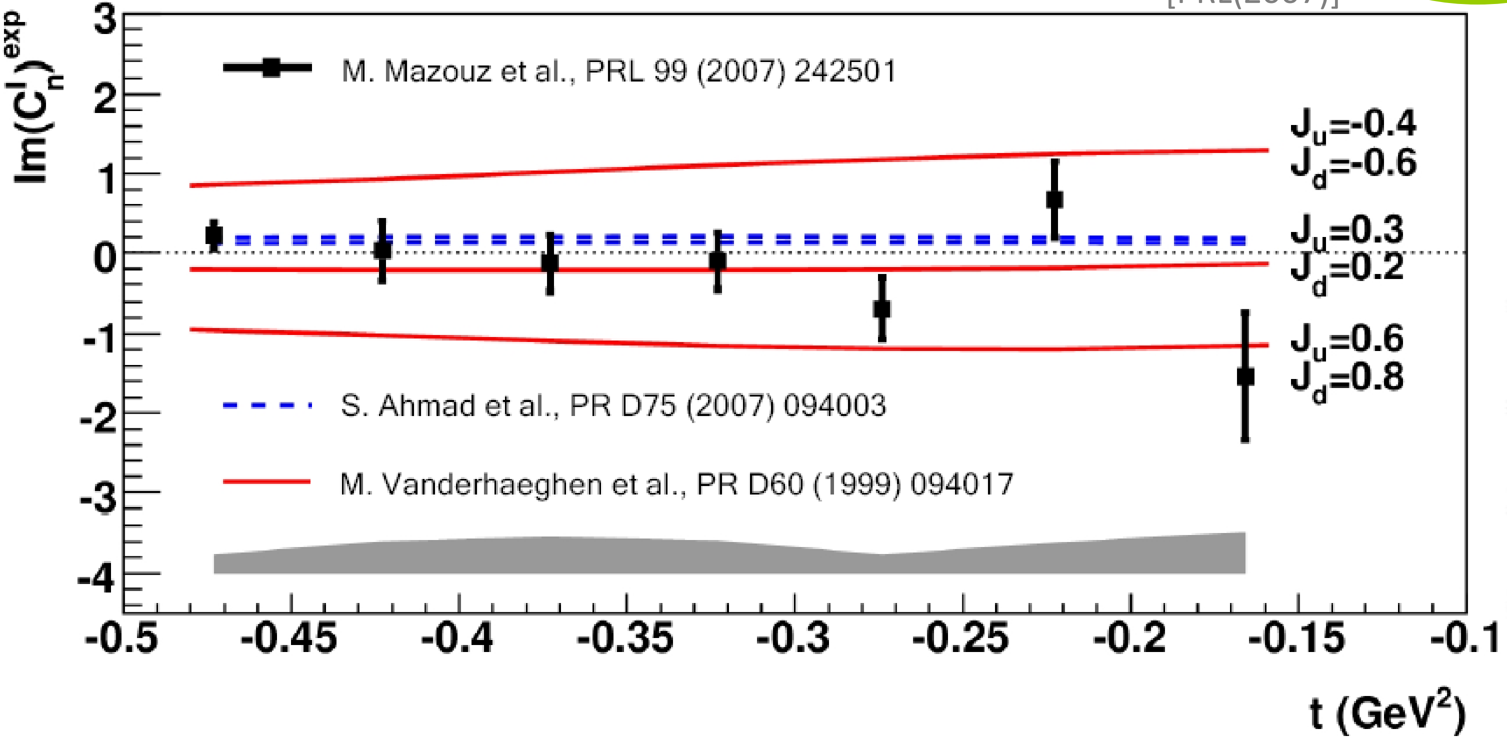
hunting the OAM

-- nDVCS : beam-spin cross section difference --

→ GPD models: J^q free parameter in ansatz for E

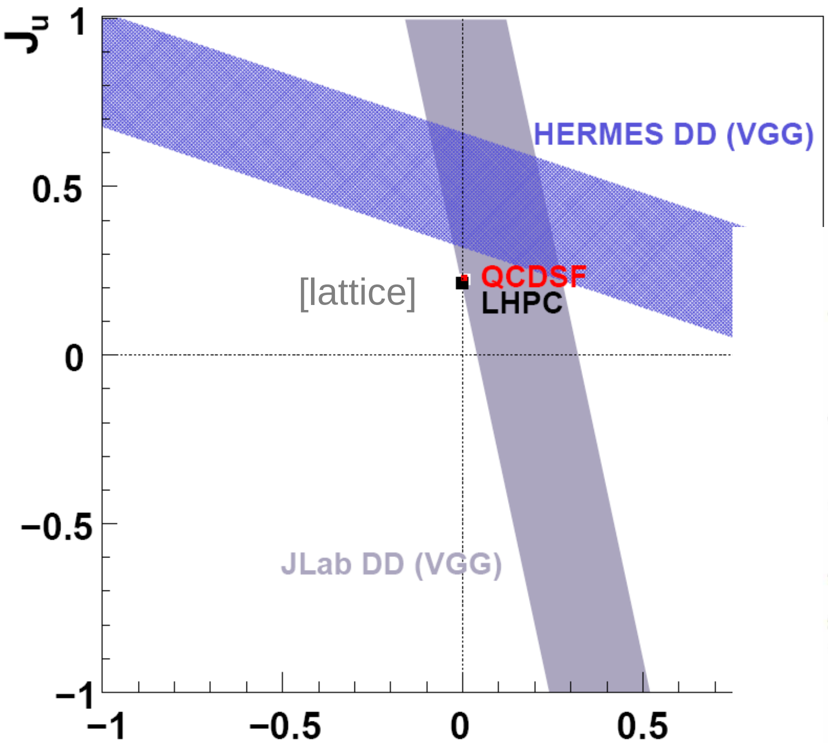
Hall-A

[PRL(2007)]

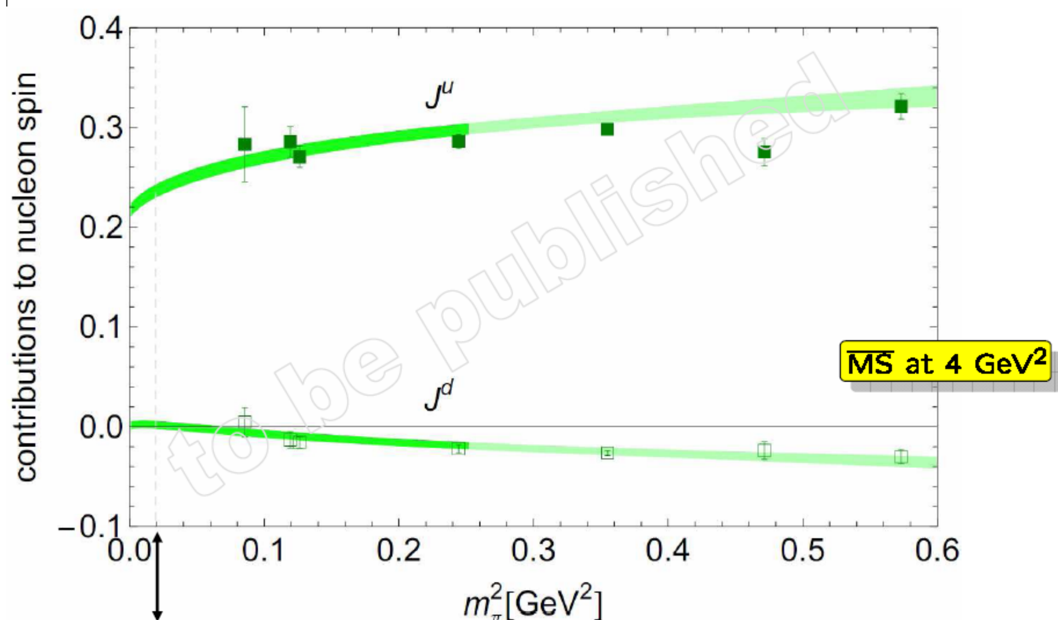


hunting the OAM

-- *model dependent* [VGG(1999)] constrain of J_u vs J_d --



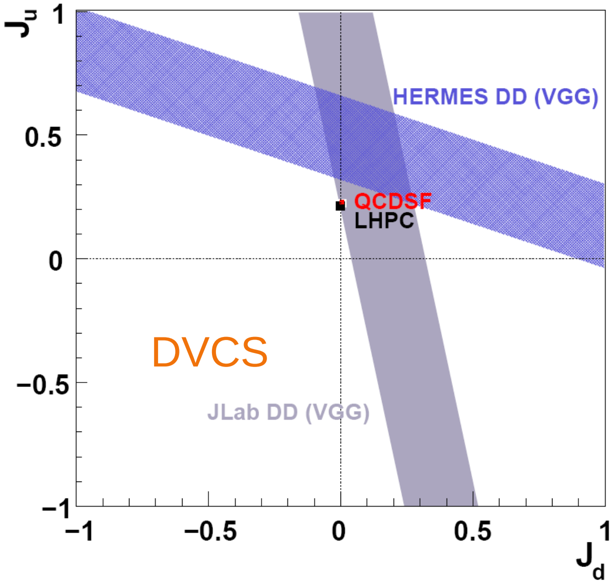
lattice in more detail:

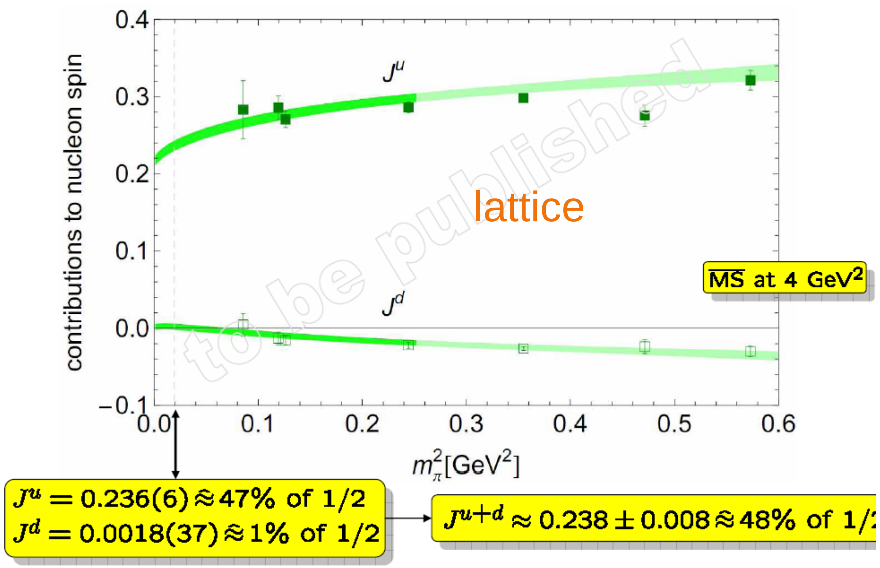


$J^u = 0.236(6) \approx 47\%$ of $1/2$
$J^d = 0.0018(37) \approx 1\%$ of $1/2$

$J^{u+d} \approx 0.238 \pm 0.008 \approx 48\%$ of $1/$

hunting the OAM





- *GPD* model tuned to VM [GK (2008)]

J^u	J^d	J^s	J^g
0.250	0.020	0.015	0.214
0.276	0.046	0.041	0.132
0.225	-0.005	-0.011	0.286
0.209	0.013	0.015	0.257
0.230	0.024	0.015	0.228
0.234	0.028	0.019	0.214

variants for GPD *E*

- *TMD* models: [→ A. Bachetta]

model dependent relation:

$$f_{1T}^{\perp(0)a}(x; Q_L^2) = -L(x)\, E^a(x, 0, 0; Q_L^2)$$

$$J^u = 0.266 \pm 0.002^{+0.009}_{-0.014},$$

$$J^d = -0.012 \pm 0.003^{+0.024}_{-0.006}$$