Exploring the proton structure with TMDs in SIDIS

Francesca Giordano
Riken, Wako, Japan, 30 June 2015

* from Symmetry Magazine

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Proton Structure

1970s:
Quantum ChromoDynamics

2015:
still not able to describe QCD fundamental state: the proton

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Small distances:
Asymptotic freedom,
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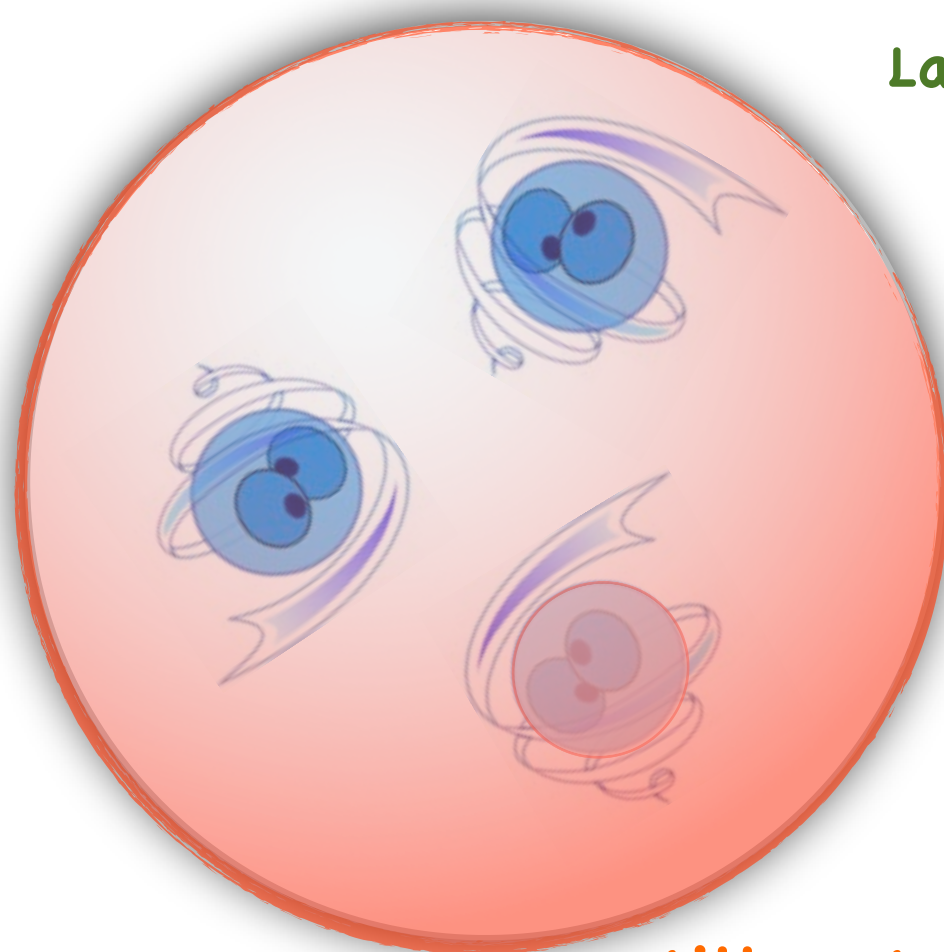

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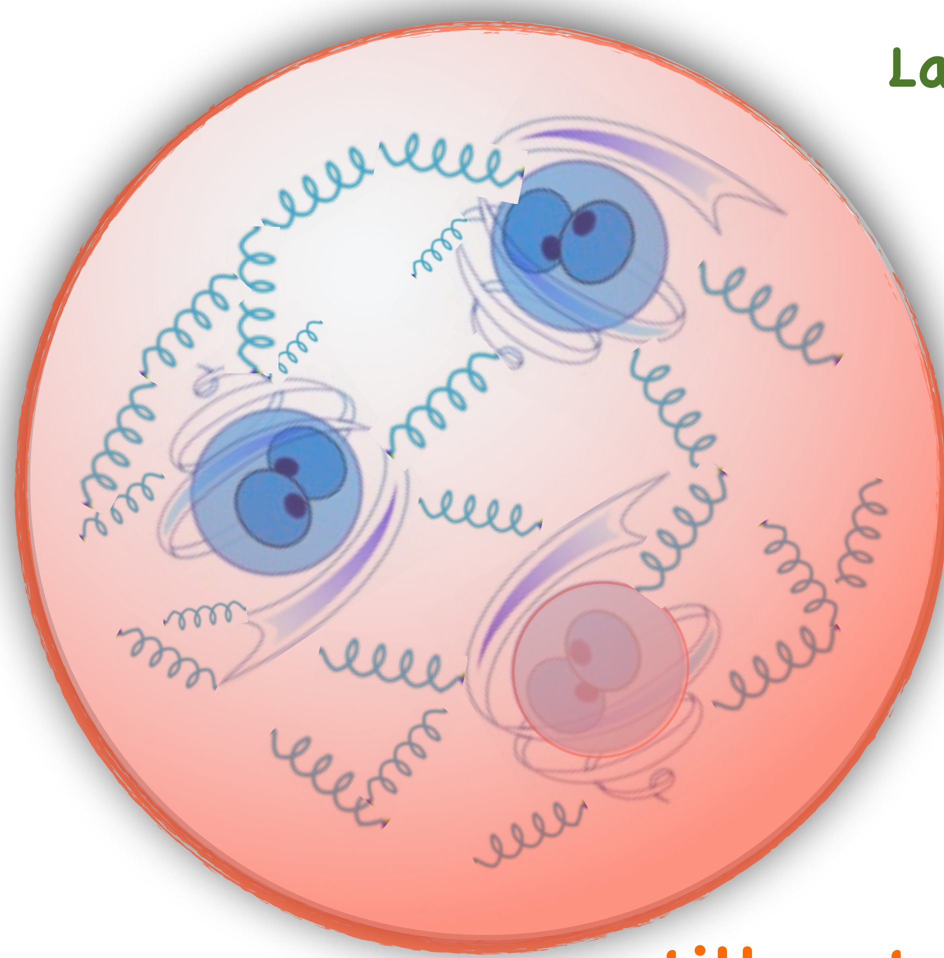

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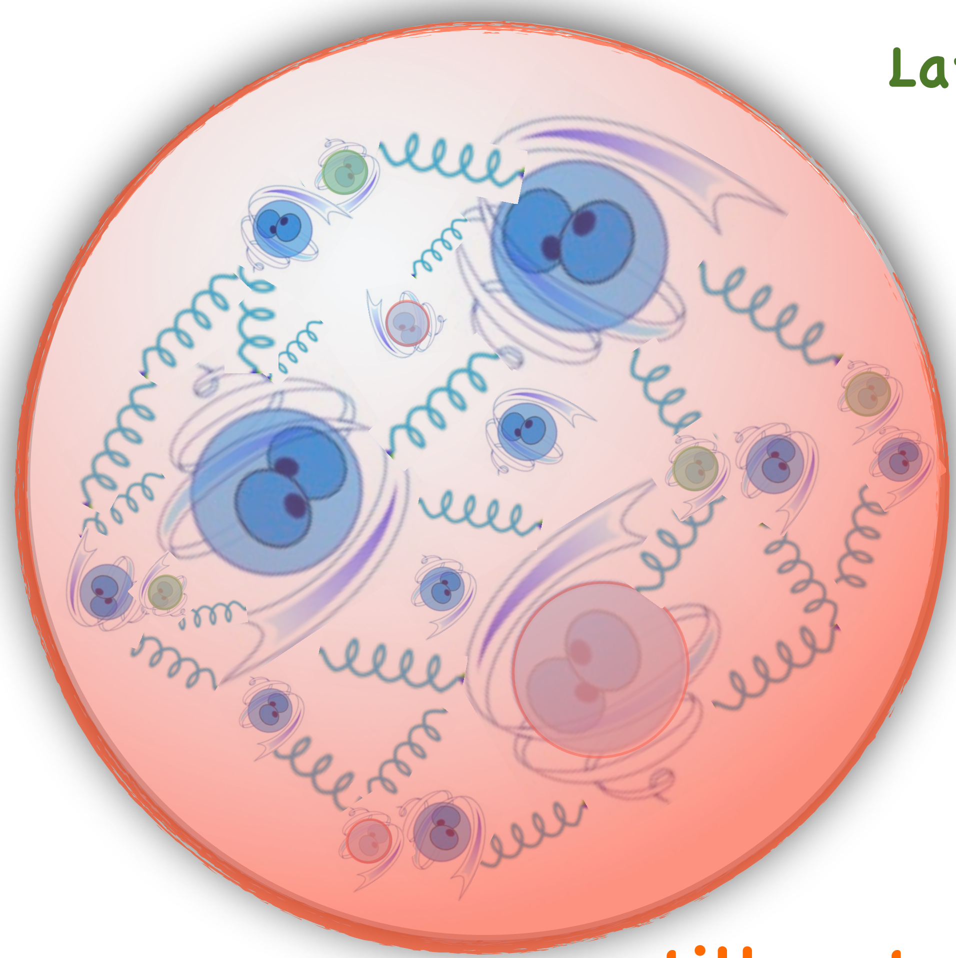

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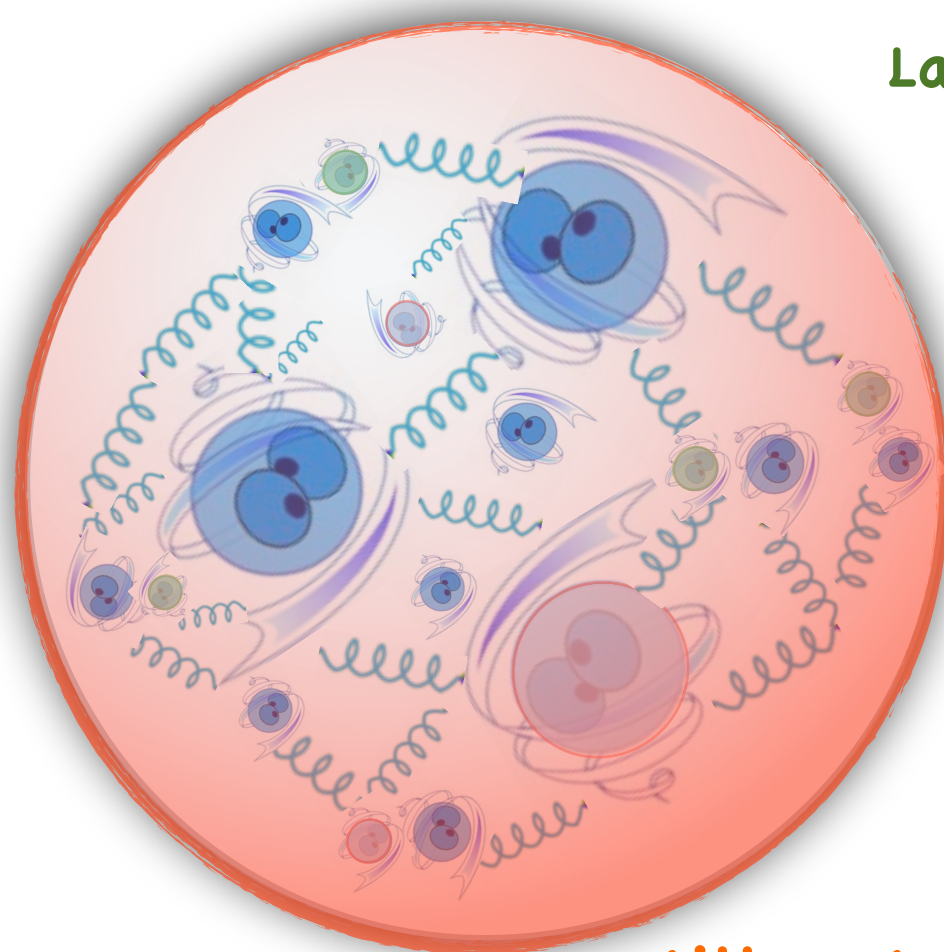

Proton Mass

Higgs ~1%

Quarks ~5%

Gluons ~95%

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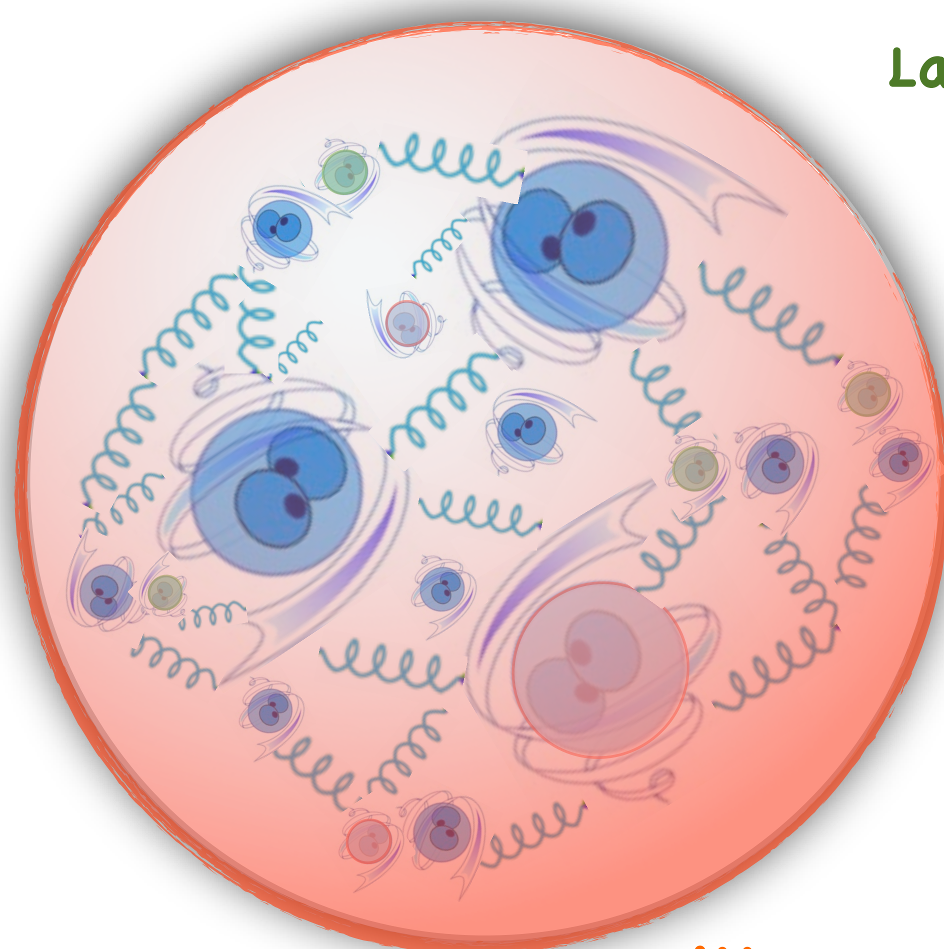

Higgs ~1%

	Proton Mass	Proton Momentum
Quarks	~5%	~50%
Gluons	~95%	~50%

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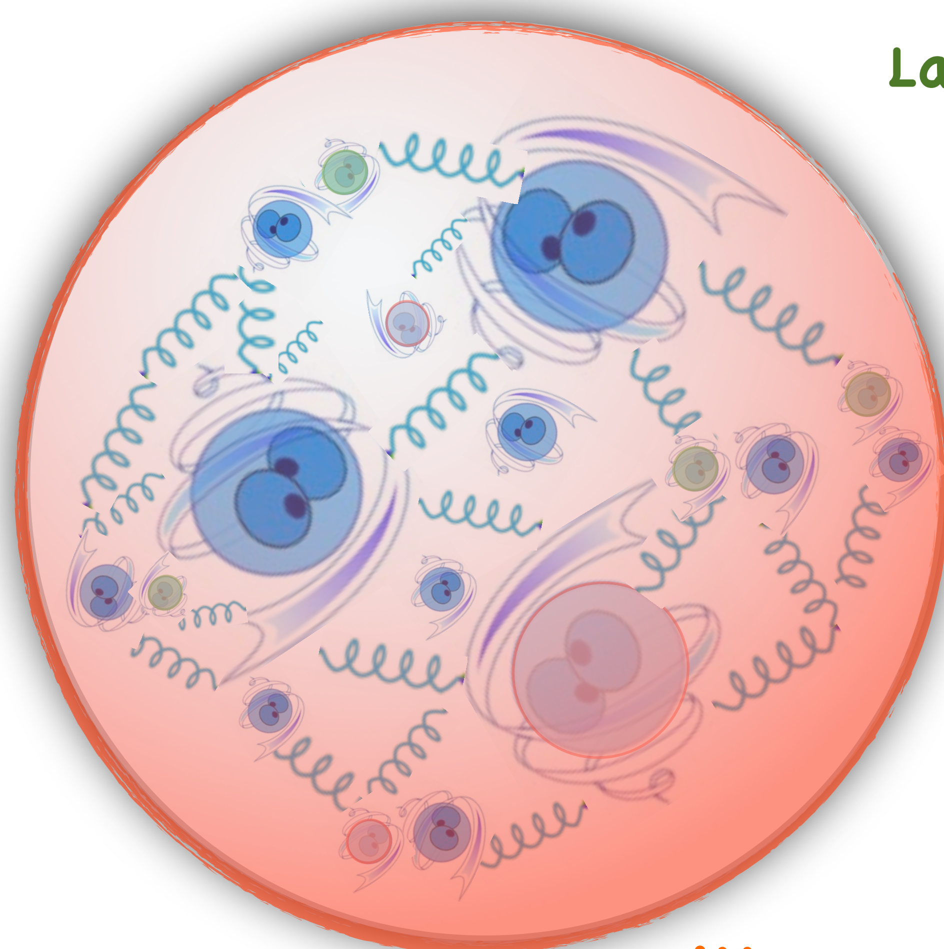

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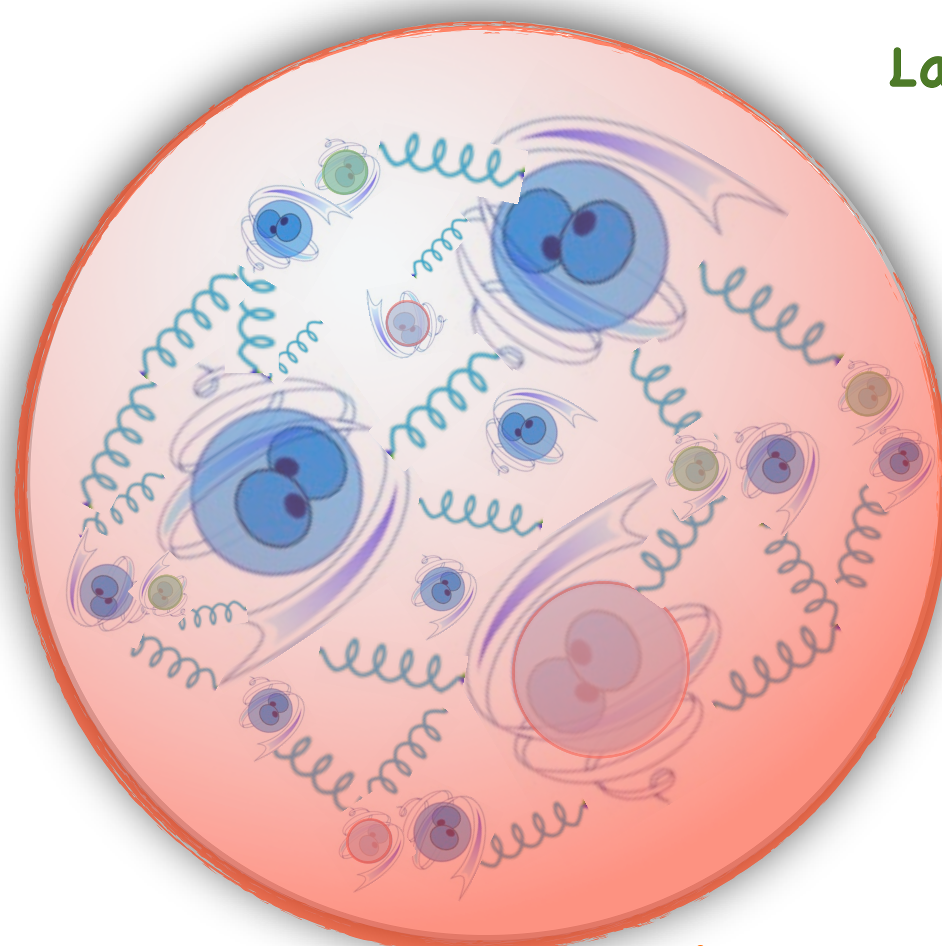
Where is the Spin of the Proton?



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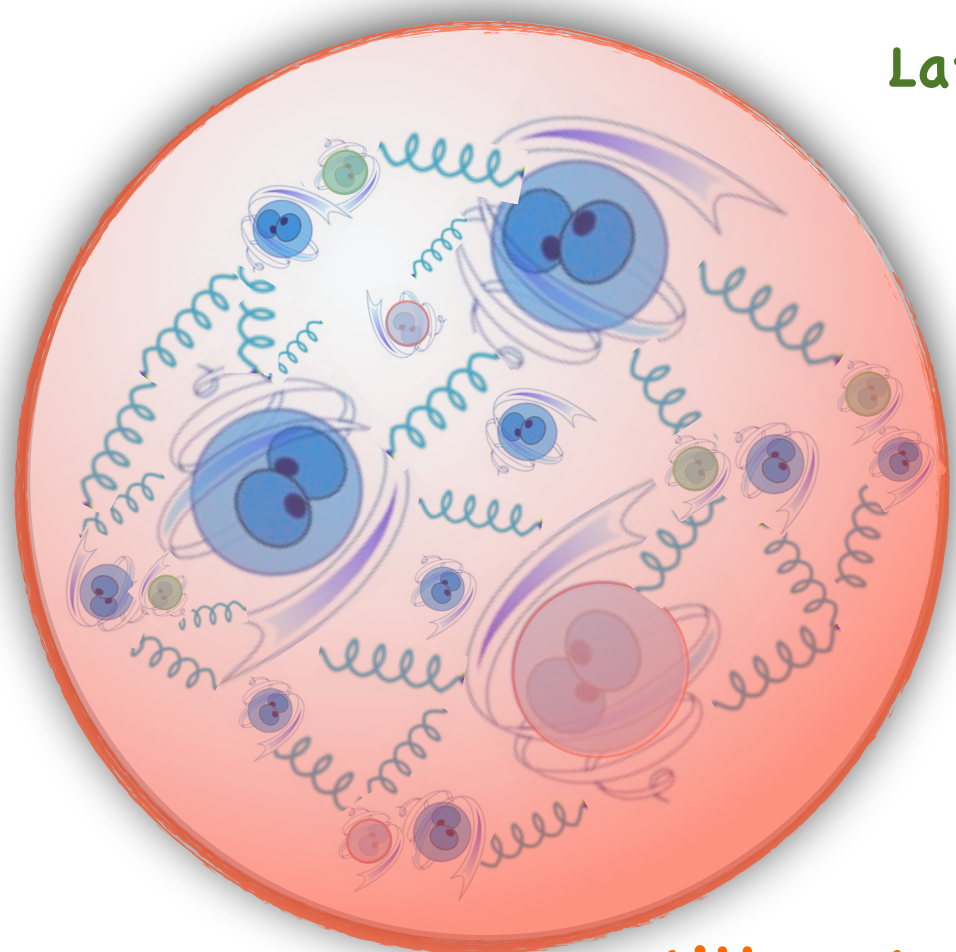
Where is the Spin of the Proton?

How are Quarks and Gluons distributed in the Proton?



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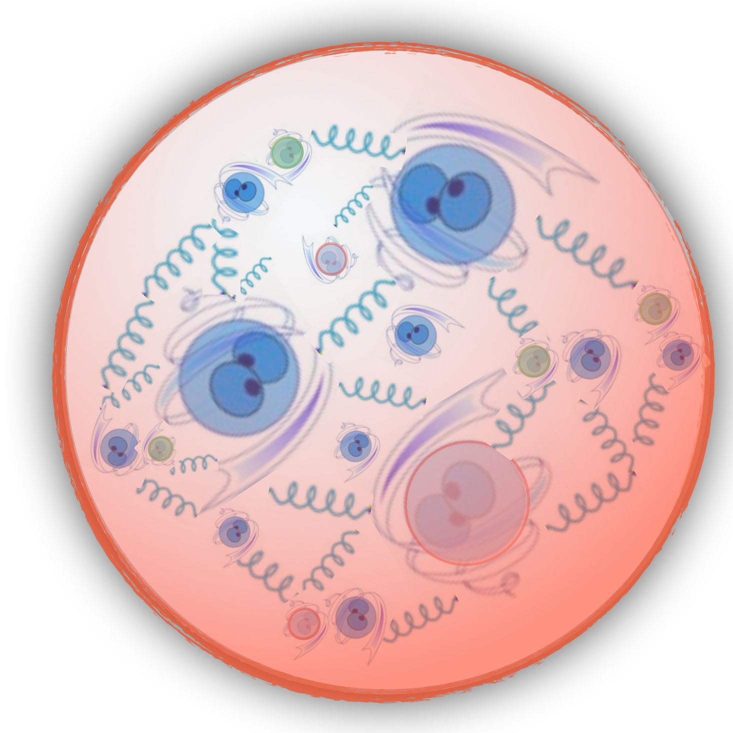

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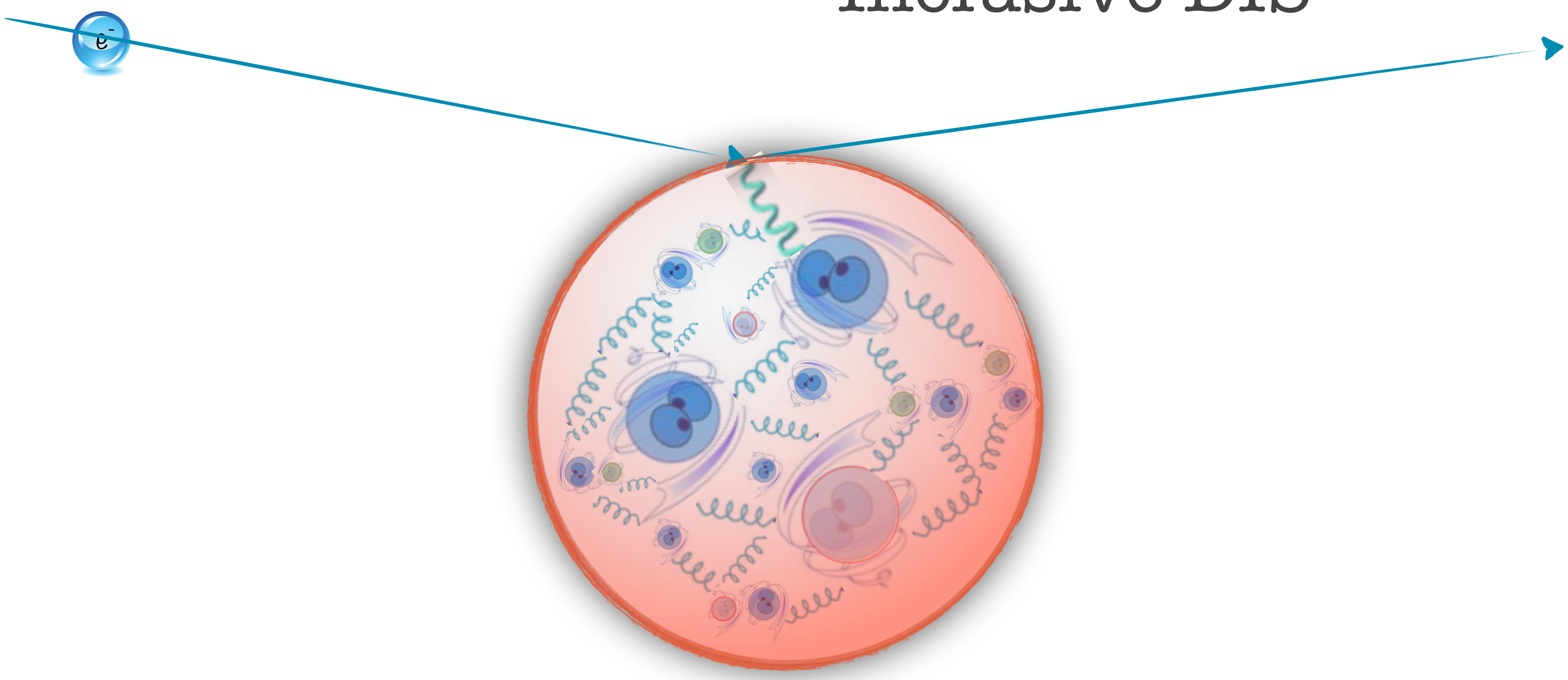

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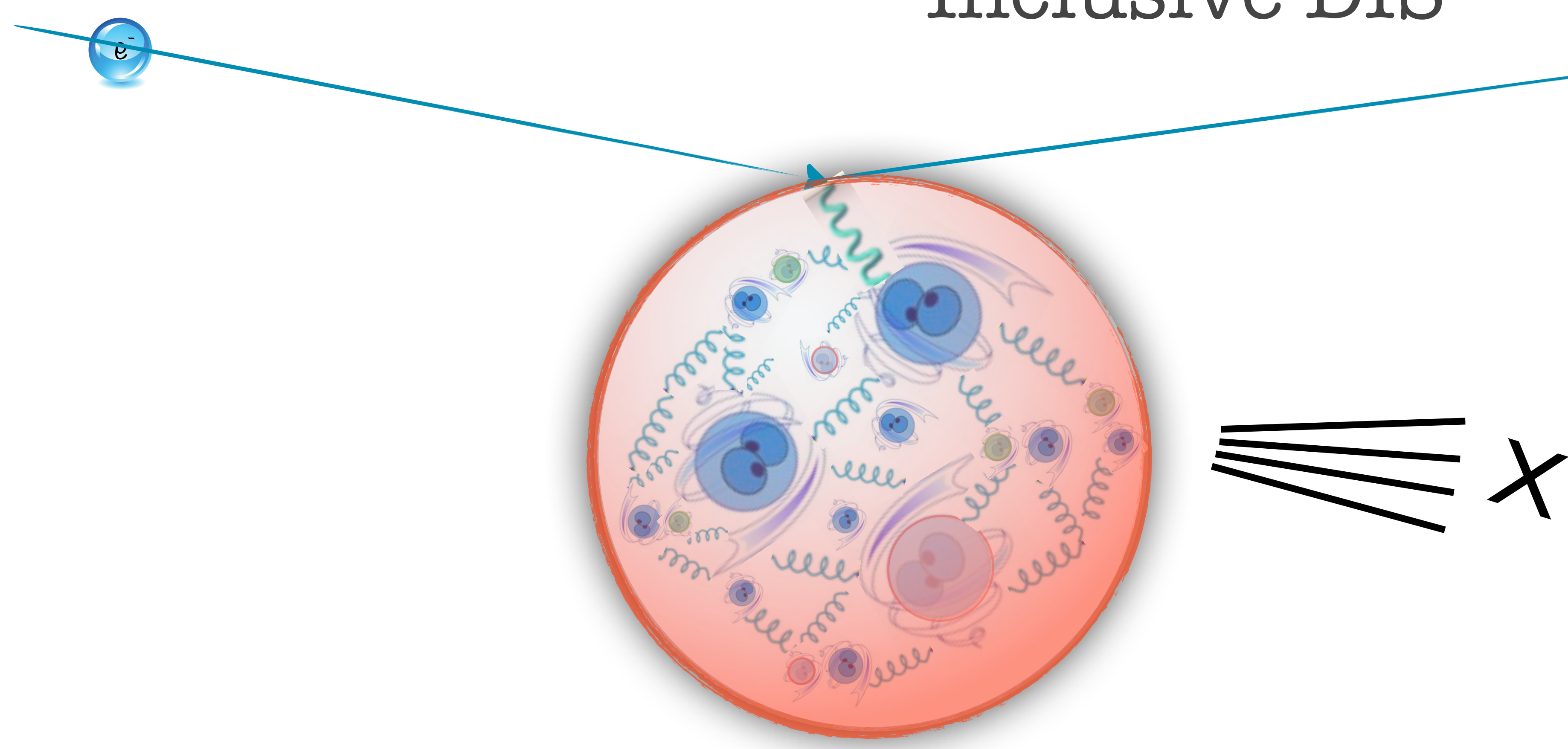

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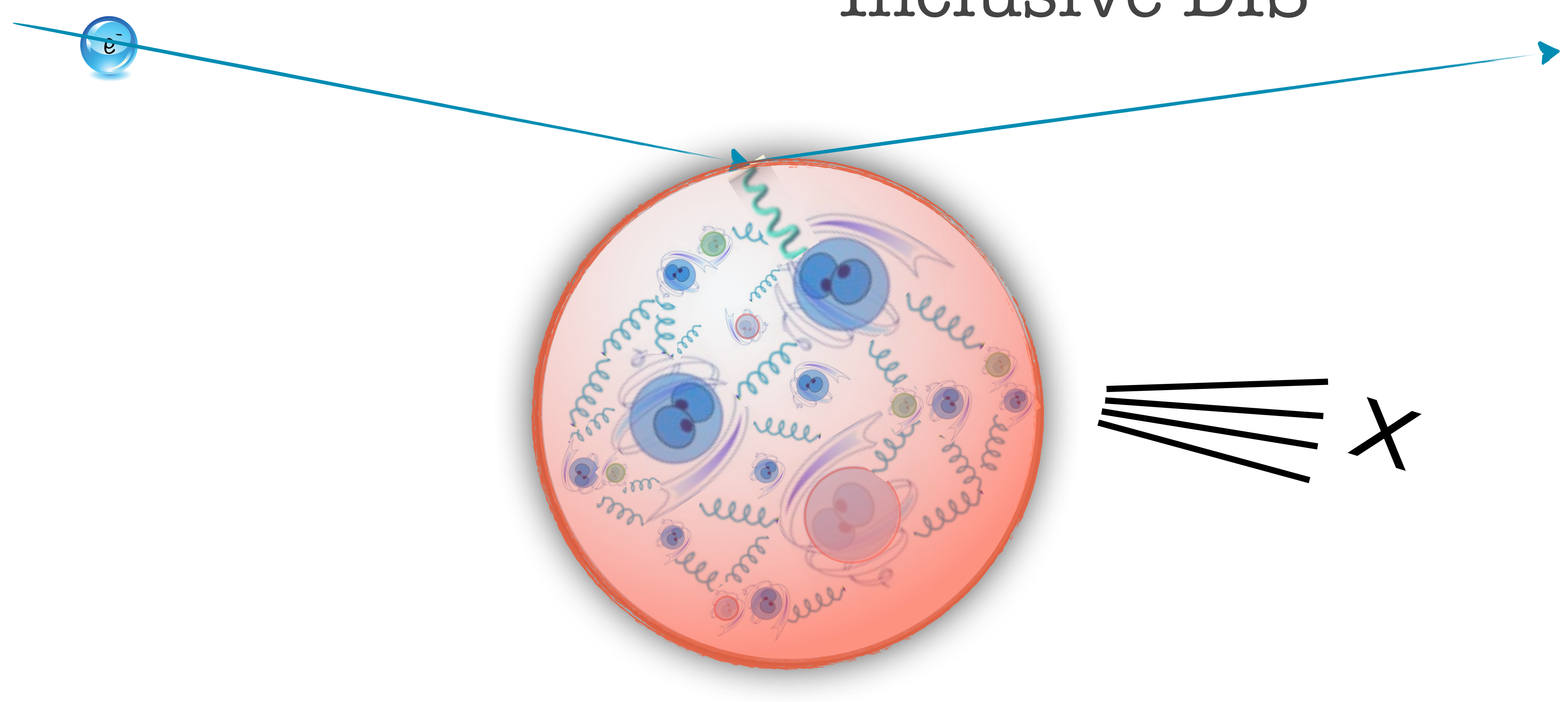

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

Proton Structure

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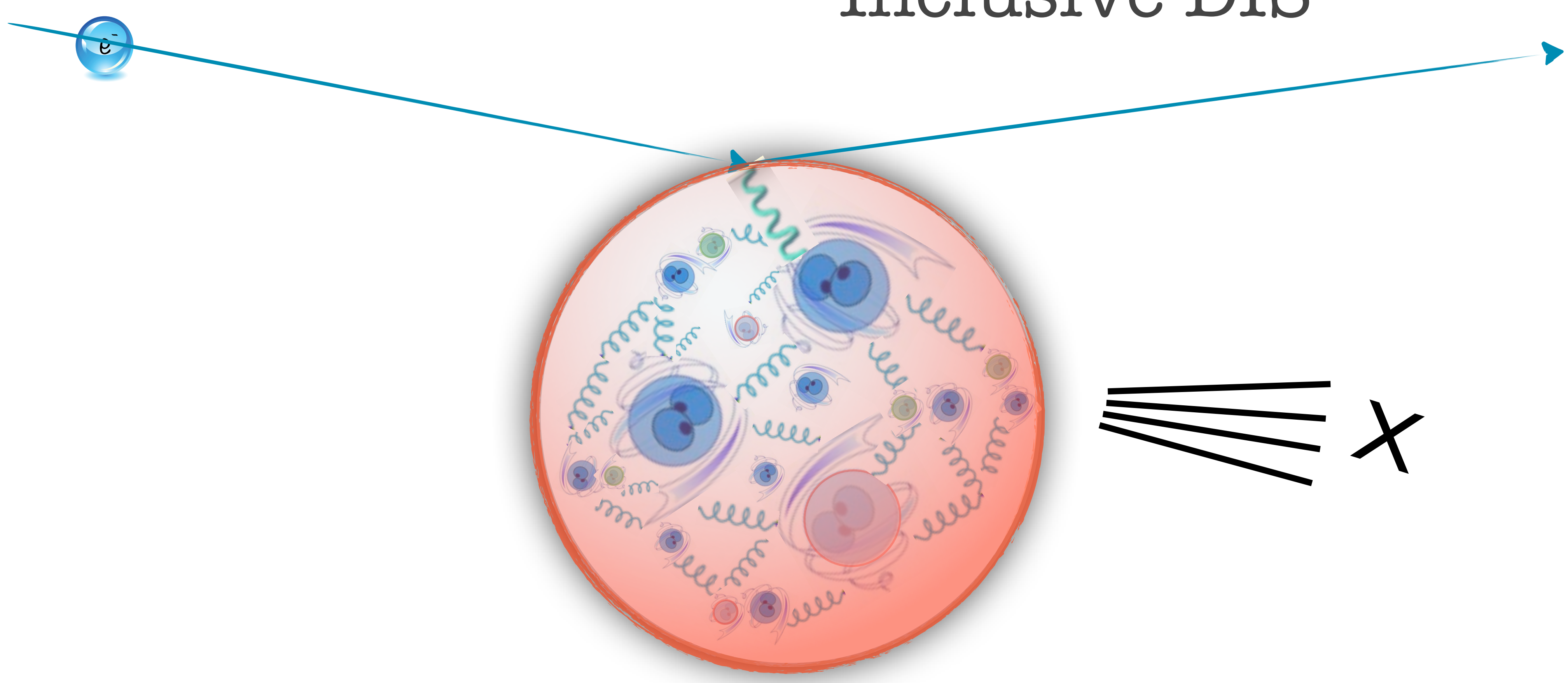

Leptonic Tensor: describes emission of single photon:
Calculable from QED

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Proton Structure

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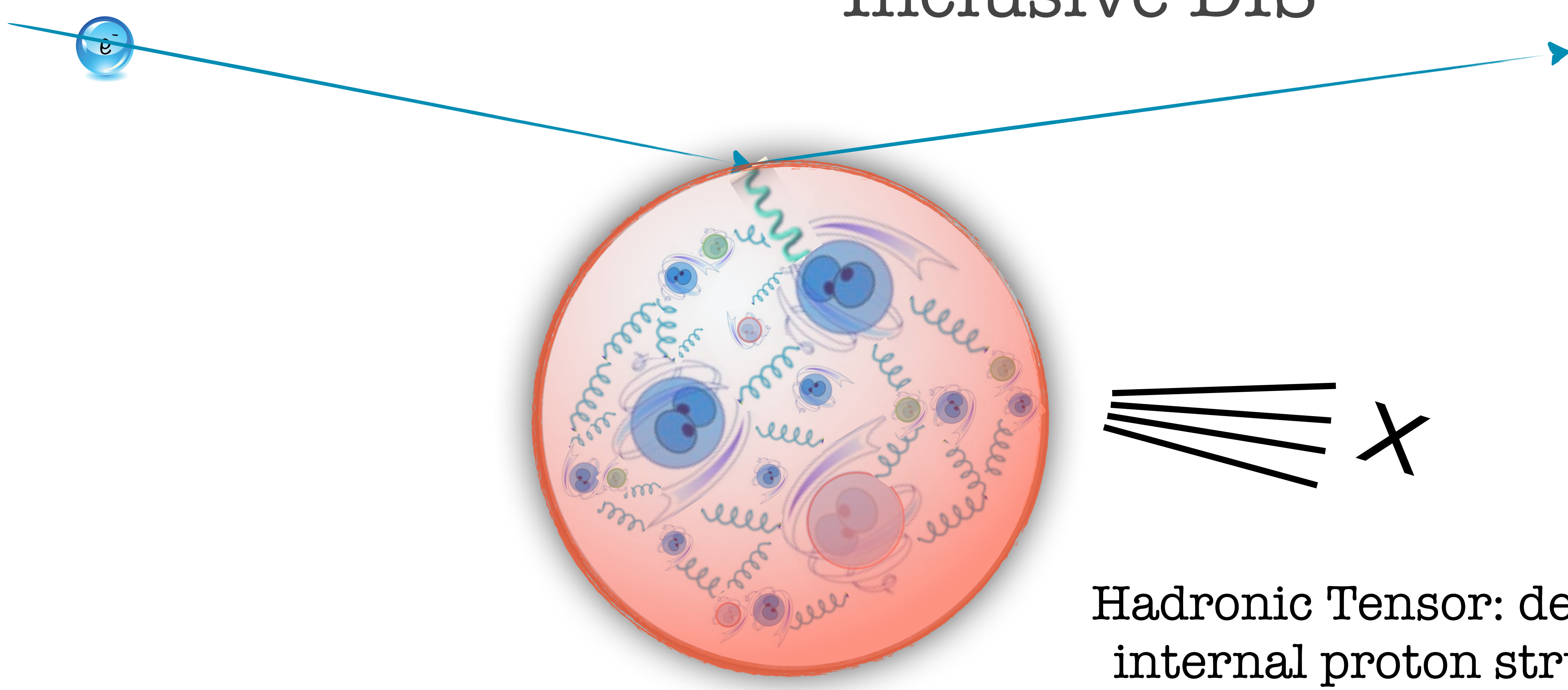

Hadronic Tensor: describes internal proton structure
Not Calculable in QCD!

Leptonic Tensor: describes emission of single photon:
Calculable from QED

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

Proton Structure

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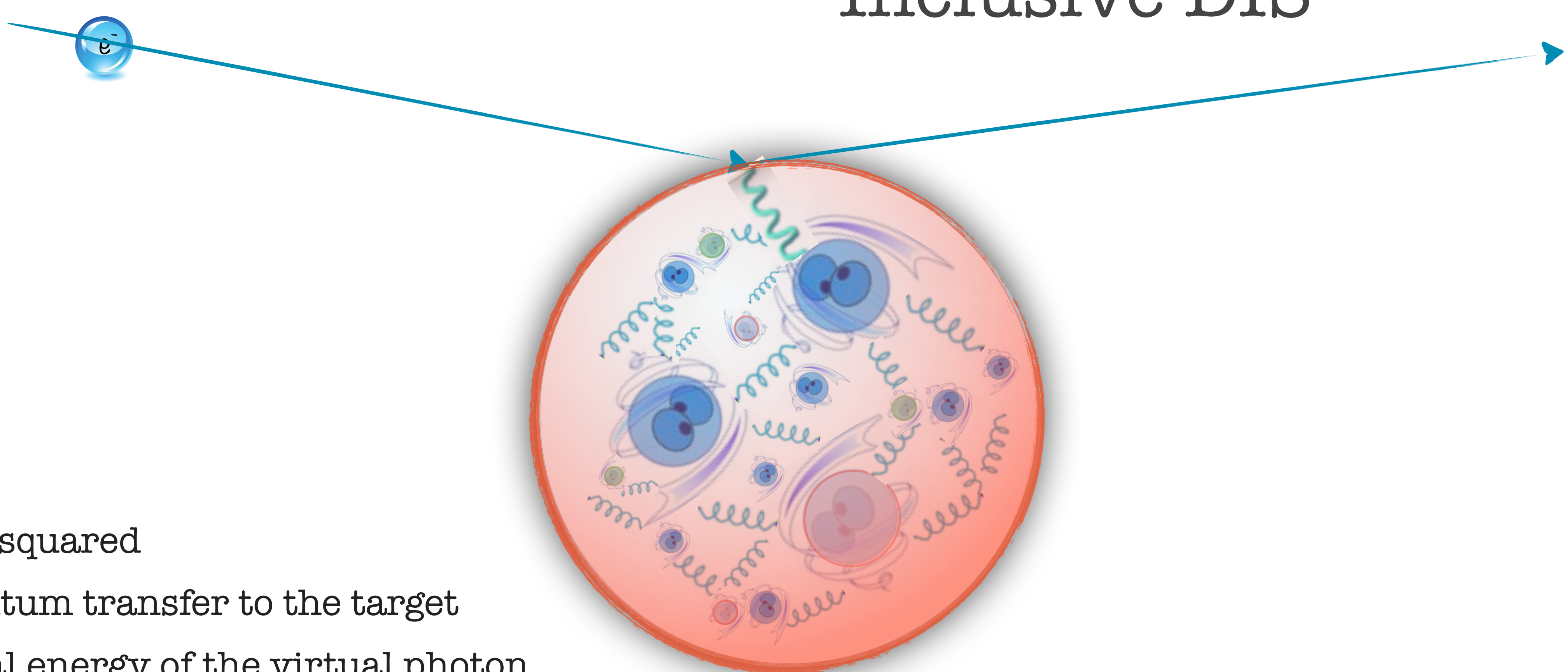


Q^2 Negative squared 4-momentum transfer to the target

y Fractional energy of the virtual photon

x Parton fractional momentum

Only basic symmetry arguments/ conservation laws: Gauge/Lorentz invariance, parity conservation No other assumption!

$$\frac{d\sigma}{dx\,dQ^2} = \frac{\alpha^2}{2sxQ^2} L^{(S)}_{\mu\nu} W^{(S)}_{\mu\nu} =$$

$$\frac{2\pi\alpha^2}{Q^4}\left\{F_1(x,Q^2)y^2 + \left(1 - y - \frac{Mxy}{2E}\right)\frac{F_2(x,Q^2)}{x}\right\}$$

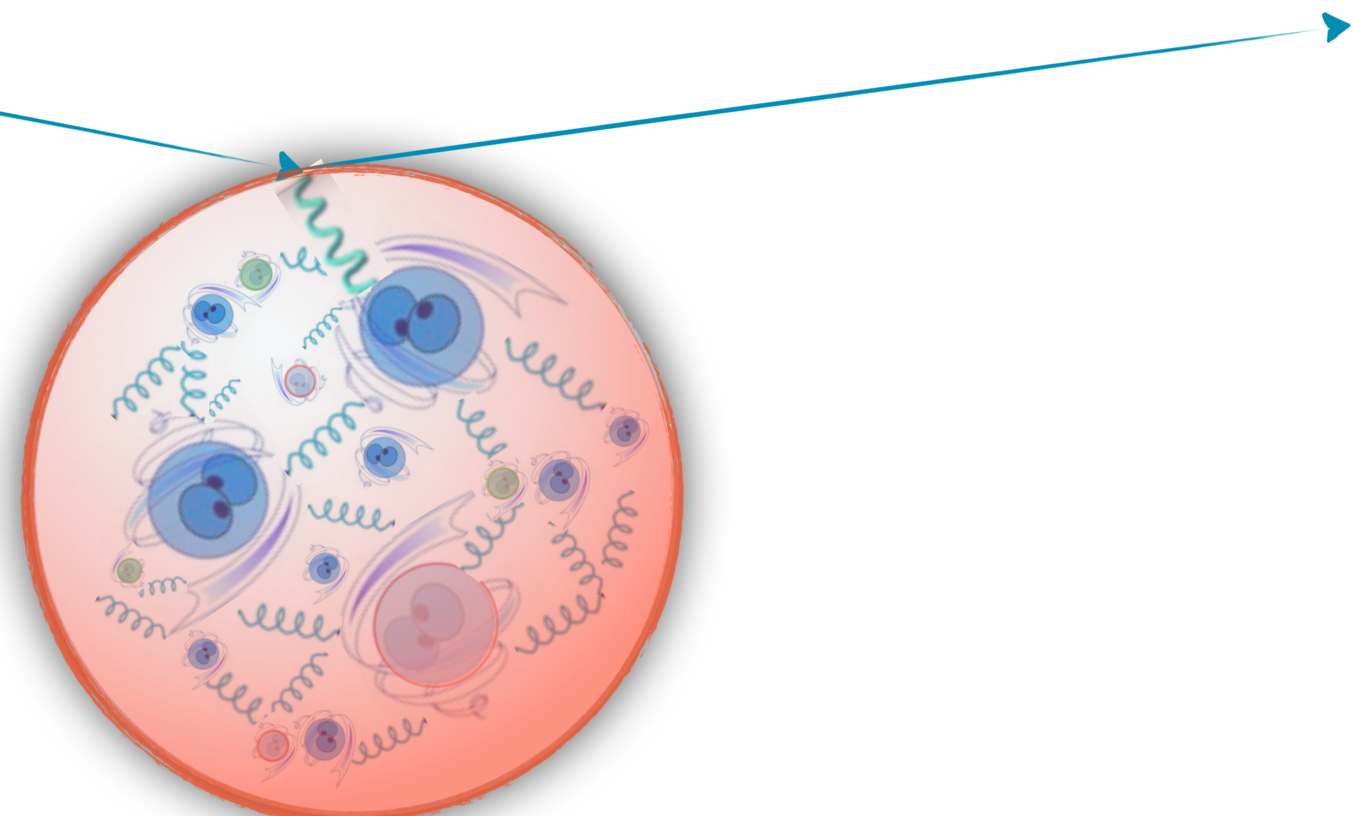
Proton Structure

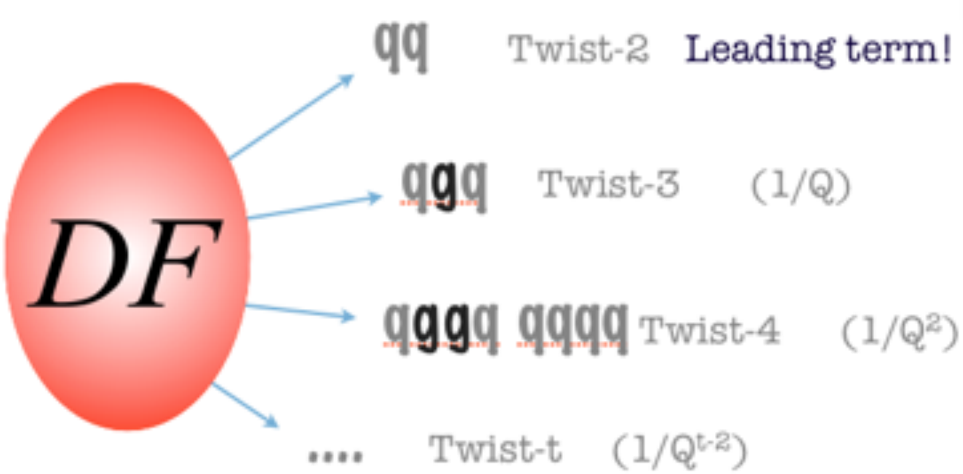
Inclusive DIS

Parton model:

$F_i \quad \Rrightarrow \quad \Sigma_p$ parton distributions

Each Structure function
expanded in 1/Q serie





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Parton Distribution Functions

Collinear case

PDFs Leading Twist Table

nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1

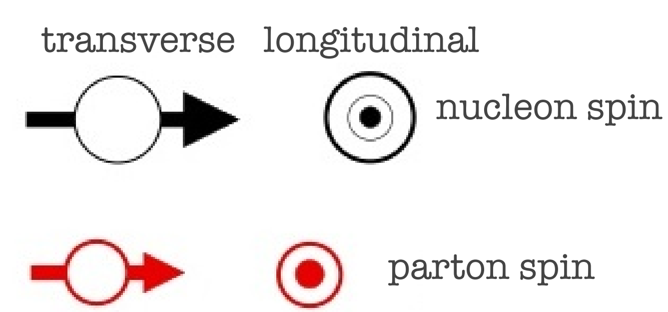
Partonic Interpretation

Factorizable in the cross-section!

Accessible in various reactions:
Universal!

x-dependence=

1D!



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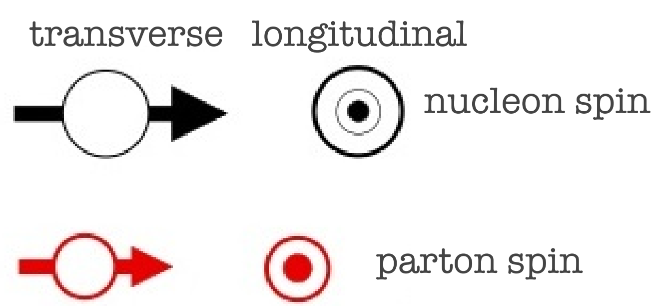

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		quark		
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	T			h_1 -

Partonic Interpretation

Factorizable in the cross-section!

Accessible in various reactions: Universal!

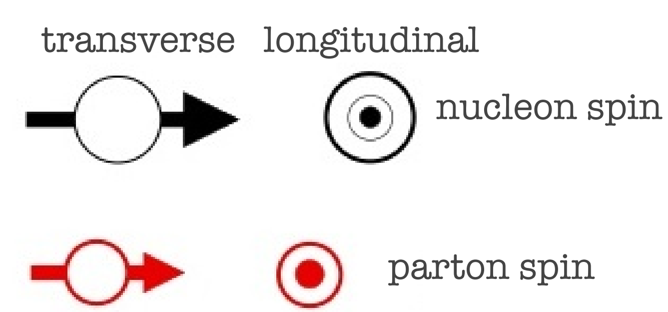
= different energies

Need for Global analyses!

DGLAP evolution

x-dependence=

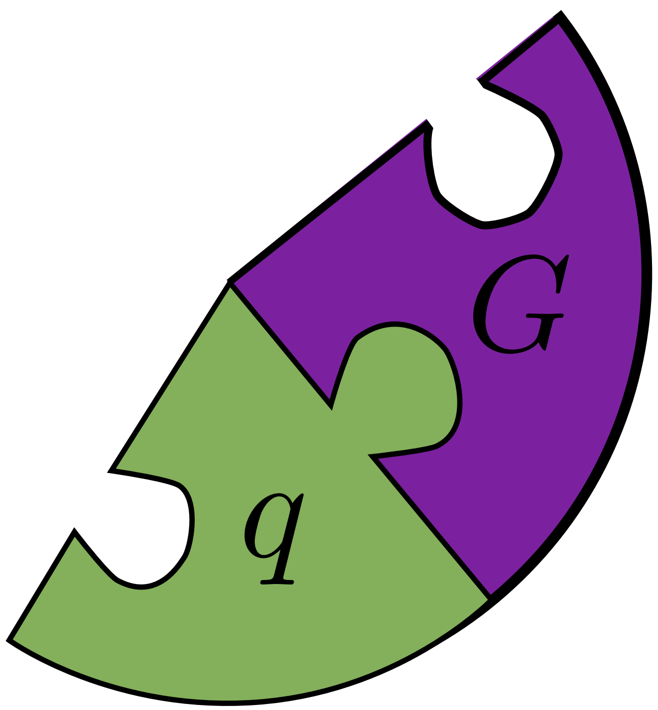
1D!

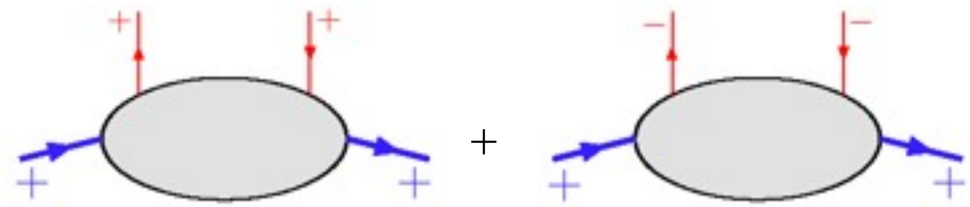


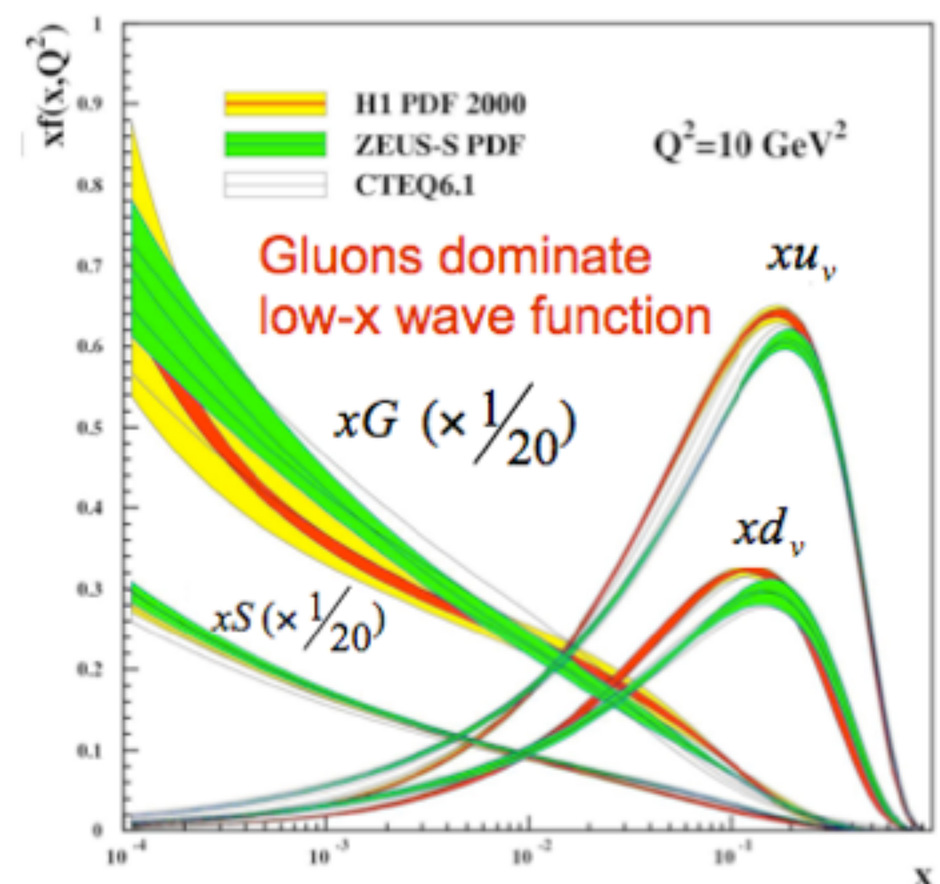
Momentum distribution

Collinear case

$$f_1^q(x) = q^{\rightrightarrows}(x) + q^{\rightleftarrows}(x)$$



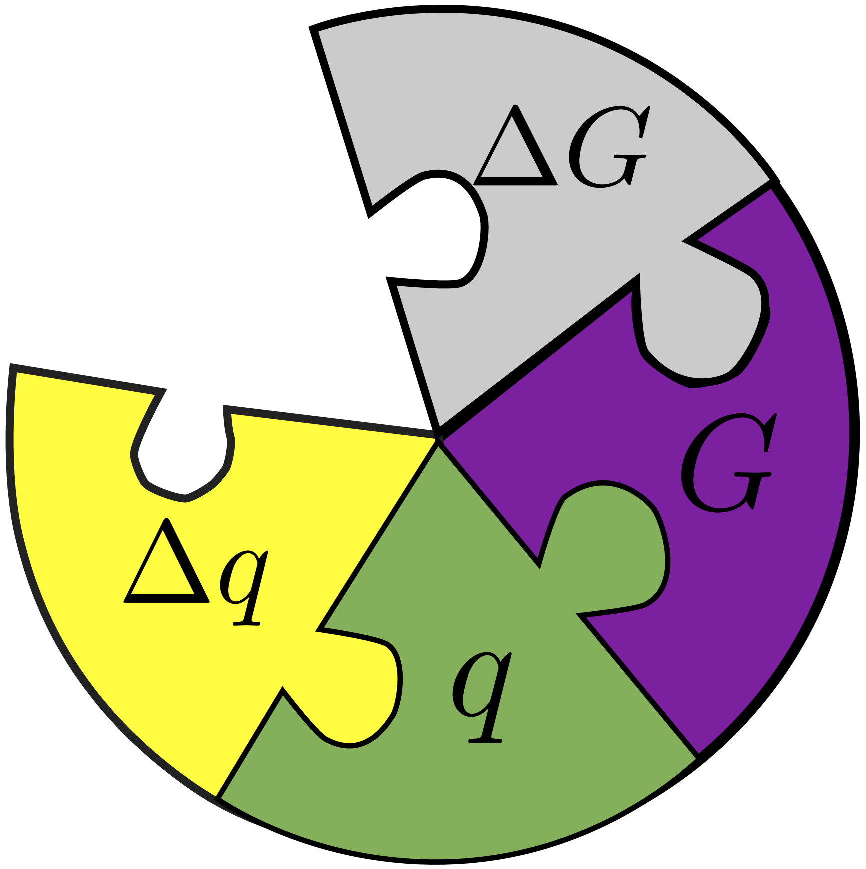




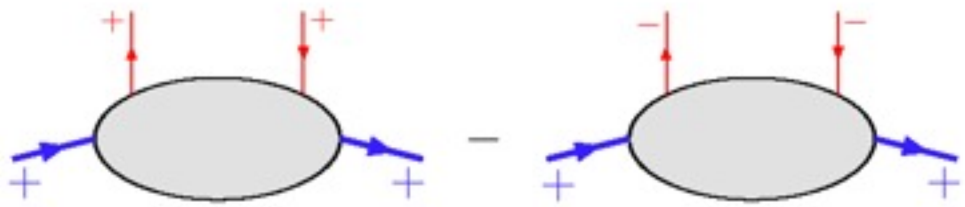
x = parton momentum fraction

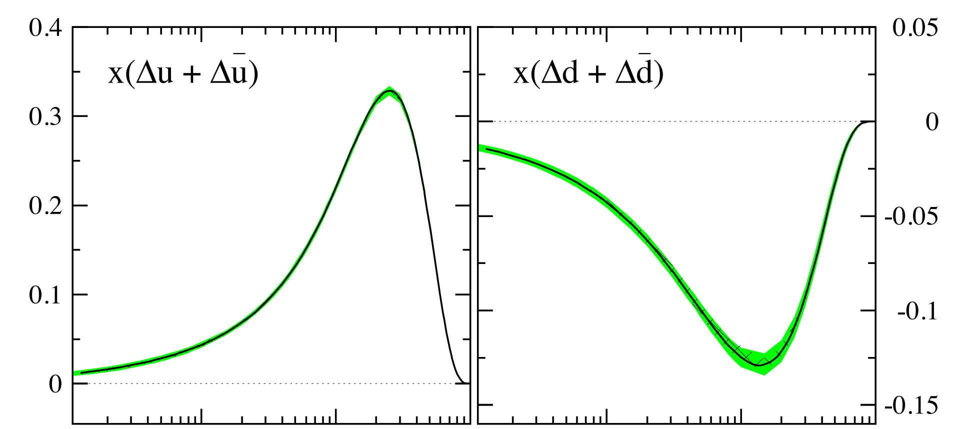
Helicity distribution

Collinear case



$$g_1^q(x) = q^{\rightrightarrows}(x) - q^{\rightleftarrows}(x)$$





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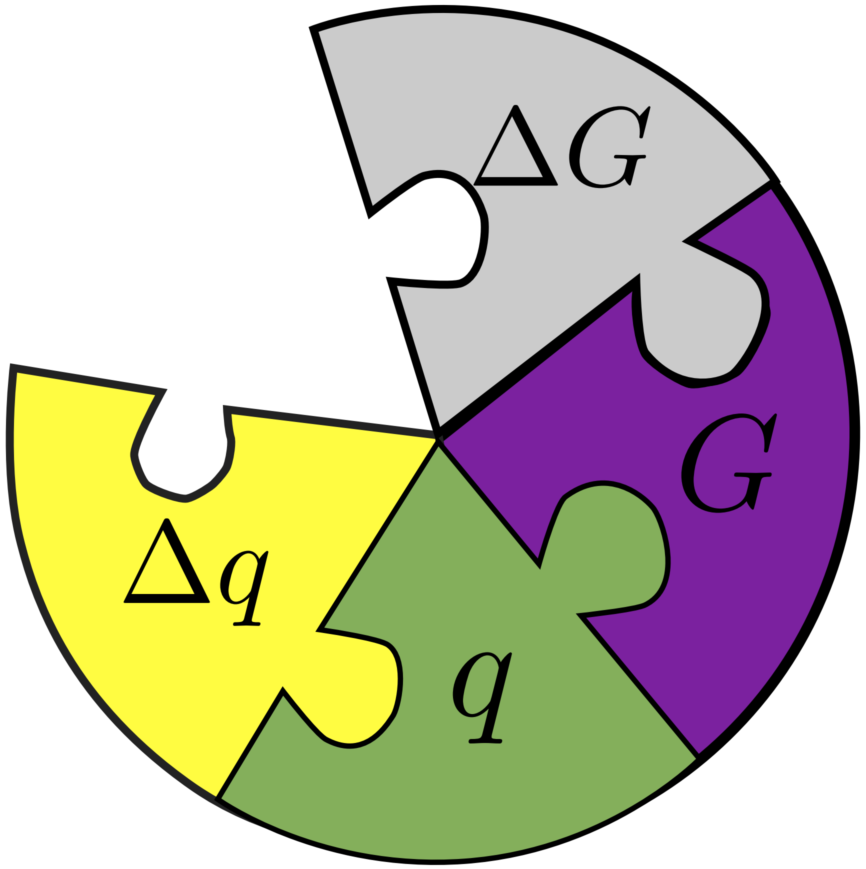

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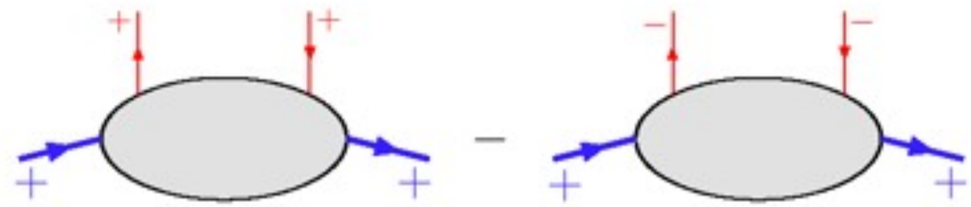
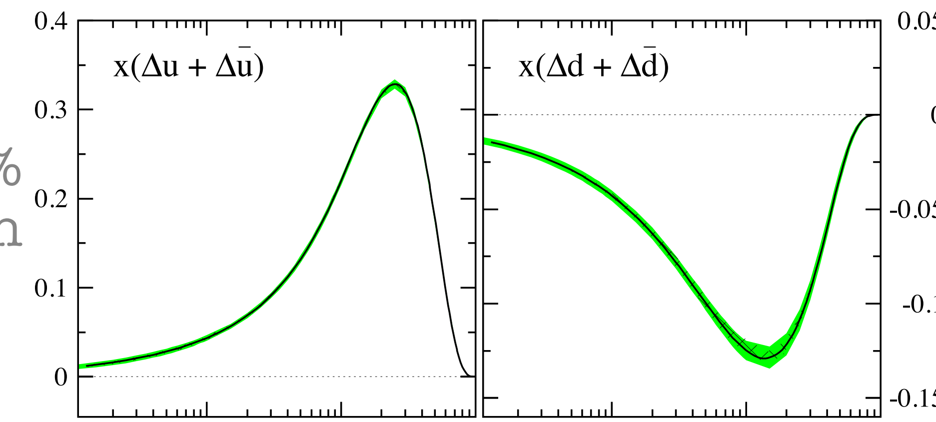


Spin crisis!!

quarks only provide ≈ 30% of the proton spin



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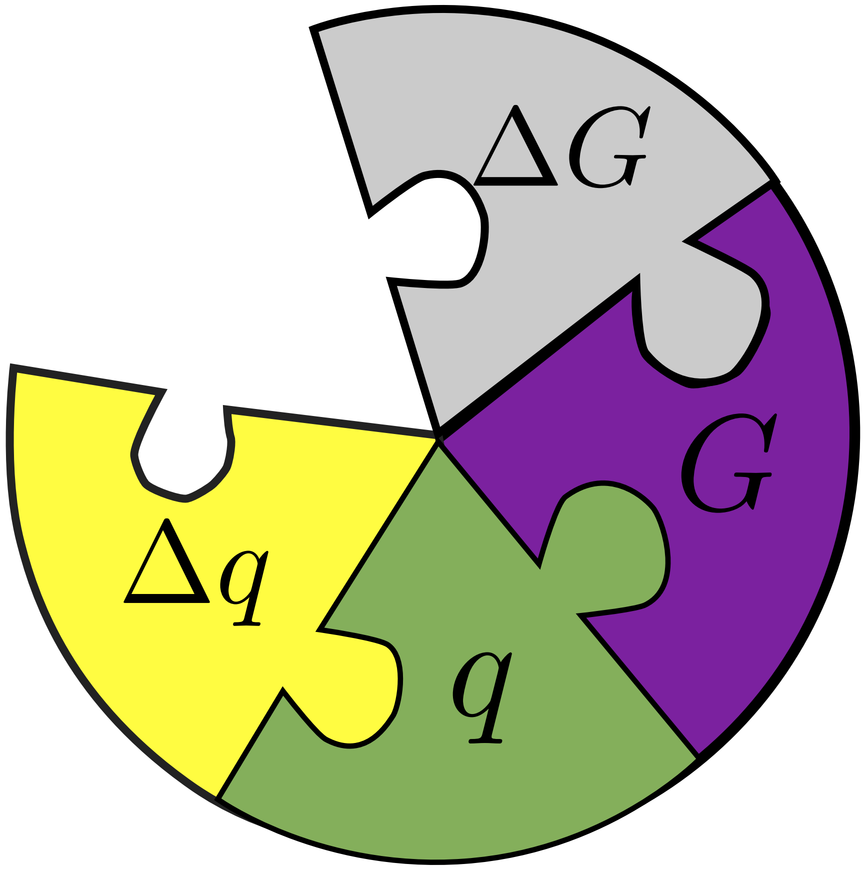

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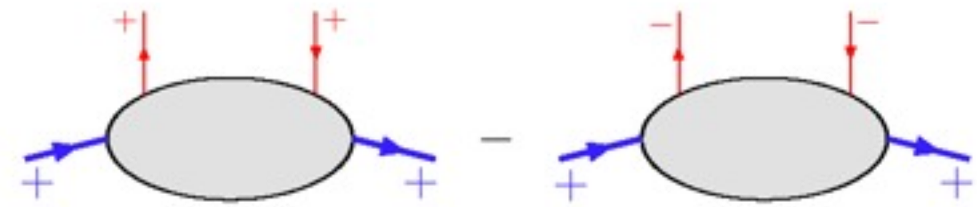

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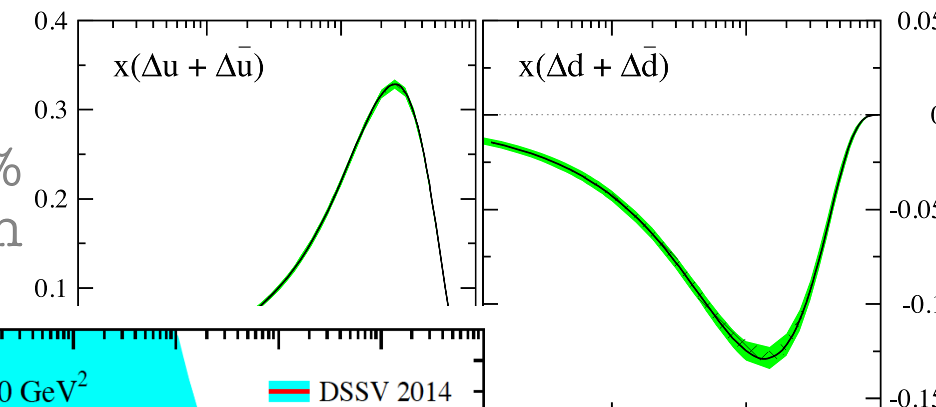
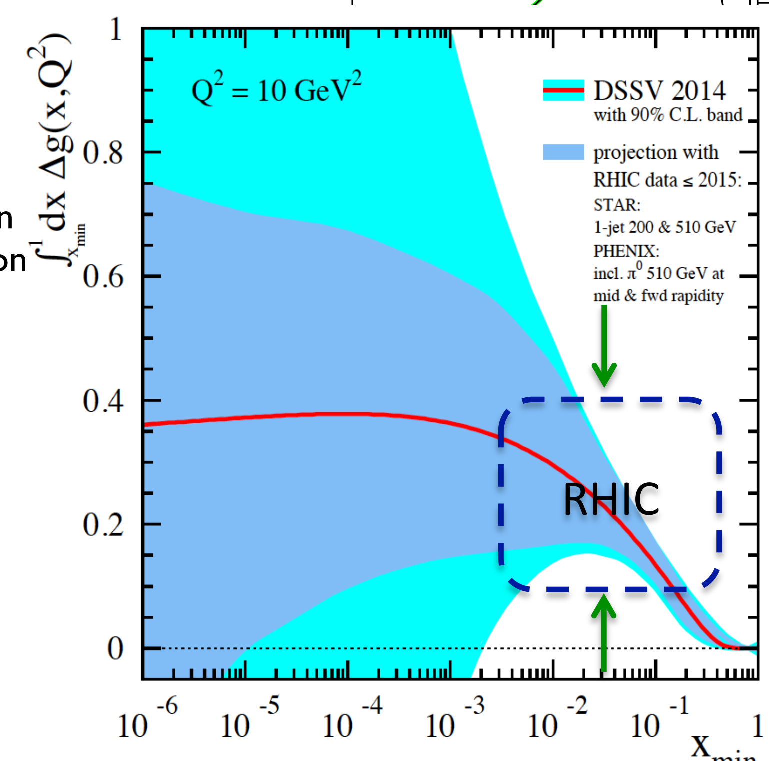


quark spins, gluon spins, quark&gluon orbital motion

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$



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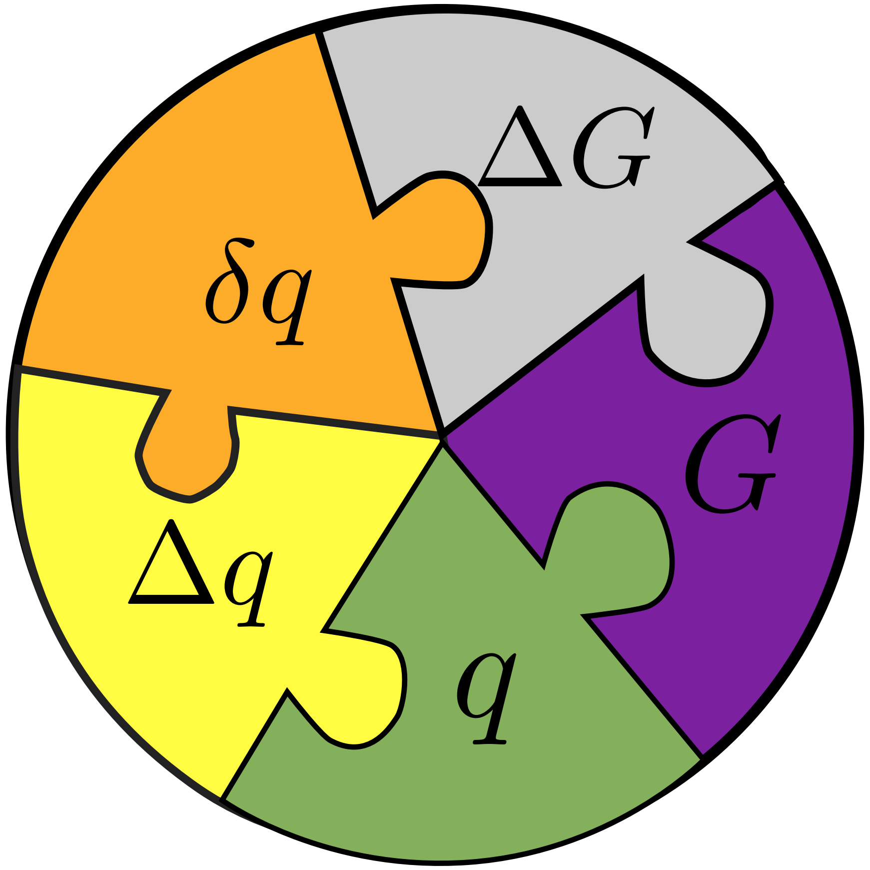
Transversity distribution

Collinear case



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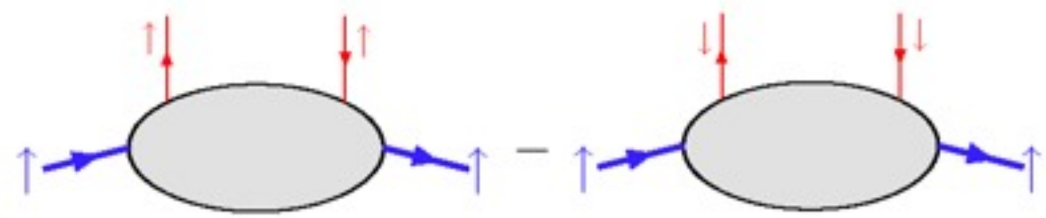

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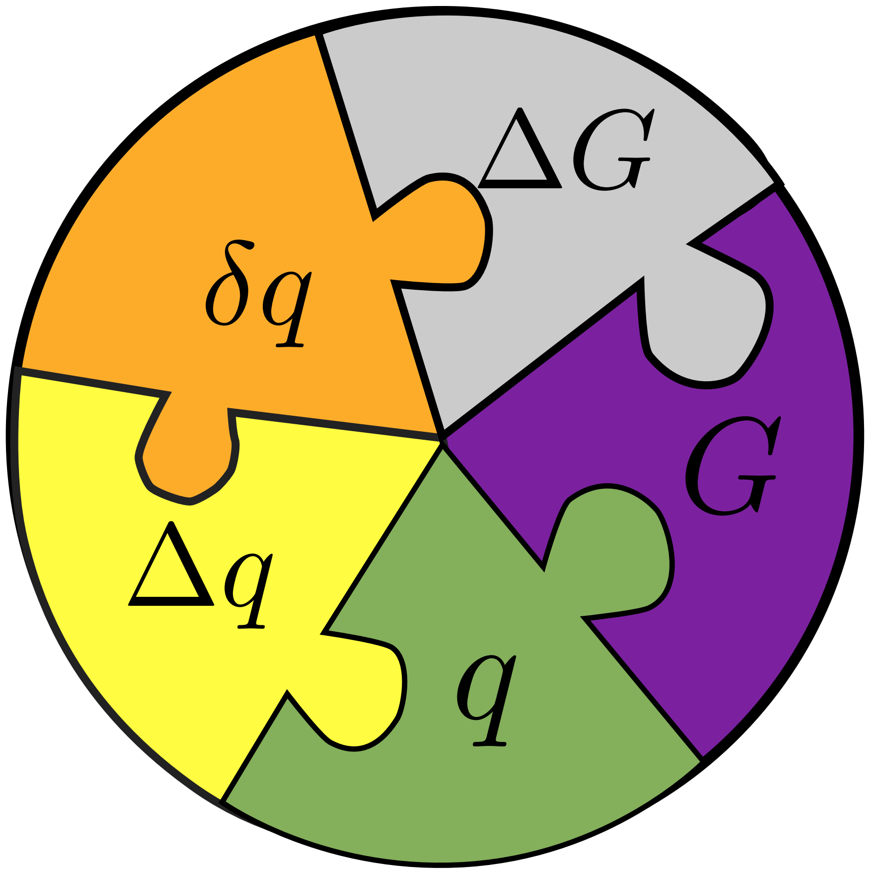

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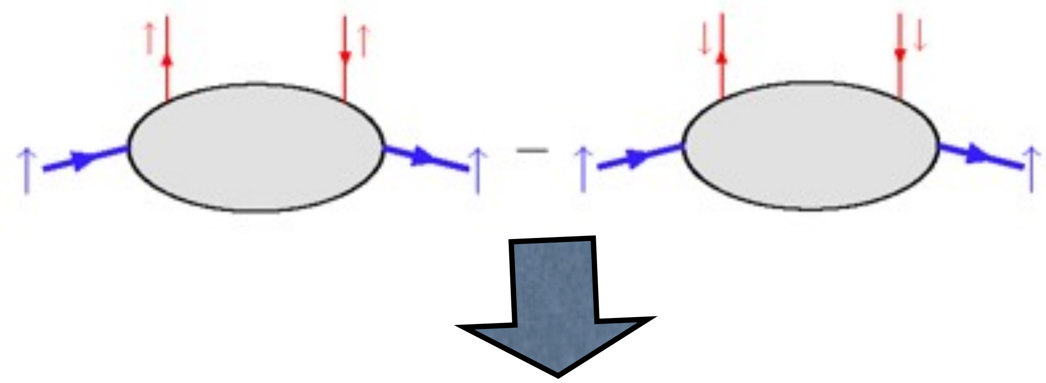
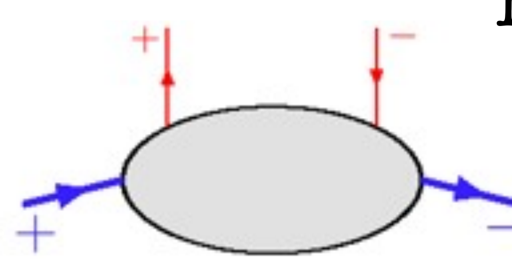


in helicity basis

$$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle \pm i|-\rangle)$$

helicity flip!

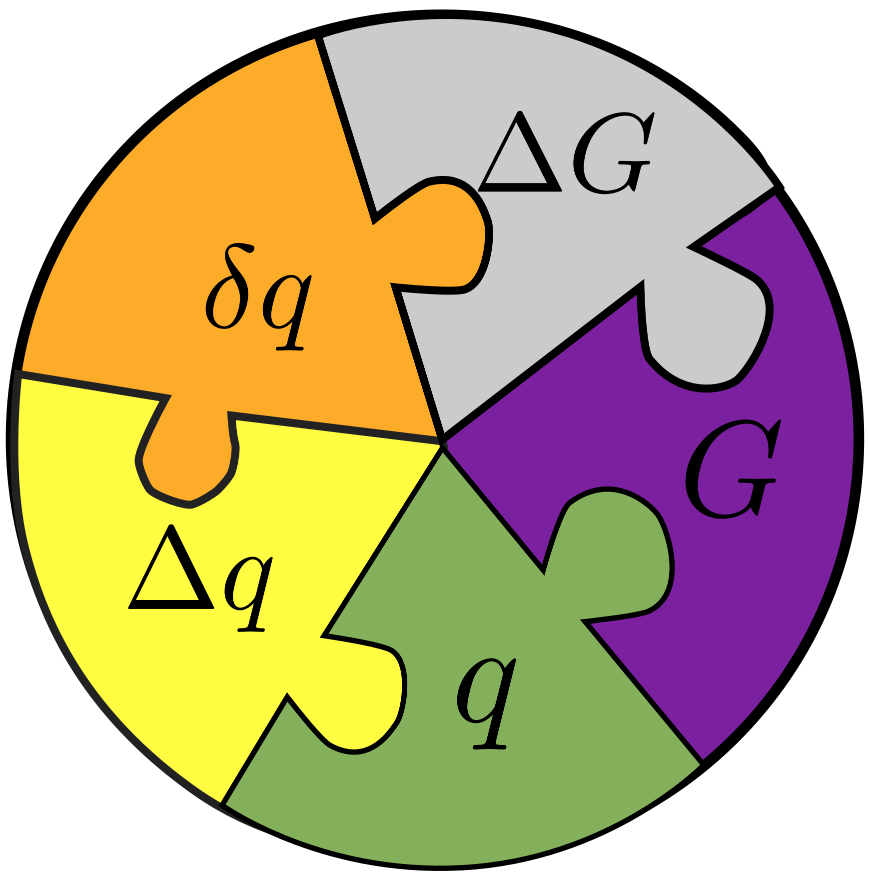


x = parton momentum fraction

Transversity is chiral-odd!

Transversity distribution

Collinear case



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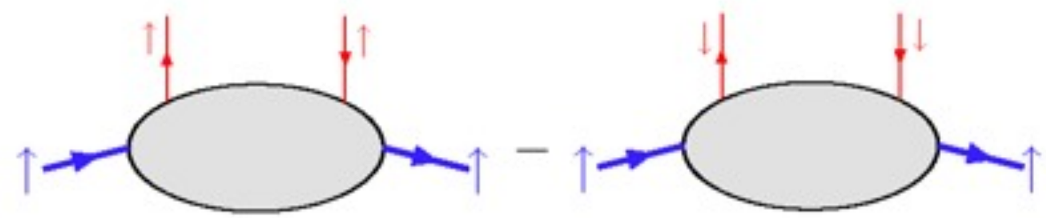

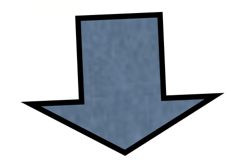

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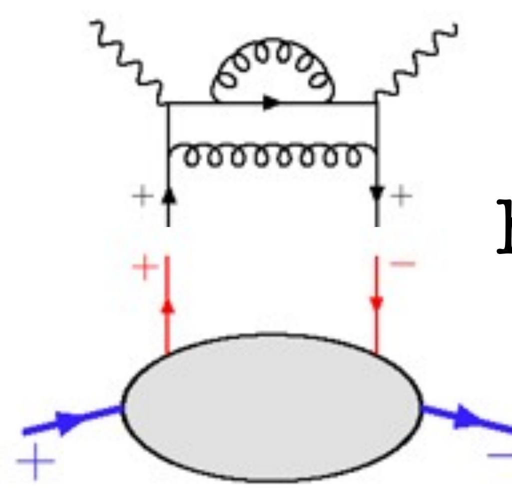

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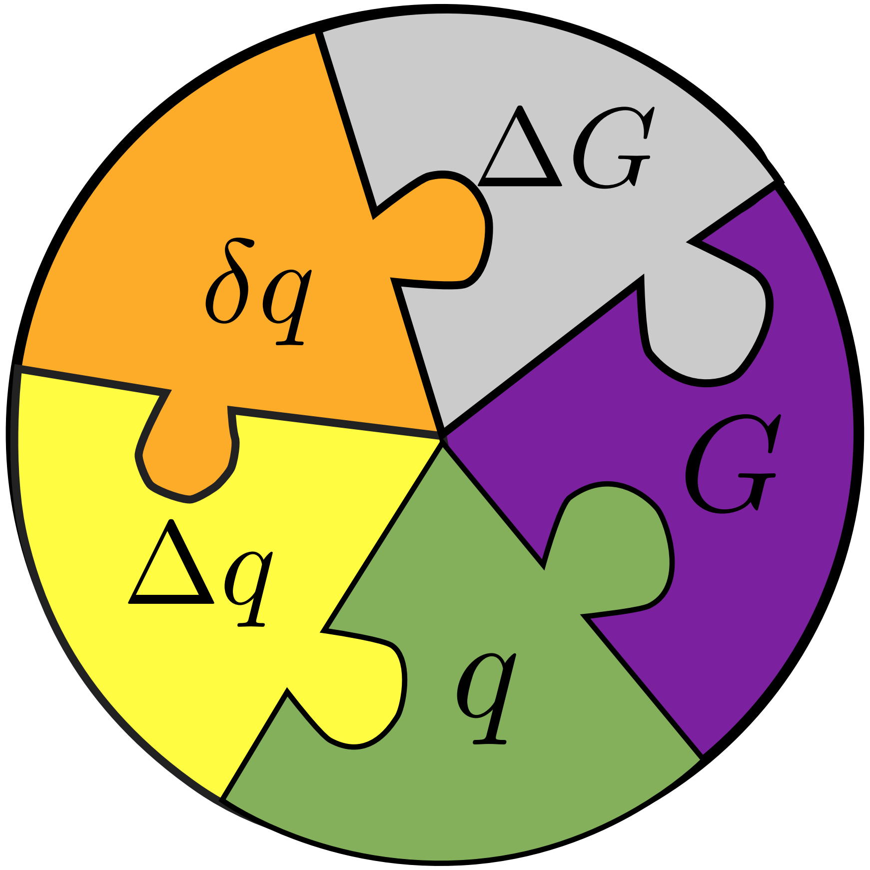

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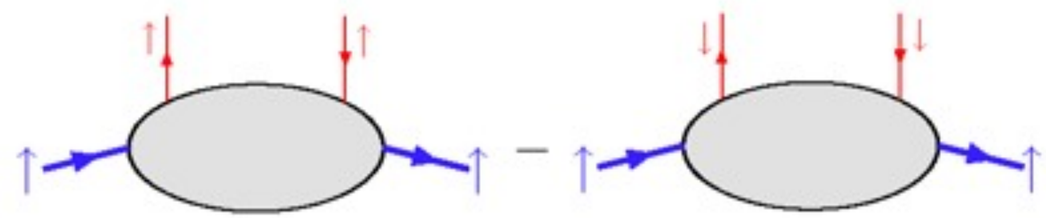

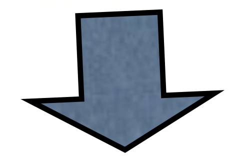

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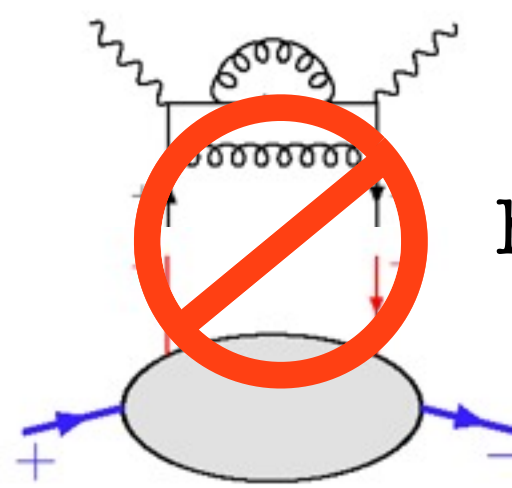

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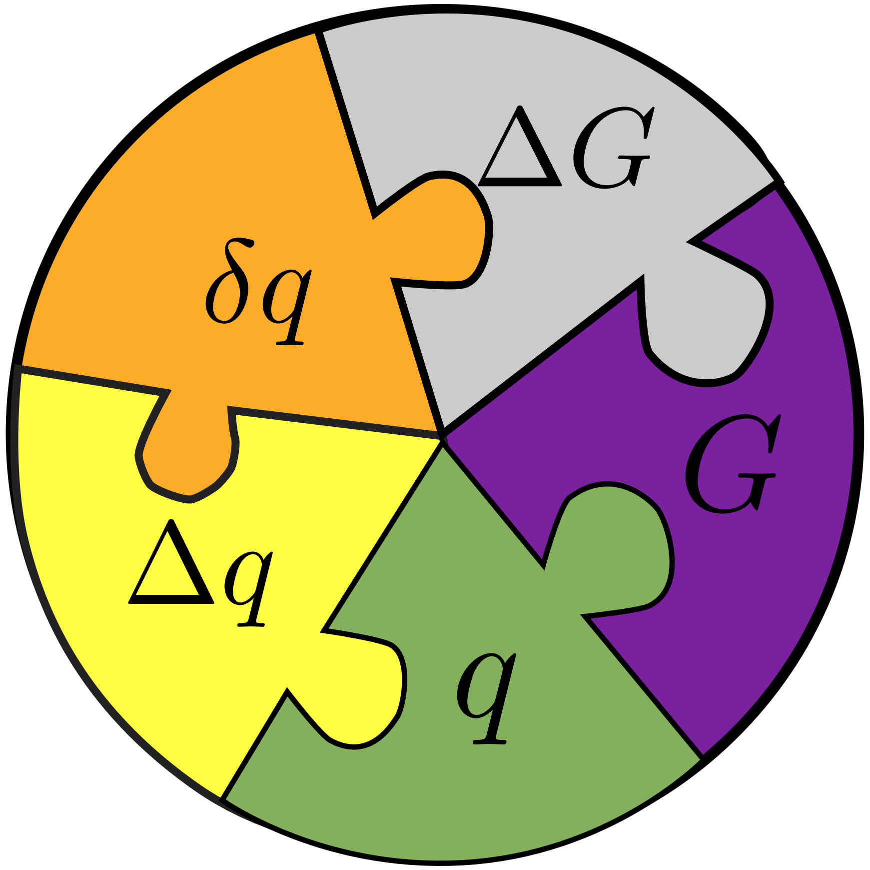

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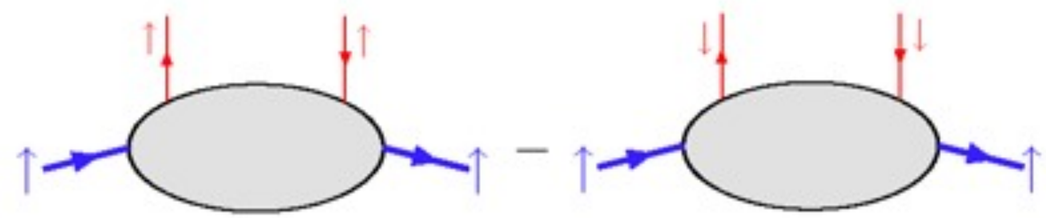

$$h_1 \otimes H$$

$$\underbrace{\text{chiral odd} \quad \text{chiral odd}}_{\text{chiral even}}$$

x = parton momentum fraction

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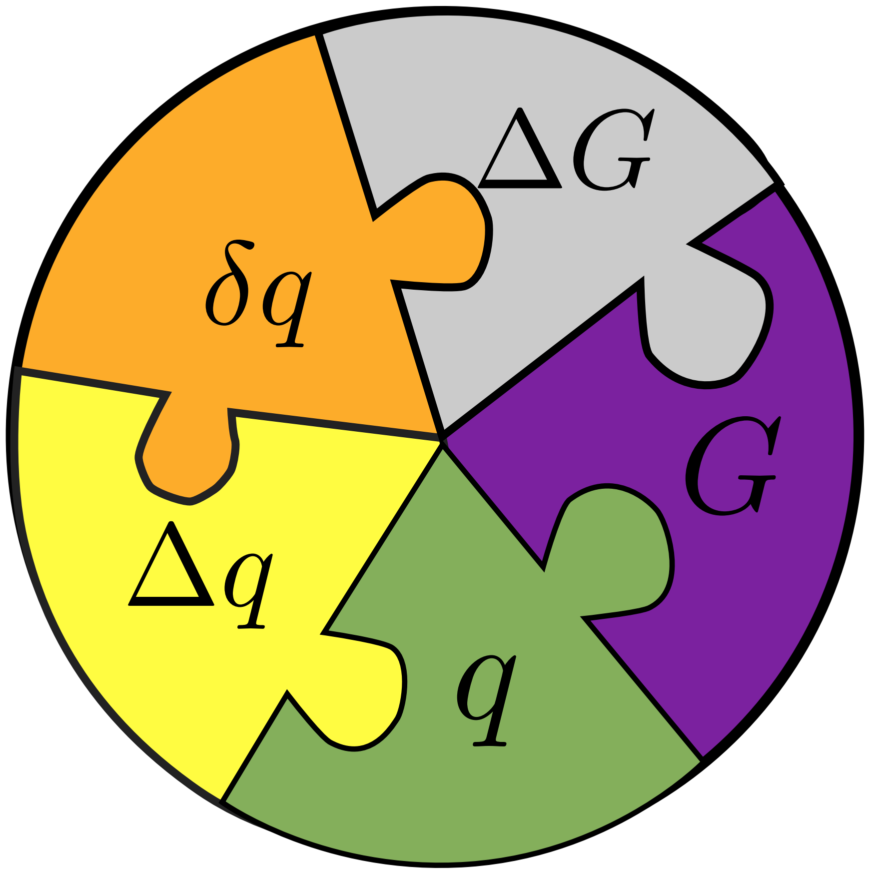

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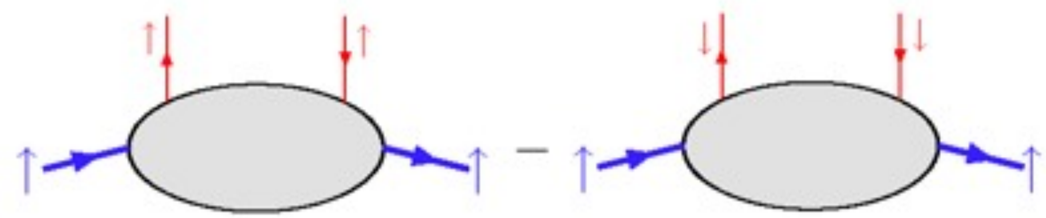
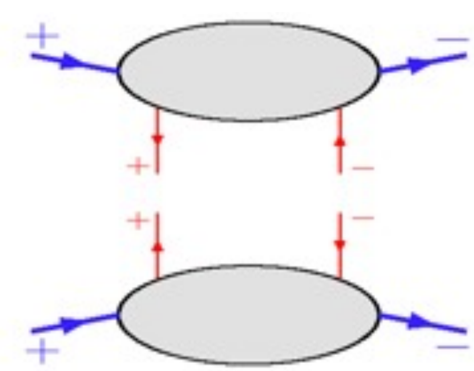
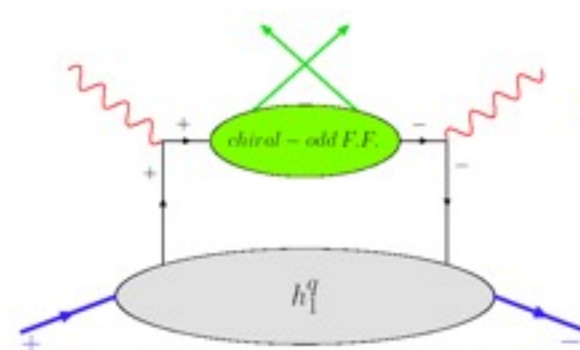


$$\underbrace{\underset{\text{chiral odd}}{h_1} \otimes \underset{\text{chiral odd}}{H}}_{\text{chiral even}}$$

Drell-Yan/pp



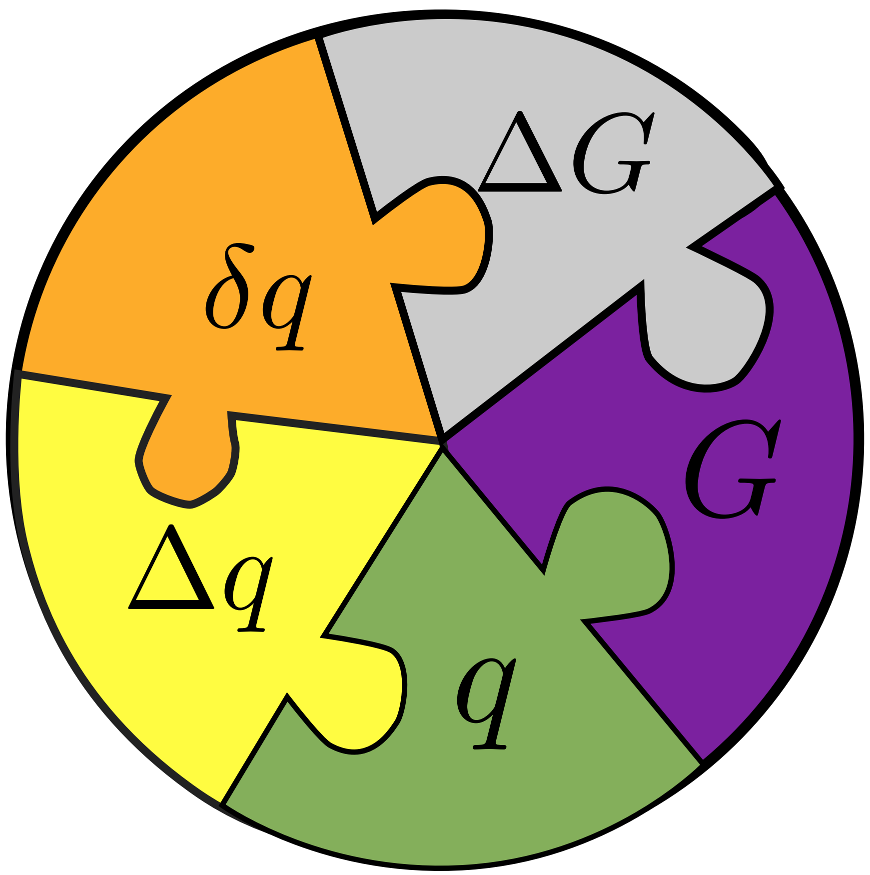
DIS reaction:
semi inclusive DIS



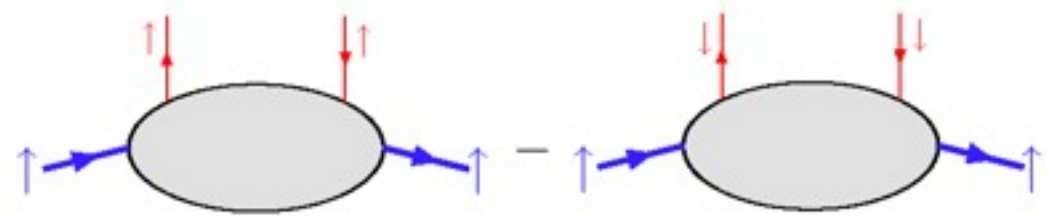
x = parton momentum fraction

Transversity distribution

Collinear case



$$h_1^q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$$

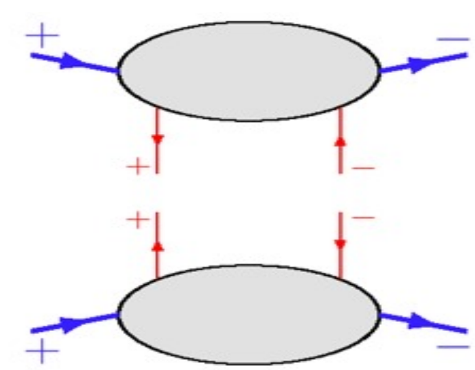


$$h_1 \quad \otimes \quad H$$

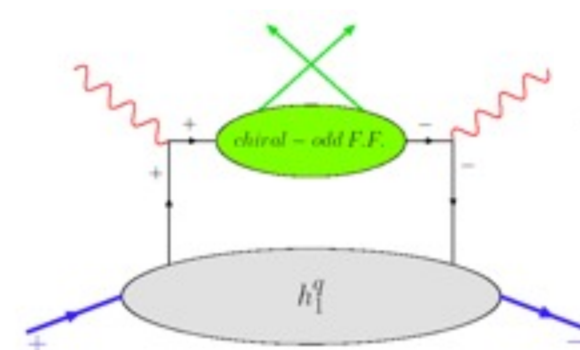
chiral odd **chiral odd**

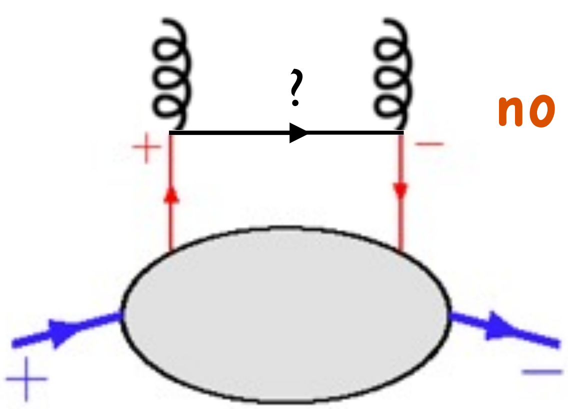
chiral even

Drell-Yan/pp



DIS reaction:
semi inclusive DIS



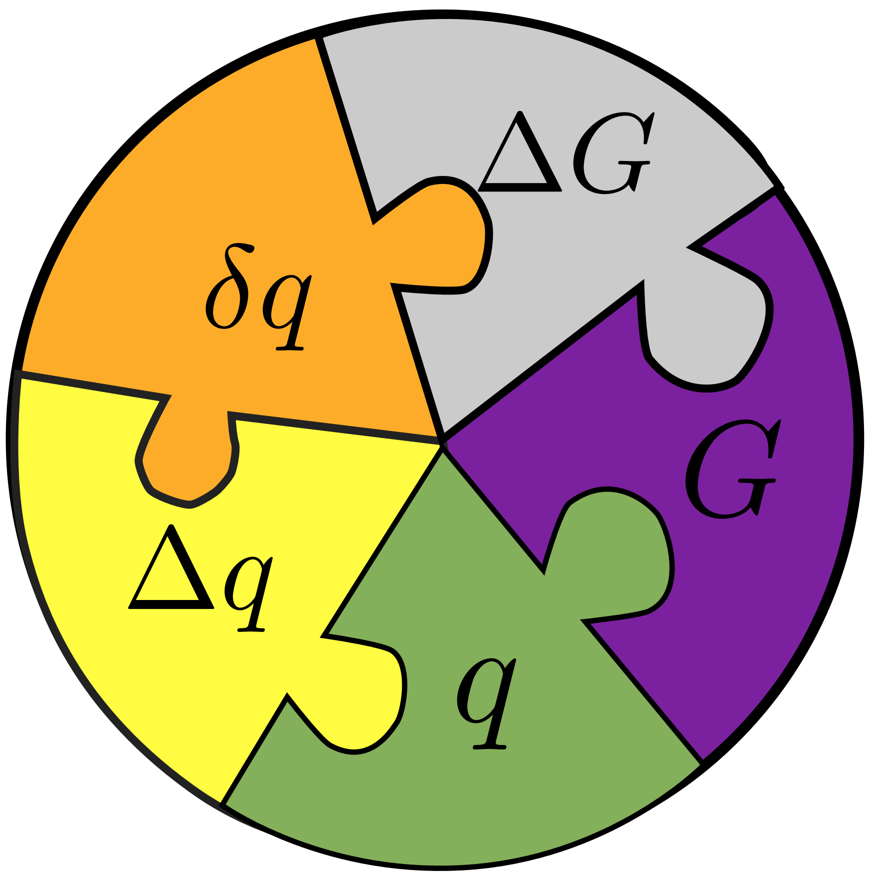


no gluon transversity (in proton)
and quark and gluon
transversities don't mix!

x = parton momentum fraction

Transversity distribution

Collinear case



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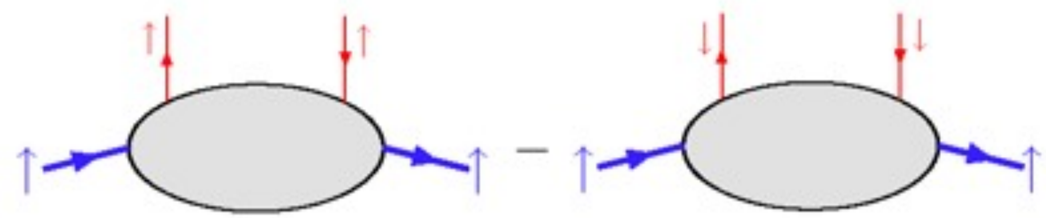

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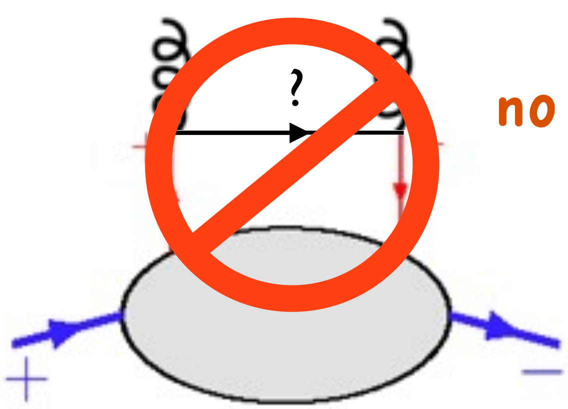

no gluon transversity (in proton) and quark and gluon transversities don't mix!

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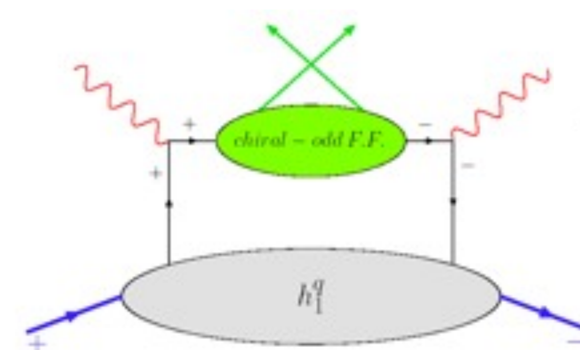
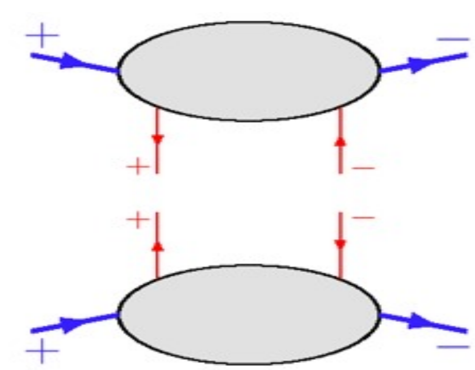


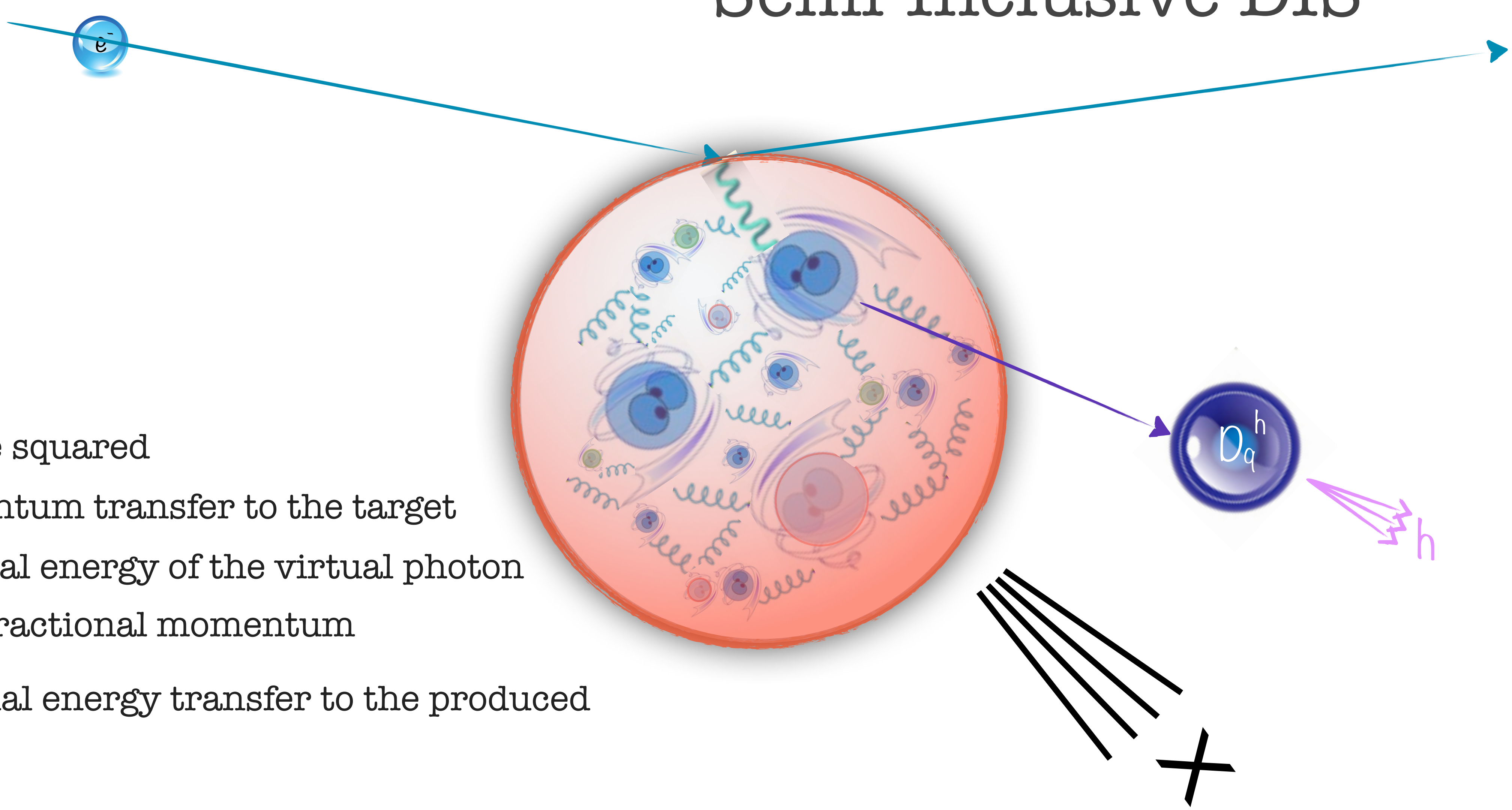
Drell-Yan/pp



x = parton momentum fraction

Proton Structure

Semi-Inclusive DIS



Q^2 Negative squared 4-momentum transfer to the target

y Fractional energy of the virtual photon

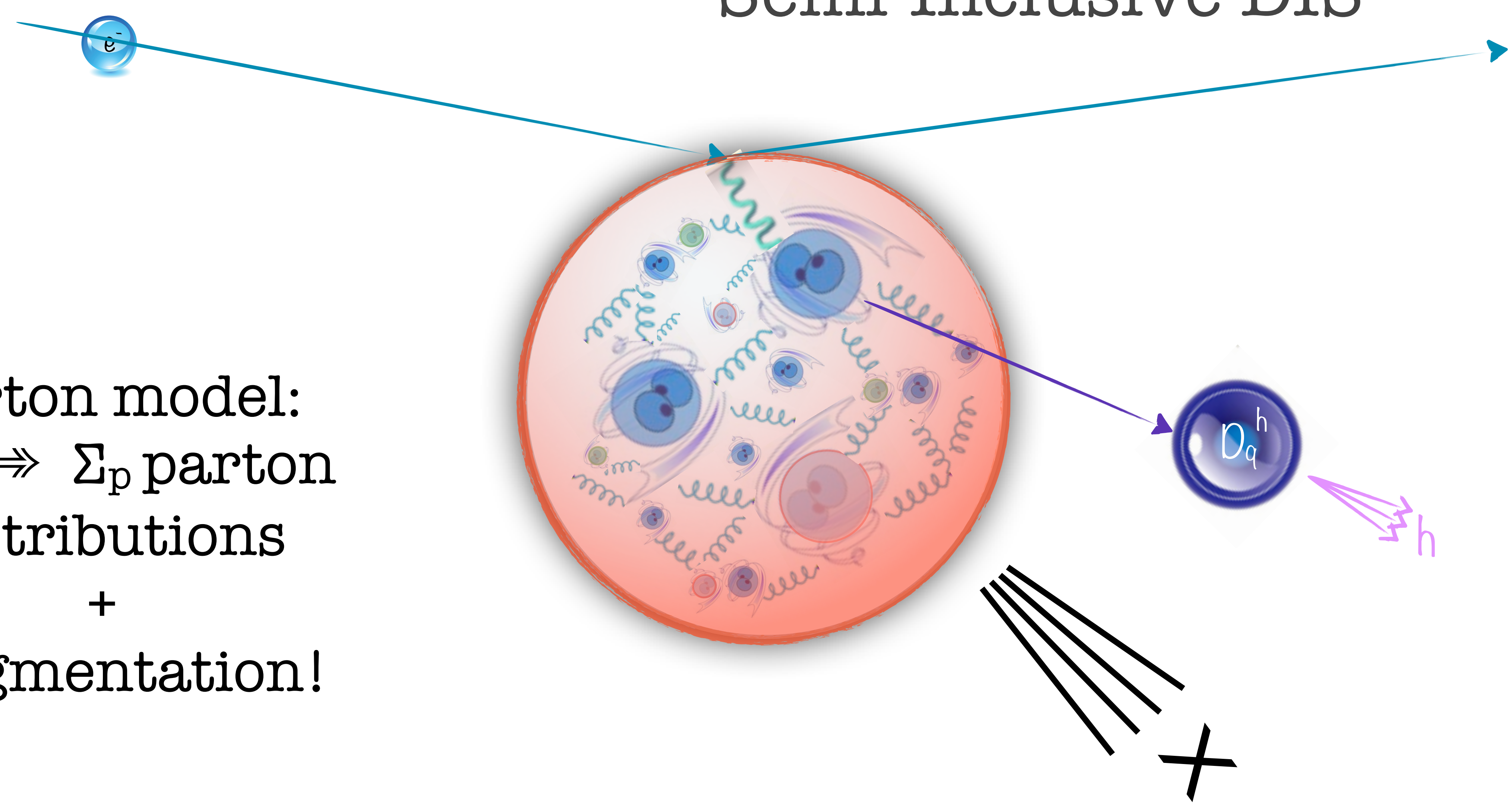
x Parton fractional momentum

z Fractional energy transfer to the produced hadron

$$\frac{d^3\sigma}{dxdydz} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)F_{UU,T} + B(y)F_{UU,L}\}$$

Proton Structure

Semi-Inclusive DIS

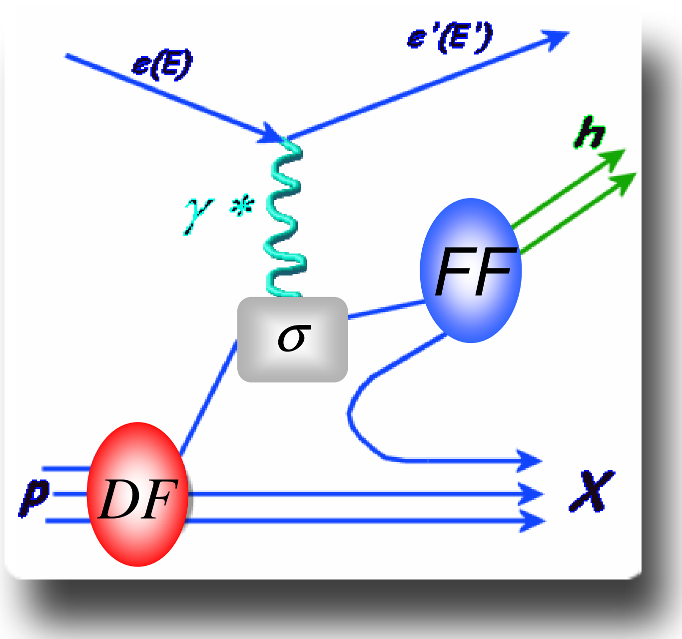


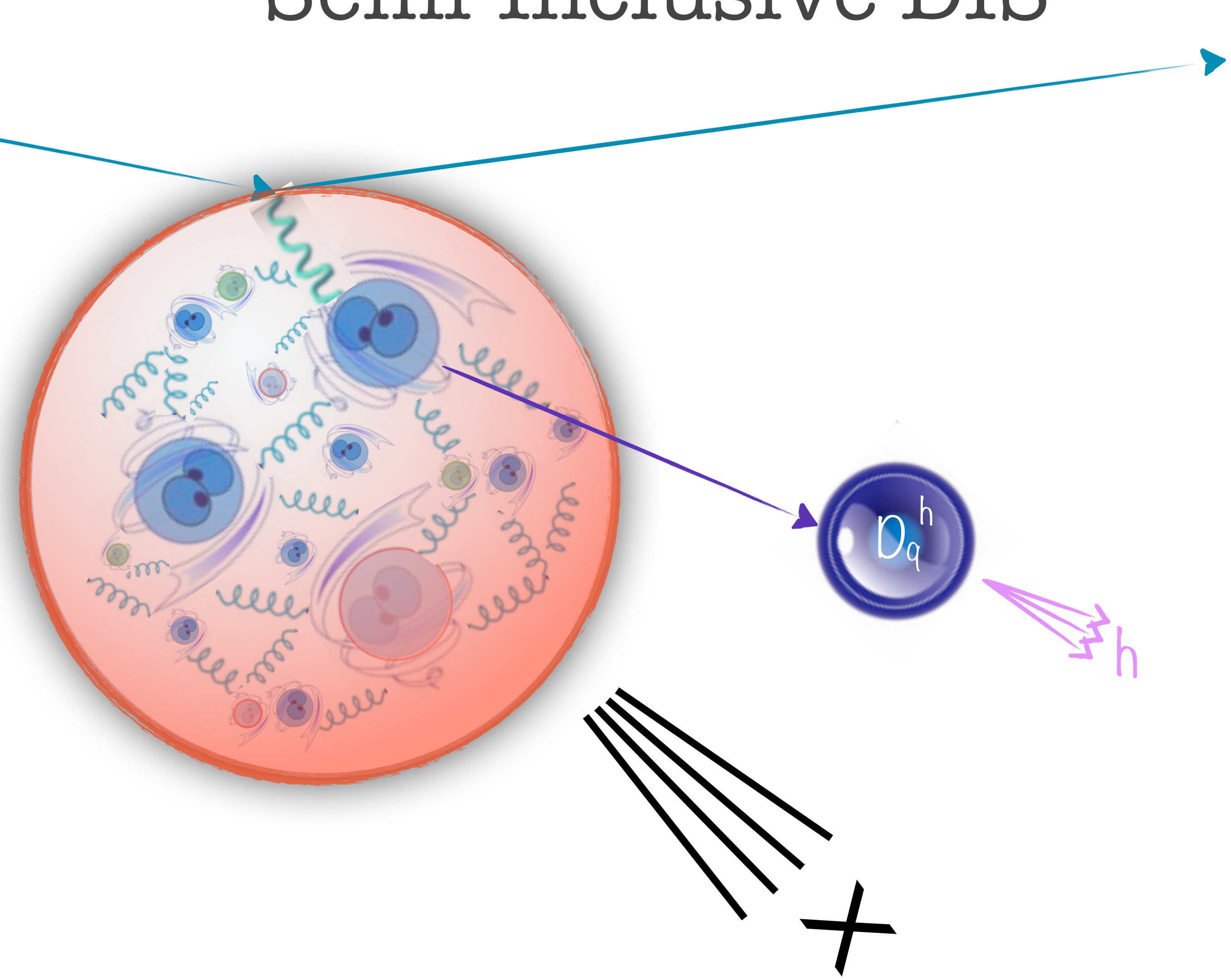
Parton model:
$F_i \Rrightarrow \Sigma_p$ parton distributions
+
Fragmentation!

$$\frac{d^3\sigma}{dx\,dy\,dz} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)F_{UU,T} + B(y)F_{UU,L}\}$$

Proton Structure

Semi-Inclusive DIS



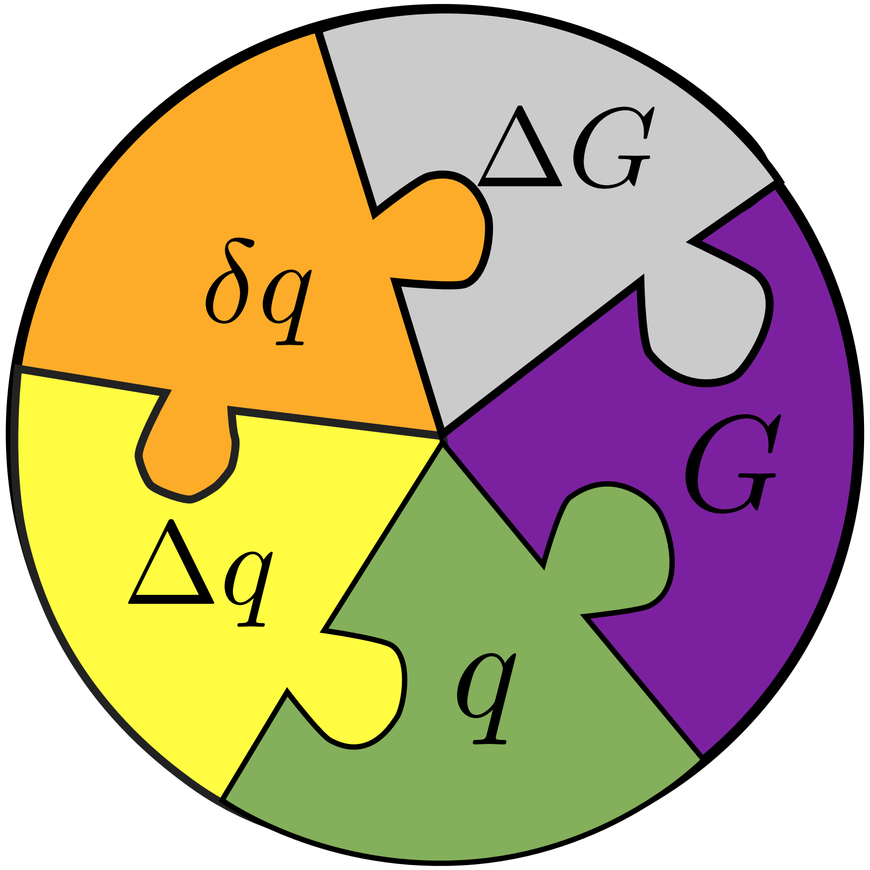


$$\sigma^{ep\rightarrow ehX} = \sum_q DF \times \sigma^{eq\rightarrow eq} \times FF$$

Factorization of Non-Perturbative Parts!

Transversity distribution

Collinear case



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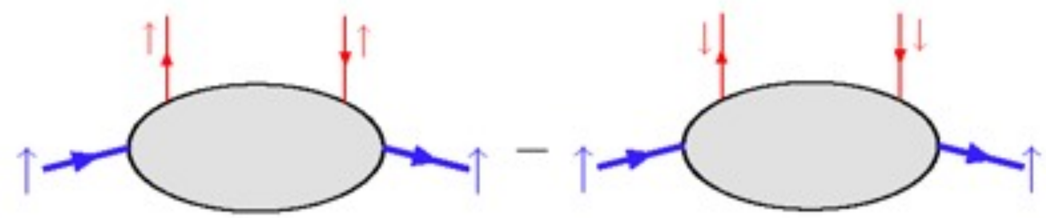
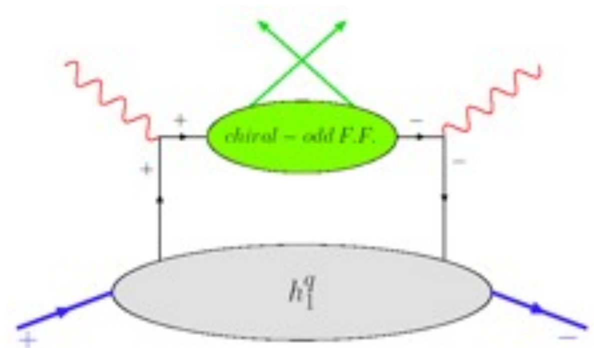


$$h_1 \otimes H$$

chiral odd **chiral odd**

chiral even

DIS reaction:
semi inclusive DIS

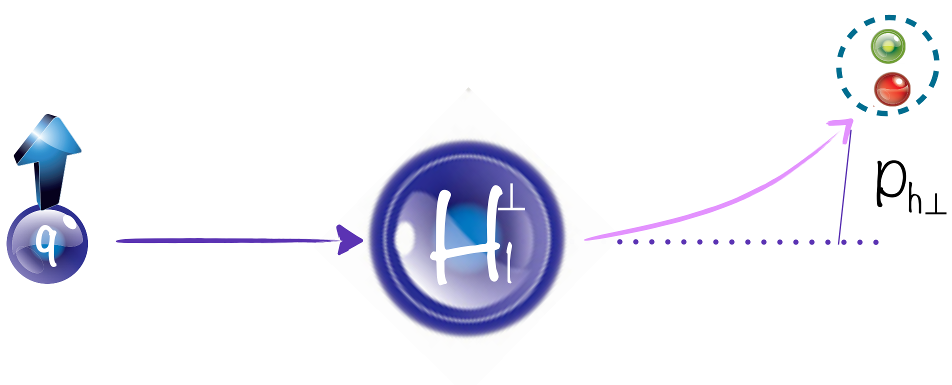


x = parton momentum fraction

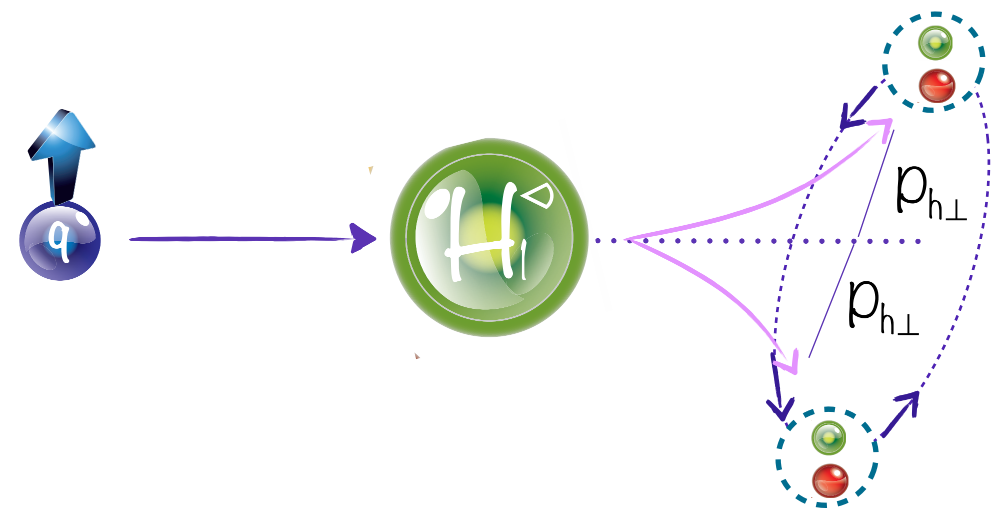
Transversity distribution

Collinear case

Collins Fragmentation



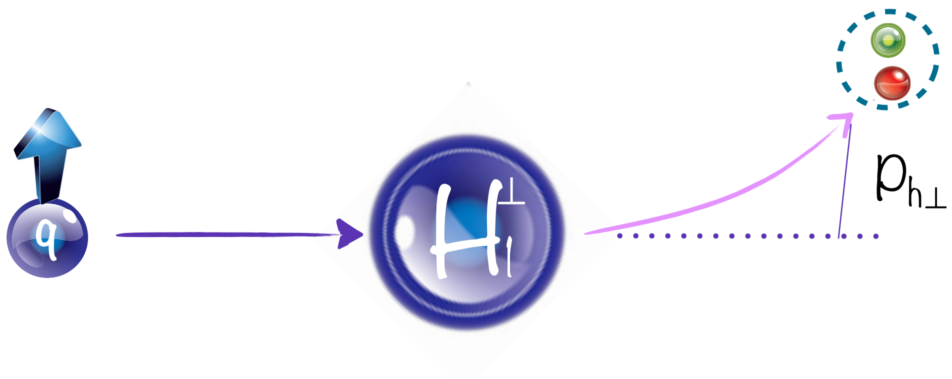
Interference Fragmentation



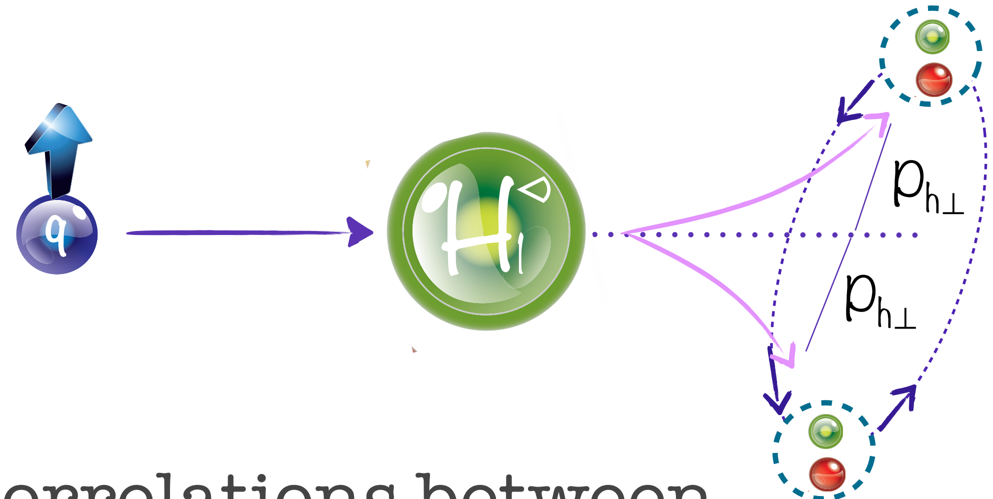
Transversity distribution

Collinear case

Collins Fragmentation



Interference Fragmentation

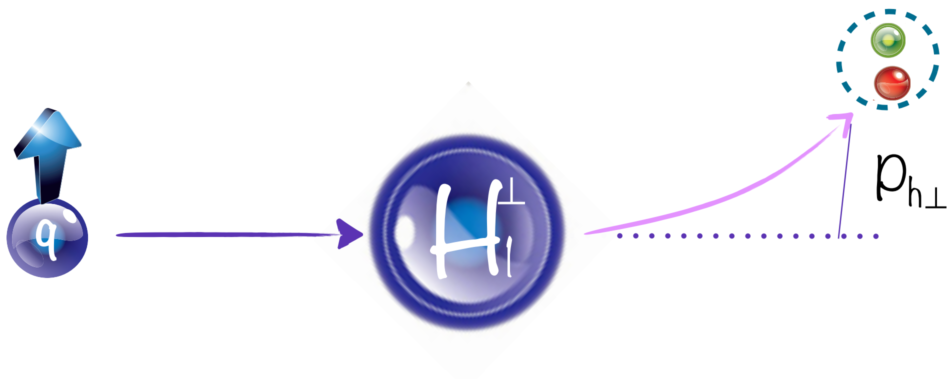


left-right asymmetry from correlations between
quark transverse spin
and

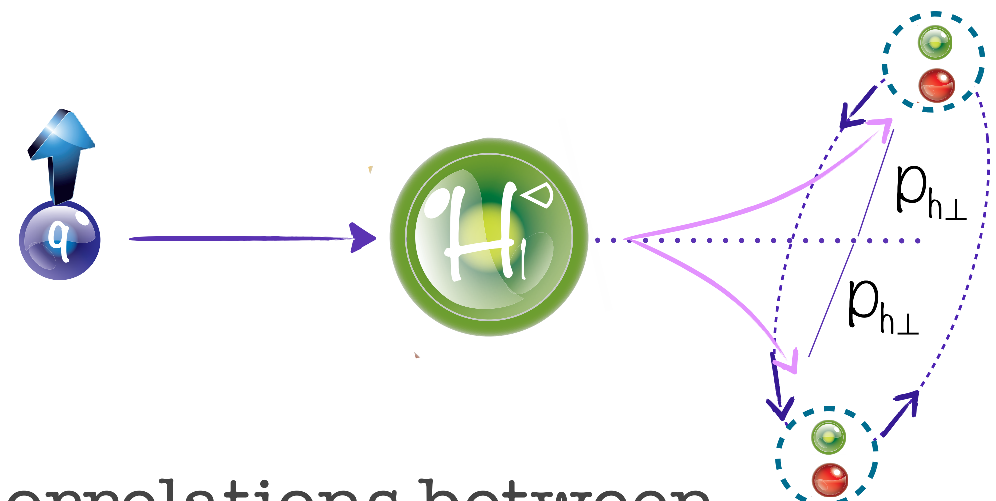
Transversity distribution

Collinear case

Collins Fragmentation



Interference Fragmentation



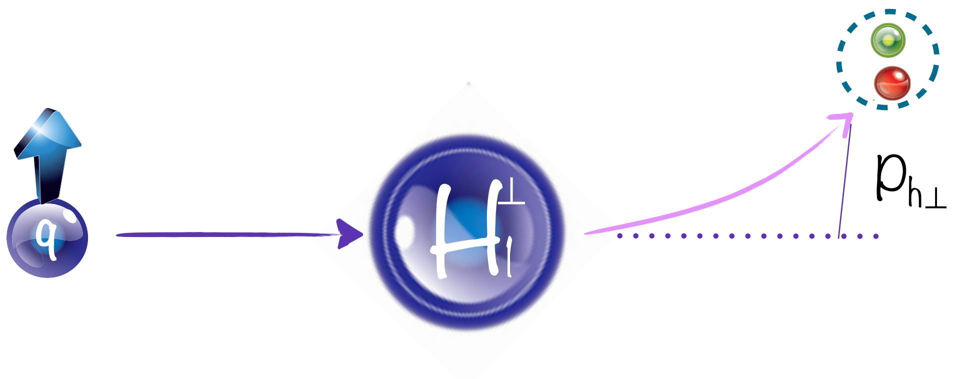
left-right asymmetry from correlations between
quark transverse spin
and

outgoing hadron direction

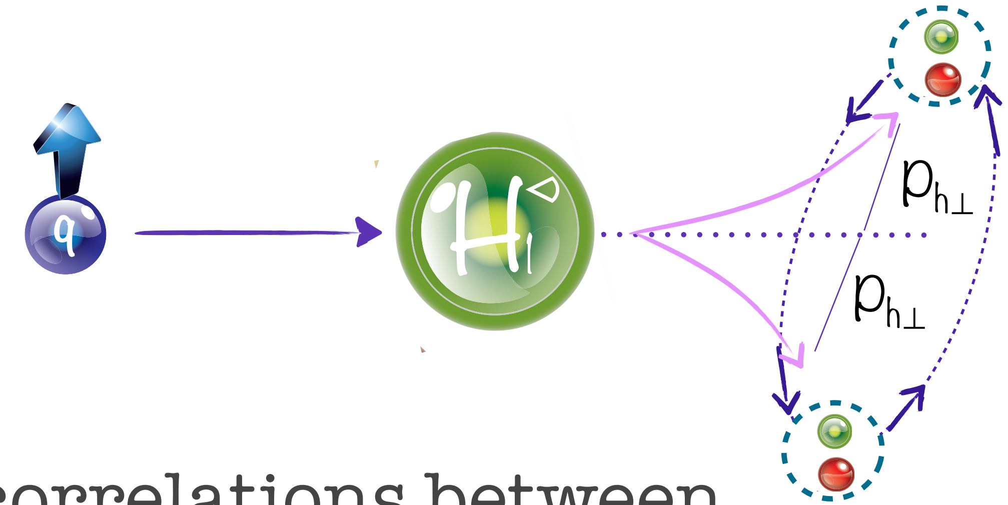
Transversity distribution

Collinear case

Collins Fragmentation



Interference Fragmentation



left-right asymmetry from correlations between
quark transverse spin
and

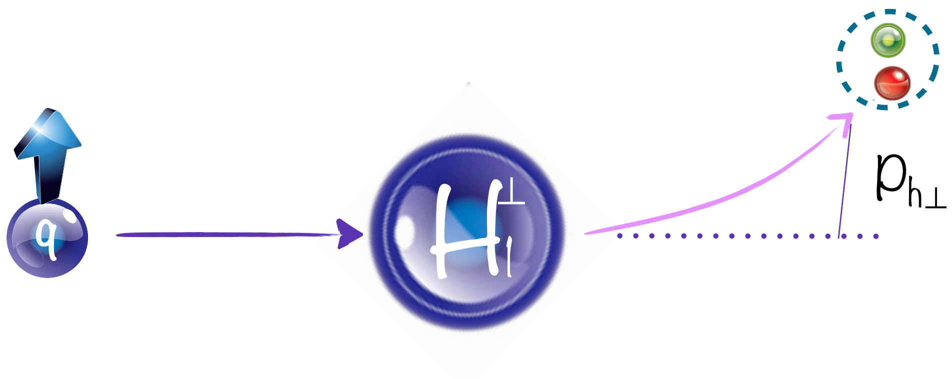
outgoing hadron direction

relative orbital angular momentum of the hadron pair

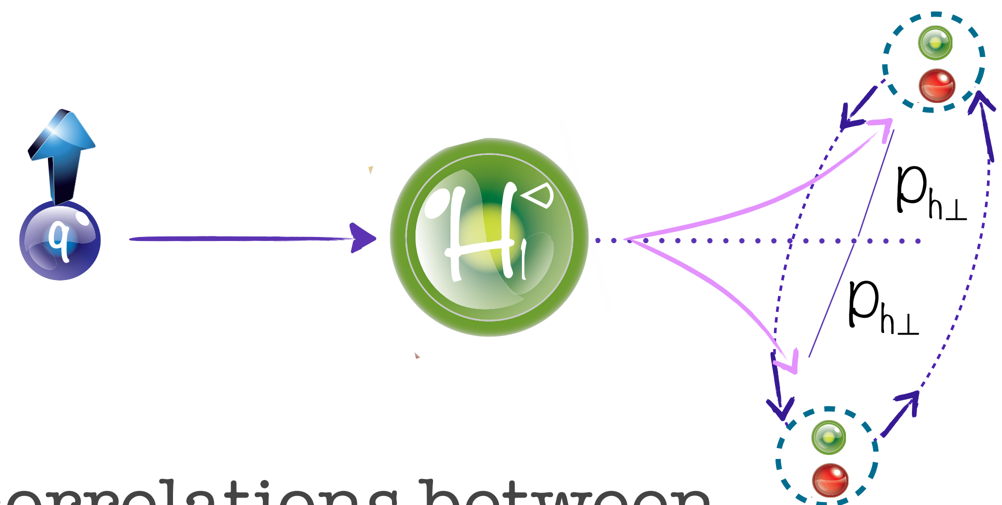
Transversity distribution

Collinear case

Collins Fragmentation



Interference Fragmentation



left-right asymmetry from correlations between

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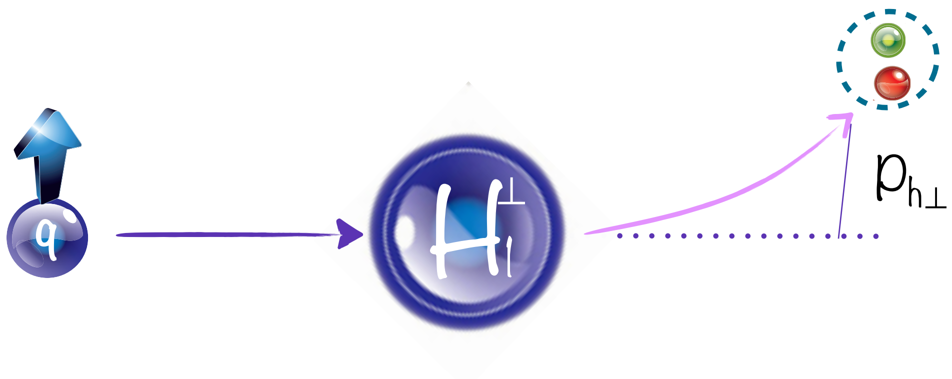
relative orbital angular momentum of the hadron pair

Collinear!

Transversity distribution

Collinear case

Collins Fragmentation



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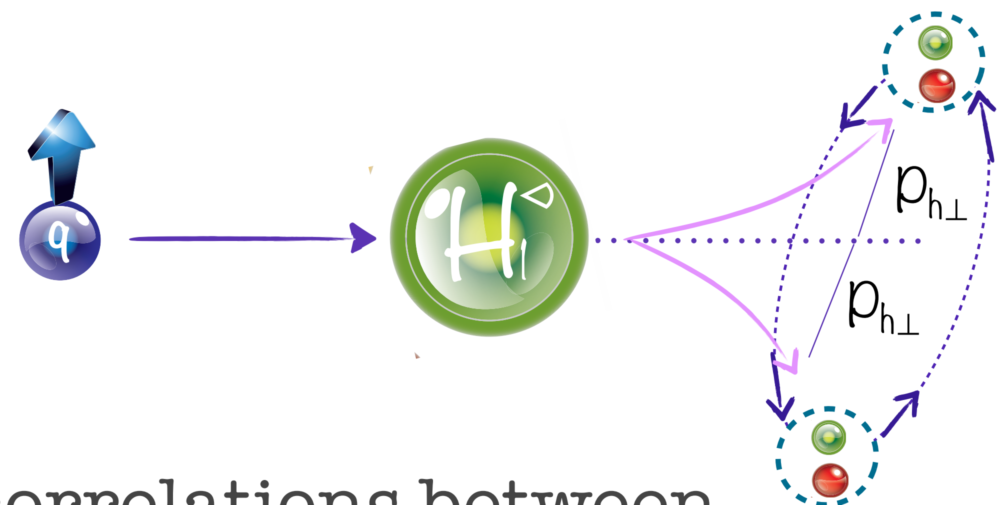


left-right asymmetry from correlations between
quark transverse spin
and

outgoing hadron direction

relative orbital angular momentum of the hadron pair

TMD!

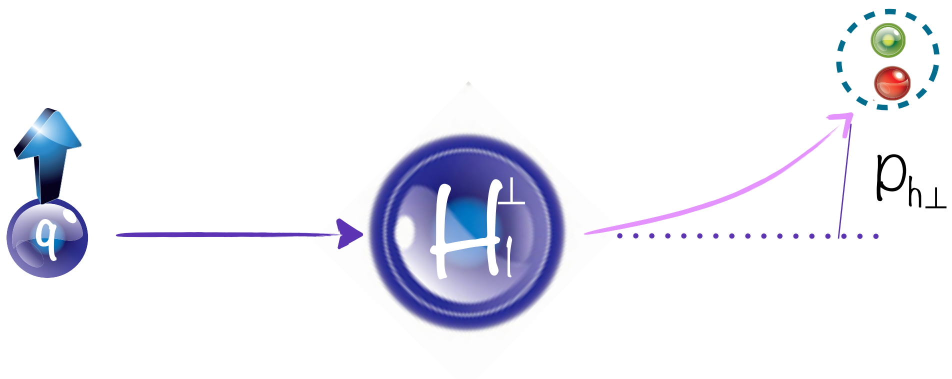
Collinear!

Transversity distribution

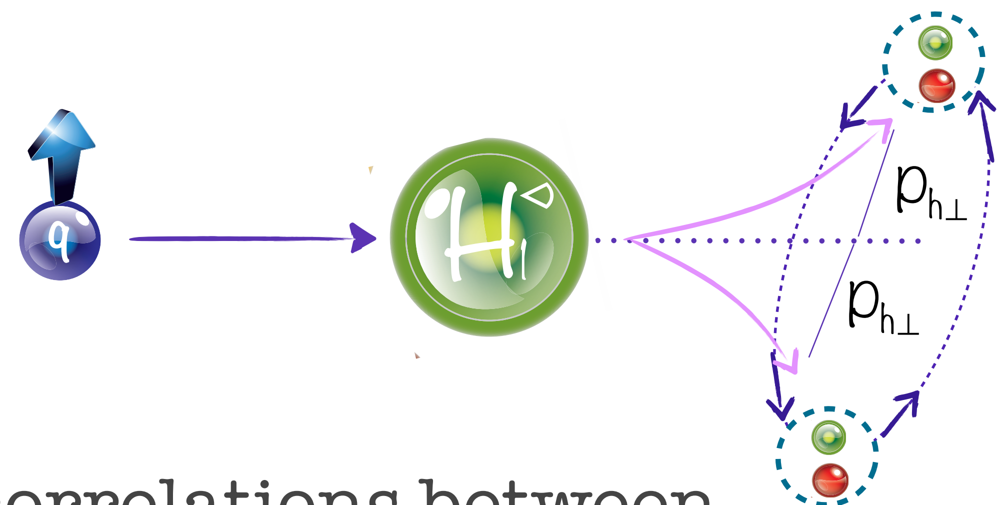
Colli~~near~~ case

Depends on transverse momentum!

Collins Fragmentation



Interference Fragmentation



left-right asymmetry from correlations between
quark transverse spin
and

outgoing hadron direction

relative orbital angular momentum of the hadron pair

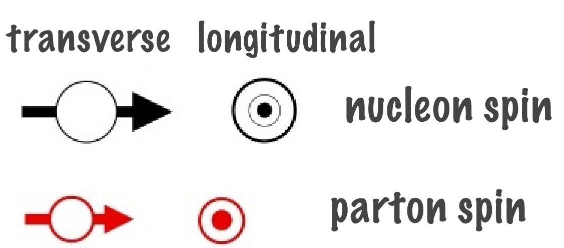
TMD!

Collinear!

Transverse Momentum dependent PDFs

		quark U	quark L	quark T
nucleon	U	f_1		
nucleon	L		g_1 -	
nucleon	T			h_1 - -

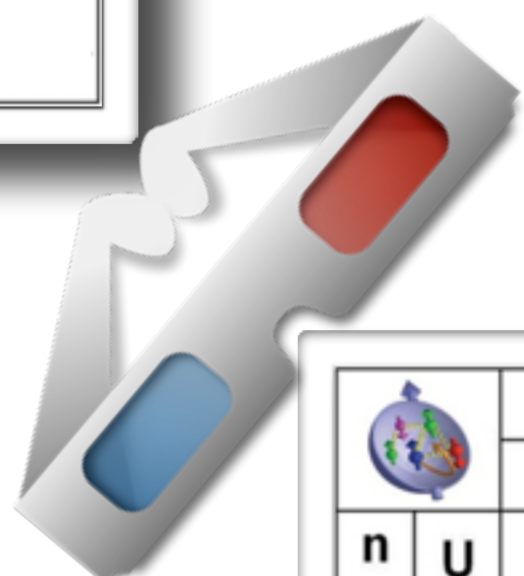
1D

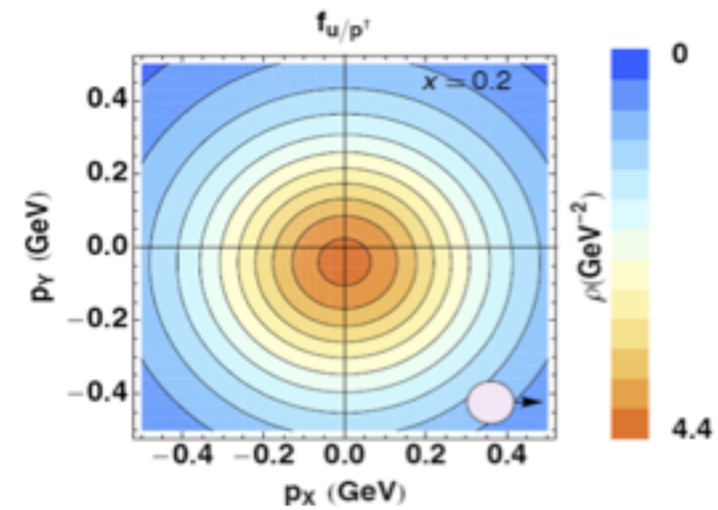


Transverse Momentum dependent PDFs

nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1

1D





A.B., F. Conti, M. Radici, PRD78 (08)

3D!

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

transverse longitudinal

nucleon spin

parton spin

parton transverse momentum

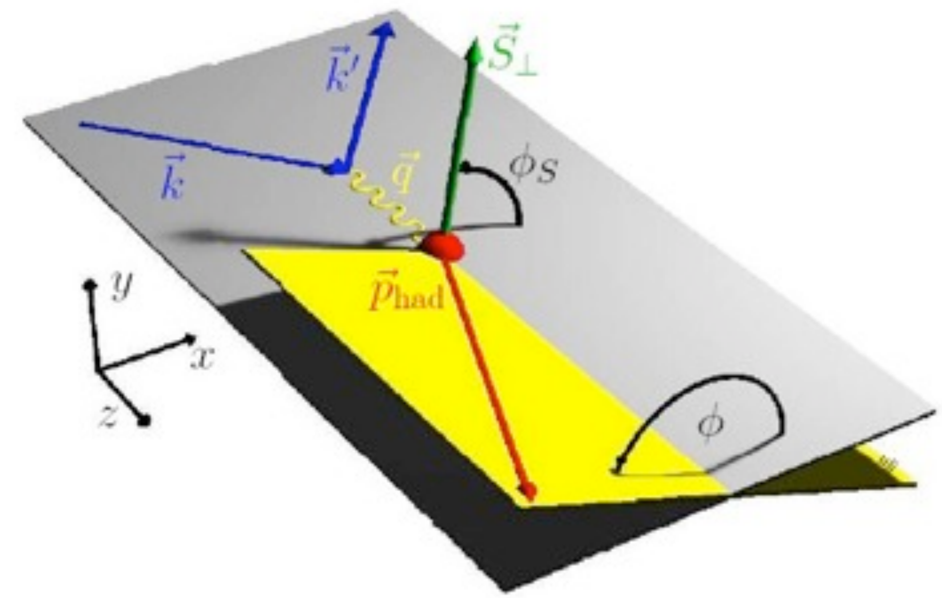
Transverse Momentum dependent PDFs

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = {} & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \; & \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ \; & S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ \; & S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ \; & S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; & S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

target polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

beam polarization **virtual photon polarization**



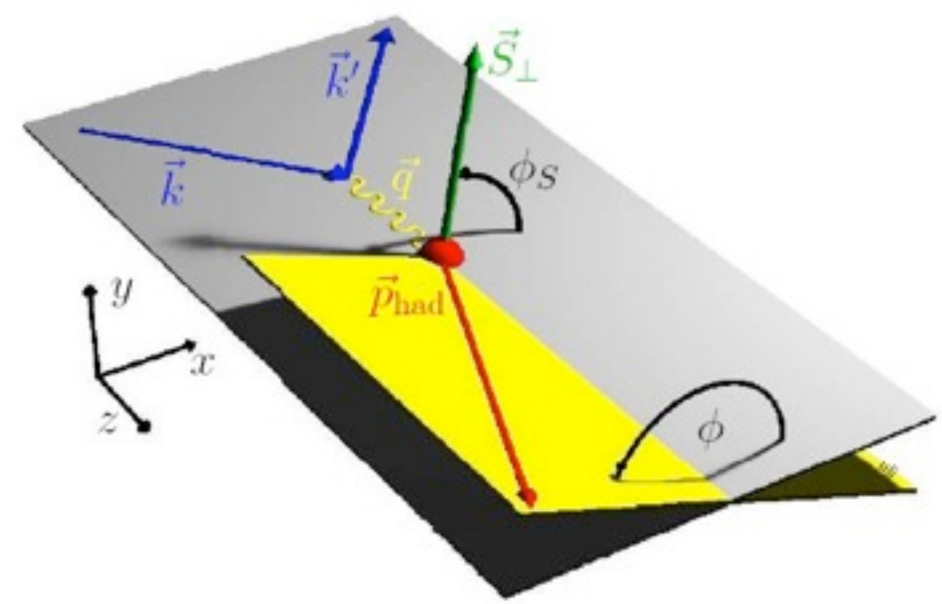
Each Structure function expanded in $P_{h\perp}/Q$ serie

$P_{h\perp} << Q$ higher twist suppressed

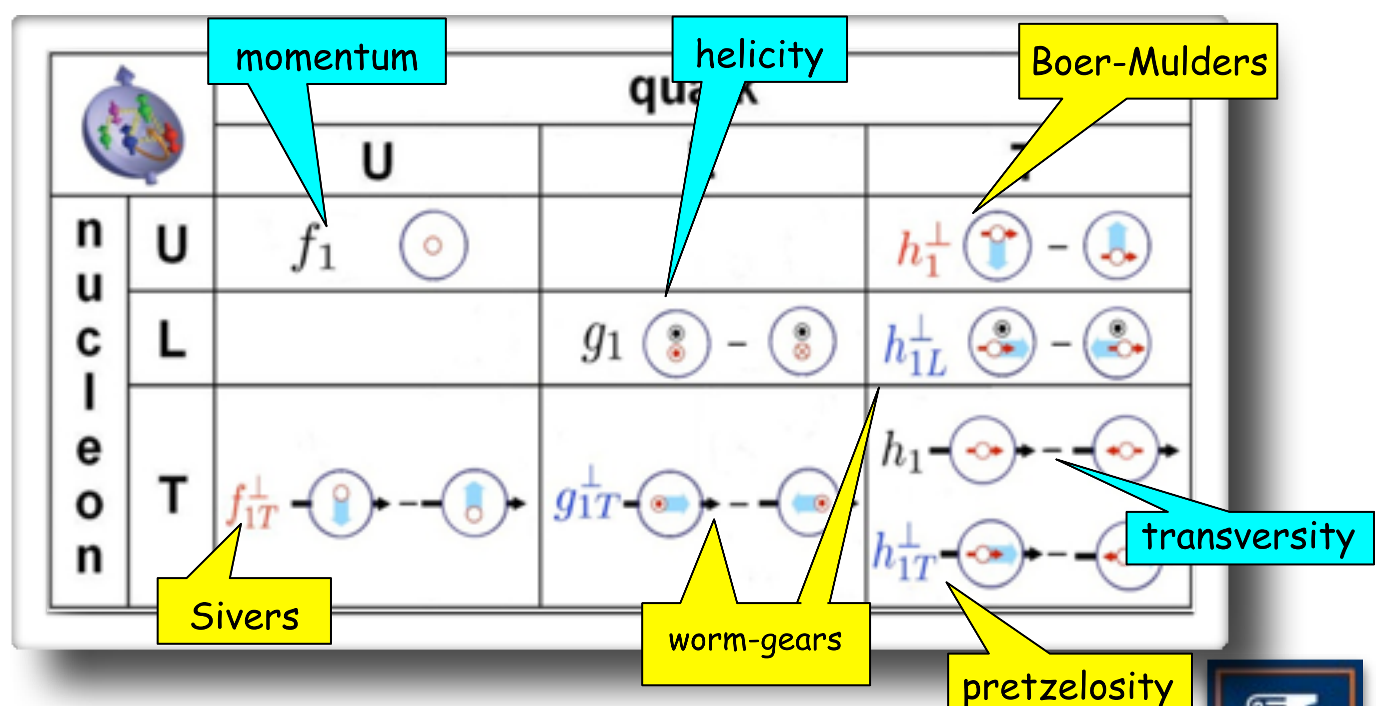
$P_{h\perp} >> Q$ higher twist contributes!

Transverse Momentum dependent PDFs

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = {} & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ {} & \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ {} & S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ {} & S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ {} & S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ {} & S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$



TMDs Leading Twist Table



target polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

beam polarization

virtual photon polarization

Transverse Momentum dependent PDFs

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}}+\epsilon F_{\mathrm{UU,L}} \\
& +\sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)}+\epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ & \lambda_l\Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ & S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)}+\epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ & S_L\,\lambda_l\Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}}+\sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ & S_T\Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)}+\epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& +\epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)}+\epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& +\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& +\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ & S_T\,\lambda_l\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& +\sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& +\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

How can we disentangle all these contributions ?

EXPERIMENT: setting the proper beam and target polarization states (U, L, T)

ANALYSIS: fitting the cross section asymmetry for opposite spin states and extracting the relevant Fourier components based on their peculiar azimuthal dependences.

$$A^h_{\mathrm{U}\perp} = \frac{\sigma^h_{\mathrm{U}\Uparrow}-\sigma^h_{\mathrm{U}\Downarrow}}{\sigma^h_{\mathrm{U}\Uparrow}+\sigma^h_{\mathrm{U}\Downarrow}}$$

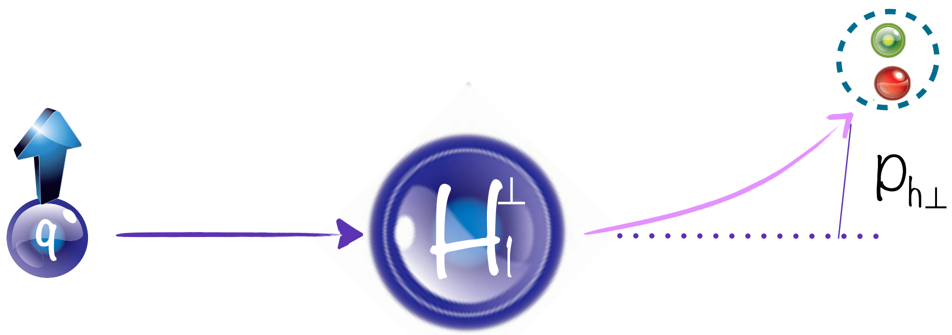
nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution

Coll~~inear~~ case

Depends on transverse momentum!

Collins Fragmentation



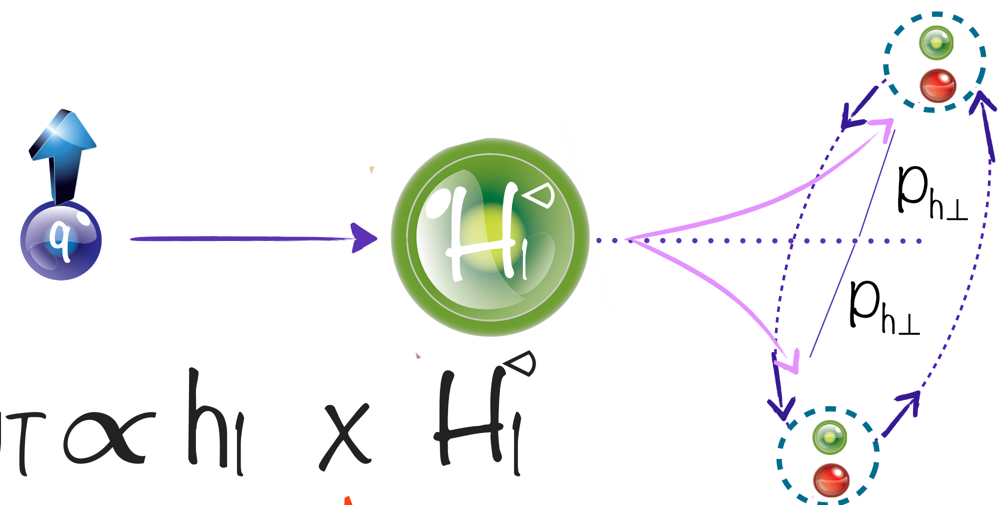
$$A_{UT} \propto h_1 \otimes H_1^\perp$$

$$\int h_1(x,p_T)\, H_1^\perp(x,k_T)\; dp_T\, dk_T$$

(and same in the denominator for the unpolarized pdfs and ffs)

TMD!

Interference Fragmentation



$$A_{UT} \propto h_1 \;\times\; H_1^\sphericalangle$$

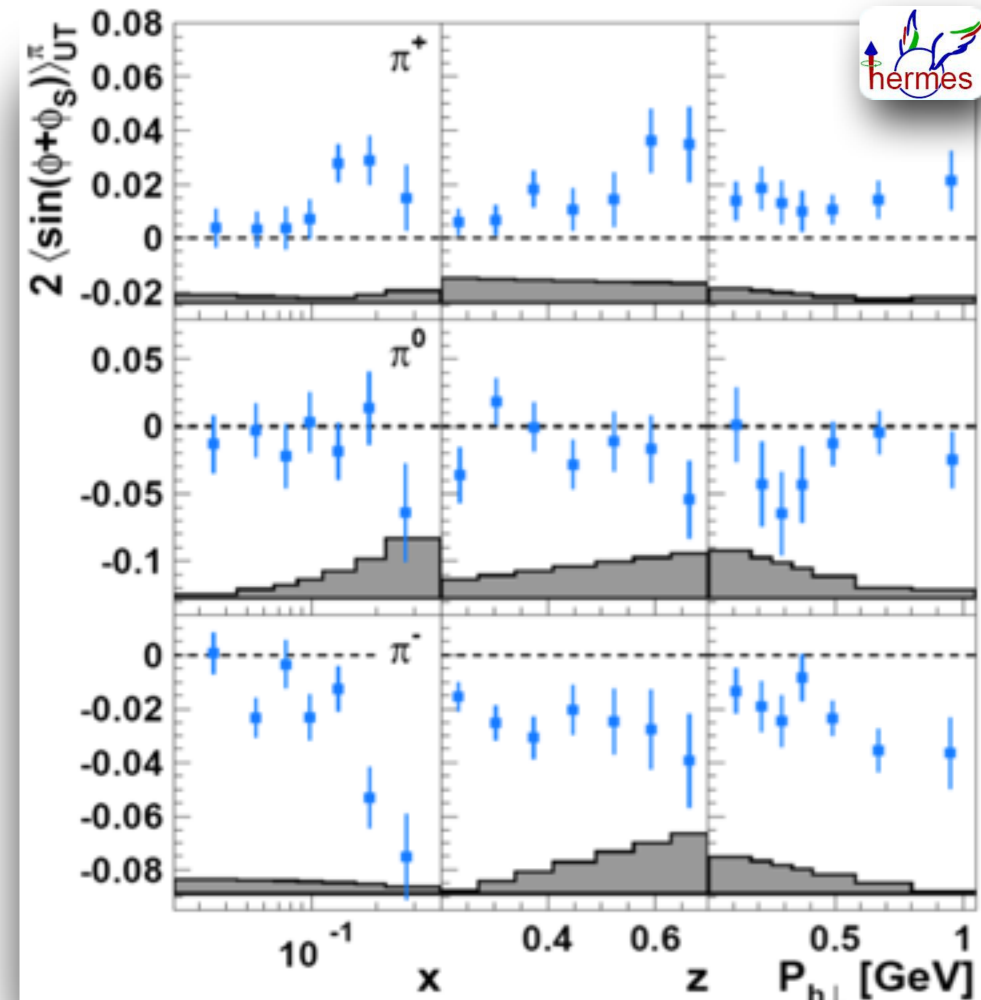
direct product!

(same in the denominator)

Collinear!

Collins amplitudes

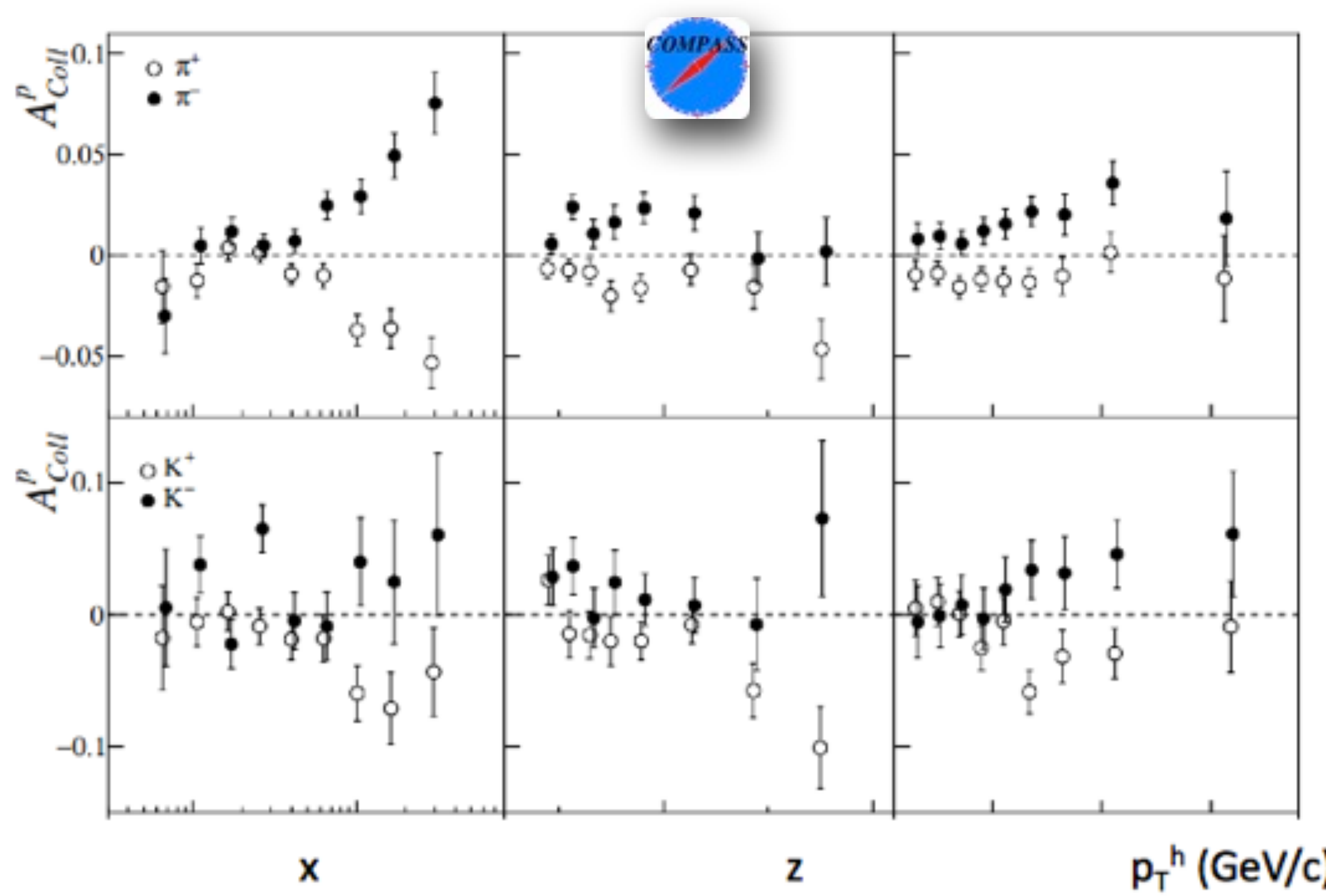
[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]



$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

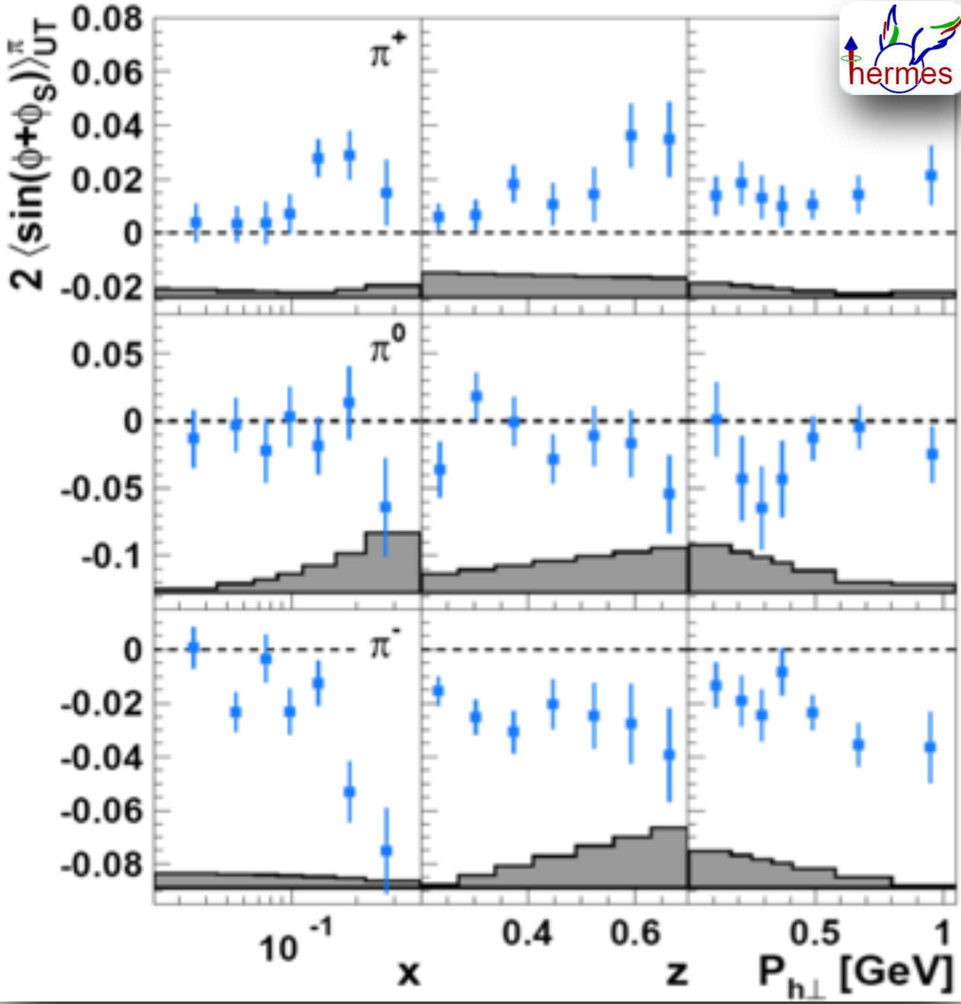
Non-zero transversity!

Opposite sign for favored and unfavored FF



Collins amplitudes

[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]

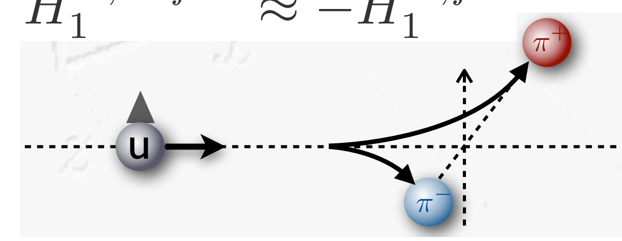


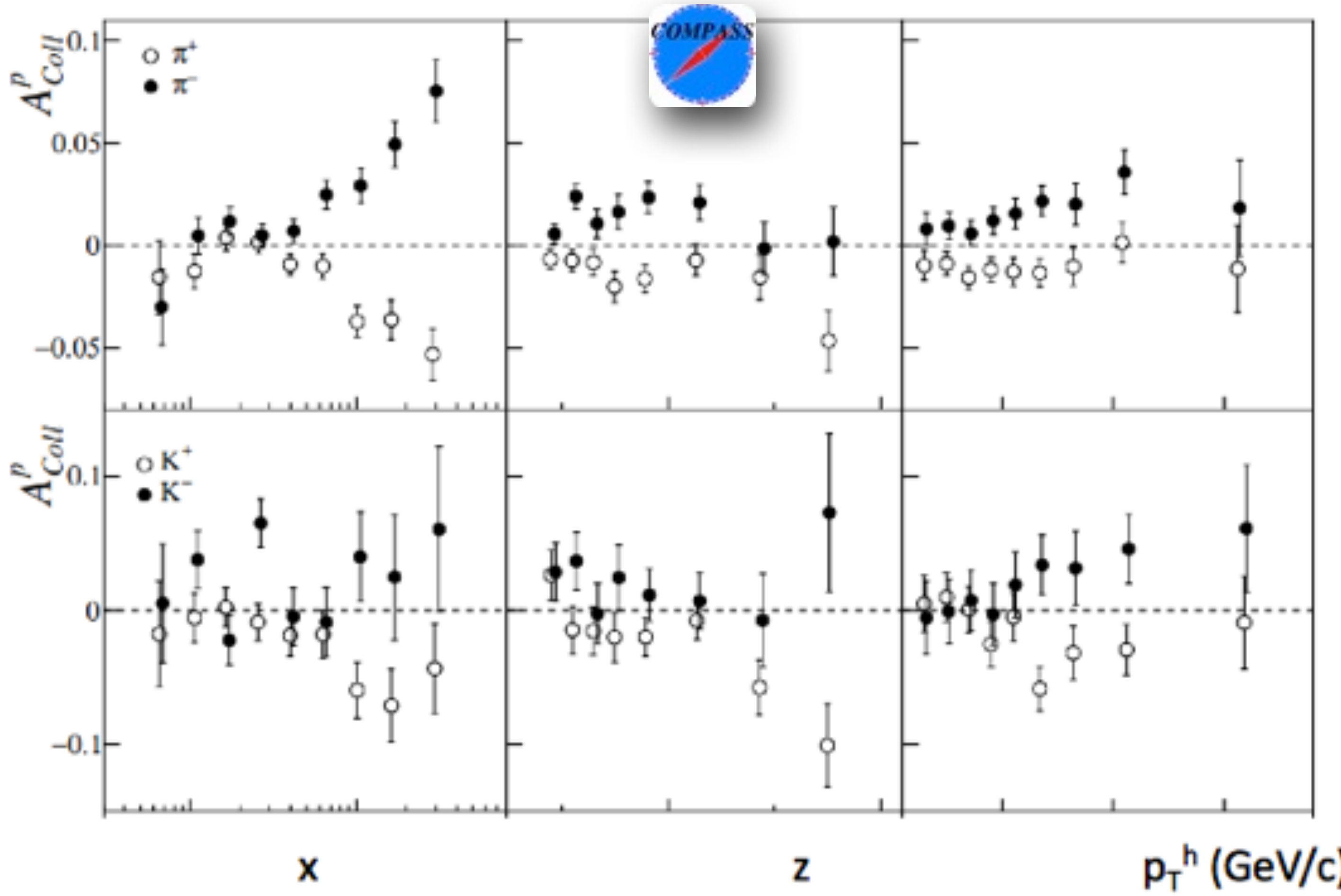
$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

Non-zero transversity!

Opposite sign for favored and unfavored FF

$$H_1^{\perp,unfav} \approx -H_1^{\perp,fav}$$





$\pi\pi$ Collins moments

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

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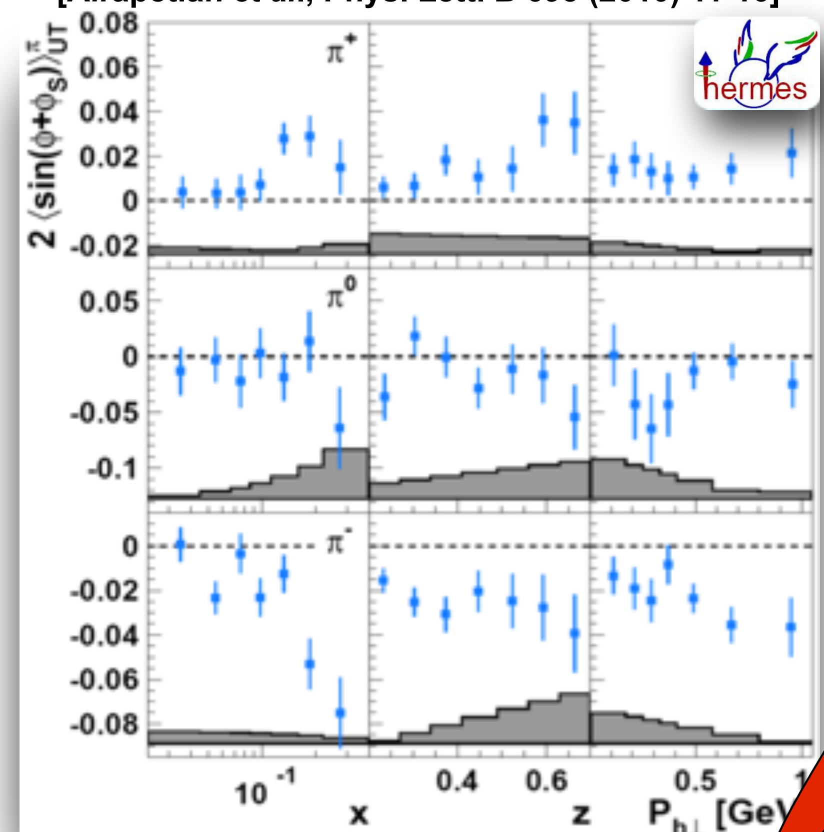
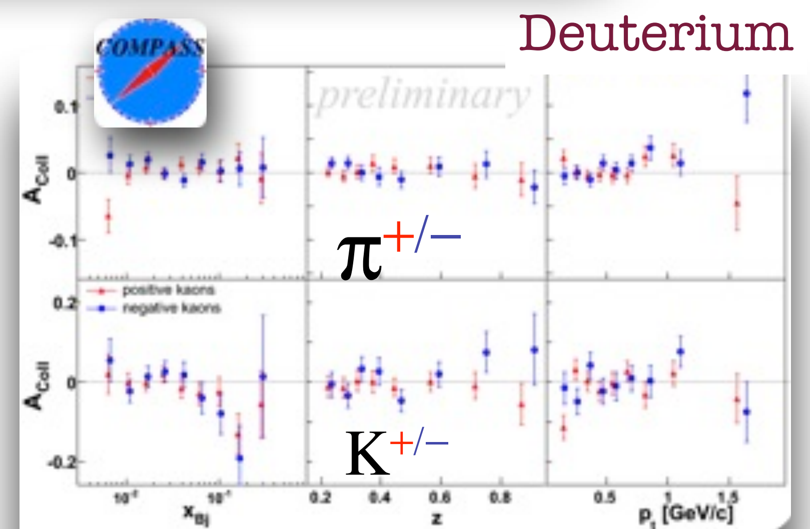
[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]



Deuterium



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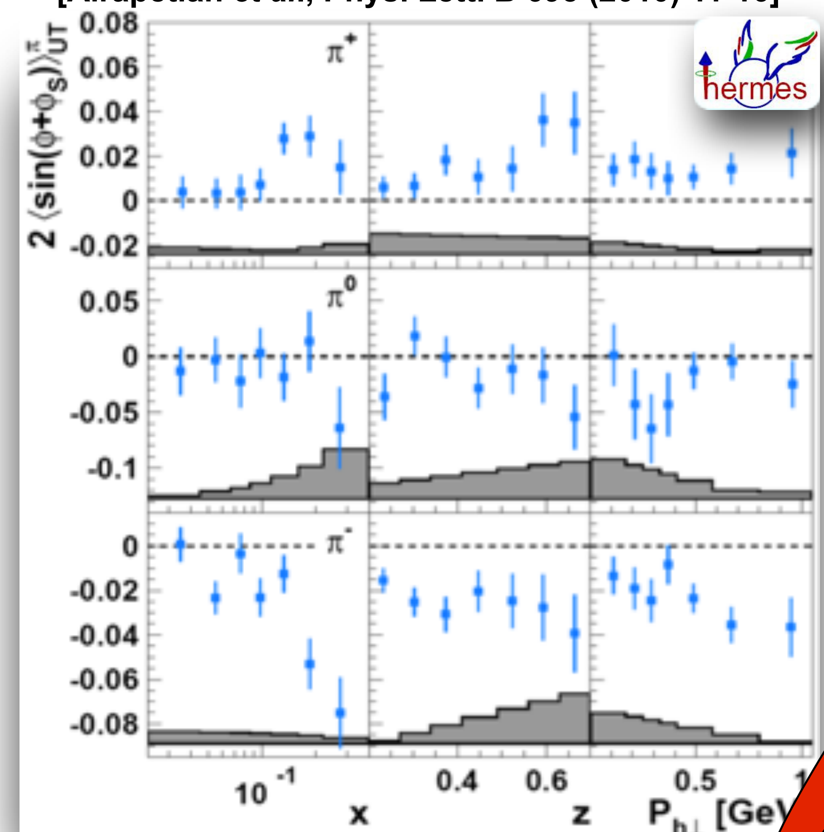
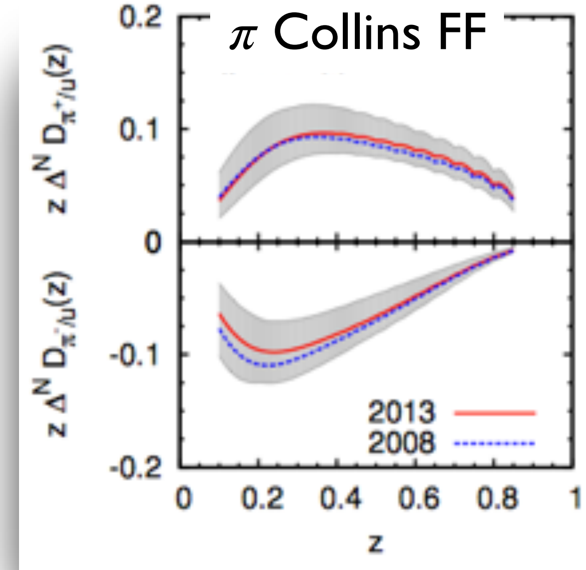
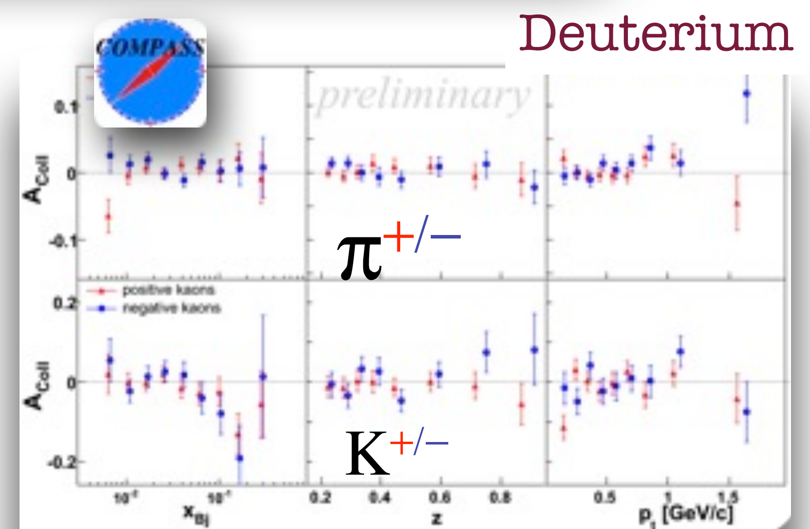
[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]



Anselmino et al.
PRD75 (2007)
PRD87 (2013)

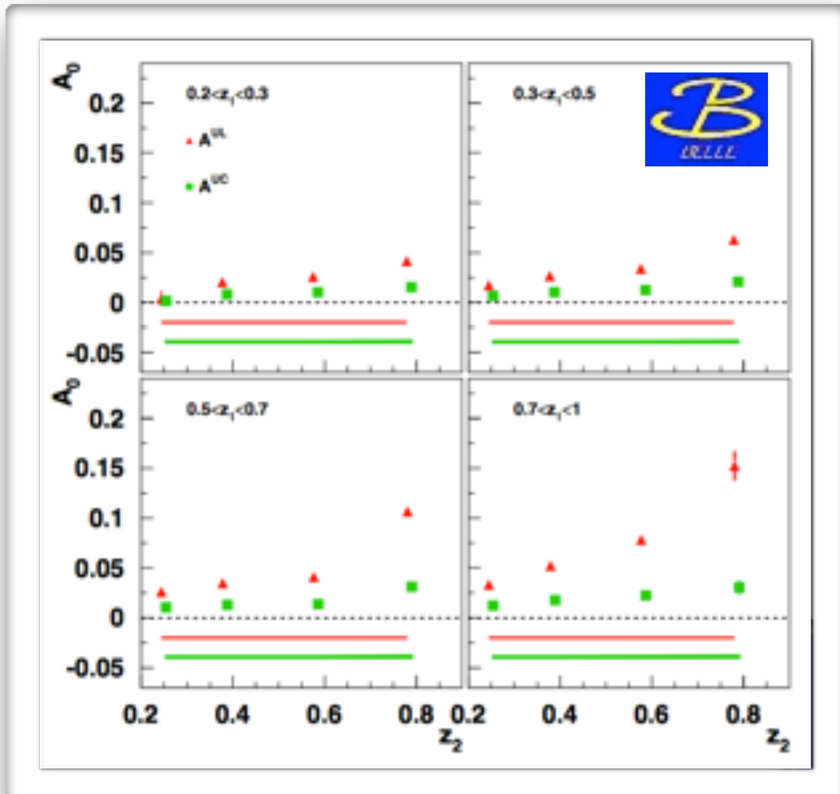




Deuterium

$\pi^{+/-}$

$K^{+/-}$



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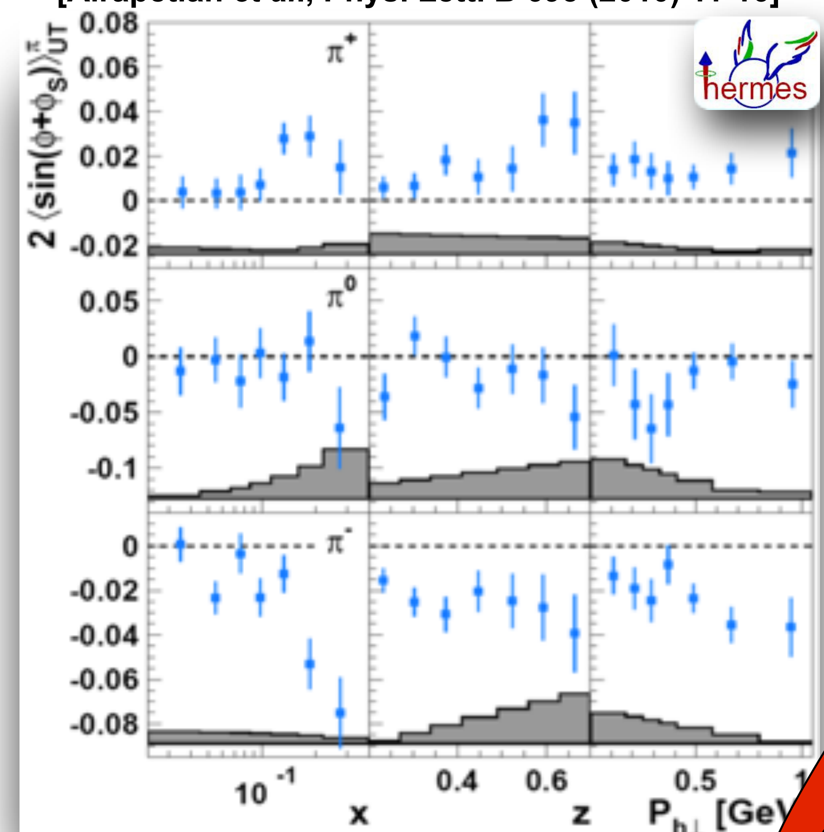
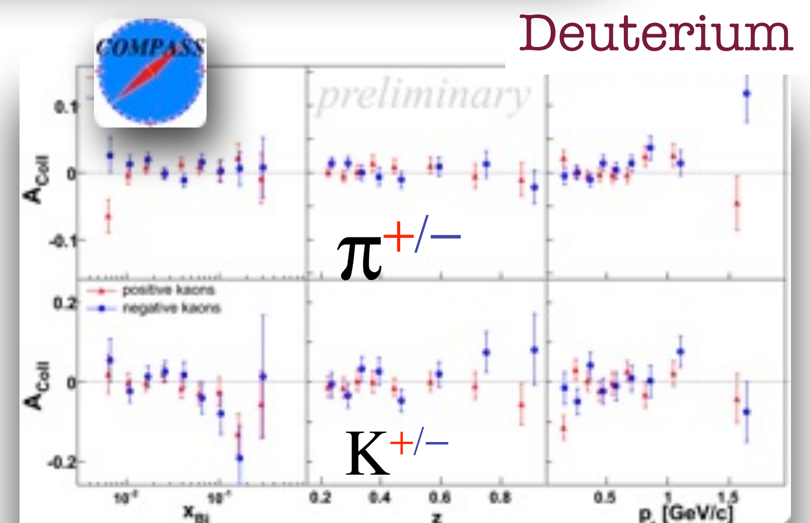
[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]



Deuterium



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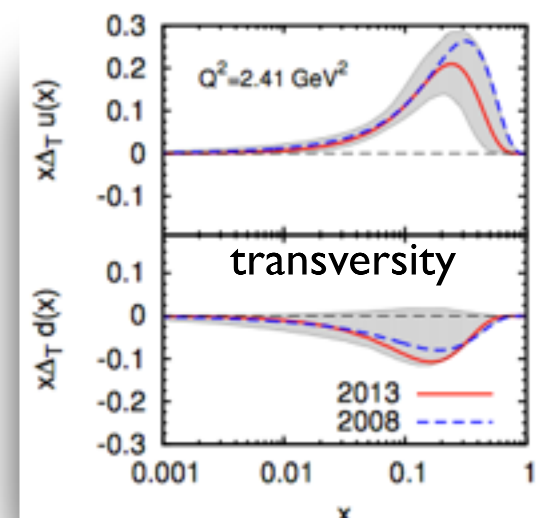

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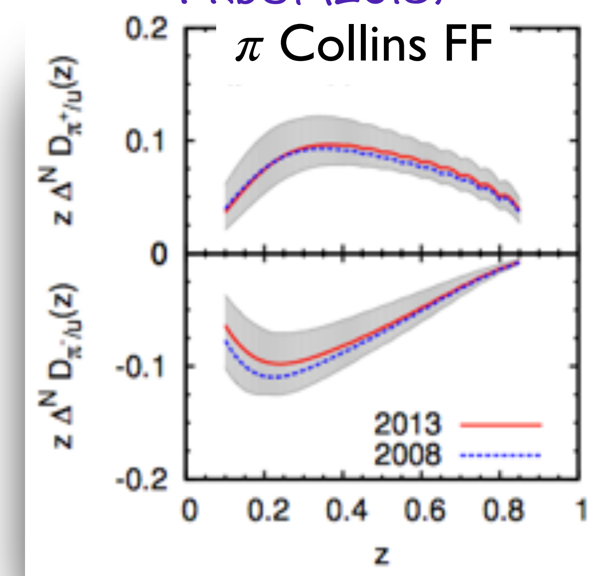
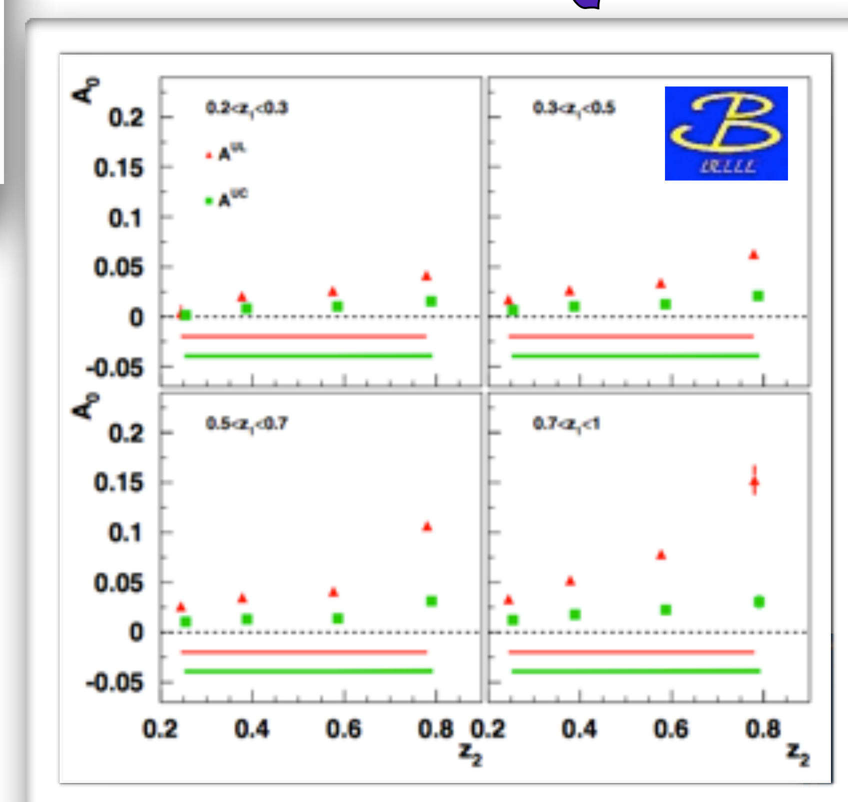




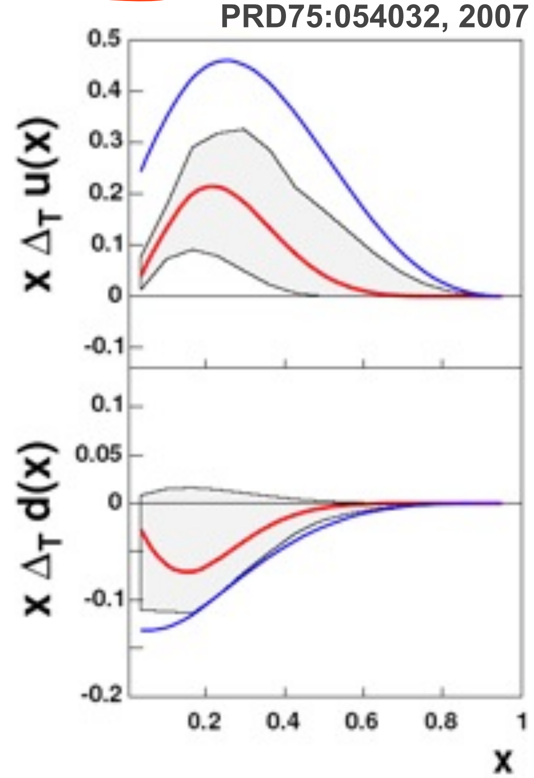
Transversity distribution

First access in SIDIS

$A_{UT} \propto h_1 \otimes H_1^{\perp}$ **TMD**

Collins FF

M. Anselmino et al., PRD75:054032, 2007



Complementary reactions

FF universality assumed

TMD factorization assumed

Transversity distribution

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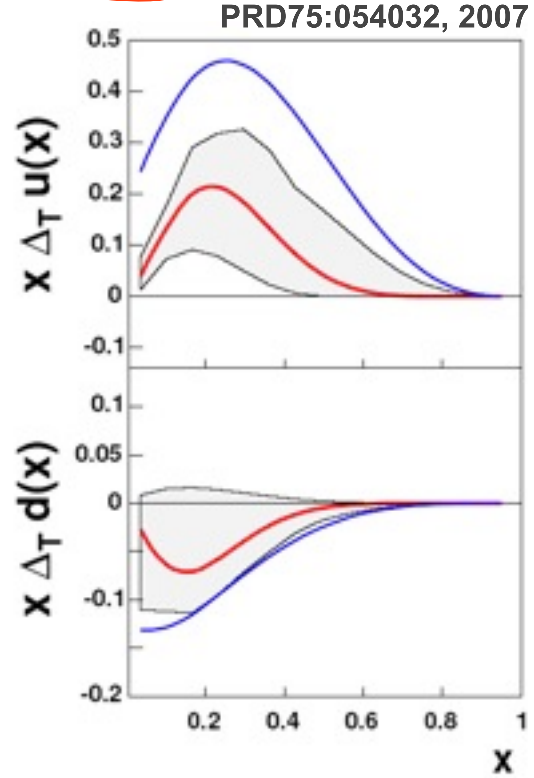

Complementary reactions

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Very different energies between Hermes/Compass and Belle: Is TMD evolution different from Collinear?

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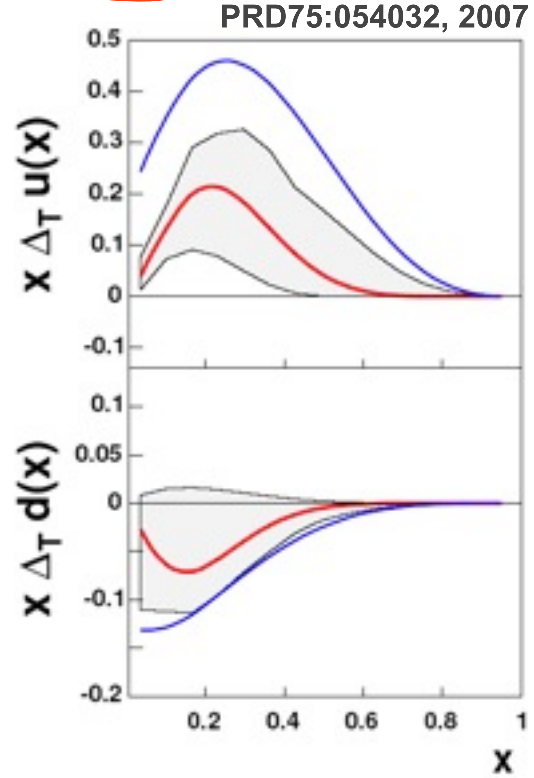
hermes COMPASS BELLE

M. Anselmino et al., PRD75:054032, 2007



Complementary reactions

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TMD factorization assumed

Very different energies between Hermes/Compass and Belle:
Is TMD evolution different from Collinear?

Collinear evolution assumed

Different energies at Hermes/Compass: how does transversity evolve?

No evolution assumed

Transversity distribution

First access in SIDIS

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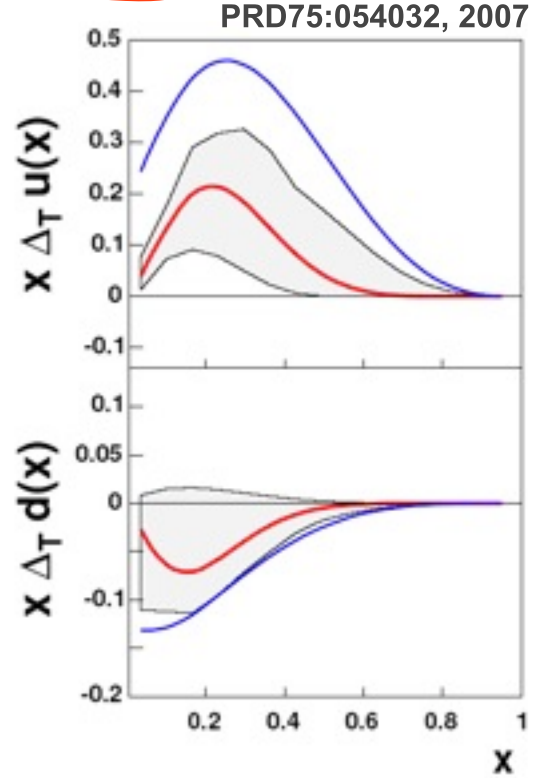


Complementary reactions

FF universality assumed

TMD factorization assumed

Very different energies between Hermes/Compass and Belle: Is TMD evolution different from Collinear?

Collinear evolution assumed

Different energies at Hermes/Compass: how does transversity evolve?

No evolution assumed

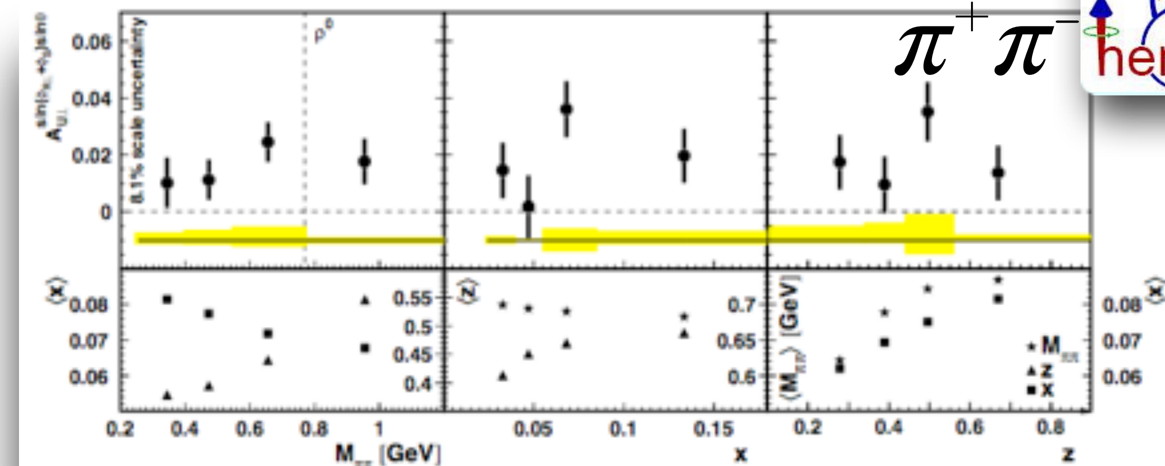
Which is the TMD transversity and the TMD Collins pT dependence? And the unpolarized TMD pT dependence?

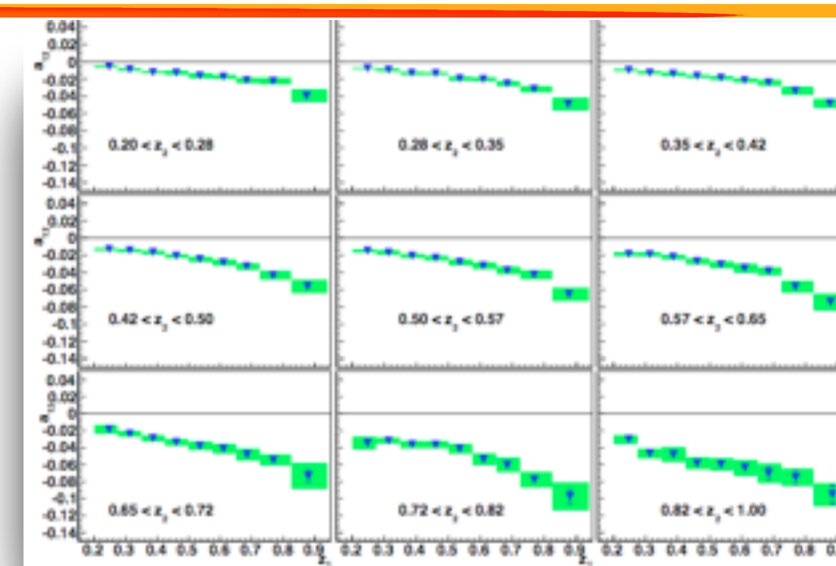
Gaussian pT dependence assumed

IFF amplitudes

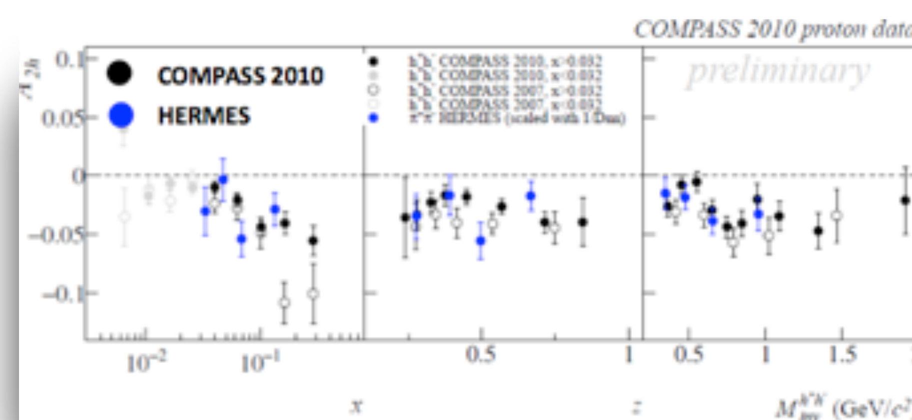
[Airapetian *et al.*, JHEP 0806:017, 2008]

$\pi^+\pi^-$

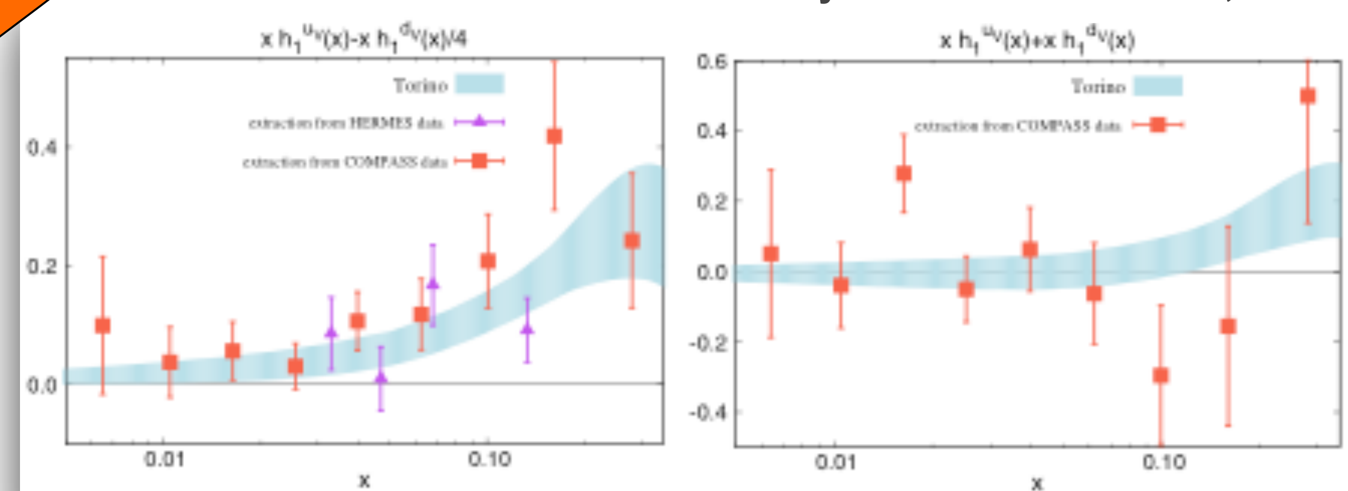




$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$



Bacchetta, Radici, Courtoy
Phys.Rev.Lett.107:012001,2011



IFF amplitudes

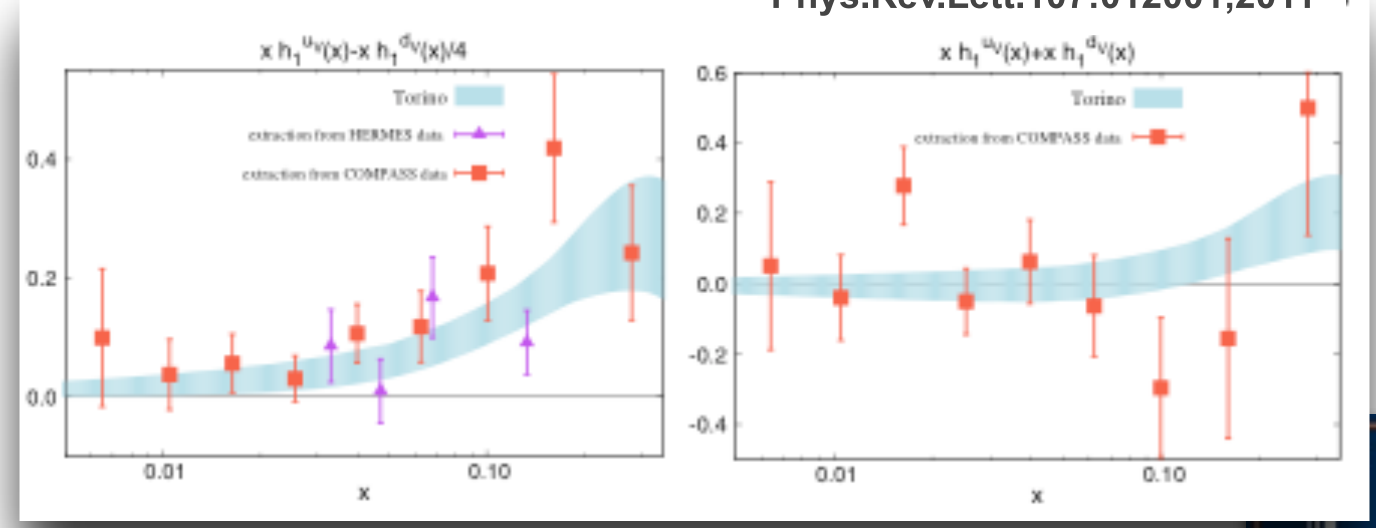
Universality & factorization
ok for collinear FF and PDF

Collinear evolution well known

pT dependence not needed

$$A_{UT} \propto h_1 \times H_1^{\sphericalangle}$$

Bacchetta, Radici, Courtoy
Phys.Rev.Lett.107:012001,2011

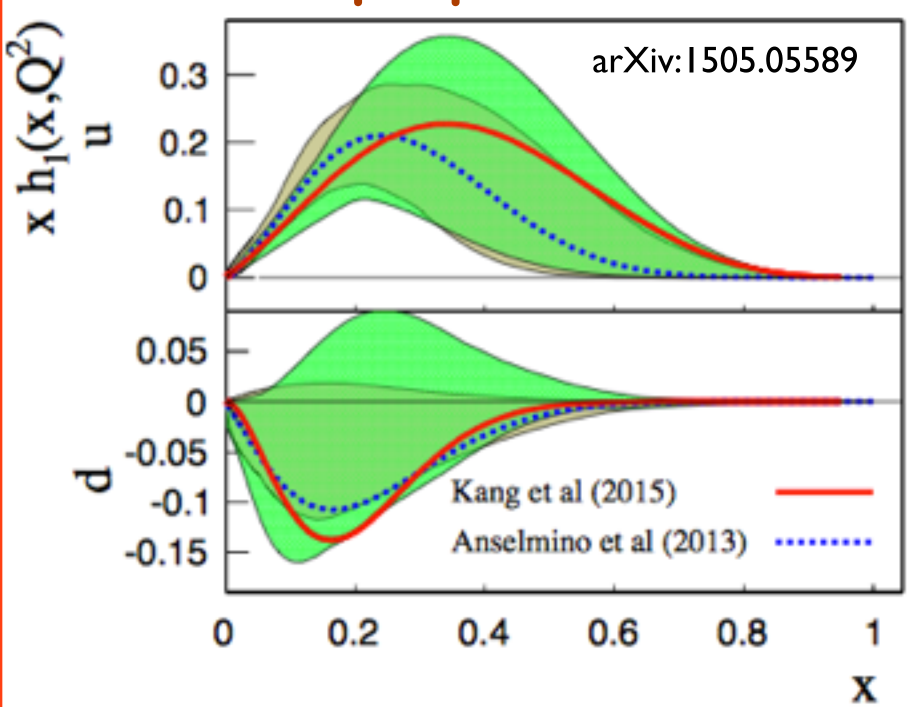


Still:
collinear and TMD transversity
extracted not in conflict!

IFF amplitudes

Universality & factorization
ok for collinear FF and PDF

Consistent with new TMD extraction
with proper TMD evolution



collinear and TMD transversity
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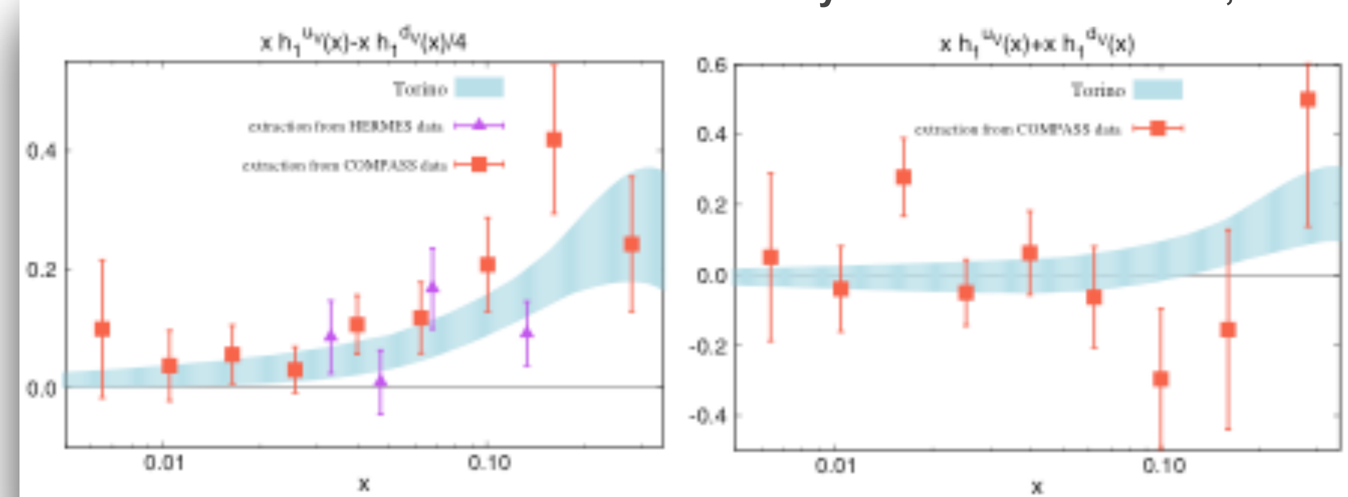
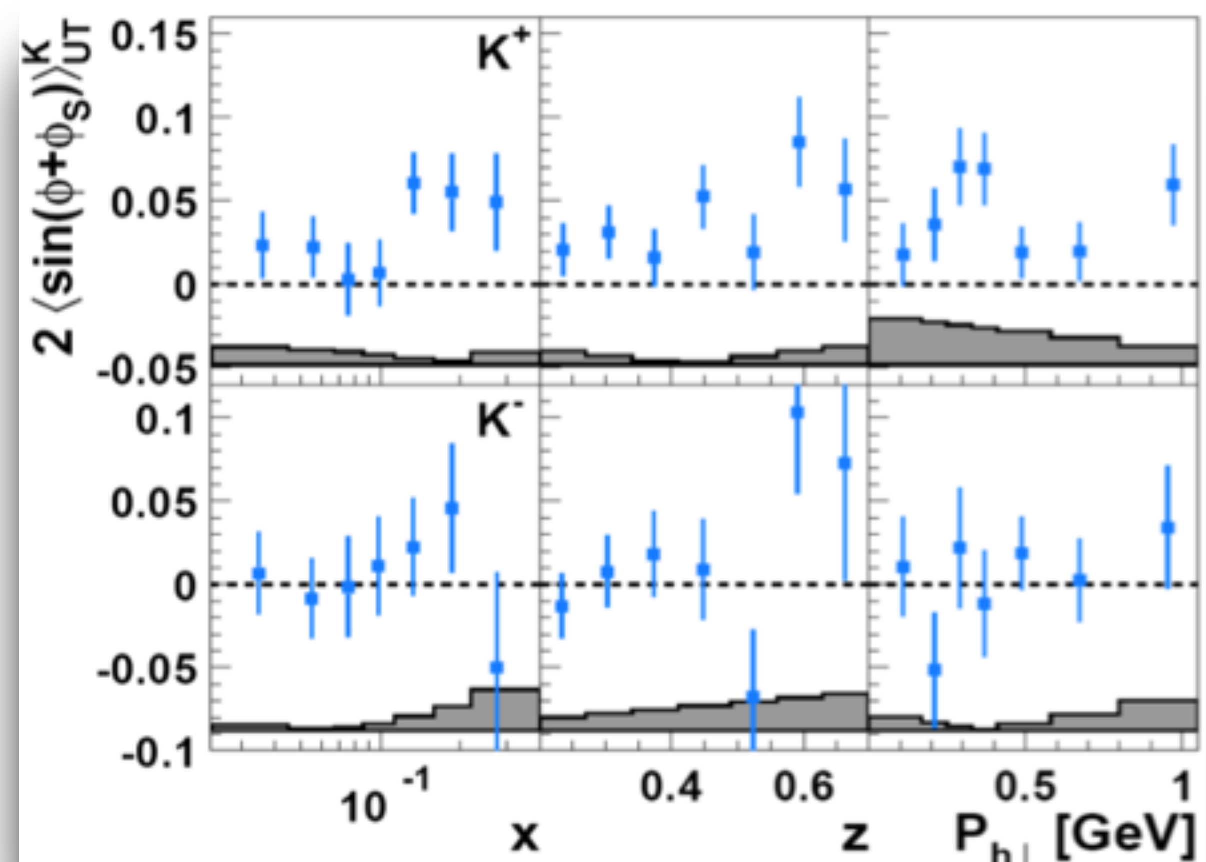
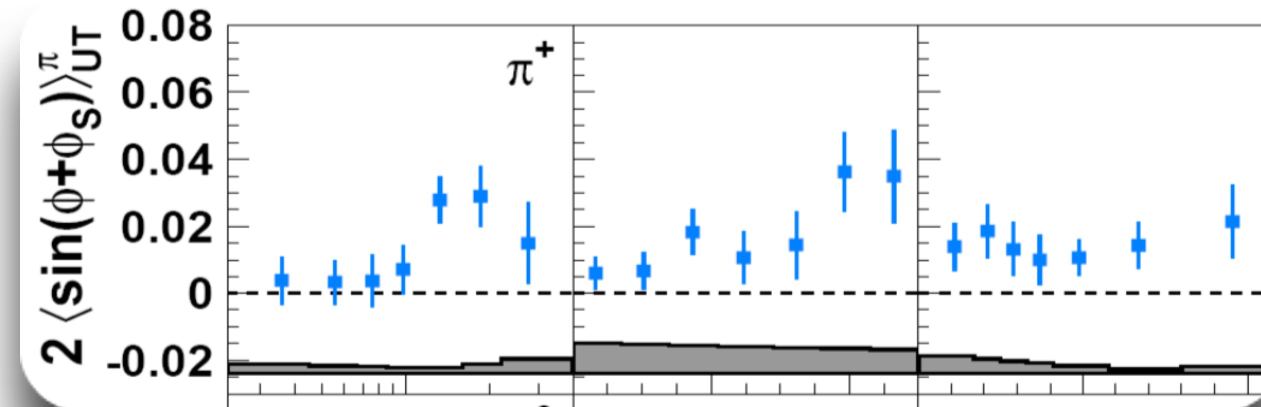
Bacchetta, Radici, Courtoy
Phys.Rev.Lett.107:012001,2011



Collins amplitudes

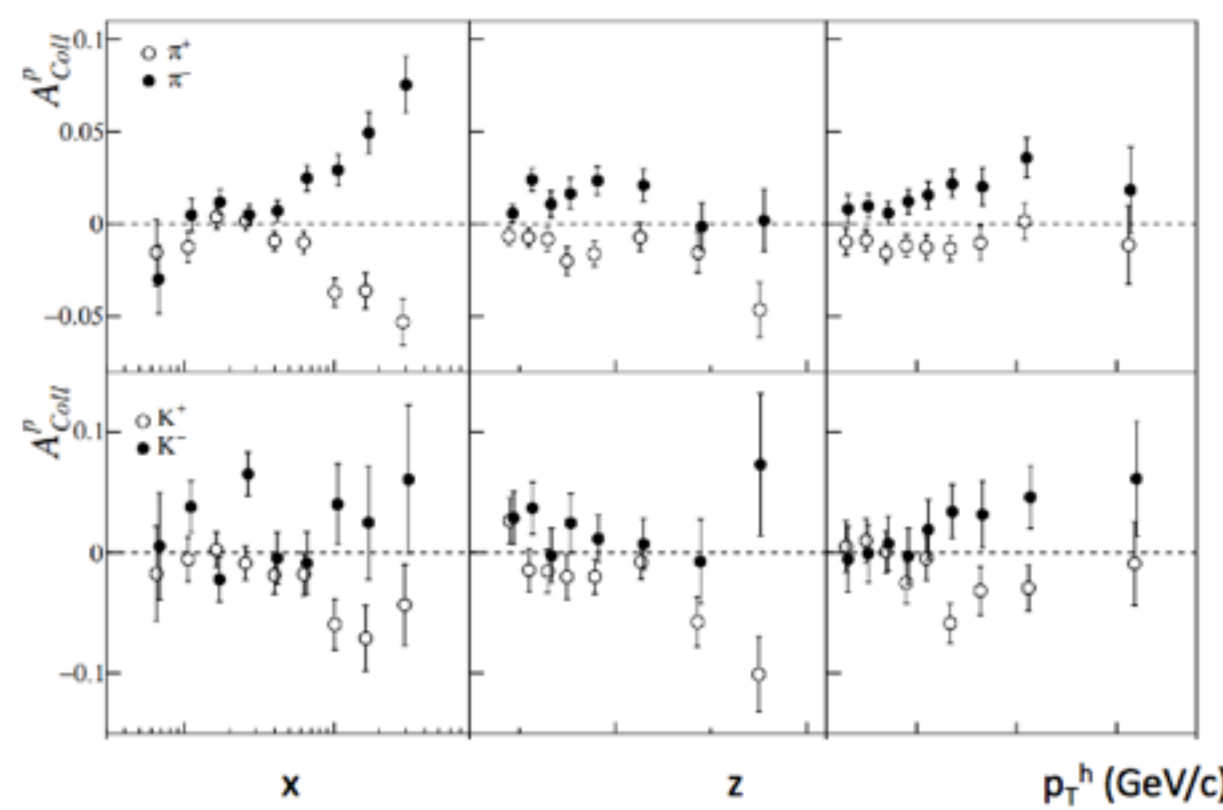
[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]





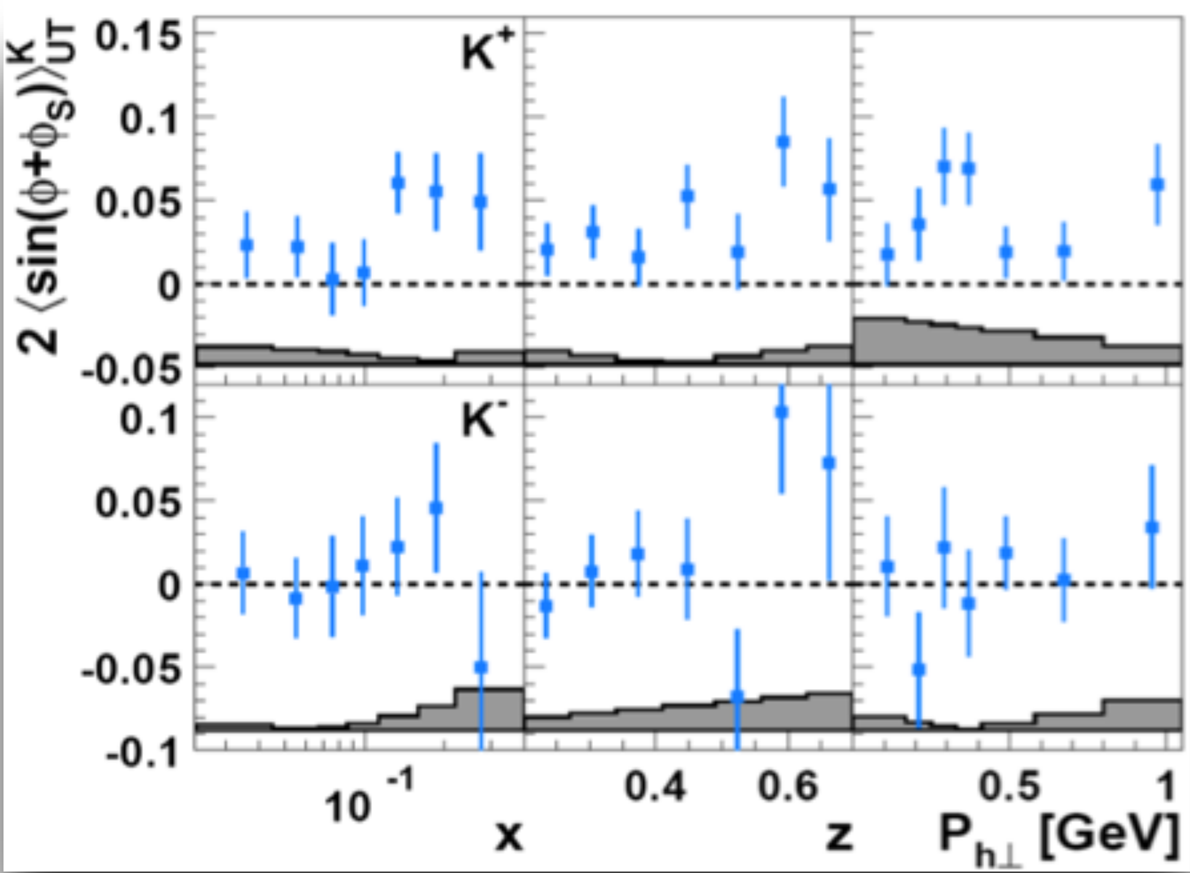
Non-zero signal for K+!

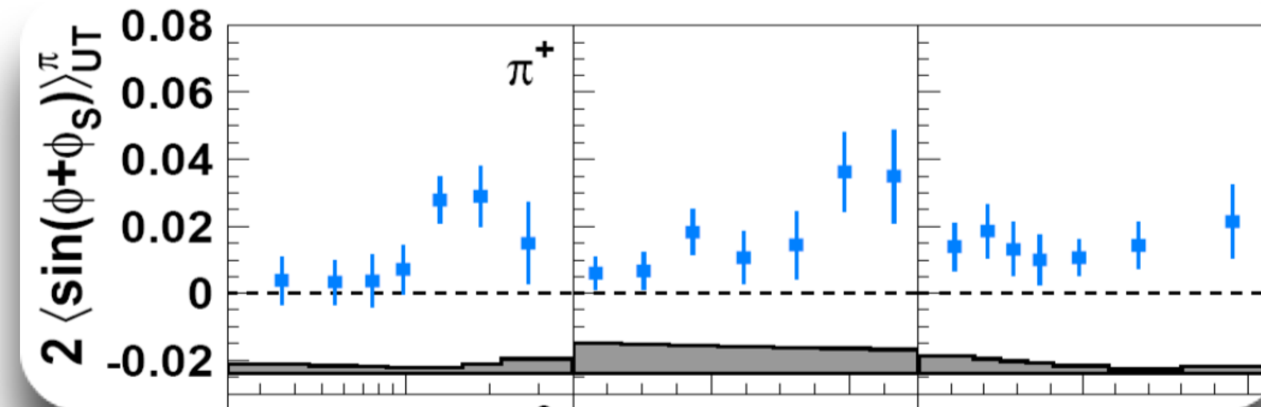
K+ amplitudes larger than π^+



Collins amplitudes

[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]

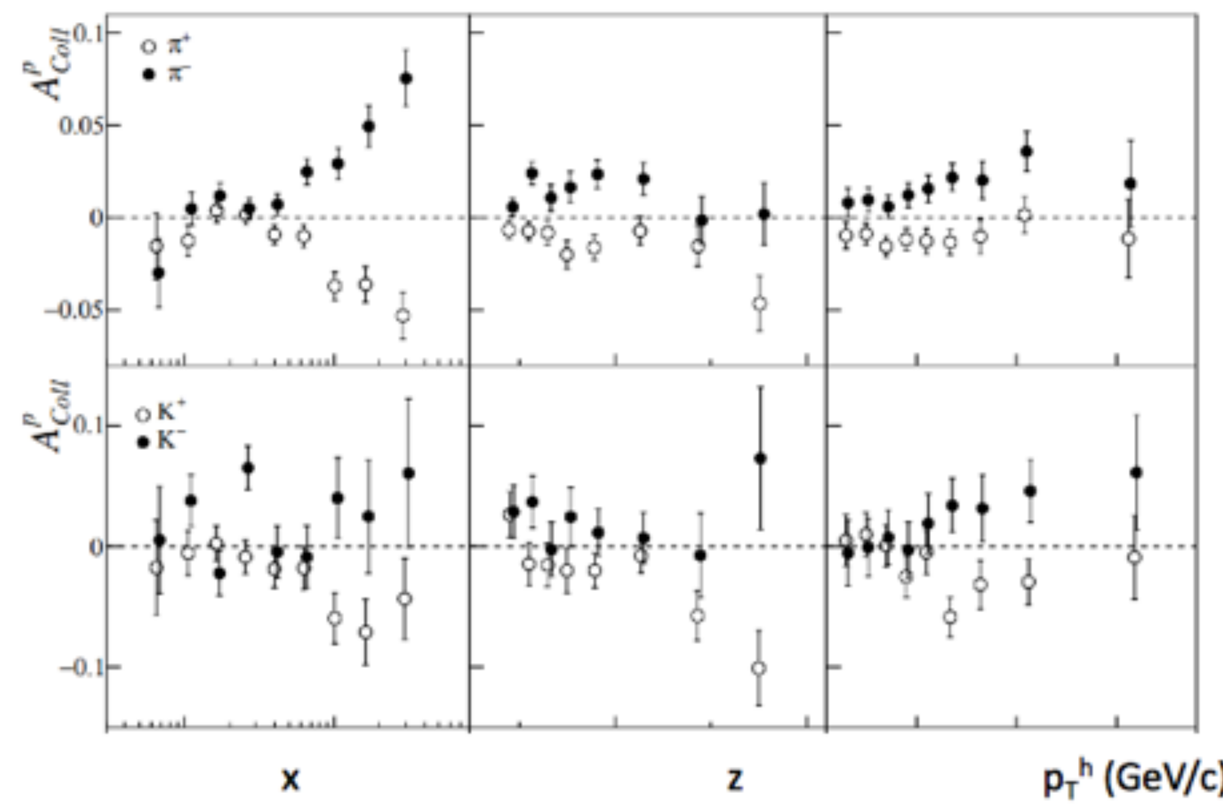




Non-zero signal for K^+!

K^+ amplitudes larger than π^+

Collins FF for kaons from Belle



Transverse Momentum dependent PDFs

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \; & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \boxed{\epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}}\Big] \\
+ \; & \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\right] \\
+ \; & S_L \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\right] \\
+ \; & S_L\,\lambda_l \left[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\right] \\
+ \; & S_T \Big[\boxed{\sin(\phi-\phi_S)\Big(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)}} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\Big) \\
& \boxed{+\epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)}} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; & S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

How can we disentangle all these contributions ?

EXPERIMENT: setting the proper beam and target polarization states (U, L, T)

ANALYSIS: fitting the cross section asymmetry for opposite spin states and extracting the relevant Fourier components based on their peculiar azimuthal dependences.

$$A_{\mathrm{U}\perp}^h = \frac{\sigma_{\mathrm{U}\Uparrow}^h - \sigma_{\mathrm{U}\Downarrow}^h}{\sigma_{\mathrm{U}\Uparrow}^h + \sigma_{\mathrm{U}\Downarrow}^h}$$

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

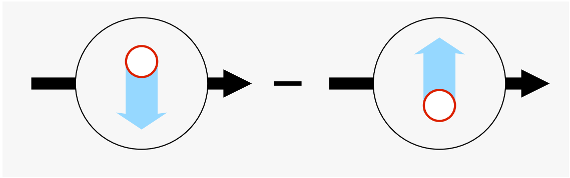
Sivers & Boer-Mulders TMDs

Azimuthal asymmetries generated by correlations between quark transverse momentum and

Sivers & Boer-Mulders TMDs

Azimuthal asymmetries generated by correlations between quark transverse momentum and

the proton transverse spin



Sivers

Sivers & Boer-Mulders TMDs

Azimuthal asymmetries generated by correlations between quark transverse momentum and

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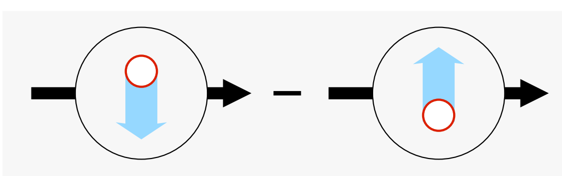
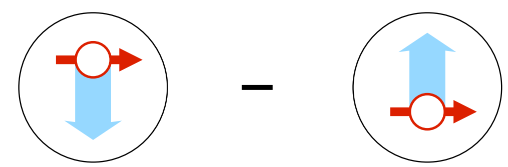


Sivers

the parton transverse spin



Boer-Mulders

Sivers & Boer-Mulders TMDs

Azimuthal asymmetries generated by correlations between quark transverse momentum and

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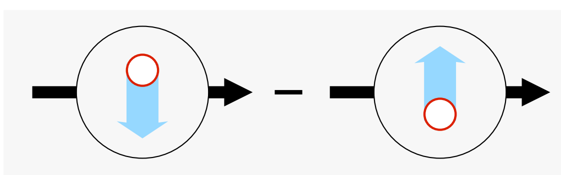
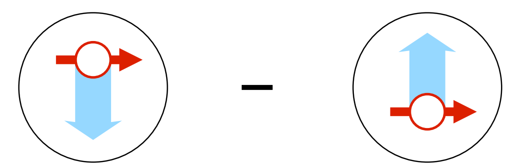
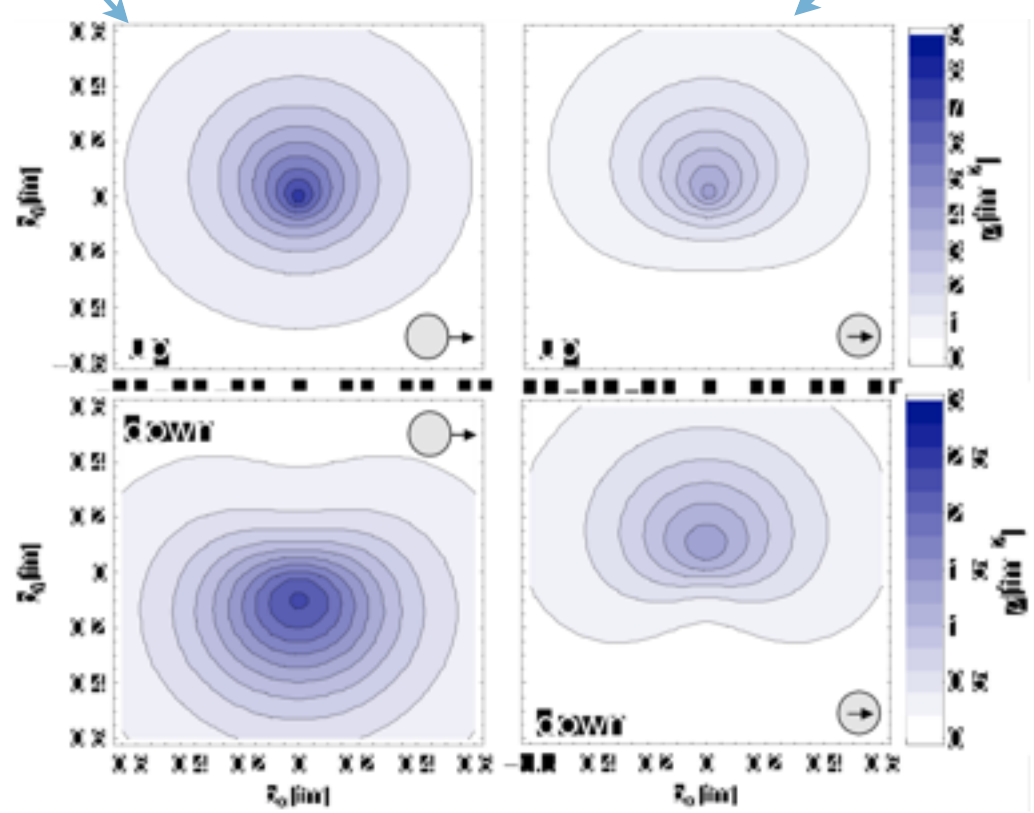


Sivers

the parton transverse spin



Boer-Mulders

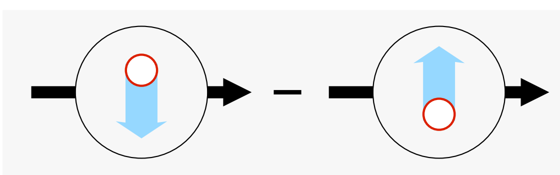


Spatial deformation due to spin-orbit correlations

Sivers & Boer-Mulders TMDs

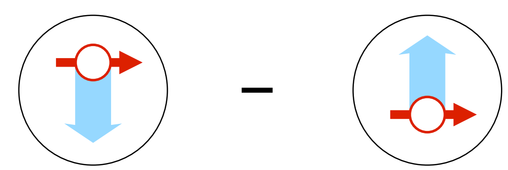
Azimuthal asymmetries generated by correlations between quark transverse momentum and

the proton transverse spin



Sivers

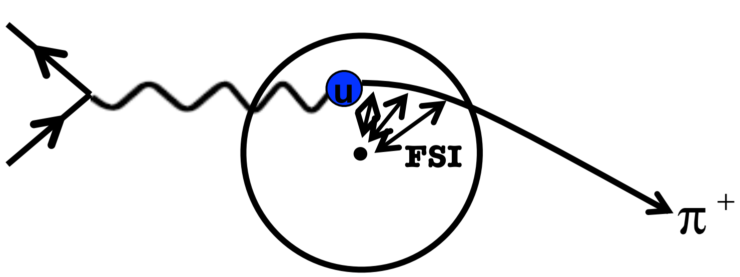
the parton transverse spin

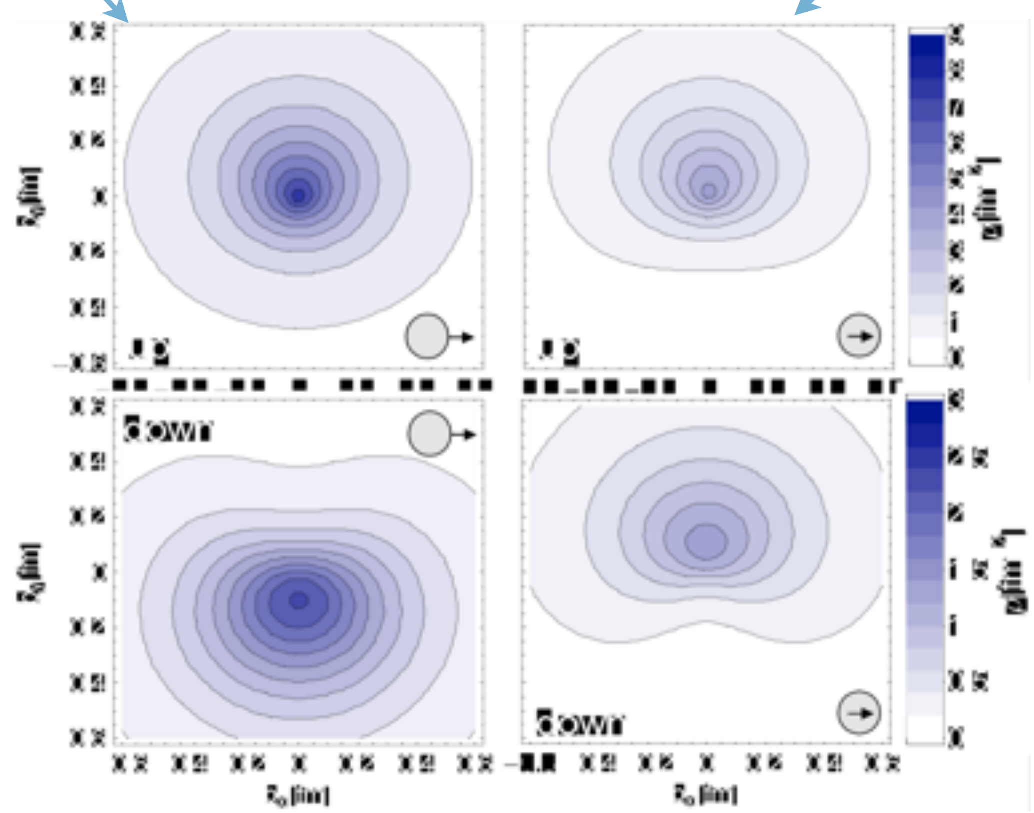


Boer-Mulders

Both are Naively T-odd

Final State Interaction





Spatial deformation due to spin-orbit correlations

Sivers & Boer-Mulders TMDs

Azimuthal asymmetries generated by correlations between quark transverse momentum and

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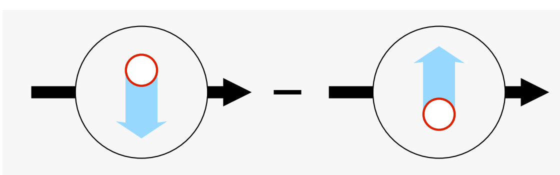
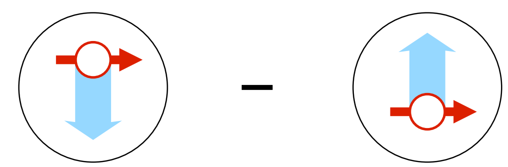


Sivers

the parton transverse spin



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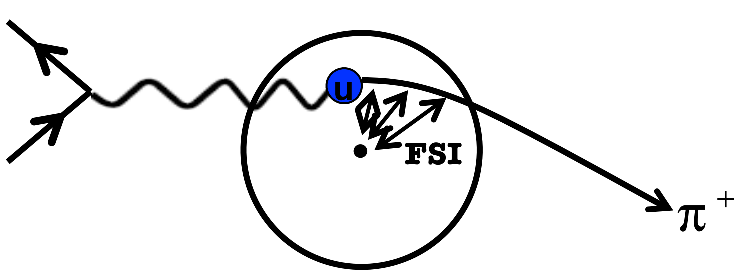
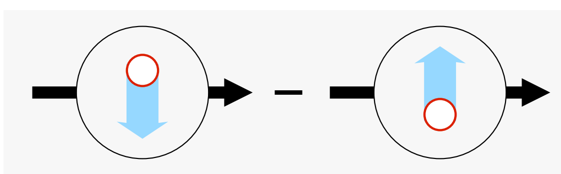


Special Universality!
Change of sign of Naive T-odd function from SIDIS to Drell-Yan

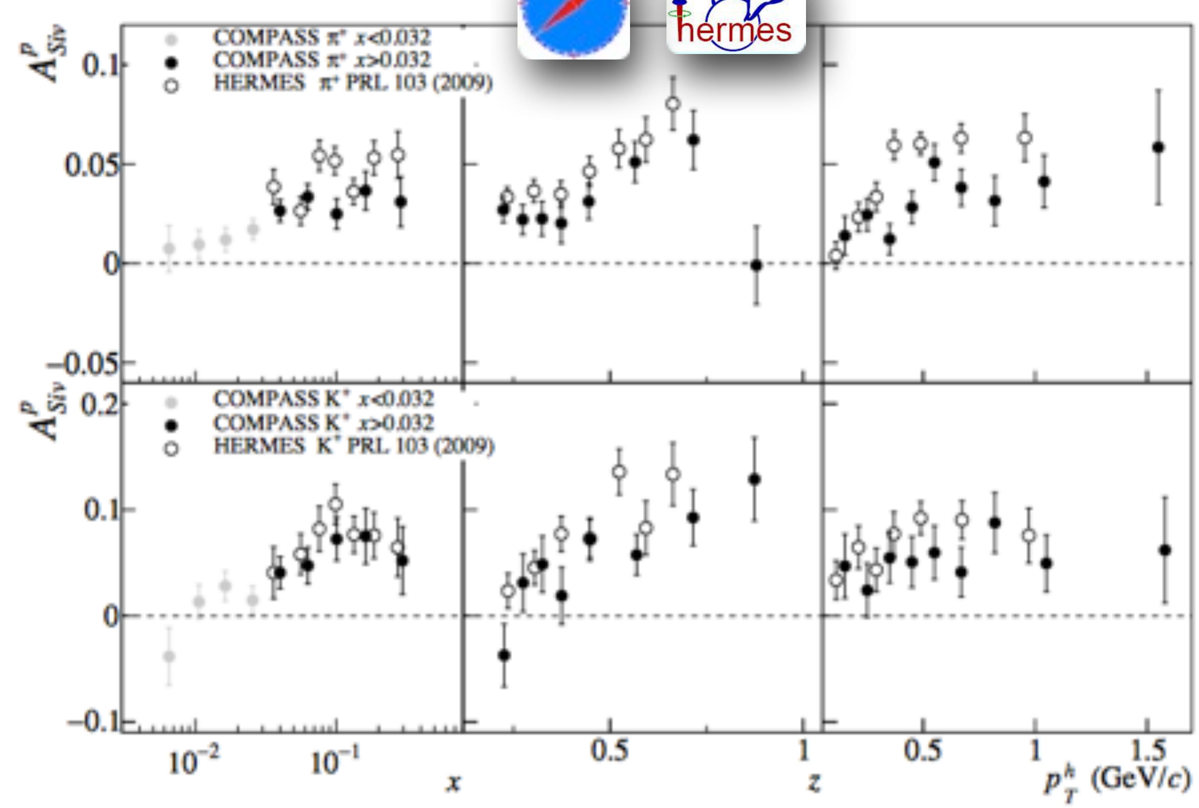
Sivers & Boer-Mulders TMDs

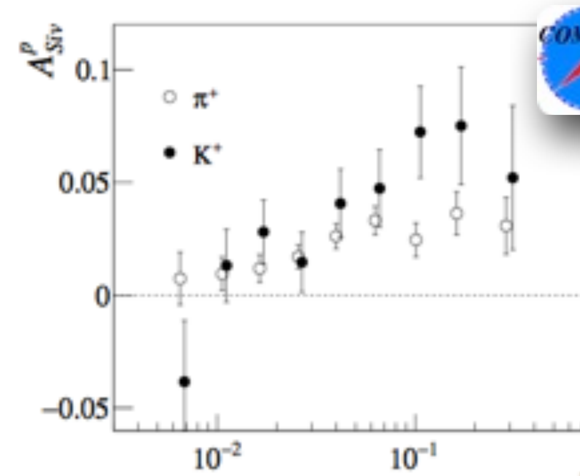
Azimuthal asymmetries generated by correlations between quark transverse momentum and

the proton transverse spin



Sivers





Sivers & Boer-Mulders TMDs

Azimuthal asymmetries generated by correlations between quark transverse momentum and

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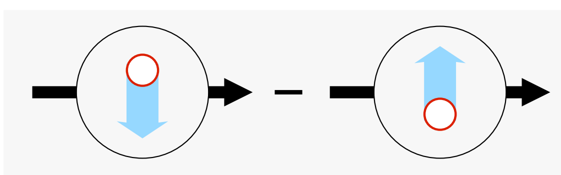
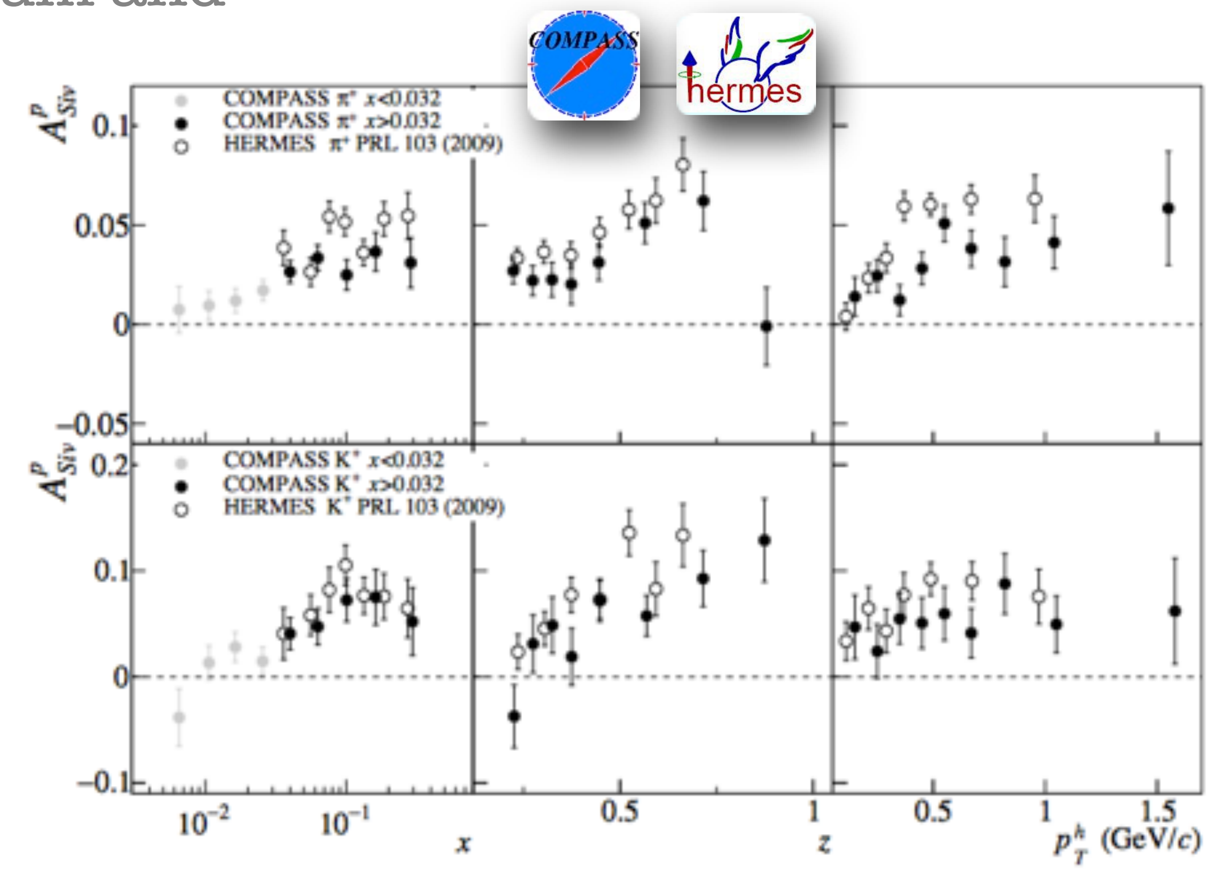
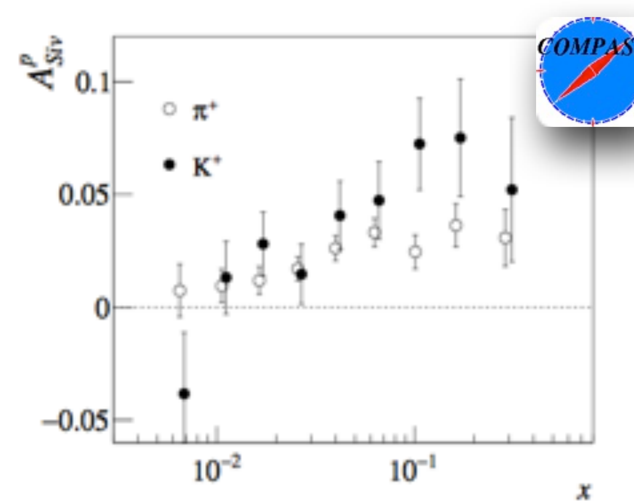


Sivers

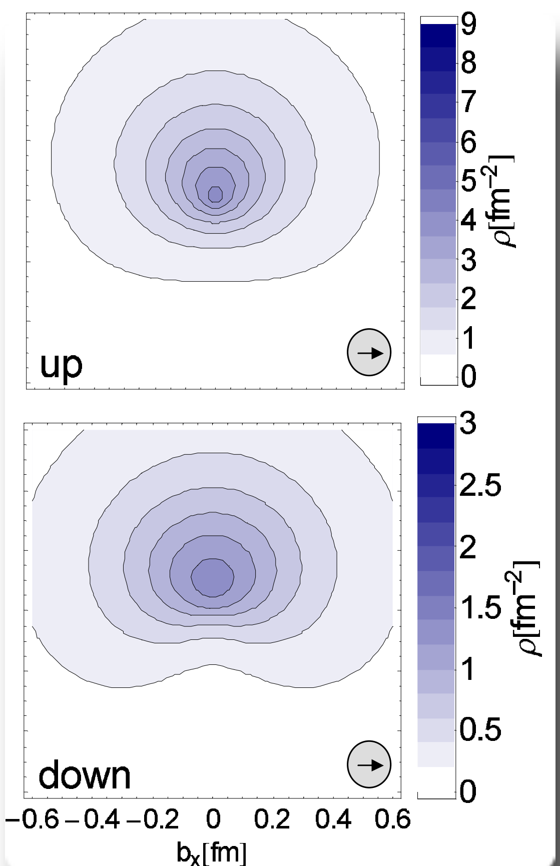
Drell-Yan run just started to observe Sivers sign!





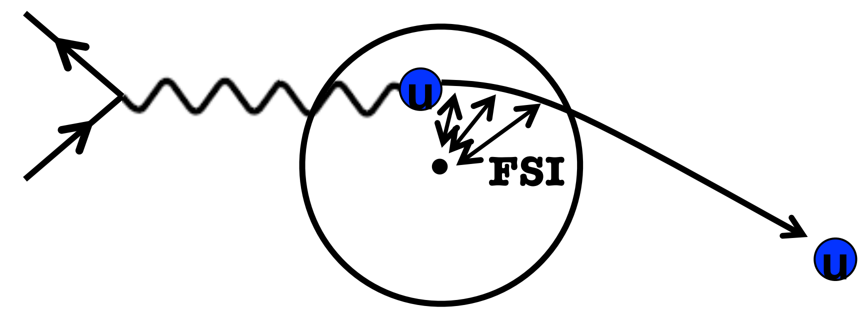
Boer-Mulders-Collins effect

Boer-Mulders



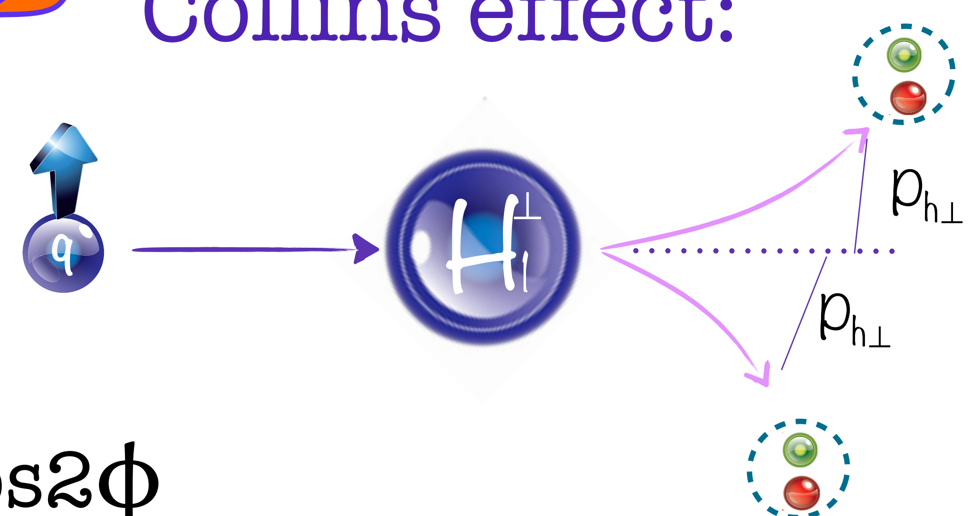
Spatial distortions due to
spin-orbit correlations

Naive T-odd:
Final State Interactions



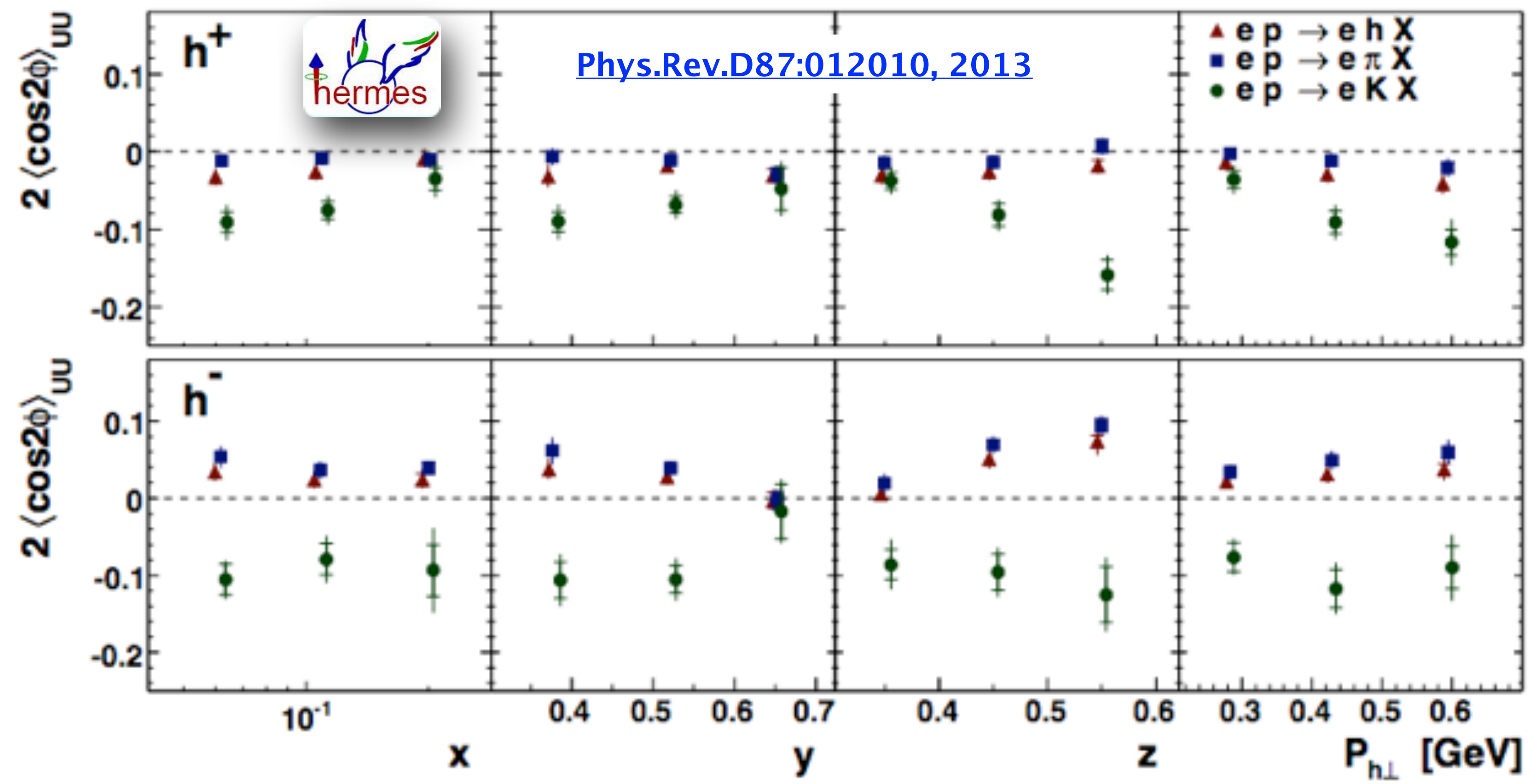
$$h_1^\perp \otimes H_1^\perp$$

Collins effect:

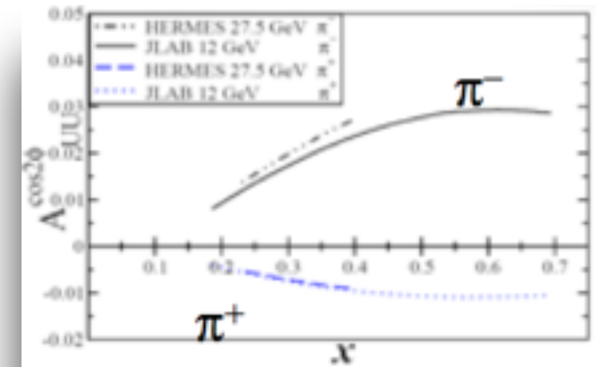


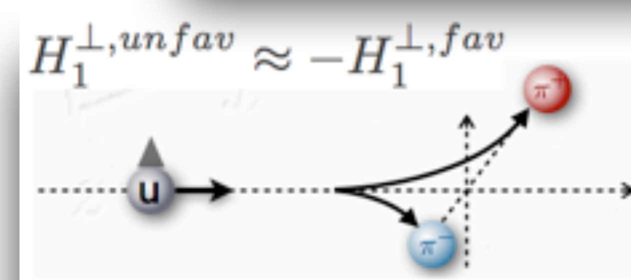
Together generate a cos2ϕ
signature in the cross section!

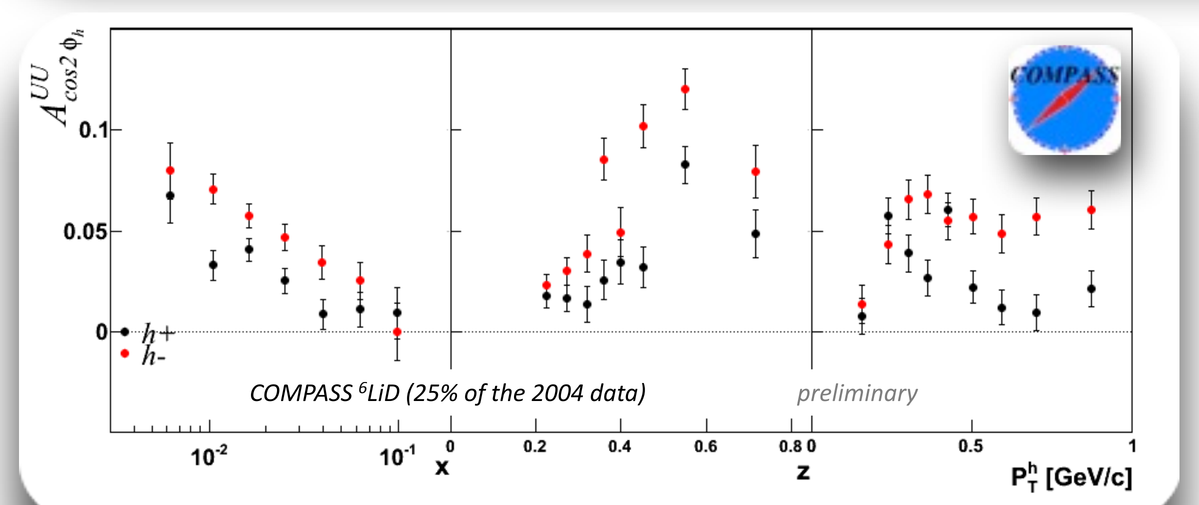
Cos2Φ: Pions & Kaons



Gamberg, Goldstein
Phys. Rev. D77:094016, 2008





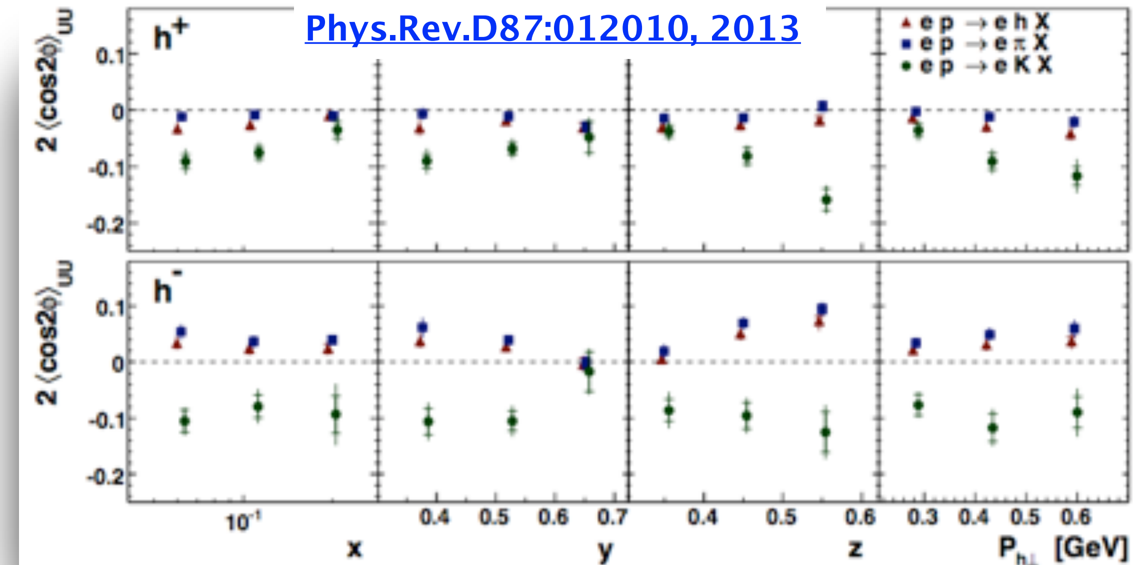


Pion and Kaon results are very different:

possibly related to fragmentation that involve the strange?

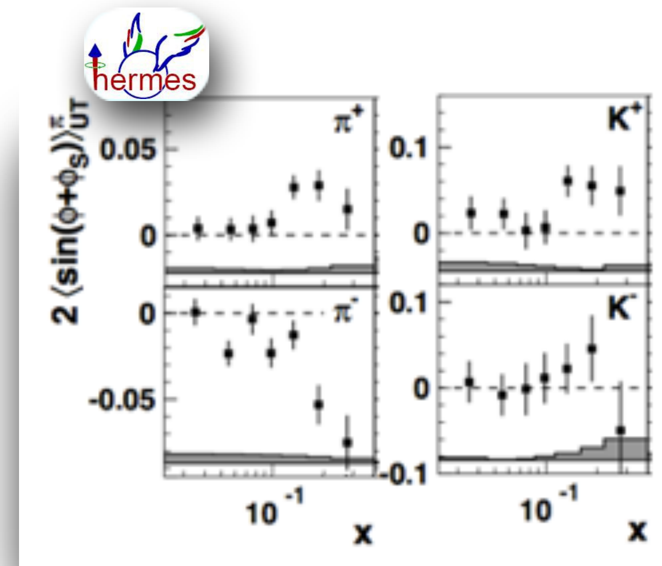
The Kaon puzzle

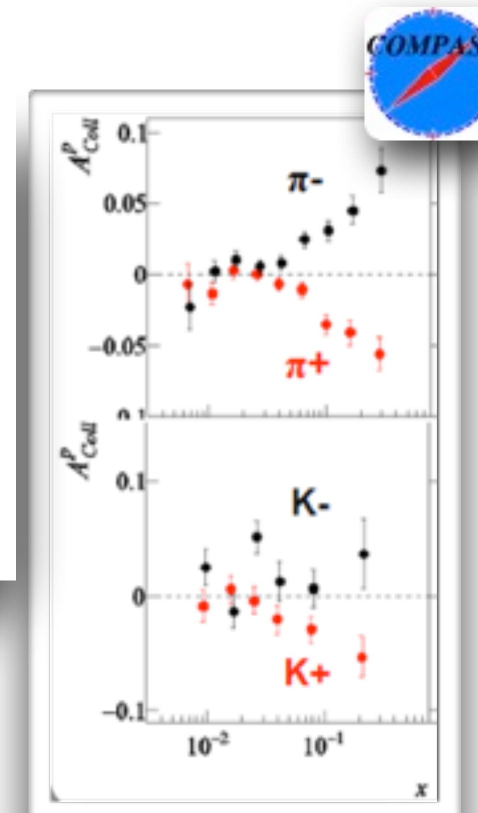
Boer-Mulders-Collins Asymmetries



Pion and Kaon results are very different:
Kaons: Larger asymmetries, same sign for K+ and K-

Transversity-Collins Asymmetries



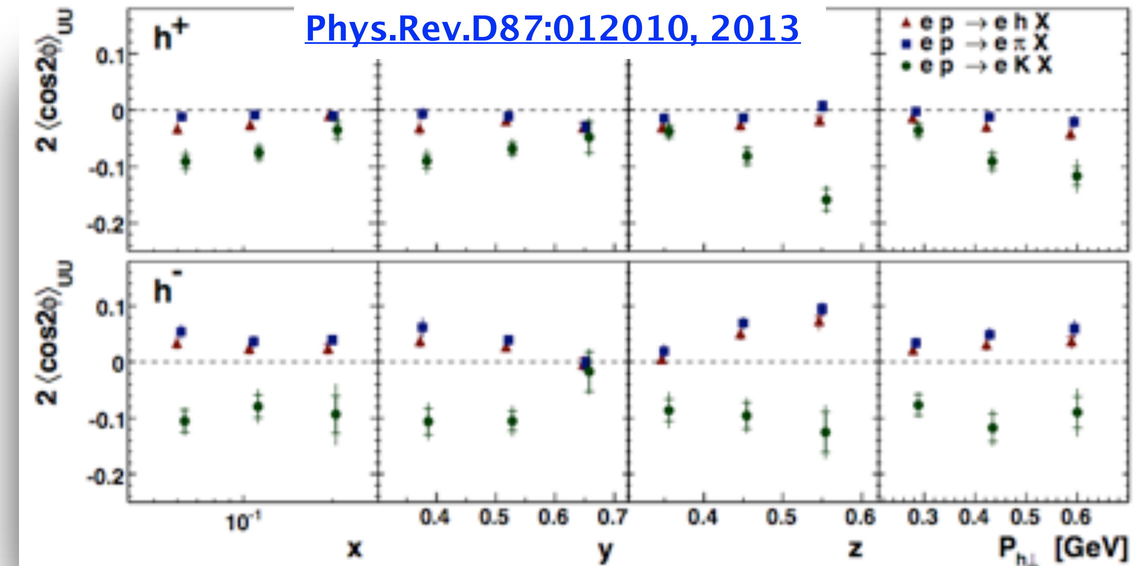


K^+ amplitudes larger than π^+?

K^- different from π^-?

The Kaon puzzle

Boer-Mulders-Collins Asymmetries



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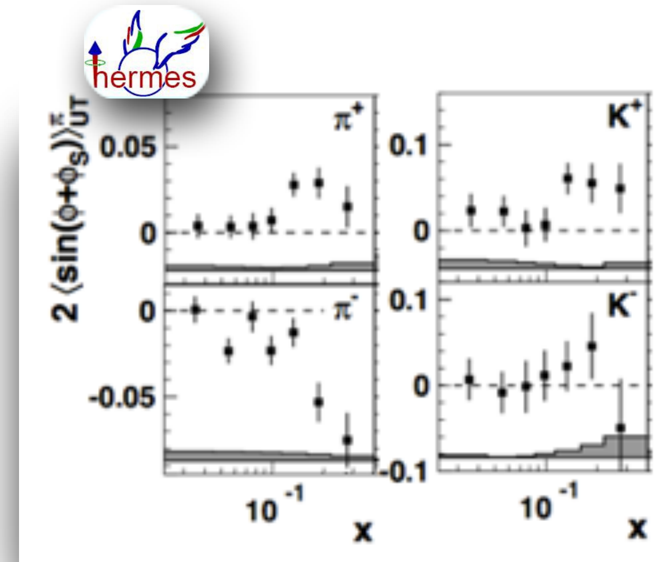
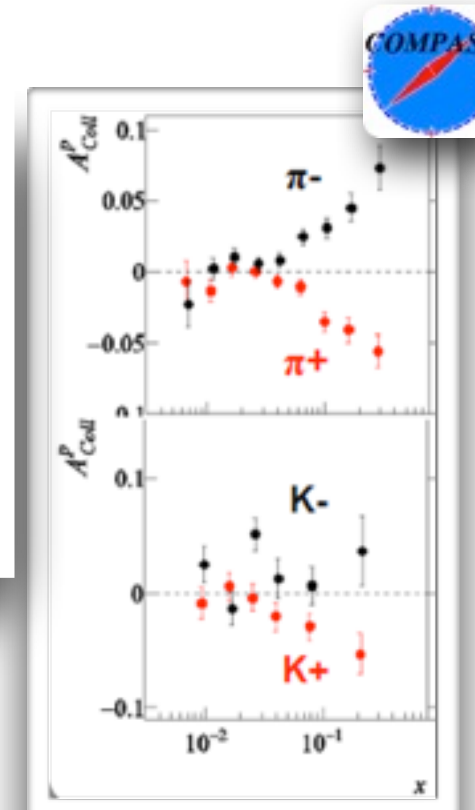
Transversity-Collins Asymmetries

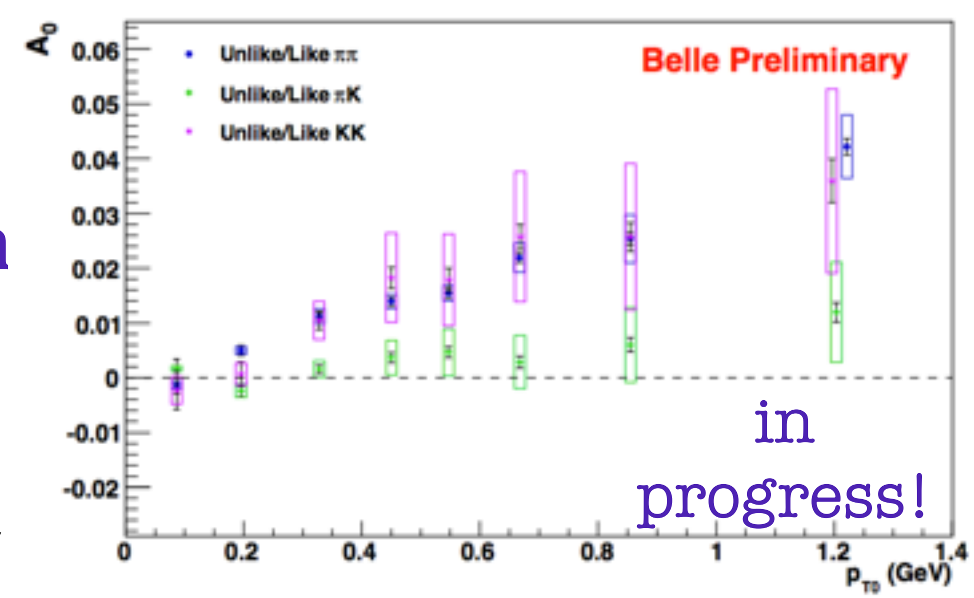




K^+ amplitudes larger than π^+?

K^- different from π^-?

Need to extract Collins fragmentation for Kaons in e^+e^- !!!



in progress!

Transverse Momentum dependent PDFs

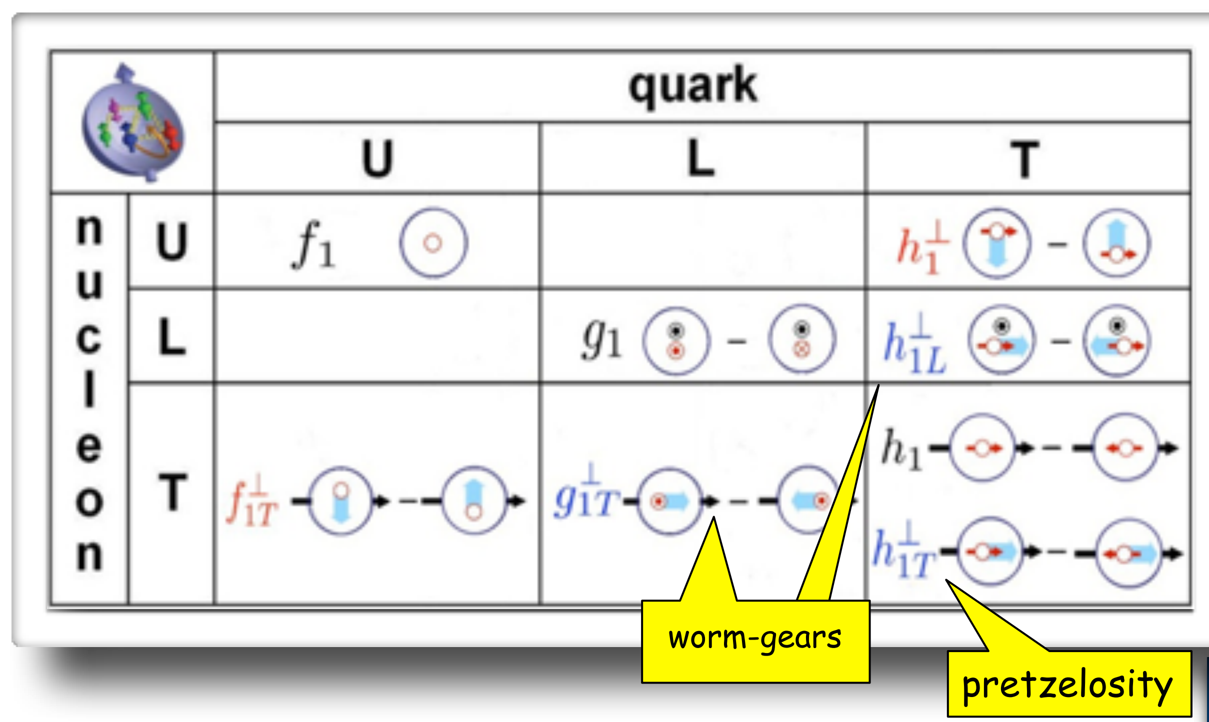
$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \; \lambda_l & \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ S_L & \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ S_L\,\lambda_l & \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ S_T & \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ S_T\,\lambda_l & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}
$$

How can we disentangle all these contributions ?

EXPERIMENT: setting the proper beam and target polarization states (U, L, T)

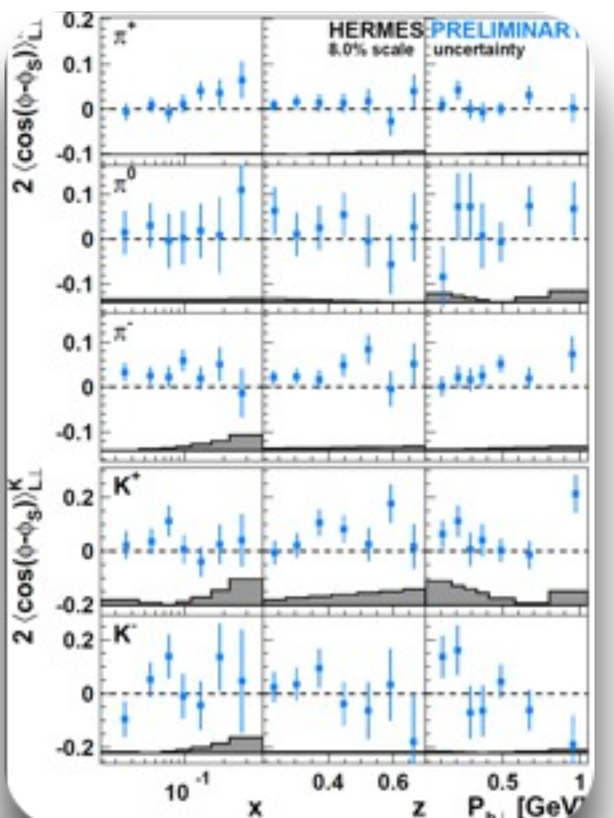
ANALYSIS: fitting the cross section asymmetry for opposite spin states and extracting the relevant Fourier components based on their peculiar azimuthal dependences.

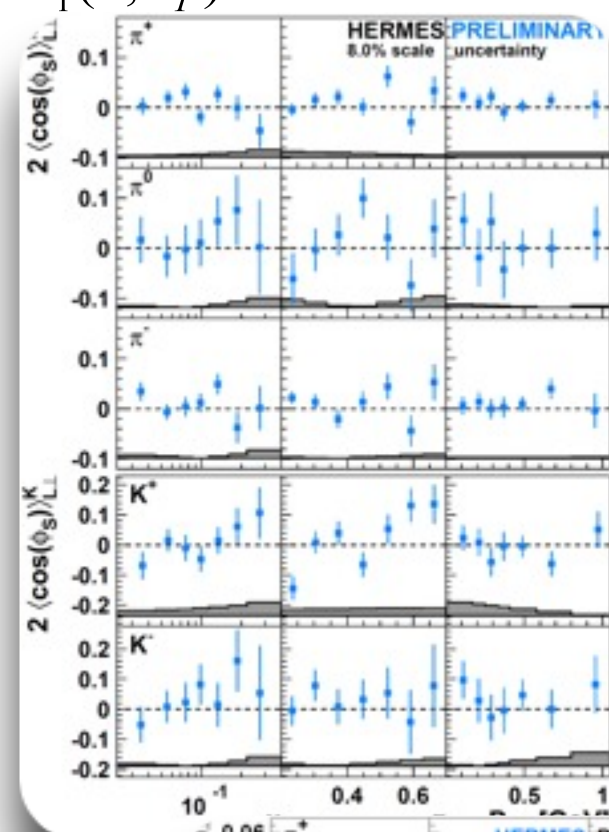
$$A_{\mathrm{U}\perp}^h = \frac{\sigma_{\mathrm{U}\Uparrow}^h - \sigma_{\mathrm{U}\Downarrow}^h}{\sigma_{\mathrm{U}\Uparrow}^h + \sigma_{\mathrm{U}\Downarrow}^h}$$



More TMDs

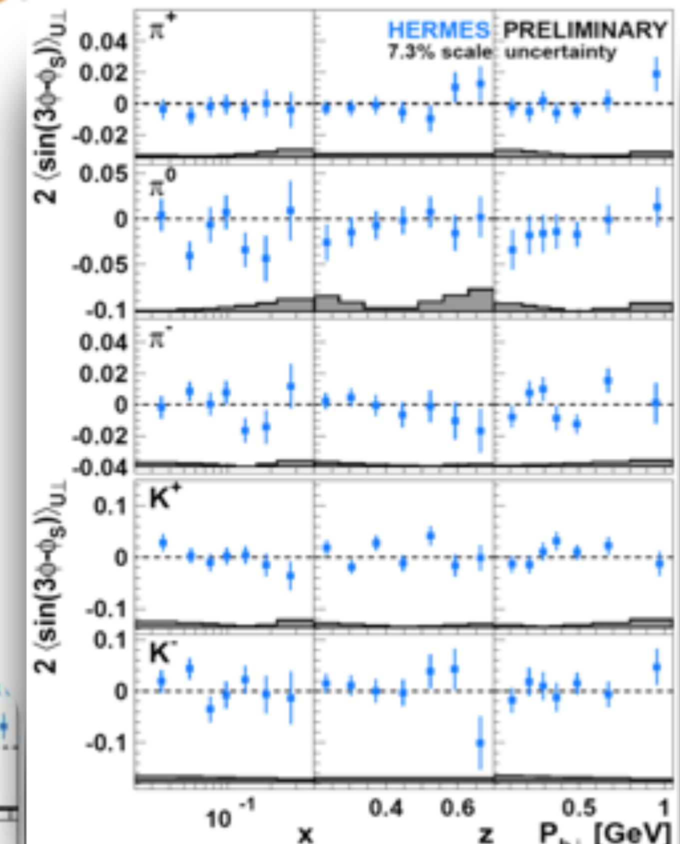
$\propto g_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$





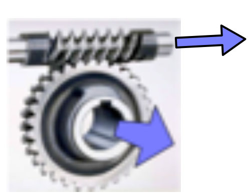
$\propto h_{1T}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

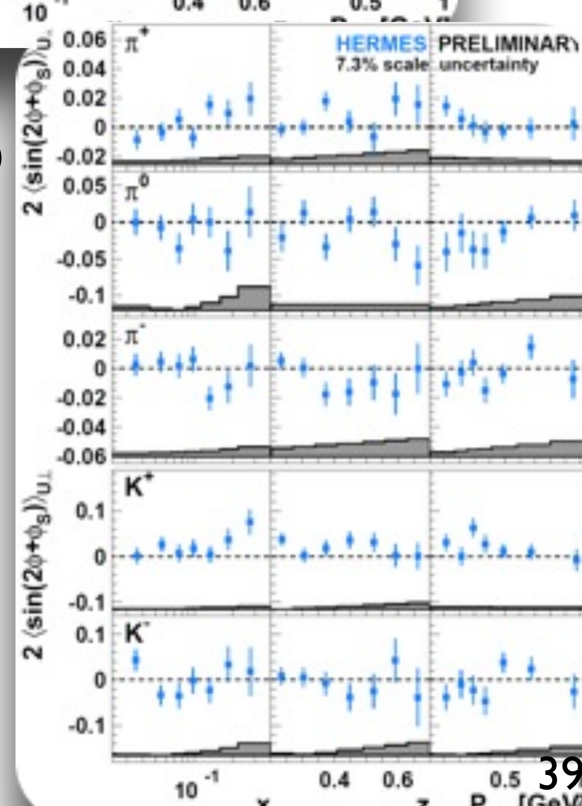
Pretzelosity

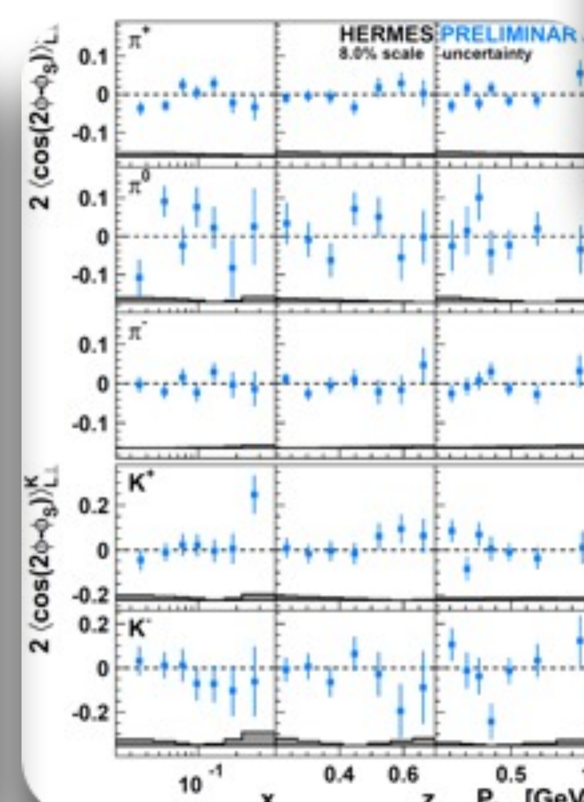


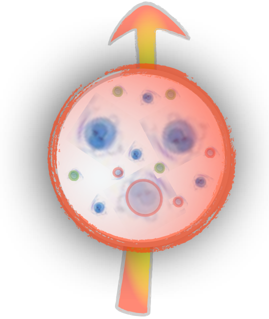
$\propto h_{1L}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

Worm-gear









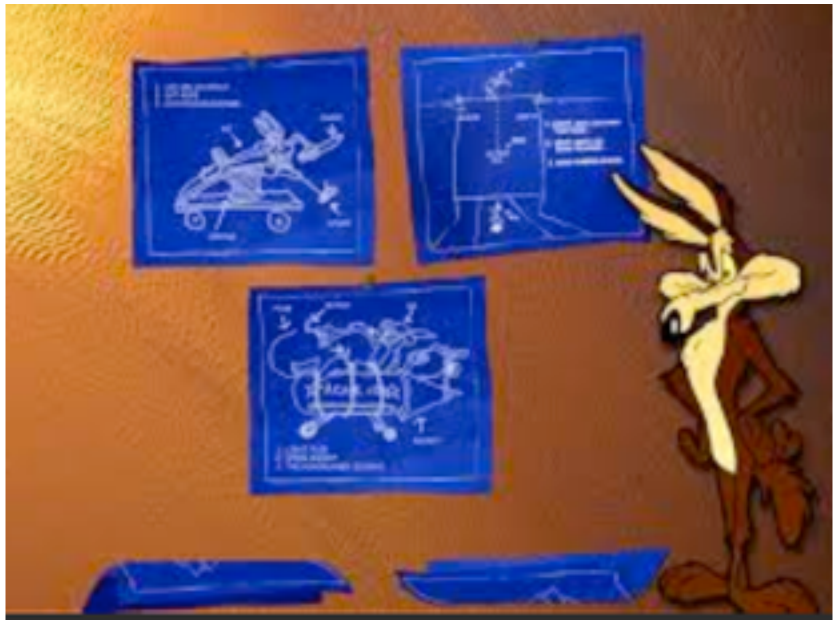
TMDs open points:

- What is the pT dependence of TMD polarized and unpolarized pdfs? And of polarized and unpolarized fragmentation functions? Mostly missing!!

- How do TMD pdfs and fragmentation functions evolve? Work in progress!!

- Do naive-T-odd TMDs obey the 'special universality'? Compass Drell-Yan run just started

Exciting times!



Babar

Belle/BelleII

Jlab12

FERMILAB

PAX?

Star

fsPHENIX

Phenix

SuperStar

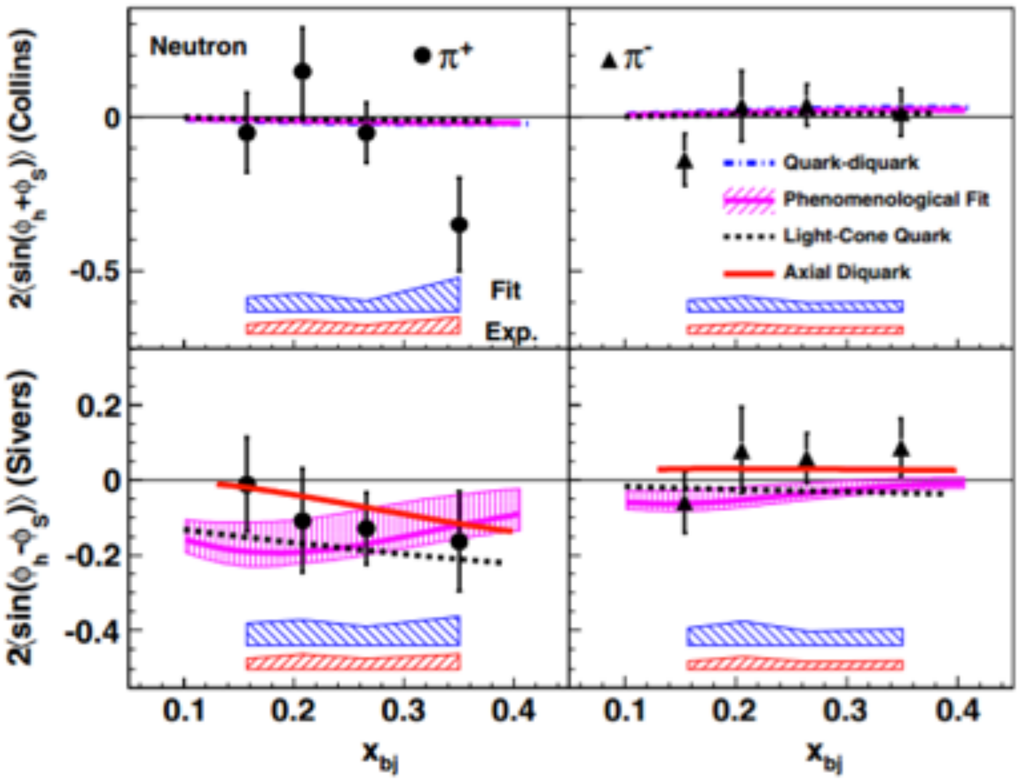
EIC

CompassII

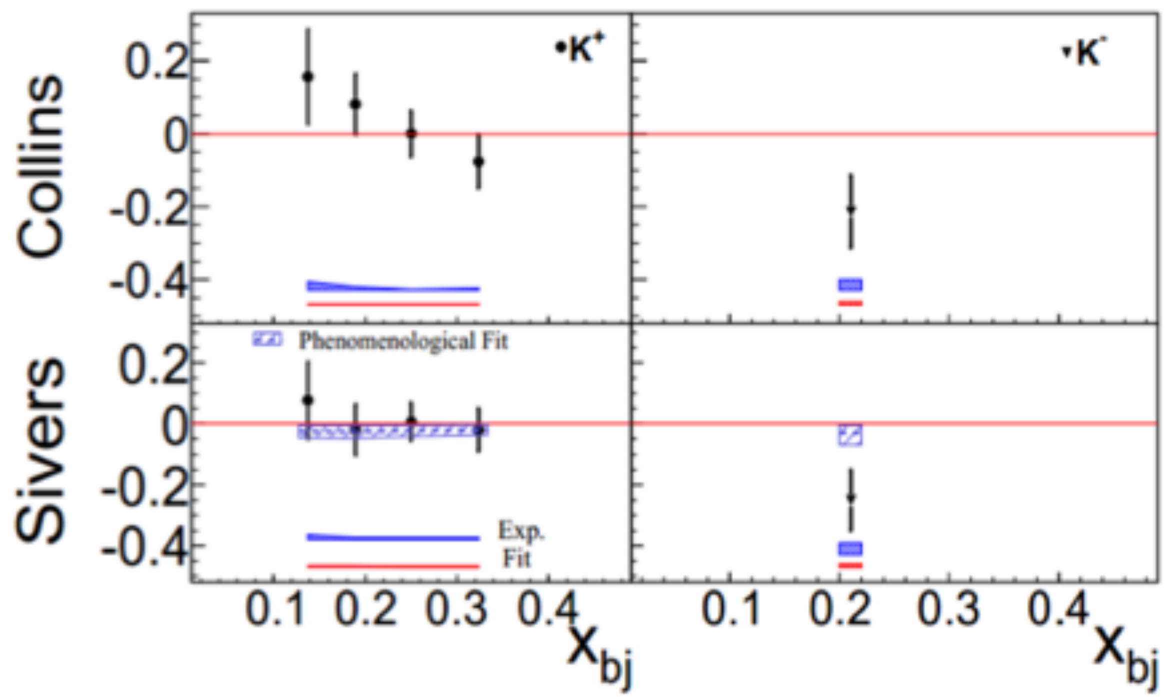
Thank you!

Backup slides

Hall A

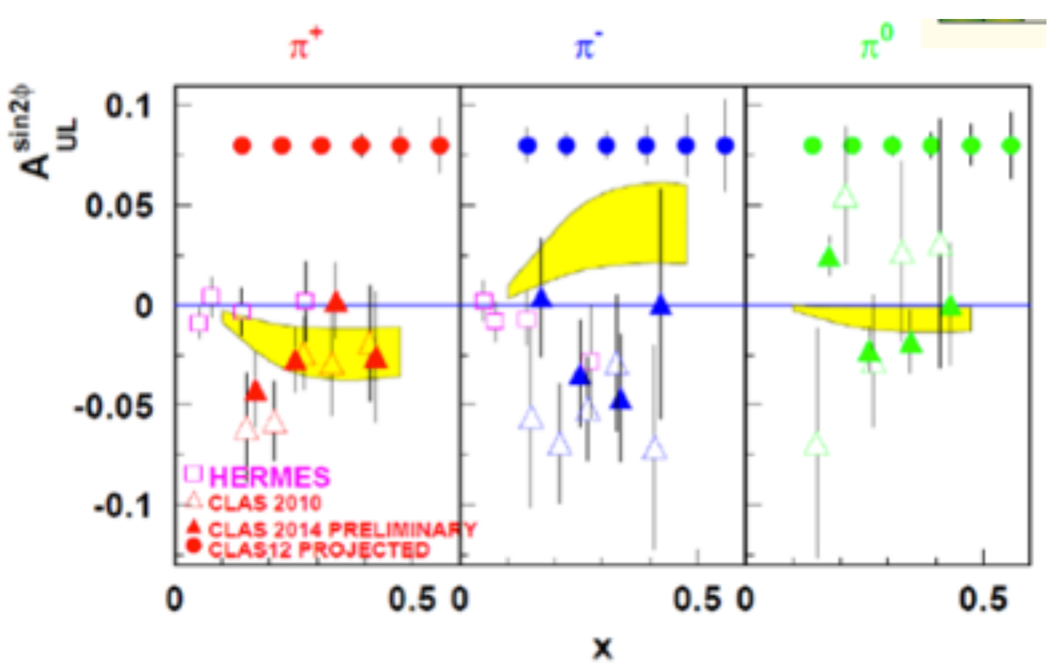


Neutron
π^+
π^-
Quark-diquark
Phenomenological Fit
Light-Cone Quark
Axial Diquark
Fit
Exp.
$2\langle\sin(\phi_h+\phi_S)\rangle$ (Collins)
$2\langle\sin(\phi_h-\phi_S)\rangle$ (Sivers)
x_{bj}



K^+
K^-
Collins
Sivers
Phenomenological Fit
Exp.
Fit
x_{bj}

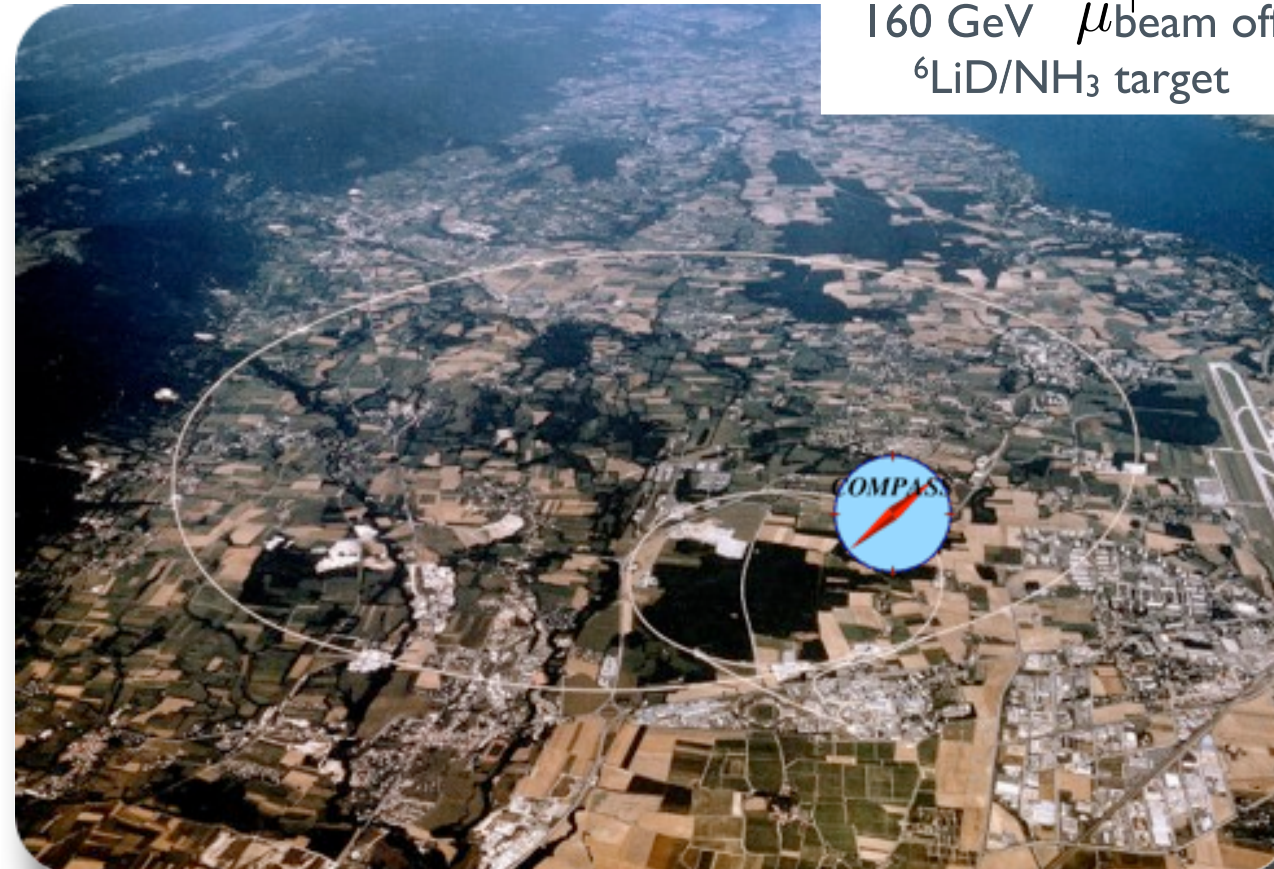
Hall B

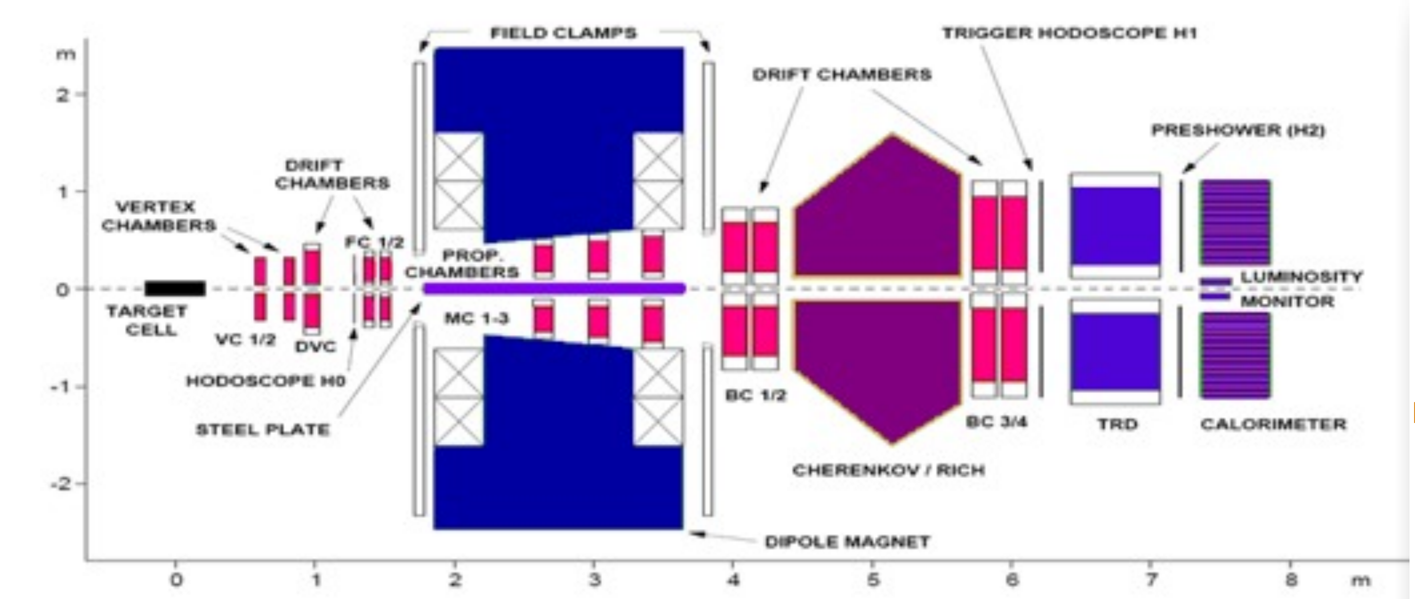


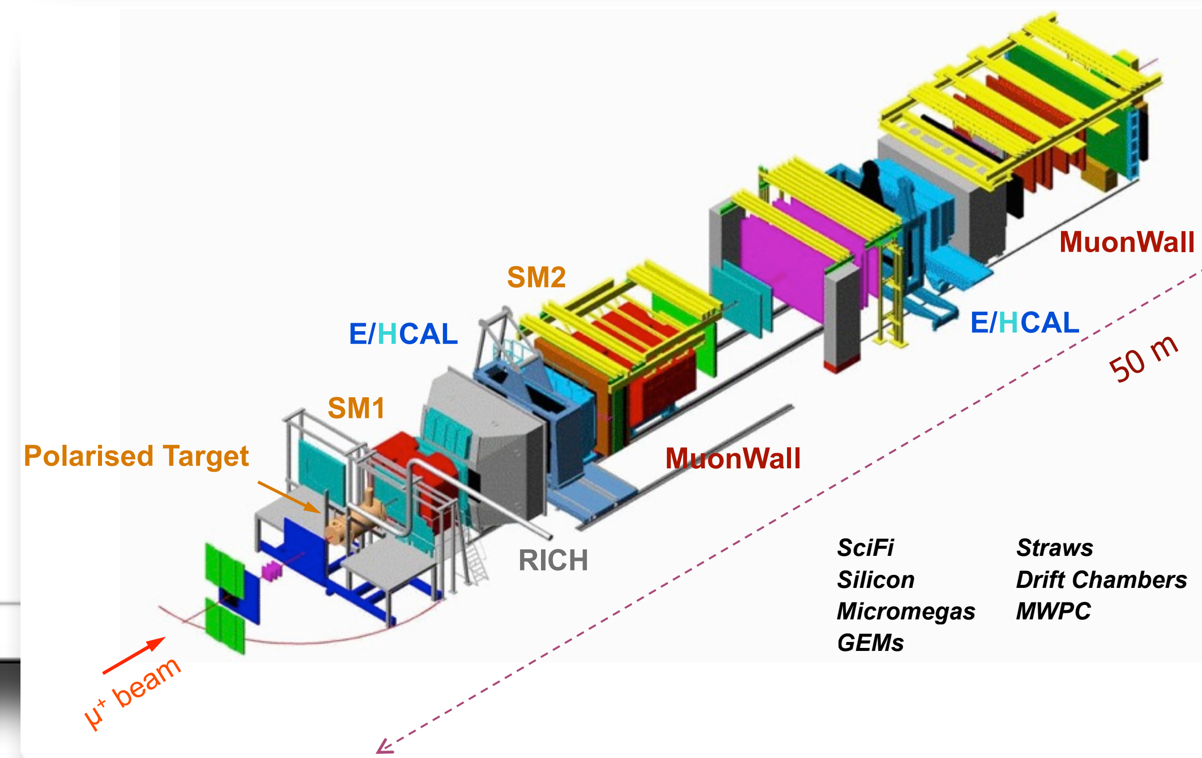
π^+
π^-
π^0
$A_{UL}^{\sin 2\phi}$
HERMES
CLAS 2010
CLAS 2014 PRELIMINARY
CLAS12 PROJECTED
x

27.6 GeV (e^+/e^-) lepton beam off D/H target

160 GeV μ^+ beam off ^{6}LiD/NH_3 target







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COMPASS@CERN

27.6 GeV (e^+/e^-) lepton beam off D/H target

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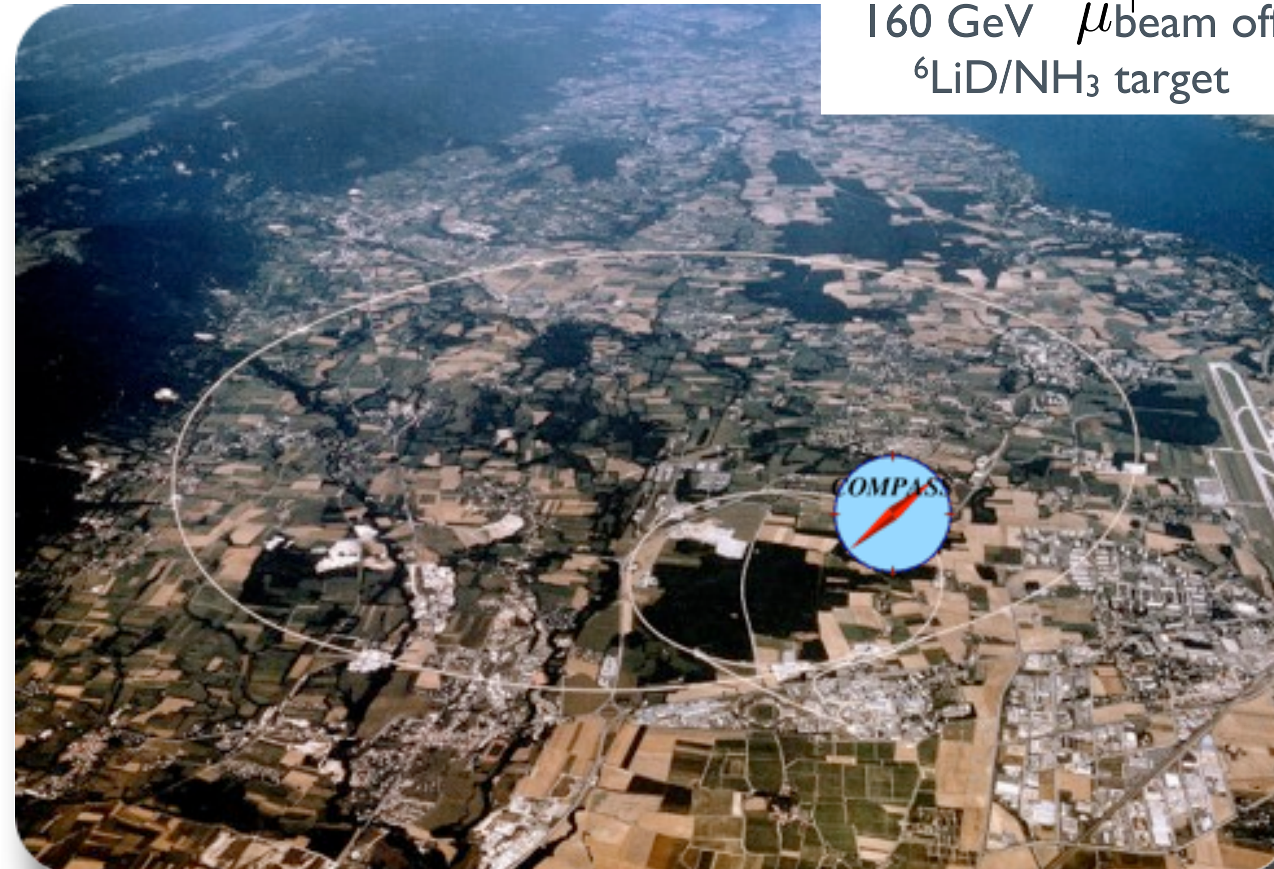

$$Q^2 > 1\,GeV^2$$
$$0.023 < x < 0.27$$
$$0.3 < y < 0.85$$
$$W^2 > 10\,GeV^2$$
$$0.2 < z < 0.75$$
$$0.05 < P_{h\perp} < 1\,GeV$$

$$Q^2 > 1\,GeV^2$$
$$0.003 < x < 0.13$$
$$0.2 < y < 0.9$$
$$W^2 > 5\,GeV^2$$
$$0.2 < z < 0.85$$
$$0.1 < P_{h\perp} < 1\,GeV$$

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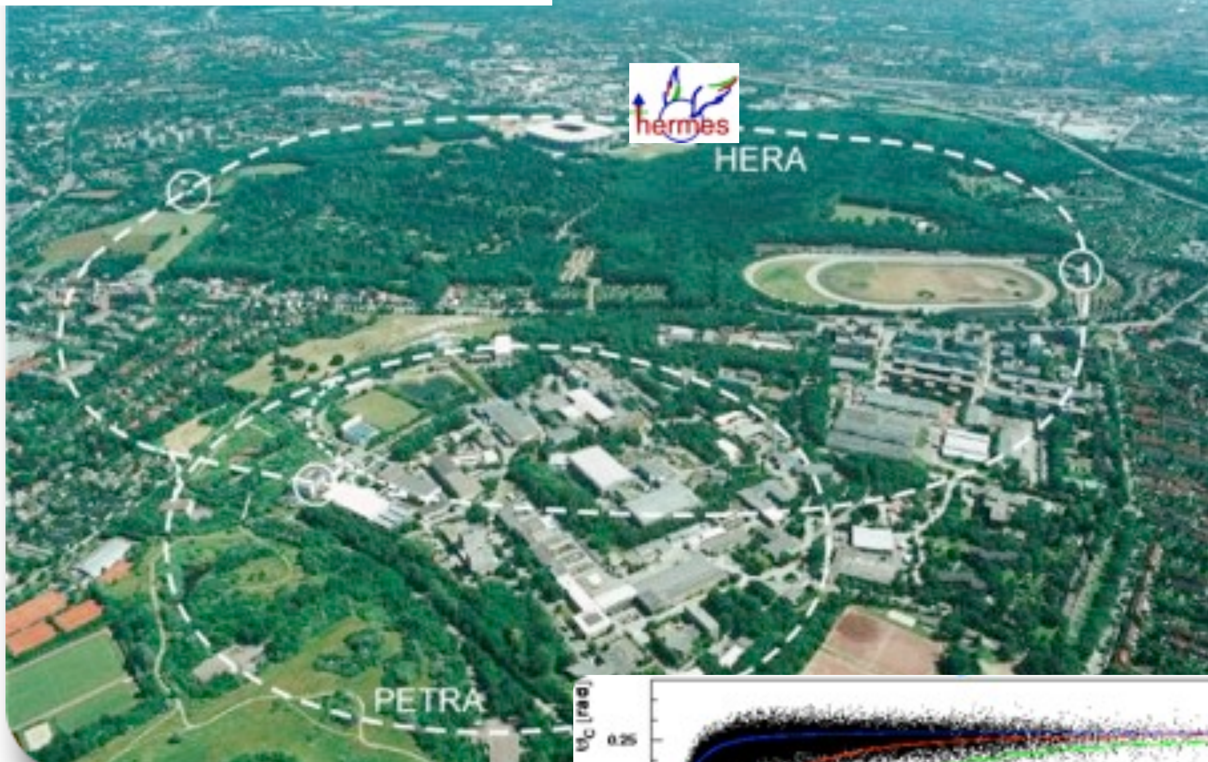
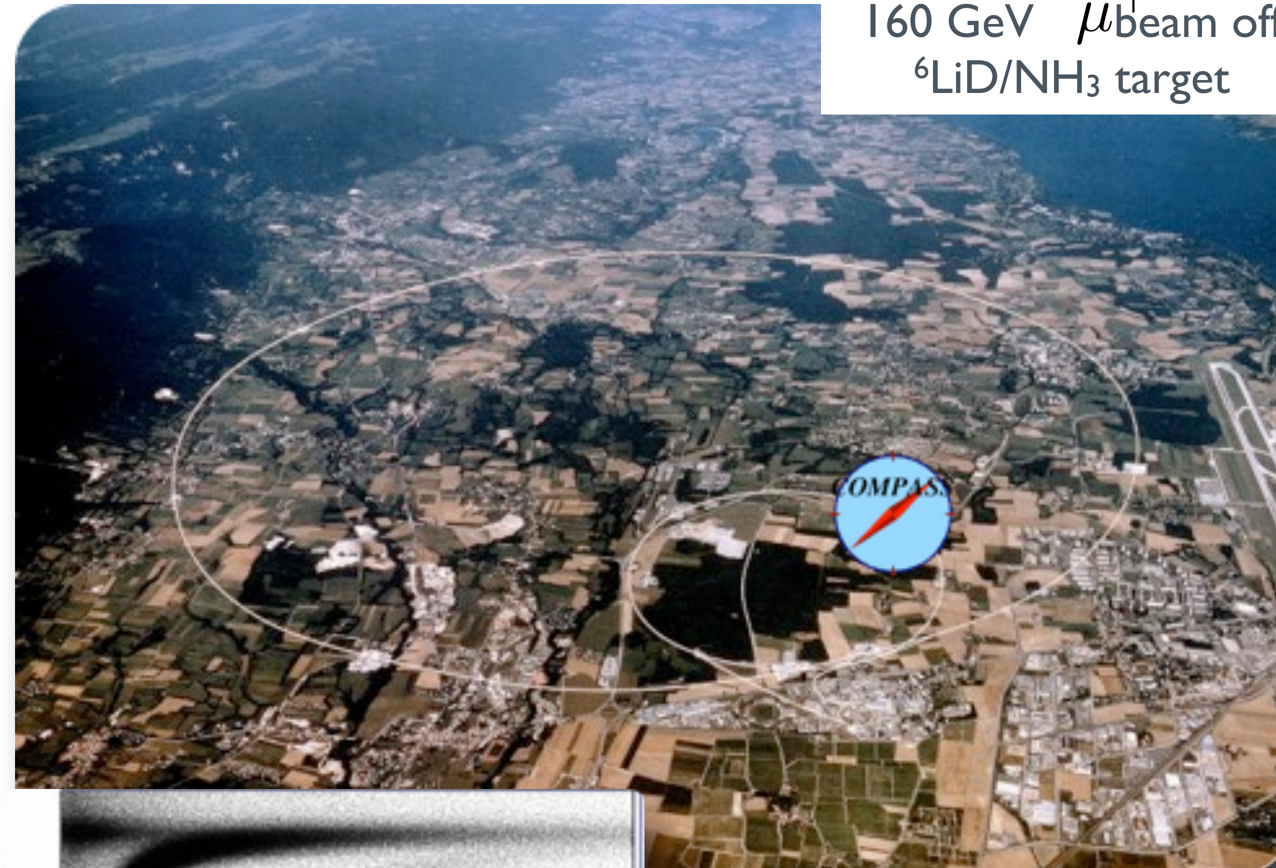
27.6 GeV (e^+/e^-) lepton beam off D/H target



160 GeV μ^+ beam off $^6LiD/NH_3$ target



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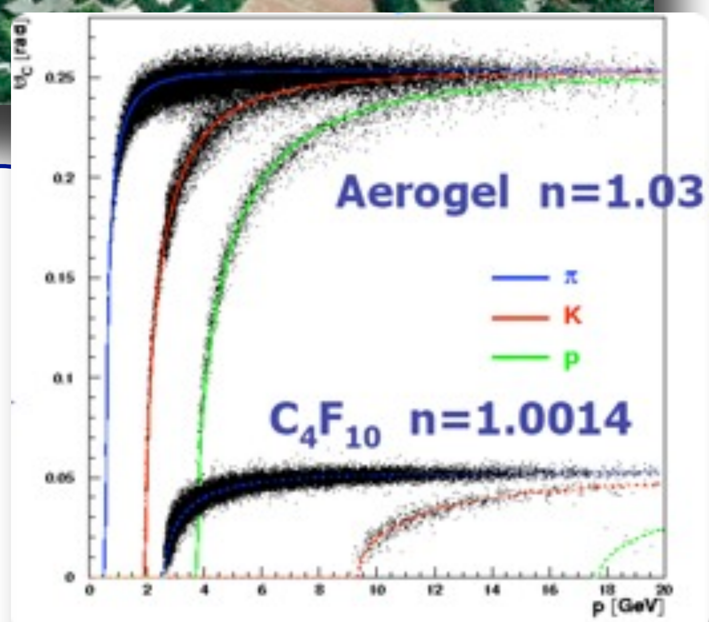

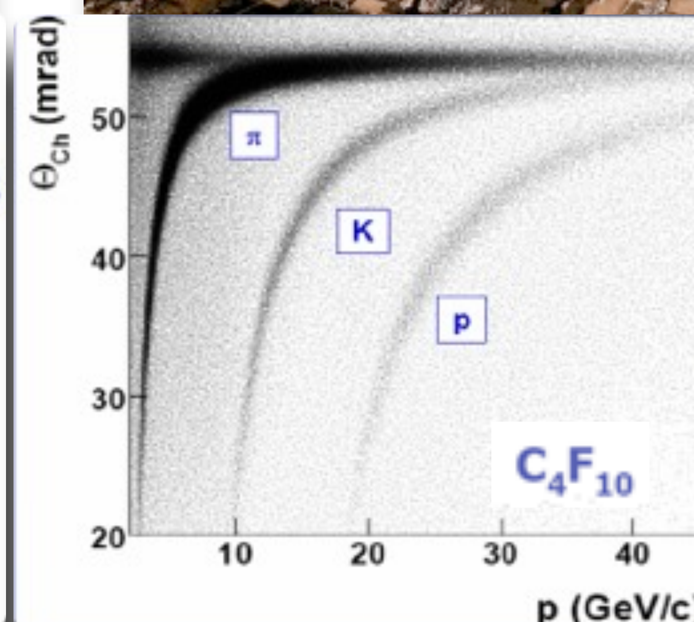

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$$0.1 < P_{h\perp} < 1\,GeV$$

$$\pi^+,\ \pi^-,\ K^+,\ K^-$$

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