# Chasing Transversity

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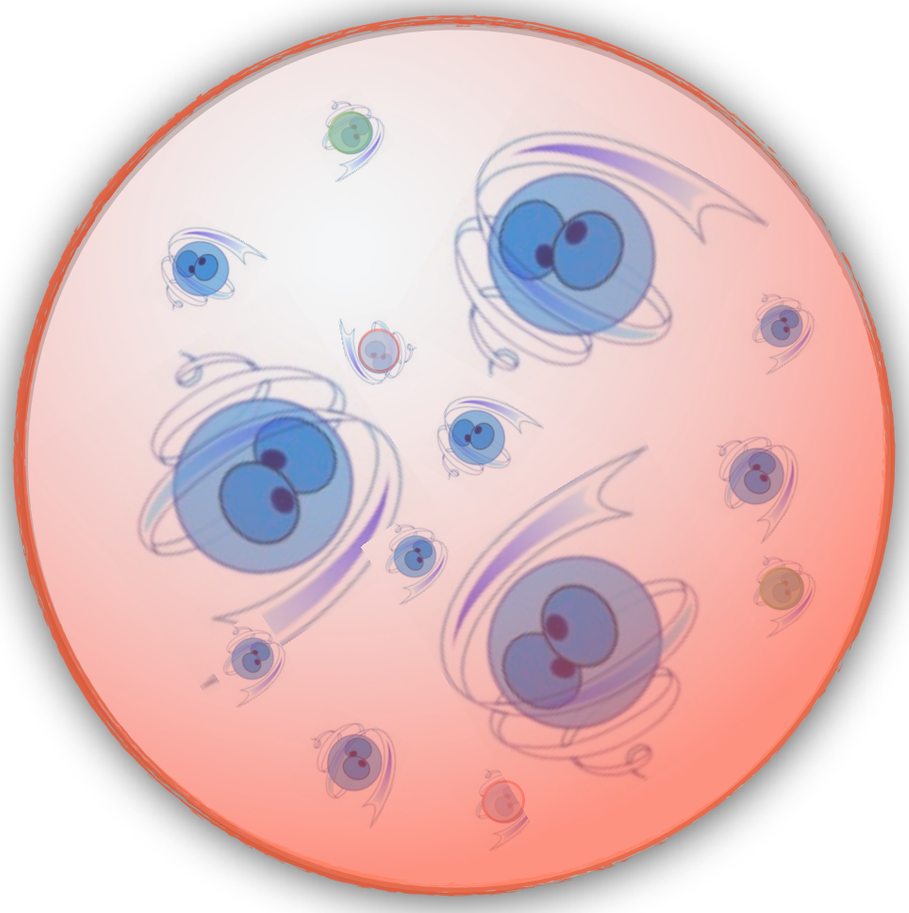
# Proton Structure

1970s:
Quantum ChromoDynamics



2013:
still not able to describe QCD
fundamental state

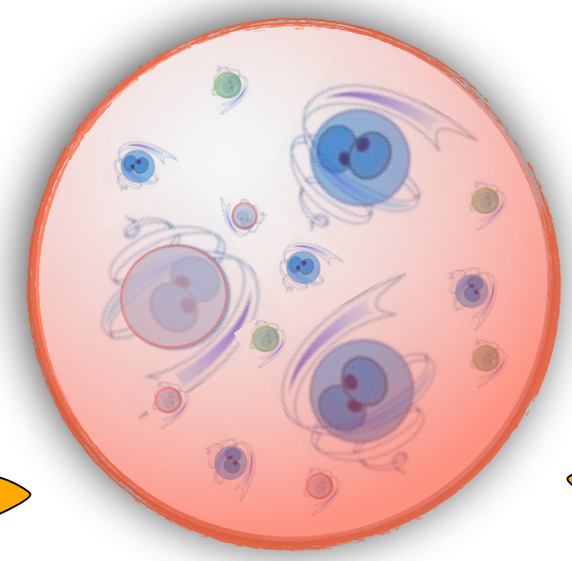
# Proton Structure

## Form Factors (t)

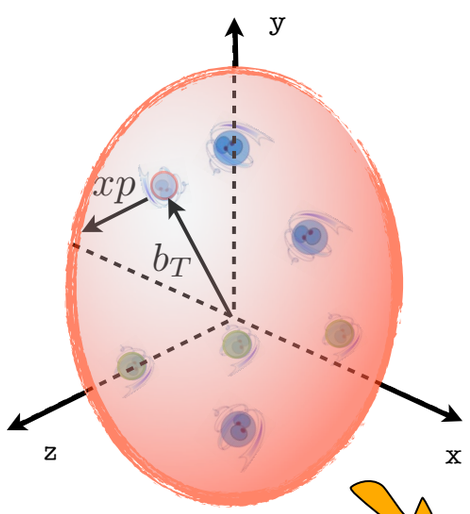
Fourier transform ($b_T$)

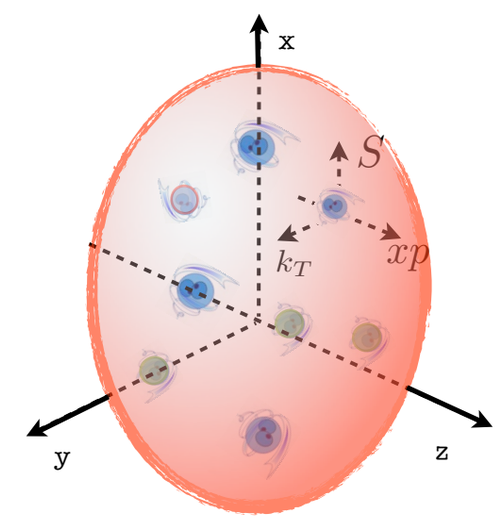
& $\int$ GPDs(x, t) ... dx

## GPDs (x, $b_T$)



## TMDs (x, $k_T$)



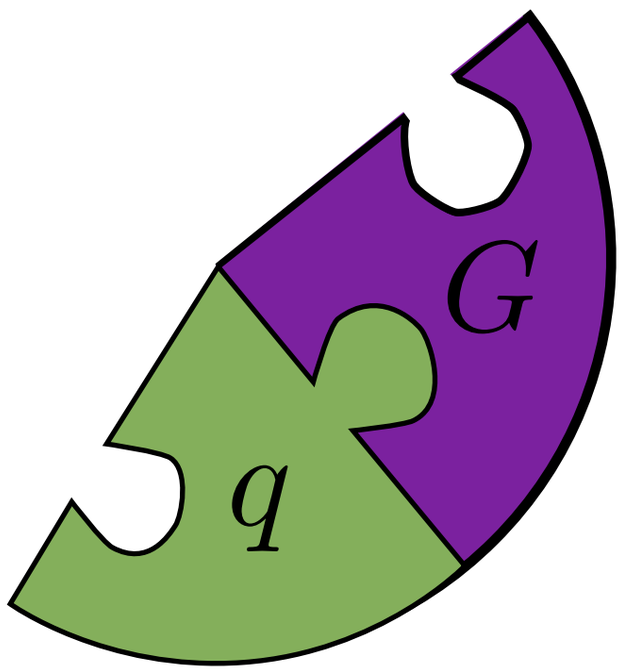




## PDFs (x)

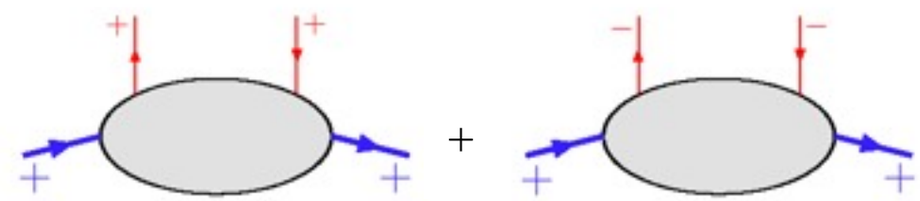
$\int$ GPDs(x,$b_T$) ... d$b_T$

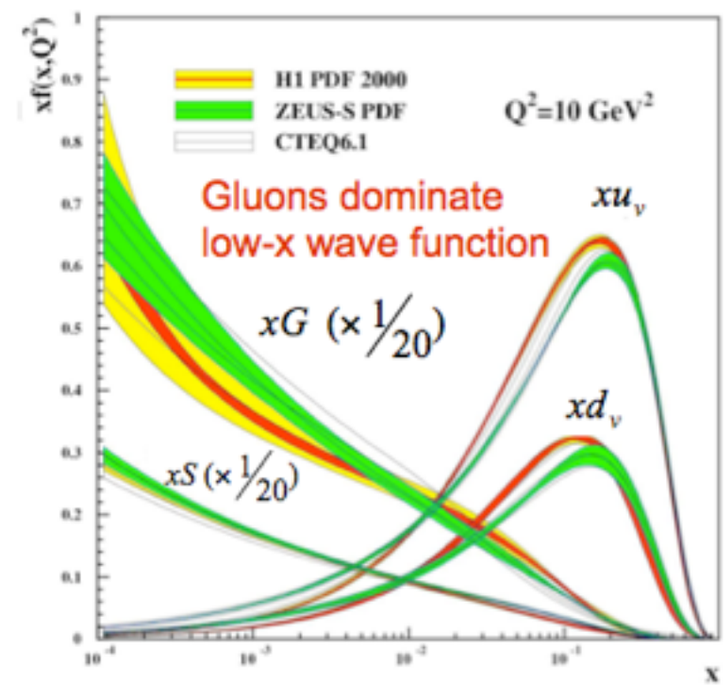
$\int$ TMDs(x,$k_T$) ... d$k_T$

# Momentum distribution

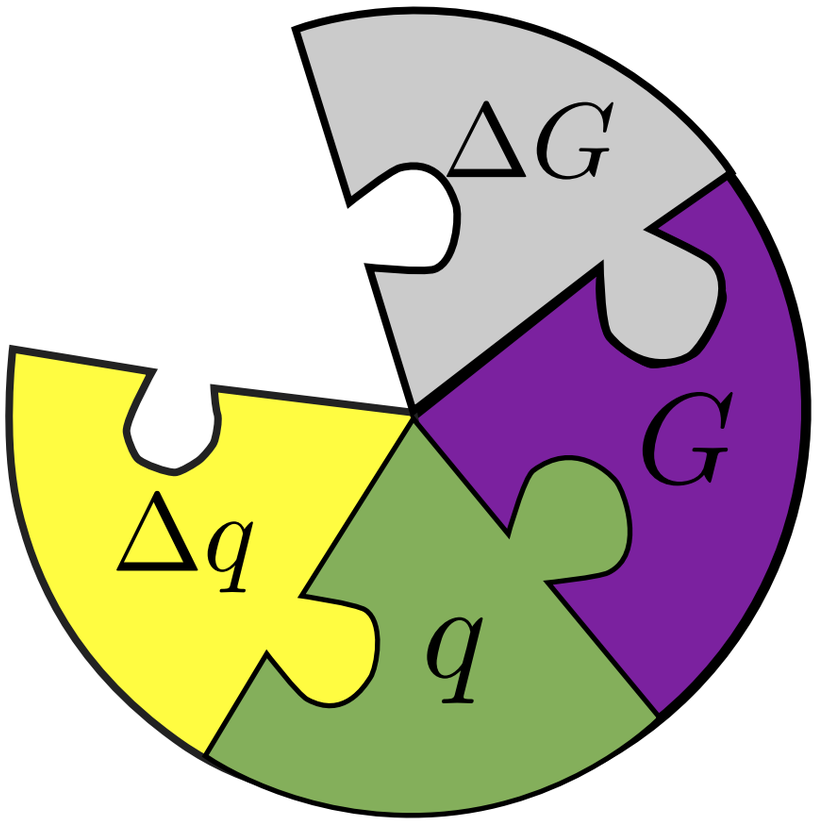



$$f_1^q(x) = q^{\rightrightarrows}(x) + q^{\rightleftarrows}(x)$$

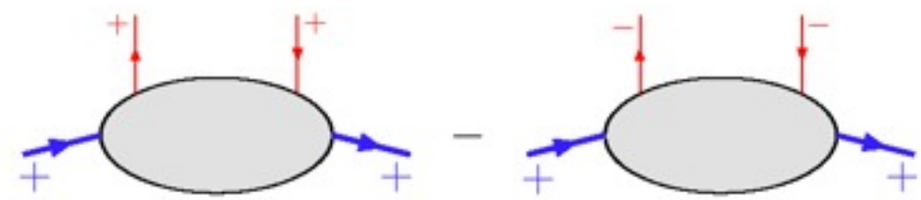


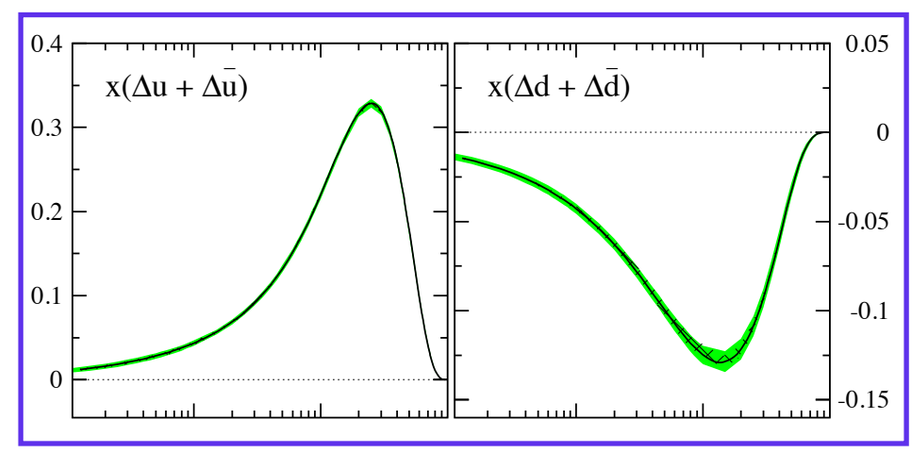



# Helicity distribution

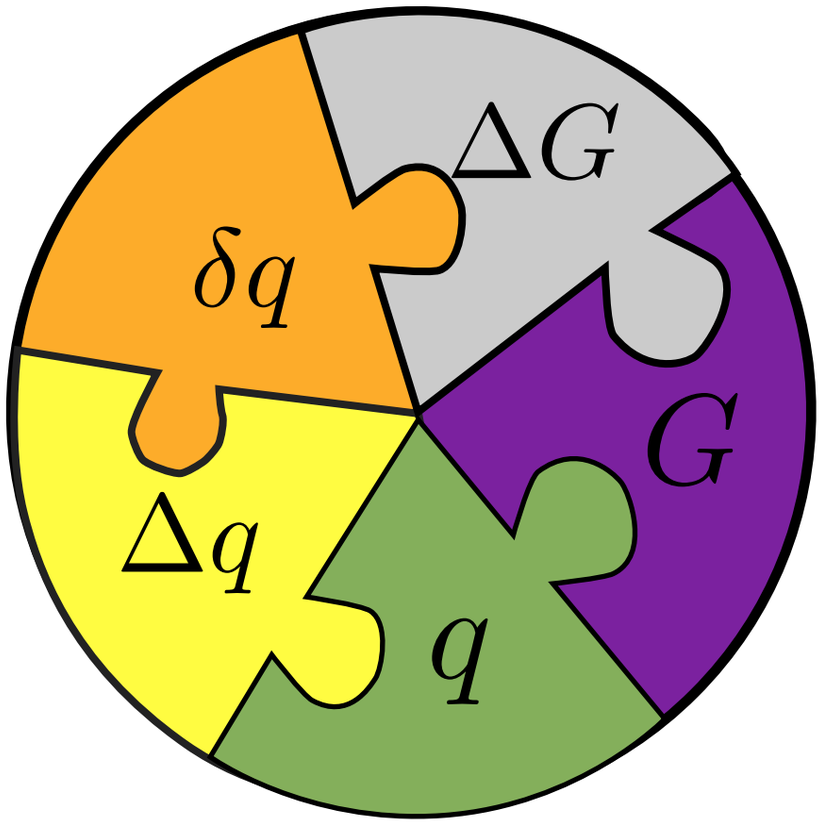



$$g_1^q(x) = q^{\rightrightarrows}(x) - q^{\rightleftarrows}(x)$$





# Transversity distribution




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

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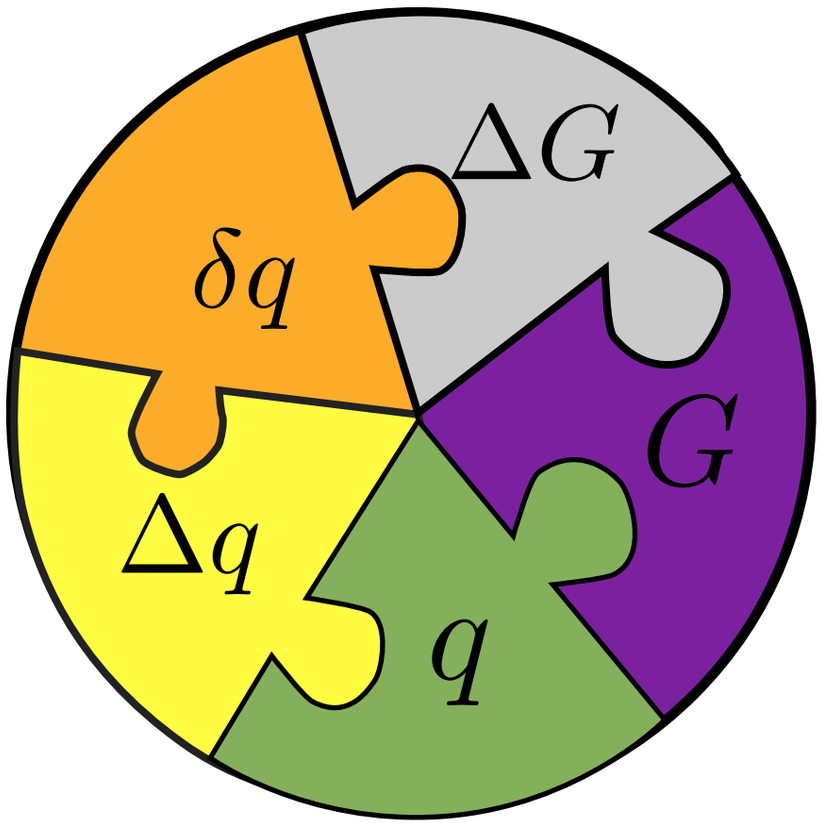
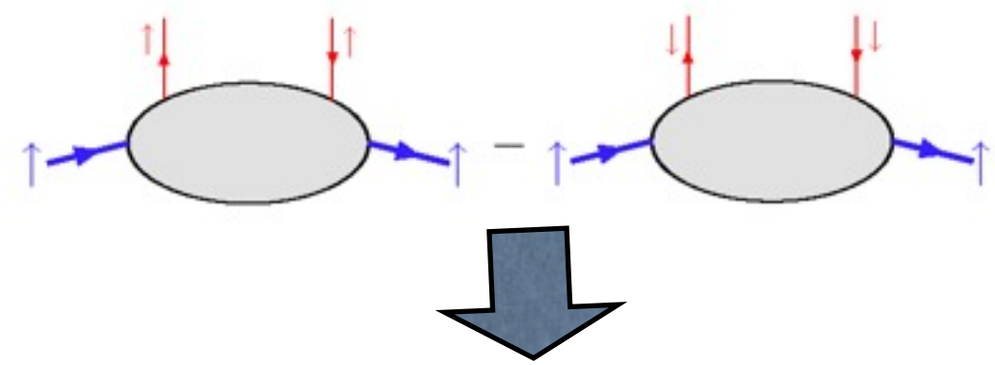



Transversity is chiral-odd!

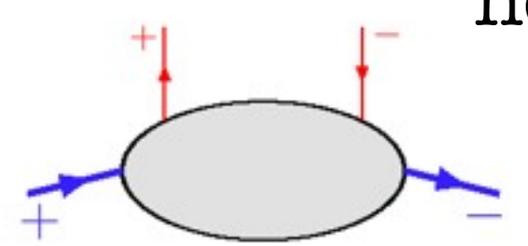
$$h_1^q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$$



in helicity basis

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

helicity flip!



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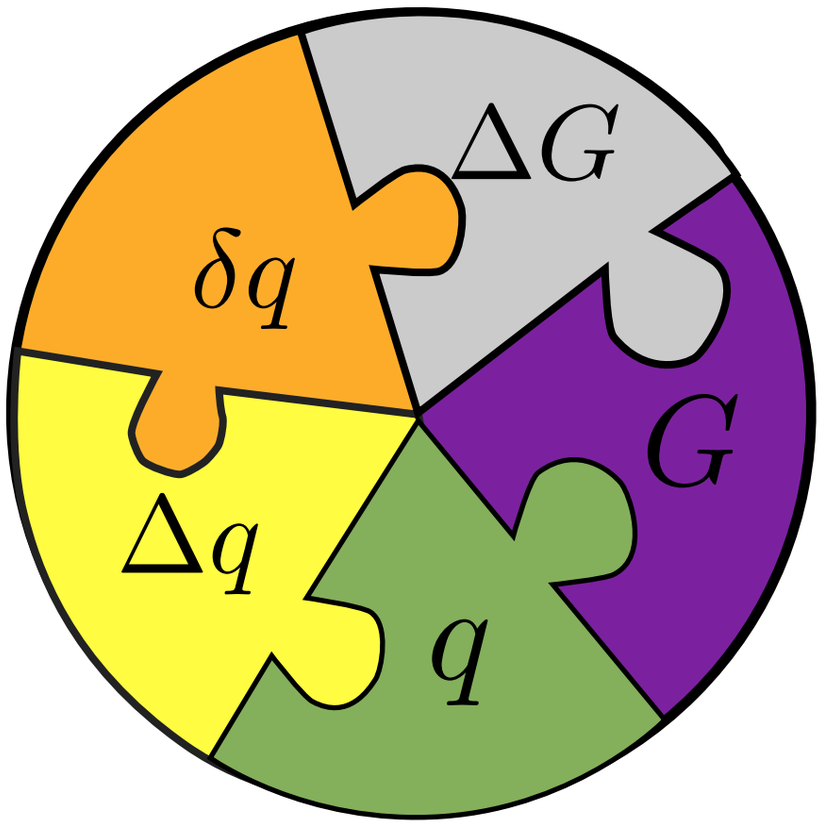


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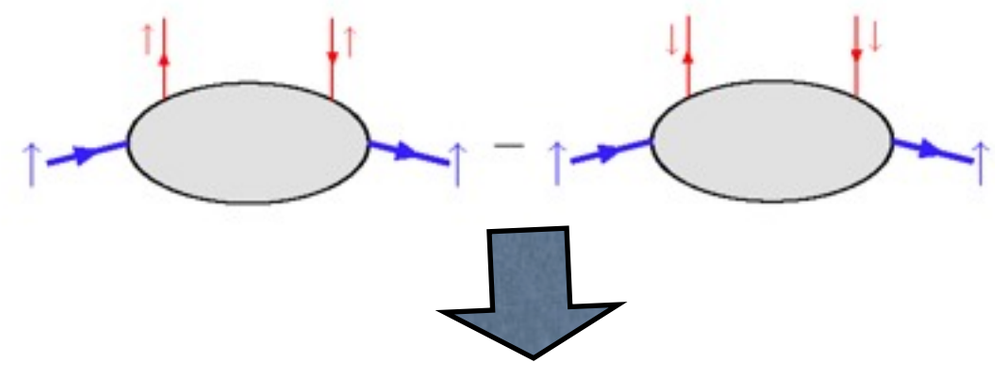

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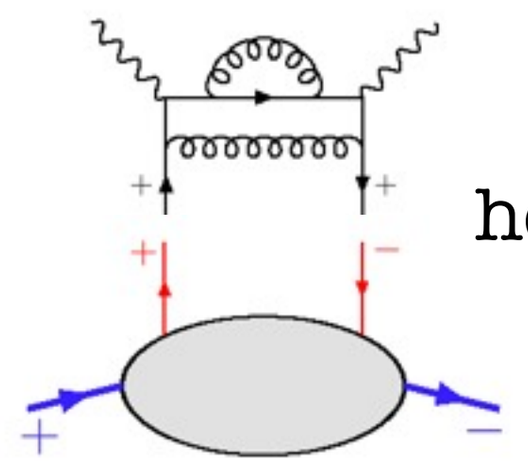

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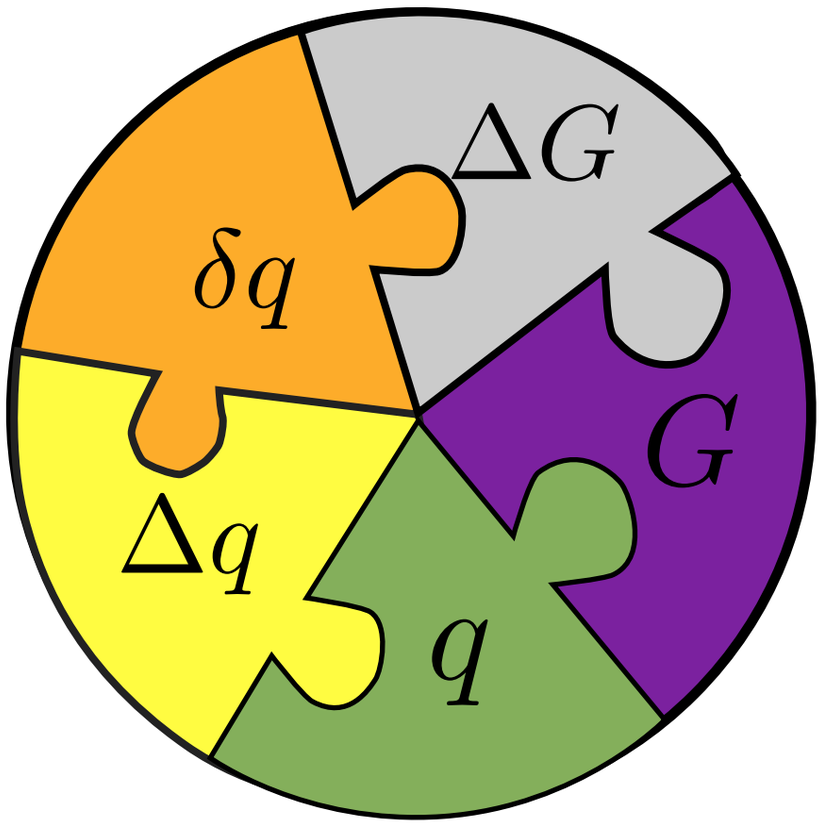


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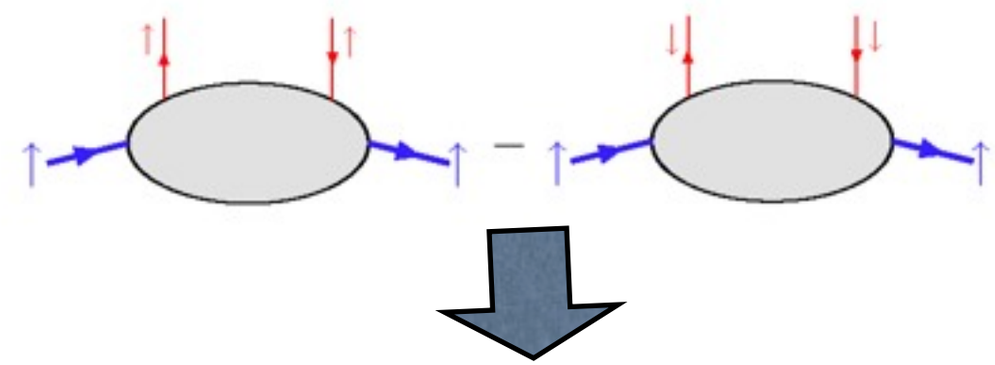

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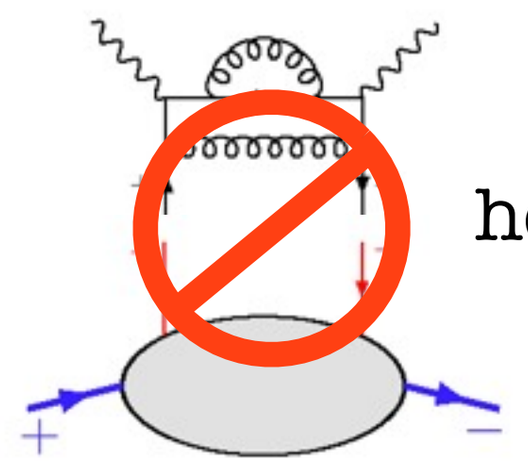

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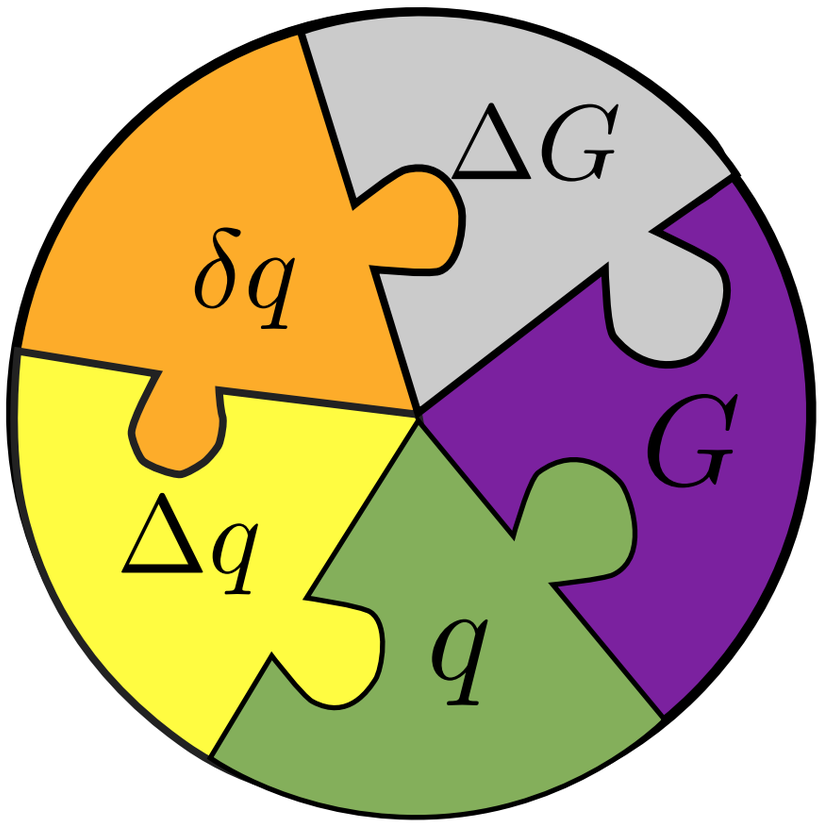


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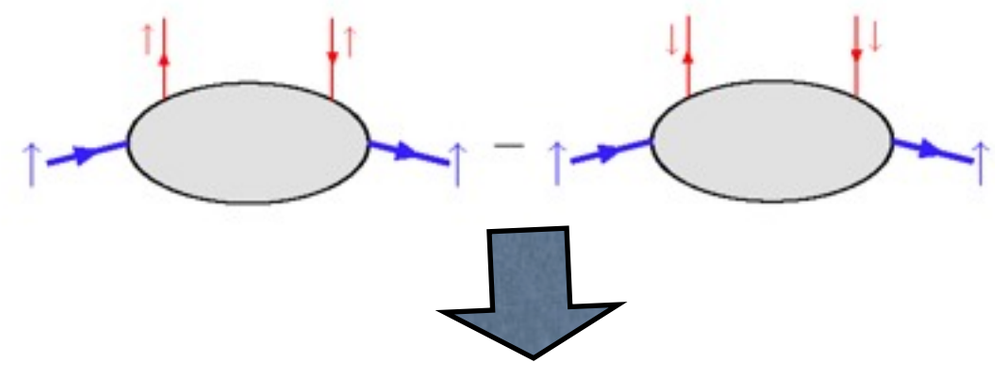

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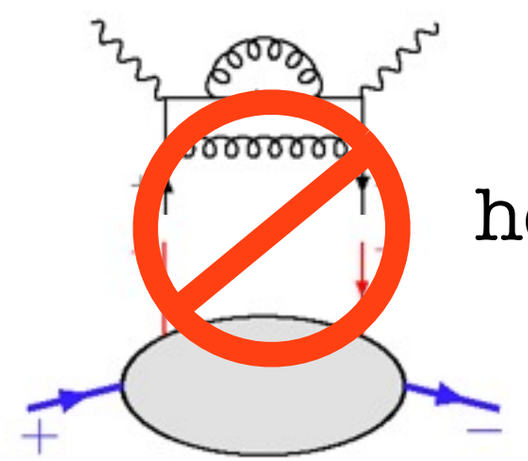
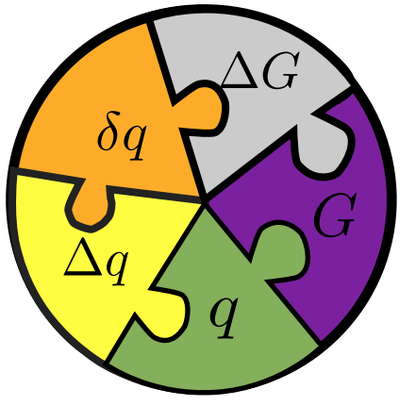


helicity flip!

(No gluon transversity in the puzzle?)

# Transversity distribution




$h_1 \quad x \quad X$

chiral odd chiral odd

chiral even observable

Transversity is chiral-odd!

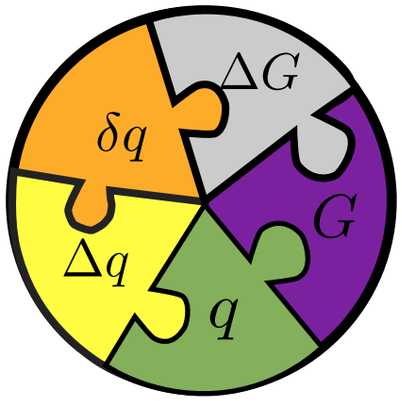
1. Can it be accessed? How?

Yes! But only in conjunction with another chiral-odd object

Accessible in different reactions

=> need of complementary reactions!

# Transversity distribution

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1. Can it be accessed? How?

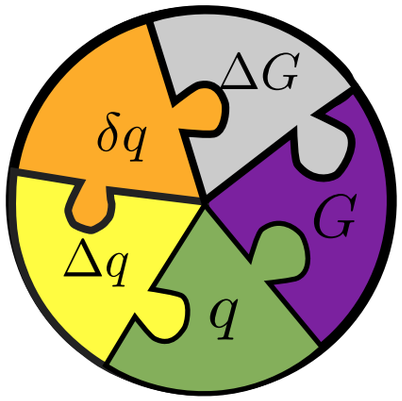
Yes! But only in conjunction with another chiral-odd object

Accessible in different reactions => need of complementary reactions!

-> each reaction covers specific kinematic ranges, and access specific features

2. Is transversity Universal?

# Transversity distribution

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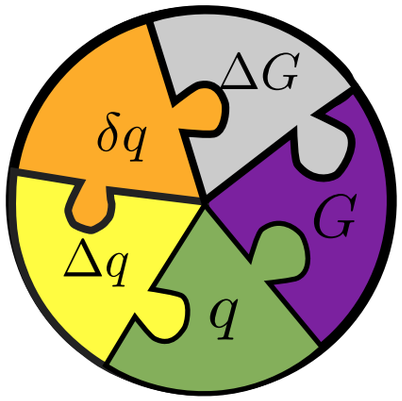
-> reactions are at different typical energies ➡ 3. How does transversity evolve?

$$g_1^q(x) = q^{\rightrightarrows}(x) - q^{\rightleftarrows}(x) \overset{?}{\sim} h_1^q(x) = q^{\uparrow\Uparrow}(x) - q^{\uparrow\Downarrow}(x)$$

No!

# Transversity distribution

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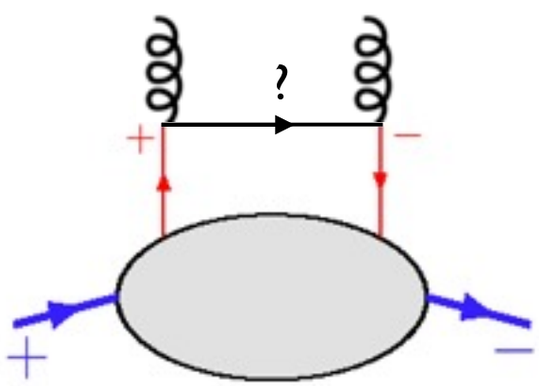


no gluon transversity (in proton) and quark and gluon transversities don't mix!

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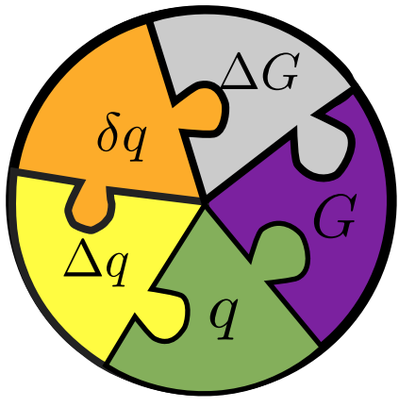


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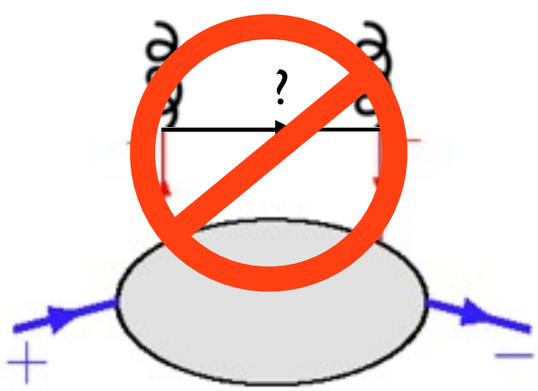


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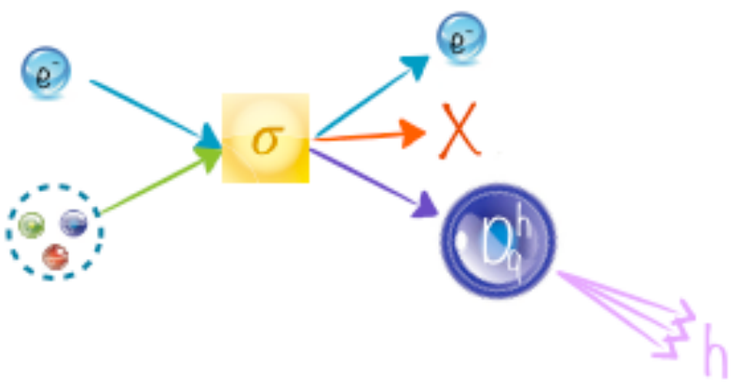
# Transversity distribution

## (some of the) Possible channels

$l\, p^{\uparrow} \rightarrow h\, X$,
$h_1 h_2\, X$, $\Lambda^{\uparrow} X$
(SIDIS)



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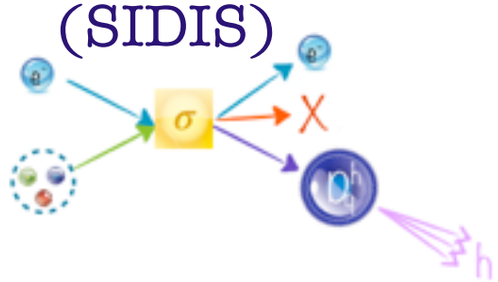


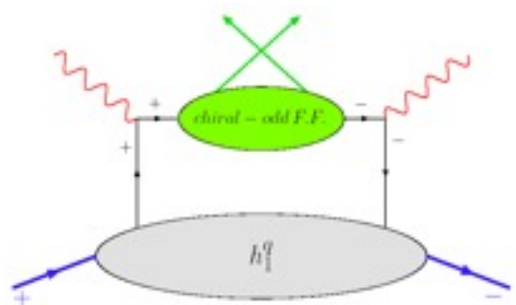


$h_1 \times FF$

chiral odd chiral odd

chiral even observable

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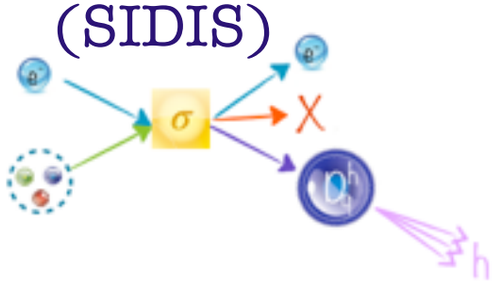


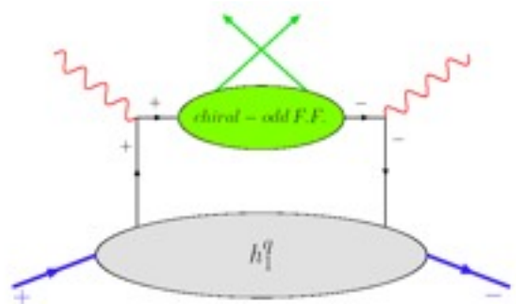


$h_1 \times FF$

- $h_1 \otimes$ Collins
- $h_1 \times IFF$
- $h_1 \times \Lambda_{FF}$

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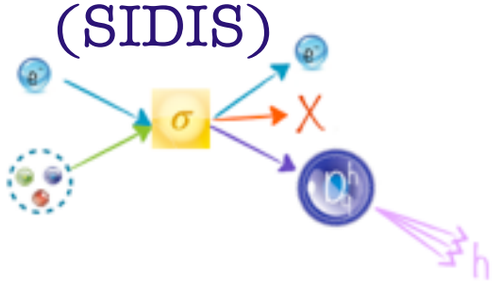


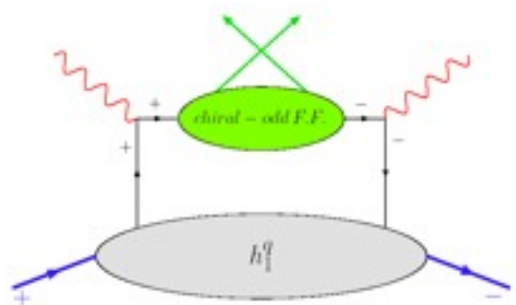


$h_1 \times FF$

- $h_1 \otimes$ Collins **TMD**
- $h_1 \times IFF$ **Collinear**
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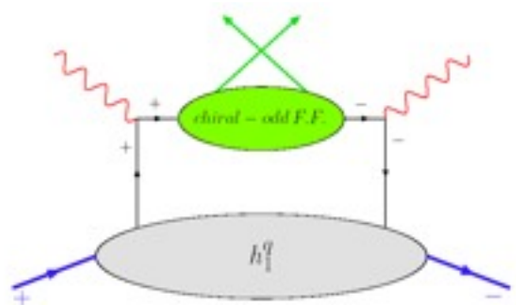


$h_1 \times FF$ → $h_1 \otimes$ Collins **TMD**
$h_1 \times IFF$ **Collinear**
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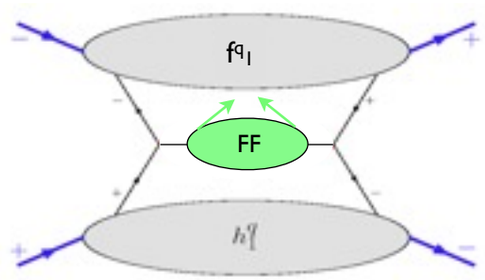
$p\, p^{\uparrow} \rightarrow h\, X$,
$h_1 h_2\, X$, jets


$f_1 \times h_1 \times FF$ → $f_1 \times h_1 \otimes$ Collins **TMD**
$f_1 \times h_1 \times IFF$ **Collinear**

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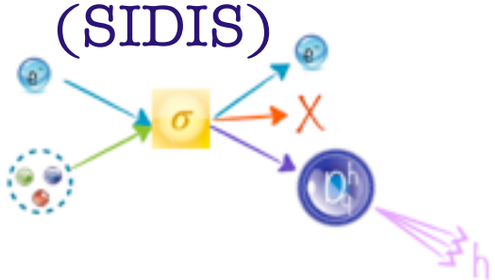


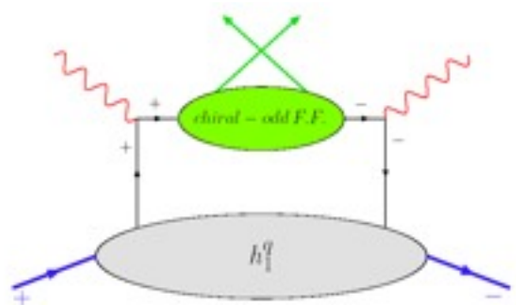


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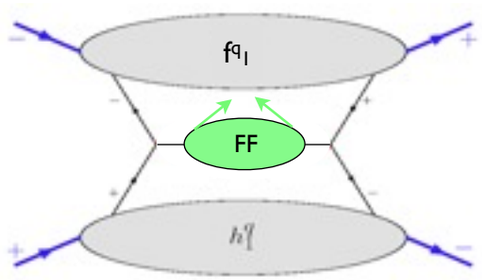
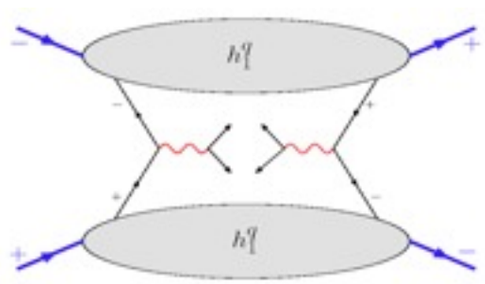



$f_1 \times h_1 \times FF$ → $f_1 \times h_1 \otimes$ Collins **TMD**
$f_1 \times h_1 \times IFF$ **Collinear**

$p^{\uparrow}\, h^{\uparrow} \to (q^{\uparrow}\, \bar{q}^{\uparrow} \to) l^+ l^-$
(Fully polarized
Drell-Yan)

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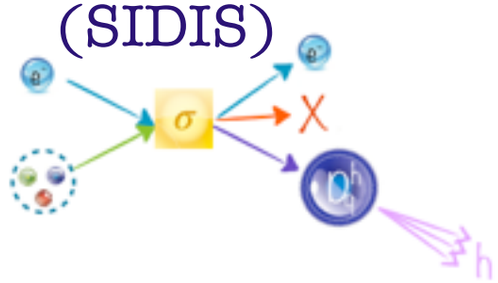


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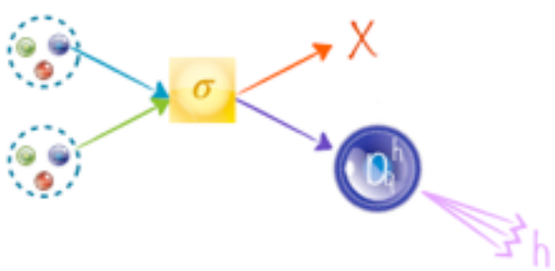



$p^{\uparrow}\, h^{\uparrow} \to (q^{\uparrow}\, \bar{q}^{\uparrow} \to) l^{+} l^{-}$
(Fully polarized Drell-Yan)


They all access transversity via single or double spin asymmetries, f.i.:

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

How well do we know the unpolarized cross-sections? In particular the TMD unpolarized ones?

$A_{UT} \propto h_1 \otimes$ Collins **TMD**

$A_{UT} \propto h_1 \times$ IFF **Collinear**

$P_T \propto h_1 \times \Lambda_{FF}$ **Collinear**

$A_N \propto f_1 \times h_1 \otimes$ Collins **TMD**

$A_N \propto f_1 \times h_1 \times$ IFF **Collinear**

$A_{TT} \propto h_1 \times h_1$ **Collinear**

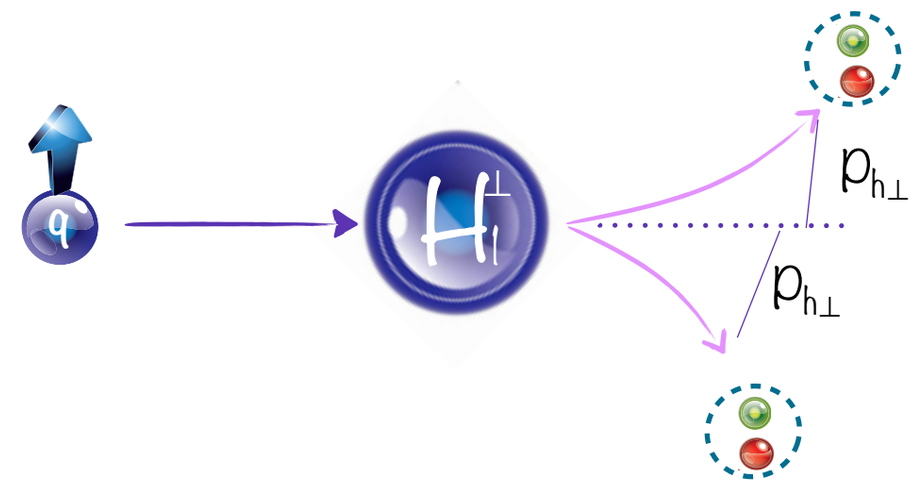
# Transversity distribution

## First access in SIDIS

Transversity coupled with a Fragmentation Function (FF)

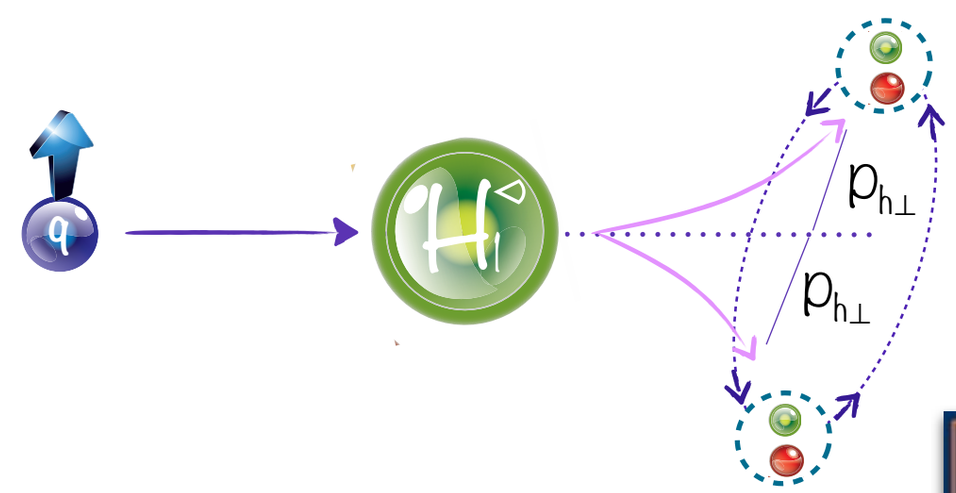
Collins FF

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




Interference FF

$$A_{UT} \propto h_1 \times \hat{H}_1$$ **Collinear**



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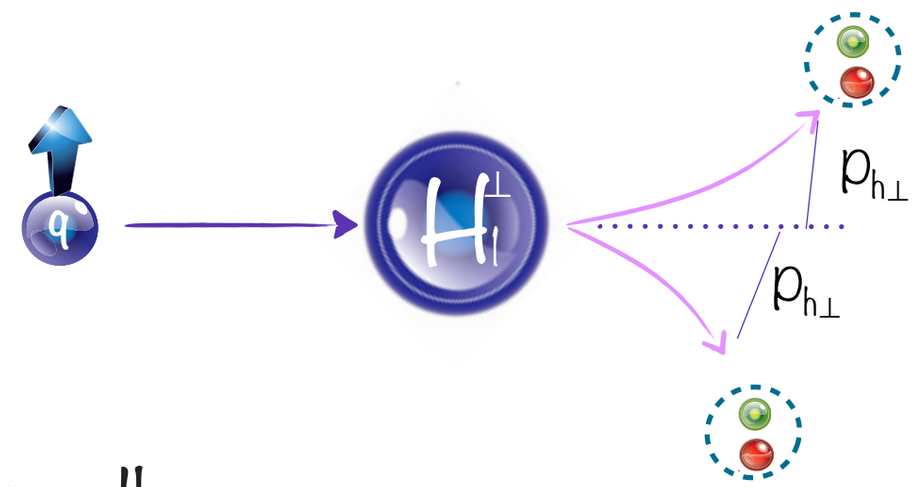
$$\int h_1(x,p_T)\, H_1^{\perp}(x,k_T)\, dp_T\, dk_T$$

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

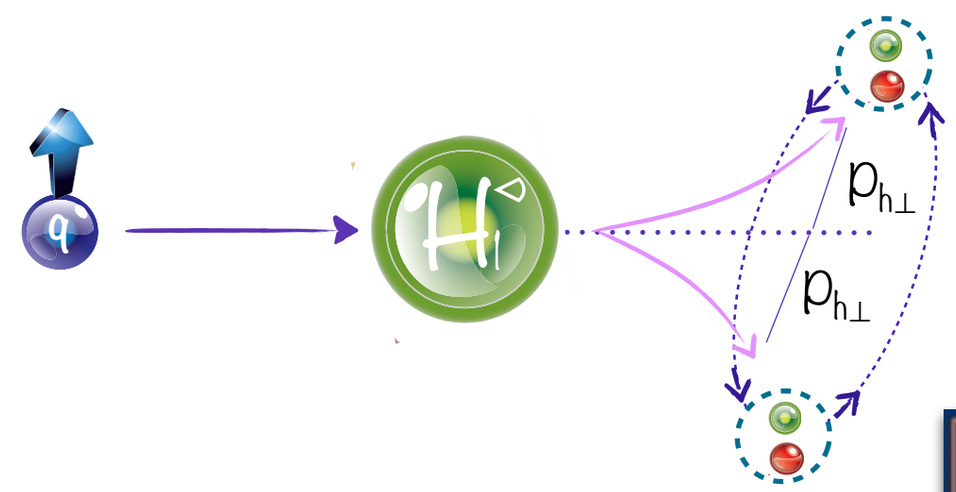



Interference FF

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

direct product!

(same in the denominator)



# Transversity distribution

## First access in SIDIS

Transversity coupled with a Fragmentation Function (FF)

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

TMD

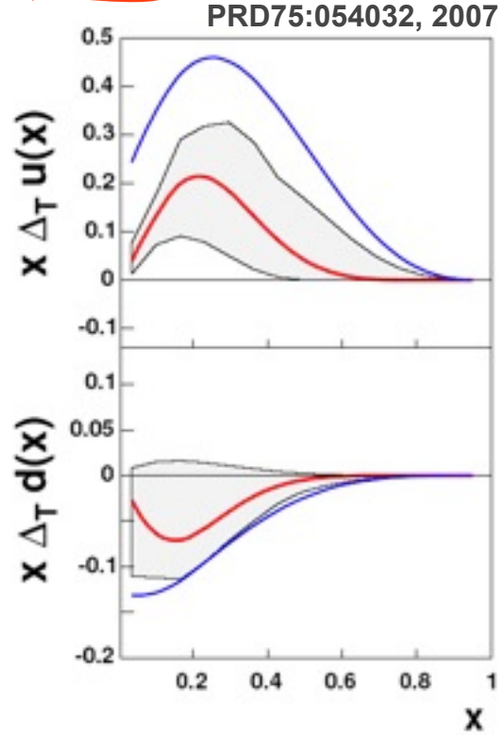
Collins FF

hermes

COMPASS

BELLE

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




Complementary reactions

FF universality assumed

TMD factorization assumed

# Transversity distribution

## First access in SIDIS

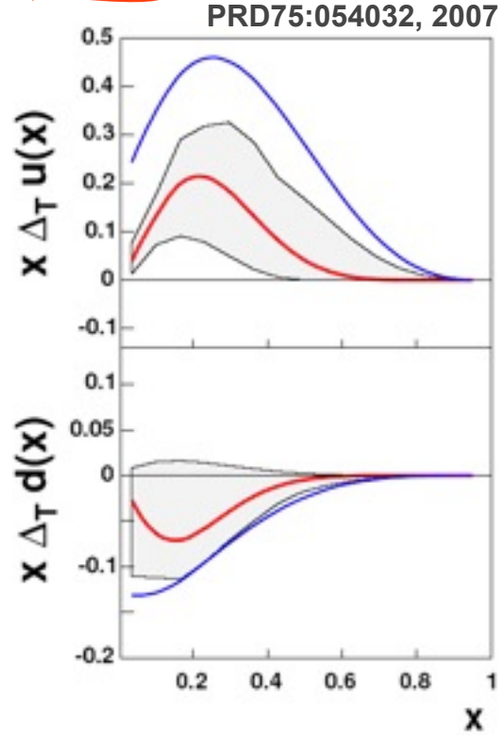
Transversity coupled with a Fragmentation Function (FF)

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

TMD

Collins FF

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




Complementary reactions

FF universality assumed

TMD factorization assumed

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

Collinear evolution assumed

# Transversity distribution

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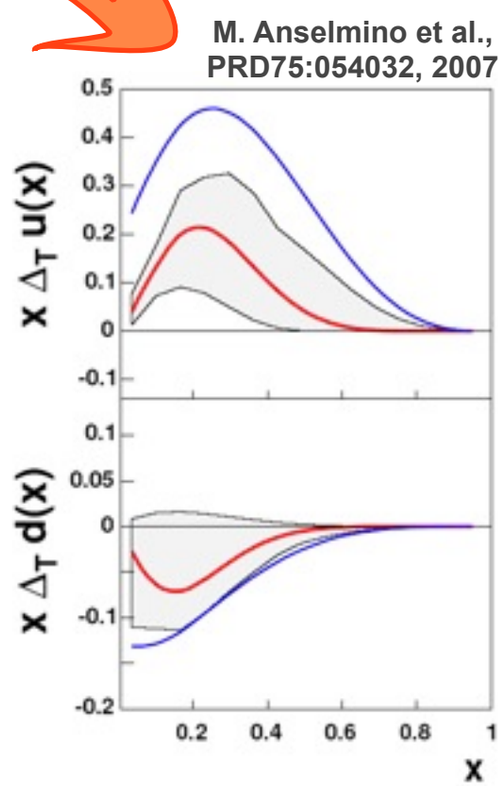
Transversity coupled with a Fragmentation Function (FF)

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

TMD

Collins FF




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

# Transversity distribution

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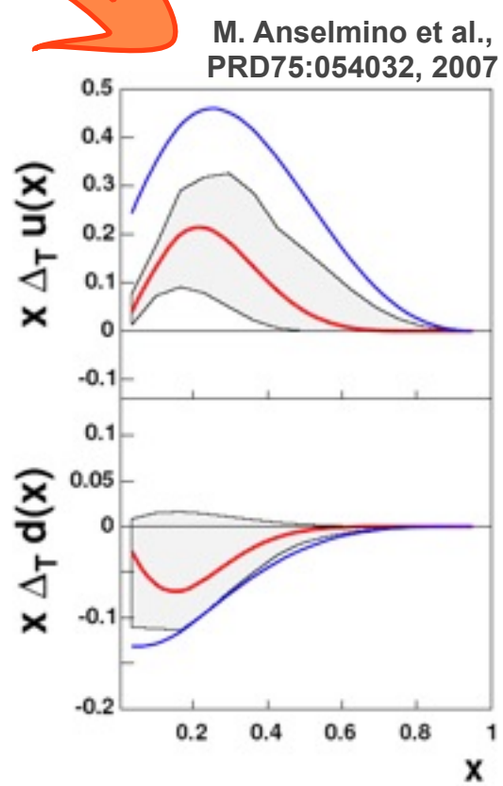
Transversity coupled with a Fragmentation Function (FF)

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

TMD

Collins FF




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

# Transversity distribution

## First access in SIDIS

Transversity coupled with a Fragmentation Function (FF)

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

Collins FF

Complementary reactions

FF universality assumed

TMD factorization assumed

Collinear evolution assumed

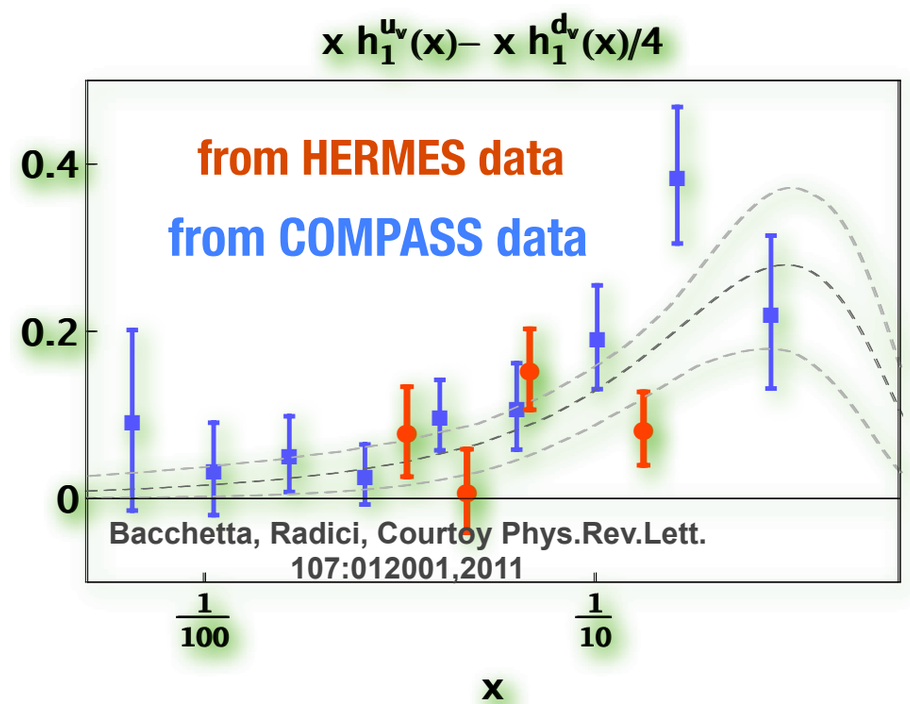
No transversity evolution assumed

Transversity and Collins Gaussian pT dependence assumed

$A_{UT} \propto h_1 \times \tilde{H}_1$

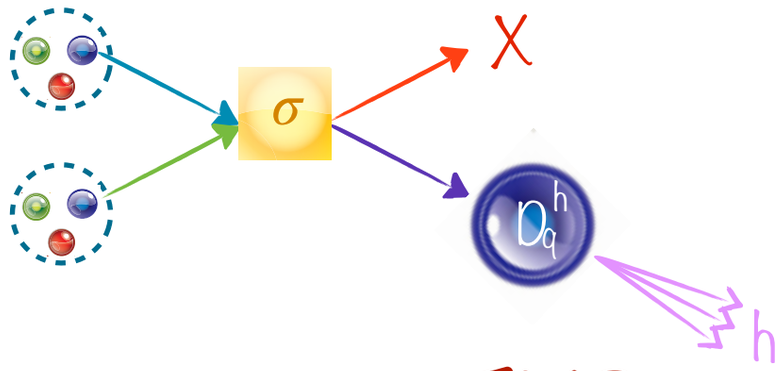
Interference FF

**Collinear**



# Transversity distribution

## Access in pp




**TMD**

$$A_N \propto f_1 \otimes h_1 \otimes H_1^{\perp}$$

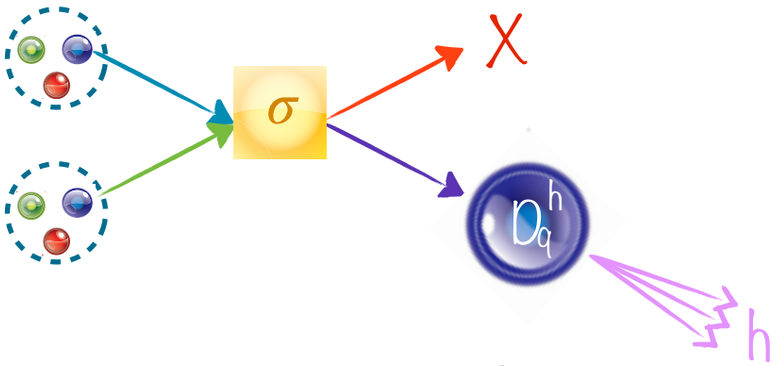
Single hadron

But! the asymmetry for single hadron comes mixed with other effects (Sivers, higher twist)

$$A_N \propto f_1 \times h_1 \times H_1^{\sphericalangle}$$

# Transversity distribution

## Access in pp

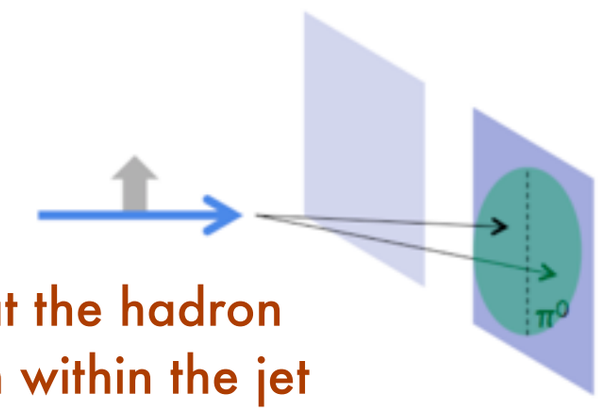



TMD

$A_N \propto f_1 \otimes h_1 \otimes H_1^{\perp}$

~~Single hadron~~

Jets

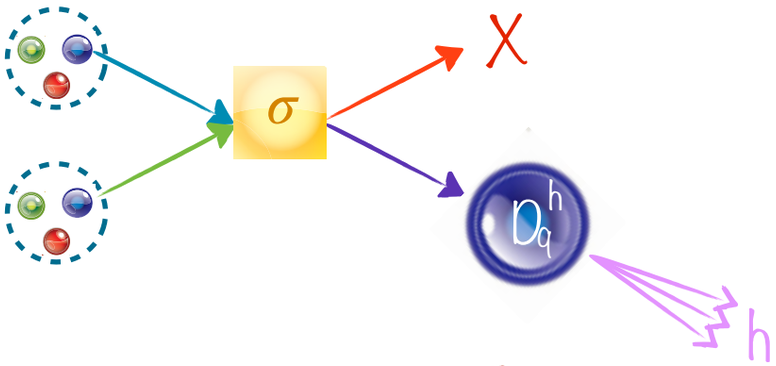



Looking at the hadron distribution within the jet

$A_N \propto f_1 \times h_1 \times H_1^{\sphericalangle}$

# Transversity distribution

## Access in pp




TMD

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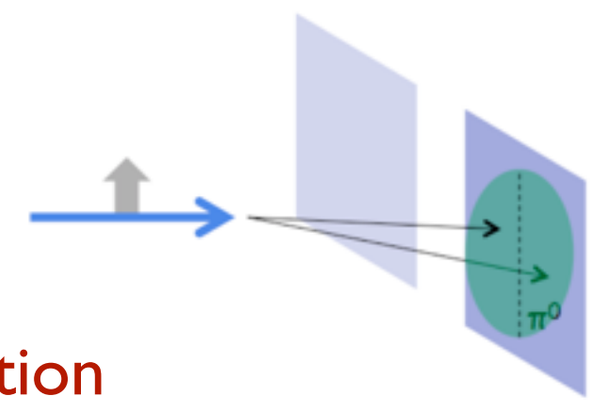
Single hadron

Jets

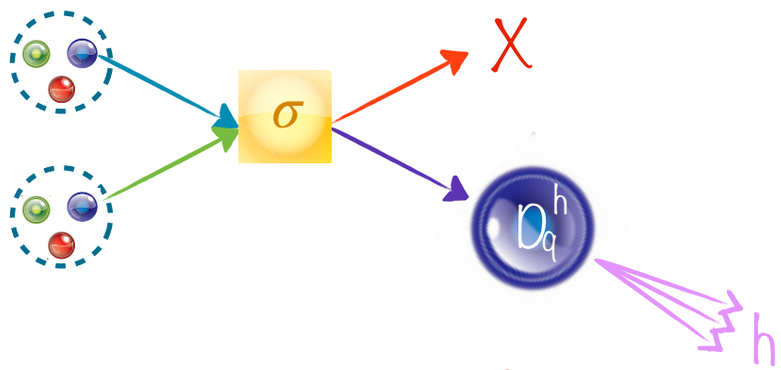



Word of caution: TMD factorization broken in pp→hadrons

$A_N \propto f_1 \times h_1 \times H_1^{\sphericalangle}$

# Transversity distribution

## Access in pp

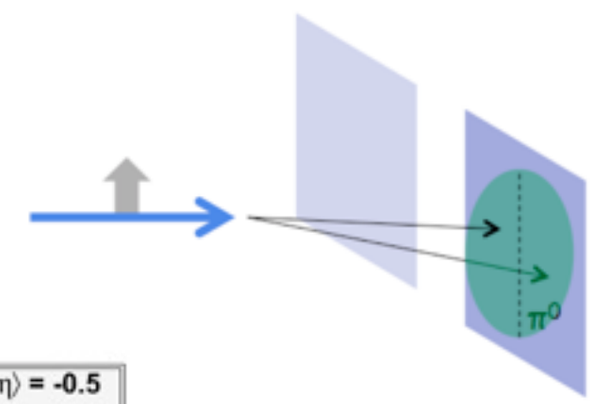



**TMD**

$A_N \propto f_1 \otimes h_1 \otimes H_1^{\perp}$

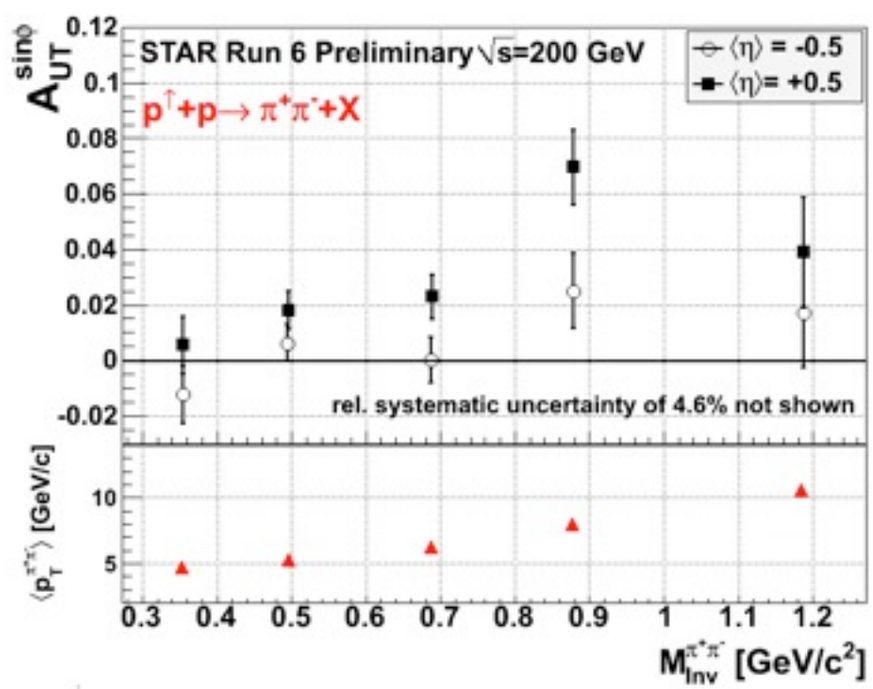
~~Single hadron~~

Jets




**Collinear!**

$A_N \propto f_1 \times h_1 \times H_1^{\sphericalangle}$



# Transversity distribution

## Access in fully polarized Drell-Yan

Double Spin asymmetry:

$$A_{TT} \propto h_1 \times h_1$$


Cleanest theoretical access:

- ➛ no input needed for fragmentation functions
- ➛ Collinear case

To enhance the signal both quark and anti-quark should come from the valence region

- medium-high x region
- preferable beam/target combination, f.i.:
  proton/anti-proton (PAX, GSI) pion/proton (COMPASS, CERN)

# Transversity distribution

## Access in fully polarized Drell-Yan

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- medium-high x region
- preferable beam/target combination, f.i.:
  proton/anti-proton (PAX, GSI) pion/proton (COMPASS, CERN)

But experimentally challenging:

- ➛ low cross-section
- ➛ background cleaning
- ➛ anti-proton polarization still not proven to work

# Present Status

| | | experimental input needed | theoretical input needed |
|---|---|---|---|
| SIDIS Collins<br>Jlab: Hall A&B | medium x | high x<br>measurement of (un)polarized pdfs and FF pT dependence | TMD Evolution |
| SIDIS IFF | medium x | high x | |
| Drell-Yan | no data! | precise measurements! | |
| pp IFF | medium x | high-x, precise measurements | Inclusion in global analysis |
| pp->jets Collins | medium x | high-x, precise measurements | TMD Evolution, TMD factorization breaking |

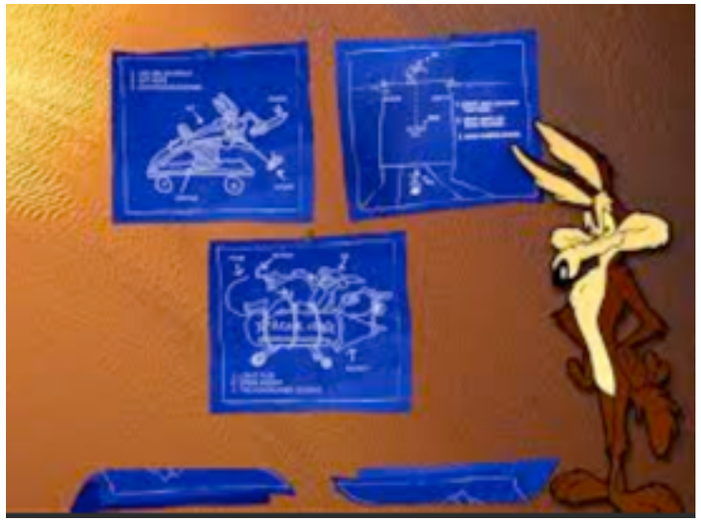
# Present Status

| | | experimental input needed | | theoretical input needed |
|---|---|---|---|---|
| SIDIS Collins | medium x | high x<br>measurement of (un)polarized pdfs and FF pT dependence | Jlab12<br>Babar<br>Belle/BelleII | TMD Evolution |
| SIDIS IFF | medium x | high x | Jlab12<br>EIC | |
| Drell-Yan | no data! | precise measurements! | COMPASSII<br>PAX?<br>FERMILAB | |
| pp IFF | medium x | high-x, precise measurements | Star<br>SuperStar<br>fsPHENIX | Inclusion in global analysis |
| pp->jets Collins | medium x | high-x, precise measurements | Star<br>SuperStar<br>fsPHENIX | TMD Evolution, TMD factorization breaking |

# ... not there yet ...

... but we took a few
feathers off ...

... and planning new experiments ...



# Stay tuned!


# Thank you!