Spin asymmetries in quarkonium production

Michela Chiosso

What is the nature of the spin of the proton?

What do spin asymmetries teach us about hadron structure?

spin is a fundamental quantity of a nucleon, yet its origin is largely unknown

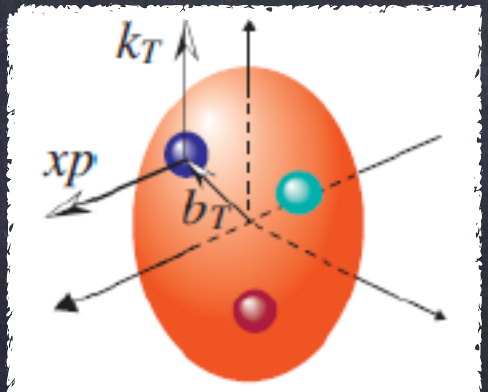
we can use spin as a unique probe to unravel the internal structure and the QCD dynamics of nucleons with unprecedented precision

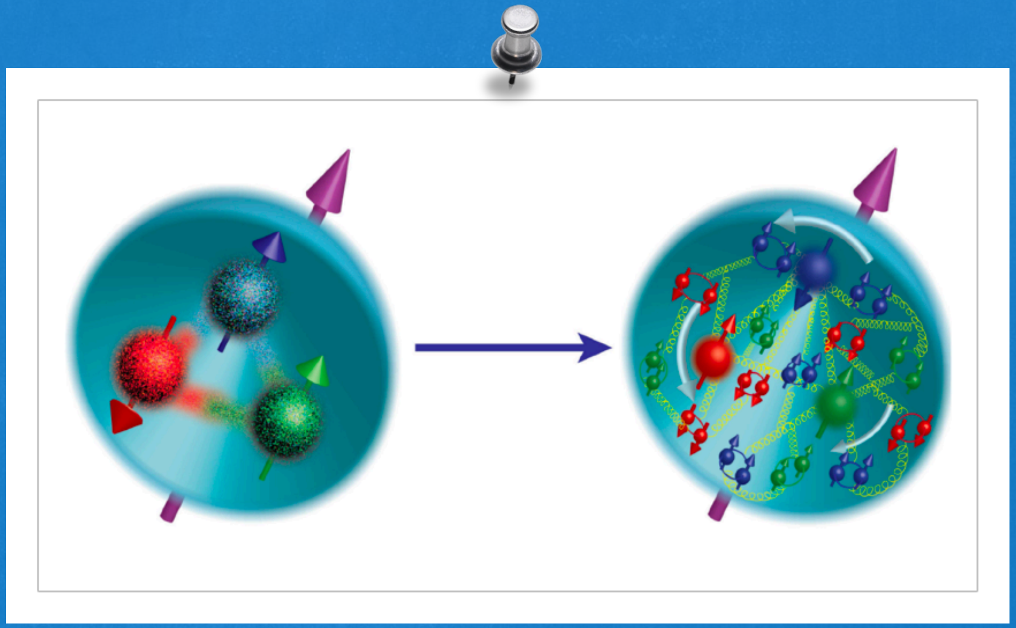
30 years since the "proton spin crisis"

$$\Delta\Sigma \sim 0.25 \ll 1$$

European Muon Collaboration, J. Ashman et al., "A Measurement of the Spin Asymmetry and Determination of the Structure Function g(1) in Deep Inelastic Muon-Proton Scattering," Phys. Lett. B206 (1988) 364

- what role do gluons play for the proton spin ?
- what orbital angular momenta do partons carry ?
- what's the 3D image of the nucleon in terms of quarks and gluons spacially (→ GPDs) ? in momentum (→ TMDs) ?





The 3D nucleon structure

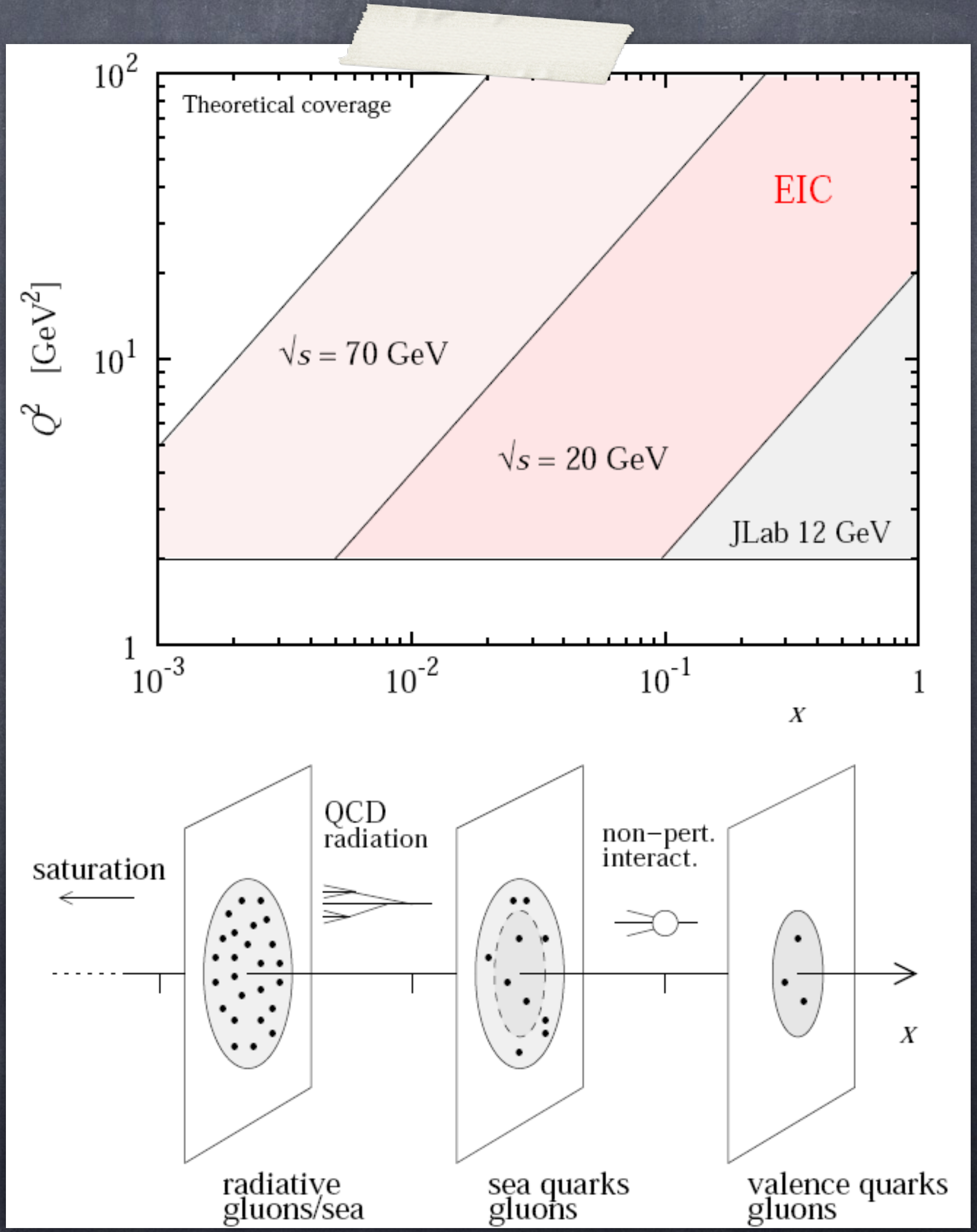
Nucleon is a many body dynamical system of quarks and gluons

Changing x we probe different aspects of nucleon wave function

How partons move and how they are distributed in space?

Technically such information is encoded into Generalised Parton Distributions (GPDs) and Transverse Momentum Dependent distributions (TMDs)

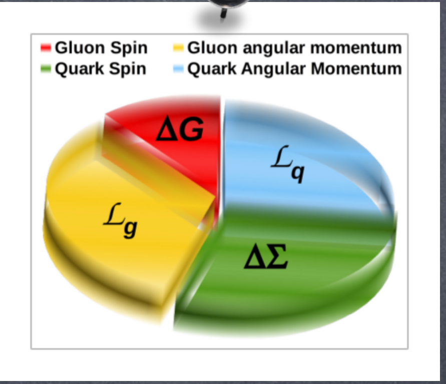
These distributions are also referred to as 3D (three-dimensional) distributions



The proton-spin puzzle

how do all the particles inside the proton conspire together to give it a ½ spin? And what might this mean for our understanding of hadrons, the particles that make up most of the visible universe?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_g$$



quark helicity

account for about 25% of proton total longitudinal spin

$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

gluon helicity

$$\Delta G = \int dx \Delta g(x)$$

quark and gluon OAM

Little known

remaining proton spin should arise from the relative dynamics of quarks and gluons

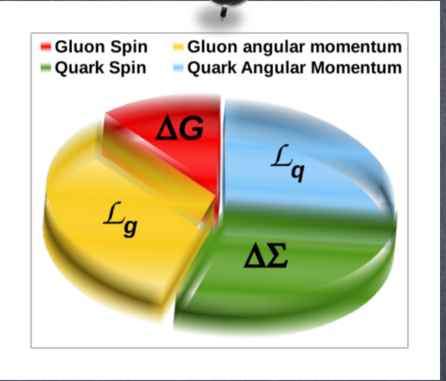
indirectly accessible via TSA

Connected to correlation between the transverse momentum of a parton inside the proton and the proton-spin. As such they contain information on orbital motion of partons in the proton

The proton-spin puzzle

how do all the particles inside the proton conspire together to give it a ½ spin? And what might this mean for our understanding of hadrons, the particles that make up most of the visible universe?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_g$$



quark helicity

account for about 25%

of proton total longitudinal spin

$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

gluon helicity

account for about 40%

of proton total longitudinal spin

$$\Delta G = \int dx \Delta g(x)$$

quark and gluon OAM

Little known

remaining proton spin should arise from the relative dynamics of quarks and gluons

accessible via GPDs

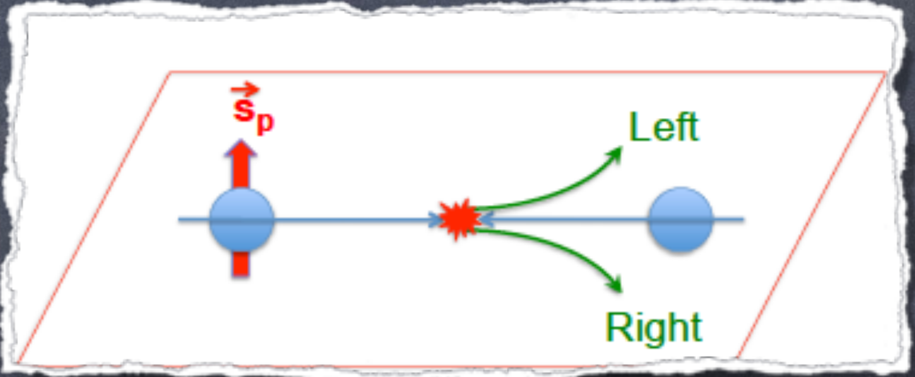
Single Transverse Spin Asymmetry

- STSA (A_N) is the amplitude of the spin-correlated azimuthal modulation of the produced particles
- it can be evaluated by studying the left-right asymmetry of the produced particles
- Equivalently it may be quantified by measuring production cross sections for reactions with the target spin polarised upwards and downwards with respect to the incoming beam direction

$$\boxed{p + p^{\uparrow} \longrightarrow \pi + X}$$

Correlation

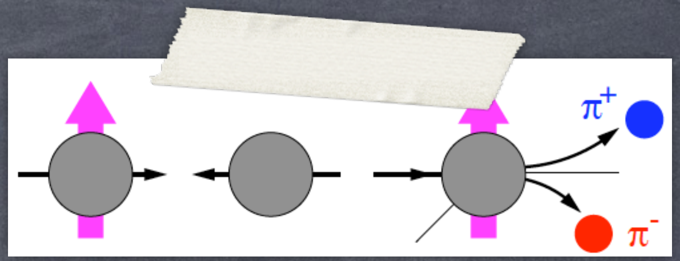
S_p vs $p_{\pi\perp}$



$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- no large STSA can be generated in the hard elementary processes
- leading-twist collinear perturbative QCD predicted it to be small ($A_N \propto m_q/p_T \sim O(10^{-4})$),
- then STSA must be related to non-perturbative properties of the nucleon structure, like parton intrinsic and orbital motion

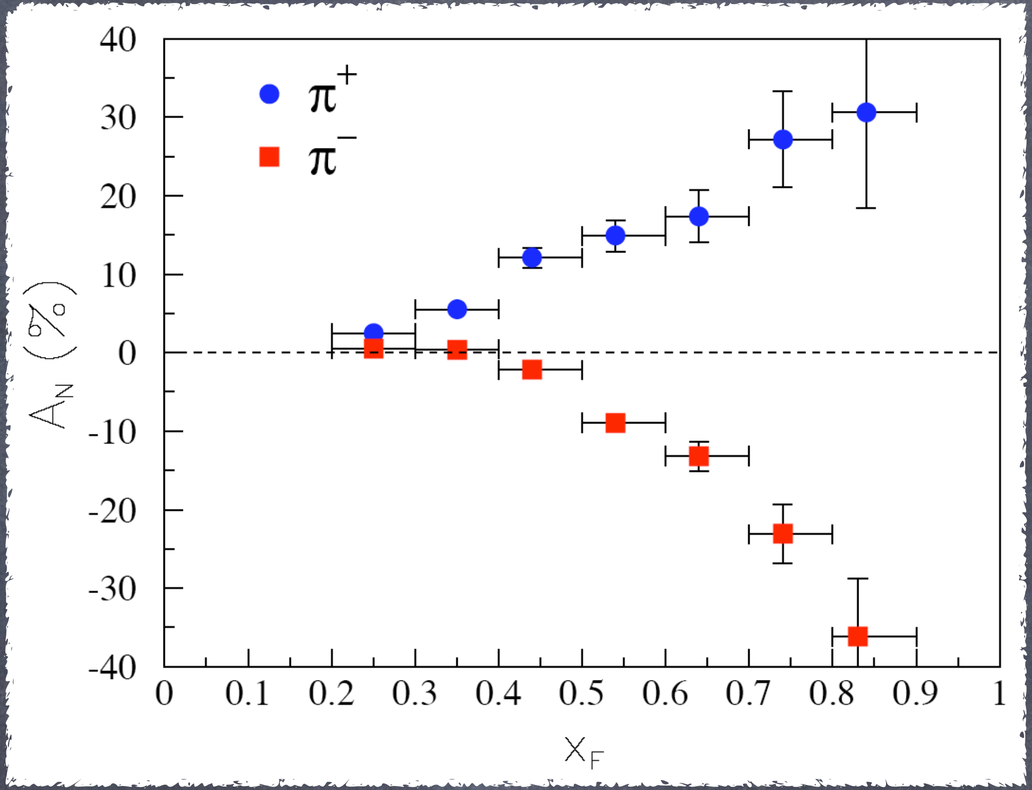
Single Transverse Spin Asymmetry



A_N in hadronic processes at high energies: more than 30 years history

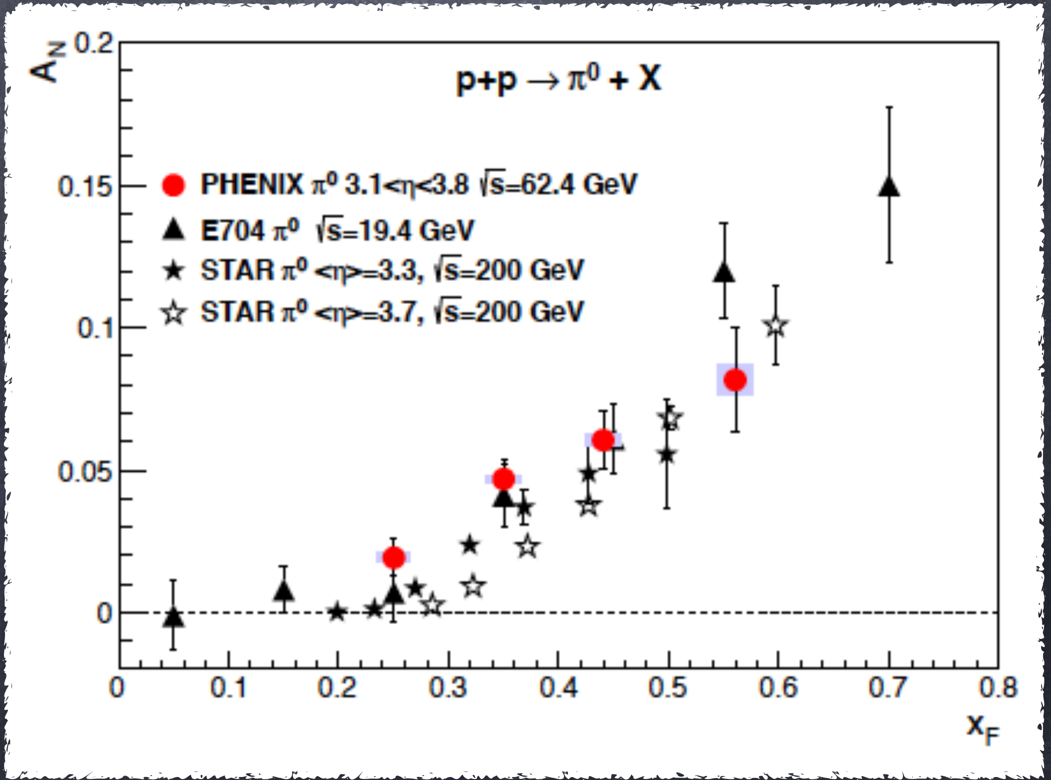
$$p^{\uparrow}\, p \rightarrow \pi\, X$$

E704 (1991)
$\sqrt{s}$ = 20 GeV
0.7 < p_T < 2.0



RHIC have extended the observations: from the fixed-target energy range to the collider regime

Large asymmetries also for π^0 at high-energies $\sqrt{s} = 200$ GeV, $p_T > 2$ GeV), where the applicability of pQCD is well established



Single Transverse Spin Asymmetry

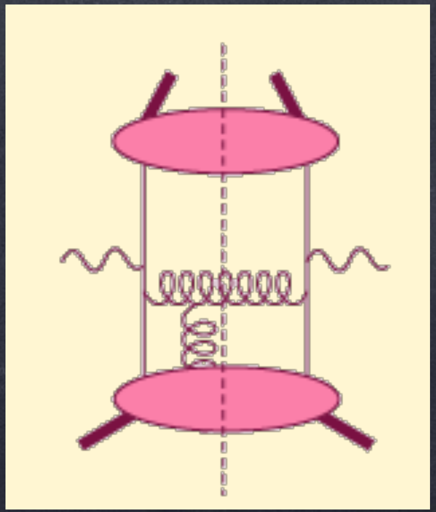
Two theoretical approaches:

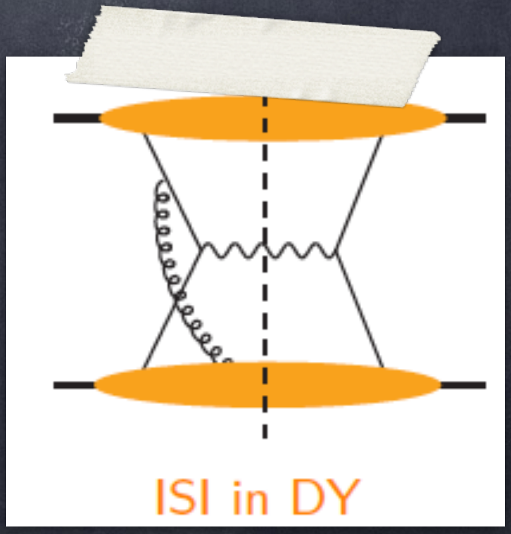
Collinear (twist-3) approach (Efremov-Taryaev, Qiu-Sterman, Kanazawa-Koike)

- based on collinear QCD factorization
- exchange of a gluon between the active parton and the color field of the IS or FS hadron
- gluon exchange generates the interference between different partonic scattering amplitudes
- this interference, described by a 3-parton (e.g. qgq, ggg) correlation function, generates the SSA

TMD Formalism (D. W. Sivers, Phys. Rev. D41 (1990) 83)

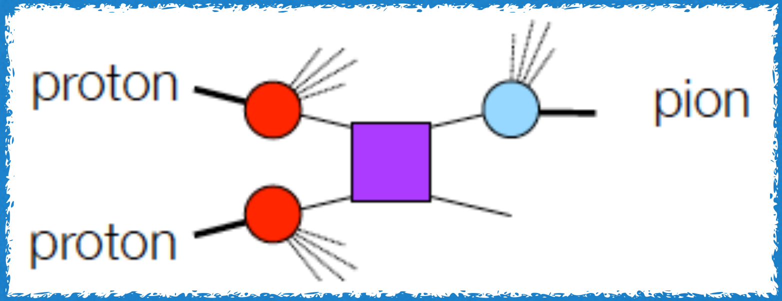
based on a more phenomenological generalisation of the Parton model, including, in the factorisation scheme, Transverse Momentum Dependent partonic distribution and fragmentation functions (TMDs), respectively the Sivers and the Collins functions



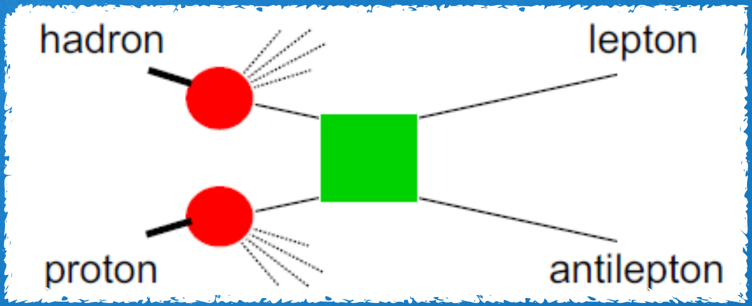


CT3 vs TMD formalism

CT3 formalism:
valid for processes with only one characteristic hard scale, for instance the transverse momentum of a produced hadron, satisfying $p_T \gg \Lambda QCD$, in a proton-proton collision



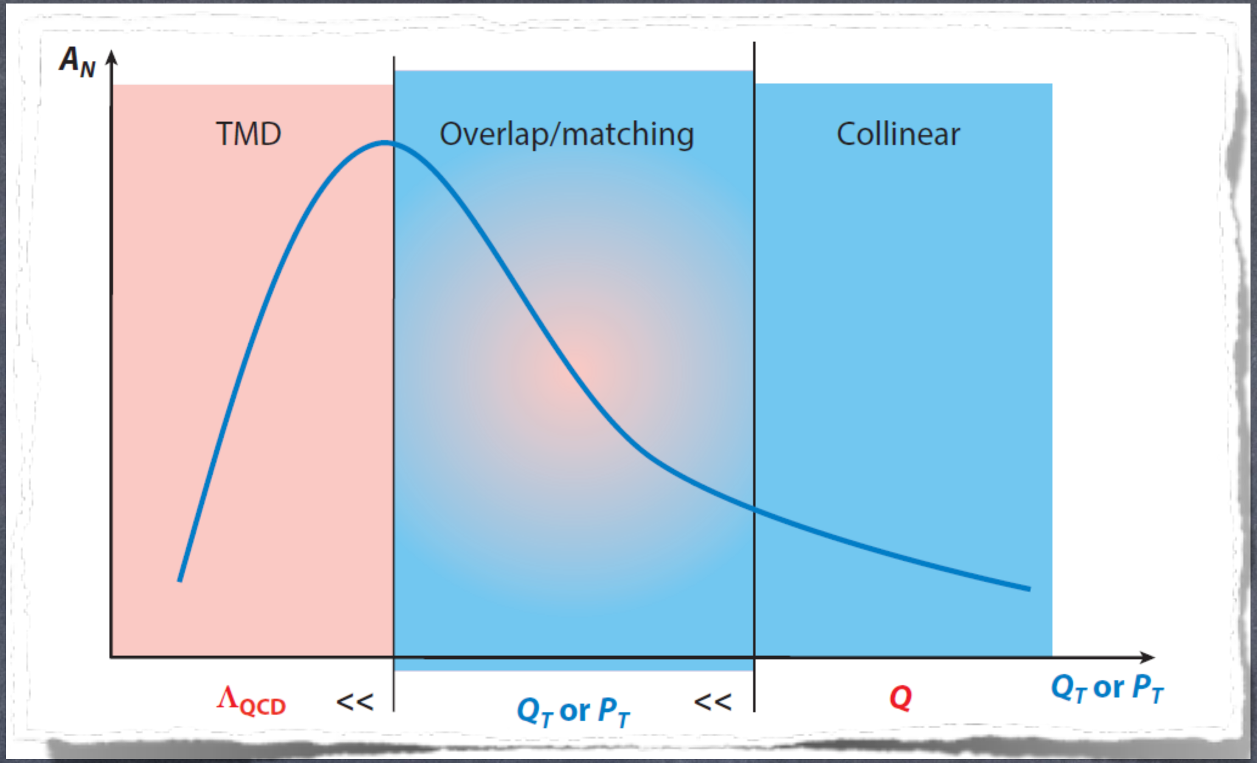
TMD Formalism
for processes with two characteristic and well-separated scales (for example, in Drell-Yan process, the mass M and the transverse momentum pT of the produced lepton pair, where $\Lambda QCD \lesssim pT \ll M$).



When the two relevant scales become comparable, the TMD formalism can be then reduced to the CT3 one

One of the most important predictions, shared by both approaches, is the predictable, but non-universal, magnitude of this asymmetry in different processes. The experimental check of this feature is one of the milestones of several physics programs, like AFTER@LHC and RHIC

CT3 vs TMD formalism



- Use TMD description (Sivers and Collins) if $p_T \ll Q$ (two well separated scales)

- Use collinear description at Twist 3 if $p_T \sim Q$ (one large scale)

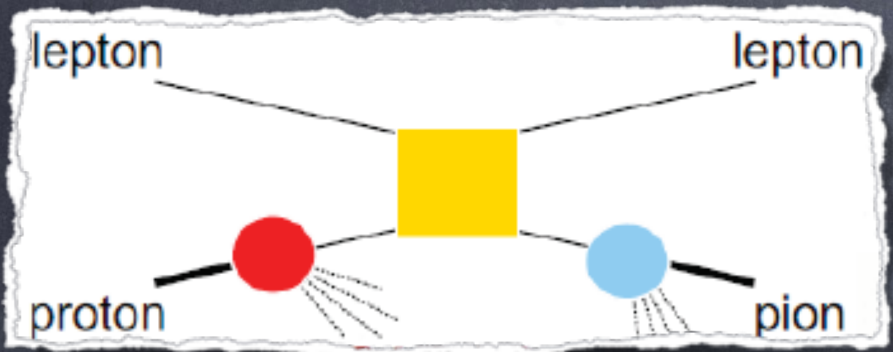
- Consistent results for TMD and Twist 3 in transition region

Sivers TMD function can be matched onto the ETQS matrix elements at large transverse momenta

$$f_{1T}^{\perp(1)q(g)}(x) = \int d^2k_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q(g)}(x, k_\perp^2) \propto T_{q(G)}(x, x)$$

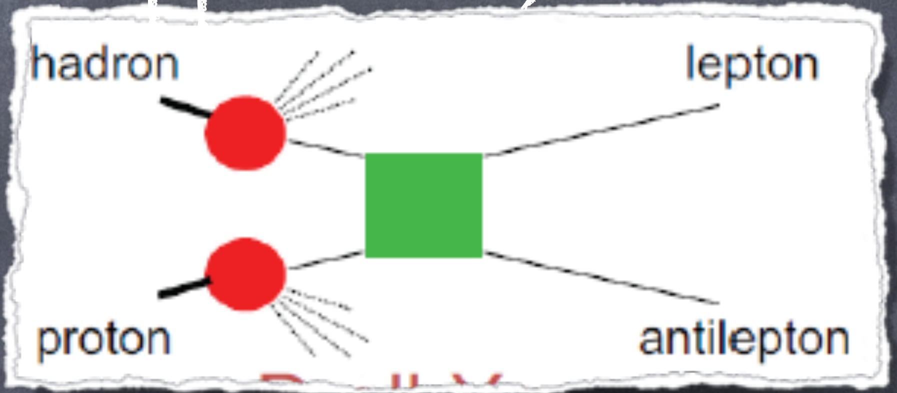
Which processes?

- SIDIS



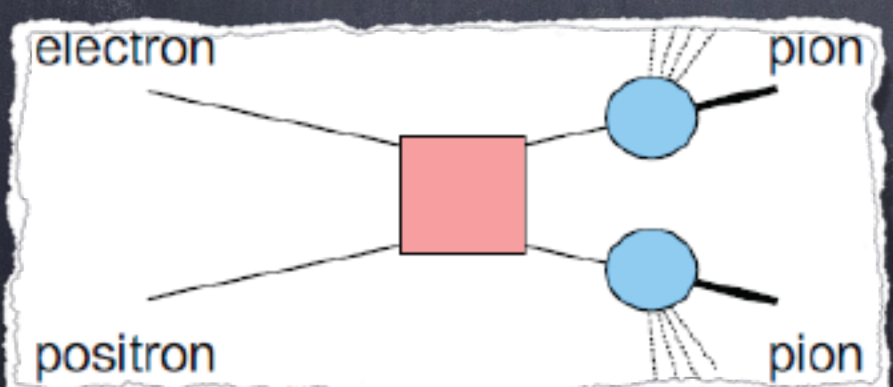
Hermes, Compass, JLAB, EIC

- Drell-Yan, $pp \to W^{\pm} X$, $Z^0 X$



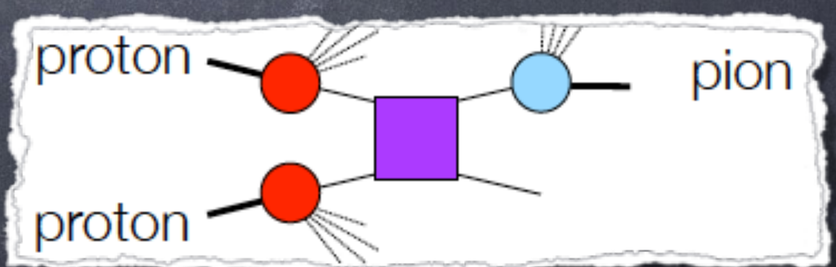
Compass, FNAL, BNL, GSI, After@LHC, JPARC

- $e^+e^- \to \pi\pi X$



BesIII, Belle, CERN, Babar

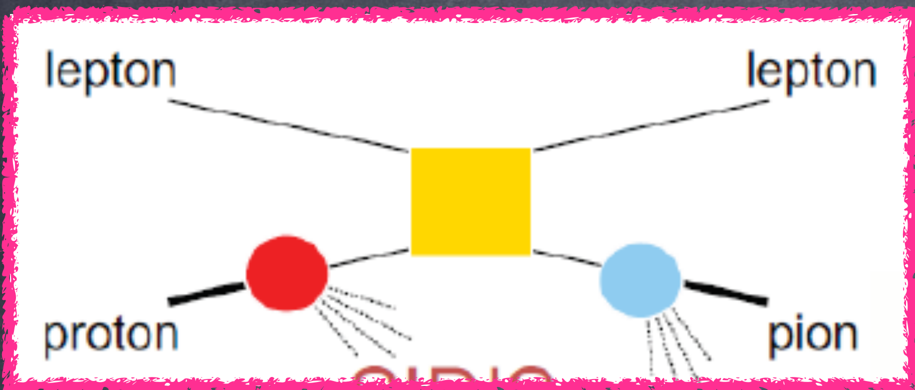
- $pp \to hX$, π jet$X$



BNL, After@LHC

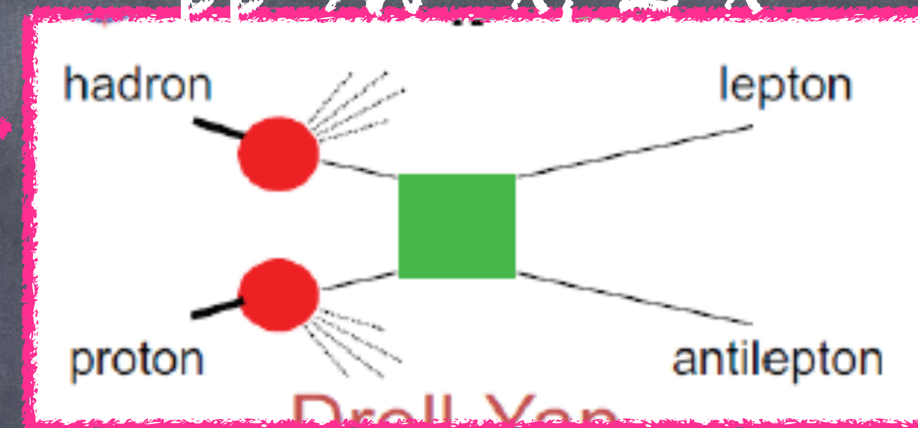
Which processes to learn about factorisation?

- SIDIS



Hermes, Compass, JLAB, EIC

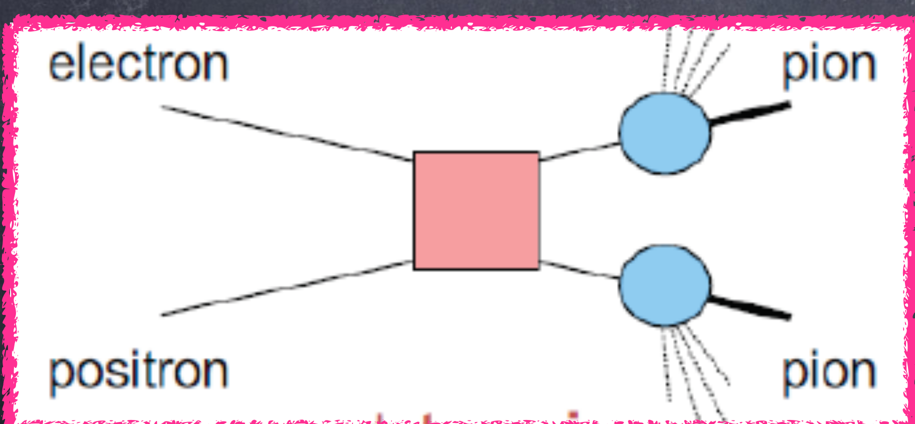
Drell-Yan, $pp \to W^{\pm} X$, $Z^0 X$



Compass, FNAL, BNL, GSI, After@LHC, JPARC

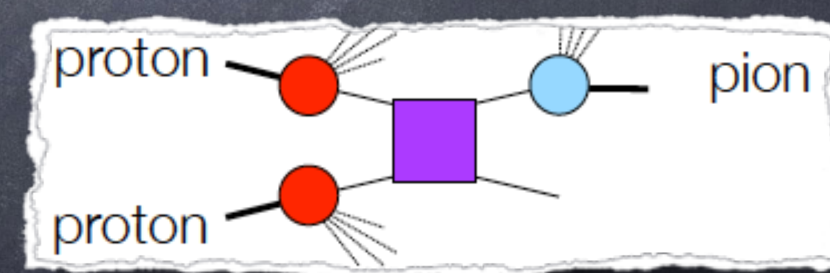
Two scales processes: TMD factorisation is not applicable?

- $e^+e^- \to \pi\pi X$



BesIII, Belle, CERN, Babar

- $pp \to hX$, jetX, γX

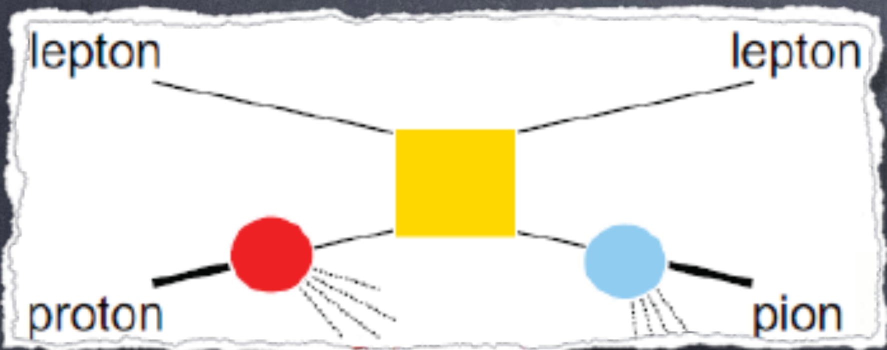


BNL, After@LHC

Only one scale is measured in PP
TMD factorisation is not applicable?

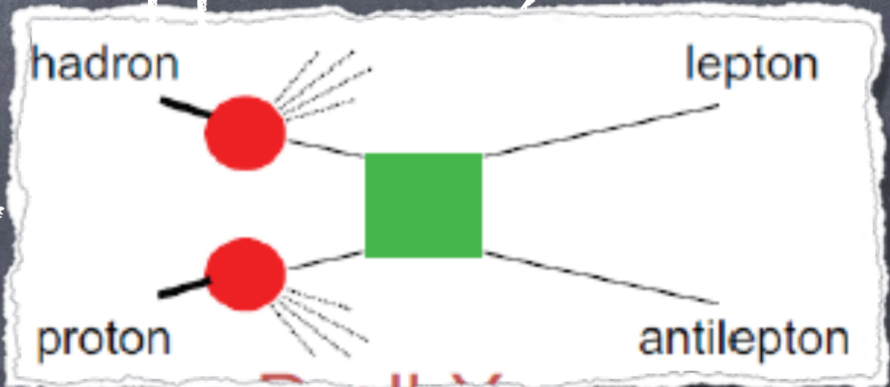
Which processes to learn about factorisation?

- SIDIS



Hermes, Compass, JLAB, EIC

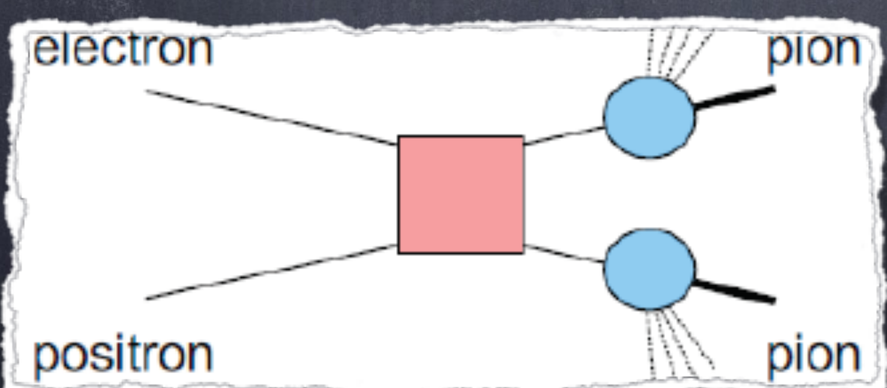
Drell-Yan, $pp \to W^{\pm} X$, $Z^0 X$



Compass, FNAL, BNL, GSI, After@LHC, JPARC

TMD evolution equations

- $e^+e^- \to \pi\pi X$

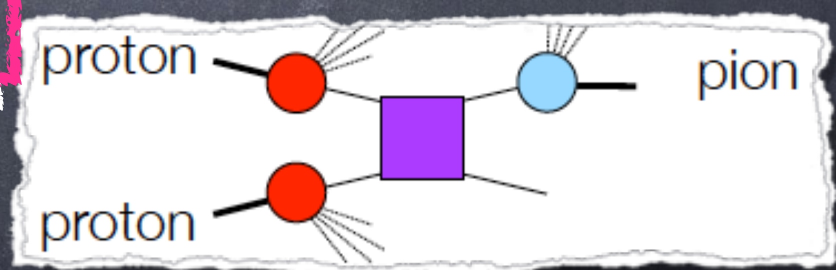


BesIII, Belle, CERN, Babar

?

Twist-3 factorization
DGLAP equations

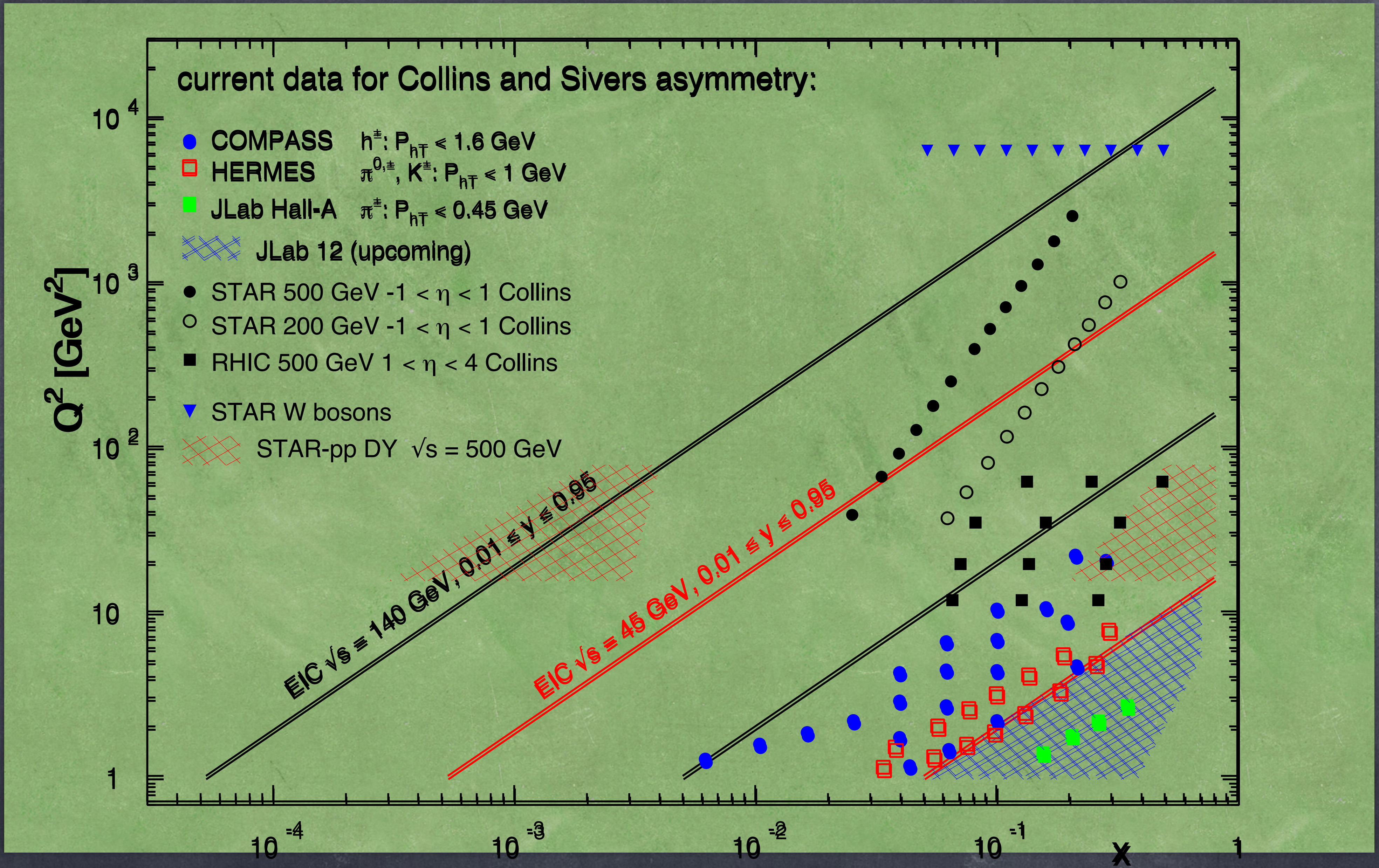
- $pp \to hX$, jetX, γX



BNL, After@LHC

Only one scale is measured in PP
TMD factorisation is not applicable?

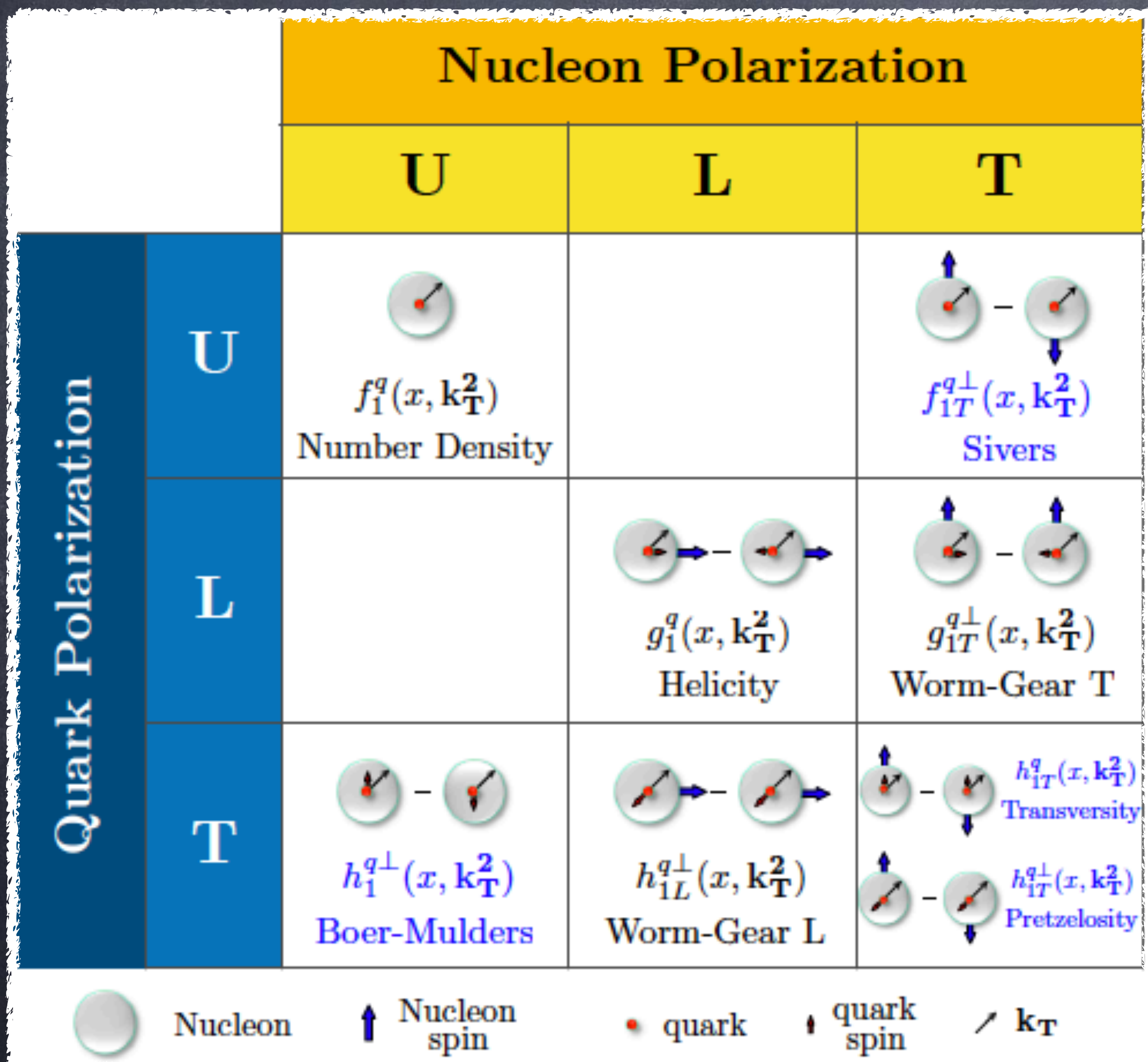
TMDs extraction



TMDs from fixed target data → high x @ low Q^2

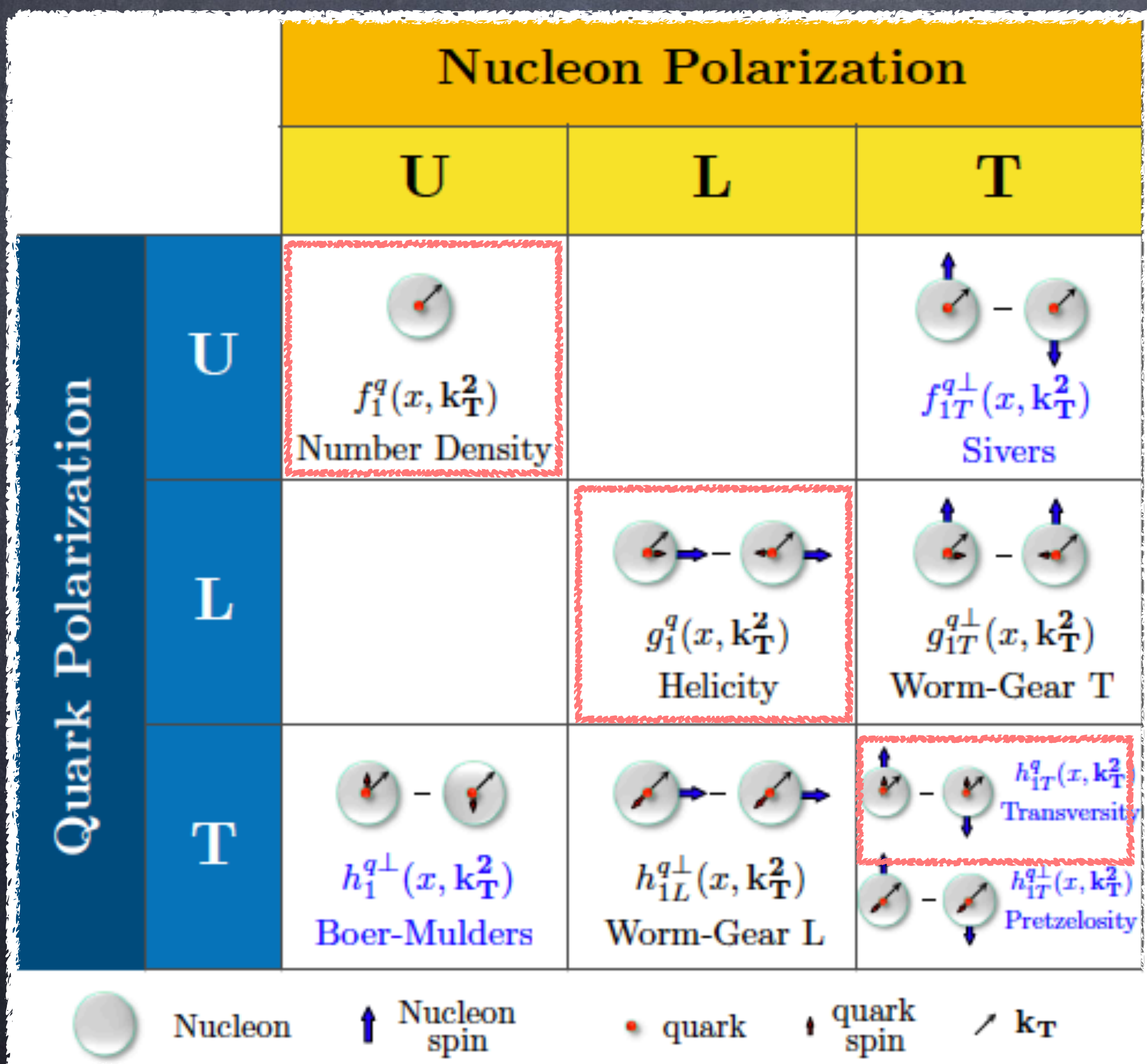
need to cover high Q^2 and wide range in x

TMD PDFs



- In the leading order QCD parton model nucleon spin-structure can be parametrized in terms of 8 twist-2 quark intrinsic transverse momentum (k_T) dependent TMD PDFs.
- Each represents different aspects of partonic structure
- Each depends on Bjorken-x, transverse momentum, the scale
- Each function is to be studied

TMD PDFs

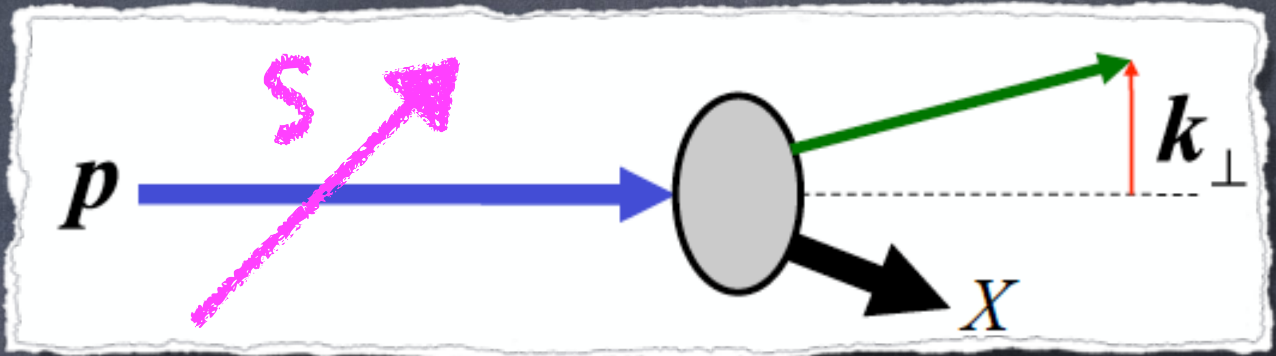


- In the leading order QCD parton model nucleon spin-structure can be parametrized in terms of 8 twist-2 quark intrinsic transverse momentum (k_T) dependent TMD PDFs.
- Each represents different aspects of partonic structure
- Each depends on Bjorken-x, transverse momentum, the scale
- Survive on the integration over K_T
- The others are sensitive to intrinsic kT in the nucleon

- Sivers function: embeds correlations between proton spin and parton transverse momentum

$$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$$

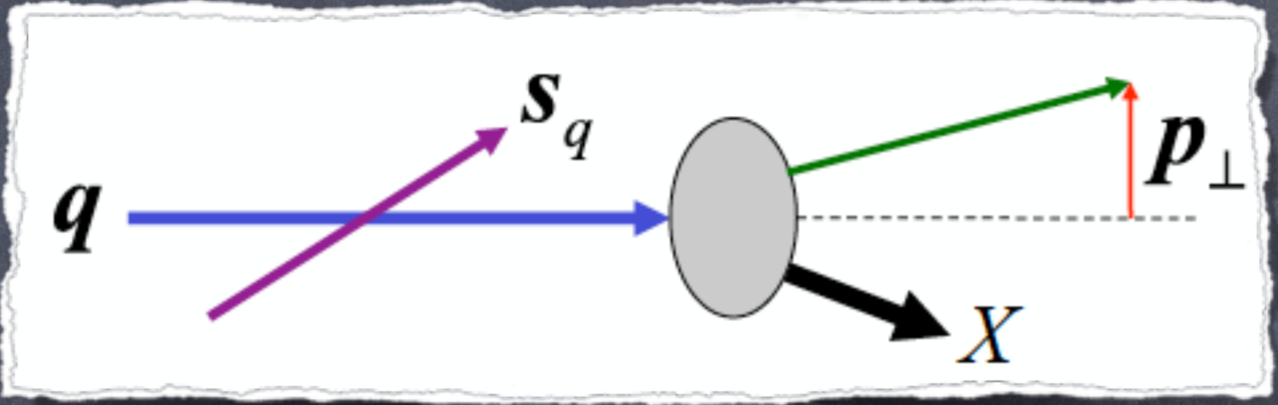
- It is related to the probability of finding an unpolarized parton inside a polarised proton



$$f_{q/p,\boldsymbol{S}}(x, \boldsymbol{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x, k_\perp)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

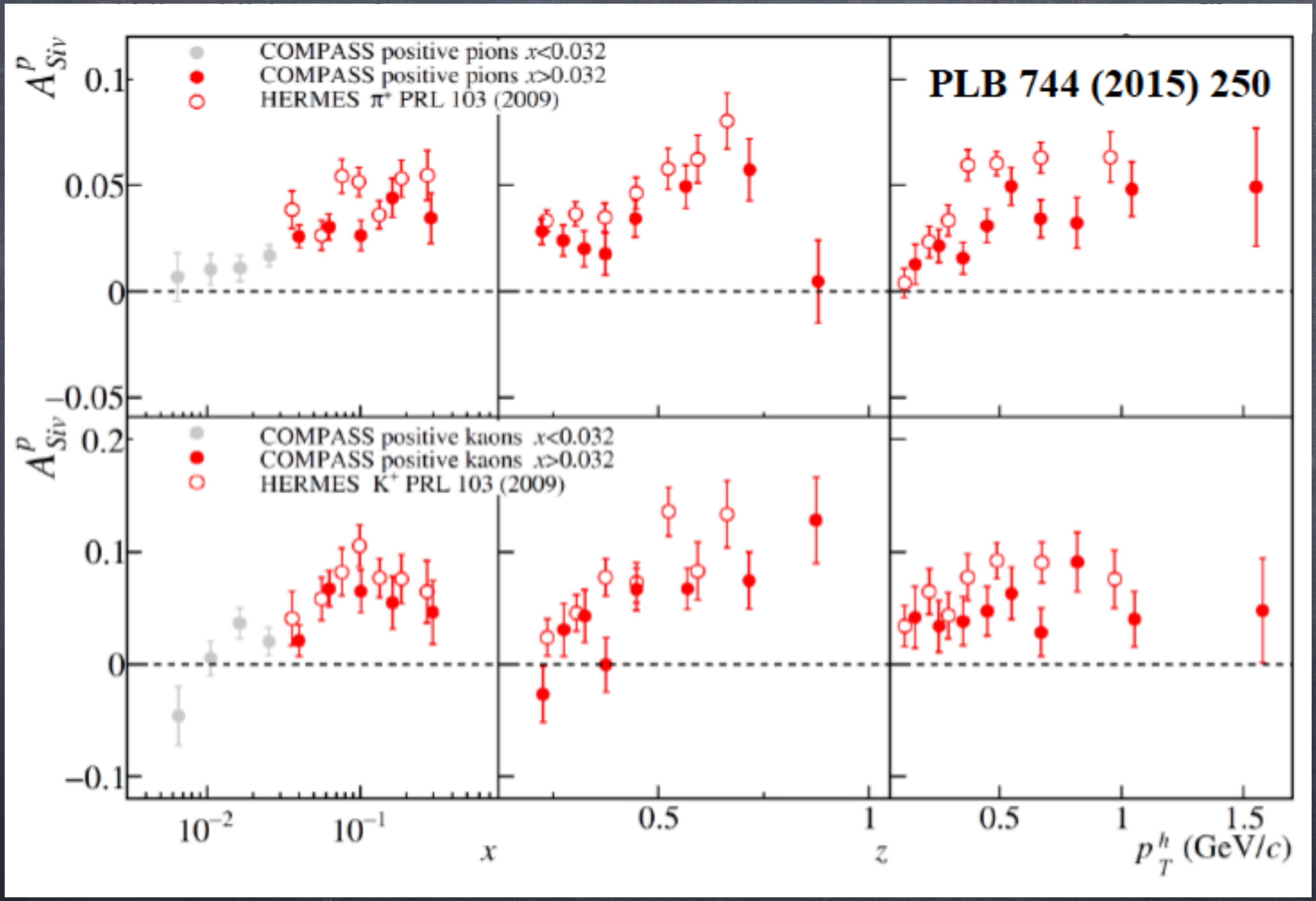
- Collins function: embeds correlations between parton spin and proton transverse momentum

$$\boldsymbol{s}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_\perp)$$

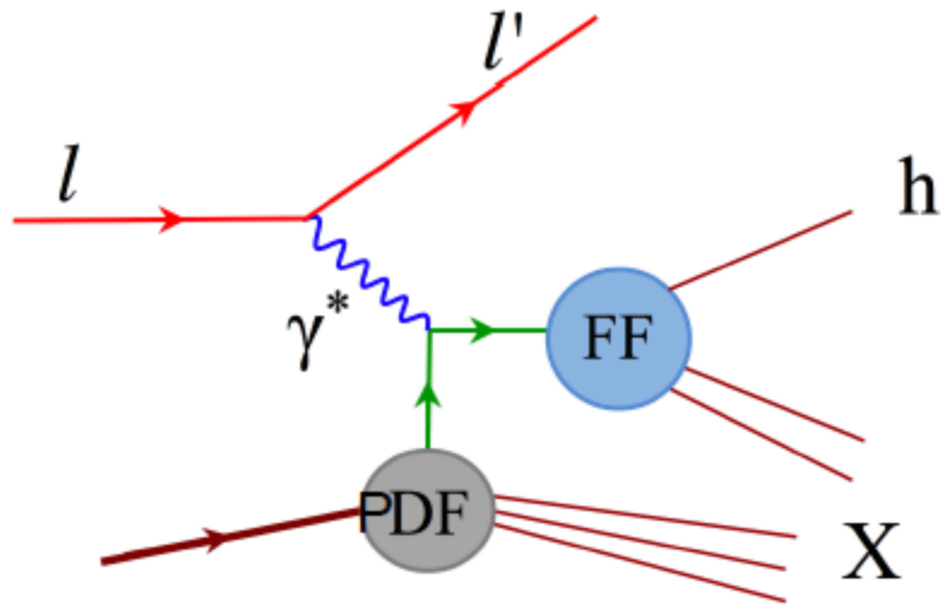


$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) \;=\; D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

Sivers Asymmetry in SIDIS process

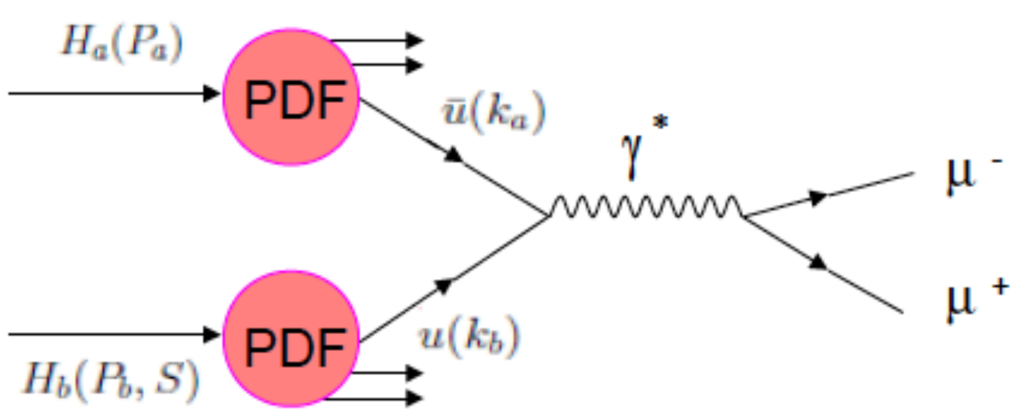


Sign change of the Sivers function



SIDIS
PDF ⊗ FF

Probe Universality



Drell-Yan
(DY)
PDF ⊗ PDF

Sign change of the Sivers function

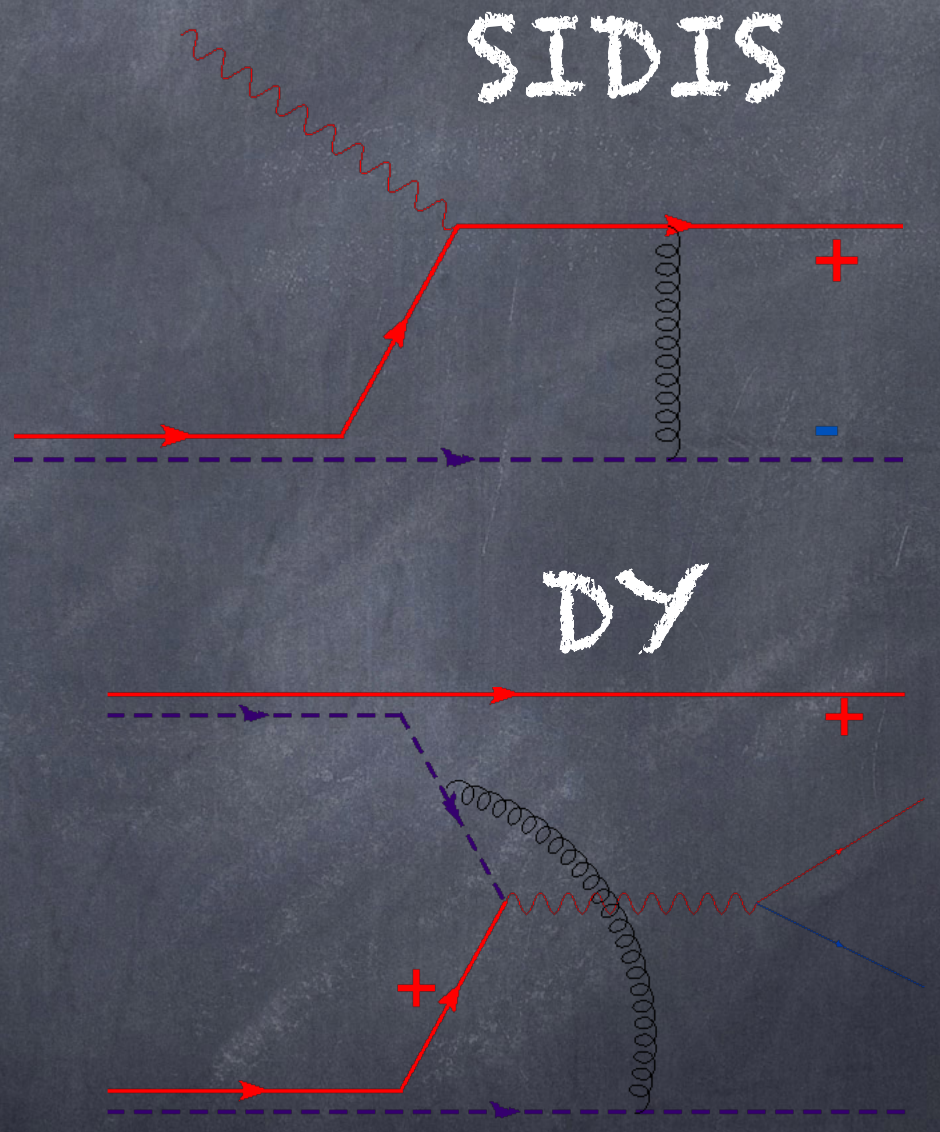
Colored objects are surrounded by gluons, profound consequence of gauge invariance:

Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)

Crucial test of TMD factorization and collinear twist-3 factorization

Several labs worldwide aim at measurement of Sivers effect in Drell-Yan

BNL, CERN, GSI, IHEP, JINR, FERMILAB etc



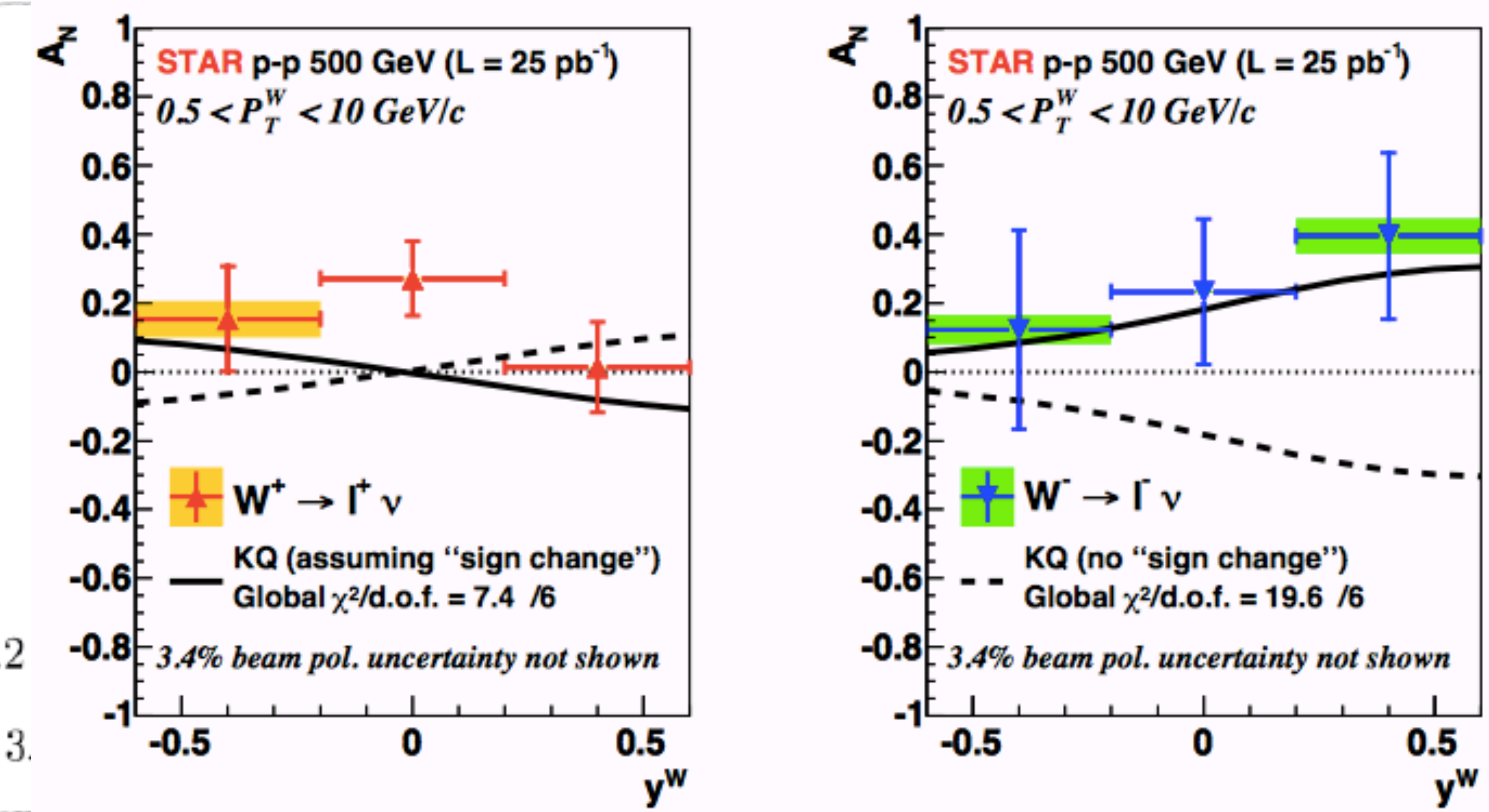
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

First experimental hint on the sign change

$p^{\uparrow}p \rightarrow W^{\pm}\ X$

STAR Collaboration,
PRL 116 (2016) 132301

- Sign change $\chi^2/d.o.f \sim 1.2$
- No sign change $\chi^2/d.o.f \sim 3.$

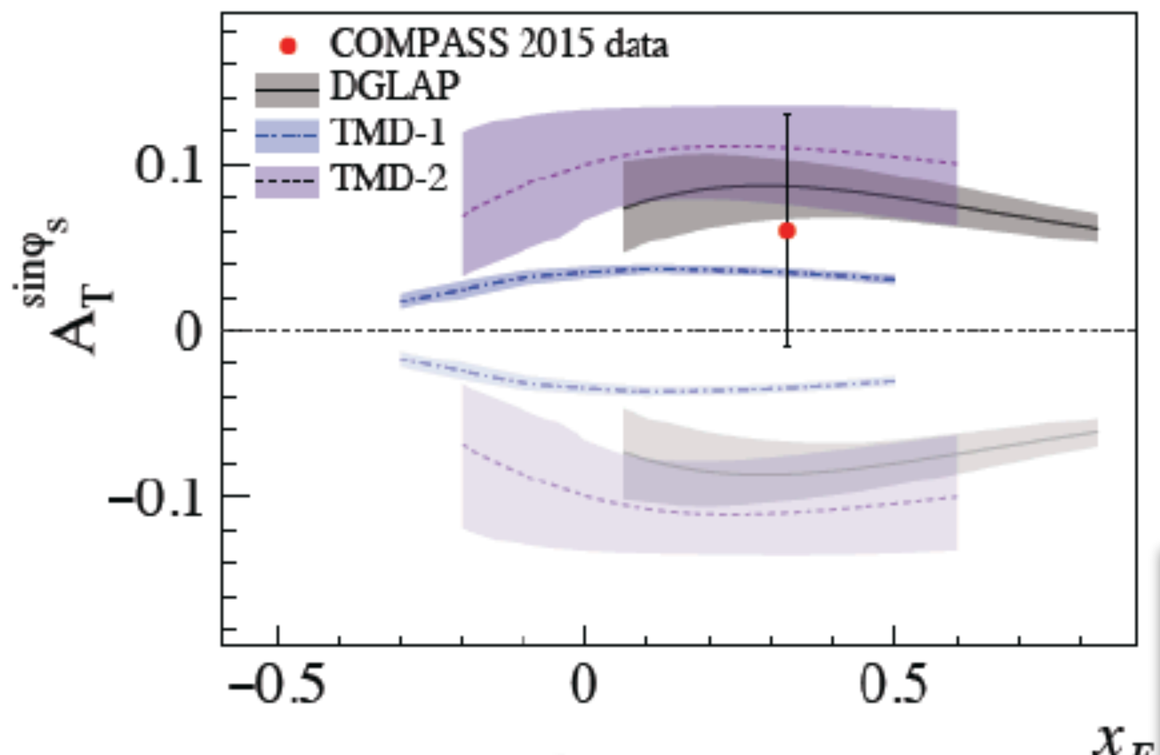


First experimental hint on the sign change

$\pi^- p^\uparrow \to \mu^+ \mu^- X$

2015 DY RUN - first polarized DY data

In the same kinematical region as that for SIDIS extraction



sign change

no sign change

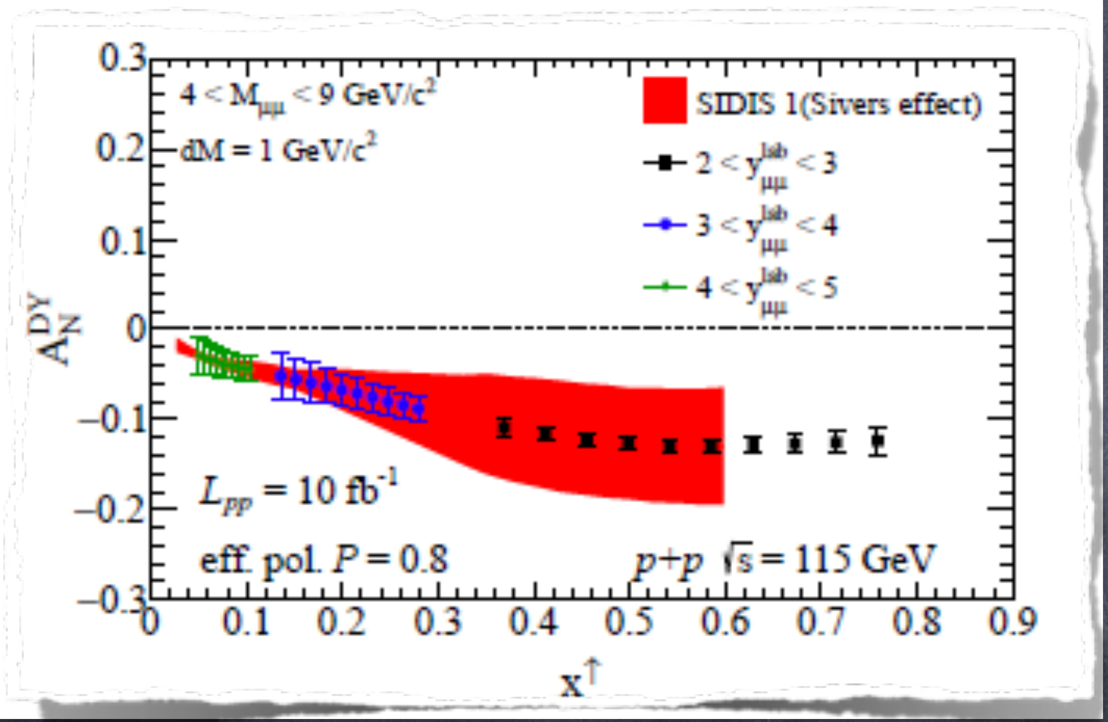
Analysis on going on 2018 data

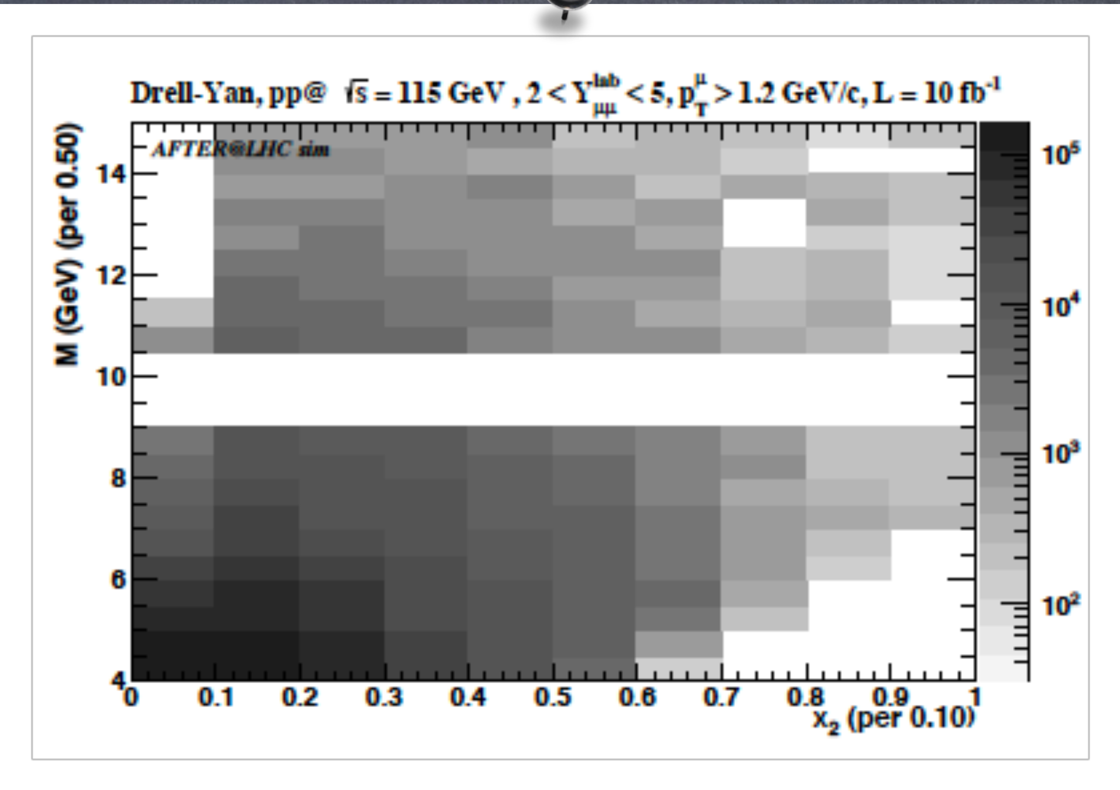
DGLAP (2016) M. Anselmino et al., arXiv:1612.06413
TMD-1 (2014) M. Echevarria et al., PRD 89 (2014) 074013,
TMD-2 (2013) P. Sun and F. Yuan, PRD 88 (2013) 114012

Sign change of the Sivers function

AFTER@LHC is a complementary facility to further investigate the quark Sivers effect by measuring DY STSAs
Capable of measuring the Drell-Yan A_N in a broad kinematic range with exceptional precision

LHCb - like detector





In addition, given that this asymmetry can be framed as well within the CT3 approach when the transverse momentum of the produced lepton pair is comparable to its mass, AFTER@LHC will also generate very useful data to constrain the ETQS 3-parton correlation functions

DY for TMDs

Future or planned Drell-Yan experiments: large variety of beam and target and kynematical ranges

Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^\uparrow$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^\uparrow$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^3\text{He}^\uparrow$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_\mu$	$p + p^\uparrow$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN) $\bar{p} + p^\uparrow$	$\pi^\pm + p^\uparrow$ $k^\pm + p^\uparrow$	190	19	$0.2 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^\uparrow + p^\uparrow$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^\uparrow$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^\uparrow + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^\uparrow + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^\uparrow + p^\uparrow$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^\uparrow$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

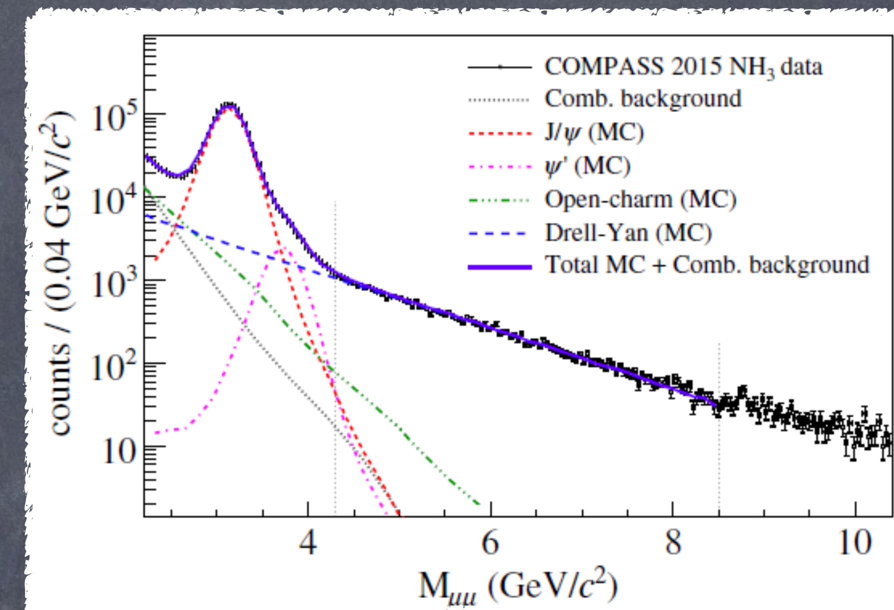
DY in the J/Psi range

Quarkonium as tool

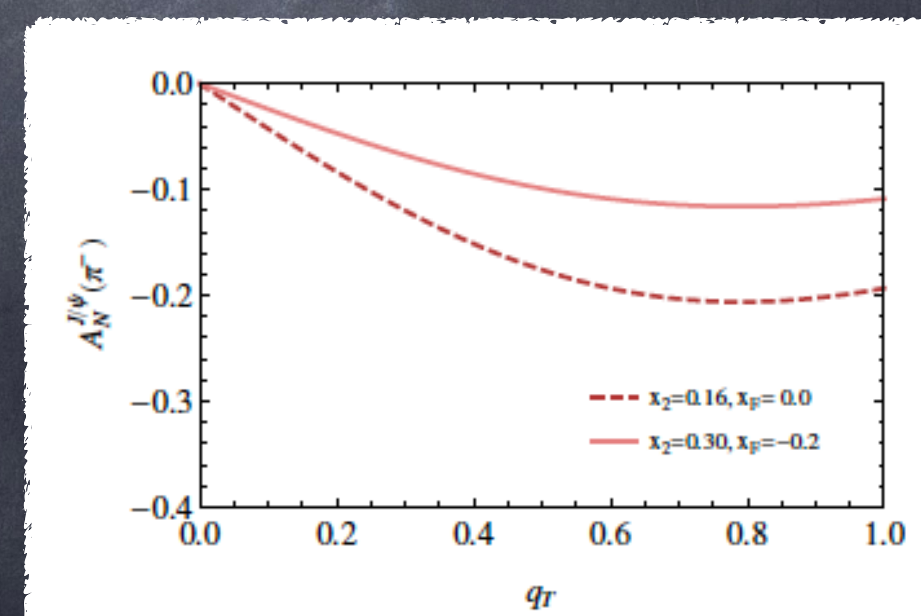
lepton pair production at COMPASS $\pi^- p^\uparrow \to l^+ l^- X$ at the J/Psi peak

$$x_1\, x_2 = M^2_{J/\Psi}/s \simeq 0.027$$

Due to the kinematical coverage, J/Psi production mainly due to valence q qbar annihilation rather than gluon-gluon fusion.



Asymmetry mainly generated by the Sivers distribution of unpolarized valence quarks inside the polarized proton: its sign reveals the sign of the corresponding Sivers function



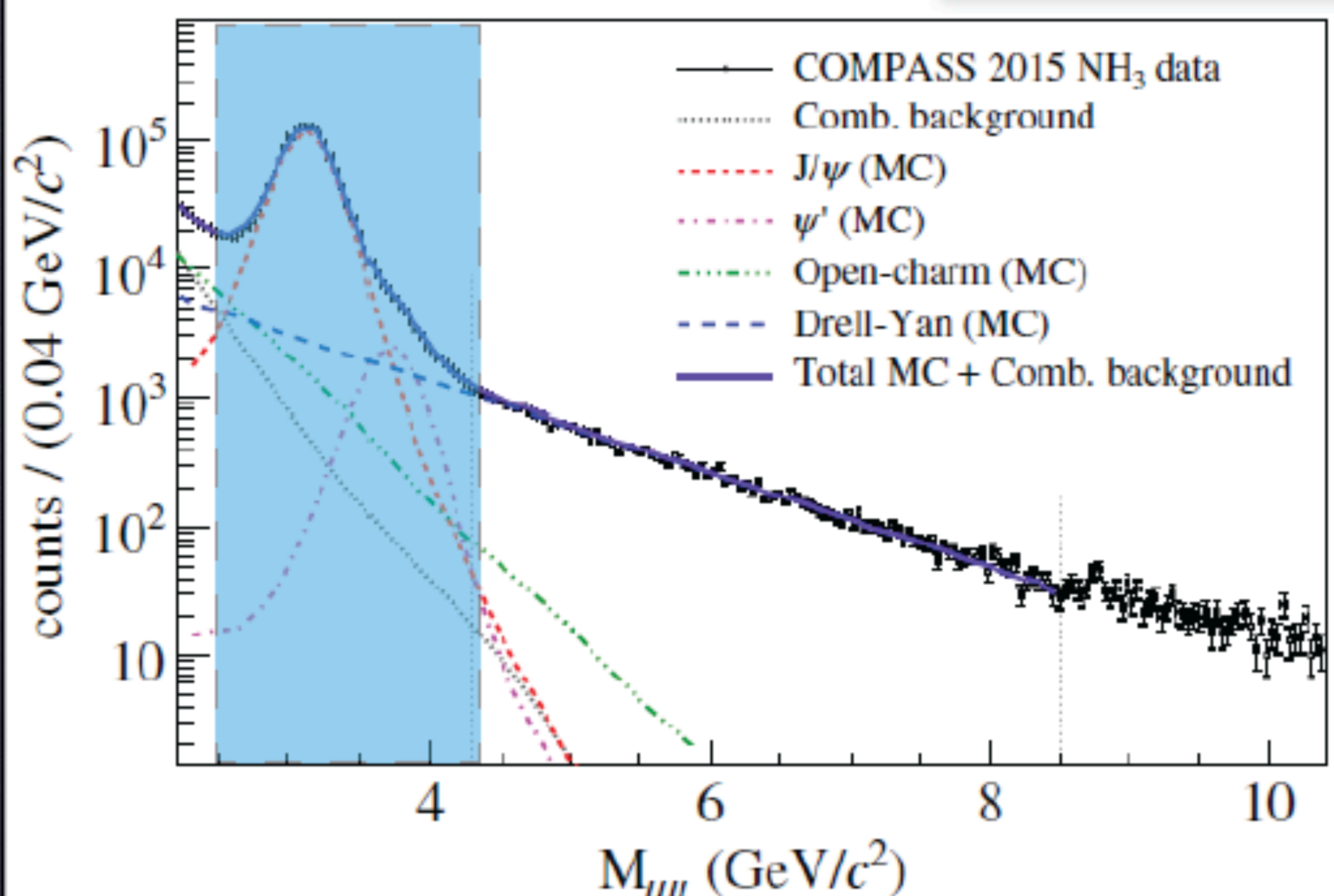
M. Anselmino, V. Barone, E. Boglione
arXiv:1607.00275v1

DY in the J/Psi range

Quarkonium as tool

@ COMPASS

Ongoing Analysis



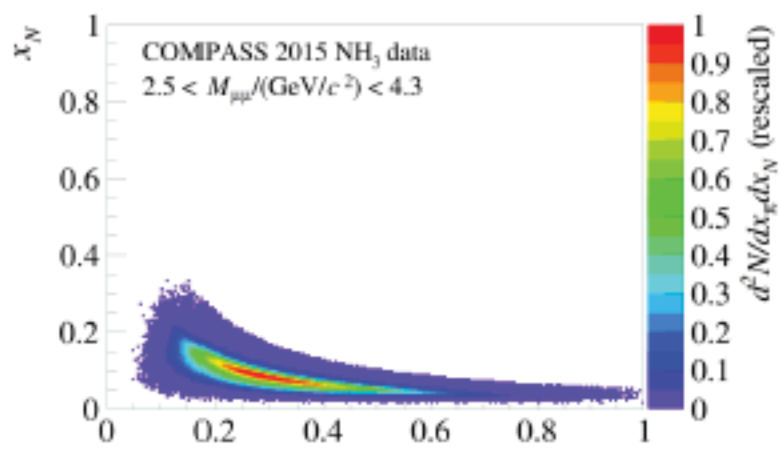
I. 1 < Mμμ/(GeV/c2) < 2, "Low mass"
- Large background contamination

II. 2 < Mμμ/(GeV/c2) < 2.5, "Intermediate mass"
- High DY cross section.
- Still low DY-signal/background ratio.

III. 2.5 < Mμμ/(GeV/c2) < 4.3, "Charmonia mass"
- Strong J/ψ signal --> Studies of J/ψ physics.
- Good signal/background.

IV. 4.3 < Mμμ/(GeV/c2) < 8.5, "High mass"
- Beyond J/ψ and ψ' peak, background < 4%.
- Valence quark region --> Largest asymmetries!
- Low DY cross-section

$<x_p> = 0.31$
$<x_N> = 0.009$
$<x_F> = 0.22$
$<q_T> = 1.1$



Probing the Gluon TMDs

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

Very significant progress in the last 15 years!

Many experiments involved:

HERMES, COMPASS, JLAB, RHIC, BELLE, BABAR, ...

First extractions from global analyses

Now entering into the precision era

nucleon	Gluon TMDs: Unpol	Circularly pol.	Linearly pol.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

- Theory framework consolidated
- ...experimental access extremely limited!
- even the unpolarised gluon TMD has not been extracted from experiments yet

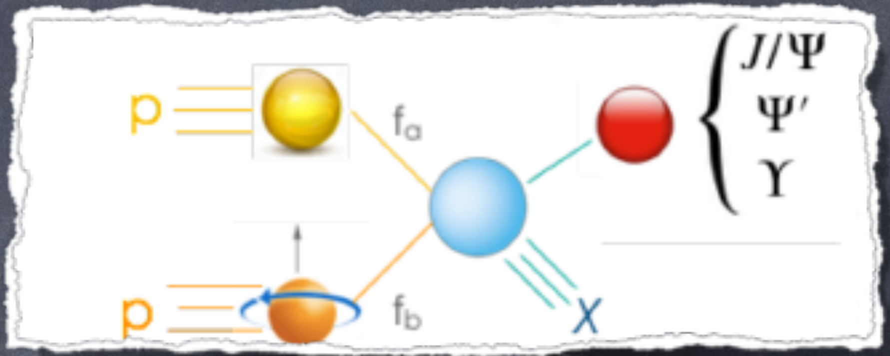
Probing the Gluon TMDs

Quarkonium as tool

Drell-Yan is the golden process to probe the quark transverse motion in the nucleon

Gluon-sensitive observables are needed

Quarkonium production is one of the best tools: gluon fusion is the dominant contribution in high energy hadron collisions



From the experimental point of view:

- Measuring quarkonia via leptonic decays became quite straightforward task
- Downside: quite small production cross-section -> requires high integrated luminosity

Probing the Gluon TMDs

Quarkonium as tool

extraction of polarized gluon PDFs through heavy-flavour observables

One main achievement would be accessing the gluon Sivers function through STSAs:

- first hints by RHIC and COMPASS, but still basically unknown!

- shed light on spin-orbit correlations of gluons inside the proton

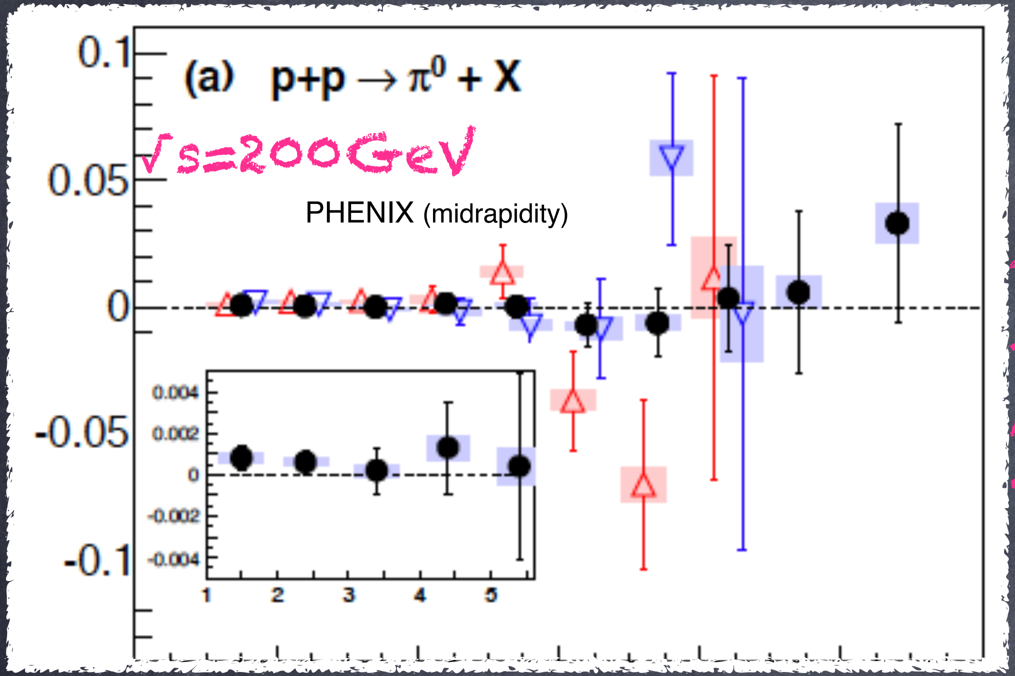
- sensitive to gluon orbital angular momentum!

		Gluon TMDs		
		Unpol	Circularly pol.	Linearly pol.
nucleon	U	f_1^g		$h_1^{\perp g}$
	L		g_1^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

Probing the gluon Sivers TMD (from RHIC data)

A_N measured vs P_T at mid-rapidity: $|\eta| < 0.35$

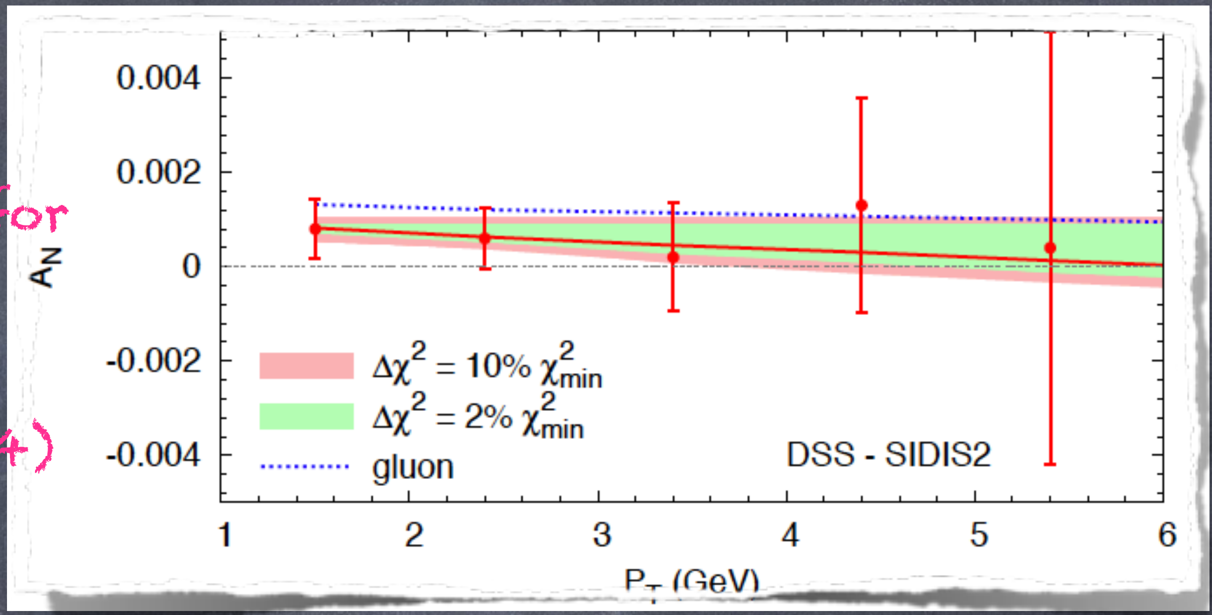
Phys. Rev. D 90, 012006 (2014)



fit to PHENIX A_N for π^0

A.Adare et al. PRD90012006(2014)

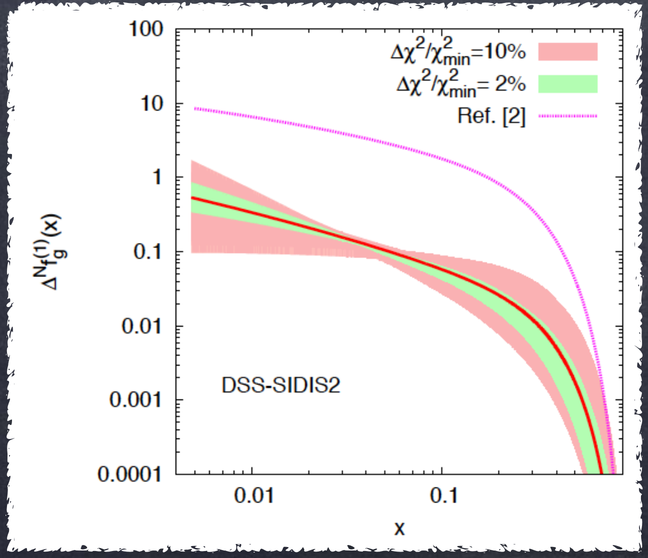
D'Alesio et al., JHEP 1509 (2015) 119



A_N estimate in the frame of GPM, based on param. from SIDIS data + FFs from DSS

First k_T-moment of the gluon Sivers function

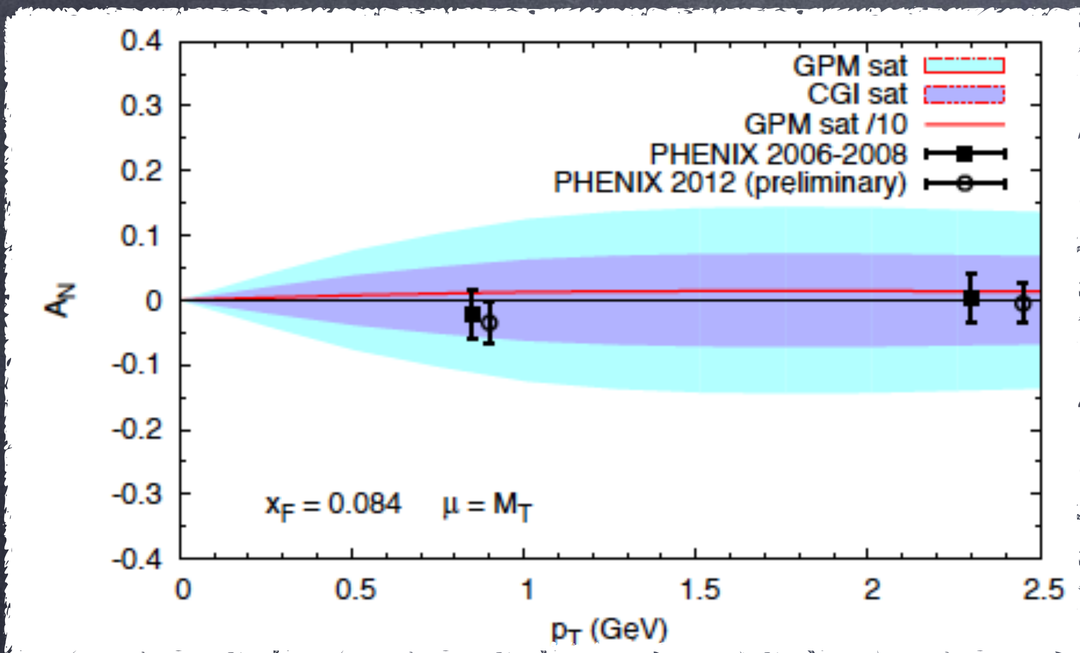
U. D'Alesio, F. Murgia, C. Pisano JHEP 1509(2015)119



Gluon Sivers TMD

Quarkonium as tool

Existing quarkonia results from PHENIX and COMPASS



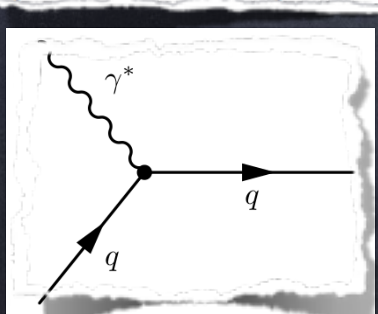
Measurement of A_N for $pp^{\uparrow} \to J/\psi X$ @Phenix

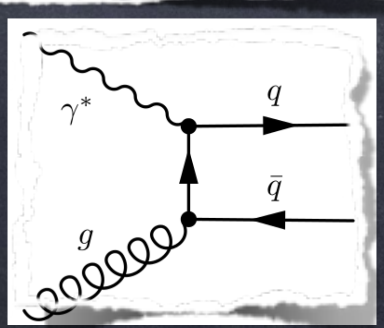
Prediction of A_N from 2 models:

- Generalized Parton Model (GPM)
- Color-Gauge Invariant GPM (CGI-GPM): takes into account the process dependence of the Sivers funct, including the effects of ISI and FSI

J/ψ lepto-production @COMPASS

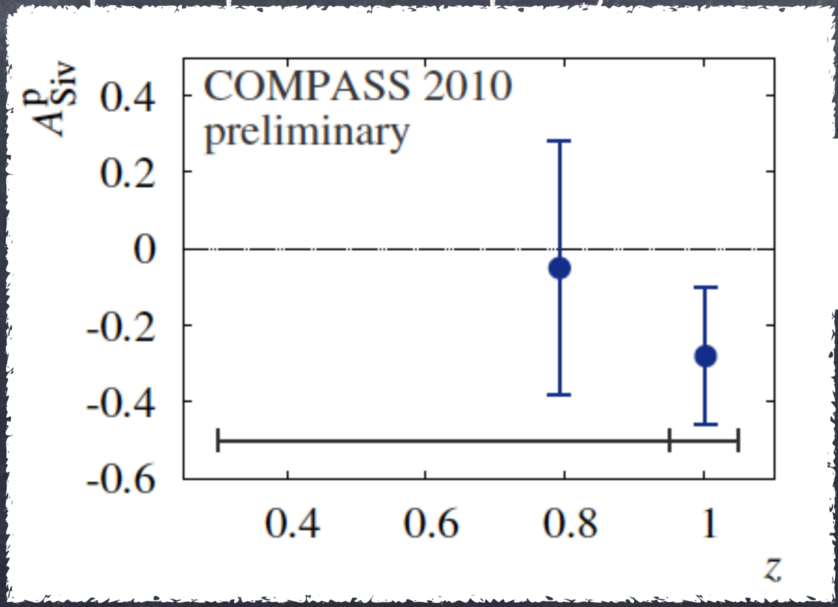
$$\mu^+ + p^{\uparrow} \to \mu^+ + J/\psi + X \to 2\mu^+ + \mu^- + X$$





LP dominates (q Sivers), how to tag the PGF?
Heavy flavors (@COMPASS only charm)

COMPASS, JoP Conf. Series,
http://iopscience.iop.org/1742-6596/678/1/012050



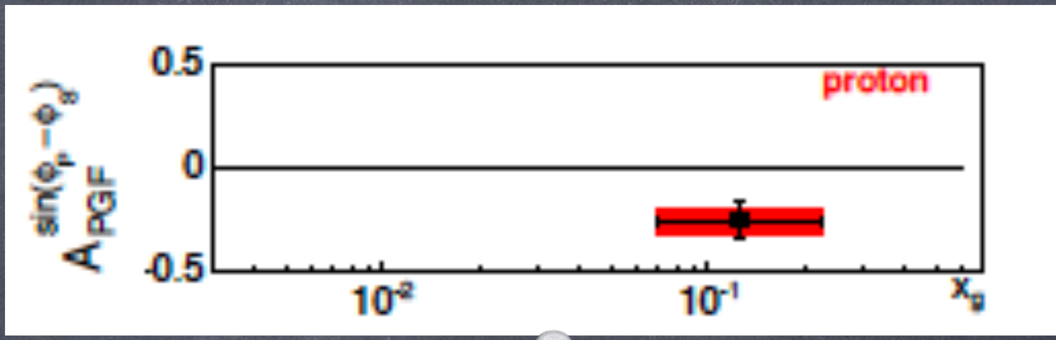
$A^{\mathrm{p}}_{\mathrm{Siv}} = -0.05 \pm 0.33$ (inclusive J/ψ)
$A^{\mathrm{p}}_{\mathrm{Siv}} = -0.28 \pm 0.18$ (exclusive J/ψ)

Gluon Sivers TMD

Quarkonium as tool

@COMPASS

Phys.Lett. B772 (2017) 854-864



$$A_{PGF}^{Siv} = -0.23 \pm 0.08(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

The gluon Sivers asymmetry also extracted from lepton nucleon DIS, in which at least two high-pT hadrons are detected

away from zero by more than two standard deviations of the quadratically combined uncertainty

Not compatible with Phenix results

The two results are obtained for different centre of mass energy and xg values.

Moreover the existence of colour gauge links complicates the picture, as they lead to two different universal gluon Sivers functions

Gluon Sivers TMD

Quarkonium as tool

Gluon Sivers TMD can be measured in p↑p and p↑A collisions (RHIC, AFTER@LHC), in processes for which TMD factorization holds or may hold (CS dominance)

$$p^\uparrow p \to \gamma\, \mathrm{jet}\, X$$

$$p^\uparrow p \to \gamma\, \gamma\, X$$

Schmidt, Soffer, Yang, 2005
Bacchetta, Bomhof, D'Alesio, Mulders, Murgia, 2007
Qiu, Schlegel, Vogelsang, 2011

$$p^\uparrow p \to J/\psi\, \gamma\, X$$

$$p^\uparrow p \to J/\psi\, J/\psi\, X$$

Dunnen, Lansberg, Pisano, Schlegel, 2014
Lansberg *et al.*, 2014; Lansberg, Shao, 2015

How does this relate to the gluon Sivers TMD from open charm and bottom quark electro-production at an EIC?

$$e\, p^\uparrow \to e'\, Q\bar{Q}\, X$$

Probing gluon TMDs

Quarkonium as tool

nucleon	Gluon TMDs: Unpol	Circularly pol.	Linearly pol.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^{g}, $h_{1T}^{\perp g}$

$ep \to e' Q\overline{Q}X$, $ep \to e'$ jet jet X probe gluon TMDs with $[++]$ gauge links

$pp \to \gamma\gamma X$ (and/or other CS final state) probes gluon TMDs with $[--]$ gauge links

$pp \to \gamma$ jet X probes an entirely independent gluon TMD: $[+-]$ links (dipole)

The gluon Sivers function is of opposite sign in

$$e\,p^{\uparrow} \to e'\,Q\bar{Q}\,X \qquad \text{versus} \qquad p^{\uparrow}\,p \to \underbrace{\gamma\,\gamma}\,X$$

Is this TMD nonuniversality a polarization issue only? No!
This process dependence is also present for the unpolarized gluon TMD, as was first realized in a small-x context
Dominguez, Marquet, Xiao, Yuan, 2011

Motivation to study gluon Sivers effects at RHIC and LHC and the EIC

AFTER@LHC

Quarkonium as tool

Different processes probe different gluon Sivers functions

All of them can be expressed in terms of two independent functions with will appear in different combination depending on the process

AFTER@LHC can disentangle them and test this generalised universality

Measurement of STSAs for η_c, χ_b, χ_c

Measurement of STSAs for J/ψ, ψ', Υ

Measurement of STSAs for associated production-channels (di-J/ψ, J/ψ-γ, Υ-γ) -> k_T evolution of the gluon Sivers function

AFTER@LHC

7 TeV proton beam on a fixed target proton:

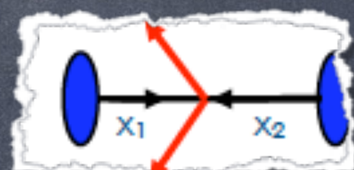
$\sqrt{s} \approx 115\ GeV$ (between SPS and RHIC)

Boost effect → access to large x_2 physics ($-1<x_F<0$)

Quarkonium as tool

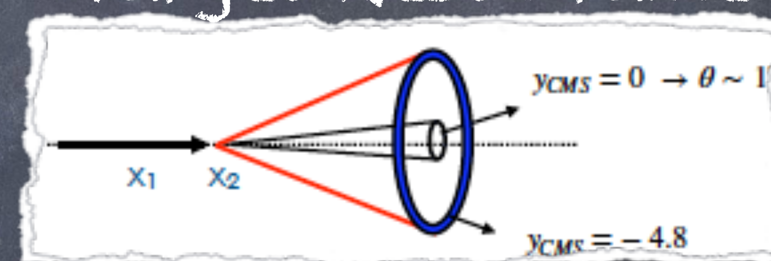
CM backward rapidity region ($-4.8 < y_{CM} < 0$)

CMS

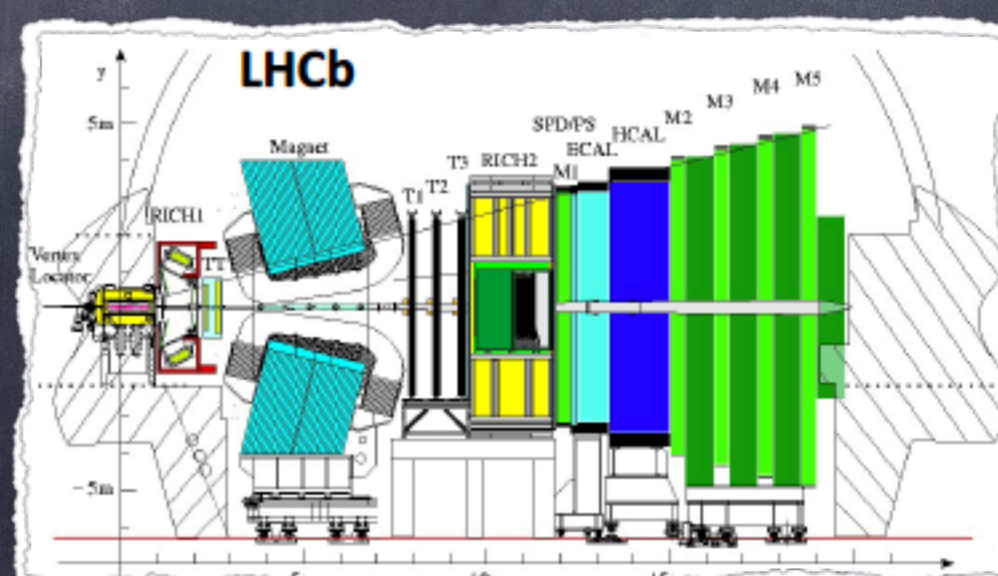


→

Target Rest Frame



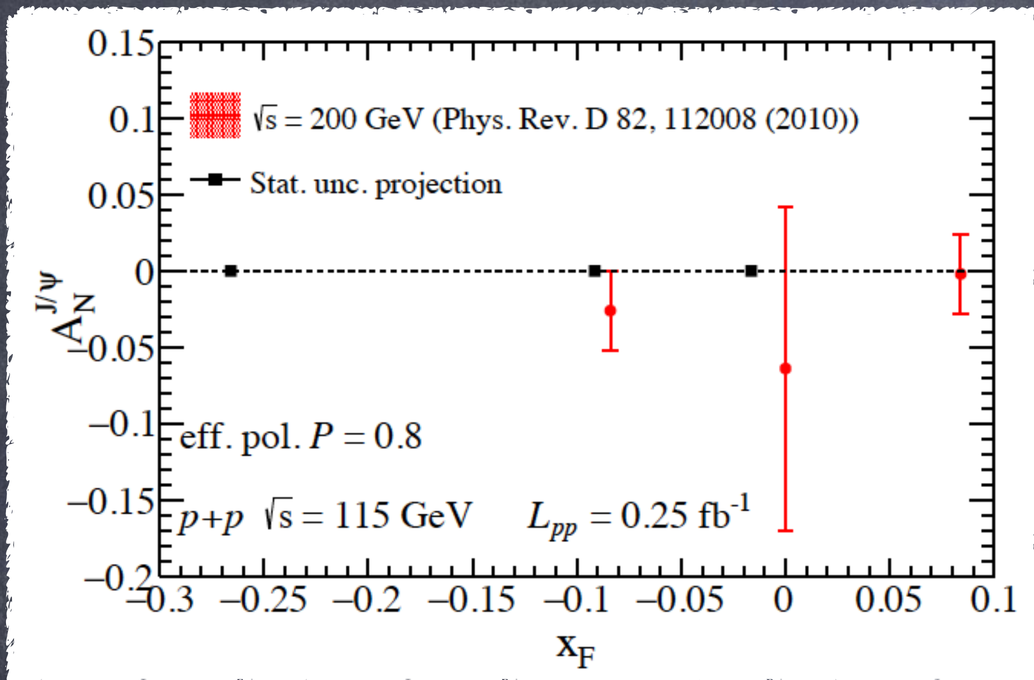
Experimentally accessible with an LHCb-like detector

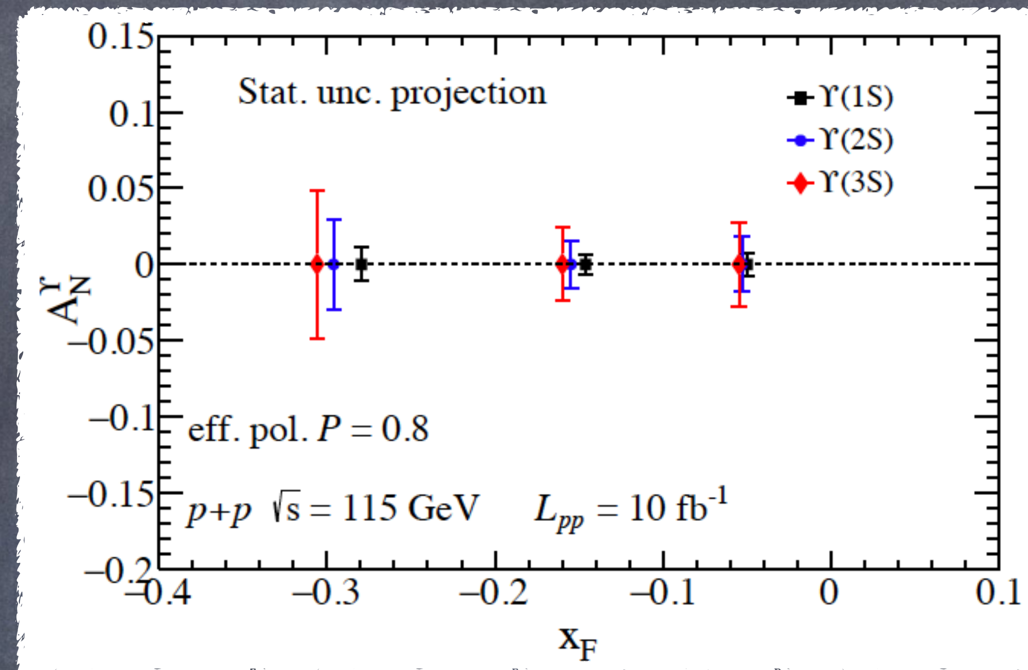


AFTER@LHC

Quarkonium as tool

AFTER@LHC arXiv:1702.01546v1)





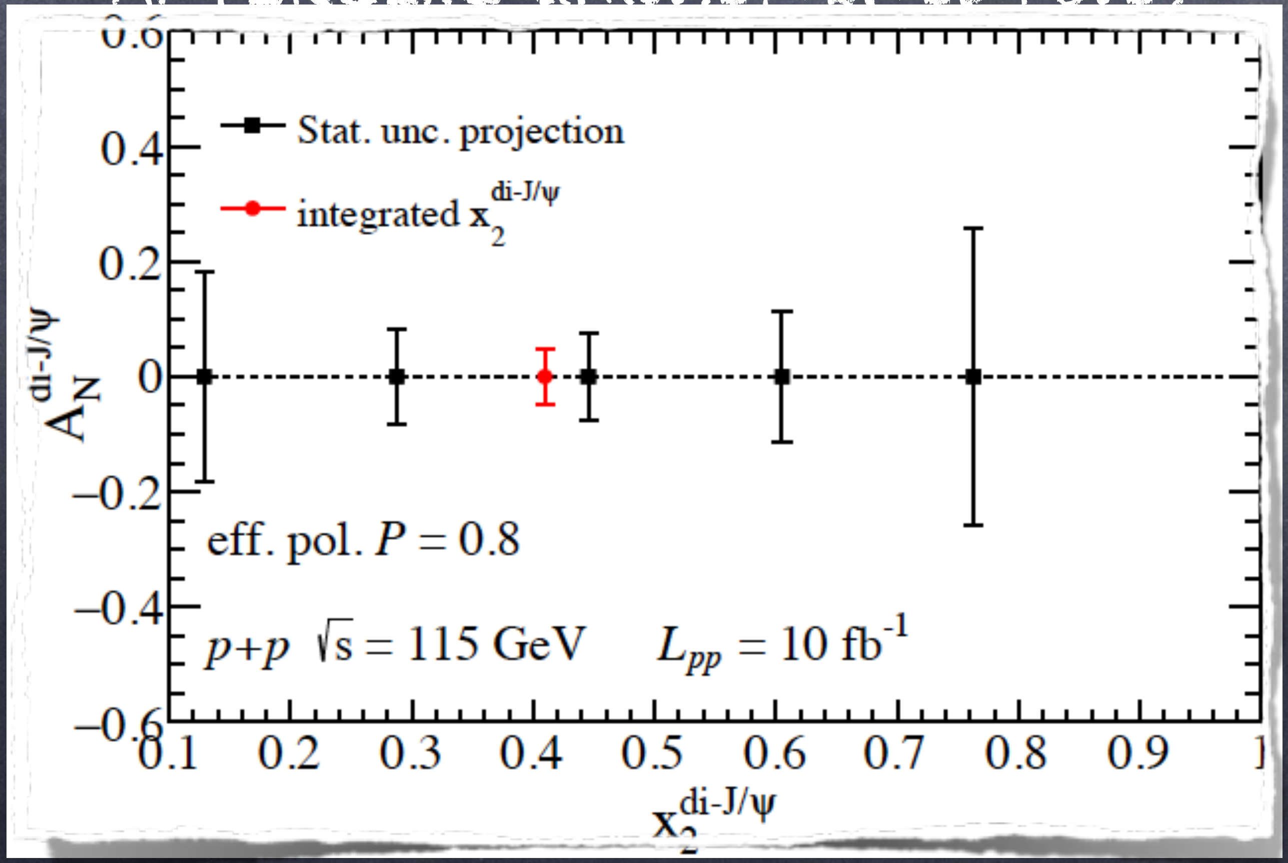
- Very low statistical uncertainties: due to an ideal acceptance with conventional detectors and the large production rates for quarkonium states expected for a single year of data taking
- A_N^{Υ} (nS) is a unique observable, which is virtually inaccessible elsewhere and which can be measured with a few per cent accuracy with AFTER@LHC.
- This level of data quality will allow to study the size of the asymmetry, its shape and the x_F dependence of quarkonium

AFTER@LHC

Quarkonium as tool

- Associated-production channels (e.g. J/ψ - J/ψ, J/ψ-γ, Υ-γ) can shed light on the p_T dependence of the gluon Sivers function

AFTER@LHC arXiv:1702.01546v1)



Summary

What is the nature of the spin of the proton?

How can we describe the multidimensional landscape of nucleons and nuclei?

Very significant progresses have been made in the last 15 years

Growing global interest worlwide, with several ongoing and upcoming experiments at existing or future hadron facilities:

COMPASS++
RHIC
AFTER@LHC
EIC

opportunities to study the polarized quark and gluon spin structure of the proton and QCD dynamics at a high energy scale

Quarkonia production has being playing an important role

A few more topics: hints for discussion

J/Ψ production in p↑Au UPC @ RICH:
-> world wide only access to GPD E for gluons

Do we care about the pion structure?
-> The gluon distribution in the pion can be accessed via direct photons and J/Ψ production @COMPASS++

Precision measurement of Δg(x)
-> extend to smaller x regime @EIC

J/Ψ production in p↑Au UPC @ RICH

Quarkonium as tool

-> world wide only access to GPD E for gluons

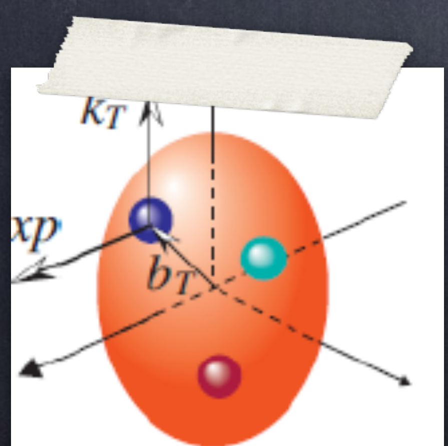
A nonzero asymmetry would be the first signature of a nonzero GPD E for gluons

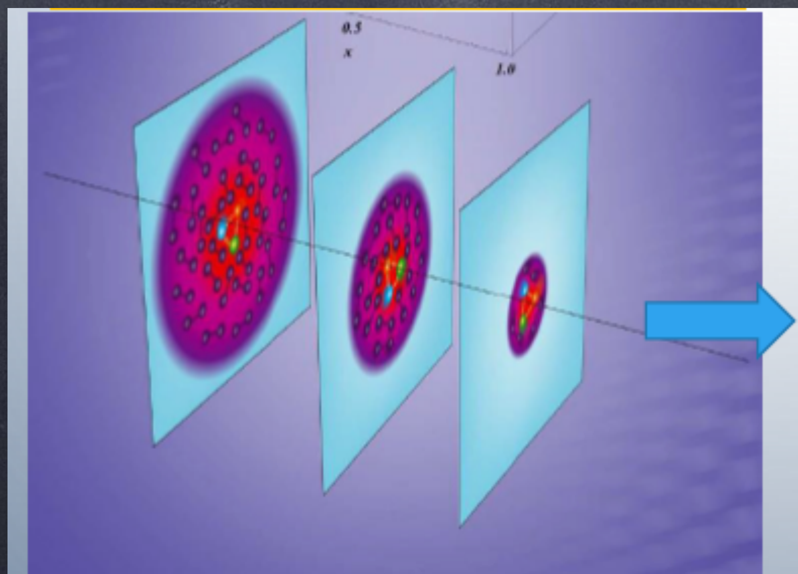
sensitive to spin-orbit correlations and intimately connected with the orbital angular momentum carried by partons in the nucleon

Spin-Sum-Rule in PRF:

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$





GPDs: PDFs that correlated parton momentum and their distributions in transverse space

Pion gluon distribution @COMPASS++/Amber

Quarkonium as tool

Pion gluon distribution: g^{π}

The gluon distribution in the pion can be accessed from:

direct photons

- From gluon Compton scattering:
  $gq(\bar{q}) \to \gamma q(\bar{q})$
- From quark-antiquark annihilation:
  $q\bar{q} \to \gamma g$

First mechanism dominates.

Important background of minimum bias photons from π^o and η decays.

$\hookrightarrow$ Past measurements from WA70 and NA24.

J/ψ

Mechanism of charmonia production not well understood, models differ:

- NRQCD (color octet+singlet):
  gg fusion dominance.
- Color Evaporation Model:
  $q\bar{q}$ annihilation dominance.

charmonia and their polarization may shed light into production mechanisms, eventually allow separation and access the gluon distribution.

Precision measurement of Δg(x)