3D Structure of the Nucleon: TMDs

Session Conveners:

A. Bacchetta, J. Drachenberg, B. Parsamyan

OUTLINE

- Transversity
- Sivers
- Unpolarized TMDs
- Summary

Vital Stats

31 Talks

- SIDIS experiments (5)
- pp/pA experiments (9)
- Theory (9)
- Phenomenology (8)

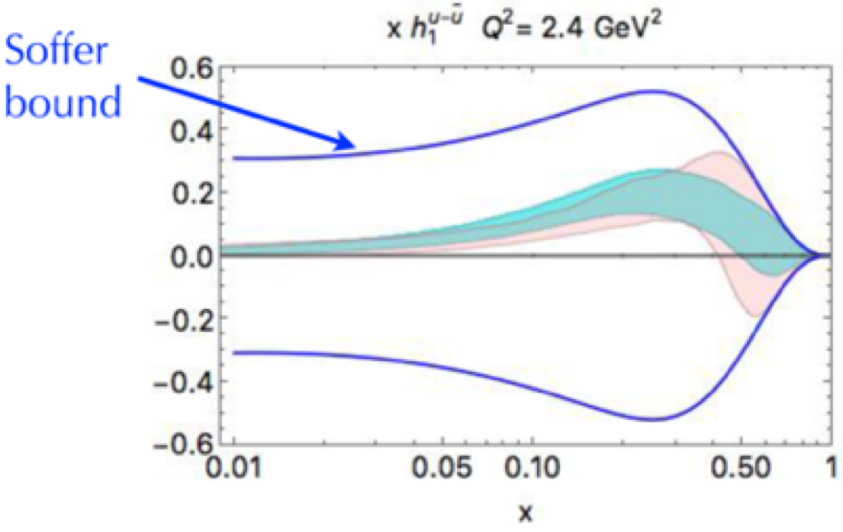
Transversity

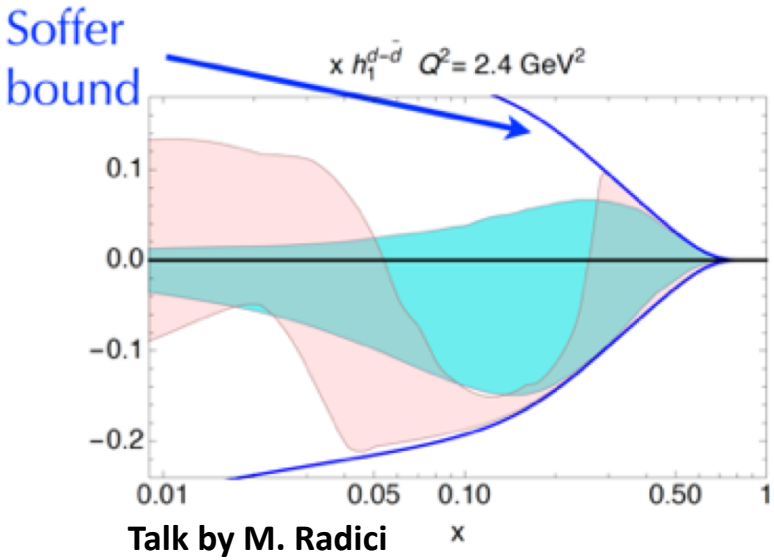
QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

Transversity Extraction

Radici & Bacchetta (Based on PRL 120 (2018) 192001, arXiv:1802.05212 + updates)





Talk by M. Radici

First transversity extraction including p+p data

- Di-hadron data (collinear factorization)
- STAR pp data increase precision of u-quark
- Resolve some tension in d-quark
- Input on ***unpolarized*** gluon FF critical!
- Future COMPASS deuteron target run (2021) promises increased precision, in particular for d-quark

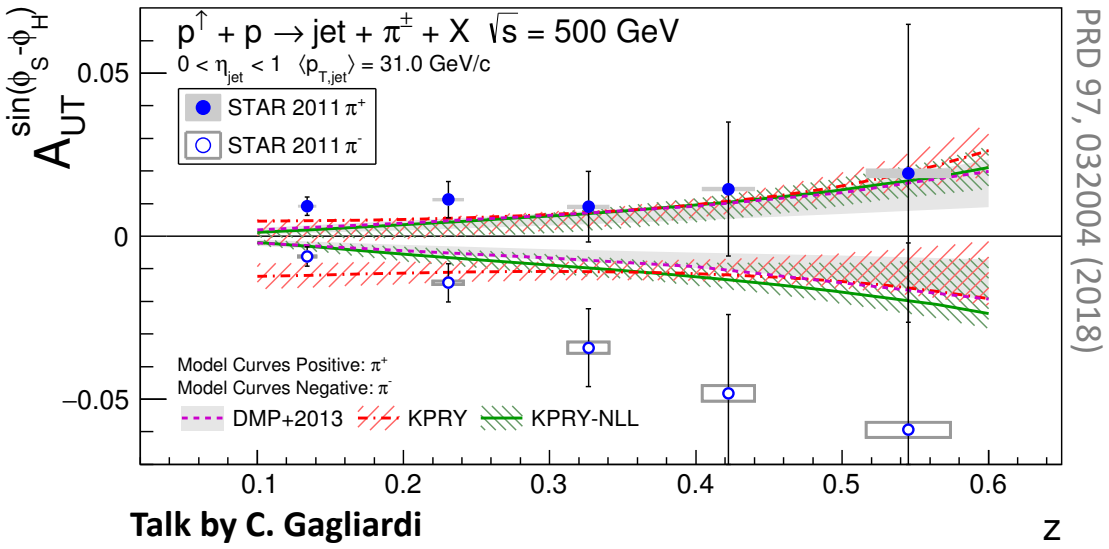
*Radici & Bacchetta, P.R.L. **120** (18) 192001*

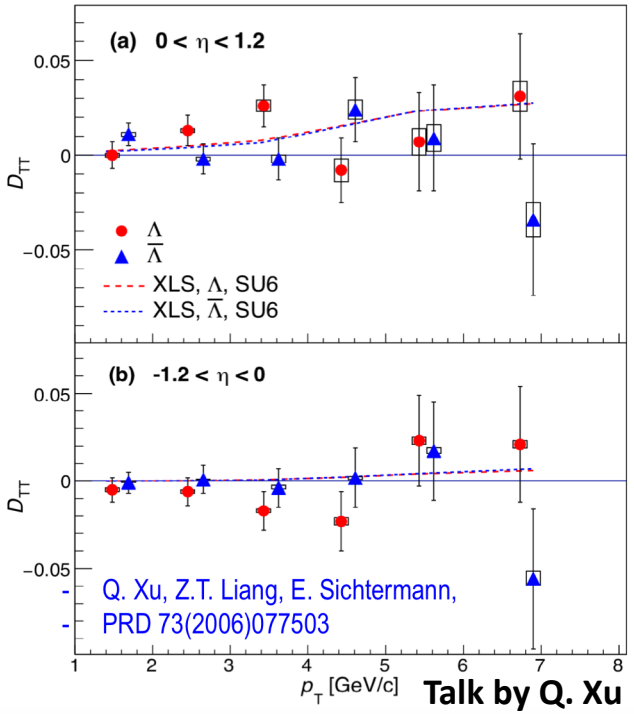
global fit

old fit

*Radici et al., JHEP **1505** (15) 123*

Transversity Results in p+p





-STAR, arXiv: 1808.0800

First observation of Collins Effect in p+p!

- Reasonably described by SIDIS-based models
- Effects of TMD evolution appear to be small

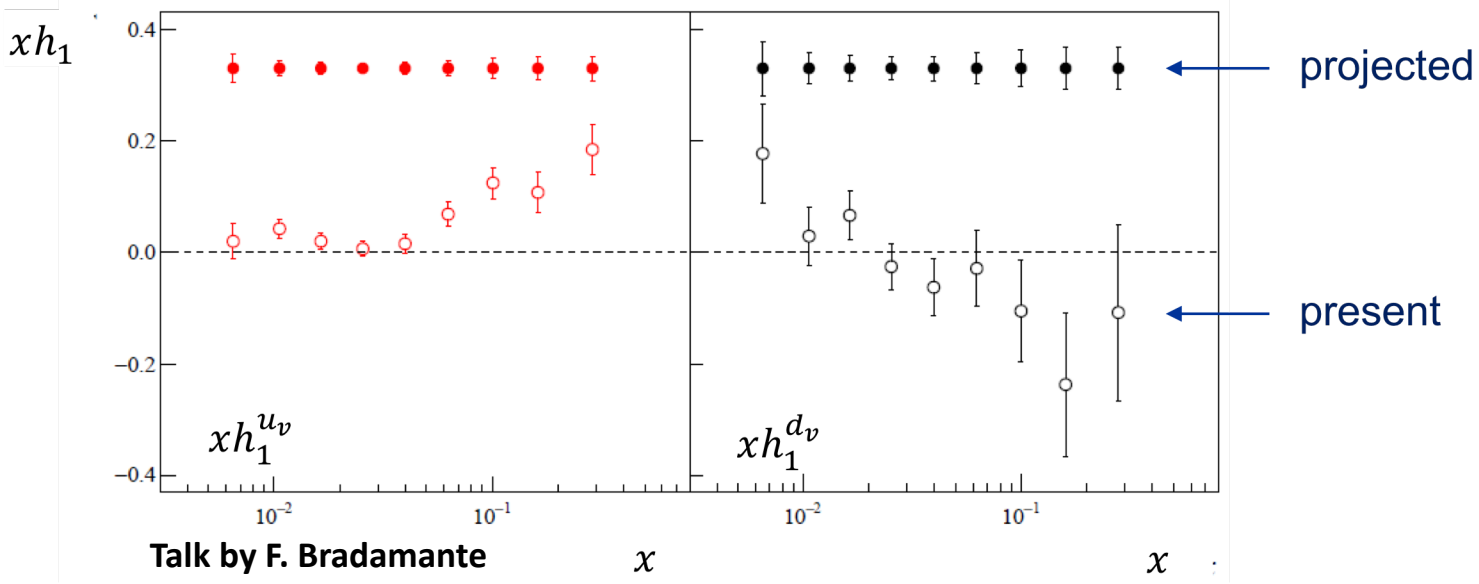
First Hyperon D_{TT} Result from STAR!

- Sensitive through transversely polarized FF
- Small but consistent with models at current precision

Recent (large!) STAR datasets currently under analysis

Proposed forward upgrade: new, innovative probes

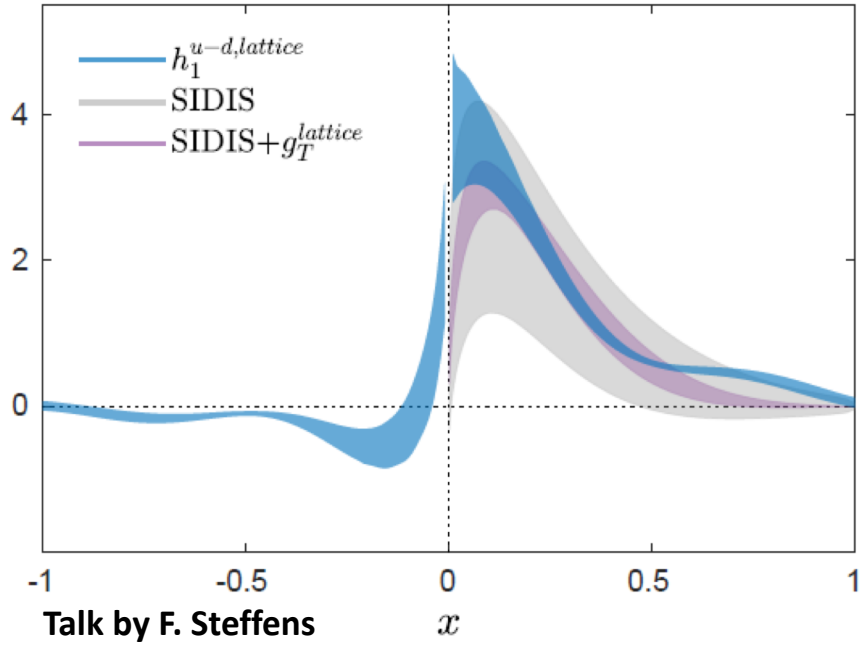
Impact of Future COMPASS Run on Transversity



COMPASS 2021 deuteron run approved

- Measure deuteron Collins asymmetry with stat. errors smaller than those for proton $\sigma_d \sim 0.62\sigma_p$ (~ 0.007 in last x bin)
- Allows much more precise extractions of transversity and Sivers PDFs
- $u_v[d_v]$transversity: reduction of stat. uncertainties by up to a factor 2 [4]
- Multi-D analysis, weighted asymmetries etc.

Transversity and Tensor Charge Calculations



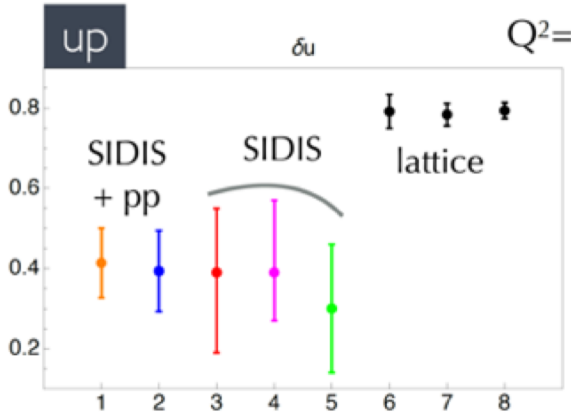
Talk by F. Steffens

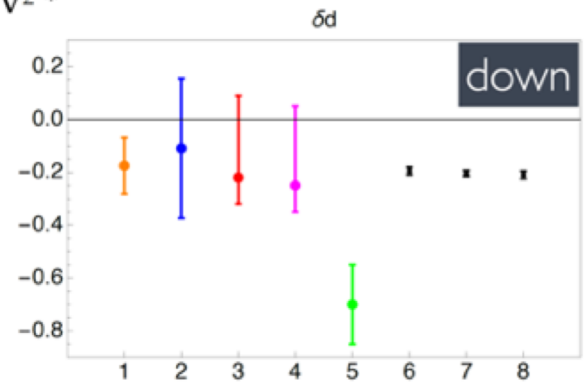
Improved calculation of transversity

- Based on quasi-PDF approach
- Allows one to obtain full x dependence, not just the moments (e.g., tensor charge)

Tensor charge calculation

- COMPASS pseudodata indicates increased precision, e.g. for d quark
- Tension between lattice & phenomenology

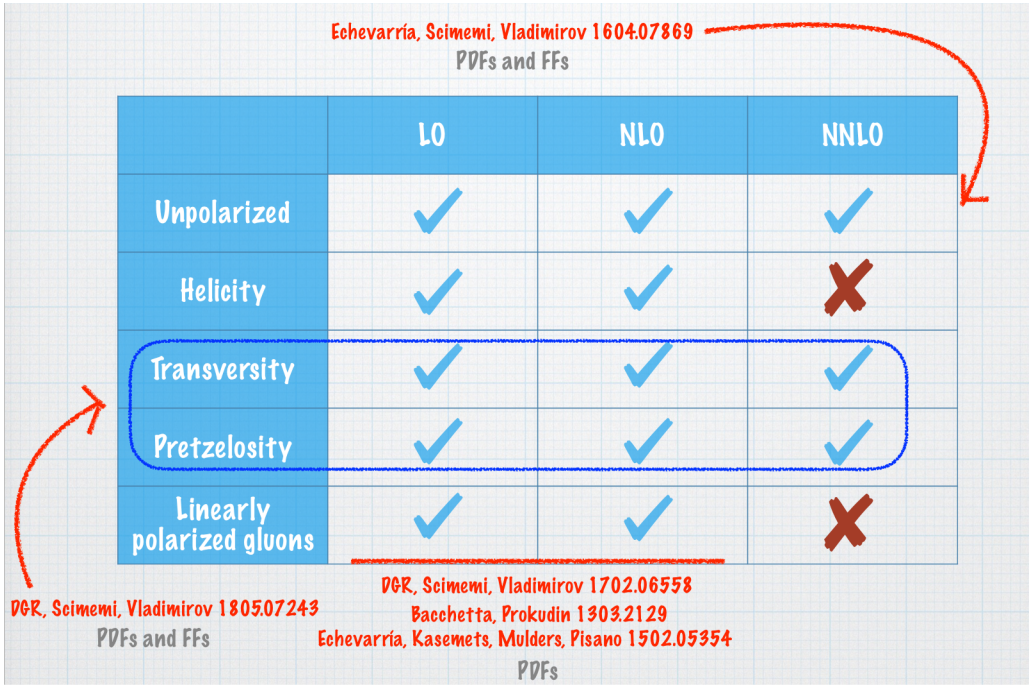




Talk by M. Radici

1- global fit + pseudodata
2- global fit Radici & Bacchetta, P.R.L. 120 (18) 192001
3- TMD fit Kang et al., P.R. D93 (16) 014009 * Q^2=10
4- Torino Anselmino et al., P.R. D87 (13) 094019 * Q^2=1
5- JAM fit Lin et al., P.R.L. 120 (18) 152502 * Q_0^2=2
6- PNDME16 Bhattacharya et al., P.R. D94 (16) 054508
7- PNDME18 Gupta et al., arXiv:1808.07597
8- ETMC17 Alexandrou et al., P.R. D95 (17) 114514; E. P.R. D96 (17) 099906

Theoretical Advancements in Transversity



Talk by D. Gutierrez Reyes

New TMD Matching Coefficients!

- Necessary perturbative ingredients for proper definition of TMDs
- Calculated up to NNLO for transversity and pretzelosity
- **Pretzelosity coefficients are always ZERO!** *Are they zero at all orders?*
  - → Would suggest pretzelosity is purely ***nonperturbative*** effect

Sivers Distribution

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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GLUONS	*unpolarized*	*circular*	*linear*
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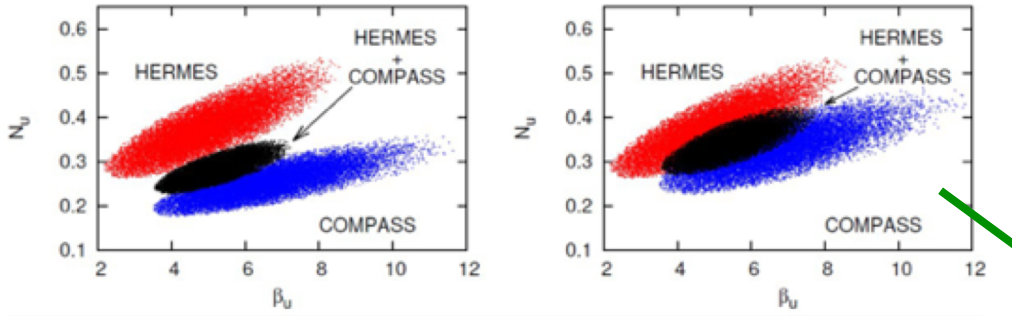
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

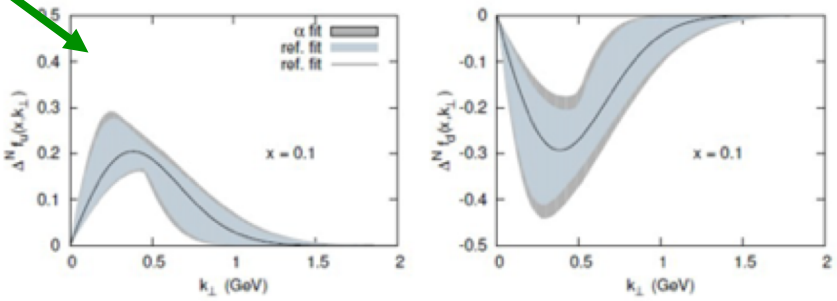
Improved Understanding of Sivers Function

Different assumptions about the unpolarized functions have dramatic effects on other extractions



Studies on asymmetries strongly depend on our Knowledge of the unpolarized TMDs.

Talk by J. Osvaldo Gonzalez-Hernandez

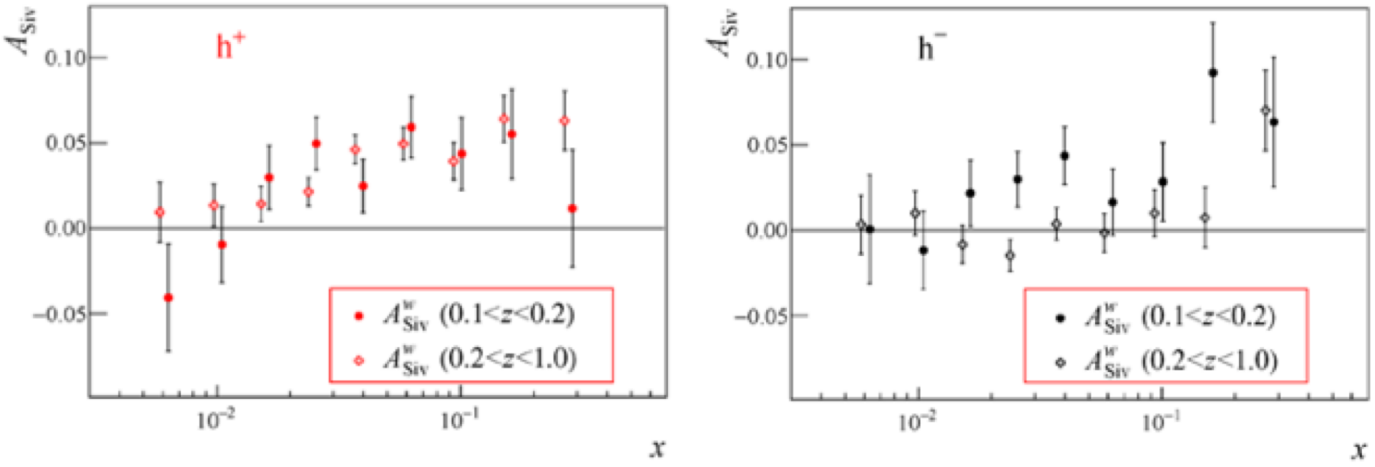


Knowledge of widths in *unpolarized* TMDs is crucial to extract *polarized* TMDs, e.g. Sivers function

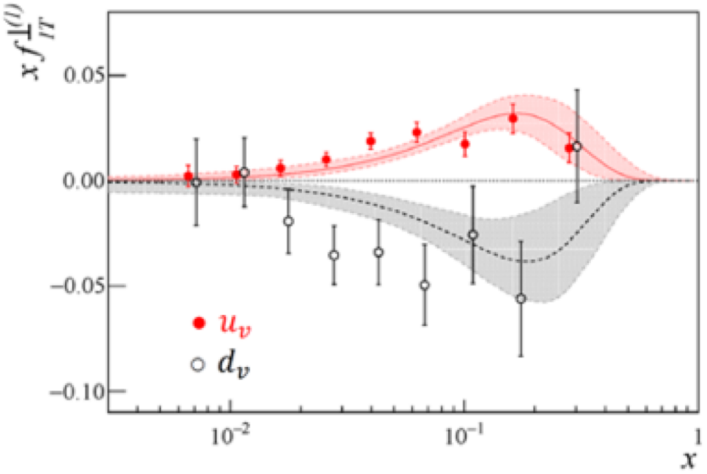
- Need different widths for HERMES and COMPASS to give suitable fit to data
- Correlations in k_T & p_T mean you can describe SIDIS data equally well with different values that yield vastly different predictions for DY

Talk by F. Murgia

Innovations in Sivers Measurements



Talk by A. Martin



bars: statistical uncertainties only

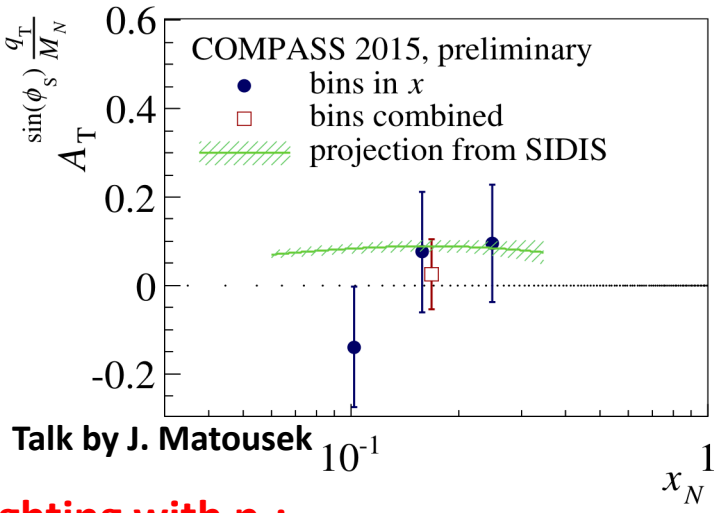
curves and bands: fit to the HERMES p and COMPASS p and d data by the Torino group
$Q^2 = 4\ \mathrm{GeV}^2$
PRD 86, 2012

at the Q^2 of the measurement (1.24 to $25.6\ \mathrm{GeV}^2$)

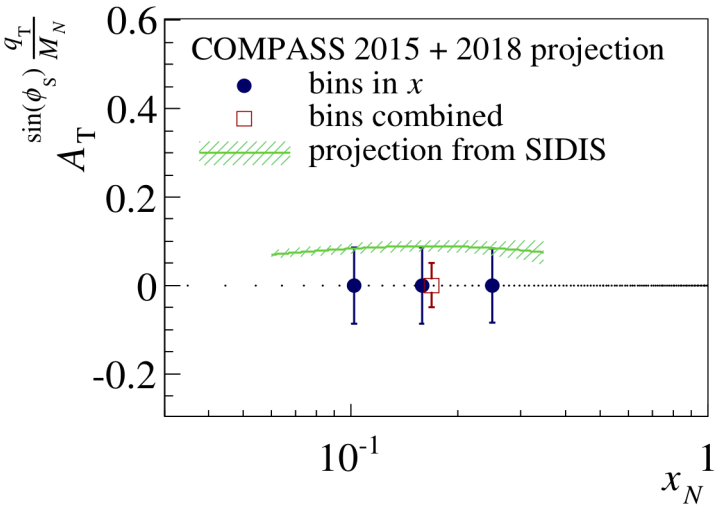
Weighting with p_T:

- removes convolution between PDF and FF
- (With some assumptions) Enables extraction of Sivers moment to compare with DY
- **caution:** Theory framework not as advanced as for unweighted observables

Innovations in Sivers Measurements



Talk by J. Matousek



Weighting with p_T:

- Transverse momentum weighted Sivers asymmetry in Drell-Yan also gives access to first k_T - moment of Sivers PDF
- Compare to (functional fit to) what was obtained in SIDIS
- **> 1.5 times statistics expected this year!**
- Timely processing of large amount of new data

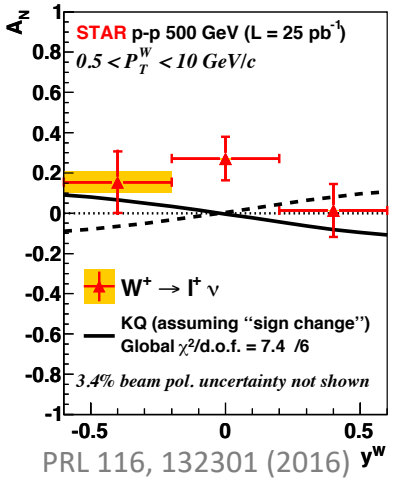
→ *process using Blue Waters supercomputer!*

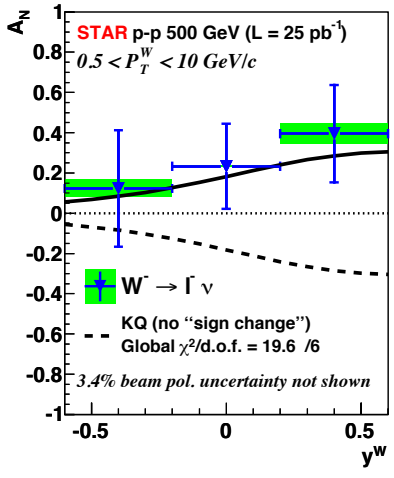
BLUE WATERS

Talk by J. Matousek

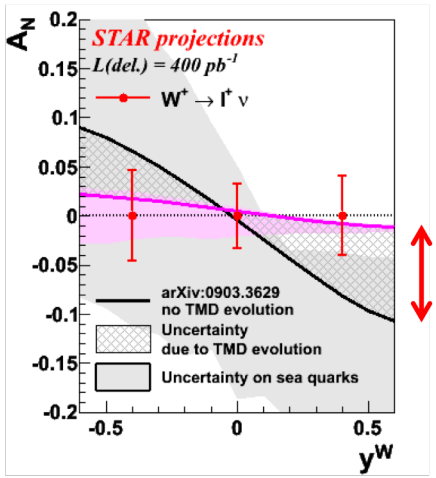
https://bluewaters.ncsa.illinois.edu/usage-project-details?project=balh

Innovations in Sivers Measurements

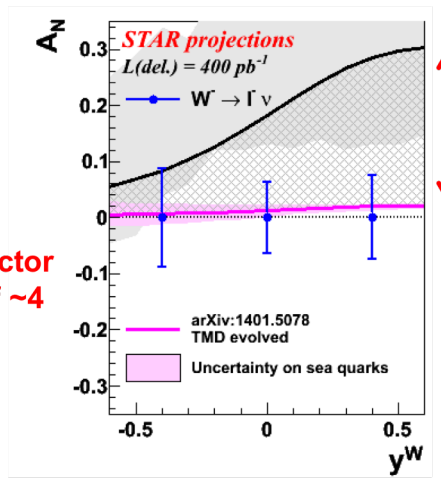




PRL 116, 132301 (2016)



Factor of ~4



Factor of ~15

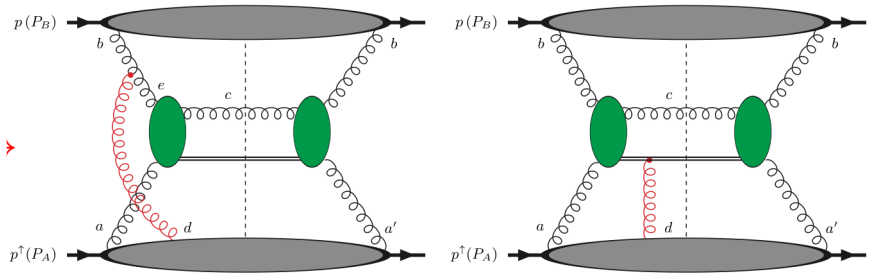
Sivers through weak bosons

- Higher scale than DY
- Sensitivity to evolution!
- **Test through W/Z, DY, and direct photon (twist-3) through 2017 data set**

Proposal for 2021

- Go beyond simply testing sign-change
- Test the magnitudes between SIDIS and p+p

Advances in Sivers Phenomenology



[Color Factors]

Talk by C. Pisano

$-f_{1T}^{\perp g\,(d)}(x) = +0.2\, f_g(x)$

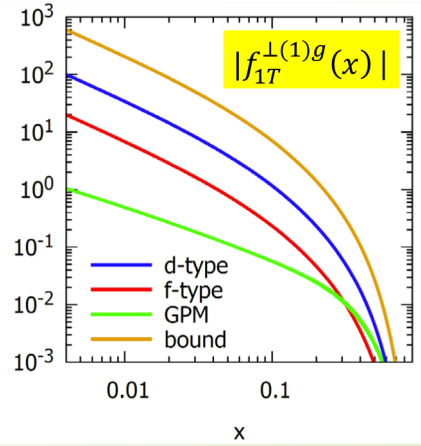
$f_{1T}^{\perp g\,(f)}(x) \cong 0$

$-f_{1T}^{\perp g\,(d)}(x) = -0.2\, f_g(x)$

$-f_{1T}^{\perp g\,(f)}(x) = 0.05\, f_g(x)$

$f_{1T}^{\perp g\,(d)}(x) \cong 0$

$-f_{1T}^{\perp g\,(f)}(x) = 0.04\, f_g(x)$

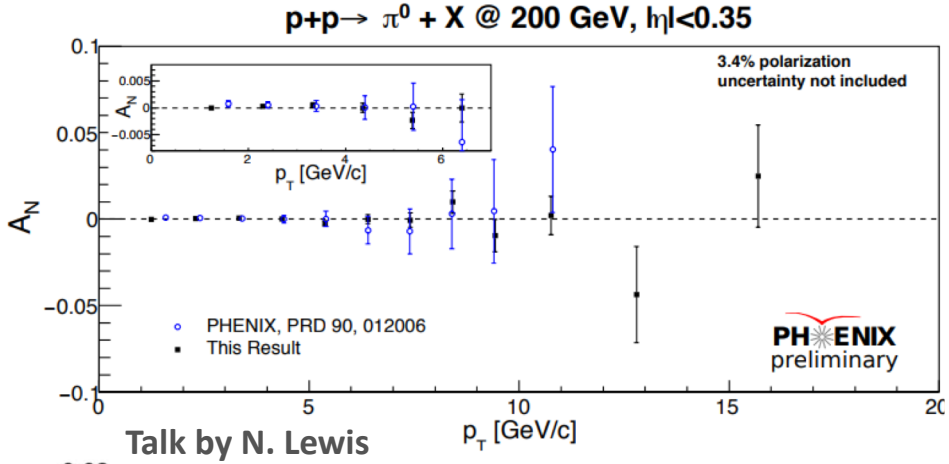


Talk by U. D'Alesio

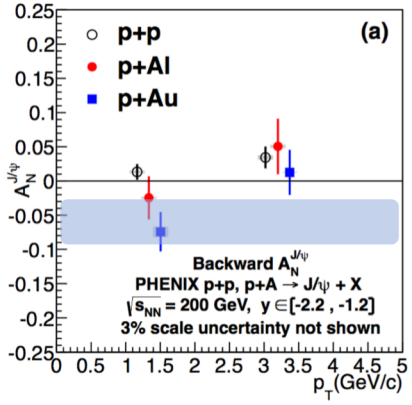
Generalized Parton Model

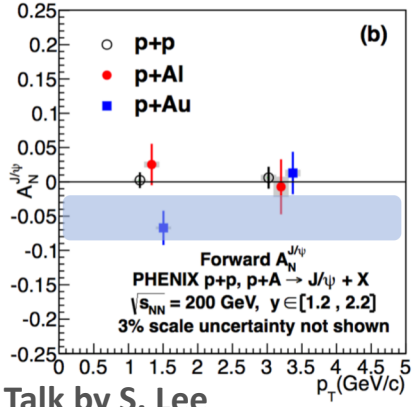
- Apply in the Color-Gauge-Invariant approach
- Alternative approach: collinear twist-3
- Two DIFFERENT gluon Sivers functions enter (the so-called f and d type)
- Multiplied by different color factors depending on the process
- Generalize the ± factors for SIDIS and DY
- Explore three different possibilities for the two gluon Sivers functions in D meson and pion production
- Present data do not discriminate between the scenarios (maybe a large f-type Sivers is disfavoured?)

New Data Sensitive to Gluon Sivers



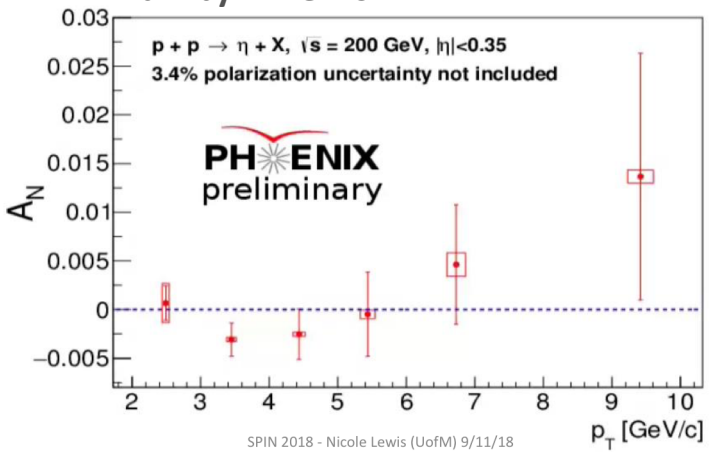
Talk by N. Lewis





Talk by S. Lee

PRD 98 (2018) 012006

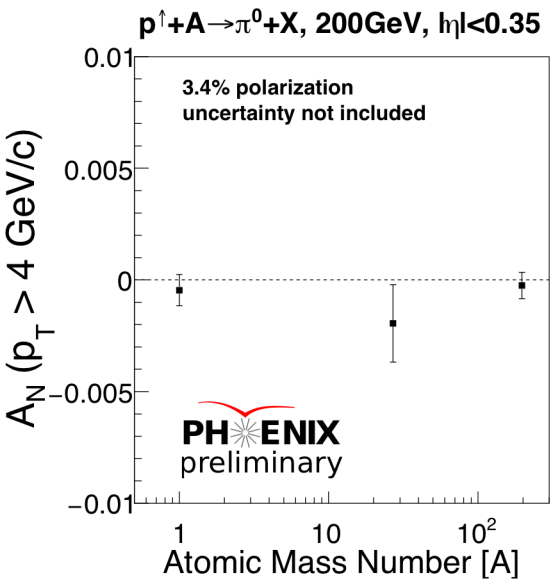


SPIN 2018 - Nicole Lewis (UofM) 9/11/18

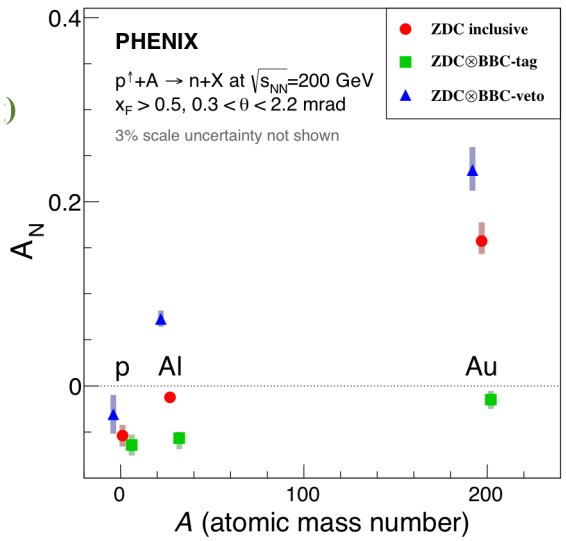
New experimental results!

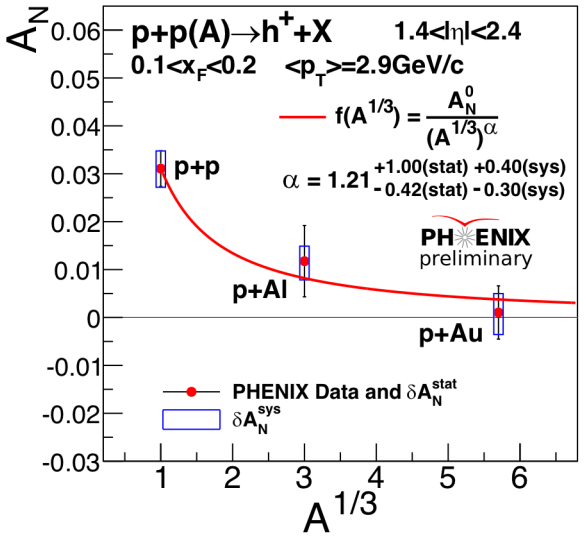
- Improved statistics for pions and etas
- Data from J/psi in p+p, p+Al, and p+Au
- Appears to be nonzero at low p_T in p+Au
- New results should provide useful information for model constraints

New Data Sensitive to Sivers and Nucleus



Talk by S. Pate

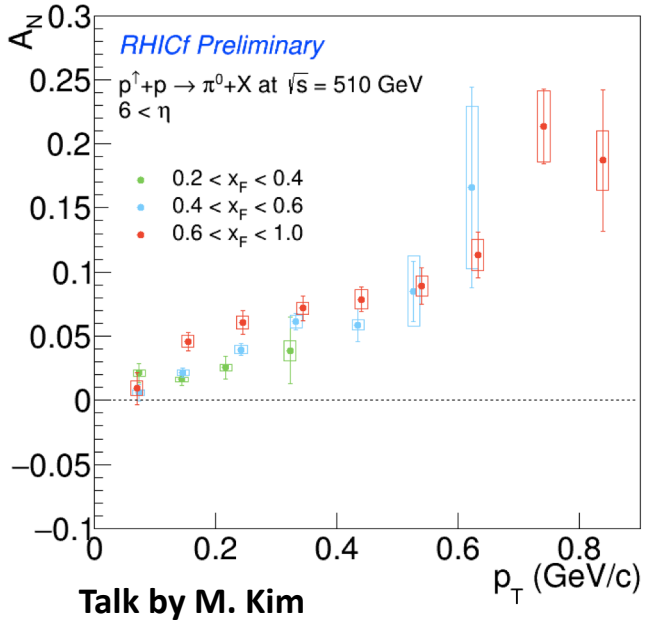




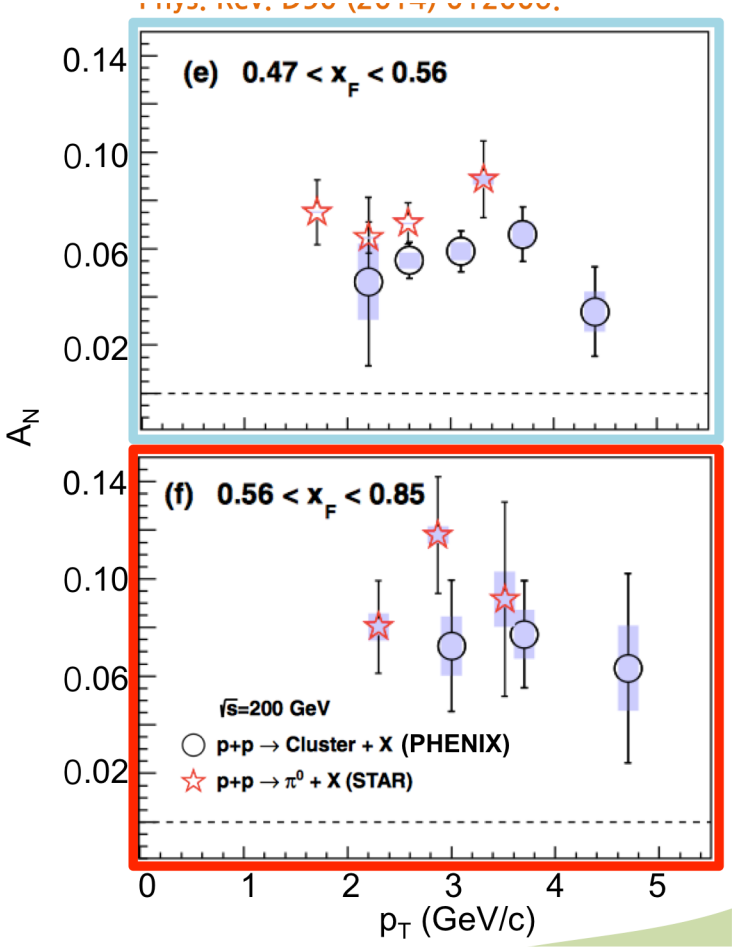
Insight from Nucleus

- Asymmetries small for pion regardless of nucleus
- Small for J/psi in p+p and negative at low p_T in p+Au?
- Large for forward charged hadrons, suppressed for large nuclei and centrality
- Large for very forward neutrons and largest for UPC

New Insights into Forward A_N



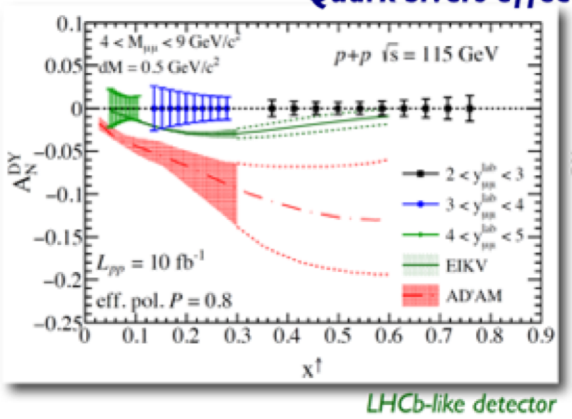
Talk by M. Kim



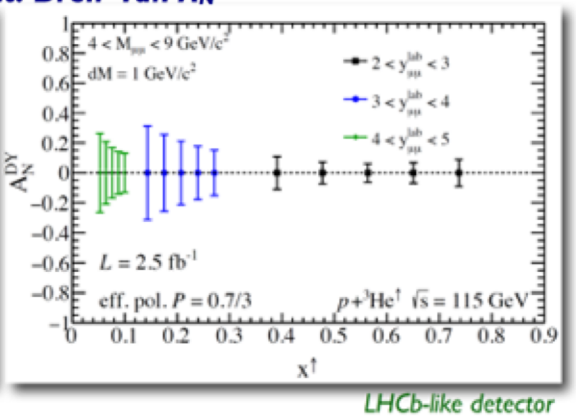
- Large pion A_N at very forward pseudorapidity
- Increases with p_T but not as strongly with x_F
- Possible diffraction contributions?
- Further studies correlated activity in STAR detectors coming soon

Future Experimental Programs

Quark Sivers effect: Drell-Yan A_N

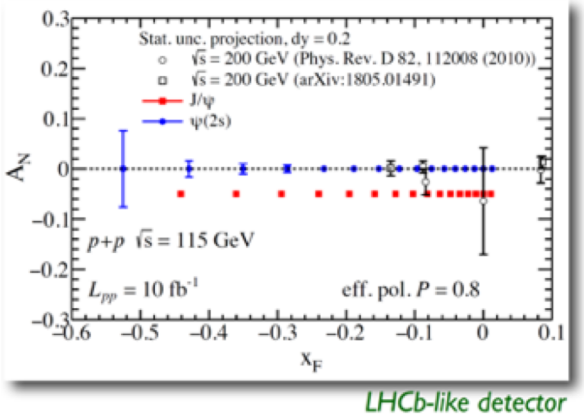


LHCb-like detector



LHCb-like detector

Gluon Sivers effect: vector quarkonium production

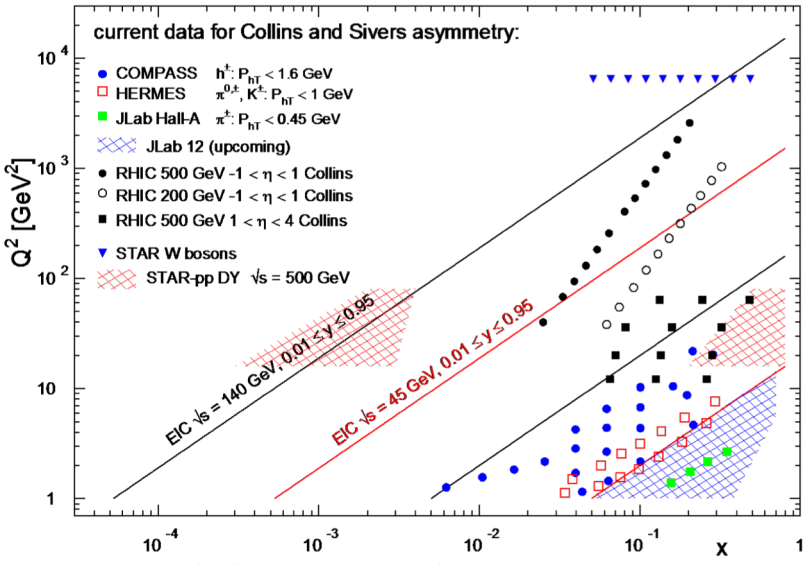


LHCb-like detector

Talk by M. Echevarría

Fixed Target at LHC

STAR Forward Upgrade



Talk by C. Gagliardi

- Proposed future programs offer suite of new / improved measurements
- Map TMDs across kinematics space and test universality / factorization / evolution
- Critical information to make the most of an EIC!

Channels to Study Linearly Polarized Gluons

$$
\begin{aligned}
W(\theta, p, p_{\bar{l}}, p_l) = \frac{1}{4} - \frac{1}{4}\{&[p^4 \sin^4\theta + m^4](\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} + [p^2(p^2-2m^2)\sin^4\theta - m^4](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} \\
&+ [p^4\sin^4\theta - 2p^2(p^2-m^2)\sin^2\theta + m^2(2p^2-m^2)](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} \\
&+ 2mp^2\sqrt{p^2-m^2}\cos\theta\sin^3\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}]\} \\
&/\left[p^2(2m^2-p^2)\sin^4\theta + 2p^2(p^2-m^2)\sin^2\theta + m^2(2p^2-m^2)\right] \qquad (20) \\
= \frac{1}{4} - \frac{1}{4}\{&[(1-\beta^2)^2 + \sin^4\theta)](\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{x}} \\
&+[-(1-\beta^2)^2 - (1-2\beta^2)\sin^4\theta](\hat{p}_{\bar{l}})_y(\hat{p}_l)_{\bar{y}} \\
&+[(1-\beta^4) - 2\beta^2\sin^2\theta + \sin^4\theta](\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{z}} \\
&+2\frac{\beta}{\gamma}\sin^3\theta\cos\theta[(\hat{p}_{\bar{l}})_x(\hat{p}_l)_{\bar{z}} - (\hat{p}_{\bar{l}})_z(\hat{p}_l)_{\bar{x}}]\Big\} \\
&/\left[(1-\beta^4) + 2\beta^2\sin^2\theta + (1-2\beta^2)\sin^4\theta\right] \qquad (21)
\end{aligned}
$$

Talk by G. Goldstein

Proposed new channels to study gluon linear polarization via heavy quark production

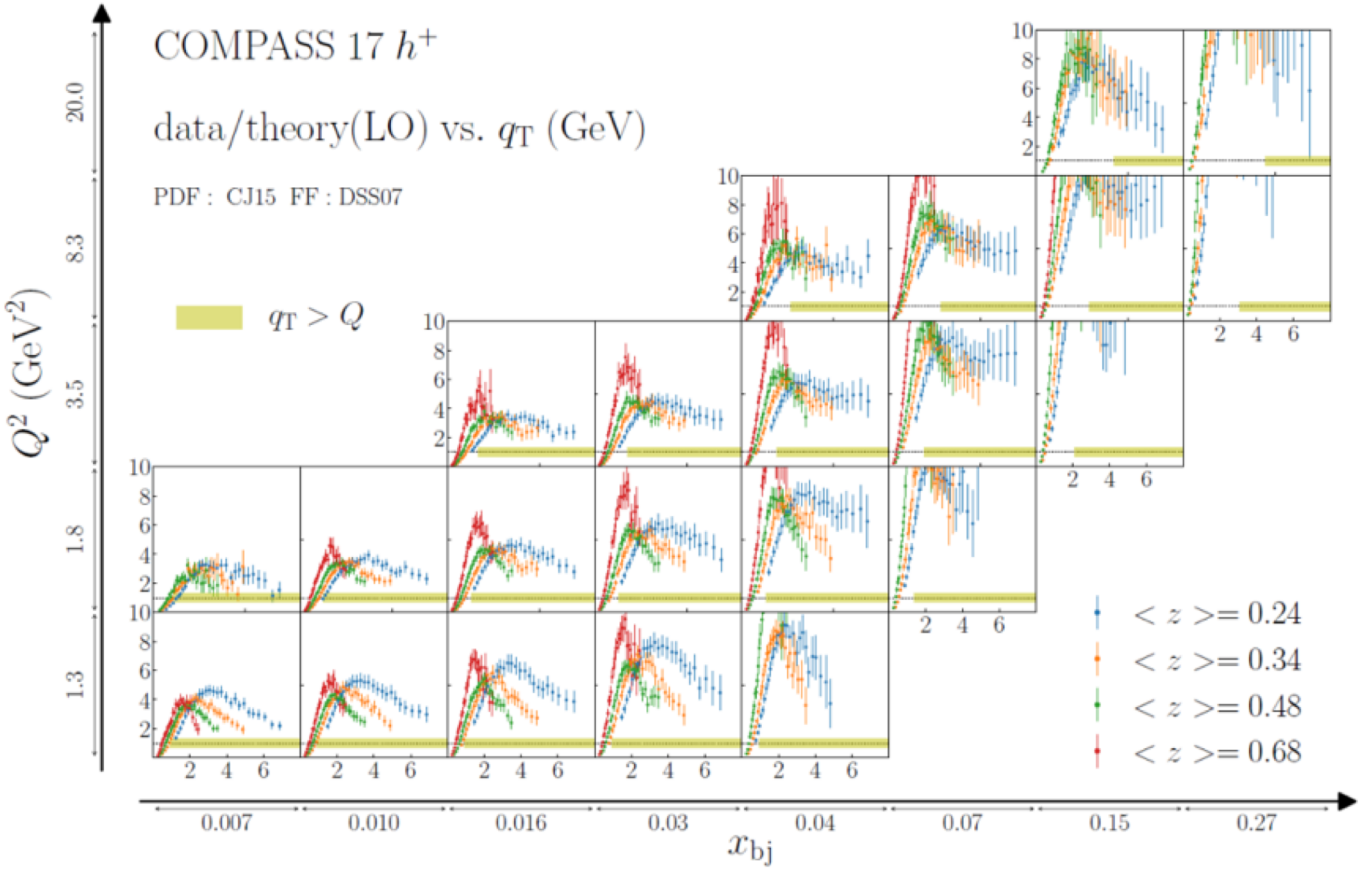
Unpolarized TMDs

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

Calculations at High Transverse Momentum

Old predictions (DSS07) @ LO

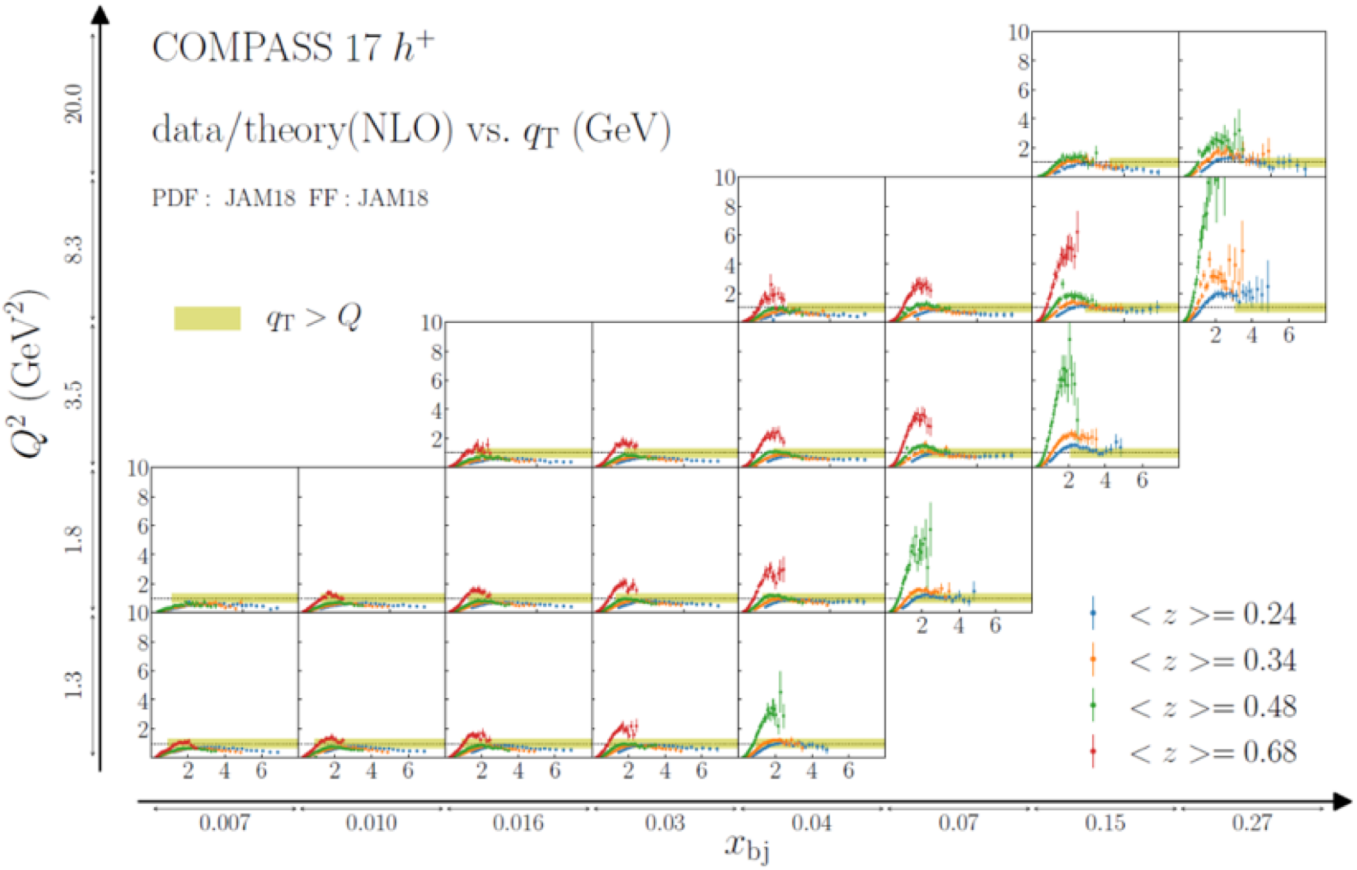


Apparent disagreement between data and FO can be resolved by tuning FFs

Talk by N. Sato

Calculations at High Transverse Momentum

New predictions (JAM18) @ NLO (DDS)

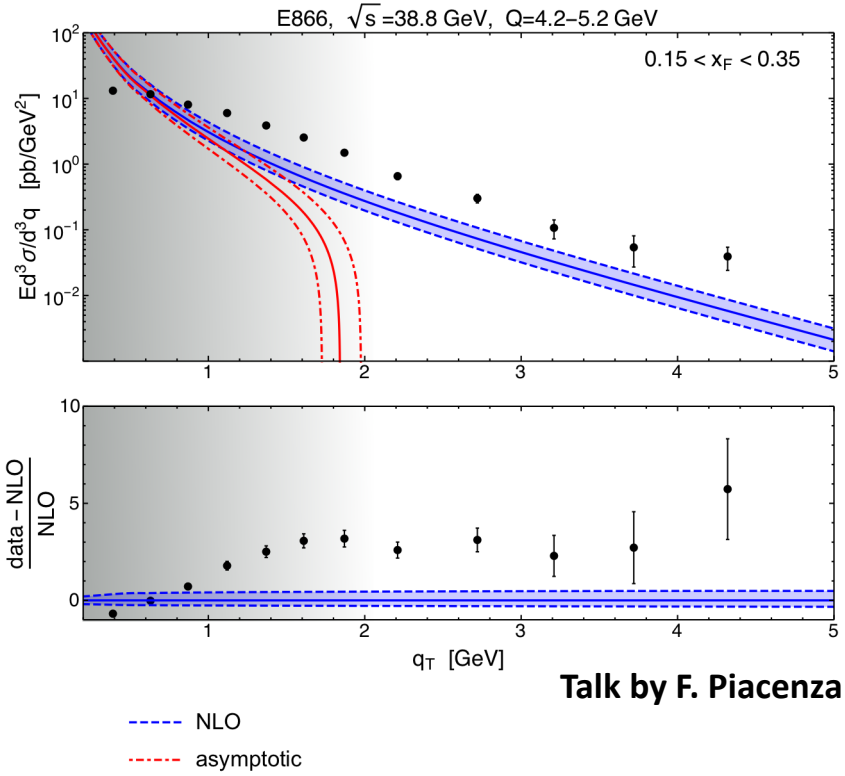


Apparent disagreement between data and FO can be resolved by tuning FFs

Talk by N. Sato

Calculations at High Transverse Momentum

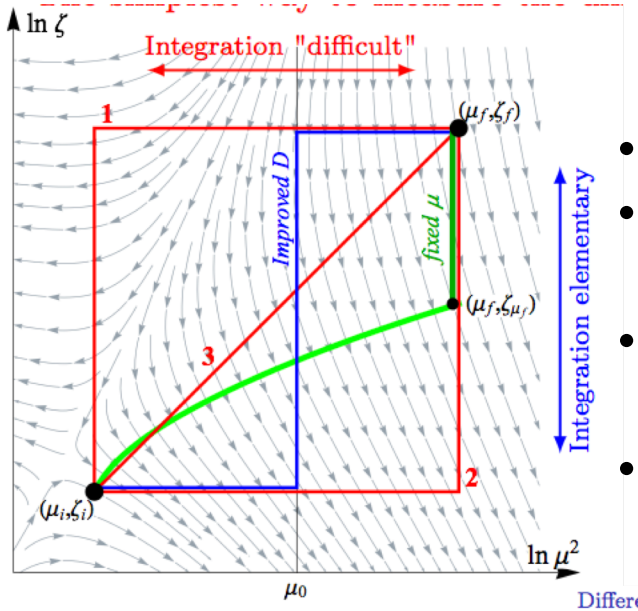
$$p\,p \rightarrow \mu^{+}\mu^{-}X \qquad \sqrt{s} = 38.8\,GeV$$



Talk by F. Piacenza

- Calculation based on collinear factorization **DRASTICALLY UNDERESTIMATES** data
- Higher order, PDF uncertainties, transverse momentum smearing, threshold resummation…none solve the issue…
- The calculation should work at high q_T (q_T~Q)

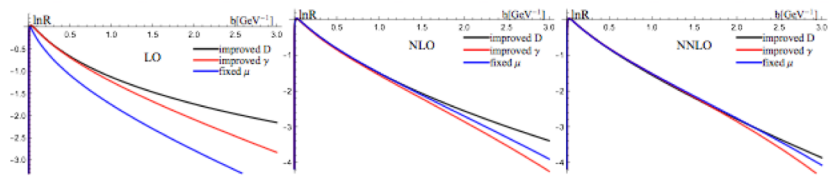
Creative Approaches to TMDs



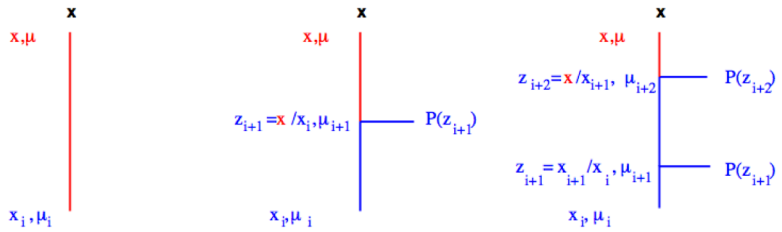
- TMD evolution is a **double-scale evolution** (μ and ζ)
- Different paths can be chosen to calculate it and may lead to different results
- Implementation can be done in different ways, similar to a "scheme choice"
- Some choices may be more convenient

Talk by A. Vladimirov

Different solutions converge with increase of PT order

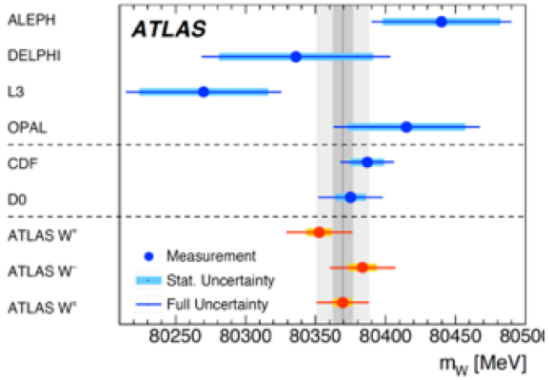


Talk by F. Hautmann



- Parton branching method that can be implemented in M.C. event generators
- Can be used for collinear as well as TMDs
- Angular ordering instead of k_T ordering

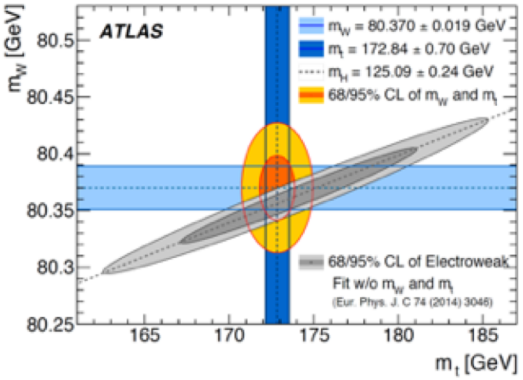
Flavor Dependence in Intrinsic Transverse Momentum



Experimental measurements

$M_W = 80.379 \pm 12$ MeV

(7 stat, 11 exp, 14 th)



Global EW fit **Talk by G. Bozzi**

$M_W = 80.356 \pm 8$ MeV

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

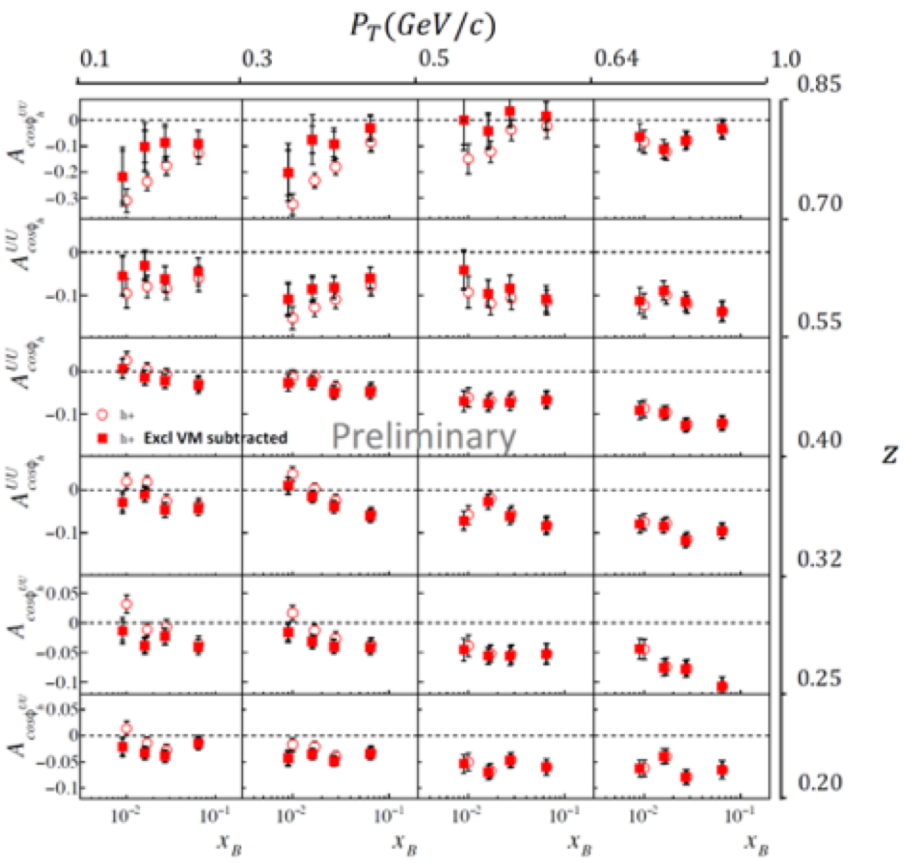
- First flavour-dependent study of the impact of intrinsic transverse momentum on the determination of the W mass
- Flavour effects are both ***important and detectable***
- No “flavour-blind” analysis allowed!

Unpolarized TMDs

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

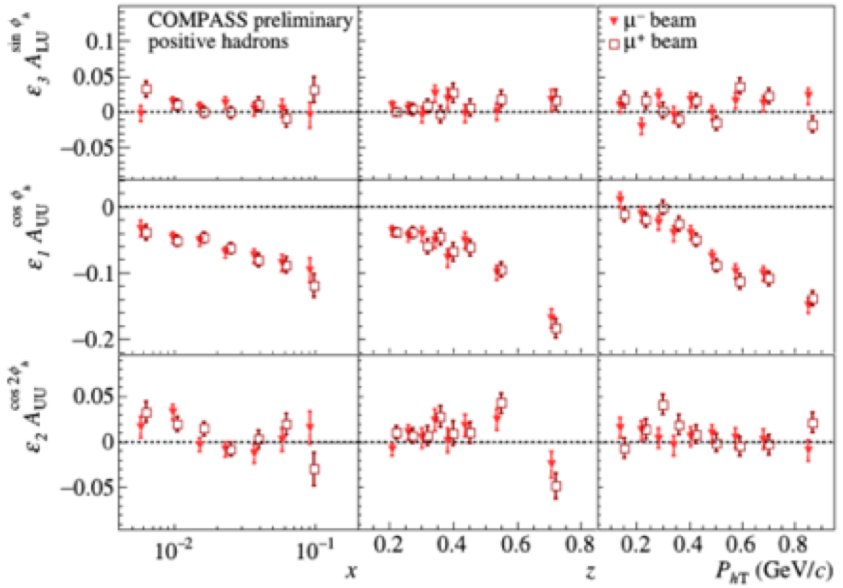
Azimuthal Asymmetries in Unpolarized SIDIS



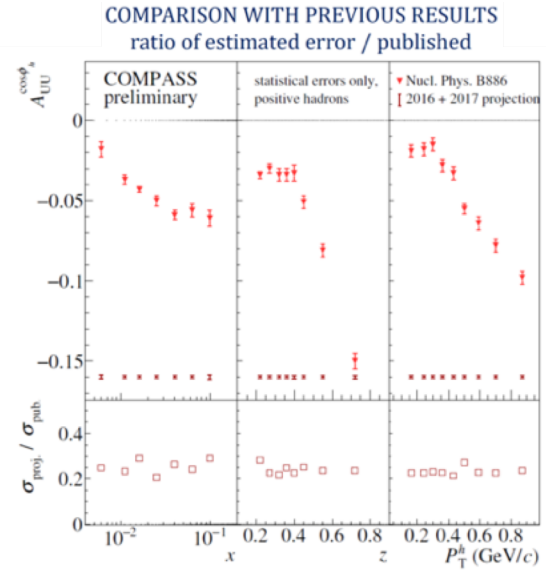
- Large contribution from hadrons from exclusive VM production to SIDIS samples (at small Q^2, large z and small P_T)
- For the first time COMPASS measures the amplitudes of azimuthal modulations for hadrons originating from the decay of exclusive VMs:
- Large amplitudes $\cos\phi_h$ and $\cos2\phi_h$ modulations
- This contribution can not be neglected and should be taken into account

Talk by Albi Kerbizi

Azimuthal Asymmetries in Unpolarized SIDIS



- Analysis of COMPASS unpolarized proton data collected in 2016/17
- First preliminary results (~4% of the statistics)
- The strong kinematic dependences of the asymmetries are confirmed



Talk by Andrea Moretti

- Considering entire 2016+2017 sample
  - Statistical error strongly reduced
  - Systematic error expected to be smaller than past measurements

Last but not Least…

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_{1T}, h_{1T}^\perp$

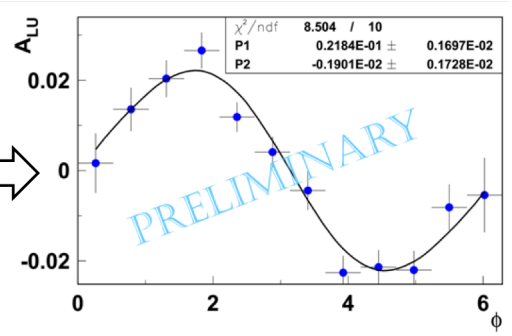
GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

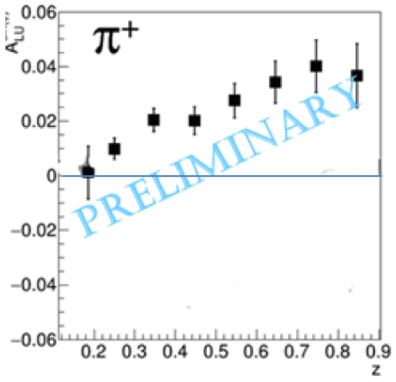
First Data from CLAS12

Pi+ Beam Spin Asymmetry

One day of data taking
Q^2>1 GeV^2 W>2 GeV

Fully integrated kinematics



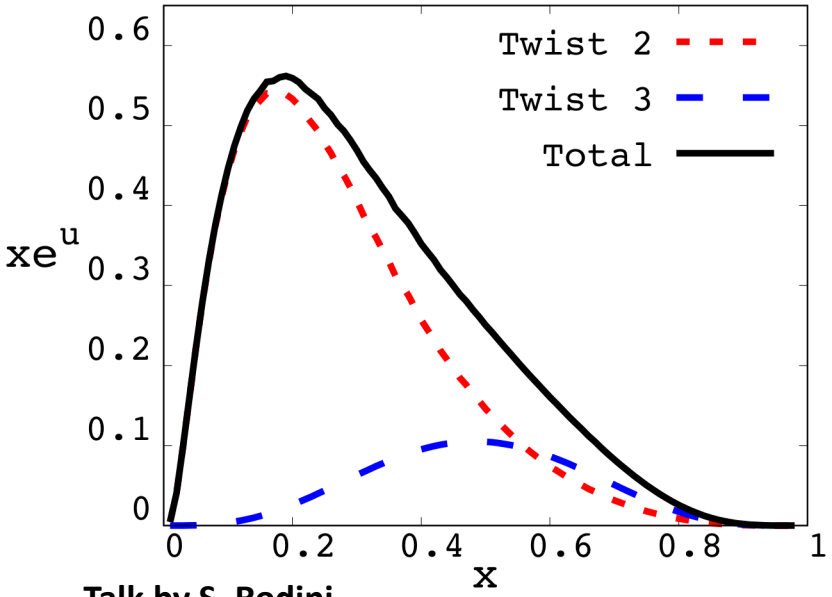


z-dependence
- positive asymmetry
- rising with z

Talk by M. Mirazita

- CLAS12 had a very successful first run during spring
- Detectors performed well and consistent with expectations
- Data analysis progressing
- ***First physics results at the APS/DNP meeting in October***
- Fall run in preparation
- Will continue up to spring 2019

Twist-3 Effects

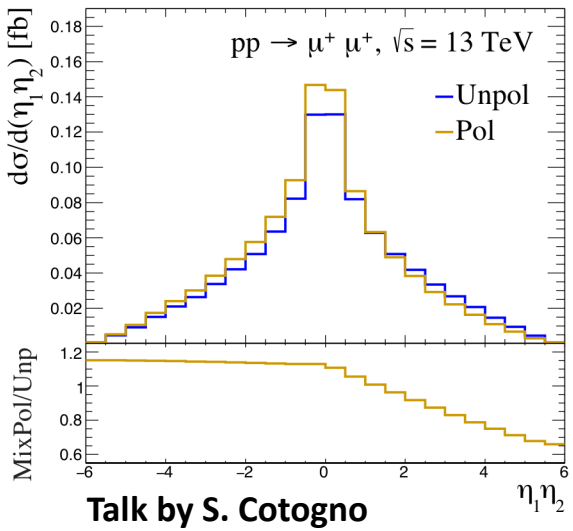


Talk by S. Rodini

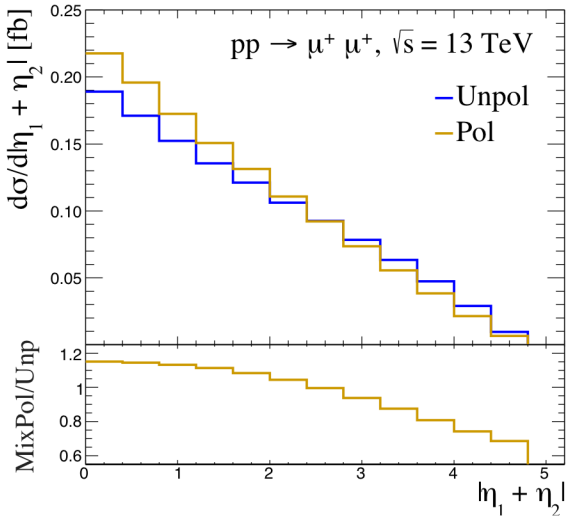
- Calculation of twist-3 e(x) PDF based on light-front wave functions
- Pure twist-3 effects can be sizable

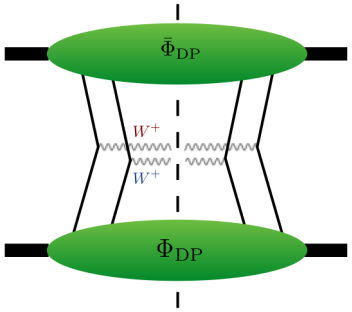
Polarized Double Parton Distributions

$$f_{\Delta q \Delta q}(x_1, x_2, \boldsymbol{y}; Q_0)$$



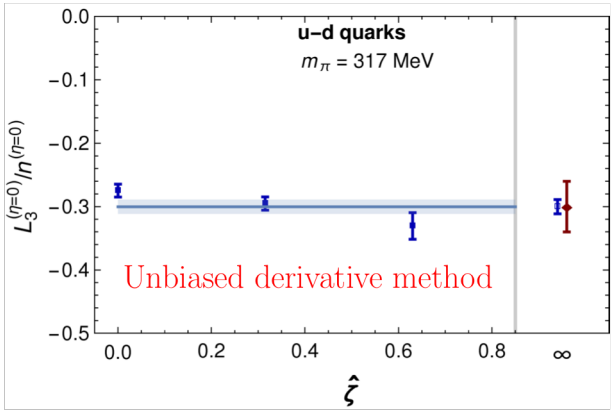
Talk by S. Cotogno





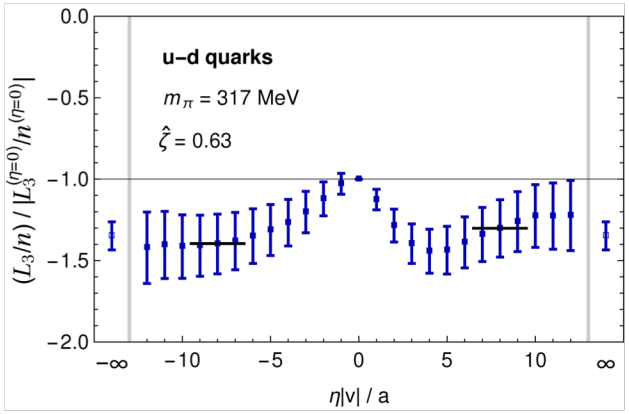
- Proposal to access POLARIZED double-parton distributions, in unpolarized collisions

Orbital Angular Momentum



Talk by M. Engelhardt

standard calculation
using GPDs



- Lattice QCD calculation of Ji's orbital angular momentum based on Wigner distributions (with straight gauge link)
- The method works!...
- …and can be used to calculated Jaffe-Manohar Orbital Angular Momentum (with staple-shaped gauge link going to infinity)
- Jaffe-Manohar OAM turns out to 40% larger than Ji OAM

Thank You!

31 Talks

- SIDIS experiments (5)
- pp/pA experiments (9)
- Theory (9)
- Phenomenology (8)