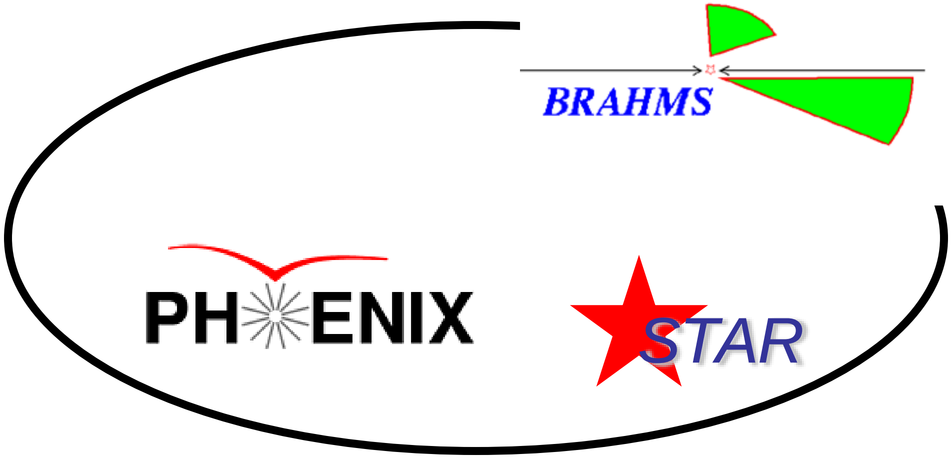
Transverse Spin Asymmetries in Proton-Proton Collisions

University of Bonn, March 18th, 2018

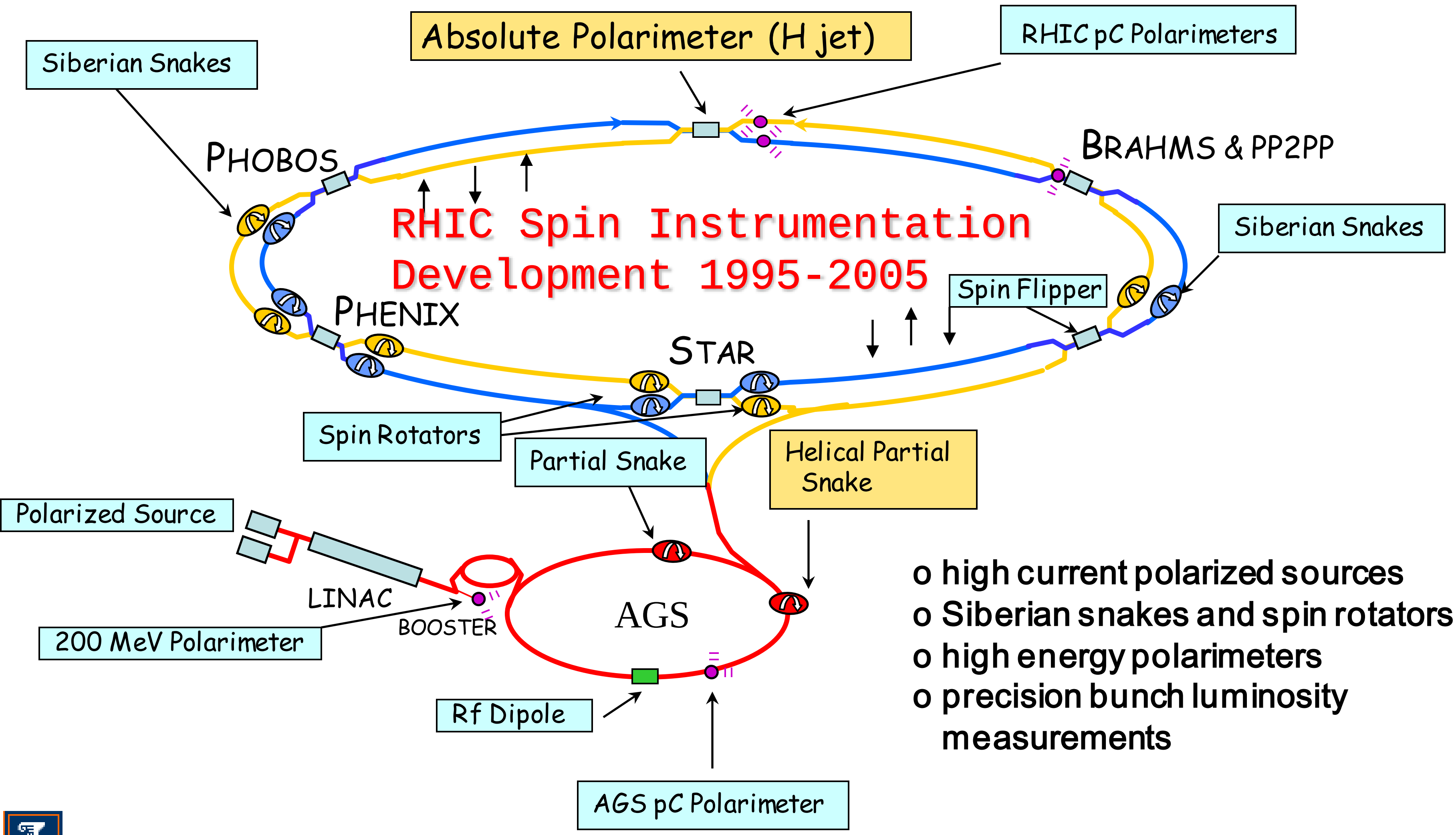


M. Grosse Perdekamp, University of Illinois

Outline

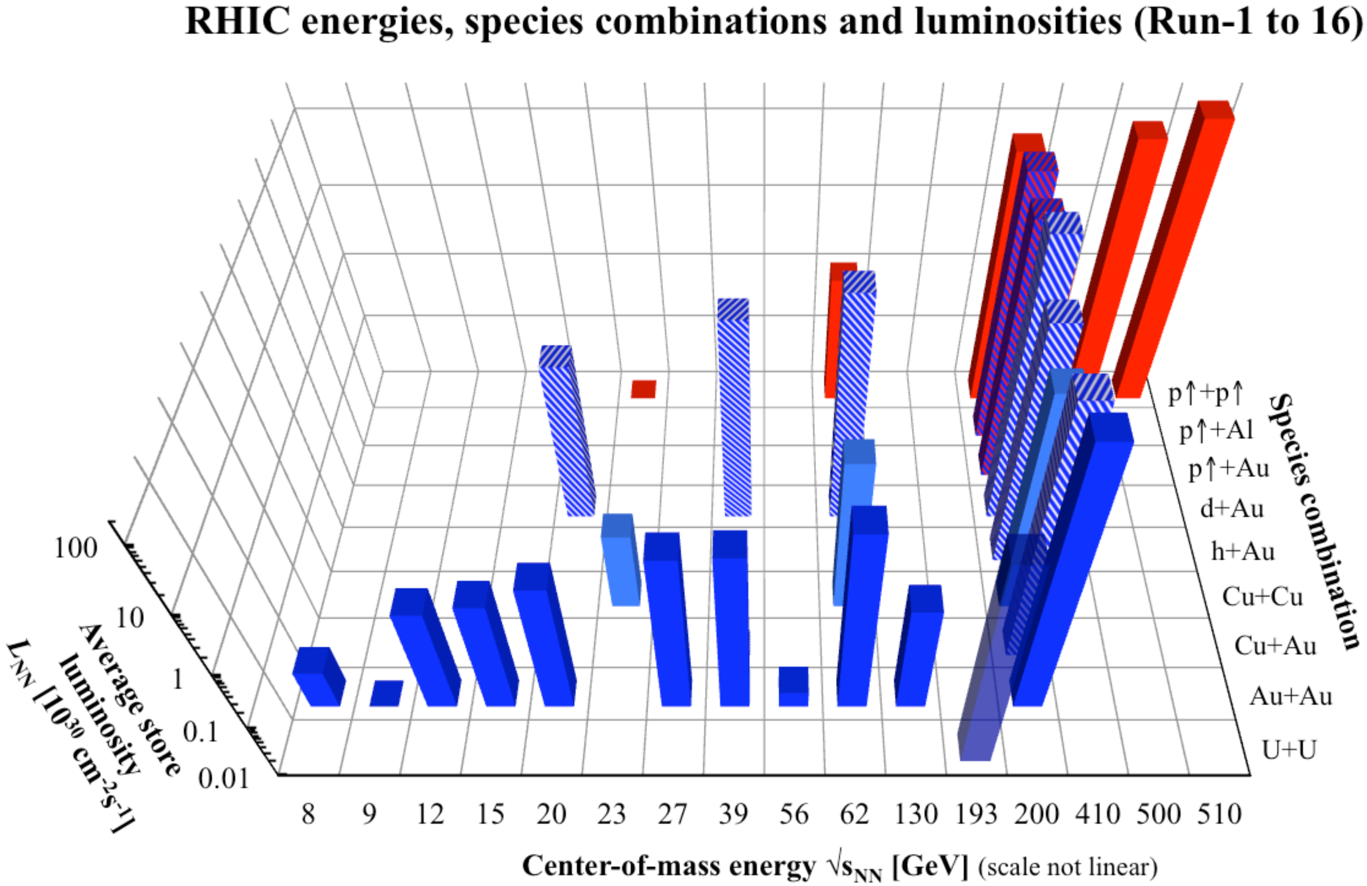
- Polarized p-p
- Observation of Large A_N and TMD Mechanisms
  - A_N in fixed target experiments
  - Explanations
  - A_N at collider energies
- The Sivers effect in p-p
- Constraining Transversity
  - Transverse spin dependent hadron fragmentation
  - Measurements with jets and di-hadrons in p-p

Experimental method: Probing Proton Spin Structure in High Energy Polarized Proton Collisions

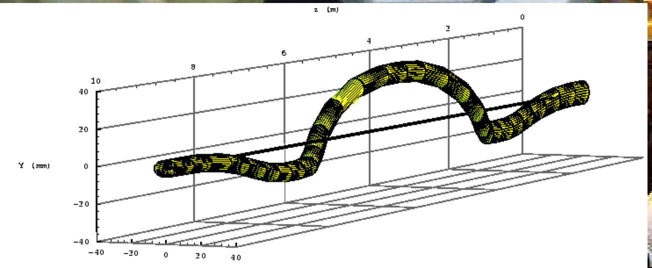


- o high current polarized sources
- o Siberian snakes and spin rotators
- o high energy polarimeters
- o precision bunch luminosity measurements

RHIC Versatile Polarized p-p and Heavy Ion Collider



Instrumentation Example: Siberian Snakes



Field rotates by 180^o
Snake like p-trajectories

Experiments at RHIC:
PHENIX Detector

The experimental task:

Observe final state of ion-ion and proton-proton collisions

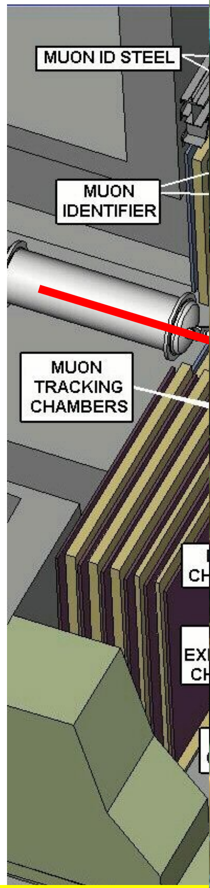
$$Au + Au \rightarrow$$

$$n \cdot \gamma + m \cdot e + o \cdot \pi^0 + \ldots$$

(a) measure momentum
+ energy of final
state particles

(b) identify final state
particles:
eg. photons vs electrons

(c) select events of interest



Example

$Au + Au$ -

Experiment: Single Transverse Spin Asymmetries (SSA) in Hadron-Hadron Collisions

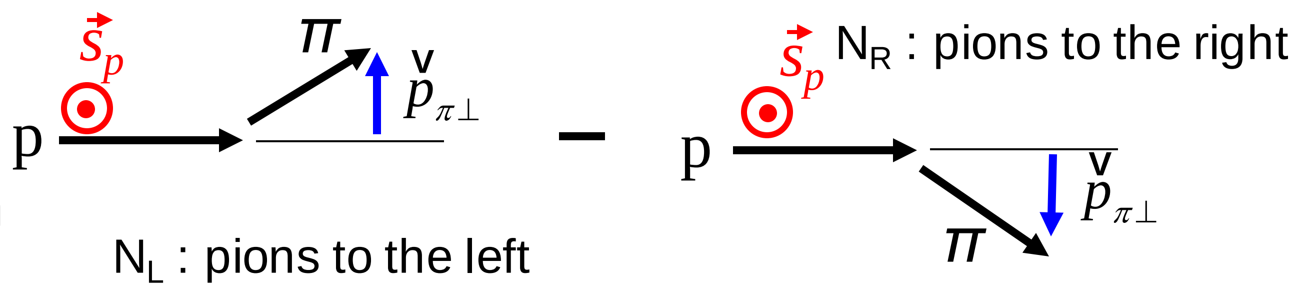
Single Transverse Spin Asymmetries (SSA) A_N in Polarized Proton-Proton Scattering

Example:
Inclusive π production
in polarized p-p

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

one proton
is polarized

Correlation proton spin
S_p vs $p_{\pi\perp}$
π transverse momentum



Single transverse
spin asymmetries A_N

$$A_N = \frac{N_L - N_R}{N_L + N_R} \neq 0 \ ?$$

For High Energy Reactions: $A_N \rightarrow 0$
QCD Test ! (Kane, Pumplin, Repko, 1978)

VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

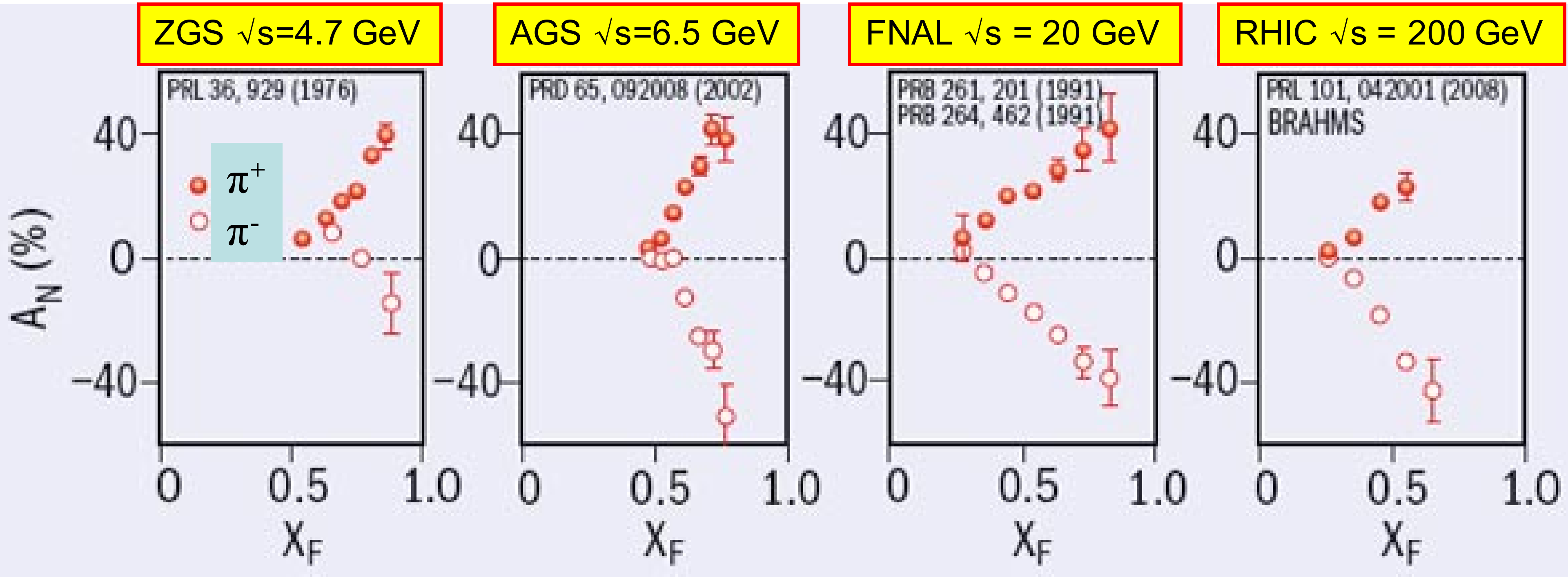
(Received 5 July 1978)

We point out that the polarization P of a scattered or produced quark is calculable perturbatively in quantum chromodynamics for $e^+e^- \rightarrow q\bar{q}$, large-$p_T$ hadron reactions, and large-Q^2 leptoproduction, and is infrared finite. The quantum-chromodynamics prediction is that $P=0$ in the scaling limit. Experimental tests are or will soon be possible in $pp \rightarrow \Lambda X$ [where presently $P(\Lambda) \simeq 25\%$ for $p_T > 2$ GeV/c] and in $e^+e^- \rightarrow$ quark jets.

$$A_N \propto \frac{\alpha_s m_q}{\sqrt{s}} \quad \text{example}, \mathrm{m_q} = 3MeV, \sqrt{s} = 20\,GeV, A_N \approx 10^{-4}$$

Experiment: Large SSA Observed over Large Range of Scales !

Experiment: $A_N >> 10^{-4}$ for 4 GeV < $\sqrt{s}$ < 200 GeV for charged pions !

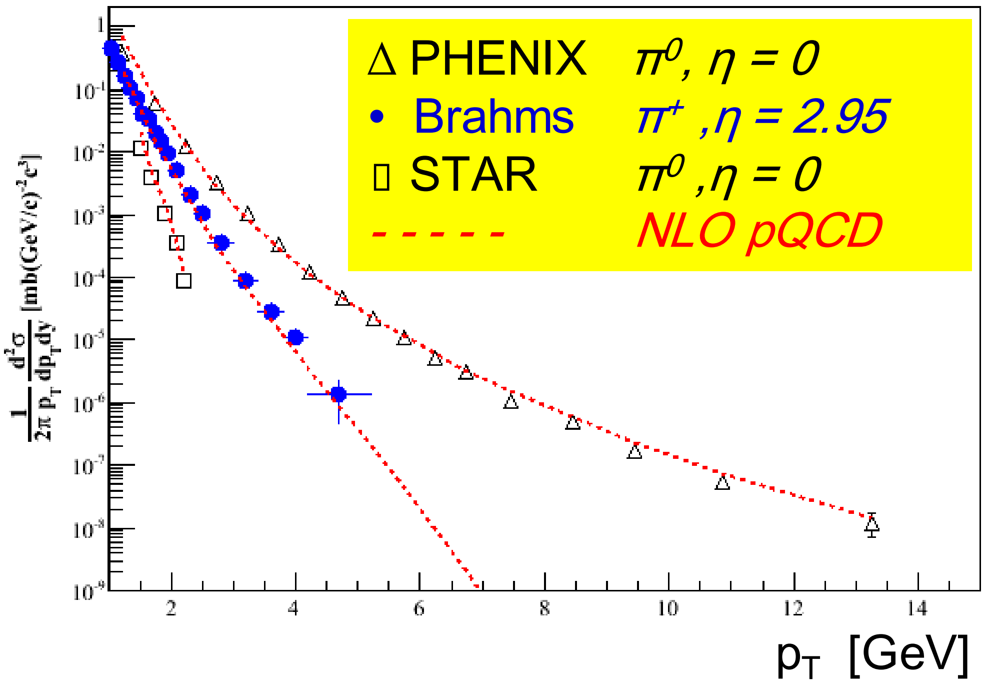


Soft effects due to QCD dynamics in hadrons remain relevant up to scales where pQCD can be used to describe the scattering process!

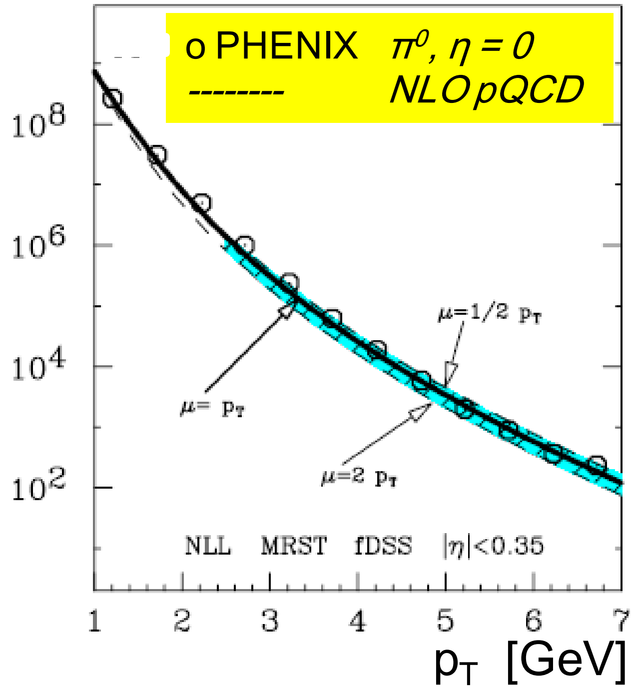
from Christine Aidala, Spin 2008 and Don Crabb & Alan Krisch in then Spin 2008 Summary, CERN Courier, 6-2009

RHIC Data are in the Scaling Limit where pQCD can be Applied!

√s = 200 GeV



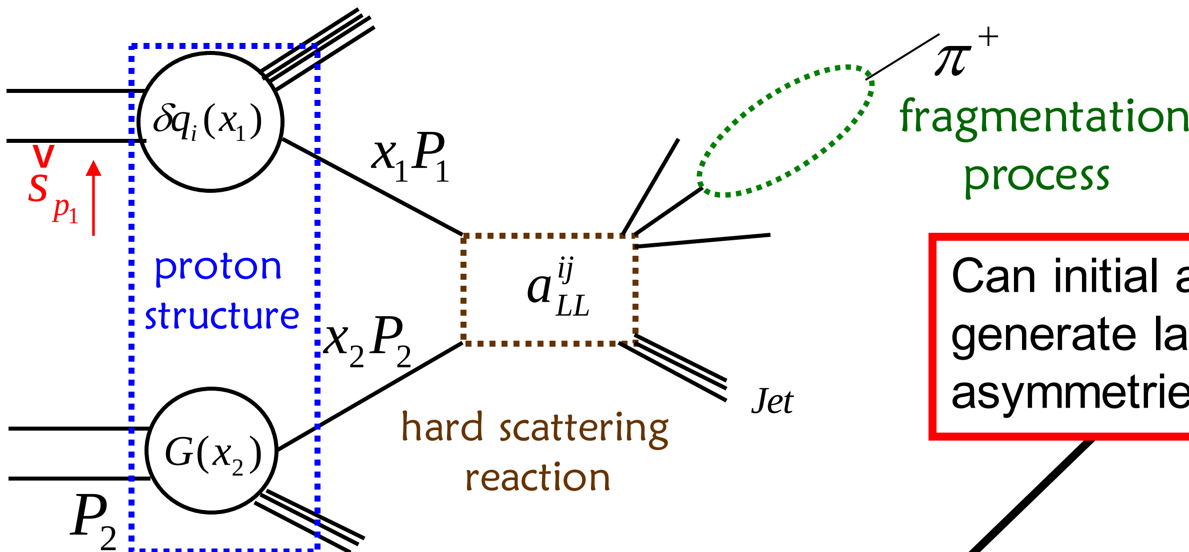
√s = 62.4 GeV



Good agreement between inclusive hadron cross sections from RHIC data and pQCD calculations !

See analysis in De Florian, Vogelsang, Wagner PRD 76,094021 (2007) and Bourrely and Soffer Eur.Phys.J.C36:371-374 (2004)

Origin of Large SSA → Inspect Factorized Components of Cross Section



Can initial and/or final state effects generate large transverse spin asymmetries? ($A_N \sim 10^{-1}$)

pQCD

$$\frac{d^3\sigma^\uparrow\left(pp^\uparrow \to \pi^+ X\right)}{dx_1 dx_2 dz} \propto q_i^\uparrow(x_1, k_{q,T}) \cdot G(x_2) \times \frac{d^3\hat{\sigma}^\uparrow(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

Initial state – proton structure

Kane, Pumplin, Repko → $a_{LL} \sim 10^{-4}$

Final state – hadron fragmentation

Transverse Spin in QCD: Three Solutions

(I) “Transversity” quark-distributions and Collins fragmentation

Correlation between proton- und quark-spin and spin dependent fragmentation

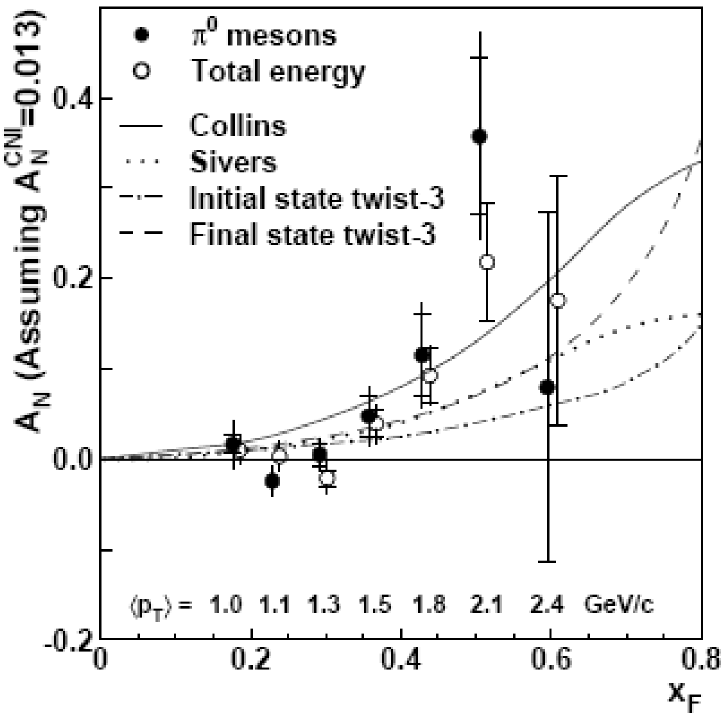
$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^{\perp}(z_2, \overline{k}_{\perp}^2)}_{\text{Collins FF}}$$

(II) Sivers quark-distribution+

Correlation between proton-spin and transverse quark momentum

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_{\perp}^2)}_{\text{Sivers distribution}} \cdot D_q^h(z)$$

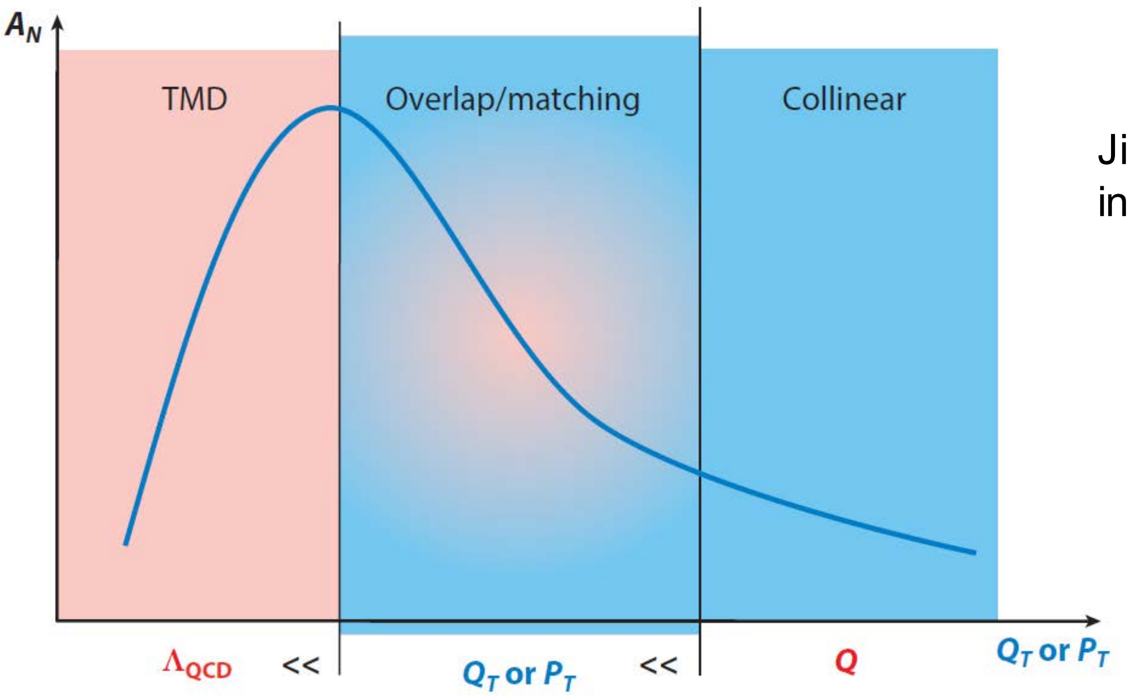
STAR, PRL-92:171801, 2004



(III) Initial or final state twist-3+

Qiu/Sterman and Koike

Unified Picture:
TMD (Sivers & Collins) vs Collinear at Twist 3



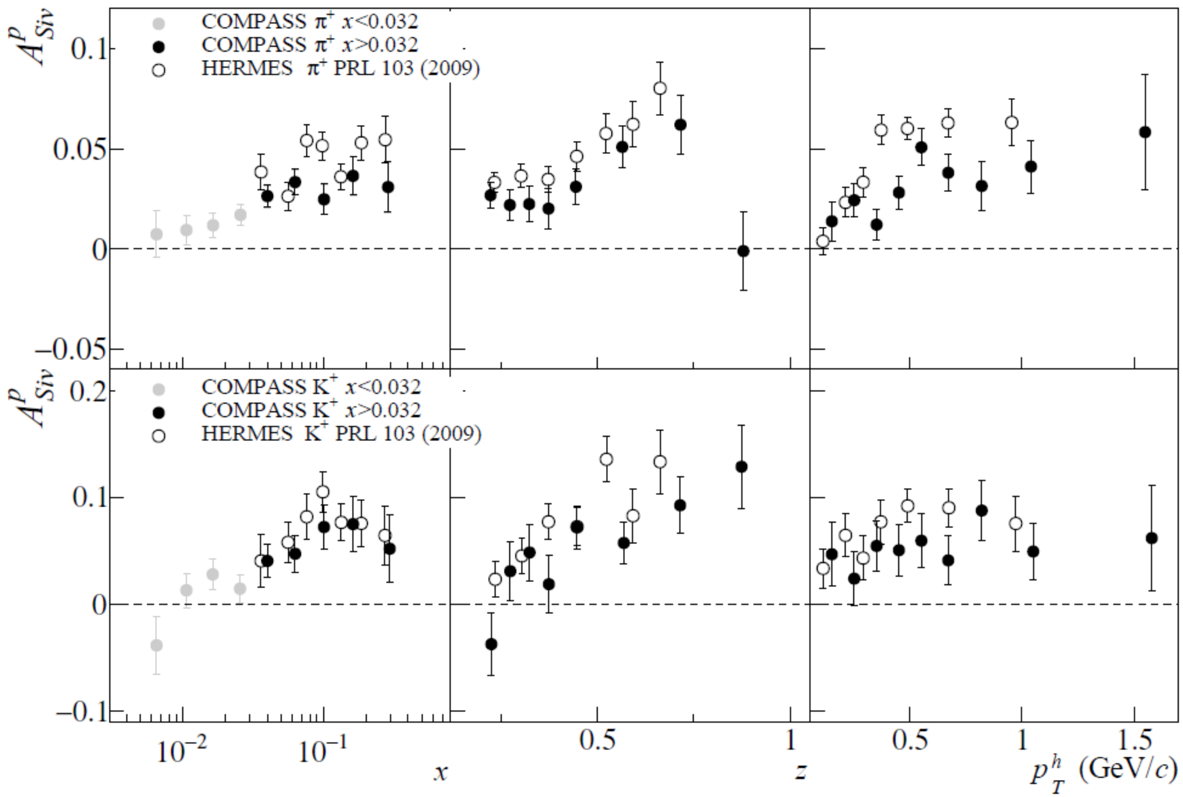
Ji, Qiu, Vogelsang and Yuan
in PRL-97:082002, 2006

Use TMD description (Sivers & Collins) if $p_T << Q$ (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!

The Sivers Effect in pp Collisions

COMPASS and HERMES Sivers Asymmetries for π^+ vs K^+

COMPASS Phys.Lett. B744:250(2015)

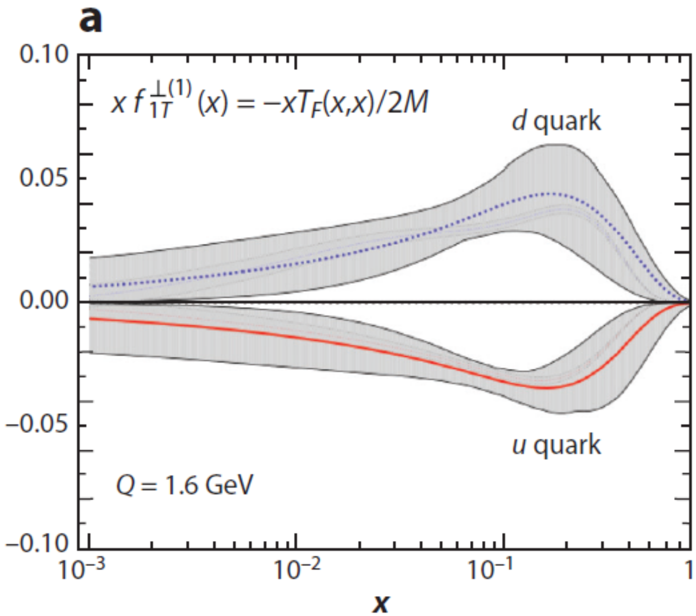


Combined 2007 and 2010 COMPASS proton data samples analyzed.

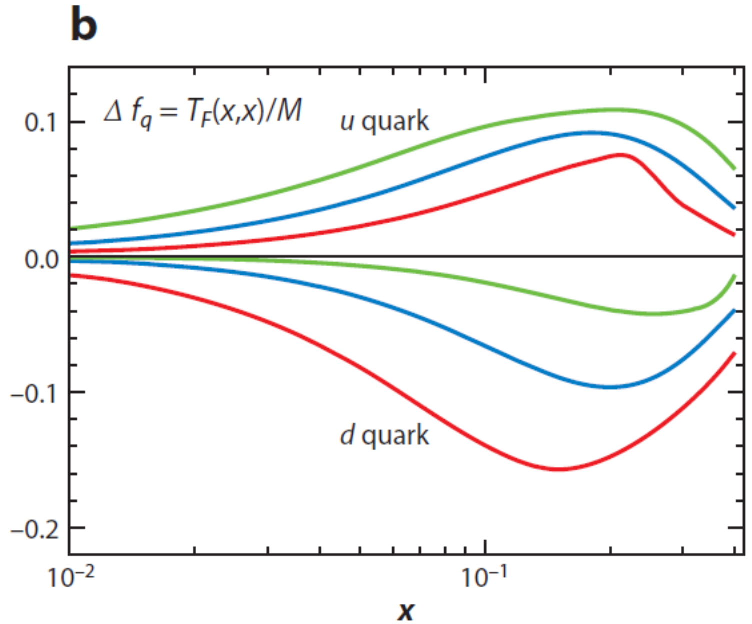
Sivers – Global Analysis of HERMES & COMPASS Data

Anselmino M, et al. arXiv:1107.4446 [hep-ph] (2011) Sun P, Yuan F. *Phys. Rev. D* 88:114012 (2013)

Leading order analysis

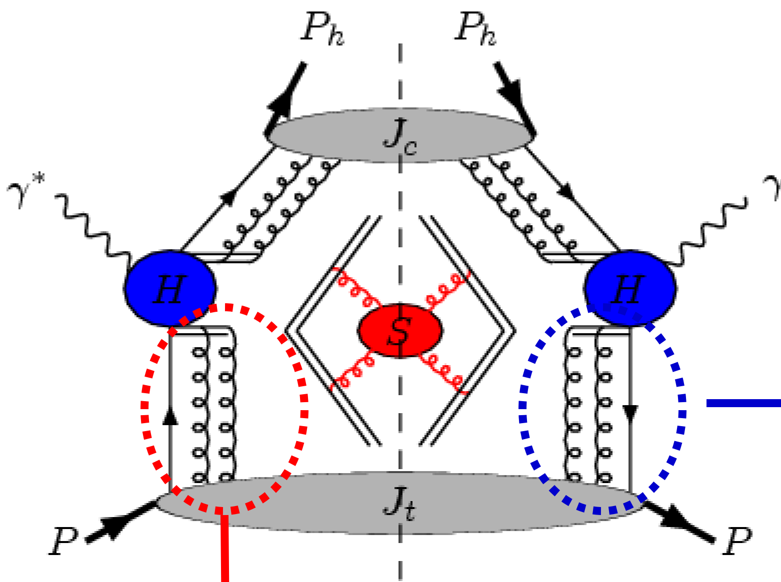


Full QCD analysis including TMD evolution



Still significant errors, no data for x>0.35

Consistent Description of TMDs: Include soft Gluon Exchange in the Initial and Final State of Hard Scattering Processes



Sum final state gluon exchange: gauge link and insert gauge link integral in hard scattering matrix element

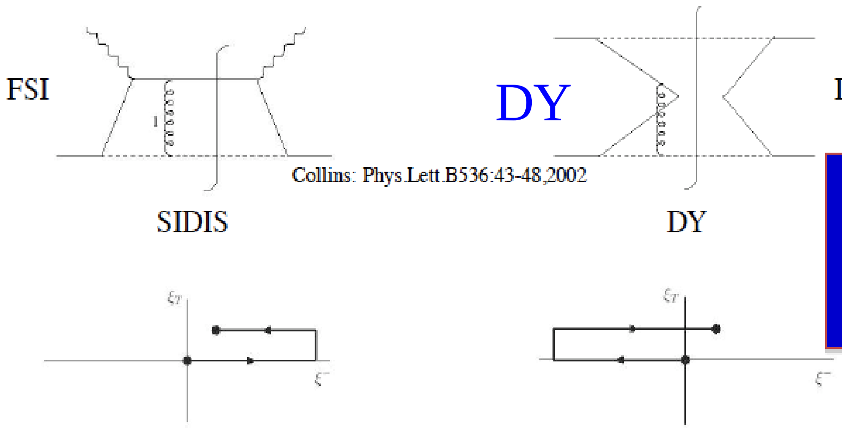
$$\sigma \sim \sum_{\mu \ldots \nu} \frac{1}{Q^{-t/2}} C_{t=d-n_{\mu \ldots \nu}}(Q^2) \langle p | O^{\mu \ldots \nu} | p \rangle$$

Sum initial state gluon exchange: gauge link and insert gauge link in hard scattering matrix element

Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and p-p

SIDIS

DY



Direction of the gauge-link integrals of k_T dep. pdfs is process-dependent and changes its sign between SIDIS and DY

Sivers $\quad f_{1T}^{\perp}(x, \mathbf{k}_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x, \mathbf{k}_T)\Big|_{DY}$

Boer-Mulders $\quad h_{1}^{\perp}(x, \mathbf{k}_T)\Big|_{SIDIS} = -h_{1}^{\perp}(x, \mathbf{k}_T)\Big|_{DY}$

Need to confirm sign reversal in polarized p-p (jets, DY, direct photons)

NSAC performance Milestone HP13 for 2015

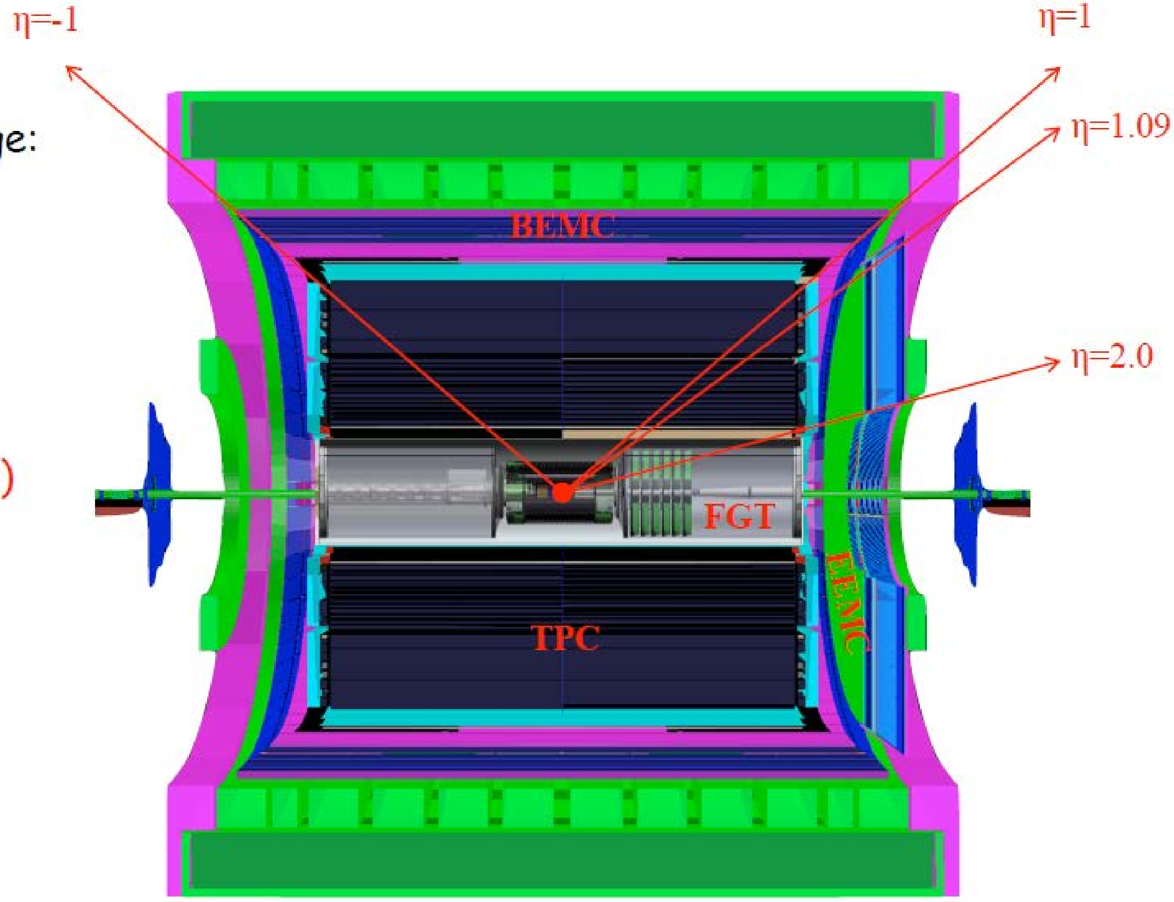
TEST "modified" universality of TMD pdfs!

The STAR Detector at RHIC

from Bernd Surrow

- Calorimetry system with 2π coveragage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
- TPC: Tracking and particle ID ($|\eta|<1.3$)
- FGT: Forward GEM Tracker (Run 13) ($1<\eta<2$)
- ZDC: Relative luminosity and local polarimetry
- BBC: Relative luminosity and Minimum bias trigger

3)



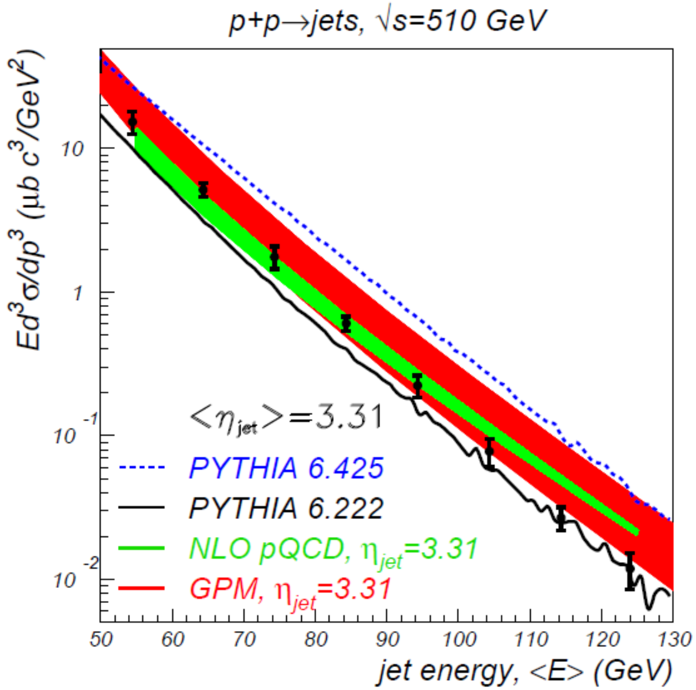
+ A_NDY: forward EMC and HCAL $2.4 < \eta < 4$

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

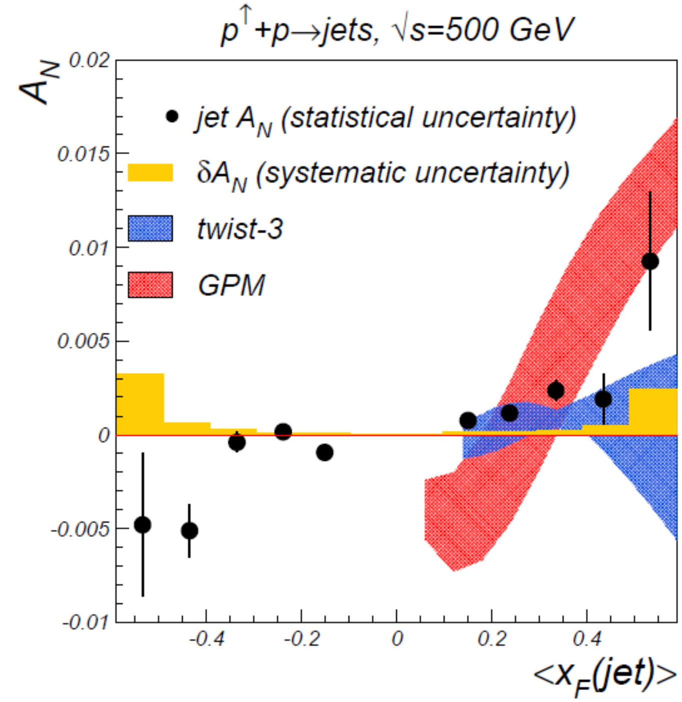
A_N for Jets: Bounds for Quark Sivers Distributions

A_NDY, Phys.Lett. B750 (2015) 660-665

A_NDY Jet-Cross Section



A_NDY Jet-A_N



Generalized Parton Model calculations

M. Anselmino *et al.*, Phys. Rev. D **88**, 054023 (2013).

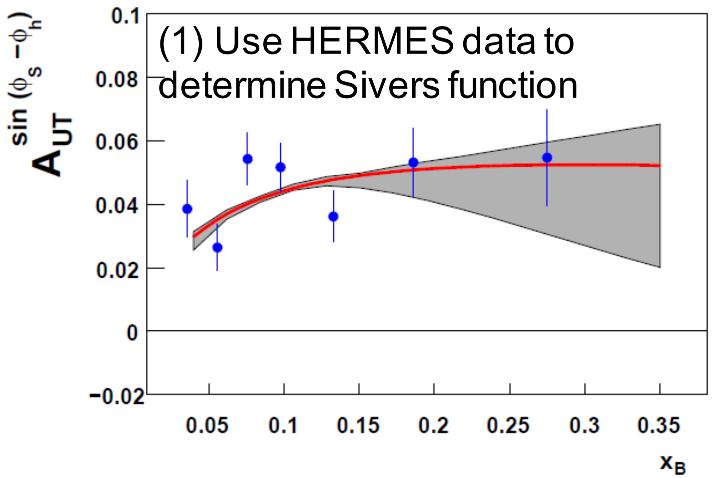
Twist-3 pQCD calculations

L. Gamberg, Z. -B. Kang, A. Prokudin, Phys. Rev. Lett. **110**, 232301 (2013)

A_N for Jets, Direct Photons and Drell-Yan

Twist-3 pQCD calculations

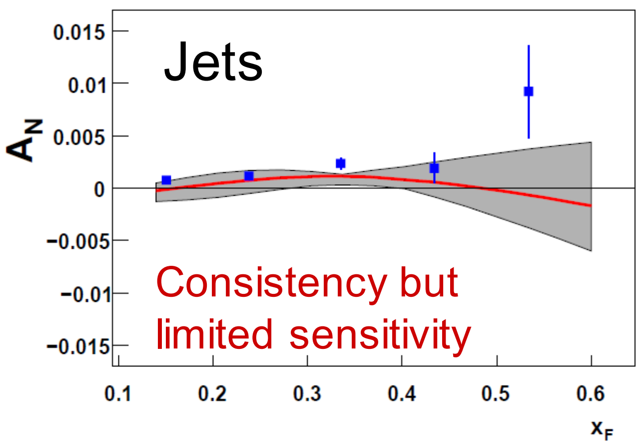
L. Gamberg, Z. -B. Kang, A. Prokudin, Phys. Rev. Lett. **110**, 232301 (2013)

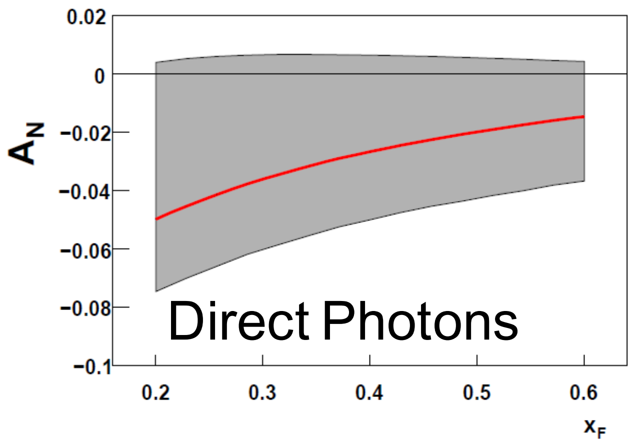


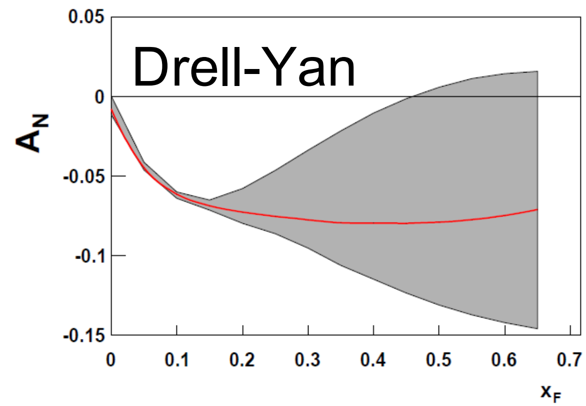
(2) Determine twist-3 3-parton correlation function (ETQS)

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x, k_\perp^2)|_{\rm SIDIS}$$

(3) Compute A_N for pp at $\eta = 3.5$ for jets, direct photons and Drell-Yan lepton pairs.

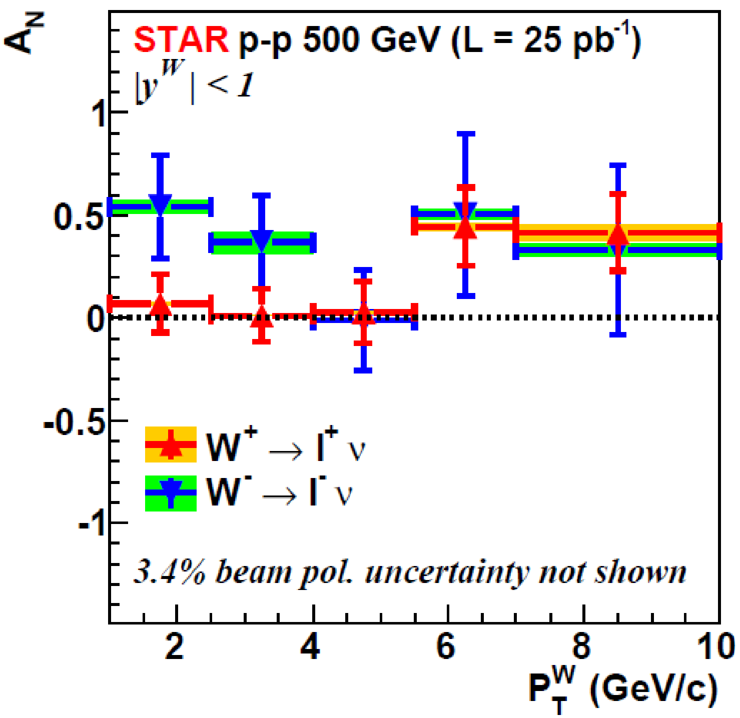






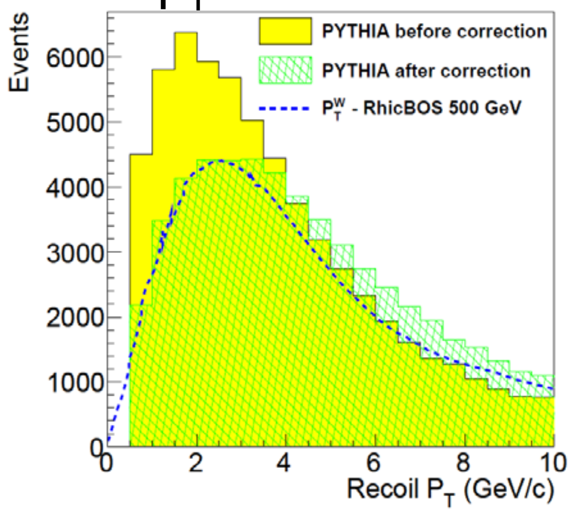
Sivers – A_N for W-Bosons in STAR

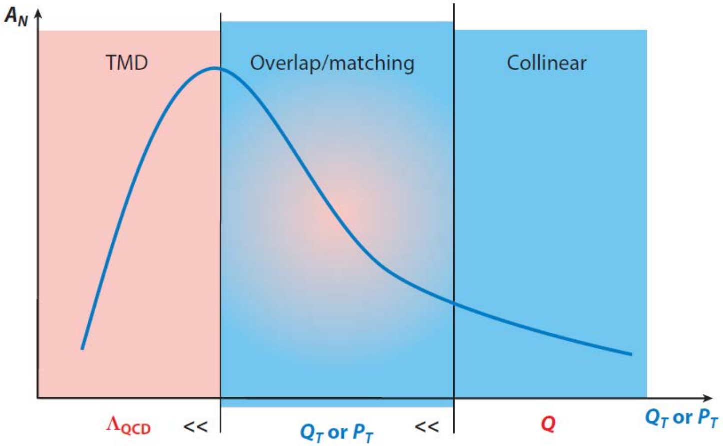
L. Adamczyk, et al., PRL, 116, 132301 (2016)



$p_T > \Lambda_{QCD}$

W-p_T





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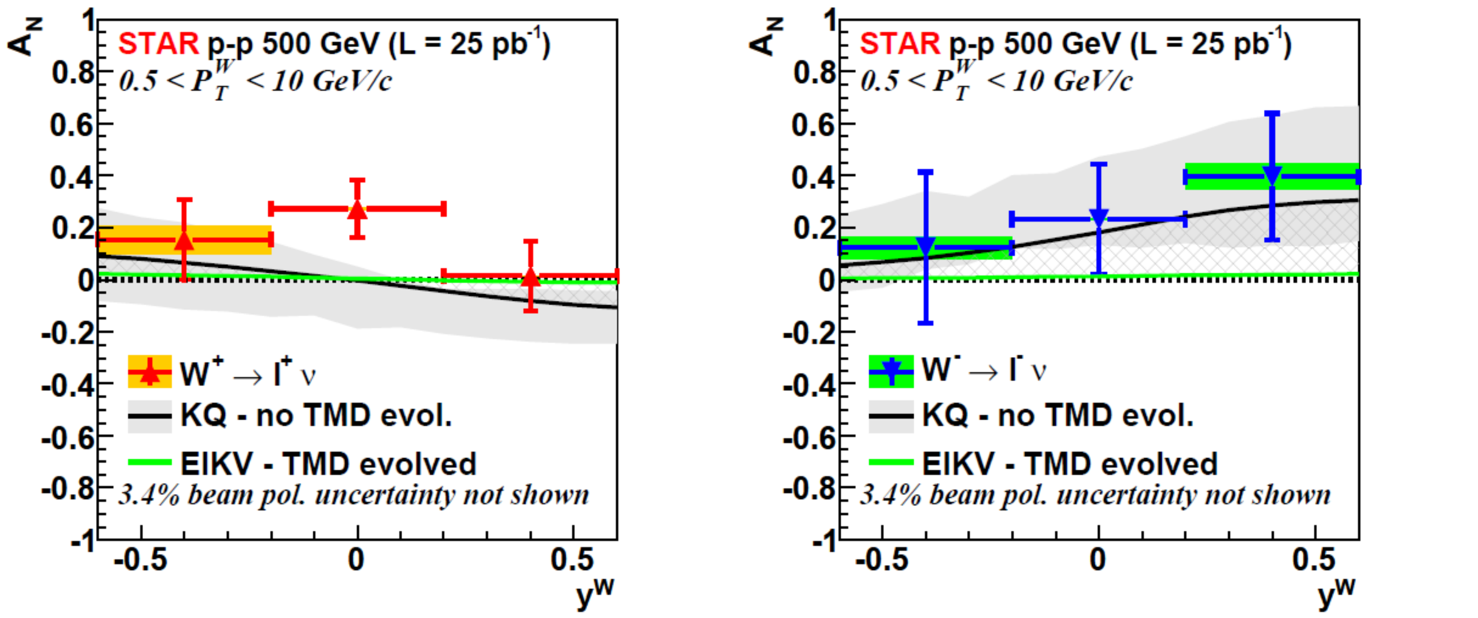
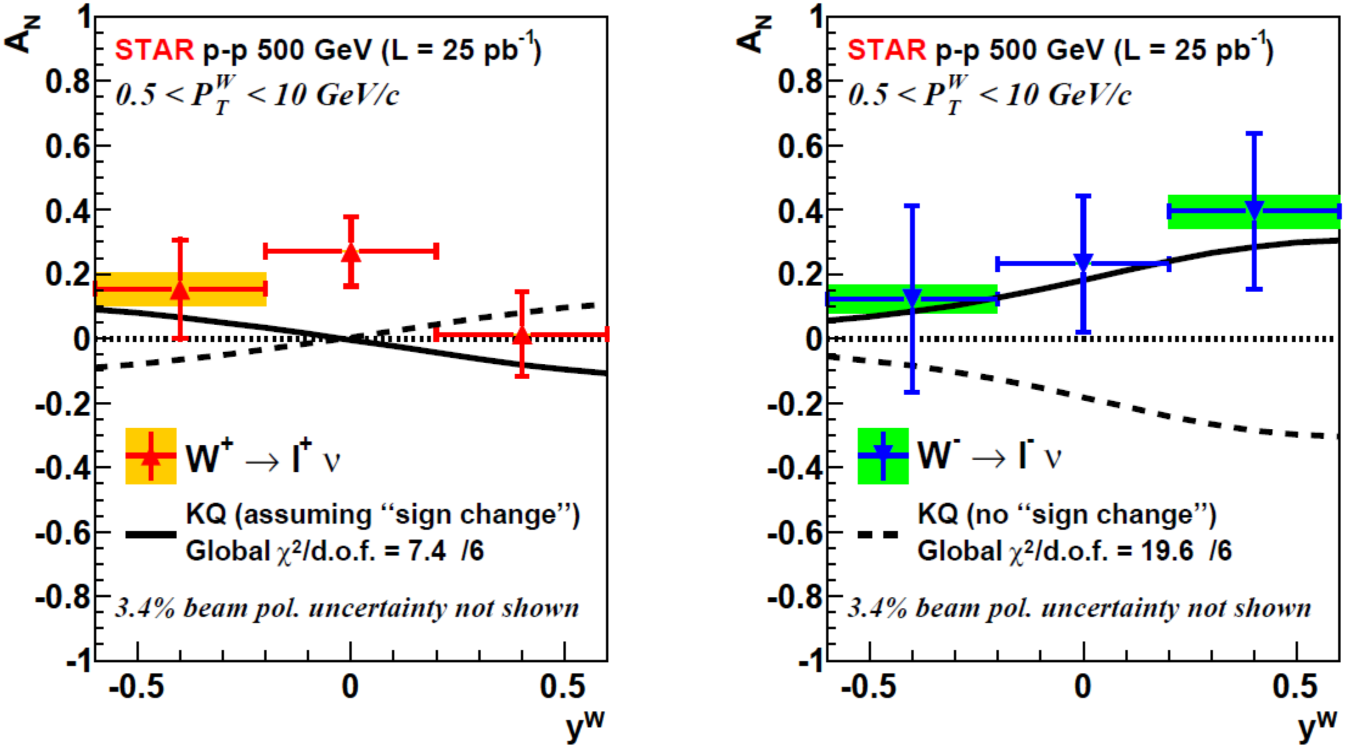


Comparison to two different evolution scenarios:
strong TMD evolution results in A_N~0

Sivers – A_N for W-Bosons in STAR

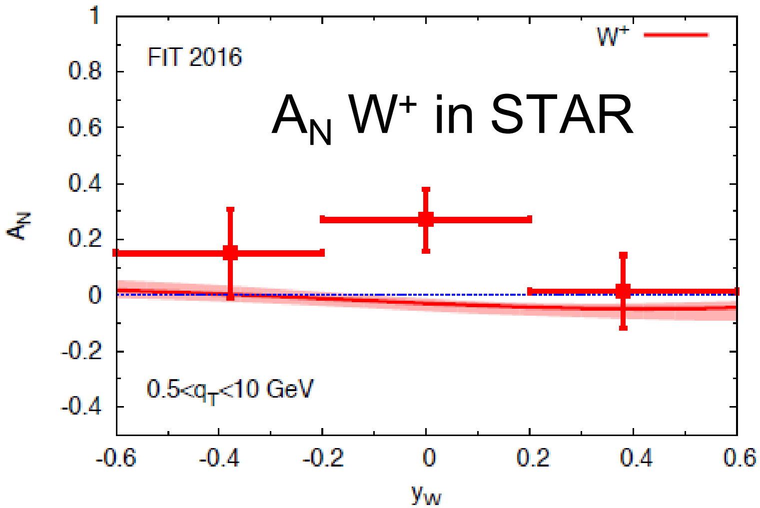
L. Adamczyk, et al., PRL, 116, 132301 (2016)

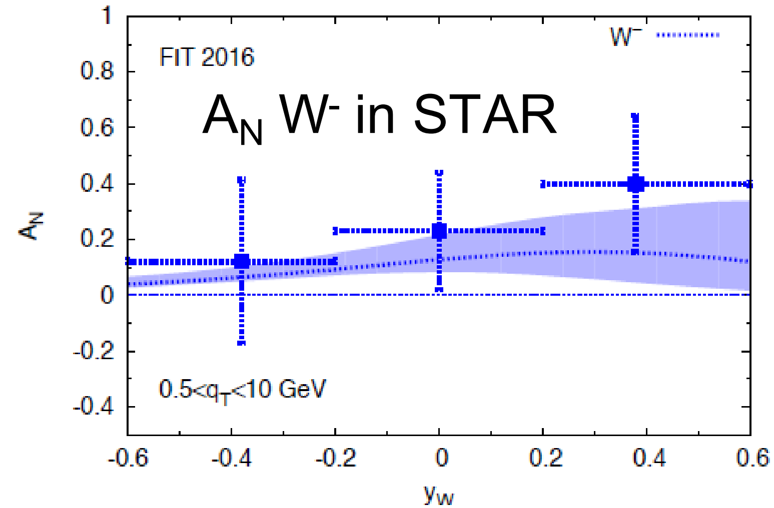


Assuming no evolution + sign change gives better chi2 !

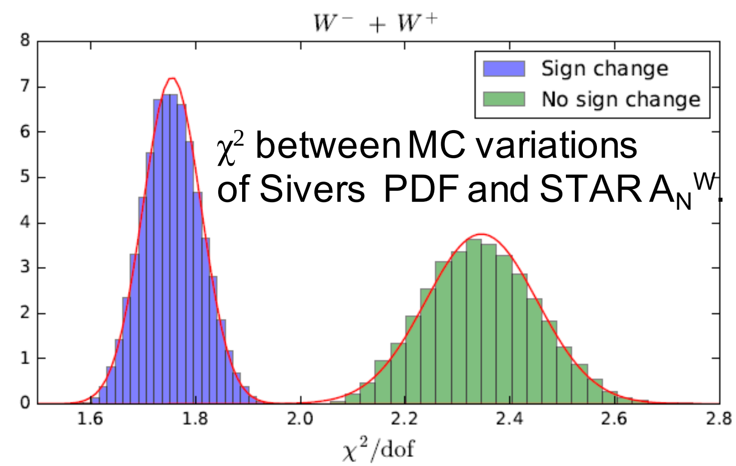
First Results on Sign Change in DY: A_N for W-Production in STAR

Comparison of A_N^W to Sivers from SIDIS by Anselmino, Boglione, D'Alesio, Murgia, JHEP 1704 (2017) 046



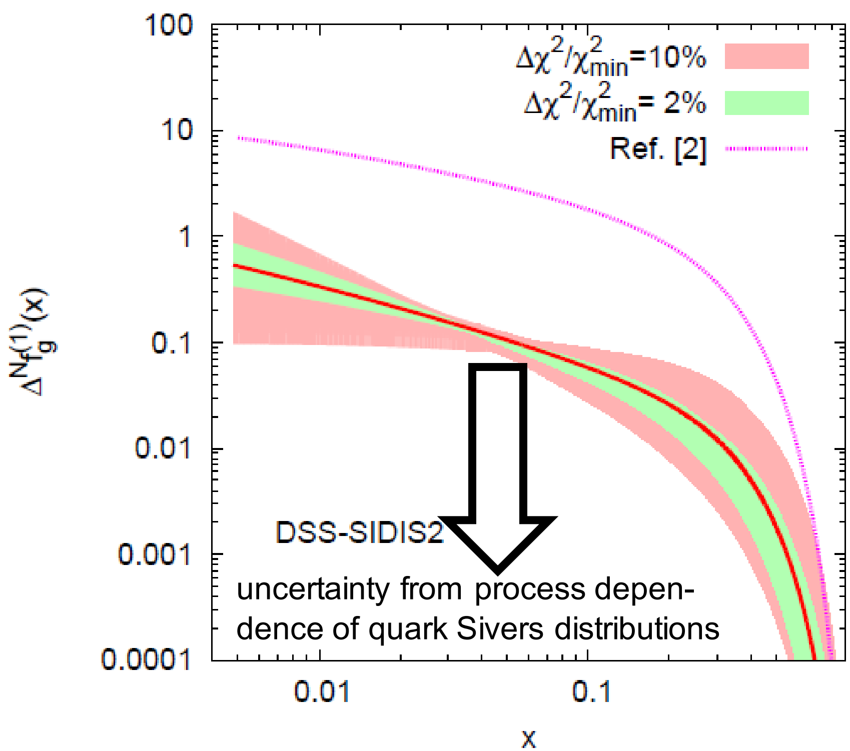


$A_N^{W+/-}$ slightly better compatible with sign change

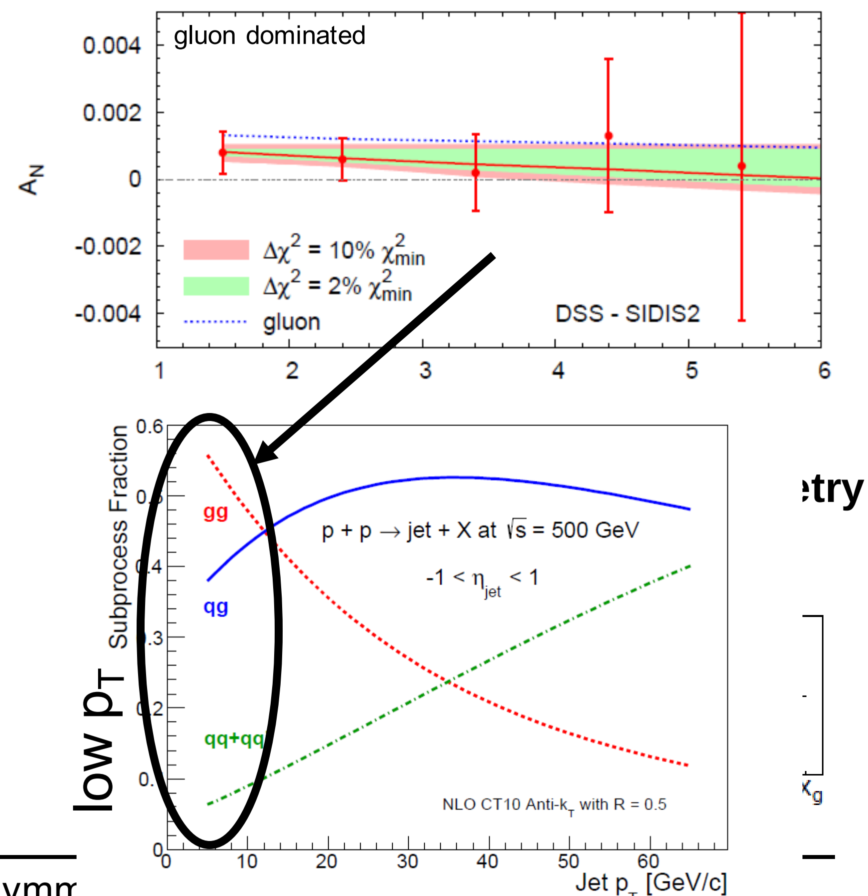


Bound on Gluon Sivers from A_N for Neutral Pions at Mid-Rapidity

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



Fit to PHENIX A_N for π^0
A. Adare et al. PRD90 012006(2014)
(Thesis John Koster, UIUC)



Constraining Transversity

Knowledge of Transversity and Tensor Charge Requires Measurements in p-p, lepton-p and e^+e^-

RBRC Transversity Workshop 2000 ➔

Measure Collins Asymmetries in SIDIS

Measure CFF and IFF asymmetries in Belle

and CFF & IFF in p-p

SIDIS

$\sim \delta q(x) \times CFF(z)$

$\sim \delta q(x) \times IFF(z)$

e^+e^-

$\sim CFF(z_1) \times CFF(z_2)$

$\sim IFF(z_1) \times IFF(z_2)$

pp → jets

$\sim G(x_1) \times \delta q(x_2) \times CFF(z)$

pp → $h^+ + h^- + X$

$\sim G(x_1) \times \delta q(x_2) \times IFF(z)$

pp → $l^+ + l^- + X$

$\sim \delta q(x_1) \times \delta q(x_2)$

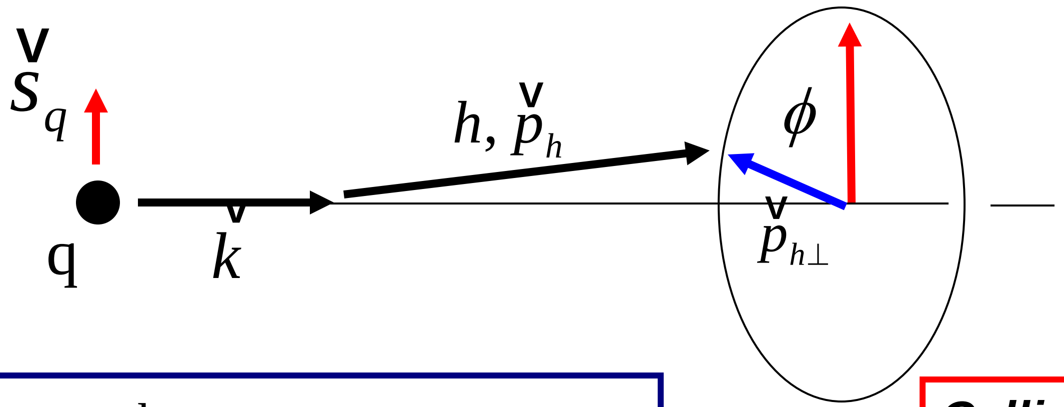
Transversity, δq(x)
Tensor Charge

Theory

Lattice QCD: Tensor Charge = $\Sigma_{q=u,d} \int_0^1 \delta q(x) dx$

Collins Effect in Quark Fragmentation

J.C. Collins, Nucl. Phys. B396, 161(1993)



$\vec{k}$: quark momentum

$\vec{s}_q$: quark spin

$\vec{p}_h$: hadron momentum

$\vec{p}_{h\perp}$: transverse hadron momentum

$z_h = E_h / E_q$

$= 2E_h/\sqrt{s}$: relative hadron momentum

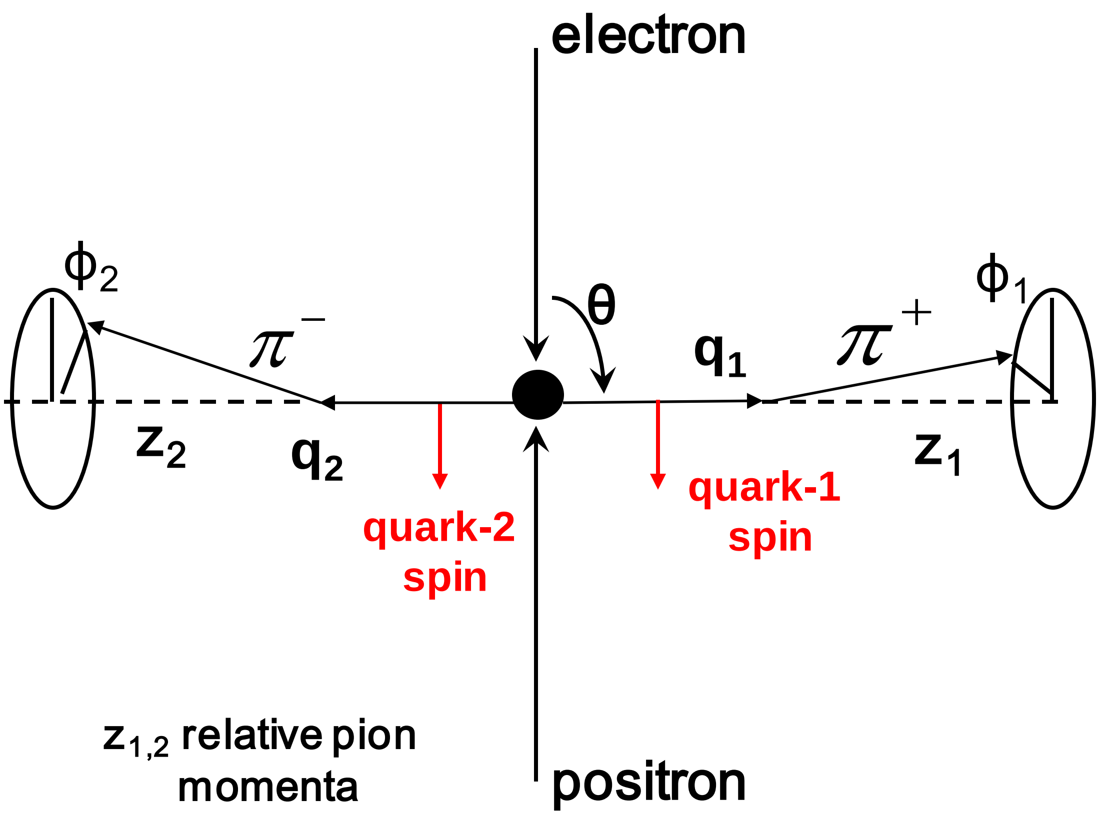
Collins Effect:

Fragmentation of a transversely polarized quark *q* into spin-less hadron *h* carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$

Collins Effect in di-Hadron Correlations In e^+e^- Annihilation into Quarks!



$z_{1,2}$ relative pion momenta

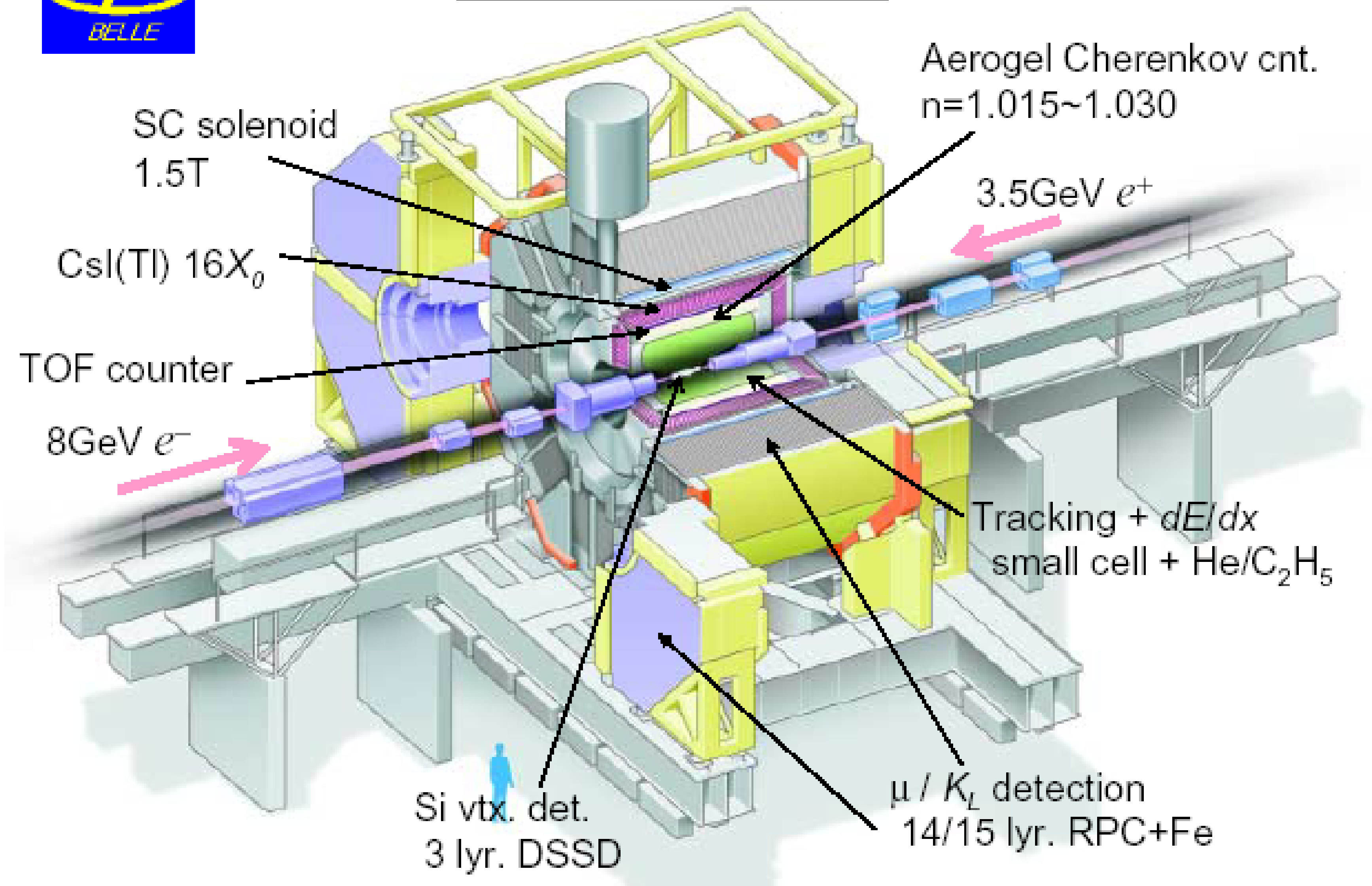
Collins effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements:

$$N_{\pi_1,\pi_2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$$

Experimental requirements:

- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets

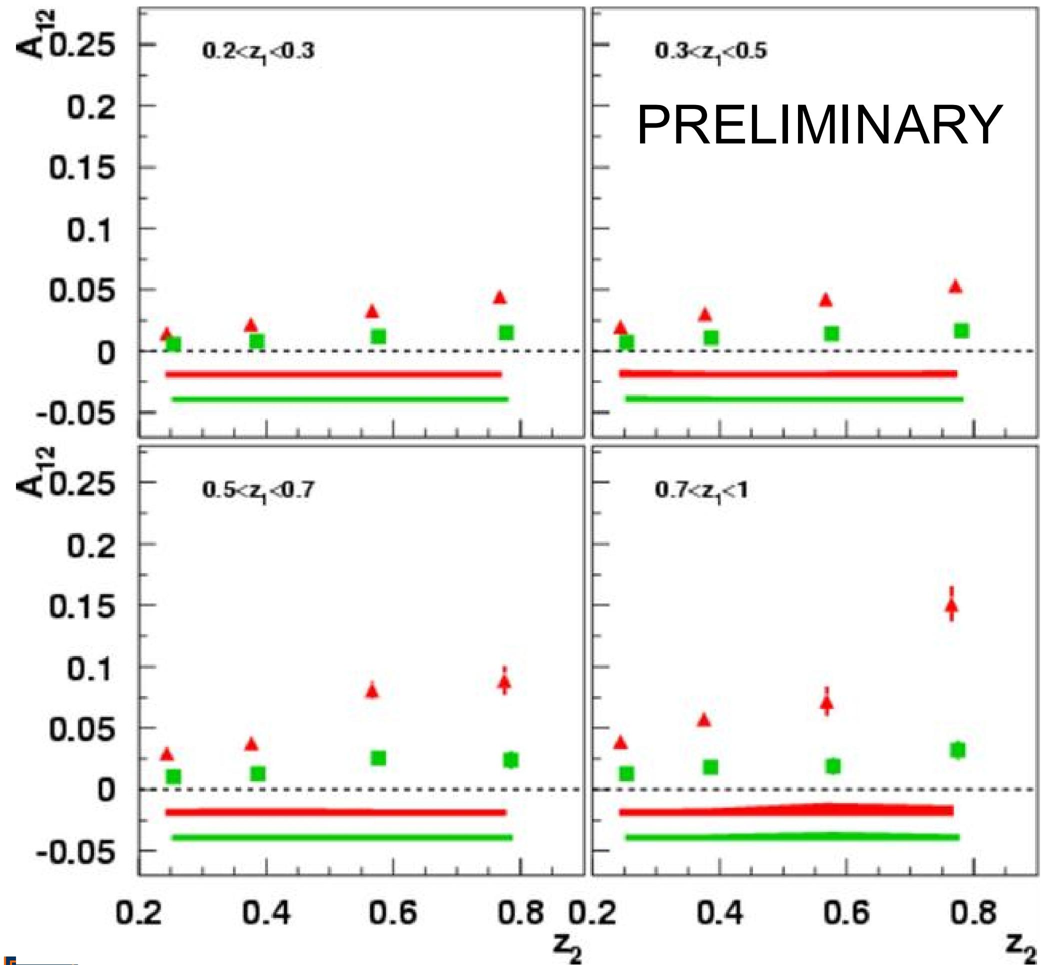
Belle Detector



Good tracking and particle identification!

Observation of the Collins Effect in e^+e^- Annihilation with Belle

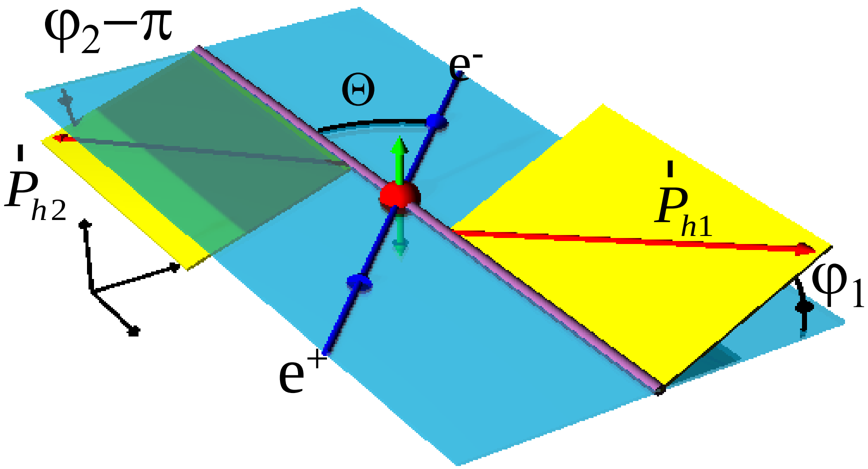
Belle (UIUC/RBRC) group



Collins Asymmetries in e^+e^- annihilation into hadrons

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

$\sim Collins(z_1) \times Collins(z_2)$



$A_{12} \cos(\phi_1+\phi_2)$

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-

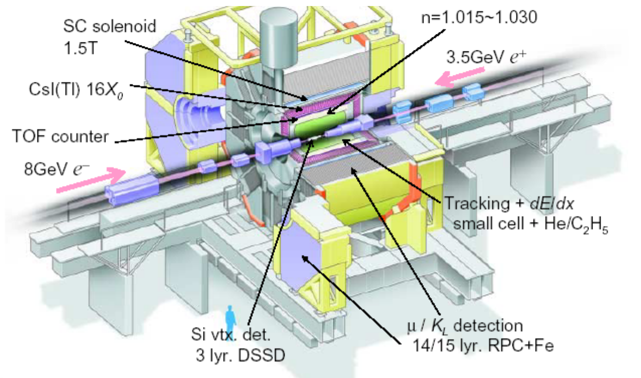
Program:

QCD analysis of Collins asymmetries in SIDIS (HERMES & COMPASS) + Collins asymmetries in e+e- (Belle)

➔ extract quark transversity distributions and Collins fragmentation functions

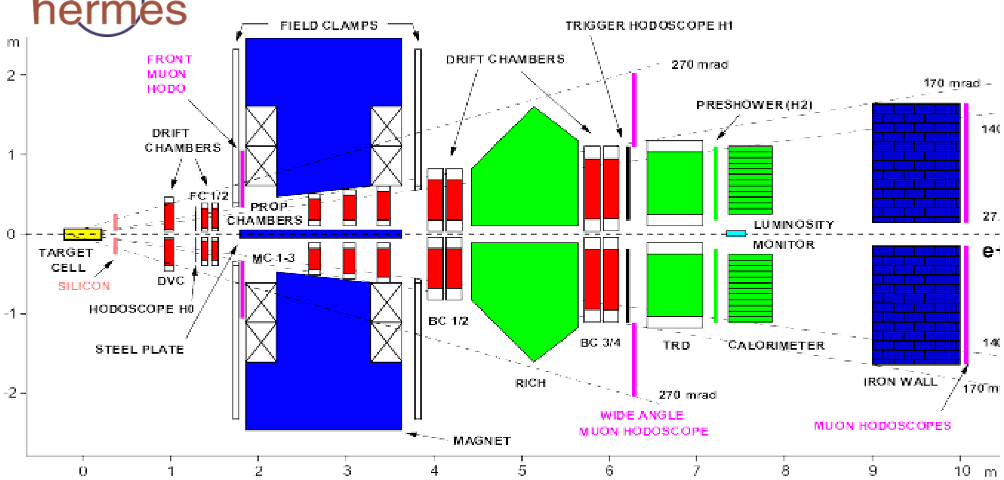
BELLE

$\sqrt{s}$=10 GeV $e^+ + e^- \rightarrow \pi^+ + \pi^- + X$



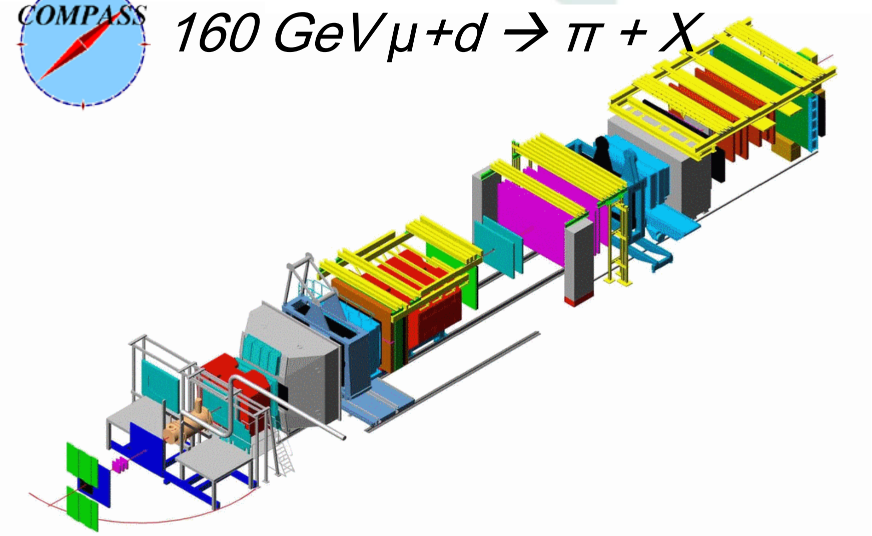
hermes

27.5 GeV $e+p \rightarrow \pi + X$



COMPASS

160 GeV $\mu+d \rightarrow \pi + X$



Transversity & Tensor Charge Extracted With TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Experiment	hadron	Target	dependence	# ndata	χ^2	$\chi^2/ndata$
COMPASS [97]	π^+	LiD	x	9	11.16	1.24
COMPASS [97]	π^-	LiD	x	9	9.08	1.01
COMPASS [97]	π^+	LiD	z	8	3.26	0.41
COMPASS [97]	π^-	LiD	z	8	7.29	0.91
COMPASS [97]	π^+	LiD	$P_{h\perp}$	6	4.19	0.70
COMPASS [97]	π^-	LiD	$P_{h\perp}$	6	4.50	0.75
COMPASS [96]	π^+	NH_3	x	9	21.46	2.38
COMPASS [96]	π^-	NH_3	x	9	6.23	0.69
COMPASS [96]	π^+	NH_3	z	8	7.80	0.98
COMPASS [96]	π^-	NH_3	z	8	10.29	1.29
COMPASS [96]	π^+	NH_3	$P_{h\perp}$	6	3.82	0.64
COMPASS [96]	π^-	NH_3	$P_{h\perp}$	6	3.85	0.64
HERMES [95]	π^+	H	x	7	5.37	0.77
HERMES [95]	π^-	H	x	7	12.61	1.80
HERMES [95]	π^+	H	z	7	3.04	0.43
HERMES [95]	π^-	H	z	7	3.23	0.46
HERMES [95]	π^+	H	$P_{h\perp}$	6	1.60	0.27
HERMES [95]	π^-	H	$P_{h\perp}$	6	4.82	0.80
JLAB [9]	π^+	^{3}He	x	4	3.90	0.98
JLAB [9]	π^-	^{3}He	x	4	3.11	0.78
				140	130.65	0.93

Experiment	Observable	dependence	# ndata	χ^2	$\chi^2/ndata$
BELLE [12]	A_0^{UL}	z	16	13.02	0.81
BELLE [12]	A_0^{UC}	z	16	11.54	0.72
$BABAR$[98]	A_0^{UL}	z	36	34.61	0.96
$BABAR$[98]	A_0^{UC}	z	36	15.17	0.42
$BABAR$[98]	A_0^{UL}	$P_{h\perp}$	9	9.09	1.01
$BABAR$[98]	A_0^{UC}	$P_{h\perp}$	9	4.33	0.48
			122	87.76	0.72

Data sets from SIDIS (HERMES, JLab, COMPASS) and e^+e^- (Belle, BaBar)

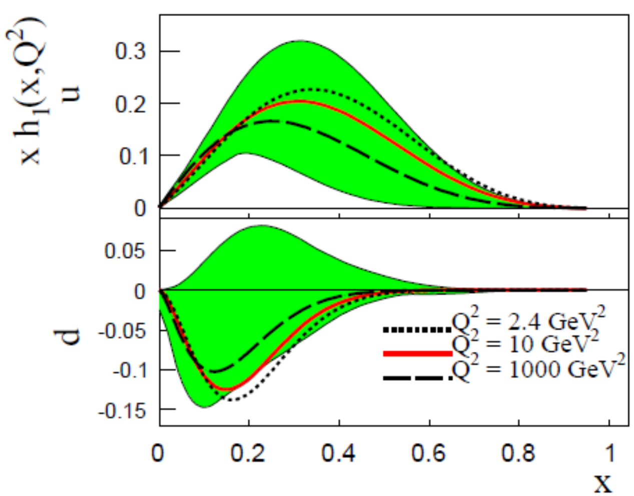
Fit describes data sets well!

Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets

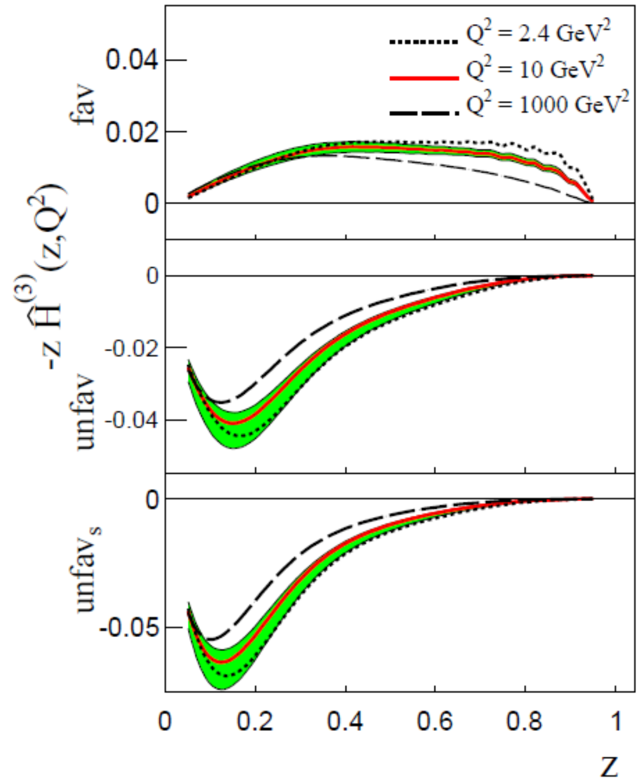
Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Results given at
Q^2=2.4, 10 and 1000 GeV^2

up and down
transversity distributions



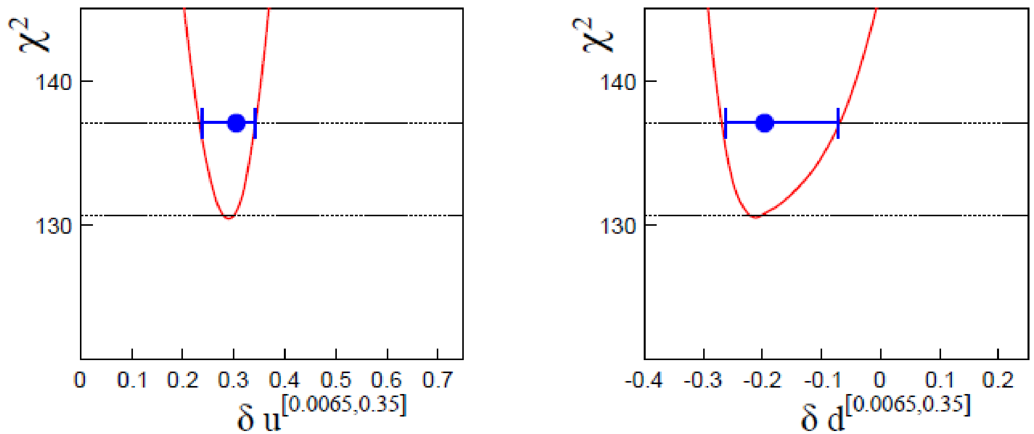
Favored and unfavored
Collins FF



Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

up and down contributions to tensor charge



Integrals in data region

$$\delta u^{[0.0065,0.35]} = +0.30^{+0.04}_{-0.07}$$

$$\delta d^{[0.0065,0.35]} = -0.20^{+0.12}_{-0.07}$$

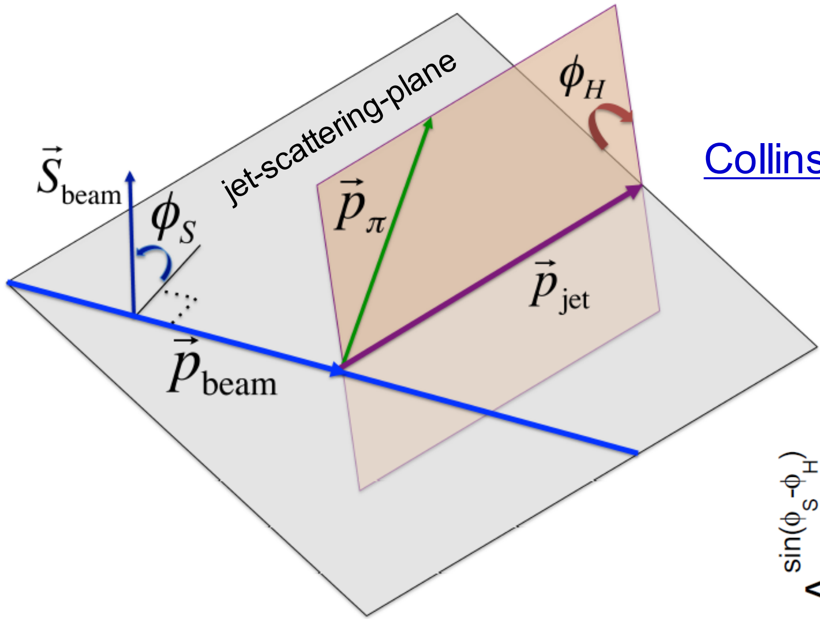
Integrals in [0,1]

$$\delta u^{[0,1]} = +0.39^{+0.07}_{-0.11}$$

$$\delta d^{[0,1]} = -0.22^{+0.14}_{-0.08}$$

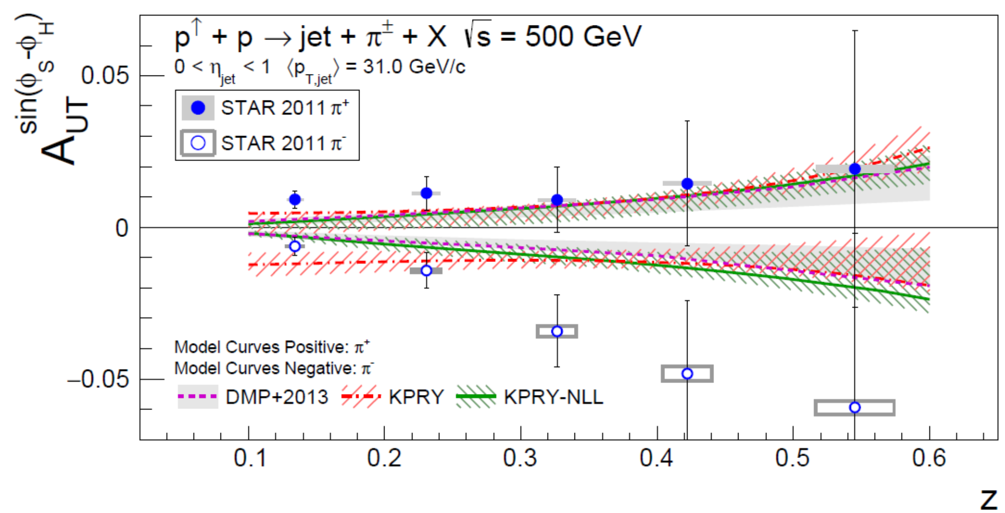
Evolution has significant effect
Need higher precision SIDIS data: COMPASS, Jlab 12 GeV
Need to extend data range to high and low x

Azimuthal asymmetries for jets and jets + hadron



$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$
$$\sim d\Delta\sigma_0 \sin(\phi_S)$$ Sivers
Collins $$+ d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H)$$
$$+ d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)$$

Charged pion Collins-modulations in jets

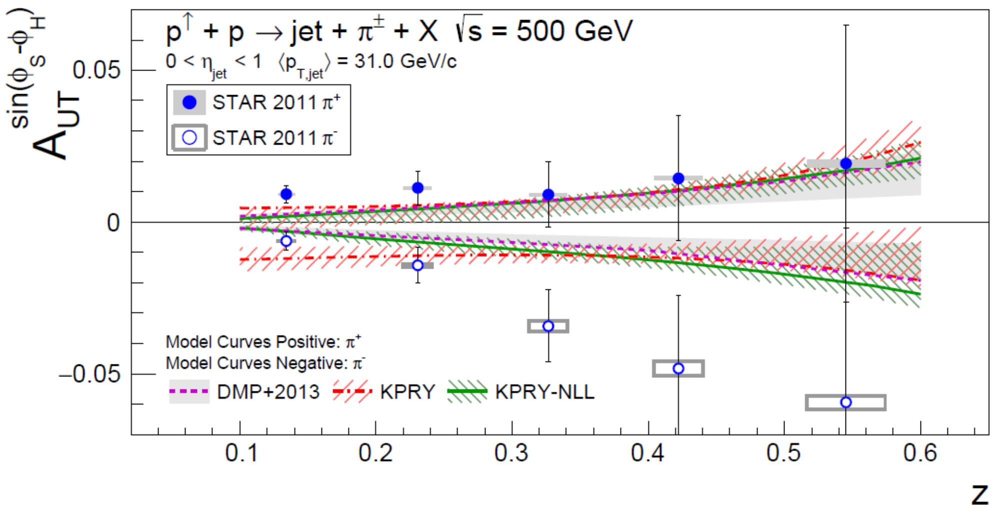


First measurement of Collins effect in jets!

STAR, Phys.Rev. D97 (2018) no.3, 032004

Collins in Jets in p-p at RHIC and e-p at EIC

Charged pion Collins-modulations in jets



First measurement of Collins asymmetries involving transversity distributions at high scales!

Comparison of e+e- & SIDIS extraction of transversity with e+e- & p-p extraction will provide information on process dependence.

Significantly more data available!

Collins-in-jet-channel will be also available at EIC!

STAR, Phys.Rev. D97 (2018) no.3, 032004!

Measurements of Transversity and Tensor charge with Transverse Momentum Independent Functions

$\bar{p}^{\uparrow} p^{\downarrow} \longrightarrow l + \bar{l} + X$ (PAX, FAIR) Drell Yan → req. polarized anti-protons

$p^{\uparrow} p^{\downarrow} \longrightarrow jet + X$ (RHIC) need to improve systematics on rel. luminosity

$ep^{\uparrow} \longrightarrow e'\Lambda^{\uparrow} + X$ (SIDIS at JLab-12 GeV, EIC) need Lambda-FF → e^+e^-

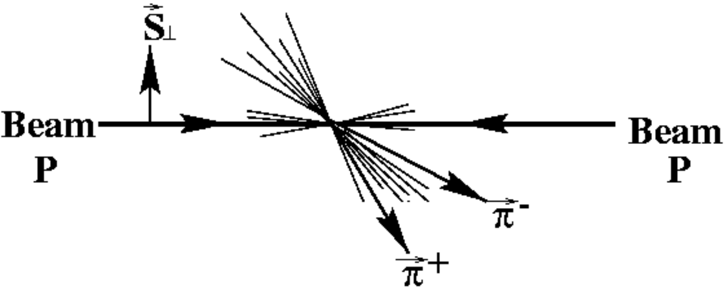
$pp^{\uparrow} \longrightarrow \Lambda^{\uparrow} + X$ (RHIC, JPARC) need Lambda-FF → e^+e^-

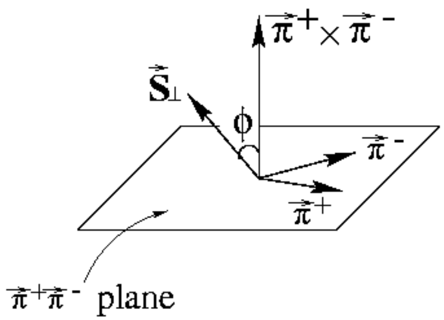
$ep^{\uparrow} \longrightarrow \pi^- + \pi^+ + X$ (SIDIS at JLab-12 GeV, EIC) need IFF → e^+e^-

$pp^{\uparrow} \longrightarrow \pi^- + \pi^+ + X$ (RHIC, JPARC) need IFF → e^+e^-

Well know co-linear evolution!

Transversity Quark Distributions at RHIC: Di-Hadron “Interference Fragmentation Functions





$N^{\rightarrow}$: Pion Pair Yield

$\delta q(x)$: Transversity quark DFs

$\delta\hat{q}(z)$: IFF Fragmentation Func.

IFF Asymmetries in proton-proton collisions

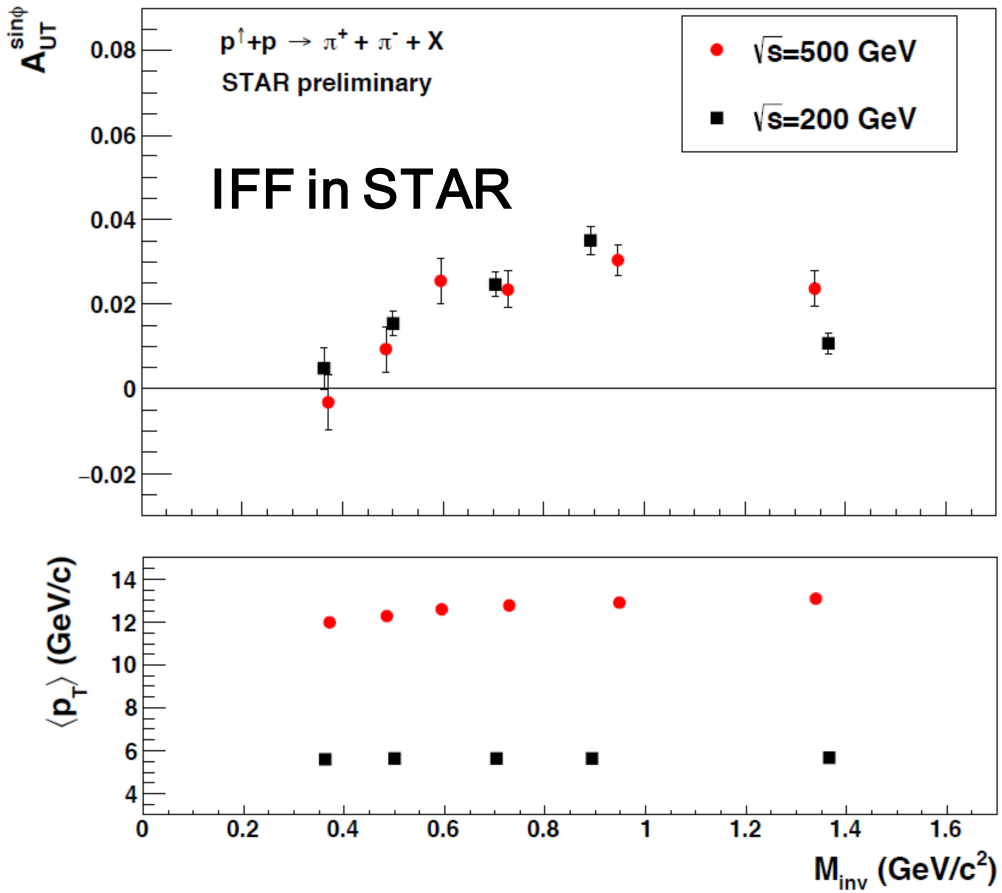
$$p+p \rightarrow \pi^{+} + \pi^{-} + X$$

~ Transversity (x) x IFF(z)

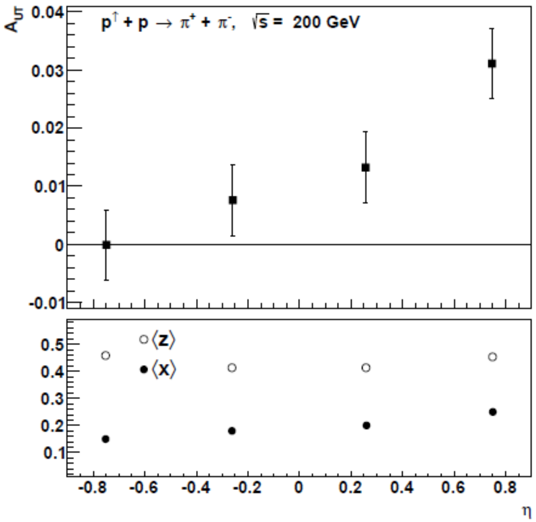
➔ **k⊥, p⊥ integrate out**

$$A_{UT} \propto \delta q(x_1) G(x_2) \cos(\phi) IFF(z)$$

First Measurement of di-Hadron IFF Asymmetries in STAR M. Ablikim et al. Phys.Rev.Lett. 115(2015)242501



η-dependence

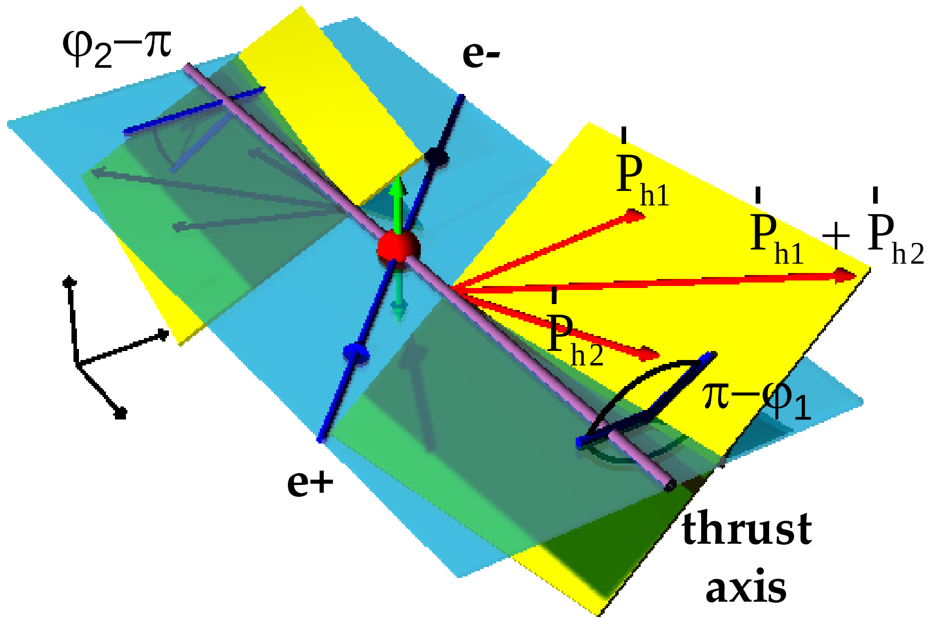


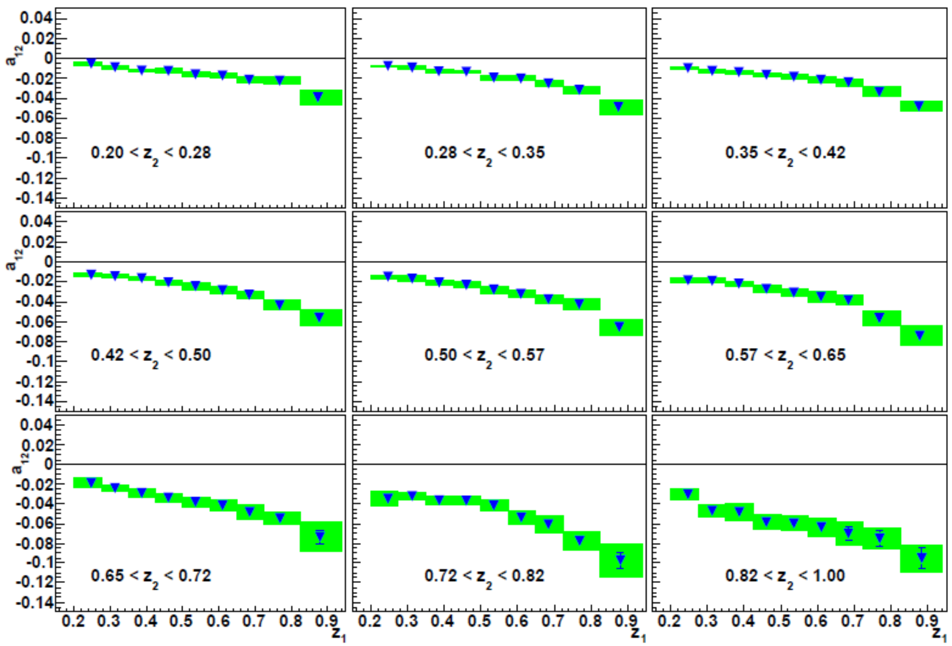
No TMD Factorization & process dependence well understood.

With upgrades, RHIC can do high precision measurement with forward upgrades including high x coverage !

IFF measurement at BELLE

A. Vossen et al., Phys. Rev. Lett. 107(2011)





$$e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$$

$$A \propto H_1^{\sphericalangle}(z_1, m_1)H_1^{\sphericalangle}(z_2, m_2)\cos(\phi_1 + \phi_2)$$

Artru and Collins, *Z. Phys. C69, 277 (1996)*

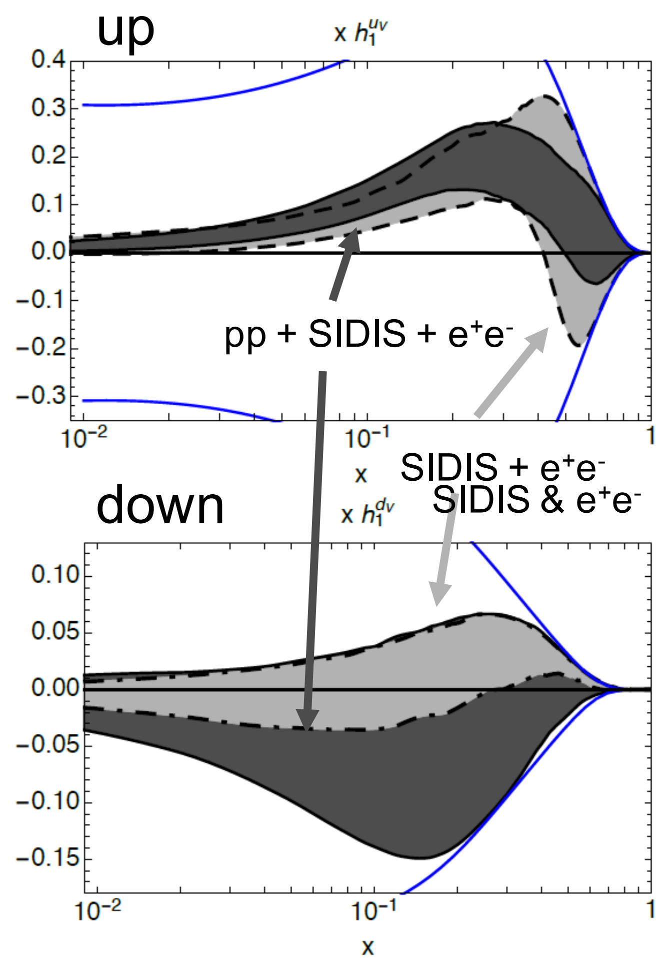
Boer, Jakob, and Radici, PRD67, 094003 (2003)

No double ratios needed to cancel radiative and acceptance effects!

Transversity First Extraction using IFF Data From SIDIS, e+e- and pp

M. Radici and A. Bacchetta arXiv:1802.052

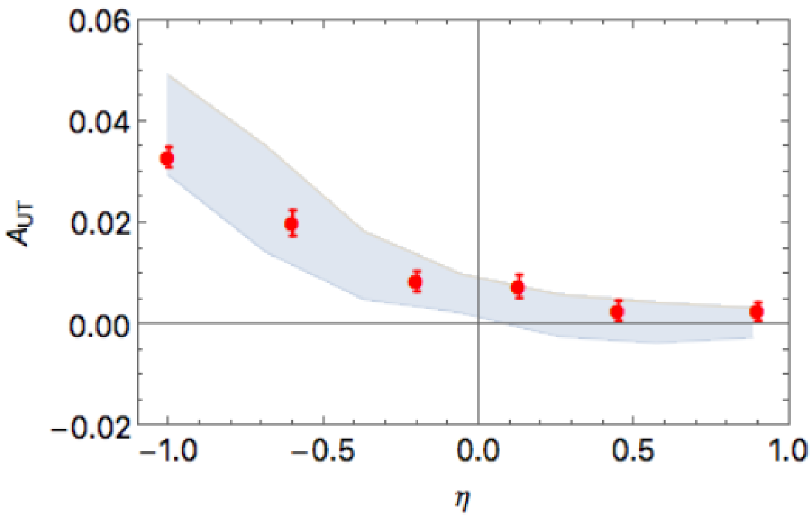
- o use standard colinear factorization for global analysis.
- o do not require information on p_T dependence of pdfs.
- o unpolarized di-hadron fragmentation currently taken from Pythia. (New data from Belle and future pp data on unpol. IFF will remove this model dependence).



Transversity Extraction using IFF

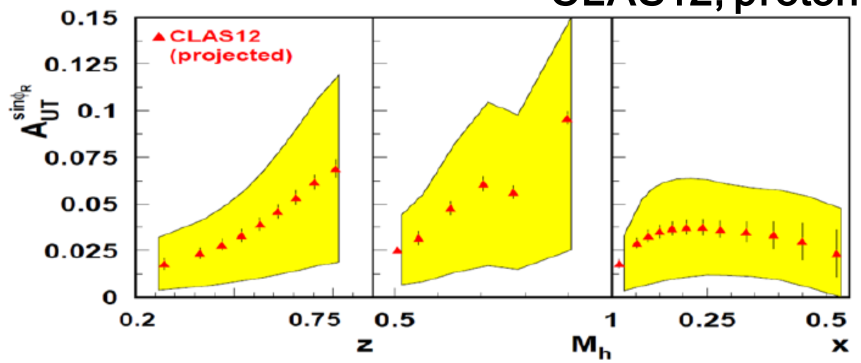
from Radici, Pisano Eur.Phys.J. A52 (2016) no.6, 155

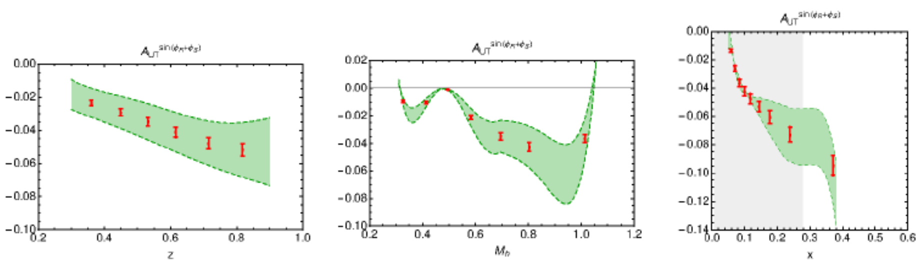
Comparison of prediction based on fit to SIDIS and e+e- IFF data & STAR IFF asymmetry data in p-p



Comparison of projections for CLAS12 and SOLID. Experimental errors vs uncertainties from fit to SIDIS and e^+e^- IFF data

CLAS12, proton





SOLID, He-3

Timeline of Transversity Measurements

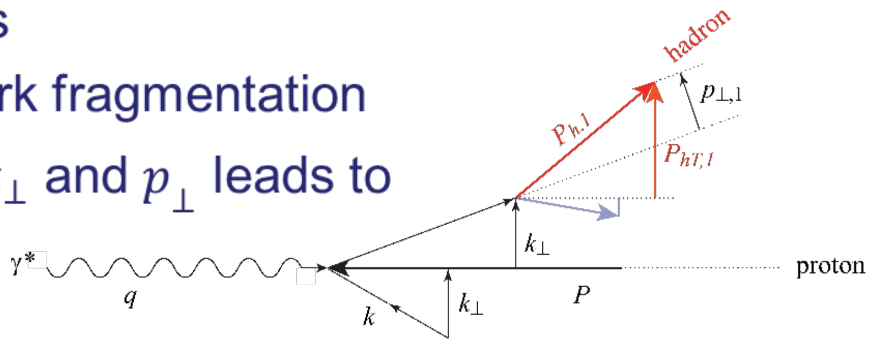
	1991	2002-2008	2009-2015	2016-2020
p+p	**E704, 1991** **Large forward SSA**	**STAR, PHENIX, BRAHMS** **Inclusive A_N**	**RHIC** **Collins in jets** **RHIC** **IFF**	
SIDIS		HERMES COMPASS Collins , (IFF)	COMPASS proton-target, CFF+IFF JLab ^{3}He	COMPASS deuteron-target CFF+IFF JLab 12 GeV Collins, IFF
$e^+ + e^-$		BELLE Collins FF	BELLE, Babar, BESII Collins, IFF, p_T dependence, π and K	BELLE II p_T dependence

TMD in pp Summary

- Large SSA for inclusive hadron production.
- First bounds on gluon and quark Sivers. Precision will greatly benefit from forward upgrades (future sPHENIX).
- First measurements of TMDs in jets.
- Non-TMD processes are available to constrain quark transversity. Within the next few years high precision measurements using di-hadron interference fragmentation functions will become available (from existing STAR data sets).
- We can aim to extract the tensor charge in an experimentally and theoretically clean way and compare to lattice QCD!

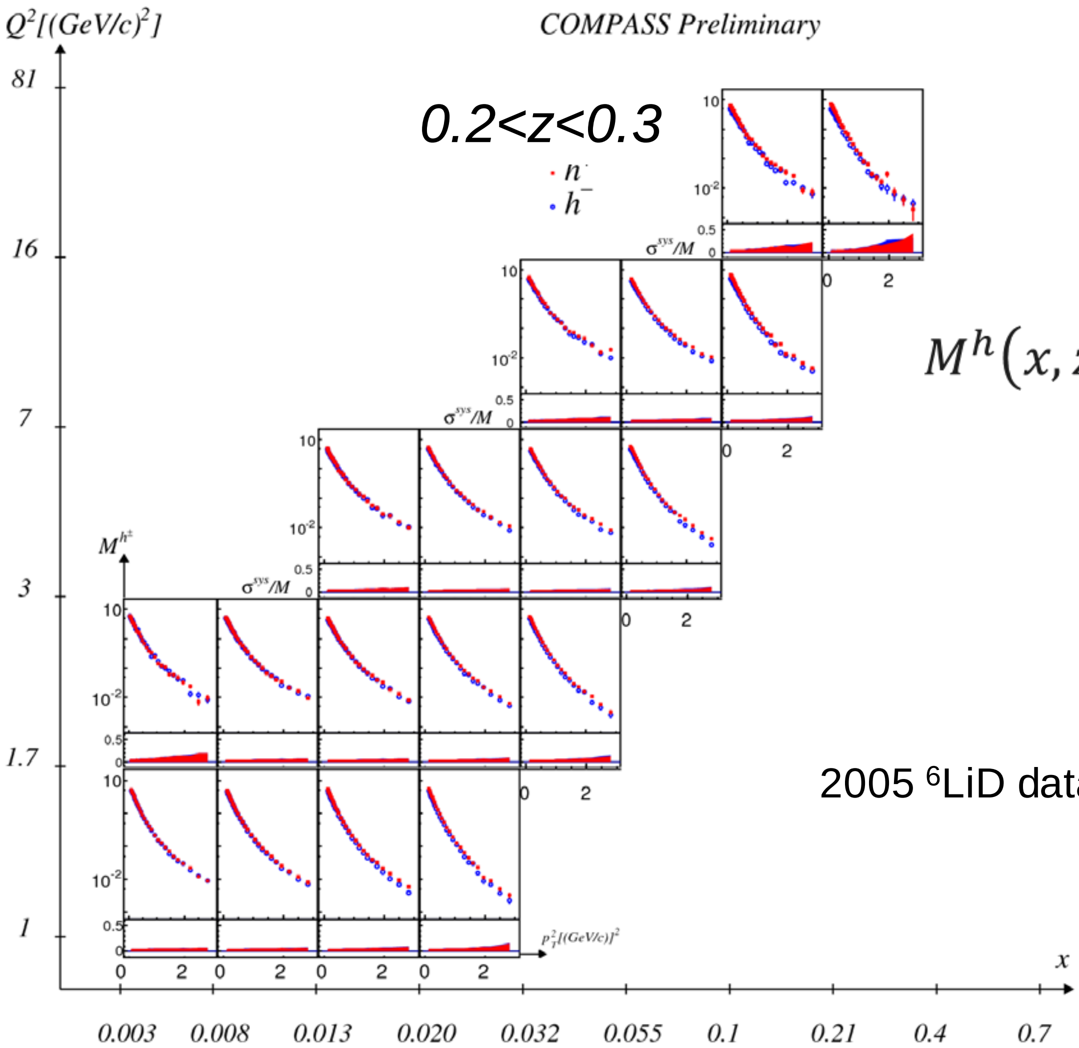
Transverse Momentum Dependence in the Unpolarized Cross Section

- The cross-section dependence on transverse hadron momentum, P_{hT}, results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



- The azimuthal modulations in the unpolarized cross-sections originate from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

Hadron Multiplicities vs x, Q^2, z and p_{hT}



$$M^h\left(x, z, P_{hT}^2; Q^2\right) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2}$$

2005 ^{6}LiD data, COMPASS preliminary at Spin 2014

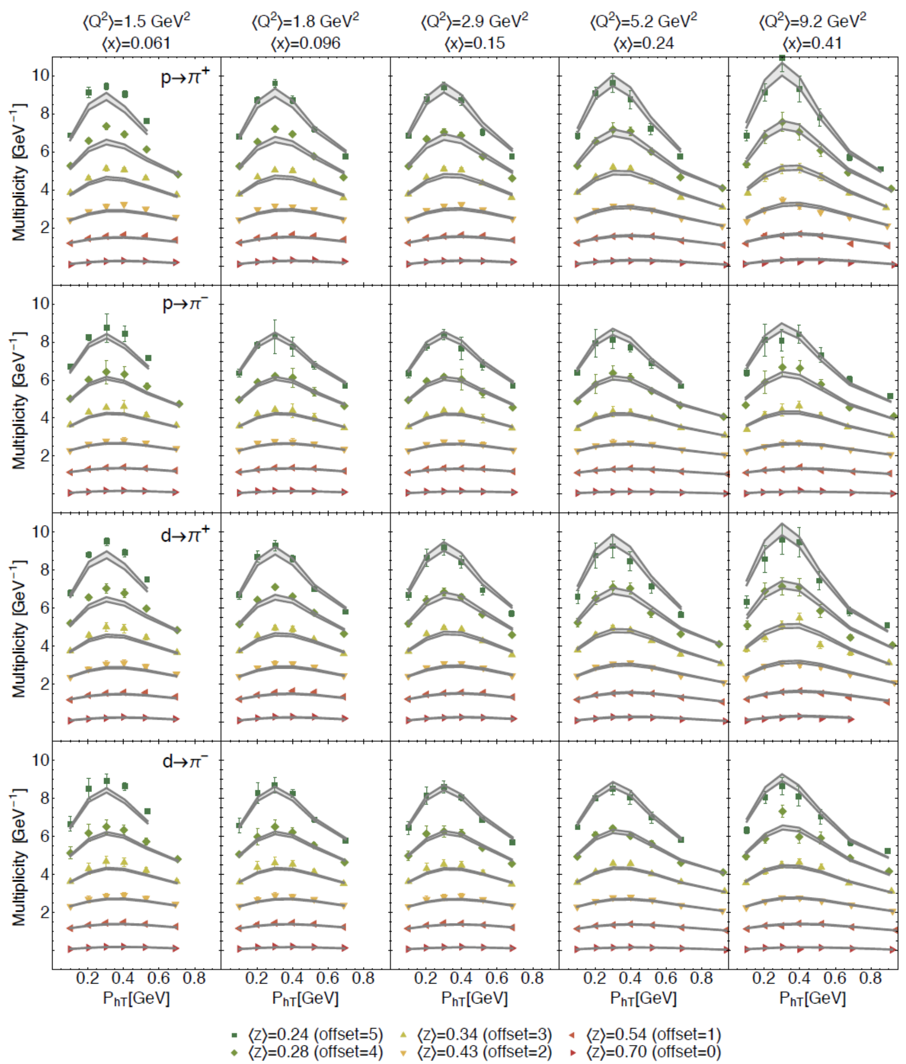
Global Analysis of Unpolarized TMD Multiplicities in SIDIS, DY and Z-Boson Production

Bacchetta, Delcarro, Pisano, Radici, Signori
JHEP 1706 (2017) 081

HERMES & COMPASS SIDIS
Multiplicities vs p_T

E288 and E605
DY cross sections vs q_T

D0 and CDF
Z-Boson cross sections vs q_T



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HERMES & COMPASS SIDIS
Multiplicities vs p_T

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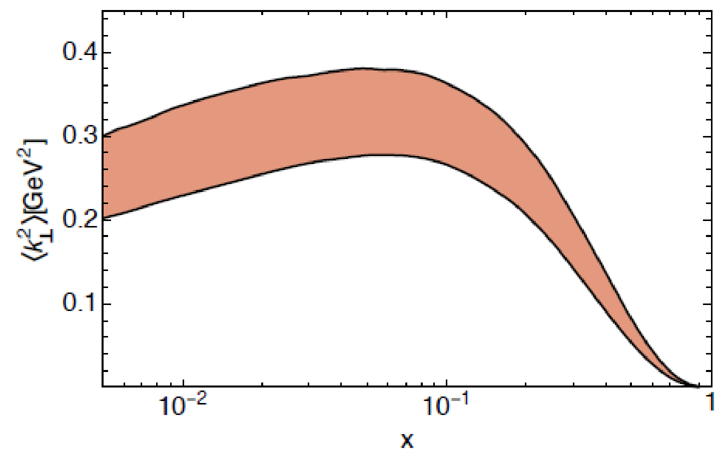
D0 and CDF
Z-Boson cross sections vs q_T

Average parton $k^2_\perp$



Average $P^2_\perp$ picked up in fragmentation