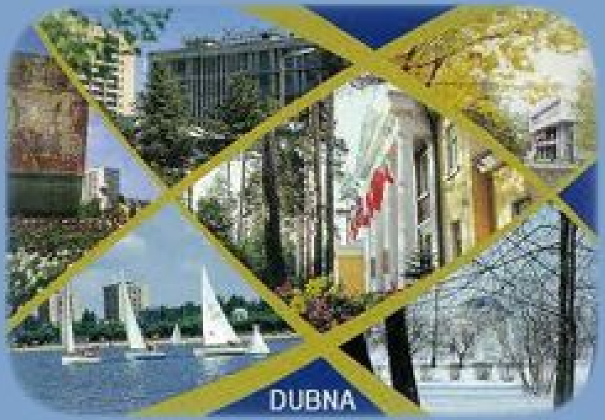


SPIN 2012, Dubna, Russia,

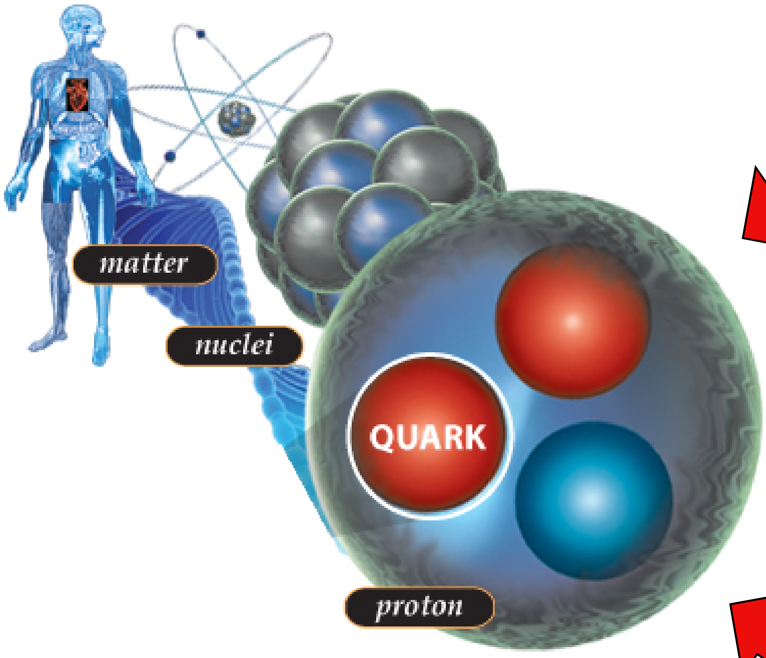
September 17-22, 2012

QCD and Spin Effects

Alexei Prokudin

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Exploring the nucleon: a fundamental quest

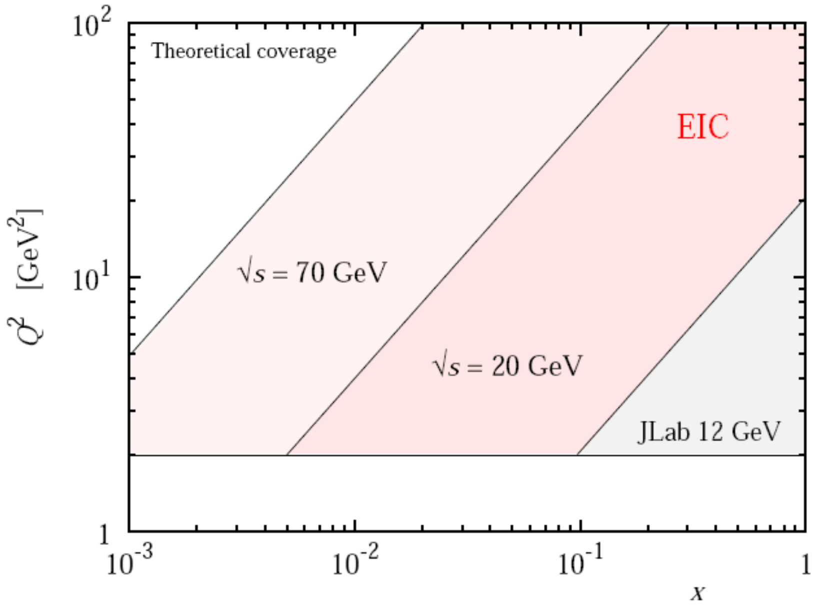


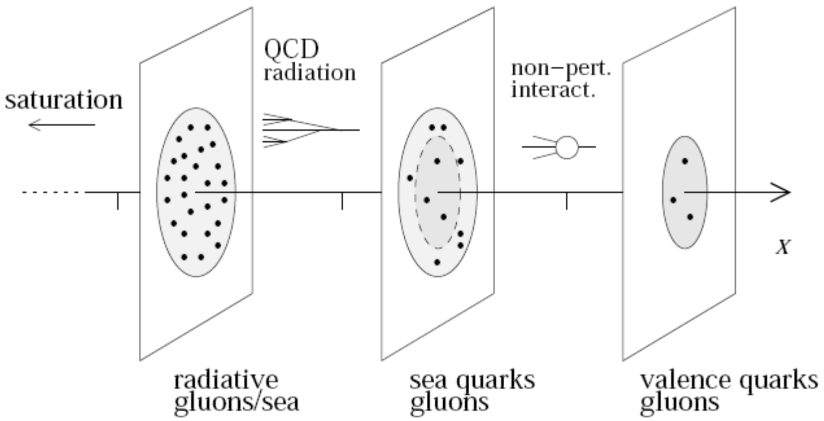
Know what we are made of !

Understand the strong force: "QCD"

Use protons as tool for discovery (e.g. LHC)

Nucleon landscape





Plot courtesy of Christian Weiss

Nucleon is a many body dynamical system of quarks and gluons

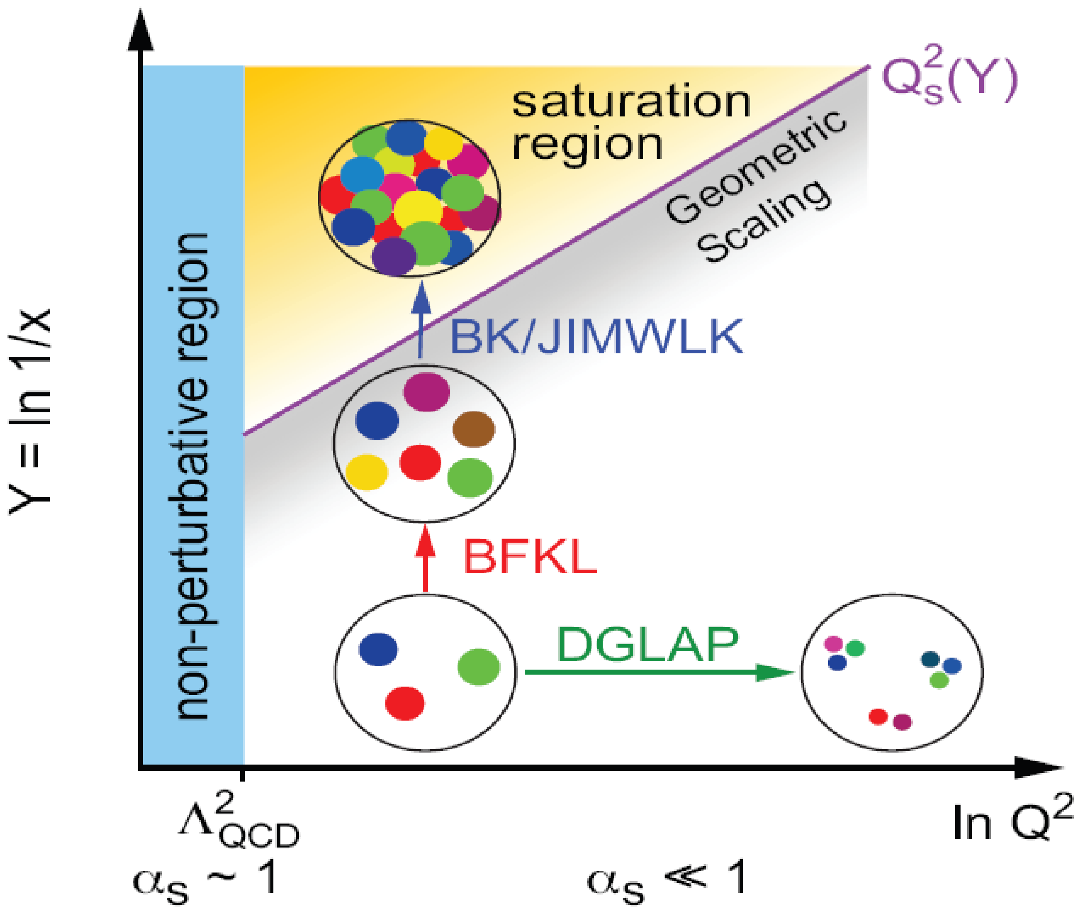
Changing x we probe different aspects of nucleon wave function

How partons move and how they are distributed in space is one of the future directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions and Transverse Momentum Dependent distributions
See talk by Peter Kroll

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

Nucleon landscape

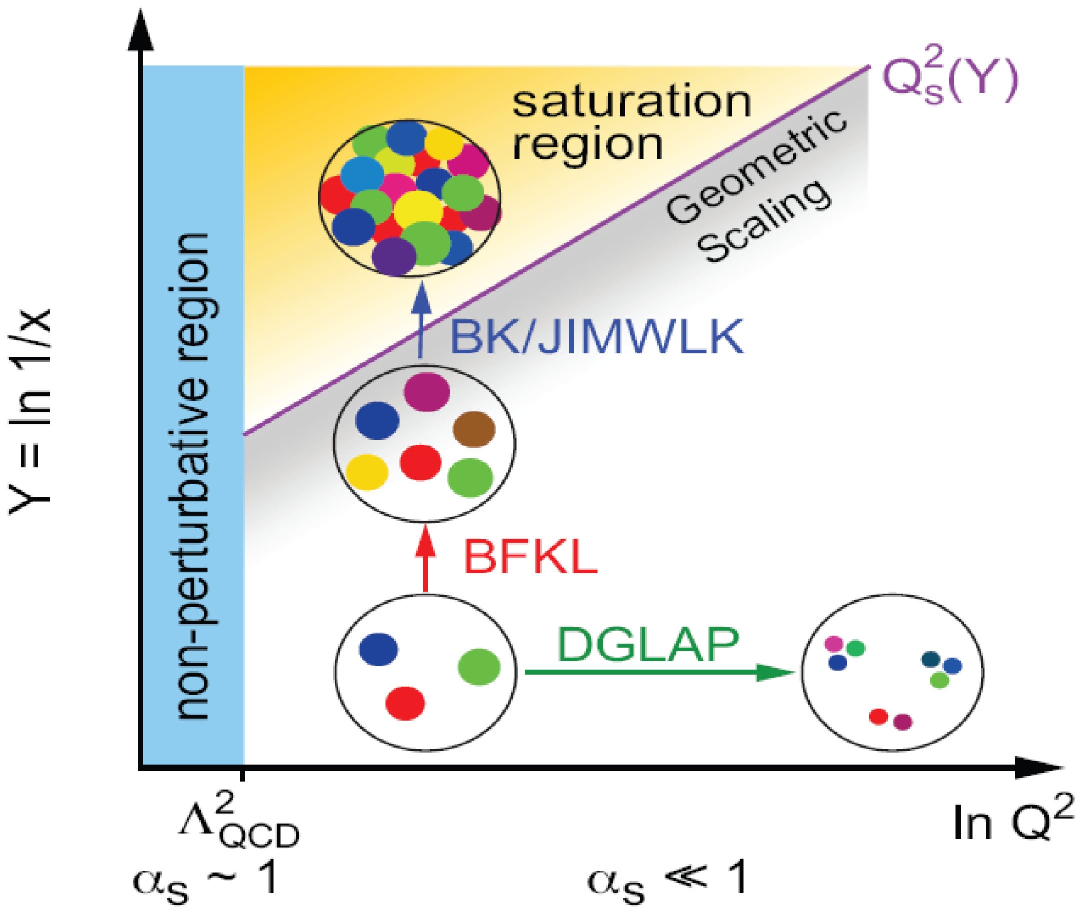


Virtual photon serves as a microscopic probe of the nucleon:

Larger Q^2 probe smaller distances – DGLAP evolution

Plot from EIC whitepaper

Nucleon landscape

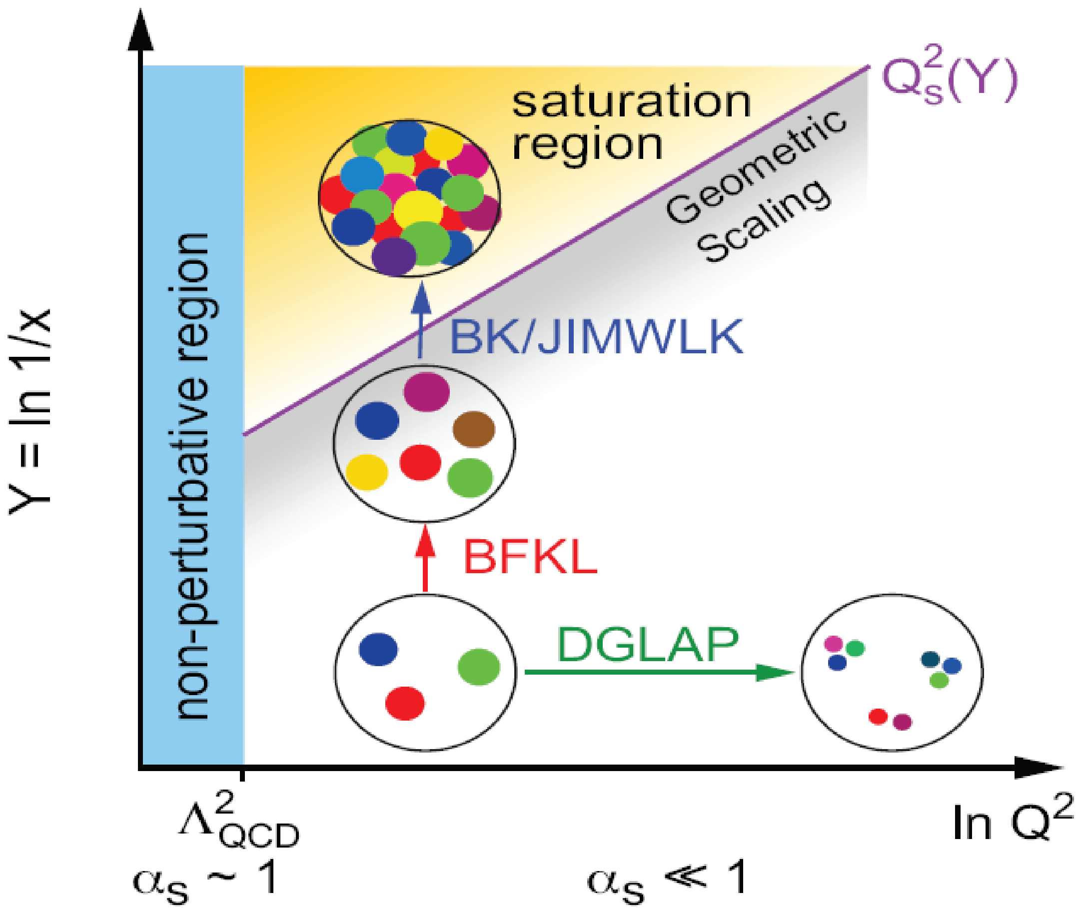


Virtual photon serves as a microscopic probe of the nucleon:

Fixing Q^2 and changing the energy we probe BFKL evolution

Plot from EIC whitepaper

Nucleon landscape



Virtual photon serves as a microscopic probe of the nucleon:

Recombination of gluons leads to non linear effects – BK/JIMWLK evolution and phenomenon of saturation. Dilute vs dense regime of QCD.

Plot from EIC whitepaper

Spin and QCD

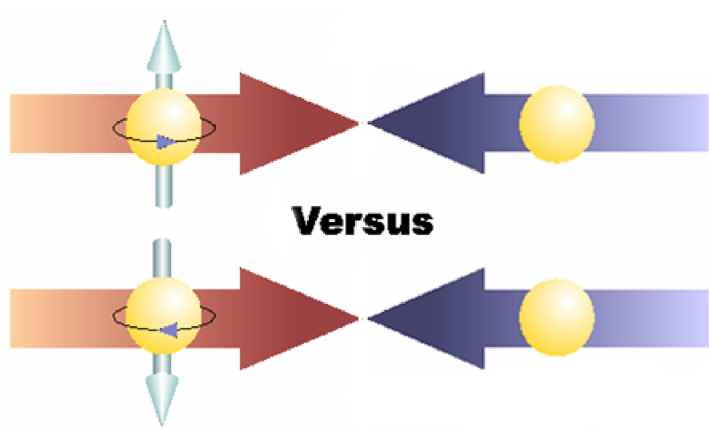
"Experiments with spin have killed more theories than any other single physical parameter"

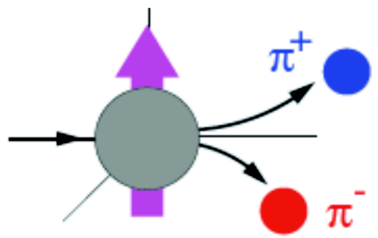
Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

"Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection."

J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

Consider A_N in hadron hadron collision:



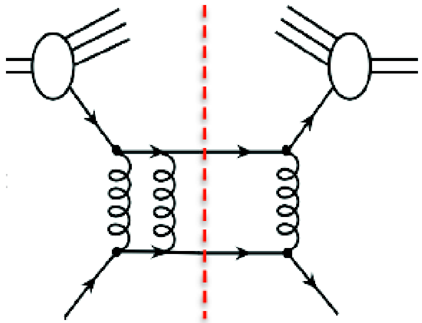


$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

Spin and QCD

QCD had a very simple prediction:

Helicity flip is proportional to the small mass of the quark, thus

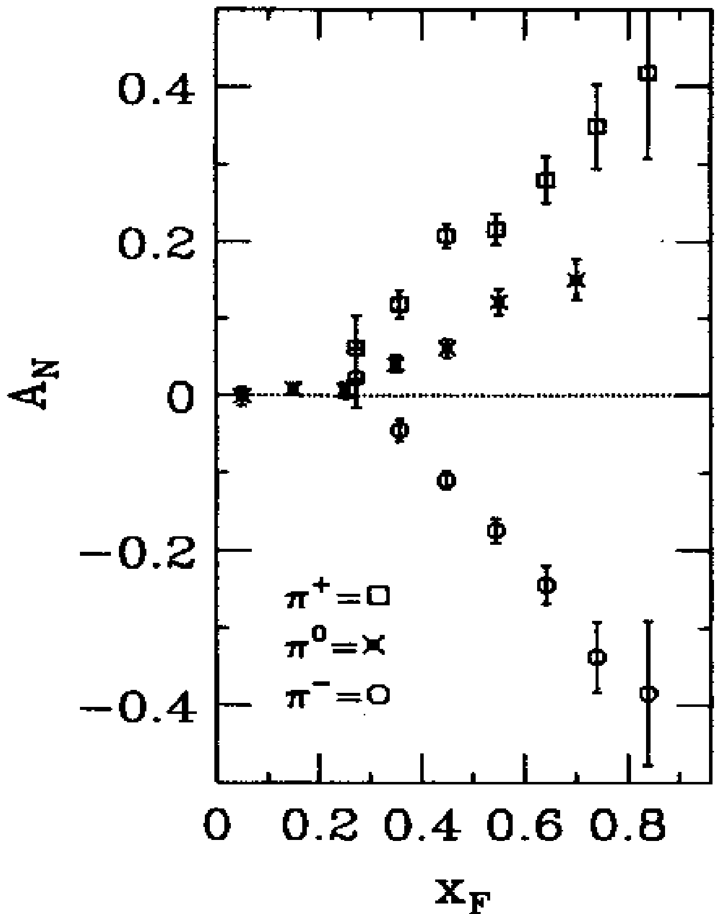


$$\propto \alpha_s \frac{m_q}{p_T} \qquad A_N \simeq 0.001$$

Kane, Pumplin and Repko (1978)

Spin and QCD

Experiment proved this prediction wrong

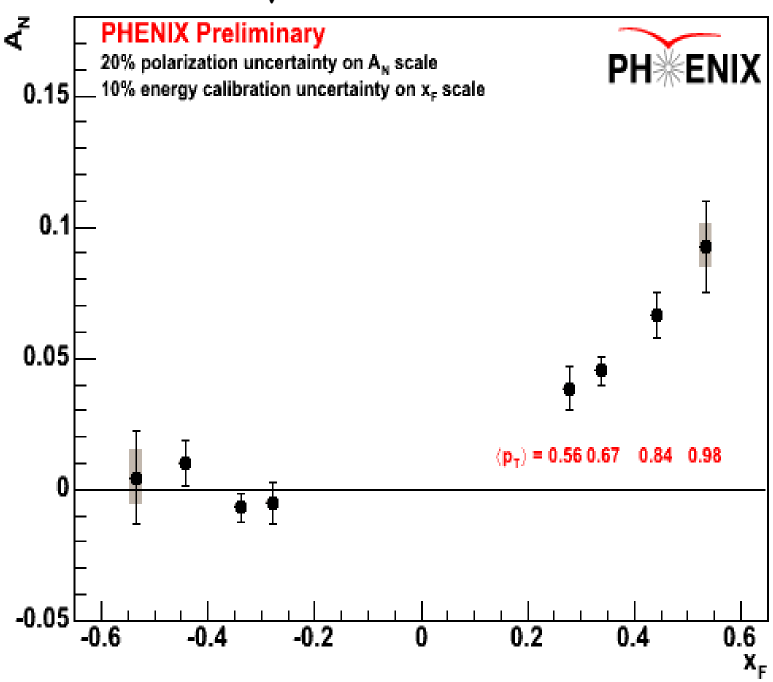


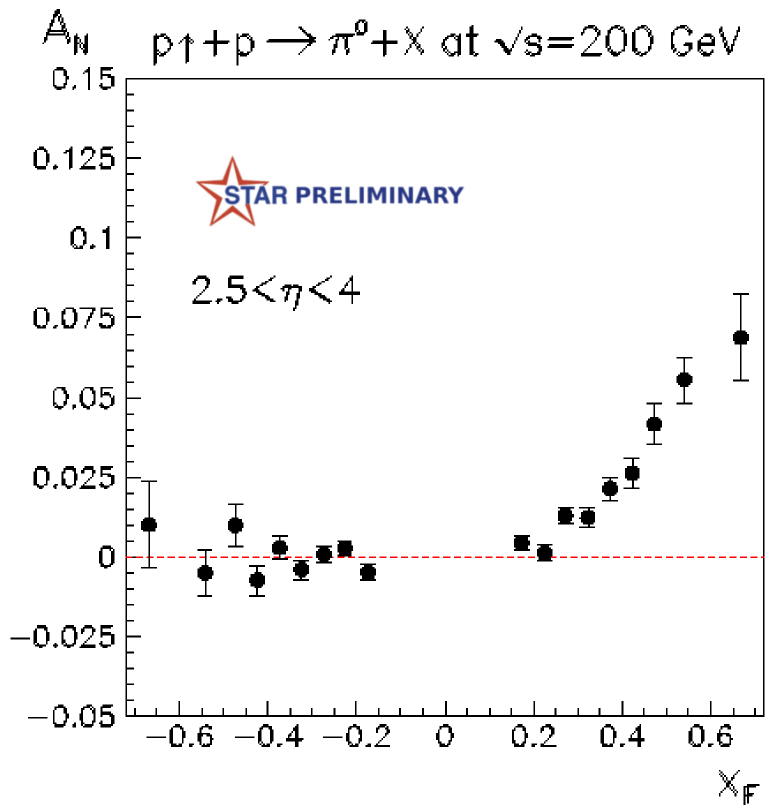
E704 (1991)

$$A_N \simeq 40\%$$

Asymmetry survives with energy

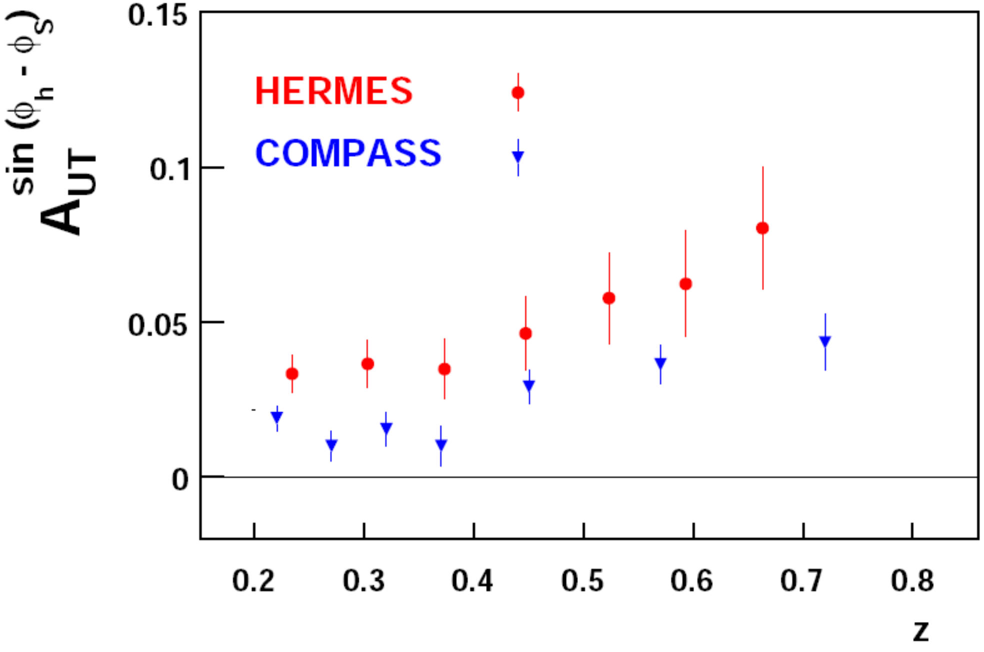
$\sqrt{s} = 62$ GeV





RHIC: STAR, BRAHMS and PHENIX

Asymmetry survives with energy



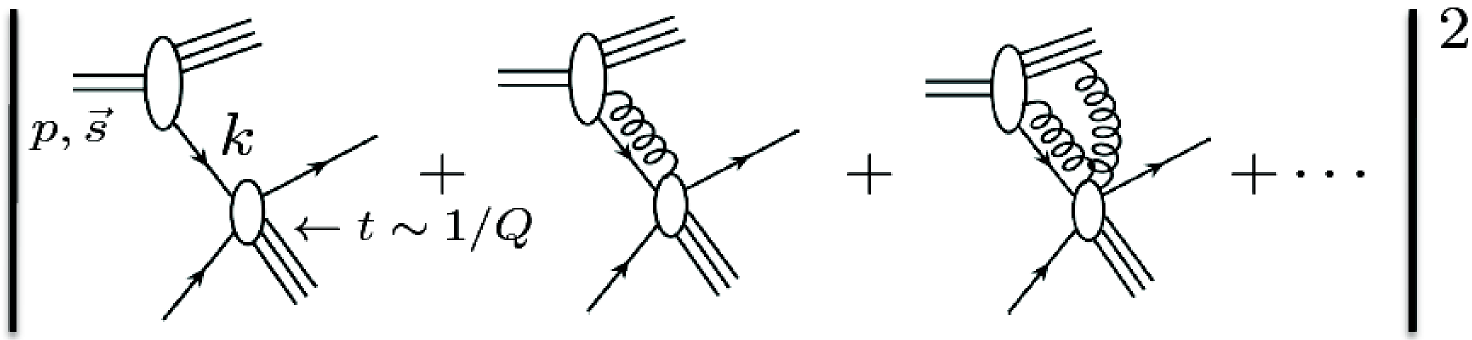
HERMES and COMPASS

Failure of QCD?

Not at all: better understanding of QCD

Better understanding of QCD

$\sigma(Q,\vec{s}) \propto$



Multy parton correlations contribute to the cross section.

These correlations are called
Efremov-Teryaev-Qiu-Sterman matrix elements,
They appear at twist-3 level in cross section.

$$\sigma = \sigma^{LT} + \frac{Q_s}{Q}\sigma^{HT} + \ldots$$

$$= H^{LT} \otimes f_2 \otimes f_2 + \frac{Q_s}{Q} H^{HT} \otimes f_3 \otimes f_2 + \ldots$$

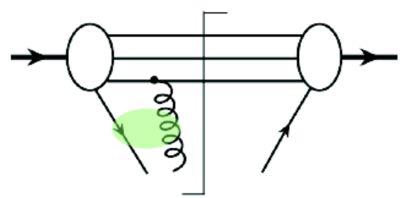
Better understanding of QCD

If only one large scale is present in the process, then

$$A_N \propto \sigma(p_T, S_\perp) - \sigma(p_T, -S_\perp)$$
$$\propto T^{(3)}(x, x, S_\perp) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x, S_\perp) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) + ...$$

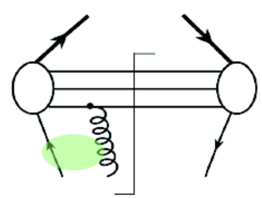
Leading power cancels

Twist-3 parton correlation functions

$T^{(3)}(x, x, S_\perp) \propto$ 

Qiu-Sterman 1991

Twist-3 parton fragmentation functions

$D^{(3)}(z, z) \propto$ 

Kang, Yuan, Zhou 2010

No probability interpretation!

Evolution of twist-3 matrix elements

One starts from factorization

$$\Delta\sigma = 1/Q H(Q/\mu_F, \alpha_s) f_2(\mu_F) f_3(\mu_F)$$

- Calculate directly

Kang, Qiu 2009
Yuan, Zhou 2009

- Calculate from scale dependence of hard part

Yuan, Vogelsang 2009

- Renormalization of twist-3 operators

Braun et al 2009

Good agreement of results!

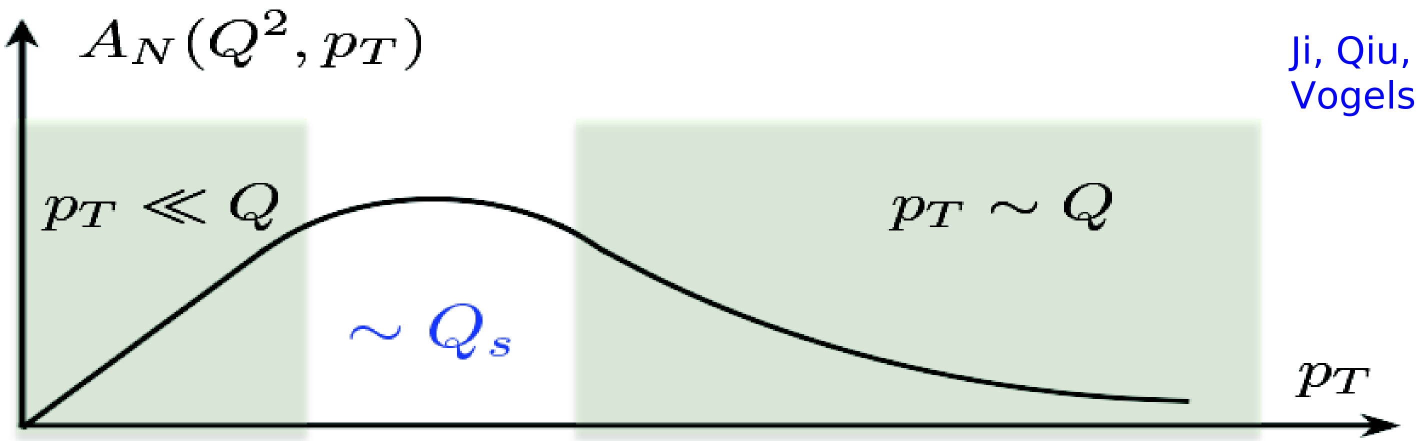
Collinear vs TMD factorization

We can consider two different kinematical regions

$$Q_1, Q_2, ... \gg \Lambda_{QCD}$$ Collinear

$$Q_1 \gg Q_2 > \Lambda_{QCD}$$ TMD

- Twist-3 – integration over parton momenta
- TMD – direct information on partonic transverse motion

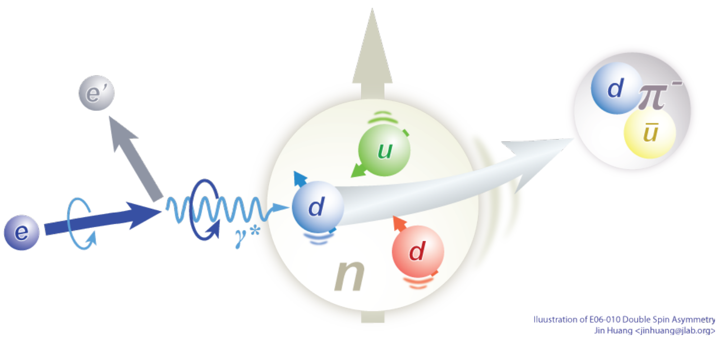


Ji, Qiu, Yuan, Vogelsang, Koike

Consistent in the overlap region!

Transverse Momentum Dependent distributions

SIDIS



$$\mathbf{l} + \mathbf{P} \rightarrow \mathbf{l}' + \mathbf{h} + \mathbf{X}$$

If produced hadron has low transverse momentum $P_{hT} \sim \Lambda_{QCD} << Q$

it will be sensitive to quark transverse momentum $k_\perp$

TMD factorization proven in QCD
Ji, Ma, Yuan (2002)
Collins (2011)
For processes with two hadrons:
SIDIS, DY, e+e-

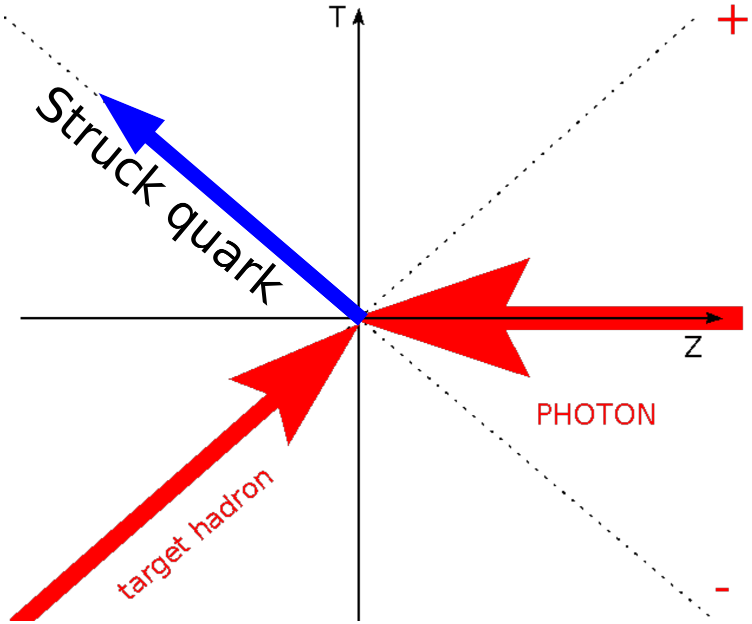
GAUGE INVARIANT

$$\Phi_{ij}(x, \mathbf{k}_\perp) = \int \frac{d\xi^-}{(2\pi)} \frac{d^2\xi_\perp}{(2\pi)^2} e^{ixP^+\xi^- - i\mathbf{k}_\perp \xi_\perp} \langle P, S_P | \bar{\psi}_j(0) \mathcal{U}(\mathbf{0}, \xi) \psi_i(\xi) | P, S_P \rangle$$

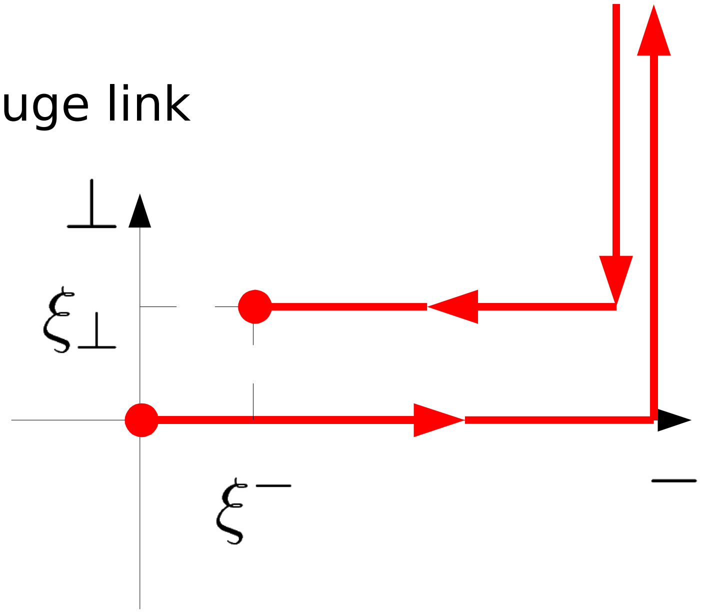
Transverse Momentum Dependent distributions

$$\Phi_{ij}(x,\mathbf{k}_\perp) = \int \frac{d\xi^-}{(2\pi)} \frac{d^2\xi_\perp}{(2\pi)^2} e^{ixP^+\xi^- - i\mathbf{k}_\perp\xi_\perp} \langle P,S_P|\bar{\psi}_j(0)\mathcal{U}(\mathbf{0},\xi)\psi_i(\xi)|P,S_P\rangle|_{\xi^+=0}$$

SIDIS in IMF:



Gauge link



$$\mathcal{U}(a,b;n) = e^{-ig\int_a^b d\lambda n\cdot A_\alpha(\lambda n)t_\alpha}$$

Ensures gauge invariance of the distribution, cannot be canceled by gauge choice

TMDs

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

8 functions in total (at leading Twist)

Each represents different aspects of partonic structure

Each function is to be studied

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

Correlation of transverse quark motion and the nucleon spin – Sivers function

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

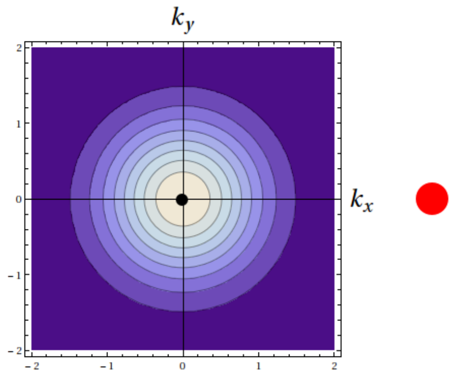
This function gives access to 3D imaging

Spin-orbit correlation

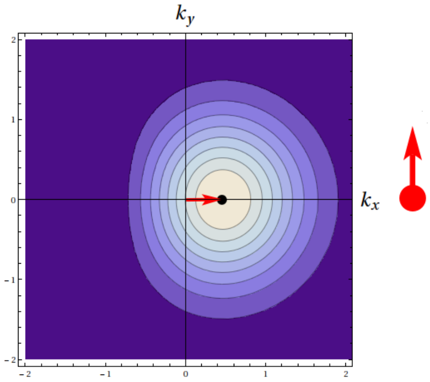
Physics of gauge links is represented

Requires Orbital Angular Momentum

No polarisation:

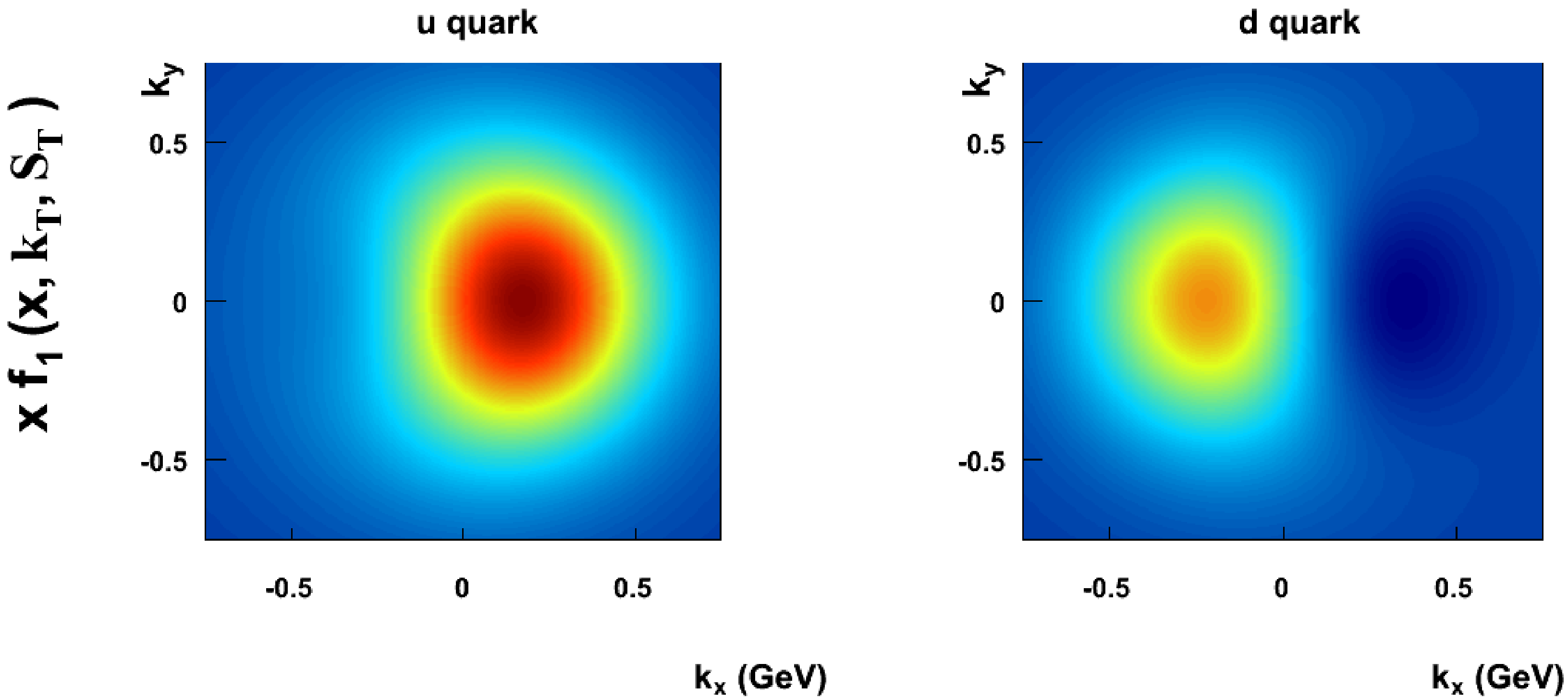


Polarisation:



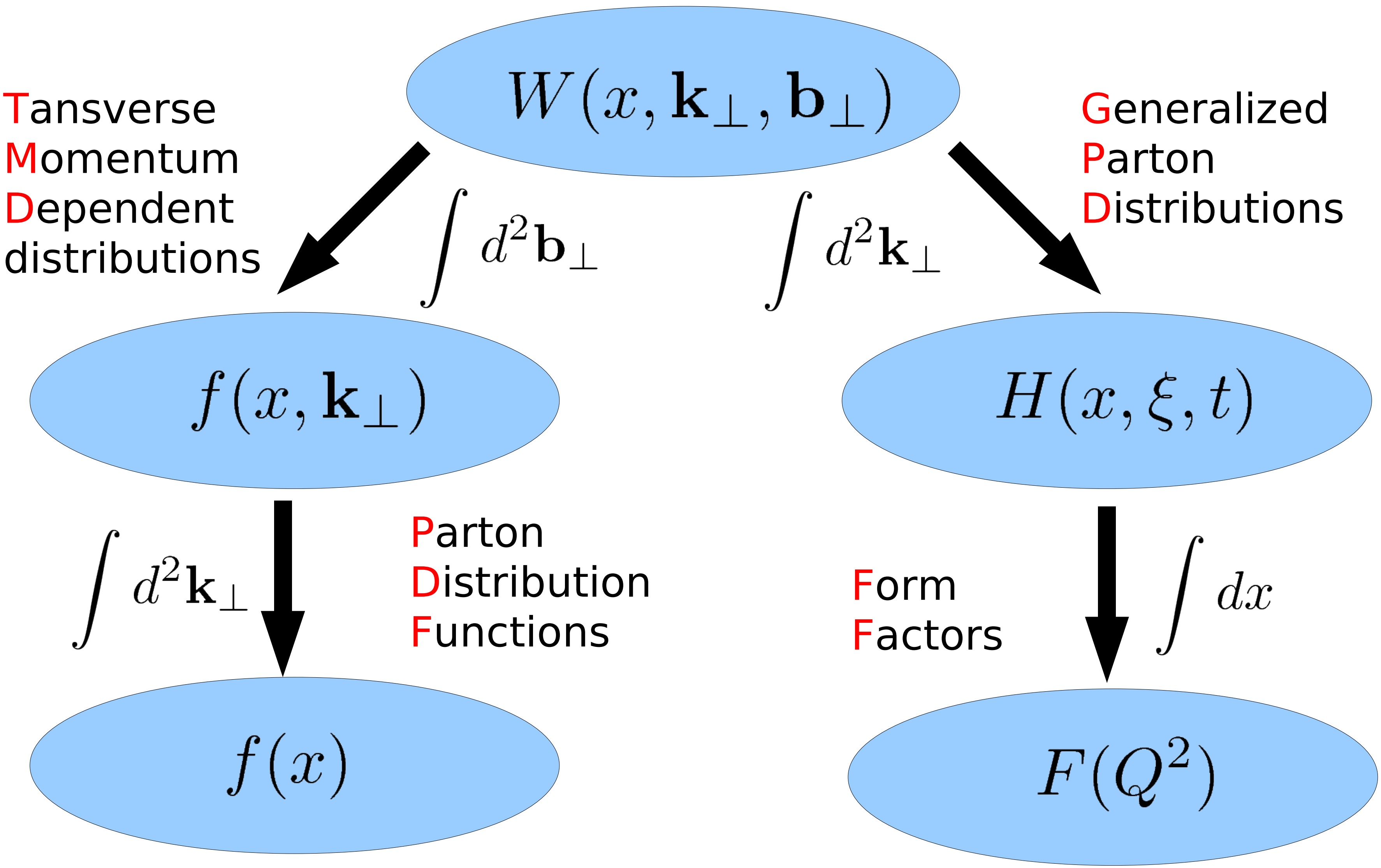
EIC report, Boer, Diehl, Milner, Venugopalan,Vogelsang et al , 2011;
Duke workshop report: Anselmino et al Eur.Phys.J.A47:35,2011
EIC Whitepaper

Tomographic scan of the nucleon



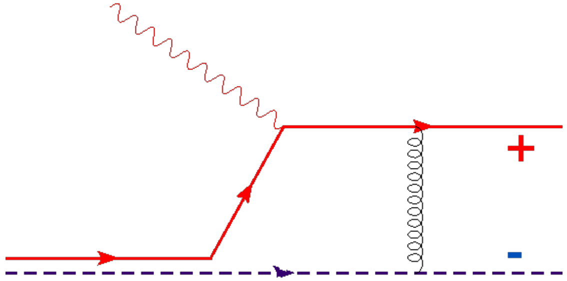
Anselmino et al 2009

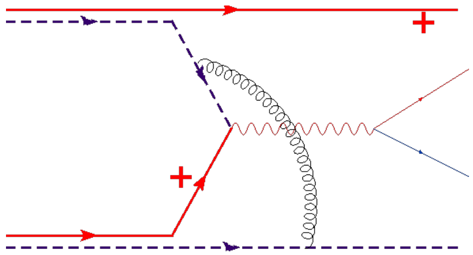
Wigner distribution



Physics of gauge links

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)





Brodsky,Hwang, Schmidt
Belitsky,Ji,Yuan
Collins
Boer,Mulders,Pijlman, etc

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

See talk by Michela Chiosso

One of the main goals is to verify this relation.
It goes beyond "just" check of TMD factorization.
Motivates Drell-Yan experiments

AnDY, COMPASS, JPARC, PAX etc
Barone et al., Anselmino et al., Yuan,Vogelsang, Schlegel et al., Kang,Qiu, Metz,Zhou

Physics of gauge links

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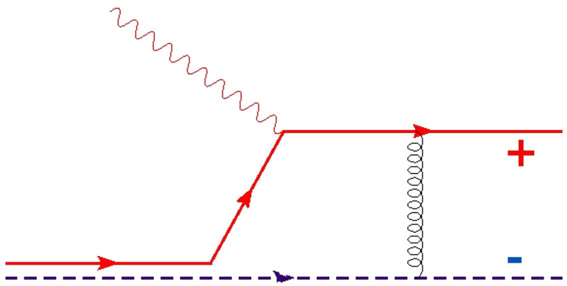


man,

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

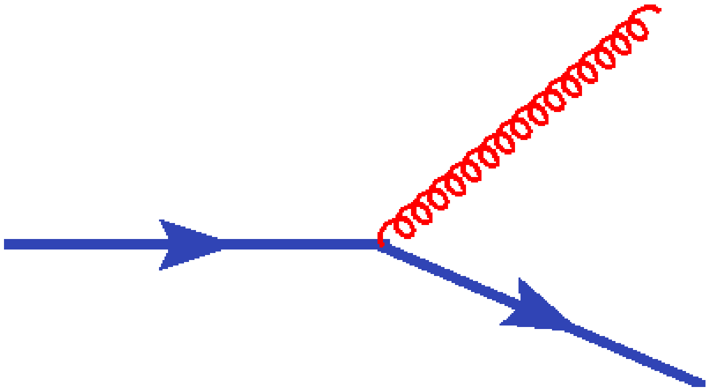
Drell-Yan is at much different resolution scale Q.
EIC will operate at higher Q.
What do we know about evolution of TMDs?

One of the main goals is to verify ution.
It goes beyond “just” check of TM ctorization.
Motivates Drell-Yan experiments

AnDY, COMPASS, JPARC, PAX etc
Barone et al., Anselmino et al., Yuan,Vogelsang, Schlegel et al., Kang,Qiu, Metz,Zhou

SIDIS and parton model

"QCD improved" parton model:



Radiation of gluons create transverse momenta

Terms like this appear

$$\left(\alpha_s\right)^n \left(\ln \frac{Q^2}{P_T^2} \right)^m$$

Result needs to be resummed for small P_T

Dokshitzer, Dyakonov, Troyan 1980
Parizi, Petronzio 1979
Collins, Soper 1982
Collins, Soper, Sterman 1985
Koike, Nagashima,Vogelsang
Kang,Xiao,Yuan

Implementation of resummation In QCD

Resummation

Dokshitzer, Dyakonov, Troyan 1980
Parizi, Petronzio 1979
Collins, Soper 1982
Collins, Soper, Sterman 1985
Koike, Nagashima,Vogelsang
Kang,Xiao,Yuan

Resummation (CSS) is in configuration space
Fourier transform is needed for observables

For Drell-Yan

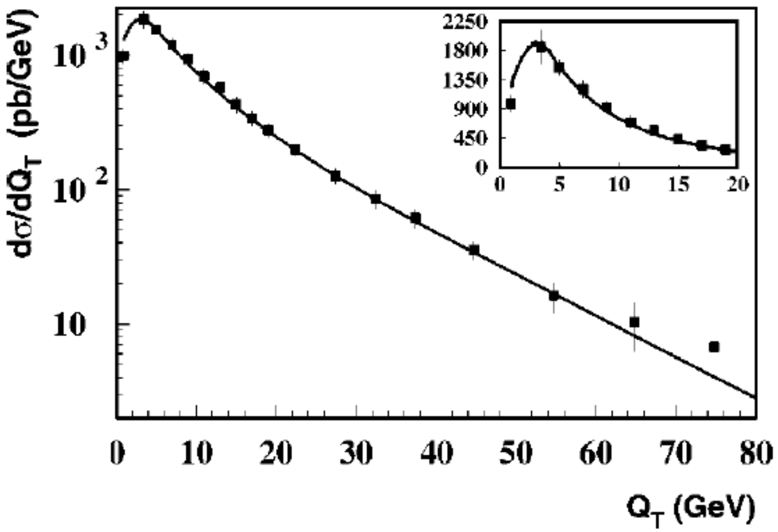
$$\frac{d\sigma}{dq_T} \sim \int d^2 b_T e^{iq_T \cdot b_T} \hat{W}(x_1, x_2, b_T) e^{-S(b_T,Q)} + Y(q_T, Q)$$

A lot of phenomenology done. Energies from 20 GeV to 2 TeV.

Brock, Landry, Nadolsky, Yuan 2003
Qiu, Zhang 2001

Drawbacks:

- Process dependent fits
- No direct connection to TMDs
- Designed for large energies



Evolution of TMDs

One needs a unique definition of TMDs

Foundations of perturbative QCD
Collins 2011

$$W^{\mu\nu} = \sum_f |H_f(Q^2, \mu|^{\mu\nu}$$

$$\times \int d^2\mathbf{k}_{1T} d^2\mathbf{k}_{2T} F_{f/P_1}(x_1, \mathbf{k}_{1T}; \mu, \zeta_F) F_{\bar{f}/P_1}(x_2, \mathbf{k}_{2T}; \mu, \zeta_F)$$

$$\times \delta^{(2)}(\mathbf{k}_{1T} + \mathbf{k}_{2T} - \mathbf{q}_T) + Y(\mathbf{q}_T, Q)$$

$F_{f/P_1}(x_1, \mathbf{k}_{1T}; \mu, \zeta_F)$ **TMD distribution of partons in a hadron**

Renorm group (RG) renormalization

Rapidity divergence regulator

Evolution of TMDs

Evolution of TMDs is done in coordinate space $\mathbf{b}_T$

$$F_{f/P}(x,\mathbf{k}_T;\mu,\zeta_F) = \frac{1}{(2\pi)^2}\int d^2\mathbf{b}_T e^{i\mathbf{k}_T\cdot\mathbf{b}_T}\tilde{F}_{f/P}(x,\mathbf{b}_T;\mu,\zeta_F)$$

Colins Soper 1982
Foundations of perturbative QCD Collins 2011

Why coordinate space?

Convolutions become simple products:

Collins, Soper 1982
Collins, Soper, Sterman 1985
Idilbi, Ji, Ma, Yuan 2004
Boer, Gamberg, Musch, AP 2011

$$W^{\mu\nu} = \sum_f |H_f(Q^2,\mu|^{\mu\nu} \times \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\mathbf{q}_T}\tilde{F}_{f/P_1}(x_1,\mathbf{b}_T;\mu,\zeta_F)\tilde{F}_{\bar{f}/P_1}(x_2,\mathbf{b}_T;\mu,\zeta_F)$$

In principle experimental study of functions in coordinate space
Is possible

Boer, Gamberg, Musch, AP 2011

TMD evolution

Energy evolution

$$\frac{\partial \ln \tilde{F}(x, b_T, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T, \mu)$$

→ Collins-Soper kernel in coordinate space

Renormalization group equations

TMD:
Collins 2011
Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\frac{d\tilde{K}(b_T, \mu)}{d \ln \mu} = -\gamma_K(g(\mu))$$

$$\frac{d \ln \tilde{F}(x, b_T, \mu, \zeta)}{d \ln \mu} = -\gamma_F(g(\mu), \zeta)$$

TMD evolution

Energy evolution

$$\frac{\partial \ln \tilde{F}(x, b_T, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T, \mu)$$

Collins-Soper kernel in coordinate space

At small $\mathbf{b}_T$ perturbative treatment is possible

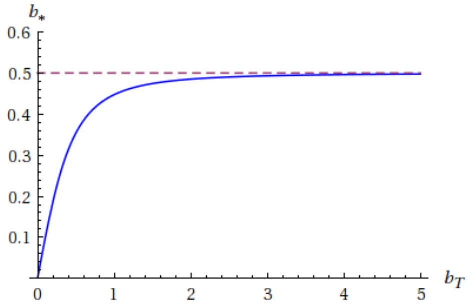
TMD:
Collins 2011
Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\tilde{K}(b_T, \mu) = -\frac{\alpha_s C_F}{\pi}\Big(\ln(\mu^2 b_T^2) - \ln 4 + 2\gamma_E\Big) + \mathcal{O}(\alpha_s^2)$$

Large $\mathbf{b}_T$ nonperturbative – matching via $\mathbf{b}_*$ Collins Soper 1982

$$b_*(b_T) = \frac{b_T}{\sqrt{1 + b_T^2/b_{max}^2}}$$

Brock, Landry, Nadolsky, Yuan 2003



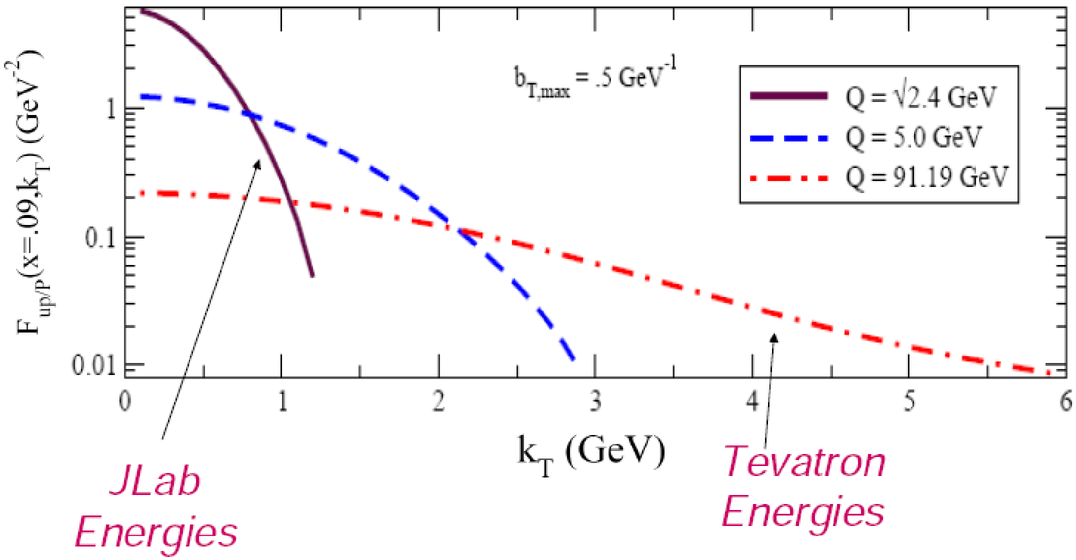
Other methods of matching are available i.e. Vogelsang et al

TMD evolution

Solution   Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\tilde{F}_{f/P}(x, b_T; Q, \zeta_F) = F_{f/P}(x; Q_0) \exp\left(- \left[\frac{\langle k_T^2 \rangle}{4} + \frac{g_2}{2} \ln \frac{Q}{Q_0} \right] b_T^2 \right)$$

Non perturbative



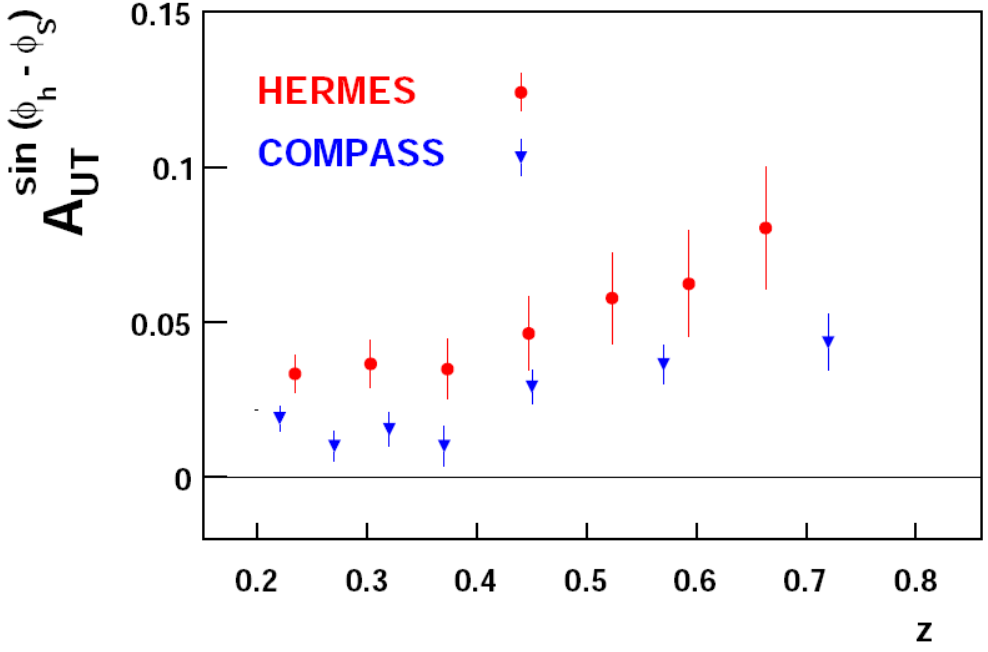
Gaussian behaviour is appropriate only in a limited range

TMDs change with energy and resolution scale

TMD evolution

Can we see signs of evolution in the experimental data?

Aybat, AP, Rogers 2011



COMPASS data is at

$$\langle Q^2 \rangle \simeq 3.6\ (GeV^2)$$

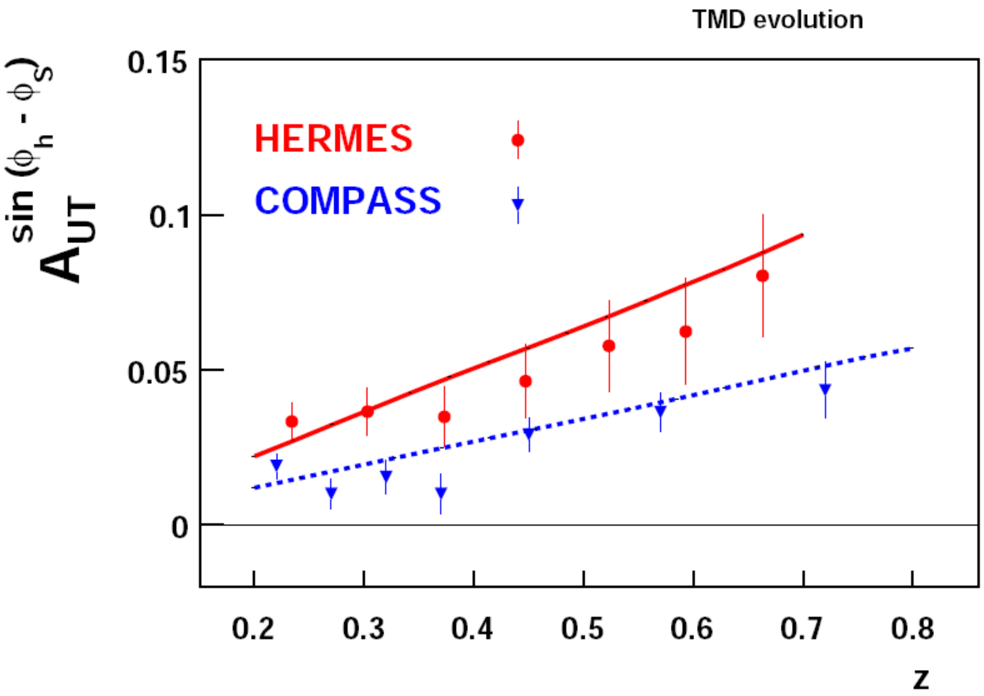
HERMES data is at

$$\langle Q^2 \rangle \simeq 2.4\ (GeV^2)$$

TMD evolution

Can we explain the experimental data?

Full TMD evolution is needed!



Aybat, AP, Rogers 2011

COMPASS dashed line

$$\langle Q^2 \rangle \simeq 3.6\ (GeV^2)$$

HERMES solid line

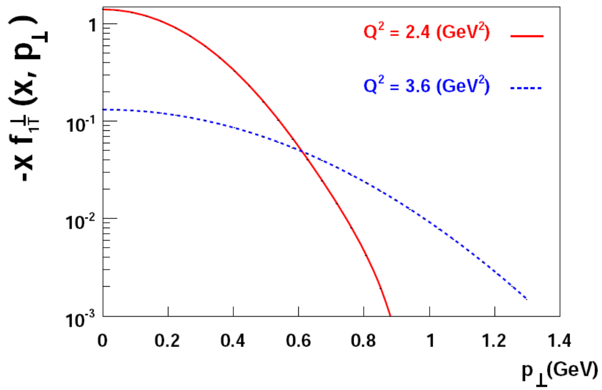
$$\langle Q^2 \rangle \simeq 2.4\ (GeV^2)$$

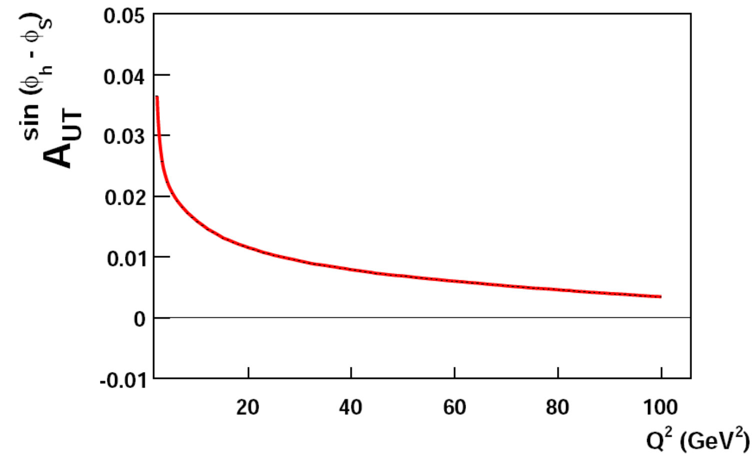
TMD evolution

This is the first implementation of TMD evolution for observable

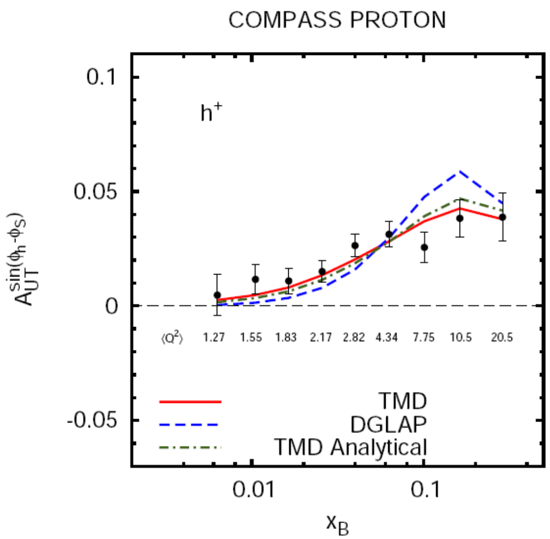
Aybat, AP, Rogers 2011

Asymmetry changes with Q^2





Functions change with energy



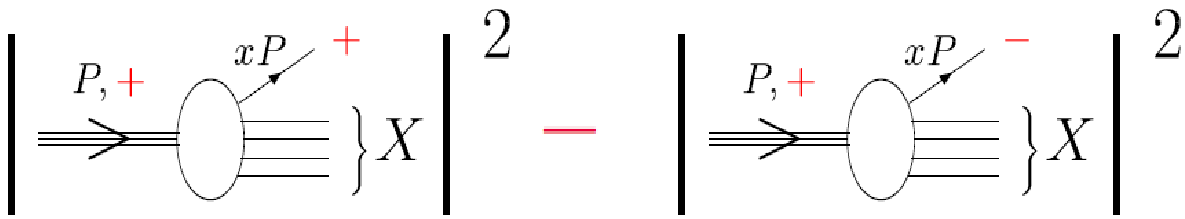
Anselmino, Boglione, Melis 2012

Solid line – TMD evolution fit
Dashed line – DGLAP fit

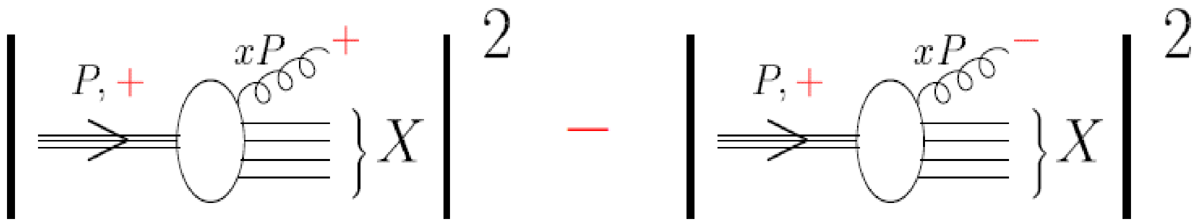
Phenomenological analysis with evolution is now possible

Helicity structure

$\Delta q(x) =$



$\Delta g(x) =$



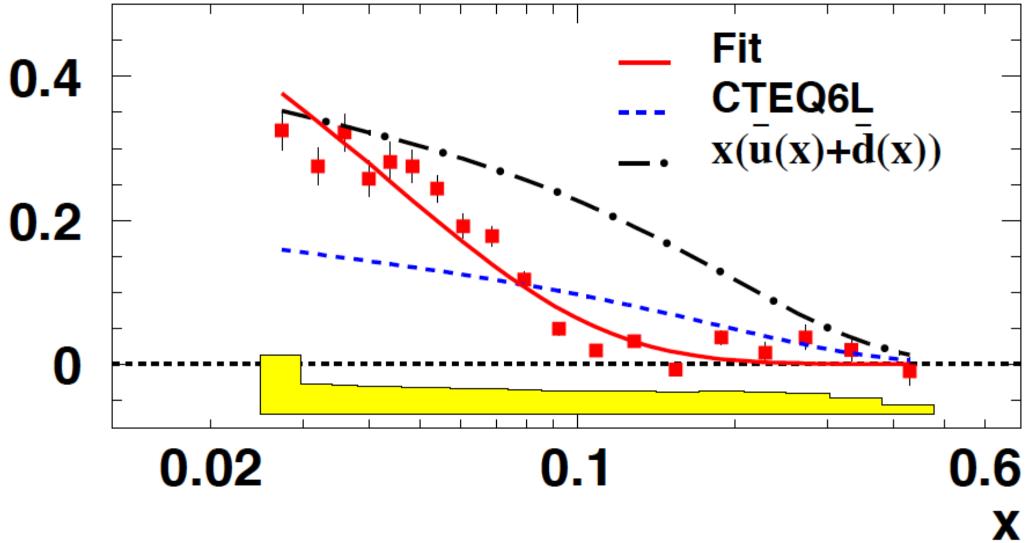
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$$\Delta\Sigma(Q^2) = \int_0^1 dx\,\left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x, Q^2)$$

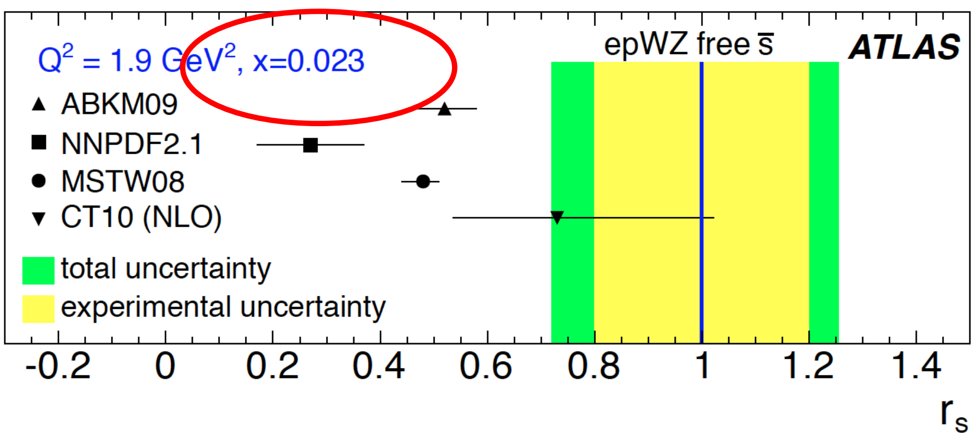
$$\Delta G(Q^2) = \int_0^1 dx\,\Delta g(x, Q^2)$$

We still have a lot to learn about strangeness:

$x(s+\bar{s})$



HERMES

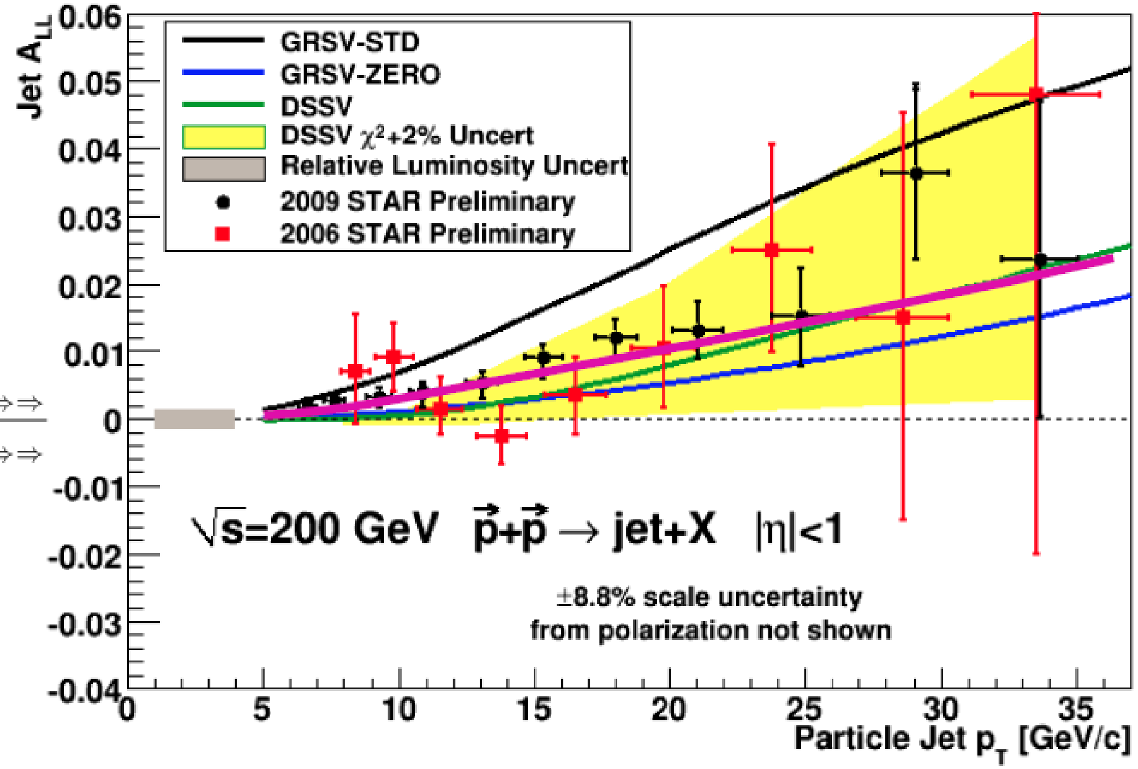


ATLAS

$$r_s = 0.5\frac{s+\bar{s}}{\bar{d}}$$

New devlopments on Δg : de Florian, Sassot, Stratmann, Vogelsang

$$A_{LL} = \frac{\sigma_{\Rightarrow\Leftarrow} - \sigma_{\Rightarrow\Rightarrow}}{\sigma_{\Rightarrow\Leftarrow} + \sigma_{\Rightarrow\Rightarrow}}$$



gives gluon with $$\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$$

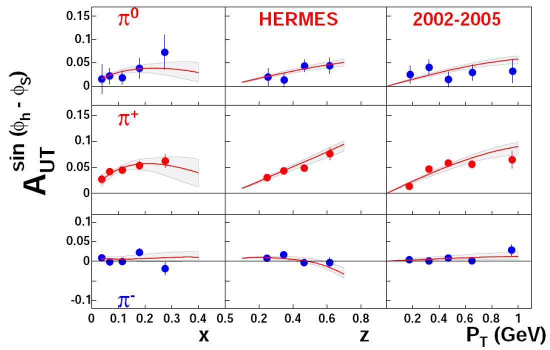
TMDs and twist-3 are related

At operator level:

$$T_F(x,x) = -\int d^2\vec{k}_\perp \frac{k_\perp^2}{M} (f_{1T}^\perp(x,k_\perp))_{SIDIS}$$

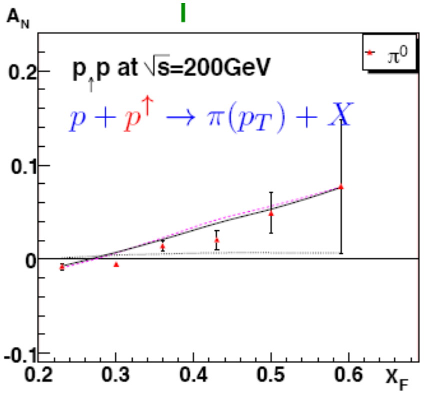
Boer,Mulders,Pijlman,
Ji, Qiu,Vogelsang,Yuan,
Koike,Vogelsang,Yuan
Zhou,Yuan,Liang
Bacchetta,Boer,Diehl,Mulders

We can compare results from SIDIS and PP:



TMD analysis:

Anselmino et al (2008)

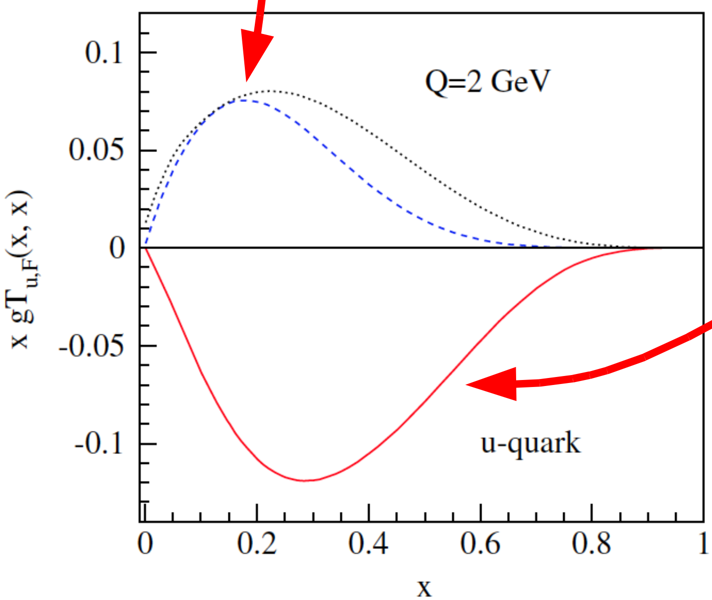


Collinear analysis: Kouvaris, Qiu, Vogelsang, Yuan (2006)

→ a sign puzzle

Kang, Qiu, Vogelsang, Yuan (2011)

from $-\int d^2\vec{k}_\perp \frac{k_\perp^2}{M} (f_{1T}^\perp(x,k_\perp))_{SIDIS}$



$T_F(x,x)$ from PP

Kang, Qiu, Vogelsang, Yuan (2011)

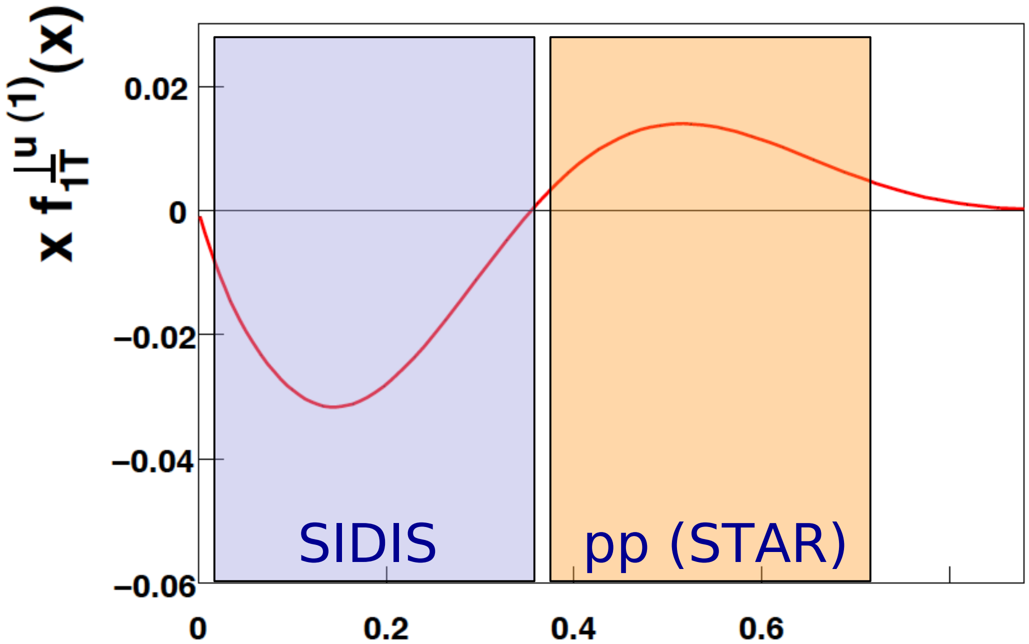
Conclusion?

Inconsistency in QCD formalism for single-spin ?

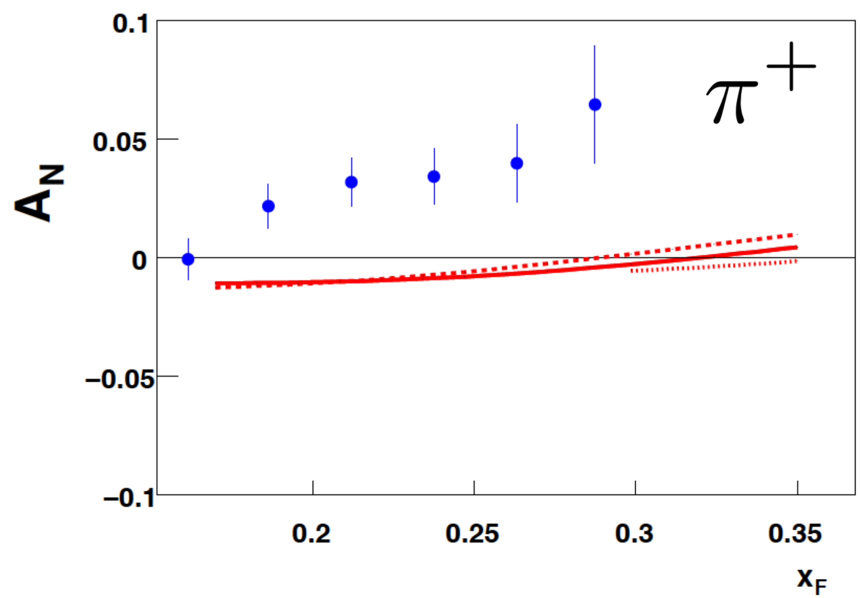
Collins-type effect dominant in $pp \to \pi X$?

Can one describes it with nodes in x or kt?

Joint fit to SIDIS and pp data:



Kang, AP (2011)

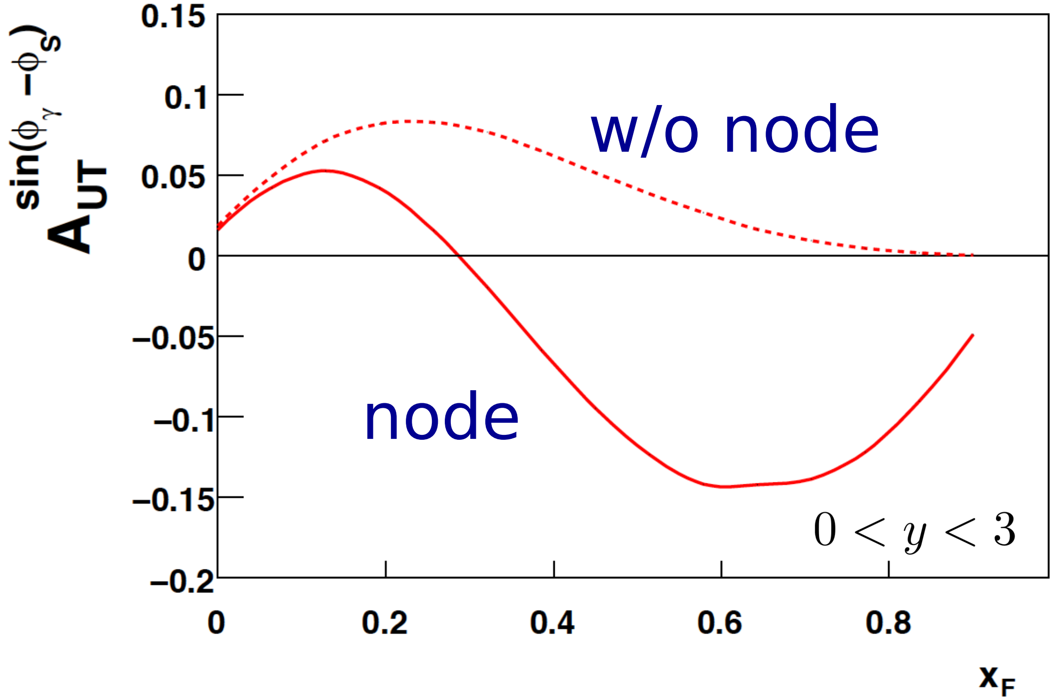


Conclusion?

Works (reasonably) well for SIDIS and STAR, but fails for BRAHMS!

Has ramifications for DY spin asymmetry:

Kang,AP (2011)

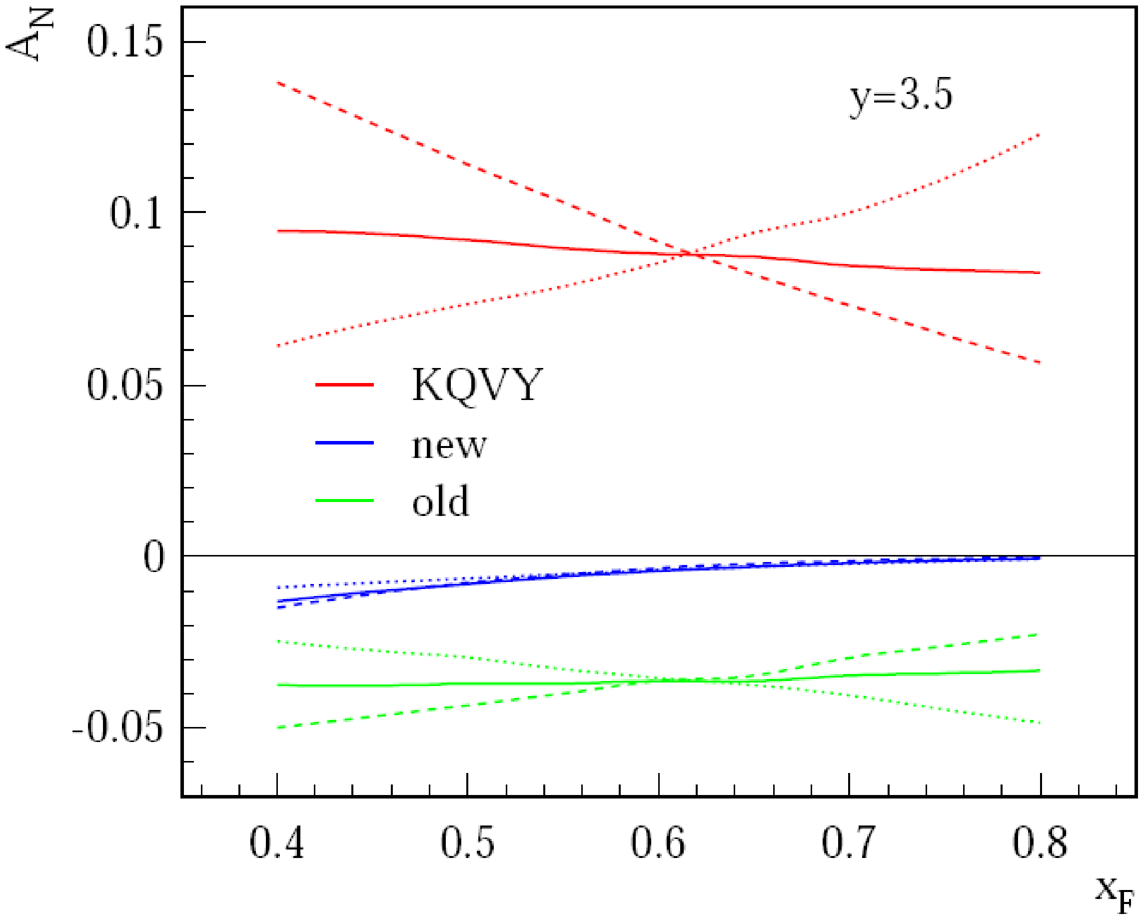


Strengthens case for study of DY “sign change” !

AnDY, COMPASS, E906,W bosons at RHIC

Direct (prompt) photon A_N

Kang,Gamberg (2012)
Kanazawa, Koike (2012)



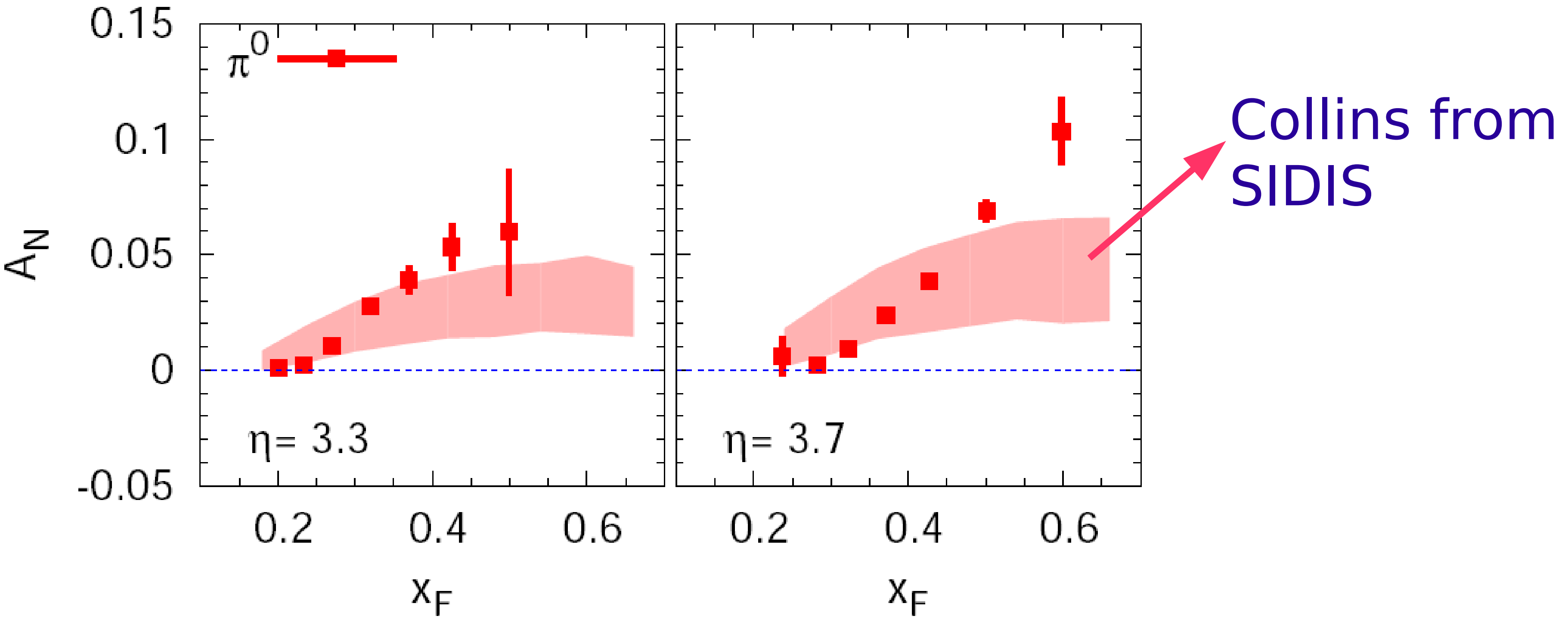
$T_F(x,x)$ from pp

$$-\int d^2\vec{k}_\perp \frac{k_\perp^2}{M}(f_{1T}^\perp(x,k_\perp))_{SIDIS}$$

Sensitivity to Sivers type of contribution only.

Collins contribution

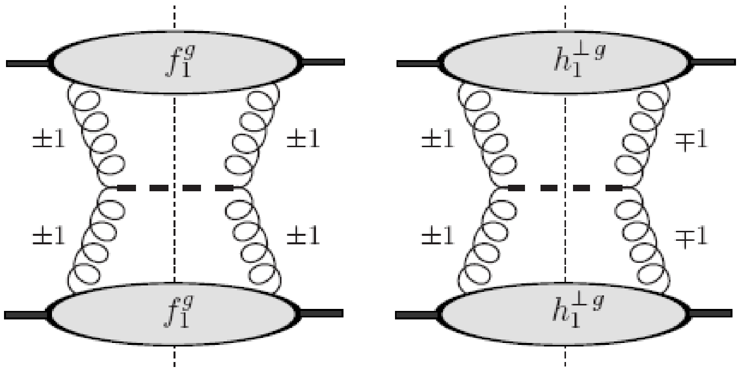
Anselmnino, Boglione, D'Alesio, Leader (5), Melis, Murgia, AP (2012)

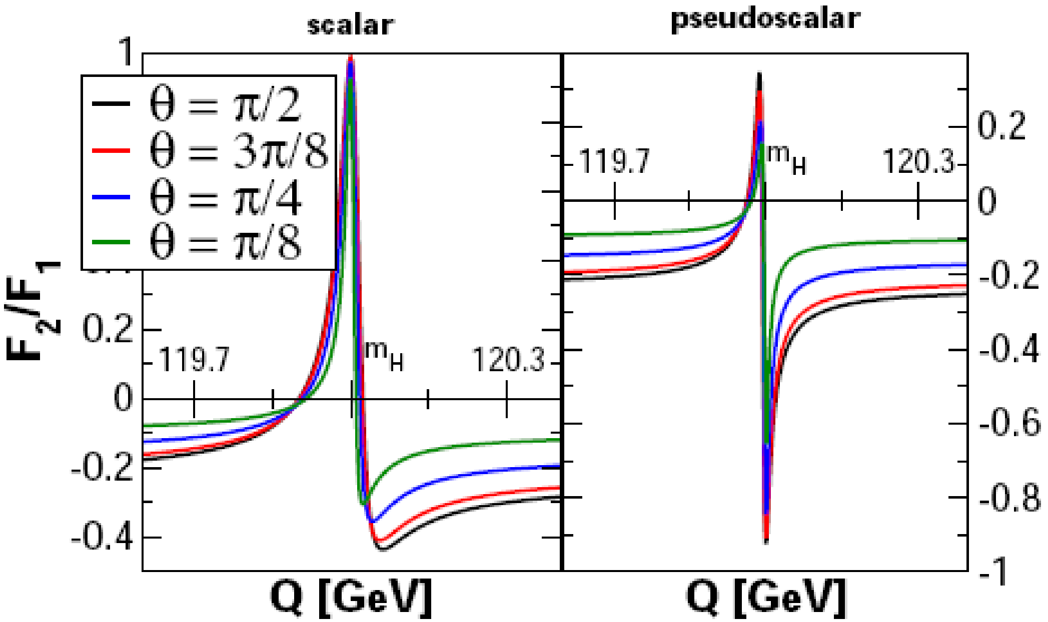


Collins contribution can be substantial

TMDs for LHC

Boer,den Dunnen,Pisano,Schlegel,
Vogelsang (2012)





Parity of the Higgs!

CONCLUSIONS

CONCLUSIONS

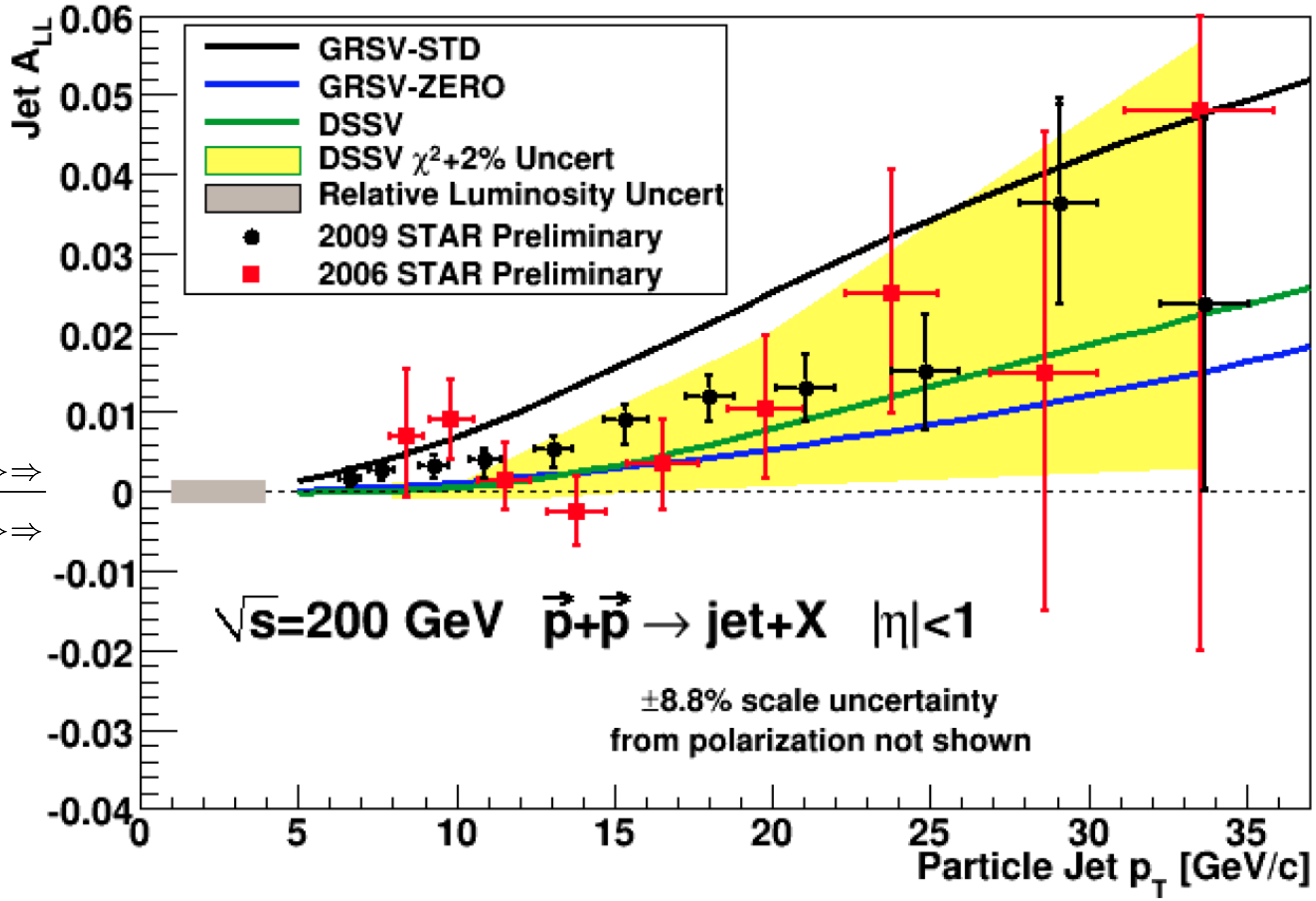
A lot of new results will be presented this week!

Enjoy SPIN 2012!

Spares to follow

New devlopments on Δg : de Florian, Sassot, Stratmann, Vogelsang

$$A_{LL} = \frac{\sigma_{\Rightarrow\Leftarrow} - \sigma_{\Rightarrow\Rightarrow}}{\sigma_{\Rightarrow\Leftarrow} + \sigma_{\Rightarrow\Rightarrow}}$$



gives gluon with $\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$

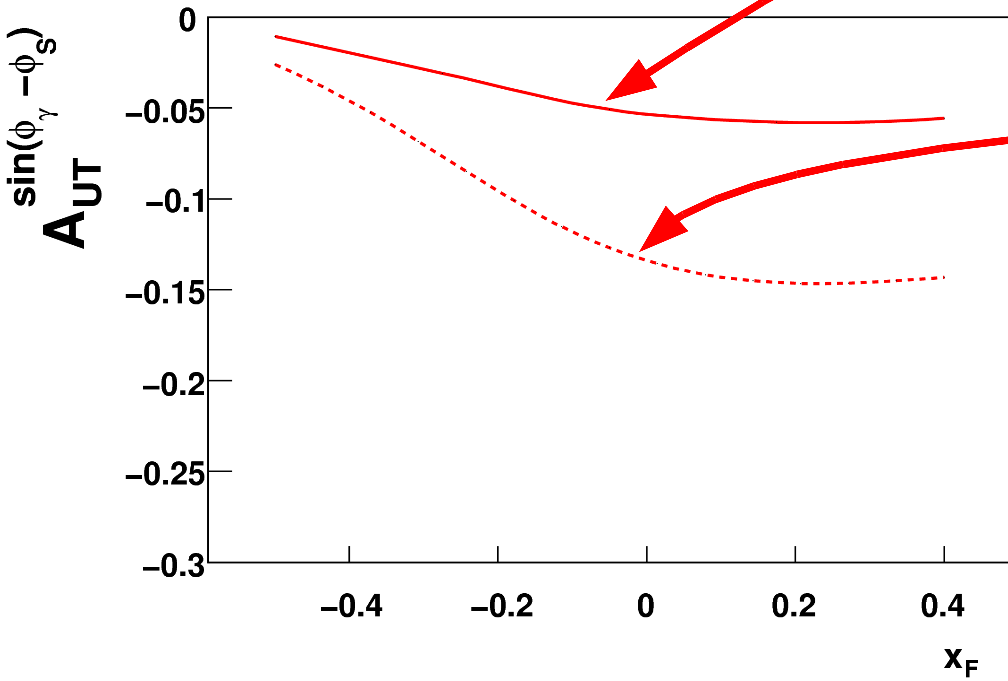
Drell Yan

$$A_N = \frac{\sum_q f_{1T}^{\perp q}(x_2, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}{\sum_q f_1^{q}(x_2, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}$$

Analysis in hadronic cm frame

With TMD evolution

No TMD evolution

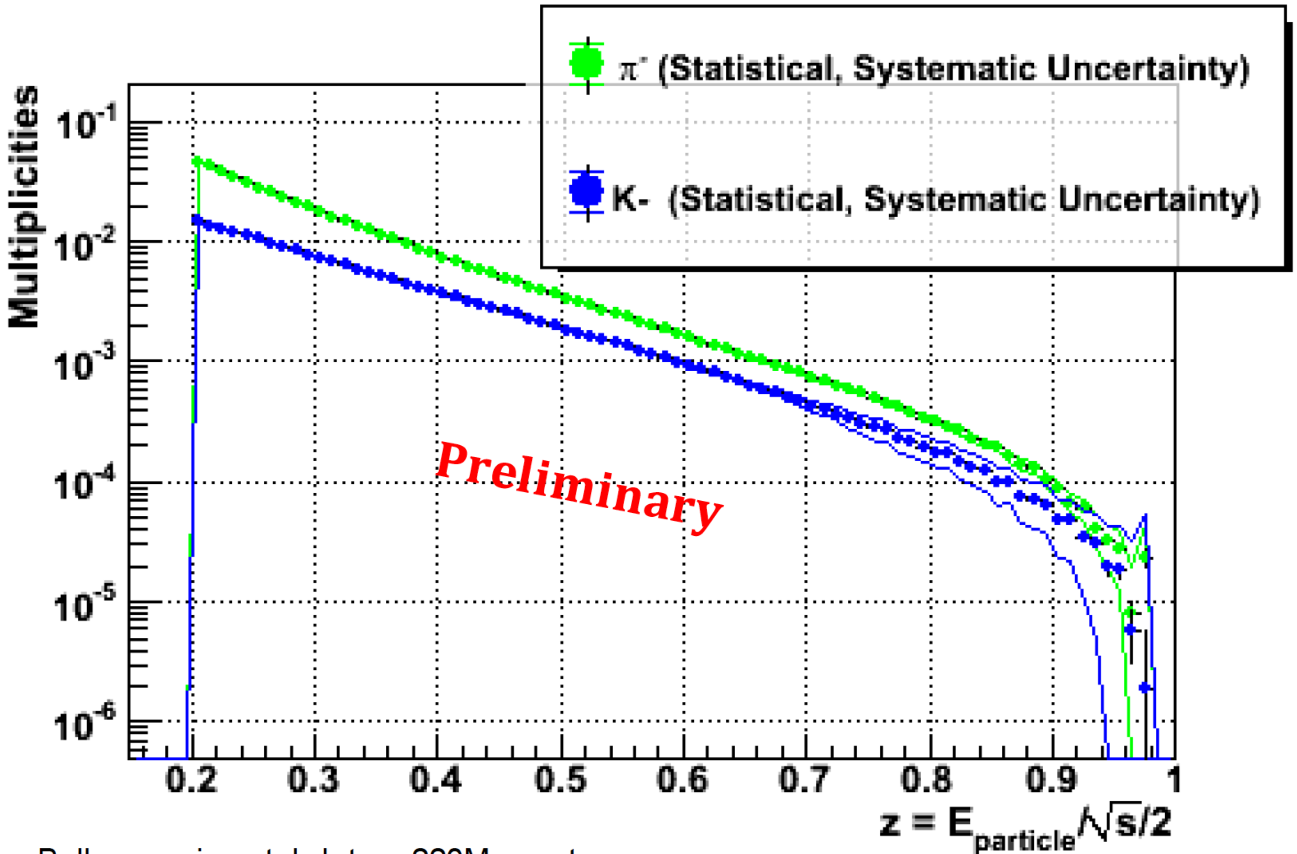


Result with TMD Evolution depends on the choice of $g_K(b_T)$

Unpolarised x-sections should be reanalyzed

Asymmetry is suppesed with respect to LO analysis

Fragmentation FF: BELLE (M. Leitgab at DIS 2012)



Belle experimental data, ~220M events

- marks new era of precision fragmentation functions.

  Evolution → D_g^h e⁺e- vs. RHIC(pp)

TMD evolution

Relation to collinear treatment:

$$\tilde{F}_f(x, b_T, \mu, \zeta) = \sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{j/f}\left(\frac{x}{\hat{x}}, b_T, \mu, \zeta\right) f_j(\hat{x}, \mu) + \mathcal{O}(\Lambda_{QCD} b_T)$$

Collins Soper 1982

Valid at small $\mathbf{b}_T$, lowest order:

$$\tilde{C}_{j/f}(\frac{x}{\hat{x}}, b_T, \mu, \zeta) = \delta_{jf}\delta\left(\frac{x}{\hat{x}} - 1\right) + \mathcal{O}(\alpha_s)$$

Higher order for TMD PDFs

Aybat Rogers 2011

Higher order for Sivers function

Kang, Xiao, Yuan 2011

TMD evolution

Solution   Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\tilde{F}_{f/P}(x, b_T; Q, \zeta_F) = \tilde{F}_{f/P}(x, b_T; Q_0, Q_0^2)$$
$$\times \exp\Big[- g_K(b_T) \ln \frac{Q}{Q_0} \Big]$$

Non perturbative

$$\times \exp\Big[\ln \frac{Q}{Q_0} \tilde{K}(b_*; \mu_b) + \int_{Q_0}^{Q} \frac{d\mu'}{\mu'} \Big[\gamma_F(g(\mu'); 1) - \ln \frac{Q}{\mu'} \gamma_K(g(\mu')) \Big]$$
$$+ \int_{Q_0}^{\mu_b} \frac{d\mu'}{\mu'} \ln \frac{Q}{Q_0} \gamma_K(g(\mu')) \Big]$$

Perturbative

Typically for TMDs:

$$\tilde{F}_{f/P}(x, b_T; Q_0, Q_0^2) = F_{f/P}(x; Q_0) \exp\Big(- \frac{\langle k_T^2 \rangle}{4} b_T^2 \Big)$$