Transversity and TMDs: an Experimental Perpective

Contalbrigo Marco
INFN Ferrara

Symposium on Hadronic Structure Physics
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The spin degree of freedom

Spin degrees of freedom can explain otherwise surprising phenomena and bring new insights into nuclear matter structure

Fundamental: do not neglect it !!

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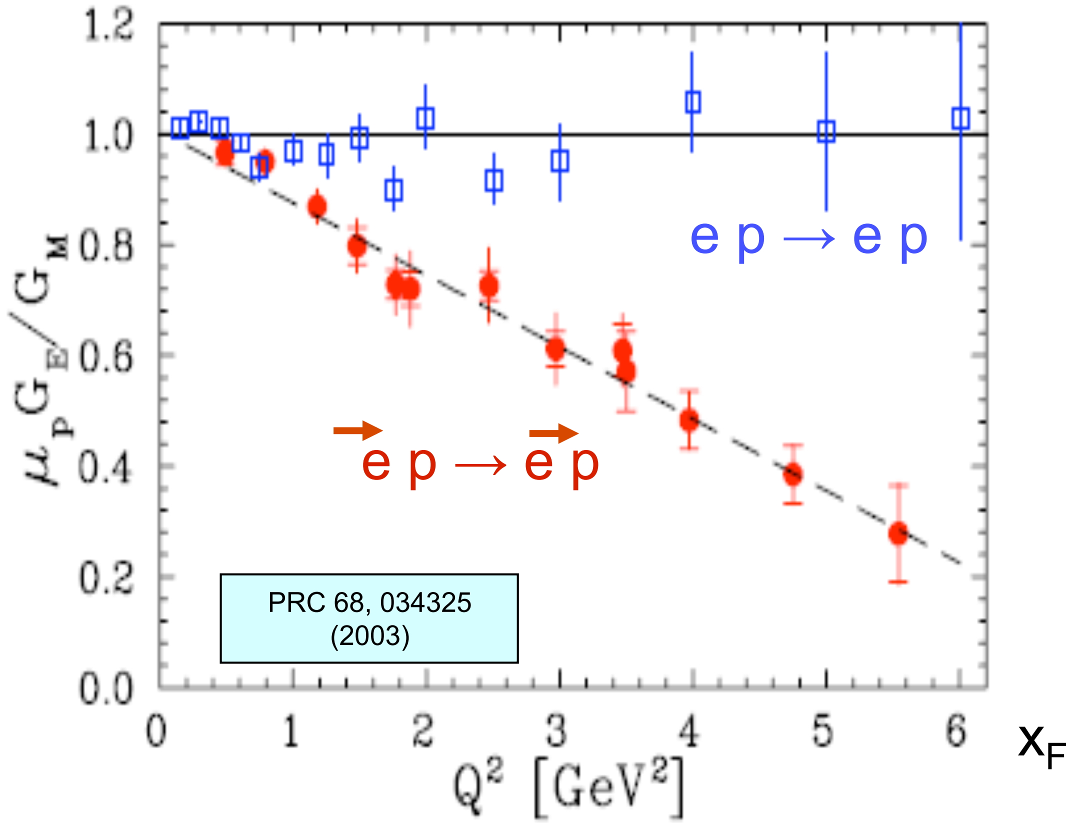
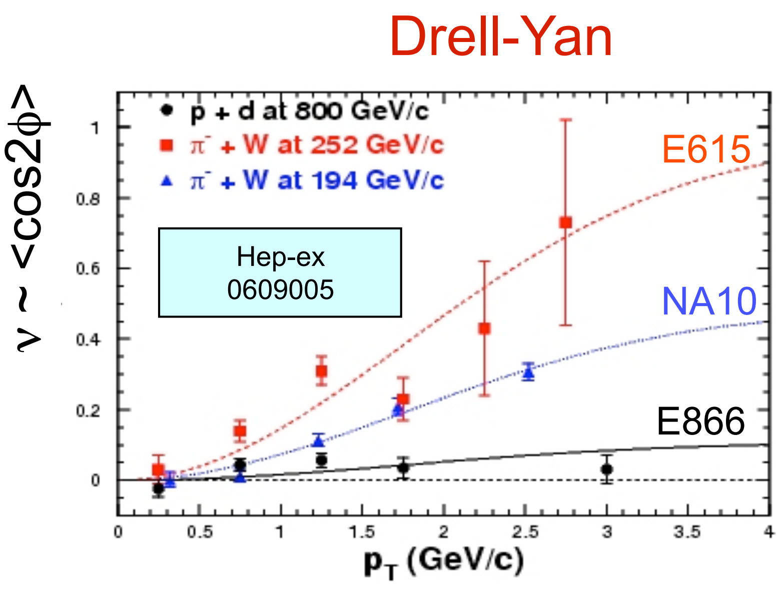
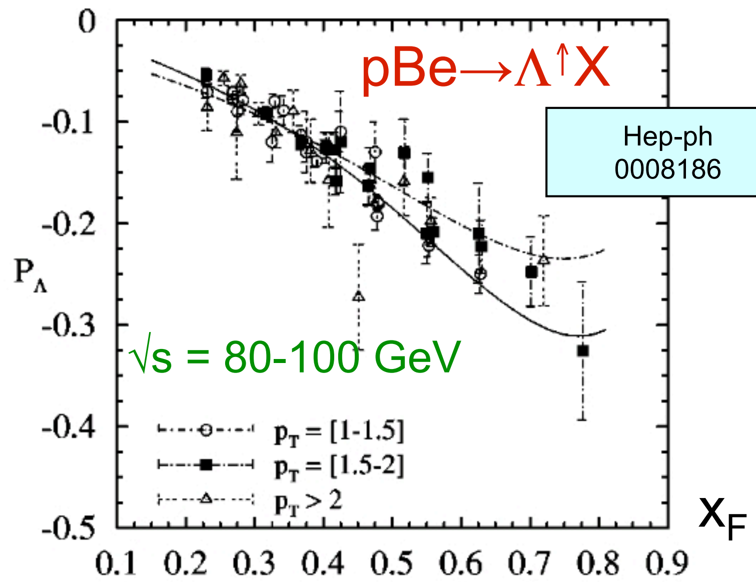
Fundamental: do not neglect it !!



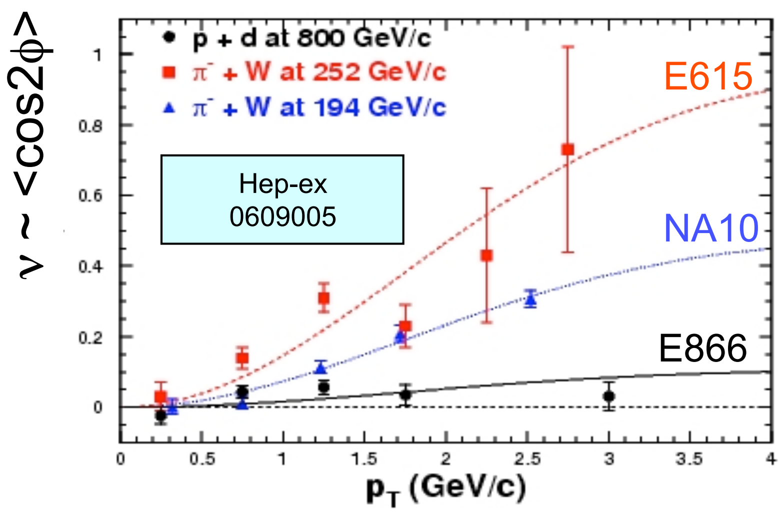
The spin surprising phenomenology

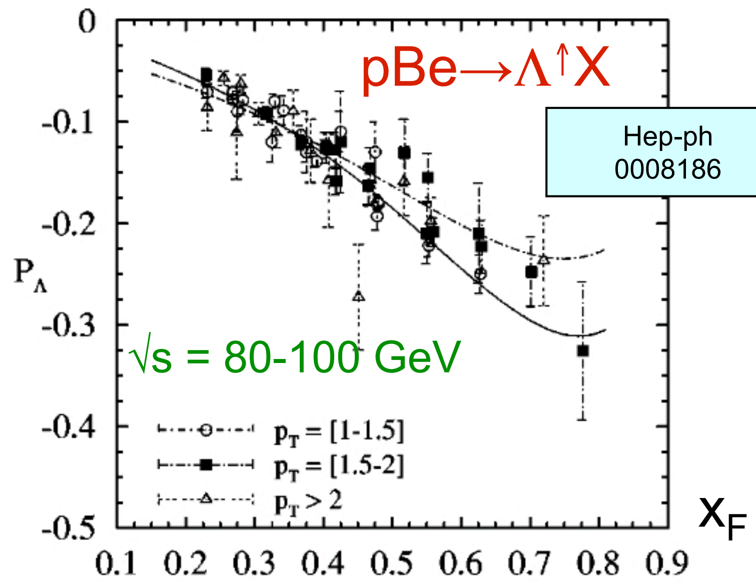


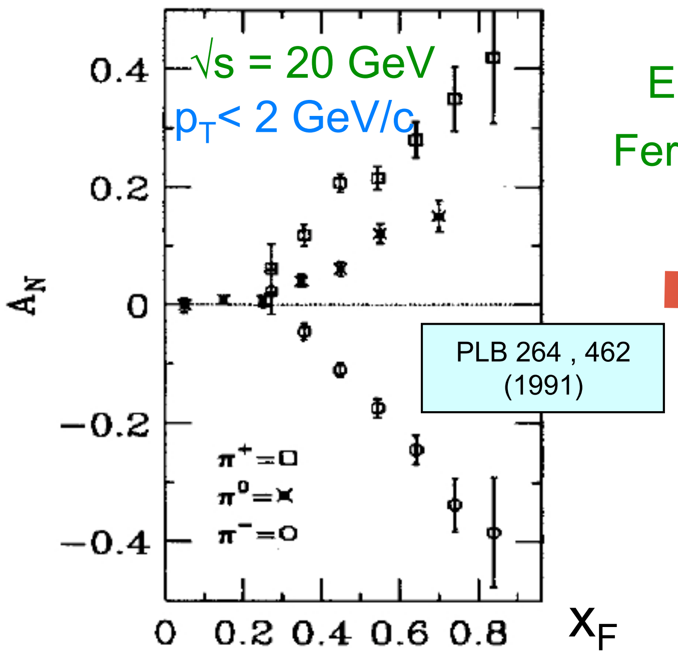


The spin surprising phenomenology

Drell-Yan







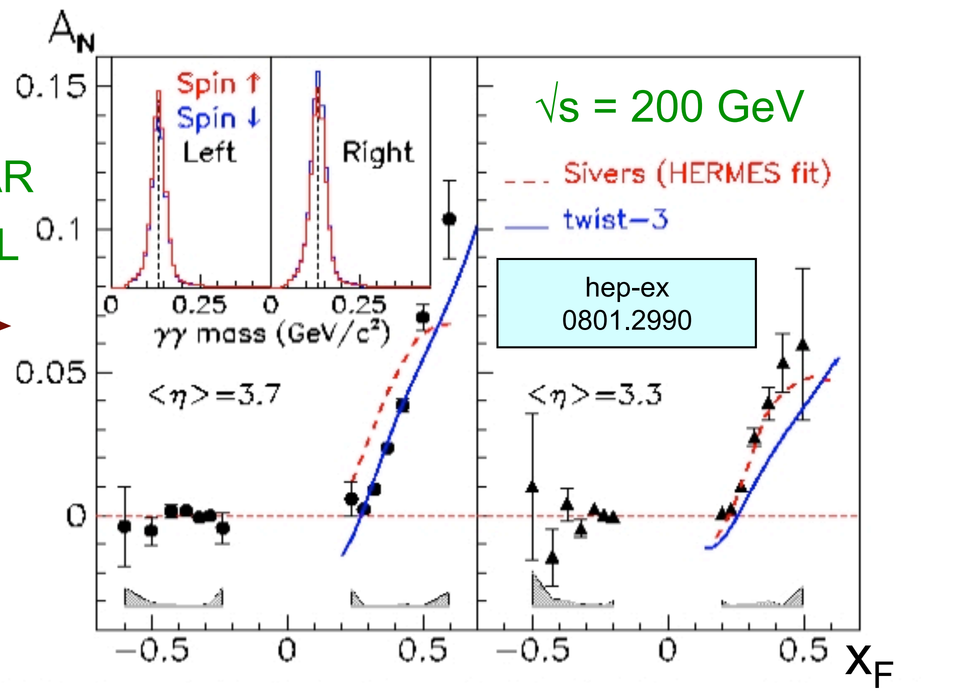
E704

Fermilab

STAR

BNL

$p^{\uparrow}p \to \pi X$



The spin structure of the nucleon

Describe the complex nucleon structure in terms of partonic degrees of freedom of QCD

Important testing ground for QCD

Latest news from Deep Inelastic Scattering (DIS)

Phys Lett B647 (2007) 8-17

Phys. Rev. D 75 (2007) 012007

$\Delta\Sigma = 0.33 \pm 0.03$

ΔG small at $0.02 < x < 0.3$

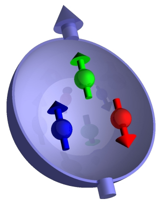
From DIS and pp scattering

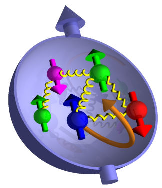
e-print 0804.0422

Proton's spin

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

J_q J_g





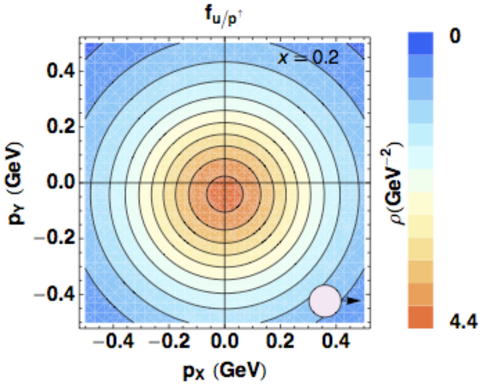
Understanding of the orbital motion of quarks is crucial!

The real experience: 3D !

Quantum phase-space distributions of quarks

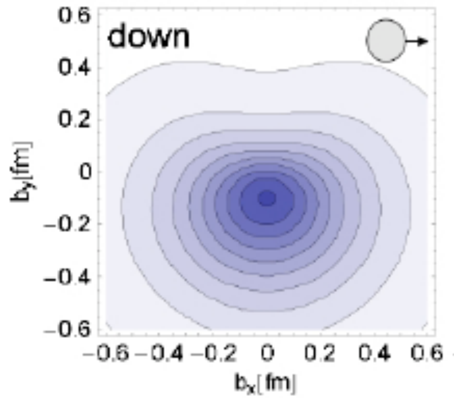
$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

Measure momentum transfer to quark
Direct info about momentum distributions

GPDs: $H_p^u(x,\xi,t)$, …

Measure momentum transfer to target
Direct info about spatial distributions

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x)$,…

Quantum phase-space distributions of quarks

$W_p^q(x, k_T, r)$ "Mother" Wigner distributions

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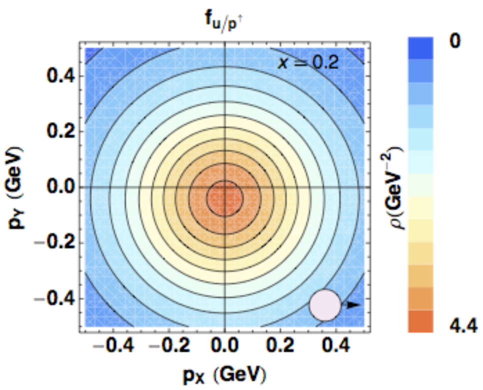

d^3r

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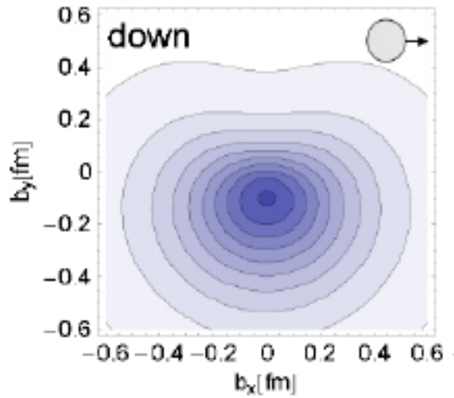


TMD PDFs: $f_p^u(x, k_T), \ldots$

Measure momentum transfer to quark
Direct info about momentum distributions

GPDs: $H_p^u(x, \xi, t), \ldots$

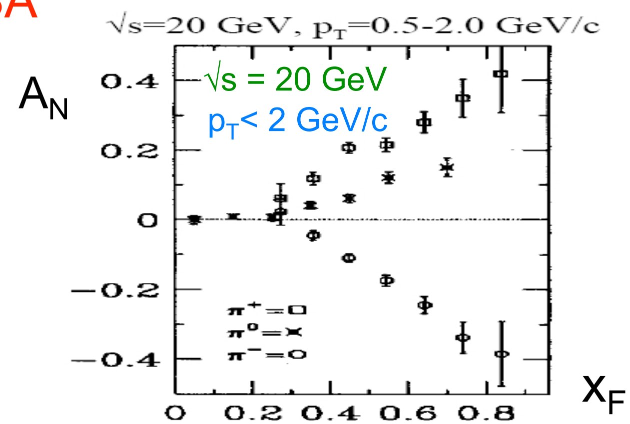
Measure momentum transfer to target
Direct info about spatial distributions

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x), \ldots$

SSA



Proton spin puzzle

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x\, [H(x,\zeta,t) + E(x,\zeta,t)]$$

TMD correlators

Distribution Functions (DF)

		quark		
		U	**L**	**T**
nucleon	**U**	q		$h_1^{\perp}$ -
	L		g_{1L} -	$h_{1L}^{\perp}$ -
	T	$f_{1T}^{\perp}$ -	$g_{1T}^{\perp}$ -	h_1 - $h_{1T}^{\perp}$ -

Off-diagonal elements are important objects:

Interference between wave functions with different angular momenta: contains infos about parton orbital angular momenta

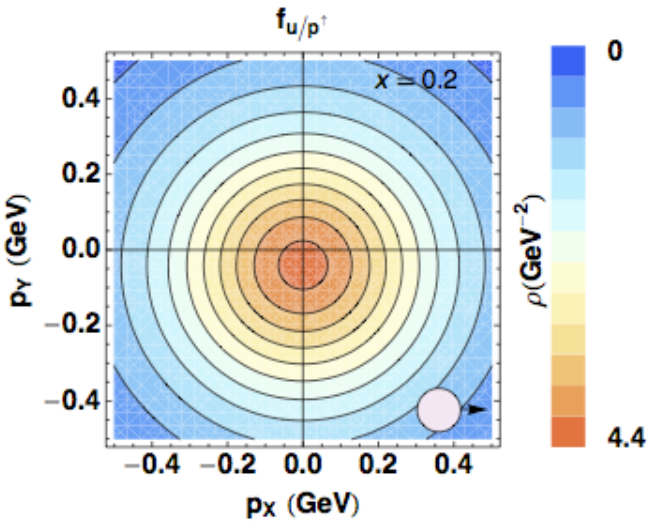
Testing QCD at the amplitude level

➜ sign change between DY and SIDIS
- universality of TMDs

Strict prediction of QCD !

3D description in momentum space

PRD 78 (2008) 074010



Fragmentation Functions (FF)

		quark		
		U	**L**	**T**
nucleon	**U**	D_1		$H_1^{\perp}$ -
	L		G_{1L} -	$H_{1L}^{\perp}$ -
	T	$D_{1T}^{\perp}$ -	G_{1T} -	H_1 - $H_{1T}^{\perp}$ -

The 3D description of the nucleon

Distribution Functions (DF)

		quark		
		U	**L**	**T**
nucleon	**U**	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq $h_{1T}^\perp$

BOER-MULDERS

Spin orbit effect

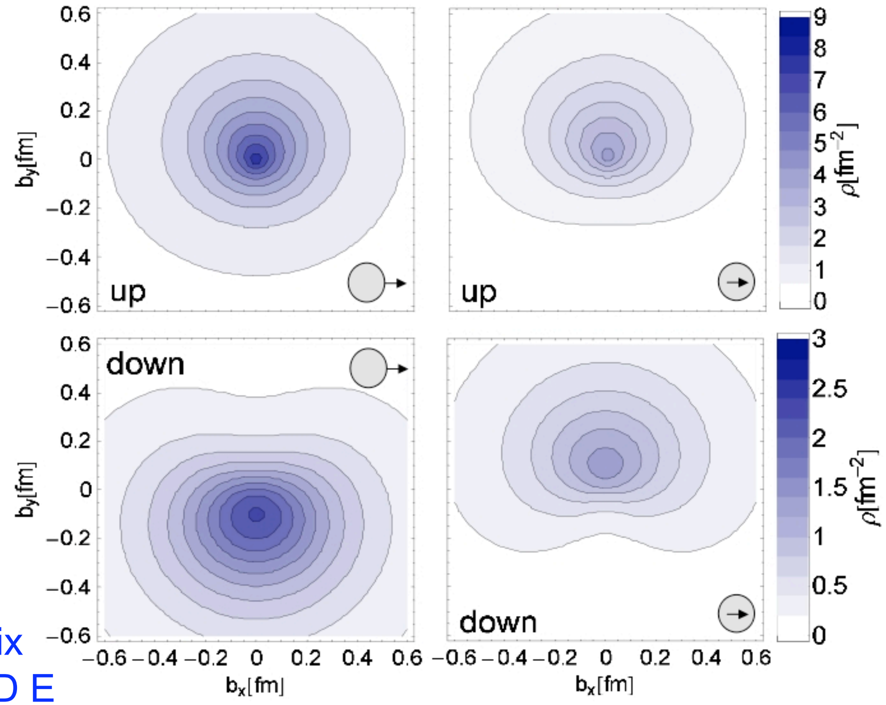
$$h_1^{\perp q} \sim -\kappa_T^q$$

Impact parameter space

Deformations by

GPD E

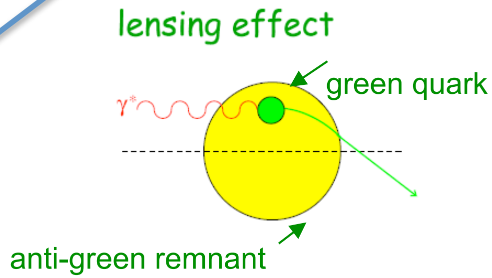
GPD $E_T+2\tilde{H}_T$



SIVERS

Quark orbital angular momentum

$$f_{1T}^{\perp q} \sim -\kappa^q$$

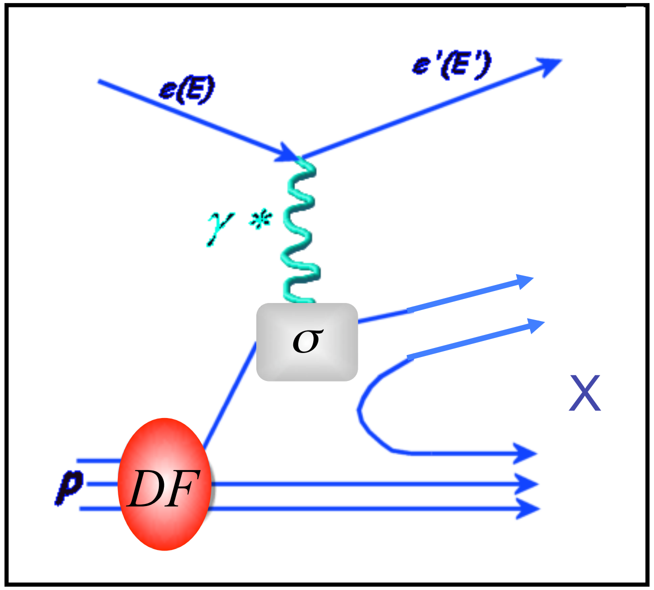


3-momentum space

i.e. Sivers: spin-orbit correlations with same matrix element of anomalus magnetic moment, and GPD E

Moving out of collinearity

Inclusive



SFs (x,Q^2)

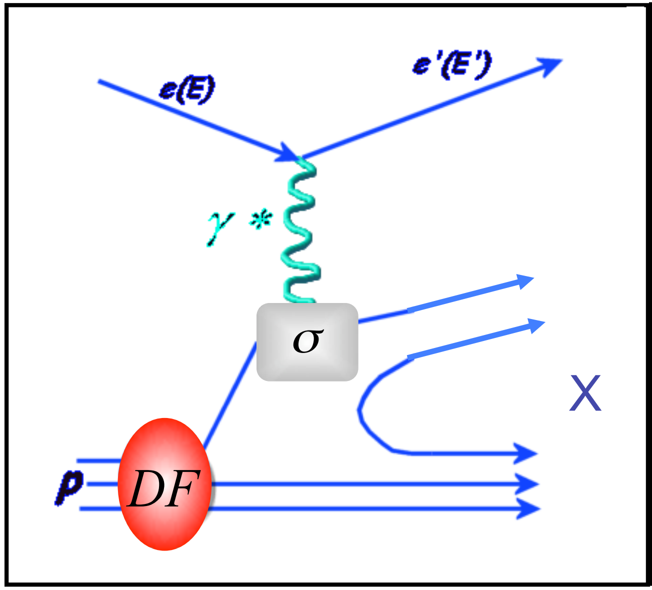
Structure functions
(unpolarized, helicity)

Sum over quark charges

$$d\sigma \propto F_2\left(=\sum_q e_q^2 q(x)\right)$$

Moving out of collinearity

Inclusive



SFs (x,Q²)

Structure functions
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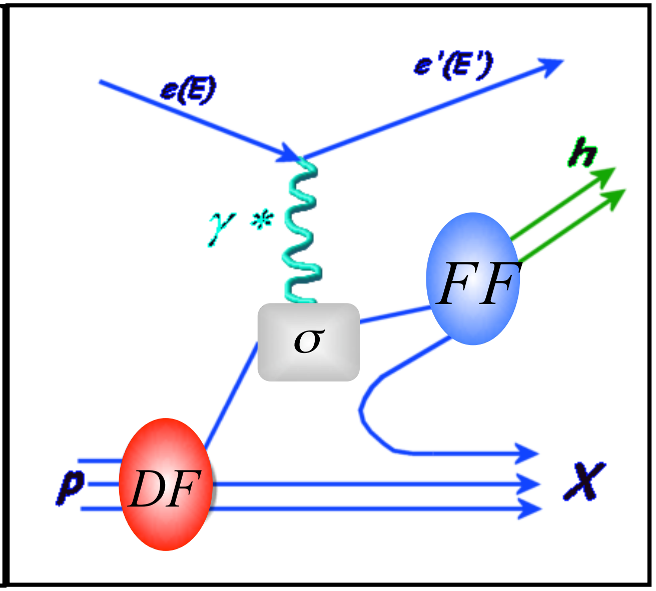
Sum over quark charges

$$d\sigma \propto F_2\left(=\sum_q e_q^2 q(x)\right)$$

Semi-inclusive



PDFs (x,z,Q^2)

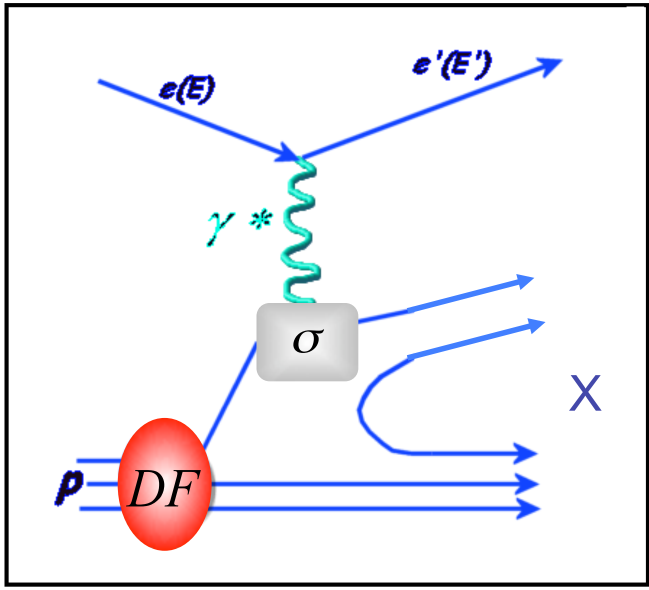
Parton distributions

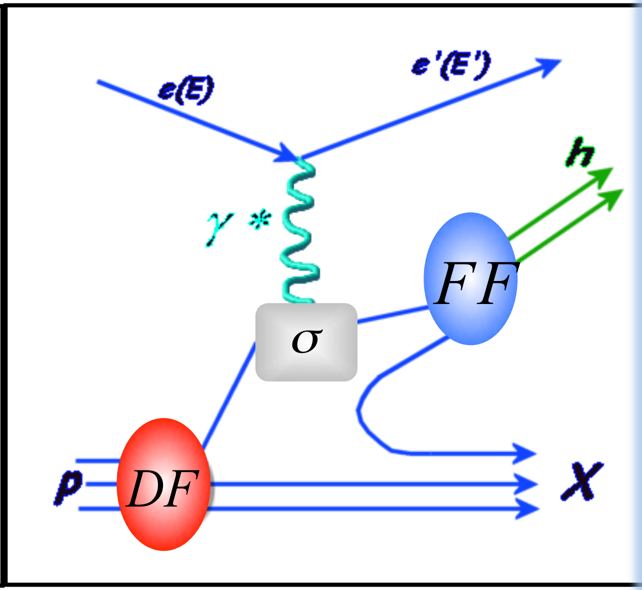
Flavor sensitivity

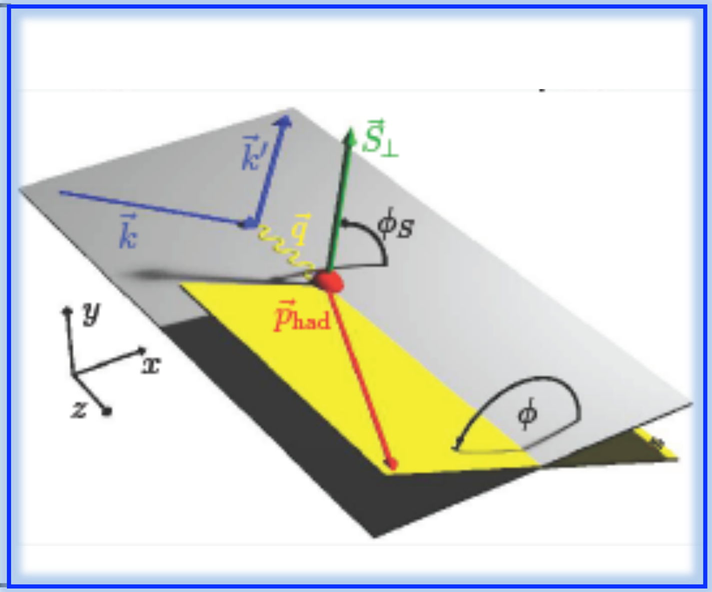
$$d\sigma^h \propto \sum_q e_q^2 q(x) D_q^h(z)$$

Moving out of collinearity

Inclusive	Semi-inclusive	Semi-inclusive







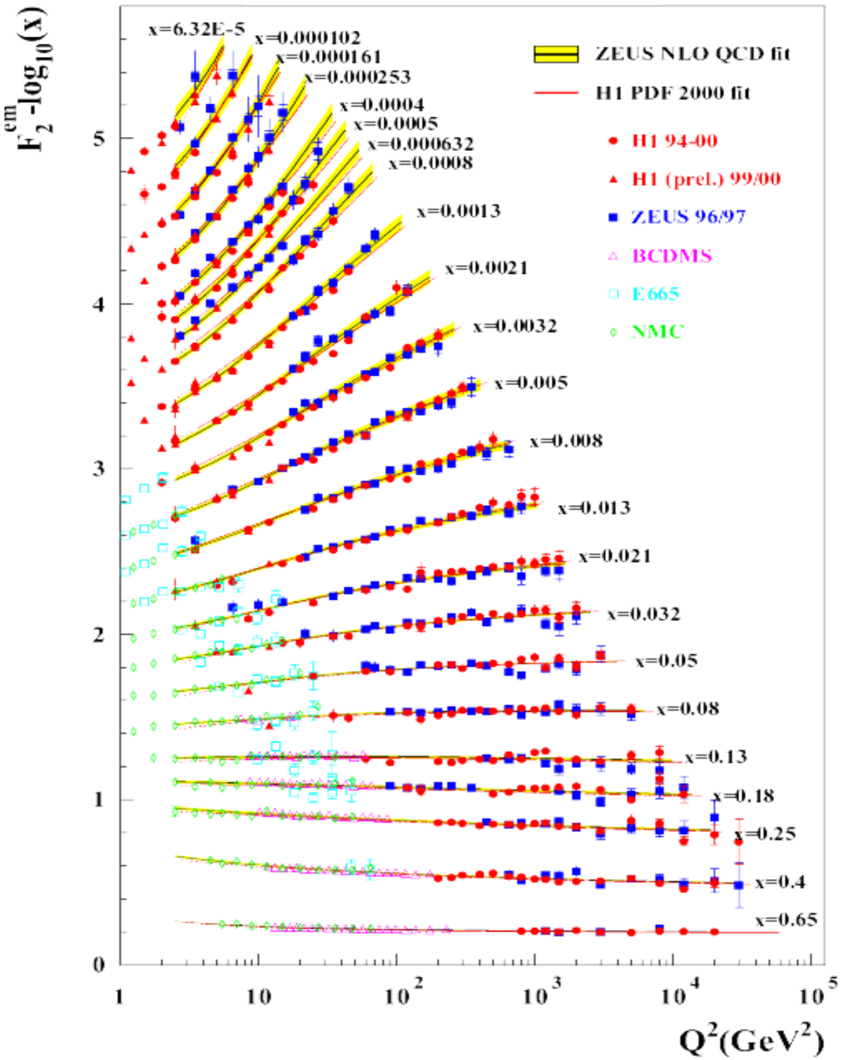
SFs (x,Q^2)	PDFs (x,z,Q^2)	TMDs $(x,z,P_{h\perp},Q^2)$
Structure functions (unpolarized, helicity)	Parton distributions	Transverse momentum dependent parton distri.
Sum over quark charges	Flavor sensitivity	Spin-Orbit effects
$d\sigma \propto F_2\left(=\sum_q e_q^2 q(x)\right)$	$d\sigma^h \propto \sum_q e_q^2 q(x) D_q^h(z)$	$d\sigma^h \propto \sum_q e_q^2 C\left[q(x,k_T) D_q^h(z,p_T)\right]$

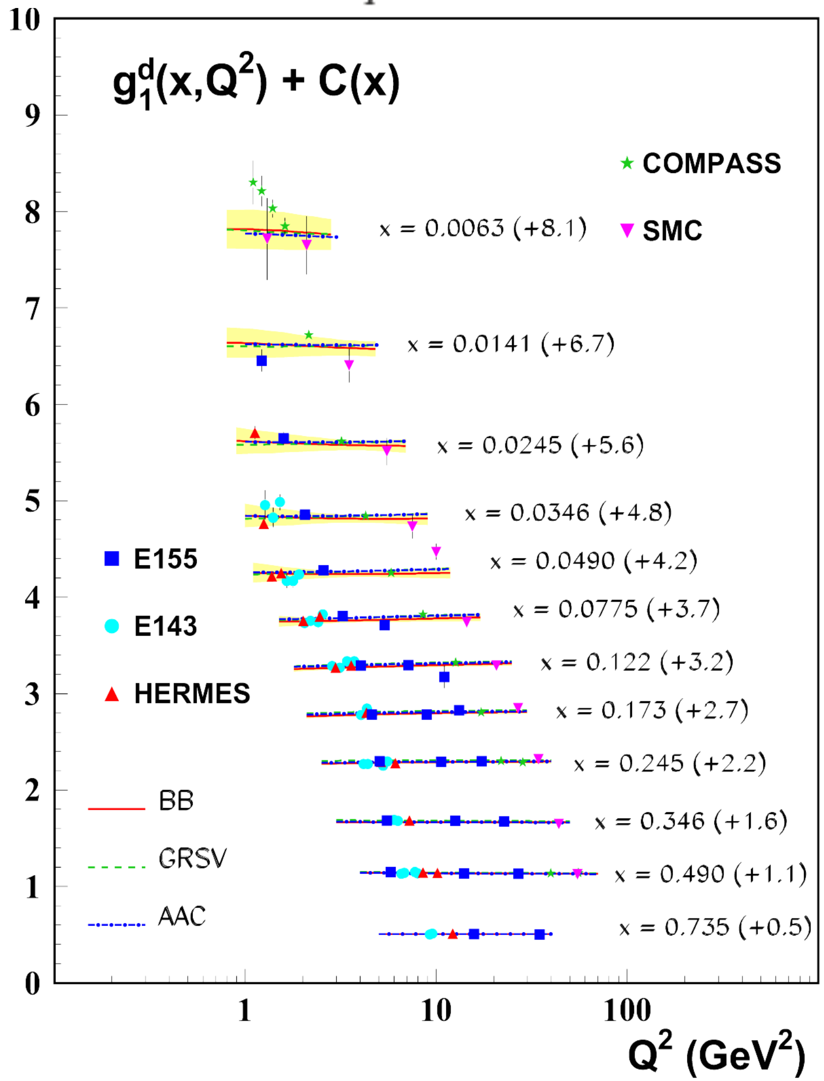
Rich and Involved phenomenology !!

The collinear case

$$F_2 = \sum_q x\, q(x, Q^2)$$

$$g_1 = \frac{1}{2} \sum_q e_q^2\, \Delta q(x, Q^2)$$



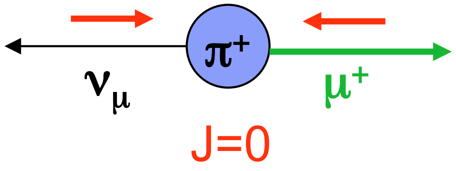


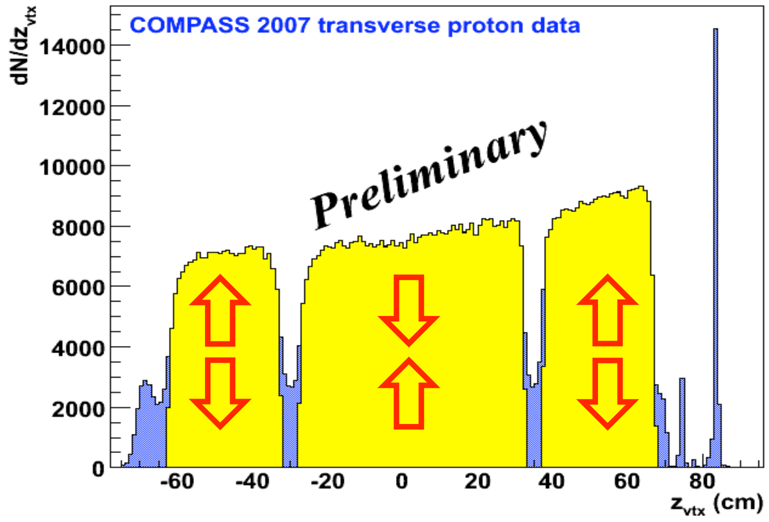
Great success, but exploiting only leptonic degrees of freedom.

Technological Challenges

COMPASS @ CERN

"Natural" muon beam polarization:
100-200 GeV muons from pion decays
low beam currents I ≈ 1 pA

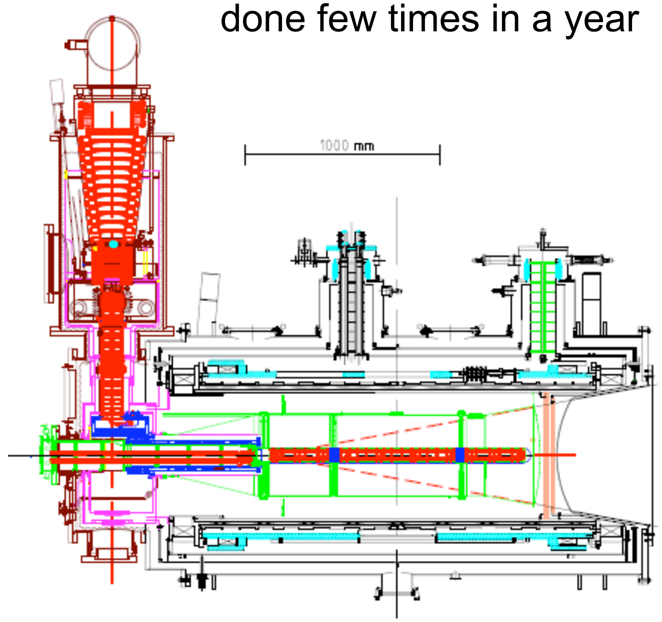




Solid state target operated in frozen spin mode
high-mass cryogenic target N ≈ 10^{24} nucleons/cm^2
small fraction of polarizable nucleons NH_3,ND_3,^{6}LiD

Polarization switching tsakes time
done few times in a year

2002-2004: ^{6}LiD (polarised deuteron)
dilution factor f = 0.38
polarization P_T = 50%

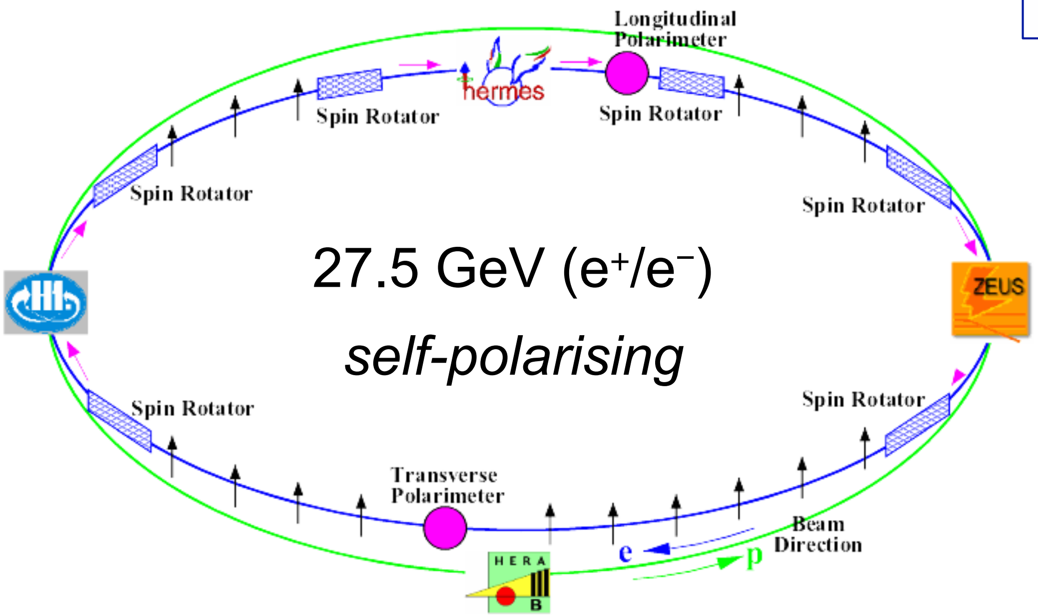


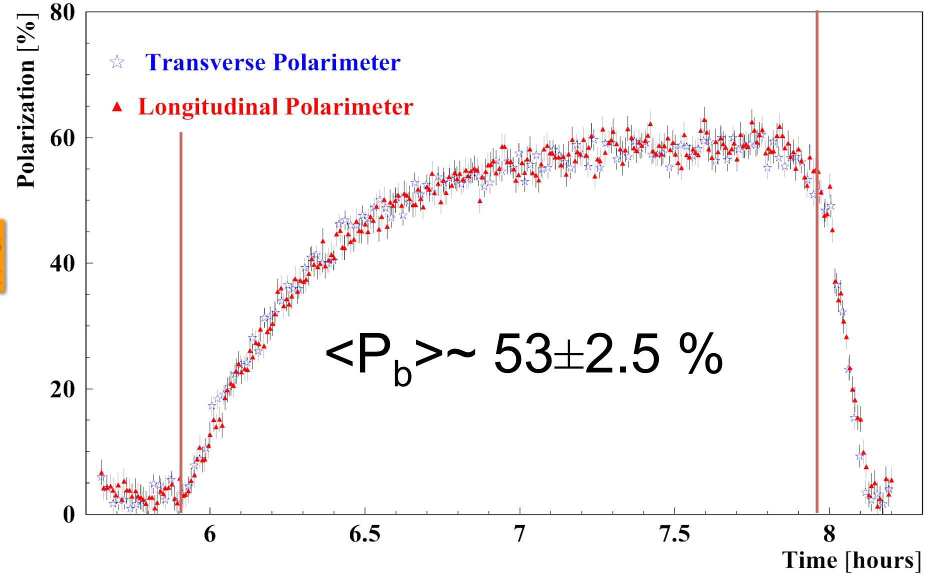
180 mrad

2007: NH_3 (polarised protons)
dilution factor f = 0.14
polarization P_T = 90%

HERMES @ DESY

Self-polarising e^+/e^- beam: Sokolov-Ternov effect

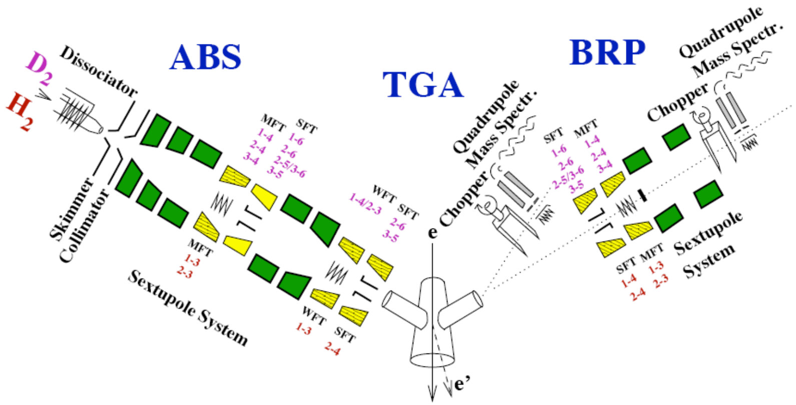


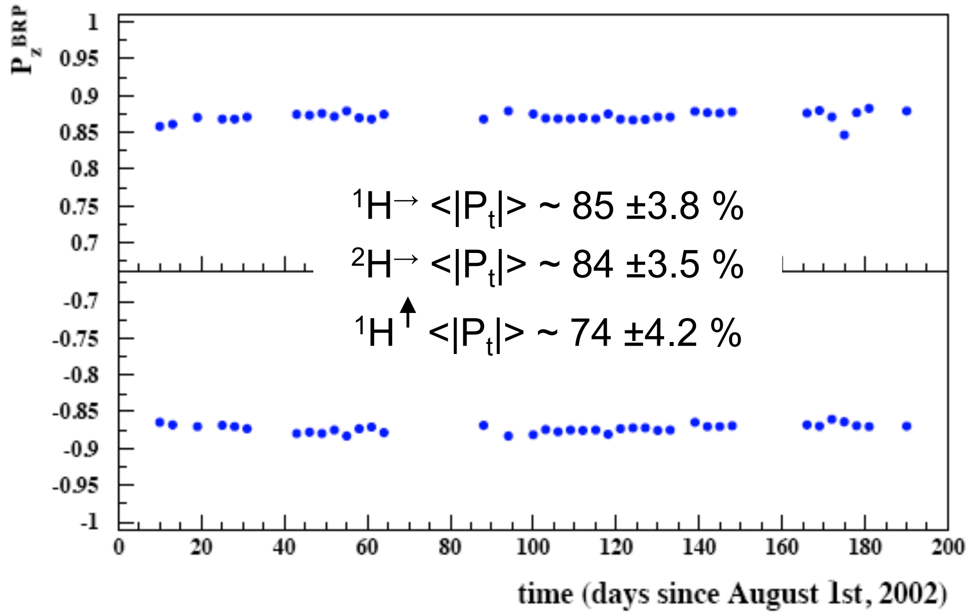


Pure nuclear-polarised H,D atomic gaseous target

ms polarization switching at 90s time intervals

L ~ $O(10^{31})$ cm^{-2} s^{-1}





HD-Ice target @ JLab

HD-Ice target vs std nuclear targets

Heat extraction is accomplished with thin aluminum wires running through the target (can operate at *T~500-750mK*)

Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

P= 95 % H , 70 % D

HD-Ice target at ~ 1-2nA
NH_3 at ~ 5-10 nA

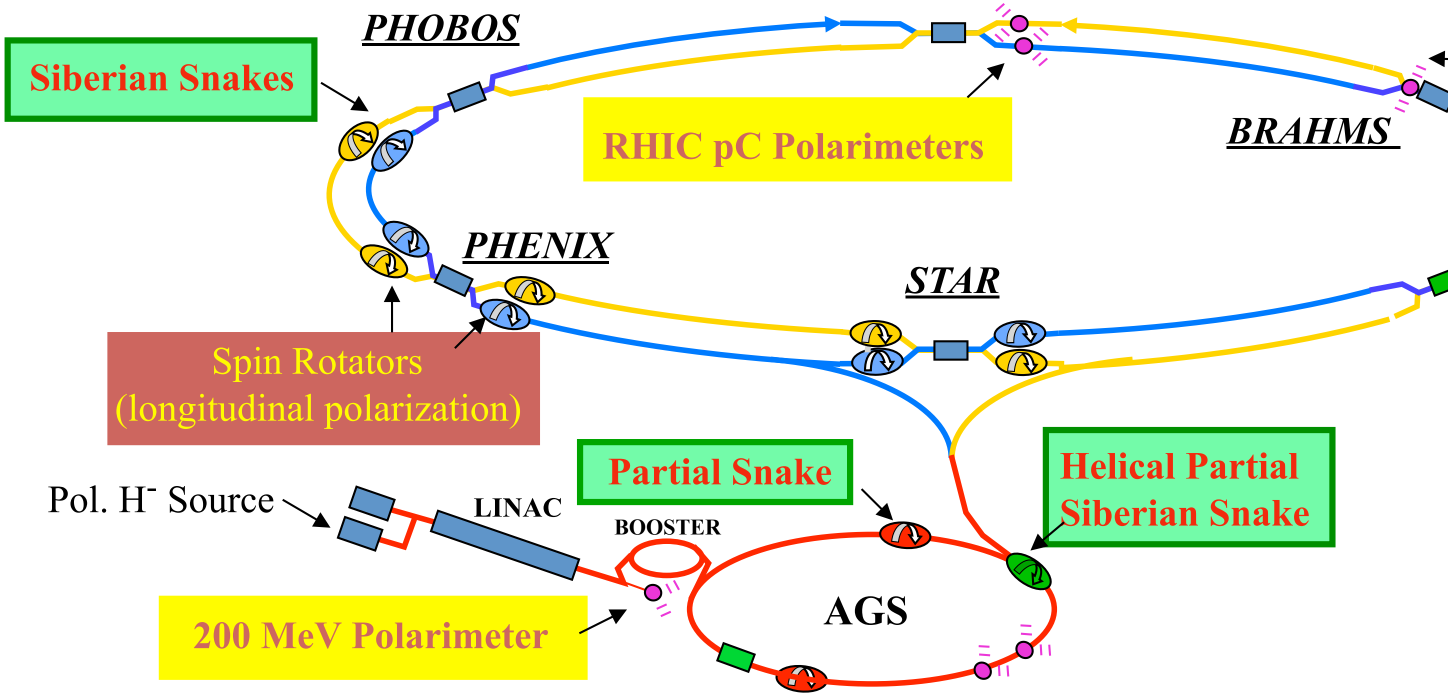
Pros

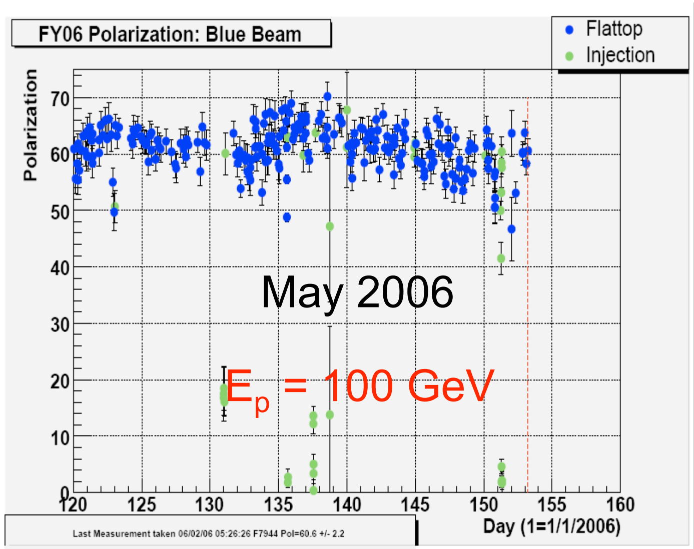
1. **Small field (*∫Bdl~0.005-0.05Tm*)**
2. **Small dilution (fraction of events from polarized material)**
3. **Less radiation length**
4. **Less nuclear background (no nuclear attenuation)**
5. **Wider acceptance much better FOM, especially for deuteron**
6. **H and D may be independently polarized**

Cons

1. **HD target is highly complex and there is a need for redundancy due to the very long polarizing times (months).**
1. **Need to demonstrate that the target can remain polarized for long periods with an electron beam with currents of order of 1-2 nA**
2. **Additional shielding of Moller electrons necessary (use minitorus)**

RHIC – polarized pp collider





Siberian Snakes suppress depolarizing resonances during accel.

AGS: variable twist helical dipoles (3T), 2.6 m

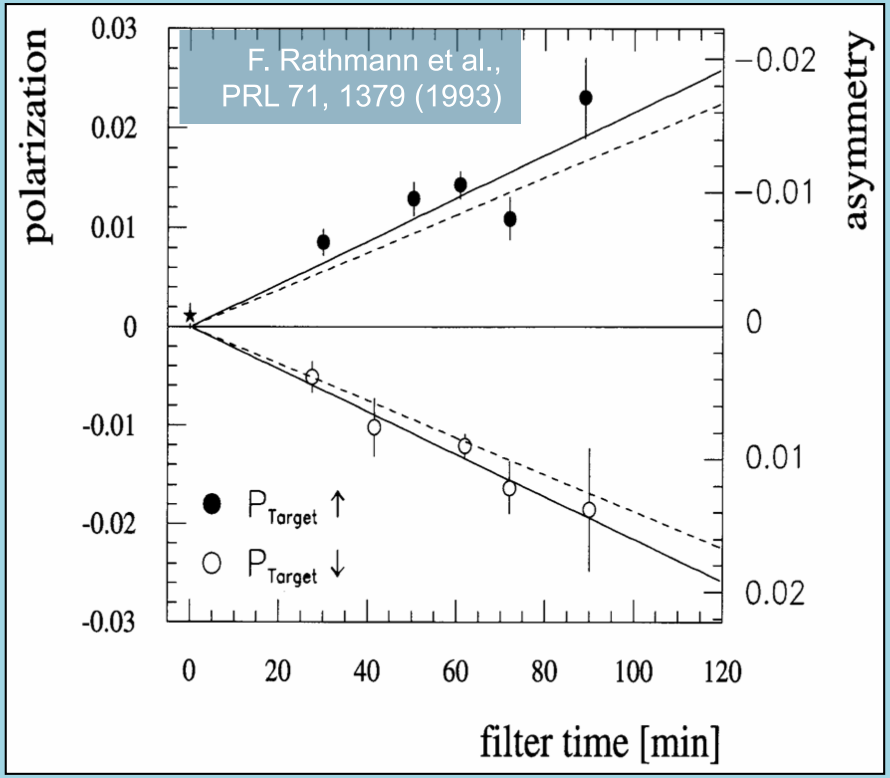
RHIC : full twist helical dipoles (4T), 2.4 m

The spin filtering

Polarized antiproton beams ⟺ polarized valence antiquarks

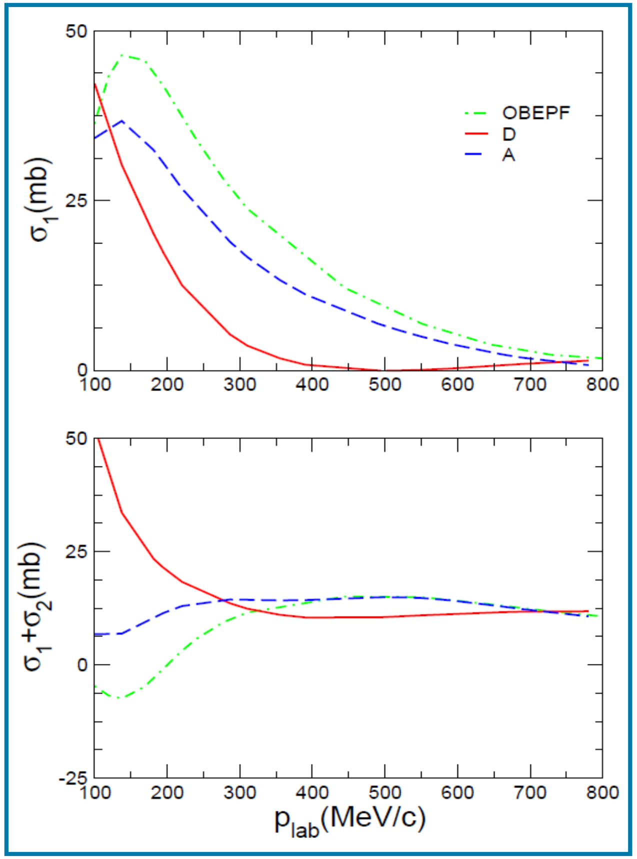
$$\sigma_{tot} = \sigma_0 + \sigma_1 \cdot \vec{P} \cdot \vec{Q} + \sigma_2 \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k})$$

P beam polarization
Q target polarization
k || beam direction



→ Spin filtering works for protons

Polarization buildup process quantitatively understood
D. Oellers et al., PLB 674 (2009) 269



Model A: T. Hippchen et al., Phys. Rev. C 44, 1323 (1991).

Model OBEPF: J. Haidenbauer, K. Holinde, A.W. Thomas, Phys. Rev. C 45, 952 (1992).

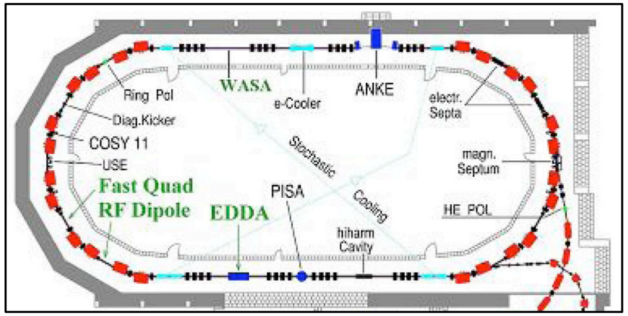
Model D: V. Mull, K. Holinde, Phys. Rev. C 51, 2360 (1995).

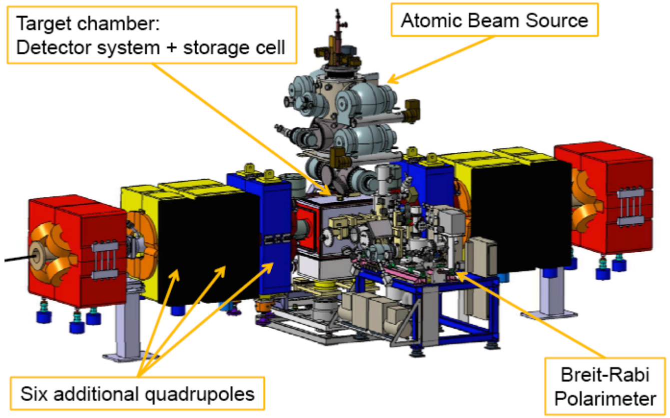
Xsec and spin correlations to be measured

The PAX phases

COSY

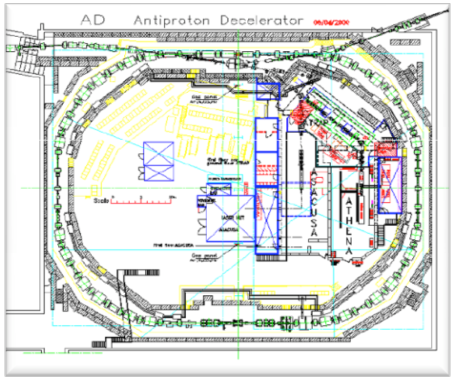
2009-2011



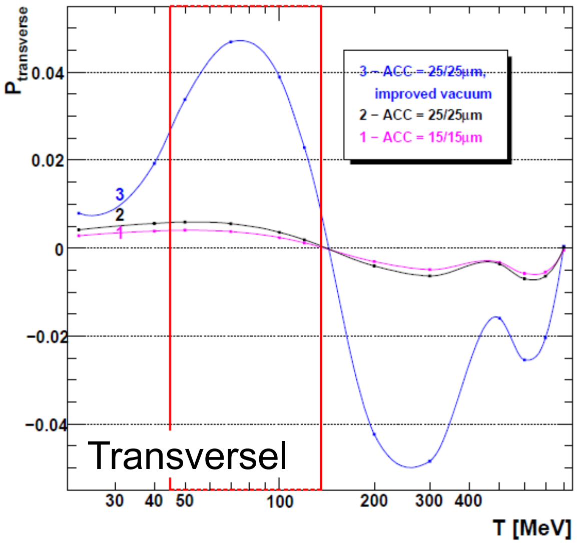


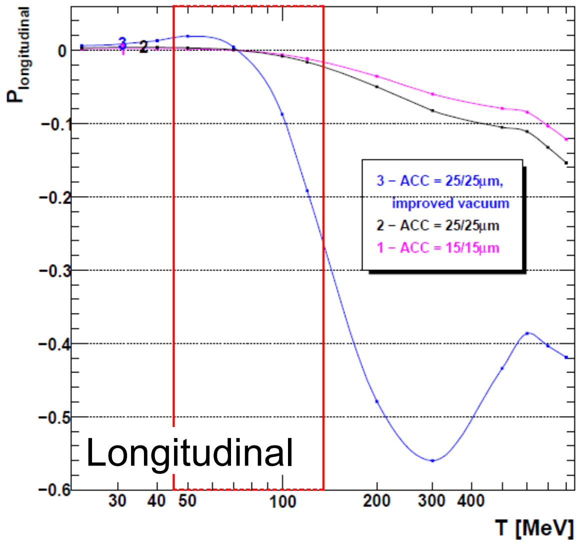
AD

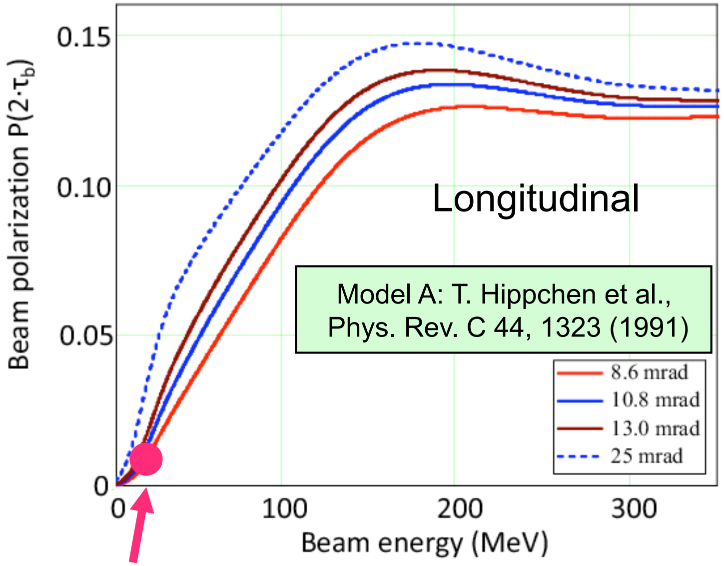
2012-2014



Strong dependence on the ring characteristics: vacuum, acceptance



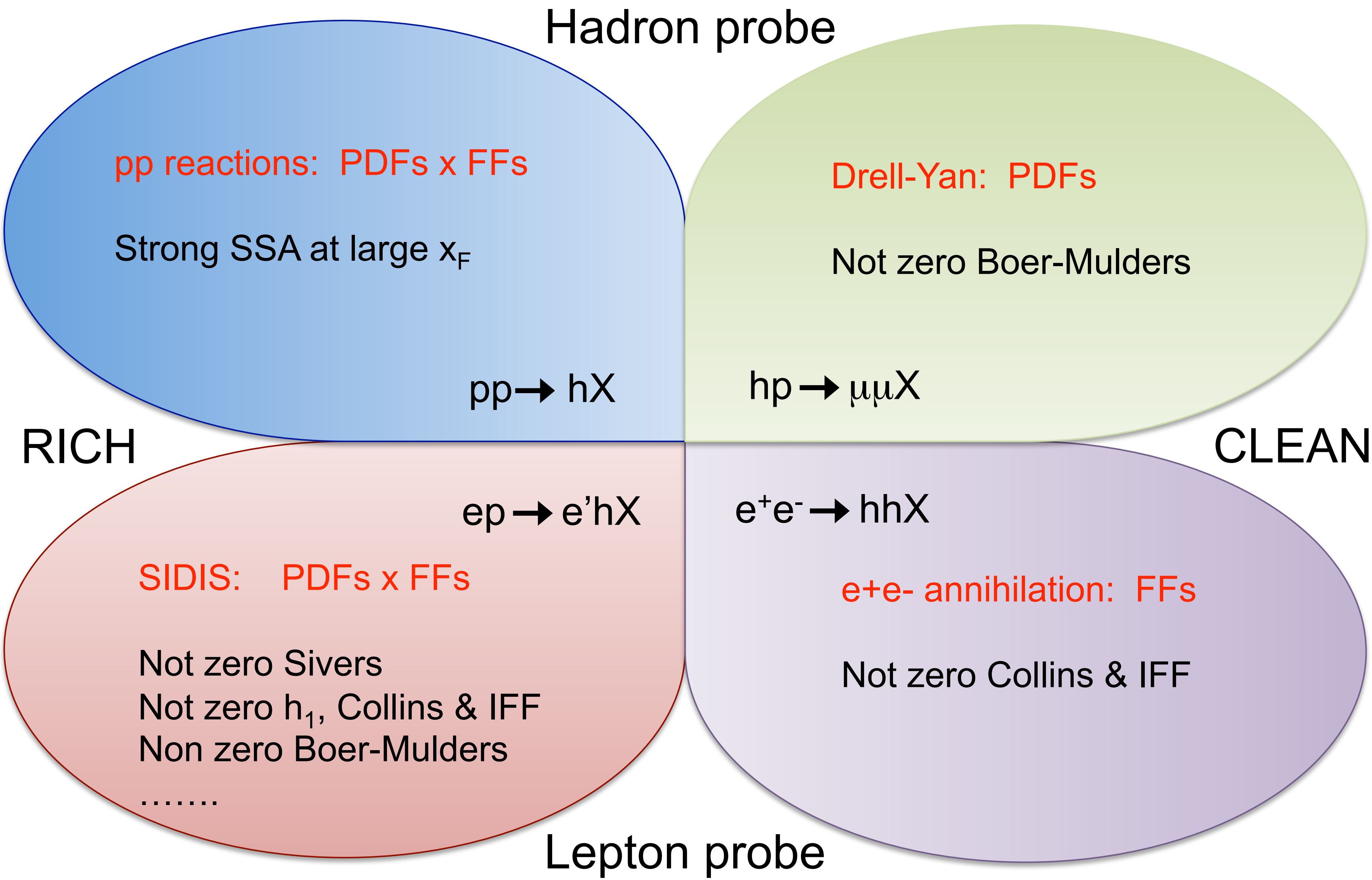




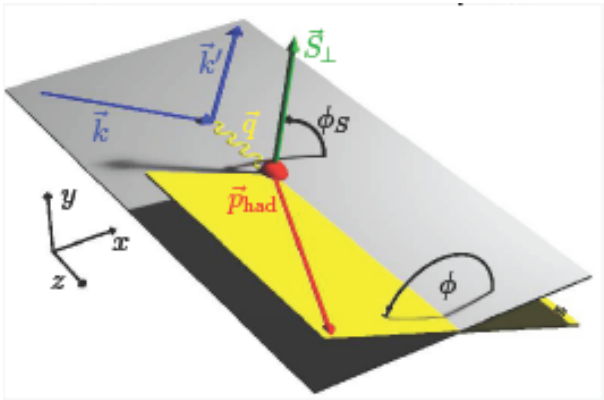
TSR: T = 23 MeV, Ψ_{acc} = 4.4 mrad

TMD Studies at Present Facilities

TMD palette


Hadron probe
pp reactions: PDFs x FFs
Strong SSA at large x_F
pp → hX
Drell-Yan: PDFs
Not zero Boer-Mulders
hp → μμX
RICH
CLEAN
ep → e'hX
SIDIS: PDFs x FFs
Not zero Sivers
Not zero h_1, Collins & IFF
Non zero Boer-Mulders
…….
e^+e^- → hhX
e+e- annihilation: FFs
Not zero Collins & IFF
Lepton probe

Transversity & Collins



SIDIS:
ep → e'hX

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^\perp$$

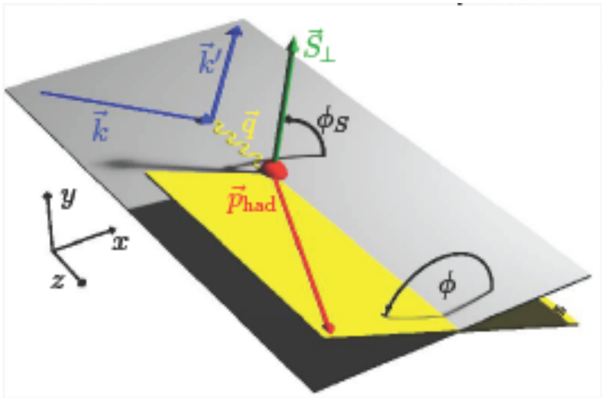
Distribution Functions (DF)

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

Fragmentation Functions (FF)

		quark U	quark L	quark T
nu…	U	D_1		$H_1^\perp$

Transversity & Collins



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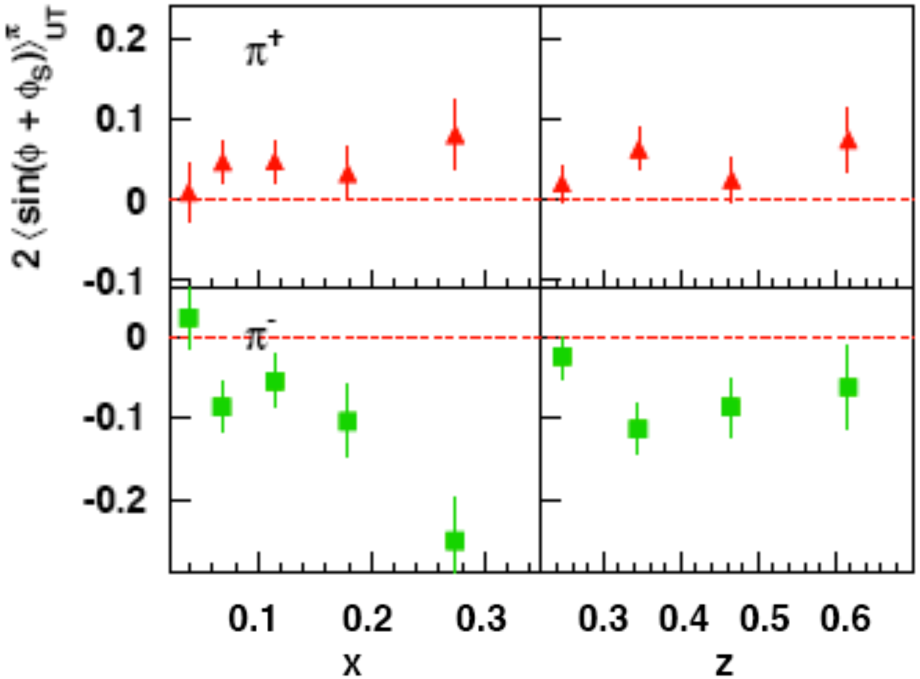
nu...	U	D_1		$H_1^\perp$

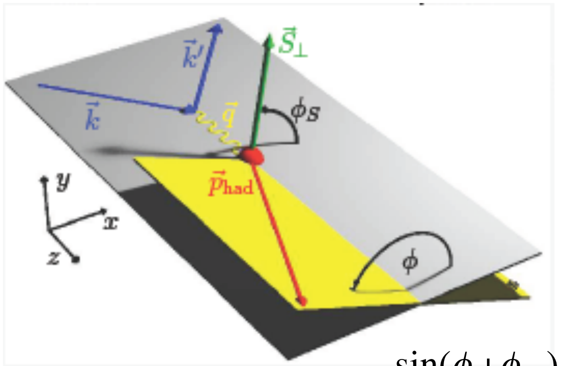
A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002

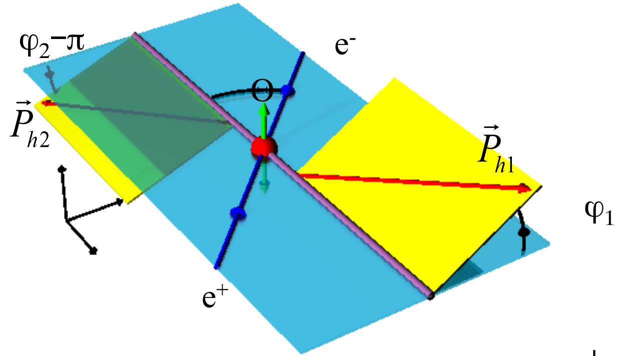


2005: First evidence from HERMES SIDIS on proton

Non-zero transversity !!
Non-zero Collins function !!

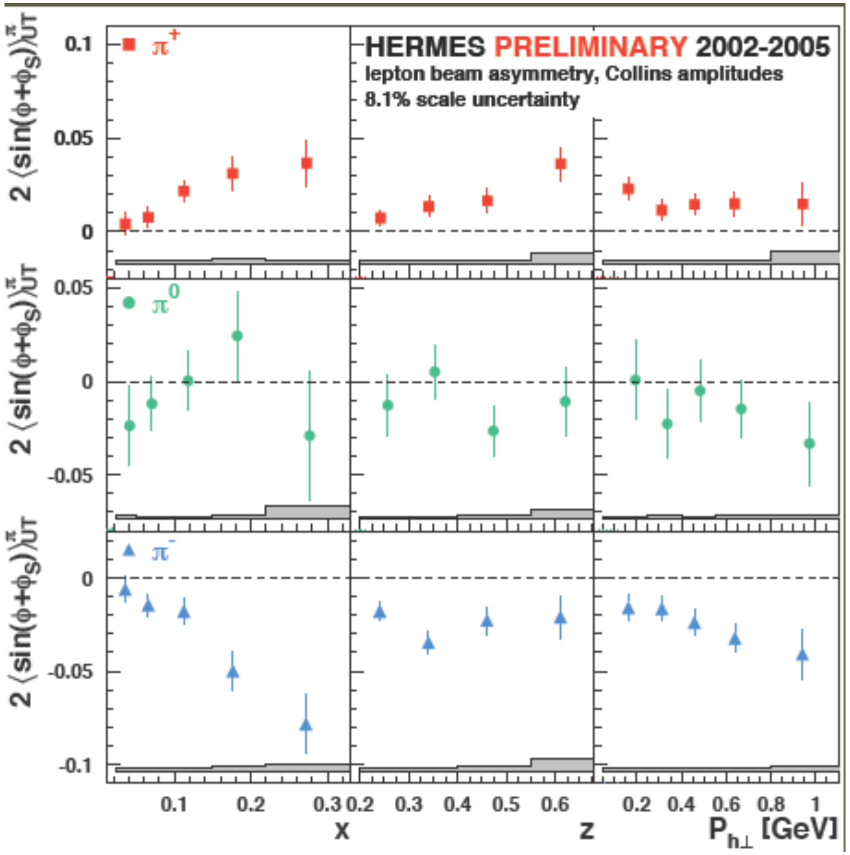
Transversity & Collins

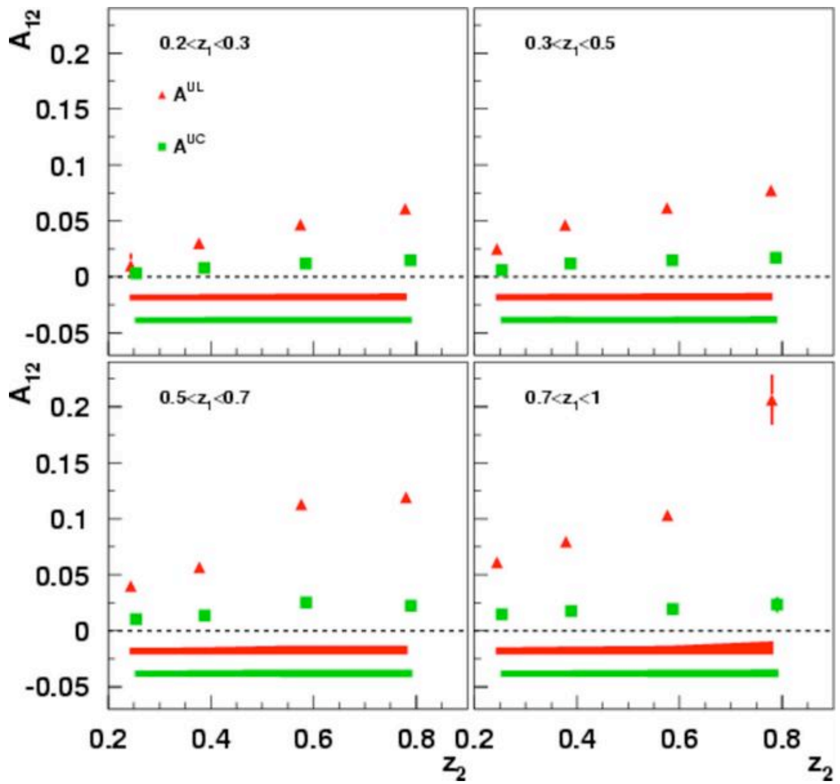




HERMES & COMPASS: $\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^\perp$

BELLE: $A_{12} \propto H_1^\perp H_1^\perp$

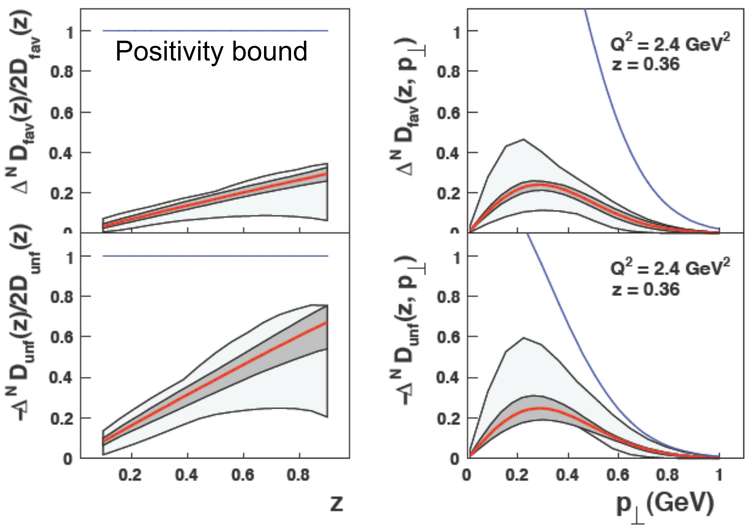




4x4 z_1 z_2 binning

Transversity & Collins

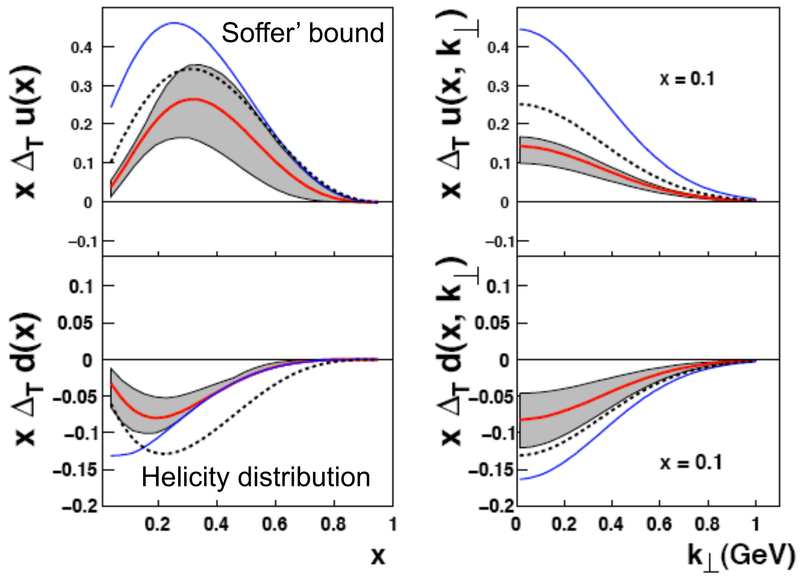
Collins fragmentation function



Gaussian alsatz

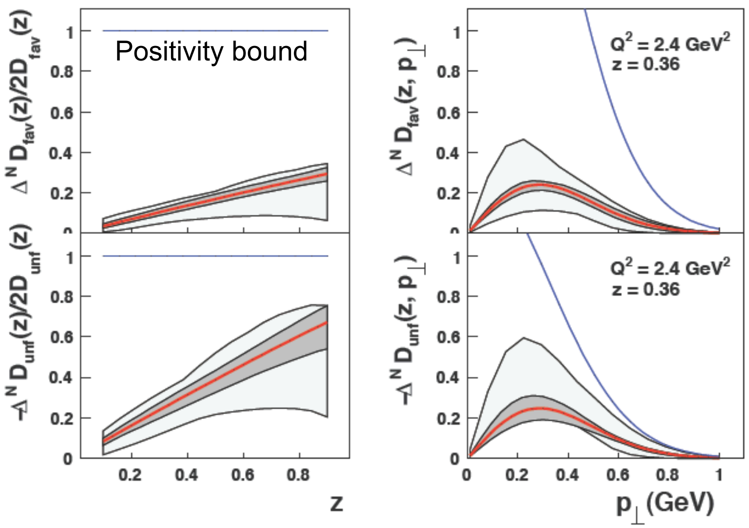
Standard evolution

Transversity



Transversity & Collins

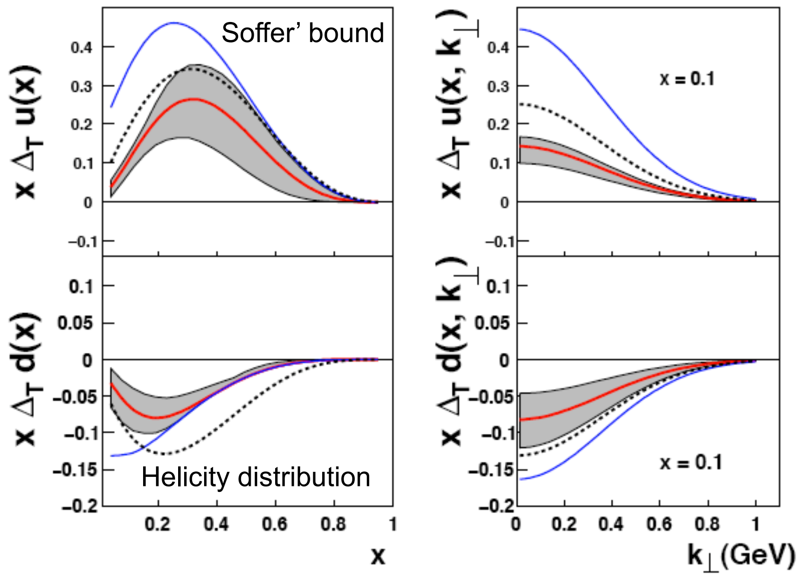
Collins fragmentation function



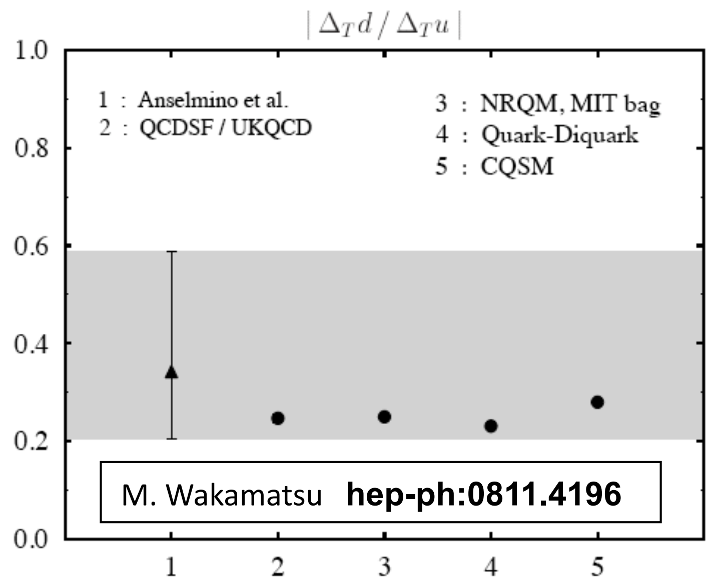
Gaussian alsatz

Standard evolution

Transversity



1. k_T dependence ?
2. Evolution ?



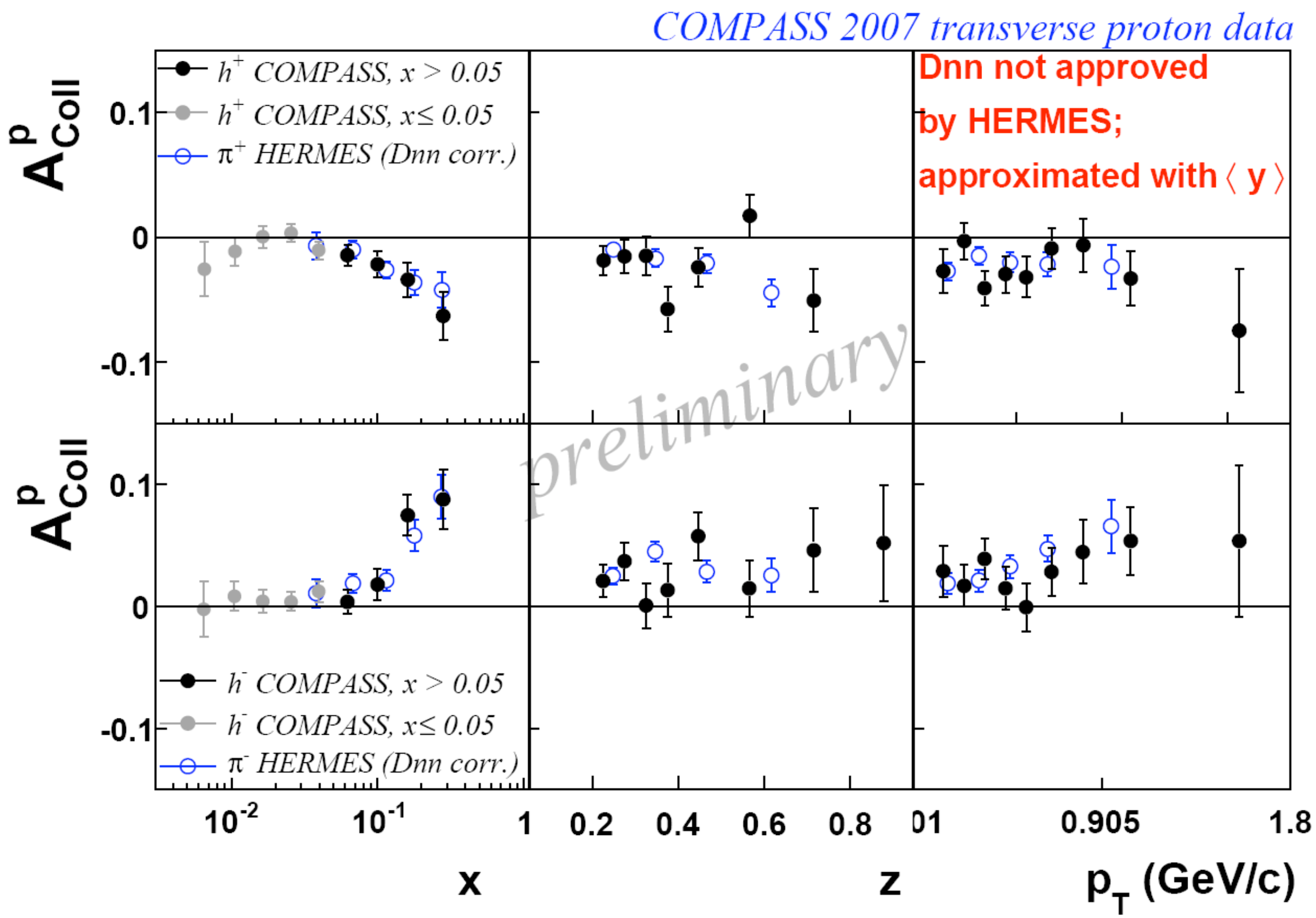
Tensor charge

$$\delta u = 0.54^{+0.09}_{-0.22}$$

$$\delta d = -0.23^{+0.09}_{-0.16}$$

M. Anselmino et al
hep-ph:0812.4366

Transversity & Collins

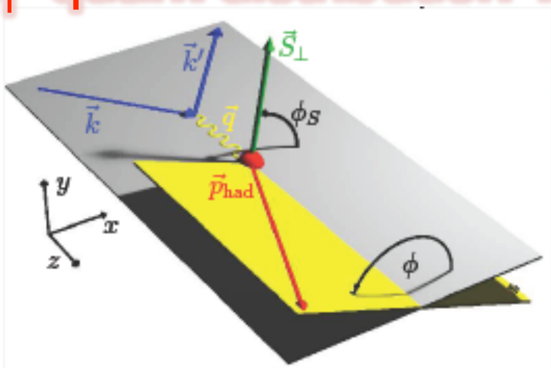


Consistent picture!

Ready to go looking for precision

Cahn effect

k_T quark distribution ?



SIDIS:
ep → e'hX

$$\sigma_{UU}^{\cos(\phi)} \propto f_1\, D_1$$

Distribution Functions (DF)

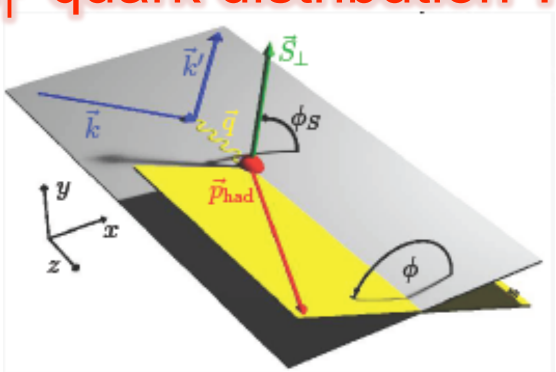
		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$ -
	L		g_{1L} -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$ -	$g_{1T}^\perp$ -	h_1 - $h_{1T}^\perp$ -

Fragmentation Functions (FF)

		quark		
		U	L	T
nu…	U	D_1		$H_1^\perp$ -

Cahn effect

k_T quark distribution ?



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	L		g_{1L}	$h_{1L}^\perp$
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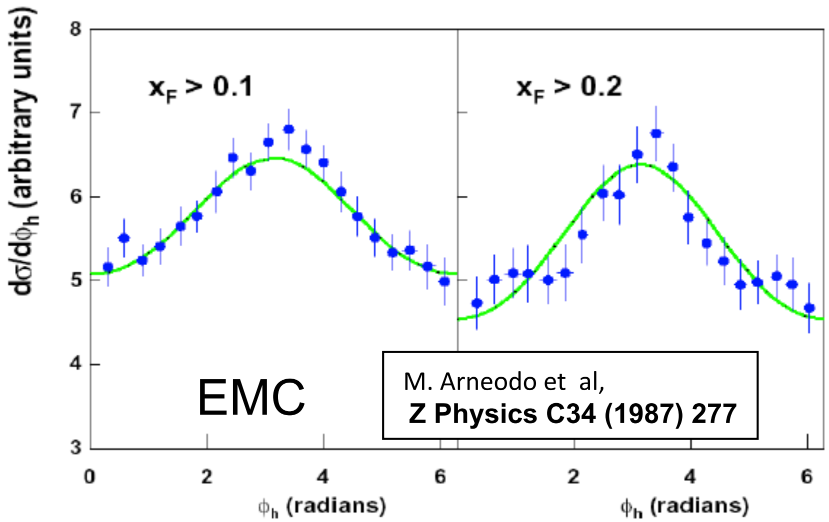
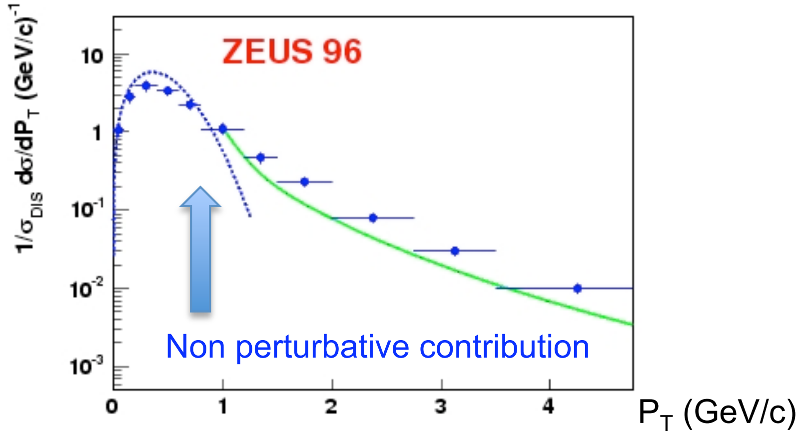
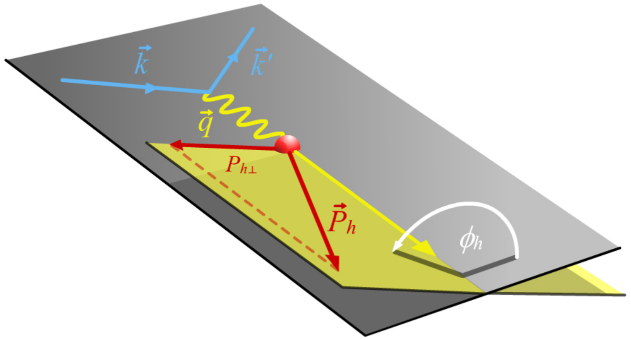


Predicted since 1978 by Cahn
Non-zero intrinsic k_T !!



Boer-Mulders function

Partonic spin-orbit effect



Distribution Functions (DF)

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

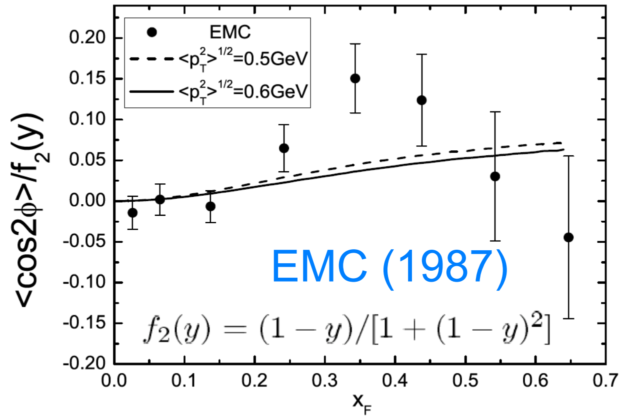
Fragmentation Functions (FF)

		quark		
		U	L	T
nu	U	D_1		$H_1^\perp$

SIDIS:

ep → e'hX

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp H_1^\perp$$



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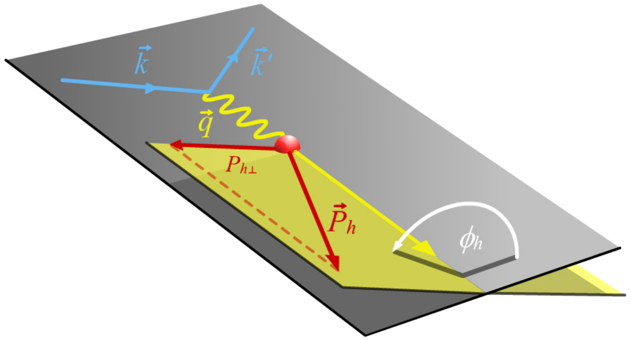

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	L		g_{1L}	$h_{1L}^\perp$
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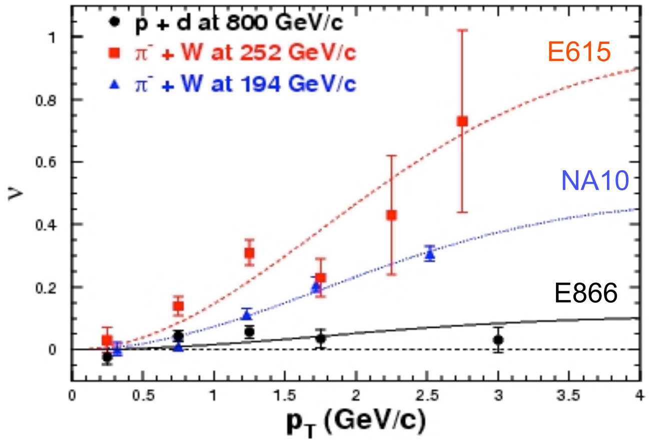
Fragmentation Functions (FF)

		quark		
		U	L	T
nu	U	D_1		$H_1^\perp$

Drell-Yan:

hp → μμX

$$\sigma_{UU}^{\cos(2\phi)} \propto h_{1q}^\perp h_{1\bar{q}}^\perp$$

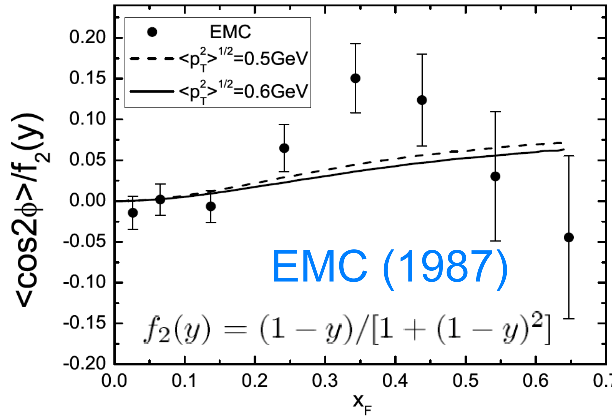


Small in the sea region ?!

SIDIS:

ep → e'hX

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp H_1^\perp$$

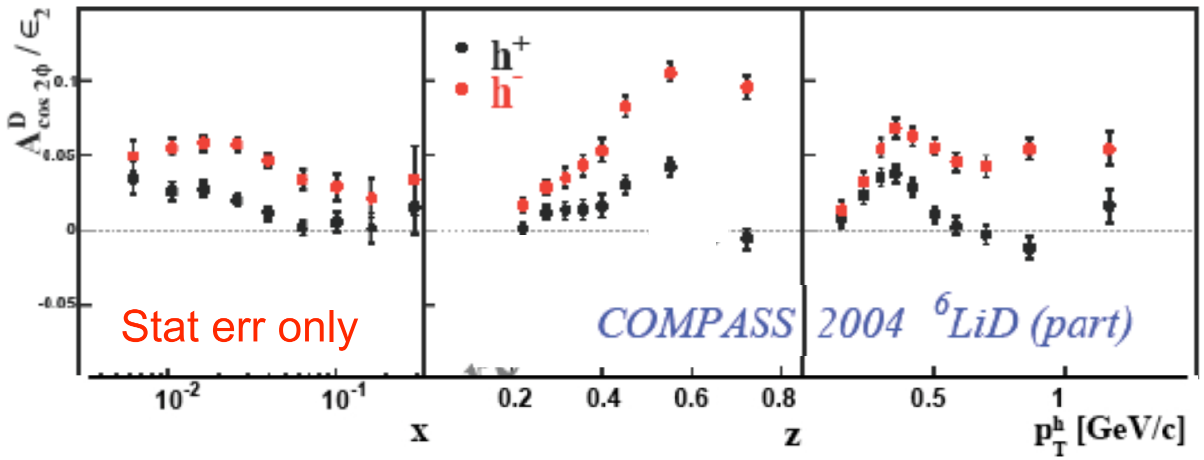


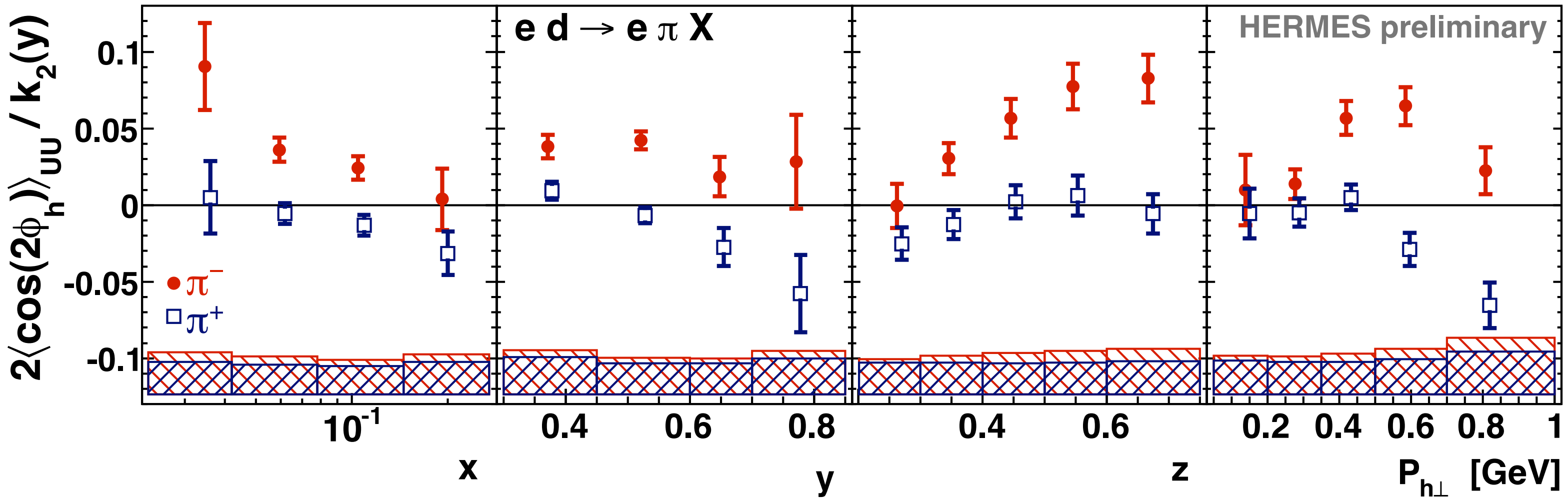
Cos2ϕ modulation

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp H_1^\perp$$

Non-zero !

Large difference in hadron charge !

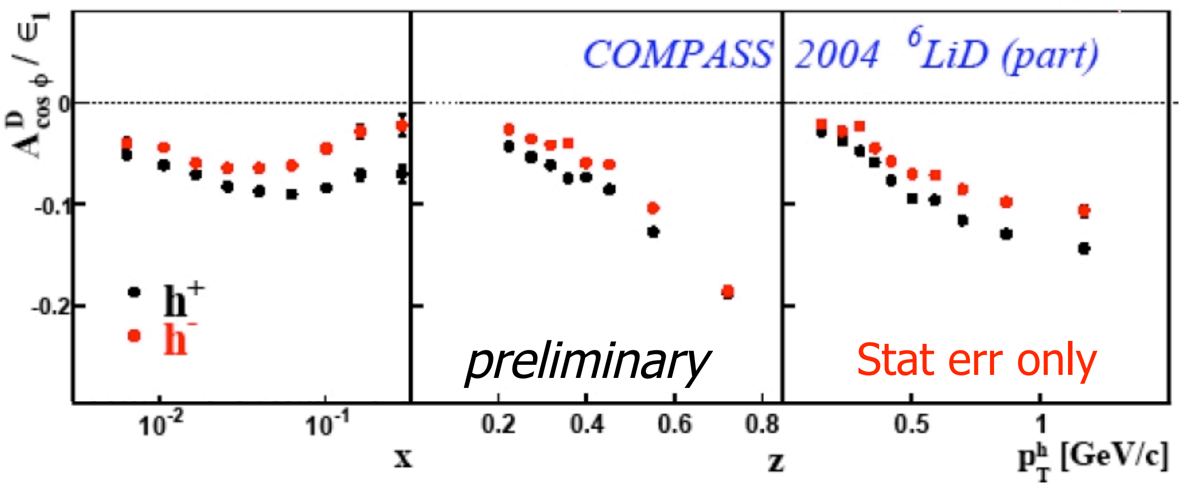




Cosϕ modulation

$$\sigma_{UU}^{\cos(\phi)} \propto \left[A\ f_1\ D_1\ + B\ h_1^{\perp} H_1^{\perp}\ + \ldots\right]/Q$$

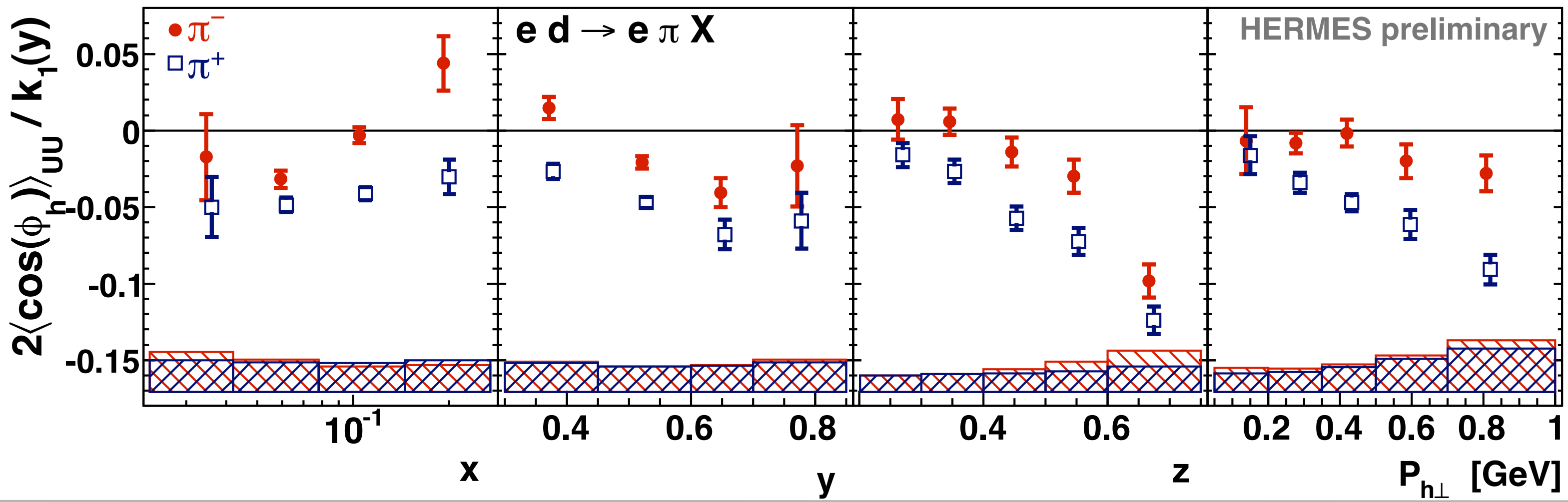
Sub-leading twist !



Observed difference in hadron charge !

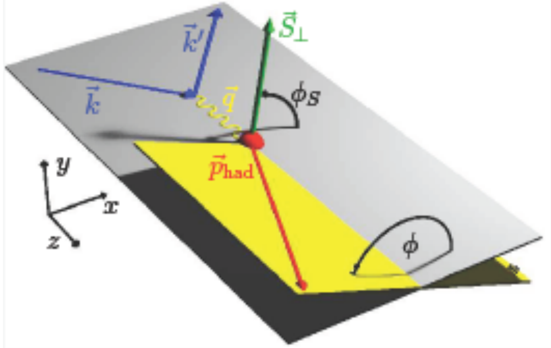
Sign of non-zero BM ?

3 Higher twists ?



Sivers

Partonic orbital motion



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Fragmentation Functions (FF)

		quark		
		U	**L**	**T**
nu	**U**	D_1		$H_1^\perp$

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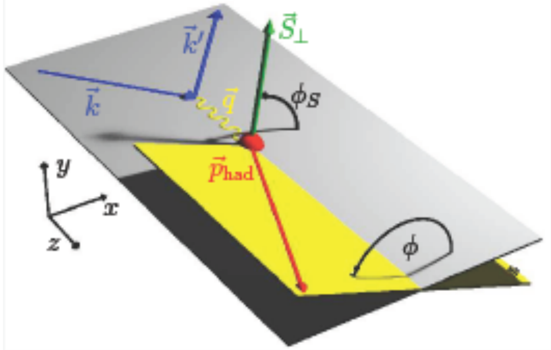
Partonic orbital motion



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Distribution Functions (DF)

		quark U	quark L	quark T
nucleon	U	q		$h_1^\perp$
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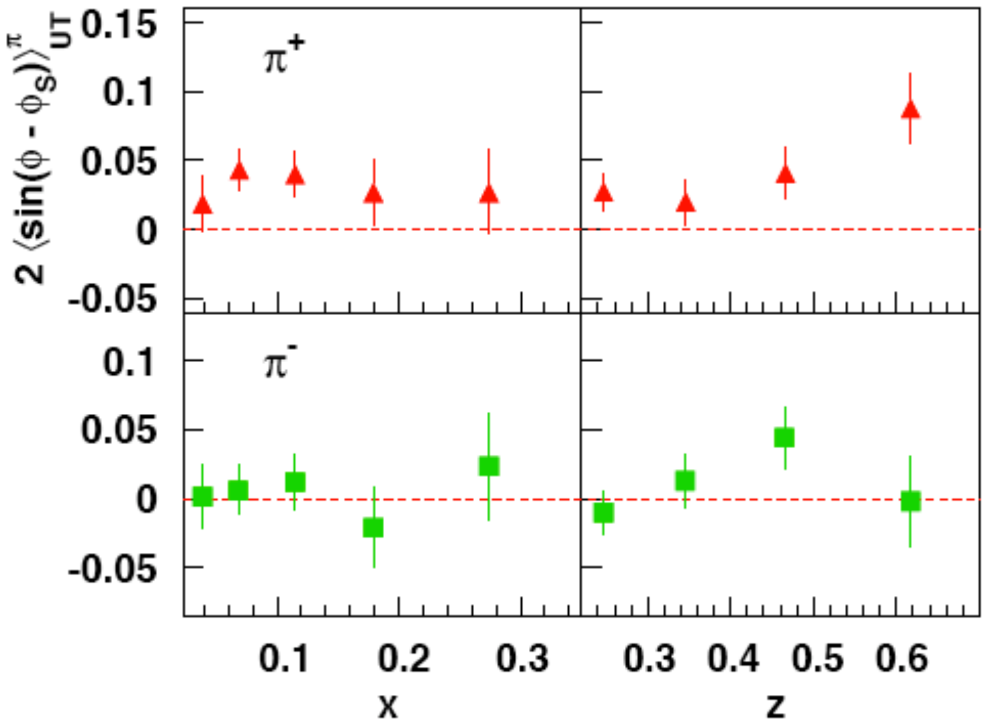
		quark U	quark L	quark T
nucleon	U	D_1		$H_1^\perp$

A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002

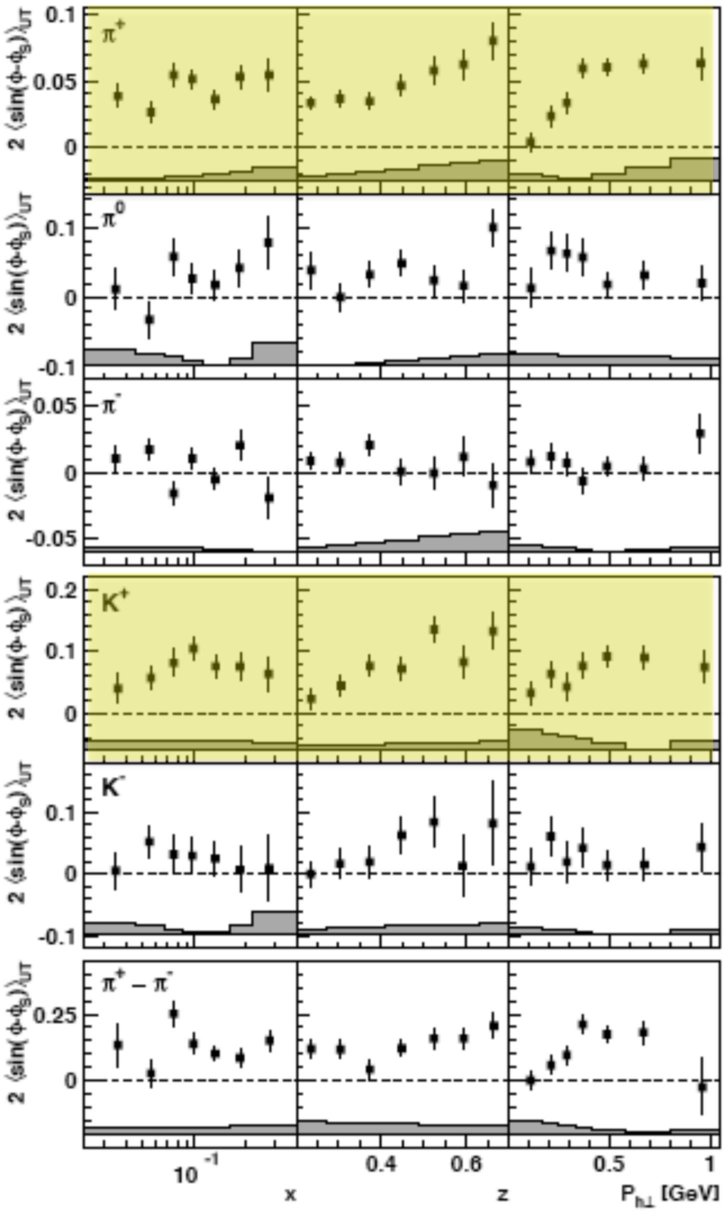


2005: First evidence from HERMES SIDIS on proton

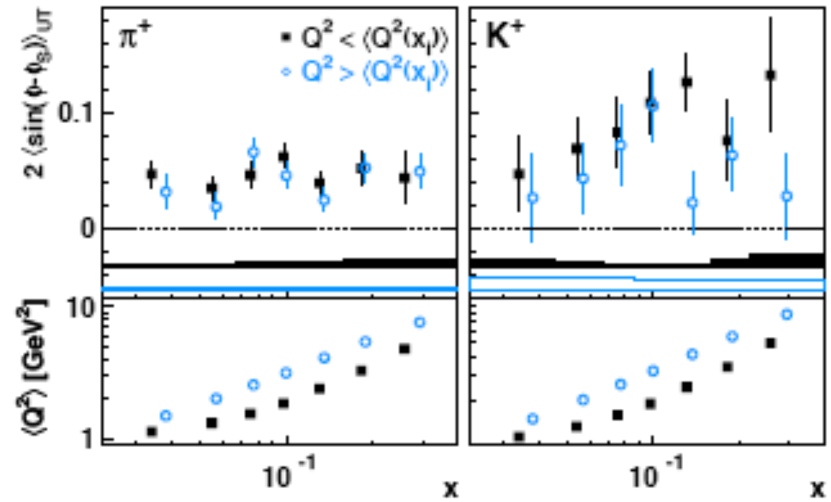
Non-zero Sivers function !!

Sivers

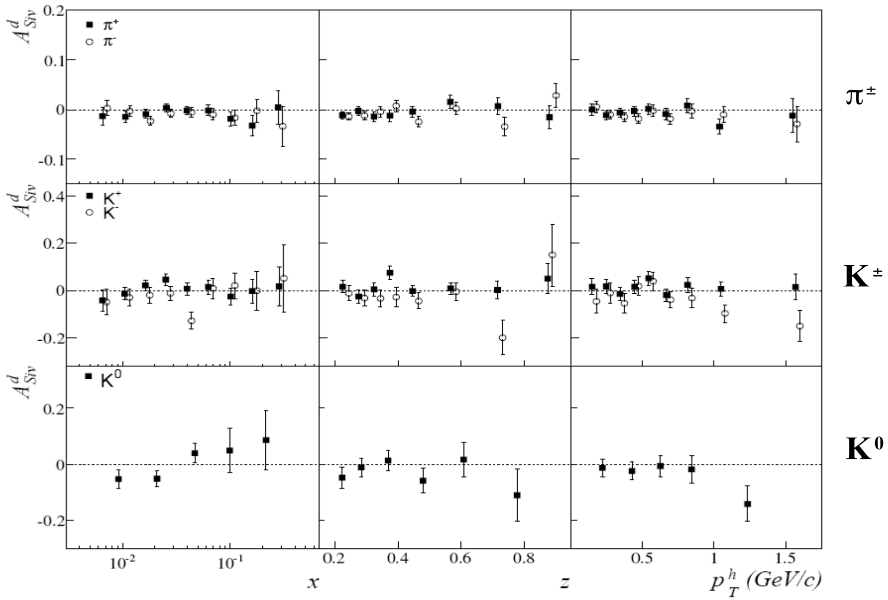
HERMES on proton:



HERMES on proton:

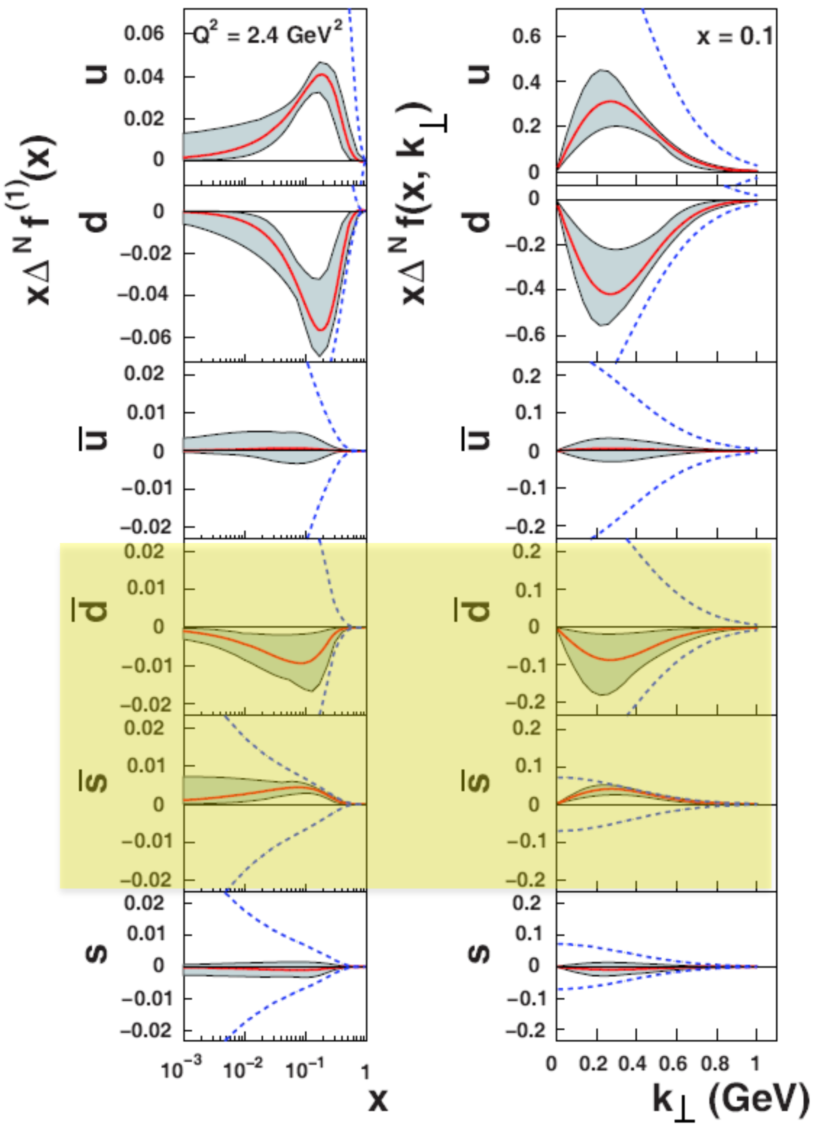


COMPASS on deuteron:



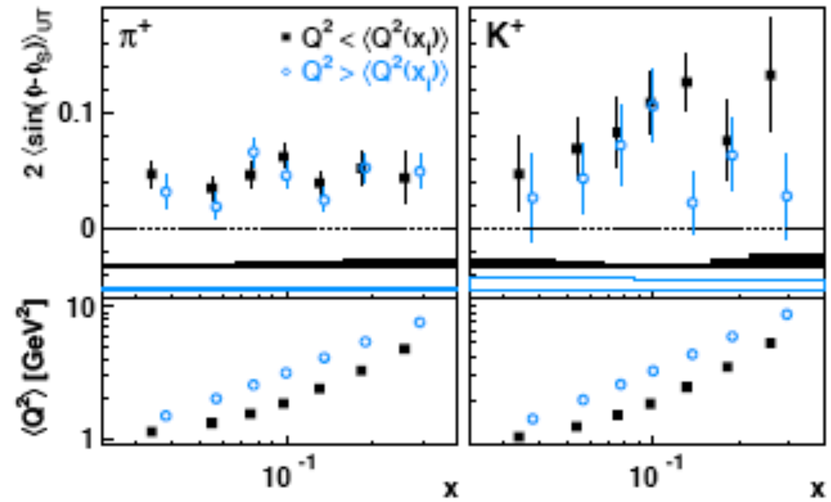
Sivers

M. Anselmino et al , **Eur. Phys. J. A39 (2009) 89**



Not negligible sea contribution !

HERMES on proton:



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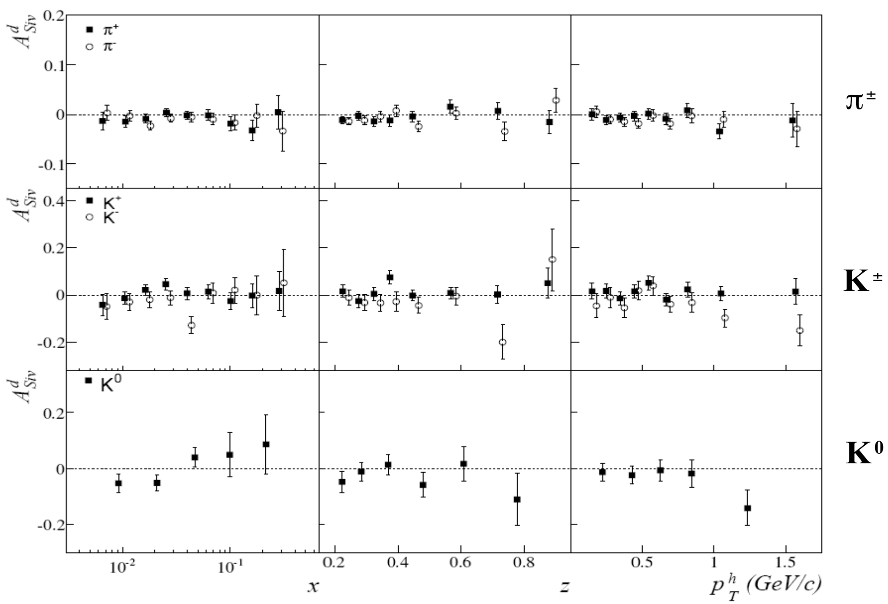
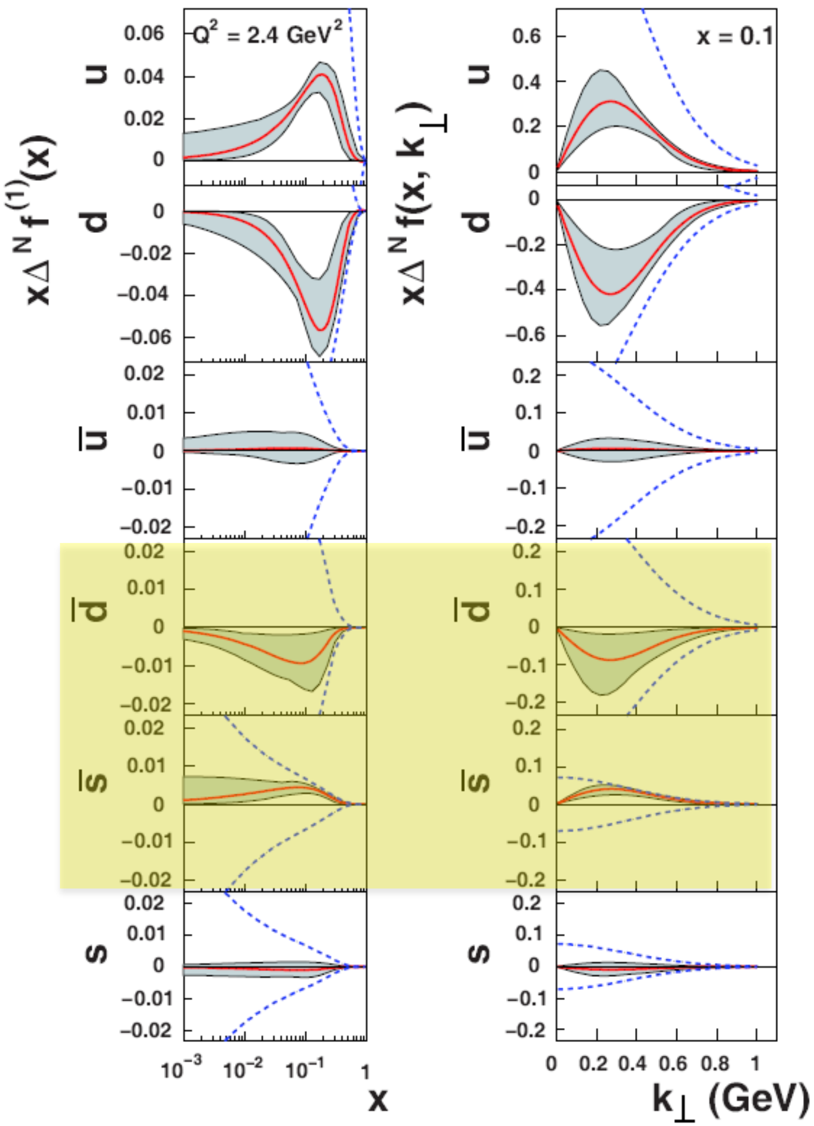


Sivers

M. Anselmino et al , **Eur. Phys. J. A39 (2009) 89**

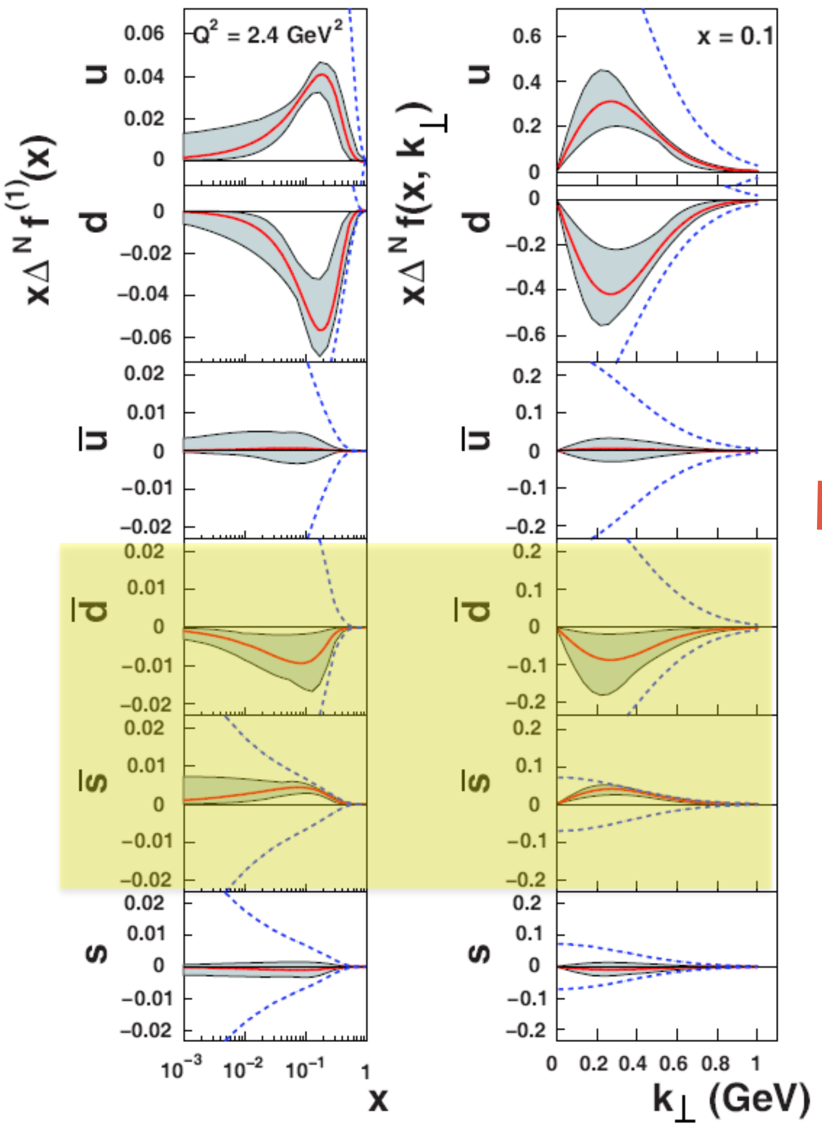


Not negligible sea contribution !

4 **Flavor decomposition ?**

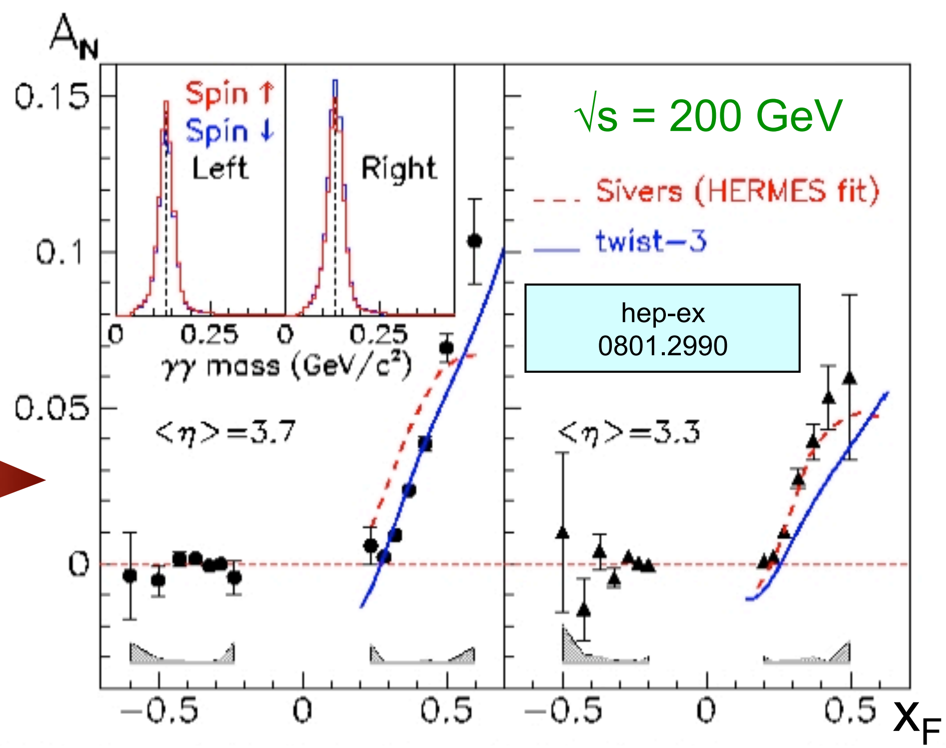
Sivers

M. Anselmino et al , **Eur. Phys. J. A39 (2009) 89**



Not negligible sea contribution !

pp SSA @ RHIC:

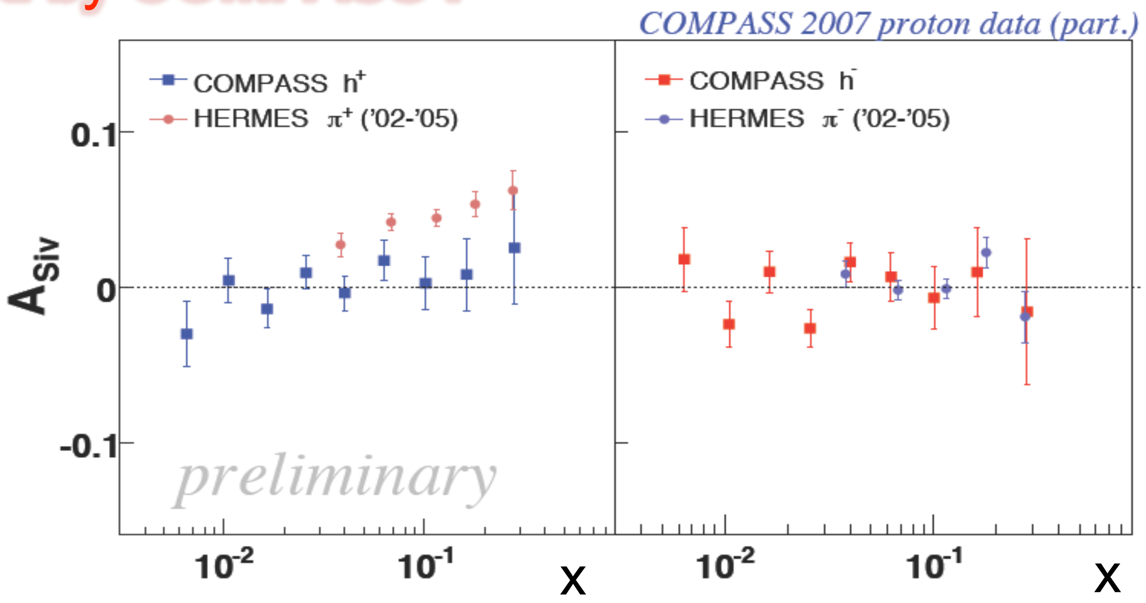


4 **Flavor decomposition ?**

5 **Universality ?**

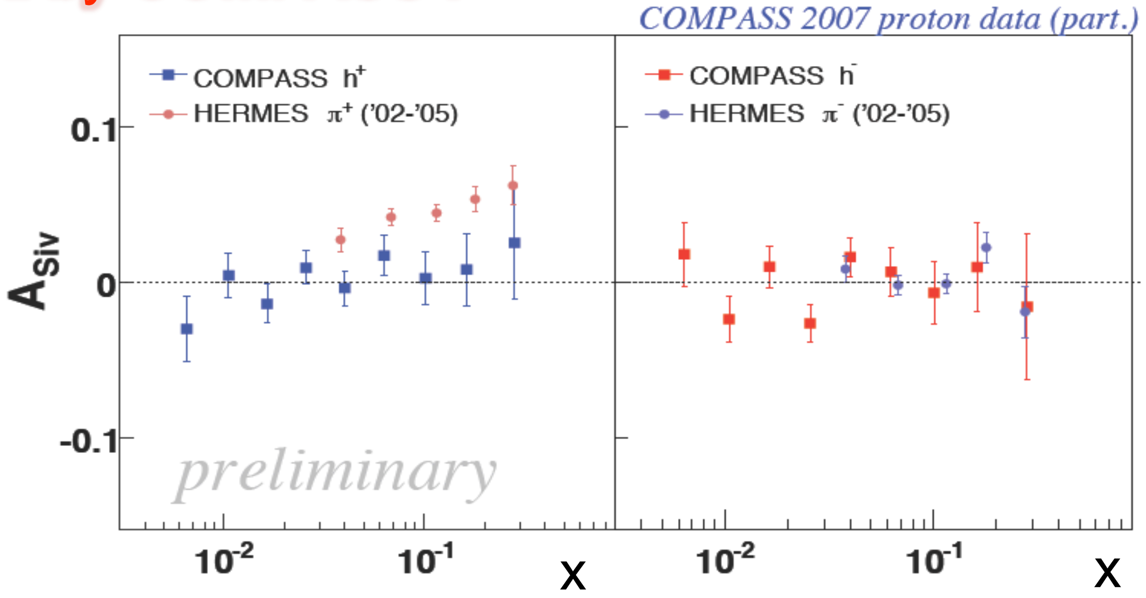
Sivers

Not yet confirmed by COMPASS !

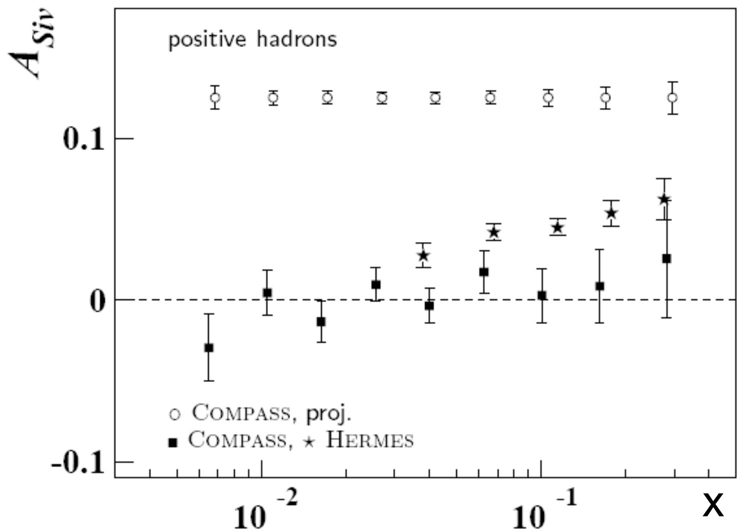


Sivers

Not yet confirmed by COMPASS !



This year



□ COMPASS 2010 h^+, projection

★ HERMES π^+, DIS2007

■ COMPASS h^+, Transversity 2008

a factor of 3 with respect to the released COMPASS data

Executive summary

TMDs are a new class of phenomena
providing novel insights into the rich nuclear structure

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Non-zero results from DIS experiments provide promises but also open questions

- Limited knowledge on transverse momentum dependences
- Flavor decomposition often missing
- Evolution properties to be defined
- Role of the higher twist to be quantified
- Universality $\longleftrightarrow$ Fundamental test of QCD in the spin sector

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Flavor decomposition often missing

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Role of the higher twist to be quantified

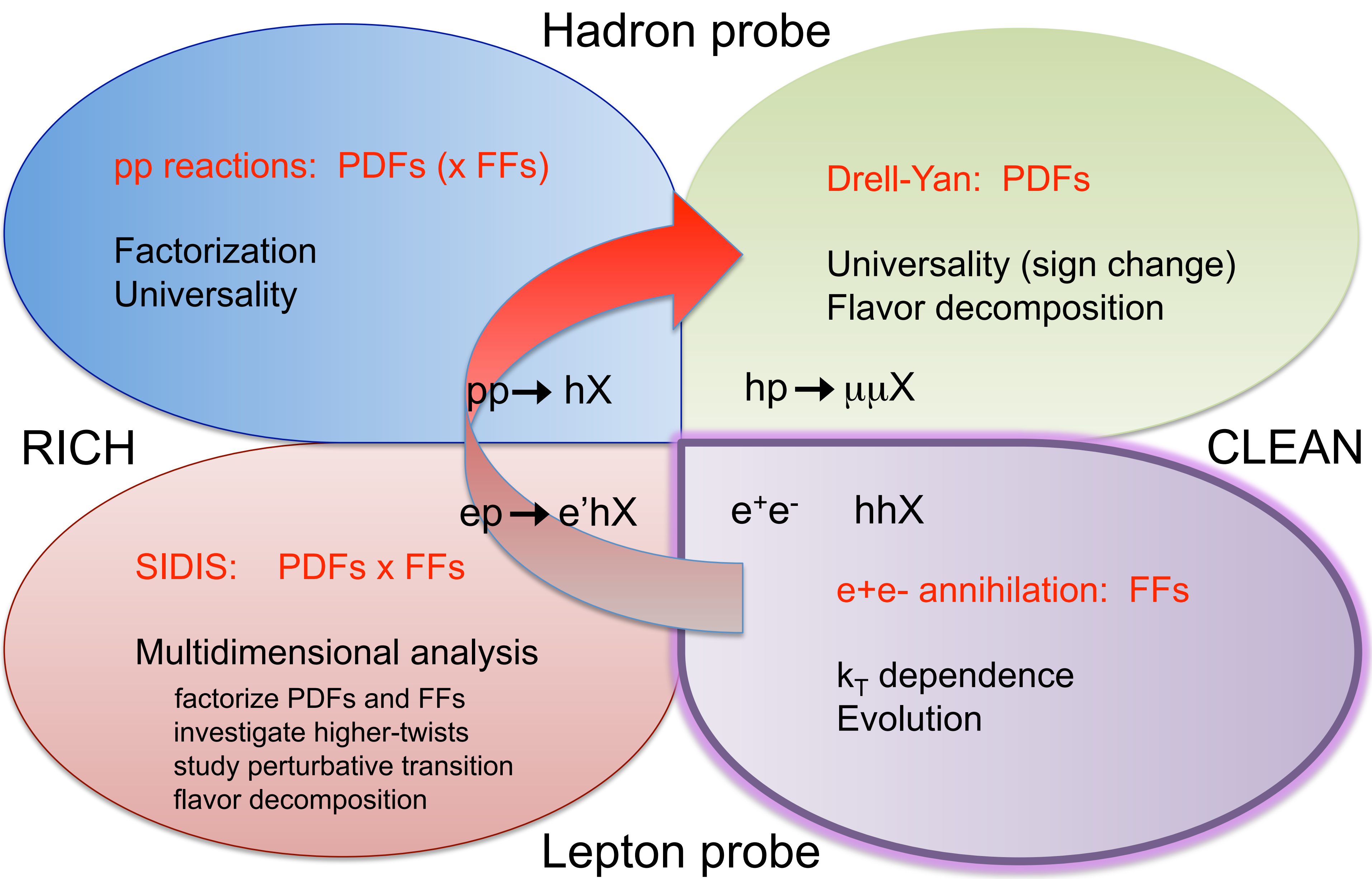
Universality ⟷ Fundamental test of QCD in the spin sector

Still incomplete phenomenology is asking for new inputs

Crucial: completeness
All reactions, flavor tagging and multi-dimensional extraction in all variables (x,z,Q^2,P_T) to have all dependencies resolved

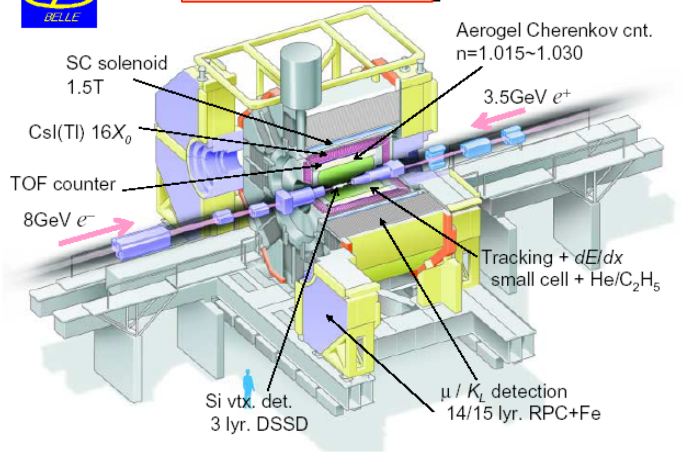
TMD Studies at Future Facilities

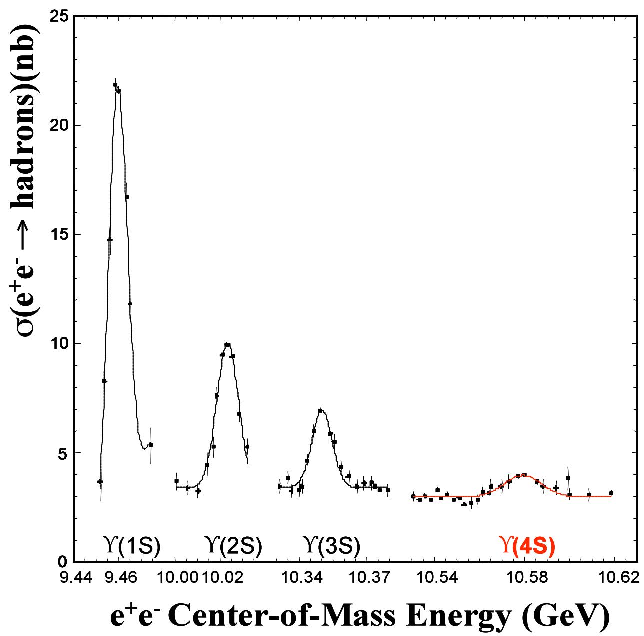
TMD palette


Hadron probe
pp reactions: PDFs (x FFs)
Factorization
Universality
Drell-Yan: PDFs
Universality (sign change)
Flavor decomposition
pp → hX
hp → μμX
RICH
CLEAN
ep → e'hX
e^+e^- hhX
SIDIS: PDFs x FFs
Multidimensional analysis
factorize PDFs and FFs
investigate higher-twists
study perturbative transition
flavor decomposition
e+e- annihilation: FFs
k_T dependence
Evolution
Lepton probe

Fragmentation @ e^+e^- colliders

Belle Detector



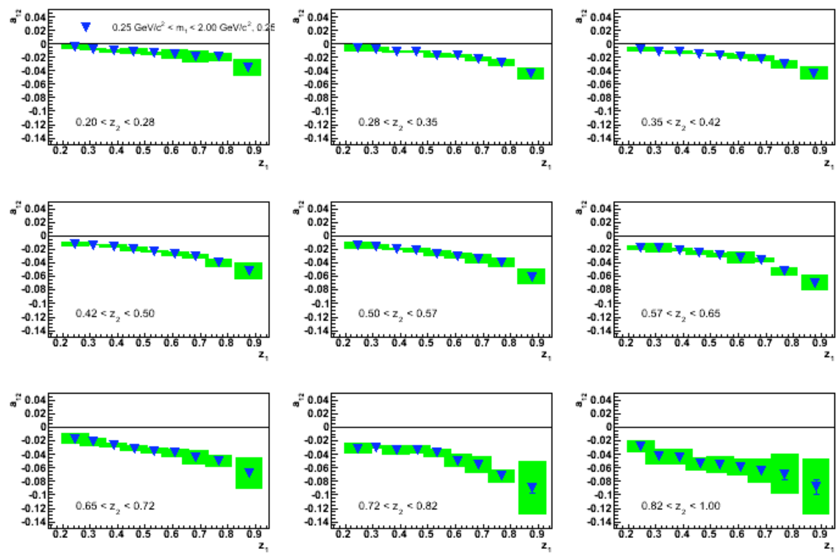


Hadrons in opposite hemispheres:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{dz_1\, dz_2\, d\Omega} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1 \bar{D}_1$$

Dependence on transverse momentum

FFs for various hadron: 2π, kaons, (ρ, … Λ)

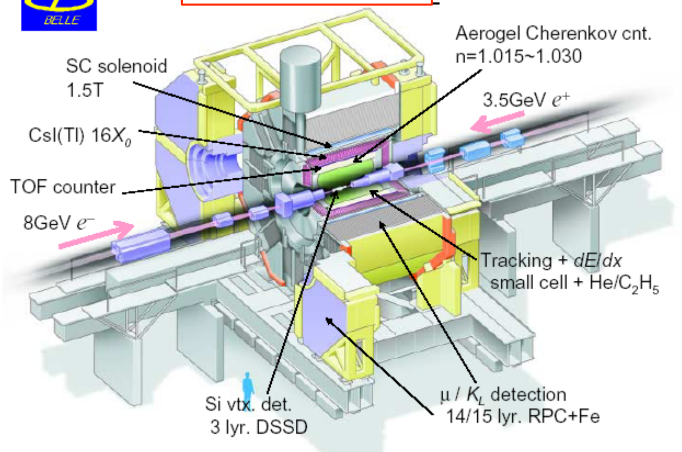


Scale dependence: look for different c.m. energies

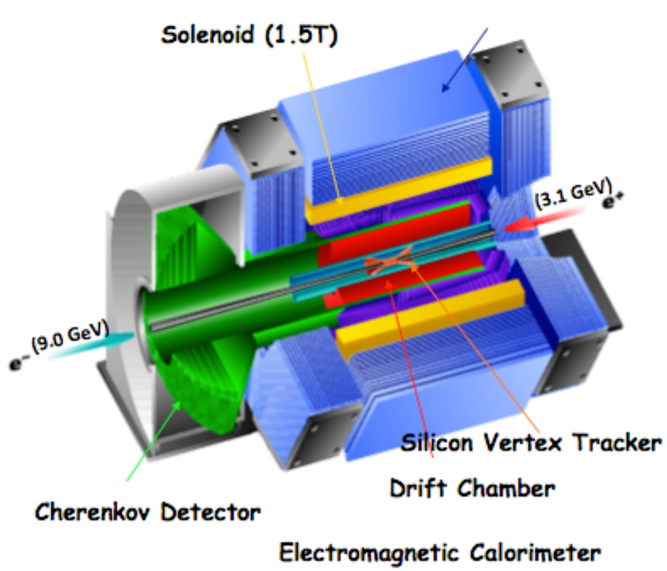
Only one experiment: validation needed !

Fragmentation @ e^+e^- colliders

Belle Detector

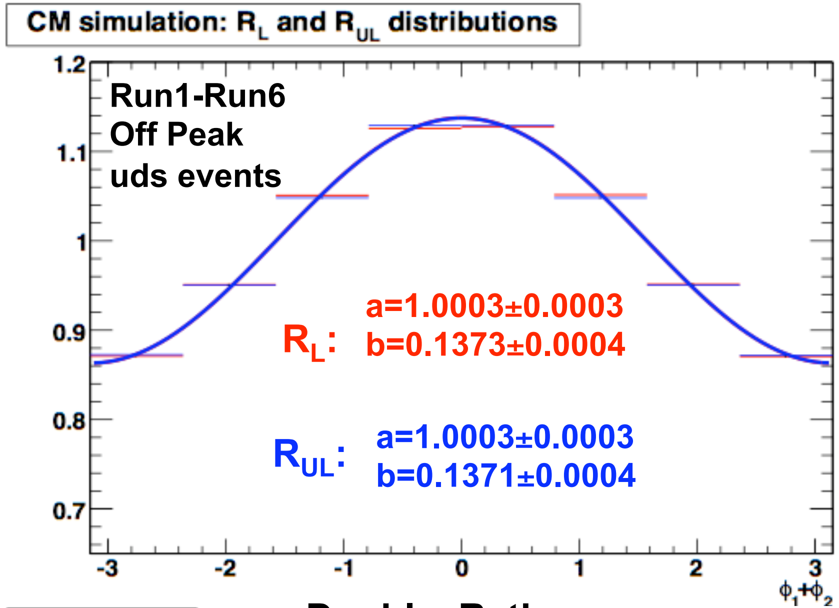


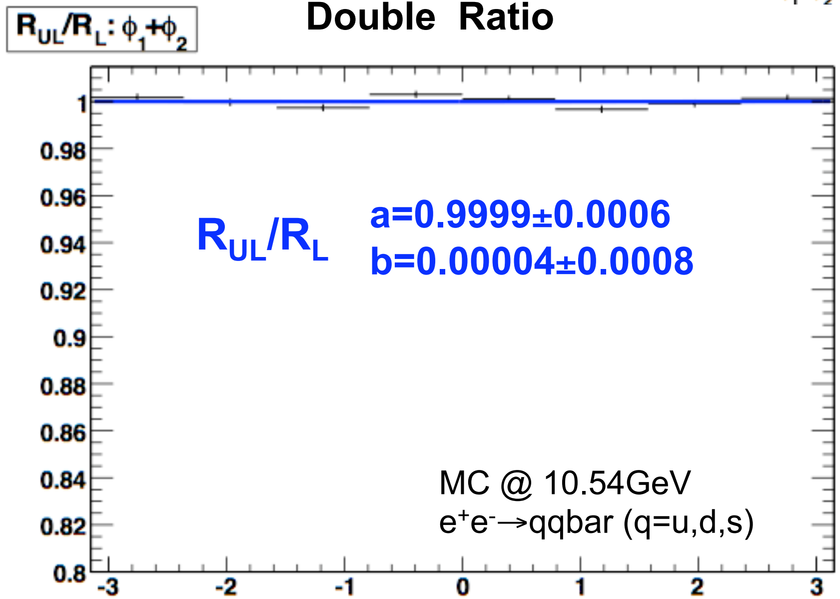
Babar Detector



Different detector: systematic check !

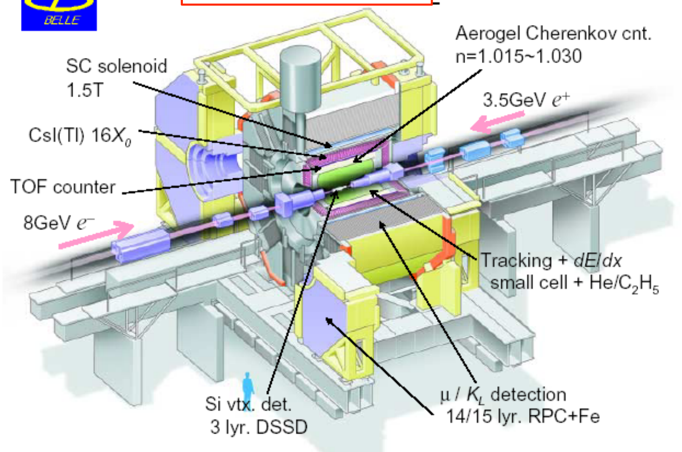
MC: thrust reference frame Qt<4.3



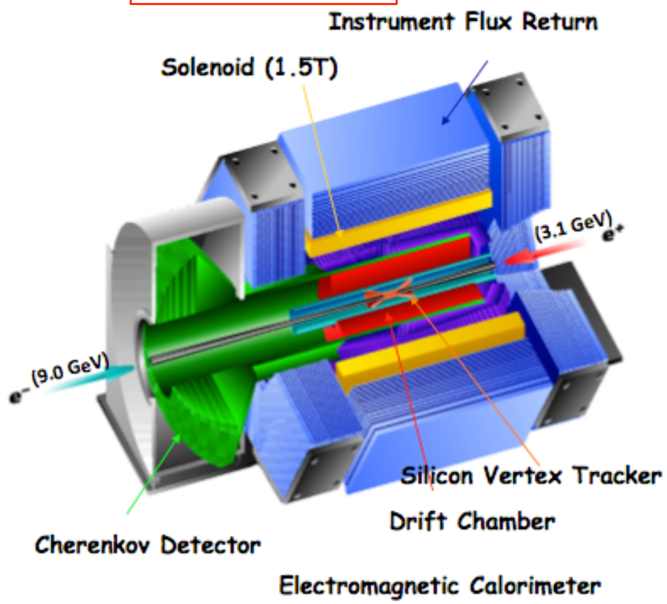


Fragmentation @ e$^+$e$^-$ colliders

Belle Detector



Babar Detector



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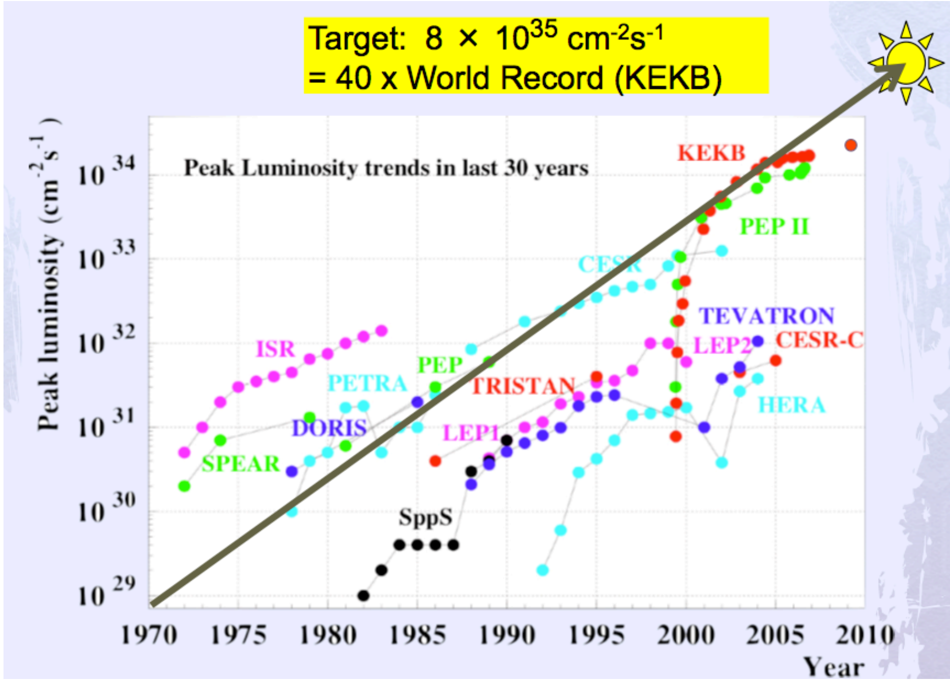
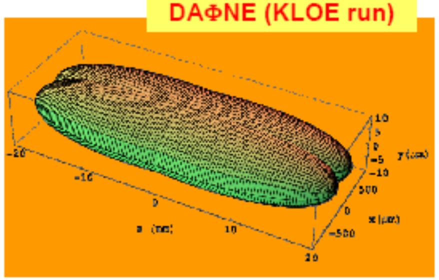
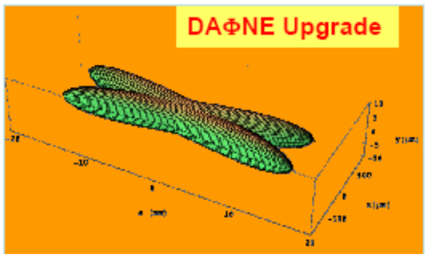
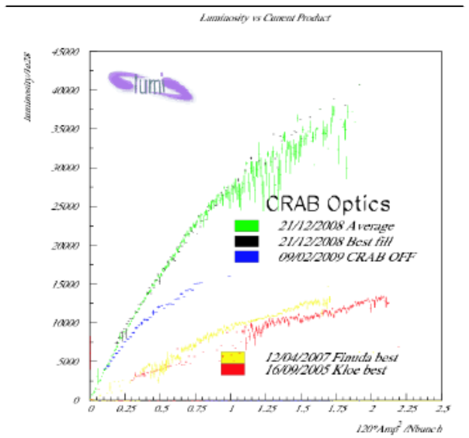








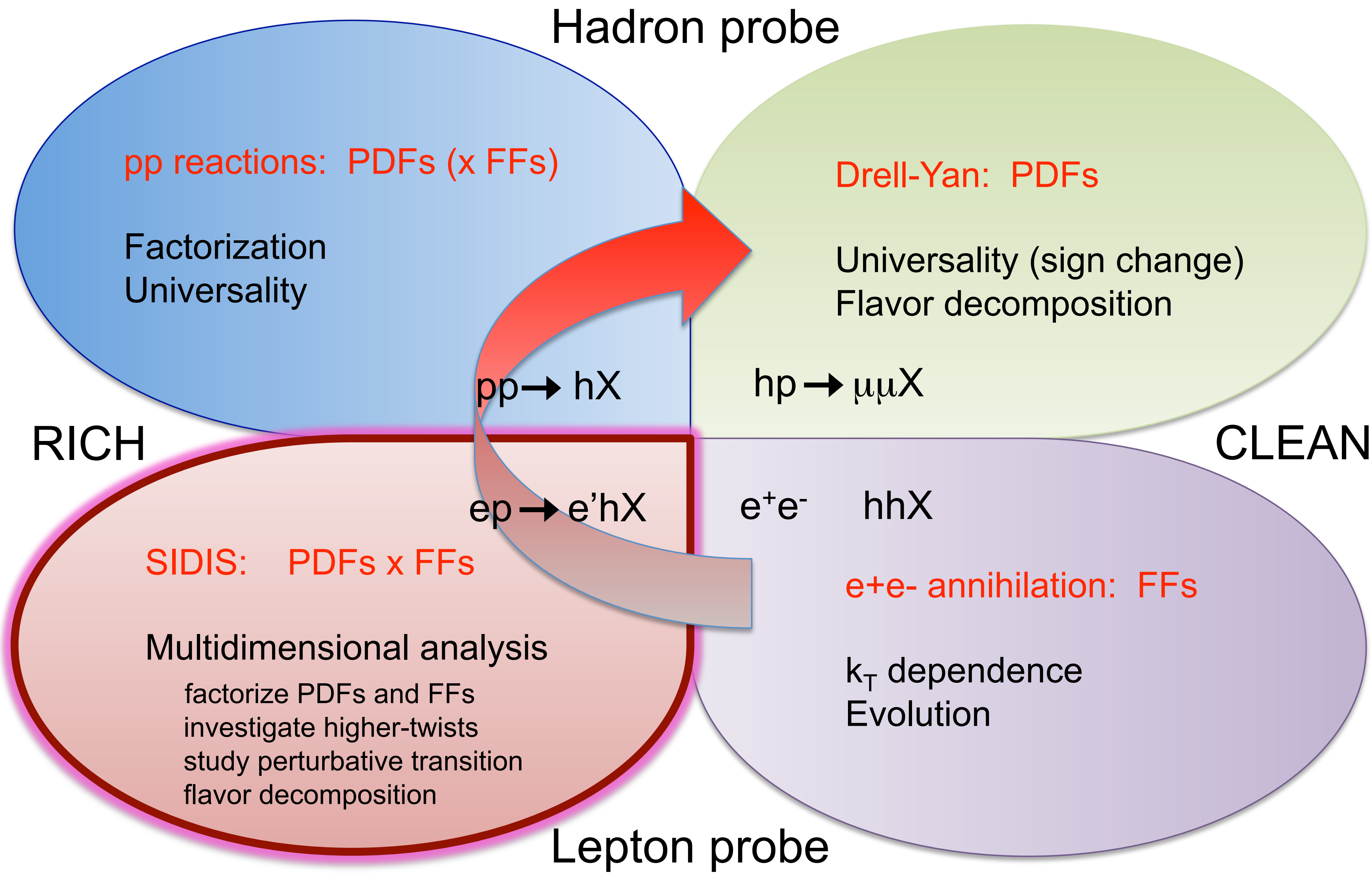
3 times more luminosity obtained with
3 times smaller vertical beam

SuperB parameters

Parameter	Requirement	Comment
Luminosity (top-up mode)	10^{36} cm^{-2}s^{-1} @ $\Upsilon(4S)$	
Integrated luminosity	75 ab^{-1}	Based on a "New Snowmass Year" of 1.5 x 10^7 seconds (PEP-II experience-based)
CM energy range	*t* threshold to $\Upsilon(5S)$	
Minimum boost	$\beta\gamma = 0.28$ (4x7 GeV)	1 cm beampipe radius. First measurement at 1.5 cm
e^- Polarization	60-85%	Enables *t CP* and *T* violation studies, measurement of *t g*-2 and improves sensitivity to lepton flavor-violating decays. Detailed simulation, needed to ascertain a more precise requirement, are in progress.

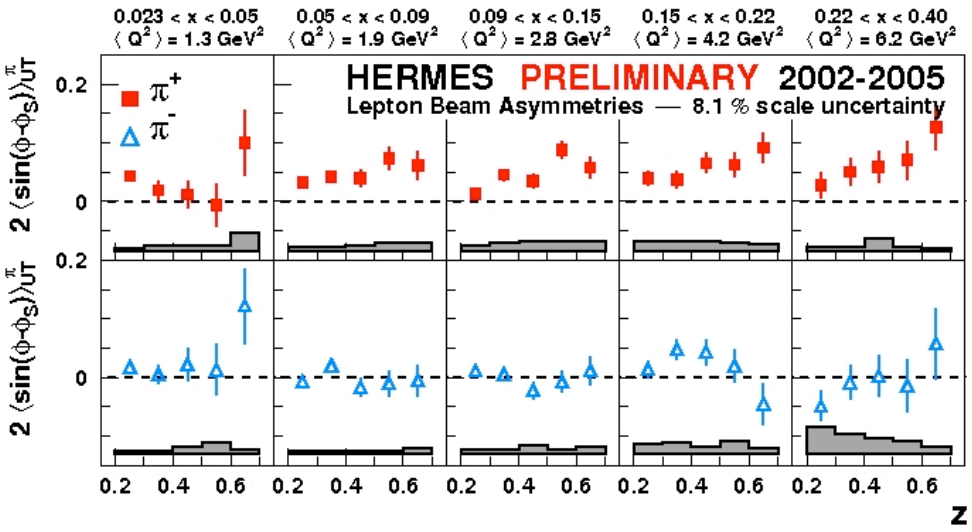
Probe TMDs evolution

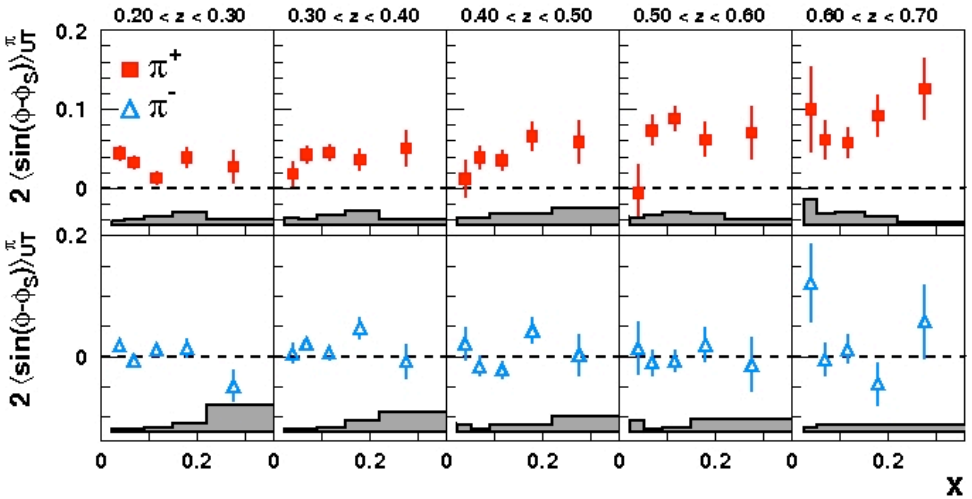
TMD palette


Hadron probe
pp reactions: PDFs (x FFs)
Factorization
Universality
Drell-Yan: PDFs
Universality (sign change)
Flavor decomposition
pp → hX
hp → μμX
RICH
CLEAN
ep → e'hX
e+e- hhX
SIDIS: PDFs x FFs
e+e- annihilation: FFs
Multidimensional analysis
factorize PDFs and FFs
investigate higher-twists
study perturbative transition
flavor decomposition
kT dependence
Evolution
Lepton probe

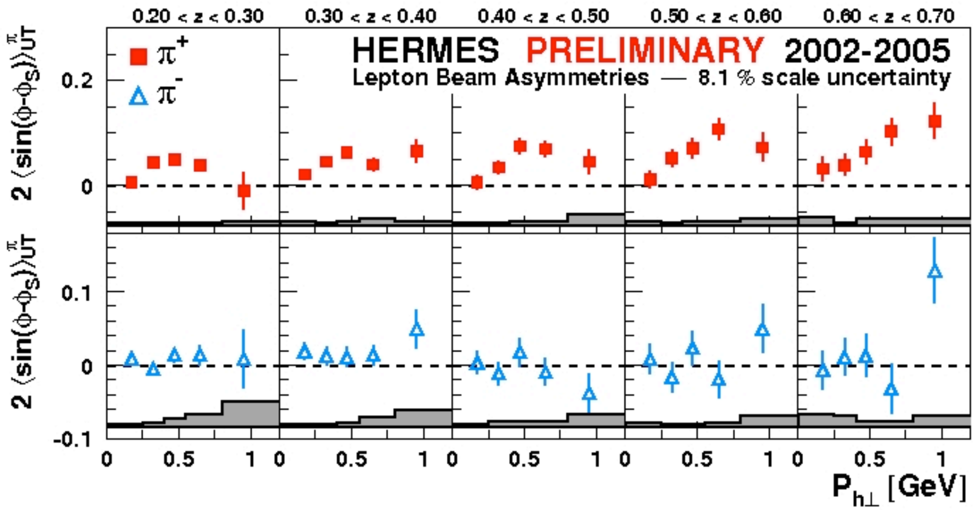
2D Sivers @ HERMES

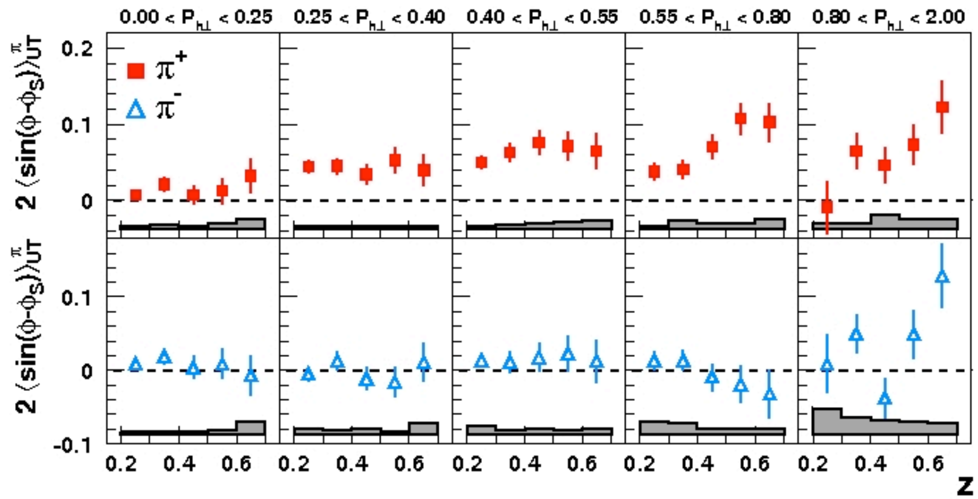
x vs z





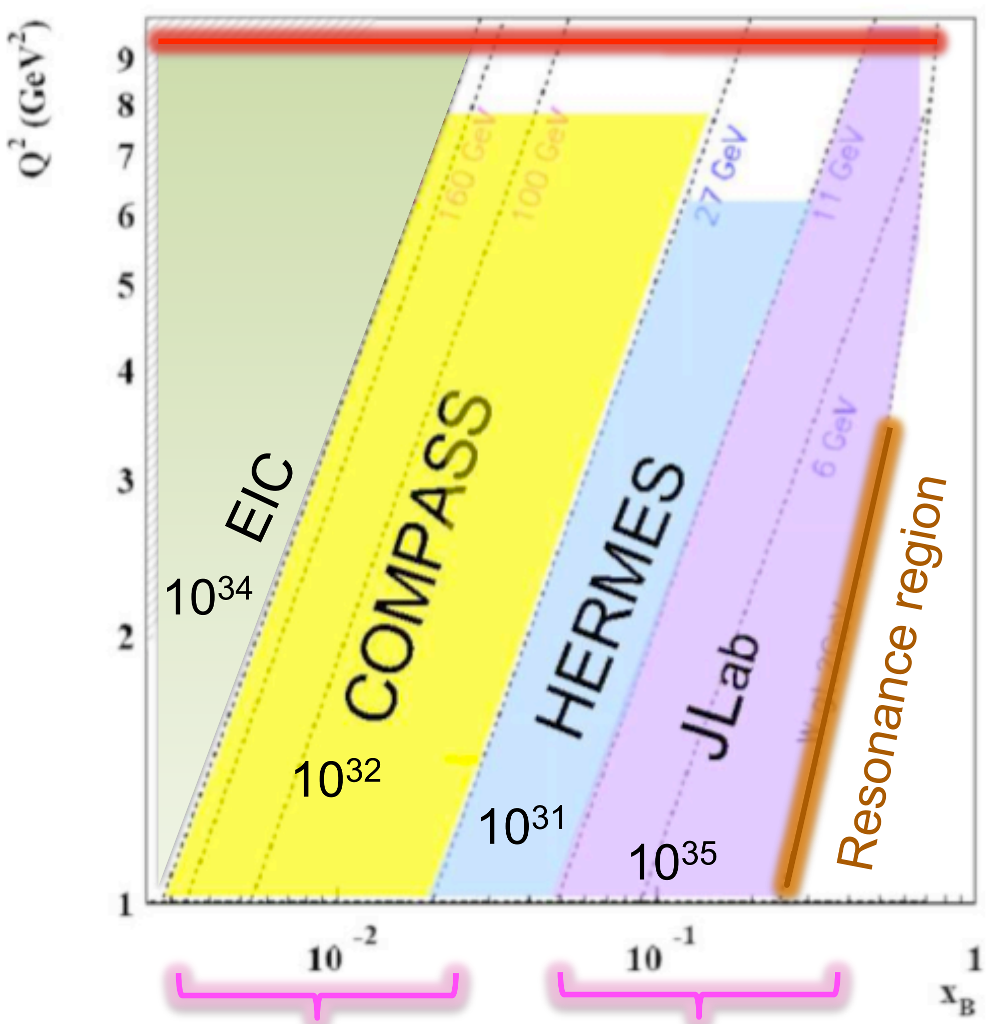
z vs $P_{h\perp}$





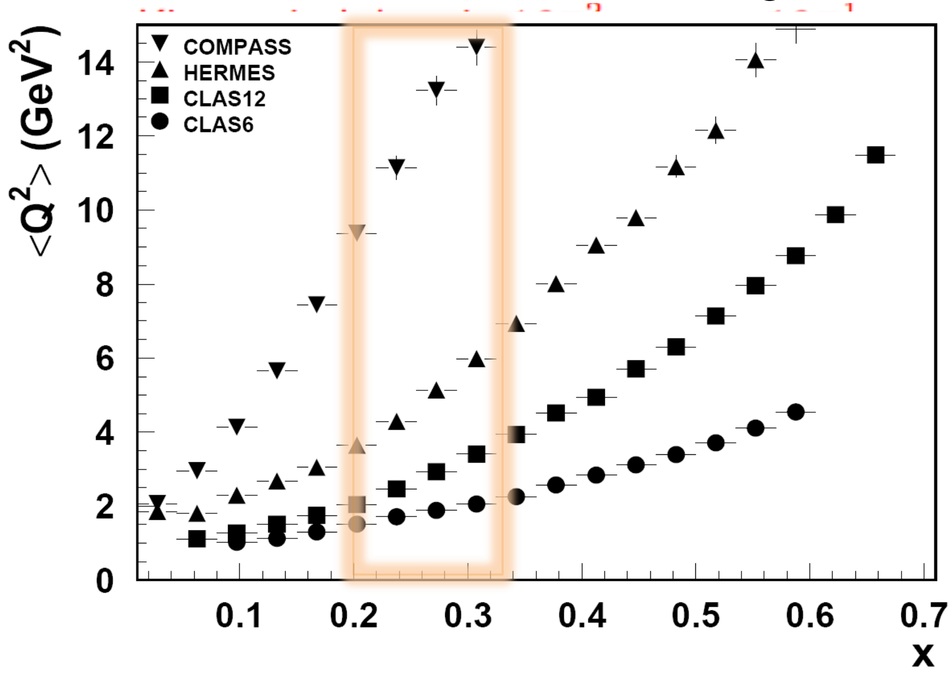
The SIDIS landscape

Limit defined by luminosity



$$\frac{d\sigma(ep \to e'hX)}{dxdy\ dzdP_{h\perp}} \propto \sum_q e_q^2 C\left[q(x,k_T)D_q^h(z,p_T)\right]$$

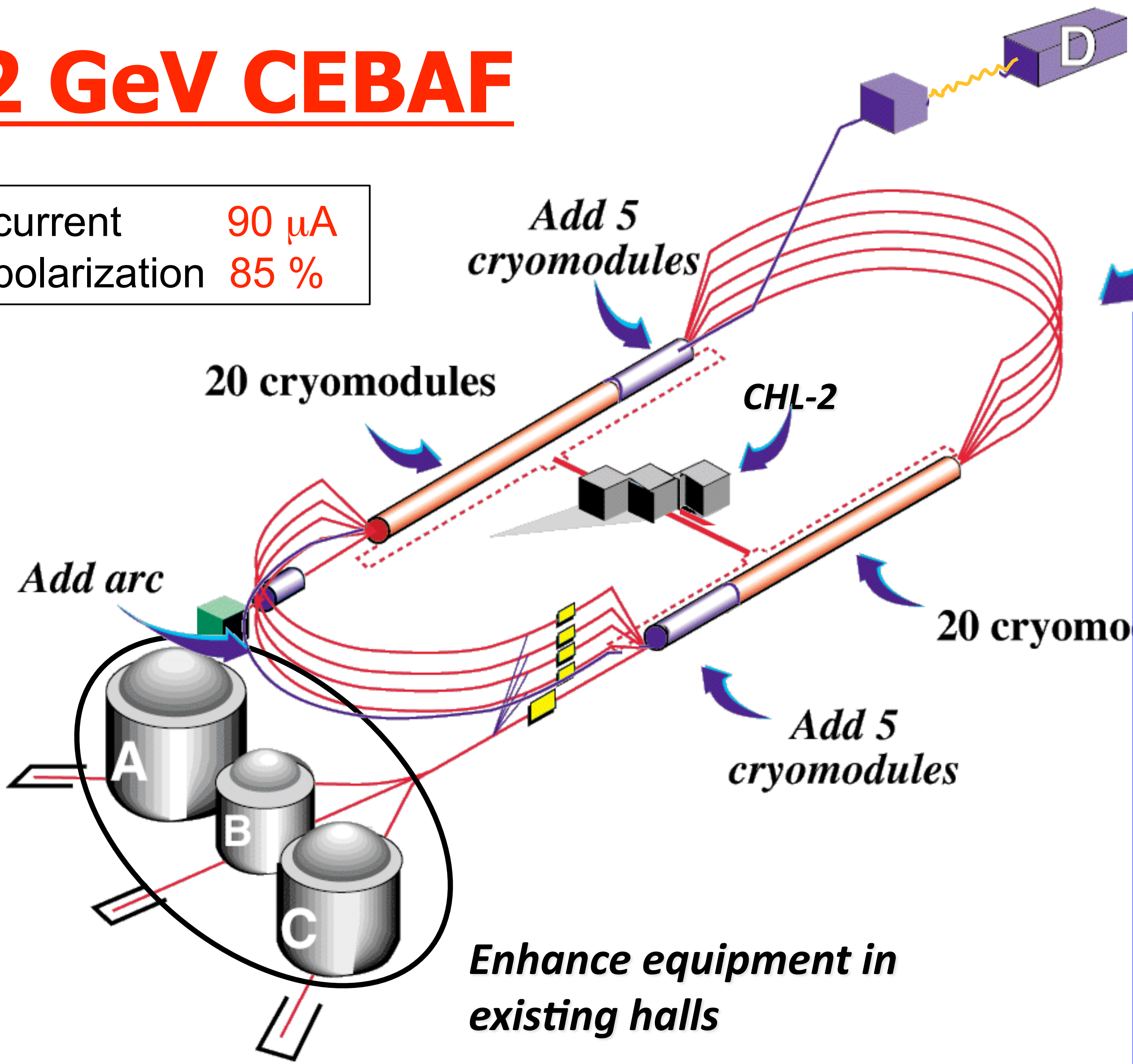
Different Q^2 for same x range



Complementary experiments

12 GeV CEBAF

Beam current	90 μA
Beam polarization	85 %



2008-2014:
Construction ***(funded at 99%)***

May 2012
6 GeV Accelerator Shutdown starts

May 2013
Accelerator Commissioning starts

October 2013
Hall Commissioning starts

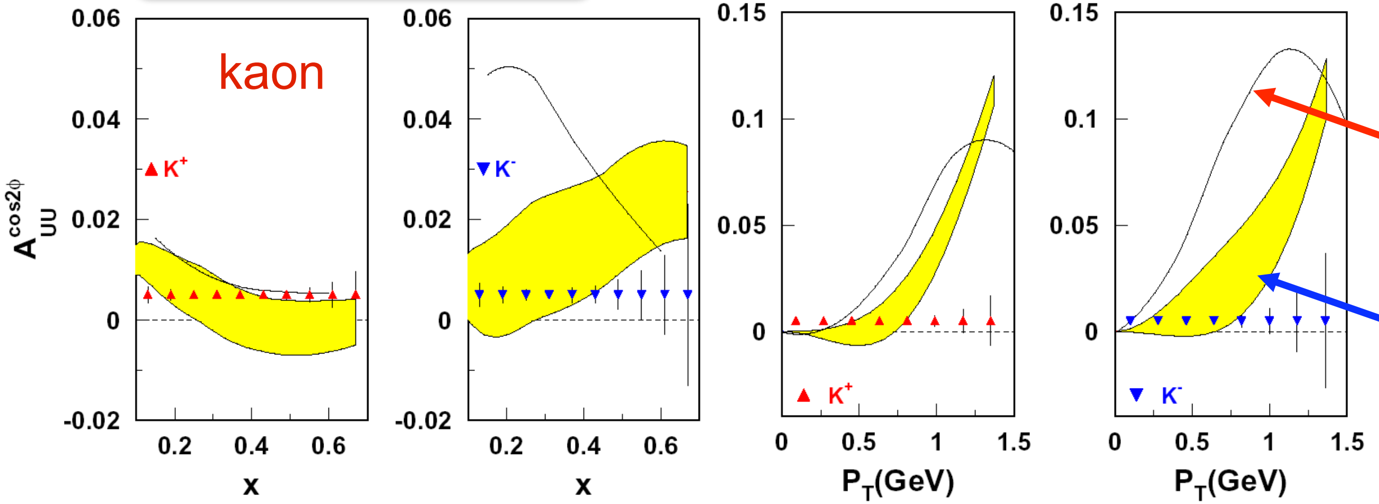
2013-2015
Pre-Ops (beam commissioning)

Unpolarized target @ CLAS12

$$F_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$

Boer-Mulders spin-orbit effect

56 d @ 10^{35} $s^{-1}cm^{-2}$
LH_2 LD_2 targets



Line: Phys Rev D78 045022
Boer-Mulders from Sivers
Collins from e+e- data

Band: Phys Rev D78 034035
Boer-Mulders from DY data
Collins from chiral limit

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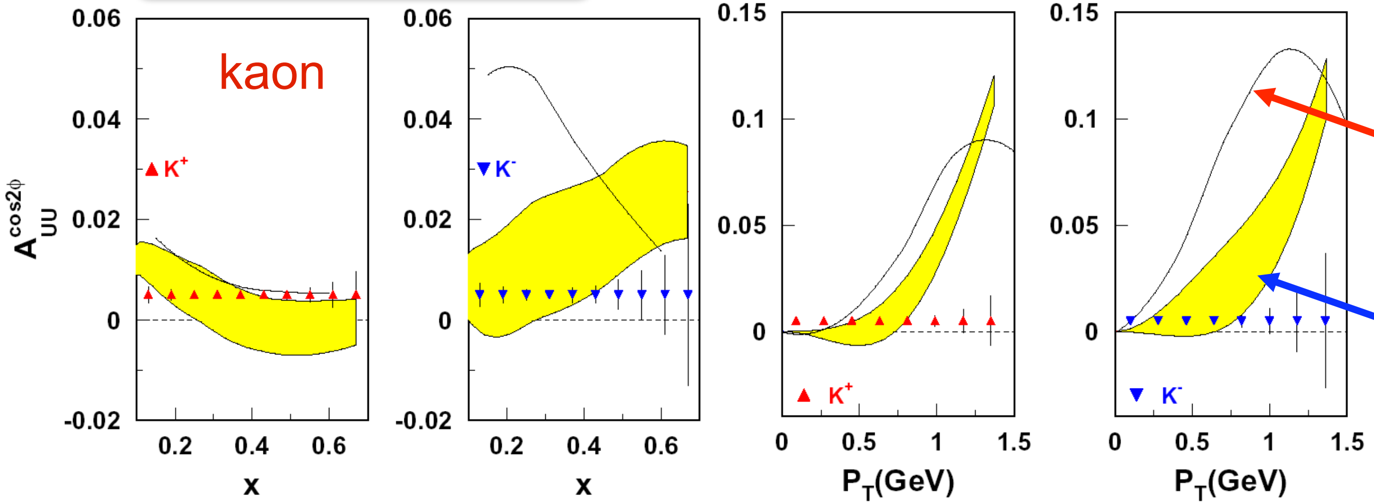
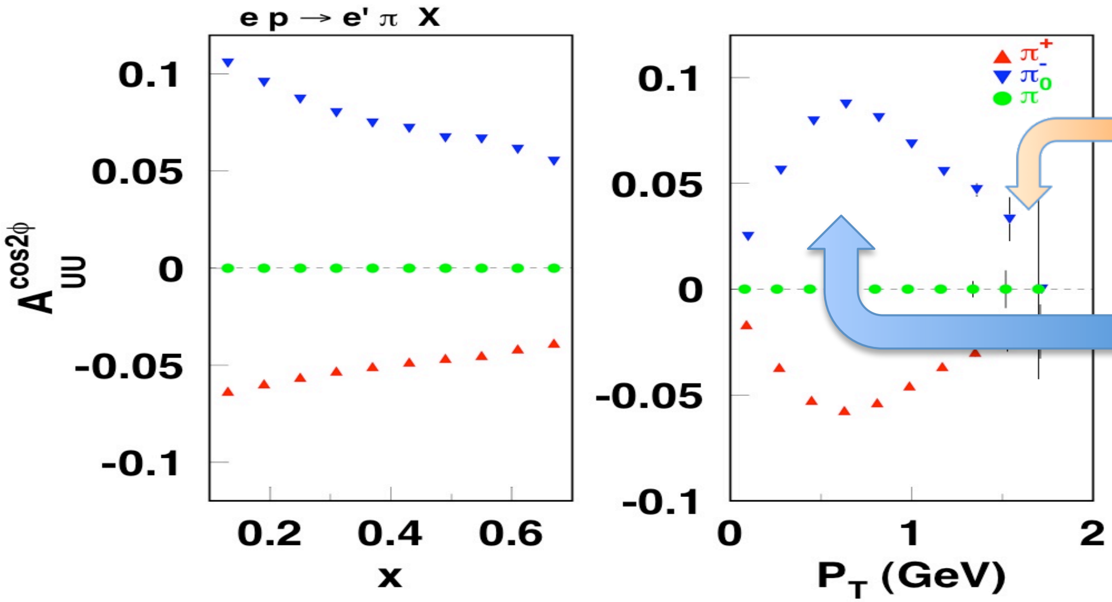


Line: Phys Rev D78 045022
Boer-Mulders from Sivers
Collins from e+e- data

Band: Phys Rev D78 034035
Boer-Mulders from DY data
Collins from chiral limit



Perturbative region
Collinear factorization

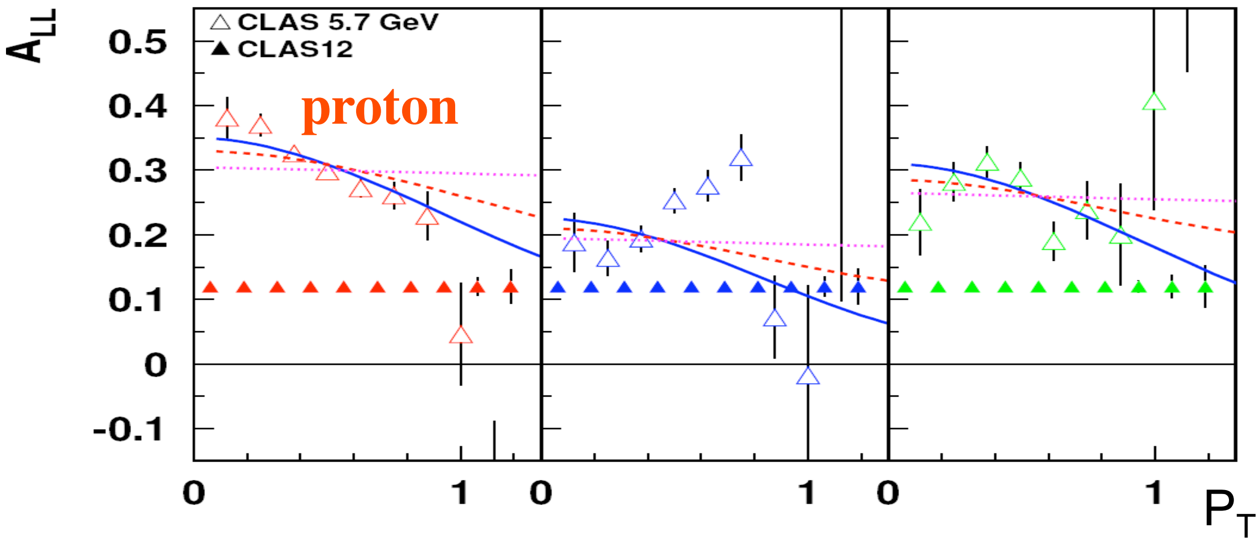
Non-perturbative
TMD factorization

$$\Lambda_{QCD} \ll P_T \ll Q$$

Polarized beam @ CLAS12

$F_{LL} \propto g_{1L} D_1$

Helicity dependence of k_T-distribution of quarks



M.Anselmino et al hep-ph/0608048
Phys.Rev.D74:074015,2006

$$f_1^q(x,k_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}exp(-\frac{k_\perp^2}{\mu_0^2})$$

$$g_1^q(x,k_\perp) = g_1^q(x)\frac{1}{\pi\mu_2^2}exp(-\frac{k_\perp^2}{\mu_2^2})$$

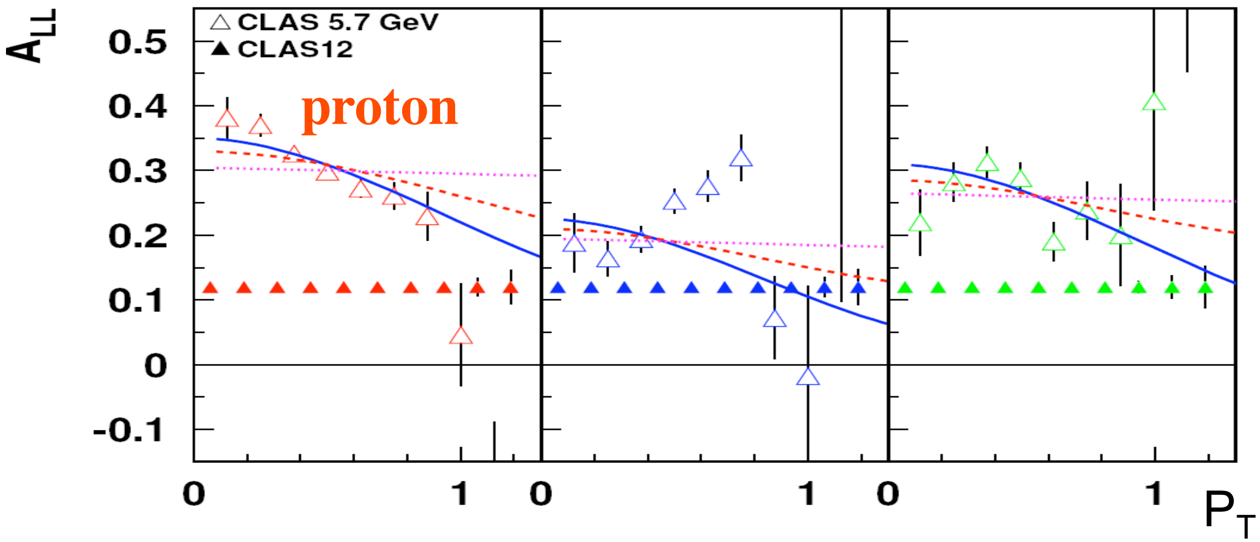
μ_0^2=0.25GeV^2 μ_D^2=0.2GeV^2

2000h @ 10^{35} $s^{-1}cm^{-2}$
NH_3 and ND_3 target
P_{beam} = 85 %

Polarized beam @ CLAS12

$$F_{LL} \propto g_{1L} D_1$$

Helicity dependence of k_T-distribution of quarks



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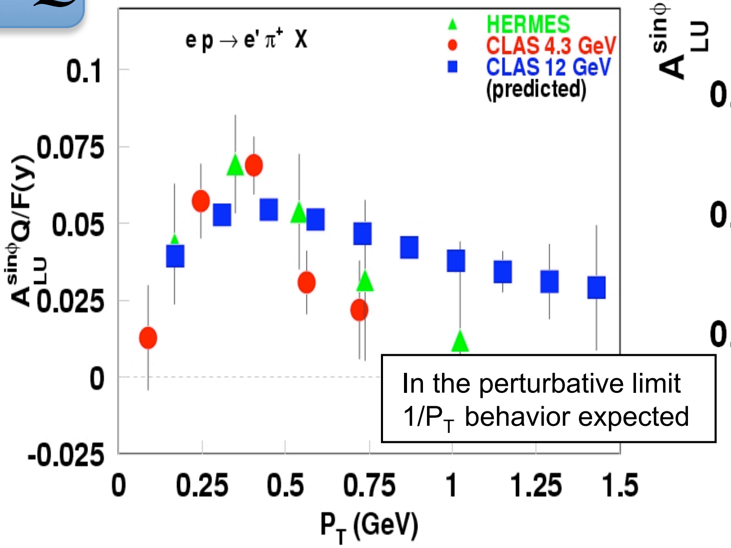
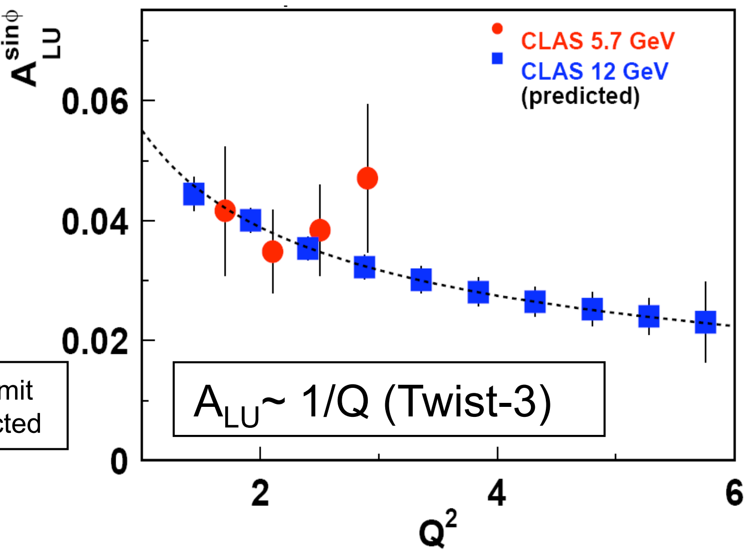
μ_0^2=0.25GeV^2 μ_D^2=0.2GeV^2

$$F_{LU}^{\sin\phi} \propto \left[e\ H_1^\perp + \ldots\right]/Q$$

Measurements of kinematic (x,Q^2,z,P_T) will probe HT distribution functions



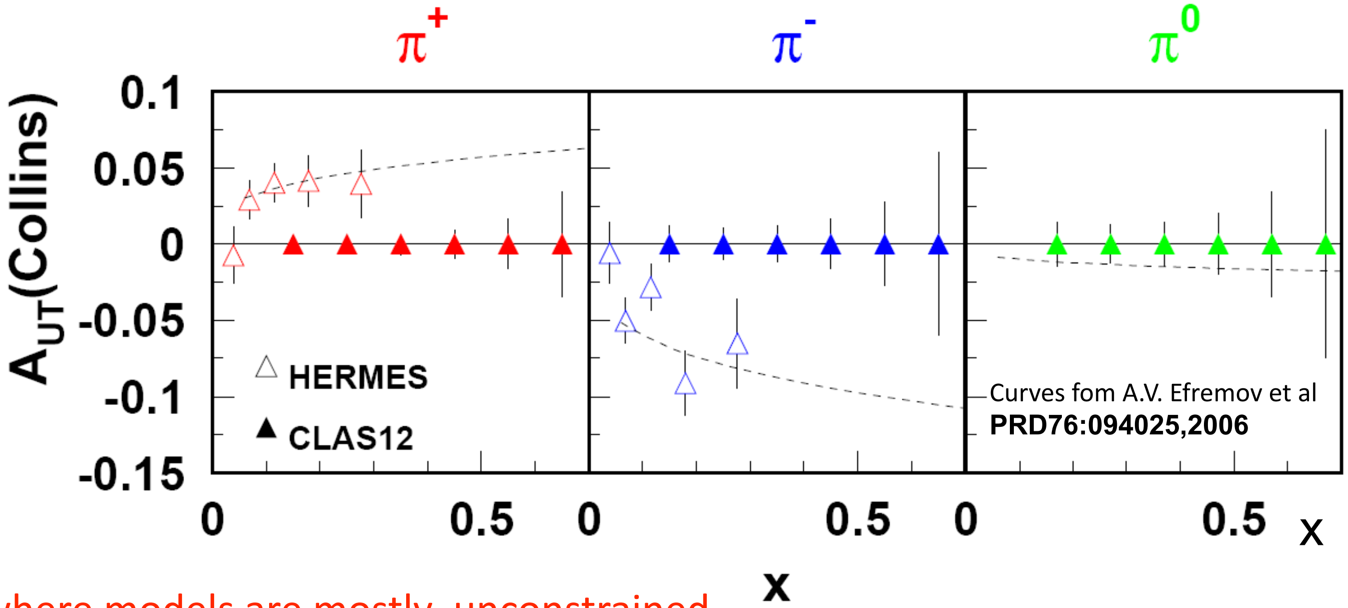


2000h @ 10^{35} $s^{-1}cm^{-2}$
NH_3 and ND_3 target
P_{beam} = 85 %

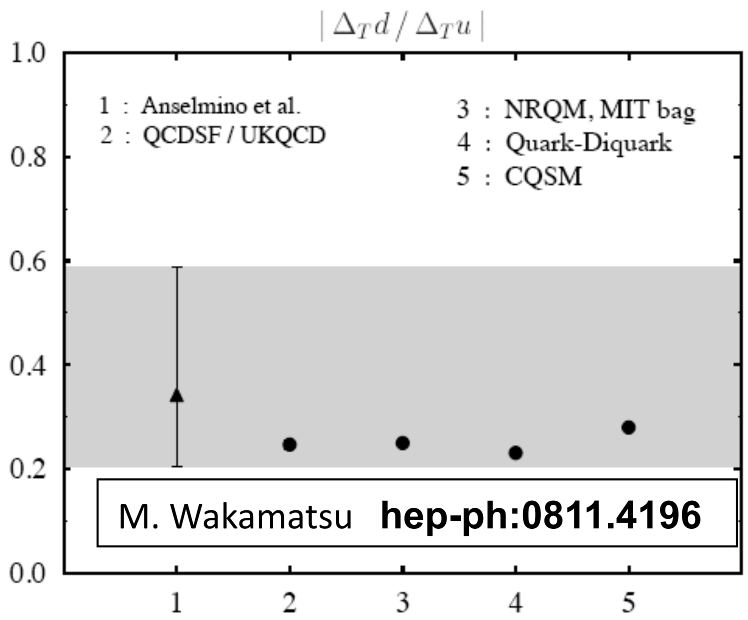
Collins asymmetry @ CLAS12

$$F_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^{\perp}$$

2000h @ 10^{34} $s^{-1}cm^{-2}$
HD-ice (P=85%)



Study A_{UT} at large x (valence) where models are mostly unconstrained

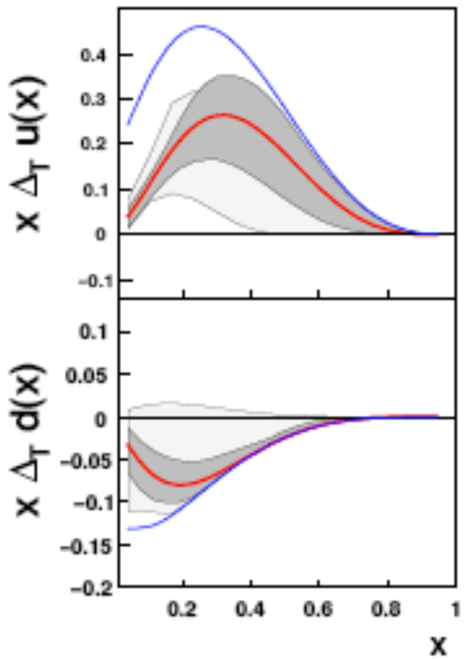


Tensor charge

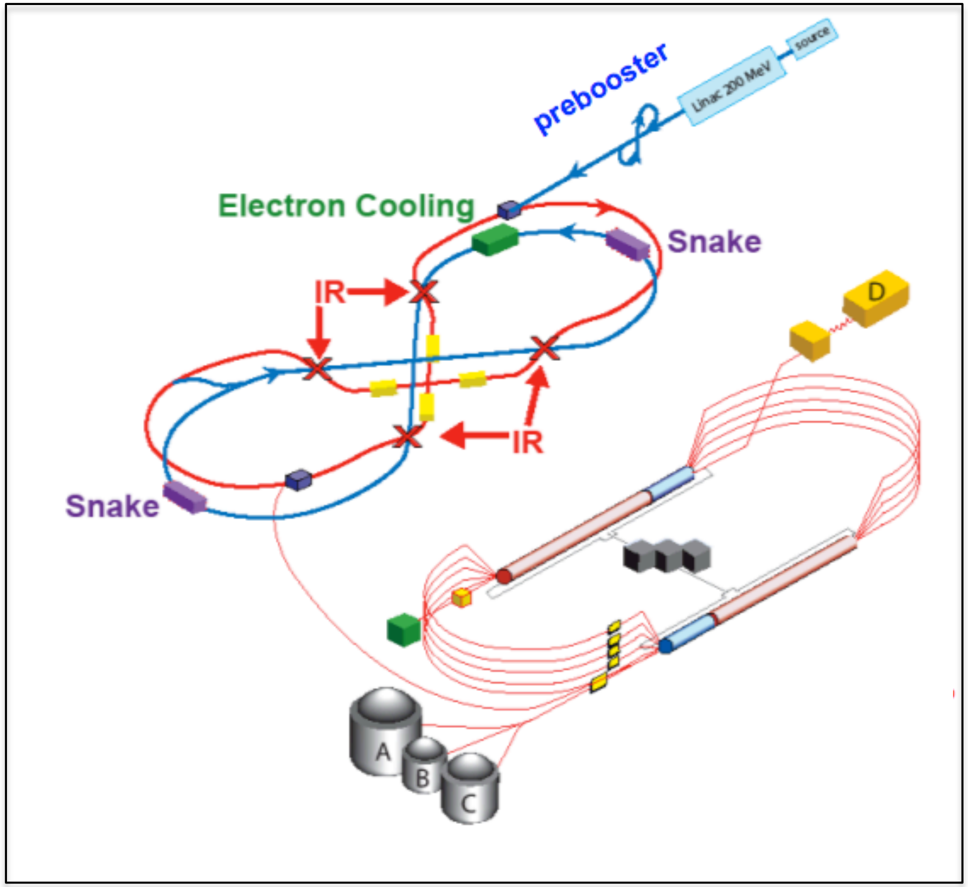
$$\delta u = 0.54^{+0.09}_{-0.22}$$

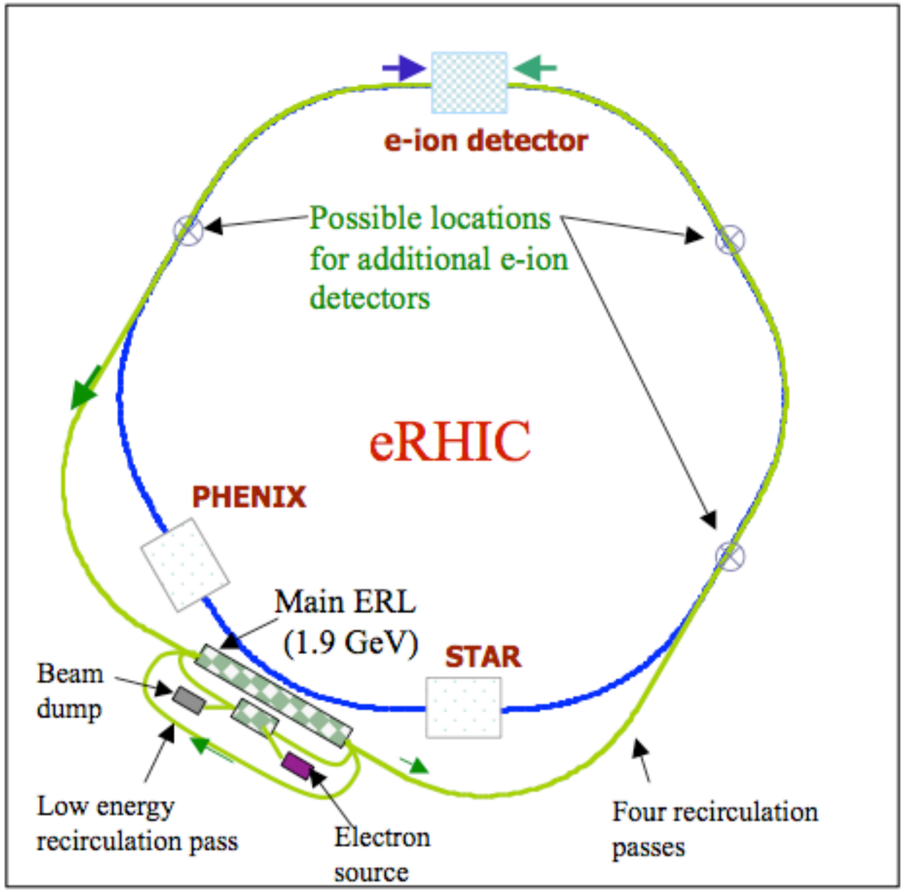
$$\delta d = -0.23^{+0.09}_{-0.16}$$

M. Anselmino et al
hep-ph:0812.4366



Electron Ion Collider





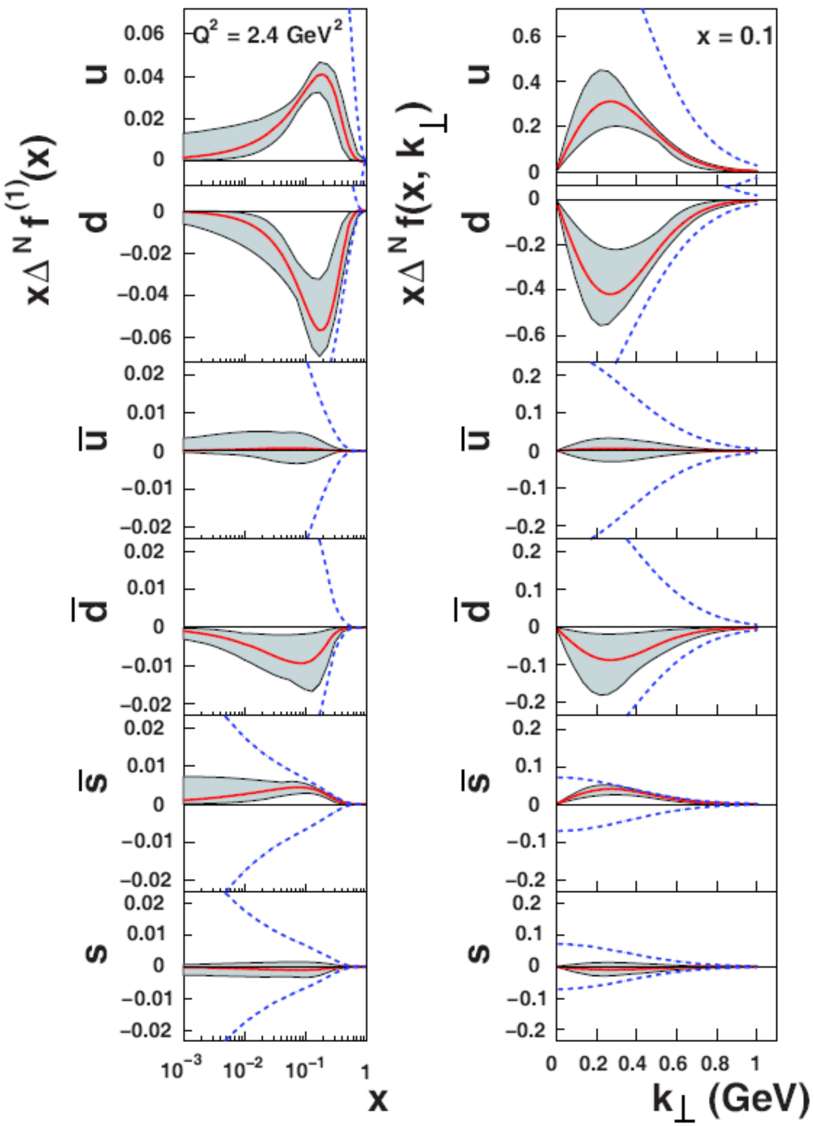
30-225 GeV protons
3 – 9 GeV electrons
√s ~ 20-90 GeV
L~ 0.7-6 10^{34} cm^{-2} s^{-1}

e,p polarization
greater than 70 %

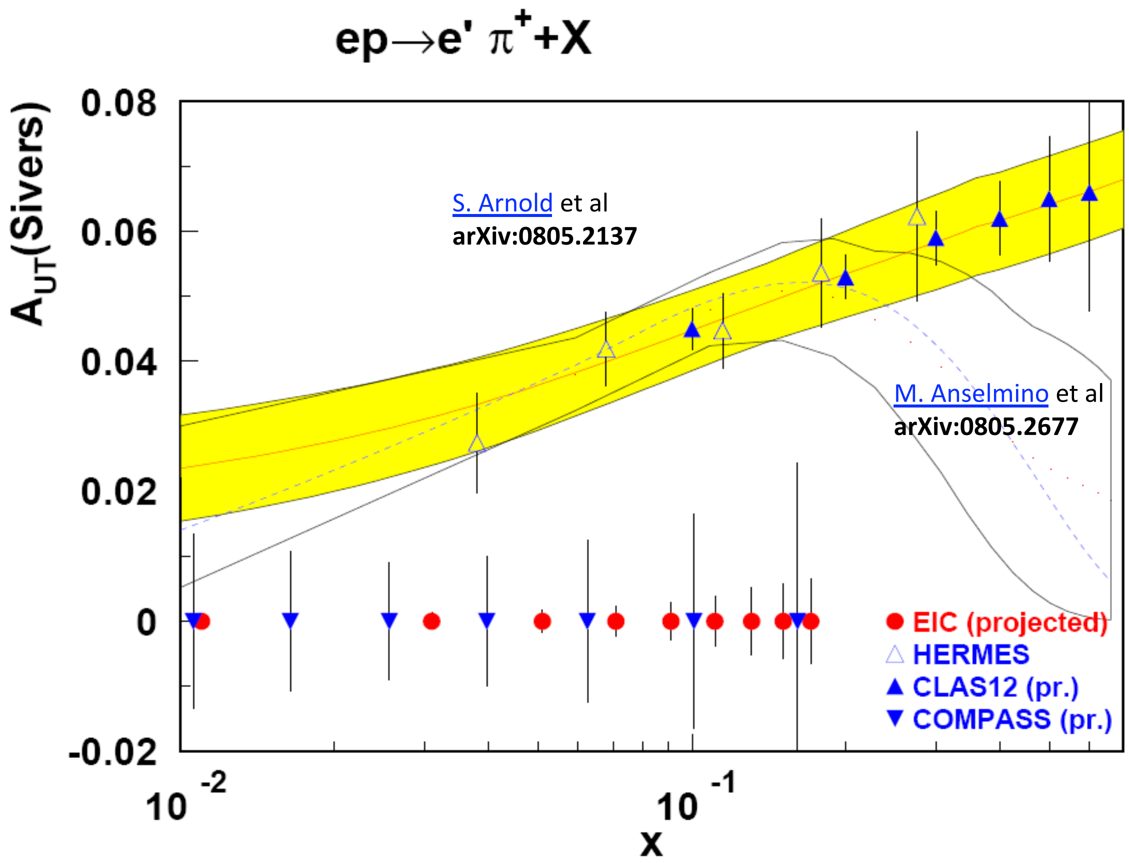
50-250 GeV protons
3 – 10 GeV electrons
√s ~ 25-100 GeV
L~ 0.5-3 10^{33} cm^{-2} s^{-1}

High luminosity is better than high-energy: Sudakov suppression (soft gluon radiation)

Sivers @ CLAS12 & EIC

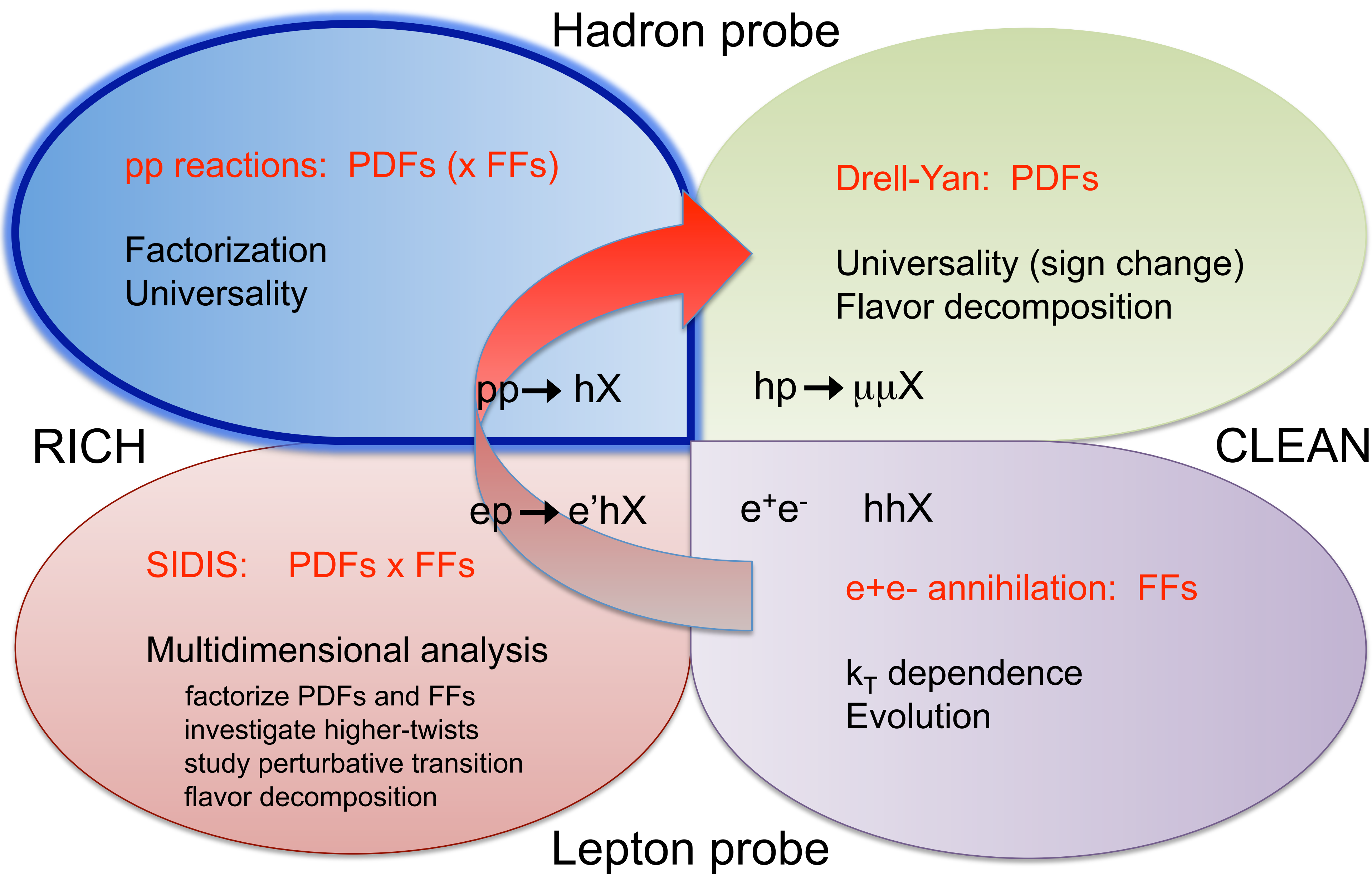


$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$



EIC measurements at small x will pin down sea contributions to Sivers function

TMD palette


Hadron probe
pp reactions: PDFs (x FFs)
Factorization
Universality
pp→ hX
Drell-Yan: PDFs
Universality (sign change)
Flavor decomposition
hp→ μμX
RICH
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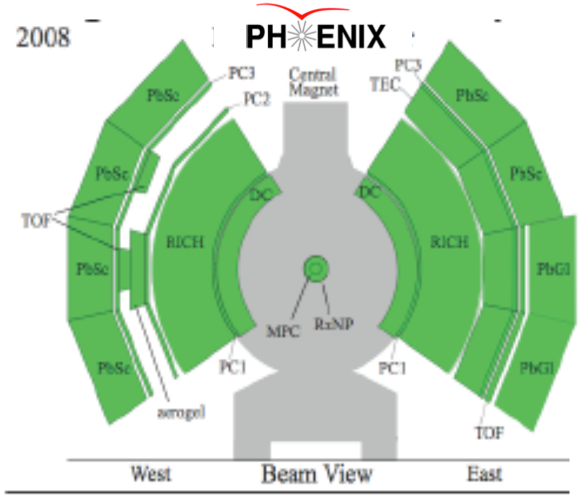
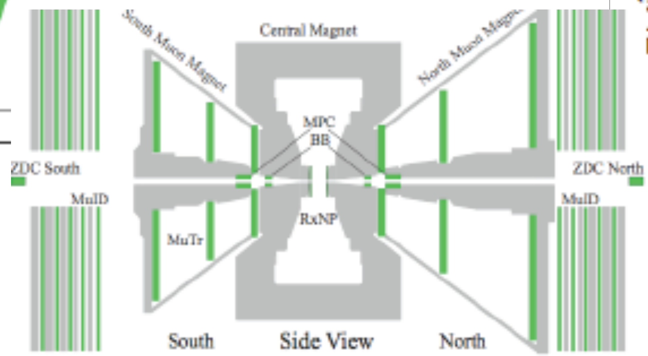
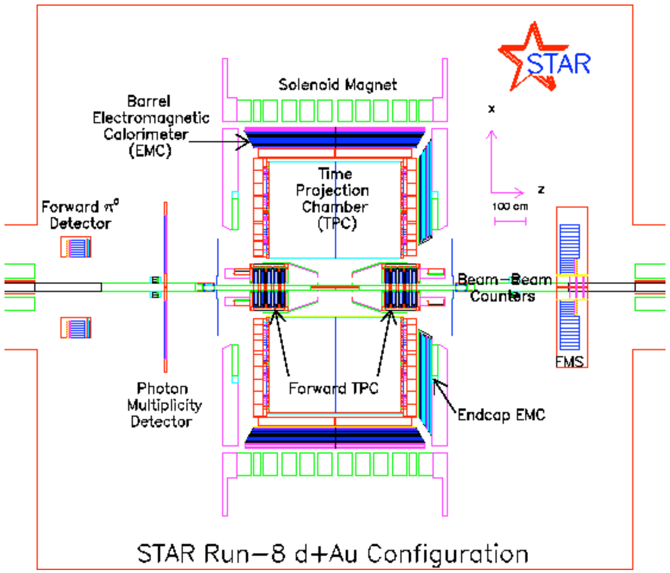
Multidimensional analysis
factorize PDFs and FFs
investigate higher-twists
study perturbative transition
flavor decomposition
e+e- hhX
e+e- annihilation: FFs
kT dependence
Evolution
Lepton probe

Particle yield in pp @ RHIC



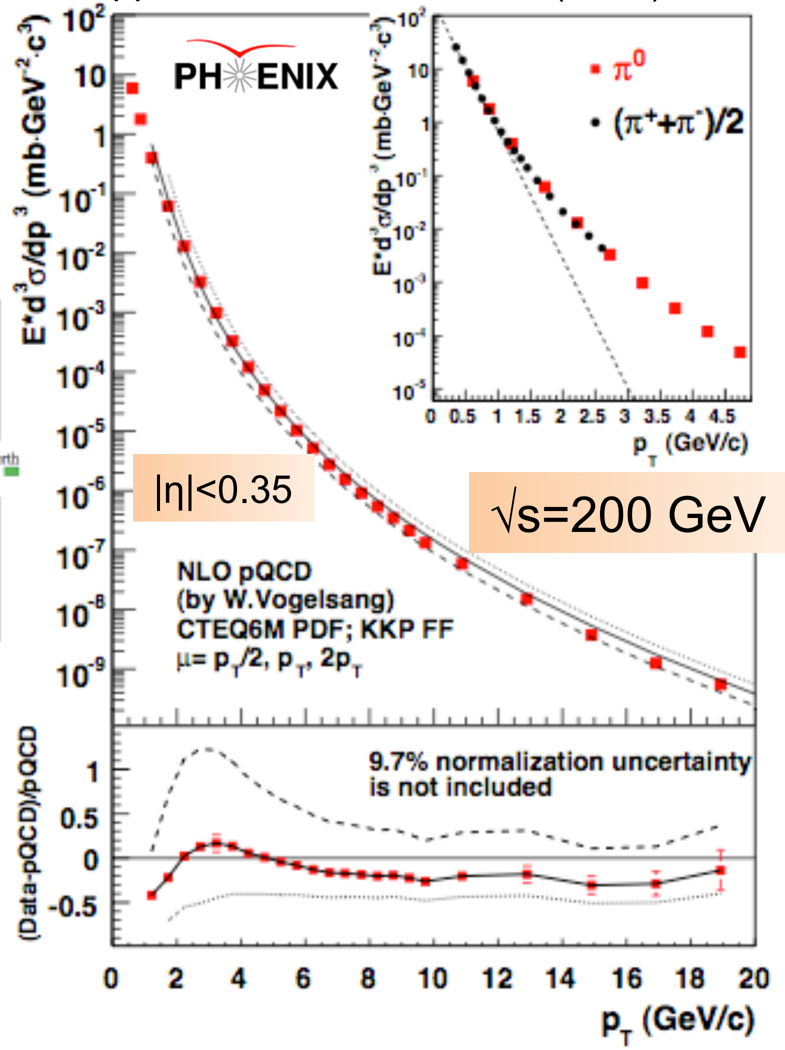
High rate
Limited acceptance
Forward muon detector





Large acceptance
Limited rate
Forward colarimeters

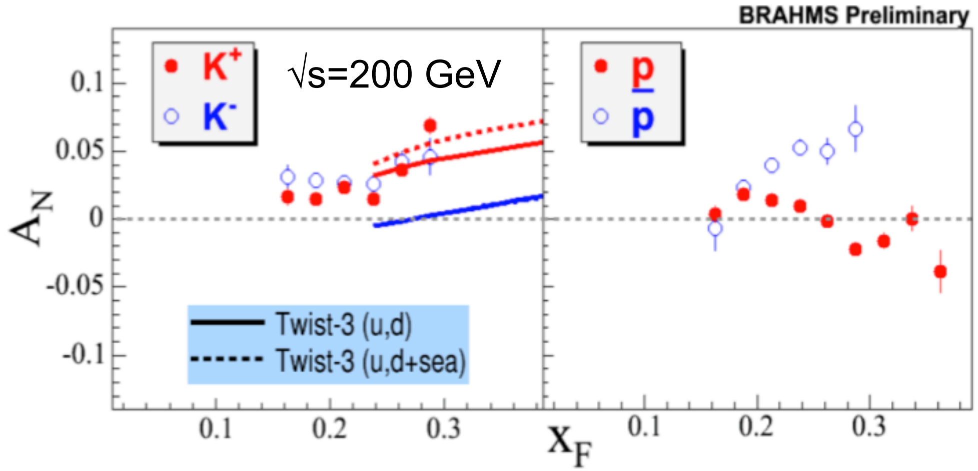
pp->π^0X:PRD76, 051106 (2007)

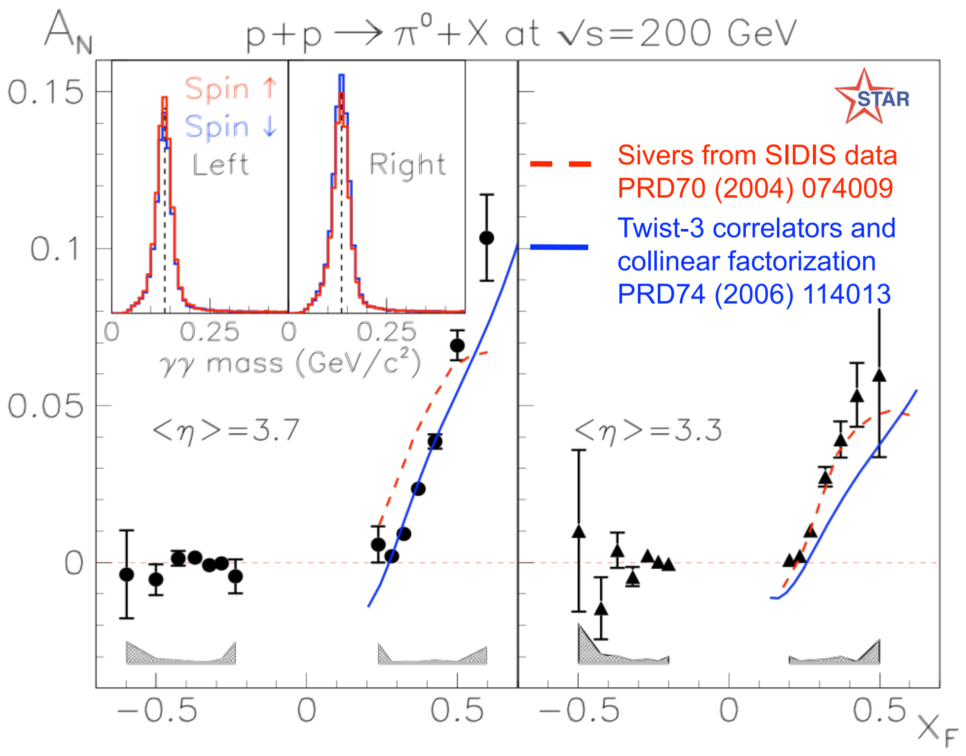


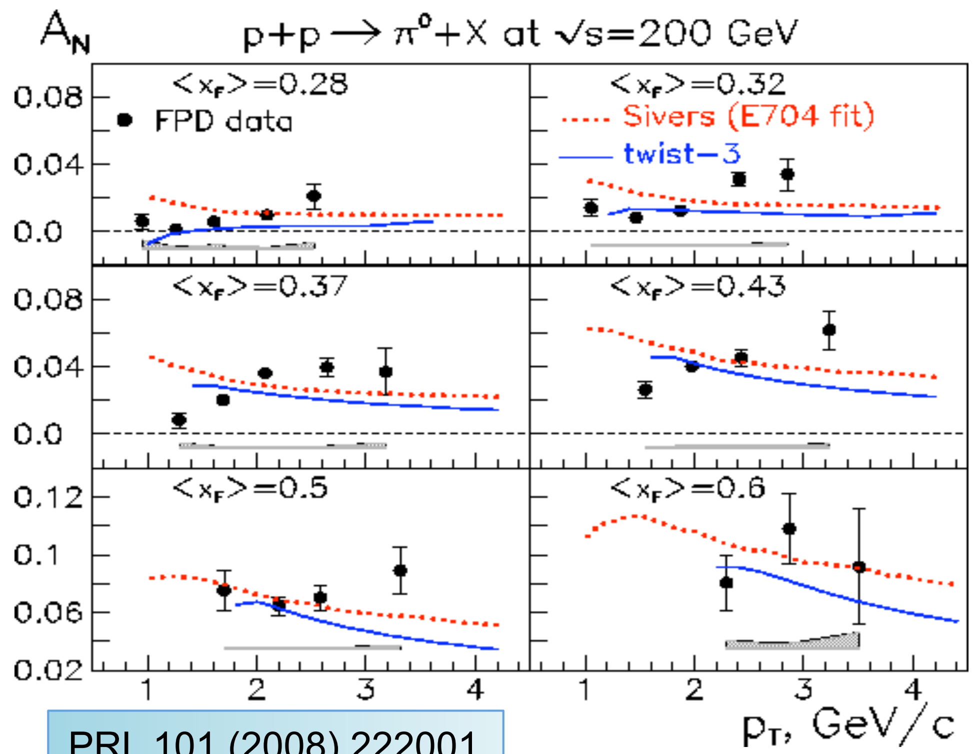
Cross-section is consistent
with NLO pQCD calculations

A_N for inclusive hadron @ RHIC

- An at positive x_F grows with increasing x_F
- x_F dependence matches theoretical model expectations qualitatively





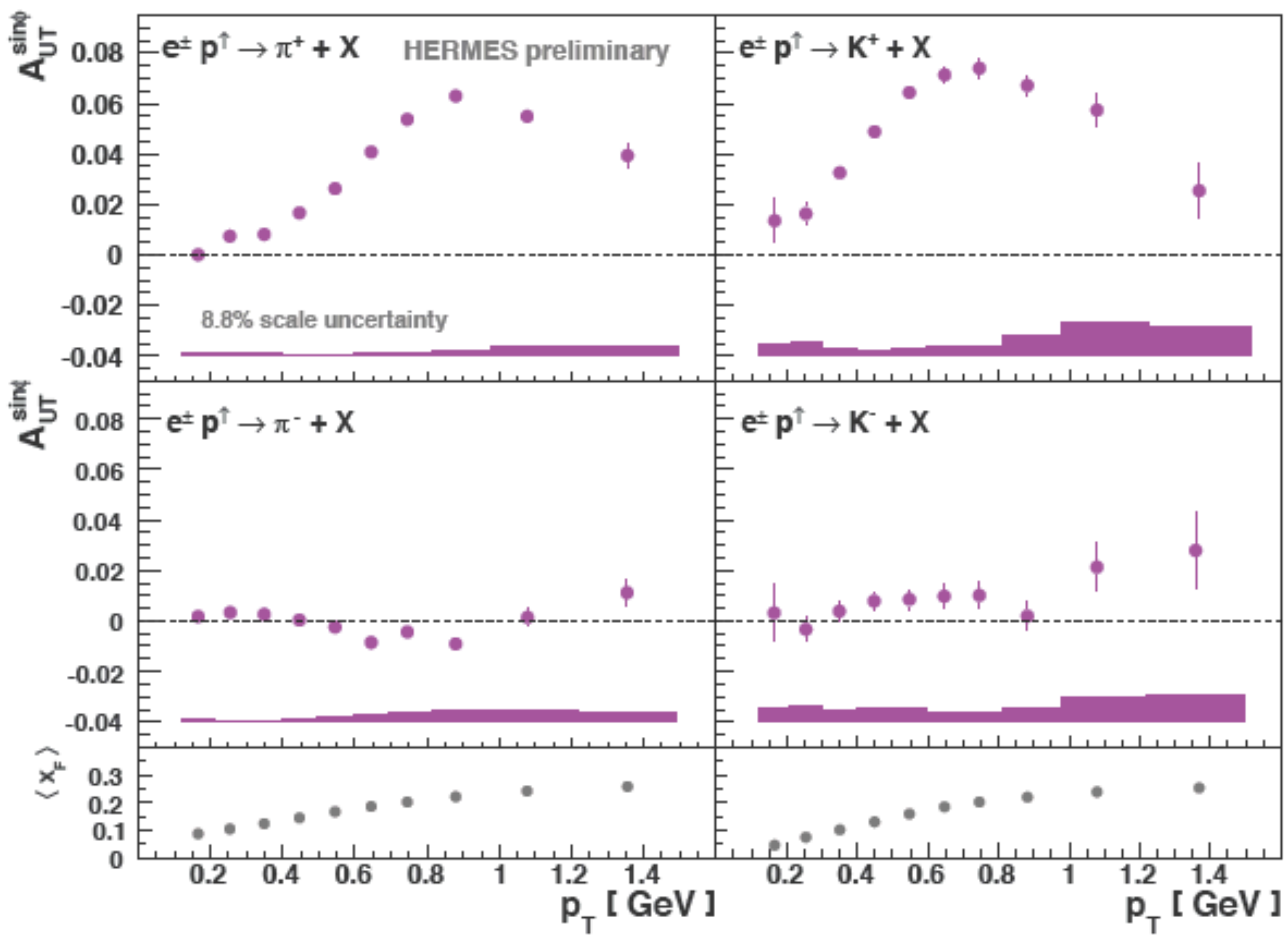


PRL 101 (2008) 222001

SIDIS A_N @ HERMES

Left-Right analyzing power for inclusive meson production

No scattered beam detected → p_T, x_F with respect to **e beam** (not q-vector)



SSA of heavy flavour @ RHIC

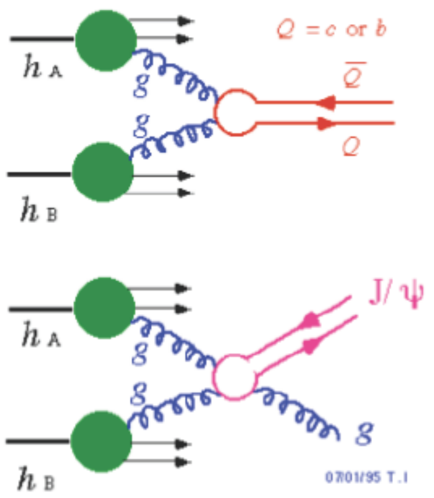
- Eliminate Collins' effects
  * heavy flavor production dominated by gluon gluon fusion at RHIC energy

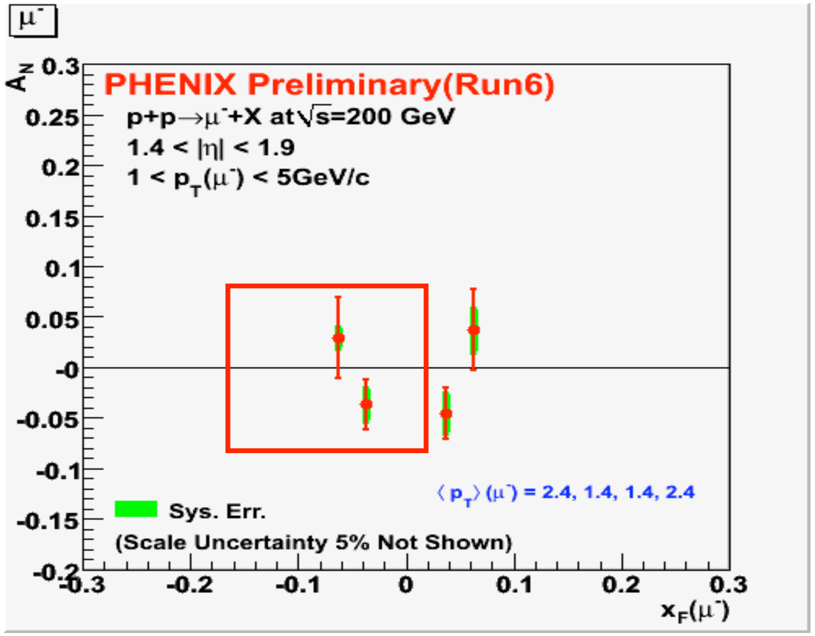
    Pythia 6.1 simulation

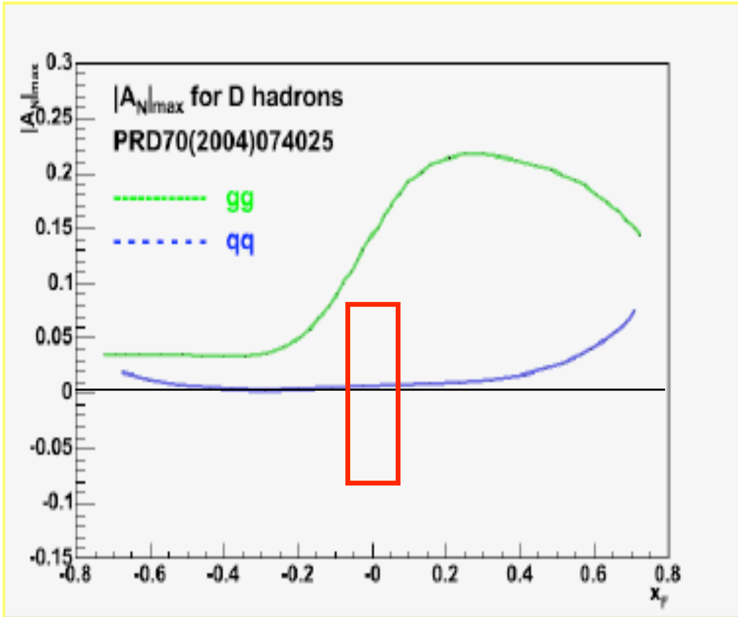
$c\bar{c}$:	$gg \to c\bar{c}$	95%
$b\bar{b}$:	$gg \to b\bar{b}$	85%

  * gluon has zero transversity
- A perfect channel for gluon Sivers function
  * Gluon's orbital angular momentum?
- Important to understand the origin of observed large A_N at large x_F

Gluon Fusion



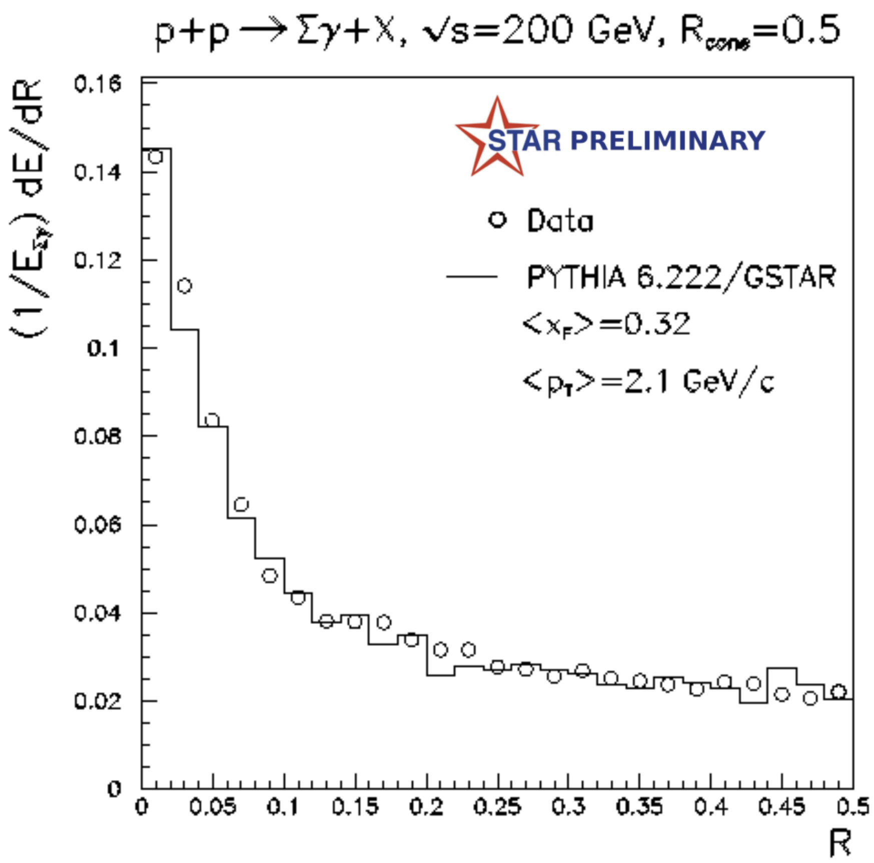


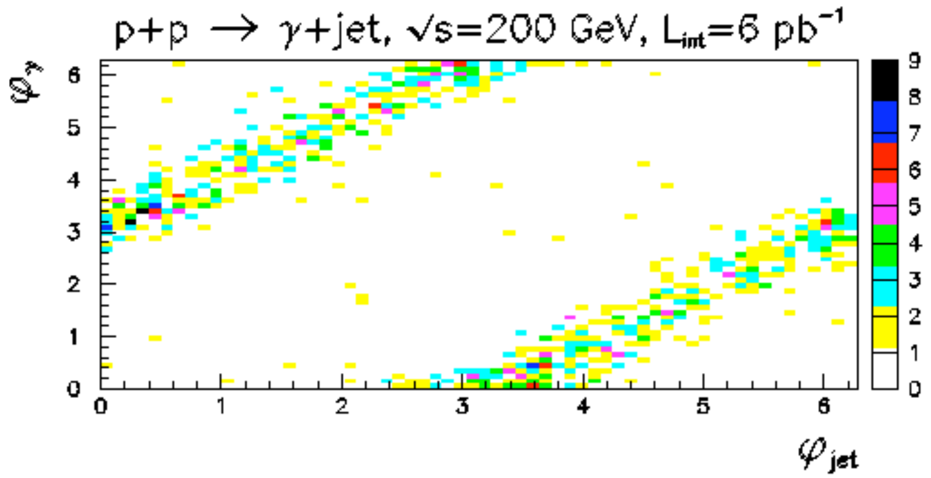


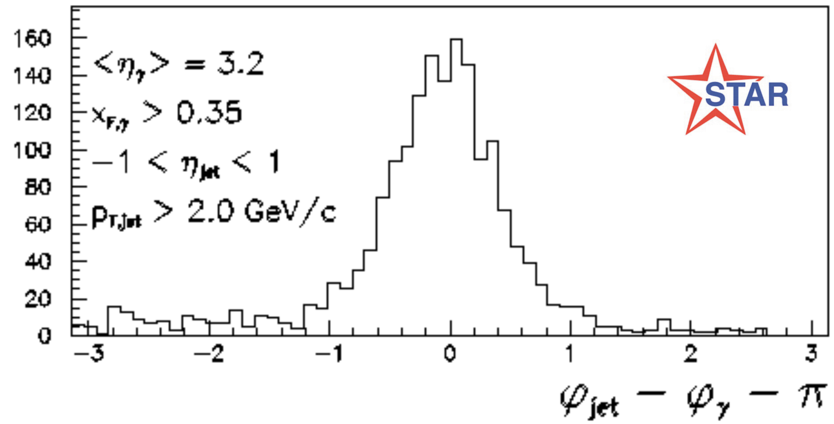
SSA for γ & jet @ RHIC

No fragmentation ⟶ No Collins effect

energy distribution within jet-like objects in the FMS as a function of distance from the jet axis.



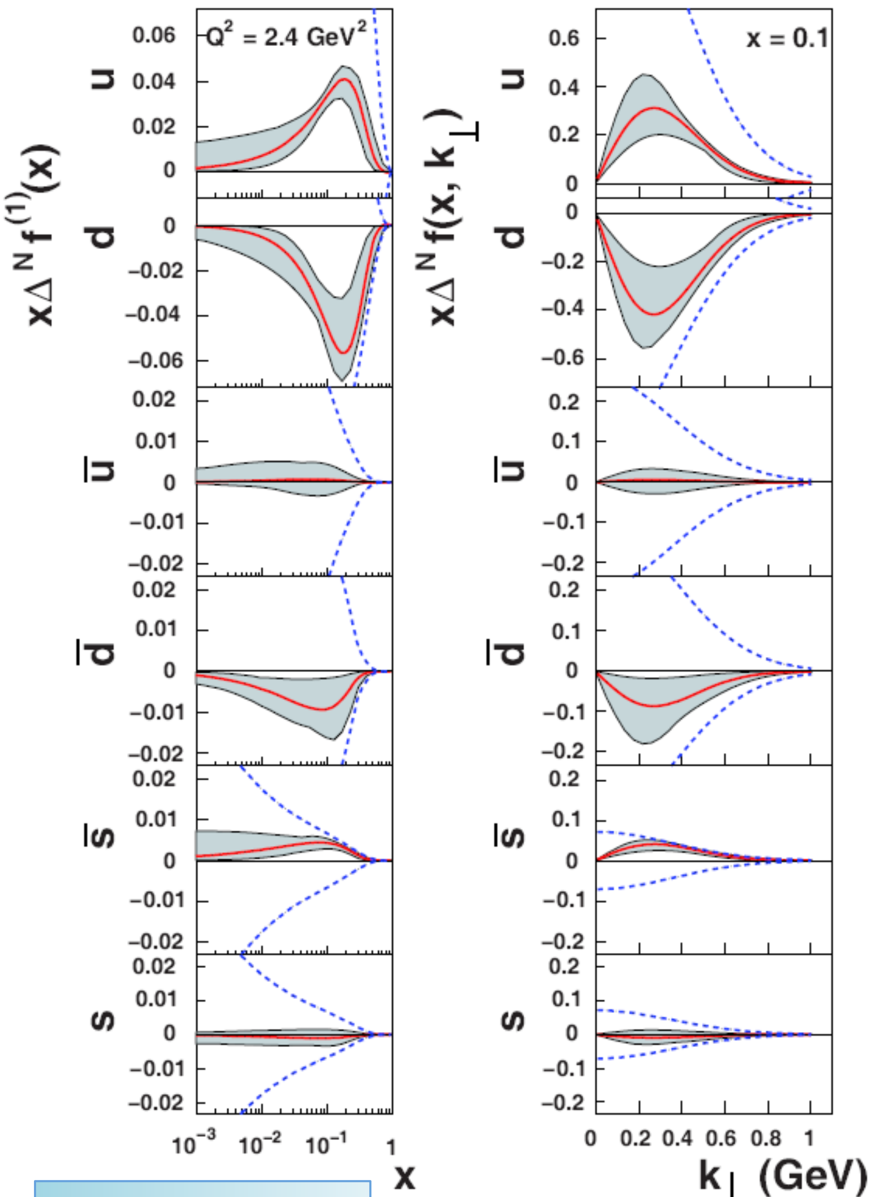




10^4 useable forward photon + jet coincidences are expected in a 30 pb^{-1} data sample with 60% beam polarization

"Jet shape" in data matches simulation well

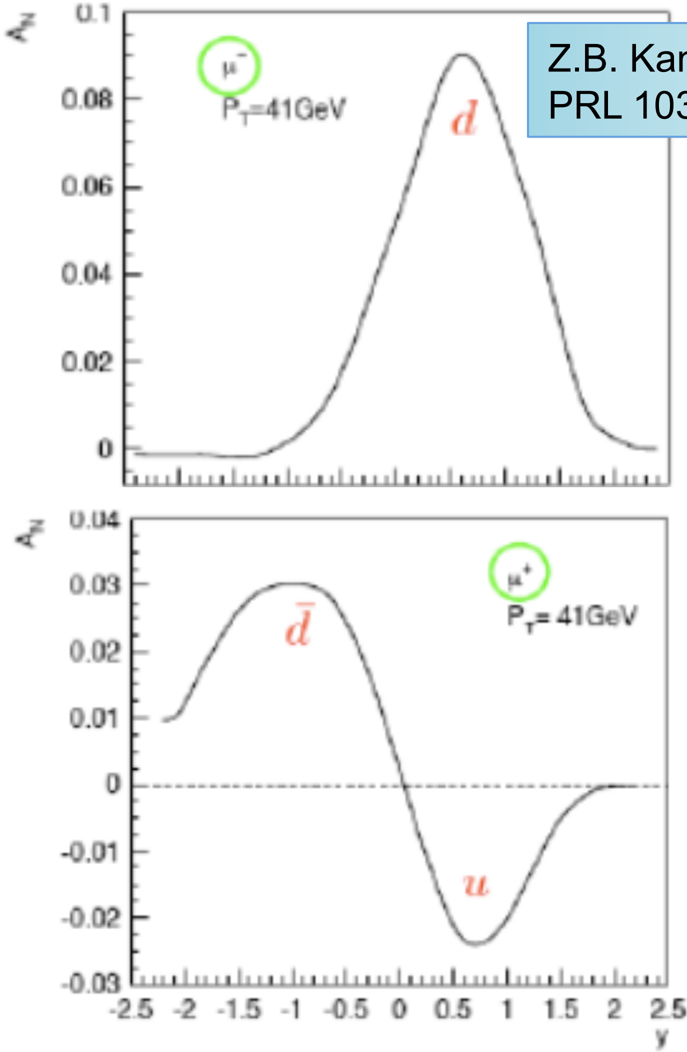
SSA of leptons from W decay @ RHIC



arXiv: 0805.2677

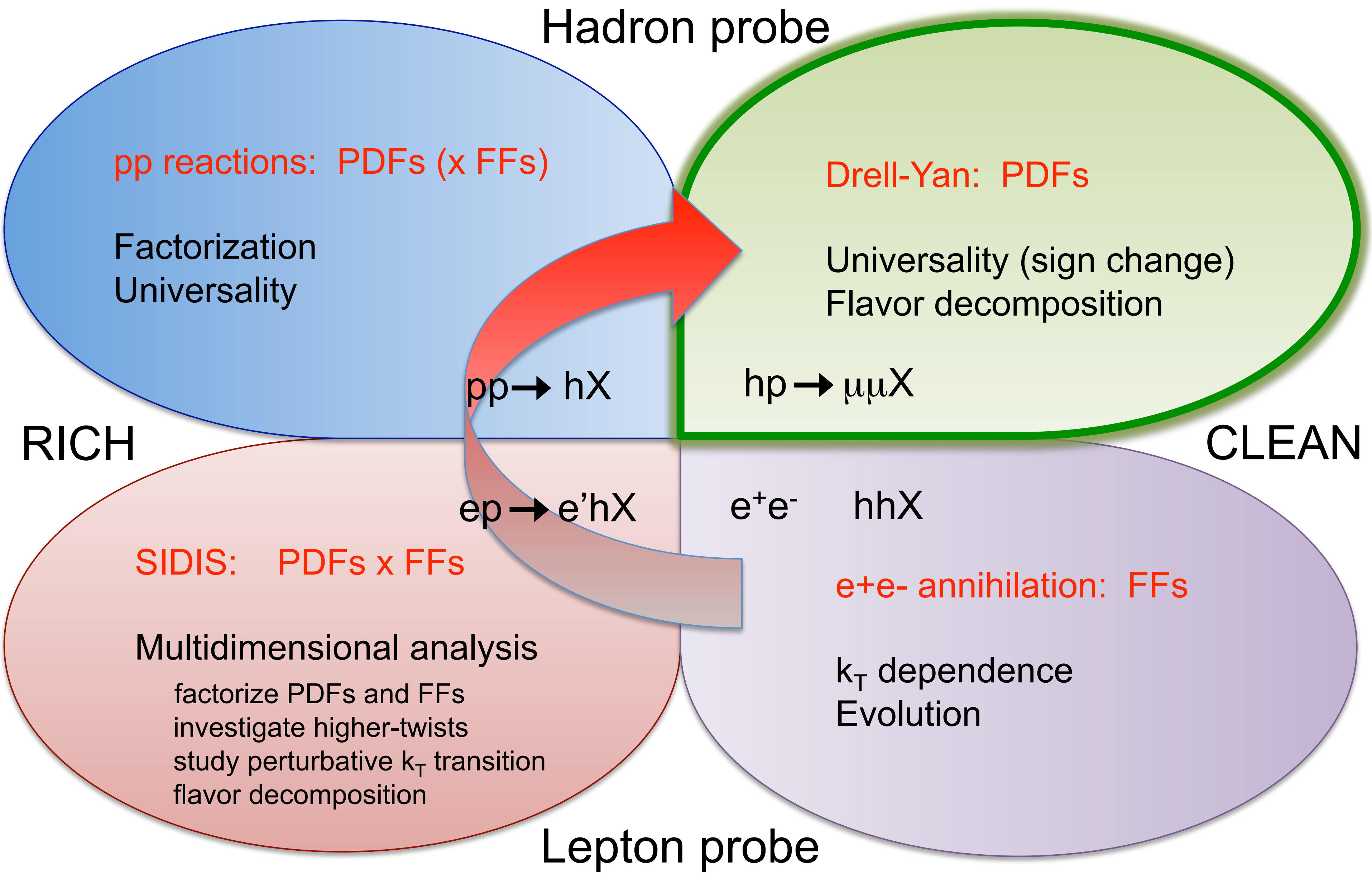
SSA survives the dilution due to W decay

Z.B. Kang, J.W. Qui
PRL 103 (2009) 172001



Flavor separation !
Z's as clean theoretically as DY

TMD palette


Hadron probe
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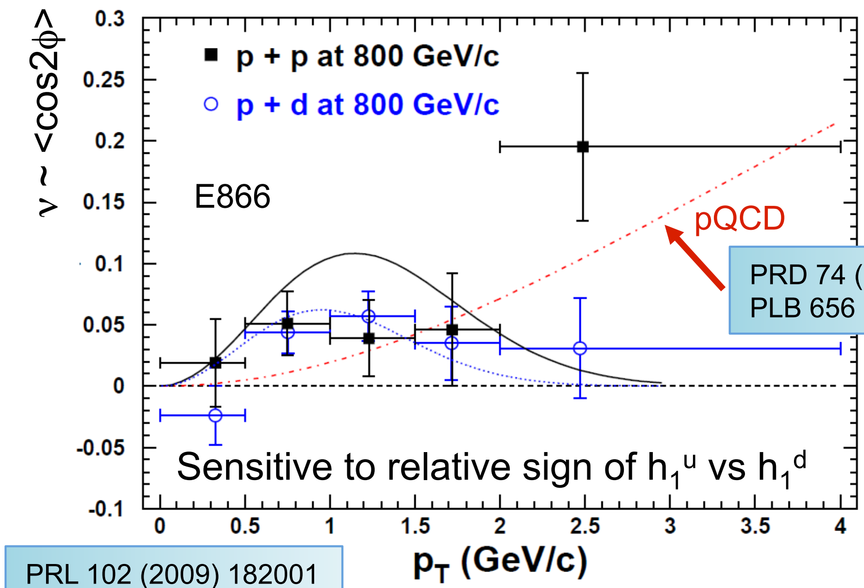
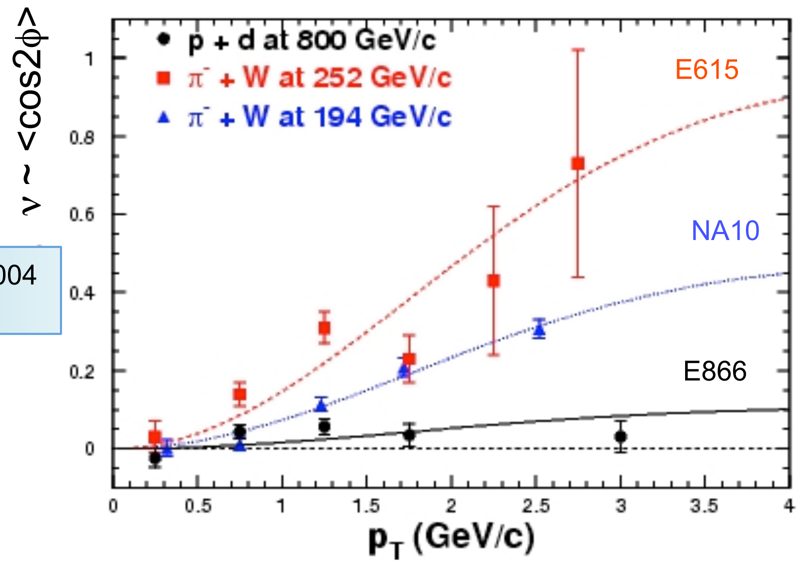
factorize PDFs and FFs
investigate higher-twists
study perturbative k_T transition
flavor decomposition
e^+e^- hhX
e+e- annihilation: FFs
k_T dependence
Evolution
Lepton probe

pp, pd Drell-Yan @ Fermilab



PRD 74 (2006) 014004
PLB 656 (2007) 74

PRL 102 (2009) 182001



E906: Data taking starts this summer

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

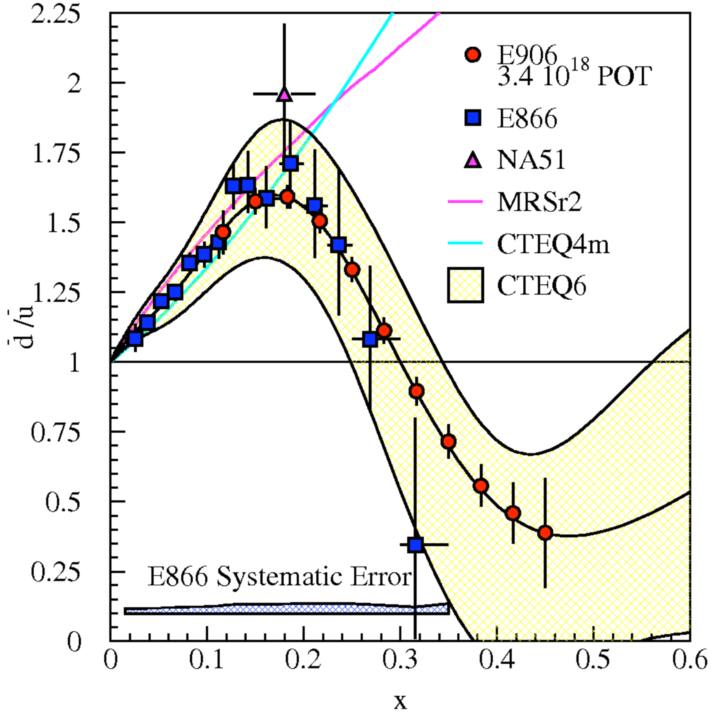
Extends E866 measurements at 120 GeV

xsec scales as 1/s

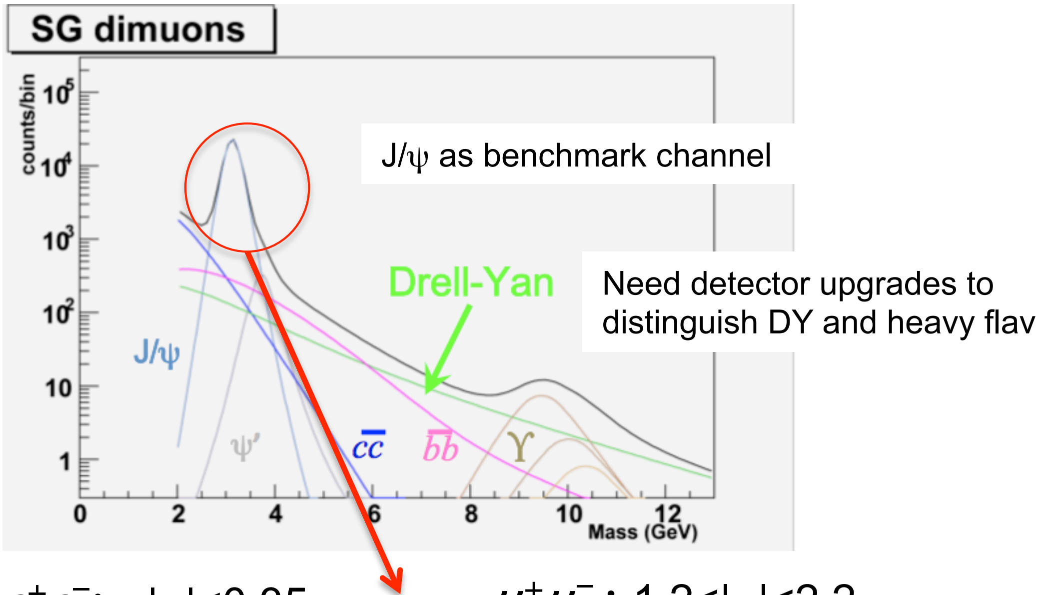
background scales as s

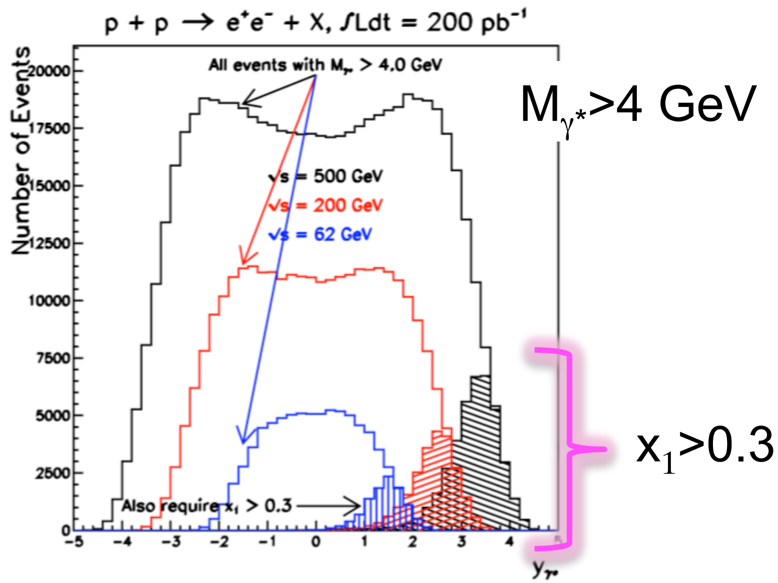
Systematic uncertainty ~1% in cross section ratio.

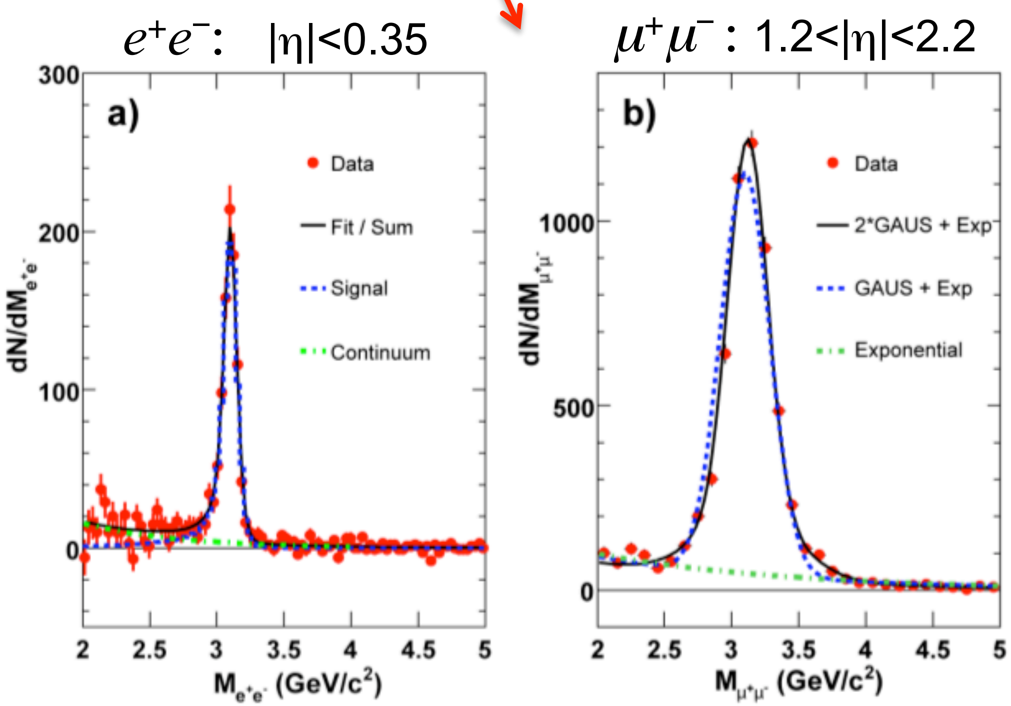
Precise measurement of Boer-Mulders

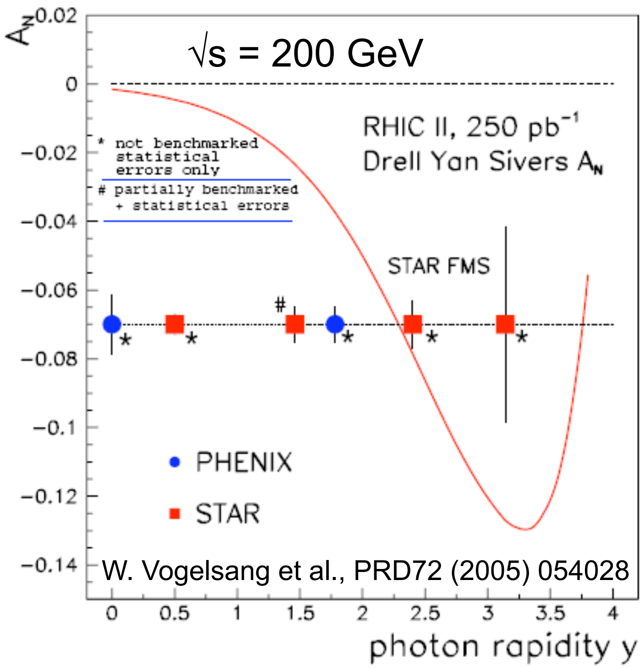


pp Drell-Yan @ RHIC







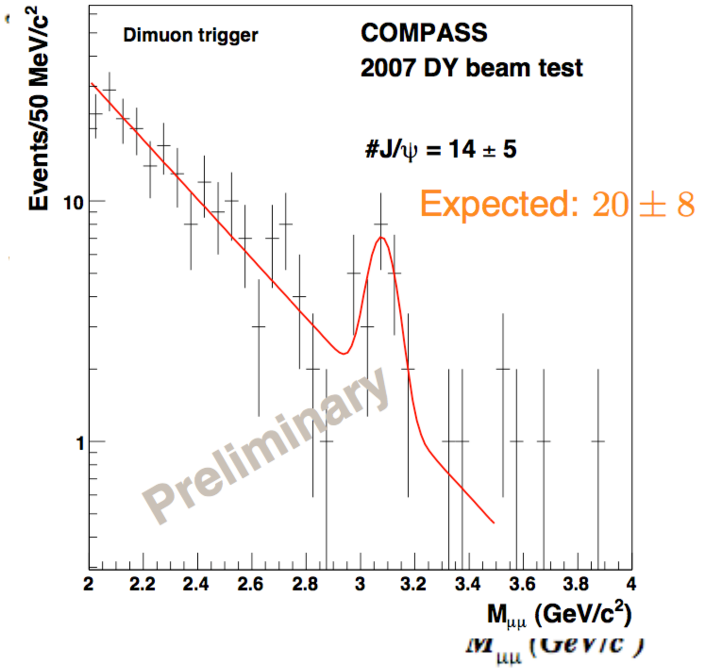


πp Drell-Yan @ CERN

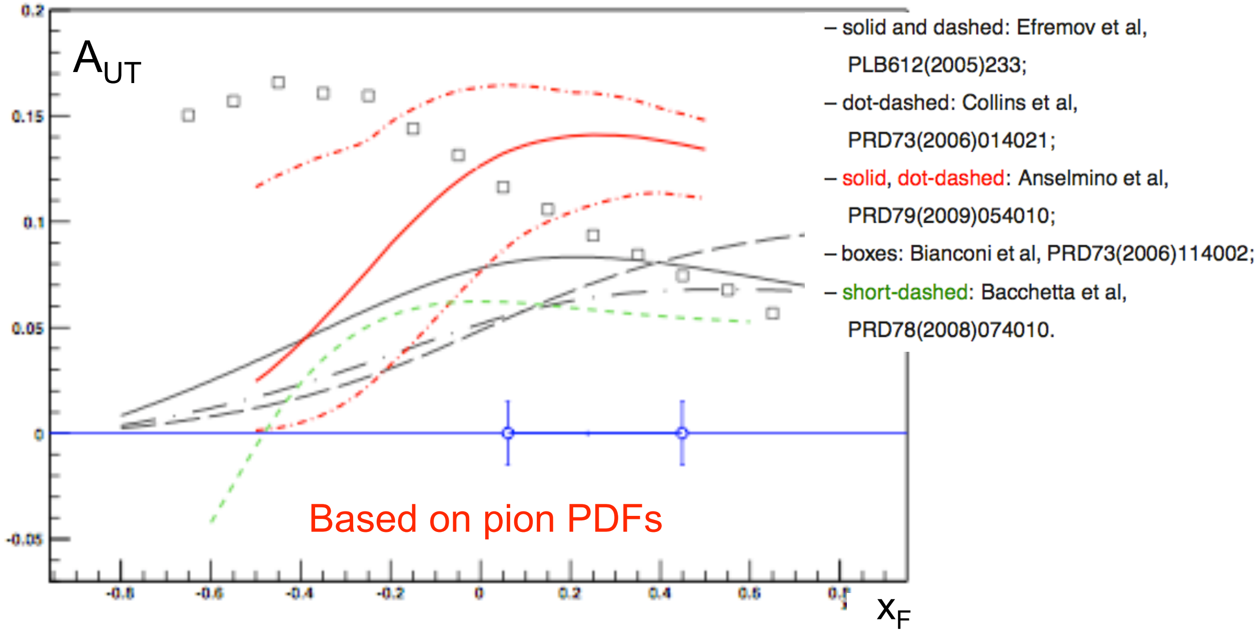
Proposal: π^- beam of 160 GeV/c on a NH_3 target

Under study is the feasibility of the measurement:

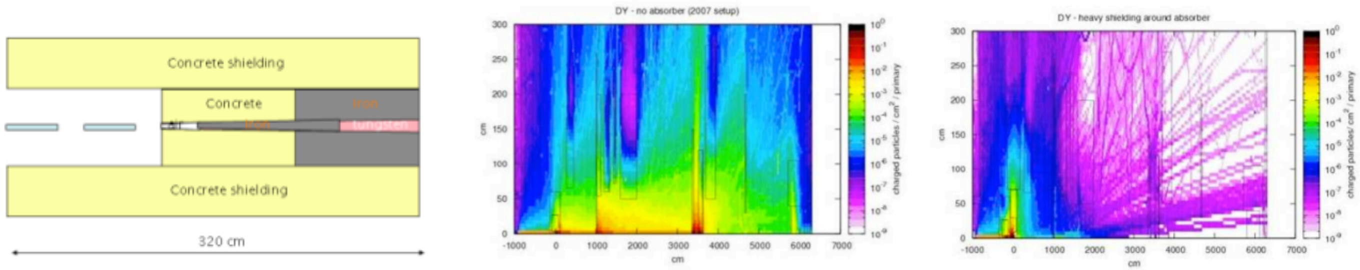
2007 12h beam test



2 years at L=1.7 10^{33} $cm^{-2}s^{-1}$



- Dimuon trigger
- Hadron absorber
- Radiation conditions



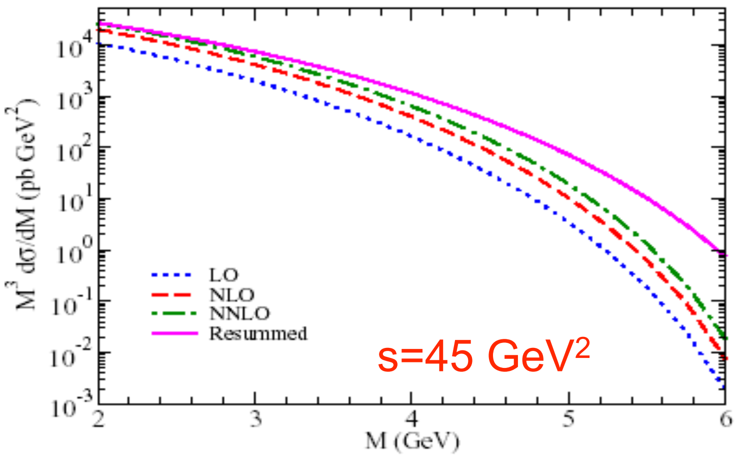
FLUKA simulations, H. Vincke, CERN

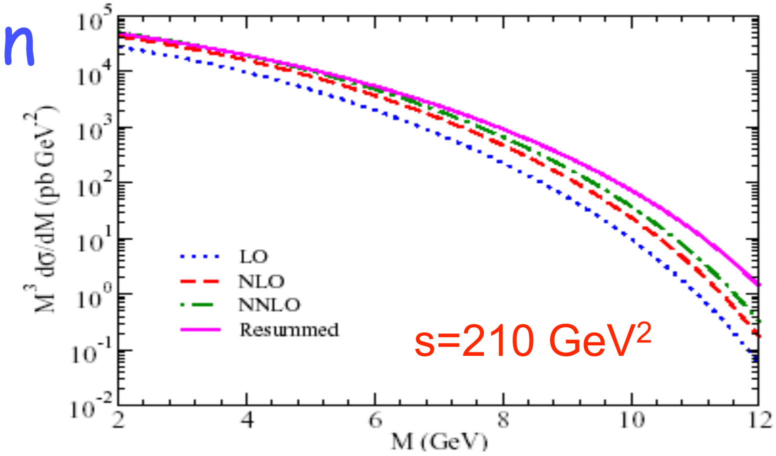
h_1 from $\bar{p}$-p Drell-Yan @ FAIR

PANDA: unpolarized target (s=30 GeV^2)

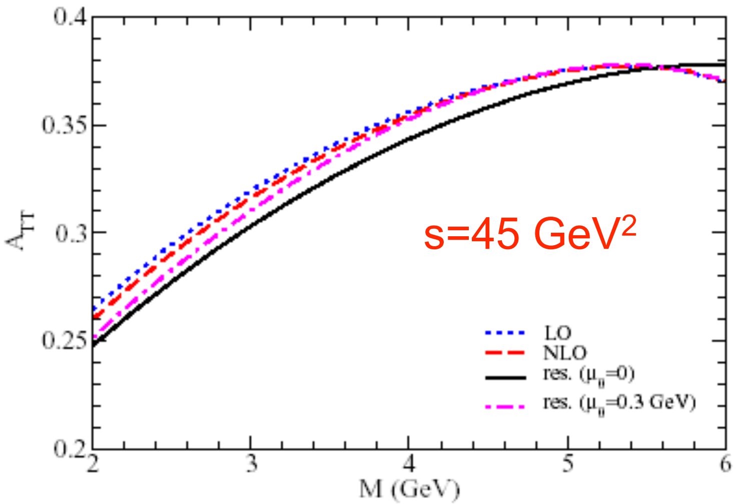
PAX: polarized collider (s=200 GeV^2)

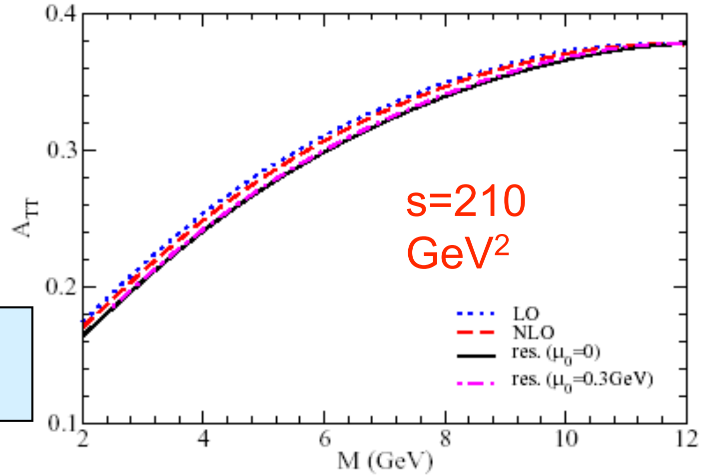
Cross-section





Asymmetry





H. Shimizu et al., hep-ph/0503270

V. Barone et al., in preparation

QCD corrections might be very large at smaller values of M,
for cross-sections, not for A_{TT}: K-factor almost spin-independent

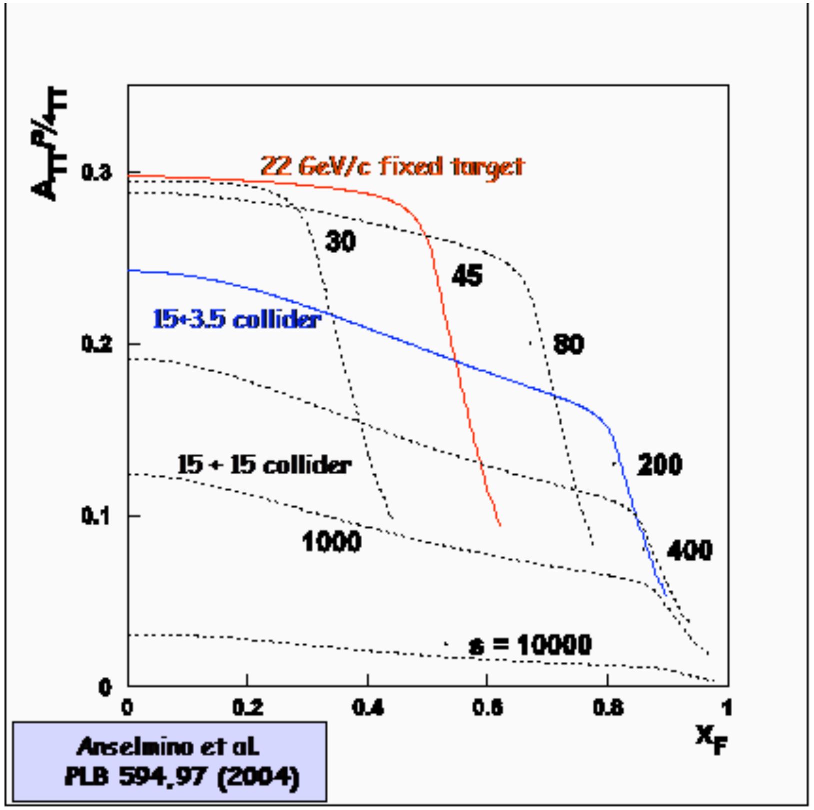
h_1 from p̄-p Drell-Yan @ FAIR

PANDA: unpolarized target ($s=30\ GeV^2$)

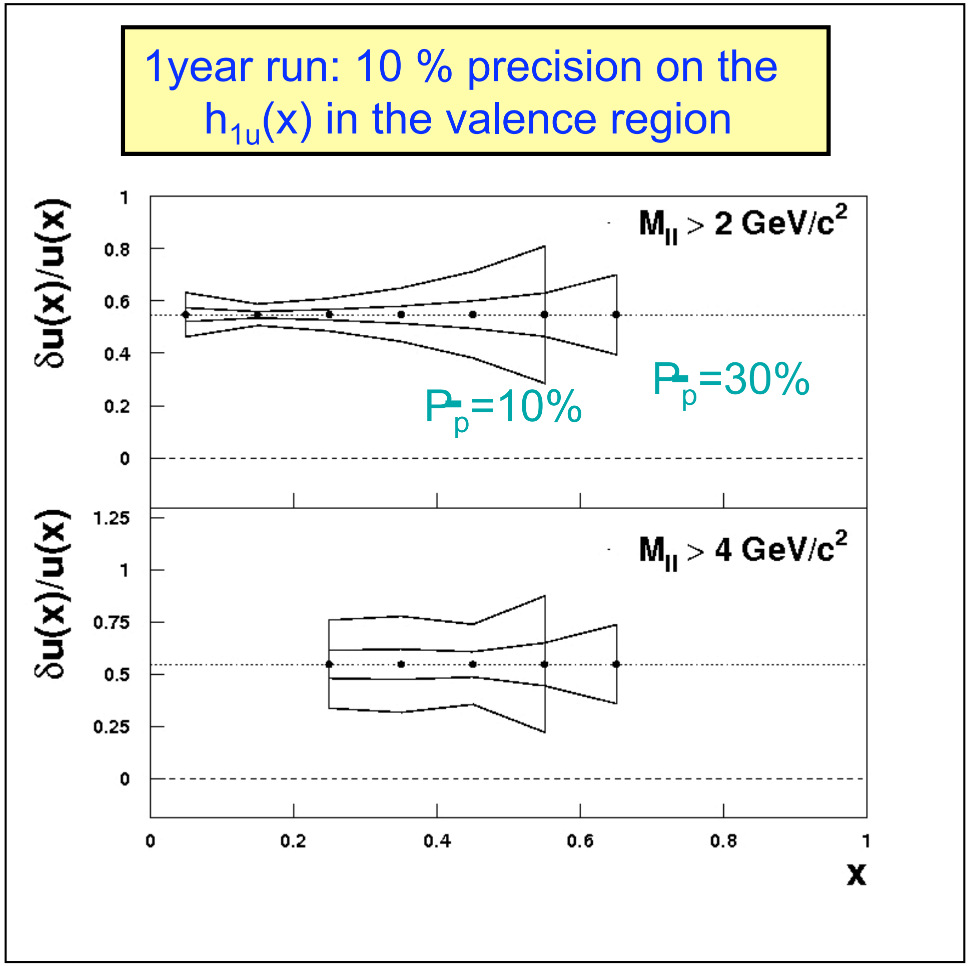
PAX: polarized collider ($s=200\ GeV^2$)

$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \approx \hat{a}_{TT} \frac{h_{1u}(x_1)\ h_{1u}(x_2)}{u(x_1)\ u(x_2)}$$

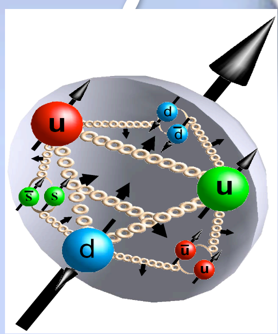
- u-dominance
- $|h_{1u}|>|h_{1d}|$



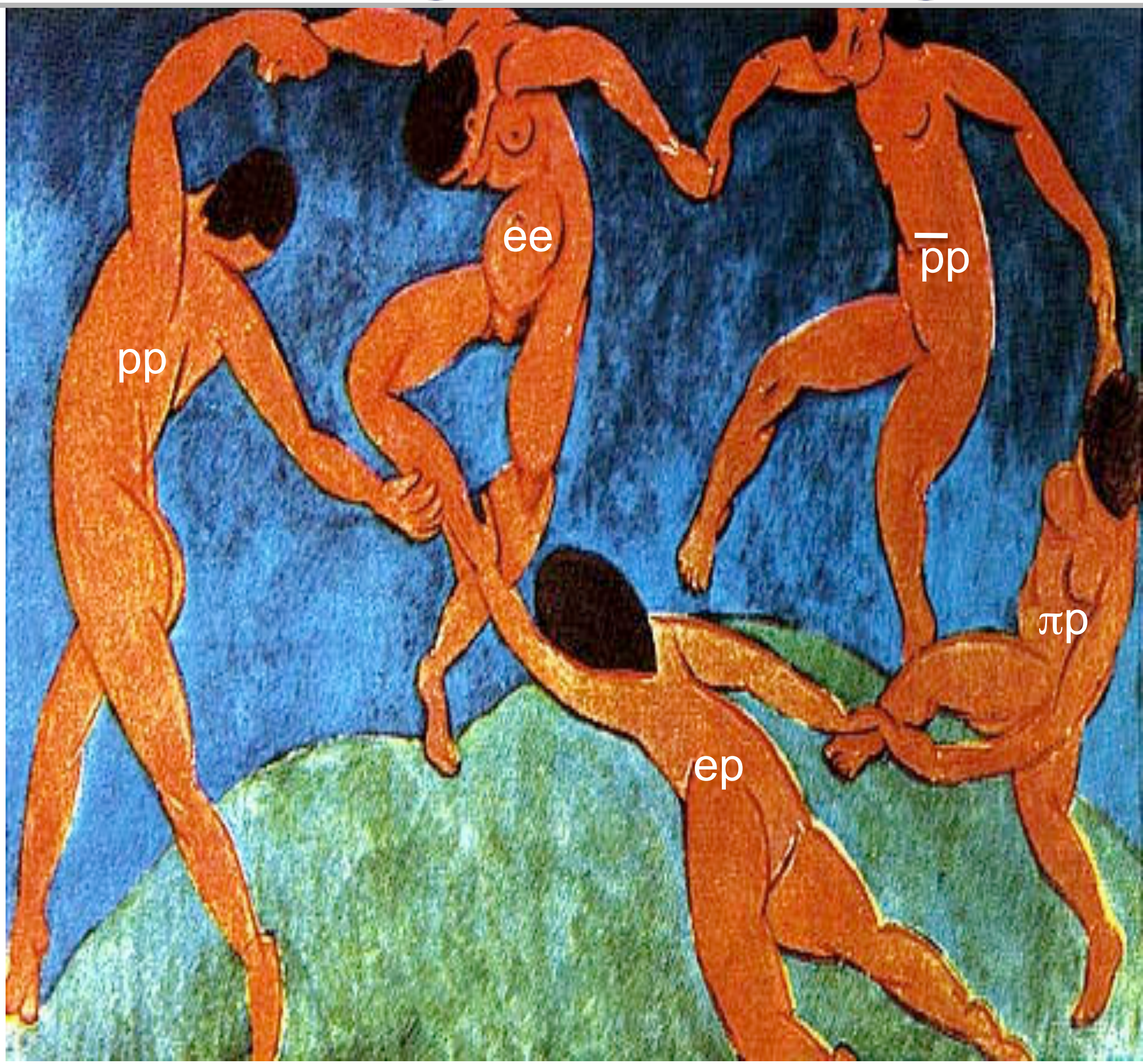
PAX : $M^2/s=x_1x_2$~0.02-0.3 valence quarks
(A_{TT} large ~ 0.2-0.3)



TMD treasure map



A 10 years party



You are welcome to join !

Spares

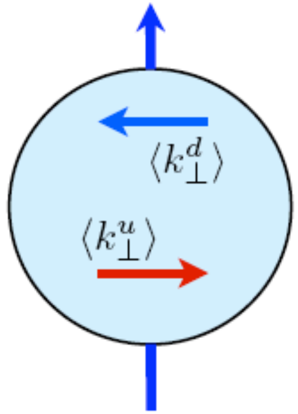
$$\sum_a \int dx\, d^2\boldsymbol{k}_\perp\, \boldsymbol{k}_\perp\, f_{a/p^\uparrow}(x, \boldsymbol{k}_\perp) \equiv \sum_a \langle \boldsymbol{k}_\perp^a \rangle = 0$$

M. Burkardt, PR **D69**, 091501 (2004)

$$\langle k_\perp^u \rangle + \langle k_\perp^d \rangle = -17^{+37}_{-55}\ (\mathrm{MeV}/c)$$

$$[\ \langle k_\perp^u \rangle = 96^{+60}_{-28} \qquad \langle k_\perp^d \rangle = -113^{+45}_{-51}\ ]$$

$$\langle k_\perp^{\bar{u}} \rangle + \langle k_\perp^{\bar{d}} \rangle + \langle k_\perp^{s} \rangle + \langle k_\perp^{\bar{s}} \rangle = -14^{+43}_{-66}\ (\mathrm{MeV}/c)$$



Burkardt sum rule almost saturated by u and d quarks alone; little residual contribution from gluons

$$-10 \le \langle k_\perp^g \rangle \le 48\ (\mathrm{MeV}/c)$$

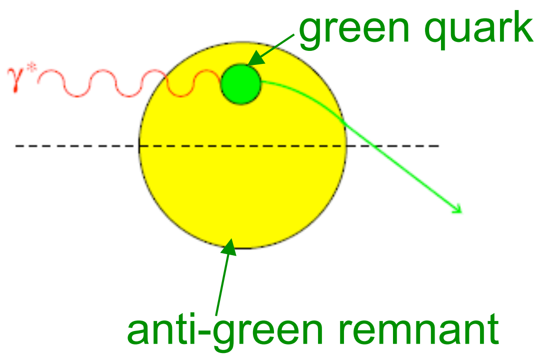
Spares

QCD prediction: $\mathbf{f_{1T}^{\perp}}(x)_{SIDIS} = -\,\mathbf{f_{1T}^{\perp}}(x)_{DY}$

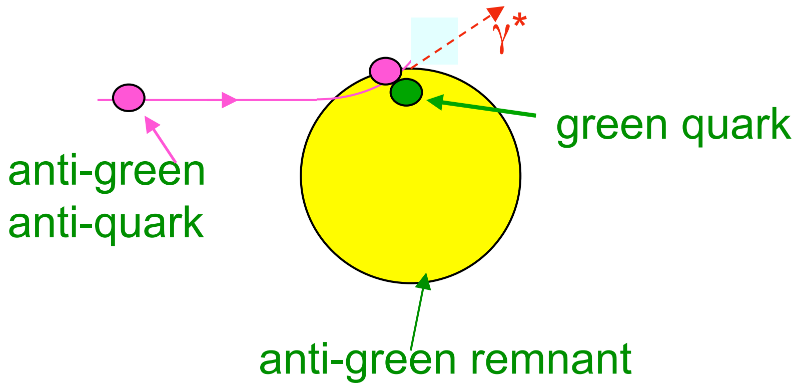
$\gamma^* q \to q$

$q\bar{q} \to \gamma^* \to \ell^+ \ell^-$

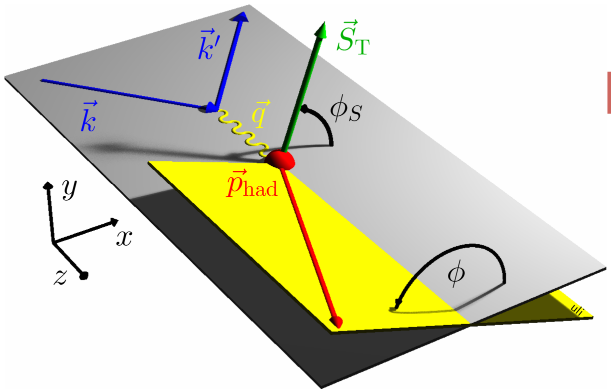
lensing effect



anti-lensing



Asymmetries and moments

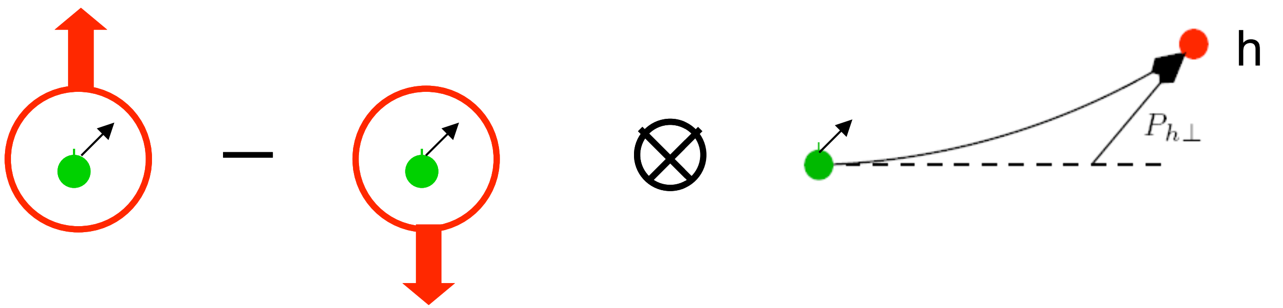


[angle and moments definitions according to Trento conventions]

$$A^h_{UT}(\phi,\phi_S) = \frac{1}{|S_T|}\frac{N^\uparrow_h(\phi,\phi_S) - N^\downarrow_h(\phi,\phi_S)}{N^\uparrow_h(\phi,\phi_S) + N^\downarrow_h(\phi,\phi_S)} =$$

Collins moment

$$\propto \ldots \sin(\phi+\phi_S)\cdot\frac{\sum_q e_q^2\, I\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]}{\sum_q e_q^2\, f_1(x)\cdot D_1^q(z)}$$



Spares

Spares