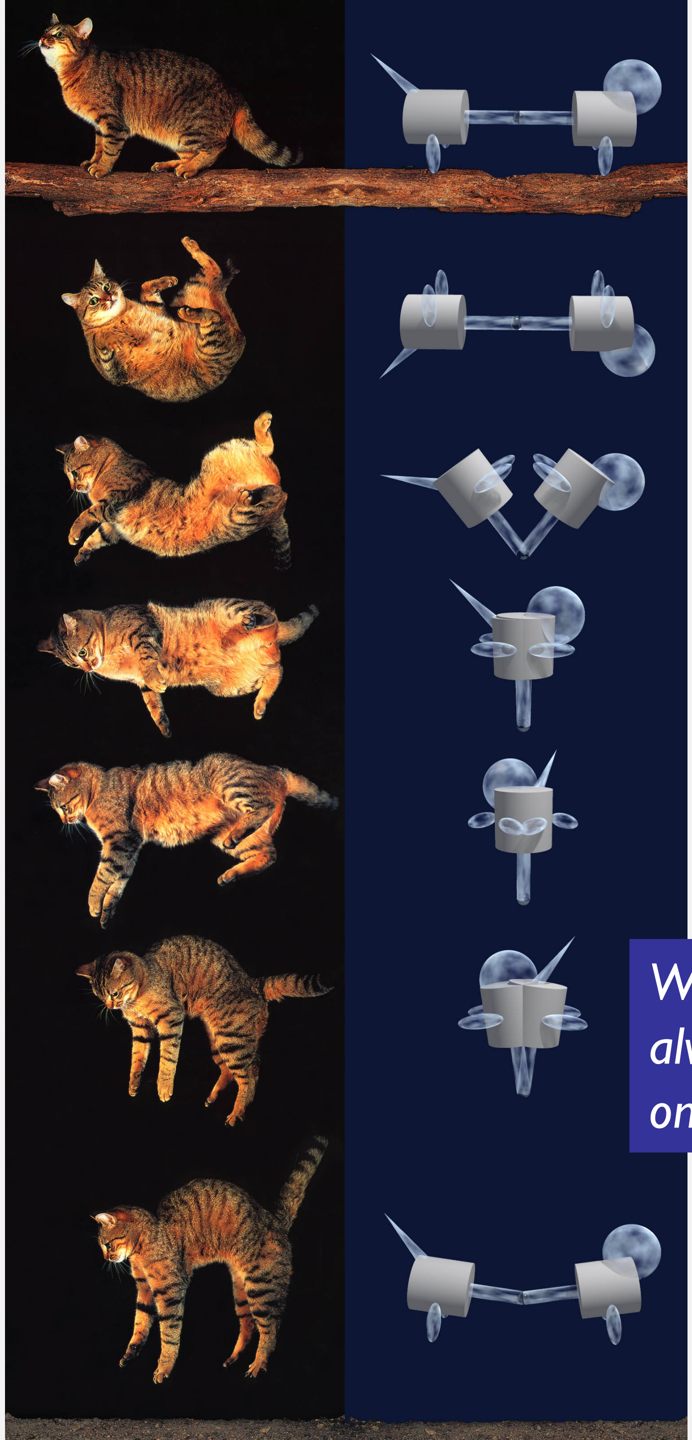
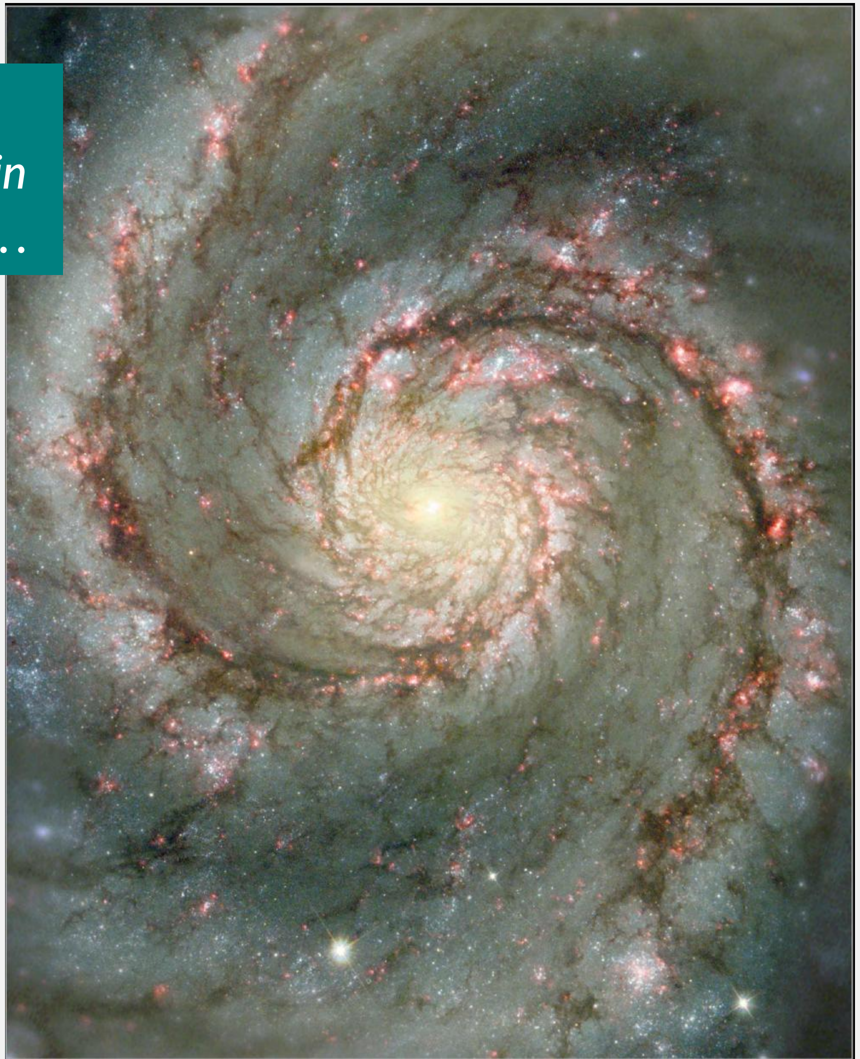
SPIN IS EVERYWHERE…



Why do cats always land on their feet?

Evidence for dark matter in the universe…



SPIN IN QUANTUM MECHANICS……

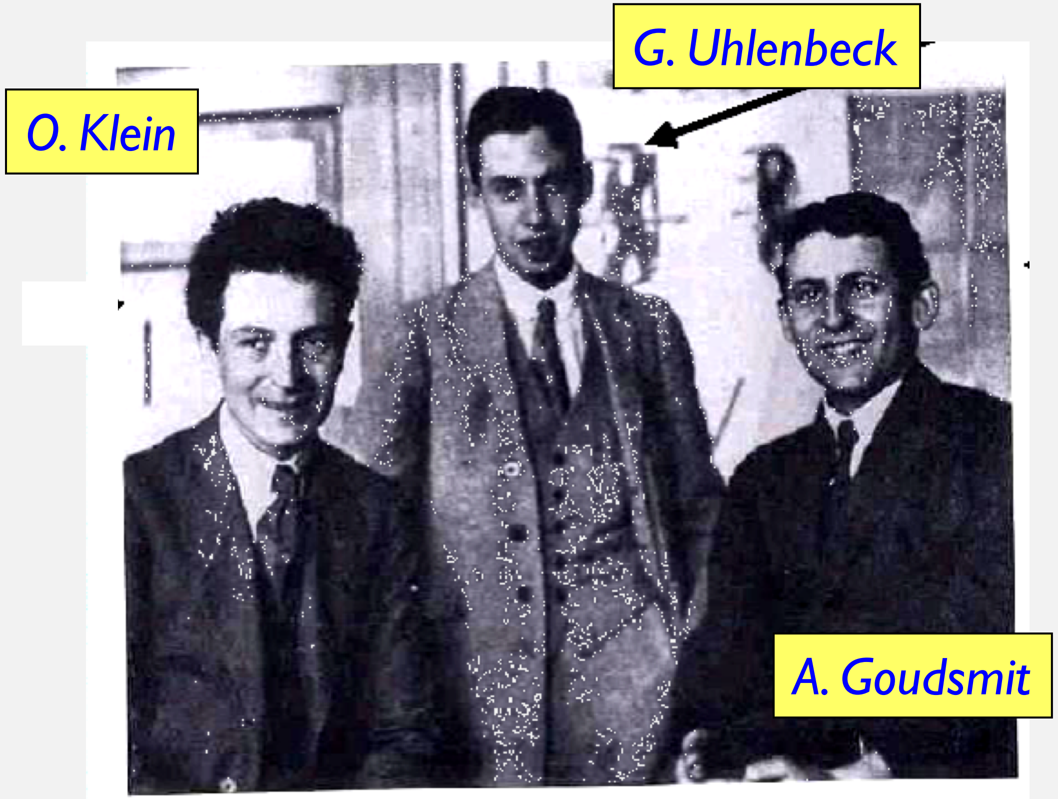
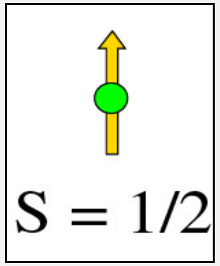


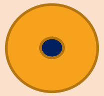
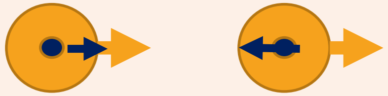
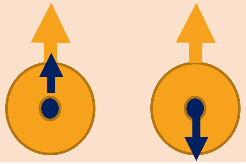
Figure 2.2 Oscar Klein (1894–1977), George E. Uhlenbeck (1900–1988), and Samuel A. Goudsmit (1902–1978), 1926. [Photograph by H. Kraus. Courtesy of AIP Emilio Segrè Visual Archives]

P. Ehrenfest (1925):
"This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything making a stupid mistake."

…. spin as a fundamental property of elementary particles:

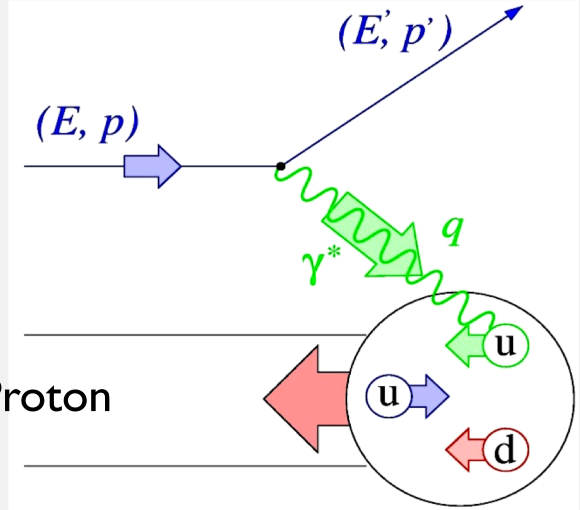


ON TO POLARIZED PDFs

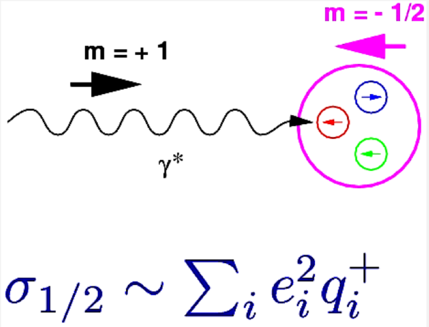
Proton Polarization → Quark Polarization ↓	Unpolarized	Longitudinal	Transverse
Unpolarized	f(x) 		
Longitudinal		g(x) 	
Transverse			h(x) 

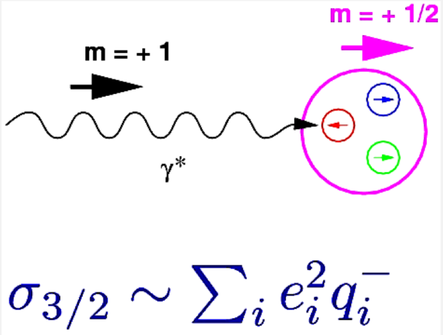
PROBES TO STUDY POLARIZED PROTON STRUCTURE

Inclusive polarized deep inelastic scattering (DIS)



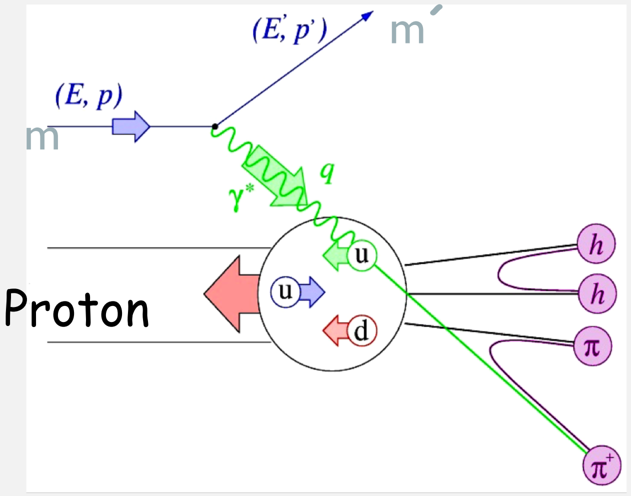
Proton



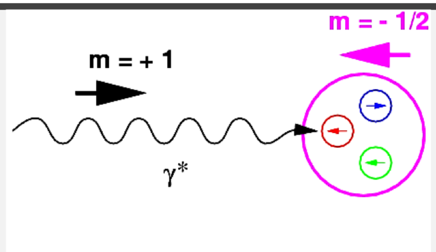


PROBES TO STUDY POLARIZED PROTON STRUCTURE

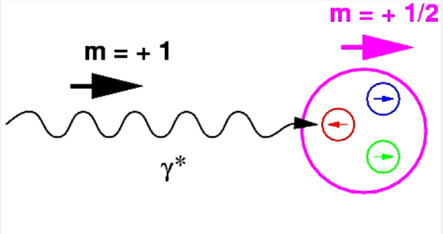
Semi-Inclusive polarized deep inelastic scattering (DIS)



Fragmentation Process:
Outgoing quark forms hadrons

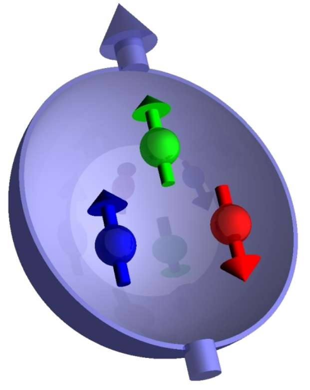


$\sigma_{1/2} \sim \sum_i e_i^2 q_i^+$

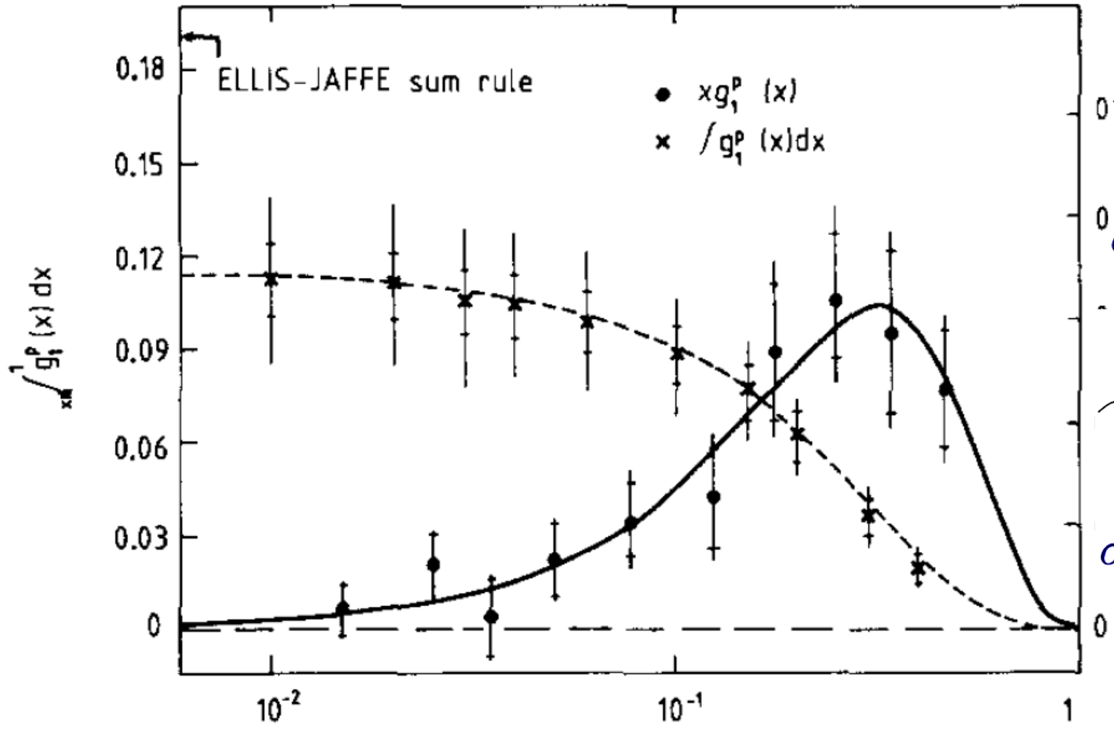


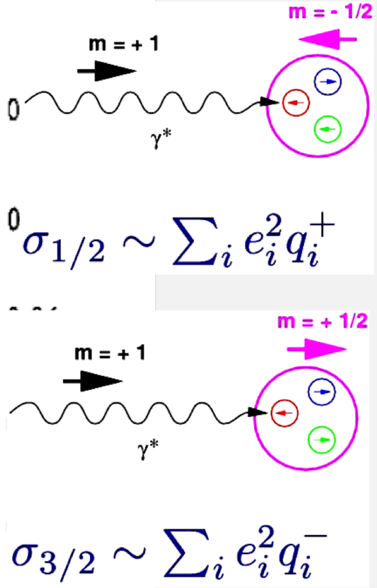
$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$

TEST OF THE SIMPLE (NON RELATIVISITIC QUARK) MODEL



Δs





EMC "Spin Crisis", or "Spin Puzzle"!

x

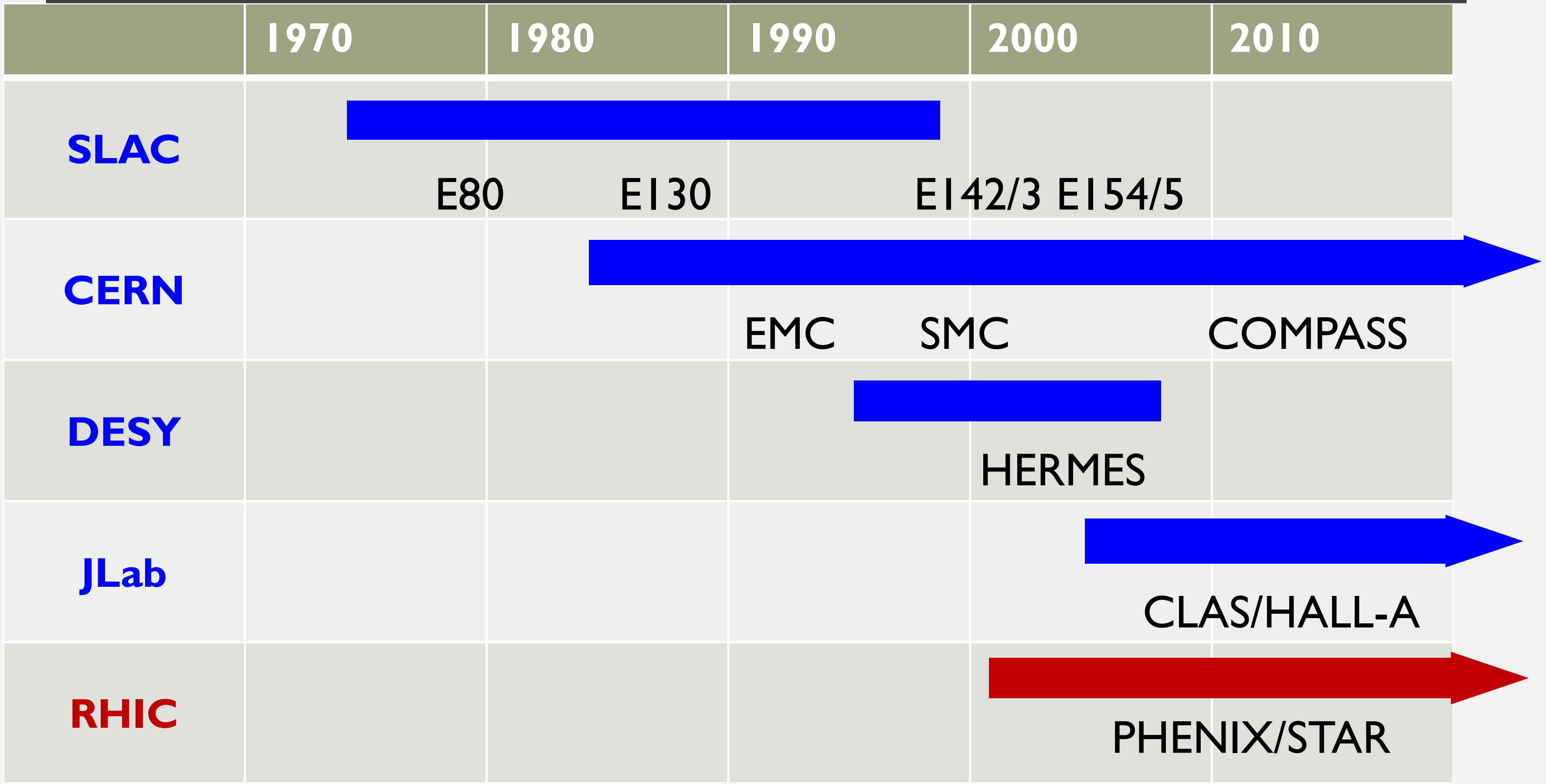
EMC, Phys. Lett. B206,2,364 1988

Compare with Expectation from SU(6) wavefunction ΔΣ=1
(But relativistic expectation is 0.7 and later measurements found ~0.3)

Spin kills more theories that any other observable!

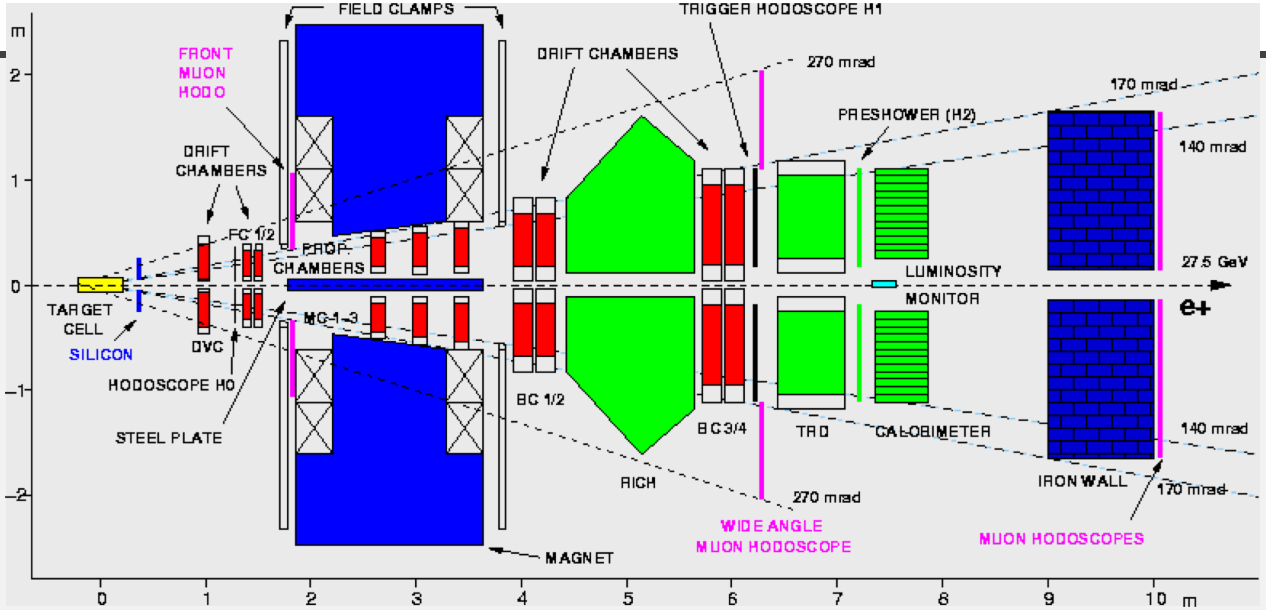
POLARIZED EXPERIMENTS

Polarized lp
Polarized pp



EIC the next big machine to measure polarized PDFs

HERMES



Beam: 27.5 GeV $e^{\pm}$; <50>% polarization

Target: polarized gas targets H, D, <85%> He^3 <50%> polarization

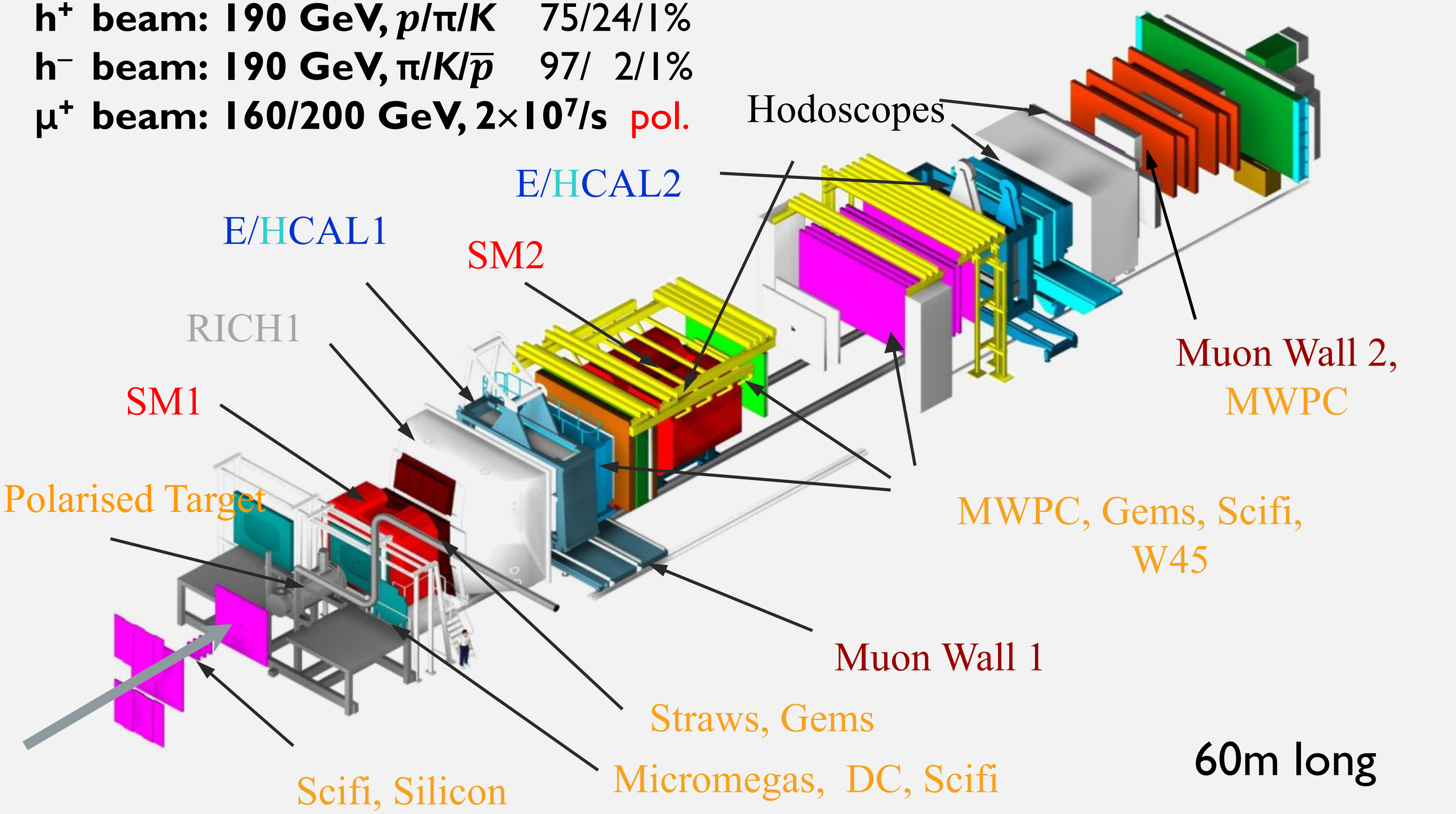
unpolarised gas targets H_2 to Xenon

Lumi: pol: 5×10^{31} cm^{-2}/s^{-1}; unpol: $3 \times 10^{32-33}$ cm^{-2}/s^{-1}

Data taking finished June 2007

COMPASS SPECTROMETER

h⁺ beam: 190 GeV, *p*/π/*K* 75/24/1%
h⁻ beam: 190 GeV, π/*K*/$\bar{p}$ 97/ 2/1%
μ⁺ beam: 160/200 GeV, 2×10⁷/s pol.



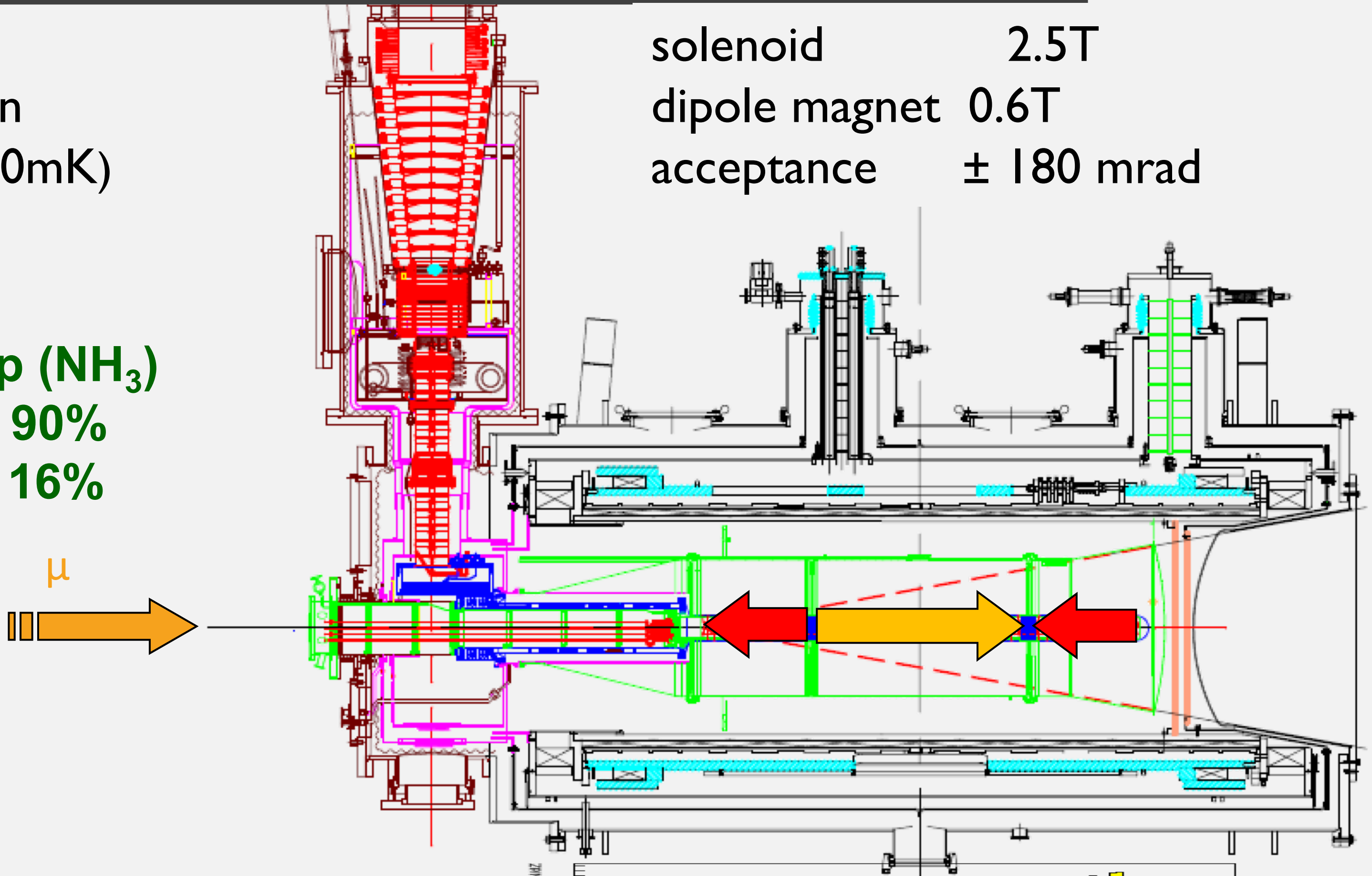
60m long

POLARIZED TARGET SYSTEM

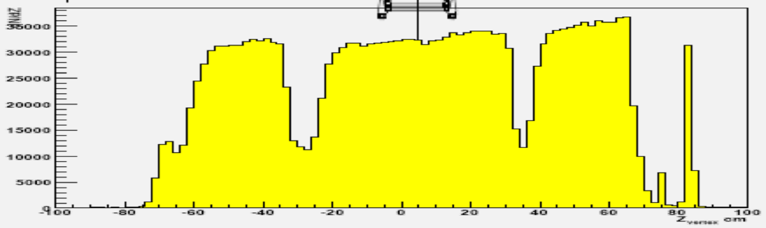
$^3He - ^4He$ dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad

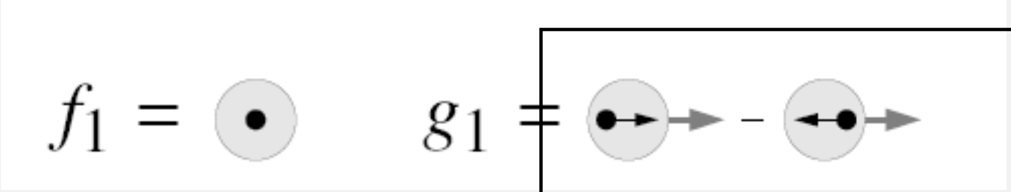
	d (^6LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%



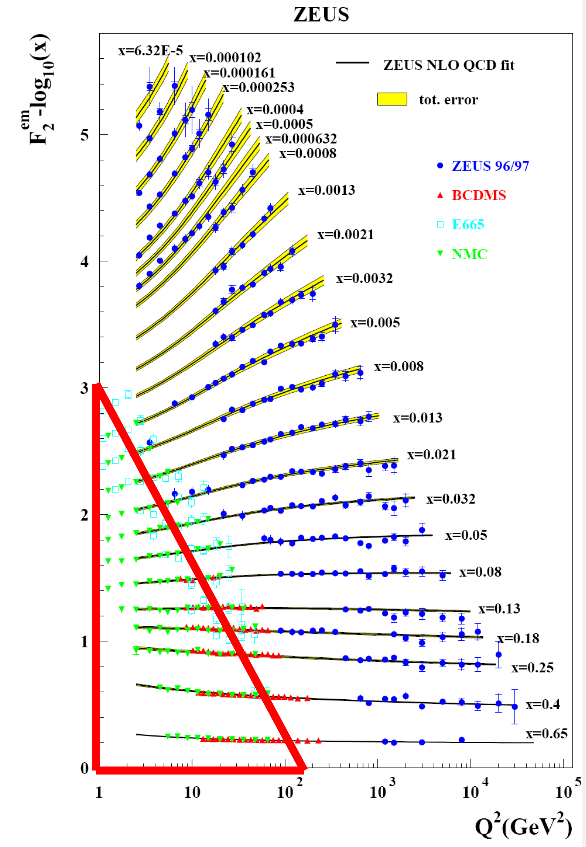
Reconstructed interaction vertices



World Data on g_1



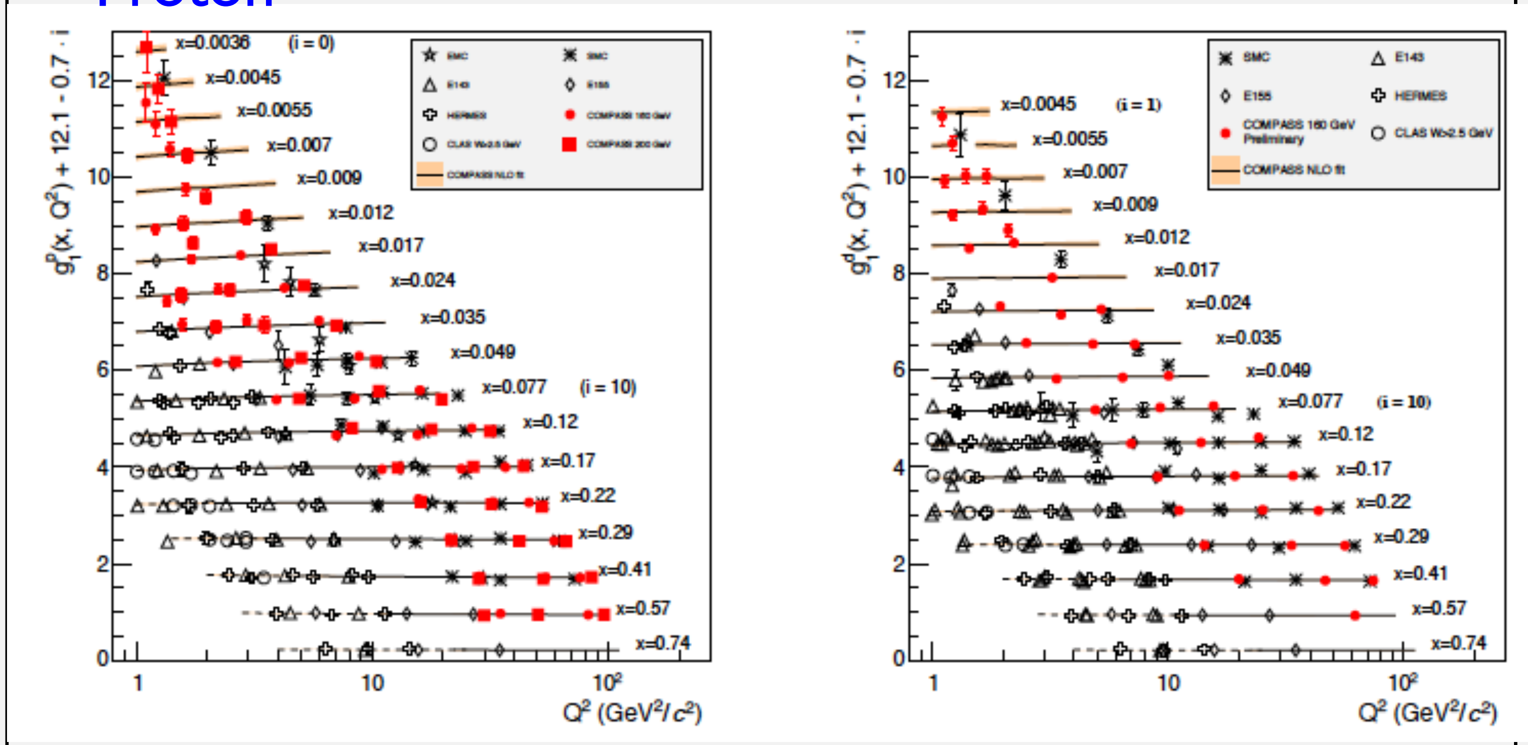
Unpolarized



$$F_2 \propto \sum_q x e_q^2 f_1^q$$

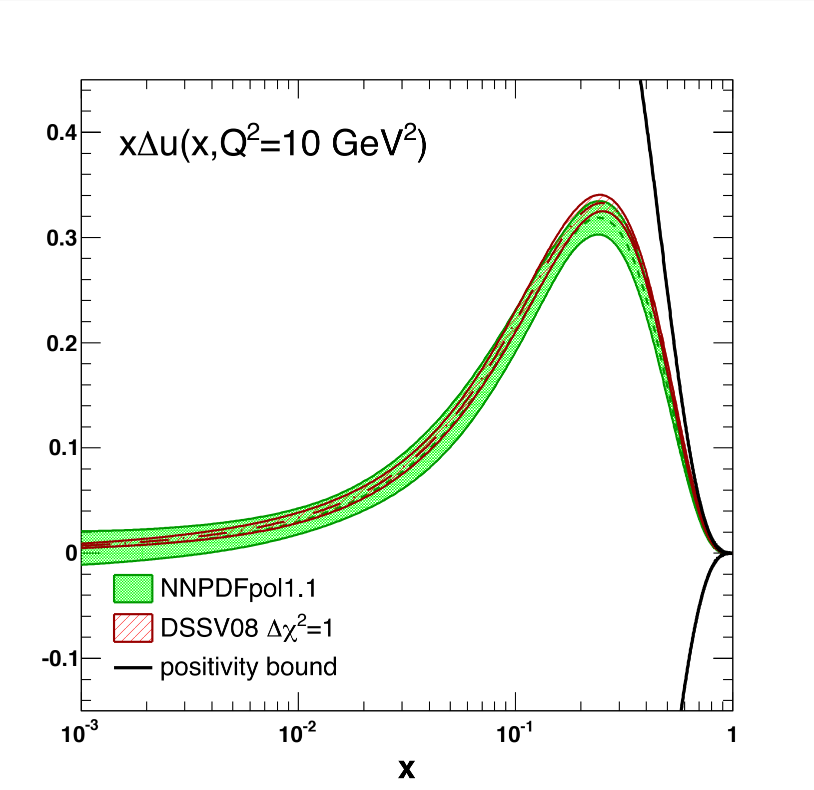
Proton

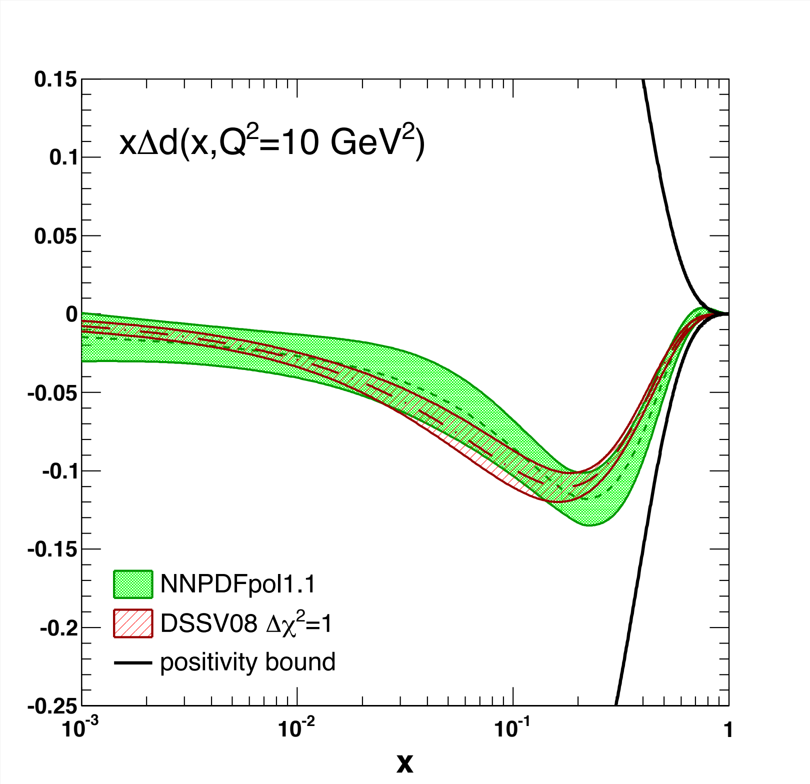
Deuterium



$$g_1 \propto \sum_q e_q^2 g_1^q$$

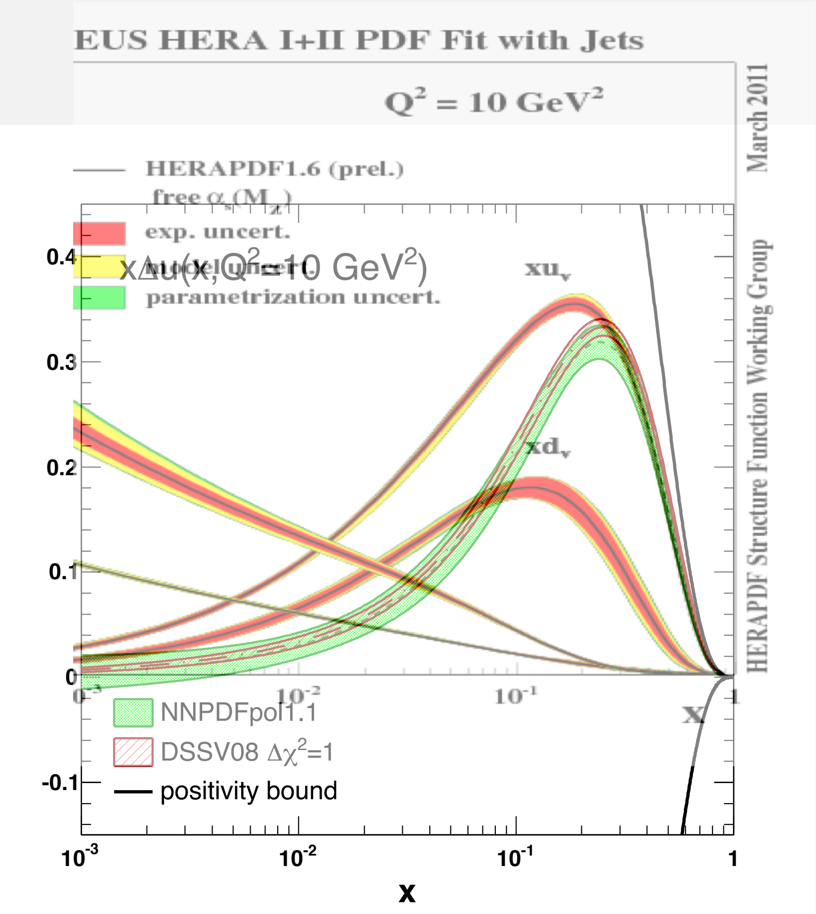
EXTRACTED HELICITY PDFS (NNPDF/DSSV)

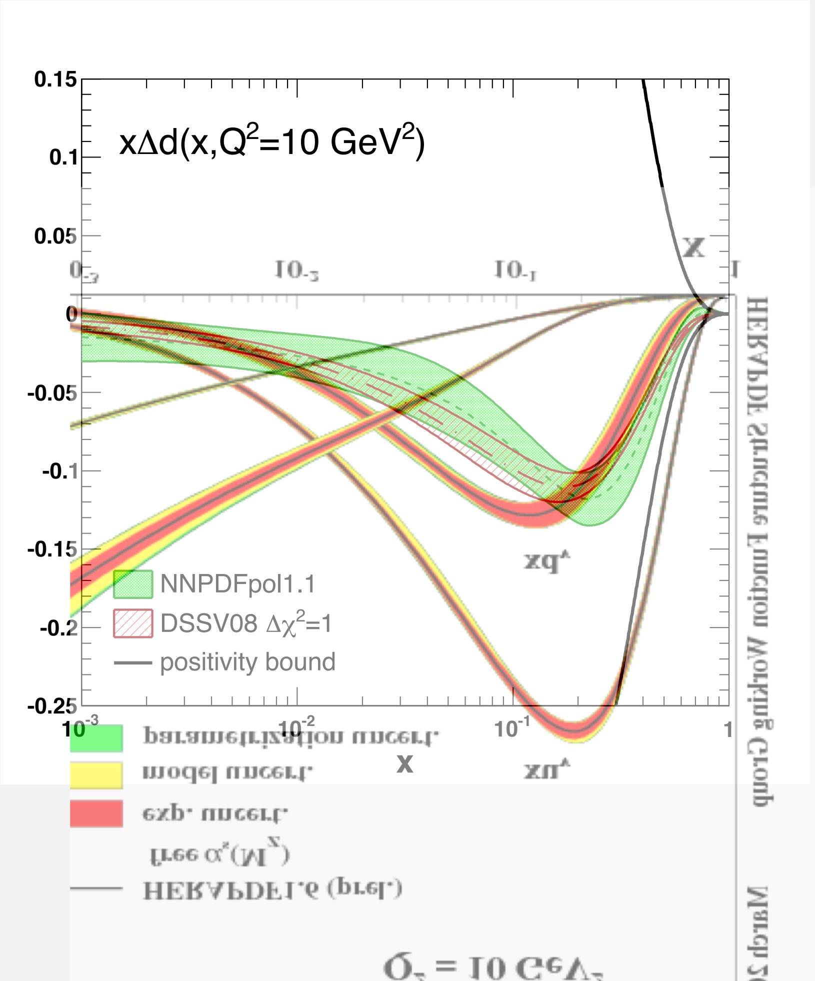




- NNPDF: Neural networks
- DSSV: parametrized

EXTRACTED HELICITY PDFS (NNPDF/DSSV)

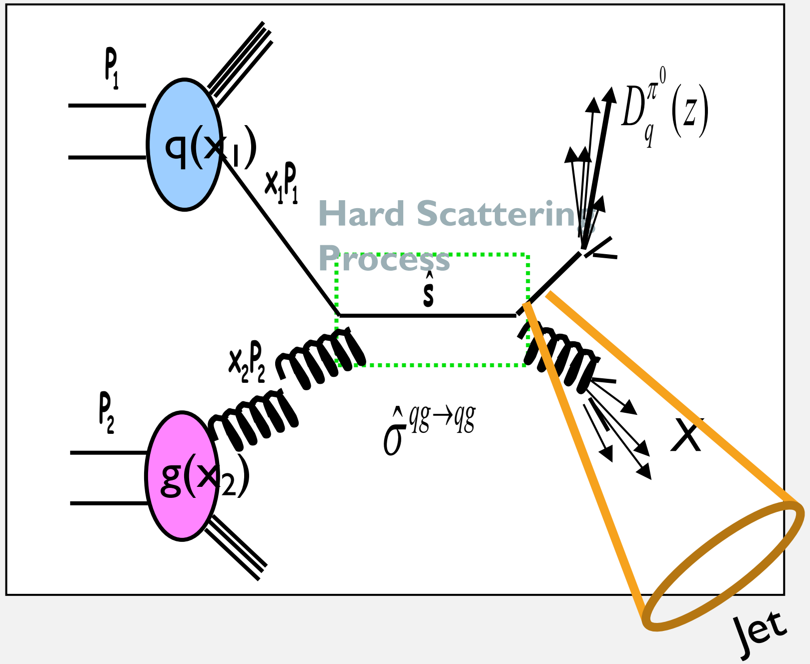




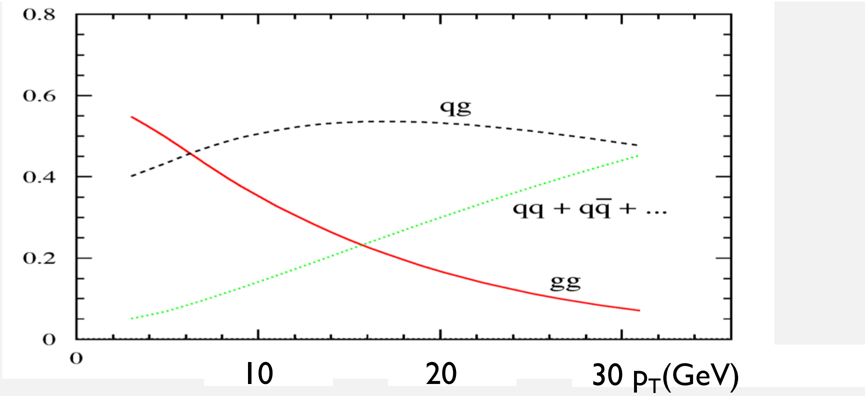
- NNPDF: Neural networks
- DSSV: parametrized

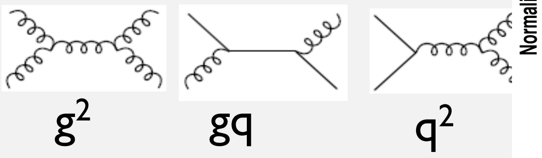
DIRECT ACCESS TO GLUON POLARIZATION AT PP COLLIDERS

- Game changers RHIC and LHC
  - No direct access to x,Q^2 but global fits can make use of results that access different Q^2/x regions
  - Jet p_T sets hard scale

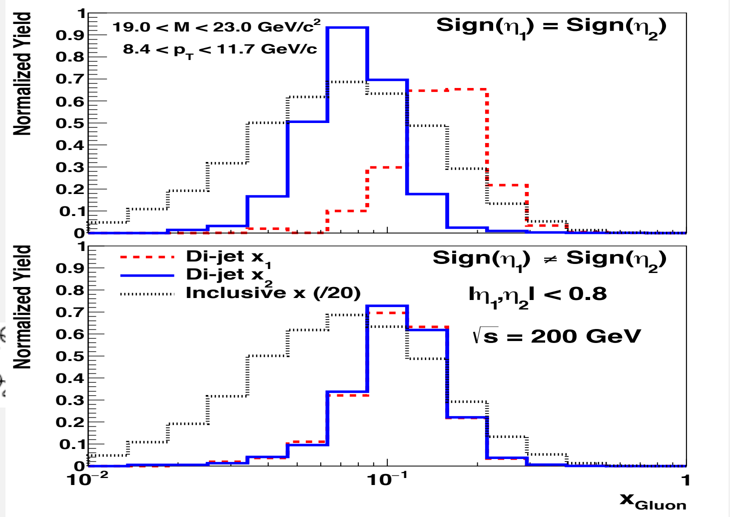


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}$$



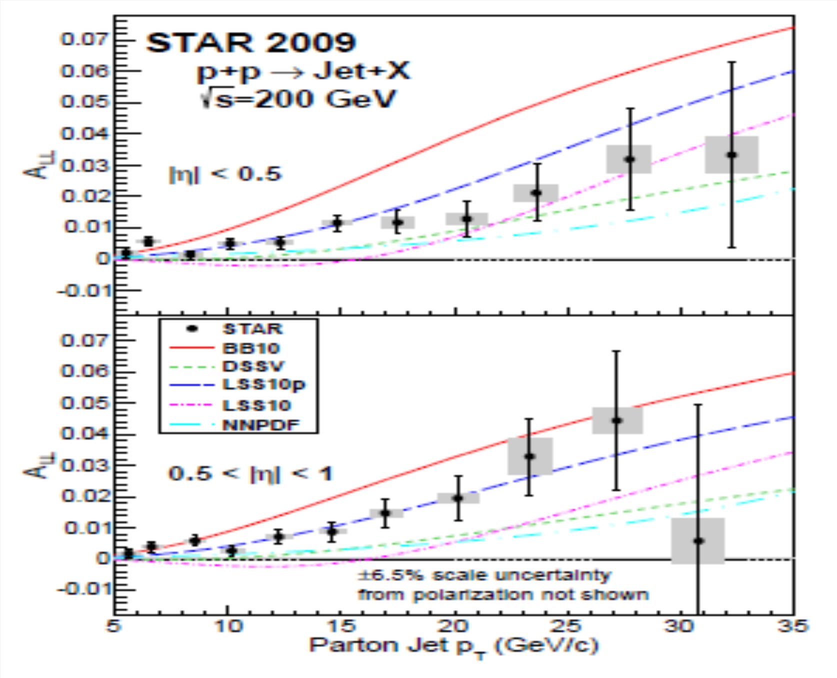


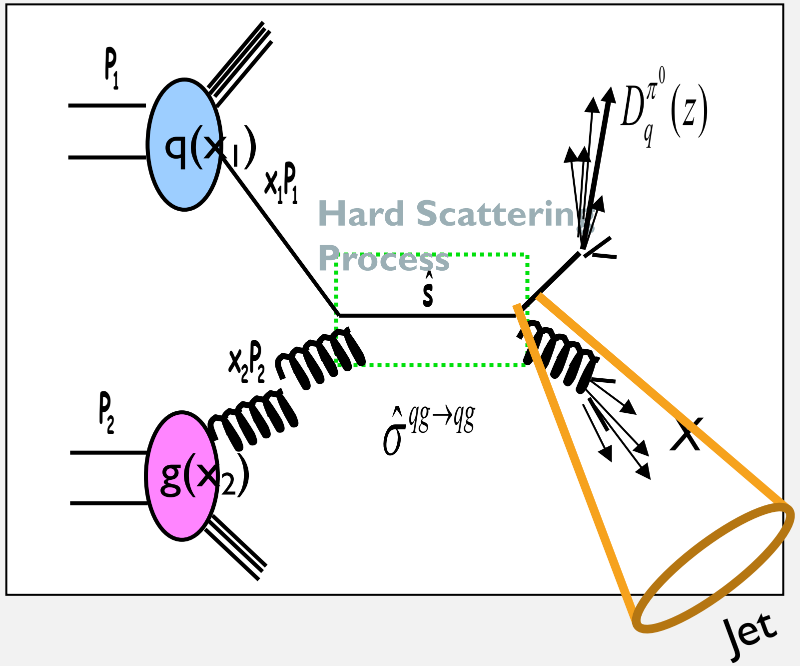
Dominates at RHIC



STAR dijets @200GeV

INDICATION OF NON-ZERO GLUON POLARIZATION FROM STAR JETS





$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}$$

And consistent with Phenix π^0 asymmetries

PRESS INTEREST IN NONZERO GLUON SPIN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Proton Spin Mystery Gains a New Clue

Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

Jul 21, 2014 | By Clara Moskowitz

Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987

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Gluons get in on proton spin

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Synopsis: Gluons Chip in for Proton Spin

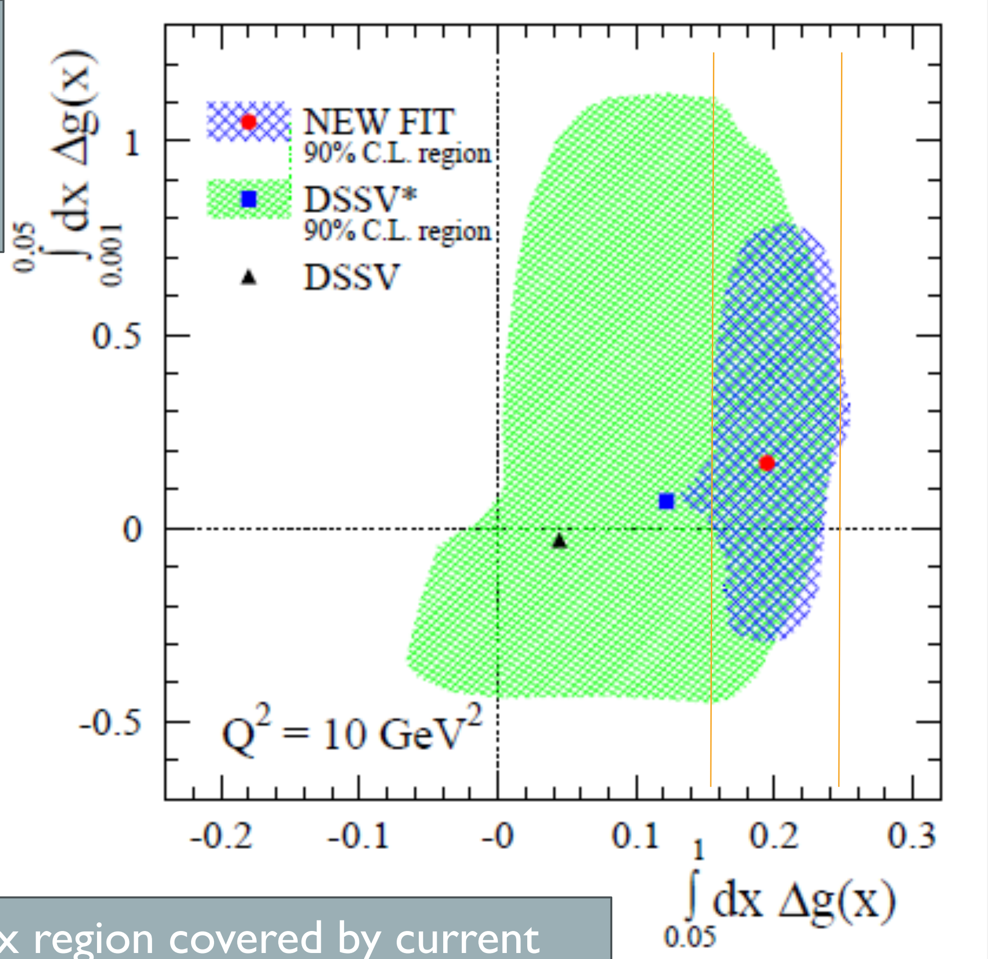
Evidence for Polarization of Gluons in the Proton

Daniel de Florian, Rodolfo Sassot, Marco Stratmann, and Werner Vogelsang

Phys. Rev. Lett. 113, 012001 (2014)

Published July 2, 2014

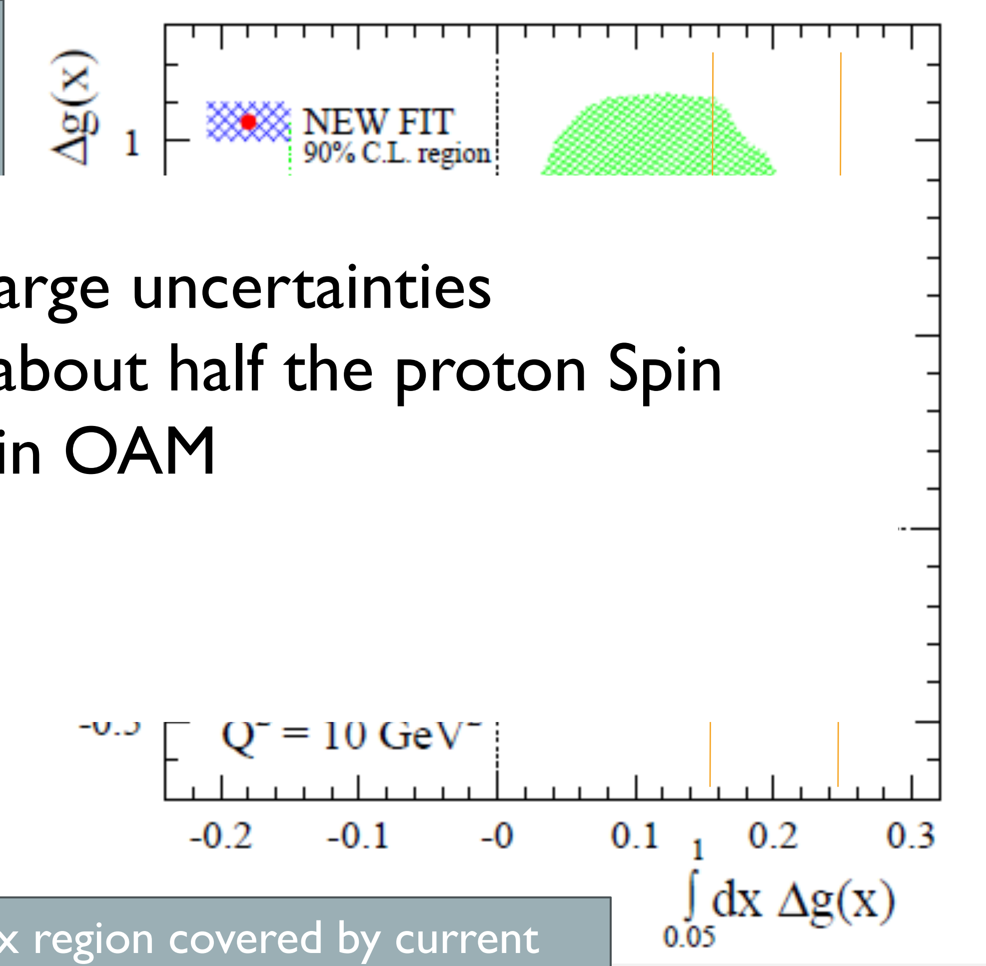
Low x, not covered so far →more forward pp, EIC



x region covered by current RHIC and DIS results

PRESS INTEREST IN NONZERO GLUON SPIN

Low x, not covered so far
→more forward



Experimental ΔG~0.2 with large uncertainties
→Quark and Gluon helicities make about half the proton Spin
→Remaining part in OAM

x region covered by current RHIC and DIS results

PRESS INTEREST IN NONZERO GLUON SPIN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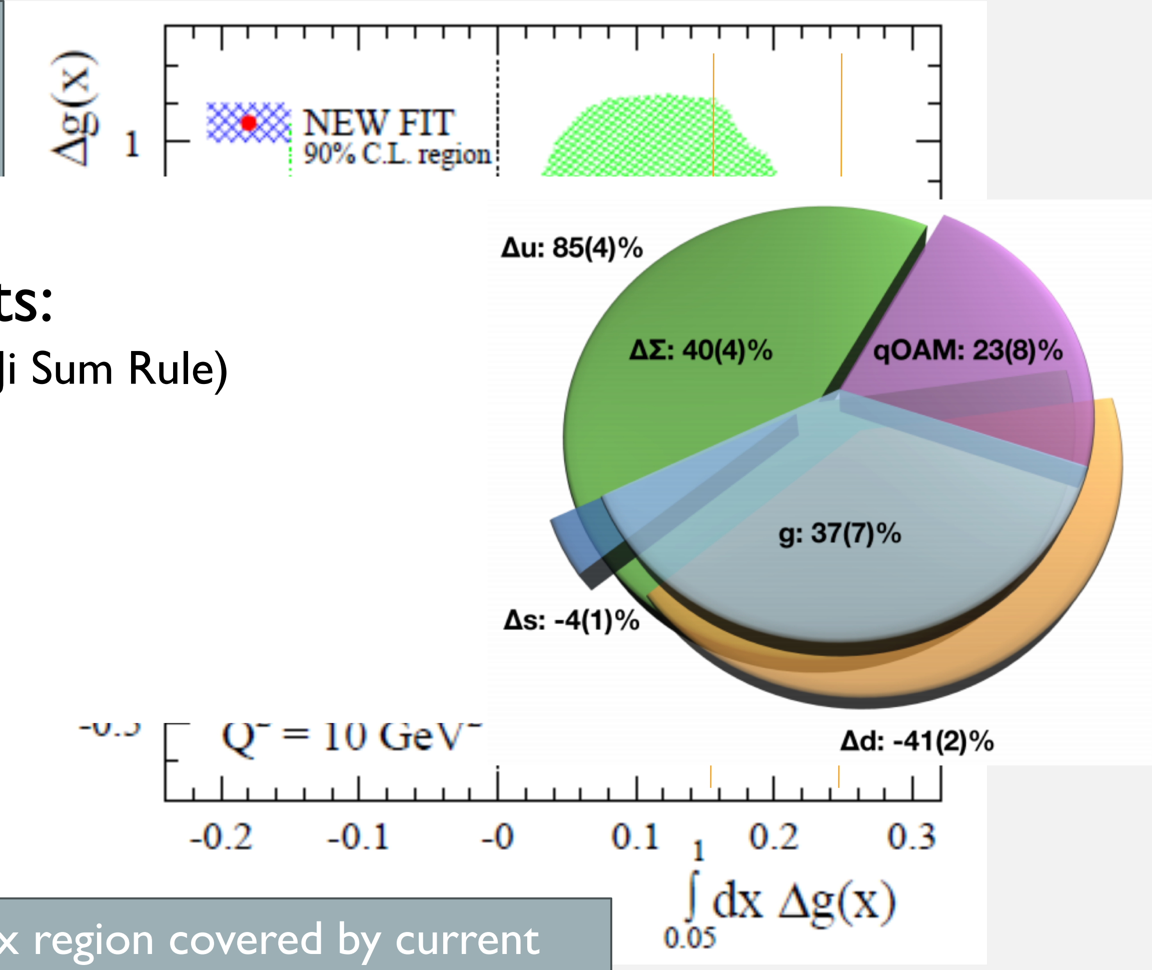
Physicists long assumed a proton's spin came from its three constituent quarks. New

Low x, not covered so far →more forward



Lattice results:

(Keh-Fei Liu at CIPANP18, Ji Sum Rule)

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Synopsis: Gluons Chip in for Proton Spin

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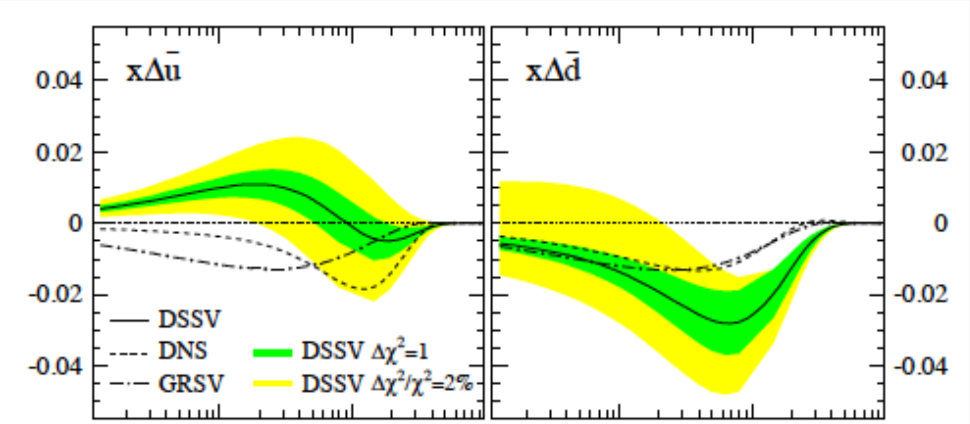
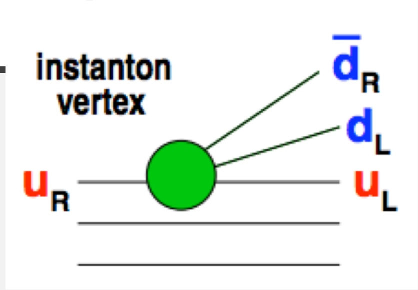
x region covered by current RHIC and DIS results

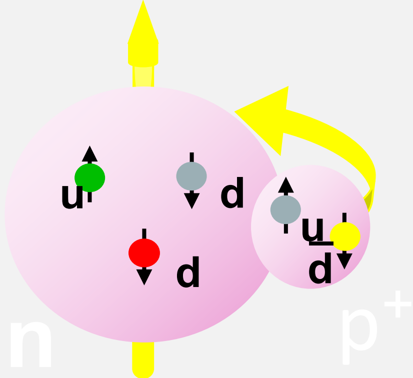
WHAT ABOUT THE SEA?

- Asymmetry in unpolarized sea quark distributions, what about polarized sea?
- Different models give different predictions, e.g. **pion cloud** $\boldsymbol{\Delta\bar{u} = \Delta\bar{d} = 0}$ (unpolarized pions), **instanton model** $\boldsymbol{\Delta\bar{u} > \Delta\bar{d}}$ since sea quark polarizations are transferred from valence quarks when they scatter with instantons

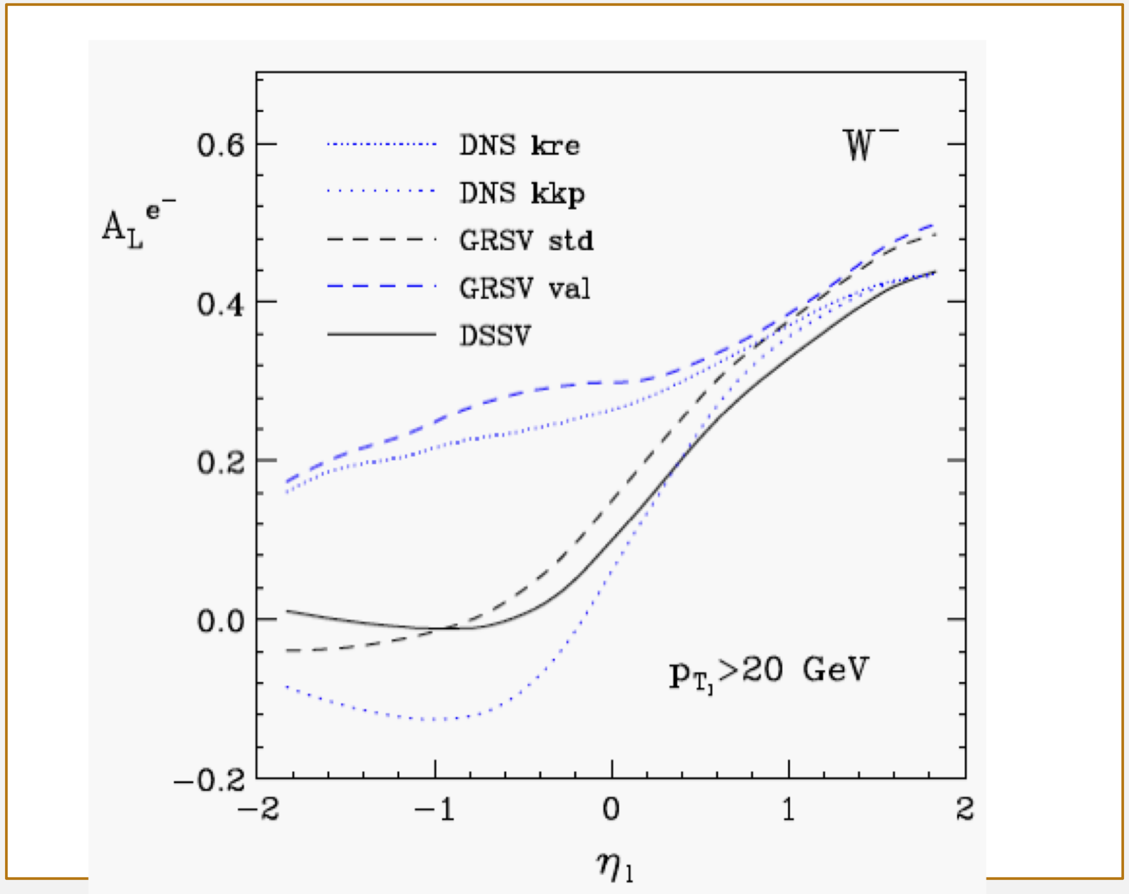


Phys.Rev.Lett. 101 (2008) 07200





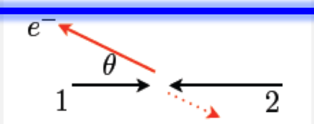
W PRODUCTION IN POLARIZED PP SCATTERING



$\hat{t}^2 \simeq (1+\cos\theta)^2$ $\qquad$ $\hat{u}^2 \simeq (1-\cos\theta)^2$

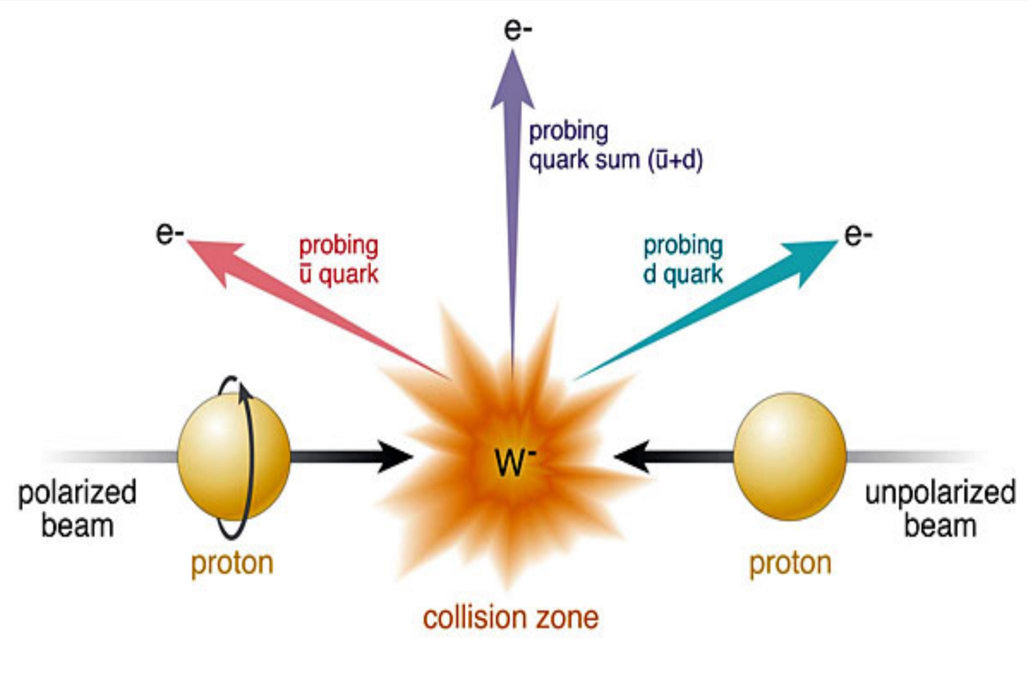
forward

x_1 small
t large

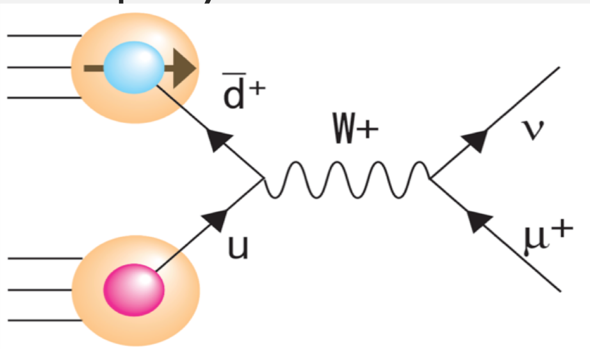


x_1 large
u large

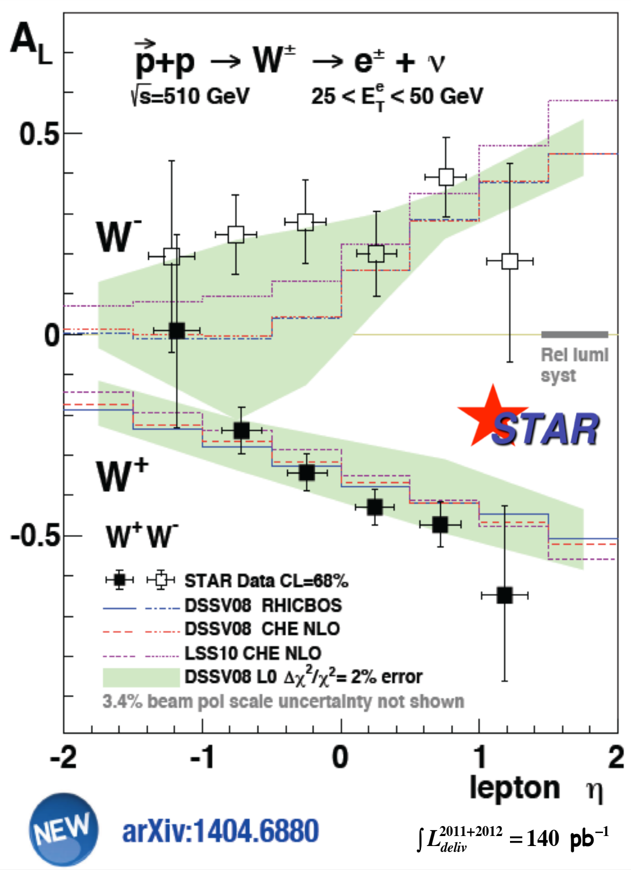
$$\Delta\bar{u}(x_1)d(x_2)(\hat{t}^2)+\Delta d(x_1)\bar{u}(x_2)(-\hat{u}^2)$$

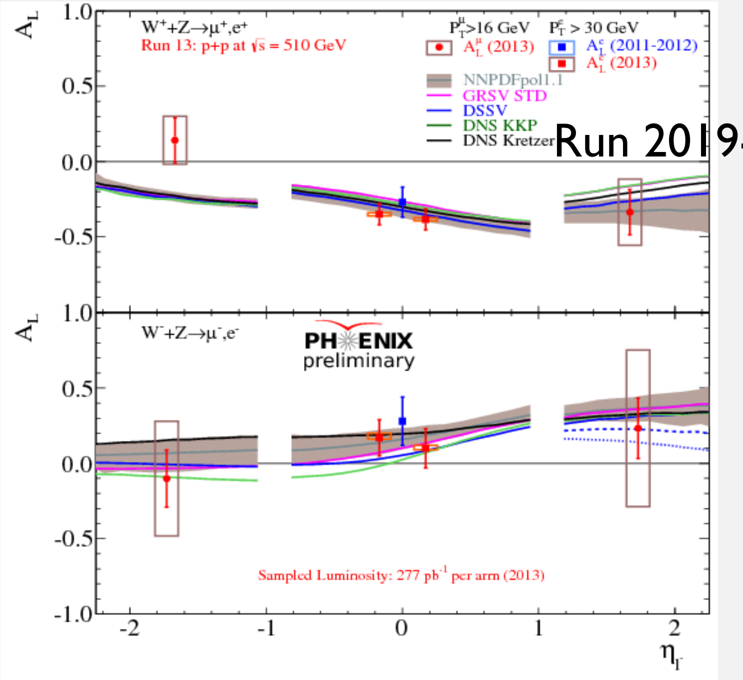


- Maximum parity violating: only couple to one polarization
- Select flavor
- Rapidity selects x

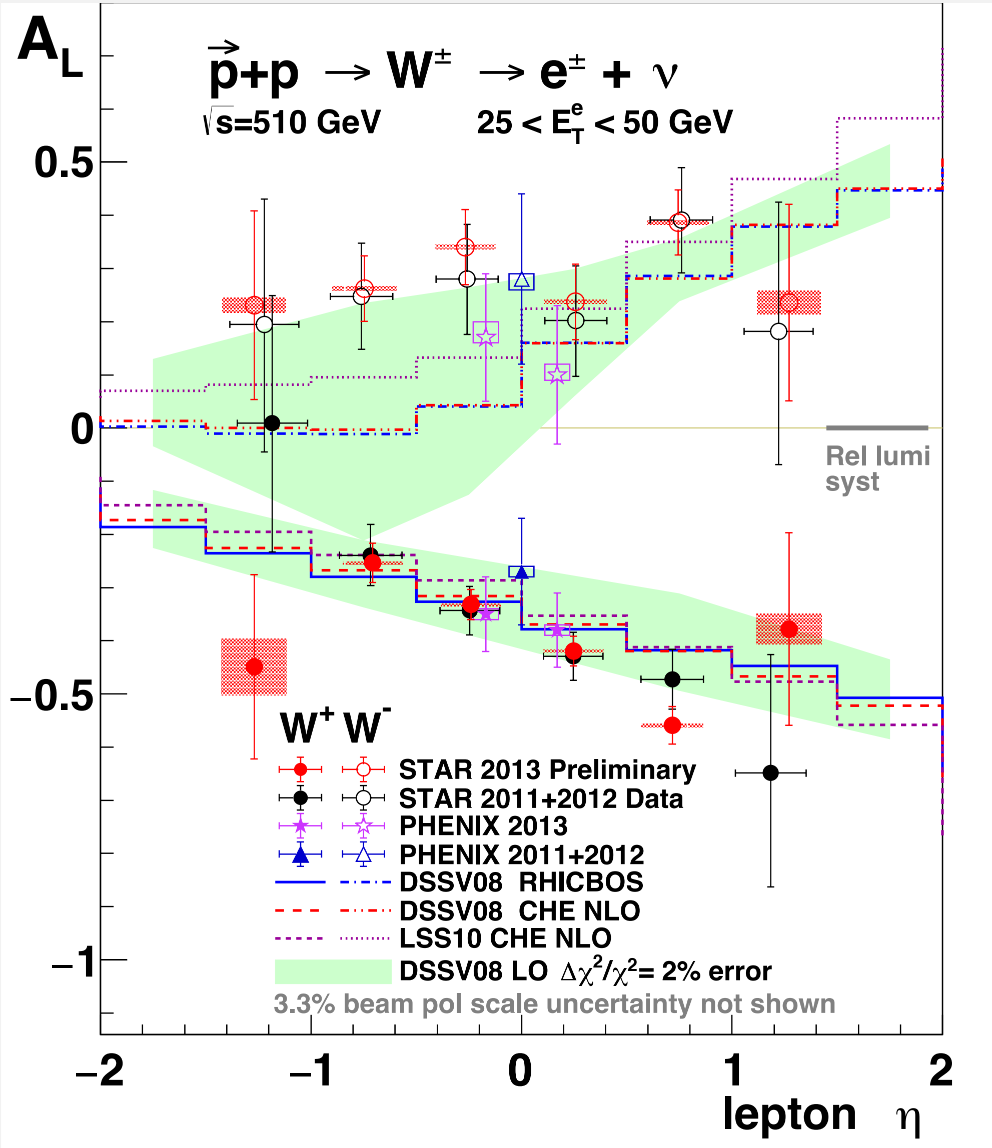


PHENIX/STAR RESULTS

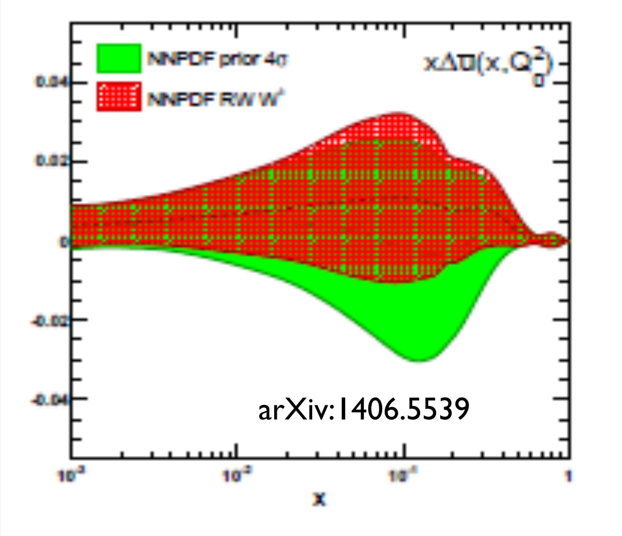




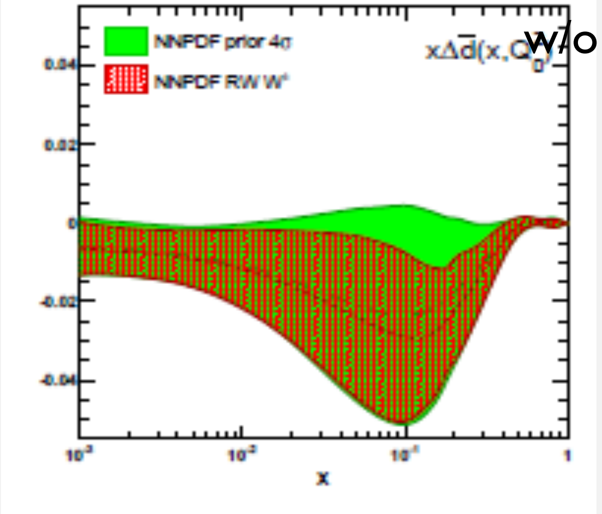
Run 2019-2013



$\Delta\bar{u}$



$\Delta\bar{d}$

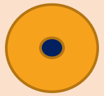
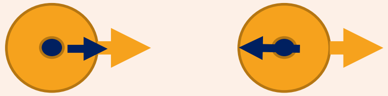
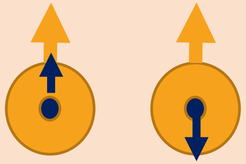


w/o STAR 2013 prelim

Future:

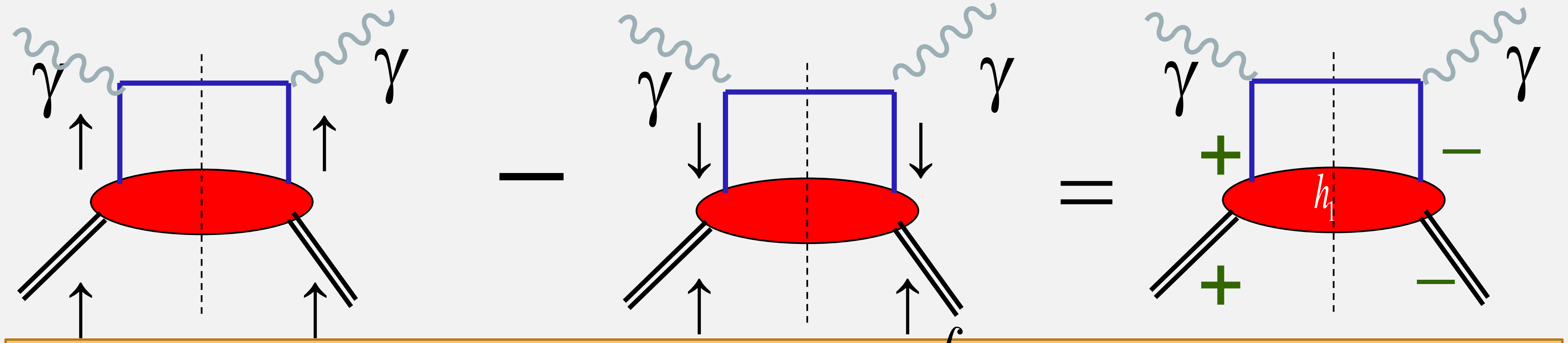
- More STAR data points
- Polarized seaquest

Transversity

Proton Polarization → Quark Polarization ↓	Unpolarized	Longitudinal	Transverse
Unpolarized	f(x) 		
Longitudinal		g(x) 	
Transverse			h(x) 

TRANSVERSITY IS CHIRAL ODD

- Transversity base:



Only Way to access tensor charge: $\langle|\sigma^{\mu\nu}|\rangle = \int dx(h_q(x) - h_{\bar{q}}(x)) = gT$

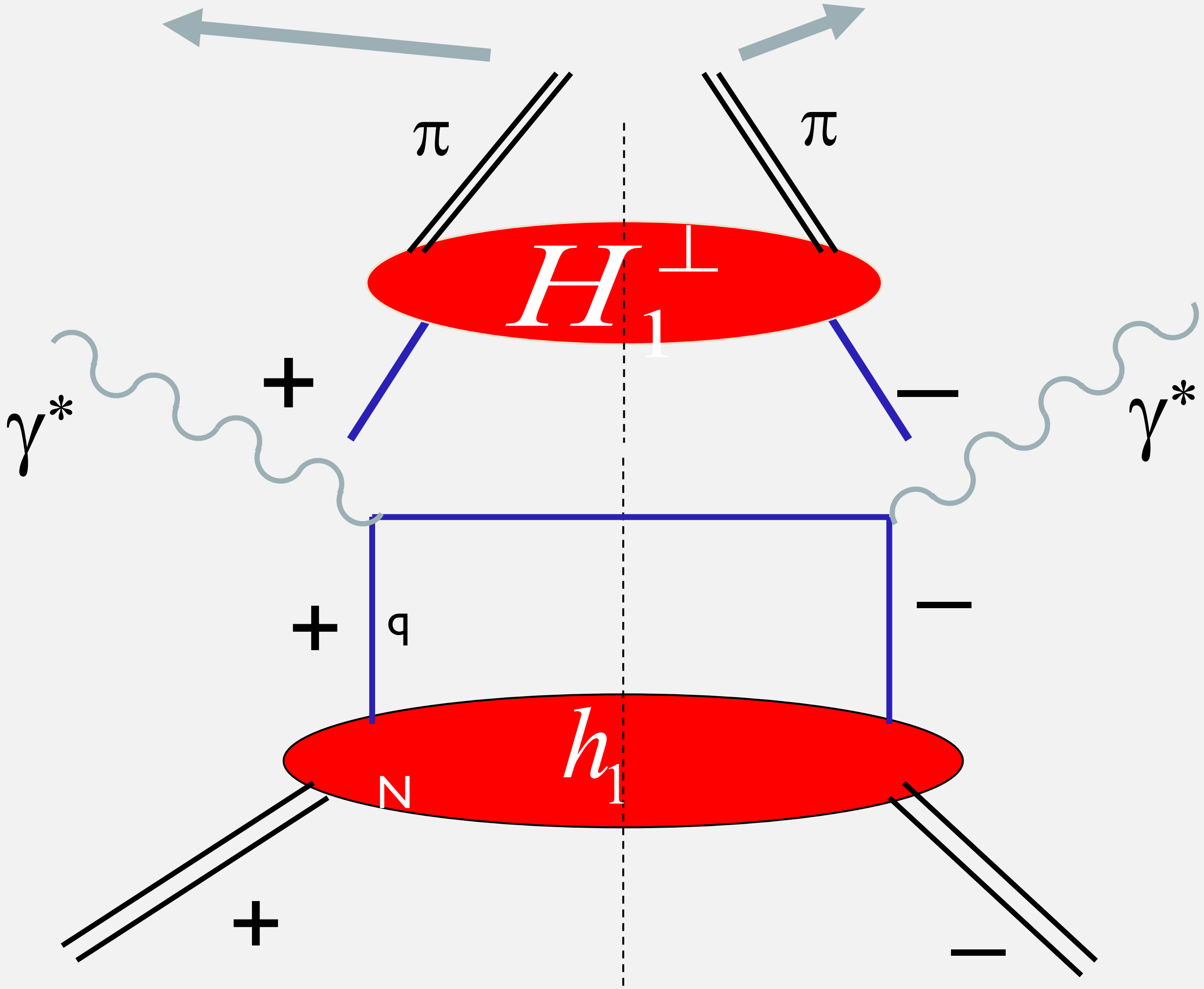
- **Appears in potential tensor coupling to new physics**
- **Tensor charge g_T can come from lattice and experiment**
- Allows first order calculations connection to experiment
- **But:**

•**Helicity base**: chiral odd

- Helicity flip needed
- **Amplitude heavily suppressed in QCD**

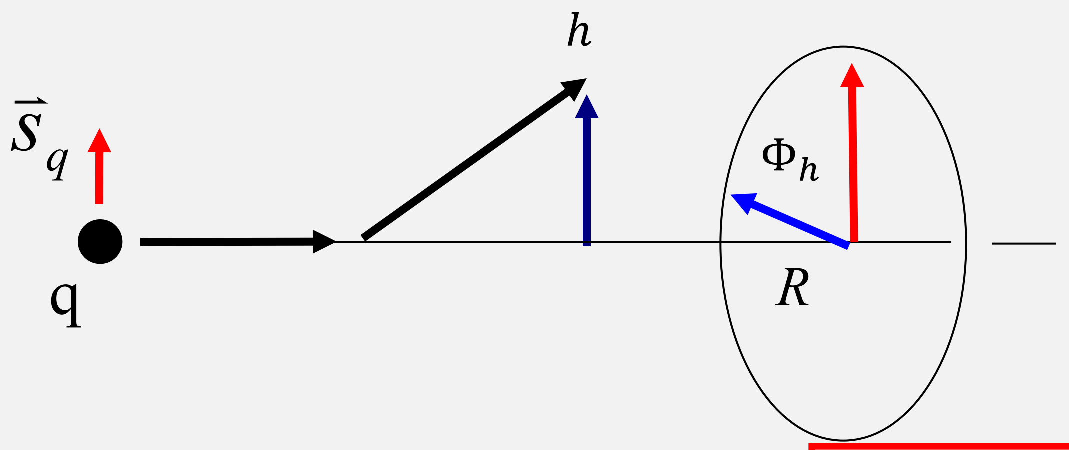
CHIRAL ODD FRAGMENTATION FUNCTIONS

Collins effect



$H_1^\perp$: **Collins FF**

Quark Polarimetry with Collins FF in Quark Fragmentation



$\vec{k}$: quark momentum
$\vec{s}_q$: quark spin
$\vec{p}_{h\perp}$: transv. hadron momentum
$z = 2E_h/\sqrt{s}$: relative hadron pair momentum

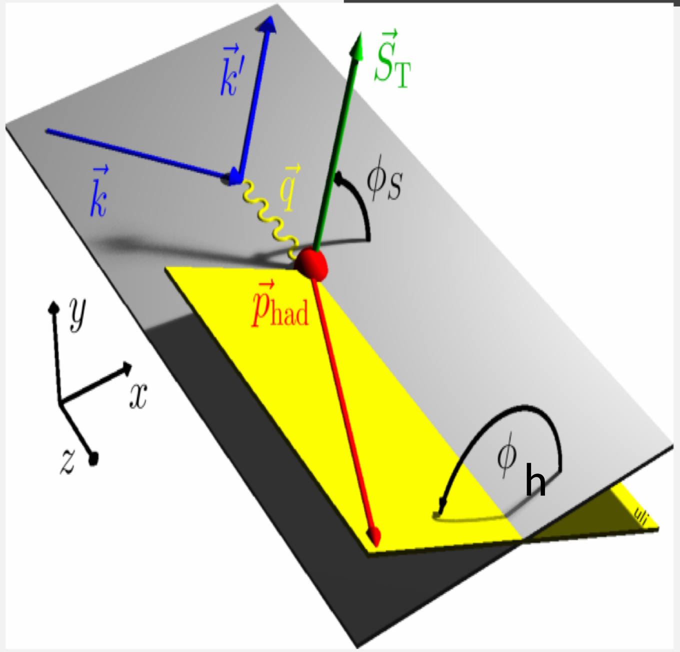
Collins Fragmentation Function:
Fragmentation of a transversely polarized quark *q* into a spin-less hadron *h* carries an azimuthal dependence:

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

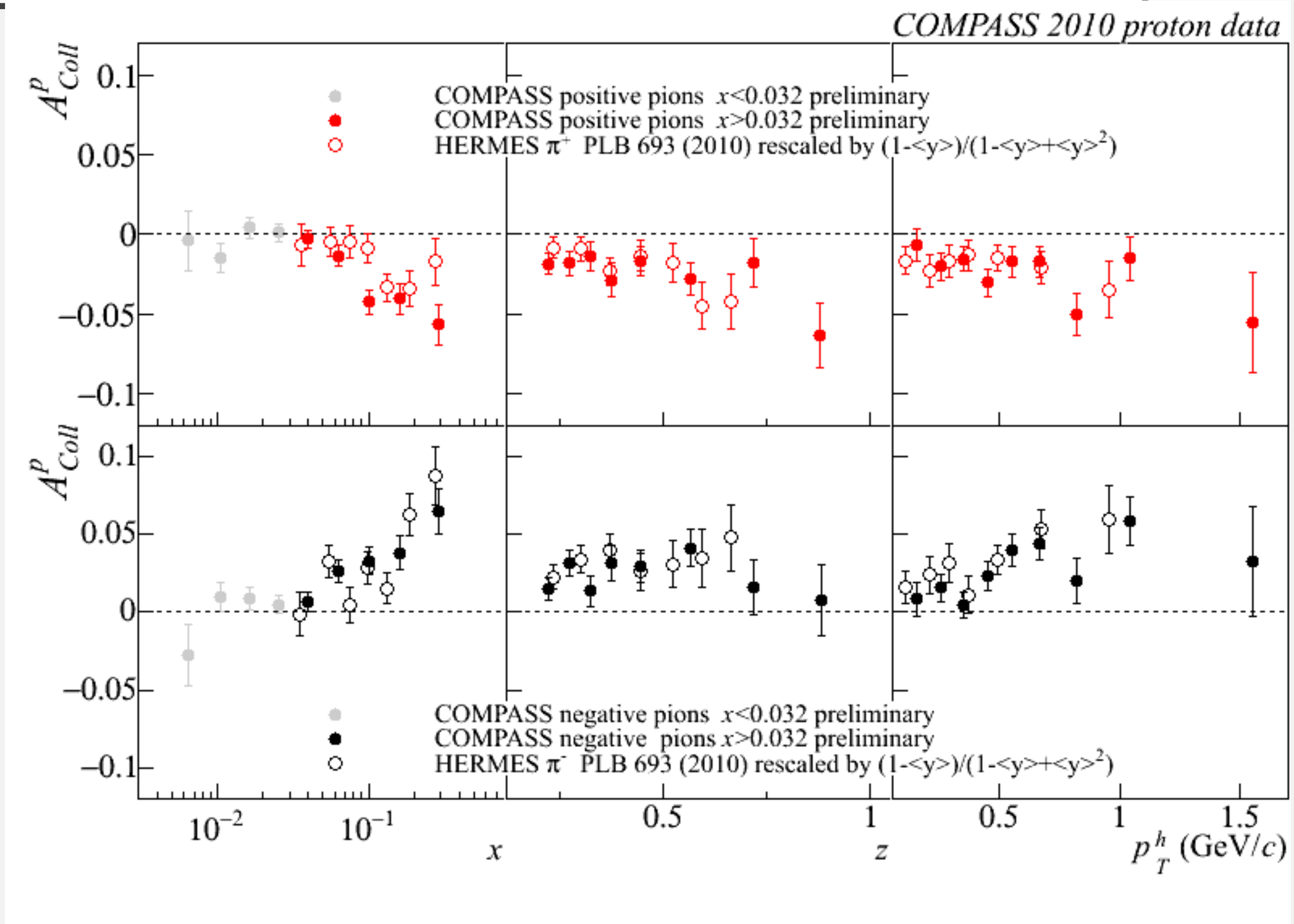
$$\propto \sin \Phi_h$$

Strength of correlation a priori unknown:
Needs independent measurement!

TRANSVERSITY: $A_{COLL} \propto H_1^{\perp} \otimes H_1^{\perp}$

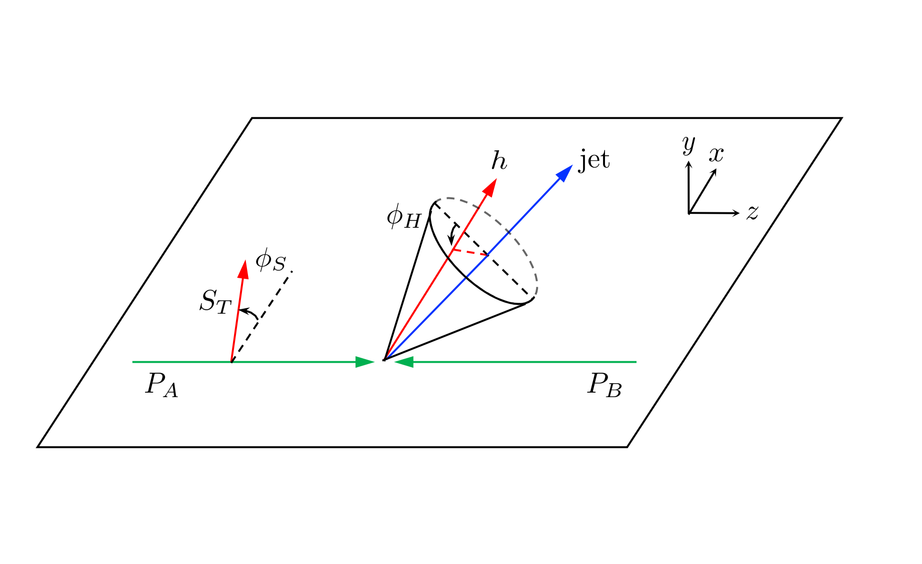


$\sigma \propto 1 + A_{Coll}\cos(\phi_h + \phi_S)$



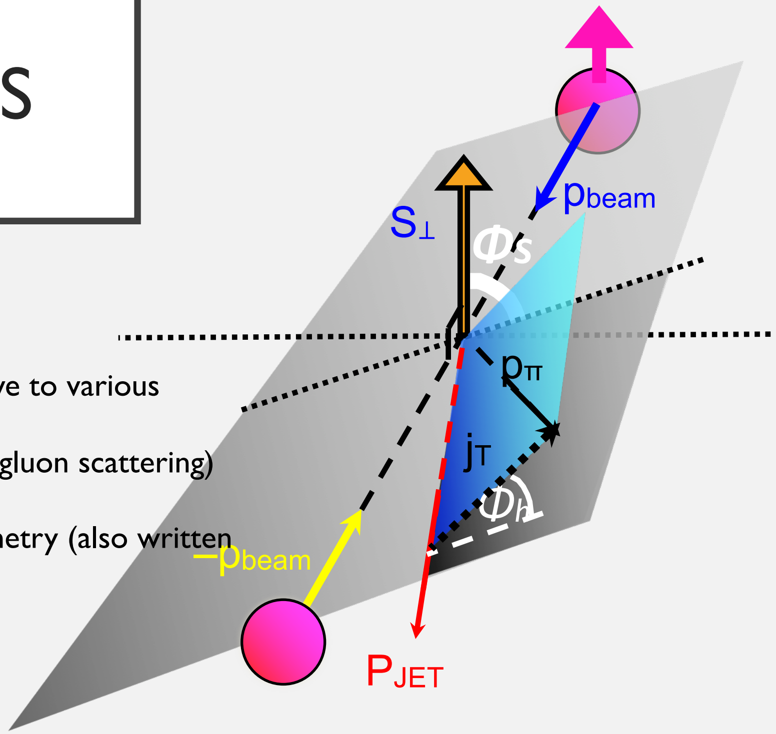
Agreement, no TMD evolution of h_1

TRANSVERSE PHYSICS THROUGH JETS

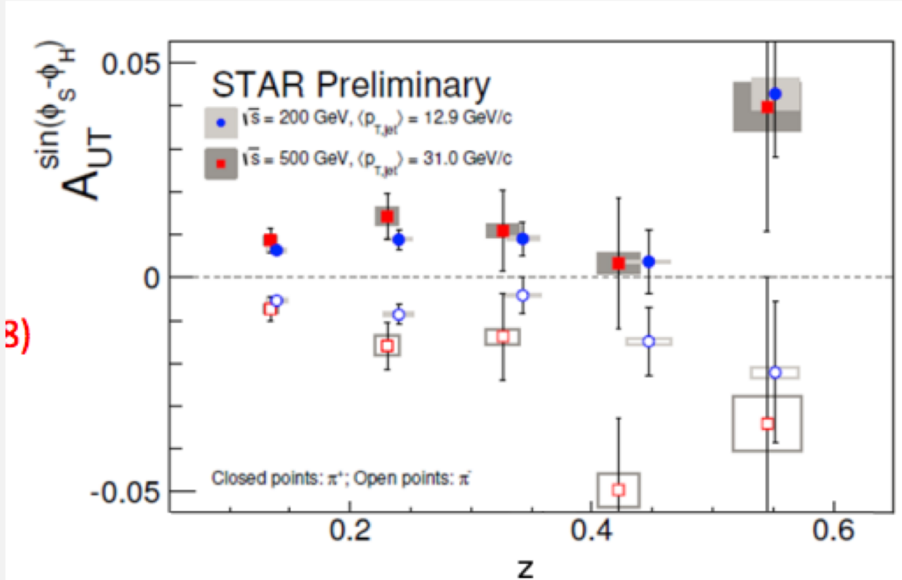


Asymmetry moments sensitive to various contributions
(analogous moments sensitive to gluon scattering)

A_{UT} – Transverse single-spin asymmetry (also written A_N)



F. Yuan, PRL 100, 032003 (2008)
D 83, 034021 (2011)



STAR: Jets reconstructed with Anti-k_t algorithm

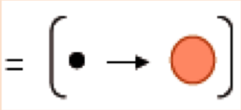
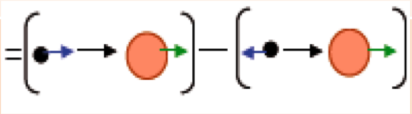
STILL NEED COLLINS FF TO EXTRACT TRANSVERSITY

AMSTERDAM NOTATION FOR FFS WITH QUARK/HADRON POLARIZATION

<u>Observables:</u>

z: fractional energy of the quark carried by the hadron

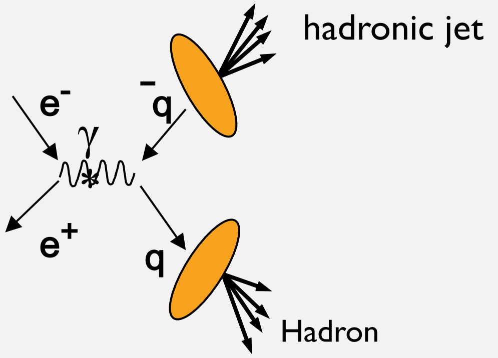
$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → Hadron Polarization ⇣	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, p_T)$ 		$H_1^{\perp h/q}(z, p_T)$ 
longitudinal		$G_1^{h/q}(z, p_T)$ 	
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z, p_T)$ 		$H_1^{q/\Lambda}(z, p_T)$ 

- Theoretically many more, in particular with polarized hadrons in the final state and transverse momentum dependence →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)

ACCESS OF FFS FOR LIGHT MESONS IN E^+E^- (SPIN AVERAGED CASE)

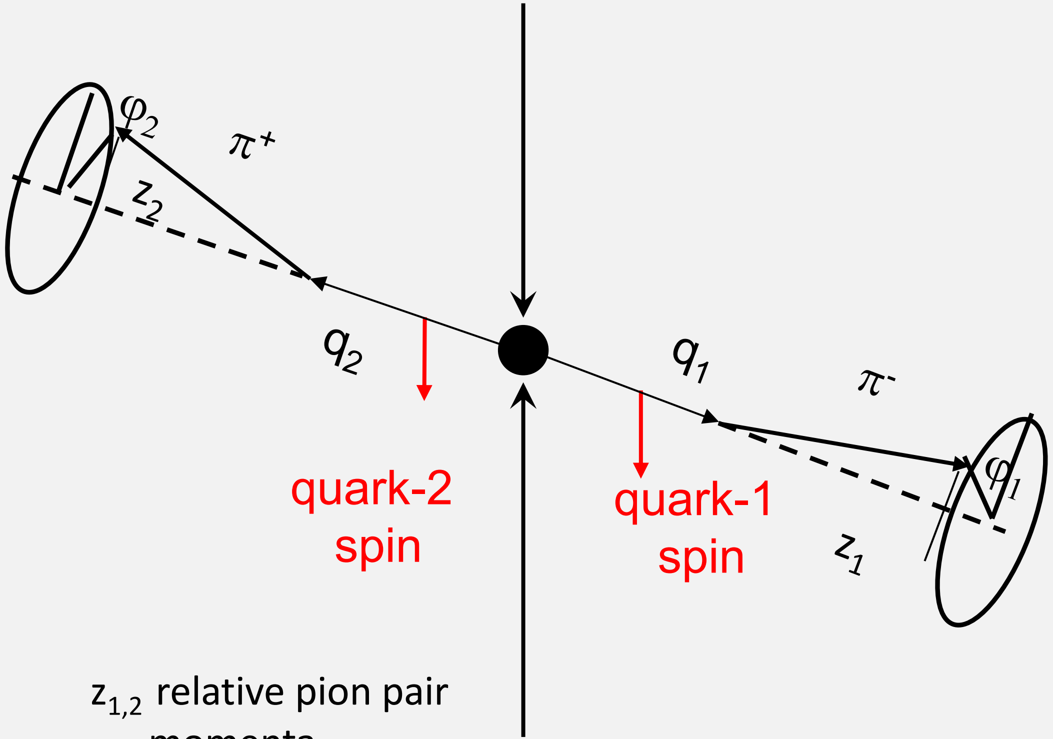
$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{e^+e^-\to hX}}{dz} = \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2) + F_L^h(z,Q^2)\right),$$



$$2F_1^h(z,Q^2) = \sum_q e_q^2\left(D_1^{h/q}(z,Q^2) + \frac{\alpha_s(Q^2)}{2\pi}\left(C_1^q \otimes D_1^{h/q} + C_1^g \otimes D_1^{h/g}\right)(z,Q^2)\right)$$

- Cleanest process
- Clean environment, hermetic dectors →can reconstruct complex final states, differentiate from feed-down
- Well understood, calculations available at NNLO
- Limited access to flavor
  - Use different couplings to γ^* and Z^0
  - Use polarization (SLD) and parity violating coupling
  - Use back-to-back correlations for different flavor combinations → see next talk
- Limited access to gluon FF
  - From evolution
  - From three jet events (but theory treatment not clear)

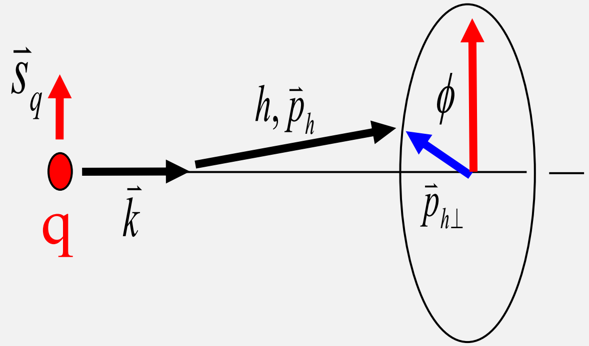
CORRELATION MEASUREMENTS IN E+E-

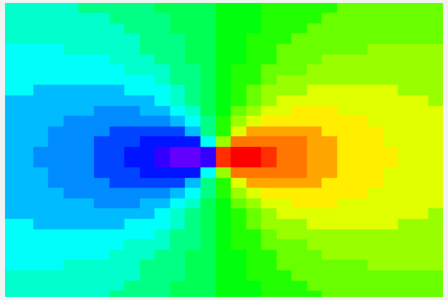


$z_{1,2}$ relative pion pair momenta

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

$$D^h_{q\uparrow}(z, P_{h\perp}) = D^h_{1,q}(z, P^2_{h\perp}) + H^{\perp h}_{1,q}(z, P^2_{h\perp}) \frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h}$$

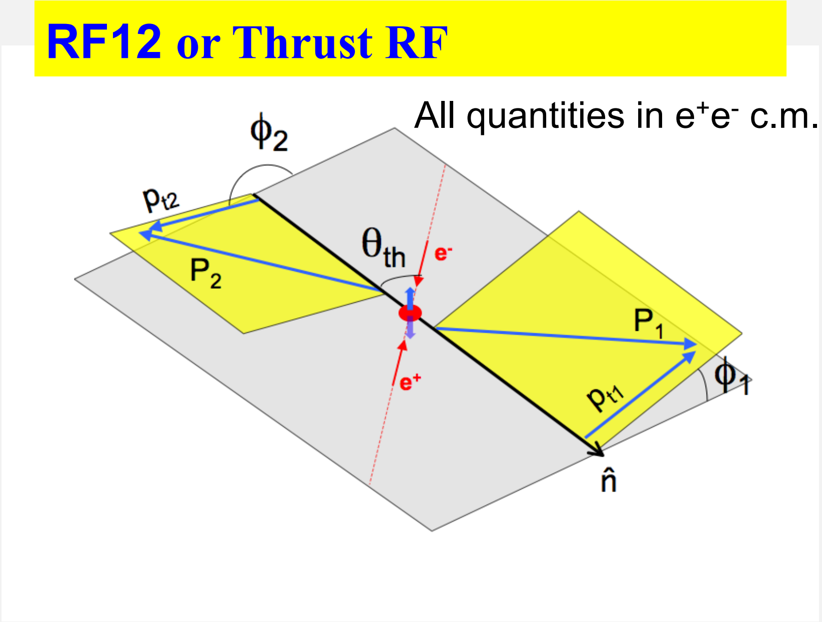




Cross-section $e^+e^- \rightarrow (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

$$\propto D_1^{\perp}\,\overline{D_1^{\perp}} + H_1^{\perp}\,\overline{H_1^{\perp}} \cos(\phi_1 + \phi_2)$$

COLLINS EFFECT



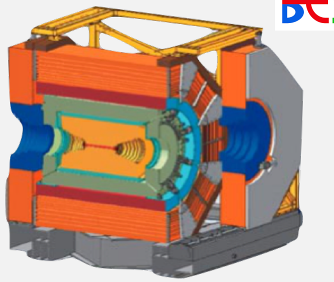
- **Thrust axis** to estimate the $q\bar{q}$ direction
- $\varphi_{1,2}$ defined using thrust-beam plane

Normalized cross-section: $e^+e^- \rightarrow (h_1 h_2)\left(\overline{h_1}\;\overline{h_2}\right) + X$

$$\propto 1 + + H_1^{\perp} \cdot \overline{H_1^{\perp}} \cos(\phi_1 + \phi_2)$$

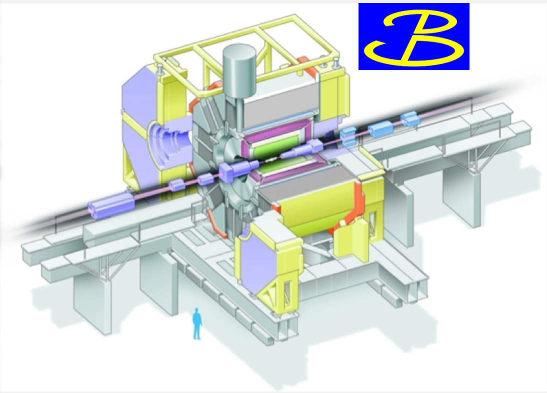
THE BESII, BELLE AND BABAR EXPERIMENTS

NIMA**614**,345(2010)



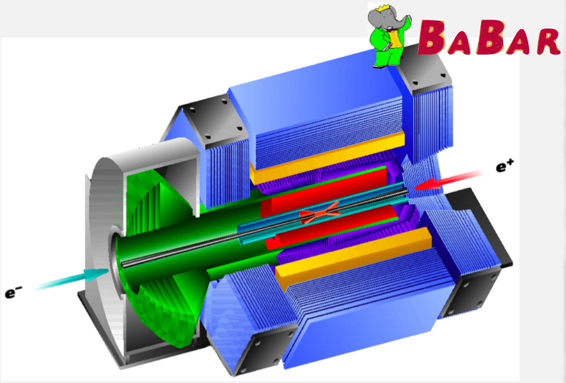
- Symmetric e^+e^- collider
- $\sqrt{s}$ = [2 - 4.6] GeV
- 62 pb^{-1} @ 3.65 GeV used for Collins studies
- Below open-charm threshold

- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma$=0.425
- L ~ 1 ab^{-1}



NIMA**479**,117(2002)

NIMA**729**,615(2013)

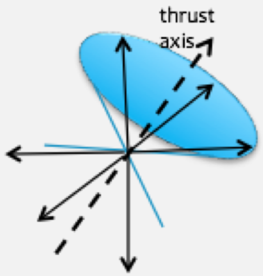


- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma$=0.65
- L ~ 500 fb^{-1}

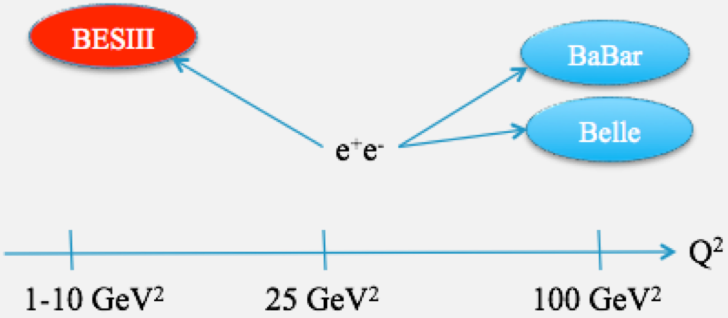
$$T = \sum_i \frac{|\mathbf{P} \cdot \hat{\mathbf{n}}|}{|P|}$$

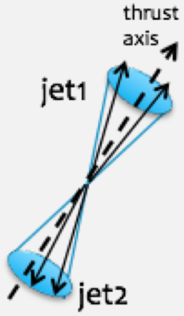
thrust axis $\equiv \hat{\mathbf{n}}$

$0.5 \leq T \leq 1$



T~0.5

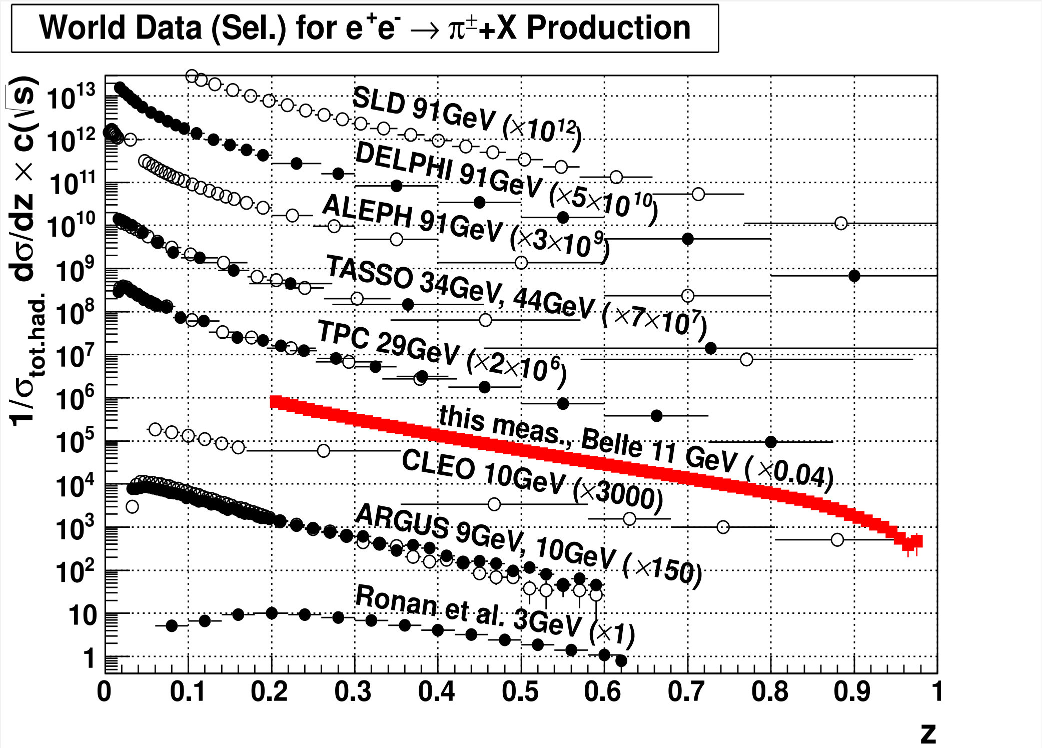




T~1

WORLD DATA ON E^+E^-

- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, D, Λ, charmed baryons…
- Pairs of π, K, p (back-to-back and same hemisphere)
- With B factory data theory and data uncertainties similar, good description by NNLO, some more work tbd at high and low z

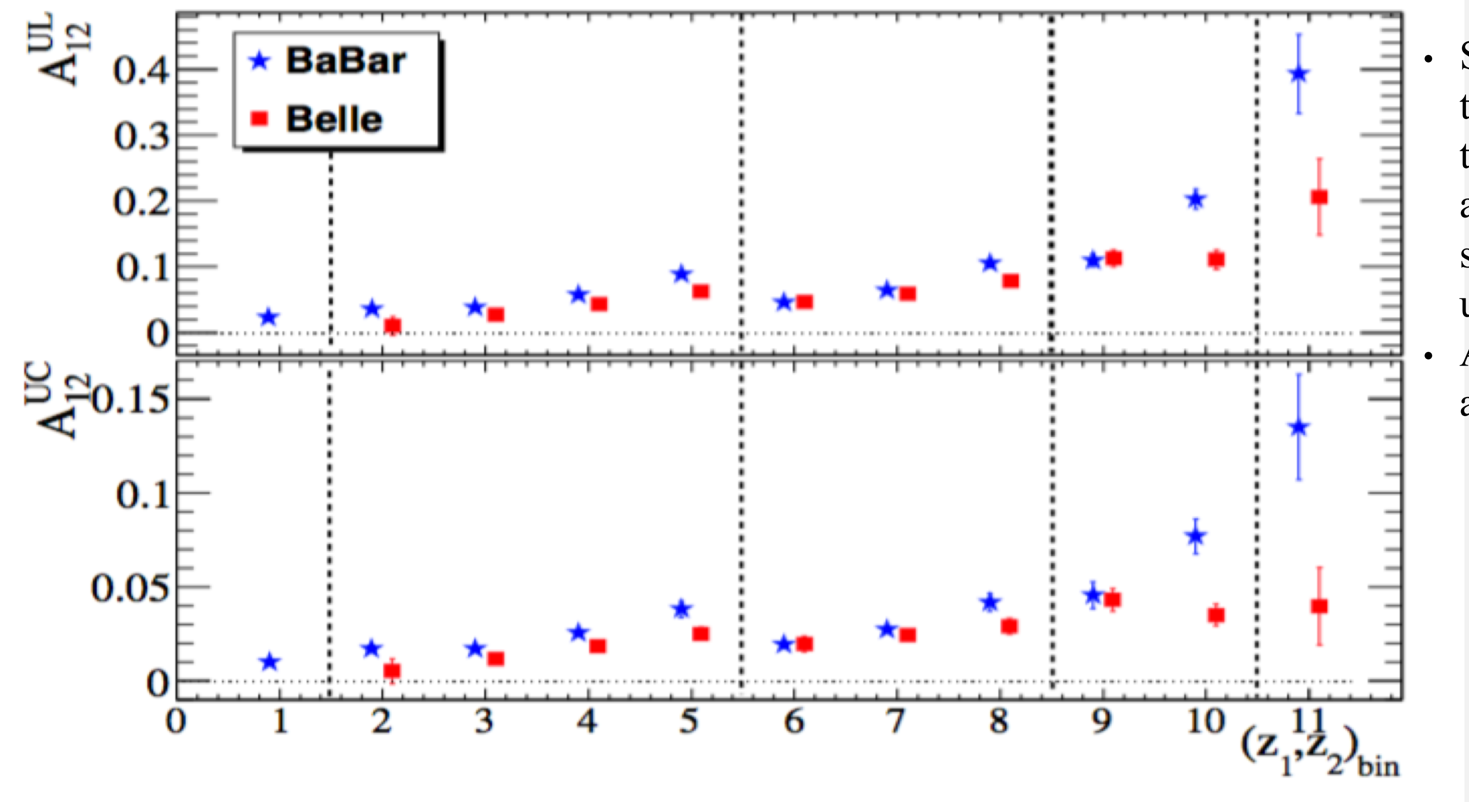


Phys.Rev.Lett. 111 (2013) 062002 (Belle)
Phys.Rev. D88 (2013) 032011 (BaBar)

Collins Effect vs (z_1,z_2): comparisons

EPJA, 52, 1-15 (2016)

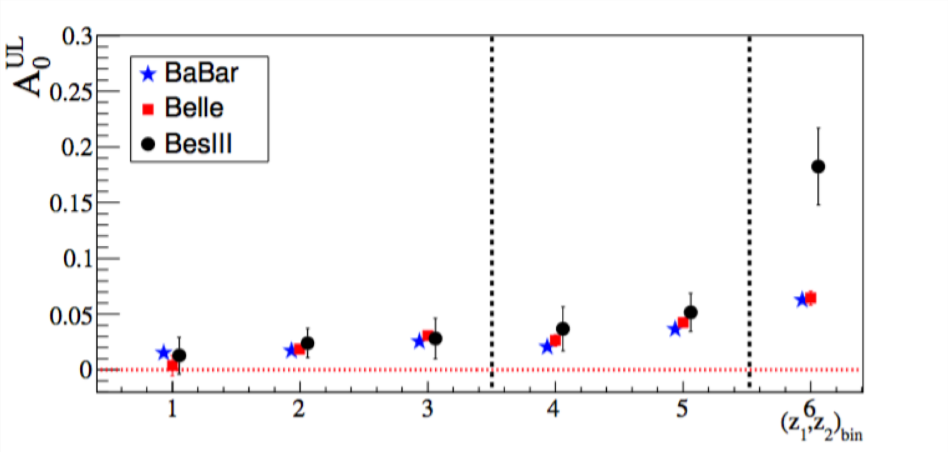
Unlike/**L**ikesign
Unlike/**C**harged
Ratios to cancel acceptance effects
Unlike:
fav*fav+dis*dis
Like:
fav*dis



- Symmetric (z_1,z_2) bins are used for the comparisons: results falling in the same large (z_1,z_2) interval are averaged taking into account statistical and systematic uncertainties
- A_{12}: some tensions between BaBar and Belle,
  - z<0.9 for BaBar, z<1 for Belle

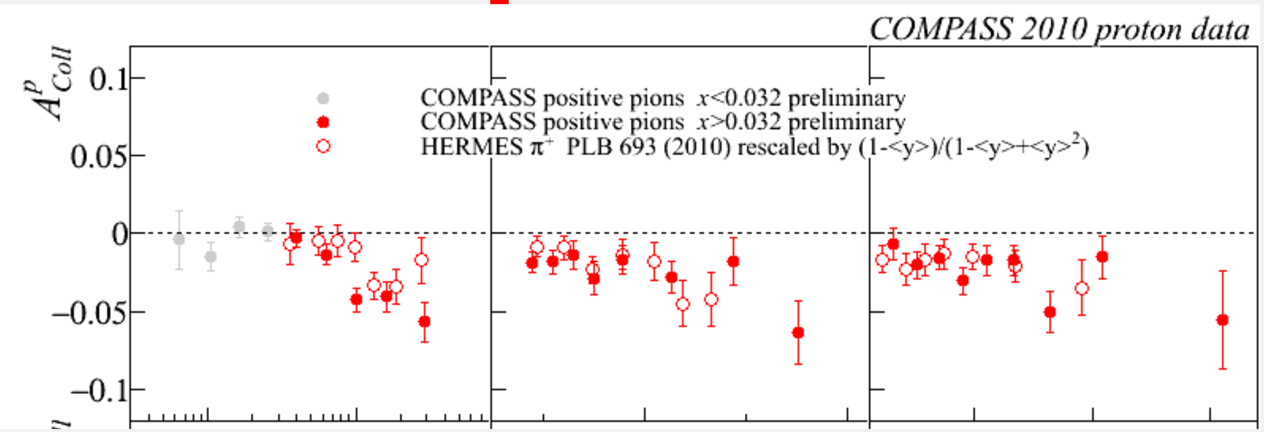
•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ √s ~ 10.6 GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to first extraction of transversity (Phys.Rev. D75 (2007) 054032) from SIDIS and e+e-
- Confirmed by BaBar @ √s ~ 10.6 GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
- Measured at BESIII @ √s = 3.65 GeV (PRL 116,42001(2016))

MEASUREMENT AT BELLE LEADS TO EXTRACTION OF TRANSVERSITY FROM GLOBAL FIT



$A_0^{UL} \propto H_1^{\perp} \otimes H_1^{\perp}$

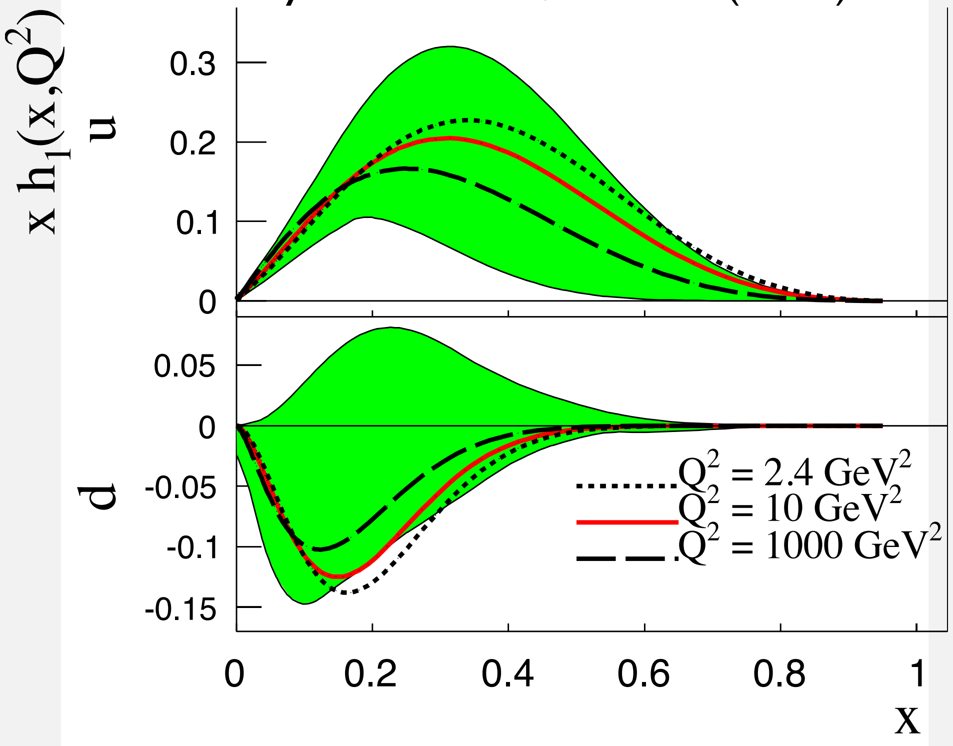
+



$A_{Coll} \propto h_1 \otimes H_1^{\perp}$

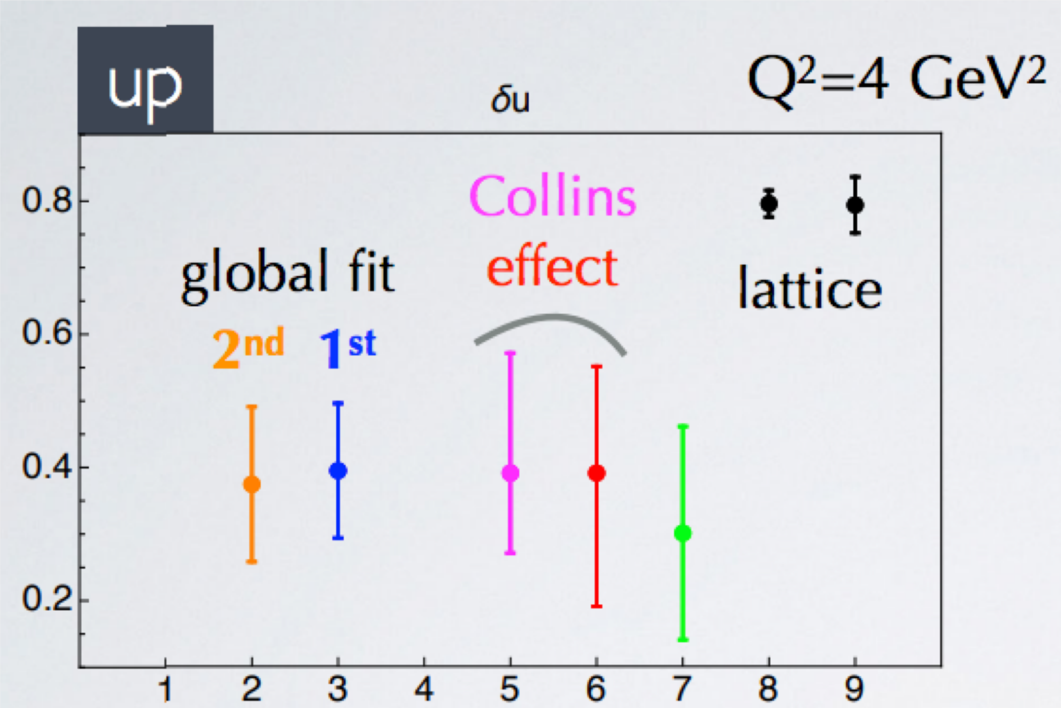
→

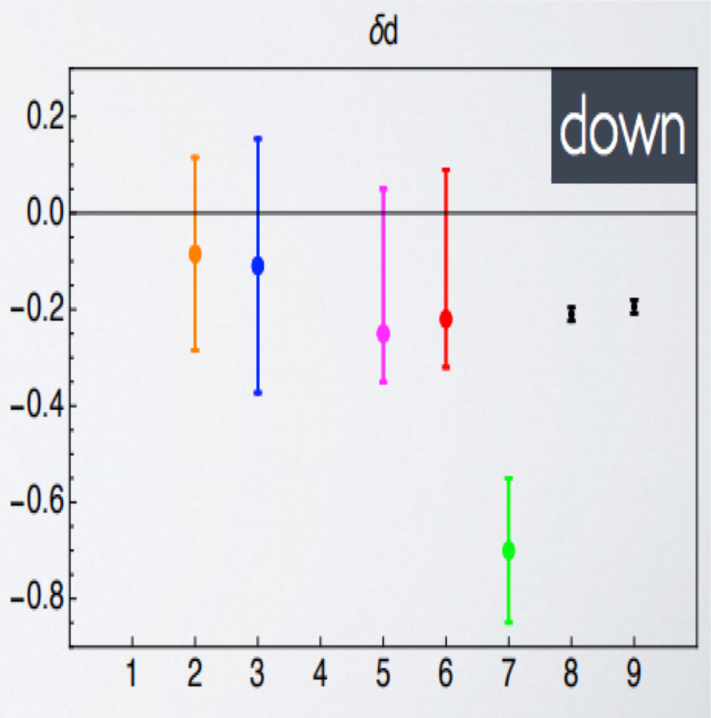
Phys. Rev. D 93, 014009 (2016)



2H extraction:
Phys.Rev.Lett. 120 (2018) no.19, 192001)

TENSOR CHARGE COMPARISON WITH LATTICE





2- global fit 2nd option

3- global fit 1st option *Radici & Bacchetta, P.R.L. 120 (18) 192001*

5- Torino *Anselmino et al., P.R. D87 (13) 094019* * $Q^2=1$

6- TMD fit *Kang et al., P.R. D93 (16) 014009* * $Q^2=10$

7- JAM fit *Lin et al., P.R.L. 120 (18) 152502* {Collins effect + lattice $g_T=\delta u-\delta d$ * $Q_0^2=2$

8- ETMC17 *Alexandrou et al., P.R. D95 (17) 114514; E P.R. D96 (17) 099906*

9- PNDME16

- Marco Radici at CIPANP 2018 (based on Phys.Rev.Lett. 120 (2018) no.19, 192001)

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\phi_h\,d\psi} = \left[\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\varepsilon F_{UU,L})\cdot$$

$$\Big(1+\cos\phi_h\,\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}+\cos 2\phi_h\,\varepsilon\,A_{UU}^{\cos 2\phi_h}$$
$$+\lambda\,\sin\phi_h\,\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LU}^{\sin\phi_h}$$
$$+S_L\left[\sin\phi_h\,\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h}+\sin 2\phi_h\,\varepsilon\,A_{UL}^{\sin 2\phi_h}\right]$$
$$+S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL}+\cos\phi_h\,\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LL}^{\cos\phi_h}\right]$$
$$+S_T\,\sin(\phi_h-\phi_S)\,A_{UT}^{\sin(\phi_h-\phi_S)}$$
$$+S_T\,\sin(\phi_h+\phi_S)\,\varepsilon\,A_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+S_T\,\sin(3\phi_h-\phi_S)\,\varepsilon\,A_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+S_T\,\sin\phi_S\,\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S}$$
$$+S_T\,\sin(2\phi_h-\phi_S)\,\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)}$$
$$+S_T\lambda\,\cos(\phi_h-\phi_S)\,\sqrt{1-\varepsilon^2}\,A_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+S_T\lambda\,\cos\phi_S\,\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos\phi_S}$$
$$+S_T\lambda\,\cos(2\phi_h-\phi_S)\,\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos(2\phi_h-\phi_S)}\Big)$$

$F_{UU,T}$: virtual photon polarization

λ beam polarization

Target polarization

S_L longitudinal

S_T transverse

Longitudinal to transverse photon flux ratio

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

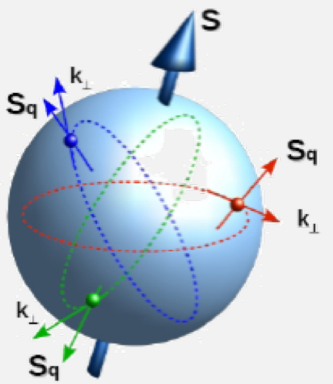
$$\gamma = \frac{2Mx}{Q}$$

TRANSVERSE MOMENTUM DEPENDENT DISTRIBUTIONS (TMDS)

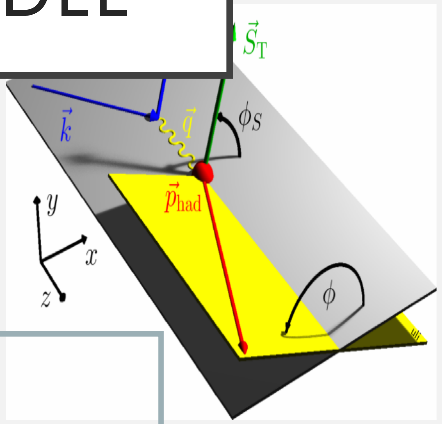
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

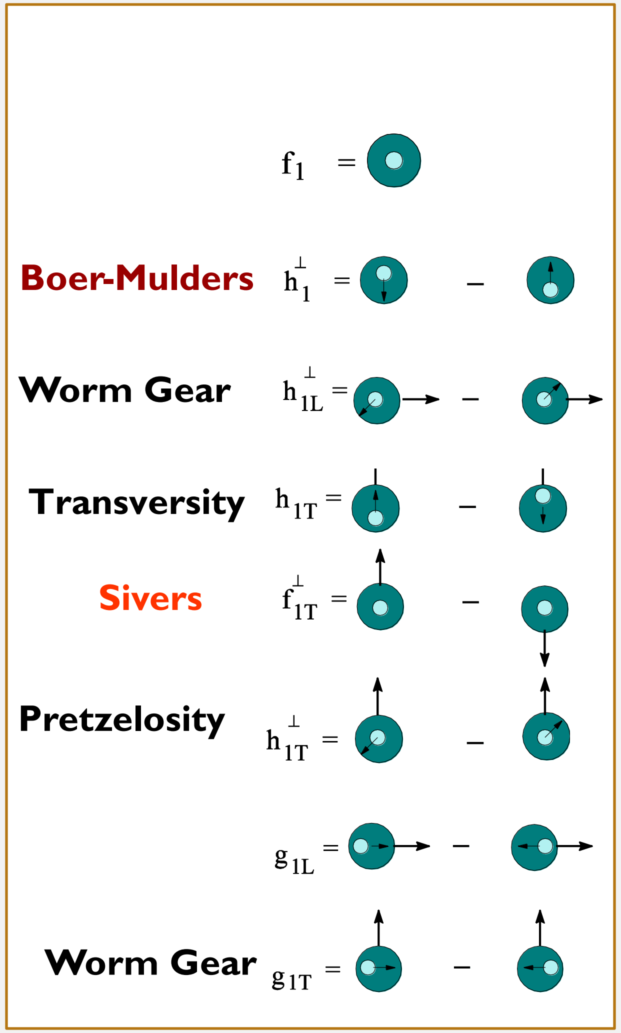
- In addition to the spin-spin correlations can have spin momentum correlations!

Spin-orbit correlations



SIDIS CROSS-SECTION IN THE PARTON MODEL





$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4} \times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

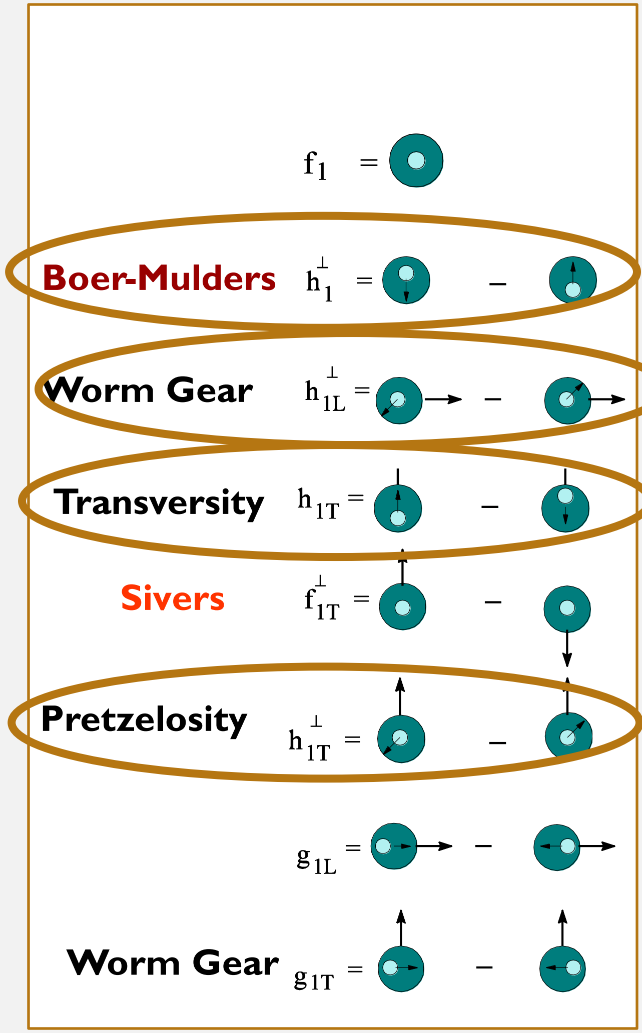
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

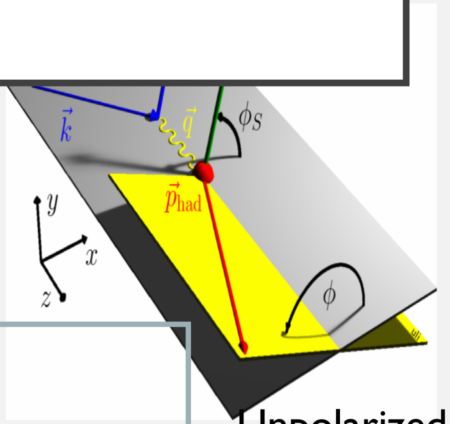
Polarzied beam and target

S_L and S_T: Target Polarizations; λe: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

CHIRAL ODD TMDS





Unpolarized

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

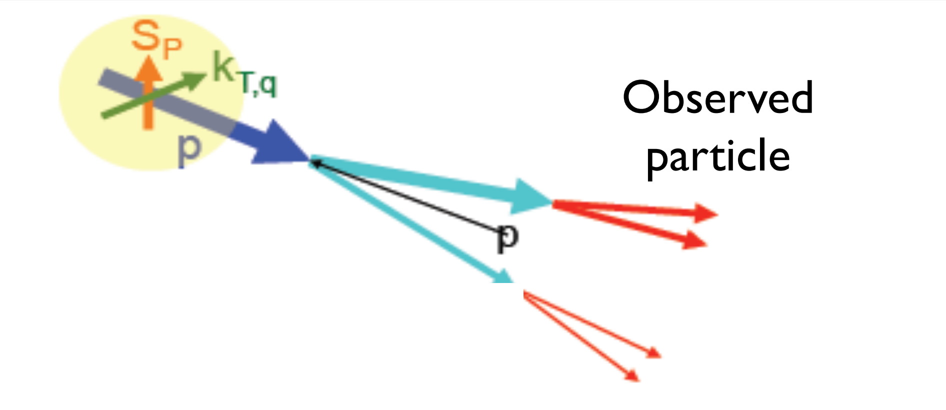
Polarzied beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

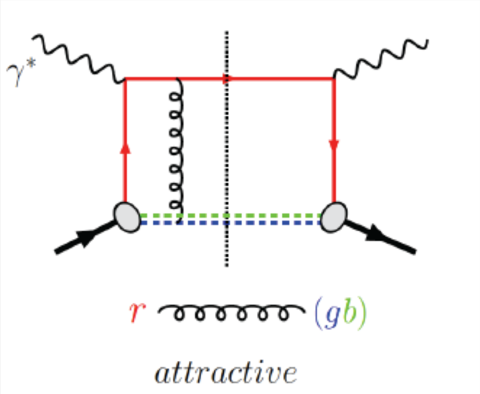
S_L and S_T: Target Polarizations; λe: Beam Polarization

SIVERS, THE "ORIGINAL TMD"



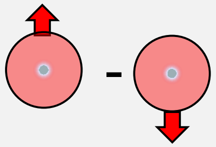
Sivers function

Hadron spin influences parton's transverse motion

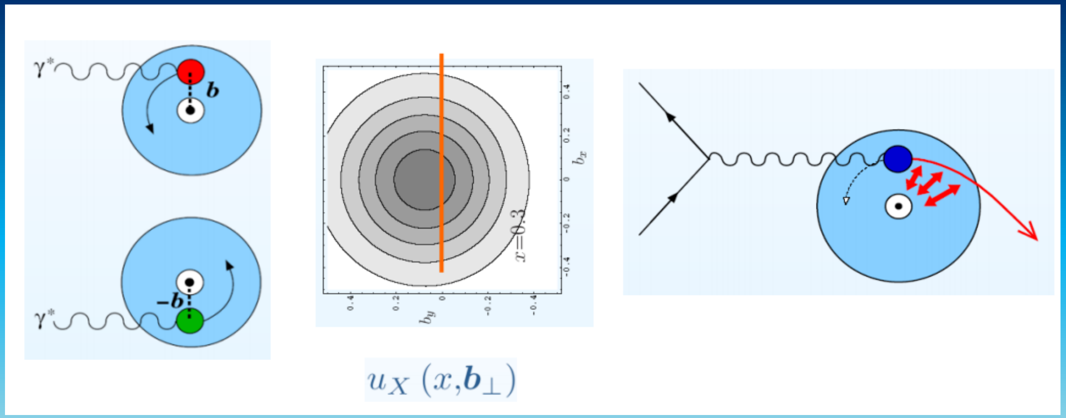


- First proposed by Sivers as a mechanism for observed left/right asymmetries : **Phys.Rev. D41 (1990) 83, Phys.Rev. D43 (1991) 261-263**
- Refuted by Collins (T-odd) **Nucl.Phys. B396 (1993) 161-182**
- Explicit model calculation by **Brodsky, Hwang, Schmidt Phys.Lett. B530 (2002) 99-107**→Interference of amplitudes with different J_z and phase shift →intrinsically linked to orbital angular momentum
- Accepted that there are T-odd functions, modified universality, Collins (**Phys.Lett. B536 (2002) 43-48**)

Sivers Asymmetries $A_{Siv}\sin(\phi_h-\phi_S)$



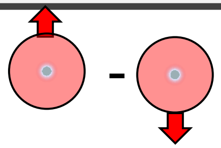
- The 'original TMD', Sivers 1990
- Correlation between quark k_T and nucleon spin
- Naïve T-odd: Needs final state interaction



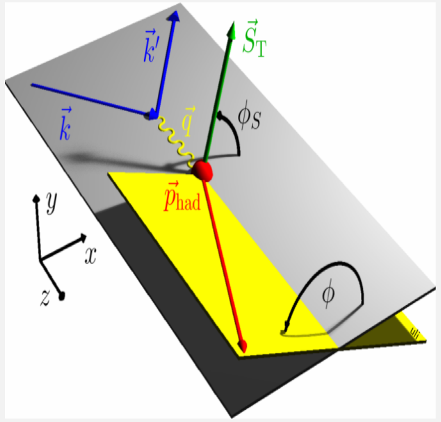
Burkardt:
"Chromodynamic Lensing"

- Model dependent connection to OAM

SIVERS ASYMMETRIES, $A^{\sin(\Phi H-\Phi S)}$ □ $F^{\perp}_{1} \otimes D_{I}$

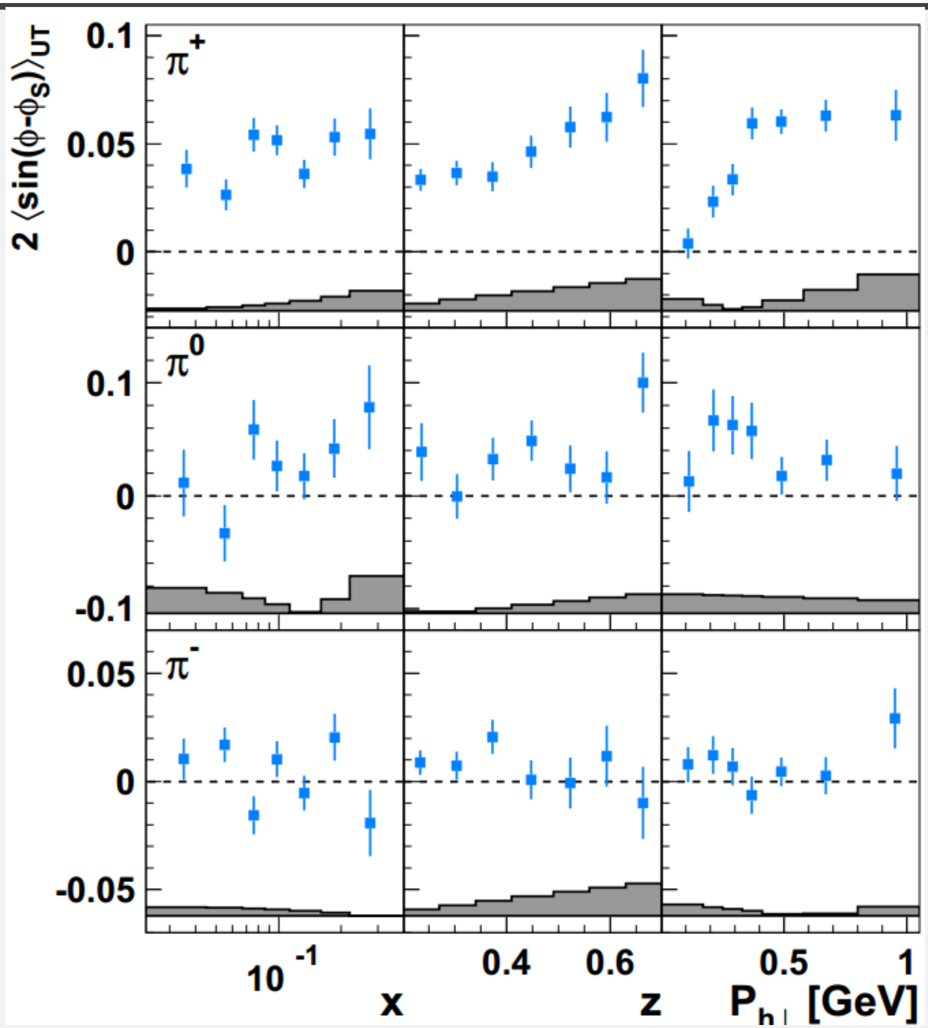


- HERMES sees significant signal on proton



$\sigma_{UT} \propto \sigma_{UU} + A_{siv}\sin(\phi_h-\phi_S)+\ldots.$

$A_{siv} \propto f^{\perp}_{1} \otimes D_{I}$



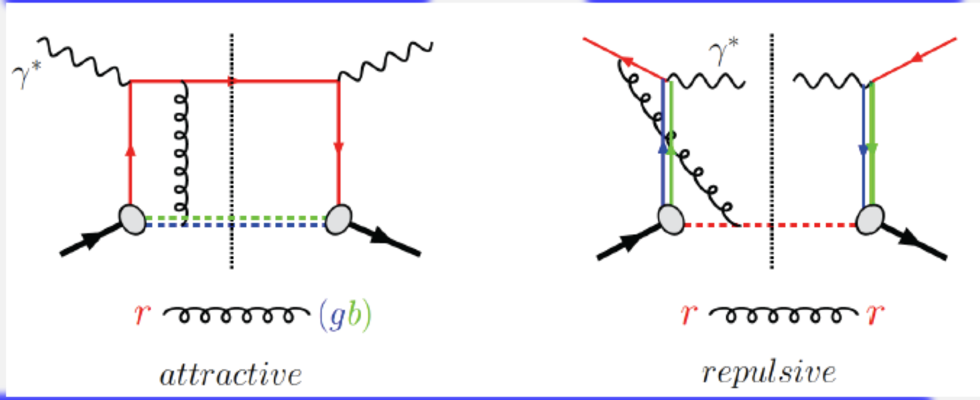
SIVERS MODIFIED UNIVERSALITY CRITICAL TEST OF QCD!

Consequence of gauge invariance of QCD

QCD:

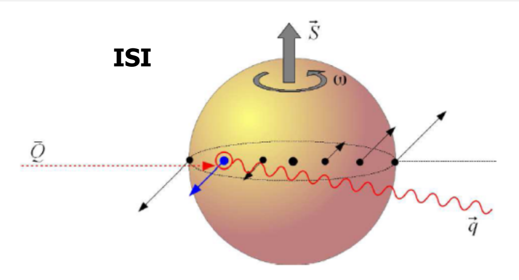
DIS: γq-scattering
attractive FSI

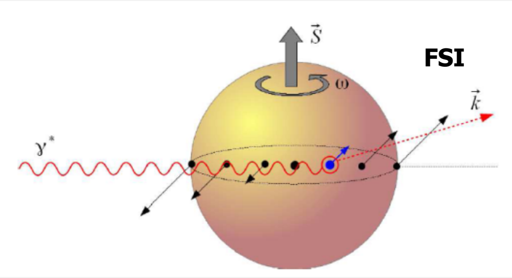
pp:
qqbar-anhilation
repulsive ISI



Drell-Yan or W productions

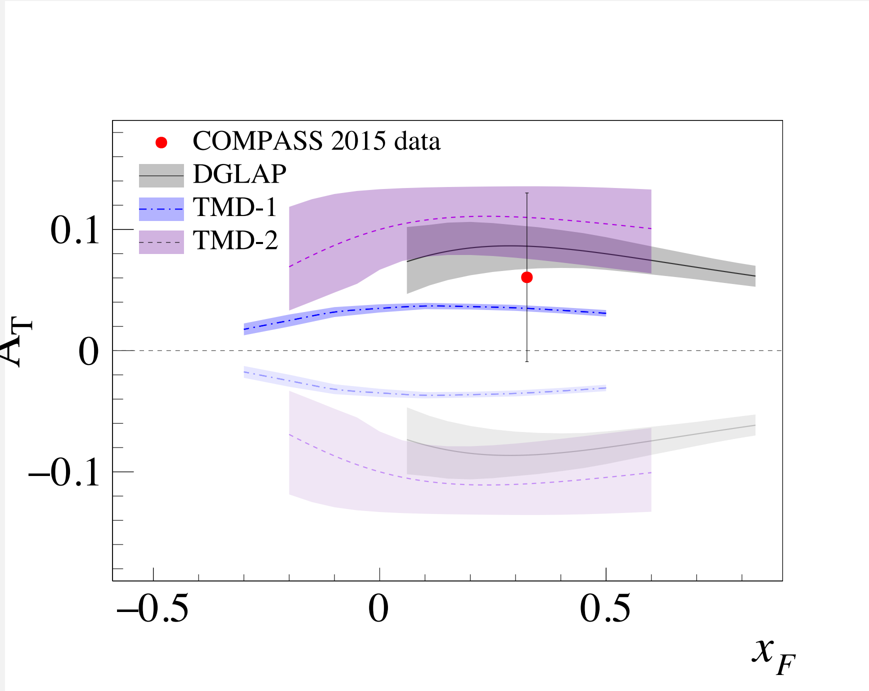
Sivers$_{DIS}$ = - (Sivers$_{DY}$ or **Sivers$_W$ or** Sivers$_{Z0}$)



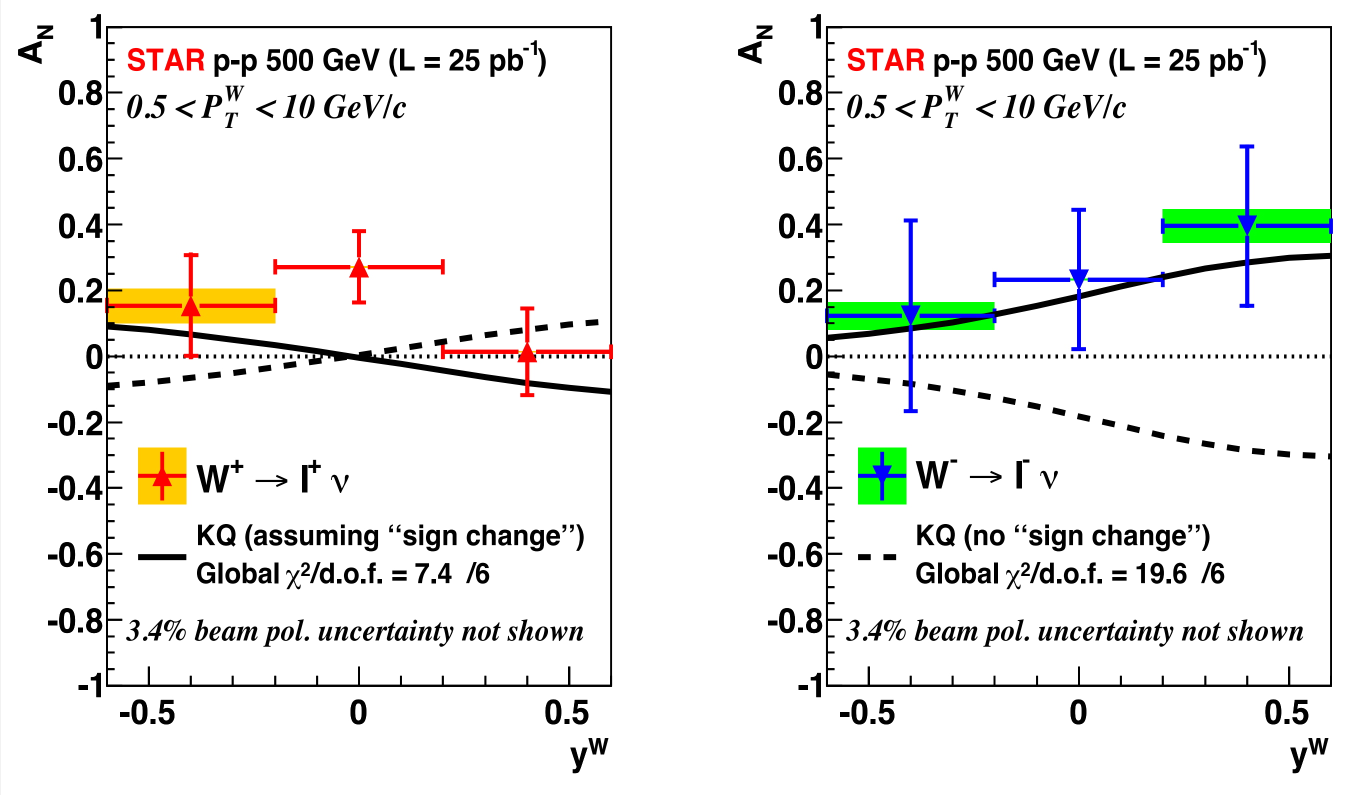


[Sievert, Kovchegov (2014)]

COMPASS AND STAR RESULTS

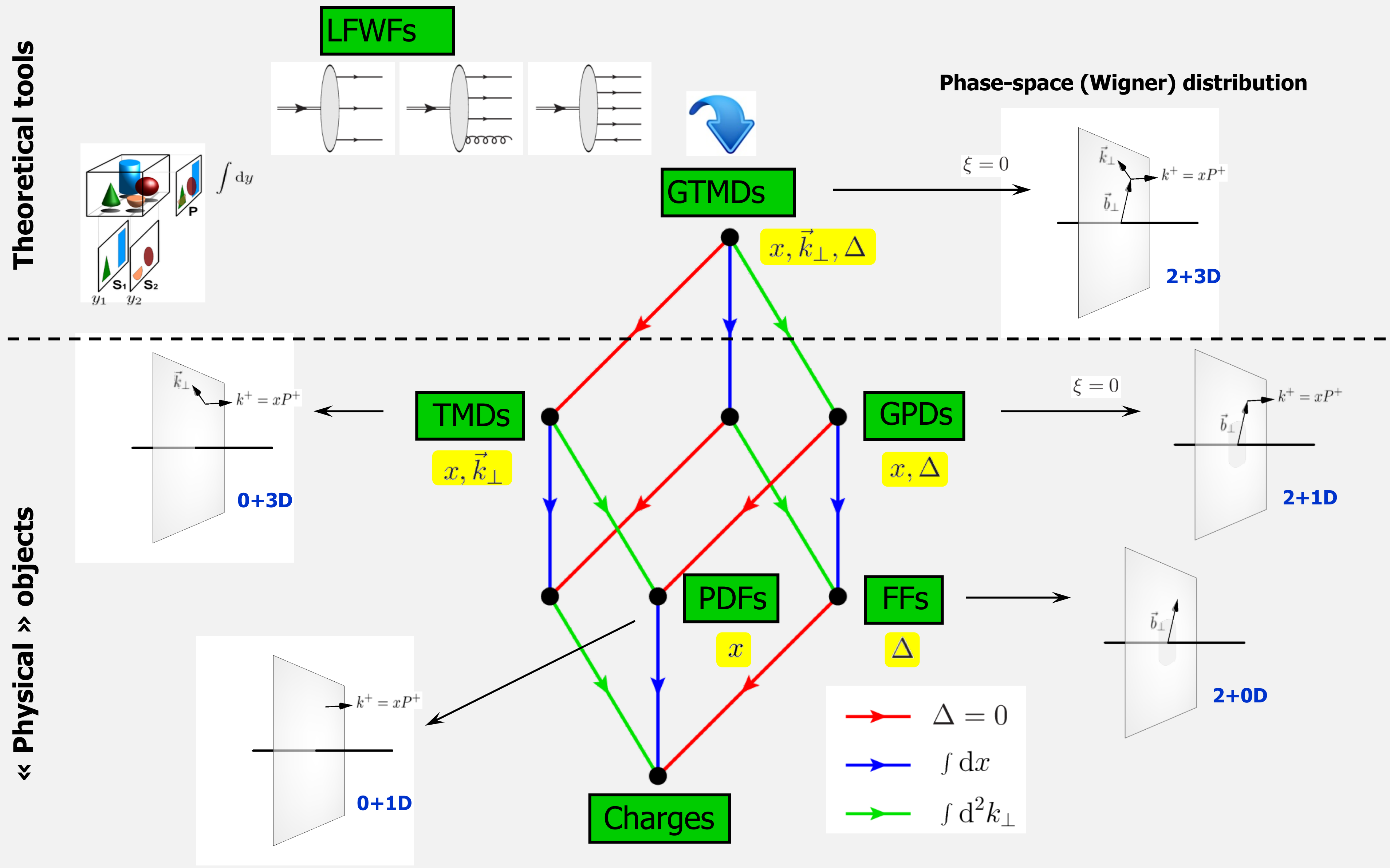


PRL 119, 112002 (2017)



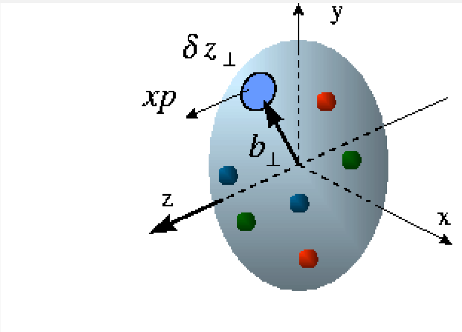
PRL. 116 (2016) no.13, 132301

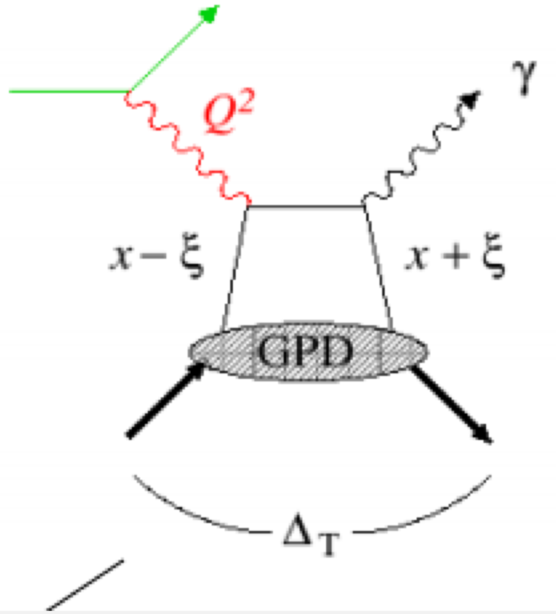
Parton distribution zoo



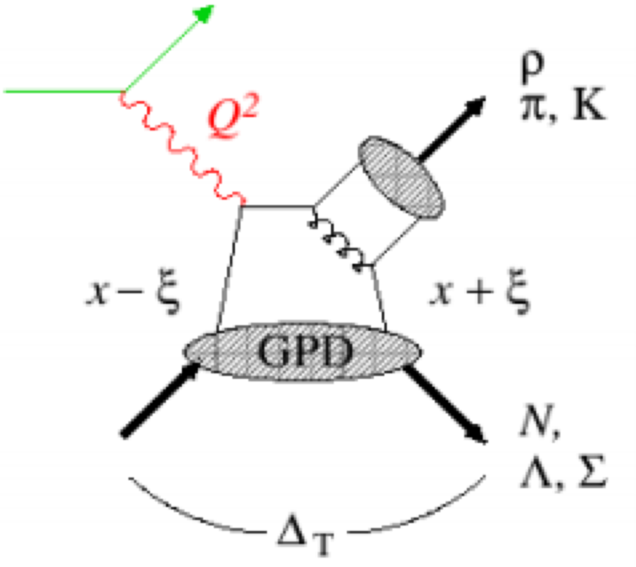
[C.L., Pasquini, Vanderhaeghen (2011)]

SHORT GPD EXCURSE





Deeply Virtual Compton Scattering



Deeply Virtual Meson Production

$$A_{DVCS}(\xi,t,Q^2) \propto \sum_q e_q^2 \int_0^1 dx \frac{2x}{x^2-\xi^2} H^q(x,\xi,t,Q^2) + \cdots$$

$$q(x,\vec{b}\,) = \int \frac{d^2\vec{q}}{4\pi^2} e^{i\vec{b}\cdot\vec{q}} \mathrm{H}^q(x,\xi=0,t=-\vec{q}^{\,2},\mu^2)$$

Connected to OAM via JI sum rule

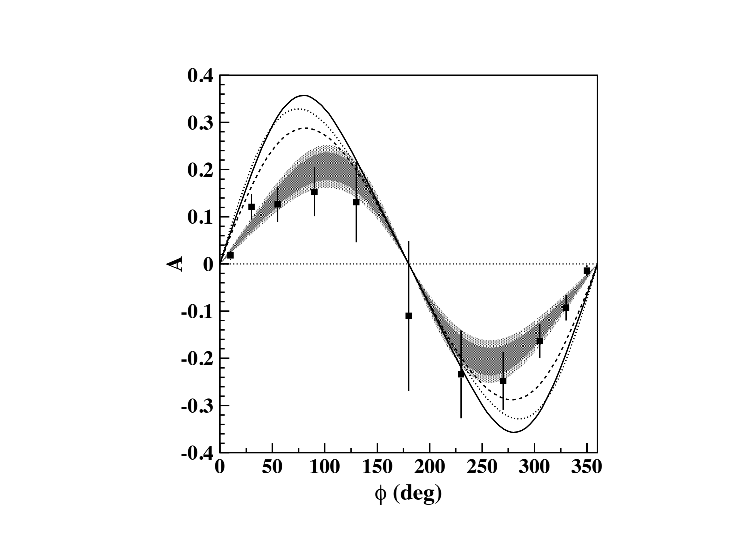
$$\frac{1}{2}\int_0^1 dx\, x\, \left[H^q(x,\xi,t=0,\mu^2) + E^q(x,\xi,t=0,\mu^2)\right] = J^q(\mu^2)$$

X. Ji , 1997

EXPERIMENTAL ASPECTS

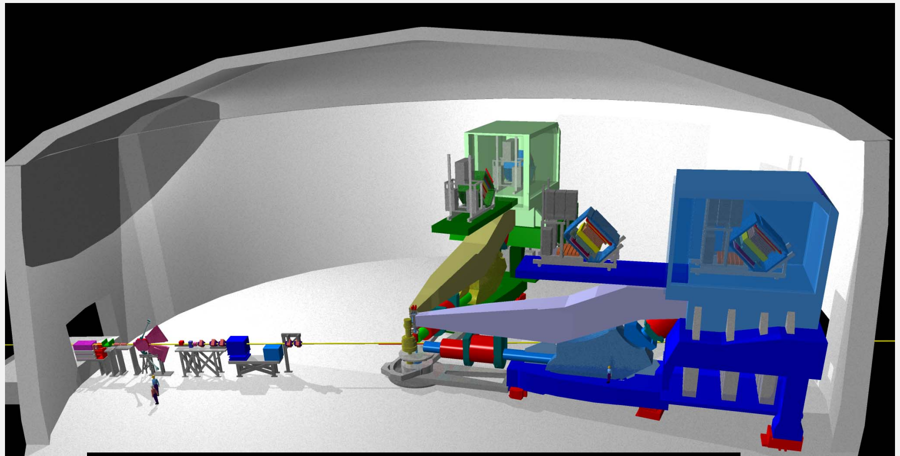
Observation of DVCS in BSAs at CLAS6

- Difficult measurement
  - Exclusive
  - Differential in 4 variables
  - Measure convolution over kinematical quantities
  - Model dependent extraction
  - Additionally the ‘usual’ complications (hight twist, radiative effects)
- **Major part of the physics program at JLab12**
  - High precision measurements + theoretical progress → exciting times to come

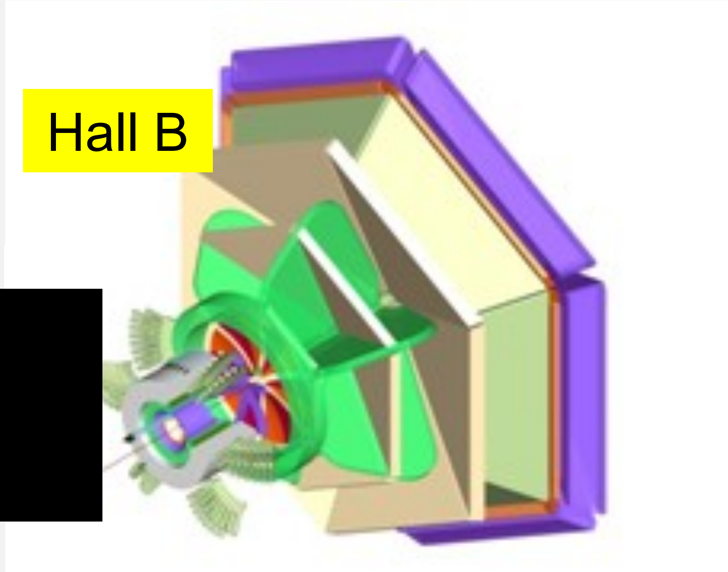


Phys.Rev.Lett. 87 (2001) 182002

JLAB AT 12 GEV

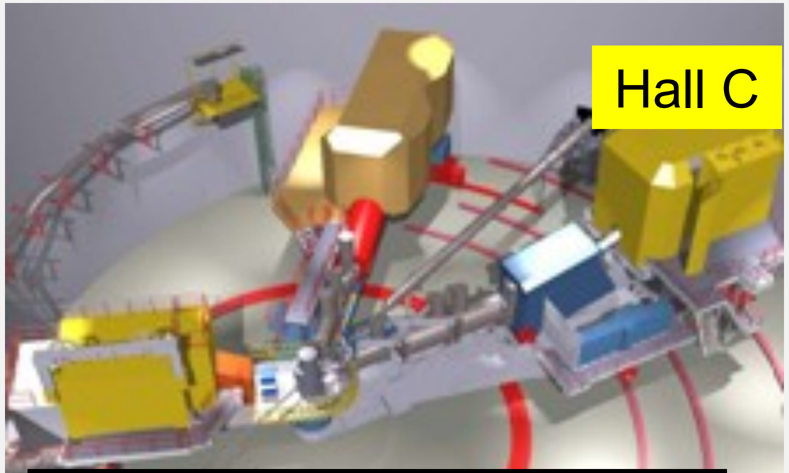


Two high-resolution spectrometers
& large installations

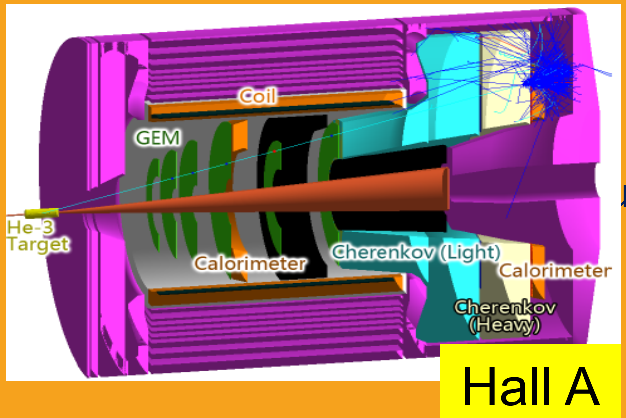


Large acceptance spect.
electron/photon beams
Lumi up to 10^{35} $cm^{-2}s^{-1}$

Beam: ≤12 GeV e^-; 85% polarization
Target: polarized targets 3He, 6LiD, NH3
several unpolarised targets
Hall-D: for spectroscopy 9GeV tagged polarised photons & a 4π detector



Super high momentum spectrometer,
high luminosity and forward angles

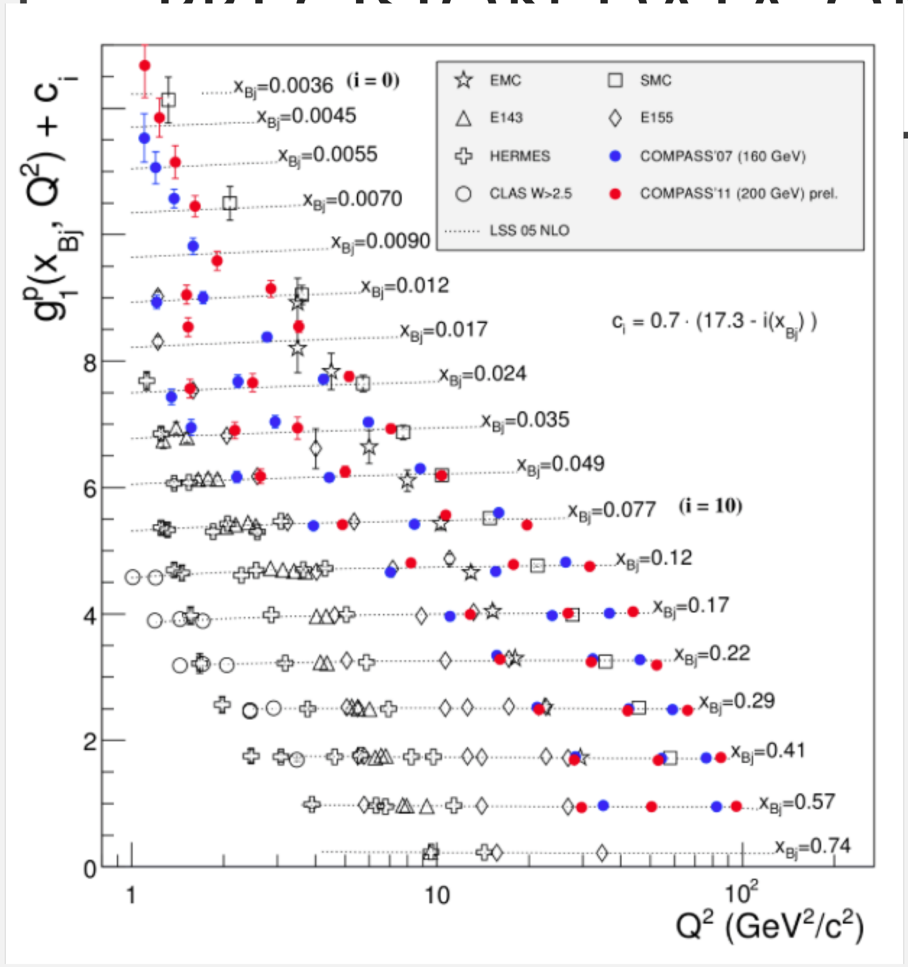


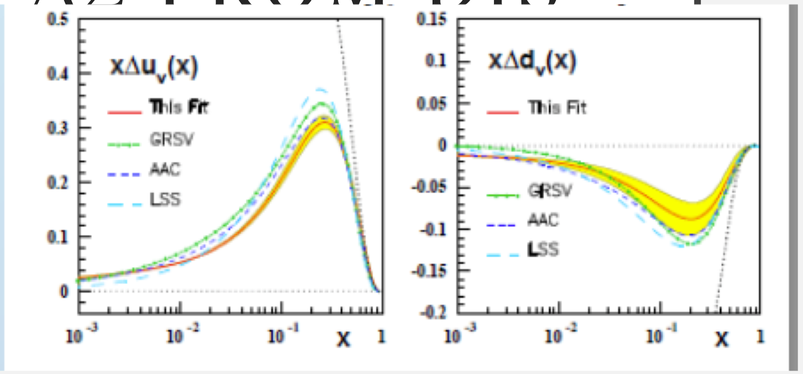
Near Future: SoLID at JLAB12
Lumi up to 10^{37}-10^{39} $cm^{-2}s^{-1}$

SUMMARY

- Spin structure tests our understanding of nucleon structure
- Transverse spin phenomena test QCD on the amplitude level
- Future projects aim at completing 3D picture by accessing TMDs and GPDs
- JLab12, RHIC are taking data, SoLID and EIC will come online over the next decade
- SoLID: precision valence structure
- EIC: gluonic degrees of freedom and the sea

PRECISION DATA ON ΔΣ FROM DIS



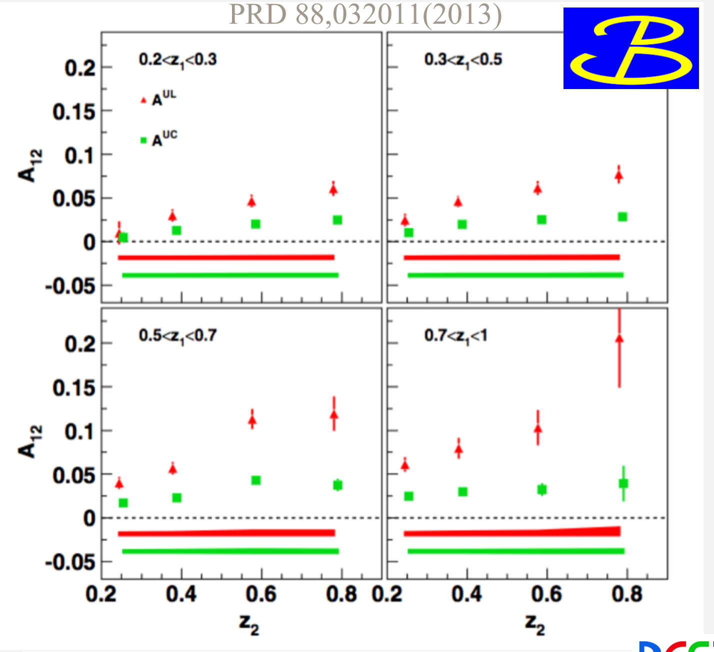


Open Questions

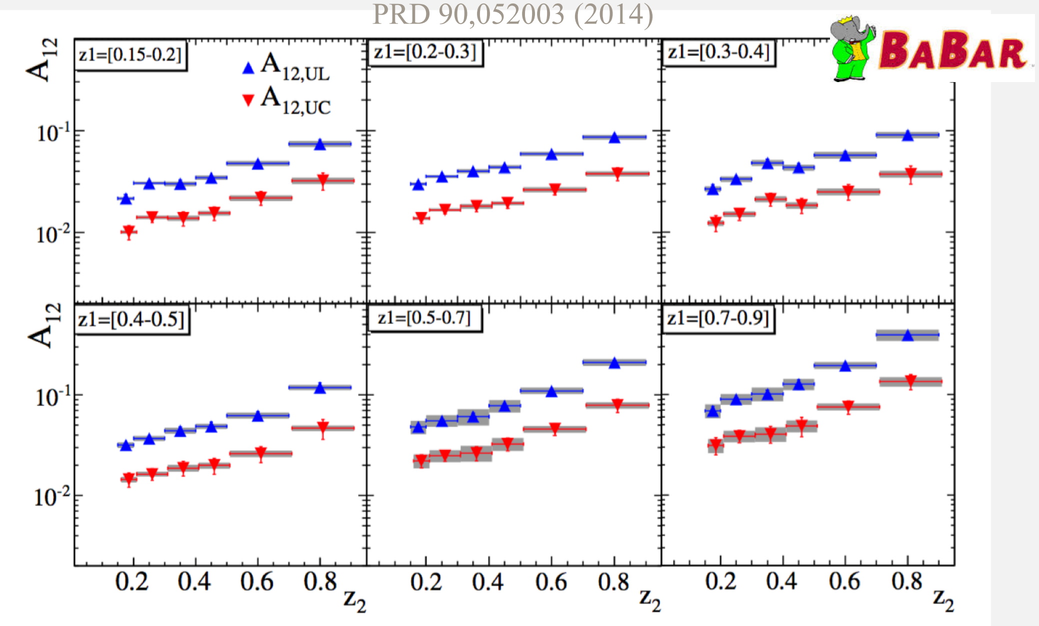
- Sea quarks follow simple perturbative models? (SU3)
- Gluons

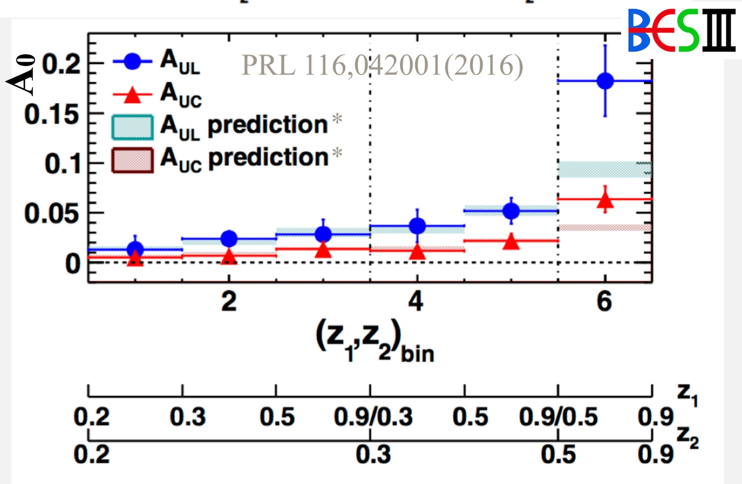
Collins Effect vs (z_1,z_2)

PRD 88,032011(2013)



PRD 90,052003 (2014)




PRL 116,042001(2016)

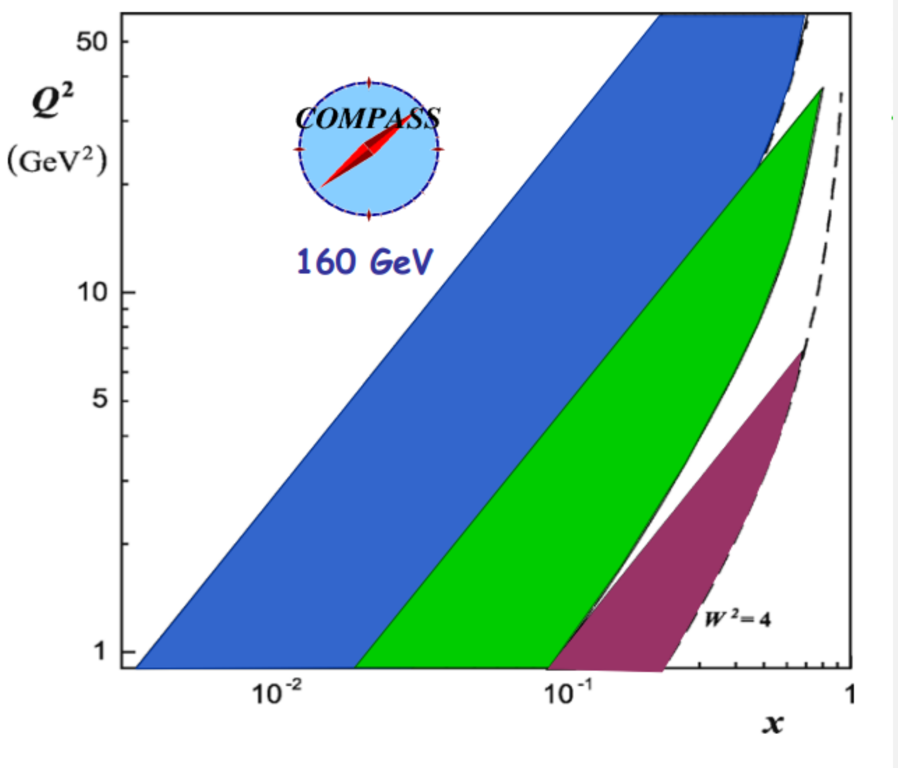
- Significant non-zero asymmetries A_{12}, A_0 in all bins
- Strong dependence on (z_1,z_2) observed in all the experiments
- $A_{UC}<A_{UL}$ as expected; complementary informations about favored and disfavored fragmentation processes

*PRD 93,014009(2016)

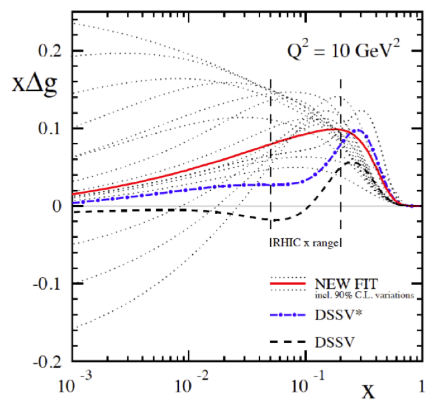
FUTURE JLAB

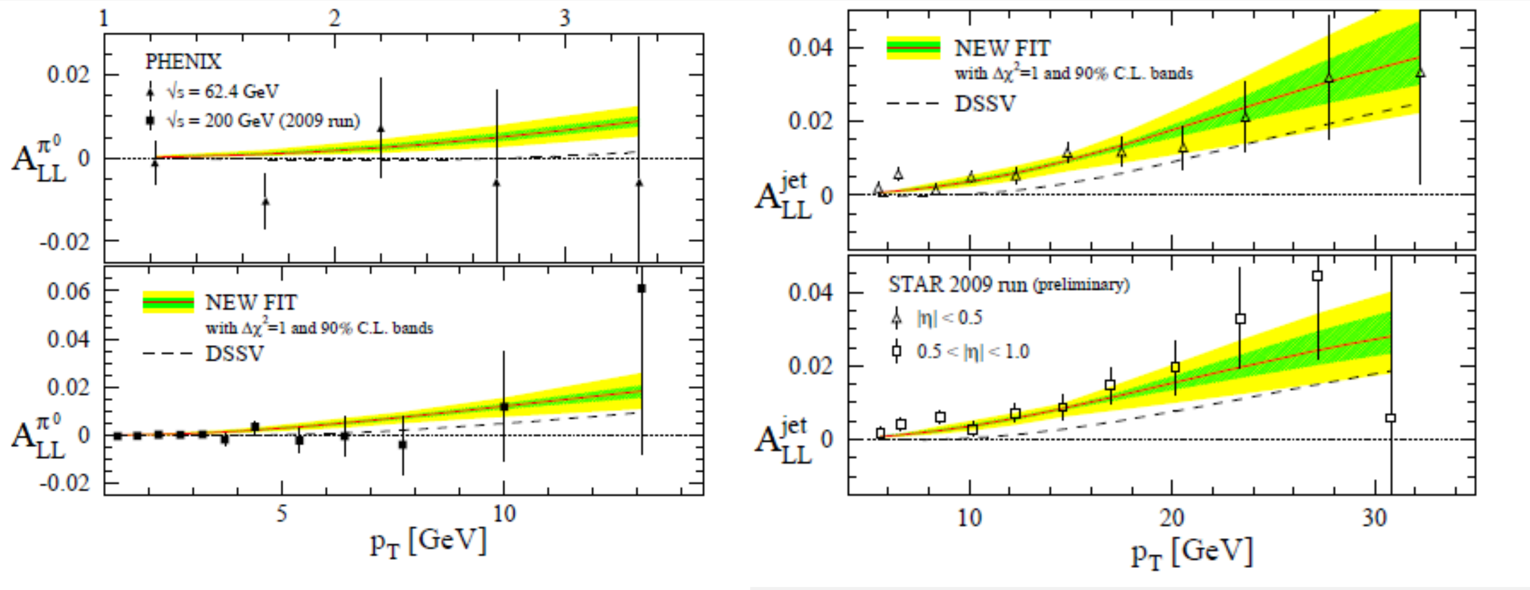
- EIC see next lecture

KNOW



NEW FIT TO RHIC DATA INCLUDING RUN9



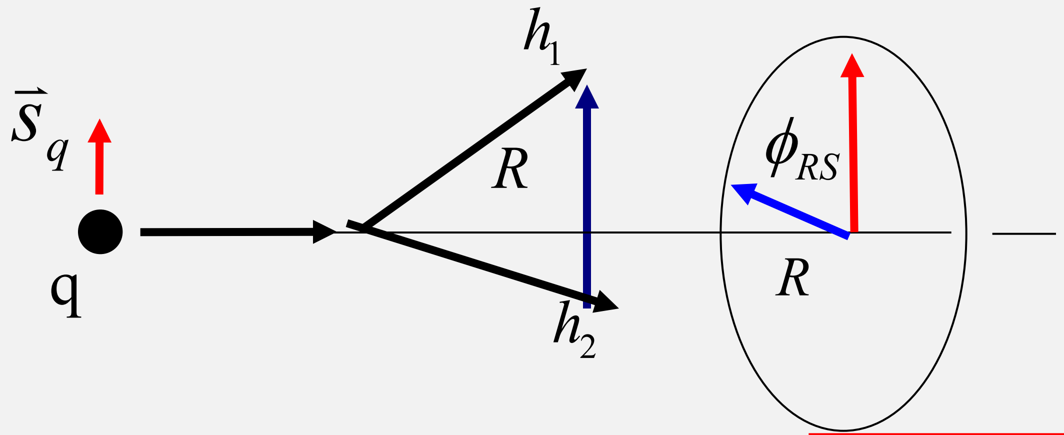


- DSSV:Phys.Rev.Lett. 113 (2014) 012001

- Nonzero gluon spin in measured x range
- Similar conclusion from NNPDFpol1.1 arXiv:1406.5539

- Pions at slightly smaller x
- and smaller Pt → Δg smaller due to evolution

Quark Polarimetry with Interference FF in Quark Fragmentation



$\vec{k}$:	quark momentum
$\vec{s}_q$:	quark spin
$\vec{R}$:	transv. hadron momentum difference
z_{pair} :	$= E_{\text{pair}}/E_q$
$= 2E_{\text{pair}}/\sqrt{s}$:	relative hadron pair momentum
m :	hadron pair invariant mass

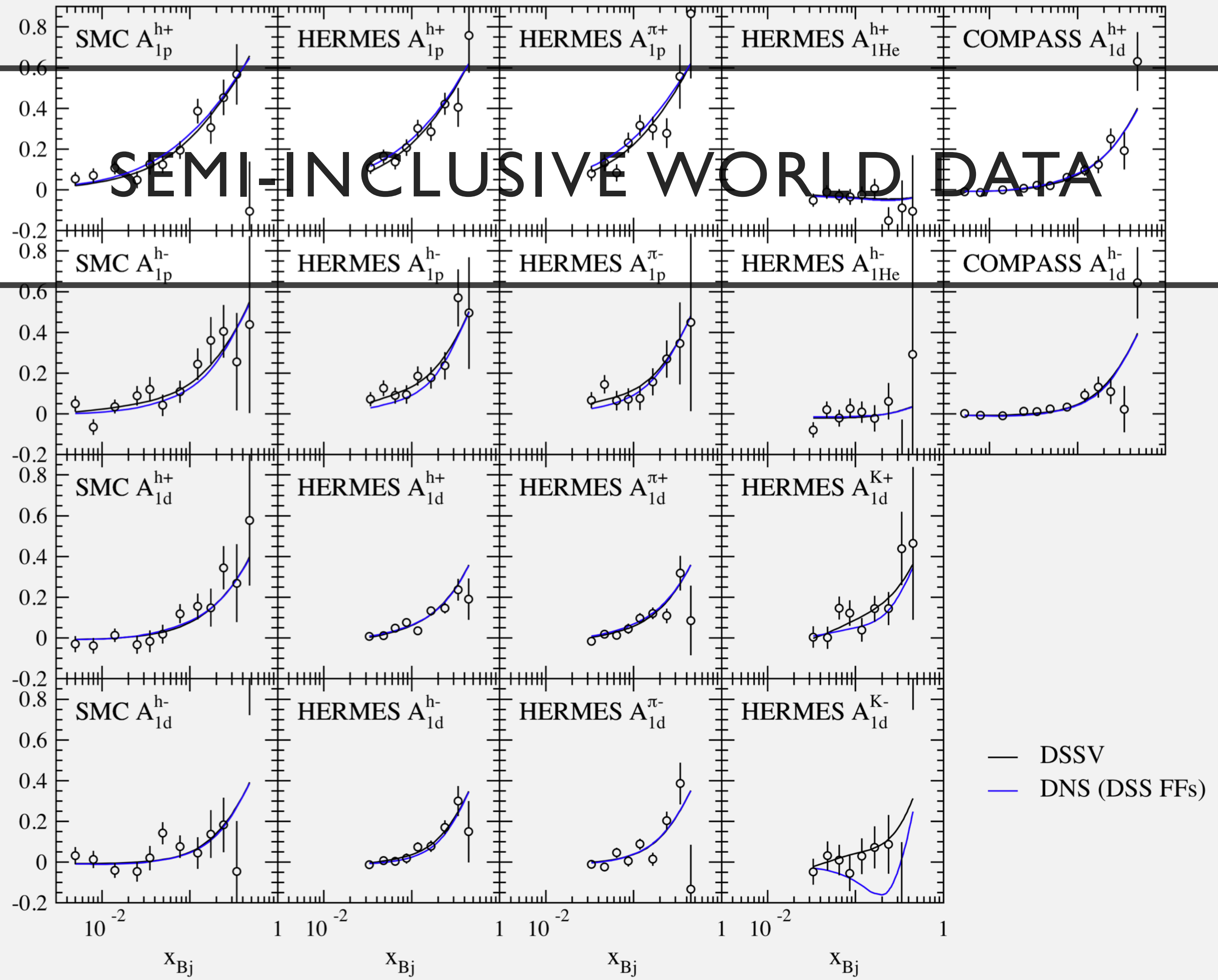
Interference Fragmentation Function:
Fragmentation of a transversely polarized quark *q* into two spin-less hadron *h1, h2* carries an azimuthal dependence:

$$\propto \left(\vec{k}\times\vec{R}_T\right)\cdot\vec{s}_q$$

$$\propto \sin\Phi_{RS}$$

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 $h_{1T}^{\perp}$

SEMI-INCLUSIVE WORLD DATA



Lets see some more modern data in more detail

COMPASS & HERMES SIDIS PROTON

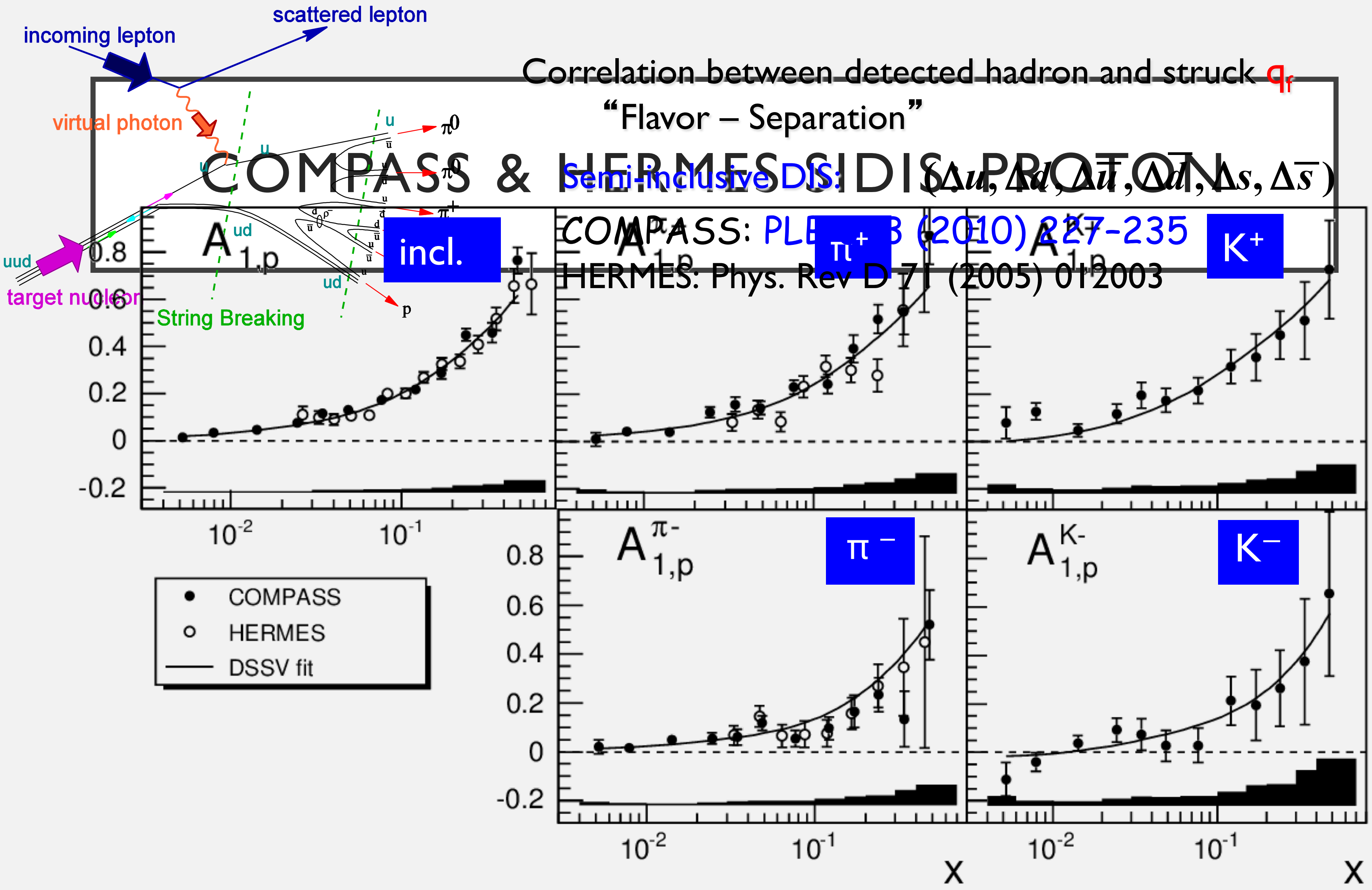
Correlation between detected hadron and struck q_f

"Flavor – Separation"

Semi-inclusive DIS: $(\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s, \Delta\bar{s})$

COMPASS: PLB 693 (2010) 227-235

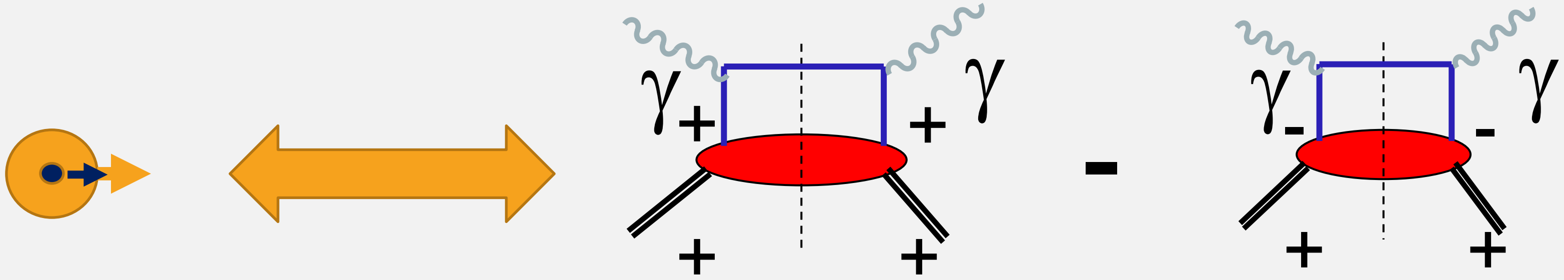
HERMES: Phys. Rev D 71 (2005) 012003



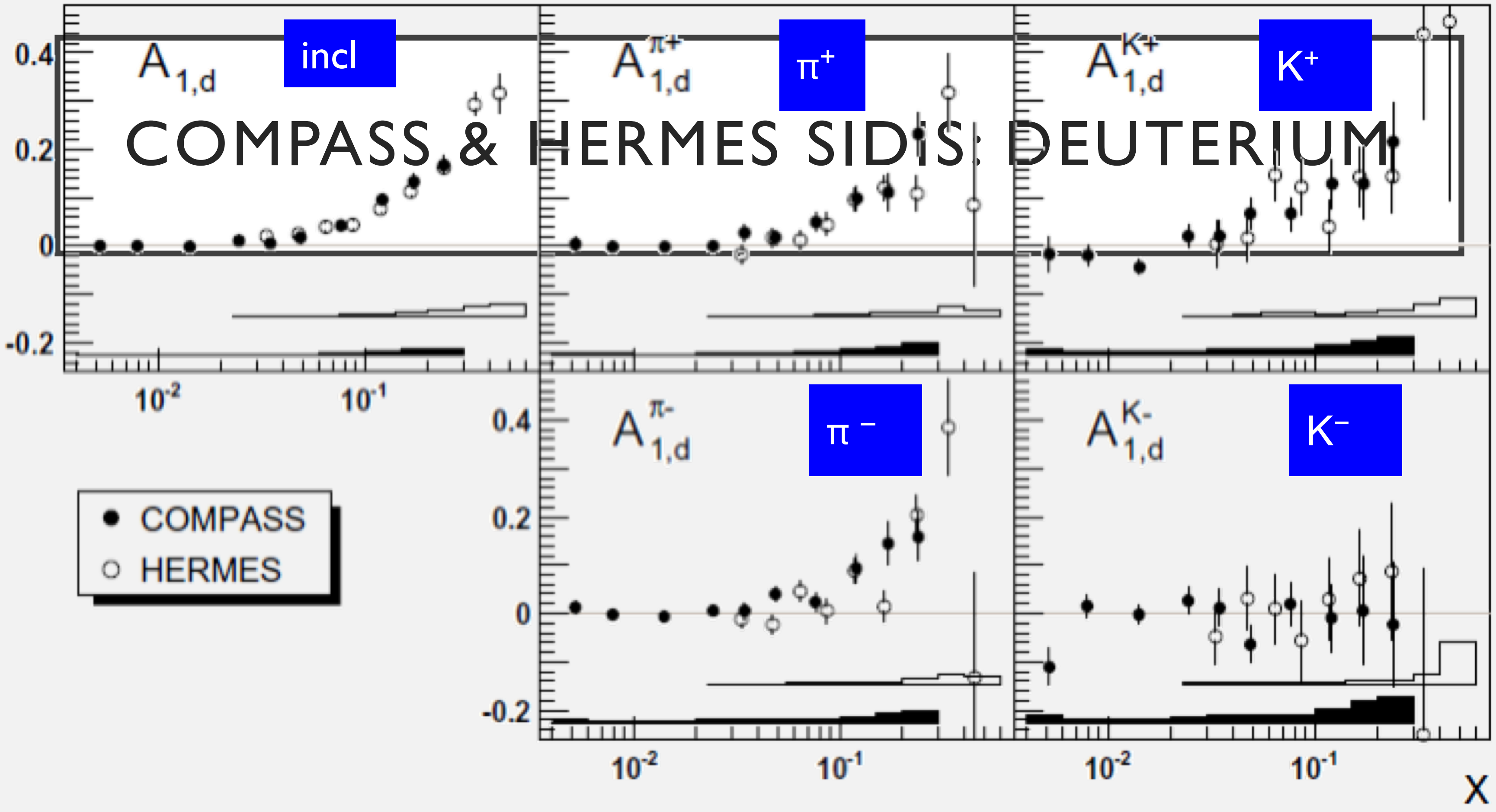
FIRST STEP: HELICITIES

- Structure function $g_1(x)$

g(x)

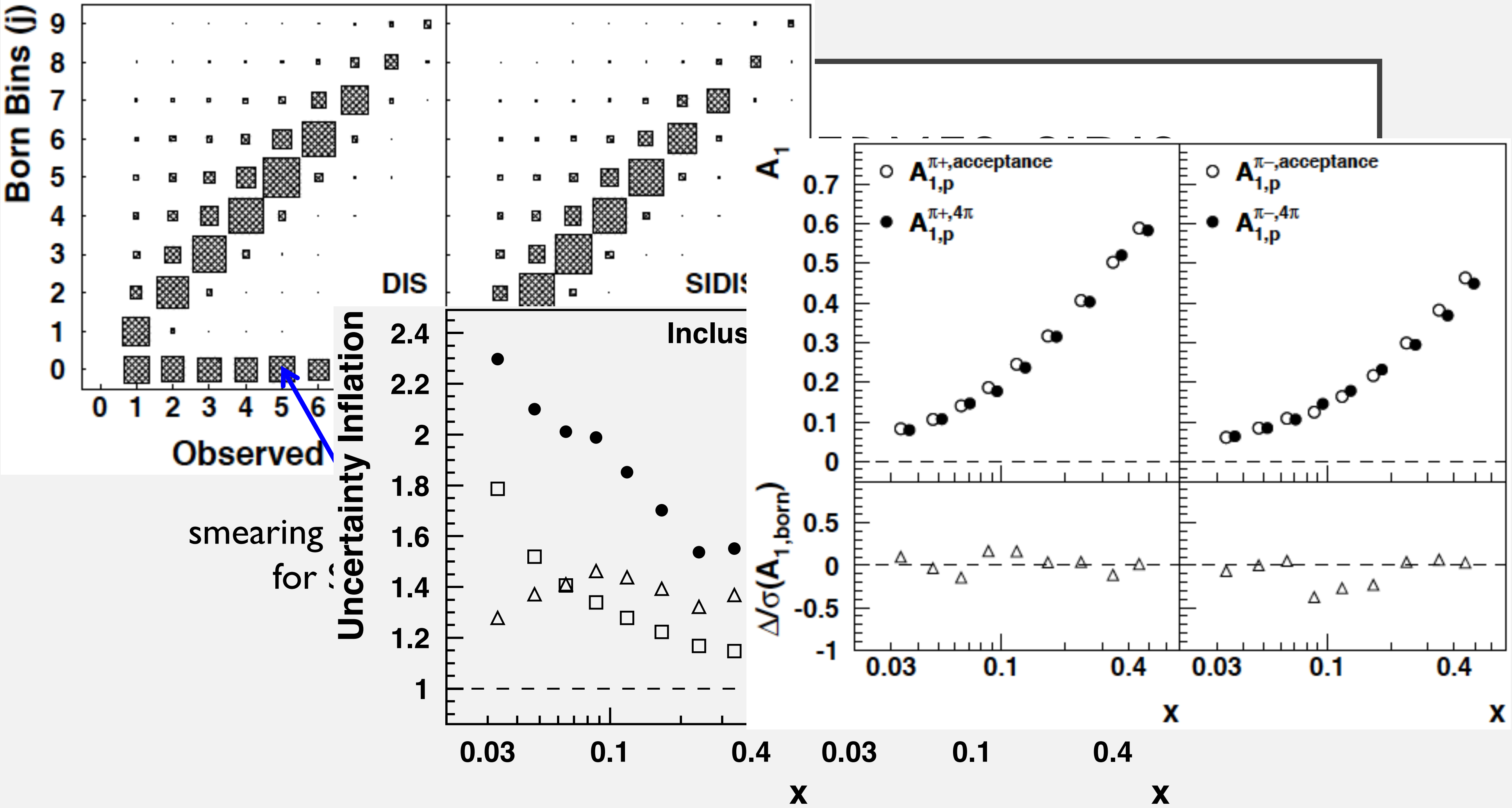


COMPASS & HERMES SIDIS: DEUTERIUM



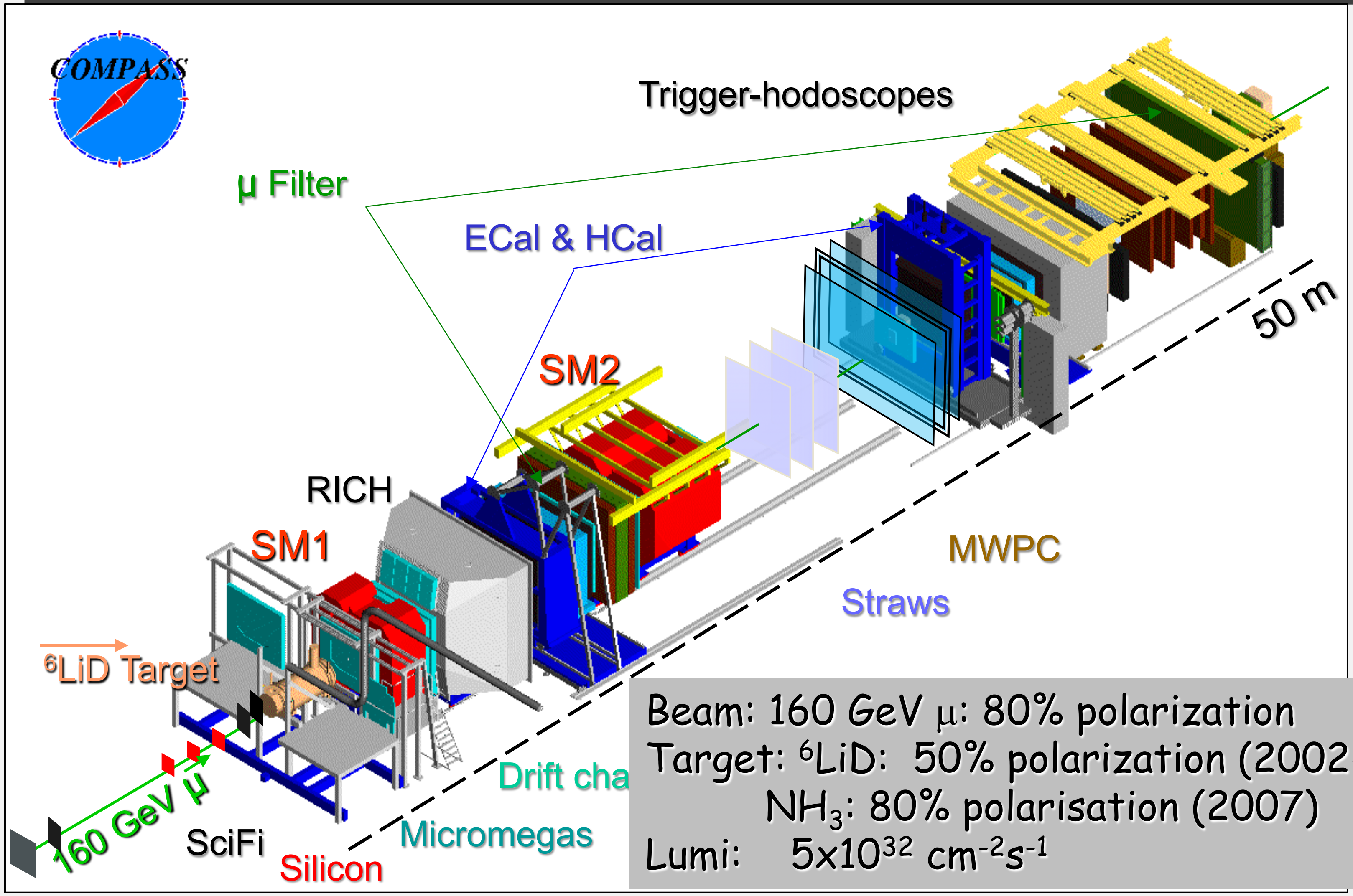
Compass: Deuteron : 2002 – 2006 PLB 680 (2009) 217

Hermes and Compass agree very well



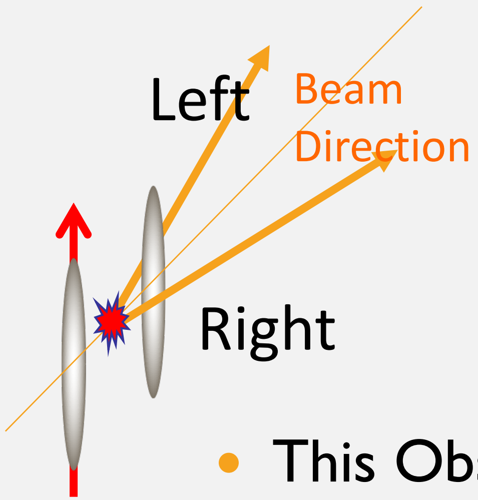
smearing
for

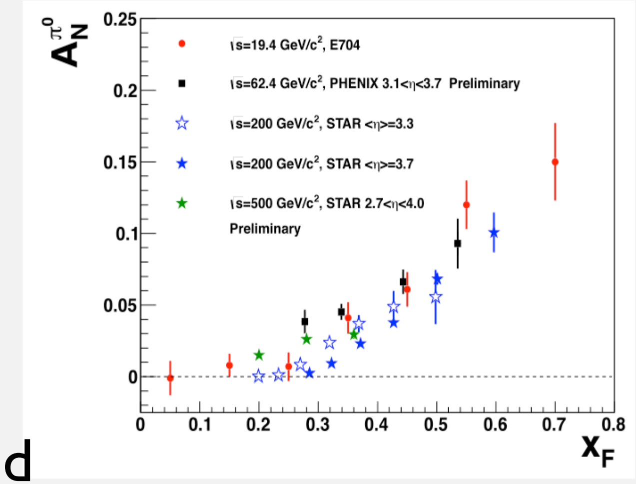
COMPASS



Beam: 160 GeV μ: 80% polarization
Target: ^{6}LiD: 50% polarization (2002-2006)
NH_3: 80% polarisation (2007)
Lumi: 5×10^{32} $cm^{-2}s^{-1}$

ONE OF THE ENDURING MYSTERIES IN P+P COLLISIONS: LARGE TRANSVERSE SINGLE SPIN ASYMMETRIES





- This Observable is (naïve) T-odd
- Spin flip needed:

$$|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow| \quad = \quad |+\rangle\langle+| + |-\rangle\langle-|$$

$$|\uparrow\rangle\langle\uparrow| - |\downarrow\rangle\langle\downarrow| \quad = \quad -i\,|+\rangle\langle-| + i\,|-\rangle\langle+| \quad \longleftarrow \sigma_y$$

$$x_F = p_L/\max p_L \sim_{LO} x_1 - x_2 \sim_{forward} x_1$$

First observation: PRL36, 1113 (1976); PRL41, 607 (1978)

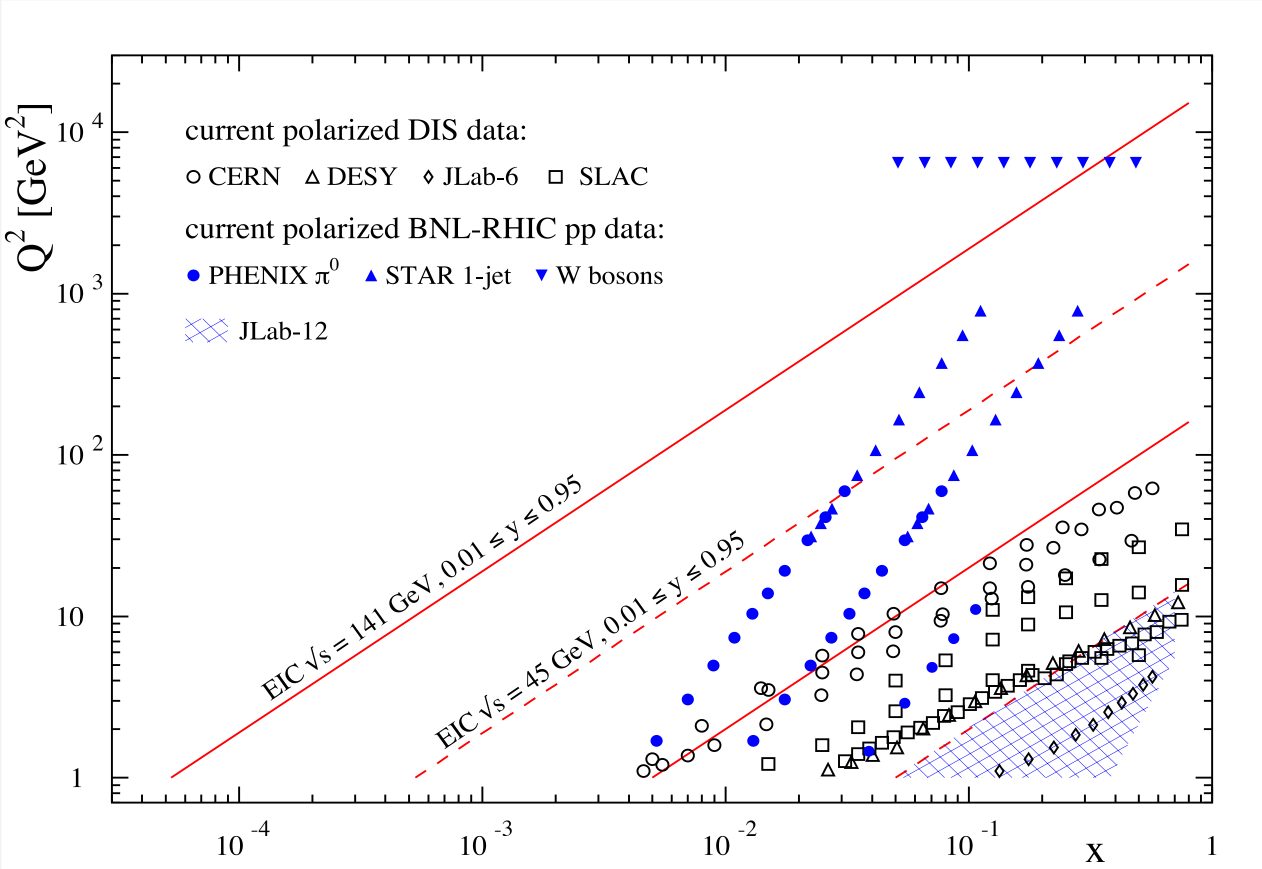
- This Observable is (naïve) T-odd

- Needs Phase shift and is intrinsically linked to transverse momentum (change in L)
- Asymmetries allow access to subleading effects

MAIN SIDIS PLAYERS

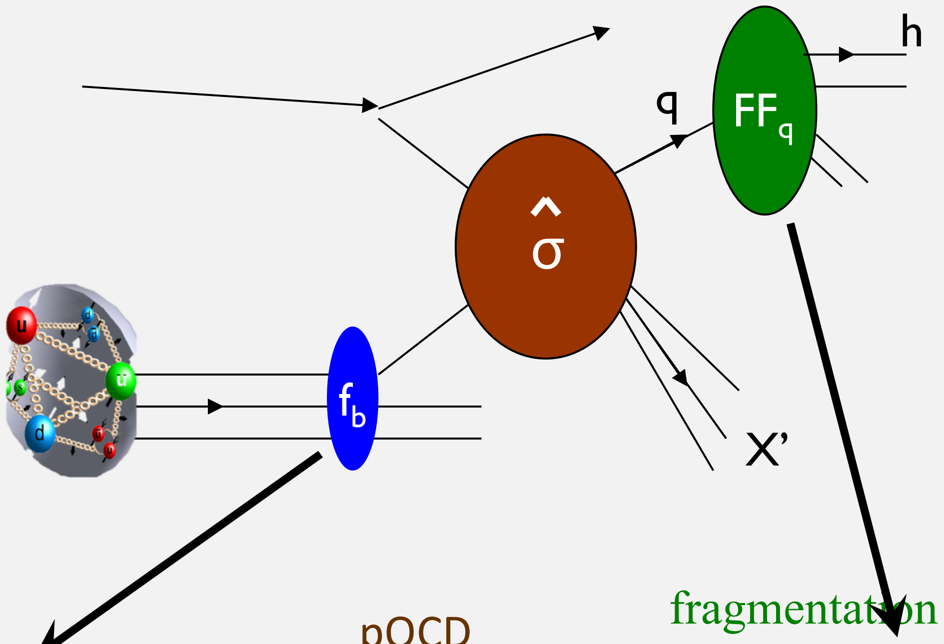
- HERMES at DESY
  - 27.5 GeV electron beam
- EMC, NMC, SMC, COMPASS at CERN
- Muon experiments at CERN SPS proposed 1972
- EMC 1974 to 1986 (polarized target 1983)
- NMC 1986 to 1990
- SMC 1990 to mid-1990s
- COMPASS mid 90s - present

  - 160 - GeV muon beam
- JLAB at 6 GeV



FRAGMENTATION FUNCTIONS APPEAR ALMOST ALWAYS WHEN ACCESSING PARTONIC STRUCTURE OF THE NUCLEON

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes
- Particular important for transverse spin structure
  →need detailed understanding of FFs to use as 'quark polarimeter'



Proton Structure | pQCD | fragmentation function

$$\frac{d^2\sigma(ep \rightarrow \pi X)}{dx\, dz} \propto q(x, k_T) \times \frac{d\sigma^2(e\, q \rightarrow e' q')}{dx} \times FF(z, p_T)$$

FFs can be extracted from semi-inclusive data if other non-perturbative functions appearing in the x-section are known

KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMI X 40

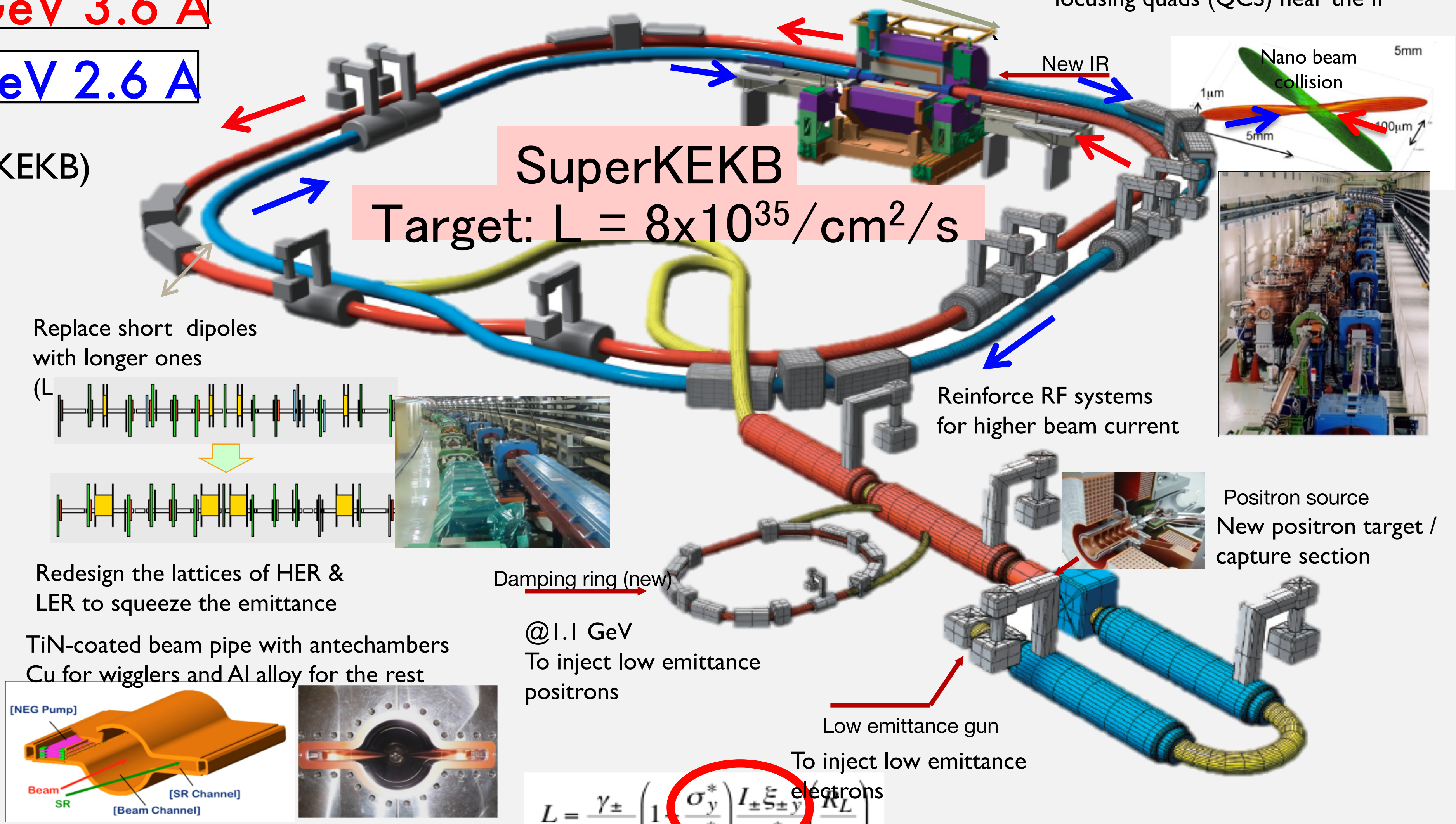
Belle II

e^+ 4GeV 3.6 A

e^- 7GeV 2.6 A

(~2x KEKB)

New superconducting final focusing quads (QCS) near the IP



Replace short dipoles with longer ones

(L

Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers
Cu for wigglers and Al alloy for the rest

Reinforce RF systems for higher beam current

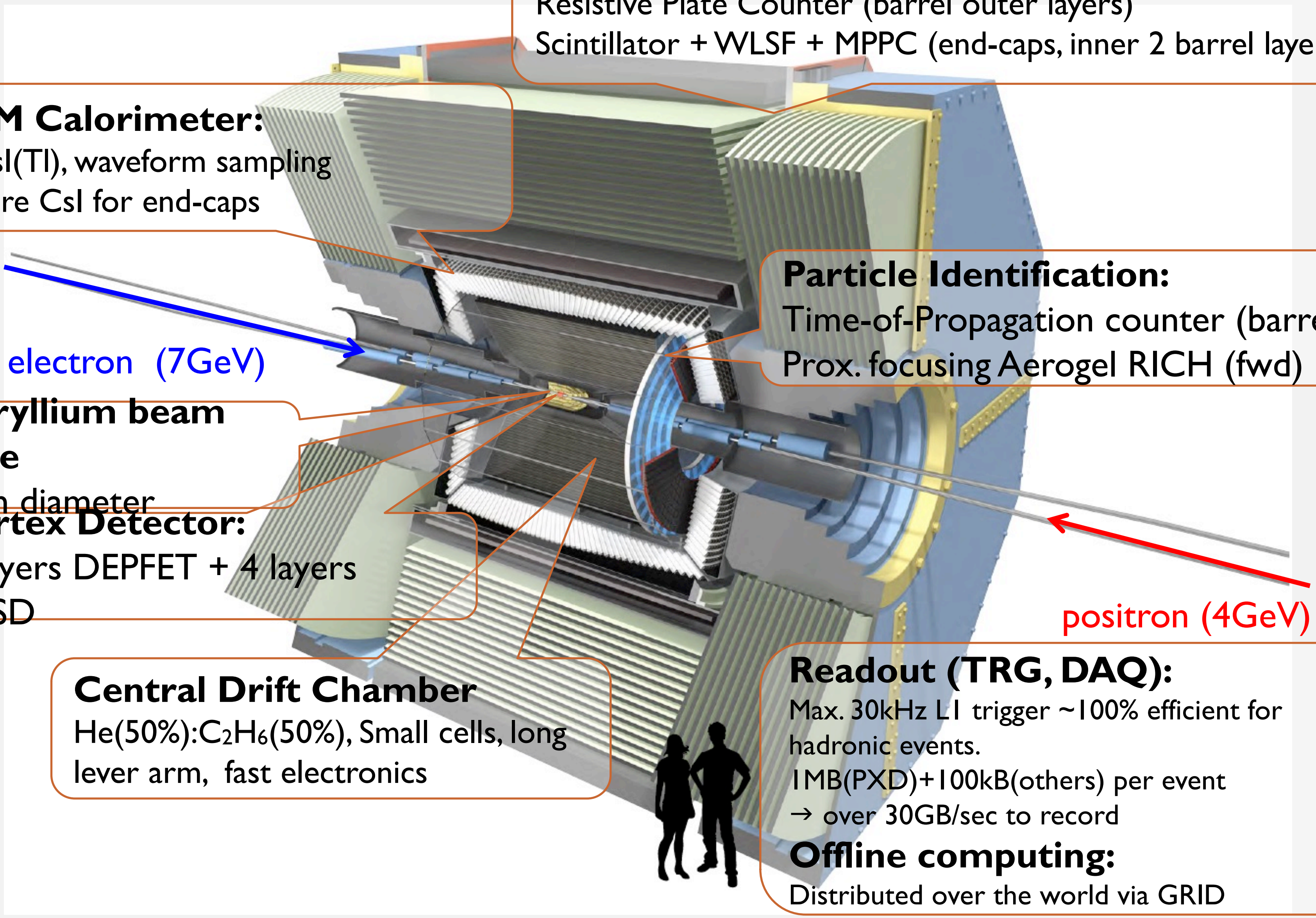
Positron source
New positron target / capture section

@1.1 GeV
To inject low emittance positrons

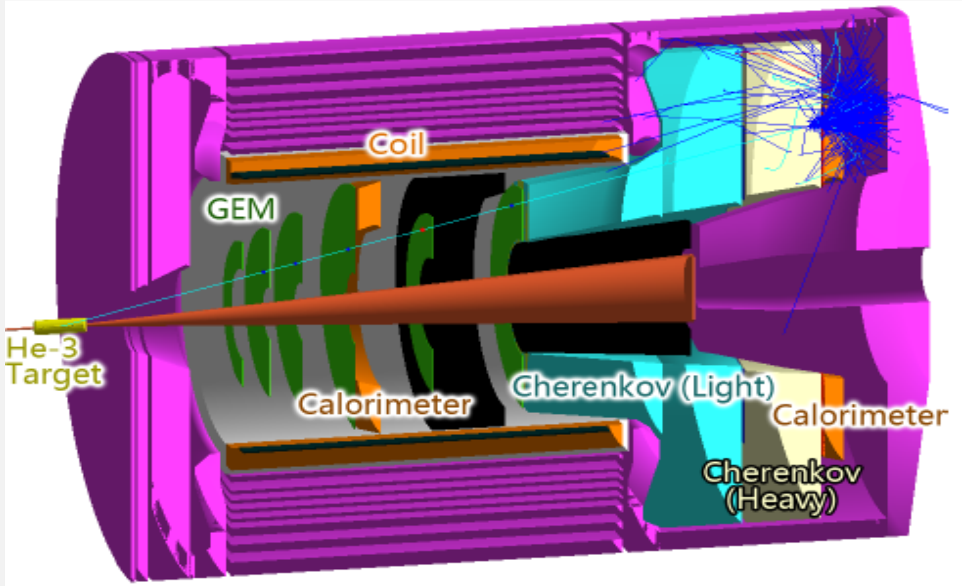
Low emittance gun
To inject low emittance electrons

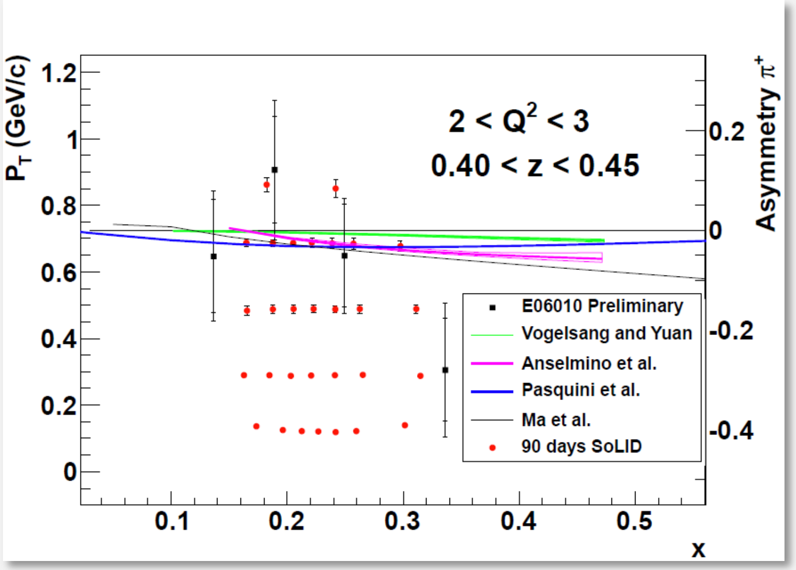
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

CUT VIEW OF BELLE II DETECTOR



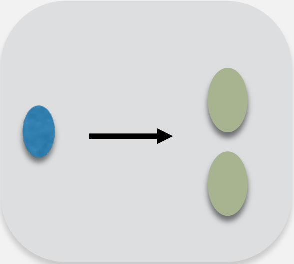
FUTURE: EXAMPLE COLLINS ASYMMETRIES WITH SOLID AT JLAB





- Capable of handling up to full 10^{39} cm^{-2}/s^{-1} luminosity of CEBAF12 (compare to 10^{35} of CLAS12)

DI-HADRON FRAGMENTATION FUNCTIONS



<u>Additional Observable:</u>

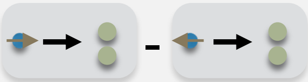
$\vec{R} = \vec{P_1} - \vec{P_2}$:

The relative momentum of the hadron pair is an additional degree of freedom:

the orientation of the two hadrons w.r.t. each other and the jet direction can be an indicator of the quark transverse spin

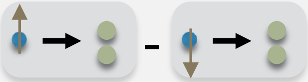
Do not need

Small $\vec{R}$: non-perturbative object.



$G_1^{\perp}$: T-odd FF

- chiral-even function
- log. polarized q → two unp. Hadrons
- →connection to jet-handedness and (possibly) QCD vacuum structure



$H_1^{\sphericalangle}$: T-odd FF

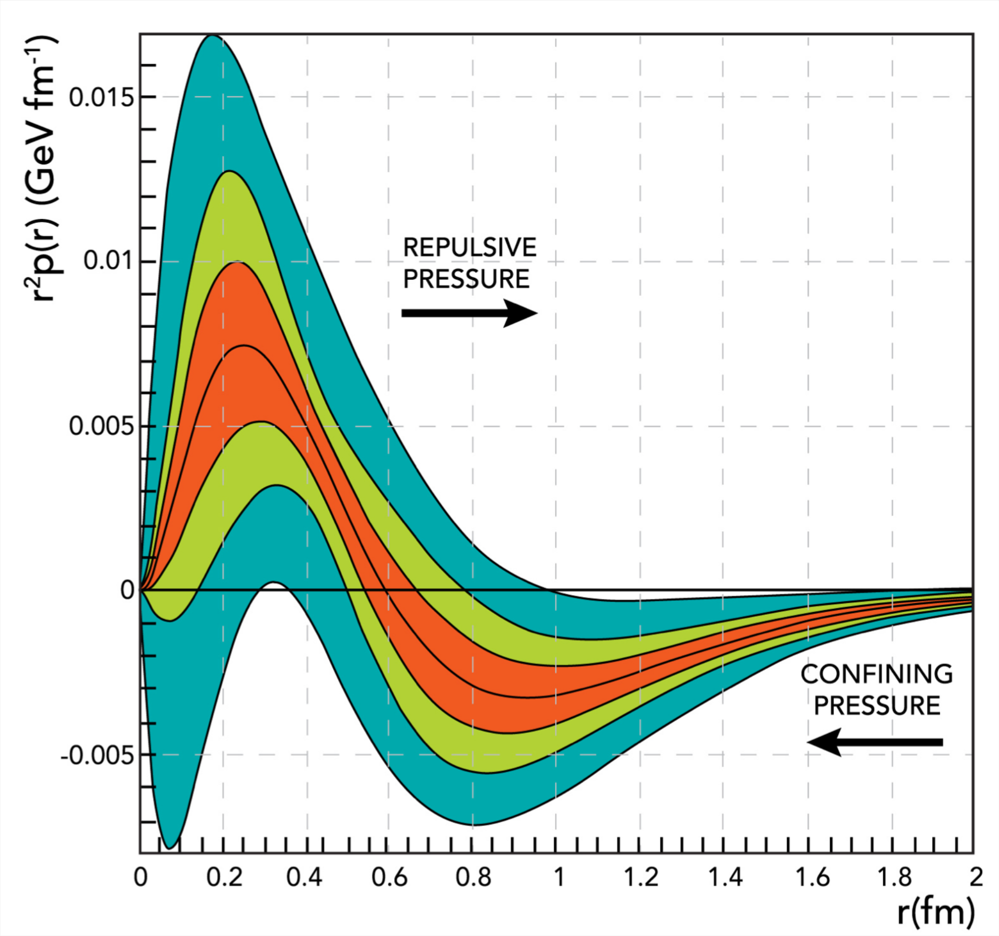
- Chiral-odd function
- Transv. polarized q → two unp. Hadrons
- →Collinear! (unlike Collins)

THE PRESSURE DISTRIBUTION INSIDE THE PROTON

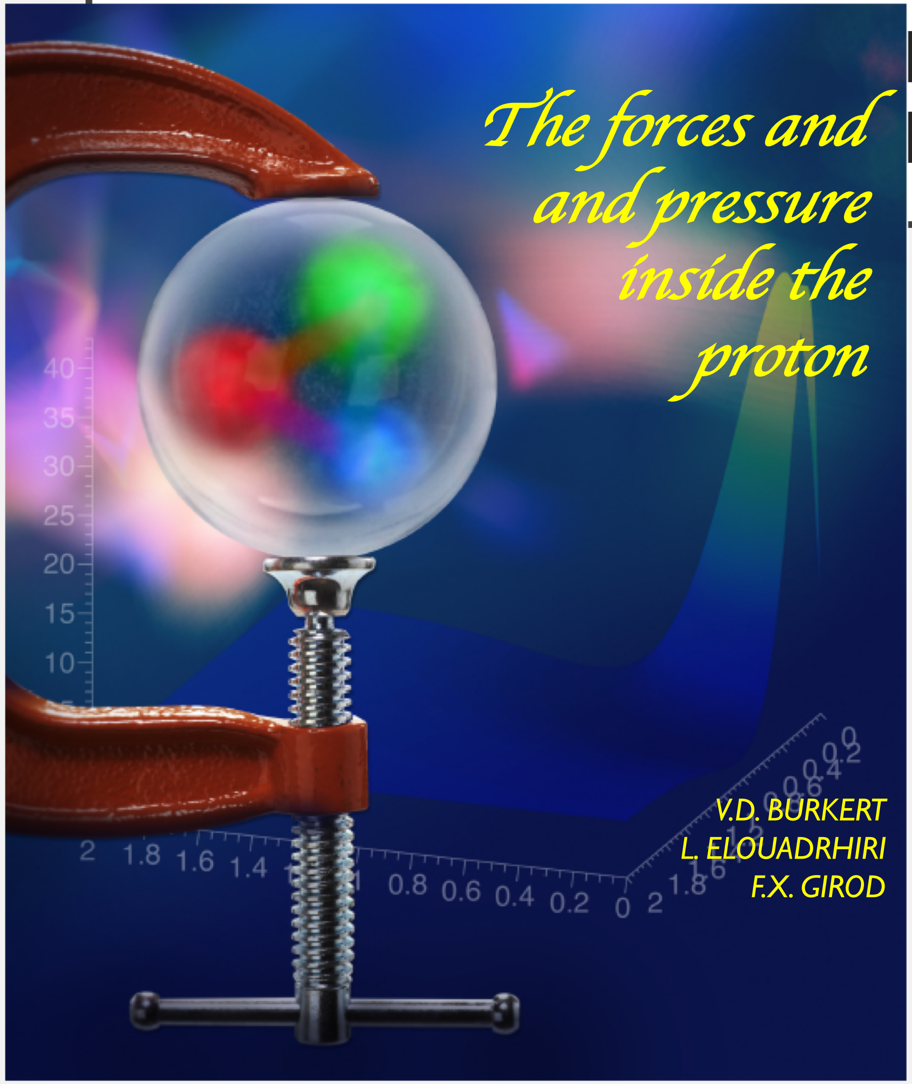
$$d_1(t) \propto \int \mathrm{d}^3\mathbf{r}\, \frac{j_0(r\sqrt{-t})}{2t}\, p(r)$$

Repulsive pressure at
r < 0.6 fm <p> 10^{35} Pa

Confining pressure at
r > 0.6 fm



Atmospheric pressure: 10^5 Pa
Pressure in the center of neutron stars < 10^{34} Pa



The pressure distribution inside the proton

V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]

The proton, one of the components of atomic nuclei, is composed of fundamental particles called quarks and gluons. Gluons are the carriers of the force that binds quarks together, and free quarks are never found in isolation—that is, they are confined within the composite particles in which they reside. The origin of quark confinement is one of the most important questions in modern particle and nuclear physics because confinement is at the core of what makes the proton a stable particle and thus provides stability to the Universe. The internal quark structure of the proton is revealed by deeply virtual Compton scattering[1,2], a process in which electrons that are scattered off quarks inside the proton subsequently emit high-energy photons, which are detected in coincidence with the scattered electrons and recoil protons. Here we report a measurement of the pressure distribution experienced by the quarks in the proton. We find a strong repulsive pressure near the centre of the proton (up to 0.6 femtometers) and a binding pressure at greater distances. The average peak pressure near the centre is about 10^{35} pascals, which exceeds the pressure estimated for the most densely packed known objects in the Universe, neutron stars[3]. This work opens up a new area of research on the fundamental gravitational properties of protons, neutrons and nuclei, which can provide access to their physical radii, the internal shear forces acting on the quarks and their pressure distributions.

The basic mechanical properties of the proton are encoded in the gravitational form factors (GFFs) of the energy–momentum tensor[1,4,5]. Graviton–proton scattering is the only known process that can be used to directly measure these form factors[4,6], whereas generalized parton distributions[2,7,8] enable indirect access to the basic mechanical properties of the proton[2].

A direct determination of the quark pressure distribution in the proton (Fig. 1) requires measurements of the proton matrix element of the energy–momentum tensor[9]. This matrix element contains three scalar GFFs that depend on the four-momentum transfer t to the proton. One of these GFFs, $d_1(t)$, encodes the shear forces and pressure distribution on the quarks in the proton, and the other two, $M_2(t)$ and $J(t)$, encode the mass and angular momentum distributions. Experimental information on these form factors is essential to gain insight into the dynamics of the fundamental constituents of the proton. The framework of generalized parton distributions (GPDs)[2,7,8] has provided a way to obtain information on $d_1(t)$ from experiments. The most effective way to access GPDs experimentally is deeply virtual Compton scattering (DVCS)[1,2], where high-energy electrons (e) are scattered from the protons (p) in liquid hydrogen as $e\,p \to e'\,p'\,\gamma$, and the scattered electron (e'), proton (p') and photon (γ) are detected in coincidence. In this process, the quark structure is probed with high-energy virtual photons that are exchanged between the scattered electron and the proton, and the emitted (real) photon controls the momentum transfer t to the proton, while leaving the proton intact. Recently, methods have been developed to extract information about the GPDs and the related Compton form factors (CFFs) from DVCS data[10–13].

To determine the pressure distribution in the proton from the experimental data, we follow the steps that we briefly describe here. We note that the GPDs, CFFs and GFFs apply only to quarks, not to gluons.

(1) We begin with the sum rules that relate the Mellin moments of the GPDs to the GFFs[1].

(2) We then define the complex CFF, $\mathcal{H}$, which is directly related to the experimental observables describing the DVCS process, that is, the differential cross-section and the beam-spin asymmetry.

(3) The real and imaginary parts of $\mathcal{H}$ can be related through a dispersion relation[14–16] at fixed t, where the term $D(t)$, or D-term, appears as a subtraction term[17].

(4) We derive $d_1(t)$ from the expansion of $D(t)$ in the Gegenbauer polynomials of ξ, the momentum transfer to the struck quark.

(5) We apply fits to the data and extract $D(t)$ and $d_1(t)$.

(6) Then, we determine the pressure distribution from the relation between $d_1(t)$ and the pressure $p(r)$, where r is the radial distance from the proton's centre, through the Bessel integral.

The sum rules that relate the second Mellin moments of the chiral-even GPDs to the GFFs are[1]:

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,dx = 2J(t)$$

$$\int xH(x,\xi,t)dx = M_2(t)+\frac{4}{5}\xi^2 d_1(t)$$

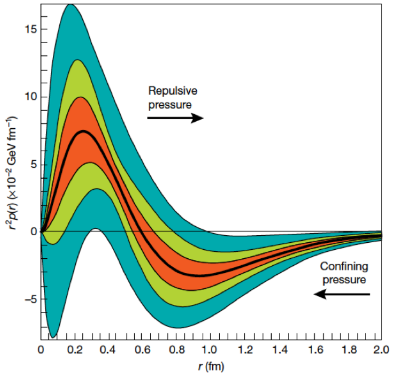


Fig. 1 | Radial pressure distribution in the proton. The graph shows the pressure distribution $r^2p(r)$ that results from the interactions of the quarks in the proton versus the radial distance r from the centre of the proton. The thick black line corresponds to the pressure extracted from the D-term parameters fitted to published data[22] measured at 6 GeV. The corresponding estimated uncertainties are displayed as the light-green shaded area shown. The blue area represents the uncertainties from all the data that were available before the 6-GeV experiment, and the red shaded area shows projected results from future experiments at 12 GeV that will be performed with the upgraded apparatus. Uncertainties represent one standard deviation.

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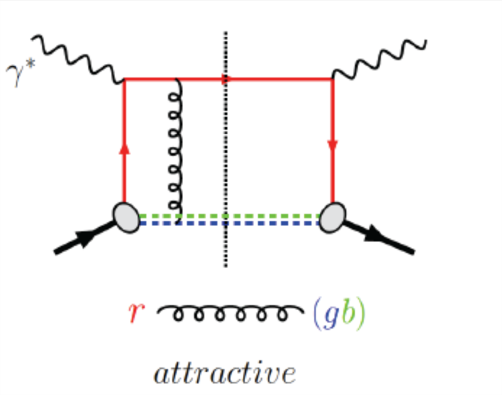
TRANSVERSE MOMENTUM DEPENDENT DISTRIBUTIONS (TMDS)

Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	$f_1 =$		$h_1^{\perp} =$ −
	L		$g_1 =$ −	$h_{1L}^{\perp} =$ −
	T	$f_{1T}^{\perp} =$ −	$g_{1T} =$ −	$h_1 =$ − $h_{1T}^{\perp} =$ −

TMDS LINK TO TRANSVERSE SINGLE SPIN ASYMMETRIES

- On amplitude level need interference and phase shift
- Linked to different L



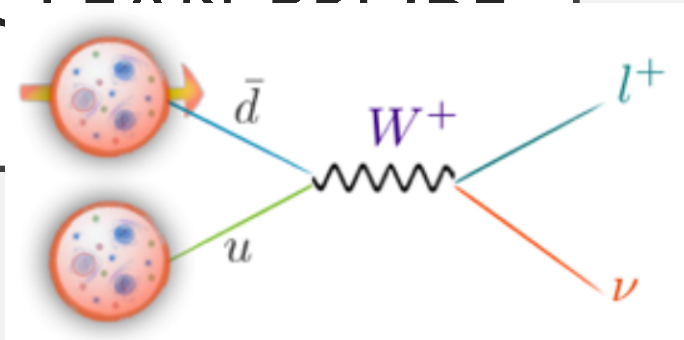
- This Observable is (naïve) T-odd
- Spin flip needed:

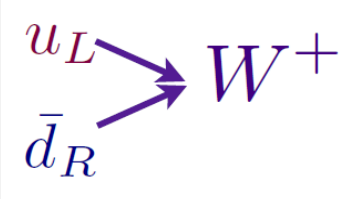
$$
\begin{aligned}
|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow| &= |+\rangle\langle+| + |-\rangle\langle-| \\
|\uparrow\rangle\langle\uparrow| - |\downarrow\rangle\langle\downarrow| &= -i\,|+\rangle\langle-| + i\,|-\rangle\langle+| \quad \longleftarrow \sigma_y
\end{aligned}
$$

- This Observable is (naïve) T-odd
- Needs Phase shift and is intrinsically linked to transverse momentum (change in L)
- Asymmetries allow access to subleading effects

W PRODUCTION IN P+P: CLEAN PROBE OF THE SEA

- Maximal parity violating coupling selects helicities



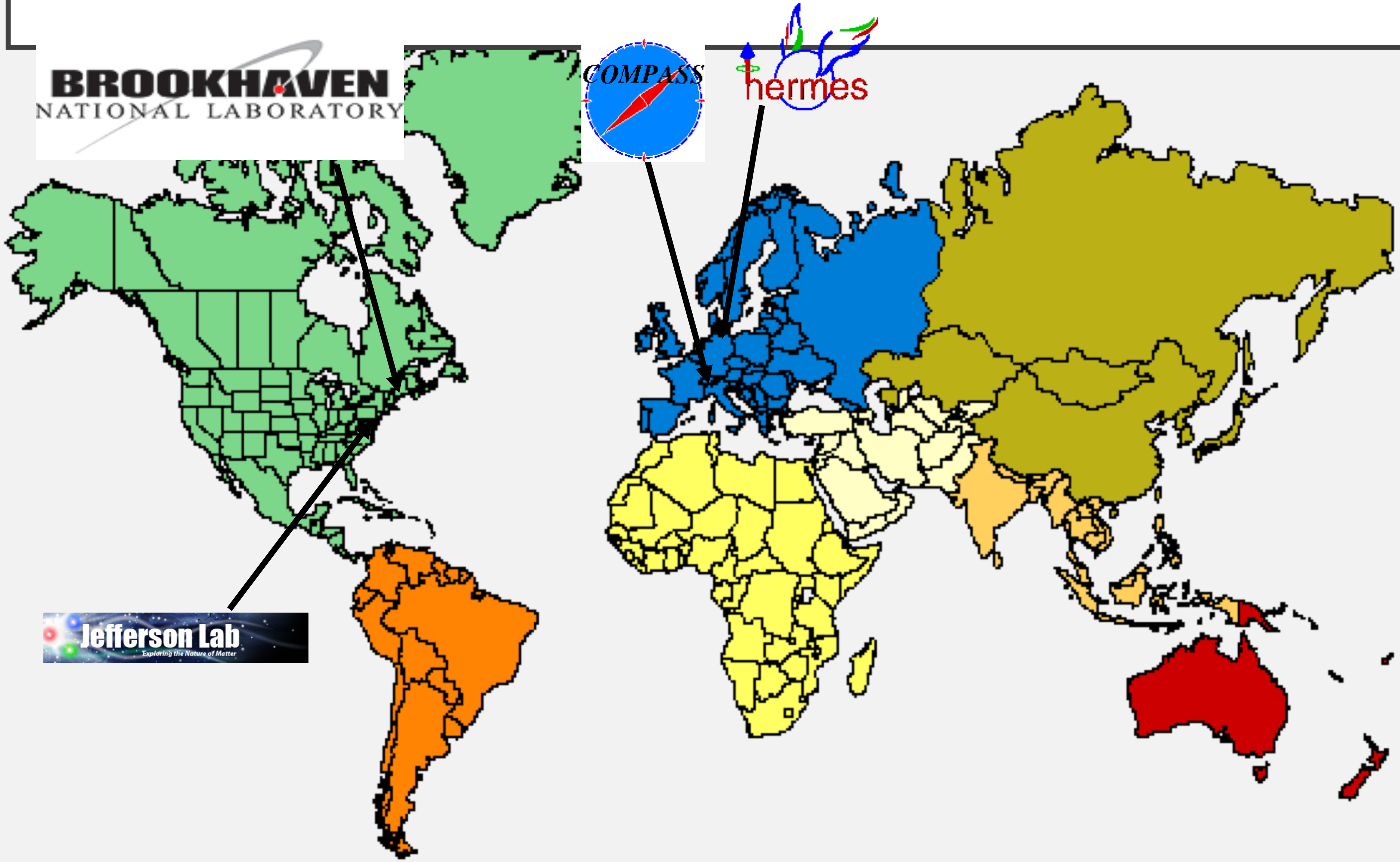


$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)}$$

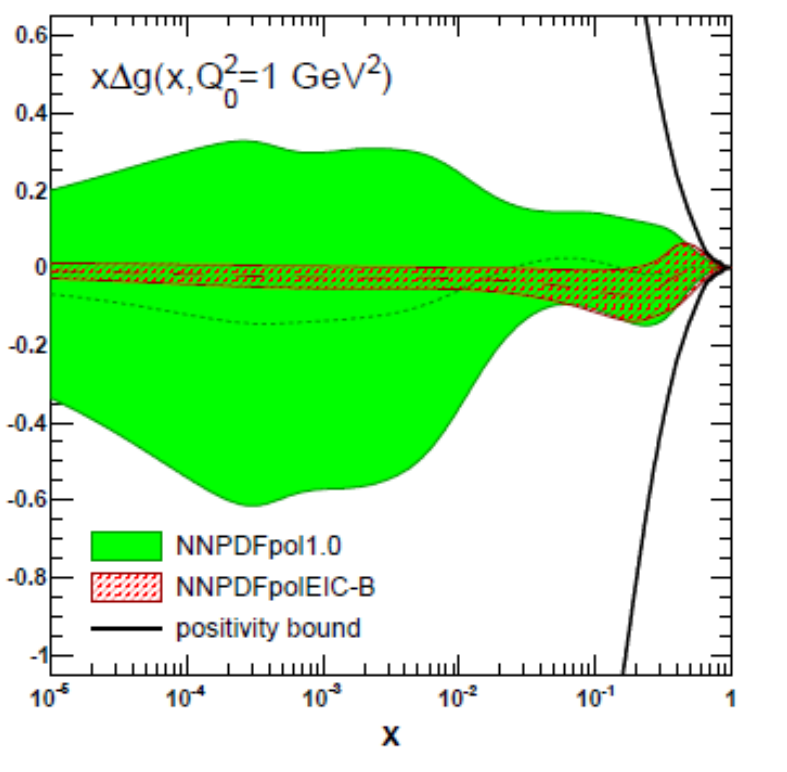
$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)}$$

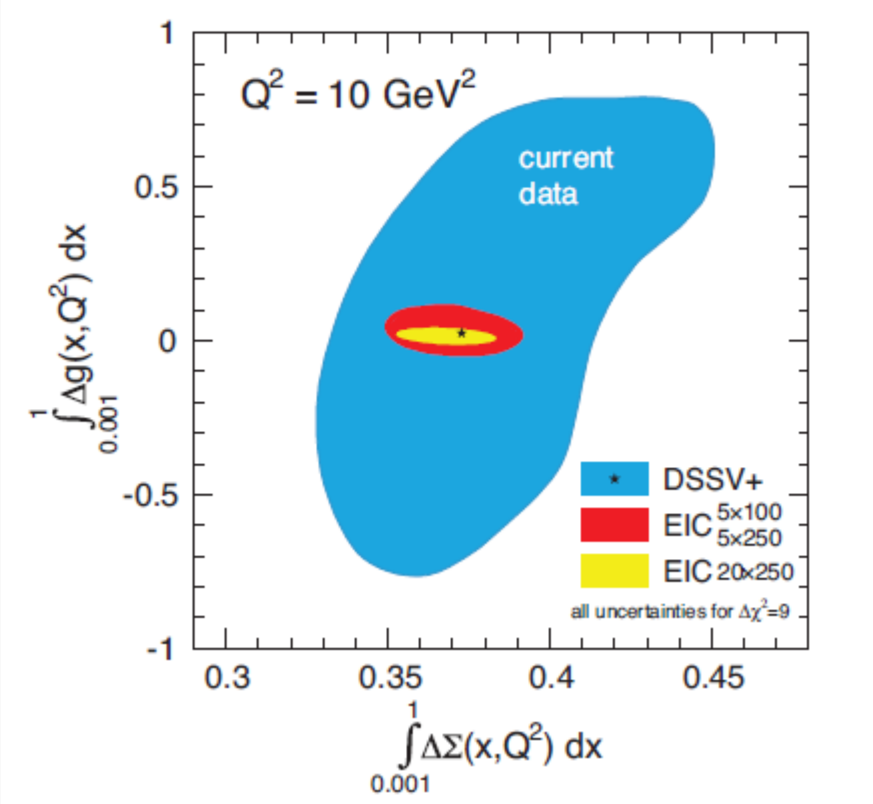
- STAR: $W^{+-} \rightarrow e^{+-}$ in $|\eta| < 1.3$
- PHENIX $W^{+-} \rightarrow e^{+-}$ central, $\rightarrow \mu$ $1<|\eta|<2$

THE CONTEMPORARY "SPIN" EXPERIMENTS



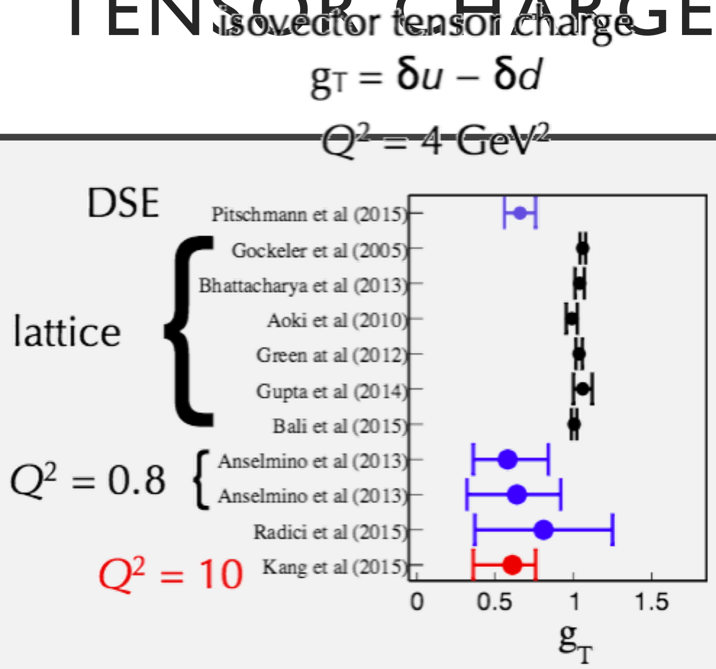
FUTURE WITH EIC

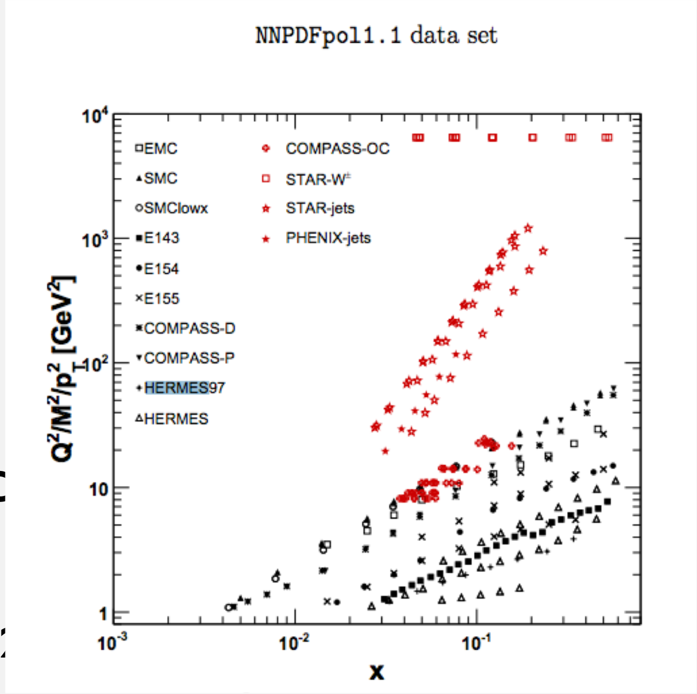




- 1 year of EIC running will pin down gluon polarization

TENSOR CHARGE



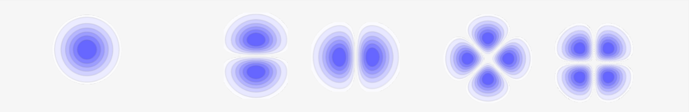


- Still a lot to do to get experimental precision to lattic predictions
- **STAR data will provide higher precision and Q**
- **JLAB12 will give high precision at high x**

Multipole structure

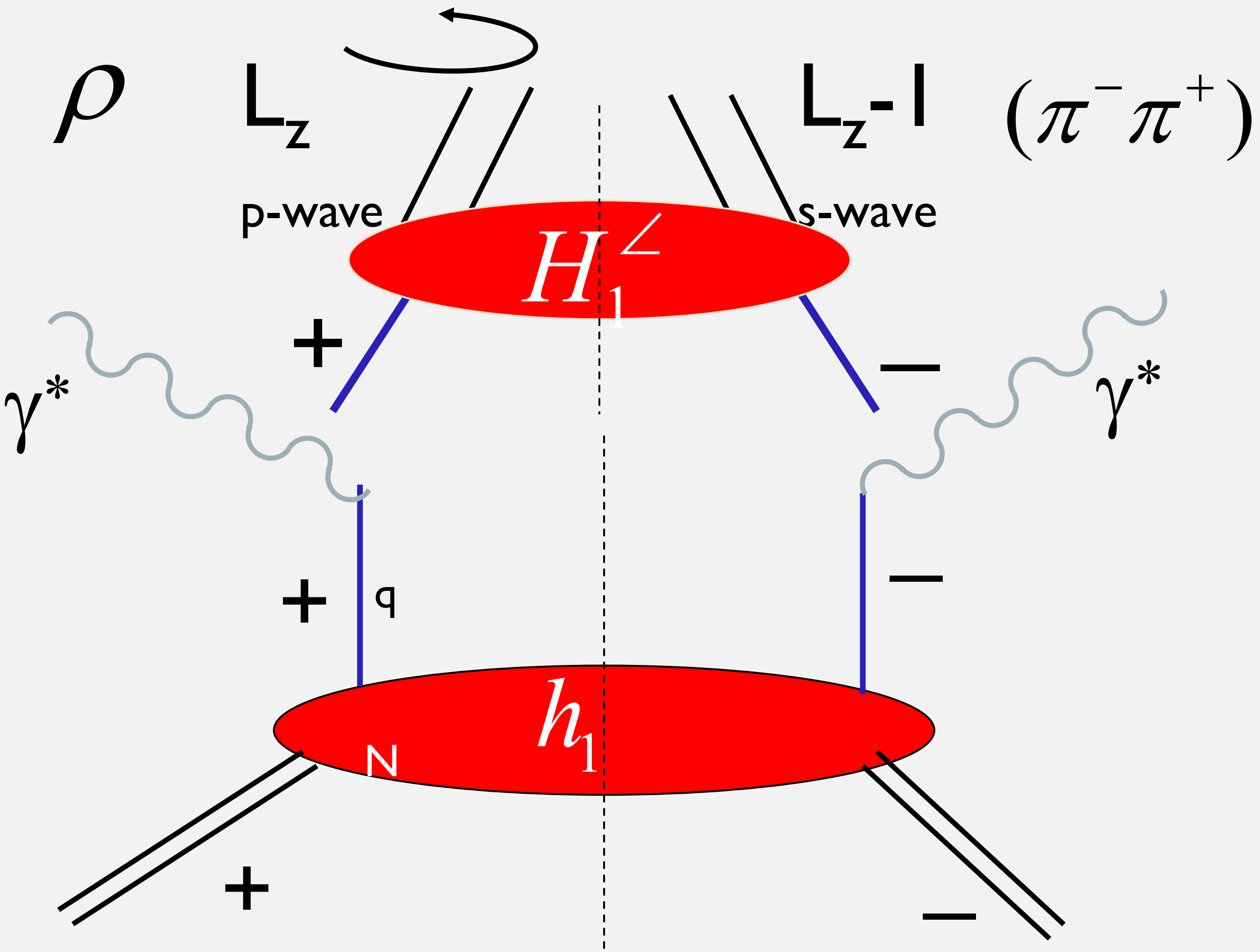
Quark polarization (columns); Nucleon polarization (rows)

	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M}\, h_1^{\perp}$	$-\frac{k_x}{M}\, h_1^{\perp}$	
T_x	$\frac{k_y}{M}\, f_{1T}^{\perp}$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^{\perp}$	$\frac{k_x k_y}{M^2}\, h_{1T}^{\perp}$	$\frac{k_x}{M}\, g_{1T}$
T_y	$-\frac{k_x}{M}\, f_{1T}^{\perp}$	$\frac{k_x k_y}{M^2}\, h_{1T}^{\perp}$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^{\perp}$	$\frac{k_y}{M}\, g_{1T}$
L		$\frac{k_x}{M}\, h_{1L}^{\perp}$	$\frac{k_y}{M}\, h_{1L}^{\perp}$	g_{1L}



Monopole **Dipole** **Quadrupole**

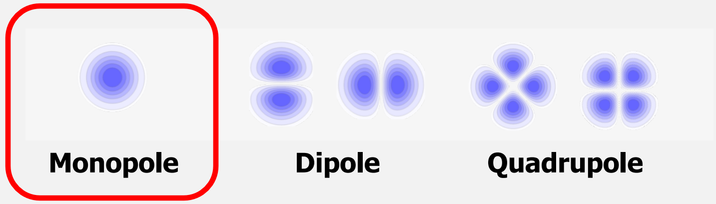
Interference Fragmentation Function



Multipole structure

Quark polarization (columns); Nucleon polarization (rows)

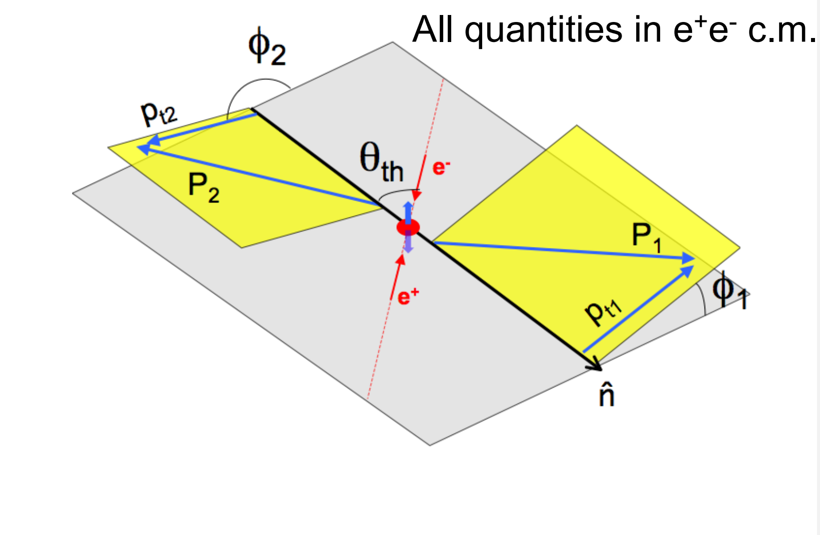
	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M}\, h_1^{\perp}$	$-\frac{k_x}{M}\, h_1^{\perp}$	
T_x	$\frac{k_y}{M}\, f_{1T}^{\perp}$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^{\perp}$	$\frac{k_x k_y}{M^2}\, h_{1T}^{\perp}$	$\frac{k_x}{M}\, g_{1T}$
T_y	$-\frac{k_x}{M}\, f_{1T}^{\perp}$	$\frac{k_x k_y}{M^2}\, h_{1T}^{\perp}$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^{\perp}$	$\frac{k_y}{M}\, g_{1T}$
L		$\frac{k_x}{M}\, h_{1L}^{\perp}$	$\frac{k_y}{M}\, h_{1L}^{\perp}$	g_{1L}



COLLINS EFFECT

RF12 or Thrust RF

BaBar
Belle
~~BESIII~~

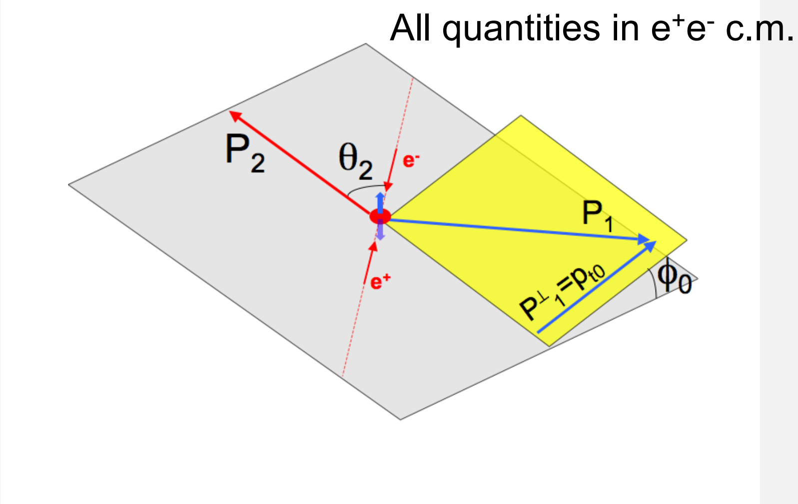


- **Thrust axis** to estimate the $q\bar{q}$ direction
- $\varphi_{1,2}$ defined using thrust-beam plane

Normalized cross-section: $e^+e^- \to (h_1 h_2)(\overline{h_1}\ \overline{h_2}) + X$

$$\propto 1 + + H_1^\perp \cdot \overline{H_1^\perp} \cos(\phi_1 + \phi_2)$$

RF0 or Second hadron momentum RF



BaBar
Belle
BESIII

- Use **one track** in a pair
- Very clean experimentally (no thrust axis)

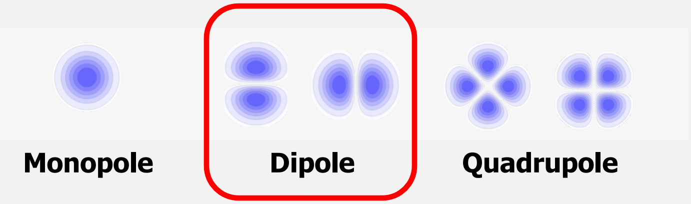
Normalized cross-section: $e^+e^- \to (h_1 h_2)(\overline{h_1}\ \overline{h_2}) + X$

$$\propto 1 + + H_1^\perp * \overline{H_1^\perp} \cos(2\phi_0)$$

Multipole structure

Quark polarization (columns) / Nucleon polarization (rows)

	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M} h_1^\perp$	$-\frac{k_x}{M} h_1^\perp$	
T_x	$\frac{k_y}{M} f_{1T}^\perp$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2} h_{1T}^\perp$	$\frac{k_x k_y}{M^2} h_{1T}^\perp$	$\frac{k_x}{M} g_{1T}$
T_y	$-\frac{k_x}{M} f_{1T}^\perp$	$\frac{k_x k_y}{M^2} h_{1T}^\perp$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2} h_{1T}^\perp$	$\frac{k_y}{M} g_{1T}$
L		$\frac{k_x}{M} h_{1L}^\perp$	$\frac{k_y}{M} h_{1L}^\perp$	g_{1L}

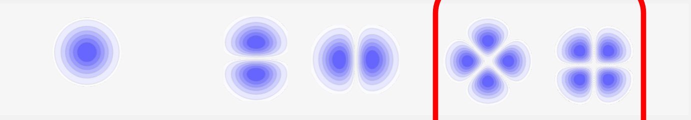


Transverse-momentum distributions (TMDs)

Multipole structure

Quark polarization (columns) / Nucleon polarization (rows)

	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M}\, h_1^{\perp}$	$-\frac{k_x}{M}\, h_1^{\perp}$	
T_x	$\frac{k_y}{M}\, f_{1T}^{\perp}$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^{\perp}$	$\frac{k_x k_y}{M^2}\, h_{1T}^{\perp}$	$\frac{k_x}{M}\, g_{1T}$
T_y	$-\frac{k_x}{M}\, f_{1T}^{\perp}$	$\frac{k_x k_y}{M^2}\, h_{1T}^{\perp}$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^{\perp}$	$\frac{k_y}{M}\, g_{1T}$
L		$\frac{k_x}{M}\, h_{1L}^{\perp}$	$\frac{k_y}{M}\, h_{1L}^{\perp}$	g_{1L}



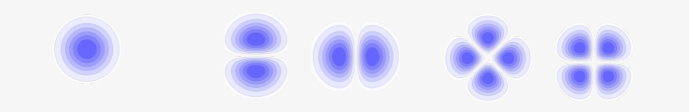
Monopole Dipole Quadrupole

Multipole structure

Quark polarization

Nucleon polarization

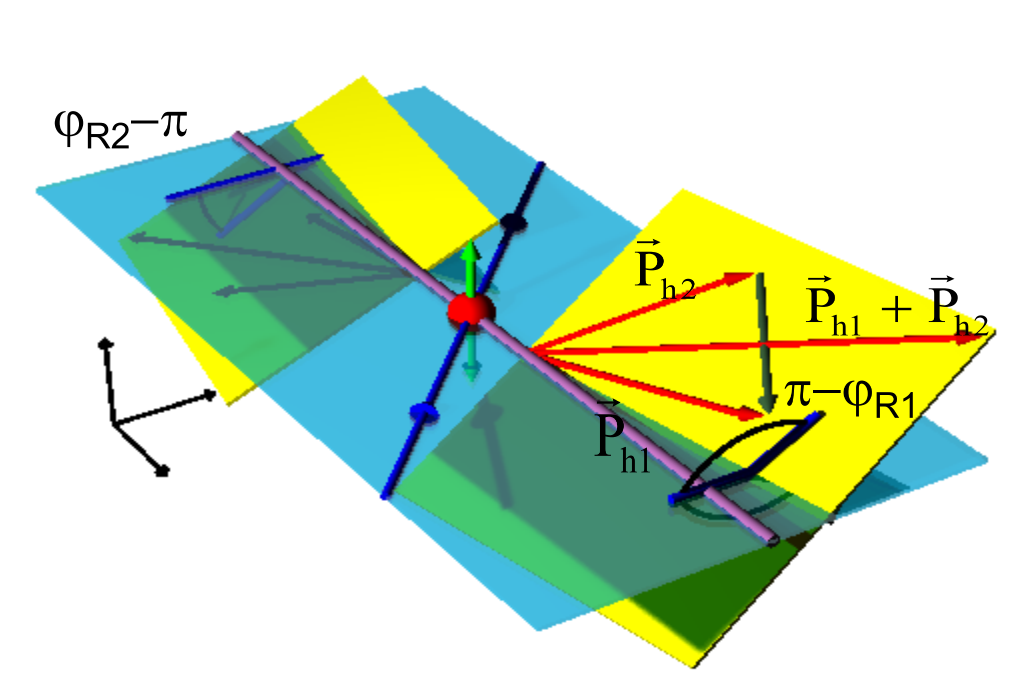
	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M}\, h_1^\perp$	$-\frac{k_x}{M}\, h_1^\perp$	
T_x	$\frac{k_y}{M}\, f_{1T}^\perp$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$\frac{k_x}{M}\, g_{1T}$
T_y	$-\frac{k_x}{M}\, f_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_y}{M}\, g_{1T}$
L		$\frac{k_x}{M}\, h_{1L}^\perp$	$\frac{k_y}{M}\, h_{1L}^\perp$	g_{1L}



Monopole Dipole Quadrupole

Naive T-odd !

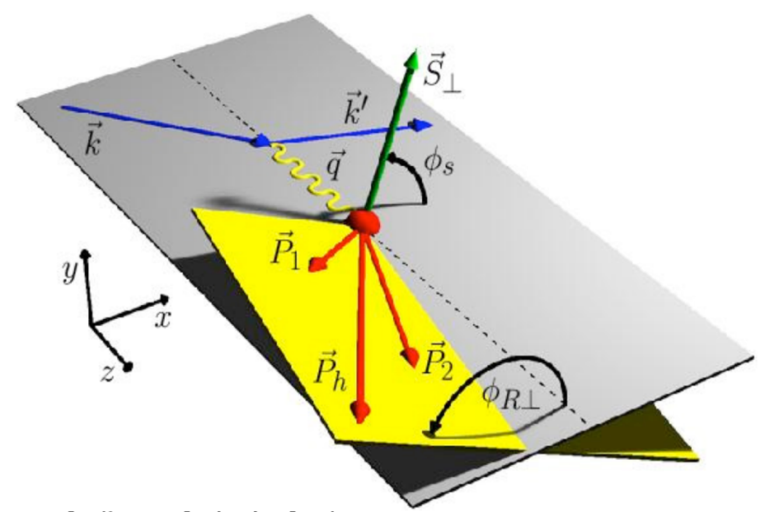
DI-HADRON ASYMMETRIES

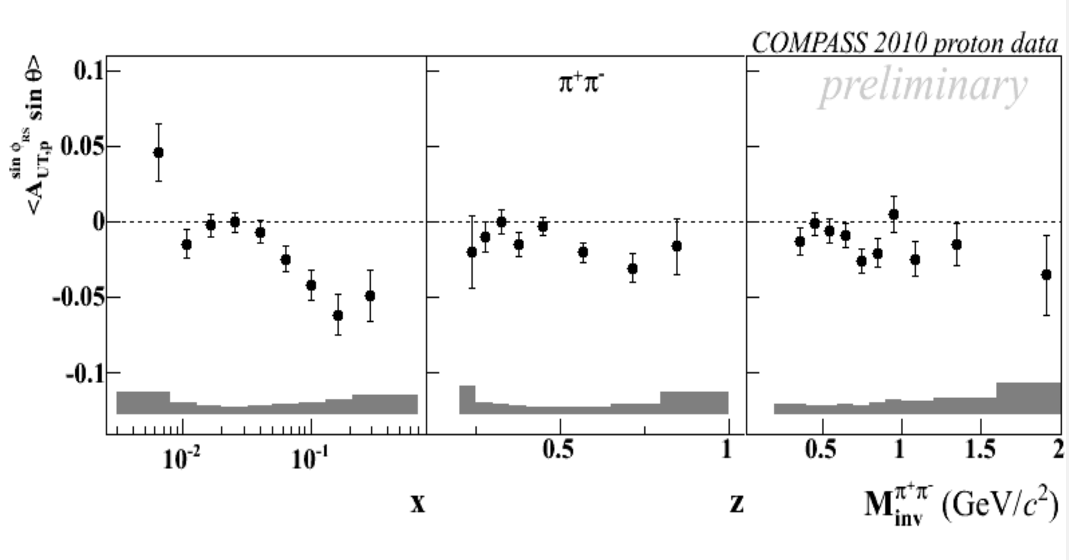


- *Conceptually similar measurement as Collins with* $\overrightarrow{P_{h\perp}} \leftrightarrow \overrightarrow{R_{\perp}}$
- *Normalized cross section:*
  $e^+e^- \to (h_1h_2)\left(\overline{h_1}\ \overline{h_2}\right) + X \propto 1 + H_1^{\angle}\overline{H_1^{\angle}}\cos(\phi_{R1} + \phi_{R2}) + G_1^{\perp}\overline{G_1^{\perp}}\cos(2(\phi_{R1} - \phi_{R2}))$
- See talks by Aram and Marco

DI-HADRON ASYMMETRIES: $A^{SIN(\Phi R+\Phi S)}$□ $H_1 \bullet H_1^{<}$

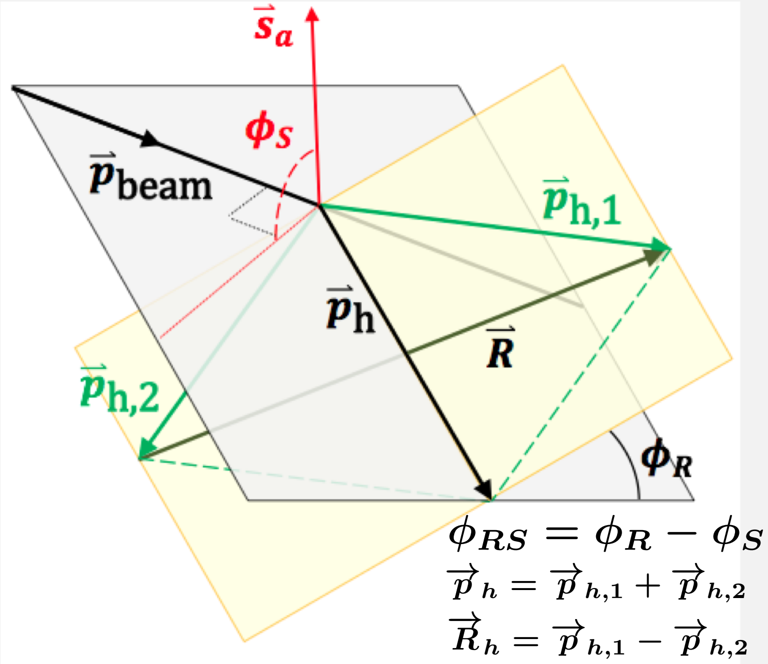
- Collinear framework



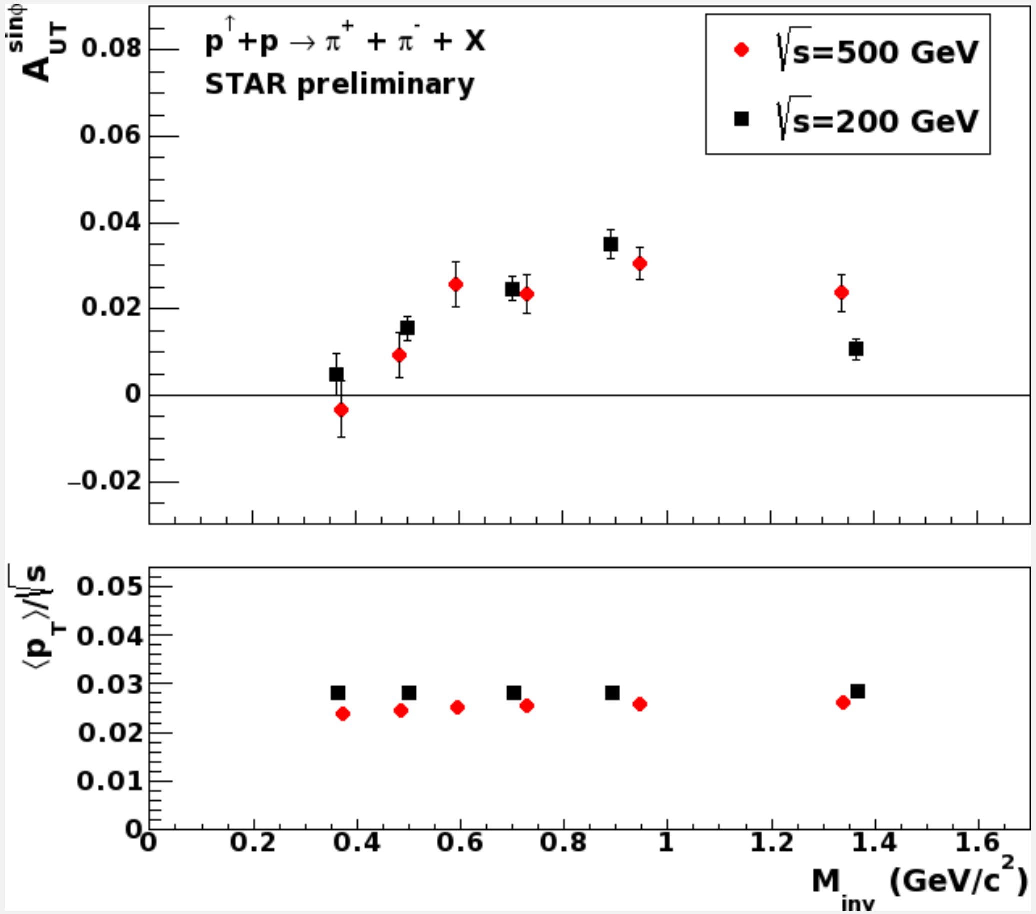


$A_{UT} \propto h_1 \bullet H_1^{<}$

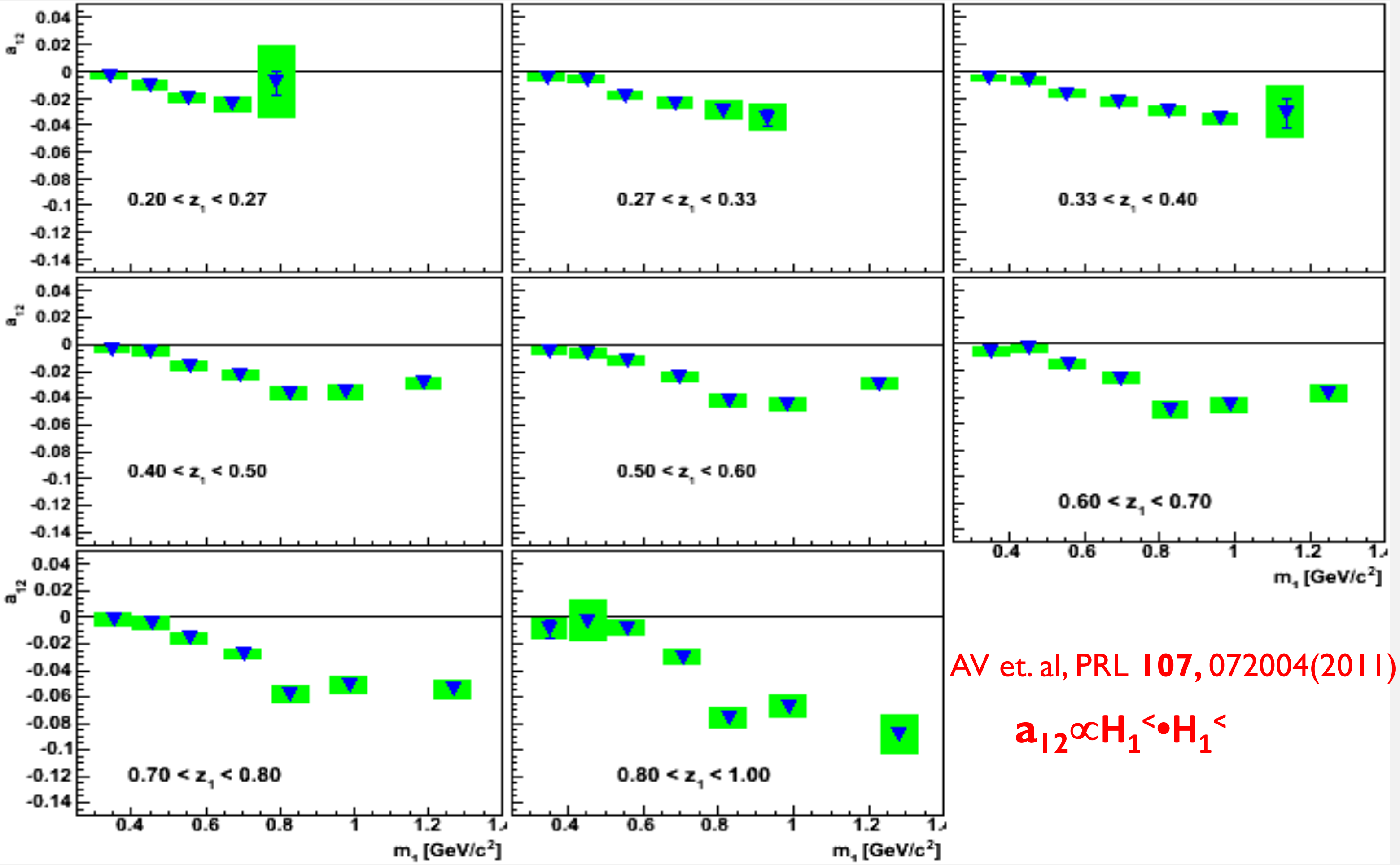
STAR DI-HADRON ASYMMETRIES



$$\phi_{RS} = \phi_R - \phi_S$$
$$\vec{p}_h = \vec{p}_{h,1} + \vec{p}_{h,2}$$
$$\vec{R}_h = \vec{p}_{h,1} - \vec{p}_{h,2}$$



Extraction of $\cos(\phi_{R_1} + \phi_{R_2})$
First measurement of Interference Fragmentation Function



See Marco's talk about Transversity extraction From di-hadrons

AV et. al, PRL **107,** 072004(2011)

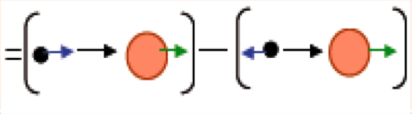
$\mathbf{a_{12} \propto H_1^{<} \cdot H_1^{<}}$

AMSTERDAM NOTATION FOR FFS WITH QUARK/HADRON POLARIZATION

Observables:

z: fractional energy of the quark carried by the hadron

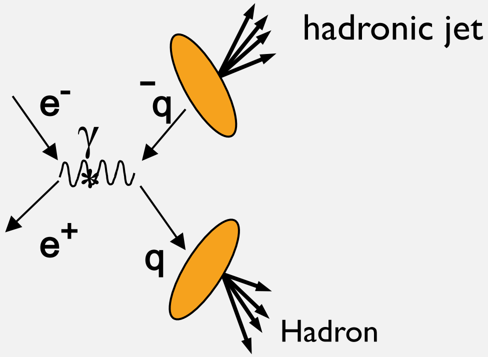
$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → **Hadron Polarization ↓**	**Spin averaged**	**longitudinal**	**transverse**
spin averaged	$D_1^{h/q}(z,p_T)$ 		$H_1^{\perp h/q}(z,p_T)$ 
longitudinal		$G_1^{h/q}(z,p_T)$ 	
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ 		$H_1^{q/\Lambda}(z,p_T)$ 

- Theoretically many more, in particular with polarized hadrons in the final state and transverse momentum dependence →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)

ACCESS OF FFS FOR LIGHT MESONS IN E^+E^- (SPIN AVERAGED CASE)

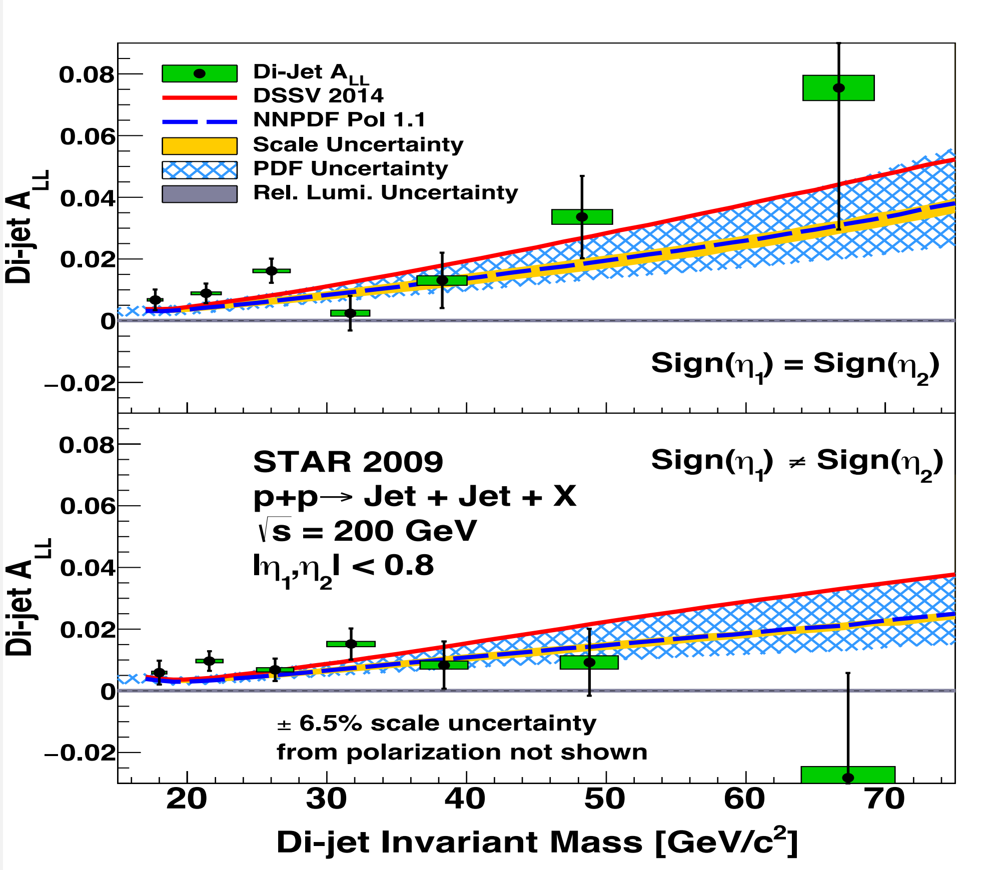
$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{e^+e^-\to hX}}{dz} = \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2)+F_L^h(z,Q^2)\right),$$

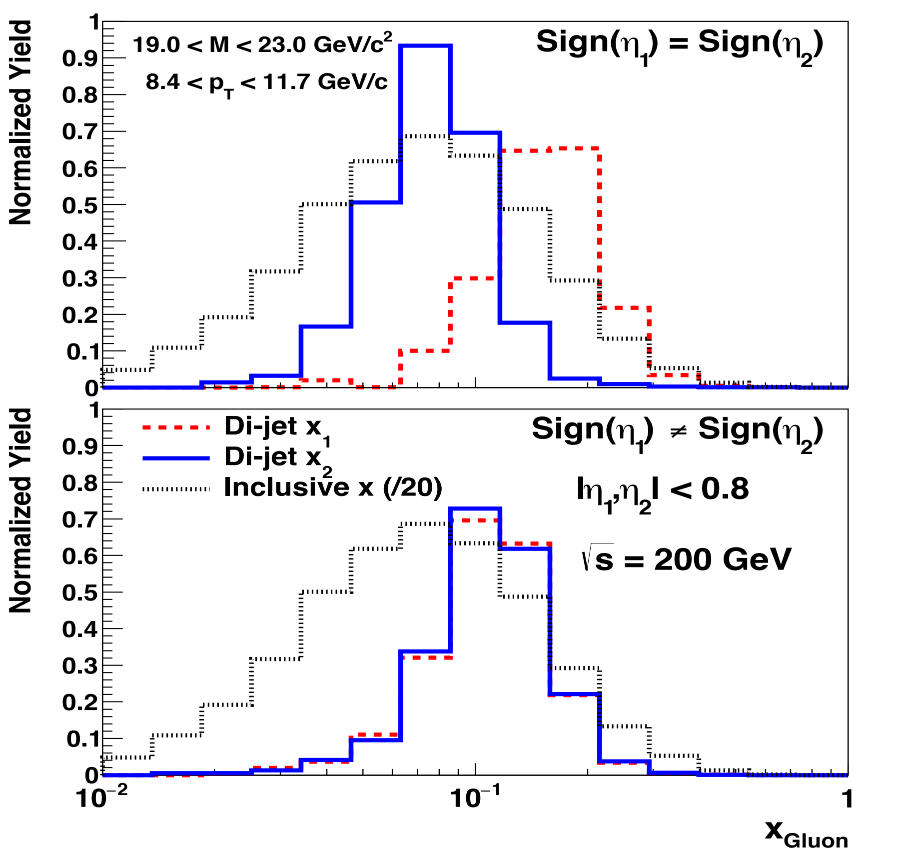


$$2F_1^h(z,Q^2) = \sum_q e_q^2\left(D_1^{h/q}(z,Q^2)+\frac{\alpha_s(Q^2)}{2\pi}\left(C_1^q\otimes D_1^{h/q}+C_1^g\otimes D_1^{h/g}\right)(z,Q^2)\right)$$

- Cleanest process
- Clean environment, hermetic dectors →can reconstruct complex final states, differentiate from feed-down
- Well understood, calculations available at NNLO
- Limited access to flavor
  - Use different couplings to γ^* and Z^0
  - Use polarization (SLD) and parity violating coupling
  - Use back-to-back correlations for different flavor combinations → see next talk
- Limited access to gluon FF
  - From evolution
  - From three jet events (but theory treatment not clear)

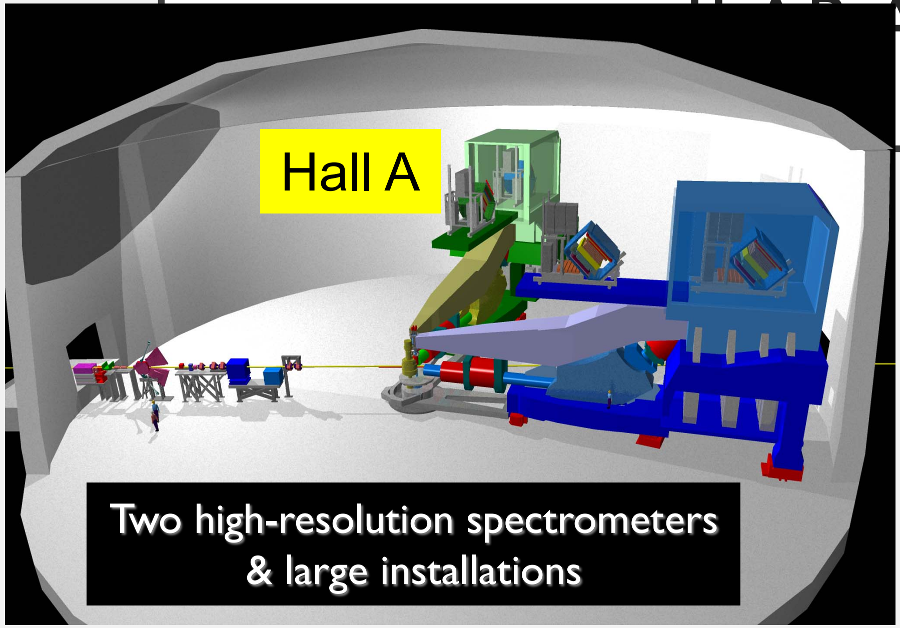
STAR DIJETS

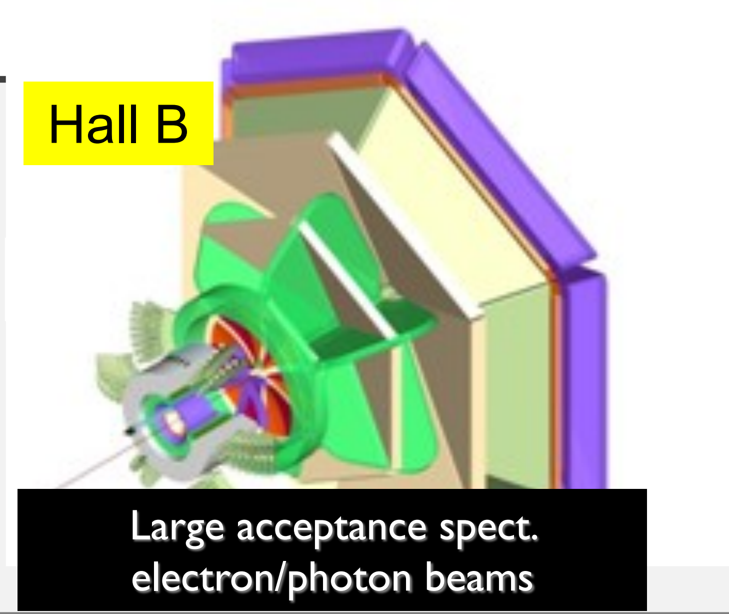


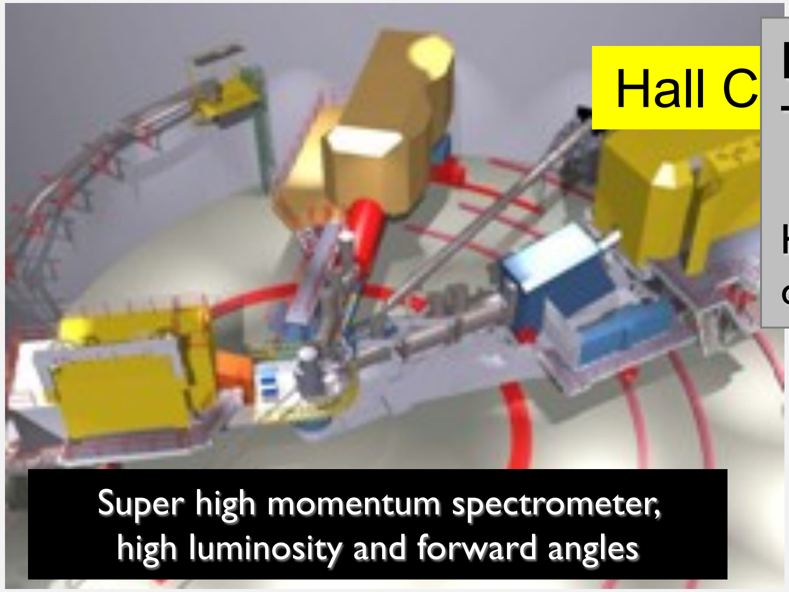


- Future results
  - Increased statistics
  - Forward jets/di-jets π^0

JLAB AT 12 GEV







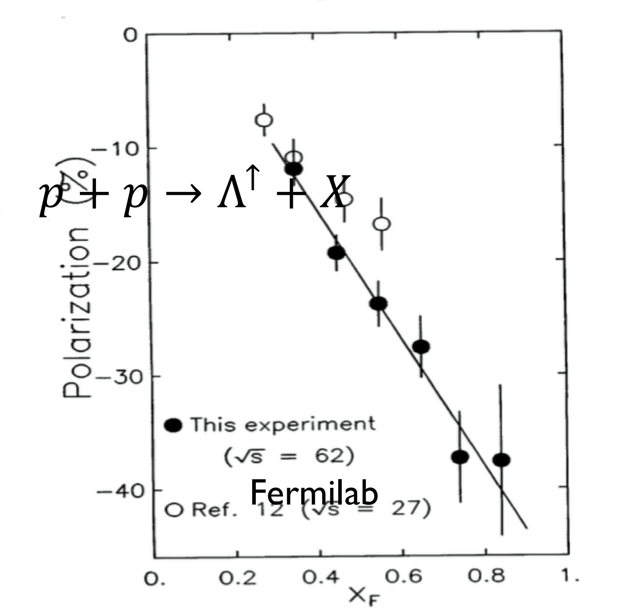
Beam: ≤12 GeV e^-; 85% polarization

Target: polarized targets 3He, 6LiD, NH3

several unpolarised targets

Hall-D: for spectroscopy 9GeV tagged polarised photons & a 4π detector

$p + p \to \Lambda^{\uparrow} + X$



ISR data

(**Phys.Lett. B185 (1987) 209)**