Transverse spin effects in SIDIS at 11 GeV with transversely polarized target using the CLAS12 detector

(A CLAS12 experiment proposal for PAC39)

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A CLAS12 Proposal For PAC38

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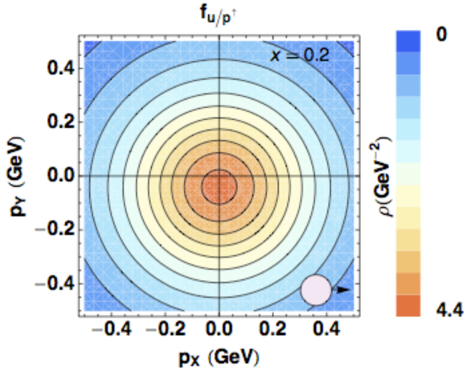
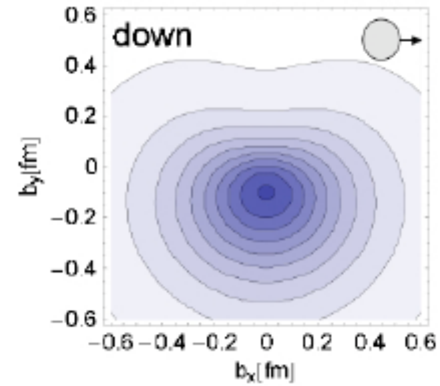
Physics motivations

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: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

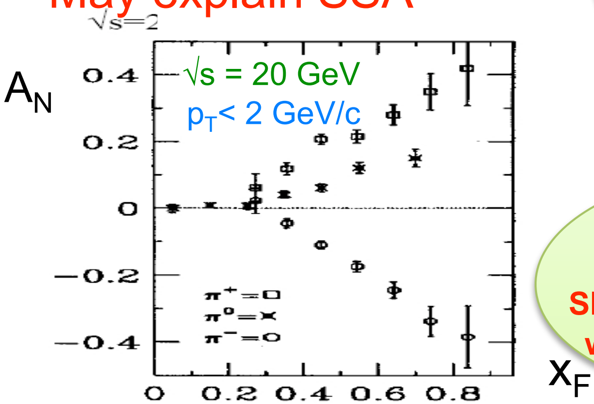
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x)$,…

May explain SSA



C 12-11-111
PR 12-12-009
SIDIS Physics: di-hadron with Transverse Target

PR 12-12-010
Exclusive Physics: DVCS with Transverse Target

May solve proton spin puzzle

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

Leading Twist TMDs

Quark polarisation

Nucleon polarisation	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

E12-06-112
E12-09-008
Boer-Mulders for pions and kaons

E12-07-107
E12-09-009
Spin-effects for pions and kaons

E12-09-007
Quark number and helicities

C12-11-111 goals:

Collinear physics
Tensor charge

Orbital quark motion
Non-trivial gauge link
Process dependence

Proton wave components with different OAM

D-wave component
Not-spherical shape of the nucleon

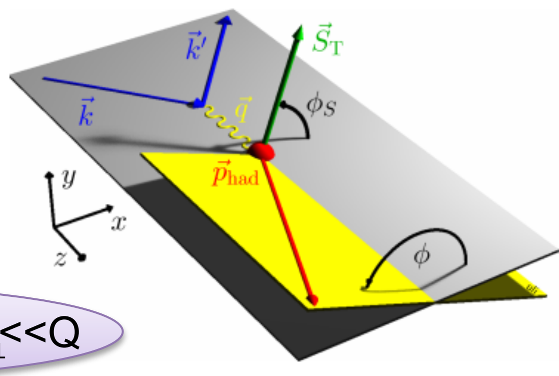
The SIDIS Case

quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^{\perp}$ *Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity*; $h_{1T}^{\perp}$ *Pretzelosity*

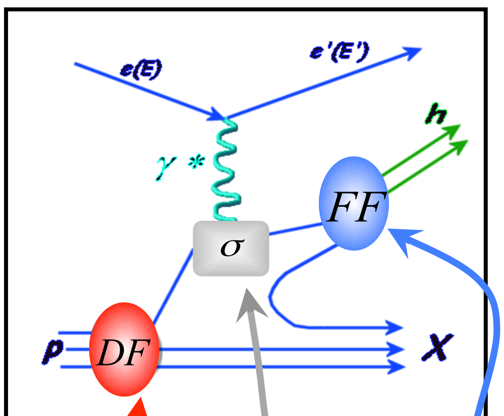
SIDIS cross section (transversely pol. target):



TMD factorization for $P_{h\perp} << Q$

$$f \otimes D = \int_q e_q^2 d^2 p_T d^2 k_T \ldots w(k_T, p_T) f^q(x, k_T^2) D^q(z, p_T^2)$$

Rich but involved phenomenology due to the convolution over transverse momentum



$$\sigma^{ep \to ehX} = \sum_q DF \otimes \sigma^{eq \to eq} \otimes FF$$

$h_1 \otimes H_1^{\perp}$

$$\frac{d^6\sigma}{dx\, dy\, dz\, d\phi_S d\phi\, dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} S_T \left\{ \sin(\phi - \phi_S) F_{UT,T}^{\sin(\phi-\phi_S)} \right\}$$

$f_{1T}^{\perp} \otimes D_1$ $\qquad$ $h_{1T}^{\perp} \otimes H_1^{\perp}$

$$+ S_T \left\{ \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \right\}$$

$g_{1T}^{\perp} \otimes D_1$

$$+ S_T \lambda_e \left\{ \sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} \right\} + \ldots$$

Transversity
Tensor charge
Collins function

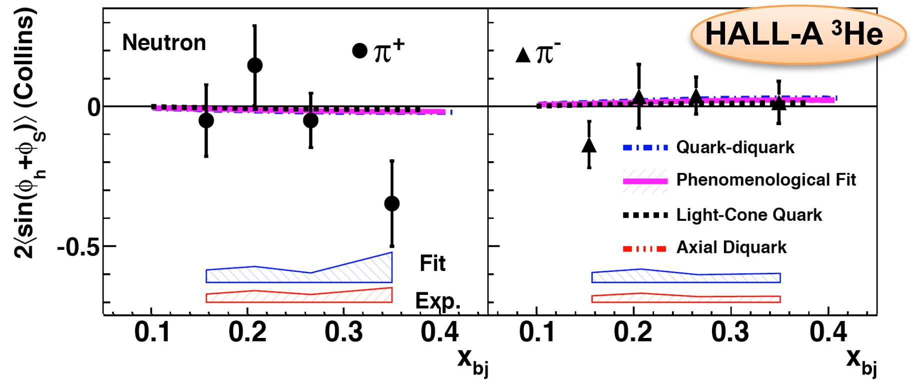
The Collins amplitude

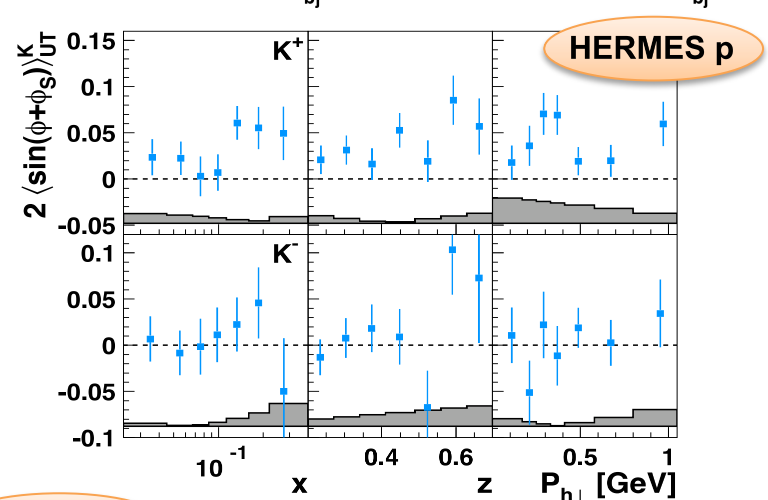
$h_1 \otimes H_1^{\perp}$

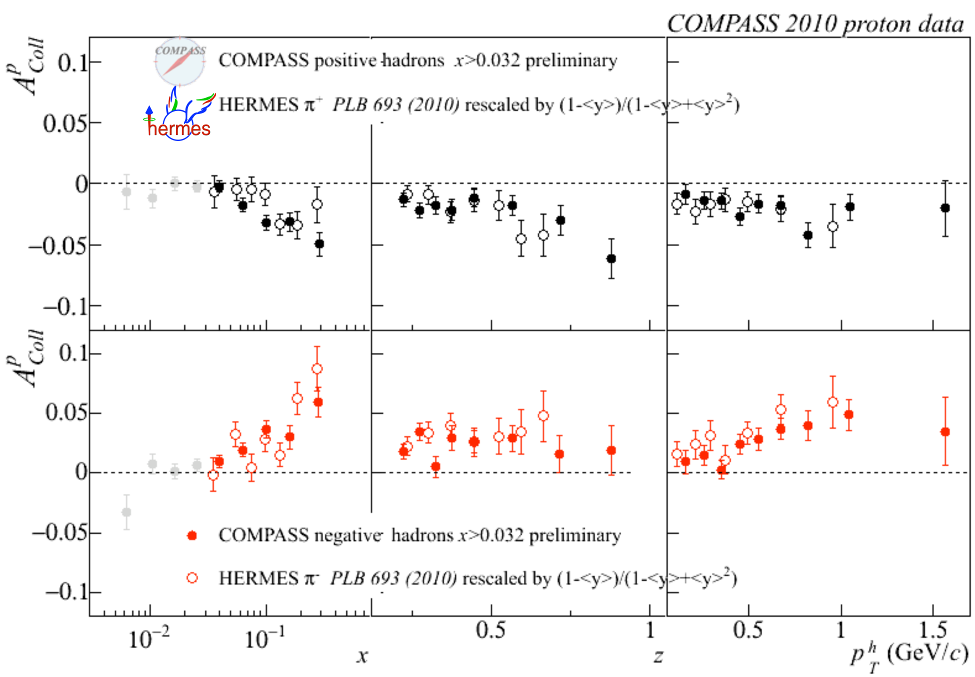
Consistent non-zero signals for pions

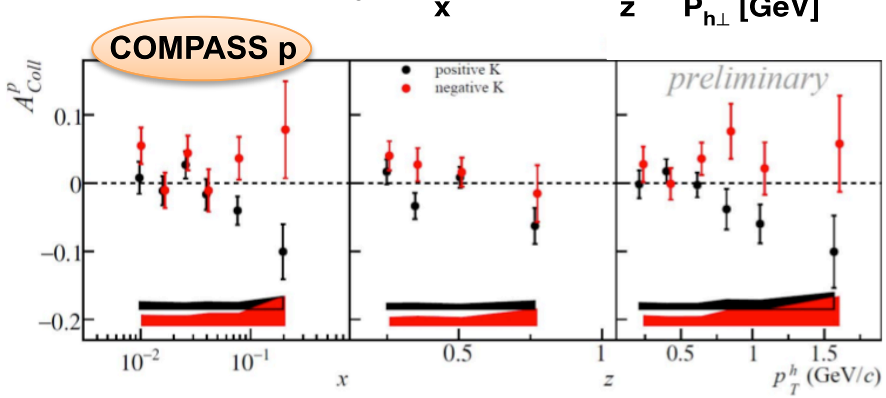
Opposite sign for pions reveal Collins features

Puzzle in (low-statistics) kaon signals:
- K^+ amplitudes larger then π^+
- K^- amplitudes are not in agreement









Transversity Signals

High-x and tensor charge ?

Gaussian ansatz & role of Q^2 evolution

Two complementary channels to help solving issues

PR 12-12-009
SIDIS Physics: di-hadron with Transverse Target

$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

$ld \to l'hX$

$lp \to l'hX$

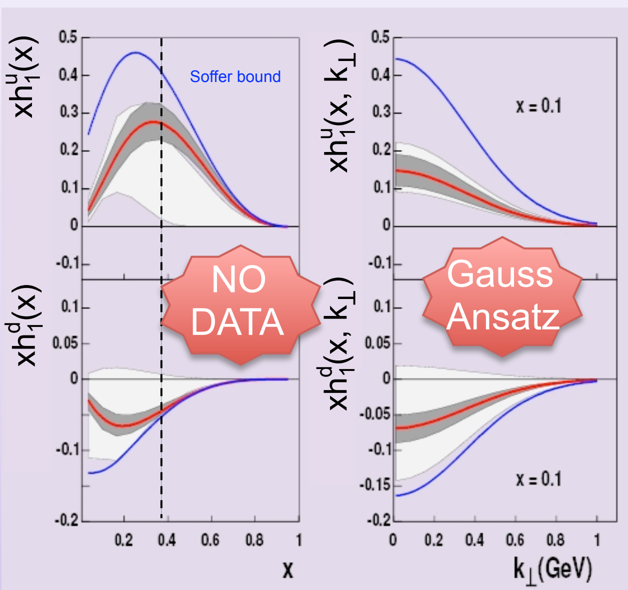
$e^+e^- \to hhX$

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \propto \sin\vartheta\, h_1(x) \cdot H_1^{\sphericalangle q}(z)$$

$lp \to l'\pi^+\pi^- X$

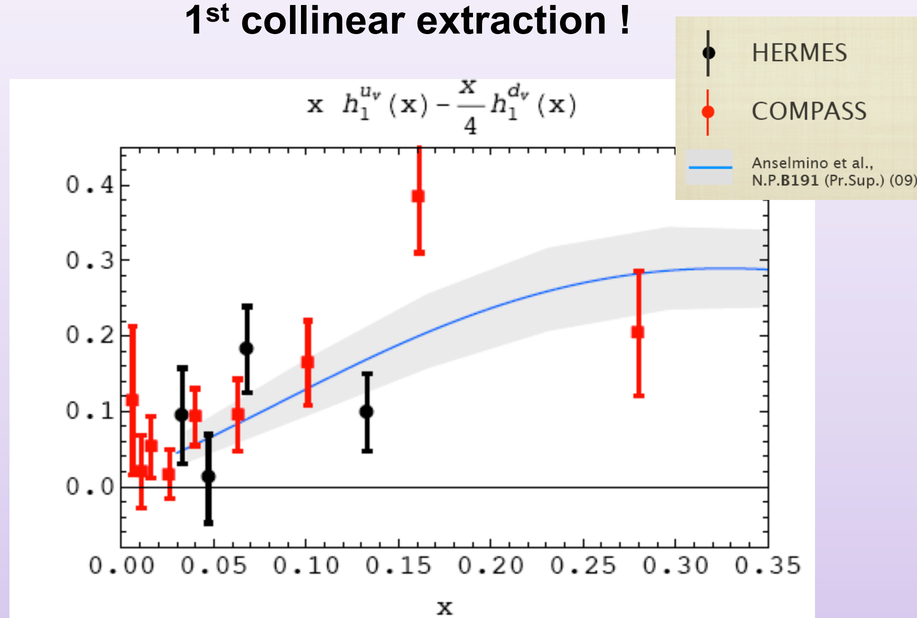
$e^+e^- \to (hh)(hh)X$

1st extraction of Transversity!



Anselmino et al. Phys. Rev. D 75 (2007)

1st collinear extraction !



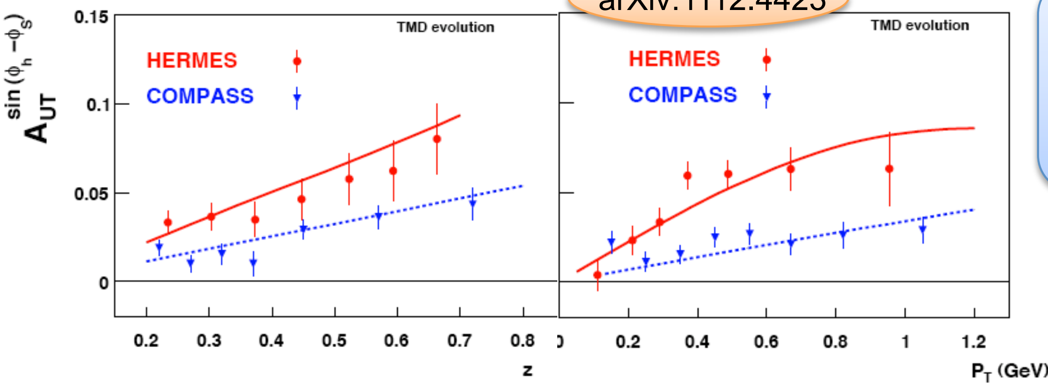
Bacchetta et al., PRL 107 (2011)

Related to quark orbital angular momentum

The Sivers effect

$f_{1T}^{\perp} \otimes D_1$

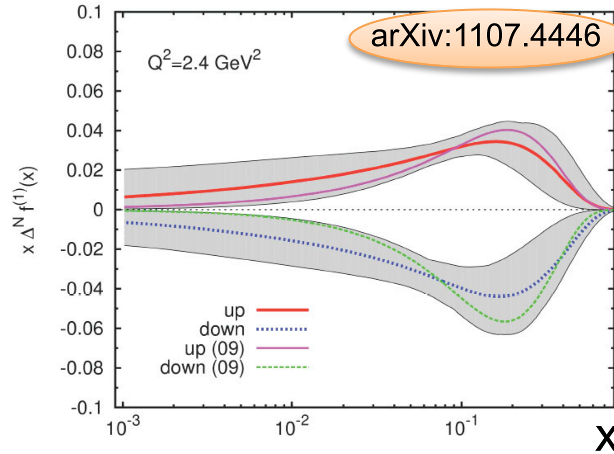
arXiv:1112.4423



Coverage at large x and relation with Drell-Yan

Sign change is a crucial test of TMDs factorization

arXiv:1107.4446

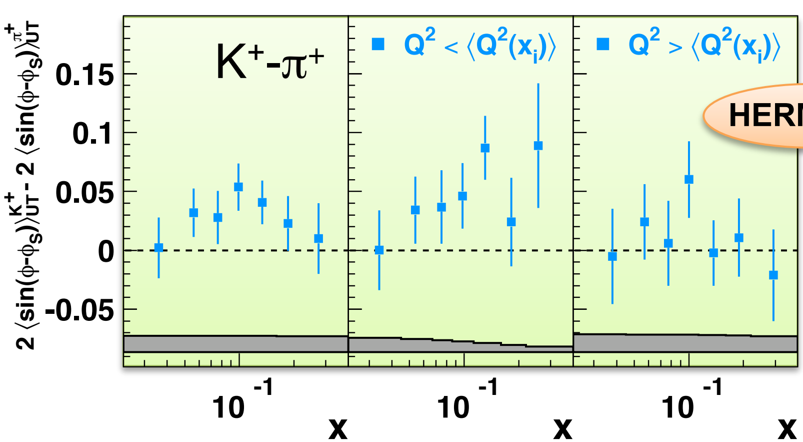


Non zero signals for π^+ and K^+

Significant Q^2 evolution ?

K^+ signals larger than π^+

HERMES p



Coverage at large p_T and relation with twist-3 collinear approach

Sign mismatch between SIDIS and pp SSA ?

T3 correlator from pp

Sivers moment from SIDIS

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

Honour and Duty

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

DIS experiments get access to all PDFs and FFs, but in a convoluted way,
first generation non-zero results provide promises but also open questions

Full coverage of valence region not achieved
Limited knowledge on $P_{h\perp}$ dependences
Flavor decomposition often missing
Evolution properties to be defined
Role of the higher twist to be quantified
Universality ⟷ Fundamental test of QCD

⟺

large x coverage
wide $P_{h\perp}$ acceptance
hadron ID
large Q^2 coverage
multi-dimensional analysis
complementary channels

Still incomplete phenomenology is asking for new inputs

Crucial: completeness
flavor tagging, wide acceptance and four-fold differential extraction in all variables (x,z,Q^2,P_T) to have all dependencies resolved

Experimental Setup

The CLAS12 Spectrometer

Luminosity up to 10^{35} cm^{-2} s^{-1}

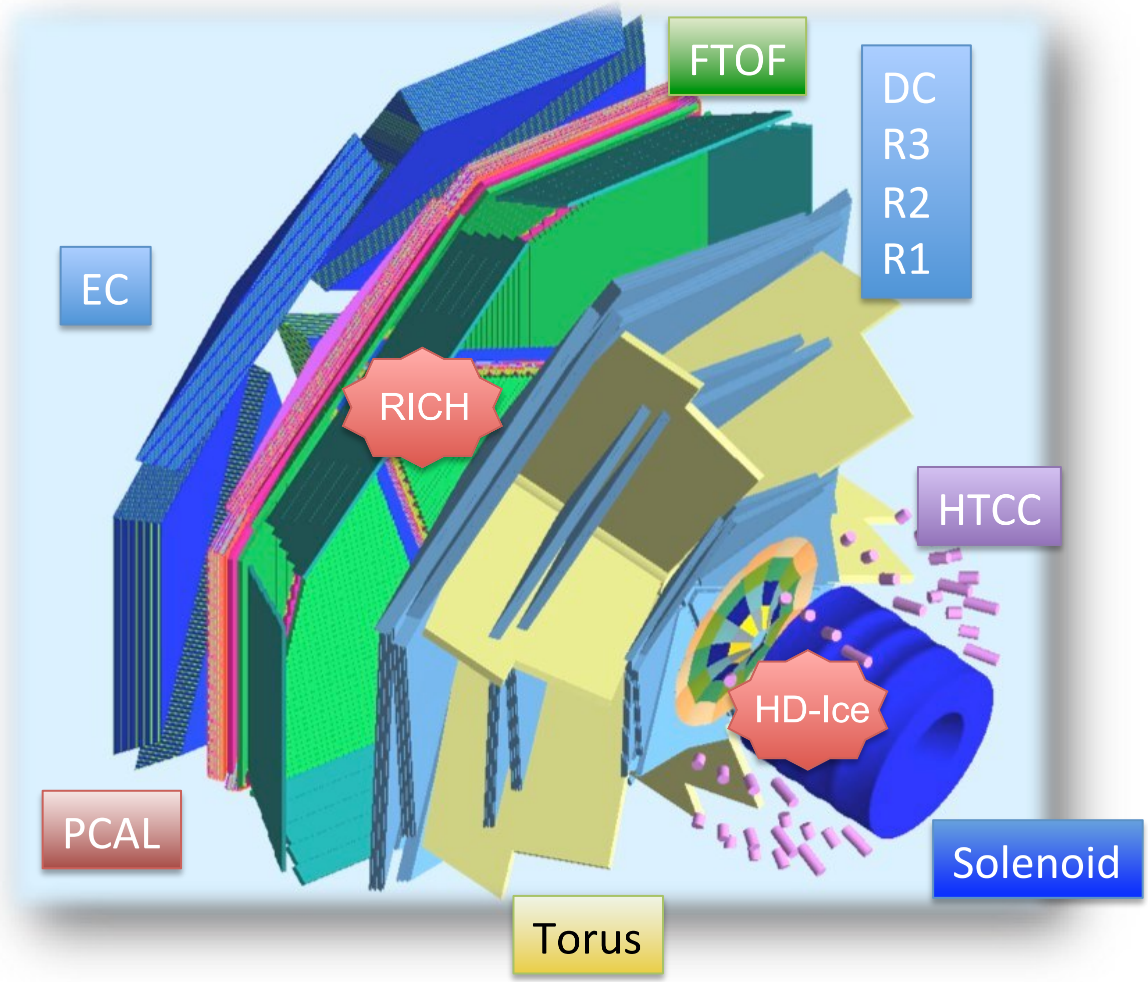
Highly polarized electron beam

H and D polarized targets

Broad kinematic range coverage
(current to target fragmentation)

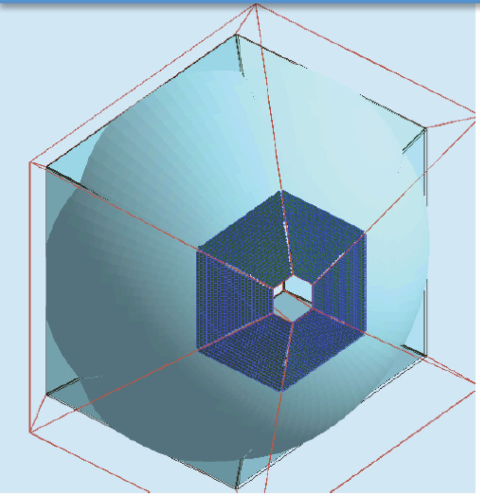
HD-Ice: Transverse Target
new concept
(commissioned with CLAS at 6 GeV
common to PR 12-009, PR 12-010)

RICH: Hadron ID
for flavor separation
(common to SIDIS approved exp.)

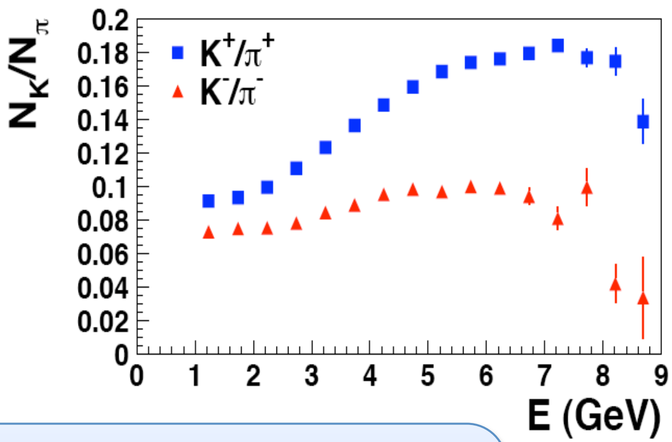


PAC30 report (2006): Measuring the kaon asymmetries is likely to be as important as pions …. The present capabilities of the present CLAS12 design are weak in this respect and should be strengthened.

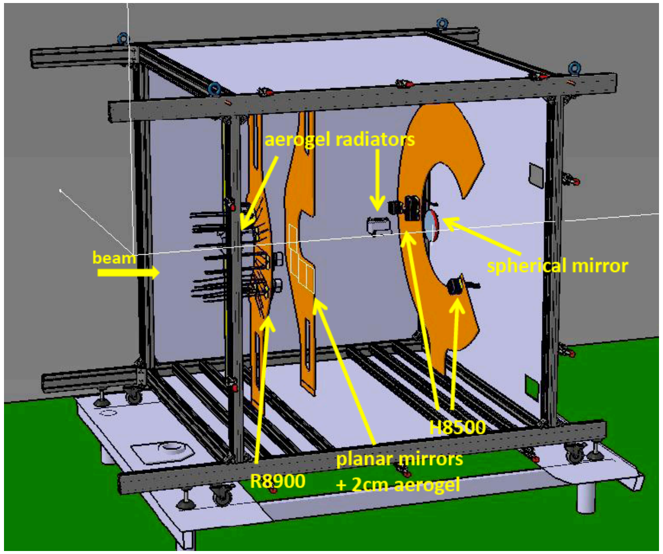
The RICH Detector



π/K/p separation for 3-8 GeV/c



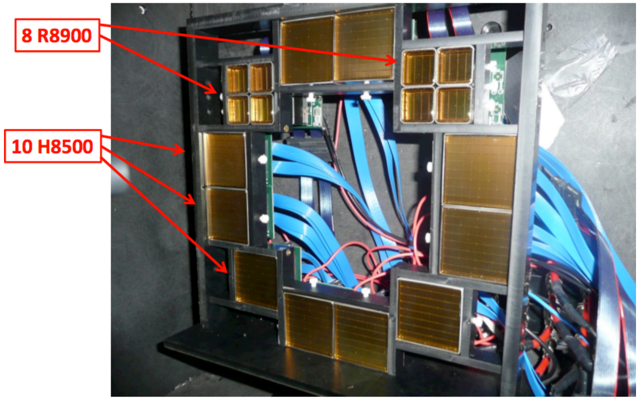
2012: component tests & realistic prototype

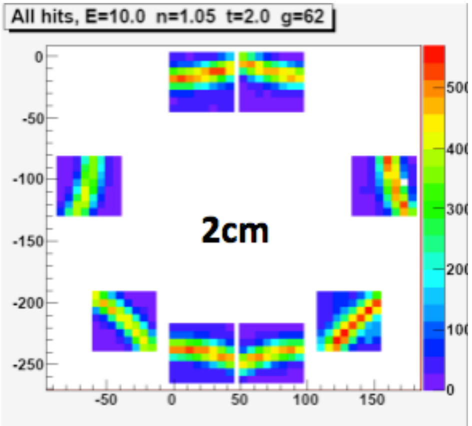


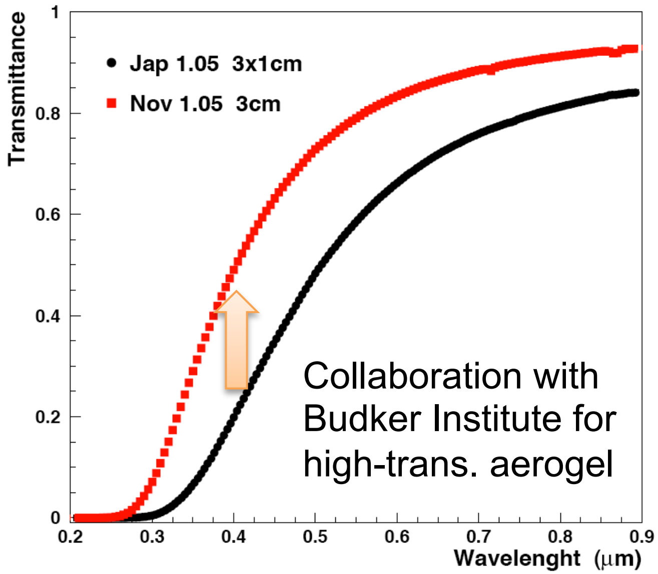
Simulation of n=1.05 aerogel + H8500:

≥ 10 p.e. for direct rings
≥ 5 p.e. for reflected rings
≥ 500 pion rejection factor @ 90% kaon efficiency

2011: preliminary test validated H8500 and N p.e.







Transversely Polarized HD-Ice Target

HD-Ice target vs standard nuclear targets (less luminosity for higher purity)

Advantages:

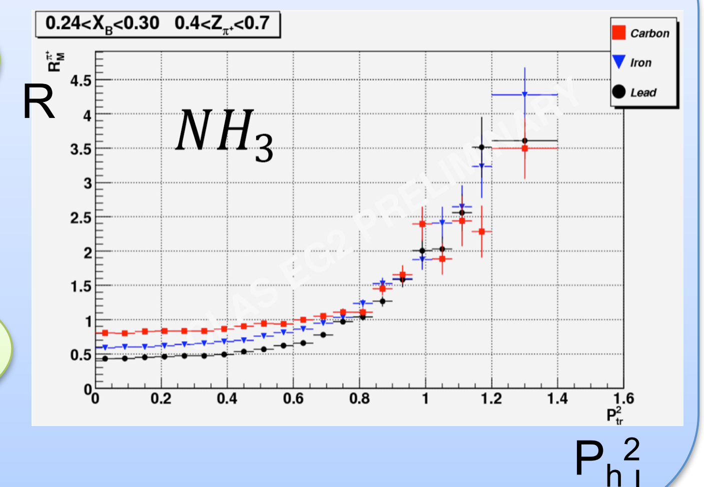
- **Minimize nuclear background**
  smaller dilution, no attenuation at large p_T
- **Weak holding field (BdL ~ 0.1 Tm)**
  wide acceptance, negligible beam deflection

Deuterium dilution is under control
E12-06-112

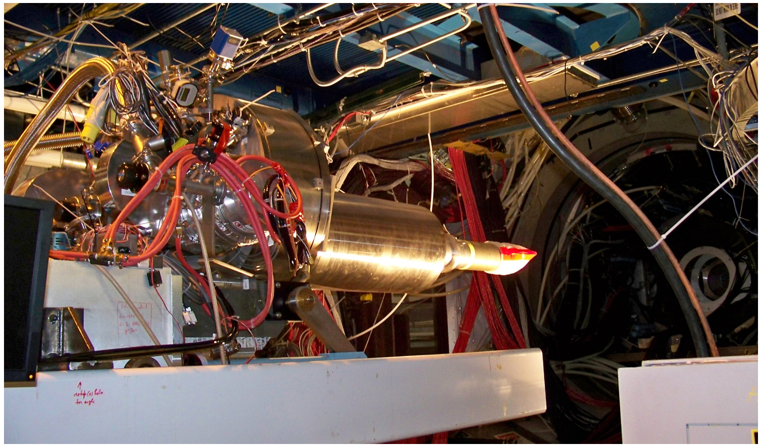
Suitable for di-hadron and recoil proton
PR12-12-009/010

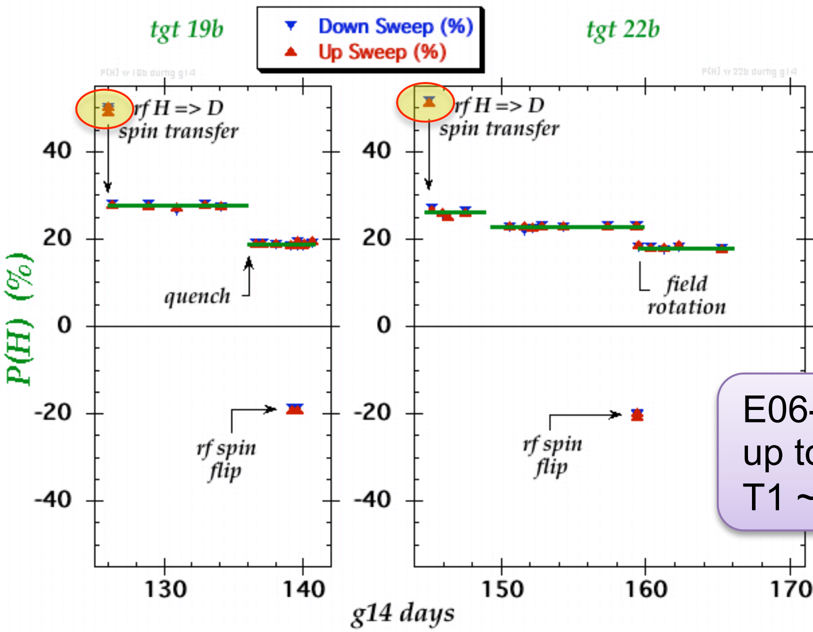
Disadvantages:

- **Very long polarizing times (months)**
- **Sensitivity to local heating by charged beams**



HD-ice ran from Nov/11 to May/12 at Jlab with 15mm Ø ×50 mm long HD cells





E06-101
up to 10^8 γ/s
T1 ~ years

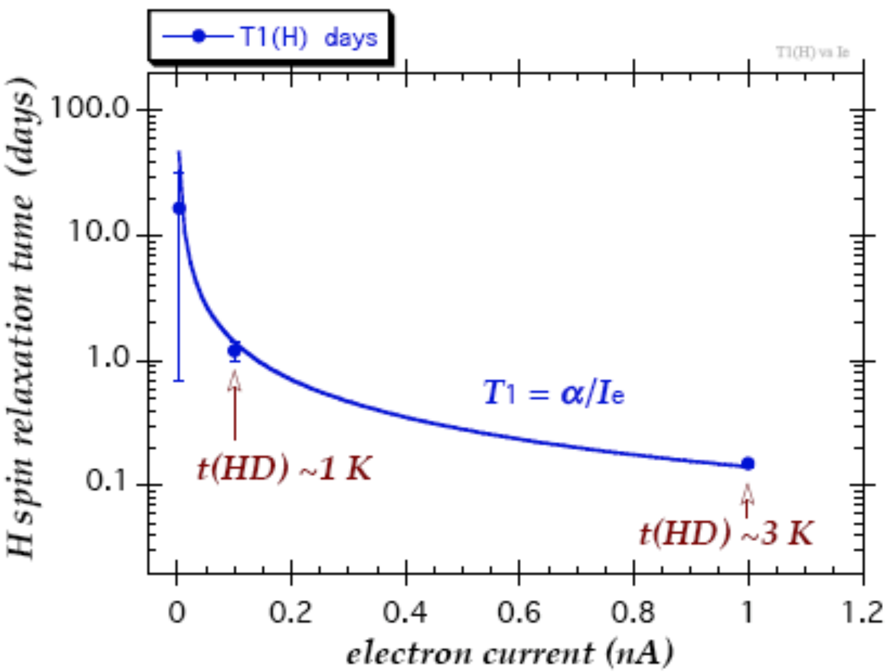
e-beam tests in Feb/12 and Mar/12

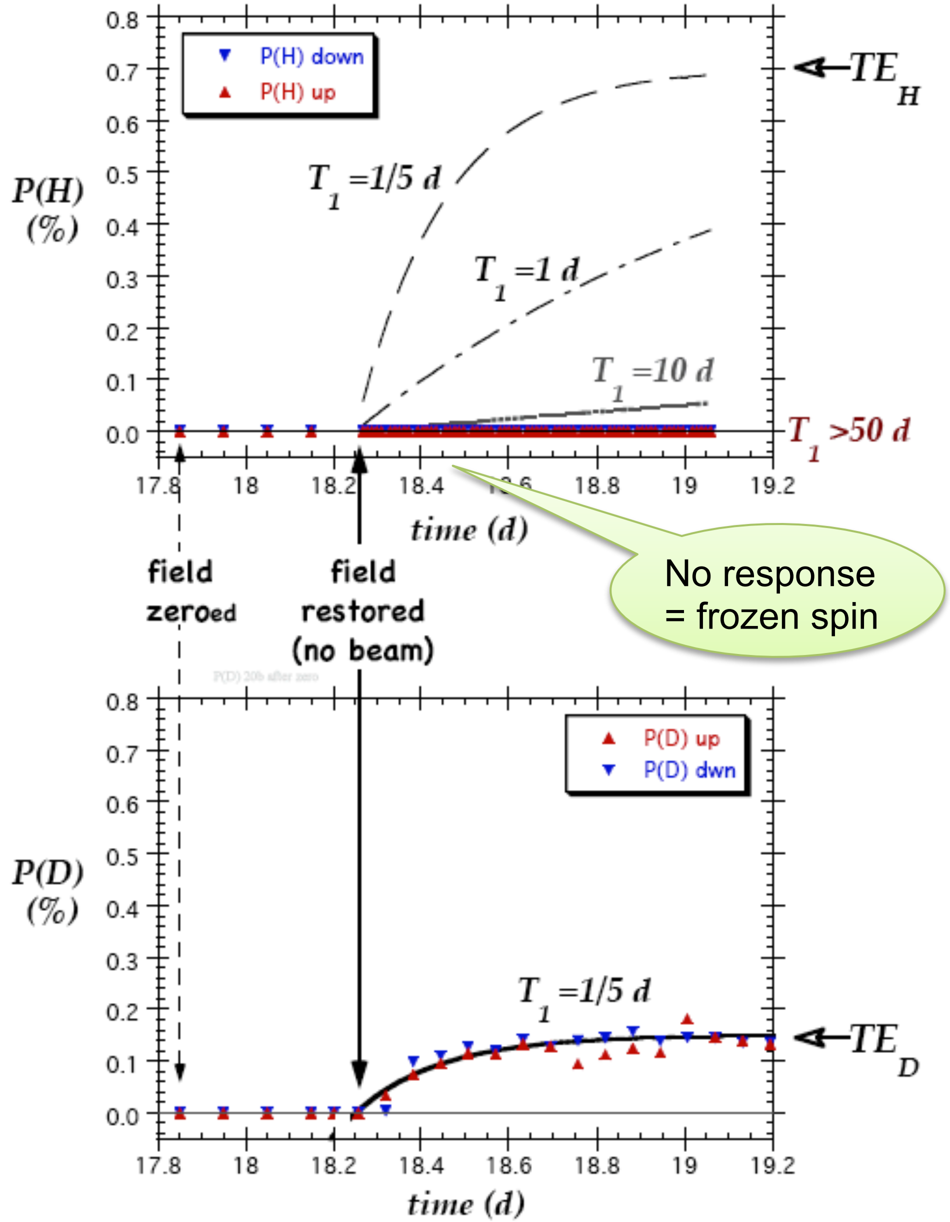
Polarization build up after rf erasing

➔ H polarization does not appear to suffer radiation damage with 1 nA; D does

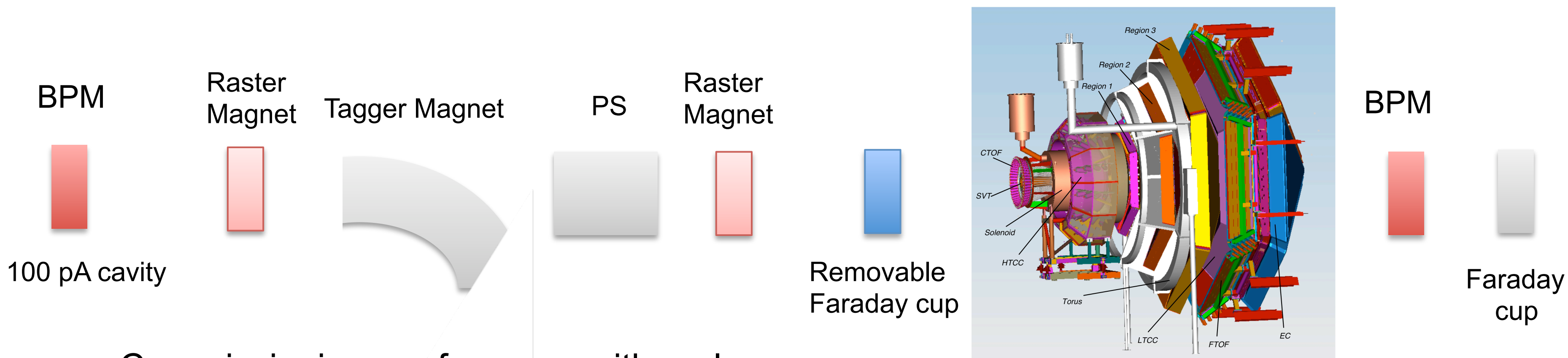
Relaxation time during beam exposure

➔ heat removal needs improvement

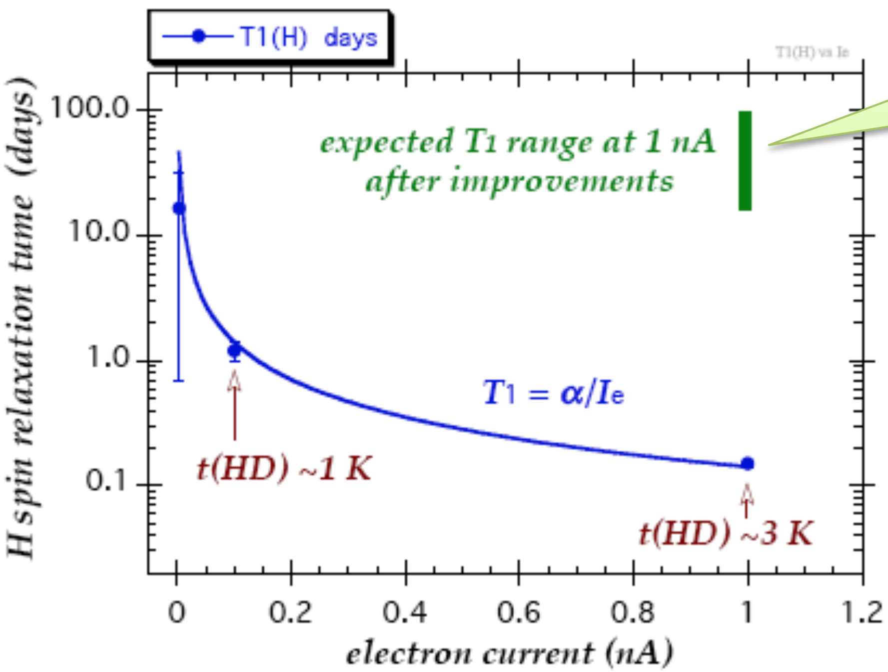




PAC38 question 1: HD-Ice vs Electron Beam



Commissioning run foreseen with early Beam (2014), before CLAS12 operations



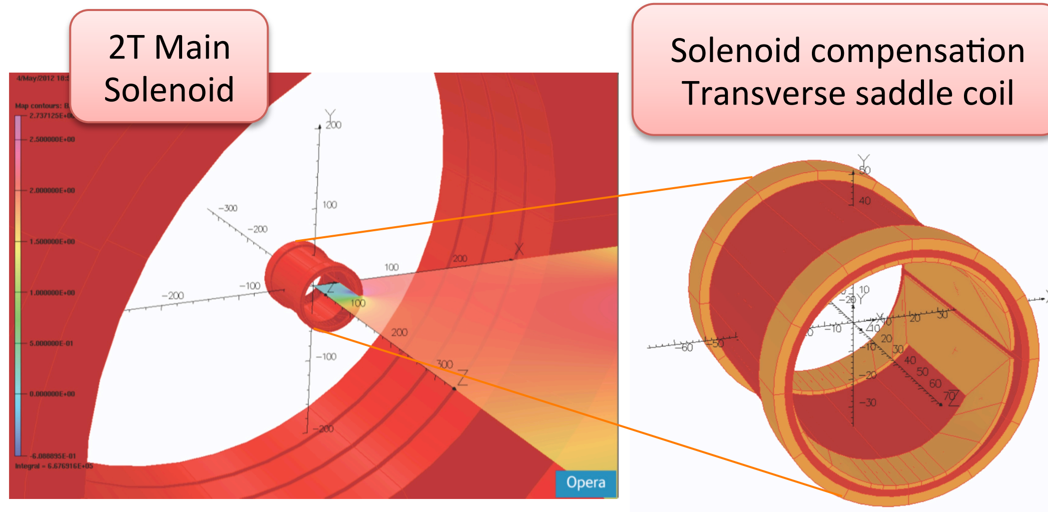
- faster raster
- larger diameter cell
- shorter cooling wires

Target wider but not-longer than the existing one (5 cm)

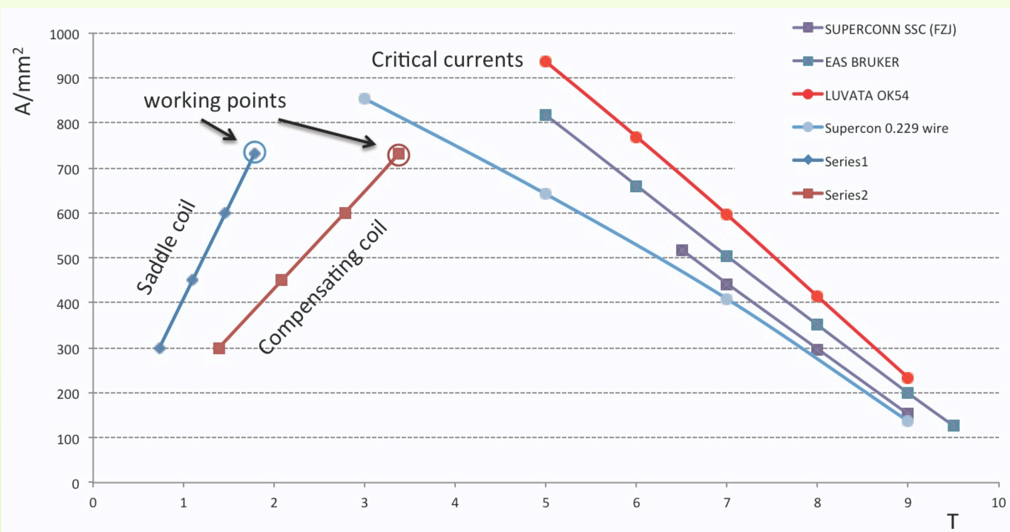
- **Luminosity 5 10^{33} cm^{2}s^{-1} (minor impact on projections)**
- **Magnet configuration simplifies (reduced zero-field volume)**

PAC38 question 2: Magnet Configuration

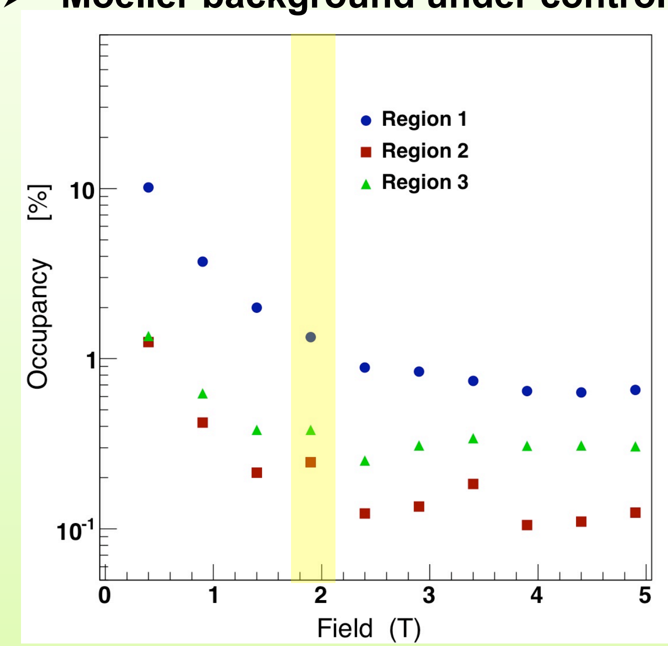
- 0.5T transverse, < 5mT long. field (@ 2T)
- Enhanced version of the existing NMR magnet system inside HD-ice cryostat
- No impact on CLAS12 central detector
- Free forward acceptance (> 35°)
- Recoiling proton detection



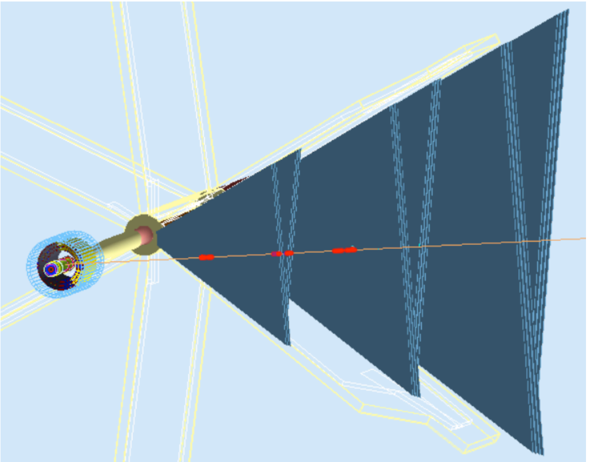
- Working point below critical current of existing SC wires
- Quench protection and static forces are not critical



- Moeller background under control

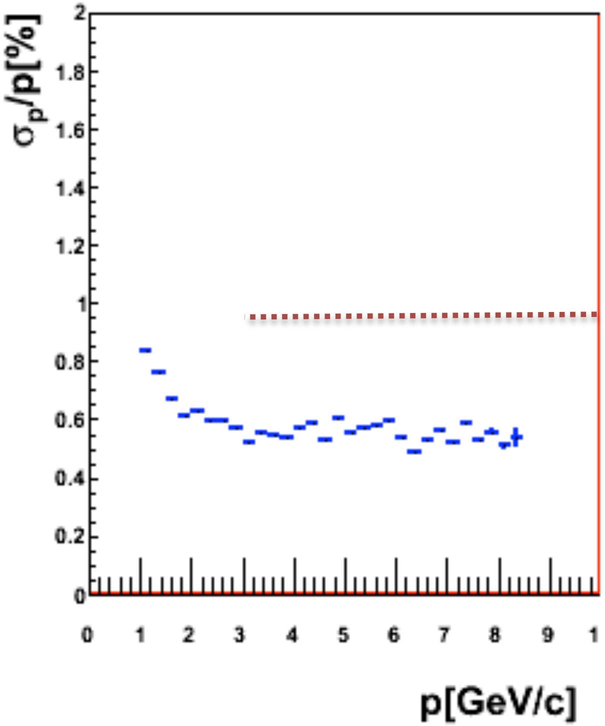


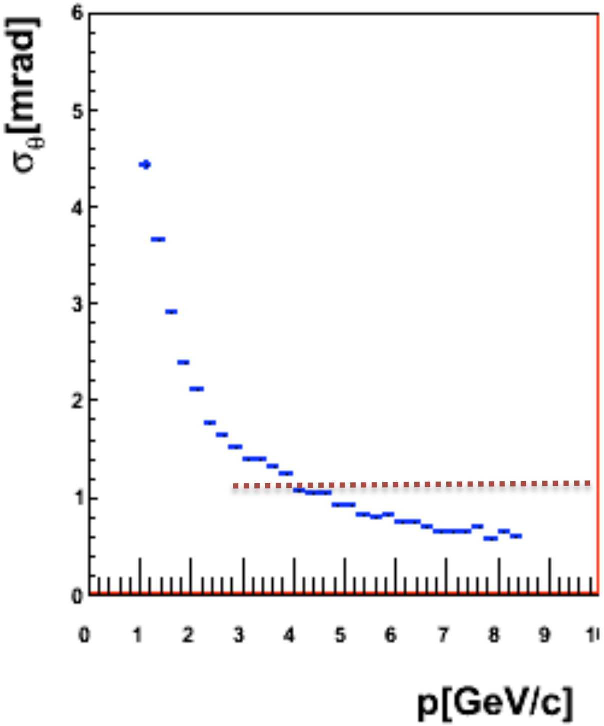
PAC38 question 3: Tracking

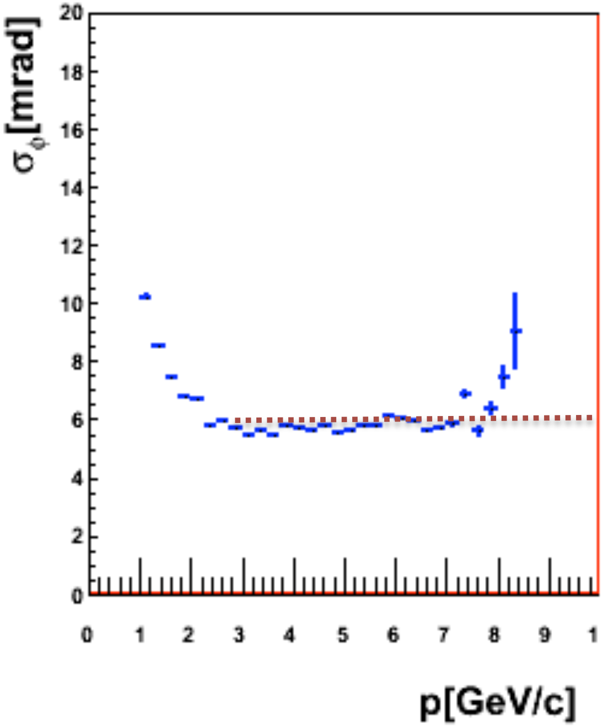


Study based on:
- Geant4 simulation
- Socrates tracking code

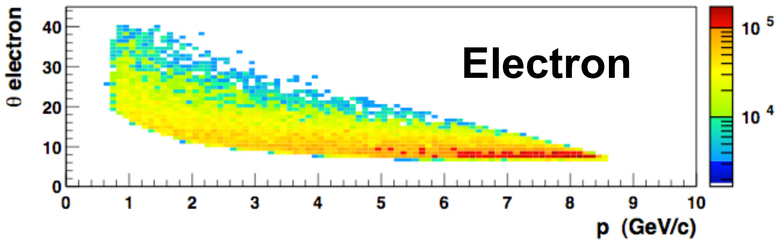
Resolutions fulfill TDR general specifications

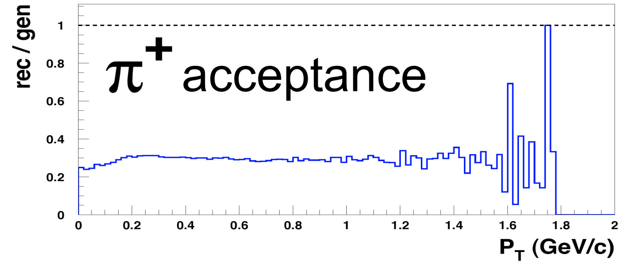






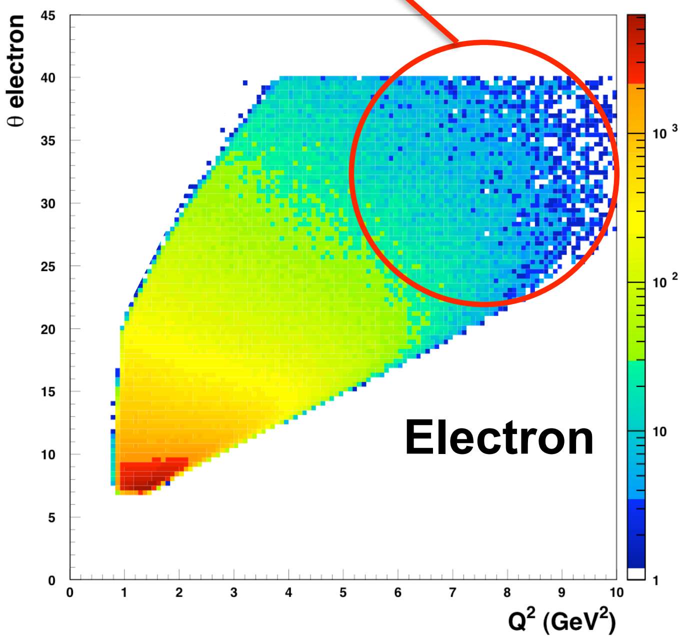
CLAS12 Kinematic Coverage

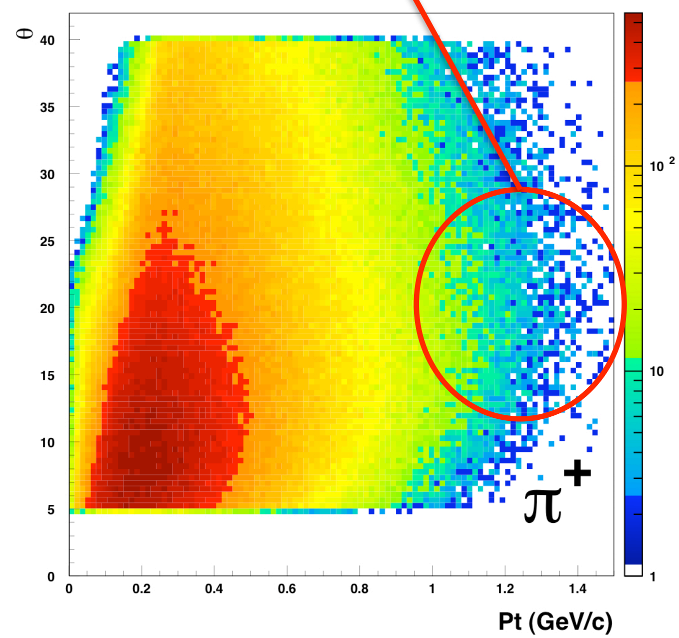




Large electron scattering angles (> 20°) mandatory to reach high Q^2 values

Intermediate anguar range (15-25°) mandatory to reach high P_T values





The CLAS12 forward detector is perfectly suitable for high-Q^2 and high-p_T measurements since designed to cover up to 40 degrees angles

Projections

Single- and Double-Spin asymmetries

CLAS12 with RICH detector and HD-Ice transversely polarized target:

60 % polarization and 1/3 dilution for Hydrogen @ 5 10^{33} cm^{-2} s^{-1}

Error source	Error type	Uncertainty
Acceptance corrections	relative	2÷4 %
Radiative corrections	relative	2 %
Target polarization	relative	4-5 %
Al background (dilution)	relative	1÷3 %
D background (dilution)	relative	1÷4 %
Total	relative	5÷8 %

Several 10^{-3} for 0.05-0.1 typical asymmetries

Estimates based on:

- Experience & methods from CLAS/HERMES measurements

Reduces with statistics and bin number (no long range integrations)

Benefits from the large acceptance (target fragmentation, vector meson decays)

- Current knowledge on HD-Ice target

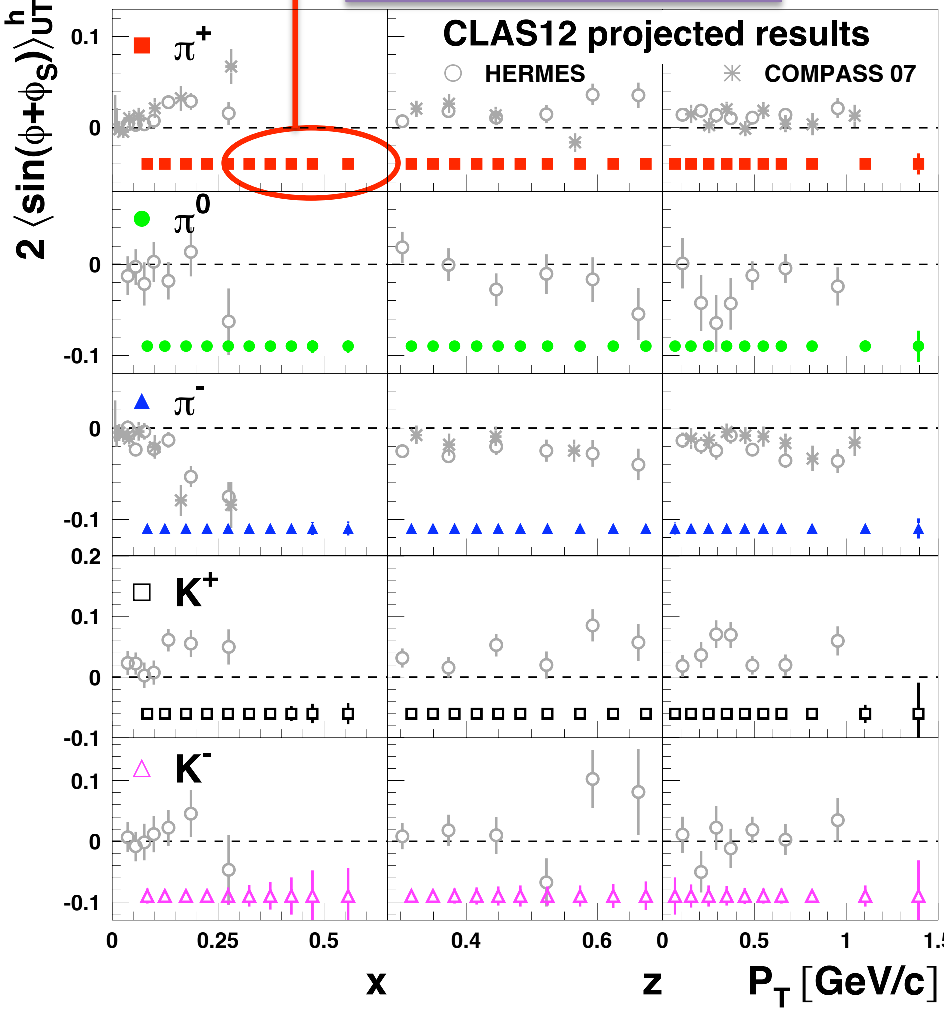
Based on NMR during the g14 run

CLAS12 Projections

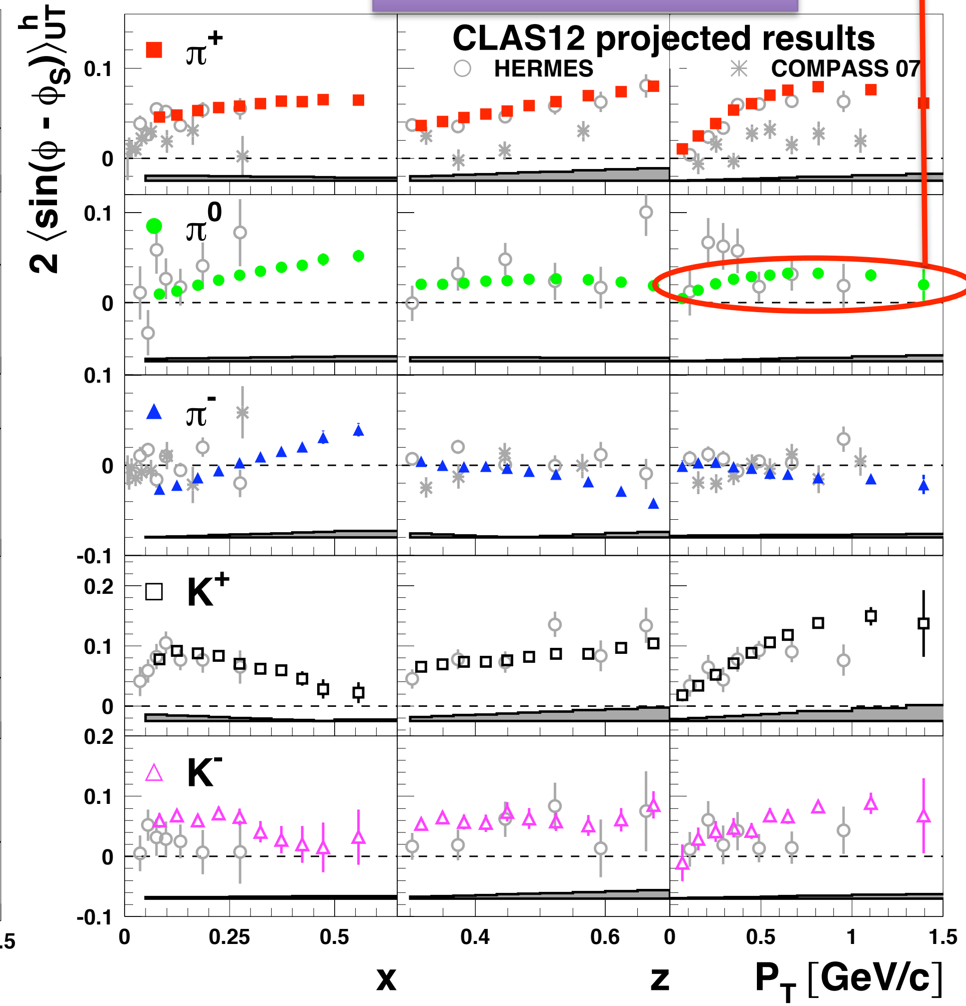
Large x important to constrain the tensor charge

High resolution and broad range in p_T to test perturb. non-perturb. transient and for Bessel function analysis

Collins asymmetry

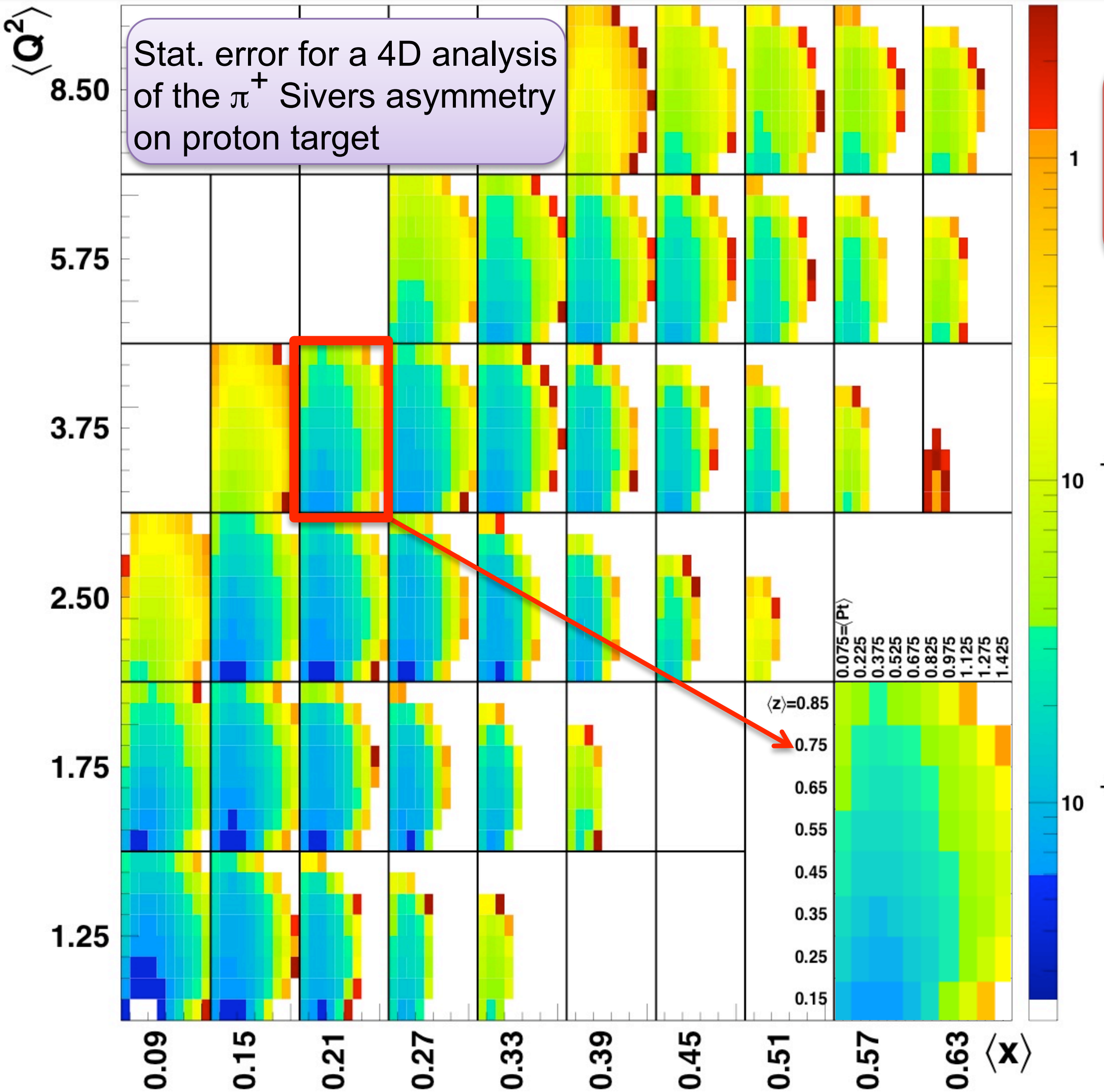


Sivers asymmetry



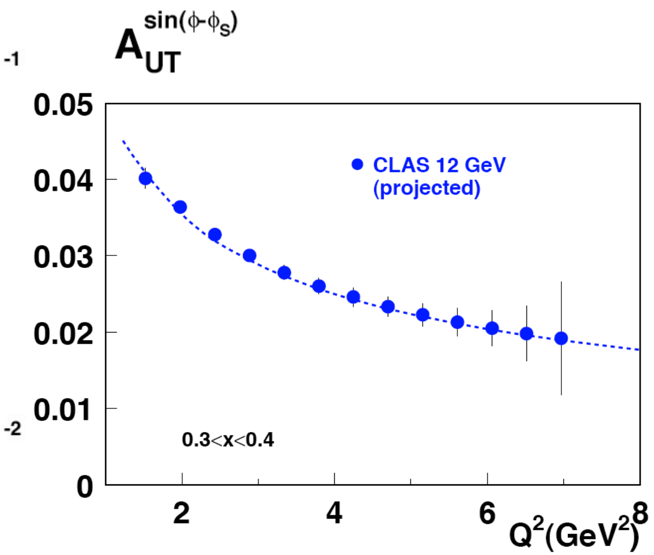
Statistical precision

Stat. error for a 4D analysis of the π^+ Sivers asymmetry on proton target



4D analysis is possible

Beam-time request is defined to achieve few % absolute error at the wanted high-Q^2 high-p_T



Q^2 dependence of Sivers asymmetry
Test of TMDs evolution

The main goals

Transverse spin effects in SIDIS at 11 GeV with transversely polarized target using the CLAS12 detector

- Access to leading-twist poorly known or unmeasured TMDs which provide 3-dimensional picture of the nucleon in momentum space (nucleon tomography);

  - * SSA: ***Transversity, Sivers, Pretzelosity functions***;
  - * DSA: ***g_{1T} worm-gear function***;

- Multi dimensional analysis in x, Q^2, z, p_T thanks to large-acceptance and high-luminosity;

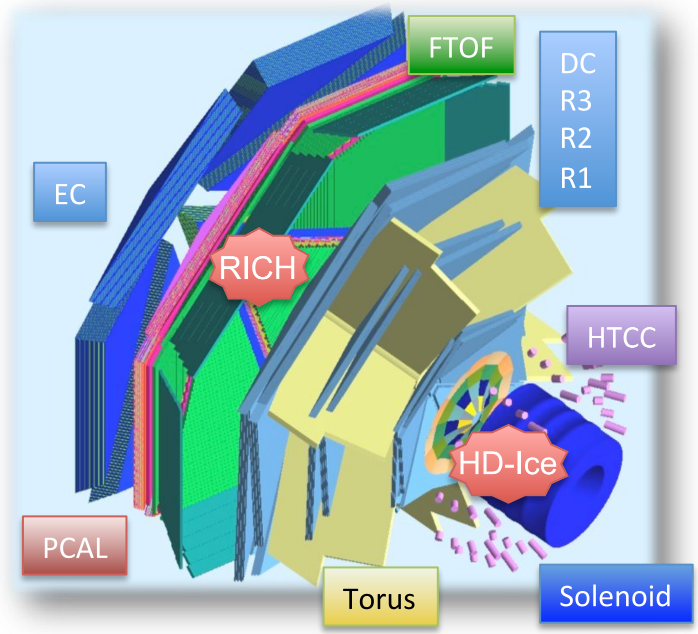
  - * ***precise mapping of the valence*** (tensor charge);
  - * ***disentangle parton distribution from fragmentation functions*** (x vs z);
  - * ***isolate sub-leading-twist effects*** from 1/Q dependence (g$_2$ as side product) ;
  - * ***flavor decomposition of pT dependence*** (Bessel analysis);
  - * ***investigate perturbative to non-perturbative QCD transient*** from p_T dependence;

- Together with already approved experiments with unpolarized and longitudinally polarized targets, ***complete the mapping of the TMD table at CLAS12***.

Beam time request

The proposed experiment requires:

- 11 GeV (highly polarized) electron beam
- CLAS12 detector equipped with:
  - HD-Ice transversely polarized target
  - Suitable magnetic system (compensation + saddle coil)
  - RICH (pion/kaon separation within 3-8 GeV/c)



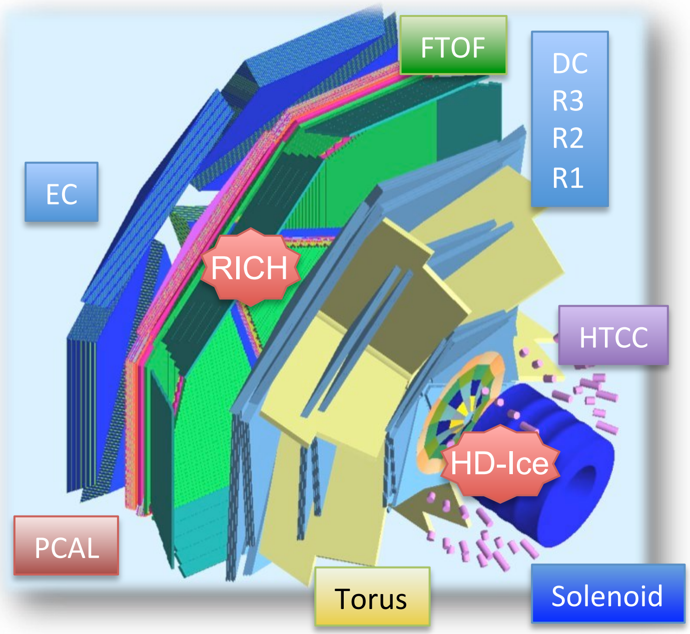
In order to reach the desired statistical precision at high-Q^2 and high-p_T (perturbative limit) for both pions and kaons, and to allow a fully differentyal analysis in x, Q^2, z, p_T

we ask the PAC to award 110 days of beam time

(including 10 days for calibrations, empty target runs, supportive tests, etc.)

Backups

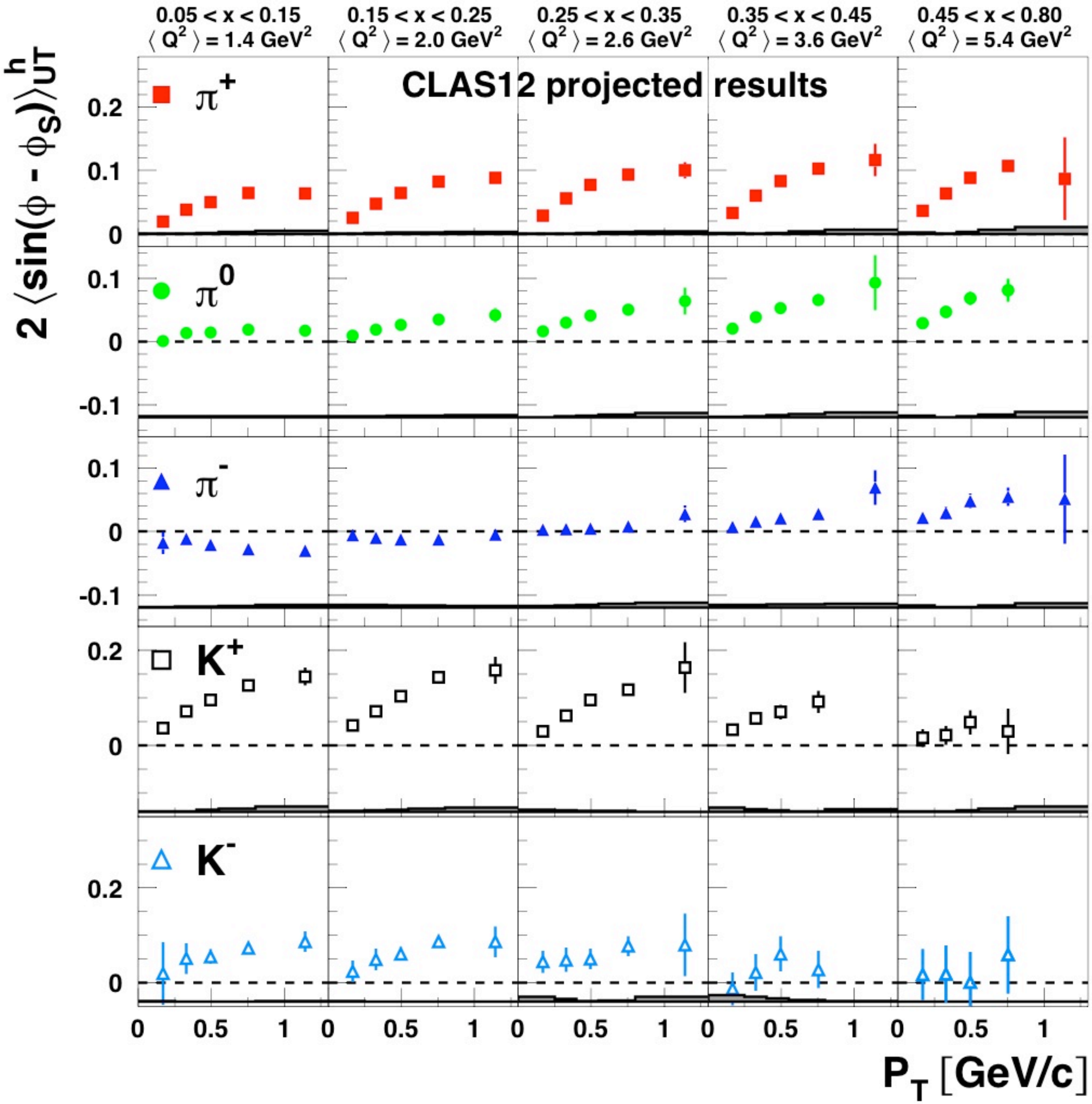
Requirements



The proposed experiment requires:

- Control over background contributions:
  - nuclear background
  - vector meson decays
  - target fragmentation
- Full kinematical coverage:
  - large pT (link to perturbative regime + Bessel extraction)
  - large Q^2 (control on higher-twists)
- Particle ID:
  - kaons versus pions
  - π^0 versus charged pions
  - di-hadrons

2D Projections



BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

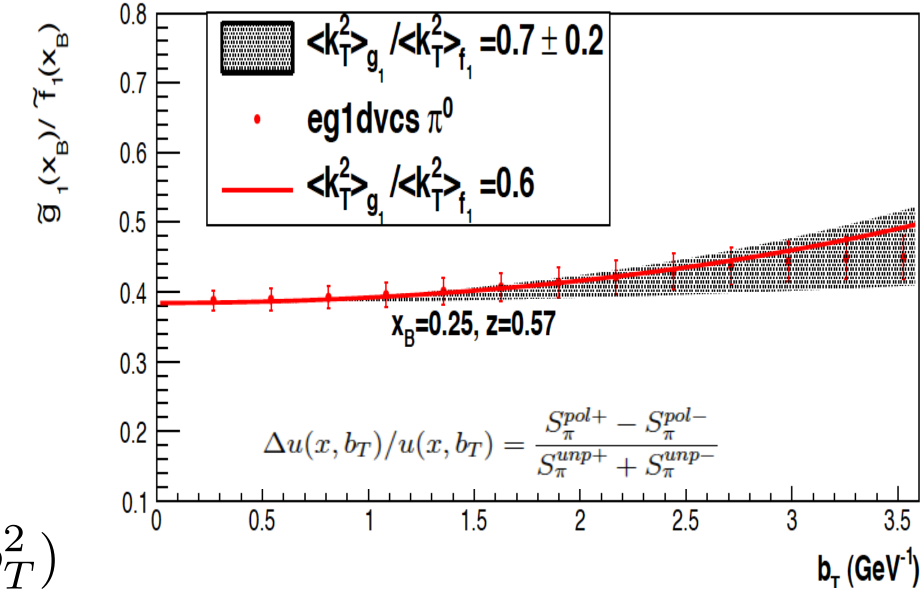
$$\int_0^\infty d|\boldsymbol{P}_{h\perp}|\,|\boldsymbol{P}_{h\perp}|\,J_0(|\boldsymbol{P}_{h\perp}||\boldsymbol{b}_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|\boldsymbol{P}_{h\perp}|d|\boldsymbol{P}_{h\perp}|}\right]$$

$$S_\pi^{unp\pm}(x_i,z_i,b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta_i/A(x_i,y_i)$$

acceptance

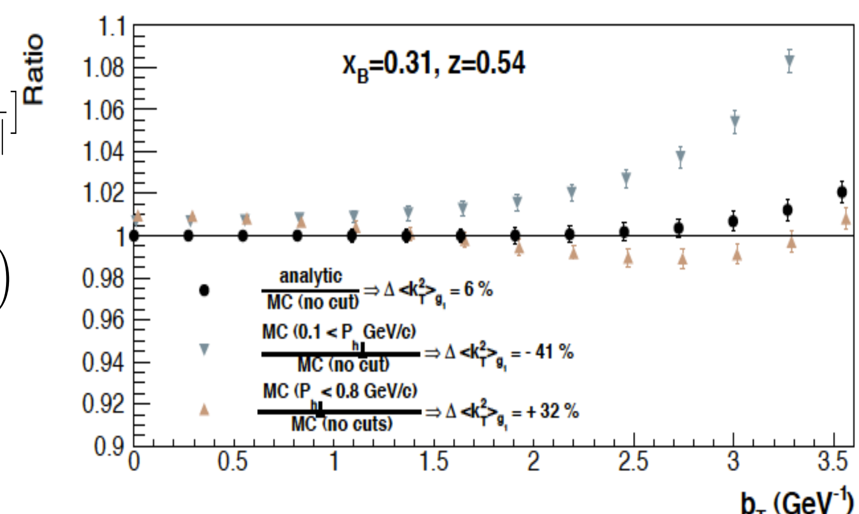
$$A(x,y)=\frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\tilde f_1^q(x,z^2b_T^2)\,\tilde D_1^{q\to\pi}(z,b_T^2)$$



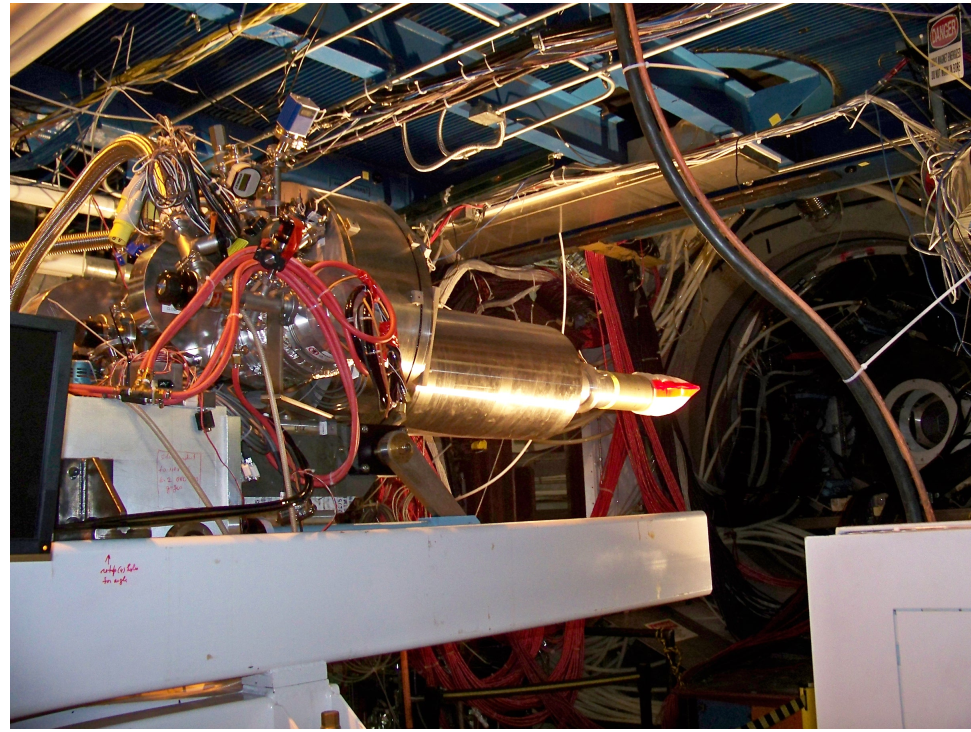
$$\int_0^{2\pi} d\phi_h \sin(\phi_h-\phi_S)\int_0^{\inf} d|\mathbf{P_{h\perp}}||\mathbf{P_{h\perp}}|\frac{2J_1(|\mathbf{P_{h\perp}}||\mathbf{b_T}|)}{zM_h|\mathbf{b_T}|}\left[\frac{d\sigma}{dxdydzd\phi_h|\mathbf{P_{h\perp}}|d|\mathbf{P_{h\perp}}|}\right]$$

$$\tilde f_{1T}^{\perp(1)q}(x,z^2b_T^2)\,\tilde D_1^{q\to\pi}(z,b_T^2)$$



- the formalism in **b_T-space** avoids convolutions $\rightarrow$ easier to perform a model independent analysis of TMDs

HDice operations during g14 / E06-101

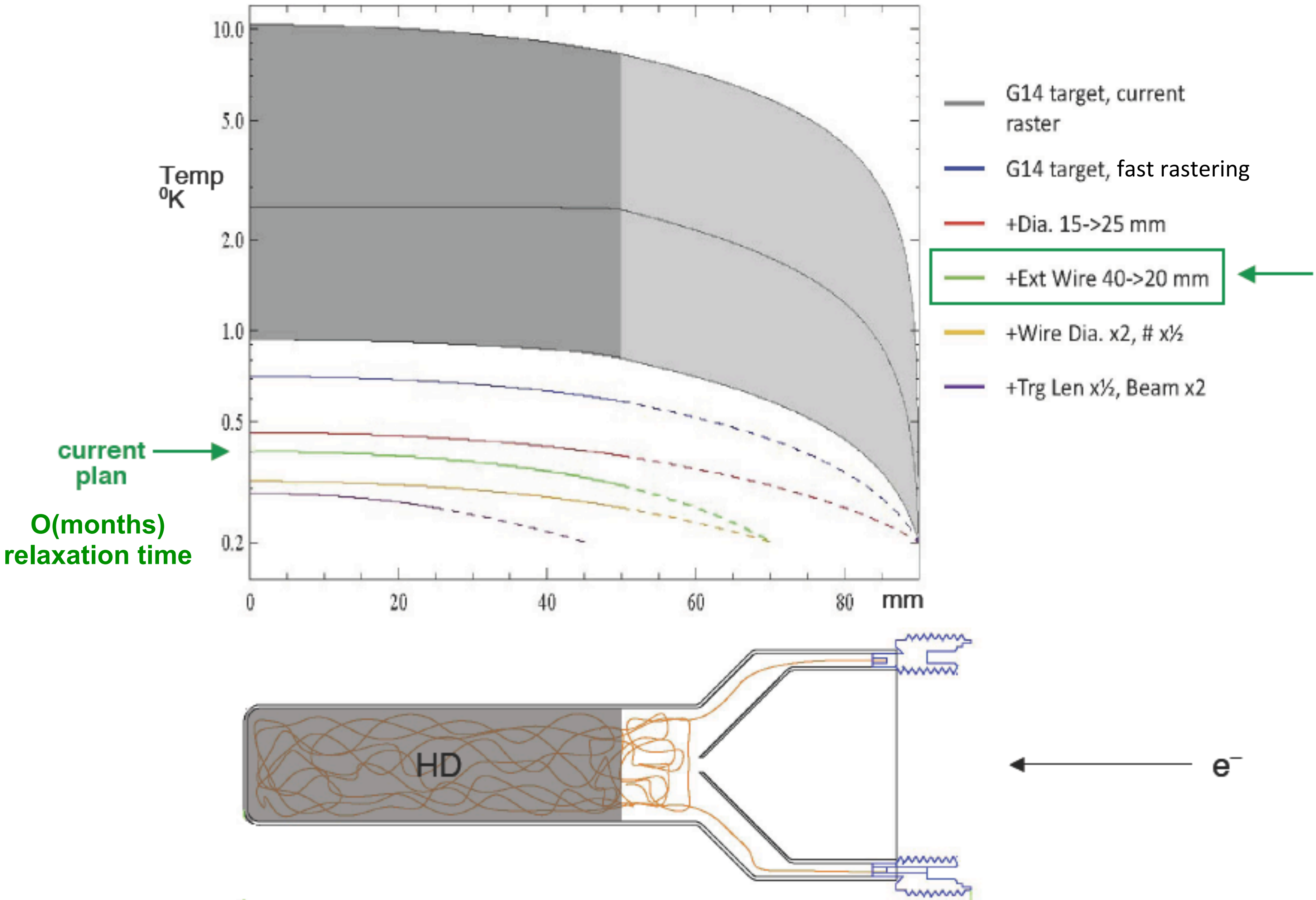


- *HD targets condensed, polarized and aged to the Frozen-Spin state in HDice Lab (TestLab annex)*
- *transferred as solid, polarized HD between cryostats; moved to Hall B*
- *In-Beam Cryostat (IBC) operates in Hall at 50 mK, 0.9 tesla*
- *g14 ran from Nov/11 to May/12 with 15mm Ø ×50mm long HD cells*
- *γ-beam lifetimes ~ years with 10^8 γ/s*
- *HD targets used for eHD tests in Feb/12 and Mar/12*

➔ *H polarization does not appear to suffer radiation damage with 1 nA; D does*

➔ *heat removal needs improvement – faster raster, larger diameter cell, additional cooling wires, …*

Peak HDice Target Temperature versus Position along Beam
due to 2.5 mW beam-heat from 1 nA electrons



Potential for transverse HD with e⁻

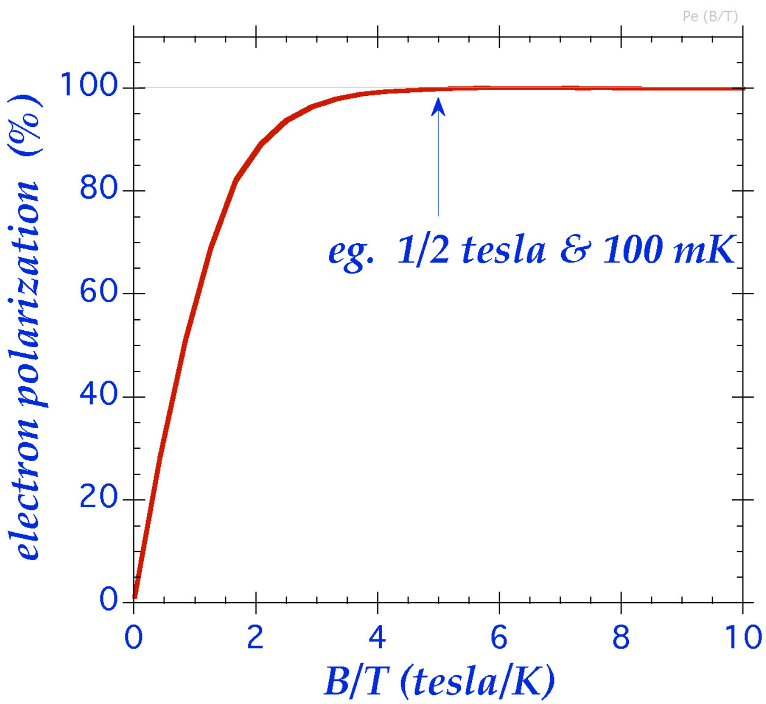
eg. 2.5 mW of beam heating for each 1nA of e^- on 5 cm of HD

- low temperatures not required to hold HD spins (polarization mechanism very different from DNP)

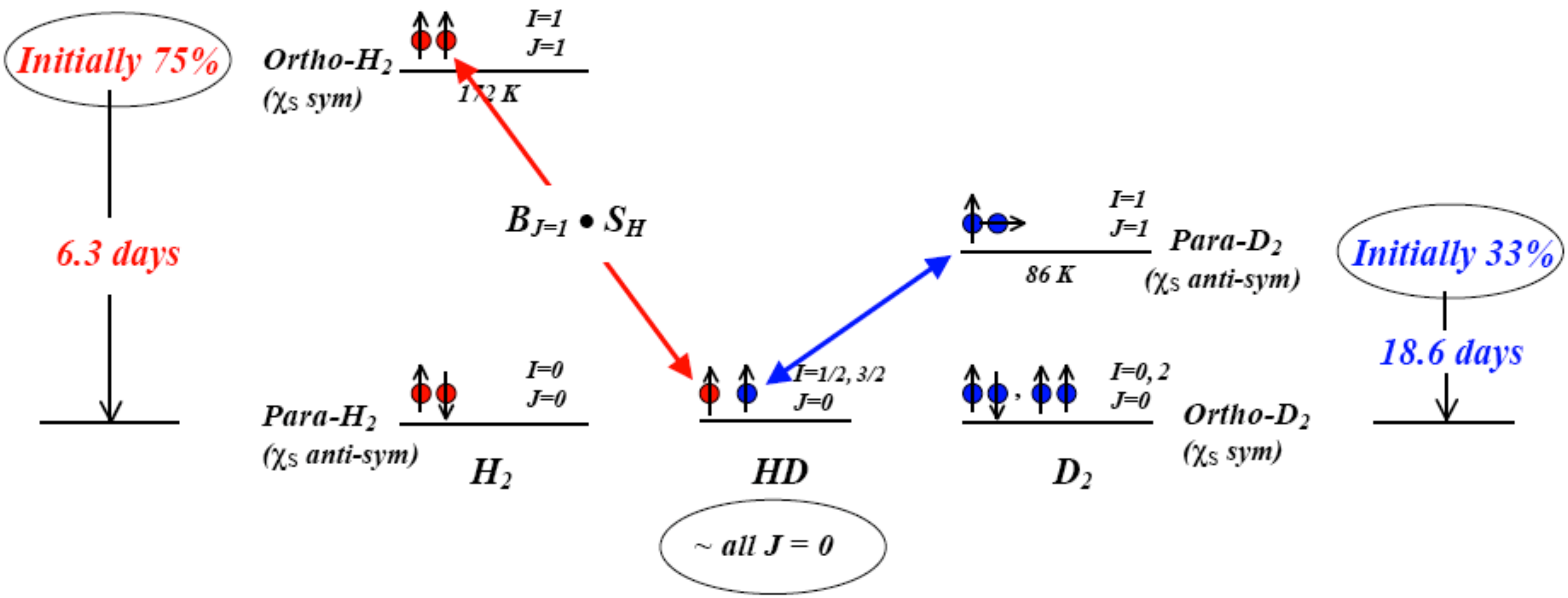
- paramagnetic centers / ionized electrons will have no effect if they are polarized

➔ requires only *short* ~1/2 tesla fields
- field uniformity not important for HD
- *BdL* ~ 0.1 *Tm* ➔ no beam deflection

➔ requires sufficient cooling to maintain a few hundred mK
- tests with Roots circulation in May/12

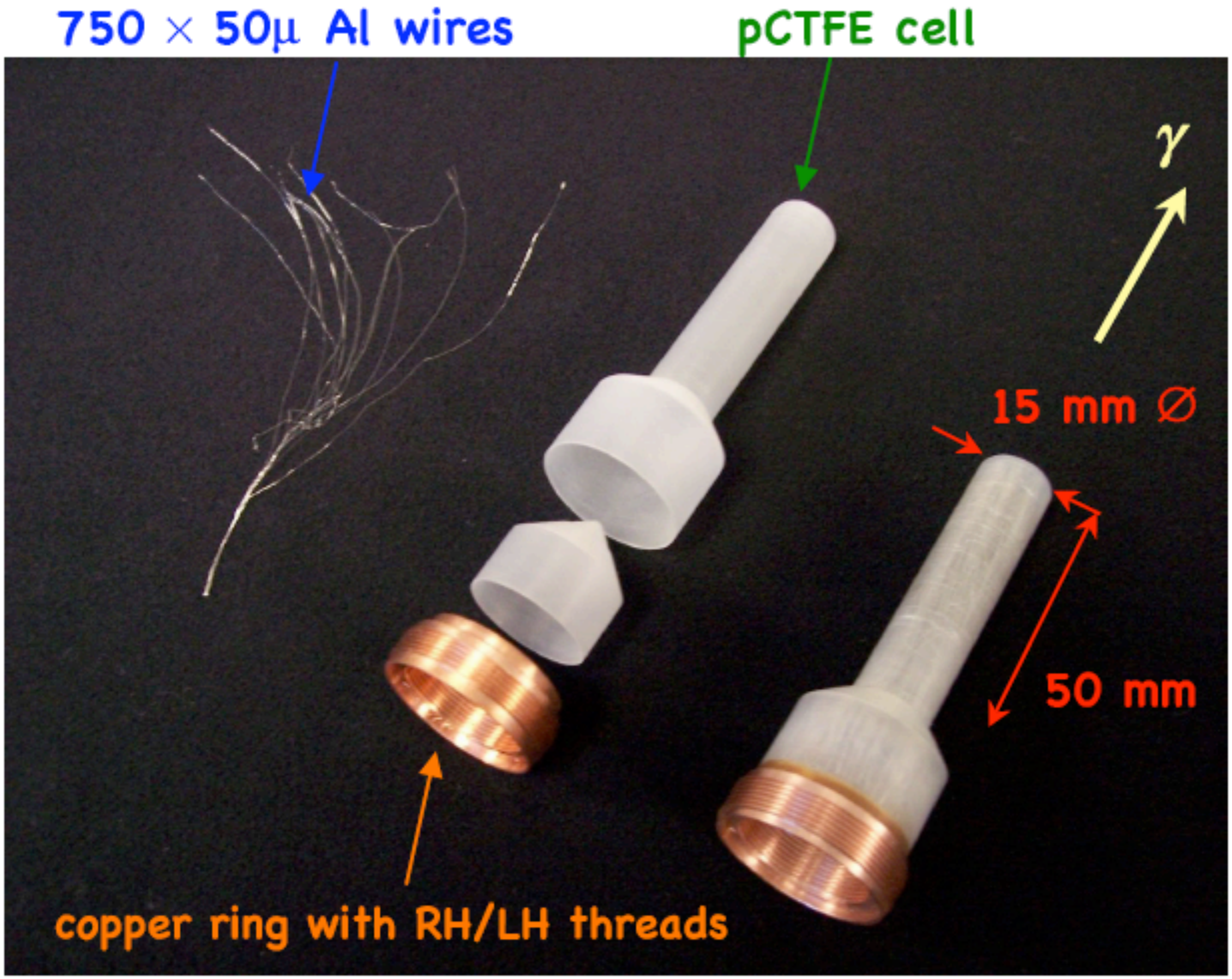


External Magnetic field rapidly aligns Ortho-H_2 and Para-D_2 then spins exchange with H and D in HD



- *relaxation switch – A. Honig, Phys. Rev. Lett.* ***19*** *(1967).*

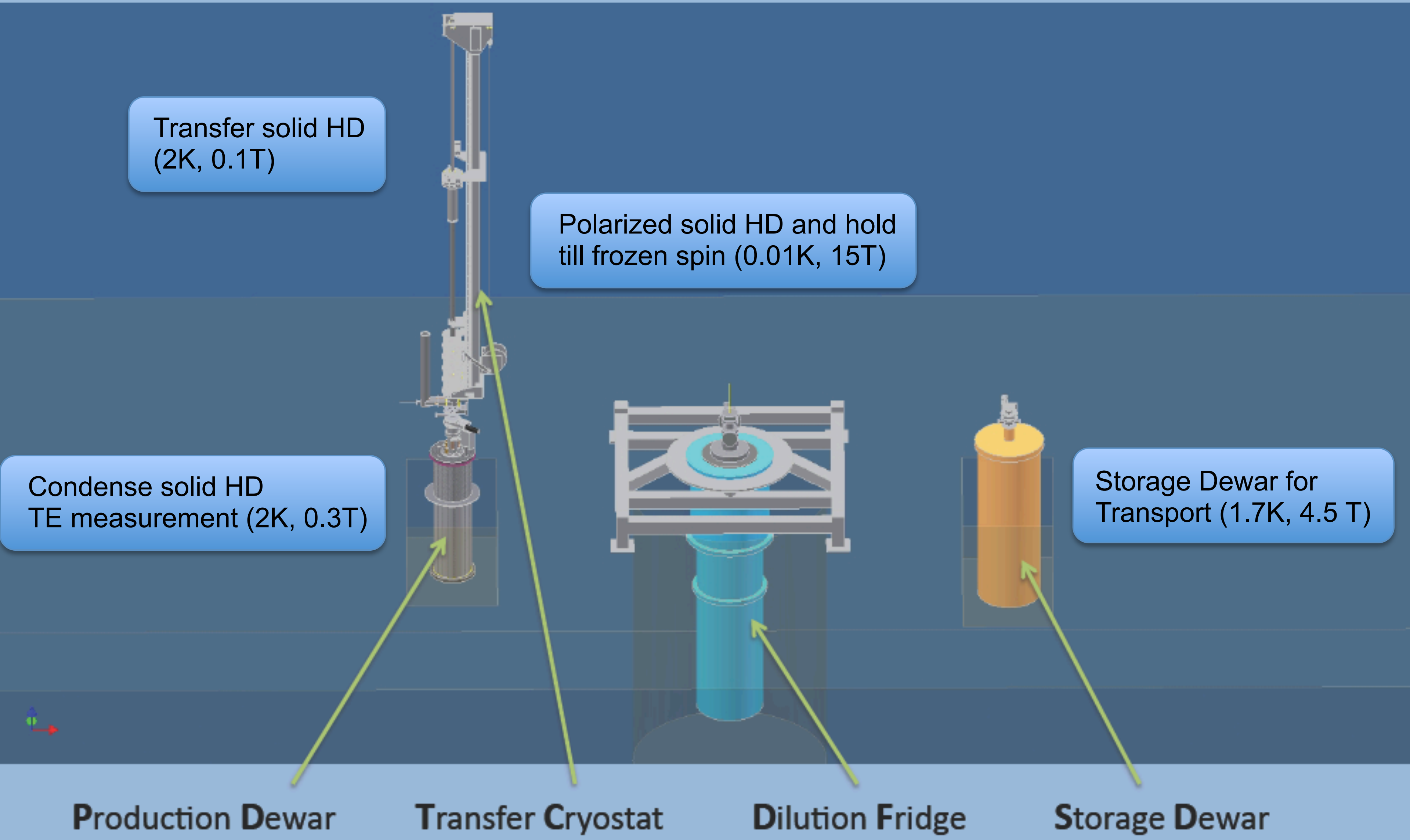
- HDice target cells:



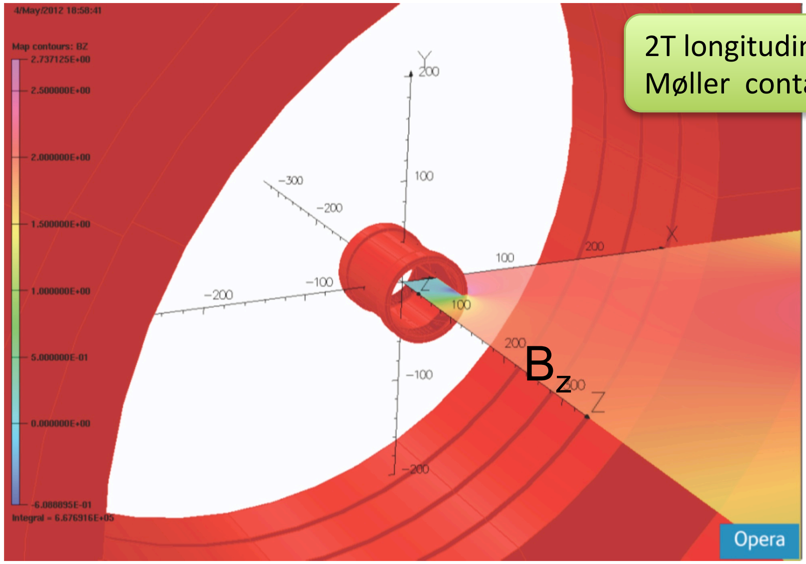
- material in the beam path:

77% HD + 17 % Al + 6% pCTFE (remove with vertex cuts)

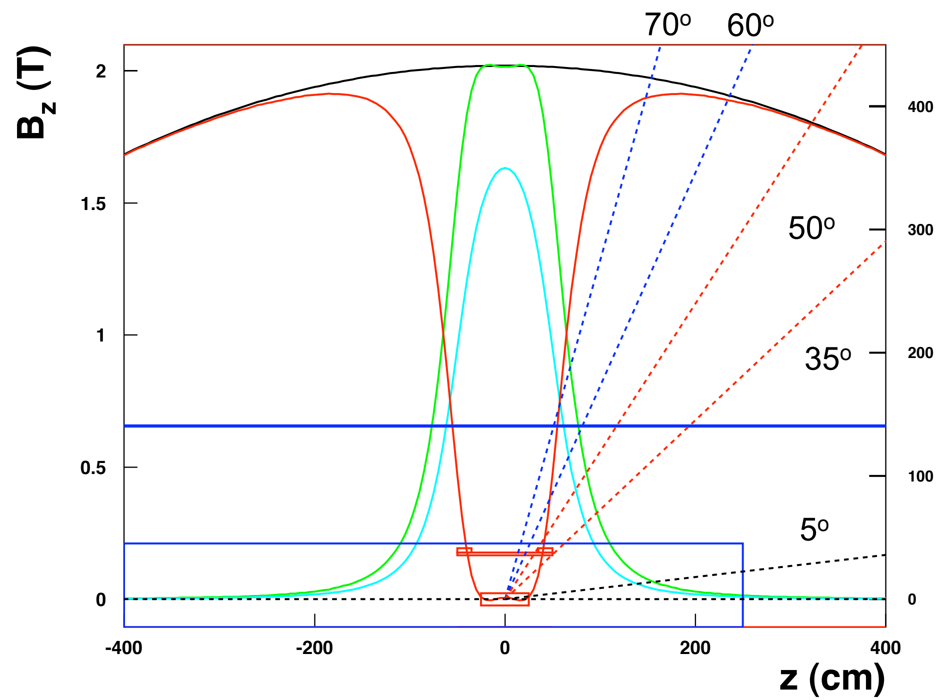
Cryostats used in HD Target Production



Question 2: Magnet Configuration



2T longitudinal field for Møller containment

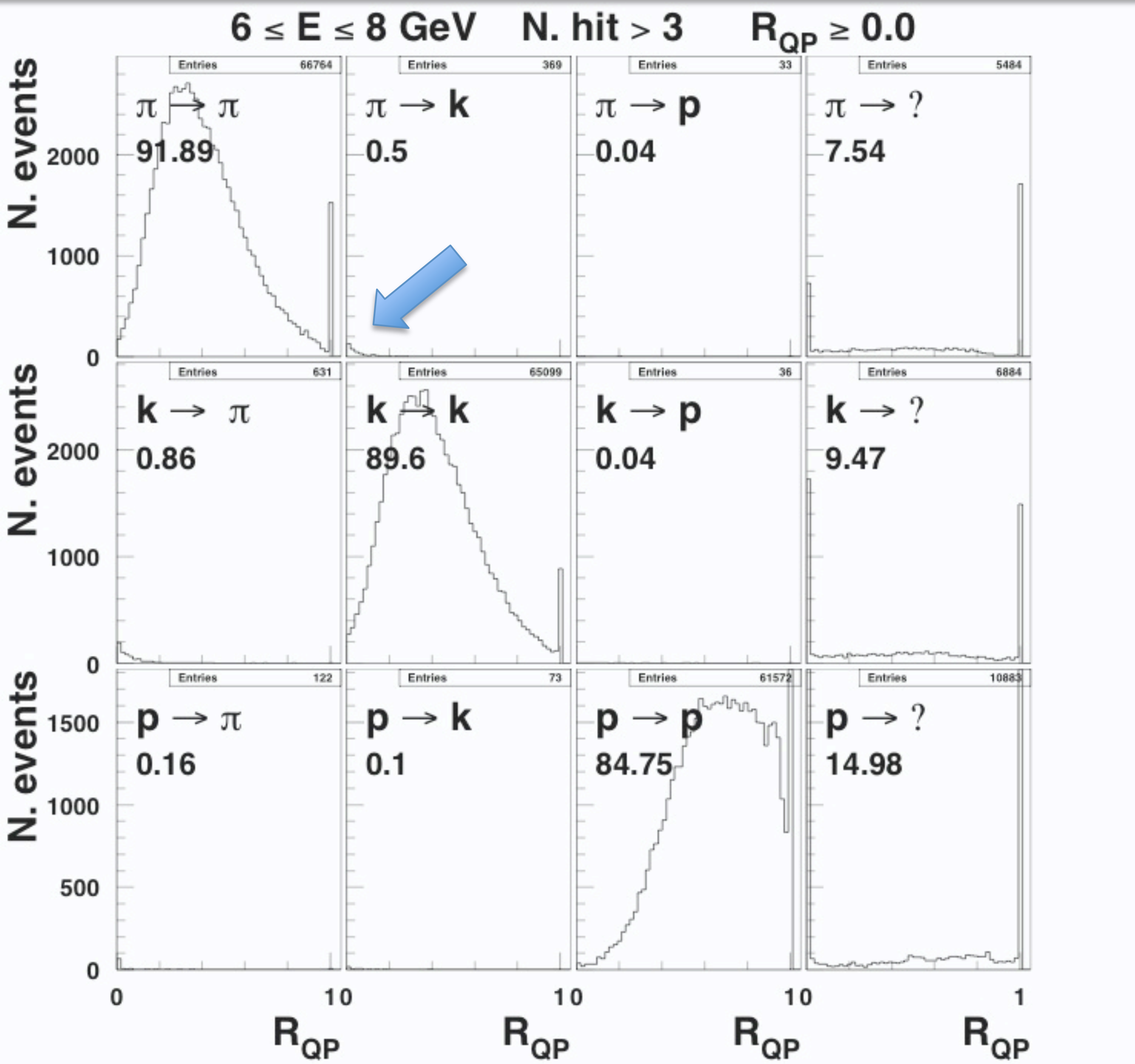


- Good homogeneity (< 5mT long. field)
- Moeller background under control
- Working point below critical current of existing SC wires
- Dimensioned for standard quench protection
- Static forces one order of magnitude smaller than G10 epoxy tensile strength

RICH Performances

Realist optical effects

- mirror reflectivity
- Rayleigh scattering



CLAS12 Kinematic Coverage

$0.05 < x < 0.6$

for $Q^2>1$ GeV^2 and $W^2 > 4$ GeV^2

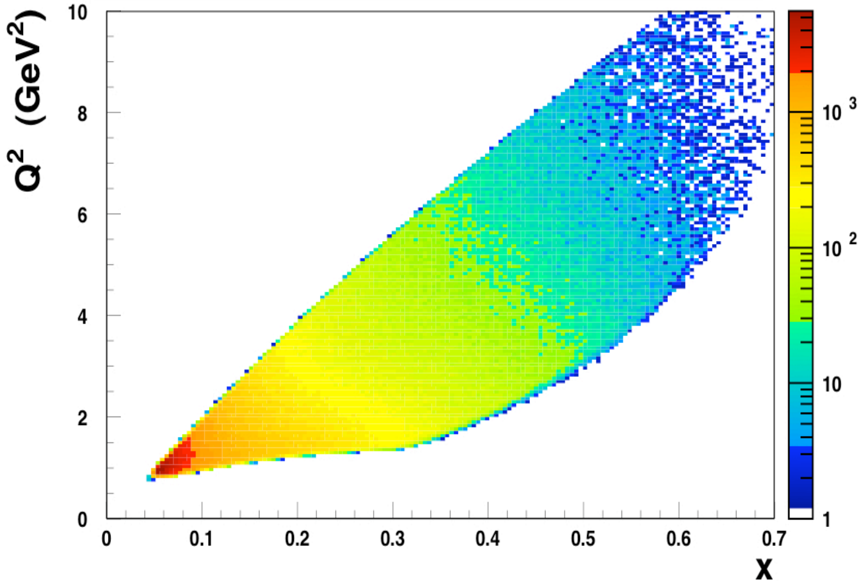
Cover valence region at several GeV Q^2
Constrain sub-leading twist terms

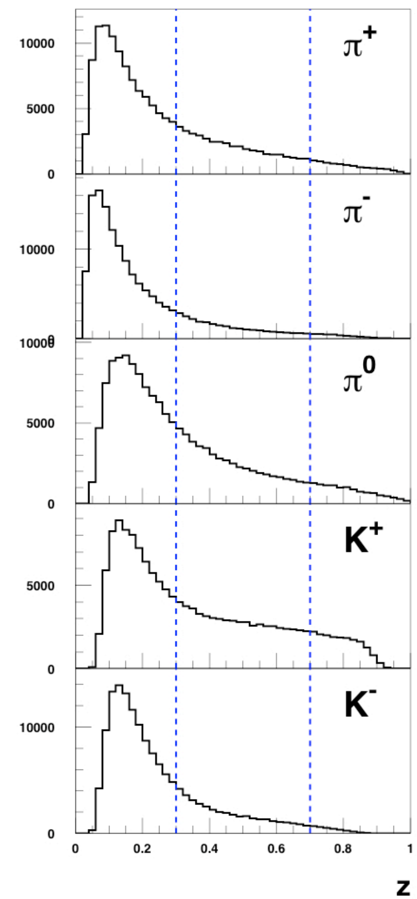
$0.3 < z < 0.7$

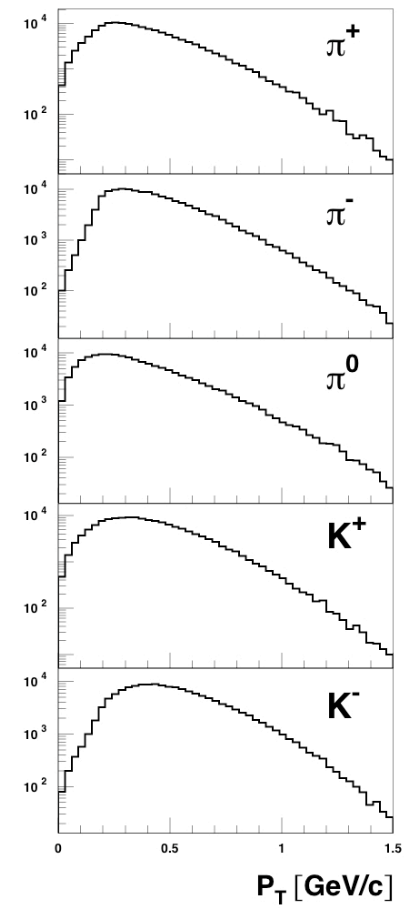
Current fragmentation
No exclusivity corner

$P_T > 1$ GeV/c

Limit given by
cross-section







Single- and Double-Spin asymmetries

- **Experiment:** CLAS12 with
  HD-Ice transversely polarized target
  60 % polarization and 1/3 dilution for Hydrogen @ 5 10^{33} cm^{-2} s^{-1}
  RICH detector for flavor tagging
  pions, kaons and protons ID in the 3-8 GeV/c momentum range

- **Event selection**:

$Q^2 > 1$ GeV^2, $x > 0.05$	select DIS region
$W^2>4$ GeV^2 , $M_X^2>2$ GeV^2	suppress resonances
$0.10 < y < 0.85$	for high detection efficiency and small radiative corrections
$0.3 < z < 0.7$	select current fragmentation and avoid exclusivity corner

- **Analysis**: in each kinematic bin, the relevant Fourier amplitudes (Collins, Sivers, etc) are extracted simultaneously, thanks to their specific azimuthal dependence, by a Maximum-Likelihood fit unbinned in ϕ,ϕ_S of the yields for opposite spin states

$$p.d.f. = \varepsilon(x,y,z,p_T,\phi,\phi_S)\sigma_{UU}(x,y,z,p_T)/\mathrm{N}\times$$

Multiplicative term : irrelevant for balanced spin samples

$$\rho(P)\ \left\{1+\ldots+P\left[A^{Coll}(\lambda_{Coll},x,y,z,p_T)\sin(\phi+\phi_S)+A^{Siv}(\lambda_{Siv},x,y,z,p)s\,\mathrm{in}(\phi-\phi_S)+\ldots\right]\right\}$$

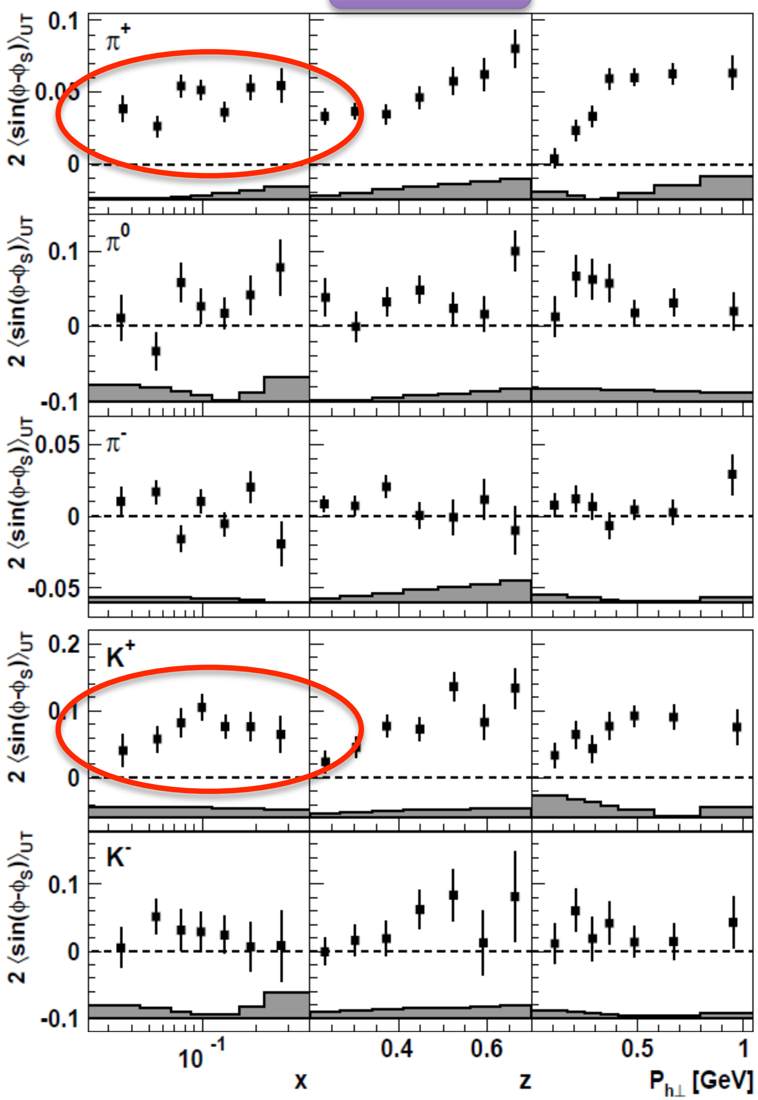
Unpolarized terms

Other polarized terms

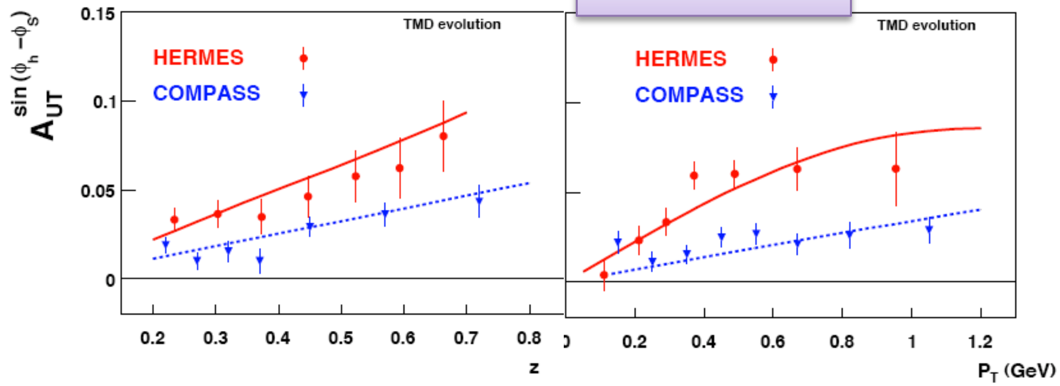
The Sivers effect

$f_{1T}^{\perp} \otimes D_1$

HERMES



arXiv:1112.4423

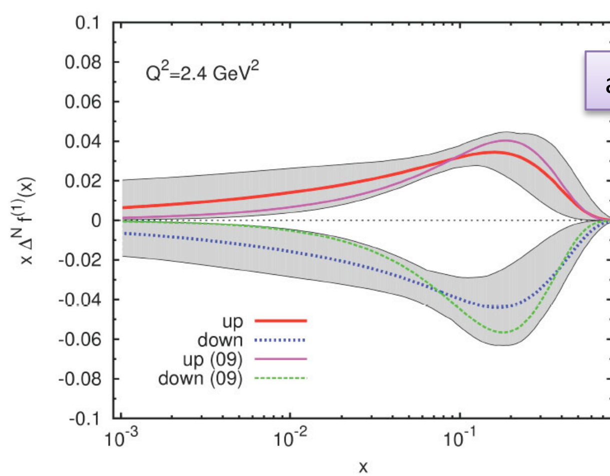


Related to quark orbital angular momentum

Non zero signals for π^+ and K^+

Significant Q^2 evolution ?

K^+ signals larger than π^+



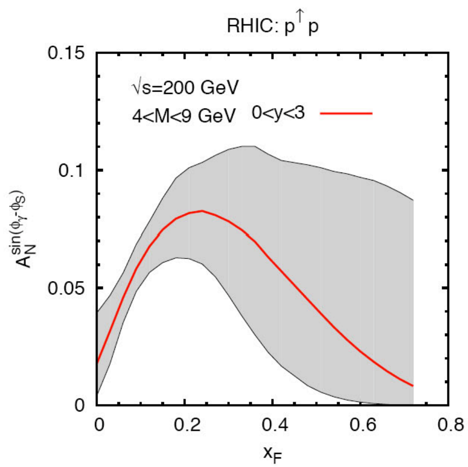
arXiv: 1107.4446

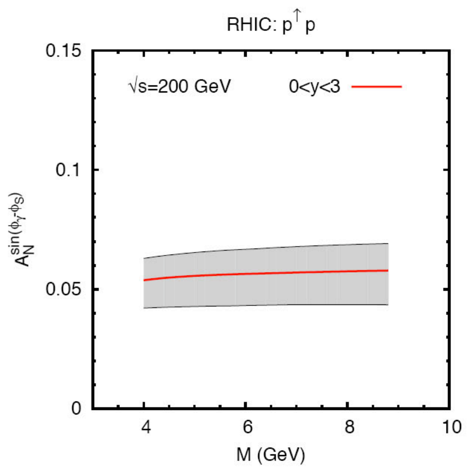
The Sivers effect

$f_{1T}^{\perp} \otimes D_1$

Sivers effect from SIDIS to Drell-Yan

arXiv: 0901.3078

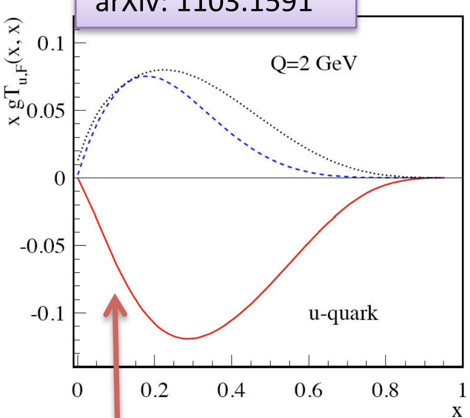


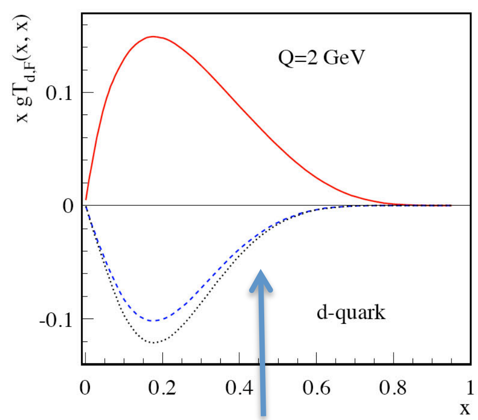


Coverage at large x and relation with Drell-Yan

Sign change is a crucial test of TMDs factorization

arXiv: 1103.1591





T3 correlator from pp

Sivers moment from SIDIS

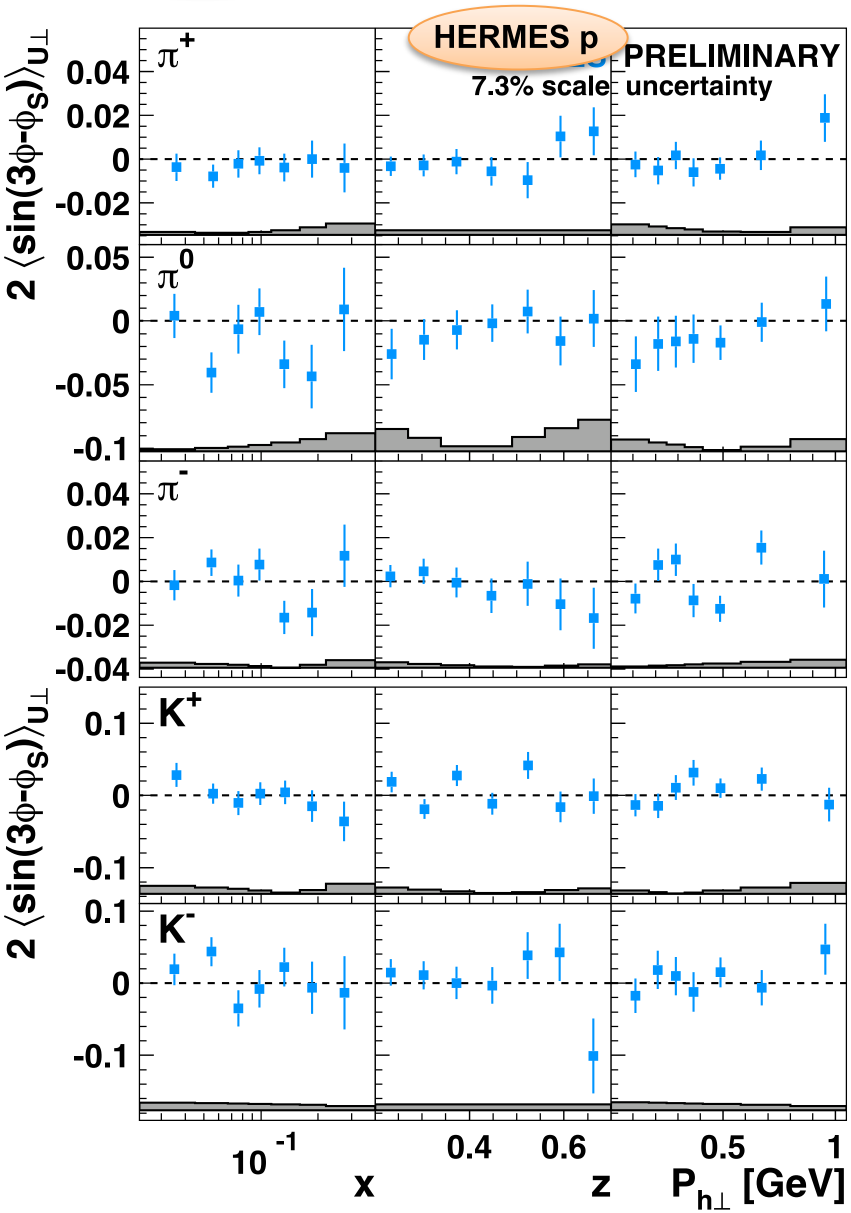
Coverage at large p_T and relation with twist-3 collinear approach

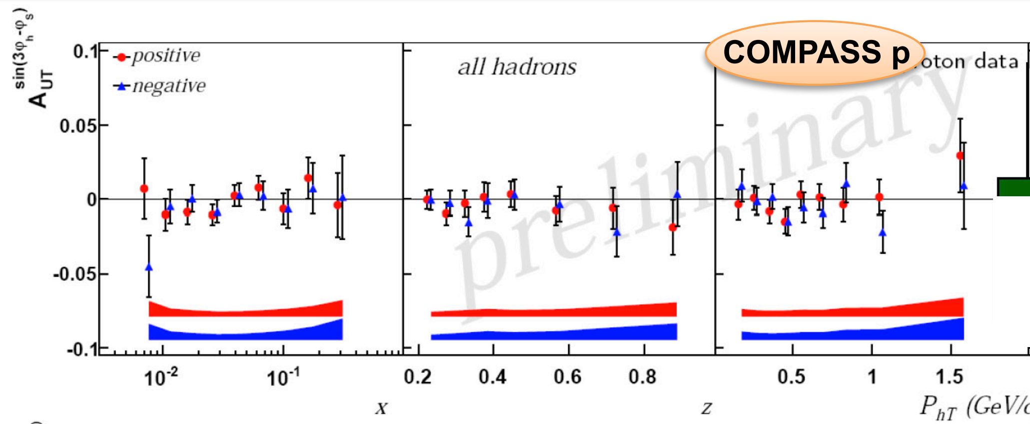
Sign mismatch between SIDIS and pp SSA ?

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

The Pretzelosity

$h_{1T}^{\perp} \otimes H_1^{\perp}$





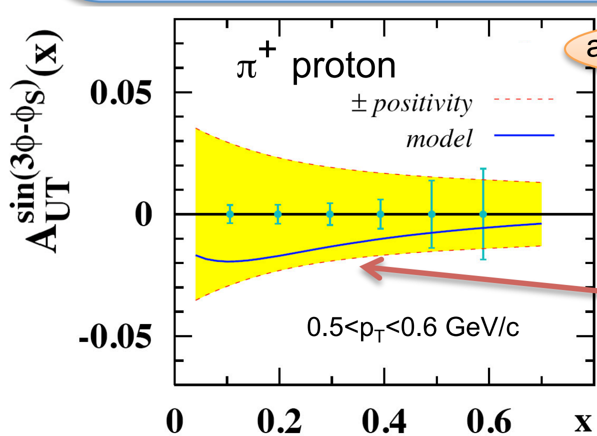
Statistical power of existing data is not enough to observe significant signals

"pretzelosity" still basically unknown

$$h_{1T}^{\perp(1)q}(x) = g_1^q(x) - h_1^q(x)$$ no-gluon models

$$\left|h_{1T}^{\perp(1)q}(x)\right| + \left|h_1^q(x)\right| \le f_1^q(x)$$ positivity bound

?



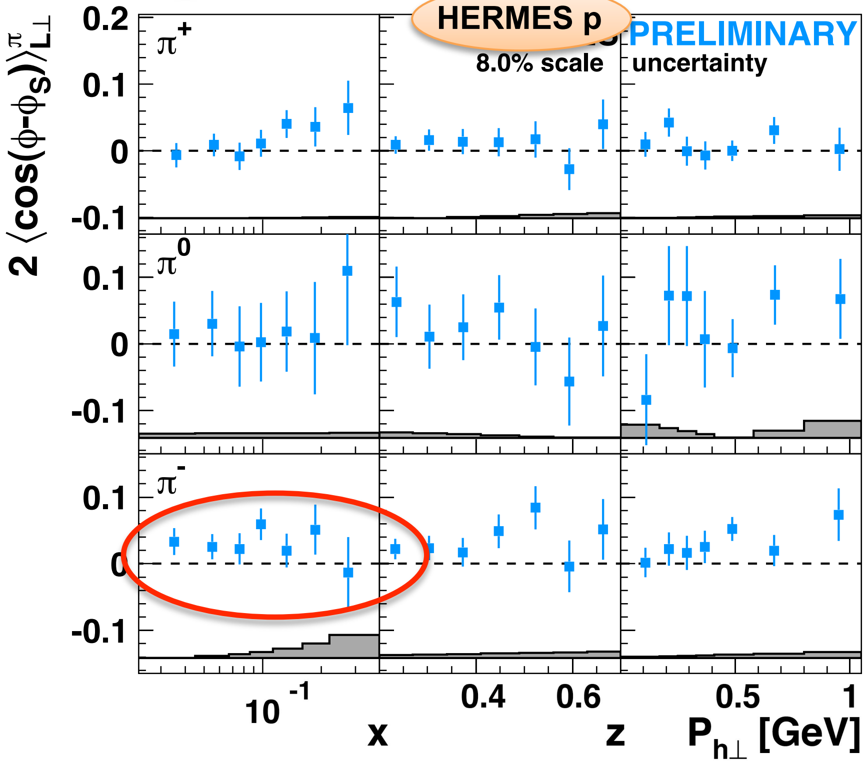
Few % signal expected at Jlab from relativistic covariant model

Nucleon wave components with different OAM

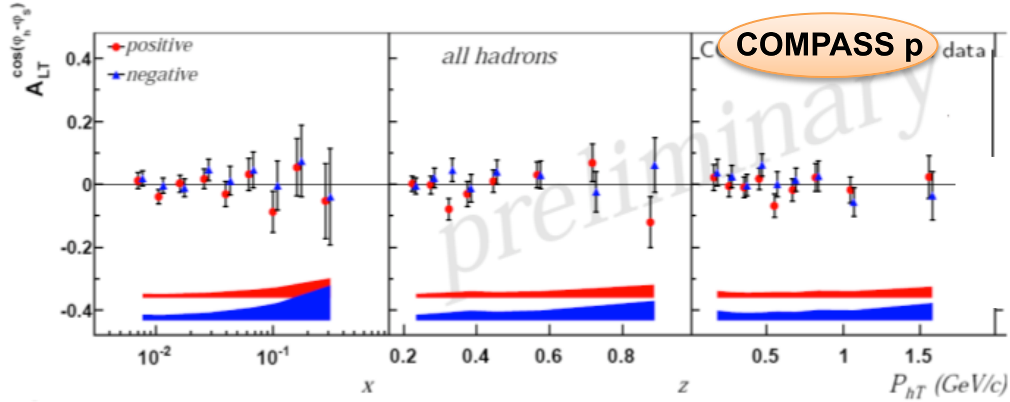
The Worm-gear function

$g_{1T}^{\perp} \otimes D_1$

HERMES p



COMPASS p

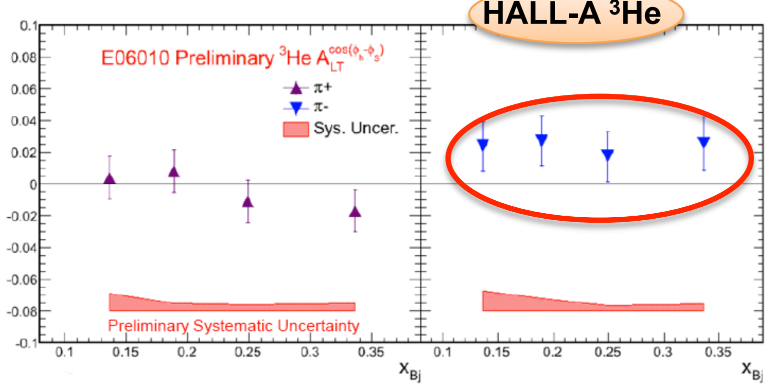


Statistics not enough to investigate relations supported by many theoretical models:

$$g_{1T}^{q} = -h_{1L}^{\perp q}$$ (supported by Lattice QCD and first data) ?

$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x\int_x^1 \frac{dy}{y} g_1^q(y)$$ (Wandura-Wilczek type approximation) ?

HALL-A ^{3}He



From constituent quark model: arXiv:0903.1271