A window of opportunity for SIDIS measurements at COMPASS beyond 2020

Outlook

- The talk is the result of the discussion in the SIDIS and Transversity groups
- It will cover these fields of interest:
  - Longitudinally polarised SIDIS
  - Transversely polarised SIDIS
  - Azimuthal asymmetries on unpolarised targets
  - Extras

WHERE DO WE STAND?

COMPASS data taking

muon beam	deuteron (^{6}LiD) PT	2002 2003 2004	80% L/20% T target polarisation
		2006	L target polarisation
	proton (NH_3) PT	2007	50% L /50% T target polarisation
Hadron	LH target	2008 2009	
muon beam	proton (NH_3) PT	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	Primakoff
muon beam	LH2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH3) DT PT	2014 2015	Pilot DY run DY run
muon beam	LH2 target	2016 2017	DVCS & unpol. SIDIS

Measurements with the target longitudinally polarized:

Year	Obs.	
2006	$A_{LL}^{2h}(Q^2<0)$	$\Delta g/g$
2007	$g_1^d(x)$,	$\Gamma_1^d, \Delta\Sigma$
2008	$A_{1,d}^{h^+-h^-}$	$\Delta u_v + \Delta d_v$
2009	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}$	$\Delta u_v + \Delta d_v, \Delta\bar{u} + \Delta\bar{d}, \Delta s (= \Delta\bar{s})$
2010	$g_1^p(x)$,	$\Gamma_1^{NS}, \lvert g_A/g_V \rvert$
2010	$A_{1,d}, A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}, A_{1,p}, A_{1,p}^{\pi^\pm}, A_{1,p}^{K^\pm}$	$\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{d}, \Delta s, \Delta\bar{s}$
2010	$\sin\phi$, $\sin 2\phi$, $\sin 3\phi$, $\cos\phi$ asyms	$h_L, f_L^\perp, h_1, f_{1T}^\perp, h_{1L}^\perp, h_{1T}^\perp, h_{1L}^\perp, g_L^\perp, g_{1T}$
2013	A_{LL}^{2h}	$\Delta g/g$
2013	$A_D^{\gamma N}$	$\Delta g/g$ in LO and NLO
2015	$g_1^p(x)$	$\Gamma_1^{NS}, \Delta\Sigma, \Delta u + \Delta\bar{u} \cdots$
2015	A_{LL}^p	NLO QCD fits for $\Delta g/g$

Measurements with the target transversely polarized:

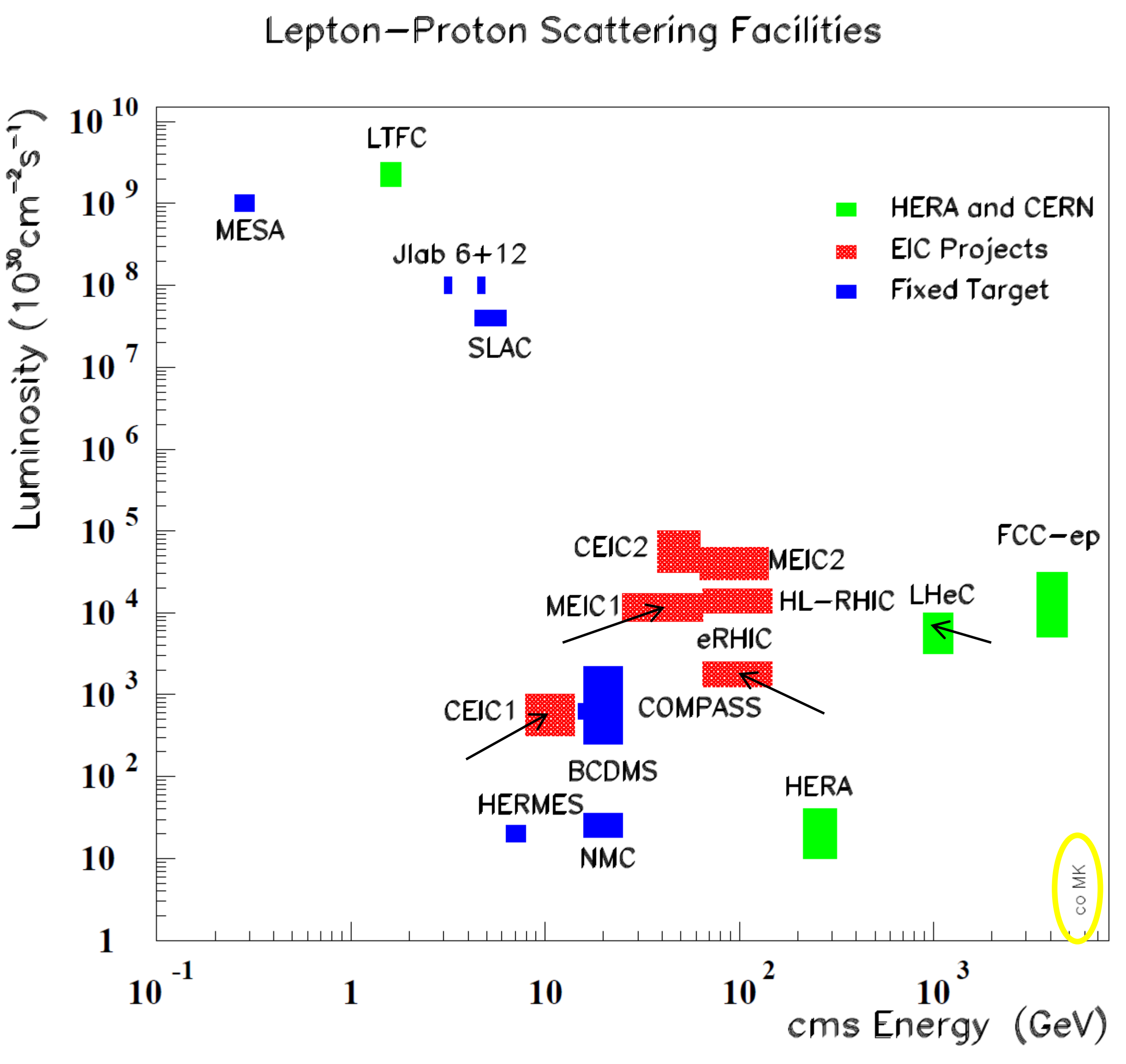
Year	Obs	
2005	$A^h_{Siv,d}, A^h_{Col,d}$	First ^{6}LiD data
2006	$A^h_{Siv,d}, A^h_{Col,d}$	Full ^{6}LiD statistics
2009	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full ^{6}LiD statistics
2010	$A^h_{Siv,p}, A^h_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD
2012	$A^h_{Siv,p}, A^h_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho - \phi_S)}_{UT,d}, A^{sin(\phi_\rho - \phi_S)}_{UT,p}$	Exclusive ρ^0
2013	$A^{(\phi_\rho, \phi_S)}_{UT,d}, A^{(\phi_\rho, \phi_S)}_{UT,p}$	Exclusive ρ^0, all asyms.
2014	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD and NH_3
2014	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^h_{Col,p}$	Full NH_3 statistics

Measurements with unpolarised targets:

Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2004
2014	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	2004, part
2016	$dn^\pi/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2016	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2006
2016	$dn^K/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006

WHAT WILL BE OUR PLAY GROUND?

The CM Energy vs Luminosity Landscape



CEIC1 = Chinese version of Electron-Ion Collider
("A dilution-free mini-COMPASS")

MEIC1 = EIC@Jlab

eRHIC = EIC@BNL

LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he
} future extensions

JLab 12

Run Group Schedule – Tentative

Run Group	Days	2015	2016	2017	2018	2019	2020	2021	Remain
All Run Groups	**936**		CND	FT RICH MM			Trans. PT	**525**	**411**
HPS	180*	2-3	7 ?						
PRad	15*		10 ?						---
CLAS12 KPP 				**15**					
RG-A (proton)	139*			20 **50**					69*
RG-F (BoNuS)	42*				**40**				2
RG-B (deut.)	90*				**45**				45*
RG-C (NH_3)	120				**15**	**45**			60
RG-C-b (ND_3)	65					**35**			30
RG-E (Hadr.)	60					**20**	**15**		25
RG-G (TT)	110*						**55**		55
RG-D (CT)	60						**30**		30
RG-K (LiD)	55							**55**	---

JLab 12- Hall B CLAS12

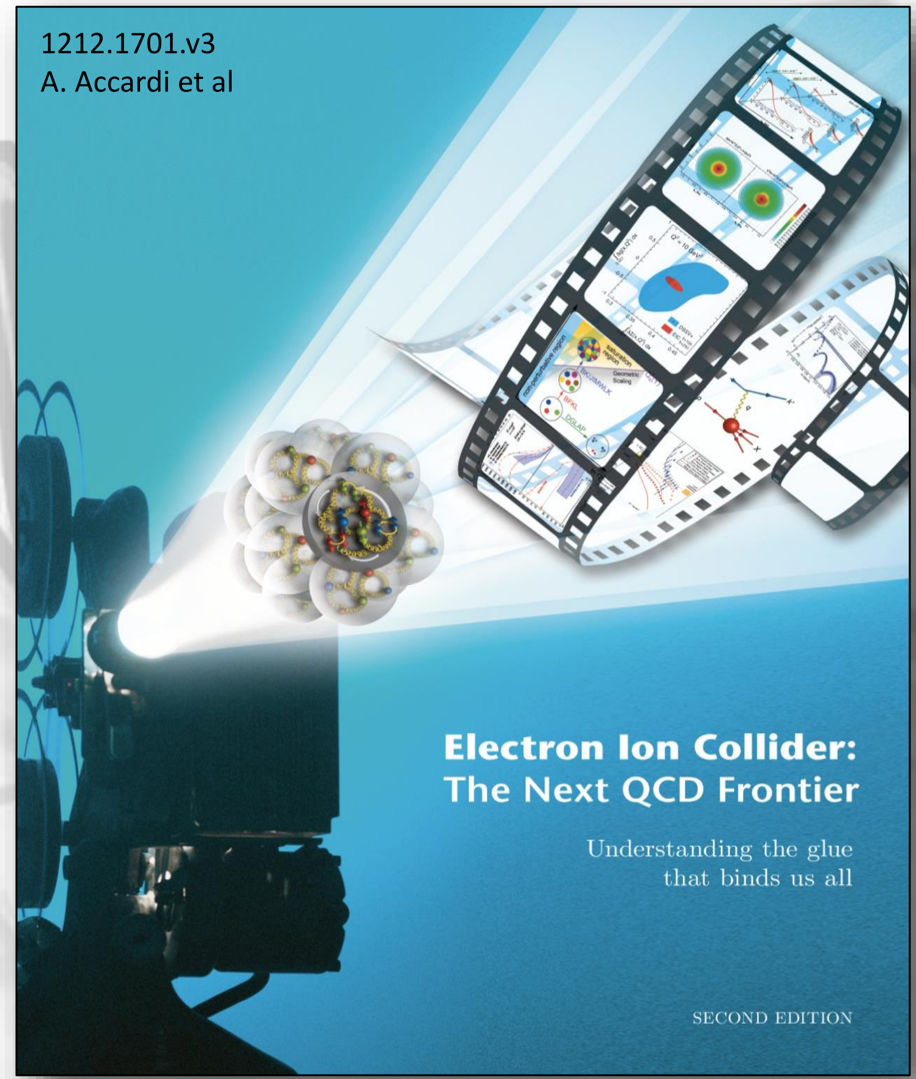
Proposal	Physics	Contact	Rating	Days	Group	New equipment	Energy	Run Group	Target
E12-06-108	Hard exclusive electro-production of π^0, η	Stoler	B	80	139	RICH (1 sector) Forward tagger	11	A F. Sabatié	liquid H_2
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60					
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	A	80					
E12-09-003	Excitation of nucleon resonances at high Q^2	Gothe	B+	40					
E12-11-005	Hadron spectroscopy with forward tagger	Battaglieri	A-	119					
E12-12-001	Timelike Compton Scatt. & J/ψ production in e+e-	Nadel-Turonski	A-	120					
E12-12-007	Exclusive φ meson electroproduction with CLAS12	Stoler, Weiss	B+	60					
E12-11-005a	Photoproduction of the very strangest baryon	Guo	NR	(120)					
E12-07-104	Neutron magnetic form factor	Gilfoyle	A-	30	90	Neutron detector RICH (1 sector) Forward tagger	11	B K. Hafidi	liquid D_2 target
PR12-11-109 (a)	Dihadron DIS production	Avakian							
E12-09-007a	Study of partonic distributions in SIDIS kaon production	Hafidi	A-	30					
E12-09-008	Boer-Mulders asymmetry in K SIDIS w/ H and D targets	Contalbrigo	A-	56					
E12-11-003	DVCS on neutron target	Niccolai	A	90					
E12-06-109	Longitudinal Spin Structure of the Nucleon	Kuhn	A	80	185	Polarized target RICH (1 sector) Forward tagger	11	C S. Kuhn	NH_3 ND_3
E12-06- 119(b)	DVCS on longitudinally polarized proton target	Sabatie	A	120					
E12-07-107	Spin-Orbit Correl. with Longitudinally polarized target	Avakian	A-	103					
PR12-11-109 (b)	Dihadron studies on long. polarized target	Avakian							
E12-09-007(b)	Study of partonic distributions using SIDIS K production	Hafidi	A-	80					
E12-09-009	Spin-Orbit correlations in K production w/ pol. targets	Avakian	B+	103					
E12-06-106	Color transparency in exclusive vector meson production	Hafidi	B+	60	60		11	D	Nuclear
E12-06-117	Quark propagation and hadron formation	Brooks	A-	60	60		11	E	Nuclear
E12-06-113	Free Neutron structure at large x	Bueltman	A	40	42	Radial TPC	11	F	Gas D_2
E12-14-001	EMC effect in spin structure functions	Brooks	B+	55	55	Pol. LiH target	11	G	LiH
TOTAL run time				1466 (1586)	631				

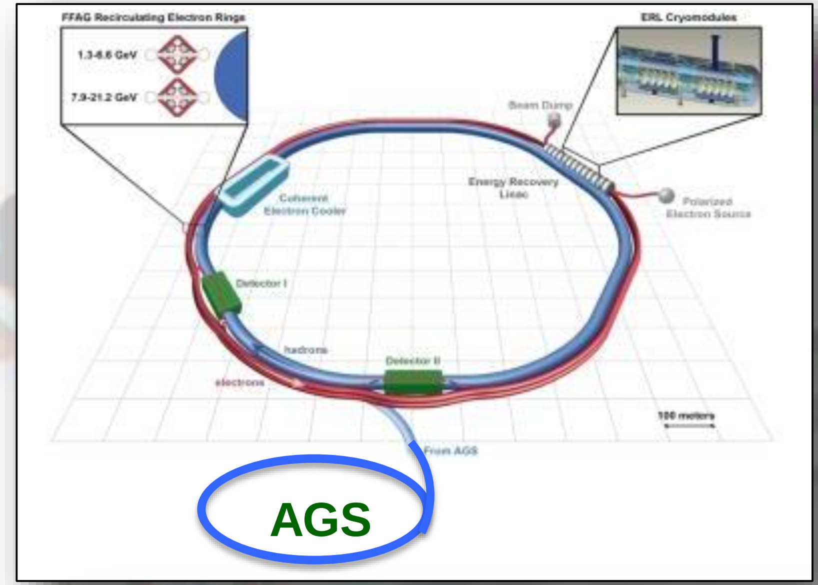
C1 approved proposals & non-CLAS12

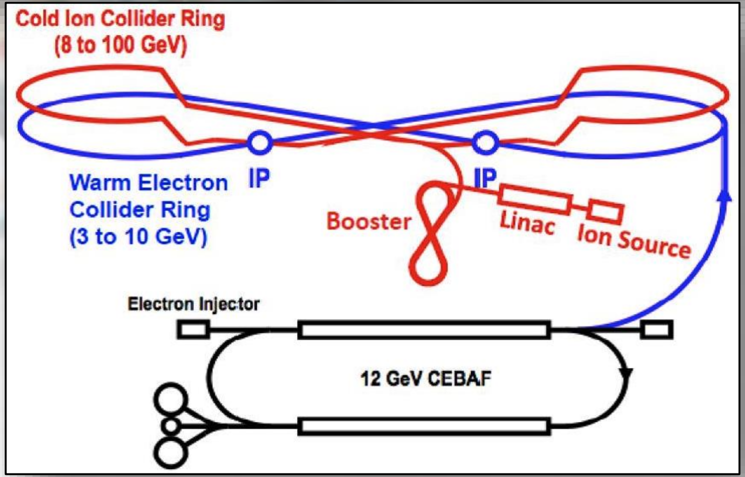
Proposal	Physics	Contact	Rating	Days	Group	Equipment	Energy	Group	Target
C12-11-111	SIDIS on transverse polarized target	Contalbrigo	A	110	110	Transverse target	11	**G**	HD
C12-12-009	Transversity w/ di-hadron on transvere target	Avakian	A	110					
C12-12-010	DVCS with transverse polarized target in CLAS12	Elouadrhriri	A	110					
All transverse target proposals				330	110				
C12-11-006	Heavy Photon Search at Jefferson Lab (HPS)	Jaros	A	180	180	New setup in alcove	2.2, 6.6	**H**	Nuclear
E12-11-106	High Precision Measurement of the Proton Charge Radius	Gasparian	A	15	15	Primex	1.1, 2.2	**I**	H2 gas
Beam time request from CLAS12 C! experiments + non-CLAS12 experiments				**525**	**305**				
Beam time from approved CLAS12 experiments (from previous page)				**1466**	**631**				
TOTAL Beam time for all Hall B experiments				**1991**	**936**				

Optimistically, we may run 90 PAC days per year. To run all experiments as run groups with full beam time will require 936/90 ≈ 10 years.

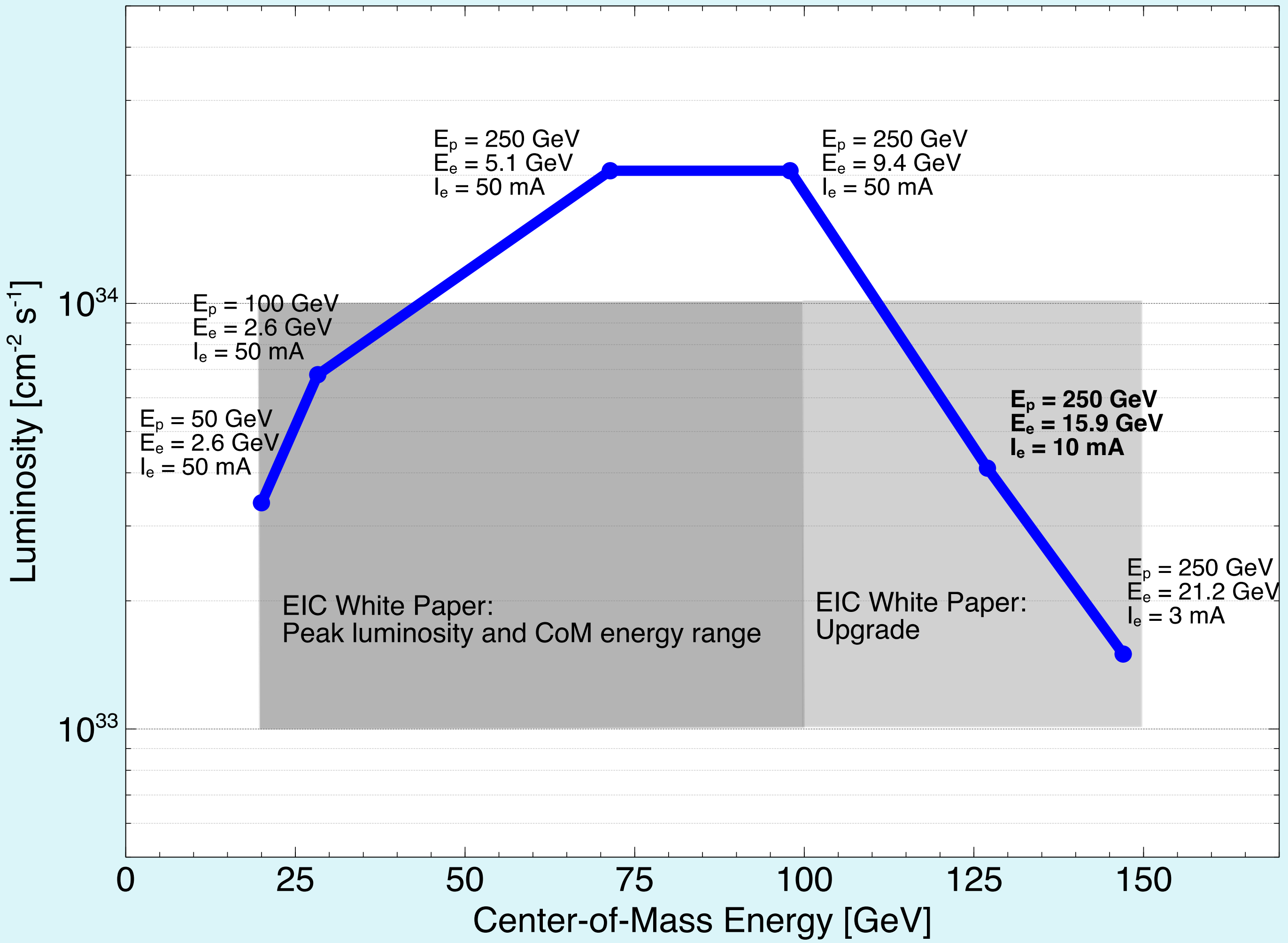
The US Electron Ion Collider Project



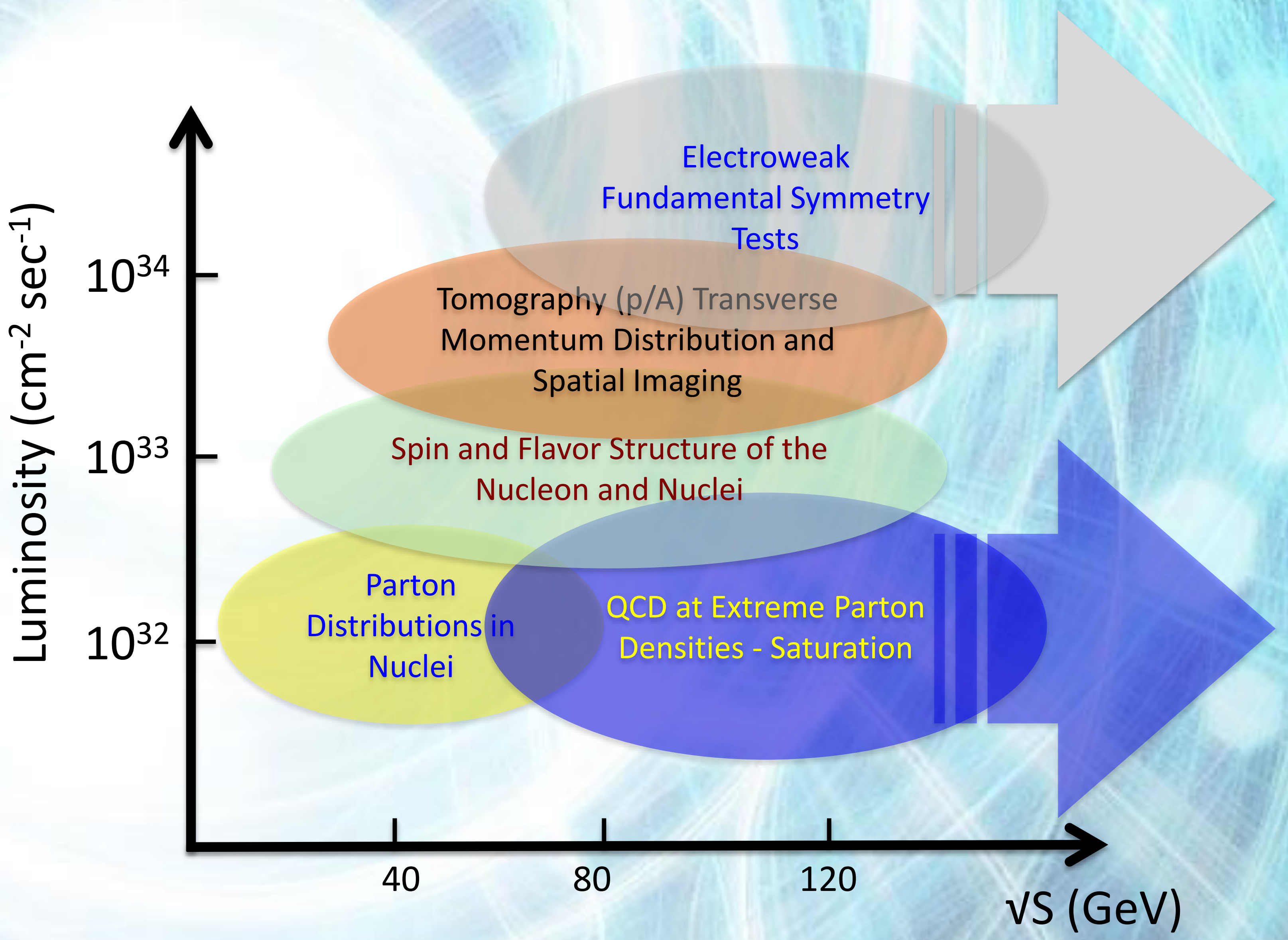




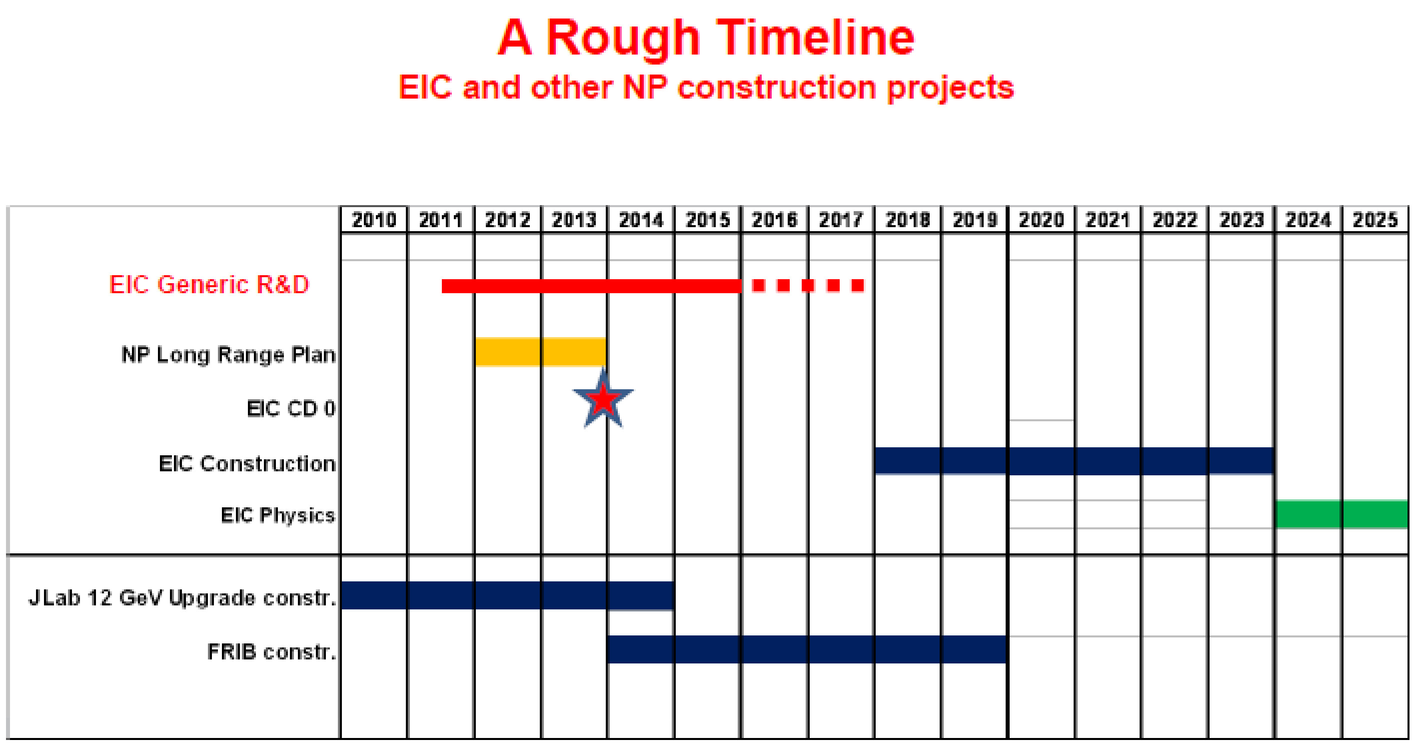
eRHIC peak luminosity vs. CoM energy



Physics vs. Luminosity & Energy



It is Good to Push, But Hazardous to Make Projections



T. Hallman

WHAT REMAINS TO BE DONE?

Suggestions from the SIDIS group

- The longitudinal SPIN physics programme has been completed
  - $\Delta q, \Gamma, \Delta\Sigma$ have been measured
  - What was possible to do for Δg has been done
  - Enough statistics will be collected in 2016/17 to measure multiplicities and fix once and for all the $s(x, Q^2)$ PDF

FOR THESE REASONS THE PROGRAM IS EXPECTED TO BE OVER WITH THE END OF PHASE-II

Suggestions from the Transversity group

- Let us start with what was sent in 2012 for the European Strategy group

Table 2: Summary of the different physics items for the far and near future. Already approved measurements are in bold.

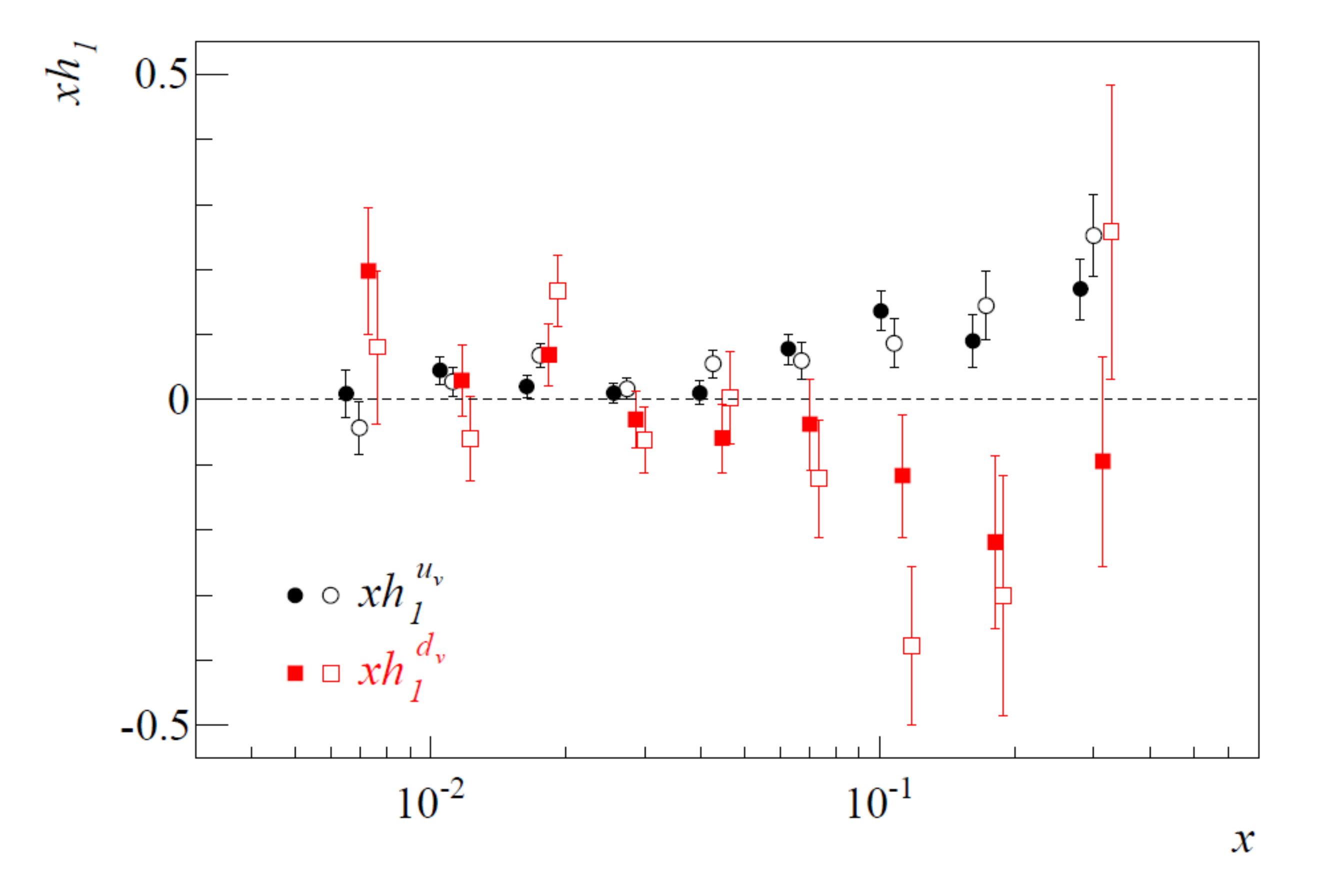
	physics item	key aspects of the measurement
GPD	**H**	**RPD, Beam Charge and Spin Asymmetries**
	***t*-slope parameter** B	$\boldsymbol{d\sigma/dt}$
	E	transversely polarized proton target
SIDIS	**hadron multiplicities for** π **and** K	**PID and absolute acceptance**
	$\boldsymbol{h_{1,u}^{\perp}, h_{1,d}^{\perp}}$	**azimuthal modulations and PID**
	h_1^d with same accuracy as h_1^u	transversely polarized deuteron target
	$f_1^{\perp}$ evolution	100 GeV and transversely polarized proton target
DY	**sign change for** $f_1^{\perp}$ **and** $h_1^{\perp}$	**transversely polarized proton target**
	universality of TMD PDFs	higher statistics with transversely polarized proton target
	flavor separation	transversely polarized deuteron target
	test of the Lam-Tung relation	hydrogen target
	EMC effect in DY	different nuclear targets

Transversity from our data

- Poin-to-poiny extraction [Physical Review D 91, 014034 (2015)]
- Keep in mind that we are the only one to have measured TSA on deuteron

Open points/squares – from dihadron

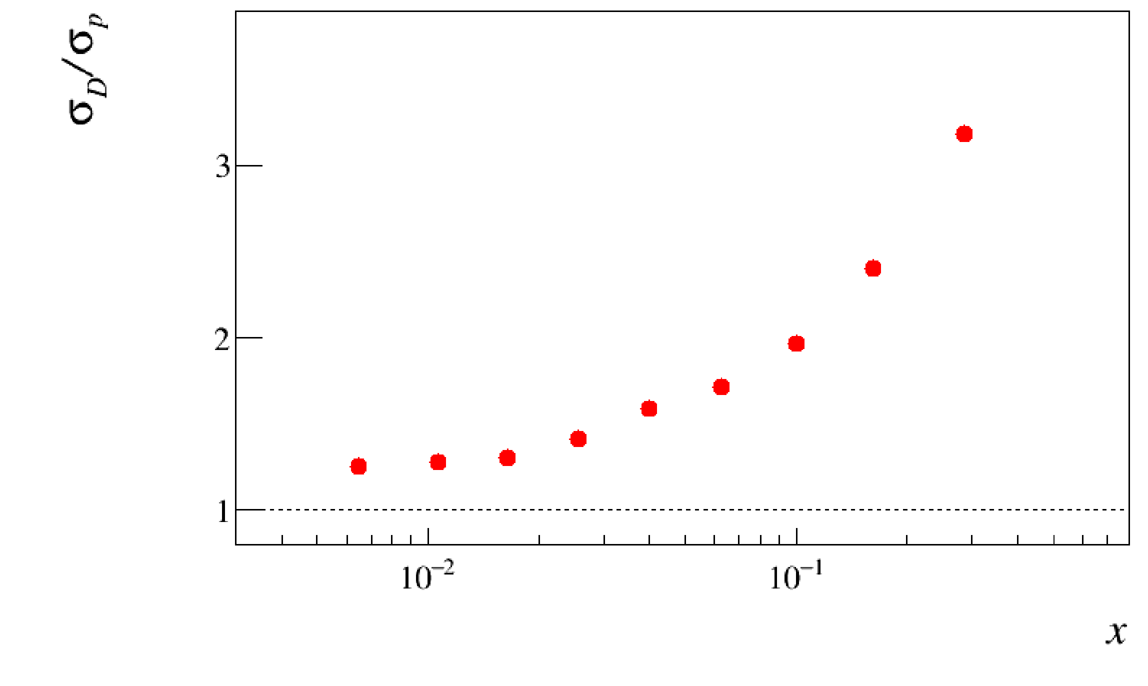
Closed points/squares – from Collins



ERRORS ON h_1^d ARE A FACTOR 4 LARGER THAT THE ONES ON h_1^u

From ^{6}LiD $(2002-2004)$ to $NH_3(2007-2010)$

- We have done many progresses:
  - New 3 cells target / 1.3 gain due to larger diameter
  - New superconducting magnet / Factor 2.5 increase of acceptance at large x
  - New large x trigger with LAST / Factor 2 increase at large x
  - Statistics (partially lost given $\frac{f_p P_{pT}}{f_D P_{DT}} = 0.6$)



ALL IN ALL A TOTAL FACTOR OF >10

From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

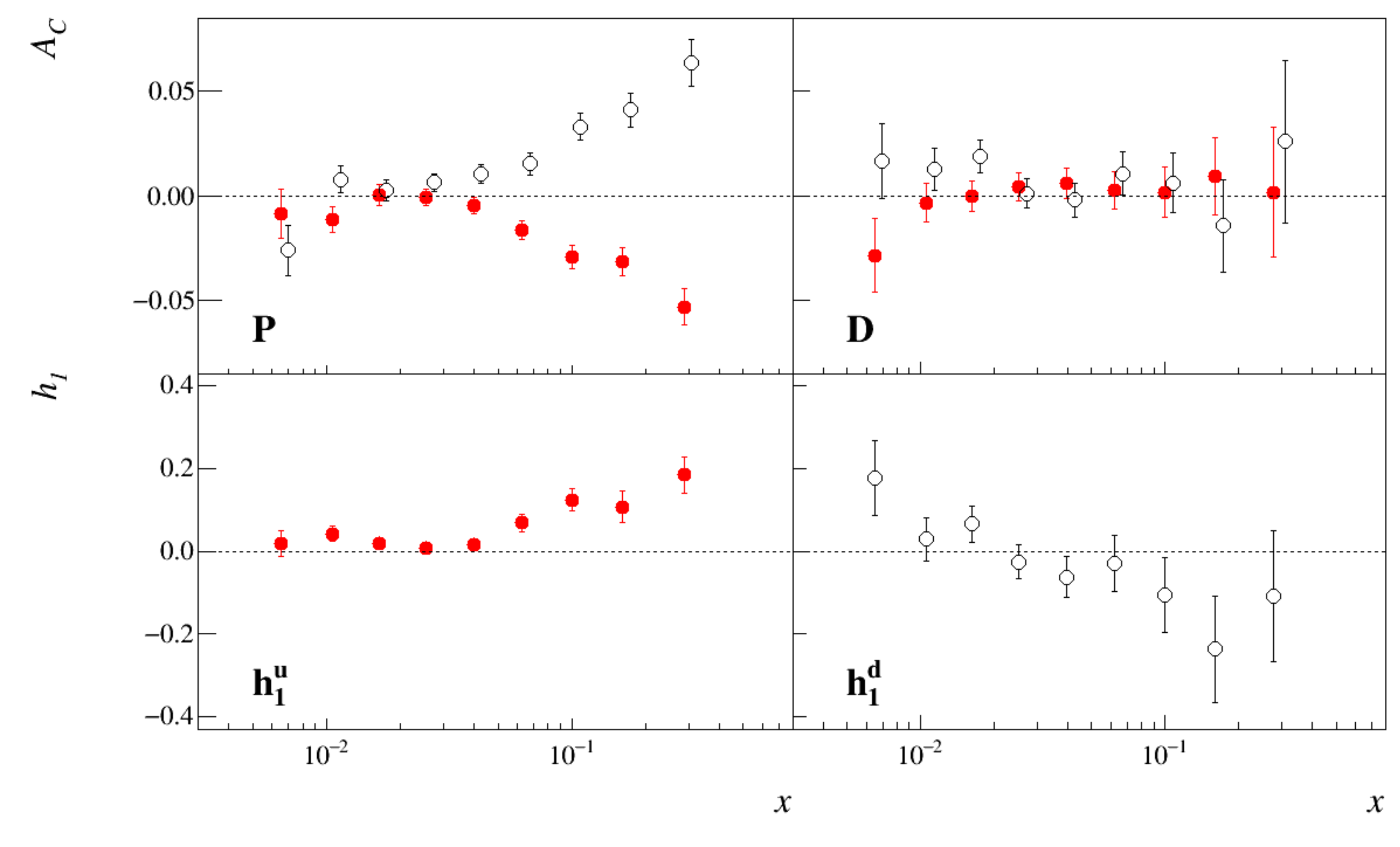
$$xh_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(xf_p^+A_p^+ - xf_p^-A_p^-\right) + \frac{1}{3}\left(xf_d^+A_d^+ - xf_d^-A_d^-\right)\right]$$

$$xh_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(xf_d^+A_d^+ - xf_d^-A_d^-\right) - \left(xf_p^+A_p^+ - xf_p^-A_p^-\right)\right]$$

With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

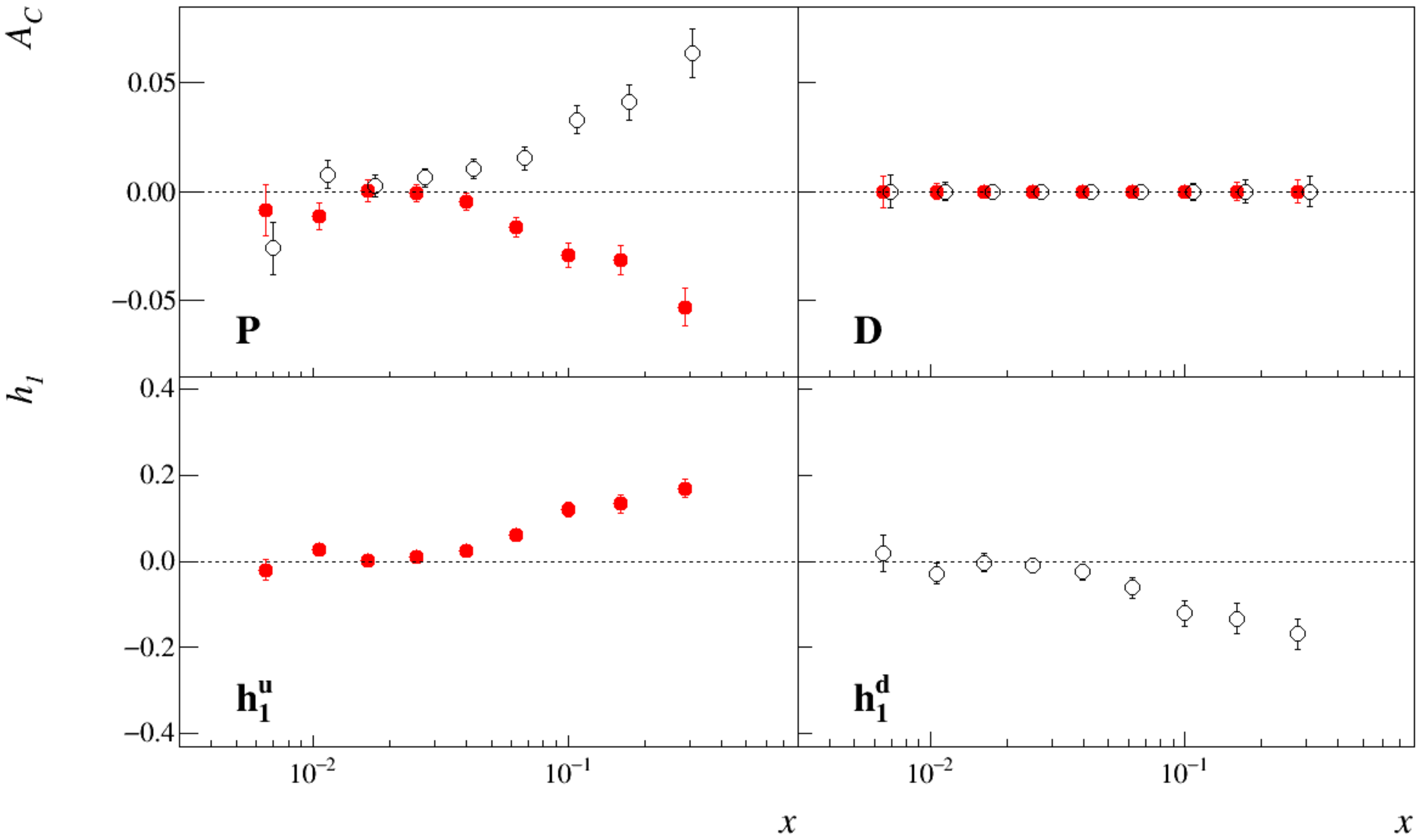
New deuteron data

- Benchmark: extraction from Collins asymmetries



New deuteron data

- 1 full year (same as 2010). We also gain from $\frac{f_p P_{pT}}{f_D P_{DT}} = \frac{0.155 \times 0.8}{0.40 \times 0.5} = 0.6$

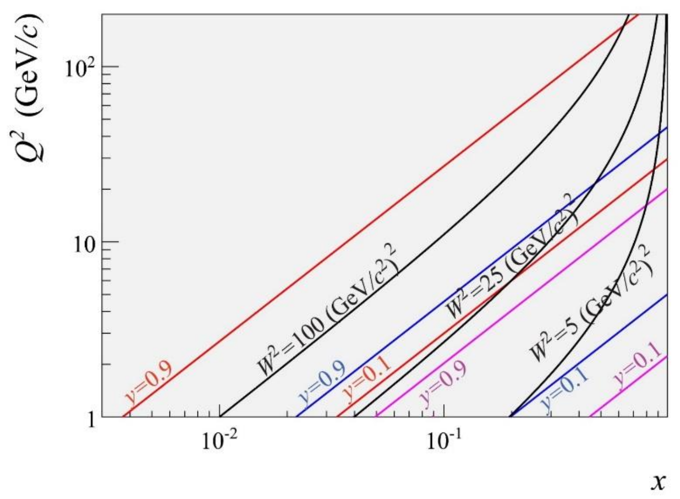


THIS IS A MEASUREMENT THAT WILL IMPACT OUR KNOWLEDGE, KEY MEASUREMENT FOR THIS OR NEXT PHASE

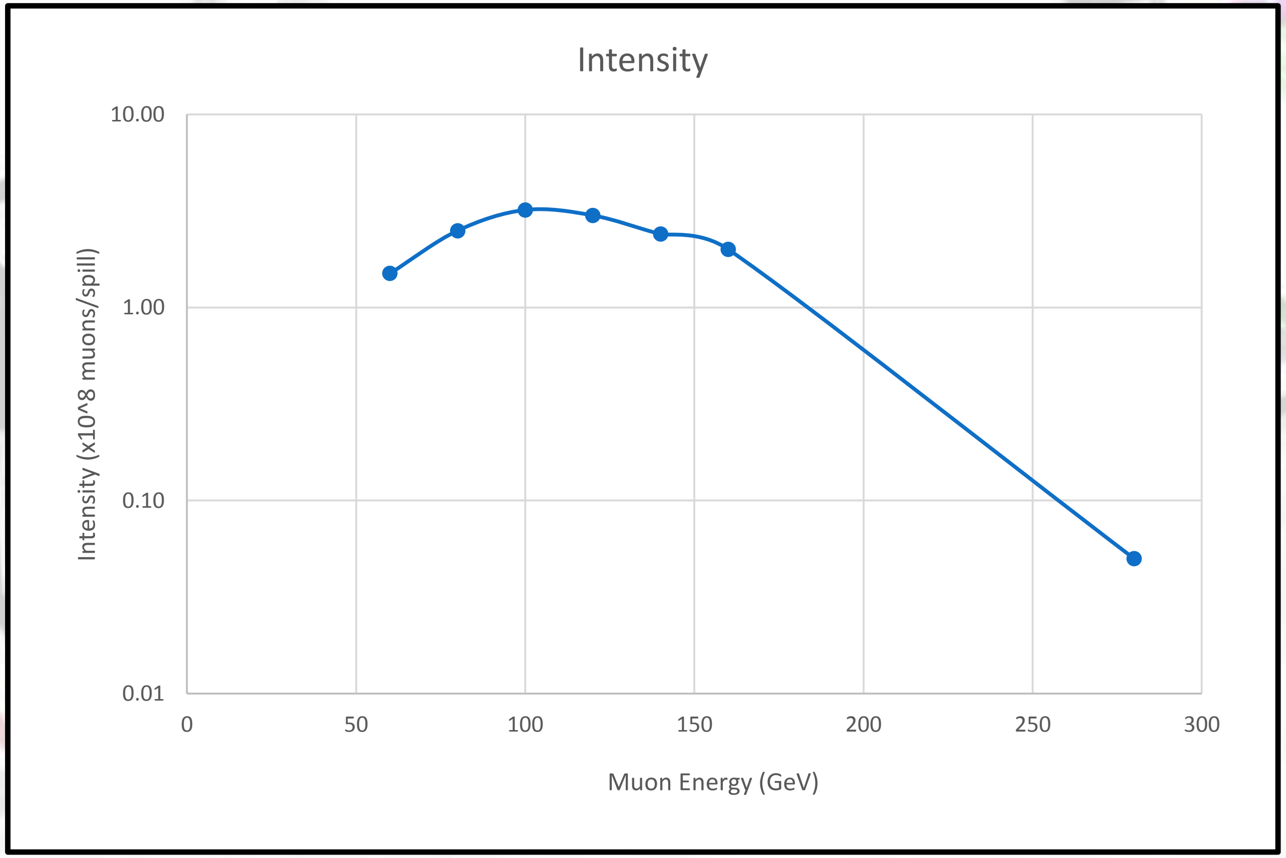
RUNNING AD DIFFERENT ENERGIES TO ADDRESS SIVERS EVOLUTION?

RANGE IN ENERGY

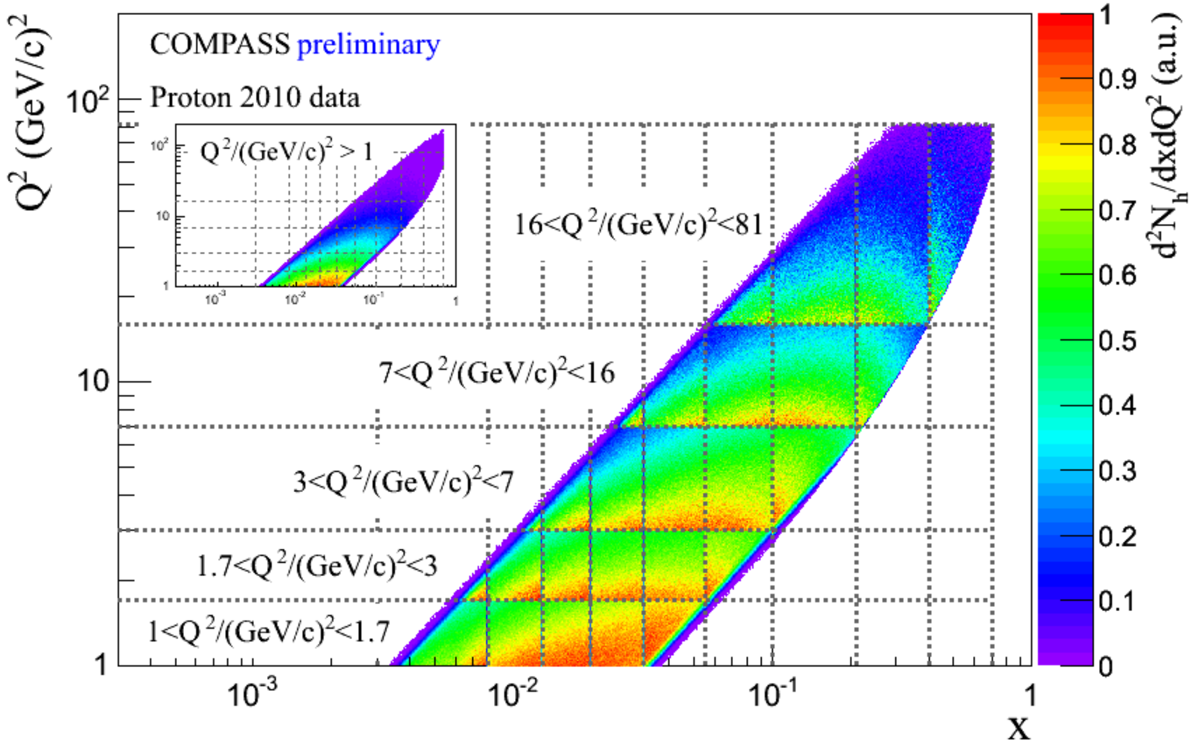
- M2 may span between 60 and 280 GeV for muons
- Let's have a look at $\begin{cases} 80 \text{ GeV}, \sqrt{s} = 10 \text{ GeV}, \sigma_{DIS} = 176 \text{ nb} \\ 160 \text{ GeV}, \sqrt{s} = 13 \text{ GeV}, \sigma_{DIS} = 178 \text{ nb} \\ 280 \text{ GeV}, \sqrt{s} = 17 \text{ GeV}, \sigma_{DIS} = 188 \text{ nb} \end{cases}$
- The low y, large Q^2 region is cut away by the $W > 5 \text{ GeV}/c^2$
- Intensity? That's a problem.
- Of course: Multi-D is mandatory

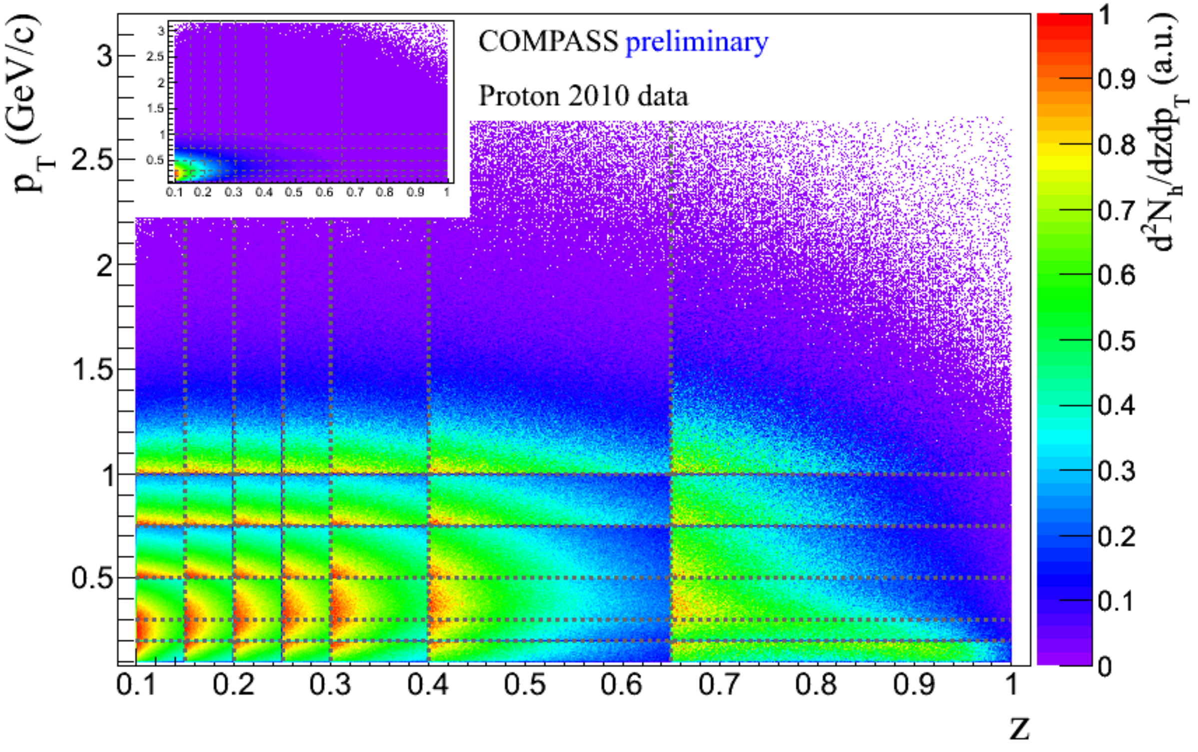


Running at different energies for evolution

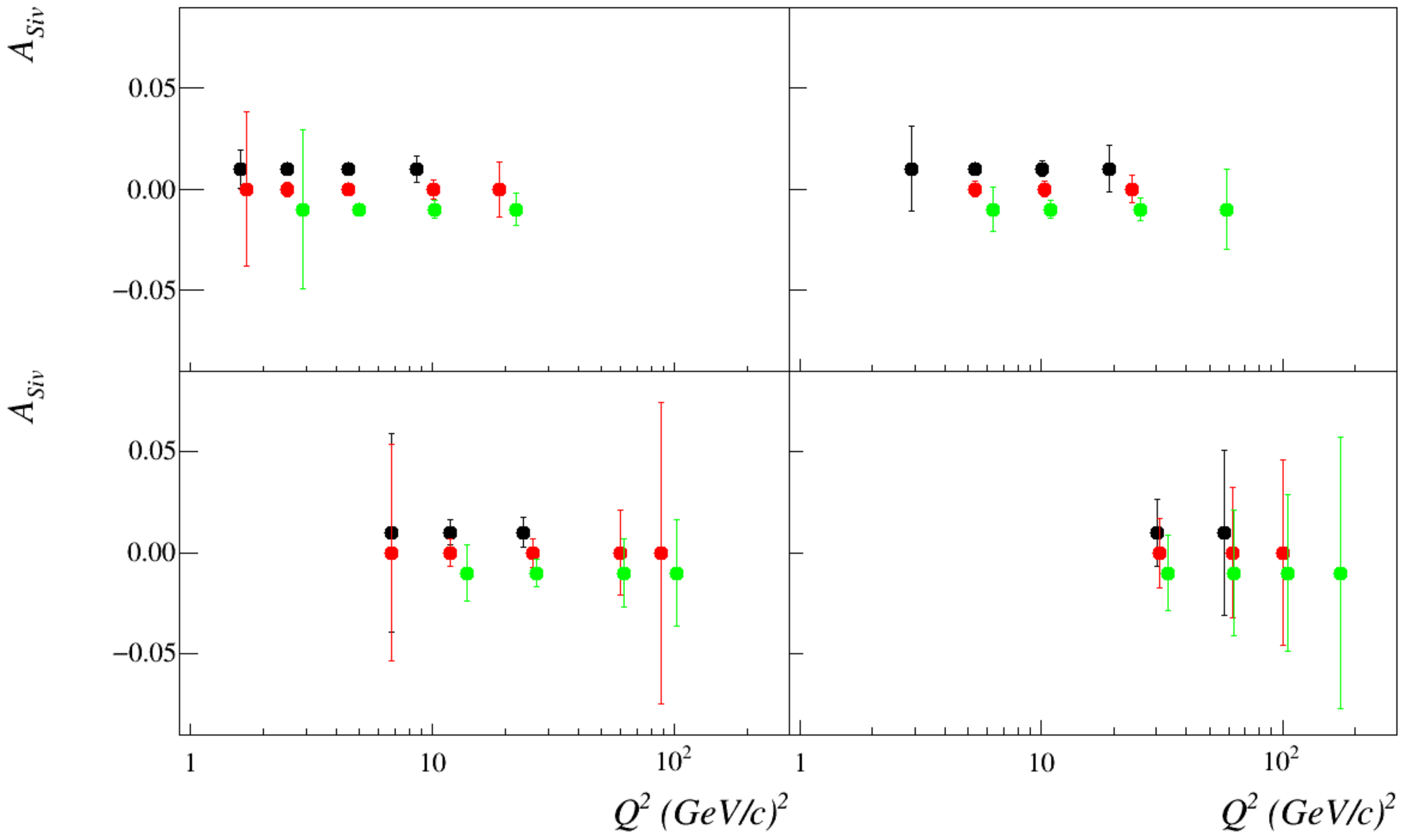


Multi D


COMPASS preliminary
Proton 2010 data
Q²/(GeV/c)² > 1
16<Q²/(GeV/c)²<81
7<Q²/(GeV/c)²<16
3<Q²/(GeV/c)²<7
1.7<Q²/(GeV/c)²<3
1<Q²/(GeV/c)²<1.7
Q² (GeV/c)²
x
d²N_h/dxdQ² (a.u.)


COMPASS preliminary
Proton 2010 data
p_T (GeV/c)
z
d²N_h/dzdp_T (a.u.)

Running at different energies for evolution

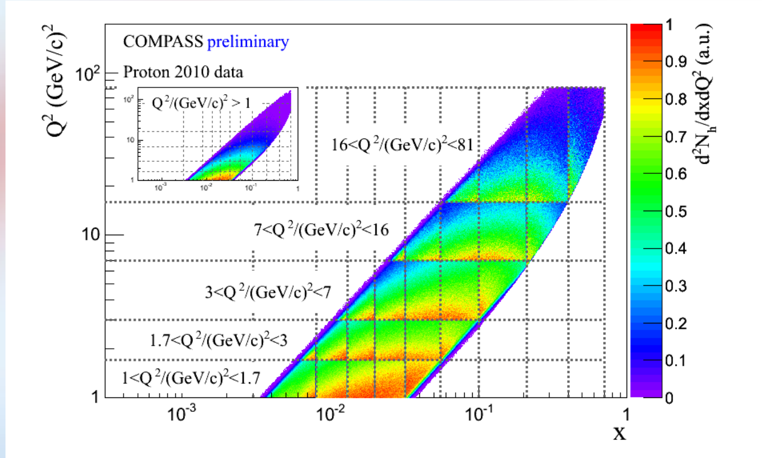


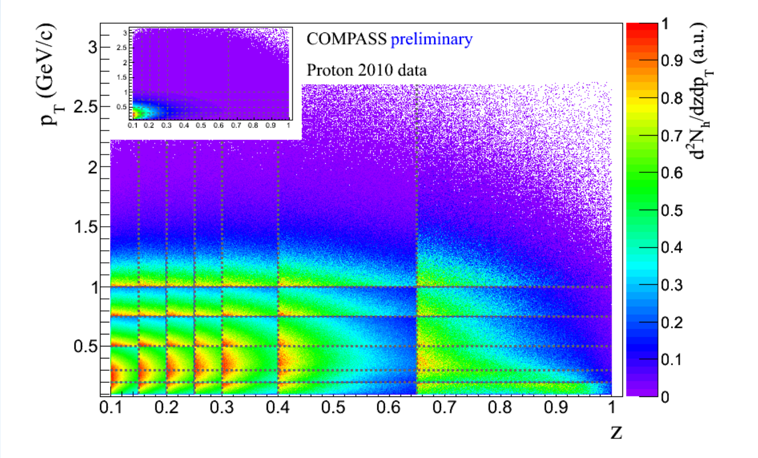
COMMENT ON TMD studies

- SIDIS has opened the way to this field about 10 years ago:
  - Collins and DiHadron asymmetries on protons are sizeable
  - The Sivers asymmetry is also different from zero and we are now probing it's pseudo universality
  - The other TMDs are small, compatible to zero in most of the cases, at present precision
  - We measured sizeable $\cos\phi$ and $\cos 2\phi$ asymmetries but we don't really know yet if the Boer-Mulder TMD PDF is different from zero
  - The measurement of the azimuthal asymmetries on protons is one of the tasks of the next two years run

STUDYING BOER-MULDERS IN THE MULTIDIMENSIONAL PHASE SPACE?

- We are again in the multi-D ground:
  - We need good statistics also in the corners of our phase space
  - We need acceptance both in ϕ and in P_{hT} in order to minimize corrections
  - We need a precise Monte Carlo (as for DVCS) to limit the systematic uncertainty





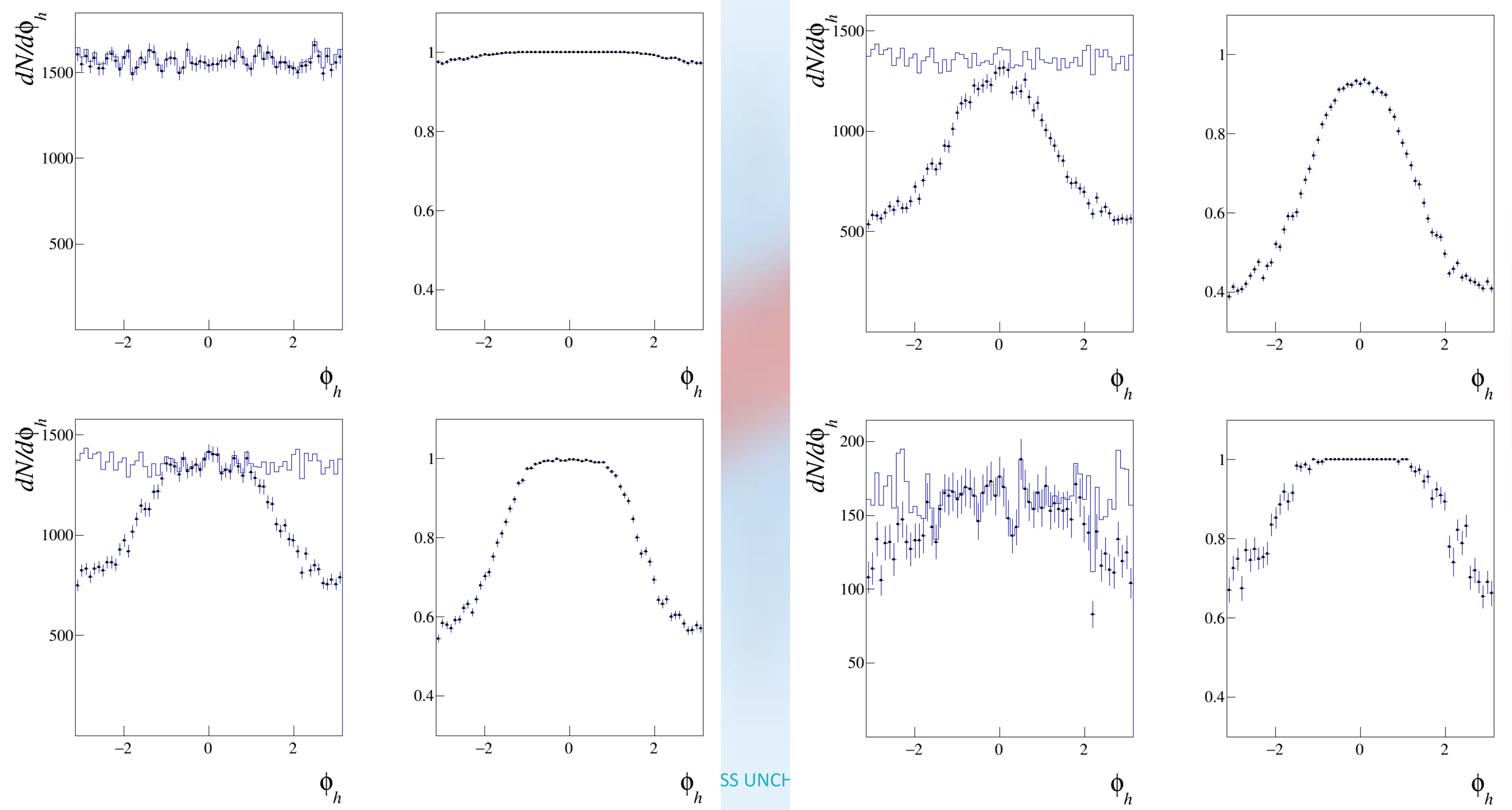
The 2016/17 setup is optimized for DVCS:

– 2.5 m long target, centered at −2m

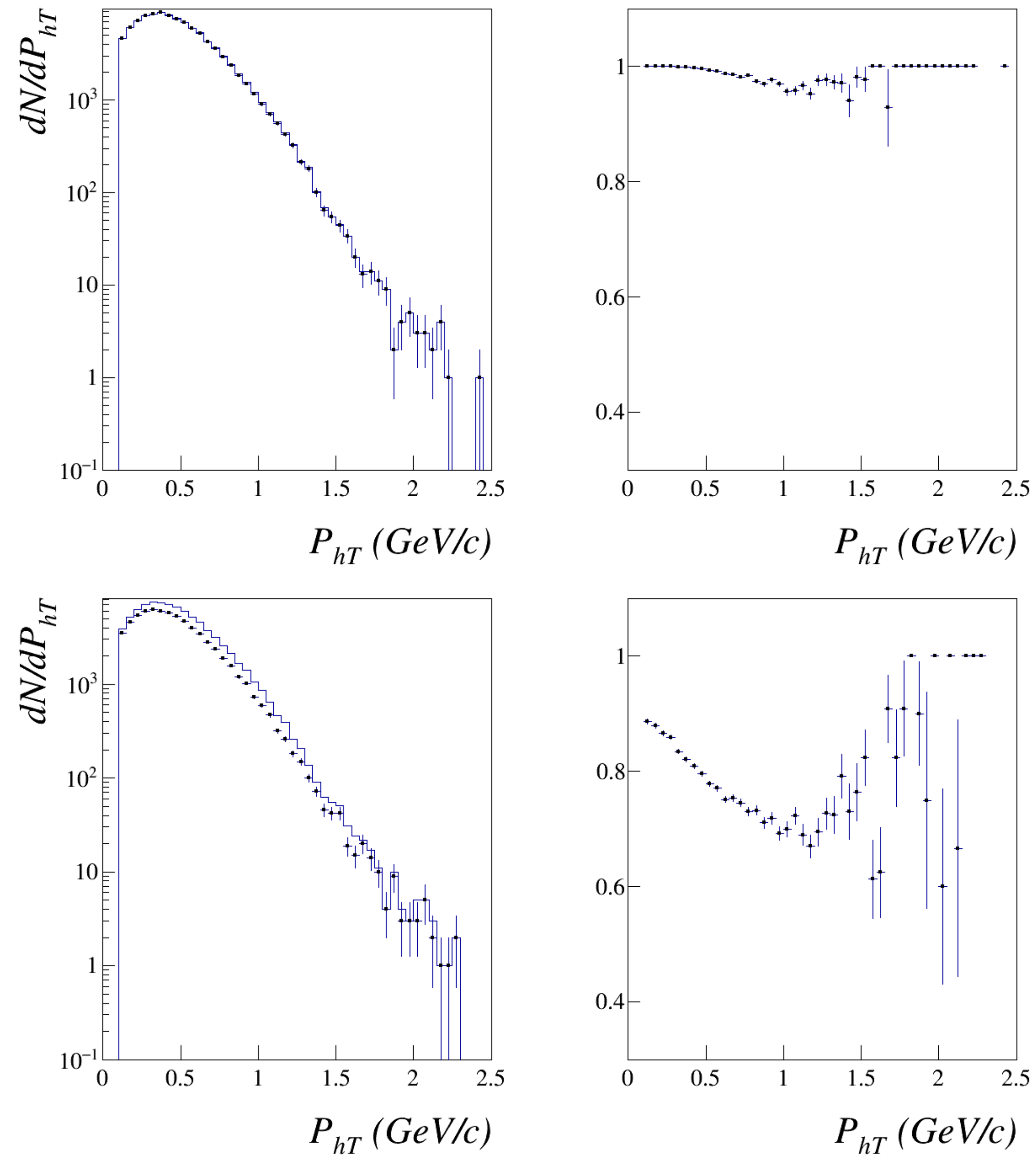
– Ecal0

and we need to check the achievable precision

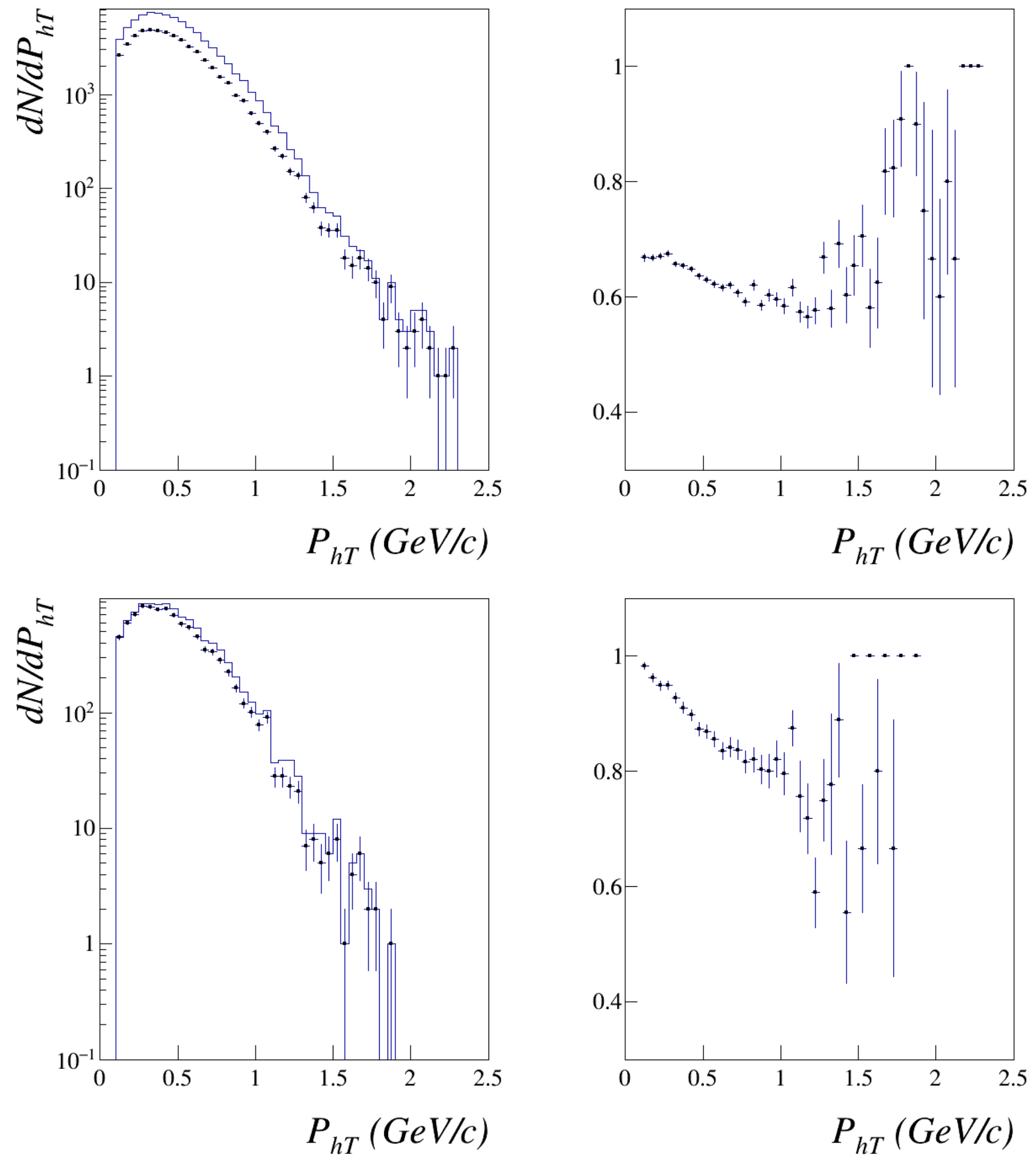
Pure geometrical acceptancs (2016 vs 2010, $0.21 < x < 0.4$)



Pure geometrical acceptancs (2016 vs 2010, $0.21 < x < 0.4$)

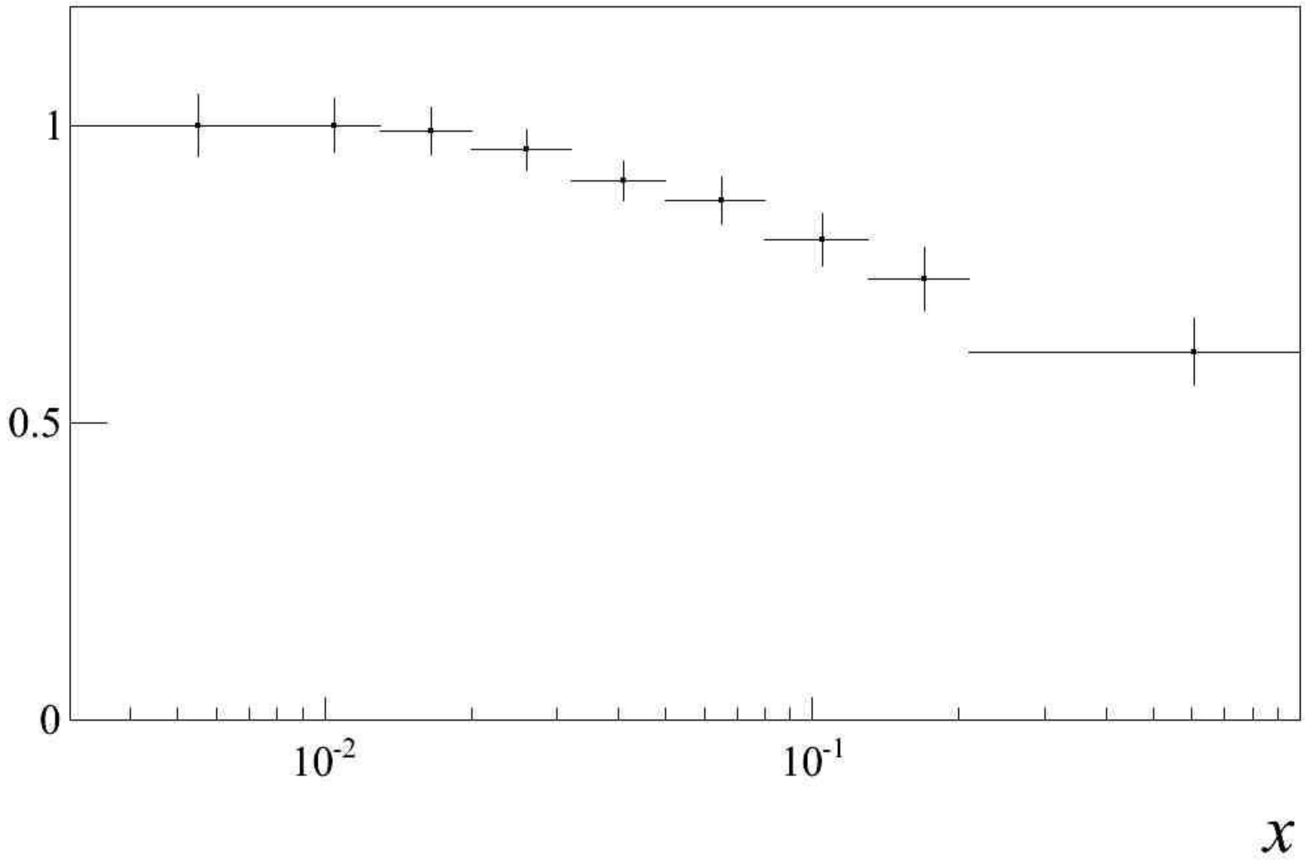


ASS UNCH



Acceptance transverse binning

All hadrons



Statistical precision in azimuthal asymmetries

- Keep in mind:
  - For the same muon flux due to the density of the LH_2 the luminosity is reduced by a factor 4 to 5
  - We will take both μ^+ and μ^- and therefore the average luminosity will be reduced further by the lower μ^- flux (factor 2 to 3)
  - Another factor 10 may eventually come from the cut on the target, i.e. by using only the last 25 cm
  - All in all the statistics may be reduced by 100 to 150

THE ACHIVABLE PRECISION OF THESE MEASUREMENT IS AT THE MOMENT UNCLEAR…

A PRECISE MEASUREMENT MIGHT STILL BE NEEDED AFTER PHASE II

New measurements?

- Aram proposed to measure
  - SIDIS in the TFR ($x_F < 0$) and
  - 2h back-to-back in C and TFR

  - First look may come from the 2016/17 run with the unpolarised target to check performances
  - An interesting option for beyond having a recoil detector for the polarised target

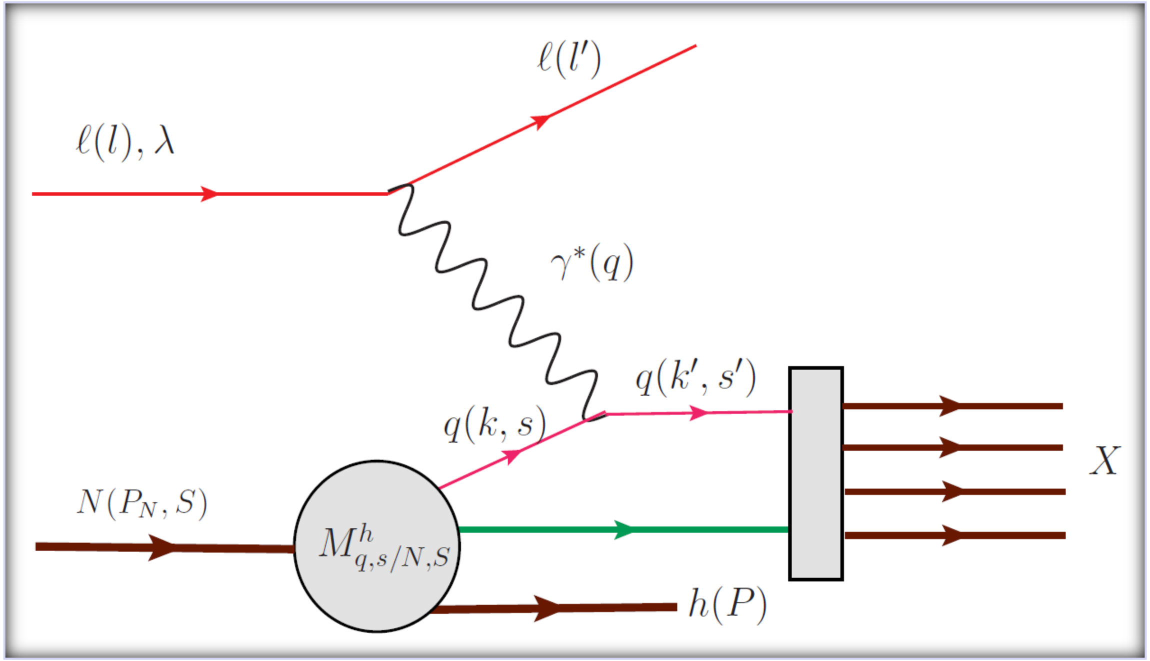
TFR of SIDIS at COMPASS with CAMERA

Aram Kotzinian

INFN, Torino & YerPhI, Armenia

- TFR: $x_F < 0$
  - 1h SIDIS in TFR
  - 2h SIDIS B2b SIDIS h_1 in CFR, h_2 in TFR.

SIDIS: TFR



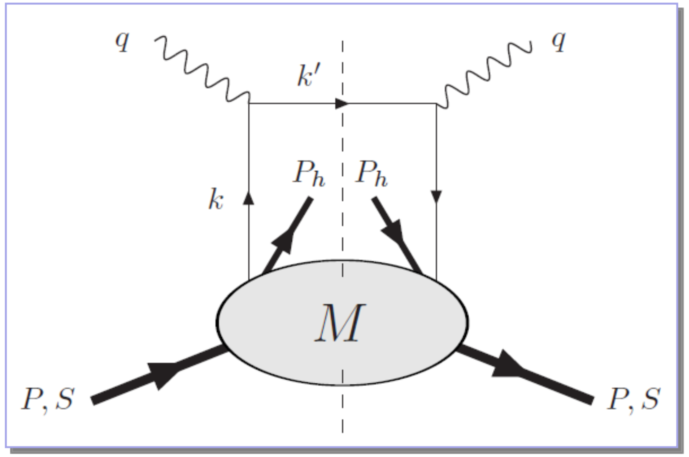
$$x_F < 0$$

M.Anselmino, V.Barone and A.K., arXiv:1102.4214; PL B699 (2011) 108

$$\frac{d\sigma^{\ell(l,\lambda)+N(P_N,S)\to\ell(l')+h(P)+X}}{dx\,dQ^2\,d\phi_S\,d\zeta\,d^2P_T} = M^h_{q,s/N,S} \otimes \frac{d\sigma^{\ell(l,\lambda)+q(k,s)\to\ell(l')+q(k',s')}}{dQ^2}$$

$$\zeta = \frac{P^-}{P_N^-} \approx x_F(1-x)$$

Quark correlator



$$M^{[\Gamma]}(x_B, \vec{k}_\perp, \zeta, \vec{P}_{h\perp}) = \frac{1}{4\zeta} \int \frac{d\xi^+ d^2\xi_\perp}{(2\pi)^6} e^{i(x_B P^- \xi^+ - \vec{k}_\perp \cdot \vec{\xi}_\perp)} \sum_X \int \frac{d^3 P_X}{(2\pi)^3 2E_X} \times$$

$$\times \langle P, S | \bar{\psi}(0) \Gamma | P_h, S_h; X \rangle \langle P_h, S_h; X | \psi(\xi^+, 0, \vec{\xi}_\perp) | P, S \rangle$$

$$\Gamma = \gamma^-, \quad \gamma^- \gamma_5, \quad i\sigma^{i-}\gamma_5$$

At LO 16 STMD fracture functions. Probabilistic interpretation at LO:

Conditional probability of finding a quark $q(x,k_\perp)$ in the fast moving

proton fragmenting to $h(\zeta,P_{h\perp})$ moving in same direction ⇒ STMD CPDFs

STMD Fracture Functions for spinless hadron production

Nucleon Polarization	Quark polarization: U	Quark polarization: L	Quark polarization: T
U	$\hat{u}_1$	$\frac{\mathbf{k}_T \times \mathbf{P}_T}{m_N\, m_h} \hat{l}_1^{\perp h}$	$\frac{\epsilon_T^{ij} P_T^{\,j}}{m_h} \hat{t}_1^{h} + \frac{\epsilon_T^{ij} k_T^{\,j}}{m_N} \hat{t}_1^{\perp}$
L	$\frac{S_L (\mathbf{k}_T \times \mathbf{P}_T)}{m_N\, m_h} \hat{u}_{1L}^{\perp h}$	$S_L \hat{l}_{1L}$	$\frac{S_L \mathbf{P}_T}{m_h} \hat{t}_{1L}^{h} + \frac{S_L \mathbf{k}_T}{m_N} \hat{t}_{1L}^{\perp}$
T	$\frac{\mathbf{P}_T \times \mathbf{S}_T}{m_h} \hat{u}_{1T}^{h} + \frac{\mathbf{k}_T \times \mathbf{S}_T}{m_N} \hat{u}_{1T}^{\perp}$	$\frac{\mathbf{P}_T \cdot \mathbf{S}_T}{m_h} \hat{l}_{1T}^{h} + \frac{\mathbf{k}_T \cdot \mathbf{S}_T}{m_N} \hat{l}_{1T}^{\perp}$	$\mathbf{S}_T \hat{t}_{1T} + \frac{\mathbf{P}_T (\mathbf{P}_T \cdot \mathbf{S}_T)}{m_h^2} \hat{t}_{1T}^{hh} + \frac{\mathbf{k}_T (\mathbf{k}_T \cdot \mathbf{S}_T)}{m_N^2} \hat{t}_{1T}^{\perp\perp} + \frac{\mathbf{P}_T (\mathbf{k}_T \cdot \mathbf{S}_T) - \mathbf{k}_T \cdot (\mathbf{P}_T \cdot \mathbf{S}_T)}{m_N m_h} \hat{t}_{1T}^{\perp h}$

Summary

- New measurements for SIDIS in TFR are proposed
- 1h SIDIS in TFR
  - Single beam spin sin(Φ) asymmetry
  - Unpolarized cross section and cos(Φ) and cos(2Φ) asymmetries
    - According to mLEPTO the contribution of Cahn effect have to be very large in cos(Φ) modulation
    - Twist 2 STMD Fracture Functions formalism predicts zero cos(2Φ) modulations
- b2b in 2h SIDIS
  - Single beam spin asymmetry
    - Twist 2 STMD Fracture Functions formalism predicts sin(ΔΦ)+ sin(2ΔΦ) + ⋯ modulations
    - Preliminary results from JLAB show up large asymmetries
- In my opinion the physics case is interesting
  - Full MC studies are needed
- It is worth to look if CAMERA can help to observe Λ production and polarization measurement in the TFR

SUMMARY

- We do have the strong case of transverse deuteron data. One year of data will strongly impact our knowledge of h_1^d!
- Precision on the multi-D phase space is next phase of TMD studies. For this we need luminosity.
- Precise P_{hT} dependent multiplicities and unpolarised azimuthal multiplicities are a must for the understanding of TMDs. These data are foreseen from this and next year…but?
- New structure function may be address in the future, having access to the TFR. First hints on COMPASS performances already from this and next year run