Physics results and achievements with CLAS

Sébastien Procureur
On behalf of the CLAS collaboration
CEA-Saclay

Outline

The CEBAF Large Angle Spectrometer @ Jefferson Lab

GPDs and Deeply Virtual Compton Scattering

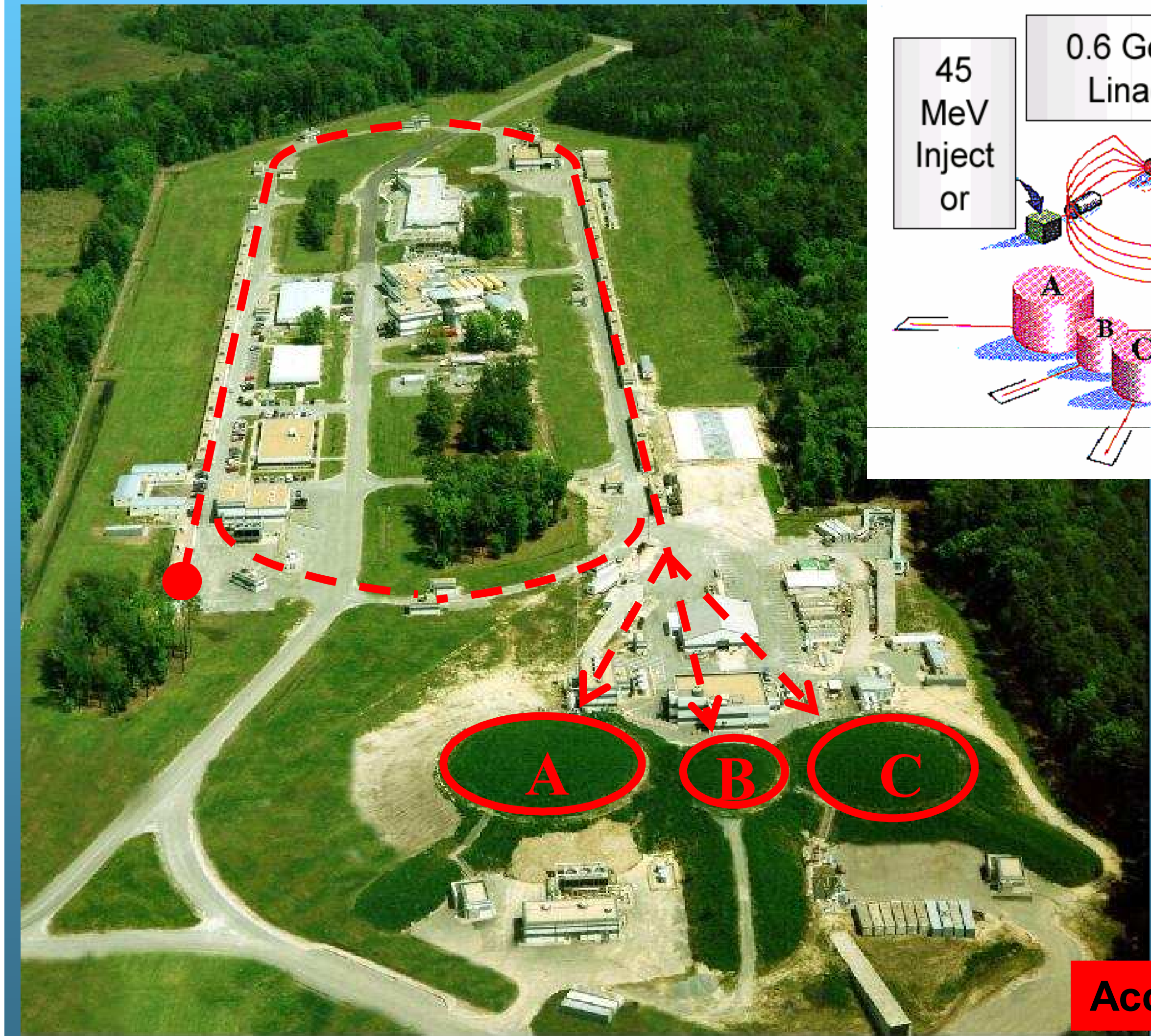
TMDs and Semi-Inclusive DIS

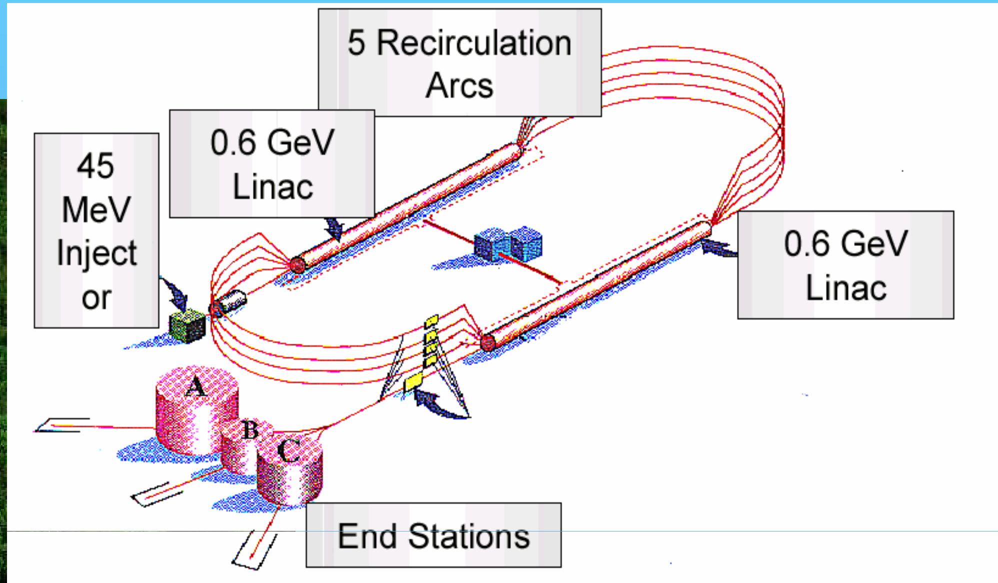
The neutron structure function F_2^n with BONUS

An experimental achievement: the HD-ice target

Conclusion and outlook (CLAS12)

Jefferson Lab (today)





Continuous electron beam

- Energy from 0.8 to 6 GeV
- Duty factor 100%
- Beam polar ~85%
- Delivered 3 halls simultaneously

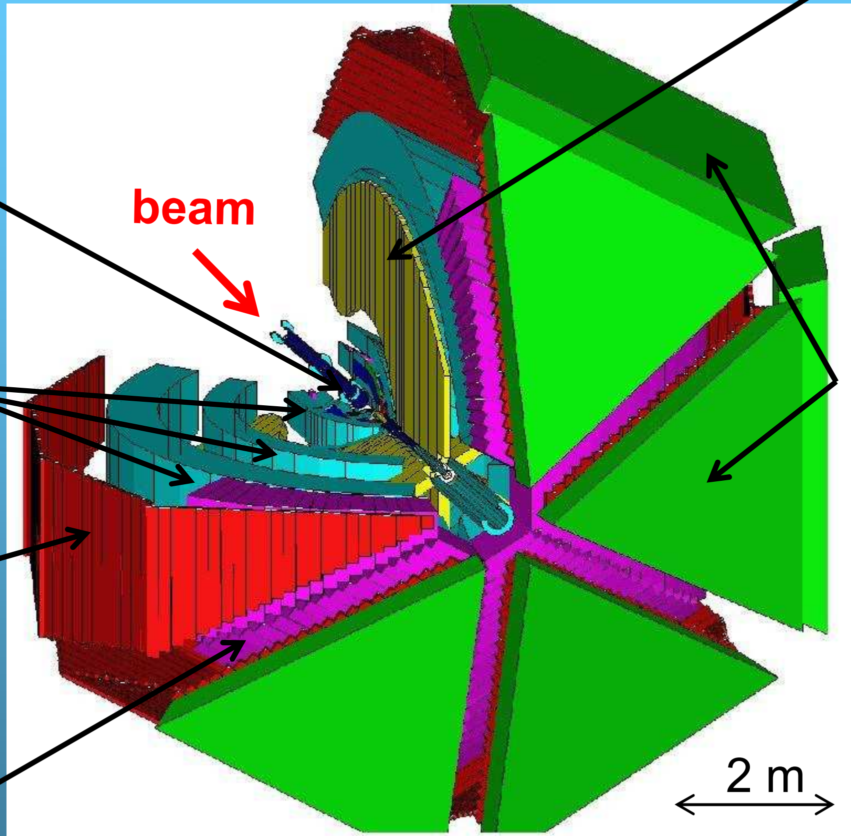
Accelerator shutdown (since May '12)

Hall B / CLAS

Torus magnet
6 superconducting coils

Targets
LH_2, LD_2, $\vec{NH_3}$, $\vec{\vec{HD}}$, etc.

Drift chambers
Argon/CO_2, 35k wires



Electromagnetic calorimeters
Lead/scintillators, 1296 PM

TOF counters
Plastic scintillators, 684 PM

B. Mecking *et al.*, NIM A 503 (2003)

Черенков counters
e^-/π separation, 216 PM, C_4F_{10}

Designed for exclusive reactions with multi-particle final states

- Large angular coverage: 8°-140° wrt beam axis

- Good momentum resolution (~0.5% @ 2 GeV/c)

- Luminosity up to 10^{34} /cm²/s

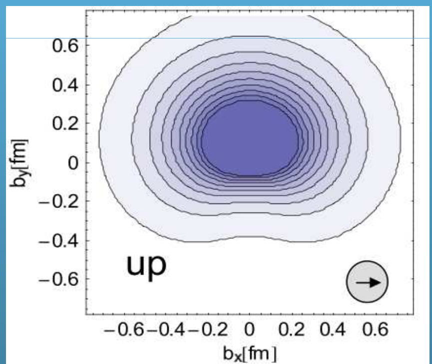
The nucleon structure

- Ultimate goal: Wigner functions

→ Probability distribution to find a quark q in a nucleon, at position **r** and with momentum **k**

- What we can access:

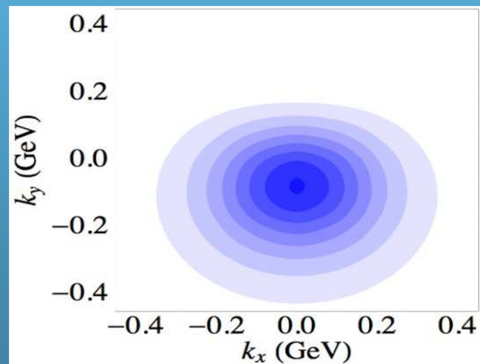
→ k_T integrated distributions ⟹ GPDs $H(x,\xi,t)$



Information on spatial distribution of quarks

Requires hard exclusive measurements (DVCS/DVMP)

→ r integrated distributions ⟹ TMDs $f(x,k_T)$



Information on transverse momentum distribution of quarks

Requires semi-inclusive measurements (SIDIS)

⟹ complementary information on the nucleon structure

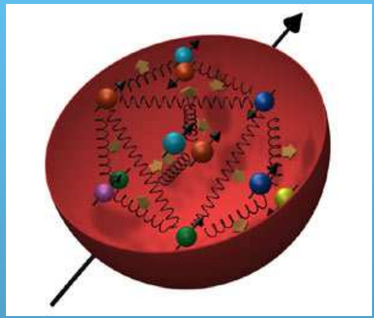
GPD and DVCS

4 GPDs for each quark flavor

- Quark helicity independent: H, E
- Quark helicity dependent: $\tilde{H}$, $\tilde{E}$

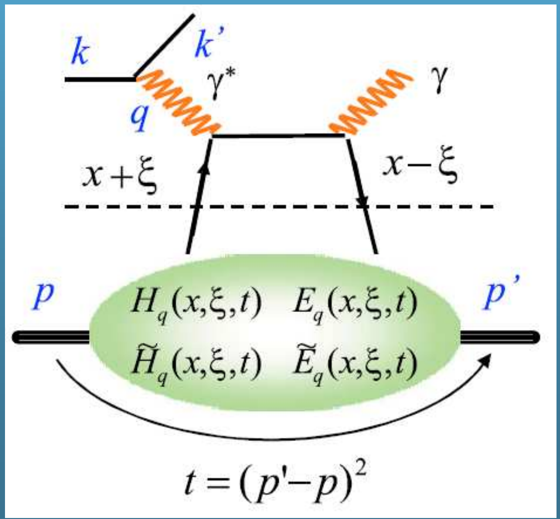
Ji's sum rule: $J^q = \frac{1}{2}\int_{-1}^{1} x dx (H^q(x,\xi,0) + E^q(x,\xi,0))$

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



Cleanest process to access GPDs: DVCS

ep→epγ



Perturbative QCD

Non-perturbative QCD: GPDs

Factorization in the Bjorken regime:

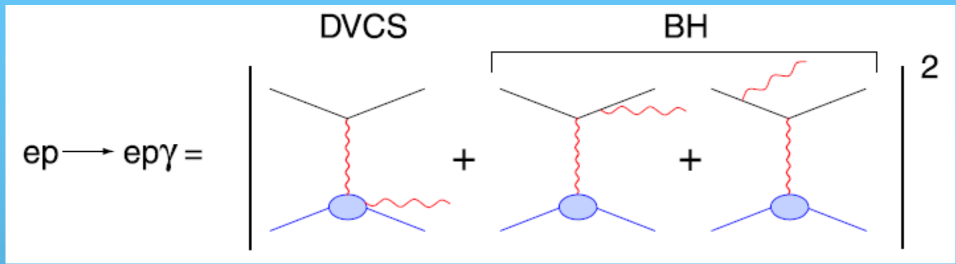
- High Q^2
- High υ
- $x_{Bj}=Q^2/2M\upsilon$ fixed
- $t \ll Q^2$

Gives access to Compton Form factors:

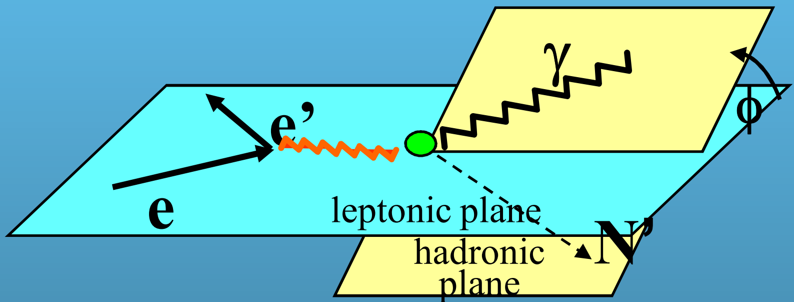
$$\mathcal{H}(\xi,t) = i\pi H(\xi,\xi,t) + P\int_{-1}^{1} dx \frac{H(x,\xi,t)}{x-\xi}$$

GPD and DVCS

Cannot distinguish experimentally DVCS from the Bethe Heitler process



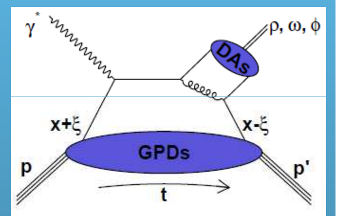
$$\frac{d^4\sigma}{dQ^2 dx_{Bj} dt d\varphi} = \left|T^{DVCS} + T^{BH}\right|^2$$



DVCS

	$\mathcal{Im}$	$\mathcal{Re}$
$\mathcal{H}$	A_{LU}	σ
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
$\mathcal{E}$	A_{UT}	

DVMP



	Meson	Flavor
$\tilde{\mathcal{H}},\tilde{\mathcal{E}}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H},\mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	s

Polarized beam, unpolarized target:

$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \approx \frac{\alpha \sin\varphi}{1 + \beta\cos\varphi} \qquad \alpha \propto Im(F_1 \mathcal{H} + \cdots)$$

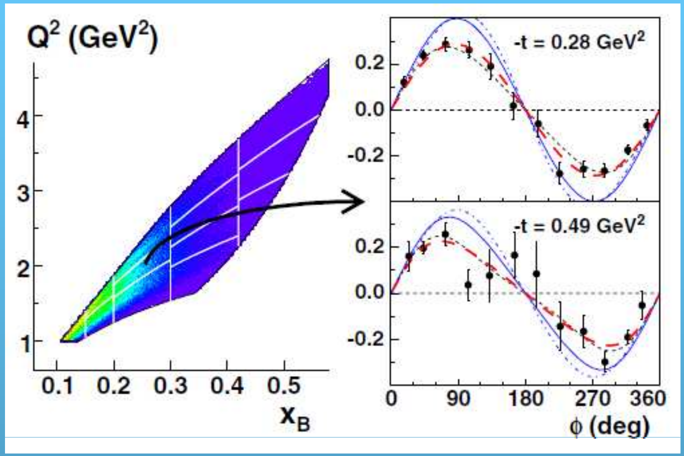
Unpolarized beam, longitudinally polarized target:

$$A_{UL} \propto \left(Im(F_1 \tilde{\mathcal{H}})\right) \sin\varphi + \cdots$$

DVCS experiments @ CLAS

e1-dvcs experiment (E01-113)

F-X. Girod et al., PRL 100 (2008), 162002



→ unpolarized proton target

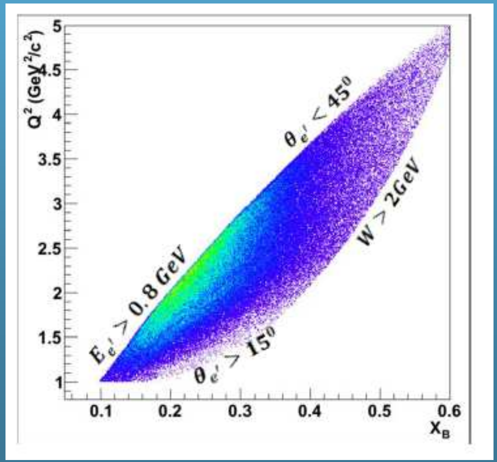
→ beam polarization ~ 80%

→ E_e ~ 5.8 GeV

→ data taken in 2005

⇨ A_{LU}, DVCS cross sections

eg1-dvcs experiment (E05-114)



→ polarized proton (80%) and deuteron (40%) targets

→ beam polarization ~ 85%

→ E_e ~ 4.7 – 5.9 GeV

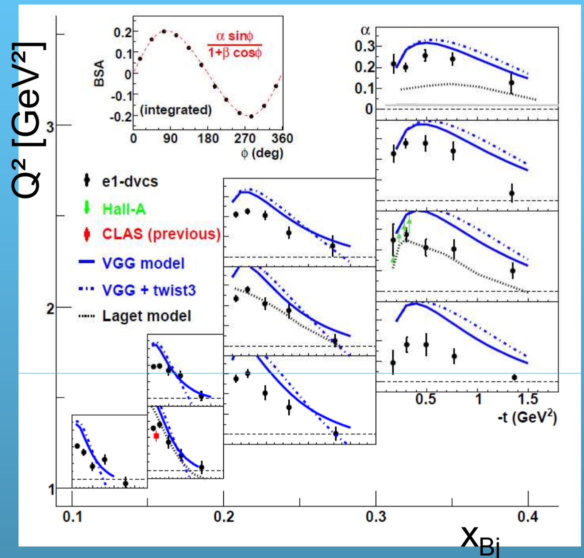
→ data taken in 2009

⇨ A_{LU}, A_{UL}, double asymmetries on p and n

DVCS: A_{LU} and A_{UL}

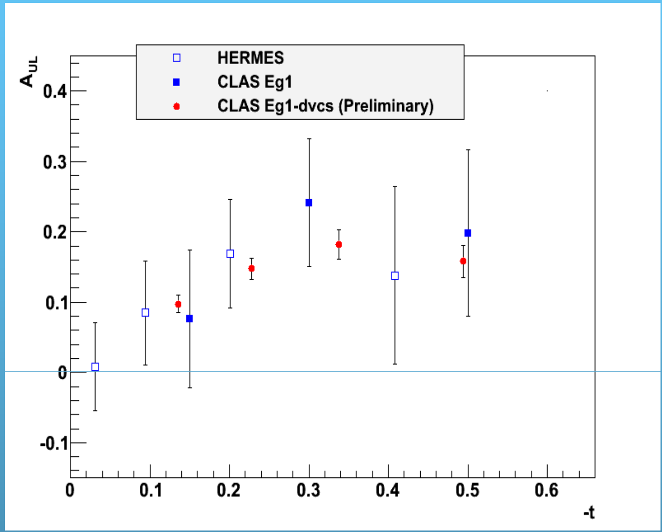
- e1-dvcs

→ A_{LU} F-X. Girod et al., PRL 100 (2008), 162002



- eg1-dvcs

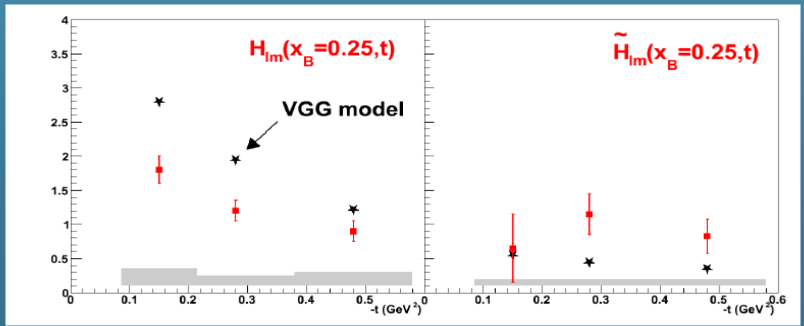
→ A_{UL}



→ not all the statistics included

→ no background subtraction (π^0)

→ A_{LU} from e1-dvcs & A_{UL} from 1st exp. used for a model independent fit of CFF



M. Guidal, Phys. Lett. B 689 (2010), 156

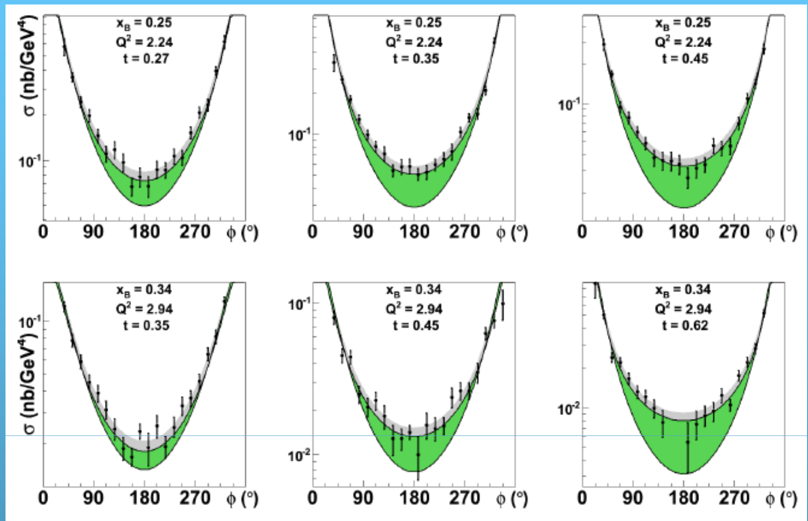
→ hints for a higher t slope for H?

→ better accuracy for H (more data)

DVCS cross sections (preliminary)

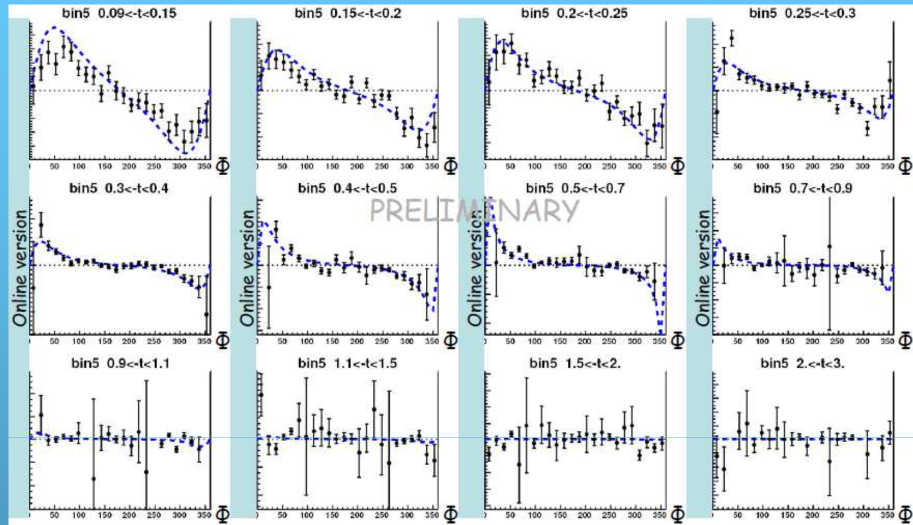
- e1-dvcs

Unpolarized cross sections

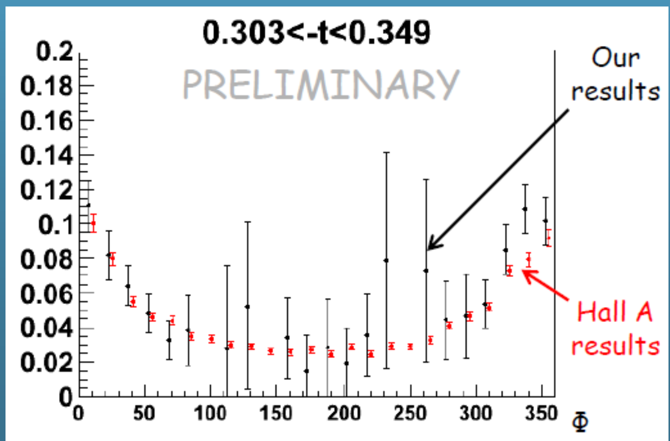


→ Green band shows difference with BH

Difference of polarized cross sections



$\propto Im(T^{DVCS}) \times T^{BH} \rightarrow H(\pm\xi, \xi, t)$



→ Good agreement with Hall A data

→ But much wider kinematical range

→ Can be added to the CFF extraction

DVCS on neutron (very preliminary)

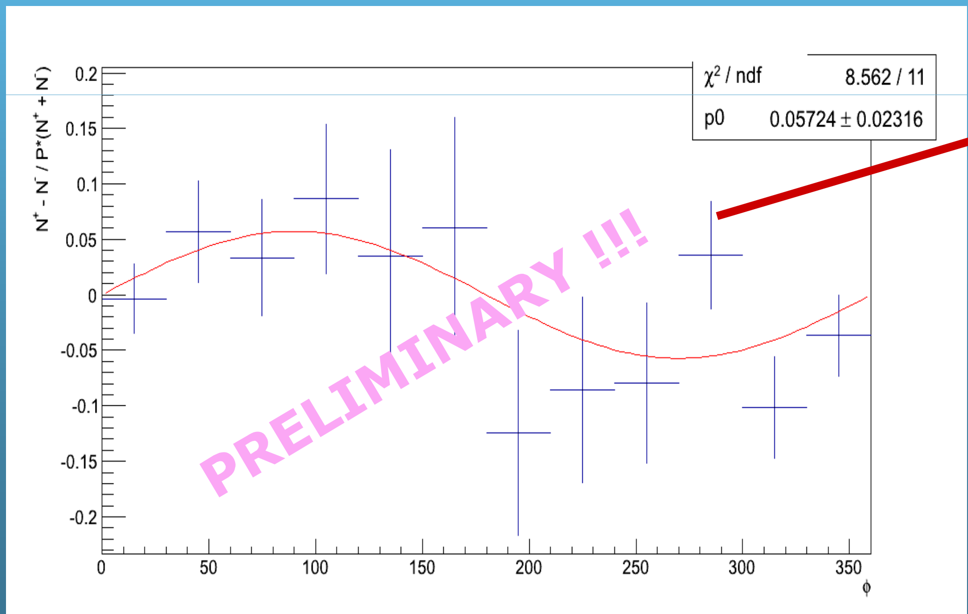
- eg1-dvcs

polarized beam, unpolarized neutron (ND_3): ed→e'nγX

$$\Delta\sigma_{LU} \propto \sin\phi\, Im(\cancel{F_1\mathcal{H}} + \cancel{\xi(F_1+F_2)\tilde{\mathcal{H}}} - kF_2\,\mathcal{E})$$

⟹ Highly sensitive to GPD E

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,(H^q(x,\xi,0) + E^q(x,\xi,0))$$



$$\frac{N^+ - N^-}{P(N^+ + N^-)} \approx 0.057 \pm 0.023$$

→ No background subtraction…

→ Integrated over the whole kinematics…

… but hints for non zero asymmetry

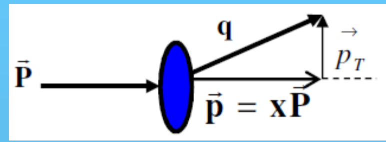
D. Sokhan (S3-IV)

TMDs and SIDIS

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



→ functions of x and p_T

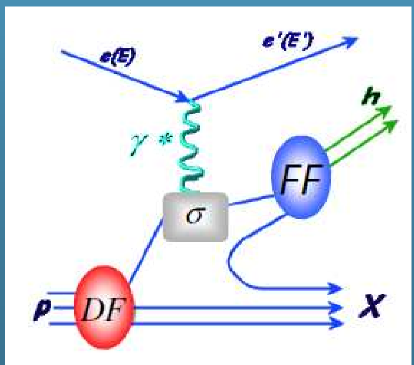
→ only (usual) diagonal elements survive to p_T integration

→ contain information on quark orbital angular motion & spin-orbit effects

Can be accessed in SIDIS:

→ Mesure single & double spin asymmetries on *e.g.* pions

→ Large acceptance needed (CLAS)



→ factorization if $p_T^2 << Q^2$

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

FF

quark polarisation

nucleon polarisation

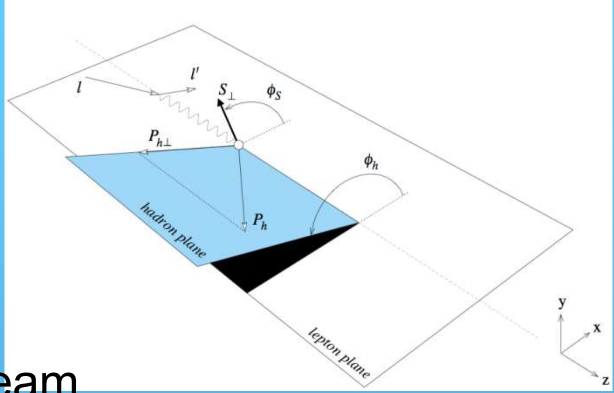
N/q	U	L	T
U	D_1 Unpolarized		$H_1^\perp$ Collins
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

SIDIS and TMDs

SIDIS cross section:

A. Bacchetta *et al.*, JHEP (2007), 0702:093

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$



unpolarized

polarized beam

polarized target

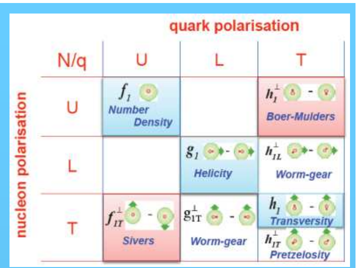
polarized beam & target

polarized target

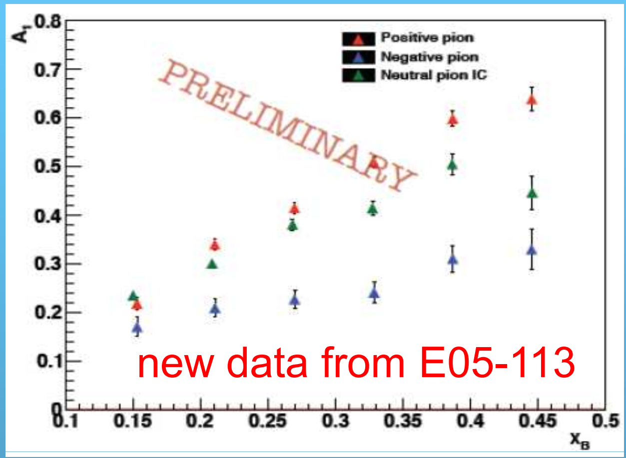
→ need asymmetry measurements in different spin configurations to access TMDs

polarized beam & target

Double spin asymmetries

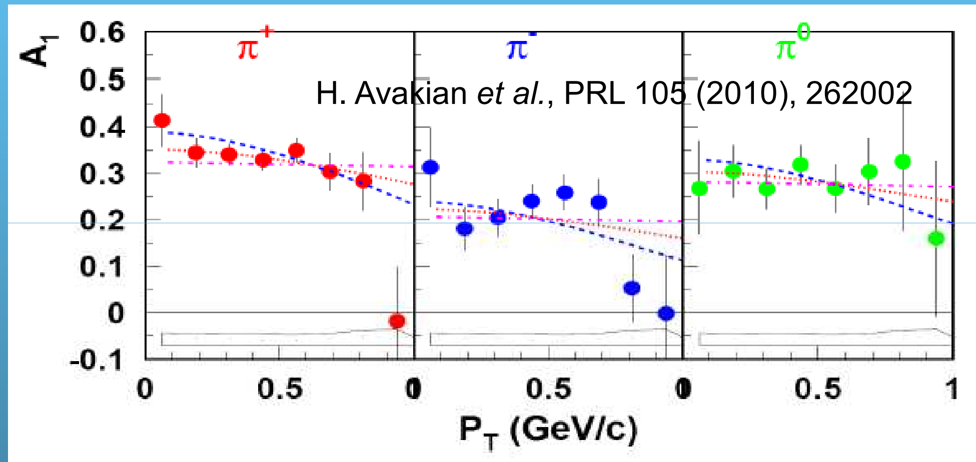


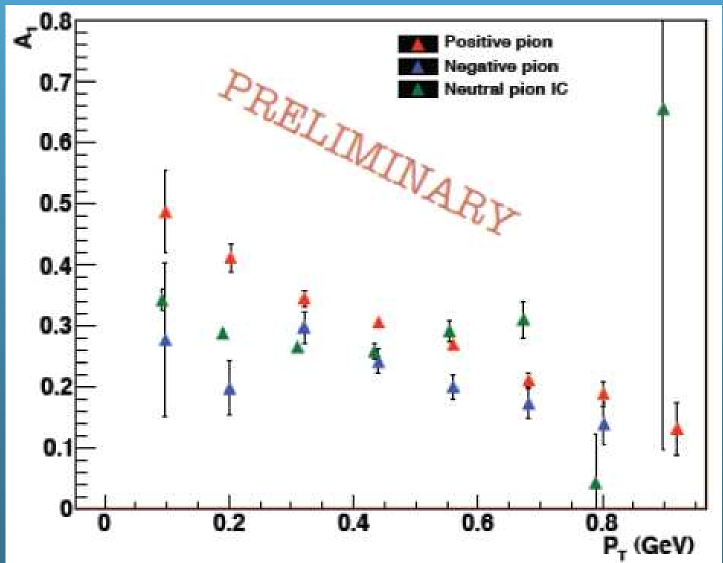
Now consider dependence in both x and p_T



$$A_1 = \frac{1}{fD'(y)P_bP_t}\frac{N^+ - N^-}{N^+ + N^-} \approx \frac{F_{LL}}{F_{UU,T}} = \frac{g_1 \otimes D_1}{f_1 \otimes D_1}$$

→ consistent with HERMES data (weak Q² dependence)





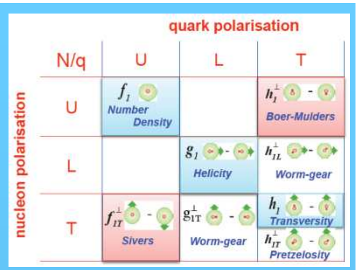
→ A_1 for π^+ may decrease with p_T

→ Suggests different k_T distributions for f_1 and g_1

$$\frac{{\sigma_{k_T}}^{g_1}}{{\sigma_{k_T}}^{f_1}} = 0.7 \pm 0.1$$

→ new preliminary data confirms p_T dependence for π^+

Target spin asymmetries

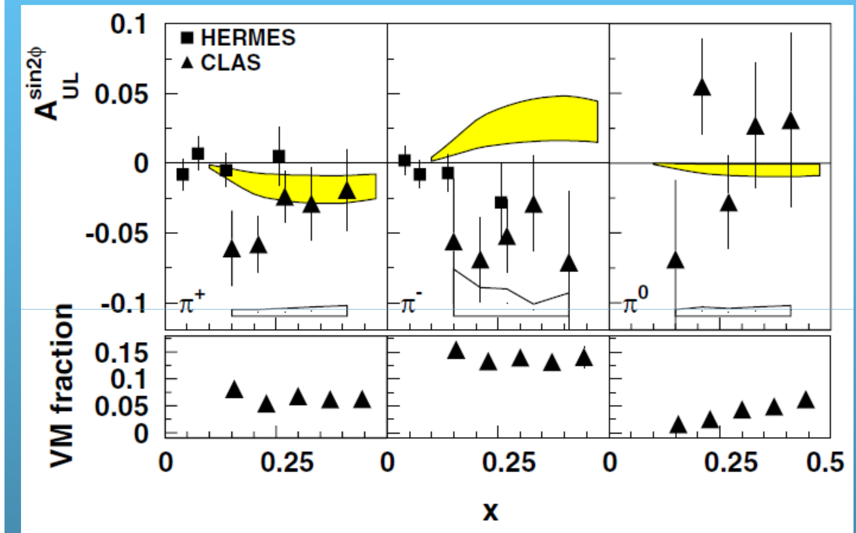


Single spin asymmetry:

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-}$$ contains $$A_{UL}^{\sin\phi_h}\sin\phi_h + A_{UL}^{\sin 2\phi_h}\sin 2\phi_h$$

Higher twist

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



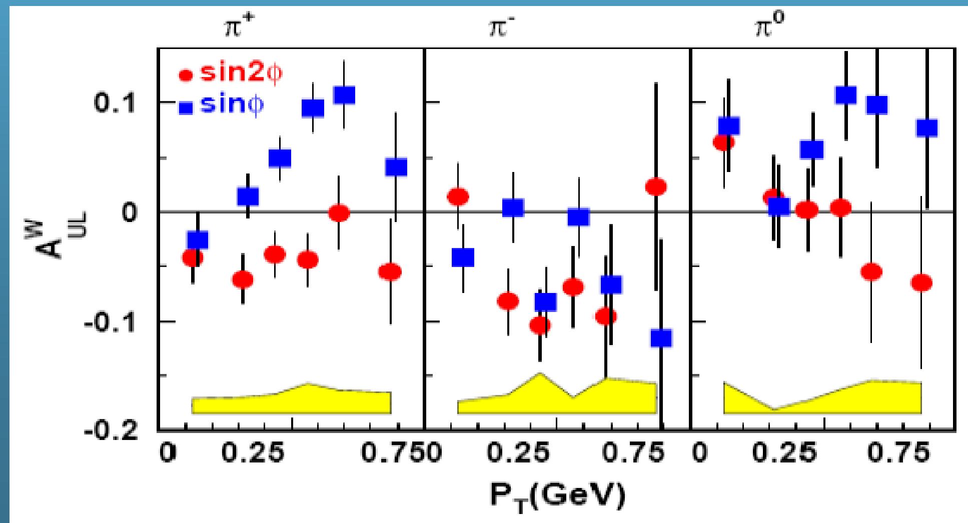
H. Avakian *et al.*, PRL 105 (2010), 262002

→ non zero asymmetry for π^+ and π^-

→ Collins function is suppressed for π^0

→ expected opposite sign for π^-

→ significant higher twist at CLAS kinematics



L. Pappalardo (S3-IV)

H. Avakian(S3-IV)

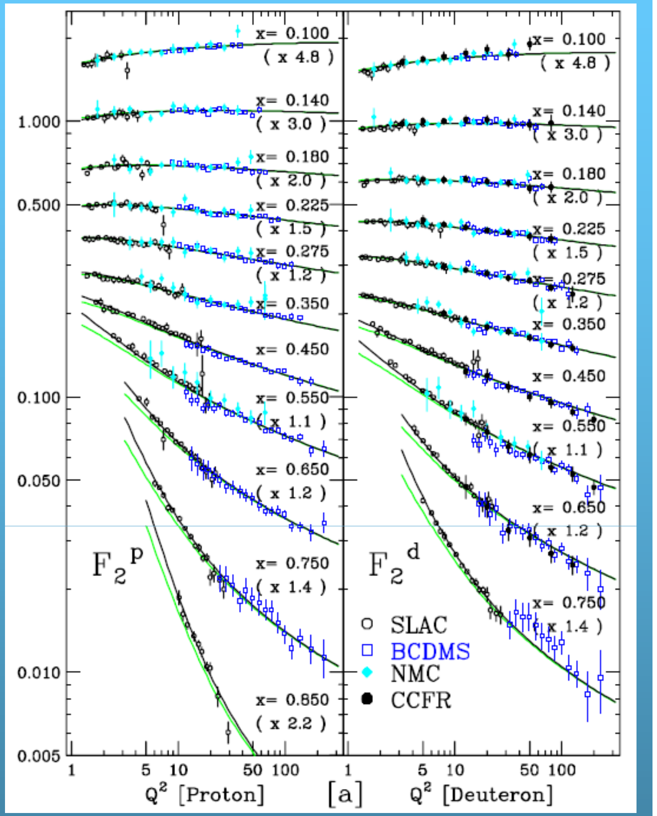
Neutron structure function F_2

- Very precise measurements for proton and deuteron SF over a large kinematic range

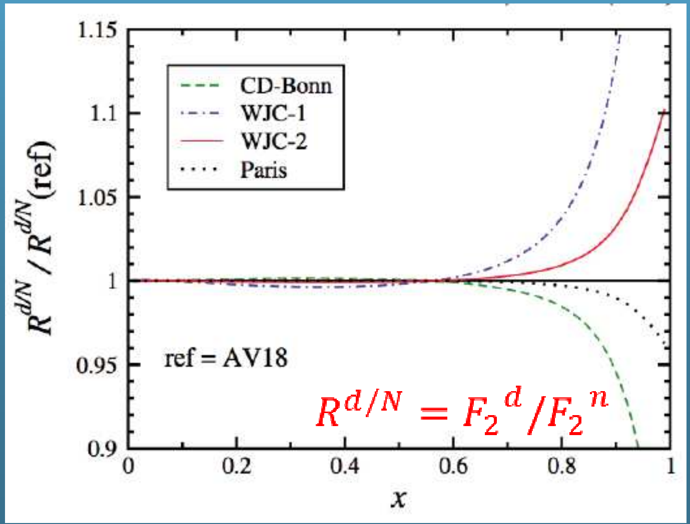
- Difficulty to access neutron SF (Fermi motion + binding + EMC effect)

$$F_2{}^n \neq F_2{}^d - F_2{}^p$$

- Still, F_2^n usually extracted from measurements with deuterium targets (bound neutrons)
  - → Non trivial corrections
  - → Large uncertainties at high x



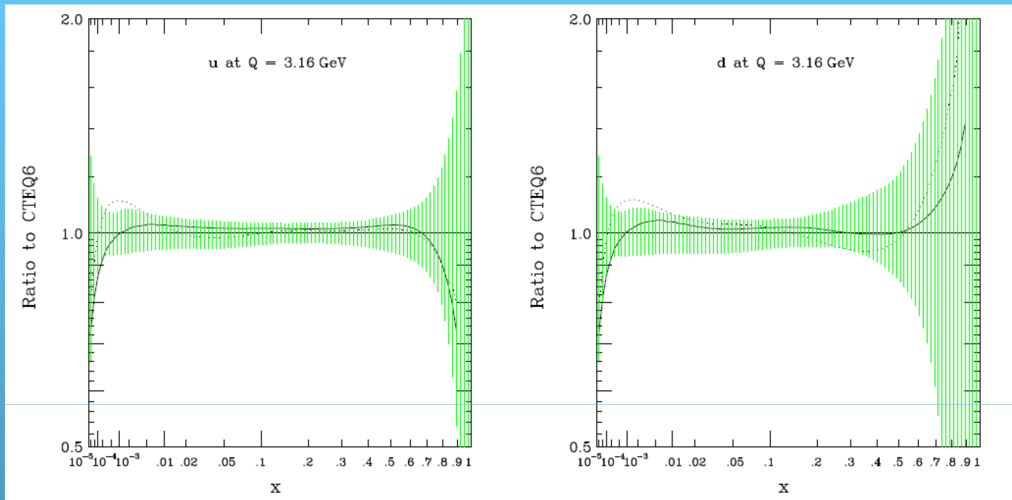
Yang & Bodek, EPJ C13 (2000), 241

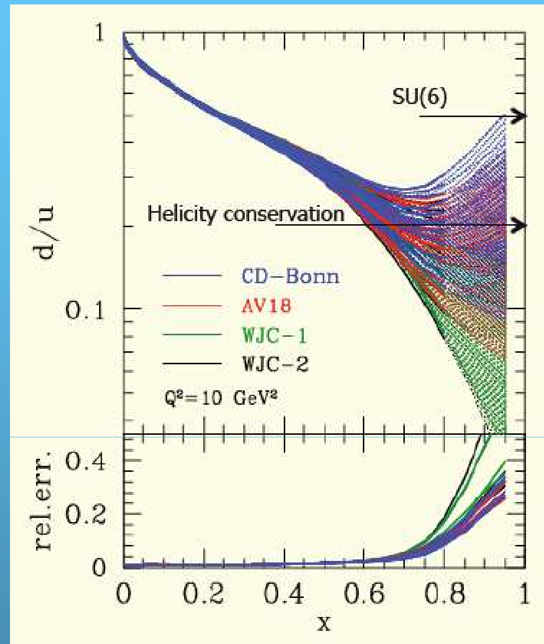


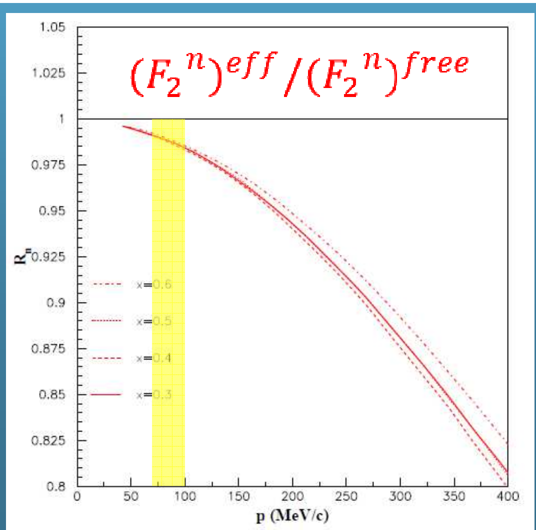
A. Accardi *et al.*, PRD D84 (2011), 014008

Neutron structure function F_2

- Neutron SF would provide information on the (d) quark distrib. & constrain d/u at large x







Luiti & Gross, PLB 356 (1995), 157

$$F_2 = x \sum_i e_i^2 q_i(x) \rightarrow \frac{F_2{}^n}{F_2{}^p} \approx \frac{1+4d/u}{4+d/u}$$

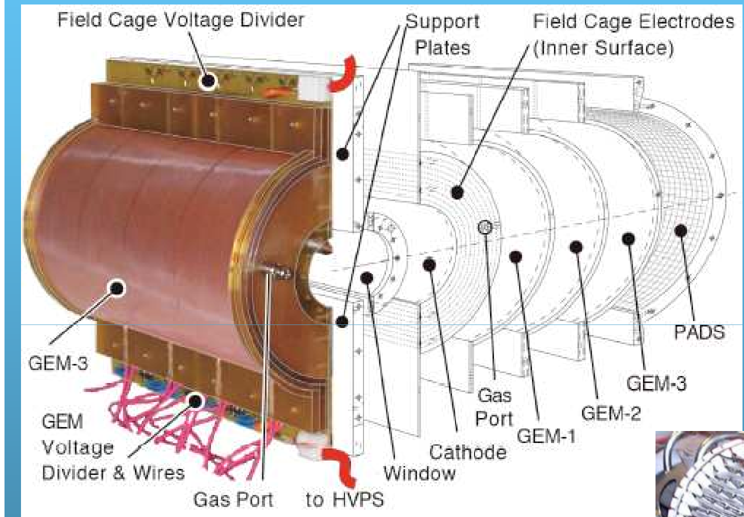
- Can be accessed from deuterium experiment and proton spectactor tagging @ low momentum (p_s < 100 MeV/c)

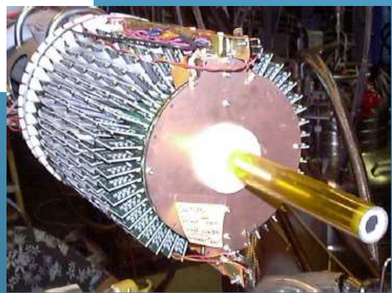
→ Off-shell corrections limited

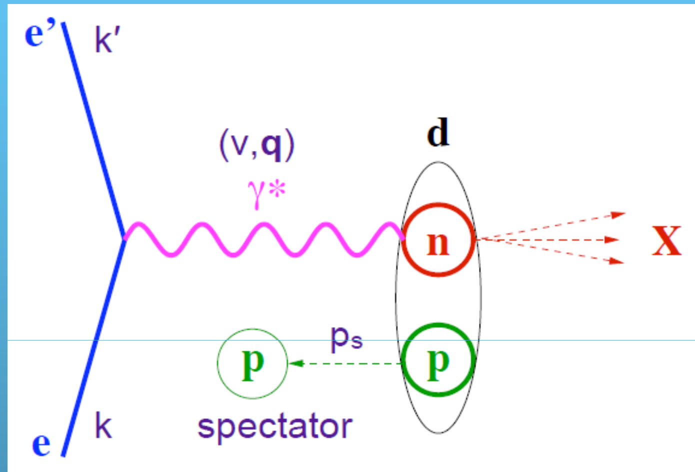
→ Small FSI effect if backward scattering angle

The BoNuS experiment (1/2)

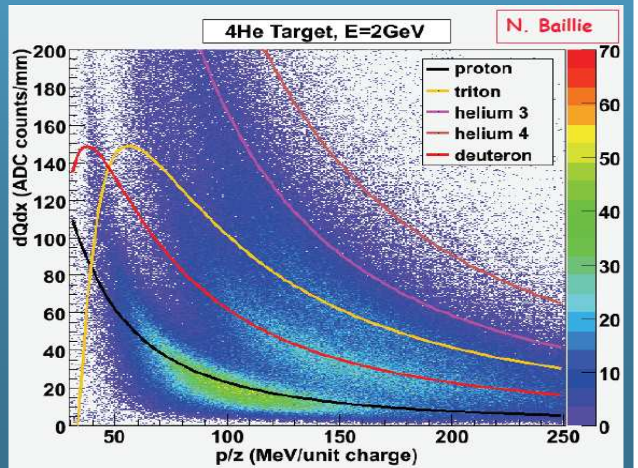
- Measurements of F_2^n through the reaction d(e,e'ps)X with spectator proton tagging
- low momentum spectator proton detected in a radial TPC → p_s > 70 MeV/c only







- E_{beam} = 2.1,;4.2; 5.3 GeV
- Luminosity ~ 5 10^{32} /cm²/s
- Momentum reconstruction using 4 T solenoid field
- PID using energy loss



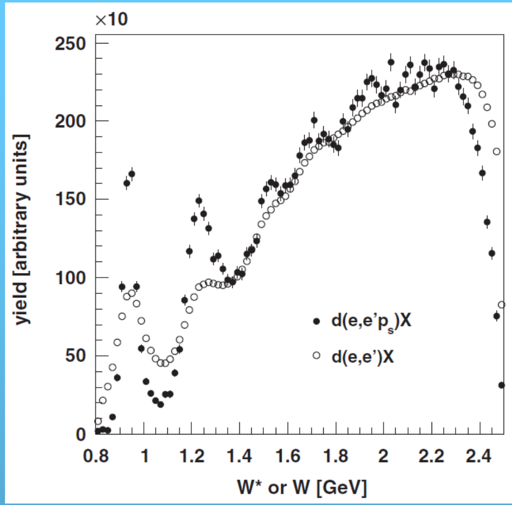
The BoNuS experiment (2/2)

- *Ratio analysis*: compute the ratio between proton tagged events and inclusive events, for a given kinematic bin

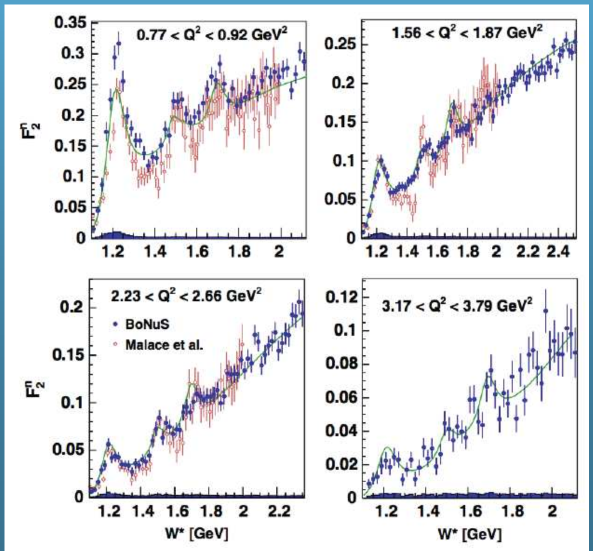
$$R_{exp} = \frac{N_{tagged}(\Delta Q^2, \Delta W^*, \Delta p_s)/A_e(Q^2, W^*)}{N_{incl}(\Delta Q^2, \Delta W)/A_e(Q^2, W)}$$

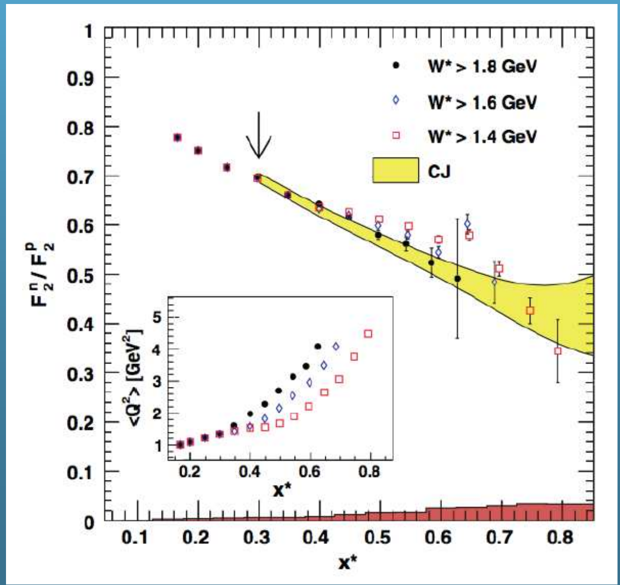
$$R_{exp} = \frac{F_2^n\,(W^*, Q^2)}{F_2^p\,(W, Q^2)} \times I_{VIP}$$

+ normalization to world data @ x = 0.3



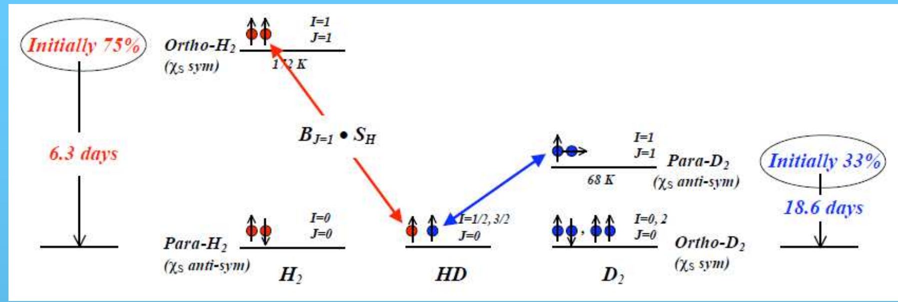
N. Baillie *et al.*, PRL 108 (2012), 142001





Experimental achievement: HD-ice target

- Polarized target in a frozen-spin state



- Procedure (very challenging):

→ Start with very pure HD sample with small H_2 and D_2 impurities (~10^{-4})
→ Polarize ortho-H_2 and para-D_2 with large B / low T (15 T / 12 mK)
→ Transfer polarization from H_2 to H and D_2 to D with spin-spin coupling
→ Wait for decays ortho-para (H_2) and para-ortho (D_2) (and evacuate heat)
→ Transfer to the experimental area (trickiest part)

- Advantages:

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

→ Good dilution factor (0.77)
→ Spin relaxation time ~ 1 year
→ Intermediate B field to maintain the polarization (<1 T)
→ Possibility to further transfer polarization from H to D

X. Wei (S7-II)

T. Kageya (S3-IV)

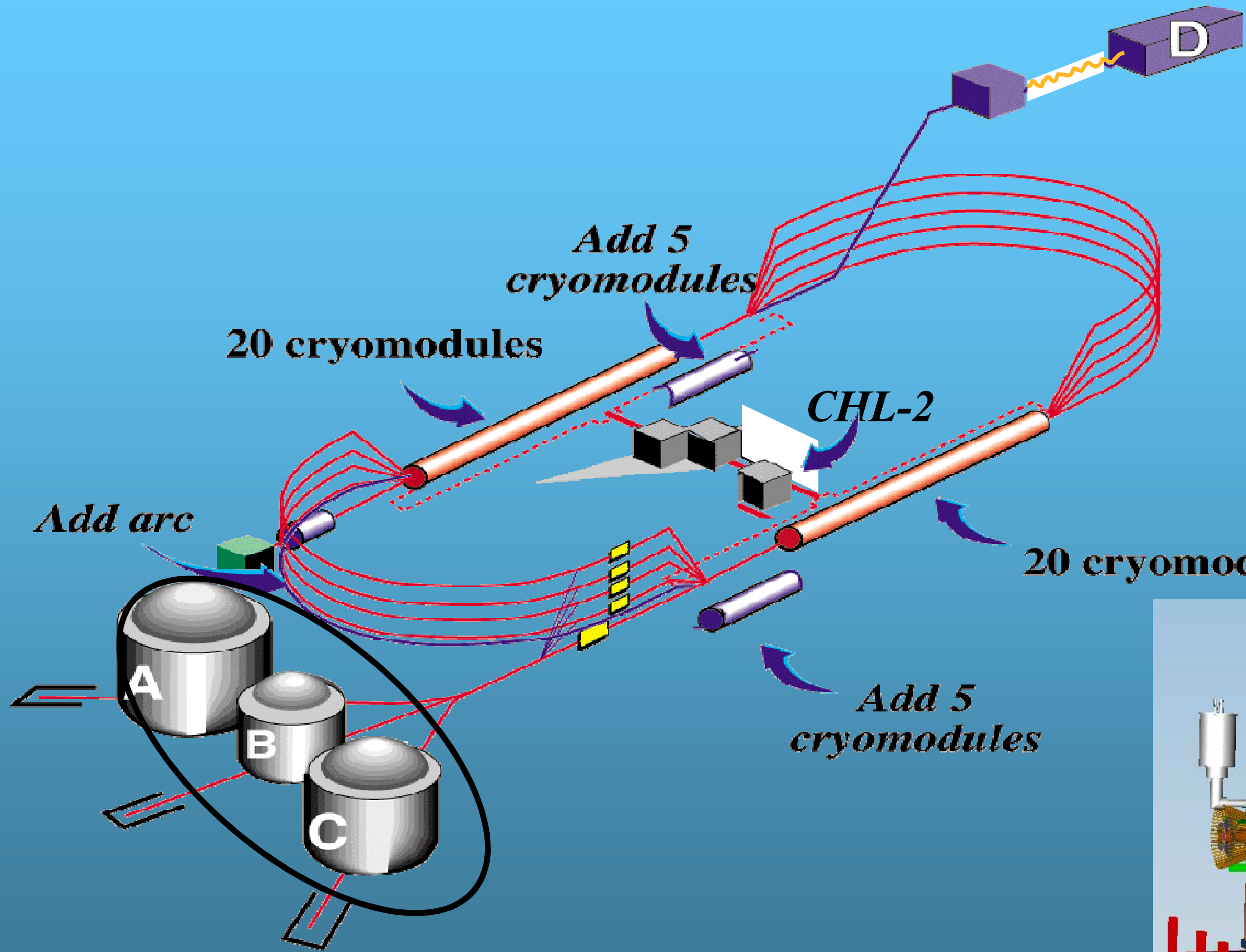
B. Briscoe (S3-IV)

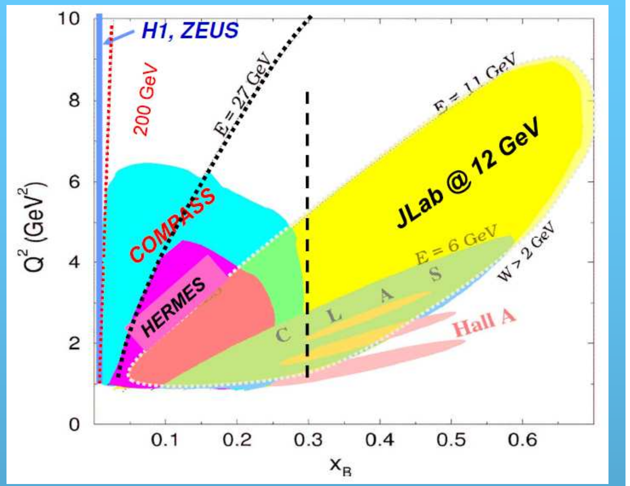
- Successfull run in 2012 with photon (g14) and tests with electron beams

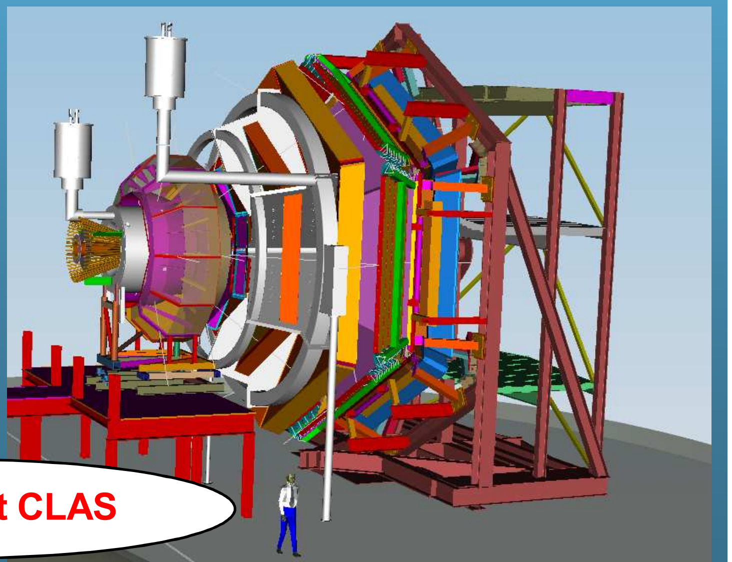
→ 5 HD targets used; p(H) ~ 0.6 <u>or</u> p(D) ~ 0.2 in average

- Offers new possibilities for transverse target exp. (*e.g.* to access the GPD E) → CLAS12

The future: the 12 GeV project

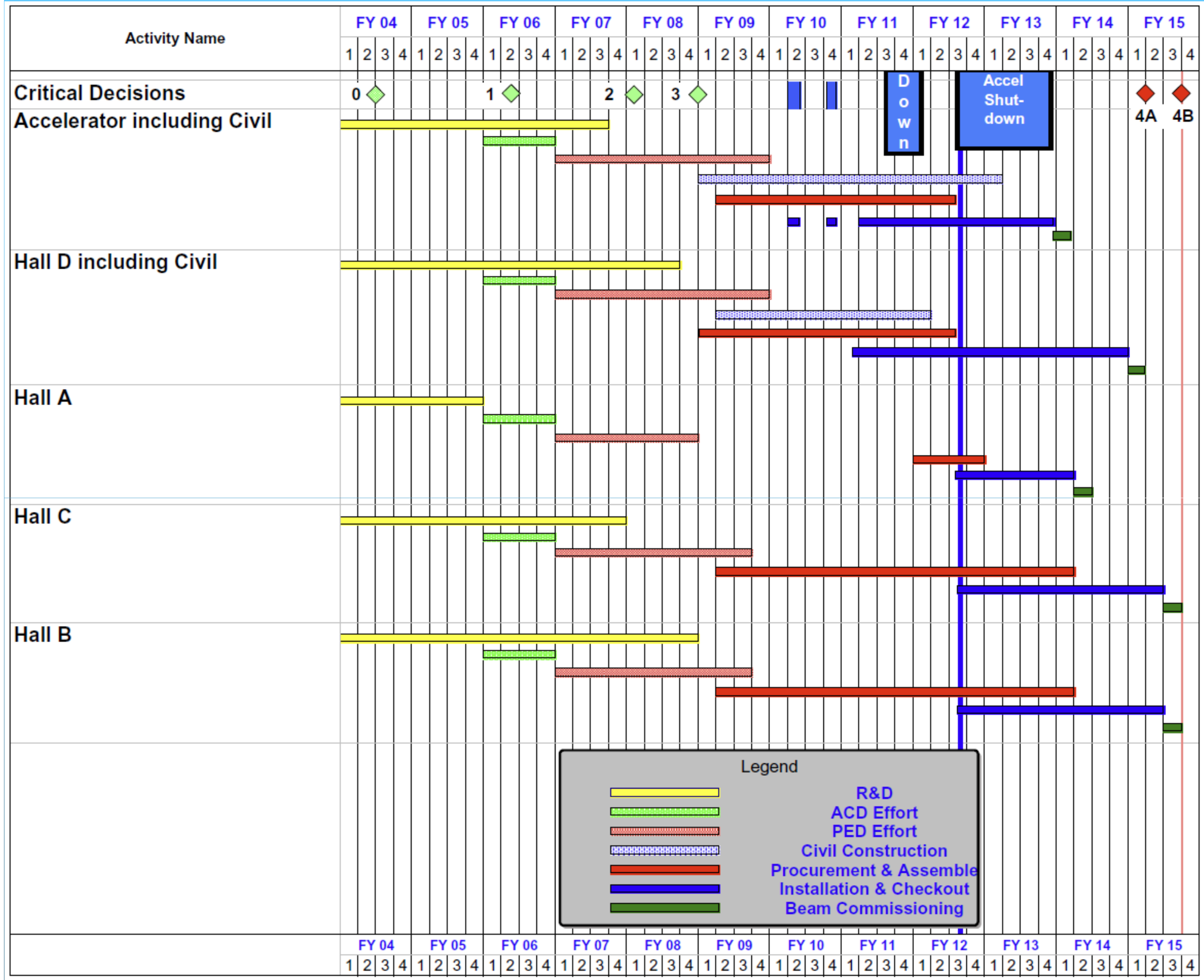






Lumi x10 wrt CLAS

Schedule of the 12 GeV project



Two short parasitic installation periods in FY2010

6-month installation May-Oct 2011

16-month installation May 2012 - Sept 2013

Hall A commissioning start Feb 2014

Hall D commissioning start Oct 2014

Halls B & C commissioning start Apr 2015

Project Completion June 2015

Conclusion (but not the end)

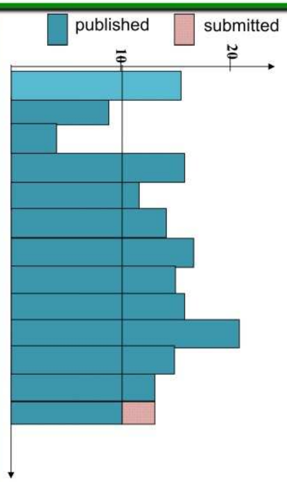
→ First generation of dedicated experiments on DVCS measurements

→ Major role on key issues for the nucleon structure (GPD, TMD, large x)

→ Many topics not covered in this talk

Hall B All Publications (refereed Journals)

	Spectroscopy & Structure	Hard Processes, Str. Func.	Nuclear Processes	Technical (NIM)	Theory & Reviews	ALL
≤ 2000	-	1	1	10	3	15
2001	2	3	-	3	1	9
2002	3	-	1			4
2003	7	4	1	2	2	16
2004	3	3	4	1	1	12
2005	7	3	2	2		14
2006	8	4	3	2		17
2007	7	2	3	2	1	15
2008	4	6	2	2	2	16
2009	8	7	4	2	1	22
2010	4	2	4	2	3	15
2011	3	1	4	4	1	13
2012	3	2	2	1	2	10
SUM	59	38	31	33	15	175



→ 128 physics papers in refereed journals (+ 33 technical papers) so far

→ 18 accepted proposals for Hall B experiments @ 12 GeV…

⇒ much more to come with CLAS12!

Backup

New equipments