Nucleon structure studies with CLAS: current status and prospects after 12 GeV Upgrade

V.I.Mokeev

Collaboration between SINP at MSU and Hall B at Jefferson Lab

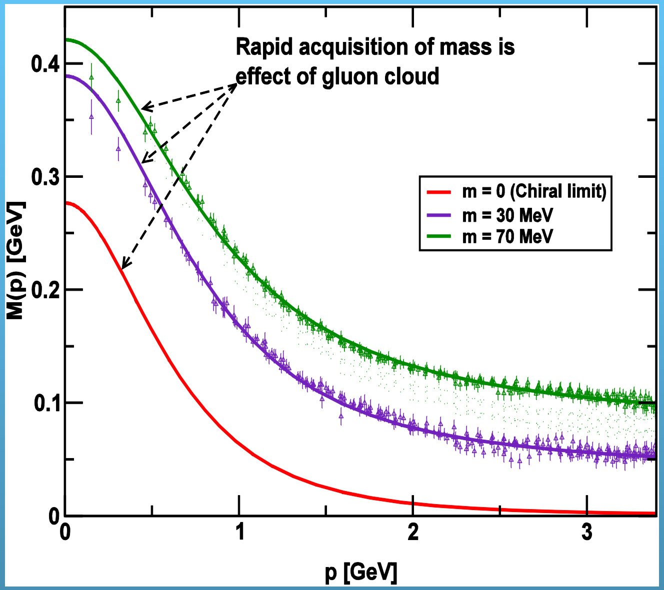
Nucleon structure studies with CLAS

- Parton distributions, twist decomposition from the studies of inclusive polarized and unpolarized structure functions
- Transversity, quark orbital angular momentum from semi- inclusive meson electroproduction
- GPD studies : 3-dimensional image of nucleon, full access to quark total angular momentum, mass and ‘pressure’ distributions in the ground nucleon state
- The studies of excited nucleon state (N*) structure through the data on transition N-N* form factors

Access to non-perturbative strong interaction mechanisms, that are responsible for baryon formation from quarks and gluons and their relation to QCD

Dressed quark properties and transition from non-perturbative to perturbative regimes of strong interactions

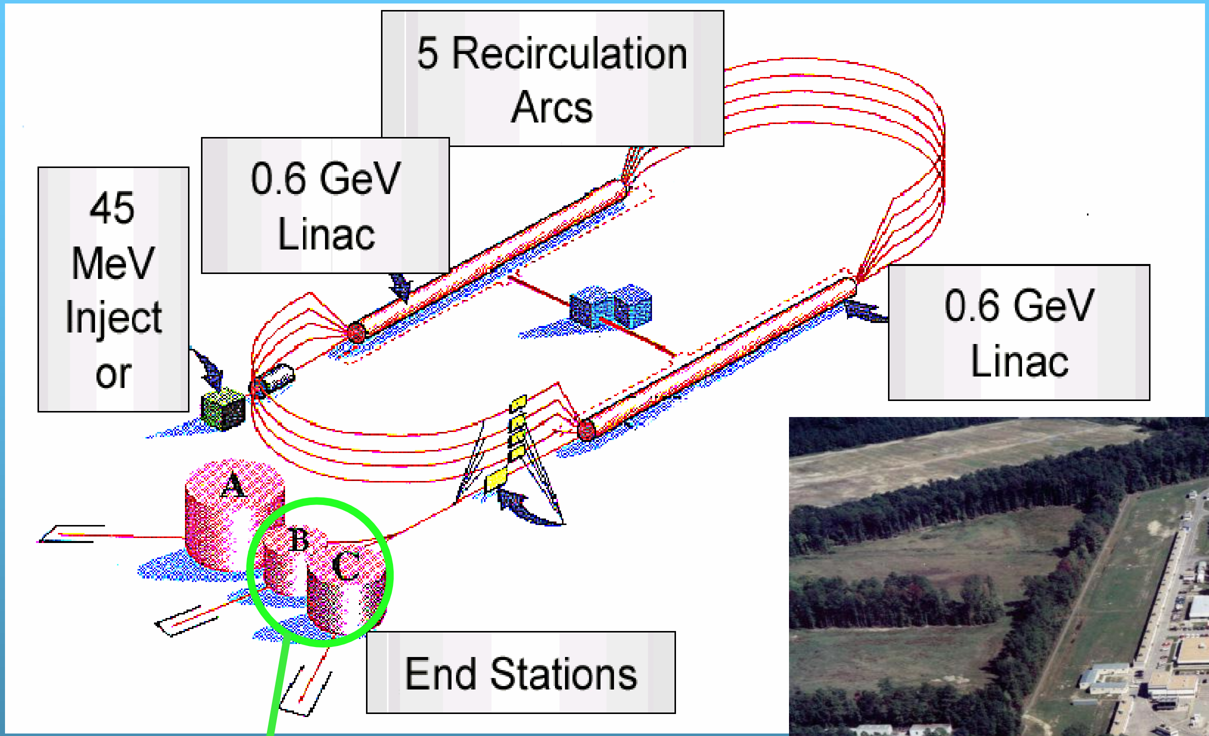
- ~few MeV current quark mass is approached at asymptotically high momentum p running over quark
- sharp mass evolution at p<2.0 GeV reflects transition between non-perturbative/perturbative regime of strong interaction
- mass dependence is directly related to QCD β–function
- >98% of nucleon mass comes from dynamical dressing of current quarks



The studies of the ground and excited nucleon state structure allow us to access properties and interactions of dressed quarks at various distance scales

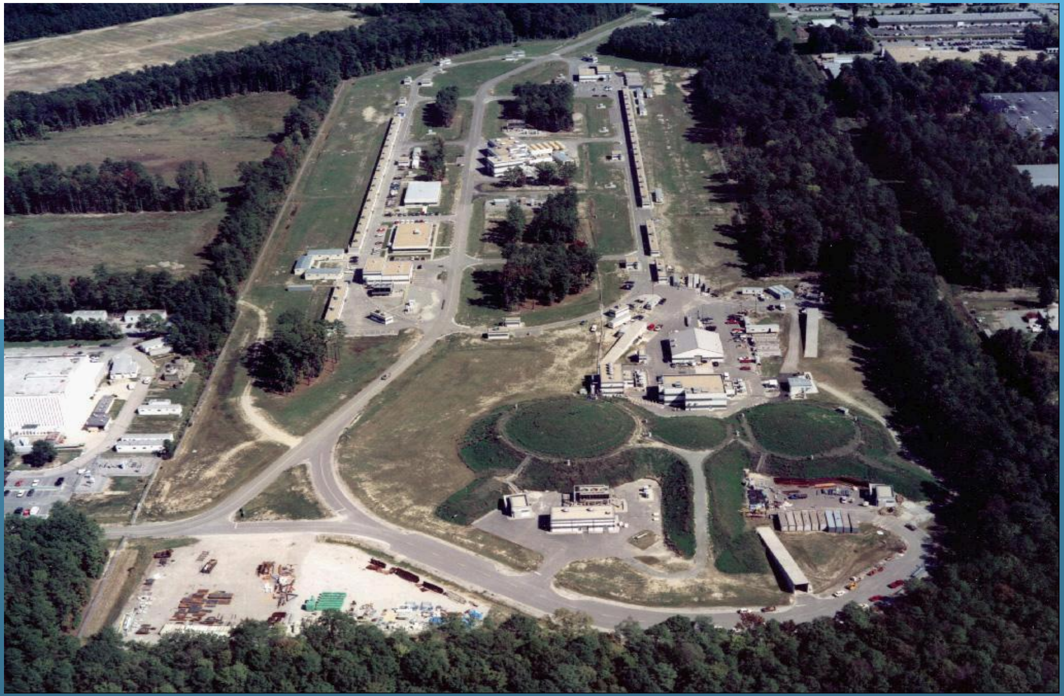
Key part in the studies of quark confinement in baryons!

Ускоритель электронов непрерывного действия в Jefferson Lab – CEBAF



CLAS

E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam P	~ 80%
E_g(tagged)	~ 0.8- 5.5 GeV



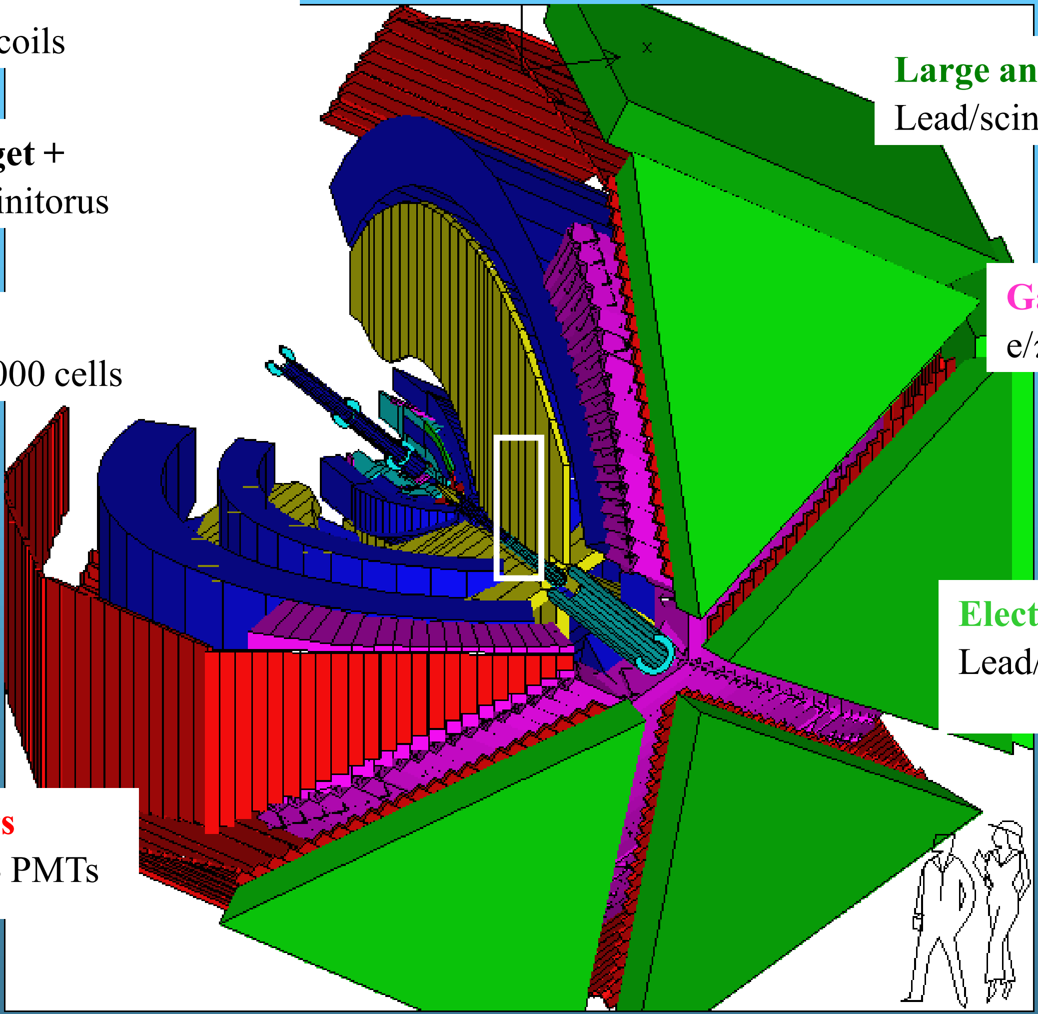
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells

Time-of-flight counters
plastic scintillators, 684 PMTs

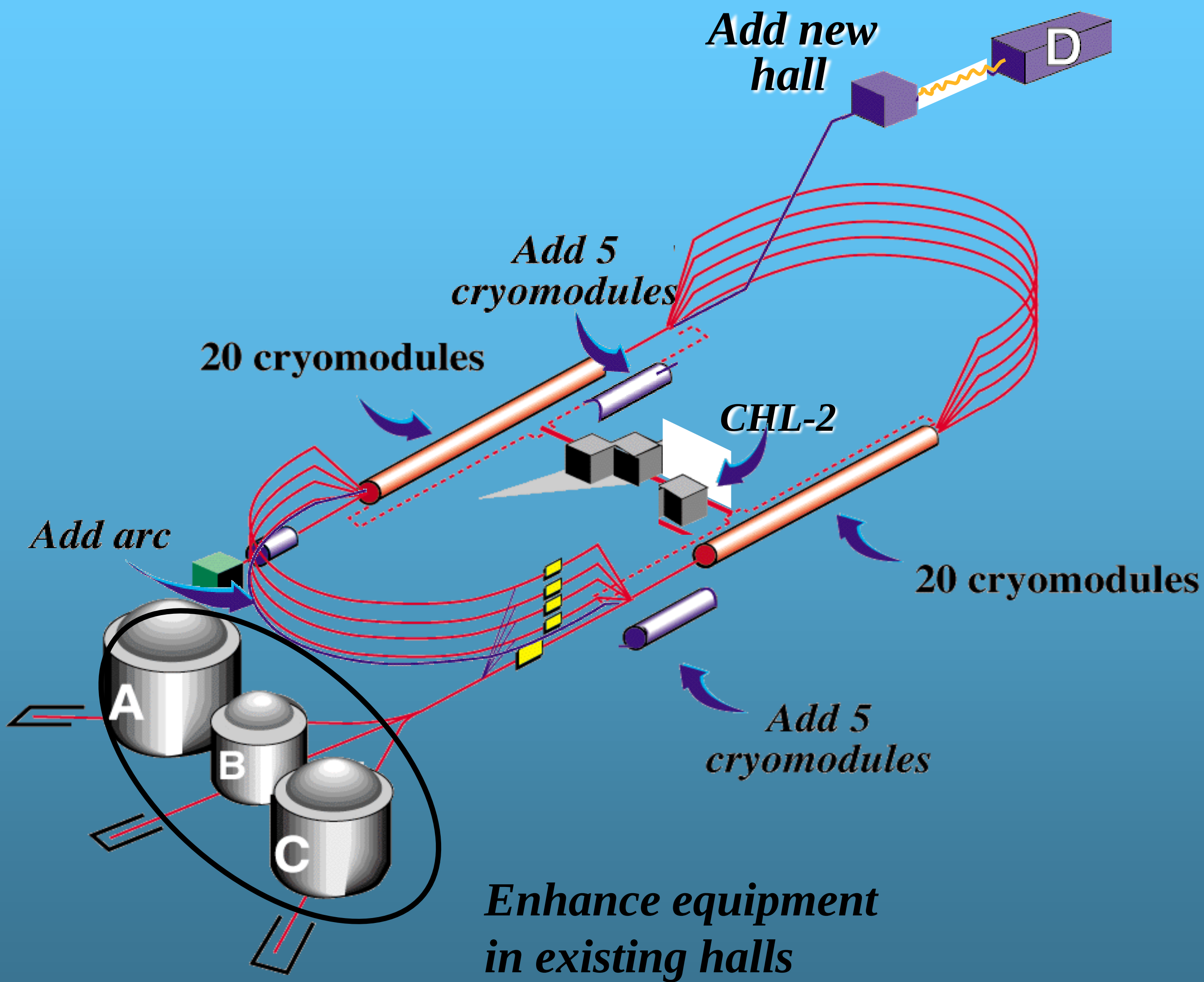


Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/π separation, 216 PMTs

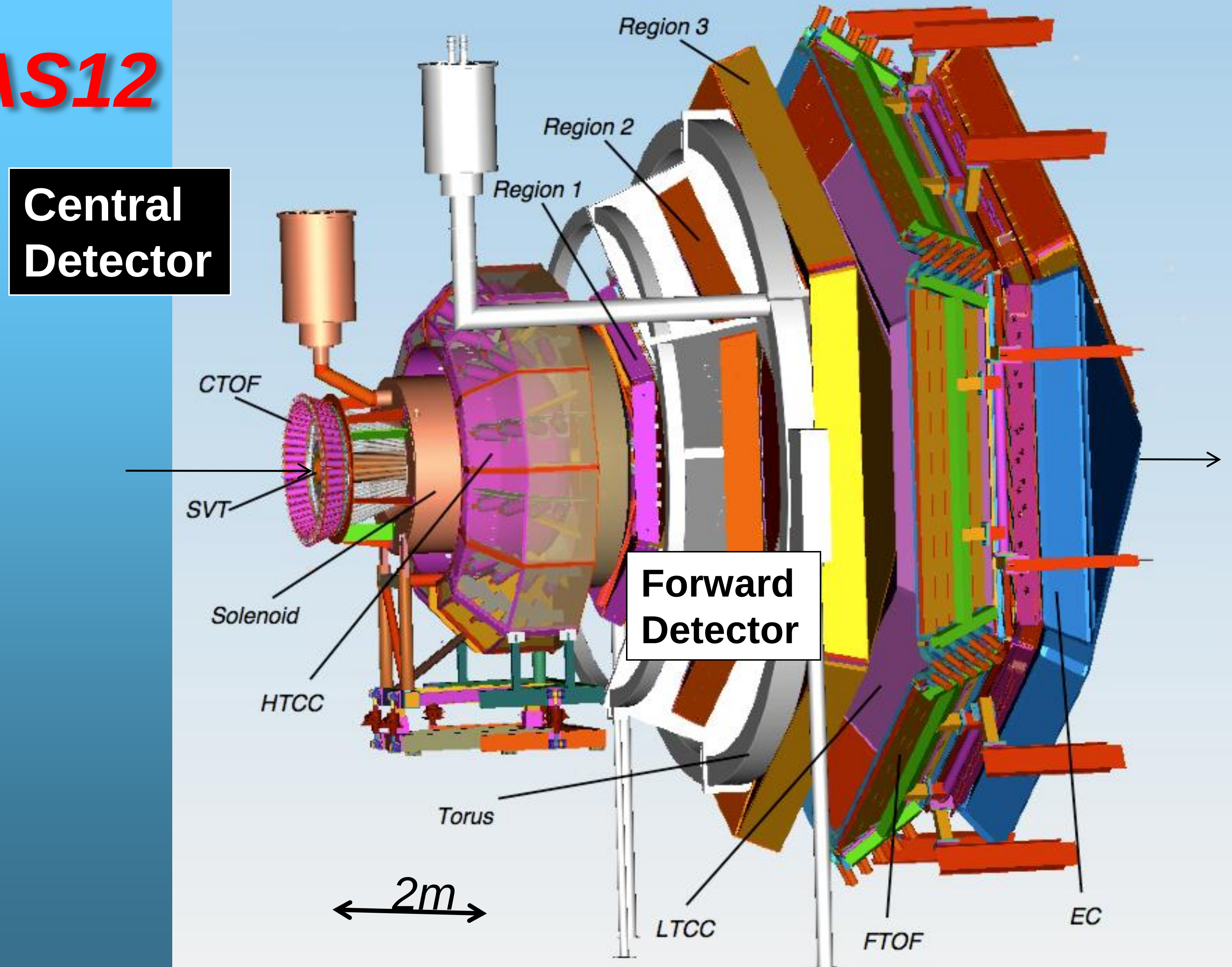
Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

12 GeV



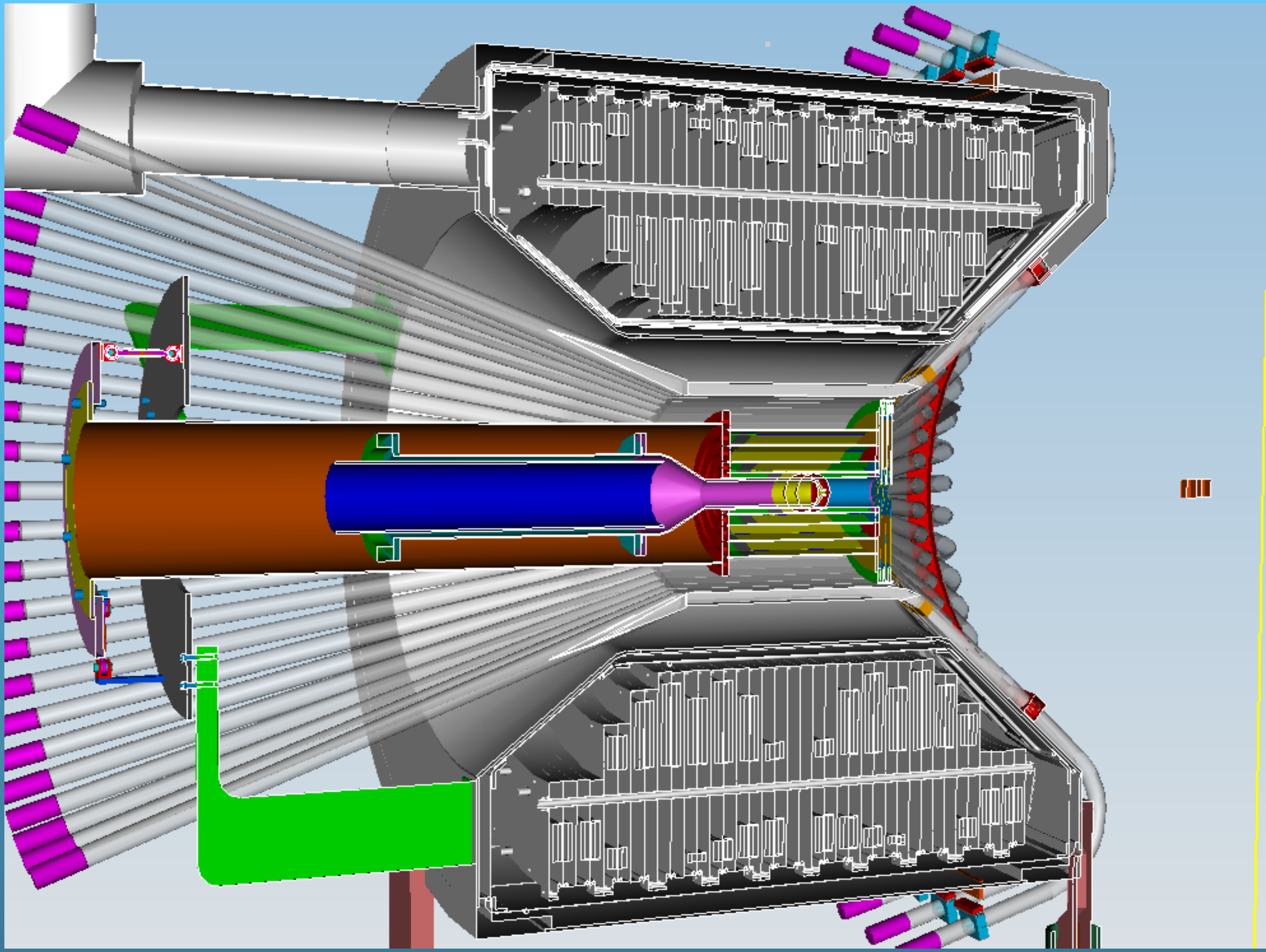
Add new hall
D
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
A
B
C
Add 5 cryomodules
Enhance equipment in existing halls

CLAS12


Central Detector
Region 3
Region 2
Region 1
CTOF
SVT
Solenoid
HTCC
Torus
Forward Detector
LTCC
FTOF
EC
2m

CLAS12 – Central Detector SVT, CTOF

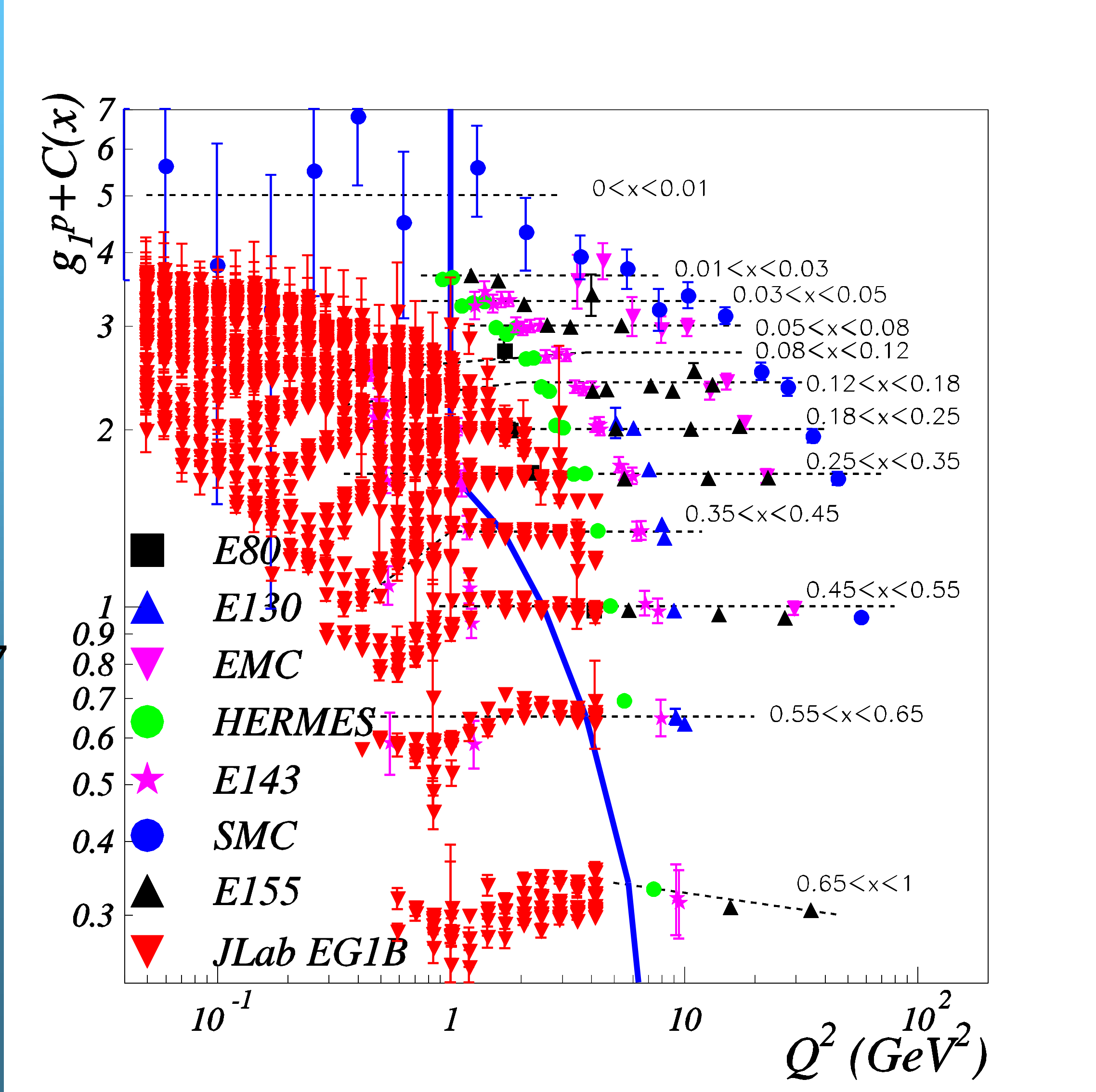
- Charged particle tracking in 5T field
- ΔT < 60psec in for particle id
- Moller electron shield
- Polarized target operation $\Delta B/B<10^{-4}$



World data on polarized structure function $g_{1p}(x,Q^2)$

CLAS provides a large body of precise g_1 data in the DIS and transition regions that can be used to improve knowledge of twist-2 PDFs.

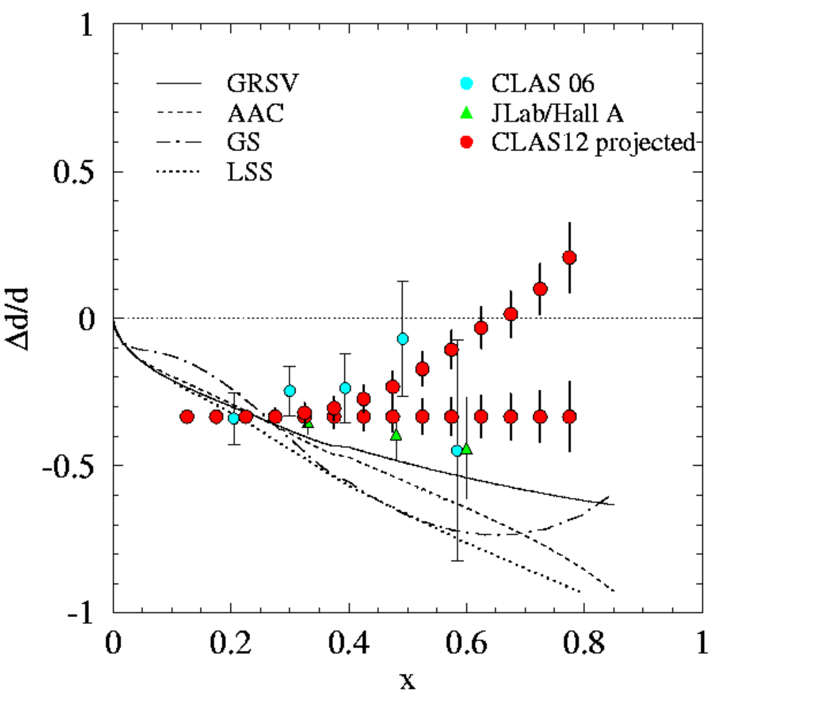
Phys. Rev.C75:035203, 2007
Phys. Lett. B 641, 11 (2006)



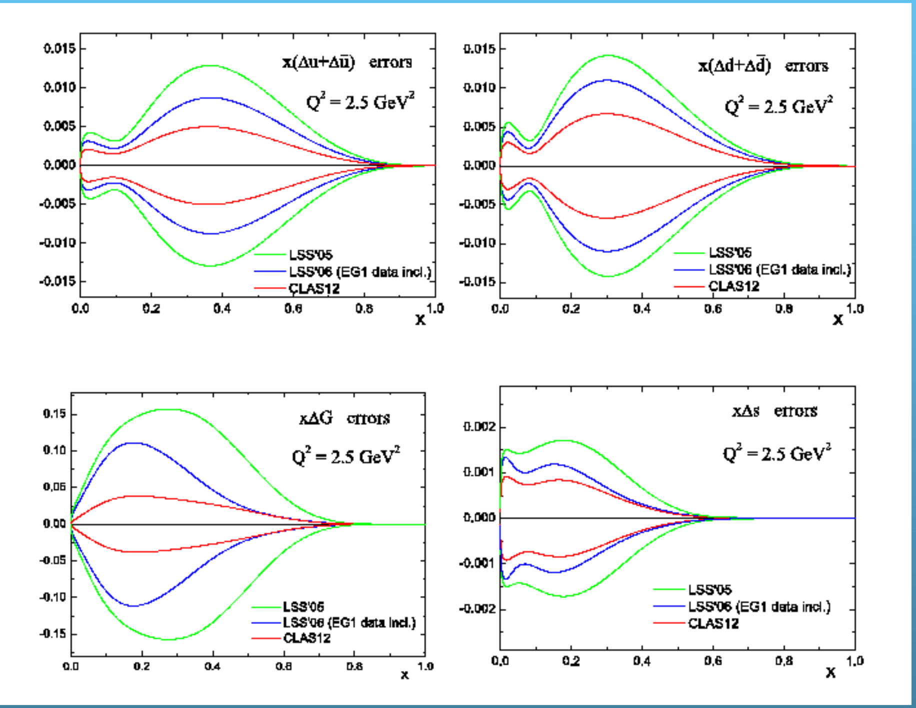
Spin structure functions – Hall B

LO extraction of quark polarization

$$A_1^{LO}(x,Q^2) = \frac{\sum e_i^2 \Delta q_i(x,Q^2)}{\sum e_i^2 q_i(x,Q^2)}$$



Effect of these data on NLO analysis



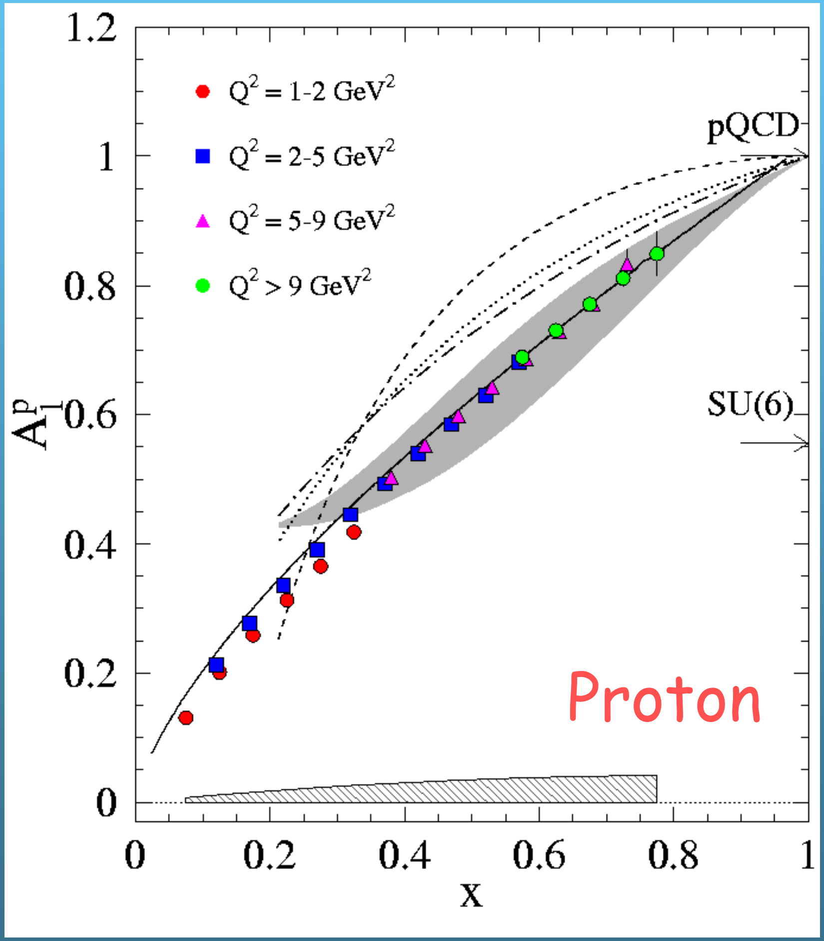
→ High discriminating power of the different models
→ High sensitivity to ΔG even if probes the valence region

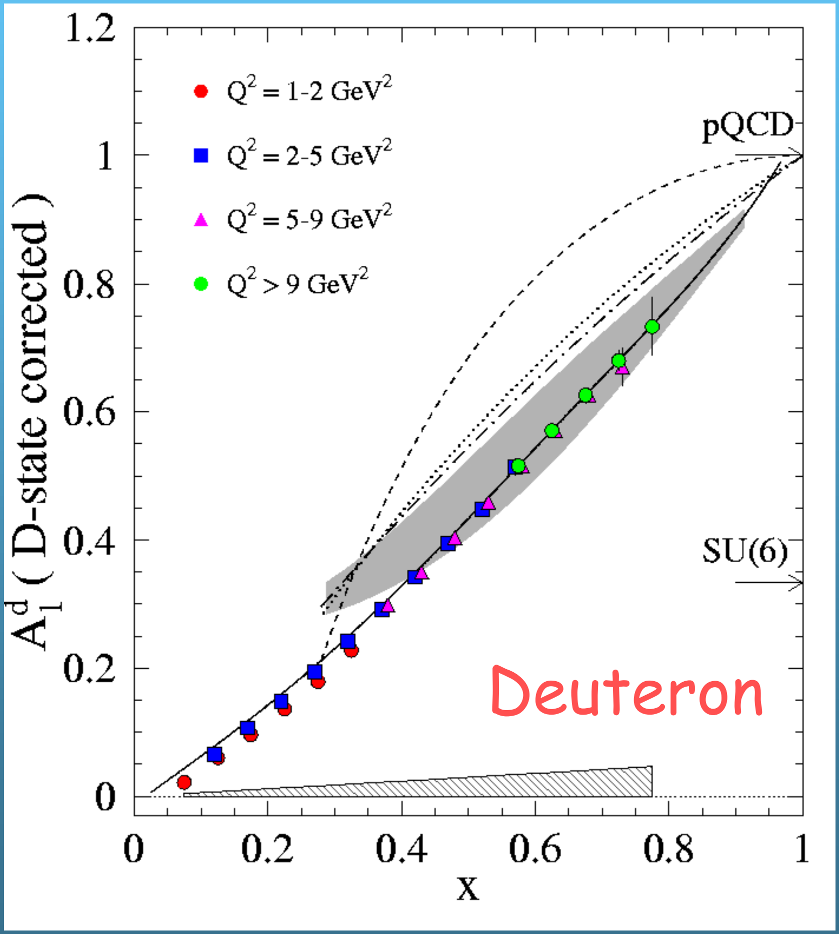
Spin structure functions – Hall B

- 30 days on NH_3 (P=0.8)
- 50 days on ND_3 (P=0.4)
- L = 10^{35} /cm²/s @ 11 GeV

$$A'_{ll} = D\left(A_1(x,Q^2) + \eta A_2(x,Q^2)\right)$$

W > 2 GeV; Q^2 > 1 GeV²





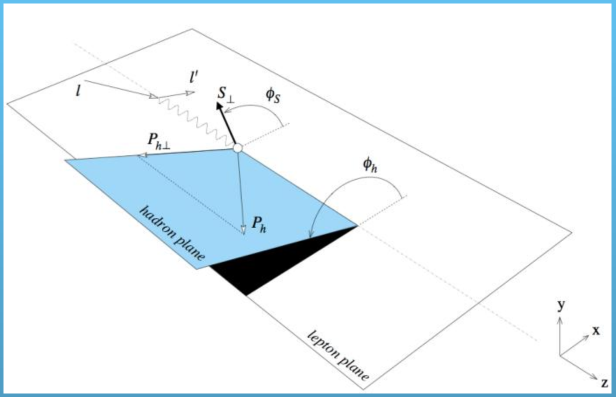
SIDIS and TMDs

- Semi-inclusive DIS allows separation of different quark contributions
- Also gives the transverse momentum distribution of quarks
- Spin-orbit correlations through azimuthal distributions

$\rightarrow$ requires non zero OAM

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

$$S \bullet (P \times k_T)$$



$$\sigma_{UU}^{\cos 2\phi} \propto 2(1-y)\cos 2\phi \sum_{q,\bar{q}} e_q^2 x h_1^{\perp q}(x) H_1^{\perp q}(z)$$

$$\sigma_{UL}^{\sin 2\phi} \propto S_L 2(1-y)\sin 2\phi \sum_{q,\bar{q}} e_q^2 x h_{1L}^{\perp q}(x) H_1^{\perp q}(z)$$

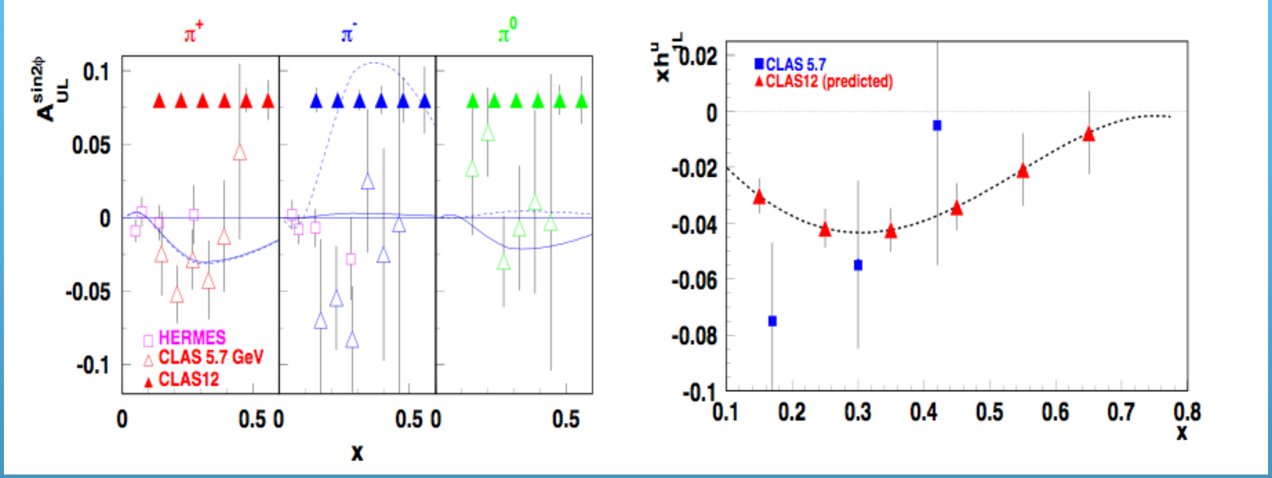
$\rightarrow$ Mesure single & double spin asymmetries on pions

$\rightarrow$ Large acceptance needed (CLAS12)

SIDIS and TMDs

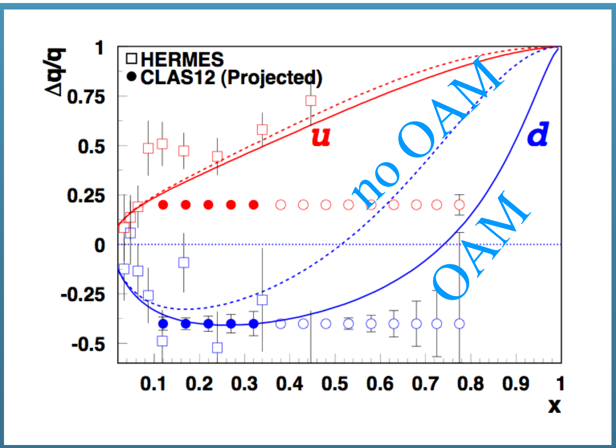
- 30 days on NH_3 (P=0.8)
- 50 days on ND_3 (P=0.4)
- L = 10^{35} /cm²/s @ 11 GeV

$$A_{UL}^{\sin 2\phi} \propto \sum_{q,\bar{q}} e_q^2 x h_{1L}^{\perp q}(x) H_1^{\perp q}(z)$$

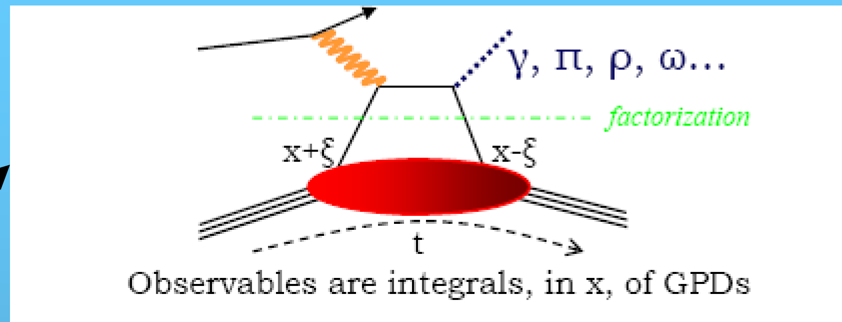


$$A_p^{\pi^+-\pi^-} = \frac{4\Delta u_V(x) - \Delta d_V(x)}{4u_V(x) - d_V(x)}$$

$$A_d^{\pi^+-\pi^-} = \frac{\Delta u_V(x) + \Delta d_V(x)}{u_V(x) + d_V(x)}$$

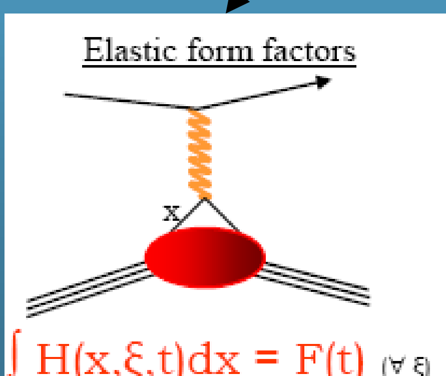


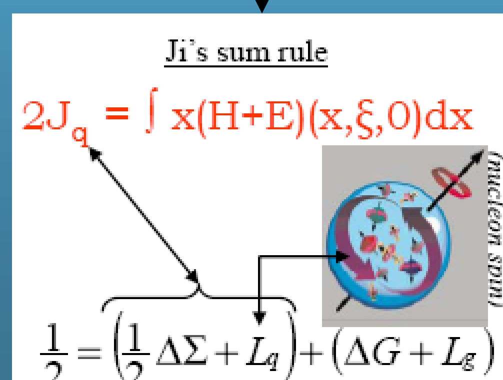
Introduction to GPDs

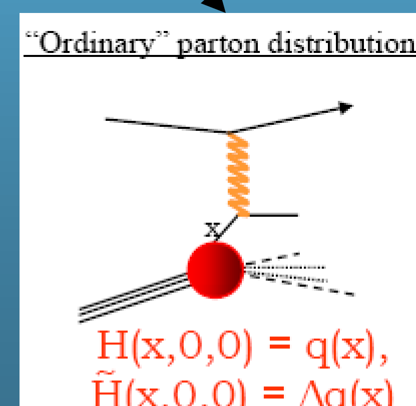


Deconvolution needed

$$H, \widetilde{H}, E, \widetilde{E}(x, \xi, t)$$





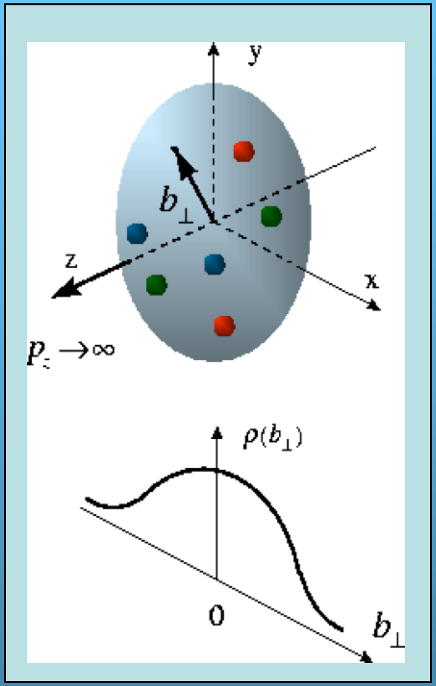


Introduction to GPDs

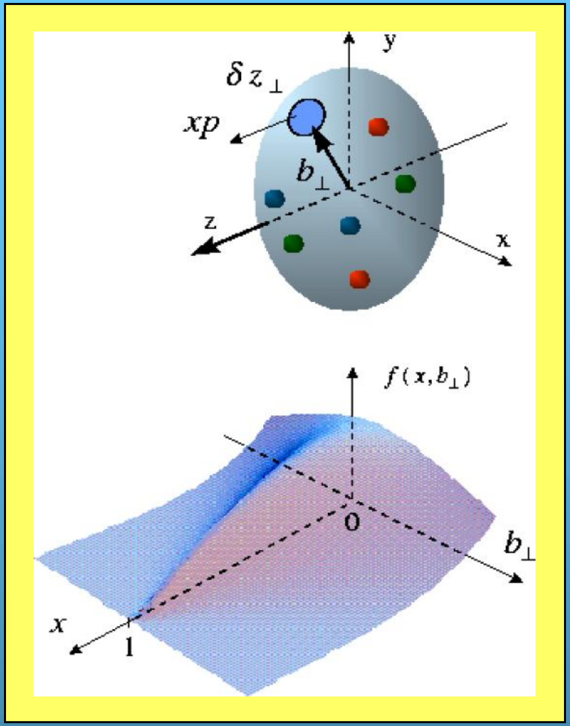
GPD

Form factors

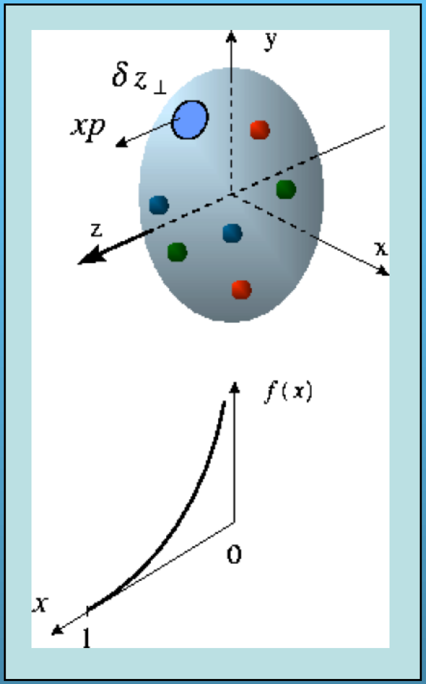
Parton distributions



Transverse charge distribution (coordinate space)



Correlation between longitudinal momentum & transverse spatial distributions



Longitudinal momentum distribution (momentum space)

Physical content of GPD *E* & *H*

Nucleon matrix element of the Energy-Momentum Tensor of QCD contains three scalar form factors (R. Pagels, 1965) and can be written as (X. Ji, 1997):

$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{U}(p_2)\left[M_2^q(t)\frac{P_\mu P_\nu}{M} + J^q(t)\frac{\imath(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]U(p_1)$$

$M_2(t)$: Mass distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Forces and pressure distribution

GPDs are related to these form factors through 2nd moments

$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\left[H^q(x,\xi,t) + E^q(x,\xi,t)\right] \quad , \quad M_2^q(t) + \frac{4}{5}d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1}\mathrm{d}x\, x H^q(x,\xi,t)$$

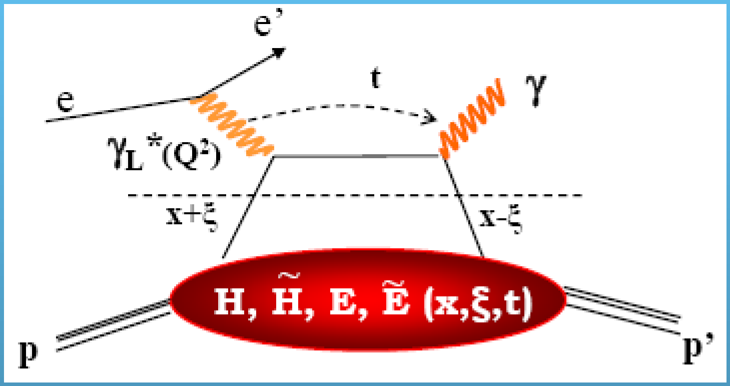
t=0: **Ji's Angular Momentum Sum Rule**

To determine $J(t)$ we need to measure the x and t dependence of GPDs.
To separate $M_2(t)$ and $d_1(t)$ we need measurements at small and large $\xi(x_B)$.

DVCS and GPDs

- Deep Virtual Compton Scattering is the most suitable process to probe GPDs
- Factorization theorem states that the « handbag » diagram is the only contribution to the DVCS amplitude in the suitable asymptotic limit

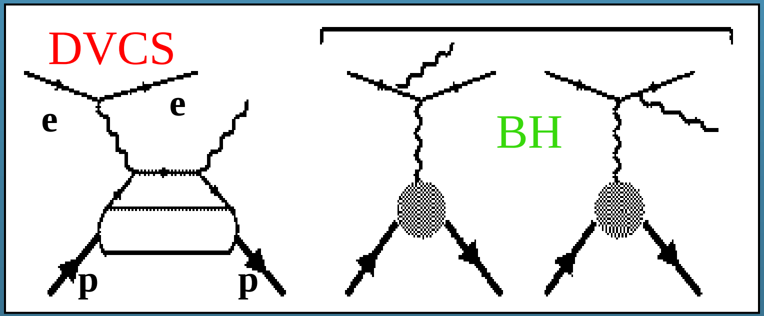
$\Rightarrow$ *requires high Q^2, ν with $t \ll Q^2$*



$$T^{DVCS} = \int_{-1}^{1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon} dx + \ldots$$

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

Experimentally: DVCS cannot be distinguished with BH process



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

T^{BH} calculable from elastic form factors

Interference gives direct access to DVCS amplitude

Extraction of GPDs

Different combinations of GPDs can be accessed with polarized beam or target

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

- Polarized beam, unpolarized target (BSA):

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \underbrace{\xi(F_1+F_2)\tilde{H} + kF_2 E}_{\text{Kinematically suppressed}}\} \longrightarrow H\ (\tilde{H}, E)$$

- Unpolarized beam, longitudinal target (TSA):

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \underbrace{\xi(F_1+F_2)(H + \xi/(1+\xi)E) - ..}_{\text{Kinematically suppressed}}\} \longrightarrow \tilde{H}\ (H, E)$$

- Unpolarized beam, transverse target (TSA):

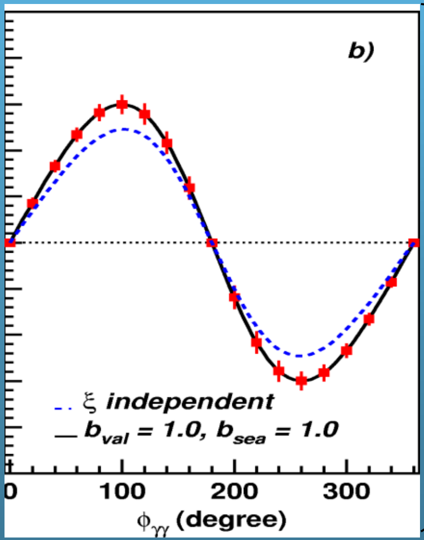
$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \underbrace{.....}_{\text{Kinematically suppressed}}\} \longrightarrow H, E$$

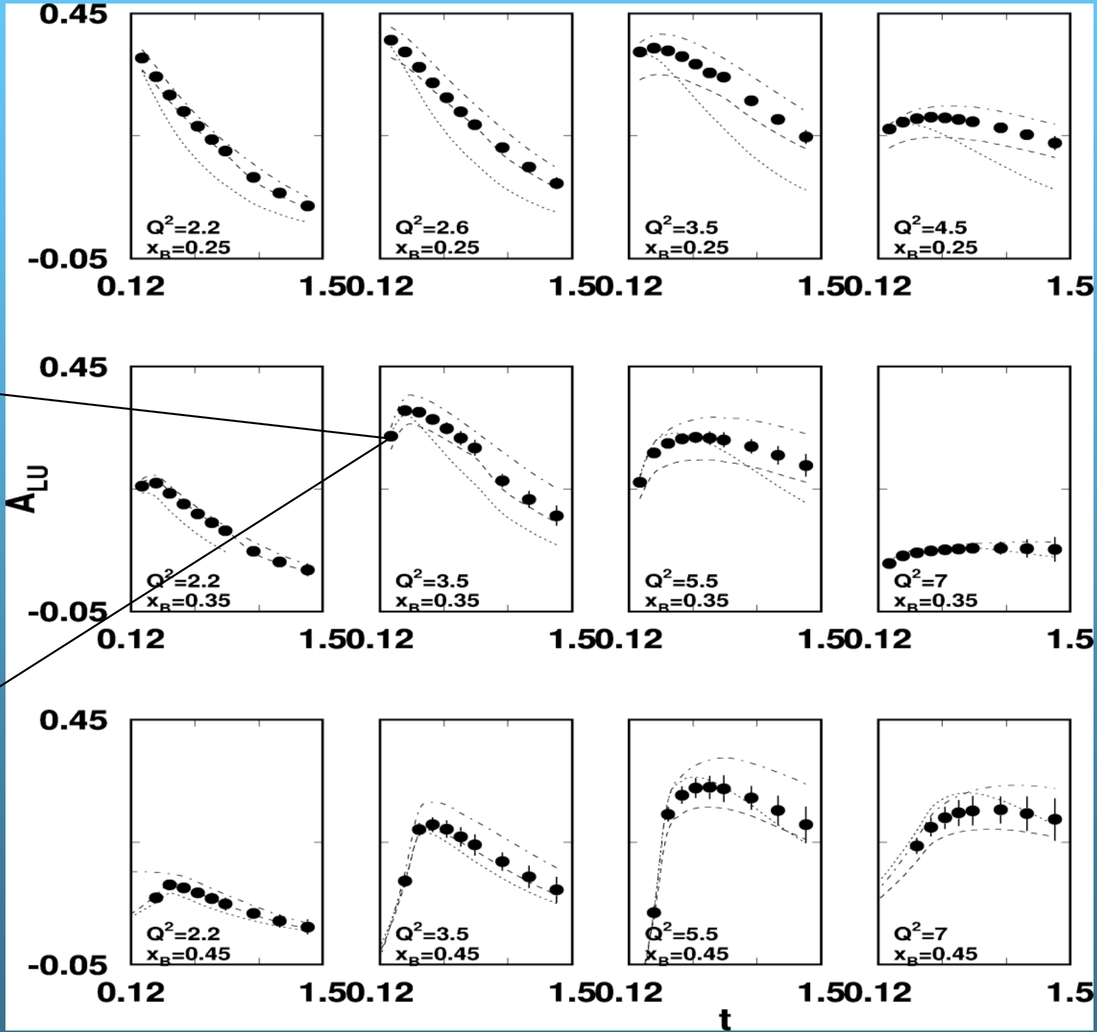
DVCS – Hall B

- 80 days of polarized beam on LH_2 target (BSA)
- $L = 10^{35}$ /cm²/s @ 11 GeV

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\Delta\sigma_{LU} \sim \sin\phi F_1 H + \ldots$





→ Extraction of H

Ground state and P11(1440) electrocouplings & quark model expectations

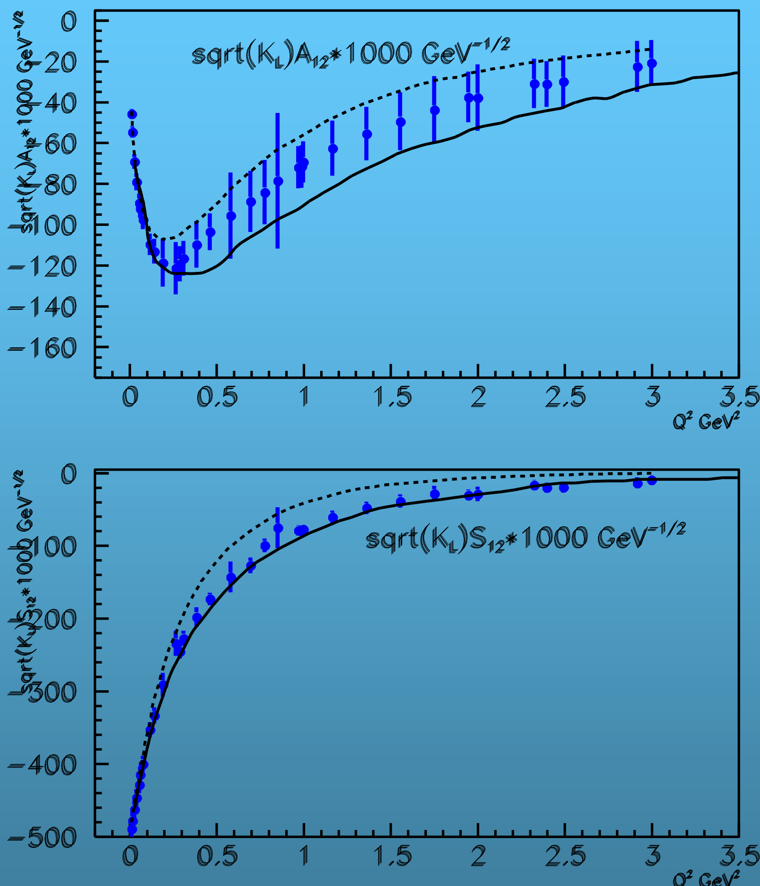
--------- S.Capstick light cone (LC) model

……… B.Metsch Bethe-Salpeter model

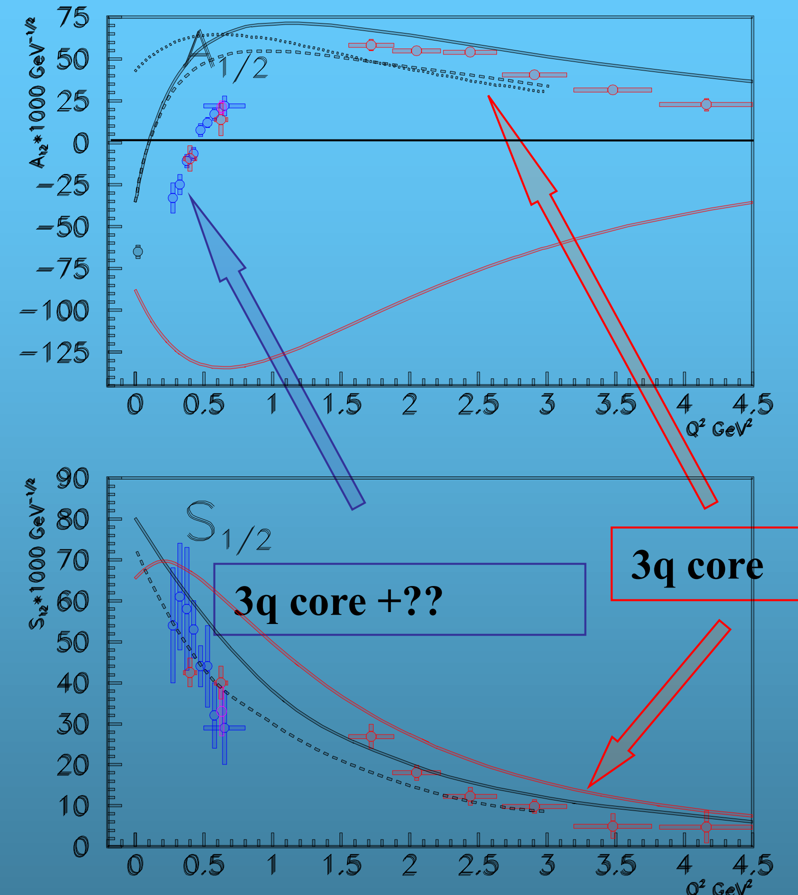
——— I.Aznauryan LC model

——— M.Giannini/ E.Santopinto hyper-centric CQM

Ground p state



P11(1440)



The studies of both the ground and excited nucleon structure are needed in order to understand how non-perturbative strong interactions create nucleons and how they emerge from QCD

The studies of excited nucleon state structure in meson electroproduction with CLAS

OEPVAYa Seminar (led by B.S.Ishkhanov) June 23, 4pm, Bld #19, room #215

Nucleon Resonance Studies with CLAS12

D. Arndt[4], H. Avakian[6], I. Aznauryan[11], A. Biselli[3], W.J. Briscoe[4], **V. Burkert[6]**,
V.V. Chesnokov[7], **P.L. Cole[5]**, D.S. Dale[5], C. Djalali[10], L. Elouadrhiri[6], G.V. Fedotov[7],
T.A. Forest[5], E.N. Golovach[7], **R.W. Gothe*[10]**, Y. Ilieva[10], B.S. Ishkhanov[7],
E.L. Isupov[7], **K. Joo[9]**, T.-S.H. Lee[1,2], **V. Mokeev*[6]**, M. Paris[4], K. Park[10],
N.V. Shvedunov[7], G. Stancari[5], M. Stancari[5], S. Stepanyan[6], **P. Stoler[8]**,
I. Strakovsky[4], S. Strauch[10], D. Tedeschi[10], M. Ungaro[9], R. Workman[4],
and the CLAS Collaboration

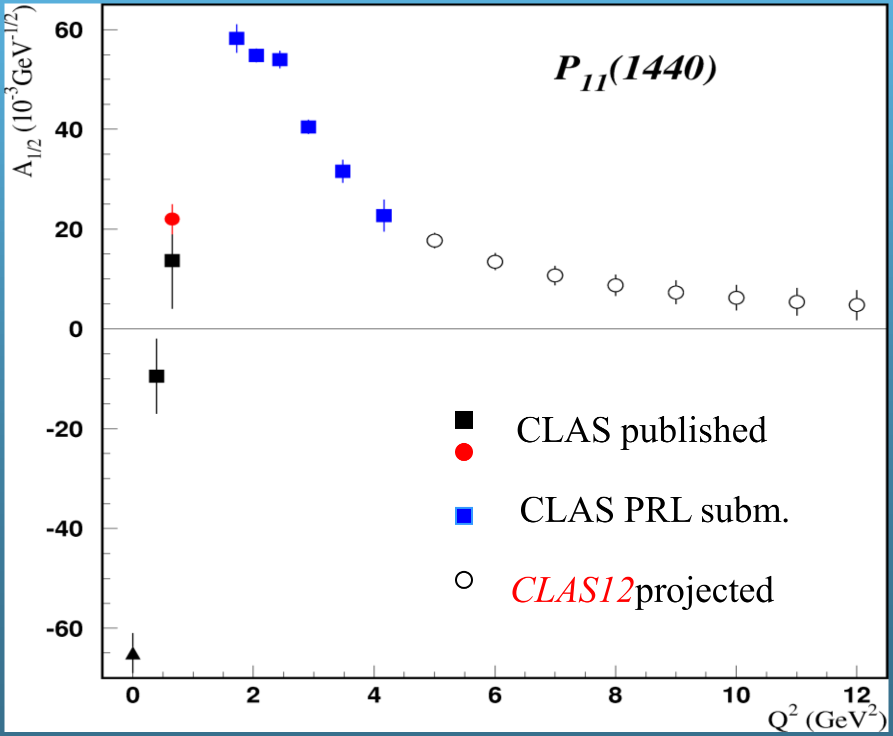
JLab PAC 34, January 26-30, 2009
Approved for 60 days beamtime

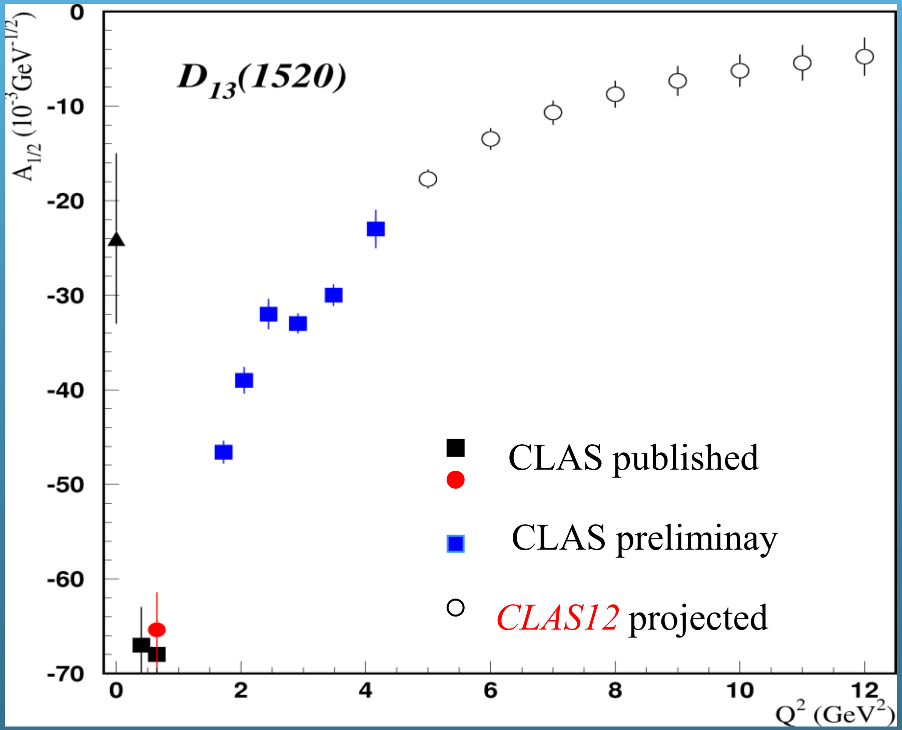
Argonne National Laboratory (IL,USA)[1], Excited Baryon Analysis Center (VA,USA)[2],
Fairfield University (CT, USA)[3], George Washington University (DC, USA)[4],
Idaho State University (ID, USA)[5], Jefferson Lab (VA, USA)[6],
Moscow State University (Russia)[7], Rensselaer Polytechnic Institute (NY, USA)[8],
University of Connecticut (CT, USA)[9], University of South Carolina (SC, USA)[10],
and Yerevan Physics Institute (Armenia) [11]

Spokesperson
Contact Person*

CLAS12 Projections for N* Transitions

For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the Q^2 regime of 5 GeV^2 to 10 GeV^2, where the quark degrees of freedom are expected to dominate. Our experimental proposal "*Nucleon Resonance Studies with CLAS12*" was approved by PAC34 for the full 60-day beamtime request. http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf.





Conclusions and outlook

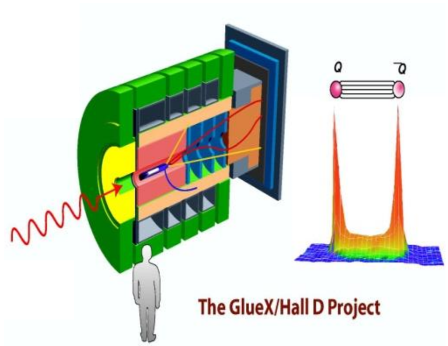
The 6 GeV Program provided:

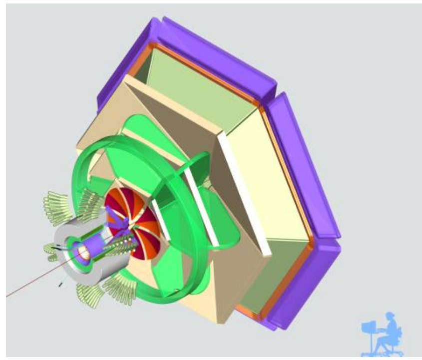
- comprehensive data on various inclusive structure functions , their moments and improve considerably our knowledge on parton distributions
- extensive information on N-N* transition amplitudes for several excited proton states at Q^2<5.0 GeV^2 for the first time determined with CLAS
- first information on various SIDIS polarization observables neded to access parton transverse distributions and quark orbital momentum in nucleons
- first data on DVCS asymmetries allowing us to access GPD structure functions

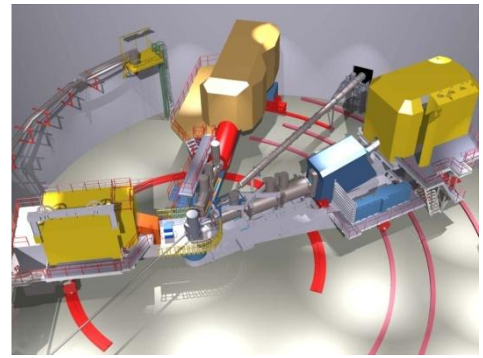
After 12 GeV Upgrade CLAS12 will be only facility foreseen worldwide, that will be capable to study nucleon structure at still fully unexplored area of 5.0<Q^2<14 GeV^2, where quark degrees of freedom are expected to dominate. Nucleon structure studies in this area will allow us to understand dressed quark interactions, that are responsible for nucleon formation and their emergence from QCD

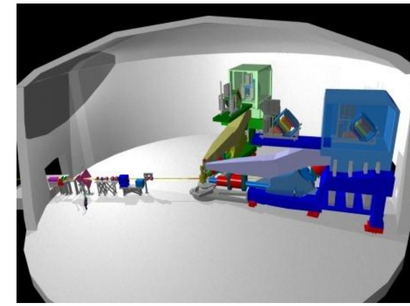
Backup

Overview of Technical Performance Requirements









<table>
<tr><th>Hall D</th><th>Hall B</th><th>Hall C</th><th>Hall A</th></tr>
<tr><td>excellent hermeticity</td><td>luminosity 10×10^{34}</td><td>energy reach</td><td>installation space</td></tr>
<tr><td>polarized photons</td><td>hermeticity</td><td>precision</td><td></td></tr>
<tr><td>E_γ~8.5-9 GeV</td><td colspan="3">11 GeV beamline</td></tr>
<tr><td>10^8 photons/s</td><td colspan="3">target flexibility</td></tr>
<tr><td colspan="2">good momentum/angle resolution</td><td colspan="2">excellent momentum resolution</td></tr>
<tr><td colspan="2">high multiplicity reconstruction</td><td colspan="2">luminosity up to 10^{38}</td></tr>
<tr><td colspan="4">particle ID</td></tr>
</table>

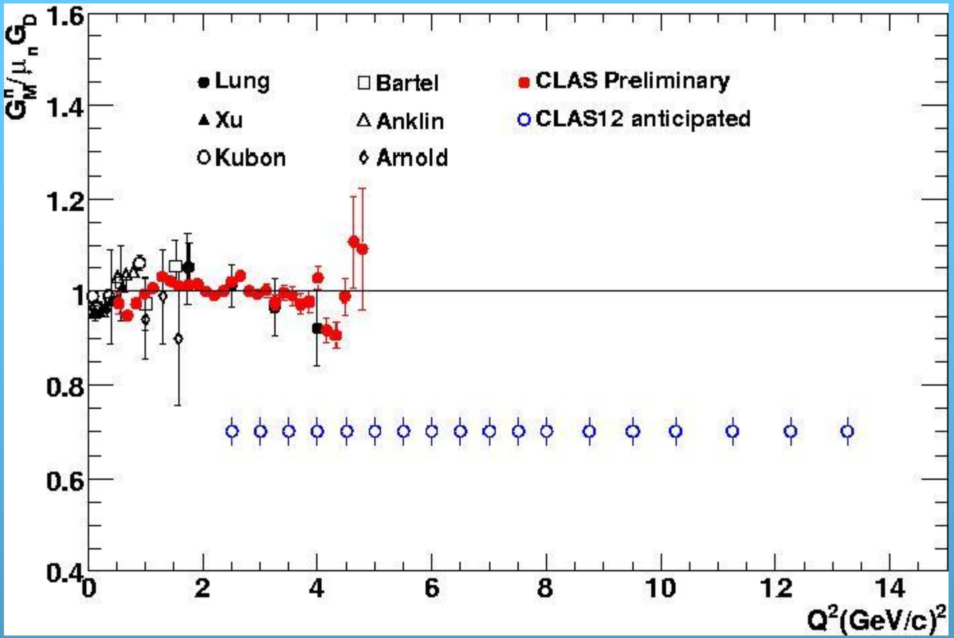
DOE critical decision schedule

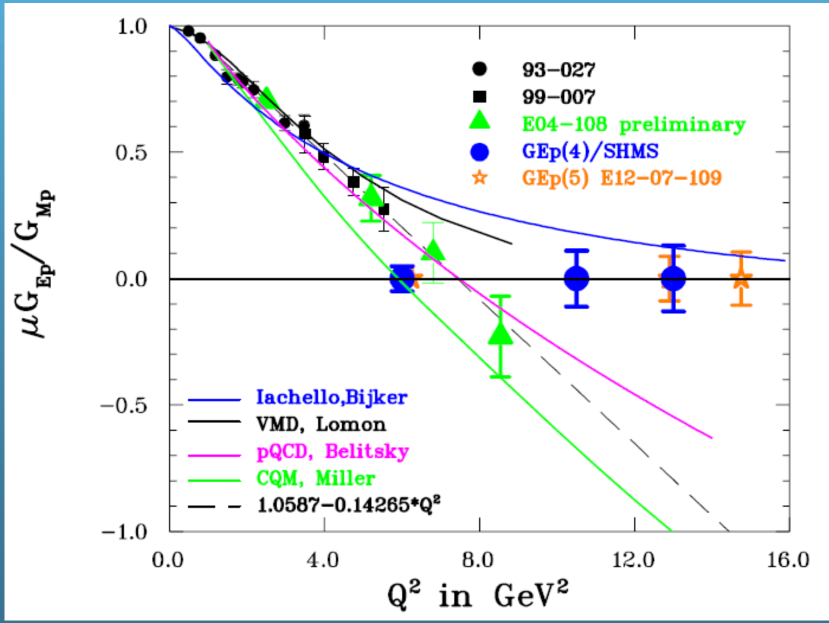
CD-0 Mission Need	MAR-2004 (A)
CD-1 Preliminary Baseline Range	FEB-2006 (A)
CD-2 Performance Baseline	NOV-2007 (A)
CD-3 Start of Construction	SEP-2008 (A)
CD-4A Accelerator Project Completion and Start of Operations	DEC-2014
CD-4B Experimental Equipment Project Completion and Start of Operations	JUN-2015

Now split in two to ease transition into operations phase

(A) = Actual Approval Date

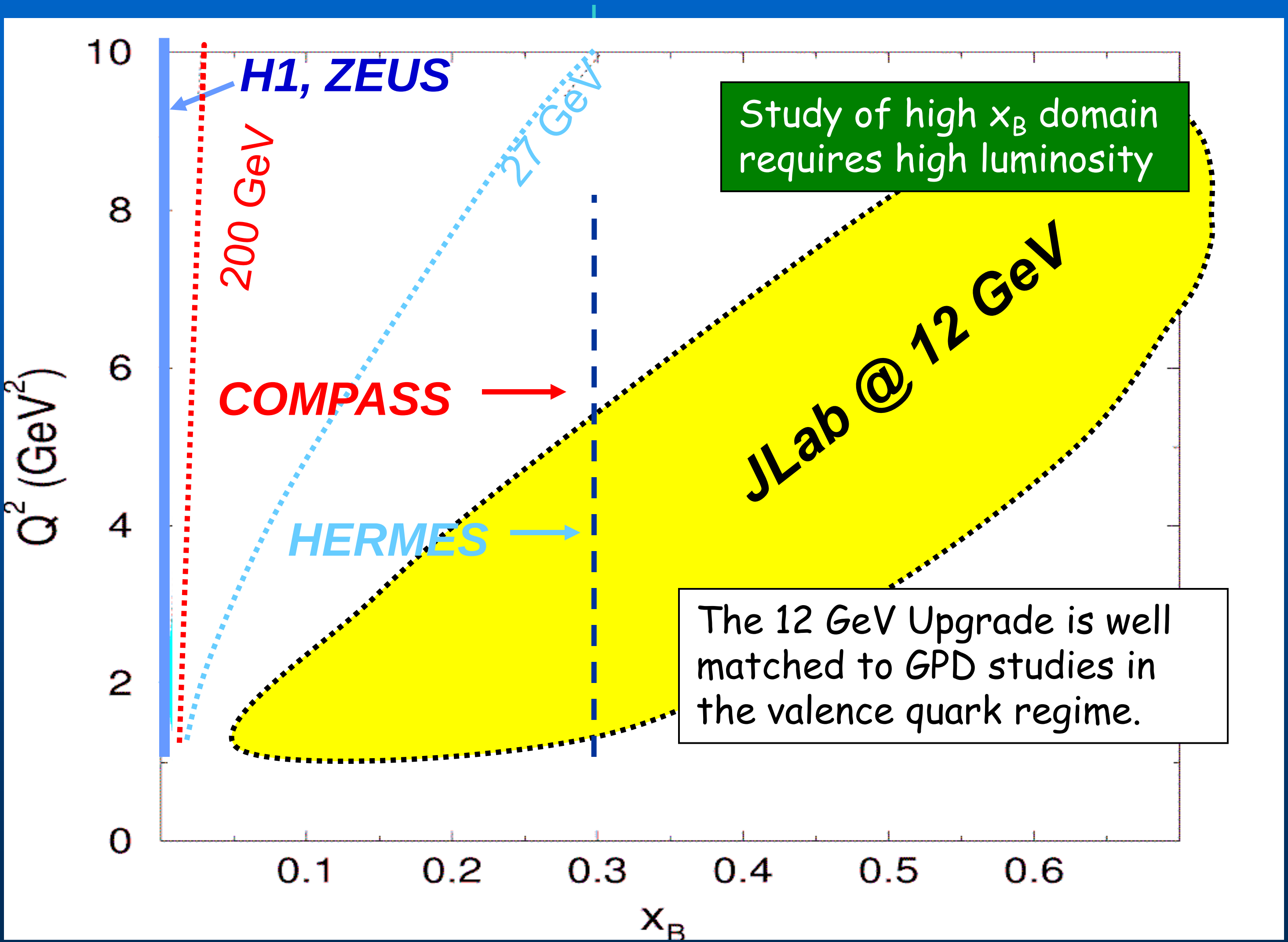
Measurements of Form Factors





E12-07-109 (Hall A)
E12-07-104 (Hall B)
PR12-09-001 (Hall C)

Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



DVCS and GPDs