$\vec{H}\vec{D}$ice

Novel Physics with Frozen-spin Polarized Solid Hydrogen

A.M. Sandorfi

Thomas Jefferson National Accelerator Laboratory (JLab)

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Q. what degrees of freedom generate the nucleon's spectrum ?
  - $\vec{\gamma} + \vec{H}\vec{D}$ "complete" experiments at JLab (2010-2011)

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Q. what degrees of freedom generate the nucleon's spectrum ?
- $\vec{\gamma}+\vec{H}\vec{D}$ "complete" experiments at JLab (2010-2011)

Q. can we construct a tomographic image of the proton ?
- Generalized Parton Distributions from $\vec{e}+\vec{H}\vec{D}$ (2011)

Polarizing HD: *the rotational levels of the solid hydrogens*

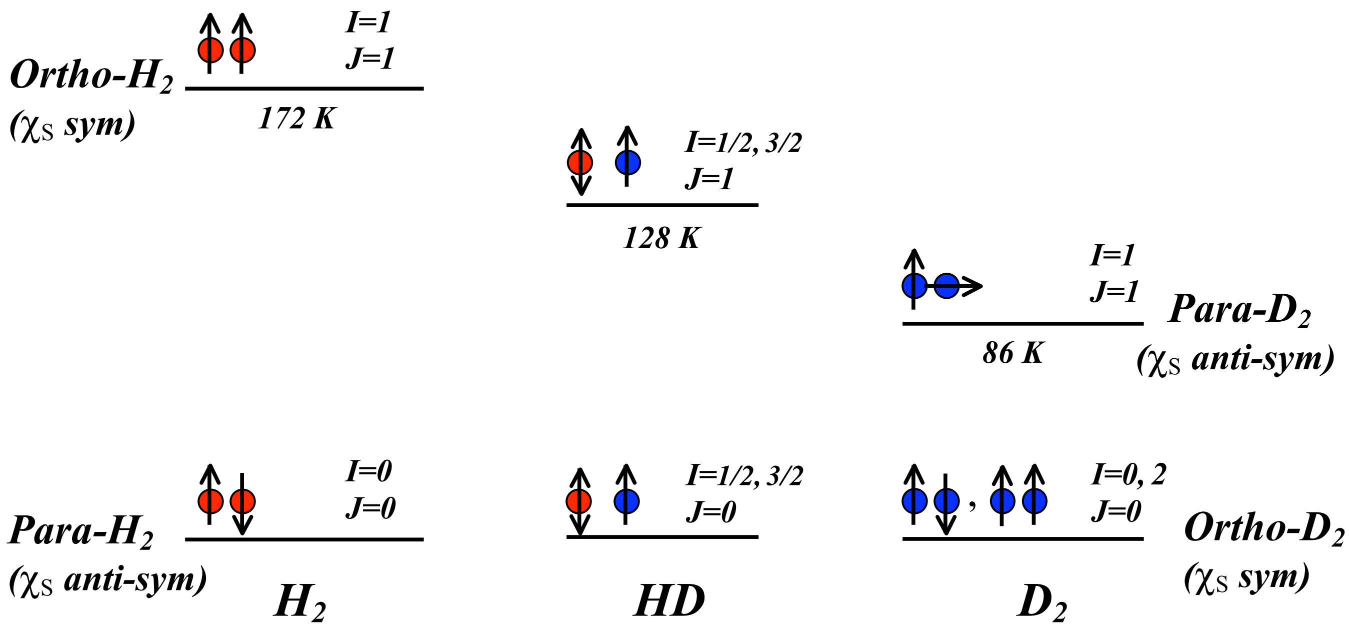


Figure. The relative energy spacing of the low-lying nuclear spin (*I*) and molecular orbital angular momentum (*J*) levels in H_2, HD and D_2. The symmetries of the nuclear spin wavefunction (χ_S) are indicated.

Polarizing options: - *2 electrons paired in a 1s molecular orbital* ✗

- *nuclear spin I≠0 ⇔ couples to B field* ✔

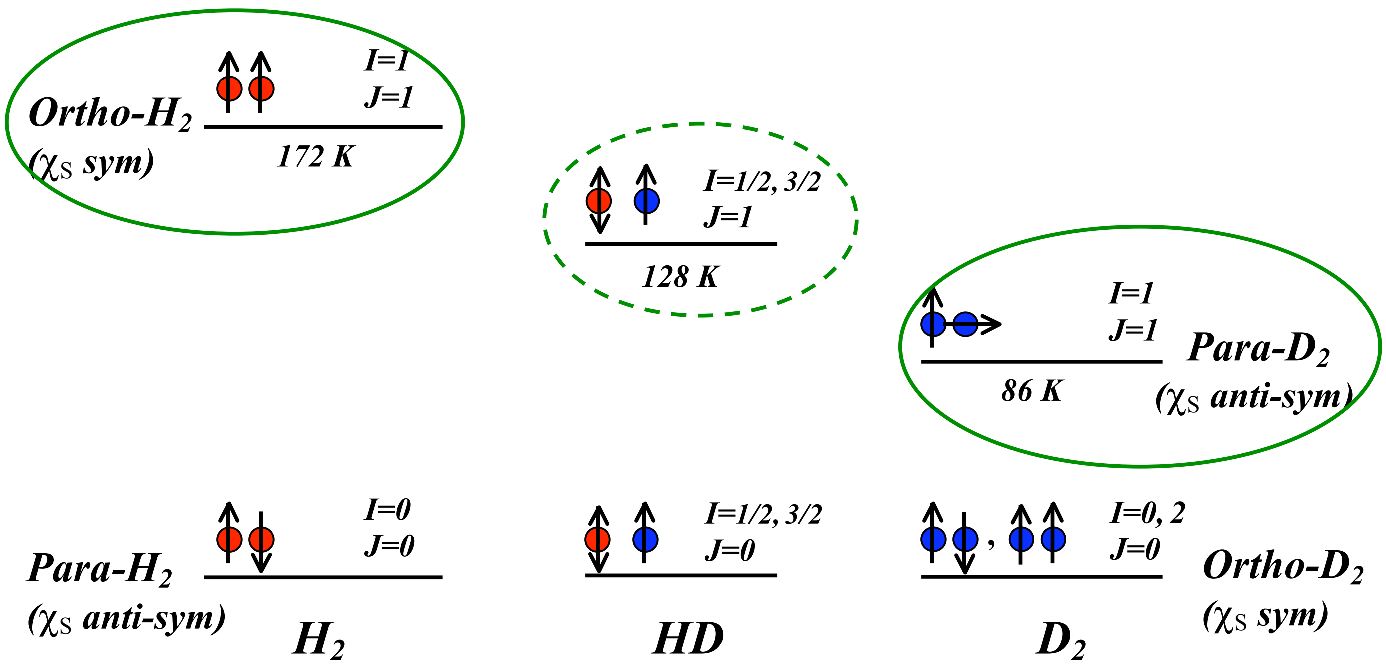
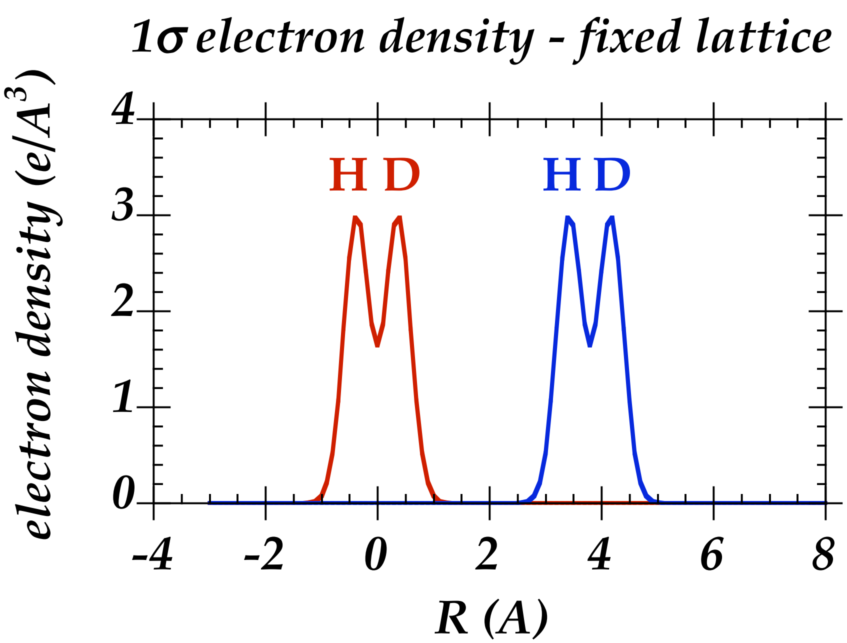


Figure. The relative energy spacing of the low-lying nuclear spin (*I*) and molecular orbital angular momentum (*J*) levels in H_2, HD and D_2. The symmetries of the nuclear spin wavefunction (χ_S) are indicated.

Dimensions in solid hydrogen

intermolecular HD spacing = 0.74 A

Lattice spacing = 3.79 A

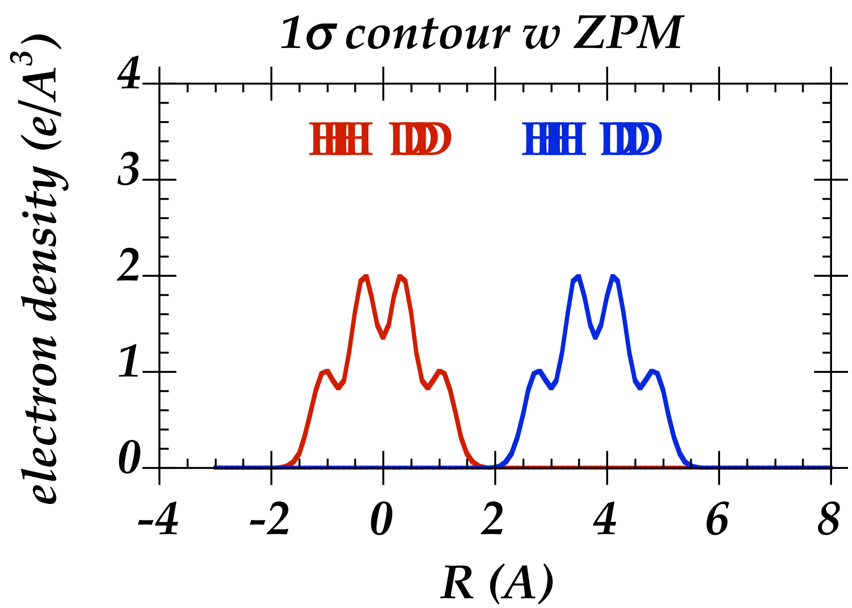


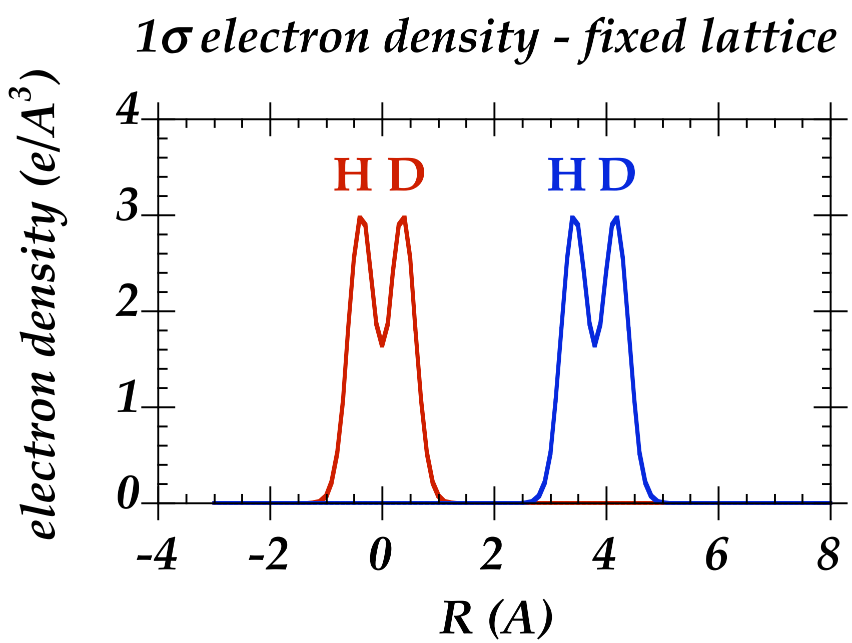
Dimensions in solid hydrogen

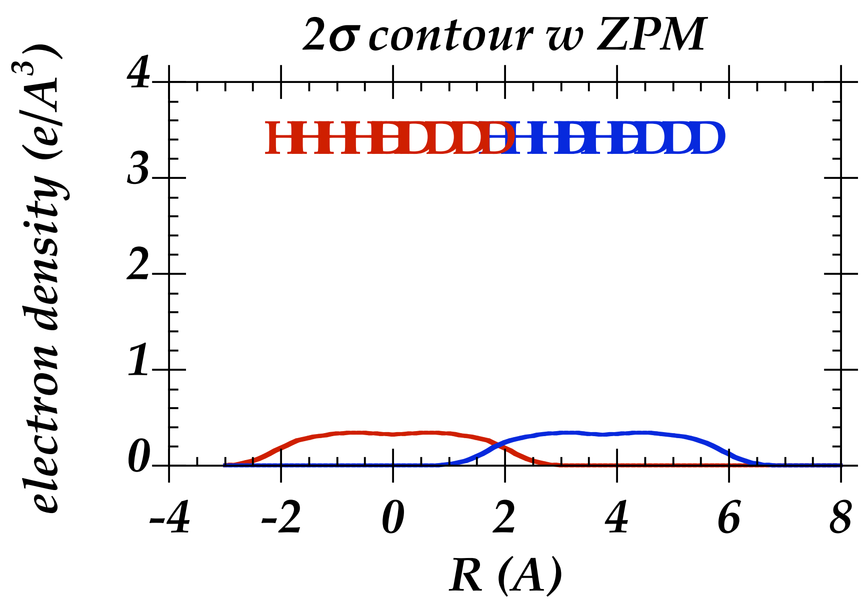
intermolecular HD spacing = 0.74 A

Lattice spacing = 3.79 A

but,
Zero-point motion = 0.68 A (rms)





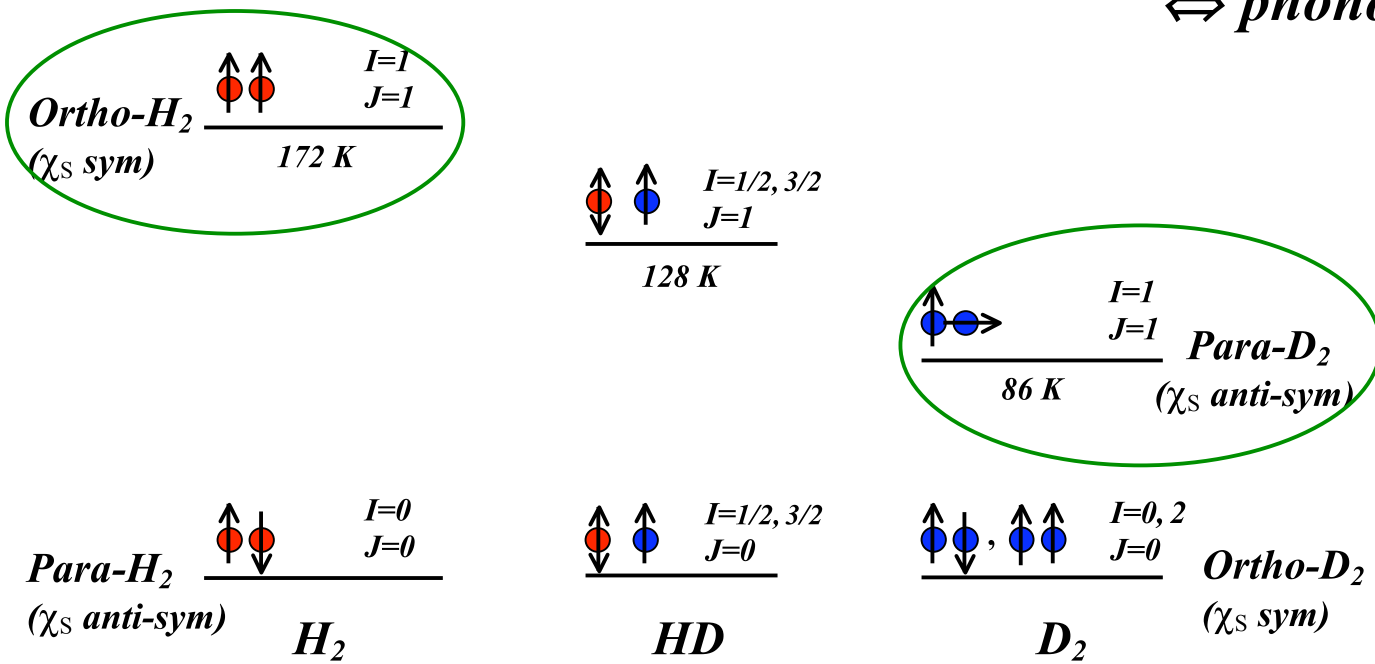


Necessary requirement: *removal of spin-heat*

- ***J=1 levels: large electric Quadrupole field***

  ⇔ creates fluctuating electric dipoles ⇔ eQQ ∝ $1/r^3$

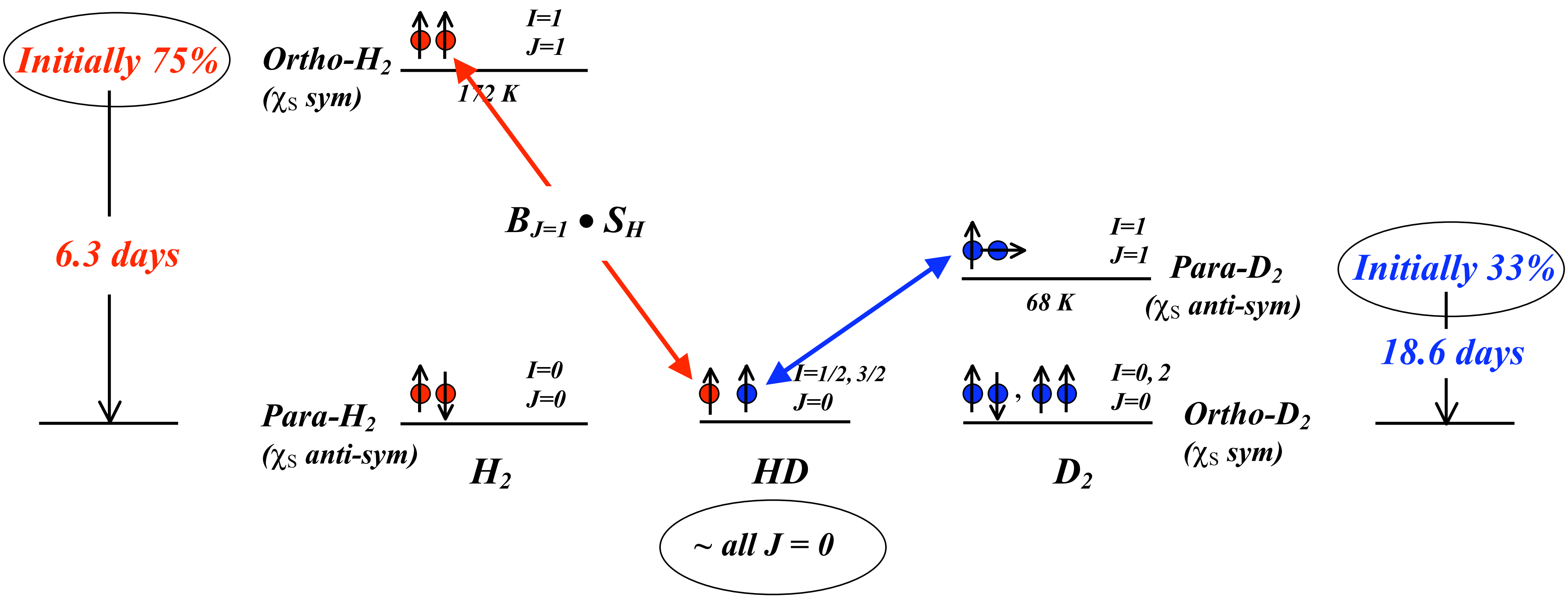
  ⇔ phonons



- ***J=0 levels: spherically symmetric***

  ⇔ no average external fields

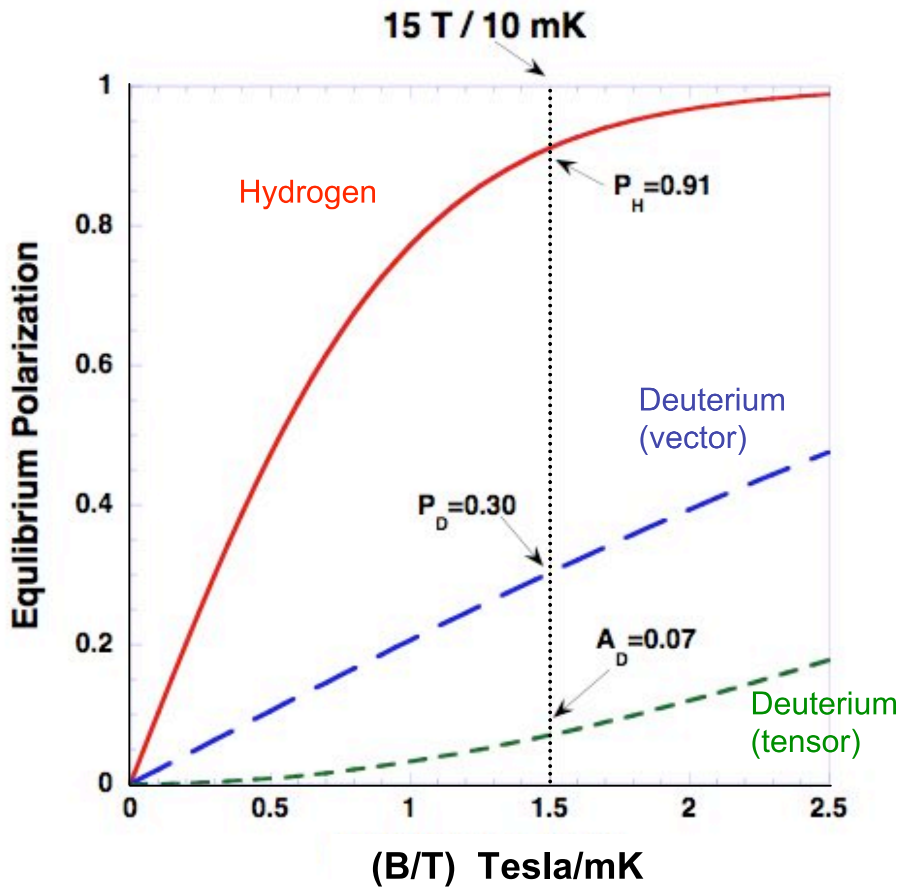
External Magnetic field rapidly aligns Ortho-H_2 and Para-D_2 then spin-exchanges with H and D in HD



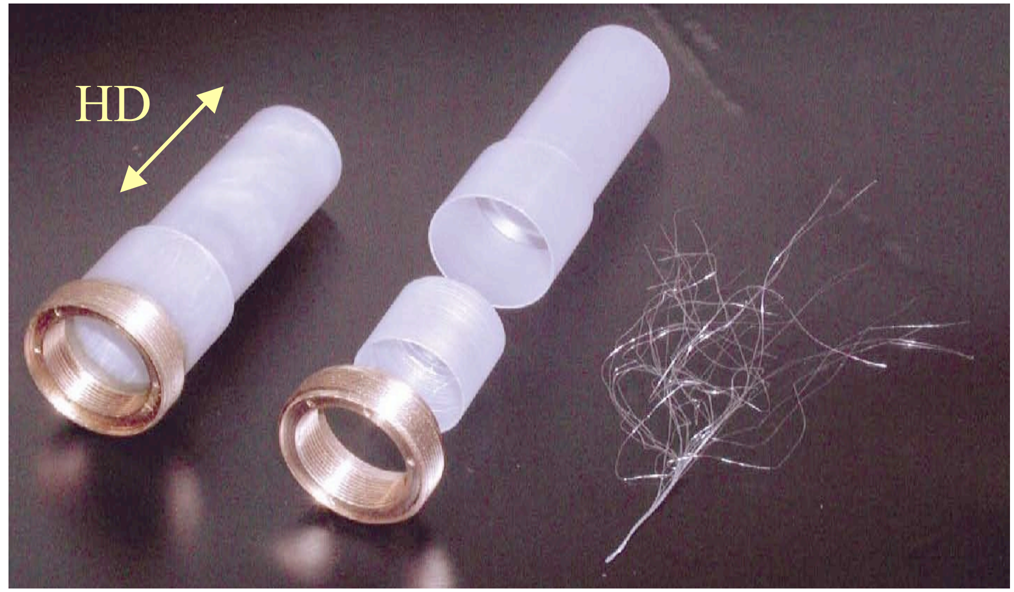
- *relaxation switch – A. Honig, Phys. Rev. Lett.* ***19*** *(1967).*

HD field/low-temp Polarization

- align spins with high B (15 Tesla) and low T (~12 mK)
- polarize small concentrations of J=1 H_2 and D_2
- o-H_2 and p-D_2 spin-exchanges and polarizes HD
- wait for J=1 H_2 and D_2 to decay



Ortho ⇔ para decays generate heat, which must be removed to polarize



- ***HD condensed into target cell with ~ 2000 50 μm Al cooling wires soldered into 60 holes in copper cooling ring***

- ***Composition of a standard target cell with 4 cm of HD (0.9 moles):***

Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

HD polarize/run sequence:

- condense HD gas → liquid → solid in 2-4 ^{o}K dewar ; *calibrate NMR*

- transfer to dilution refrigerator
  - polarize at 15 tesla and 12-16 mK
  - hold for 2-6 months, waiting for ortho-H_2 and para-D_2 to decay away

- transfer to 2-4 K dewar for polarization measurement

- transfer to In-Beam-Cryostat
  - hold target for experiment at 0.2 – 0.7 ^{o}K and ~0.1 to 0.9 tesla

  ⇒ *Spin-relaxation (T_1) decay times ~ a year*

- transfer to 2-4 K dewar for post-experiment polarization measurement

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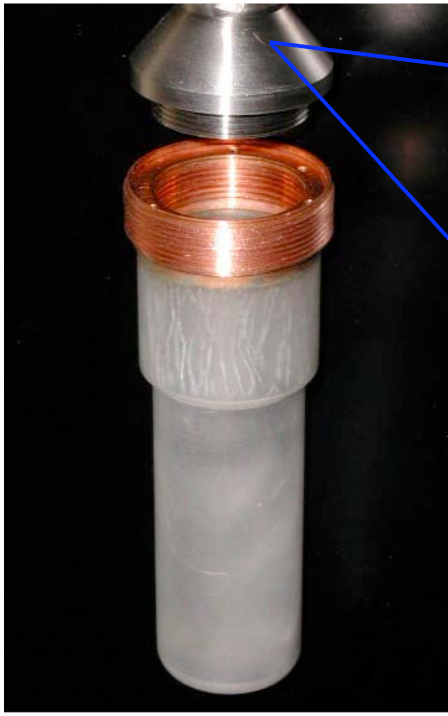
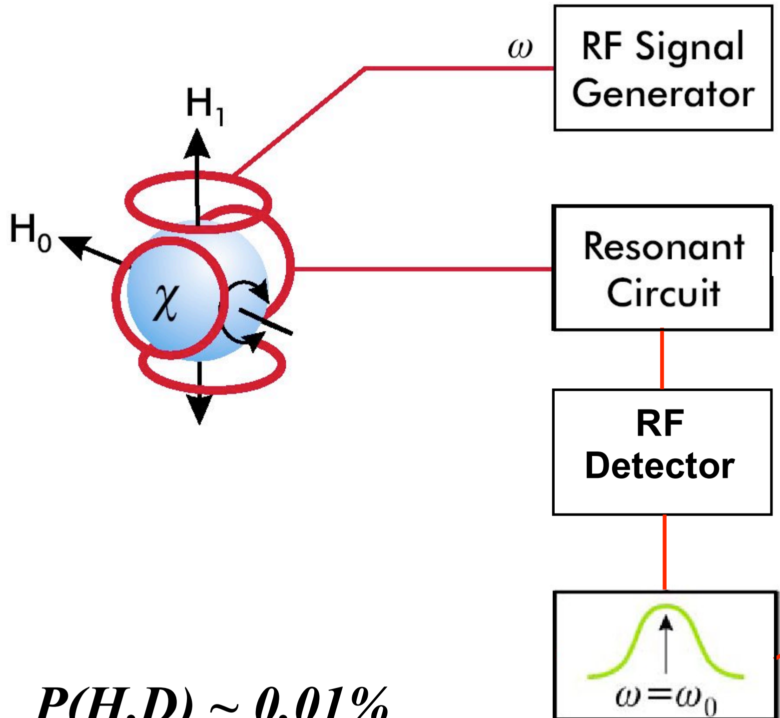
- ***inject HD gas through capillary tool and condense in Production Dewar (PD);***

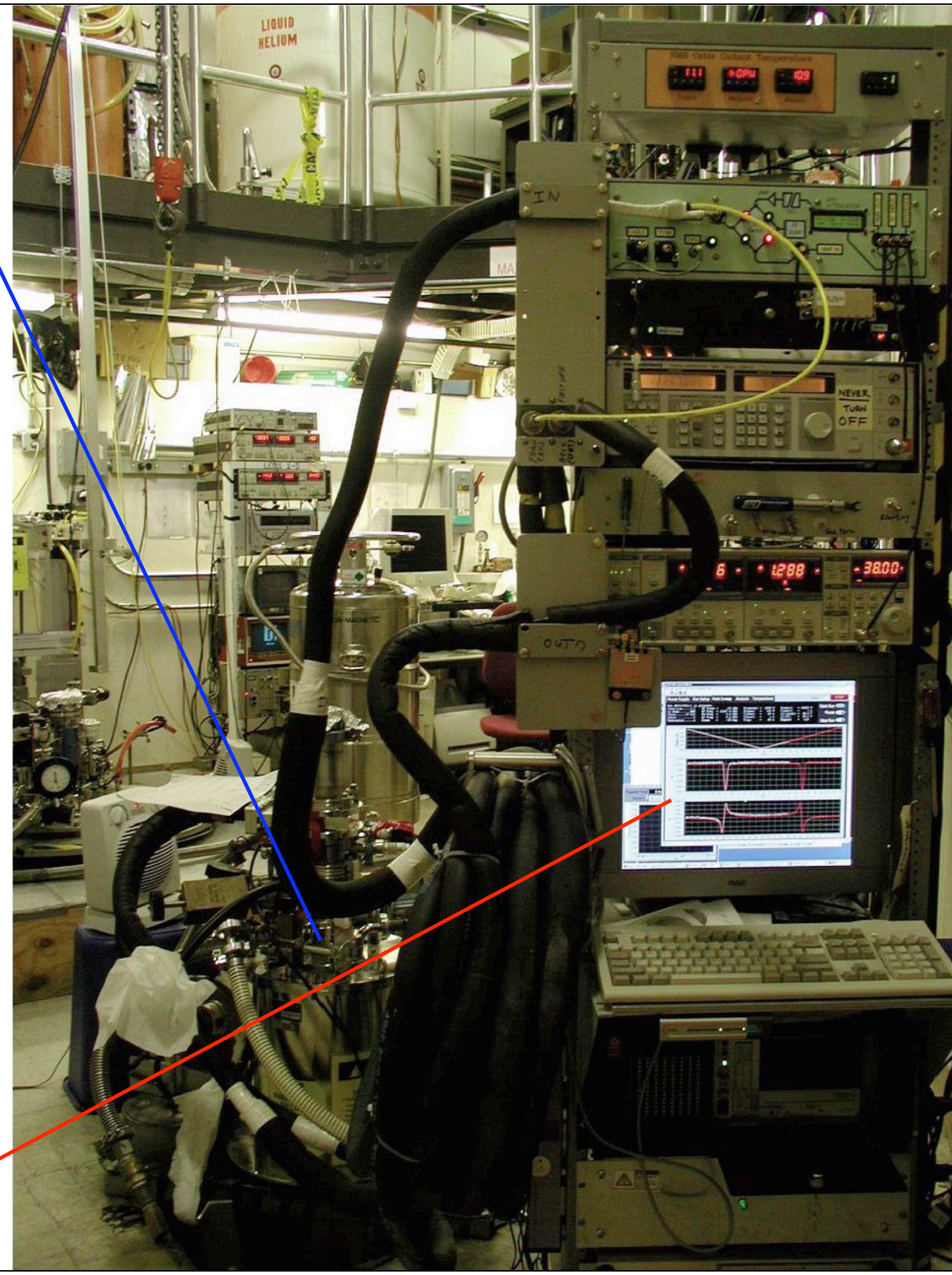


pass through triple-point (~127 mbar at 4K) to form a quasi-crystal;
release from injection tool;
cool to 2K

- ***Polarization monitoring***
  - in a 2K/4K
  Production Dewar (PD)

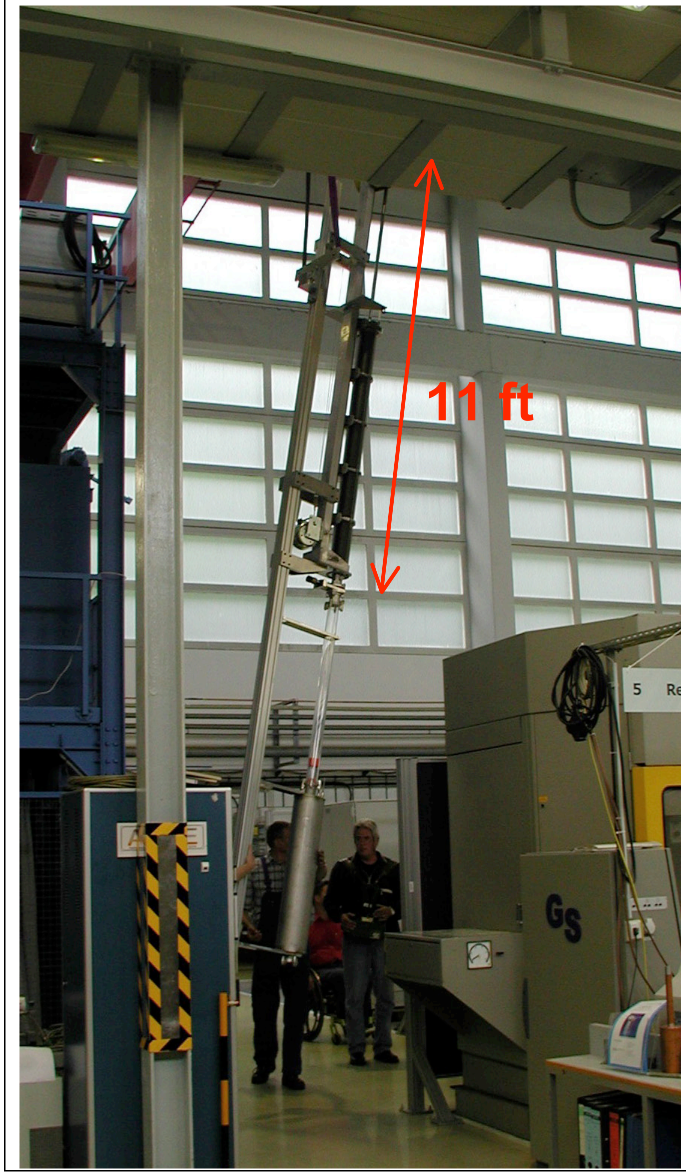
- ***thermal equilibrium NMR calibration***

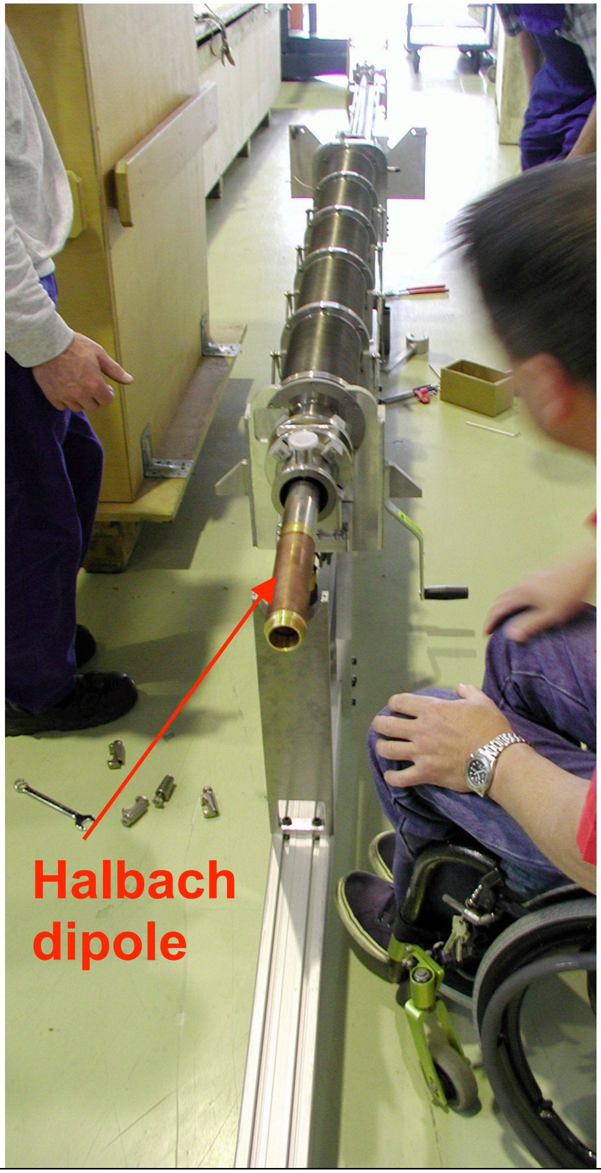




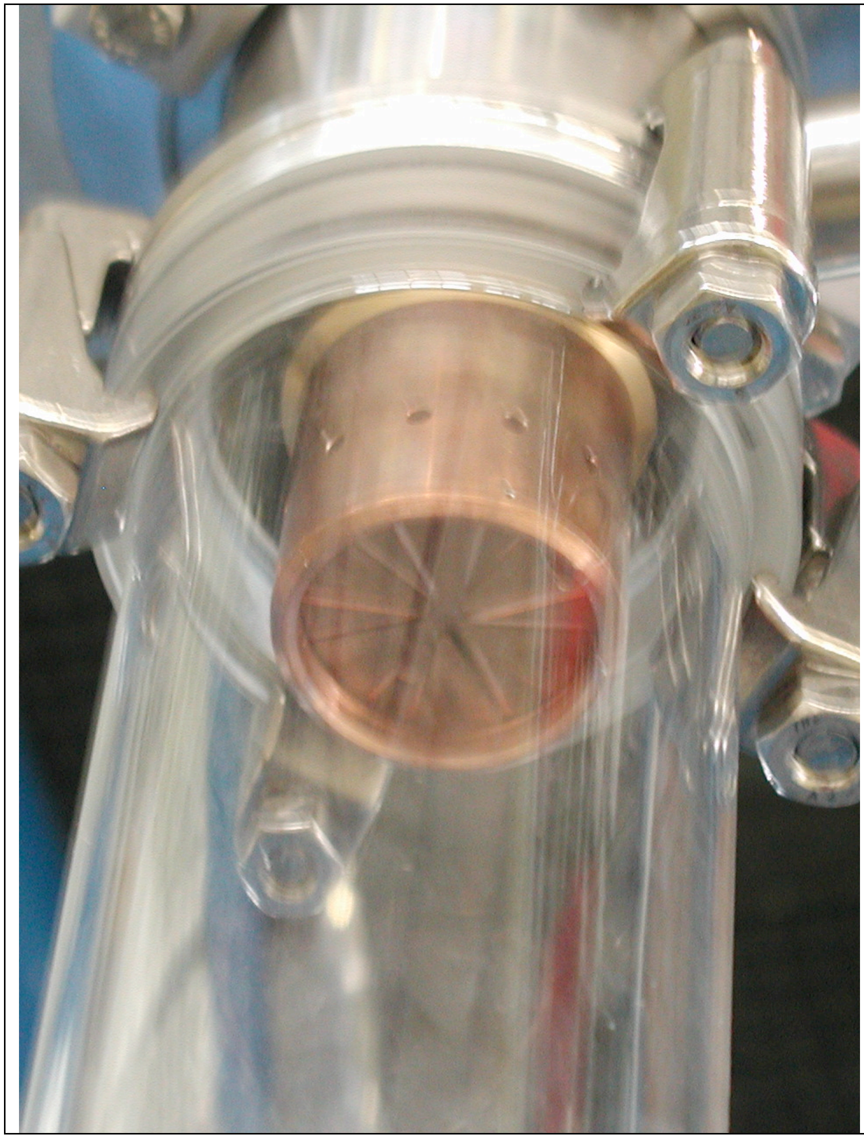
P(H,D) ~ 0.01%

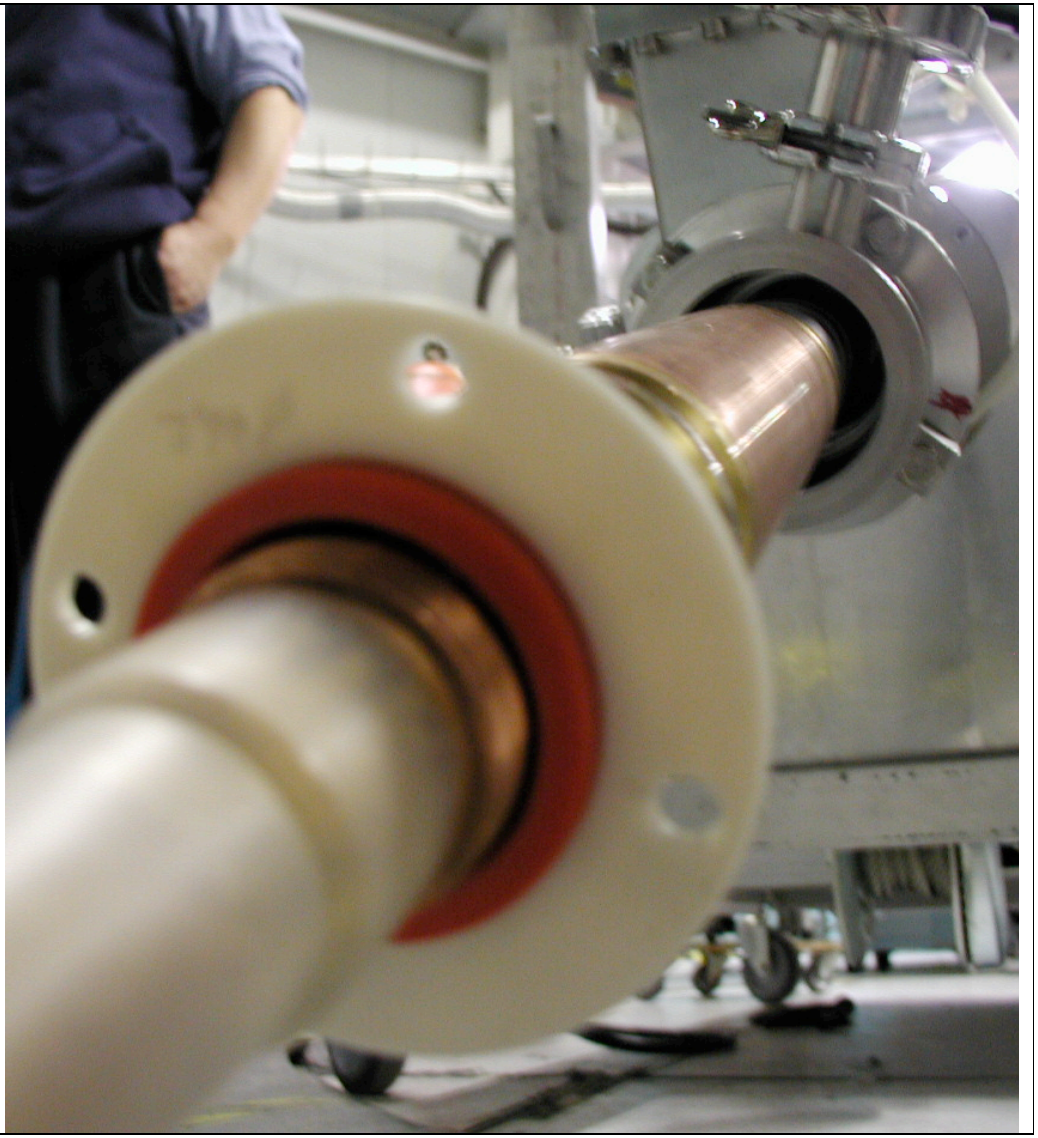
BNL-Jülich Transfer-Cryostat - *moves solid HD between dewars*





TC 77 K Radiation shutter





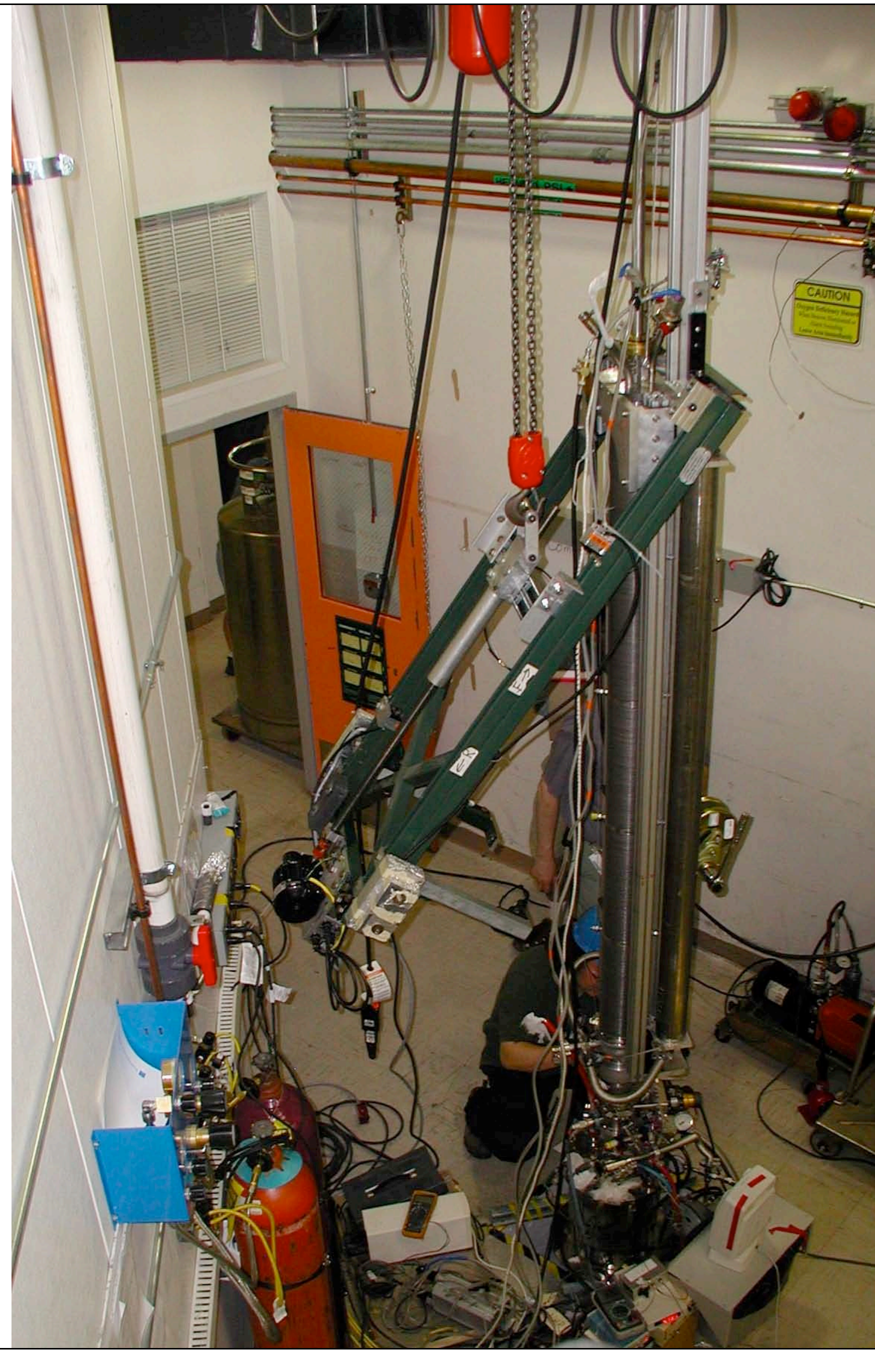
- *extract from PD with 2K transfer Cryostat (TC), containing 0.12 T Halbach rare-earth dipole*

  - transfers are most problematic steps, requiring lots of prep

  - alignment: TC turns a 1” thread on the end of an 11 ft screw-driver

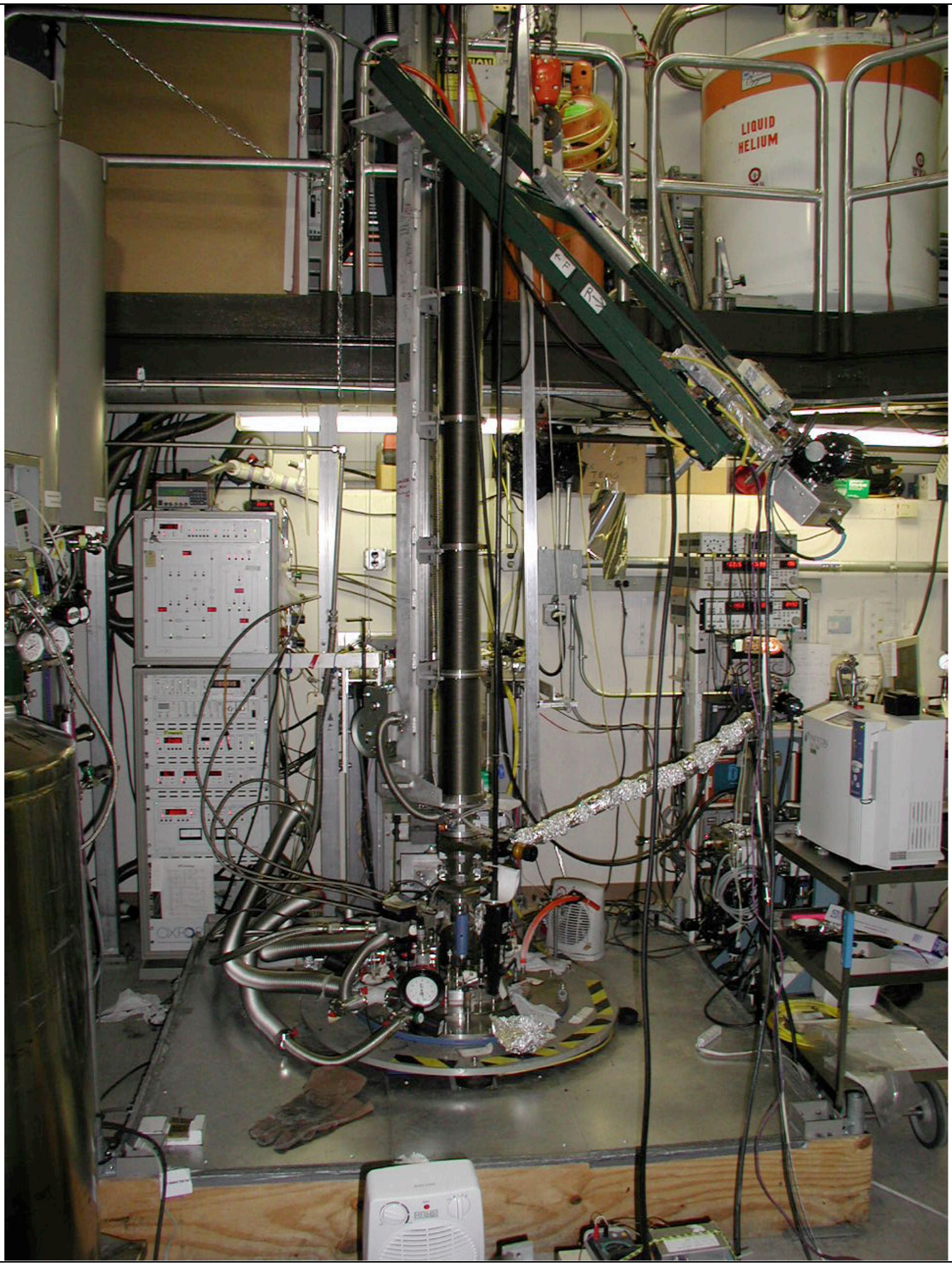
  - 77 K radiation shutter leaves are few inches from 2K HD and are crucial

  - failure rate ~ 1/12 transfers



- ***transfer to dilution refrigerator (DF);***
  polarize at high field (15 T) and low temp (~12 mK);
  hold there for >2 months

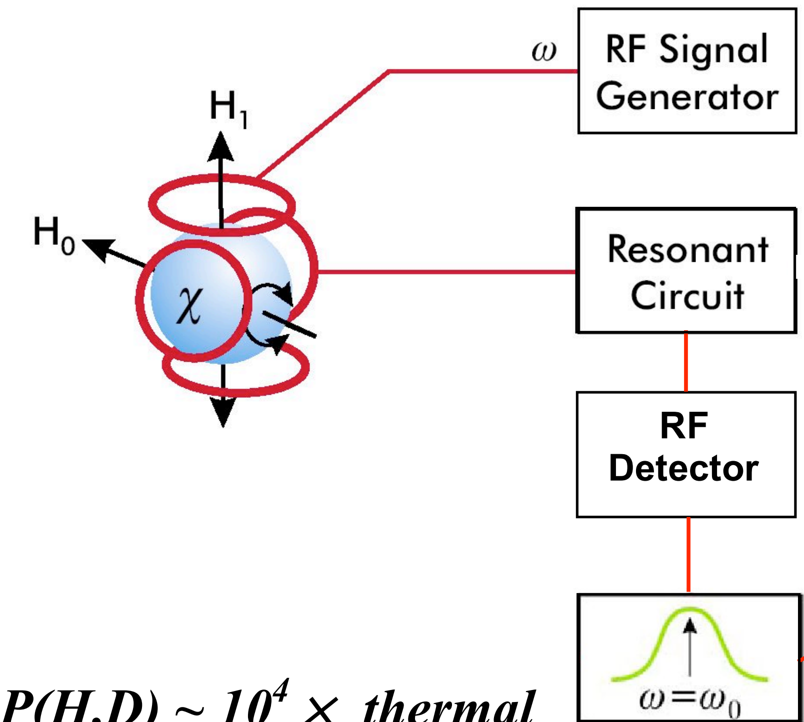
  - DF and PD suspended in pits so that top flanges are at same height



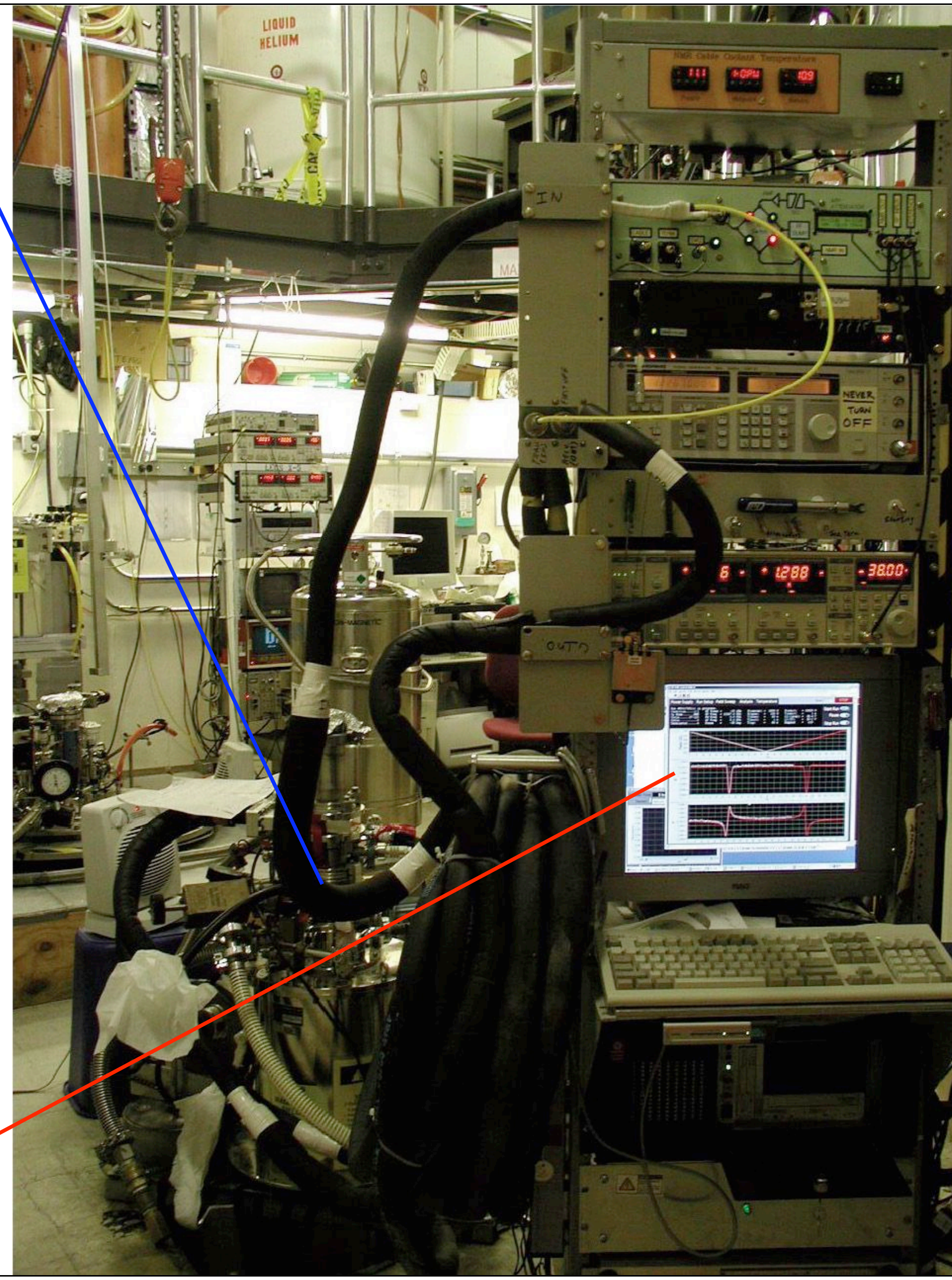
- ***transfer from DF back to PD to measure frozen-spin polarization***

- ***Transfer back to to Production Dewar (PD)***

- ***NMR***
  - measure frozen-spin polarization



P(H,D) ~ 10^4 × thermal



- ***transfer to In-Beam Cryostat (IBC);***

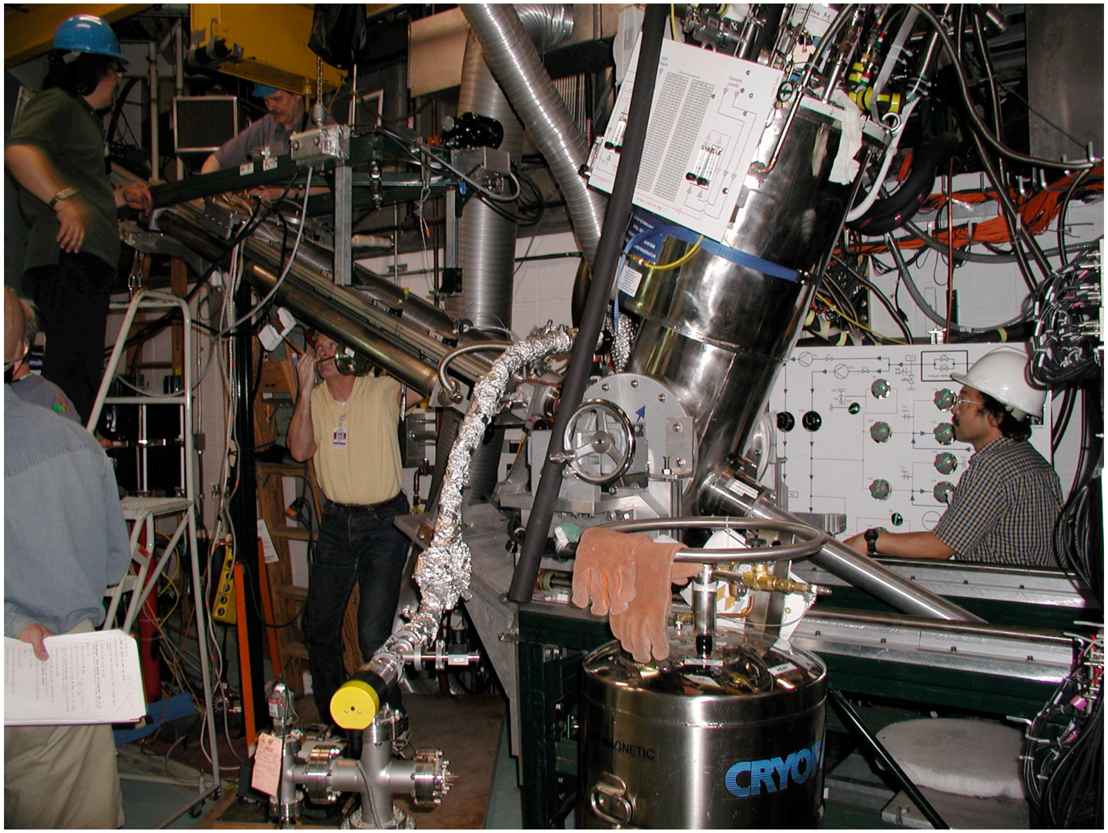
  - IBC tipped > 25 ^{o}

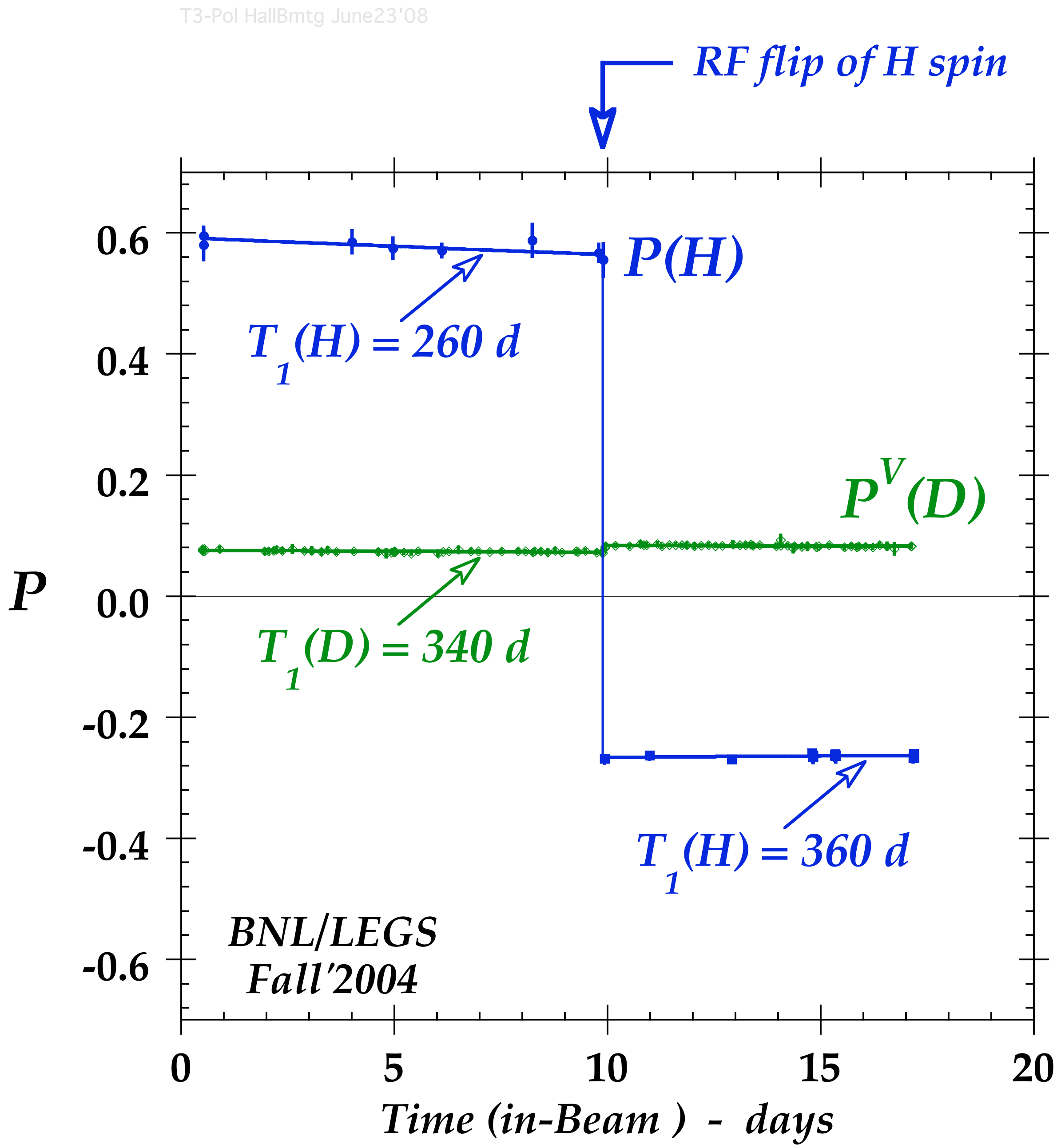
  - measure NMR in IBC;

  - transfer to PD , measure transfer loss;

  - transfer back to IBC for experiment;

eg. transfer to IBC in BNL/LEGS




T3-Pol HallBmtg June23'08
RF flip of H spin
P(H)
T1(H) = 260 d
P^V(D)
T1(D) = 340 d
T1(H) = 360 d
BNL/LEGS
Fall'2004
P
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
5
10
15
20
Time (in-Beam) - days

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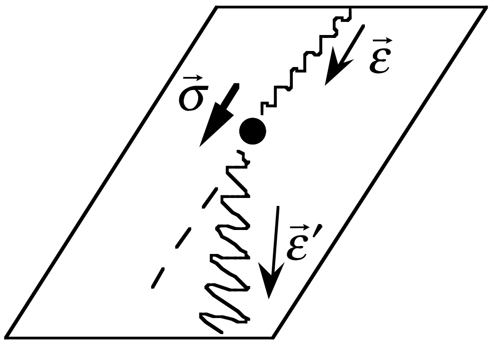
Forward elastic (Compton) photon scattering

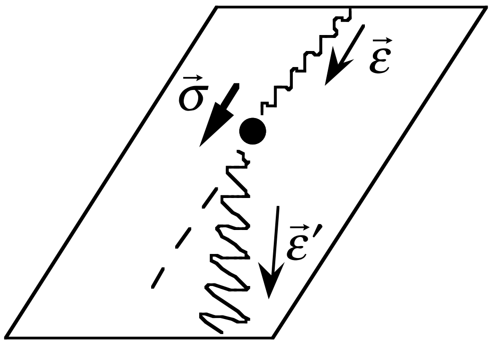


as energy $\omega \rightarrow 0$, angle $\theta \rightarrow 0$

$$A(\omega) = f(\omega^2)\vec{\varepsilon}' \cdot \vec{\varepsilon} + i\omega\, g(\omega^2)\vec{\sigma} \cdot (\vec{\varepsilon}' \times \vec{\varepsilon})$$

Gell-Mann, Goldberger, Thirring, PR95(54)

Forward elastic (Compton) photon scattering



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Gell-Mann, Goldberger, Thirring, PR95(54)

Thompson = $-\alpha / m$

$$f(\omega^2) = f(0) + f'(0)\ \omega^2 + O(\omega^4)$$

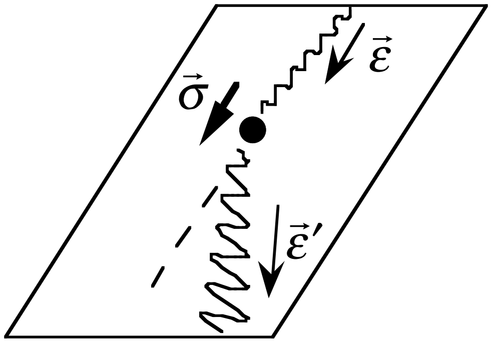
charge polarizability

magnetic = $-\alpha\, \kappa^2 / 2m^2$

$$g(\omega^2) = g(0) + g'(0)\ \omega^2 + O(\omega^4)$$

spin polarizability

Forward elastic (Compton) photon scattering



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$$g(\omega^2) = g(0) + g'(0)\ \omega^2 + O(\omega^4)$$

spin polarizability

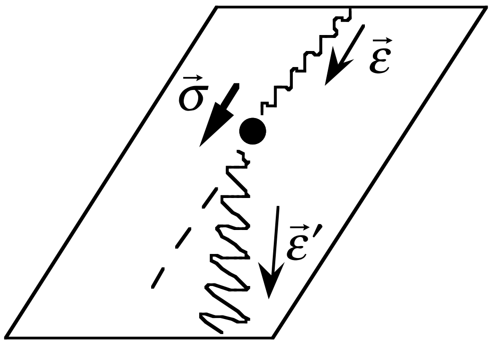
GGT: σ(reaction)

⇓

$A(\gamma,\gamma)$

$$\frac{1}{4\pi^2}\int_{\omega_o}^{\infty} \frac{\sigma_A - \sigma_P}{\omega}\, d\omega = g(0) - g(\infty)$$

Forward elastic (Compton) photon scattering



as energy $\omega \to 0$*, angle* $\theta \to 0$

$$A(\omega) = f(\omega^2)\vec{\varepsilon}' \cdot \vec{\varepsilon} + i\omega\, g(\omega^2)\vec{\sigma} \cdot (\vec{\varepsilon}' \times \vec{\varepsilon})$$

Gell-Mann, Goldberger, Thirring, PR95(54)

Thompson $= -\alpha / m$ ↕

$$f(\omega^2) = f(0) + f'(0)\ \omega^2 + O(\omega^4)$$

↕ *charge polarizability*

magnetic $= -\alpha\,\kappa^2 / 2m^2$ ↕

$$g(\omega^2) = g(0) + g'(0)\ \omega^2 + O(\omega^4)$$

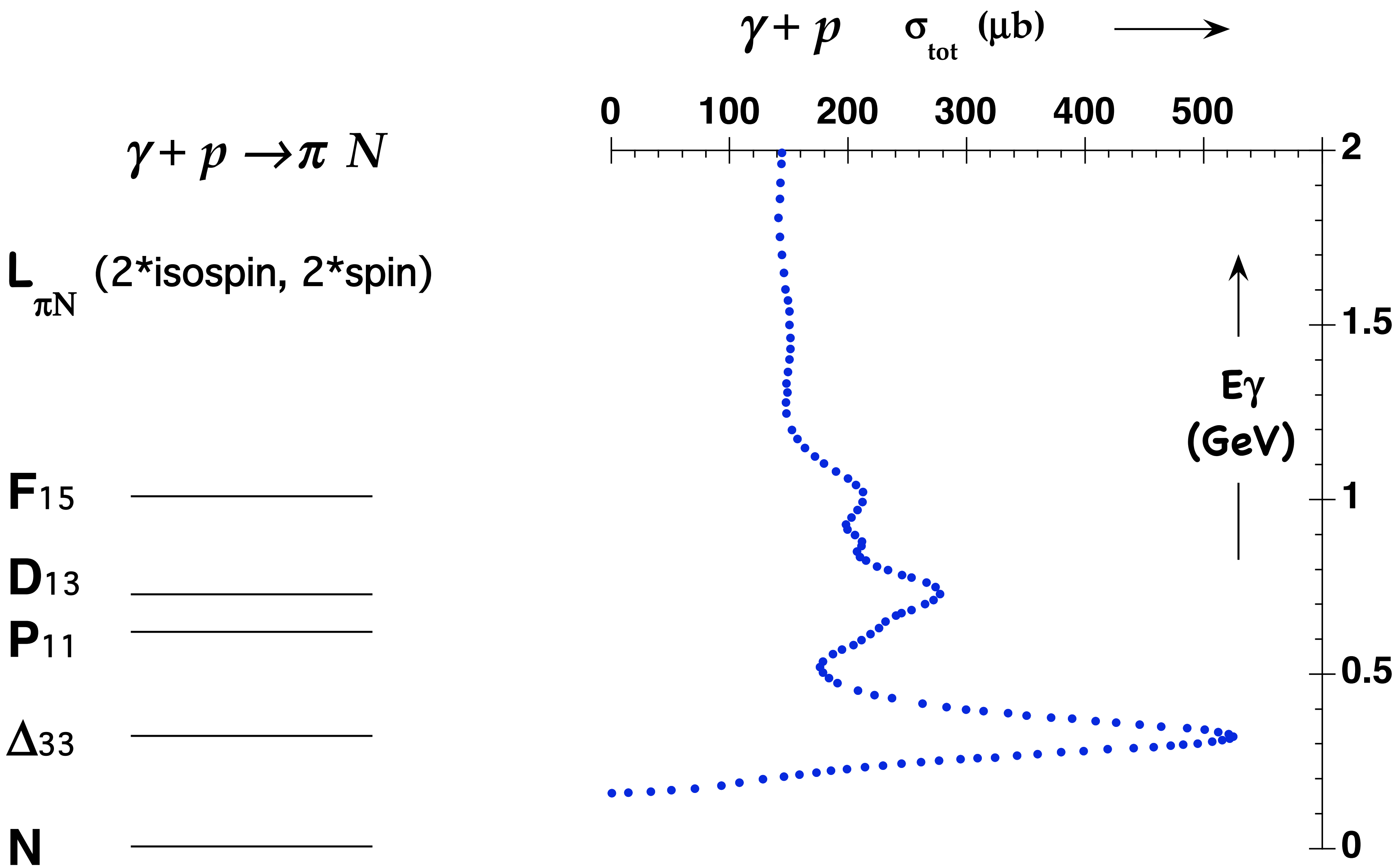
↕ *spin polarizability*

GGT: σ(reaction)
⇓
$A(\gamma,\gamma)$

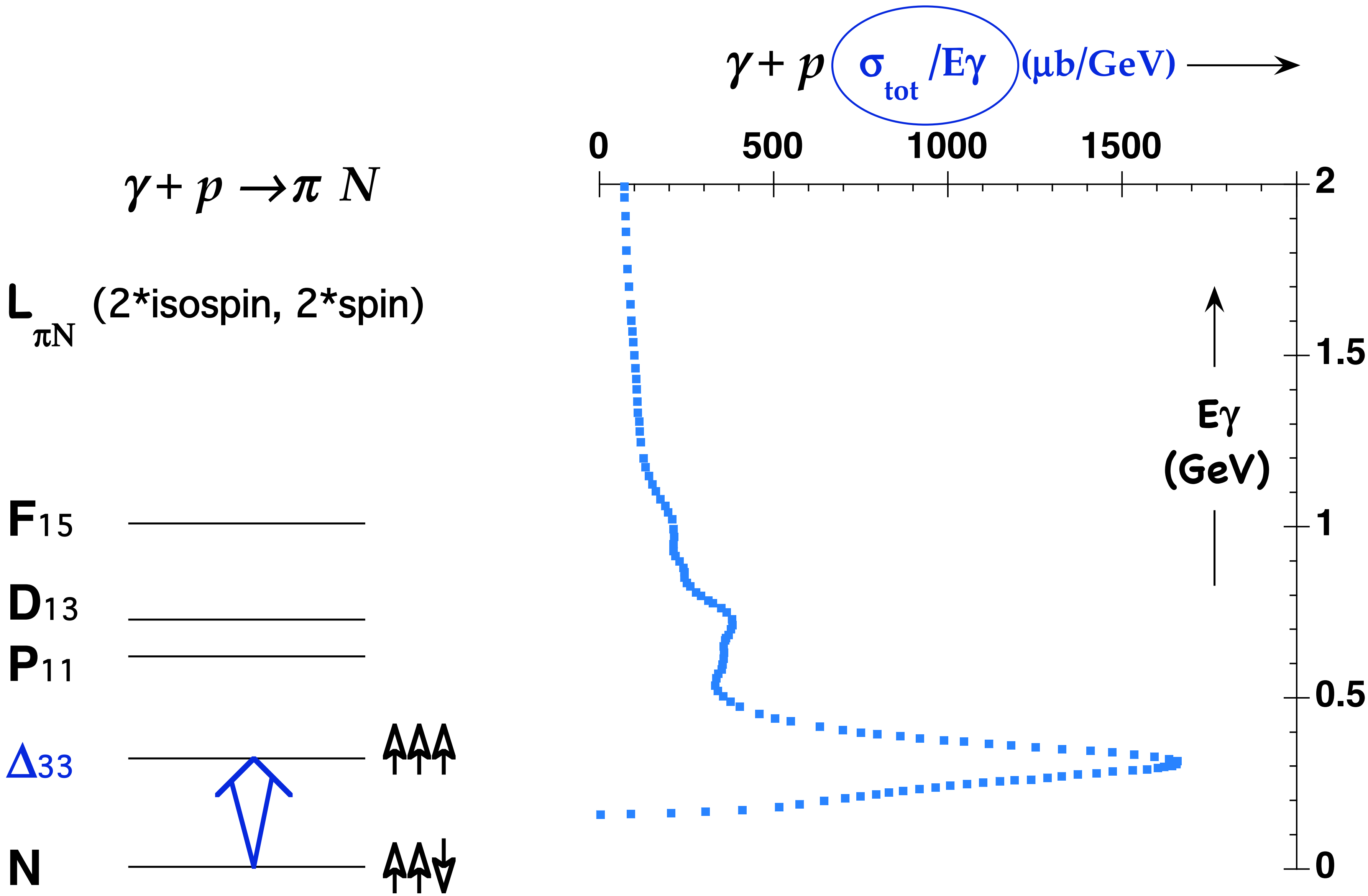
$$\frac{1}{4\pi^2}\int_{\omega_o}^{\infty} \frac{\sigma_A - \sigma_P}{\omega}\, d\omega = g(0) - g(\infty)$$

Gerisamov, Drell-Hearn,
Hosoda-Yamamoto ('66): *maybe* $g(\infty) = 0$?

Excitation spectrum of the Nucleon



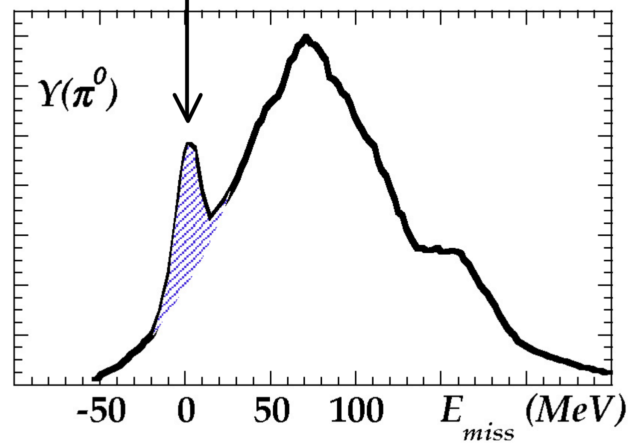
Energy-weighted Excitation spectrum of the Nucleon

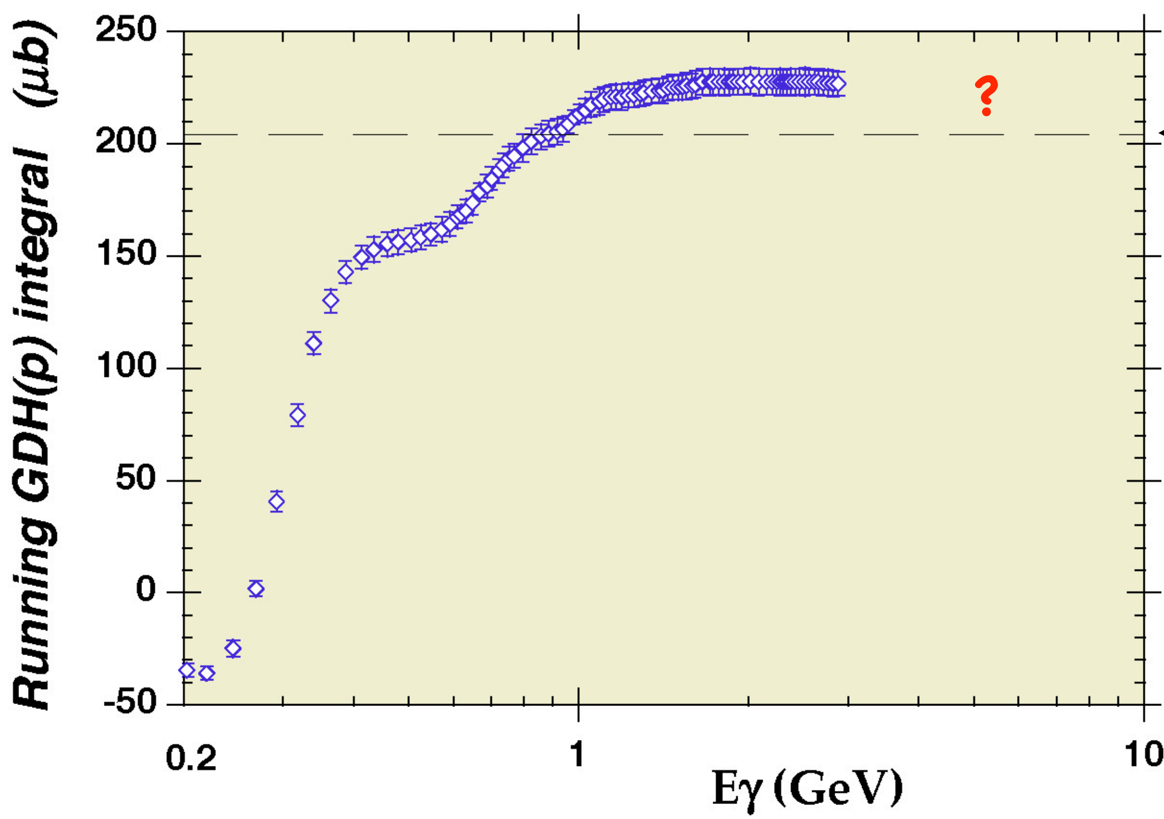


Mainz+Bonn measurements on polarized protons in C_4H_9OH

if $g(\omega) \rightarrow 0$ *faster than* $1/\ln \omega$

$$\Rightarrow GDH \equiv \int_{\omega_o}^{E_\gamma} \frac{\sigma_P - \sigma_A}{\omega} d\omega = S \frac{4\pi^2 \alpha}{m^2} \kappa^2$$

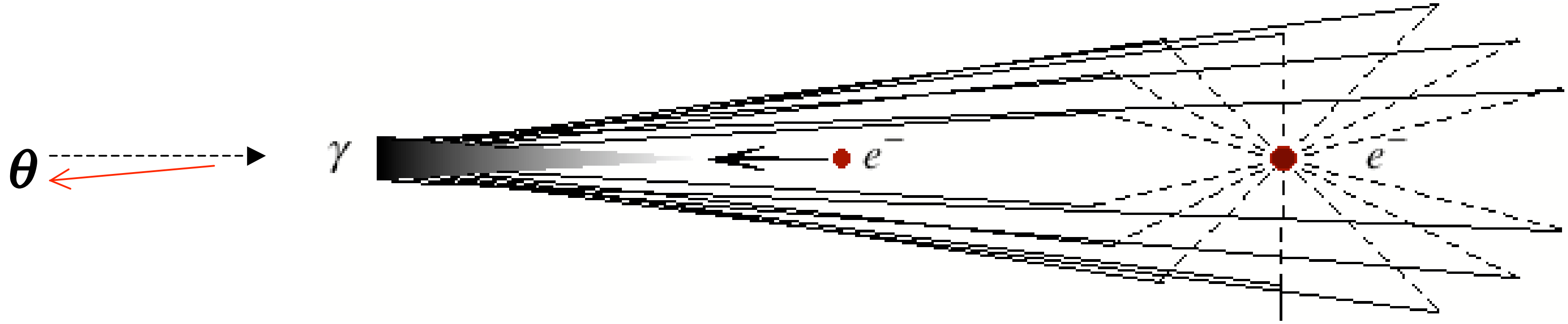




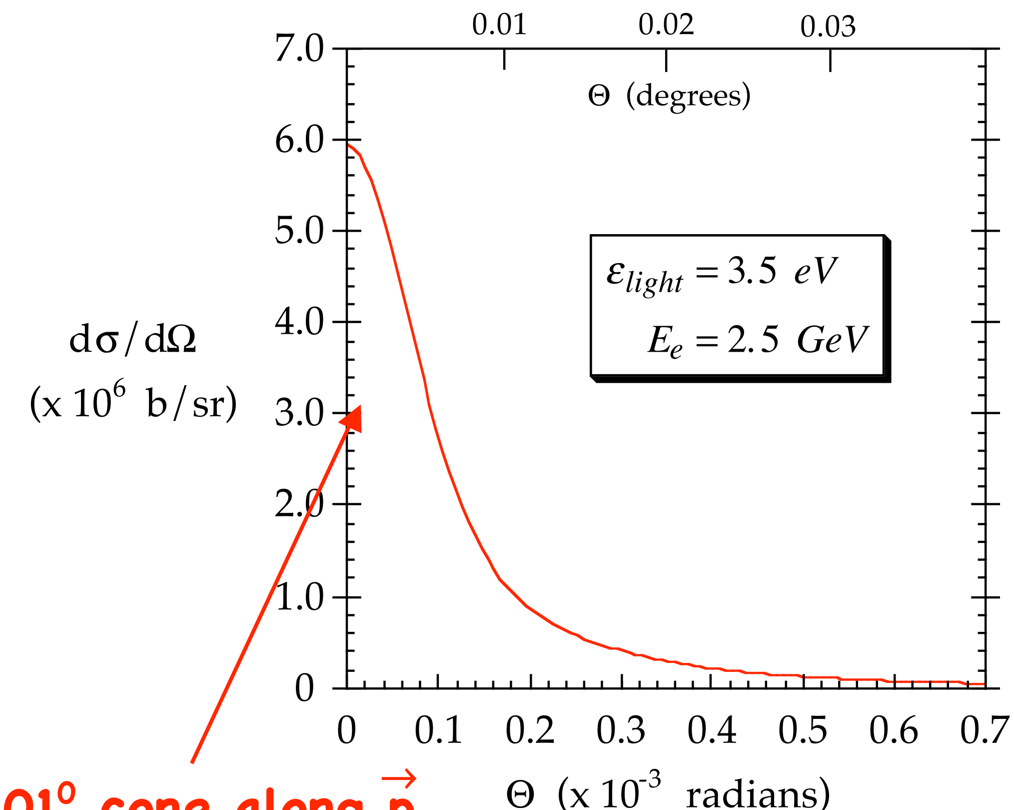
GDH(p) = 204 μb

PRL 93, 32003 (2004)

LEGS - γ *beams* from boosted light + e^- scattering



scattering viewed in the Lab ← light+e^- scattering in CM

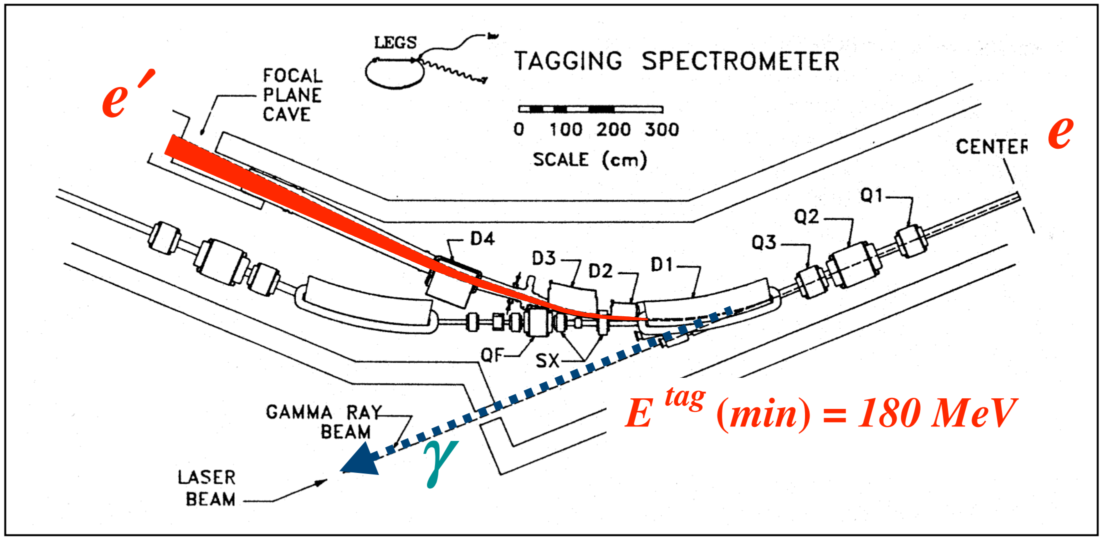


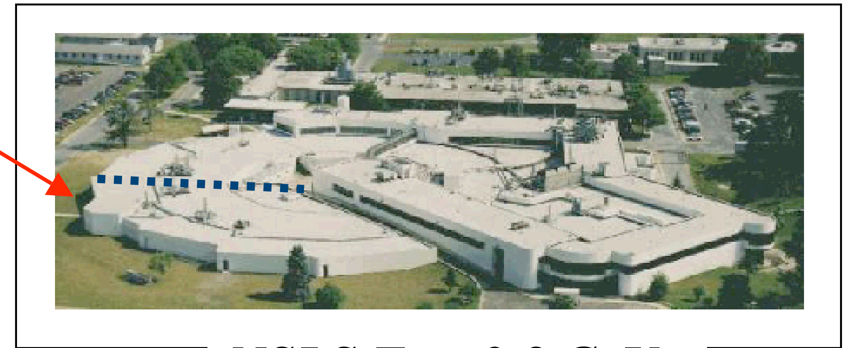
0.01° cone along $\vec{p}_e$

$$E_\gamma = \frac{4\gamma^2 \varepsilon_\ell}{1 + \frac{4\gamma\,\varepsilon_\ell}{m_e c^2} + \theta^2\gamma^2}$$

$$\approx \frac{4 \times \left({}^{2500}/_{0.5}\right)^2 \times \varepsilon_\ell}{1.1 + \theta^2 \times \left({}^{2500}/_{0.5}\right)^2}$$

*L*aser-*E*lectron-*G*amma-*S*ource (LEGS)



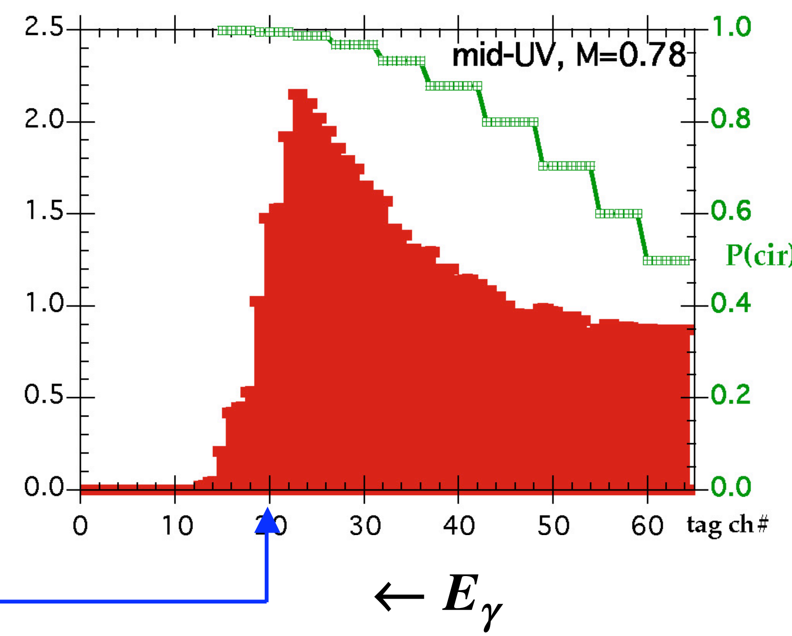


NSLS $E_e = 2.8$ *GeV*

γ beam energy determined by e′ tagging

$$E_\gamma = E_e - E_{e'}\ , \quad \Delta E_\gamma = 3\ \text{MeV}$$

	Ar-Ion laser			
λ(nm)	300	351	488	515
E_γ (max)	*421 MeV*	*368 MeV*	*275 MeV*	*262 MeV*



The LEGS-Spin Collaboration

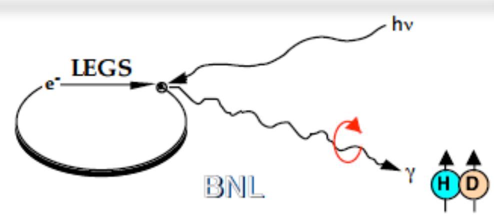
- Brookhaven National Laboratory
  A. Caracappa, S. Hoblit, O. Kistner, F. Lincoln, L. Miceli, M. Lowry, **A.M. Sandorfi ***, C. Thorn, X. Wei
- Forschungszentrum Jülich GmbH
  M. Pap, H. Glückler, H. Seyfarth, H. Ströher
- James Madison University
  C. S. Whisnant
- Norfolk State University
  M. Khandakar
- Ohio University
  C. Bade, **K. Hicks ***, M. Lucas, J. Mahon, S. Kizigul
- Syracuse University
  A. Honig
- University di Roma - Tor Vergata
  A. D'Angelo *, D. Moricciani, C. Schaerf, R. Di Salvo, A. Fantini
- University of South Carolina
  K. Ardashev, C. Gibson, **B. M. Preedom ***, A. Lehmann
- University of Virginia
  S. Kucuker, R. Lindgren, B. Norum, K. Wang
- Virginia Polytechnic Institute & State University
  M. Blecher, T. Kageya

37 people from

10 institutions in

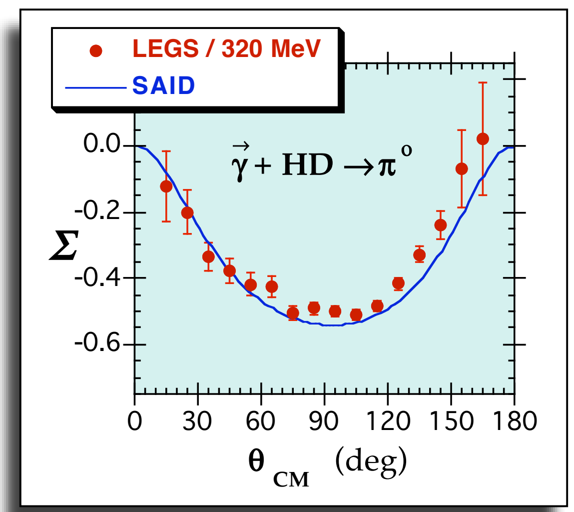
3 countries

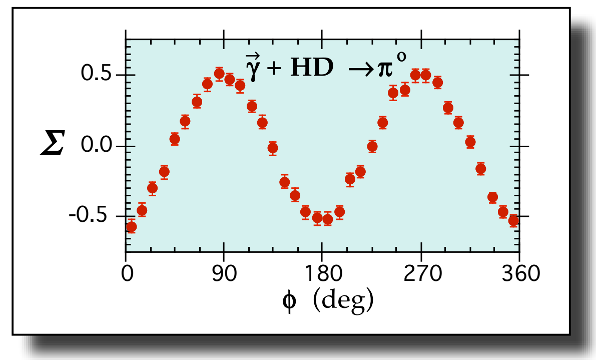
Post-Docs (NSF)
Grad Students
* LSC Executive com



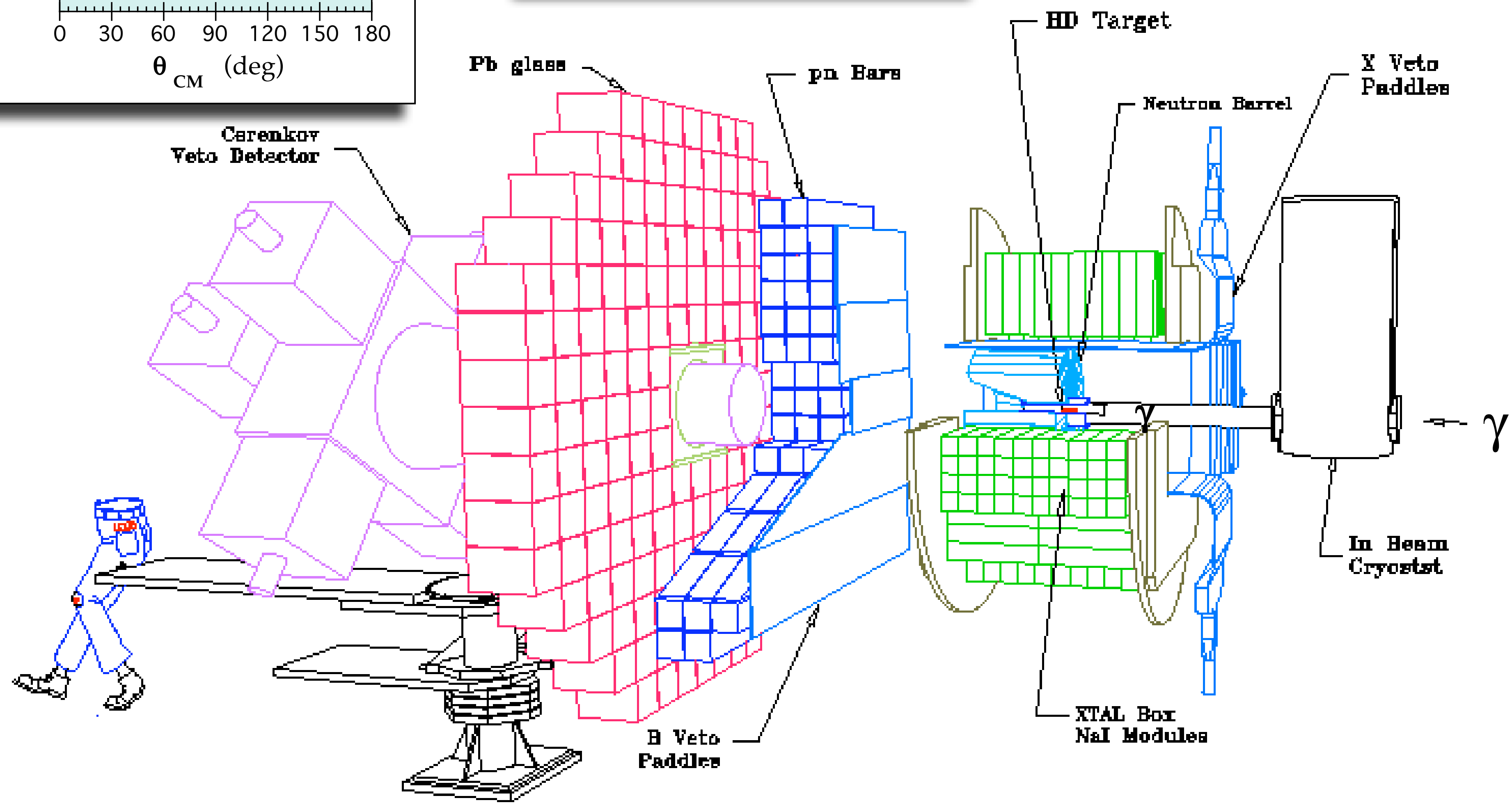
LSC list May'05

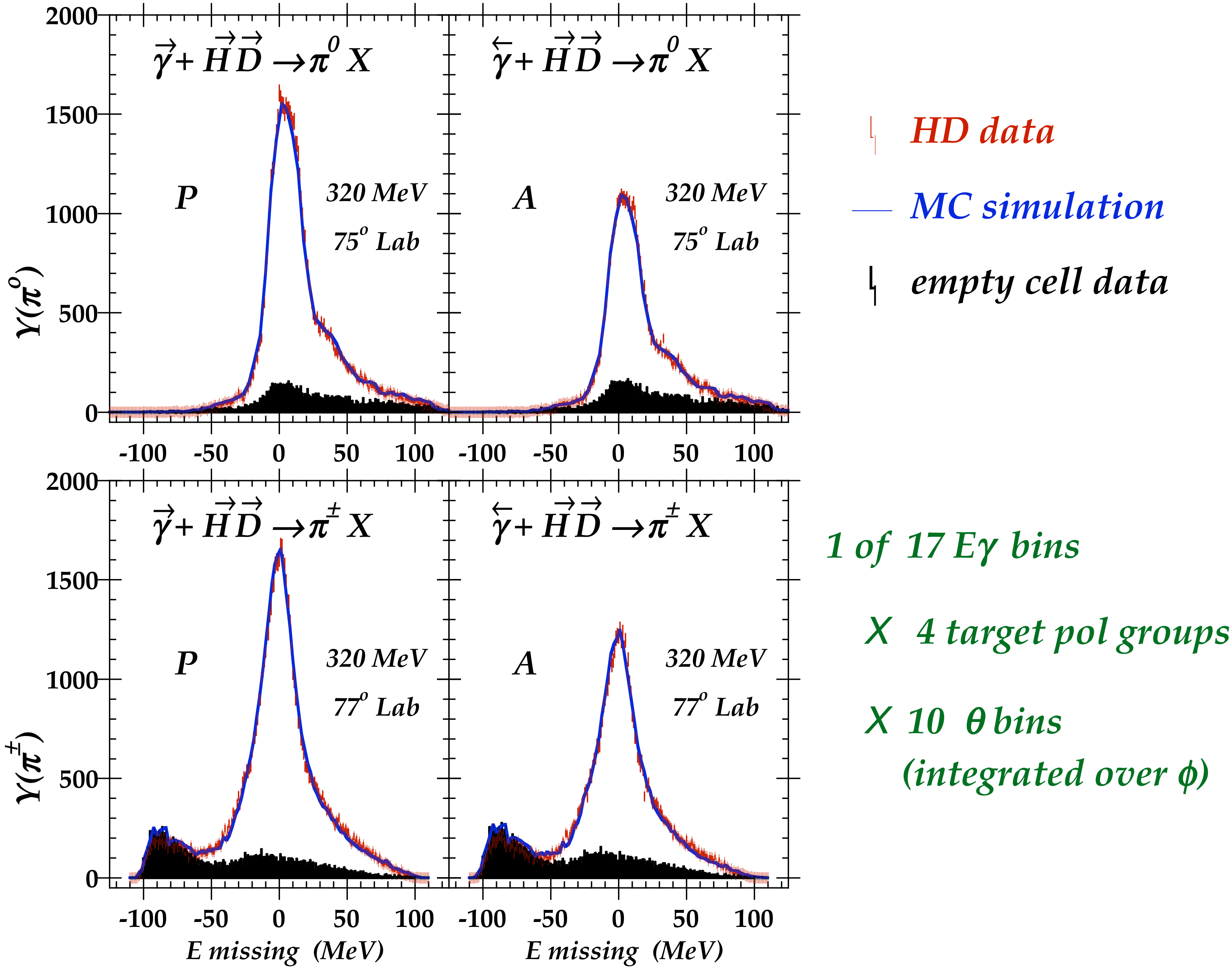
LEGS *S*pin *ASY*mmetry array (*SASY*)





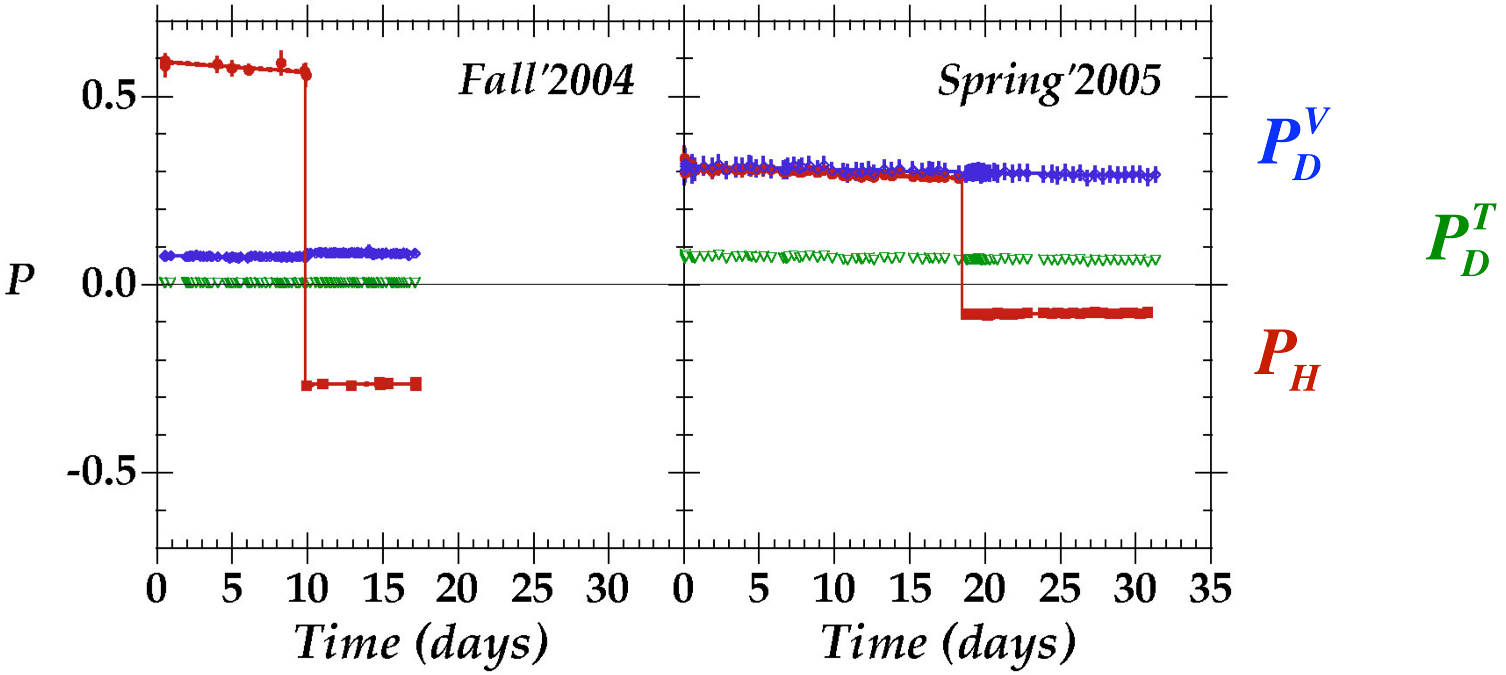
~ 4π acceptance for π^0





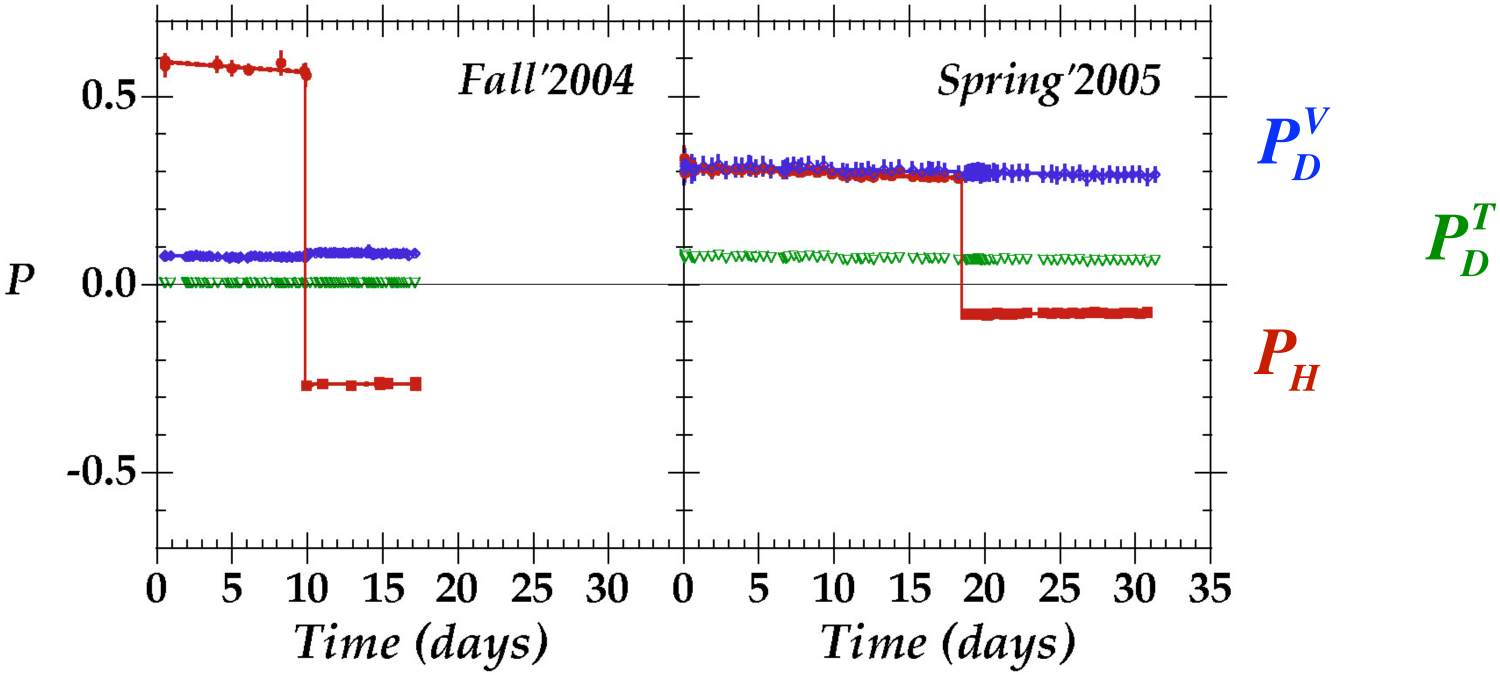
$\vec{\gamma} + \vec{H}\vec{D} \rightarrow \pi^0 X$
P
320 MeV
75° Lab
$\overleftarrow{\gamma} + \vec{H}\vec{D} \rightarrow \pi^0 X$
A
320 MeV
75° Lab
$\vec{\gamma} + \vec{H}\vec{D} \rightarrow \pi^\pm X$
P
320 MeV
77° Lab
$\overleftarrow{\gamma} + \vec{H}\vec{D} \rightarrow \pi^\pm X$
A
320 MeV
77° Lab
$Y(\pi^0)$
$Y(\pi^\pm)$
2000
1500
1000
500
0
-100
-50
0
50
100
E missing (MeV)
HD data
MC simulation
empty cell data
1 of 17 Eγ bins
X 4 target pol groups
X 10 θ bins
(integrated over φ)

$\vec{\gamma} + \vec{H}\ \vec{D}$



T3/T4 in-beam pol

$\vec{\gamma} + \vec{H}\ \vec{D}$

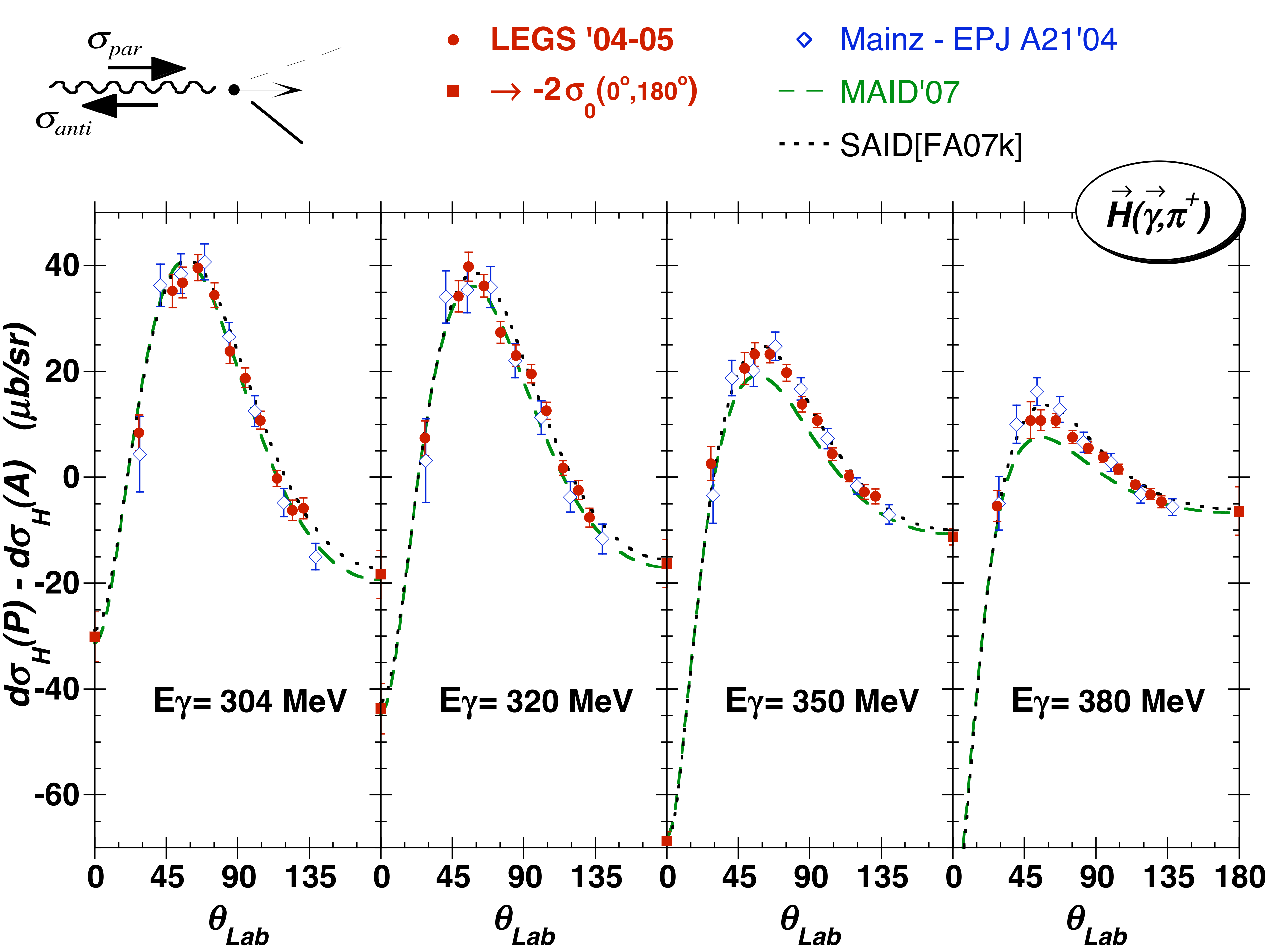


$$\int {}^{d\sigma}\!/_{d\Omega}\, d\phi \,:$$

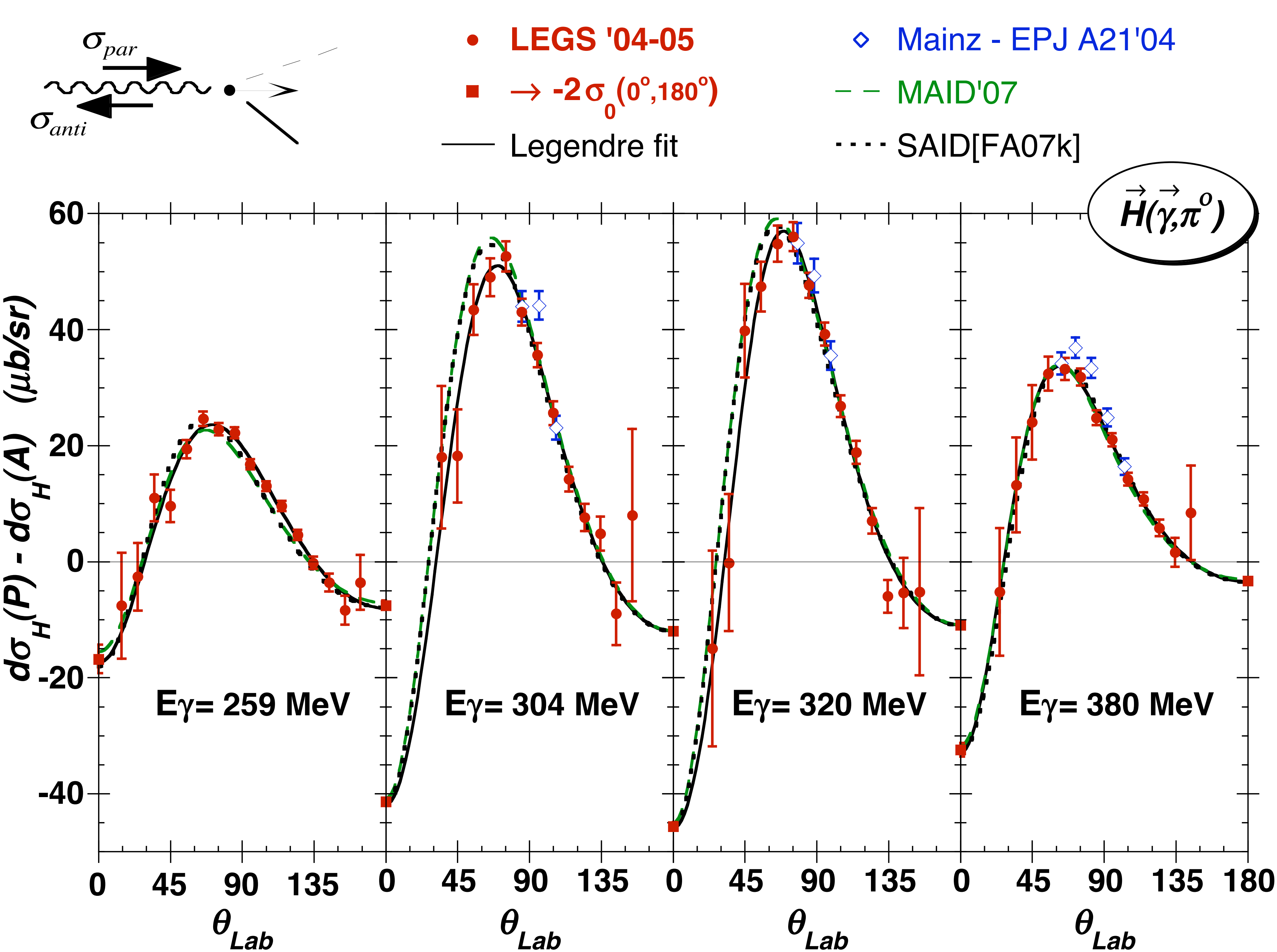
$$\hat{E}_{H,D} = \tfrac{1}{2}[d\sigma^{H,D}(A) - d\sigma^{H,D}(P)]$$

$$d\sigma(\theta, E_\gamma) = d\sigma_0^{HD} - P_\gamma^c P_H \hat{E}_H - P_\gamma^c P_D^V \hat{E}_D + \sqrt{\tfrac{1}{2}}\, P_D^T \hat{T}_{20}^0$$

$$\sqrt{\tfrac{1}{2}}\,\hat{T}_{20}^0 = \tfrac{1}{2}[d\sigma^D(A) + d\sigma^D(P) - 2d\sigma_0^D]$$

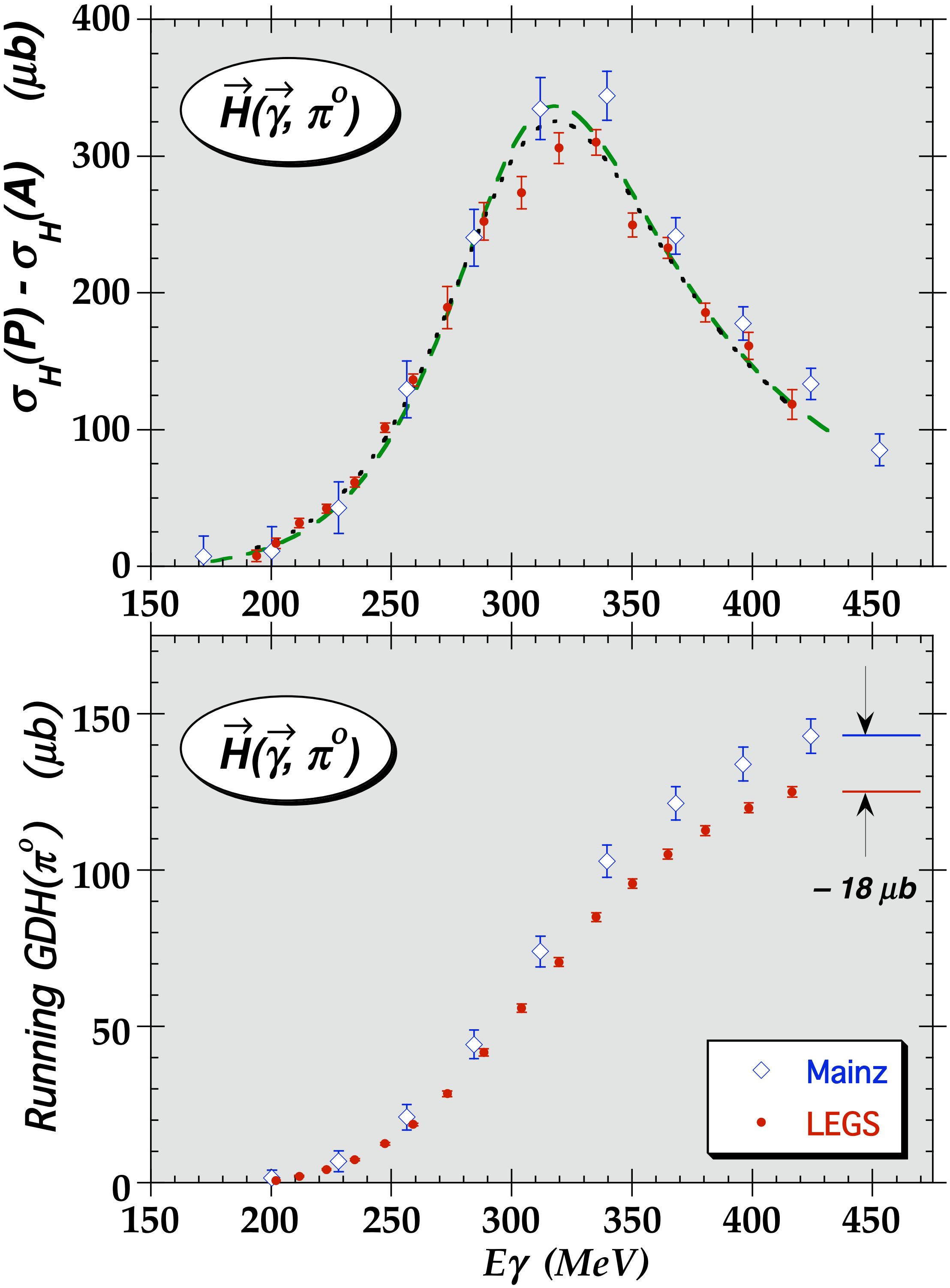


σpar
σanti
LEGS '04-05
→ -2σ0(0°,180°)
Mainz - EPJ A21'04
MAID'07
SAID[FA07k]
H(γ,π+)
dσH(P) - dσH(A) (μb/sr)
Eγ= 304 MeV
Eγ= 320 MeV
Eγ= 350 MeV
Eγ= 380 MeV
θLab
θLab
θLab
θLab



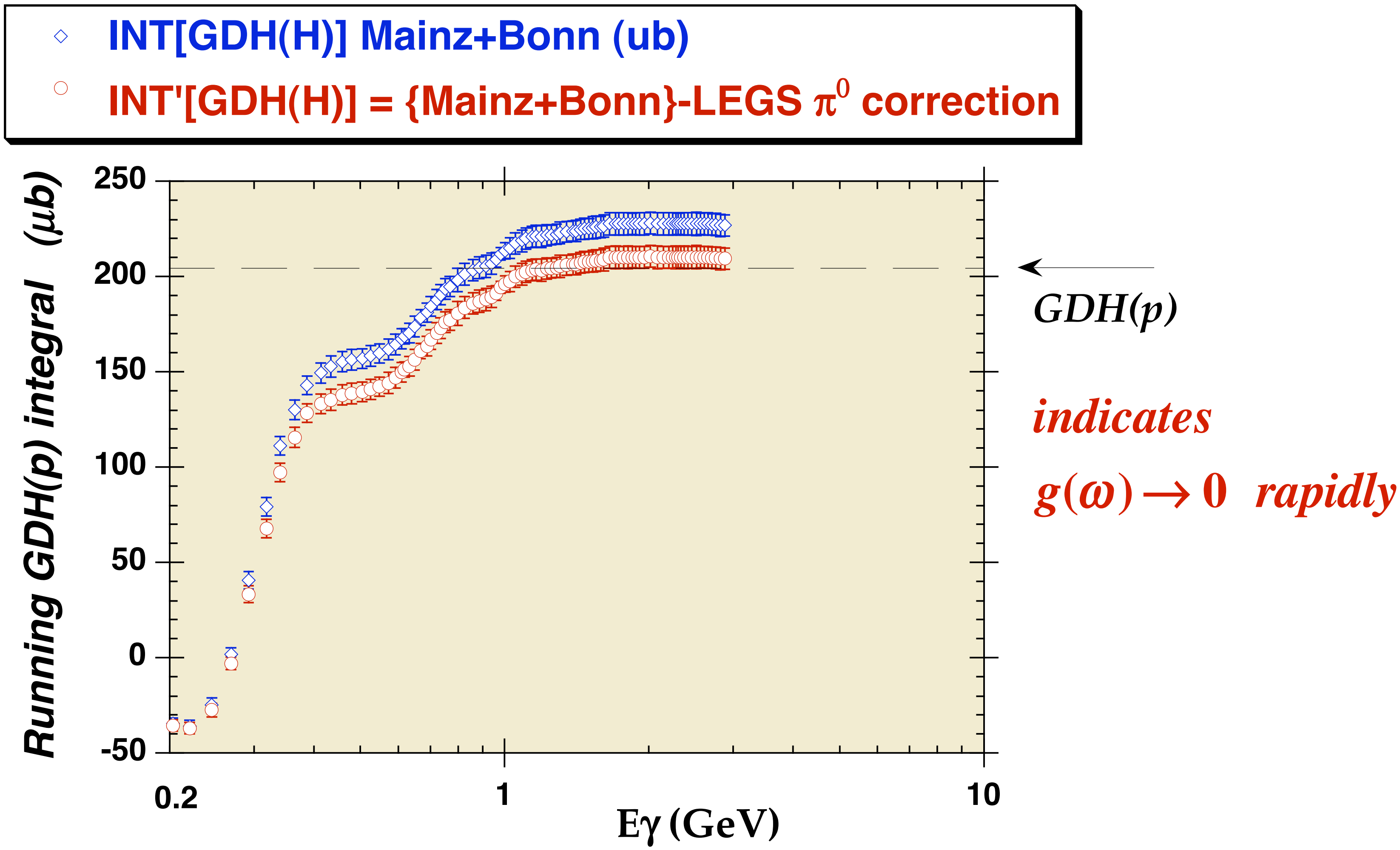
σ_{par}
σ_{anti}
LEGS '04-05
$\rightarrow -2\sigma_0(0^o,180^o)$
Legendre fit
Mainz - EPJ A21'04
MAID'07
SAID[FA07k]
$\vec{H}(\vec{\gamma},\pi^o)$
$d\sigma_H(P) - d\sigma_H(A)$ ($\mu b/sr$)
Eγ= 259 MeV
Eγ= 304 MeV
Eγ= 320 MeV
Eγ= 380 MeV
60
40
20
0
-20
-40
0
45
90
135
180
θ_{Lab}

arXiv-0808.2183



Running $INT_{GDH}(E_\gamma)$

$$= \int^{E_\gamma} \frac{\sigma(P) - \sigma(A)}{E} \, dE$$


INT[GDH(H)] Mainz+Bonn (ub)
INT'[GDH(H)] = {Mainz+Bonn}-LEGS π0 correction
Running GDH(p) integral (μb)
250
200
150
100
50
0
-50
0.2
1
10
Eγ (GeV)
GDH(p)
indicates
g(ω) → 0 rapidly

- the GDH sum rule should hold for any spin system:

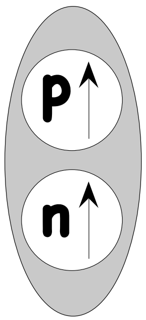
$$\int_{E_0}^{\infty} \frac{\sigma(P)-\sigma(A)}{E_\gamma} dE_\gamma = S\frac{4\pi^2\alpha}{m^2}K + g_{\gamma,\gamma}(\infty)$$

$\Uparrow$

provided $g_{\gamma,\gamma} \rightarrow 0$

faster than *1/ln(*E_γ*)*

GDH for γ + Deuteron



K(p) = +2.79 m_N

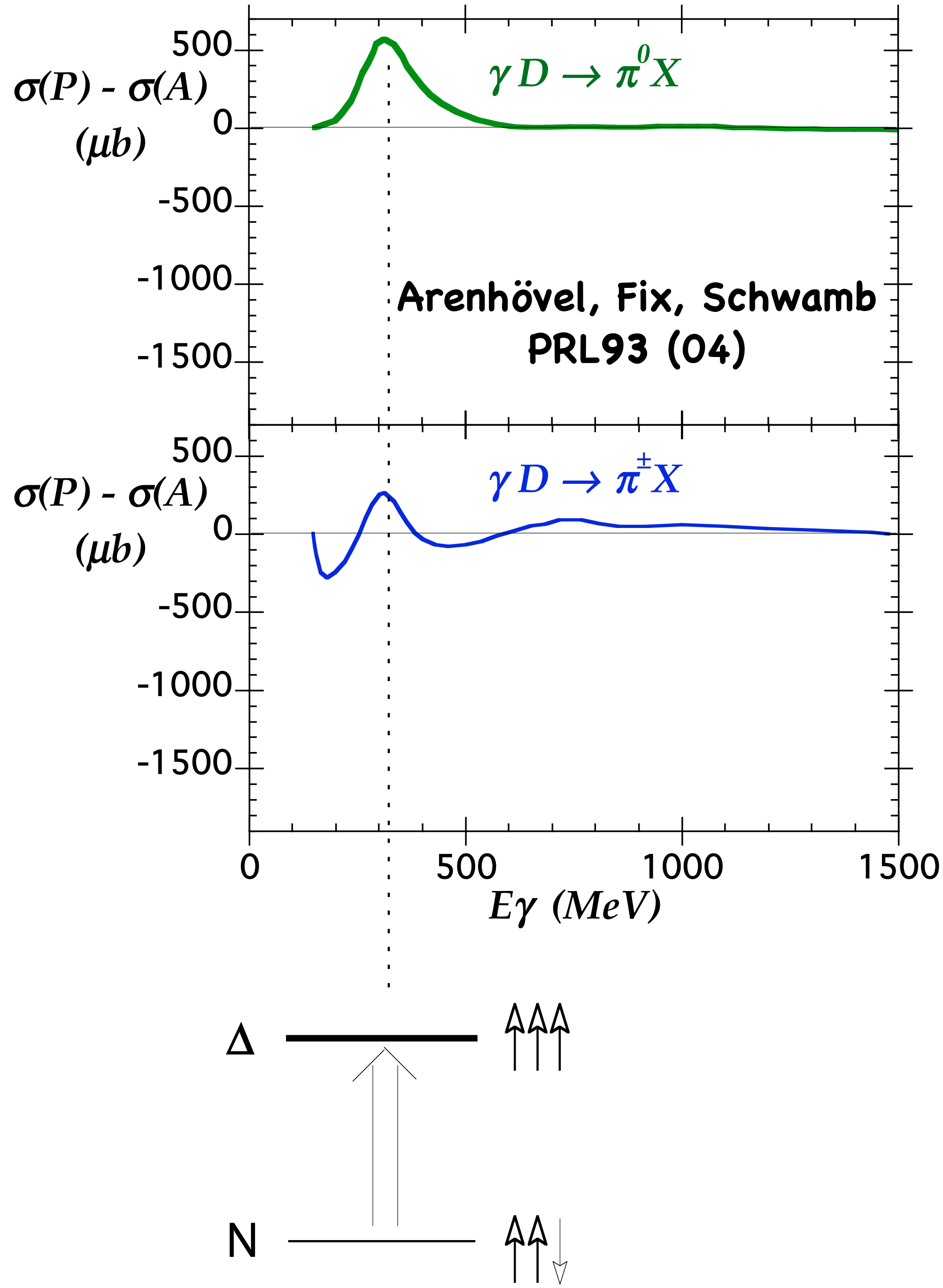
K(n) = - 1.91 m_N

S = 1 K(D) = - 0.14 m_N

$$\int_{E_0}^{\infty} \frac{\sigma(P)-\sigma(A)}{E_\gamma}\, dE_\gamma$$

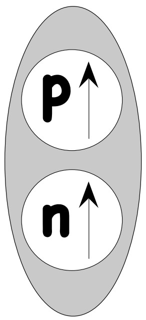
$$= (S=1)\frac{4\pi^2\alpha}{m_D^2}K(D)$$

$$\rightarrow \; 0.65\ \mu b$$



Layout-Lin (a)

GDH for γ + Deuteron



K(p) = +2.79 m_N

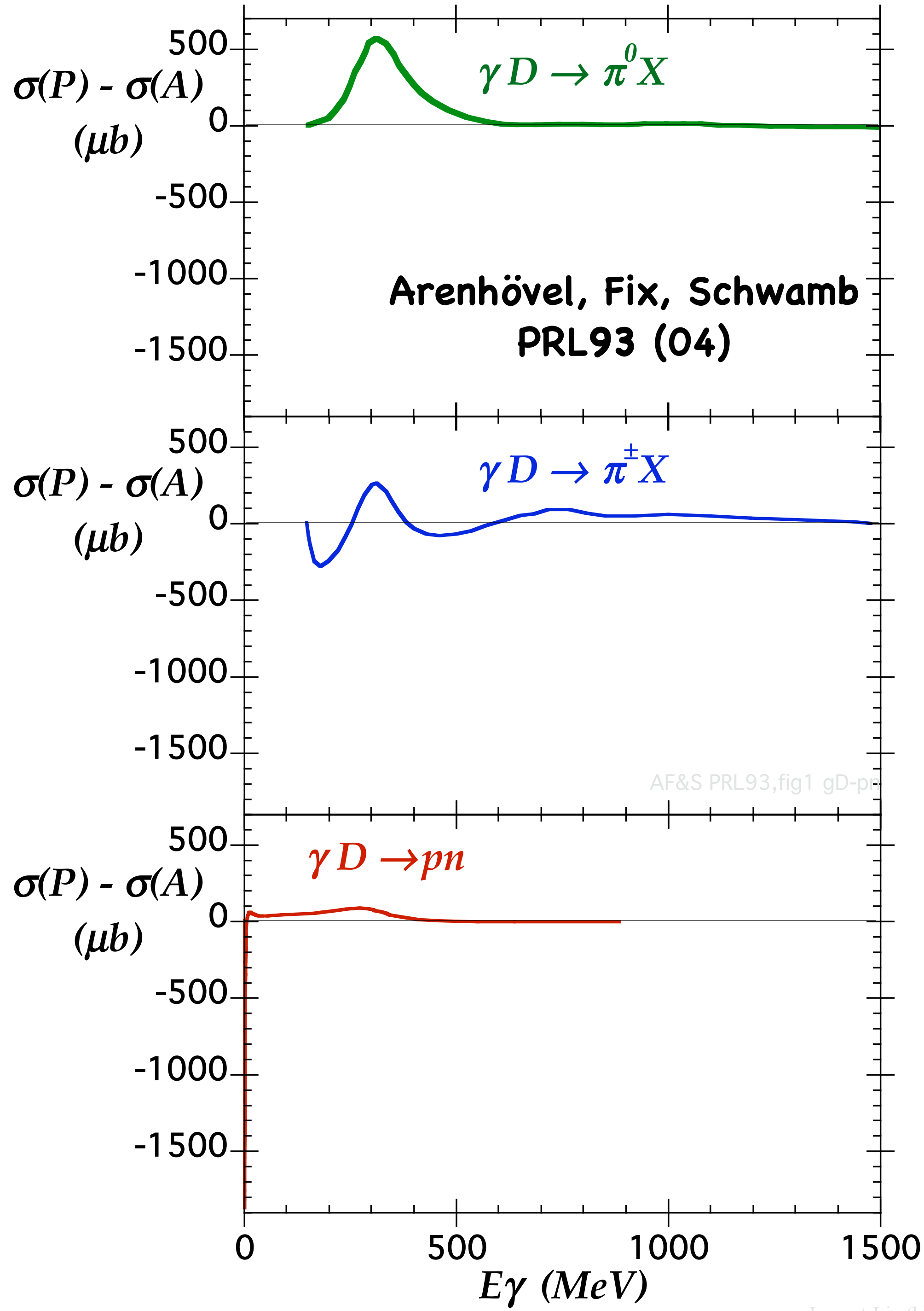
K(n) = - 1.91 m_N

S = 1 K(D) = - 0.14 m_N

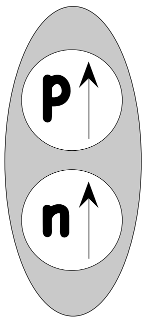
$$\int_{E_0}^{\infty} \frac{\sigma(P)-\sigma(A)}{E_\gamma}\, dE_\gamma$$

$$= (S=1)\frac{4\pi^2\alpha}{m_D^2}K(D)$$

$$\rightarrow\ 0.65\ \mu b$$



GDH for γ + Deuteron



K(p) = +2.79 m_N

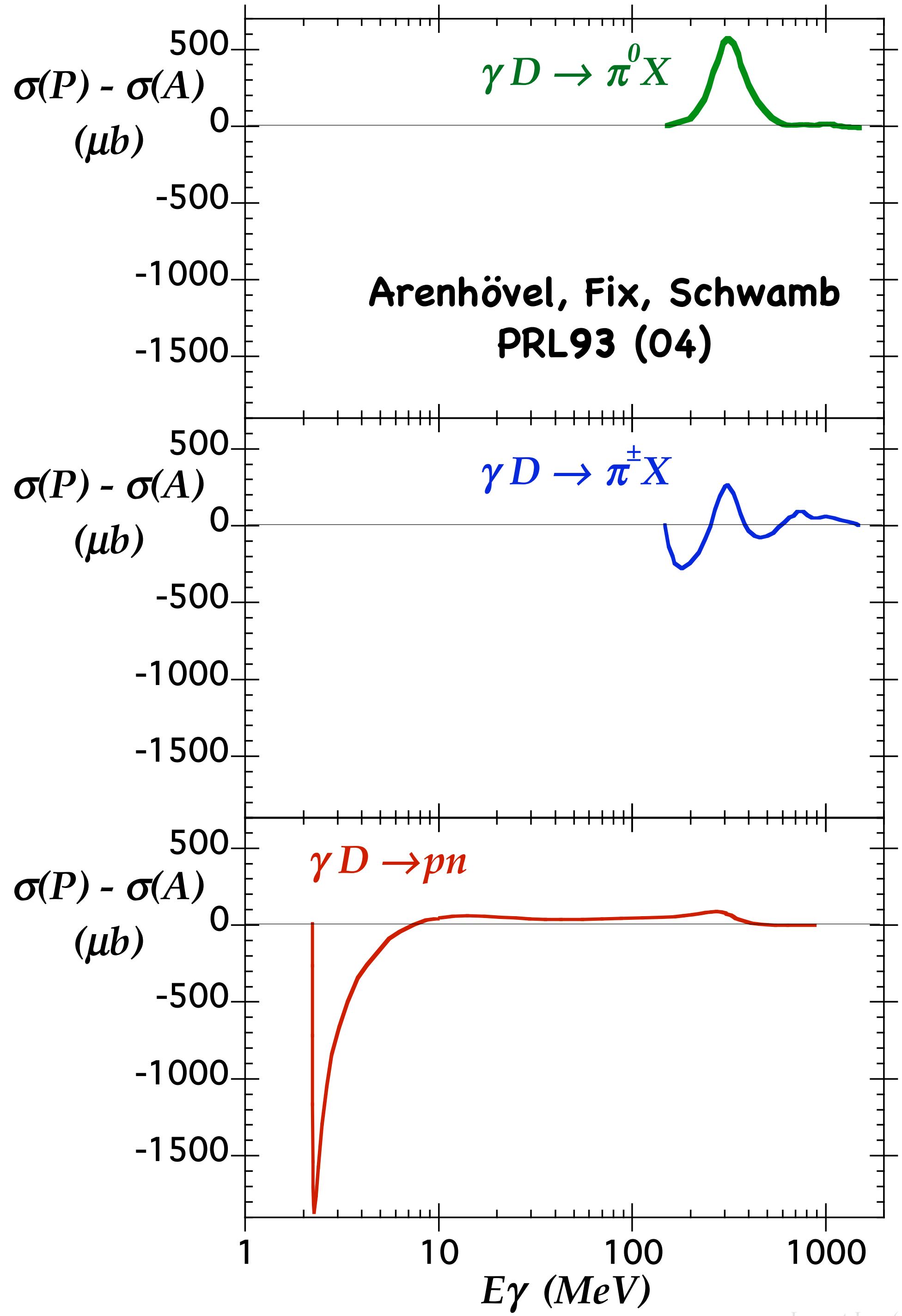
K(n) = - 1.91 m_N

S = 1 K(D) = - 0.14 m_N

$$\int_{E_0}^{\infty} \frac{\sigma(P)-\sigma(A)}{E_\gamma}\, dE_\gamma$$

$$= (S=1)\frac{4\pi^2\alpha}{m_D^2}K(D)$$

$$\rightarrow \; 0.65\ \mu b$$



γ + D, reactions on the "Diplon"

⇔ the 1st photo-nuclear reactions

- Chadwich & Goldbaber, Nature 134 (1934)

Current state-of-the-art calculations:

- Arenhövel, Fix & Schwamb
- Lee, Sato & coll.

A 'NUCLEAR PHOTO-EFFECT': DISINTEGRATION OF THE DIPLON BY γ-RAYS

BY

DR. J. CHADWICK, F.R.S.,

AND

M. GOLDHABER

BY analogy with the excitation and ionisation of atoms by light, one might expect that any complex nucleus should be excited or 'ionised', that is, disintegrated, by γ-rays of suitable energy. Disintegration would be much easier to detect than excitation. The necessary condition to make disintegration possible is that the energy of the γ-ray must be greater than the binding energy of the emitted particle. The γ-rays of thorium C'' of $h\nu = 2{\cdot}62 \times 10^6$ electron volts are the most energetic which are available in sufficient intensity, and therefore one might expect to produce disintegration with emission of a heavy particle, such as a neutron, proton, etc., only of those nuclei which have a small or negative mass defect; for example, D^2, Be^9, and the radioactive nuclei which emit α-particles. The emission of a positive or negative electron from a nucleus under the influence of γ-rays would be difficult to detect unless the resulting nucleus were radioactive.

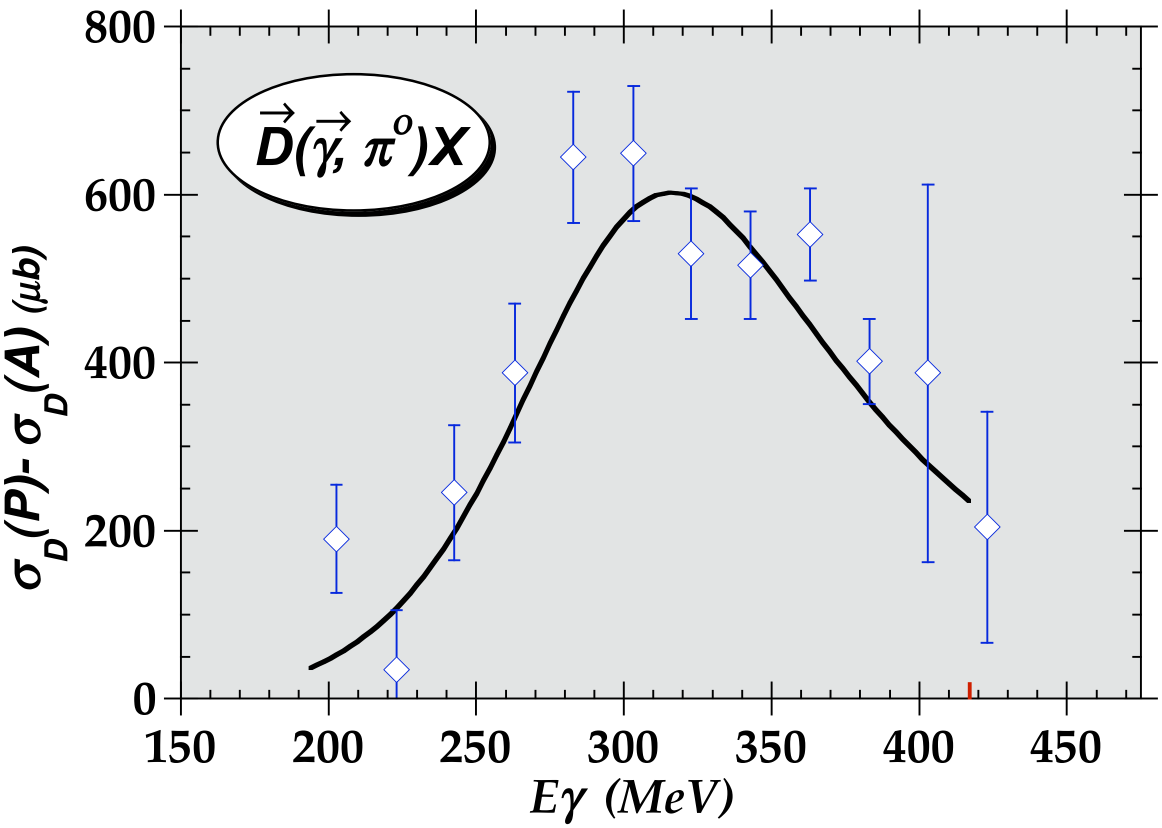
Heavy hydrogen was chosen as the element first to be examined, because the diplon has a small mass defect and also because it is the simplest of all nuclear systems and its properties are as important in nuclear theory as the hydrogen atom is in atomic theory. The disintegration to be expected is

$${}_1D^2 + h\nu \rightarrow {}_1H^1 + {}_0n^1 \quad \ldots\ldots\ldots \quad (1).$$

Since the momentum of the quantum is small and the masses of the proton and neutron are nearly the same, the available energy, $h\nu - W$, where W is the binding energy of the particles, will be divided nearly equally between the proton and the neutron.

γ + D expectation:
Arenhövel, Fix, Schwamb PRL93 (04)

◇ Mainz, PRL97 (06)

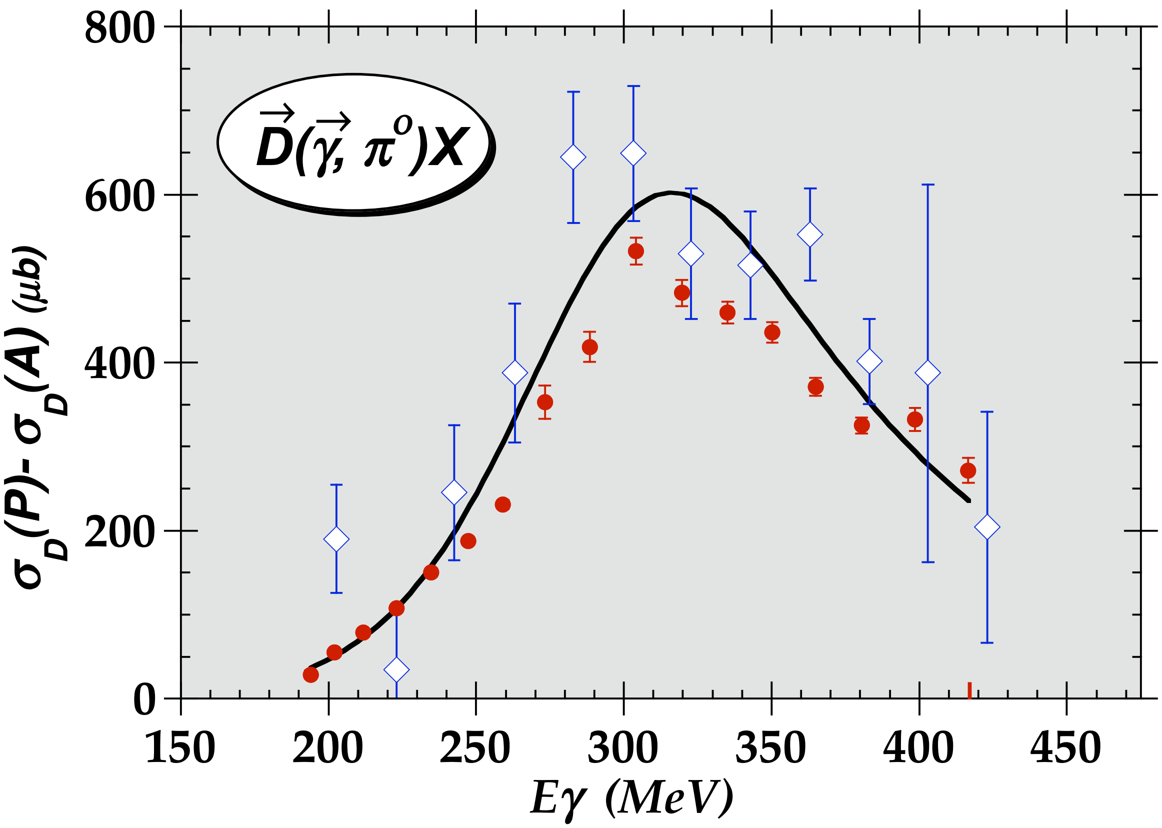


γ + D expectation:

Arenhövel, Fix, Schwamb PRL93 (04)

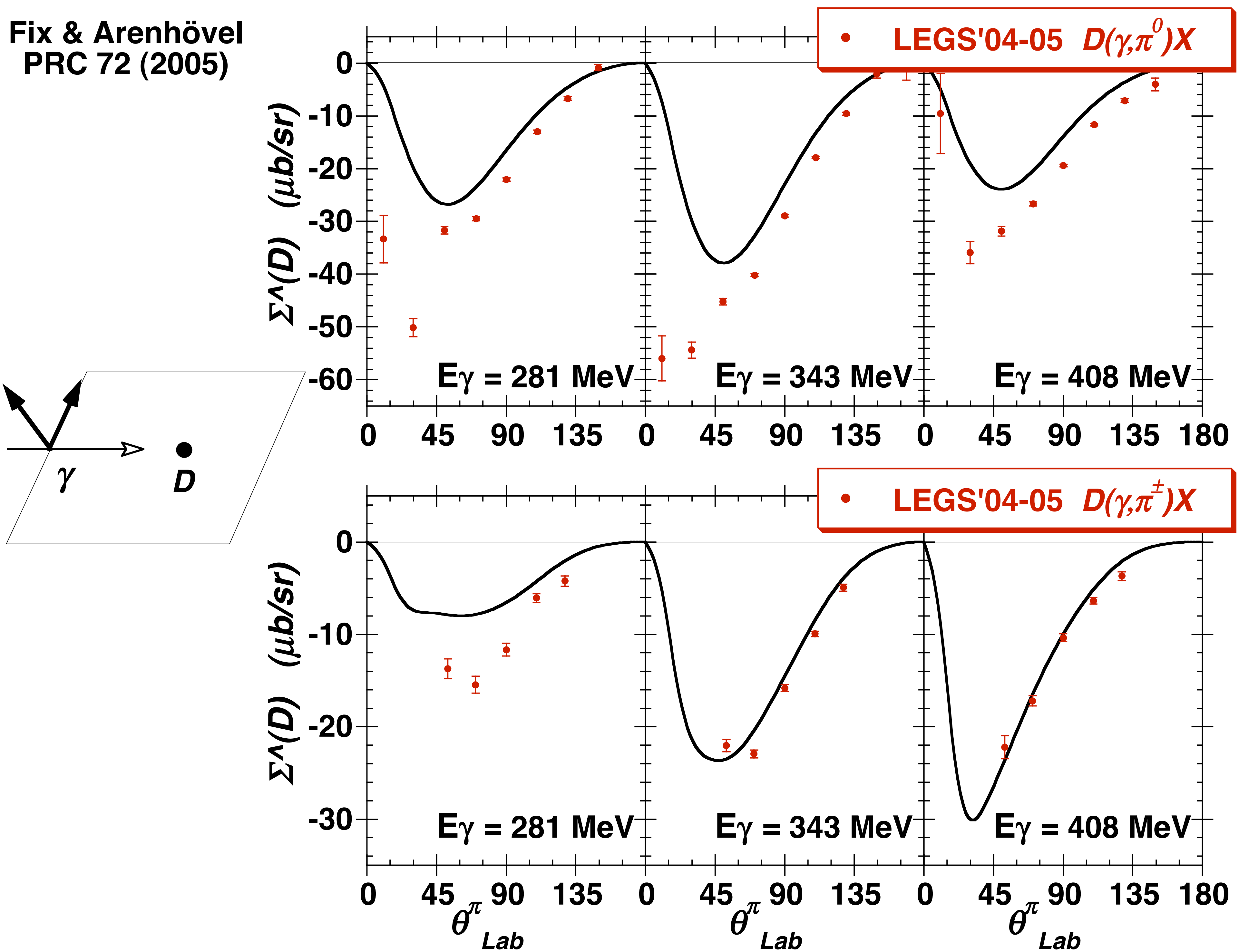
◇ Mainz, PRL97 (06)

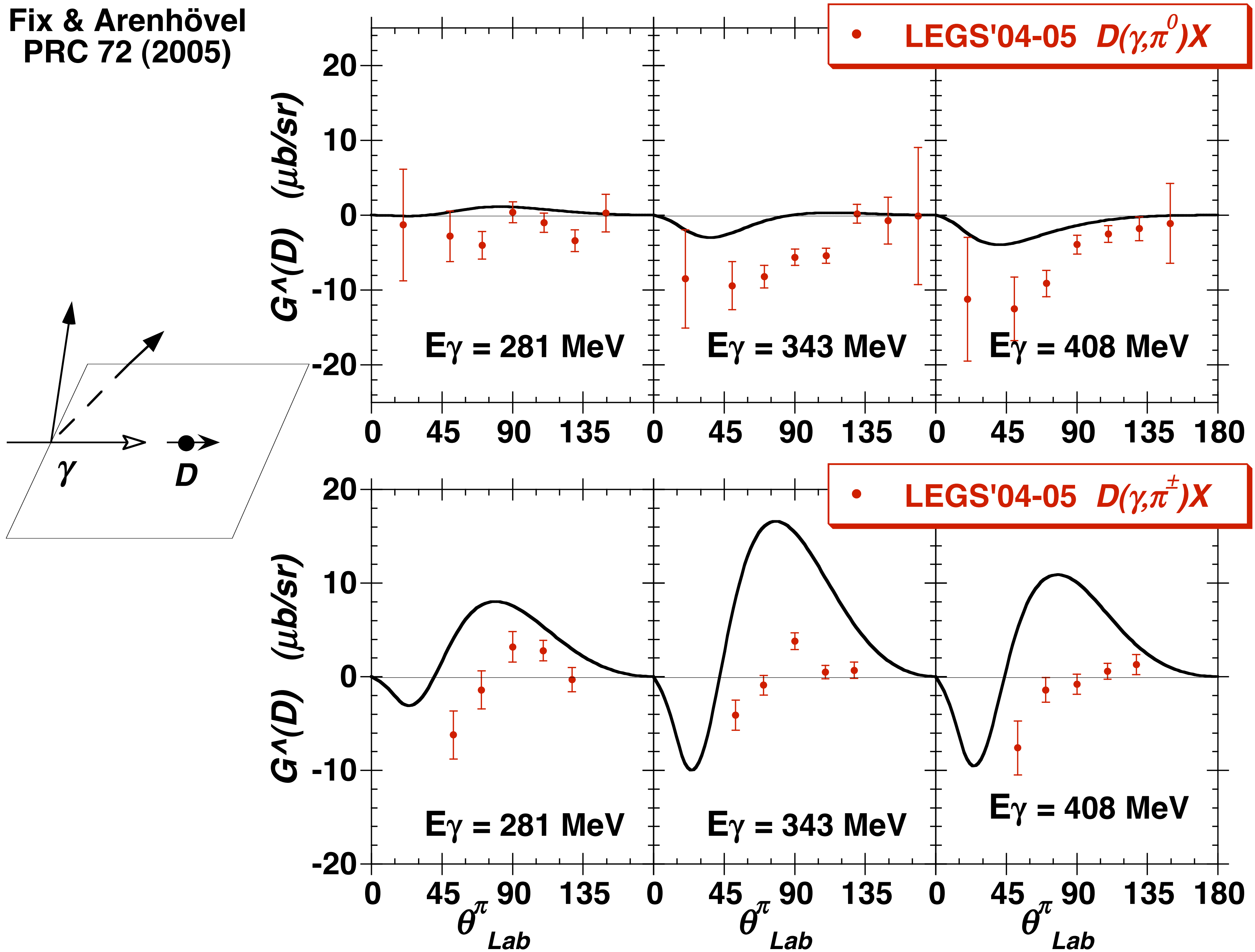
• LEGS, arXiv-0808.2183



But, spin can be the notorious *dust under the theoretical rug*

- **how well do the calculations reproduce other non-GDH spin observables ?**


Fix & Arenhövel
PRC 72 (2005)
LEGS'04-05 D(γ,π⁰)X
LEGS'04-05 D(γ,π±)X
Σ^(D) (μb/sr)
Eγ = 281 MeV
Eγ = 343 MeV
Eγ = 408 MeV
0
-10
-20
-30
-40
-50
-60
0 45 90 135 180
γ
D
θ^π_Lab



Fix & Arenhövel
PRC 72 (2005)
LEGS'04-05 D(γ,π⁰)X
LEGS'04-05 D(γ,π±)X
G^(D) (μb/sr)
Eγ = 281 MeV
Eγ = 343 MeV
Eγ = 408 MeV
θπ Lab
γ
D

Inclusive GDH(D) and GDH(^{3}He) experiments:

- in analysis or planned at Mainz, LEGS, HIγS, LEPS

- we will surely learn a lot about NN interaction and dynamics !

- a personal prediction:
  I doubt we will learn much about $g_{\gamma,\gamma}$ or sum rule for light nuclei

Exclusive GDH(D) and GDH(^{3}He) experiments to test GDH(n):

- in analysis or planned at LEGS, JLab, LEPS

- fewer intermediate states $\Rightarrow$ nuclear corrections might be smaller

no personal predictions yet !

$\vec{H}\vec{D}$ice

Novel Physics with Frozen-spin Polarized Solid Hydrogen

A.M. Sandorfi
Thomas Jefferson National Accelerator Laboratory (JLab)

- "freezing" spins in a solid HD quantum crystal
  - gymnastics with solid hydrogen

Q. when a bullet hits a house, does the house move ?
- the $\vec{\gamma} + \vec{H}\vec{D}$ GDH sum rule experiments at BNL (2004-2006)

Q. what degrees of freedom generate the nucleon's spectrum ?
- $\vec{\gamma} + \vec{H}\vec{D}$ "complete" experiments at JLab (2010-2011)

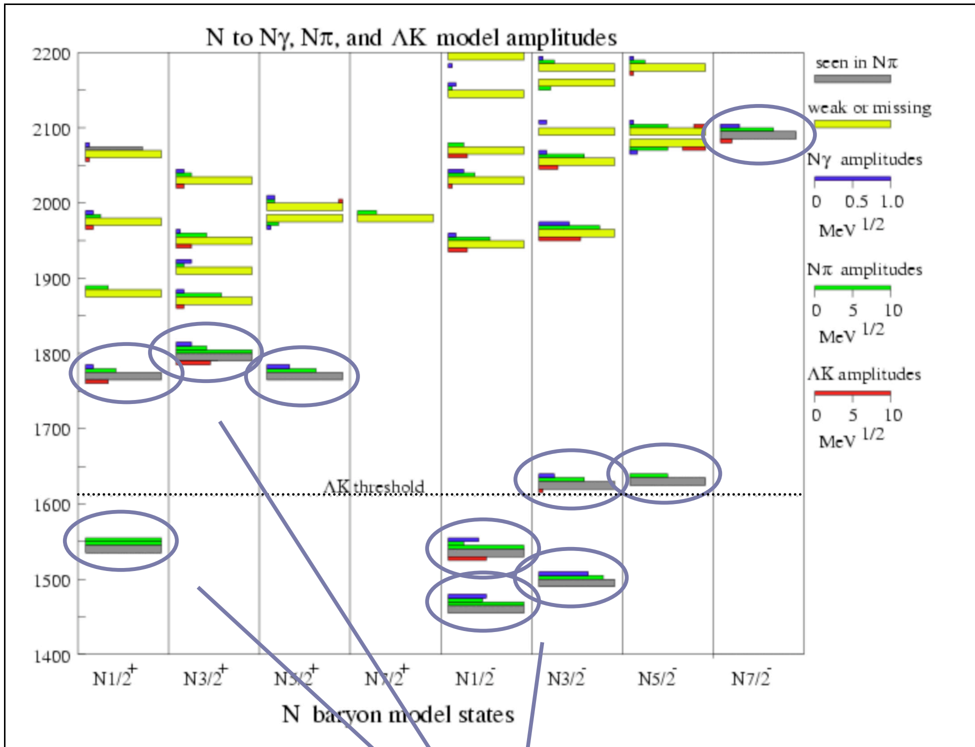
All the excited states of the proton and neutron that we know about were determined from πN scattering

qqq ⇔ *conventional quark model*	q (qq) ⇔ *di-quark models*
• predict many more resonances than have been observed (in πN) • $g(\pi N)$ couplings predicted to decrease rapidly with mass in each oscillator band • "*missing resonances*" may have much larger couplings to lower cross section channels: $\pi\pi N$, ρN, ηN, $K\Lambda$ or $K\Sigma$	• two quarks are quasi-bound • fewer degrees of freedom • there are no "*missing*" states

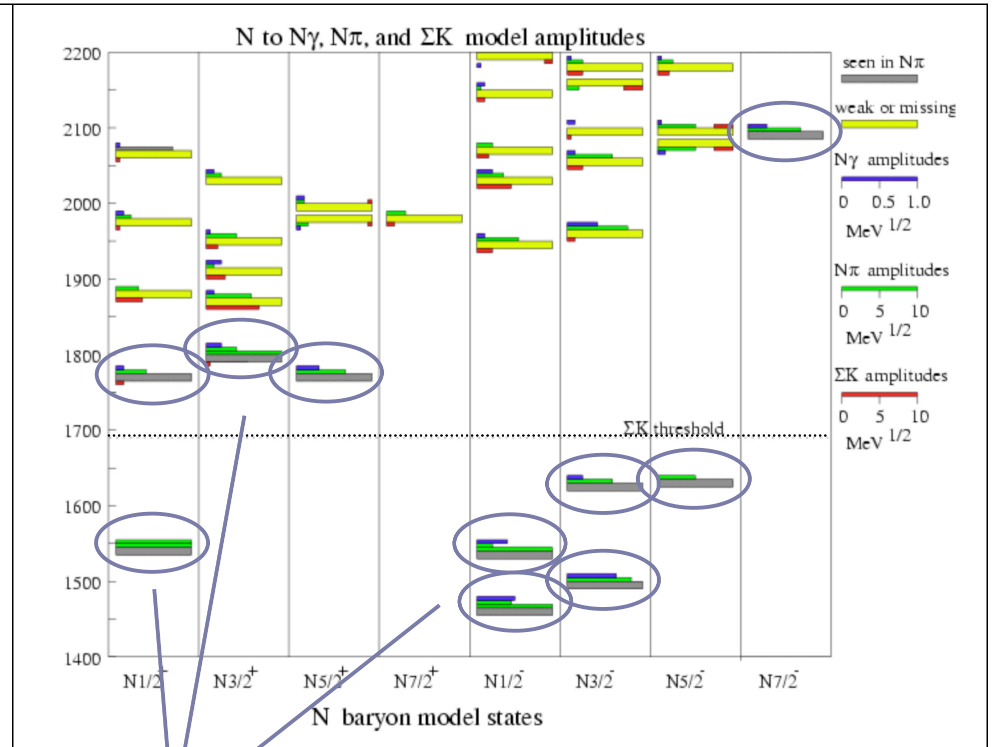
KY channels:

- **are QM states *missing* because they couple more to *KΛ or to KΣ* ?**

QM states coupling to *KΛ*



QM states coupling to *KΣ*



Capstick & Roberts, PRD58 (98)

baryon states seen in πN scattering

(*lowest few in each oscillator band*)

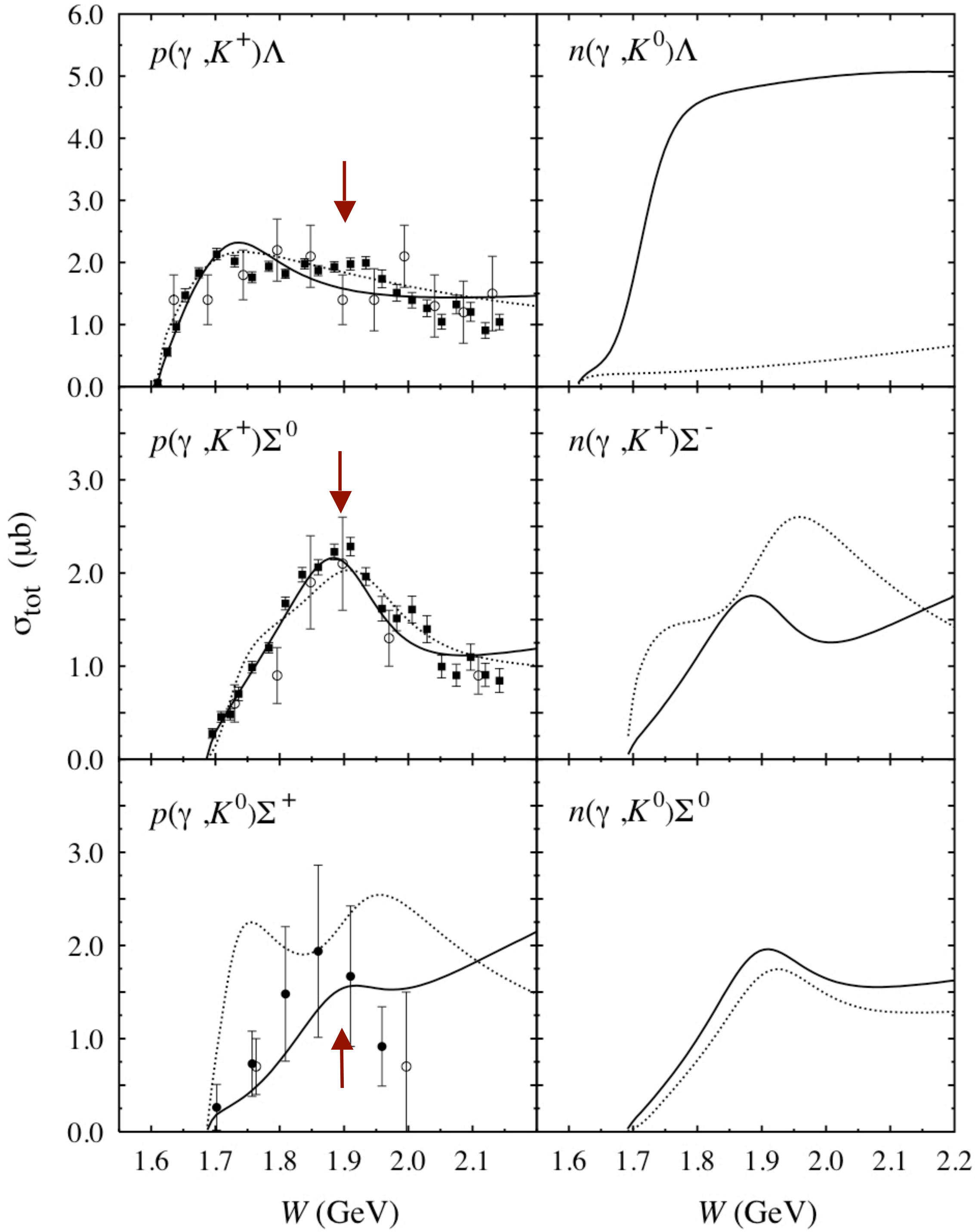
γp and γn KY reactions

Mart & Bennhold:

——— *including D_{13}(1895)*

············ *without D_{13}(1895)*

⇔ subtle effects in σ



p and n KY - Mart & Bennhold06

γp and γn KY reactions

Mart & Bennhold:

——— ***including D_{13}(1895)***

········· ***without D_{13}(1895)***

⇔ subtle effects in σ

History

D_{13}(1895) -2000

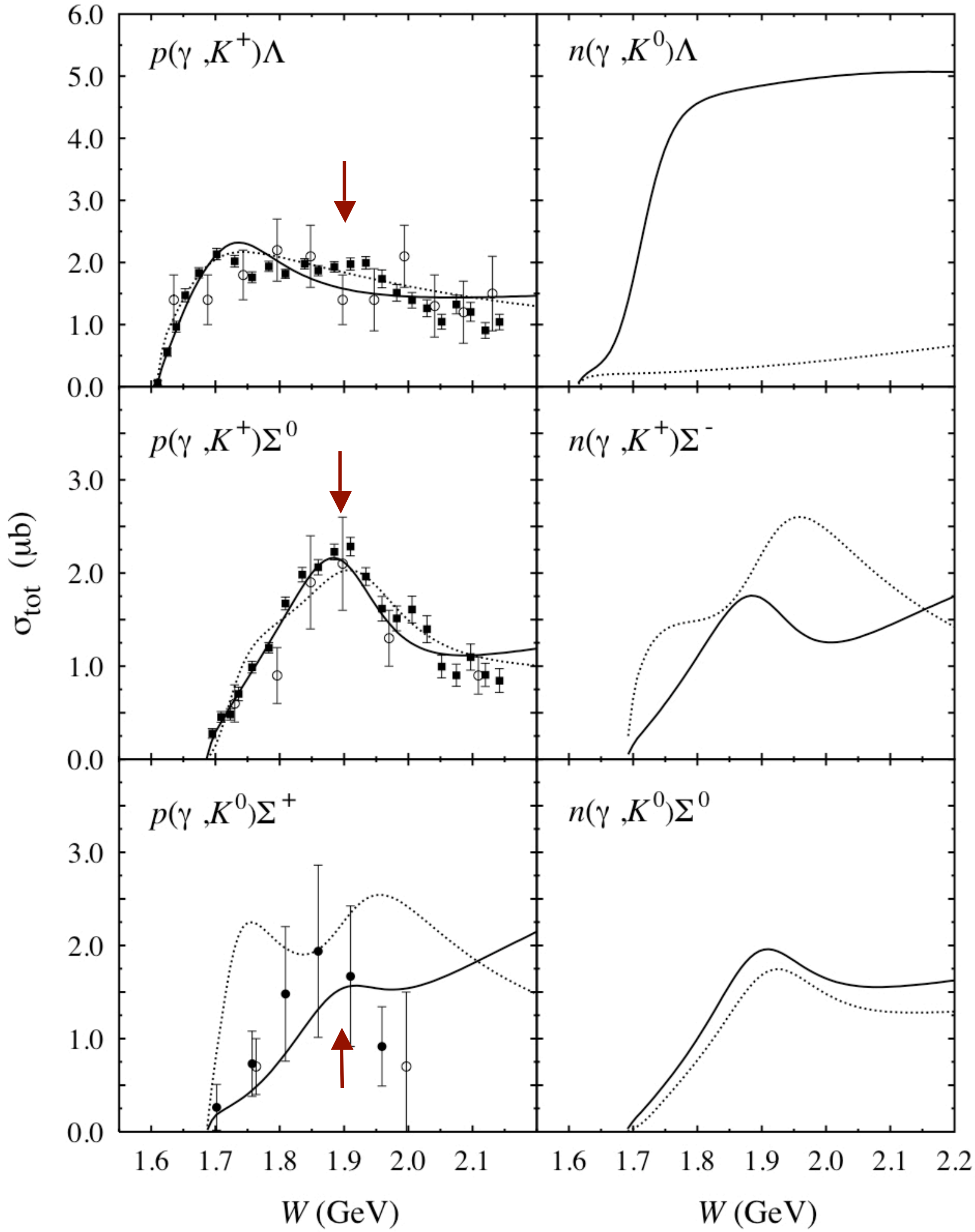
⇒ D_{13}(1895)+P_{13}(1720) -2000

⇒ ~~D_{13}(1900)~~ -2002

⇒ D_{13}(1740) -2003

⇒ D_{13}(1870)=[D_{13}(1520)]* -2005

⇒ D_{13}(1912) -2006



Requirements from experiments ?

Pseudoscalar-meson production: $\gamma + N \rightarrow (J^{\pi} = 0^{-}) + N$

- ***2 X 2 spin-states*** $\rightarrow$ ***4 complex amplitudes***

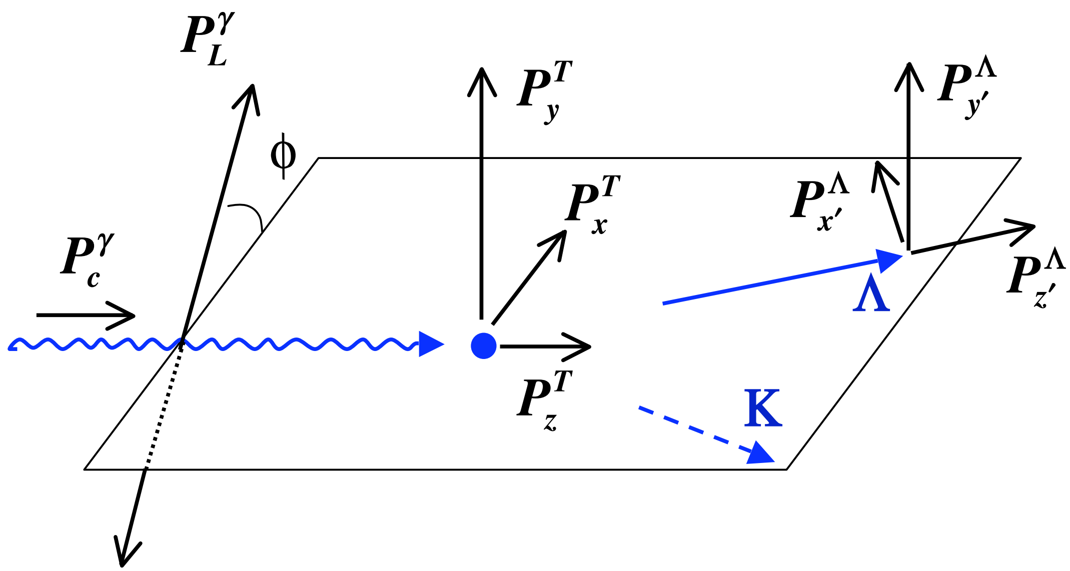
Large number of spin observables needed to define amplitude:

- ***8*** *for* $A(\gamma N)$
- ***12*** *for* $A(\gamma^{*} N)$

(both) *for* ***both*** $N = n, p$

Polarized Pseudoscalar meson photo-production:

$$\vec{\gamma} + \vec{N} \rightarrow K + \vec{\Lambda}$$



Polarization observables in $J^{\pi} = 0^{-}$ meson photo-production :

- ***single-pol observables measured from double-pol asy***
- ***double-pol observables measured from triple-pol asy***

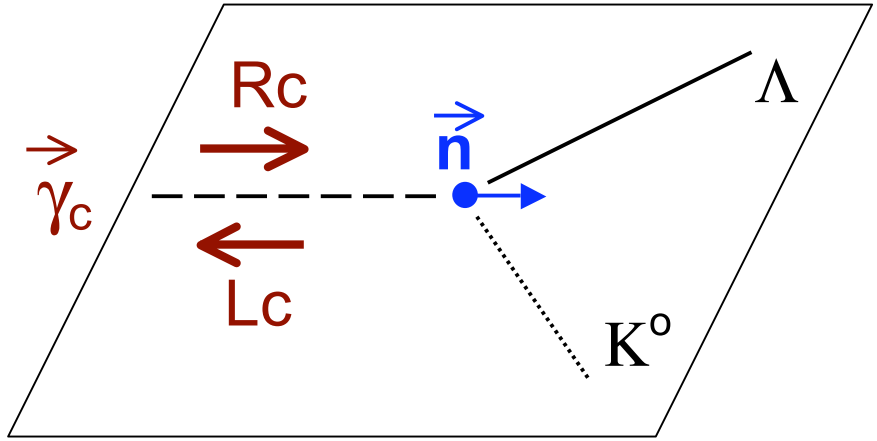
Photon beam		***Target***			***Recoil***			***Target - Recoil***								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		***T***			***P***		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_{γ}	Σ	***H***	***P***	***G***	$O_{x'}$	***T***	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	***E***		***F***	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_{γ}		***F***		***E***	$C_{x'}$		$C_{z'}$		$O_{z'}$		***G***		***H***		$O_{x'}$	

- ***16 different spin observables***

E asymmetry

leading Pol dependence

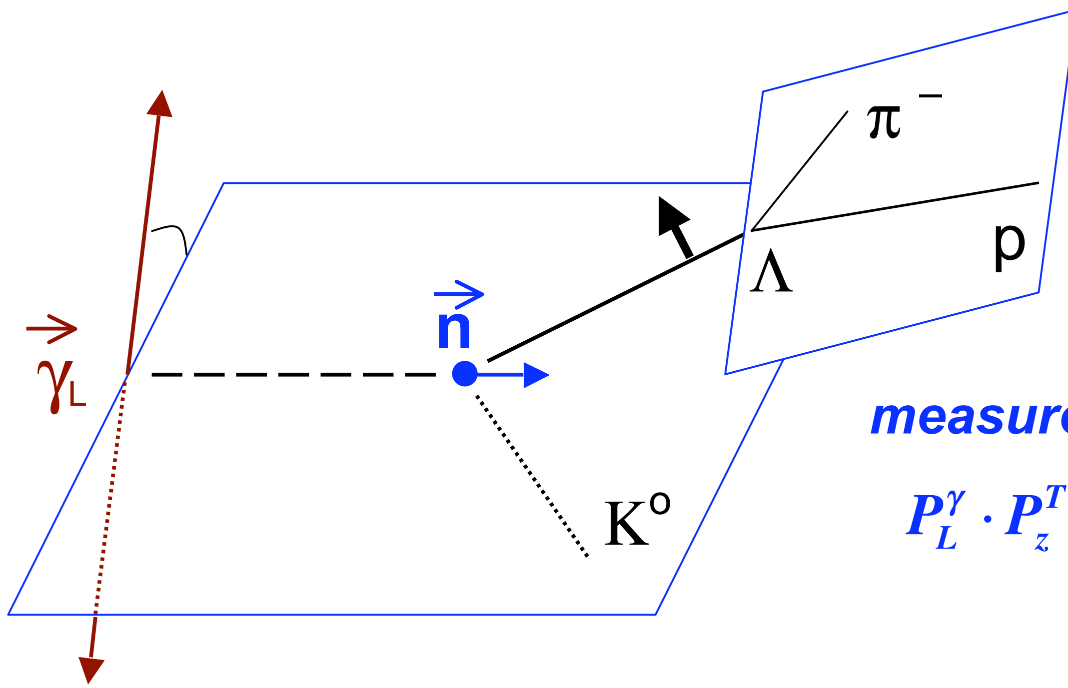
$$P_c^\gamma \cdot P_z^T$$



$T_{z'}$ asymmetry

leading Pol dependence

$$P_x^T \cdot P_{z'}^\Lambda$$

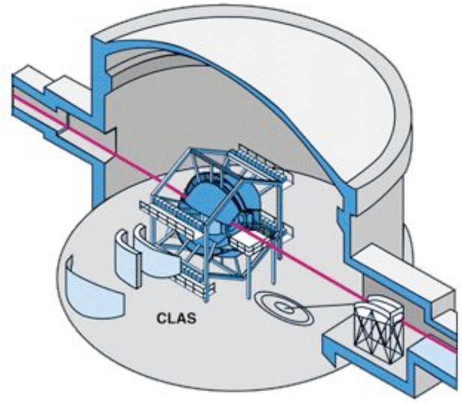


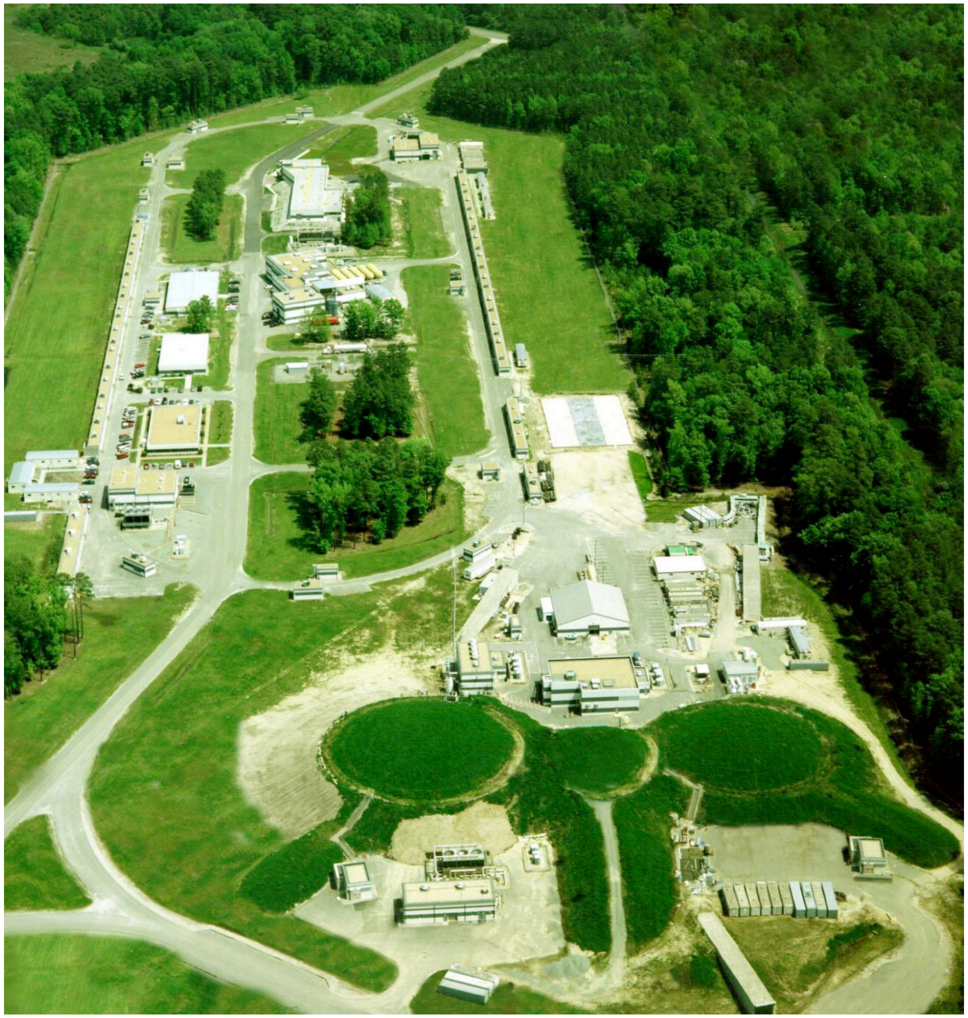
measured via

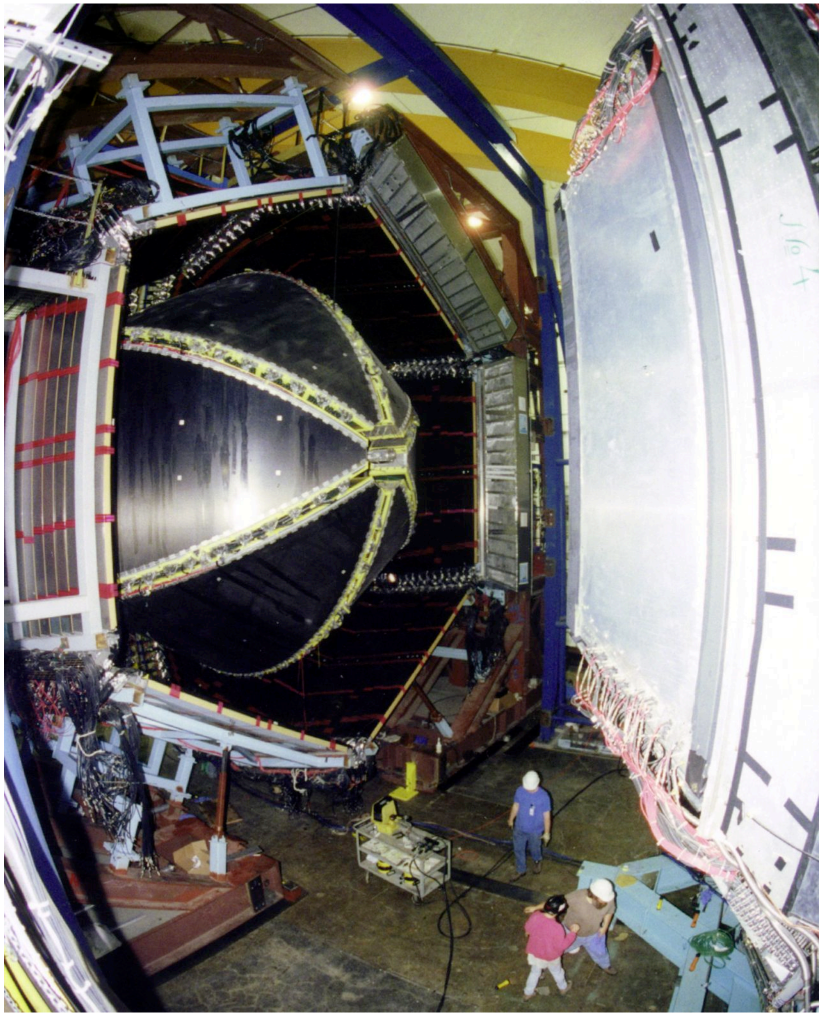
$$P_L^\gamma \cdot P_z^T \cdot P_{x'}^\Lambda$$

Jefferson Lab - CEBAF
Large Acceptance Spectrometer (CLAS)

Hall-B







$\gamma + n(p) \rightarrow K^0\Lambda(p)$ *measurements with* $\vec{H}\cdot\vec{D}$

coherent e-brem

$\vec{e}$ *-brem*

$\Downarrow$

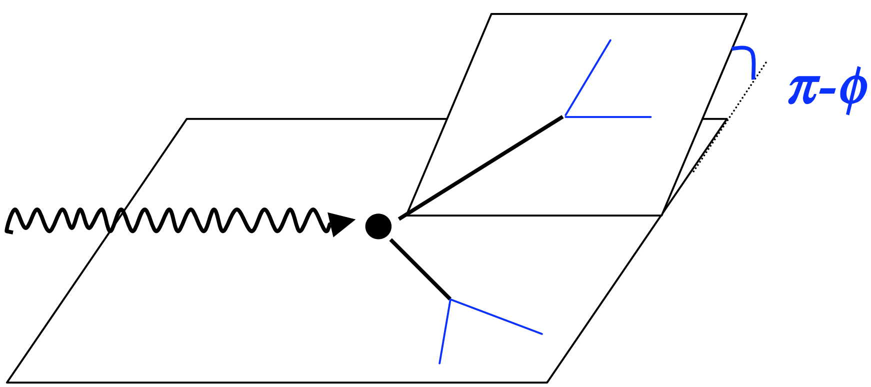
$$\gamma + n(p) \rightarrow K^0 + \Lambda\,(p)$$

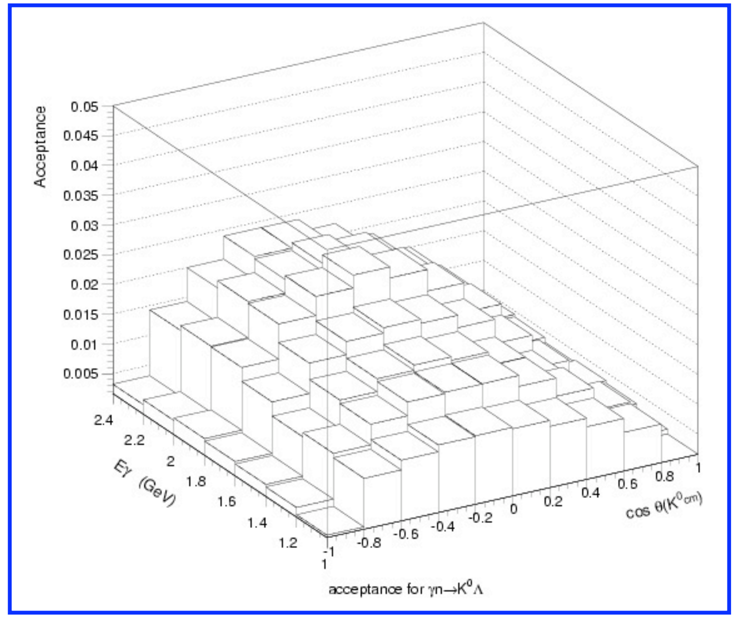
$$\rightarrow [\pi^+\pi^-][p\ \pi^-](p)$$

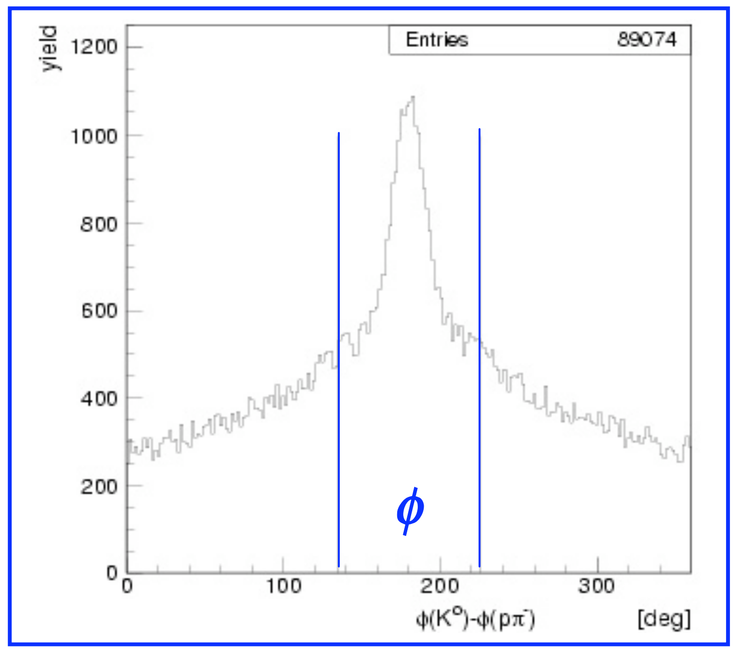
$\Uparrow$ $D\cdot H$

$\Uparrow$ *detect 4 charged particles in CLAS*

- *coplanarity* $\Rightarrow$ *free neutron*







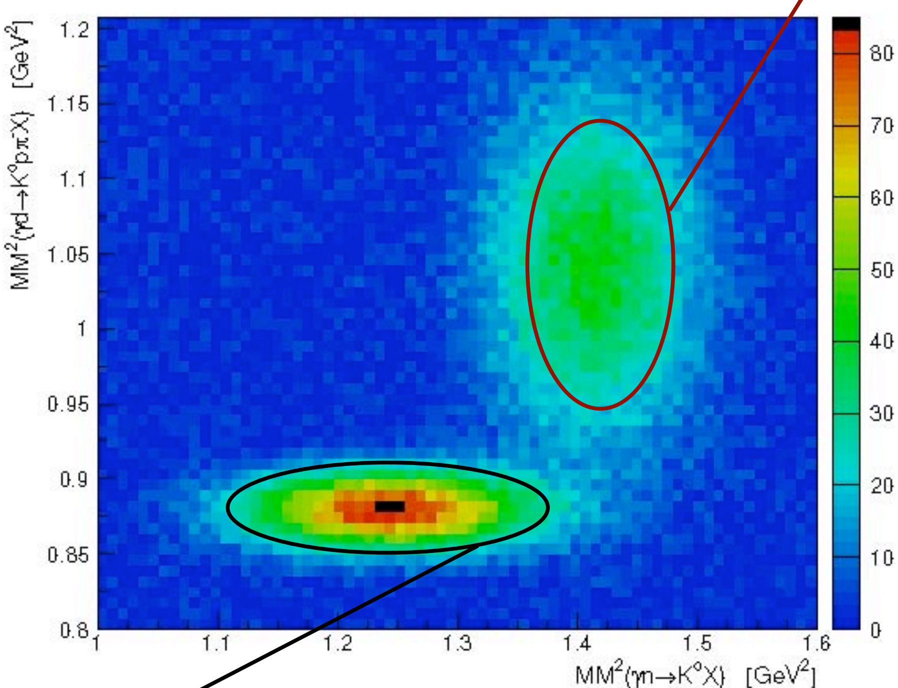
(Missing-Mass)^2 distributions:

After cuts:

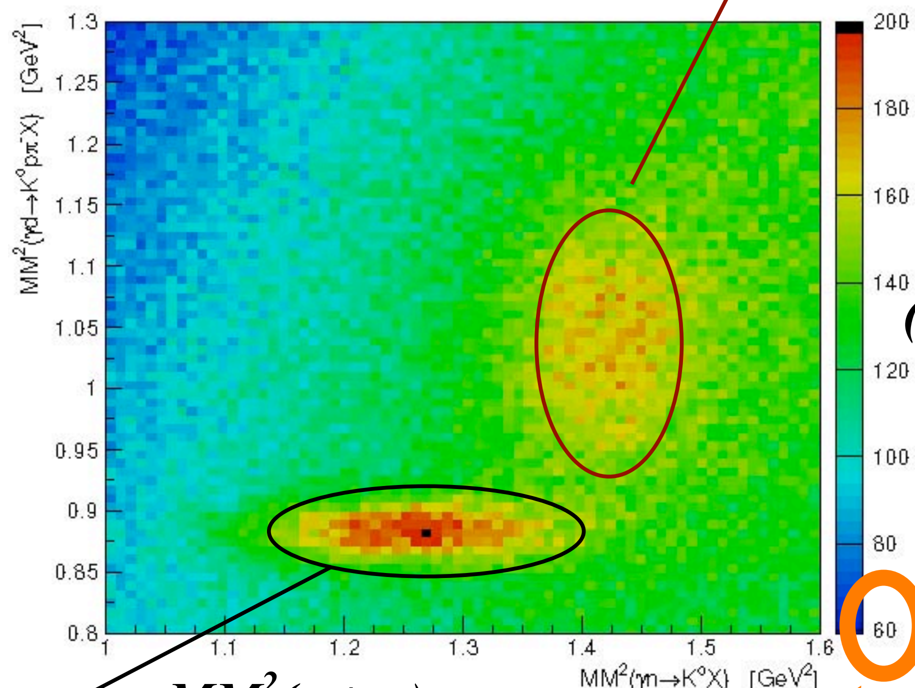
- *inv* mass($K^0 = \pi^+\pi^-$)
- < K^0 - [$p\pi^-$] > *coplanarity*

$$\gamma n(p) \rightarrow K^0\Sigma^0(p) \rightarrow K^0 + \Lambda\gamma + (p)$$
$$\rightarrow [\pi^+\pi^-][p\pi^-](\gamma p)$$

$\vec{\gamma} + H \cdot \vec{D}$



$\vec{\gamma} + C_4 \cdot \vec{D}_9 \cdot O \cdot \vec{D}$



MM^2 $(\gamma + D)$

$MM^2(\gamma + n)$

$$\gamma n(p) \rightarrow K^0 + \Lambda + (p)$$
$$\rightarrow [\pi^+\pi^-][p\pi^-](p)$$

suppressed zero

MM2(K0L) HD,FROST

Approved Beam-time:

Setting	***E_0*** ***(GeV)***	***E_γ*** ***(GeV)***	***P_γ***	***$H\vec{D}$*** *(days)* **KΛ, KΣ**
Circular	1.7	0.7 - 1.6	41 - 79%	**11**
Circular	2.6	1.5 - 2.5	58 - 79%	**14**
Linear	3.0	0.7 - 0.9	89%	**3**
Linear	3.0	0.9 - 1.1	85%	**3**
Linear	4.5	1.1 - 1.3	90%	**7**
Linear	4.5	1.3 - 1.5	87%	**7**
Linear	5.5	1.5 - 1.7	88%	**7**
Linear	5.5	1.7 - 1.9	85%	**7**
Linear	5.5	1.9 – 2.1	82%	**8**
Linear	5.5	2.1 – 2.3	79%	**8**
				75

Approved Beam-time: | Butanol alternative

Setting	***E_0* (GeV)**	***E_γ* (GeV)**	***P_γ***	***$H\vec{D}$* *(days)* KΛ, KΣ**	***$C_4\vec{D}_9O\vec{D}$* *(days)* KΛ *only***	***$C_4\vec{D}_9O\vec{D}$* *(days)* KΛ, KΣ**
Circular	1.7	0.7 - 1.6	41 - 79%	**11**	200	600
Circular	2.6	1.5 - 2.5	58 - 79%	**14**	230	700
Linear	3.0	0.7 - 0.9	89%	**3**	45	110
Linear	3.0	0.9 - 1.1	85%	**3**	45	110
Linear	4.5	1.1 - 1.3	90%	**7**	105	260
Linear	4.5	1.3 - 1.5	87%	**7**	105	260
Linear	5.5	1.5 - 1.7	88%	**7**	105	260
Linear	5.5	1.7 - 1.9	85%	**7**	105	260
Linear	5.5	1.9 – 2.1	82%	**8**	120	285
Linear	5.5	2.1 – 2.3	79%	**8**	120	285
				75	**1150**	**3130**

$\gamma + n(p) \rightarrow K^0\Lambda$ *experiments at JLab with HDice:*

- ***single-pol observables measured from double-pol asy***
- ***double-pol observables measured from triple-pol asy***

Photon beam		Target			Recoil			Target - Recoil								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

$\Uparrow$

simultaneous B-R with HD $\Leftrightarrow$ ***Full set of 16***

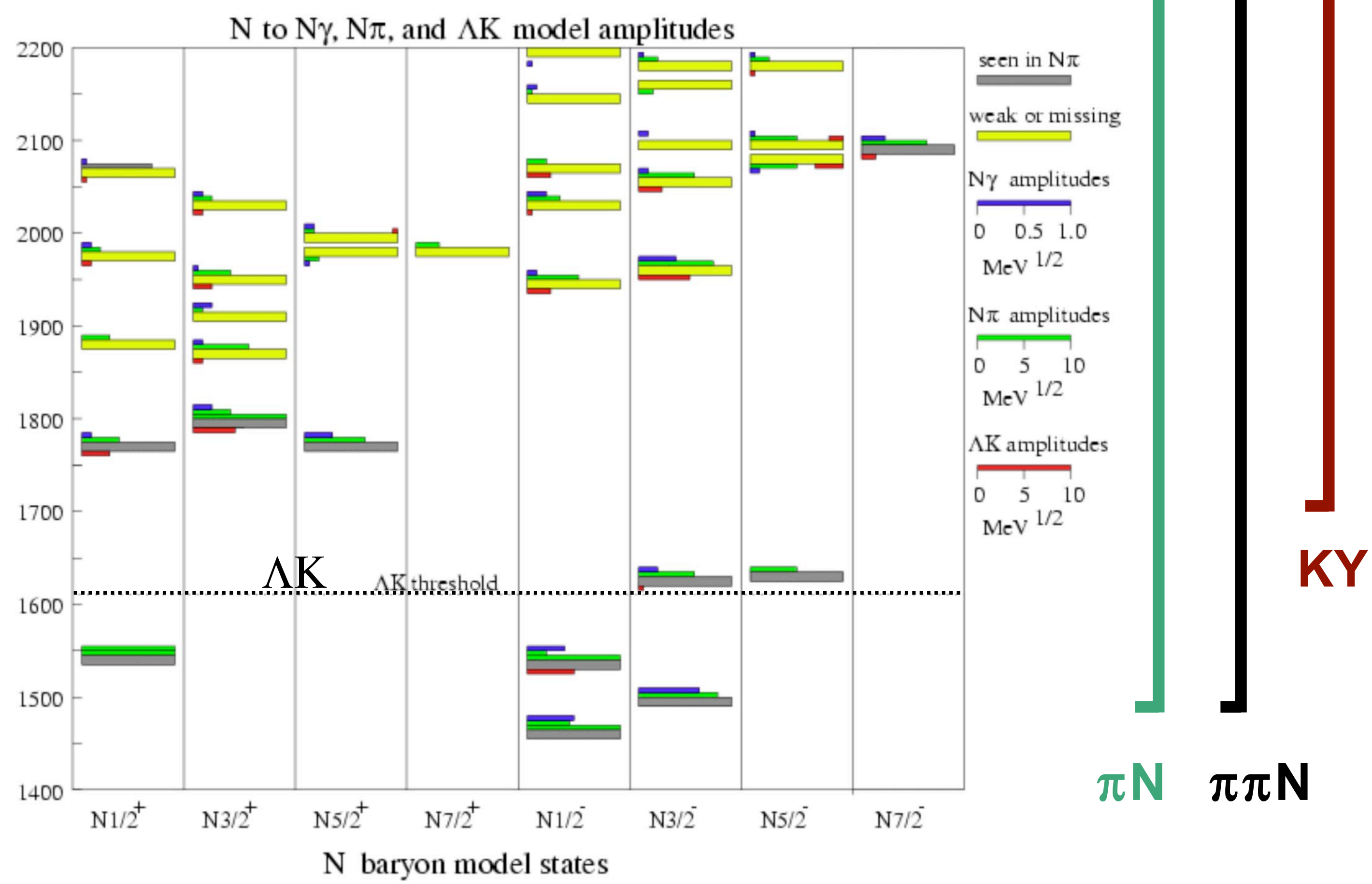
schedule	CLAS run period	beam	target	spokesmen
2010-2011	g14	$\vec{\gamma}_L$, $\vec{\gamma}_c$	$H \cdot \vec{D}$ ice	Sandorfi/Klein

Summary

- ***1st large data set for γ+n → πN, $\pi\pi$N, KΛ, KΣ*** ⇔ **common systematics**
- ***1st complete (over-)determination in 0⁻ photo-production: γ+n → $K^0\Lambda$***

E_γ		W
2.3	⇔	2.28
1.5	⇔	1.92
0.7	⇔	1.48

existing γ+n data: sparce 0 0



A unique opportunity to either expose a new rich spectroscopy or to alter the traditional picture of baryon structure

$\vec{H}\vec{D}$ice

Novel Physics with Frozen-spin Polarized Solid Hydrogen

A.M. Sandorfi
Thomas Jefferson National Accelerator Laboratory (JLab)

- "freezing" spins in a solid HD quantum crystal
  - gymnastics with solid hydrogen

Q. when a bullet hits a house, does the house move ?
  - the $\vec{\gamma} + \vec{H}\vec{D}$ GDH sum rule experiments at BNL (2004-2006)

Q. what degrees of freedom generate the nucleon's spectrum ?
  - $\vec{\gamma} + \vec{H}\vec{D}$ "complete" experiments at JLab (2010-2011)

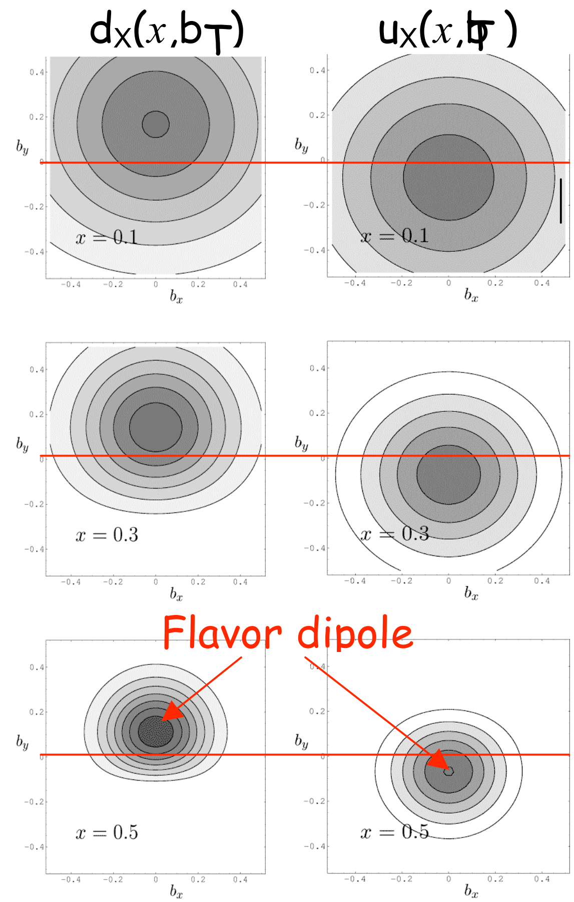
Q. can we construct a tomographic image of the proton ?
  - Generalized Parton Distributions from $\vec{e} + \vec{H}\vec{D}$ (2011)

Novel Questions with Frozen-Spin Polarized Solid Hydrogen

- $\vec{e} + \vec{H}\vec{D}$ for proton tomography (2011) from Generalized Parton Distributions

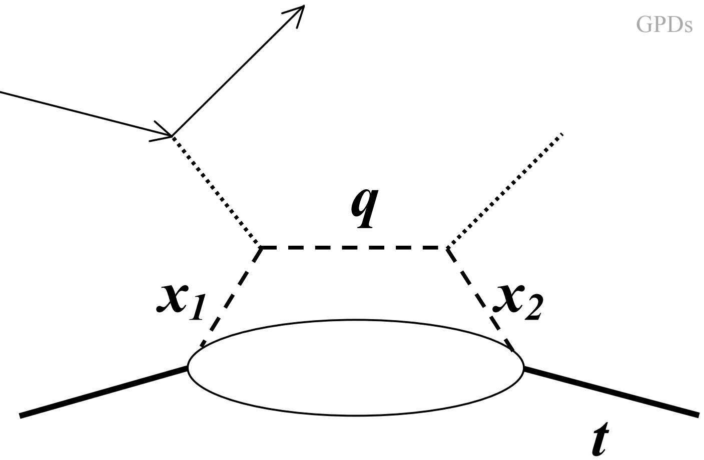
2(xy) + 1(z) Dim Cat scan of the human brain

2(xy) + 1(p) Dim scan of the nucleon



Target polarization

Generalized Parton Distributions



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

- average longitudinal momentum fraction, $x = \frac{1}{2}(x_2 + x_1)$
- momentum fraction difference, $\xi = \frac{1}{2}(x_2 - x_1)$
- momentum transferred to nucleon, t

GPDs provide underlying framework; observables calc as integrals

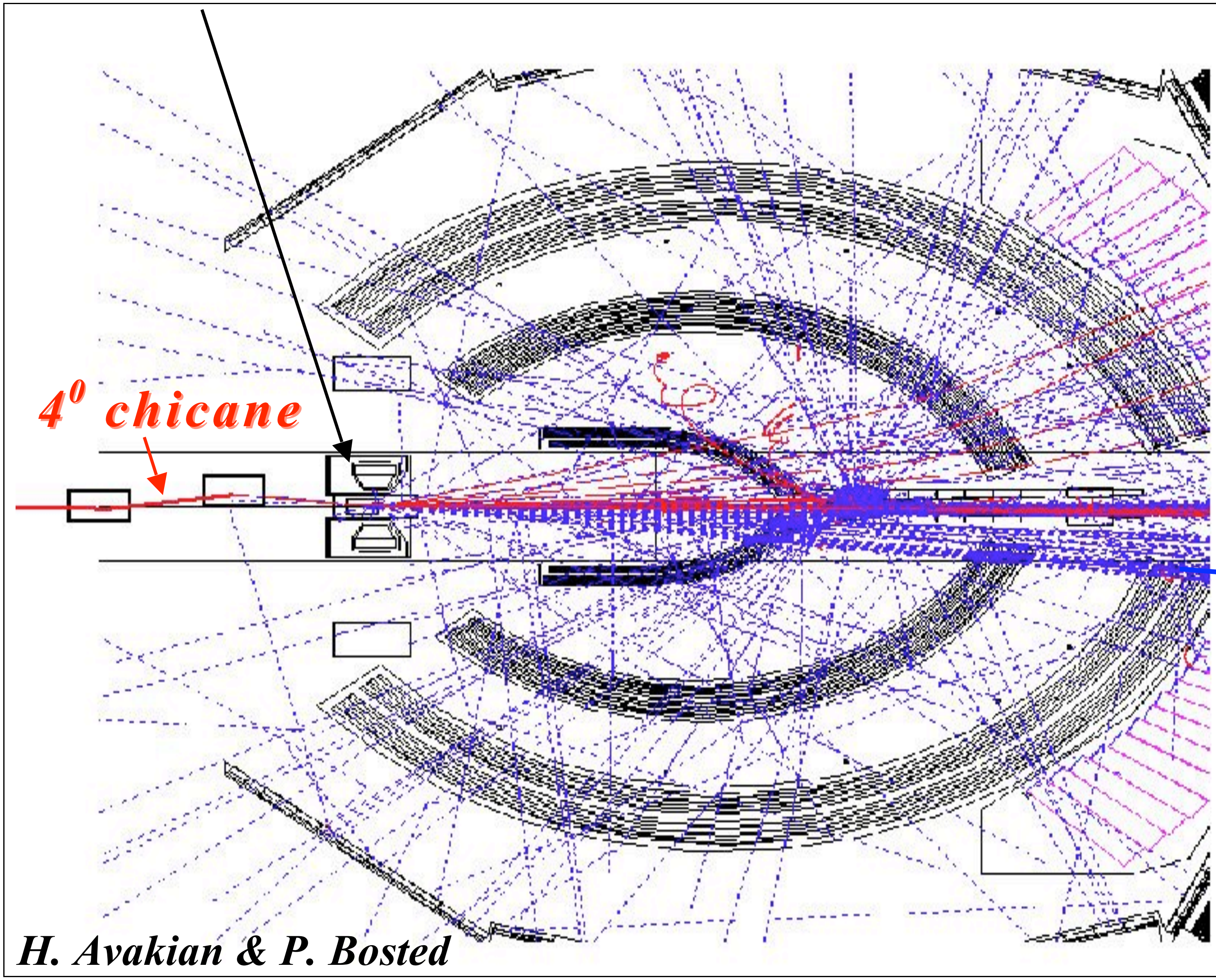
- DIS quark momentum distributions $\Leftrightarrow\ \xi = t = 0$
- Form Factors(t) $\Leftrightarrow \int dx\ GPD$
- tomographic distributions: $q(x, b_\perp) = \frac{1}{4\pi^2} \int e^{i\sqrt{t}b_\perp} E(x,t) d^2t$

$\Uparrow$

transverse target polarization asymmetries required to access E

UVa (Oxford) Transverse $N\vec{H}_3$ / $N\vec{D}_3$ target with CLAS

$BdL \approx 4.2\ T \times 0.3\ m$



- *large transverse field compensated by chicane*
- *brem γ's peaked along incoming e at ~4^0*

⇒ *"Sheet of flame"* 4^0

⇒ *large background*

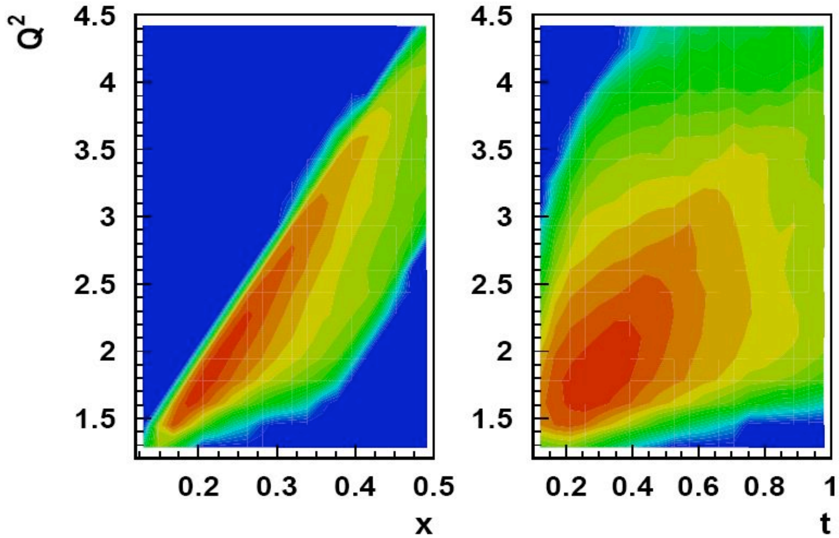
- *limited acceptance in θ and Q^2*

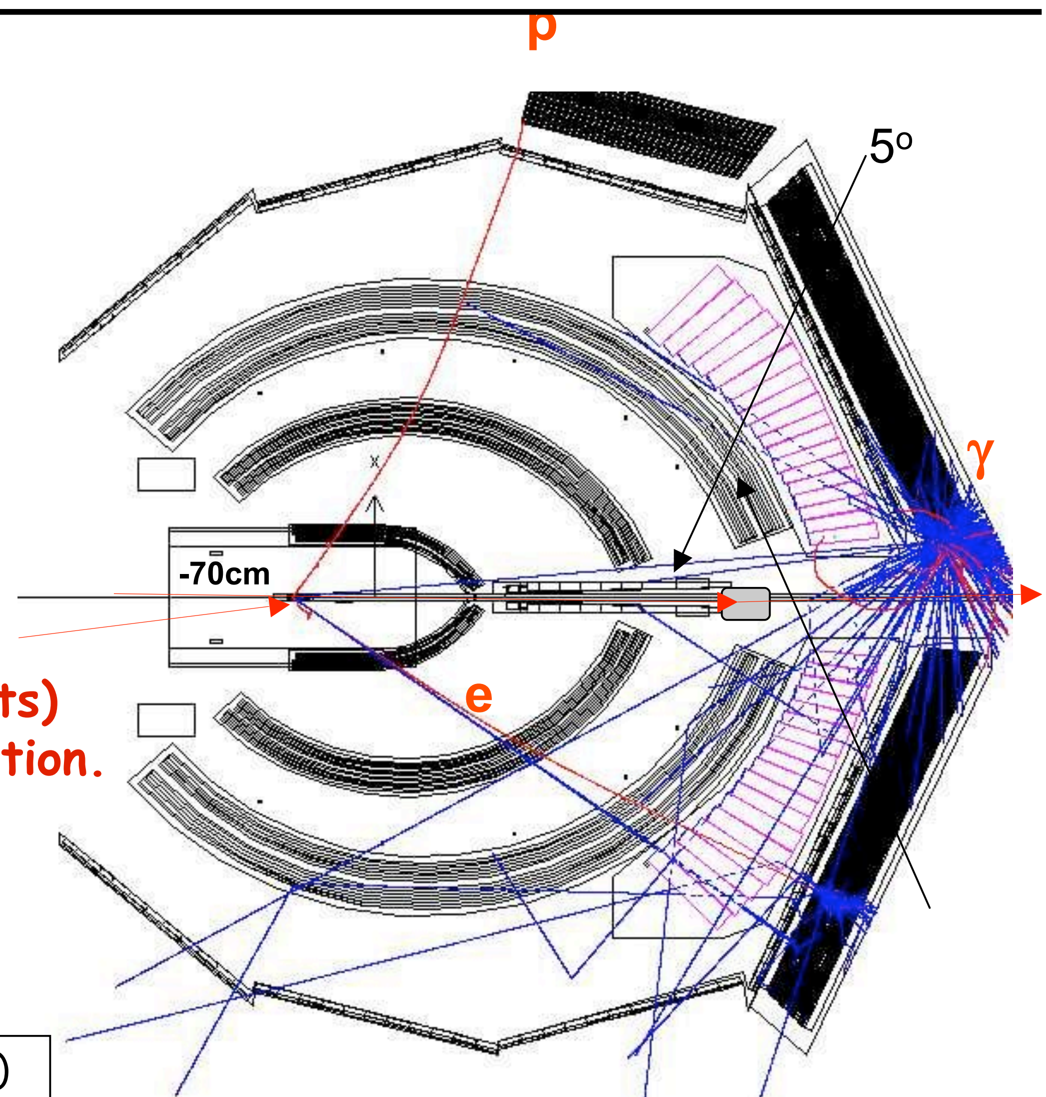
Expected spin-relaxation times for appropriately prepared targets

	measured (γ)		projected	
B	***0.89 tesla***	***0.01 tesla***	***0.40 tesla***	***0.04 tesla***
B × dL (for L=0.12m)	***0.108 tesla-m***	***0.001 tesla-m***	***0.048 tesla-m***	***0.005 tesla-m***
orientation	***solenoid***	***solenoid***	***saddle***	***saddle***
$T_1(H)$	***> 300 d***	***8 d***	***>200 d***	***~ 30 d***
$T_1(D)$	***> 500 d***	***55 d***	***>300d***	***~200 d***

compare to 1.4 T-m with NH_3/ND_3

E08-021 simulation with transversely polarized HD in CLAS





- Beam on target at ~0.2°, parallel at center (use small steering magnets)
- HD holding field corrects e deflection.

Run conditions

- 25 days of HD (+5 days of H, D, empty target)
- 4cm HD, 2 nA
- beam polarization 80%
- **HD-Ice target polarization (H-75%,D-25%)**

Depolarization of frozen-spin $\vec{H}\vec{D}$ with electrons

- ***beam heating***

  - 5 nA of 10 GeV electrons ⇒ 5 mW heat in 2 cm of HD (GEANT)
    ≈ cooling power of BNL In-Beam Cryostat at 0.5 K (can be increased)

  - 4 times lower heating than FROST(Butanol), due to lower Z
  - spin-relaxation time (T_1) for HD ~ a year at these temperatures

- ***spin-diffusion of paramagnetic centers***

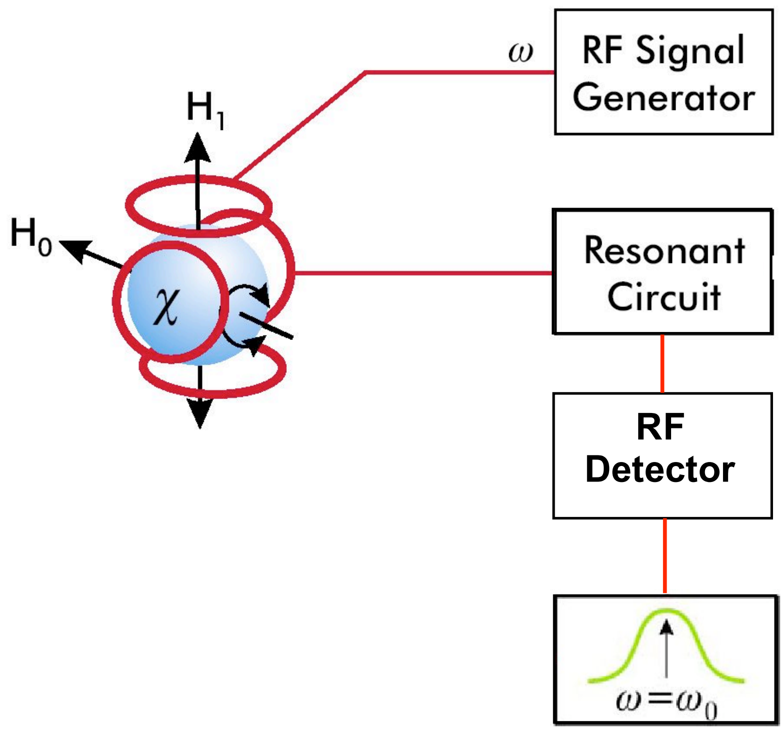
  - *e brem* creates free radicals with randomly oriented nuclear spin;
    absolute number are small, but these can be *sinks* for polarization

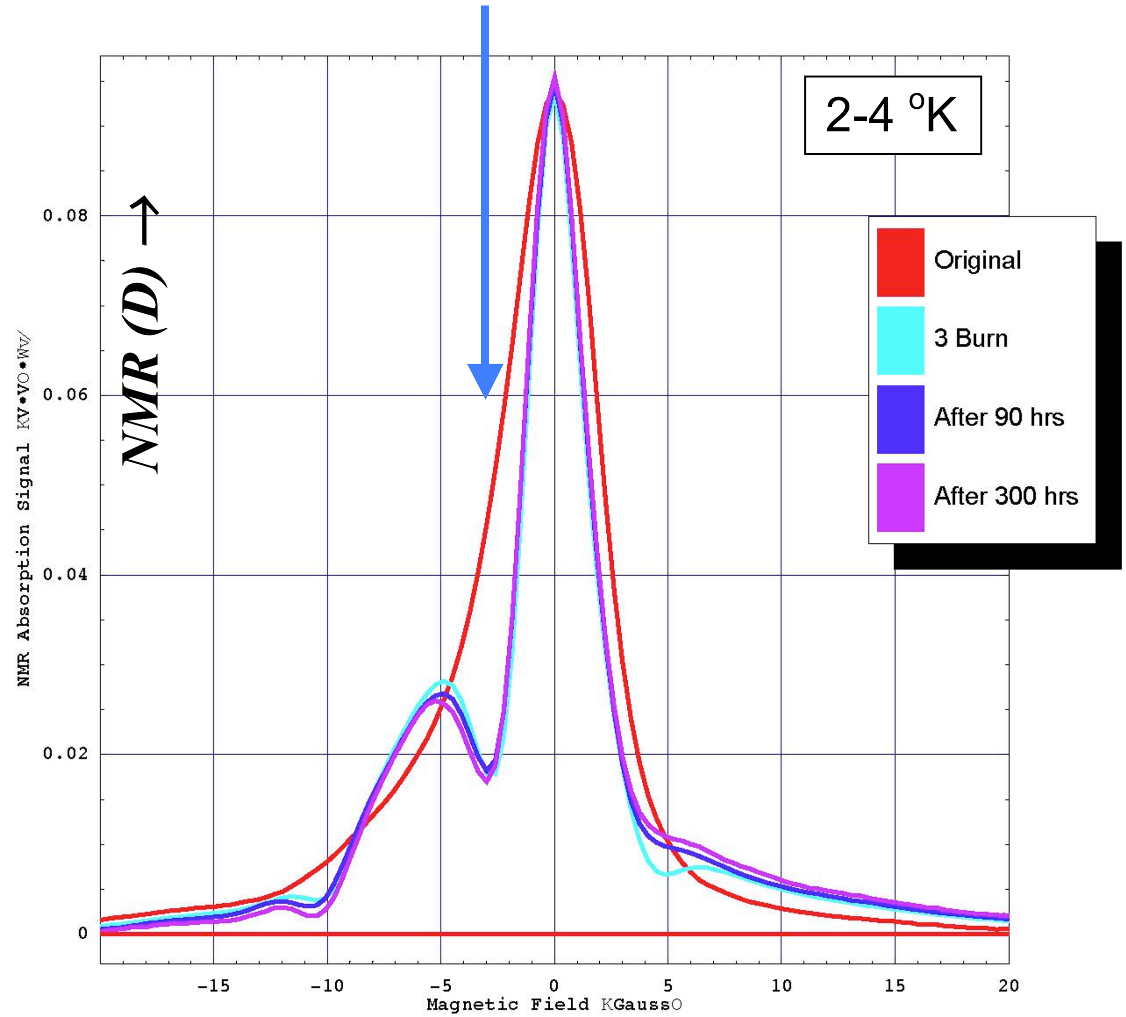
  - *spin-diffusion* time measured at 2 K: ~ 1 day for $\vec{H}$
    ~ ∞ for $\vec{D}$ (unmeasurable in 2 weaks)

  (*spin-diffusion* times could increase at lower T ?)

Burning an RF polarization hole

- *cross-coil NMR*
- *field scan at fixed frequency*





H_o (∝ position) →

- *H_o inhomogeneity ⇒ D-line width*
- *field and position are correlated*
- *no change in the D-polarization hole after 2 weeks ⇒ D spin diffusion extremely slow*

Electron experiments with transversely polarized $\vec{H}$ and $\vec{D}$

- ***DVCS, DVMP :***

  $\Rightarrow$ ***E GPD*** $\rightarrow$ ***2+1 dimensional tomography*** $\Leftarrow$

  $\rightarrow$ ***quark orbital angular momentum***

- ***Semi-inclusive-DIS :***

  $\Rightarrow$ ***Collins function*** $\rightarrow$ ***transverse $\vec{q}q \rightarrow$ Asy in hadron fragmentation***

  $\rightarrow$ ***transverse quark orbital angular momentum***

  $\Rightarrow$ ***Sivers function*** $\rightarrow$ ***u-d separation in $\vec{N}^{\perp} \rightarrow$ single-spin Asy***

- ***Inclusive-DIS :***

  $\Rightarrow$ ***g_2, A_2 PDF*** $\rightarrow$ ***color-polarizability of the gluon field***

- ***N* transition form factors :***

  $\rightarrow$ ***constraining structure of baryons***

HDice Timeline

- move equipment from BNL to JLab ✔
- HDice Lab building construction – Feb – June’09
- Installation of Cryogenic equipment into HDice Lab – beginning June’09
- polarize sets of targets for E06-101 – Mar-June’10; Aug-Dec’10
- Installation in Hall B – July-Sept’10
- E06-101 run: $\vec{\gamma} + \vec{H} \cdot \vec{D}$ – Sept’10-April’11
- e+HD test – April’11
- polarized targets for e+HD DVCS – June-Oct’11
- E08-021 run: $\vec{e} + \vec{H} \cdot \vec{D}$ – Nov-Dec’11