Proton remains puzzling

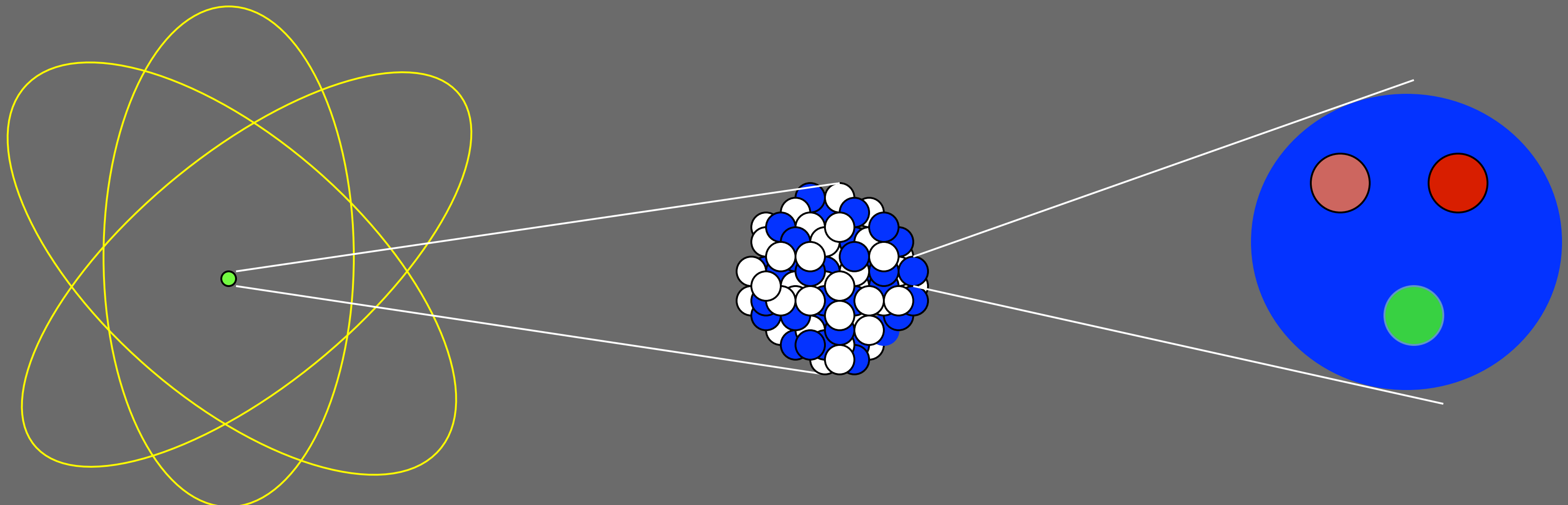
Proton mass, spin, charge radius and even new physics

Haiyan Gao

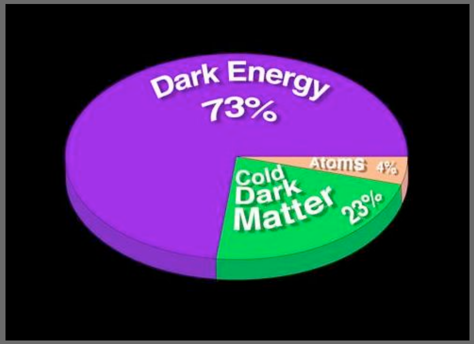
Duke University and Duke Kunshan University

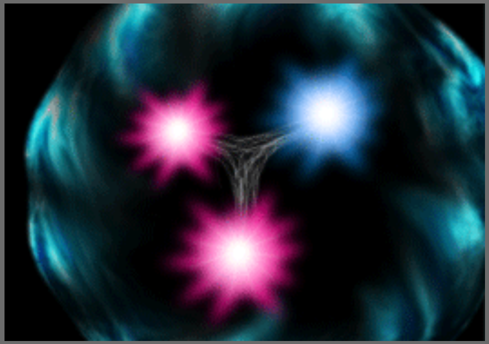
Nuclear physics is the study of the structure of matter

- **Most of the visible mass and energy in the universe around us comes from nuclei and nuclear reactions.**
- **The nucleus is a unique form of matter in that all the forces of nature are present : (strong, electromagnetic, weak, and of course gravity).**

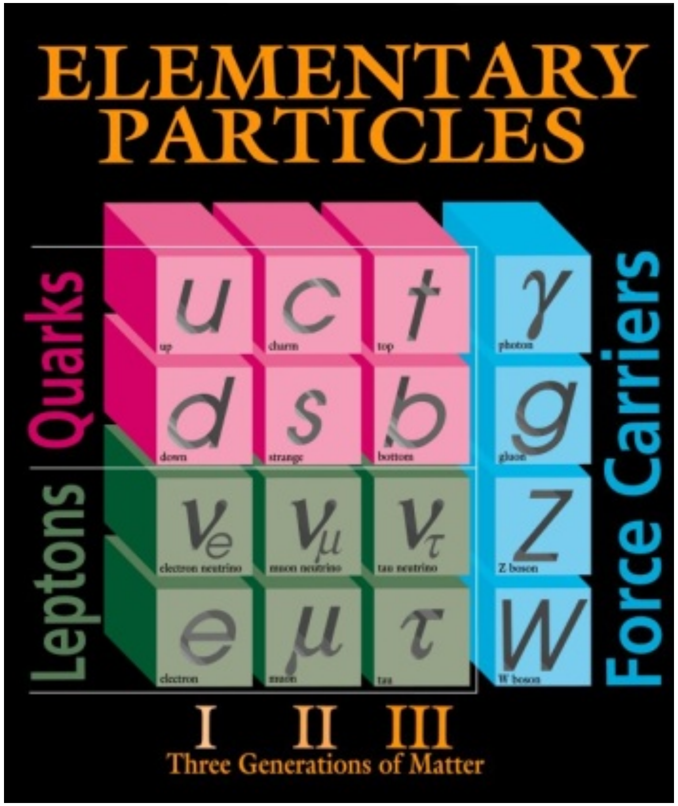


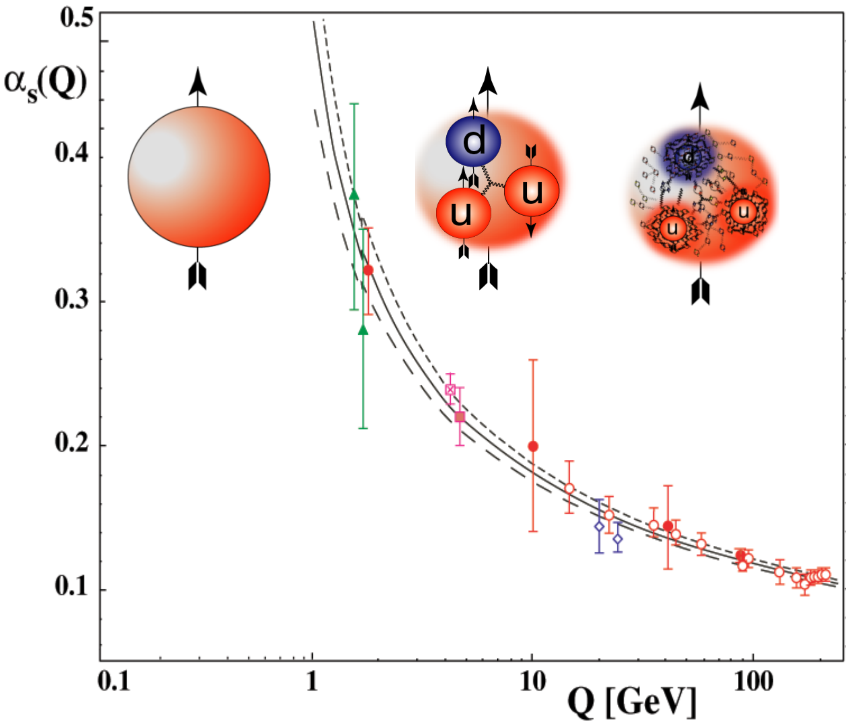
atom: **10^{-10} m** nucleus: **10^{-14} m** nucleon: **10^{-15} m**





QCD: still unsolved in non-perturbative region





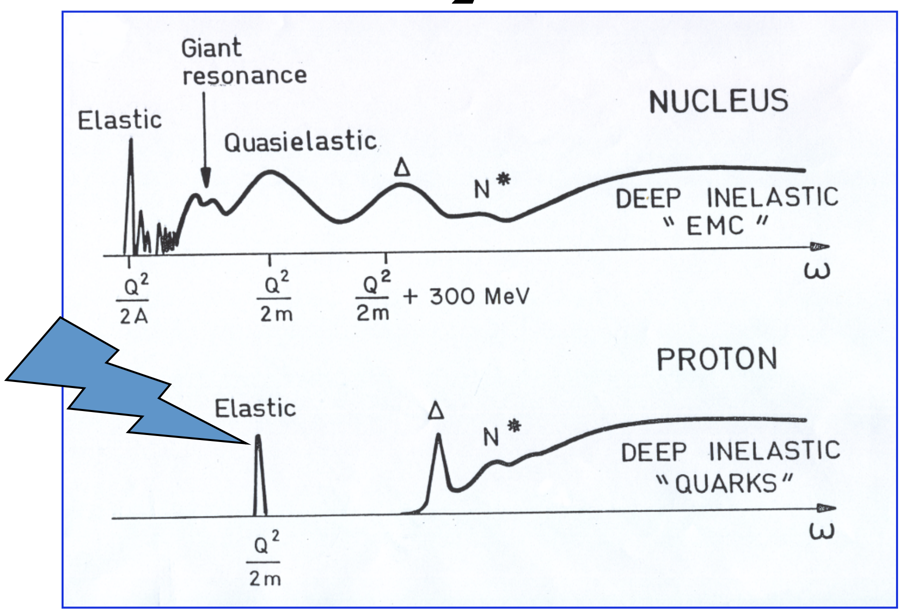
Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom''*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *Nucleon structure is one of the most active areas*

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed (two-photon physics)***
- ***Vary the wave-length of the probe to view deeper inside***

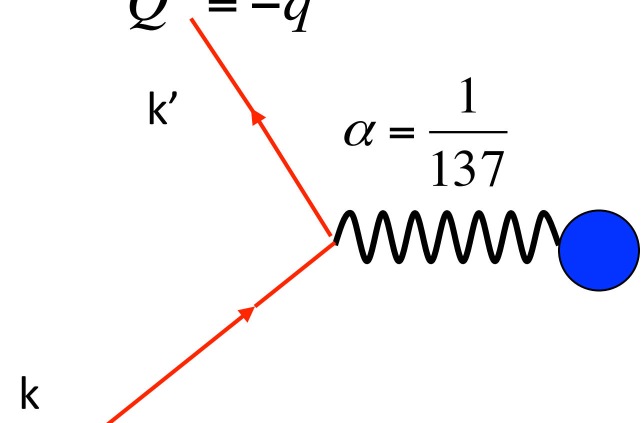
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \right) \qquad \tau = -q^2 / 4M^2$$



Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$



$$\alpha = \frac{1}{137}$$

What is inside the proton/neutron?

1933: Proton's magnetic moment


Nobel Prize
In Physics 1943

Otto Stern

"for … and for his discovery of the magnetic moment of the proton".

$g \neq 2$

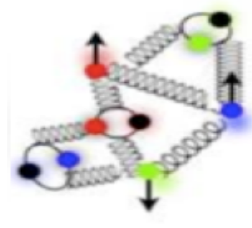
1960: Elastic e-p scattering


Nobel Prize
In Physics 1961

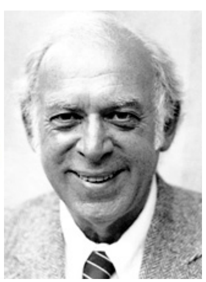
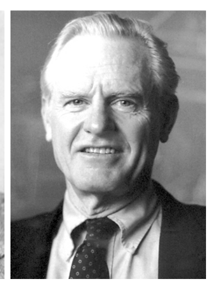
Robert Hofstadter

"for … and for his thereby achieved discoveries concerning the structure of the nucleons"

Form factors $\rightarrow$ Charge distributions



1969: Deep inelastic e-p scattering


Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

Jian-Wei Qiu

1974: QCD Asymptotic Freedom



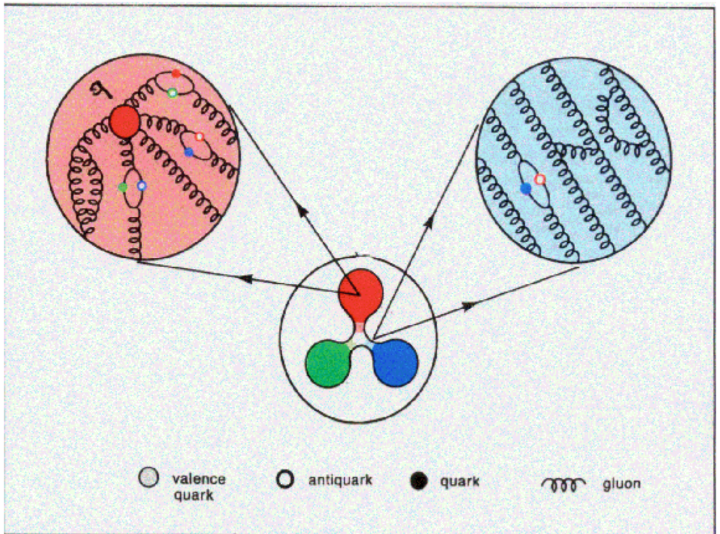

Nobel Prize in Physics 2004

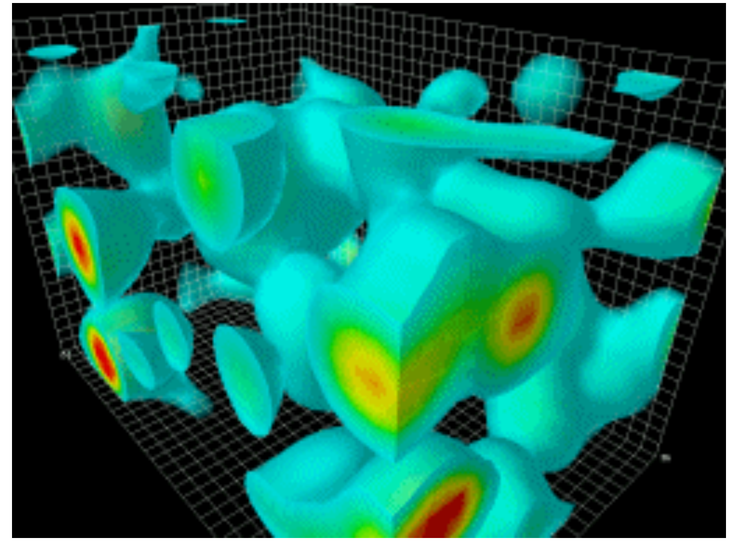
David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Proton: a fascinating many-body relativistic system

Higgs discovery almost irrelevant to proton mass





$$H_{QCD} = H_q + H_m + Hg + H_a$$

$H_q =$ Quark energy $\int d^3x\ \psi^\dagger\left(-i\mathbf{D}\cdot\alpha\right)\psi$

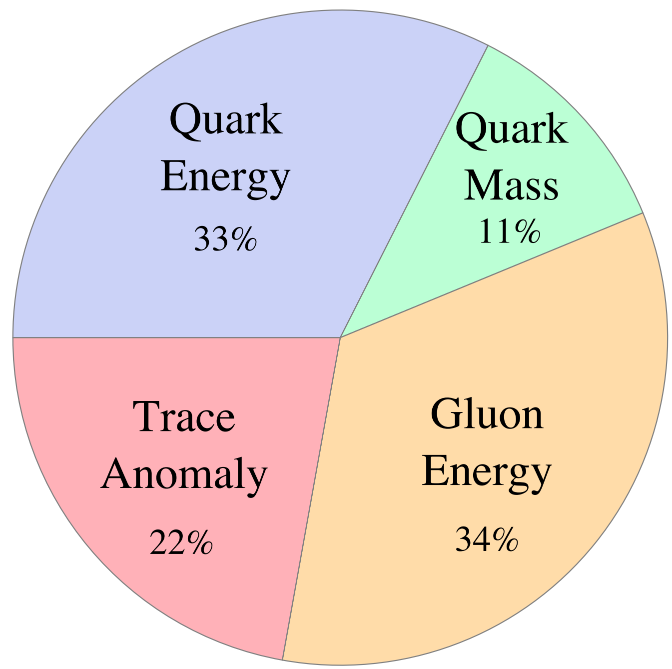
$H_m =$ Quark mass $\int d^3x\ \bar{\psi}m\psi$

$H_g =$ Gluon energy $\int d^3x\ \frac{1}{2}\left(\mathbf{E^2}+\mathbf{B^2}\right)$

$H_a =$ Trace anomaly $\int d^3x\ \frac{9\alpha_s}{16\pi}\left(\mathbf{E^2}-\mathbf{B^2}\right)$

Sets the scale for the Hadron mass!

X. Ji PRL 74 1071 (1995)



Spin Milestones and Proton Spin Puzzle

- Spin Milestones: (Nature)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - **1980s: "Proton spin crisis" (now puzzle)**
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: "New breakthrough in spin physics"?

topological insulator, quantum anomalous Hall effect, etc..

Pauli and Bohr watch a spinning top

Proton spin taken for granted for coming from the spin of the quarks!!

Nature: http://www.nature.com/milestones/milespin/index.html

Impressive experimental progress in QCD spin physics in the last 25 years

- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C

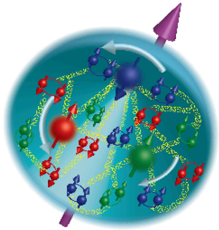
- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab

- **Polarized pp collisions**
  - BNL: PHENIX & STAR

- **Polarized e+e- collisions**
  - KEK: Belle

Z. Meziani

Nucleon Spin Decomposition



Proton spin puzzle

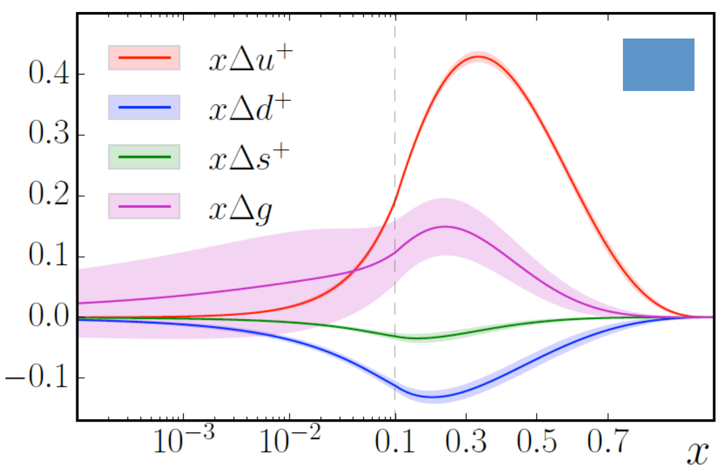
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

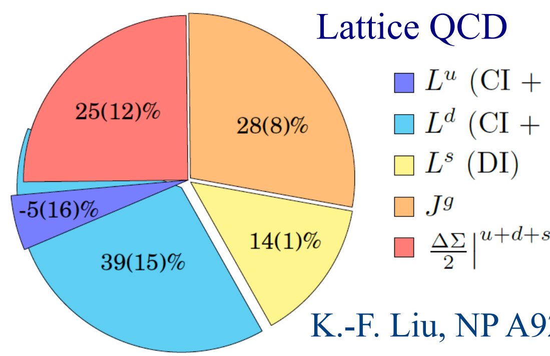
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PRD (2016).



K.-F. Liu, NP A928, 99 (2014).

Access to $L_{q/g}$

It is necessary to have transverse information.

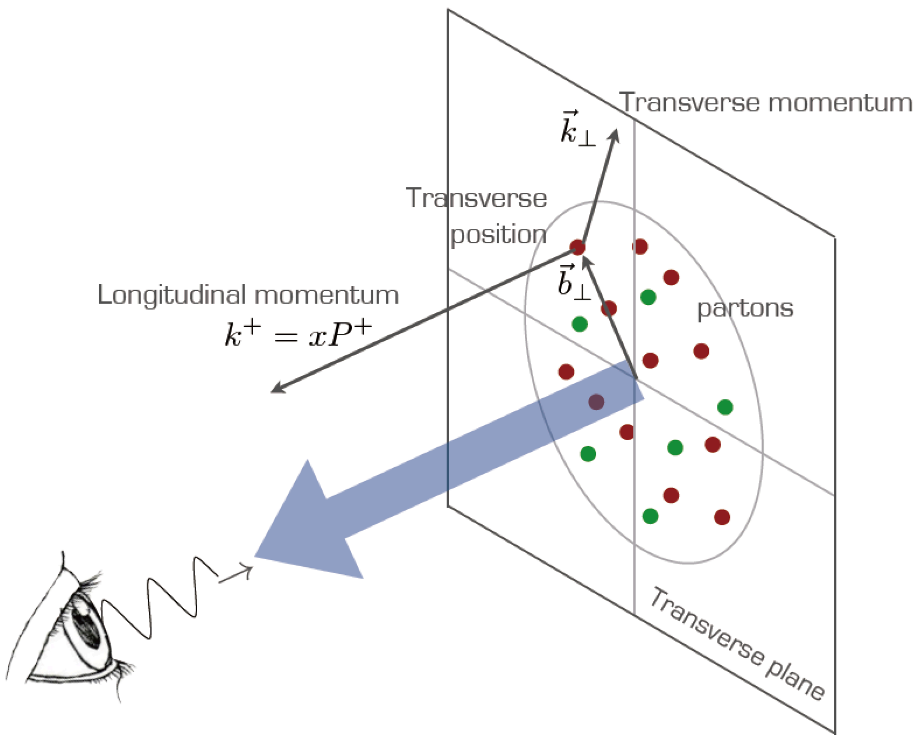
Coordinate space: GPDs

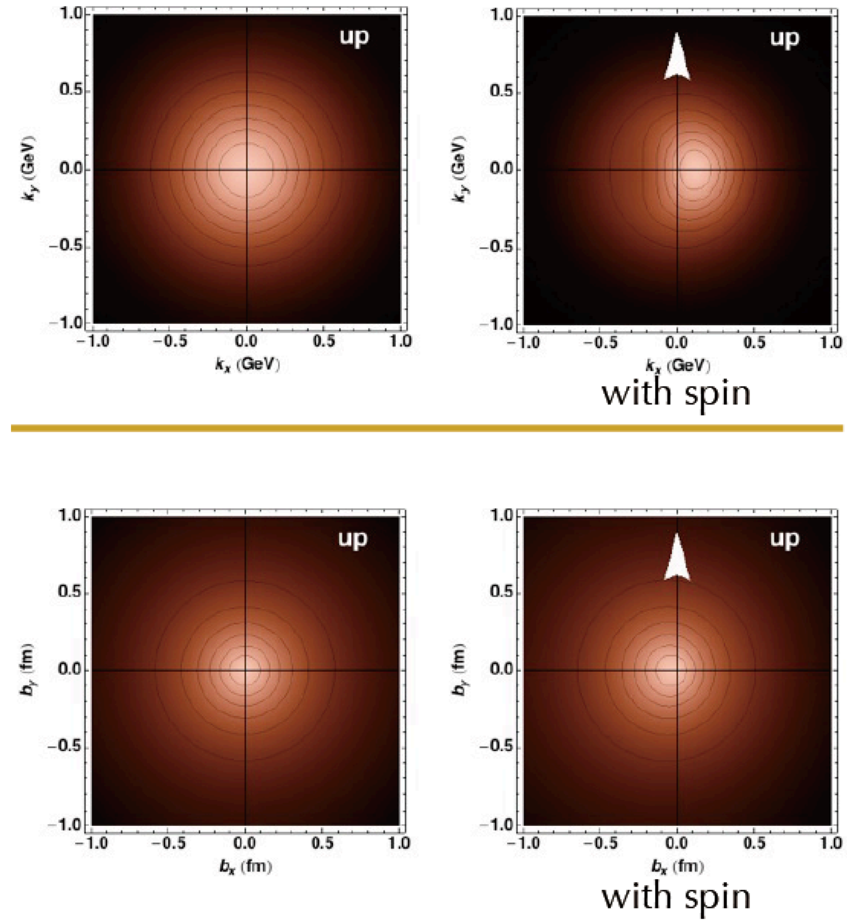
Momentum space: TMDs

3D imaging of the nucleon.

Latest Lattice QCD results suggest 50% from gluon spin (Phys. Rev. Lett. 118, 102001)

Nucleon Structure from 1D to 3D – important program at JLab 12-GeV

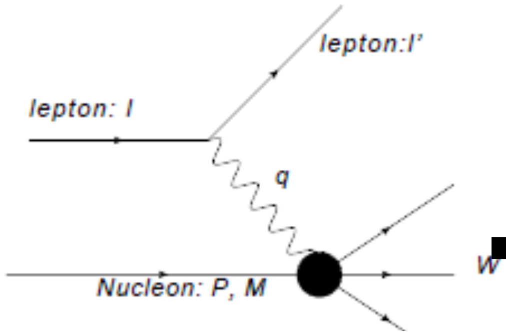


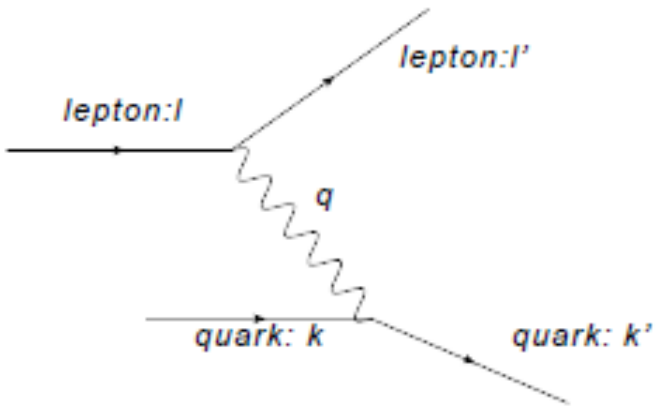


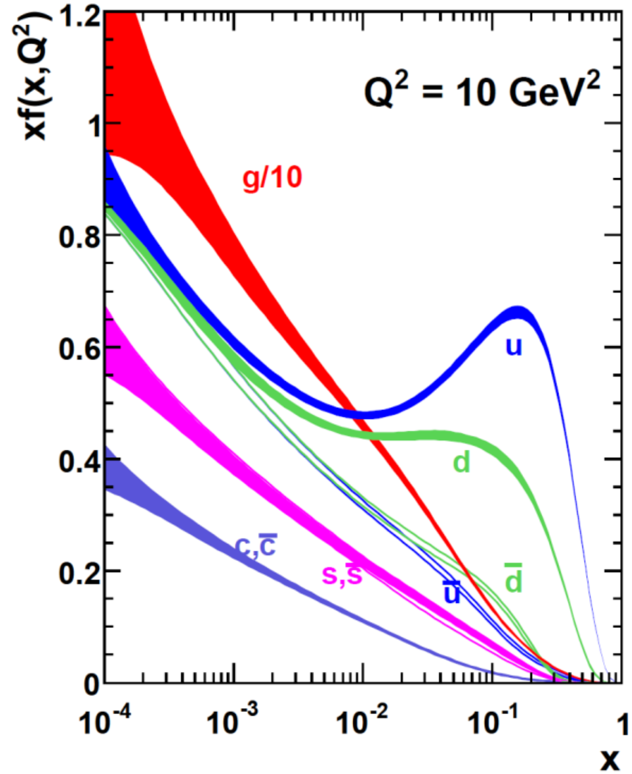
Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

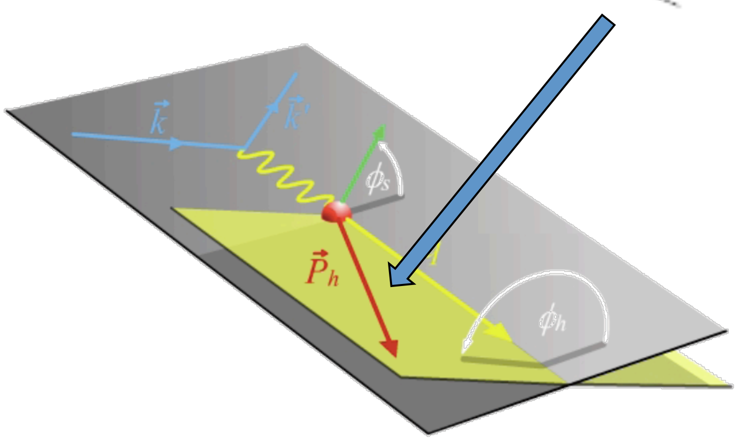
[Bacchetta's talk (2016)]

Lepton Scattering ----- A powerful tool









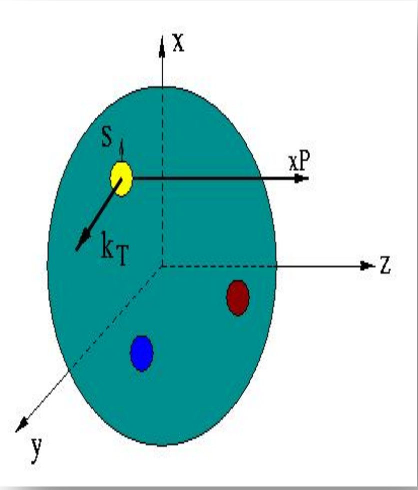
tagging the struck quark through leading hadrons
(semi-inclusive DIS)
to image in 3-momentum space

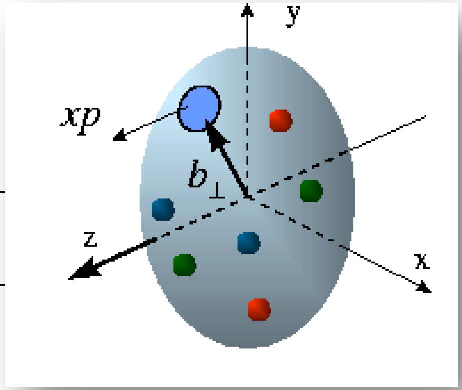
8 New TMD PDFs
$f_1(x,k_T)$, .. $h_1(x,k_T)$

Unified View of Nucleon Structure

$W_p^u(x, k_T, \boldsymbol{r_T})$ Wigner distributions

5D Dist.





$d^2\boldsymbol{r_T}$ → TMD PDFs: $f_1^u(x, k_T)$, .., $h_1^u(x, k_T)$

d^2k_T → GPDs/IPDs

3D imaging

TMD PDFs — d^2k_T → PDFs

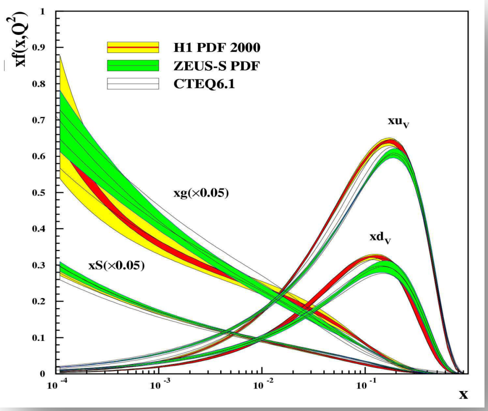
GPDs/IPDs — d^2r_T → PDFs

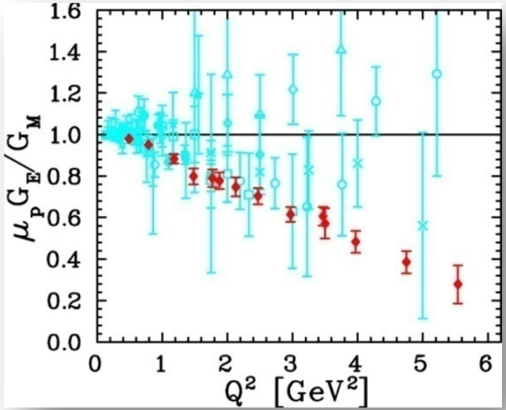
GPDs/IPDs — dx & Fourier Transformation → Form Factors

PDFs: $f_1^u(x)$, .., $h_1^u(x)$

1D

Form Factors: $G_E(Q^2)$, $G_M(Q^2)$



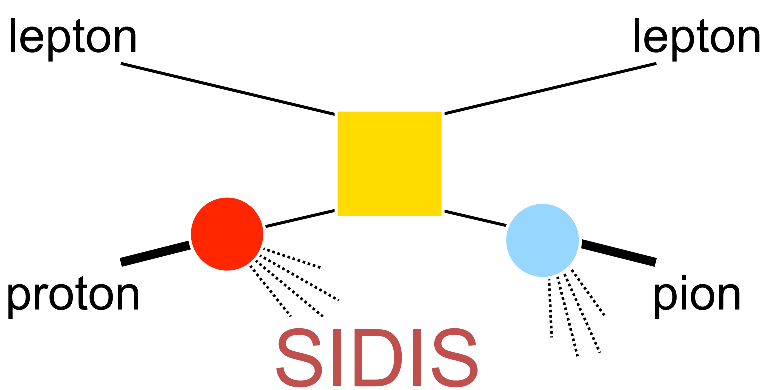


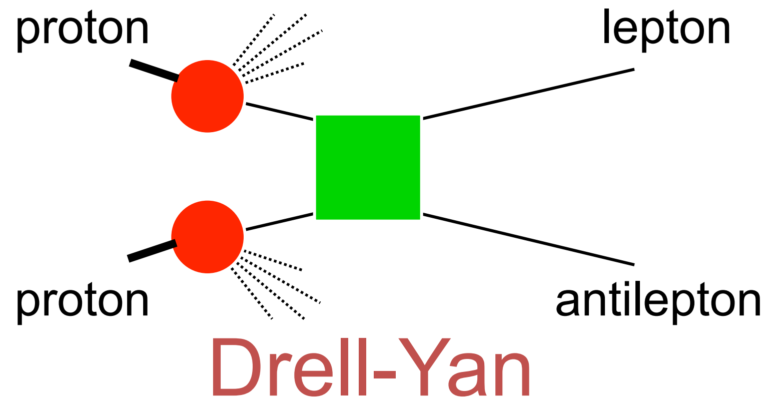
Leading Twist TMDS

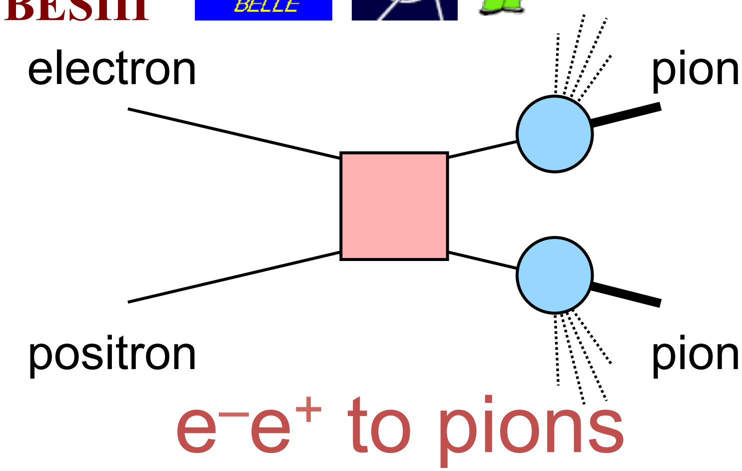
→ Nucleon Spin
→ Quark Spin

Nucleon Polarization	Quark polarization: Un-Polarized	Quark polarization: Longitudinally Polarized	Quark polarization: Transversely Polarized
U	$f_1 =$		$h_1^{\perp} = \; - \;$ **Boer-Mulder**
L		$g_1 = \; - \;$ **Helicity**	$h_{1L}^{\perp} = \; - \;$
T	$f_{1T}^{\perp} = \; - \;$ **Sivers**	$g_{1T}^{\perp} = \; - \;$	$h_{1T} = \; - \;$ **Transversity** $h_{1T}^{\perp} = \; - \;$ **Pretzelosity**

Access TMDs through Hard Processes







- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

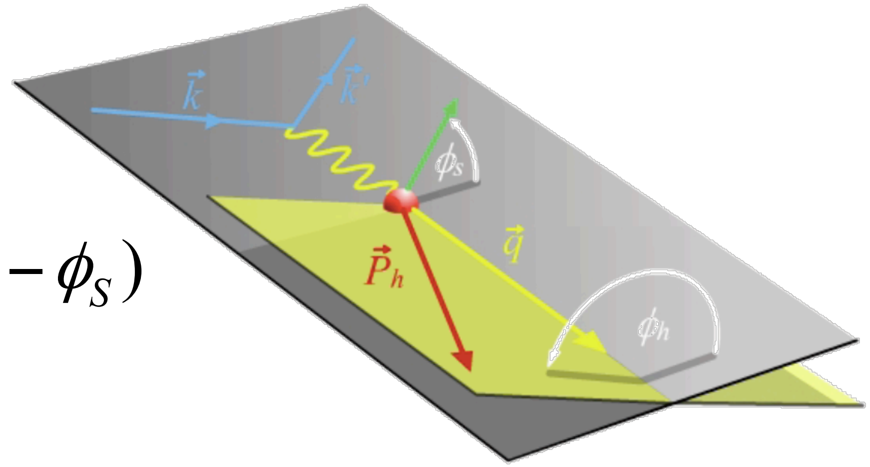
RHIC Transverse Spin Program

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$



$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S)\rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S)\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

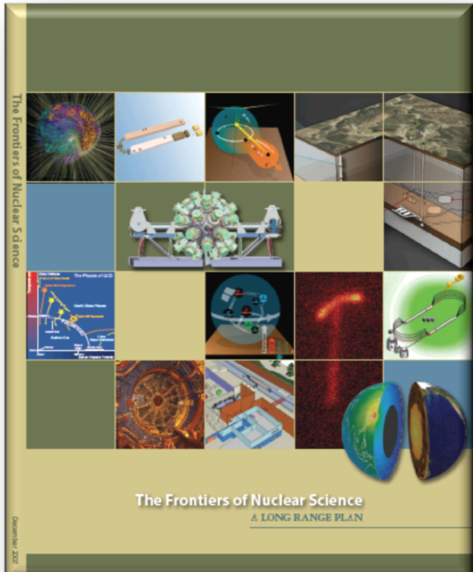
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S)\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

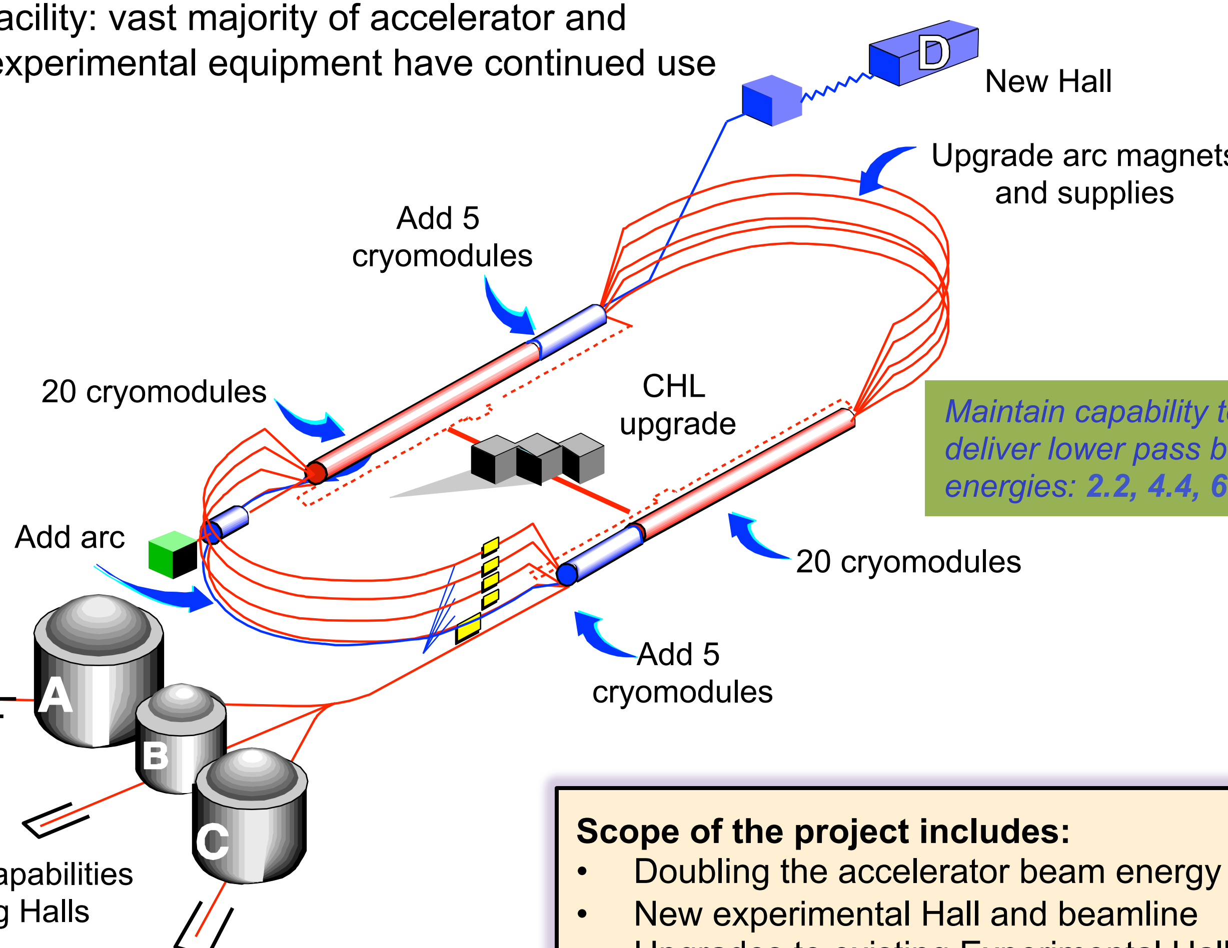
SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

12 GeV Upgrade at JLab



Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Scope of the project includes:

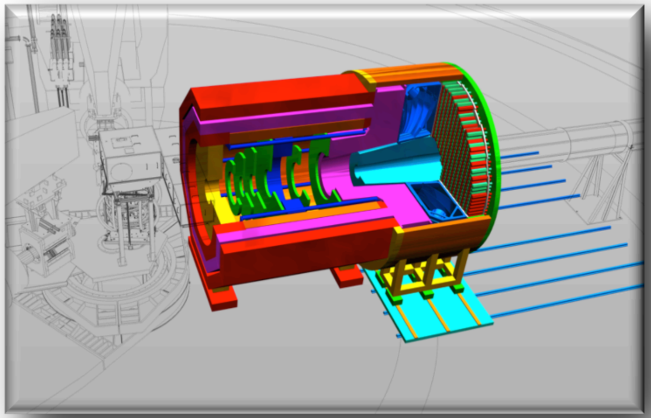
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

Solenoidal Large Intensity Device (SoLID) proposed for Hall A

Solenoidal Large Intensity Device (SoLID) Physics

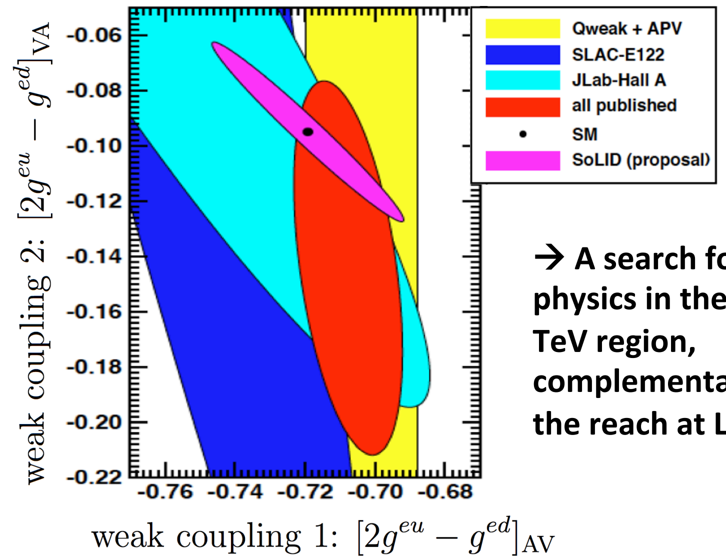
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage



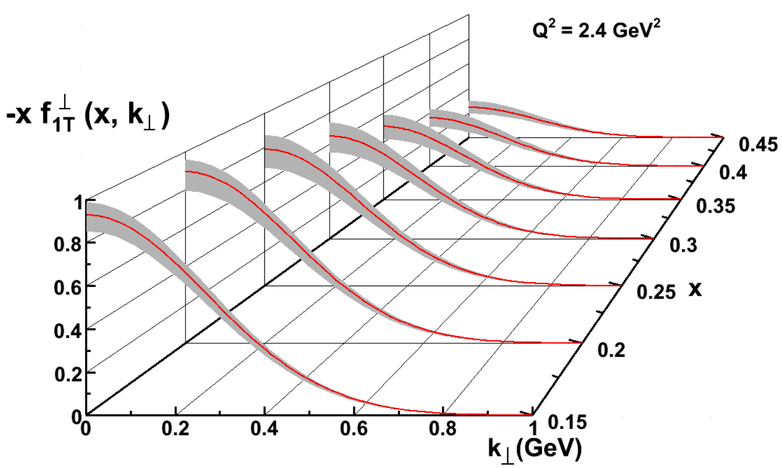
→ multi-purpose program to maximize the 12-GeV science potential

2) Precise determination of the electroweak couplings

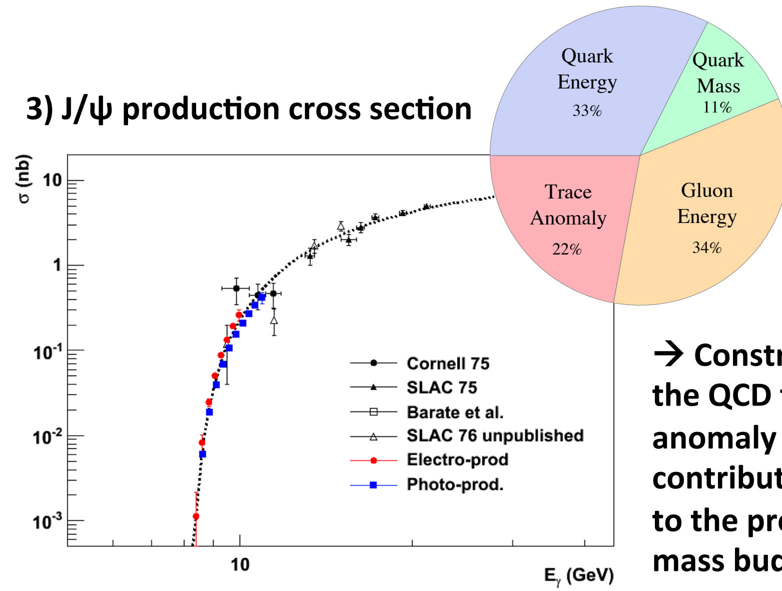


→ A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.

1) Precision in 3D momentum space imaging of the nucleon



3) J/ψ production cross section

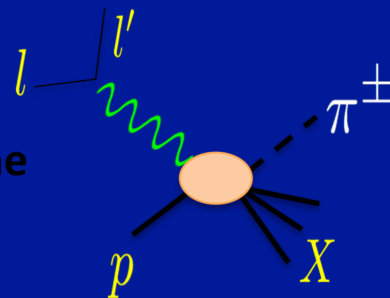


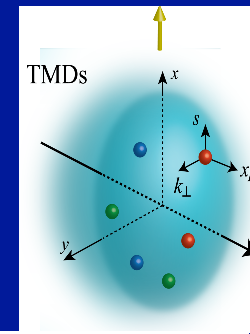
→ Constrain the QCD trace anomaly contribution to the proton mass budget

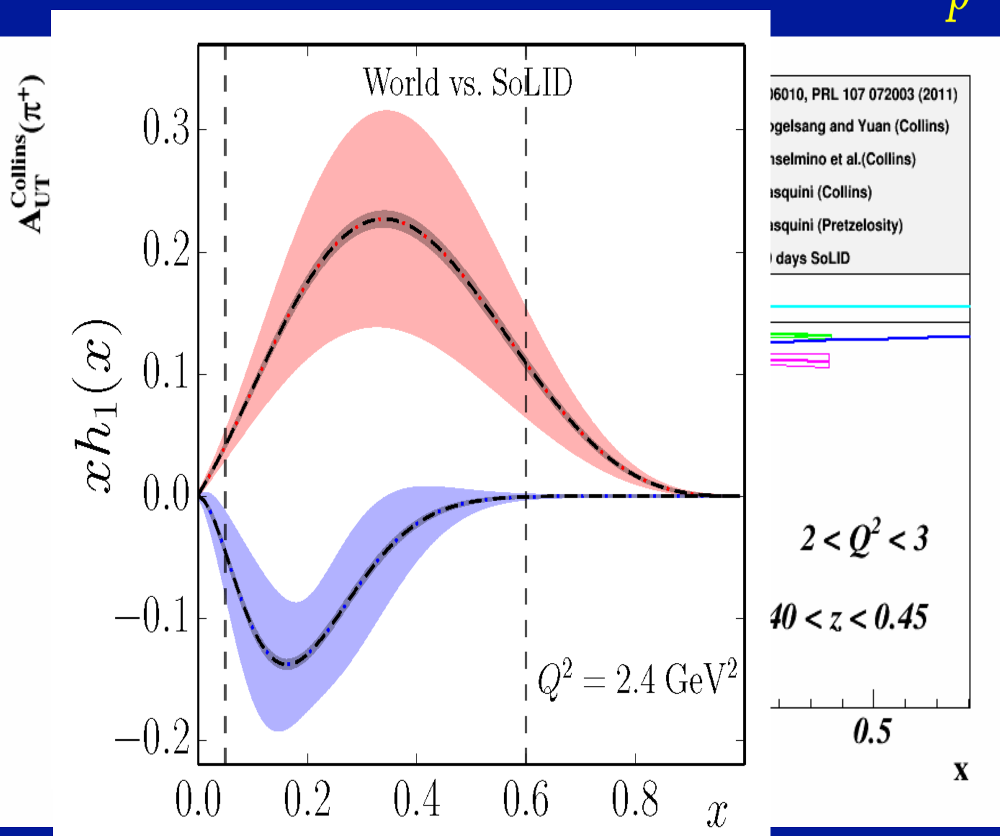
SIDIS @ SoLID:

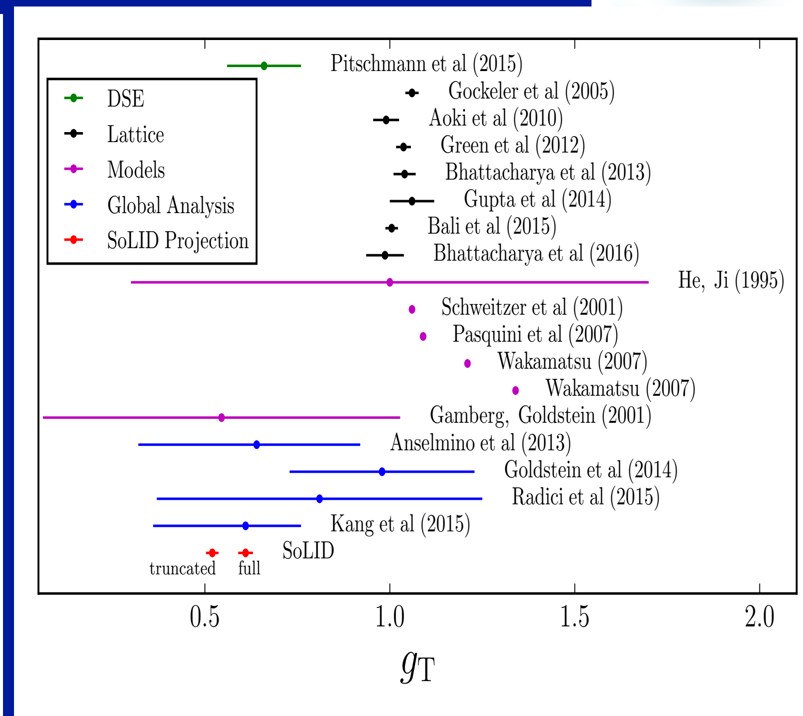
An unprecedented tool to unravel the rich structure and dynamics of nucleon structure in the valence region and the inner working of QCD

Impact of SoLID on our knowledge of the Transversity distributions



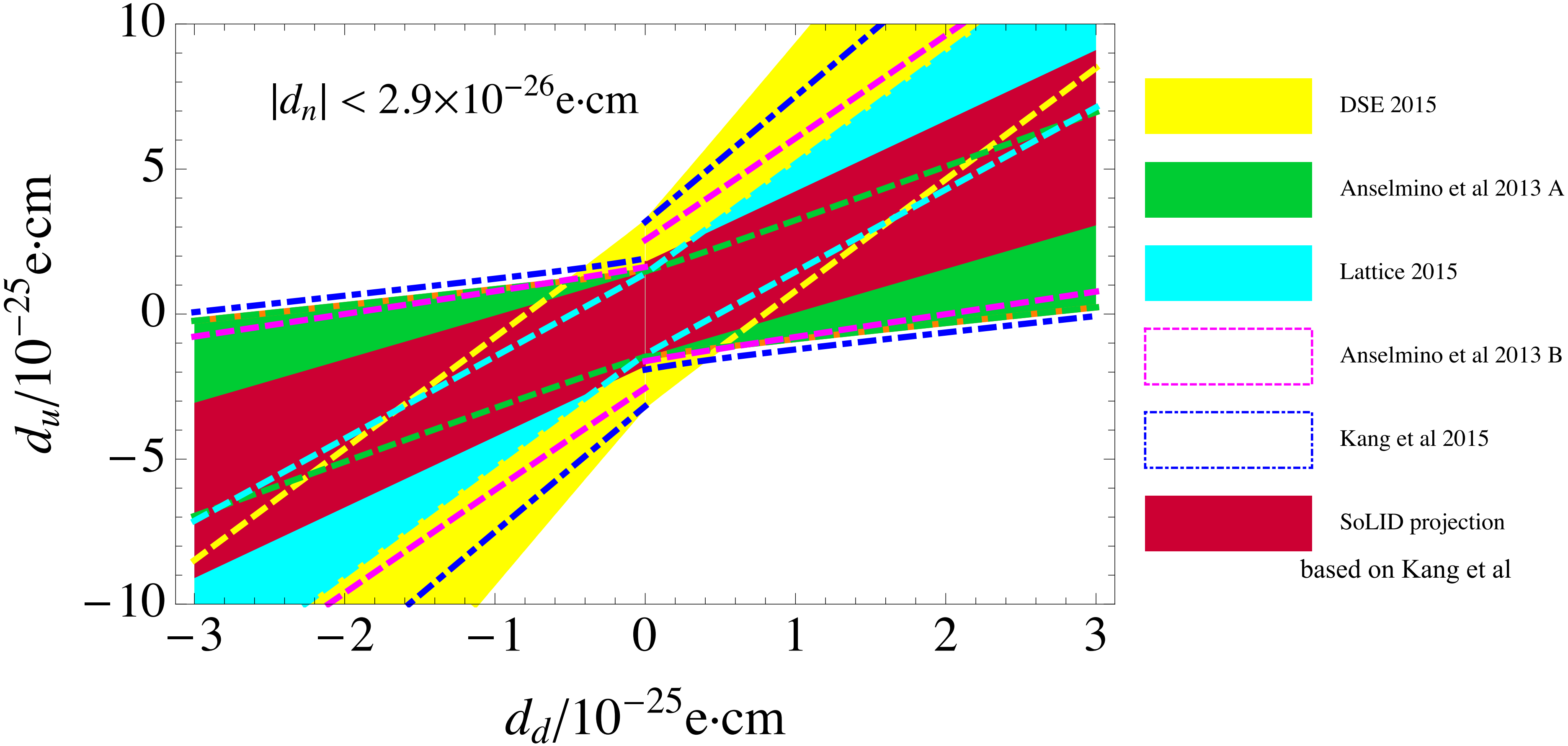






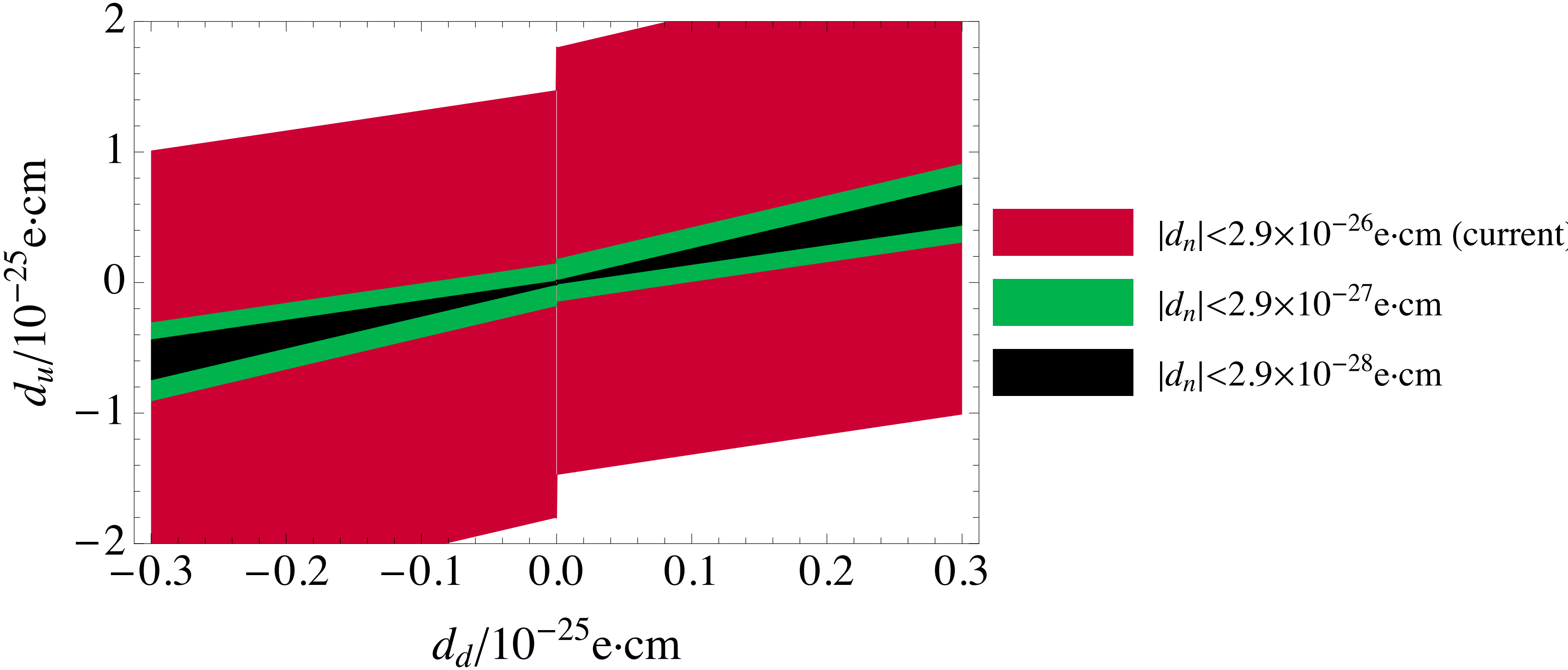
Tensor Charge, an intrinsic property as important axial vector charge, charge and magnetic moment of the nucleon

Tensor charge & EDM

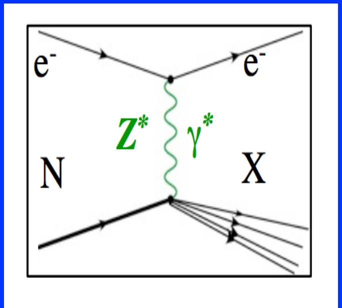


$d_n = \delta_T u\, d_u + \delta_T d\, d_d + \delta_T s\, d_s$ neglect strange quark contribution

Next generation nEDM constraint



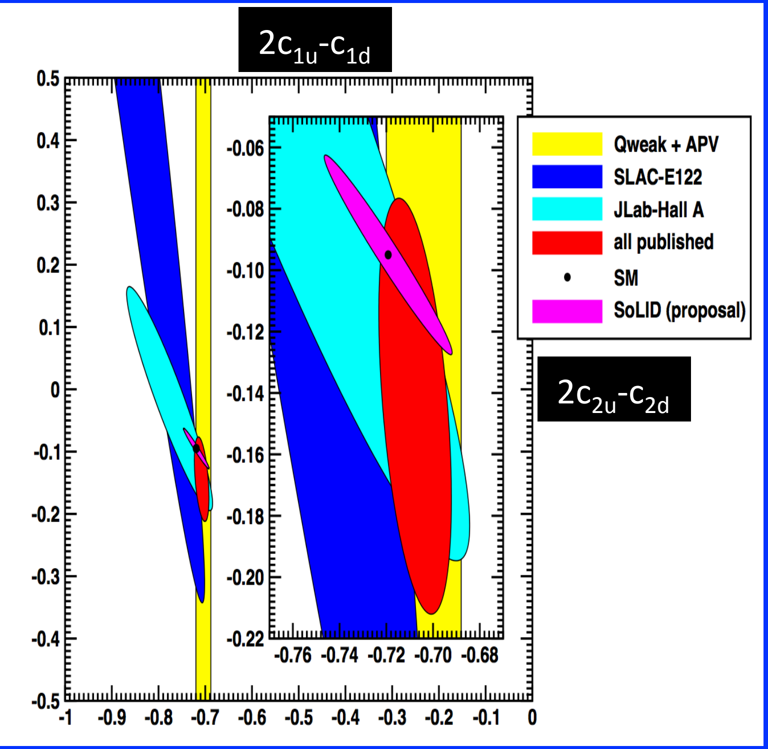
SoLID projections based on Kang et al 2015
using different nEDM upper limits



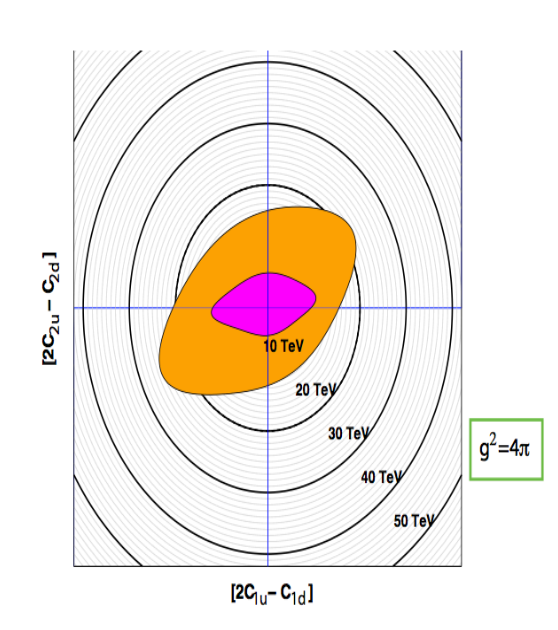
PVDIS@SoLID: Ultimate PVDIS measurement

Searching for Physics Beyond the Standard Model

An asymmetry is measured: $A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$



- Sensitive to fundamental couplings $2C_{2u}$-C_{2d}
- Charge symmetry violation in the parton distribution functions
- Clean measurement of d/u ratio in the valence region



Projected mass limits for composite models.

Purple region is excluded by published data

Orange region is the projected reach with SoLID and final Qweak result

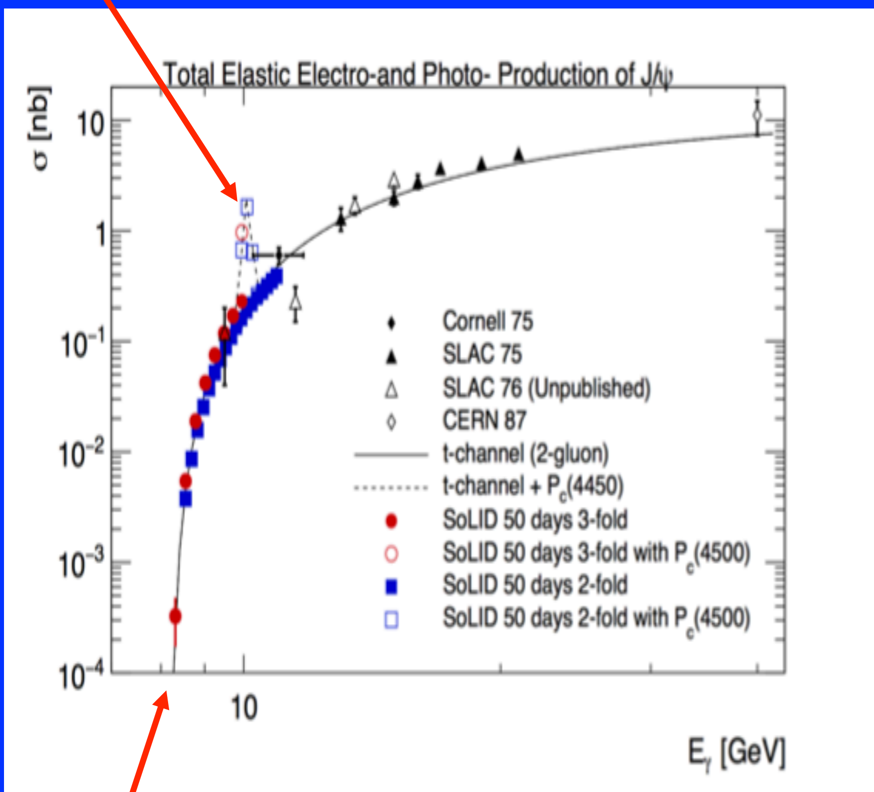
Results from the PVDIS experiment, Wang et al., Nature 506 N0. 7486, 67 (2014) together with projected results from PVDIS@SoLID

Sensitive to new physics, example: Leptophobic Z’

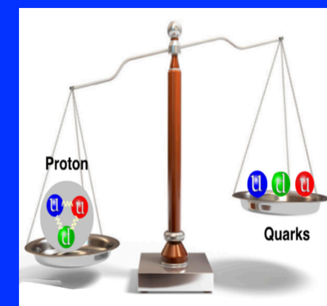
J/Psi@ SoLID: The threshold region, the mass of the proton and the LHCb charmed pentaquark

- Measure the contribution of the gluons to the mass of the proton directly.
- Poduce and determine the quantum numbers of the LHCb pentaquark if it exist.

LHCb Pentaquark production



Threshold



How does QCD generate the mass of the proton?

- Trace of the QCD energy-momentum tensor:

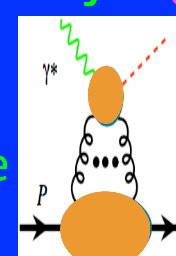
$$T^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q (1+\gamma_m) \bar{\psi}_q \psi_q$$

QCD trace anomaly

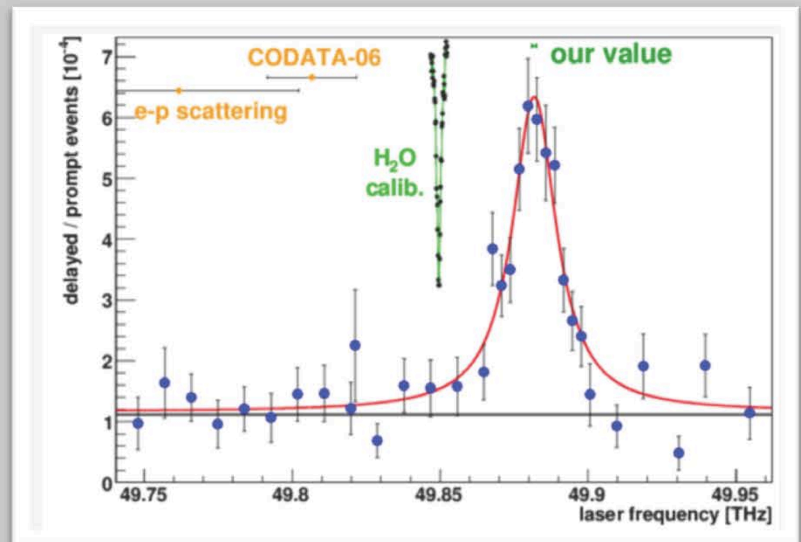
$$\beta(g) = -(11 - 2n_f/3) g^3/(4\pi)^2 + \ldots$$

J/Ψ, Υ, …

Heavy quarkonium production near the threshold, from JLab12 to EIC



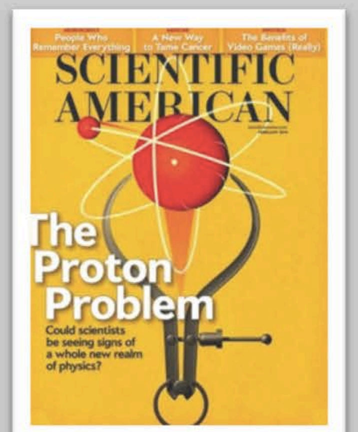
The Proton Size Puzzle



The New York Times

Süddeutsche Zeitung

DIE ZEIT



SPIEGEL ONLINE

la Repubblica

Neue Zürcher Zeitung

NATIONAL GEOGRAPHIC

Los Angeles Times

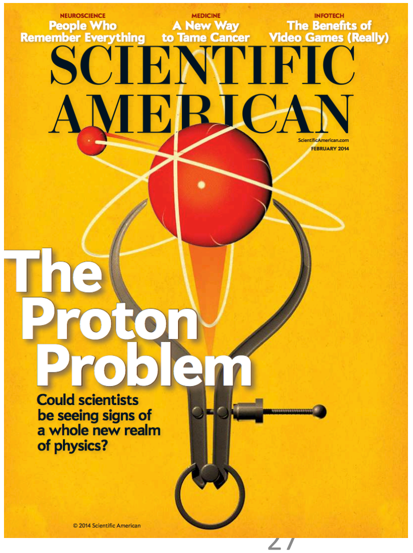
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Challenge to Lattice QCD (exciting new results, Alexandrou et al.)
  - An important physics input to the bound state QED calculations, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

$$\sqrt{<r^2>} = \sqrt{-6\frac{dG(q^2)}{dq^2}|_{q^2=0}}$$

- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift

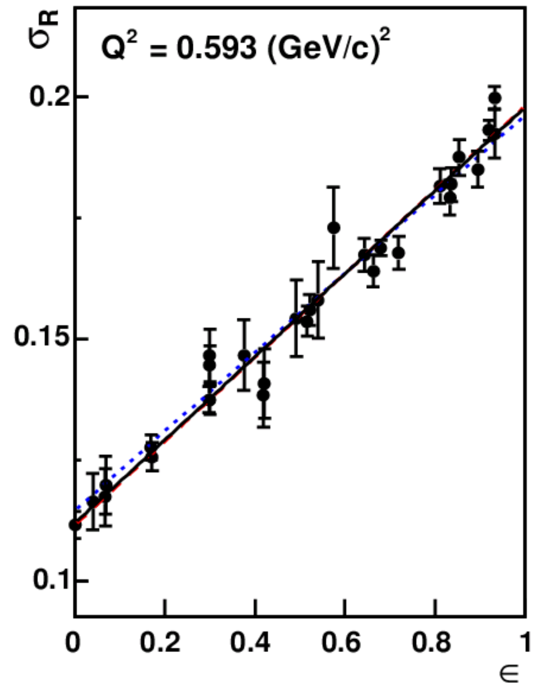


Unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- Elastic e-p cross section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E} \left(\frac{G_E^{p\,2} + \tau G_M^{p\,2}}{1+\tau} + 2\tau G_M^{p\,2} \tan^2\frac{\theta}{2} \right)$$
$$= \sigma_M f_{rec}^{-1} \left(A + B \tan^2\frac{\theta}{2} \right)$$



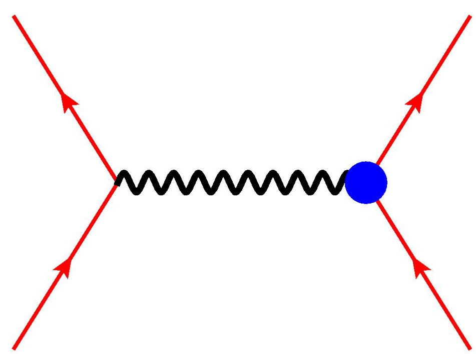
- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - Low Q^2 by G_E
    - High Q^2 by G_M

$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

$$\tau = \frac{Q^2}{4M^2}$$

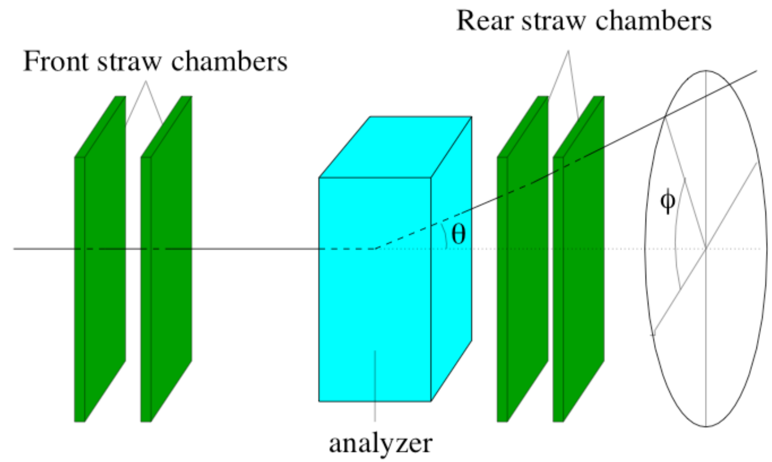
$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

G_E or G_M



Electron-proton elastic scattering with longitudinally polarized electron beam and recoil proton polarization measurement

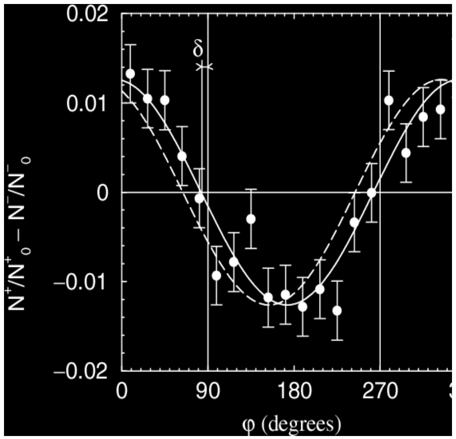
Polarization Transfer → $\dfrac{G_E^p}{G_M^p}$

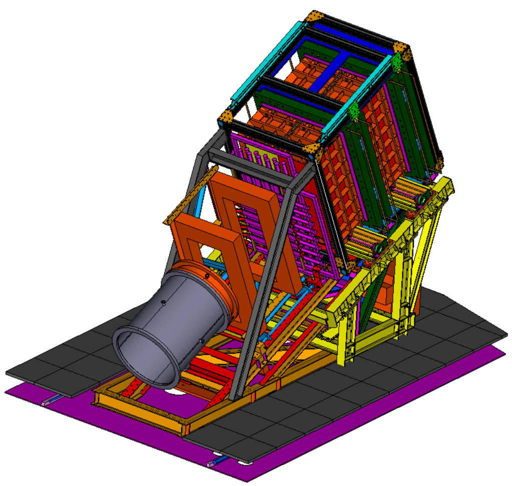


- Recoil proton polarization

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\frac{\theta}{2}$$

- Focal Plane Polarimeter
  - recoil proton scatters off secondary ^{12}C target
  - P_t, P_l measured from φ distribution
  - P_b, and analyzing power cancel out in ratio





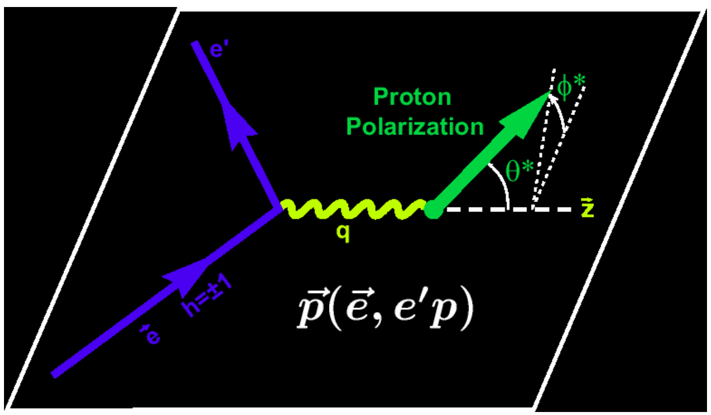
Focal-plane polarimeter

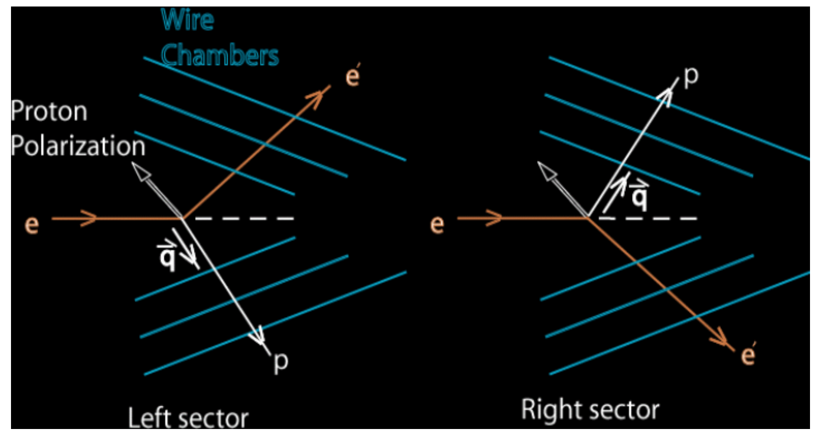
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

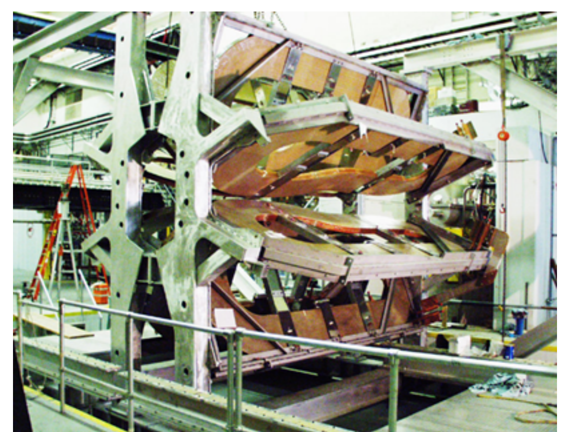
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)}\, v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





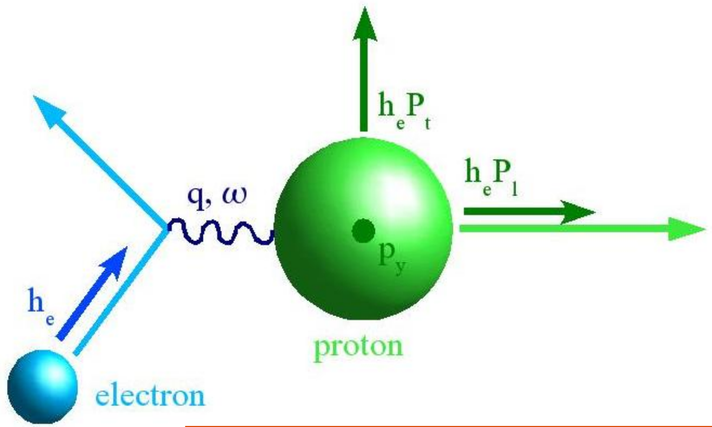
- Super-ratio

$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p / G_M^p}{a_2 - b_2 \cdot G_E^p / G_M^p}$$

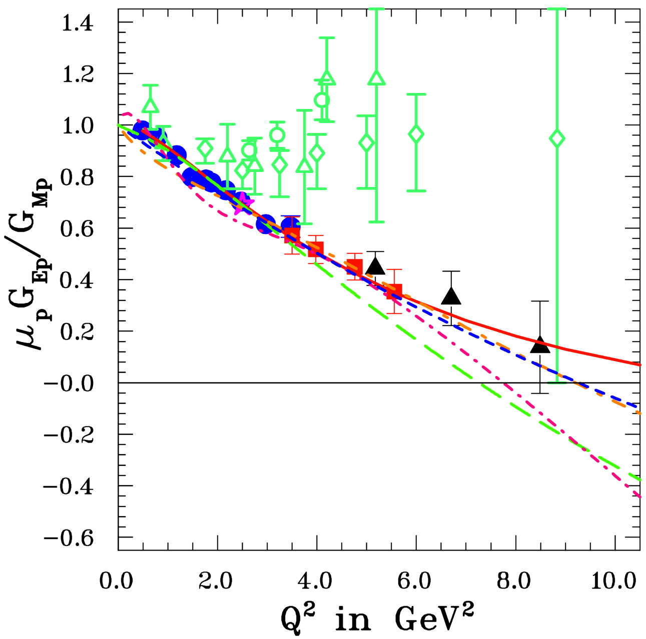


BLAST pioneered the technique, later also used in Jlab Hall A experiment

Tremendous advances in electron scattering



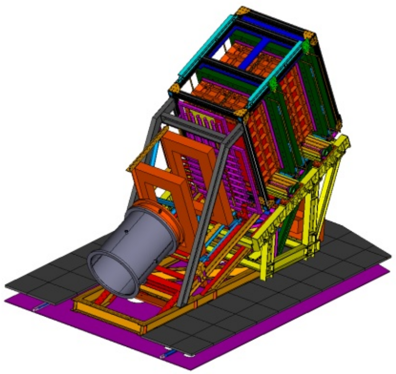
$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2M}\tan(\frac{\theta_e}{2})$$



Unprecedented capabilities:

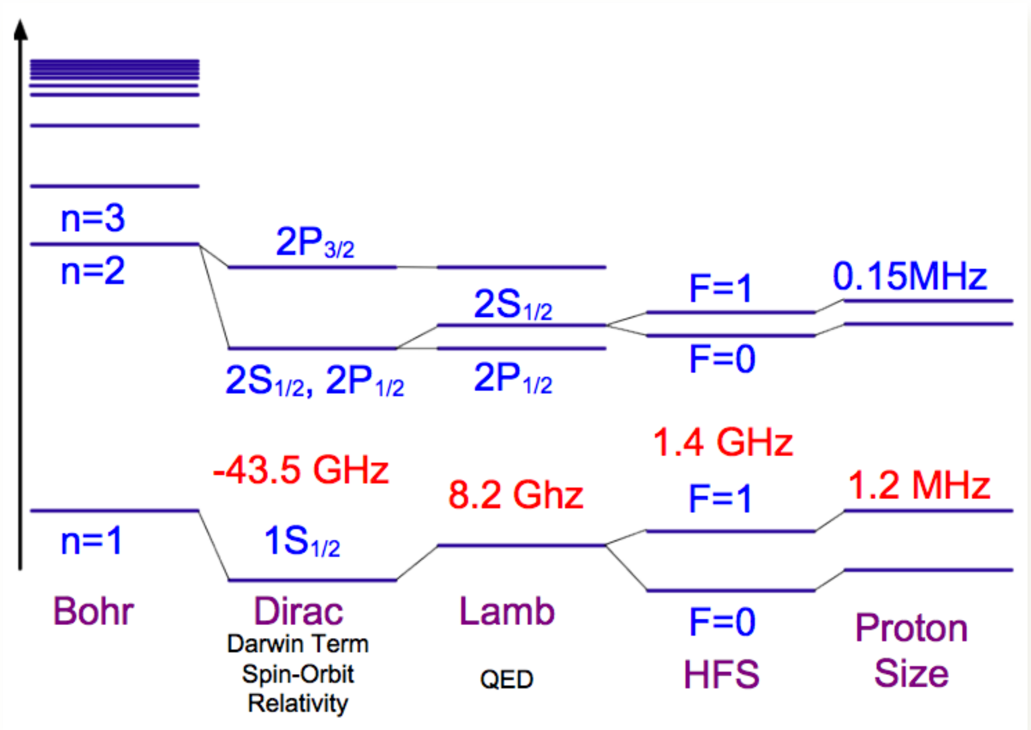
- High Intensity
- High Duty Factor
- High Polarization
- Parity Quality Beams
- Large acceptance detectors
- State-of-the-art polarimetry, polarized targets

Polarized ^3He target



Focal plane polarimeter – Jefferson Lab

Hydrogen Spectroscopy



The absolute frequency of H energy levels has been measured with an accuracy of 1.4 part in 10^{14} via comparison with an atomic cesium fountain clock as a primary frequency standard.

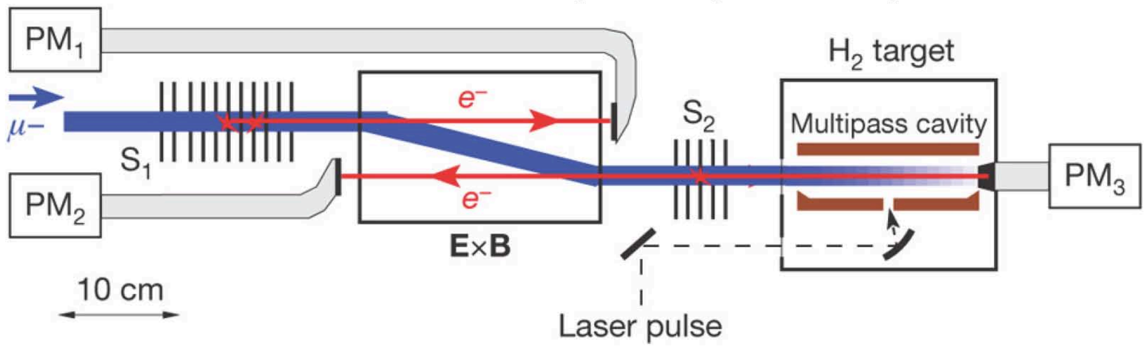
Yields R_∞ (the most precisely known constant)

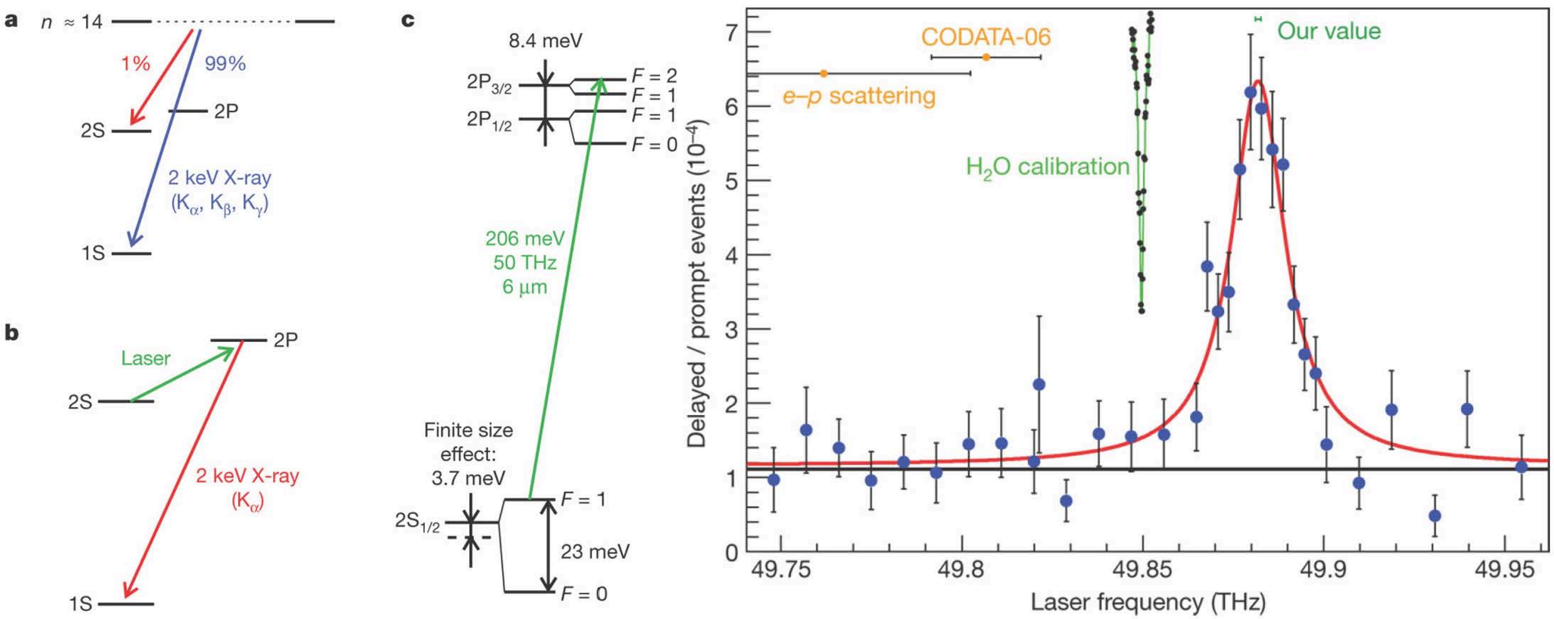
Comparing measurements to QED calculations that include corrections for the finite size of the proton provide an indirect but very precise value of the rms proton charge radius

Proton charge radius effect on the muonic hydrogen Lamb shift is 2%

Muonic hydrogen Lamb shift at PSI (2010, 2013)

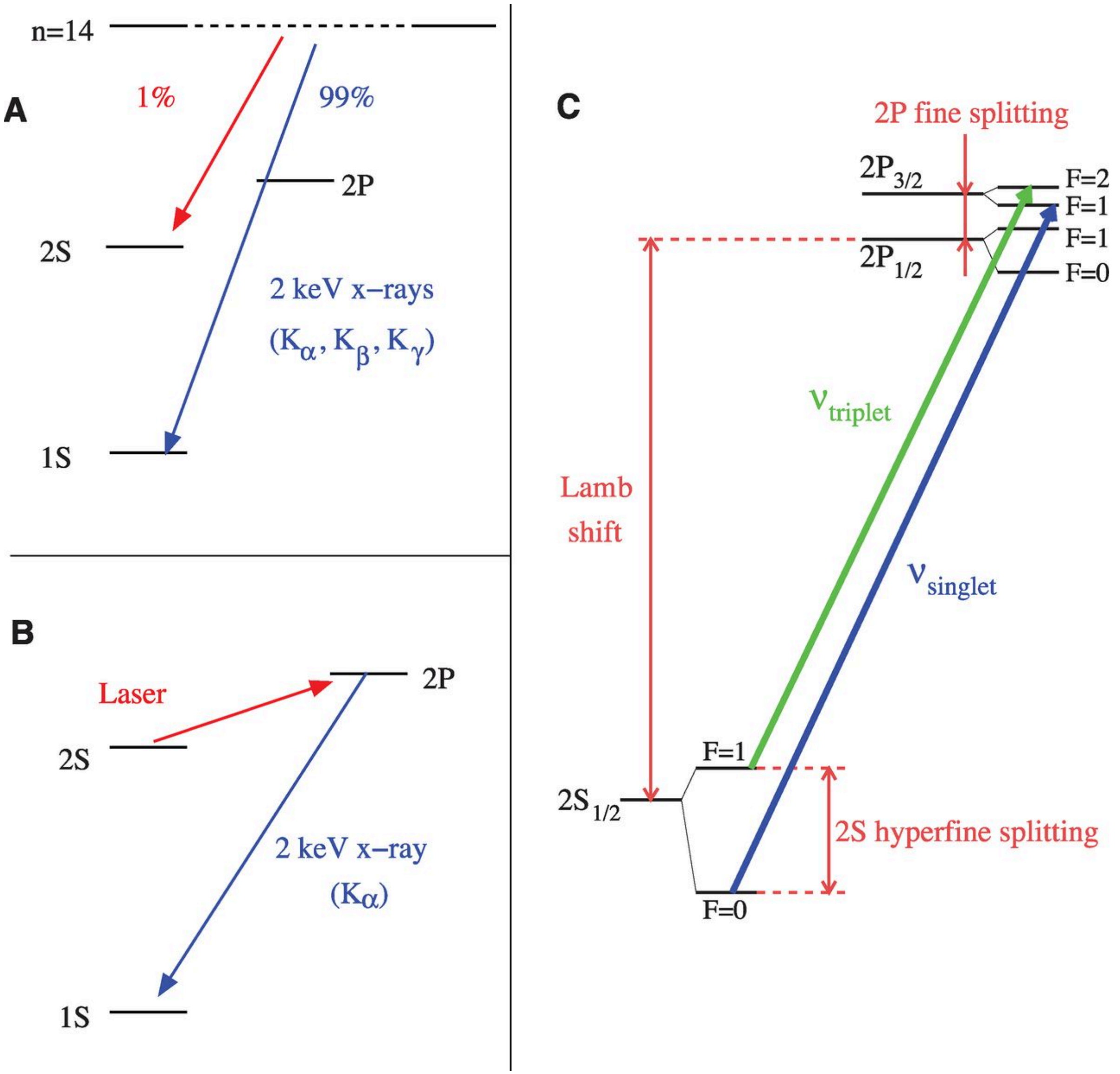
Nature **466**, 213-216 (8 July 2010)





2010: new value is r_p = 0.84184(67) fm

New PSI results reported in Science 2013

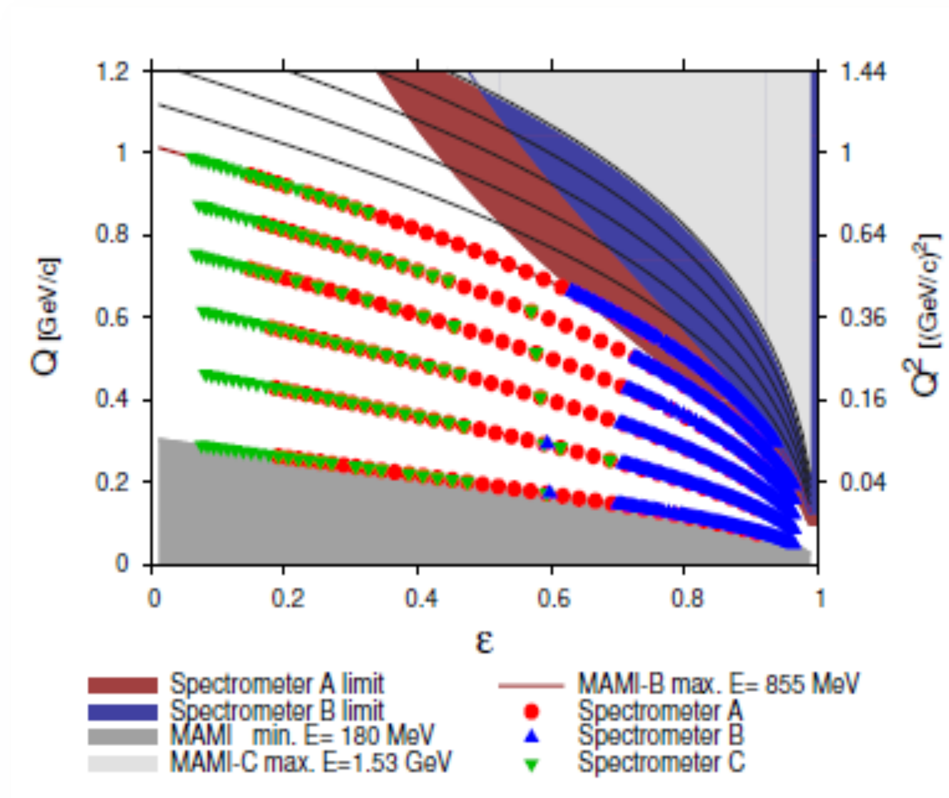


2013: r_p = 0.84087(39) fm, A. Antognini *et al.*, Science 339, 417 (2013)

Recent ep Scattering Experiments

Three spectrometer facility of the A1 collaboration:

Measurements @ Mainz



– Large amount of overlapping data sets
– Statistical error $\leq 0.2\%$
– Luminosity monitoring with spectrometer

- $Q^2 = 0.004 - 1.0\ (\mathrm{GeV}/c)^2$

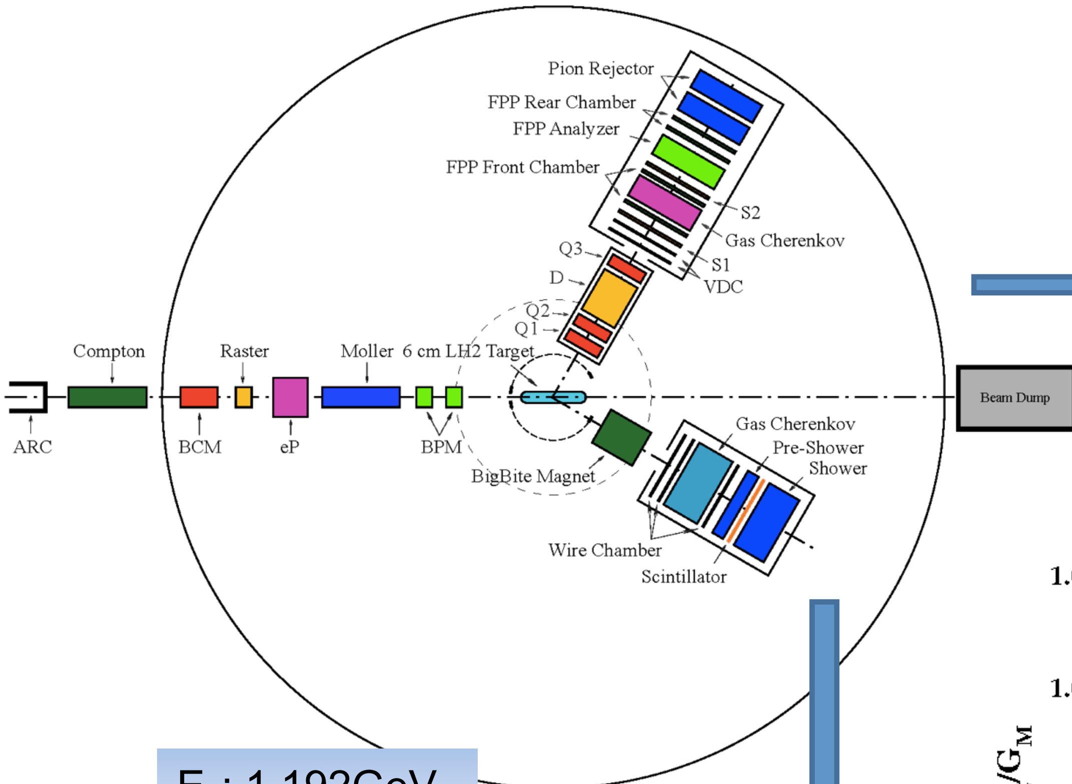
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

JLab Recoil Proton Polarization Experimental



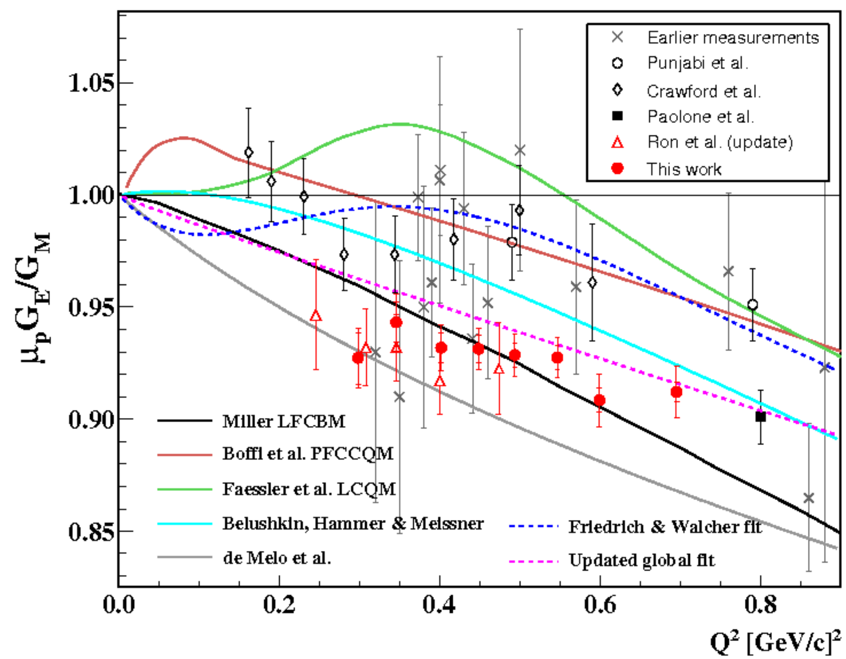
LHRS

- $\Delta p/p0$: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- $\Delta\Omega$: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

E_e: 1.192GeV
P_b: ~83%

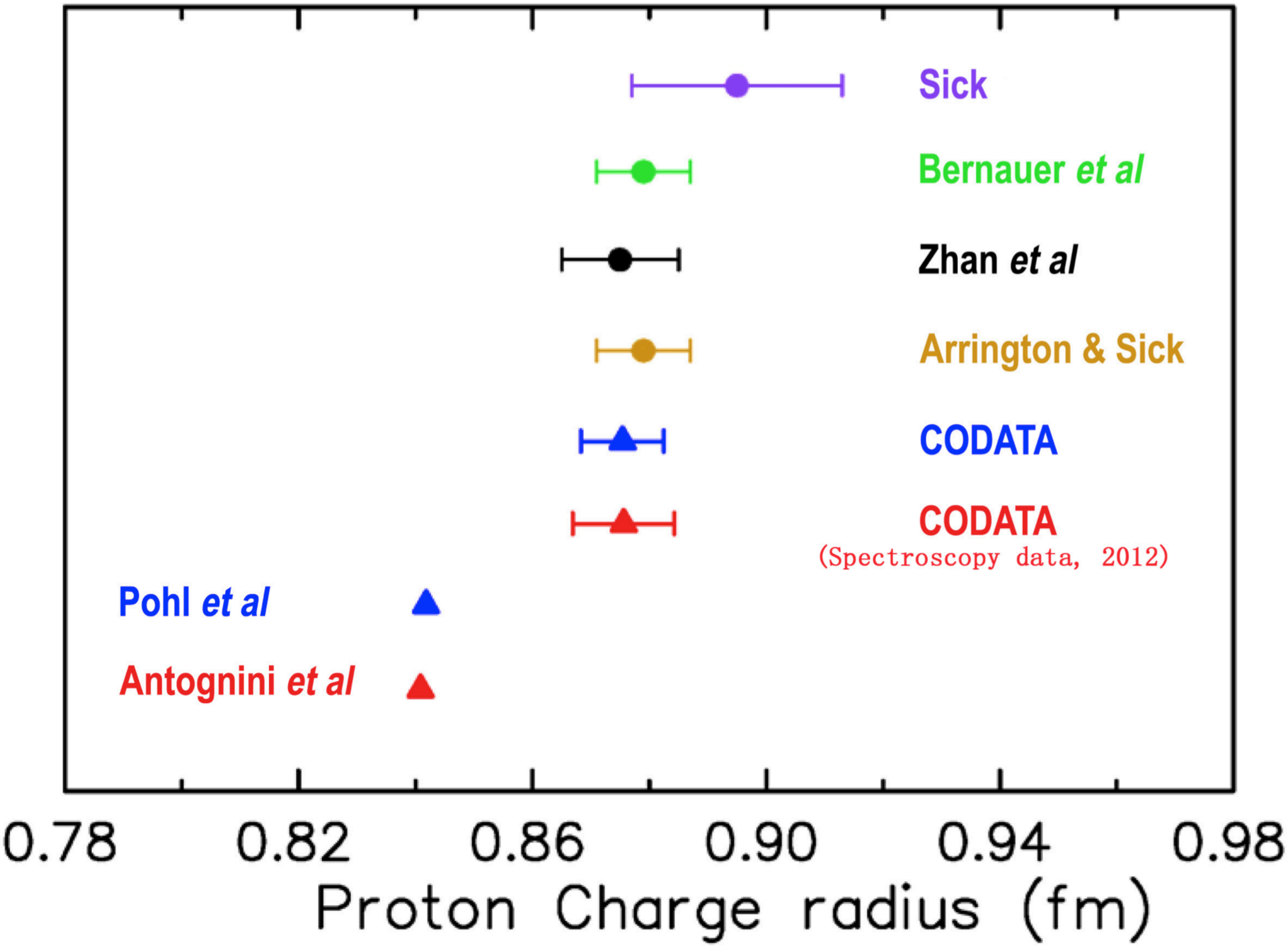
BigBite

- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - $\Delta\Omega$: 96msr
- PS + Scint. + SH



X. Zhan et al. Phys. Lett. B 705 (2011) 59-64
C. Crawford et al. PRL98, 052301 (2007)

Proton Charge Radius from recent experiments and analyses



Revisits QED Calculations….

An additional 0.31 meV to match CODATA value

Contribution		Value [meV]	Uncertainty [10^{-4} meV]
Uehling		205.0282	
Källen–Sabry		1.5081	
VP iteration		0.151	
Mixed $\mu - e$ VP		0.00007	
Hadronic VP [21,23]		0.011	20
Sixth order VP [24]		0.00761	
Whichmann–Kroll		−0.00103	
Virtual Delbrück		0.00135	
Light–by–light		–	10
Muon self–energy and muonic VP (2^{nd} order)		−0.66788	
Fourth order electron loops		−0.00169	
VP insertion in self energy [17]		−0.0055	10
Proton self–energy [18]		−0.0099	
Recoil [17,43]		0.0575	
Recoil correction to VP (one–photon)		−0.0041	
Recoil (two–photon) [19]		−0.04497	
Recoil higher order [19]		−0.0096	
Recoil finite size [32]		0.013	10
Finite size of order $(Z\alpha)^4$ [32]	$-5.1975(1)\,r_p^2$	−3.979	(620)
Finite size of order $(Z\alpha)^5$	$0.0347(30)\,r_p^3$	0.0232	(20)
Finite size of order $(Z\alpha)^6$		−0.0005	
Correction to VP	$-0.0109\,r_p^2$	−0.0083	
Additional size for VP [19]	$-0.0164\,r_p^2$	−0.0128	
Proton polarizability [18,33]		0.015	40
Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$		8.352	10
$2P_{3/2}^{F=2}$ hyperfine splitting		1.2724	
$2S_{1/2}^{F=1}$ hyperfine splitting [42], (−22.8148/4)		−5.7037	20

Evaluation by Jentschura, Annals Phys. 326, 500 (2011)
Recent summary by A. Antognini et al., arXiv:1208.2637

Birse and McGovern, arXiv:1206.3030
0.015(4) meV (proton polarizability)

J.M. Alarcon, et al. 1312.1219
0.008 meV

G.A. Miller, arXiv:1209.4667

New experiments at HIGS and Mainz on proton polarizabilities

Revisits of e-p scattering data (just 2015)

- Re-analysis of existing proton form factor data
  - D. W. Higinbotham, arXiv:1510.01293: two parameter dipole form fit describes the data at both low Q^2 and high Q^2 well, and the result is consistent with PSI value
  - K. Griffioen, C. Carson, S. Maddox, arXiv:1509.06676: re-analysis of Mainz data, focusing on the low Q^2 part with a polynomial form fit.
  - M. Horbatsch and E. A. Hessels, arXiv:1509.05644: re-analysis of Mainz data, simple fits (one-parameter model, dipole model, linear model) for low Q2 data, and spline extension to high Q2 data, these fits can all describe data well, but the extracted radius varies from 0.84 ~ 0.89 fm. So current data is not able to resolve the puzzle.
  - J. Arrington, arXiv:1506.00873: re-analysis of world data, found the previous scattering results might underestimate the uncertainty.
  - **Distler, Walcher, and Bernauer, arXiv1511.00479**

All these studies emphasize even more the importance of low Q^2 e-p scattering data

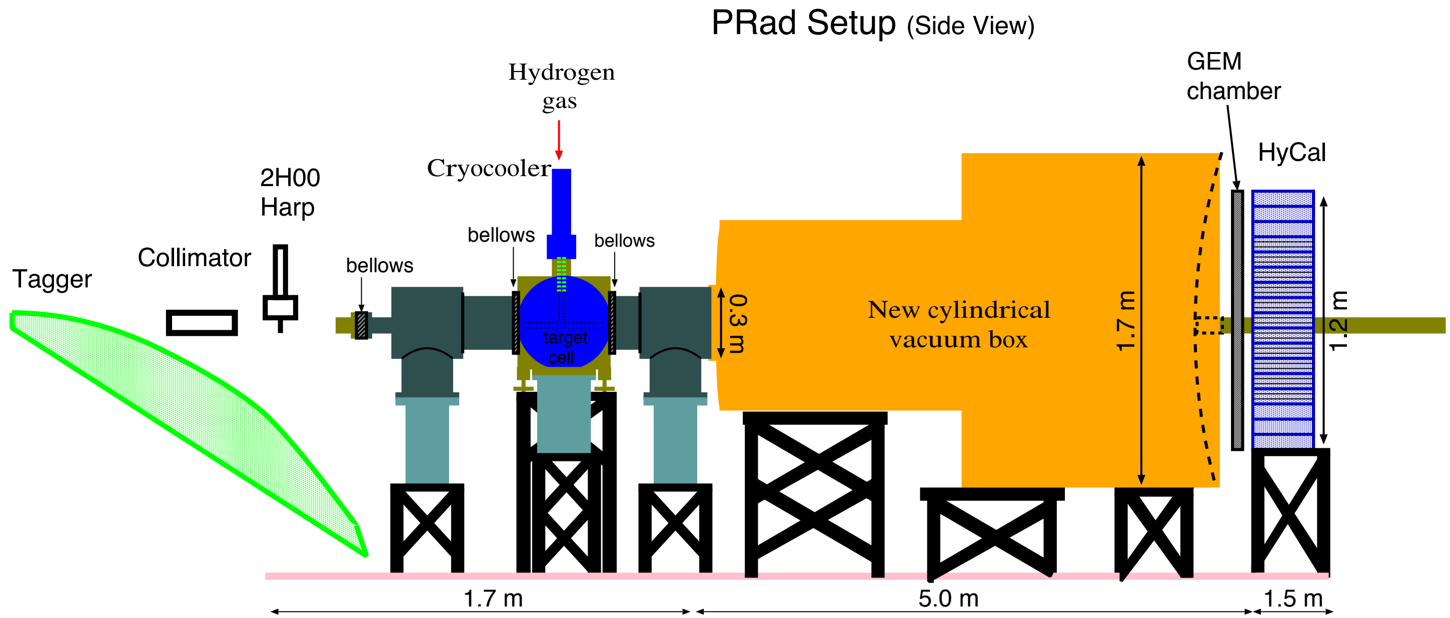
New Physics or what? - Incomplete list

- New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller,….New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio;…….
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen,; Jentschura, Borie, Carroll et al, Hill and Paz, Birse and McGovern, G.A. Miller, J.M. Alarcon, Ji, Peset and Pineda….
- Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher,…..
- J.A. Arrington, G. Lee, J. R. Arrington, R. J. Hill discuss systematics in extraction from ep data, no resolution on discrepancy
- Donnelly, Milner and Hasell discuss interpretation of ep data,………

Discrepancy explained by some but others disagree

- Dispersion relations: Lorentz et al.
- Frame transformation: D. Robson
- **New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H Lamb shift**

PRad Experimental Setup in Hall B at JLab



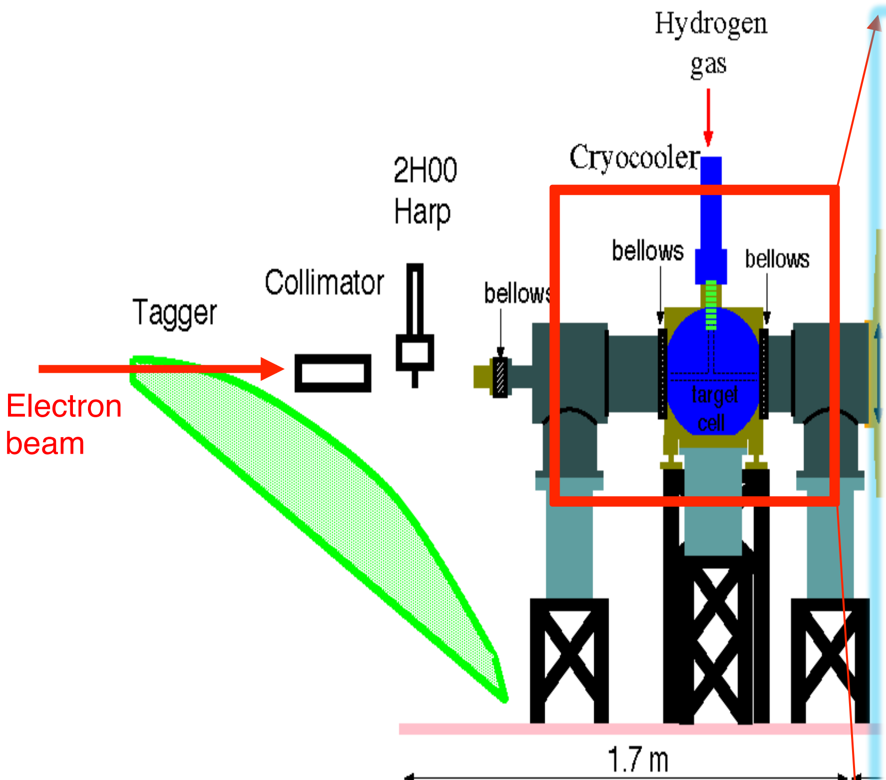
- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of $2x10^{-4}$ – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

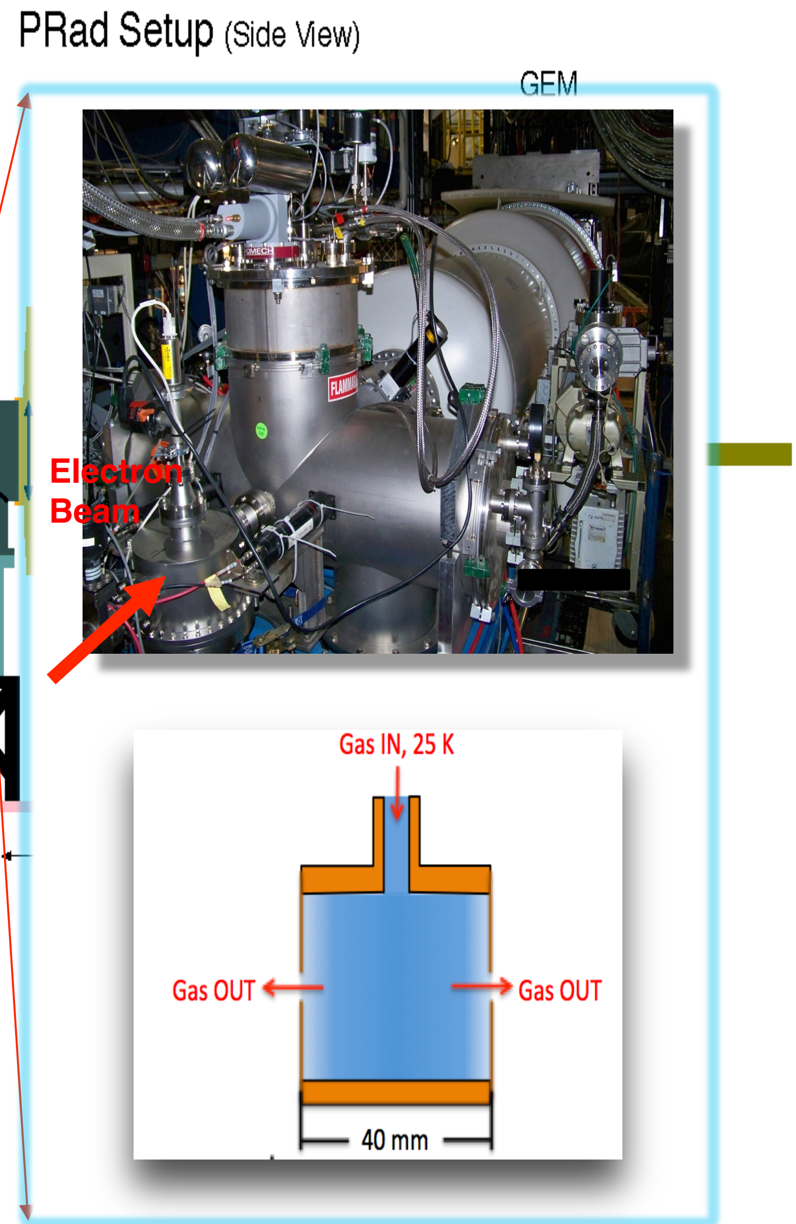
Spokespersons: D. Dutta, H. Gao, A. Gasparian, M. Khandaker

Sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

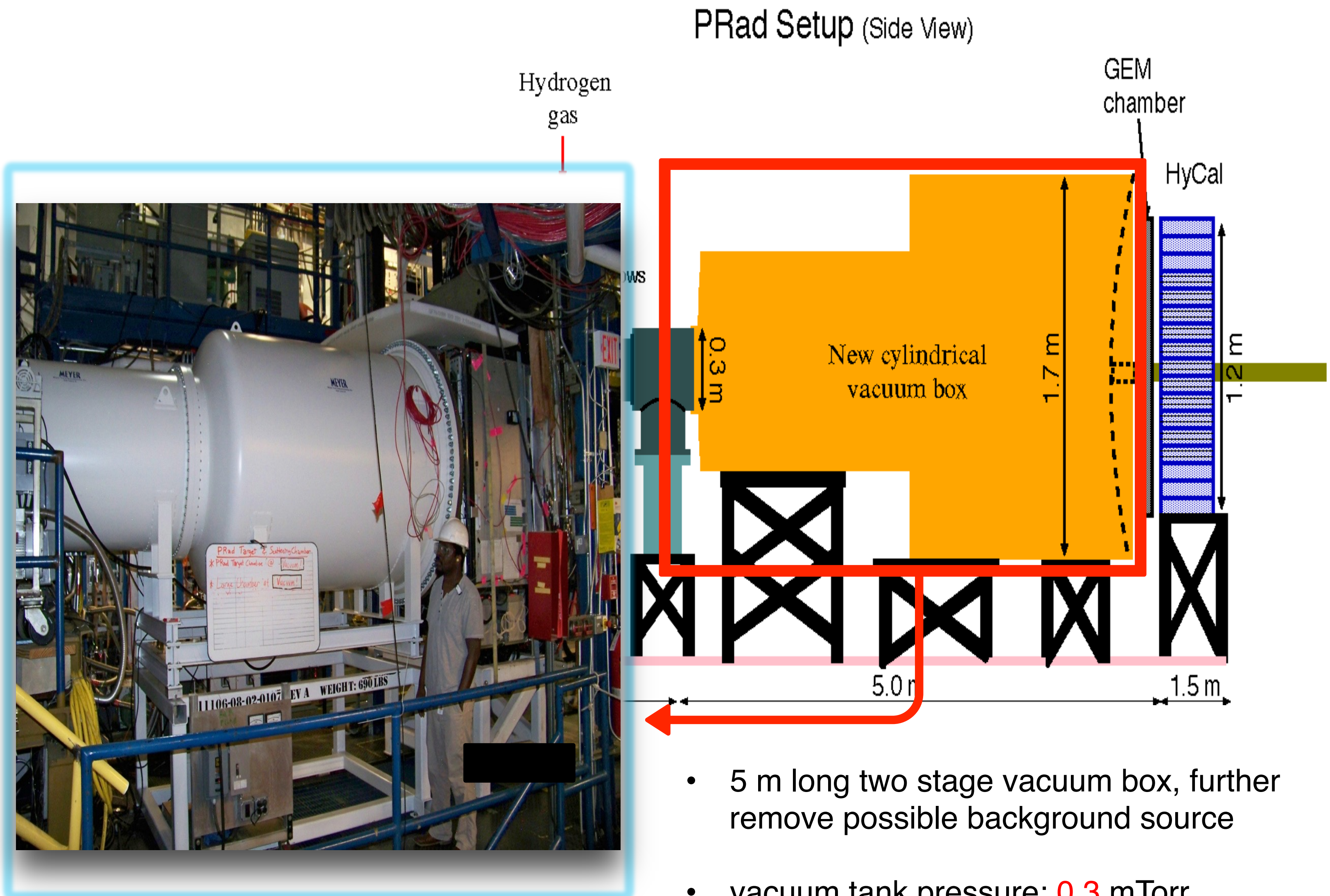
PRad Experimental Apparatus





- 8 cm dia x 4 cm long target cell
- 2 mm holes open at front and back kapton foils, allows beam to pass through
- Target thickness: ~2 x 10^{18} H atoms / cm^2

PRad Experimental Apparatus

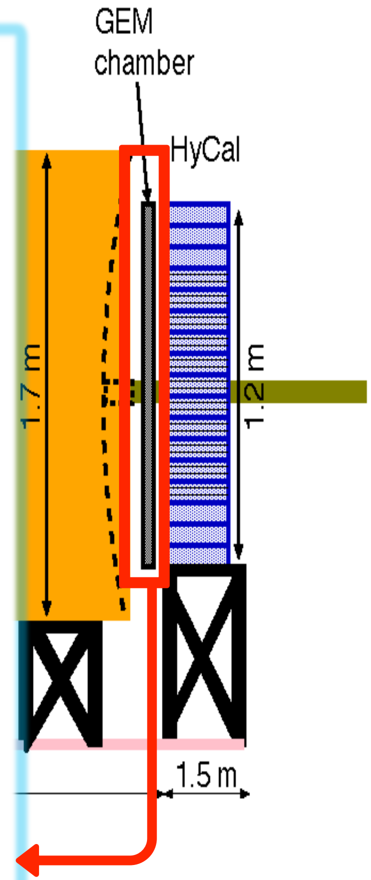


- 5 m long two stage vacuum box, further remove possible background source
- vacuum tank pressure: 0.3 mTorr

PRad Experimental Apparatus

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)
- Improve position resolution of the setup by > 20 times
- Similar improvement for Q^2 determination at small angle

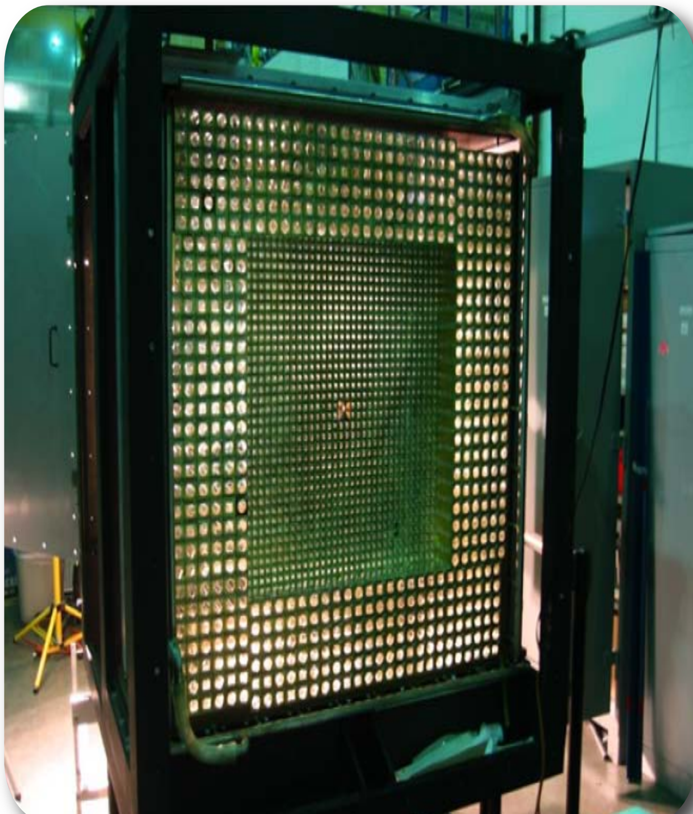
PRad Setup (Side View)



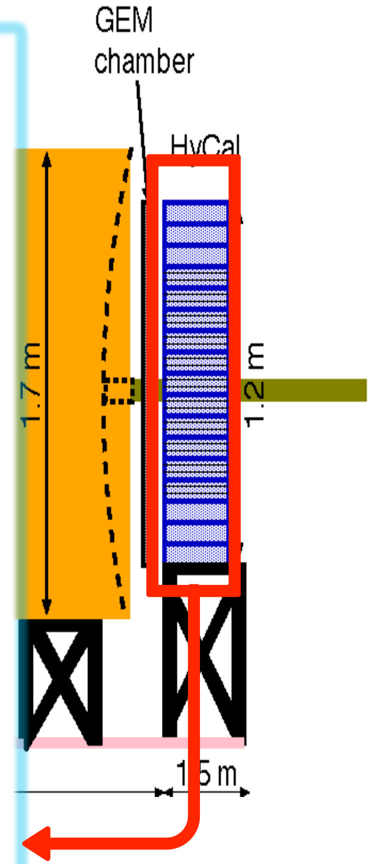
More details see presentation of X. Bai in session E12

PRad Experimental Apparatus

PRad Setup (Side View)

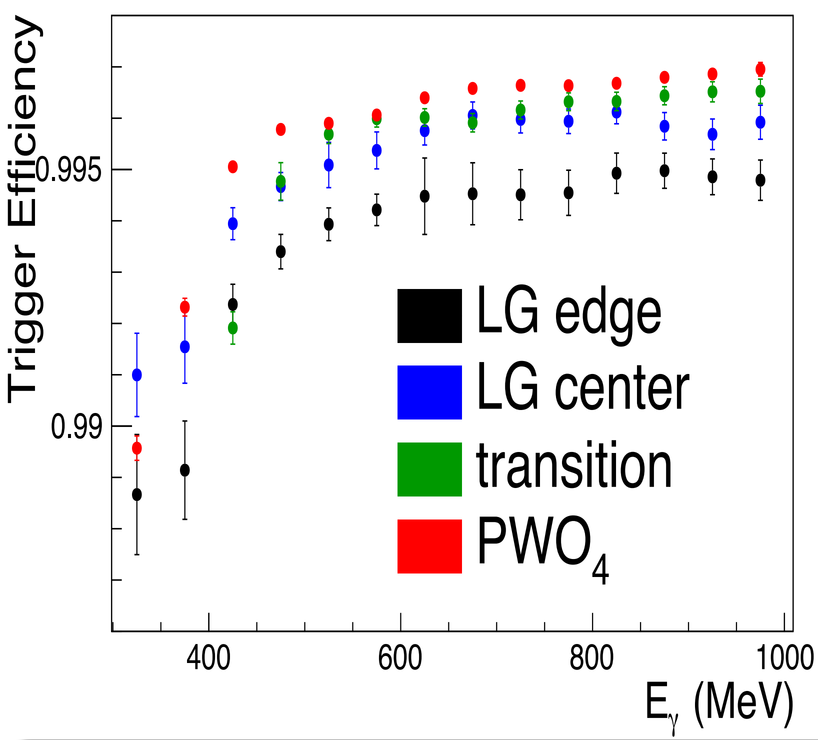


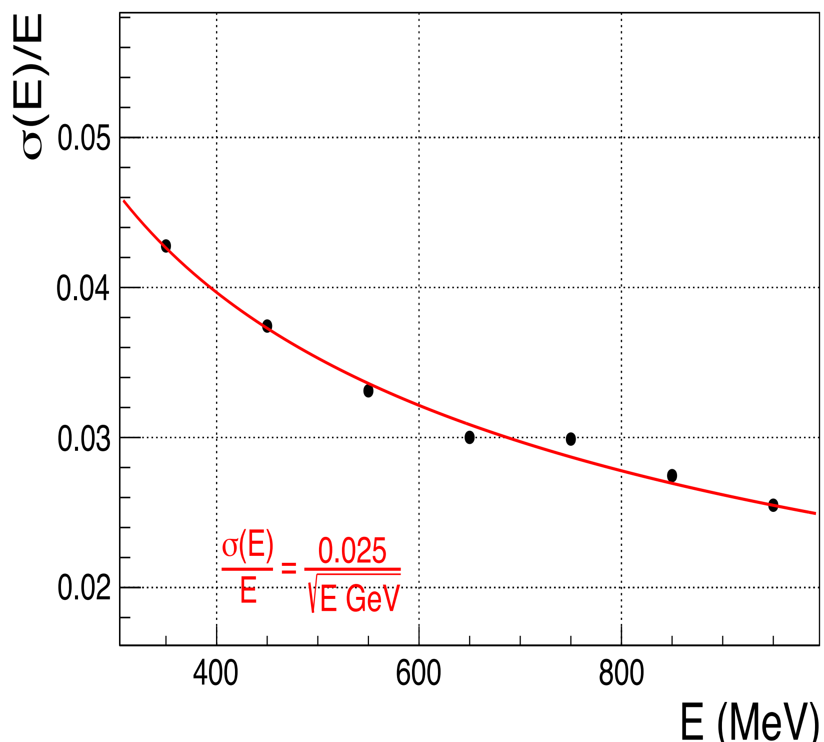
- Hybrid EM calorimeter (HyCal)
  - Inner 1156 PWO_4 modules
  - Outer 576 lead glass modules
- 5.8 m from the target
- Scattering angle coverage: ~ 0.6° to 7.5°
- Full azimuthal angle coverage
- High resolution and efficiency



HyCal Resolution and Efficiency

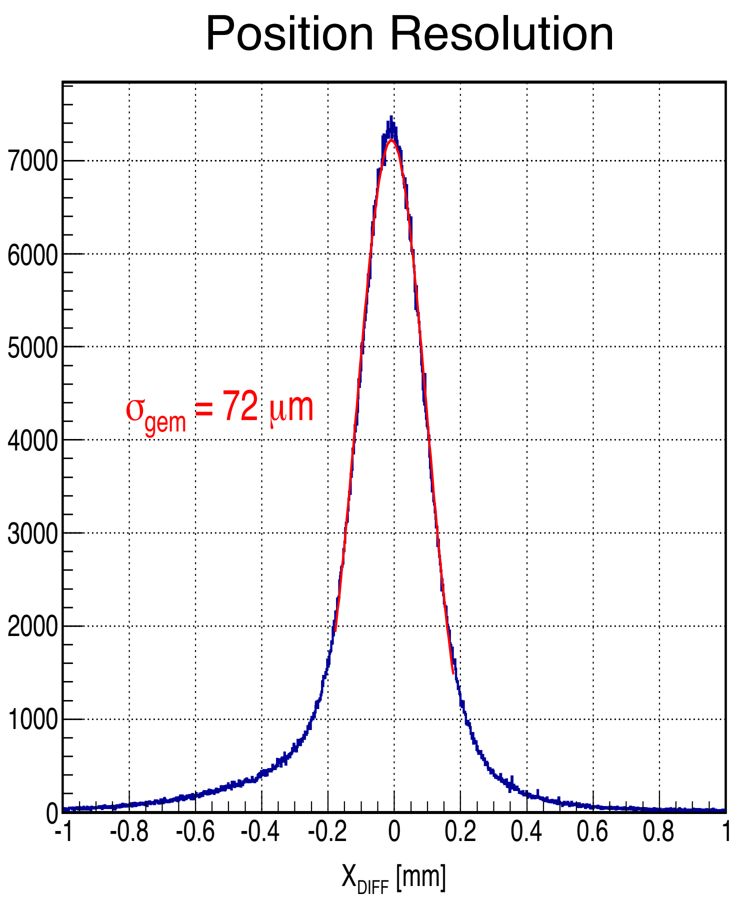
- HyCal energy resolution and trigger efficiency extracted using high energy photon beam from Hall B at Jlab
  - > 99.5% trigger efficiency obtained for $E_\gamma > 500$ MeV, for various parts of HyCal
  - Energy resolution ~2.5% for PWO_4 part, lead glass part about 2.5 time worse

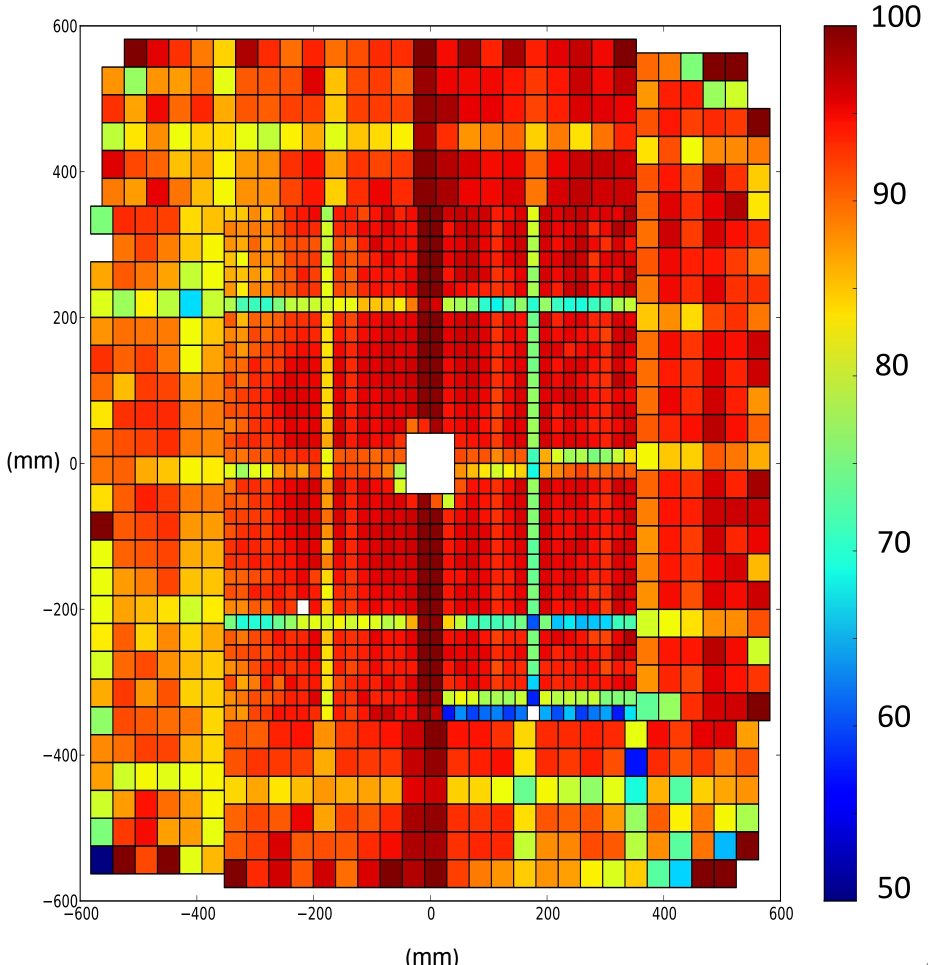




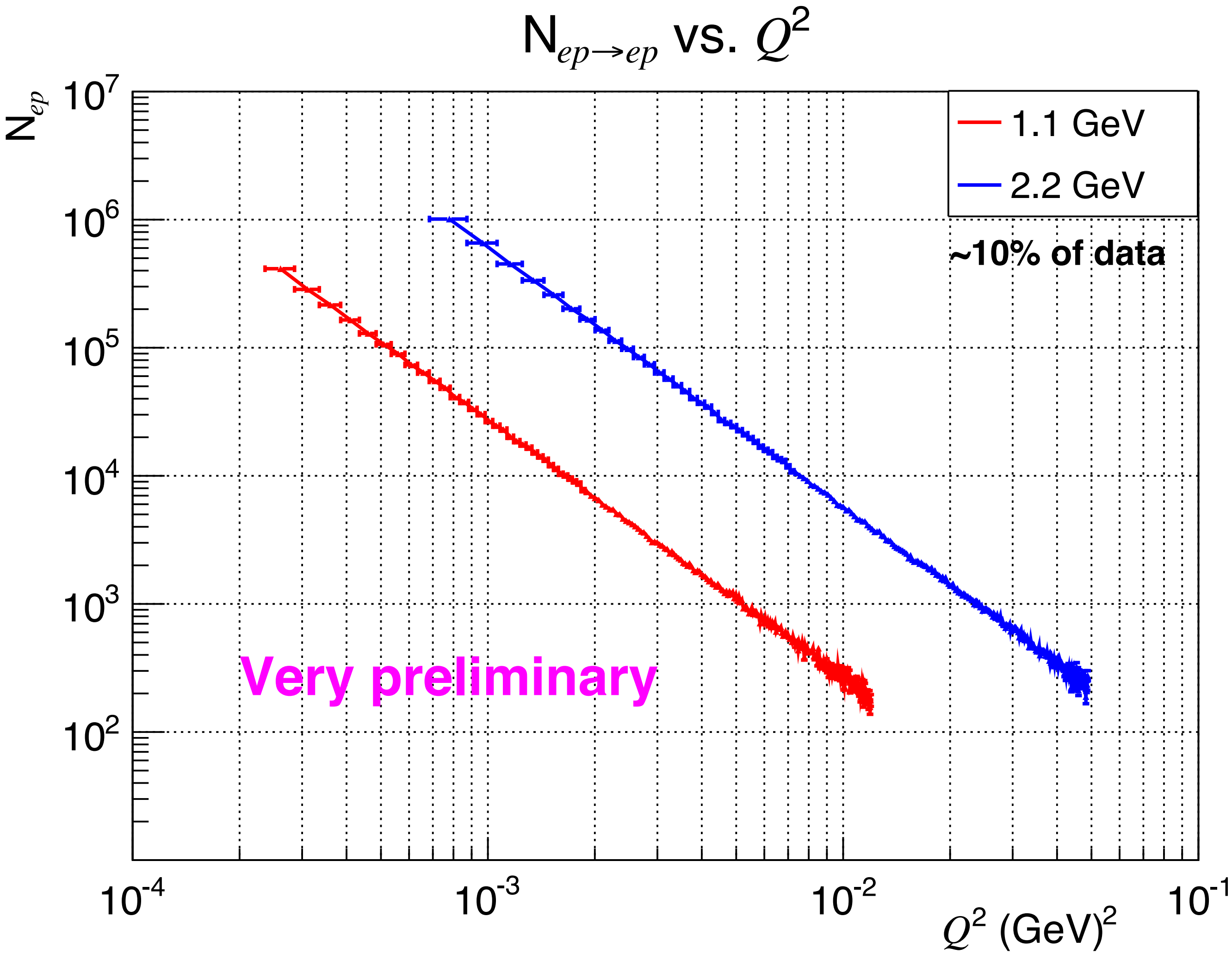
Performance of GEM Detectors

- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (ep and ee)
- Using overlap region of GEMs to measure position resolution (72 **μ**m)

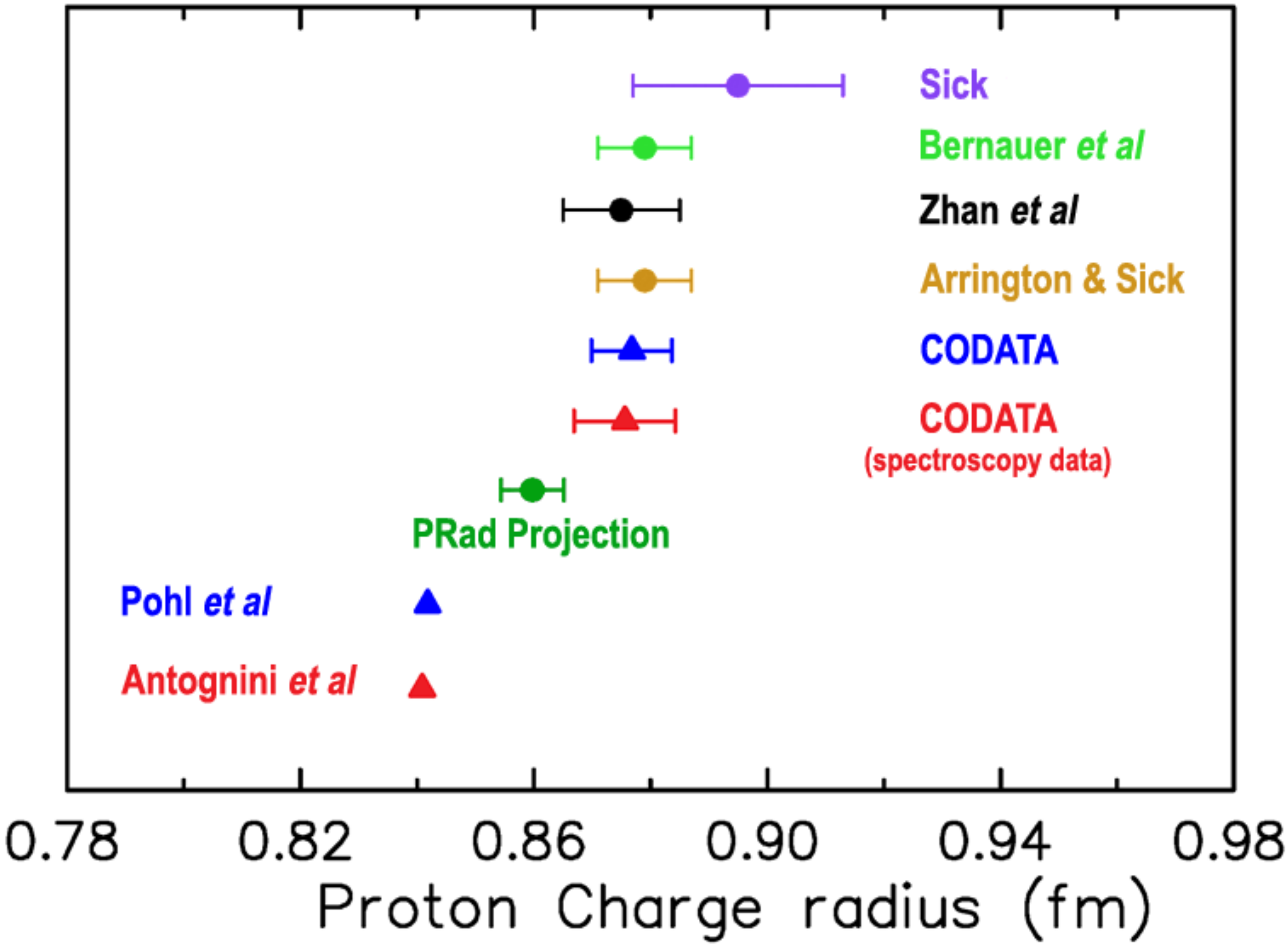




Preliminary Results:



PRad Projected Result with world data



Summary and outlook

- After decades of study, proton remains puzzling
- Proton spin puzzle: orbital angular momentum through 3-d tomography (JLab 12 program, SoLID, and others) and future Electron Ion Collider
- Proton charge radius puzzle: PRad experiment and others –Stay tuned for more news about proton charge radius
- Proton mass puzzle: SoLID near-threshold J/psi production

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