proton structure, spin, charge and QED expansion

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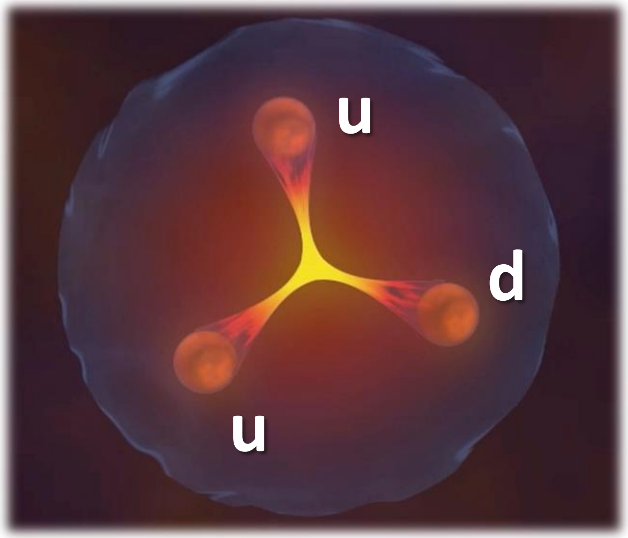
CEA - Saclay

The proton: is it so well understood?

main constituent
- of our bodies
- of fuel of stellar furnaces
- of matter in the visible universe

$p + e^- : H_{atom}$ ➔ QED revolution 1920

p+p ➔ Higgs boson discovery 2012



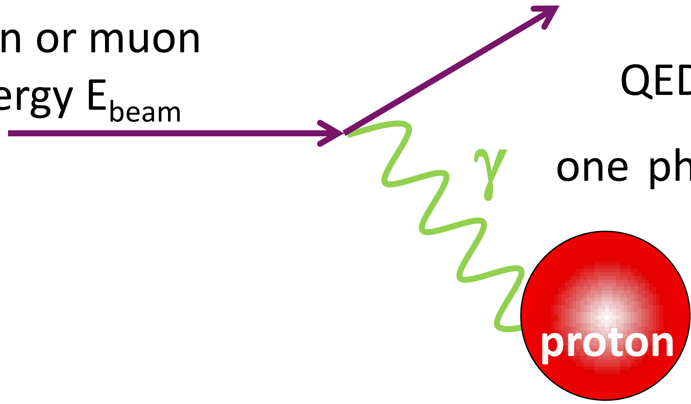
The nucleon is the best laboratory to study QCD

- PART I: Charge , Form Factors and proton charge radius
- PART II: Spin, quark and gluon distributions and 3D imaging of the nucleon

Only a selection of a few results

The electromagnetic probe

Lepton : electron or muon
of energy E_{beam}



QED: $\alpha = 1/137$

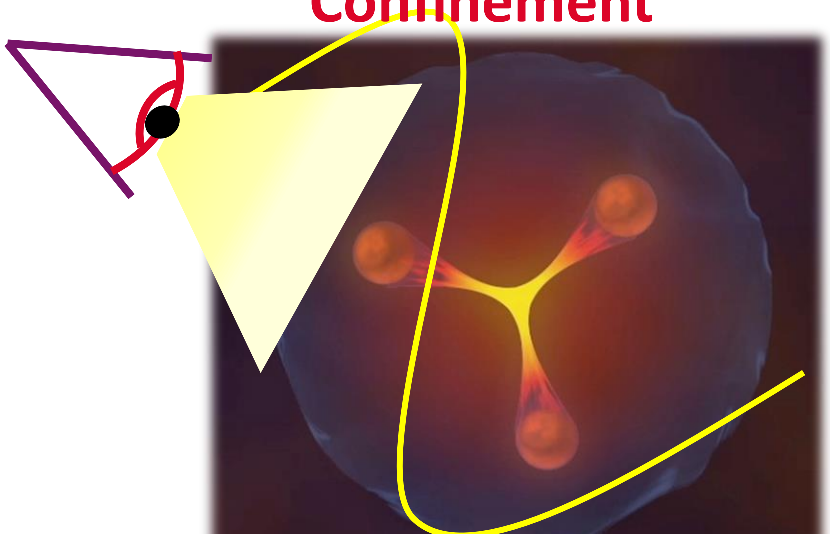
one photon exchange dominates

momentum $\vec{q}$ and energy υ

$Q^2 = \upsilon^2 - q^2$ and $x_B \overset{lab}{=} Q^2/2m\upsilon$

$Q^2 \rightarrow 0$

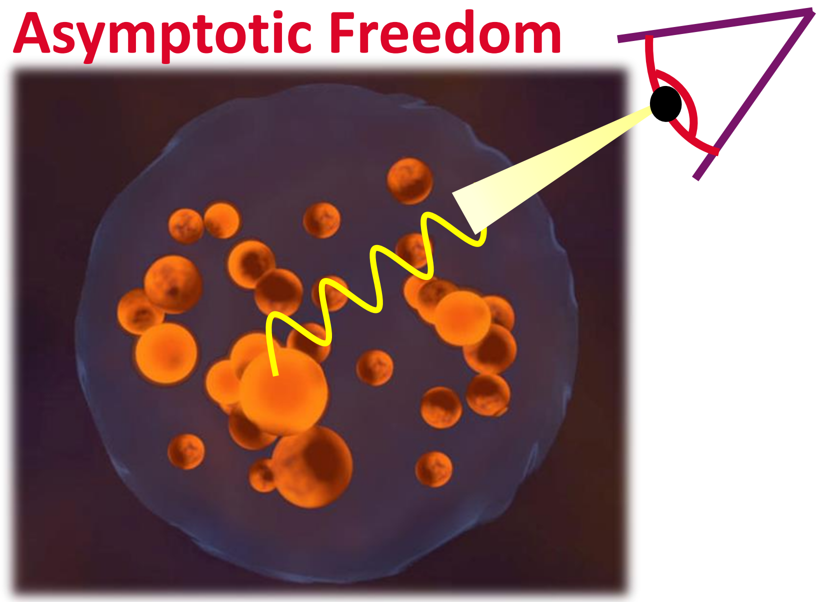
Confinement



Effective models based on chirality, pion cloud…
Lattice QCD calculations

$Q^2 \rightarrow \infty$

Asymptotic Freedom



Perturbative QCD

PART 1: Charge, Form Factors and proton radius

The elastic scattering: ep→ ep

$$\frac{d\sigma_{\text{ep}\rightarrow\text{ep}}}{d\Omega} = \frac{d\sigma_{\text{Mott}}}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right]$$

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

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

Point-like particle
Spin 1/2

Form factors (FFs)
Internal structure

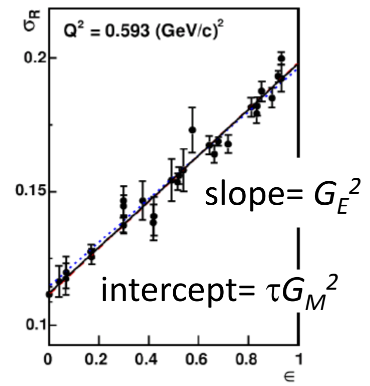
Charge distribution $G_E^p(0) = 1 \quad G_E^n(0) = 0$

Distribution of magnetic moment $G_M^p = 2.793 \quad G_M^n = -1.91$

The different techniques to extract FFs

1- Rosenbluth separation

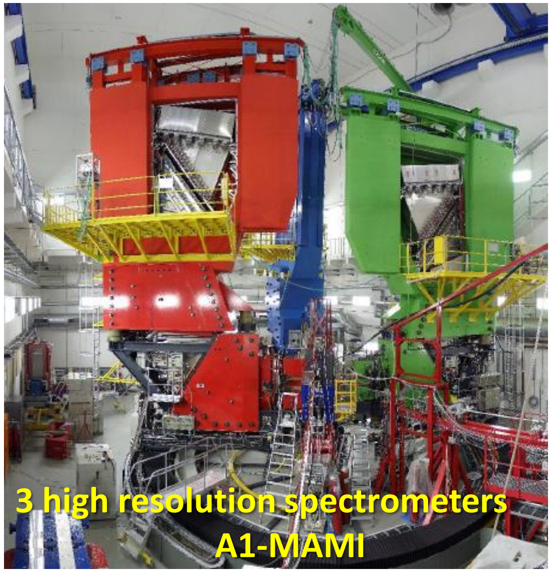
$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

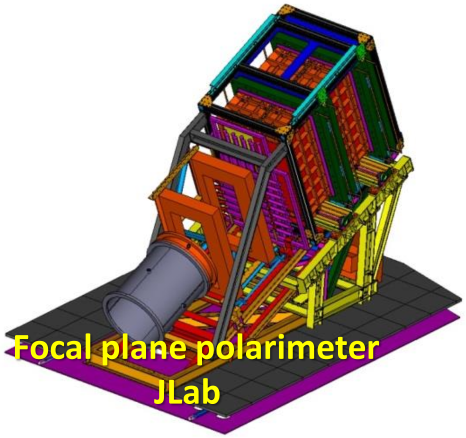


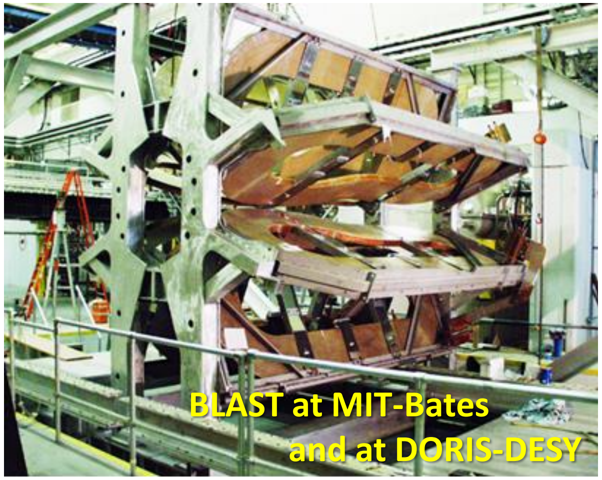
2- Double Polarization technique

Polarized beam and recoil proton polarization
or Polarized beam and polarized target

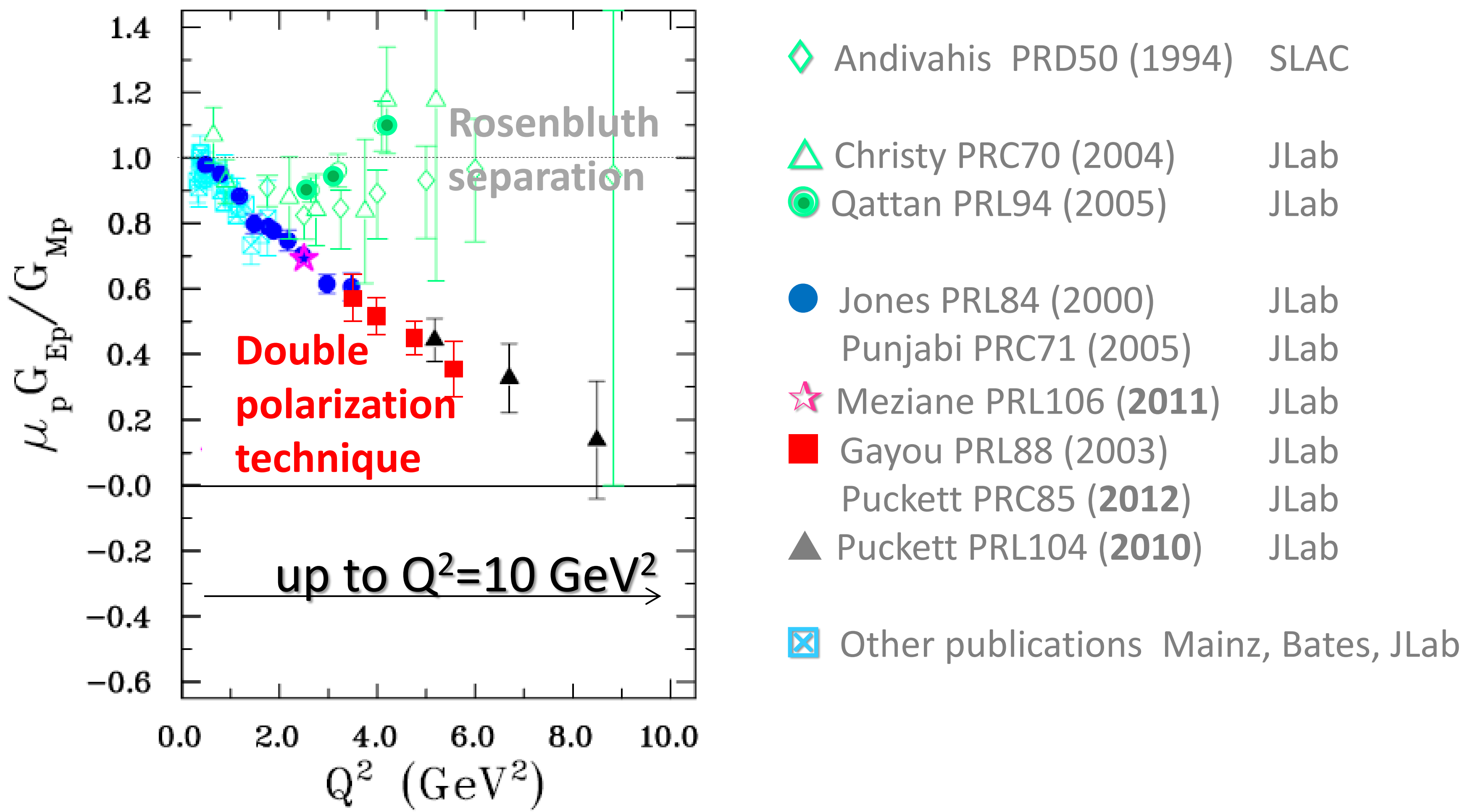
➔ Direct measurement of the ratio G_E/G_M





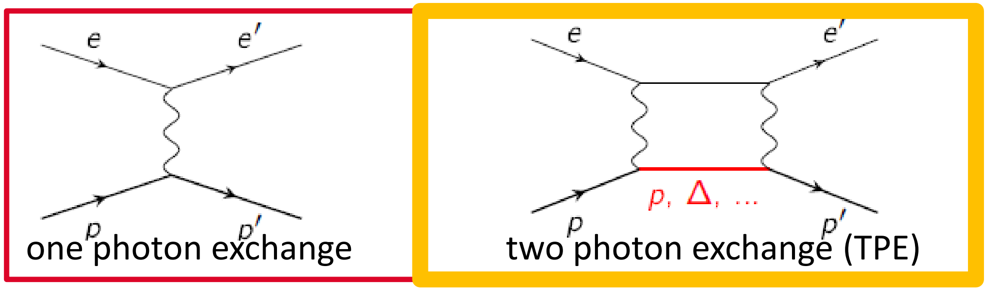


$\mu G_E / G_M$ by the 2 methods



Discrepancy between the 2 methods

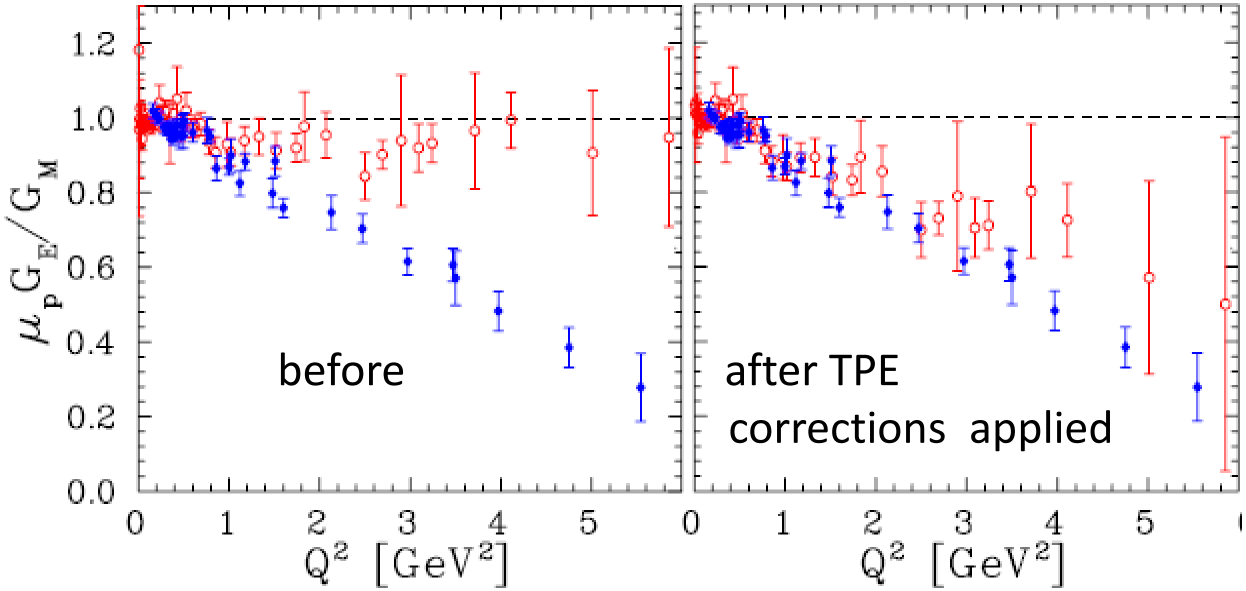
Two Photon exchange to solve the problem?



RADIATIVE CORRECTIONS:

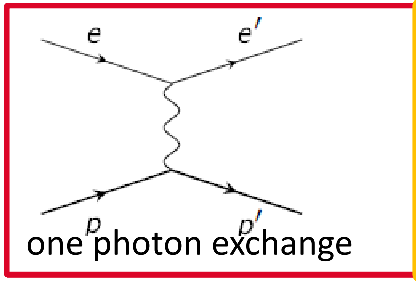
the hadron structure dependent part of the **two photon exchange (TPE)** was neglected

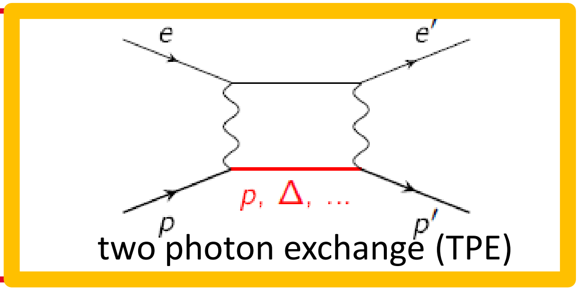
- ✓ large radiative corrections for σ
- ✓ negligible effect for G_E/G_M (similar effect for the numerator and denominator of the ratio)



Guichon, Vanderhaeghen, PRL91 (2003)
Blunden et al., PRC72 (2005)
Afanassev et a., PRC72 (2005)
Arrington et al.,PPNP66 (2011)

Stringent comparison: e^+ and e^- scattering





$$\sigma(e^- p) = |M_{1\gamma}|^2 \alpha^2 - 2\,|M_{1\gamma}|\,|M_{2\gamma}|\,\alpha^3 + \dots$$

$$\sigma(e^+ p) = |M_{1\gamma}|^2 \alpha^2 + 2\,|M_{1\gamma}|\,|M_{2\gamma}|\,\alpha^3 + \dots$$

$$R = \frac{\sigma(e^+ p)}{\sigma(e^- p)} = 1 + \frac{4\,\Re(M_{1\gamma}^\dagger M_{2\gamma})}{|M_{1\gamma}|^2}$$

3 experiments on going

- ✓ **Olympus: BLAST @ DORIS @ DESY**

  DORIS e-/e+ storage ring

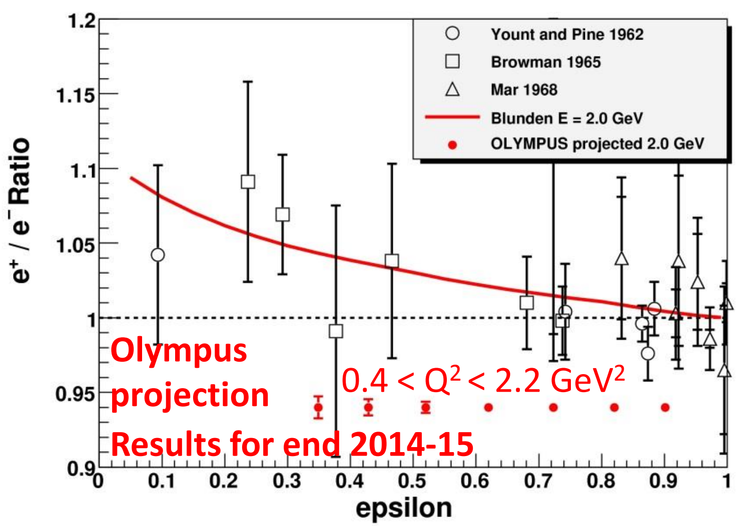
  BLAST detector + internal target

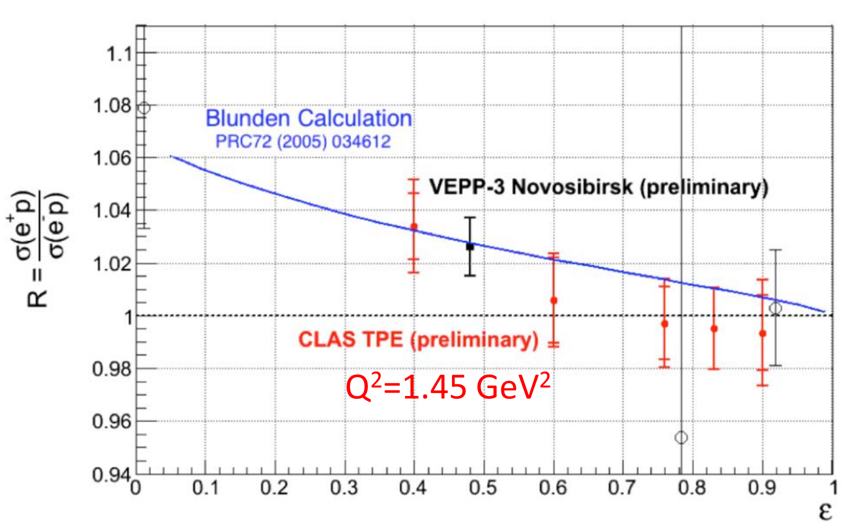
- ✓ **VEPP-3 @ Novosibirsk**

  e-/e+ storage ring, internal target

- ✓ **CLAS-PR04-116 @ Jlab**

  e-/e+ pair production from photon beam





Shape of the nucleon

NON RELATIVISTIC INTERPRETATION

classical picture in the Breit frame (q=Q)

the Form Factors are the Fourier Transform of the charge and magnetization distributions

$$F(\vec{q}) = \int \rho(\vec{r}) e^{i\vec{q}\vec{r}} d^3\vec{r}$$

$$= \frac{4\pi}{q} \int_0^\infty \rho(r) \sin(qr) r\, dr$$

$$= 1 - \frac{\vec{q}^{\,2}}{6} \langle r^2 \rangle + \frac{\vec{q}^{\,2}}{120} \langle r^4 \rangle + \ldots$$

Taylor expans.

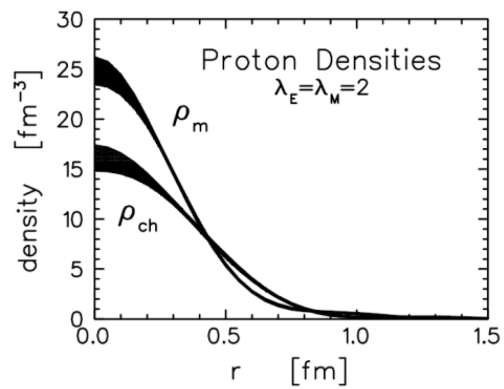
$$r_p^2 \equiv -6 \frac{dG_E}{dQ^2}\Big|_{Q^2=0}$$

This is a definition

RELATIVISTIC INTERPRETATION

light front picture in the Infinite Momentum Frame

2D or **transverse** (⊥ to boost) **spatial distrib**



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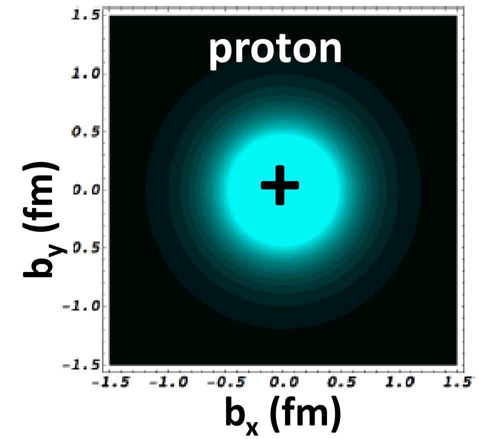

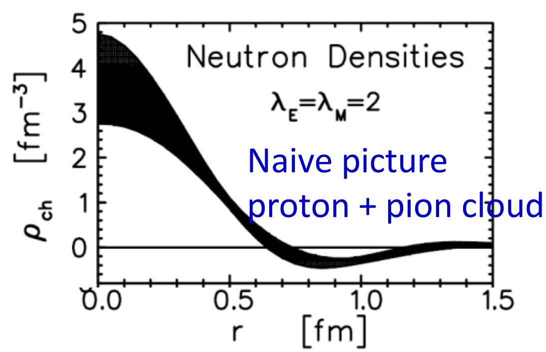

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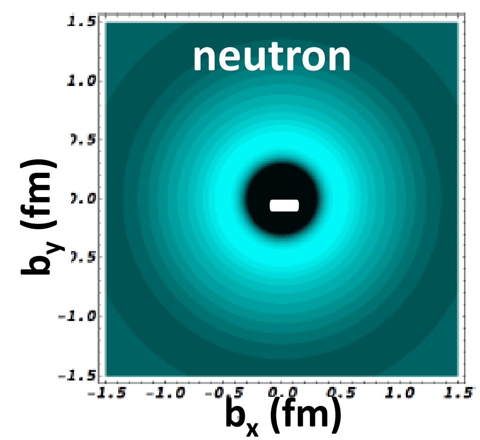


Kelly PRC66 (2002); Miller PRL99 (2007)
Perdrisat et al., PPNP59 (2007)
Vanderhaeghen et al., Phys. News 21 (2011)

Proton radius from ep scattering at low Q^2

MAMI – A1

High precision and redundancy

3 high resolution spectrometers

1400 measured cross sections (stat < 0.1%)

$0.003 < Q^2 < 1$ GeV^2

Super-Rosenbluth technique

Fit of form factor models directly

Wide range of parametrizations

$r_p = 0.879 \pm 0.008$ fm

Bernauer et al. , PRL105 (2010)
& PRC90 (2014) Including TPE and all world data

JLAB - HallA

using recoil polarimetry to get G_E/G_M

Exp E05-103: Ron et al. PRL99 (2007)
update PRC84 (2011)

Exp E08-107: Zhan et al. PLB 705 (2011)

$Q^2 > 0.2$ GeV^2

In the near future
results from the 2nd part of E08-107
polarized beam - polarized NH3 target asymm.

$0.01 < Q^2 < 0.16$ GeV^2

$r_p = 0.875 \pm 0.010$ fm

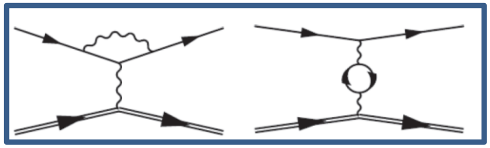
Zhan et al. PLB 705 (2011)

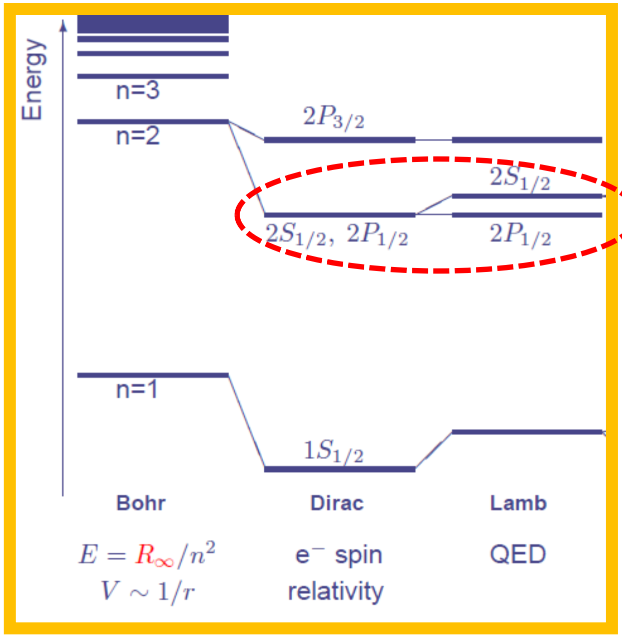
Proton radius from muonic hydrogen Lamb shift

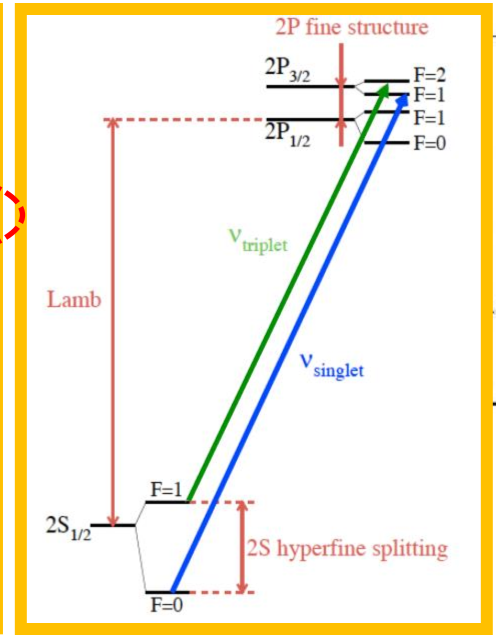
Lamb shift (1947): pure radiative QED effects such as 'self energy' and 'vacuum polarization'

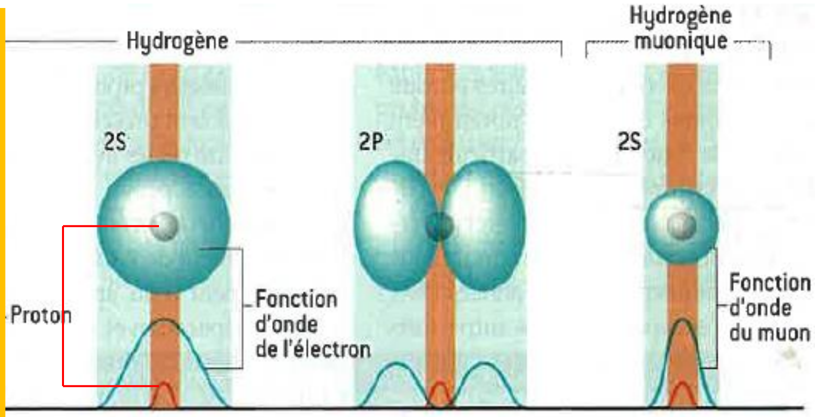
The perturbation causes a fluctuation in the position of the electron (or muon).

➔ subtle difference between the binding energies of the 2S½ and 2P ½









Probability for the lepton to be within the volume of the proton

$= (r_p/r_{Bohr})^3 \sim (\alpha\, m_{lepton}\, r_p)^3$

➔ $\mathcal{P}roba\,(\mu) = 8 \times 10^6\ \mathcal{P}roba\,(e)$

With the new 5keV muon beam line at PSI:

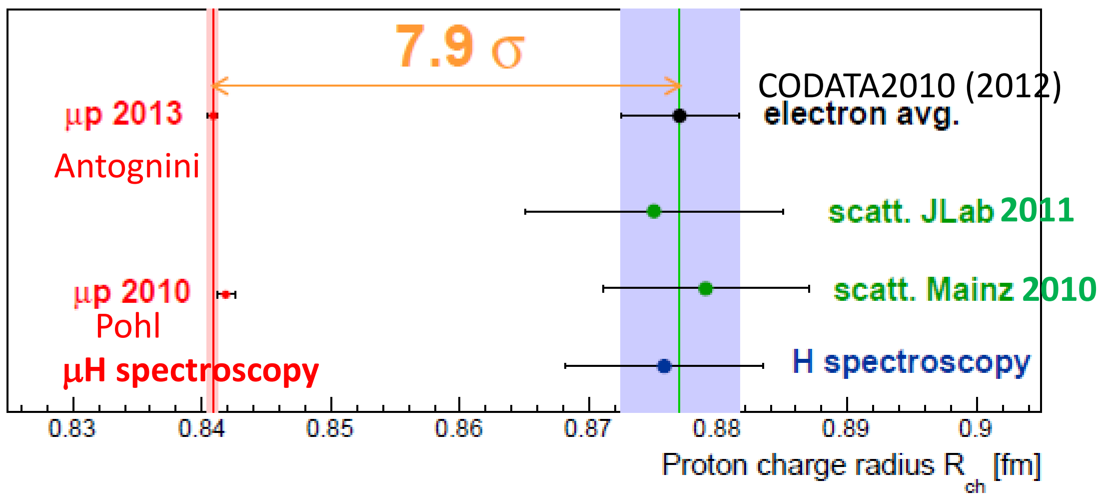
- Pohl et al., Nature 466 (**2010**): **2S ➔ 2P Lamb shift** ➔ r_p=0.84184 ±0.00067 fm
- Antognini et al., Science 339 (**2013**): **2S ➔ 2P Lamb shift**

$\Delta E(\text{meV}) = 206.0336(15) - 5.2275(10)\, r_p^2 + 0.0332(20)_{TPE}$ ➔ r_p=0.84087 ±0.00039 fm

Proton radius puzzle

Discrepancy between

muonic and **electronic** measurements



Particle Data Group: “ Until the difference between the **ep** and μ**p** values is understood, it does not make much sense to average all the values together. For the present, we stick with the less precise (and provisionally suspect) CODATA 2010 value.

It is up to workers in this field to solve this puzzle.”

Possible origins of the disagreement

Pohl, Gilman, Miller, Pachuki, Annu. Rev. Nucl. Part. Sci. 63 (May 2013)

- The ep scattering experiments are not at enough low Q^2

  ➔ **2 new experiments: Jlab ($Q^2 = 10^{-3} - 10^{-4}$ GeV^2) ,MAMI (Initial State Radiation)**

- QED calculations not enough accurate to compare ep and μp spectroscopy

  ## Proton structure effect:

  the TPE term (in m^4_{lepton}) depending on proton polarizability corrections could be not correct

- ## Novel Beyond Standard Model Physics:

  Electron and muon really do have different interactions with the proton

  ## Failure in the electron-muon Universality?

  The muon anomalous magnetic moment $(g-2)_\mu$ exceeds the SM expectation by 3σ

  Search for dark photon – light weakly coupled U(1) gauge boson

➔ **The MUSE experiment at PSI will use the world's most powerful low-energy separated e/π/μ beam for a direct comparison for $0.002 < Q^2 < 0.07$ GeV^2**

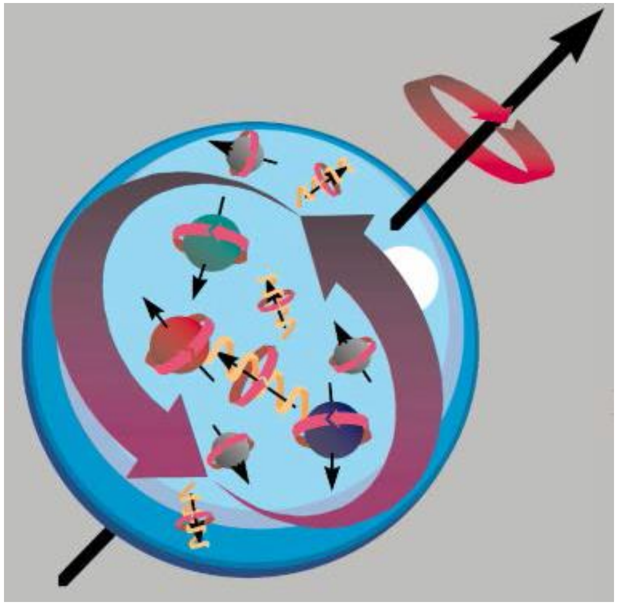
e^+p, e^-p, μ^+p, μ^-p

r_p (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060	???

PART 2: The proton spin puzzle

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

Quark spin | Quark OAM | Gluon spin | Gluon OAM



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

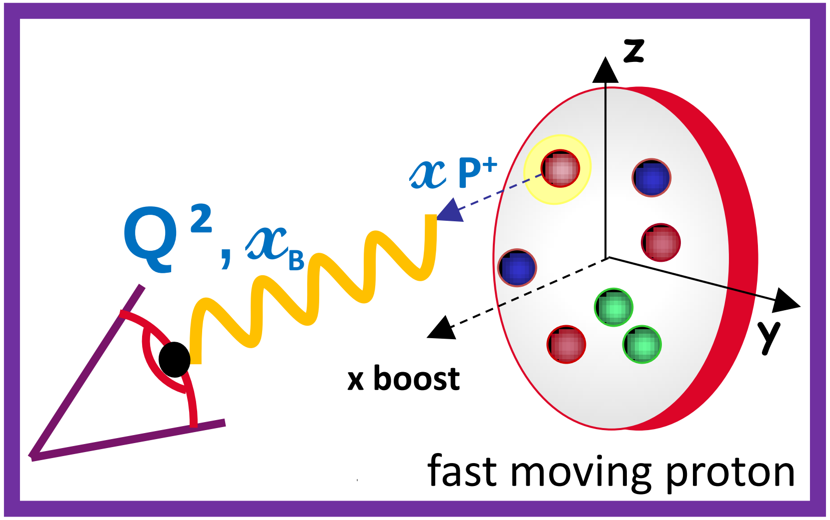
Only **30%** of proton spin comes from spin of quarks and antiquarks.
Where does the rest come from **?**

$\Delta G = \int_0^1 \Delta g(x)\, dx$

In A+=0 light-cone gauge
Not unique decomposition (Jaffe / Ji)

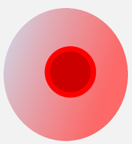
and **Orbital Angular Momentum (OAM)**

Proton picture: 1D



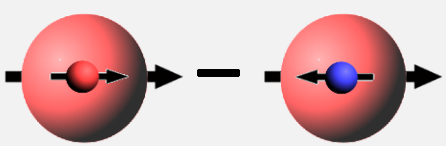
Longitudinal momentum

$q(x)$ or $f_1^q(x)$



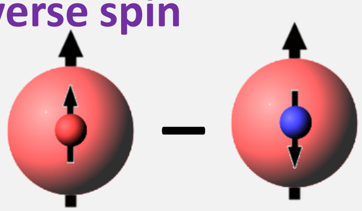
Longitudinal spin

$\Delta q(x) = \overrightarrow{q}(x) - \overleftarrow{q}(x)$

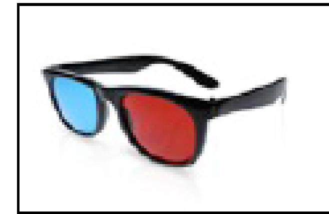


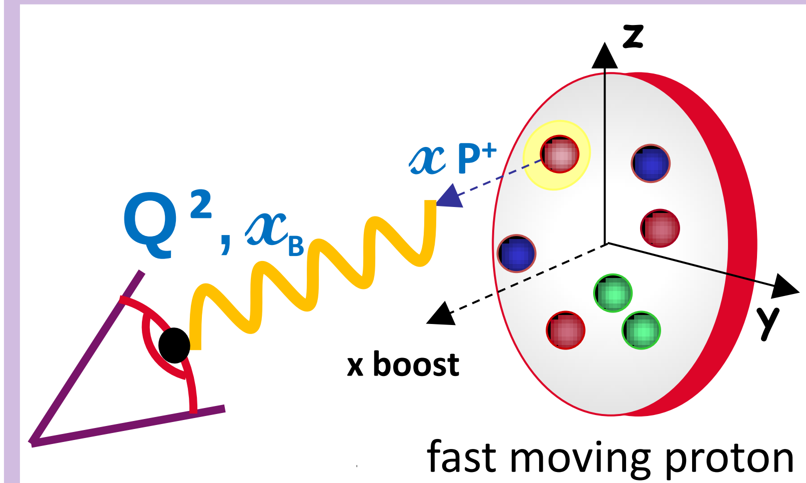
Transverse spin

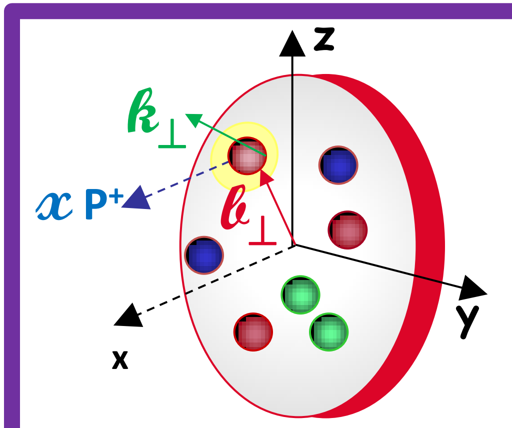
$\Delta_T q\ (x)$ or $h_1\ (x)$



Proton picture: 1D → 1+2D







$\mathcal{W}\,(x, k_\perp, b_\perp)$

Quantum tomography of the nucleon

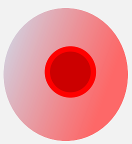
Meissner et al, PRD76 (2007)
Lorcé et al, JHEP1105 (2011)

$\int db_\perp$ → **Transverse momentum**

$\int dk_\perp$ → **Transverse position**

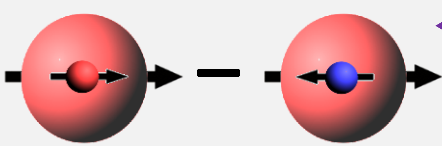
Longitudinal momentum

q(x) or $f_1^q(x)$



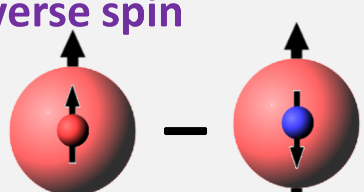
Longitudinal spin

$\Delta q(x) = \vec{q}(x) - \overleftarrow{q}(x)$



Transverse spin

$\Delta_T q$ or $h_1(x)$



Transverse momentum

$\int dk_\perp$ ←

8 TMDs$(x, k_\perp)$

Sivers,
the most famous TMD

Transverse position

8 GPDs $(x, b_\perp)$ $\int dx$ → Form Factors

H (x,x′,**t**)

E (x,x′,**t**)

Ji sum rule:

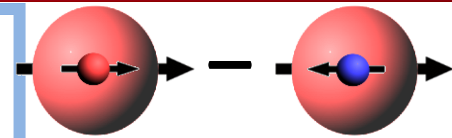
$2J^q = \int dx\, x\,(H^q(x,x',0) + E^q(x,x',0))$

holy grail for OAM

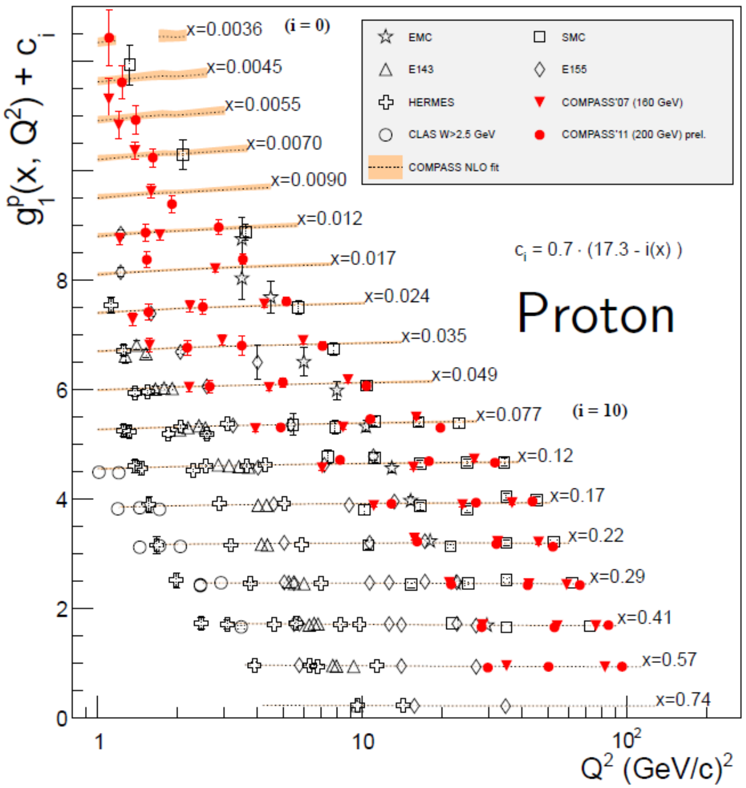
The longitudinal spin structure, ΔΣ and ΔG

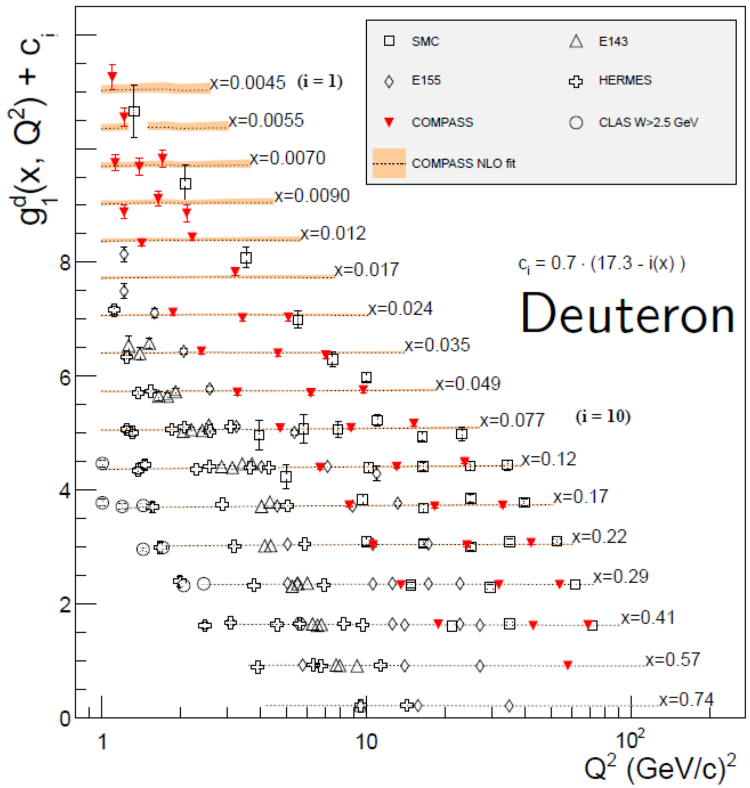
DIS: $\vec{\ell}\,\vec{p} \rightarrow \ell\, X$

$$A_1(x,Q^2) = \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$



$\Delta q(x) = \vec{q}(x) - \overleftarrow{q}(x)$





New **COMPASS-CERN** data with **polarized muon beams of 160 and 200 GeV** (for low x and high Q^2)

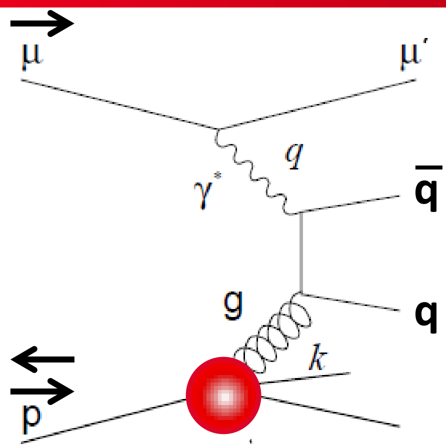
g_1 input to global NLO QCD fits for extraction of Δq and Δg

$\int g_1 dx \rightarrow$ **0.26 < ΔΣ < 0.34**

$\frac{d}{d \ln Q^2} g_1 \rightarrow$ **ΔG**

but x and Q2 coverage
not yet sufficient
for precise ΔG

Gluon spin from photon-gluon fusion in SIDIS



Two channels: $A_{LL}=\Delta g/g$ + bg

q=c ● **open charm (NLO)**

scale=$\mu^2 \approx 13 \text{GeV}^2$

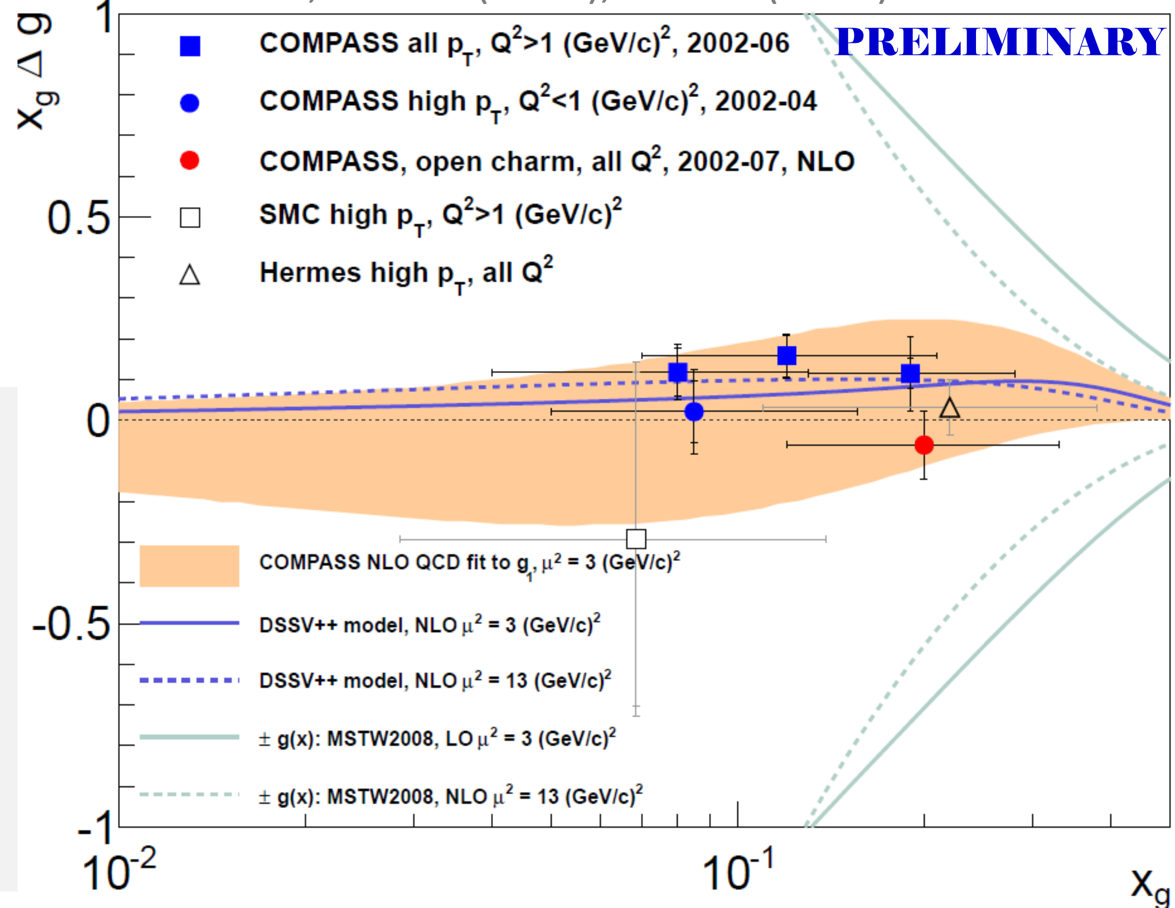
q=u,d,s

● high-p_T **(LO)**

■ all p_T **(LO)** ← **NEW**

scale=$\mu^2 \approx 3$ GeV^2

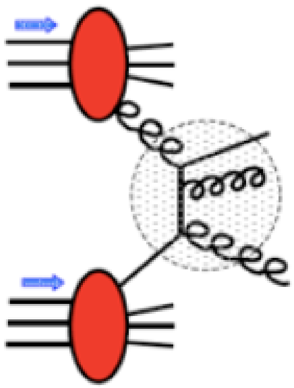
COMPASS, PLB718(2013), PRD87 (2013)



All direct measurements compatible $\int_{0.05}^{0.3} \Delta g(x)\, dx$ **significantly positive**

Note that these data are not included in the global fit DSSV++

Gluon spin from $\vec{p}\,\vec{p}$ collisions at RHIC

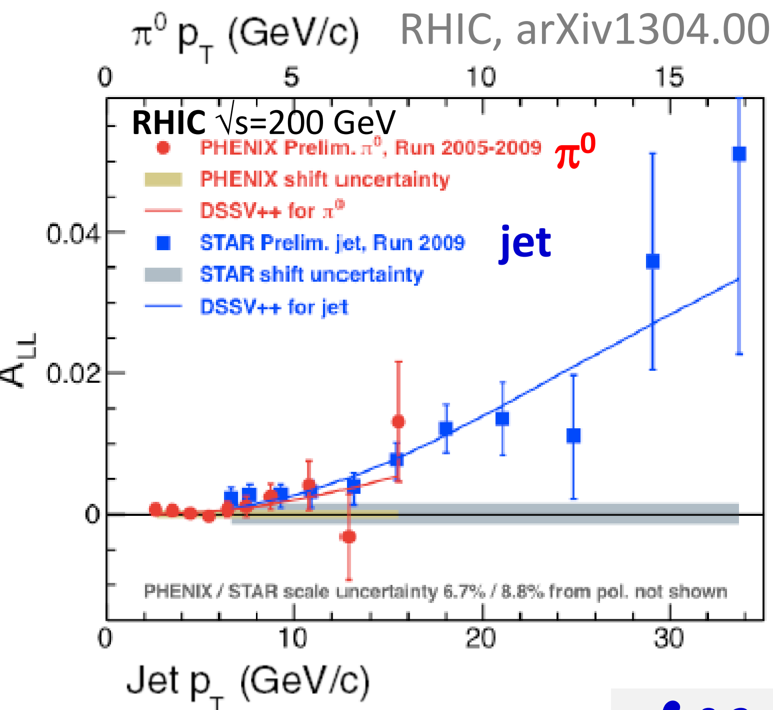


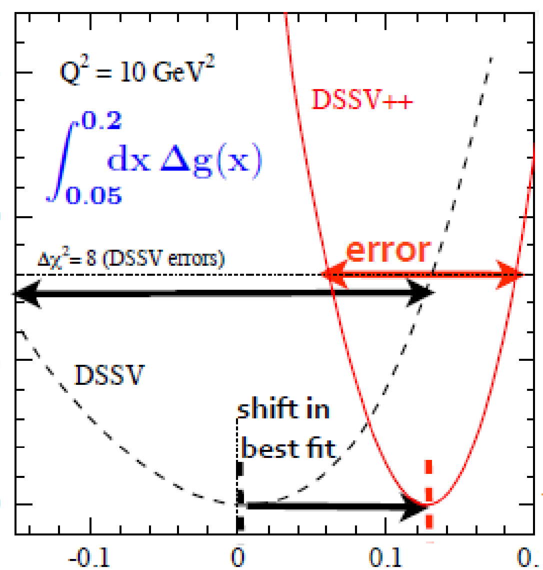
$$A_{LL}(P_T) \propto \frac{\Delta g\, \Delta q}{g\ \ q} + \frac{\Delta g\, \Delta g}{g\ \ g} + \ldots$$

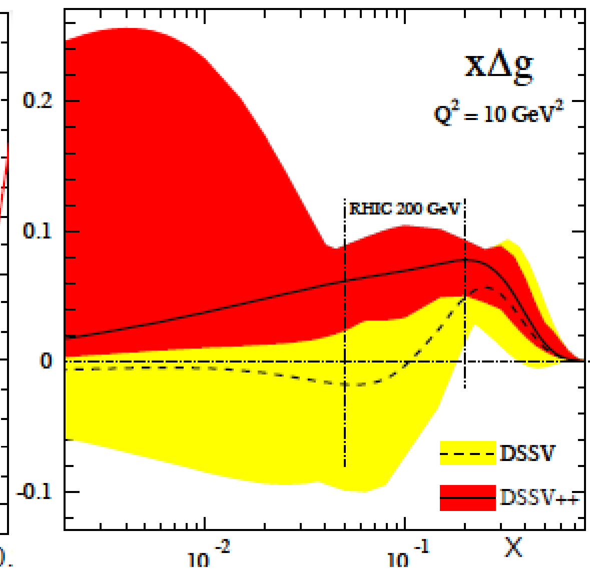
Measure double spin asymmetry
Compare data to global fits

RHIC, arXiv1304.0079 (2013)

DSSV: De Florian, Sassot, Stratmann, Volgelsang, PRL113(2014)







$$\int_{0.05}^{0.2} \Delta g(x)\, dx = 0.1 \pm^{0.06}_{0.07}$$

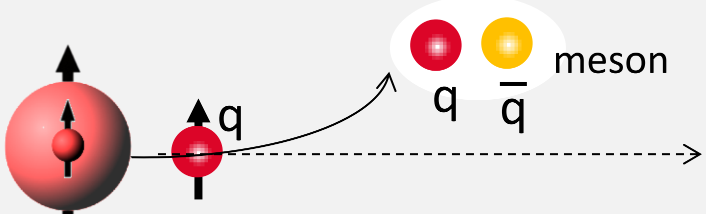
Large uncertainties in the unmeasured small x domain

Transverse spin and transverse momentum in SIDIS

The **transversity** h_1 or $\Delta_T q$

Measures the diff. of density of quarks with spin // and anti// to the transverse spin of the nucleon

Chiral-odd ➔ **Collins** odd FF

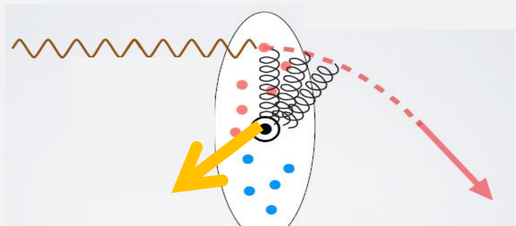


$$A_{Coll} \approx \frac{\sum_q e_q^2\, h_1^q(x) \otimes H_{1q}^{\perp h}(z, p_T^h)}{\sum_q e_q^2\, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$

The **Sivers** $f_{1T}^{\perp}$ PDF

correlates the quark k_T and the nucleon transv . spin

Chiral-even and T-odd



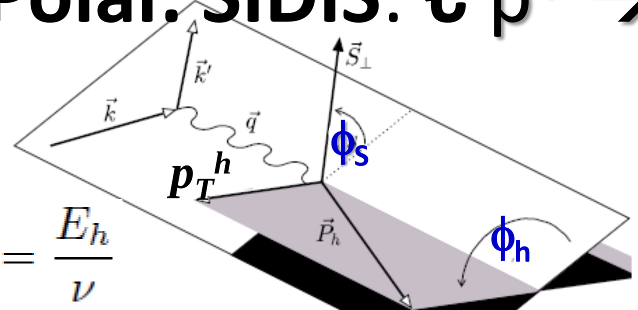
FSI
OAM

$$A_{Siv} \approx \frac{\sum_q e_q^2\, f_{1T}^{\perp q}(x) \otimes D_{1q}^h(z, p_T^h)}{\sum_q e_q^2\, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$

Transv. Polar. SIDIS: $\ell\, p^{\uparrow} \rightarrow \ell\, h^{\pm} X$

Collins asymmetry

in sin ($\phi_h+\phi_S-\pi$)



$$z = \frac{E_h}{\nu}$$

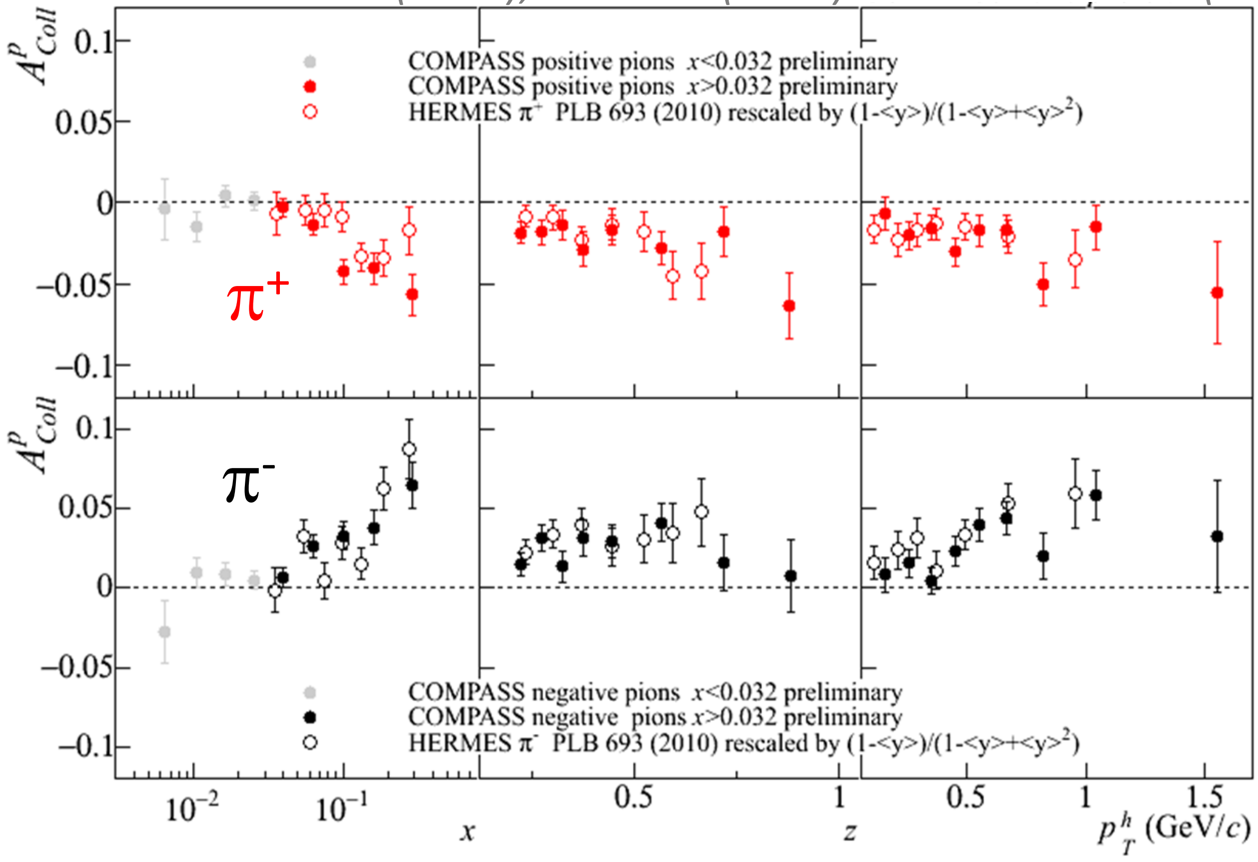
Sivers asymmetry

in sin ($\phi_h-\phi_S$)

Transverse spin and Collins effect in SIDIS

Collins asymmetry

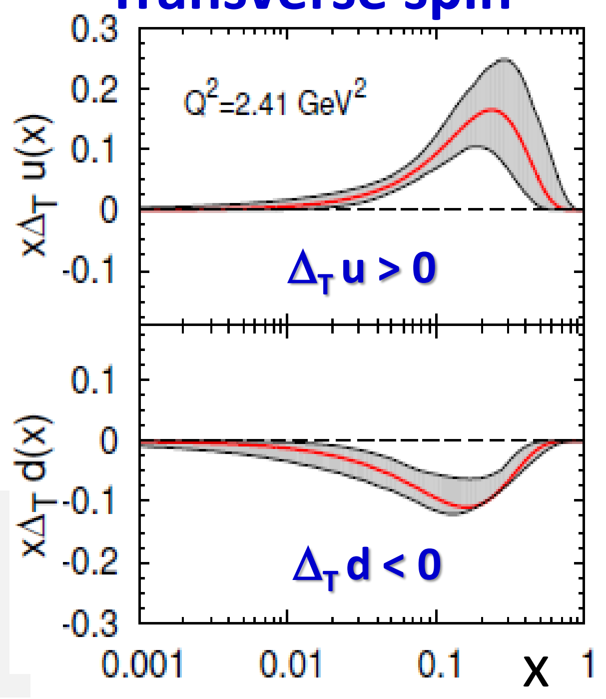
COMPASS:PLB 692 (2010), PLB 717 (2012) HERMES: PLB693(2010)



Global fit
using data from
HERMES p,
COMPASS p and d,
Belle e+e- (→FF)

Bacchetta et al., JHEP1303 (2013)
Anselmino at al. PRD87 (2013)

Transverse spin



Large effect of opposite sign for π^+ and π^-

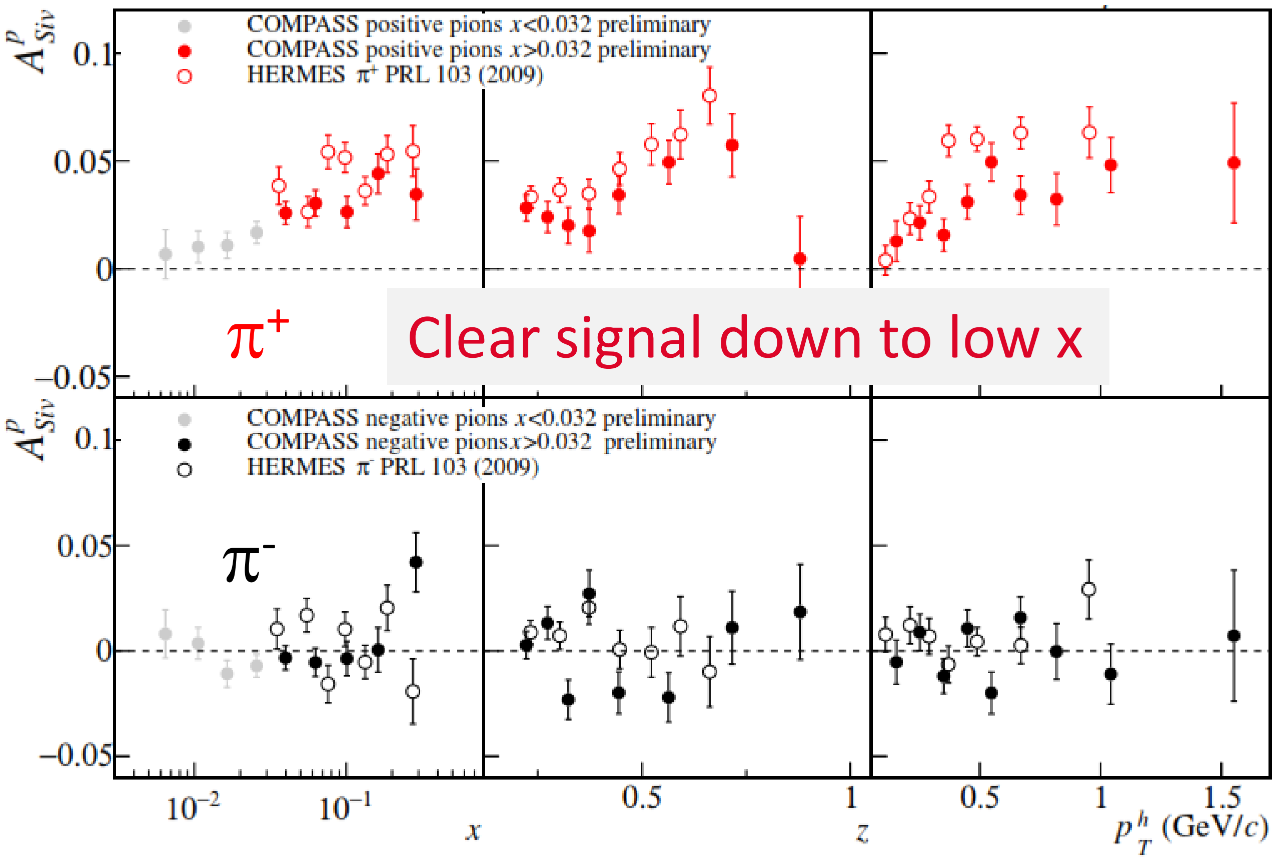
Good agreement between COMPASS and HERMES for x > 0.032

Not obvious as the COMPASS Q^2 domain is larger by a factor of about 2or 3

Sivers in SIDIS

Sivers asymmetry

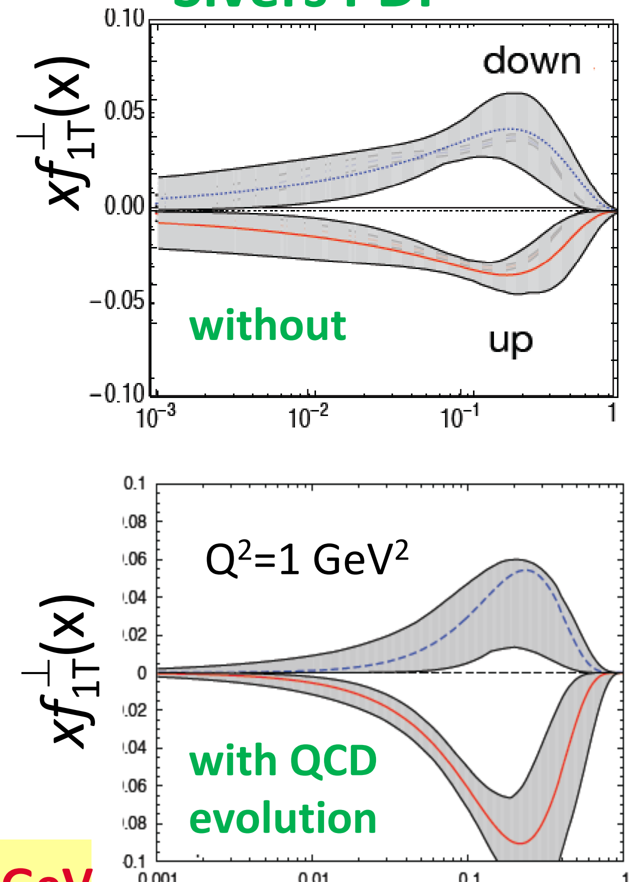
COMPASS:PLB 692 (2010), PLB 717 (2012) HERMES: PRL103(2009)



agreement between COMPASS and HERMES for x > 0.032
but clear indication that the strengh ↘ when Q^2 ↗

predictions
Aybat, Prokudin, Rogers, PRL108(2012) (2013)

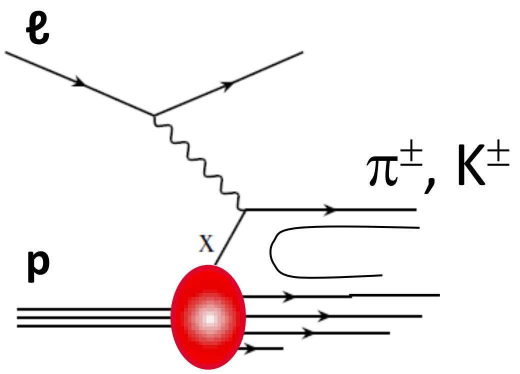
Sivers PDF



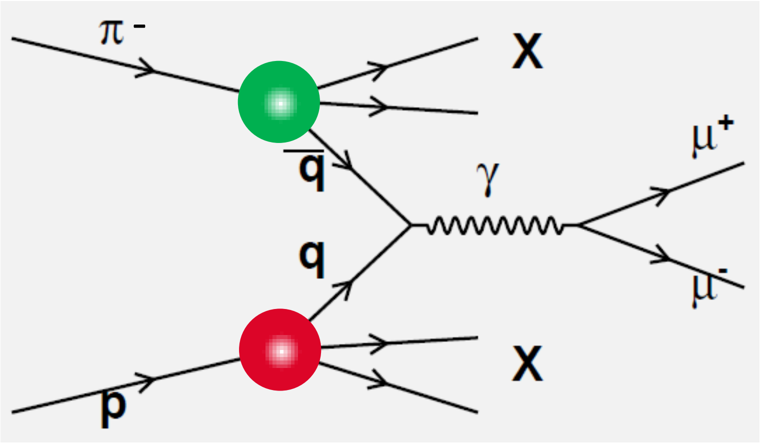
Extended TMD program in SIDIS at COMPASS and Jlab 12GeV

Test of Universality

SIDIS: $\ell\, p^{\uparrow} \rightarrow \ell\, h^{\pm} X$



Drell-Yan (DY)



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$

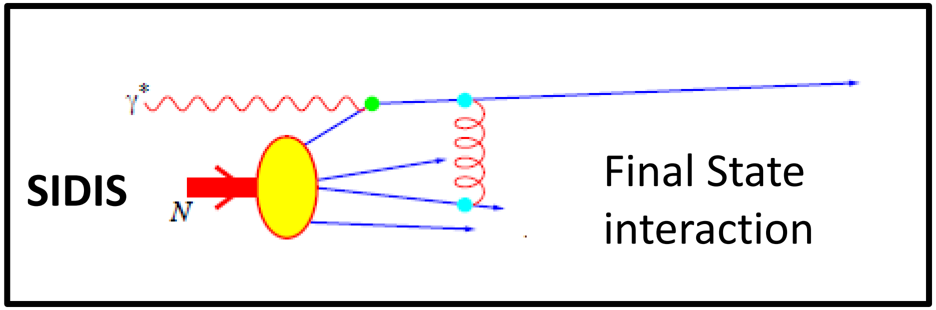
→ test of universality

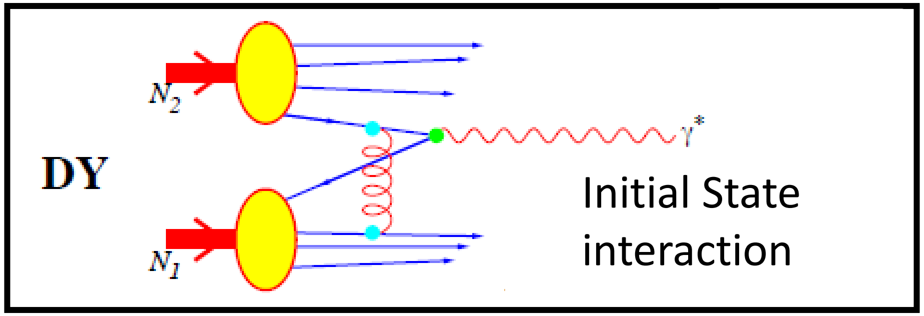
Test of Universality

T-odd character of the Sivers functions

In order not to be forced to vanish by time-reversal invariance
the SSA requires an interaction phase generated by
a rescattering of the struck parton in the field of the hadron remnant

Time reversal





Test of Universality

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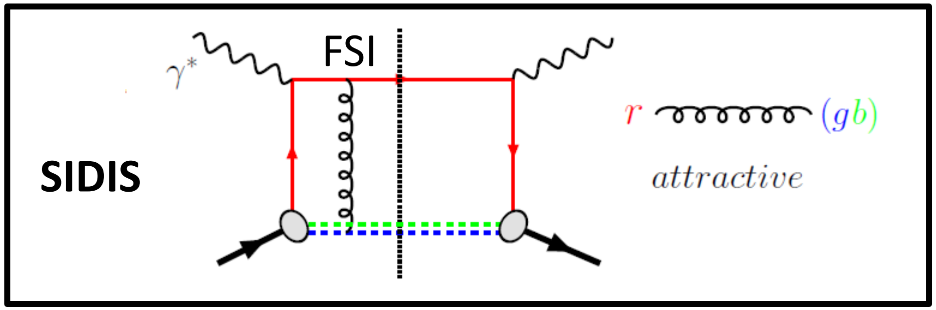
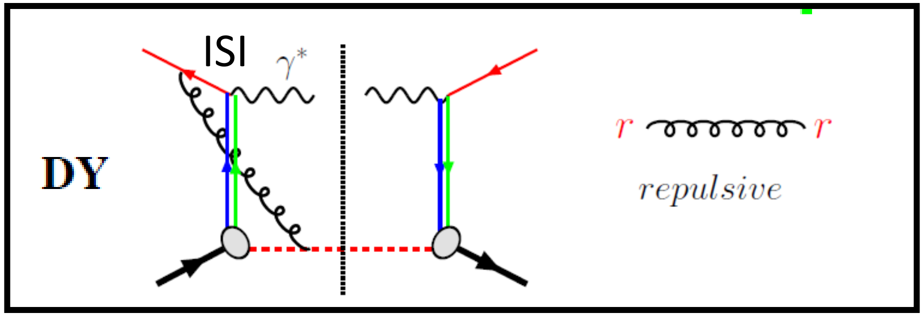




The Sivers function is process dependent, it changes sign to provide the gauge invariance

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

COMPASS end 2014 and 2015 with pion beam and polarized target:

1st ever experimental check of the change of sign of Sivers confronting polarized Drell-Yan and SIDIS results

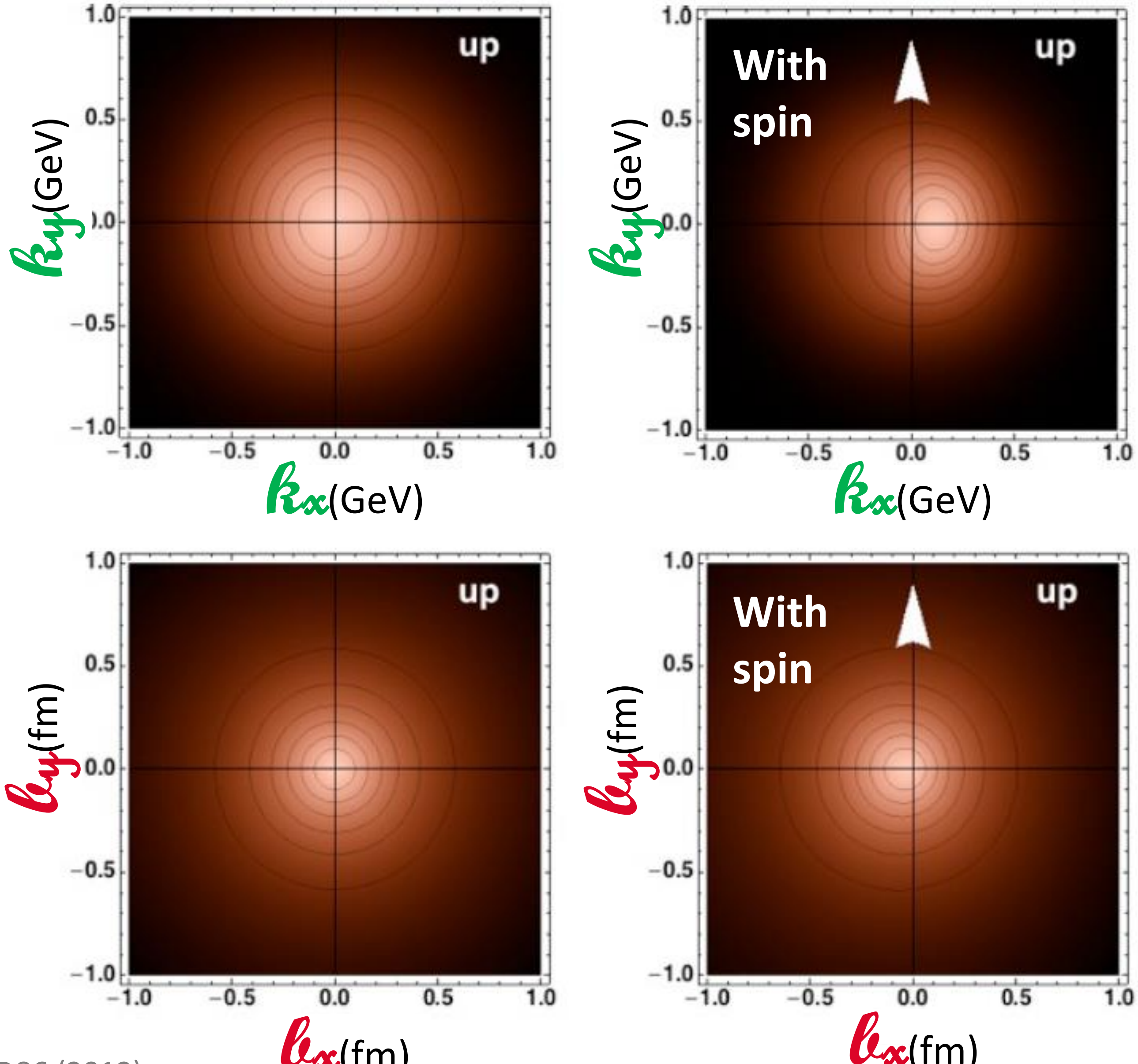
other DY programs in the world (Fermilab, RHIC, FAIR, NICA, JPARC)

3D imaging: mapping in the transverse plane

Proton
moving
towards us

Transverse momentum maps with TMDs

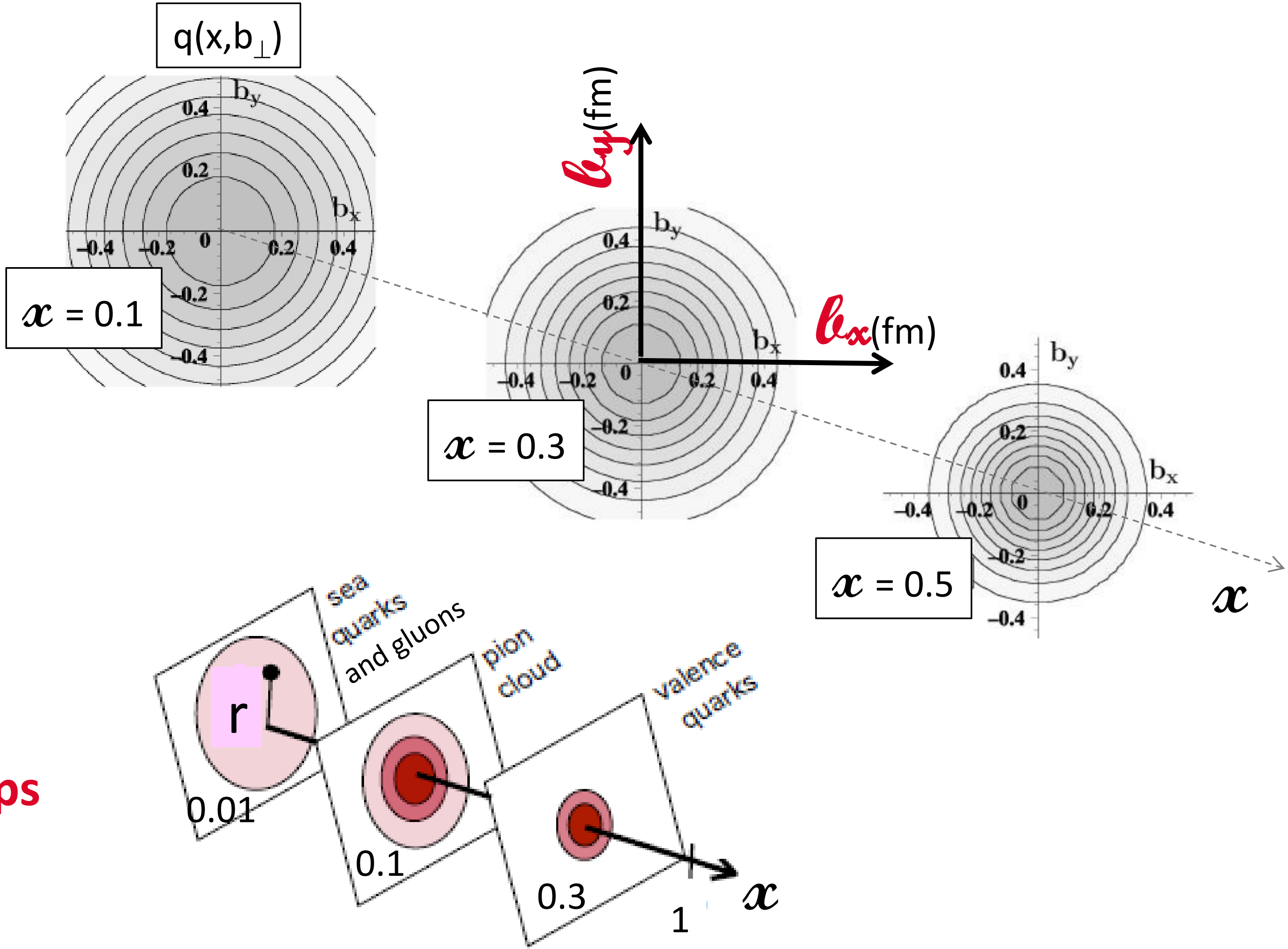
Transverse position maps with GPDs



Bacchetta, Radici, PRL107 (2011)
Anselmino et al., EPJA39(2009), PRD86 (2012)

3D imaging: mapping in the transverse plane

Proton
moving
towards us

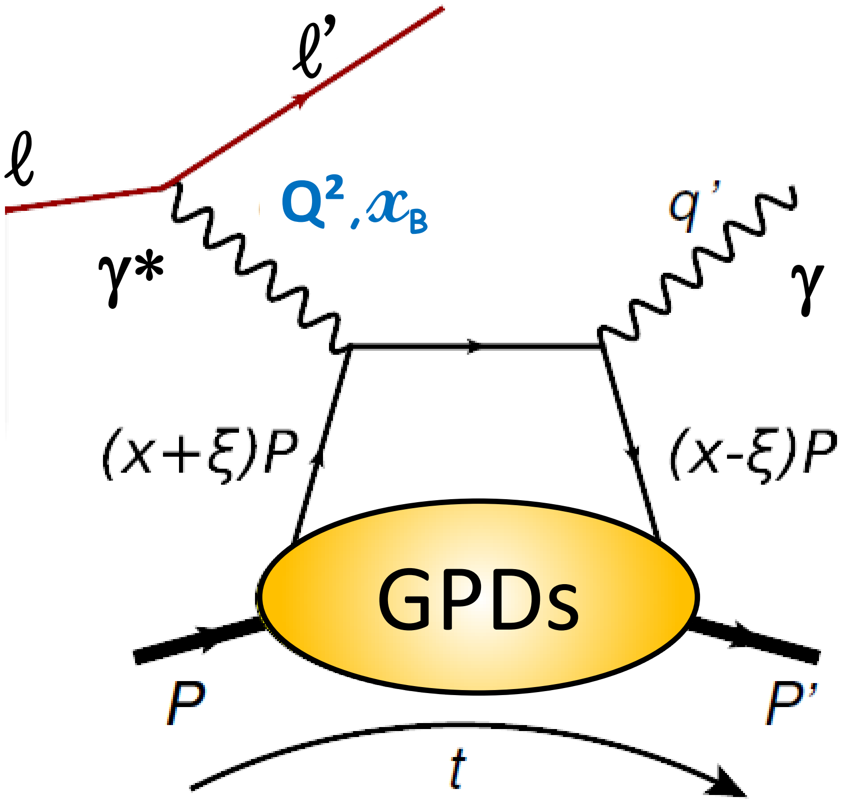


Transverse position maps with GPDs

Burkardt, PRD66(2002)

Deeply virtual Compton scattering (DVCS)

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)



Definition of variables:

x: average long. momentum

ξ: long. mom. difference $\simeq x_B/(2 - x_B)$

t: four-momentum transfer
related to $b_\perp$ via Fourier transform

DVCS: $\ell p \to \ell' p' \gamma$

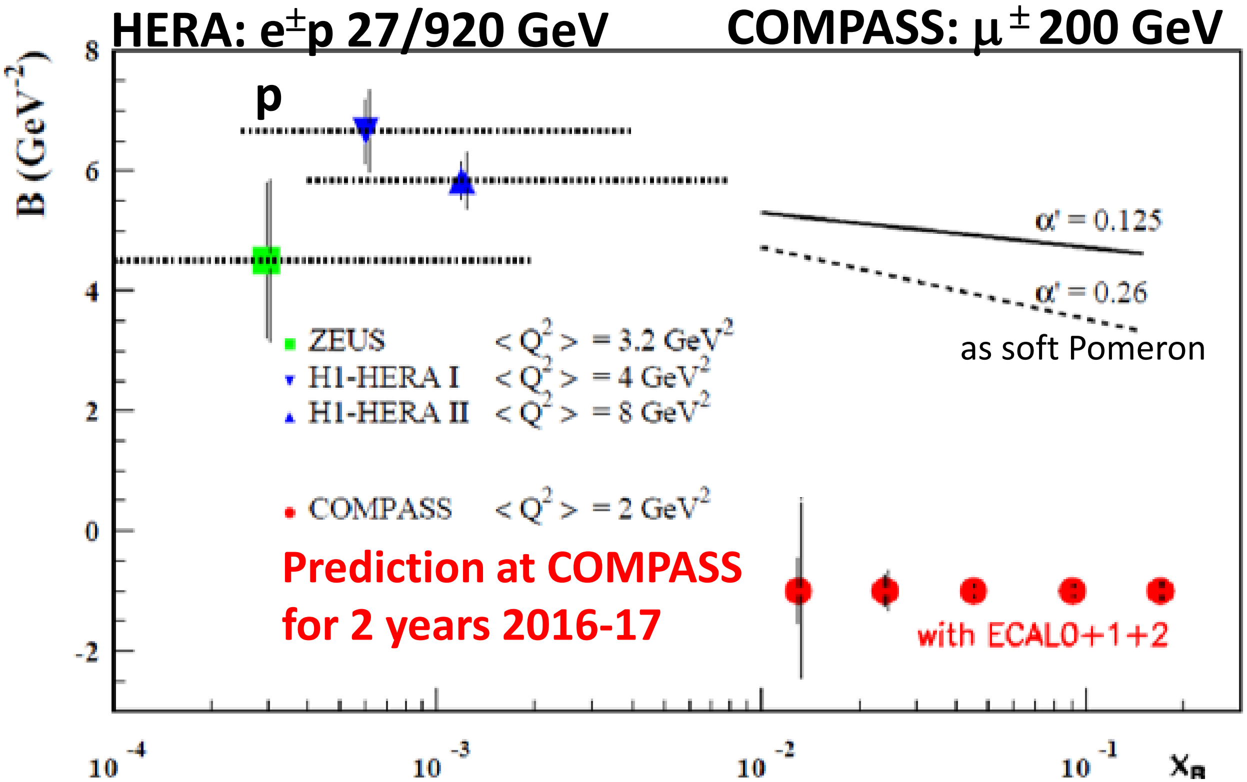
the golden channel
because its interferes with
the Bethe-Heitler process

important parameters:

- high luminosity
- different beam energies
- polarized leptons
- positive and negative leptons

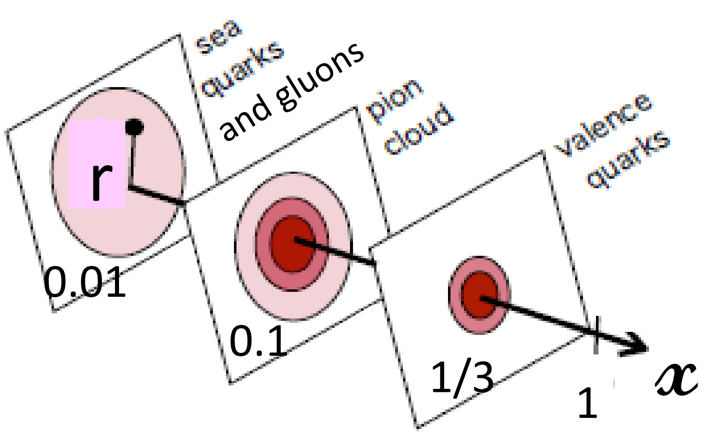
also meson production
$\ell p \to \ell' p' \rho$ or ϕ or $J/\psi, \cdots$

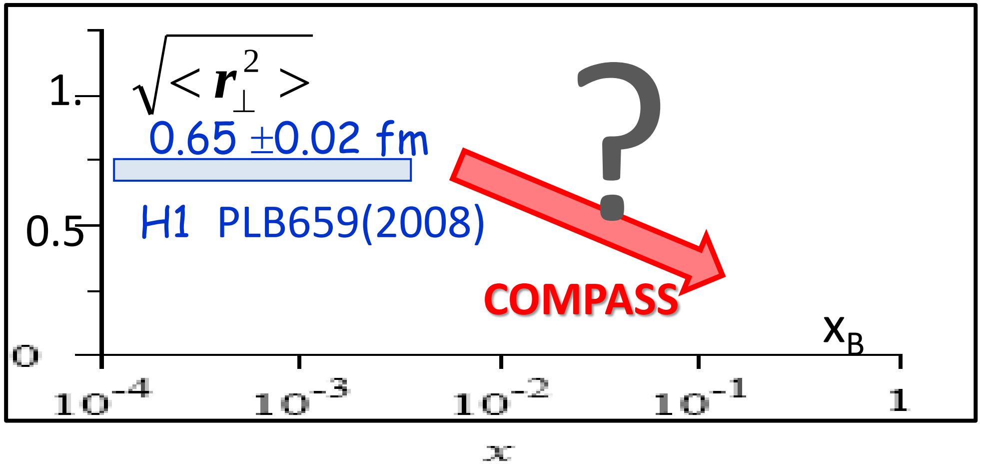
Gluon and sea quark imaging



$$d\sigma^{DVCS}/dt = e^{-Bt}$$

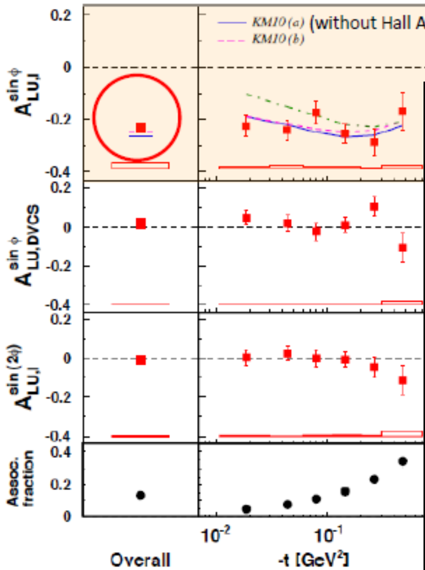
$$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$





Beam Spin Asymmetry with HERMES

A. Airapetian et al, JHEP 07 (2012) 032



sin φ term
Im F1 *H*

KM: Kumerički and Müll...

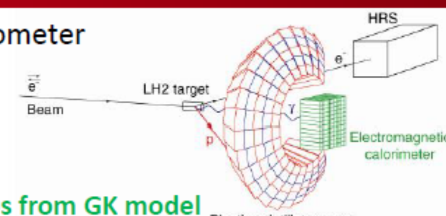
GHL11: G. Goldstein, J. Her...

Beam Spin Diff and Sum – Jlab HallA

E00-110 pioneer experiment with magnetic spectrometer

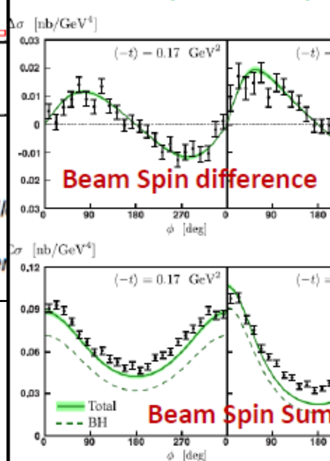
3 measurements: x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV²

$\vec{e}\,p \rightarrow e\,\gamma\,p$



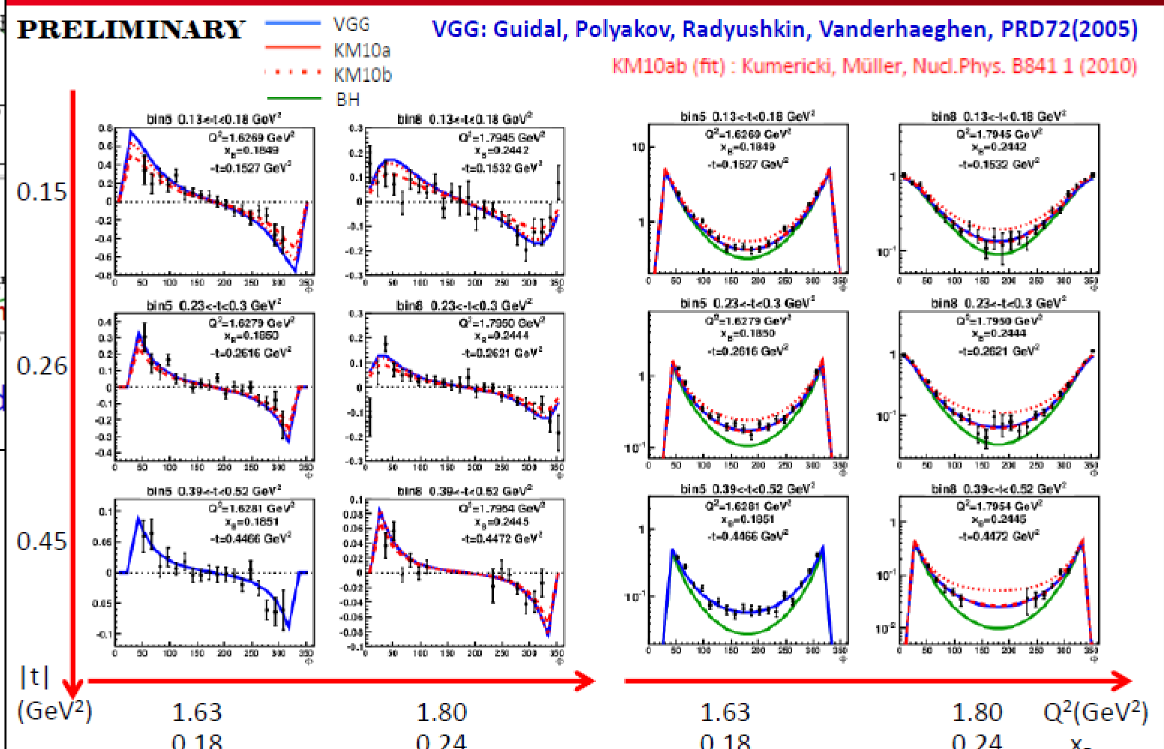
Data: Munoz et al. PRL97, 262002 (2006)

Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model



Do we und...

Beam Spin Diff and Sum – Jlab CLAS



Important activities to get *Im* DVCS and *Re* DVCS

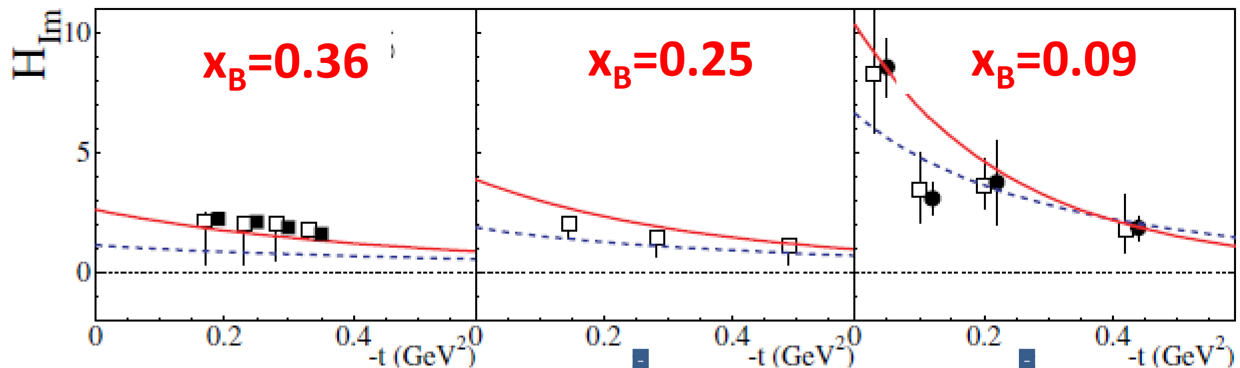
- ✓ tricky data analyses
- ✓ models and fits

Valence quark imaging

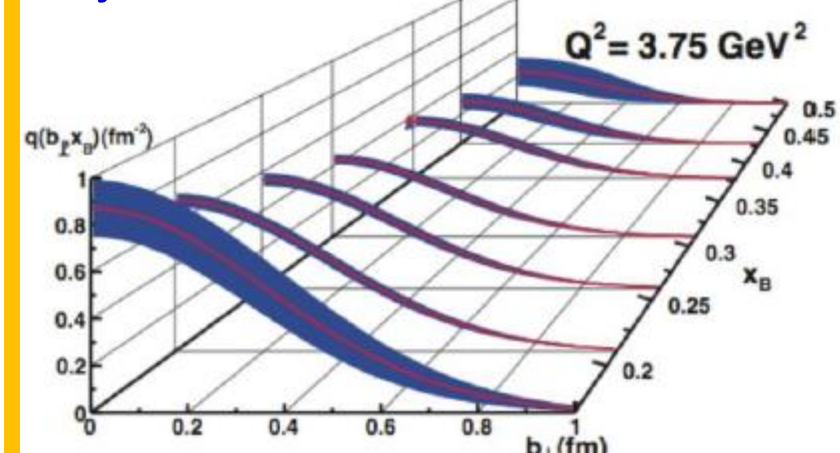
the GPD H in *Im* DVCS

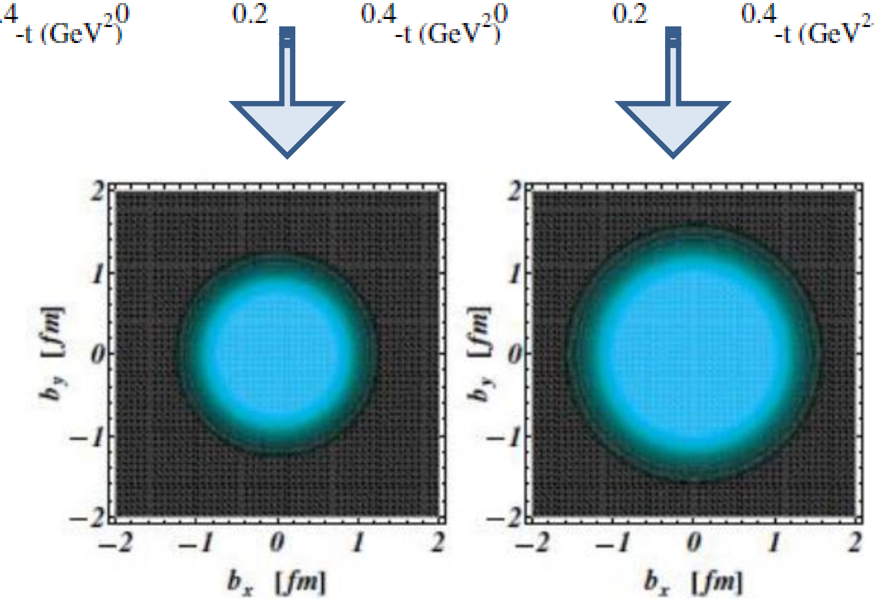
e⁻ 6 GeV		$e^{\pm}$ 27 GeV
Jlab Hall A	**Jlab CLAS**	**HERMES**
Beam Spin Diff	Beam Spin Asym	Beam Spin Asym
Beam Spin Sum	Long Pol targ Asym	Beam Charge Asym

Different local fits
VGG model
KM10 global fit on the world data ranging from H1,ZEUS to HERMES, JLab



Projection for Jlab 12 GeV



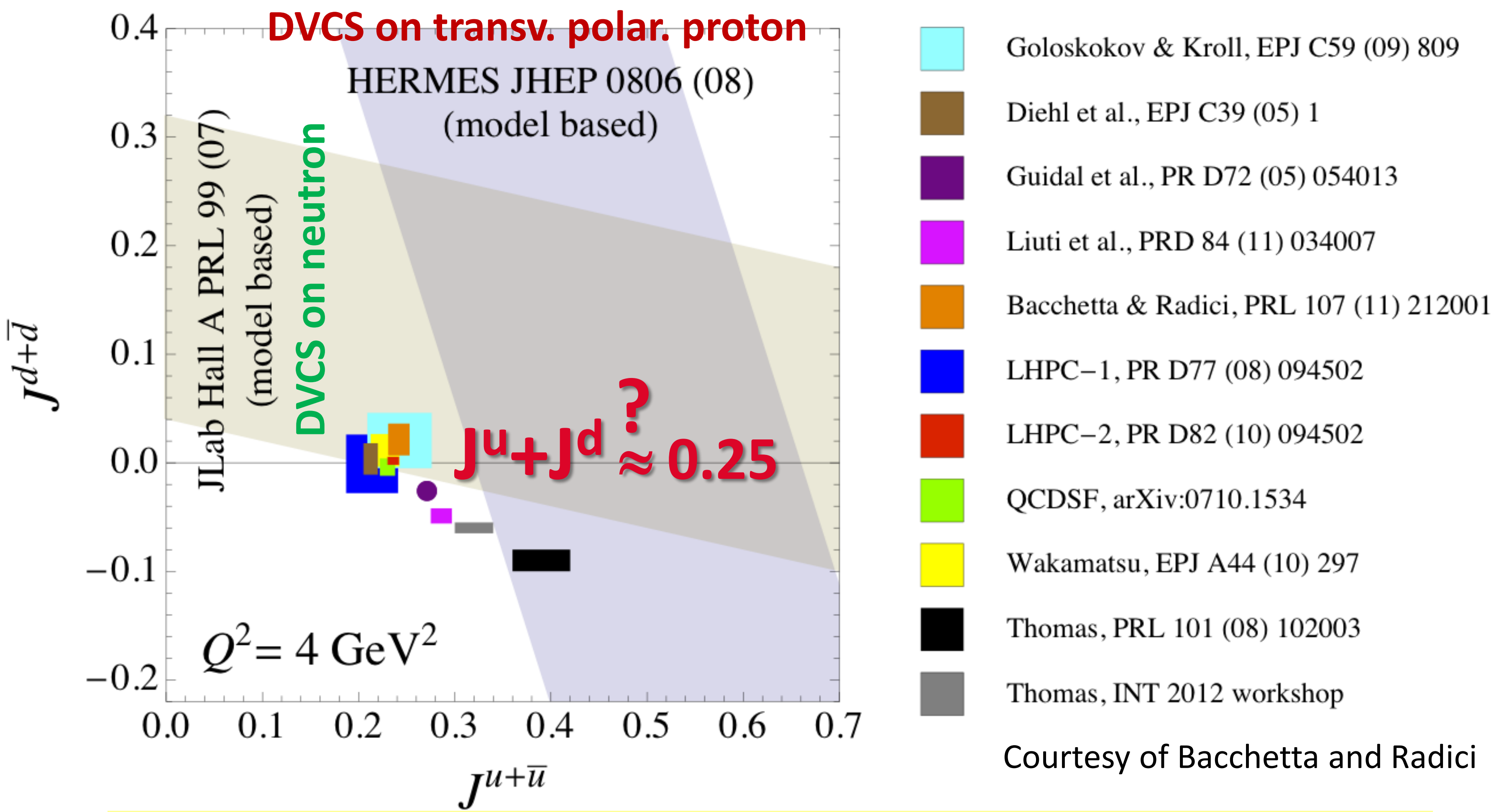


Dudek et al., EPJA48 (2012)

Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

Model dependent extraction of J^u and J^d

the GPD E, holy grail for OAM



Courtesy of Bacchetta and Radici

GPD major program for JLab 12 GeV, COMPASS and for a future electron-proton collider

Understanding the structure of the nucleon is still an exciting and vibrant area of research

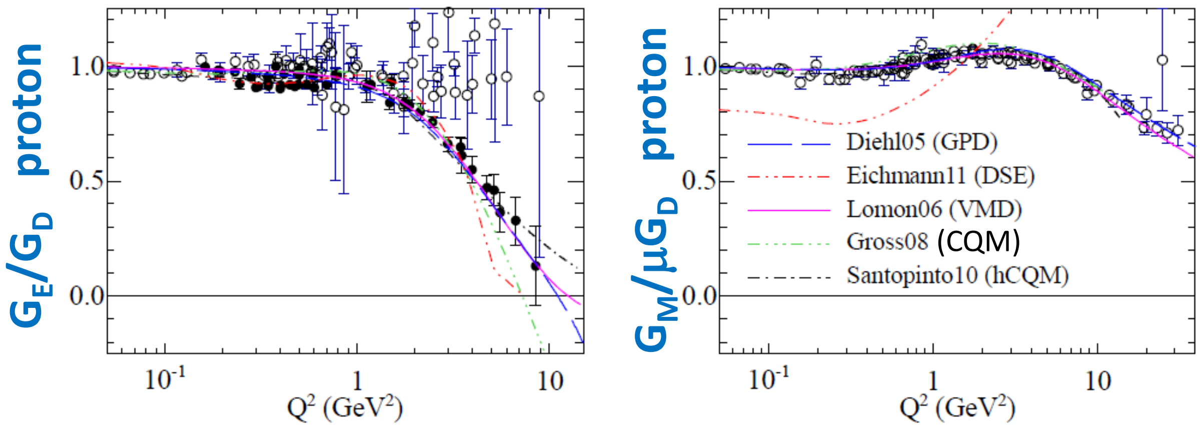
Tremendous experimental effort matched to theoretical progress

Many details given in the parallel sessions
''Quarks and Gluons in hadrons, the hadron spectrum''

Many slides for a longer talk!

The proton Form Factors

From Puckett et al., PRC85 (2012)



The form factors deviate from a dipolar approximation

pQCD: G_E^p/G_M^p should be constant at very high Q^2 ➔ No scaling before Q^2 =10 GeV^2

Lattice calculations QCDSF/UKQCD Collaboration, Collins et al., PRD84 (2011)

Progress with small lattice spacing, large V (>3.5fm), m_π ~180MeV and chiral extrapolation

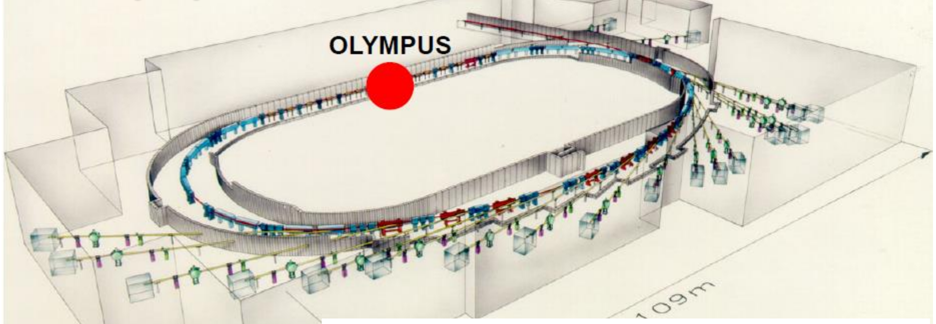
Many Models:

- Vector Meson Dominance (VMD)
- Dispersion Analysis
- Generalized Parton Distr. (GPD)
- Dyson-Schwinger Equations (DSE)
  ab-initio calculation in npQCD

- Relativistic Constituent Quarks(CQM) with OAM
- Pion cloud
  Chiral quark soliton

Stringent comparison: e^+ and e^- scattering

✓ **Olympus: BLAST @ DORIS @ DESY**



DORIS storage ring
2 GeV beam; e-/e+ switch frequently

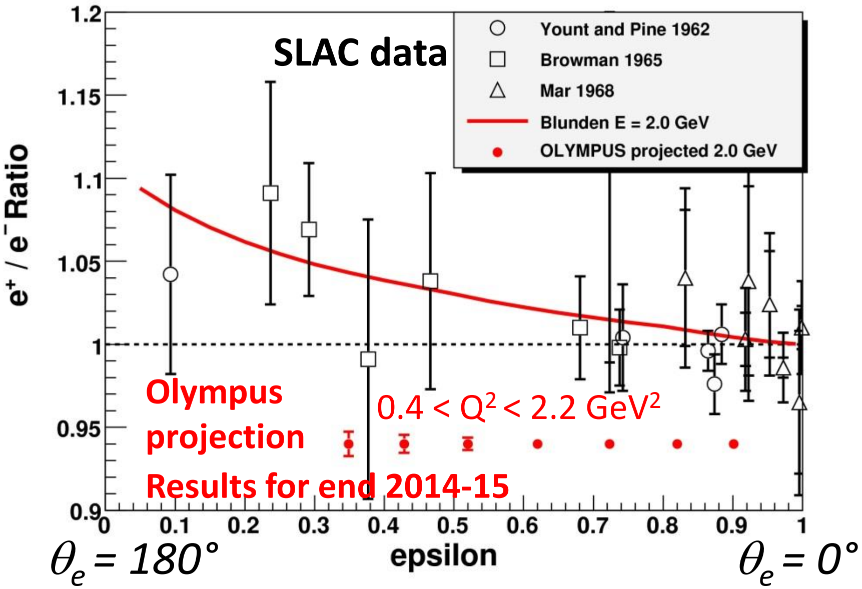
Former BLAST experiment
large acceptance left/right symmetric
internal target

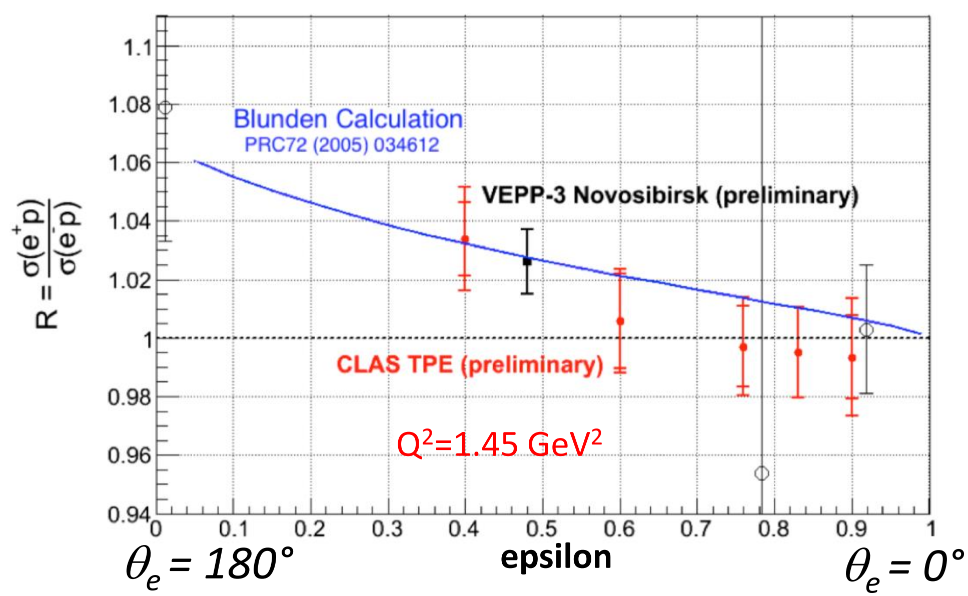
✓ **VEPP-3 à Novosibirsk**

e-/e+ storage ring + internal target
Q^2= 1.6 GeV^2 and ε=0.47

✓ **CLAS-PR04-116 @ Jlab**

e-/e+ pair production from photon beam
simultaneous measurements
several Q^2 measurements between 0.5 - 1.5 GeV^2
$0.2 < \varepsilon < 0.9$





Proton radius from MAMI ep scattering at low Q^2

High precision and redundancy

MAMI-A1 -3 high resolution spectrometers

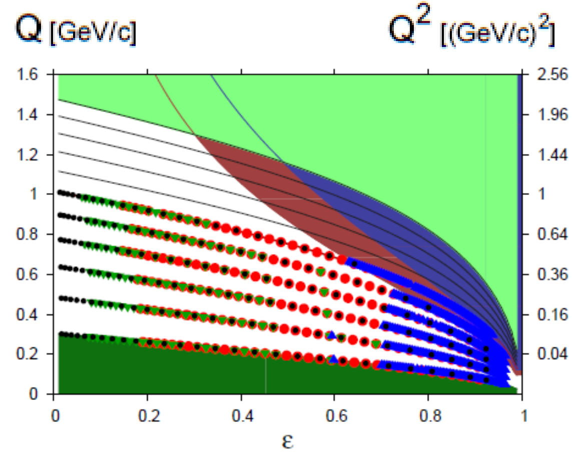
1400 settings $0.003 < Q^2 < 1\ \text{GeV}^2$

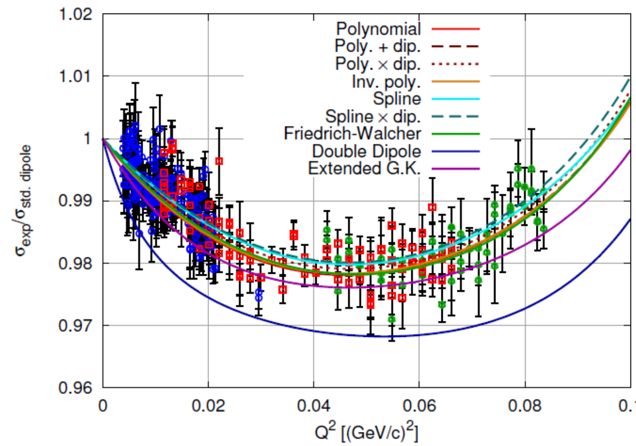
Statistics <0.1%

Control of Luminosity with the 3rd spectro

Measure at the same angle with 2 spectros

- spectrometer A
- spectrometer B
- spectrometer C





Super-Rosenbluth technique

Fit of form factor models

Directly to cross section

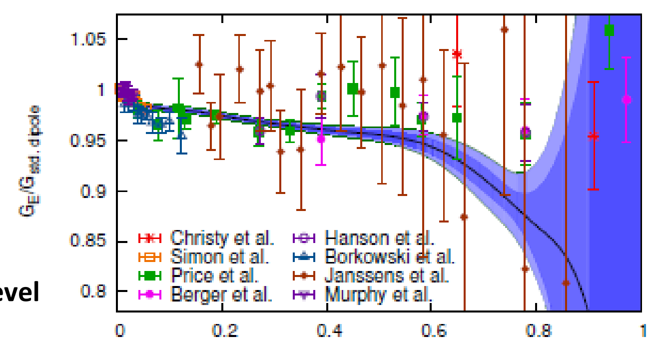
All Q2 and ε data used in one fit

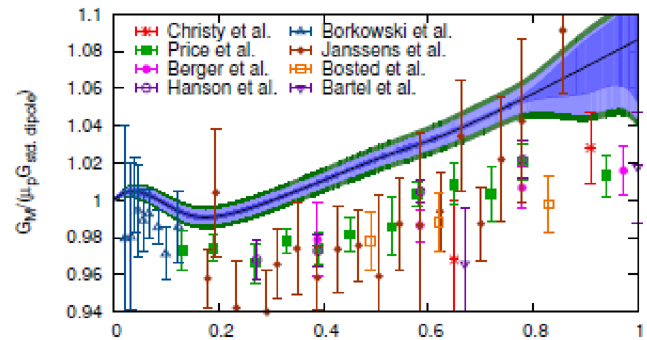
Wide range of ≠ paramatrizations

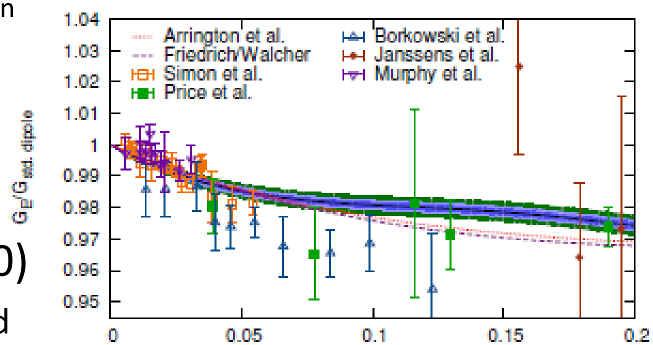
- Best fit
- + stat. 68% confidence level
- + syst errors
- + 50% Coulomb correction

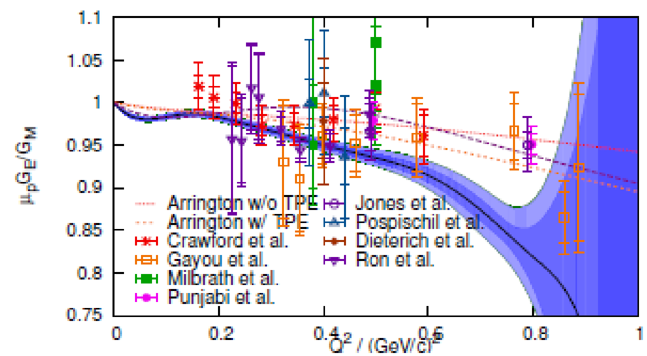
$r_E^p = 0.879 \pm 0.008$ fm

Bernauer et al. , PRL105 (2010) & PRC90 (2014) Including TPE and all world data







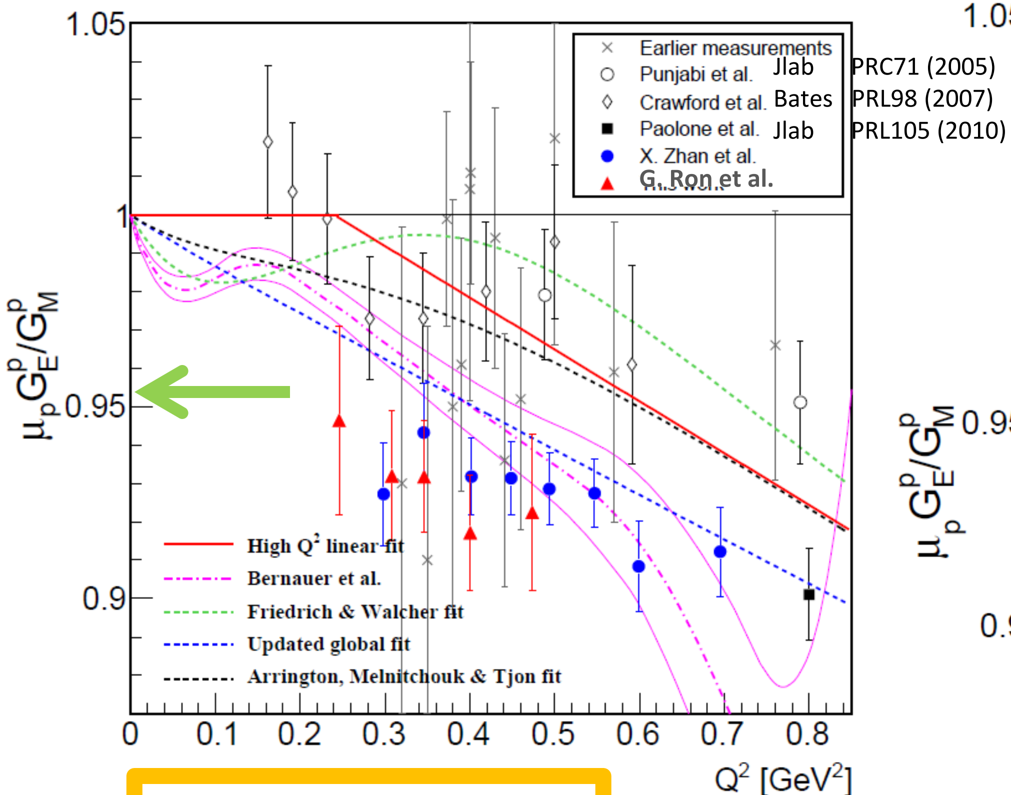


Proton radius from JLab ep scattering at low Q^2

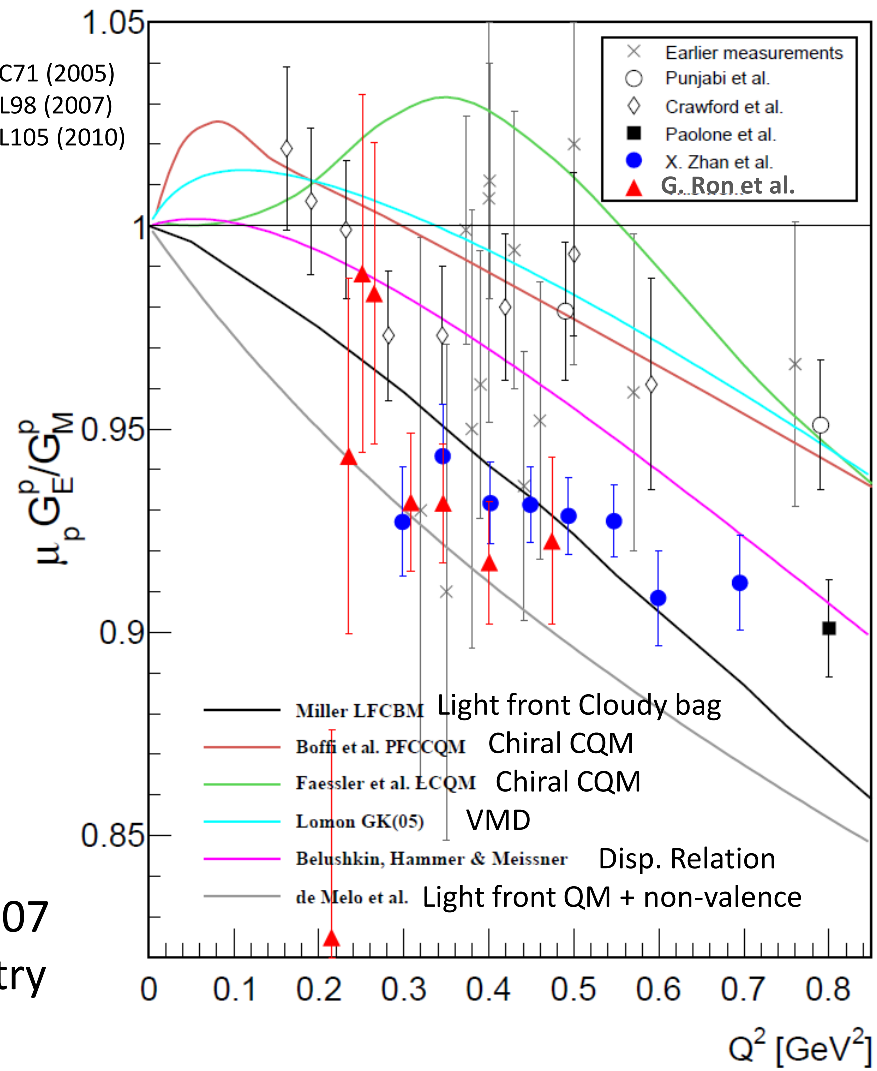
JLab Hall A using recoil polarimetry:

Exp E05-103: Ron et al. PRL99 (2007), update PRC84 (2011)

Exp E08-107: Zhan et al. PLB 705 (2011)



$r_E^p = 0.875 \pm 0.010$ fm



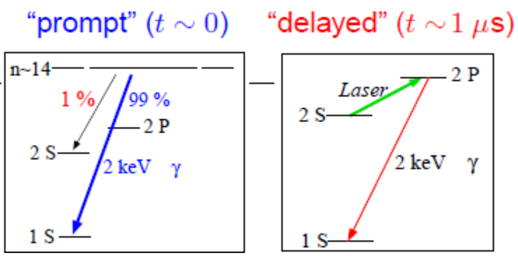
in near future results from the 2nd part of E08-107 polarized beam - polarized NH3 target asymmetry

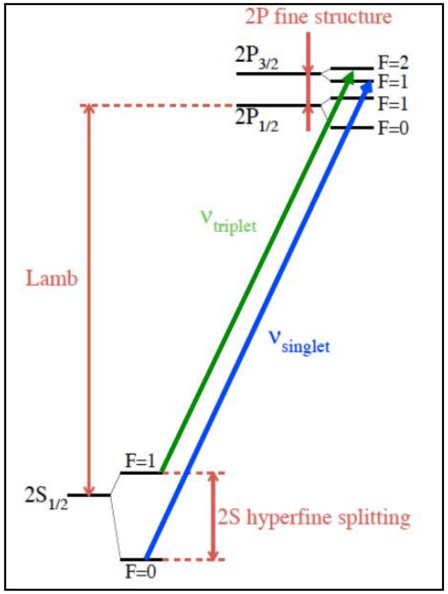
$0.01 < Q^2 < 0.16$ GeV^2

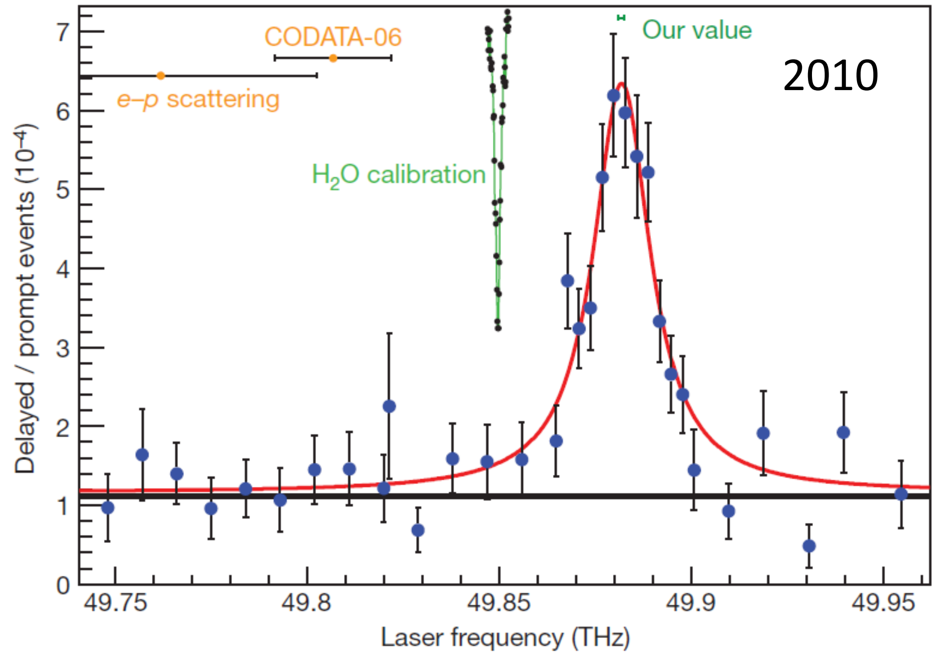
Proton radius from muonic hydrogen Lamb shift

New 5keV muon beam line at PSI

Muons stopped in H2 gas at low pressure ➔ excited μp atoms (n=14) are formed







Pohl et al., Nature 466 (2010): **2S ➔ 2P Lamb shift**

$\Delta E_1(\text{meV}) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3$ ➔ $r_p = 0.84184 \pm 0.00067$ fm

Antognini et al., Science 339 (2013): **2S ➔ 2P Lamb shift + 2S-HFS**

$\Delta E_2(\text{meV}) = 206.0336(15) - 5.2275(10)\, r_p^2 + 0.0332(20)_{\text{TPE}}$ ➔ $r_p = 0.84087 \pm 0.00039$ fm

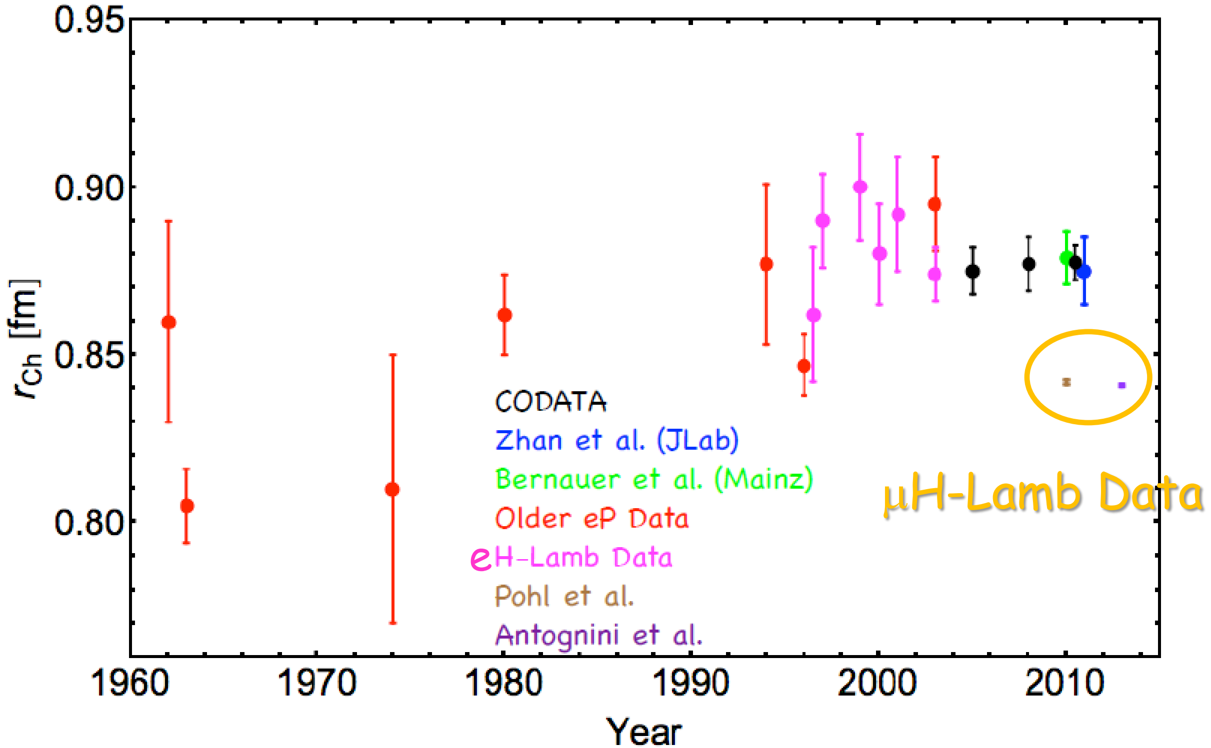
Time evolution of the proton radius from H Lamb shift and ep scattering

PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§‖¶

R. W. McAllister and R. Hofstadter
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California
(Received January 25, 1956)

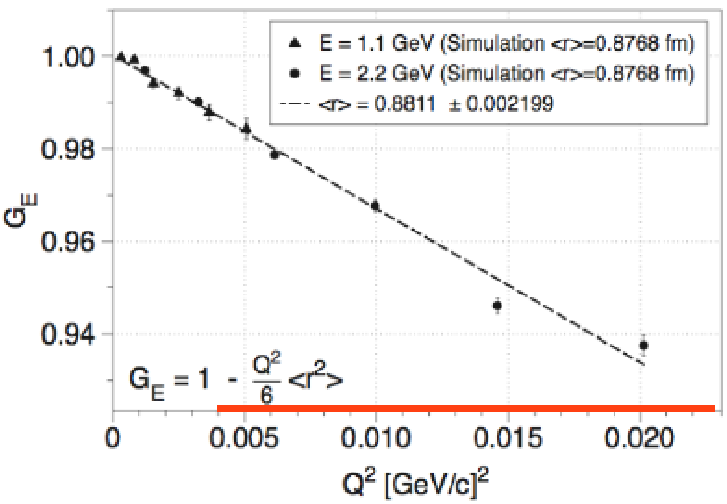
The root-mean-square radii of charge and magnetic moment are each $(0.74\pm0.24)\times10^{-13}$ cm.



UNEXPECTED !

Experiments at very low Q^2

The PRAD proton radius proposal at JLab

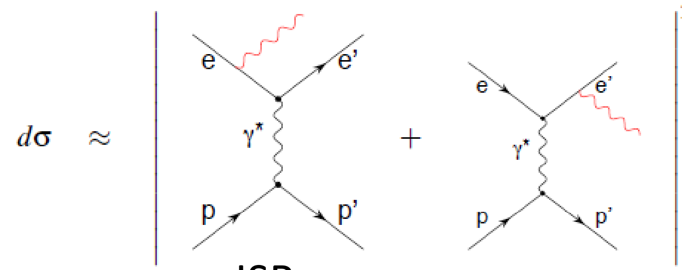


Lower $Q^2 = 2 \times 10^{-4}$ GeV^2

Low intensity beam in Hall B
into windowless target

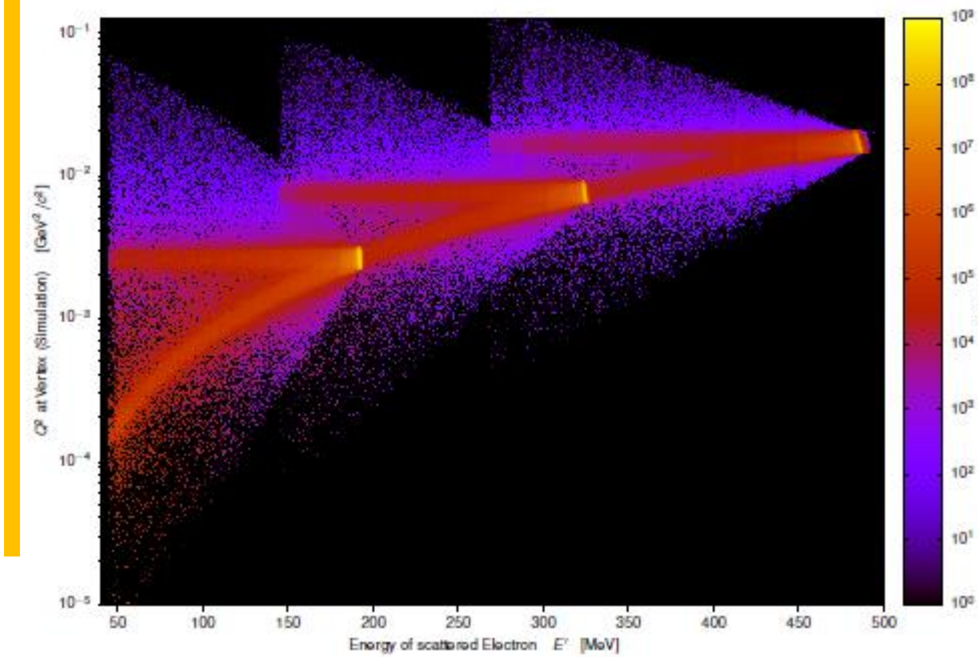
Scattered ep and Moller electrons (for normalisation) into an EM calorimeter at 0°

Initial State Radiations at MAMI



ISR
Continuous
Q^2 range

FSR
Q^2 constant



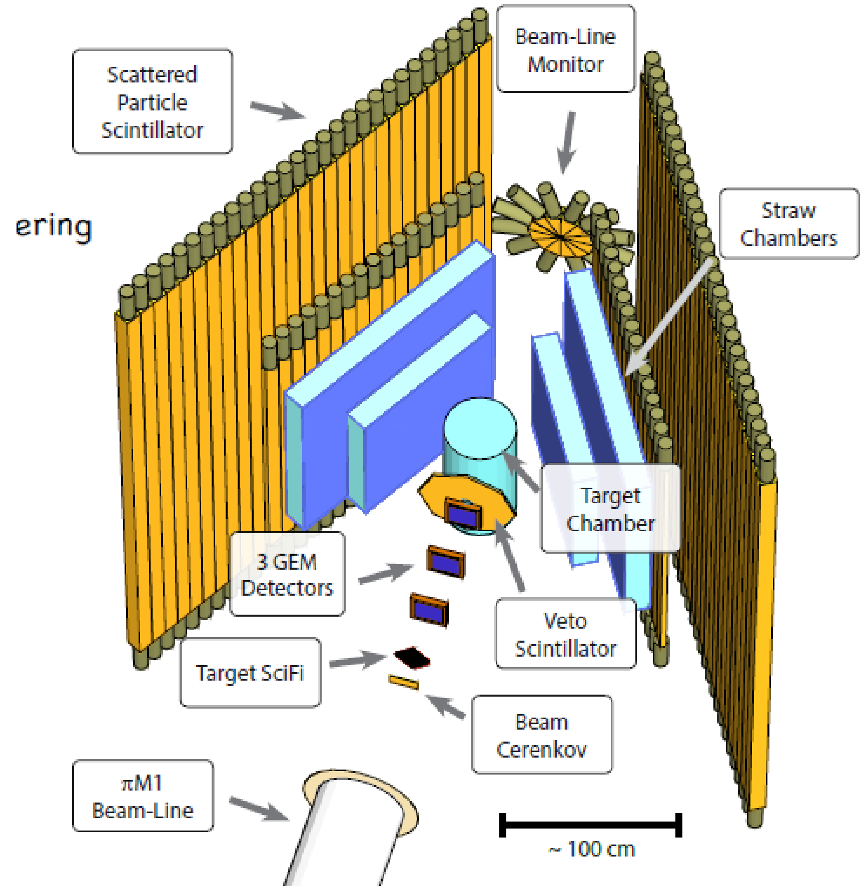
The MUSE experiment at PSI

r_p (fm)	ep	μp
Spectroscopy	0.8758 ± 0.077	0.84087 ± 0.00039
Scattering	0.8770 ± 0.060	???

use the world's most powerful low-energy separated e/π/μ beam

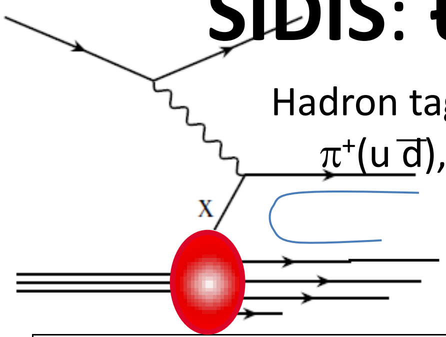
for a direct comparison

- if ep and μp scattering different?
- if TPE are different
  using e+ e- μ+ μ- beams?



Quark spin from semi-inclusive DIS

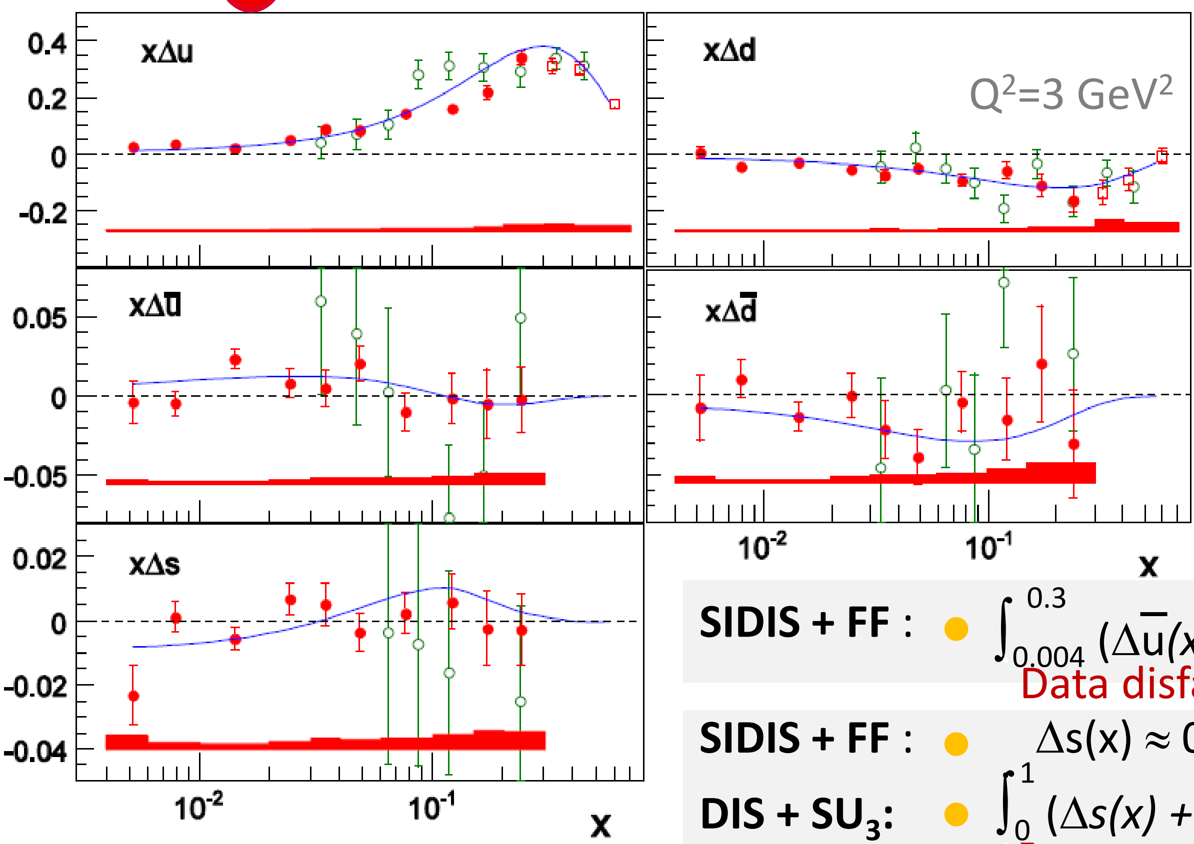
SIDIS: $\vec{\ell}\ \vec{p} \rightarrow \ell\ h^{\pm} X$



Hadron tags quark flavor
$\pi^+(u\bar{d})$, $K^+(u\bar{s})$

PDF* ⊗ *Fragmentation Fonction FF

$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)} \qquad z = \frac{E_h}{\nu}$$



LO extraction from A_1^h

- COMPASS μ 160GeV
  using DSS FF
  PLB693(2010)227
- HERMES e 27 GEV
  PRD71(2005)012003

NLO QCD fit

— DSSV prediction: De Florian, Sassot, Stratmann, Volgelsang , PRL101(2008), PRD80(2009)

SIDIS + FF : • $\int_{0.004}^{0.3} (\Delta\bar{u}(x) - \Delta\bar{d}(x))\, dx = 0.06 \pm 0.04 \pm 0.02$

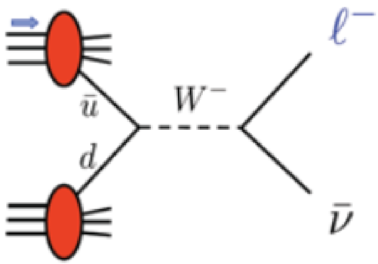
Data disfavor a large unsymmetric sea

SIDIS + FF : • $\Delta s(x) \approx 0$ in the range $x > 0.004$

DIS + SU$_3$: • $\int_0^1 (\Delta s(x) + \Delta\bar{s}(x))\, dx = -0.08 \pm 0.01 \pm 0.02$?

➔ a precise determination of FF @ COMPASS

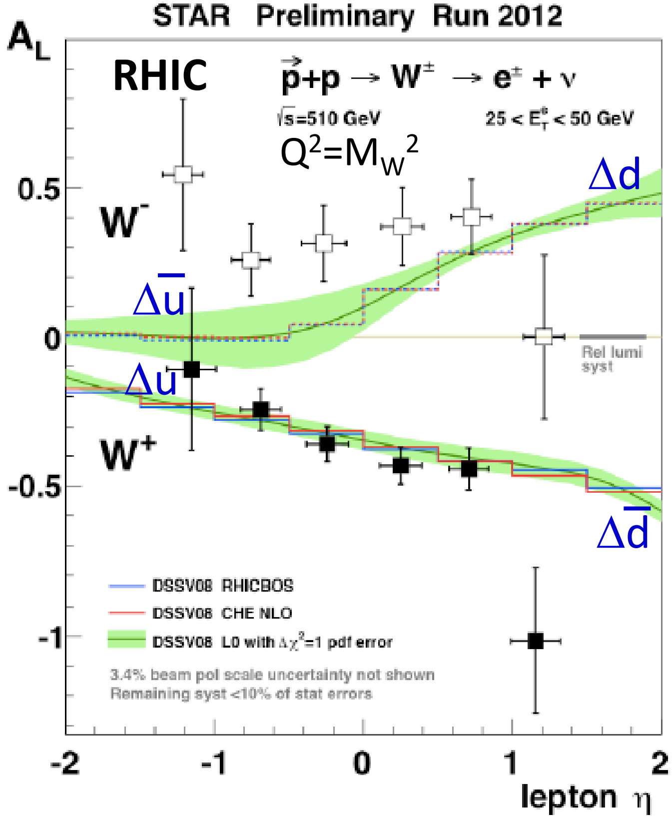
Sea quark spin from W production in $\vec{p}\,p$



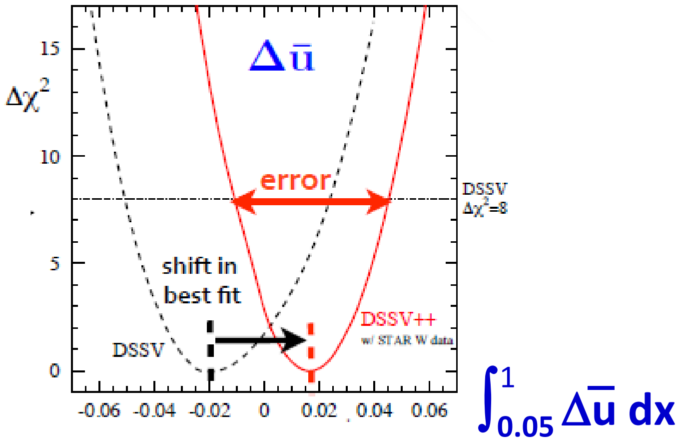
$$\vec{p} + p \rightarrow W^{\pm} + X \rightarrow l^{\pm} + X$$

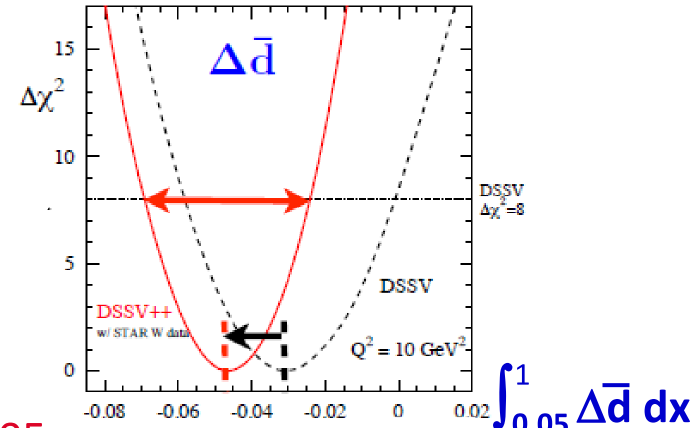
Measure of the parity –violating single spin asymmetry

$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$



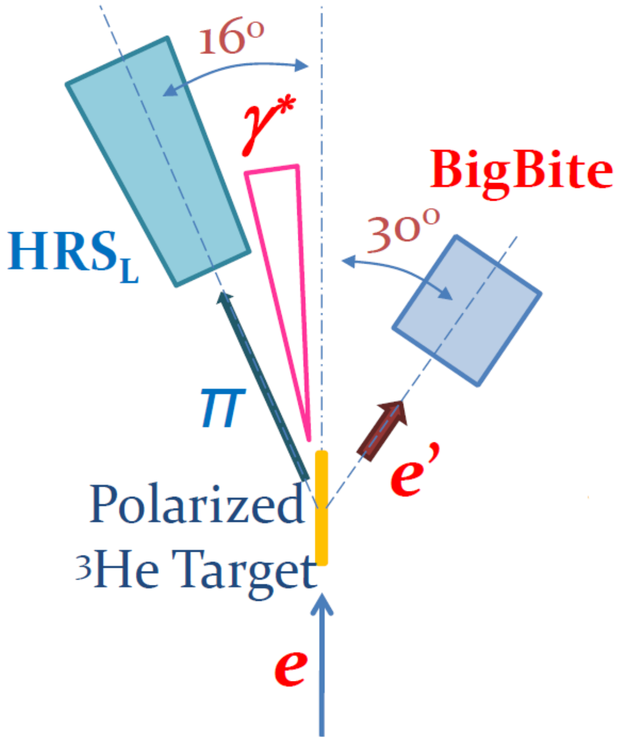
RHIC, arXiv1304.0079 (2013)



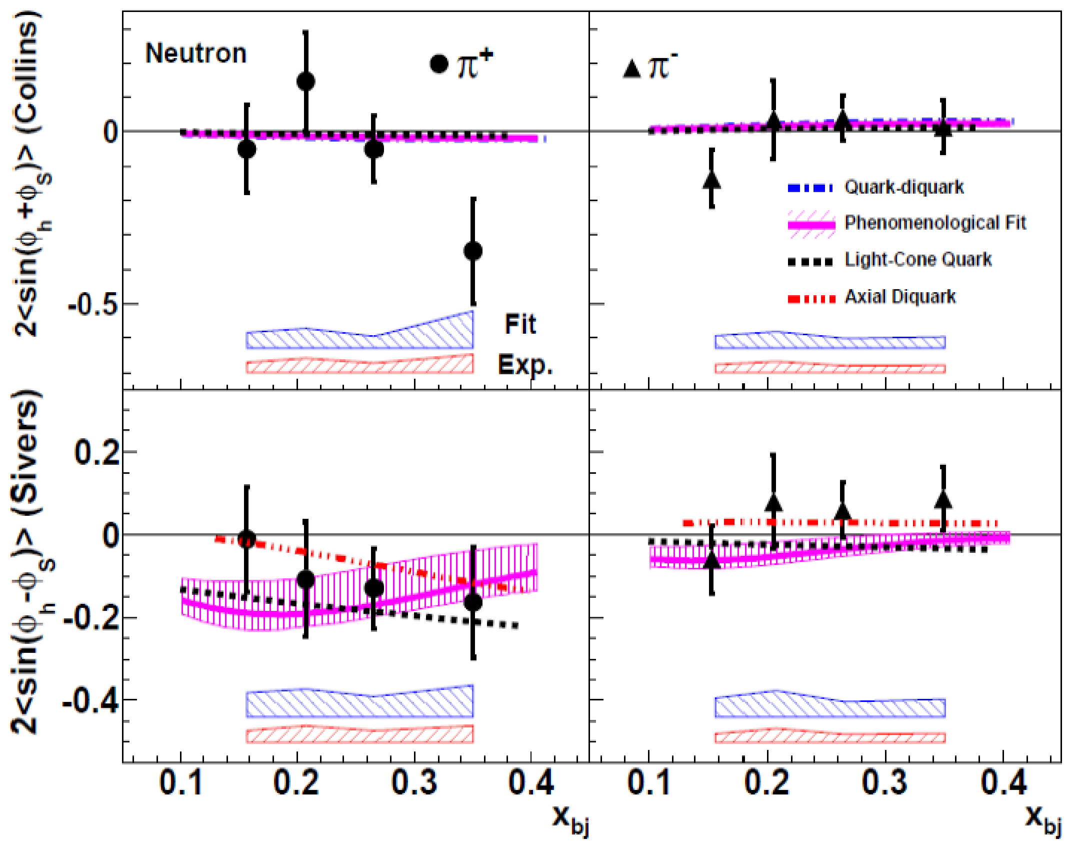


Preference for $\Delta\bar{u} > \Delta\bar{d}$ in the range $x > 0.05$

Collins and Sivers asymmetries on the neutron at Jlab

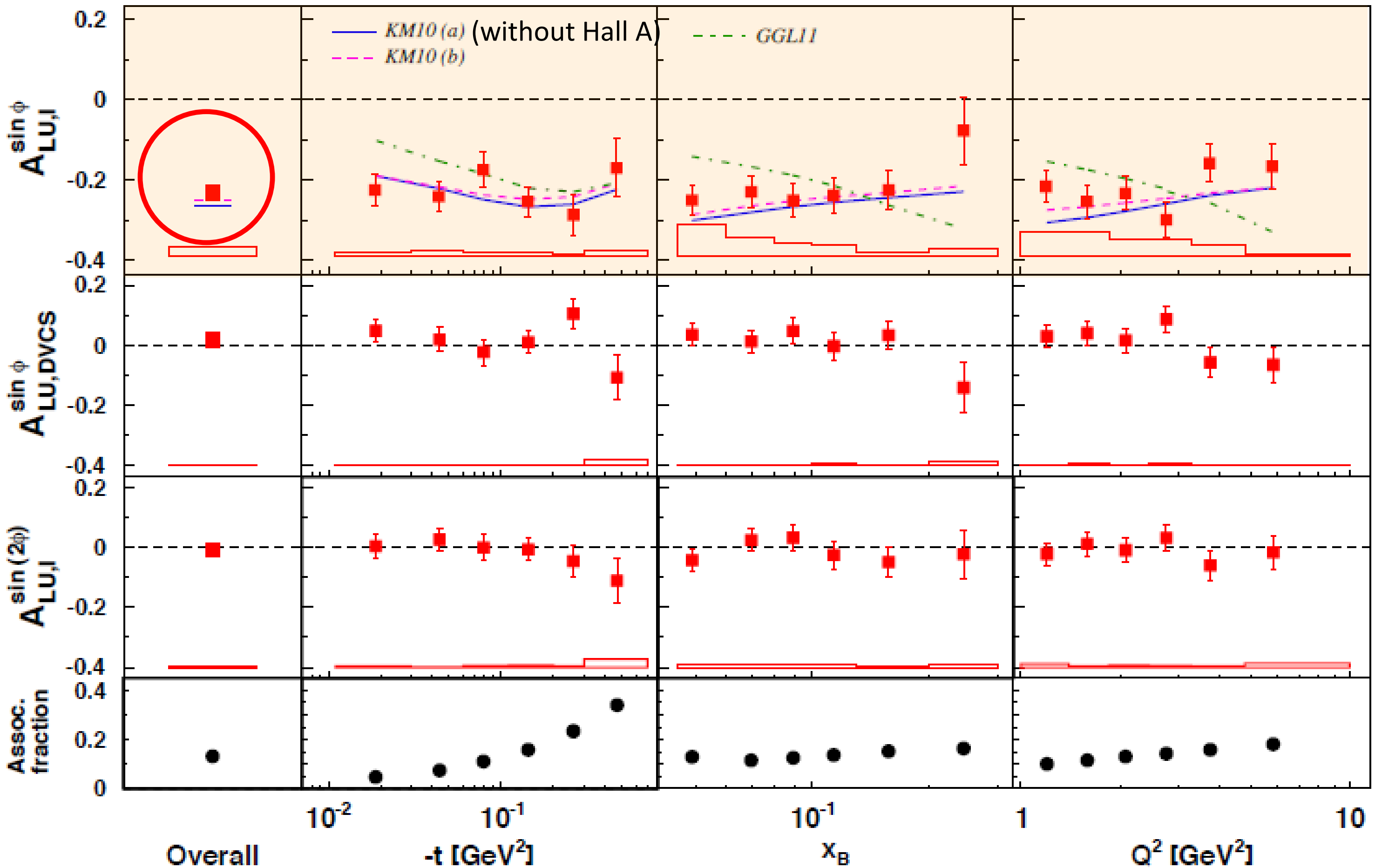


Qian et al., PRL107 (2011)



Beam Spin Asymmetry with HERMES

A. Airapetian et al, JHEP 07 (2012) 032



sin ϕ term
Im **F1** $\mathcal{H}$

sinϕ term
from DVCS^2

sin 2ϕ term
higher twist

resonant fraction
ep → eγΔ$^+$

KM: *Kumerički and Müller, Nucl. Phys.* ***B841*** *(2010)*

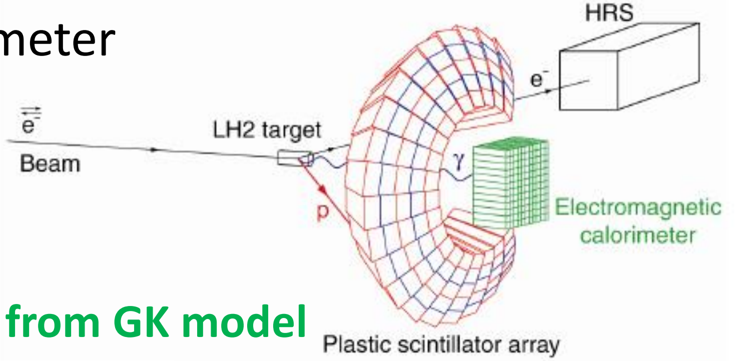
GHL11: *G. Goldstein, J. Hernandez and S. Liuti,* ***Phys. Rev. D84*** *(2011)*

Beam Spin Diff and Sum – Jlab HallA

E00-110 pioneer experiment with magnetic spectrometer

3 measurements: x_B=0.36 Q^2= 1.5, 1.9, 2.3 GeV^2

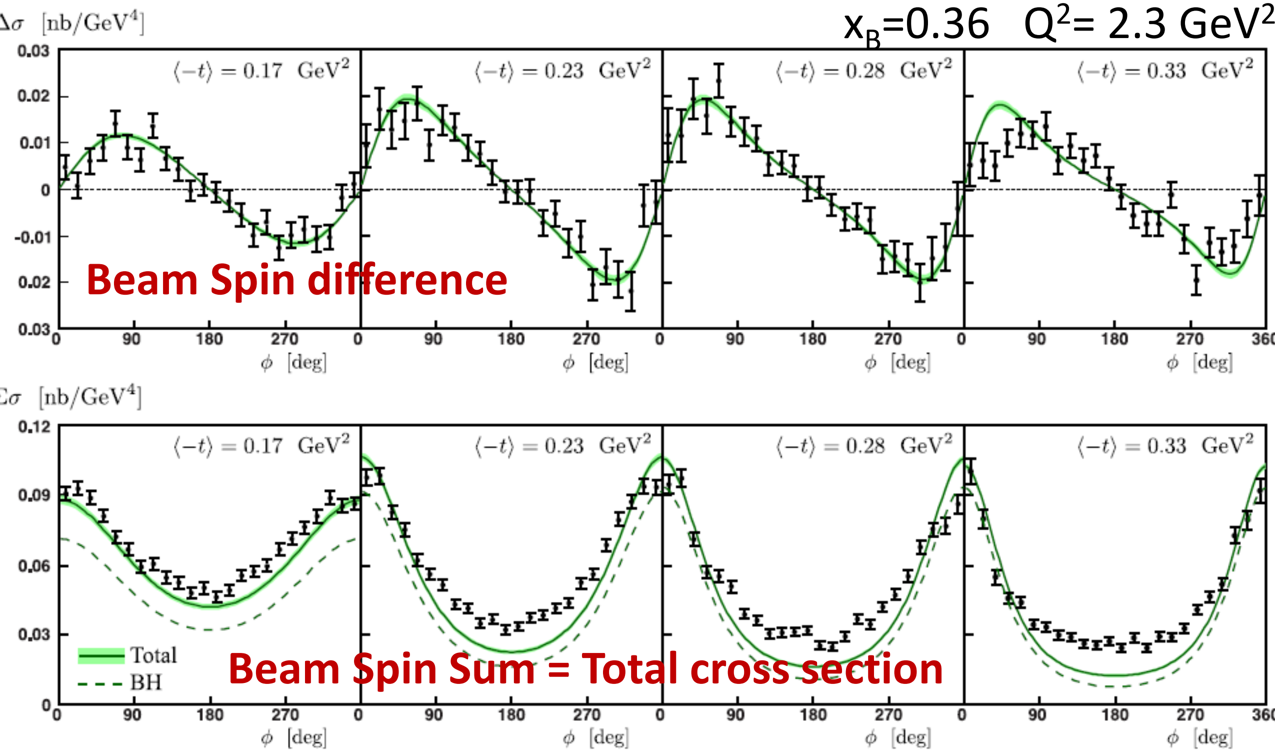
$\vec{e}\, p \rightarrow e\, \gamma\, p$



Data: Munoz et al. PRL97, 262002 (2006)

Model: Kroll, Moutarde, Sabatié, EPJC73 (2013) with GPDs from GK model

x_B=0.36 Q^2= 2.3 GeV^2



News:
- Re-analysis of the data (MC, RC, normalisation/DIS)
- 2010: run E07-007 Rosenbluth-like $DVCS^2$/Int sparation
- 2014: HallA with 11 GeV
- 2018: HallC with 11 GeV

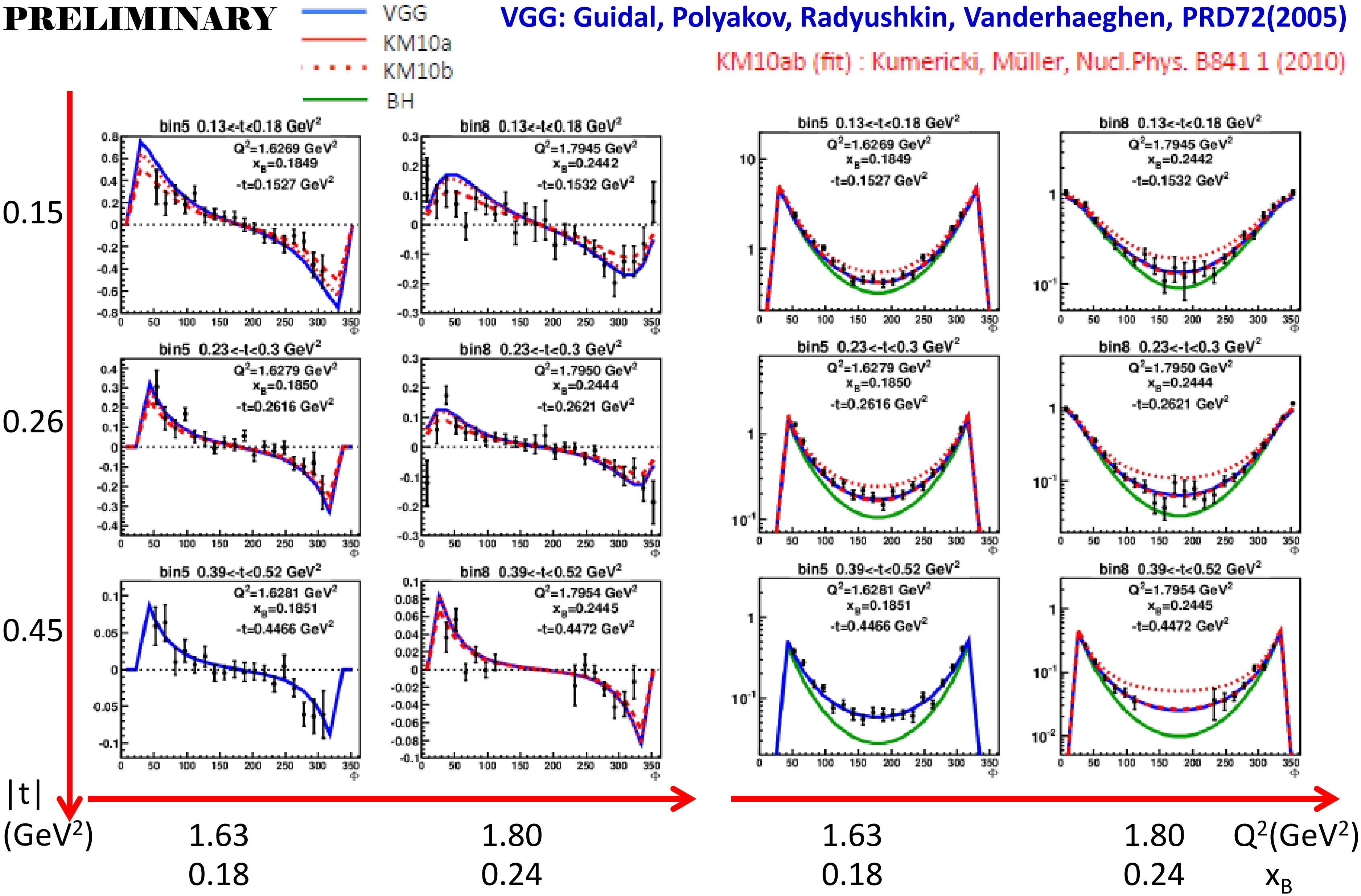
Do we understand Hall A data?

Beam Spin Diff and Sum – Jlab CLAS

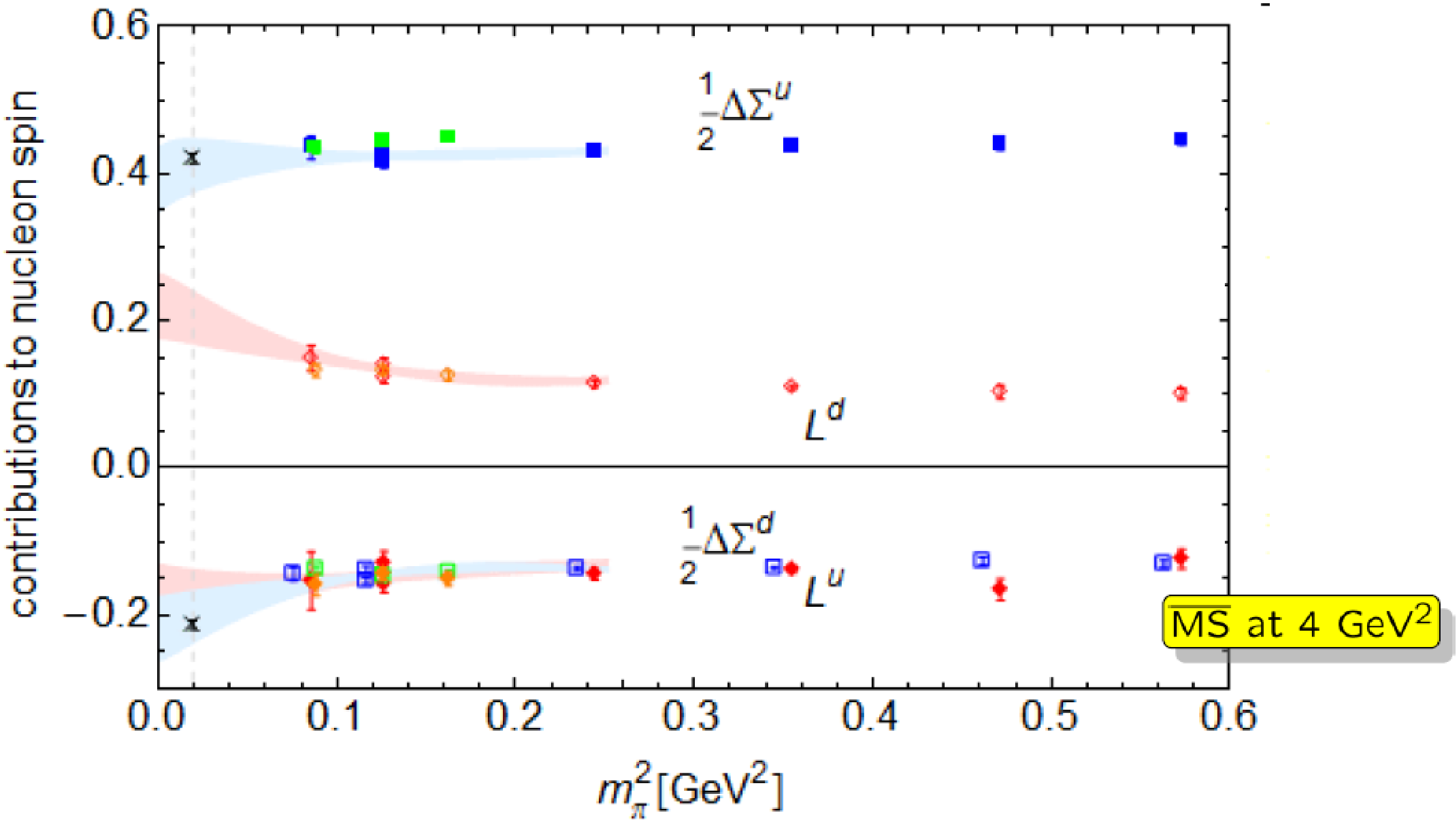
PRELIMINARY

VGG: Guidal, Polyakov, Radyushkin, Vanderhaeghen, PRD72(2005)

KM10ab (fit) : Kumericki, Müller, Nucl.Phys. B841 1 (2010)



Spin prediction in Lattice Calculations



$J^u \approx 0.236 \pm 0.006 \mathrel{\hat{=}} 48\%$ of $1/2$

$J^d \approx 0.002 \pm 0.004$

$L^d \approx -L^u \approx 0.185 \pm 0.06 \approx 36\%$ of $1/2$

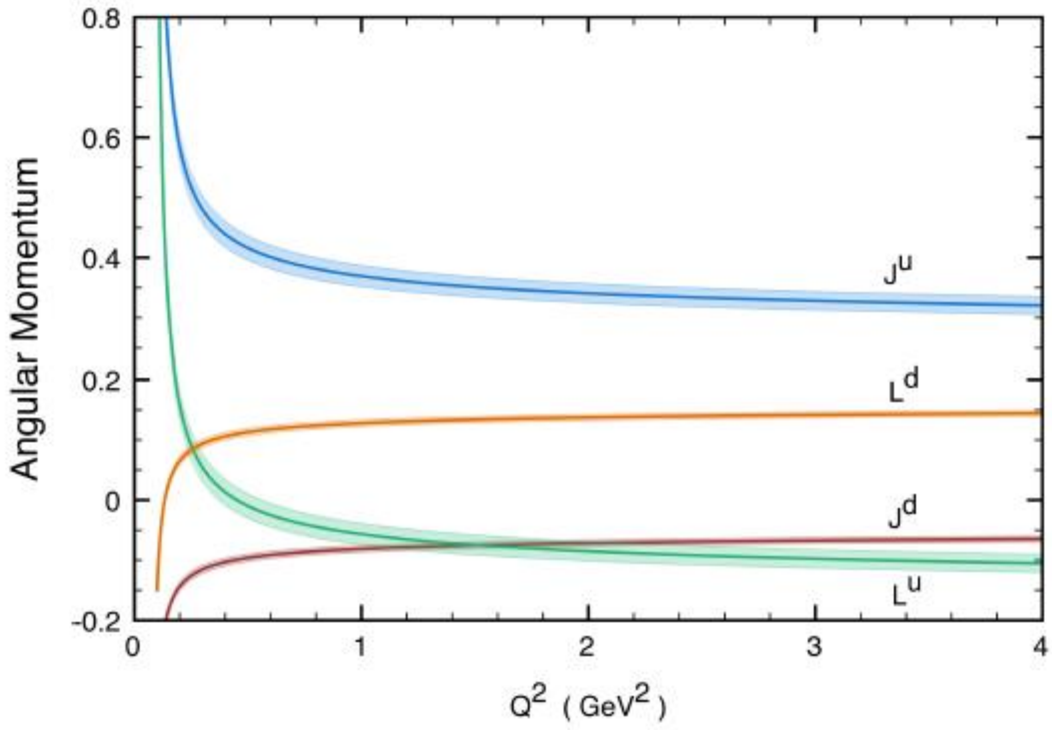
$L^{u+d} \approx 0.030 \pm 0.012 \approx 6\%$ of $1/2$

pioneering lattice calculations by Gadiyak, Ji and Jung in 2001

$\kappa^{u+d} = 3\kappa^{p+n} = -0.36$

Ph. Hägler, MENU 2010, W&M

Spin prediction in Cloudy Bag Model

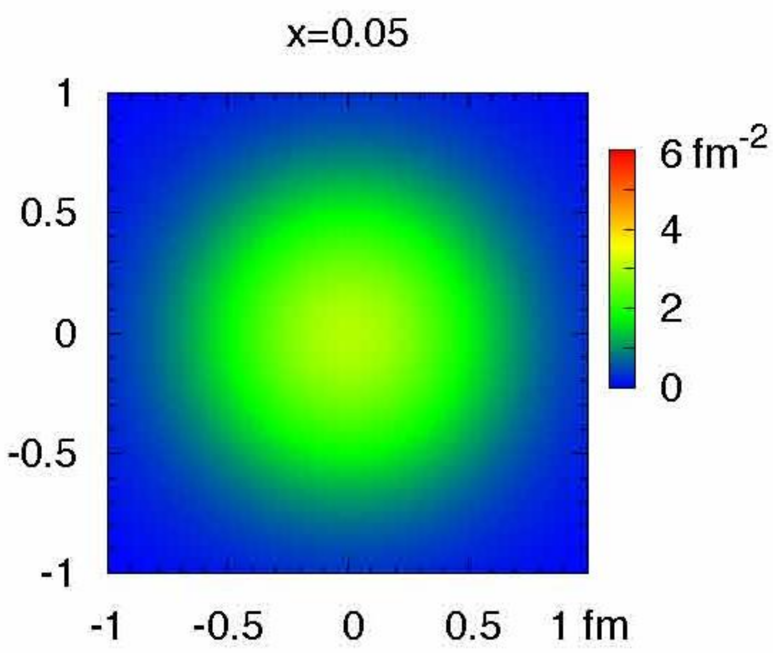


Calculation in NLO QCD evolution - Cloudy bag model
Thomas et al., Int. J. Mod. Phys A25 (2010)

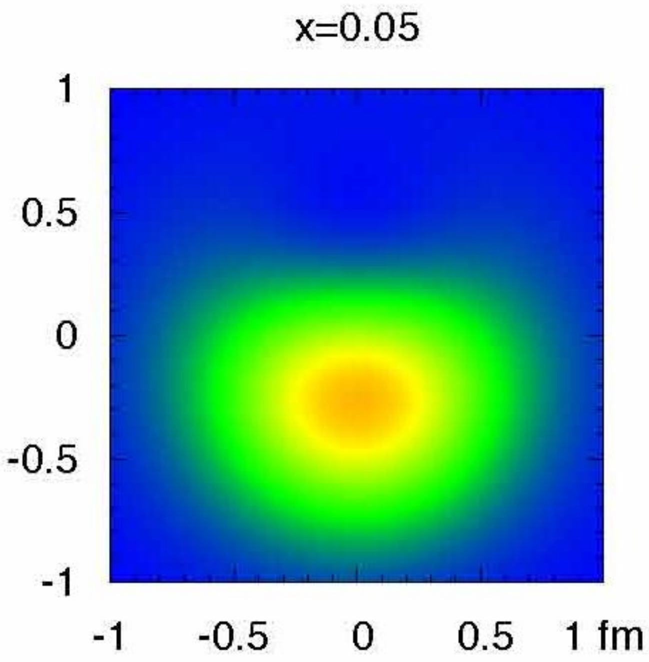
Spin prediction in GPD Model

evaluate parton angular momenta from Ji's sum rule

$J^u = 0.25 \pm 0.03 \qquad J^d = 0.02 \pm 0.03 \qquad J^s = 0.02 \pm 0.03 \qquad J^g = 0.21 \pm 0.06$



unpolarized



polarized proton

P. Kroll