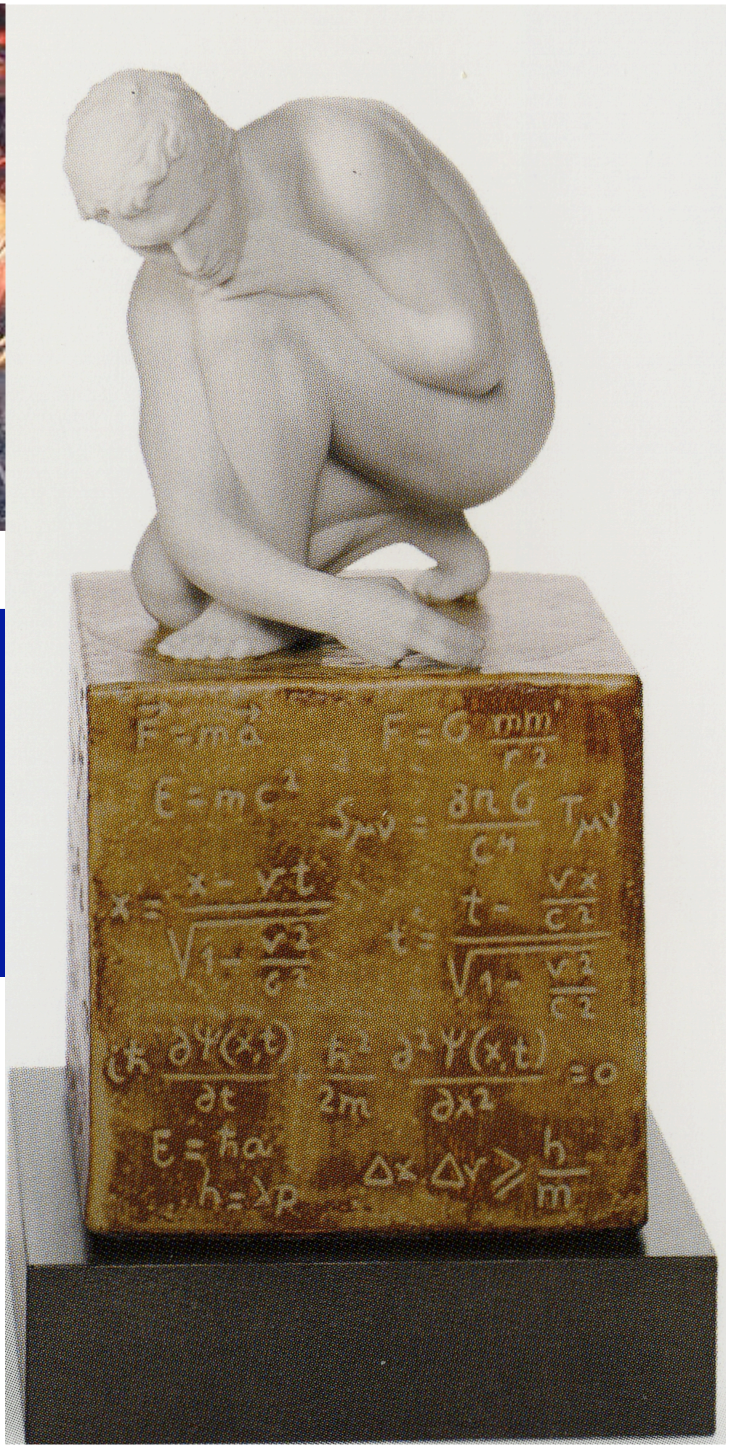


Probing Hadrons and Nuclei: An Experimental Overview

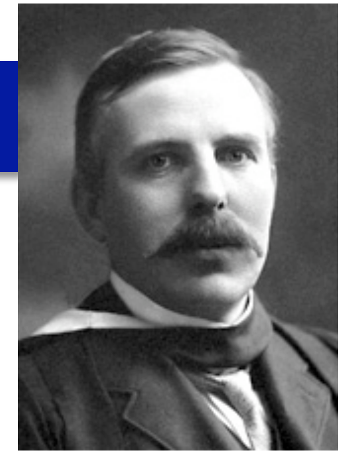
EINN09, Milos, Greece

September 28, 2009

Zein-Eddine Meziani

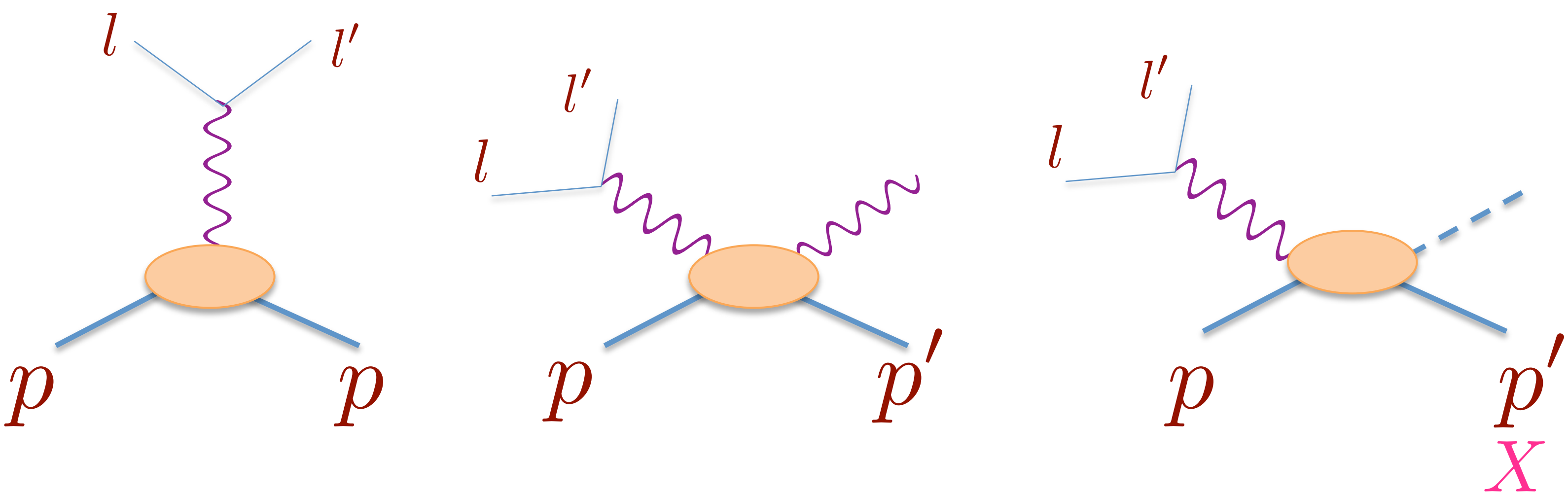
Temple University

Experimental tools: Scattering



Rutherford, 1908, Chem. N.P.

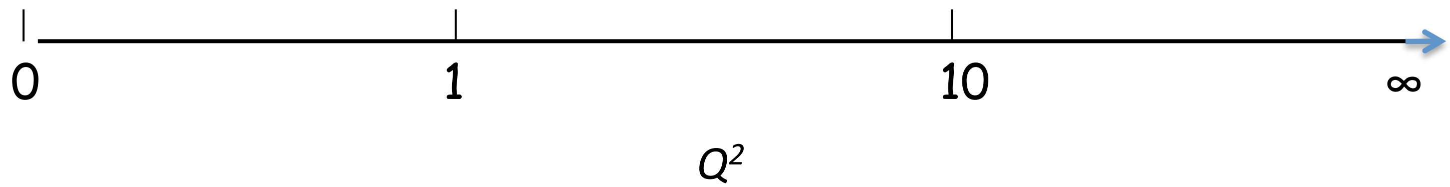
- Use of lepton and hadron beams
  - Polarized beams of e-, e+, μ+, μ-, p
- Use of proton and nuclei targets
  - Targets in many cases are polarized (p, D, NH_3, ND_3, ^3He,)
- Electromagnetic probe: Compton scattering, real and virtual
  - Exclusive, semi-inclusive or inclusive (elastic scattering, inelastic scattering)



Compton, 1927, Phys. N.P.

Resolution of the probe and scale of theory tools

Models



χPT *OPE* *pQCD*

Lattice QCD

Memory Lane

- Proton is not pointlike

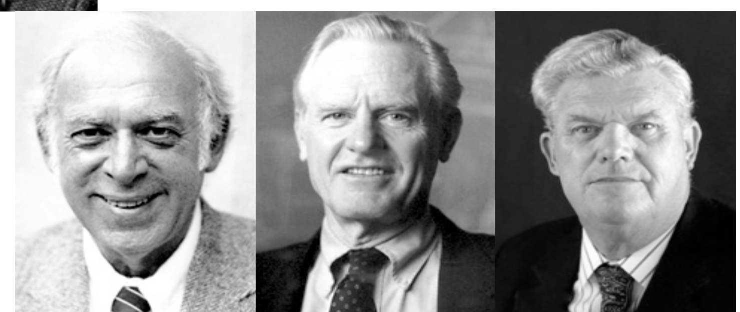
Robert Hofstadter
N.P. 1961

- Quarks as constituents of hadrons
  - ➠ Today's constituent quarks

Gell-Mann
N.P. 1969

- Partons as constituents of the nucleon
  - ➠ Today's current quarks and (gluons)

Friedman, Kendall and Taylor
1991 N.P.



Feynman, Bjorken

Gross, Politzer and Wilczek

- Asymptotic freedom discovery
  - ➠ pQCD works

The Science Problem ?

Quantum Chromodynamics (QCD) and confinement

What do we know?

QCD works in the perturbative (weak) regime

Many experimental tests led to this conclusion

But

Confinement in QCD is still a puzzle and among the 10 top problems in Physics! (Gross, Witten,….)

Strings 2000

Lattice, AdS/CFT …….?!

STRINGS MICHIGAN THEORY

July 10-15, 2000 University of Michigan Ann Arbor

"Millennium Madness"

Physics Problems for the Next Millennium

In 1900 the world-renowned mathematician David Hilbert presented twenty-three problems at the

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature?
   Louise Dolan, University of North Carolina, Chapel Hill
   Annamaria Sinkovics, Spinoza Institute
   Billy & Linda Rose, San Antonio College

8. What is the resolution of the black hole information paradox?
   Tibra Ali, Department of Applied Mathematics and Theoretical Physics, Cambridge
   Samir Mathur, Ohio State University

9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles?
   Matt Strassler, Institute for Advanced Study, Princeton

10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap?
    Igor Klebanov, Princeton University
    Oyvind Tafjord, McGill University

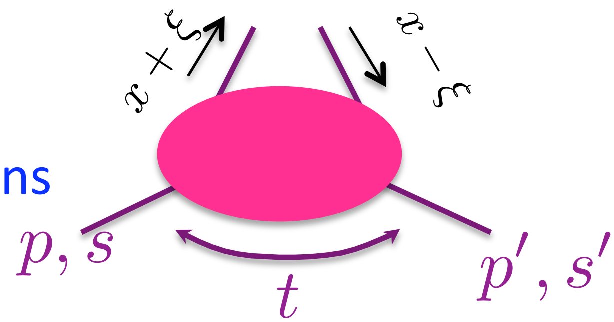
These ten questions were presented by David Gross at the closing of the conference on Saturday July 15, 2000.

Theoretical Framework in QCD

Generalized Parton Distributions

- Matrix elements of non-local operators with quarks and gluon field

$$\langle p|\mathcal{O}|p\rangle$$



- Depend on two longitud. momentum fractions

$$x,\ \xi \text{ and } t=(p-p')^2$$

- For unpolarized quarks we have two distributions:

H^q *conserves proton helicity*

E^q *flips proton helicity*

$$p=p' \Longrightarrow \qquad H^q(x,0,0)=\begin{cases} q(x) & \text{for } x>0 \\ -\bar{q}(x) & \text{for } x<0 \end{cases}$$

Continued

- Integrating

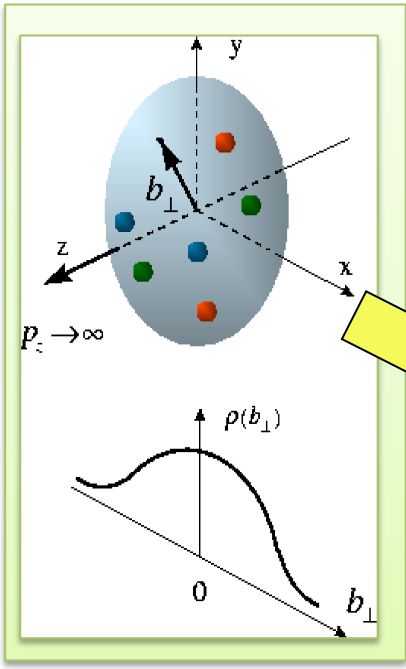
$\int dx\, x^n\, \text{GPD}(x, \xi, t) \to$ local operators $\to$ form factors

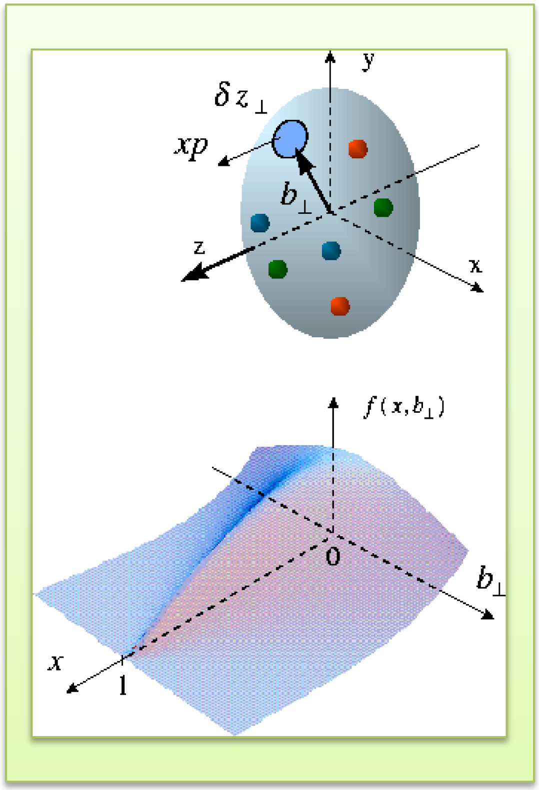
$$\sum_q e_q \int_{-1}^{1} dx\, H^q(x, \xi, t) = F_1(t) \qquad \text{Dirac}$$

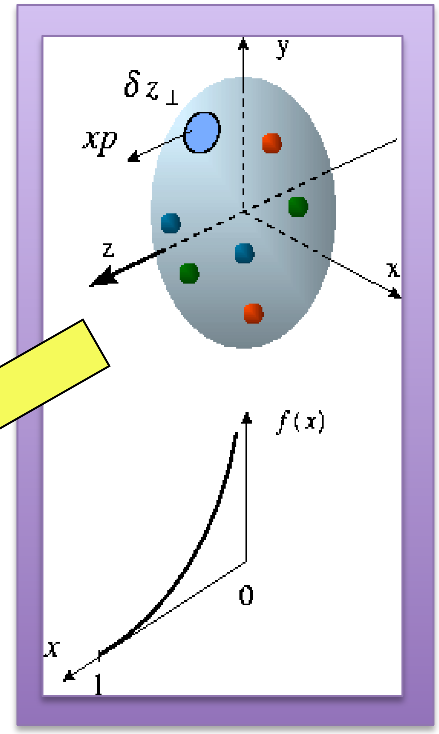
$$\sum_q e_q \int_{-1}^{1} dx\, E^q(x, \xi, t) = F_2(t) \qquad \text{Pauli}$$

Generalized Parton Distributions

X. Ji, D. Mueller, A. Radyushkin (1994-1997)







Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Impact parameter picture: M. Burkhardt

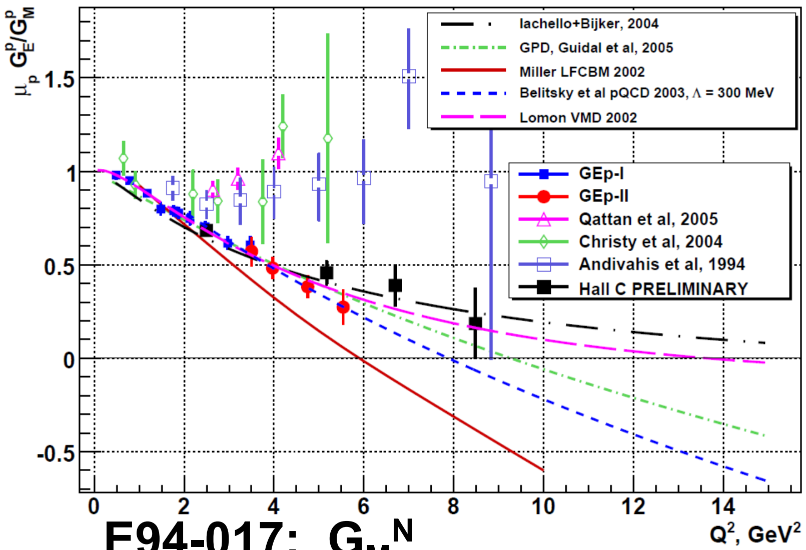
Hadron Electromagnetic Form Factors

- Elastic form factors (with flavor decomposition)
  - Measured to high momentum transfer using polarization techniques, either the beam, the target or the recoil particle is polarized.
  - Light cone frame interesting for a description consistent with DIS and GPDs.
  - Measurements have been extended to a larger momentum transfer for the proton and the neutron
  - New precision measurements at low Q^2

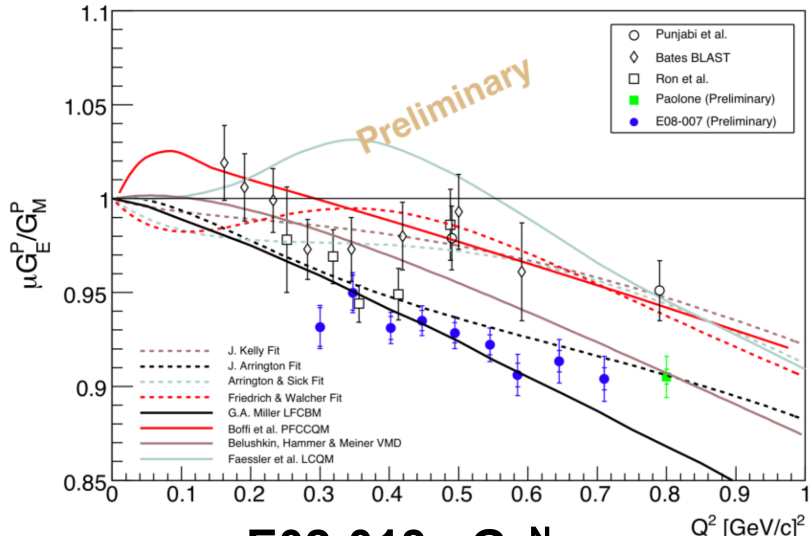
See talks by Liyanage, Kivel, Haegler

Progress on the Nucleon EM Form Factors

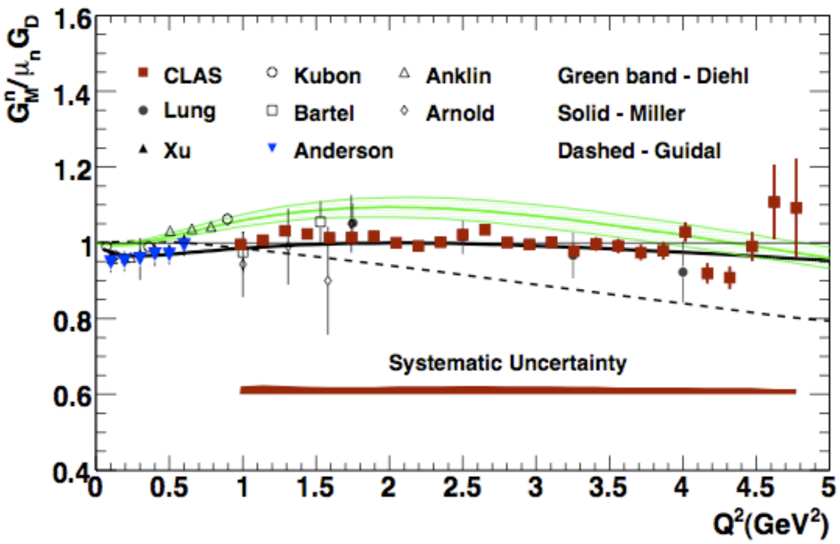
E04-108 G_E^P-III



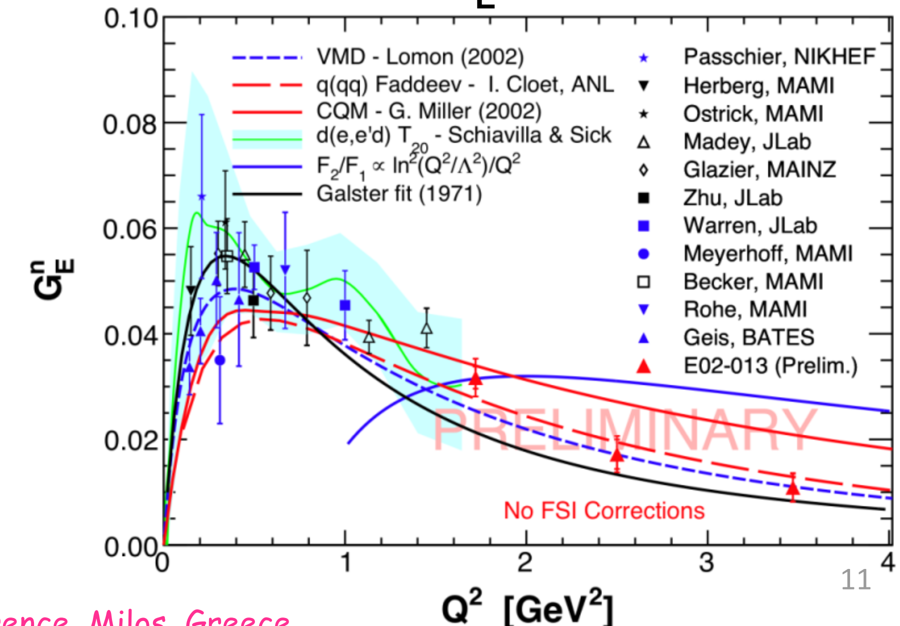
E08-007: High Precision Low Q^2 G_E^P



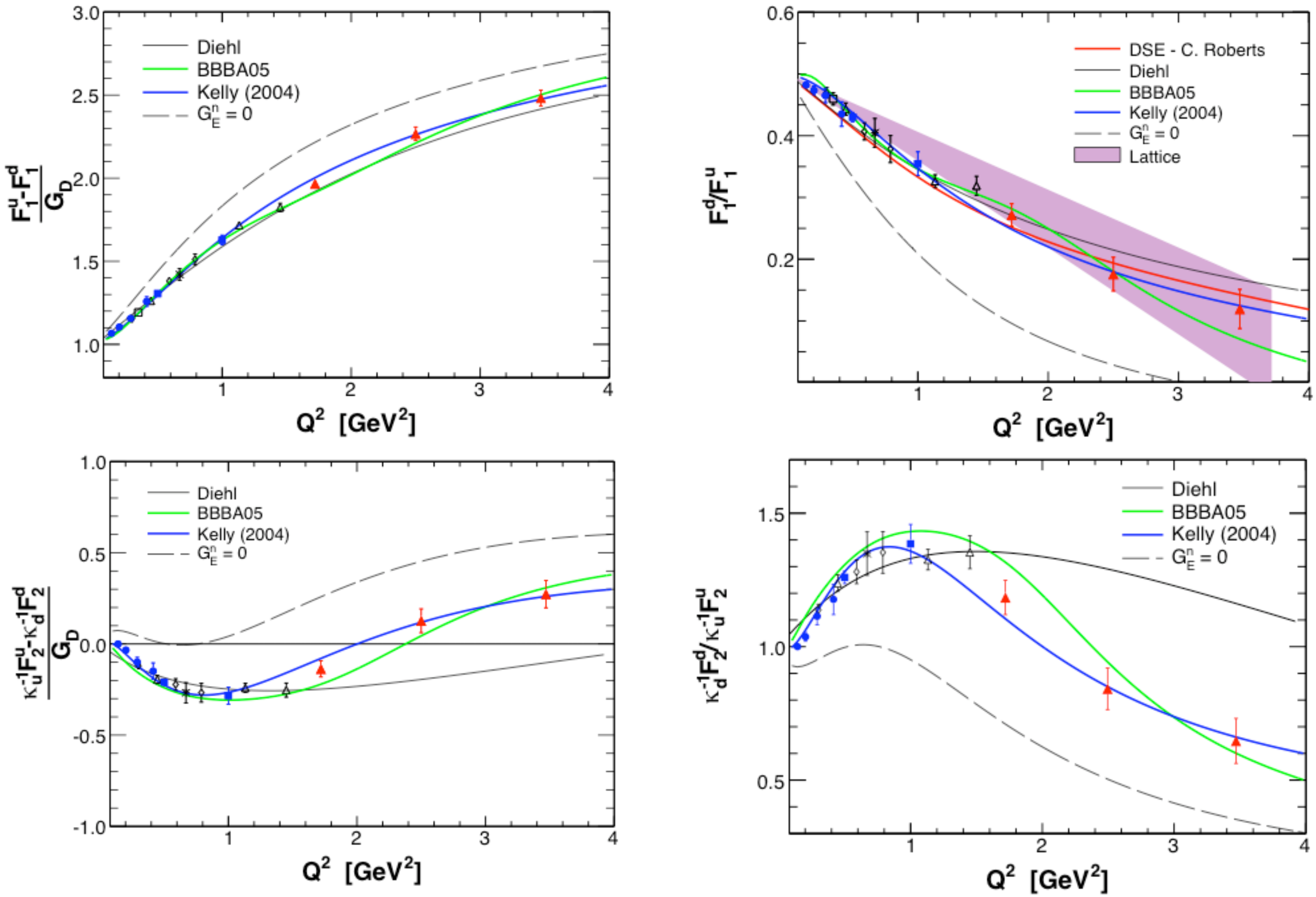
E94-017: G_M^N



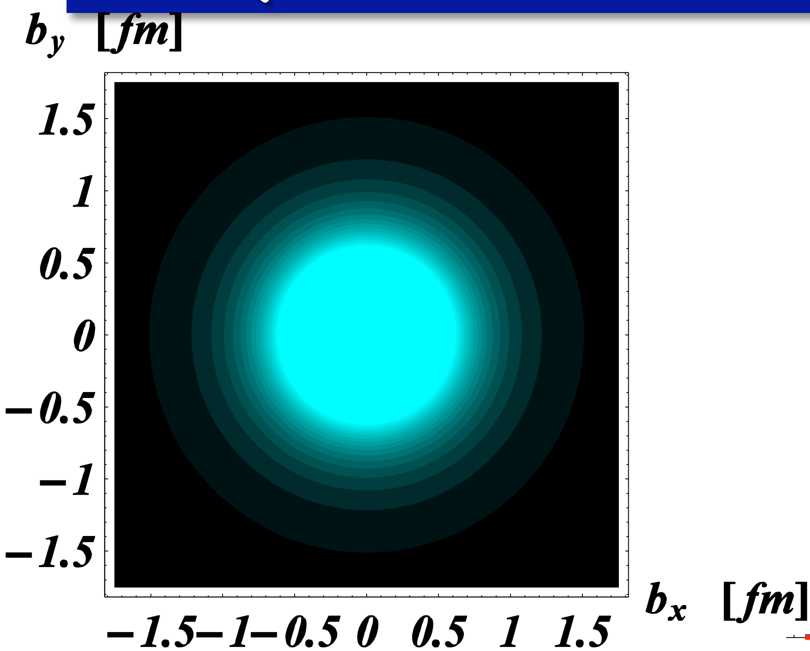
E02-013: G_E^N

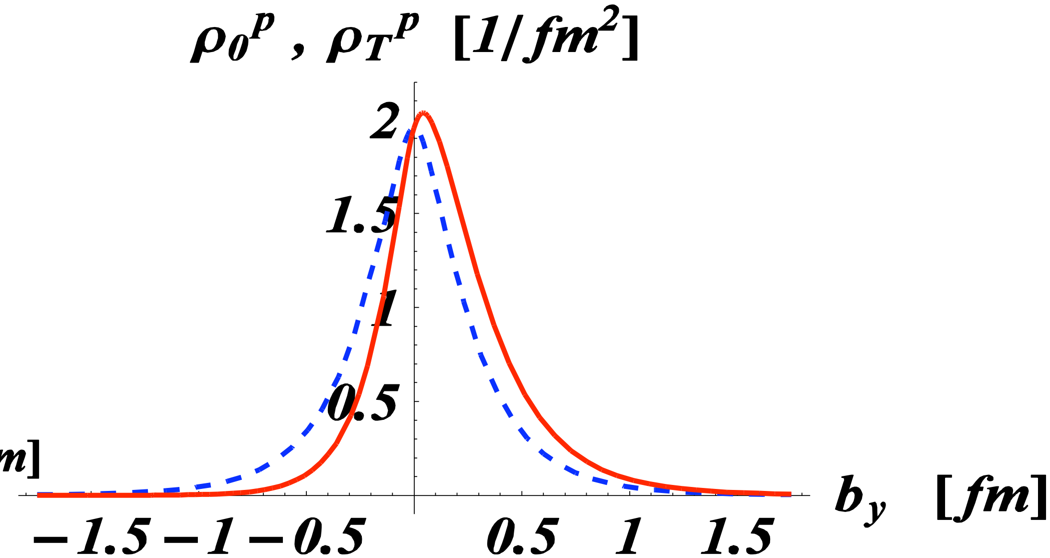


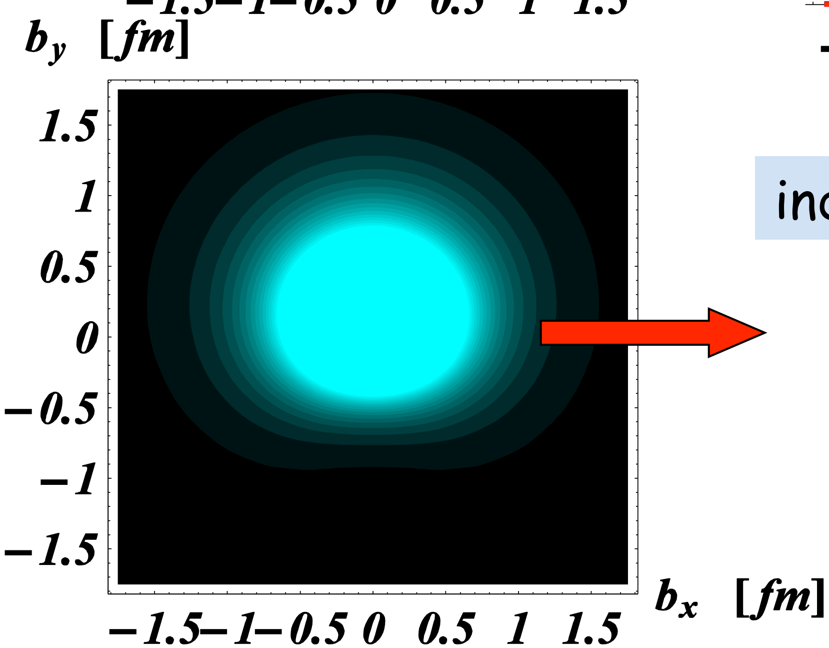
Flavor separated form factors



Quark transverse densities in proton







induced EDM : $d_y = F_{2p}(0) \cdot e / (2 M_N)$

data : Arrington, Melnitchouk, Tjon (2007)

densities : Miller (2007); Carlson, Vdh (2007)

Courtesy of Vanderhaeghen

Experimental Flavor separation of E&M Form Factors

- Assuming charge symmetry:

$$G_{E,M}^{u,p} = \left(3 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} - G_{E,M}^{Z,p}$$

$$G_{E,M}^{d,p} = \left(2 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p}$$

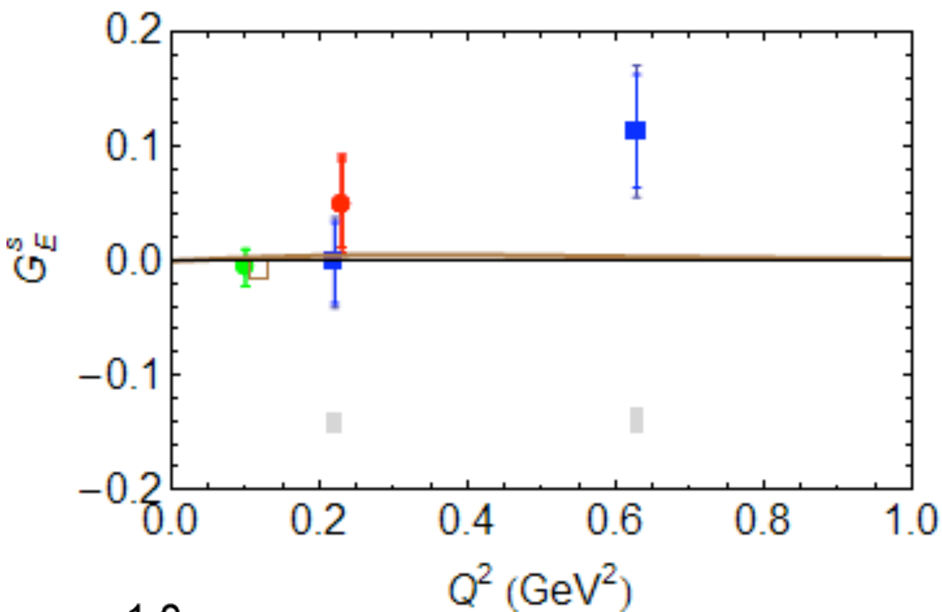
$$G_{E,M}^{s,p} = \left(1 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p}$$

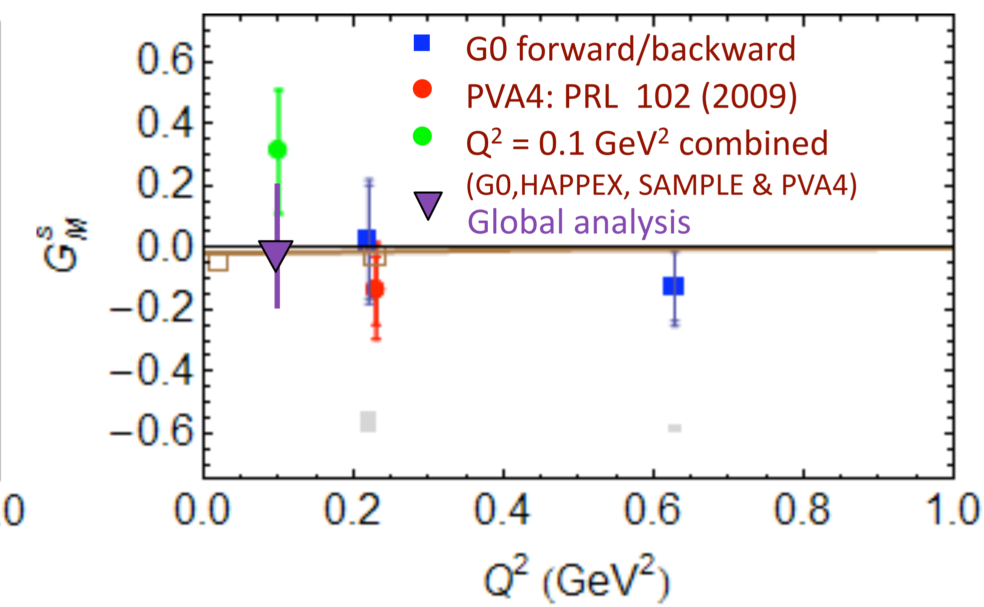
- Need three independent observables to extract individual

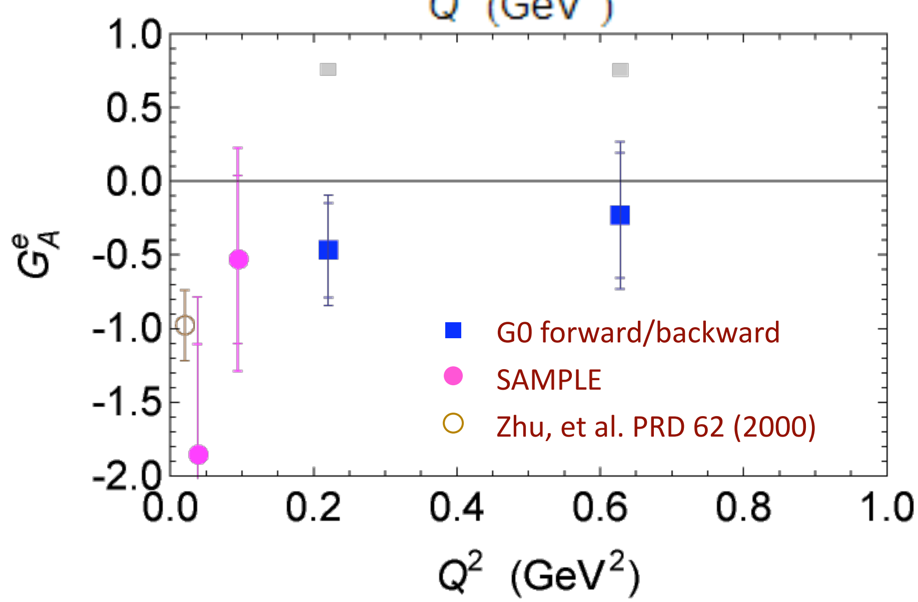
  quark contributions to form factors

Strange Form Factors Results

- Using interpolation of G0 forward measurements







Global uncertainties

Some calculations:

Leinweber, et al. PRL 97 (2006) 022001

Leinweber, et al. PRL 94 (2005) 152001

Wang, et al arXiv:0807.0944 (Q^2 = 0.23 GeV^2)

Doi, et al, arXiv:0903.3232

E. Beise

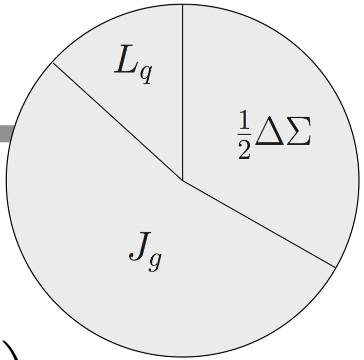
Nuclei Form Factors
Preliminary Hall A E04-018 Results

- Preliminary results rule out the long-standing dimensional scaling quark prediction.
- Both ^{3}He and ^{4}He data are in qualitative agreement with the conventional nucleon-meson theoretical framework predictions

Talk by J. Gomez

Total Angular Momentum of the Nucleon (1)

Ji-decomposition



- Ji (1997)

$$\frac{1}{2} = \sum_q J_q + J_g = \sum_q \left(\frac{1}{2}\Delta q + L_q\right) + J_g$$

with ($P^\mu = (M,0,0,1)$, $S^\mu = (0,0,0,1)$)

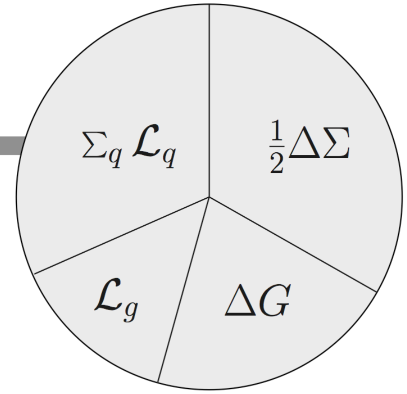
$$\begin{aligned}\frac{1}{2}\Delta q &= \frac{1}{2}\int d^3x \left\langle P,S\right| q^\dagger(\vec{x})\Sigma^3 q(\vec{x}) \left|P,S\right\rangle \qquad \Sigma^3 = i\gamma^1\gamma^2 \\ L_q &= \int d^3x \left\langle P,S\right| q^\dagger(\vec{x}) \left(\vec{x}\times i\vec{D}\right)^3 q(\vec{x}) \left|P,S\right\rangle \\ J_g &= \int d^3x \left\langle P,S\right| \left[\vec{x}\times\left(\vec{E}\times\vec{B}\right)\right]^3 \left|P,S\right\rangle\end{aligned}$$

- $i\vec{D} = i\vec{\partial} - g\vec{A}$

M. Burkardt

Total Angular Momentum of the Nucleon (2)

Jaffe/Manohar decomposition



- in light-cone framework & light-cone gauge $A^+ = 0$ one finds for $J^z = \int dx^- d^2\mathbf{r}_\perp M^{+xy}$

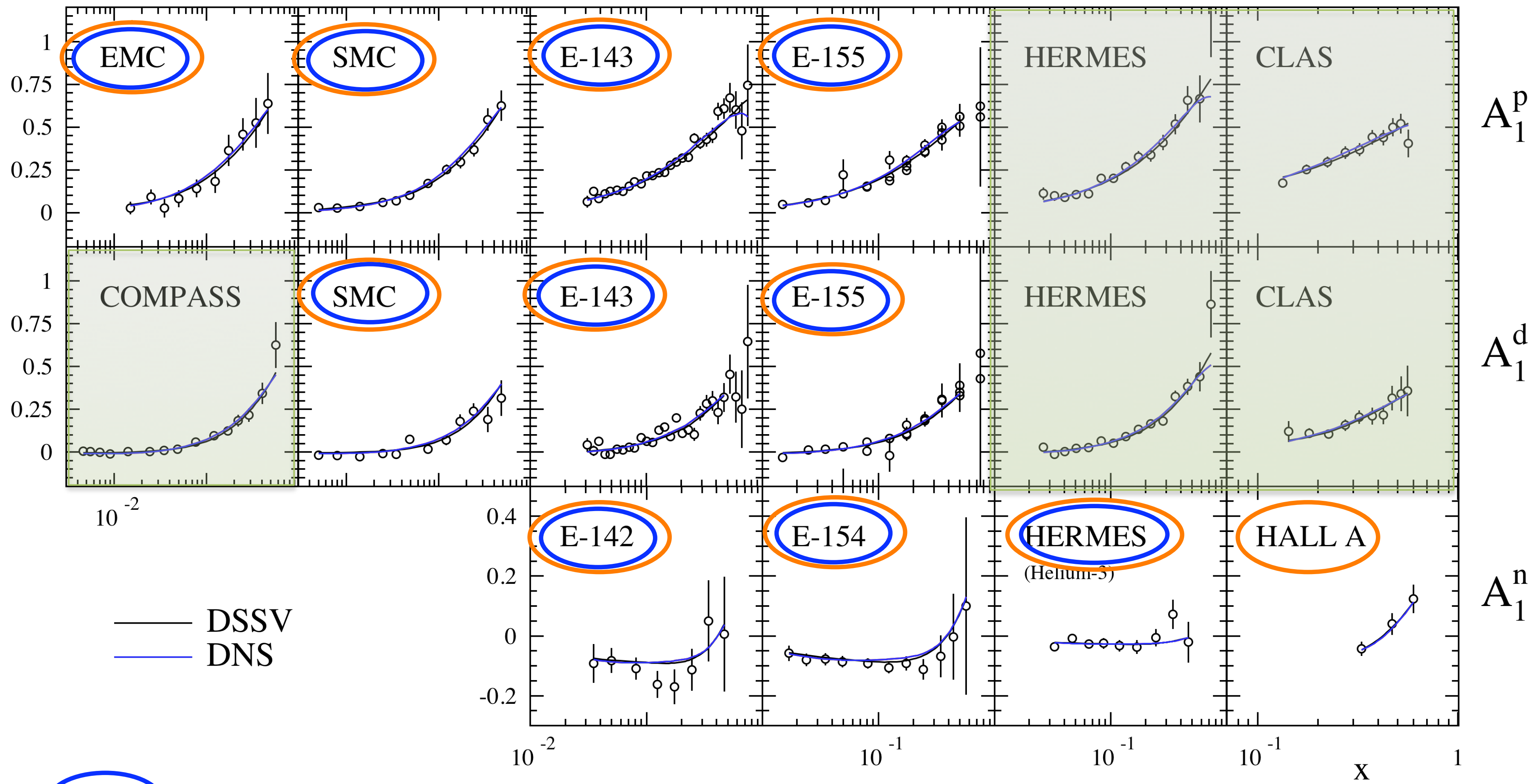
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

where ($\gamma^+ = \gamma^0 + \gamma^z$)

$$\begin{aligned}
\mathcal{L}_q &= \int d^3r \, \langle P,S| \, \bar{q}(\vec{r})\gamma^+ \left(\vec{r} \times i\vec{\partial}\right)^z q(\vec{r}) \, |P,S\rangle \\
\Delta G &= \varepsilon^{+-ij} \int d^3r \, \langle P,S| \, \mathrm{Tr} F^{+i} A^j \, |P,S\rangle \\
\mathcal{L}_g &= 2 \int d^3r \, \langle P,S| \, \mathrm{Tr} F^{+j} \left(\vec{x} \times i\vec{\partial}\right)^z A^j \, |P,S\rangle
\end{aligned}$$

Inclusive Longitudinal Spin Asymmetries

D. De Florian et al. arXiv:0804.0422



: input to the old GRSV-analysis

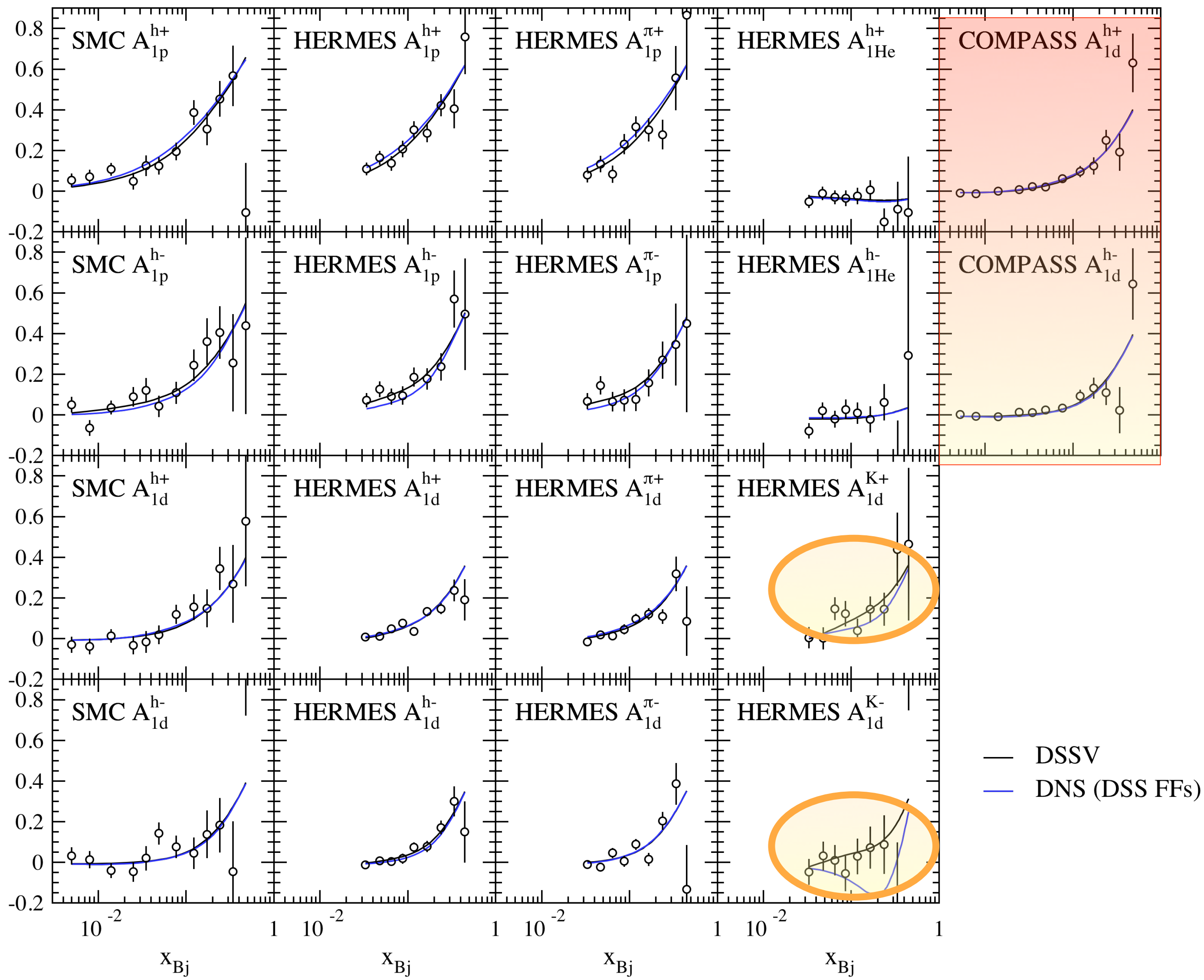
: input to the DIS & SIDIS – analysis by DNS

See talk by de Florian

Semi-Inclusive longitudinal spin asymmetries

D. De Florian et al. arXiv:0804.0422

not in DNS

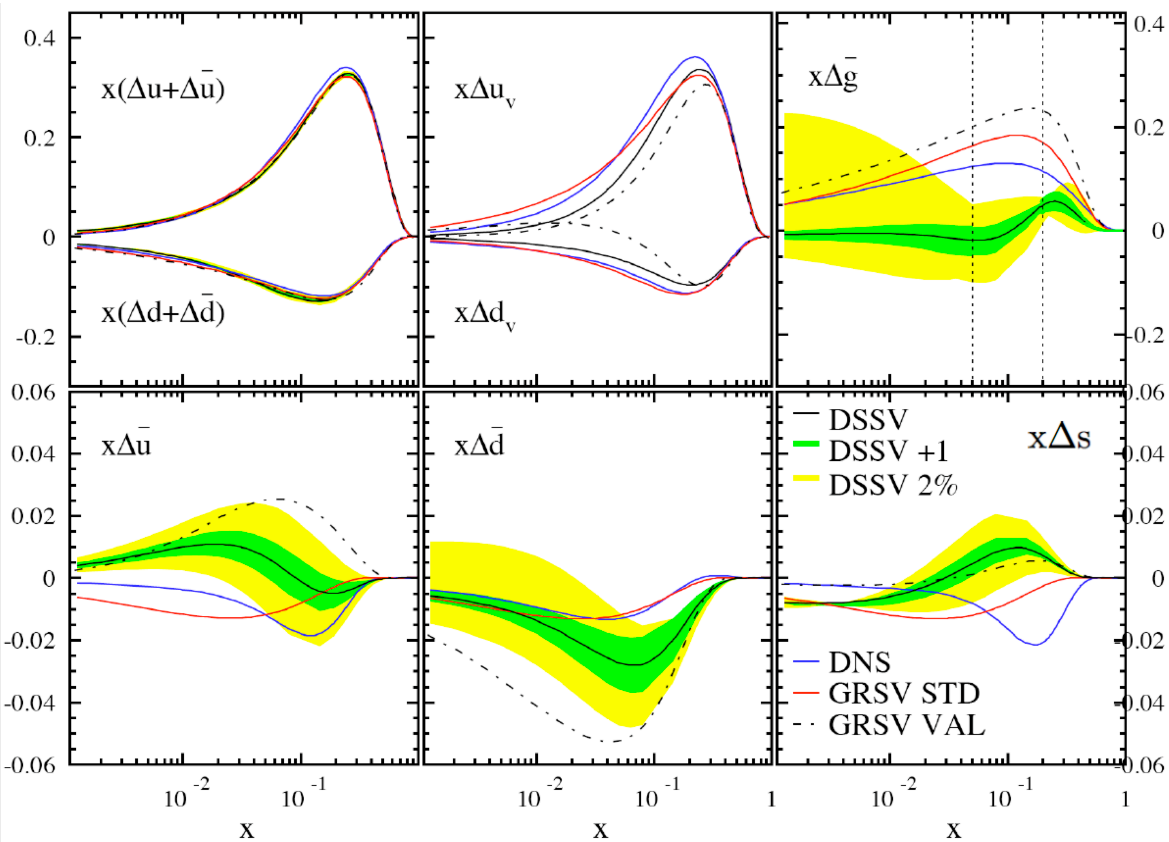


NLO FIT to World Data

D. De Florian et al. arXiv:0804.0422

NLO @ Q^2=10 GeV^2

	χ^2_{DIS}	χ^2_{SIDIS}	Δu_v	Δd_v	$\Delta\bar{u}$	$\Delta\bar{d}$	Δs	Δg	$\Delta\Sigma$
Kretzer	206	225	0.94	−0.34	−0.049	−0.055	−0.051		0.28
KKP	206	231	0.70	−0.26	0.087	−0.11	−0.045		0.31
DSSV			0.813	−0.458	0.036	−0.115	−0.057		0.242



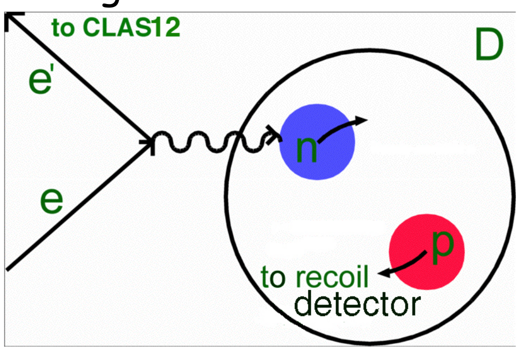
For more details see talks by:
De Florian, Boyle and Kabuss

- includes all world data from DIS, SIDIS and pp

Neutron to Proton ratio at large x

Spectator tagging

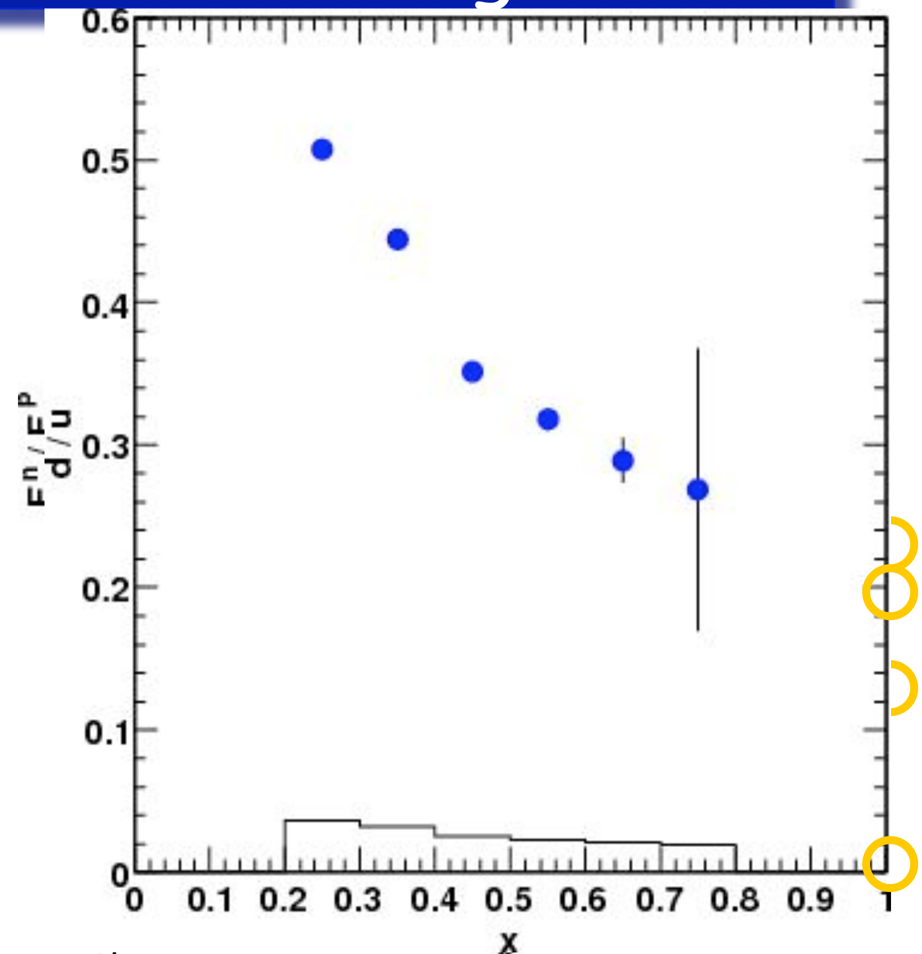
- Nearly free neutron target by tagging low-momentum proton from deuteron at backward angles



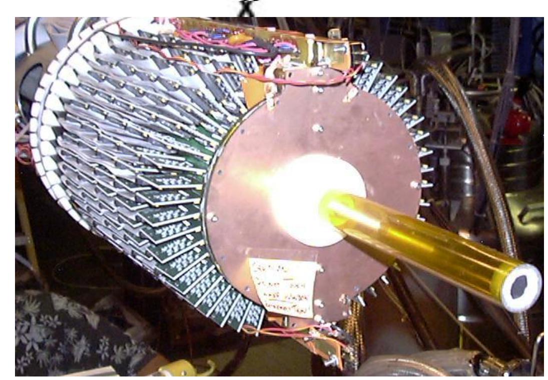
- Small p (70-100 MeV/c)
  - Minimize on-shell extrapolation (neutron only 7 MeV off-shell)
- Backward angles (q_{pq}> 110°)
  - Minimize final state interactions

@ x = 1 $F_2^n/F_2^p \rightarrow 0.25$ (d/u → 0) for scalar diquarks

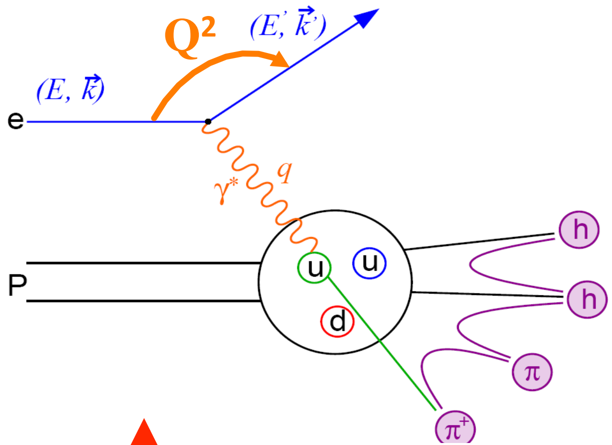
$F_2^n/F_2^p \rightarrow 3/7$ (d/u → 1/5) for hard gluon exchange



How: Slow (2-7 MeV) proton recoil detector (radial TPC)

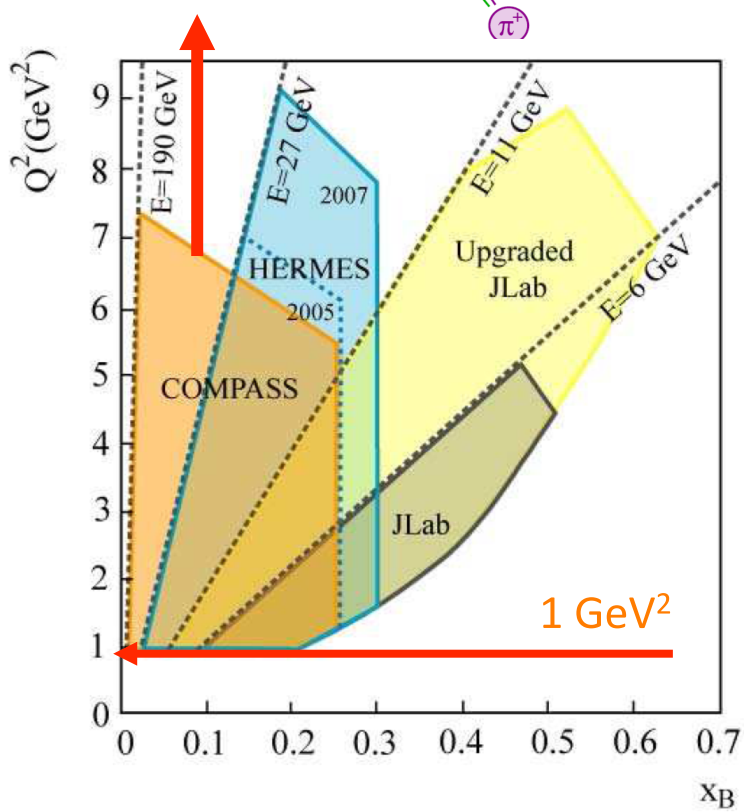


Semi-Inclusive Deep-Inelastic Scattering

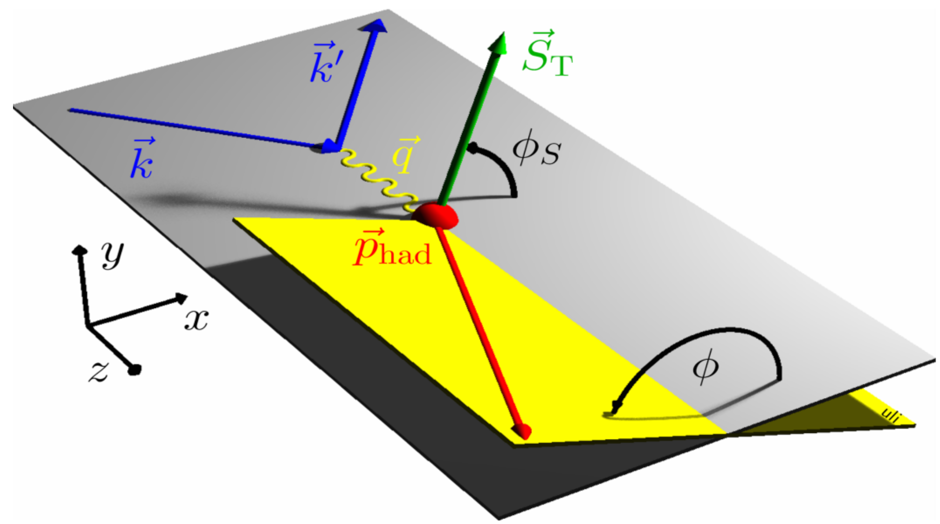


Factorization

$$\sigma^{h}_{l,S} \propto \sum_{f} \sigma^{q_f} \otimes pdf(x) \otimes frag^{q_f,g\rightarrow h}(z)$$



- Beam polarized
- Target polarized transverse (T) or longitudinal (L)



Transverse momentum Distributions

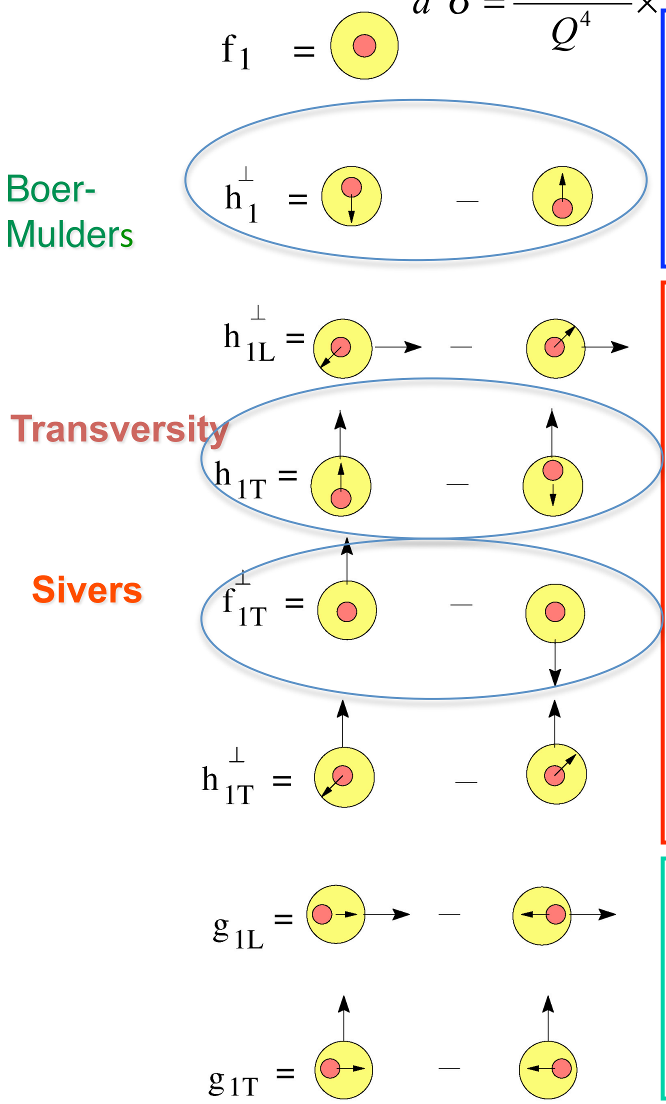
- Transverse Momentum Distributions
  - Semi-Inclusive DIS, polarized pp, Drell-Yan
  - While there has been a strong activity recently with new discoveries this avenue started in the 70's when people were looking for "clean test of QCD".
    - Transversity (integrated with respect to k_T) → Tensor charge
    - Collins fragmentation function
    - Sivers distribution function (final state interaction)
    - Boer-Mulder distribution function (initial state correlation)

An important test "Universality"

$$Sivers(SIDIS) = -Sivers(Drell - Yan)$$

See M. Burkardt talk for possible connections between GPDs and TMDs

All Eight Quark Distributions are Probed in Semi-Inclusive DIS



$$d^6\sigma = \frac{4\pi\alpha^2 s x}{Q^4} \times$$

Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

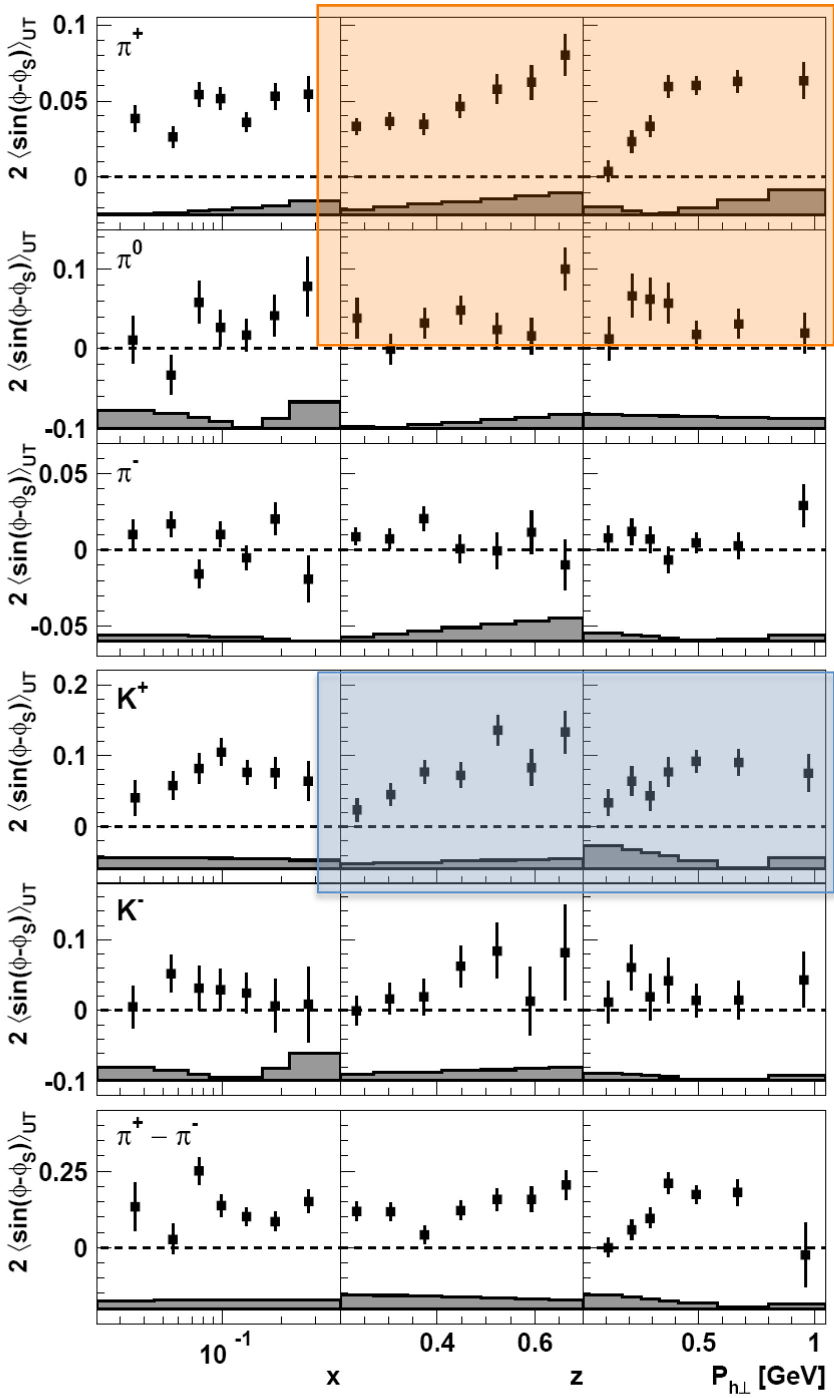
$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

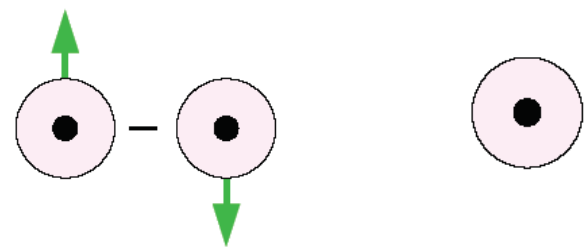
S_L and S_T: Target Polarizations; l_e: Beam Polarization



Sivers amplitudes

[arXiv:**0906.3918**]

$$f_{1T}^{\perp q}(x, k_T) \otimes D_1^q(z)$$



first observation of T-odd Sivers effect in SIDIS (PRL 94, 2005)

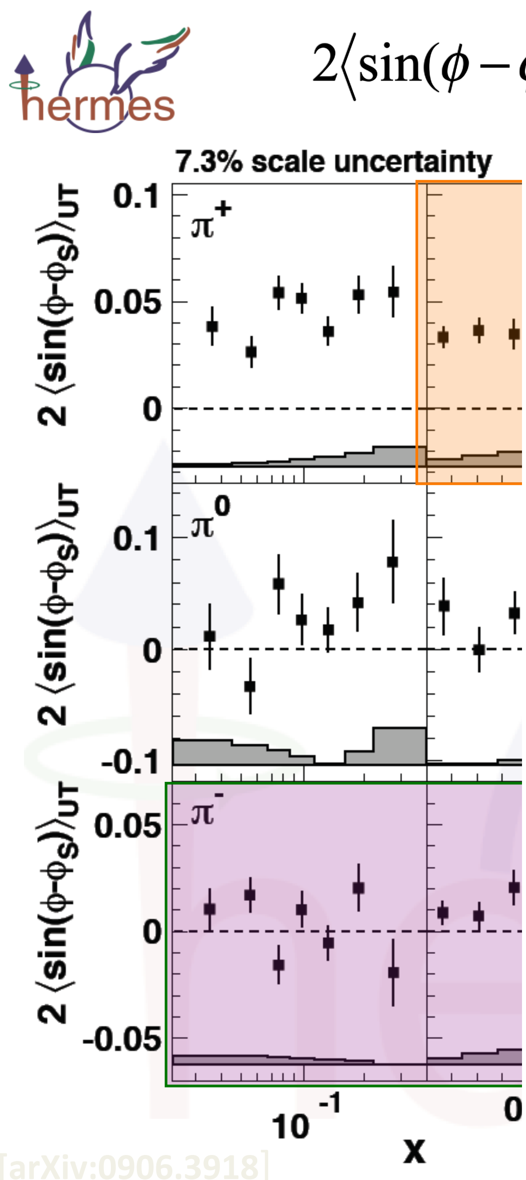
u quark dominance suggests sizable u quark orbital motion

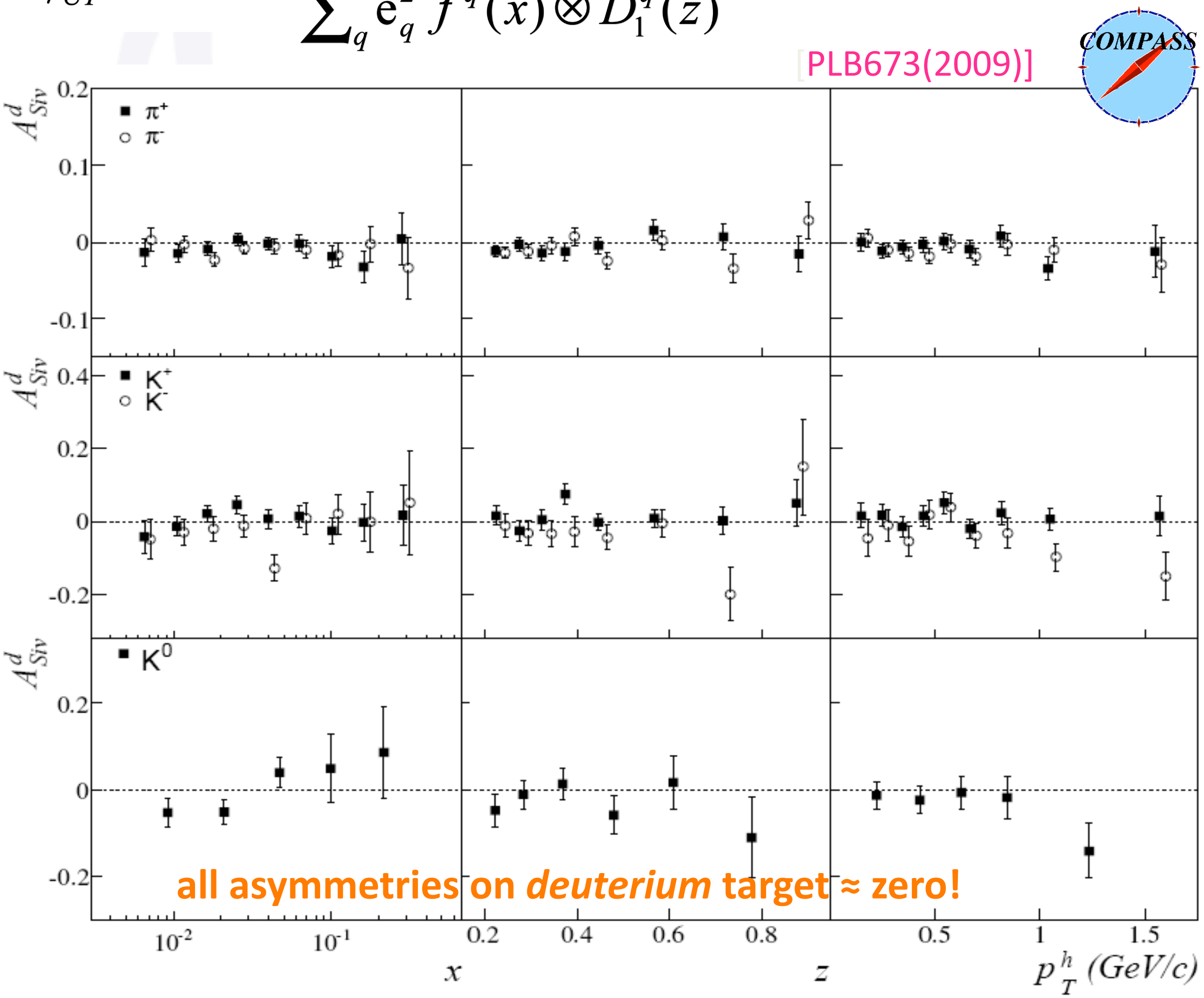
cancellation for π^- :

u and d quark Sivers DF of opposite sign

See talk by hermes

$$2\langle \sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2\, f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,k_T^2)}{\sum_q e_q^2\, f^q(x)\otimes D_1^q(z)}$$



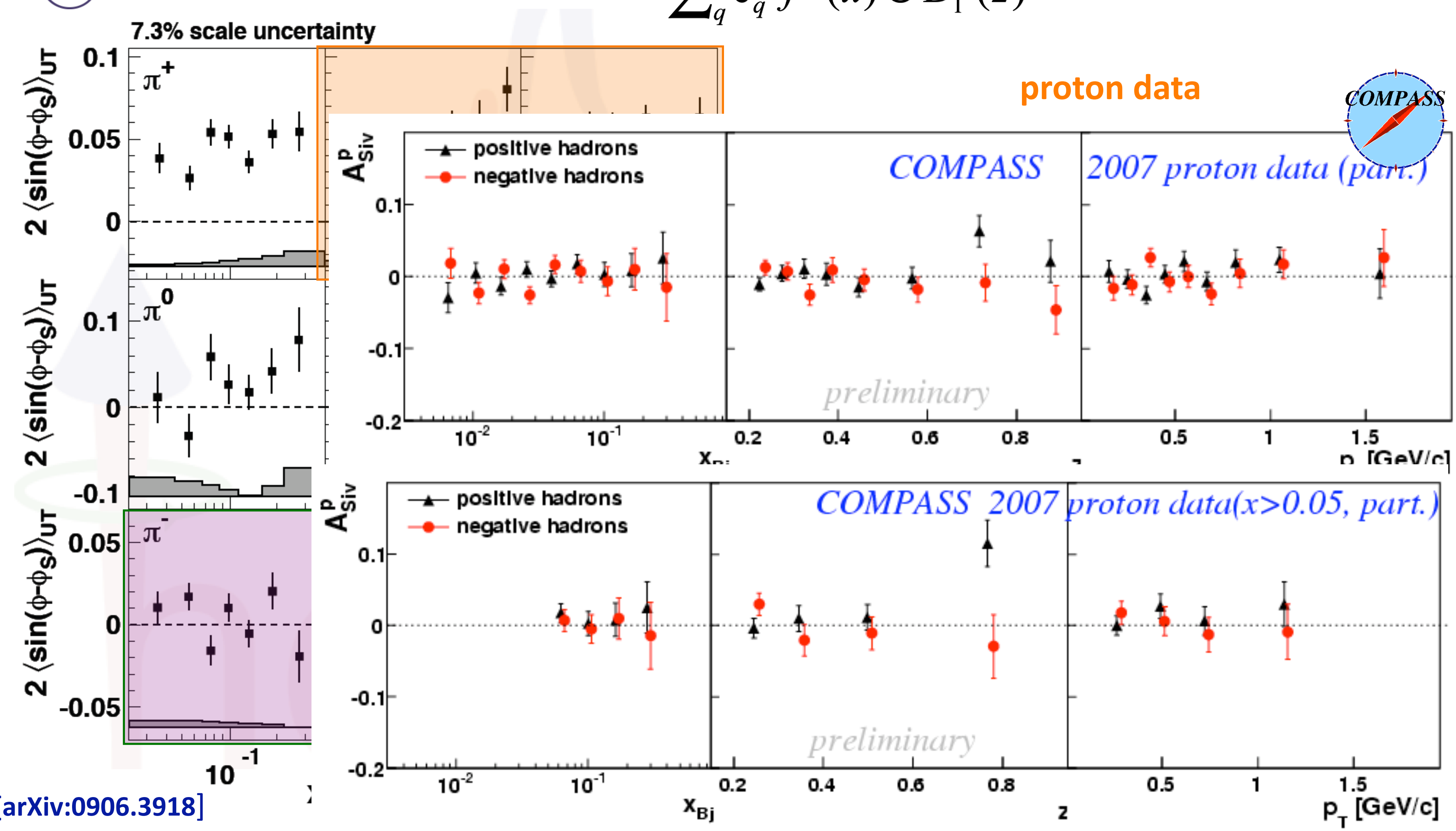


all asymmetries on *deuterium* target ≈ zero!

Sivers amplitudes for p

$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2\, f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,k_T^2)}{\sum_q e_q^2\, f^q(x)\otimes D_1^q(z)}$$

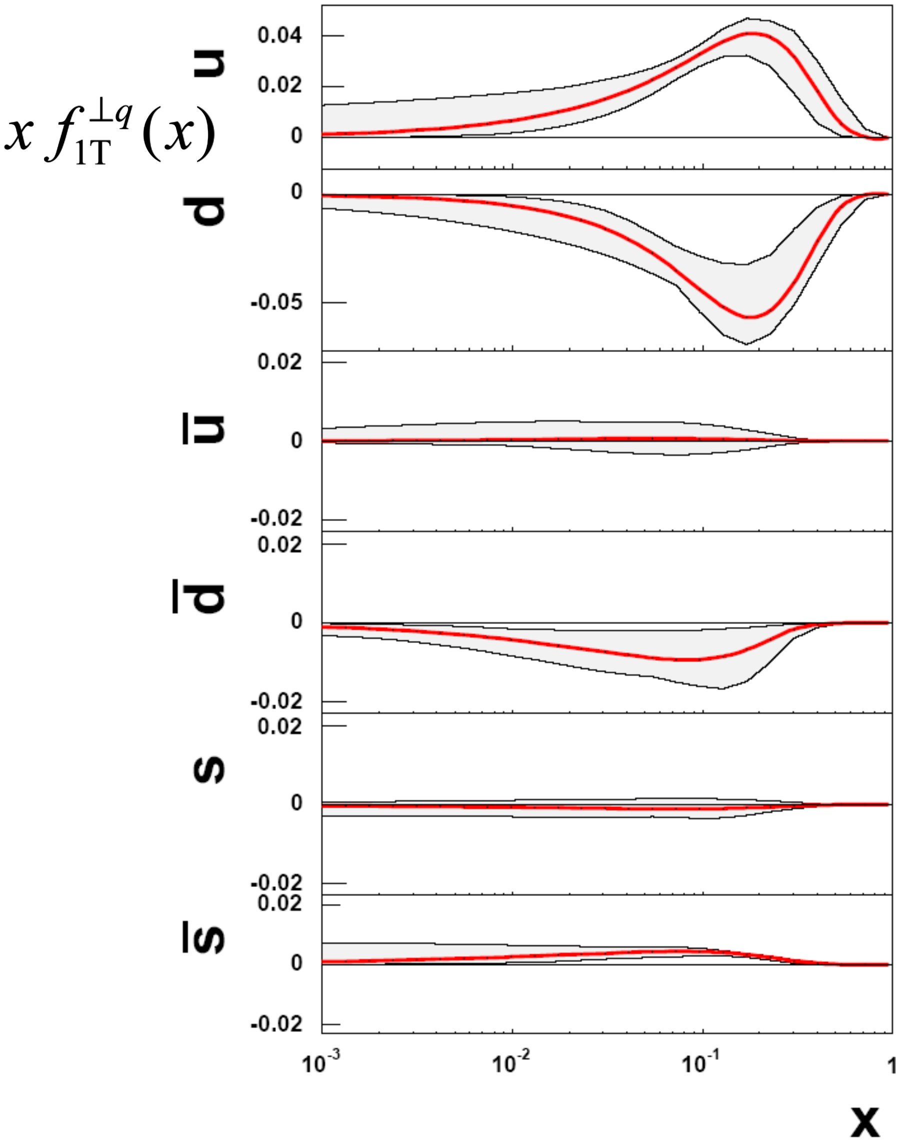
proton data



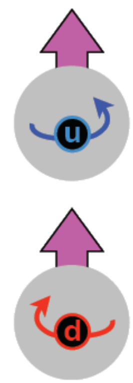
[arXiv:0906.3918]

Sivers function extracted through a combined analysis

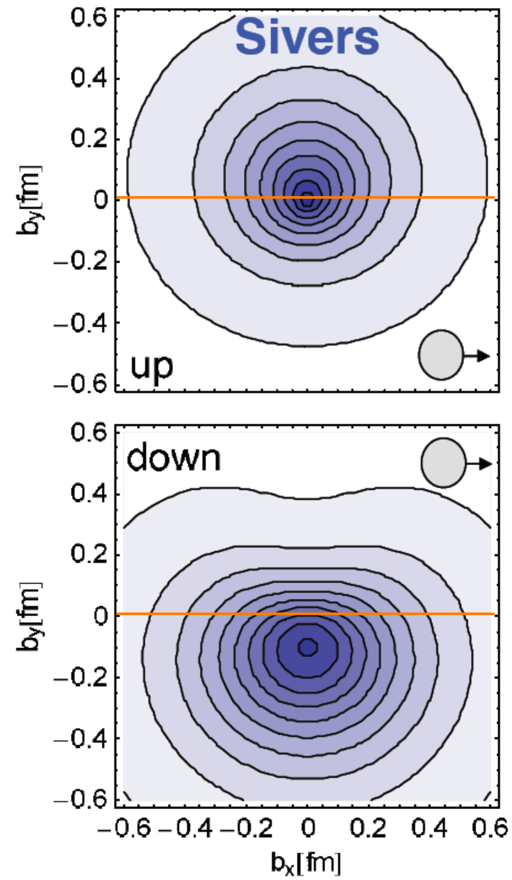
[Anselmino et al., EPJA(2009),89]



combined analysis:



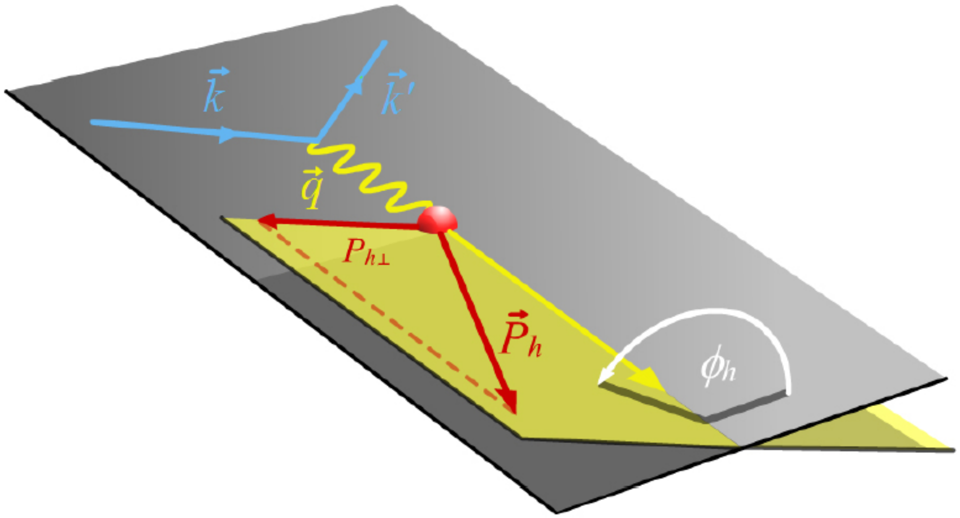
Lattice [Haegeler et al.]

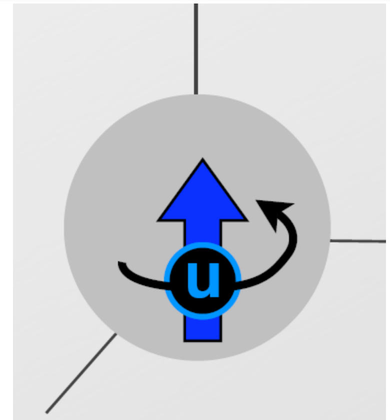


$L_u>0$

$L_d<0$

Azimuthal dependence of the unpolarized cross section





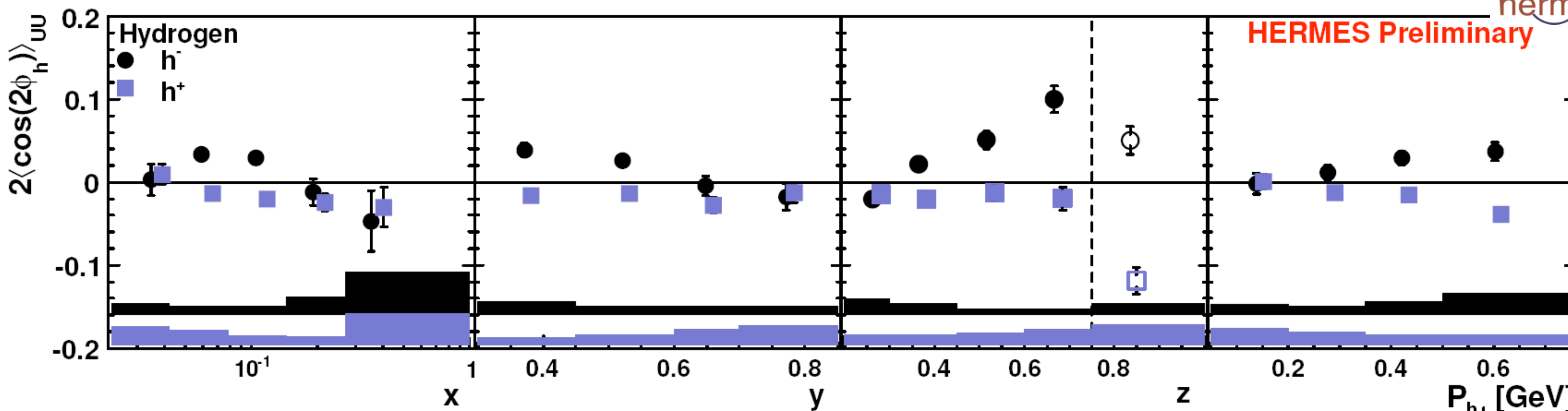
$$h_1^\perp(x, k_T)$$

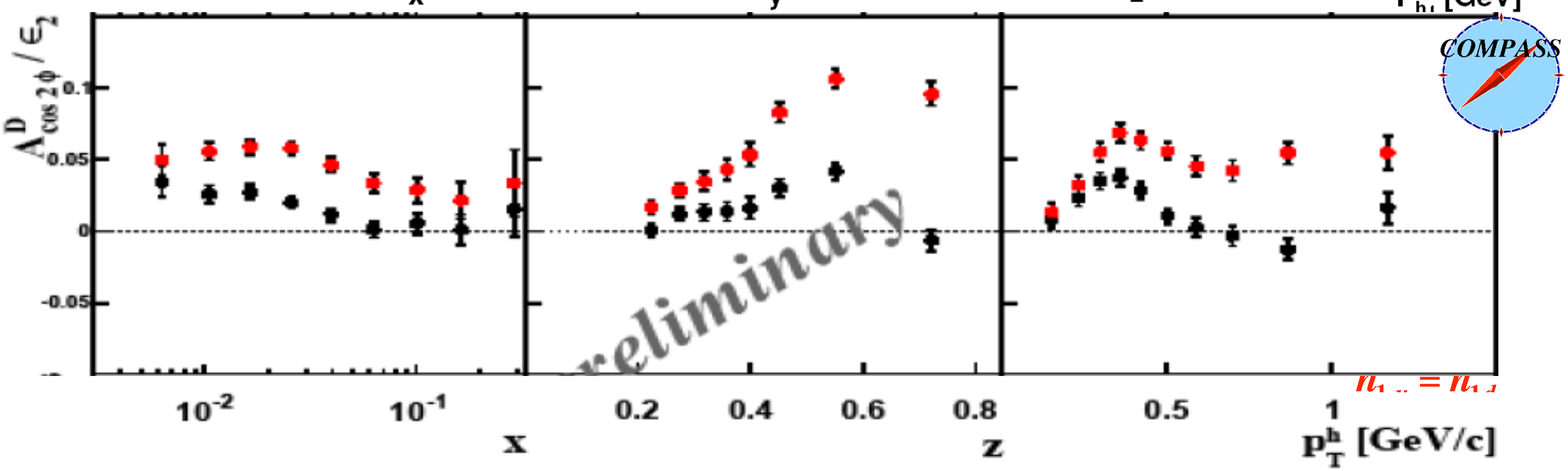
spin-orbit effect (Boer-Mulders Distribution Function):

correlation between quark transverse motion and transverse spin

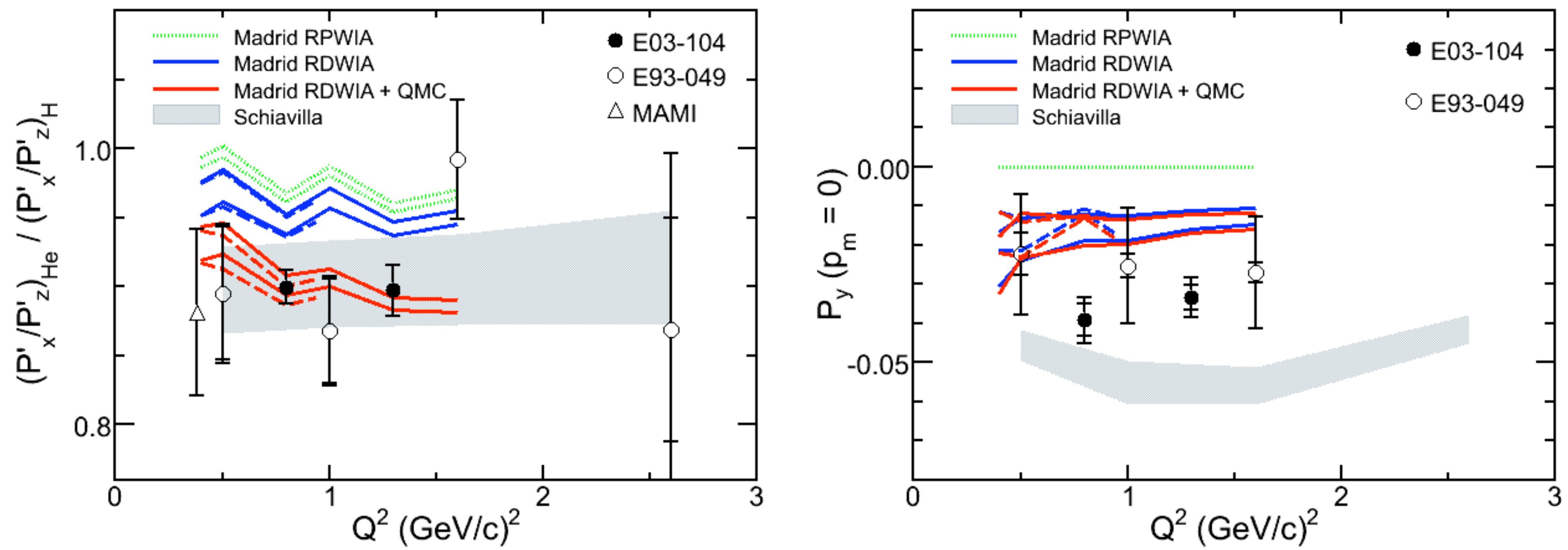
Boer-Mulders Distribution Function

$$\frac{d\sigma}{dxdydzd\Phi dP_{h\perp}^2} = 2\pi \frac{a^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})[F_{UU,T} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\Phi F_{UU}^{\cos\Phi} + \varepsilon\cos(2\Phi)F^{\cos(2\Phi)}]$$





E03-104: Polarization transfer and induced polarization in $^{4}He(\vec{e},e'\vec{p})^{3}H$



- Calculations of both the Madrid group (medium modification of the proton) and Schiavilla et al. (spin-dependent charge exchange in FSI) are shown
- The inner error bars are statistical only. Total error bars include systematic uncertainties
- False asymmetries are controlled at an unprecedented level of < 0.005, allowing for the 1st time a comparison of induced polarization versus p_m.
- The induced polarization data are corrected for acceptance to facilitate the comparison to Schiavilla et al. The latter calculation overestimates the data.
- Both explanations of the data seem to do equally well (or poorly).

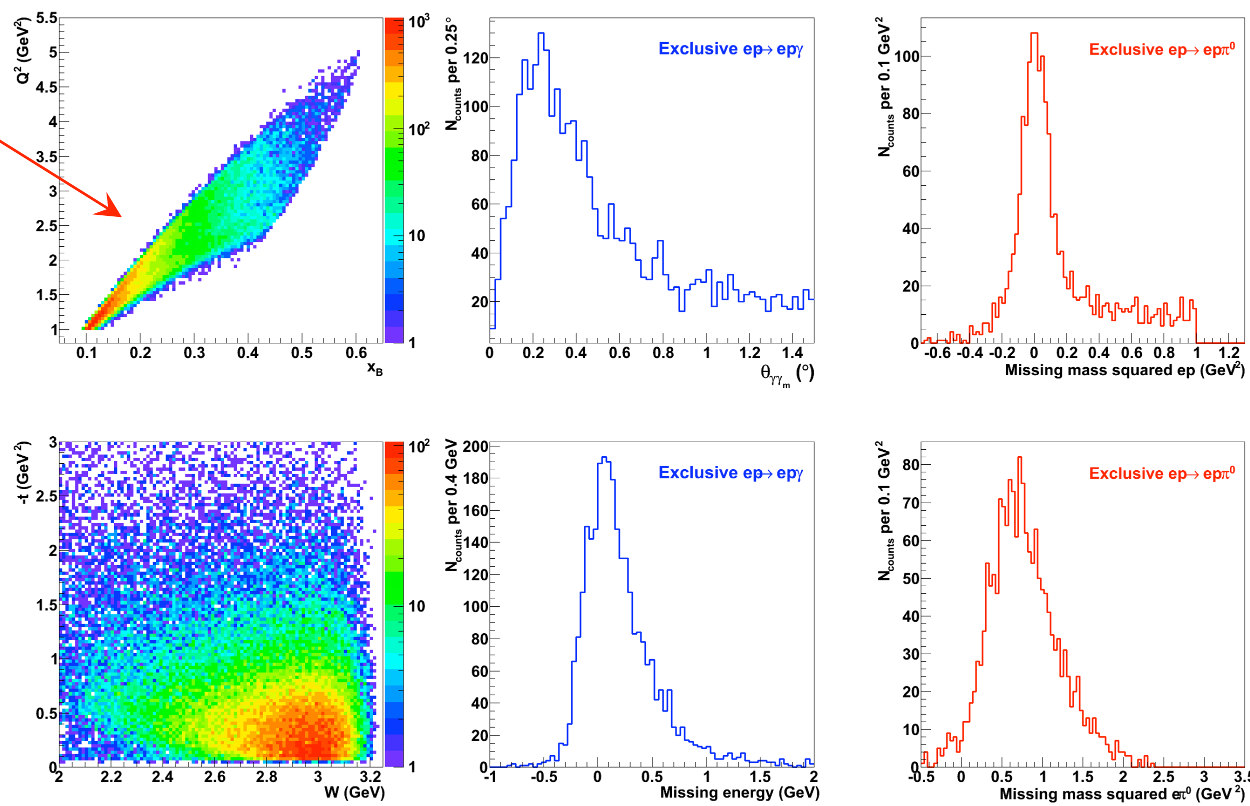
CLAS

Deeply Virtual Compton Scattering - e1-DVCS (2)

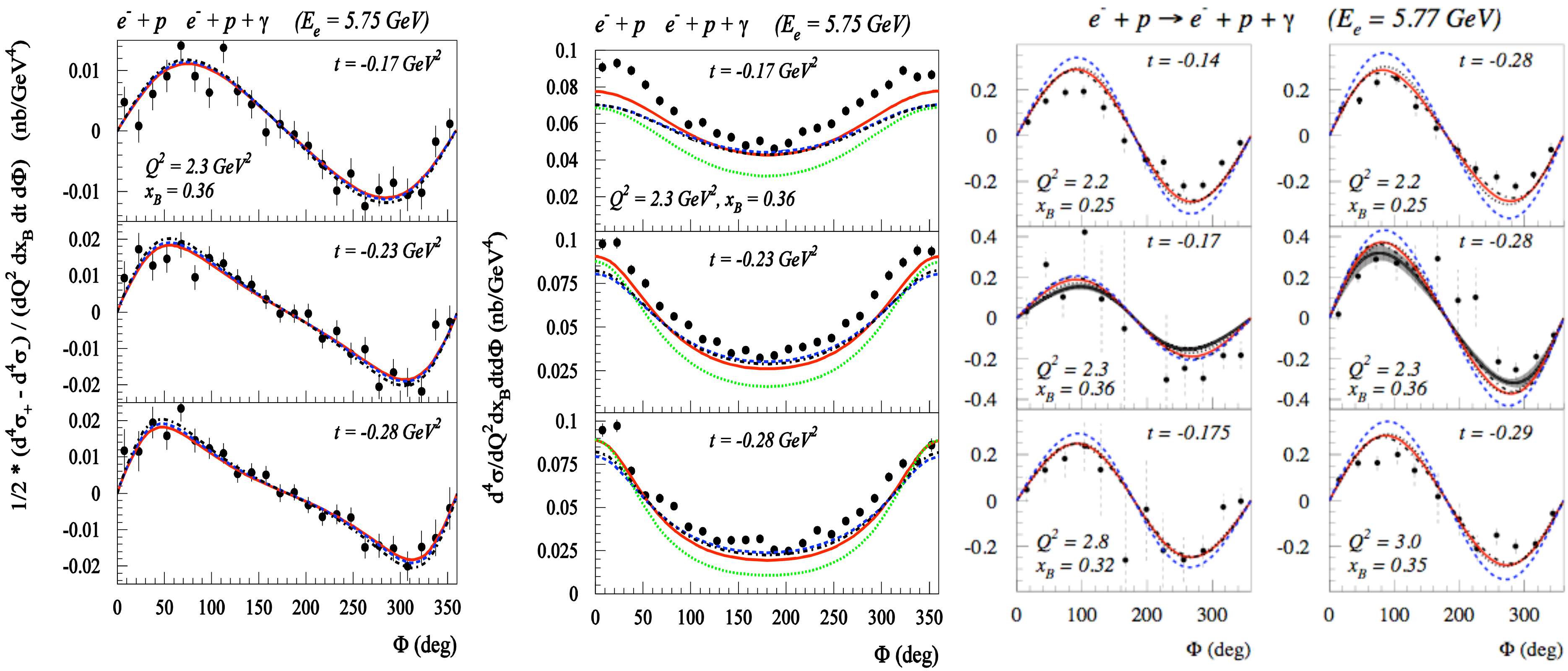
E06-003

- The second part of e1-dvcs took data from 10/12/2008 until 01/23/2009 and accumulated about 90% of the projected charge.
- All 3 particles in the final state [e, p, g (π^0)] were detected.
- The graphs show kinematical coverage, exclusivity of reaction, and missing mass resolution

Data set covers a broad range of x_B and Q^2



Generalized Parton Distributions (GPDs)



Unprecedented set of Deeply Virtual Compton Scattering data accumulated in Halls A and B and more to come

See talk by F.X. Girod

CLAS Deeply Virtual $\rho^{0,}$ ρ^{+} production and GPDs

E-99-105

Exploration of GPD application in meson sector.

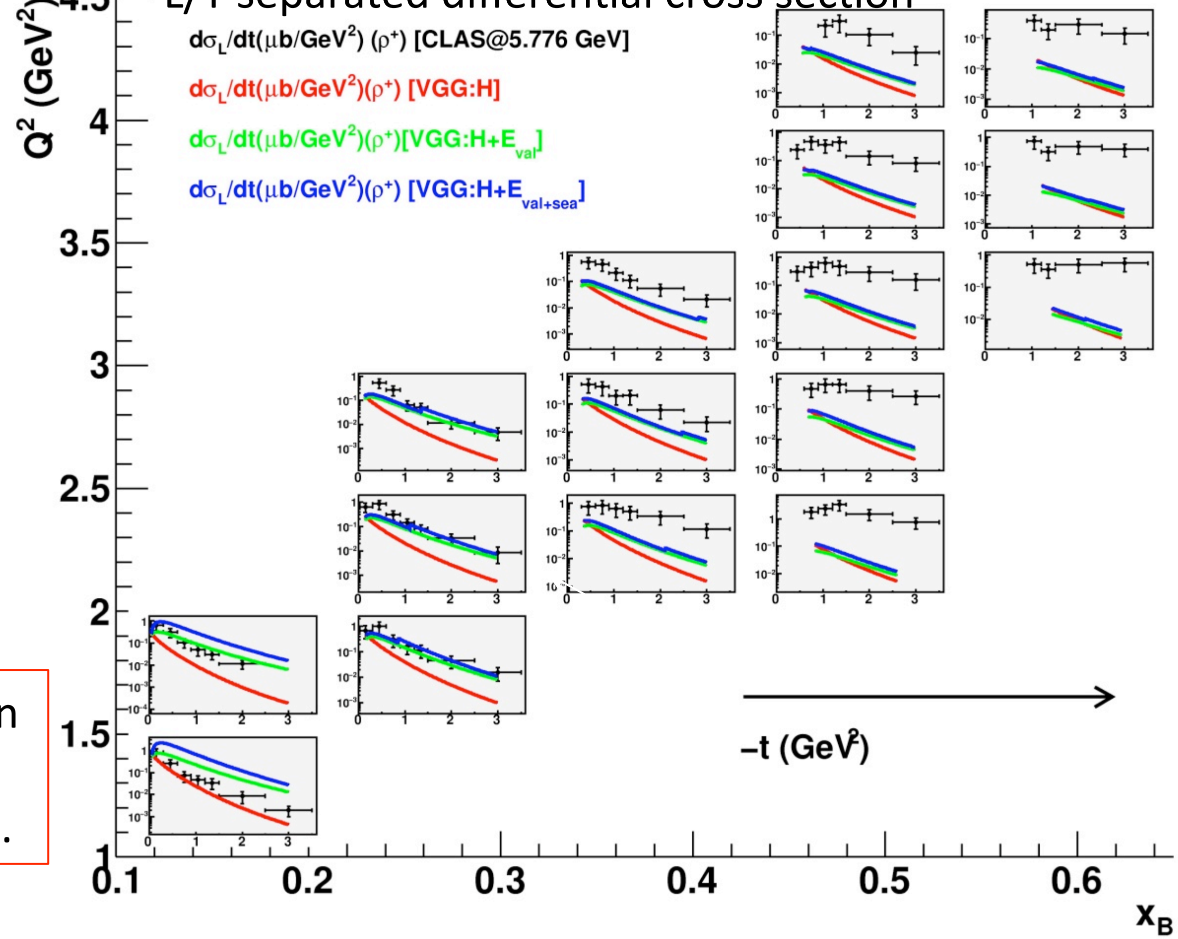
ρ^0: Eur.Phys.J.A39:5-31 ,2009
ρ^+: In preparation

GPDs model agrees fairly with the data at low x_B (high W)

Hint of GPD E dominance at low x_B (high W)

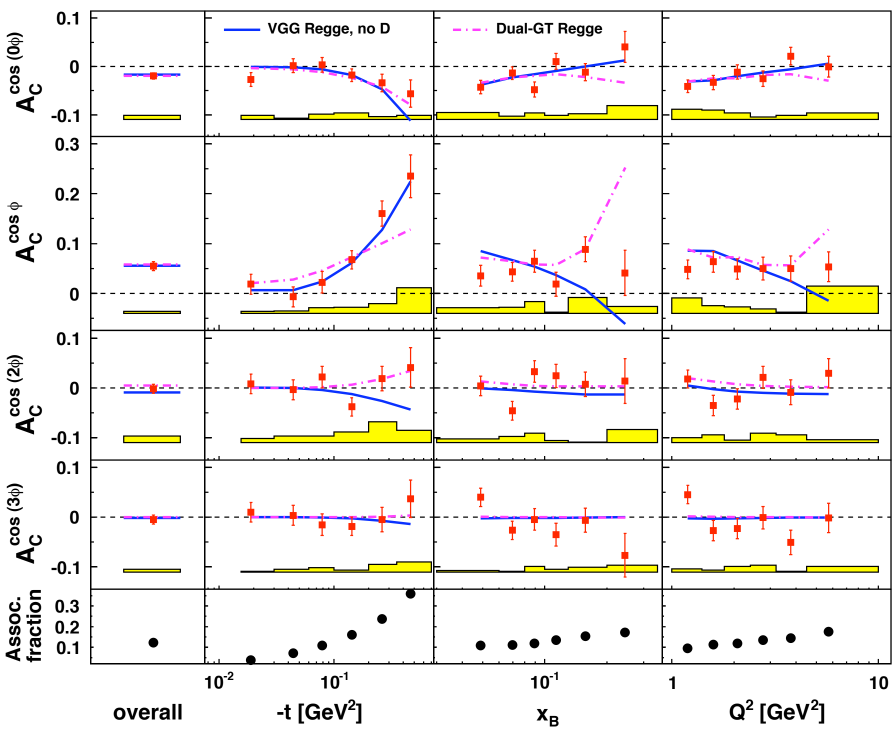
Differences of GPD prediction and measurements shrink with increasing Q^2 at fixed x_B.

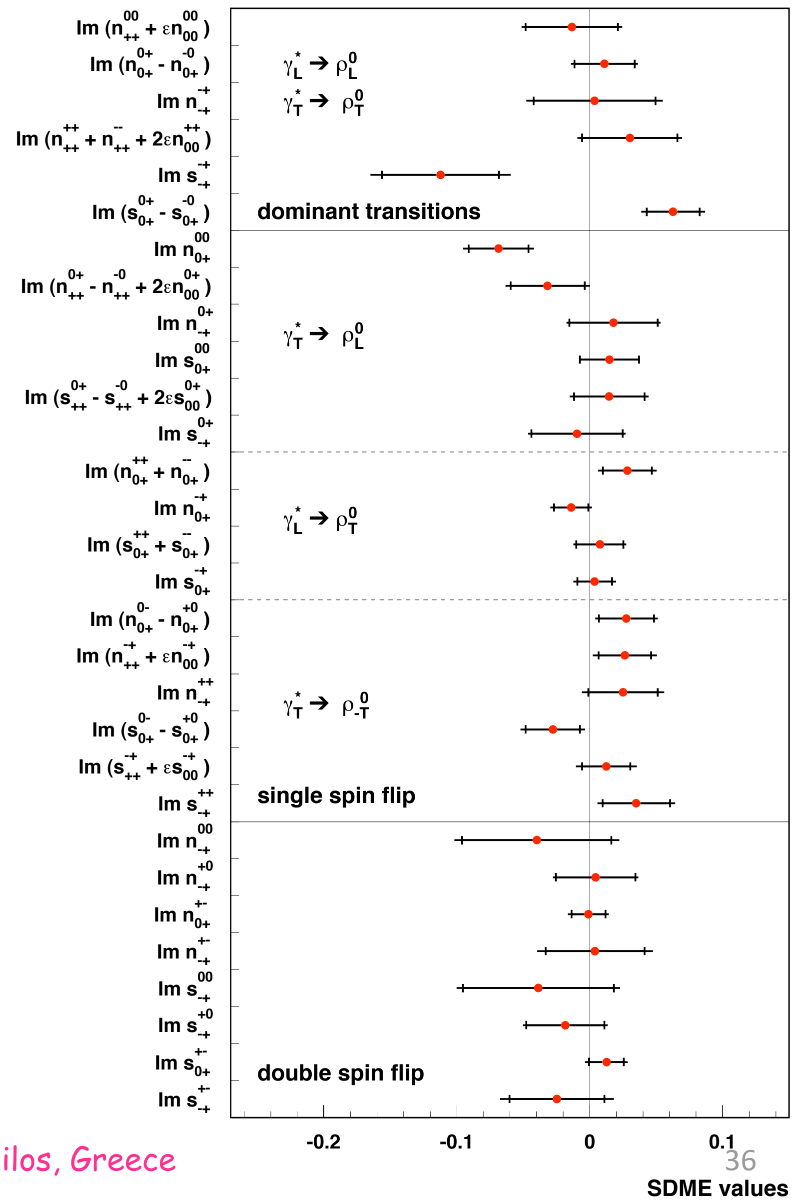
L/T separated differential cross section



See talk by F.-X. Girod

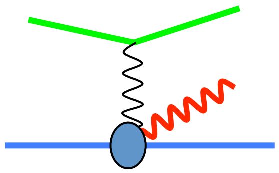
HERMES DVCS Beam Charge Asymmetry in DVCS and Spin Density Matrices in rho production



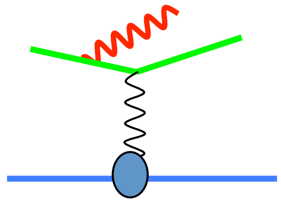


See talk by Mussgiler

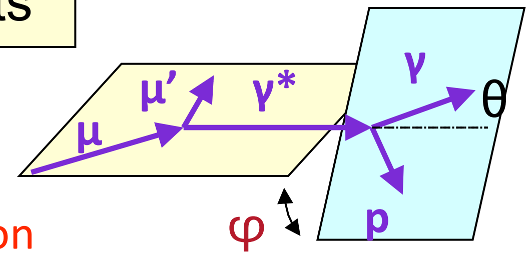
Azimuthal distribution for exclusive single photon events

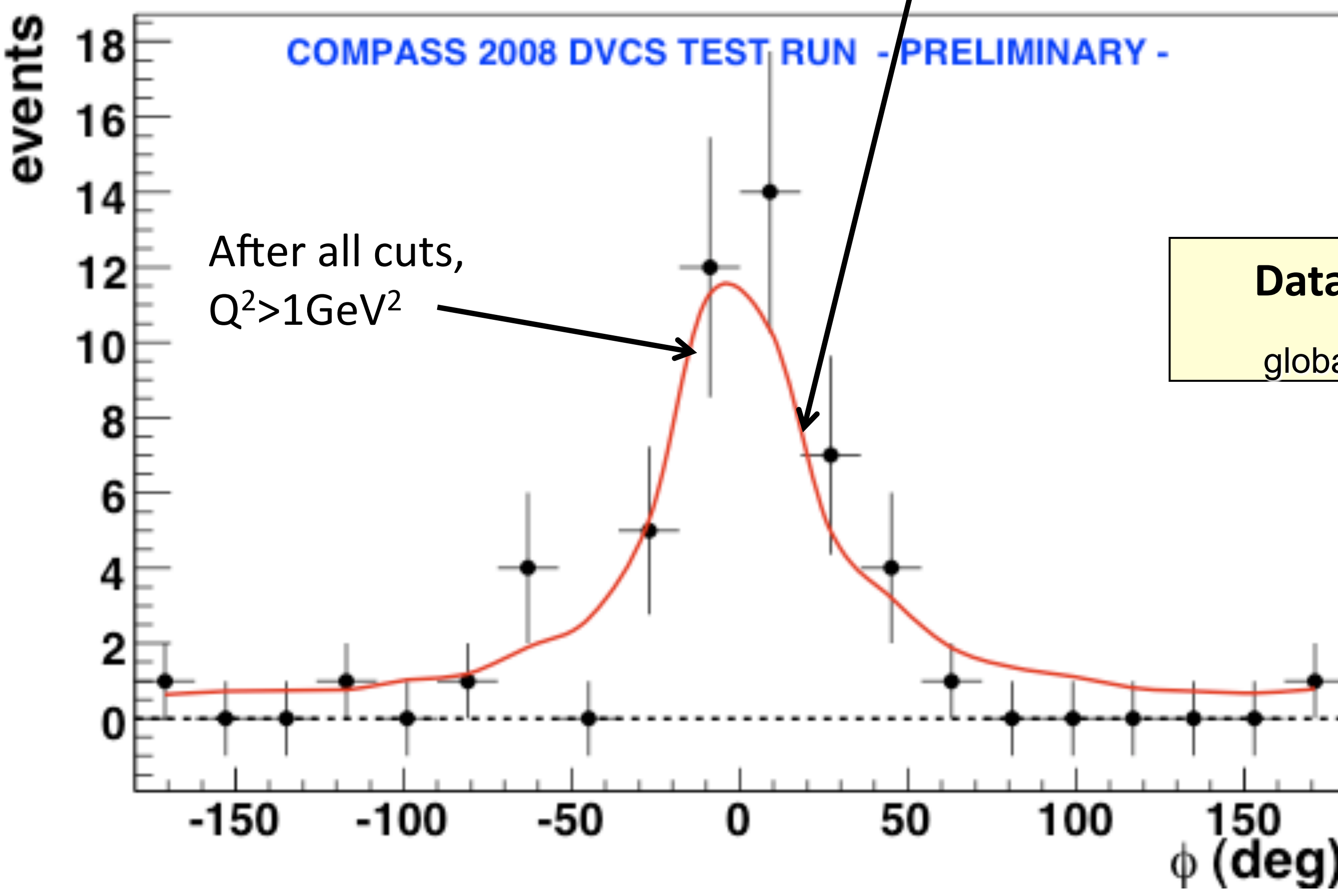


DVCS



Bethe-Heitler





Data & MC =>
$_{global}$ = 13%±5%

N. D'hose

Clear signature of dominant BH events

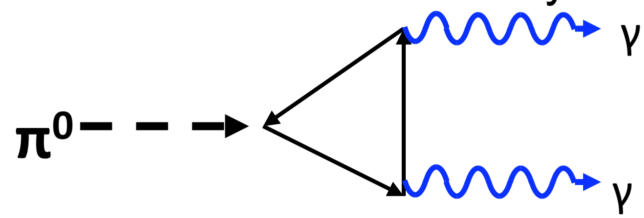
PrimEx Decay Width for $\Gamma(\pi^0\rightarrow\gamma\gamma)$ HALL B

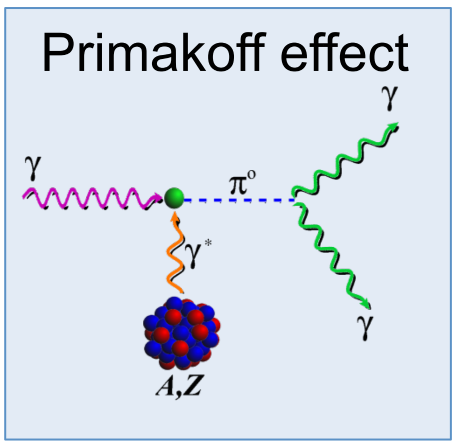
E02-103

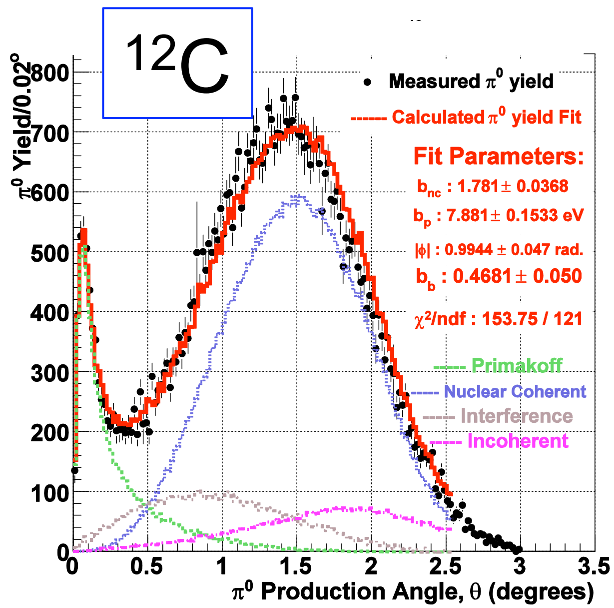
Precision measurement of π^0 life time

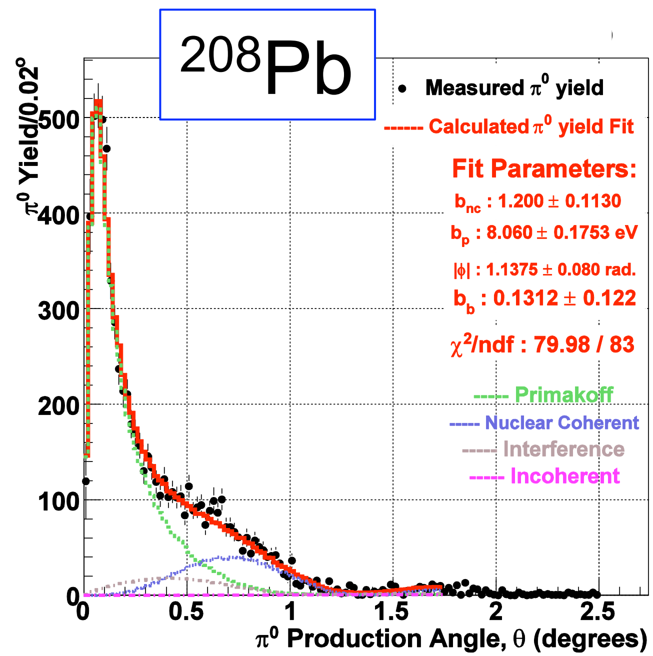
Chiral anomaly of QCD predicts exact value of decay width.

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{\alpha^2 N_C^2 m_{\pi^0}^3}{576\pi^3 F_{\pi^0}^2} = 7.725eV$$

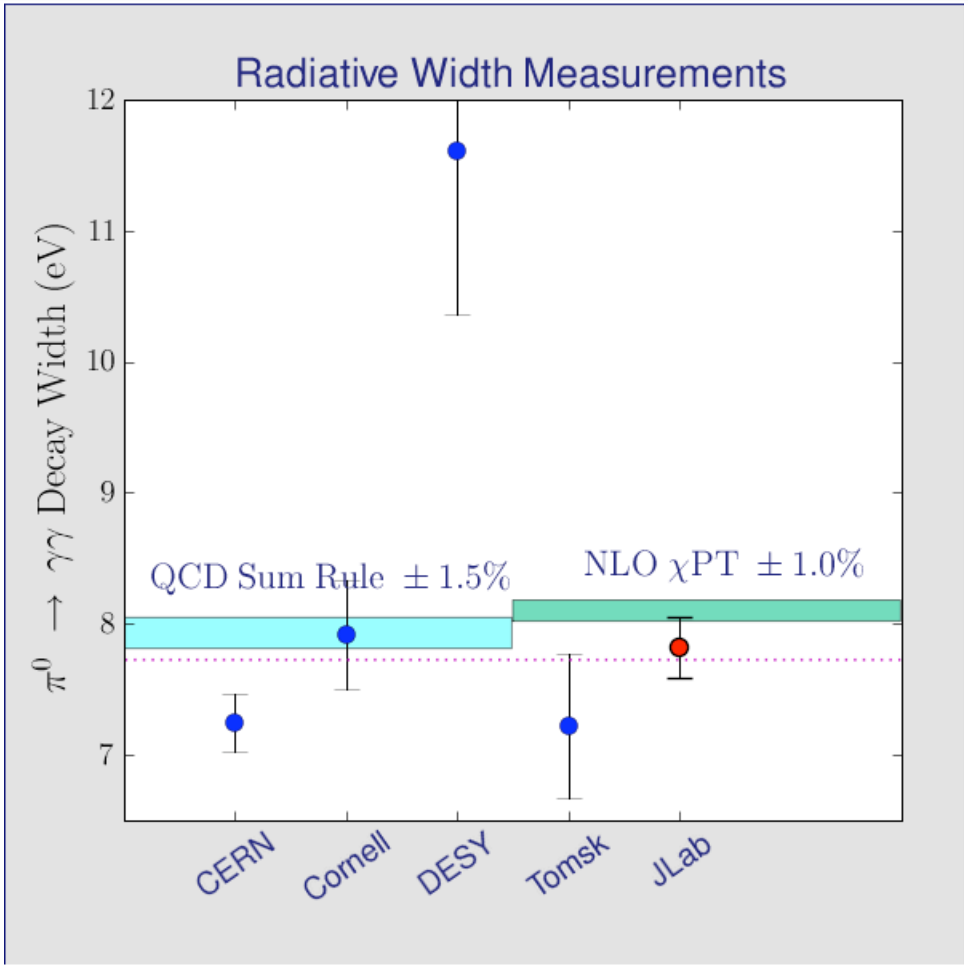








PrimEx-I Final Result



$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.82\text{eV} \pm 2.2\%\text{stat.} \pm 2.1\%\text{syst.}$
($\pm$ 3.0% total)

Conclusion

- A large number of new results as this conference will prove it.
- Serious progress in many fronts but still a lot to do.
- More to come for the next meeting.
- Stay inspired and share the excitement!