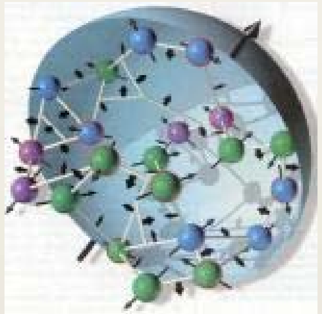
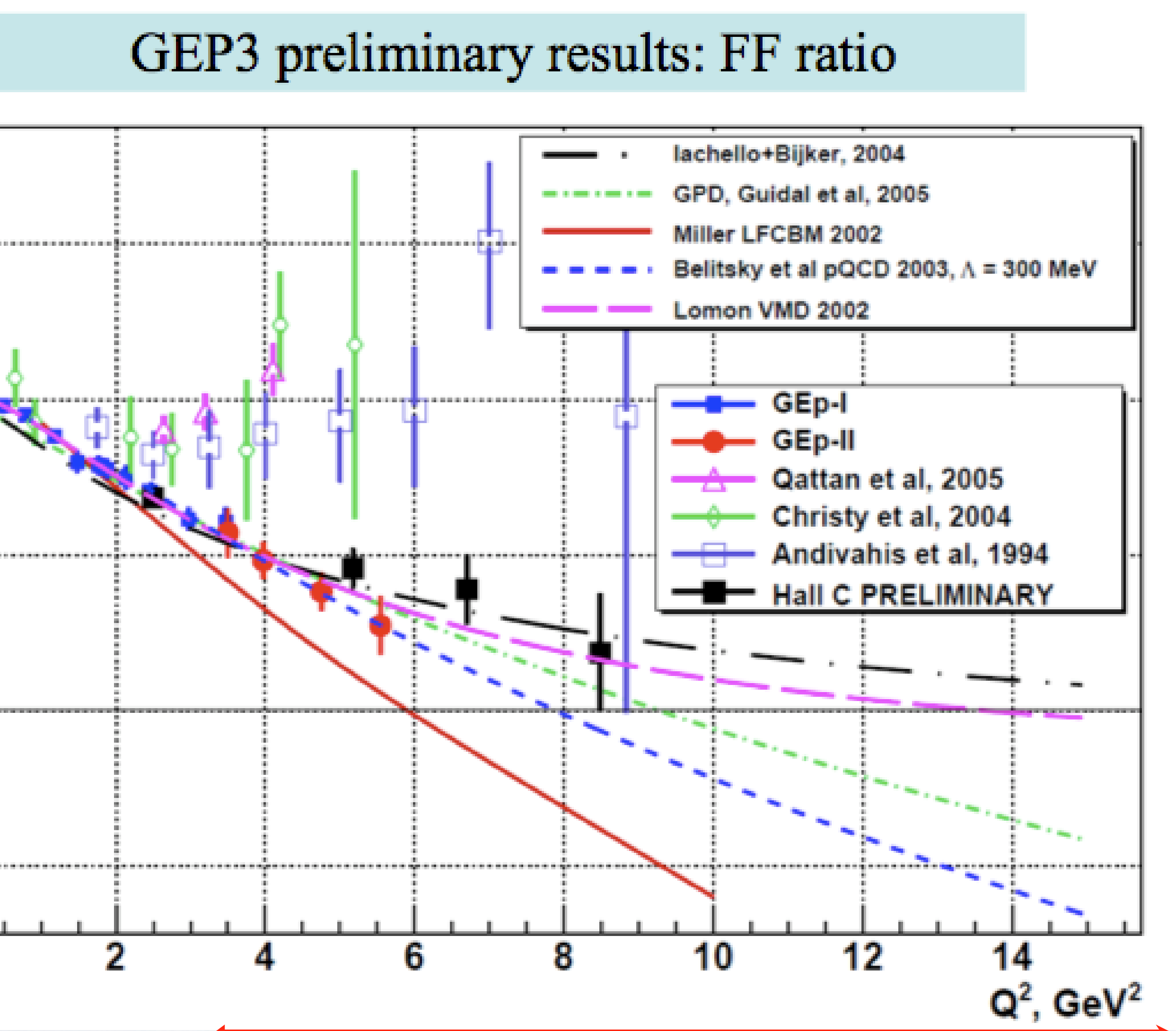
Two Photon Exchange in elastic electron-proton scattering: QCD factorization approach

Nikolai Kivel

in collaboration with

M. Vanderhaeghen





? pQCD in TPE

Theory

Chen, Afanasev et al PRL93(20

GPD-model

Blunden Melnitchouk Tjon PRL91

hadronic model

TPE can explain the large
of the discrepancy in the F
extraction

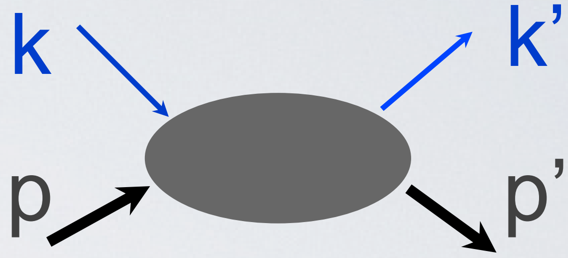
Experiment:

TPE mechanism can be
studied experimentally

ture

ab Hall A/C PR-07-109/09-001 pol G_E/G_M Q^2=6-14.8GeV^2

hon Vanderhaeghen, 2003

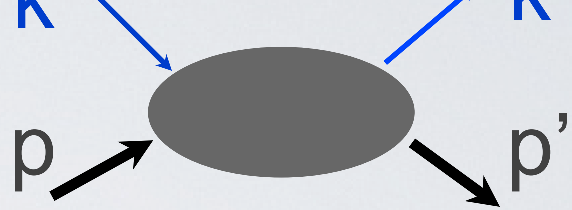


$$A_{ep} = \frac{e^2}{Q^2}\, \bar{l}'\gamma^\mu\, l$$

$$\times \bar{N}' \left(\tilde{G}_M\, \gamma^\mu - \tilde{F}_2\, \frac{1}{2M}(p+p')^\mu + \tilde{F}_3\, \frac{1}{4M^2}(p+p')^\mu\, \gamma.(k+k') \right) N$$

$$\ldots_{ep} = \frac{e^2}{Q^2}\, \bar{l}'\gamma^\mu\, l$$

$$\ldots \bar{N}' \left(\tilde{G}_M\, \gamma^\mu - \tilde{F}_2\, \frac{1}{2M}(p+p')^\mu + \tilde{F}_3\, \frac{1}{4M^2}(p+p')^\mu\, \gamma.(k+k') \right) N$$

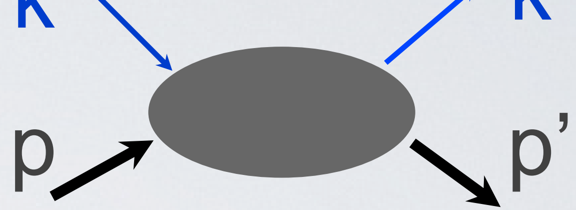


- and 2γ- ff's

1γ exch

$$\tilde{G}_M = G_M + \delta\tilde{G}_M \qquad \tilde{F}_2 = F_2 + \delta\tilde{F}_2 \qquad \tilde{F}_3$$

2γ exch



$$T_{ep} = \frac{e^2}{Q^2}\,\bar{l}'\gamma^\mu\, l$$

$$\bar{N}'\left(\tilde{G}_M\,\gamma^\mu - \tilde{F}_2\,\frac{1}{2M}(p+p')^\mu + \tilde{F}_3\,\frac{1}{4M^2}(p+p')^\mu\,\gamma.(k+k')\right)N$$

and 2γ- ff's

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2γ exch

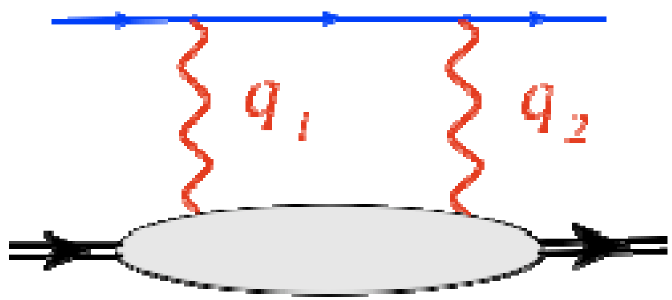
rge Q^2 asymptotic (pQCD)

$$G_M \sim F_1 \sim \alpha_S^2/Q^4$$

$$F \sim 1/Q^6$$

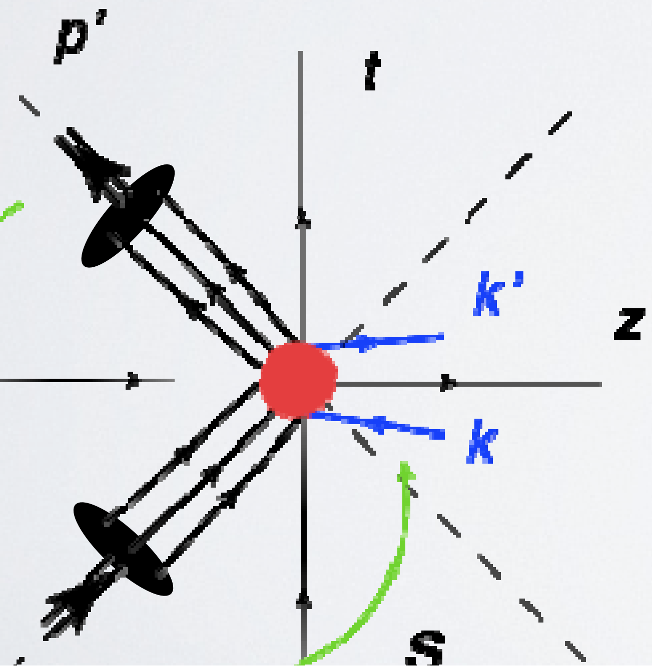
n photons have large
alities

$$q_2^2 \sim q^2 = (p' - p)^2 \equiv -Q^2$$



+ crossed

Breit frame

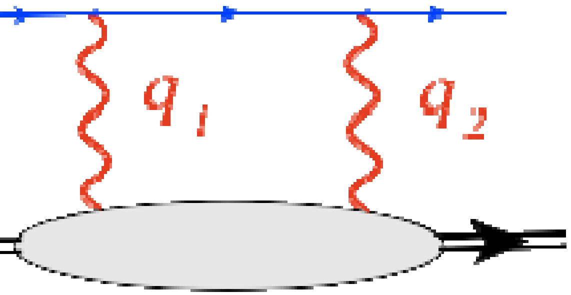


$\bar{n}$=(1,0,0,1)   n=(1,0,0,-1)

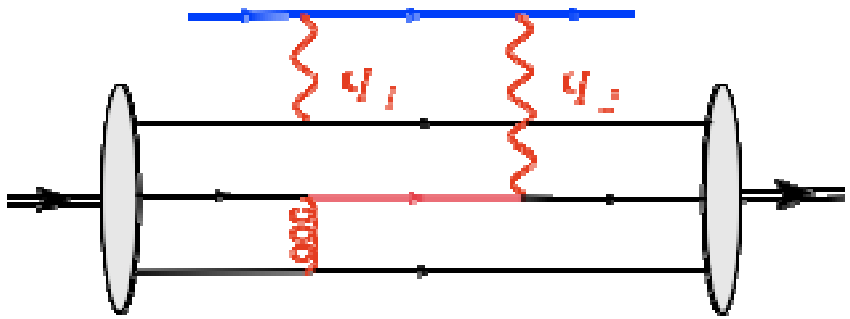
$$p \simeq Q\frac{\bar{n}}{2} \quad p' \simeq Q\frac{n}{2}$$

$s \rightarrow \infty$ $Q^2/s = z$ fixed $0 < z < 1$

$$k = \frac{1}{\;}Q\frac{\bar{n}}{\;} + \frac{\bar{z}}{\;}Q\frac{n}{\;} + k_\perp \qquad k_\perp^2 = \frac{\bar{z}^2}{\;}Q^2$$

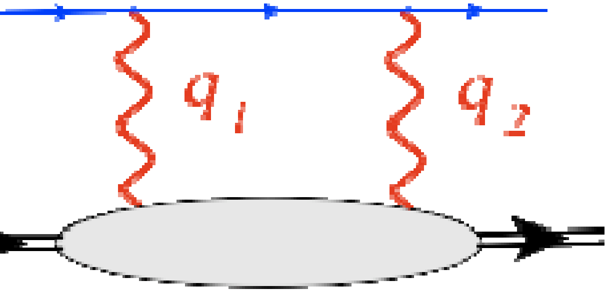


+ crossed =

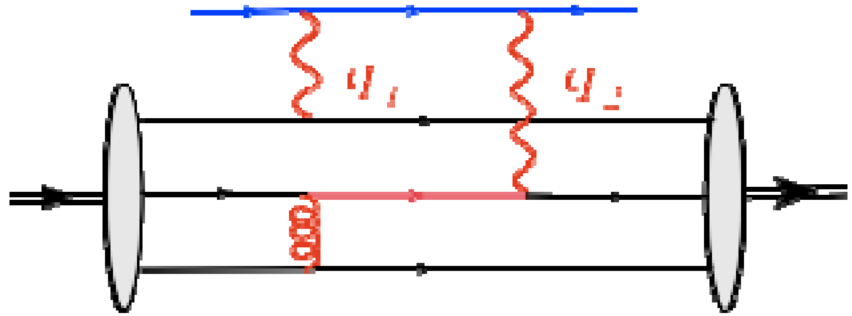


+ others
23 graph

Lowest order graphs to turn 3 collinear quark
into 3 collinear quarks moving in opposite direc



+ crossed =

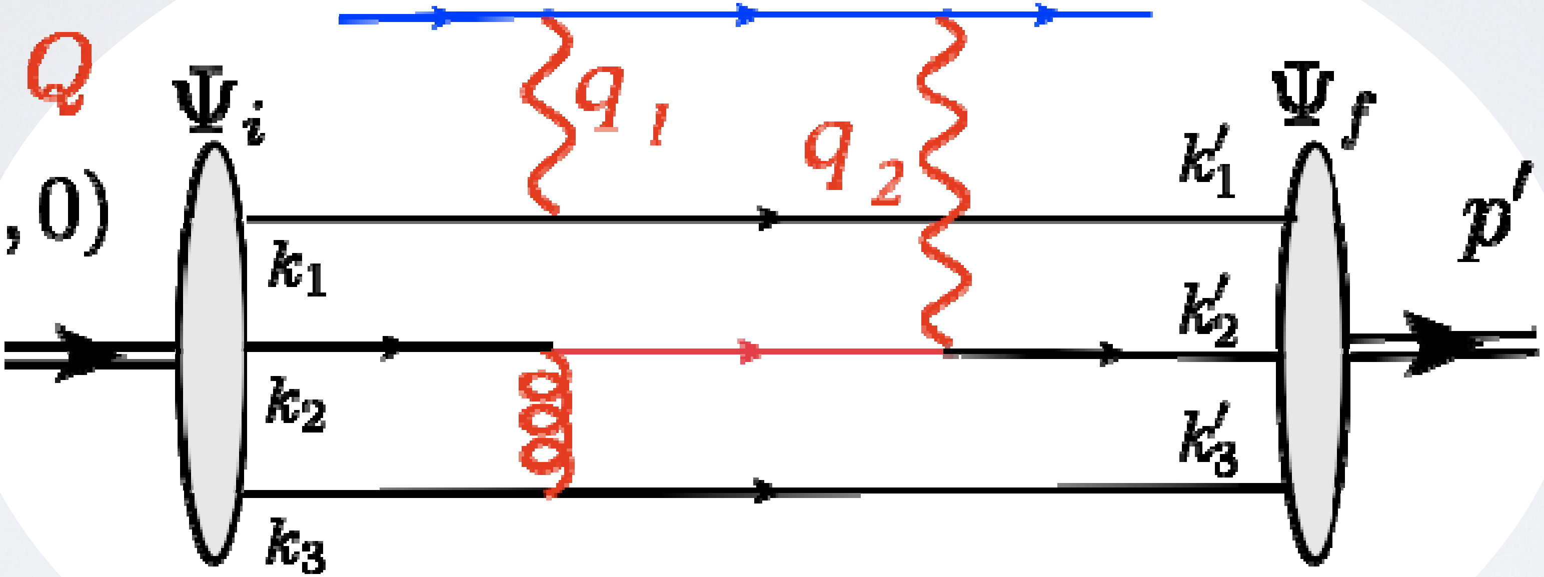


+ othe

23 grap

$\sim p'_- \sim Q$

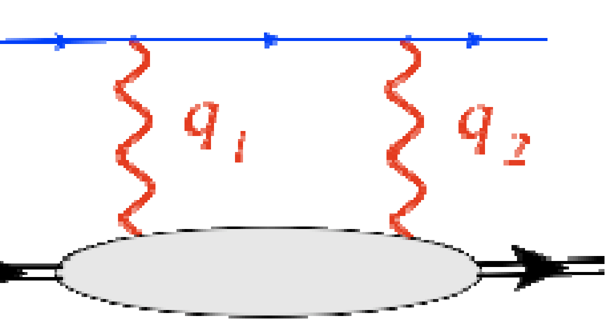
$(p_+, 0_\perp, 0)$



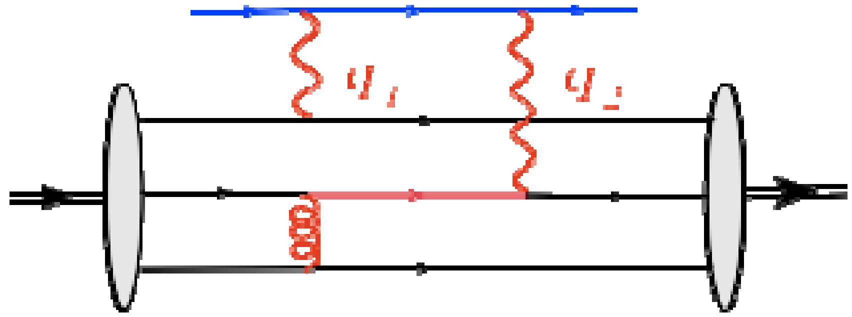
$p' = (0, 0_\perp,$

$= x_i p + k_{i\perp}$ $\quad k_{i\perp} \sim k'_{i\perp} \sim \Lambda_{QCD} \ll Q$

$= x'_i p + k'_{i\perp}$



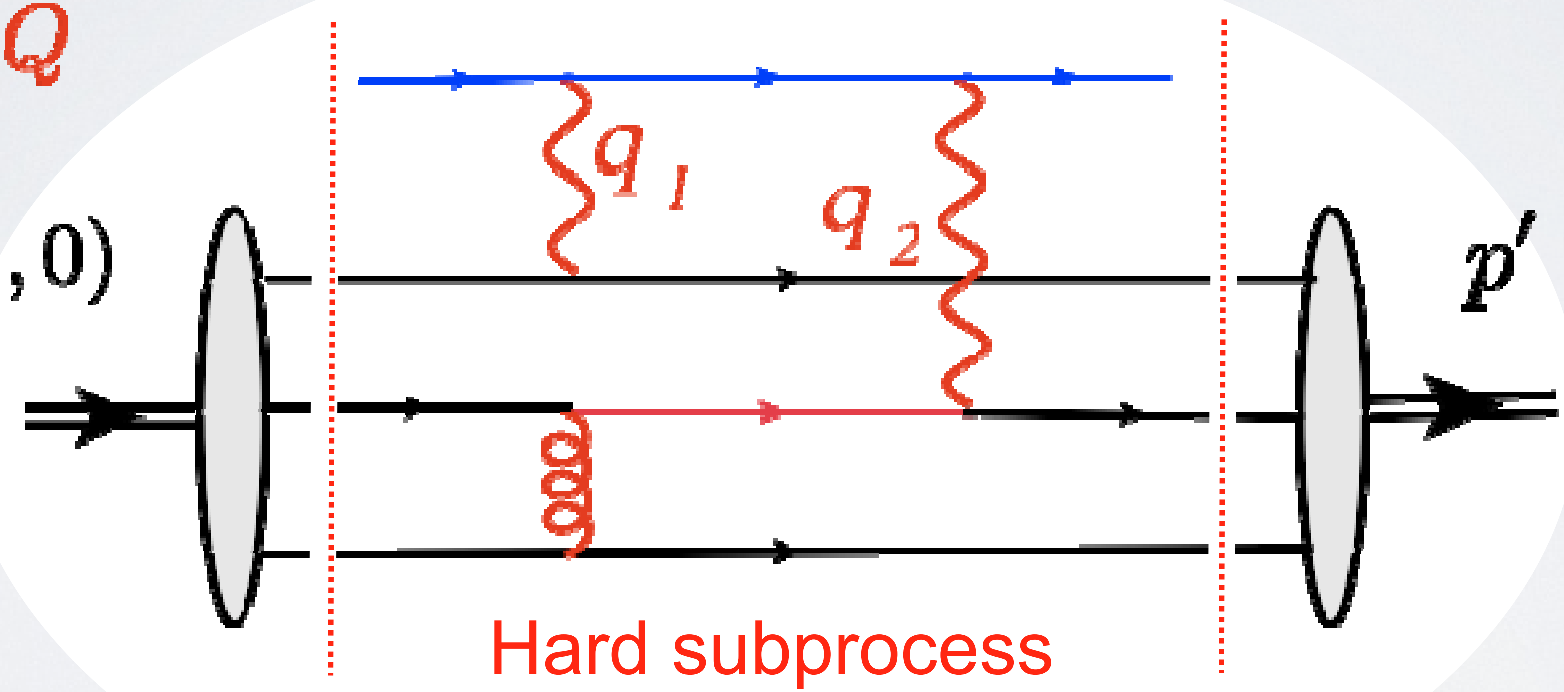
+ crossed =



+ othe
23 grap

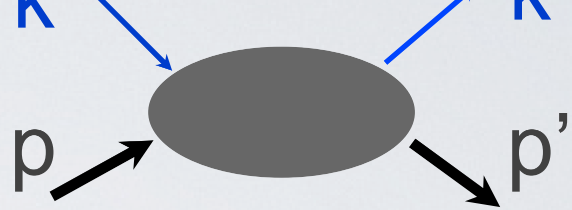
$\sim p'_{-} \sim Q$

$(p_{+}, 0_{\perp}, 0)$



$p' = (0, 0_{\perp},$

$$\Phi(x_i) * \quad T(x_i, x'_i | z, Q^2) \quad * \Phi(x'_i)$$



$$\ldots_{ep} = \frac{e^2}{Q^2}\, \bar{l}' \gamma^\mu\, l$$

$$\bar{N}' \left(\tilde{G}_M\, \gamma^\mu - \tilde{F}_2\, \frac{1}{2M}(p+p')^\mu + \tilde{F}_3\, \frac{1}{4M^2}(p+p')^\mu\, \gamma.(k+k') \right) N$$

- and 2γ- ff's

1γ exch

$$\tilde{G}_M = G_M + \delta\tilde{G}_M \qquad \tilde{F}_2 = F_2 + \delta\tilde{F}_2 \qquad \tilde{F}_3$$

2γ exch

rge Q^2 asymptotic (pQCD)

$$\tilde{G}_M \sim F_1 \sim \alpha_S^2/Q^4$$

$$\delta\tilde{G}_M \sim \frac{(PK)}{M^2}\tilde{F}_3 \sim \alpha_{em}\alpha_S/Q^4$$

CD FF's:

$$** \equiv \int d^3x d^3x' \delta(1-\sum x_i)\delta(1-\sum x_i')$$

$$\ldots_M \quad \ldots \tilde{F}_3 \Big\} = \mathcal{K}\left\{ \begin{array}{c} T_M \\ T_3 \end{array} \right\}(x_i, x_i'|z) ** \{ Q_u Q_d [\varphi_N(x_i')\varphi_N(x_i) + \ldots] + Q_u^2[\ldots] + Q_u Q \ldots$$

$$\mathcal{K} = -\frac{\alpha_{em}\alpha_s(\mu^2)}{Q^4}\left(\frac{2\pi}{3}\right)^2 \frac{Q^2(s-u)}{s^2}$$

$$\ldots \Big\}(x_i, x_i') = \left\{ \begin{array}{c} 4x_2x_2' \\ 2(x_2 + x_2' - 2x_2x_2') \end{array} \right\} \left[\frac{1}{x_1'x_2'(1-x_2')} \frac{1}{x_2' - x_2 + x_2(1-x_2')Q^2/s + i0} \times (x \leftrightarrow x') \right.$$

pole in the lepton propaga

□ nontrivial Im part

ll integrals are IR-finite

cleon DA

$$\varphi_N(132) \simeq 120\, f_N\, x_1 x_2 x_3 (1 + r_-(x_1 - x_2) + r_+(1 - 3x_3) + ...)$$

- assumption: drop the highest conformal moments

r. uncertainties: renorm. scale (NLO) $\alpha_S(\mu)$

helicity flip FF: $\delta\tilde{G}_E - \delta\,\tilde{F}_1 - \tau\,\delta\,\tilde{F}_2$

3 non-perturbative parameters

odels for DA :

D SR (1988), COZ

LCSR (2006),

f_N (10^{-3} GeV^2)	r_-	r_+
5.0 ± 0.5	4.0 ± 1.5	$1.1 \pm$

n Vanderhaeghen PRL91(2003)

$$= G_M^2 + \frac{\varepsilon}{\tau} G_E^2 + 2 G_M \mathcal{R}\left(\delta\tilde{G}_M + \varepsilon\frac{\nu}{M^2}\tilde{F}_3\right) + 2\frac{\varepsilon}{\tau} G_E \mathcal{R}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) +$$

Born app

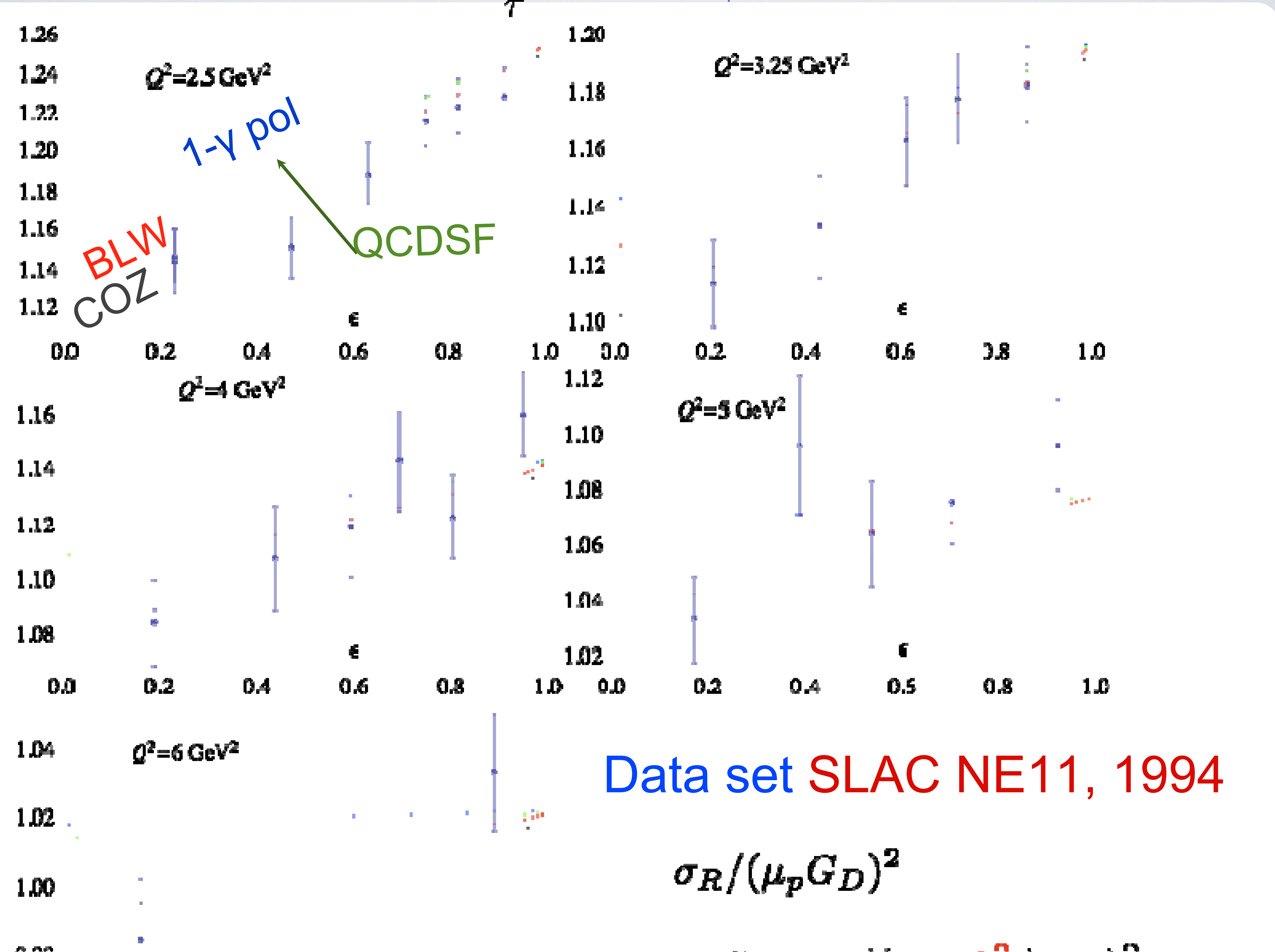
Re part of TPE

Empirical fit for the ratio and form factor:

$$(\mu_p G_E/G_M)_{exp} = 1 - 0.13(Q^2 - 0.04) \quad 0.5\mathrm{GeV}^2 < Q^2 < 5.6\mathrm{GeV}^2$$

JLab Hall A, 2002

$$G_M = \frac{\mu_p\ \theta(0.1 < Q^2 < 6)}{(1 + 0.116Q + 2.874Q^2 + 0.241Q^3 + 1.00Q^4 + 0.345Q^5)}$$

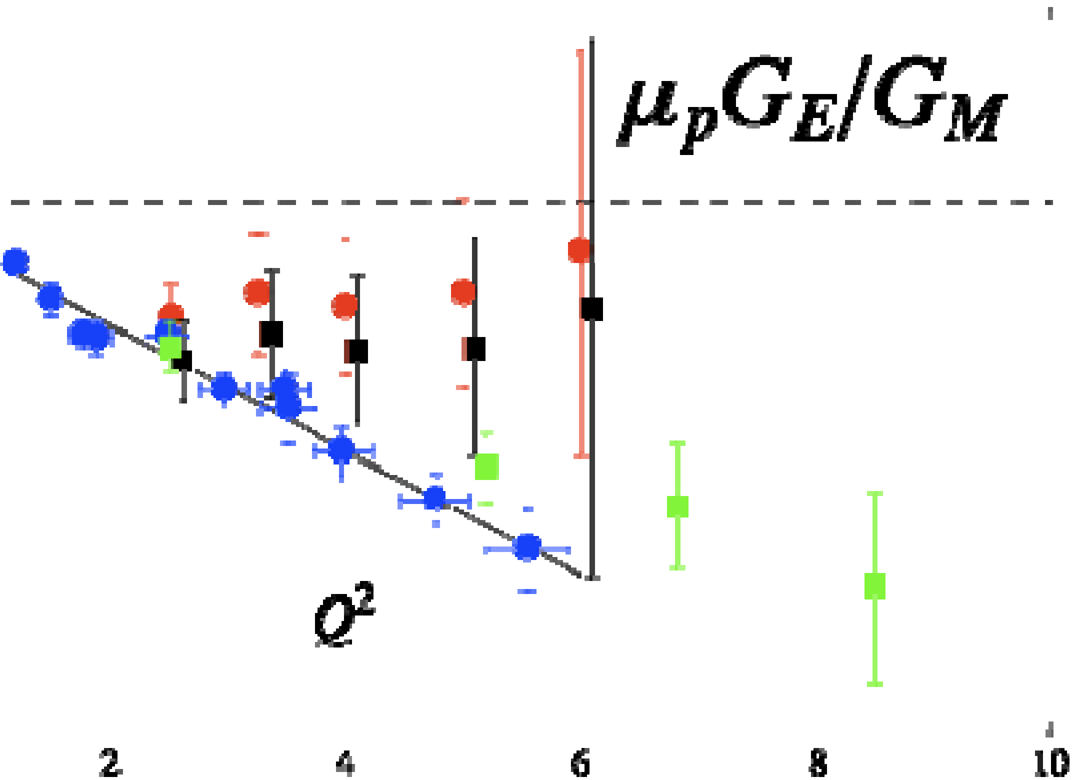


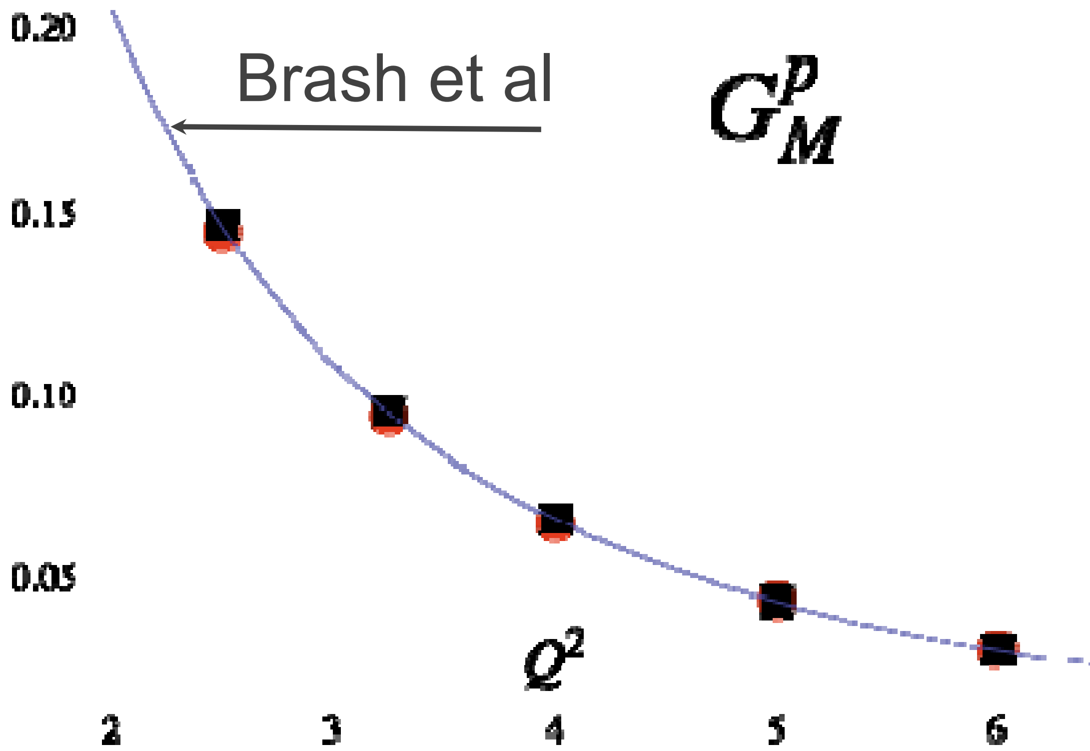
Q²=2.5 GeV²
1-γ pol
QCDSF
BLW
COZ
Q²=3.25 GeV²
Q²=4 GeV²
Q²=5 GeV²
Q²=6 GeV²
ε
Data set SLAC NE11, 1994
$\sigma_R/(\mu_p G_D)^2$

s section $\sigma_R = G_M^2 + \frac{\varepsilon}{\tau} G_E^2 + \Delta\sigma_{2\gamma}$ Data set SLAC NE11, 199

NK, Vanderhaeghen, in prep.

● BLW ■ COZ





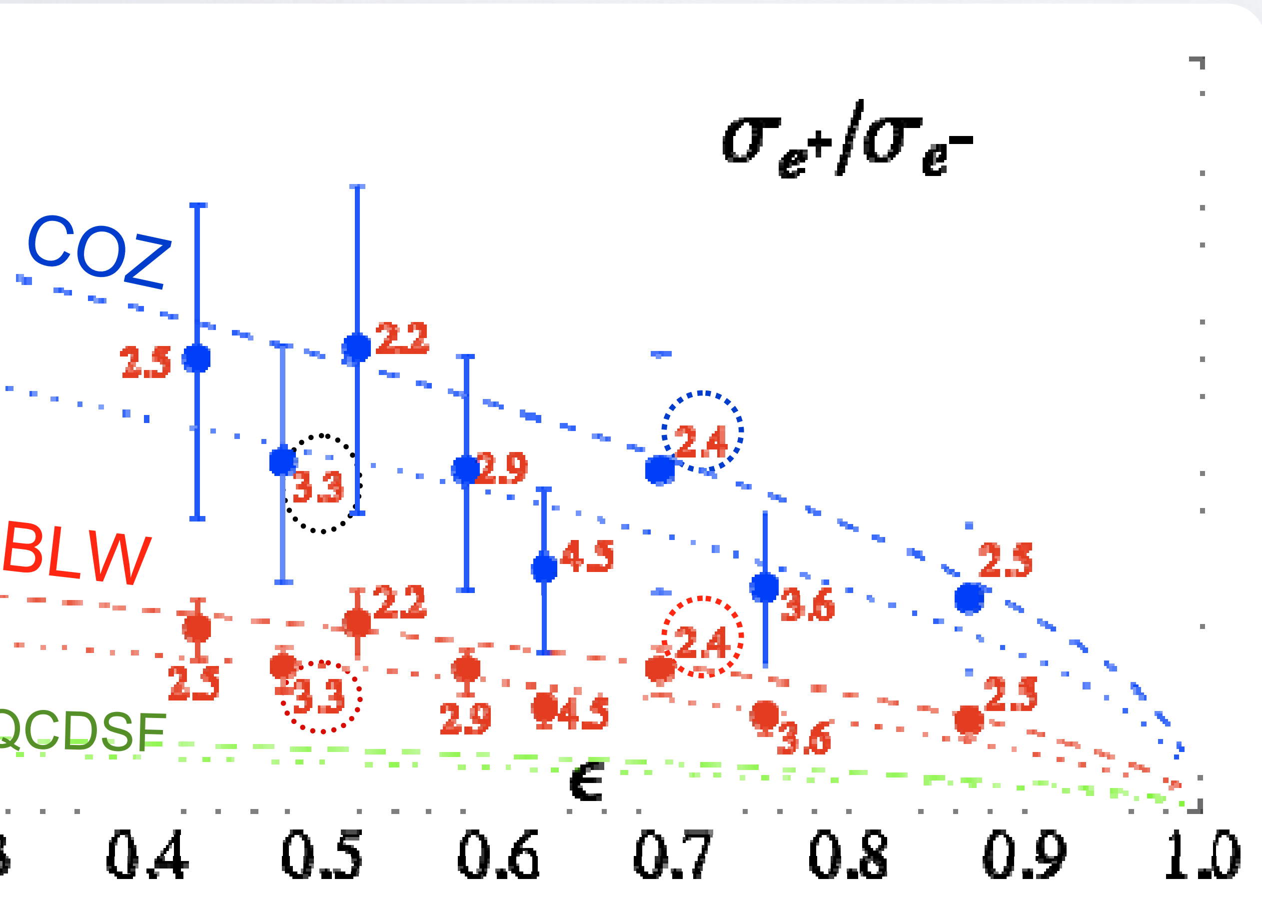
✹JLab Class PR-07-005 Q^2=.5-2.5 GeV^2 ε=.1

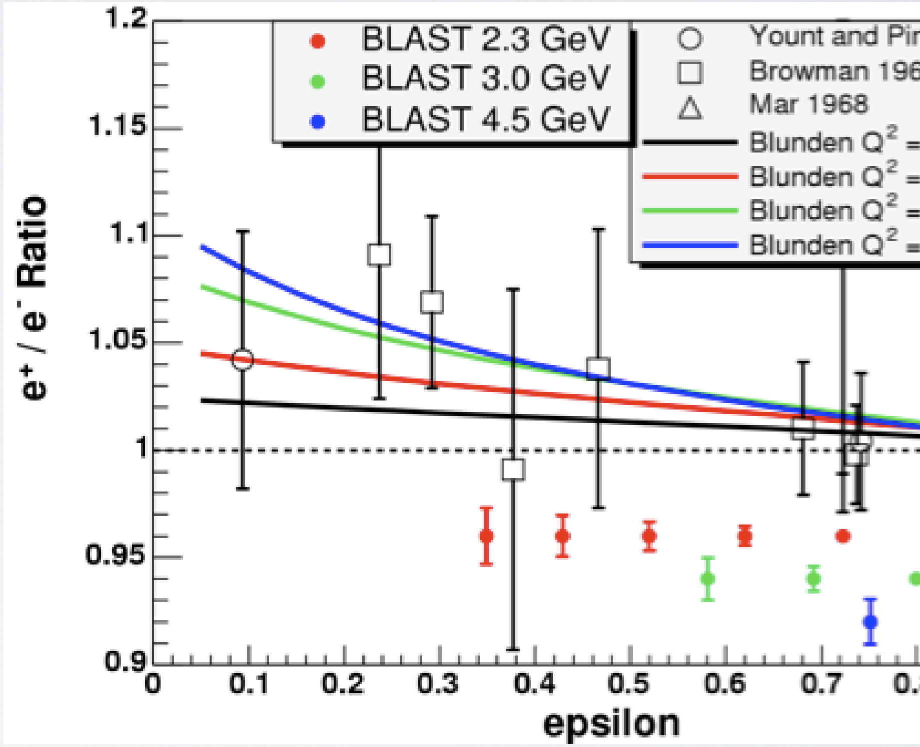
ure experiments:

✹VEPP-3 Novosibirsk Q^2=1.6 GeV^2 ε=.44, .9

✹ Olympus@Desy Q^2=.8-4.5 GeV^2 ε=.4-.9

CD estimate





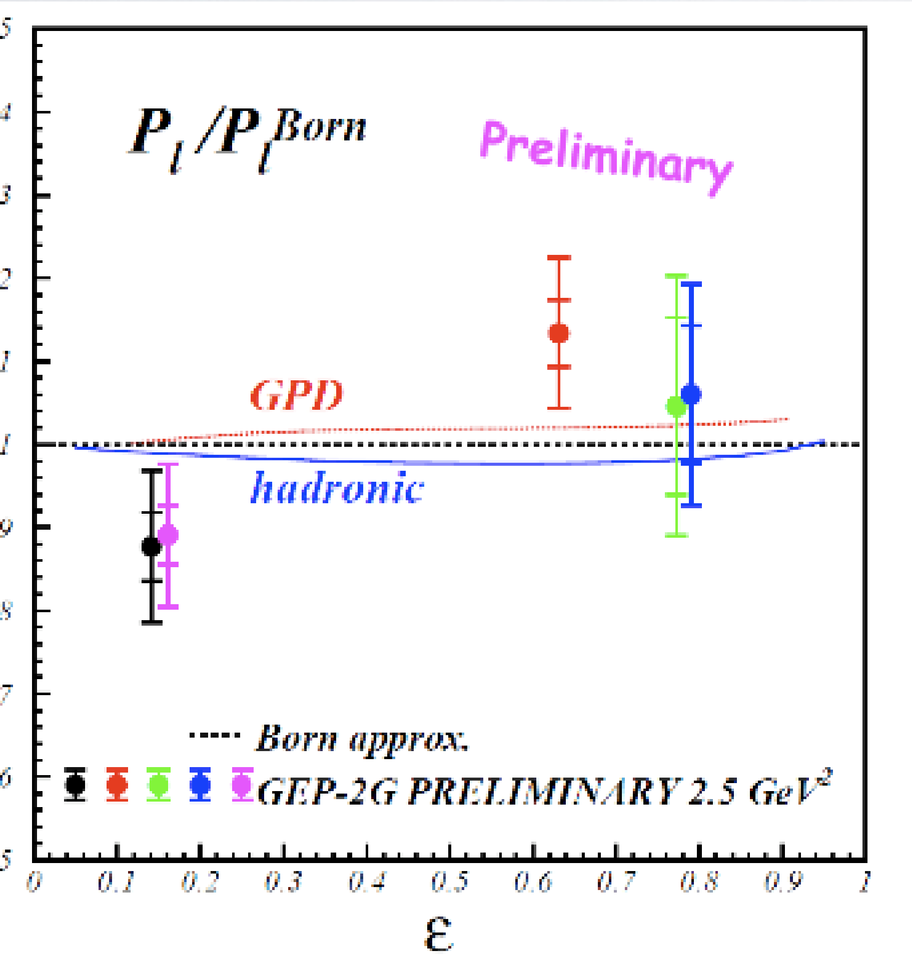
Expected accuracy <

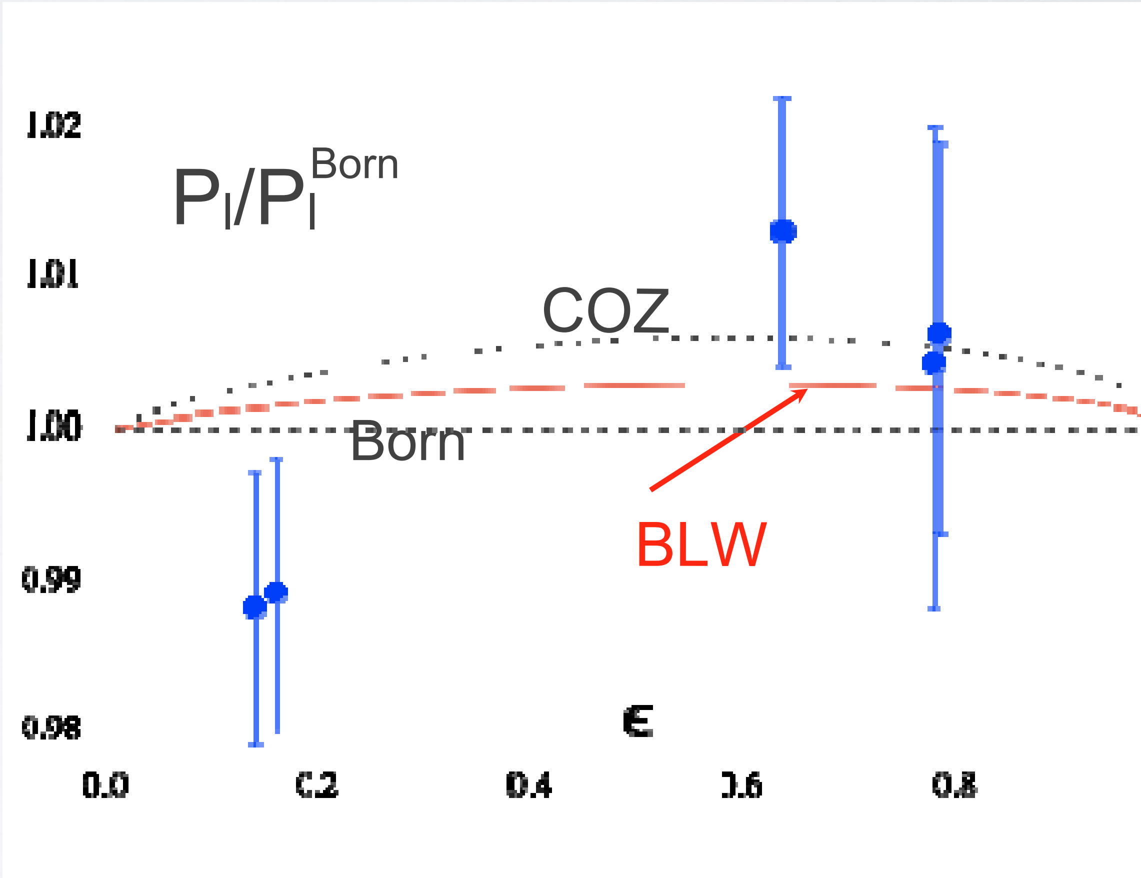
$$P_l = \sqrt{1-\varepsilon^2}\,\frac{1}{\sigma_R}\left\{G_M^2 + 2\,G_M\,\mathcal{R}\left(\delta\tilde{G}_M + \frac{\varepsilon}{1+\varepsilon}\frac{\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(e^4)\right\}$$

Hall C E-04-119, preliminary

5 GeV^2 ε=.14,.63,.785

pQCD, different models





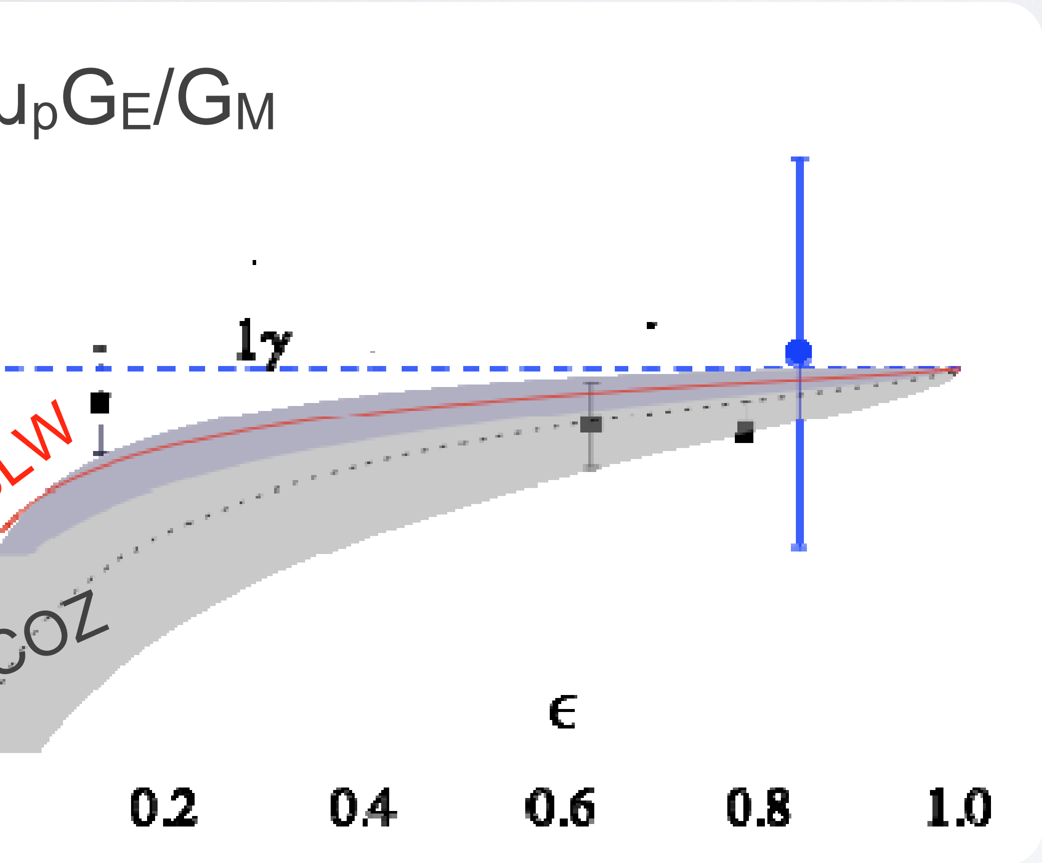
$$= -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\,\frac{1}{\sigma_R}\left\{G_E G_M + G_E\,\mathcal{R}\left(\delta\tilde{G}_M\right) + G_M\,\mathcal{R}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + \mathcal{O}(e^4)\right\}$$

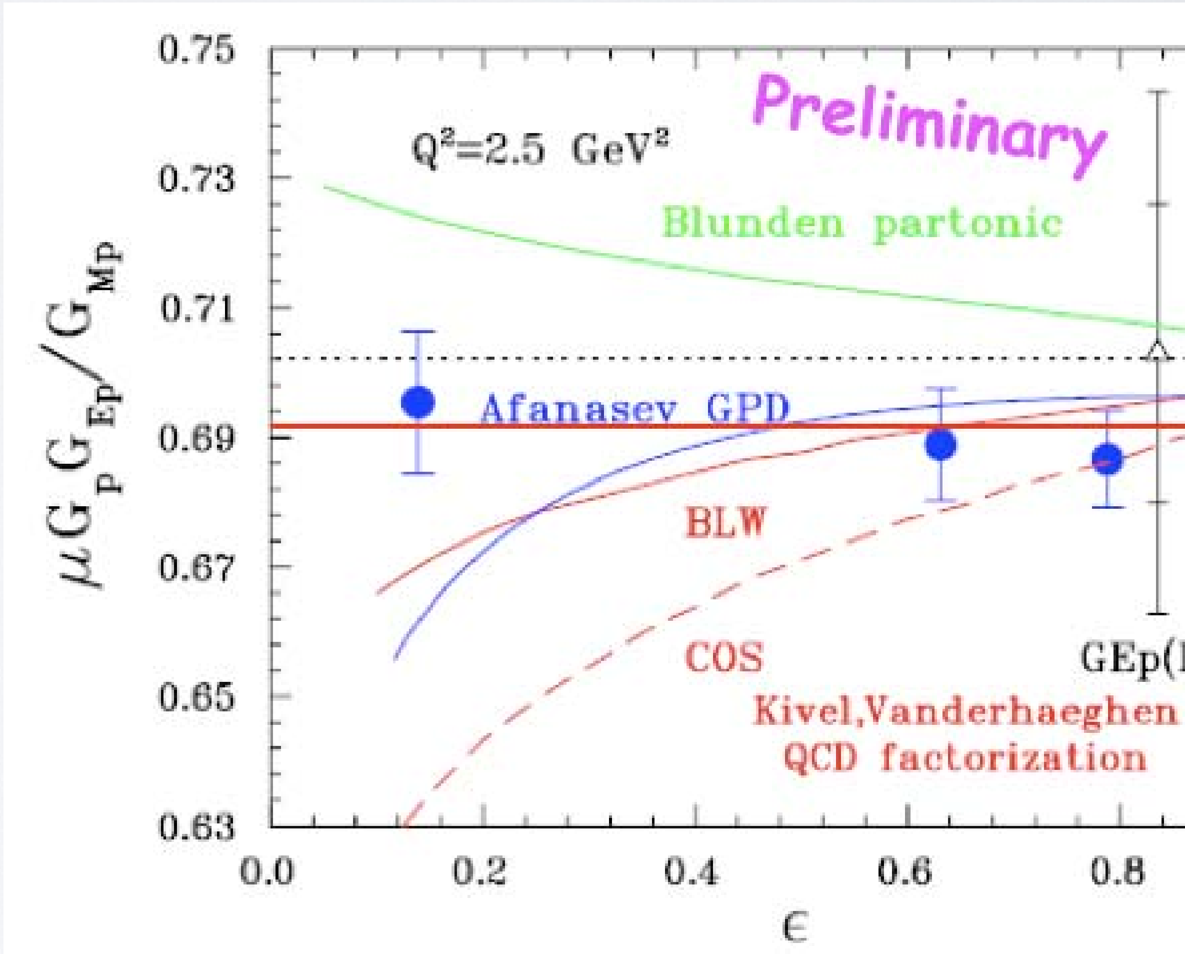
$$_E \sim \lambda\delta\tilde{G}_M \quad \lambda = 0,1$$

CD, different models

JLab Hall C E-04-119, preliminar

Q^2=2.5 GeV^2 ε=.14,.63,.785





Target Normal Spin Asymmetry

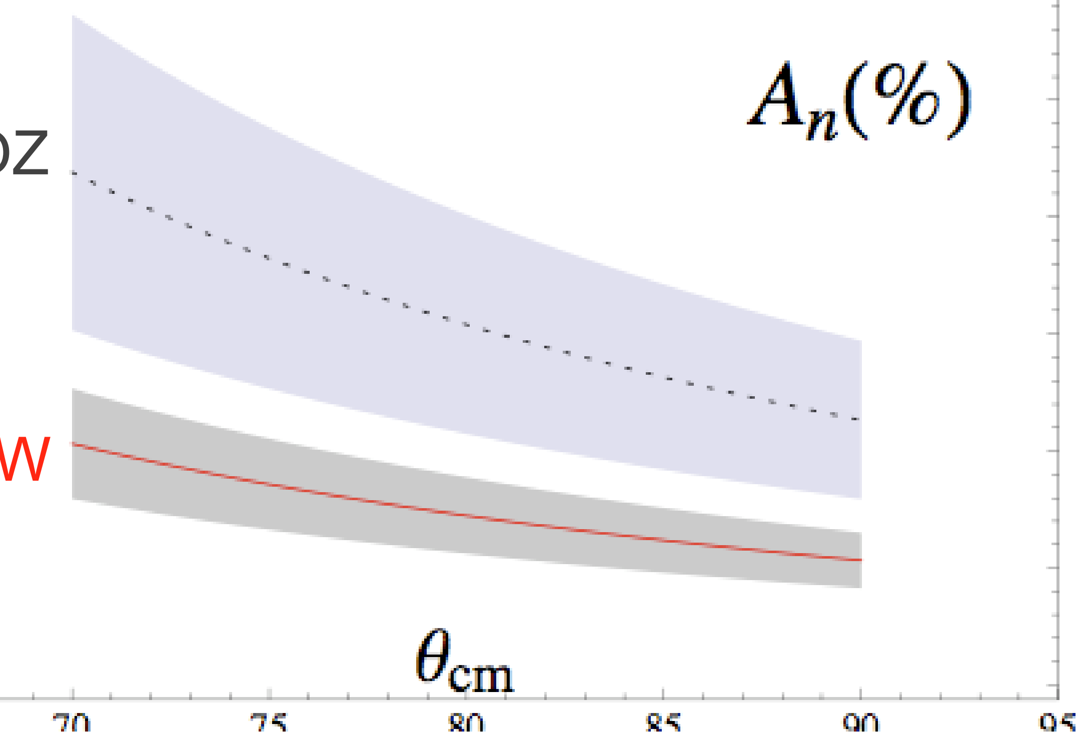
$$= \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}} \frac{1}{\sigma_R} \left(-G_M \mathrm{Im}\left\{\delta\tilde{G}_E + \frac{(K\cdot P)}{M^2}\tilde{F}_3\right\} + G_E \mathrm{Im}\left\{\delta\tilde{G}_M + \frac{2\varepsilon}{1+\varepsilon}\frac{(K\cdot P)}{M^2}\tilde{F}\right.\right.$$

$/G_M \simeq 0.35$ E-02-013 Hall-C, preliminary

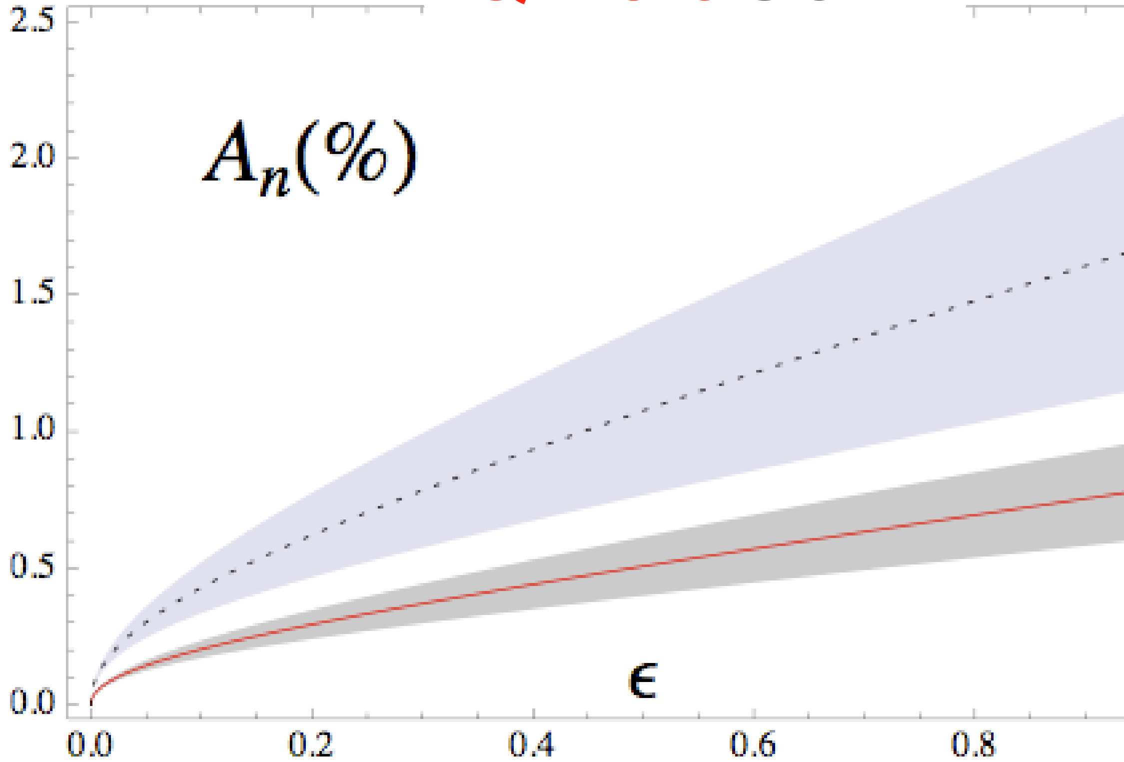
$G_M \simeq \mu_n G_D$ CLASS, 2009 Q^2=1.-4.5GeV^2

Hall-A, E-05-015 E_{lab}= 3.3, 5.3 GeV

E_{lab}= 4.8 GeV



Q^2=3.5GeV^2



ard QCD contribution in TPE at large Q^2 is not small and
ust be considered accurately

PE at large Q^2 depends on the structure of target
nd can provide us information about nucleon DA

xperiments at higher Q^2 where the theory works better is a
ood opportunity to check pQCD predictions

arge power corrections and/or NLO can change
ptimistic picture. This question must be studied.