Generalized Parton Distributions from the Lattice

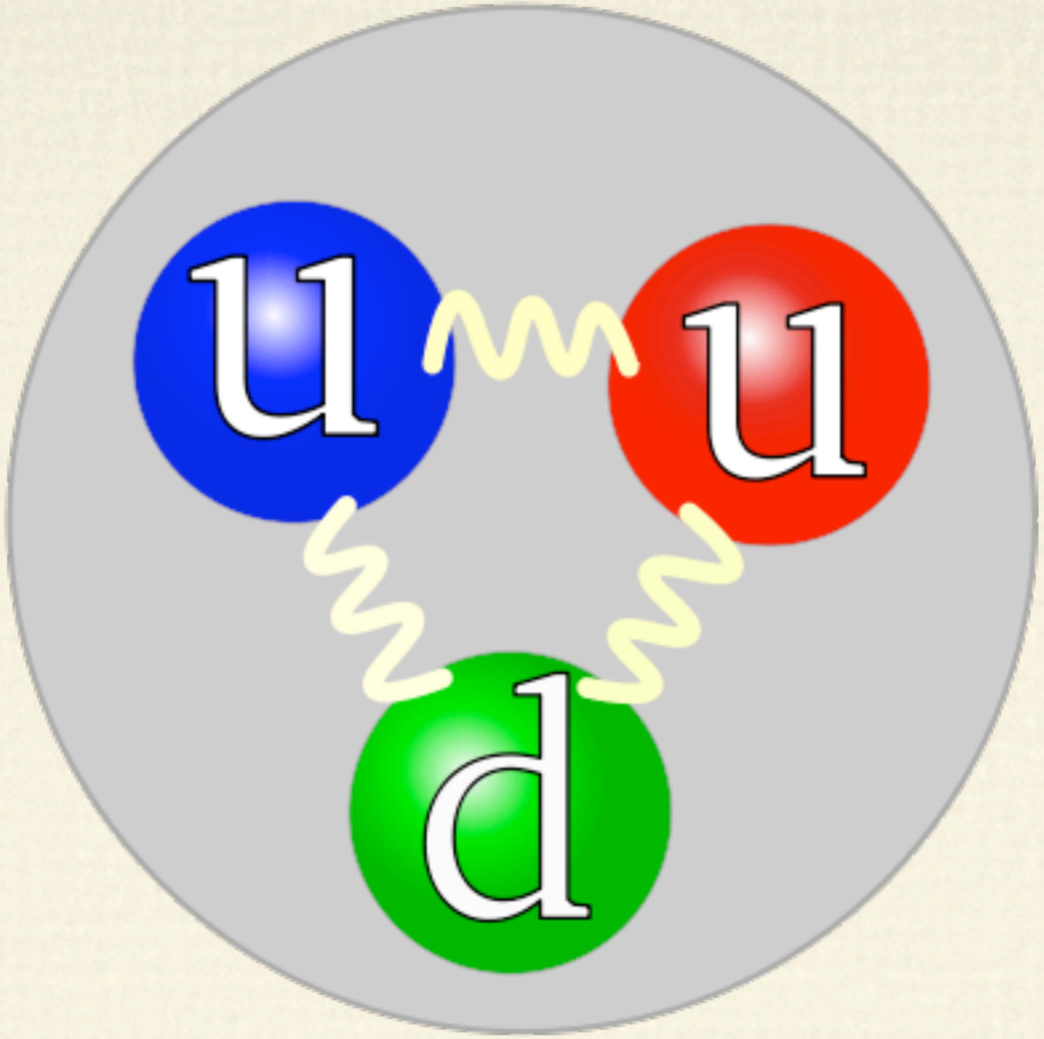
施羅斯

Wolfram Schroers

Outline

- Nucleon structure
- Lattice simulations & their challenges
- Achievements: Three key calculations
- Summary
- Outlook

Nucleon structure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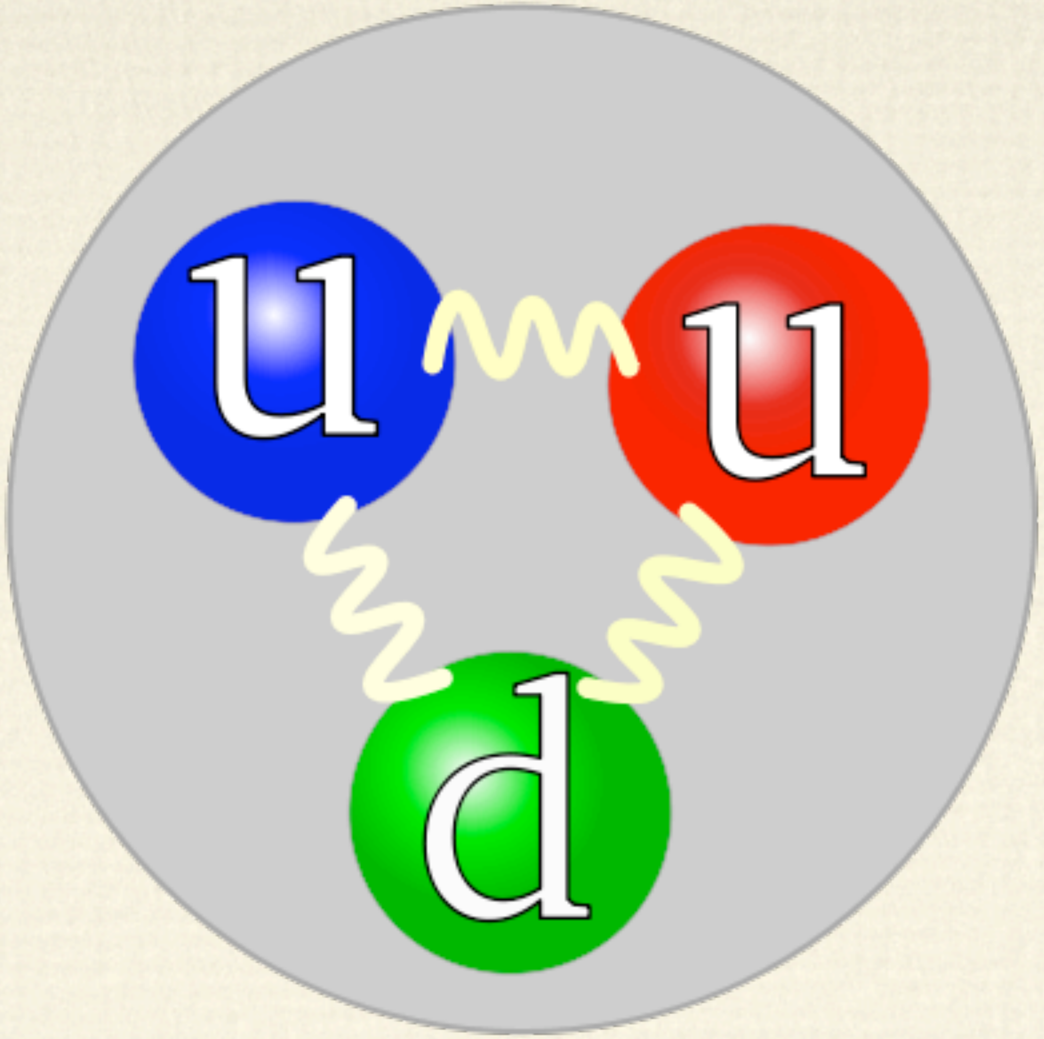
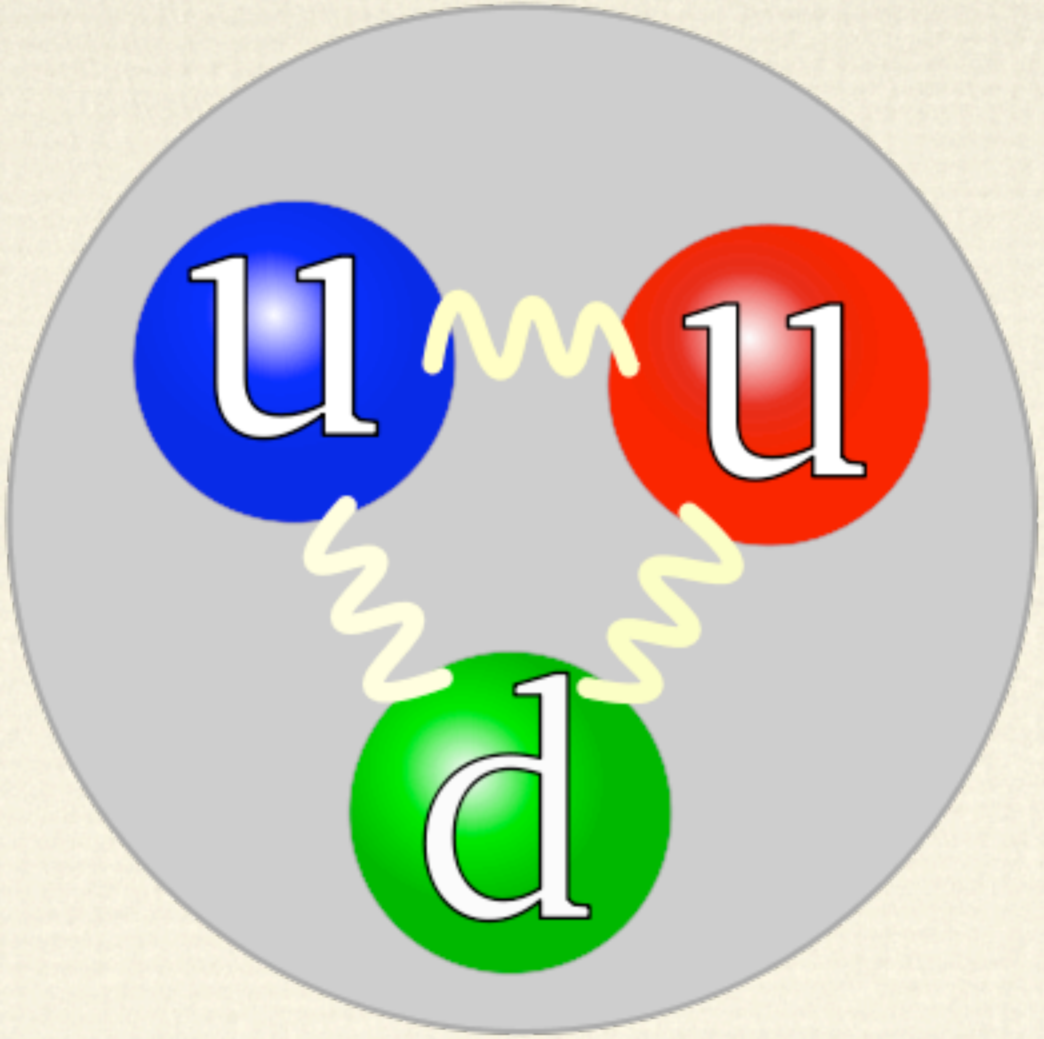
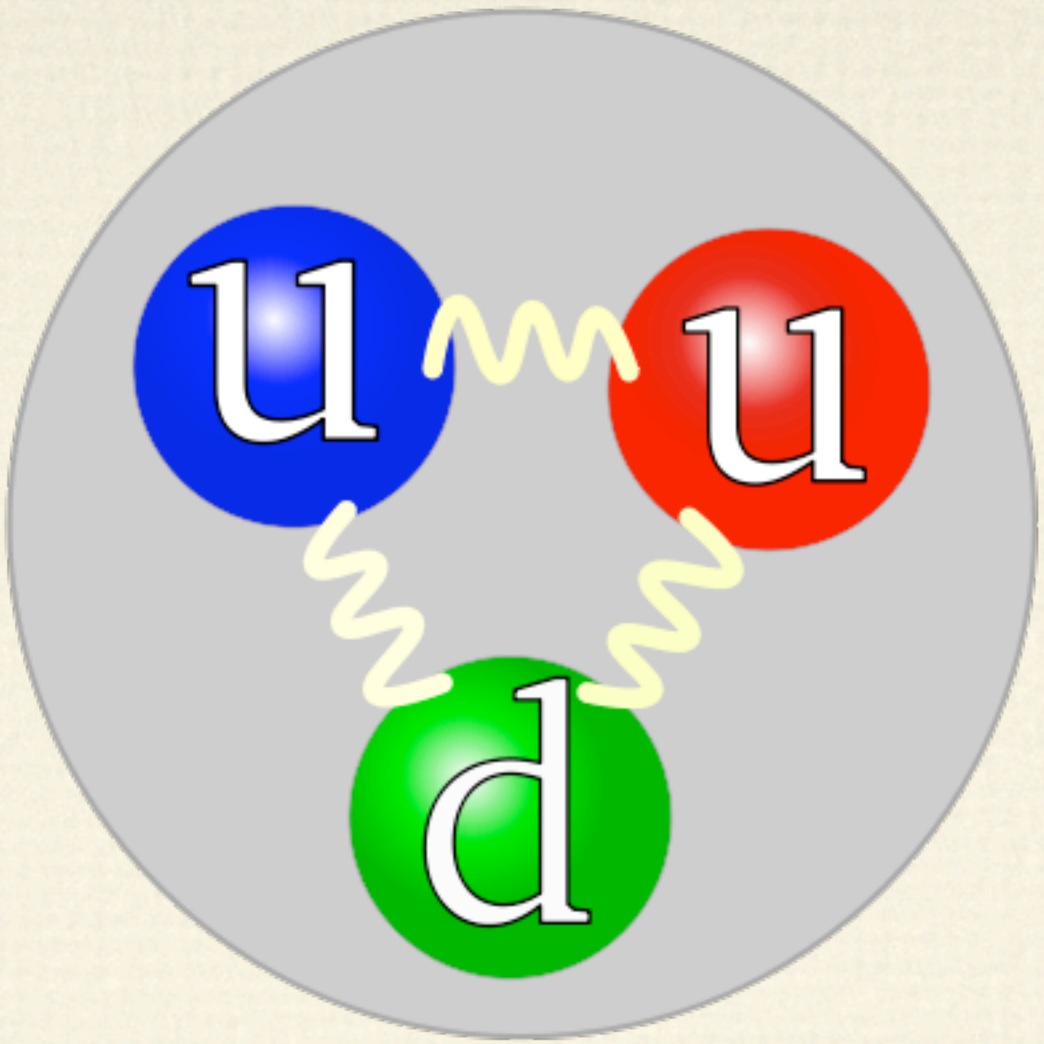


How do we know?



How do we know?

Scattering experiments:
Exclusive
Inclusive



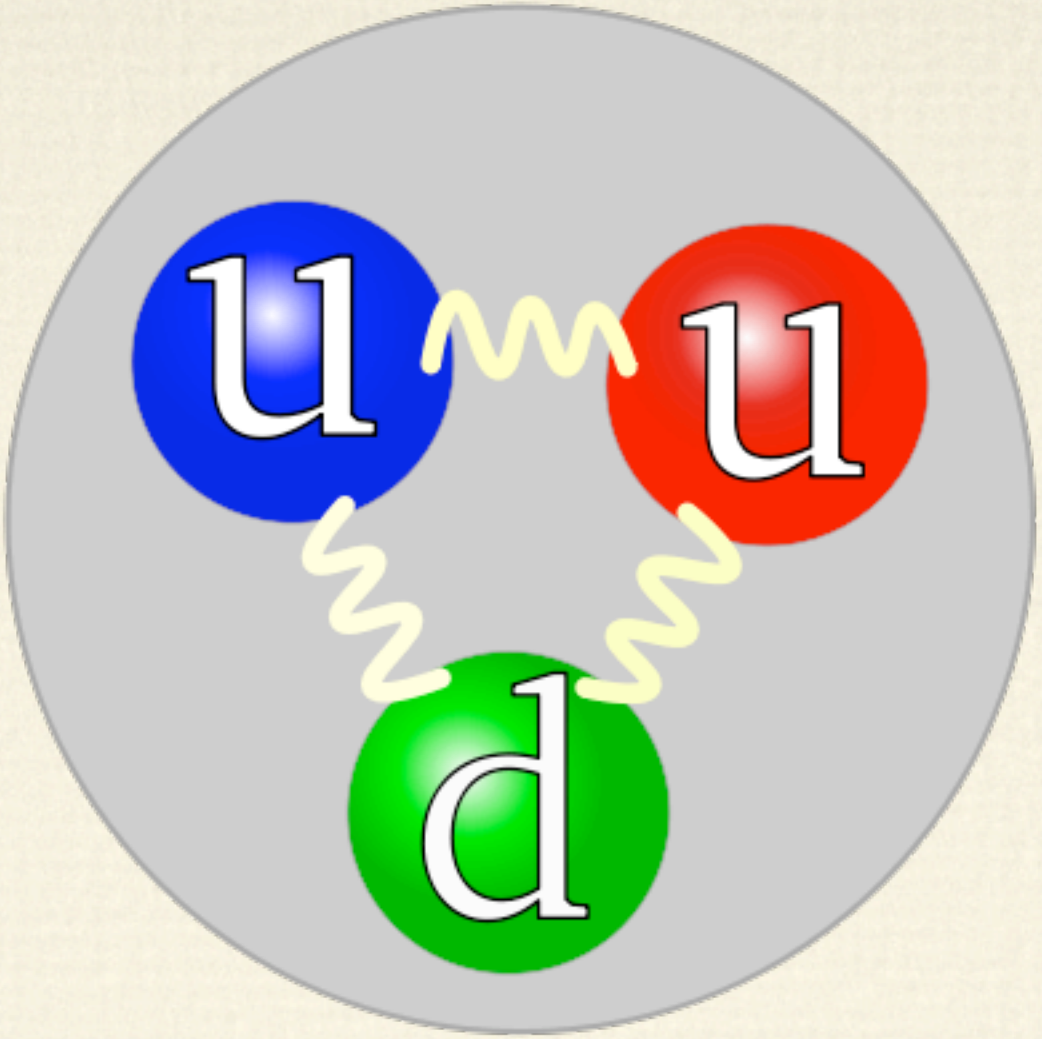
How do we know?

Scattering experiments:

Exclusive

Inclusive

e.g. Form factors



How do we know?

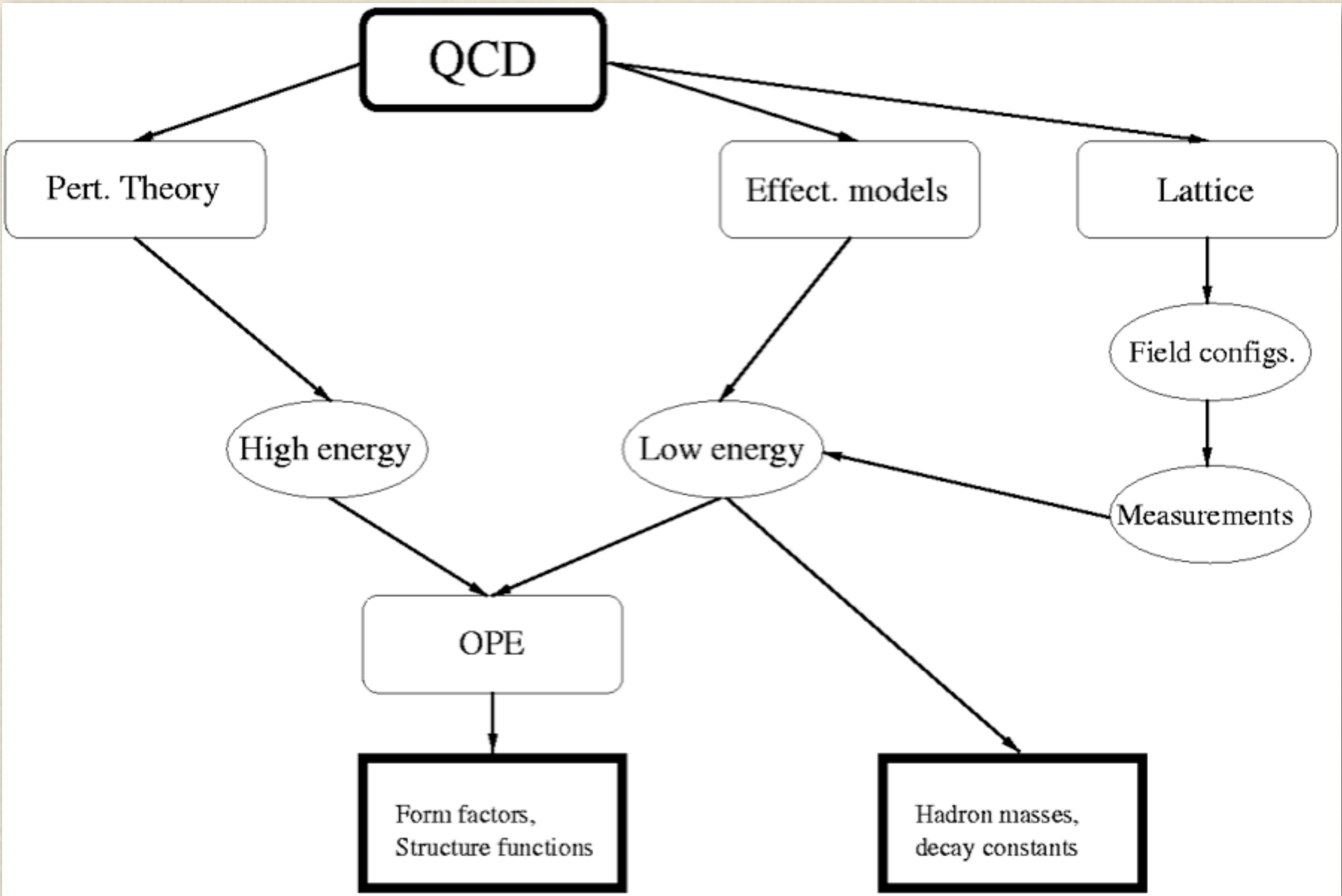
Scattering experiments:

Exclusive

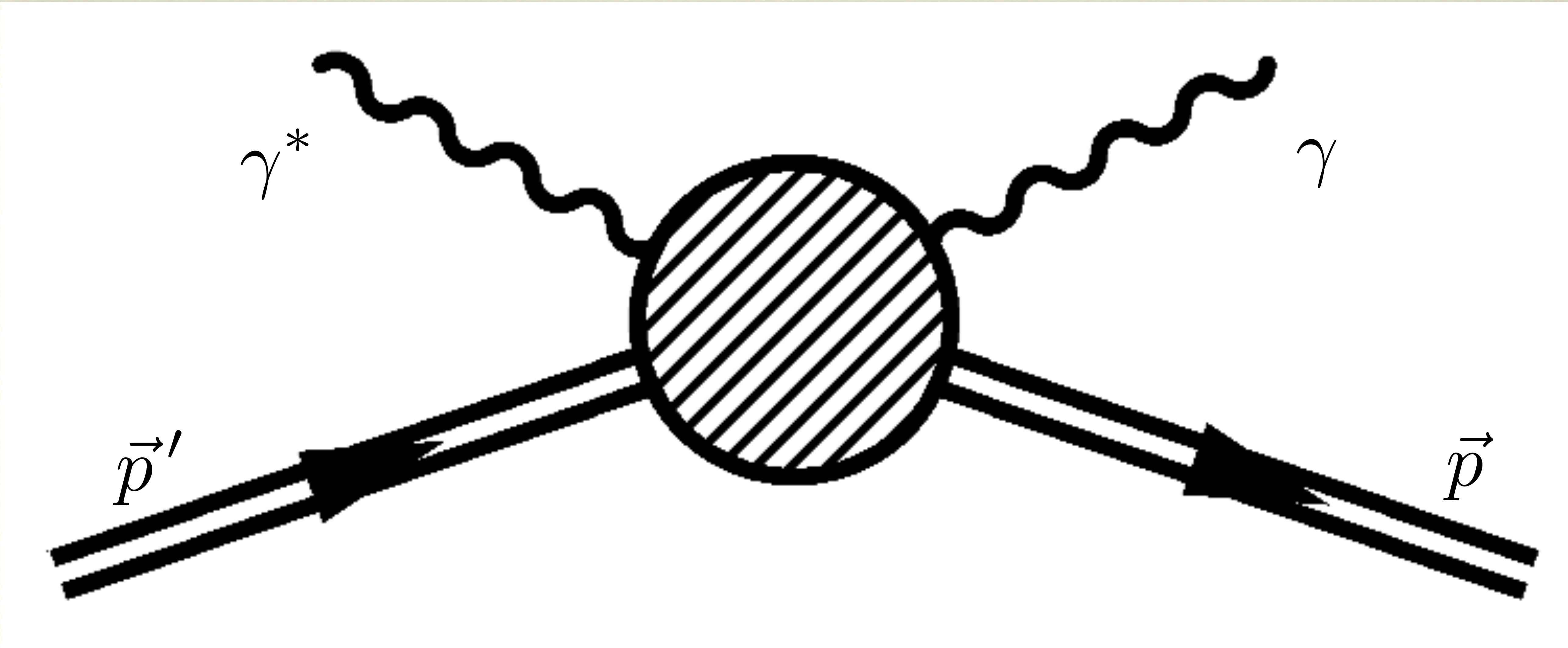
Inclusive

e.g. Form factors

e.g. parton distributions

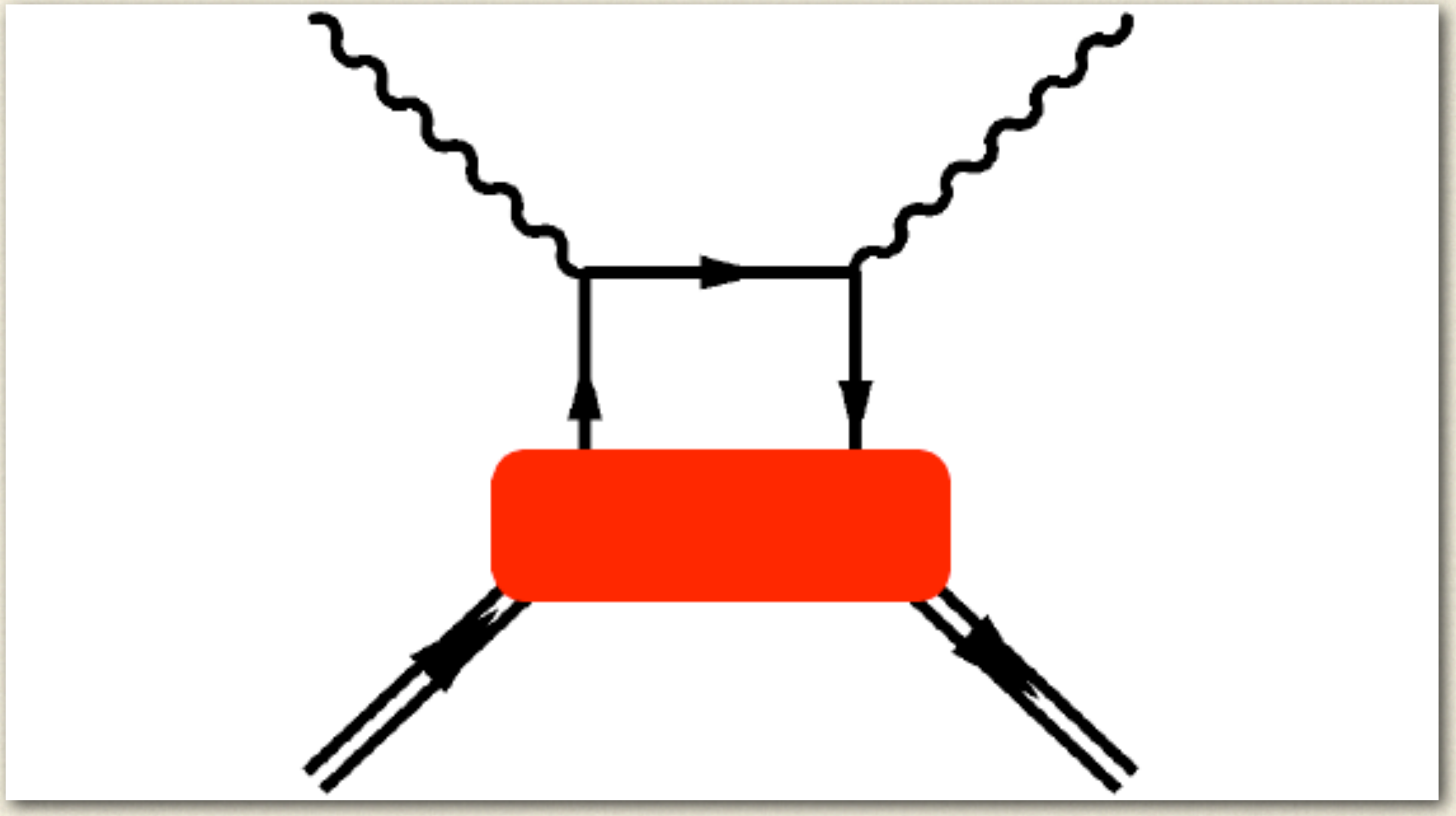

QCD
Pert. Theory
Effect. models
Lattice
Field configs.
High energy
Low energy
Measurements
OPE
Form factors,
Structure functions
Hadron masses,
decay constants

DVCS



Signature: $e + p \to e + p + \gamma$

Factorization ansatz



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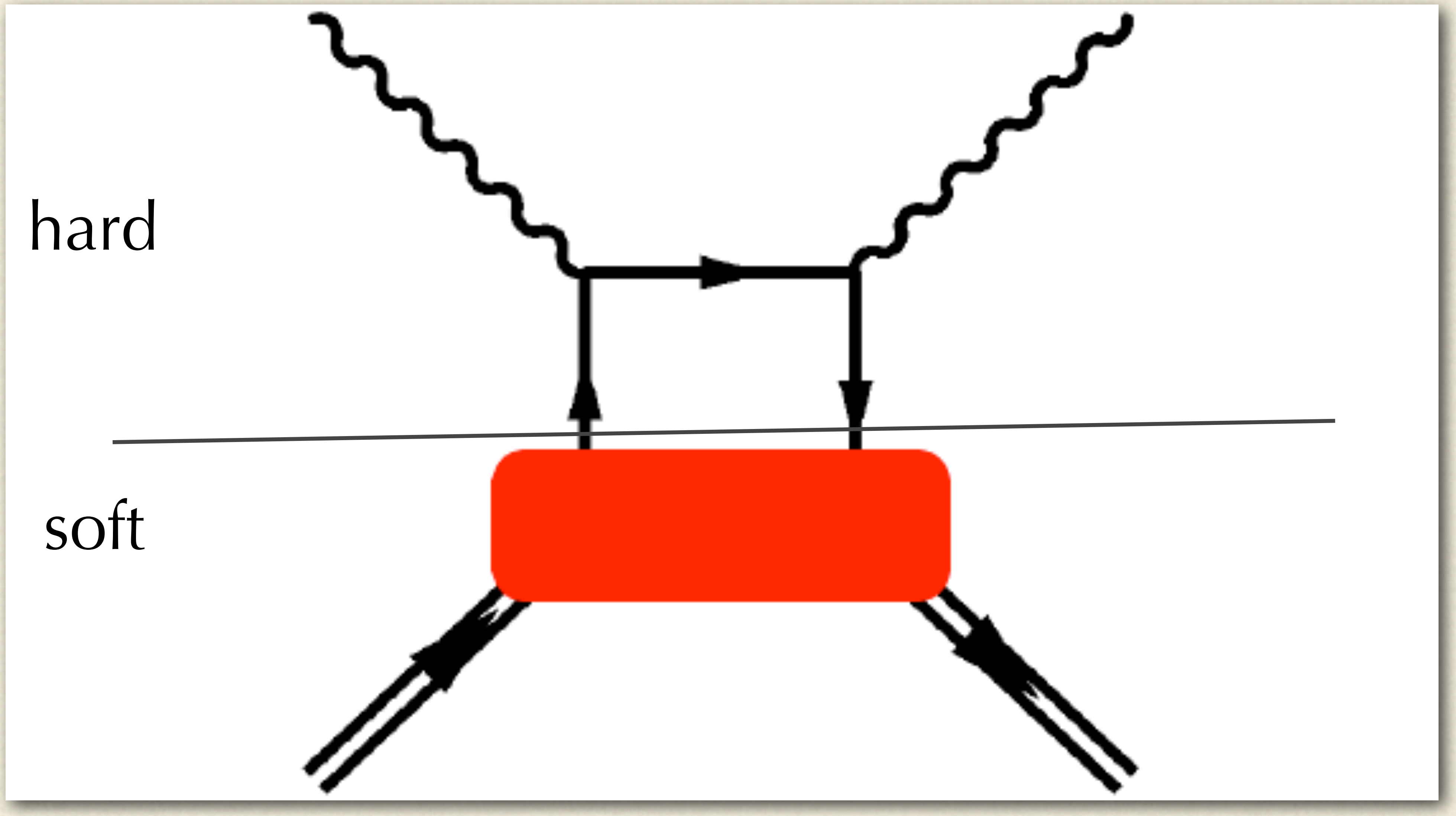

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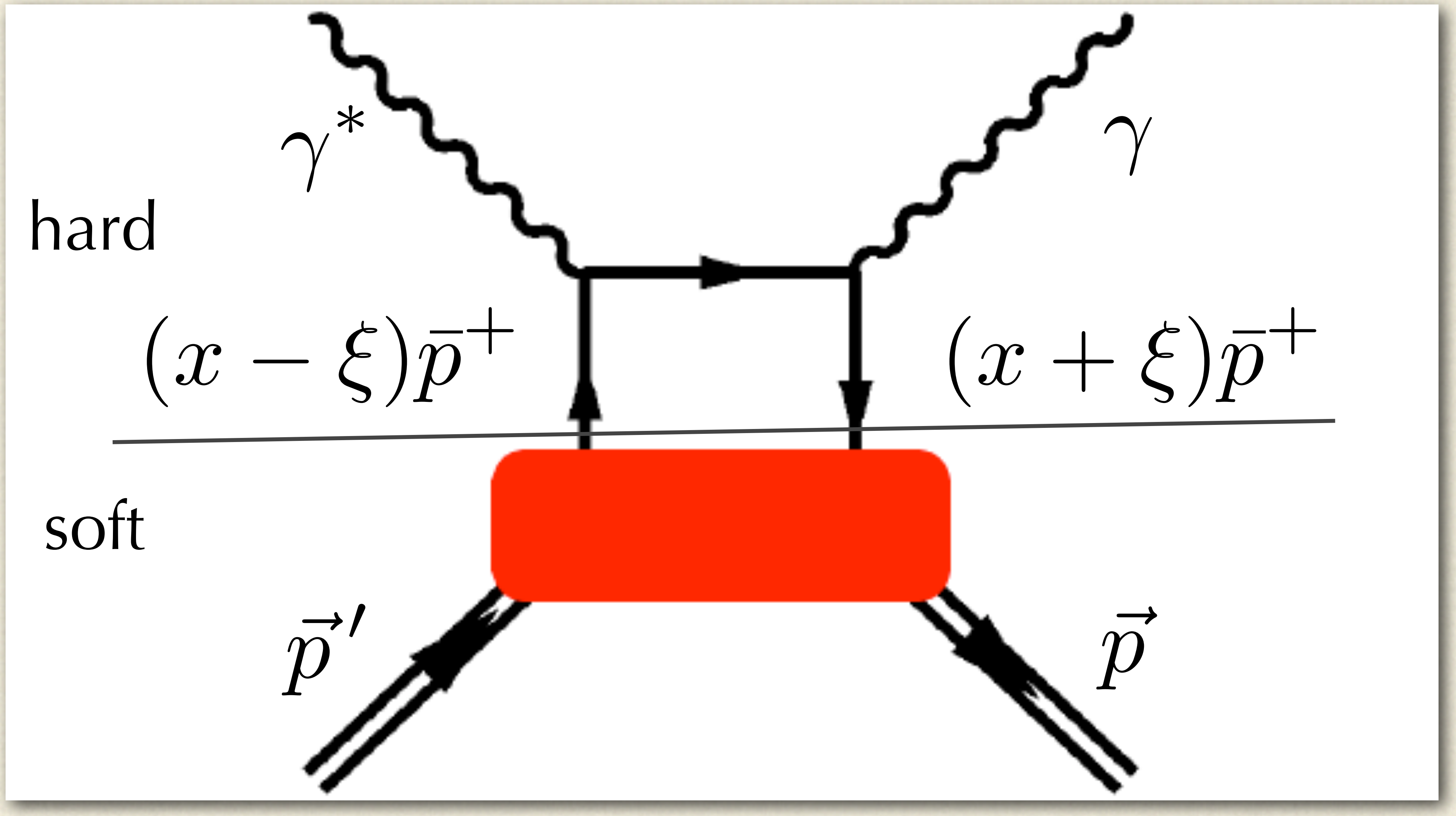

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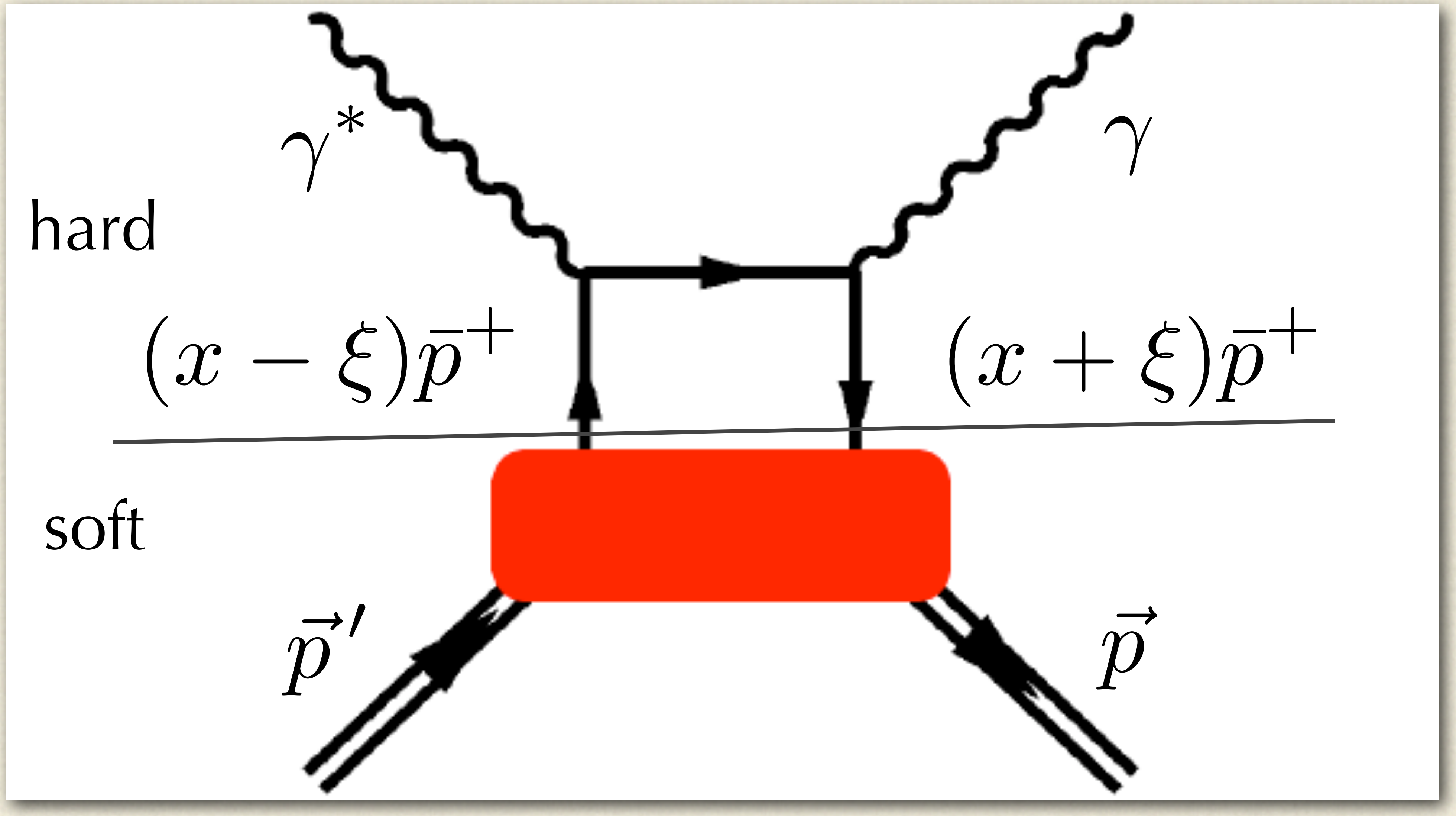
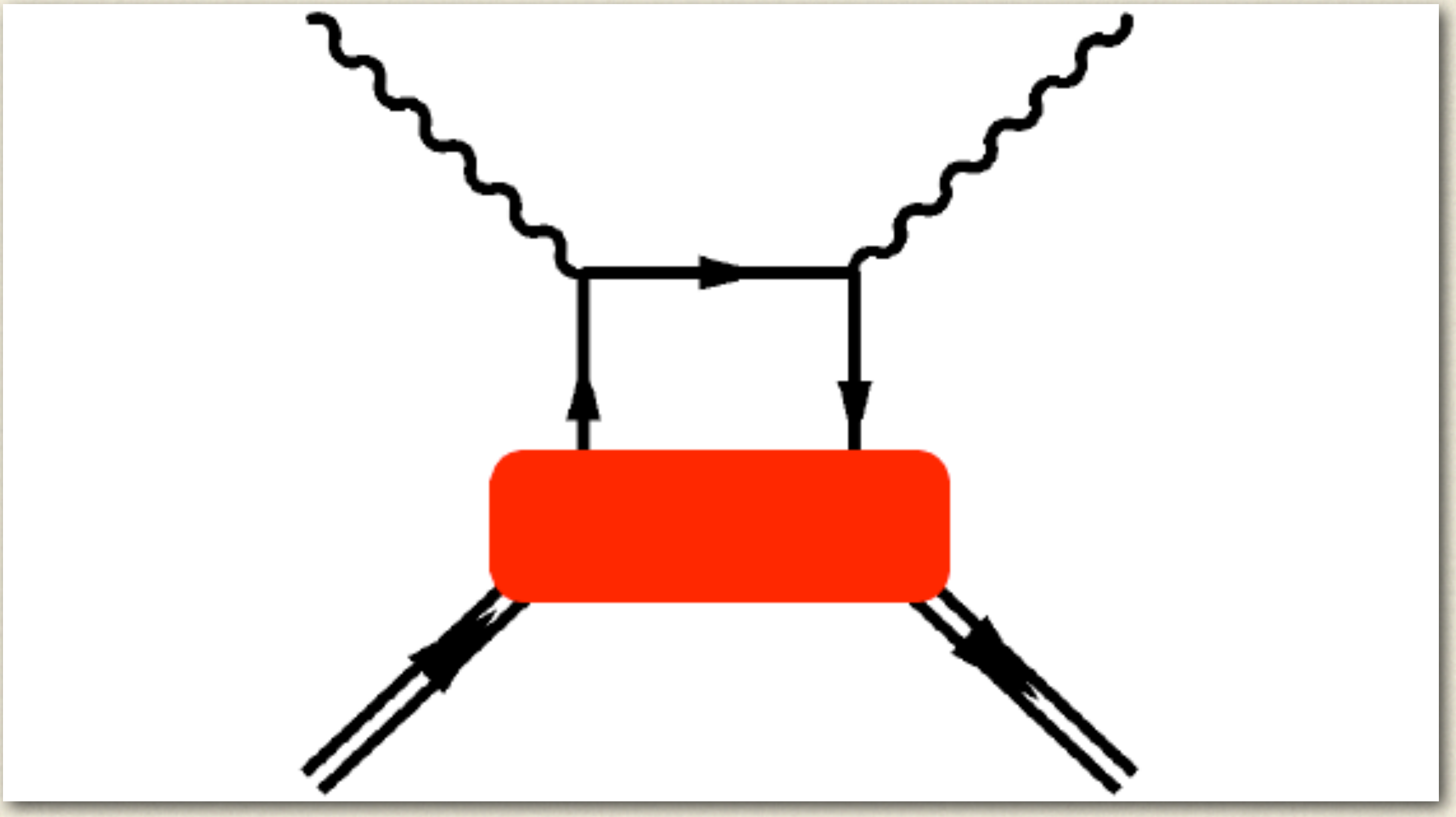


x	average long. mom
ξ	long. mom transfer
$t = \Delta^2 = (p'-p)^2$	virtuality

Forward limit



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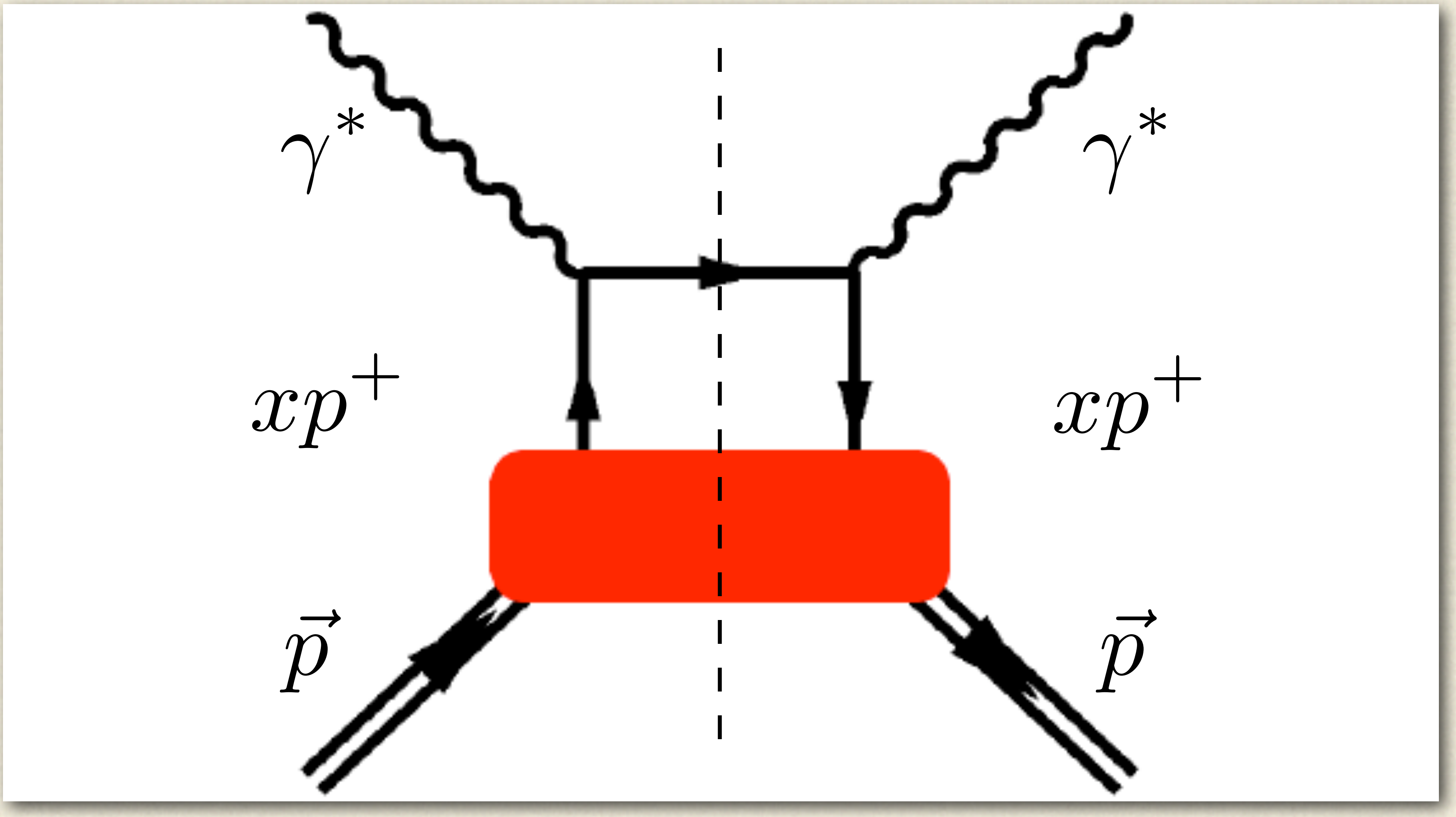

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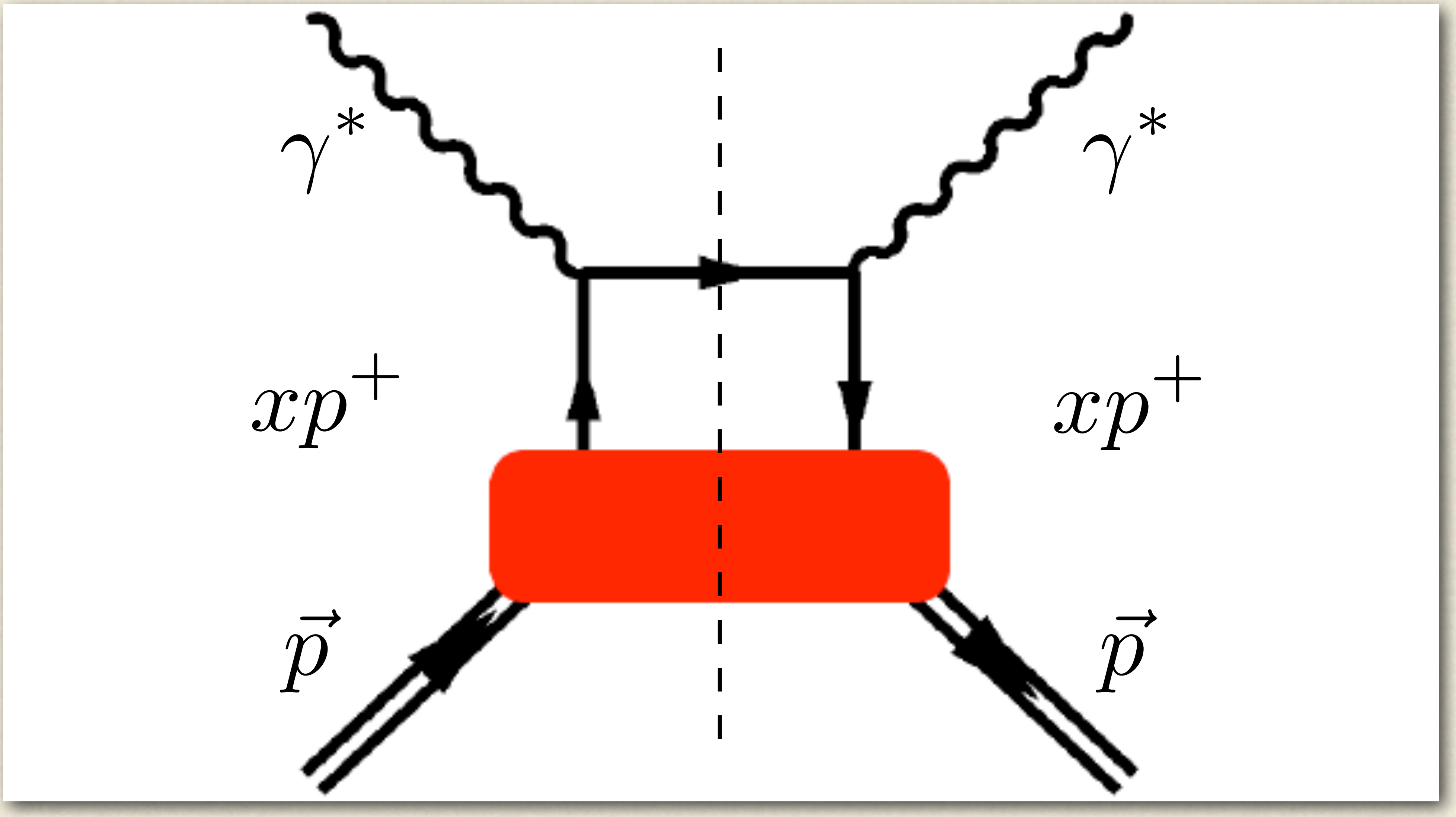
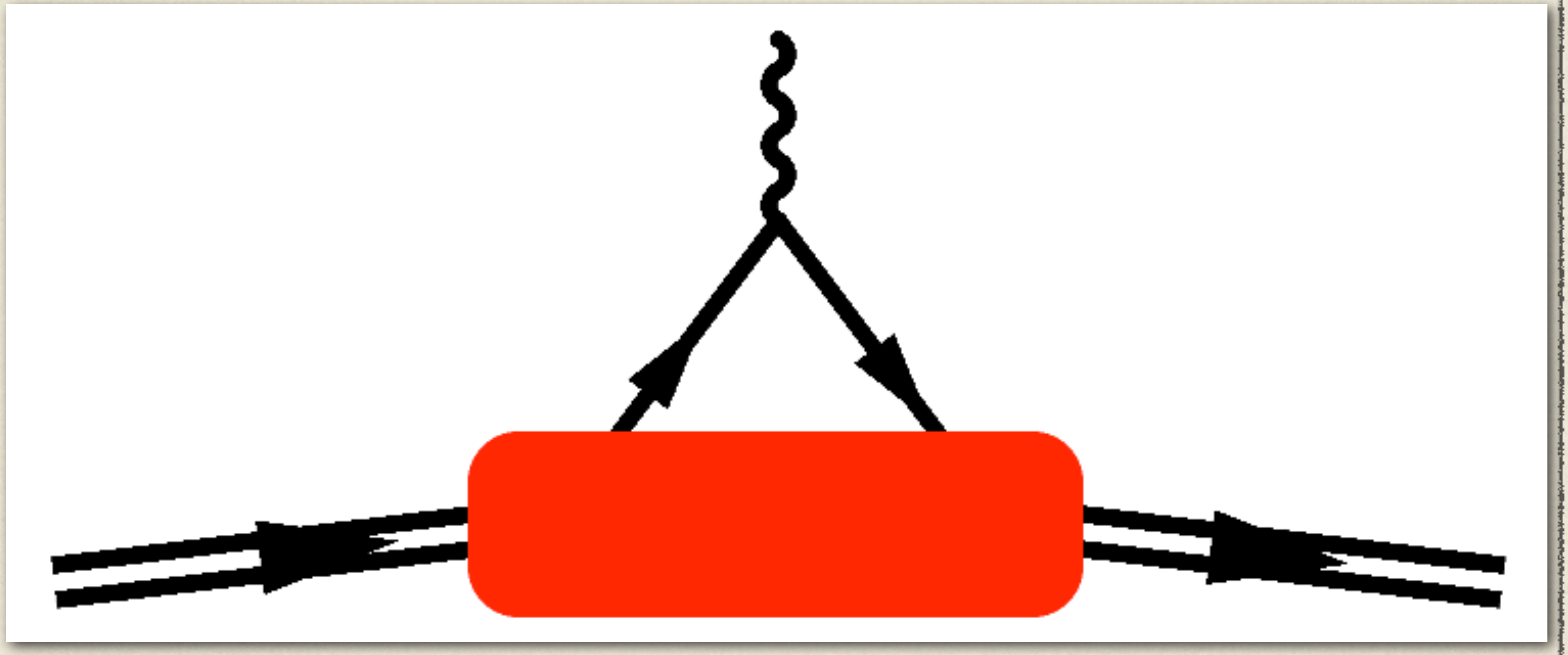
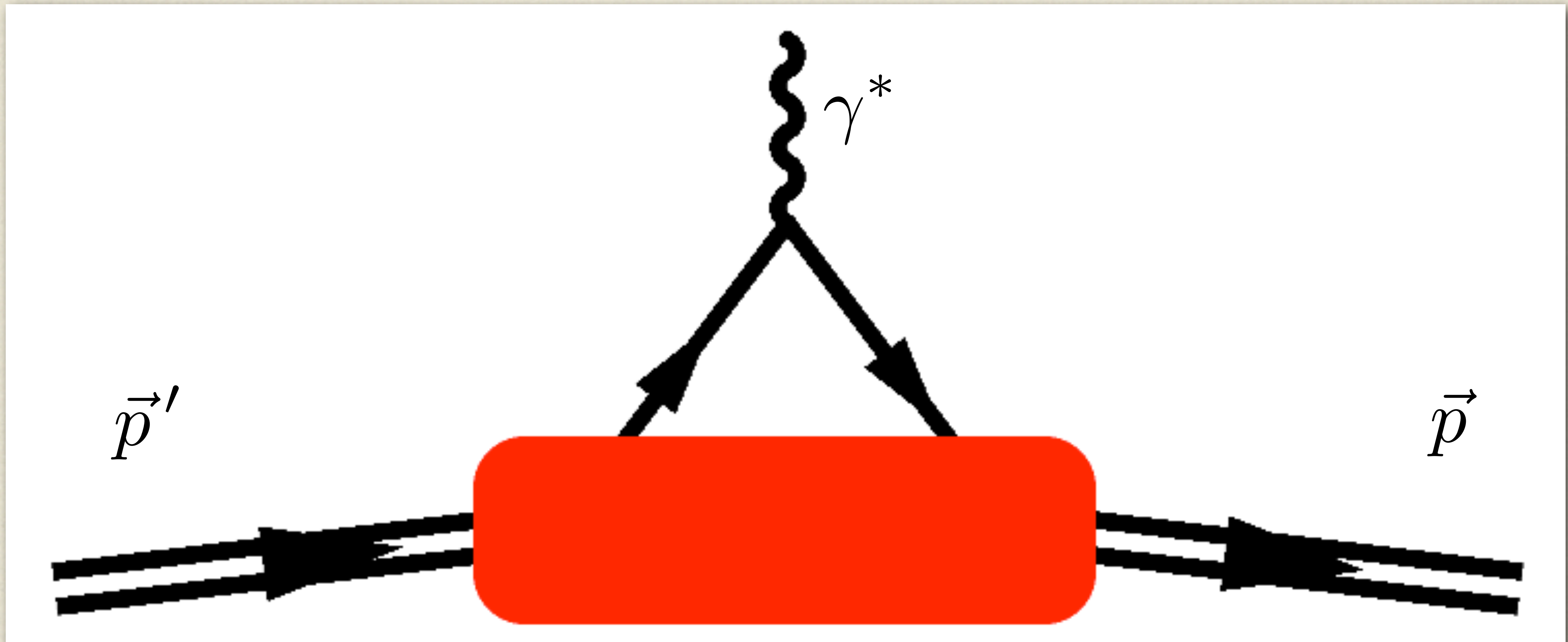


⇒ Recover forward parton distributions

Local limit



Local limit



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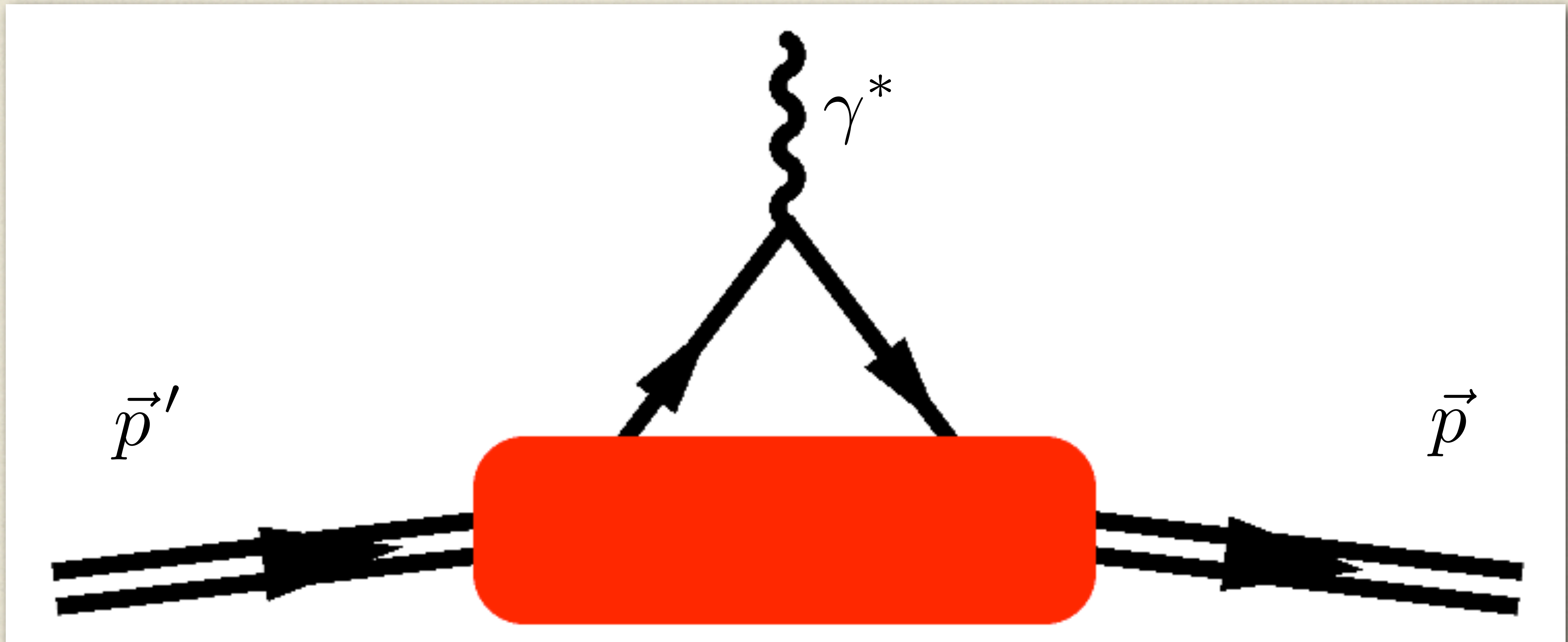
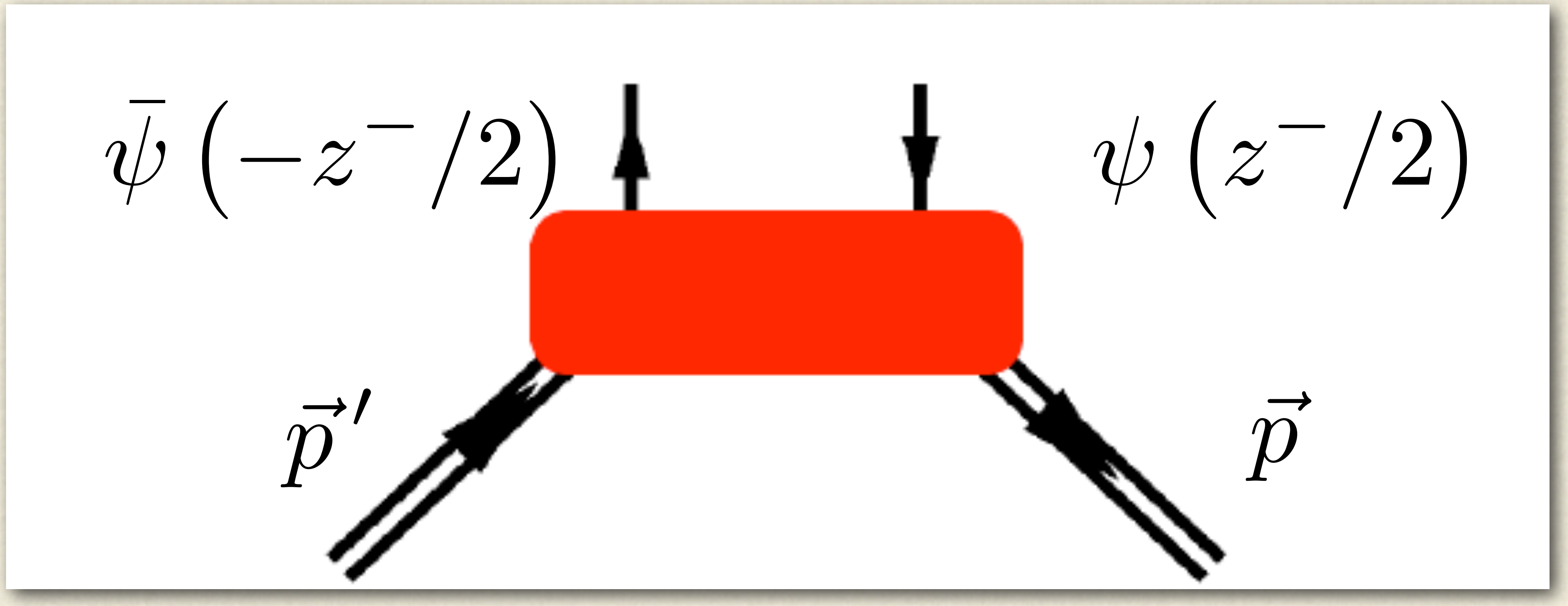


$\Rightarrow$ Recover form factors

Generalized parton distributions

- Describe both exclusive and inclusive processes
- Pioneering paper:
  D.Müller et.al., Fortschr.Phys. 42, 101 (1994)
- Became really popular with
  Phys.Rev.Lett. 78, 610 (1997)
  Phys.Rev. D56, 5524 (1997)

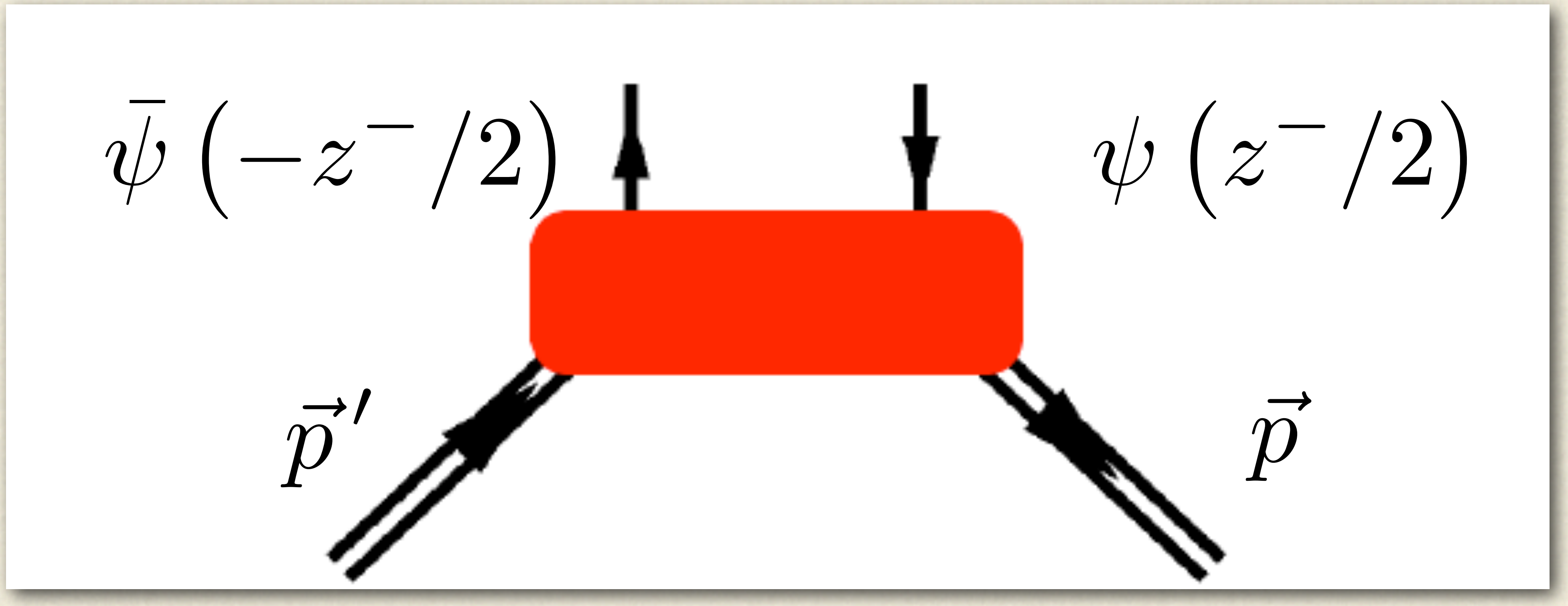
QCD matrix element



$$\bar{p}^{+}\int\frac{dz^{-}}{2\pi}e^{\mathrm{i}x\bar{p}^{+}z^{-}}\langle p'|\bar{\psi}(-\frac{1}{2}z^{-})\mathcal{A}\gamma^{+}\psi(\frac{1}{2}z^{-})|p\rangle$$

$$=H(x,\xi,t)\langle\langle\gamma^{+}\rangle\rangle+E(x,\xi,t)\frac{\mathrm{i}}{2m}\langle\langle\sigma^{+\alpha}\Delta_{\alpha}\rangle\rangle$$

QCD matrix element



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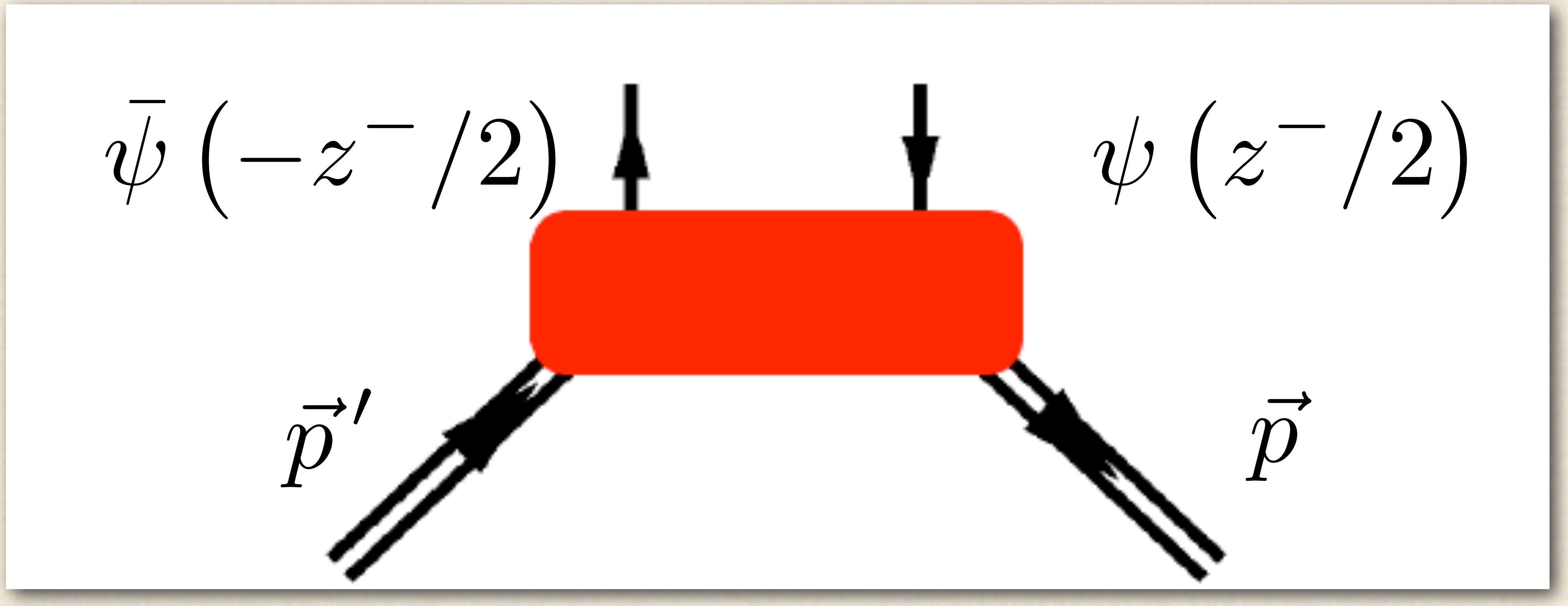
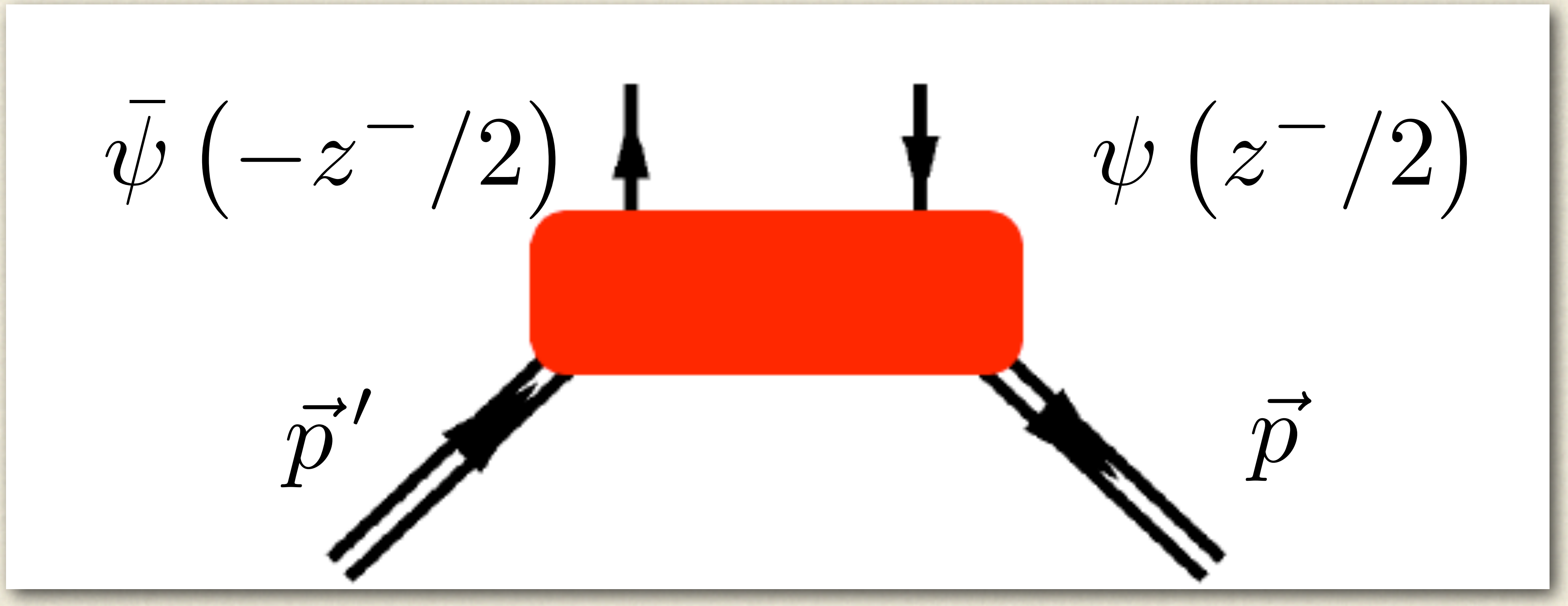


$$\bar{p}^+ \int \frac{dz^-}{2\pi} e^{\mathrm{i}\bar{p}^+ z^-} \langle p' | \bar{\psi}\left(-z^-/2\right) \gamma_5 \gamma^+ \psi\left(z^-/2\right) | p \rangle$$
$$= \tilde{H}(x,\xi,t) \langle\!\langle \gamma_5 \gamma^+ \rangle\!\rangle - \tilde{E}(x,\xi,t) \frac{\Delta^+}{2m} \langle\!\langle \gamma_5 \rangle\!\rangle$$

QCD matrix element



$$\bar{p}^{+}\int\frac{dz^{-}}{2\pi}e^{\mathrm{i}\bar{p}^{+}z^{-}}\langle p'|\bar{\psi}\left(-z^{-}/2\right)\gamma_5\gamma^{+}\psi\left(z^{-}/2\right)|p\rangle$$
$$=\tilde{H}(x,\xi,t)\langle\langle\gamma_5\gamma^{+}\rangle\rangle-\tilde{E}(x,\xi,t)\frac{\Delta^{+}}{2m}\langle\langle\gamma_5\rangle\rangle$$

Collection of GPDs

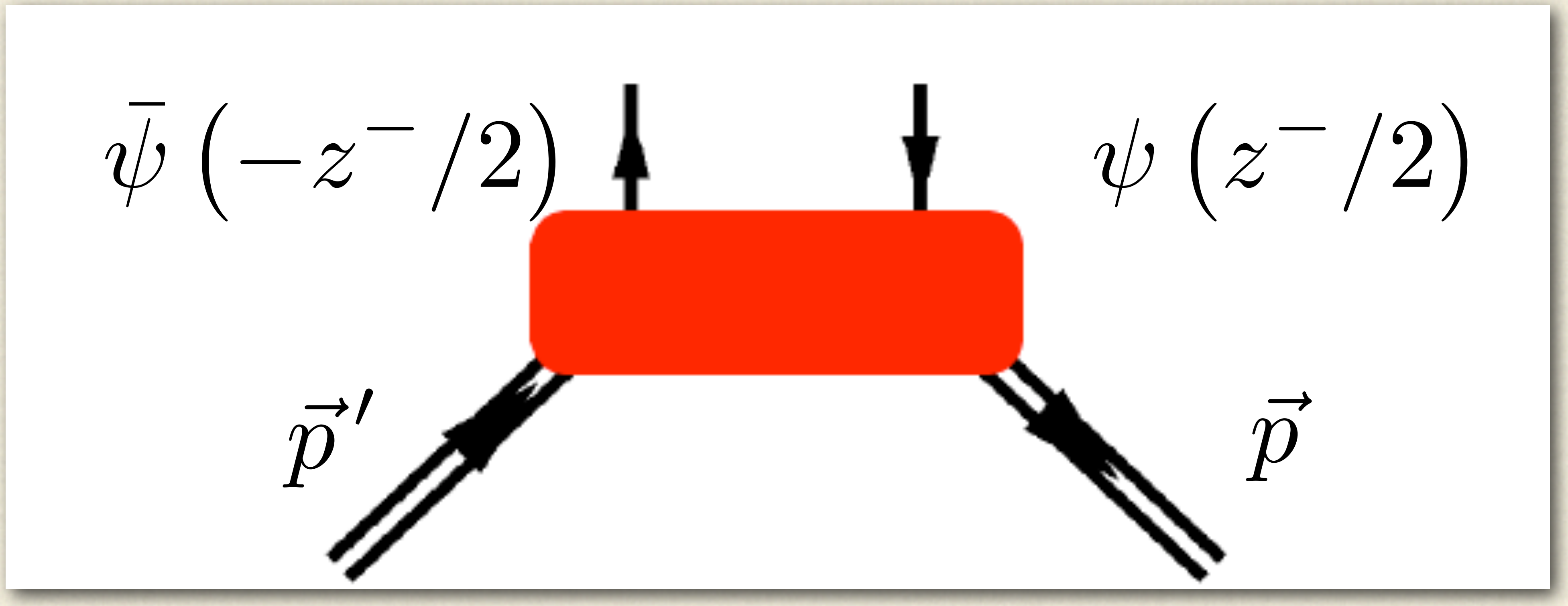
$$\langle p'|\bar{\psi}\gamma^\mu\psi|p\rangle \Rightarrow H(x,\xi,t)\,\&\,E(x,\xi,t)$$

$$\langle p'|\bar{\psi}\gamma_5\gamma^\mu\psi|p\rangle \Rightarrow \tilde{H}(x,\xi,t)\,\&\,\tilde{E}(x,\xi,t)$$

+ four more fermion GPDs for transversity

+ eight more gluon GPDs

Interpreting GPDs



- Quark emitted and absorbed with l.m.f. (x+ξ) and (x-ξ)
- Quark/antiquark pair emitted with l.m.f. (ξ+x) and (ξ-x)

Phenomenology

- Deeply virtual-wide-angle Compton scattering
- Exclusive meson production
- Form factors, Deep-inelastic scattering
- Three-dim. hadron structure
- Angular momentum sum rule

Recent review: Phys.Rept. 388:41-277 (2003)

Phenomenology

Where has the *lattice* contributed?

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Phys.Rev.D68:034505(2003)
Phys.Rev.Lett.92:042002(2004)
Phys.Rev.D77:094502(2008)

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Extracting GPDs

- *x*-dependence: as Mellin-moments
- ξ-dependence: analytically
- *t*-dependence: via external momenta
- On the lattice: model-independent results
- Experimentally: difficult to extract functions of three variables
  $\Rightarrow$ Combine lattice, models, and experiment

Lattice simulations & their challenges

Lattice QCD for predictions

- **Goal:** Qualitative & quantitative results from first principles

  ⇒ Comparison of theory ⇔ experiment

  ⇒ Credibility for predictions

- Vary parameters, e.g. m_q, N_c, N_f

- Test models of QCD
  ⇒ Insight into how QCD works

Regimes of quark masses

- **Heavy quark regime:**

  confinement, flux tubes, adiabatic potential

- **Light quark regime:**

  chiral symmetry breaking, instantons, chiral perturbation theory

Regimes of quark masses

Major source of uncertainty:

Quark masses!

tic potential

ntons, chiral

Fermion discretizations

- (Improved) Wilson fermions
- (Improved) staggered fermions
- Twisted mass Wilson fermions
- Ginsparg-Wilson fermions
  - Domain-wall
  - Overlap

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Practically **very** important question!

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Fermion discretizations

Simple, well understood

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Small m_{PS} problematic

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Cheap

Small mps problematic

Chiral, $O(a^2)$, **but** expensive

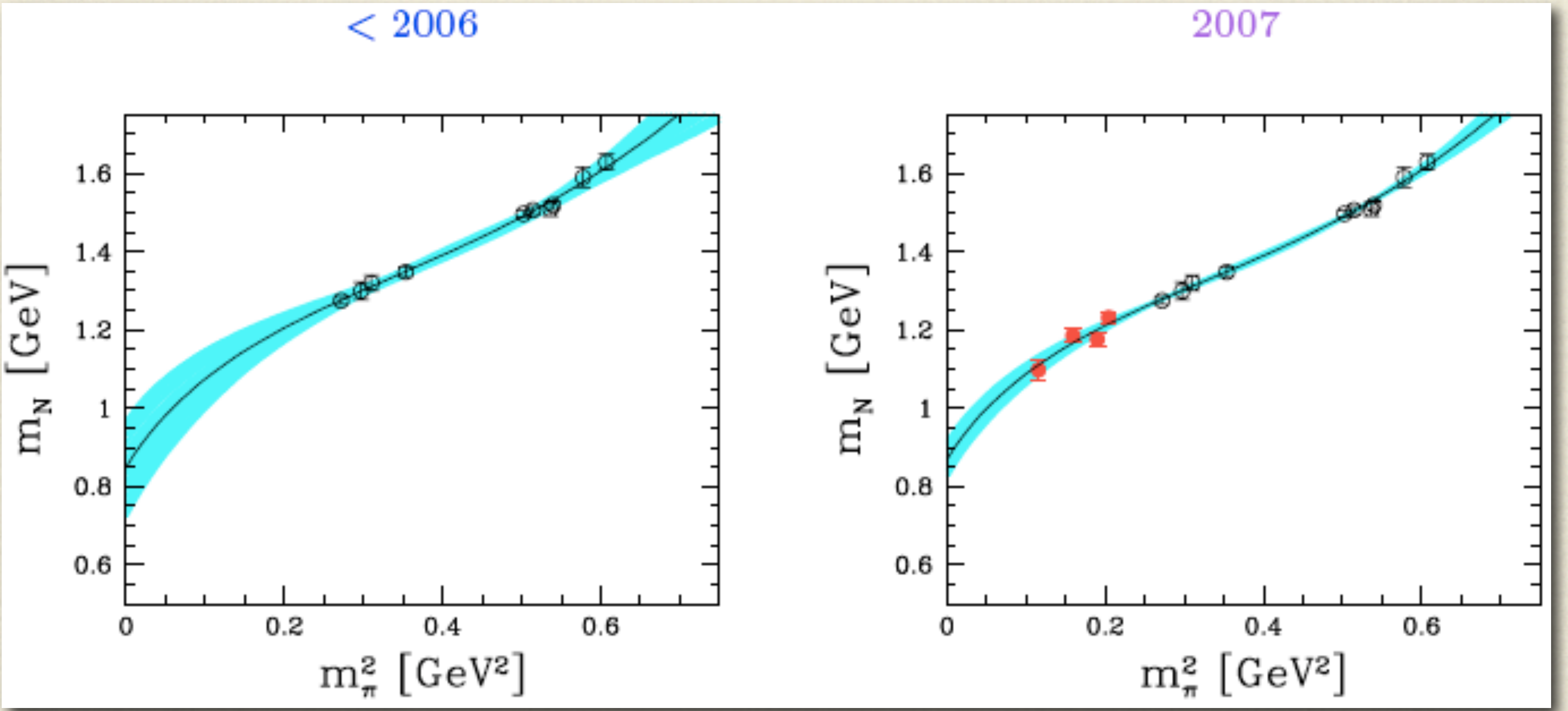
The challenge

- Light valence fermions possible today
- Light sea quarks remain major issue

Possible solutions:

- Hybrid calculations
- Full GW: Either full DWF or Overlap
- Full Wilson-type fermions (Clover/Twisted mass)

Nucleon mass (QCDSF)



GPDs on the lattice

Original definition: *non-local* matrix elements

On the lattice: we can only do *local* matrix elements

Similar to PDs use the light-cone OPE

$$\langle p|\mathcal{O}_q^{\{\mu_1\ldots\mu_n\}}|p\rangle$$

$$\mathcal{O}_q^{\{\mu_1\ldots\mu_n\}} = \bar{\psi}_q\gamma^{\{\mu_1}\mathrm{i}\mathcal{D}^{\mu_2}\ldots\mathrm{i}\mathcal{D}^{\mu_n\}}\psi_q$$

Generalized form factors

Expand generalized local currents
in
Lorentz-invariant functions

$$\langle p'|\mathcal{O}_q^{\{\mu_1\ldots\mu_n\}}|p\rangle$$

$\Rightarrow$ Generalized form factors

e.g.:
$$\begin{aligned}\langle p'|\mathcal{O}^{\{\mu\nu\}}|p\rangle \quad = \quad & A_{20}(t)\bar{p}^{\{\mu}\bar{u}(p')\gamma^{\nu\}}u(p) \\ & +B_{20}(t)\frac{\mathrm{i}}{2m}\bar{p}^{\{\mu}\bar{u}(p')\sigma^{\nu\}\alpha}u(p)\Delta_\alpha \\ & +C_2(t)\frac{1}{m}\Delta^{\{\mu}\Delta^{\nu\}}\end{aligned}$$

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GFFs as Mellin transforms

Explicitly for ξ=0:

$$\int dx\, x^{n-1} H(x,0,t) = A_{n0}(t)$$

$$\int dx\, x^{n-1} E(x,0,t) = B_{n0}(t)$$

Higher moments are always polynomials in $(2\xi)^2$:

$$\int dx\, x H(x,\xi,t) = (2\xi)^2 C_2(t) + A_{20}(t)$$

$$\int dx\, x E(x,\xi,t) = (2\xi)^2 C_2(t) + B_{20}(t)$$

LHPC: Hybrid calculations

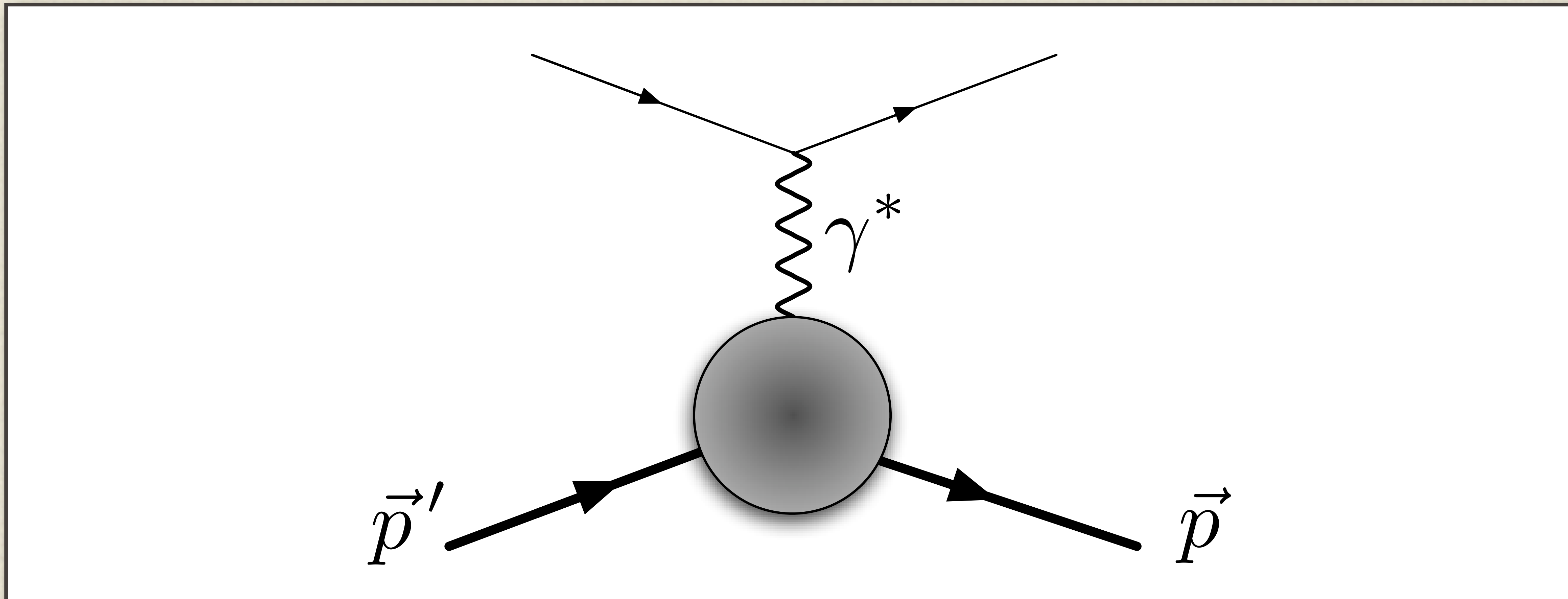
- Hybrid approach: unitarity & square root? Lattice artifacts?
- Achievement: 5 quark masses, full QCD down to m_π=354 MeV
- Lattice sizes $(2.5\text{fm})^3$ and $(3.5\text{fm})^3$

Achievements

Key calculations

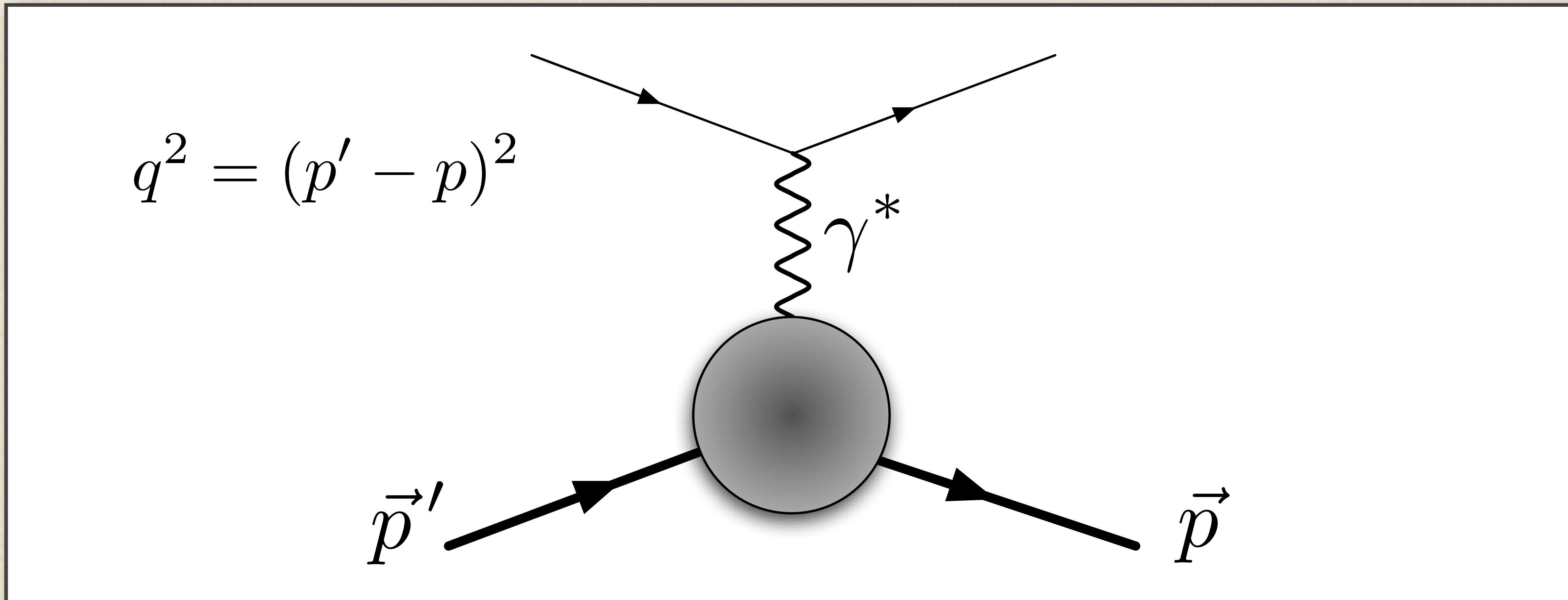
- **Three key calculations** from the lattice:
  - $N \rightarrow N$ & $N \rightarrow \Delta$ transition form factors
  - GPDs - The nucleon spin & transverse structure
  - Nucleon axial coupling g_A :
    First quantitative result!

Electromagnetic form factors



$$\langle p'|J_\mu|p\rangle = \bar{u}(p')\Big[\gamma_\mu F_1(q^2) + \frac{\mathrm{i}q^\alpha}{2m_N}\sigma_{\alpha\mu}F_2(q^2)\Big]u(p)$$

Electromagnetic form factors



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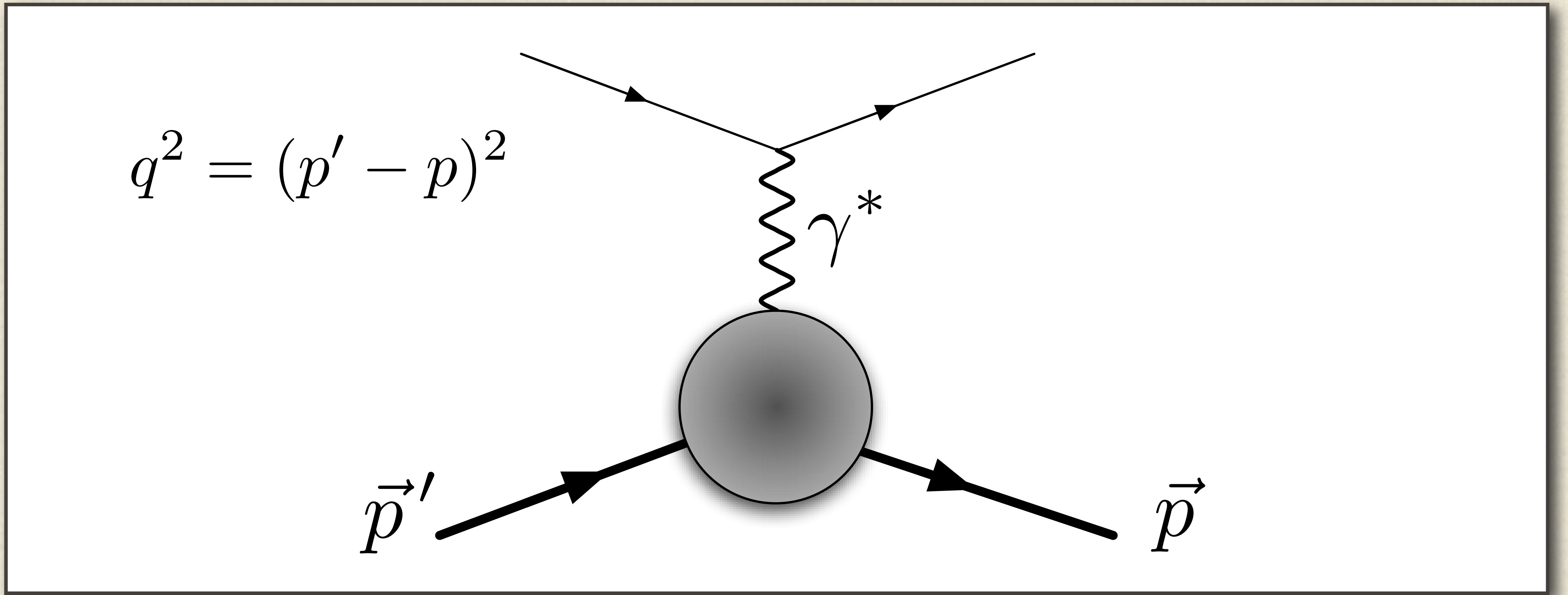

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Experiment

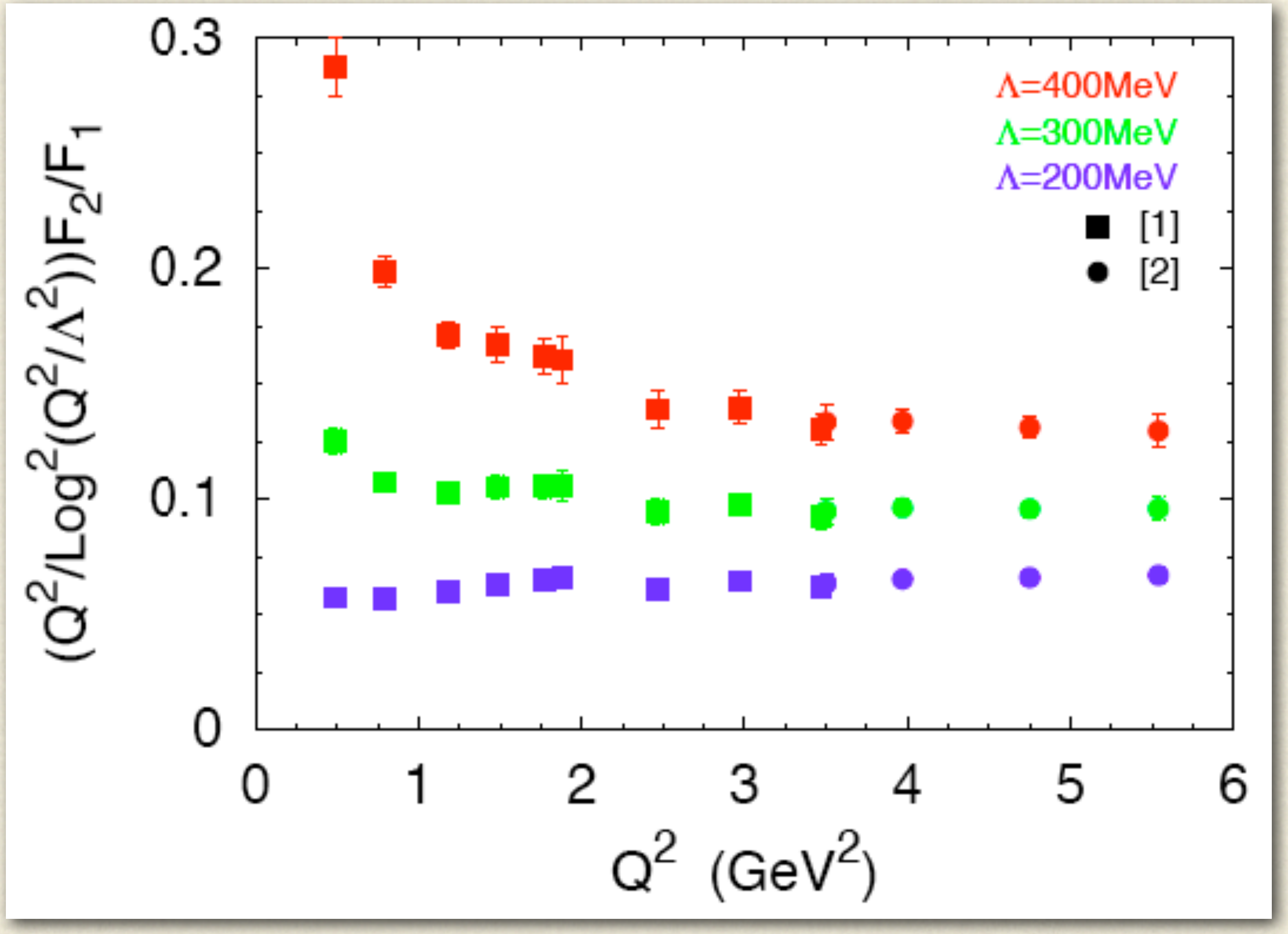
- Recent reviews: Phys.Rev. C71:055202 (2005) J.Phys. G34:S23-S25(2007)
- Two techniques:
  - Rosenbluth: elastic scattering $\sigma(e + p \to e + p)$
  - Spin-transfer: $\vec{e} + \vec{p} \to e + p$
    $\vec{e} + p \to e + \vec{p}$
- Around for several decades, but ***surprising new insights*** recently

Form factors

$t = Q^2$ dependence

$\frac{tF_2(t)}{F_1(t)}$	$\propto$ const.	Naive quark counting rules
$\frac{\sqrt{t}F_2(t)}{F_1(t)}$	$\propto$ const.	JLab spin transfer experiment
$\frac{tF_2(t)}{\log^2(t)F_1(t)}$	$\propto$ const.	Phys.Rev.Lett. 91:092003 (2003)

Form factors in Nature



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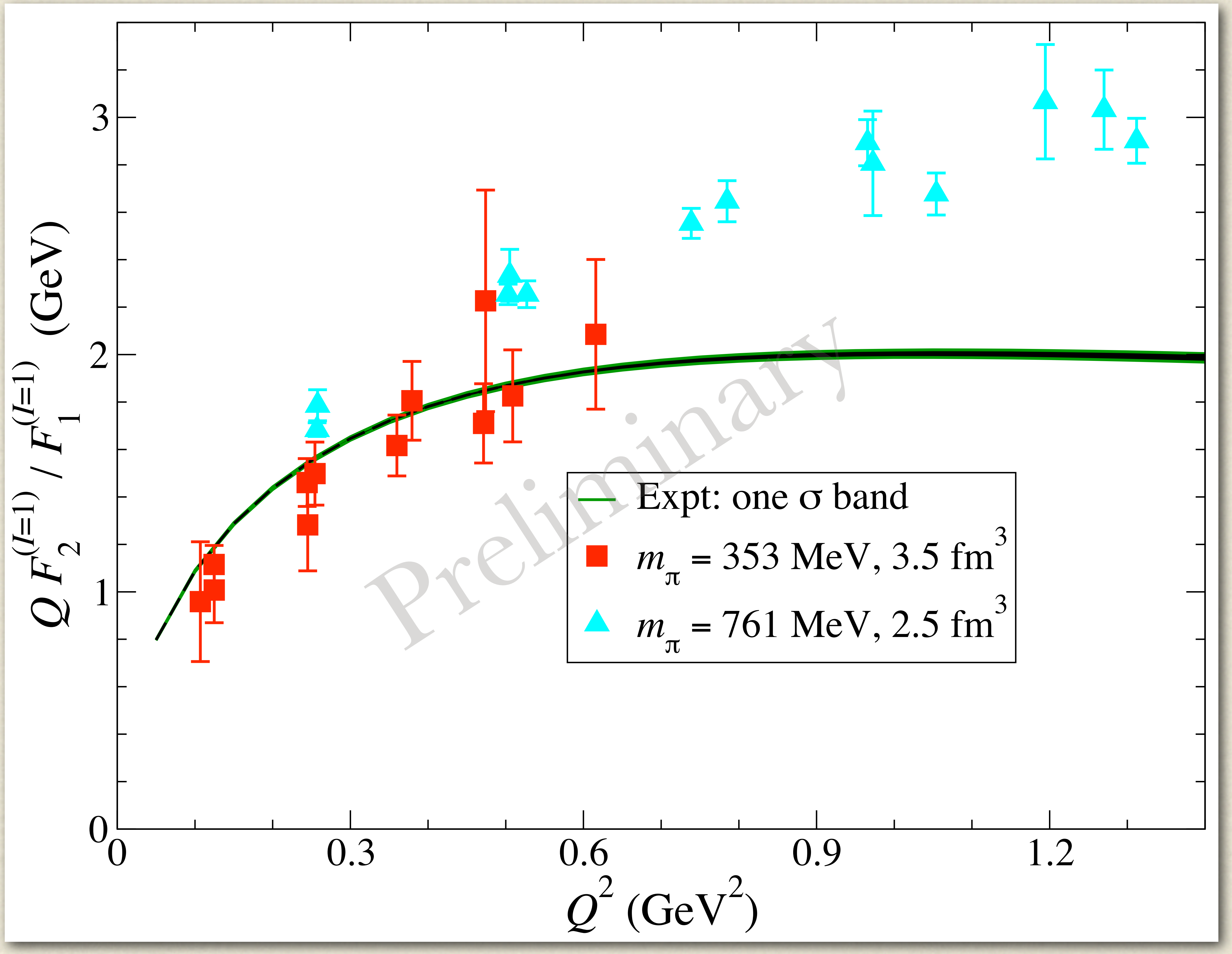
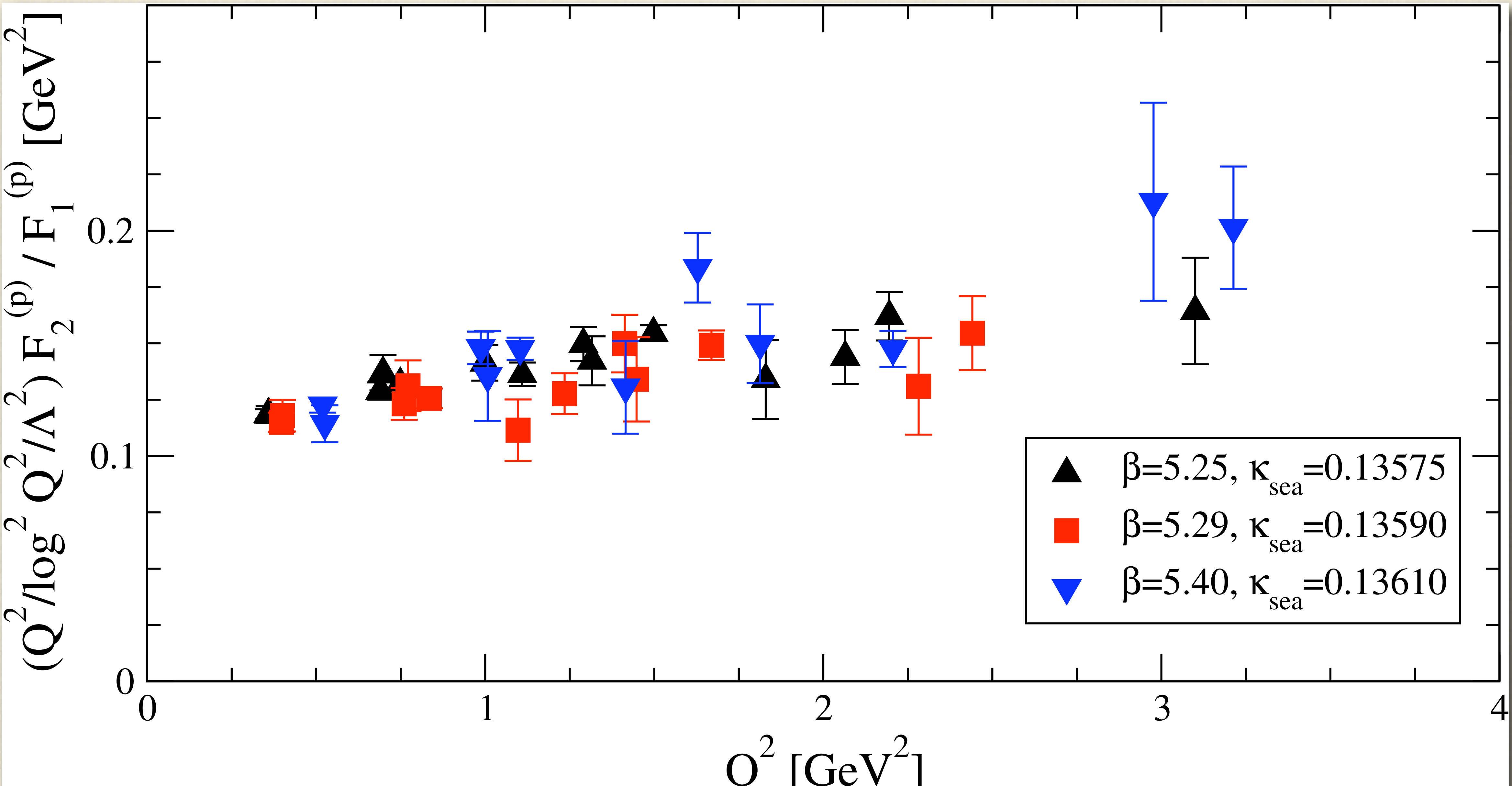


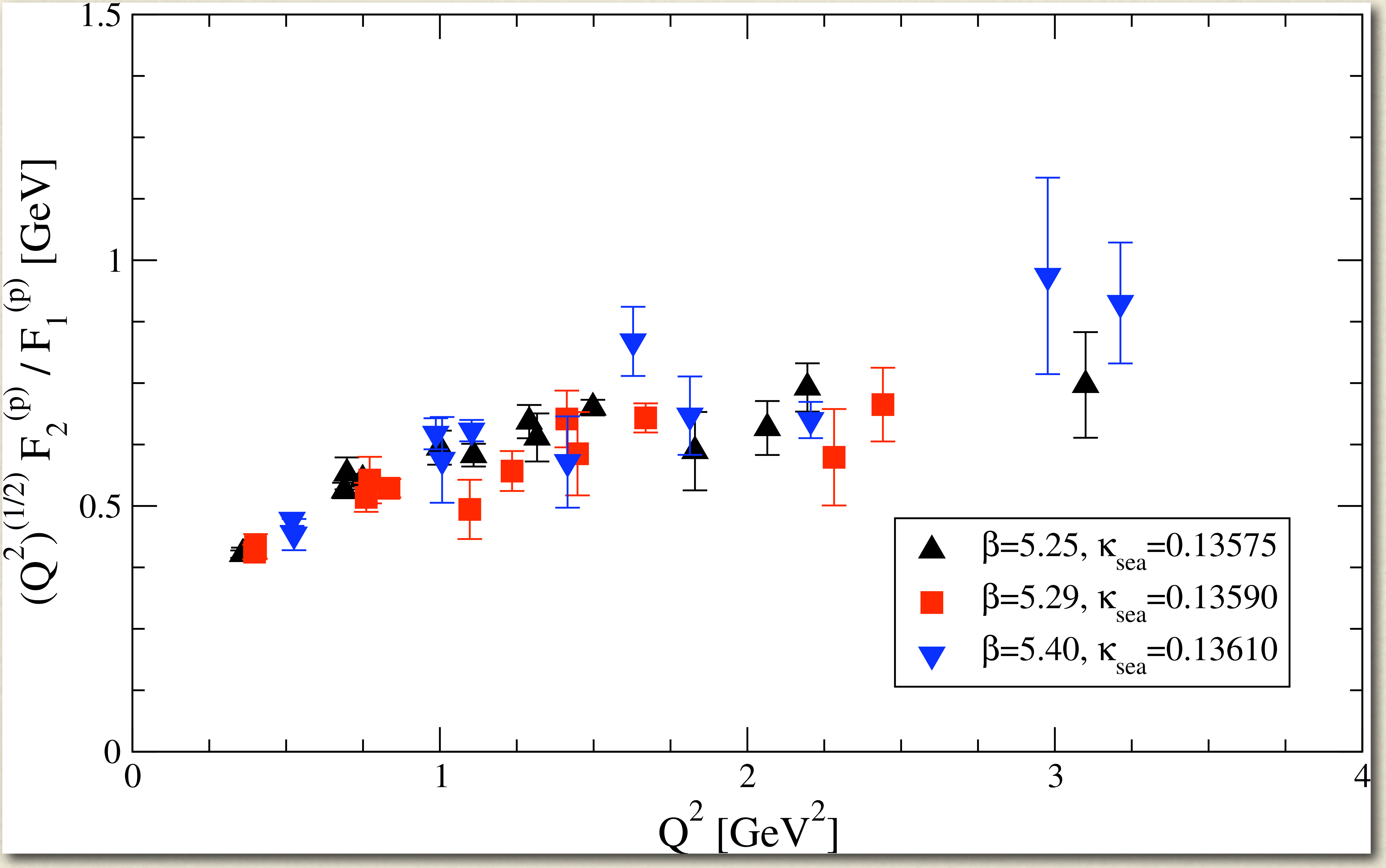
LHPC collaboration, in preparation

Form factor scaling

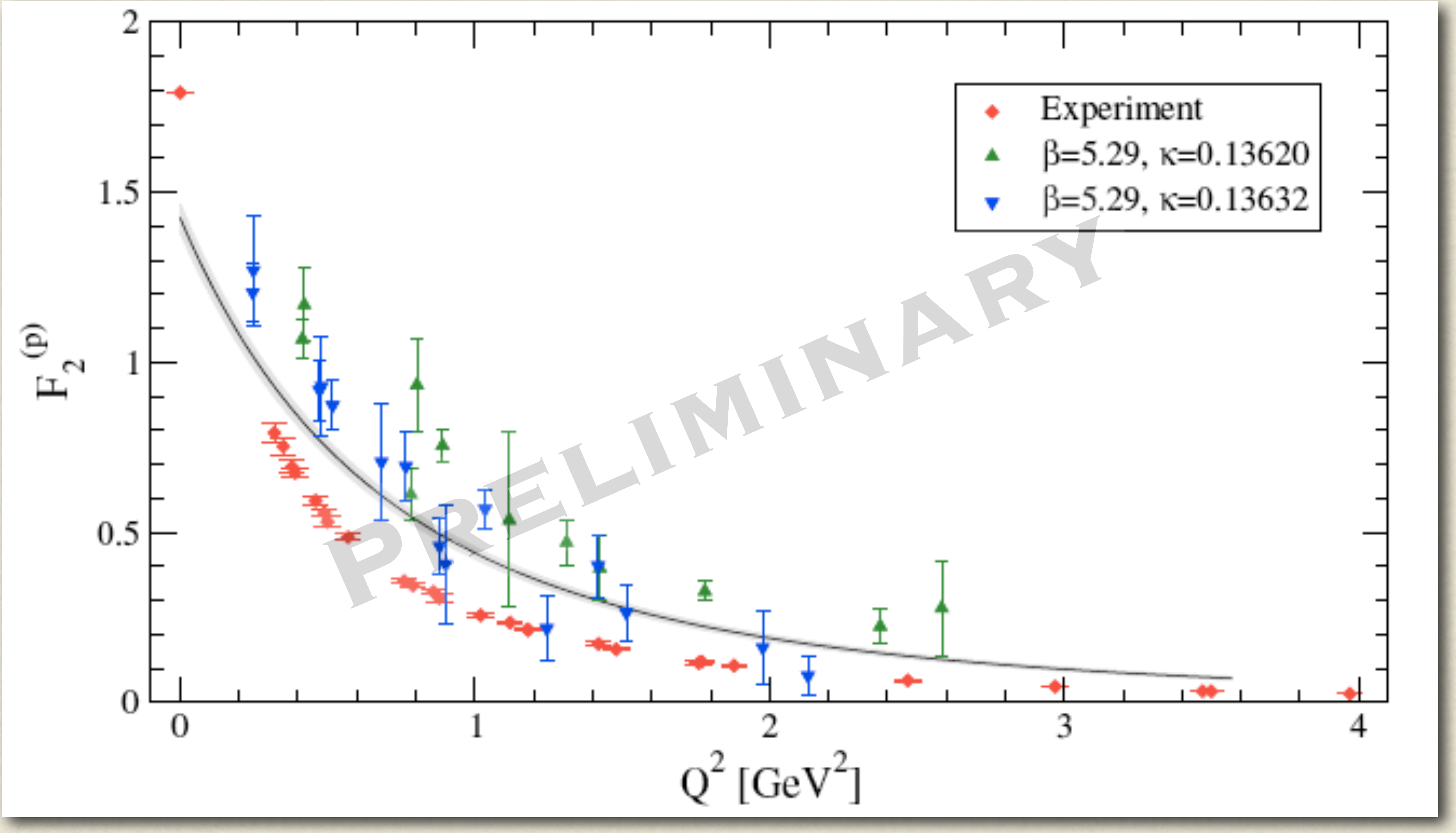


$m_{PS} \approx 600$ MeV, a=0.070...0.084 fm

Form factor scaling



F_2^p Lattice vs Expmt.



Large distance behavior

- Charge radii:

$$F_i(q^2) = F_i(0)\left(1 + \frac{1}{6} r_i^2 q^2 + \mathcal{O}(q^4)\right)$$

- Magnetic moment:

$$\mu \equiv F_1(0) + F_2(0) \equiv 1 + \kappa$$

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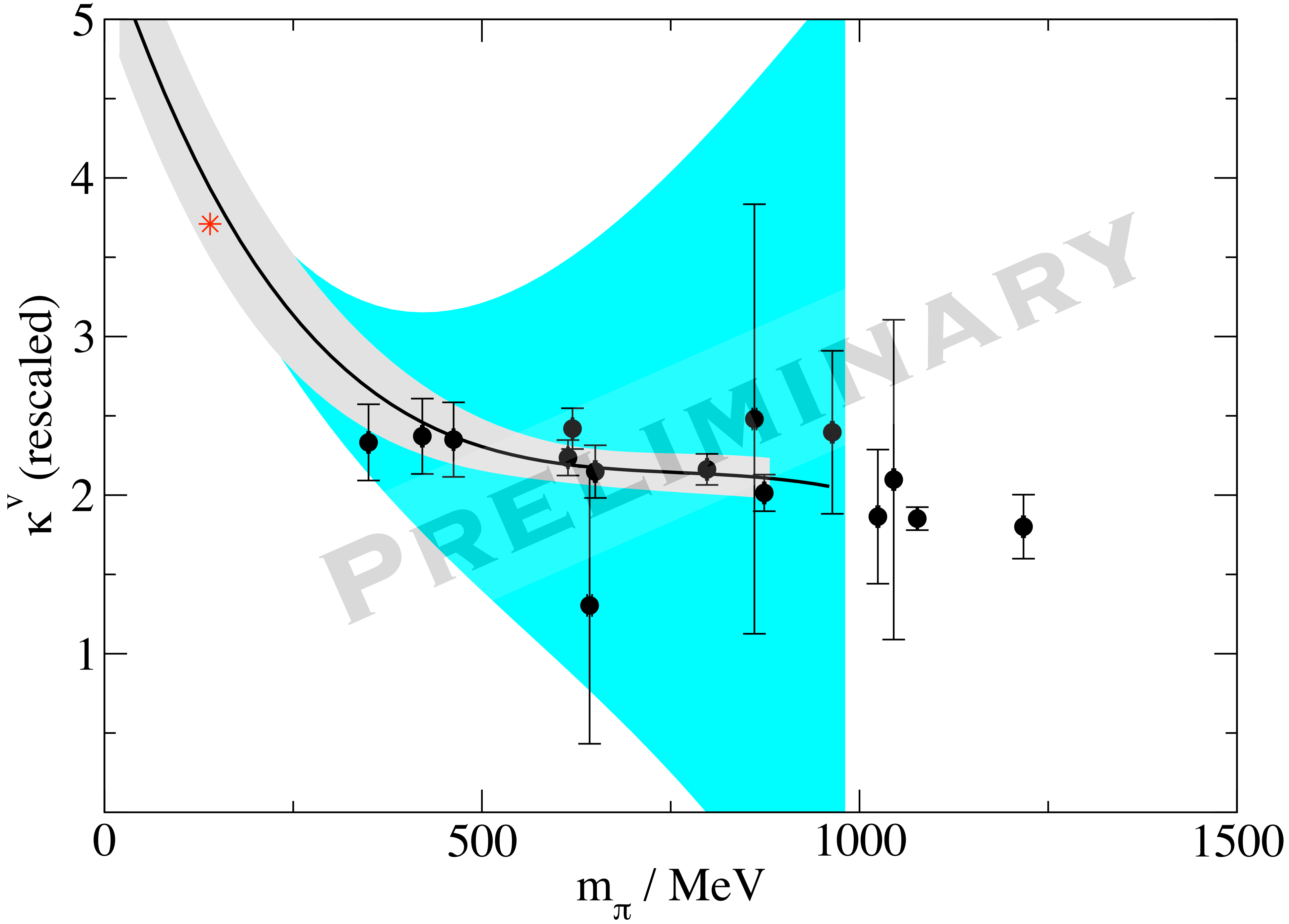
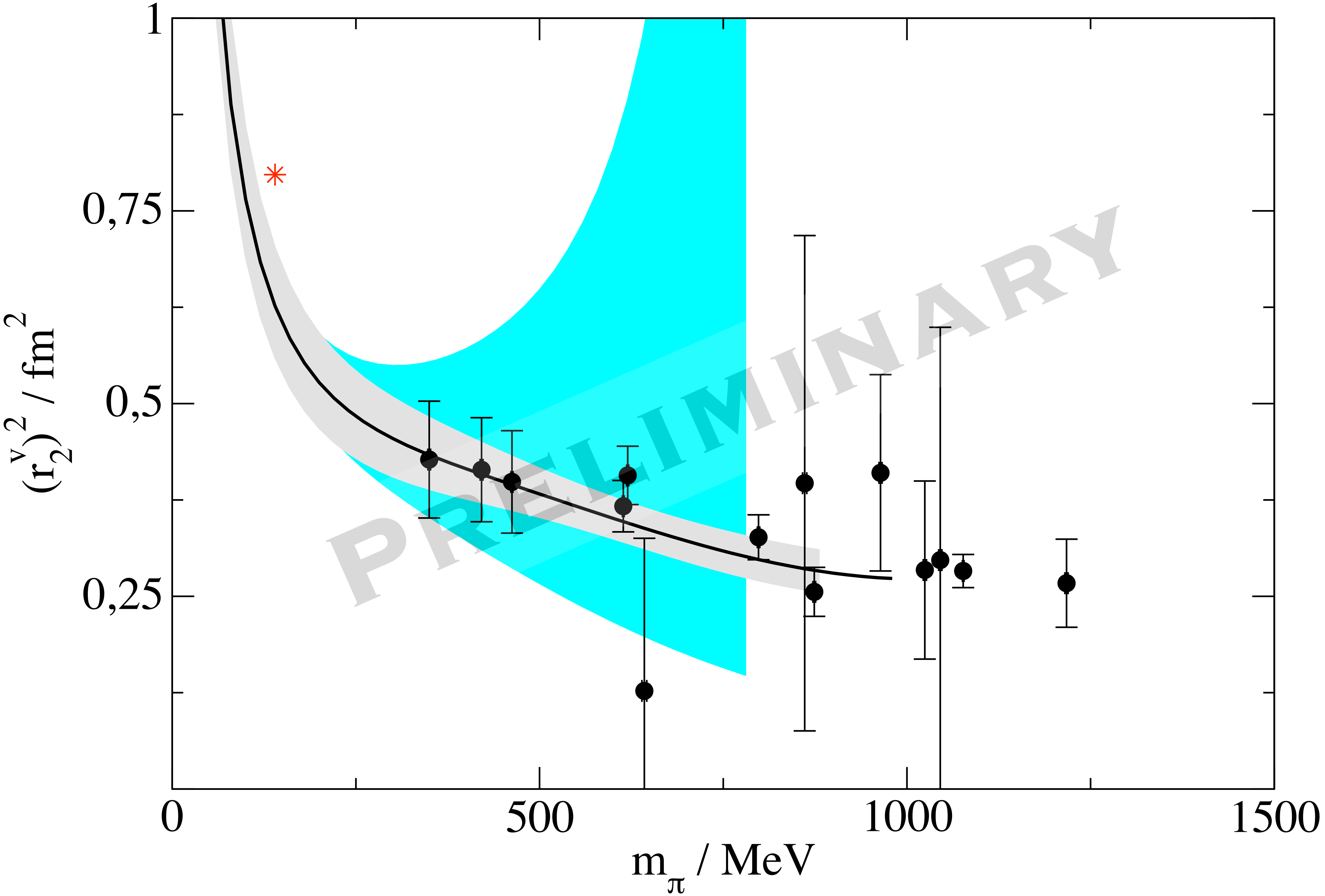


Fitting formula from Phys.Rev. D71:034508 (2005)



1
0,75
0,5
0,25
0
500
1000
1500
$(r_2^v)^2$ / fm^2
m_π / MeV
PRELIMINARY

Hadron deformation

- **How to measure?**
  - Quadrupole moment of ground state
    $\Rightarrow$ vanishes for spin-1/2 system
  - Excitation spectrum of the system
    $\Rightarrow$ exceedingly complicated,
    broad & overlapping resonances
  - Radiation of emitted de-excitation radiation
    $\Rightarrow$ viable from $\Delta^{+}(1232)$

Transition form factors

Electromagnetic current (local operator):

$$\langle \text{state}|\bar{\psi}\gamma^\mu\psi|\text{state}\rangle$$

Expand m.e. in terms of scalar functions ("(generalized) form factors"):

$$\langle n(p')|\bar{\psi}\gamma^\mu\psi|n(p)\rangle = \mathcal{P}_1^\mu F_1(t) + \mathcal{P}_2^\mu F_2(t)$$

Transition form factors:

$$\langle \Delta^\sigma(p')|\bar{\psi}\gamma^\mu\psi|n(p)\rangle = \mathcal{A}_1^{\sigma\mu}\mathcal{G}_{M1}(t) + \mathcal{A}_2^{\sigma\mu}\mathcal{G}_{E2}(t) + \mathcal{A}_3^{\sigma\mu}\mathcal{G}_{C2}(t)$$

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Expand m.e. in terms of scalar functions ("(generalized) form factors"):

$$\langle n(p')|\bar{\psi}\gamma^\mu\psi|n(p)\rangle = \mathcal{P}_1^\mu F_1(t) + \mathcal{P}_2^\mu F_2(t)$$

Transition form factors:

$$\langle \Delta^\sigma(p')|\bar{\psi}\gamma^\mu\psi|n(p)\rangle = \mathcal{A}_1^{\sigma\mu}\mathcal{G}_{M1}(t) + \mathcal{A}_2^{\sigma\mu}\mathcal{G}_{E2}(t) + \mathcal{A}_3^{\sigma\mu}\mathcal{G}_{C2}(t)$$

Transition form factors

Electromagnetic current (local operator):

$$\langle \text{state} | \bar{\psi} \gamma^{\mu} \psi | \text{state} \rangle$$

Expand m.e. in terms of scalar functions
("(generalized) form factors"):

$$\langle n(p') | \bar{\psi} \gamma^{\mu} \psi | n(p) \rangle = \mathcal{P}_1^{\mu} F_1(t) + \mathcal{P}_2^{\mu} F_2(t)$$

Transition form factors:

$$\langle \Delta^{\sigma}(p') | \bar{\psi} \gamma^{\mu} \psi | n(p) \rangle = \mathcal{A}_1^{\sigma\mu} \mathcal{G}_{M1}(t) + \mathcal{A}_2^{\sigma\mu} \mathcal{G}_{E2}(t) + \mathcal{A}_3^{\sigma\mu} \mathcal{G}_{C2}(t)$$

Observables & lattice m.e.

- Matrix element

$$\langle \Delta^\sigma(p')|\bar{\psi}\gamma^\mu\psi|n(p)\rangle = \mathcal{A}_1^{\sigma\mu}\mathcal{G}_{M1}(t) + \mathcal{A}_2^{\sigma\mu}\mathcal{G}_{E2}(t) + \mathcal{A}_3^{\sigma\mu}\mathcal{G}_{C2}(t)$$

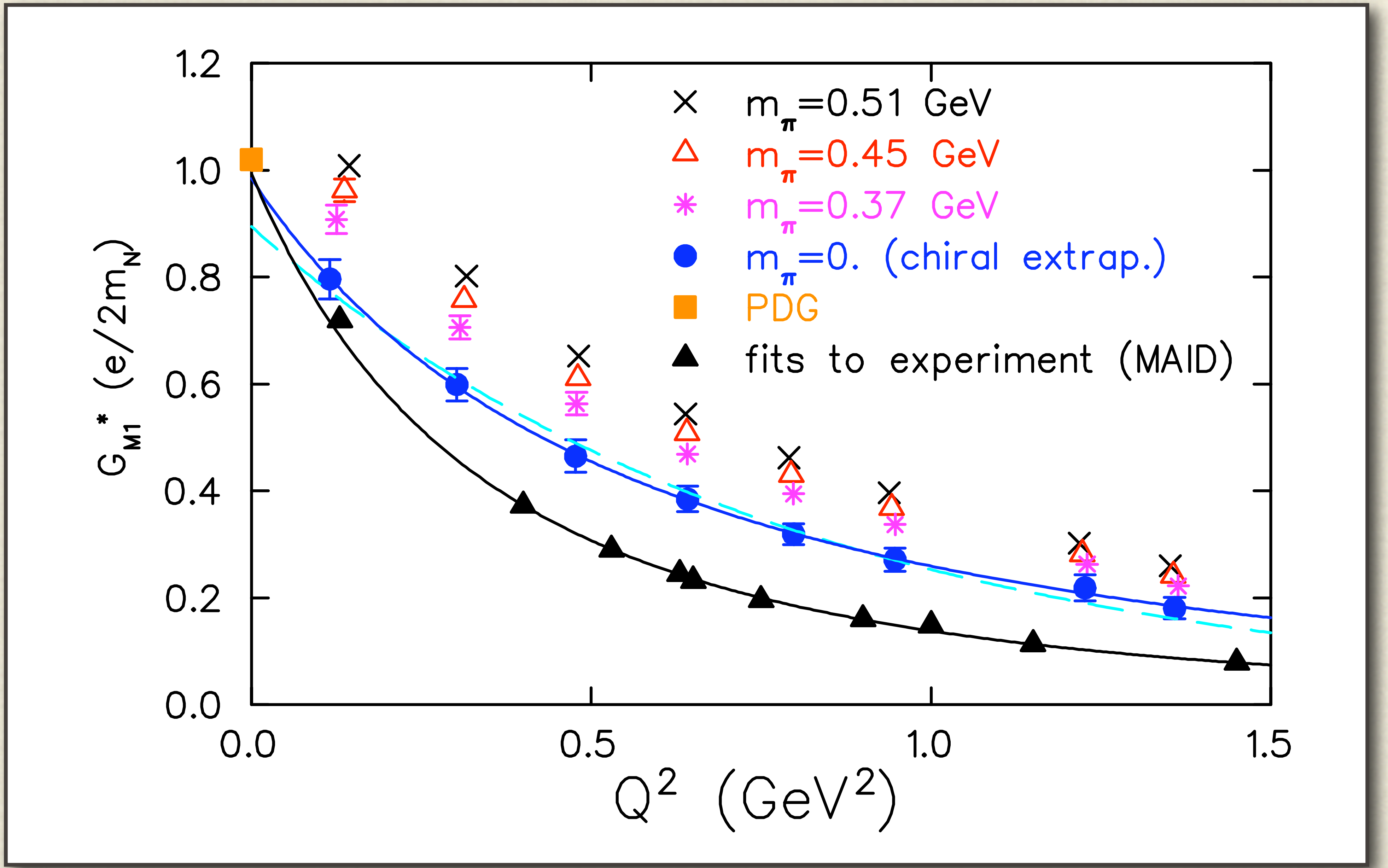
- Signal for deformation:
  spherical ⇒ M1
  deformed ⇒ M1, E2, C2

- Ratios: $R_{EM} = -\dfrac{\mathcal{G}_{E2}(t)}{\mathcal{G}_{M1}(t)}\,, \quad R_{SM} = -\dfrac{|\Delta|}{2m_\Delta}\dfrac{\mathcal{G}_{C2}(t)}{\mathcal{G}_{M1}(t)}$

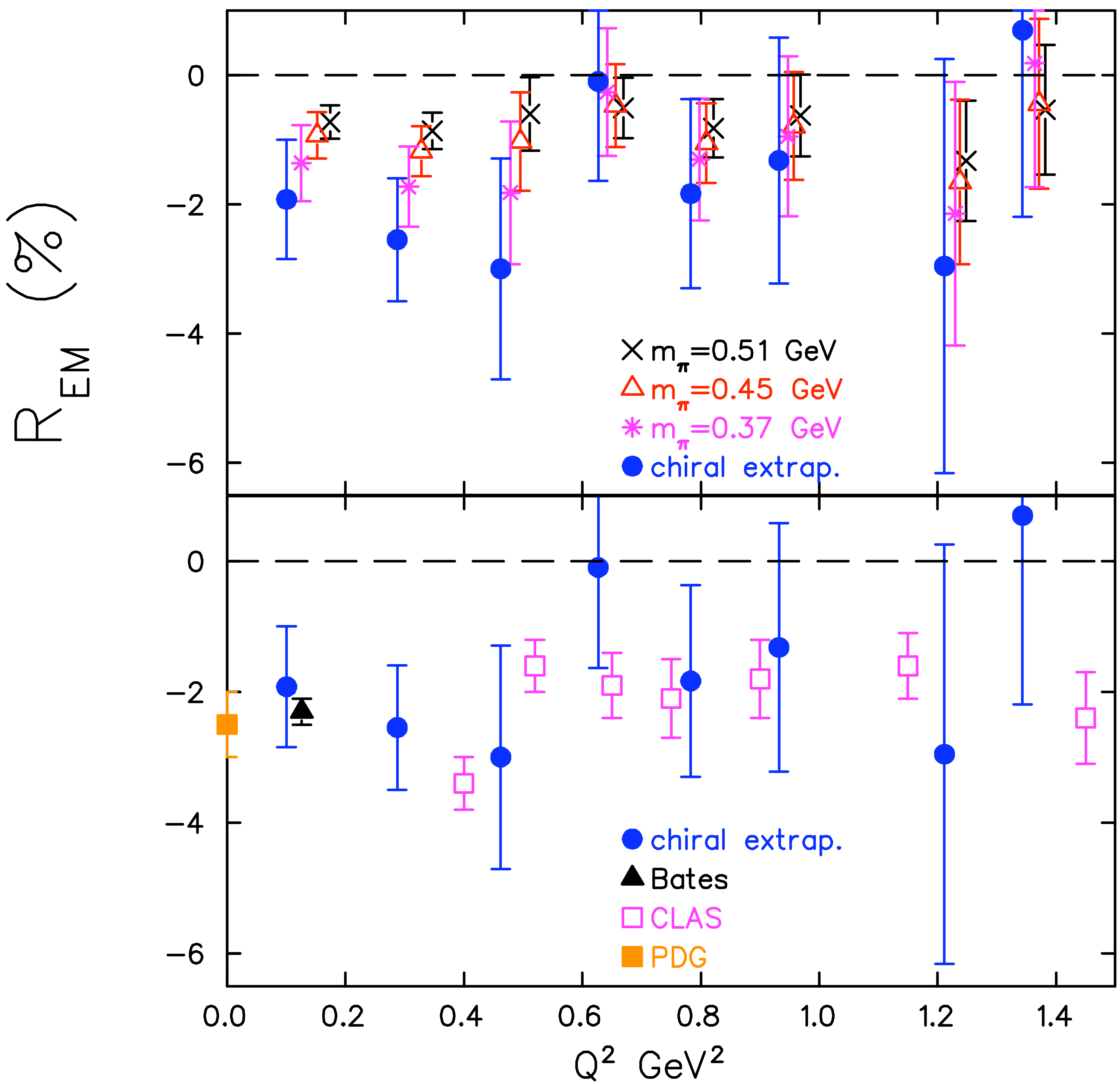
First results

- M1 transition form factor: nucl-th/0012046
  quark models predict M1 30% too small
- Phys.Rev.D66:094503(2002) $\Rightarrow R_{EM}, R_{SM}$
- Phys.Rev.Lett. 86,2963(2001)
- Phys.Rev.Lett. 88:122001(2002)
- Eur.Phys.J.A18,141(2003)
  Eur.Phys.J.A17,349(2003)

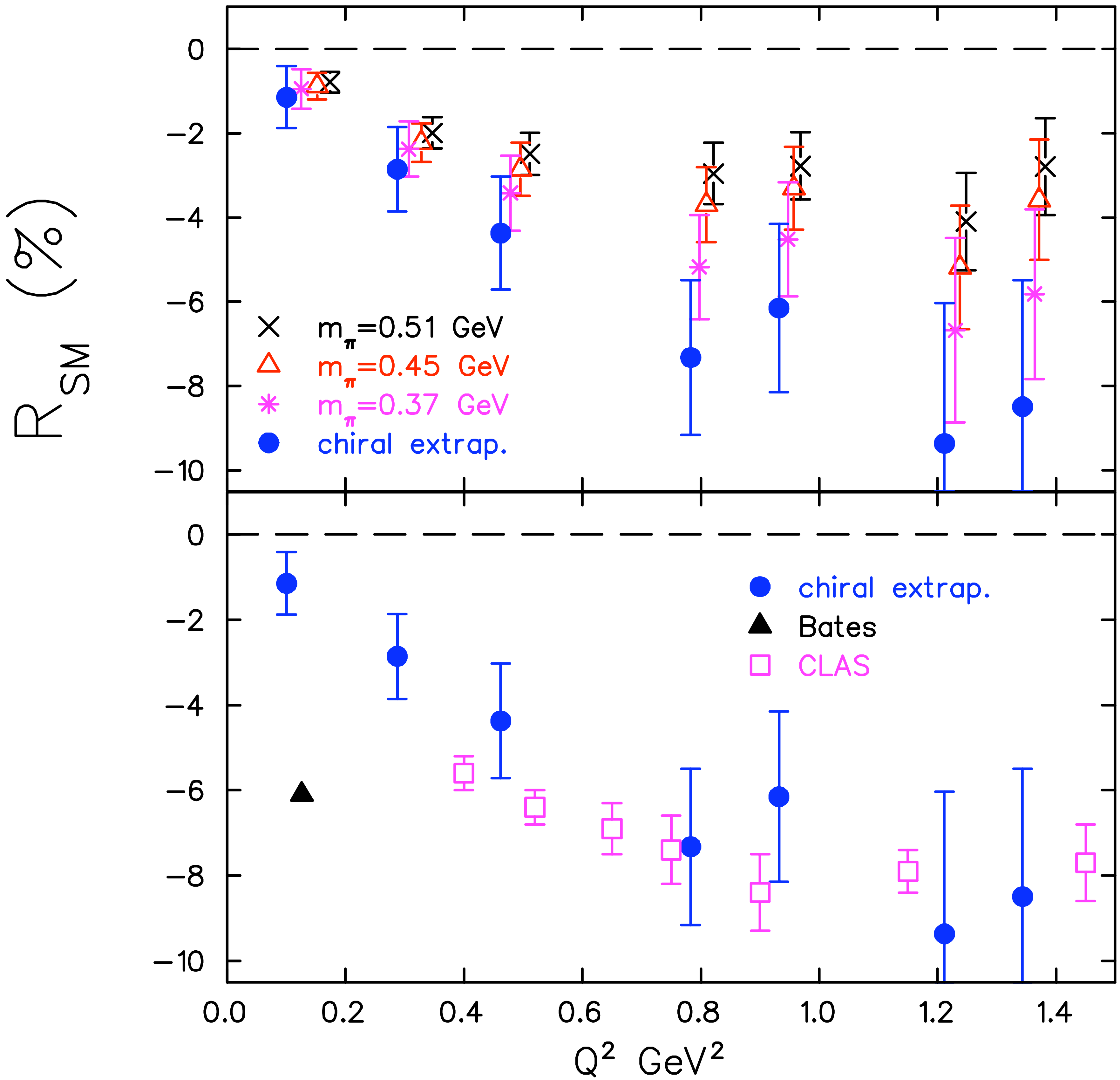
Quenched results



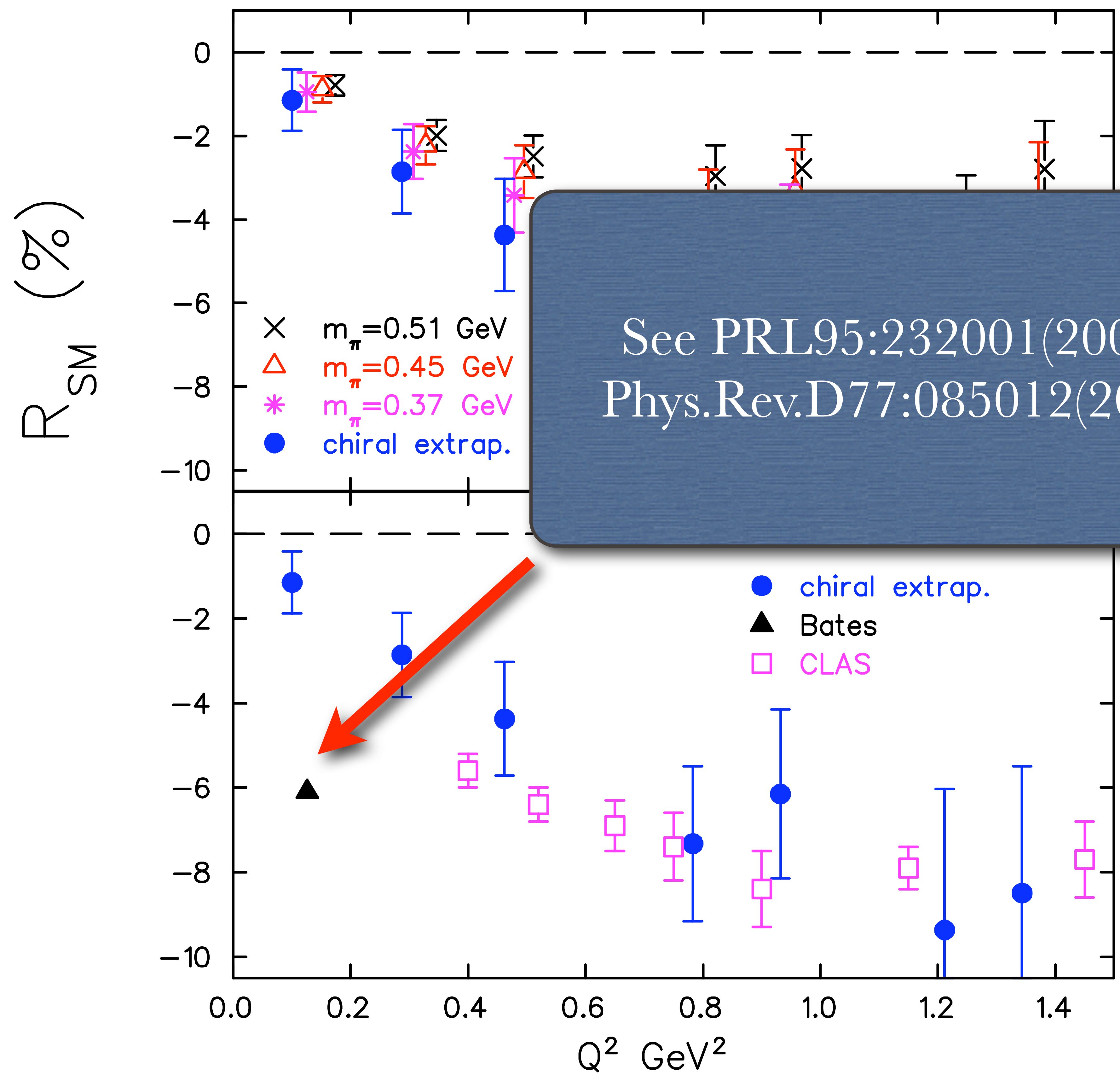
Phys.Rev.Lett. 94:021601 (2005)



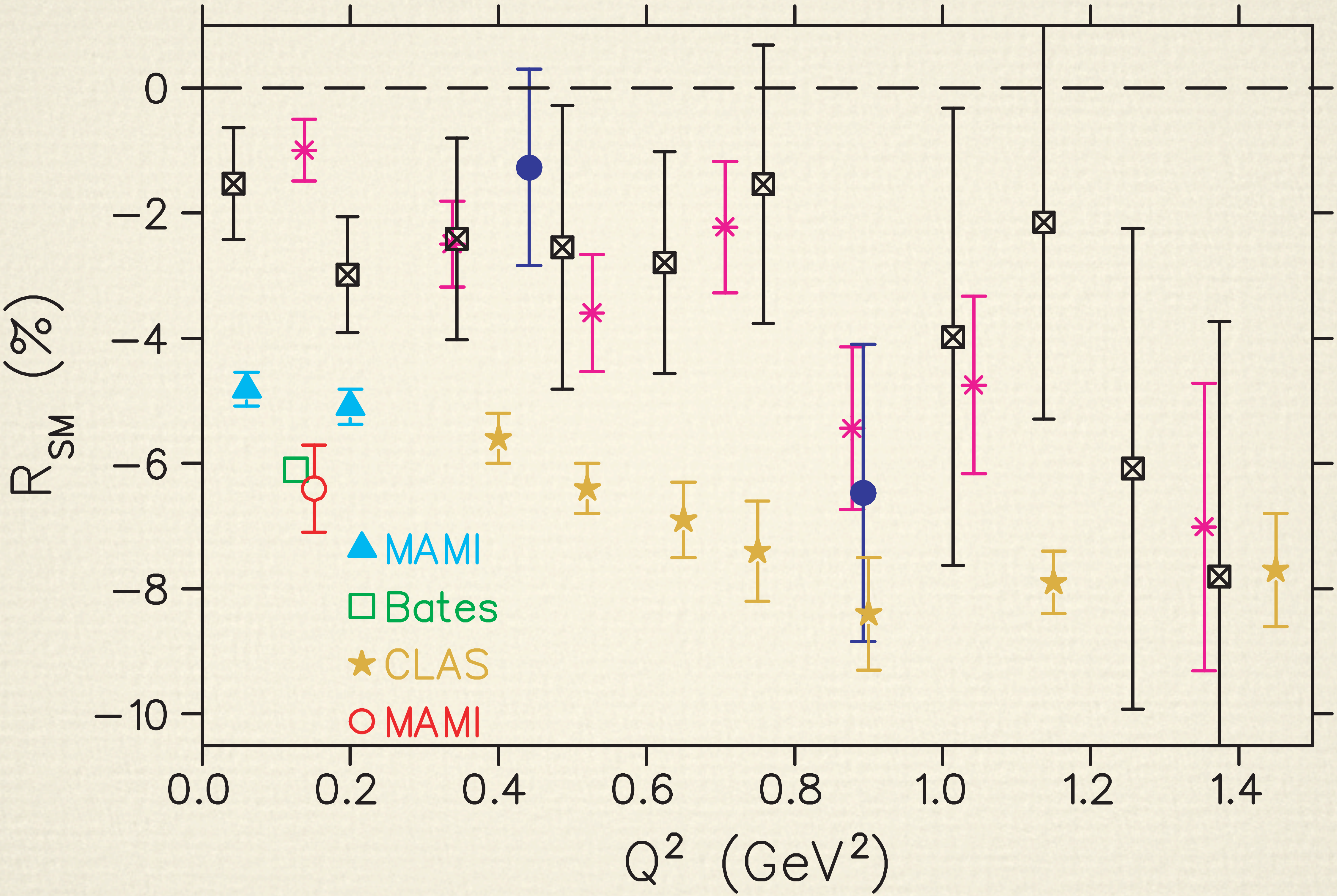
R_{EM} (%)
0
−2
−4
−6
m_π=0.51 GeV
m_π=0.45 GeV
m_π=0.37 GeV
chiral extrap.
Bates
CLAS
PDG
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Q^2 GeV^2



R_{SM} (%)
m_π=0.51 GeV
m_π=0.45 GeV
m_π=0.37 GeV
chiral extrap.
chiral extrap.
Bates
CLAS
0
−2
−4
−6
−8
−10
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Q^2 GeV^2



See PRL95:232001(2005), Phys.Rev.D77:085012(2008)



Phys.Rev.D77:085012(2008)

Quark spin contribution

Decomposition of nucleon spin:

$$\frac{1}{2} = J_q + J_g = \frac{1}{2}\Sigma + L_q + J_g$$

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Quark spin contribution

Decomposition of nucleon spin:

$$\frac{1}{2} = J_q + J_g = \frac{1}{2}\Sigma + L_q + J_g$$

Total quark contribution:

$$\vec{J}_q = \int d^3r \left[\vec{r} \times \vec{T}\right]$$

$$= \int d^3r \, \psi^\dagger \left[\vec{\Sigma}/2 + \vec{r} \times (-\mathrm{i}\vec{D})\right] \psi$$

Energy momentum tensor

$$\langle p'|\bar{\psi}_q \gamma^{\{\mu} \mathrm{i} D^{\nu\}} \psi_q |p\rangle = \begin{array}{l} A^q_{20}(t) \langle\!\langle \gamma^{\{\mu} \rangle\!\rangle \bar{p}^{\nu\}} \\ + B^q_{20}(t) \frac{\mathrm{i}}{2m} \langle\!\langle \gamma_5 \rangle\!\rangle \bar{p}^{\{\mu} \Delta^{\nu\}} \\ + C^q_2(t) \frac{1}{m} \langle\!\langle 1 \rangle\!\rangle \Delta^\mu \Delta^\nu \end{array}$$

After some algebra we find

$$J_q = \sum_{q=u,d} \lim_{t \to 0} \left(A^q_{20}(t) + B^q_{20}(t) \right)$$

See Phys.Rev.Lett. 78:610 (1997) (X.D. Ji)

Nucleon axial structure

$$\langle p'|\bar{\psi}_q \gamma^\mu \gamma_5 \psi_q|p\rangle = \tilde{A}^q_{10}(t)\langle\!\langle \gamma^\mu\gamma_5 \rangle\!\rangle + \tilde{B}^q_{10}(t)\frac{\mathrm{i}}{2m}\langle\!\langle \gamma_5 \rangle\!\rangle \Delta^\mu$$

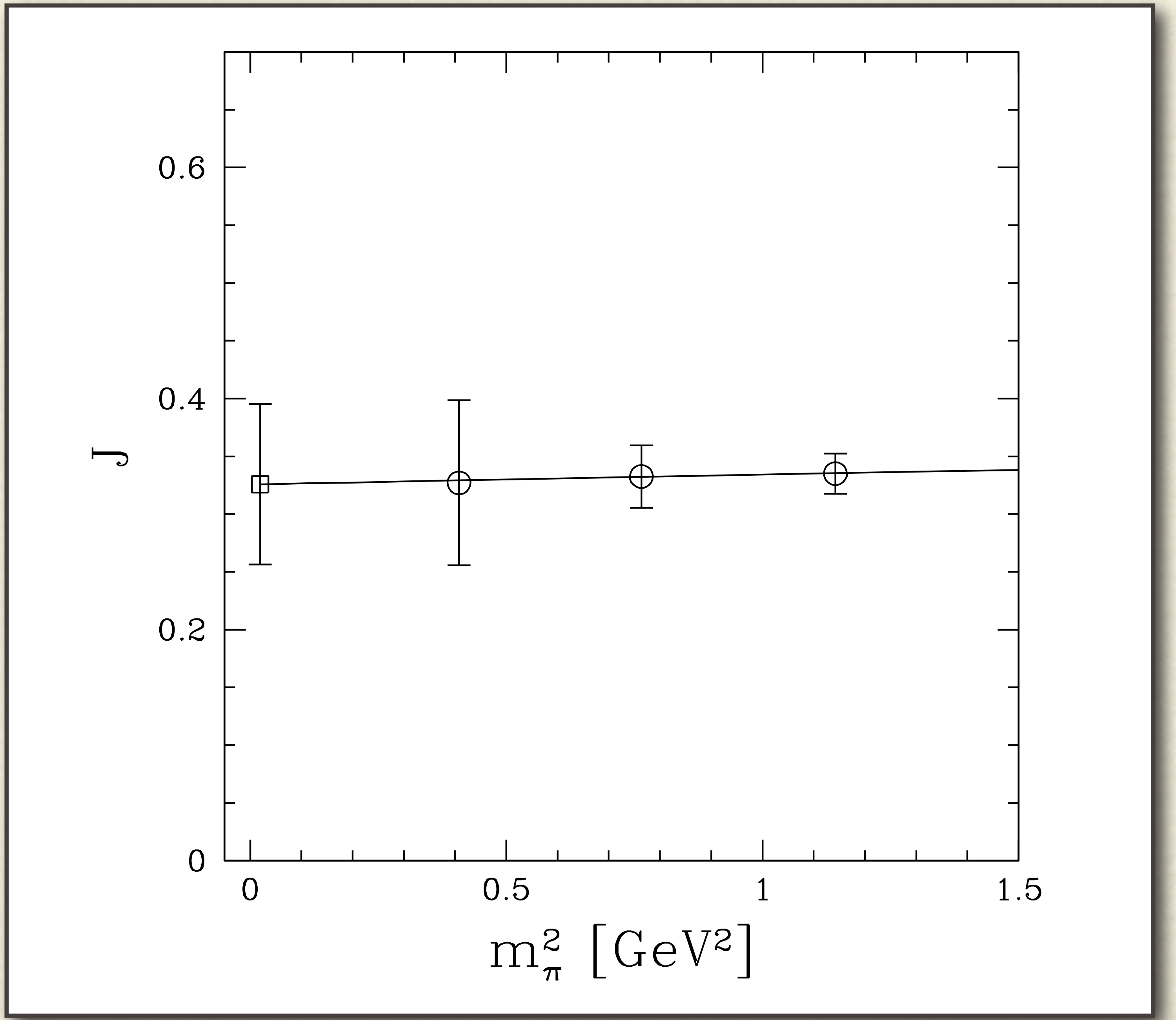
Now one obtains

$$\frac{1}{2}\Sigma = \tilde{A}^{\mathrm{u+d}}_{10}(0)$$

Then we can deduce

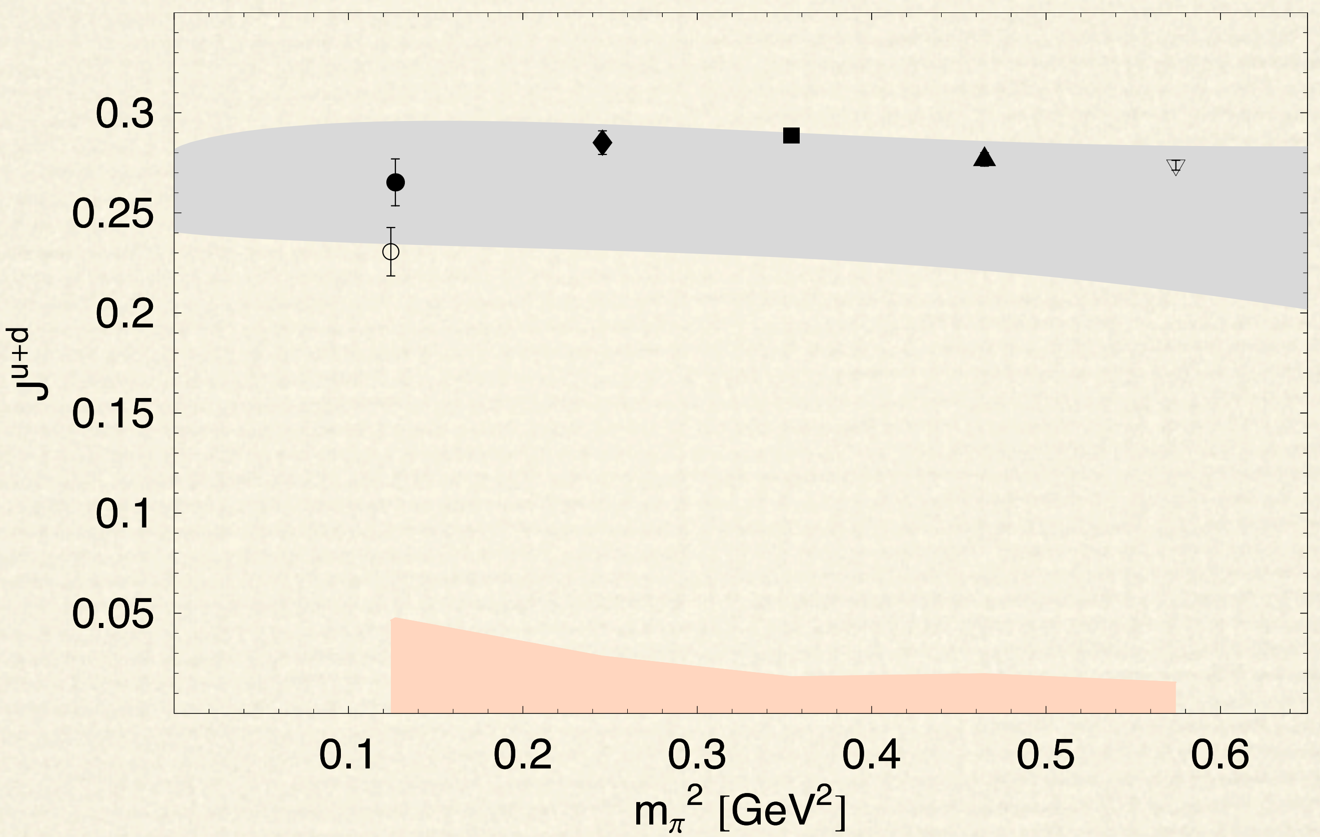
$$L_q \equiv J_{\mathrm{u+d}} - \frac{1}{2}\Sigma$$

Quark spin contribution



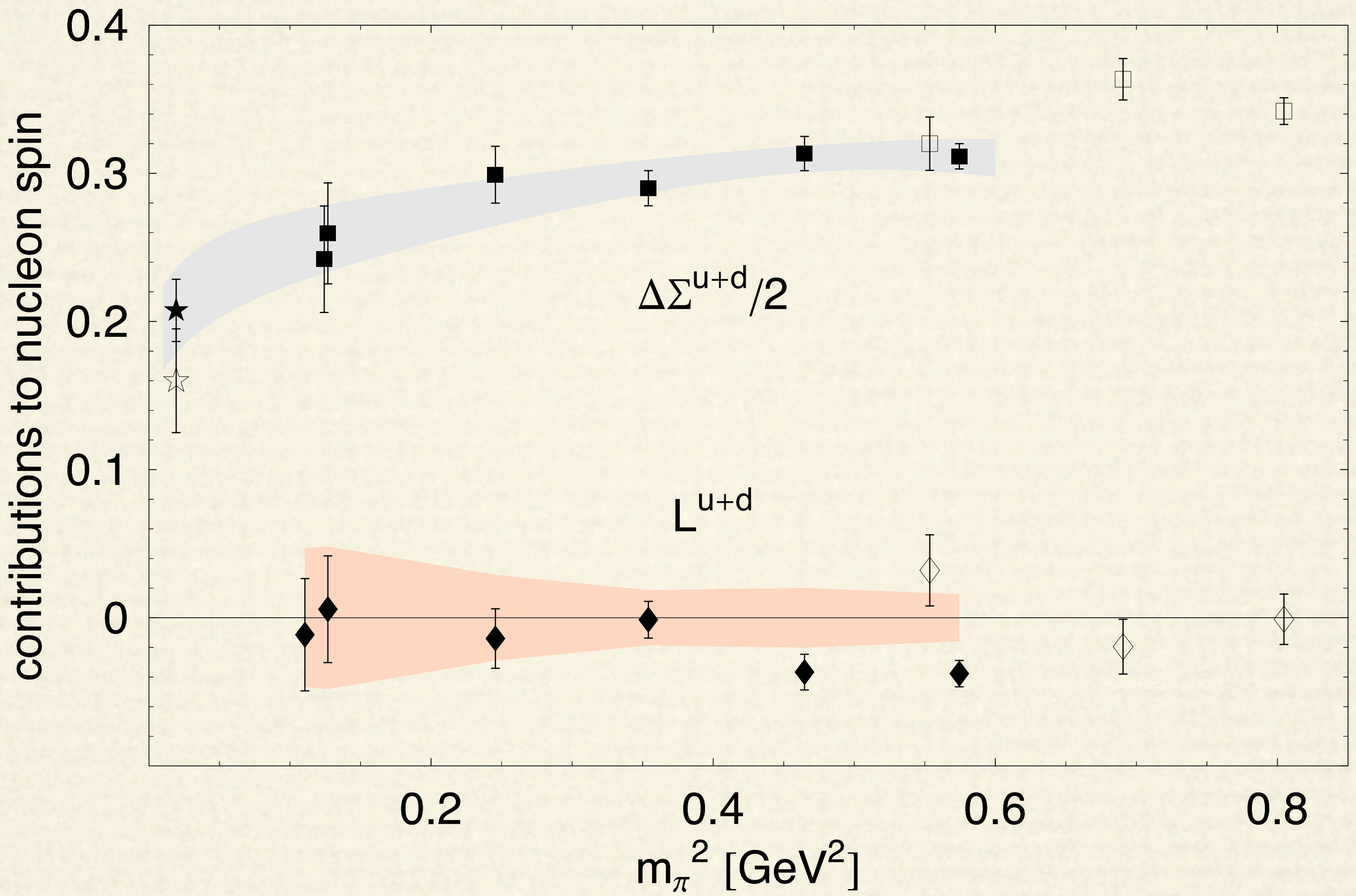
Phys.Rev.Lett. 92:042002 (2004)

LHPC hybrid action



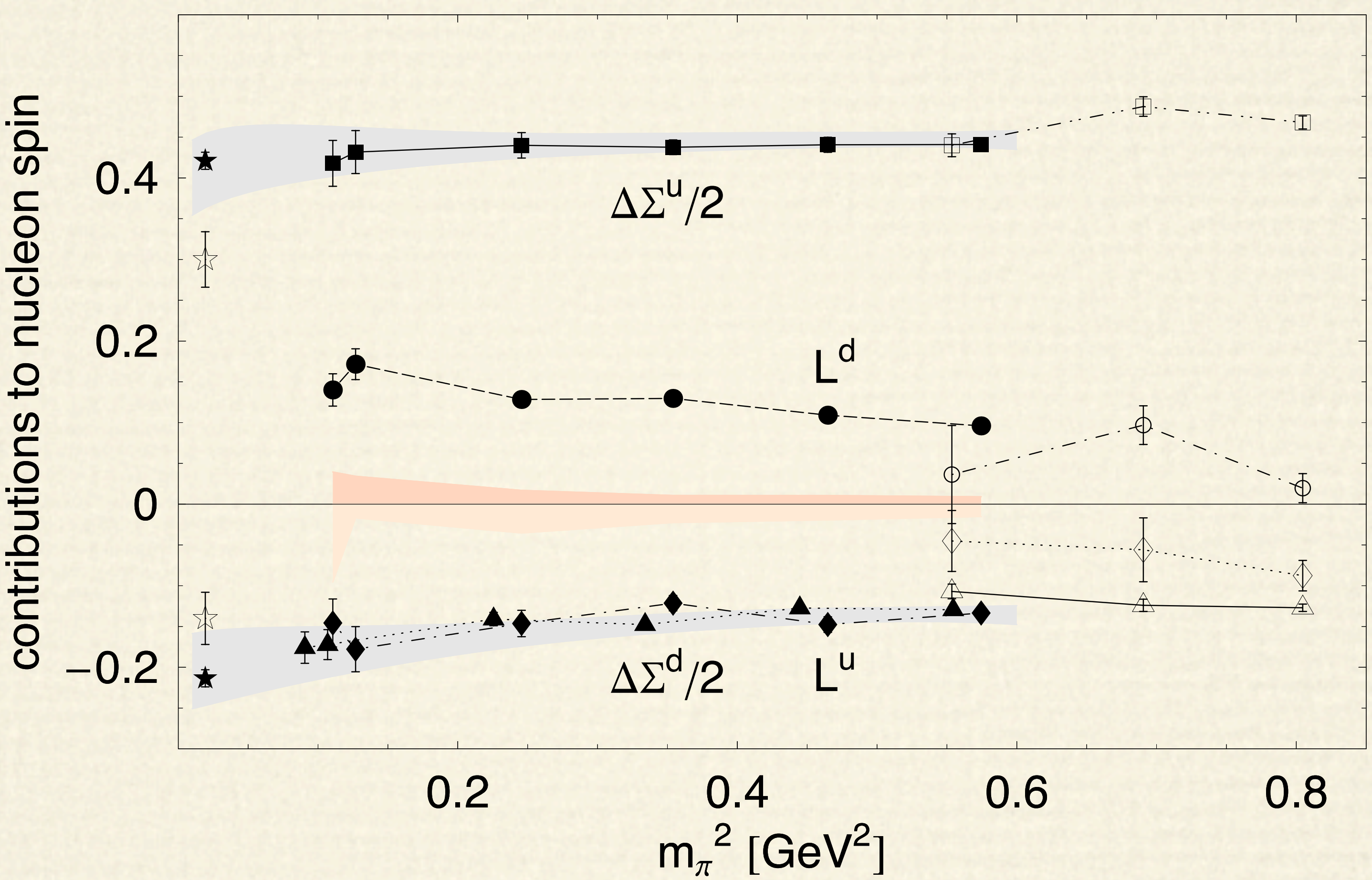
Phys.Rev.D77:094502(2008)

LHPC hybrid action



Phys.Rev.D77:094502(2008)

LHPC hybrid action



Phys.Rev.D77:094502(2008)

Remarkable Features

- Cancellation of OAM for u+d quarks
- Cancellation between OAM and spin contribution for down quarks
- Qualitative features over entire mass range

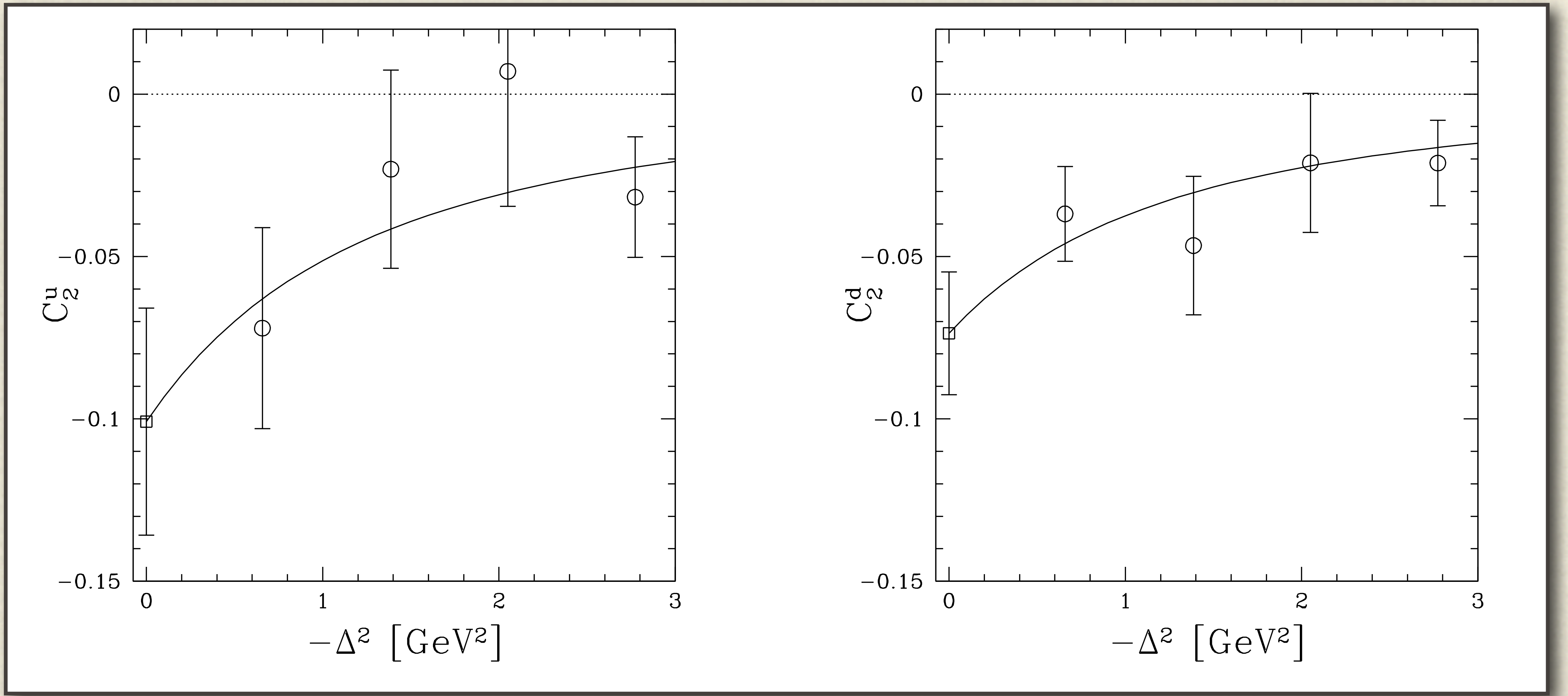
Other Publications

- Similar approach: PRD62:114504 (2000)
- Alternative approach:
  Direct computation of $\langle\vec{p}|y_j J_i(y)|\vec{p}\rangle$

  PD65:094510 (2002) (V. Gadiyak et al)

  But: see PD66:017502 (2002) (W. Wilcox)

The “D”-term



From Phys.Rev.Lett. 92:042002 (2004)
Compare to Phys.Rev. D63:114014 (2001)

Hadron transverse structure

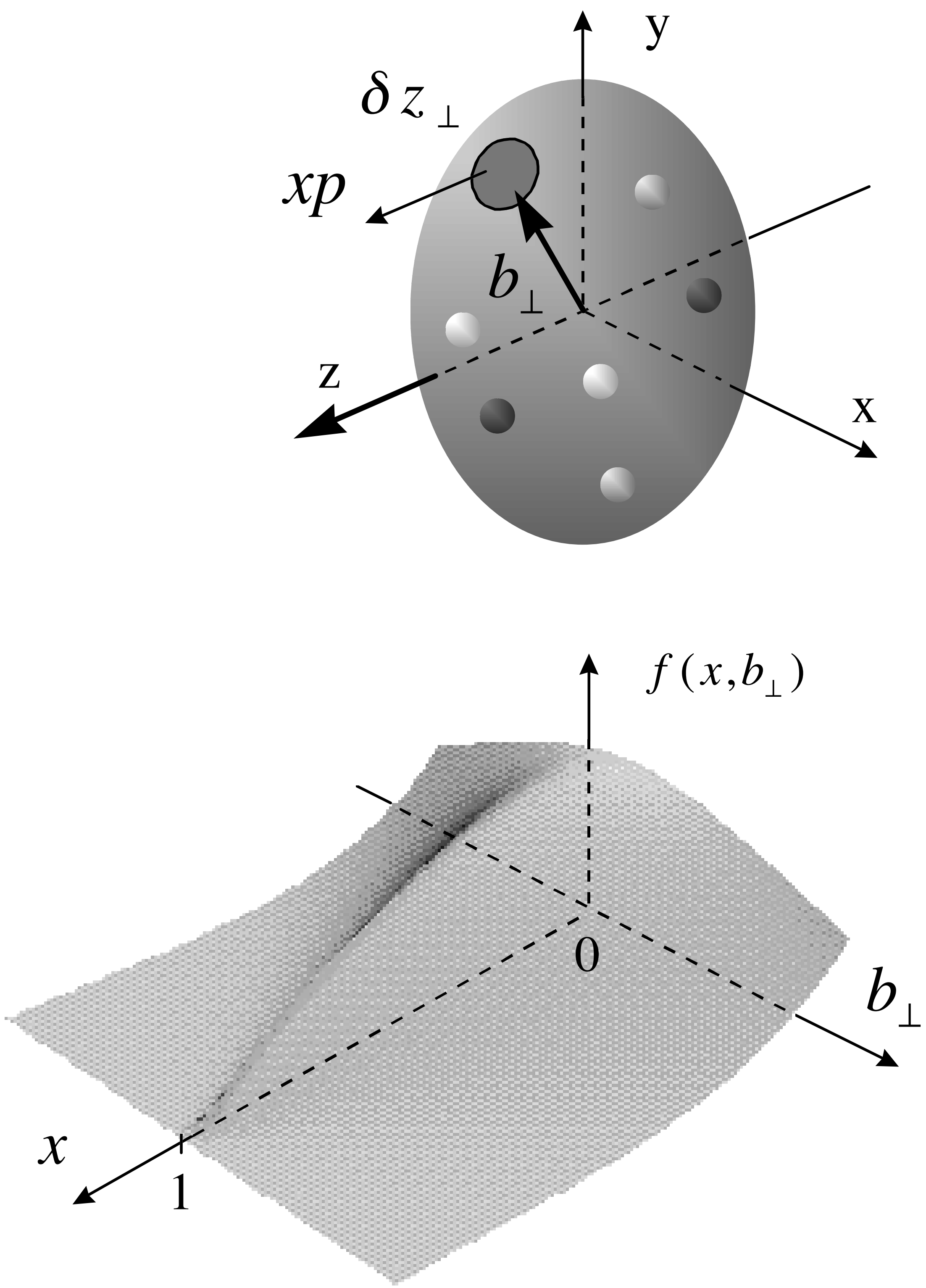
$$H(x, \xi = 0, -\Delta_\perp^2)$$

measures Fourier transform of

$$q(x, b_\perp)$$

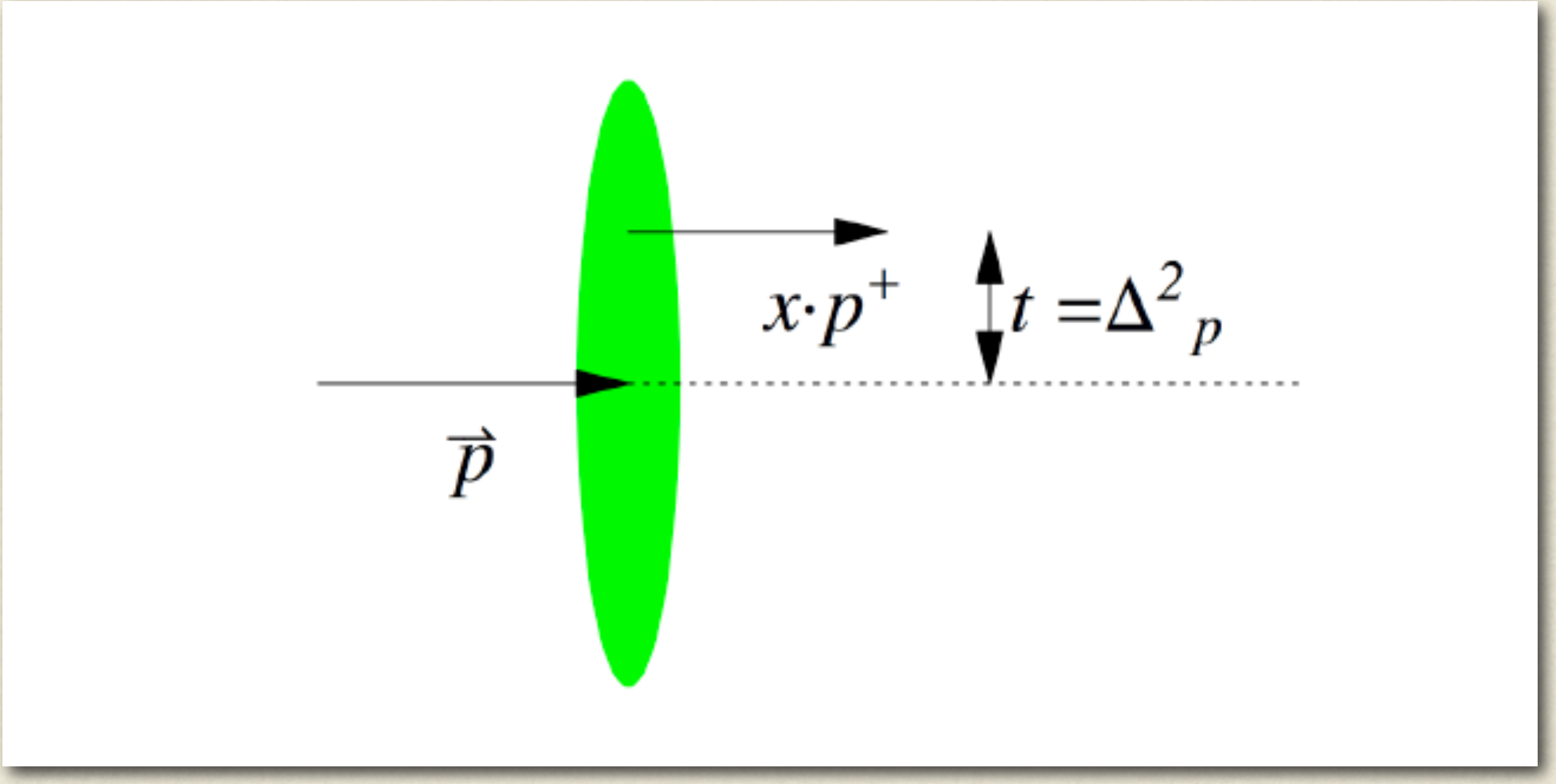
Phys.Rev. D62:071503 (2000) (M. Burckardt)
For $\xi \neq 0$: Phys.Rev. D66:111501 (2002) (Ralston,Pire)
Eur.Phys.J. C25:223 (2002) (M. Diehl)

- Generalized parton distribution at η=0



Nucl.Phys.Proc.Suppl. 128:203-210 (2004)

Schematic in i.m.f.

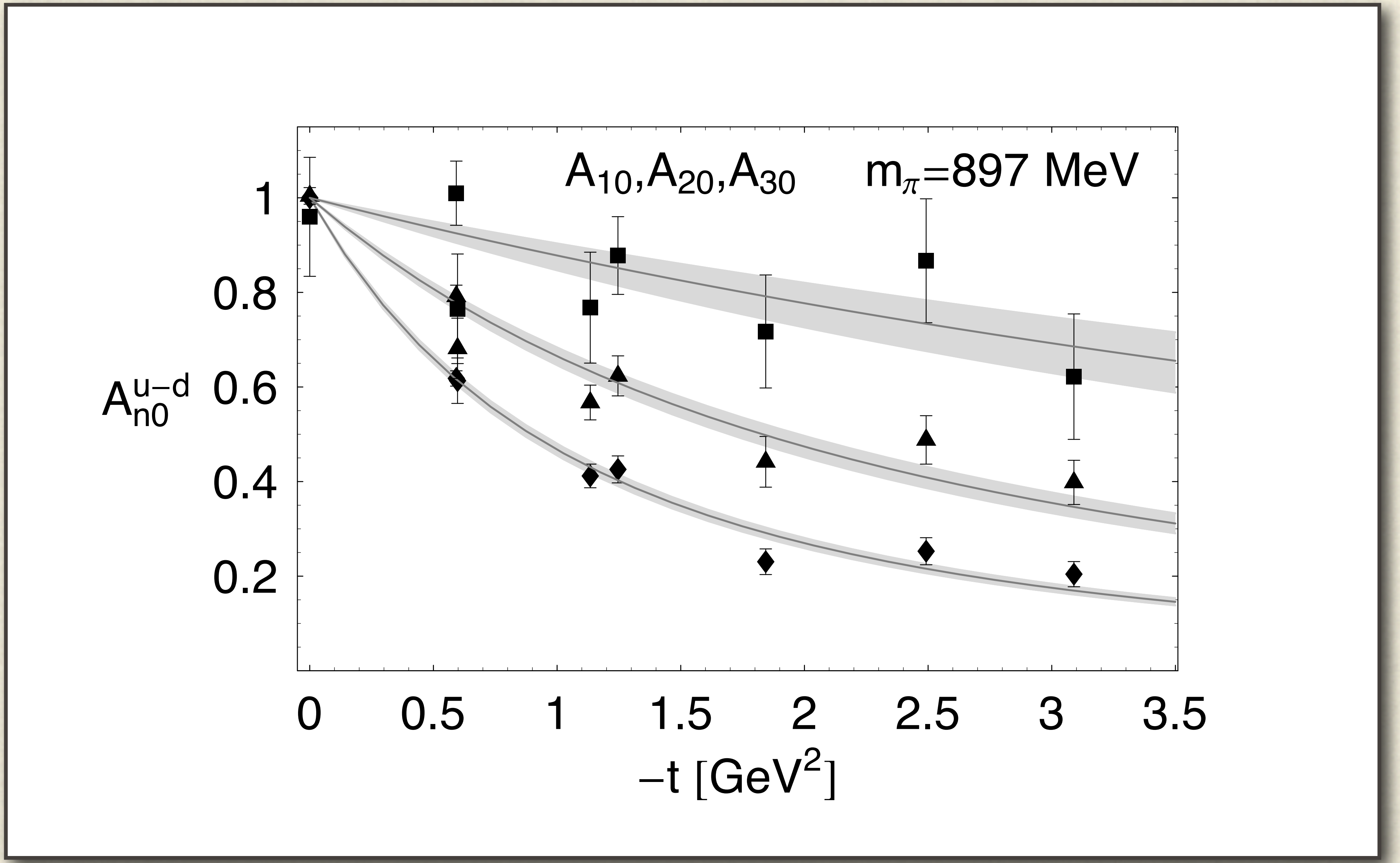


Moments of GPDs

Do the moments depend on ***n*** or not?

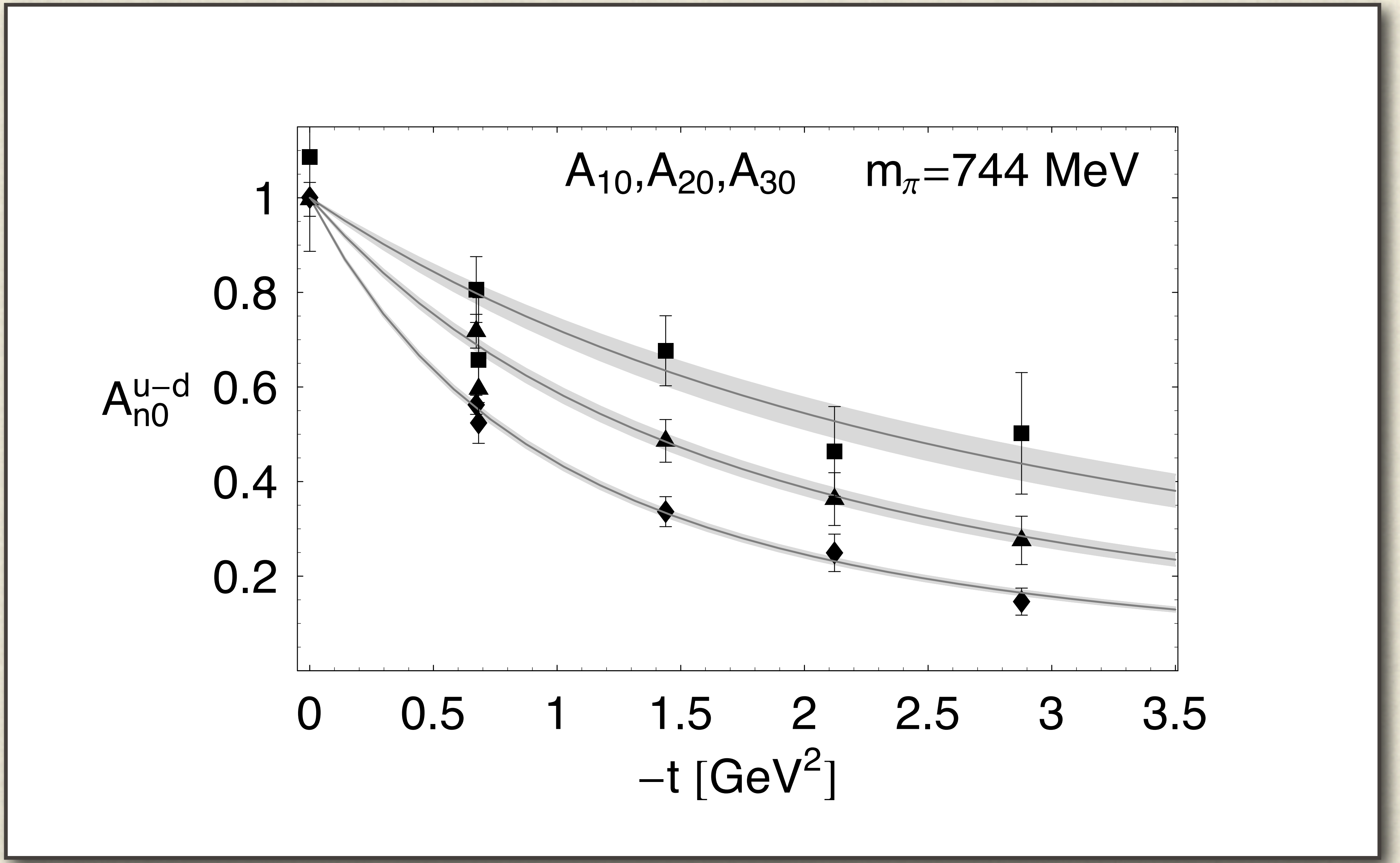
$$A_{n0}(-\Delta_\perp^2) \equiv \int d^2b_\perp\, dx\; x^{n-1} q(x, b_\perp) e^{\mathbf{i}\vec{b}_\perp \cdot \vec{\Delta}_\perp}$$

Does x-dep. factorize?

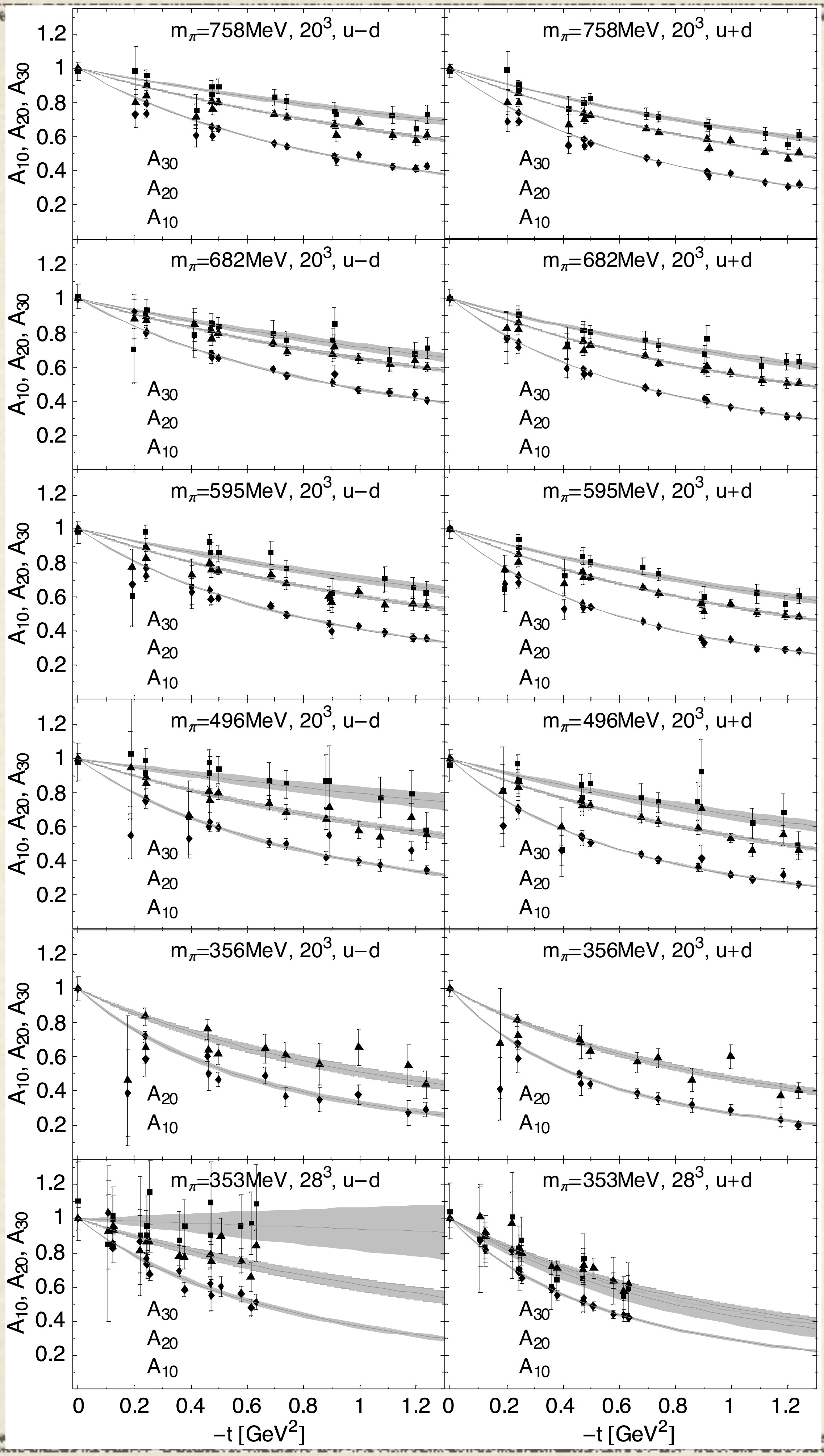


Phys.Rev.Lett. 93:112001(2004)

Also for lighter quarks



Phys.Rev.Lett. 93:112001(2004)



LHPC,
Phys.Rev.
D77:094502(2008)

The axial coupling g_A

- Fundamental property of the nucleon
- Governs β-decay
- Quantitative measure of spont. χSB in hadronic physics
- Known to high accuracy experimentally from neutron β-decay
- Forward limit of nucleon axial form factor

Chiral expansions

- Phys.Rev. D70:074029 (2004) (Beane&Savage)
- Phys.Rev. D71:054510 (2005) (Detmold & Lin)
- Phys.Rev. D68:075009 (2003) (Hemmert et.al.)
- Phys.Rev. D66:054501 (2002) (Detmold et.al.)
- Phys.Rev. D74:094508 (2006) (QCDSF coll.)

Chiral expansions

Our (LHPC) paper

- Phys.Rev. D70:074029 (2004) (Beane&Savage)
- Phys.Rev. D71:054510 (2005) (Detmold & Lin)
- Phys.Rev. D68:075009 (2003) (Hemmert et.al.)
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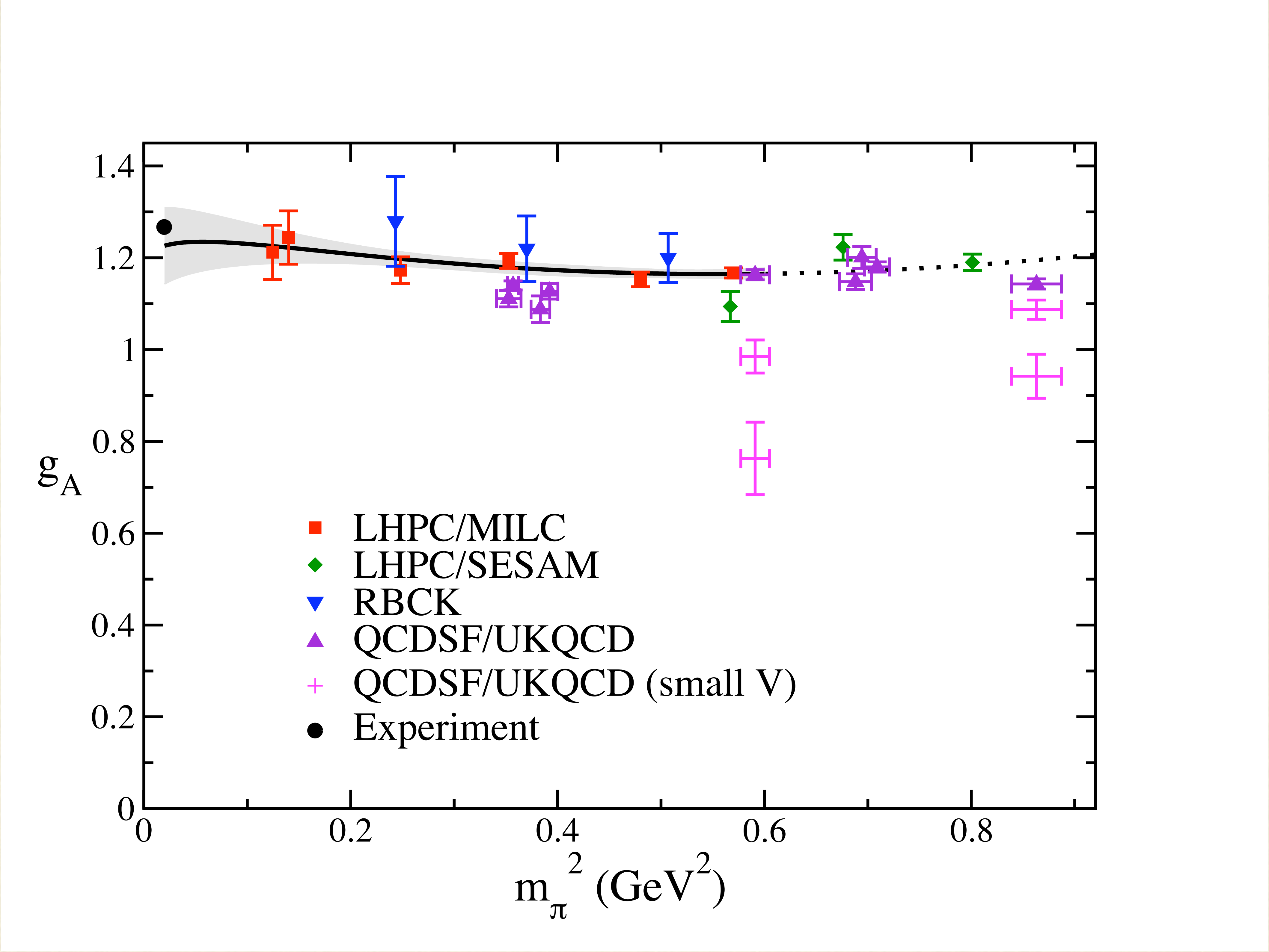
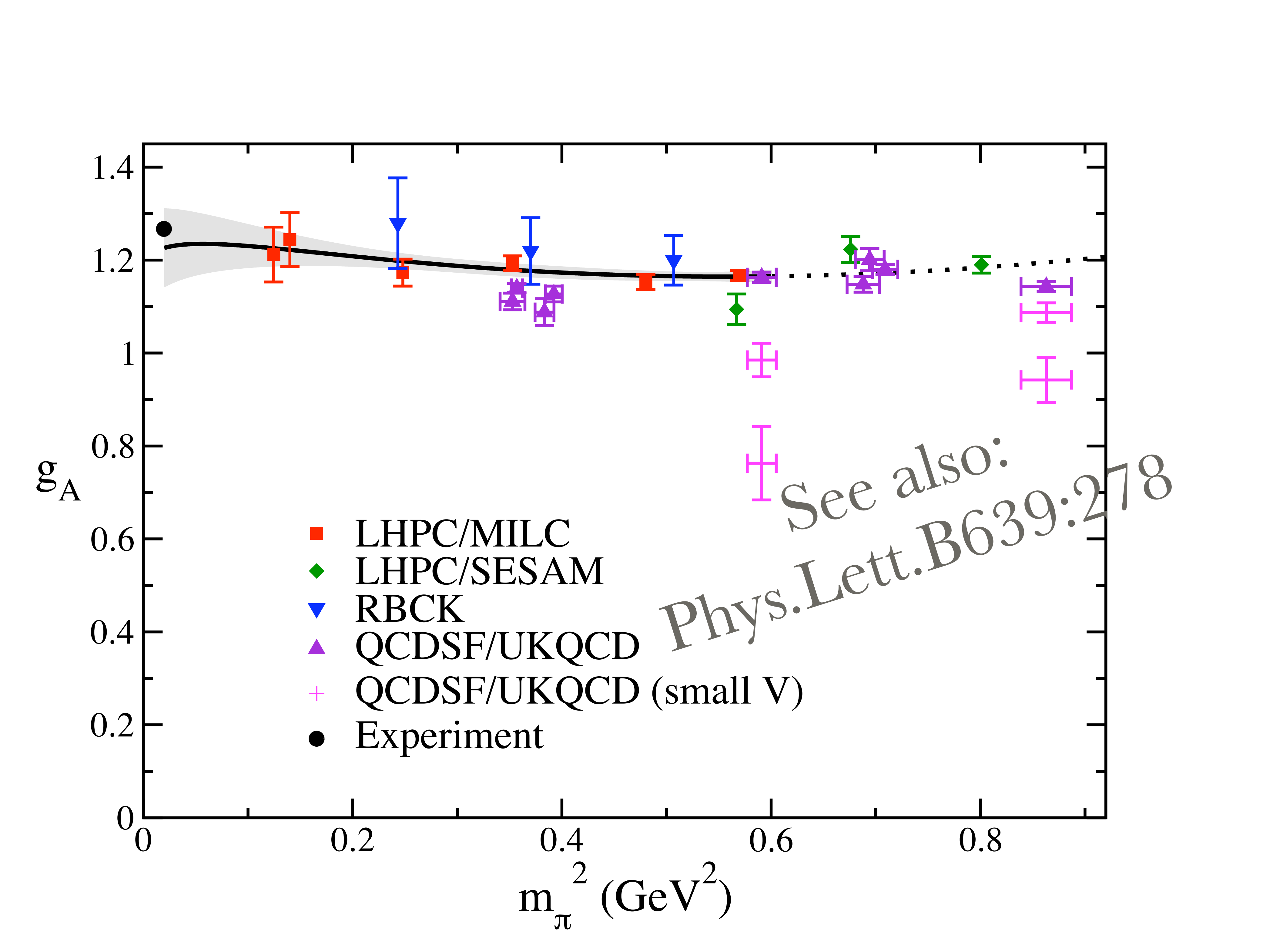


Phys.Rev.Lett. 96:052001 (2006)
W. Schroers, EPJ A31:784 (2007)



Phys.Rev.Lett. 96:052001 (2006)
W. Schroers, EPJ A31:784 (2007)

Summary: g_A

Experiment (neutron β decay)	$g_A = 1.2695(29)$
PRL 96:052001 (2006)	$g_A = 1.226(84)$
PR D74:094508 (2006)	$g_A = 1.31(9)(7)$

Summary & Outlook

Summary

- Three key applications
- Major progress in lattice simulations
- Qualitative insight into nucleon structure
- Quantitative results slowly becoming available
- Progress benefits from χEFT

Outlook

- QCDSF simulations reach down to m_{PS}≈350 MeV (2006), currently running m_{PS}≈250 MeV (2009)
- Hope to reach m_{PS}≈200 MeV by the end of this decade
- LHPC focusses on full DWF, similar quark masses
- TWQCD/JLQCD: Full optimal DW +disconnected diagrams