Lattice QCD calculation of the Compton subtraction function

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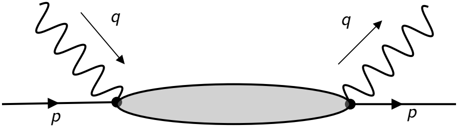
Eddie Sankey

In collaboration with QCDSF/UKQCD

Forward Compton Amplitude

- The process of virtual scattering on a hadron (we will consider a proton)



- $Q^2 = -q^2$ - Photon virtuality
- $x = \frac{Q^2}{2p \cdot q}$ - Bjorken scaling variable
- $\omega = \frac{1}{x}$ - Inverse Bjorken scaling variable

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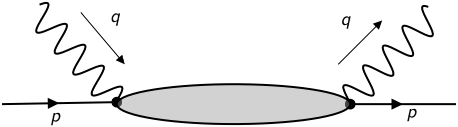

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Spin-averaged Compton amplitude:

$$T_{\mu\nu}(p,q) = i \int d^4 z \; e^{iq\cdot z} \rho_{s,s'} \langle p, s' | \mathcal{T}\{\mathcal{J}_\mu(z)\mathcal{J}_\nu(0)\} | p, s \rangle$$

Subtraction function

- Compton amplitude can be decomposed into Lorentz invariant structure functions

$$T_{\mu\nu}(p,q) = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) T_1(\omega, Q^2) + \left(p_\mu - \frac{p\cdot q}{q^2} q_\mu\right)\left(p_\nu - \frac{p\cdot q}{q^2} q_\nu\right) \frac{T_2(\omega, Q^2)}{p\cdot q}$$

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- T_1 and T_2 be related to DIS structure functions F_1 and F_2:
- Recently calculated using Feynman-Hellmann methods (K. U. Can et al. Phys. Rev. D 102, 114505)

$$T_1(\omega, Q^2) - T_1(0, Q^2) = 4\omega^2 \int_0^1 dx \frac{xF_1(x, Q^2)}{1 - x^2\omega^2 - i\epsilon}$$

$$T_2(\omega, Q^2) = 4\omega \int_0^1 dx \frac{F_2(x, Q^2)}{1 - x^2\omega^2 - i\epsilon}$$

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$$\boxed{\text{Define: } S_1(Q^2) \equiv T_1(0, Q^2)}$$

- Inaccessible directly from experiment

Why do we care?

- Renewed interest;
  - F. Hagelstein, V. Pascalutsa arXiv:2010.11898 [hep-ph] (2020)
  - J. Gasser, H. Leutwyler, A. Rusetsky Phys. Letters B, Volume 814, (2021)
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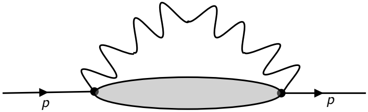
Proton-Neutron mass difference

- The Cottingham sum rule relates the electromagnetic self-energy δM^{γ} to forward Compton scattering
- The need for a subtraction contribution has long been understood



André Walker-Loud et al. arXiv:1210.7777 [hep-lat]

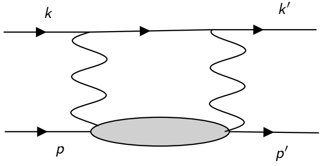
$$M_p - M_n = \delta M^{\gamma} + \delta M^{m_u - m_d}$$

$$\text{with } \delta M^{\gamma} = \delta M^{el} + \delta M^{inel} + \delta M^{subt} + \delta \tilde{M}^{ct}$$

- Subtraction function contribution is dominating uncertainty

Muonic-hydrogen Lamb shift

- Corrections of the two-photon exchange contribution to the Lamb shift are explicitly dependent on the Compton structure functions



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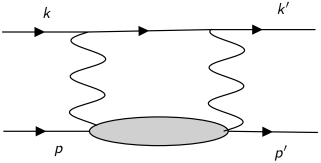

M.Gorchtein, F.J.lanes-Estrada and A. P. Szczepaniak, Phys. Rev. A87, 052501 (2013)

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- These corrections are needed to extract the proton charge radius

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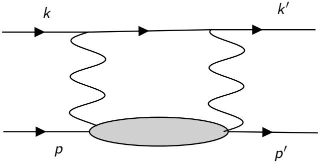

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Dominant uncertainties to two precision calculations. A model independent calculation of the subtraction function is needed.

Preliminary calculations

Operator product expansion (OPE) predictions of the asymptotic behaviour give:

$$S_1(Q^2_{\text{large}}) \propto \frac{1}{Q^2}$$

Calculating Compton amplitude with appropriate kinematics we can access $S_1(Q^2)$

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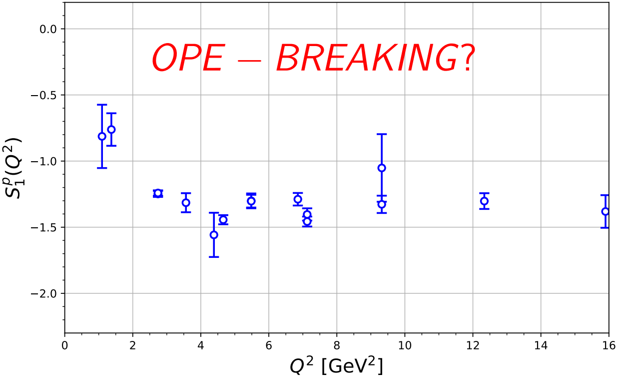

Data from: K.Y. Somfleth, PhD thesis, Uni. of Adelaide (2020)

Second order Feynman Hellmann

- A weakly coupled external field is introduced to the lattice action, $S \mapsto S(\lambda)$
- Calculate energy shifts to access matrix elements

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equating to second derivative of the spectral decomposition (See K. U. Can et al. Phys. Rev. D 102, 114505 for full derivation with a linear action shift):

$$\text{2nd order FH:} \quad \left. \frac{\partial^2 E_{N,\lambda}(\vec{p})}{\partial \lambda^2} \right|_{\lambda=0} = -\frac{T_{\mu\mu}(p,q) + T_{\mu\mu}(p,-q)}{2E_N} + \left\langle \mathcal{G} \frac{\partial^2 S(\lambda)}{\partial \lambda^2} \right\rangle$$

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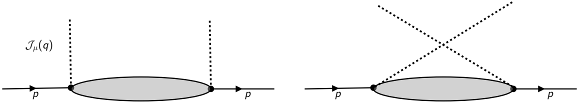
Diagrams introduced through action shift:



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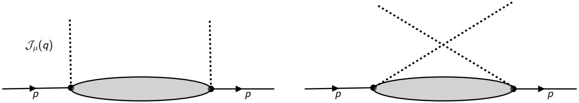

In our chosen kinematics $p = q_z = 0$ with $\mu = 3$

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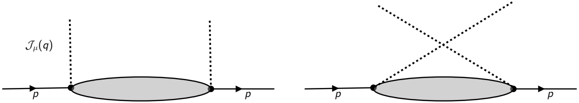

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Current discretisations

Commonly implemented current "Connected local vector current"
Recall the fermion action

$$S_F = a^4 \sum_{n,m \in \Lambda} \bar{q}(n)\mathcal{D}(n,m)q(m).$$

Introducing the quark bilinear to connected part of the action

$$S_F \mapsto S_F(\lambda) = S_F + \lambda \sum_{n \in \Lambda} \left(e^{i\mathbf{q}\cdot\mathbf{n}} + e^{-i\mathbf{q}\cdot\mathbf{n}}\right) V_\mu^{loc}(n),$$

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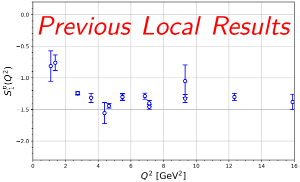

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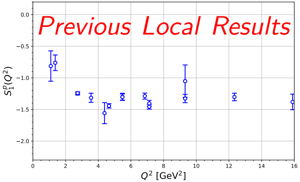

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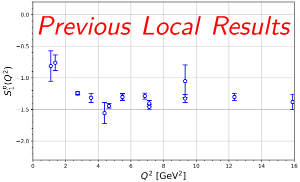

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- Is this OPE-breaking behaviour a result of our current implementation?

Conserved current

To implement a conserved vector current we transform the gauge links:

$$U_\mu(n) \to U_\mu(n) e^{i\lambda\phi(n)} \approx U_\mu(n) + i\phi(n)\lambda U_\mu(n) + \mathcal{O}(\lambda^2), \quad \phi(n) = e^{i\mathbf{q}\cdot\mathbf{n}} + e^{-i\mathbf{q}\cdot\mathbf{n}}.$$

Taking the derivative of our modified Wilson fermion action:

$$\frac{\partial S_F(\lambda)}{\partial \lambda} = a^4 \sum_n i\phi(n) V_\mu^{cons}(n) + \mathcal{O}(\lambda),$$

for some specified direction μ.

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Conserved current results

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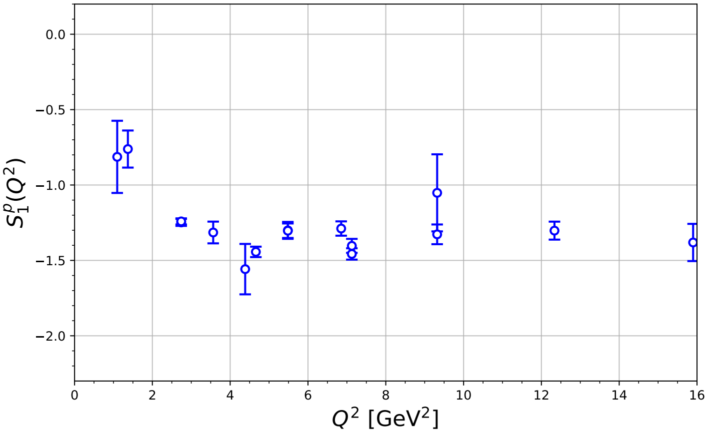

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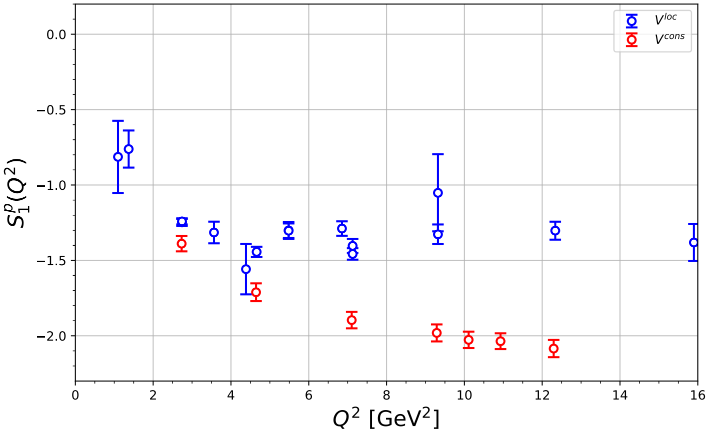

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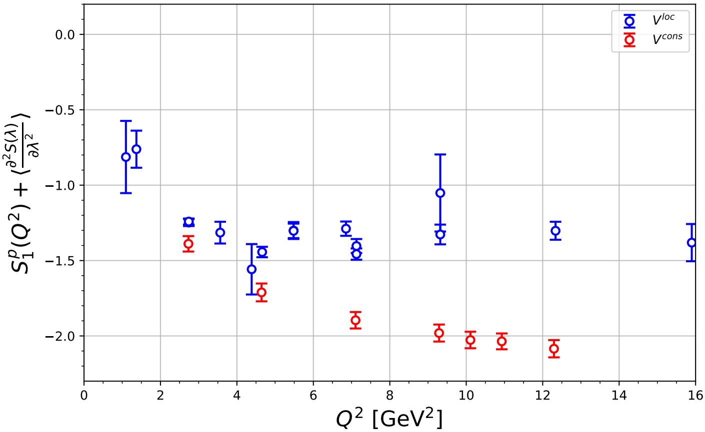
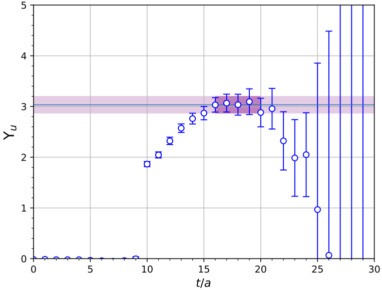
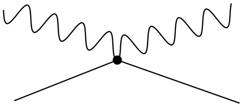


The extra $\left\langle \frac{\partial^2 S(\lambda)}{\partial \lambda^2} \right\rangle$ needs to be accounted for in order to isolate the subtraction function.

Seagull

- $\Upsilon = \phi^2 \bar{q}(n) \sum_{n,m\in\Lambda} \left[\frac{1}{2}(r+\gamma_3) U_3^\dagger(n) \delta_{n,m-\hat{z}} + \frac{1}{2}(r-\gamma_3) U_3(n) \delta_{n,m+\hat{z}} \right] q(m)$
- Can be calculated using regular 3pt methods





- Independent of Q^2, only needs to be calculated once!

$$\Upsilon_u = 3.03 \pm 0.17 \quad \Upsilon_d = 2.08 \pm 0.12$$

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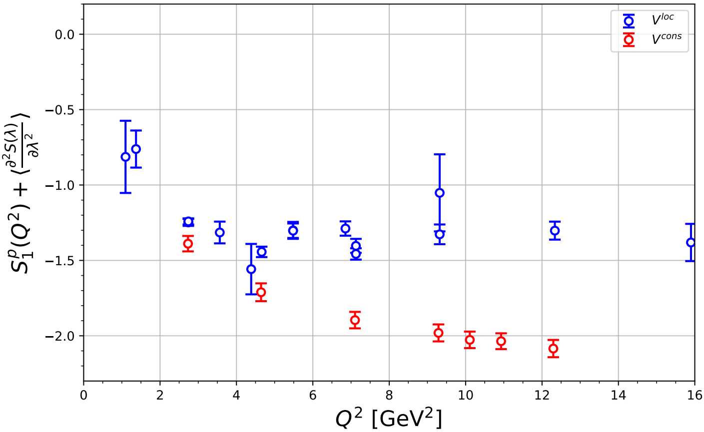

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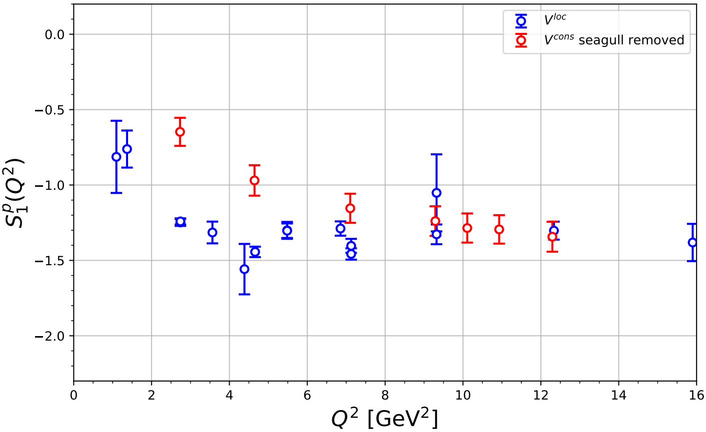
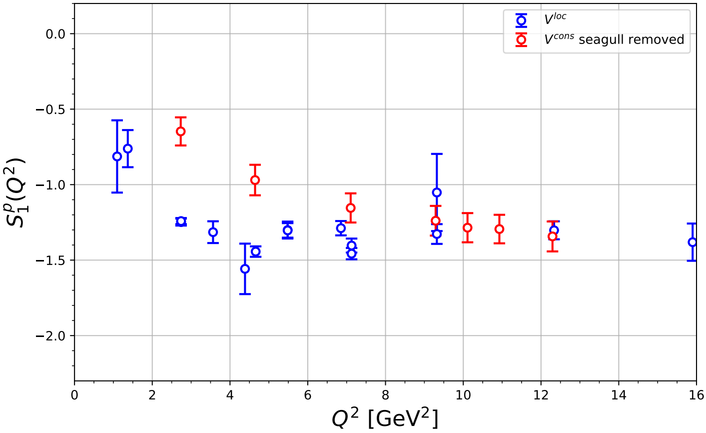


Lattice spacing/volumes

- Does this OPE-breaking behaviour survive the continuum limit?
- How sensitive is this to lattice spacing/volume?

Lattice spacing/volumes

$L^3 \times T$	J_μ	β	$a[fm]$	$m_\pi [GeV]$	$Q^2 [GeV^2]$	N_{conf}
$32^3 \times 64$	V_3^{loc}	5.50	0.074	0.467	$\in [0.247, 15.9]$	$600 - 10000$
	V_3^{cons}	5.50	0.074	0.467	$\in [2.7, 15.9]$	1000
$48^3 \times 96$	V_3^{loc}	5.65	0.068	0.410	$\in [1.43, 9.29]$	1600
		5.80	0.058	0.427	$\in [4.80, 9.62]$	300, 620, 180



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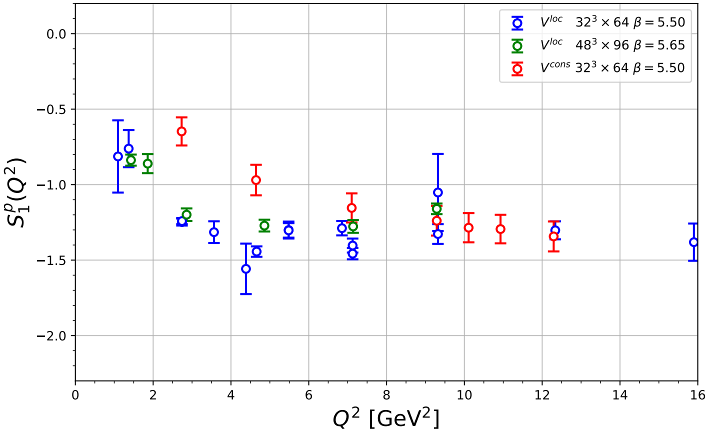

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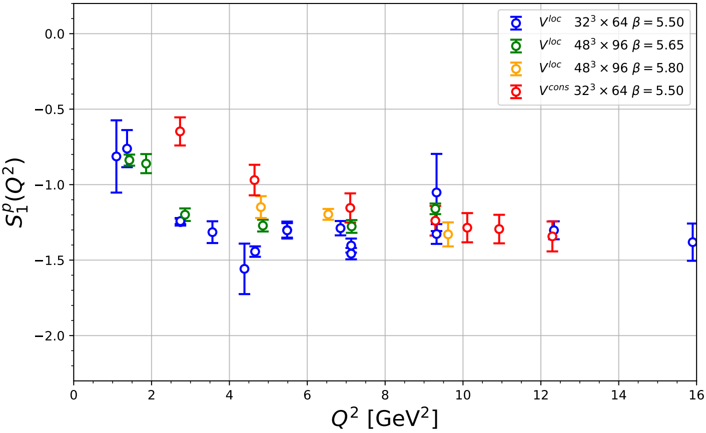
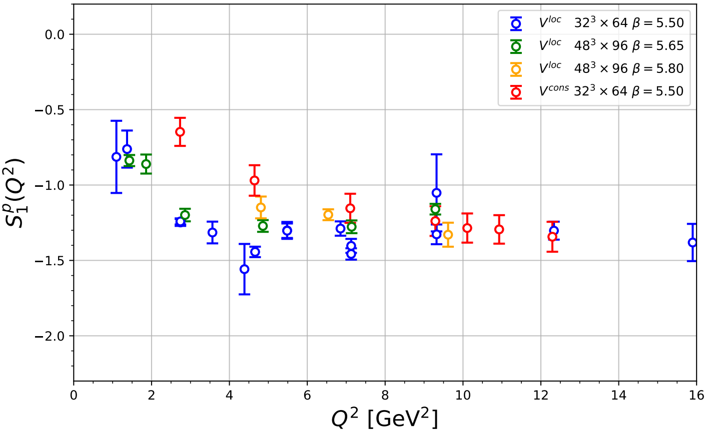


Lattice spacing/volumes

Some minor evidence of spacing and volume dependence

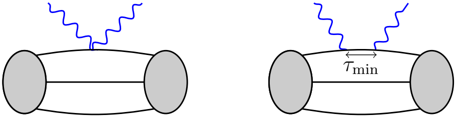


What is issue?

Current work

- Feynman-Hellmann methods feature a sum over time-slices
- Leads to temporal contact terms

- Implementing our currents such that they are ‘interlaced’ temporally
- Reduces OPE-breaking behaviour significantly
- So far has only been applied to local results



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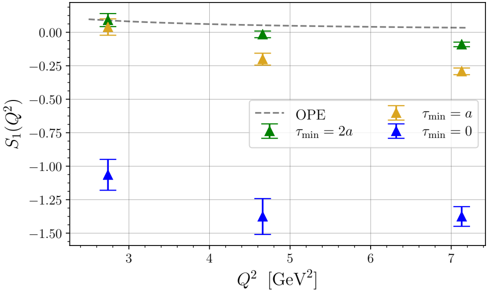

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Outlook

- Apply interlacing method to full set of current results including conserved current
- Quantify effect of temporal contact terms and the continuum limit
- Compare structure of $S_1(Q^2)$ with existing parametrisations

Thank you for listening! Questions?