A universal holographic wavefunction for hadrons

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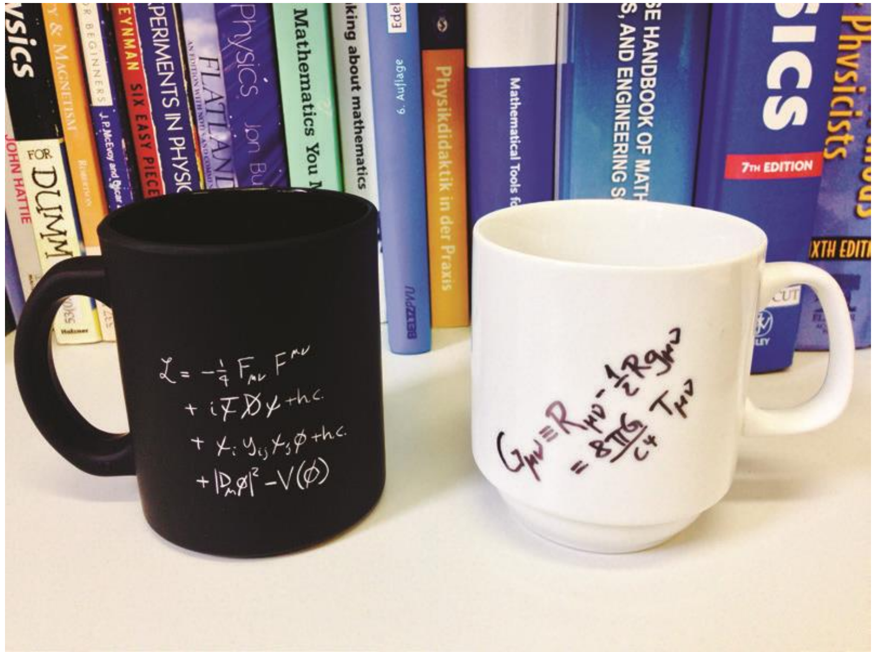
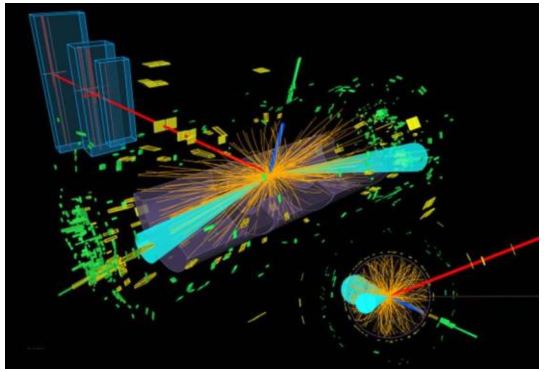
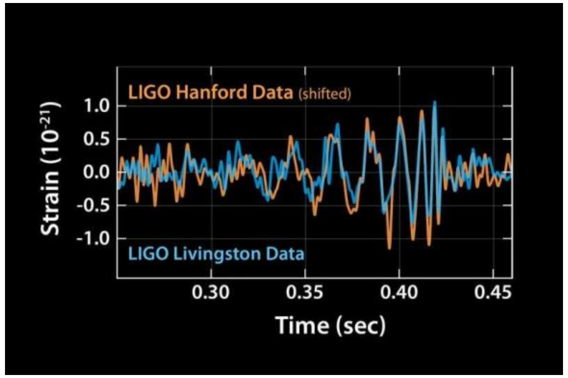
Standard Model and General Relativity





Higgs boson: 1964
Discovery: 2012 at LHC



Gravity waves: 1915
Discovery: 2016 at LIGO

- Gravity: Einstein's General Relativity
- Strong, weak and EM interactions: Standard Model
- GR seems incompatible with SM
- Caveat: in same number of spacetime dimensions

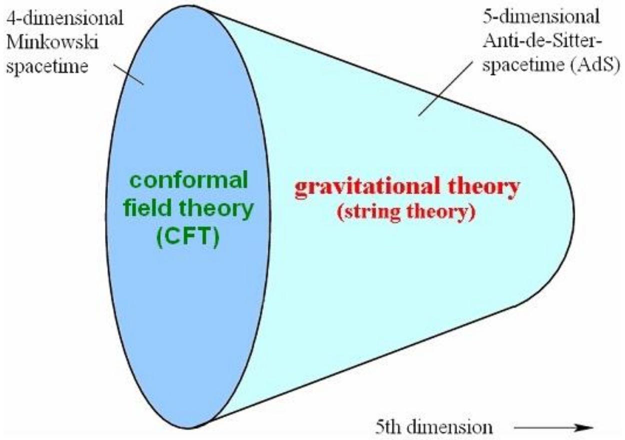
The holographic principle

Maldacena: AdS=CFT

Conformal Field Theory in 4-dim spacetime dual to string theory in higher dimensional curved spacetime

AdS_5 metric

$$ds^2 = \frac{R^2}{z_5^2}\left(h_{mn} dx^m dx^n - dz_5^2\right)$$



Weak-strong duality

- Conformal symmetry implies scale invariance: no mass scale in theory
- When CFT is strongly coupled, gravity dual is weakly coupled and vice-versa

Anti de Sitter spacetime

$$G_{\mu\upsilon} + \Lambda g_{\mu\upsilon} = \frac{8\pi G}{c^4} T_{\mu\upsilon}$$

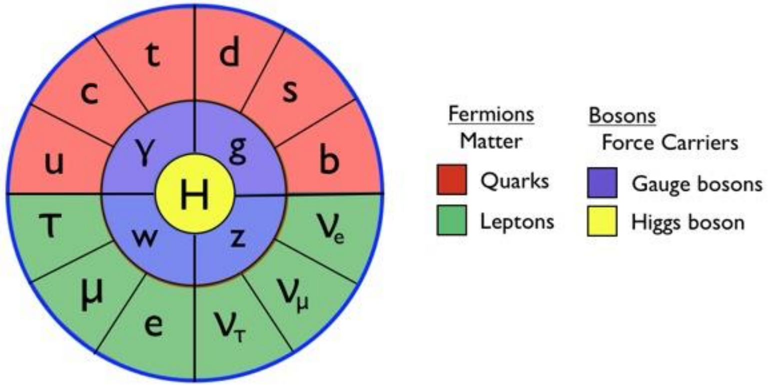
Cosmological constant: Λ

spacetime geometry　　　　matter-energy

$T_{\mu\upsilon} = 0$

- $\Lambda > 0$: de Sitter spacetime (4-dim de Sitter is what our Universe looked like during inflation)
- $\Lambda < 0$: Anti de Sitter (AdS) spacetime
- $\Lambda = 0$: Minkowski (flat) spacetime

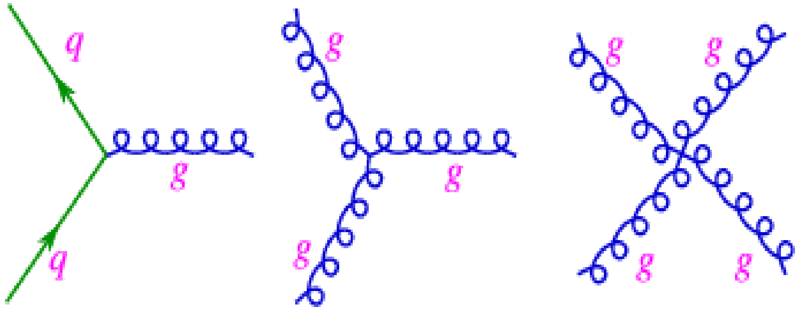
Quantum Chromodynamics



Particles of the Standard Model

QCD: Exact SU(3) gauge symmetry

- Quarks and gluons have color charge
- Quarks interact by exchanging gluons
- Gluons interact by exchanging gluons

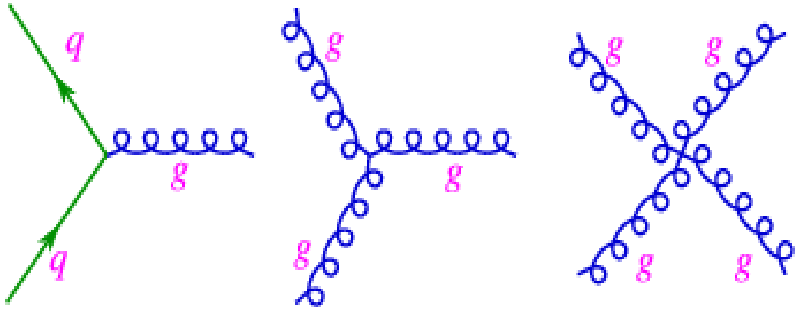


QCD is part of the SM and is the theory for the strong interaction

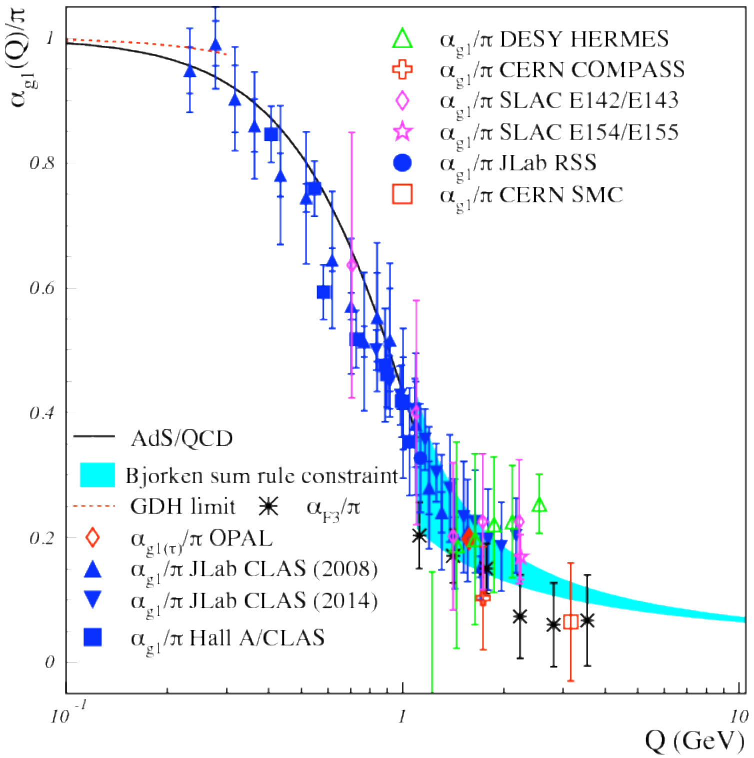
Asymptotic freedom to confinement

$$\mathcal{L}_{\mathrm{QCD}} = \overline{\Psi}(i\gamma^\mu D_\mu - m)\Psi - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}$$

$$D_\mu = \partial_\mu - ig_s A^a_\mu T^a$$



$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s c^{abc} A^b_\mu A^c_\nu$$



Nobel Prize 2004 (Politzer, Gross, Wilczek)

- Weak coupling (asymptotic freedom): perturbation theory is very successful
- Strong coupling (confinement): perturbation theory fails, no exact solutions

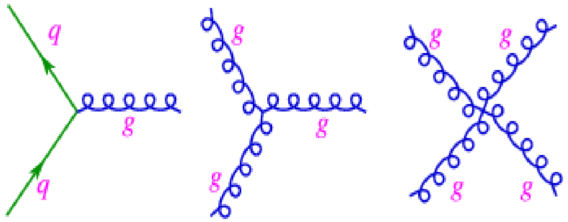
Open problem

QCD has an underlying conformal symmetry

Current quark mass

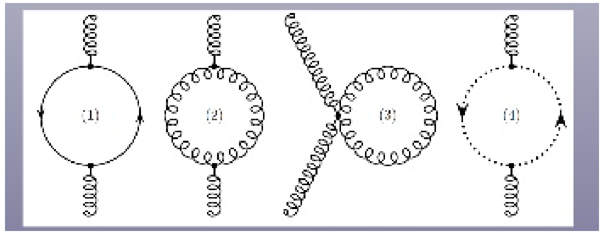
$$\mathcal{L}_{\text{QCD}} = \overline{\Psi}(i\gamma^{\mu}D_{\mu} - m)\Psi - \frac{1}{4}G^{a}_{\mu\nu}G^{a\mu\nu}$$

- Current quark masses: m



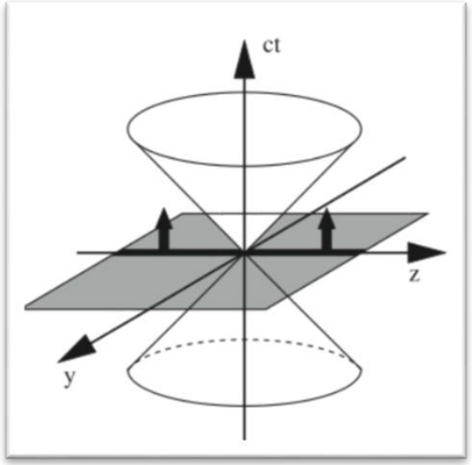
- Another mass scale appears upon perturbative renormalization scale of loops: Λ_{QCD}

$\Lambda_{QCD} \approx$ 200 MeV
$m_{u/d}(2\ GeV) \approx 4\ MeV$

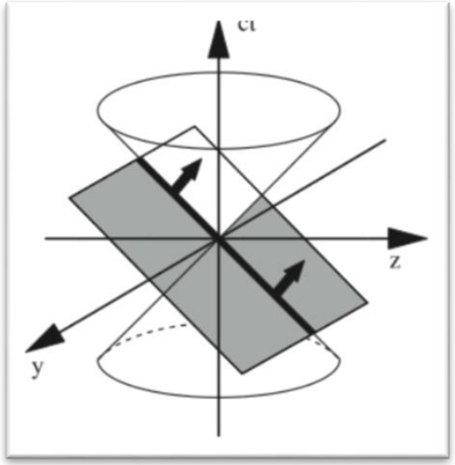


- Massless quarks: chiral symmetry
- Massless quarks and no loops: conformal symmetry

Light-front QCD



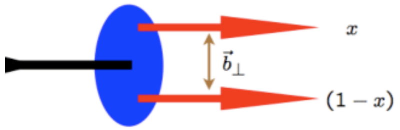
Ordinary time



Light-front time

$$x^{+} = x^{0} + x^{3}$$

LF Schrodinger-like Equation in the conformal limit



$$\left(-\frac{\mathrm{d}^2}{\mathrm{d}\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U_{\mathrm{eff}}(\zeta)\right)\phi(\zeta) = M^2\phi(\zeta)$$

$$\zeta = \sqrt{\frac{x}{(1-x)}}\left|\sum_{j=1}^{N-1} x_j \mathbf{b}_{\perp,j}\right|$$

$$x = \frac{k^{+}}{P^{+}}$$

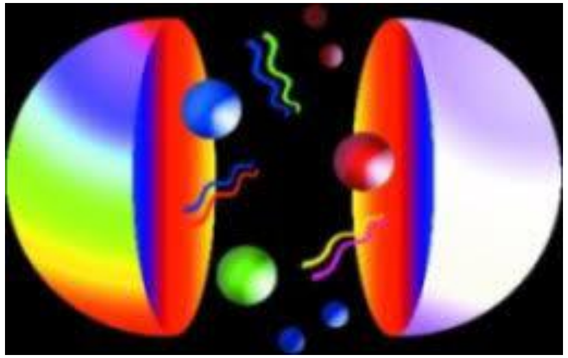
Holographic dictionary

Light front transverse distance maps onto 5th dimension of AdS

$$\zeta \leftrightarrow z_5$$

(Orbital angular momentum)^2 maps onto (AdS mass parameter x radius)^2 and spin

$$L^2 = (\mu R)^2 + (2 - J)^2$$



Unique confinement potential

- The dilaton field distorts the pure AdS geometry and drives confinement in physical spacetime
- Underlying conformal symmetry requires the dilaton to be quadratic
- The confinement potential is uniquely fixed by conformal symmetry and holographic mapping

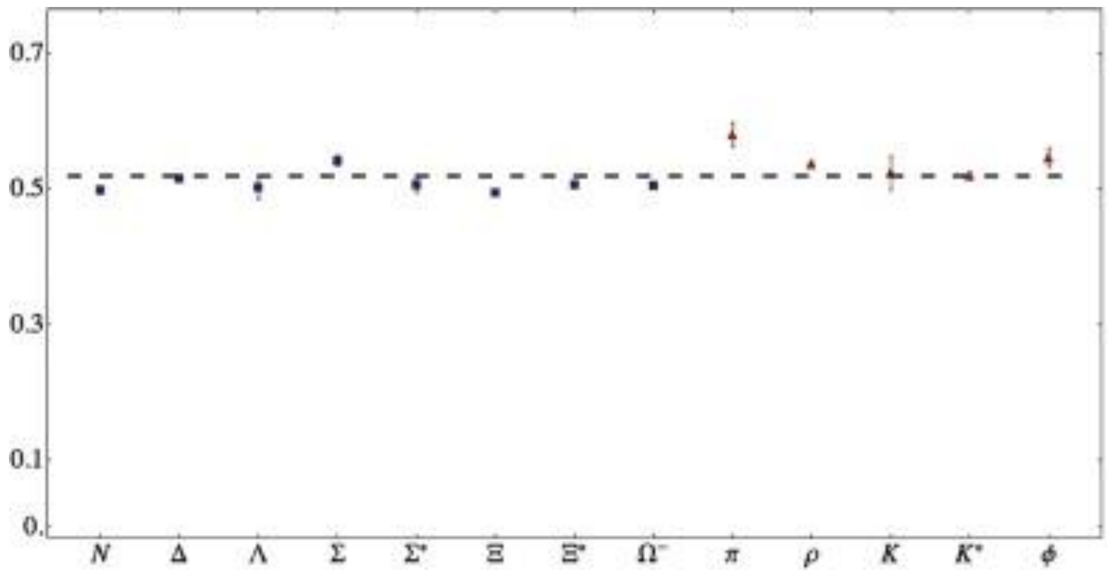
$$U(\zeta) = \frac{1}{2}\varphi''(\zeta) + \frac{1}{4}\varphi'(\zeta)^2 + \frac{2J-3}{2\zeta}\varphi'(\zeta)$$

$$\varphi = \kappa^2 z_5^2$$

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (J-1)$$

κ : emerging mass scale !

A universal holographic mass scale



$$\kappa = 523 \pm 24 \text{ MeV}$$

Brodsky, de Teramond, Dosch, Lorce (2013)

Universal holographic wavefunction for ground state

$$\Psi(x, k_\perp^2) \propto \frac{1}{\sqrt{x\bar{x}}} \exp\left(-\frac{M^2}{2\kappa^2}\right) \qquad M^2 = k_\perp^2/x\bar{x}$$

Fourier conjugate to ζ

Quark masses and spins

- For a successful phenomenology, we need to account for dynamical effects of quark masses and spins

$$\Psi^{\mathcal{P},\mathcal{V}}_{h,\bar{h}}(x,\mathbf{k}) = S^{\mathcal{P},\mathcal{V}}_{h,\bar{h}}(x,\mathbf{k})\Psi(x,k_\perp^2),$$

Mesons (quark-antiquark)

$$S^{V(\lambda)}_{h_q h_{\bar{q}}}(x,\mathbf{k}) \propto \frac{\bar{v}_{h_{\bar{q}}}((1-x)P^+,-\mathbf{k})}{\sqrt{\bar{x}}}[\epsilon^\lambda_V\cdot\gamma]\frac{u_{h_q}(xP^+,\mathbf{k})}{\sqrt{x}}$$

$$S^{P}_{h_q h_{\bar{q}}}(x,\mathbf{k}) \propto \frac{\bar{v}_{h_{\bar{q}}}(\bar{x}P^+,-\mathbf{k})}{\sqrt{\bar{x}}}[\gamma^5]\frac{u_{h_q}(xP^+,\mathbf{k})}{\sqrt{x}}$$

Nucleons (quark-diquark)

$$S^{N(\lambda)}_{h_N h_q}(x,\mathbf{k}) \propto \frac{\bar{u}_{h_q}(xP^+,\mathbf{k})}{\sqrt{x}}[(\epsilon^\lambda_D\cdot\gamma)\gamma^5]\frac{u_{h_N}(P^+,\mathbf{0})}{\sqrt{1}}$$

$$S^{N}_{h_N h_q}(x,\mathbf{k}) \propto \frac{\bar{u}_{h_q}(xP^+,\mathbf{k})}{\sqrt{x}}[\mathbb{1}]\frac{u_{h_N}(P^+,\mathbf{0})}{\sqrt{1}}$$

EM transition form factors

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Light-front holographic radiative transition form factors for light mesons

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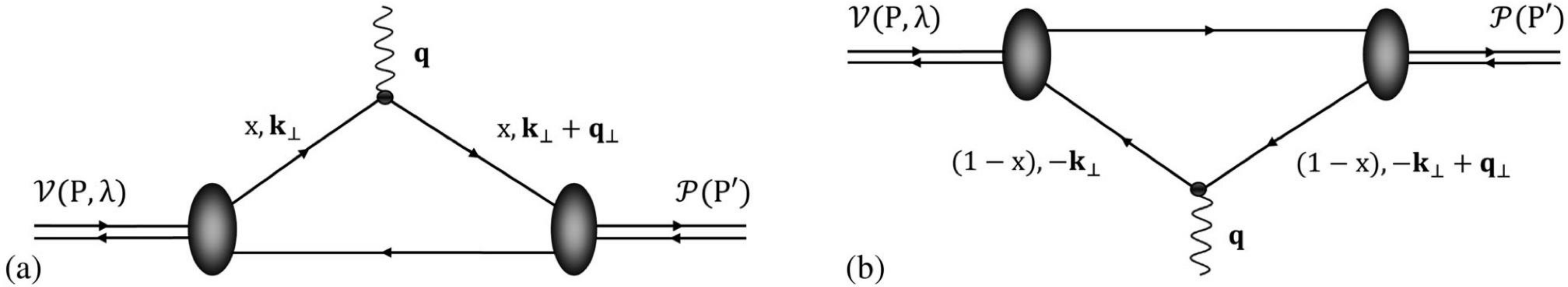
$$V \rightarrow P + \gamma^*$$

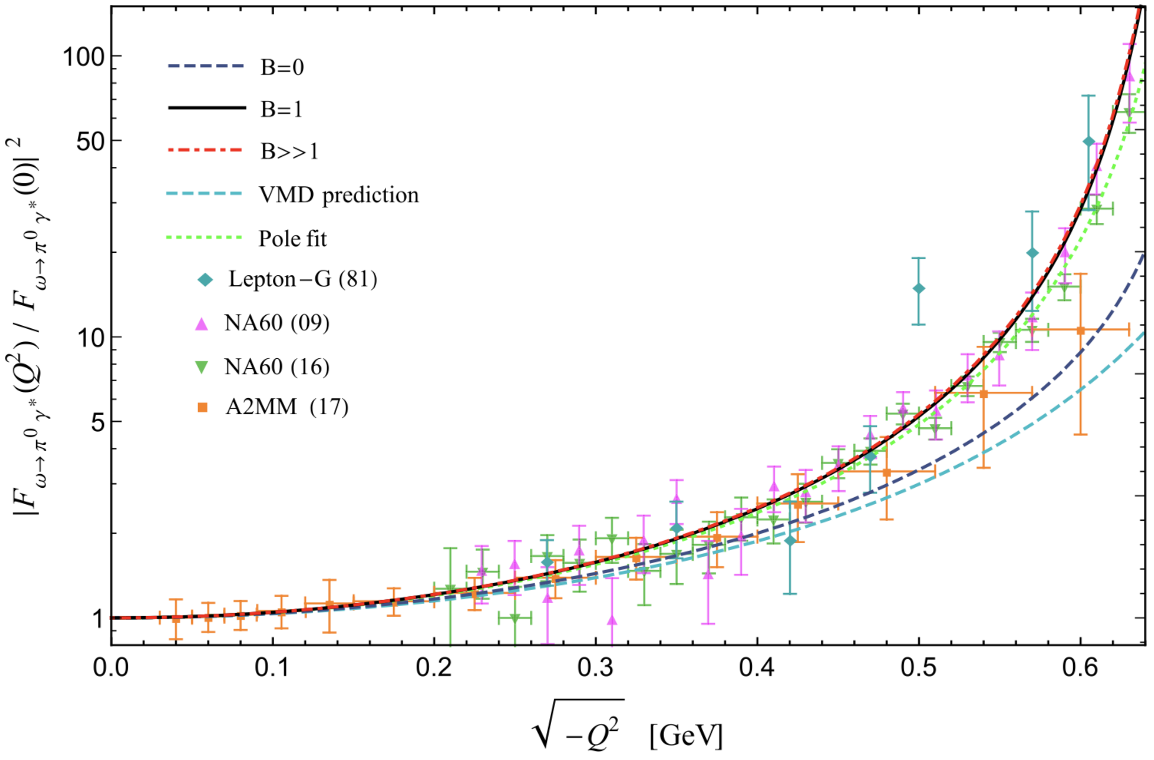


Predictions for radiative decay widths

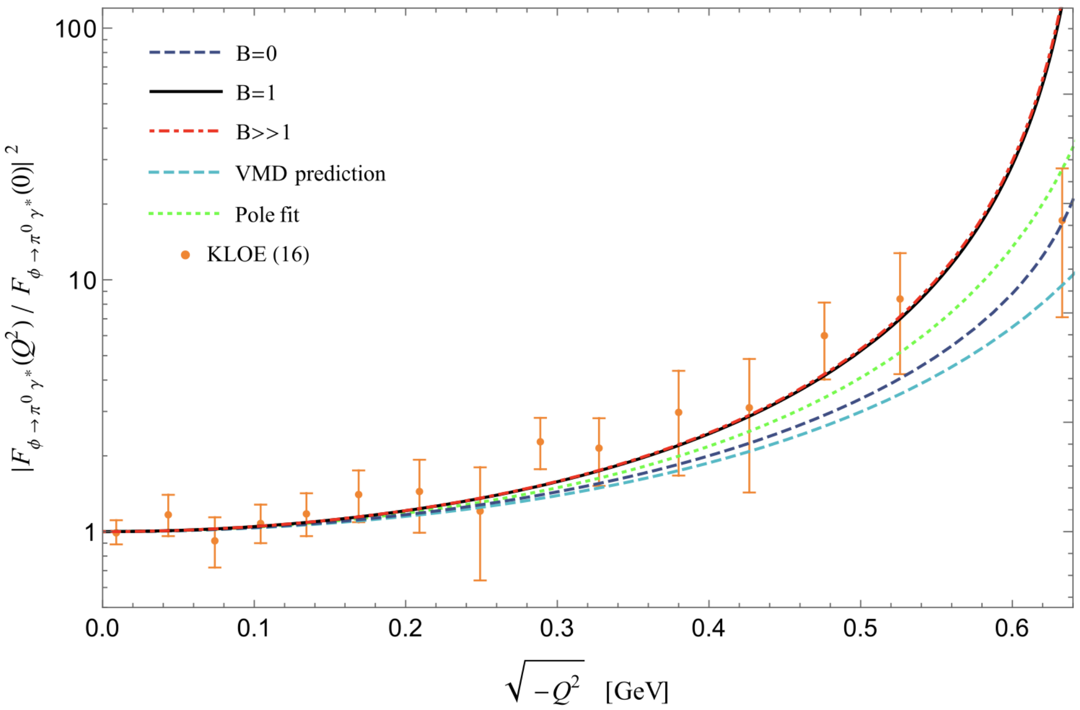
TABLE I. Our predictions for the $(\rho, \omega, \phi) \to \pi\gamma$ decay widths, compared to the PDG averages [2].

	Spin-improved LFH [keV]			
Decay widths	$B = 0$	$B = 1$	$B \gg 1$	PDG (2018) [keV]
$\Gamma(\rho^\pm \to \pi^\pm\gamma)$	23.46 ± 3.12	64.52 ± 6.94	66.37 ± 7.00	67.10 ± 7.82
$\Gamma(\rho^0 \to \pi^0\gamma)$	23.46 ± 3.12	64.52 ± 6.94	66.37 ± 7.00	70.08 ± 9.32
$\Gamma(\omega \to \pi^0\gamma)$	221.03 ± 29.90	607.96 ± 65.44	625.38 ± 66.03	713.16 ± 25.40
$\Gamma(\phi \to \pi^0\gamma)$	1.84 ± 0.33	5.06 ± 0.80	5.21 ± 0.82	5.52 ± 0.22

Predictions for the transition form factors

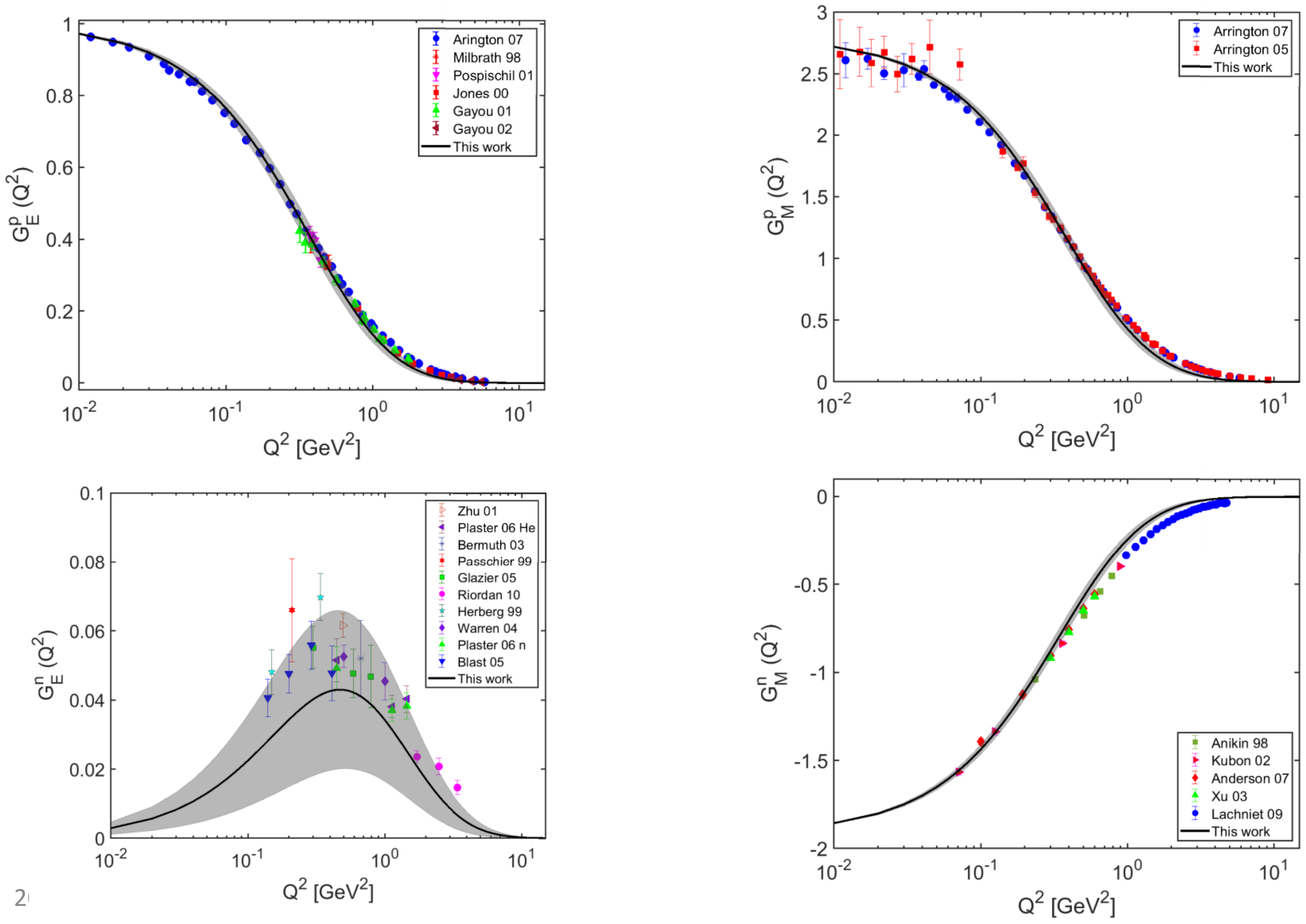


$\omega \to \pi + \gamma^*$



$\varphi \to \pi + \gamma^*$

Nucleon EM elastic form factors



- M. Ahmady, D. Chakraborti, C. Mondal, R. Sandapen, [E-print: 2105.02213] [hep-ph]
- Excellent agreement at low momentum transfer
- Large uncertainties for neutron where LO contributions tend to cancel out

Predictions for the EM radii of nucleons

Radius	Our prediction	Experimental data
$\langle r_E \rangle_p$ fm	0.833 ± 0.010	0.833 ± 0.010 [48]; 0.831 ± 0.019 [50] ; 0.841 ± 0.084 [49]
$\langle r_M \rangle_p$ fm	0.7985 ± 0.0313	0.851 ± 0.026 [52]
$\langle r_E^2 \rangle_n$ fm^2	-0.0704 ± 0.0434	-0.1161 ± 0.0022 [52]; -0.110 ± 0.008 [53]
$\langle r_M \rangle_n$ fm	0.8388 ± 0.0288	$0.864^{+0.009}_{-0.008}$ [52]

Conclusions & Acknowledgements

- Light hadrons share a universal holographic wavefunction which is modified differently by their spin structures

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