Hadronic structure, QCD & BSM

INSTITUTE OF PARTICLE PHYSICS

Town Hall meeting, July 2020

Ruben Sandapen

on behalf of the Atlantic Canada Particle Theory Group

Mount Allison University

Acadia University

Grenfell Campus | Memorial University

The Atlantic Particle Theory Group

➢ Who we are?

- Acadia: Ruben Sandapen
- Mount Allison: Mohammad Ahmady
- MUN-Grenfell: Aleks Aleksejevs and Svetlana Barkanova
- Undergraduate HQP : 23 honors theses since 2002
- New graduate program started at MUN-Grenfell in 2014
- MUN-Grenfell: 3 MSc + 1 PhD by 2020

HQP-EDI

➢ How we contribute?

- Theoretical developments
- Phenomenological: establishing mutually reinforcing links between theory and experiment (Ex: MOLLER, Chiral Belle, P2)
- Computational: developing new techniques for EW loop corrections, use of ACENET, etc. (ideal subprojects for undergrads)

Precision Scattering: MOLLER

Process: $e^- e^- \to e^- e^- (n\gamma)$

Asymmetry is an observable which is directly related to the interference term:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \simeq \frac{2Re(M_\gamma M_Z^+ + M_\gamma M_{NP}^+ + M_Z M_{NP}^+)_{LR}}{\sigma_L + \sigma_R} \sim (10^{-5}\ to\ 10^{-4}) \cdot Q^2$$

To access multi-TeV electron scale it is required to measure: $\delta(\sin^2\theta_W) < 0.002$

MOLLER and P2 experiments offer a unique opportunity to reach multi-TeV scale and will become complimentary to the LHC direct searches of the BSM physics.

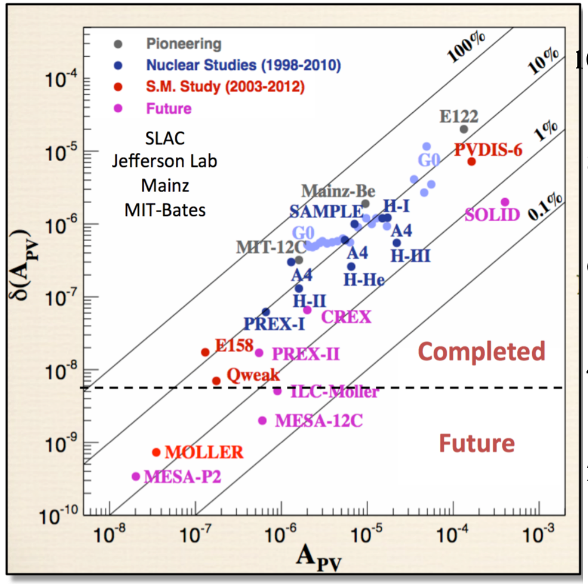
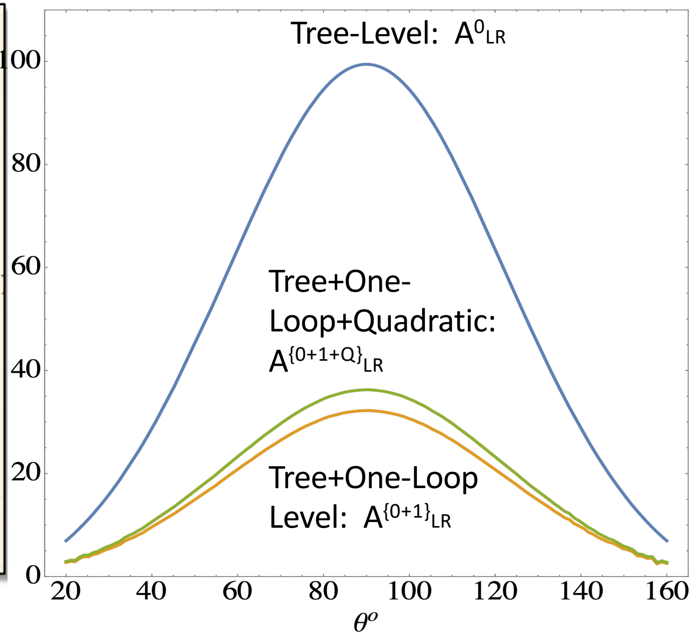
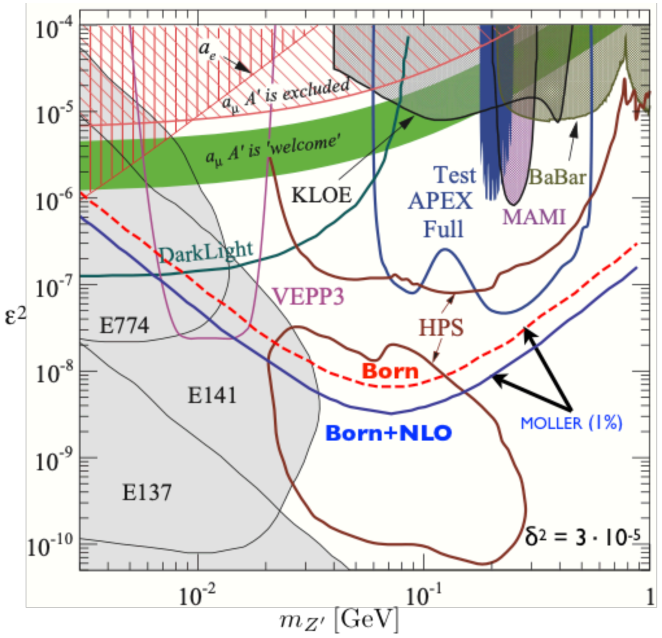


Figure courtesy of Kent Paschke





A. Aleksejevs, S. Barkanova, Y. Kolomensky, E. Kuraev, V. Zykunov, Phys. Rev. D 85 (2012) 013007
A. Aleksejevs, S. Barkanova, Y. Kolomensky, E. Kuraev, V. Zykunov, Nuovo Cim. C035N04 (2012) 192-197
A. Aleksejevs, S. Barkanova, Y. Bystritskiy, A. Ilyichev, E. Kuraev, V. Zykunov, Phys. Rev. D 85 (2012) 013007
A. Aleksejevs, S. Barkanova, Y. Bystritskiy, E. Kuraev, V. Zykunov, Phys. Part. Nucl. Lett. 12(2015) 5 645-656
A. Aleksejevs, S. Barkanova, Y. Bystritskiy, E. Kuraev, V. Zykunov, Phys. of Part. and Nucl. Letters, (2016), 13-3, 310–317

A. Aleksejevs, S. Barkanova, V. Zykunov and S. Wu, Nucl. Part. Phys. Proc 237-235(2016) 2259-2264.

Precision Scattering: Chiral Belle

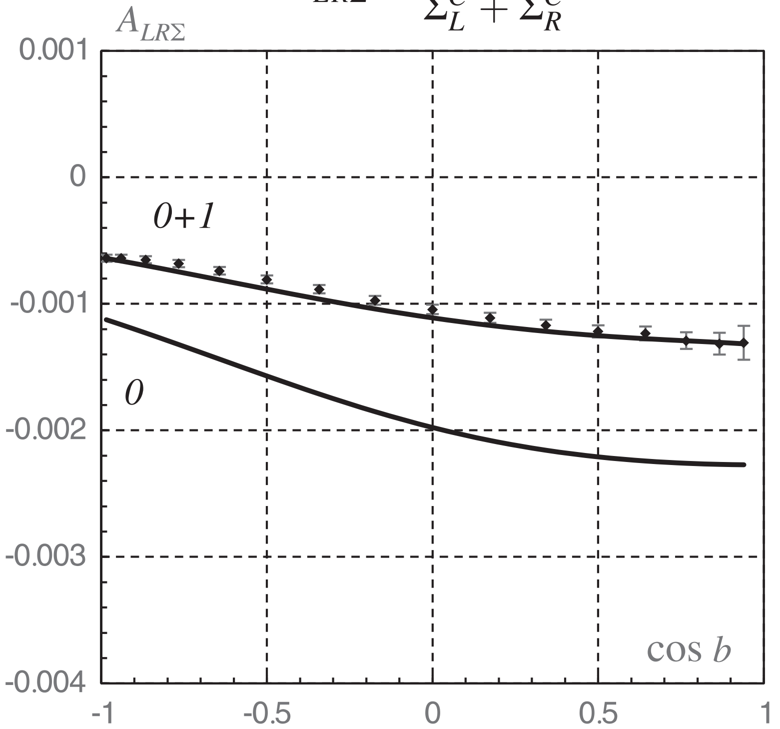
Process: $e^+e^- \to \mu^+\mu^-(n\gamma)$

Integrated LR asymmetry for polarized electron beam at Belle is directly proportional to the 1-4s_W^2, and hence very sensitive to the variation of s_W^2.

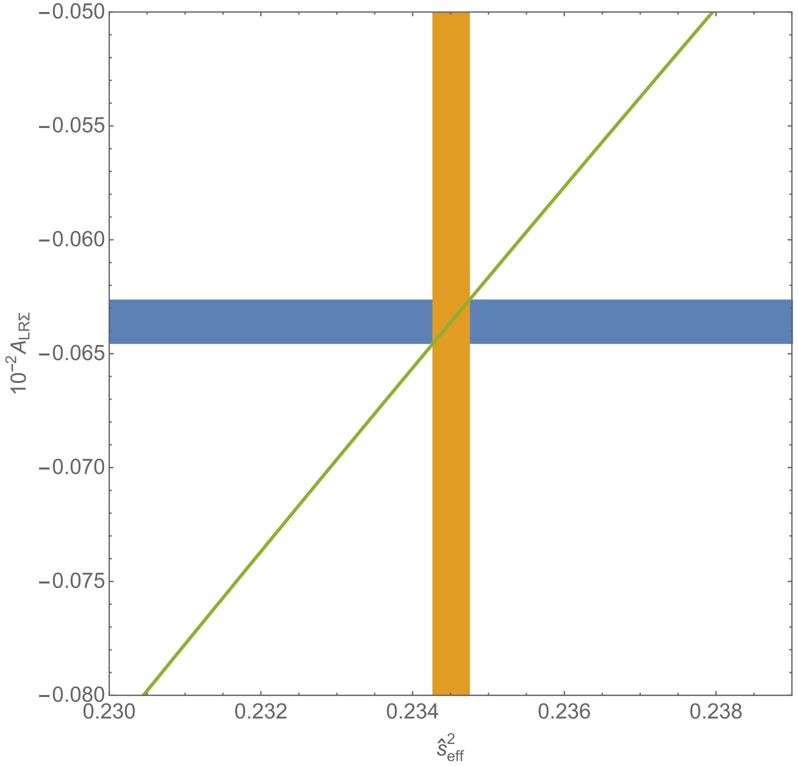
$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \qquad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

$$A_{LR\Sigma}^C = \frac{\Sigma_L^C - \Sigma_R^C}{\Sigma_L^C + \Sigma_R^C}.$$

$$A_{LR\Sigma}^0\Big|_{0^\circ}^{180^\circ} = -\frac{s}{8m_W^2}\frac{1-4s_W^2}{s_W^2} = -\frac{2s}{m_Z^2} a_e v_\mu$$



One-loop corrected integrated asymmetry

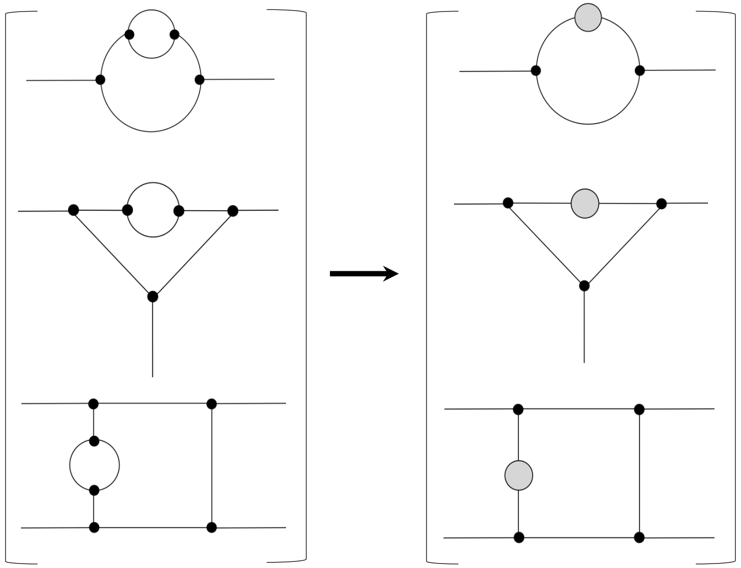


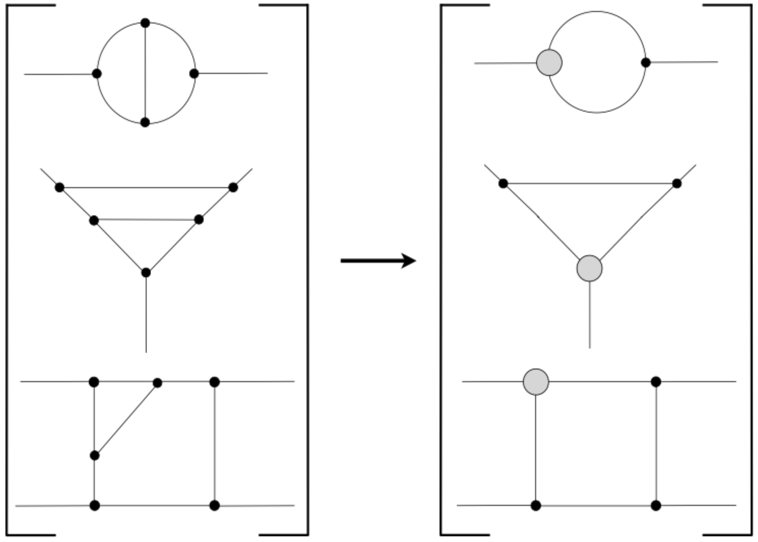
$$A_{LR\Sigma}^{0+1} = -0.00063597 \pm 0.0000097$$

This translates to the 0.21% uncertainty on s_W^2.

A. Aleksejevs, S. Barkanova, C. Miller, J. M. Roney, V. Zykunov, Phys. Rev. D, 101, 053003 (2020).

Multi-Loop Calculations in Precision Search of BSM

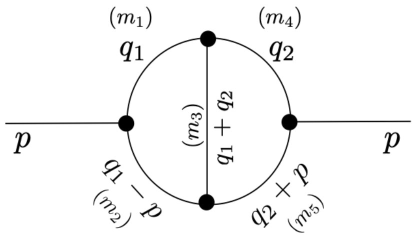




$$L(q^2) = \frac{1}{\pi}\int_{s_0}^{\infty} ds \frac{\Im L(s)}{s - q^2 - i\epsilon}$$

- Replace one-loop insertion by effective propagator
- Dispersive representation of one-loop sub-loop has propagator like structure with mass s.

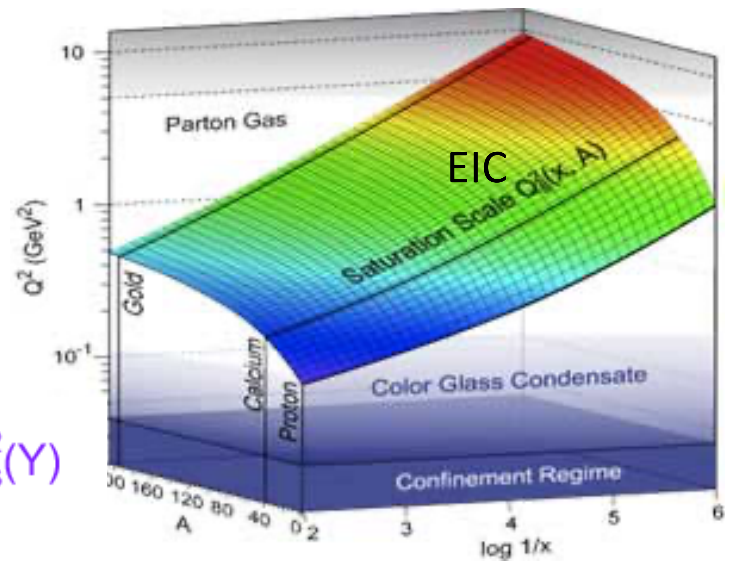
p^2 (GeV)^2	This work	[13]
-50.0	-0.08296	-
-10.0	-0.18399	-
-5.0	-0.22178	-
-1.0	-0.26919	-
-0.5	-0.27712	-
-0.1	-0.28360	-
0.1	-0.28714	-0.28701
0.5	-0.29443	-0.29479
1.0	-0.30449	-0.30493
5.0	-0.45230	-0.45241
10.0	-0.48810 - 0.35318 i	-0.48825 - 0.35333 i
50.0	0.17335 - 0.11781 i	0.17391 - 0.11807 i



[This work] A. Aleksejevs, Phys. Rev. D 98, 036021 (2018)

[13] S. Bauberger, M. Bohm, Nucl. Phys. B 445, 25-46 (1995)

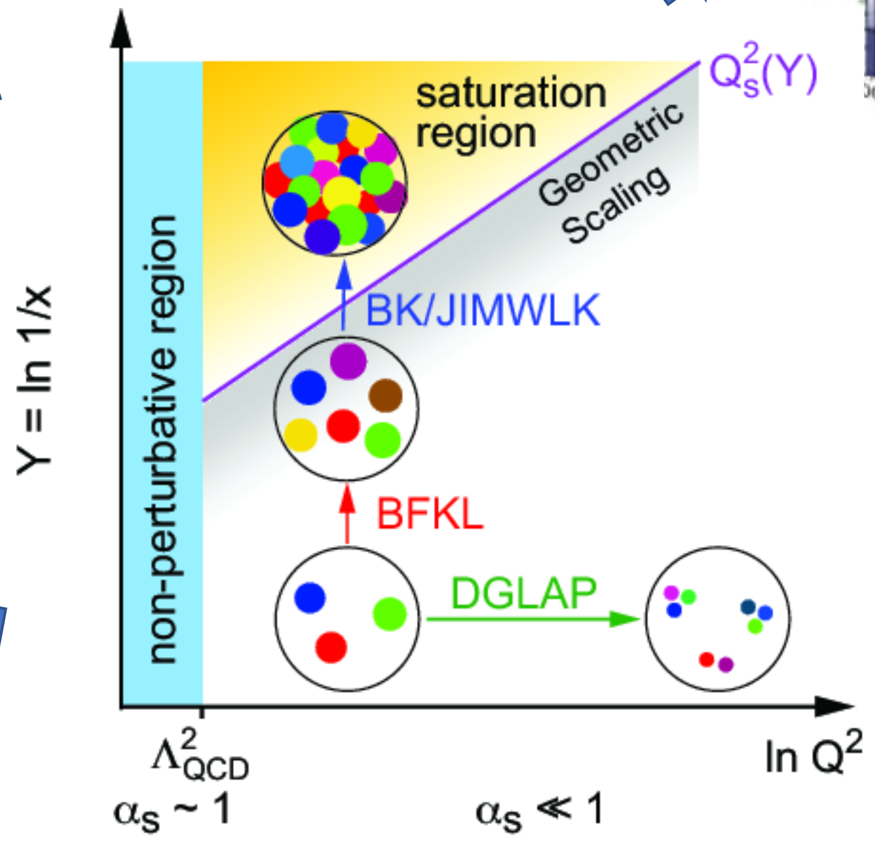
QCD

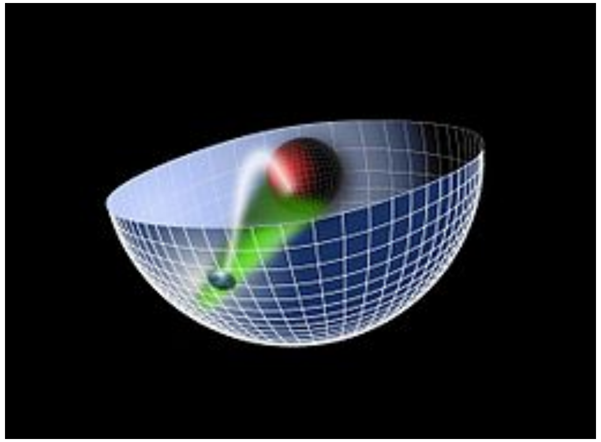


EIC

Lattice, QCD Sum Rules, ChPT

Crucial for physics
(especially NP) at LHC





Gauge-gravity duality or anti-de Sitter/conformal field theory (AdS-CFT) correspondence

Chiral Pertubation Theory

Hadronic formfactors and polarizabilities still remain a challenge for both experiment and theory.

Example: Different theoretical models predict quite different values of pion polarizabilities. Need a measurement. (GlueX)

Model	Parameter	$[10^{-4} fm^3]$
χPT	$\alpha_\pi - \beta_\pi$	5.7 ± 1.0
	$\alpha_\pi + \beta_\pi$	0.16
NJL	$\alpha_\pi - \beta_\pi$	9.8
QCM	$\alpha_\pi - \beta_\pi$	7.05
	$\alpha_\pi + \beta_\pi$	0.23
QCD sum rules	$\alpha_\pi - \beta_\pi$	11.2 ± 1.0
Dispersion sum rules	$\alpha_\pi - \beta_\pi$	13.60 ± 2.15
	$\alpha_\pi + \beta_\pi$	0.166 ± 0.024

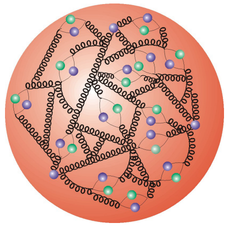
ChPT predictions up to $O(p^4)$ with our Computational Hadronic Model (see A. Aleksejevs and M. Butler, J.Phys. G37 (2010) 035002.

$(10^{-4}\ fm^3)$	$\alpha - \beta$	$\alpha + \beta$
$\pi^\pm$	5.59	0.07
π^0	-1.76	0.74
η	-0.046	0
$K^\pm$	1.23	0
K^0	0.19	0

A. Aleksejevs and S. Barkanova study *dynamical* polarizabilities of baryons and mesons from the perspective of *relativistic Chiral Perturbation Theory* (ChPT).

How do hadrons emerge from QCD?

QCD

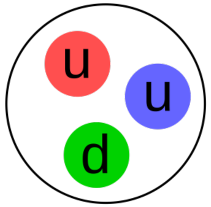


quarks and gluons

?

Light-front QCD

Quark model



valence quarks

$$H_{\mathrm{LF}}^{\mathrm{QCD}}|\Psi(P)\rangle = M^2|\Psi(P)\rangle$$

Conformal limit

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right)\Phi(\zeta) = M^2\Phi(\zeta),$$

SuSy

S. J. Brodsky, G. de Teramond, H. G. Dosch et al.

Review: Phys. Rep. (2015)

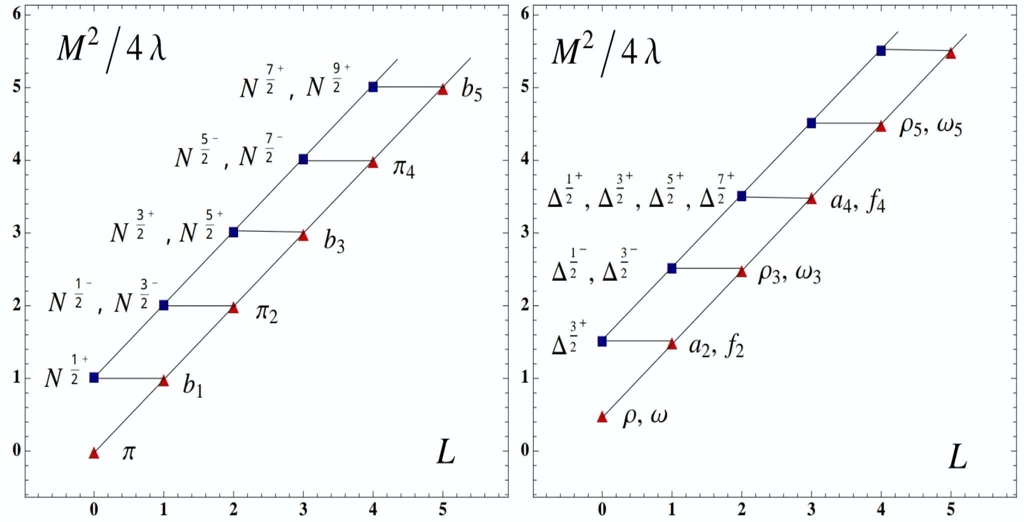
Mapping to AdS + conformal symmetry breaking

AdS/QCD mass scale

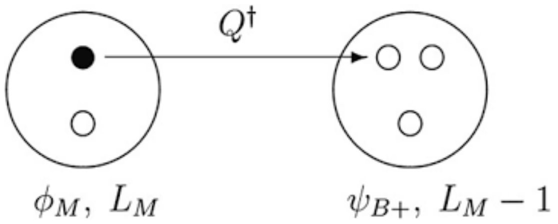
$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(J-1).$$

κ replaces Λ_{QCD}

$\kappa = 523$ MeV



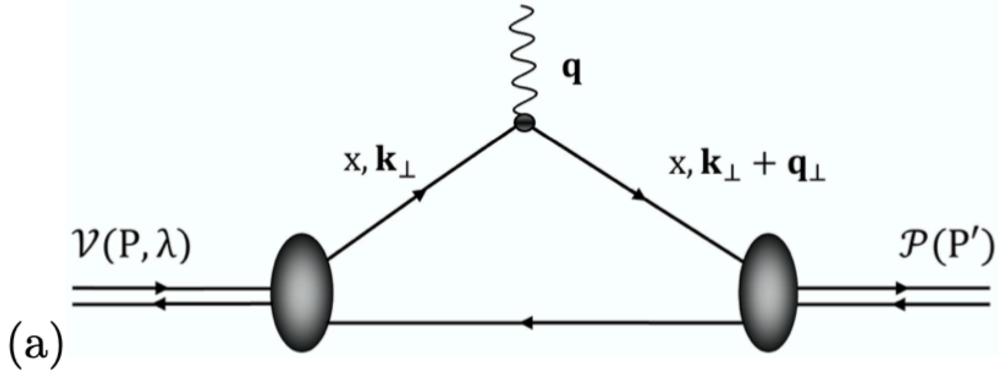
- SuSy: meson-baryon as superpartners (no NP!)
- Pion is predicted to be massless
- $\lambda = \kappa^2$



Universal holographic wavefunction for all hadrons

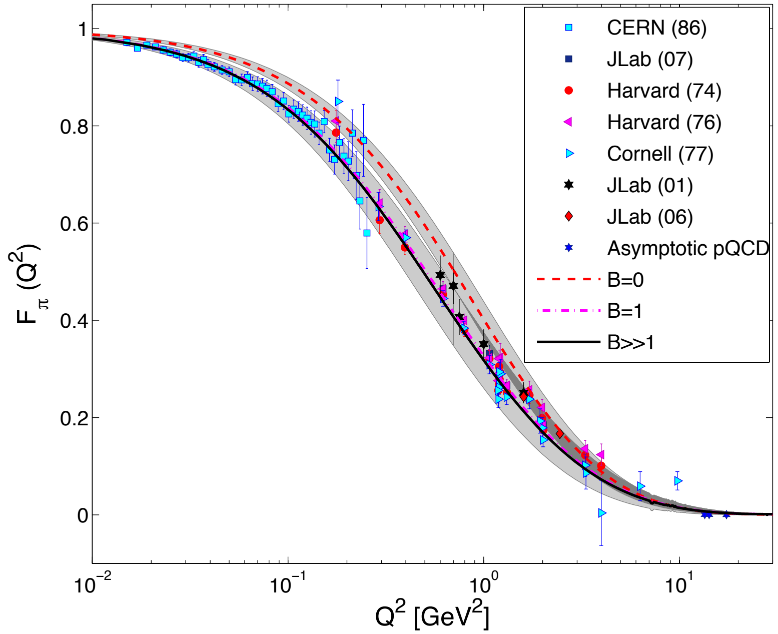
Light pseudoscalar and vector mesons

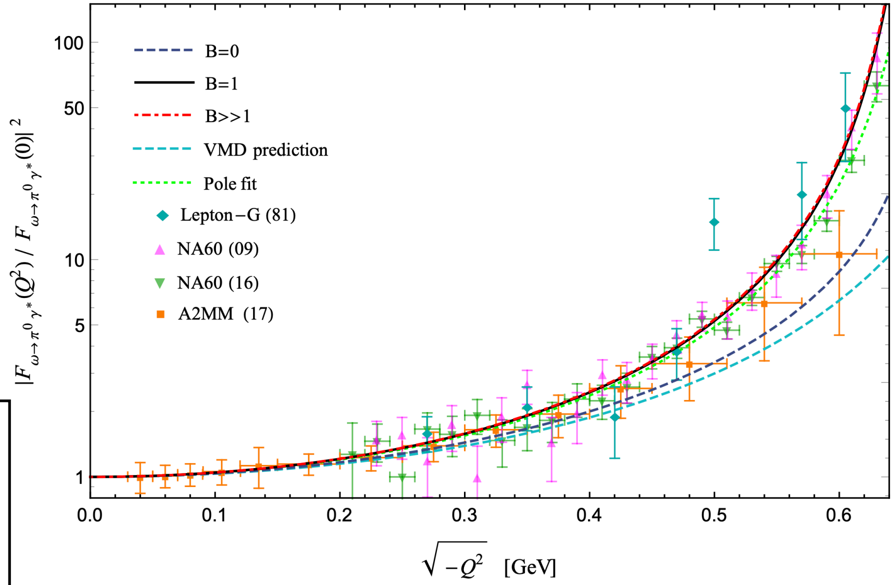
EM form factors



Universal holographic wavefunction modified differently by quark mass and spin effects describe simultaneously all light meson EM data

Decay widths	Spin-improved LFH [keV]			PDG (2018) [keV]
	B = 0	B = 1	B >> 1	
$\Gamma(\rho^\pm \to \pi^\pm\gamma)$	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





M. Ahmady, F. Chishtie, R. Sandapen, PRD95 (2017) 7, 074008

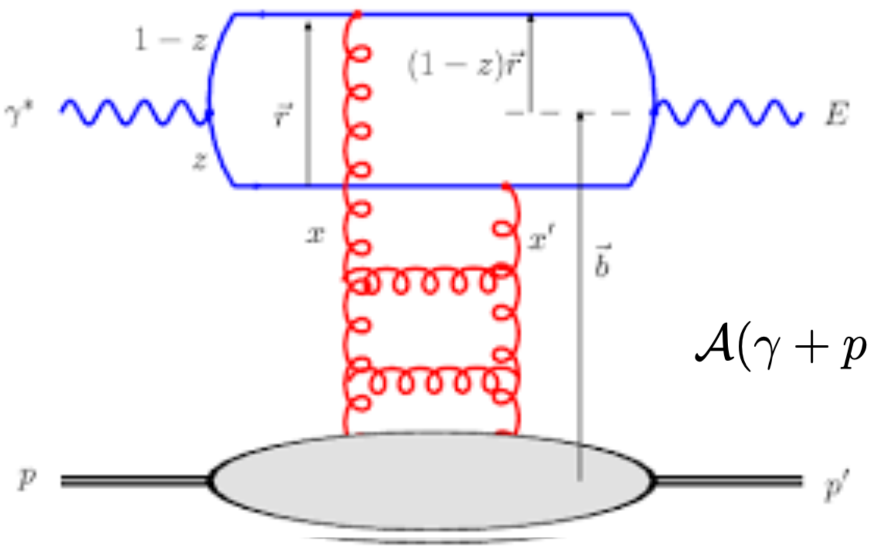
M. Ahmady, C. Mondal, R. Sandapen, PRD98 (2018) 3, 034010; PRD100 (2019) 100, 054005

M. Ahmady, S. Kaur, C. Mondal, R. Sandapen, arXiv: 2006.07675 [hep-ph]

Diffractive electroproduction of light vector mesons

High energy factorization

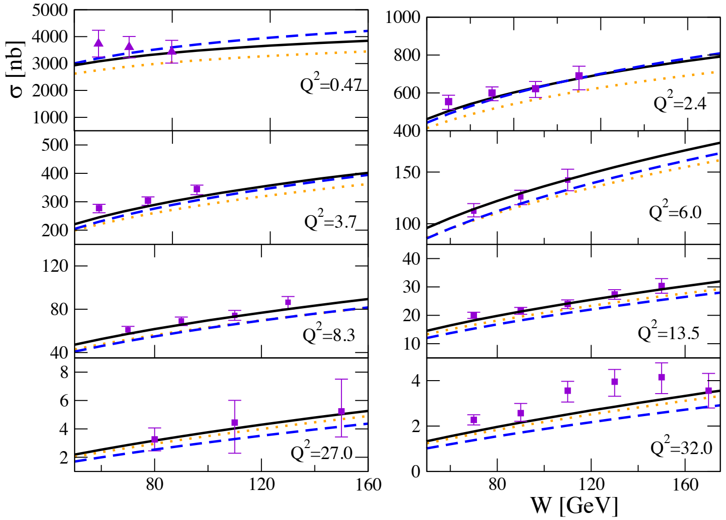
$$e + p \rightarrow e + (\rho, \varphi) + p$$

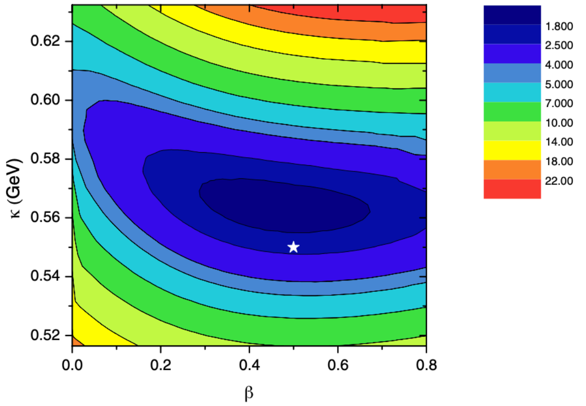


Gluon saturation

Holographic wavefunction

$$\mathcal{A}(\gamma + p \rightarrow Xp) = \int \psi_\gamma^{\text{in}} \, \hat{\sigma} \, \psi_X^{\text{out}}$$





- HERA data prefer holographic meson wavefunction
- Relevant for EIC to probe gluon saturation

J. R. Forshaw, R. Sandapen, PRL 109 (2012) 081601
M. Ahmady, N. Sharma, R. Sandapen, PRD 94 (2016) 7, 074018
B. E. Cox, J. R. Forshaw, R. Sandapen, JHEP 06 (2009) 034 (saturation at LHC)

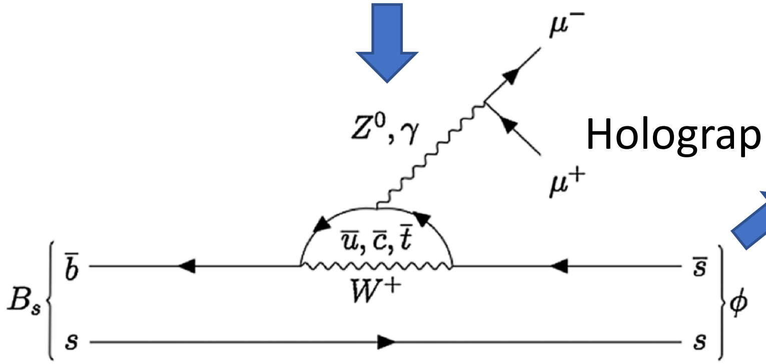
- ➢ Universal $\kappa = 540$ MeV
- ➢ Effective quark mass, $m = 140$ MeV

New Physics in rare B decays ?

$B_s \to \phi\mu^+\mu^-$

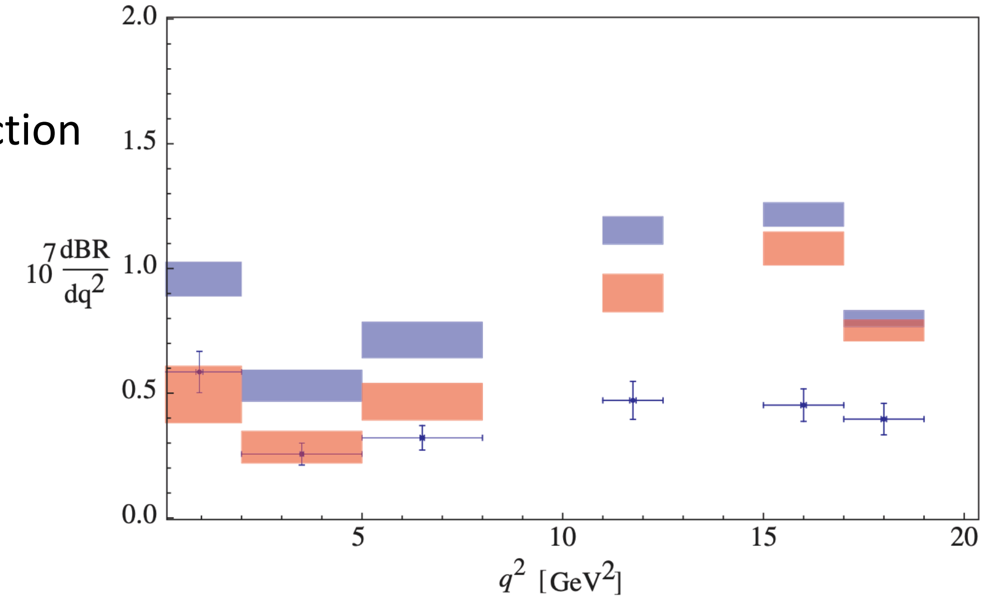
EW transition form factors

NP ?



Holographic wavefunction

$$\langle\phi(k,\varepsilon)|\bar{s}\gamma^\mu(1-\gamma^5)b|B_s(p)\rangle$$
$$= \frac{2iV(q^2)}{m_{B_s}+m_\phi}\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma - 2m_\phi A_0(q^2)\frac{\varepsilon^*\cdot q}{q^2}q^\mu$$
$$-(m_{B_s}+m_\phi)A_1(q^2)\left(\varepsilon^{\mu *} - \frac{\varepsilon^*\cdot q q^\mu}{q^2}\right)$$
$$+A_2(q^2)\frac{\varepsilon^*\cdot q}{m_{B_s}+m_\phi}\left[(p+k)^\mu - \frac{m^2_{B_s}-m^2_\phi}{q^2}q^\mu\right]$$



- Blue: holographic wavefunction
- Red: QCD Sum Rules
- NP? Hadronic uncertainties?

Undergrad HQP contributions

M. Ahmady, R. Sandapen, PRD88 (2013) 014042; PRD87 (2013) 5, 054013
M. Ahmady, R. Campbell, S. Lord, R. Sandapen, PRD88 (2013) 7,074031; PRD89(2014)7, 074021
M. Ahmady, S. Lord, R. Sandapen, PRD 90 (2014) 7, 074010
M. Ahmady, D. Hatfield, S. Lord, R. Sandapen, PRD92 (2015), 11, 114028
M. Ahmady, A. Leger, Z. McIntyre, A. Morrison, R. Sandapen, PRD98 (2018) 5, 053002
M. Ahmady, S. Keller, M. Thibodeau, R. Sandapen, PRD100 (2019) 11, 113005

Summary & Outlook

BSM physics in precision scattering

- Parity-violating Experiments such as MOLLER, P2 and Chiral Belle will push the boundaries of BSM searches to multi TeV scale
- Weinberg mixing angle will be determined with unprecedented precision
- Precision experiments precision radiative corrections, which we address by advancing techniques of multi-loop calculations

QCD and hadronic structure

- Heavy quarks: diffractive J-Psi electroproduction and B meson transition form factors
- Nucleon EM form factors within same framework as for mesons
- Connection between χPT and light-front holographic QCD

HQP & EDI

- Maintain our successful role at Acadia and Mt. A of channeling HQP to Canadian graduate schools
- Expand new graduate program at Grenfell-MUN, funding permitting
- Contribute to Canadian postdoc supervision, funding permitting, great potential to attract HQP to Atlantic Canada
- Science outreach including underrepresented groups in Atlantic Canada