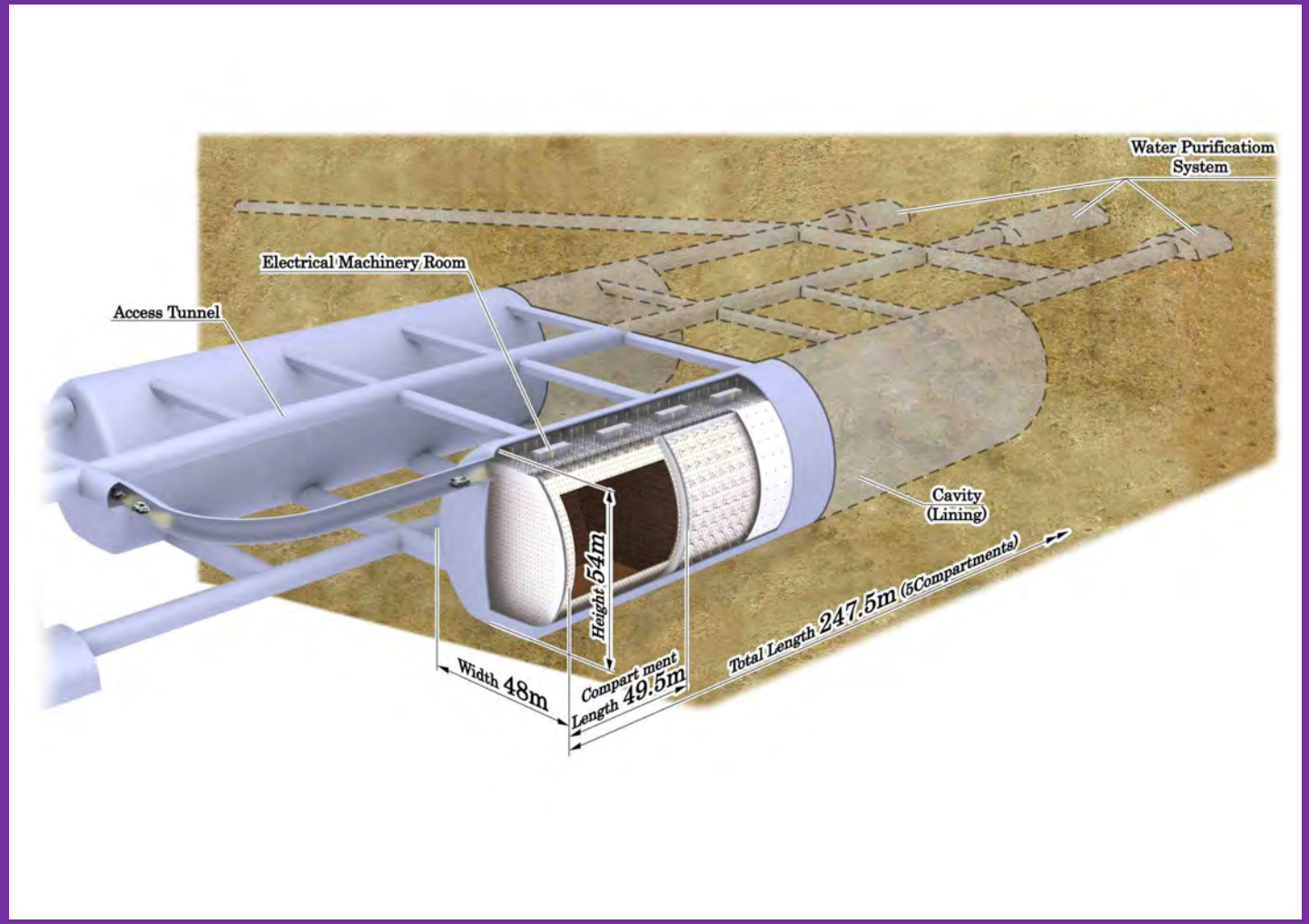
Cooling Dark Matter

Mount Saint Mary's University
LOS ANGELES

Noah Bray-Ali 6-9 November 2023 BSM-23 Hurghada

Physics Case: Neutrino Oscillations and *CP* Violation

Hyper-K, Letter of Intent (2011)

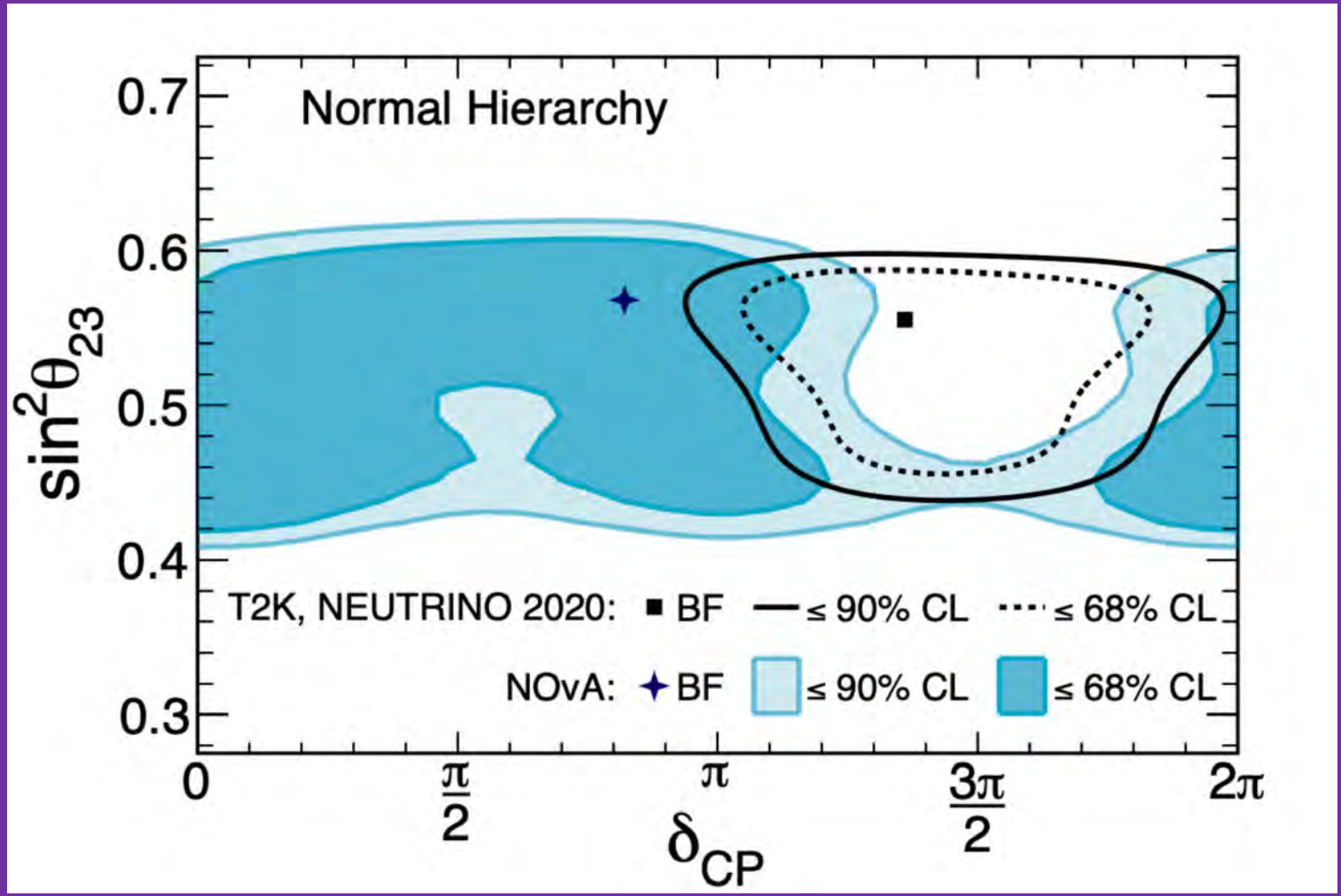


"One of the goals of the Hyper-K experiment is to…discover leptonic *CP* violation using a J-PARC muon neutrino beam."

"*CP* asymmetry originating from flavor mixing among…neutrinos might have played an important role creating the observed matter-antimatter asymmetry in the universe."

Neutrino Oscillations and *CP* Violation

Z. Vallari (NOvA), doi:10.26081/K6G053 (2022)



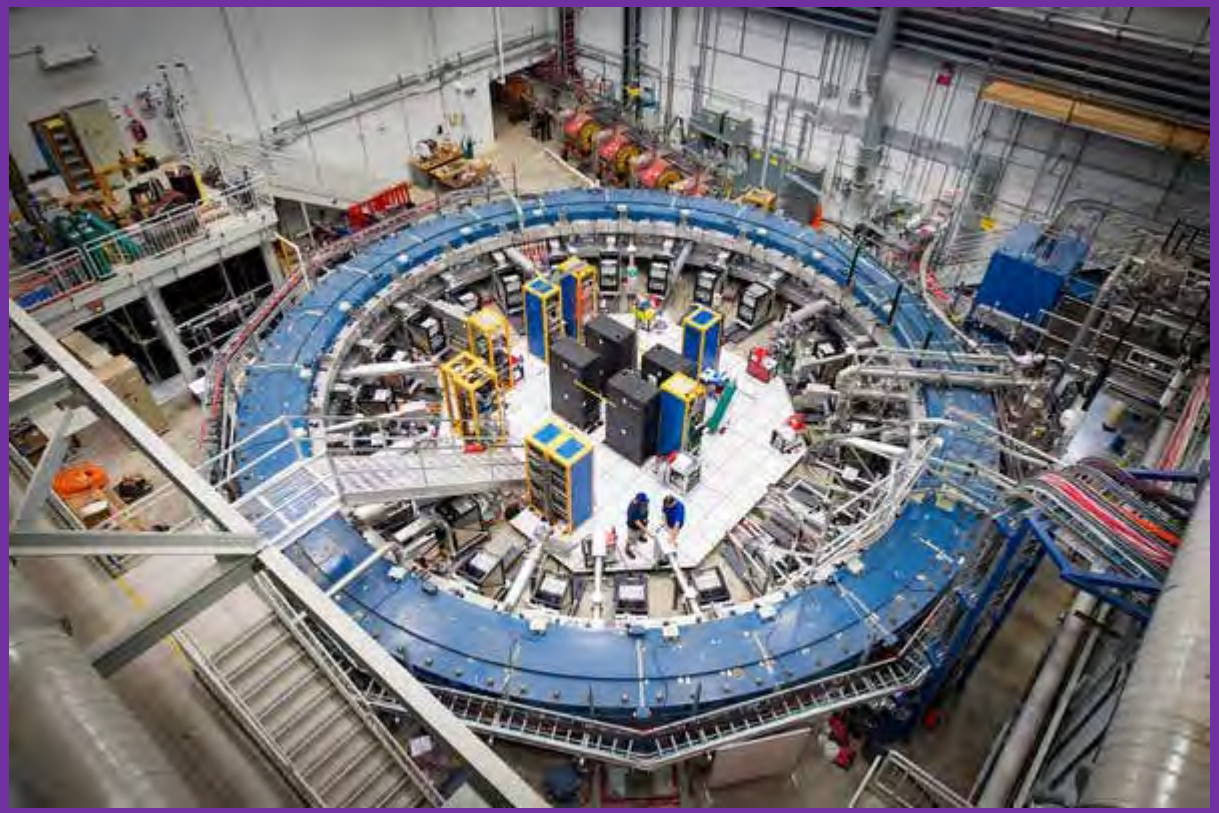
Charge Asymmetry in Long-Lived Neutral Kaons N. Bray-Ali, arXiv.org:2108.12243 (2021)

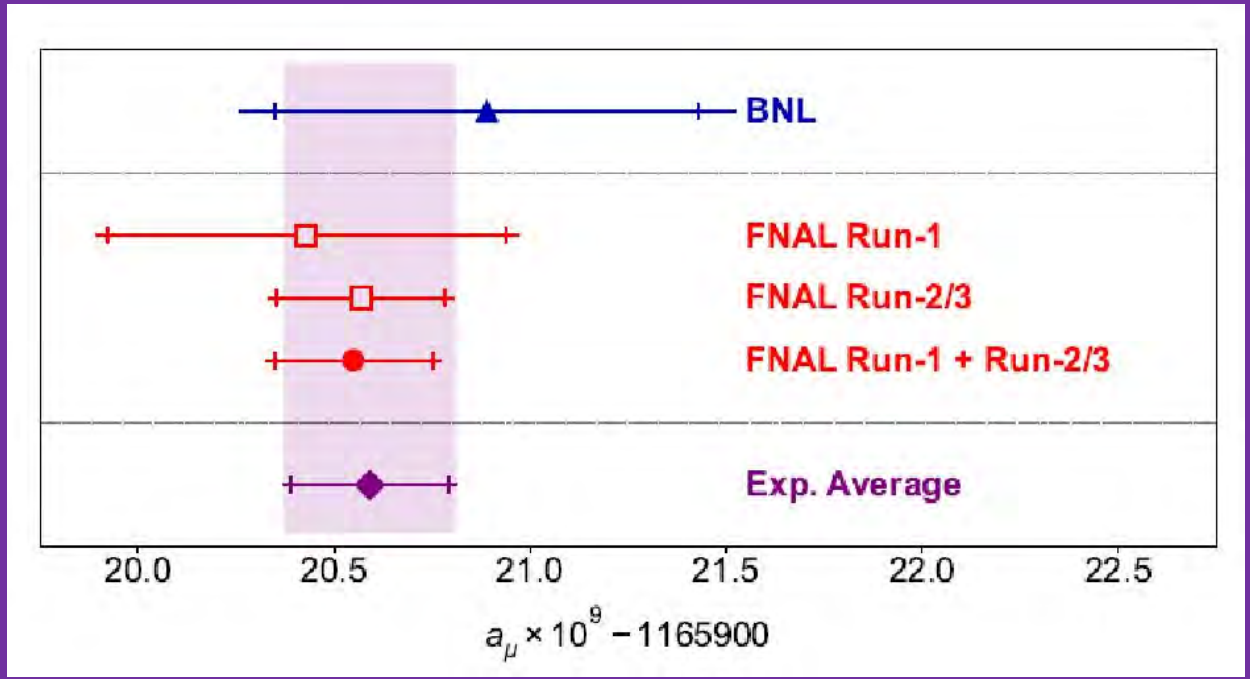
Kaon Decay Length (cm)	Charge Asymmetry (10^{-3})	Prediction (10^{-3})	Kaon Experiment Reference
375	2.24 (36)	2.54 (18)	S. Bennett et al., Phys. Rev. Lett. 19, 993 (1967).
500	3.32 (8)	3.44 (24)	A. Alavi-Harati et al. (FNAL KTeV Collab.), Phys. Rev. Lett. 88, 181601 (2002).

$$A_L(e) = \frac{\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \overline{\nu}_e)}{\Gamma(\pi^- e^+ \nu_e) + \Gamma(\pi^+ e^- \overline{\nu}_e)} = 4\pi C_{A\pi} \frac{f_\pi \sqrt{\rho_A hc}}{m_A f_A} L_K$$

Muon *g*-2 Now More than 5 Sigma from "Standard Model"

Muon *g*-2, 10 August 2023

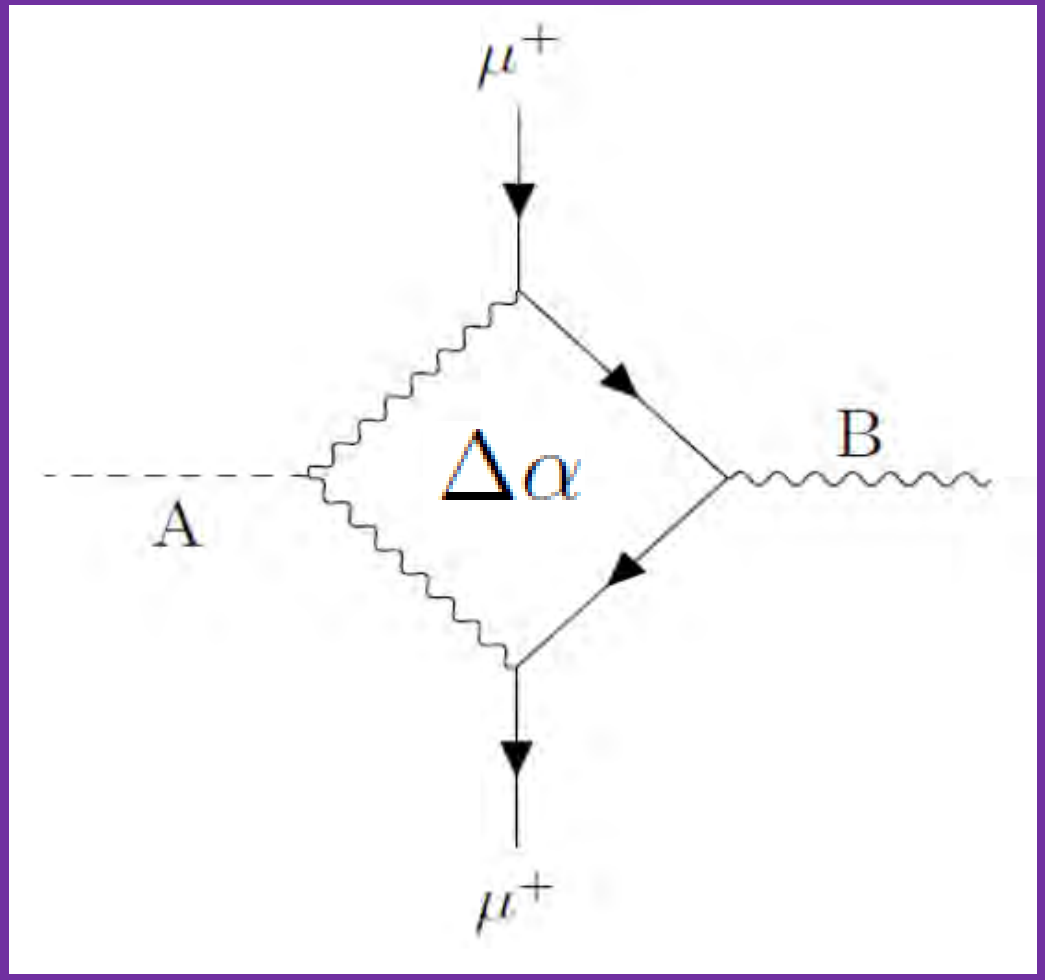




Dark Matter and Muon *g*-2

N. Bray-Ali, arXiv.org:2108.12243 (2021)

$$\Delta a_\mu = (165 \pm 10) \times 10^{-11} \left(\frac{N_\mu}{1.93 \times 10^3} \right)^{1/2} \times \left(\frac{V_\mu}{3.12 \times 10^4 \text{ cm}^3} \right)^{1/2} \left(\frac{T_\mu}{64.4\ \mu\text{s}} \right)^{1/2} = (165 \pm 10) \times 10^{-11},$$

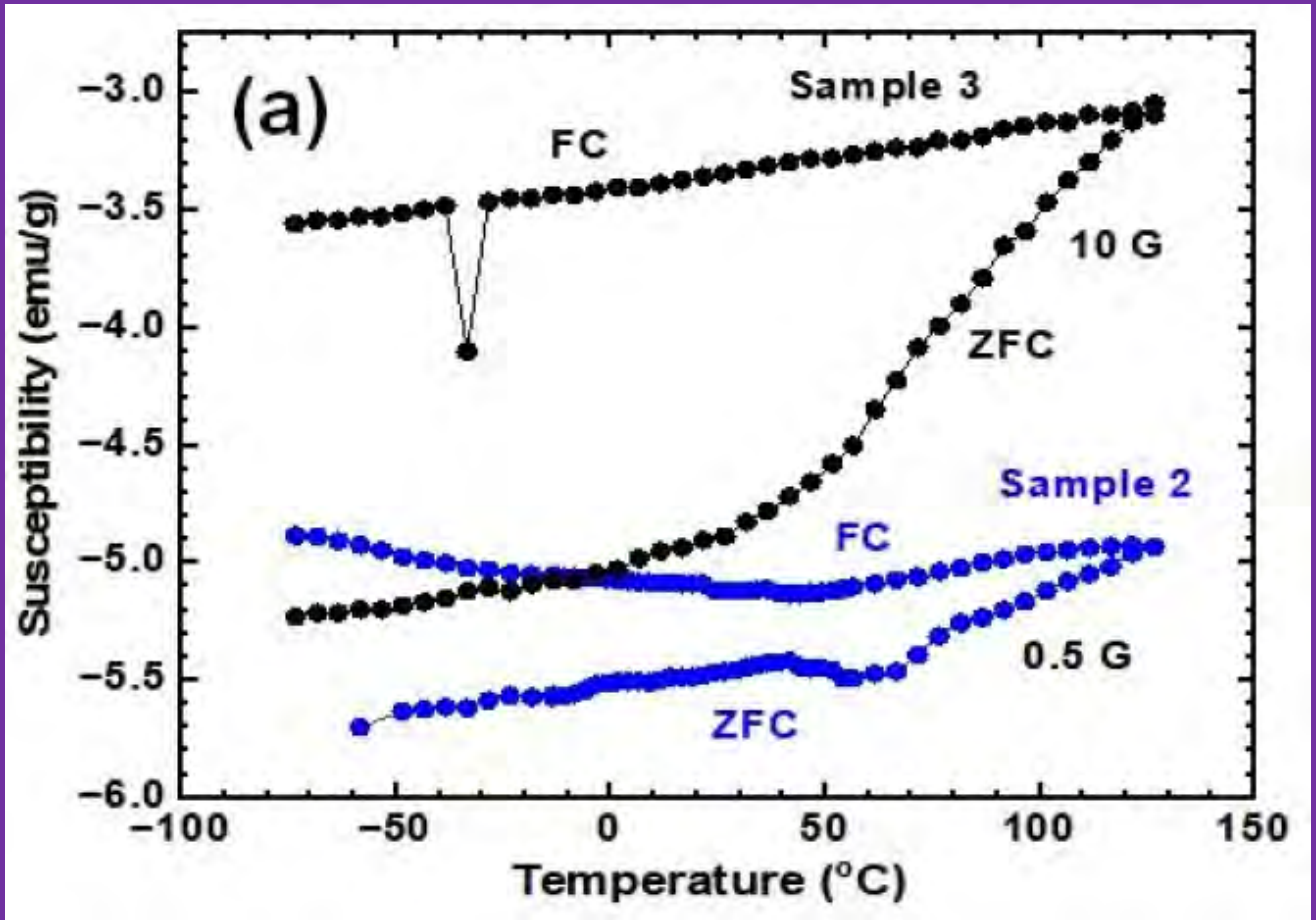


Experiment (Exp) 3.4σ from Standard Model (SM):

BMW (Lattice QCD)	7075 (55) e-11
CMD-3 (Neutral Rho)	7020 (59) e-11
BELLE+ALEPH(Charged Rho)	7030 (44) e-11

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (140 \pm 41) \times 10^{-11}$$

Ambient Superconductivity in Copper-Doped Apatite S. Lee et al., arXiv.org:2307.12008 (2023)



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Axion Sum Rule in Apatite Raman Spectroscopy

R. L. Frost +, Polyhedron **26**, 4533 (2007)

Apatite Sample	$\omega_\theta/(2\pi c)$ (cm^{-1})	$\omega_{A\theta}/(2\pi c)$ (cm^{-1})	$\omega_{\mathrm{low}}/(2\pi c)$ (cm^{-1})	$\omega_A/(2\pi c)$ (cm^{-1})
Pb 1	575	3395	155	4125
Pb 3	579	3386	145	4110
Pb 5	574	3383	157	4114
Ca	573	3383	146	4102
Average	575 (2)(2)	3387 (2)(5)	151 (2)(5)	4113 (2)(8)

$$\omega_\theta + \omega_{A\theta} + \omega_{\mathrm{low}} \approx \omega_A = 2\pi c \times (4096 \pm 40)\ \mathrm{cm}^{-1}$$

$$\frac{n_A}{n_\gamma} = 6 \times \left(\frac{4096 \pm 40}{4113 \pm 9}\right) = 5.98 \pm 0.06$$

Cooling Dark Matter

N.Bray-Ali, arXiv.org:2108.12243 (2021)

$$A_M = M_L^- \overline{M}_R^- - M_R^- \overline{M}_L^- - M_L^+ \overline{M}_R^+ + M_R^+ \overline{M}_L^+$$

$$n_A / n_\gamma = |M| / |H| = 6$$

$$m_A = 2.70\ kT_\gamma \left(\frac{n_A}{n_\gamma}\right)^{-1} \frac{\Omega_A h^2}{\Omega_\gamma h^2} = (0.508 \pm 0.004)\ \text{eV}$$

CMD-3 Lands 5.1 Sigma from KLOE

CMD-3, arXiv:2302.08834 (2023)

Collider	σ_x (μm)	σ_y (μm)	σ_z (cm)
DAΦNE [48]	2000	20	3.0
DAΦNE [49]	260	4.8	2.0
BEPC-2 [49]	347	4.5	1.2
VEPP-2M [50]	400	10	3.0
VEPP-2M [50]	35	35	3.0
PEP-II [49]	157	4.7	1.05

$$a_\mu^{\pi\pi}(\mathrm{CMD3}) - a_\mu^{\pi\pi}(\mathrm{KLOE})$$

$$= (187 \pm 37) \times 10^{-11}$$

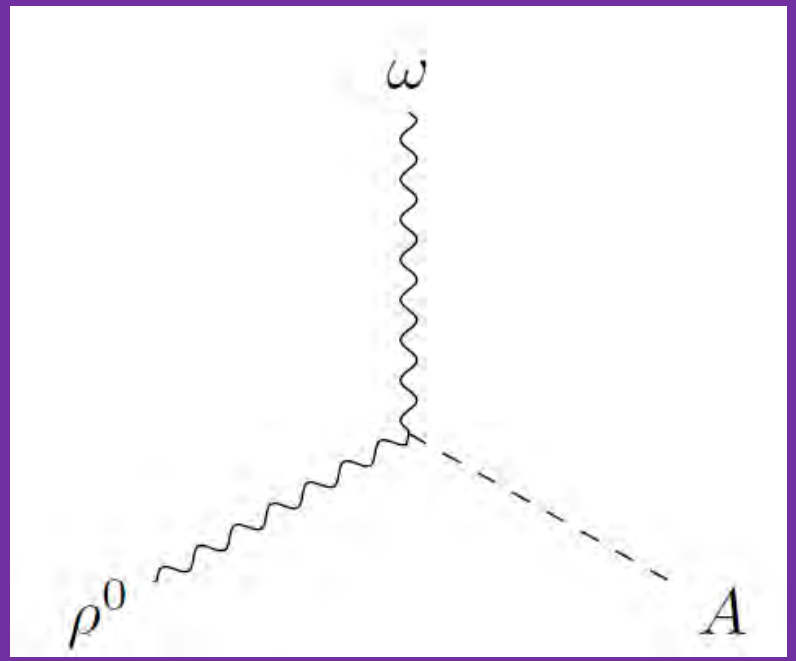
Experiment	Collider	E (MeV)	E_ρ (MeV)
KLOE	DAΦNE	510	805
BES-III	BEPC-2	1885	1966
CMD-2	VEPP-2M	388	775
BABAR	PEP-II	5282	3131

Dark Matter and "SM" Muon *g*-2 N. Bray-Ali, arXiv.2308.11650 [hep-ph] (2023)

$$\Delta a_\mu(\mathrm{KLOE}) - \Delta a_\mu(\mathrm{CMD3}) = (167 \pm 10) \times 10^{-11}$$

$$a_\mu^{\pi\pi}(\mathrm{CMD3}) - a_\mu^{\pi\pi}(\mathrm{KLOE}) = (187 \pm 37) \times 10^{-11}$$

$$\Delta a_\mu^{\pi\pi} = (19.6 \pm 1.2) \times 10^{-11} \left(\frac{E_\rho}{1000\ \mathrm{MeV}}\right) \left(\frac{\sigma_x}{100\ \mu\mathrm{m}}\right)^{1/2} \times \left(\frac{\sigma_y}{10\ \mu\mathrm{m}}\right)^{1/2} \left(\frac{\sigma_z}{1\ \mathrm{cm}}\right), \quad (1)$$



CDF II Lands 7 Sigma from Standard Model (SM)

CDF II, Science **376**, 170 (2022)

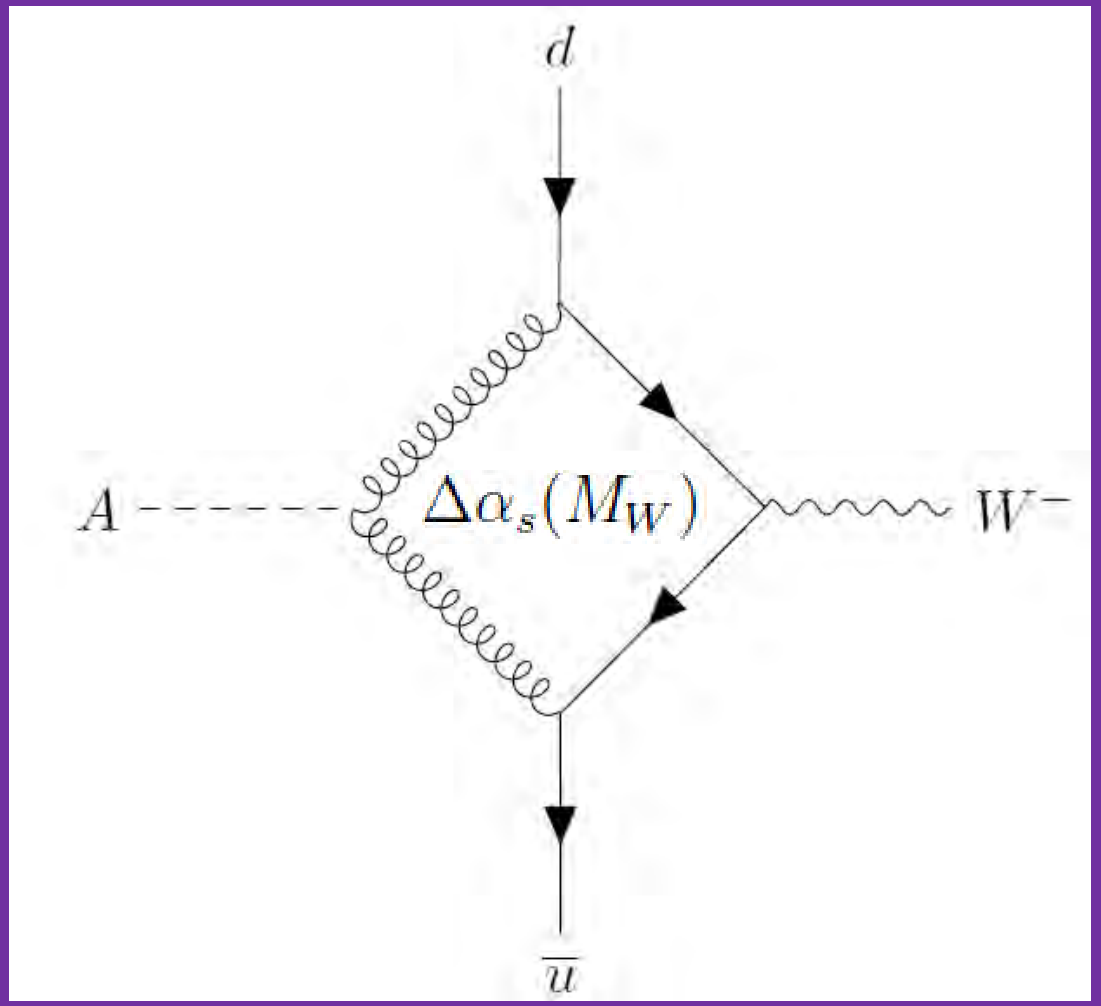
$$M_W(\text{CDF}) - M_W(\text{SM}) = (77 \pm 11)\ \text{MeV}/c^2$$

Experiment	Collider	Type	Q (GeV/c)
CDF II	Tevatron Run 2	$p\bar{p}$	6.24 [2]
ATLAS	LHC 2011	pp	6.24 [2]
TASSO	PETRA	$e\bar{e}$	35 [9]
JADE	PETRA	$e\bar{e}$	35 [9]

Collider	$\sigma_x(\mu\text{m})$	$\sigma_y(\mu\text{m})$	$\sigma_z(\text{cm})$
Tevatron Run 2	22	22	47.5
LHC 2011	18.8	18.8	9.4
PETRA	430	13	1.3

Dark Matter and the *W* Mass

N. Bray-Ali, submitted to Phys. Rev. Lett (2023)



$$\Delta M_W = M_W \log\left(\frac{M_Z}{M_W}\right) \frac{\Delta\alpha_s(M_W)}{\alpha_s(M_W)}$$
$$= (75 \pm 5)\ \mathrm{MeV/c^2},$$

$$M_W(\mathrm{CDF}) - M_W(\mathrm{SM}) = (77 \pm 11)\ \mathrm{MeV/c^2}$$

$$\frac{\Delta\alpha_s(M_W)}{\alpha_s(M_W)} = (1.14 \pm 0.07) \times 10^{-3} \left(\frac{p_W}{10\ \mathrm{GeV}}\right)$$
$$\times \left(\frac{\sigma_x}{10\ \mu\mathrm{m}}\right)^{1/2} \left(\frac{\sigma_y}{10\ \mu\mathrm{m}}\right)^{1/2} \left(\frac{\sigma_z}{10\ \mathrm{cm}}\right)$$

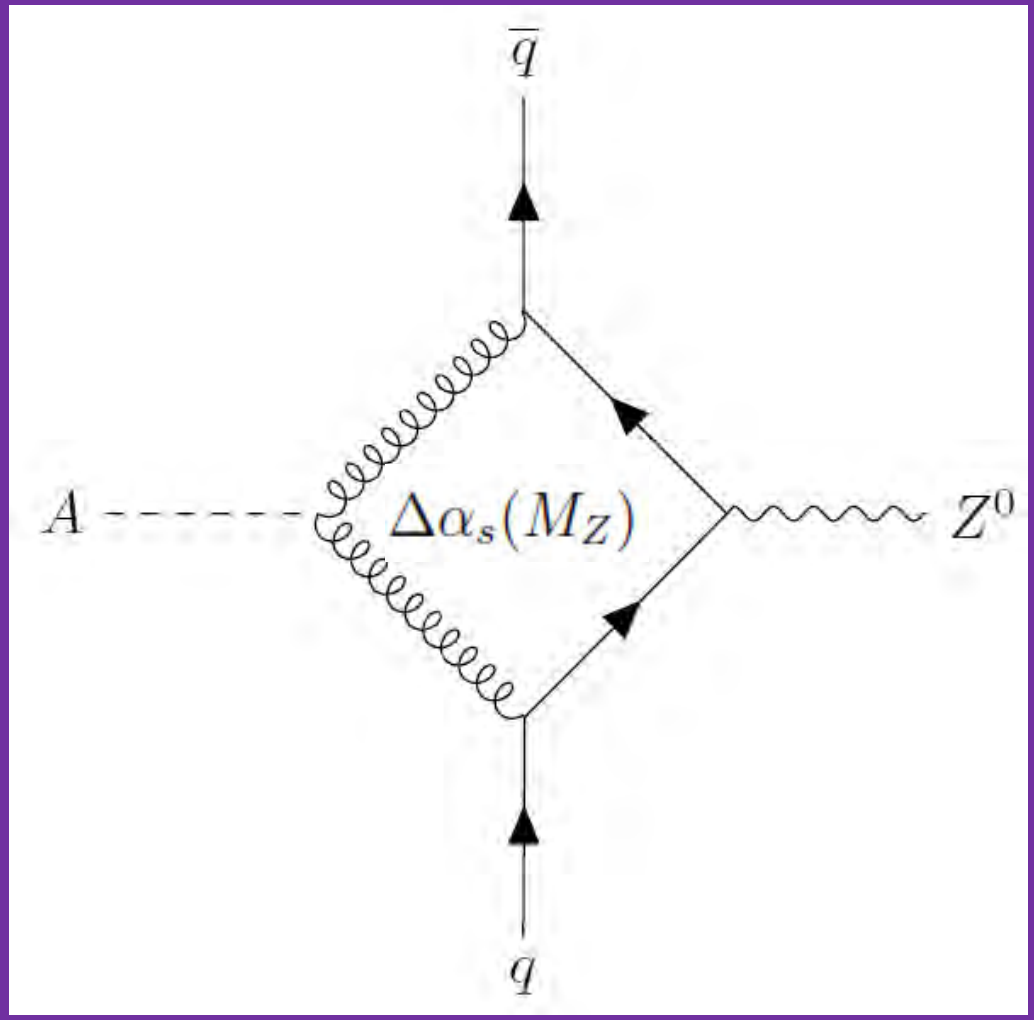
Dark Matter and the QCD Coupling Constant

N. Bray-Ali, submitted to Phys. Rev. Lett (2023)

$$\alpha_s(M_Z, \text{Thrust}) - \alpha_s(M_Z, \text{Lattice}) = -(47 \pm 13) \times 10^{-4}$$

"…the deviation from HPQCD is 3.5σ."
(Abbate+, 2010)

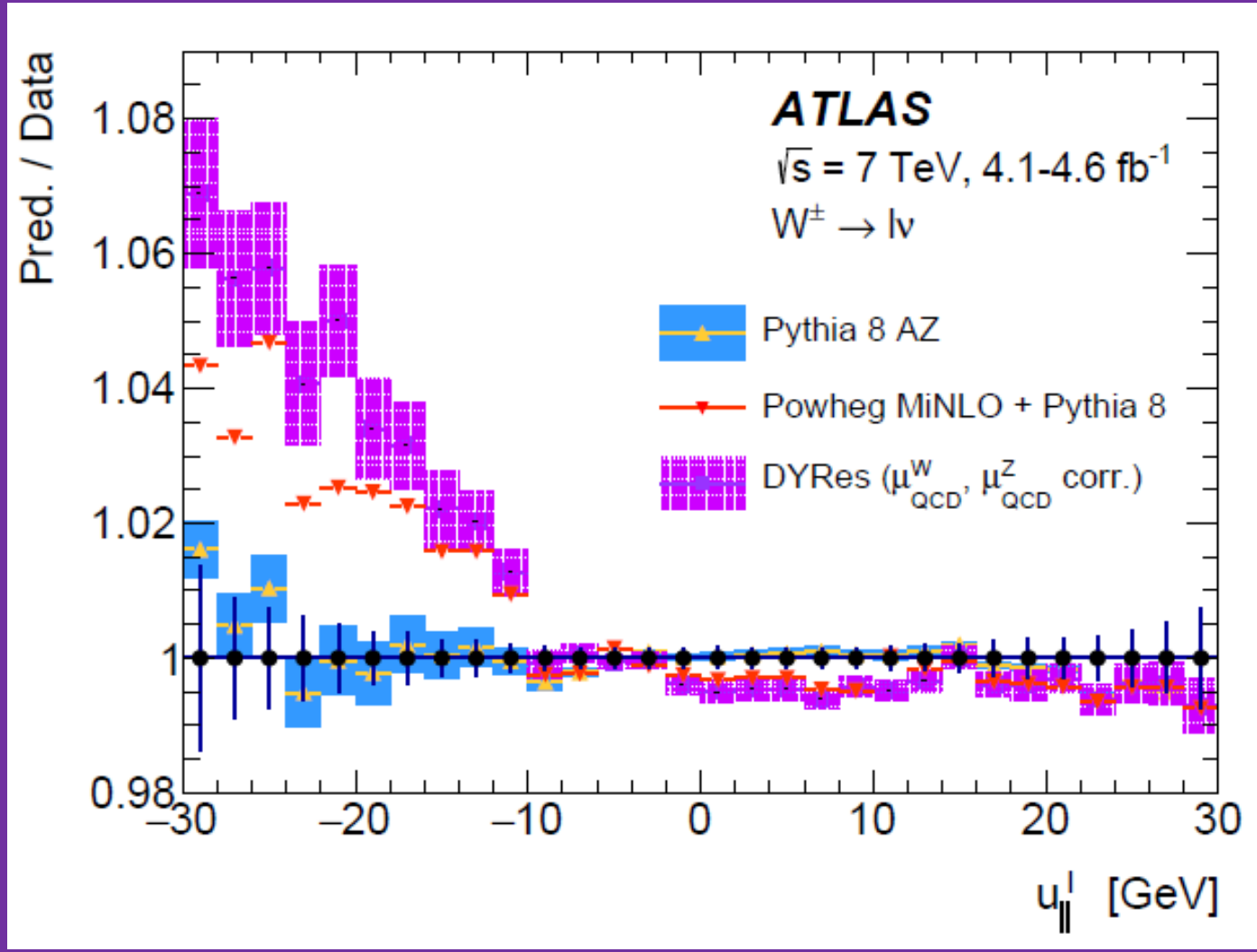
$$\begin{aligned}\Delta\alpha_s(M_Z) &= -(1.32 \pm 0.08) \times 10^{-4} \left(\frac{35\ \text{GeV}}{10\ \text{GeV}}\right) \\ &\times \left(\frac{430\ \mu\text{m}}{10\ \mu\text{m}}\right)^{1/2} \left(\frac{13\ \mu\text{m}}{10\ \mu\text{m}}\right)^{1/2} \left(\frac{1.3\ \text{cm}}{10\ \text{cm}}\right) \\ &= -(45 \pm 3) \times 10^{-4},\end{aligned}$$



Clue from ATLAS (using SM *W* mass)

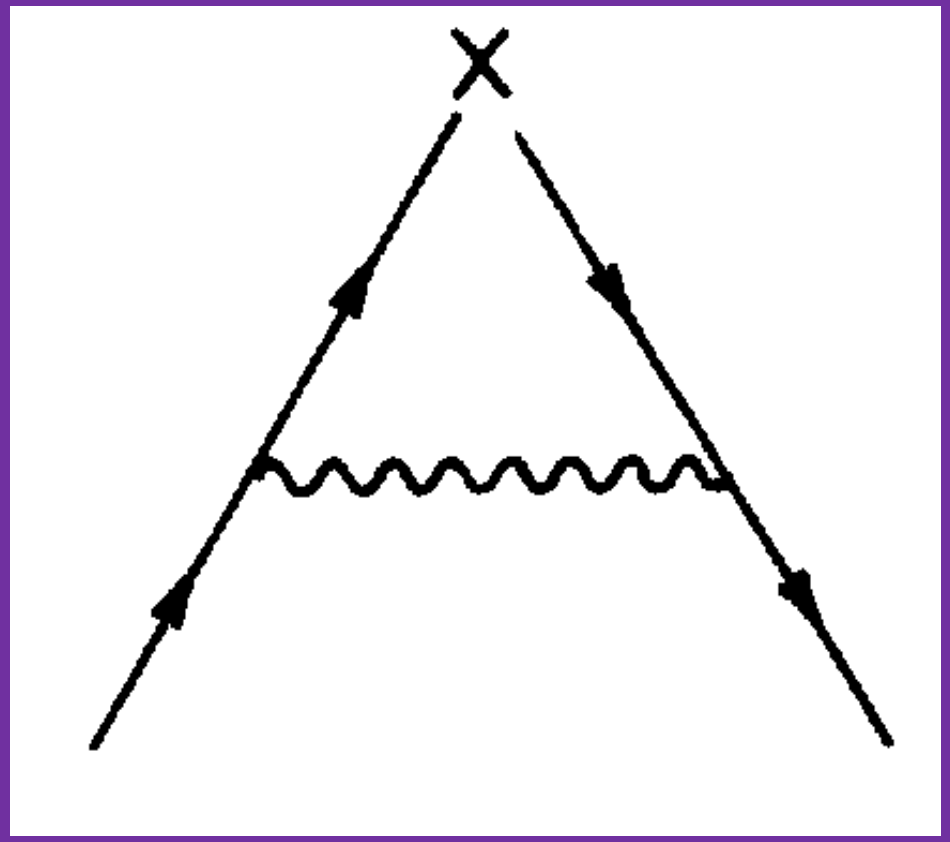
ATLAS, EPJ C **78**, 110 (2017)

…“predictions matched to the NLO [pQCD] *W*+jet cross section are in disagreement with the observed [hadronic recoil momentum] distribution…”



Electroproduction Scaling in NLO pQCD

H. Georgi and D. Politzer PRD **9**, 416 (1974)



$$\frac{g^2}{16\pi^2}\ln\left(\frac{-p^2}{M^2}\right)$$