Precision Electroweak Physics at Low Energy

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History of Radiative Corrections to β Decay

1950's: V - A Fermi theory;

$$\mathcal{L} \;=\; -\frac{G_\mu}{\sqrt{2}}[\bar{\psi}_{\nu_\mu}\gamma^\mu(1-\gamma_5)\psi_\mu][\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_{\nu_e}] + \mathrm{h.c.}$$

Calculating radiative corrections to muon decay: important evidence for V-A theory

RC to muon decay - UV finite for V and A interactions but UV divergent for S, PS

$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} F(x)[1+\delta_\mu]$$

Tree-level phase space: $F(x) = 1 - 8x - 12x^2 \ln x + 8x^3 - x^4$ $\quad x = m_e^2/m_\mu^2$

RC (2-loop): $\delta_\mu = \frac{\alpha}{2\pi}\left(\frac{25}{4}-\pi^2\right)\left[1+\frac{2\alpha}{3\pi}\ln\left(\frac{m_\mu}{m_e}\right)\right] + 6.700\left(\frac{\alpha}{\pi}\right)^2 + \cdots = -4.19818\times 10^{-3}$

Precise measurement of muon lifetime: $\tau_\mu = 2196980.3(2.2)ps$

Precise determination of Fermi constant: $G_F = G_\mu = 1.1663788(7)\times 10^{-5} GeV^{-2}$

History of Radiative Corrections to β Decay

$$\mathcal{L}_{\beta-\mathrm{decay}} = -\frac{G_V}{\sqrt{2}}[\bar{\psi}_p\gamma^\mu(1-\gamma_5)\psi_n][\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_{\nu_e}] + \mathrm{h.c.}$$

However, RC to neutron decay - UV divergent even in V-A theory

Uncorrected spectrum for Fermi transition: $$P^0 d^3p = \frac{8G_V^2}{(2\pi)^4}(E_m - E)^2 d^3p$$

UV cut-off

RC to spectrum: $$\Delta P d^3p = \frac{\alpha}{2\pi} P^0 d^3p \left\{6\ln\left(\frac{\Lambda}{m_p}\right) + g(E, E_m) + \frac{9}{4}\right\}$$

Sirlin's function:
(QED beyond Coulomb distortion)

$$g(E,E_m) = 3\ln\left(\frac{m_p}{m_e}\right) - \frac{3}{4} - \frac{4}{\beta}\mathrm{Li}_2\left(\frac{2\beta}{1+\beta}\right) + 4\left[\frac{\tanh^{-1}\beta}{\beta} - 1\right]\left[\frac{(E_m-E)}{3E} - \frac{3}{2} + \ln\left\{\frac{2(E_m-E)}{m_e}\right\}\right]$$
$$+\frac{\tanh^{-1}\beta}{\beta}\left[2(1+\beta^2) + \frac{(E_m-E)^2}{6E^2} - 4\tanh^{-1}\beta\right],$$

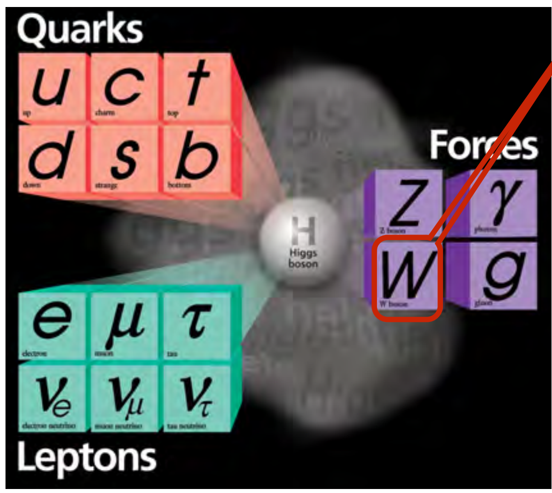
Current algebra: UV div. part $\quad \dfrac{\alpha}{2\pi}P^0 d^3p \; 3[1+2\bar{Q}]\ln(\Lambda/M)$

$\bar{Q}$: average charge of fields involved: $1 + 2\bar{Q}_{\mu,\nu_\mu} = 0$ but $1 + 2\bar{Q}_{n,p} = 2$

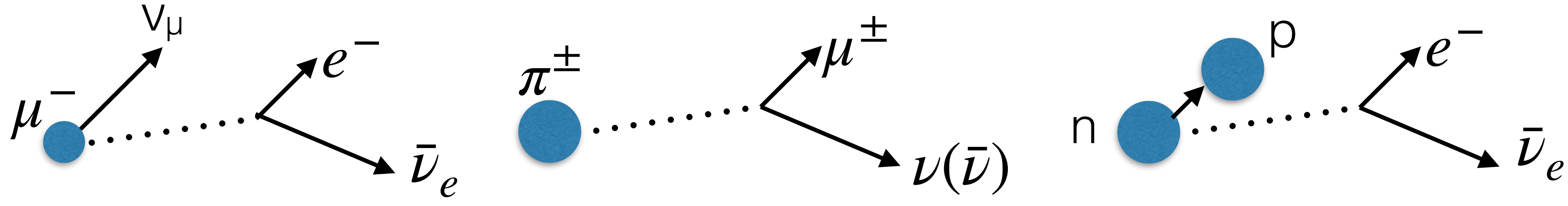
Neutron and nuclear beta decay rates: $G_V < G_\mu$
Kaon and hyperon decays? ($\Delta S = 1$)
Is weak interaction universal? Strong interaction effects?

Quark Mixing & CKM Unitarity

1960's: electroweak theory - $SU(2)_L \times U(1)_Y$, massive W, Z bosons, EW mixing, …



Charged current interaction - β-decay (μ, π±, n)



Weak interaction of lepton and quarks is universal
But its strength is distributed among quark families

Cabbibo-Kabayashi-Maskawa: mass vs. flavor eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM unitarity - measure of completeness of the SM: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Status of Top-Row CKM Unitarity

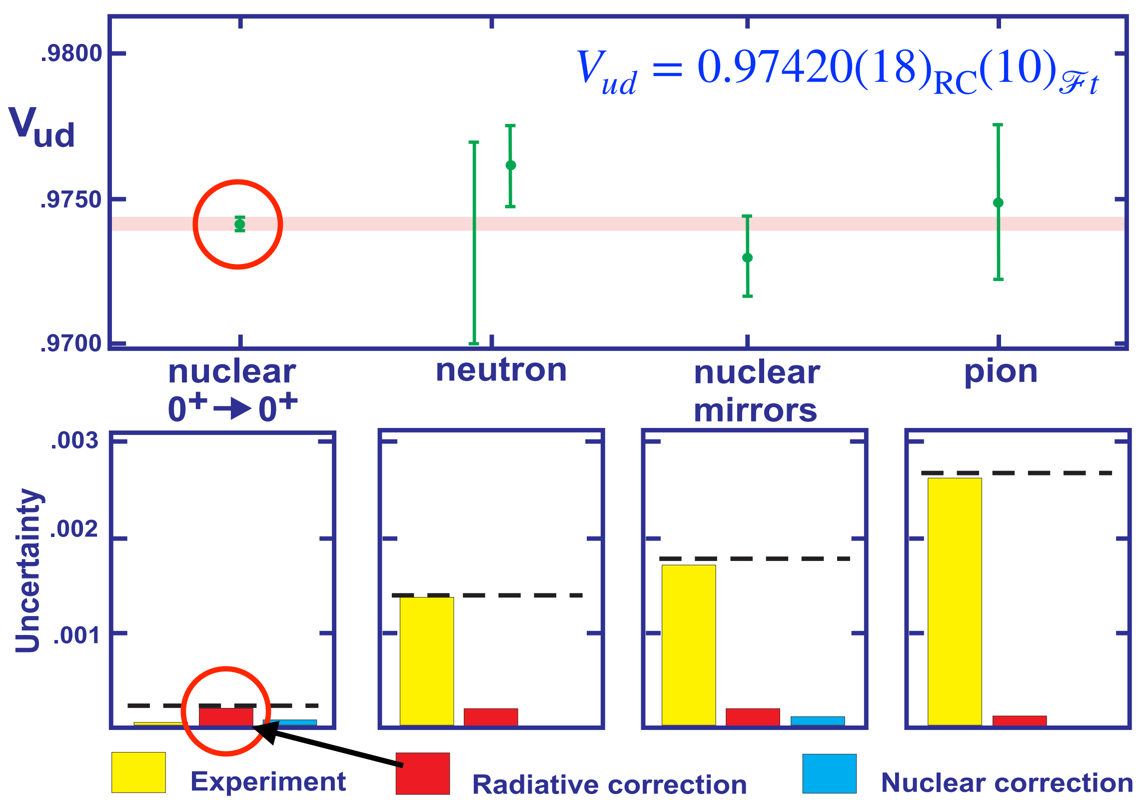
PDG 2018:

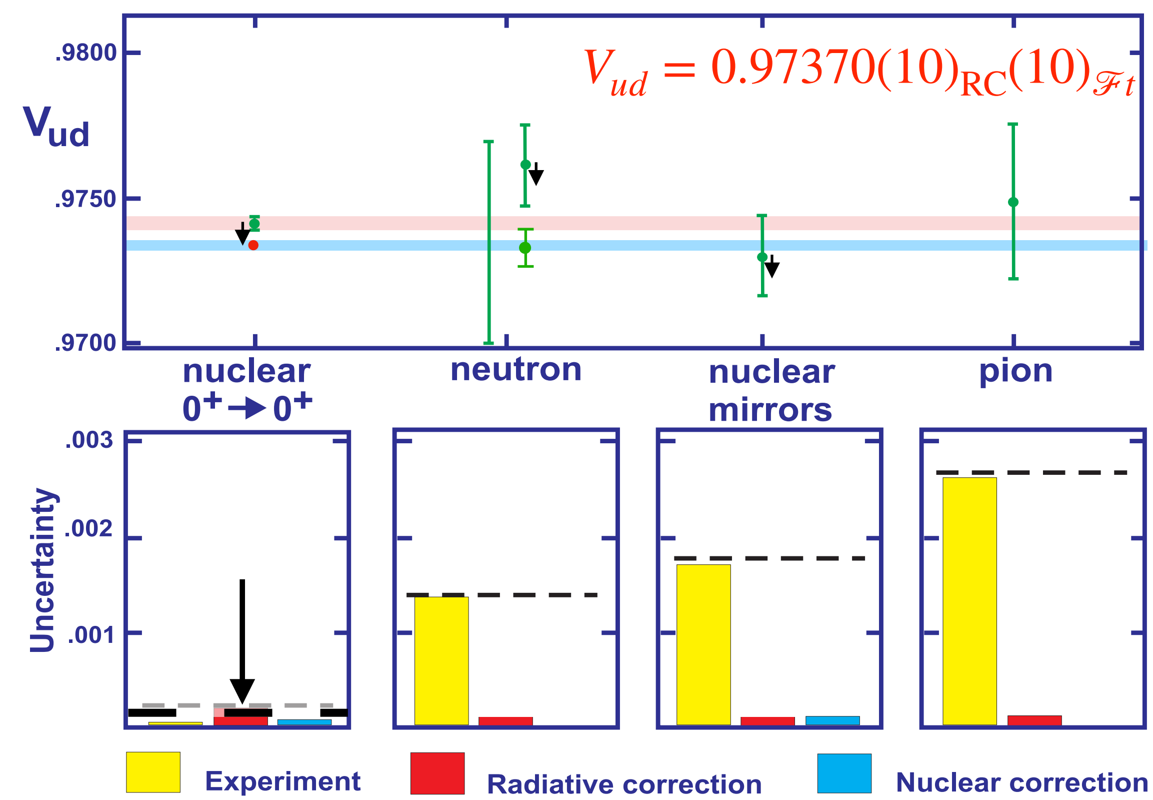
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)_{V_{ud}}(2)_{V_{us}}$$

~ 0.95 ~ 0.05 ~ 0.00002

PDG 2020:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(3)_{V_{ud}}(4)_{V_{us}}$$





Improvement in universal RC (1/2 uncertainty but central value shifted)

Seng, MG, Patel, Ramsey-Musolf, 1807.10197
Seng, MG, Ramsey-Musolf, 1812.03352

Additionally: g_A from neutron decay asymmetry improved by factor 4

$$V_{ud} = 0.9763(5)_{\tau_n}(15)_{g_A}(2)_{\rm RC} \longrightarrow V_{ud} = 0.9735(5)_{\tau_n}(3)_{g_A}(1)_{\rm RC}$$

PERKEO-III
Märkisch et al., 1812.04666

Status of V_{ud}: superallowed nuclear decays

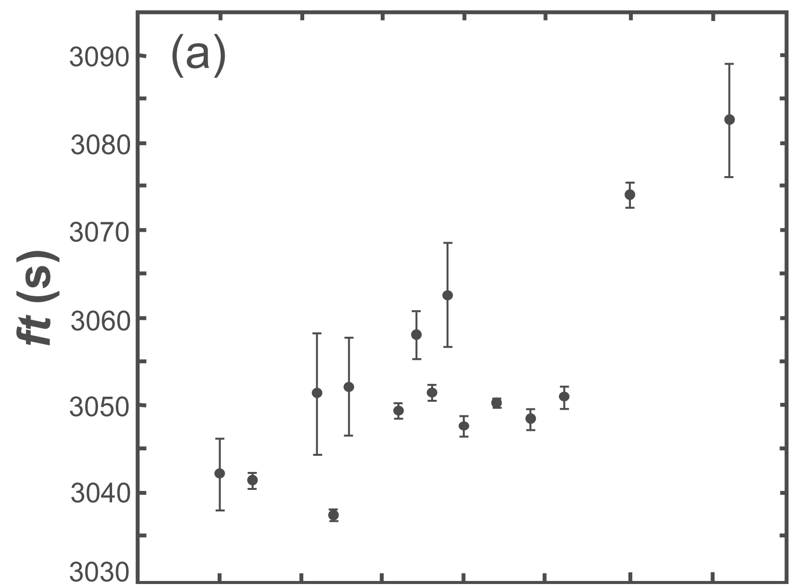
Superallowed $0^+ - 0^+$ decays

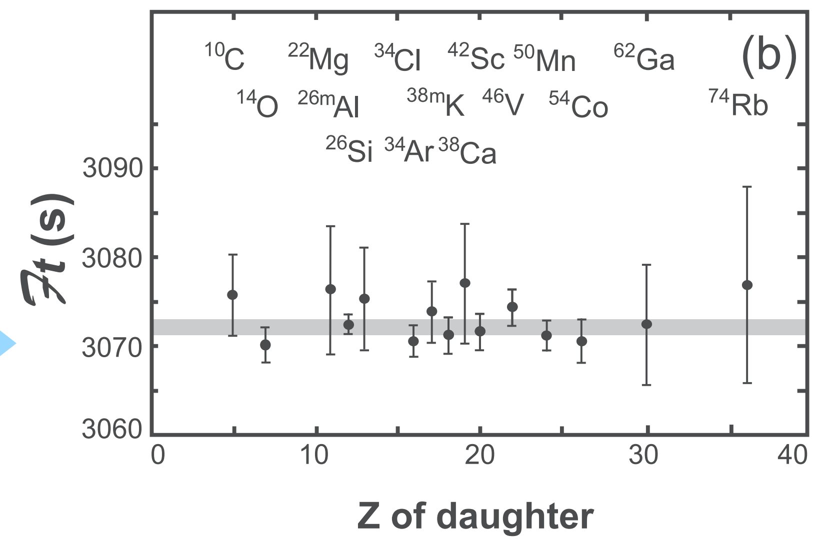
$$|V_{ud}|^2 = \frac{2984.43s}{\mathscr{F}t(1+\Delta_R^V)}$$

$\mathscr{F}t$: experiment + nucleus-specific QED + nuclear corrections
Δ_R^V: universal RC (common to all nuclear decays & free neutron)
Only vector current involved — CVC protects from strong renorm.

$$\mathcal{F}t = ft(1+\delta'_R)[1-(\delta_C-\delta_{NS})]$$

Phase space f, half-life t



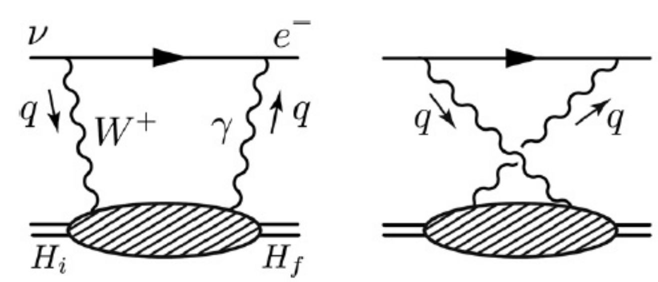


Hardy, Towner 2020
$\overline{\mathscr{F}t} = 3072.24(57)_{\rm stat}(36)_{\delta'_R}$

Major source of the theory uncertainty: γW-box

Marciano, Sirlin PRL 2006: $\Delta_R^V = 0.02361(38)$

Novel dispersion theory evaluation
Seng, MG, Patel, Ramsey-Musolf 2018 $\Delta_R^V = 0.02467(22)$



Confirmed by several independent studies

Czarnecki, Marciano, Sirlin 1907.06737
Hayen 2010.07262
Shiells, Blunden, Melnitchouk, 2012.01580

Status of V_{ud}: free neutron decay

$$|V_{ud}|^2 = \frac{5099.34s}{\tau_n(1+3g_A^2)(1+\Delta_R)}$$

Axial current not protected from strong renormalization, $g_A \neq 1$

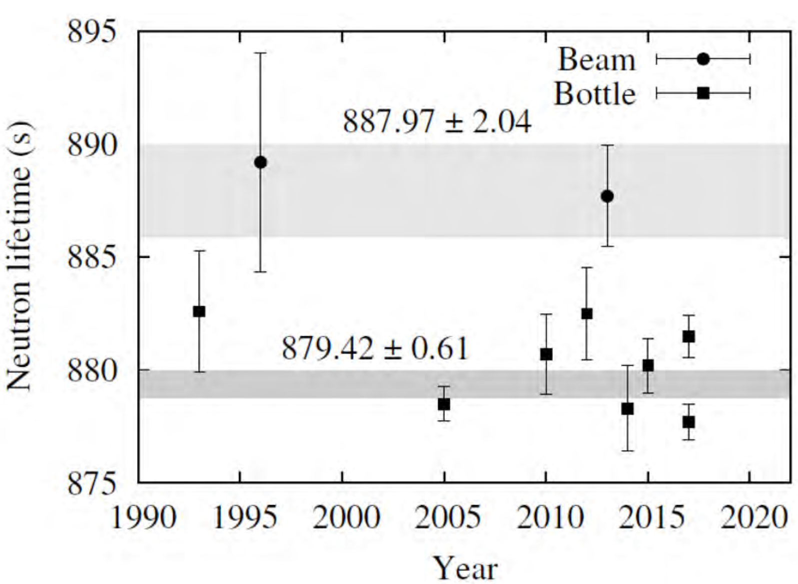
$$g_A = -1.2723(23) \longrightarrow g_A = -1.2764(6)$$

PERKEO-III

Märkisch et al., 1812.04666

$$|V_{ud}| = 0.9735(5)_{\tau_n}(3)_{g_A}(1)_{\mathrm{RC}}$$

Current limitation: neutron lifetime
Beam-bottle discrepancy
(cold neutrons vs. UCN)



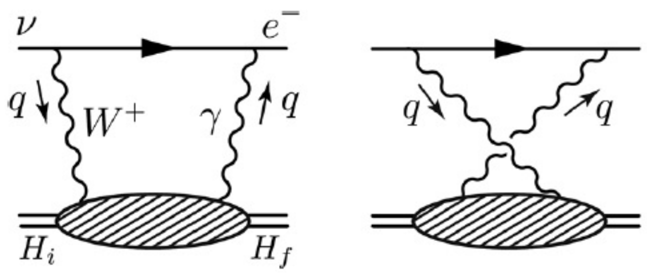
Will improve within the next decade

Coefficient	Precision goal	Experiment (Laboratory)	Comments
τ_n	1.0 s; 0.1 s [210]	BL2, BL3 (NIST) [210]	In preparation; two phases
	1.0 s; 0.3 s [214]	LiNA (J-PARC) [211, 214]	In preparation; two phases
	0.2 s [215]	Gravitrap (ILL) [203, 215]	Apparatus being upgraded
	0.3 s [201]	Ezhov (ILL) [201]	Under construction
	0.1 s [222]	PENeLOPE (Munich) [222]	Being developed
	$\lesssim$ 0.1 s [223]	UCNτ (LANL) [188, 189, 223, 224]	Ongoing
	0.5 s [225]	HOPE (ILL) [188, 225, 226]	Proof of principle Ref. [226]
	1.0 s; 0.2 s [188]	τSPECT (Mainz) [188, 227]	Taking data; two phases
β-spectrum	$\mathcal{O}(0.01)$ [256]	Supercond. spectr. (Madison) [256]	Shape factor Eq. (51). Ongoing
β-spectrum	$\mathcal{O}(0.01)$ [253]	Si-det. spectr. (Saclay) [253, 254]	Shape factor Eq. (51). Ongoing
b_{GT}	0.001	Calorimetry (NSCL) [115, 260]	Analysis ongoing (^{6}He, ^{20}F)
	$\mathcal{O}(0.001)$ [270]	miniBETA (Krakow-Leuven) [263–265, 270]	Being commissioned
	$\mathcal{O}(0.001)$ [276]	UCNA-Nab-Leuven (LANL) [271, 272, 276]	Analysis ongoing (^{45}Ca)
b_n	< 0.05 [293, 294]	UCNA (LANL) [390]	Ongoing with A_n data
	0.03 [295]	PERKEO III (ILL) [295]	Possible with A_n data
	0.003 [289]	Nab (LANL) [188, 289, 357, 358]	In preparation
	0.001 [291]	PERC (Munich) [291, 292]	Planned
a_F	0.1% [306]	TRINAT (TRIUMF) [306, 310]	Planned (^{38}K)
	0.1% [343]	TAMUTRAP (TA&M) [343]	Superallowed $\beta\,p$ emitters
	0.1% [79]	WISArD (ISOLDE) [79, 177]	In preparation (^{32}Ar $\beta\,p$ decay)
a	not stated	Ne-MOT (SARAF) [311, 312]	In preparation (^{18}Ne, ^{19}Ne, ^{23}Ne)
a_{GT}	$\mathcal{O}(0.1)$% [315]	^{6}He-MOT (Seattle) [313, 315]	Ongoing (^{6}He)
	not stated	EIBT (Weizmann Inst.) [316–318]	In preparation (^{6}He)
	0.5% [182]	LPCTrap (GANIL) [182, 321, 323, 324]	Analysis ongoing (^{6}He, ^{35}Ar)
a_{mirror}	0.5% [273]	NSL-Trap (Notre Dame) [273, 344, 345]	Planned (^{11}C, ^{13}N, ^{15}O, ^{17}F)
$\tilde{a}_n$	1.0% [350]	aCORN (NIST) [350, 352–354]	Data taking ongoing
a_n	1.0 – 1.5% [351]	aSPECT (ILL) [228, 229, 351]	Analysis being finalized
	0.15% [188, 358]	Nab (LANL) [188, 289, 357, 358]	In preparation
$\tilde{A}_n$	0.14% [391]	UCNA (LANL) [390]	Data taking planned
	0.18% [295]	PERKEO III (ILL) [295]	Analysis ongoing
$\tilde{A}_{mirror}$	$\mathcal{O}(0.1)$% [78]	TRINAT (TRIUMF) [78]	Planned
$\tilde{B}_n$	0.01% [397]	UCNB (LANL) [397]	Planned
$\tilde{A}_n$ $(a_n, \tilde{B}_n, \ldots)$	0.05% [291]	PERC (Munich) [291, 292]	In preparation
$\tilde{A}_n$ $(a_n, \tilde{B}_n, \ldots)$	$< \mathcal{O}(0.1)$% [399]	BRAND (ILL/ESS) [399, 400]	Proposed
D	$\mathcal{O}(10^{-4})$ [418]	MORA (GANIL / JYFL) [418]	In preparation (^{23}Mg)
R	$\mathcal{O}(10^{-3})$ [427]	MTV (TRIUMF) [427–429]	Data taking ongoing (^{8}Li)
D, R	$\mathcal{O}(0.1)$% [399]	BRAND (ILL) [399, 400]	Proposal

Gonzalez Alonso, Naviliat-Cuncic, Severijns PPNP 104, 2019

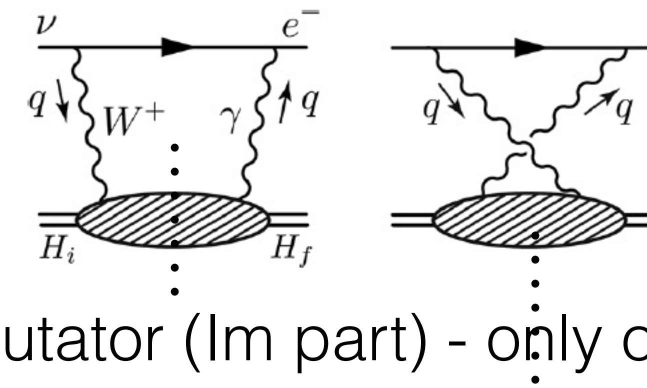
Universal RC from dispersion relations

Model-dependent part or RC: γW-box $\qquad \Delta_R^V = 2\,\Box_{\gamma W}^{VA}$ + model-independent



Generalized Compton tensor
time-ordered product — complicated!

$$\int dx e^{iqx} \langle H_f(p) \,|\, T\{J^\mu_{em}(x) J^{\nu,\pm}_W(0)\} \,|\, H_i(p) \rangle$$



Commutator (Im part) - only on-shell
hadronic states — related to data

$$\int dx e^{iqx} \langle H_f(p) \,|\, [J^\mu_{em}(x), J^{\nu,\pm}_W(0)] \,|\, H_i(p) \rangle$$

Physics of model dependence: virtual photon polarizes the nucleus;
Long-range part of the box sensitive to hadronic polarizabilities;
Polarizabilities are related to the excitation spectrum via a dispersion relation (sum rule)

Interference γW structure function

$$\mathrm{Im} T^{\mu\nu}_{\gamma W} = \ldots + \frac{i\varepsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta}{2(pq)} F_3^{\gamma W}(x, Q^2)$$

Box ~ 1st Nachtmann moment of $F_3^{\gamma W(0)}$
Symmetry: only isoscalar photons contribute

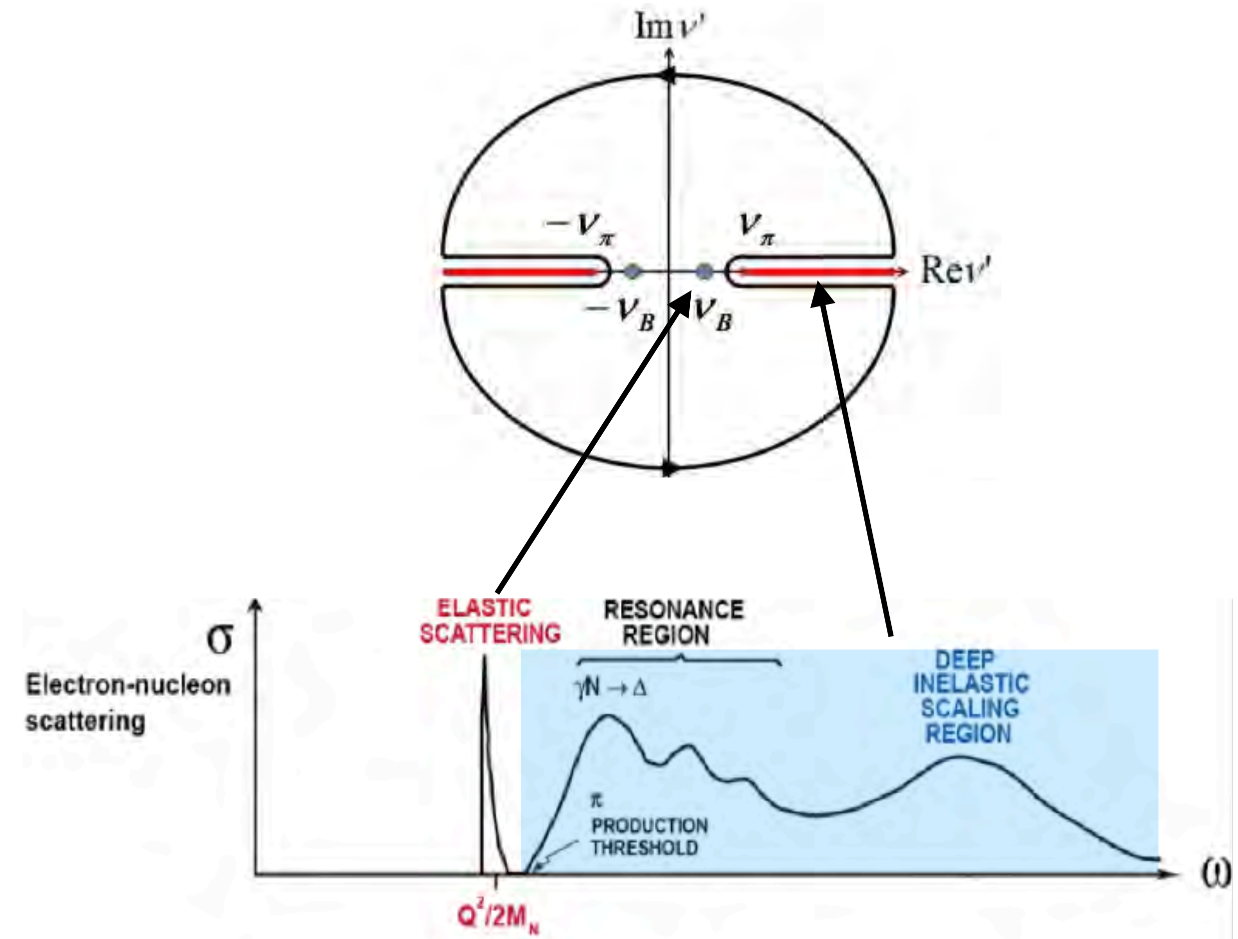
$$\Box_{\gamma W}^{VA} = \frac{3\alpha}{2\pi} \int_0^\infty \frac{dQ^2}{Q^2} \frac{M_W^2}{M_W^2 + Q^2} M_3^{\gamma W(0)}(Q^2)$$

Nachtmann moments:

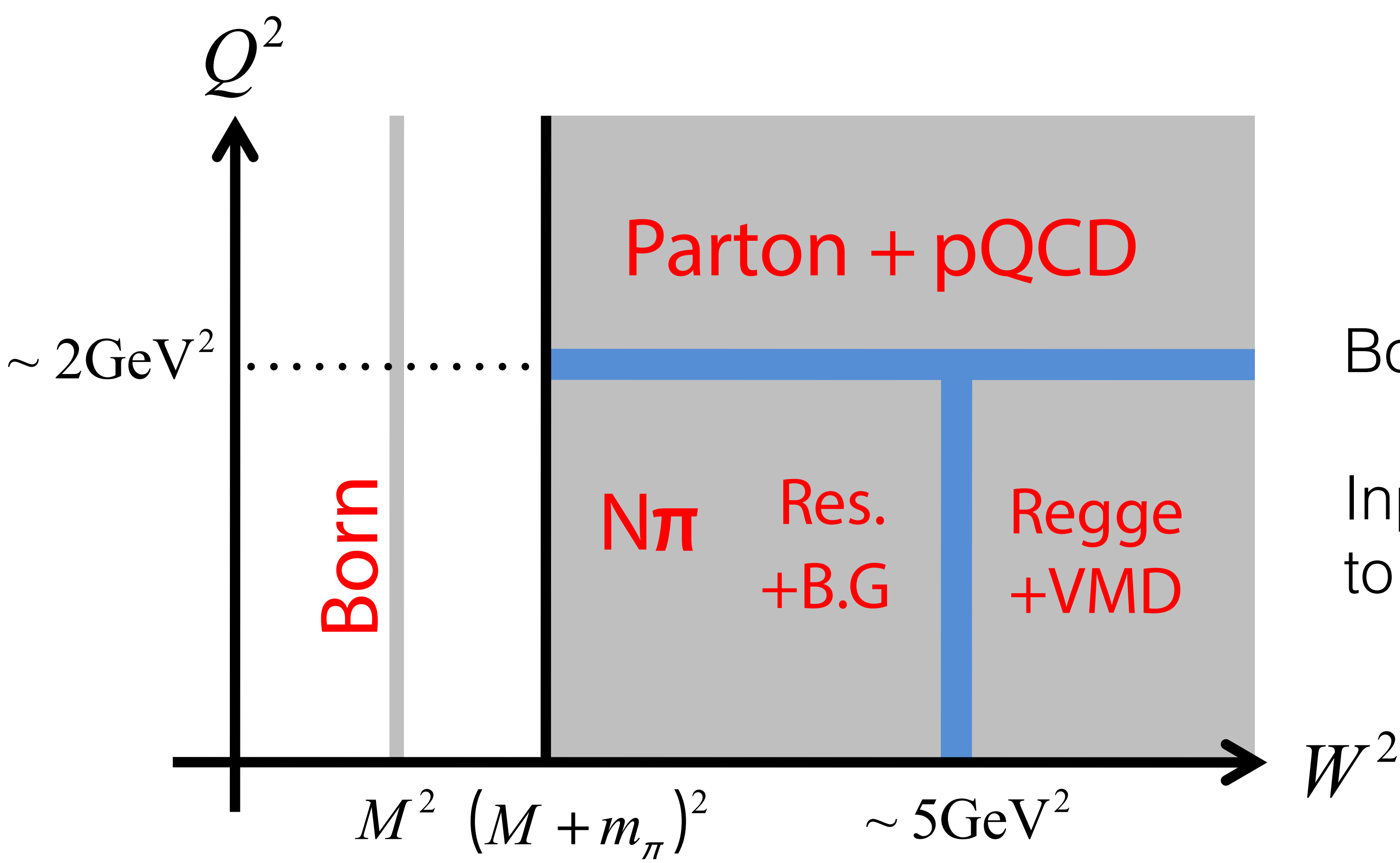
$$M_3(n, Q^2) = \frac{n+1}{n+2} \int_0^1 \frac{dx \xi^n}{x^2} \frac{2x(n+1) - n\xi}{n+1} F_3(x, Q^2), \qquad \xi = \frac{2x}{1 + \sqrt{1 + 4M^2 x^2/Q^2}}$$

Input into dispersion integral

Dispersion in energy: $W^2 = M^2 + 2M\nu - Q^2$
scanning hadronic intermediate states



Dispersion in Q²:
scanning dominant physics pictures



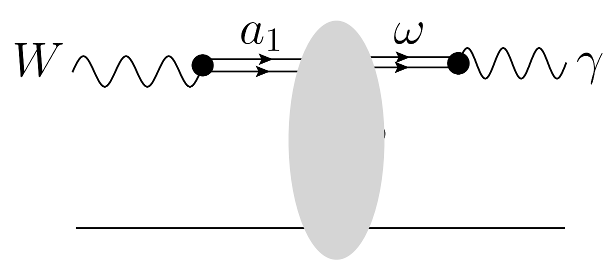
Boundaries between regions - approximate

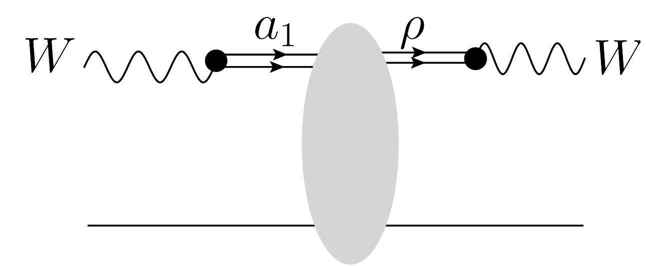
Input in DR related (directly or indirectly) to experimentally accessible data

Input into dispersion integral - $\nu/\bar{\nu}$ data

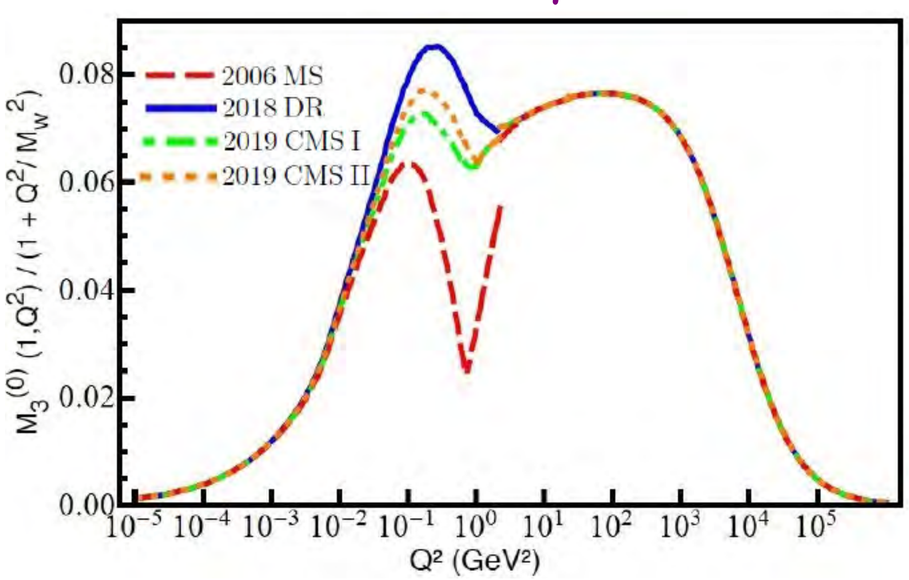
Isospin symmetry: vector-isoscalar current related to vector-isovector current

Mixed CC-NC γW SF (no data) <—> Purely CC SF (inclusive neutrino data)

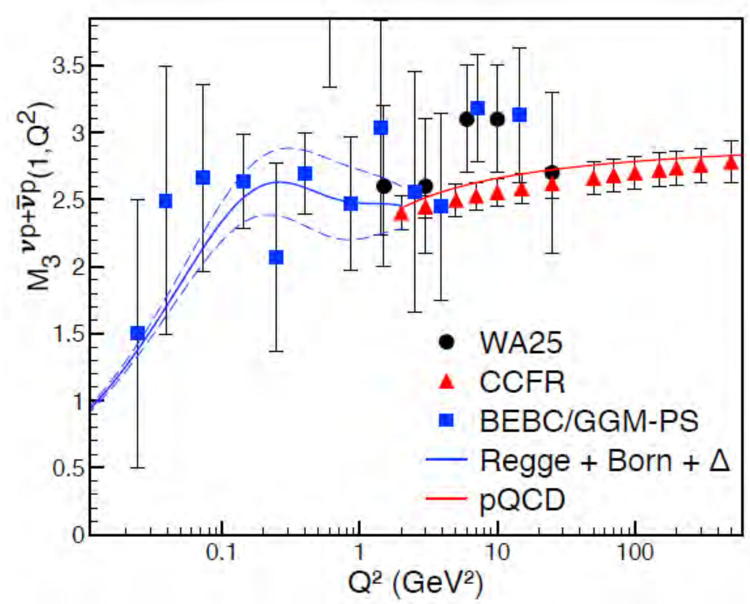




Free neutron γW box



Neutrino scattering data



Marciano, Sirlin 2006: $\Delta_R^V = 0.02361(38)$ —> $|V_{ud}| = 0.97420(10)_{Ft}(18)_{RC}$

DR (Seng et al. 2018): $\Delta_R^V = 0.02467(22)$ —> $|V_{ud}| = 0.97370(10)_{Ft}(10)_{RC}$

Main limitation: low quality of neutrino data (old bubble-chamber experiments)
Better neutrino data from DUNE (Snowmass 2021 LOI in preparation)
Next breakthrough: first principle calculation on the lattice

First lattice QCD calculation of γW-box

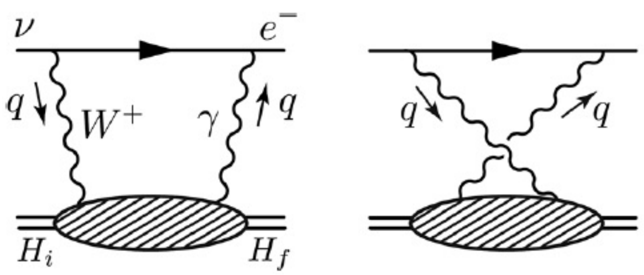
Neutron γW-box - complicated

Address (very rare! BR ~ 10^{-8}) pion decay $\pi^+ \to \pi^0 + e^+ + \nu_e$

Partial decay width: $$\Gamma_{\pi\ell 3} = \frac{G_F^2 |V_{ud}|^2 m_\pi^5 |f_+^\pi(0)|^2}{64\pi^3}(1+\delta)I_\pi = 0.3988(23)\,\mathrm{s}^{-1}$$

Form factor: well under control

RC: estimate in χPT: $\delta = 0.0334(10)_{\mathrm{LEC}}(3)_{\mathrm{HO}}$ *Cirigliano et al., 2003*



$$\Box_{\gamma W}^{VA} = \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2}{Q^2}\frac{M_W^2}{M_W^2+Q^2}M_{3\pi}^{\gamma W(0)}(Q^2)$$

All values of Q contribute to the integral

Use perturbative QCD expansion for $Q^2 \geq 2\,\mathrm{GeV}^2$

pQCD at 4-loop: $$M_\pi(Q^2) = \frac{1}{12}\left[1 - \tilde{C}_1\left(\frac{\alpha_S}{\pi}\right) - \tilde{C}_2\left(\frac{\alpha_S}{\pi}\right)^2 - \tilde{C}_3\left(\frac{\alpha_S}{\pi}\right)^3 - \tilde{C}_4\left(\frac{\alpha_S}{\pi}\right)^4 - \dots\right]$$

$$\begin{aligned} \tilde{C}_1 &= 1 \\ \tilde{C}_2 &= 4.583 - 0.333 n_f \\ \tilde{C}_3 &= 41.44 - 7.607 n_f + 0.177 n_f^2 \\ \tilde{C}_4 &= 479.4 - 123.4 n_f + 7.697 n_f^2 - 0.1037 n_f^3 \end{aligned}$$

Baikov, Chetyrkin and Kuhn, 2010 PRL

First lattice QCD calculation of γW-box

For low $Q^2 \leq 2\,\mathrm{GeV}^2$: direct lattice calculation of the generalized Compton tensor

Feng, MG, Jin, Ma, Seng 2003.09798

Main executors: Xu Feng (Peking U.), Lu-Chang Jin (UConn/RIKEN BNL)
Supercomputers: Blue Gene/Q Mira computer (Argonne, USA),
Tianhe 3 prototype (Tianjin, China)

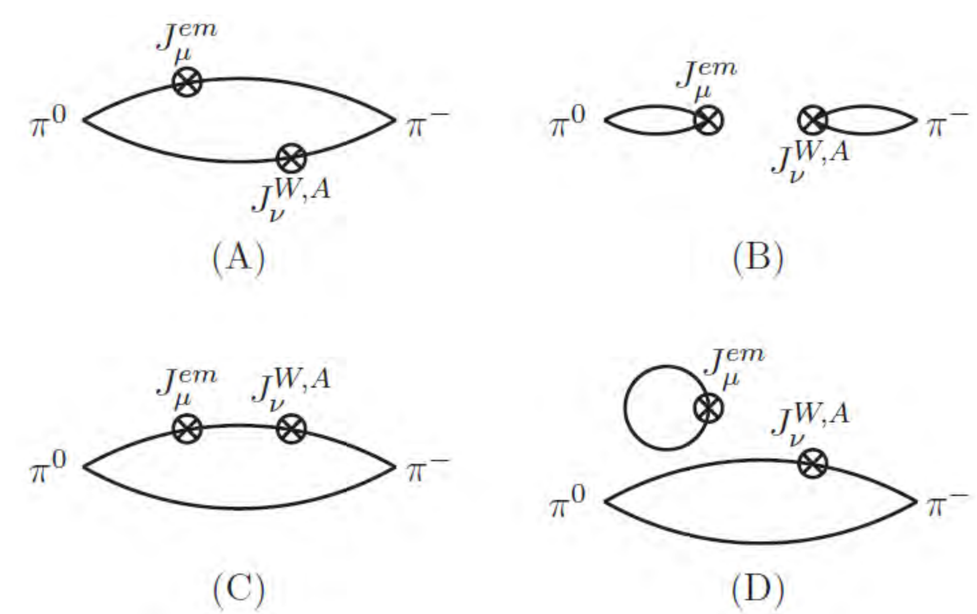
$$\mathcal{H}^{VA}_{\mu\nu}(t,\vec{x}) \equiv \langle H_f(P)|T\left[J^{em}_\mu(t,\vec{x})J^{W,A}_\nu(0)\right]|H_i(P)\rangle$$

$$M^{\gamma W(0)}_{3\pi}(Q^2) = -\frac{1}{6\sqrt{2}}\frac{Q}{m_\pi}\int d^4x\,\omega(Q,x)\epsilon_{\mu\nu\alpha 0}x_\alpha \mathscr{H}^{VA}_{\mu\nu}(x)$$

Lattice setup:
5 LQCD gauge ensembles at physical pion mass
Generated by RBC and UKQCD collaborations
w. 2+1 flavor domain wall fermion

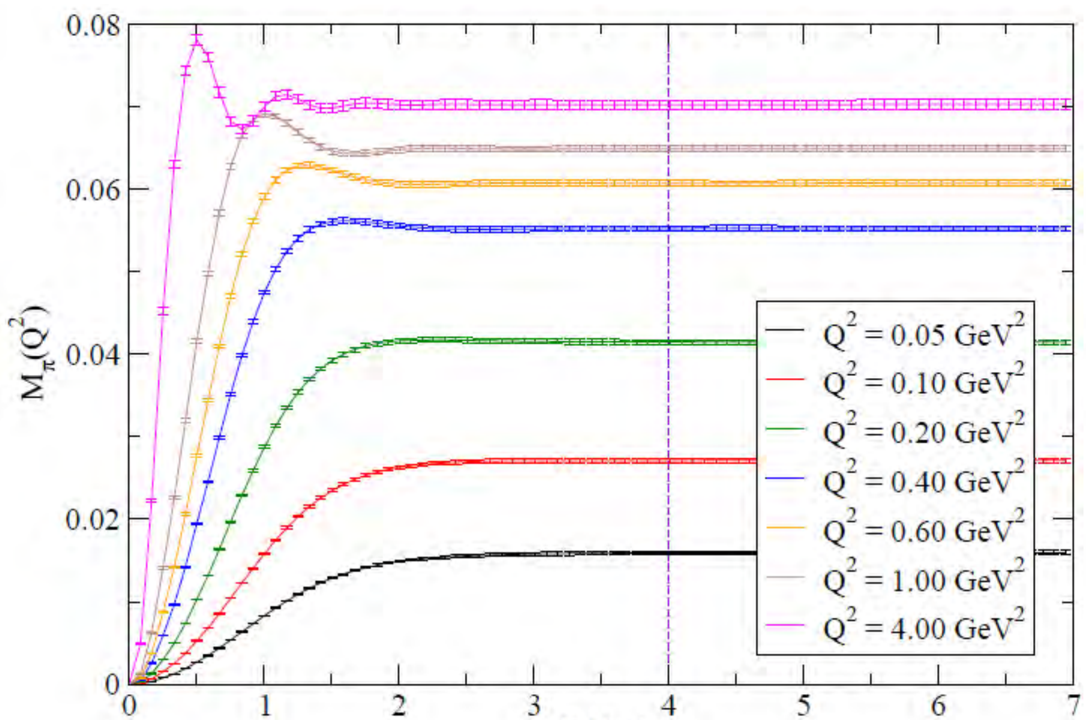
Ensemble	m_π [MeV]	L	T	a^{-1} [GeV]	$N_{\rm conf}$	N_r	$\Delta t/a$
24D	141.2(4)	24	64	1.015	46	1024	8
32D	141.4(3)	32	64	1.015	32	2048	8
32D-fine	143.0(3)	32	64	1.378	71	1024	10
48I	135.5(4)	48	96	1.730	28	1024	12
64I	135.3(2)	64	128	2.359	62	1024	18

Blue: DSDR
Red : Iwasaki

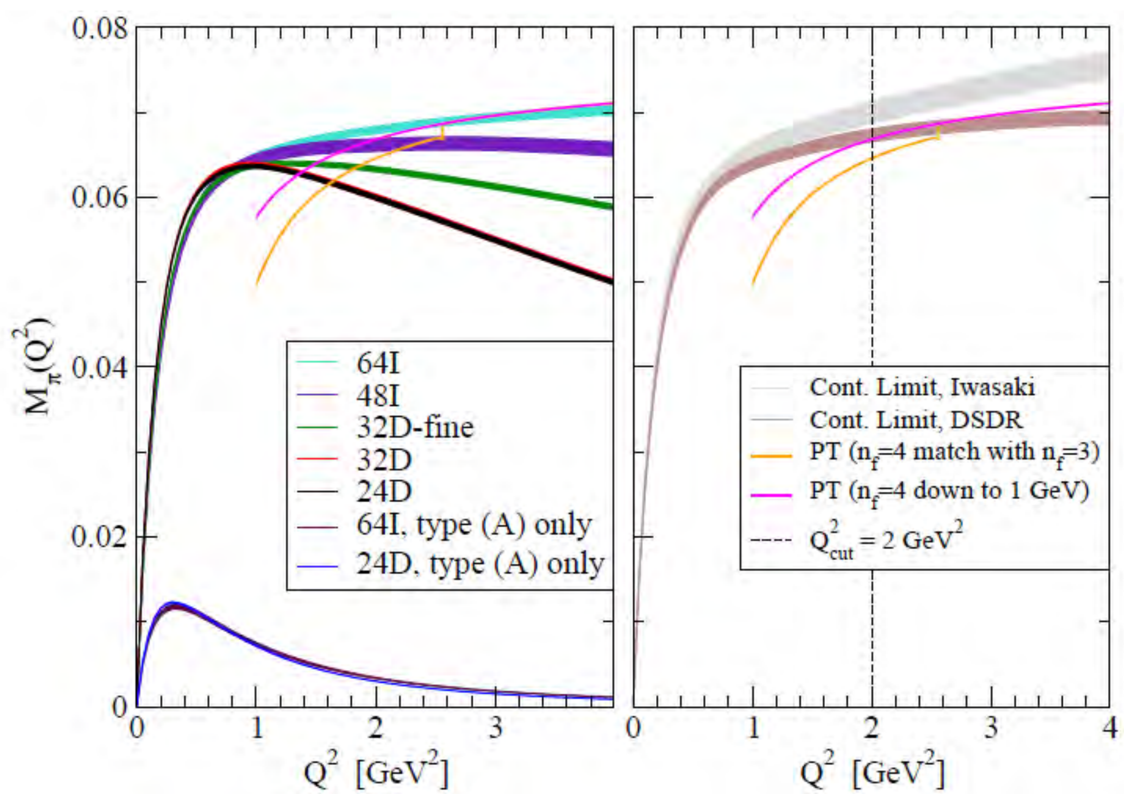


Quark contraction diagrams

First lattice QCD calculation of γW-box



(integral range, 64I)



(before cont. extrapolation) (after cont. extrapolation)

Estimate of major systematic effects:

- **Lattice discretization effect**: Estimated using the discrepancy between DSDR and Iwasaki
- **pQCD calculation**: Estimated from the difference between 3-loop and 4-loop results
- **Higher-twist effects at large Q^2**: Estimated from lattice calculation of type (A) diagrams

Final result: $\Box^{VA}_{\gamma W}\big|_\pi = 2.830(11)_{\rm stat}(26)_{\rm syst} \times 10^{-3}$

Significant reduction of the uncertainty! $\delta: \quad 0.0334(10)_{\rm LEC}(3)_{\rm HO} \rightarrow 0.0332(1)_{\gamma W}(3)_{\rm HO}$

Cleanest way to access V_{ud} theoretically: $|V_{ud}| = 0.9740(28)_{\rm exp}(1)_{\rm th}$

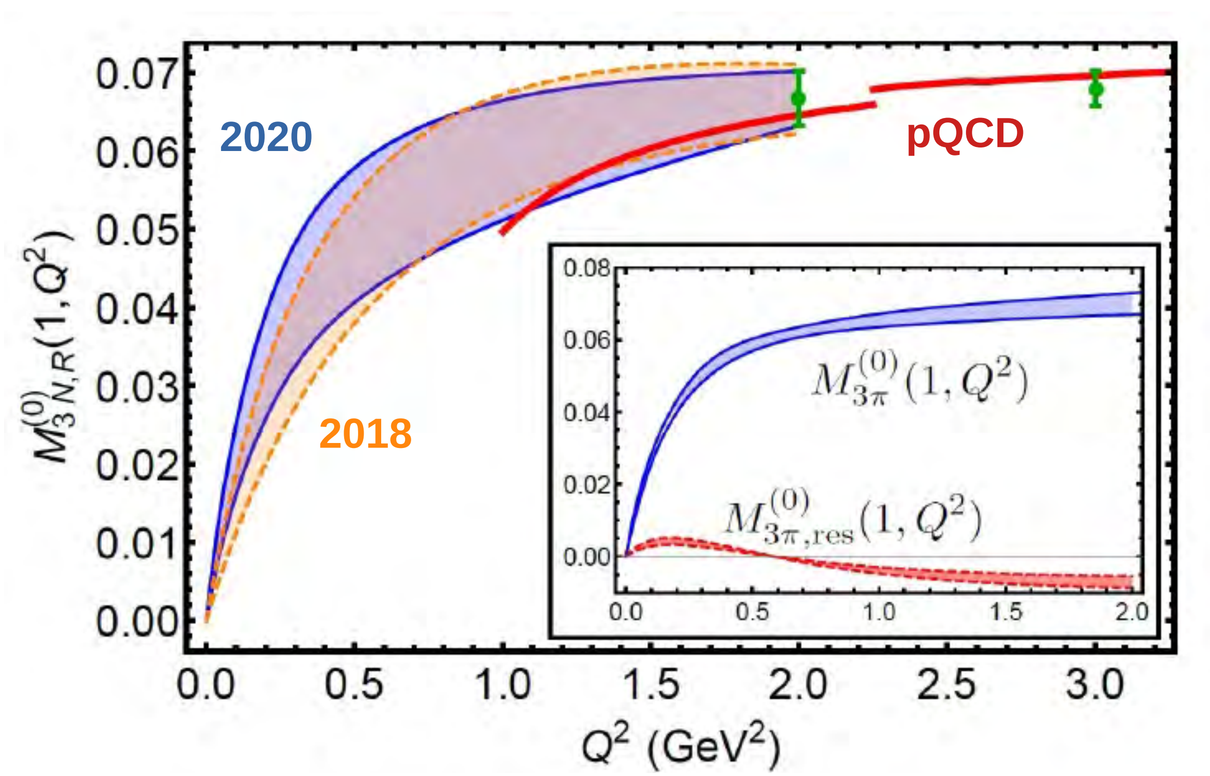
Next-gen experiments: aim at 1 o.o.m. exp. uncertainty improvement (Snowmass 2021 LOI)

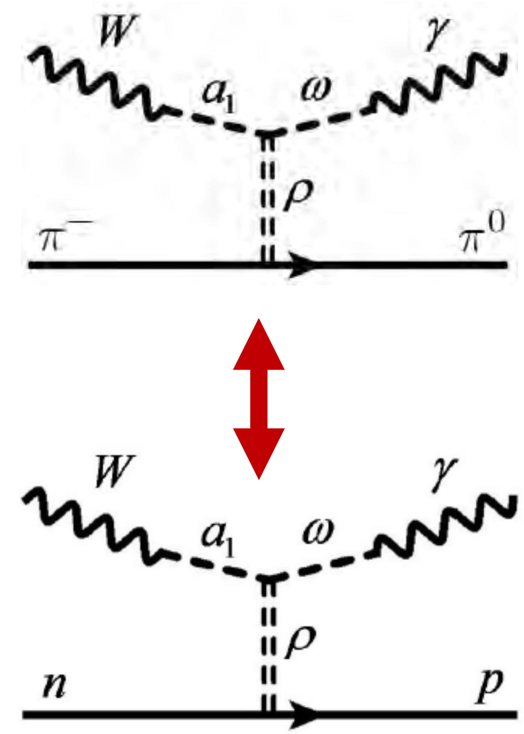
Implications for the free nucleon γW-box

Main uncertainty of the DR calculation of the free neutron γW-box:
Poorly constrained parameters of the Regge contribution which dominates the Nachtmann moment at $Q^2 \sim 1 - 2\,\mathrm{GeV}^2$
Use the Regge universality and a body of $\pi\pi$, πN, NN scattering data.

$$\frac{T^{\rho}_{W^+ + \pi^- \to \gamma + \pi^0}}{T^{\rho}_{W^+ + n \to \gamma + p}} = \frac{T^{\rho}_{\pi\pi\to\pi\pi}}{T^{\rho}_{\pi N\to\pi N}} = \frac{T^{\rho}_{\pi N\to\pi N}}{T^{\rho}_{NN\to NN}}$$

Seng, MG, Feng, Jin, 2003.11264





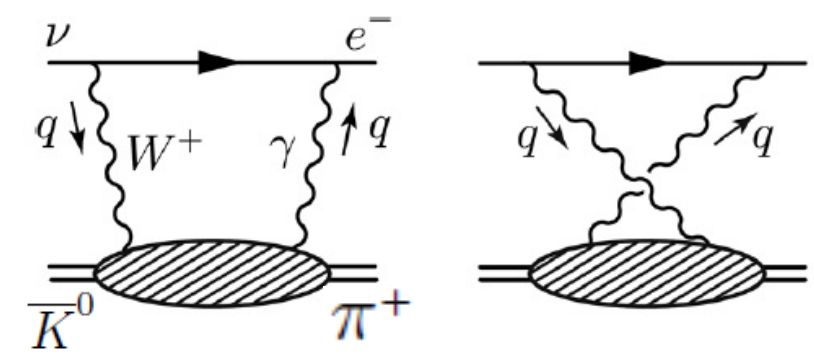
Independent confirmation of the empirical DR result AND uncertainty

$$\Delta_R^V = 0.02467(22)_{\mathrm{DR}} \to 0.02477(24)_{\mathrm{LQCD+DR}}$$

Implications for semileptonic kaon decays

A direct calculation of the γW-box for transition $K\pi$
In the flavor SU(3) limit:
Allowed to fix relevant LEC's of χPT analysis

Ma, Feng, MG, Jin, Seng 2102.12048



Allowed to reduce the uncertainty of the long-range e.-m. RC
by an order of magnitude ($10^{-3} \to 10^{-4}$)

Seng, Galviz, MG, Meißner 2103.00975, 2103.04843

New proposal to extract V_{us}/V_{ud} (alternative to $K\ell 2/\pi\ell 2$):

$$R_V = \frac{\Gamma_{Ke3}}{\Gamma_{\pi e3}} \propto \frac{|V_{us}|^2}{|V_{ud}|^2}$$

Czarnecki, Marciano, Sirlin 2020

Potentially the most precise V_{us}/V_{ud} determination when improved measurements of $\pi\ell 3$ partial width will become available

Major advance in RC to beta decays via a combination of dispersion theory, direct lattice calculations and EFT methods;
Further goals: nuclear corrections,
direct LQCD γW-box for neutron and kaon beyond SU(3)

Sensitivity to BSM in the LHC era

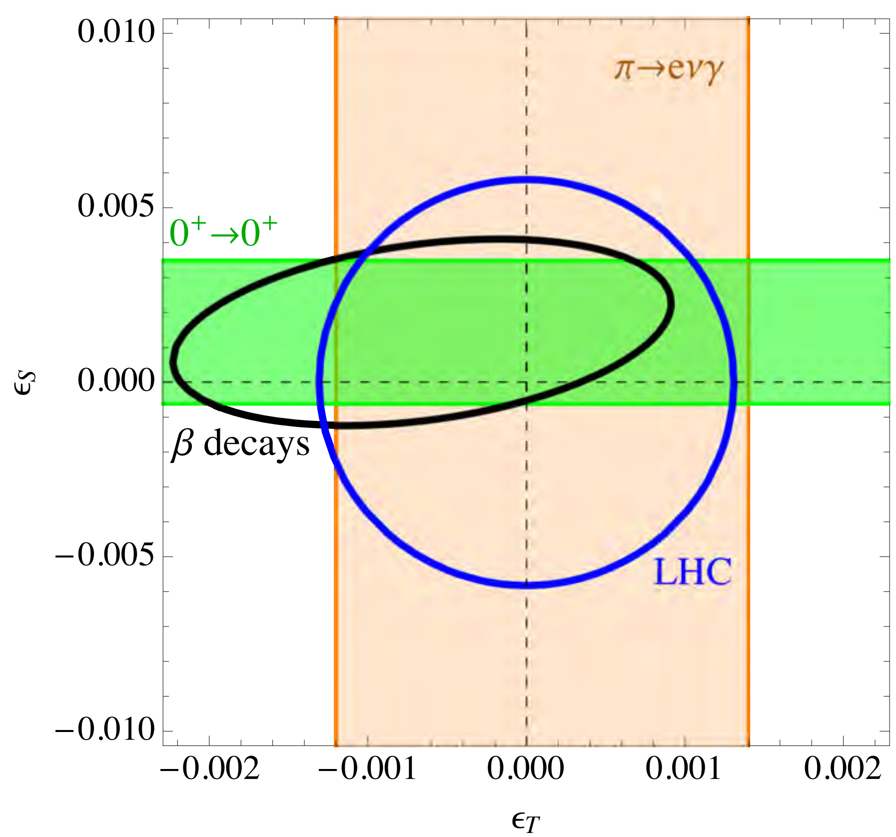
$$\mathcal{L}_{\rm eff} \;=\; -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu \left[1-(1-2\epsilon_R)\,\gamma_5\right] d$$

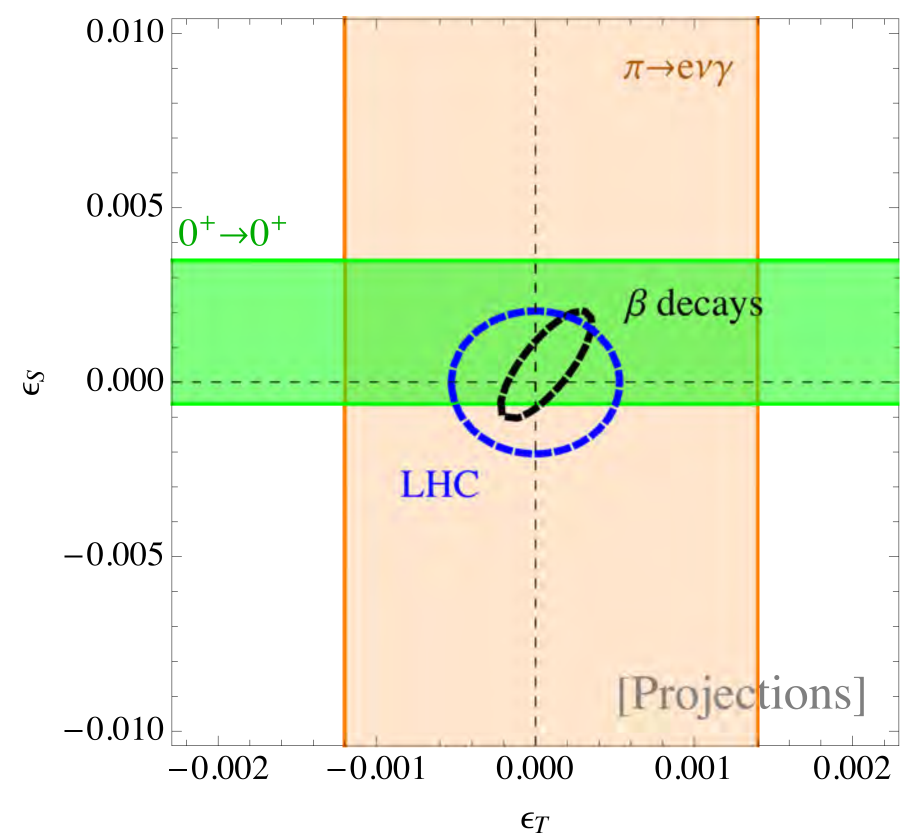
$$+\, \epsilon_S\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d - \;\epsilon_P\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d + \;\epsilon_T\; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big\} + \text{h.c.}$$

$$\tilde{V}_{ud} \equiv V_{ud}\,(1+\epsilon_L+\epsilon_R)\left(1-\frac{\delta G_F}{G_F}\right)$$

Beta decay vs. LHC on non-SM S,T

LHC: pp —> e + MET + X



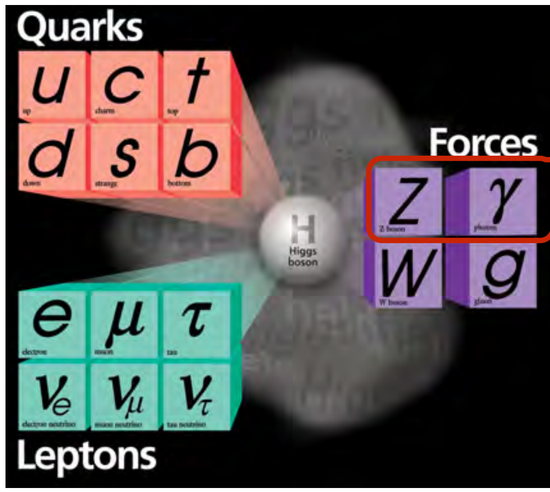


Gonzalez Alonso, Naviliat-Cuncic, Severijns 2019

Complementarity w. LHC now and in the future!

Precise determination of the weak mixing angle

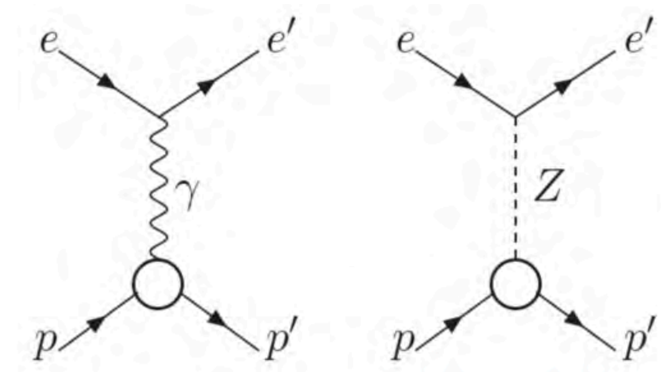
Precision measurements of weak mixing angle



Weak mixing angle - mixing of the NC gauge fields

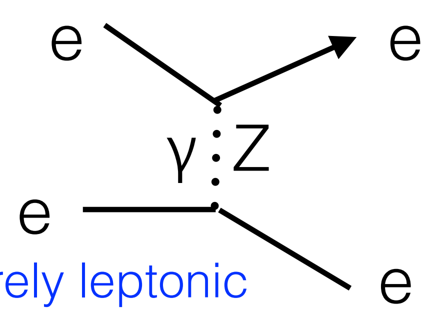
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

WMA determines the relative strength of the weak NC vs. e.-m. interaction



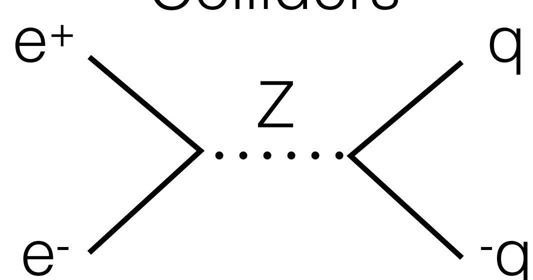
$Q^p = +1$ $\qquad$ $Q^p_W = 1 - 4\sin^2\theta_W$

Møller scattering



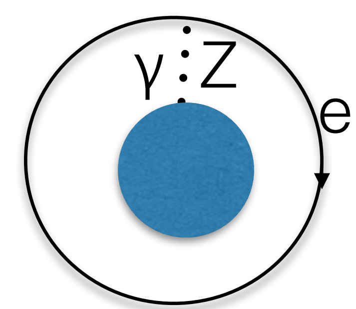
Purely leptonic

Colliders



Z-pole measurement

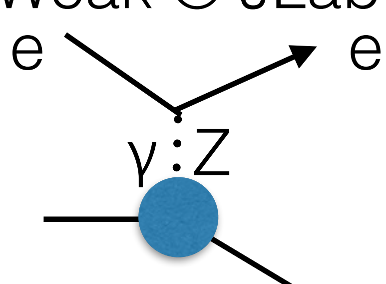
Atomic PV



Coherent quarks in a nucleus

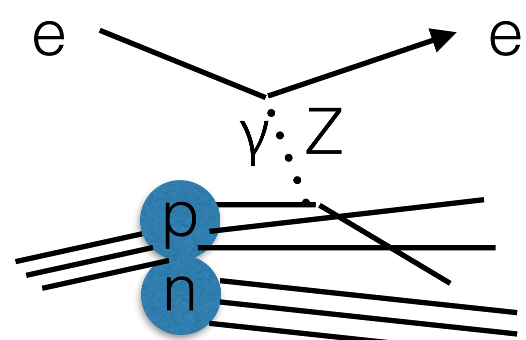
P2 MESA @ Mainz

Q-Weak @ JLab



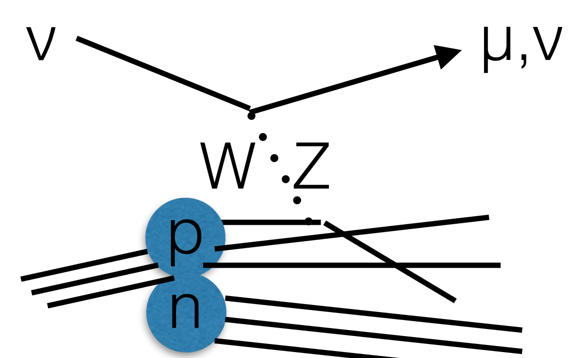
Coherent quarks in p or ^{12}C

e-DIS @ JLab, EIC



Incoherent e-q scattering

ν-DIS @ NuTEV



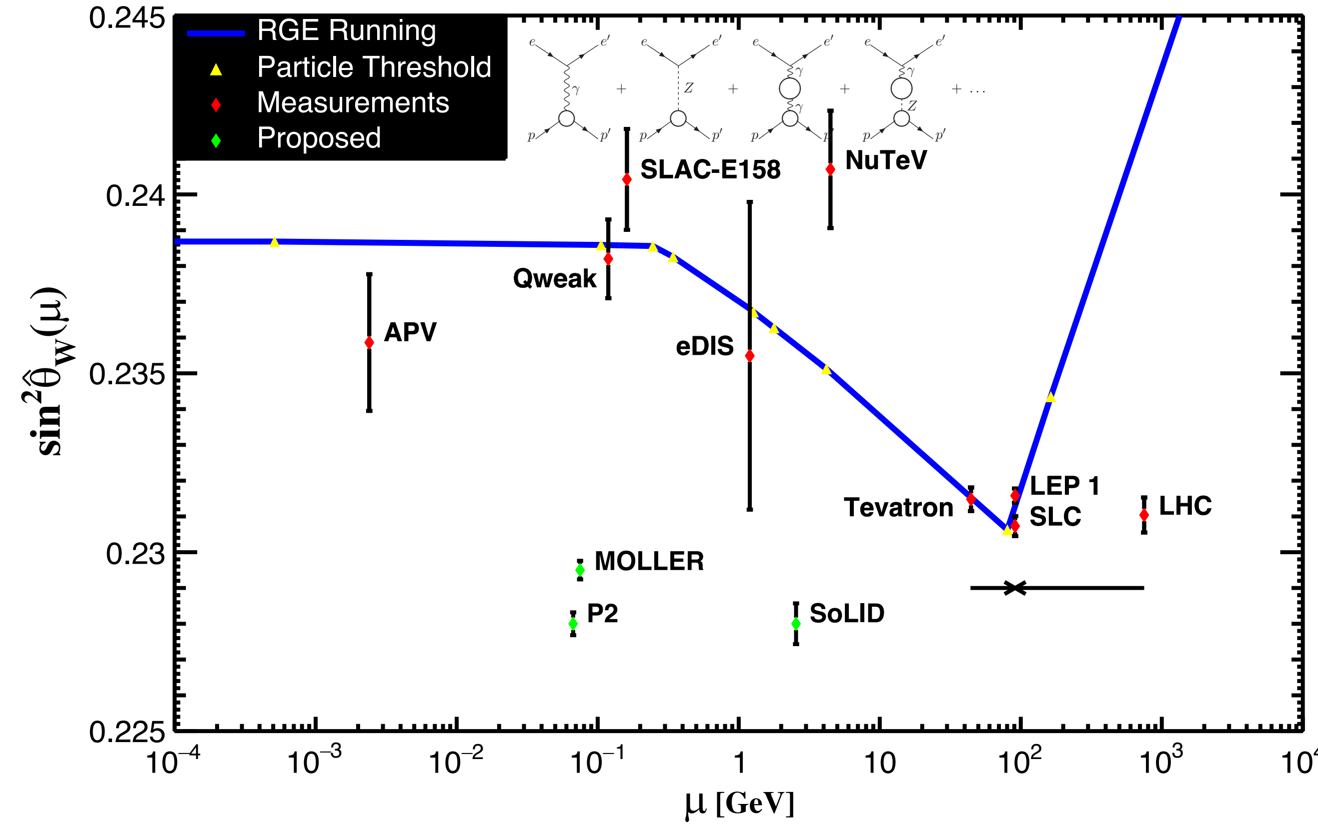
Incoherent ν-q scattering

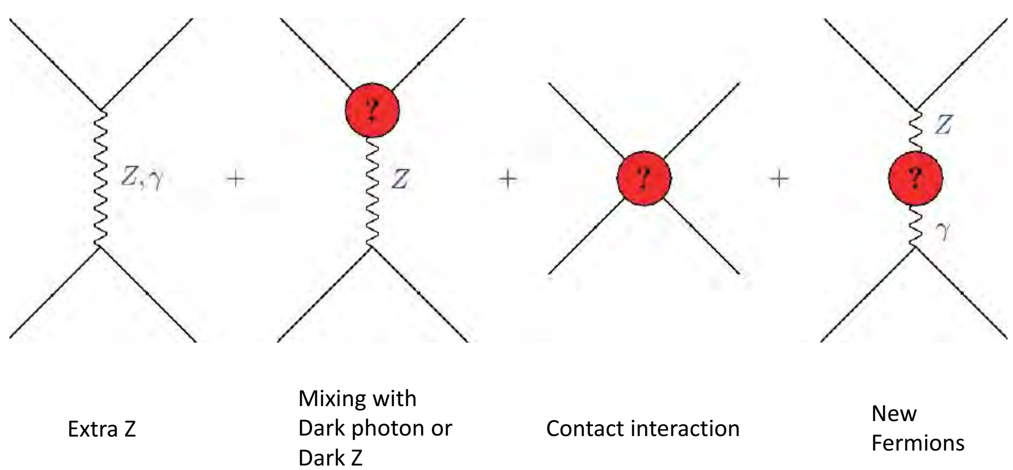
SM running of the weak mixing angle

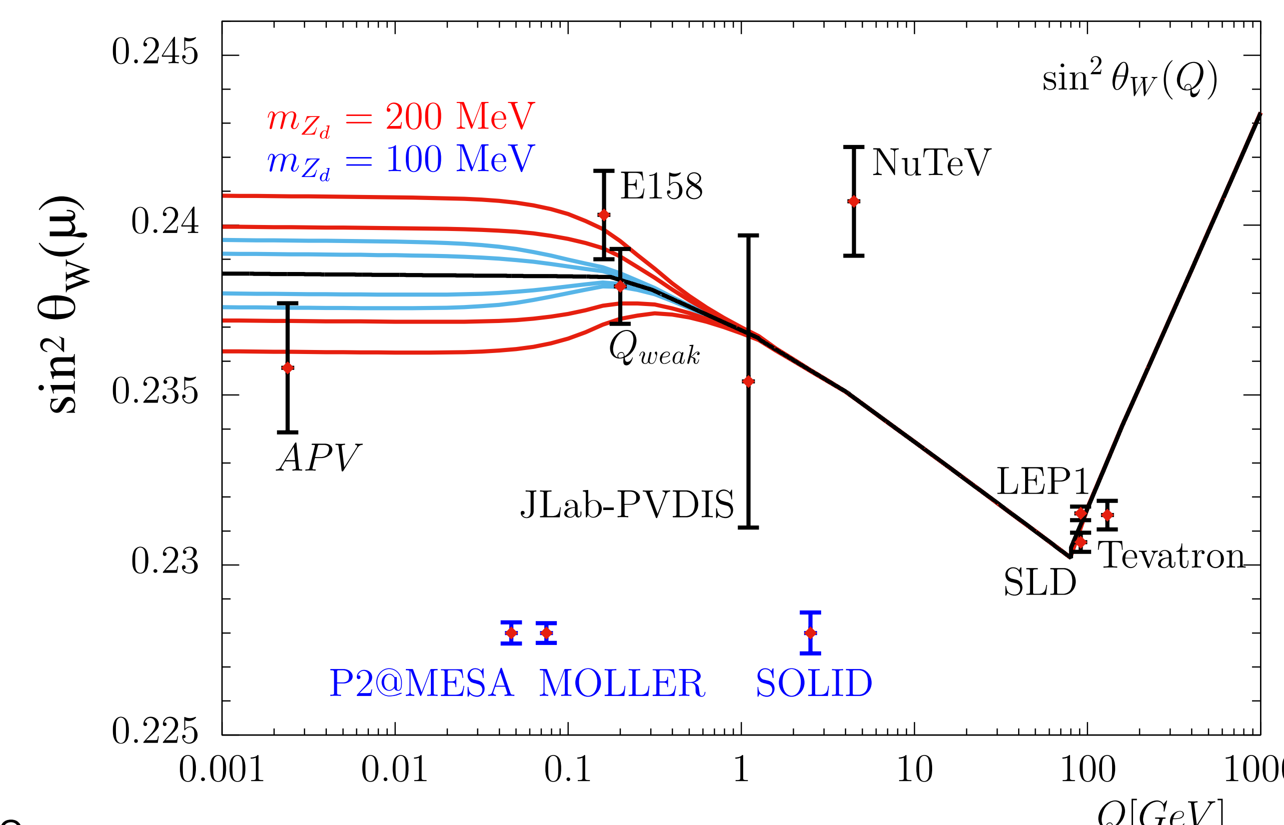
Universal quantum corrections can be absorbed into running, scale-dependent $\sin^2\theta_W(\mu)$

SM uncertainty: few x 10^{-4}

Universal running - clean prediction of SM
Deviation anywhere - BSM signal



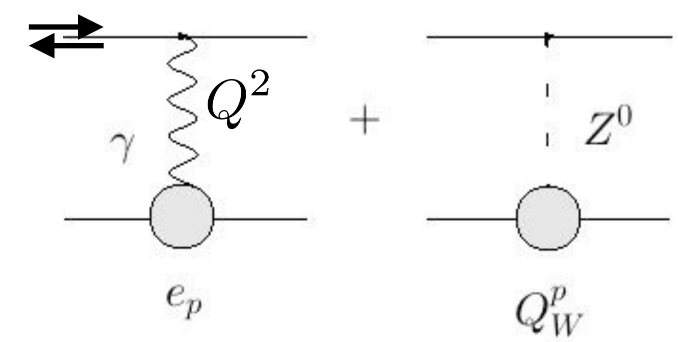




Heavy BSM reach: up to 50 TeV
Light dark gauge sector: down to 70 MeV
Complementary to colliders

Weak charge of the proton from PVES

Elastic scattering of polarized electrons off unpolarized protons at low momentum transfer



$$A^{PV} = \frac{\sigma_\rightarrow - \sigma_\leftarrow}{\sigma_\rightarrow + \sigma_\leftarrow} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + Q^2 B(Q^2)\right]$$

Effects of hadronic structure (size, spin, strangeness) kinematically suppressed

Qweak@JLab: Q^2~0.03 GeV^2 $A^{PV} = -(226.5 \pm 9.3)\,\mathrm{ppb}$ $Q_W^p = 0.0718 \pm 0.0044$ (rel. 6%)

D. Androic et al [Qweak Coll.], Nature 557 (2018), 207

P2 @ MESA/Mainz: go down to Q^2~0.005 GeV^2 — tiny asymmetry to 1.5-2%

The reward: $Q_W^p = 1-4\sin^2\theta_W \sim 0.07$ in SM

$$\frac{\delta\sin^2\theta_W}{\sin^2\theta_W} = \frac{1-4\sin^2\theta_W}{4\sin^2\theta_W}\frac{\delta Q_W^p}{Q_W^p}$$

Need to know radiative corrections sufficiently precise

Hadronic effects under control

$$Q_W^p = \boxed{(1+\Delta_\rho+\Delta_e)(1-4\sin^2\hat{\theta}_W+\Delta_e') + \Box_{WW} + \Box_{ZZ}} + \boxed{\Box_{\gamma Z}}$$

Marciano, Sirlin, '85; Ramsey-Musolf, '99

Sensitive to hadronic structure

γZ-box correction to hadronic weak charges

γZ-box: steep dependence on the electron energy

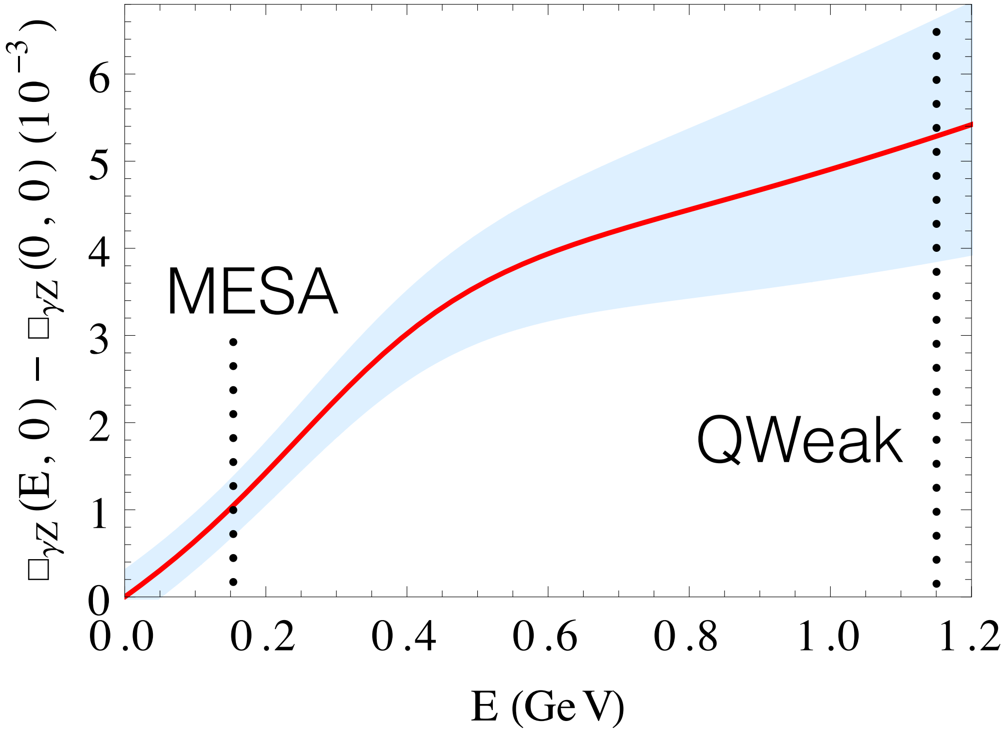
First application of dispersion theory to EW boxes

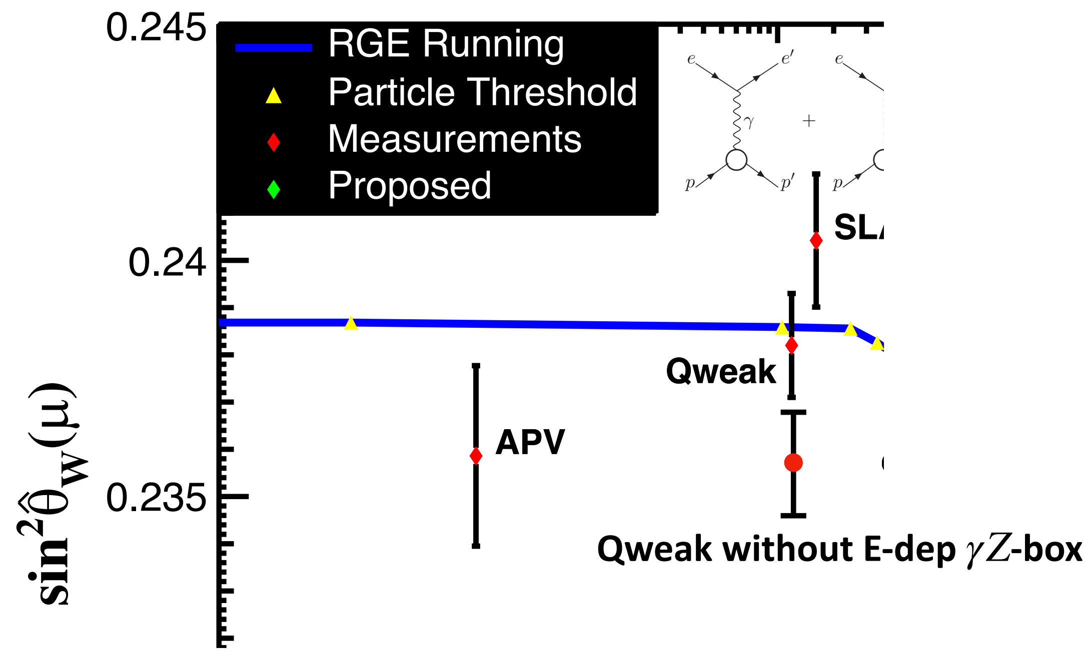
MG, Horowitz PRL 2009

Motivated theoretical activity:

Sibirtsev, Blunden, Melnitchouk, Thomas, PRD 2010
Rislow, Carlson, PRD 2011
MG, Horowitz, Ramsey-Musolf, PRC 2011
Blunden, Melnitchouk, Thomas, PRL 2011
Blunden, Melnitchouk, Thomas, PRL 2012
Rislow, Carlson, PRD 2013
Hall, Blunden, Melnitchouk, Thomas, PLB 2013
MG, Zhang PLB 2015
MG, Spiesberger, Zhang PLB 2016
MG, Spiesberger PRC 2016
Erler, MG, Koshchii, Seng, Spiesberger PRD 2019

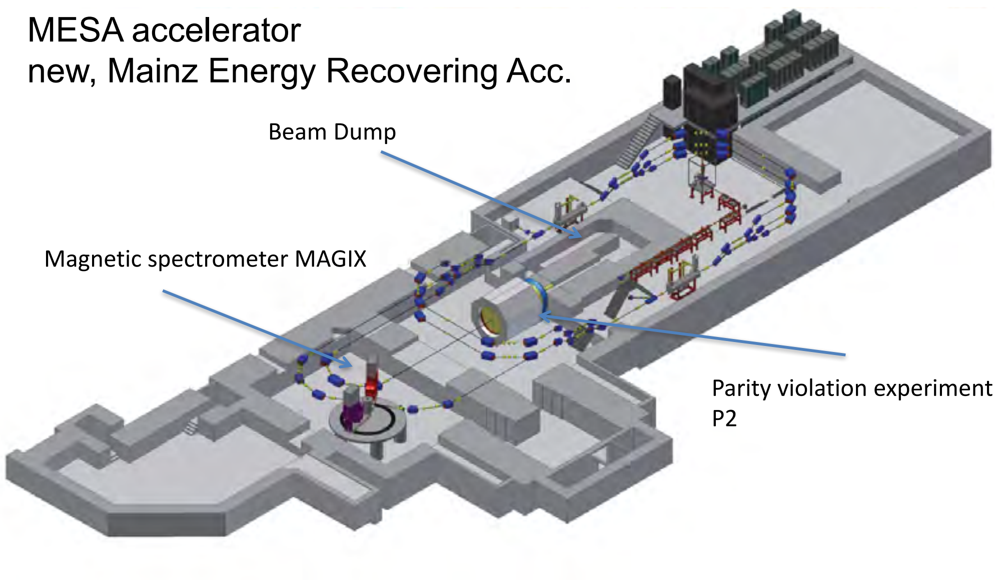
Ensured correct interpretation of QWeak

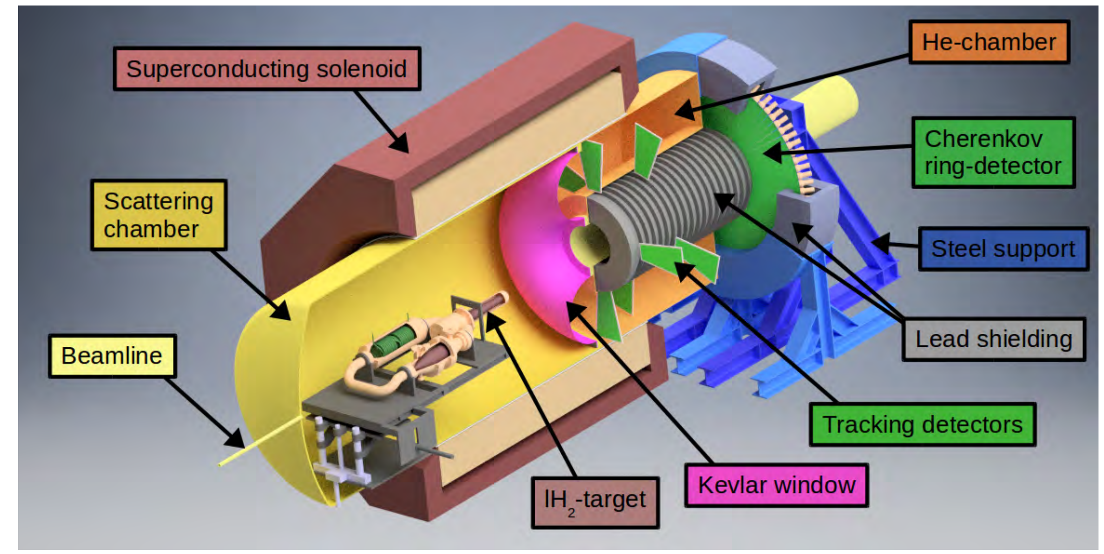




Motivated PVES program at Mainz at lower energy to minimize γZ-box uncertainty

P2 experiment @ MESA





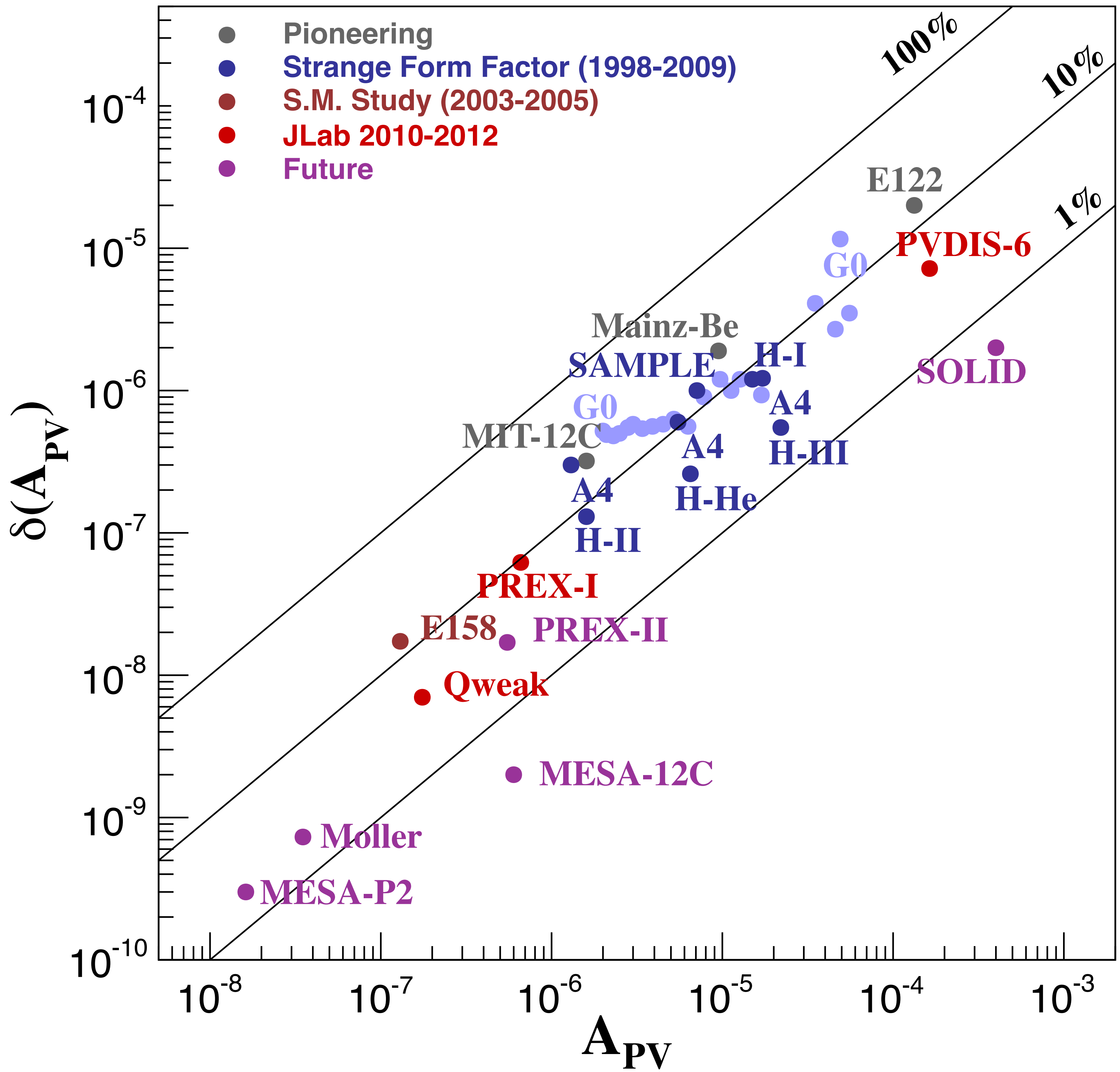
E_{beam}	155 MeV
$\bar{\theta}_f$	35°
$\delta\theta_f$	20°
$\langle Q^2\rangle_{L,\ \delta\theta_f}$	$6\times10^{-3}\,(\mathrm{GeV/c})^2$
$\langle A^{exp}\rangle$	-39.94 ppb
$(\Delta A^{exp})_{Total}$	0.68 ppb (1.70 %)
$(\Delta A^{exp})_{Statistics}$	0.51 ppb (1.28 %)
$(\Delta A^{exp})_{Polarization}$	0.21 ppb (0.53 %)
$(\Delta A^{exp})_{Apparative}$	0.10 ppb (0.25 %)
$(\Delta A^{exp})_{\Box_{\gamma Z}}$	0.08 ppb (0.20 %)
$(\Delta A^{exp})_{nucl.\ FF}$	0.29 ppb (0.72 %)
$\langle \hat{s}^2_Z\rangle$	0.23116
$(\Delta \hat{s}^2_Z)_{Total}$	3.34×10^{-4} (0.14 %)
$(\Delta \hat{s}^2_Z)_{Statistics}$	2.68×10^{-4} (0.12 %)
$(\Delta \hat{s}^2_Z)_{Polarization}$	1.01×10^{-4} (0.04 %)
$(\Delta \hat{s}^2_Z)_{Apparative}$	5.06×10^{-5} (0.02 %)
$(\Delta \hat{s}^2_Z)_{\Box_{\gamma Z}}$	4.16×10^{-5} (0.02 %)
$(\Delta \hat{s}^2_Z)_{nucl.\ FF}$	1.42×10^{-4} (0.06 %)

Principal goal: PVES on proton
200 days of data - 150 μA beam - 85% polarization

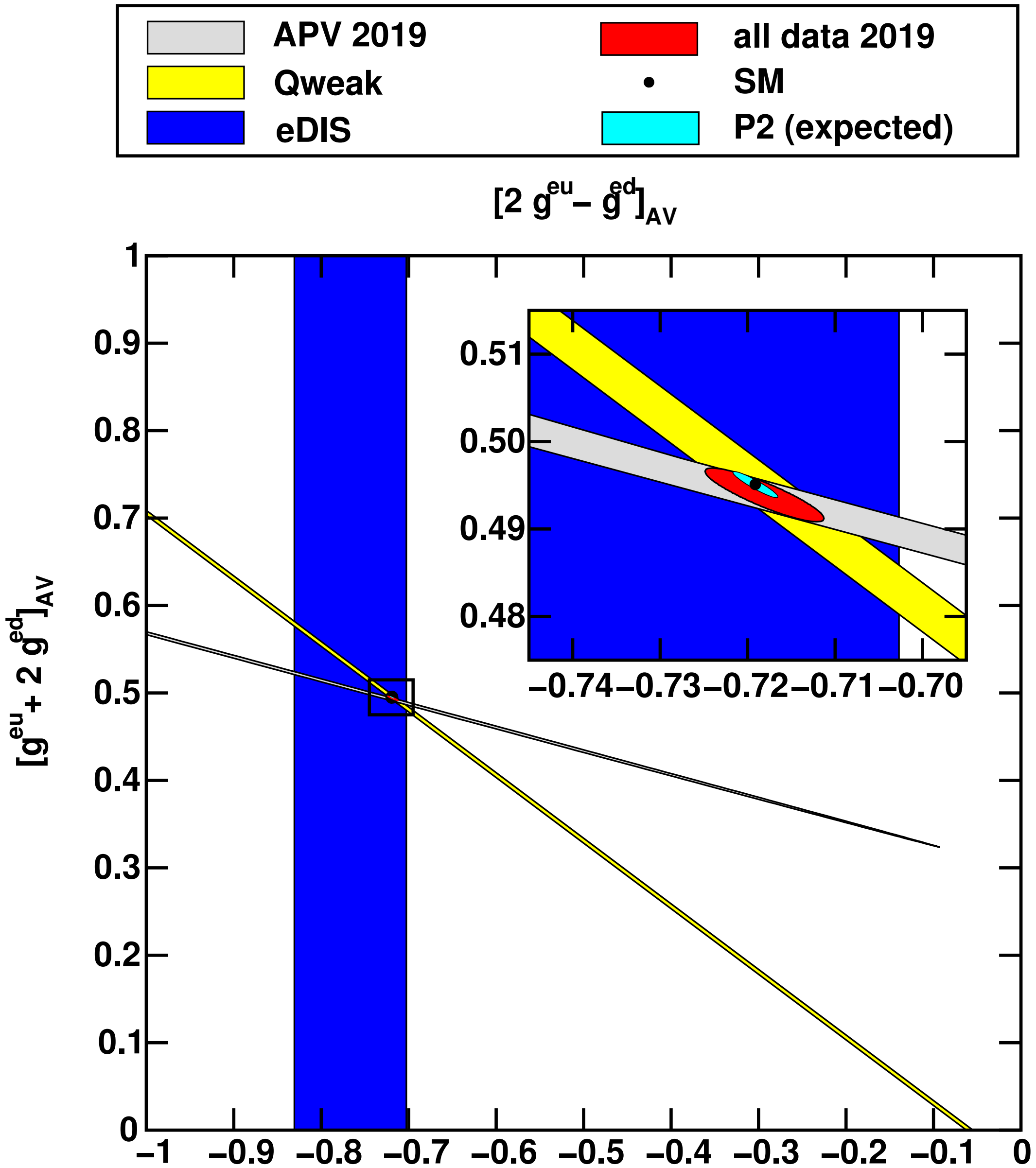
Additionally: A^{PV} measurement on C-12
Asymmetry is 15 times larger than p;
Cross sections 36 times larger than p;
2500h data - 0.3% on $\sin^2\theta_W$ possible!

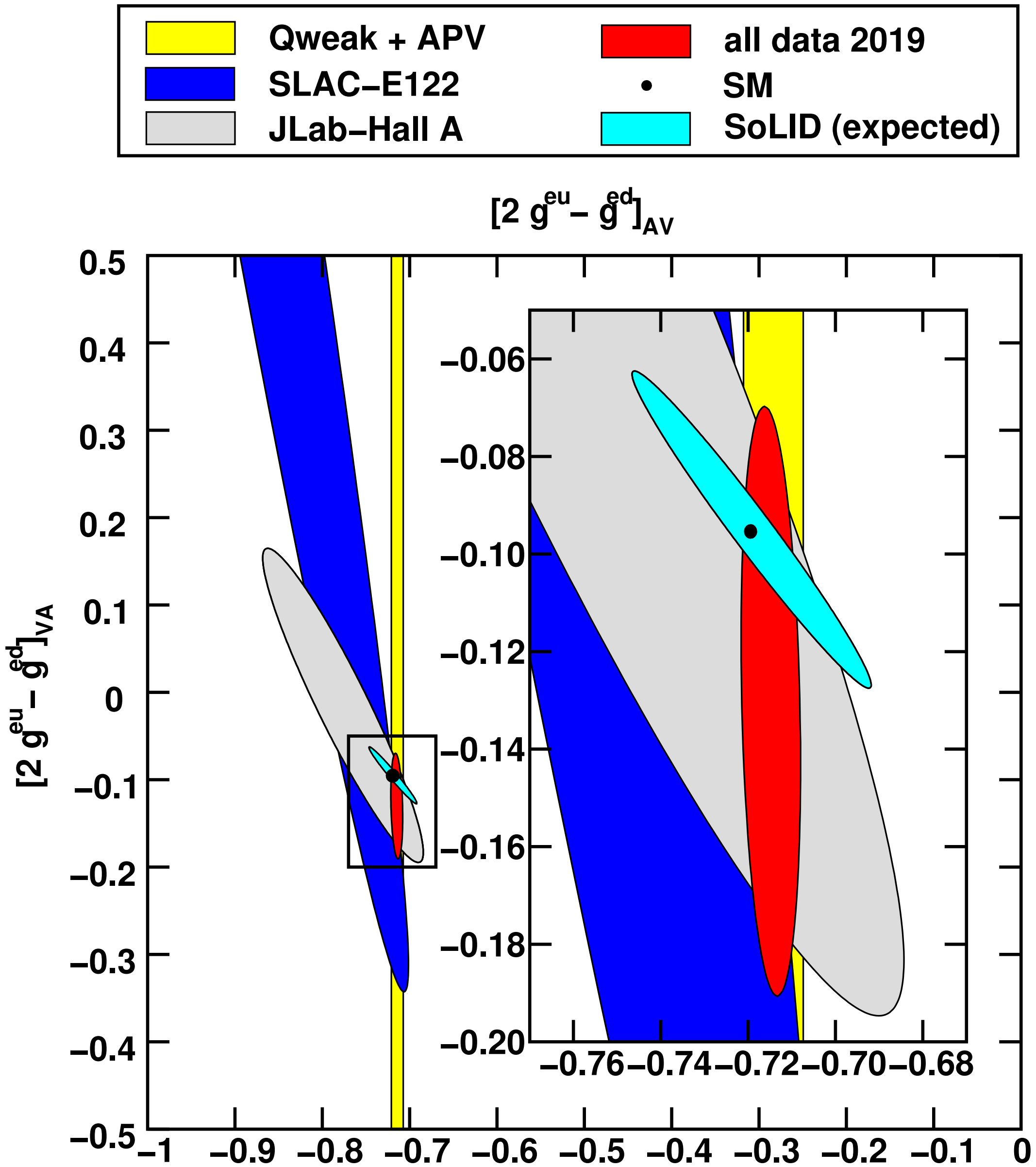
Production: 2023 on

PVeS Experiment Summary



Parity-violating 4-fermion electron-quark couplings





Summary and Outlook

Precision low-energy tests — sensitivity to BSM complementary to LHC

CKM unitarity deficit observed ($\sim 3\sigma$) in the top row could be

New development in theory of EW radiative corrections:
Electroweak boxes from dispersion theory + lattice QCD + χEFT

Theoretical uncertainties reduced over the past 2 years, more to come

Experiment on beta decays and PVES doing a tremendous progress

Precision tests will stay in the game even with the high-lumi LHC