Box Diagrams for Elastic PVES and Relevance for DIS

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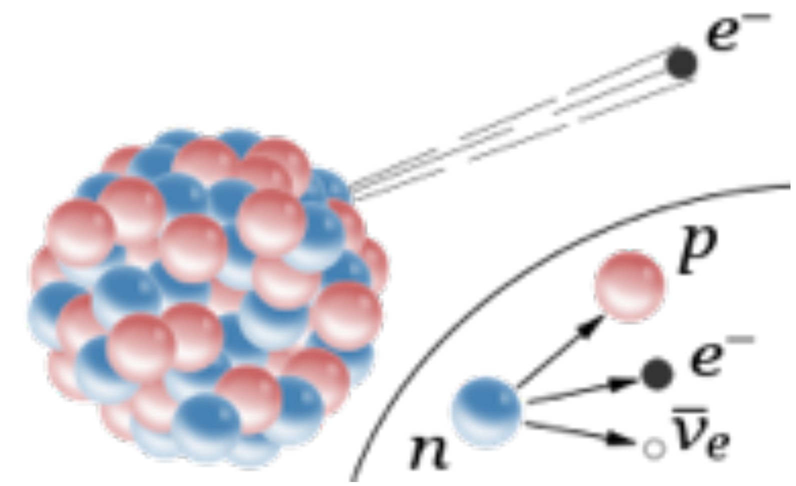
Johannes Gutenberg-Universität Mainz



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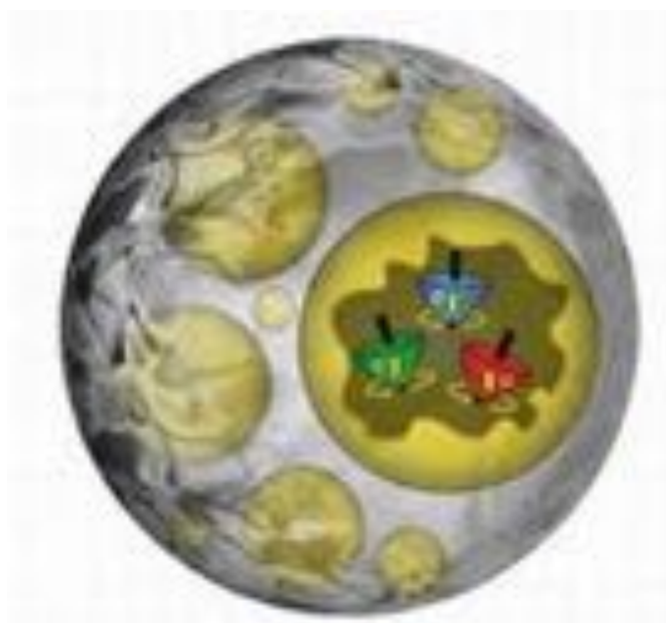
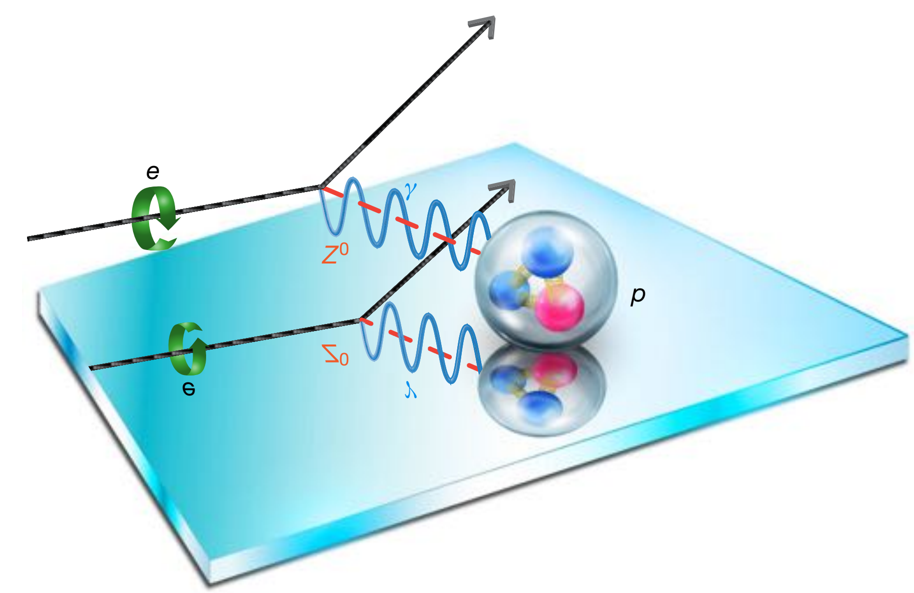


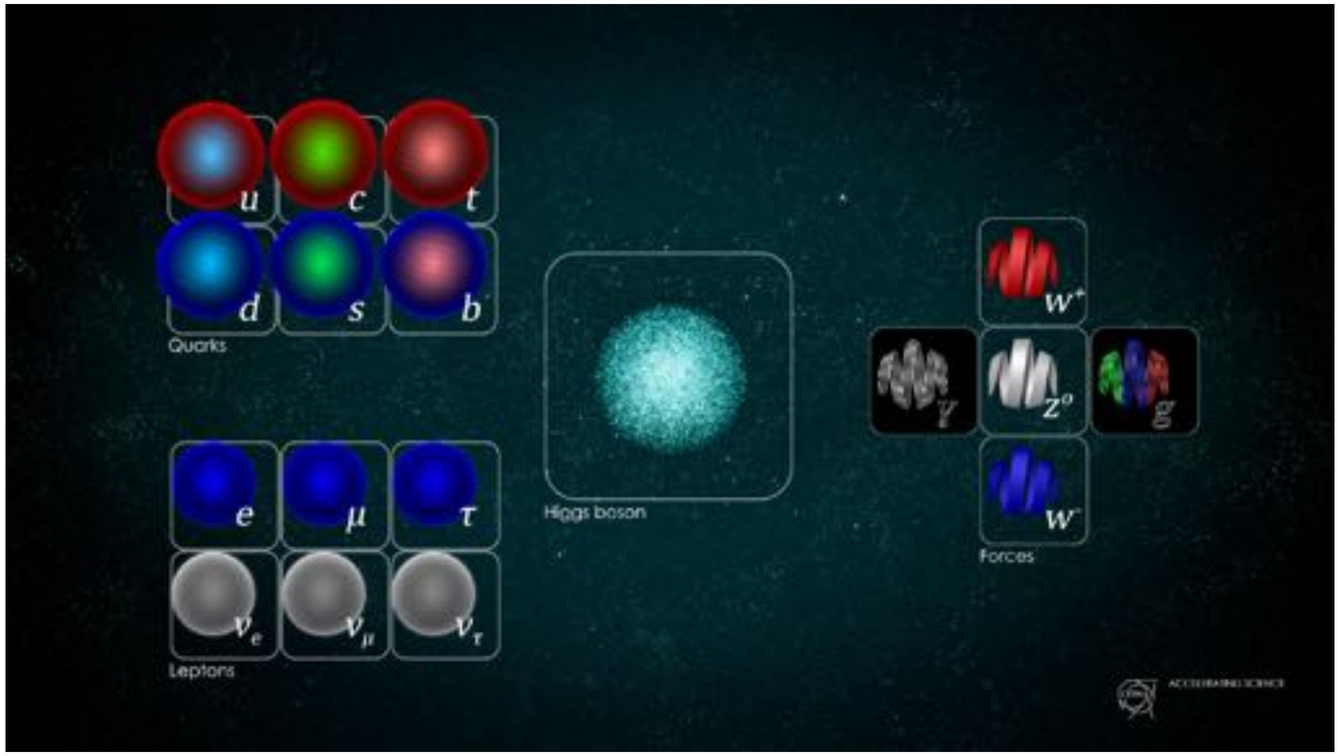


INT Workshop "Parity-Violation and other Electroweak Physics at JLab 12 GeV and Beyond" - June 29, 2022

Standard Model: success story with open questions

Standard Model:

- Renormalizable non-Abelian gauge field theory
- Incorporates observed symmetries
- Symmetry breaking
- “small” number of parameters



Together with gravity describes how things work on Earth, in the solar system, in stars

Yet it is also notoriously insufficient (Dark Matter & Dark Energy, Matter-Antimatter asymmetry in the Universe, Hierarchy problem, Fine tuning of SM parameters, …)

Searches for beyond Standard Model (BSM) particles and interaction along three frontiers: High-Energy frontier; Astrophysics frontier; Precision frontier

Low-Energy precision tests: compare accurate experimental measurements with equally accurate theory calculations and deduce information about BSM from this comparison

Precision tests of SM at low energies - basics

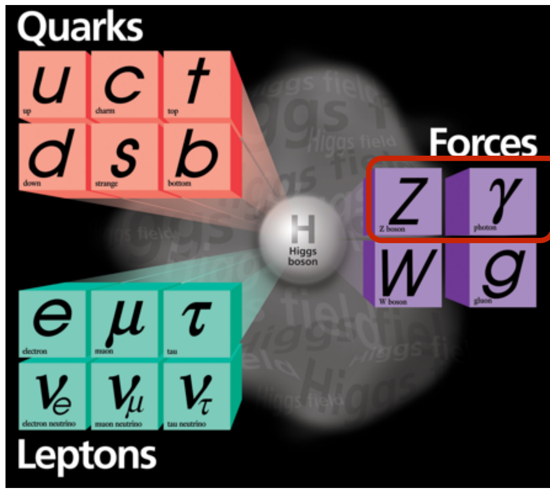
- SM parameters: charges, masses, mixing
- At low energy quarks are bound in hadrons - how can we access their fundamental properties through hadronic mess?
- A **charge associated with a conserved current** is not renormalized by strong interaction - the charge of a composite = ∑ charges of constituents
- Strong interaction may modify observables at NLO in $\alpha_{em}/\pi \approx 2 \cdot 10^{-3}$
- Experiment + pure EW RC - accuracy at 10^{-4} level or better
- This accuracy corresponds to ~50 TeV scale of heavy BSM particles
- In many low-energy tests hadron structure effects is the main limitation!

Precise determination of SM mixing parameters:

Weak mixing angle $\sin^2\theta_W$

Cabibbo angle V_{ud}

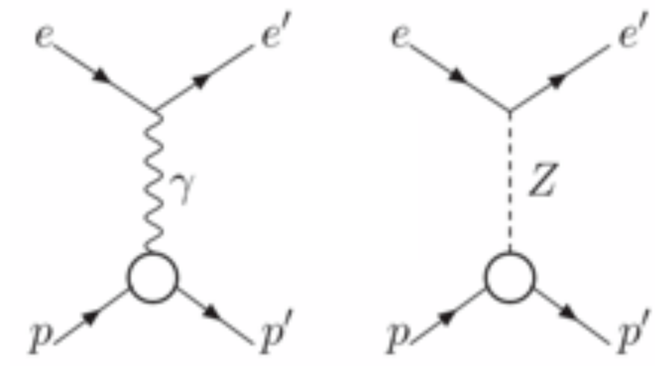
Precision measurements of weak mixing angle



Weak mixing angle - mixing of the NC gauge fields

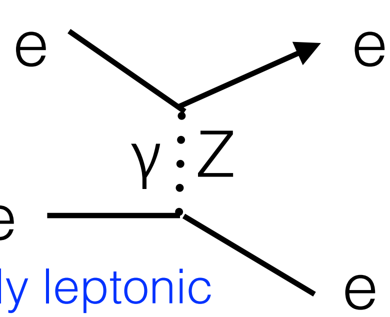
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

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



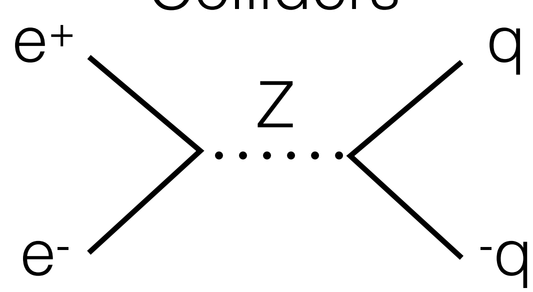
$Q^p = +1$ $Q^p_W = 1 - 4\sin^2\theta_W$

Møller scattering



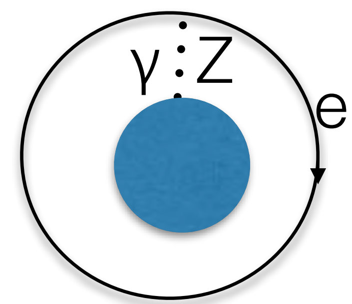
Purely leptonic

Colliders



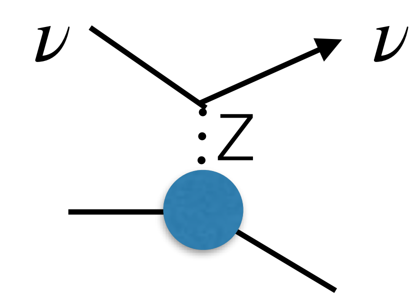
Z-pole measurement

Atomic PV



Coherent quarks in nuclei

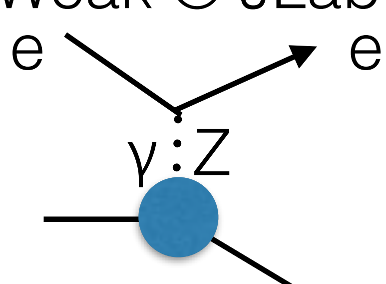
CEνNS



Coherent quarks in nuclei

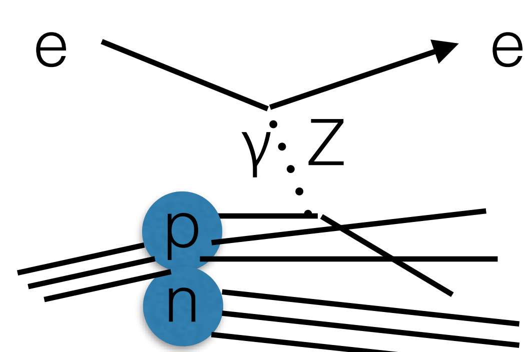
P2 MESA @ Mainz

Q-Weak @ JLab



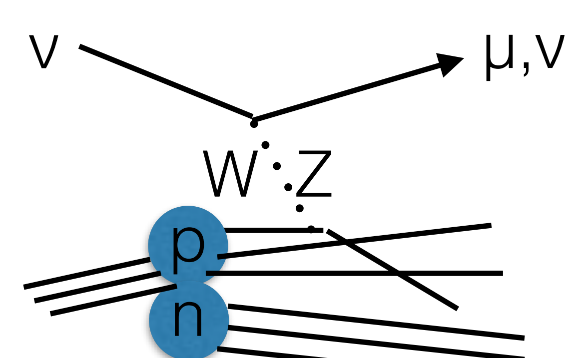
Coherent quarks in p or ^{12}C

e-DIS @ JLab, EIC



Incoherent e-q scattering

ν-DIS @ NuTEV



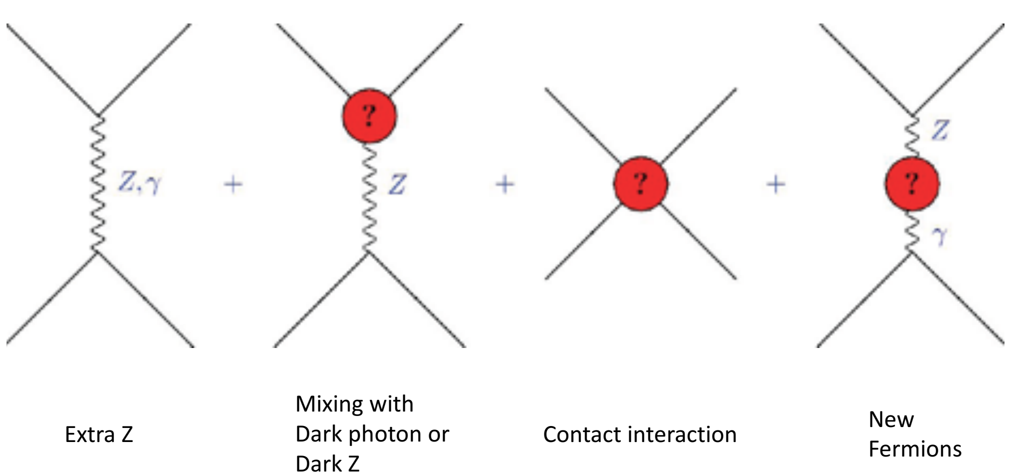
Incoherent ν-q scattering

SM running of the weak mixing angle

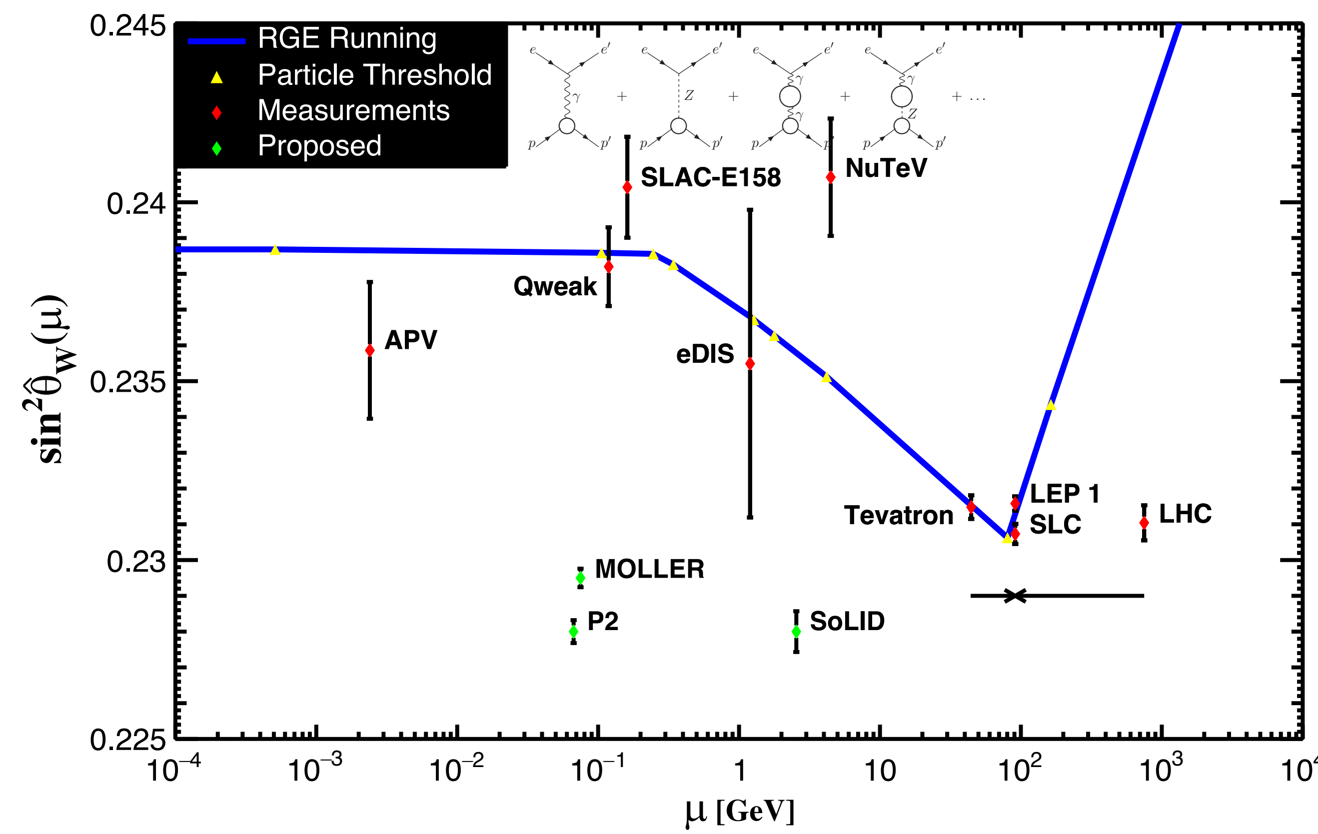
Universal quantum corrections can be absorbed into running, scale-dependent $\sin^2\theta_W(\mu)$

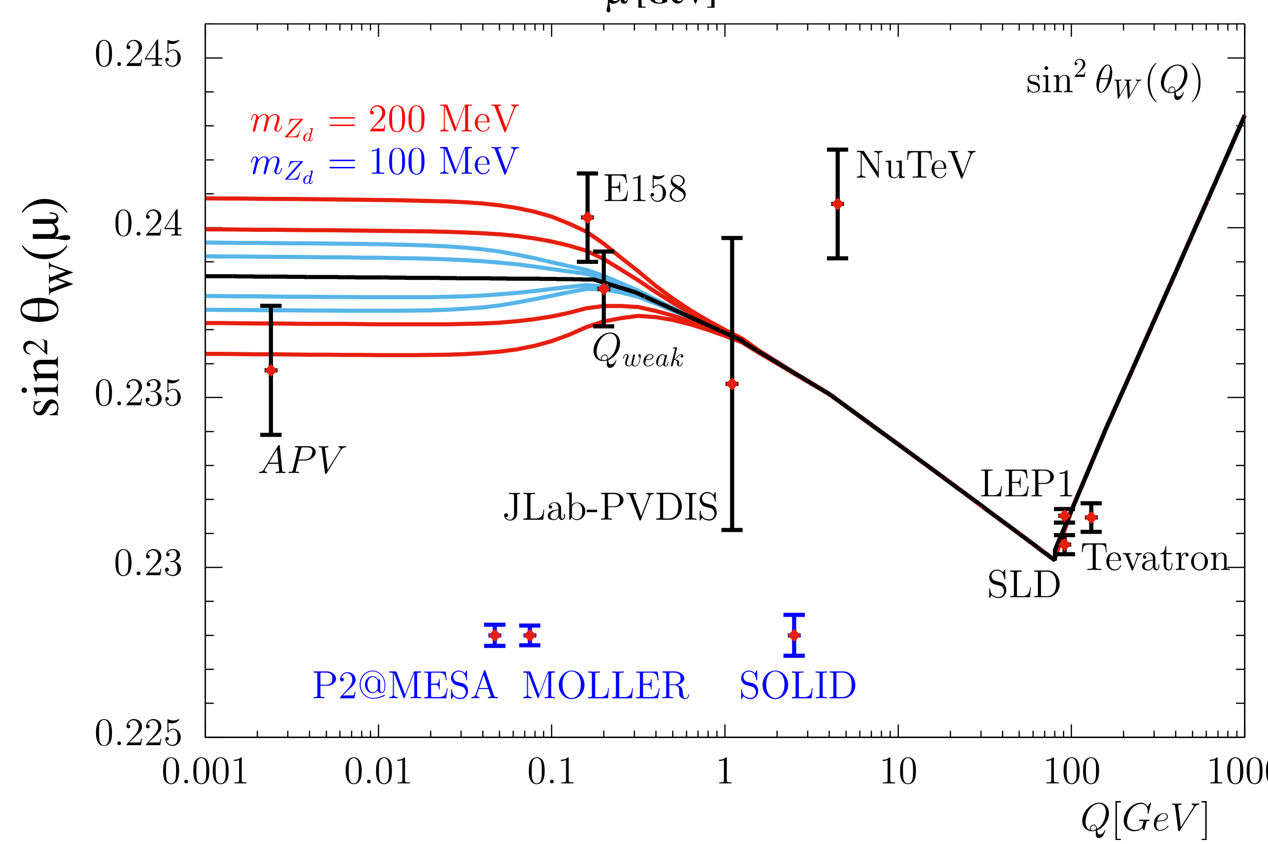
SM uncertainty: few x 10^{-5}

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

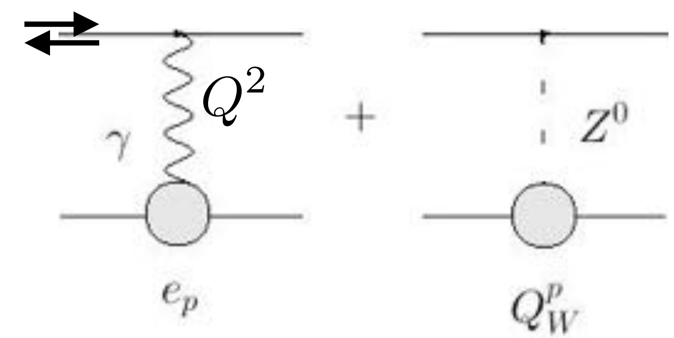




Talks by H. Davoudiasl, A. Thomas

Hadronic weak charges from PVES

Elastic scattering of longitudinally polarized electrons off unpolarized nuclei at low momentum transfer



$$A^{\rm PV} = \frac{\sigma_\rightarrow - \sigma_\leftarrow}{\sigma_\rightarrow + \sigma_\leftarrow} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{Q_W}{Z}(1+\Delta)$$

Nuclear weak charge $Q_W(Z,N) = -N + Z(1 - 4\sin^2\theta_W)$

Proton (Z=1, N=0): $Q_W^p = 1 - 4\sin^2\theta_W \approx 0.07$ in SM

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%

Talk by M. Wilfert

$$Q_W^{\rm p,\,1-loop} = (1 + \Delta_\rho + \Delta_e)(1 - 4\sin^2\hat\theta_W + \Delta_e') + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

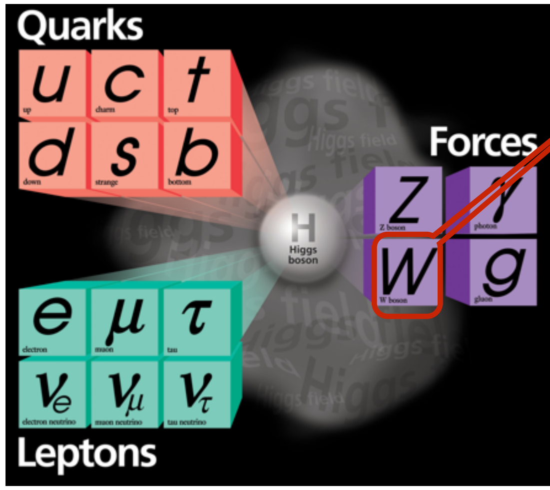
Marciano, Sirlin PRD 1984

Δ: hadronic structure (size, spin, strangeness; suppressed at low Q^2; trivial E-dependence)

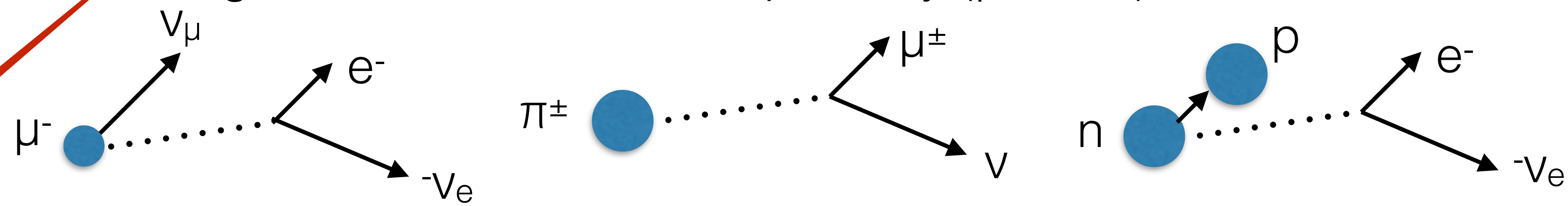
Non-universal RC: boxes ($\alpha_{em}/\pi \sim 10^{-3}$; unsuppressed by Q^2; nontrivial E-dependence)

Talk by P. Blunden

Precise beta decays: universality of weak interaction



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



Rates close but not the same: CKM mixing matrix + Radiative Corrections
Crucial ingredients for establishing the Standard Model

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

CKM - Determines the relative strength of the weak CC interaction of quarks vs. that of leptons

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

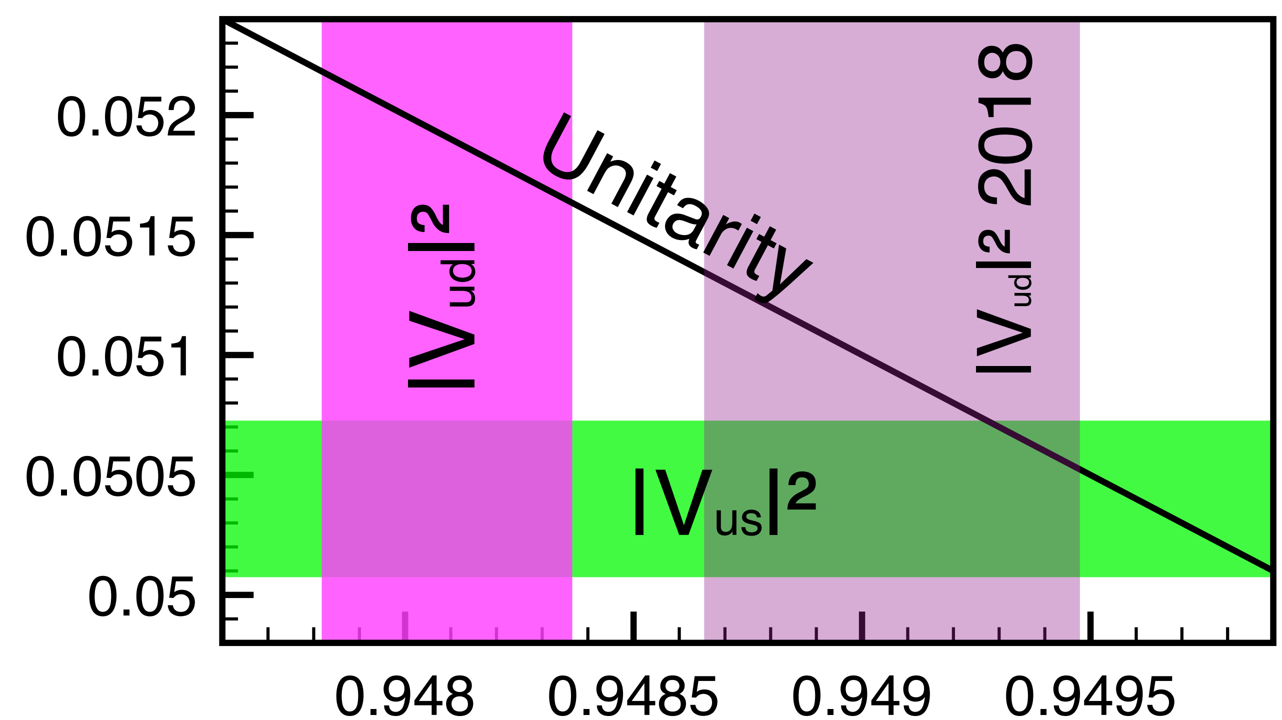
Neglecting $V_{ub} \sim 10^{-3}$: Cabibbo angle θ_C

$$|V_{ud}| = \cos\theta_C, \; |V_{us}| = \sin\theta_C$$

PDG 2022:

$$\cos^2\theta_C + \sin^2\theta_C = 0.9985(3)_{V_{ud}}(4)_{V_{us}}$$

Reason: re-evaluation of SM RC to V_{ud} (γW-box)



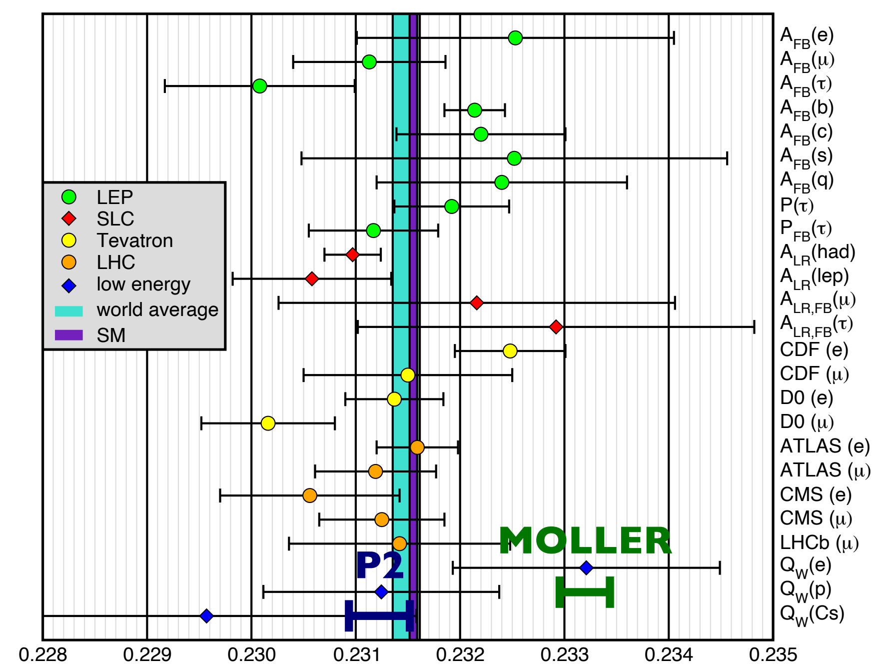
BSM searches at low energies vs. colliders

WMA measurements on the Z-pole most straightforward:
Z on-shell, corrections non-resonant

Downside: BSM enters quadratically
SM amplitude imaginary,
BSM amplitude real

Low energies:
BSM in linear interference with SM
Sensitivity to heavy and light BSM

Weak mixing angle measurements

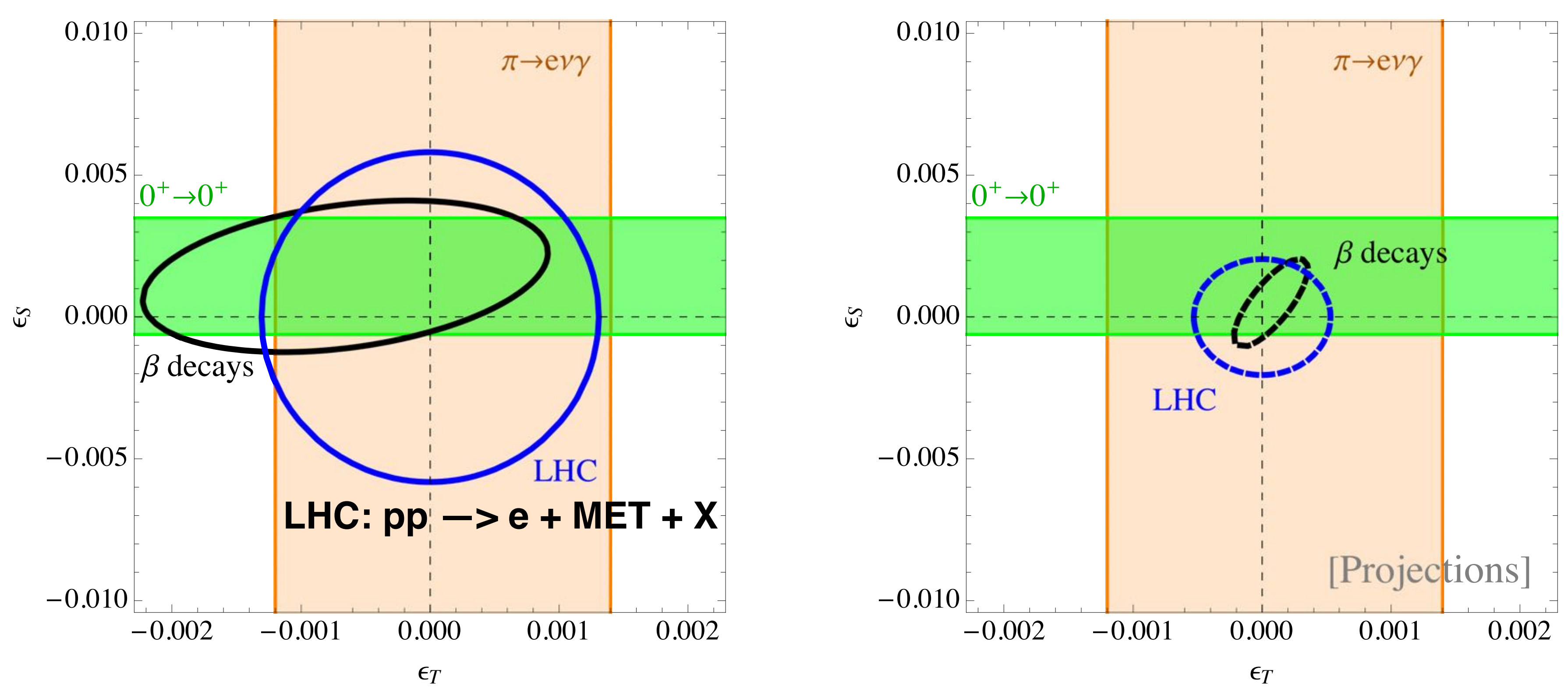


LEP & SLC:
0.23151 ± 0.00016
Tevatron:
0.23148 ± 0.00033
LHC:
0.23129 ± 0.00033

average direct
0.23148 ± 0.00013
global fit
0.23153 ± 0.00004

BSM searches:
LHC vs β-decays

Constraints on non-standard Scalar/Tensor CC interactions
Complementarity to LHC
Now and in the future



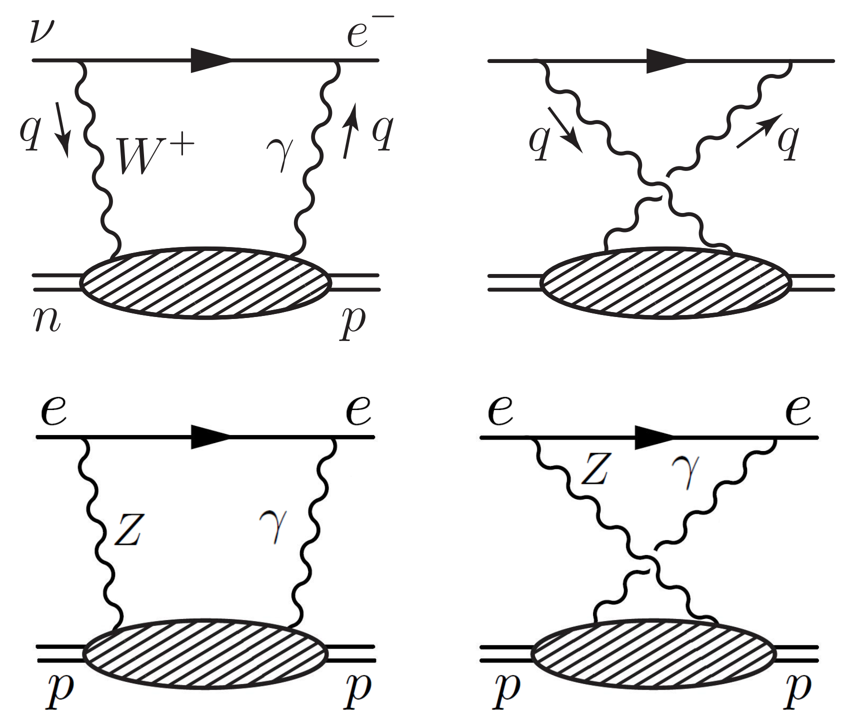
Gonzalez Alonso et al, PPNP 2019

γZ and γW boxes from dispersion relations

Unified approach in PVES and β decays

Dispersion theory of electroweak boxes

Evaluate the box at zero momentum transfer



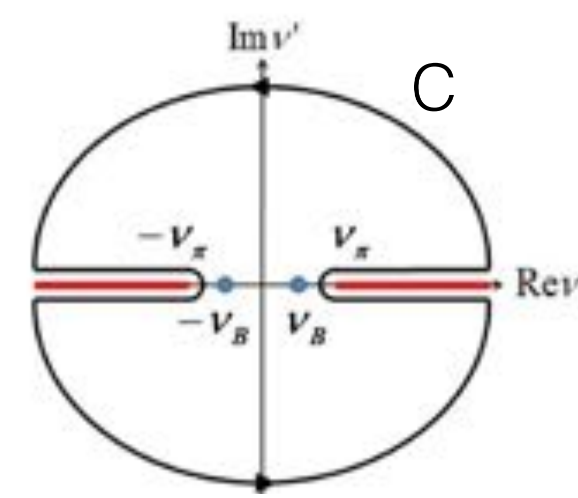
E.g., for γW-box (γZ-box analogous)

$$T_{\gamma W} = -\sqrt{2}e^2 G_F V_{ud} \int \frac{d^4q}{(2\pi)^2} \frac{\bar{u}_e \gamma^\mu (\not{k} - \not{q} + m_e)\gamma^\nu (1-\gamma_5) v_\nu T^{\gamma W}_{\mu\nu}}{q^2[(k-q)^2 - m_e^2][1 - q^2/M_W^2]}$$

Generalized Compton tensor (lower blob):
incorporate all symmetries; consider spin-independent part only (vector charges)

$$T^{\mu\nu}_{\gamma W} = \left[-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right] T_1 + \frac{\hat{p}^\mu \hat{p}^\nu}{(p\cdot q)} T_2 + \frac{i\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta}{2(p\cdot q)} T_3$$

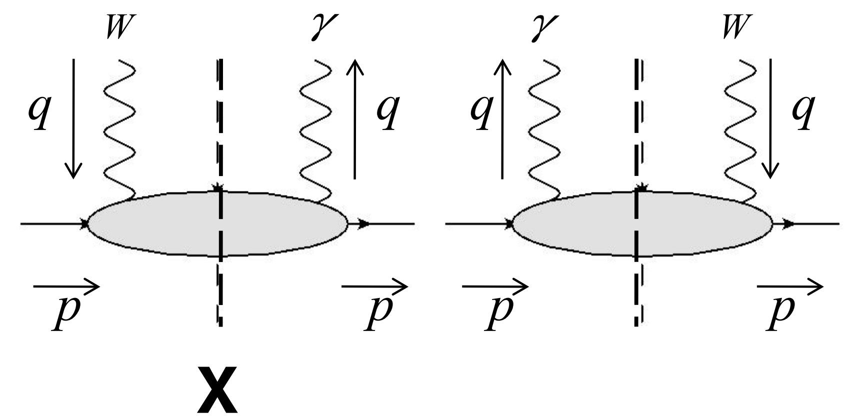
To evaluate the loop — need to know forward Compton amplitudes $T_{1,2,3}$ - analytic functions inside C in the complex ν-plane determined by singularities on the real axis: poles + cuts



Forward box: only ν-analyticity needed;
if finite t also t-analyticity generally required - complicated

Dispersion theory of electroweak boxes

Forward amplitudes T_i - unknown;
Their absorptive parts can be related to production of on-shell intermediate states
—> a γW (γZ) structure functions $F_{1,2,3}$



$$\mathrm{Im}\, T_i^{\gamma W}(\nu, Q^2) = 2\pi F_i^{\gamma W}(\nu, Q^2)$$

$$\mathrm{Im}\, T_i^{\gamma Z}(\nu, Q^2) = 2\pi F_i^{\gamma Z}(\nu, Q^2)$$

X = inclusive strongly-interacting on-shell physical states

Structure functions $F_i^{\gamma Z}$ are data
Structure functions $F_i^{\gamma W}$ are NOT data but can be related to data

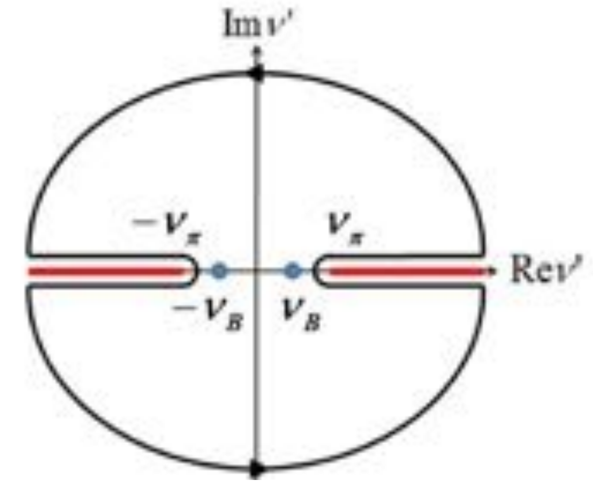
Define box corrections according to

$$T_W + T_{\gamma W} = -\sqrt{2} G_F V_{ud} \bar{u}_e \; \not{p}(1-\gamma_5) v_\nu (1 + \Box_{\gamma W})$$

$$T_Z + T_{\gamma Z} = -\frac{G_F}{2\sqrt{2}} \bar{u}_e \; \not{p}(1-\gamma_5) u_e F_{\rm weak}(Q^2)[Q_W + \Box_{\gamma Z}(E, Q^2)]$$

Dispersion representation of $\Box_{\gamma W/\gamma Z}$

Dispersion representation of Compton amplitudes:
Combine left-hand and right-hand singularities



$$\mathrm{Re}\, T_i(\nu, Q^2) = \frac{1}{\pi}\int_0^\infty d\nu' \left[\frac{1}{\nu'-\nu} \pm \frac{1}{\nu'+\nu}\right] \mathrm{Im}\, T_i(\nu', Q^2)$$

Crossing behavior

γZ: same initial and final state —> definite crossing: T_1 even, $T_{2,3}$ odd function of ν

γW: initial and final state different —> mixed crossing, depends on the isospin of γ

$$T_i^{\gamma W} = T_i^{(I_\gamma=0)} + T_i^{(I_\gamma=1)}$$

with $T_1^{(0)}$, $T_{2,3}^{(1)}$ even,

$T_1^{(1)}$, $T_{2,3}^{(0)}$ odd function of ν

Dispersion theory of $\Box_{\gamma W}$: relevant scales

Radiative corrections to tree-level amplitude $\sim \alpha/2\pi \approx 10^{-3}$

Precision goal for Vud extraction 1×10^{-4}

Electron carries away energy E < Q-value of a decay

E-dep RC: $\frac{\alpha}{2\pi}\left(\frac{E}{\Lambda}, \ln\frac{E}{\Lambda}, \ldots\right)$

Energy scales Λ

Λ

Weak boson scale
$M_Z, M_W \sim 90\,\mathrm{GeV}$

Hadronic scale
$\Lambda_{\mathrm{had}} = 300\,\mathrm{MeV}$

Nuclear scale
$\Lambda_{\mathrm{nuc}} = 10 - 30\,\mathrm{MeV}$

Decay Q-value (endpoint energy)
$Q_{if} = M_i - M_f = 1 - 10\,\mathrm{MeV}$

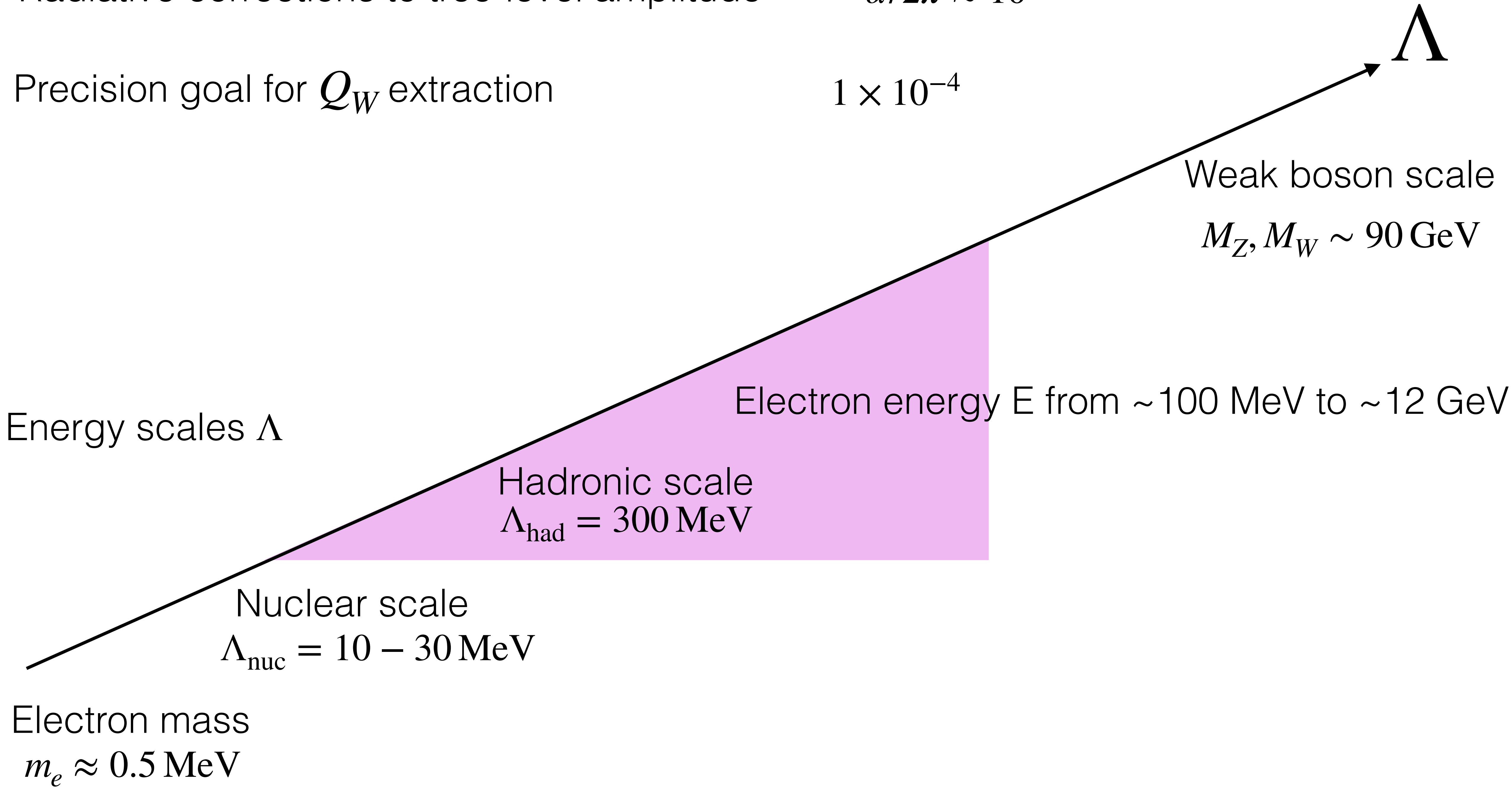
Electron mass
$m_e \approx 0.5\,\mathrm{MeV}$

Leading energy behavior (E^0, E^1) sufficient

Dispersion theory of $\Box_{\gamma Z}$: relevant scales

Radiative corrections to tree-level amplitude $\sim \alpha/2\pi \approx 10^{-3}$

Precision goal for Q_W extraction 1×10^{-4}



Full energy dependence necessary!

Dispersion representation of $\Box_{\gamma W/\gamma Z}$

γZ-box:

Even: $$\Box^A_{\gamma Z}(E) = \frac{1}{2\pi ME}\int_0^\infty dQ^2 \frac{v_e(Q^2)\alpha(Q^2)}{1+Q^2/M_Z^2}\int_0^\infty \frac{d\nu}{\nu}\left[\ln\left|\frac{E+E_m}{E-E_m}\right| + \frac{\nu}{2E}\ln\frac{|E^2-E_m^2|}{E_m^2}\right]F_3^{\gamma Z}$$

Odd: $$\Box^V_{\gamma Z}(E) = \frac{\alpha}{\pi}\int_0^\infty \frac{dQ^2}{1+\frac{Q^2}{M_Z^2}}\int_0^\infty d\nu\left\{\left[\frac{1}{2E}\ln\left|\frac{E+E_m}{E-E_m}\right| - \frac{1}{E_m}\right]\frac{F_1^{\gamma Z}}{ME} + \frac{F_2^{\gamma Z}}{2E\nu E_m}\right.$$
$$\left. + \left[\left(1-\frac{Q^2}{4E^2}\right)\ln\left|\frac{E+E_m}{E-E_m}\right| + \frac{\nu}{E}\ln\frac{|E^2-E_m^2|}{E_m^2}\right]\frac{F_2^{\gamma Z}}{\nu Q^2}\right\}$$

$$E_m = \frac{\nu + \sqrt{\nu^2+Q^2}}{2}$$

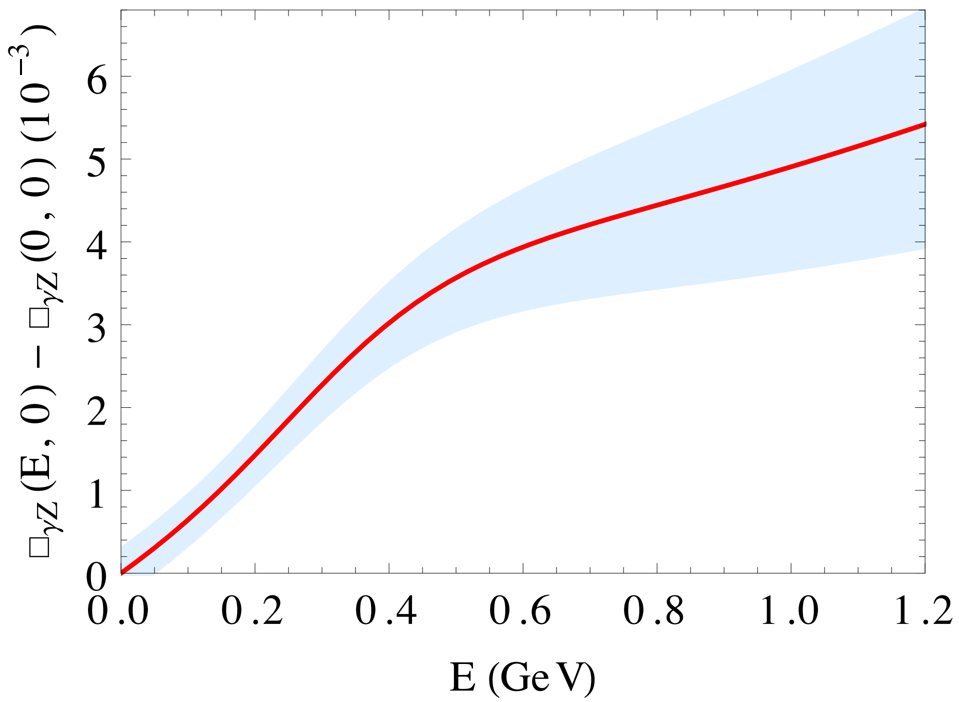
γW-box: $$\Box^{\text{even}}_{\gamma W} = \frac{\alpha}{\pi M}\int_0^\infty dQ^2\int_{\nu_{thr}}^\infty d\nu \frac{\nu+2q}{\nu(\nu+q)^2}F_3^{(0)}(\nu,Q^2) + O(E^2)$$

$$\Box^{\text{odd}}_{\gamma W} = \frac{2\alpha E}{3\pi M}\int_0^\infty dQ^2\int_{\nu_{thr}}^\infty d\nu \frac{\nu+3q}{\nu(\nu+q)^3}F_3^{(1)}(\nu,Q^2) + O(E^3)$$

Only E = 0 (EVEN) results were included in the original RC analysis of Marciano & Sirlin

Energy dependence of the γZ-box

Reference value: 1-loop SM $Q_W^{p,\,\mathrm{SM}} = 0.0713(7)$ Erler, Ferro-Hernandez, arXiv:1712.09146



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Erler, MG, Koshchii, Seng, Spiesberger, PRD100 (2019), 053007

Steep energy dependence observed - added strong motivation for P2 @ MESA

Talk by P. Blunden

$\square_{\gamma Z}$ by different groups (parametrizations & uncertainty treatments) closely agree

(Theory is) looking forward to new measurements of WMA at low energies!

γW box from dispersion relations:

Taming the uncertainties

Dispersion representation of $\Box_{\gamma W}$

γW-box at zero energy

$$\Box^{even}_{\gamma W} = \frac{\alpha}{\pi M}\int_0^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}\int_0^\infty \frac{d\nu}{\nu}\frac{\nu+2q}{(\nu+q)^2}F_3^{(0)}(\nu,Q^2)$$

$$\Box^{odd}_{\gamma W}(E=0)=0$$

Rewrite in terms of the first Nachtmann moment of F_3

$$M_3^{(0)}(1,Q^2) = \frac{4}{3}\int_0^1 dx \frac{1+2\sqrt{1+4M^2x^2/Q^2}}{(1+\sqrt{1+4M^2x^2/Q^2})^2}F_3^{(0)}(x,Q^2)$$

$$x = \frac{Q^2}{2M\nu}$$

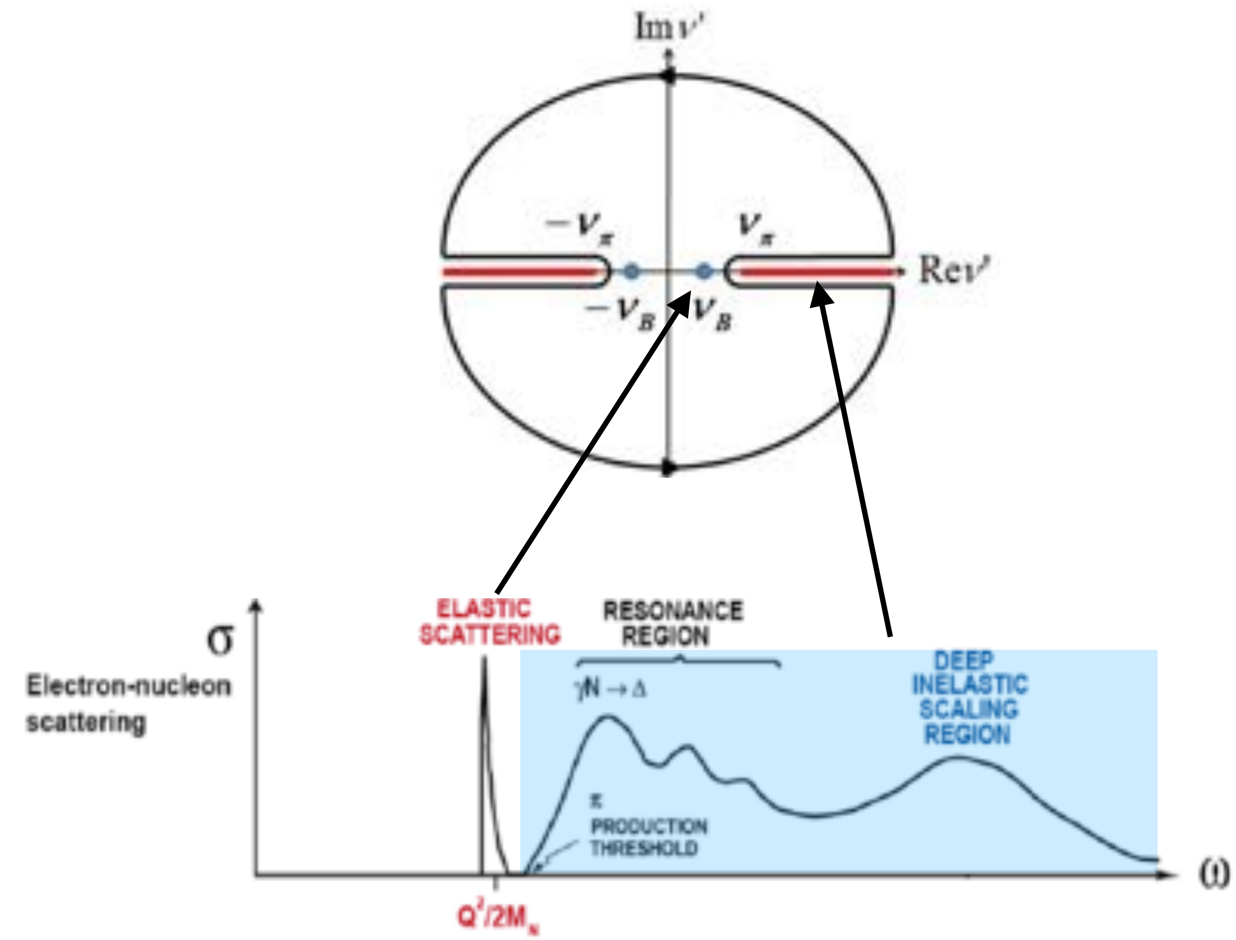
$$\Box^{even}_{\gamma W} = \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2 M_W^2}{Q^2(M_W^2+Q^2)}M_3^{(0)}(1,Q^2)$$

First Nachtmann moment of F_3 was studied extensively in 1980-1990's in $\nu/\bar{\nu}$ scattering in the context of the Gross-Llewellyn-Smith (GLS) sum rule.

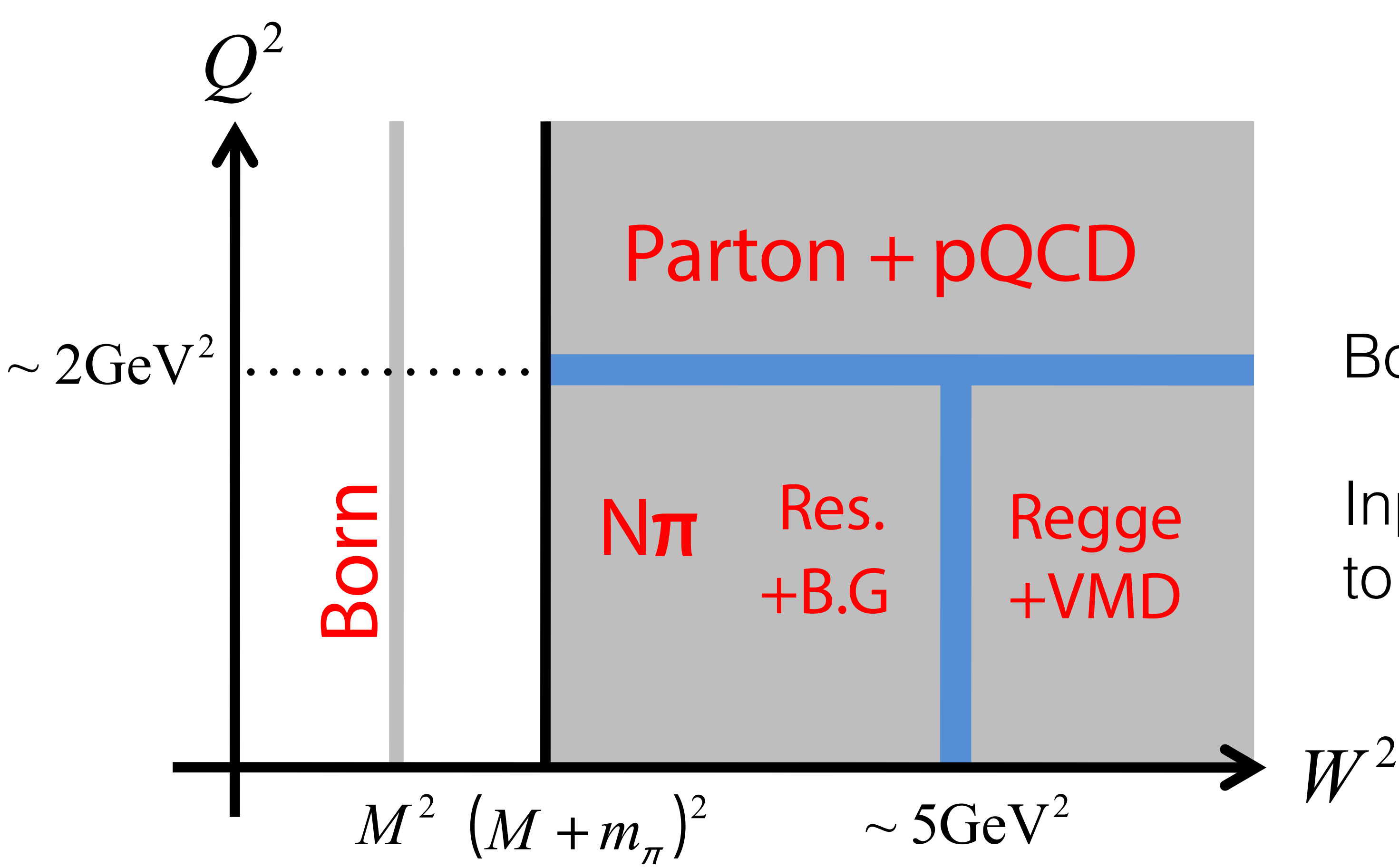
In a nutshell: the use of those data allowed to improve the $\Box_{\gamma W}$ calculation

Input into dispersion integral

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



Dispersion in Q^2:
scanning dominant physics pictures



Boundaries between regions - approximate

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

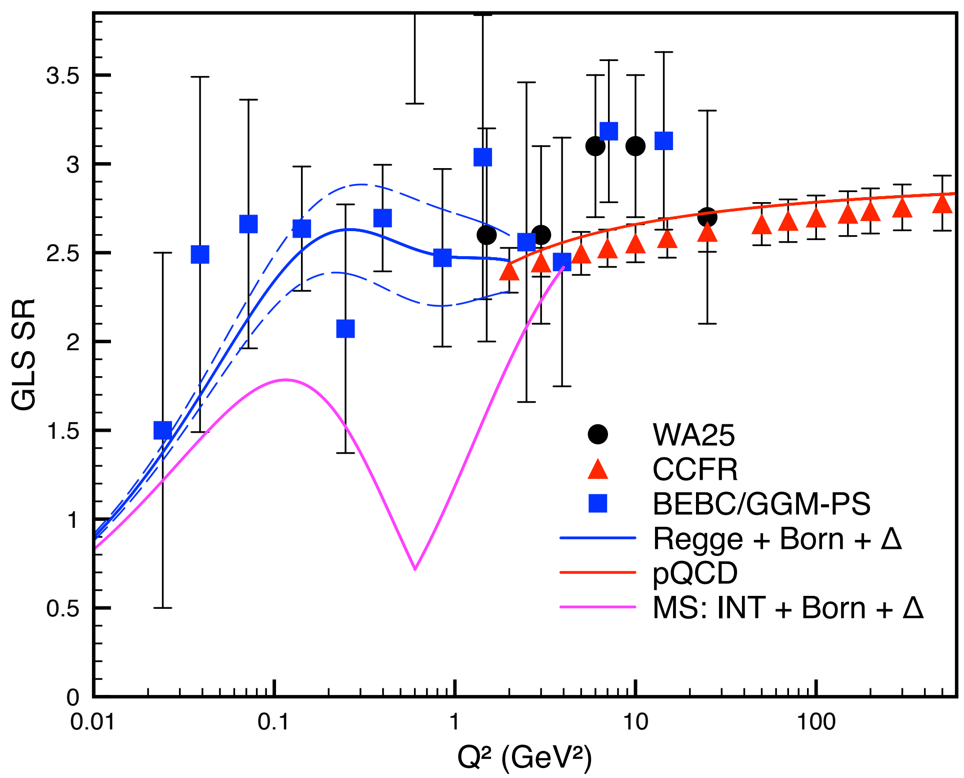
Input into dispersion integral

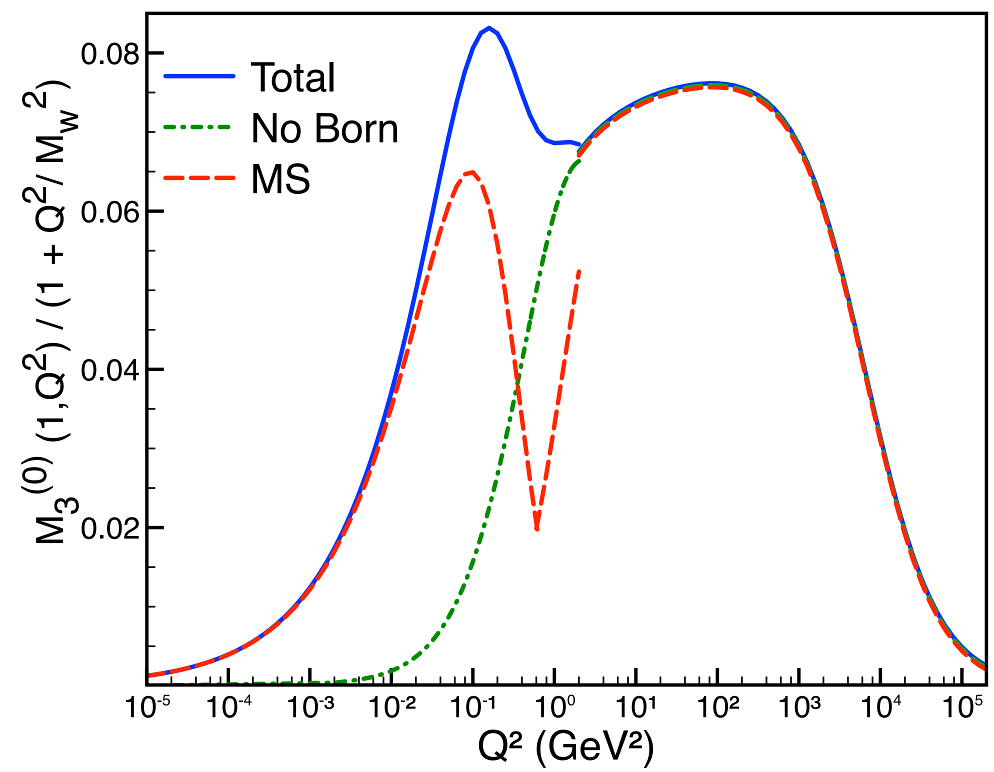
Unfortunately, no data can be obtained for $F_3^{\gamma W\,(0)}$

Data exist for the pure CC processes $\sigma^{\nu p} - \sigma^{\bar{\nu} p} \sim F_3^{\nu p} + F_3^{\bar{\nu} p} = u_v^p(x) + d_v^p(x)$

Gross-Llewellyn-Smith sum rule $\int_0^1 dx (u_v^p(x) + d_v^p(x)) = 3$

$M_3^{WW}(1,Q^2)$ Isospin symmetry $M_3^{\gamma W}(1,Q^2)$





Previous calculation by Marciano&Sirlin '06:
No use of neutrino data, ad-hoc connection of low and high scales

$\text{M \& S}: \quad \Box_{\gamma W}^{(0)} = 0.00324 \pm 0.00018$

$\text{New DR}: \quad \Box_{\gamma W}^{(0)} = 0.00379 \pm 0.00010$

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)

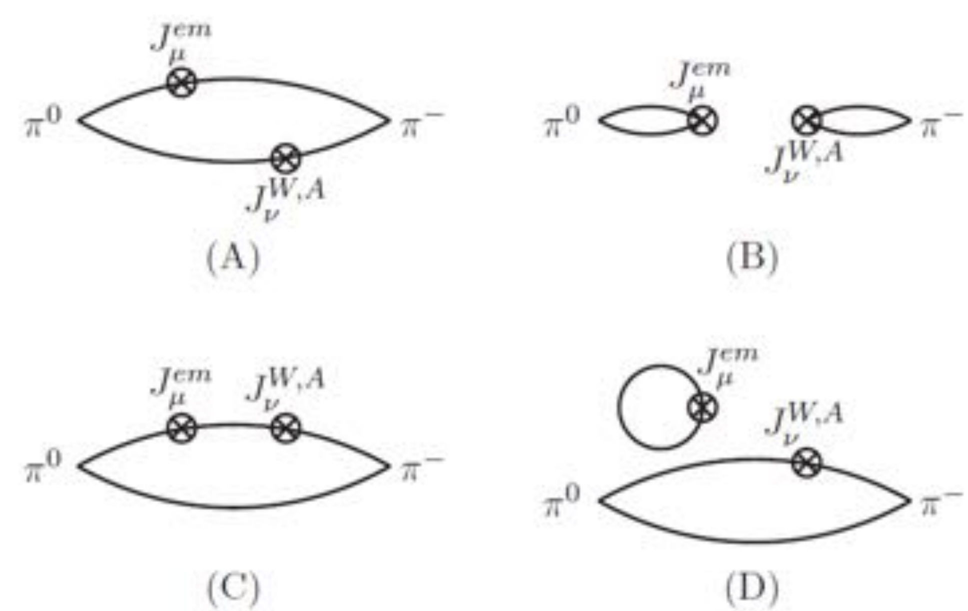
$$\mathcal{H}^{VA}_{\mu\nu}(t,\vec{x}) \equiv \langle H_f(P)|T\left[J^{em}_\mu(t,\vec{x})J^{W,A}_\nu(0)\right]|H_i(P)\rangle$$

$$M^{\gamma W(0)}_{3\pi}(Q^2) = -\frac{1}{6\sqrt{2}}\frac{Q}{m_\pi}\int d^4x\,\omega(Q,x)\varepsilon_{\mu\nu\alpha0}x_\alpha \mathscr{H}^{VA}_{\mu\nu}(x)$$

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

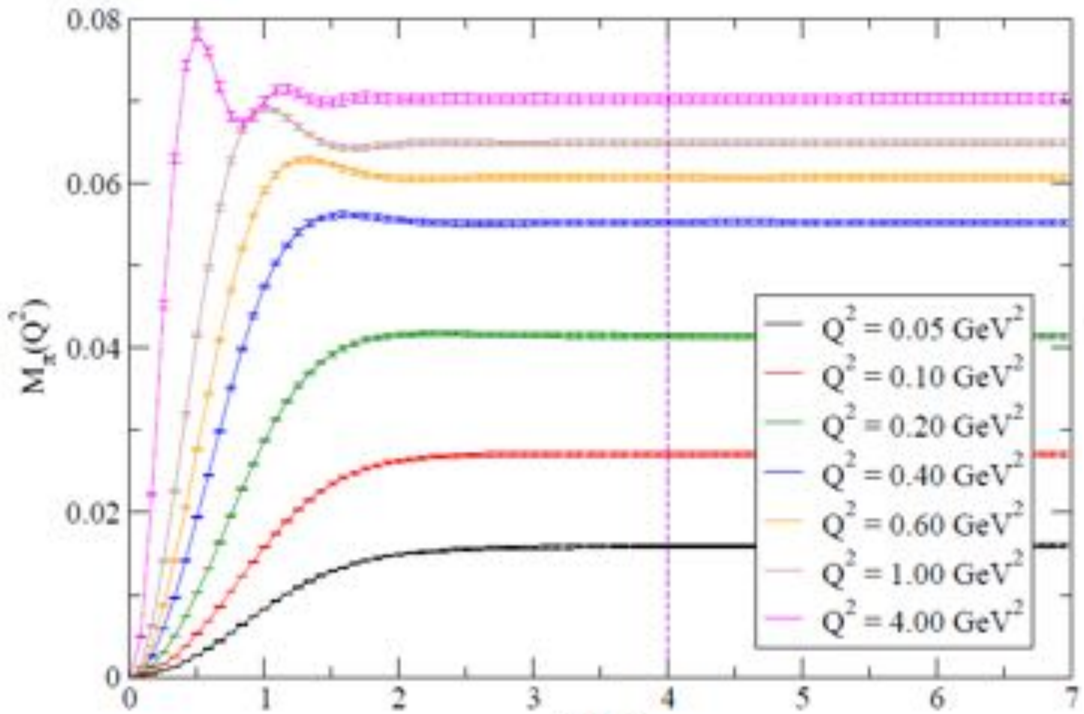
Ensemble	m_π [MeV]	L	T	a^{-1} [GeV]	$N_{\rm conf}$	N_r	$\Delta t/a$
24D	141.2(4)	24	64	1.015	46	1024	8
32D	141.4(3)	32	64	1.015	32	2048	8
32D-fine	143.0(3)	32	64	1.378	71	1024	10
48I	135.5(4)	48	96	1.730	28	1024	12
64I	135.3(2)	64	128	2.359	62	1024	18

Blue: DSDR
Red : Iwasaki

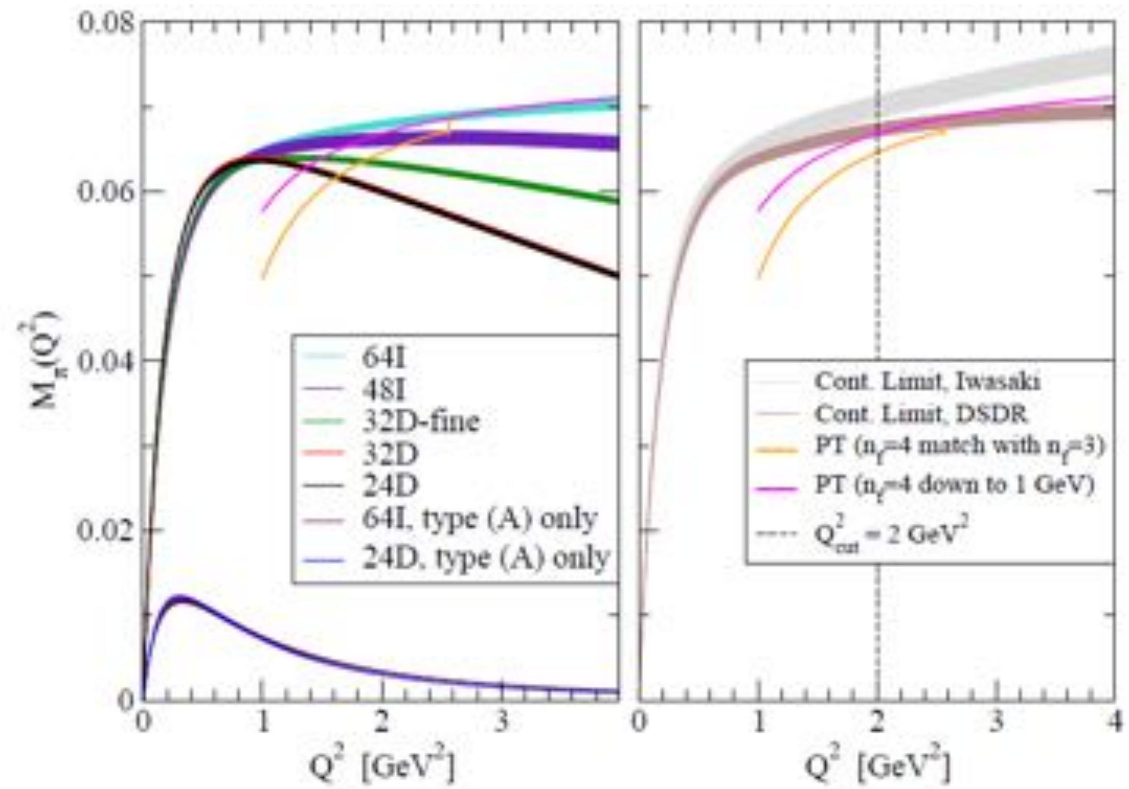


Quark contraction diagrams

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

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

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

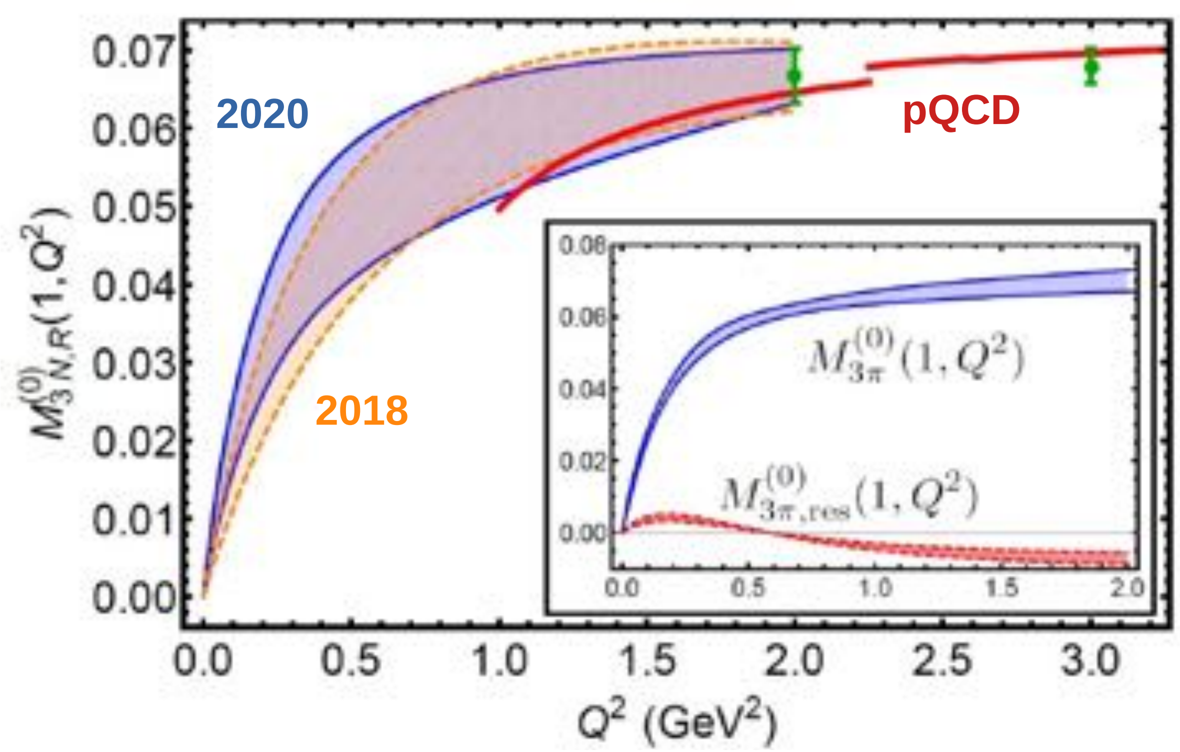
Next-gen experiments: aim at 1 o.o.m. exp. uncertainty improvement

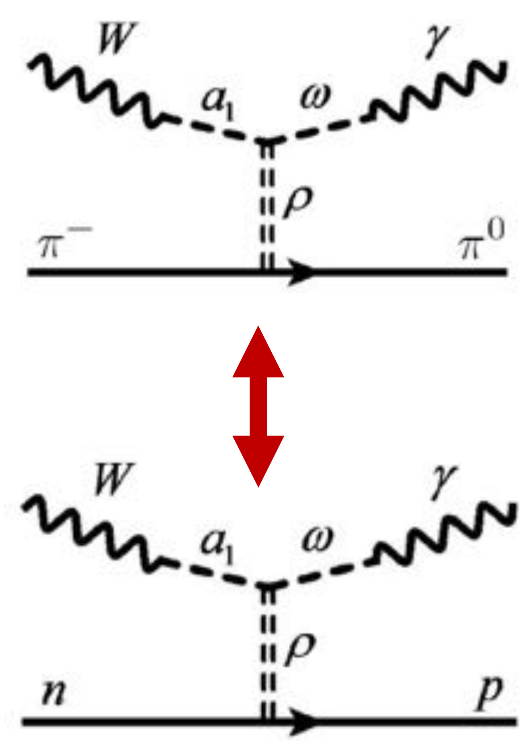
Implications for the free nucleon γW-box

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

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

V_{ud} extraction and CKM unitarity

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

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

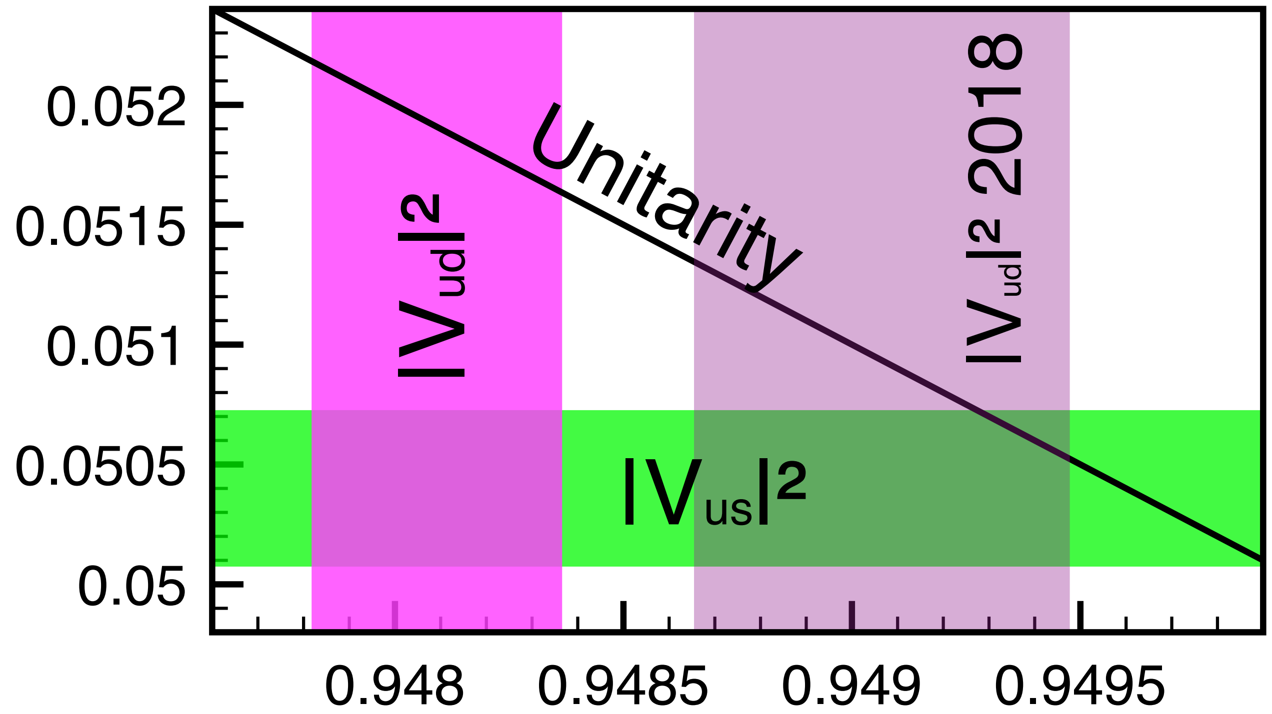
In July 2019 Czarnecki, Marciano and Sirlin published an update ***1907.06737***

$$\Delta_R^V = 0.02421(32) \text{ —> } |V_{ud}| = 0.97391(10)_{Ft}(15)_{RC}$$

DR (Shiells, Blunden, Melnitchouk) ***2012.01580*** — closely agrees with Seng et al.

$$\Delta_R^V = 0.02472(18) \text{ —> } |V_{ud}| = 0.97368(14)$$

With new RC $\sim 3\sigma$ unitarity deficit (a.k.a. Cabibbo angle anomaly)



V_{ud} in Presence of Nuclear Structure Effects

0+-0+ nuclear decays $$|V_{ud}|^2 = \frac{2984.43s}{\mathscr{F}t(1+\Delta_R^V)}$$

$$\Delta_R^V = \frac{\alpha}{2\pi}\left[3\ln\frac{M_Z}{M} + \ln\frac{M_Z}{M_W}\right] + 2\Box_{\gamma W}^V$$

General structure of RC for nuclear decay

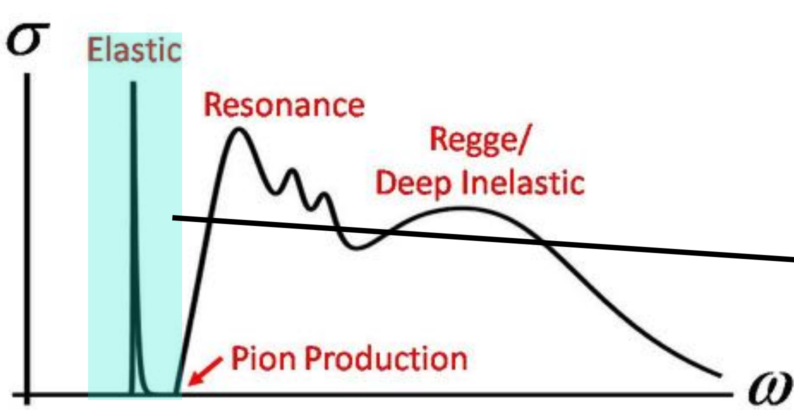
$$ft(1+RC) = Ft(1+\delta_R')(1-\delta_C+\delta_{NS})(1+\Delta_R^V)$$

NS correction reflects this extraction of the free box

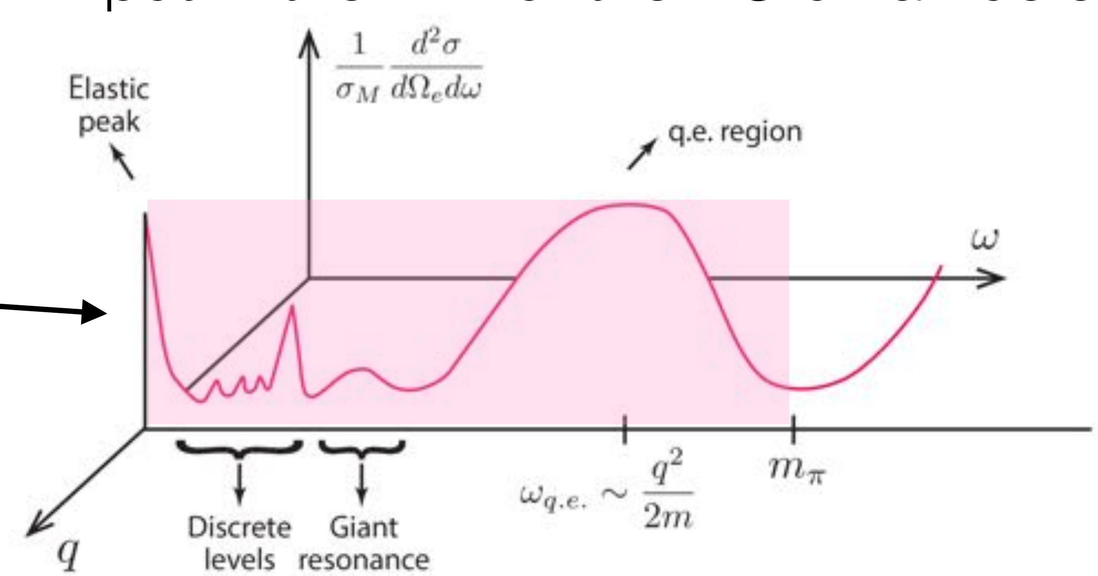
$$\Box_{\gamma W}^{\mathrm{VA,\ Nucl.}} = \Box_{\gamma W}^{\mathrm{VA,\ free\ n}} + \left[\Box_{\gamma W}^{\mathrm{VA,\ Nucl.}} - \Box_{\gamma W}^{\mathrm{VA,\ free\ n}}\right]$$

Nuclear modification in the lower part of the spectrum

Input in the DR for the universal RC



Input in the DR for the RC on a nucleus



Nuclear Structure Modification

C-Y Seng, MG, M J Ramsey-Musolf, arXiv: 1812.03352
MG, arXiv: 1812.04229

δ_{NS} from DR with energy dependence averaged over the spectrum

$$\delta_{NS} = \frac{2\alpha}{\pi N M}\int_0^{1\,\mathrm{GeV}^2} dQ^2 \int_{\nu_{thr}}^{\nu_\pi} \frac{d\nu}{\nu}\left[\frac{\nu+2q}{(\nu+q)^2}\left(F_3^{(0)\,Nucl.} - F_3^{(0),\,B}\right) + \frac{2\langle E\rangle}{3}\frac{\nu+3q}{(\nu+q)^3}F_3^{(-)\,Nucl.}\right]$$

Hardy & Towner 1994 on: ad hoc description by nuclear quenching of spin operators

Compare the effect on the average Ft value:

HT value 2018: $\mathscr{F}t = 3072.1(7)s$

Old estimate: $\delta\mathscr{F}t = -(1.8 \pm 0.4)s \;+\; (0 \pm 0)s$

New estimate: $\delta\mathscr{F}t = -(3.5 \pm 1.0)s \;+\; (1.6 \pm 0.5)s$

Two 2σ corrections that cancel each other;
The cancellation is delicate: the two terms are highly correlated
Larger E-dep. term will correspond to a smaller negative E-indep. term and vv.

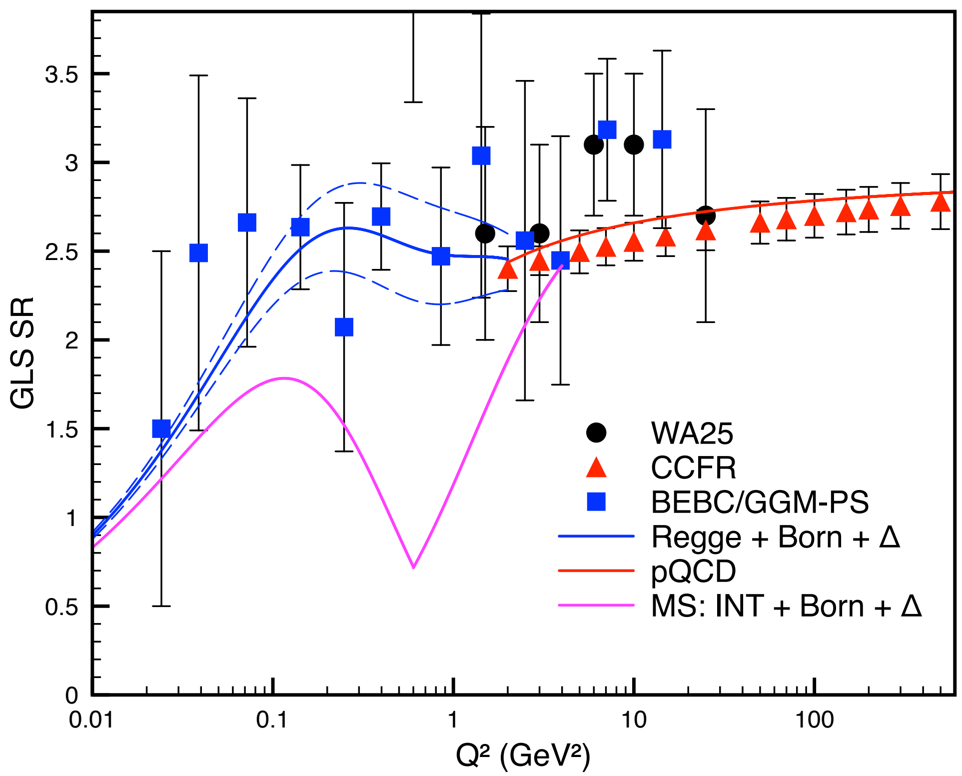
Conservative uncertainty estimate: 100% $\quad \mathscr{F}t = (3072 \pm 2)s$

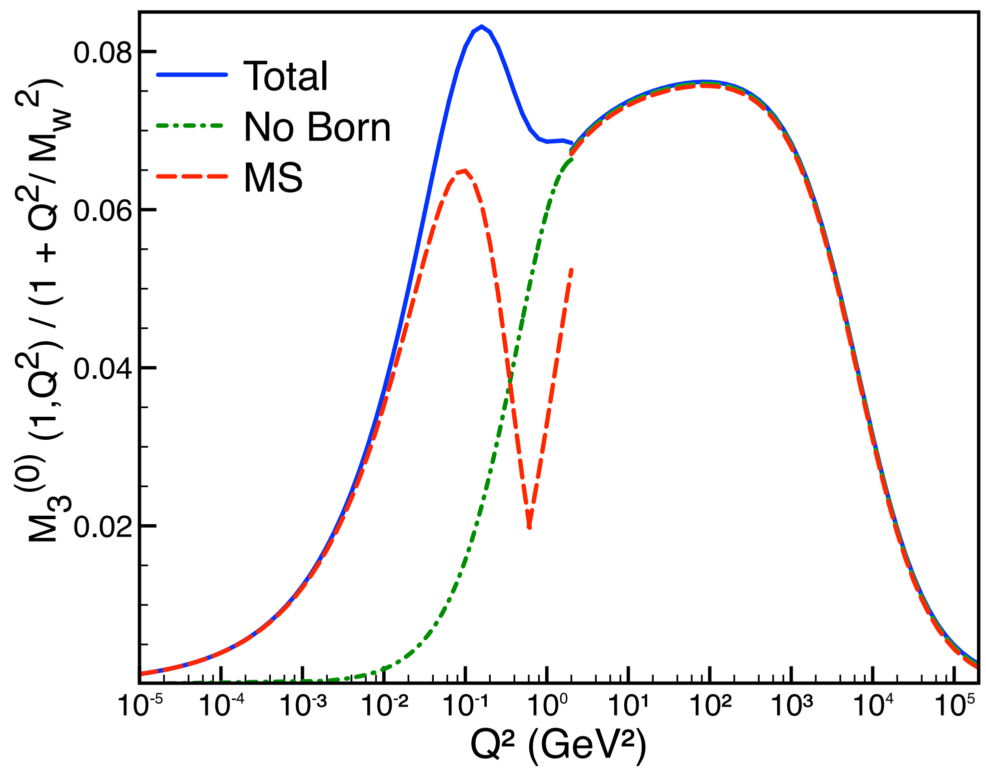
Future developments

Improvement in $\Box_{\gamma Z}$ and $\Box_{\gamma W}$ achieved thanks to:

Use of dispersion relations + data + isospin symmetry + lattice QCD — TEST!

$M_3^{WW}(1,Q^2)$ Isospin symmetry $M_3^{\gamma W}(1,Q^2)$





Each calculation of $\Box_{\gamma Z}$ and $\Box_{\gamma W}$ contains a prediction for EW structure functions

Can and should be tested by confronting with new, high quality data!

NC program @ JLab, EIC

Neutrino program @ DUNE (bubble chambers, H/D targets)

Snowmass white papers arXiv: 2203.11298, 2203.11319

Nuclear modification of structure functions and their moments

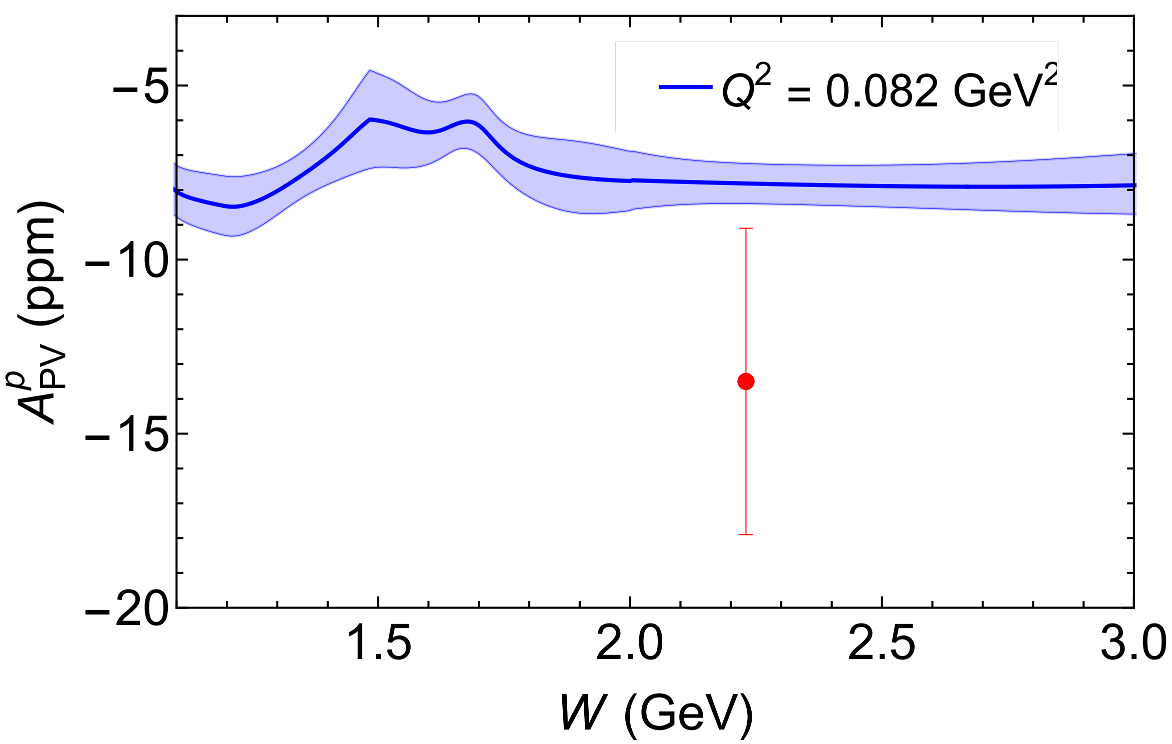
New Data: may be a challenge!

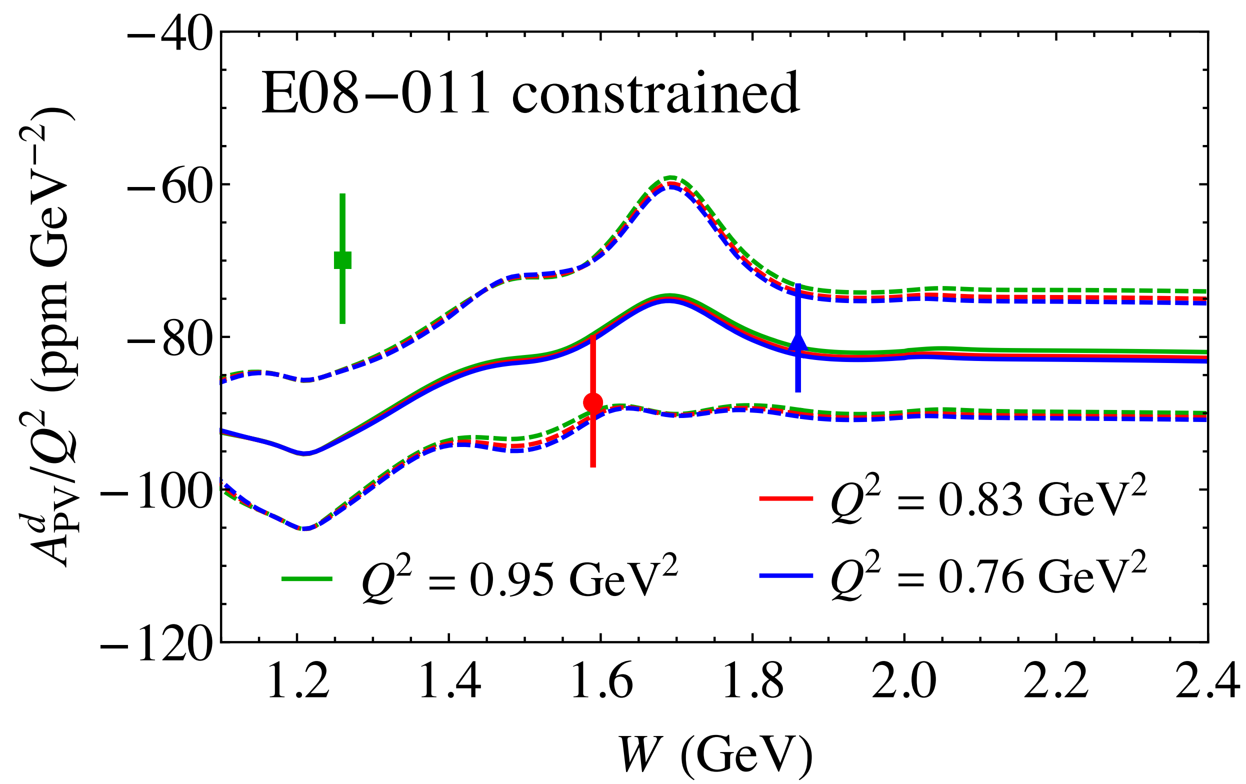
Significant interest in new/better data on PV structure function F_3

This SF is C-parity odd: opposite sign for particles and antiparticles

In neutrino scattering: need ν and $\bar{\nu}$ beam — challenging (systematics)
In PVES can be deduced from e^+/e^- data? However suppressed by small g_V^e

In general: how should we use new data?
Recent example: inelastic PV asymmetry in PVDIS and QWeak





Conclusions

- Sensitive tests of SM and beyond with PVES and beta decays
- Need for a reliable calculation of box diagrams for a 10^{-4} precision goal
- Consistent dispersive treatment of the γW-box correction to neutron and nuclear β-decay, and the γZ-box correction to PVES and weak charges
- pQCD, hadronic and nuclear contributions treated in a unified framework
- γW-box calculation confirmed by a first-ever direct lattice calculation
- New more precise data on EW structure functions $F^{\gamma Z}_{1,2,3}$ (JLab, EIC)
- New more precise data on EW structure functions $F^{WW}_{1,2,3}$ (DUNE)
- Test of Lattice QCD predictions for moments at low Q^2
- Test of pQCD running at high Q^2
- What if model and data disagree?