SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI · PRISMA · JOHANNES GUTENBERG UNIVERSITÄT MAINZ · Deutsche Forschungsgemeinschaft DFG · STRONG-2020

Box Diagrams for Elastic PVES and Relevance for DIS

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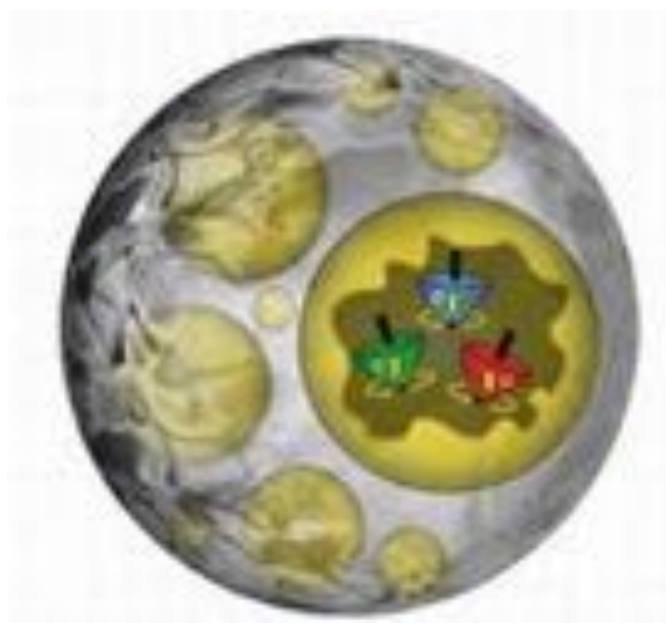

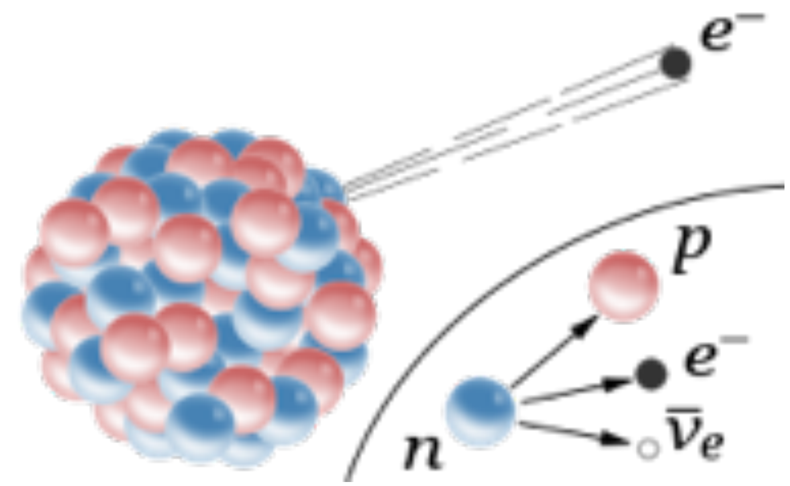

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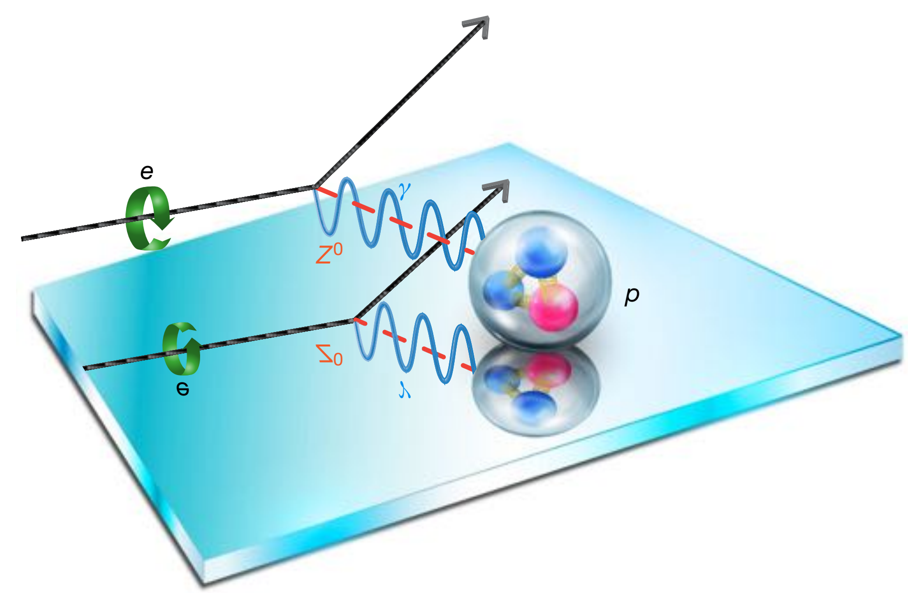
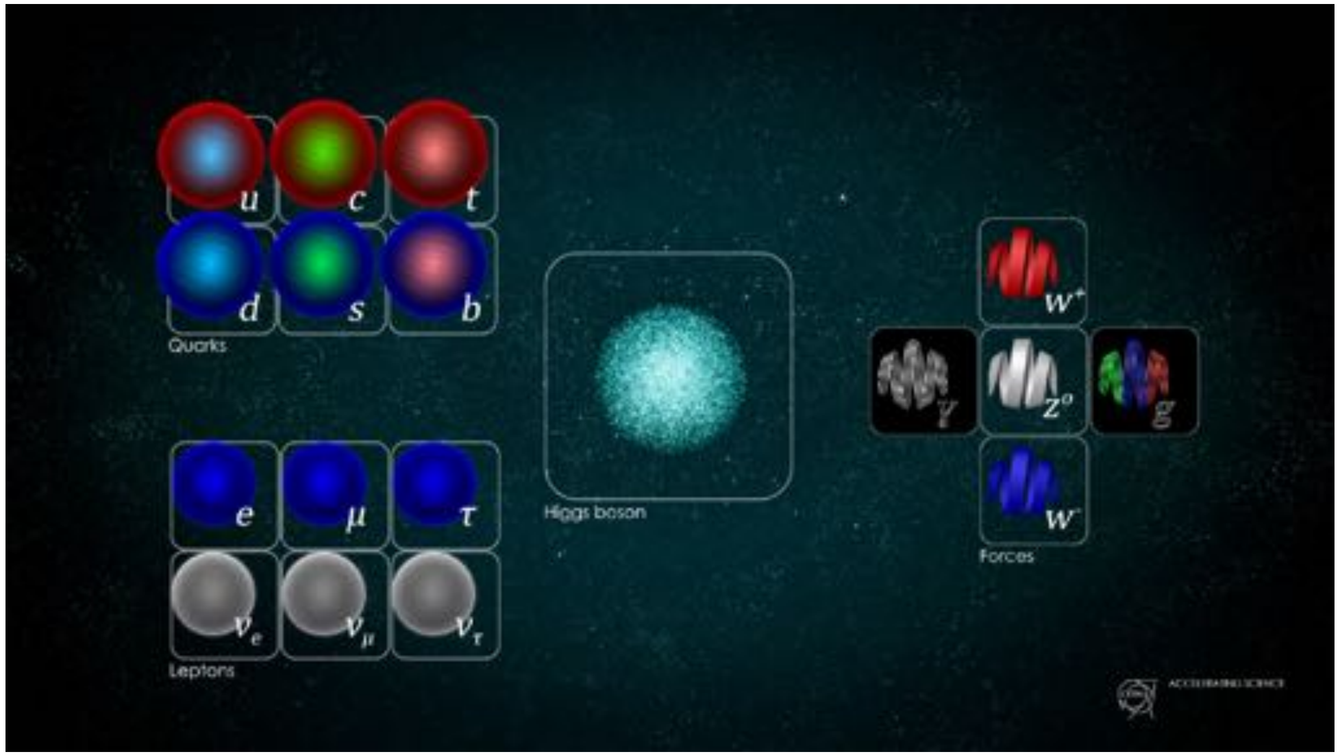


ECT Workshop "Radiative corrections from medium to high energy experiments" - July 19, 2022*

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

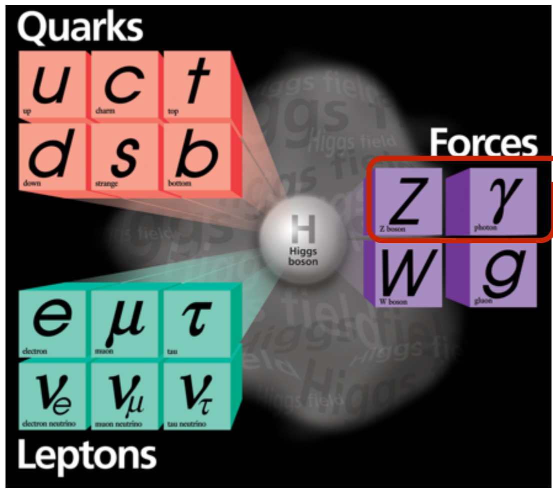
- SM parameters: charges, masses, mixing
- At low energy quarks are bound in hadrons - how can we access their fundamental properties through hadronic mess?
- A **charge associated with a conserved current** is not renormalized by strong interaction - the charge of a composite = ∑ charges of constituents
- 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}

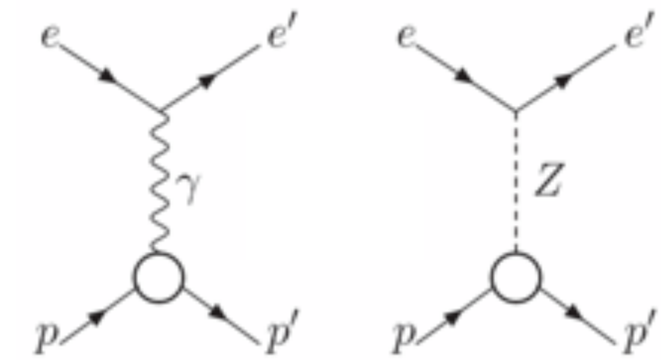
Precision measurements of weak mixing angle



Weak mixing angle - mixing of the NC gauge fields

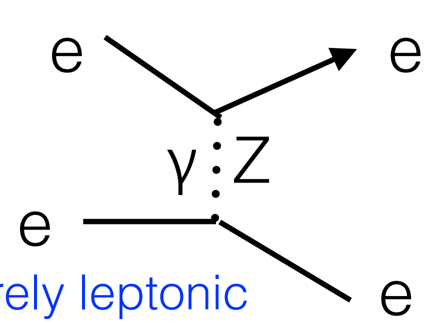
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

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



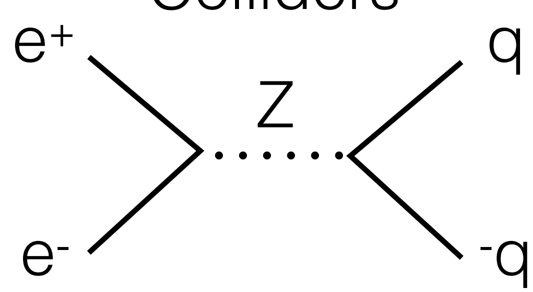
$Q^p = +1$ $Q^p_W = 1 - 4\sin^2\theta_W$

Møller scattering



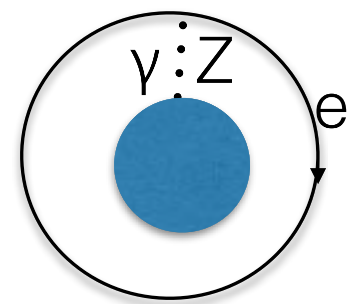
Purely leptonic

Colliders



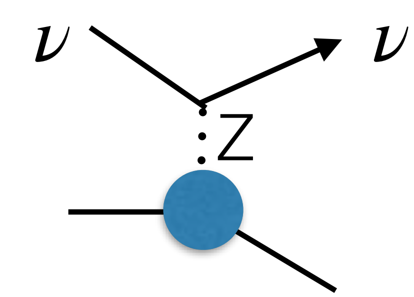
Z-pole measurement

Atomic PV



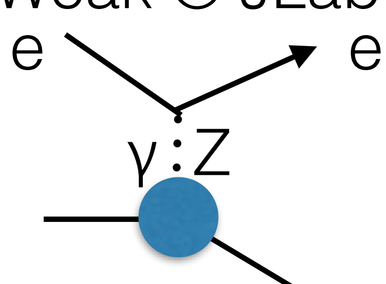
Coherent quarks in nuclei

CEvNS



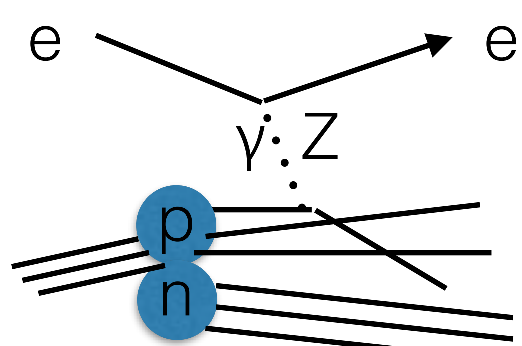
Coherent quarks in nuclei

P2 MESA @ Mainz
Q-Weak @ JLab



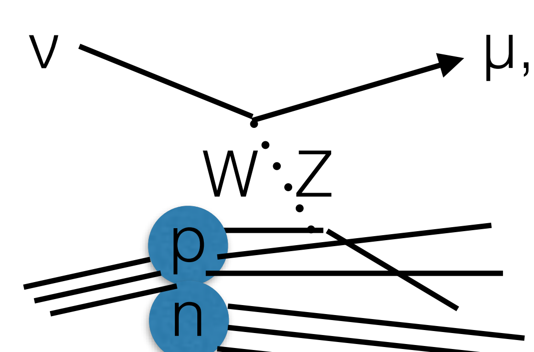
Coherent quarks in p or ^{12}C

e-DIS @ JLab, EIC



Incoherent e-q scattering

ν-DIS @ NuTEV

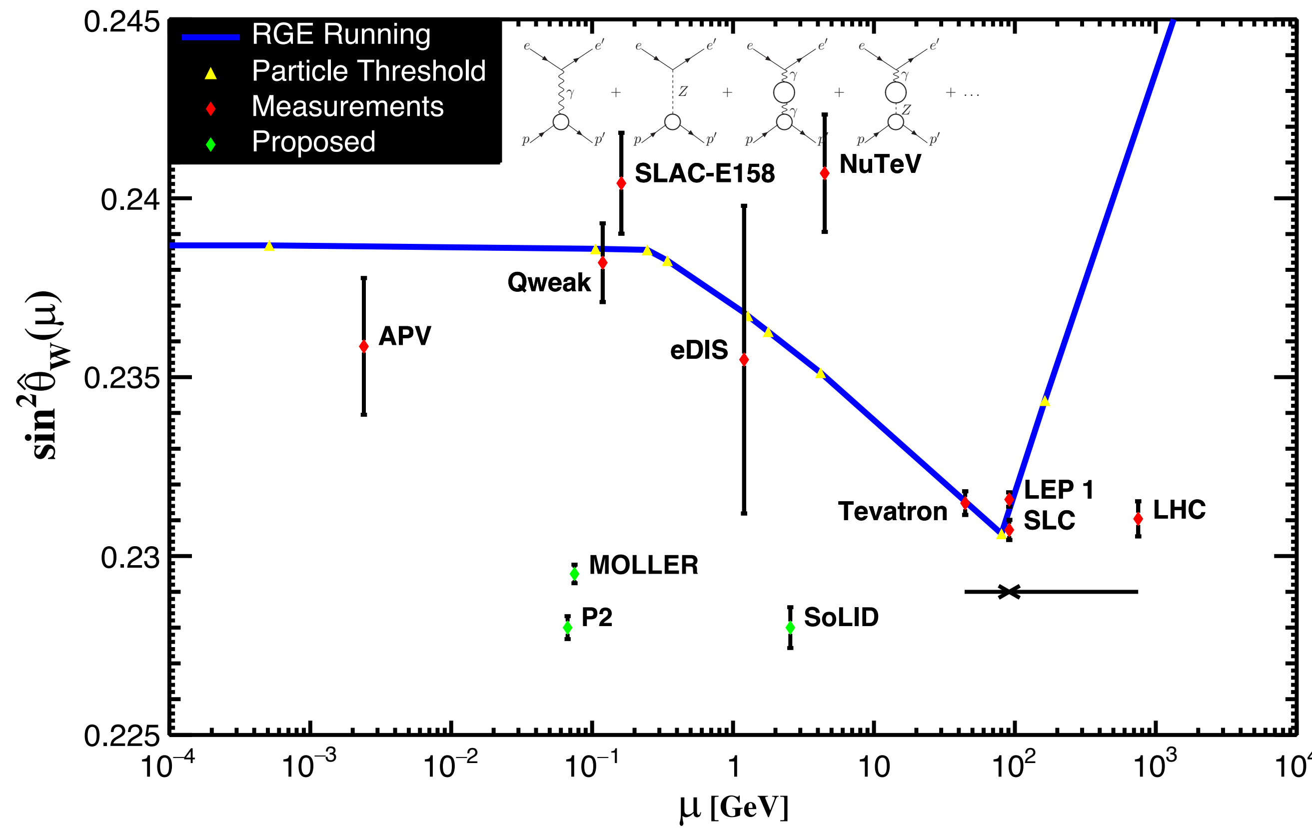


Incoherent ν-q scattering

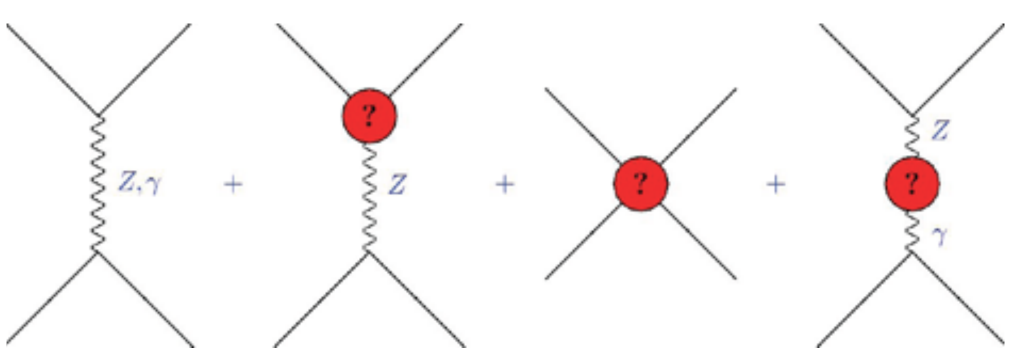
SM running of the weak mixing angle

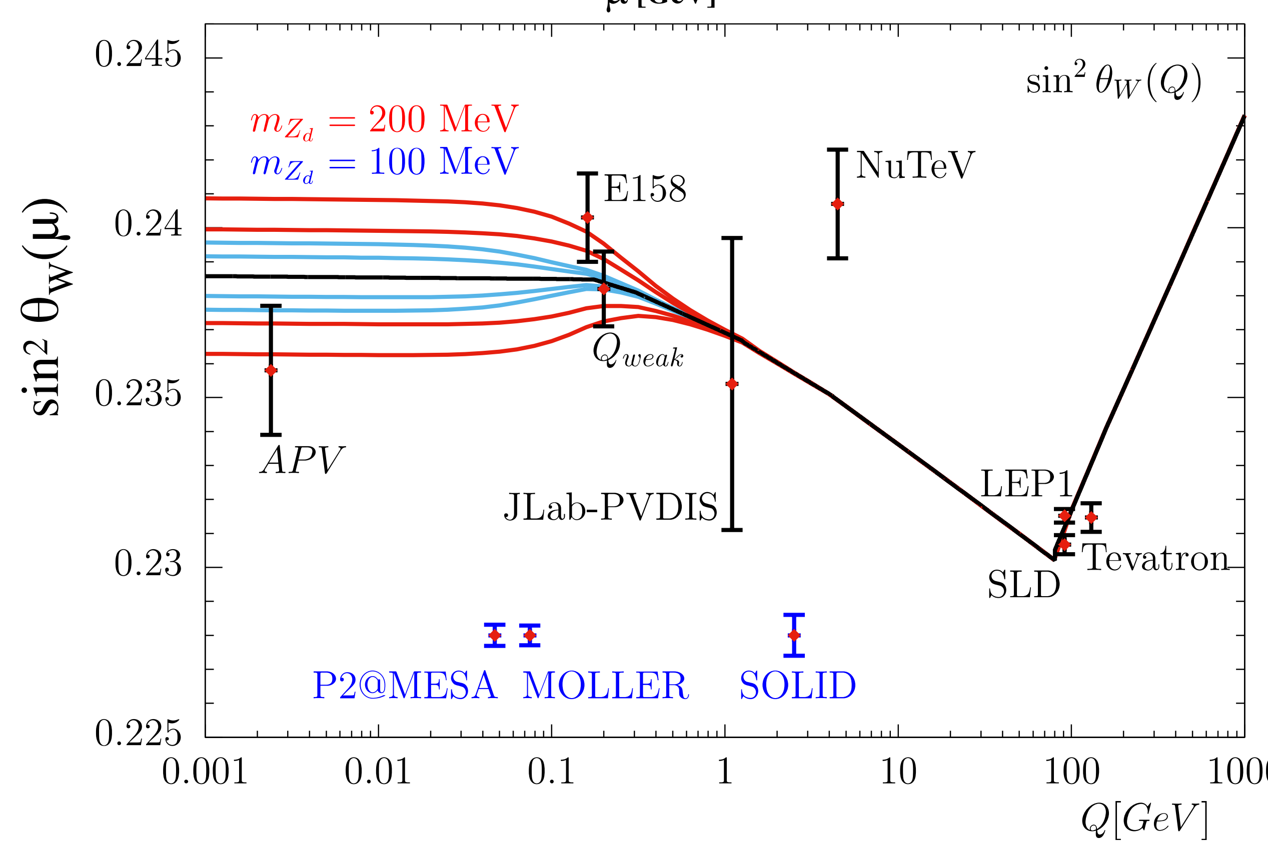
Universal quantum corrections can be absorbed into running, scale-dependent $\sin^2\theta_W(\mu)$

SM uncertainty: few x 10^{-5}



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

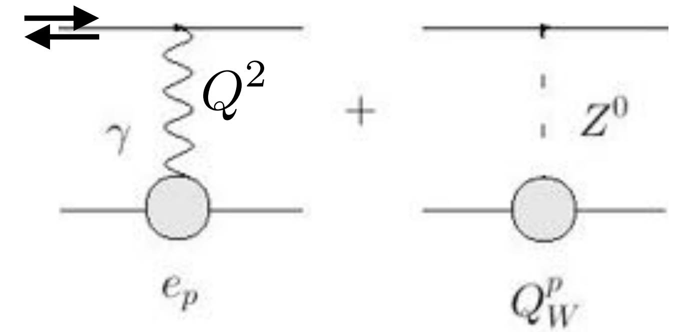




Heavy BSM reach: up to 50 TeV
Light dark gauge sector: down to 70 MeV
Complementary to colliders

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: Q²~0.03 GeV² $A^{PV} = -(226.5 \pm 9.3)\,\text{ppb}$ $Q_W^p = 0.0718 \pm 0.0044$ (rel. 6%)

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

P2 @ MESA/Mainz: go down to Q² ~ 0.005 GeV² — tiny asymmetry to 1.5-2%

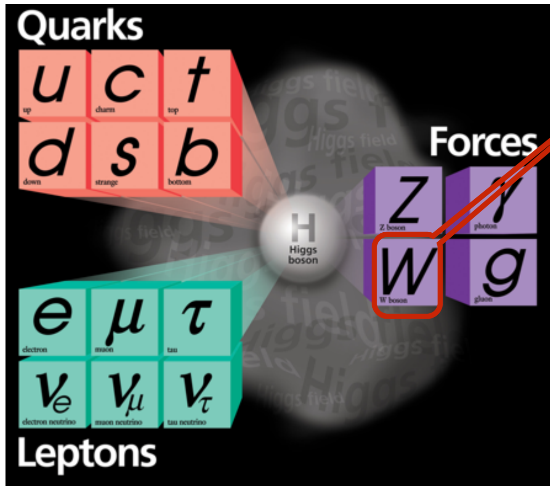
$$Q_W^{\rm p,\,1-loop} = (1 + \Delta_\rho + \Delta_e)(1 - 4\sin^2\hat{\theta}_W + \Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Marciano, Sirlin PRD 1984

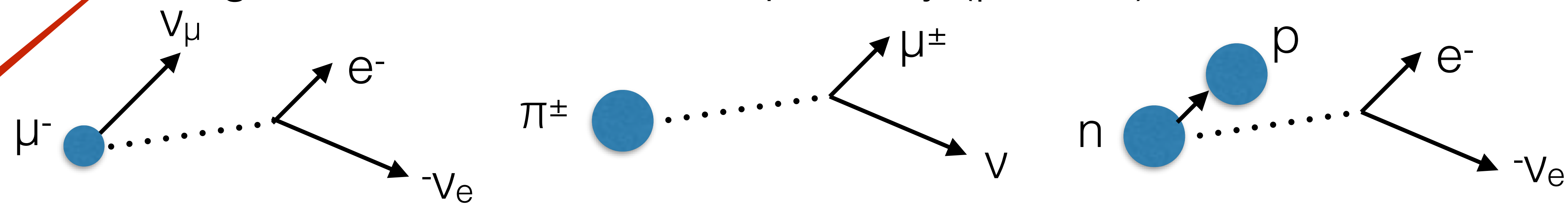
Δ: hadronic structure (size, spin, strangeness; suppressed at low Q^2; trivial E-dependence)

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

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

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

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

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

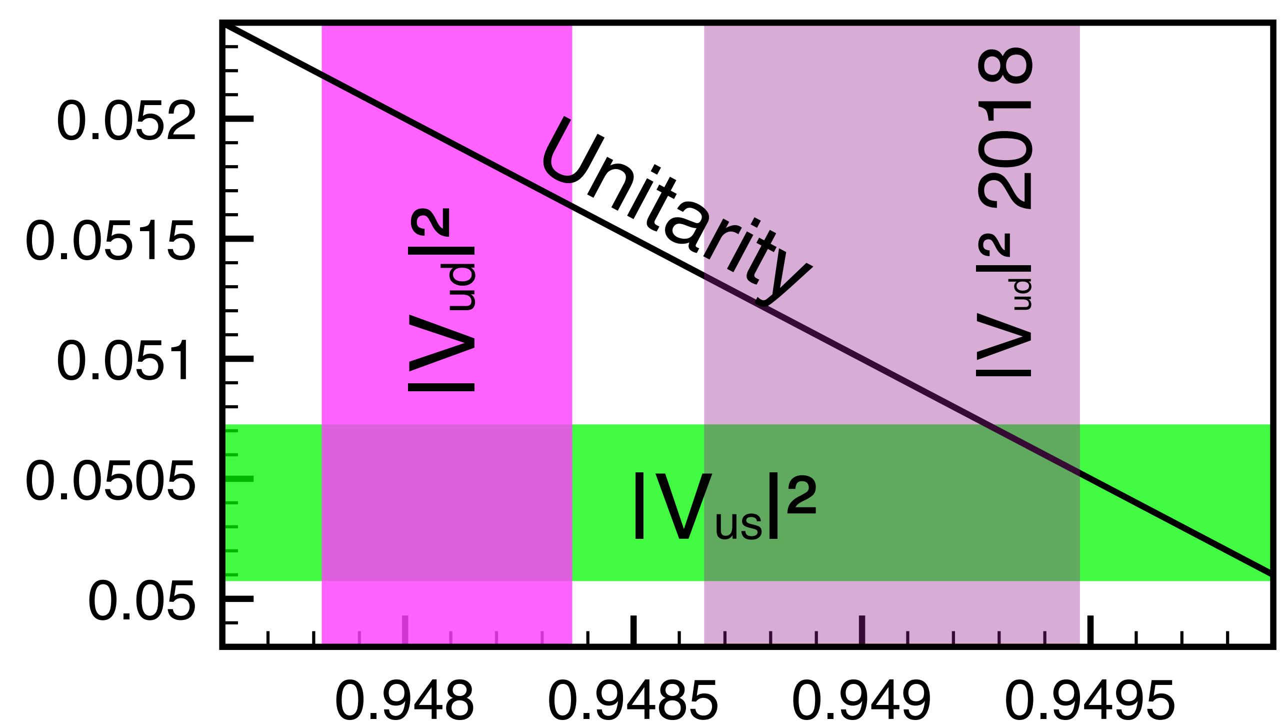
Neglecting $V_{ub} \sim 10^{-3}$: Cabibbo angle θ_C

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

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)



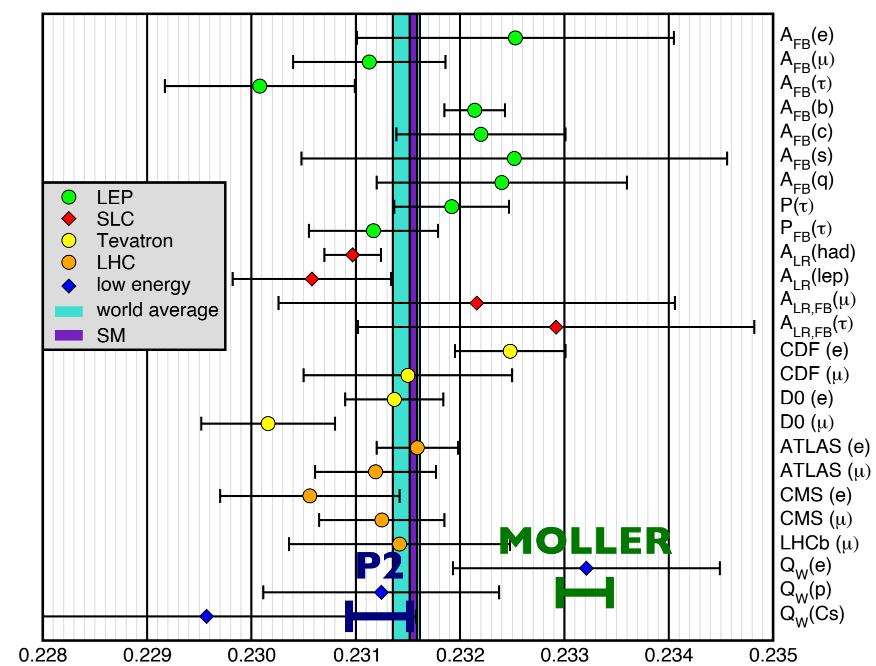
BSM searches at low energies vs. colliders

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

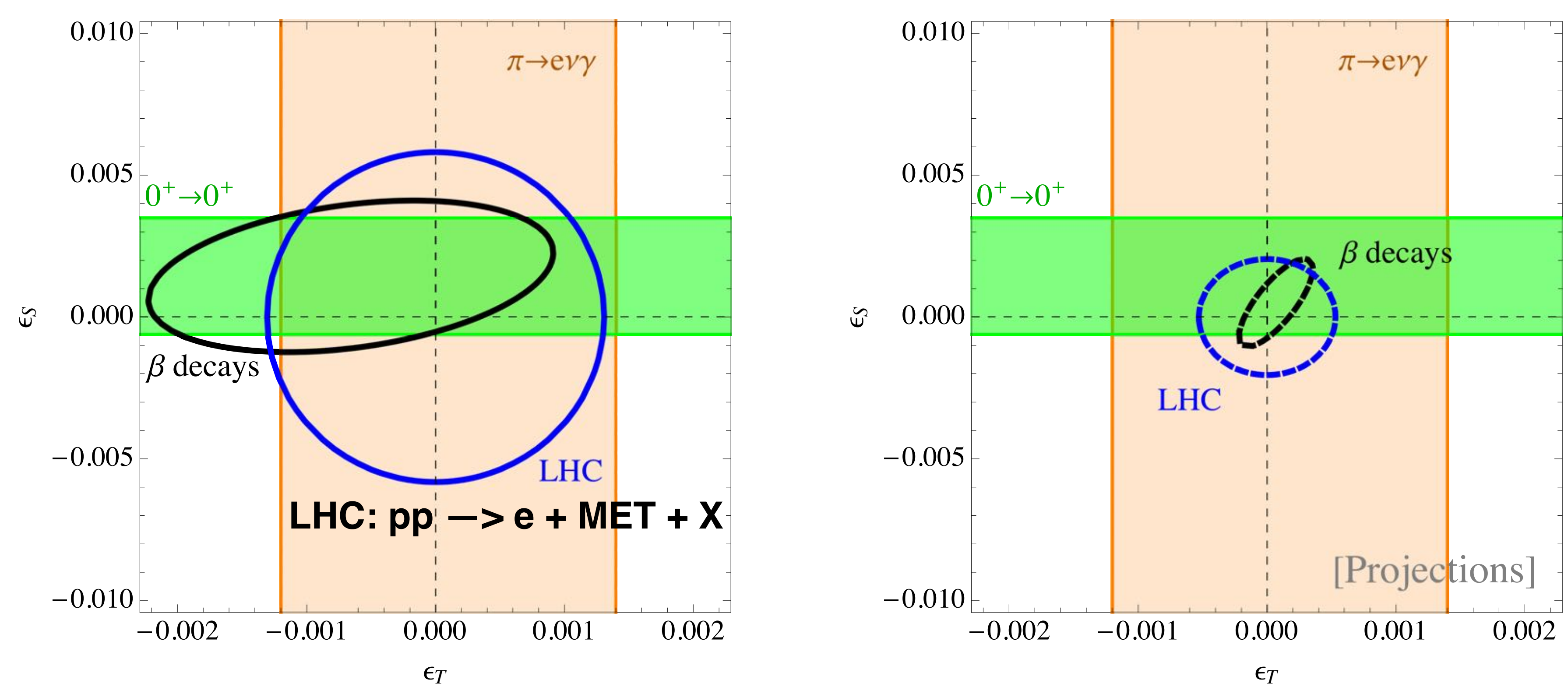


LEP & SLC:
0.23151 ± 0.00016
Tevatron:
0.23148 ± 0.00033
LHC:
0.23129 ± 0.00033

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



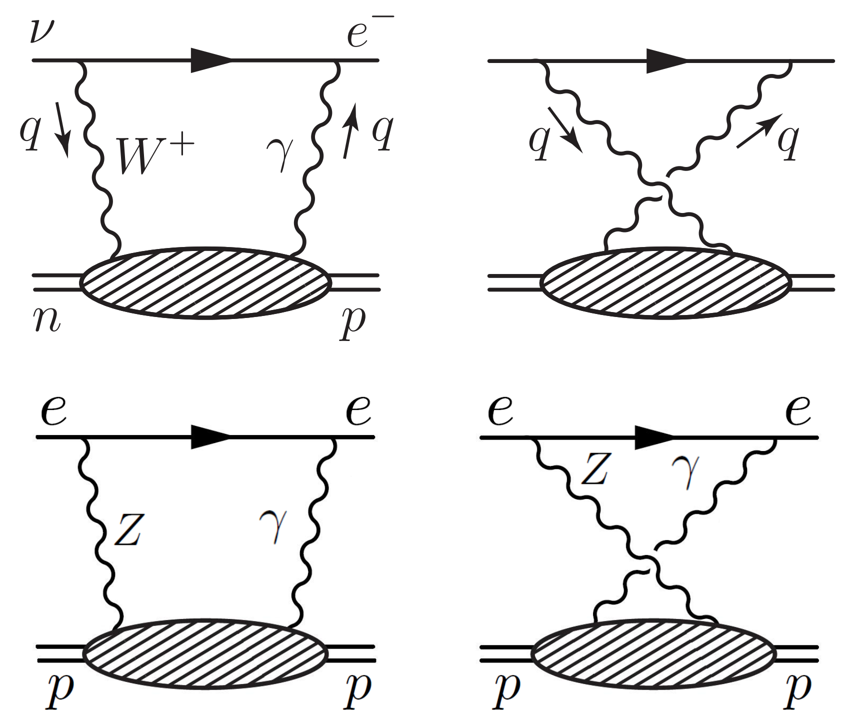
Gonzalez Alonso et al, PPNP 2019

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



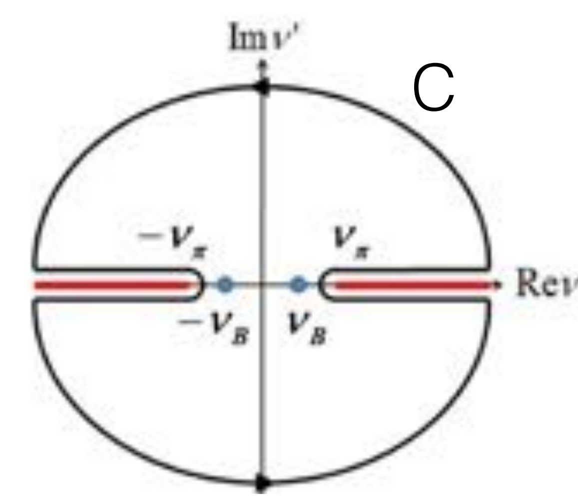
E.g., for γW-box (γZ-box analogous)

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

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

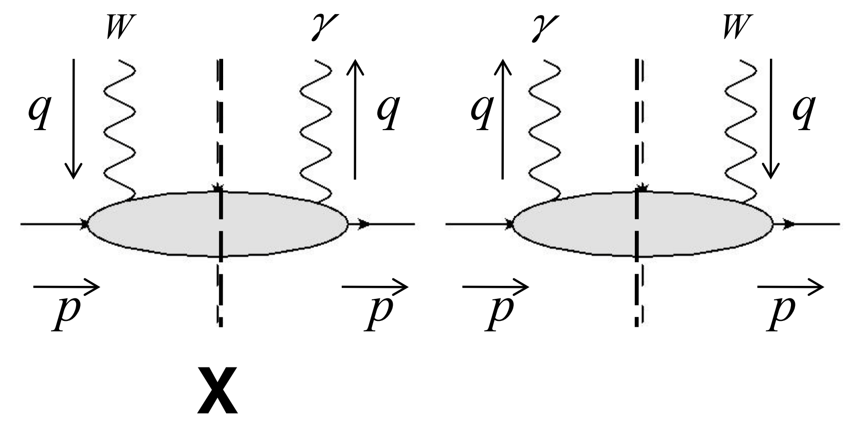


Forward box: only ν-analyticity needed;
if finite *t* also *t*-analyticity generally required - complicated

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

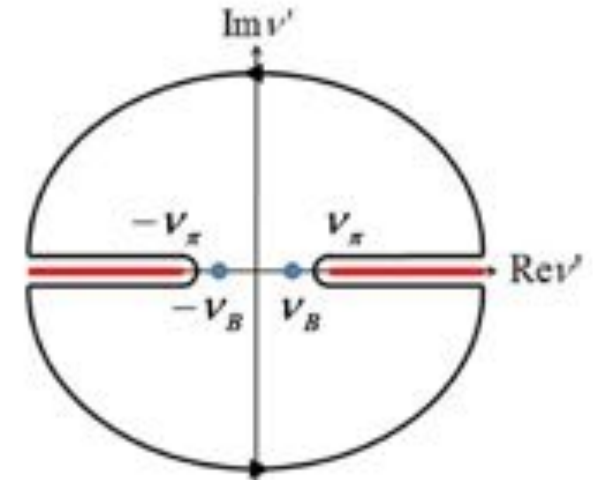
Structure functions $F_i^{\gamma Z}$ are data
Structure functions $F_i^{\gamma W}$ are NOT data but can be related to data

Define box corrections according to

$$T_W + T_{\gamma W} = -\sqrt{2} G_F V_{ud} \bar{u}_e \not{p}(1-\gamma_5) v_\nu (1 + \Box_{\gamma W})$$
$$T_Z + T_{\gamma Z} = -\frac{G_F}{2\sqrt{2}} \bar{u}_e \not{p}(1-\gamma_5) u_e F_{\mathrm{weak}}(Q^2)[Q_W + \Box_{\gamma Z}(E, Q^2)]$$

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)
$Q_{if} = M_i - M_f = 1 - 10\,\mathrm{MeV}$

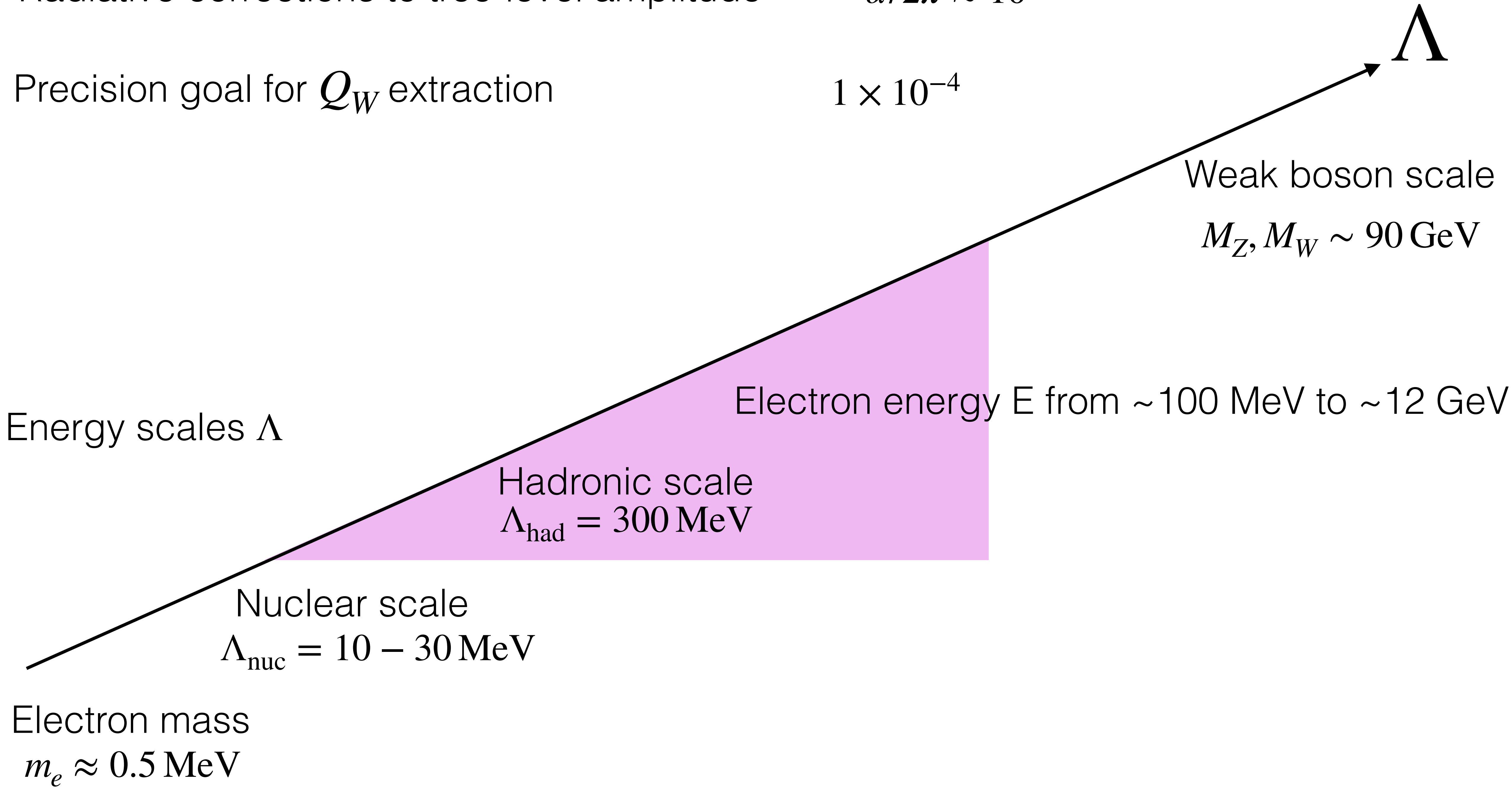
Electron mass
$m_e \approx 0.5\,\mathrm{MeV}$

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

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

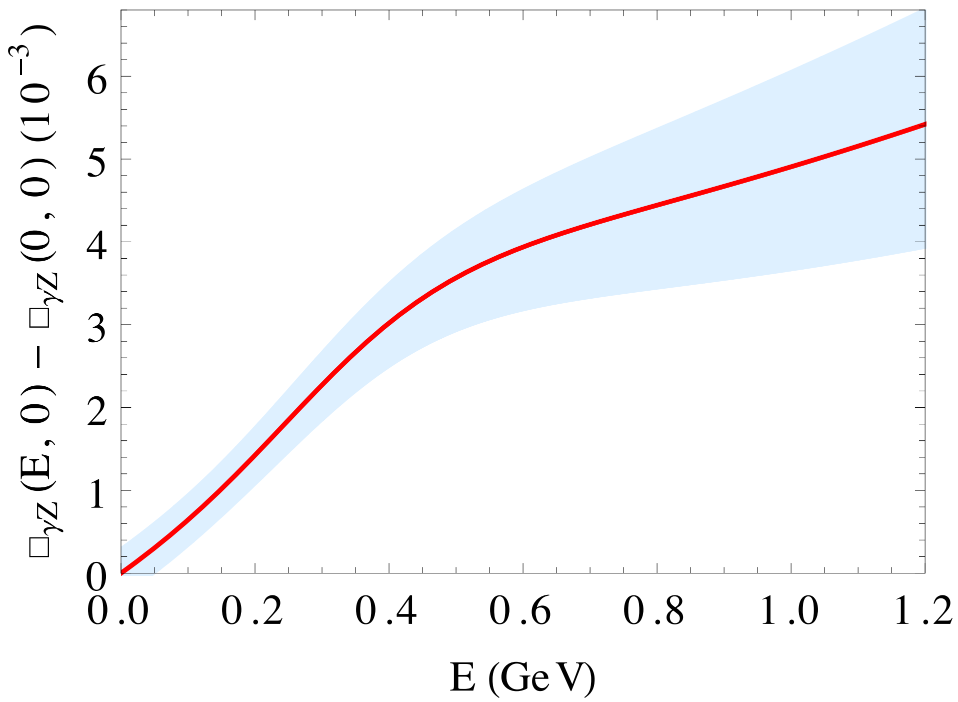
γW-box: $$\Box^{\rm even}_{\gamma W} = \frac{\alpha}{\pi M}\int_0^\infty dQ^2\int_{\nu_{thr}}^\infty d\nu\frac{\nu+2q}{\nu(\nu+q)^2}F_3^{(0)}(\nu,Q^2) + O(E^2)$$

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

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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MG, Spiesberger, Zhang, PLB 752 (2016) 135;
Erler, MG, Koshchii, Seng, Spiesberger, PRD100 (2019), 053007

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

See also 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

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

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

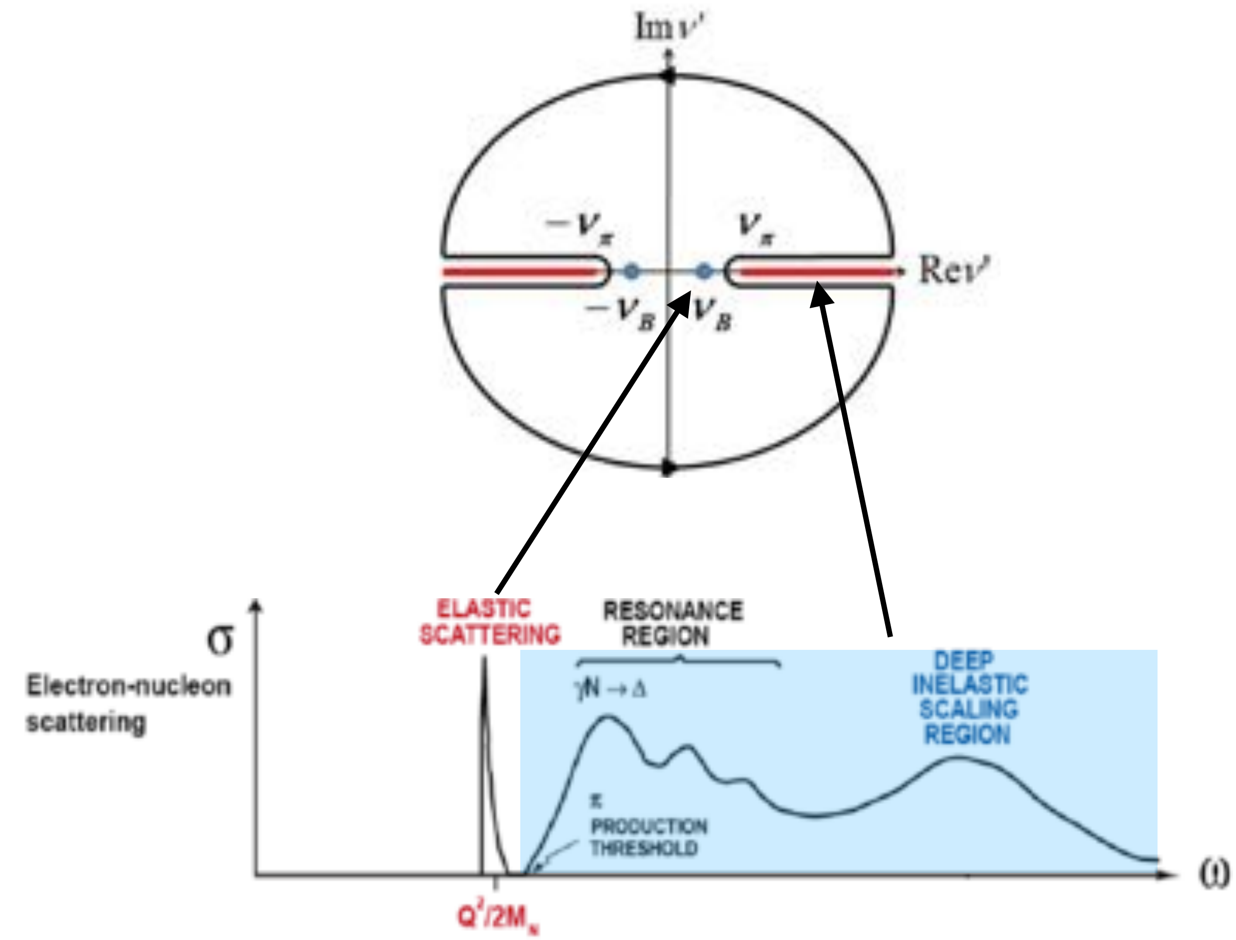
$$\Box^{even}_{\gamma W} = \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2 M_W^2}{Q^2(M_W^2+Q^2)}M_3^{(0)}(1,Q^2)$$

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.

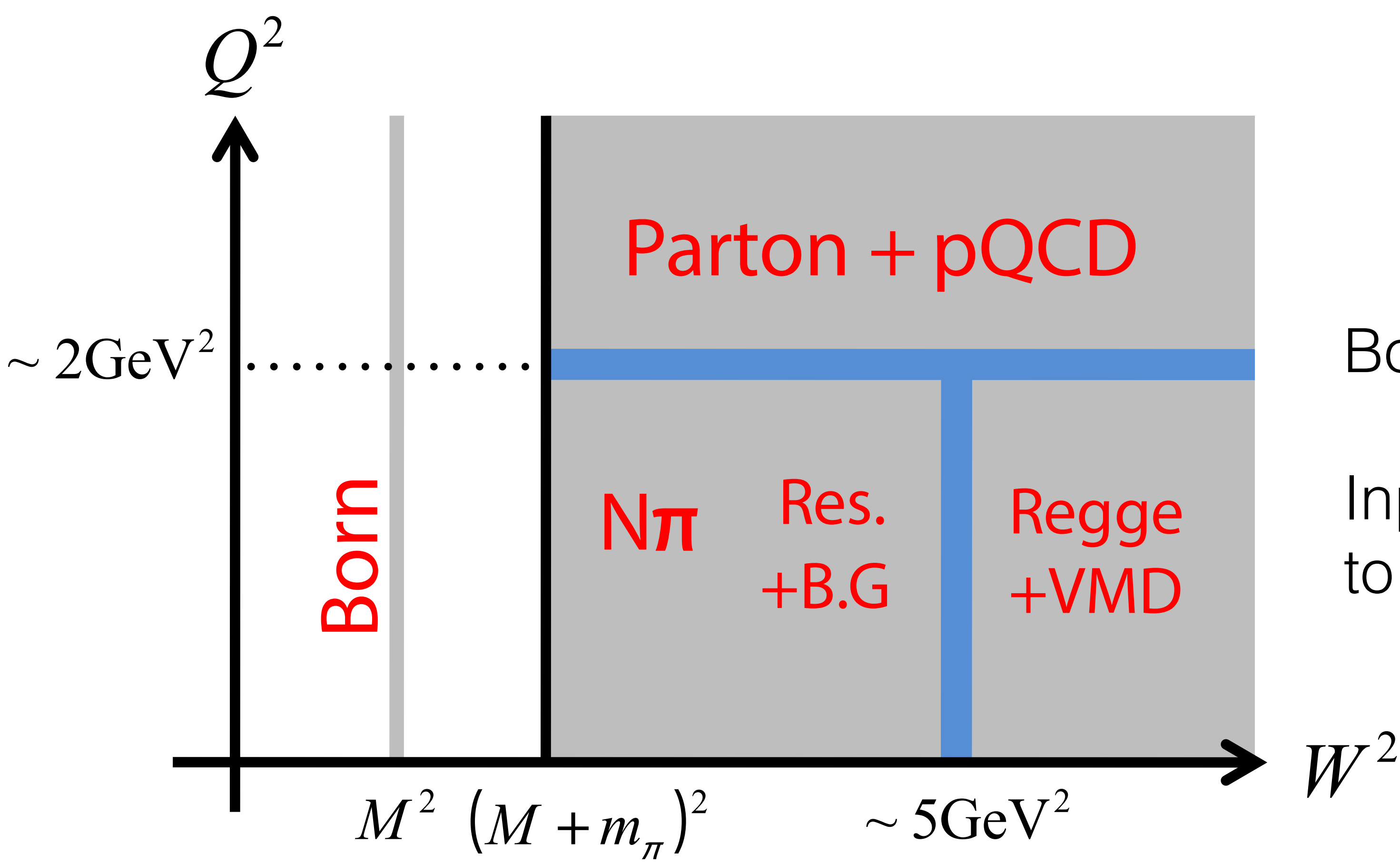
In a nutshell: the use of those data allowed to improve the $\Box_{\gamma W}$ calculation

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

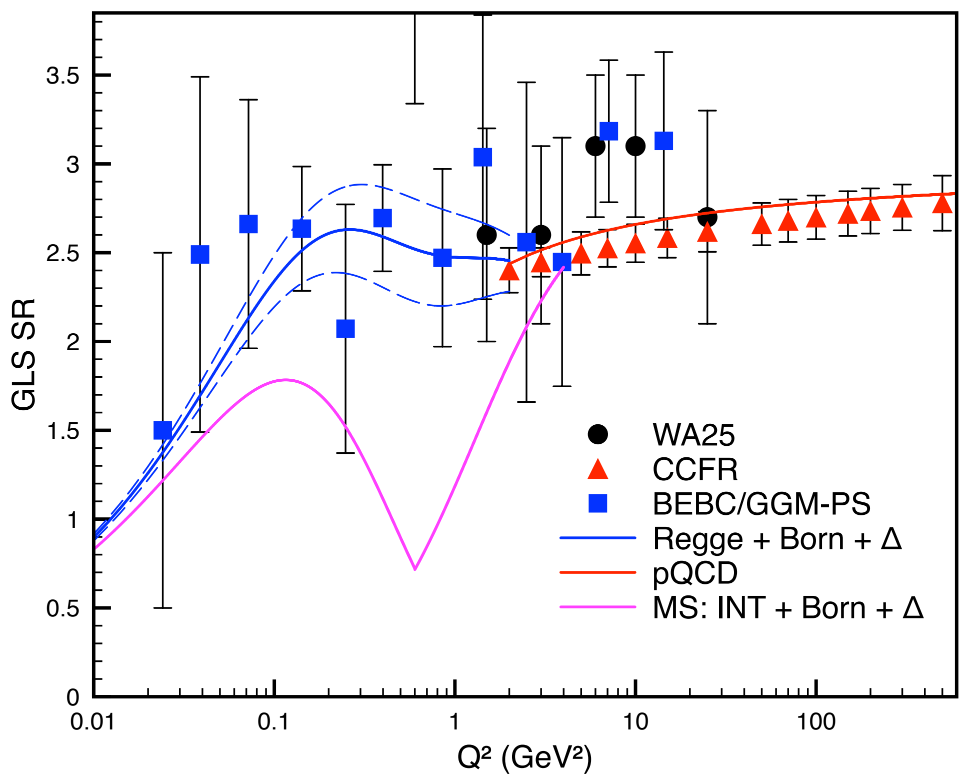
Input into dispersion integral

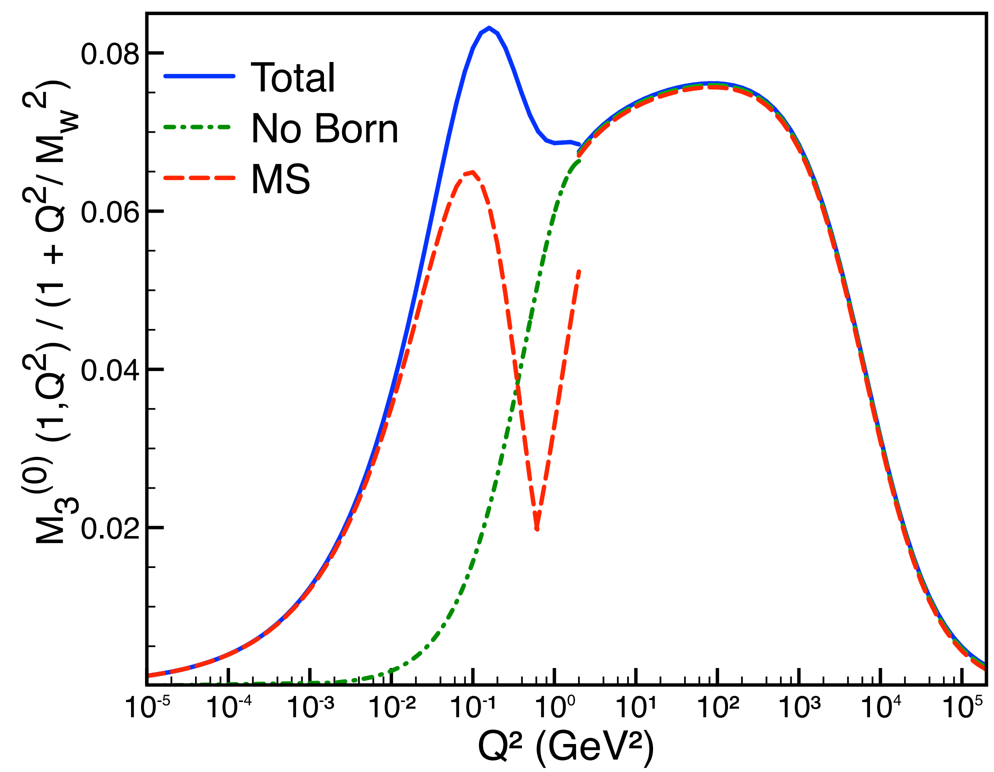
Unfortunately, no data can be obtained for $F_3^{\gamma W\,(0)}$

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

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

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

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)

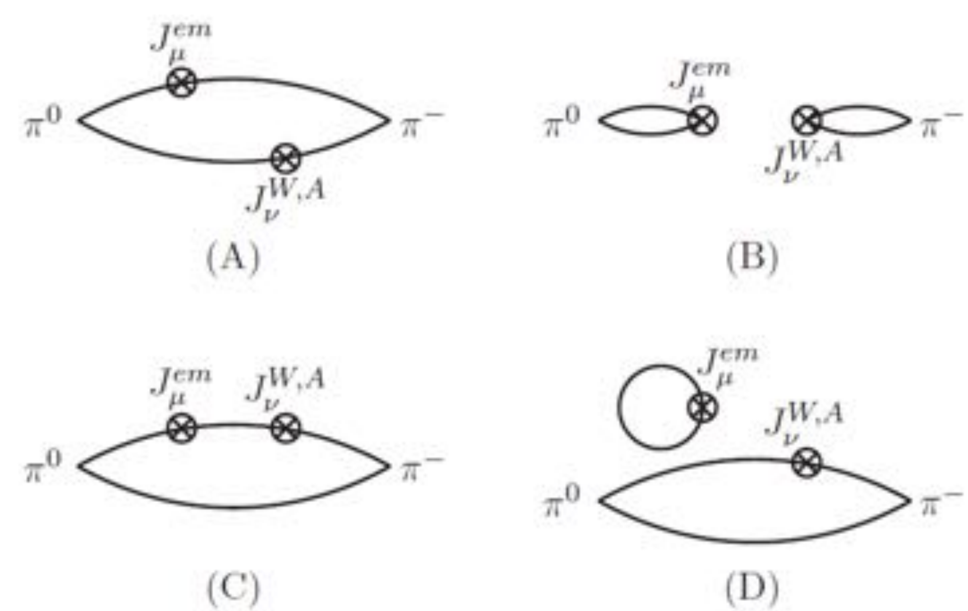
$$\mathcal{H}^{VA}_{\mu\nu}(t,\vec{x}) \equiv \langle H_f(P)|T\left[J^{em}_{\mu}(t,\vec{x})J^{W,A}_{\nu}(0)\right]|H_i(P)\rangle$$

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

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

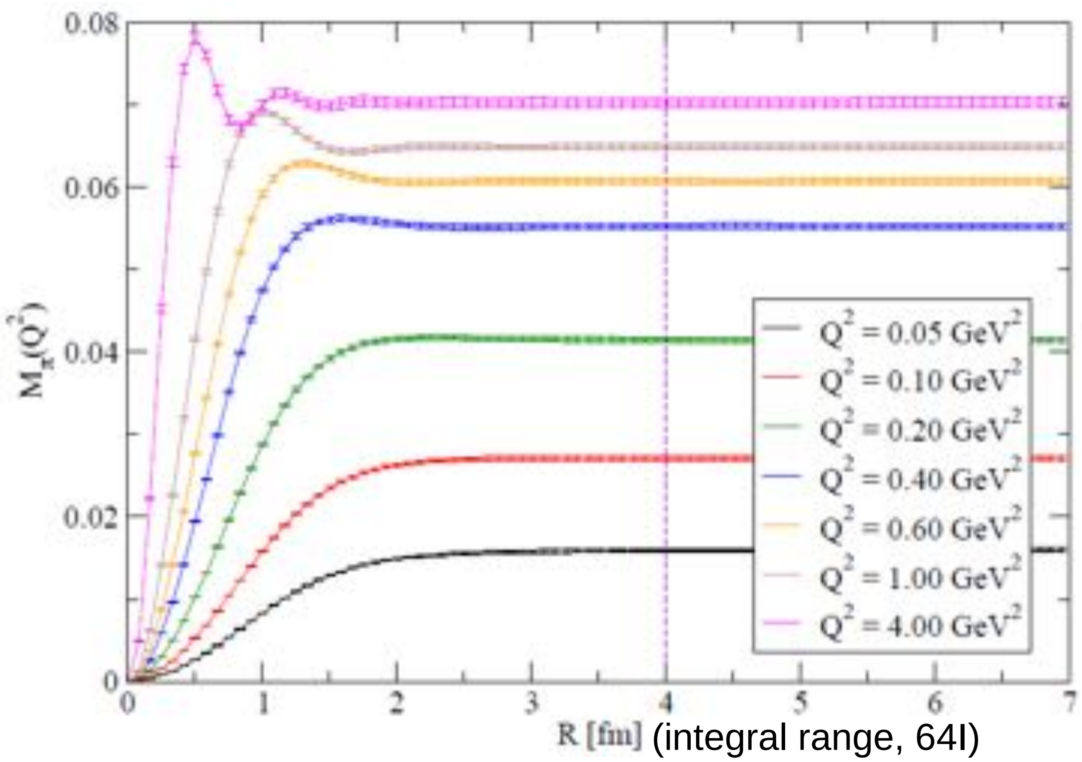
Ensemble	m_π [MeV]	L	T	a^{-1} [GeV]	N_{conf}	N_r	$\Delta t/a$
24D	141.2(4)	24	64	1.015	46	1024	8
32D	141.4(3)	32	64	1.015	32	2048	8
32D-fine	143.0(3)	32	64	1.378	71	1024	10
48I	135.5(4)	48	96	1.730	28	1024	12
64I	135.3(2)	64	128	2.359	62	1024	18

Blue: DSDR
Red : Iwasaki

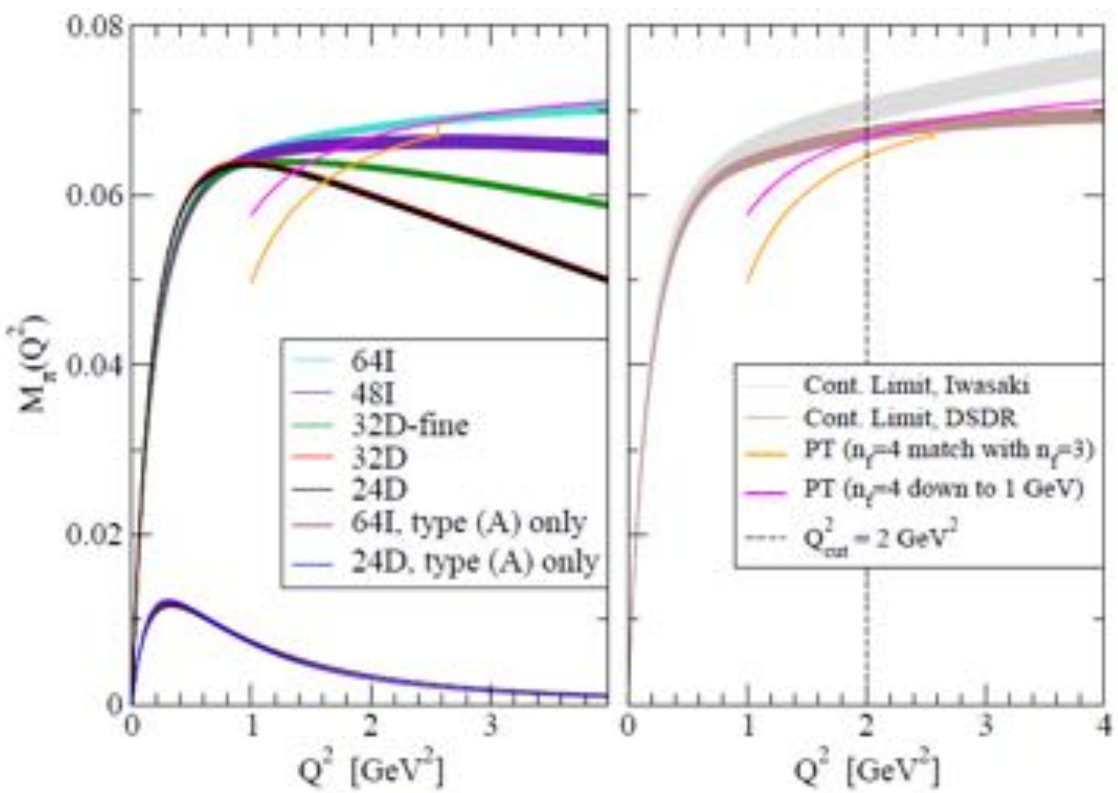


Quark contraction diagrams

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

Uncertainty of RC to $\pi e3$: 1 o.o.m. reduction $\delta: \quad 0.0334(10)_{\rm LEC}(3)_{\rm HO} \to 0.0332(1)_{\gamma W}(3)_{\rm HO}$

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

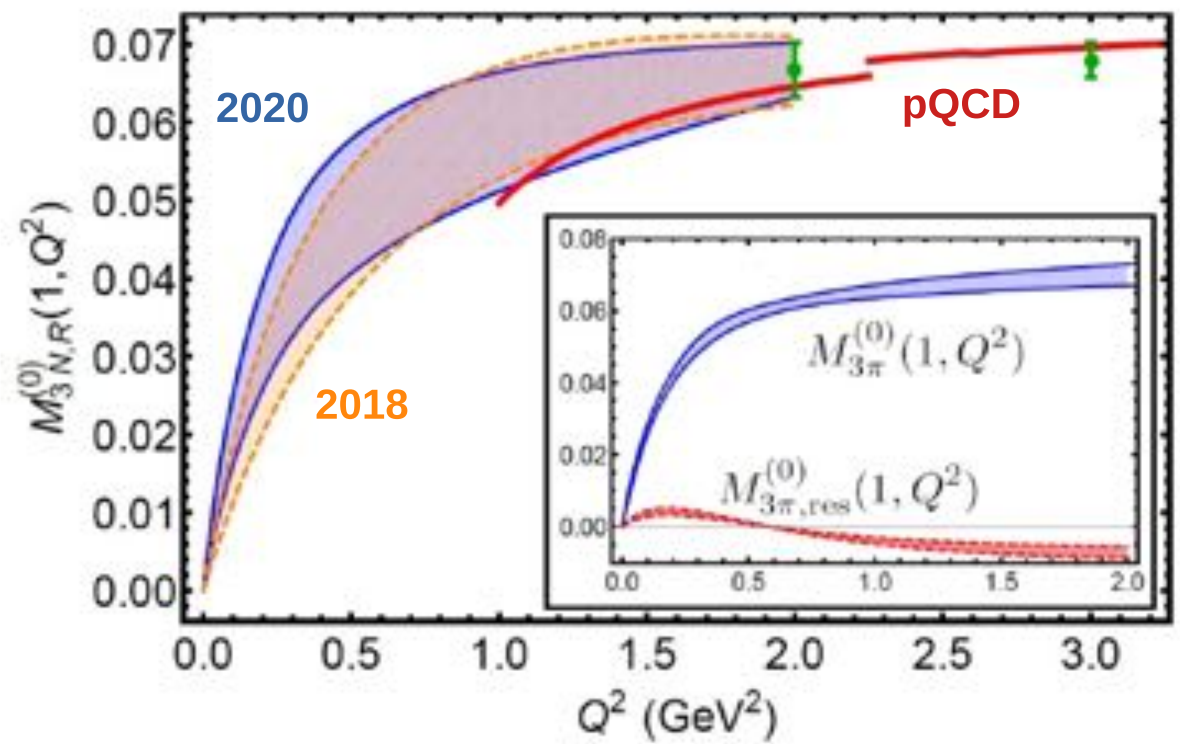
Next-gen experiments: aim at 1 o.o.m. exp. uncertainty improvement

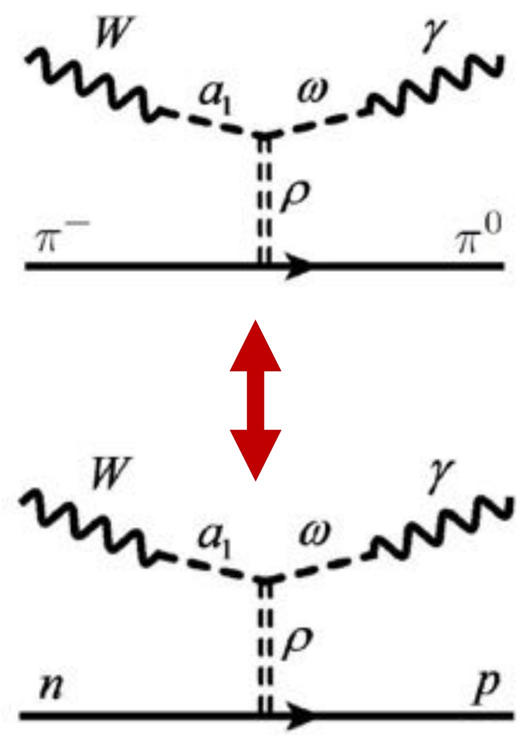
Implications for the free nucleon γW-box

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

$$\Box^{(0)}_{\gamma W} = 0.00379(10)_{\mathrm{DR}} \to 0.00384(11)_{\mathrm{LQCD+DR}}$$

V_{ud} extraction and CKM unitarity

Combine γW-box with other universal RC $\quad \Delta_R^V = \frac{\alpha}{2\pi}\left[3\ln\frac{M_Z}{M} + \ln\frac{M_Z}{M_W}\right] + 2\Box_{\gamma W}^V$

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

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

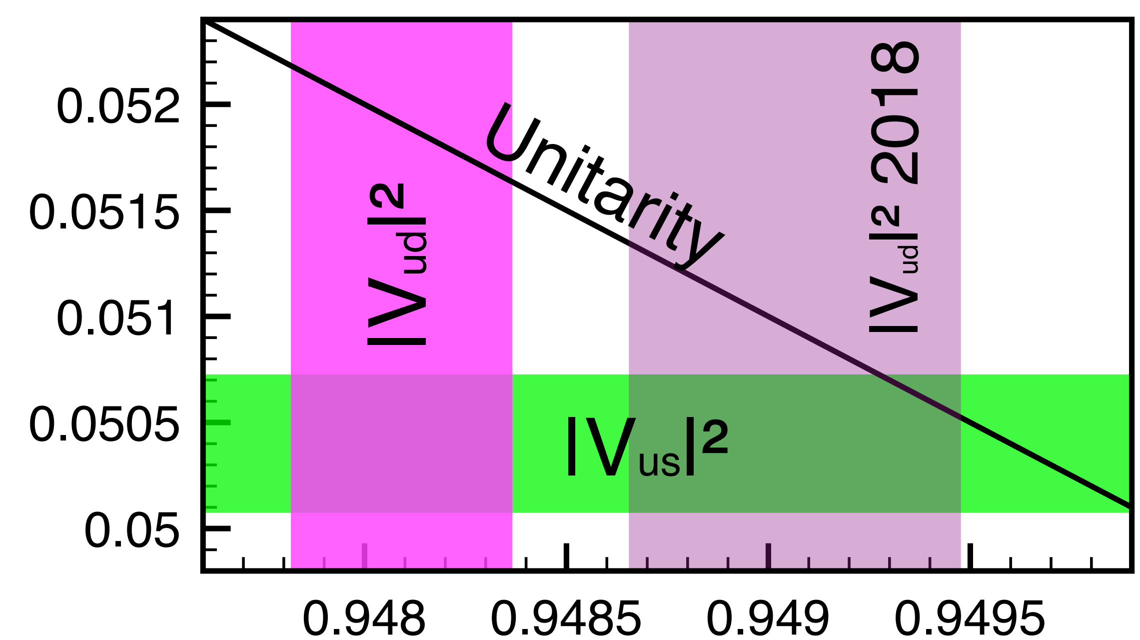
In July 2019 Czarnecki, Marciano and Sirlin published an update ***1907.06737***

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

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)

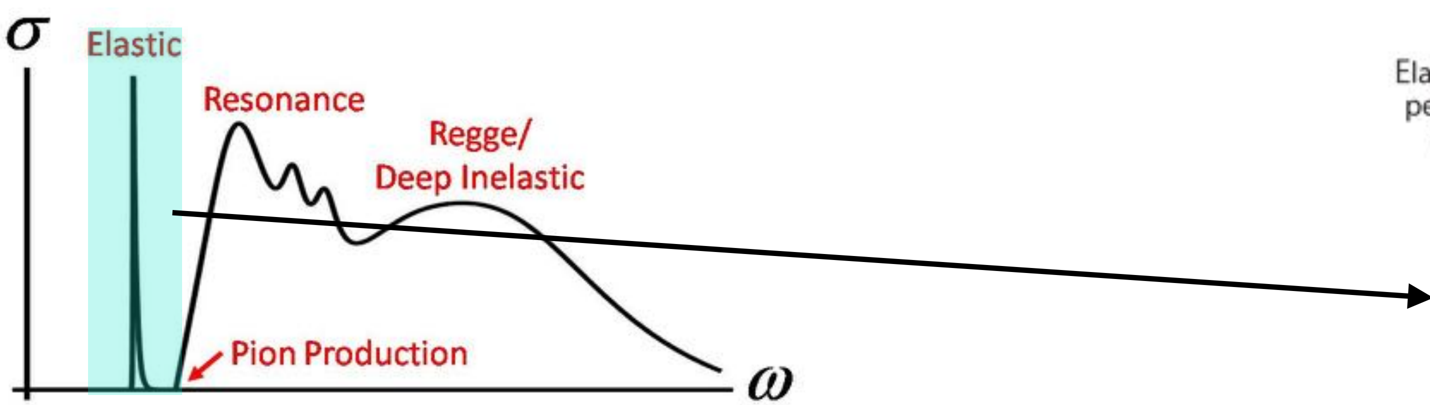


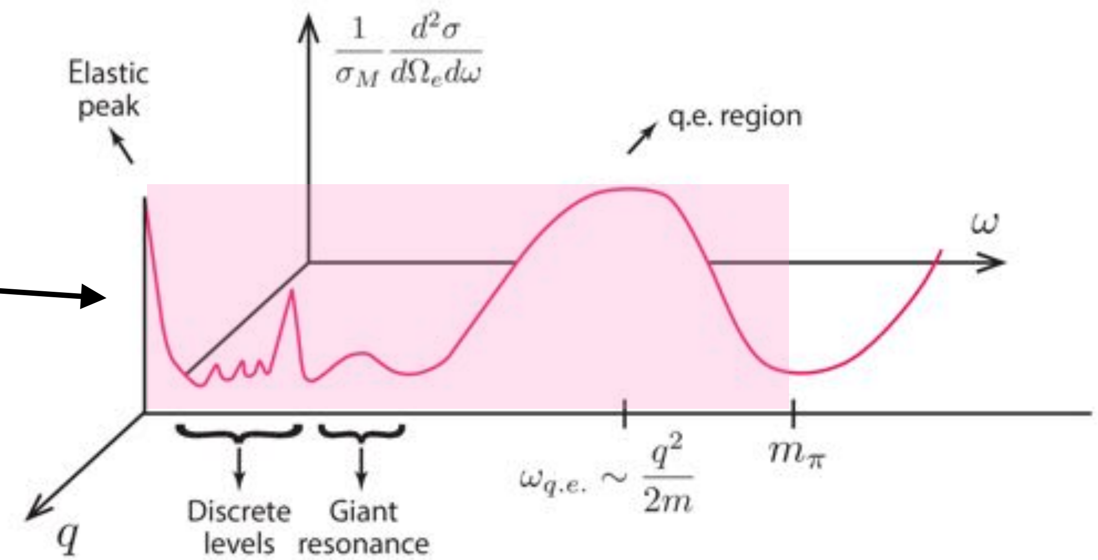
γW box on nuclei

Nuclear Corrections to V_{ud} and Weak Charges

Nuclear effects modify the free-nucleon structure functions: $F^A_{1,2,3} \neq \sum_{N\in A} F^N_{1,2,3}$

Low-energy part of the spectrum is qualitatively modified in nuclei

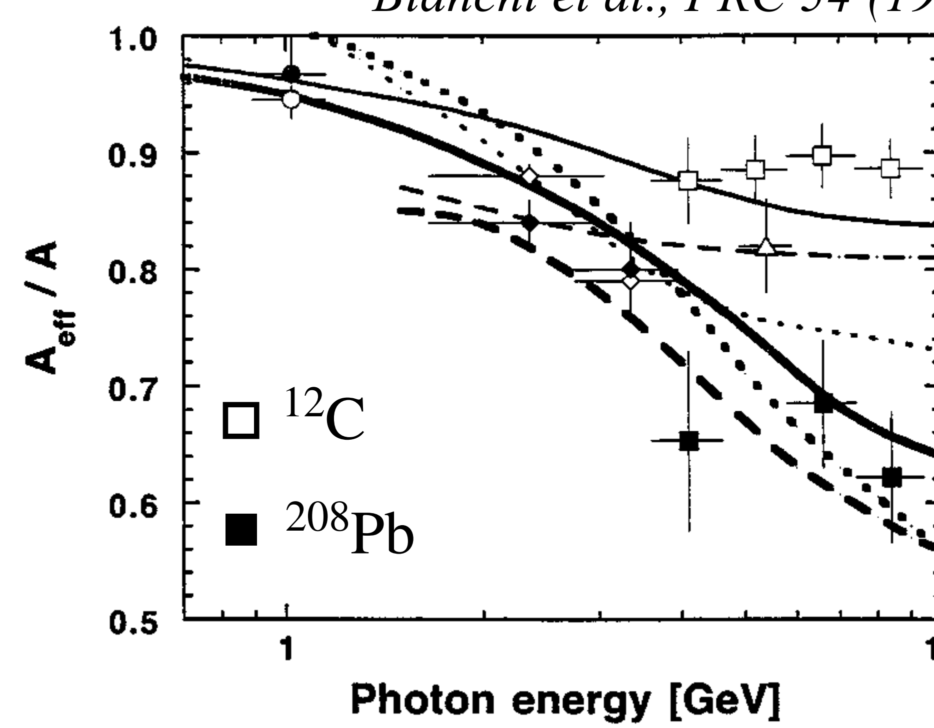




High-energy part of the spectrum: shadowing
Extensively studied in HE real photoabsorption

$$A_{eff}/A = \frac{\sigma_{\gamma A}}{Z\langle\sigma_{\gamma p}\rangle + N\langle\sigma_{\gamma n}\rangle}$$

Bianchi et al., PRC 54 (1996)



Medium Q^2 also modified (e.g. EMC effect)

At asymptotic Q^2: expect to recover OPE

Nuclear Corrections to V_{ud} and Weak Charges

General structure of RC in 0+-0+ nuclear decays: $|V_{ud}|^2 = \dfrac{2984.43s}{\mathcal{F}t(1+\Delta_R^V)}$

Universal (free-nucleon) RC $$\Delta_R^V = \frac{\alpha}{2\pi}\left[3\ln\frac{M_Z}{M} + \ln\frac{M_Z}{M_W}\right] + 2\Box_{\gamma W}^V$$

Decay-specific ft (phase-space, rate, BR) —> absorb decay-specific RC —> universal Ft

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

Exp

QED beyond Coulomb

Isospin breaking

NS correction reflects the extraction of the free-n box $\delta_{\mathrm{NS}} = 2\Box_{\gamma W}^{\mathrm{Nucl}} - 2\,\Box_{\gamma W}^{\mathrm{free\ n}}$

This representation of δ_{NS} is new: can be computed in the same formalism as Δ_R^V
Previously: Δ_R^V by loop methods, δ_{NS} in shell model — matching?

Nuclear Structure Modification

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

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

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

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

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

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% $\qquad \mathscr{F}t = (3072 \pm 2)s$

As of now only exploratory QE calculation in free Fermi model exists!

Nuclear Structure Corrections - Future plans

Low-energy nuclear effects need to be checked in modern nuclear theory

Collaborations started for $\delta_{\rm NS}$ in $^{10}{\rm C} \to {}^{10}{\rm B}$ decay:
Navratil & Gennari (No-Core Shell Model)
Pastore & King (Green's Function Monte Carlo)

Expect results soon

High-energy nuclear effects (shadowing etc) — no calculations exist

How to match shadowing of real photons with the restoration of OPE at high Q^2 ?

How important is the effect on V_{ud}, given the 10^{-4} precision?

How important for nuclear weak charges & radii — less so, only 10^{-3} precision feasible

Work in progress

Conclusions & Outlook

- 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 $F_{1,2,3}^{\gamma Z}$ (JLab, EIC)
- New more precise data on EW structure functions $F_{1,2,3}^{WW}$ (DUNE)
- A new program on $\delta_{\rm NS}$ from ab-initio methods started — keep tuned!
- Application to PVES on nuclei