Precision tests of SM at low energy: Hadronic structure corrections

Misha Gorshteyn - Universität Mainz

56th International Winter Meeting on Nuclear Physics - Bormio - Italia

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL
FROM QUARKS AND GLUONS TO HADRONS AND NUCLEI

PRISMA

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Work being done together with

Chuck Horowitz
Michael Ramsey-Musolf
Hubert Spiesberger
Xilin Zhang
Chien-Yeah Seng
Hiren Patel

Precision tests of SM at low energies - basis

- Goal: measure parameters of the Standard Model to high precision
  Confront with precision calculations in SM
  Constrain/discover New Physics via deviations

- SM parameters: charges, masses, mixing

- At low energy quarks are bound in hadrons - how can we access their fundamental properties through hadronic mess?

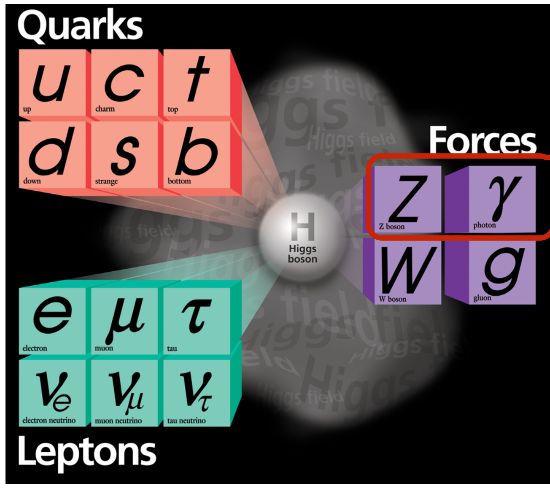
- A charge associated with a conserved current is not renormalized by strong interaction - the charge of a composite = ∑ charges of constituents

- 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

- In many low-energy tests hadron structure effects is the main limitation!

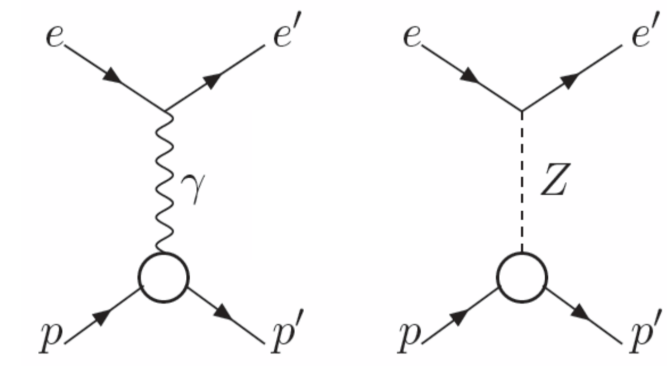
Precision measurements of weak mixing angle



Weak mixing angle - mixing of the NC gauge fields

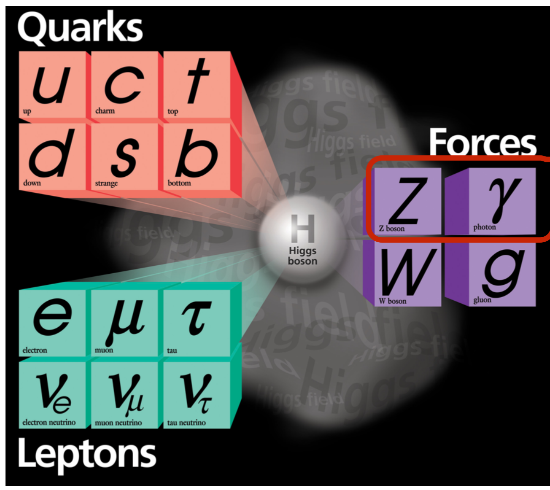
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

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



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

Precision measurements of weak mixing angle



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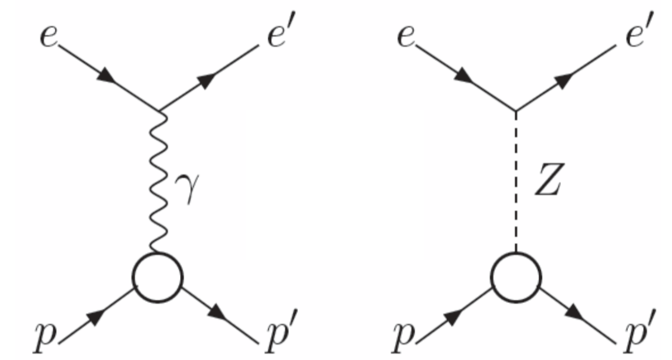

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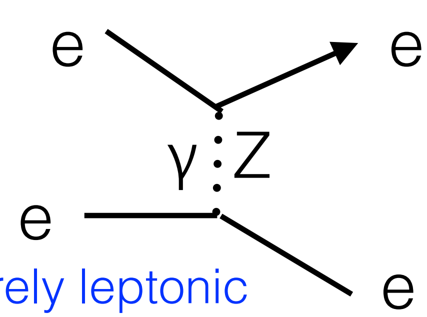
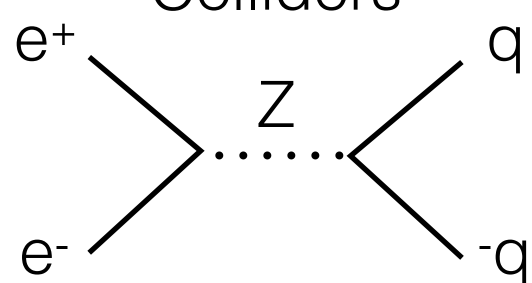
Møller scattering



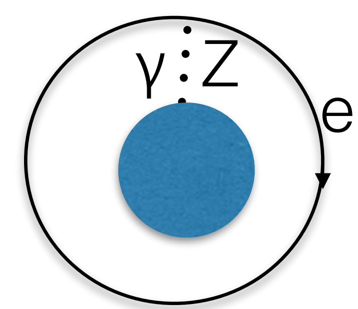
Purely leptonic

Colliders



Z-pole measurement

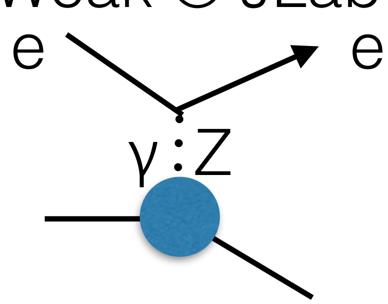
Atomic PV



Coherent quarks in a nucleus

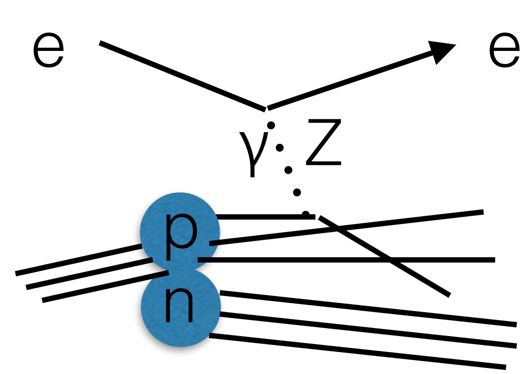
P2 MESA @ Mainz

Q-Weak @ JLab



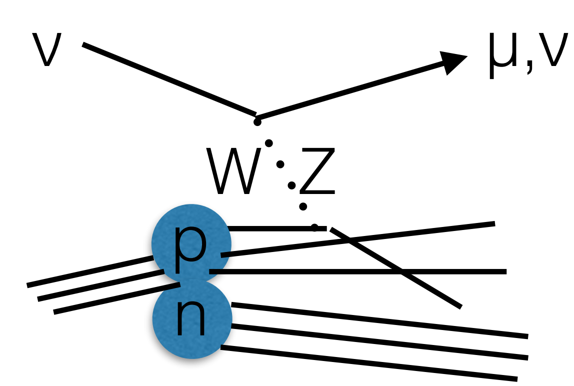
Coherent quarks in p

e-DIS @ JLab, EIC



Incoherent e-q scattering

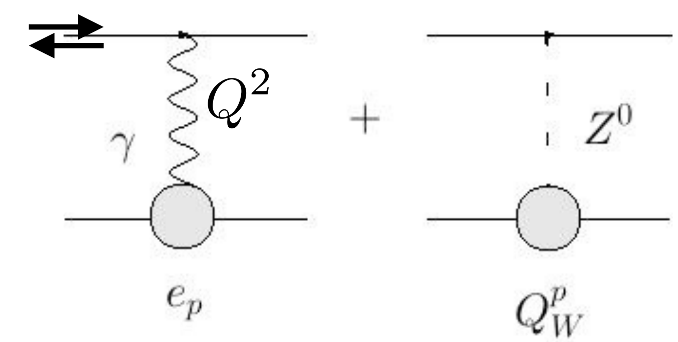
ν-DIS @ NuTEV



Incoherent ν-q scattering

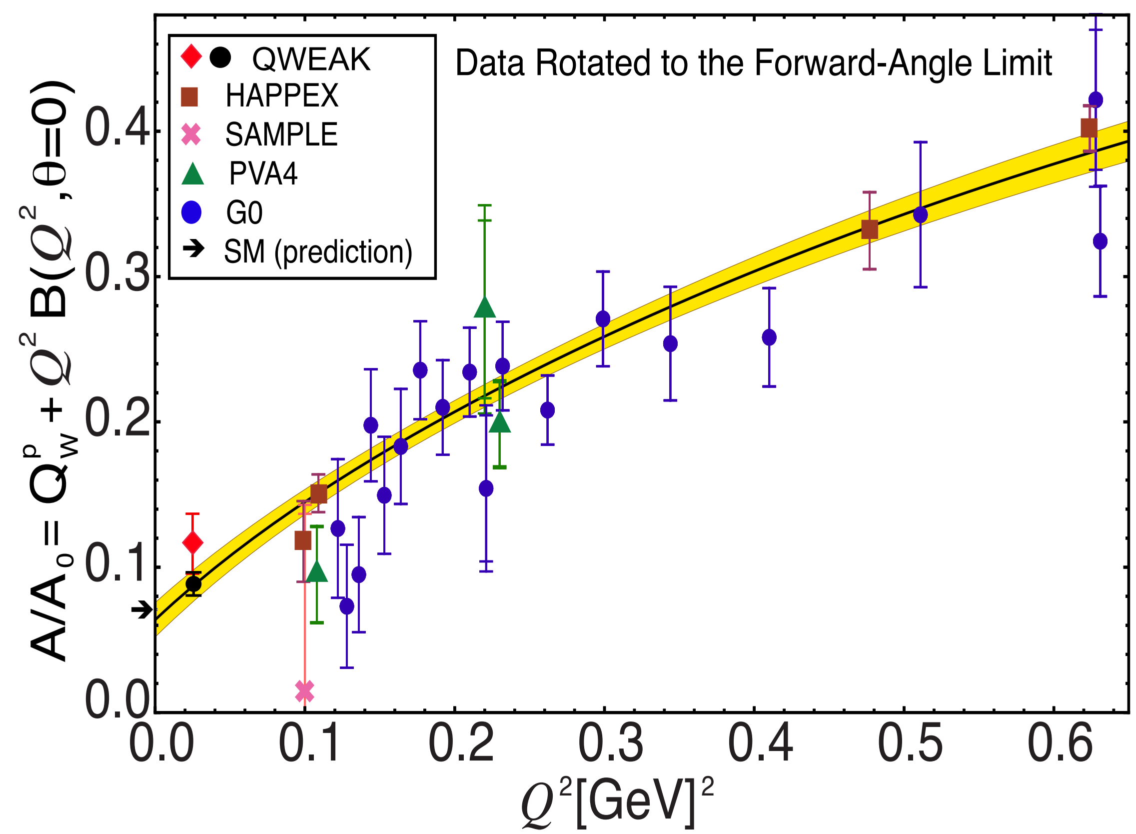
Weak charge of the proton from PVES

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
Existing hadronic data used to obtain B and δB

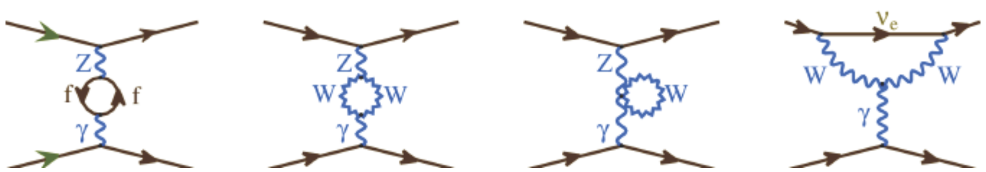


Go down to $Q^2 \leq 0.03$ GeV^2
Unprecedented challenge: tiny asymmetry to 1-2 %

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

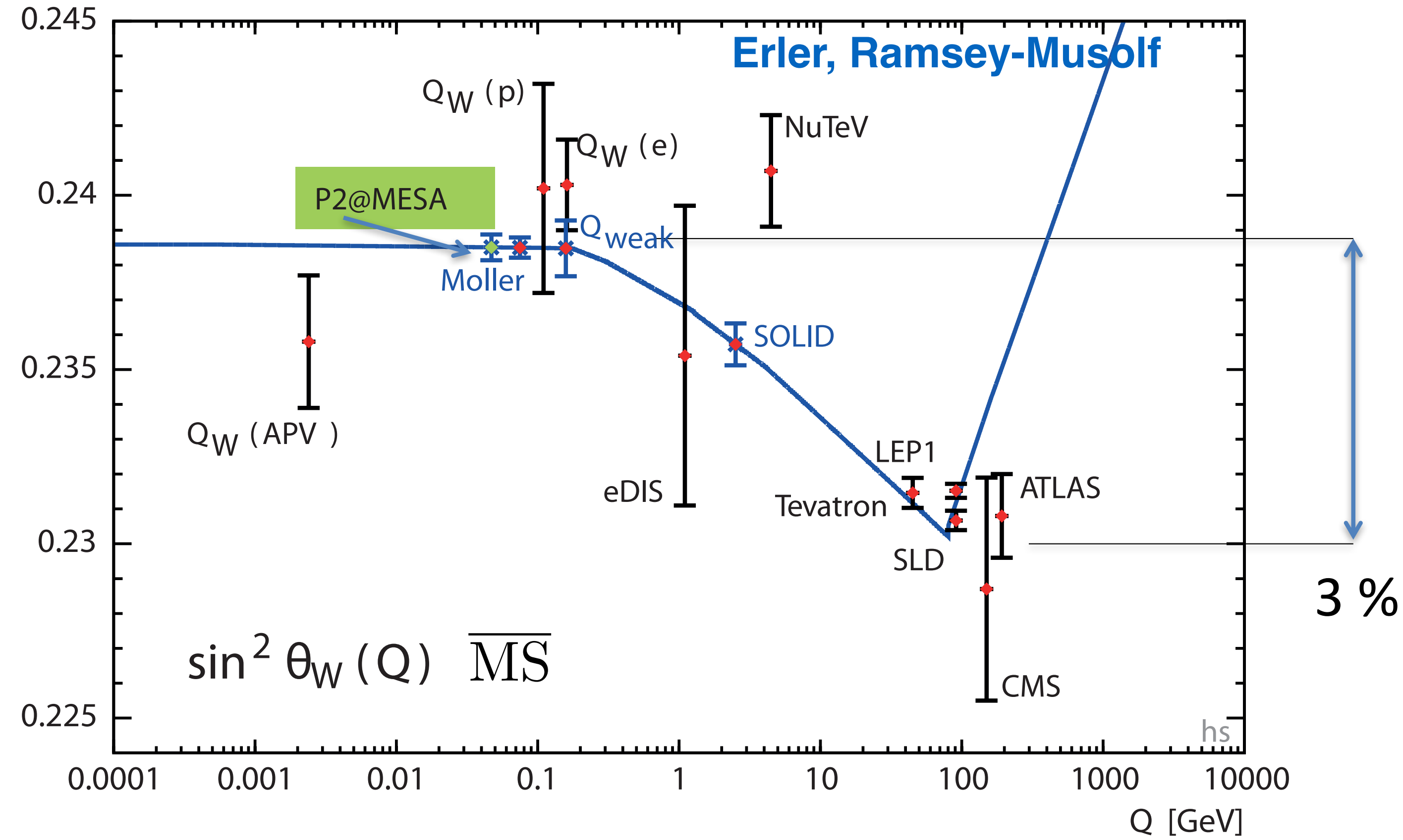
$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W}\frac{\delta Q_W^p}{Q_W^p}$$

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}



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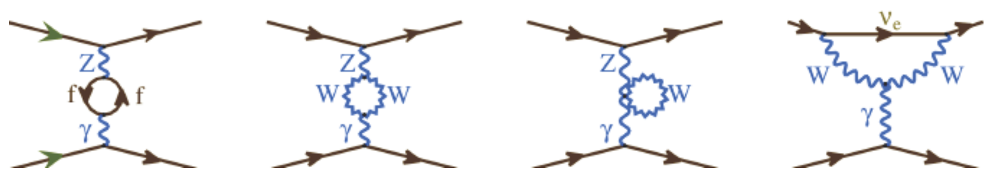

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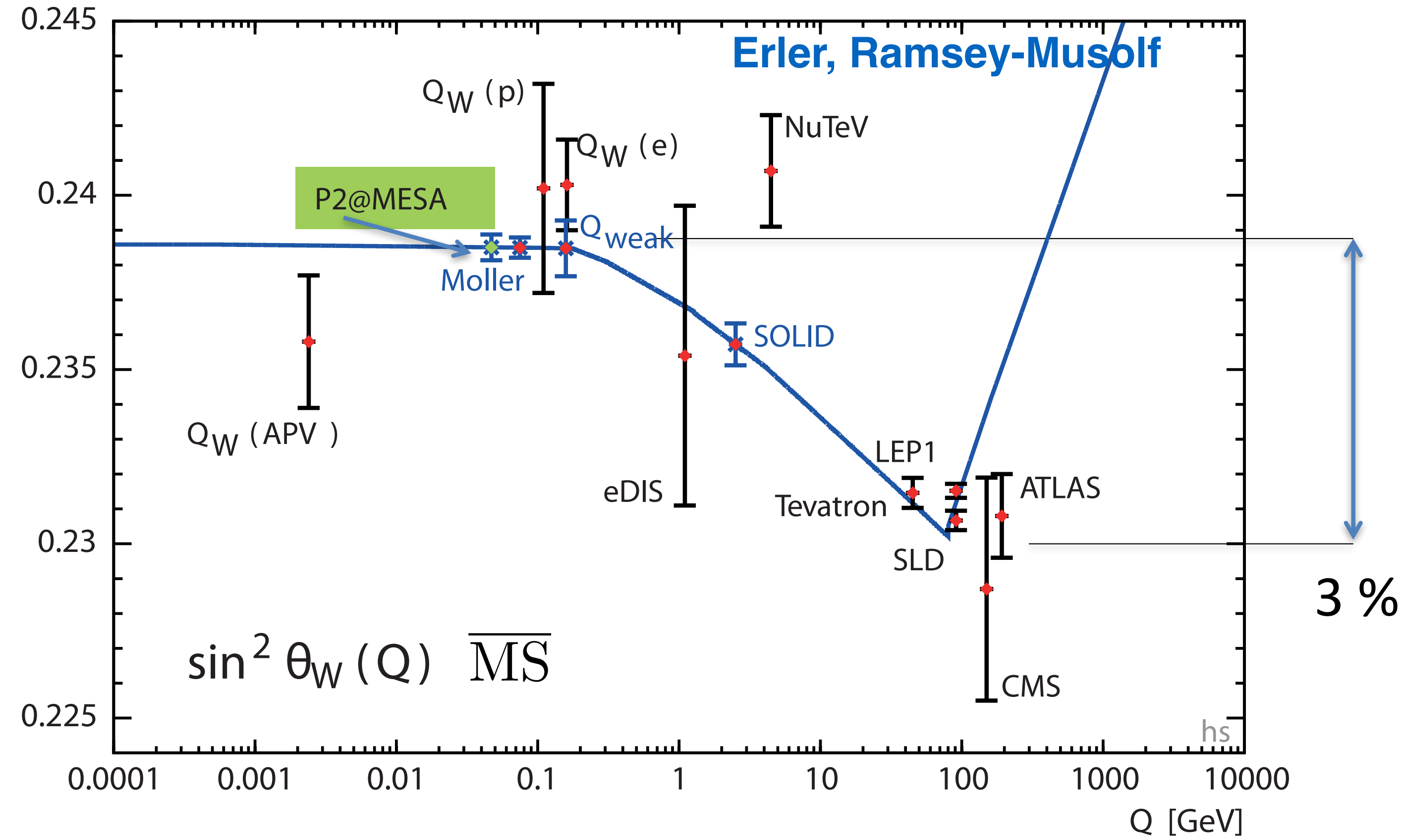
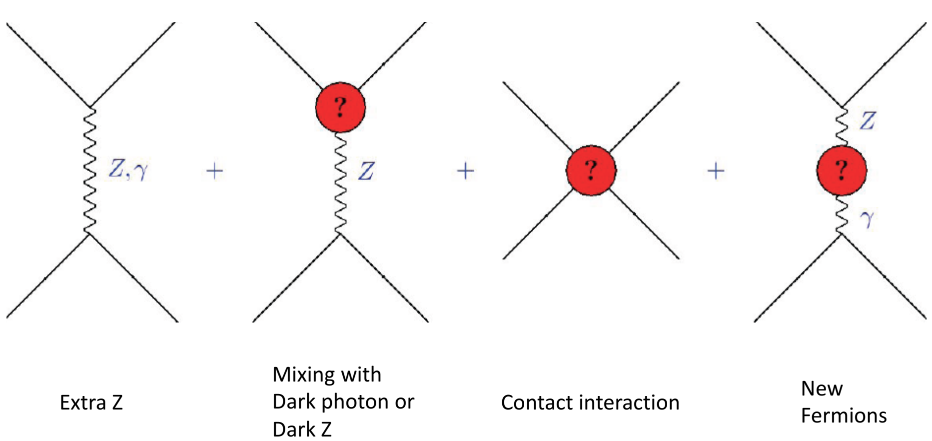
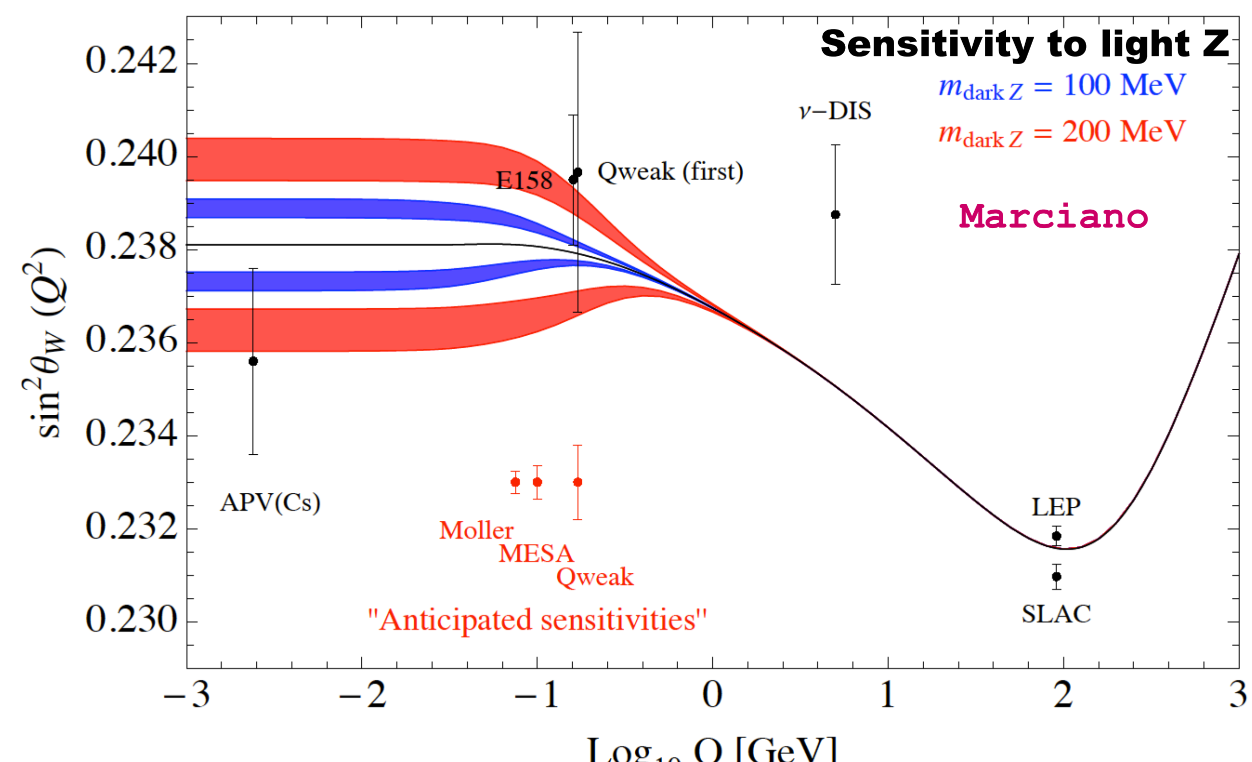


Universal running - clean prediction of SM
Deviation anywhere - BSM signal





Heavy BSM reach: up to 49 TeV
Sensitivity to light dark gauge sector
Complementary to colliders

Electroweak boxes: non-universal corrections

Hadronic effects under control

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

Marciano, Sirlin '83,84; Erler, Musolf '05

Non-universal correction - depends on kinematics and hadronic structure

Marciano and Sirlin:
γZ-box mainly universal (large log)
same for PV in atoms and e-scattering
Residual dependence on hadronic scale Λ

$$\Box_{\gamma Z} = \frac{5\hat{\alpha}}{2\pi}(1-4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

0.0037±0.0004 (5.3 ± 0.6%)

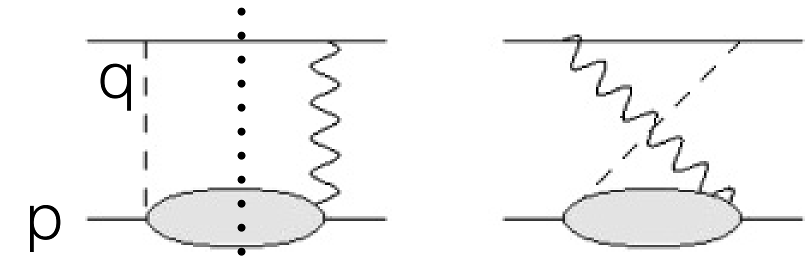
Until recently: 1-loop SM result $Q^p_W = 0.0713 \pm 0.0008$

This formulation was used to plan Qweak @ JLab

1.165 GeV beam; Q^2=0.03 GeV^2
Combined Theo+Exp. uncertainty - 4%
$\Delta\sin^2\theta_W/\sin^2\theta_W = 0.3\%$

Electroweak boxes: non-universal corrections

γZ-box from forward dispersion relation



Compute the imaginary part first
Real part from unitarity + analyticity + symmetries

MG, Horowitz '09; MG, Horowitz, Ramsey-Musolf '11

Lower blob: γZ-interference structure functions

$$\mathrm{Im}W^{\mu\nu} = -\hat{g}^{\mu\nu}F_1^{\gamma Z} + \frac{\hat{p}^\mu \hat{p}^\nu}{(p\cdot q)}F_2^{\gamma Z} + \frac{i\epsilon^{\mu\nu\alpha\beta}p_\alpha q_\beta}{2(p\cdot q)}F_3^{\gamma Z}$$

Sum rule for the γZ-box correction

Known kinematical functions

$$\Box_{\gamma Z}(E) = \frac{\alpha}{\pi}\int_0^\infty dQ^2 \int_{thr}^\infty dW^2 \left[A(E,W,Q^2)F_1^{\gamma Z} + B(E,W,Q^2)F_2^{\gamma Z} + C(E,W,Q^2)F_3^{\gamma Z}\right]$$

Inelastic PVES data

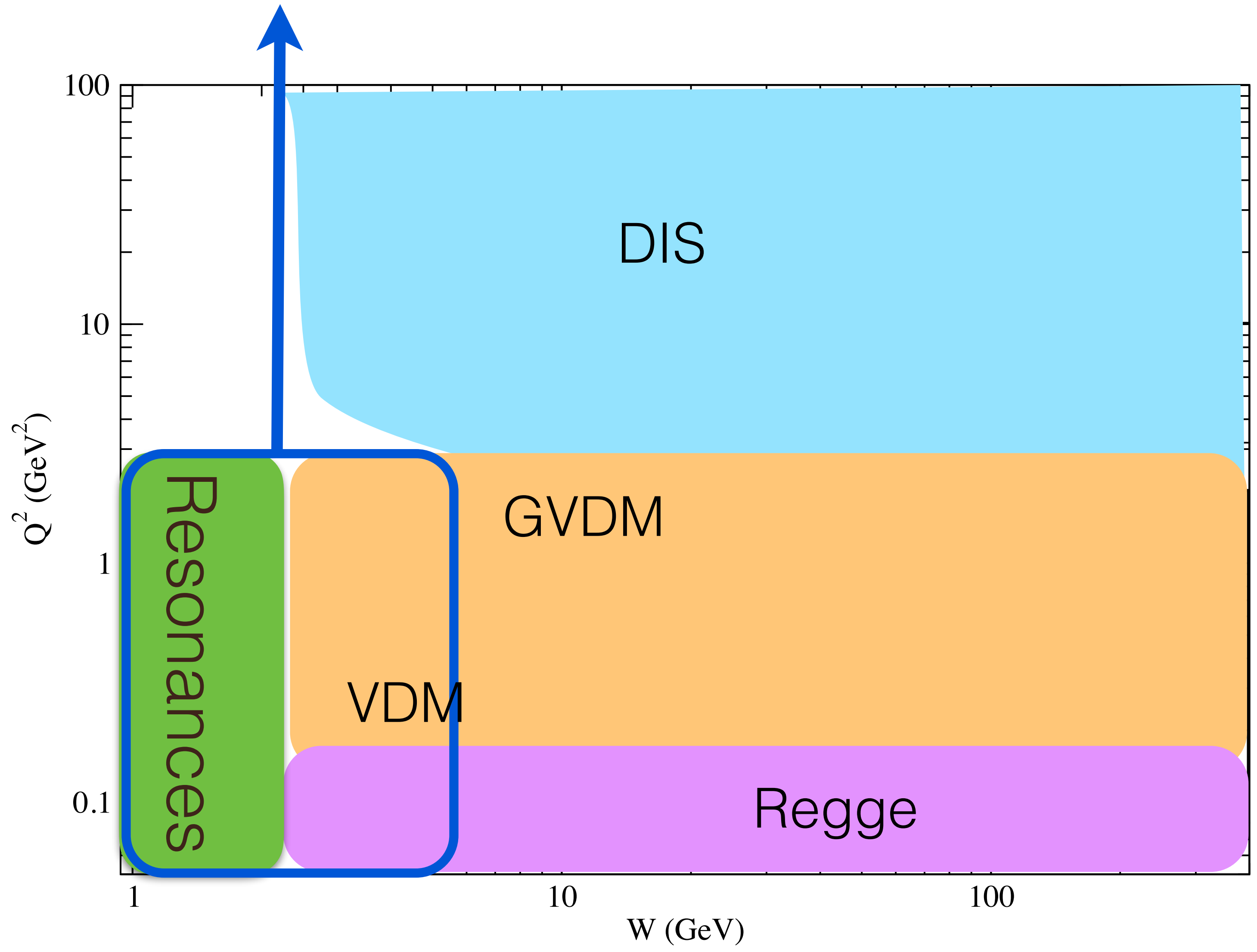
Model-independent (if data available); E-dependence calculable in each exp. kinematics

Input to the dispersion integral

No or very little inelastic PVES data available;
Use electromagnetic data + isospin symmetry
to obtain the input in the dispersion integral

All kinematics contribute; not all contribute equally.
Main support in the “shadow region” -

Main contribution: $W < 5$ GeV, $Q^2 < 2$ GeV^2

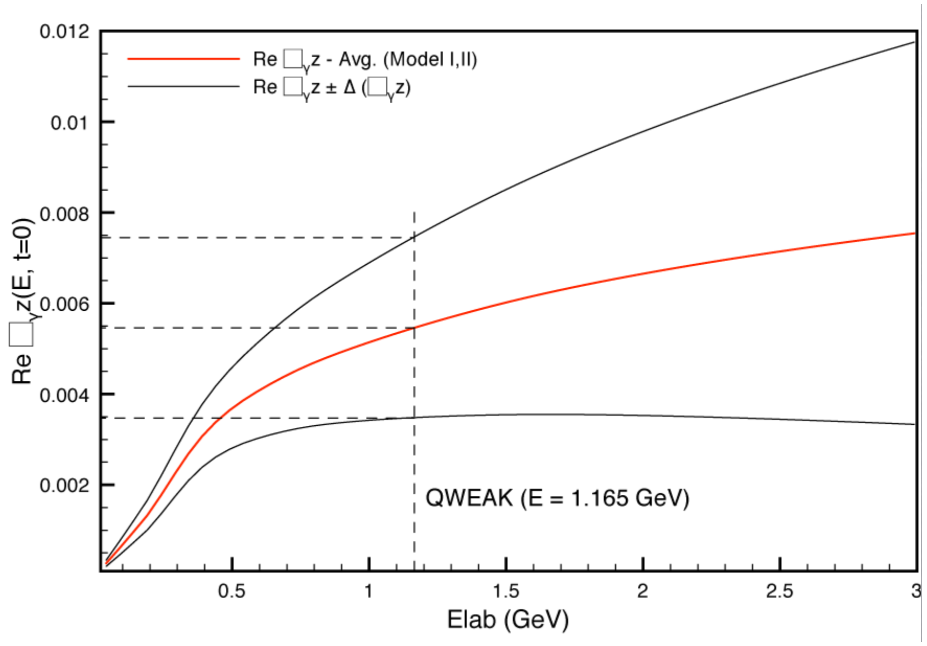


Energy-dependent γZ-box

Reference value: 1-loop SM $Q_W^p(SM) = 0.0713 \pm 0.0008$

7.6% of Q_W^p correction in Q-Weak kinematics
- missed in the original analysis

$\Box_{\gamma Z}(E = 1.165\,\mathrm{GeV}) = (5.4 \pm 2.0) \times 10^{-3}$



MG, Horowitz, PRL 102 (2009) 091806;
Nagata, Yang, Kao, PRC 79 (2009) 062501;
Tjon, Blunden, Melnitchouk, PRC 79 (2009) 055201;
Zhou, Nagata, Yang, Kao, PRC 81 (2010) 035208;
Sibirtsev, Blunden, Melnitchouk, PRD 82 (2010) 013011;
Rislow, Carlson, PRD 83 (2011) 113007;
MG, Horowitz, Ramsey-Musolf, PRC 84 (2011) 015502;
Blunden, Melnitchouk, Thomas, PRL 107 (2011) 081801;
Rislow, Carlson PRD 85 (2012) 073002;
Blunden, Melnitchouk, Thomas, PRL 109 (2012) 262301;
Hall et al., PRD 88 (2013) 013011;
Rislow, Carlson, PRD 88 (2013) 013018;
Hall et al., PLB 731 (2014) 287;
MG, Zhang, PLB 747 (2015) 305;
Hall et al., PLB 753 (2016) 221;
MG, Spiesberger, Zhang, PLB 752 (2016) 135;

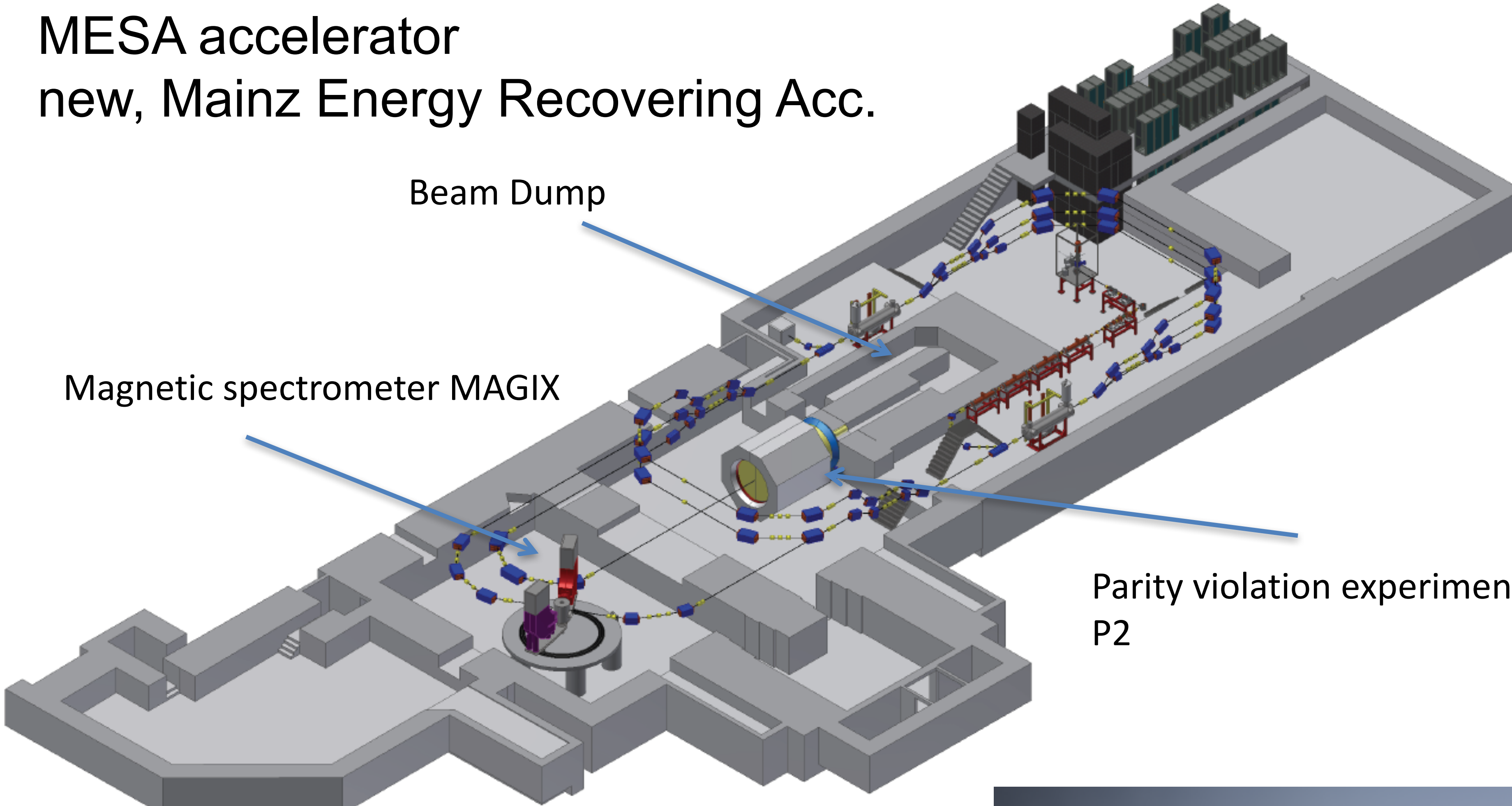
QWEAK collaboration recently finalized their result: $Q^p_W = 0.0716 \pm 0.0048$
The error mostly experimental (6% rather than planned 4%)

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

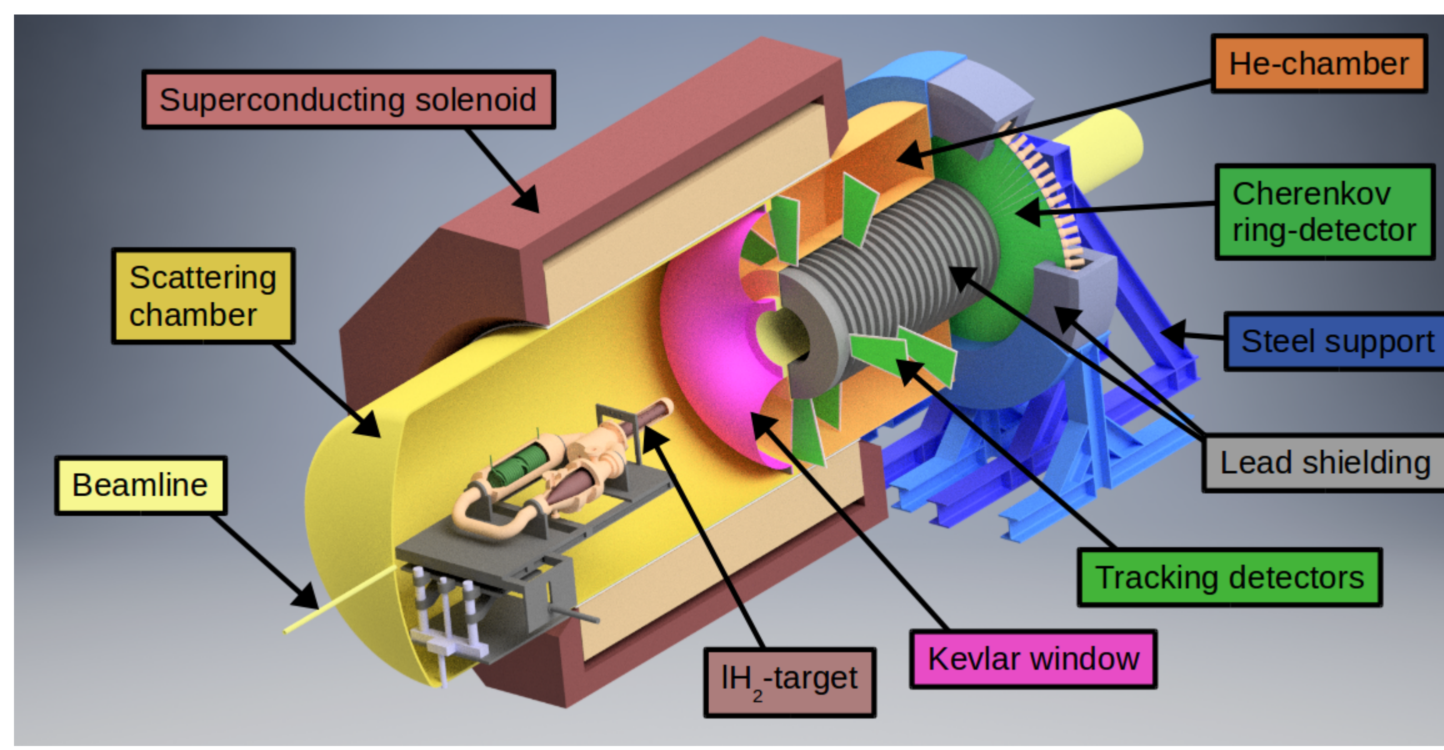
$\Box_{\gamma Z}(E = 0.155\,\mathrm{GeV}) = (1.1 \pm 0.3) \times 10^{-3}$

P2 experiment @ MESA

MESA accelerator
new, Mainz Energy Recovering Acc.



P2 detector



P2 experiment @ MESA

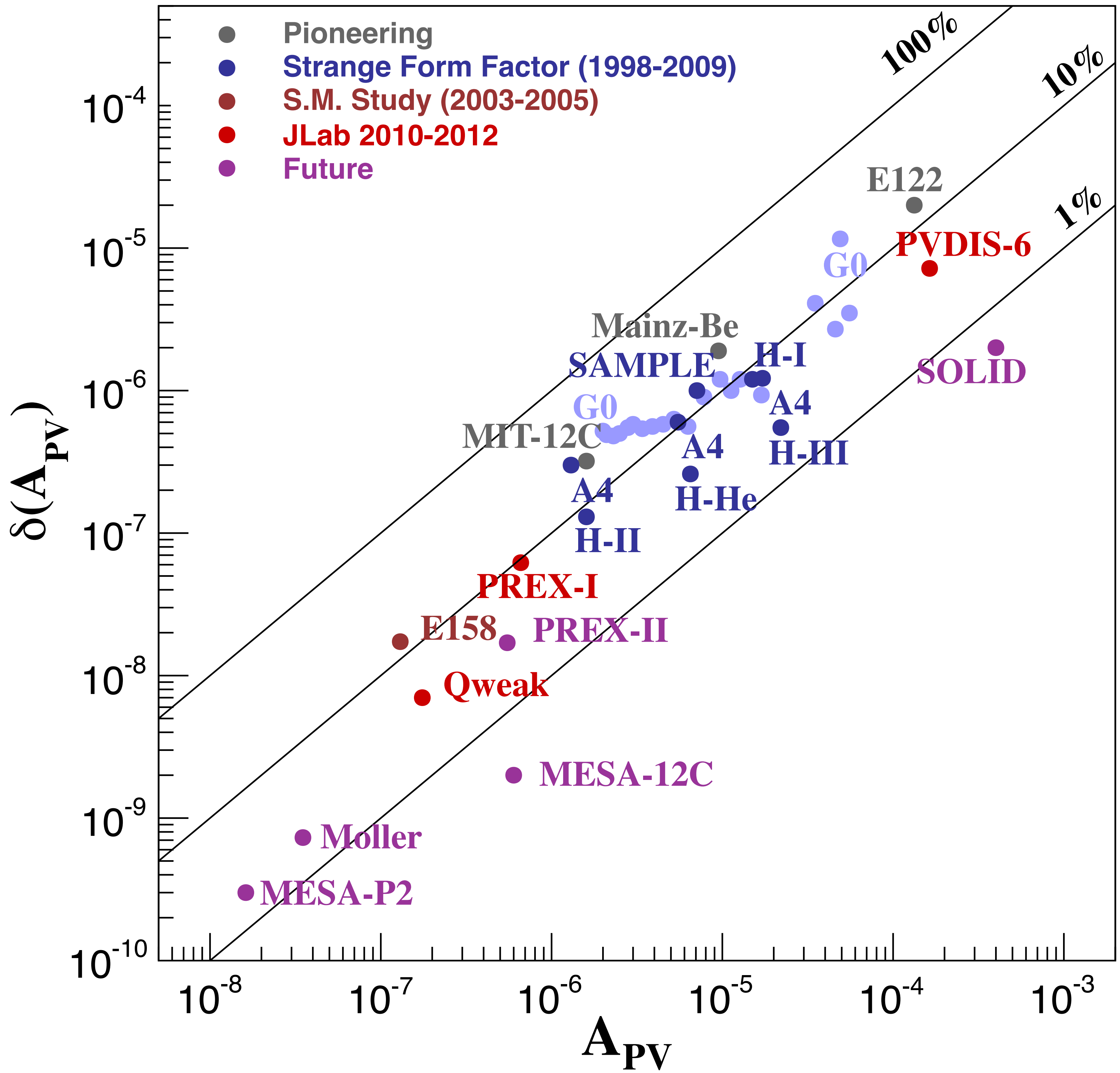
200 days of data;
150 μA beam
85% polarization

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

Additionally: A^{PV} measurement on C-12
Asymmetry ~ $4\sin^2\theta_W$ - no gain in precision but 15 times larger than p;
Cross sections 36 times larger than p;
2500h data - 0.3% on $\sin^2\theta_W$ possible!

Production: 2019-2020

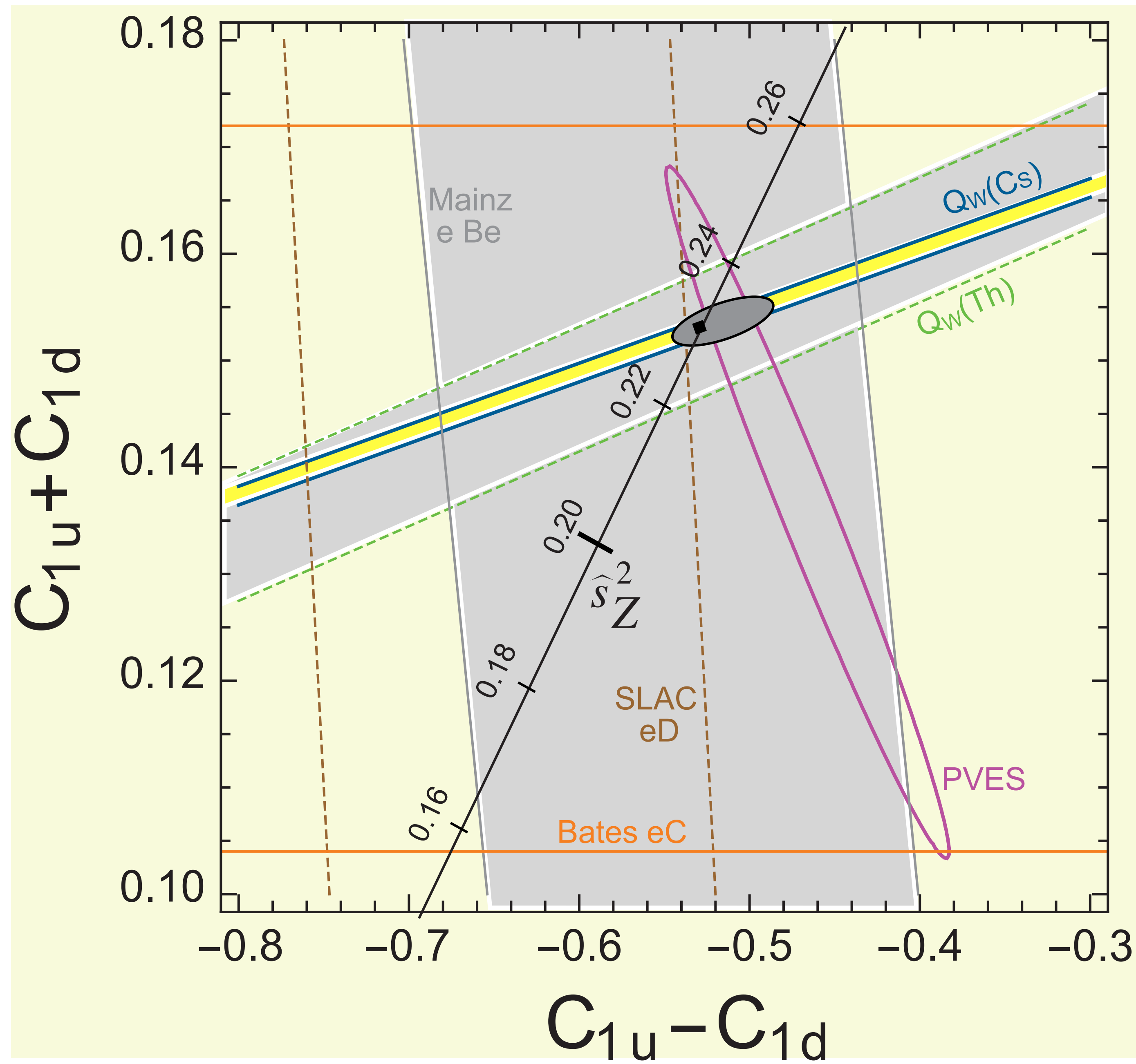
PVeS Experiment Summary



P2 @ MESA to test Standard Model

Impact of Qweak and MESA on effective e-q operators:

$$\mathcal{L} = -(G_F/\sqrt{2}) C_1^q \bar{e}\gamma_\mu\gamma_5 e \bar{q}\gamma^\mu q$$



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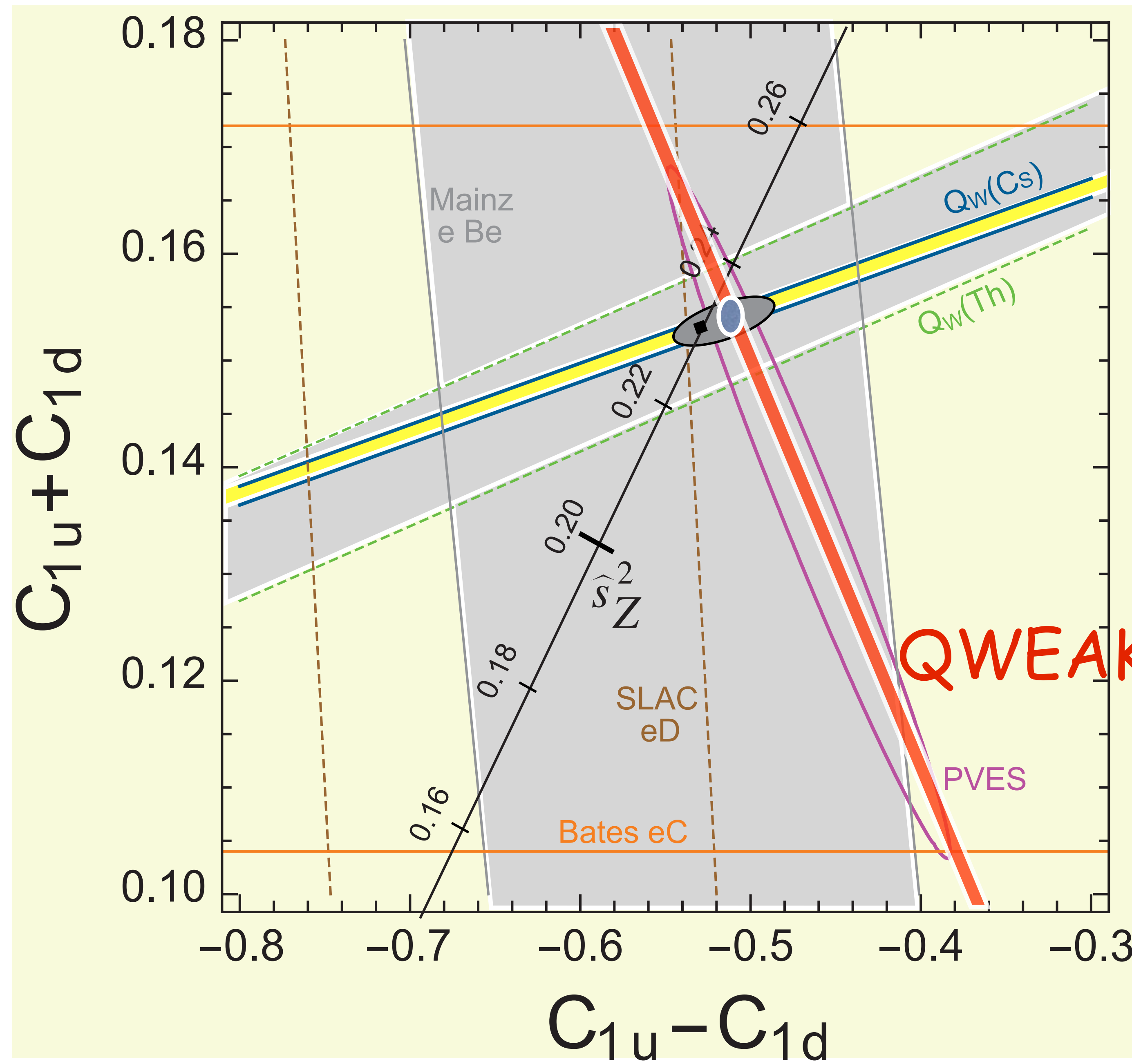

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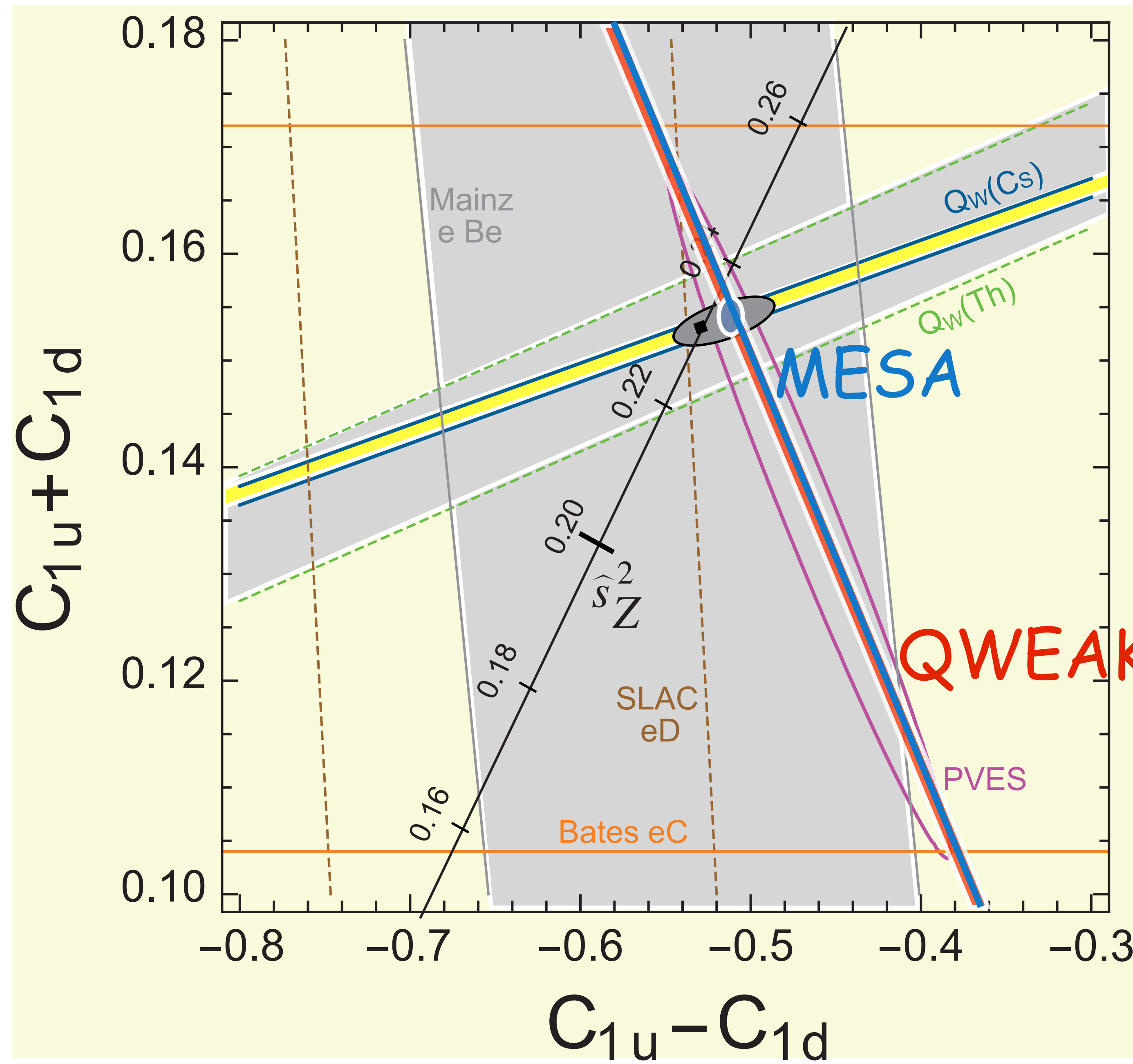

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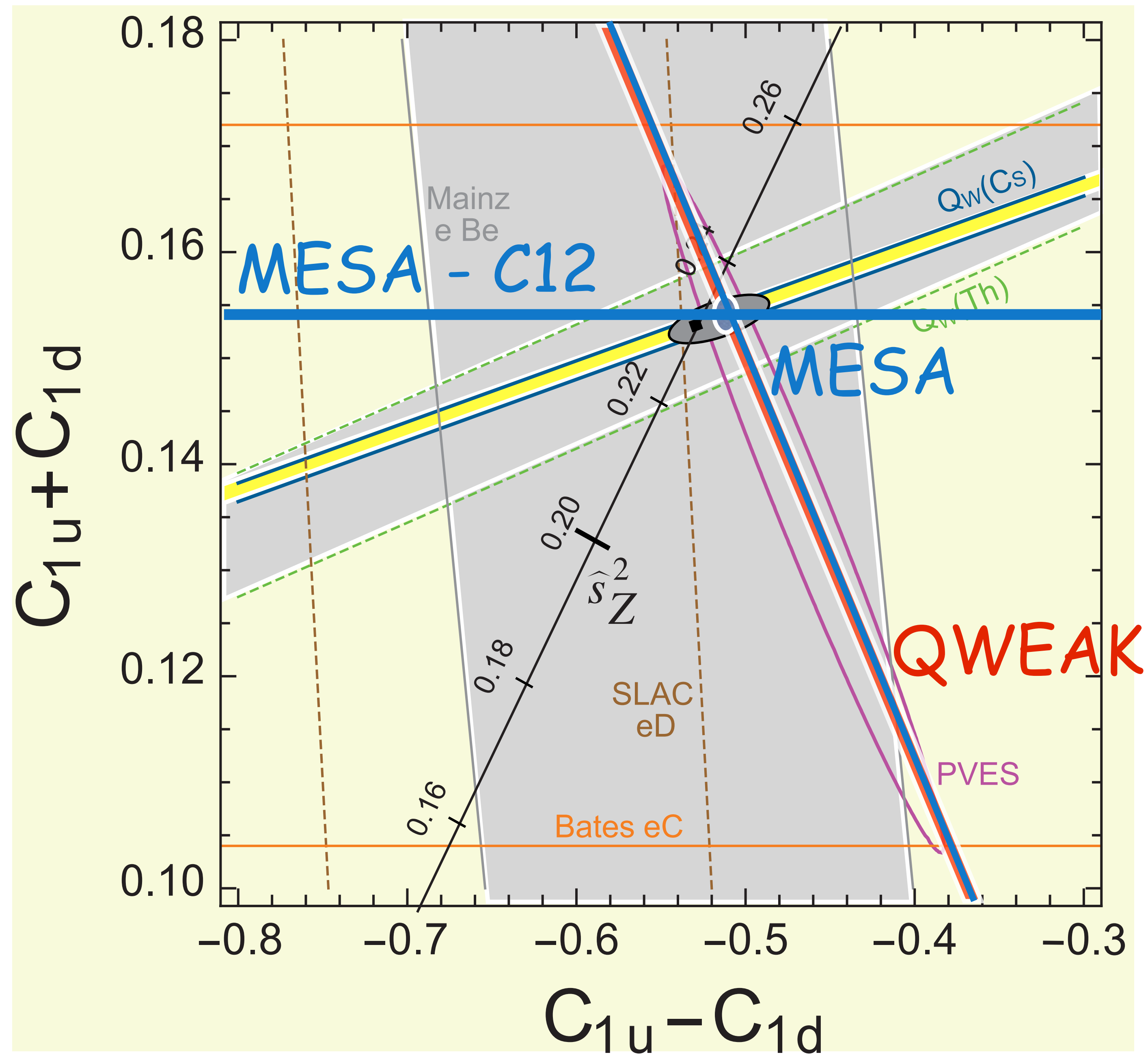
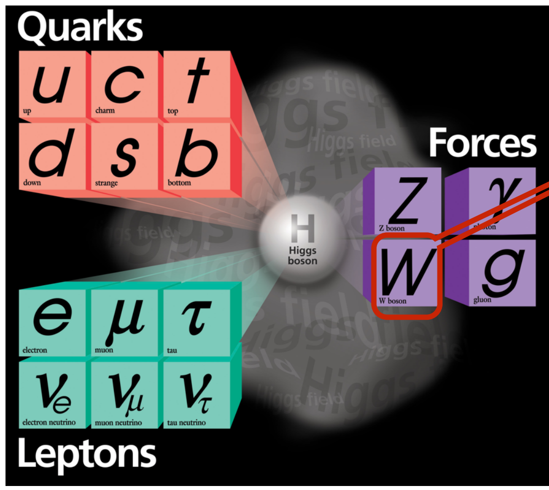
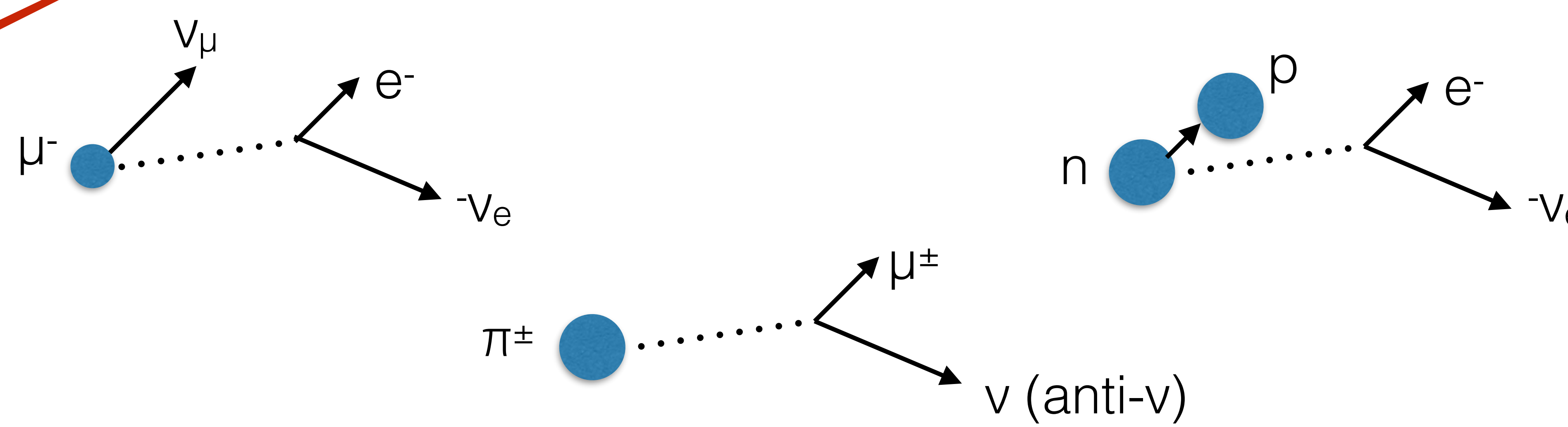
MESA - C12:
a 0.3% measurement of A^{PV}
= 0.3% meas. of $\sin^2\theta_W$
Access the isoscalar combination of C_1's



Precision measurements of V_{ud}



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



W coupling to leptons and hadrons very close but not exactly the same:
quark mixing - Cabbibo-Kabayashi-Maskawa matrix

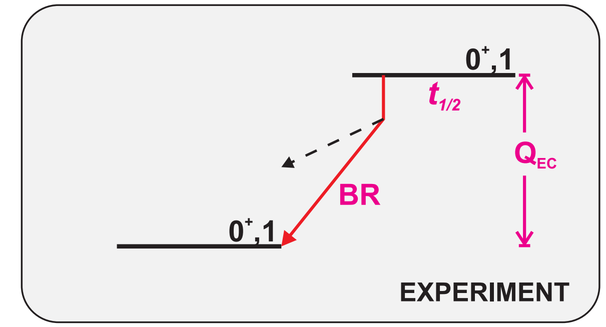
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boxed{V_{ud} \quad V_{us} \quad V_{ub}} \\ V_{cd} \quad V_{cs} \quad V_{cb} \\ V_{td} \quad V_{ts} \quad V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

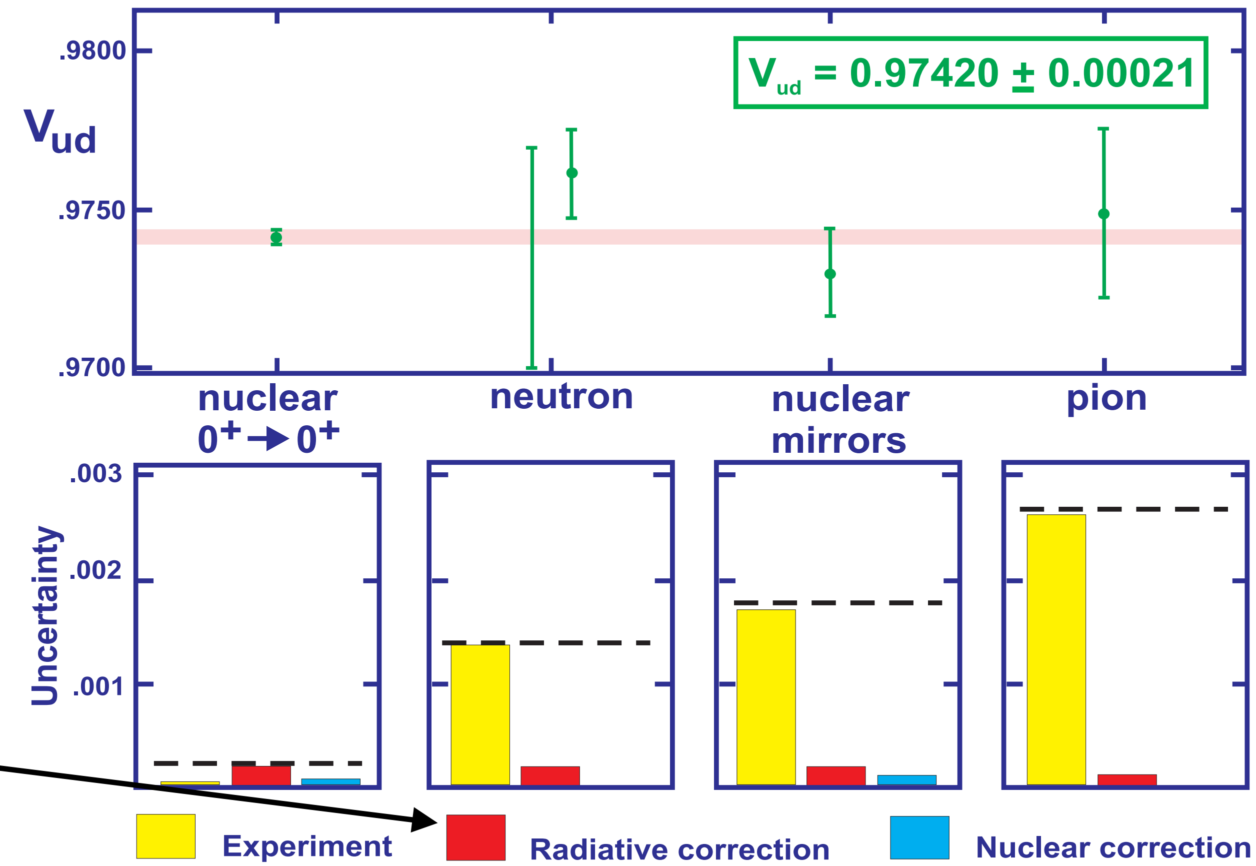
CKM - Determines the relative strength of the weak CC interaction of quarks vs. that of leptons

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

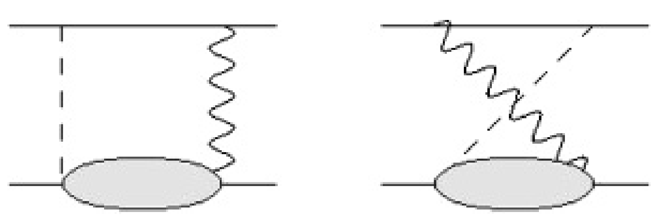
Current status of V_{ud} and CKM unitarity

Experiment measures Q-value, BR, half-life
Theory: universal and process-specific RC
Allows to jointly analyze many decays

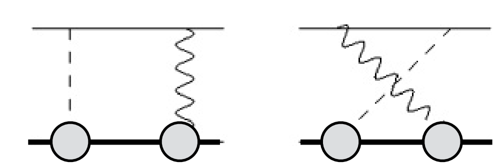




Marciano and Sirlin, ’87; ’06
γW-box on a free neutron



Large log from DIS - Add elastic box (FF) - Interpolate between



$$\Box_{\gamma W}(0) = \frac{\alpha}{\pi}\int_0^\infty dQ^2 \int_{thr}^\infty dW^2 C(W,Q^2) F_3^{\gamma W} \to \frac{\alpha}{2\pi}\left[\ln\frac{M_Z}{\Lambda} + 2C_B\right]$$ $\sim (7 \pm 0.2) \times 10^{-3}$

Current status of V_{ud} and CKM unitarity

CKM unitarity: V_{ud} the main contributor to the sum and the uncertainty - γW-box drives this uncertainty, too

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99962 \pm 0.00049$$

V_{ud}^2 nuclear decays muon decay
0.94906 ± 0.00041

V_{us}^2 PDG kaon decays
0.05054 ± 0.00027

V_{ub}^2 B decays
0.00002

It is time for M&S result to be independently checked/improved

New challenges: γW-box for beta decays with controlled precision
Non-negligible energy dependence?
Nuclear structure beyond Marciano & Sirlin, Hardy & Towner?

γZ-box for PVES off C-12 to 10^{-4} - nuclear excitations, … ?

Can be formulated in the dispersion relation language

$$\Box_{\gamma W}(0) = \frac{\alpha}{\pi} \int_0^\infty dQ^2 \int_{thr}^\infty dW^2 C(W,Q^2) F_3^{\gamma W} \; + \; \ldots$$

DR allow to formulate the precision of the EW box calculations through that of the input

Electroweak boxes - plans

Input necessary for EW box calculations

$$\mathrm{Im}\langle N|T[J_Z^\mu J_\gamma^\nu]|N\rangle = \sum_X \rho_X \langle N|J_Z^\mu|X\rangle\langle X|J_\gamma^\nu|N\rangle$$

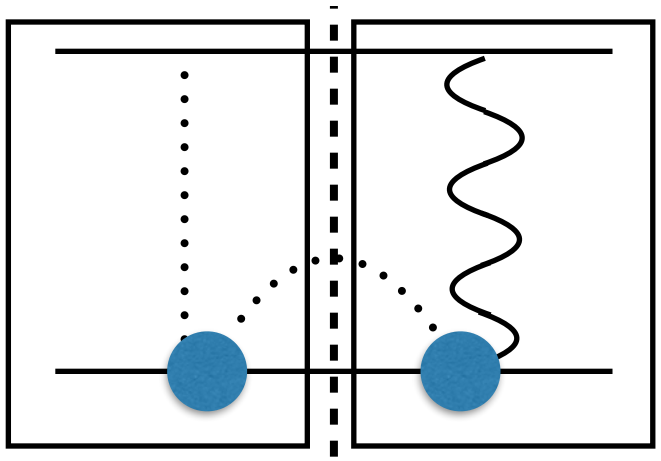
$$\mathrm{Im}\langle N|T[J_W^\mu J_\gamma^\nu]|N\rangle = \sum_X \rho_X \langle N|J_W^\mu|X\rangle\langle X|J_\gamma^\nu|N\rangle$$

X = πN, ηN, η´N, KΛ, KΣ, …

PWA for weak production

Needed at

Q^2 < 2 GeV^2, W<4 GeV



Existing e.-m. data

PWA (MAID, SAID, …)

Q^2 < 2 GeV^2, W<2 GeV

Meson production in e$^-$ scattering (PC and PV) and ν(anti-ν) scattering

Theory input is needed for extracting neutrino oscillation parameters

- inelastic data exist (Minerva, MiniBooNE, SciBooNE, NOMAD, NOvA, T2K)

and more to come (T2HK, MicroBooNE, DUNE)

WW-box - an important uncertainty in 0νββ - an alternative method

Talks by J. Carlson, U. Mosel

Summary

- Low energy tests of SM - nice complementarity to collider searches
- Current precision ~10^{-4} promotes hadronic effects to an important source of uncertainty
- Need for a reliable calculation of EW boxes
- Dispersive methods - relate EW boxes to data and allow for a “model-independent” uncertainty estimate
- Input to the DR - combine data on electron and neutrino scattering
- Synergy between tests of SM with PVES, beta decay, atomic PV, and determination of the neutrino masses, mixing and nature