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

PRISMA

JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Deutsche Forschungsgemeinschaft
DFG

Physics Case of Measuring the Weak Charge of Carbon-12 at MESA

Misha Gorshteyn

C-12 Workshop - IF UNAM, Mexico City - April 1st, 2019

CONACYT

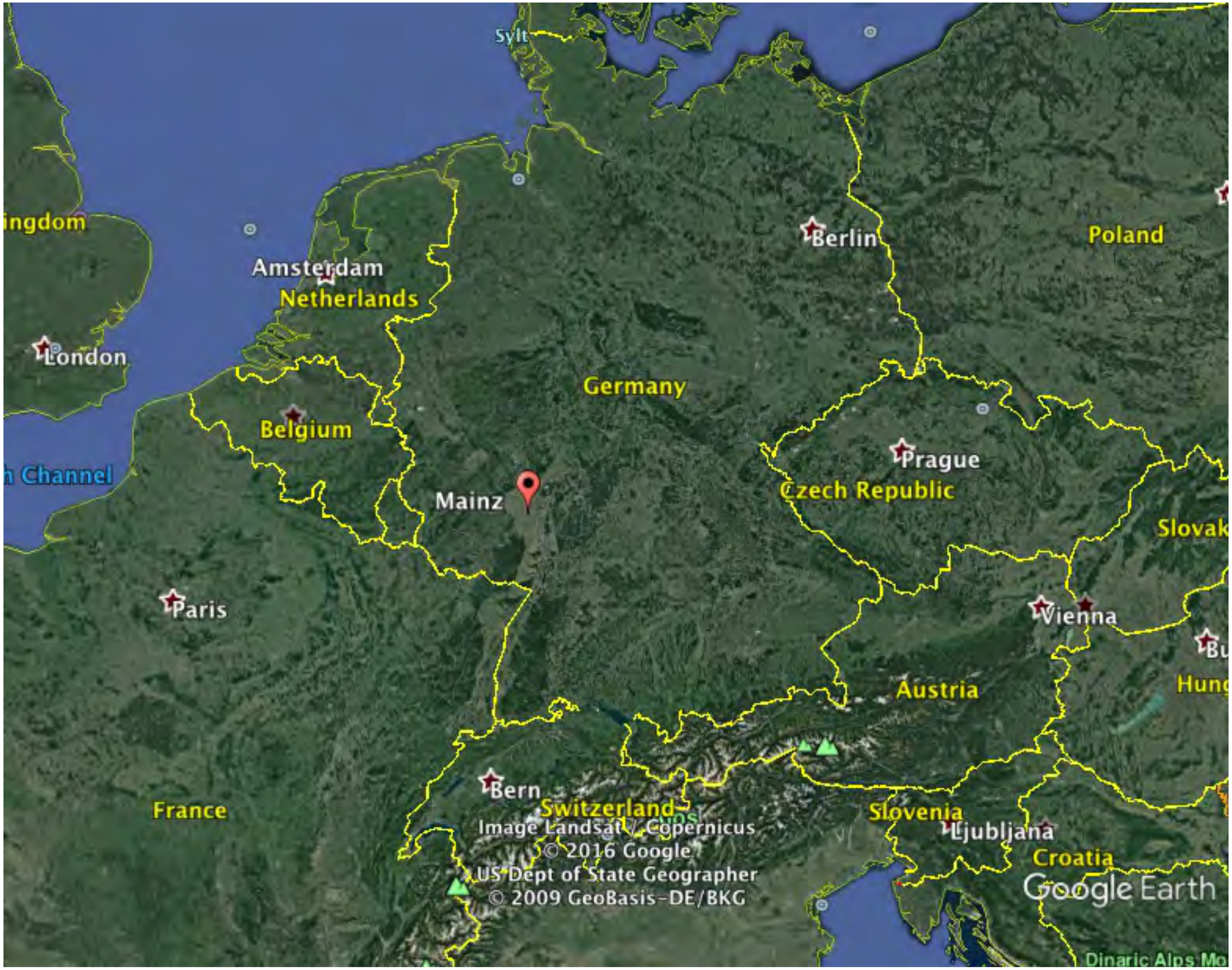
Why are we here?

DFG (Mainz) - CONACyT (UNAM) Cooperation Project

“Constraints on Physics Beyond the Standard Model from Lower Energy Electron Scattering”

- Granted in Fall 2017 - 3 years duration
- The goal: interpretation of a future experiment at Mainz
- In parallel: experimentalists study the feasibility of the measurement

Europe - Germany - Mainz



University of Mainz:

1477: founded by Archbishop of Mainz, Prince-Elector Adolf II von Nassau;
1792: came to a halt due to French revolutionary wars and political turmoil;
1823: last academic program (medicine) ceases;
1946: re-founded during French occupation after WWII;

MAinz MIcrotron MAMI:

1975: first proposal of a microtron;
1979: first electron beam MAMI A1 - 14 MeV;
1983: upgrade MAMI A2 - 183 MeV;

1990: second upgrade MAMI B - 855 MeV;
1992: polarized electrons source;

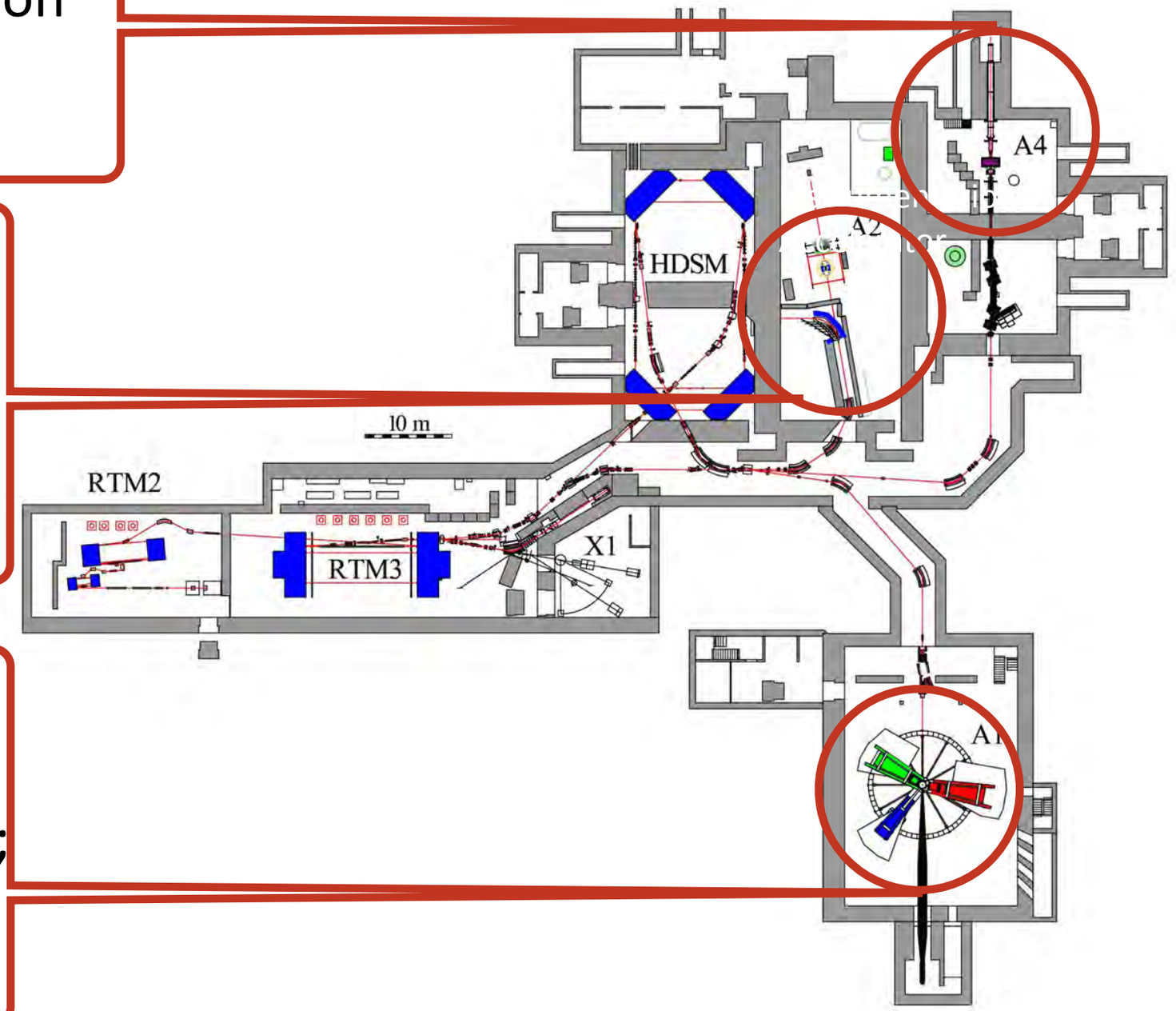
2006: upgrade MAMI C - 1.5 GeV, 100 µA

Research highlights @ MAMI

A4 Collaboration: polarized electrons
PV asymmetries ~ $10^{-5/6}$
Strange form factors of the nucleon
Two-photon exchange
Compton polarimetry

A2 Collaboration: tagged real γ's
4π-detectors (TAPS, Crystal Ball)
Nucleon polarizabilities;
GDH sum rule verification;
Pion photoproduction

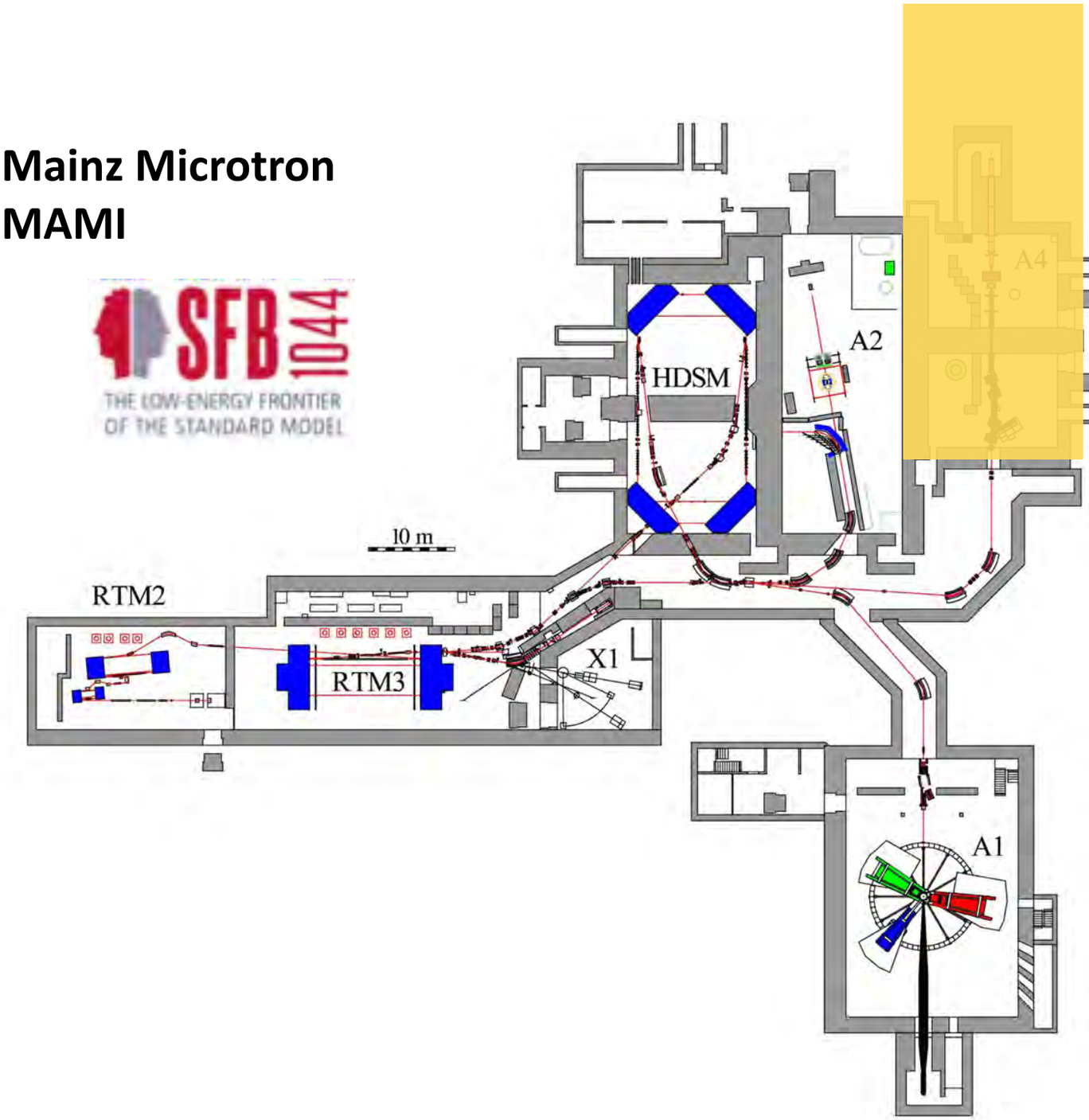
A1 Collaboration: e-scattering
3 spectrometer arrangement
QE e-scattering; e-m nucleon FFs;
VCS & generalized nucleon pol.
Dark photon search



Low-energy physics in Mainz: old and new

Mainz Microtron
MAMI

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

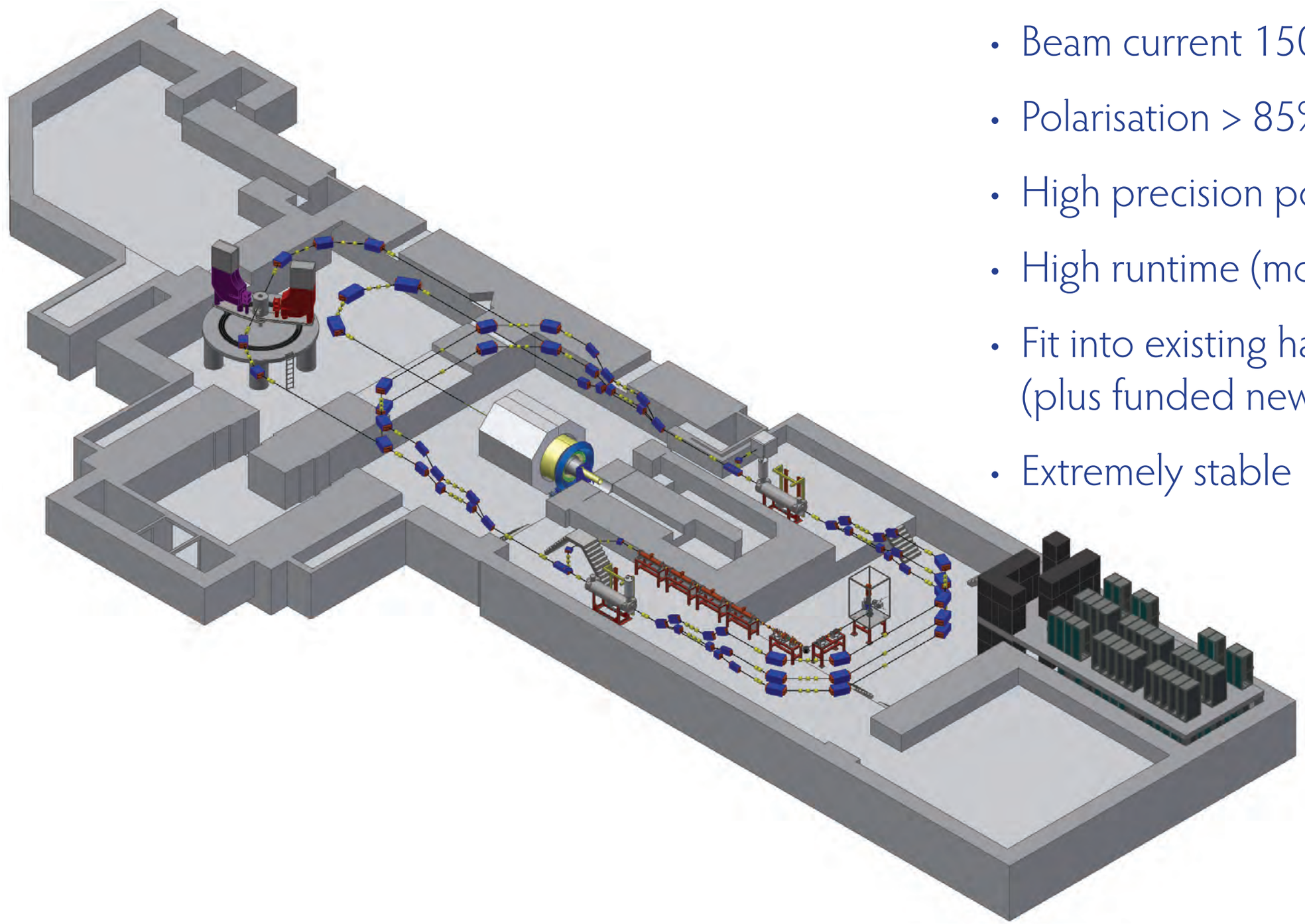


PRISMA

MESA
Accelerator

MESA

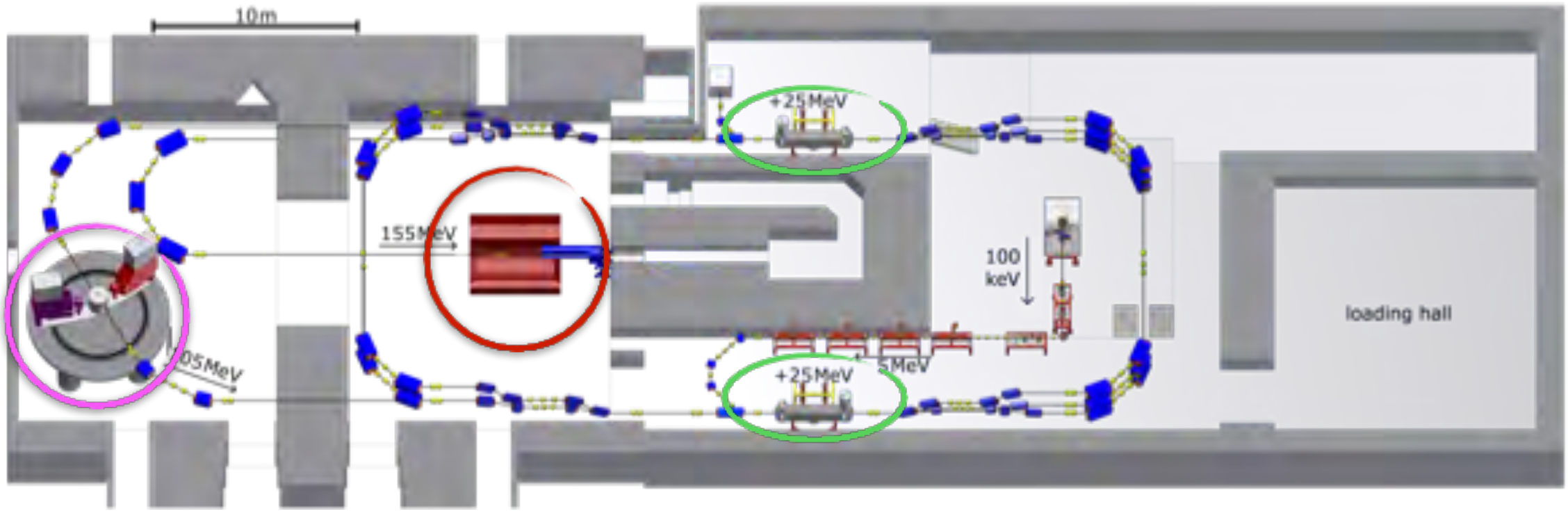
Mainz Energy-recovery Superconducting Accelerator



- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry
- High runtime (more than 4000 h/year)
- Fit into existing halls at MAMI (plus funded new hall)
- Extremely stable

MESA

Mainz Energy-recovery Superconducting Accelerator



MAGIX P2 Superconducting cavities

"Extracted Beam" vs. "Energy Recovery" modes:
155 MeV, 150 µA vs. 105 MeV, up to 10 mA

Deutsche Forschungsgemeinschaft DFG

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

Collaborative Research Center CRC 1044

The low-energy frontier of the Standard Model
From quarks and gluons to hadrons and nuclei

Sub-projects:

P: Implications of hadron physics to Precision tests of Standard Model
- P1: $(g-2)_\mu$ and $\alpha_{em}(M_Z^2)$
- P2: proton's weak charge and weak mixing angle at low energy

S: Hadron Structure via spacelike and timelike processes
- S1: Baryon form factors
- S2: Polarizabilities
- S3: Light hadron spectroscopy

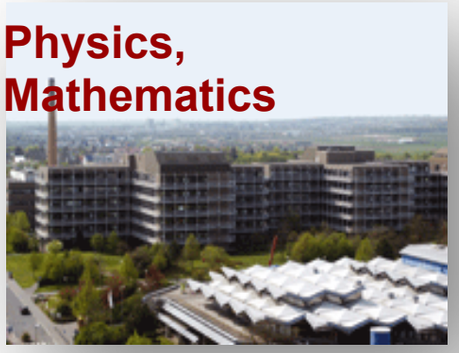
M: Meson structure, decays and spectroscopy
- M1: γγ physics
- M2: Meson dynamics

N: Interactions in Nuclear systems, baryon interactions from QCD

Cluster of Excellence PRISMA+

Participating institutes:

Physics, Mathematics



Nuclear Physics

Helmholtz Institute Mainz

Nuclear Chemistry

★ **Precision Physics, Fundamental Interactions and Structure of Matter**

Research Areas:

A: Exploring intensity frontier with MESA

B: Precision physics at low-energy frontier

C: Exploring the weakly-interacting universe

D: Physics at high-energy accelerators

E: Theory and phenomenology of fundamental interactions

Structural Initiatives:

Electron Accelerator MESA

TRIGA Reactor and User Facility

Mainz Institute for Theoretical Physics

Detector Laboratory

Precise measurement of the Weak Mixing Angle with polarized e-p scattering @ MESA

Weak mixing angle:
central role in the SM

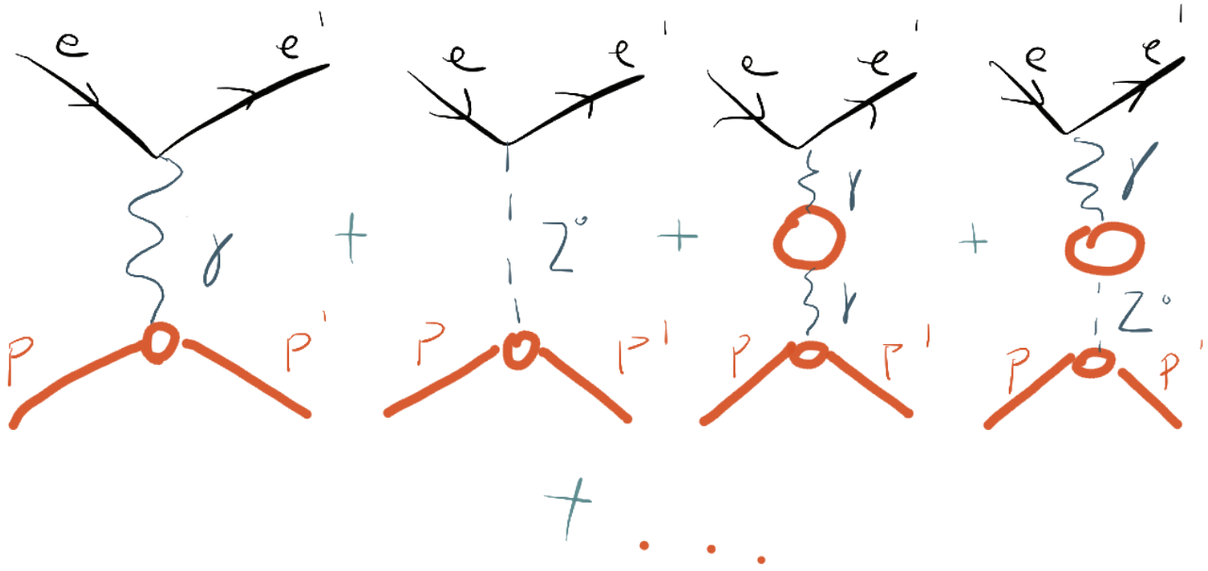
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

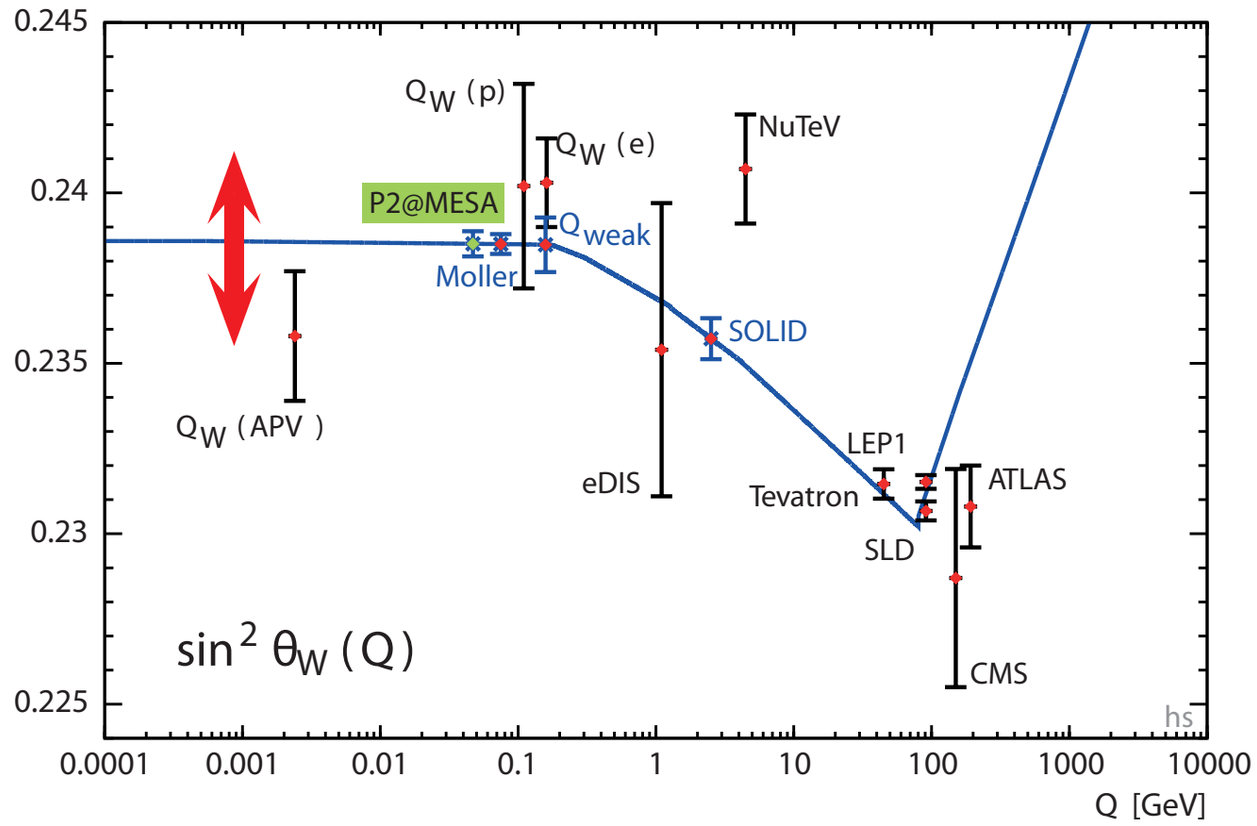
Tree-level:

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = \frac{g'^2}{g^2 + g'^2}$$

Radiative Corrections: scale dependence

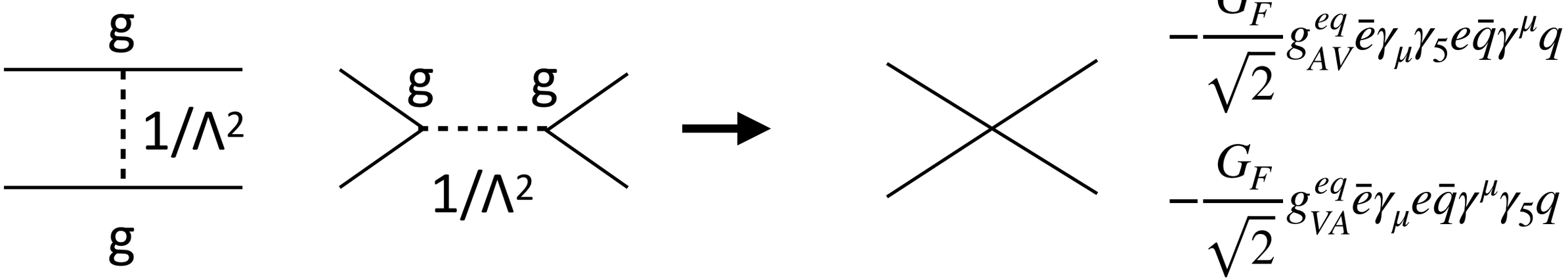
The running is specific for each theory - test of SM





Test of the Standard Model running of $\sin^2\theta_W$

Constraints on SM extensions



$$-\frac{G_F}{\sqrt{2}} g_{AV}^{eq} \bar{e}\gamma_\mu\gamma_5 e\bar{q}\gamma^\mu q$$

$$-\frac{G_F}{\sqrt{2}} g_{VA}^{eq} \bar{e}\gamma_\mu e\bar{q}\gamma^\mu\gamma_5 q$$

In SM at tree level: $\left(g_{AV}^{eu}\right)^{SM,tree} = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W$ $\left(g_{AV}^{ed}\right)^{SM,tree} = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$

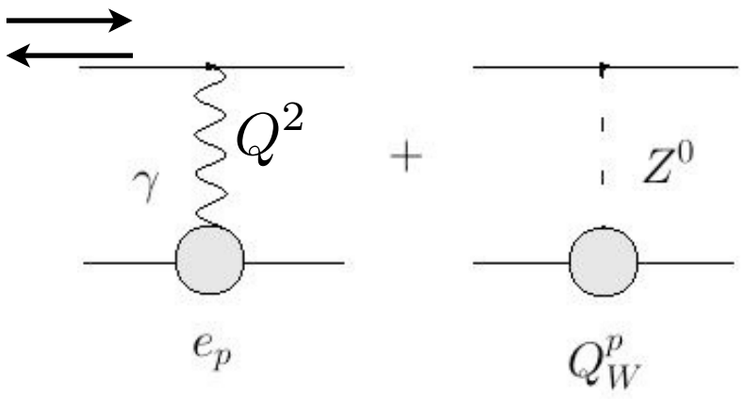
$$Q_W^p = 2(2g_{AV}^{eu} + g_{AV}^{ed}) = 1 - 4\sin^2\theta_W \qquad Q_W^n = 2(g_{AV}^{eu} + 2g_{AV}^{ed}) = -1$$

Importantly: vector current is conserved - is not renormalized by QCD

Heavy New Physics: $\delta g_{AV}^{eq} \sim \frac{g_{NP}^2}{g_{SM}^2}\frac{M_Z^2}{\Lambda^2} \sim g_{NP}^2\frac{v^2}{\Lambda^2}$

Measure the deviations from SM values - discover/constrain BSM

Weak charge of the proton with PV electron scattering



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

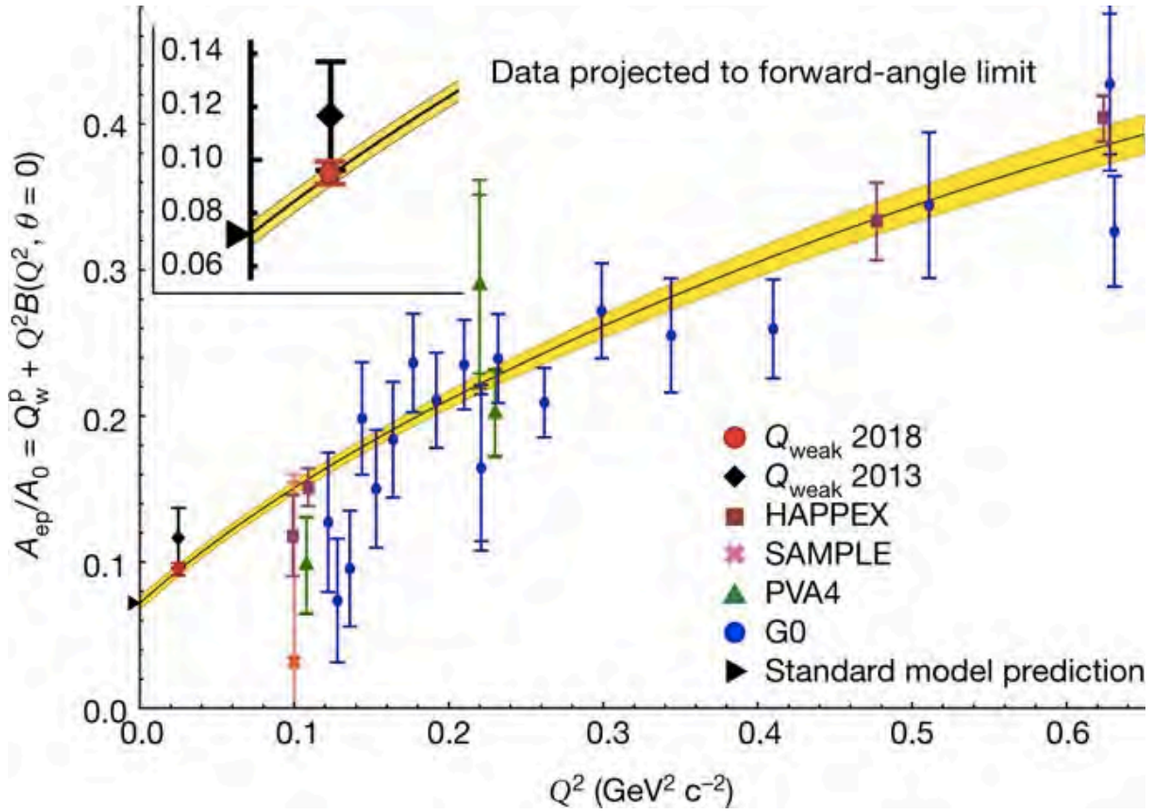
Q_W^p in SM accidentally suppressed $\quad Q_W^{p,\,\mathrm{tree}} = 1 - 4\sin^2\theta_W \approx 0.07$

Sensitive test of running of θ_W at low energy $\quad \frac{\delta Q_W^p}{Q_W^p} = \frac{4\sin^2\theta_W}{1-4\sin^2\theta_W}\frac{\delta\sin^2\theta_W}{\sin^2\theta_W} \approx 12\frac{\delta\sin^2\theta_W}{\sin^2\theta_W}$

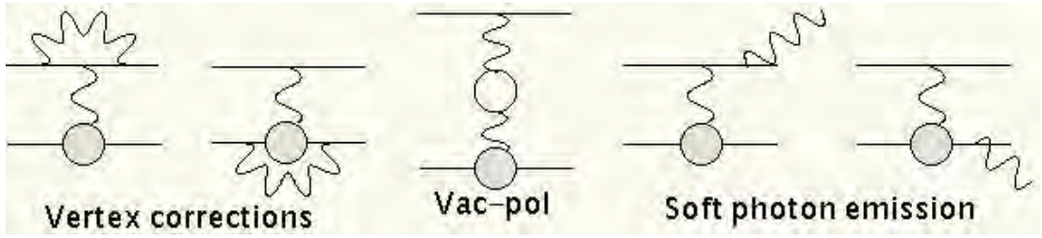
$B(Q^2)$ - from non-forward PVES data

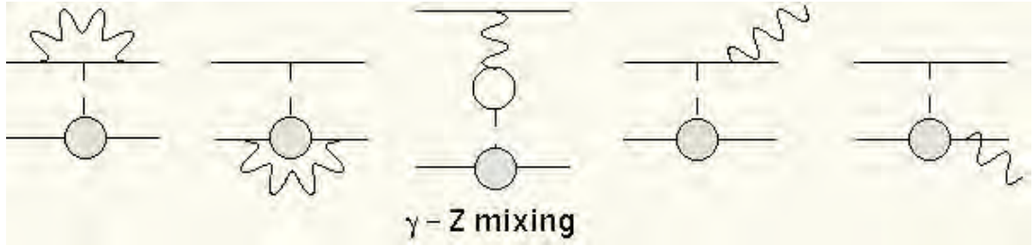
Young et al. ’07;
Androic et al. [Qweak Coll.], ‘13

Plot from Q-Weak publication (Nature 2018)



Need to worry about radiative corrections

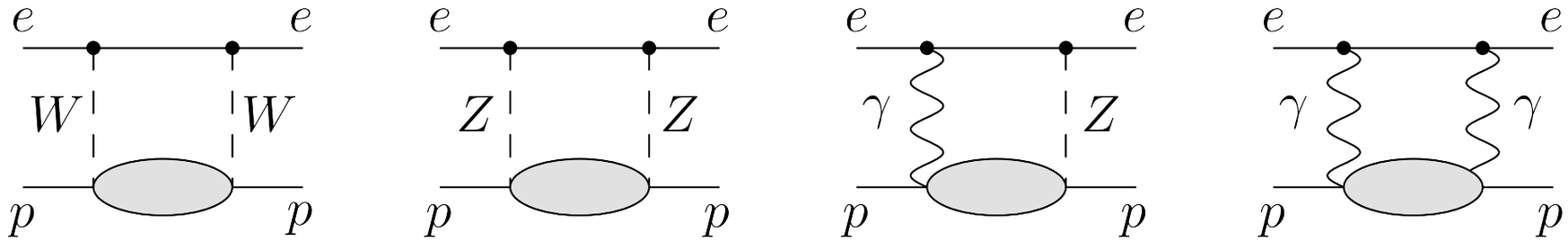




Hadronic structure effects are under control

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

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

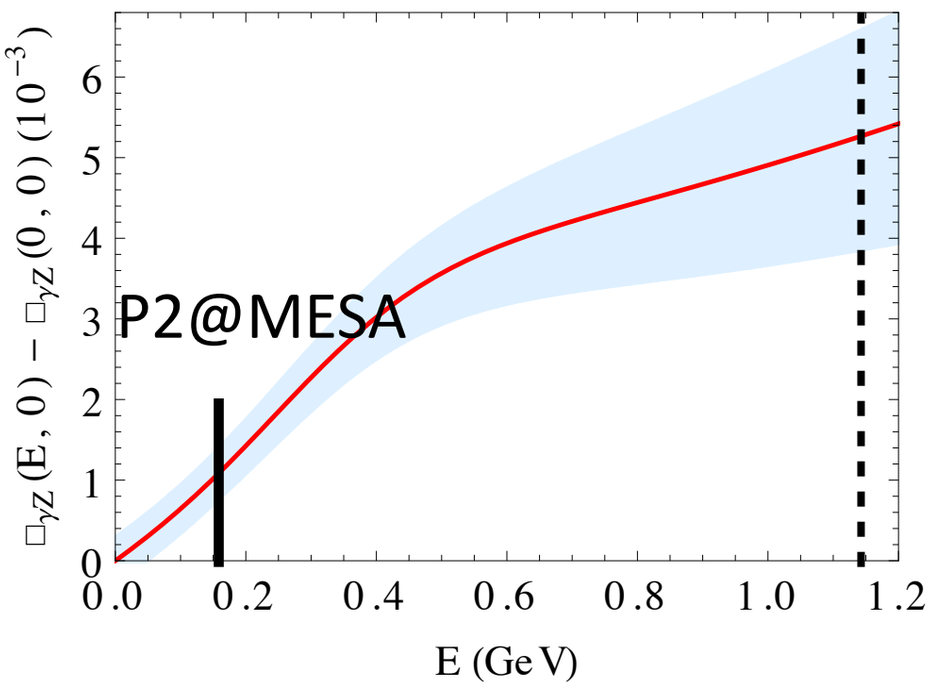


Q-Weak@JLab

EW boxes: special attention

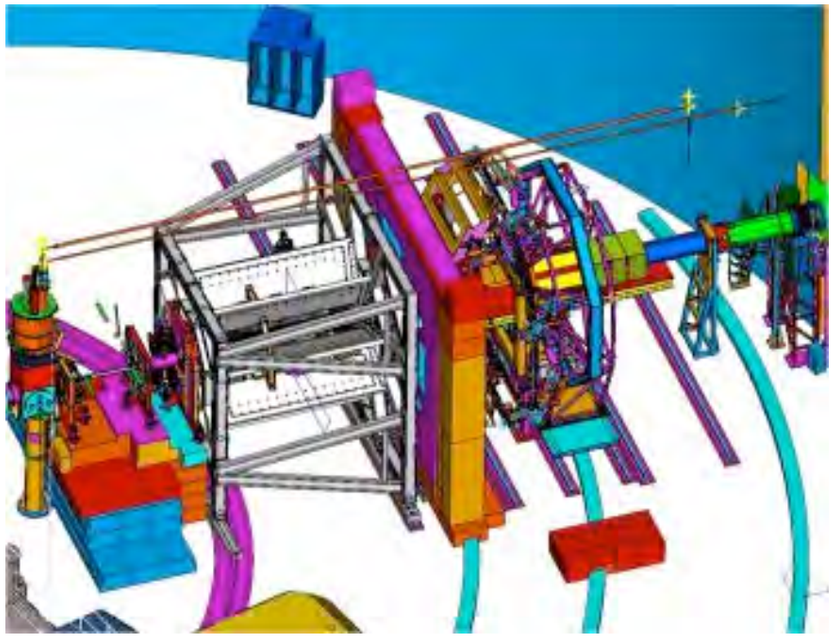
γZ-box: steep energy dependence,
correction & uncertainty rise with energy

MG, Horowitz ’09;
MG, Horowitz, Ramsey-Musolf ’11;
….

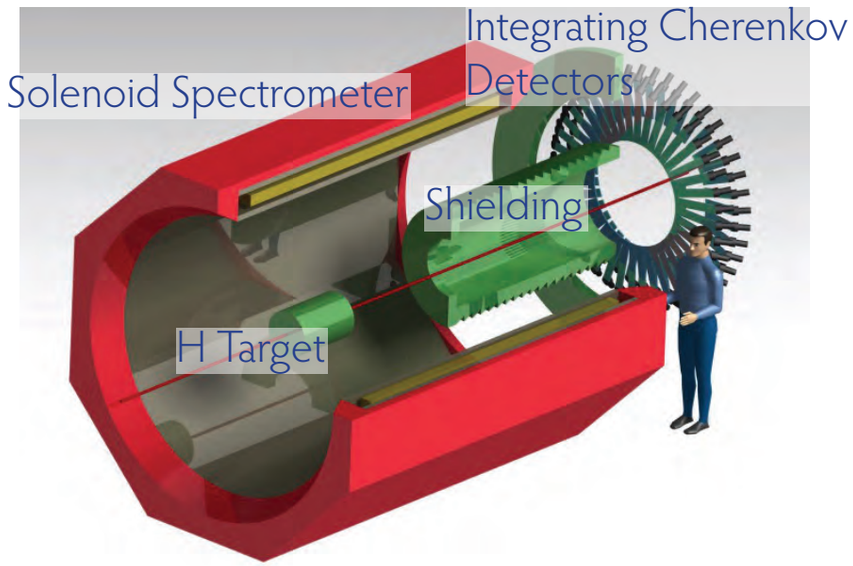


WMA with Qweak@JLab and P2@MESA

Qweak - published in Nature 2018
1.16 GeV beam; Q^2=0.03 GeV^2
PV asymmetry to 5% precision;
Combined Theo+Exp. uncertainty - 6%
$\Delta\sin^2\theta_W/\sin^2\theta_W$ = 0.5%

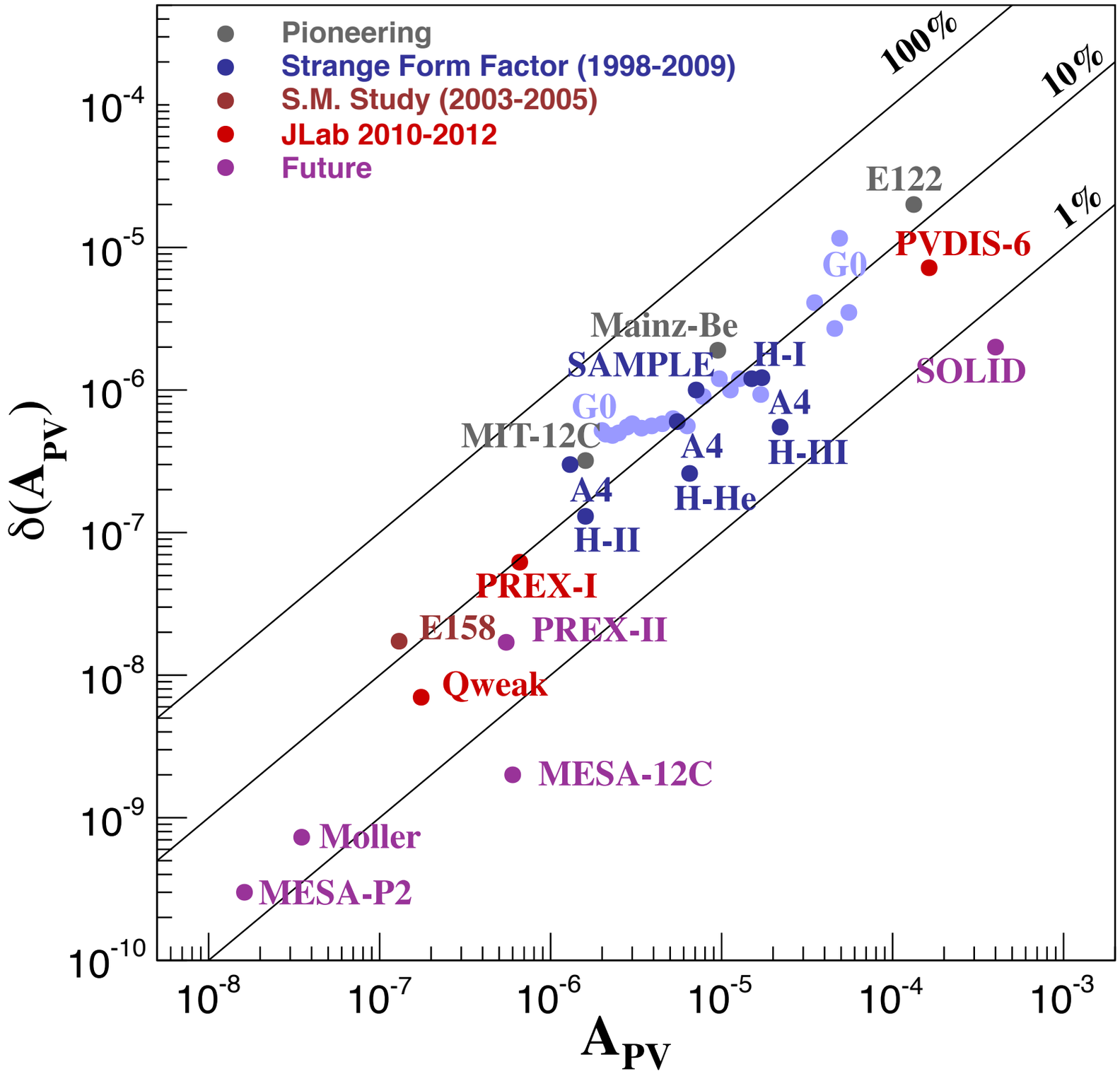


MESA/P2:
155 MeV beam; Q^2=0.0045 GeV^2
PV asymmetry to 1.5% precision (Exp+Th);
$\Delta\sin^2\theta_W/\sin^2\theta_W$ = 0.13%

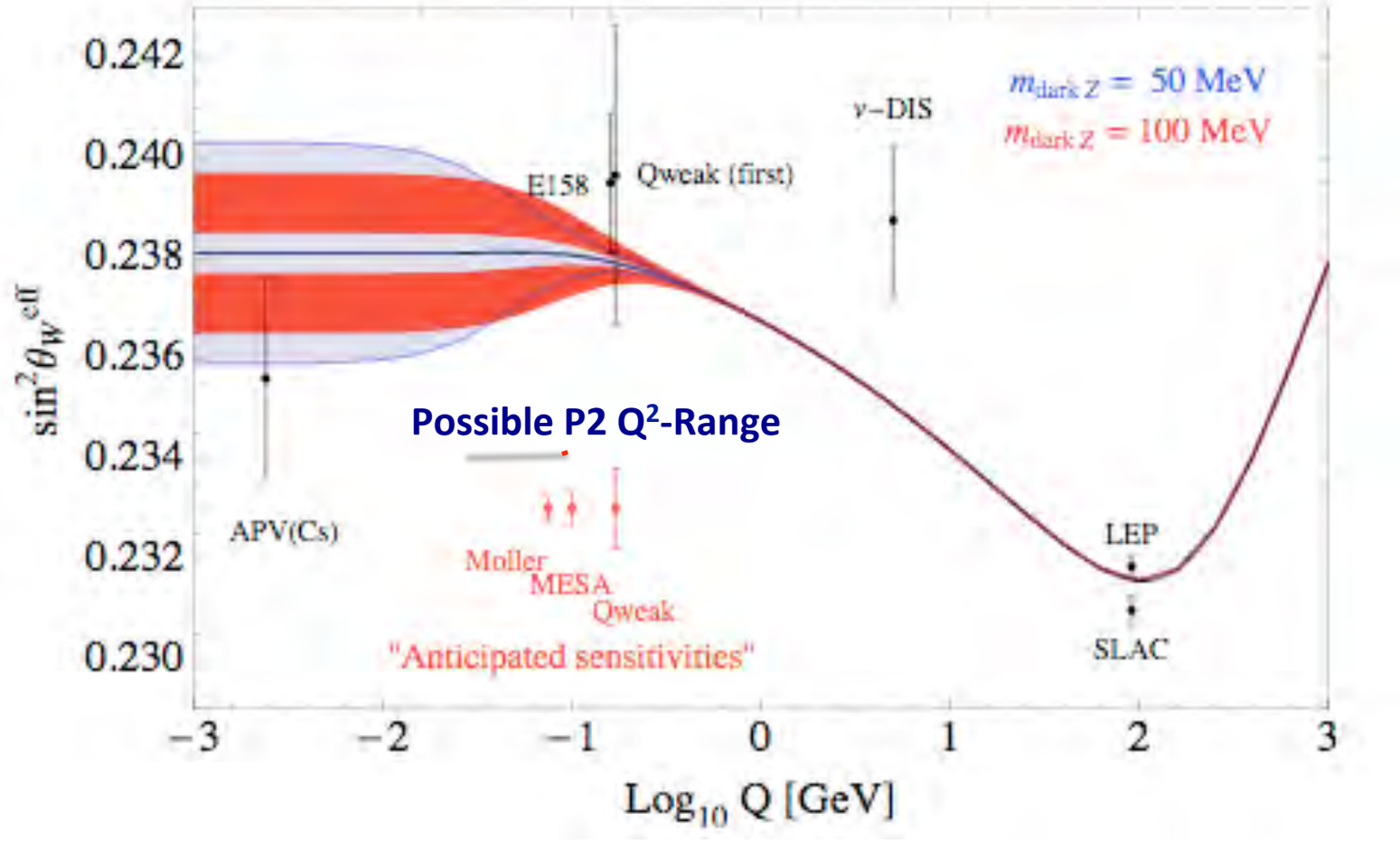


Physics reach up to 49 TeV (comparable to LHC)

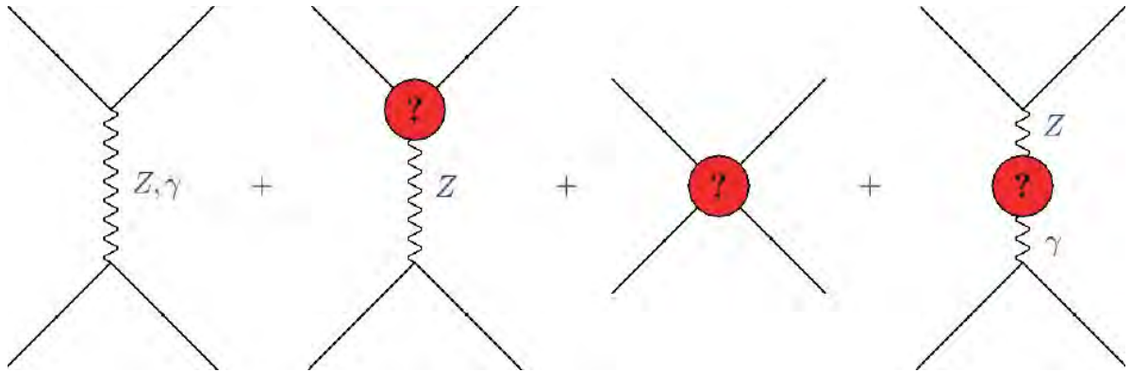
Evolution of PVES experiments



Running $\sin^2\theta_W$ and Dark Parity Violation



Bill Marciano



Dark Z

Mixing w. dark Z or γ

New contact interactions

New fermions

Proposal to enhance the physics reach of P2 experiment

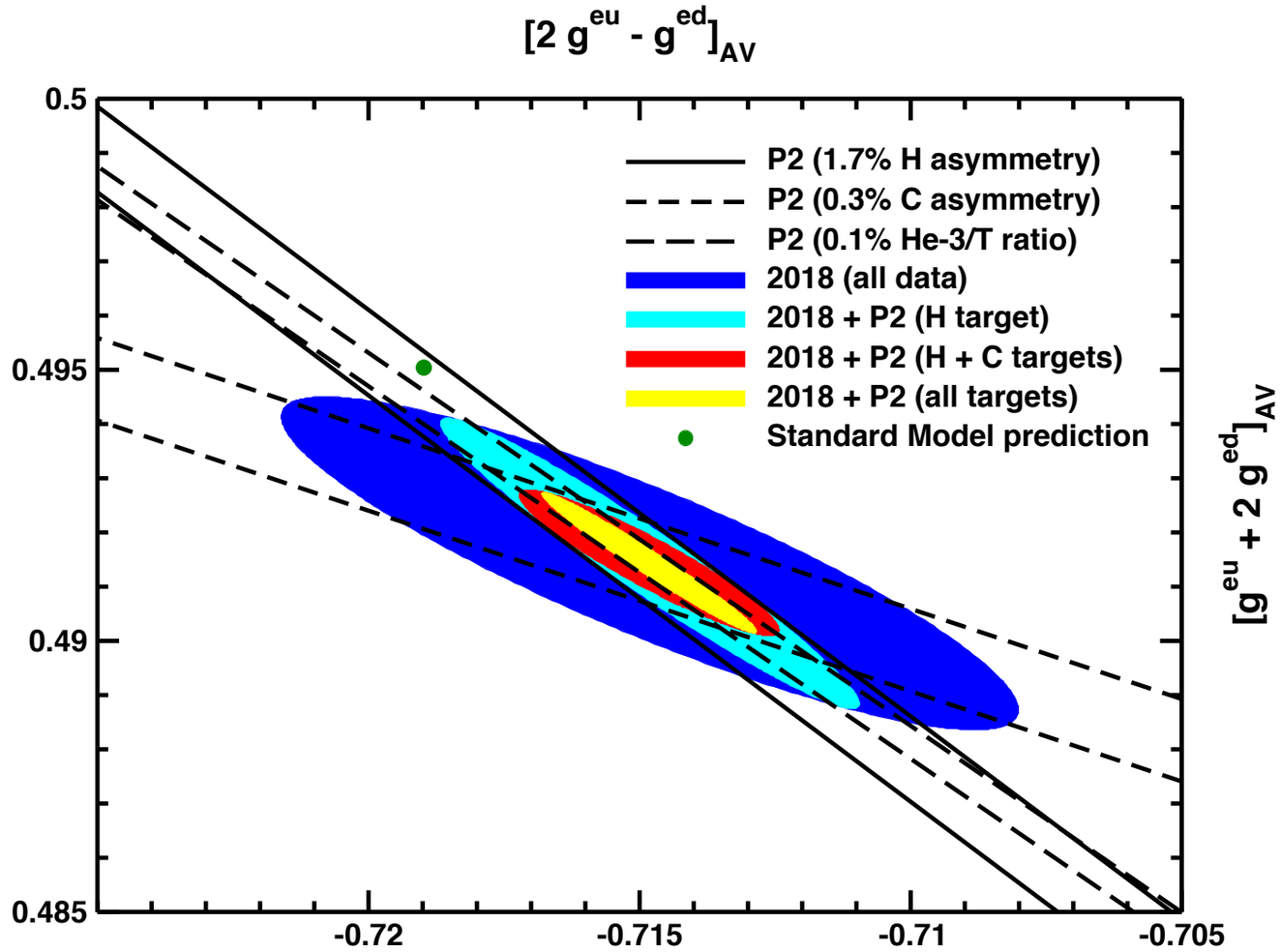
Additional measurement of PV asymmetry on Carbon-12

Why carbon-12? $Q_W^{C-12} = 6(Q_W^p + Q_W^n) = -24 \sin^2 \theta_W$

- A different isospin combination of g^{eq}_{AV}
- Spin-0 target - simpler interpretation (e.g. smaller correction B)
- Larger cross section, larger asymmetry - “easy” experimentally
- Tree-level term large — corrections relatively small
- But: need a sub-% measurement - is everything under control???

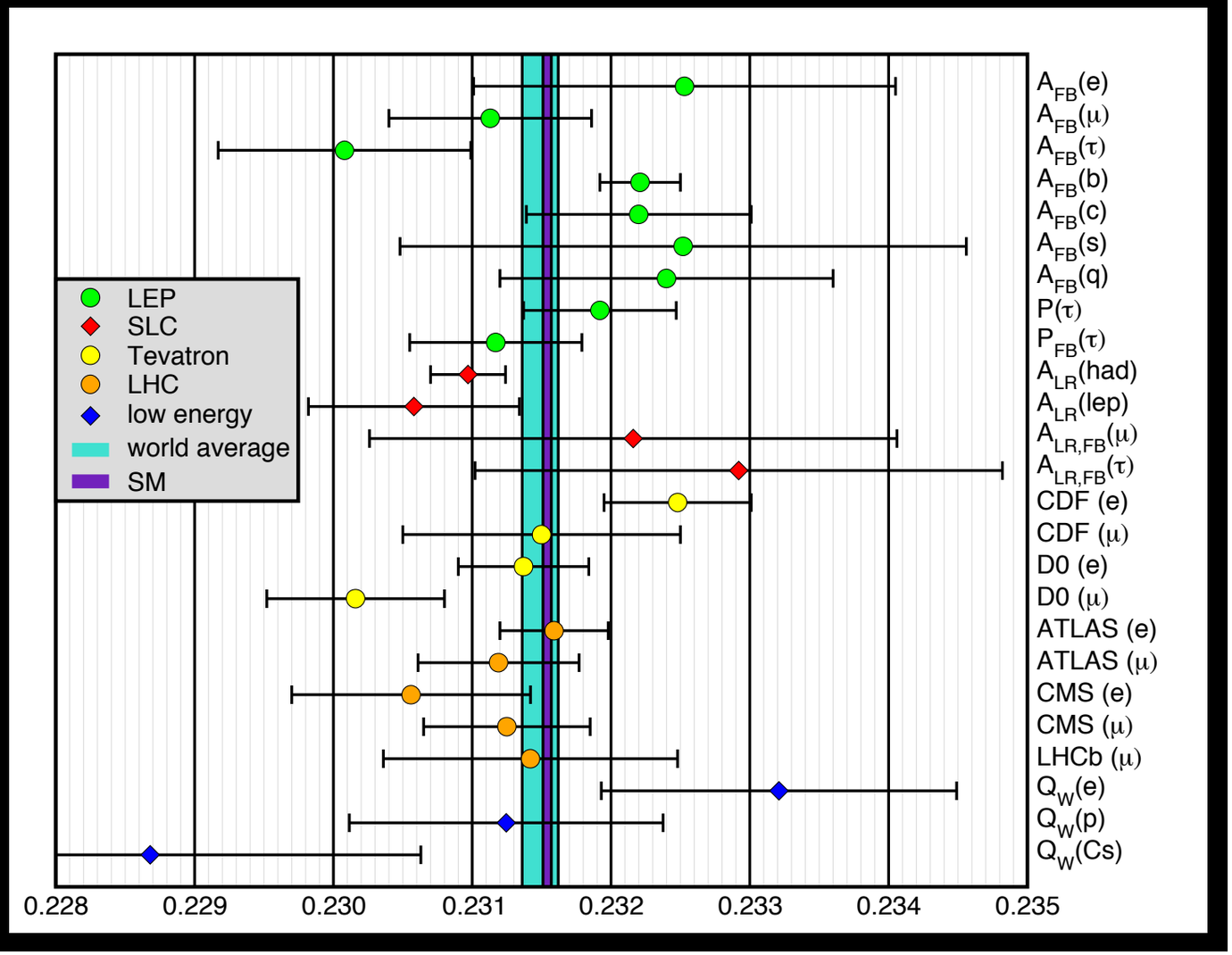
Impact of Qweak and MESA on effective e-q operators:

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



SOME CONTEXT

- weak mixing angle $\sin^2\theta_W = g'^2/(g^2 + g'^2)$
- many ways to measure in SM (flavor, Q^2, …)
- differences may reveal BSM physics (heavy or light Z', dim-6 operators)



Slide stolen from Jens's talk

Goal of this project and this workshop:

Ensure theory uncertainties for PVES on ^{12}C are below 0.3% level;
Hope that all experimental issues are solvable (and solved);

Experiment:

- Tracking (PV asymmetry ~ Q^2 - should be known to below 0.3%)
- Polarimetry (should be known to below 0.3%)
- Electronics
- …
- **Frank Maas talk on Thursday, April 4** + Krishna Kumar in the crowd

Theory side:

Overview talks:

Jens (Opening talk **Tuesday, March 19**)

Hubert (e-p scattering from low to high energy, **Wed. April 3**)

QED corrections:

Bremsstrahlung (correct Q^2 reconstruction)

- **Razvan's talk Monday April 1 (today)**

Coulomb distortion and interplay with neutron skin program

- **Sasha's talk Thursday April 4**

Electroweak corrections:

SM running (get the connection $\sin^2\theta_W(0)$ <—> $\sin^2\theta_W(M_Z^2)$ right)

- **Rodolfo's talk Friday April 5** (*+ new ideas on BSM ν interactions*)

Precise heavy quark masses from QCD sum rules for running $\sin^2\theta_W$

- **Pere's talk on Tuesday, March 26**

Precise γZ-box calculation (connection to β decays and ν scattering)

- **Chien Yeah's talk Tuesday April 2**

Theory continued:

Nuclear structure and nuclear astrophysics:

Neutron stars <—> neutron skins from PVES and PV in atoms

- **Jorge P.'s seminar Wednesday March 20**

BSM constraints between low-energy and high energy frontier:

Interplay with colliders and flavor physics

- **Jorge M. C.'s colloquium Thursday March 21**

Connection to other low-energy tests:

Coherent neutrino scattering

- **Eric V.-J.'s talk Thursday April 4**

Neutrinoless double-beta decay

- **KK's colloquium Friday April 5**

Extracurricular activities:

Scalar charges of the nucleon @ JLab

- **Aurore's talk Tuesday April 2**

T-violation with ultra cold neutrons

- **Libertad's talk Thursday April 4**

D-meson physics

- **Genaro's talk Thursday April 4**

All the talks are/will be available on the indico page!

https://indico.mitp.uni-mainz.de/event/193/

Further highlights:

- Amazing history, sightseeing, food, hospitality
- Key to successful work: excellent espresso all day long
- We are having great time - many thanks to local organizers!