Marc Vanderhaeghen

Institute for Nuclear Physics
Johannes Gutenberg University Mainz

The Low-Energy Frontier of the Standard Model & Precision Hadron Physics

The basic ideas and concepts behind the modern High-Energy Physics and Cosmology
Truskavets (Ukraine), October 5 - 16, 2018

Outline of the lectures

Lecture 1: Tests of the Standard Model at low-energies

- Introduction: Frontiers of the Standard Model
- Low-energy tests of the weak mixing angle
- Search for a dark photon and light dark matter

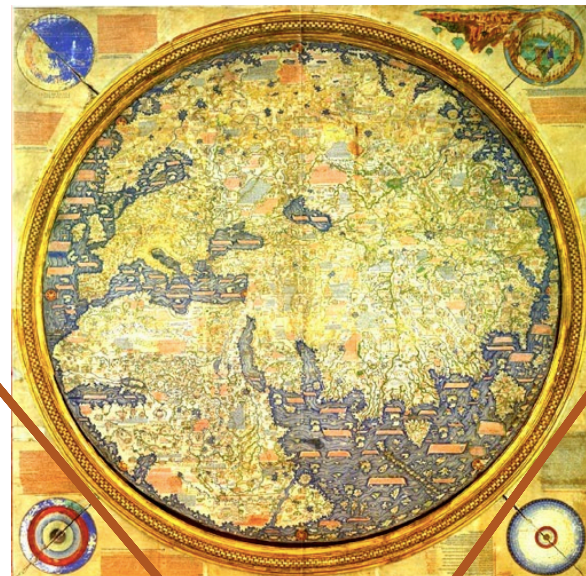
Lecture 2: Modern Topics in Precision Hadron Physics

Lecture 3: **given by Dr. Vladyslav Pauk**
Precision physics: the anomalous magnetic moment of the muon

Frontiers of the Standard Model

High-energy Frontier

Precision Frontier



Fra Mauro(1459)

Low-energy Frontier

Frontiers of the Standard Model

New Physics

High-Energy Frontier

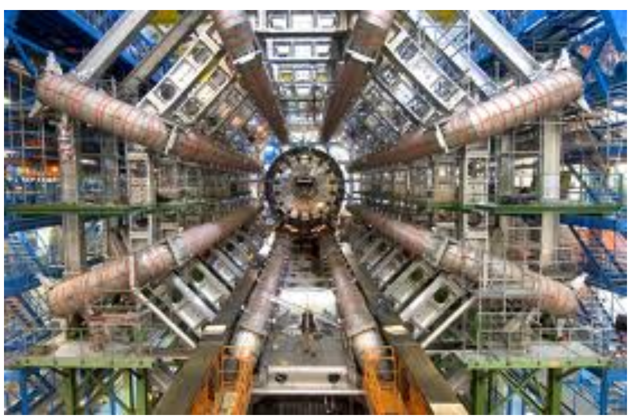
Precision Frontier

Low-Energy Frontier

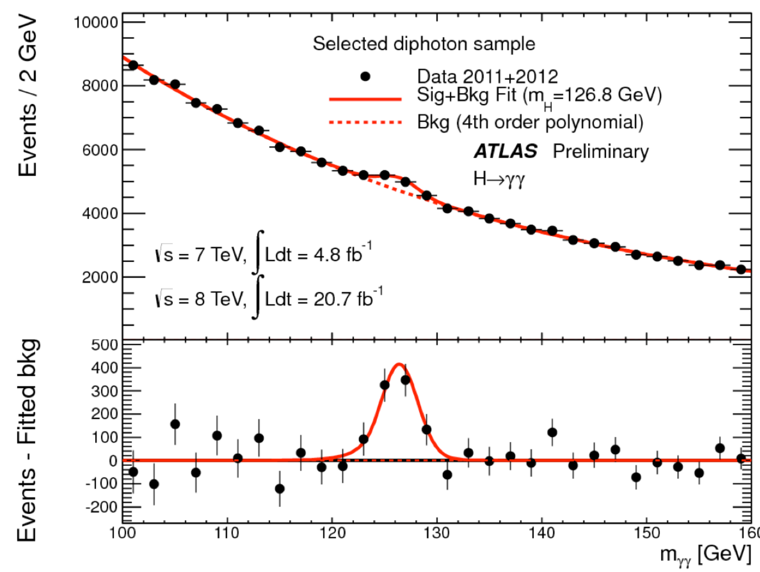
LHC

Higgs discovery
Production of new physics particles
Later: ILC

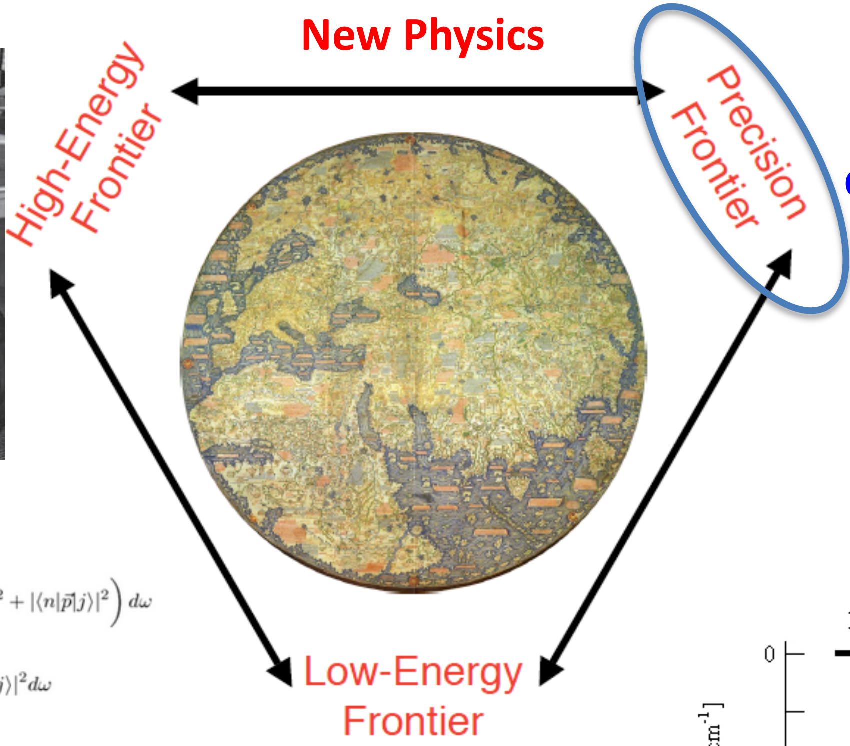
Englert, Higgs Nobel prize 2013



Higgs discovery



Frontiers of the Standard Model



Testing SM at low energies, quantum loop corrections

$\sin^2\theta_W$

$(g-2)\mu$

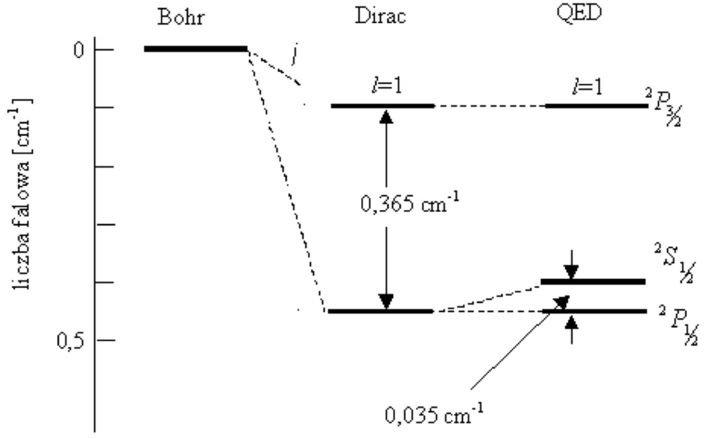
EDM

Flavor physics

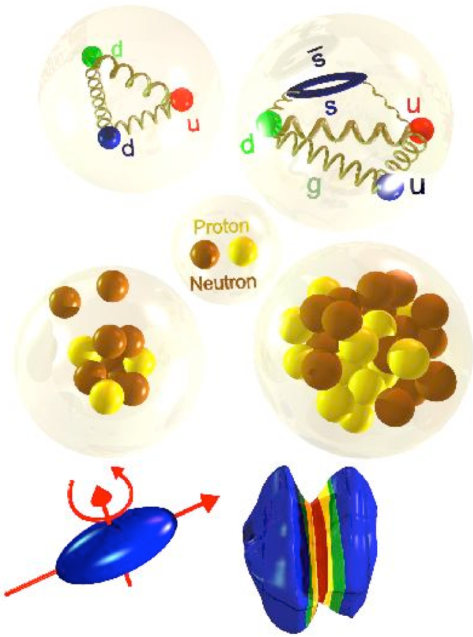
Atomic physics

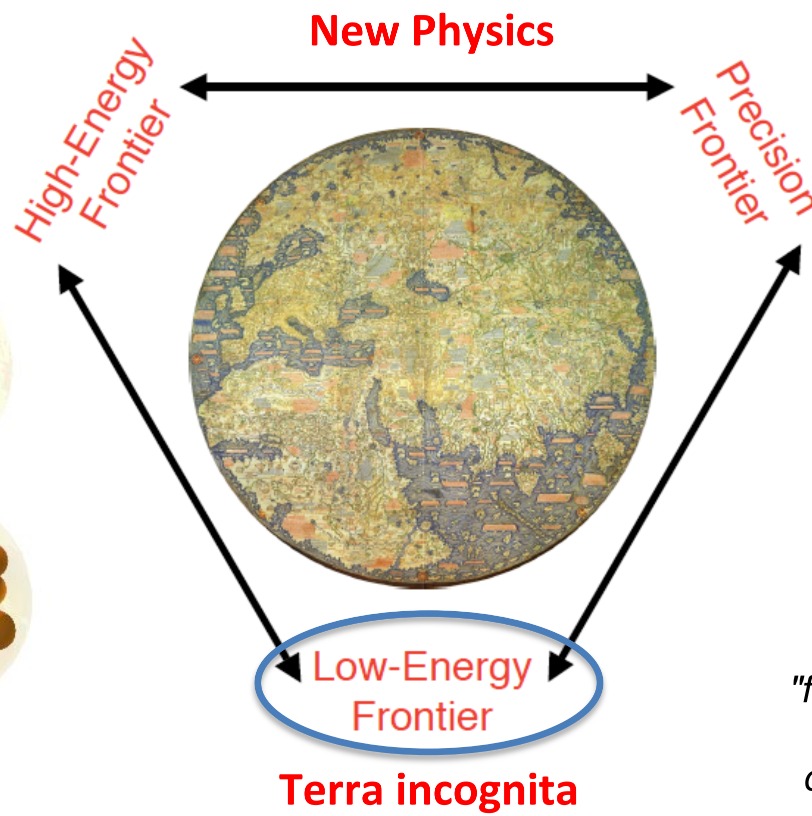
$$
\begin{aligned}
\Delta E_n^{(obs)} &= \frac{2\alpha\hbar}{3\pi m^2c^2} \int_0^{\omega_{cut-off}} \sum_j \left(\frac{\omega}{(\omega_{nj}-\omega)} |\langle n|\vec{p}|j\rangle|^2 + |\langle n|\vec{p}|j\rangle|^2 \right) d\omega \\
&= \frac{2\alpha\hbar}{3\pi m^2c^2} \int_0^{\omega_{cut-off}} \sum_j \frac{\omega + (\omega_{nj}-\omega)}{(\omega_{nj}-\omega)} |\langle n|\vec{p}|j\rangle|^2 d\omega \\
&= -\frac{2\alpha\hbar}{3\pi m^2c^2} \sum_j \int_0^{\omega_{cut-off}} \frac{\omega_{nj}}{\omega-\omega_{nj}} |\langle n|\vec{p}|j\rangle|^2 d\omega \\
&= -\frac{2\alpha\hbar}{3\pi m^2c^2} \sum_j \omega_{nj} \left[\log(\omega-\omega_{nj})\right]_0^{\omega_{cut-off}} |\langle n|\vec{p}|j\rangle|^2 \\
&= \frac{2\alpha\hbar}{3\pi m^2c^2} \sum_j \omega_{nj} \left[\log(|\omega_{nj}|) - \log(\omega_{cut-off}-\omega_{nj})\right] |\langle n|\vec{p}|j\rangle|^2 \\
&\approx \frac{2\alpha\hbar}{3\pi m^2c^2} \sum_j \omega_{nj} \left[\log(|\omega_{nj}|) - \log(\omega_{cut-off})\right] |\langle n|\vec{p}|j\rangle|^2 \\
&= \frac{2\alpha\hbar}{3\pi m^2c^2} \sum_j \omega_{nj} \log\left(\frac{|\omega_{nj}|}{\omega_{cut-off}}\right) |\langle n|\vec{p}|j\rangle|^2
\end{aligned}
$$

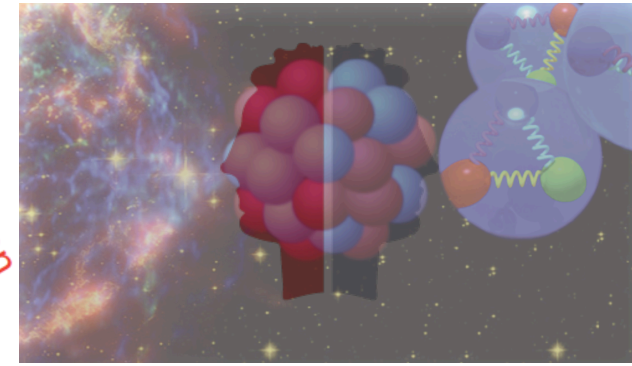
H. Bethe(1947)



Frontiers of the Standard Model







from quarks to stars:

looking outward
vs looking inward

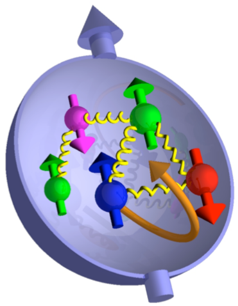
Hans Bethe:
Nobel prize 1967

"for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

Hadron physics: Strong interactions, Complex systems

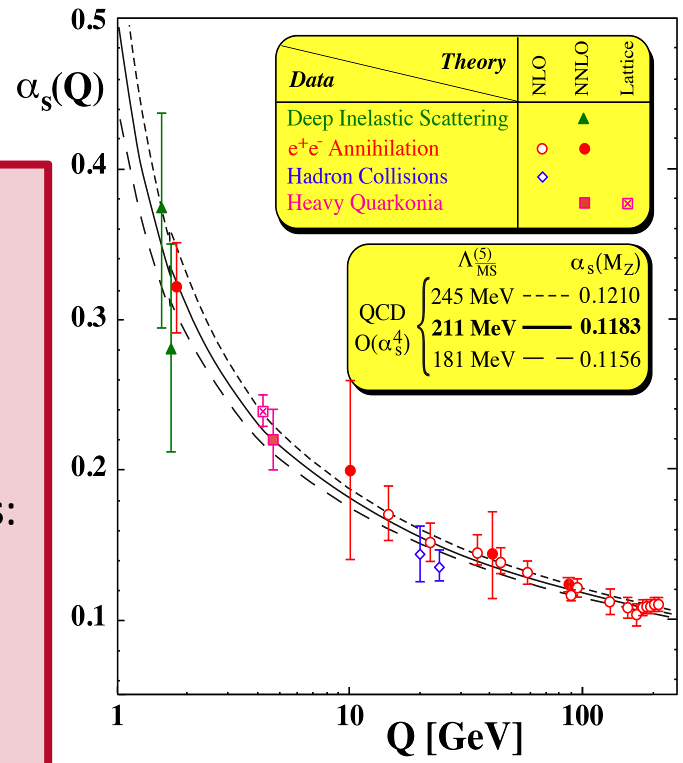
How do quarks/gluons merge into hadrons (mass, spin,…) ?
How does hadron structure **emerge** from basic constituents?

Dual behavior of strong interactions QCD



Differently from electromagnetic and weak interaction perturbation QCD: theory only simple at high energies -> asymptotic freedom

strong coupling: the world of hadrons



- **Unraveling strong QCD**
  Origin of mass, spin, hadron imaging

- **Precision hadron physics**
  impact on new physics searches:
  $(g\text{-}2)_\mu$, dark photon search, proton radius puzzle, weak mixing angle

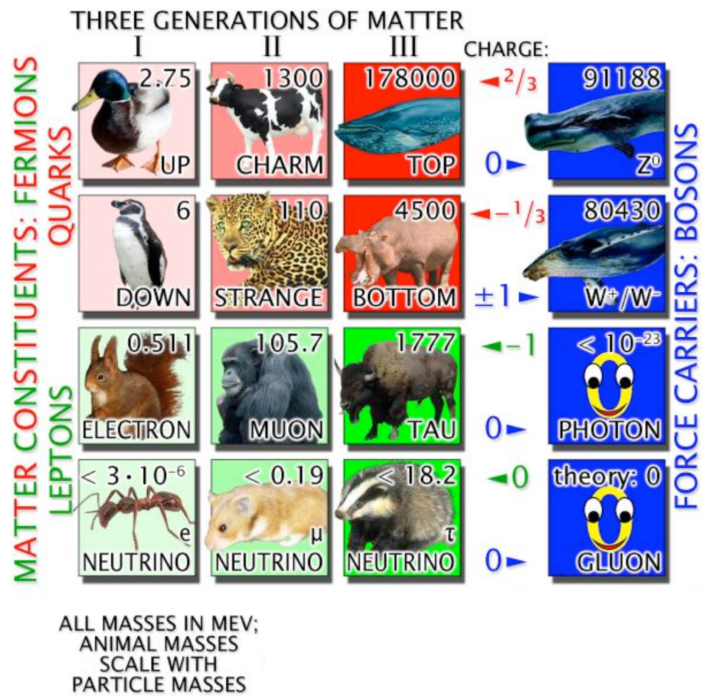
- **Theory tools**
  lattice QCD: ab initio
  EFT/phenomenology: interplay with precision hadron data

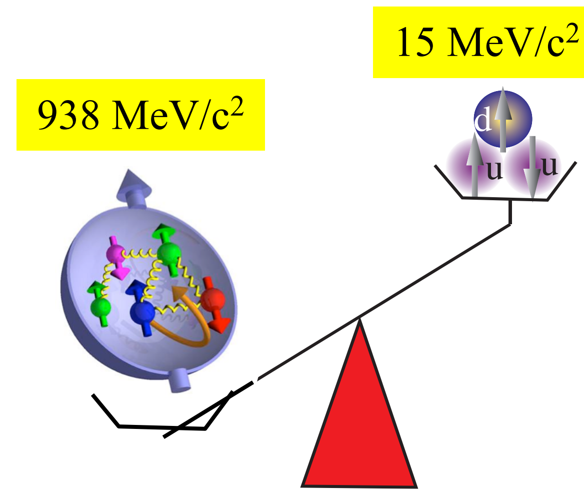
Nobel prize 2004

Gross Politzer Wilczek

weak coupling: asymptotic freedom

Challenges for the Standard Model





Search for New Physics

Generally believed to consist of particles beyond the Standard Model

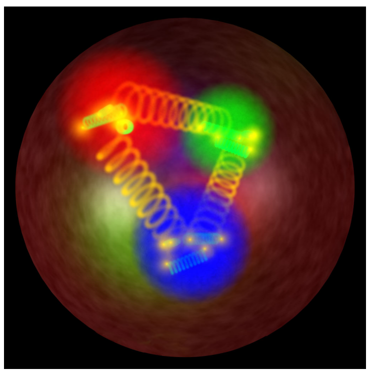
Understanding Low-Energy QCD

The world of Hadrons as bound systems of quarks/gluons

Low-energy frontier of the Standard Model

Hadron physics (= The Low-Energy Frontier of the Standard Model)

plays a central and connecting role in interpretation of measurements at the precision frontier of the Standard Model



SFB 1044

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

$\sin^2\theta_W$

$(g-2)_\mu$

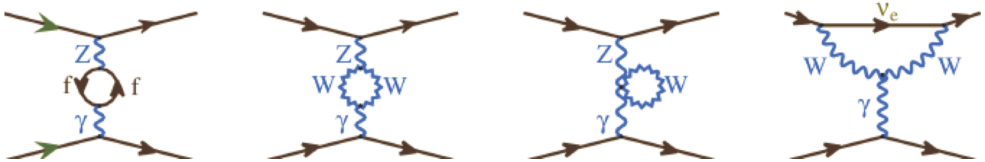
R_E Proton charge radius

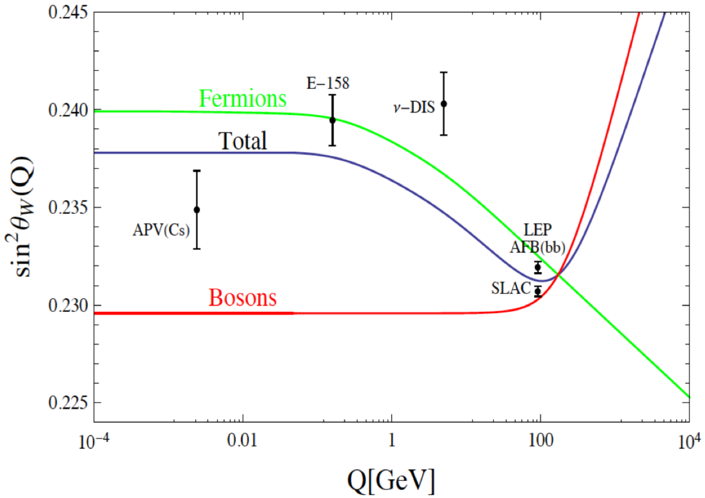
Dark Photon

Nuclear EOS

Strong interactions	⟷	**Particle physics**
Hadron structure		**Atomic physics**
Hadron spectroscopy		**Astro(particle) physics**

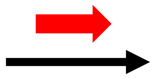
Low-Energy Tests of the Weak Mixing Angle



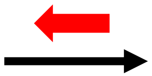


Electroweak sector of Standard Model

Right/left handed fermion fields



$$\psi^R = \frac{1}{2}(1+\gamma_5)\psi$$



$$\psi^L = \frac{1}{2}(1-\gamma_5)\psi$$

SU(2): weak isospin gauge symmetry

	t	t_3
$\Psi^L = \begin{pmatrix} \nu_l^L \\ l^L \end{pmatrix}$	$1/2$ $1/2$	$+1/2$ $-1/2$
$\psi^R = l^R$	0	0

$$\mathcal{L}^{SU(2)} = \bar{\Psi}^L i\gamma^\mu \left(\partial_\mu + igt_i W_{i\,\mu}\right)\Psi^L + \bar{\psi}^R i\gamma^\mu \partial_\mu \psi^R$$

t_i (i = 1,2,3): generators of SU(2)

$W_{1\mu}$, $W_{2\mu}$, $W_{3\mu}$: 3 gauge fields

charged current (CC) interaction

Charged gauge fields:

$$W^\mu = \left(W_1^\mu - iW_2^\mu\right)/\sqrt{2}$$

$$W^{\mu\dagger} = \left(W_1^\mu + iW_2^\mu\right)/\sqrt{2}$$

$$\mathcal{L}_{int}^{SU(2)} = \mathcal{L}_{CC} - \frac{g}{4}\left\{\bar{\psi}_{\nu_l}\gamma^\mu\left(1-\gamma_5\right)\psi_{\nu_l} \; - \; \bar{\psi}_l\gamma^\mu\left(1-\gamma_5\right)\psi_l\right\}W_{3\,\mu}$$

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\left\{\bar{\psi}_{\nu_l}\gamma^\mu\left(1-\gamma_5\right)\psi_l W_\mu \; + \; \bar{\psi}_l\gamma^\mu\left(1-\gamma_5\right)\psi_{\nu_l} W_\mu{}^\dagger\right\}$$

Electroweak sector of Standard Model

U(1)$_Y$: weak hypercharge gauge symmetry

2 neutral currents:

- 3rd component of weak isospin: $$J_3^\mu = \frac{1}{2}\bar{\psi}_{\nu_l}^L \gamma^\mu \psi_{\nu_l}^L - \frac{1}{2}\bar{\psi}_l^L \gamma^\mu \psi_l^L$$
- electromagnetic current: $$J_{em}^\mu = -\left(\bar{\psi}_l^L \gamma^\mu \psi_l^L + \bar{\psi}_l^R \gamma^\mu \psi_l^R\right)$$

Combine them by introducing weak hypercharge quantum number Y such that electric charge

$$Q = Y/2 + t_3$$

	t	t_3	Y	Q
$\Psi^L = \begin{pmatrix} \nu_l^L \\ l^L \end{pmatrix}$	$1/2$ $1/2$	$+1/2$ $-1/2$	-1 -1	0 -1
$\psi^R = l^R$	0	0	-2	-1

$$\mathcal{L}_{int}^{U(1)_Y} = -\frac{g'}{2}\left\{-\bar{\psi}_{\nu_l}^L \gamma^\mu \psi_{\nu_l}^L - \bar{\psi}_l^L \gamma^\mu \psi_l^L - 2\bar{\psi}_l^R \gamma^\mu \psi_l^R\right\} B_\mu$$

Electroweak sector of Standard Model

Structure of electroweak neutral current (NC)

$$\mathcal{L}_{int}^{NC} = -g\bar{\Psi}_l^L\gamma^\mu t_3\Psi_l^L\, W_3^\mu + g'\bar{\psi}_{\nu_l}^L\gamma^\mu\frac{1}{2}\psi_{\nu_l}^L\, B_\mu + g'\bar{\psi}_l^L\gamma^\mu\frac{1}{2}\psi_l^L\, B_\mu + g'\bar{\psi}_l^R\gamma^\mu\psi_l^R\, B_\mu$$

$$= -\frac{1}{2}\bar{\psi}_{\nu_l}^L\gamma^\mu\psi_{\nu_l}^L\,\underbrace{(gW_3^\mu - g'B_\mu)}_{\text{should not contain photon field}} + \frac{1}{2}\bar{\psi}_l^L\gamma^\mu\psi_l^L\,(gW_3^\mu - g'B_\mu) + \underbrace{\left(\bar{\psi}_l^L\gamma^\mu\psi_l^L + \bar{\psi}_l^R\gamma^\mu\psi_l^R\right)}_{\text{Electromagnetic current}} g'B_\mu$$

should not contain photon field

Electromagnetic current

Electroweak unification: weak mixing angle

Glashow-Salam-Weinberg model (1967, 1968)

$$\begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z^\mu \\ A^\mu \end{pmatrix}$$

A^μ : photon field

$$g\sin\theta_W = g'\cos\theta_W = e$$

Electroweak sector of Standard Model

Electroweak neutral current (NC) in Standard Model

$$\mathcal{L}_{int}^{NC} = -eJ_{em}^{\mu}A_{\mu} - \frac{g}{\cos\theta_W}J_{NC}^{\mu}Z_{\mu}$$

$$J_{em}^{\mu} = -\left(\bar{\psi}_l^L\gamma^{\mu}\psi_l^L + \bar{\psi}_l^R\gamma^{\mu}\psi_l^R\right)$$

$$J_{NC}^{\mu} = J_3^{\mu} - \sin^2\theta_W J_{em}^{\mu} = \frac{1}{4}\bar{\psi}_{\nu_l}\gamma^{\mu}(1-\gamma_5)\psi_{\nu_l} - \frac{1}{4}\bar{\psi}_l\gamma^{\mu}\left([1-4\sin^2\theta_W]-\gamma_5\right)\psi_l$$

Vector interaction is suppressed

Determination from electroweak precision observables:

$\sin^2\theta_W \approx 0.23 \rightarrow 1-4\sin^2\theta_W \approx 0.08$

Accessing $\sin^2 \theta_W$: proton weak charge

JG|U

Electroweak Lagrangian → Parity-Violating electron-quark term:

$$\mathcal{L}_{PV}^{EW} = \frac{G_F}{\sqrt{2}}\left[g_A^e(\bar{e}\gamma_\mu\gamma_5 e)\cdot\sum_q g_V^q(\bar{q}\gamma^\mu q) + g_V^e(\bar{e}\gamma_\mu e)\cdot\sum_q g_A^q(\bar{q}\gamma^\mu\gamma_5 q)\right]$$

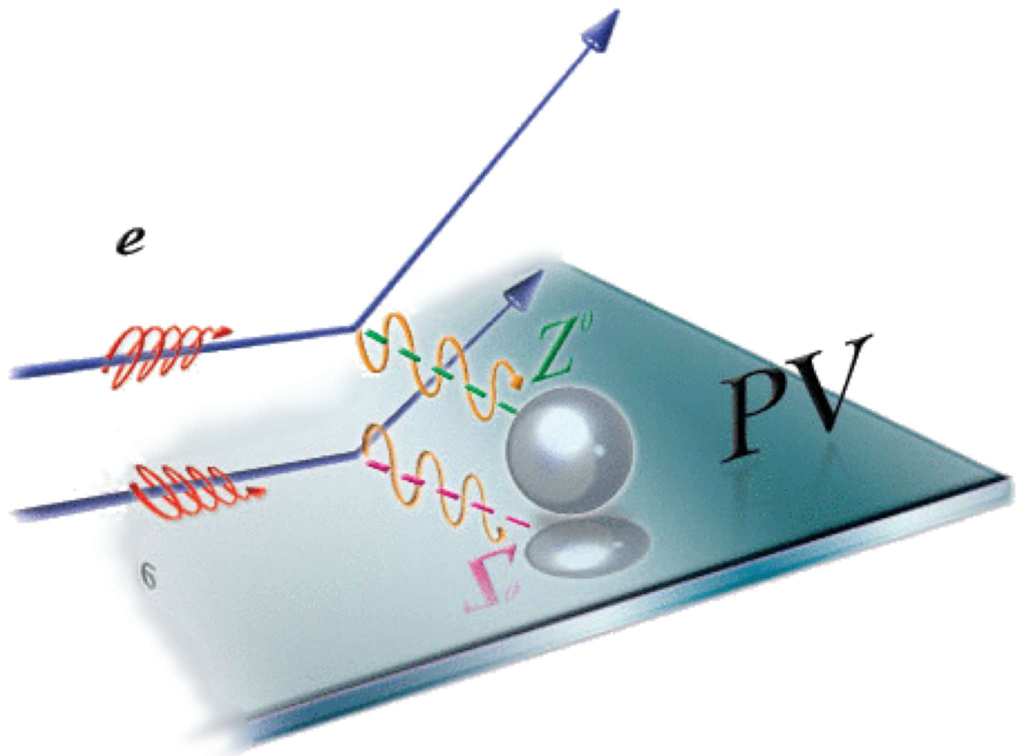
$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \qquad C_{1q} = 2g_A^e g_V^q$$

-Electroweak Charges-

Particle	Electric Charge	Weak Vector Charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$

← Proton's Weak Charge

Parity violating electron scattering



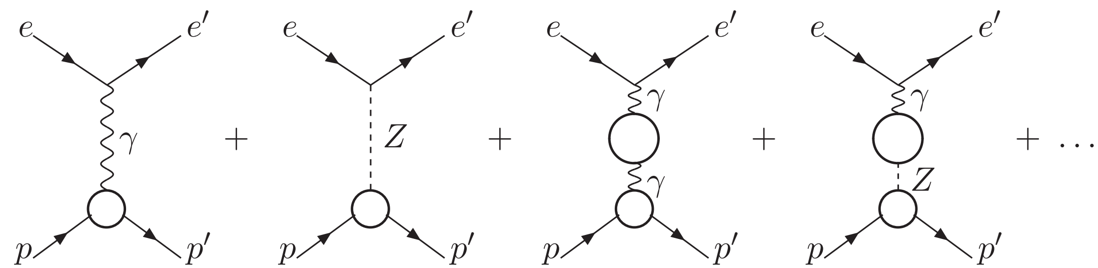
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{2M^*_{EM} M_{Weak}}{|M_{EM}|^2}$$

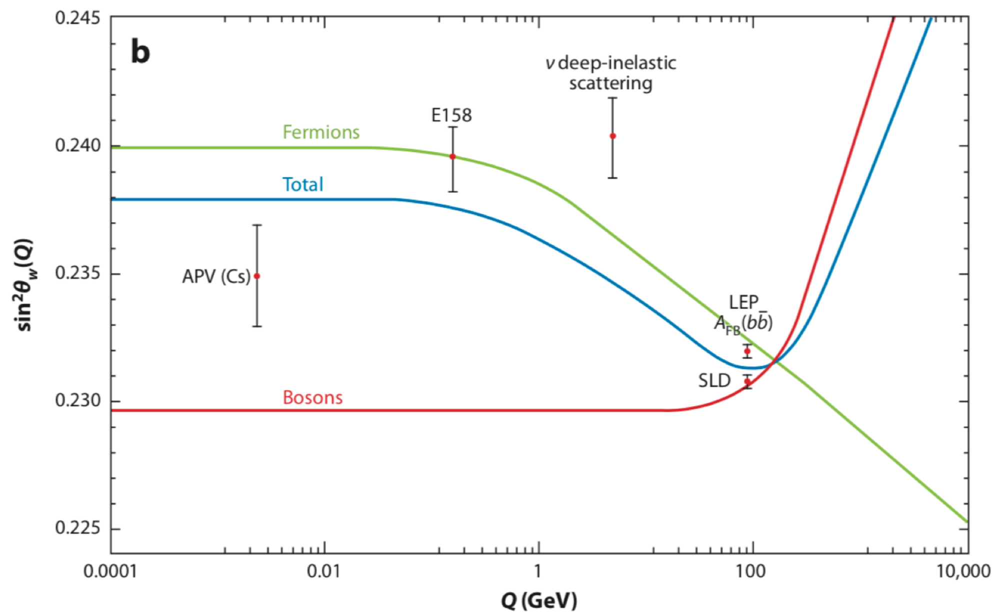
For forward angle scattering at low Q^2 :
A_{PV} accesses Q_W^p

Running of $\sin^2\theta_W$ *: Standard Model test*

SM: universal quantum corrections leads to a scale dependent, „running" $\sin^2\theta_W(Q)$

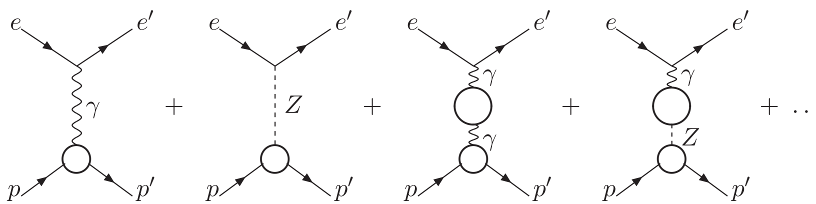
$$\sin^2\theta_W(Q) = e^2(Q)/g^2(Q)$$



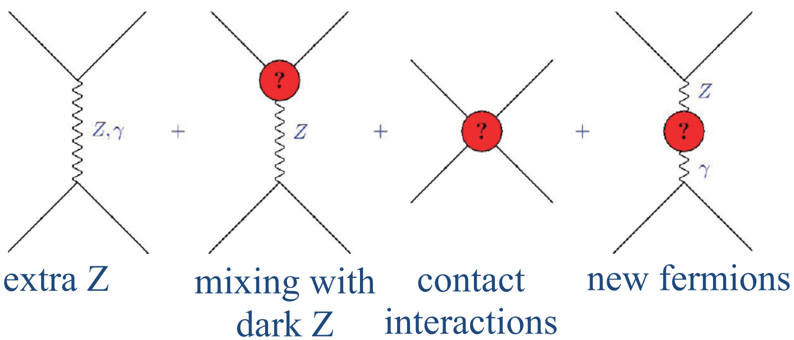


Running of $\sin^2\theta_W$: New Physics Search

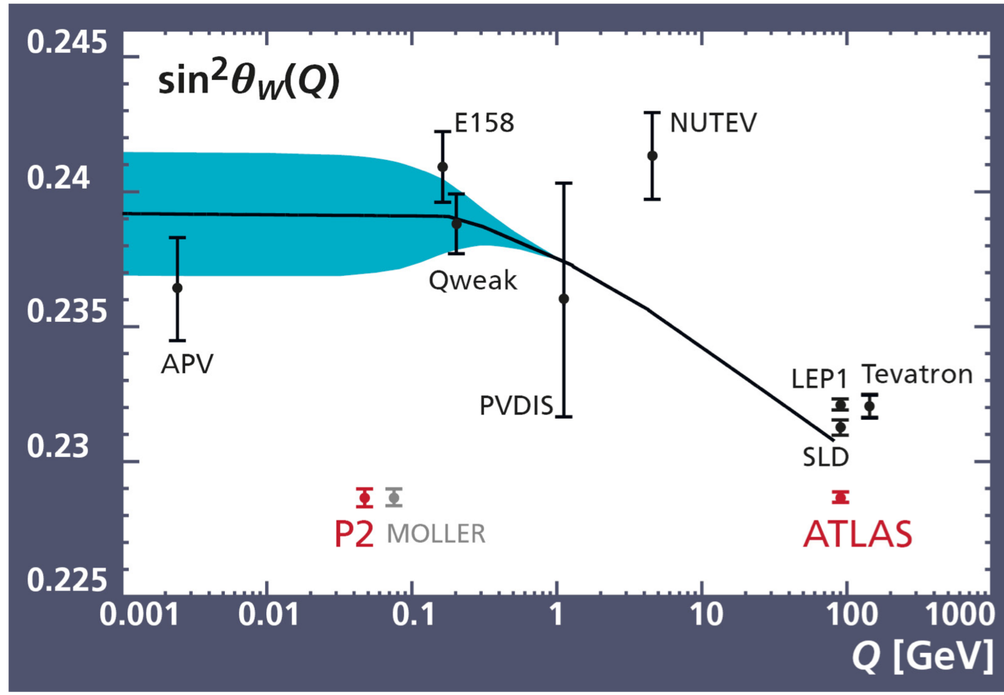
SM: universal quantum corrections leads to a scale dependent, „running“ $\sin^2\theta_W(Q)$



Sensitivity to new beyond SM physics:



contact int: $\Lambda_{new} \approx 17$ TeV (E158@SLAC)

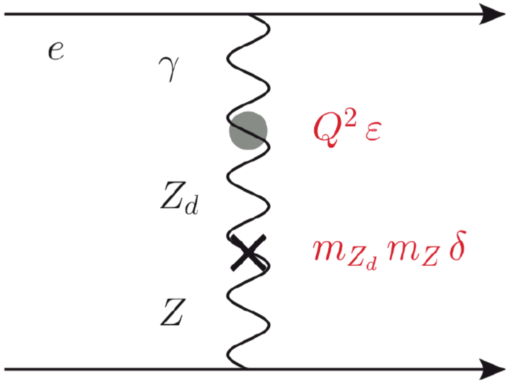


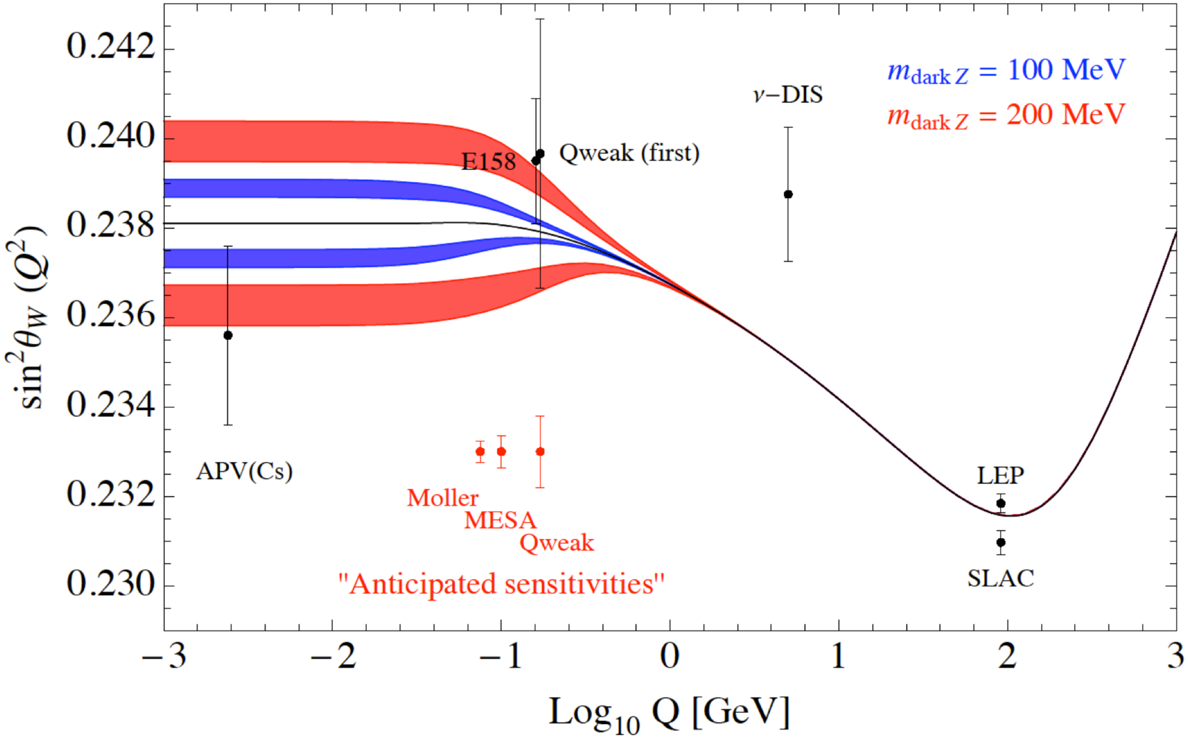
P2@MESA: 0.13 % measurement of $\sin^2\theta_W$
$\Lambda_{new} \approx$ **49 TeV**

exceeding scale in direct LHC searches
complementarity with precision searches @ LHC

Running of $\sin^2\theta_W$: New Physics Search

Marciano (2014)





MESA Accelerator

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA
JG|U

Mainz Energy-Recovering Superconducting Accelerator

Extracted Beam Mode

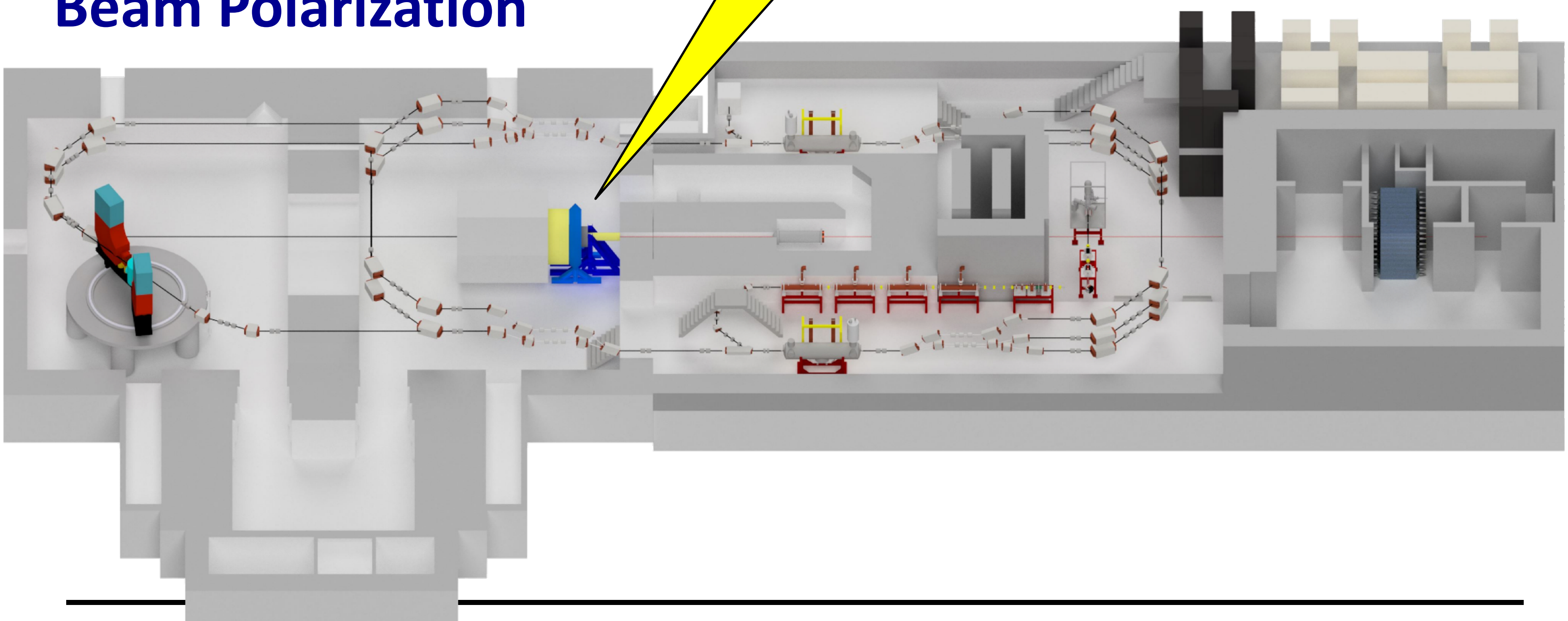
E_{max} = 155 MeV

I_{max} = 150 µA

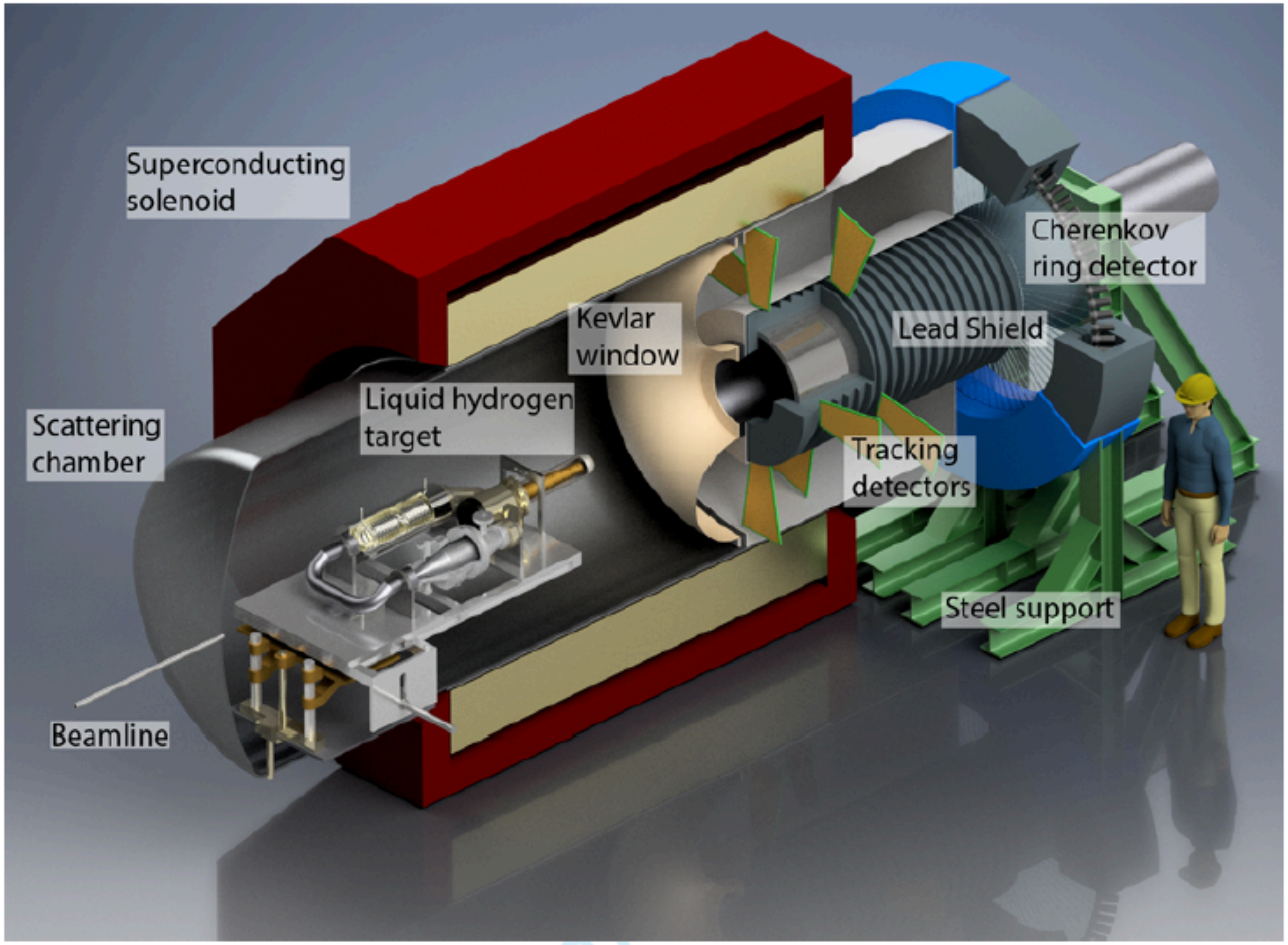
Beam Polarization

Mode 1:
Extracted Beam
P2 Experiment

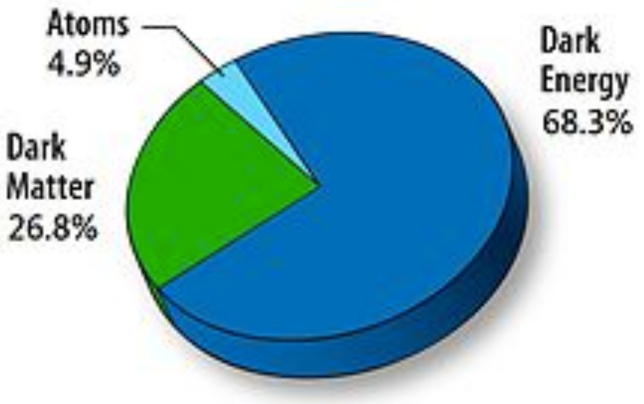
3 recirculations → 6 passes through SRF cavities



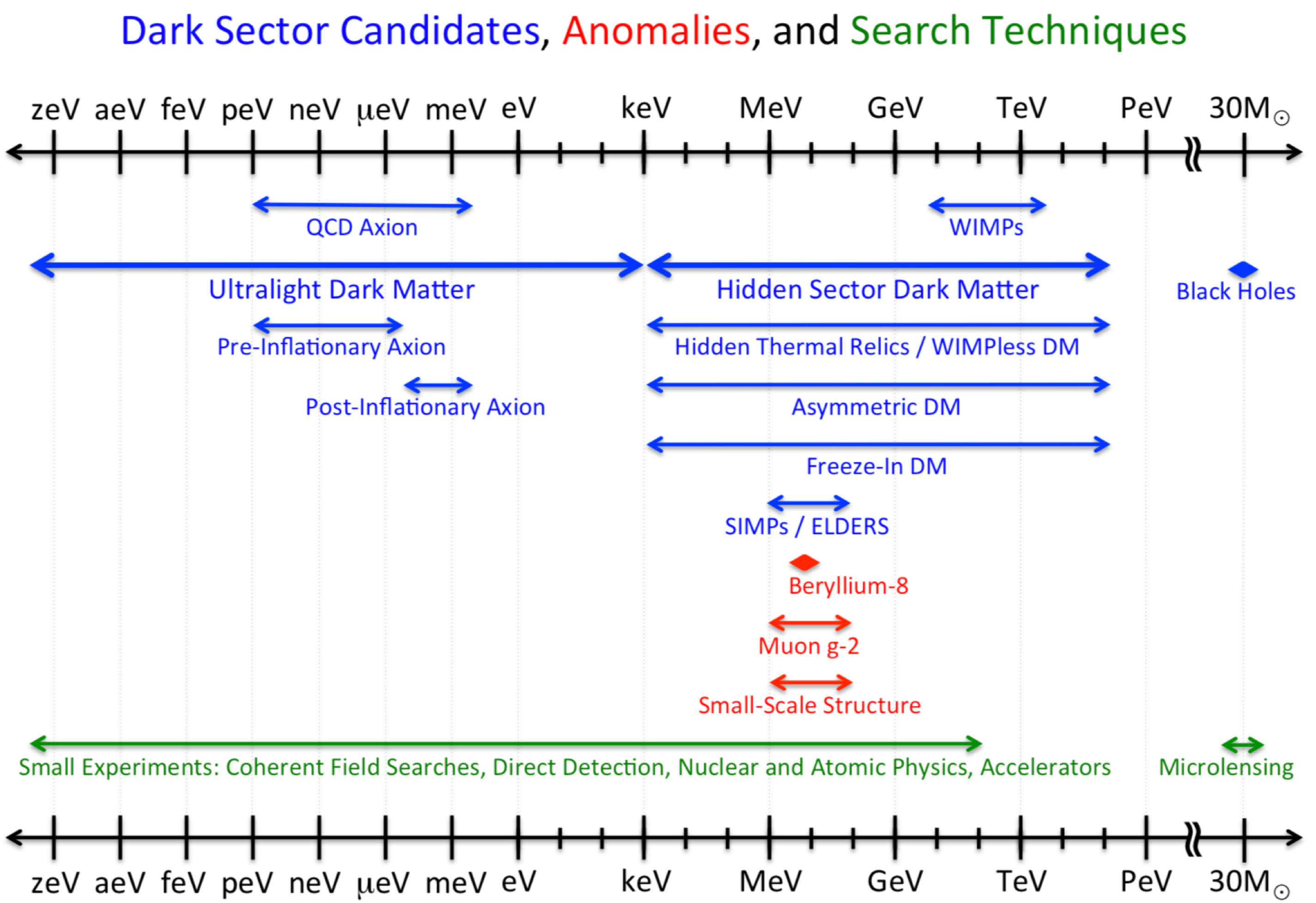
A Low-Q^2 Measurement of $\sin^2\theta_W$ at MESA



Search for a
Dark Photon &
Light dark matter



Dark Sector searches: worldwide effort

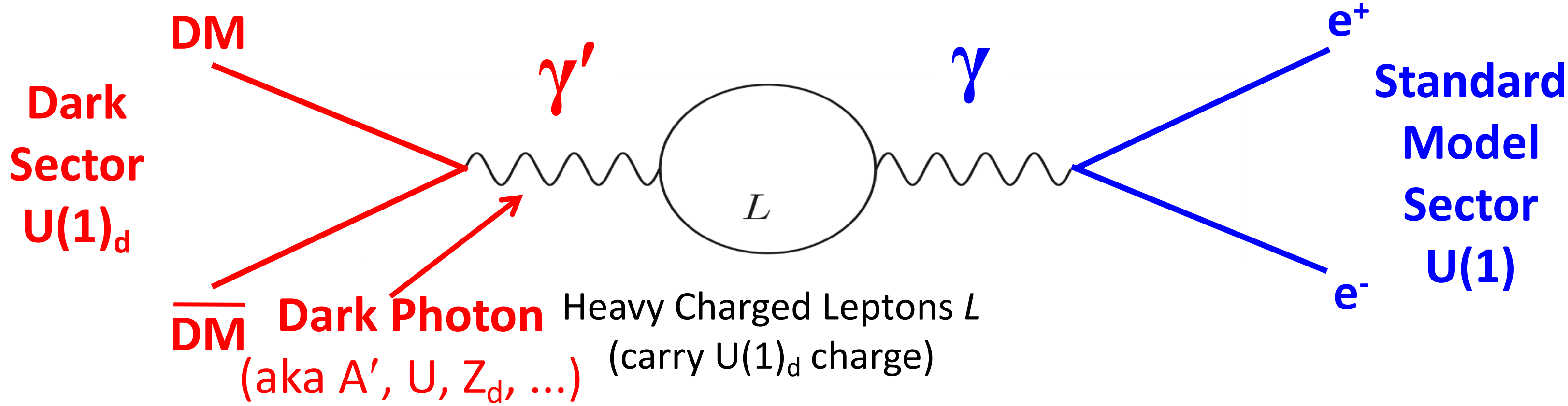


US cosmic visions Community Report: arXiv1707:04591 [hep-ph]

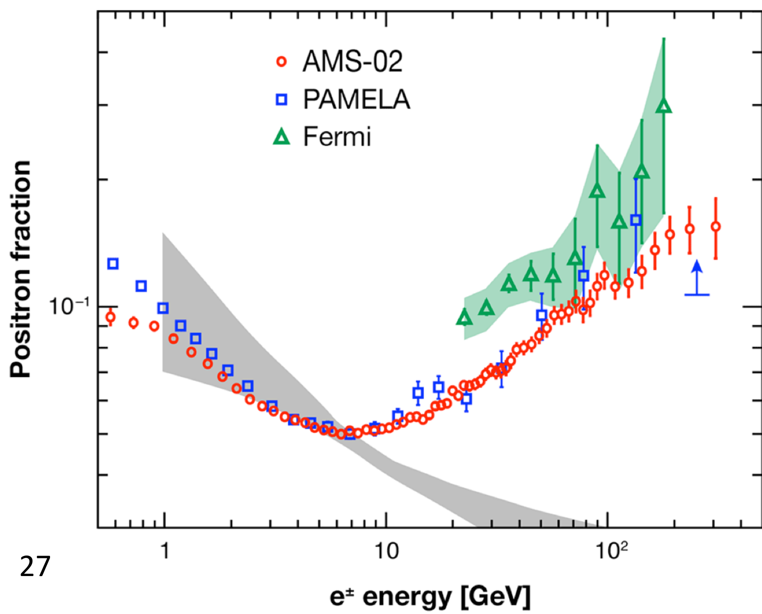
Kinetic Mixing: Dark photon/Dark Matter

A way to relate the dark sector to the SM (coupling ~ ε²)

Holdom (1986)

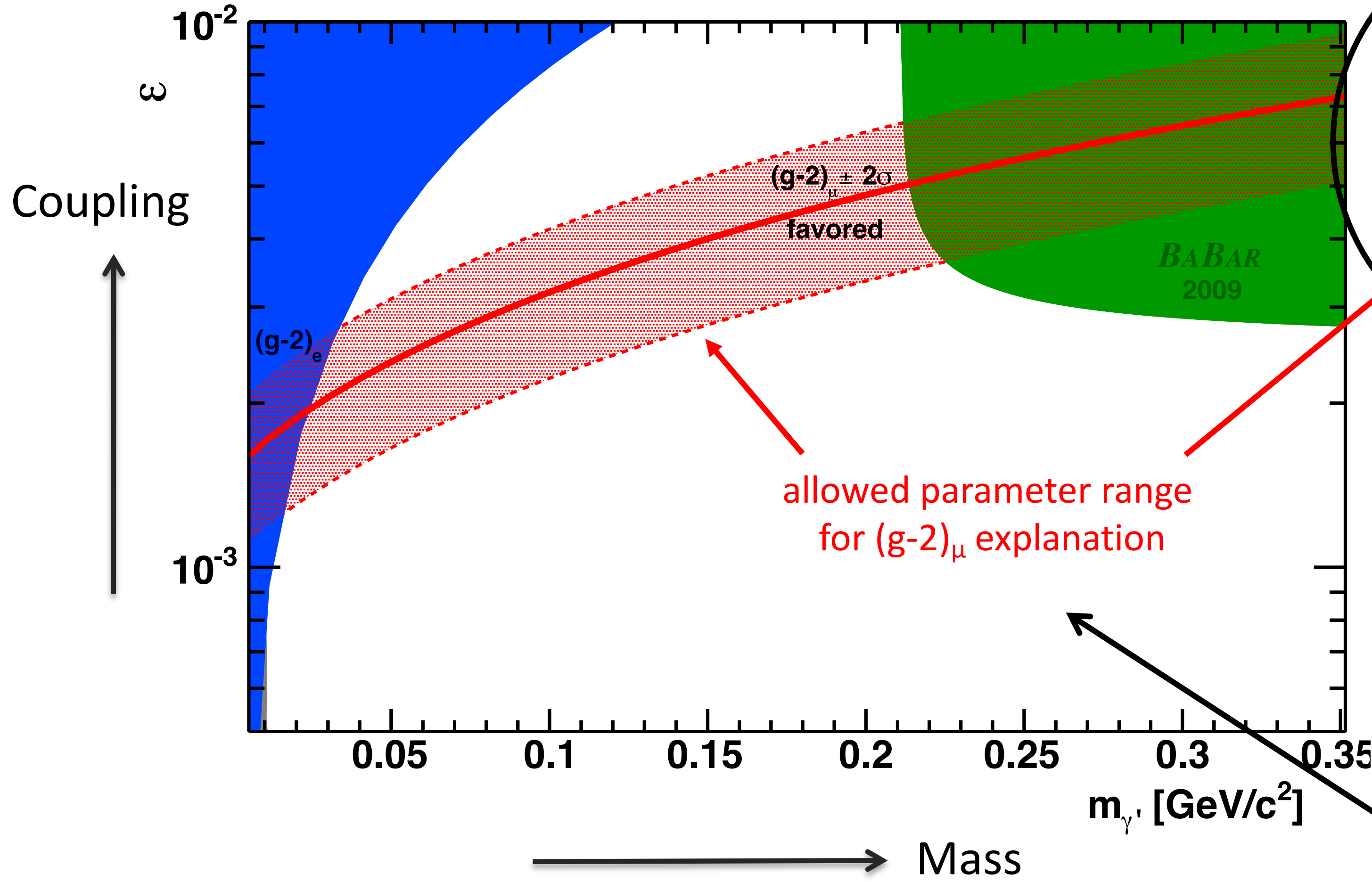


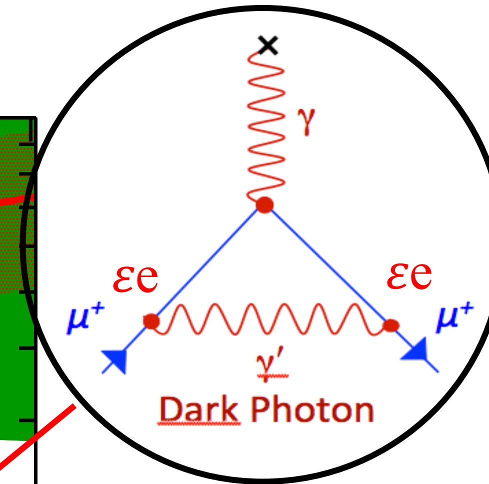
Excess of positrons in cosmic ray spectrum due to Dark Matter annihilation?



Dark Photon Status in 2010

Year 2010





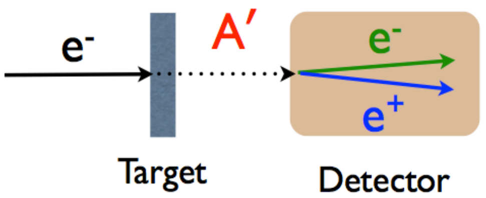
Pospelov (2008)

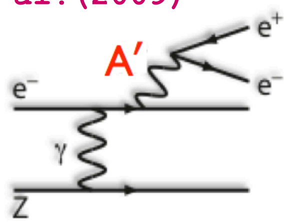
terra incognita
white region
motivated by
dark matter !

Results from past years

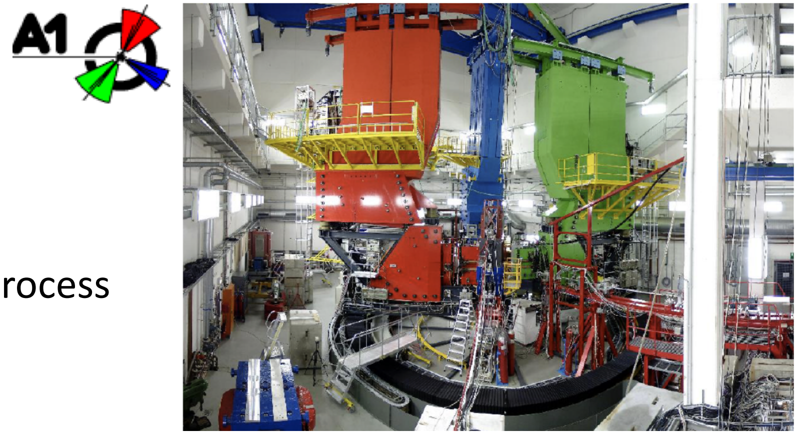
Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search

Bjorken et al. (2009)

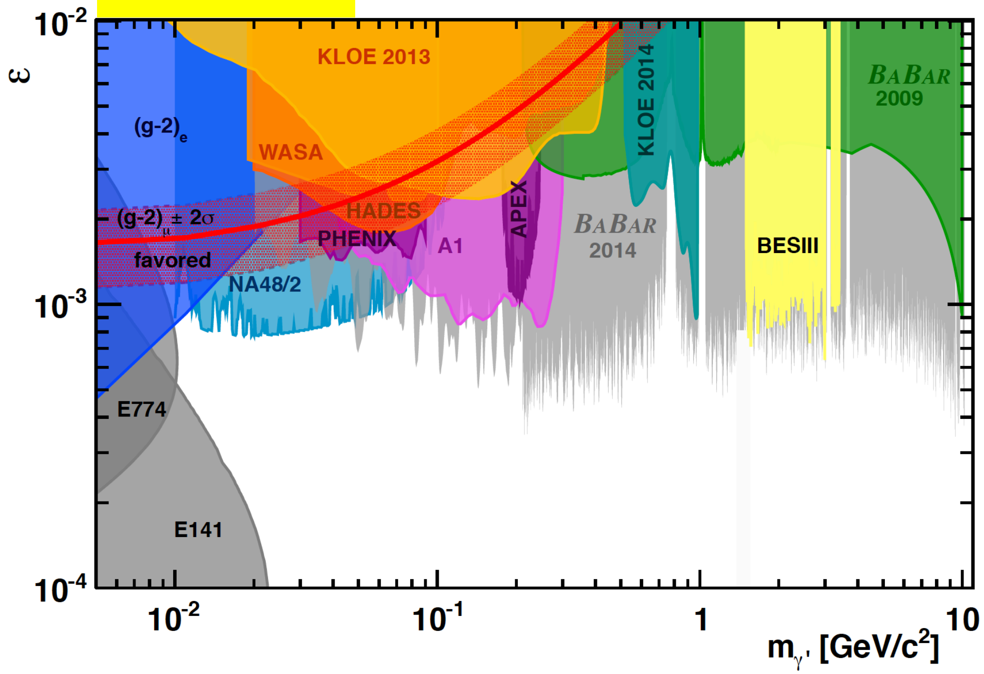




Bethe-Heitler type process



Year 2015



Dark Photon as explanation for $(g\text{-}2)_\mu$ (almost) ruled out !

… at least in most straight-forward model

Low-mass range will be covered by MESA project

MESA Accelerator

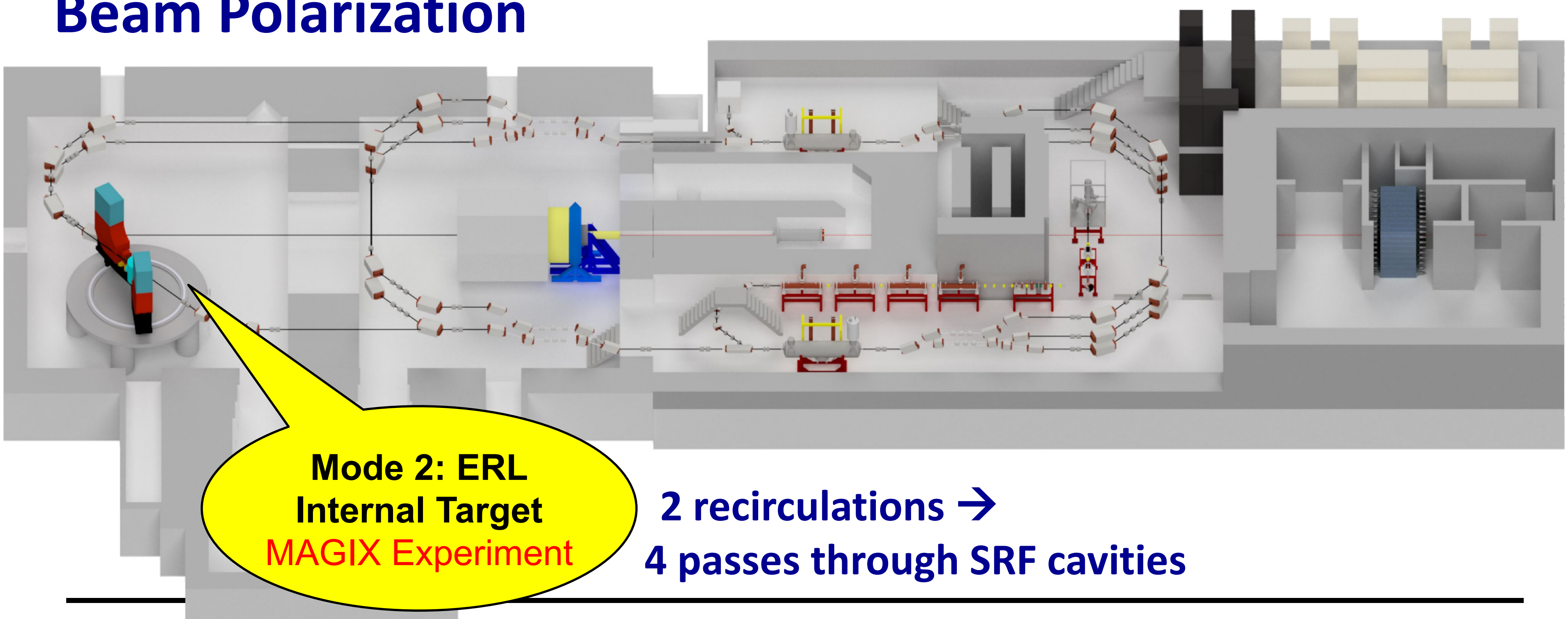
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL Mode

E_{max} = 105 MeV

I_{max} > 1 mA

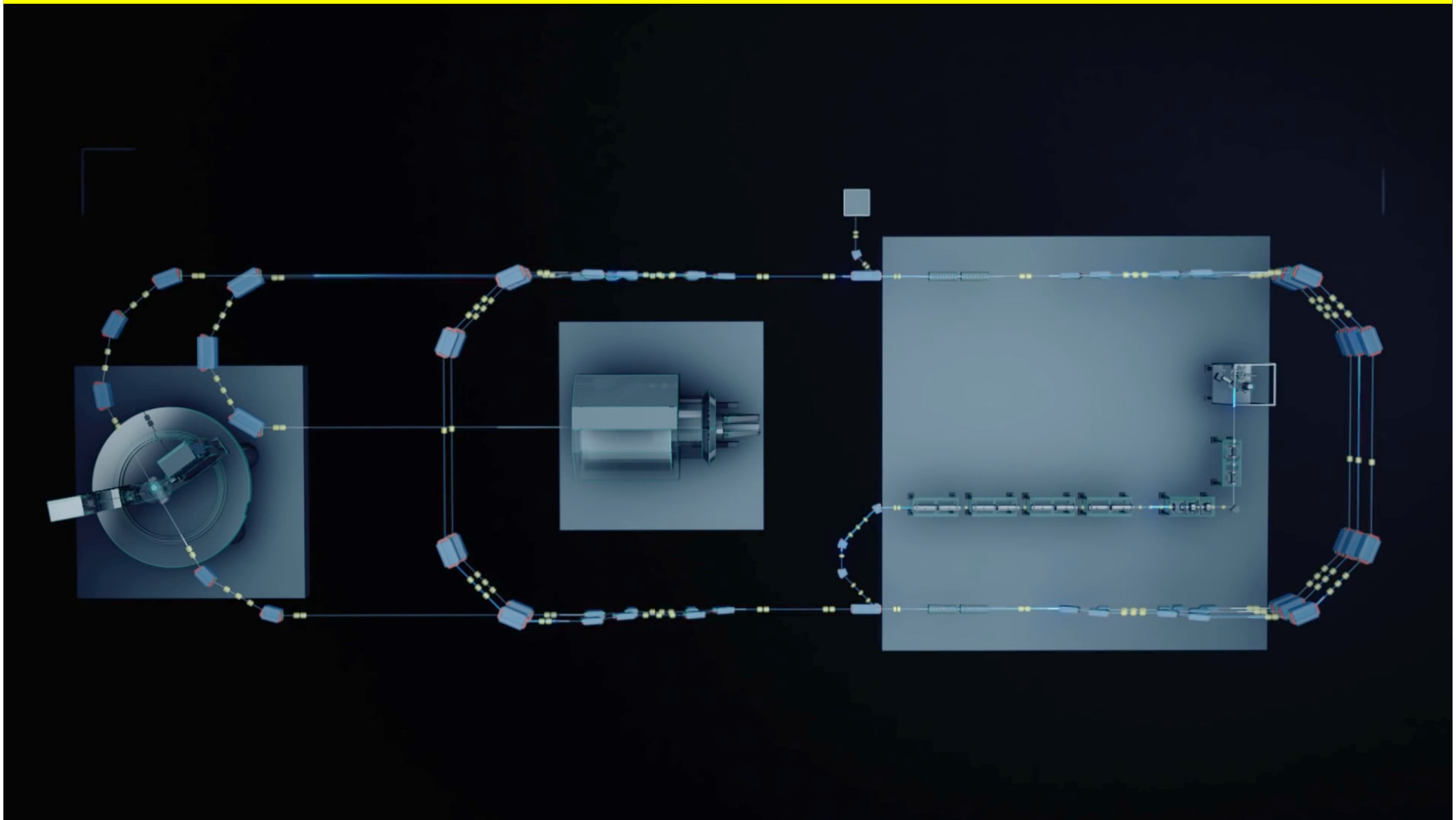
Beam Polarization



2 recirculations →
4 passes through SRF cavities

Internal Expt. MAGIX @ MESA ERL Mode

Operation of a high-intensity (polarized) ERL beam
in conjunction with light internal target
→ a novel technique in nuclear and particle physics
→ precise measurement of low momenta tracks at competitive luminosities

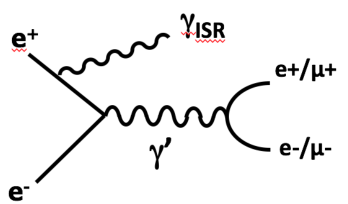


Dark Sector Searches at MAGIX

Visible Dark Photon Model

$M_{Dark\ Photon} << M_{Dark\ Matter}$

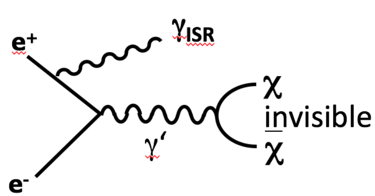
Dark Photon decaying into SM particles

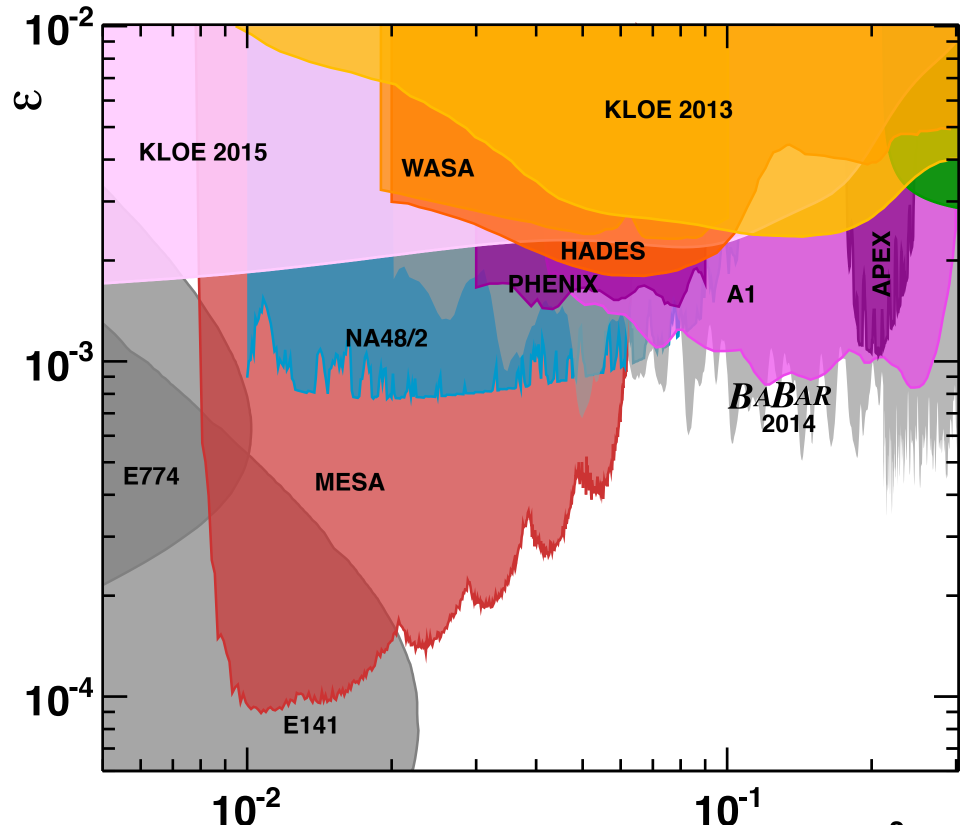


Invisible Dark Photon Model

$M_{Dark\ Photon} > M_{Dark\ Matter}$

Dark Photon decaying into Dark matter particles



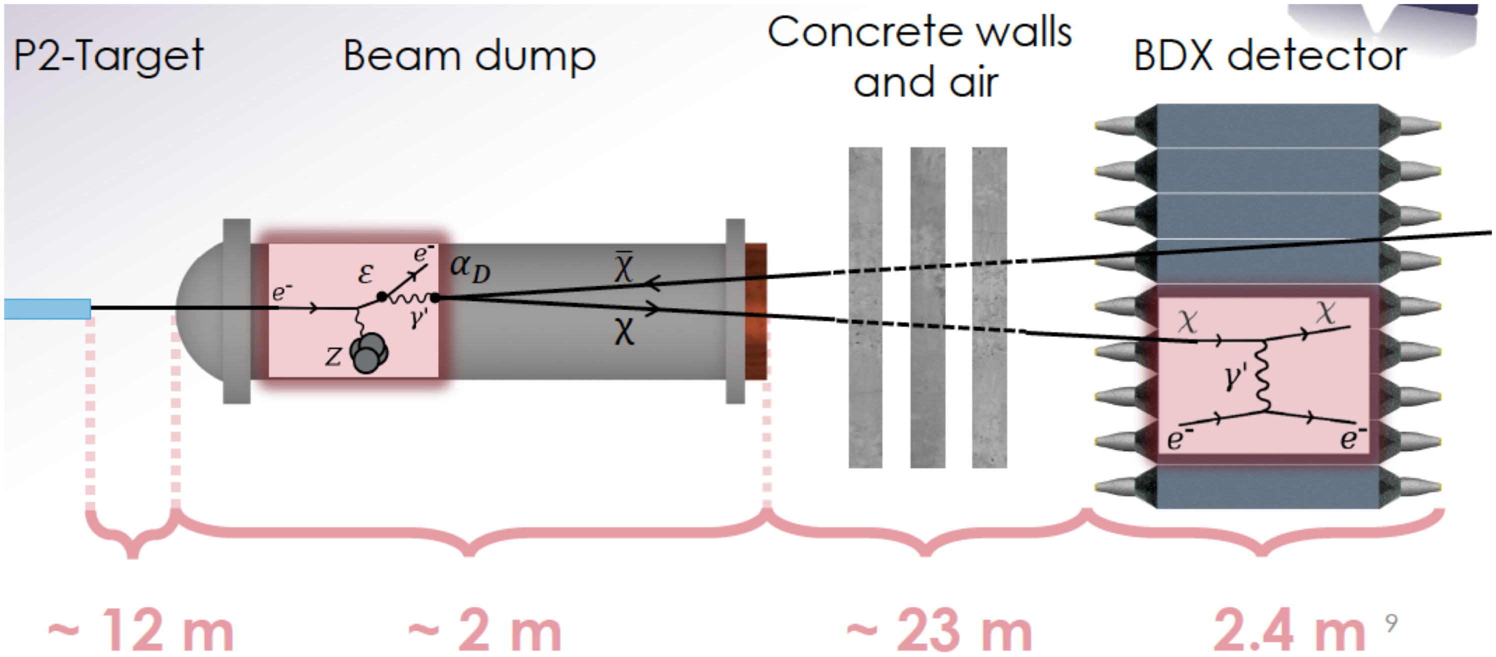


Features:

- Xe gas target
- Luminosity $10^{35}\ cm^{-2}s^{-1}$
- 6 month of data taking

Beam Dump Experiment (BDX) @ MESA

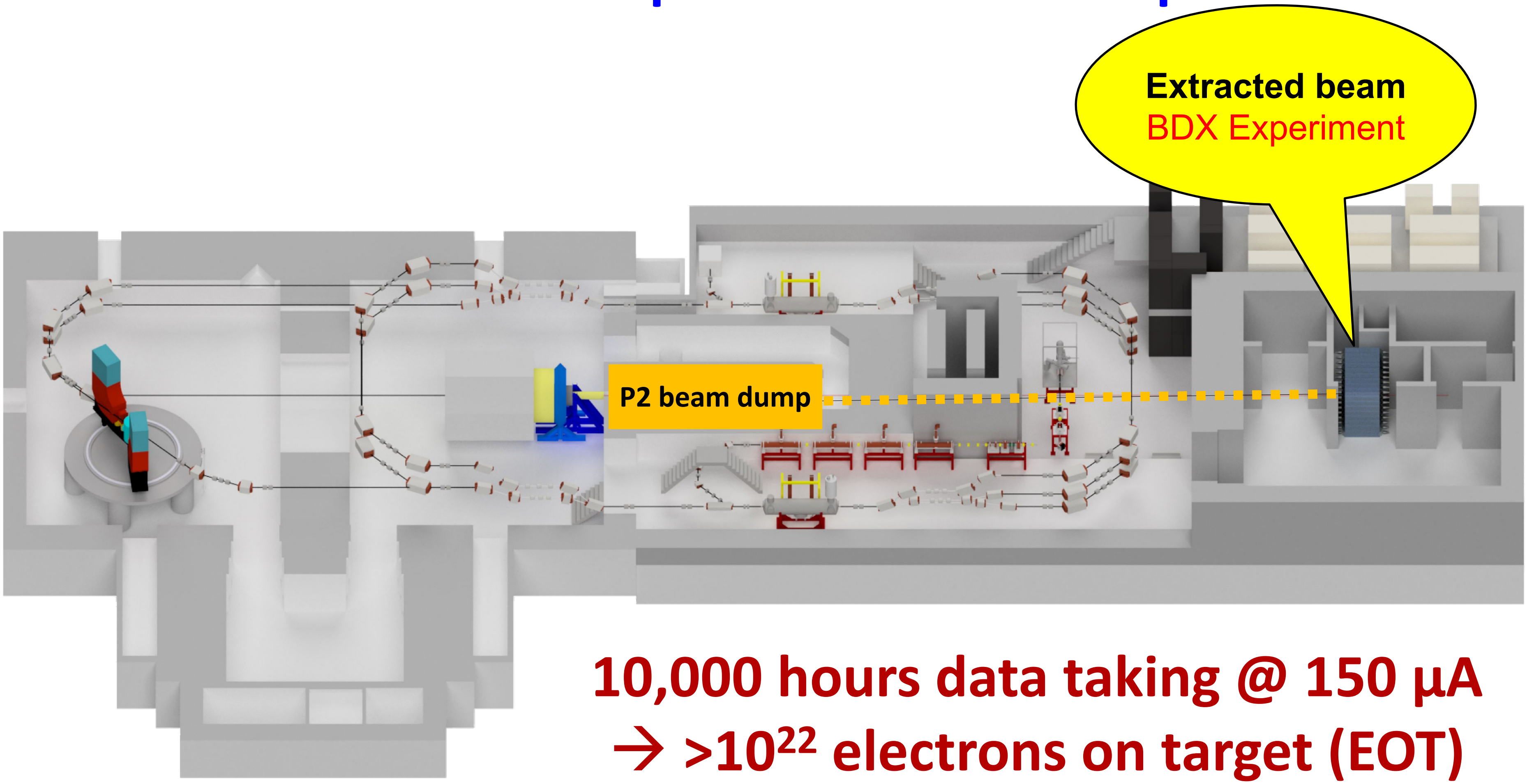
Electron Scattering (MESA) on Beam Dump
→ Collimated pair of Dark Matter particles !



10,000 hours data taking @ 150 μA
→ >10^{22} electrons on target (EOT)

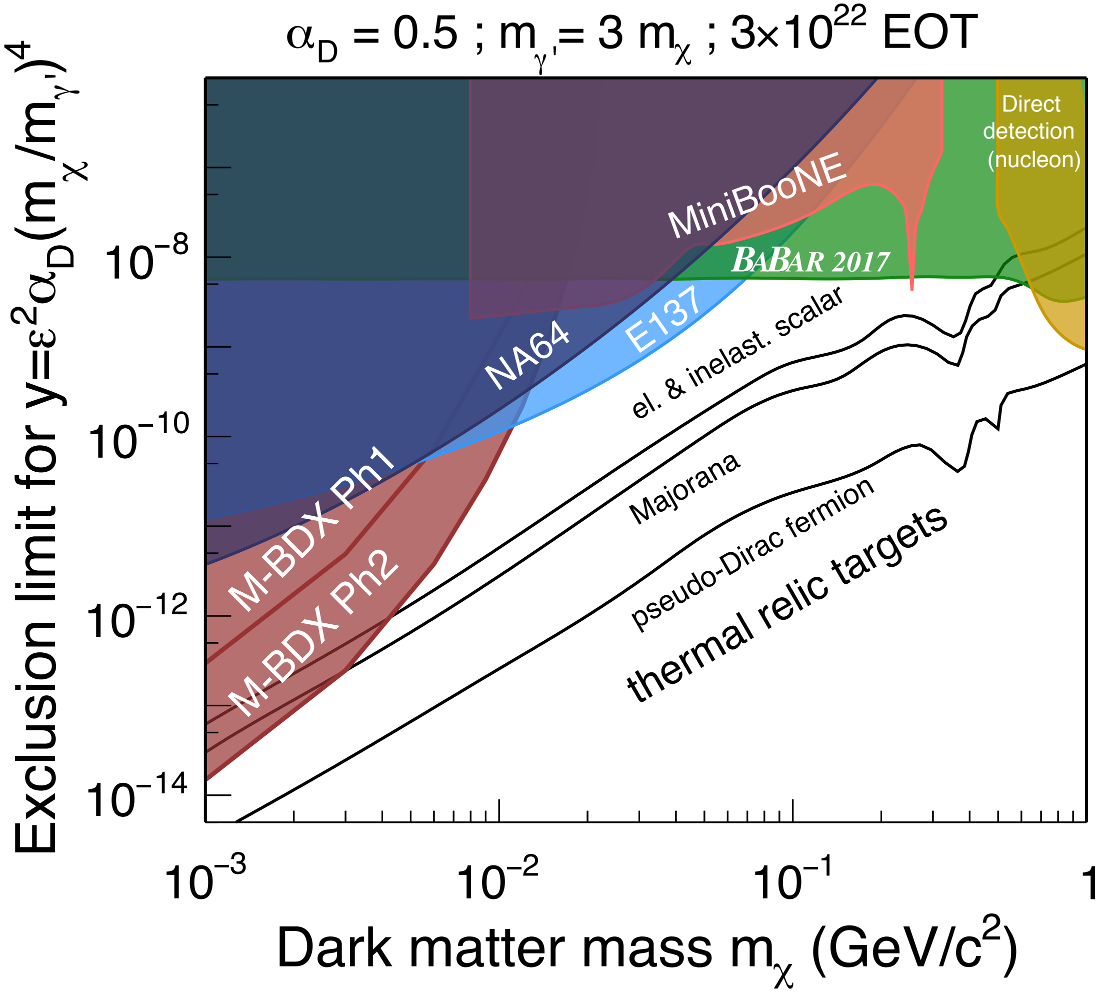
Beam Dump Experiment (BDX) @ MESA

Electron Scattering (MESA) on Beam Dump
→ Collimated pair of Dark Matter particles !



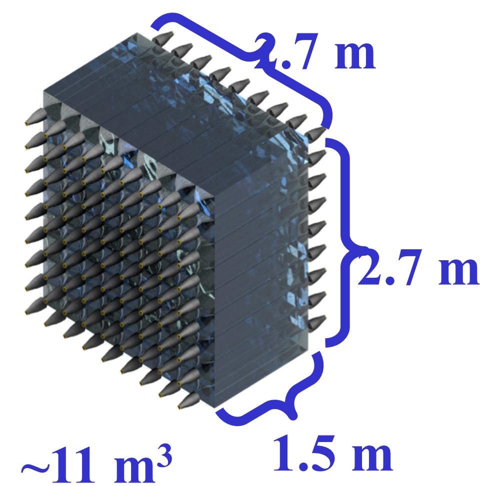
10,000 hours data taking @ 150 μA
→ >10^{22} electrons on target (EOT)

Beam Dump Experiment (BDX) @ MESA

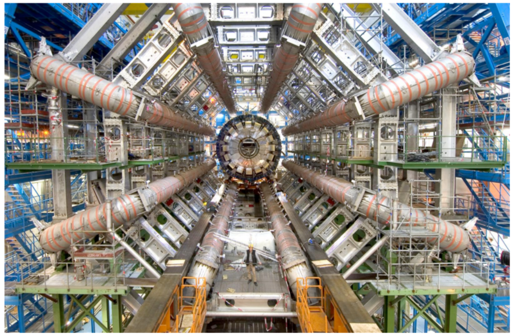


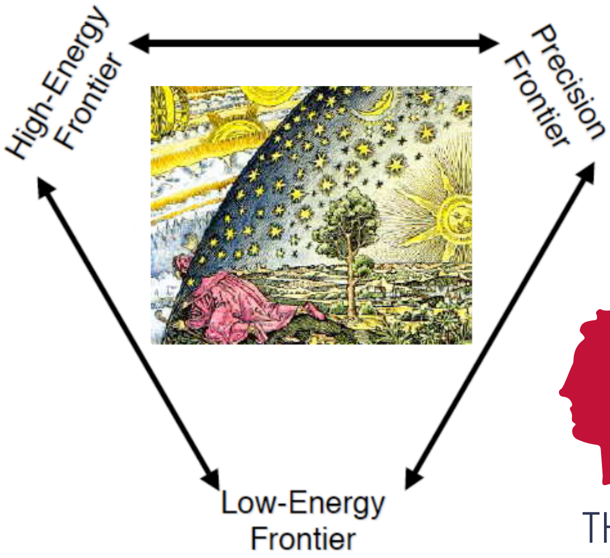
Detector layouts:

- Phase 1: existing PbF2 crystals of A4 experiment ($0.13\ m^3$ volume)
- Phase 2: $11 m^3$ Leadglass calorimeter



Conclusions

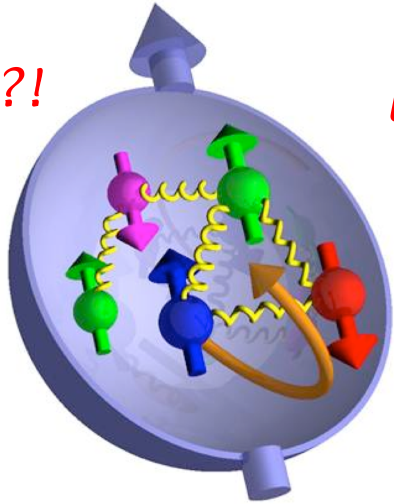




SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Puzzles at low Energies ?!

- Proton Radius
- $(g\text{-}2)_\mu$
- Dark Photon



Low Energy experiments study the structure of particles and more than that !

→ *New tools: MESA*