Electroweak Physics and Fundamental Symmetries

Jens Erler (IF–UNAM)

IUPAP WG.9 Nuclear Science Symposium

LN di Frascati, Italy *31 May 2013*

Outline

Outline

- Introduction (SM and generalities)

Outline

- Introduction (SM and generalities)
- Neutrino mass

Outline

- Introduction (SM and generalities)
- Neutrino mass
- Parity-violating and neutrino scattering

Outline

- Introduction (SM and generalities)
- Neutrino mass
- Parity-violating and neutrino scattering
- Dipole moments

Outline

- Introduction (SM and generalities)
- Neutrino mass
- Parity-violating and neutrino scattering
- Dipole moments
- Flavor violation

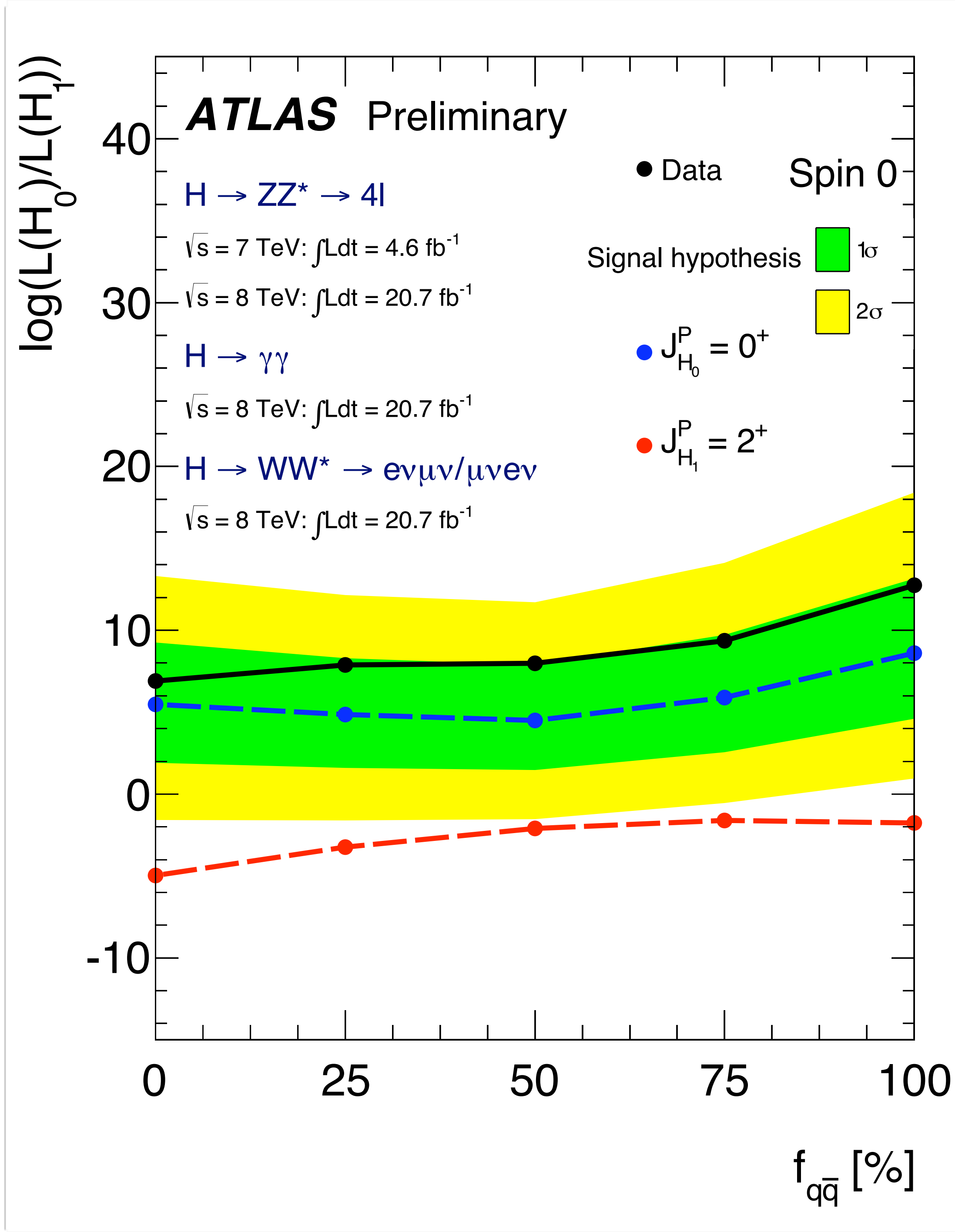
Outline

- Introduction (SM and generalities)
- Neutrino mass
- Parity-violating and neutrino scattering
- Dipole moments
- Flavor violation
- Conclusions

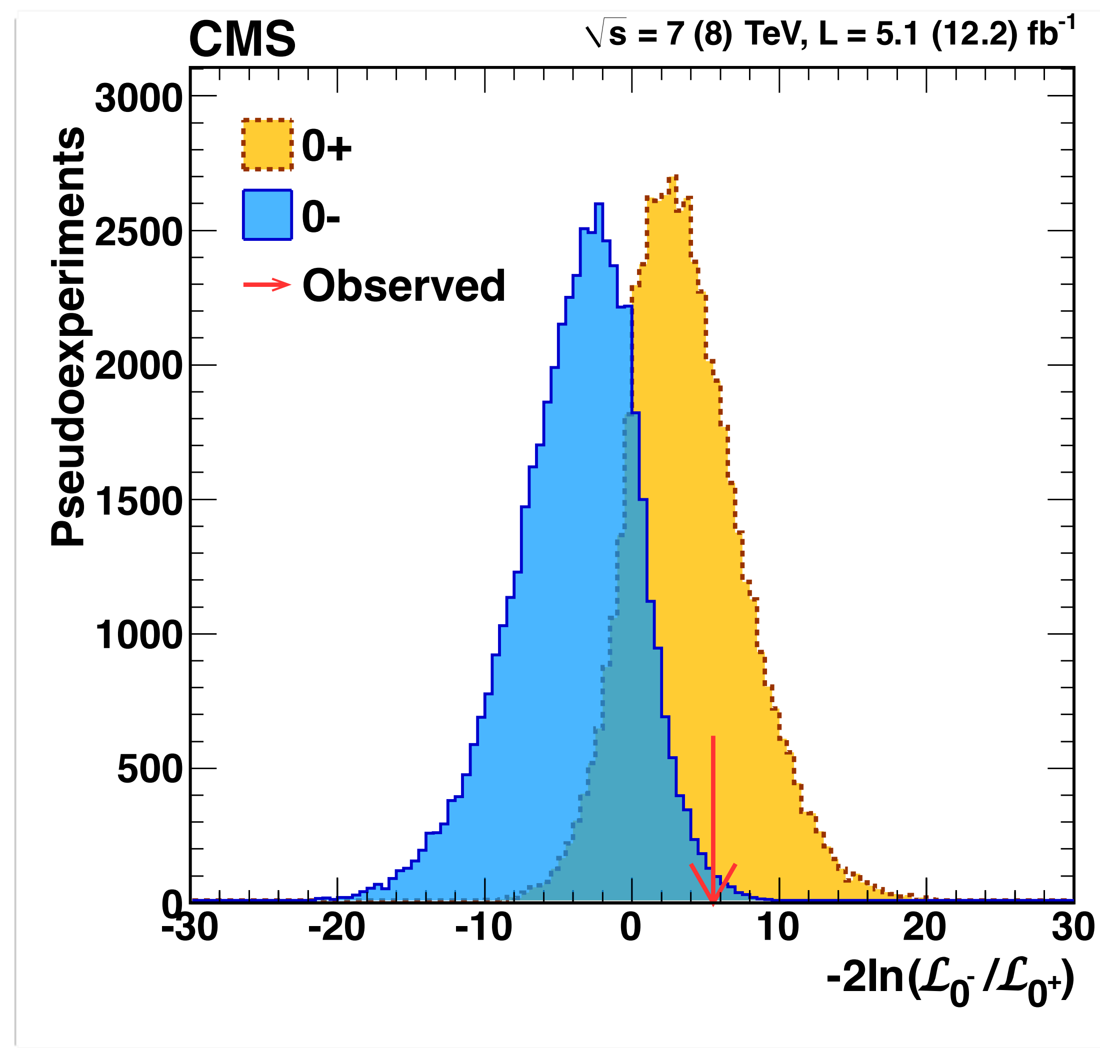
Table of the Elementary Particles

ν_τ s=½ ~ 0	τ^- s=½ 1.9075	τ^+ s=½ 1.9075	t s=½ 176	t s=½ 176	t s=½ 176	$\bar{t}$ s=½ 176	$\bar{t}$ s=½ 176	$\bar{t}$ s=½ 176	b s=½ 4.5	b s=½ 4.5	b s=½ 4.5	$\bar{b}$ s=½ 4.5	$\bar{b}$ s=½ 4.5	$\bar{b}$ s=½ 4.5
ν_μ s=½ ~ 0	μ^- s=½ 0.11343	μ^+ s=½ 0.11343	c s=½ 1.4	c s=½ 1.4	c s=½ 1.4	$\bar{c}$ s=½ 1.4	$\bar{c}$ s=½ 1.4	$\bar{c}$ s=½ 1.4	s s=½ 0.1	s s=½ 0.1	s s=½ 0.1	$\bar{s}$ s=½ 0.1	$\bar{s}$ s=½ 0.1	$\bar{s}$ s=½ 0.1
ν_e s=½ ~ 0	e^- s=½ 0.00055	e^+ s=½ 0.00055	u s=½ 0.003	u s=½ 0.003	u s=½ 0.003	$\bar{u}$ s=½ 0.003	$\bar{u}$ s=½ 0.003	$\bar{u}$ s=½ 0.003	d s=½ 0.005	d s=½ 0.005	d s=½ 0.005	$\bar{d}$ s=½ 0.005	$\bar{d}$ s=½ 0.005	$\bar{d}$ s=½ 0.005
H s=0 134	$H^\pm$ s=0 86.3 ξ	Z s=1 97.9	W^- s=1 86.3	W^+ s=1 86.3	g |h|=1 0	g |h|=1 0	g |h|=1 0	g |h|=1 0	g |h|=1 0	g |h|=1 0	g |h|=1 0	g |h|=1 0	γ |h|=1 0	G |h|=2 0

Spin-parity of very Higgs-like state at LHC



- ATLAS disfavors a *specific* spin 2 alternative (massive graviton) at > 99.9% CL
- CMS excludes pseudoscalar with 97.6% CL



SM interactions

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^{\pm}$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^\pm$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^\pm$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^\pm$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^\pm$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$
- QED (γ): charged leptons, all quarks and antiquarks, $W^\pm$ (charge e)

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^\pm$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^\pm$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$
- QED (γ): charged leptons, all quarks and antiquarks, $W^\pm$ (charge e)
- QCD (g) Yang-Mills interaction + θ_{QCD}-term : quarks and antiquarks (g_s)

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) $V-A$ interactions ($W^{\pm}$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^{\pm}$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$
- QED (γ): charged leptons, all quarks and antiquarks, $W^{\pm}$ (charge e)
- QCD (g) Yang-Mills interaction + θ_{QCD}-term : quarks and antiquarks (g_s)
- Yukawa couplings ($H\bar{\psi}\psi$): all massive fermions (except neutrinos?)

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^\pm$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^\pm$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$
- QED (γ): charged leptons, all quarks and antiquarks, $W^\pm$ (charge e)
- QCD (g) Yang-Mills interaction + θ_{QCD}-term : quarks and antiquarks (g_s)
- Yukawa couplings ($H\bar{\psi}\psi$): all massive fermions (except neutrinos?)
- scalar potential interactions ($[H^*H]^2$): H

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^\pm$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^\pm$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$
- QED (γ): charged leptons, all quarks and antiquarks, $W^\pm$ (charge e)
- QCD (g) Yang-Mills interaction + θ_{QCD}-term : quarks and antiquarks (g_s)
- Yukawa couplings ($H\bar{\psi}\psi$): all massive fermions (except neutrinos?)
- scalar potential interactions ($[H^*H]^2$): H
- non-renormalizable interactions consistent with the gauge symmetries

SM interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y \times SO(1,3)$ gauge theory

- weak charged current (CC) V−A interactions ($W^\pm$): left-handed leptons and quarks and their right-handed antiparticles (gauge parameter g)
- neutral current (NC) interactions (Z): all fermions, $W^\pm$, described by fundamental parameter $\sin^2\theta_W$ where $e = g \sin\theta_W = g' \cos\theta_W$
- QED (γ): charged leptons, all quarks and antiquarks, $W^\pm$ (charge e)
- QCD (g) Yang-Mills interaction + θ_{QCD}-term : quarks and antiquarks (g_s)
- Yukawa couplings ($H\bar{\psi}\psi$): all massive fermions (except neutrinos?)
- scalar potential interactions ($[H^*H]^2$): H
- non-renormalizable interactions consistent with the gauge symmetries
- gravitational interaction (G): all (Planck length $\kappa_P = \sqrt{8\pi G_N}$)

Dynamic symmetries

Dynamic symmetries

- reductionist view (Weinberg):
    - we observe what should be expected except supersymmetry
    - origin of equivalence principle and gauge symmetries understood
    - these are renormalizable

Dynamic symmetries

- reductionist view (Weinberg):
  - we observe what should be expected except supersymmetry
  - origin of equivalence principle and gauge symmetries understood
  - these are renormalizable
- Lorentz invariance at the quantum level $\Rightarrow$ QFT (our tool) and dynamic symmetries (yielding our most cherished theories):
  - spin 1: gauge invariance (exact, realized in Goldstone mode)
  - spin 2: general coordinate and local Lorentz invariance (equivalence principle, exact, realized in Wigner mode)
  - spin 3/2: supersymmetry (explicitly broken in models, realized?)

Dynamic symmetries

- reductionist view (Weinberg):
  - we observe what should be expected except supersymmetry
  - origin of equivalence principle and gauge symmetries understood
  - these are renormalizable
- Lorentz invariance at the quantum level ⇒ QFT (our tool) and dynamic symmetries (yielding our most cherished theories):
  - spin 1: gauge invariance (exact, realized in Goldstone mode)
  - spin 2: general coordinate and local Lorentz invariance (equivalence principle, exact, realized in Wigner mode)
  - spin 3/2: supersymmetry (explicitly broken in models, realized?)
- the higher the spin the more complicated the interactions, but the better our understanding

Discrete symmetries

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)
- CP: accidentally small effects in SM (window to 100 PeV scale)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)
- CP: accidentally small effects in SM (window to 100 PeV scale)
- T: electric dipole moments (EDMs)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)
- CP: accidentally small effects in SM (window to 100 PeV scale)
- T: electric dipole moments (EDMs)
- CLFV: negligible in SM (window to multi-PeV scale)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)
- CP: accidentally small effects in SM (window to 100 PeV scale)
- T: electric dipole moments (EDMs)
- CLFV: negligible in SM (window to multi-PeV scale)
- FCNC: in SM suppressed by GIM mechanism (window to PeV scale)

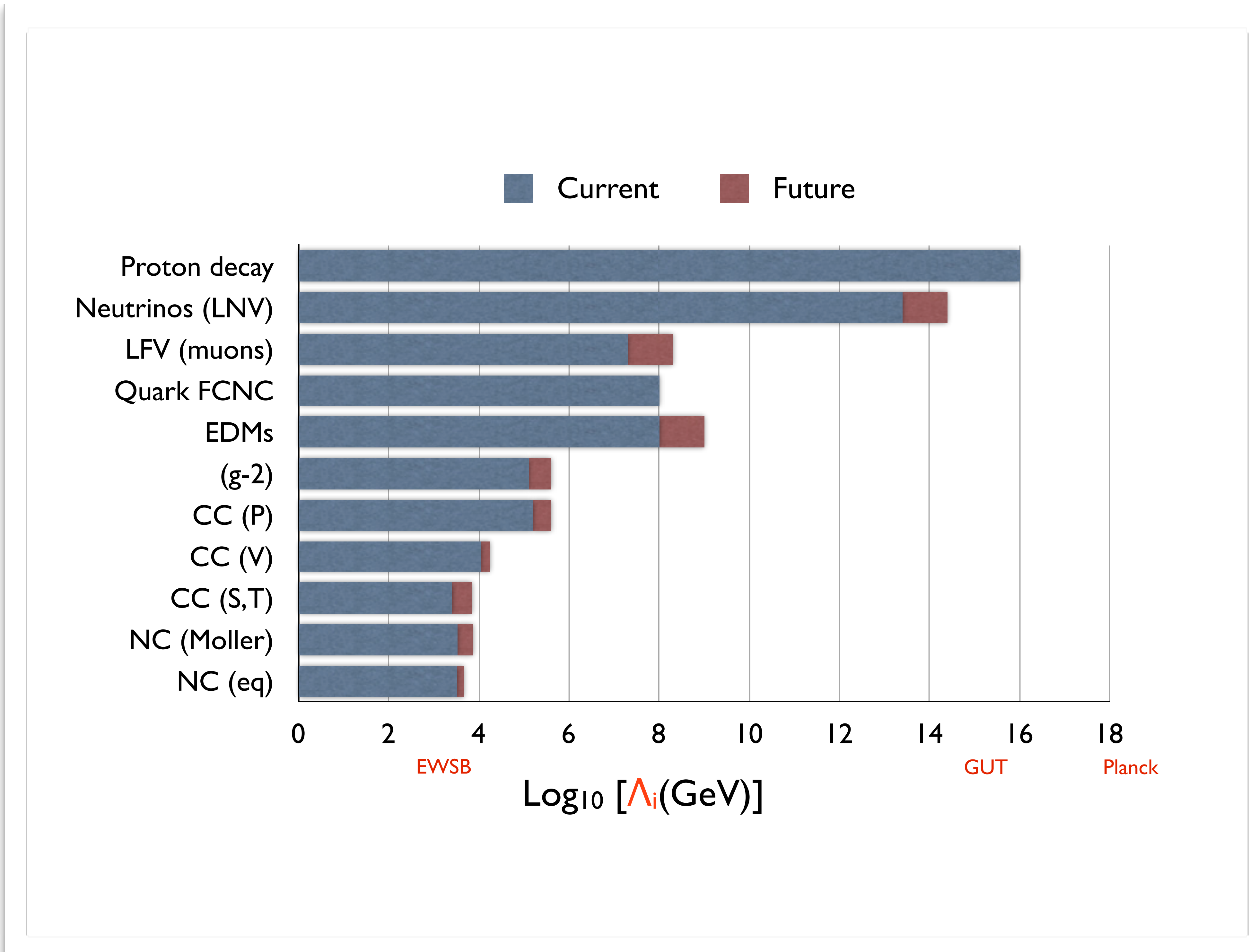
Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)
- CP: accidentally small effects in SM (window to 100 PeV scale)
- T: electric dipole moments (EDMs)
- CLFV: negligible in SM (window to multi-PeV scale)
- FCNC: in SM suppressed by GIM mechanism (window to PeV scale)
- FCCC: unitarity and universality tests (window to 10 TeV scale)

Discrete symmetries

- CPT: predicted, exact (window to Planck scale)
- B: accidentally exact at renormalizable level; if violated then p-decay and $n\bar{n}$-oscillations (window to sub-Planck scale)
- L: accidentally exact at renormalizable level; if violated then $0\nu\beta\beta$-decay (window to GUT scale)
- CP: accidentally small effects in SM (window to 100 PeV scale)
- T: electric dipole moments (EDMs)
- CLFV: negligible in SM (window to multi-PeV scale)
- FCNC: in SM suppressed by GIM mechanism (window to PeV scale)
- FCCC: unitarity and universality tests (window to 10 TeV scale)
- P: polarized e^--scattering, APV (window to multi-TeV scale)

Cirigliano, Ramsey-Musolf 2013



Mysteries

Mysteries

- naturalness of fundamental scales
  - cosmological constant
  - Fermi scale (Higgs vacuum expectation value, v)
  - stabilizing v (Planck−weak hierarchy) quite generically implies rich new physics at the EW scale or slightly above
  - in most models designed to address or solve the hierarchy problem, there is a dark matter candidate with desired properties

Mysteries

- naturalness of fundamental scales
  - cosmological constant
  - Fermi scale (Higgs vacuum expectation value, v)
  - stabilizing v (Planck−weak hierarchy) quite generically implies rich new physics at the EW scale or slightly above
  - in most models designed to address or solve the hierarchy problem, there is a dark matter candidate with desired properties
- fermion content and its consistency with SU(5) representations

Mysteries

- naturalness of fundamental scales
  - cosmological constant
  - Fermi scale (Higgs vacuum expectation value, v)
  - stabilizing v (Planck−weak hierarchy) quite generically implies rich new physics at the EW scale or slightly above
  - in most models designed to address or solve the hierarchy problem, there is a dark matter candidate with desired properties
- fermion content and its consistency with SU(5) representations
- values of the fundamental parameters or their small size
  - m_e, m_ν, θ_{QCD}, CKM mixing, …

Mysteries

- naturalness of fundamental scales
  - cosmological constant
  - Fermi scale (Higgs vacuum expectation value, v)
  - stabilizing v (Planck−weak hierarchy) quite generically implies rich new physics at the EW scale or slightly above
  - in most models designed to address or solve the hierarchy problem, there is a dark matter candidate with desired properties
- fermion content and its consistency with SU(5) representations
- values of the fundamental parameters or their small size
  - m_e, m_ν, θ_{QCD}, CKM mixing, …
- very strong arguments to pursue all possible searches for New Physics beyond the SM

NP hints from observations

NP hints from observations

- dark matter

NP hints from observations

- dark matter
- Baryon Asymmetry in the Universe (BAU)

NP hints from observations

- dark matter
- Baryon Asymmetry in the Universe (BAU)
- ν-oscillations and mass ⇒
  - non-renormalizable operator LLHH

    ν are Majorana fermions (new type of particle) ⇒ 0νββ-decay
  - right-handed ν (new particle)

    need HLν-Yukawa couplings of < $\mathcal{O}(10^{-12})$ and impose L by hand
  - or both

NP hints from observations

- dark matter
- Baryon Asymmetry in the Universe (BAU)
- ν-oscillations and mass $\Rightarrow$
  - non-renormalizable operator LLHH

    ν are Majorana fermions (new type of particle) $\Rightarrow$ $0\nu\beta\beta$-decay
  - right-handed ν (new particle)

    need $HL\nu$-Yukawa couplings of $< \mathcal{O}(10^{-12})$ and impose L by hand
  - or both
- muon $g-2$ and some other smaller SM deviations in precision observables

Example: supersymmetry (SUSY)

Example: supersymmetry (SUSY)

- a theorist's dream
  - SUSY required if massless spin 3/2 particle present
  - unique non-trivial extension of Poincaré group ***Haag, Sohnius, Łopuszański 1984***
  - only superstrings contain fermions and are free of tachyons

Example: supersymmetry (SUSY)

- a theorist's dream
  - SUSY required if massless spin 3/2 particle present
  - unique non-trivial extension of Poincaré group ***Haag, Sohnius, Łopuszański 1984***
  - only superstrings contain fermions and are free of tachyons
- phenomenology of minimal model of weak scale SUSY (MSSM)
  - perturbative stabilization of Fermi scale
  - $M_H \lesssim 130$ (150) GeV predicted in MSSM (extensions)
  - perfect one-loop gauge coupling unification (separate at two loops)
  - unification scale almost coincides with (reduced) Planck scale
  - roughly consistent with $m_b - m_\tau$ unification
  - account for muon g−2 (in a rapidly shrinking corner of parameter space)

Ideas and top-down scenarios

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory

12

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)

12

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)
- warped extra dimensions Randall, Sundrum

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)
- warped extra dimensions Randall, Sundrum
- grand unified theories

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)
- warped extra dimensions Randall, Sundrum
- grand unified theories
- anthropic principle and the landscape

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)
- warped extra dimensions Randall, Sundrum
- grand unified theories
- anthropic principle and the landscape

★ but concrete models either baroque or ruled out, most notably by precision measurements

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)
- warped extra dimensions Randall, Sundrum
- grand unified theories
- anthropic principle and the landscape

★ but concrete models either baroque or ruled out, most notably by precision measurements

- the flavor, CP and LHC problems of new physics

Ideas and top-down scenarios

- string theory (finite, predicts GR) and M-theory
- supersymmetry and supergravity
- technicolor and other strong dynamics (disfavored)
- warped extra dimensions Randall, Sundrum
- grand unified theories
- anthropic principle and the landscape

★ but concrete models either baroque or ruled out, most notably by precision measurements

- the flavor, CP and LHC problems of new physics
- need urgently guidance from experiment

Bottom-up models

Bottom-up models

- spin 0: extra Higgs doublets (THDM, SUSY)

Bottom-up models

- spin 0: extra Higgs doublets (THDM, SUSY)
- spin 1/2: extra fermions (extra generations, technicolor, ν_R)

Bottom-up models

- spin 0: extra Higgs doublets (THDM, SUSY)
- spin 1/2: extra fermions (extra generations, technicolor, ν_R)
- spin 1: extra gauge bosons (Z', W')

Bottom-up models

- spin 0: extra Higgs doublets (THDM, SUSY)
- spin 1/2: extra fermions (extra generations, technicolor, ν_R)
- spin 1: extra gauge bosons (Z', W')
- spin 3/2: gravitino (SUGRA)

Bottom-up models

- spin 0: extra Higgs doublets (THDM, SUSY)
- spin 1/2: extra fermions (extra generations, technicolor, ν_R)
- spin 1: extra gauge bosons (Z', W')
- spin 3/2: gravitino (SUGRA)
- spin 2: KK gravitons (TeV scale extra dimensions)

Bottom-up models

- spin 0: extra Higgs doublets (THDM, SUSY)
- spin 1/2: extra fermions (extra generations, technicolor, ν_R)
- spin 1: extra gauge bosons (Z', W')
- spin 3/2: gravitino (SUGRA)
- spin 2: KK gravitons (TeV scale extra dimensions)
- an uncountable number of concrete models …

Strategies

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
    - study particles which only participate in the weak interaction (ν)

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
    - study particles which only participate in the weak interaction (ν)
    - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
  - study particles which only participate in the weak interaction (ν)
  - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)
  - SM parity violation (PV) is both signal (measuring the weak mixing angle) and BG for NP searches (needs understanding with high precision and confidence)

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
  - study particles which only participate in the weak interaction (ν)
  - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)
  - SM parity violation (PV) is both signal (measuring the weak mixing angle) and BG for NP searches (needs understanding with high precision and confidence)
  - expect that TeV scale NP appears chiral with respect to part of gauge group $\Rightarrow$ PV

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
  - study particles which only participate in the weak interaction (ν)
  - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)
  - SM parity violation (PV) is both signal (measuring the weak mixing angle) and BG for NP searches (needs understanding with high precision and confidence)
  - expect that TeV scale NP appears chiral with respect to part of gauge group $\Rightarrow$ PV
  - exploit that some discrete symmetry violations are strongly suppressed or quasi-forbidden in some observables

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
  - study particles which only participate in the weak interaction (ν)
  - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)
  - SM parity violation (PV) is both signal (measuring the weak mixing angle) and BG for NP searches (needs understanding with high precision and confidence)
  - expect that TeV scale NP appears chiral with respect to part of gauge group $\Rightarrow$ PV
  - exploit that some discrete symmetry violations are strongly suppressed or quasi-forbidden in some observables
  - signal is then tantamount to the discovery of NP. Downside: what NP?

Strategies

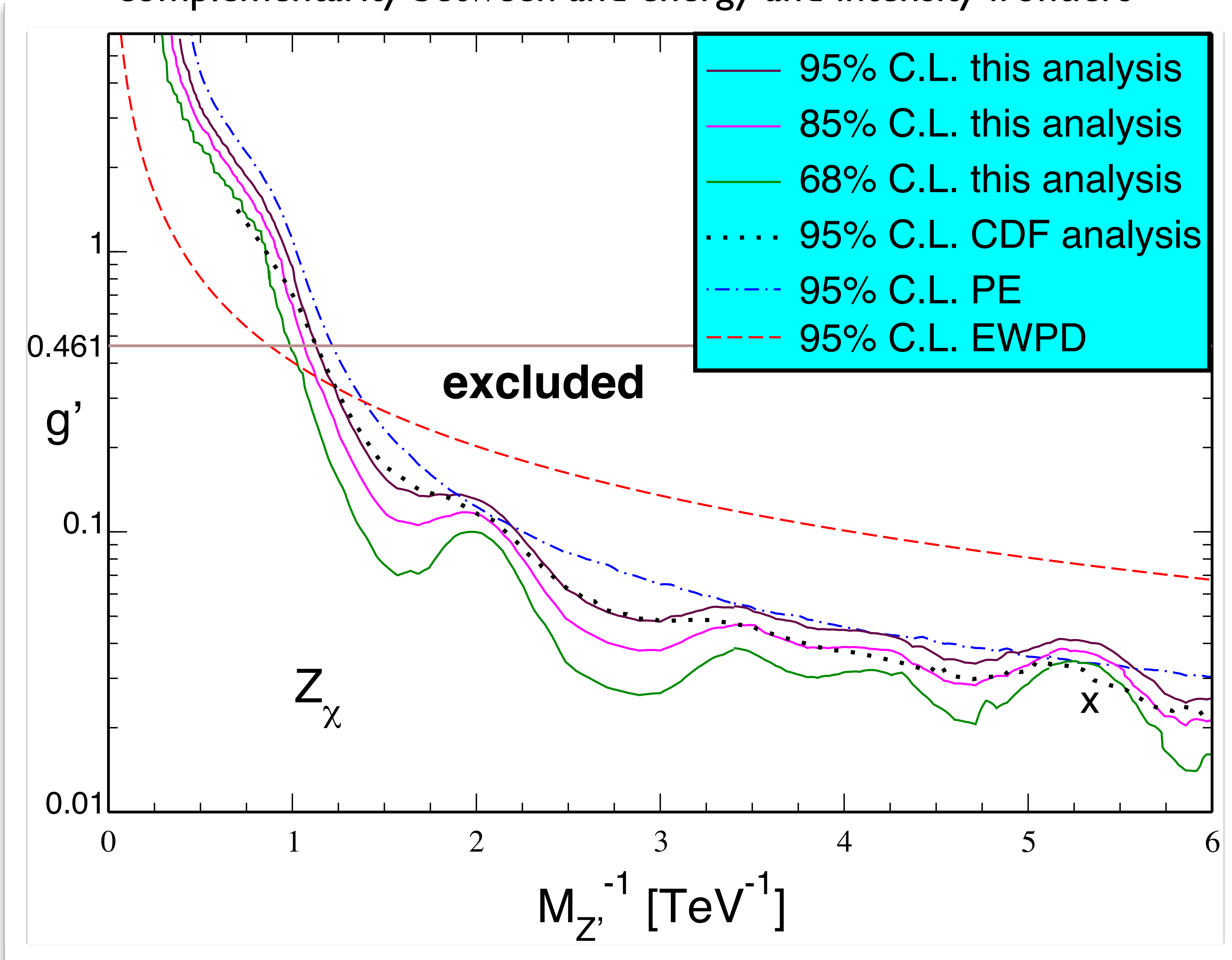
- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
  - study particles which only participate in the weak interaction (ν)
  - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)
  - SM parity violation (PV) is both signal (measuring the weak mixing angle) and BG for NP searches (needs understanding with high precision and confidence)
  - expect that TeV scale NP appears chiral with respect to part of gauge group $\Rightarrow$ PV
  - exploit that some discrete symmetry violations are strongly suppressed or quasi-forbidden in some observables
  - signal is then tantamount to the discovery of NP. Downside: what NP?
  - expect NP to introduce new sources of CP and flavor violations, as new interactions allow more complex phases which cannot be absorbed

Strategies

- discovery of new particles & precision measurements at the high energy frontier (EF): LEP, SLC, Tevatron, LHC, ILC, CLIC, VLHC, muon collider
- discovery of new effects & precision measurements at the intensity frontier (IF):
  - study particles which only participate in the weak interaction (ν)
  - exploit that only weak interaction (and θ_{QCD}-term) violates P (filters out the much stronger EM and strong forces)
  - SM parity violation (PV) is both signal (measuring the weak mixing angle) and BG for NP searches (needs understanding with high precision and confidence)
  - expect that TeV scale NP appears chiral with respect to part of gauge group $\Rightarrow$ PV
  - exploit that some discrete symmetry violations are strongly suppressed or quasi-forbidden in some observables
  - signal is then tantamount to the discovery of NP. Downside: what NP?
  - expect NP to introduce new sources of CP and flavor violations, as new interactions allow more complex phases which cannot be absorbed
  - ultra-high precision (muon $g-2$)

Erler, Langacker, Munir, Rojas 2011

complementarity between and energy and intensity frontiers



Organizing principle: effective field theory

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)
- non-observation of NP at LHC: emerging little hierarchy $v \ll \Lambda_{new}$

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)
- non-observation of NP at LHC: emerging little hierarchy $v \ll \Lambda_{new}$
- write most general Lagrangian consistent with (exact) gauge symmetries

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)
- non-observation of NP at LHC: emerging little hierarchy $v \ll \Lambda_{new}$
- write most general Lagrangian consistent with (exact) gauge symmetries
- renormalizable at any given finite order

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)
- non-observation of NP at LHC: emerging little hierarchy $v \ll \Lambda_{new}$
- write most general Lagrangian consistent with (exact) gauge symmetries
- renormalizable at any given finite order
- dimension 0 and 2: cosmological constant and hierarchy problems

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)
- non-observation of NP at LHC: emerging little hierarchy $v \ll \Lambda_{new}$
- write most general Lagrangian consistent with (exact) gauge symmetries
- renormalizable at any given finite order
- dimension 0 and 2: cosmological constant and hierarchy problems
- dimension 4: strong CP problem, $\theta_{QCD} = \mathcal{O}(10^{-10})$
  - Higgs portal: spin 0 singlet operator $(HH^*)(HH^*)$ ***Schabinger, Wells 2005***
  - ν portal: spin ½ singlet operator $HL\nu$ ***Falkowski, Juknevich, Shelton 2009***
  - U(1) portal: spin 1 singlet operator $F^{\mu\nu} F_{\mu\nu}$ ***Holdom 1986***

Organizing principle: effective field theory

- expansion in v/Λ_{new} (model independent)
- non-observation of NP at LHC: emerging little hierarchy $v \ll \Lambda_{new}$
- write most general Lagrangian consistent with (exact) gauge symmetries
- renormalizable at any given finite order
- dimension 0 and 2: cosmological constant and hierarchy problems
- dimension 4: strong CP problem, $\theta_{QCD} = \mathcal{O}(10^{-10})$
  - Higgs portal: spin 0 singlet operator $(HH^*)(HH^*)$ ***Schabinger, Wells 2005***
  - ν portal: spin ½ singlet operator $HL\nu$ ***Falkowski, Juknevich, Shelton 2009***
  - U(1) portal: spin 1 singlet operator $F^{\mu\nu} F_{\mu\nu}$ ***Holdom 1986***
- dimension 5 (unique): HHLL ($\Delta L = 2$) ***Weinberg 1979***
  → Majorana mass terms $\propto v^2/\Lambda_{new}$ (special case: seesaw mechanism)

ν oscillations and mass

ν oscillations and mass

- ν oscillation and thus ν flavor violation (νFL) has been established by the observation
  - of the disappearance of solar ($\nu_e \nrightarrow \nu_e$), reactor ($\bar{\nu}_e \nrightarrow \bar{\nu}_e$), atmospheric and accelerator ($\nu_\mu \nrightarrow \nu_\mu$ and $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$) neutrinos
  - of the appearance of new neutrino flavors from solar ($\nu_e \rightarrow \nu_{\mu,\tau}$), atmospheric ($\nu_\mu \rightarrow \nu_\tau$) and accelerator ($\nu_\mu \rightarrow \nu_e$) neutrinos

ν oscillations and mass

- ν oscillation and thus ν flavor violation (νFL) has been established by the observation
  - of the disappearance of solar ($\nu_e \nrightarrow \nu_e$), reactor ($\bar{\nu}_e \nrightarrow \bar{\nu}_e$), atmospheric and accelerator ($\nu_\mu \nrightarrow \nu_\mu$ and $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$) neutrinos
  - of the appearance of new neutrino flavors from solar ($\nu_e \rightarrow \nu_{\mu,\tau}$), atmospheric ($\nu_\mu \rightarrow \nu_\tau$) and accelerator ($\nu_\mu \rightarrow \nu_e$) neutrinos
- this can be understood if (and almost certainly only if) the masses of the three ν_i all differ and there is a misalignment between mass and CC eigenstates, parameterized by the PMNS matrix with (marginalized over sign choices) ***Fogli et al. 2012***

$$\Delta m^2_\odot \equiv m_2^2 - m_1^2 = (8.69 \pm 0.14 \text{ meV})^2$$

$$|\Delta m^2_A| \equiv |m_3^2 - (m_1^2 + m_2^2)/2| = (49.0 \pm 0.9 \text{ meV})^2$$

$$\theta_\odot \equiv \theta_{12} = 33.7° \pm 1.1° \text{ where } \theta_{12} < 45° \text{ from matter (MSW) effect}$$

$$\theta_A \equiv \theta_{23} = 39.1 \pm 1.9°$$

$$\theta_{13} = 8.9 \pm 0.5°$$

ν spectrum

ν spectrum

- sign of Δm^2_A unknown:
  - normal hierarchy (NH): $m_1 \ll m_2 < m_3$ ($m_3^2 \approx \Delta m^2_A$)
  - inverted hierarchy (IH): $m_3 \ll m_1 < m_2$ ($m_1^2 \approx m_2^2 \approx \Delta m^2_A$)
  - quasi-degeneracy (QD): $m_1 \approx m_2 \approx m_3$ ($m_i^2 \gg \Delta m^2_A$)

ν spectrum

- sign of Δm^2_A unknown:
  - normal hierarchy (NH): $m_1 \ll m_2 < m_3$ ($m_3^2 \approx \Delta m^2_A$)
  - inverted hierarchy (IH): $m_3 \ll m_1 < m_2$ ($m_1^2 \approx m_2^2 \approx \Delta m^2_A$)
  - quasi-degeneracy (QD): $m_1 \approx m_2 \approx m_3$ ($m_i^2 \gg \Delta m^2_A$)
- to determine it can use (the relatively large θ_{13} helps here)
  - long-baseline accelerator ν (NOνA, ...) with large matter effects
  - atmospheric ν traversing the Earth by studying subdominant $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$.
  - resonance-like enhancement (but not MSW) of $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) for normal (inverted) hierarchy ***Petcov 1998***
  - reactor $\bar{\nu}_e$ (challenging but not impossible if $\theta_{13} \gtrsim 4°$) ***Ghoshal, Petcov 2011***
  - improve β-decay experiments (below) by factor 4 to reach $|\Delta m^2_A|$

Open questions

Open questions

- absolute m_ν scale (only Δm^2 known)?
  - ^3H β-decay experiments like KATRIN will improve $m_{\bar{\nu}} < 2.05$ eV (Troitsk) by factor 10 and probe QD spectrum
  - ΛCDM cosmology (6 parameter model): $\sum_i m_\nu \lesssim 230$ meV (relativistic)

19

Open questions

- absolute m_ν scale (only Δm^2 known)?
  - ^3H β-decay experiments like KATRIN will improve $m_{\bar{\nu}} < 2.05$ eV (Troitsk) by factor 10 and probe QD spectrum
  - ΛCDM cosmology (6 parameter model): $\sum_i m_\nu \lesssim 230$ meV (relativistic)
- CP violation in ν sector?
  - look for difference between ν and corresponding $\bar{\nu}$ oscillations in long-baseline experiments (T2K, …)
  - the two Majorana phases do not enter into oscillations ***Bilenky, Hosek, Petcov 1980***
  - in one scenario can get BAU from leptogenesis if $\theta_{13} \gtrsim 5°$ ***Pascoli, Petcov, Riotti 2007***

Open questions

- absolute m_ν scale (only Δm^2 known)?
  - ^{3}H β-decay experiments like KATRIN will improve $m_{\bar{\nu}} < 2.05$ eV (Troitsk) by factor 10 and probe QD spectrum
  - ΛCDM cosmology (6 parameter model): $\sum_i m_\nu \lesssim 230$ meV (relativistic)
- CP violation in ν sector?
  - look for difference between ν and corresponding $\bar{\nu}$ oscillations in long-baseline experiments (T2K, …)
  - the two Majorana phases do not enter into oscillations ***Bilenky, Hosek, Petcov 1980***
  - in one scenario can get BAU from leptogenesis if $\theta_{13} \gtrsim 5°$ ***Pascoli, Petcov, Riotti 2007***
- ν counting: sterile neutrinos?

Open questions

- absolute m_ν scale (only Δm^2 known)?
  - ^3H β-decay experiments like KATRIN will improve $m_{\bar{\nu}} < 2.05$ eV (Troitsk) by factor 10 and probe QD spectrum
  - ΛCDM cosmology (6 parameter model): $\sum_i m_\nu \lesssim 230$ meV (relativistic)
- CP violation in ν sector?
  - look for difference between ν and corresponding $\bar{\nu}$ oscillations in long-baseline experiments (T2K, …)
  - the two Majorana phases do not enter into oscillations *Bilenky, Hosek, Petcov 1980*
  - in one scenario can get BAU from leptogenesis if $\theta_{13} \gtrsim 5°$ *Pascoli, Petcov, Riotti 2007*
- ν counting: sterile neutrinos?
- LSND and MiniBooNE anomaly? observed $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ which would need two extra νs with $m_\nu = \mathcal{O}(1 \text{ eV})$

Open questions

- absolute m_ν scale (only Δm^2 known)?
  - ^{3}H β-decay experiments like KATRIN will improve $m_{\bar{\nu}} < 2.05$ eV (Troitsk) by factor 10 and probe QD spectrum
  - ΛCDM cosmology (6 parameter model): $\sum_i m_\nu \lesssim 230$ meV (relativistic)
- CP violation in ν sector?
  - look for difference between ν and corresponding $\bar{\nu}$ oscillations in long-baseline experiments (T2K, …)
  - the two Majorana phases do not enter into oscillations *Bilenky, Hosek, Petcov 1980*
  - in one scenario can get BAU from leptogenesis if $\theta_{13} \gtrsim 5°$ *Pascoli, Petcov, Riotti 2007*
- ν counting: sterile neutrinos?
- LSND and MiniBooNE anomaly? observed $\bar{\nu}_\mu \to \bar{\nu}_e$ which would need two extra νs with $m_\nu = \mathcal{O}(1\ \text{eV})$
- ν nature: Majorana (strictly neutral) or Dirac?

$0\nu\beta\beta$ decay

20

$0\nu\beta\beta$ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \rightarrow (A, Z{+}2) + 2\,e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

0νββ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \to (A, Z+2) + 2\,e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation

0νββ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \to (A, Z+2) + 2\,e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation
  - determine the ν nature to be Majorana

$0\nu\beta\beta$ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \rightarrow (A, Z{+}2) + 2\,e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation
  - determine the ν nature to be Majorana
  - inform about Majorana phases in PMNS matrix U_{ij}

$0\nu\beta\beta$ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \to (A, Z+2) + 2\, e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation
  - determine the ν nature to be Majorana
  - inform about Majorana phases in PMNS matrix U_{ij}
  - inform about absolute m_ν scale

$0\nu\beta\beta$ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \rightarrow (A, Z+2) + 2\, e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation
  - determine the ν nature to be Majorana
  - inform about Majorana phases in PMNS matrix U_{ij}
  - inform about absolute m_ν scale
  - measure $\langle m_{\beta\beta} \rangle \equiv | U^2_{e1}\, m_1 + U^2_{e2}\, m_2\, e^{i\alpha} + U^2_{e3}\, m_3\, e^{i\beta} |$

$0\nu\beta\beta$ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \to (A, Z+2) + 2\,e^-$

  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation
  - determine the ν nature to be Majorana
  - inform about Majorana phases in PMNS matrix U_{ij}
  - inform about absolute m_ν scale
  - measure $\langle m_{\beta\beta} \rangle \equiv |\, U^2_{e1}\, m_1 + U^2_{e2}\, m_2\, e^{i\alpha} + U^2_{e3}\, m_3\, e^{i\beta}\,|$
  - inform about the type of ν spectrum

$0\nu\beta\beta$ decay

- observation and sufficiently accurate measurement of

  $(A, Z) \to (A, Z+2) + 2\, e^-$

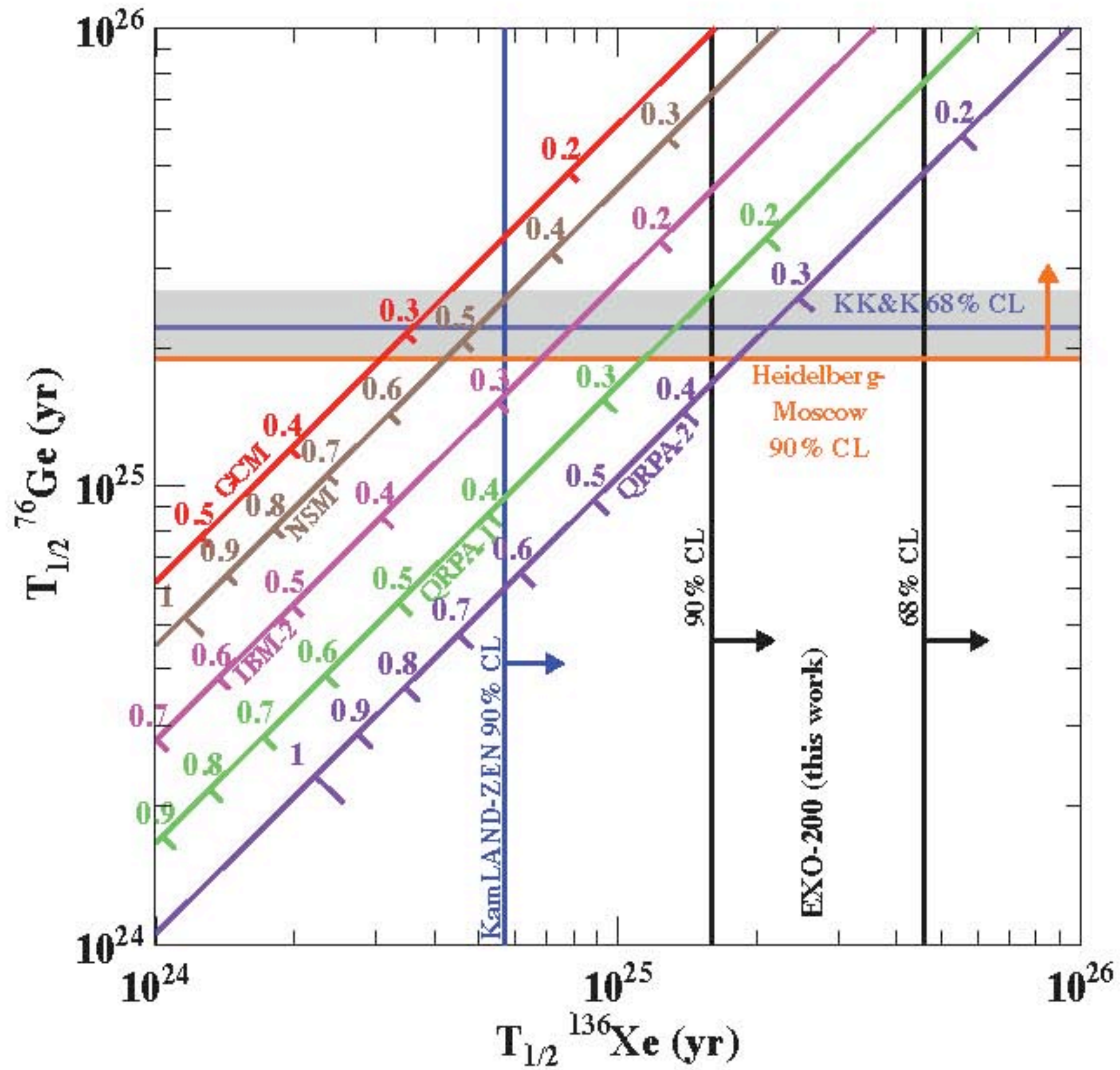
  would (assuming a Majorana ν mass is the dominant mechanism)

  - establish L violation
  - determine the ν nature to be Majorana
  - inform about Majorana phases in PMNS matrix U_{ij}
  - inform about absolute m_ν scale
  - measure $\langle m_{\beta\beta} \rangle \equiv | U^2_{e1}\, m_1 + U^2_{e2}\, m_2\, e^{i\alpha} + U^2_{e3}\, m_3\, e^{i\beta} |$
  - inform about the type of ν spectrum

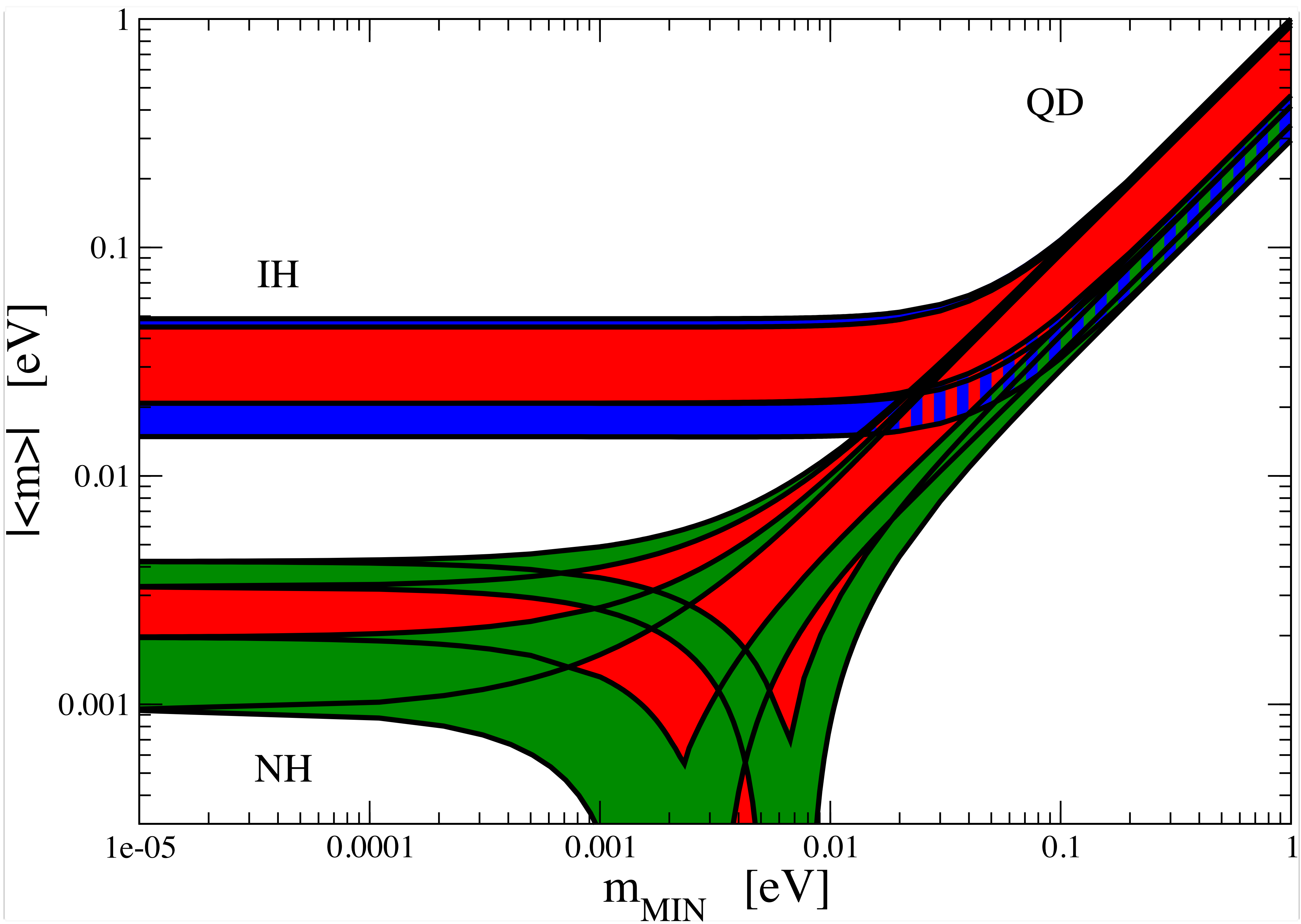
- need to confirm or reject the claimed evidence in ^{76}Ge of

  $T_{1/2} \approx 2\times10^{25}\,\text{y} \to \langle m_{\beta\beta} \rangle \sim 0.32\,(0.03)_{exp}\,(0.10)_{th}$ eV ***Klapdor-Kleingrothaus et al. 2001***

de Gouvêa, Vogel 2013



Pascoli, Petcov 2012



EFT at d = 6

23

EFT at d = 6

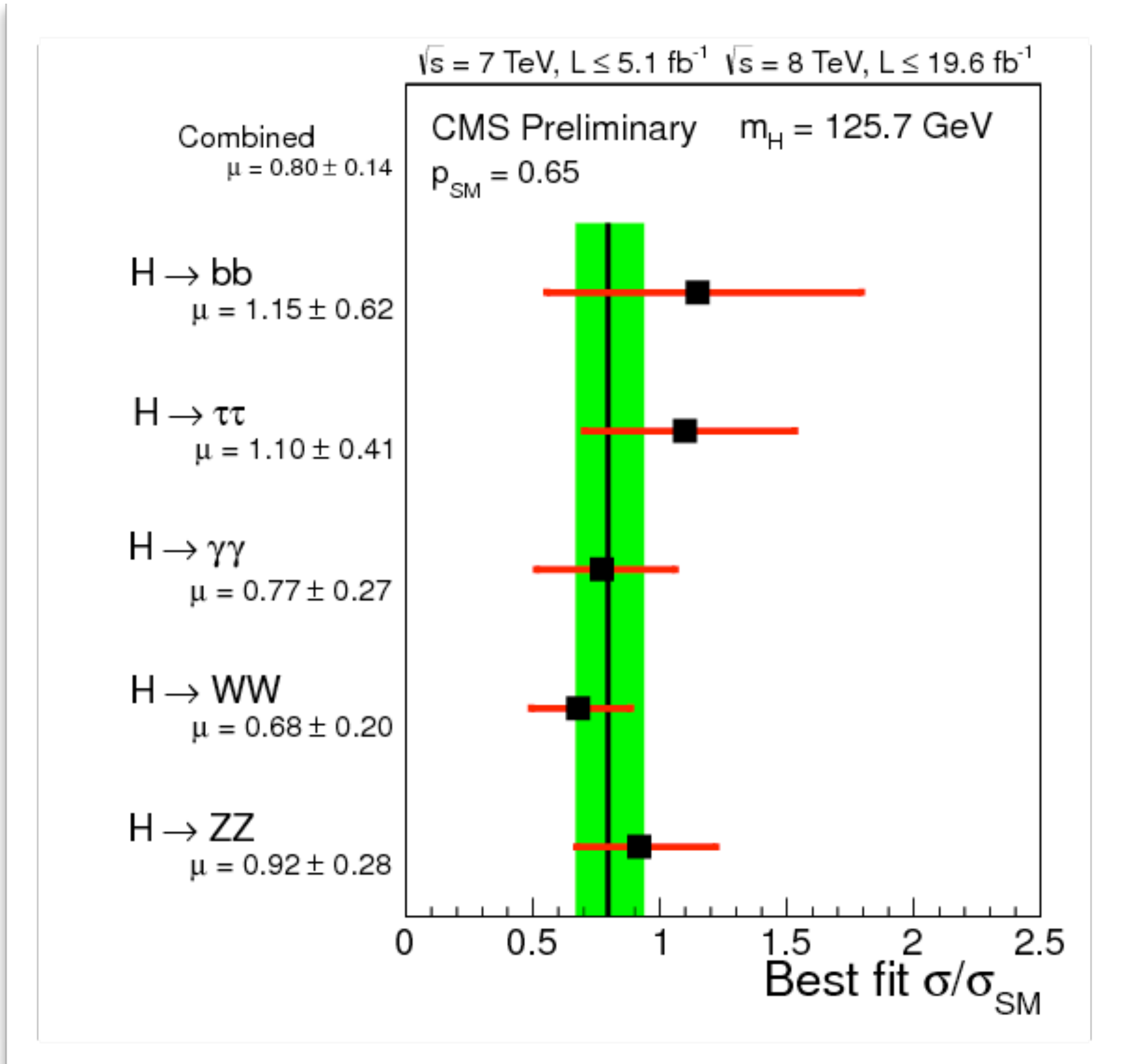
- 16 types of bosonic operators ***Grzadkowski, Iskrzyński, Misiak and Rosiek 2010***
  - 4 affect triple gauge couplings: 2 G^3, 2 W^3 (CP even and odd)
  - 11 affect Higgs couplings: 2 H^2G^2, 2 H^2W^2, 2 H^2B^2, 2 H^2WB, H^6, $(HDH)^2$, $H^2D^2H^2$

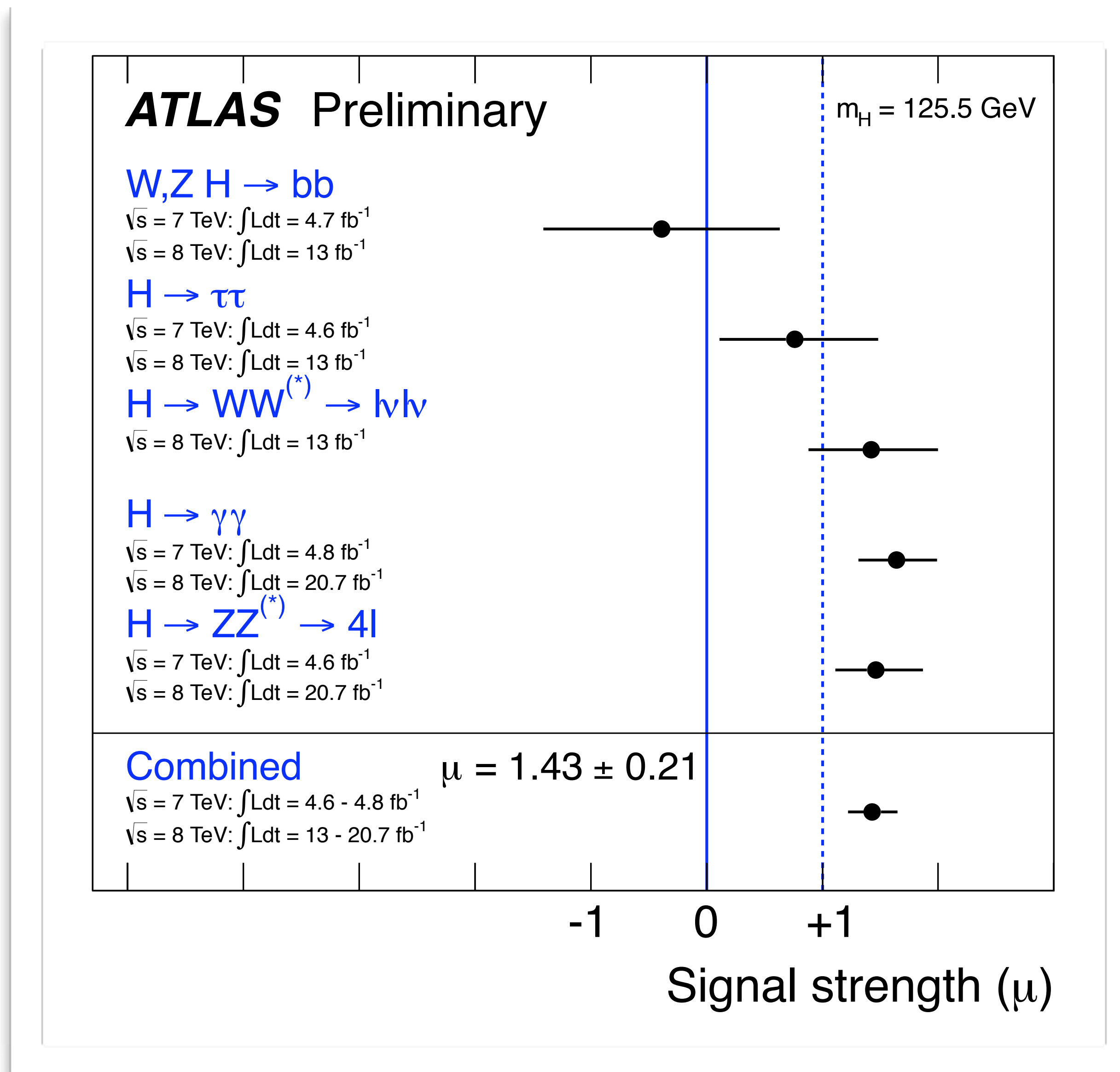
EFT at d = 6

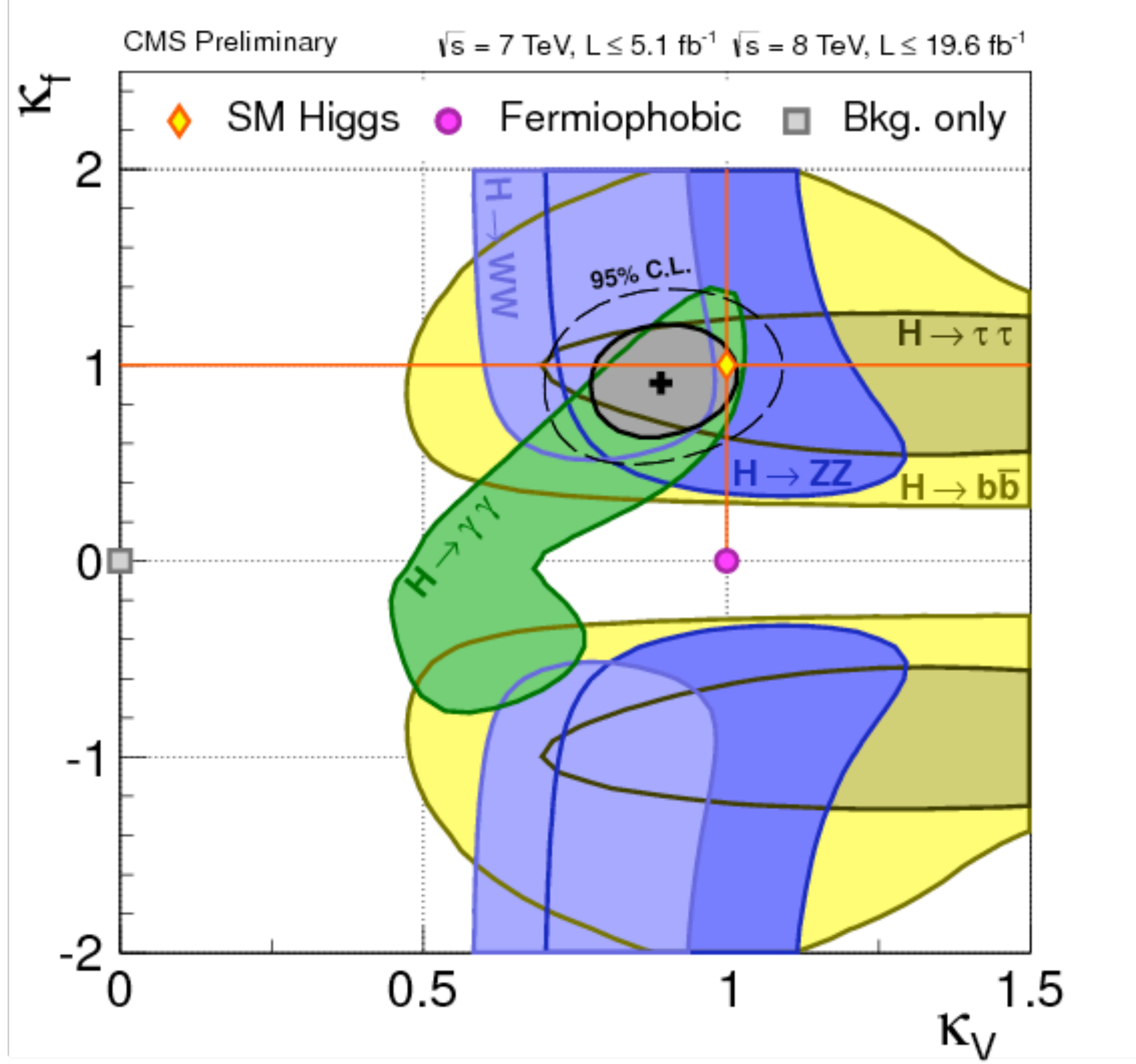
- 16 types of bosonic operators ***Grzadkowski, Iskrzyński, Misiak and Rosiek 2010***
  - 4 affect triple gauge couplings: 2 G^3, 2 W^3 (CP even and odd)
  - 11 affect Higgs couplings: 2 H^2G^2, 2 H^2W^2, 2 H^2B^2, 2 H^2WB, H^6, $(HDH)^2$, $H^2D^2H^2$
- 19 mixed types (one fermion bilinear)
  - 3 affect fermion mass matrices: H^3F^2
  - 8 affect fermion dipole moments: 2 HGF^2, 3 HWF^2, 3 HBF^2 (important for CPV)
  - 8 affect fermion couplings to gauge bosons: $(HDH)F^2$

EFT at d = 6

- 16 types of bosonic operators ***Grzadkowski, Iskrzyński, Misiak and Rosiek 2010***
  - 4 affect triple gauge couplings: 2 G^3, 2 W^3 (CP even and odd)
  - 11 affect Higgs couplings: 2 H^2G^2, 2 H^2W^2, 2 H^2B^2, 2 H^2WB, H^6, $(HDH)^2$, $H^2D^2H^2$
- 19 mixed types (one fermion bilinear)
  - 3 affect fermion mass matrices: H^3F^2
  - 8 affect fermion dipole moments: 2 HGF^2, 3 HWF^2, 3 HBF^2 (important for CPV)
  - 8 affect fermion couplings to gauge bosons: $(HDH)F^2$
- 30 types (up to flavor structures) of fermionic operators (four-Fermi)
  - LLLL
  - 10 QQQQ
  - 12 QQLL ($\Delta B = 0$)
  - 5 QQQL ($\Delta B = 1$)


√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
CMS Preliminary
mH = 125.7 GeV
pSM = 0.65
Combined
μ = 0.80 ± 0.14
H → bb
μ = 1.15 ± 0.62
H → ττ
μ = 1.10 ± 0.41
H → γγ
μ = 0.77 ± 0.27
H → WW
μ = 0.68 ± 0.20
H → ZZ
μ = 0.92 ± 0.28
0
0.5
1
1.5
2
2.5
Best fit σ/σSM

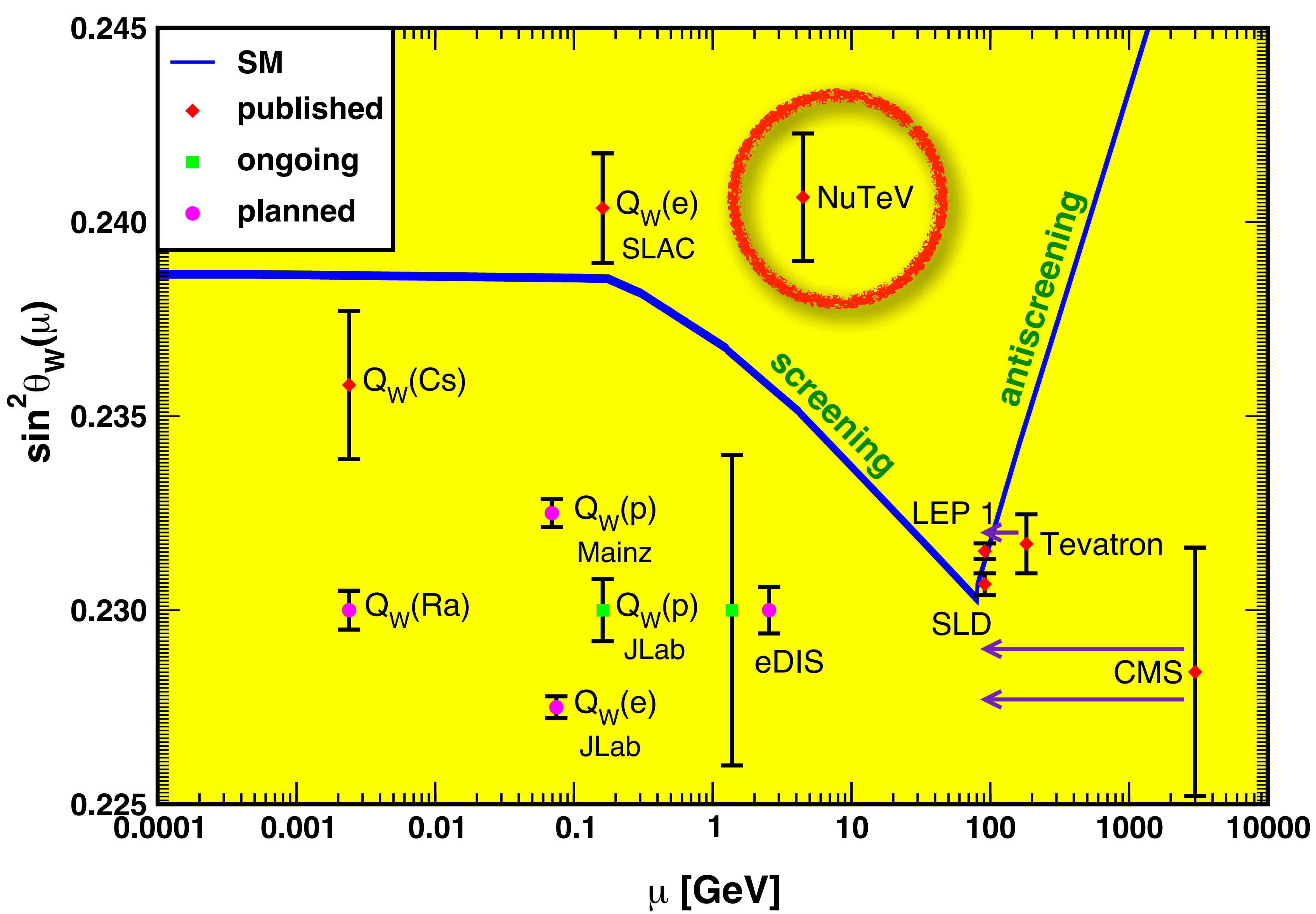

ATLAS Preliminary
mH = 125.5 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb-1
√s = 8 TeV: ∫Ldt = 13 fb-1
H → ττ
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 13 fb-1
H → WW(*) → lνlν
√s = 8 TeV: ∫Ldt = 13 fb-1
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
Combined
μ = 1.43 ± 0.21
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb-1
√s = 8 TeV: ∫Ldt = 13 - 20.7 fb-1
-1
0
+1
Signal strength (μ)


CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
SM Higgs
Fermiophobic
Bkg. only
95% C.L.
H → WW
H → ττ
H → ZZ
H → bb̄
H → γγ
κf
κV
2
1
0
-1
-2
0
0.5
1
1.5

25

ν scattering

Erler, Su 2013



ν scattering

ν scattering

- most precise measurements in deep inelastic scattering (νDIS) from iso-scalar targets
  - gives coupling combinations $g_L^2 \equiv g_{Lu}^2 + g_{Ld}^2$ and $g_R^2 \equiv g_{Ru}^2 + g_{Rd}^2$
  - nominally 2.7 σ deviation (NuTeV) in g_L^2
  - possible explanations within SM (e.g. iso-vector EMC effect *Cloet, Bentz, Thomas 2009*)
  - need theory and experiments testing it (e.g. PREX)
  - $\sin^2\theta_W$ less precise than PVES experiments, but important for ν 4-Fermi operators
  - improve using superbeams and ν-factory (intensity and composition)

ν scattering

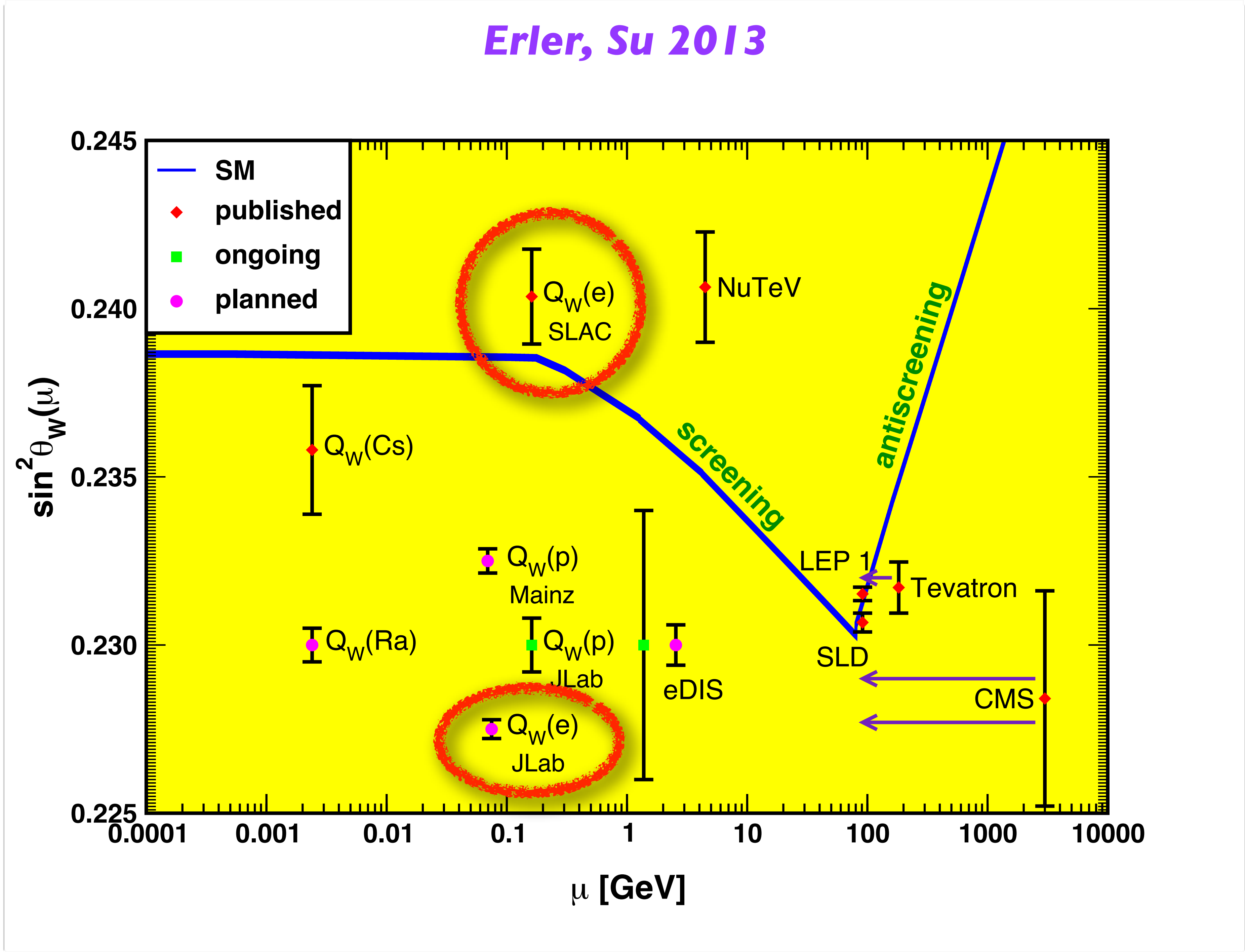
- most precise measurements in deep inelastic scattering (νDIS) from iso-scalar targets
  - gives coupling combinations $g_L^2 \equiv g_{Lu}^2 + g_{Ld}^2$ and $g_R^2 \equiv g_{Ru}^2 + g_{Rd}^2$
  - nominally 2.7 σ deviation (NuTeV) in g_L^2
  - possible explanations within SM (e.g. iso-vector EMC effect *Cloet, Bentz, Thomas 2009*)
  - need theory and experiments testing it (e.g. PREX)
  - $\sin^2\theta_W$ less precise than PVES experiments, but important for ν 4-Fermi operators
  - improve using superbeams and ν-factory (intensity and composition)
- also need iso-vector couplings $h_L^2 \equiv g_{Lu}^2 - g_{Ld}^2$ and $h_R^2 \equiv g_{Ru}^2 - g_{Rd}^2$
  - ν-induced coherent π^- production

    e.g. as $\nu A \to \nu A \pi_0 \Rightarrow$ axial-vector combination $\beta \equiv h_L^2 - h_R^2$
  - elastic scattering from protons (also νDIS from nucleons?)

    difficult to interpret (s-quark contribution)

    future: use β-beams (for ν spectra) and universal analyses (with PVES)

Polarized Møller scattering



Polarized Møller scattering

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W \Rightarrow$

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W$ $\Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$

29

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto 1 - 4\sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$
- MOLLER (JLab) will be competitive with LEP/SLC

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$
- MOLLER (JLab) will be competitive with LEP/SLC
- may resolve LEP/SLC discrepancy (at least one is "wrong")

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$
- MOLLER (JLab) will be competitive with LEP/SLC
- may resolve LEP/SLC discrepancy (at least one is "wrong")
- can access higher order "oblique" corrections to W and Z propagators ("X parameter")

Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4 \sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$
- MOLLER (JLab) will be competitive with LEP/SLC
- may resolve LEP/SLC discrepancy (at least one is "wrong")
- can access higher order "oblique" corrections to W and Z propagators ("X parameter")
- can access new physics mimicking the X parameter (dark Z)

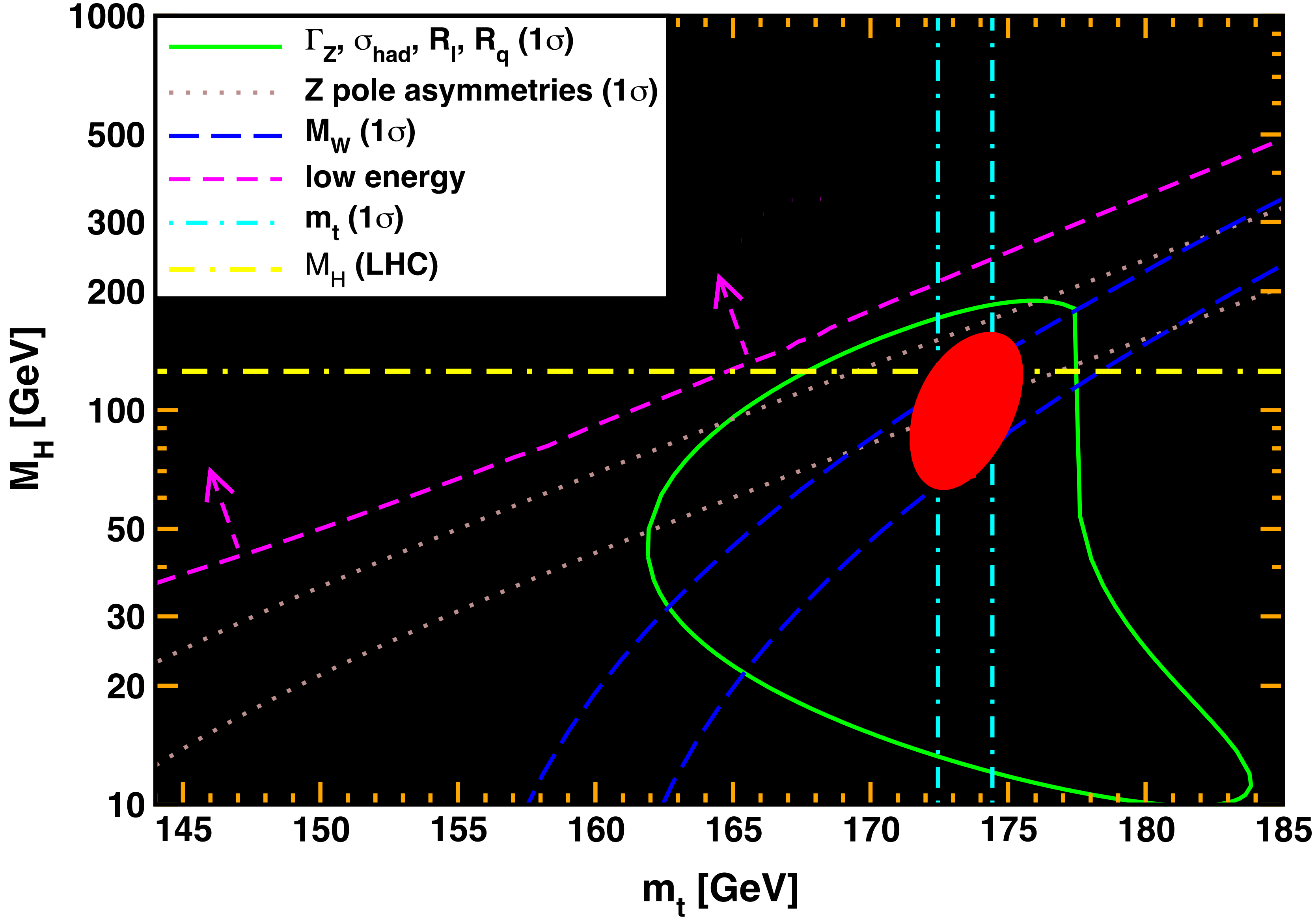
Polarized Møller scattering

- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$
- MOLLER (JLab) will be competitive with LEP/SLC
- may resolve LEP/SLC discrepancy (at least one is "wrong")
- can access higher order "oblique" corrections to W and Z propagators ("X parameter")
- can access new physics mimicking the X parameter (dark Z)
- new PV amplitudes which are strongly suppressed at Z-pole (e.g. Z')

Polarized Møller scattering

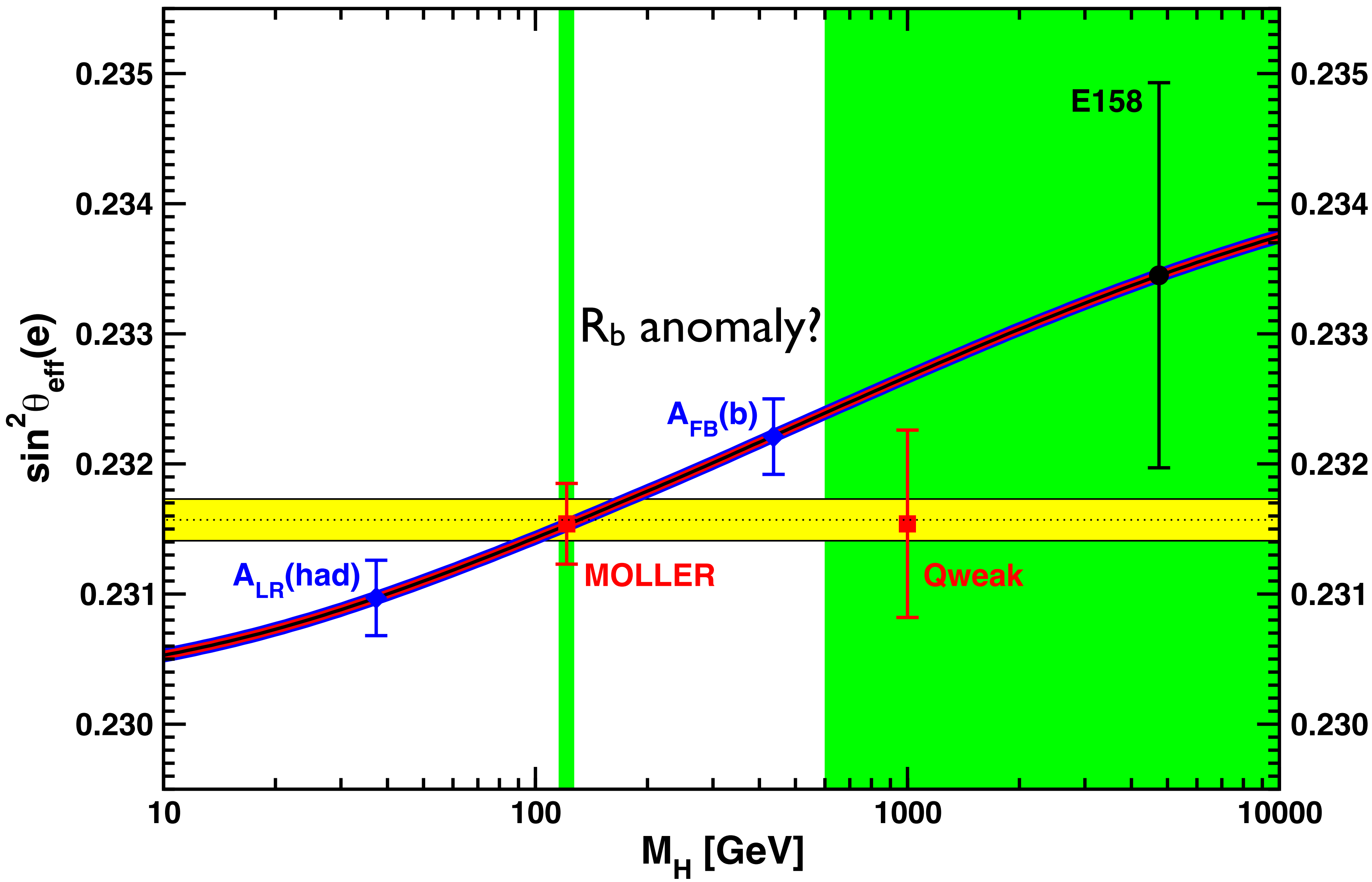
- tiny (order 10^{-7}) polarization asymmetry $\propto$ $1 - 4\sin^2\theta_W \Rightarrow$
- very clean (leptonic) low-energy determination of $\sin^2\theta_W$
- SLAC-E158 established "running" of $\sin^2\theta_W$
- MOLLER (JLab) will be competitive with LEP/SLC
- may resolve LEP/SLC discrepancy (at least one is "wrong")
- can access higher order "oblique" corrections to W and Z propagators ("X parameter")
- can access new physics mimicking the X parameter (dark Z)
- new PV amplitudes which are strongly suppressed at Z-pole (e.g. Z')
- new (PV) coupling combination not accessible at Z-pole

Erler 2013

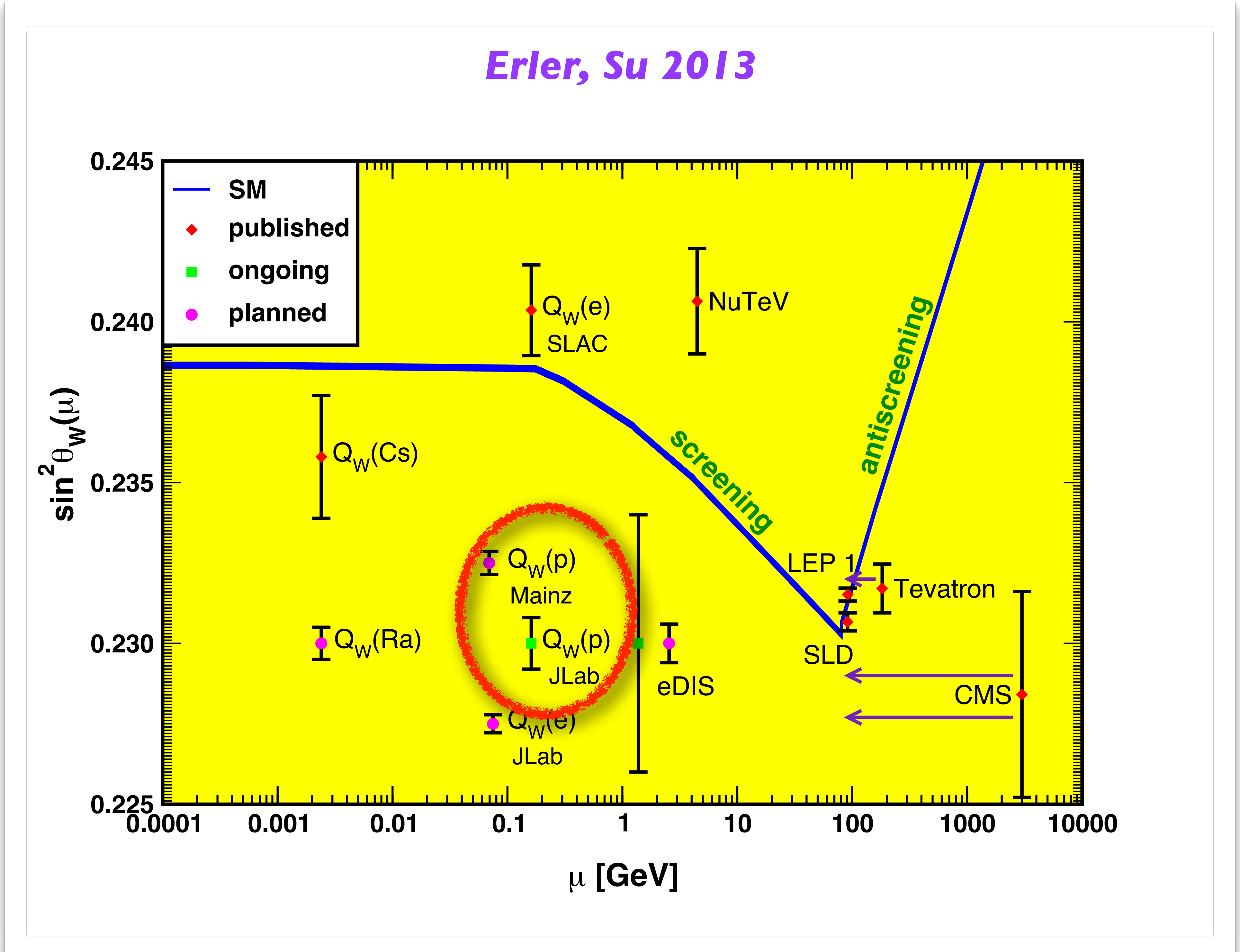


Γ_Z, σ_{had}, R_l, R_q (1σ)
Z pole asymmetries (1σ)
M_W (1σ)
low energy
m_t (1σ)
M_H (LHC)
1000
500
300
200
100
50
30
20
10
145
150
155
160
165
170
175
180
185
M_H [GeV]
m_t [GeV]

Erler, Su 2013



Polarized ep scattering



Polarized ep scattering

33

Polarized ep scattering

- polarization asymmetry in elastic scattering from proton as a whole
  $\Rightarrow$ $g_{AV}^{p} \equiv 2\, g_{AV}^{u} + g_{AV}^{d} = -\, 1/2 + 2\, \sin^2\theta_W$

Polarized ep scattering

- polarization asymmetry in elastic scattering from proton as a whole
  $\Rightarrow \; g_{AV}^{p} \equiv 2\, g_{AV}^{u} + g_{AV}^{d} = -\,1/2 + 2\,\sin^2\theta_W$
- low Q^2 important to keep y^2-term and associated hadronic uncertainties below experimental error (not an option in ν-scattering)

Polarized ep scattering

- polarization asymmetry in elastic scattering from proton as a whole
  $\Rightarrow$ $g_{AV}^{p} \equiv 2\, g_{AV}^{u} + g_{AV}^{d} = -\,1/2 + 2 \sin^2\theta_W$
- low Q^2 important to keep y^2-term and associated hadronic uncertainties below experimental error (not an option in ν-scattering)
- $y \to 0$ extrapolation using other (higher Q^2) asymmetry results

Polarized ep scattering

- polarization asymmetry in elastic scattering from proton as a whole $\Rightarrow$ $g_{AV}^p \equiv 2\, g_{AV}^u + g_{AV}^d = -1/2 + 2 \sin^2\theta_W$
- low Q^2 important to keep y^2-term and associated hadronic uncertainties below experimental error (not an option in ν-scattering)
- $y \to 0$ extrapolation using other (higher Q^2) asymmetry results
- Qweak ($y = 0.0085$) completed data taking and will extract the weak charge of the proton $Q_W^p \approx -2\, g_{AV}^p$ to 4% and $\sin^2\theta_W$ to 0.3%

Polarized ep scattering

- polarization asymmetry in elastic scattering from proton as a whole $\Rightarrow$ $g_{AV}^p \equiv 2\, g_{AV}^u + g_{AV}^d = -\,1/2 + 2 \sin^2\theta_W$
- low Q^2 important to keep y^2-term and associated hadronic uncertainties below experimental error (not an option in ν-scattering)
- $y \to 0$ extrapolation using other (higher Q^2) asymmetry results
- Qweak ($y = 0.0085$) completed data taking and will extract the weak charge of the proton $Q_W^p \approx -\,2\, g_{AV}^p$ to 4% and $\sin^2\theta_W$ to 0.3%
- P2 (Mainz): y^2-term not $1 - 4 \sin^2\theta_W$ suppressed, contributing 1/3 to asymmetry and 1.5% to error $\Rightarrow$ go to even lower $y = 0.0038$

Polarized ep scattering

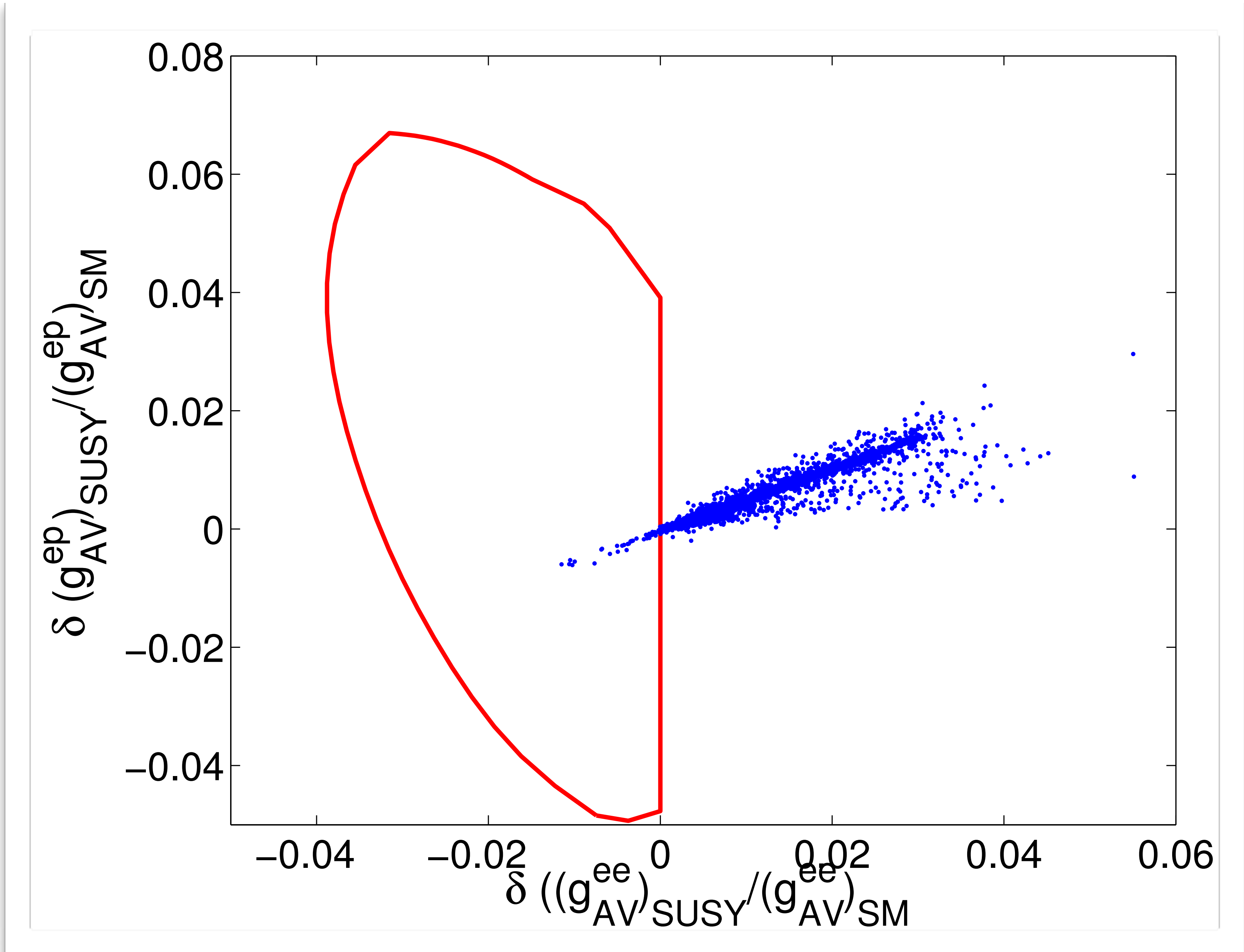
- polarization asymmetry in elastic scattering from proton as a whole $\Rightarrow$ $g_{AV}^{p} \equiv 2\, g_{AV}^{u} + g_{AV}^{d} = -1/2 + 2\sin^2\theta_W$
- low Q^2 important to keep y^2-term and associated hadronic uncertainties below experimental error (not an option in ν-scattering)
- $y \rightarrow 0$ extrapolation using other (higher Q^2) asymmetry results
- Qweak ($y = 0.0085$) completed data taking and will extract the weak charge of the proton $Q_W^p \approx -2\, g_{AV}^{p}$ to 4% and $\sin^2\theta_W$ to 0.3%
- P2 (Mainz): y^2-term not $1 - 4\sin^2\theta_W$ suppressed, contributing 1/3 to asymmetry and 1.5% to error $\Rightarrow$ go to even lower $y = 0.0038$
- will also reduce additional γ-Z box uncertainty ***Gorchtein, Horowitz 2009***

Polarized ep scattering

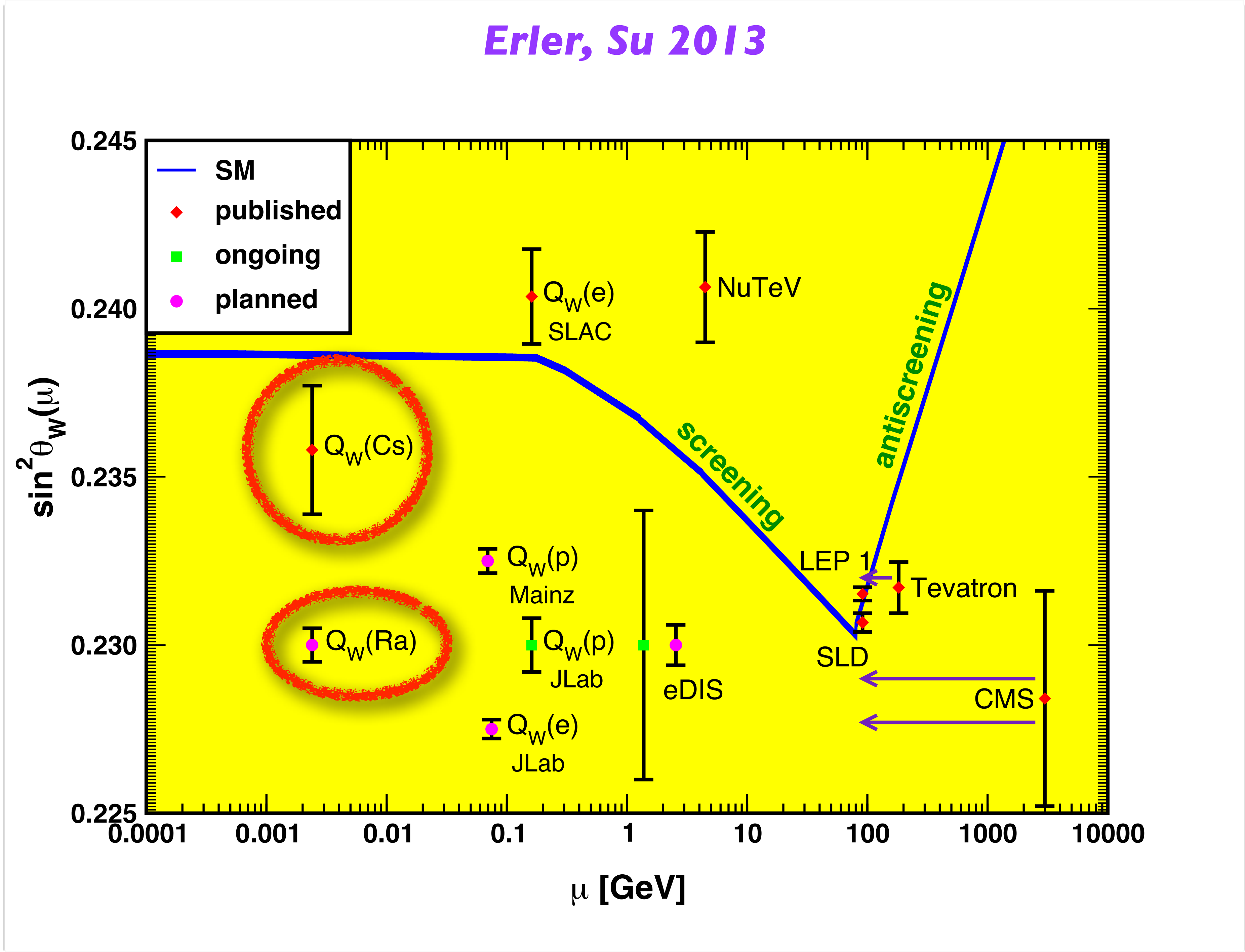
- polarization asymmetry in elastic scattering from proton as a whole $\Rightarrow$ $g_{AV}^{p} \equiv 2\, g_{AV}^{u} + g_{AV}^{d} = -1/2 + 2 \sin^2\theta_W$
- low Q^2 important to keep y^2-term and associated hadronic uncertainties below experimental error (not an option in ν-scattering)
- $y \to 0$ extrapolation using other (higher Q^2) asymmetry results
- Qweak ($y = 0.0085$) completed data taking and will extract the weak charge of the proton $Q_W^p \approx -2\, g_{AV}^{p}$ to 4% and $\sin^2\theta_W$ to 0.3%
- P2 (Mainz): y^2-term not $1 - 4 \sin^2\theta_W$ suppressed, contributing 1/3 to asymmetry and 1.5% to error $\Rightarrow$ go to even lower $y = 0.0038$
- will also reduce additional γ-Z box uncertainty ***Gorchtein, Horowitz 2009***
- P2 goal: 2% in Q_W^p

PVES and SUSY

Erler, Su 2013



Atomic Parity Violation (APV)



APV

36

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)

36

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions

36

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)
- state-of-the-art many body calculation ***Porsev, Beloy, Derevianko 2009***

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)
- state-of-the-art many body calculation ***Porsev, Beloy, Derevianko 2009***
- moving history of Cs result (Boulder): currently 1.5 σ SM deviation ***Dzuba, Berengut, Flambaum, Roberts 2012***

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)
- state-of-the-art many body calculation ***Porsev, Beloy, Derevianko 2009***
- moving history of Cs result (Boulder): currently 1.5 σ SM deviation ***Dzuba, Berengut, Flambaum, Roberts 2012***
- Yb (Berkeley) isotope ratios (R) (atomic physics cancels ***Bouchiat, Pottier 1986***)

APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)
- state-of-the-art many body calculation ***Porsev, Beloy, Derevianko 2009***
- moving history of Cs result (Boulder): currently 1.5 σ SM deviation ***Dzuba, Berengut, Flambaum, Roberts 2012***
- Yb (Berkeley) isotope ratios (R) (atomic physics cancels ***Bouchiat, Pottier 1986***)
- single trapped Ra^+ and Ba^+ promising (much larger PV effect) KVI, Seattle

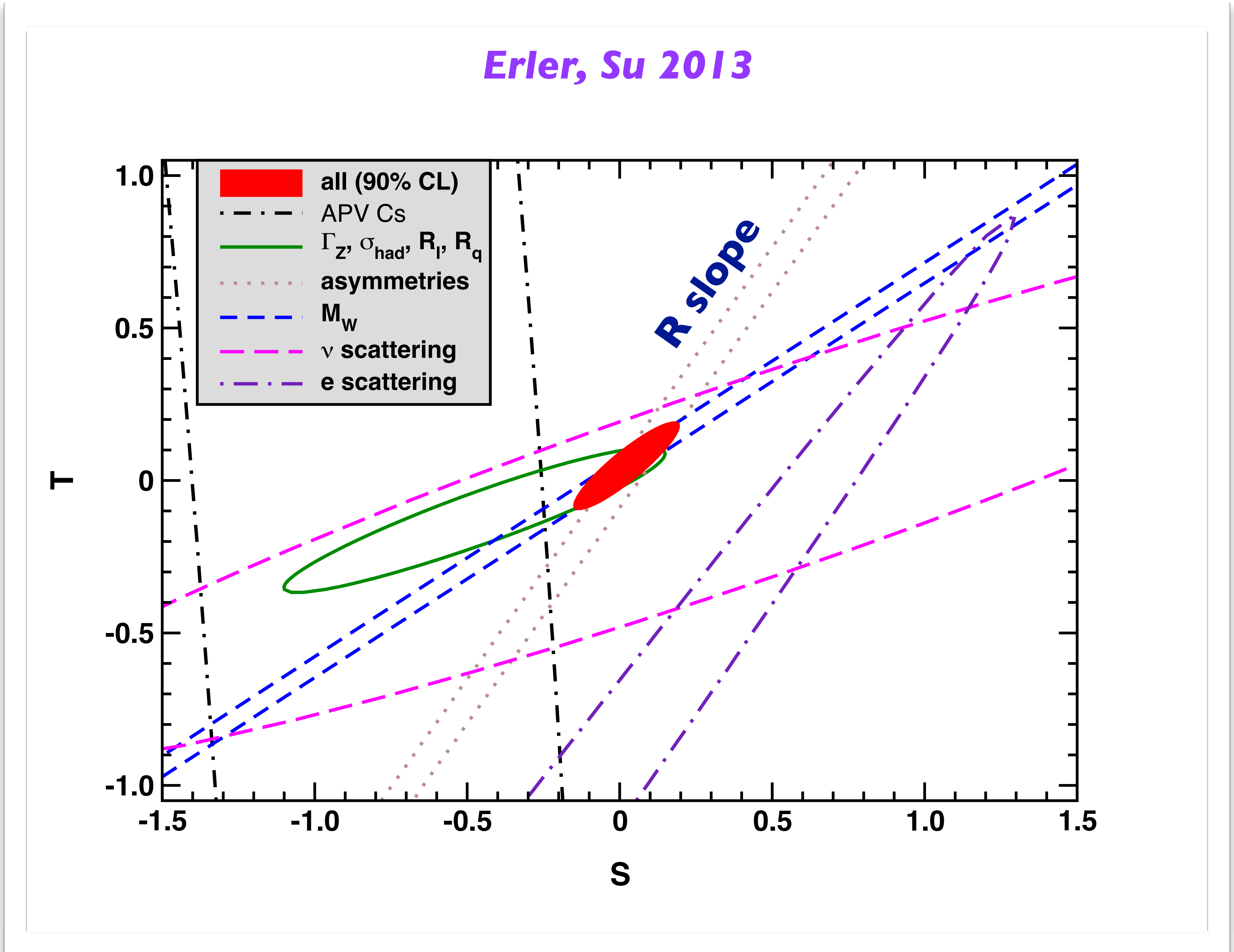
APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)
- state-of-the-art many body calculation *Porsev, Beloy, Derevianko 2009*
- moving history of Cs result (Boulder): currently 1.5 σ SM deviation *Dzuba, Berengut, Flambaum, Roberts 2012*
- Yb (Berkeley) isotope ratios (R) (atomic physics cancels *Bouchiat, Pottier 1986*)
- single trapped Ra^+ and Ba^+ promising (much larger PV effect) KVI, Seattle
- trapped Fr atoms TRIUMF

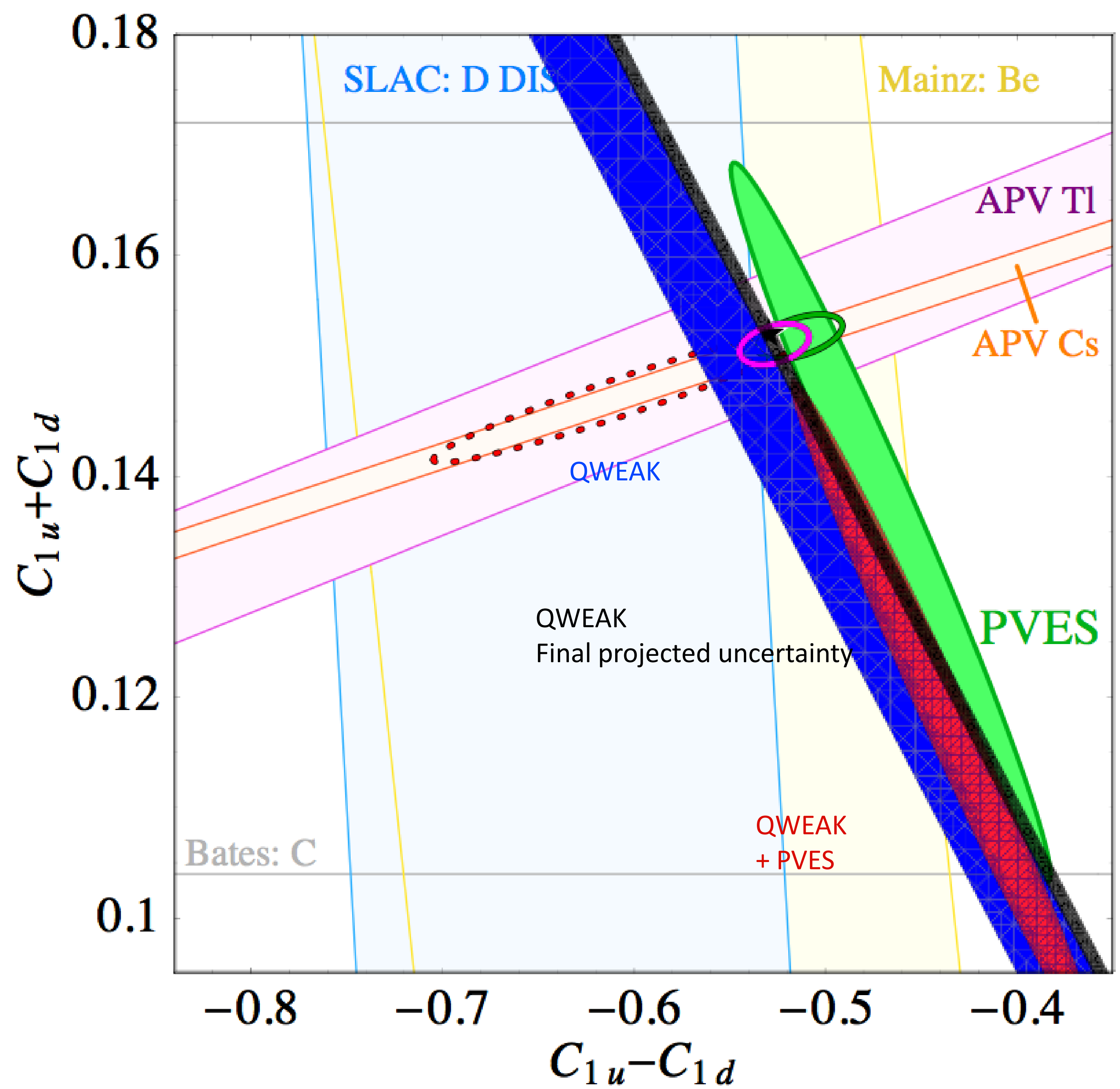
APV

- effects tiny and ~ Z^3 → seen only in heavy atoms (~ $g_{AV}^u + g_{AV}^d$)
- g_{AV} add up coherently → nuclear spin-independent interaction
- spin-dependent g_{VA} clouded by dominant nuclear anapole moment
- separate g_{AV} and g_{VA} by measuring different hyperfine transitions
- good understanding of atomic structure crucial → Cs (Tl)
- state-of-the-art many body calculation ***Porsev, Beloy, Derevianko 2009***
- moving history of Cs result (Boulder): currently 1.5 σ SM deviation ***Dzuba, Berengut, Flambaum, Roberts 2012***
- Yb (Berkeley) isotope ratios (R) (atomic physics cancels ***Bouchiat, Pottier 1986***)
- single trapped Ra^+ and Ba^+ promising (much larger PV effect) KVI, Seattle
- trapped Fr atoms TRIUMF
- ideally measure APV in H and D ***Dunford, Holt 2007***

Oblique parameters

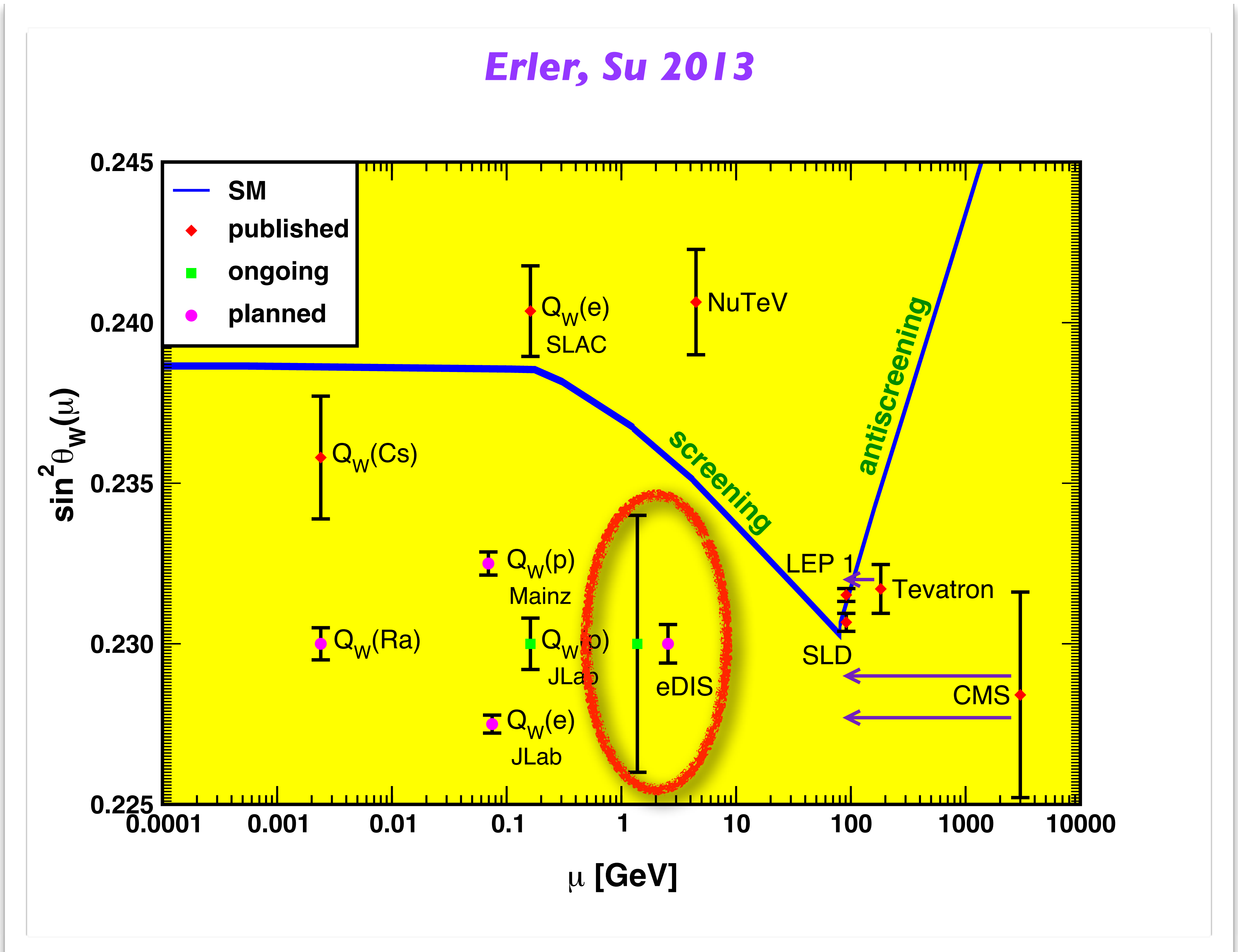


Qweak 2012



0.18
0.16
0.14
0.12
0.1
−0.8
−0.7
−0.6
−0.5
−0.4
$C_{1u}+C_{1d}$
$C_{1u}-C_{1d}$
SLAC: D DIS
Mainz: Be
APV Tl
APV Cs
QWEAK
QWEAK
Final projected uncertainty
PVES
QWEAK
+ PVES
Bates: C

eDIS


Erler, Su 2013
SM
published
ongoing
planned
0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
Q_W(e)
SLAC
NuTeV
Q_W(Cs)
screening
antiscreening
Q_W(p)
Mainz
Q_W(Ra)
Q_W(p)
JLab
eDIS
Q_W(e)
JLab
LEP 1
Tevatron
SLD
CMS
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
μ [GeV]

eDIS

eDIS

- eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering

eDIS

- eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering
- sensitive to $\sim (2\, g_{VA}{}^{u} - g_{VA}{}^{d}) - 0.84\, (2\, g_{VA}{}^{u} - g_{VA}{}^{d})$

eDIS

- eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering
- sensitive to $\sim (2\, g_{VA}^{u} - g_{VA}^{d}) - 0.84\, (2\, g_{VA}^{u} - g_{VA}^{d})$
- measured to ~ 10% at SLAC at $0.92\ \mathrm{GeV}^2 < Q^2 < 1.96\ \mathrm{GeV}^2$

Prescott et al 1979

eDIS

- eDIS asymmetries much larger ($\gtrsim 10{-}4$) than in elastic scattering
- sensitive to $\sim (2\, g_{VA}^{u} - g_{VA}^{d}) - 0.84\, (2\, g_{VA}^{u} - g_{VA}^{d})$
- measured to ~ 10% at SLAC at $0.92\ \text{GeV}^2 < Q^2 < 1.96\ \text{GeV}^2$

  Prescott et al 1979

- JLab Hall A Collaboration took 2 further points (currently analyzed) at $Q^2 = 1.1$ and $1.9\ \text{GeV}^2$ to ~ 2.5%

eDIS

- eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering
- sensitive to ~ $(2\, g_{VA}{}^{u} - g_{VA}{}^{d}) - 0.84\, (2\, g_{VA}{}^{u} - g_{VA}{}^{d})$
- measured to ~ 10% at SLAC at 0.92 GeV^2 < Q^2 < 1.96 GeV^2

  Prescott et al 1979

- JLab Hall A Collaboration took 2 further points (currently analyzed) at Q^2 = 1.1 and 1.9 GeV^2 to ~ 2.5%
- SOLID will measure large array of kinematic points up to 9.5 GeV^2 (0.5% precision in coupling combination)

eDIS

- eDIS asymmetries much larger ($\gtrsim 10^{-4}$) than in elastic scattering
- sensitive to ~ $(2\, g_{VA}^u - g_{VA}^d) - 0.84\, (2\, g_{VA}^u - g_{VA}^d)$
- measured to ~ 10% at SLAC at $0.92\ \mathrm{GeV}^2 < Q^2 < 1.96\ \mathrm{GeV}^2$

  Prescott et al 1979
- JLab Hall A Collaboration took 2 further points (currently analyzed) at $Q^2 = 1.1$ and $1.9\ \mathrm{GeV}^2$ to ~ 2.5%
- SOLID will measure large array of kinematic points up to 9.5 GeV^2 (0.5% precision in coupling combination)
- remaining g_{VA} combination: elastic scattering at background angles, but obstructed by strange quarks and nucleon anapole moment (universal analyses with ν scattering)

Kumar, Mantry, Marciano, Souder 2013

Muon g−2

Muon g−2

- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ (BNL-E821)

Muon g−2

- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ (BNL-E821)
- SM: $a_\mu \equiv (1165918.41 \pm 0.36_{\text{vac pol}} \pm 0.32_{\gamma\times\gamma})\times 10^{-9}$

42

Muon g−2

- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ (BNL-E821)
- SM: $a_\mu \equiv (1165918.41 \pm 0.36_{\text{vac pol}} \pm 0.32_{\gamma\times\gamma})\times 10^{-9}$
- 3.0 σ deviation (includes e^+e^- and τ-decay data): SUSY?

Muon g−2

- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ (BNL-E821)
- SM: $a_\mu \equiv (1165918.41 \pm 0.36_{\text{vac pol}} \pm 0.32_{\gamma\times\gamma})\times 10^{-9}$
- 3.0 σ deviation (includes e^+e^- and τ-decay data): SUSY?
- improve measurement to ± 10^{-10} (FNAL, J-PARC) ⇒ $\Lambda/g \gtrsim 1$ TeV in loops

Muon g−2

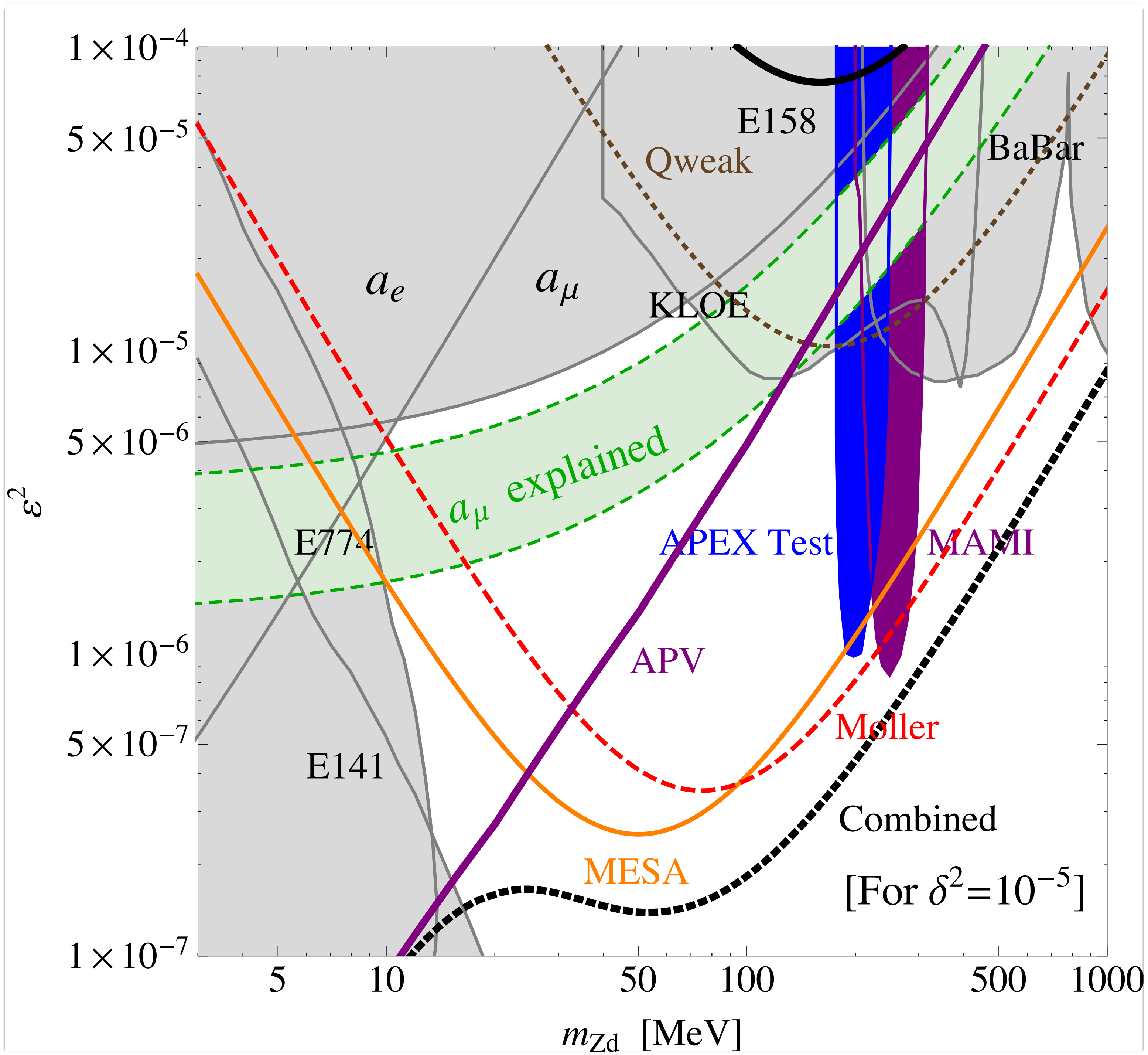
- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ (BNL-E821)
- SM: $a_\mu \equiv (1165918.41 \pm 0.36_{\text{vac pol}} \pm 0.32_{\gamma\times\gamma})\times 10^{-9}$
- 3.0 σ deviation (includes e^+e^- and τ-decay data): SUSY?
- improve measurement to $\pm\ 10^{-10}$ (FNAL, J-PARC) $\Rightarrow$ $\Lambda/g \gtrsim 1$ TeV in loops
- reduce hadronic uncertainties by at least factor 2 (overall error by factor 3)

Muon g−2

- $a_\mu \equiv (1165920.80 \pm 0.63)\times 10^{-9}$ (BNL-E821)
- SM: $a_\mu \equiv (1165918.41 \pm 0.36_{\text{vac pol}} \pm 0.32_{\gamma\times\gamma})\times 10^{-9}$
- 3.0 σ deviation (includes e^+e^- and τ-decay data): SUSY?
- improve measurement to $\pm 10^{-10}$ (FNAL, J-PARC) ⇒ $\Lambda/g \gtrsim 1$ TeV in loops
- reduce hadronic uncertainties by at least factor 2 (overall error by factor 3)
- vacuum polarization: low-energy part correlated with running α and $\sin^2\theta_W$
  - e^+e^- based (annihilation & radiative return): 3.6 σ

    2.3 σ discrepancy with measured $\mathcal{B}(\tau^- \to \nu\, \pi^0\, \pi^-)$
  - τ based: 2.4 σ
  - 1.9 σ conflict between KLOE and BaBar (which is not inconsistent with τ-data)
  - charm threshold and continuum regions for m_c and $\Delta\alpha$ (for M_H prediction)

Davoudiasl, Lee, Marciano, 2012



Electric Dipole Moments (EDMs)

Electric Dipole Moments (EDMs)

- violate P and CP with SM contribution many orders of magnitude below current limits

Electric Dipole Moments (EDMs)

- violate P and CP with SM contribution many orders of magnitude below current limits
- diamagnetic atoms are mostly sensitive to the nuclear Schiff moment, the nucleon EDMs d_p, d_n and one QQLL operator, and probe θ_{QCD} ***Engel, Ramsey-Musolf, van Kolck 2013***

  $|d_{Hg}| < 2.0\times10^{-29}$ e cm (1σ) ≈ 2500 e l_P ⇒ $|\theta_{QCD}| < 10^{-10}$

Electric Dipole Moments (EDMs)

- violate P and CP with SM contribution many orders of magnitude below current limits
- diamagnetic atoms are mostly sensitive to the nuclear Schiff moment, the nucleon EDMs d_p, d_n and one QQLL operator, and probe θ_{QCD} ***Engel, Ramsey-Musolf, van Kolck 2013***

  $|d_{Hg}| < 2.0\times10^{-29}$ e cm $(1\sigma) \approx 2500$ e $l_P \Rightarrow |\theta_{QCD}| < 10^{-10}$
- polar molecules & paramagnetic atoms sensitive to d_e and another QQLL combination

  Yb F ***Hudson et al. 2011*** $\Rightarrow |d_e| < 2\times10^{-17}$ $e/m_e = e\, v/(76\ \text{PeV})^2$ (1σ) superseding Tl limit

Electric Dipole Moments (EDMs)

- violate P and CP with SM contribution many orders of magnitude below current limits
- diamagnetic atoms are mostly sensitive to the nuclear Schiff moment, the nucleon EDMs d_p, d_n and one QQLL operator, and probe θ_{QCD} ***Engel, Ramsey-Musolf, van Kolck 2013***

  $|d_{Hg}| < 2.0\times10^{-29}$ e cm (1σ) ≈ 2500 e $l_P \Rightarrow |\theta_{QCD}| < 10^{-10}$
- polar molecules & paramagnetic atoms sensitive to d_e and another QQLL combination

  Yb F ***Hudson et al. 2011*** $\Rightarrow |d_e| < 2\times10^{-17}$ e/m_e = e v/(76 PeV)^2 (1σ) superseding Tl limit
- measure or set limits on as many different EDMs as possible
  - measure EDMs of charged nuclei in storage ring experiments
  - improve $|d_n| < 9\times10^{-13}$ e/m_n (1σ) as competitor to probe θ_{QCD}
  - compare patterns like 0.01 e/m_n $\theta_{QCD} \sim d_n \simeq -d_p \simeq -3\, d_d$ ***Pospelov, Ritz 2005***

    with SUSY: $d_d \simeq 20\, d_n \simeq 200\, d_e \simeq$ e v/(2.2 PeV)^2
  - $|d_\mu| < 10^{-6}$ e/m_μ (E-821) to be competitive gradually improve to

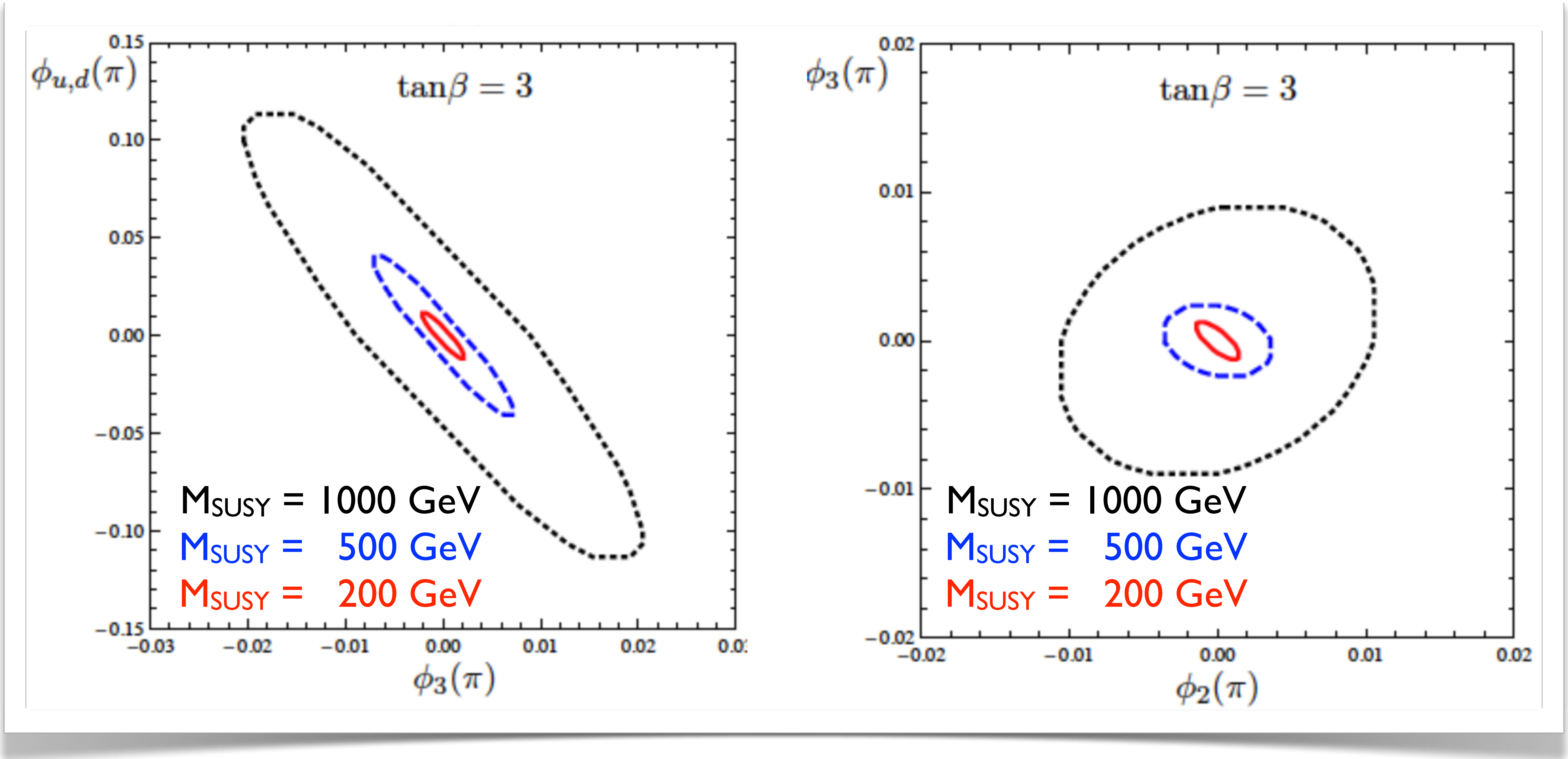
    10^{-12} e/m_μ = e v/(5 PeV)^2 (PSI, FNAL, J-PARC)

Engel, Ramsey-Musolf, van Kolck 2013

Wilson Coefficient	Operator (dimension)	Number	Systems
$\bar{\theta}$	theta term (4)	1	hadronic & diamagnetic atoms
δ_e	electron EDM (6)	1	paramagenetic atoms
$\mathrm{Im}\, C_{\ell equ}^{(1,3)}$, $\mathrm{Im}\, C_{\ell eqd}$	semi-leptonic (6)	3	& molecules
δ_q	quark EDM (6)	2	hadronic &
$\tilde{\delta}_q$	quark chromo EDM (6)	2	diamagnetic atoms
$C_{\tilde{G}}$	three-gluon (6)	1	
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	four-quark (6)	2	
$\mathrm{Im}\, C_{\varphi ud}$	induced four-quark (6)	1	
total	(first generation only)	13	

Li, Profumo, Ramsey-Musolf 2010

ϕ_i: gauge-Higgs SUSY soft phases ϕ_f: trilinear SUSY soft phases (A-terms)



CP phases too small for BAU unless one relaxes universality and allows cancellations

Charged Lepton Flavor Violation (CLFV)

Charged Lepton Flavor Violation (CLFV)

- hopelessly negligible in SM $\Longrightarrow$ directly probing new physics

Charged Lepton Flavor Violation (CLFV)

- hopelessly negligible in SM $\Rightarrow$ directly probing new physics
- $\mu^+ \to e^+ \gamma$
  - current MEG limit: BR < 5.7×10^{-13}
  - improve to 10^{-13} and perhaps 10^{-14} (challenging)
  - probes effective operator like $m_\mu/\Lambda^2 \, \bar{\mu} \, \sigma^{\mu\nu} \, e \, F_{\mu\nu}$ at tree level

Charged Lepton Flavor Violation (CLFV)

- hopelessly negligible in SM ⇒ directly probing new physics
- $\mu^+ \to e^+ \gamma$
  - current MEG limit: BR < 5.7×10^{-13}
  - improve to 10^{-13} and perhaps 10^{-14} (challenging)
  - probes effective operator like $m_\mu/\Lambda^2\, \bar{\mu}\, \sigma^{\mu\nu}\, e\, F_{\mu\nu}$ at tree level
- $\mu^+ \to e^+ e^- e^+$
  - current SINDRUM limit: BR < 1.0×10^{-12}
  - improve to 10^{-15} and perhaps 10^{-16} (challenging)
  - probes effective operator like $1/\Lambda^2\, \bar{\mu}\, \gamma^\mu\, e\, \bar{e}\, \gamma_\mu\, e$ at tree level

Charged Lepton Flavor Violation (CLFV)

- hopelessly negligible in SM $\Rightarrow$ directly probing new physics
- $\mu^+ \to e^+ \gamma$
  - current MEG limit: BR < 5.7×10^{-13}
  - improve to 10^{-13} and perhaps 10^{-14} (challenging)
  - probes effective operator like $m_\mu/\Lambda^2\, \bar{\mu}\, \sigma^{\mu\nu}\, e\, F_{\mu\nu}$ at tree level
- $\mu^+ \to e^+ e^- e^+$
  - current SINDRUM limit: BR < 1.0×10^{-12}
  - improve to 10^{-15} and perhaps 10^{-16} (challenging)
  - probes effective operator like $1/\Lambda^2\, \bar{\mu}\, \gamma^\mu\, e\, \bar{e}\, \gamma_\mu\, e$ at tree level
- $K_L \to \mu^\pm e^\mp$

Charged Lepton Flavor Violation (CLFV)

- hopelessly negligible in SM ⇒ directly probing new physics
- $\mu^+ \to e^+ \gamma$
  - current MEG limit: BR < 5.7×10^{-13}
  - improve to 10^{-13} and perhaps 10^{-14} (challenging)
  - probes effective operator like $m_\mu/\Lambda^2\, \bar{\mu}\, \sigma^{\mu\nu}\, e\, F_{\mu\nu}$ at tree level
- $\mu^+ \to e^+ e^- e^+$
  - current SINDRUM limit: BR < 1.0×10^{-12}
  - improve to 10^{-15} and perhaps 10^{-16} (challenging)
  - probes effective operator like $1/\Lambda^2\, \bar{\mu}\, \gamma^\mu\, e\, \bar{e}\, \gamma_\mu\, e$ at tree level
- $K_L \to \mu^\pm e^\mp$
- $\mu^+ e^- \leftrightarrow \mu^- e^+$

Charged Lepton Flavor Violation (CLFV)

- hopelessly negligible in SM $\Rightarrow$ directly probing new physics
- $\mu^+ \to e^+ \gamma$
  - current MEG limit: BR $< 5.7 \times 10^{-13}$
  - improve to 10^{-13} and perhaps 10^{-14} (challenging)
  - probes effective operator like $m_\mu/\Lambda^2\ \bar{\mu}\ \sigma^{\mu\nu}\ e\ F_{\mu\nu}$ at tree level
- $\mu^+ \to e^+ e^- e^+$
  - current SINDRUM limit: BR $< 1.0 \times 10^{-12}$
  - improve to 10^{-15} and perhaps 10^{-16} (challenging)
  - probes effective operator like $1/\Lambda^2\ \bar{\mu}\ \gamma^\mu\ e\ \bar{e}\ \gamma_\mu\ e$ at tree level
- $K_L \to \mu^\pm e^\mp$
- $\mu^+ e^- \leftrightarrow \mu^- e^+$
- CLFV involving τ leptons (currently 10^{-8} level) competitive in specific scenarios
  - may improve to $< 10^{-9}$ at super-B factories

Muon capture

48

Muon capture

- 0νμ− capture (current SINDRUM-II limit: BR < 7 $\times 10^{-13}$ on Au)

48

Muon capture

- $0\nu\mu-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)

48

Muon capture

- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$ (ordinary muon capture)

Muon capture

- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ (CLFV)

Muon capture

- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \to e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \to e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}

48

Muon capture

- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}
    - PRIME: 3×10^{-19} (single event sensitivity)

48

Muon capture

- 0νμ− capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \to e^+ + (A, Z-2)$ (not the 0νββ L-operator)
  - normalization process: $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \to e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}
    - PRIME: 3×10^{-19} (single event sensitivity)
    - $\Lambda_{NP} /g \sim [3\times10^{-19}]^{1/4}\, v \sim 10$ PeV = 10,000 TeV

Muon capture

- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \to e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \to e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}
    - PRIME: 3×10^{-19} (single event sensitivity)
    - $\Lambda_{NP}/g \sim [3\times10^{-19}]^{1/4}\, v \sim 10$ PeV = 10,000 TeV
    - most likely the ultimate CLFV test

Muon capture

- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}
    - PRIME: 3×10^{-19} (single event sensitivity)
    - $\Lambda_{NP}/g \sim [3\times10^{-19}]^{1/4}\, v \sim 10$ PeV = 10,000 TeV
    - most likely the ultimate CLFV test
    - probes effective operator like $1/\Lambda^2\, \bar{\mu}\, \gamma^\mu\, e\, \bar{q}\, \gamma_\mu\, q$ at tree level

Muon capture

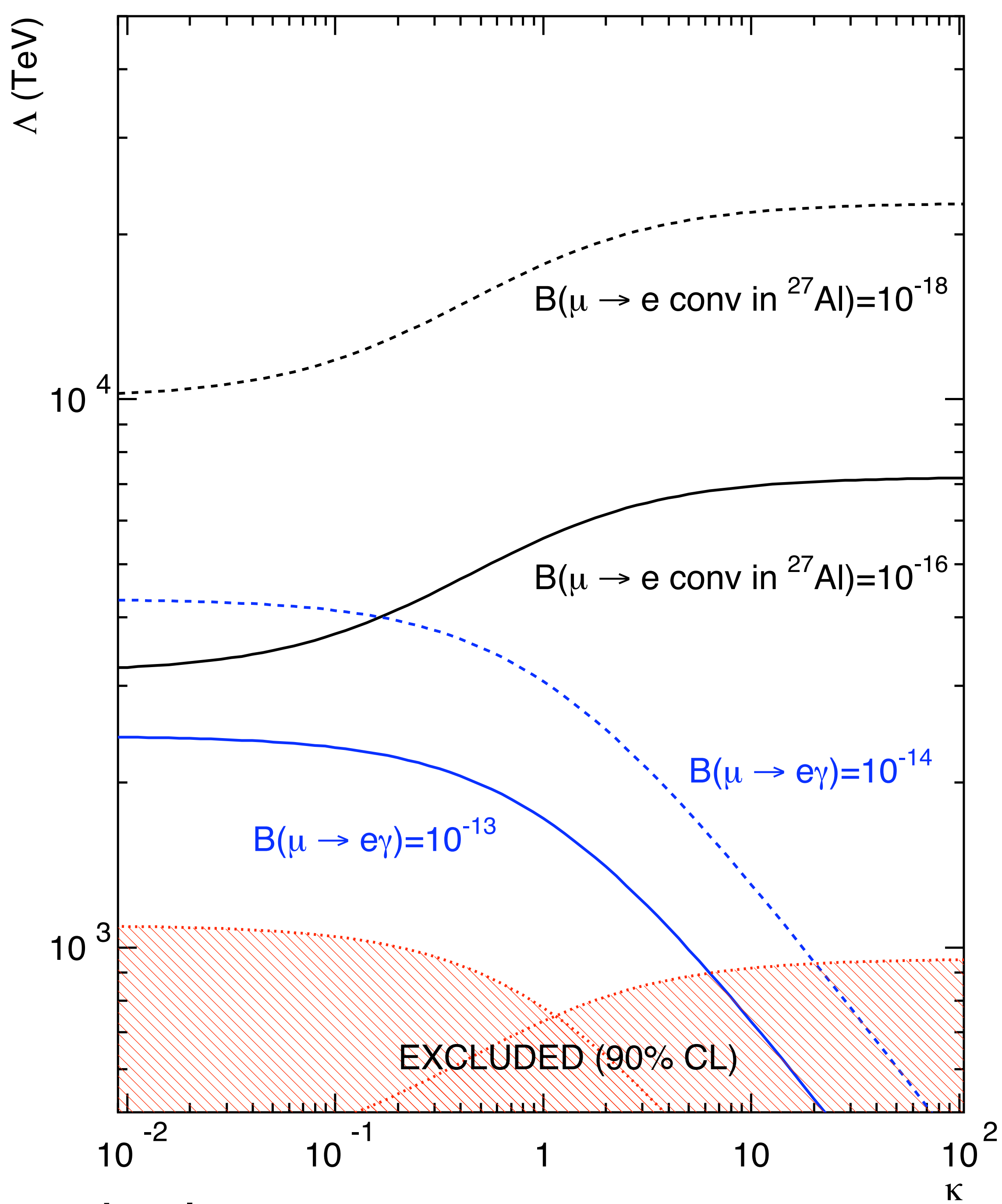
- $0\nu\mu^-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}
    - PRIME: 3×10^{-19} (single event sensitivity)
    - $\Lambda_{NP}/g \sim [3\times10^{-19}]^{1/4}\, v \sim 10$ PeV = 10,000 TeV
    - most likely the ultimate CLFV test
    - probes effective operator like $1/\Lambda^2\, \bar{\mu}\, \gamma^\mu\, e\, \bar{q}\, \gamma_\mu\, q$ at tree level
    - need ratios of target nuclei (ideally light / heavy) to disentangle operators
      Cirigliano, Kitano, Okada, Tuzon 2009

48

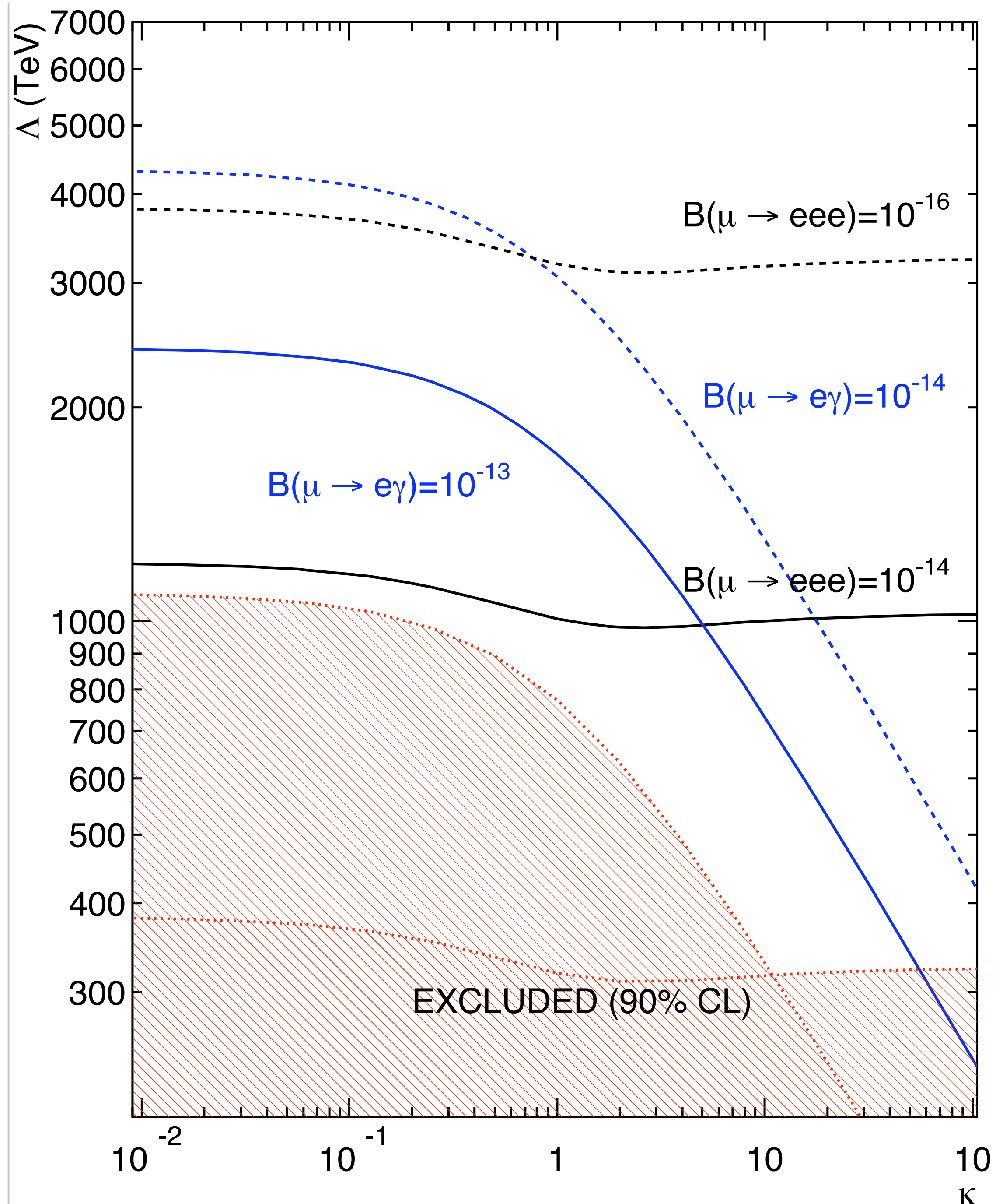
Muon capture

- $0\nu\mu-$ capture (current SINDRUM-II limit: BR < 7×10^{-13} on Au)
  - μ^- to e^+ conversion: $\mu^- + (A, Z) \rightarrow e^+ + (A, Z-2)$ (not the $0\nu\beta\beta$ L-operator)
  - normalization process: $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$ (ordinary muon capture)
  - μ^- to e^- conversion: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ (CLFV)
    - Mu2e and COMET: 10^{-16}
    - PRIME: 3×10^{-19} (single event sensitivity)
    - $\Lambda_{NP}/g \sim [3\times10^{-19}]^{1/4}\, v \sim 10$ PeV = 10,000 TeV
    - most likely the ultimate CLFV test
    - probes effective operator like $1/\Lambda^2\ \bar{\mu}\ \gamma^\mu\ e\ \bar{q}\ \gamma_\mu\ q$ at tree level
    - need ratios of target nuclei (ideally light / heavy) to disentangle operators
      Cirigliano, Kitano, Okada, Tuzon 2009
    - perfect opportunities for facilities like J-PARC and Project X

de Gouvêa, Vogel 2013



dipole operator ↔ contact operator



dipole operator ↔ contact operator

Rare and forbidden decays

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

$$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times 10^{-4} \;\Rightarrow\; \Lambda \gtrsim 9\,\text{TeV}$$

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times10^{-4} \Rightarrow \Lambda \gtrsim 9$ TeV

- lepton universality: $R_{e/\mu} = \Gamma[\pi \to e\,\nu\,(\gamma)] / \Gamma[\pi \to \mu\,\nu\,(\gamma)]$

  helicity suppressed in SM: $(1.2310 \pm 0.0037)\times10^{-4}$ PSI, TRIUMF

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times 10^{-4} \Rightarrow \Lambda \gtrsim 9\ \text{TeV}$

- lepton universality: $R_{e/\mu} = \Gamma[\pi \to e\,\nu\,(\gamma)]/\Gamma[\pi \to \mu\,\nu\,(\gamma)]$

  helicity suppressed in SM: $(1.2310 \pm 0.0037)\times 10^{-4}$ PSI, TRIUMF

- bright future: 5×10^{-8} PIENU, PEN

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times 10^{-4} \Rightarrow \Lambda \gtrsim 9\ \text{TeV}$

- lepton universality: $R_{e/\mu} = \Gamma[\pi \to e\,\nu\,(\gamma)]/\Gamma[\pi \to \mu\,\nu\,(\gamma)]$

  helicity suppressed in SM: $(1.2310 \pm 0.0037)\times 10^{-4}$ PSI, TRIUMF

- bright future: 5×10^{-8} PIENU, PEN

- kaons: 10^{-7} CERN

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times 10^{-4} \;\Rightarrow\; \Lambda \gtrsim 9$ TeV

- lepton universality: $R_{e/\mu} = \Gamma[\pi \to e\,\nu\,(\gamma)]/\Gamma[\pi \to \mu\,\nu\,(\gamma)]$

  helicity suppressed in SM: $(1.2310 \pm 0.0037)\times 10^{-4}$ PSI, TRIUMF

- bright future: 5×10^{-8} PIENU, PEN
- kaons: 10^{-7} CERN
- departure from V−A (S, P, T, V+A currents)

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times 10^{-4} \Rightarrow \Lambda \gtrsim 9$ TeV

- lepton universality: $R_{e/\mu} = \Gamma[\pi \to e\, \nu\, (\gamma)] / \Gamma[\pi \to \mu\, \nu\, (\gamma)]$

  helicity suppressed in SM: $(1.2310 \pm 0.0037)\times 10^{-4}$ PSI, TRIUMF

- bright future: 5×10^{-8} PIENU, PEN
- kaons: 10^{-7} CERN
- departure from V−A (S, P, T, V+A currents)
  - μ-decay (Sirlin-Michel parameters) TWIST

Rare and forbidden decays

β-decay of (ultra-)cold neutrons, trapped nuclei and mesons

- Cabibbo (CKM) universality:

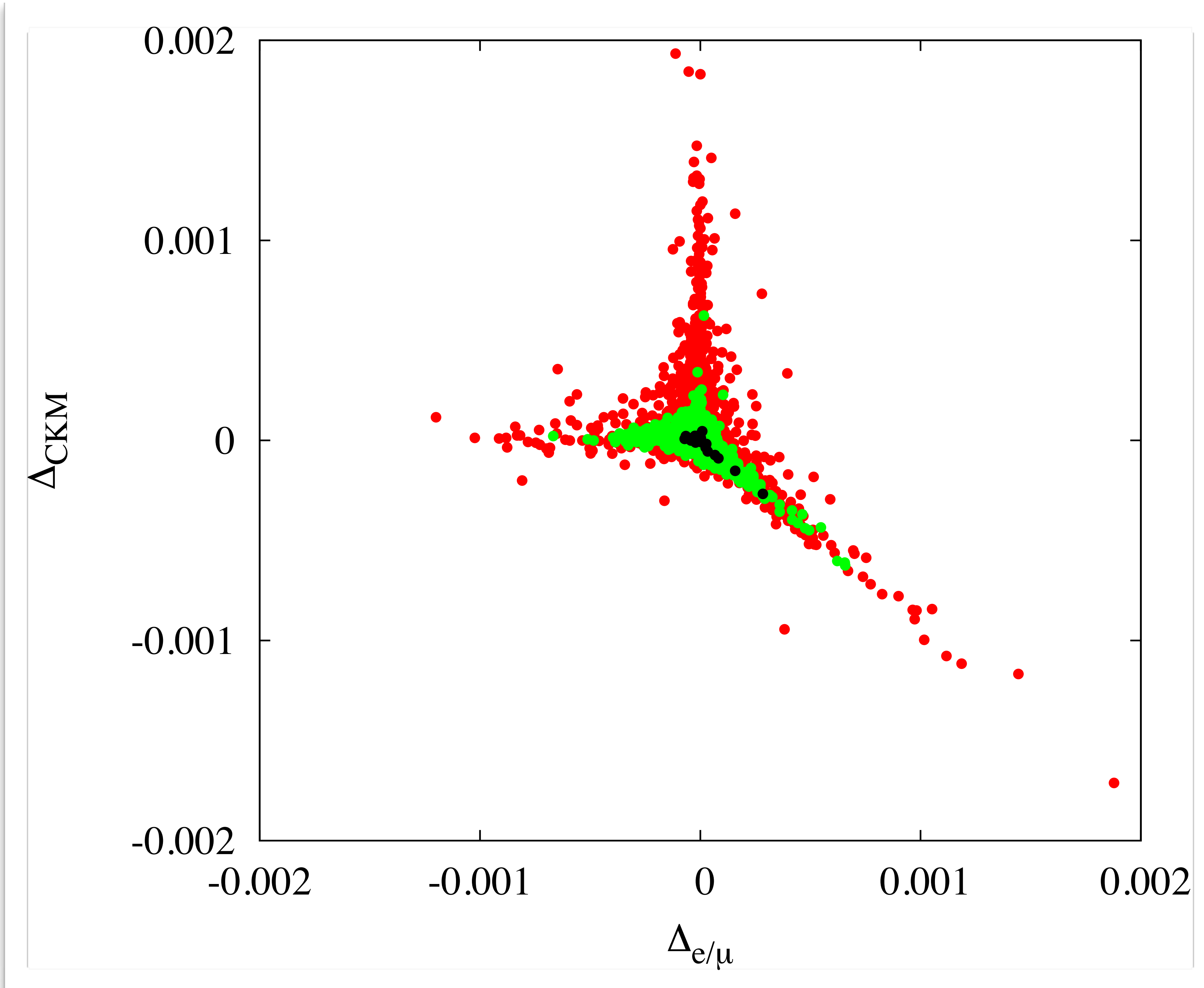
  $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (1 \pm 6)\times 10^{-4} \Rightarrow \Lambda \gtrsim 9\,\text{TeV}$

- lepton universality: $R_{e/\mu} = \Gamma[\pi \to e\,\nu\,(\gamma)]/\Gamma[\pi \to \mu\,\nu\,(\gamma)]$

  helicity suppressed in SM: $(1.2310 \pm 0.0037)\times 10^{-4}$ PSI, TRIUMF

- bright future: 5×10^{-8} PIENU, PEN
- kaons: 10^{-7} CERN
- departure from V−A (S, P, T, V+A currents)
  - μ-decay (Sirlin-Michel parameters) TWIST
  - nuclear decay distributions ***Cirigliano, Gardner, Holstein 2013***

MSSM with R-parity



Δ_{CKM}

$R_{e/\mu}$

STU

LHC bounds

combined

Bauman, Erler, Ramsey-Musolf 2012

Flavor-changing neutral currents (FCNC)

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV

52

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV
- theoretically very clean (in SM, loop and CKM suppressed)

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV
- theoretically very clean (in SM, loop and CKM suppressed)
- can be improved to 10^{-11} CERN-NA62

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV
- theoretically very clean (in SM, loop and CKM suppressed)
- can be improved to 10^{-11} CERN-NA62
- KOPIO concept 10^{-14} ($\Lambda \gtrsim 800$ TeV)

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV
- theoretically very clean (in SM, loop and CKM suppressed)
- can be improved to 10^{-11} CERN-NA62
- KOPIO concept 10^{-14} ($\Lambda \gtrsim 800$ TeV)
- CPV mode: $K^0 \to \pi^0 \nu \bar{\nu}$ KEK, J-PARC

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV
- theoretically very clean (in SM, loop and CKM suppressed)
- can be improved to 10^{-11} CERN-NA62
- KOPIO concept 10^{-14} ($\Lambda \gtrsim 800$ TeV)
- CPV mode: $K^0 \to \pi^0 \nu \bar{\nu}$ KEK, J-PARC
- K^+ (K^0) can determine modulus (Im) of $V_{td}V_{ts}^*$

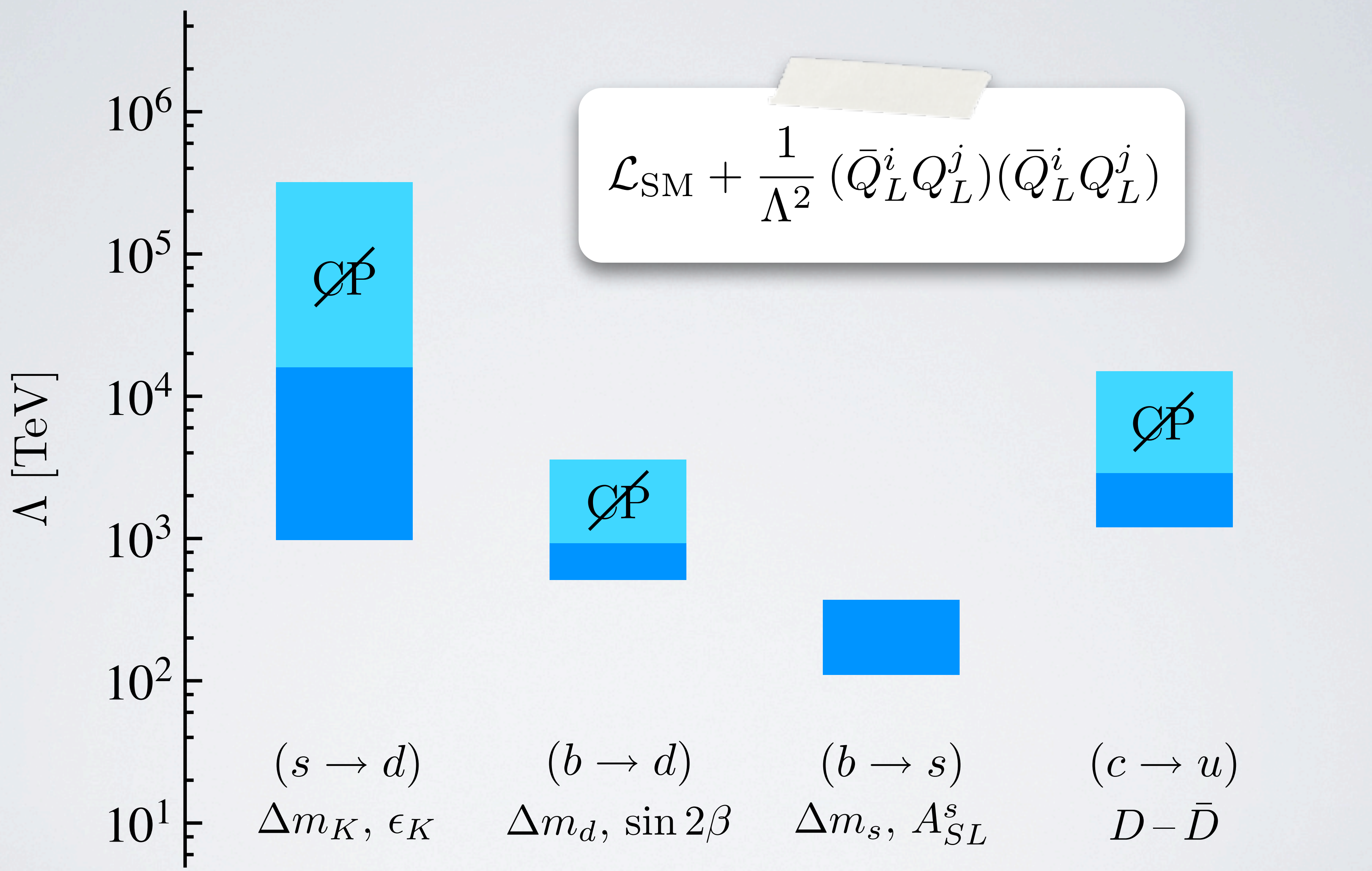
52

Flavor-changing neutral currents (FCNC)

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$ BNL-E787 $\Rightarrow \Lambda \gtrsim 76$ TeV
- theoretically very clean (in SM, loop and CKM suppressed)
- can be improved to 10^{-11} CERN-NA62
- KOPIO concept 10^{-14} ($\Lambda \gtrsim 800$ TeV)
- CPV mode: $K^0 \to \pi^0 \nu \bar{\nu}$ KEK, J-PARC
- K^+ (K^0) can determine modulus (Im) of $V_{td} V_{ts}^*$
- superior to V_{ub}

Haisch 2010

BOUNDS ON GENERIC FLAVOR VIOLATION



53

Proton decay

Proton decay

- the next best thing after a GUT or Planck scale accelerator

Proton decay

- the next best thing after a GUT or Planck scale accelerator
- $\tau(p \to e^+ \pi_0) > 8.2 \times 10^{33}$ a (Super-Kamiokande) ⇒

Proton decay

- the next best thing after a GUT or Planck scale accelerator
- $\tau(p \to e^+ \pi_0) > 8.2\times10^{33}$ a (Super-Kamiokande) $\Rightarrow$
- $\Gamma/m = C/16\pi\ (360\ \text{MeV}\ g/\Lambda)^4 < (4.1\times10^{-17})^4 \Rightarrow$

Proton decay

- the next best thing after a GUT or Planck scale accelerator
- $\tau(p \to e^+ \pi_0) > 8.2\times10^{33}$ a (Super-Kamiokande) $\Rightarrow$
- $\Gamma/m = C/16\pi\,(360\text{ MeV } g/\Lambda)^4 < (4.1\times10^{-17})^4 \Rightarrow$
- $\Lambda > 3.3\times10^{15}$ GeV (for $C = g = 1$) $\approx 10^{-3}\, M_P$

Proton decay

- the next best thing after a GUT or Planck scale accelerator
- $\tau(p \to e^+ \pi_0) > 8.2\times10^{33}$ a (Super-Kamiokande) $\Rightarrow$
- $\Gamma/m = C/16\pi\ (360\ \mathrm{MeV}\ g/\Lambda)^4 < (4.1\times10^{-17})^4 \Rightarrow$
- $\Lambda > 3.3\times10^{15}$ GeV (for $C = g = 1$) $\approx 10^{-3}\ M_P$
- $C \approx 30$ in minimal SUSY-SU(5), where

  $\Lambda_{SUSY\text{-}GUT} = 2\times10^{16}$ GeV, but excluded through

  $\tau(p \to K+ \bar{\nu}) > 2.3\times10^{33}$ a ***Murayama, Pierce 2002***

Proton decay

- the next best thing after a GUT or Planck scale accelerator
- $\tau(p \to e^+ \pi_0) > 8.2 \times 10^{33}$ a (Super-Kamiokande) $\Rightarrow$
- $\Gamma/m = C/16\pi\ (360\ \text{MeV}\ g/\Lambda)^4 < (4.1 \times 10^{-17})^4 \Rightarrow$
- $\Lambda > 3.3 \times 10^{15}$ GeV (for $C = g = 1$) $\approx 10^{-3}\ M_P$
- $C \approx 30$ in minimal SUSY-SU(5), where

  $\Lambda_{SUSY\text{-}GUT} = 2 \times 10^{16}$ GeV, but excluded through

  $\tau(p \to K + \bar{\nu}) > 2.3 \times 10^{33}$ a ***Murayama, Pierce 2002***

➡ complementarity is crucial even testing the highest scales

Variations at d > 6

Variations at d > 6

- dimension 7 needed for transition magnetic moments of Majorana neutrinos ***Bell et al. 2006***

Variations at d > 6

- dimension 7 needed for transition magnetic moments of Majorana neutrinos ***Bell et al. 2006***
- 129 dimension 8 operators with $\Delta L = 2, \Delta B = 0$ ***Babu, Leung 2001, de Gouvea, Jenkins 2007***

Variations at d > 6

- dimension 7 needed for transition magnetic moments of Majorana neutrinos ***Bell et al. 2006***
- 129 dimension 8 operators with $\Delta L = 2, \Delta B = 0$
  Babu, Leung 2001, de Gouvea, Jenkins 2007
- dimension 9
  - needed for $n\bar{n}$-oscillations
  - alternative mechanism for $0\nu\beta\beta$-decay;
    - cataloged by ***Prezeau, Ramsey-Musolf, Vogel 2003***
    - Heidelberg-Moscow Ge experiment $\Rightarrow \; \Lambda_9/g \gtrsim 3\,\text{TeV}$
    - angular distribution may distinguish “long-distance” (m_ν) and “short-distance” models ***Ali, Borisov, Zhuridov 2006***

Conclusions

56

Conclusions

- fundamental symmetry tests probe new physics at the PeV scale

Conclusions

- fundamental symmetry tests probe new physics at the PeV scale
- already severely constrain the flavor and CP structures of any scenario addressing the hierarchy problem

Conclusions

- fundamental symmetry tests probe new physics at the PeV scale
- already severely constrain the flavor and CP structures of any scenario addressing the hierarchy problem
- a positive signal would not point to a specific theory or model (neither can Λ_{NP} be deduced)

Conclusions

- fundamental symmetry tests probe new physics at the PeV scale
- already severely constrain the flavor and CP structures of any scenario addressing the hierarchy problem
- a positive signal would not point to a specific theory or model (neither can Λ_{NP} be deduced)
- it is therefore of paramount importance to pursue
  - as many different types of symmetry tests as possible
    - B, L, LF, CP, P, …
  - and within each type of test aim at various kinds of processes
    - $\mu \to e\,\gamma$, $\mu \to 3\,e$, $\mu \to e$, …
  - and within each kind of process vary and take combinations of projectiles and targets
    - A, Z, lepton flavor, …
  - and where possible obtain final state information
    - spin, flavor, energy, scattering angle, …

Conclusions

- fundamental symmetry tests probe new physics at the PeV scale
- already severely constrain the flavor and CP structures of any scenario addressing the hierarchy problem
- a positive signal would not point to a specific theory or model (neither can Λ_{NP} be deduced)
- it is therefore of paramount importance to pursue
  - as many different types of symmetry tests as possible
    - B, L, LF, CP, P, …
  - and within each type of test aim at various kinds of processes
    - $\mu \to e\,\gamma$, $\mu \to 3\,e$, $\mu \to e$, …
  - and within each kind of process vary and take combinations of projectiles and targets
    - A, Z, lepton flavor, …
  - and where possible obtain final state information
    - spin, flavor, energy, scattering angle, …
- field moving towards being a backup if nothing (except for the Higgs) is seen at the LHC