Acknowledgements:
R. Bernstein, A. Bodek, B. Casey, V. Cirigliano, J. Erler, A. Kotwal, J. Singh…

Many thanks to numerous collaborators for ideas, photos, slides, text….

BSM Searches at the Intensity Frontier

Experimental Overview

Krishna Kumar
University of Massachusetts, Amherst

EIC BSM Workshop, INT, Seattle
February 12, 2024

Outline

- Broad Context for the Experiments Pursued and the Tools
- Overview of the 4 Classes of Measurements (my classification)
- A closer look at Precision Electroweak Physics
- General Framework: Neutral Current Electron-Nucleon scattering
- Summary

I have had to work hard to find resources for this talk; I havent done that in a while!

Disclaimers

- I wish I had planned better to spend more time to gather the relevant information! Apologies!
- I have taken the point of view that this talk is to give EIC practitioners a better feel for the broader context of BSM searches world-wide; apologies to those who are already close to such initiatives in HEP and/or in Fundamental Symmetries in NP
- The organizers are to be commended: there is a great program over the next few days. I have not really attempted to call out all the talks; obviously all are relevant! I apologize in advance for not specifically calling out relevant talks.
- There is some overlap with Vincenzo's talk. Sorry for the repetition!

Must be as model-independent as possible

Comprehensive Experimental Strategy

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

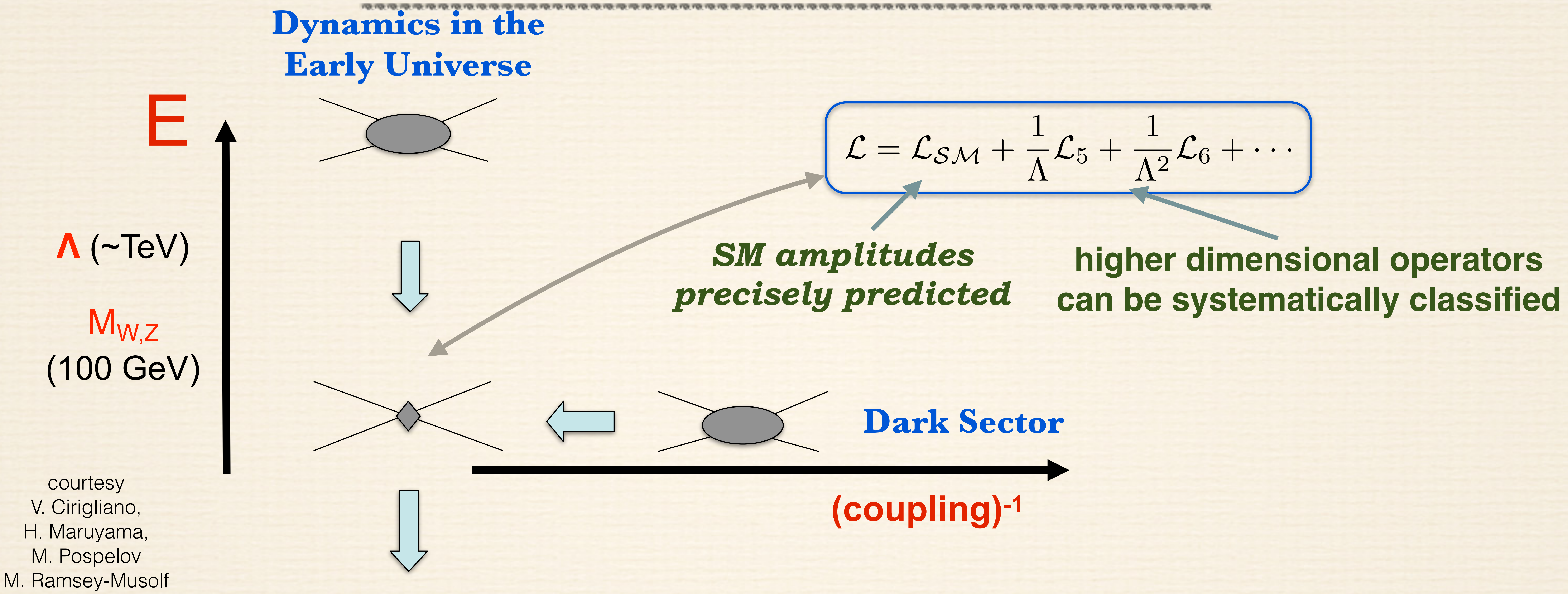
A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

- ✦ **Measurements of Neutrino Properties**
- ✦ **Direct and Indirect Searches for Dark Matter**
- ✦ **Violation of Accidental (?) Symmetries**
- ✦ **Precise Measurements of SM observables**

Observables at scales much lower than the scale of EW Symmetry Breaking

Intensity Frontier Strategy



$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

In most cases, observables exploit a symmetry principle

Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

Tools

Experimental Facilities/Initiatives/Programs

- ***Electron Beams:*** *Weak charged and neutral current couplings, precision weak mixing angle, dark photons, charged lepton flavor violation*
  - ➡ *JLab, Mainz MESA,* ***Electron Ion Collider***
- ***Muons, Kaons, Pions:*** *Lifetimes, Precision Branching ratios, Flavor Universality, muon g-2, EDMs*
  - ➡ *BNL, PSI, TRIUMF, FNAL, J-PARC*
- ***Neutrons:*** *Lifetime, Asymmetries, EDM*
  - ➡ *LANSCE, NIST, SNS, other international labs..*
- ***Underground Detectors:*** *Direct Dark Matter, Double-Beta Decay*
  - ➡ *SURF, SNOLAB, LNGS, Jinping, Kamioka…*
- ***Nuclei:*** *Precision Weak Decays, Atomic Parity Violation, EDMs*
  - ➡ *FRIB, ANL, TAMU, Tabletop…*

P5 Report: Relevant Facts

- **Highest Priority**
  - ***First phase of DUNE and PIP-II 1.2 MW***
  - ***Continued support for medium scale:***

    1. NOVA, SBN, T2K
    2. DarkSide-20k, LZ, SuperCDMS, XENONnT
    3. Belle-II, LHCb, Mu2e
- **Next Priority**
  - ***DUNE phase-II, 2 MW upgrade ACE-MIRT, third far detector, upgraded near detector***
  - ***Reach the "neutrino fog" with ultimate G3 dark matter experiment***
- **Third Priority**
  - ***Create an improved balance between small-, medium- and large-scale projects***
  - ***ASTAE, MSRI, MRI…***

2023 NSAC LRP: Relevant Facts

- **Recommendation 1**
  - *Effective operation of CEBAF and FRIB*
  - *Enhanced research budget*
- **Recommendation 2**
  - *Ton-scale neutrinoless double-beta decay PROGRAM*
- **Recommendation 3**
  - *Expeditious completion of the EIC*
- **Recommendation 4**
  - *Strategic Opportunities*

    1. SOLID
    2. Smaller scale EDM projects
    3. Other neutrino, beta decay and rare decay projects

Neutrino Properties Summary

- **Neutrino Oscillation Program**
  - *DUNE: Definitive measurement of mass ordering in a decade of operation*
  - *Combine DUNE with short baseline and upgraded solar neutrino detectors to probe non-standard (beyond 3 neutrino) scenarios with high sensitivity*
  - *Envisioned upgrades to both long and short baseline program into the 2040's will allow exploration of non-standard neutrino interactions and precision EW physics with neutrino scattering*
- **Coherent Neutrino Scattering**
  - *Large number of experiments pursuing both accelerator and reactor-based measurements over a range of nuclei*
  - *New exploration of few 10's of MeV inelastic neutrino scattering: relevance for axial-current*
- **Absolute Neutrino Mass**
  - *After KATRIN completion (late 2020's), the next frontier is ~ 40 meV with Project-8 (mid-2030s)*
  - *Complementary efforts (^{163}Ho, ultra-low-Q processes) for cross-checks and sterile neutrinos*

Dark Matter Summary

- **Ongoing Program**
  - *Direct production: LHC*
  - *Direct Detection: LZ, ADMX-G2, DarkSide-20k, XENONnT, SuperCDMS*
  - *Spin-dependent and Ultra-Heavy: IceCube*
- **Next Phase**
  - *Support for one G3 experiment capable of completely reaching the "neutrino fog"*
  - *Will require upgrade of SURF to site in the US*
- **New Initiative: A portfolio of Agile Projects for Dark Matter**
  - *Part of the newly recommended ASTAE program by the P5 report*
  - *Low mass dark matter searches*
  - *Both hidden sector models and QCD axion models provide benchmarks for new ideas*

Rare or Forbidden Processes Overview

- **Search for EDMs**
  - *Neutrons: nEDM was been terminated but there are ongoing efforts with reduced sensitivity*
  - *A variety of smaller efforts on atomic and nuclear EDMs will push beyond the Hg-199 limit*
- **Search for Neutrinoless Double-Beta Decay**
  - *Focus over the next decade is on the 3 ton-scale efforts: CUPID, LEGEND and nEXO*
  - *R&D is already under way to set up go well beyond the ton-scale to the normal heirarchy*
- **Search for Charge Lepton Flavor Violation**
  - *One of the most promising avenues to reach 100's of TeV new physics sensitivity*
  - *Important to explore all the possible flavor combinations for comprehensive search*
- **Tests of Flavor Universality**
  - *Testing flavor universality at ~ 10^{-4} level is a complementary probe of BSM physics (PIONEER)*

Neutron EDM Summary

Town Hall report 2304.03451

Experiment: Facility	Neutron Source	Measurement Cell	Measurement Techniques	90% C.L. (10^{-28} e-cm) With 300 Live Days	Year 90% C.L. Data Acquired
Crystal: JPARC	Cold Neutron Beam	Solid	Crystal Diffraction (High Internal $\vec{E}$)	< 100	Development
Beam: ESS	Cold Neutron Beam	Vacuum	Pulsed Beam	< 50	~ 2030
PNPI: ILL	ILL Turbine (UCN) PNPI/LHe (UCN)	Vacuum	Ramsey Technique, $\vec{E} = 0$ Cell for Magnetometry	Phase 1 < 100 < 10	Development Development
n2EDM: PSI	Solid D_2 (UCN)	Vacuum	Ramsey Technique, External Cs Magnetometers, Hg Co-Magnetometer	< 15	~ 2026
PanEDM ILL/Munich	Superfluid ^{4}He (UCN), Solid D_2 (UCN)	Vacuum	Ramsey Technique, Hg Co- External ^{3}He and Cs Magnetometers	< 30	~ 2026
TUCAN: TRIUMF	Superfluid ^{4}He (UCN)	Vacuum	Ramsey Technique, Hg Co-Magnetometer, External Cs Magnetometers	< 20	~ 2027
nEDM: LANL	Solid D_2 (UCN)	Vacuum	Ramsey Technique, Hg Co-Magnetometer, Hg External Magnetometer, OPM	< 30	~ 2026
nEDM@SNS: ORNL	Superfluid ^{4}He (UCN)	^{4}He	Cryogenic High Voltage, ^{3}He Capture for ω, ^{3}He Co-Magnetometer with SQUIDs, Dressed Spins, Superconducting Magnetic Shield	< 20 < 3	~ 2029 ~ 2031

TABLE II: Summary of neutron EDM experiments under development worldwide, with projected 90% C.L. sensitivity (in units of 10^{-28} e-cm, and the projected date by which data will be acquired to achieve the projected sensitivity.

To get to 10^{-28}, will need new ideas and upgrades in the 2030s, building on ongoing initiatives

Slide courtesy: Jaideep Singh

EDMs: Future Prospects

The best limit on atomic EDM:

Stable Hg-199 in a vapor cell using laser probing

EDM(^{199}Hg) < 0.74×10^{-29} *e*-cm (95% C.L.)

PRL 116:161601 (2016)

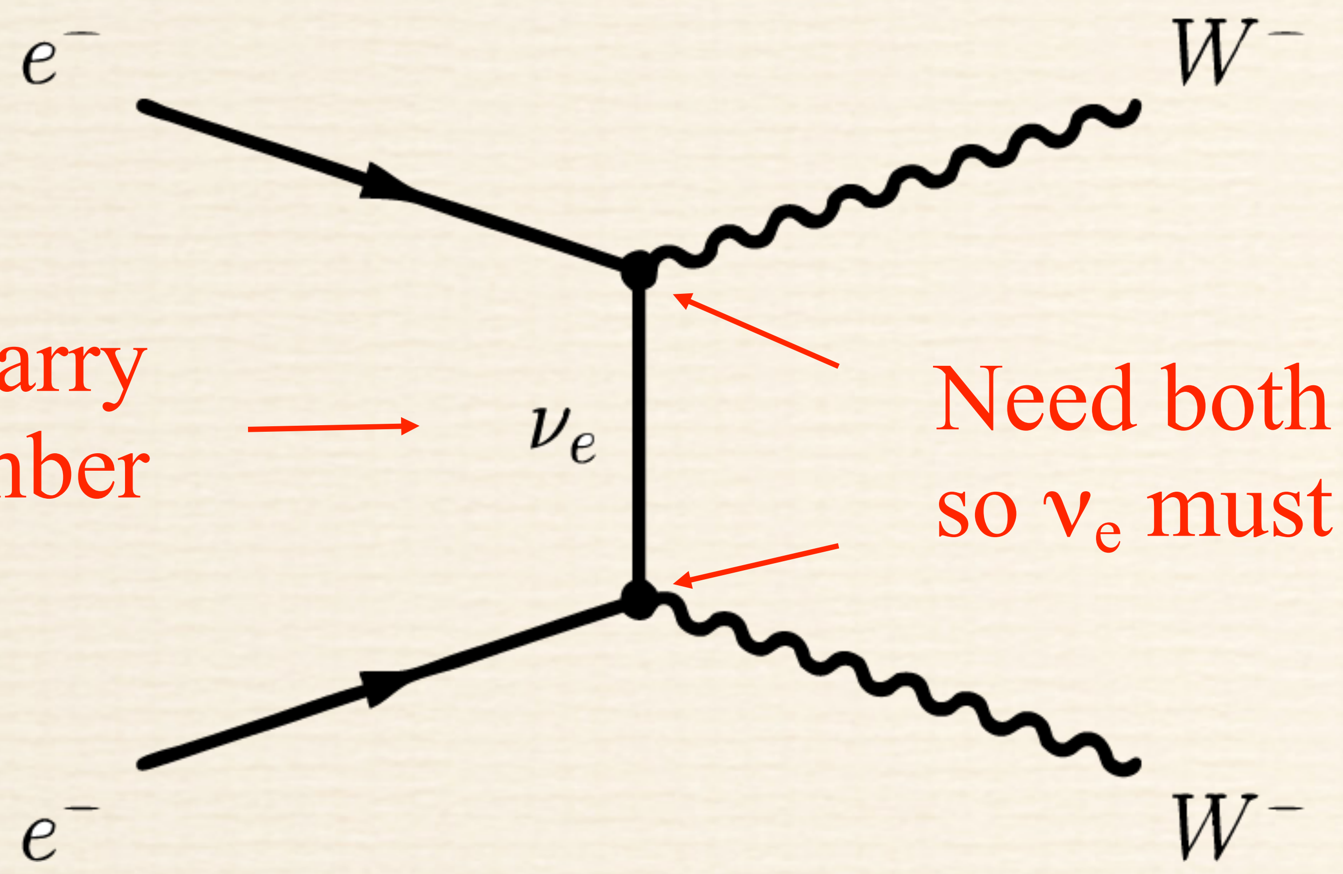
- **Planned and ongoing CP-violation search experiments** using ^{129}Xe atoms, ^{225}Ra atoms, ^{173}YbOH molecules, and ^{205}TlF molecules **are poised to match or exceed** the new physics sensitivity of **the state-of-the-art ^{199}Hg EDM experiment** by about an order of magnitude.

- Several **next generation** CP-violation search schemes using **pear-shaped nuclei inside of molecules** are currently being developed and have new physics sensitivities that are **several orders of magnitude beyond the state-of-the-art ^{199}Hg EDM experiment**.

Double-Beta Decay is really about Lepton Number Violation

L +1 +1 0 0

$e^- + e^- \Rightarrow W^- + W^-$

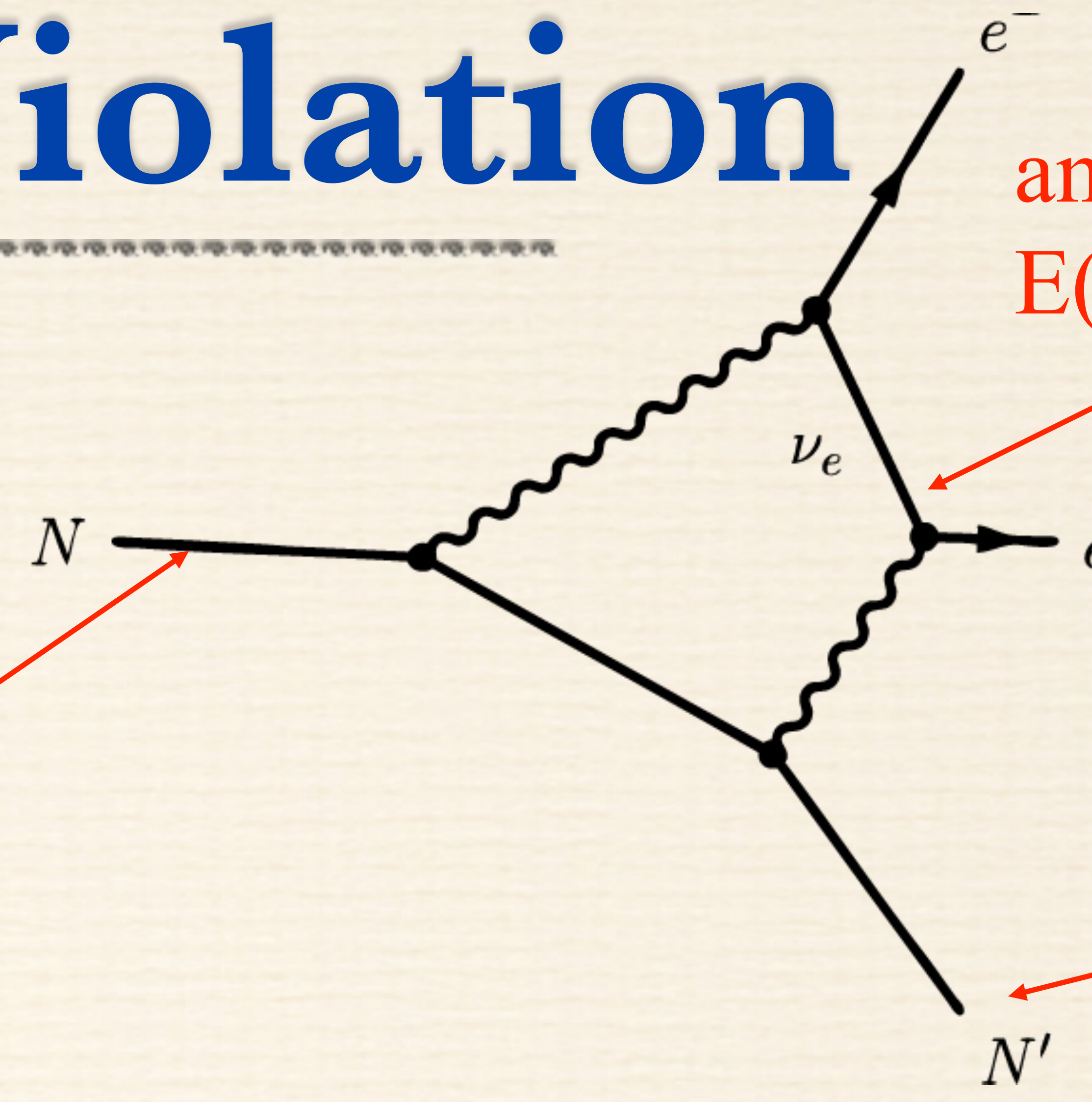


must not carry lepton number

Need both helicities, so ν_e must be massive

Lepton number changes by two units: ΔL=2

For light neutrinos, this cross-section is unobservably small

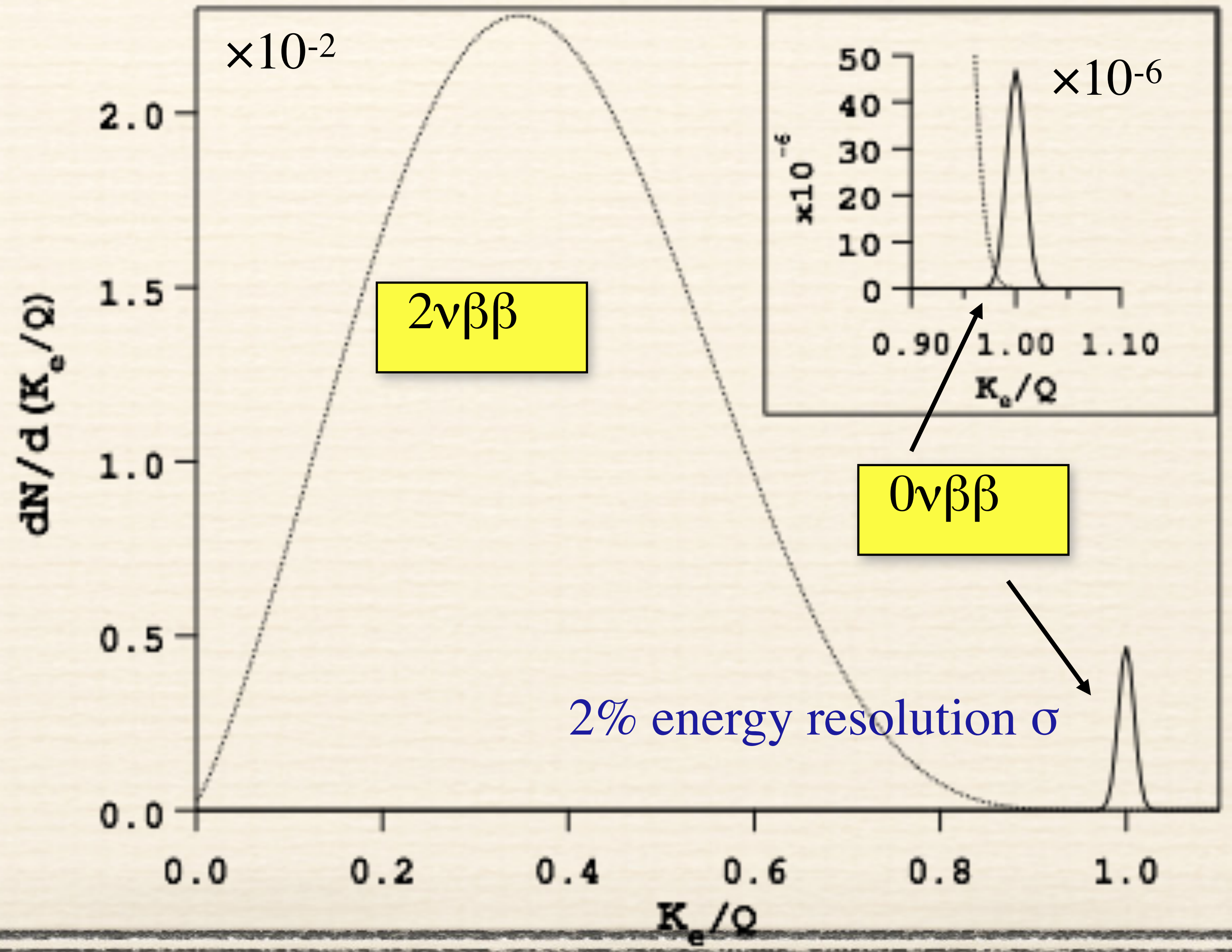


amplitude ~ m(ν)/E(ν), E(ν) ~ 100 MeV

N(Z,A)

N(Z+2,A)

“Neutrino mass mechanism” for double beta decay



If observed, it would unambiguously signal that Lepton Number is NOT a conserved quantity, and that neutrinos are Majorana particles i.e. their own anti-particles

Experiments: Very Long Half-Lives!

Typical 2$\nu\beta\beta$ half-life is very long: second-order weak process

$$\frac{1}{T^{0\nu}_{\frac{1}{2}}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

Atomic mass affected by nuclear pairing term: even A nuclei occupy 2 parabolas, even-even below odd-odd

$$\frac{1}{G^{2\nu}} \simeq 10^{20} \text{ years}$$

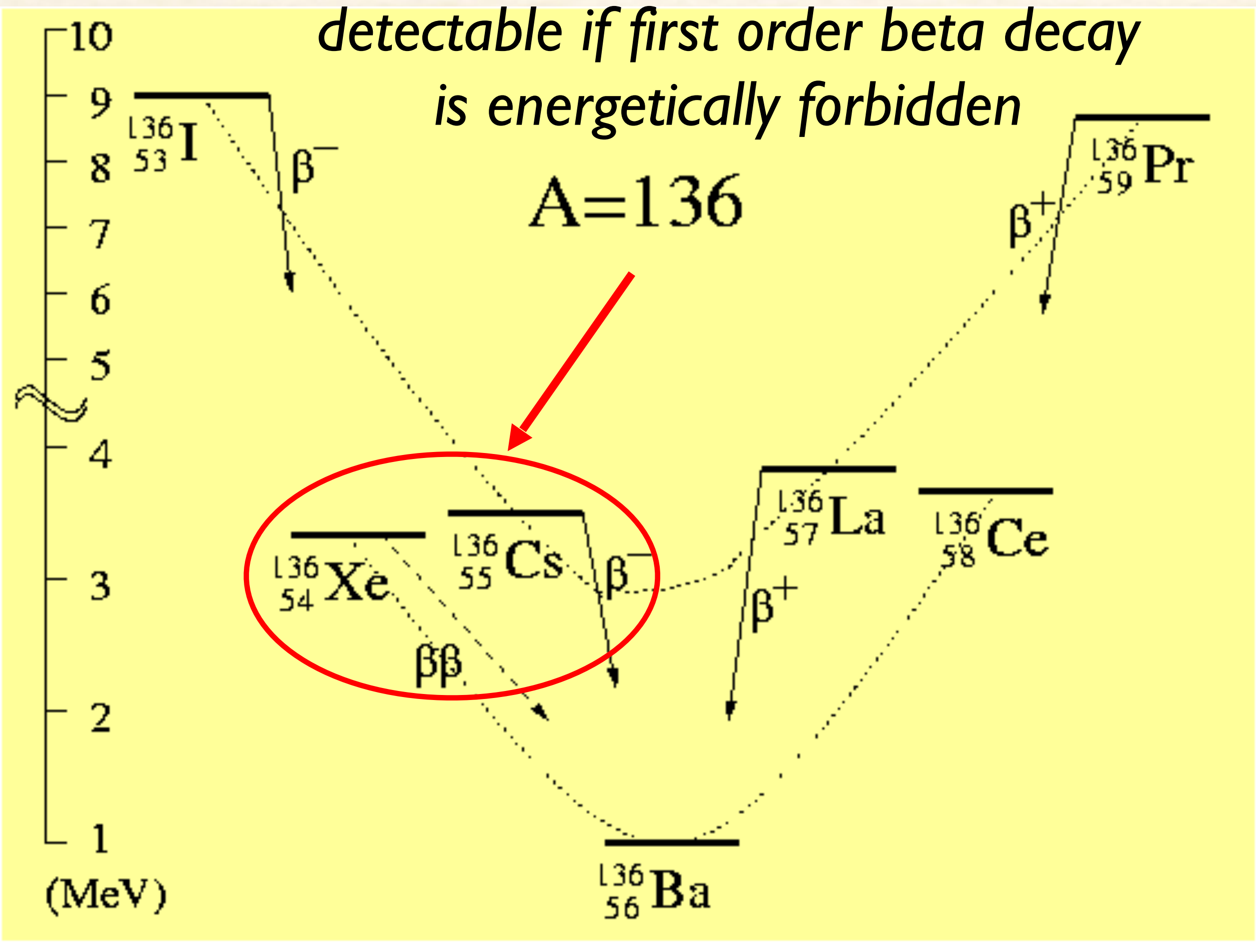
Choose nuclei where single beta decay forbidden

but double-beta decay is possible

Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Double-beta decay:
a second-order process only detectable if first order beta decay is energetically forbidden



A potential 0$\nu\beta\beta$ half-life will be even longer!

Transition Probability

$$\Gamma^{0\nu} = G(Q,Z)|M(A,Z)\eta|^2$$

$\alpha \frac{m}{Q^2}$ $(Q \sim m_e)$ Phase Space Factor $G \sim G_F^4 g_A^4 m_e^5$

$M(A,Z)$ Nuclear Matrix Element

η Particle Physics of the Black Box

For light neutrino exchange

PMNS Matrix

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$

$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years

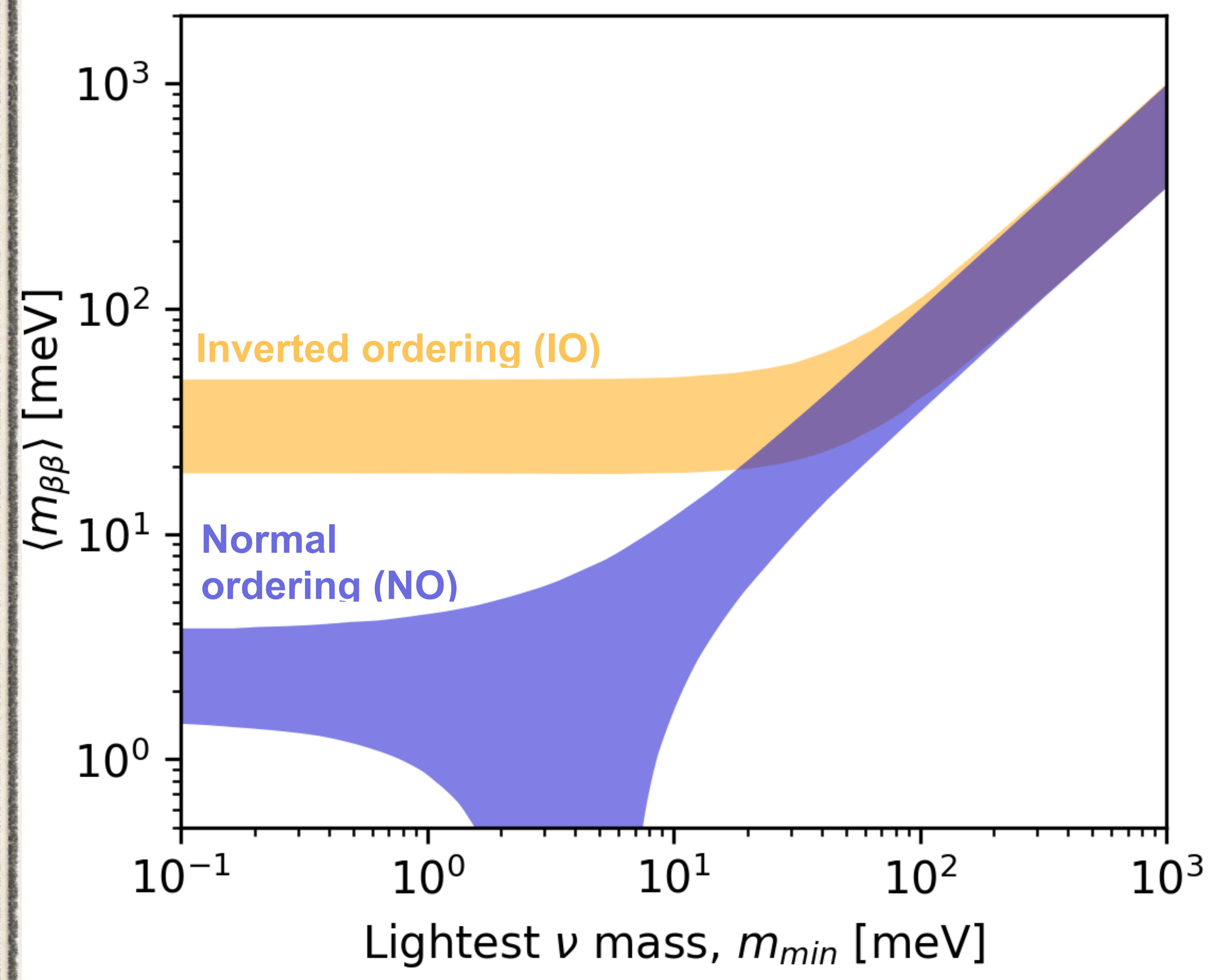
$m_{\beta\beta} \sim 0.1$ eV $\Longrightarrow T_{1/2} \sim 10^{26}$ years

$m_{\beta\beta} \sim 0.01$ eV $\Longrightarrow T_{1/2} \sim 10^{28}$ years

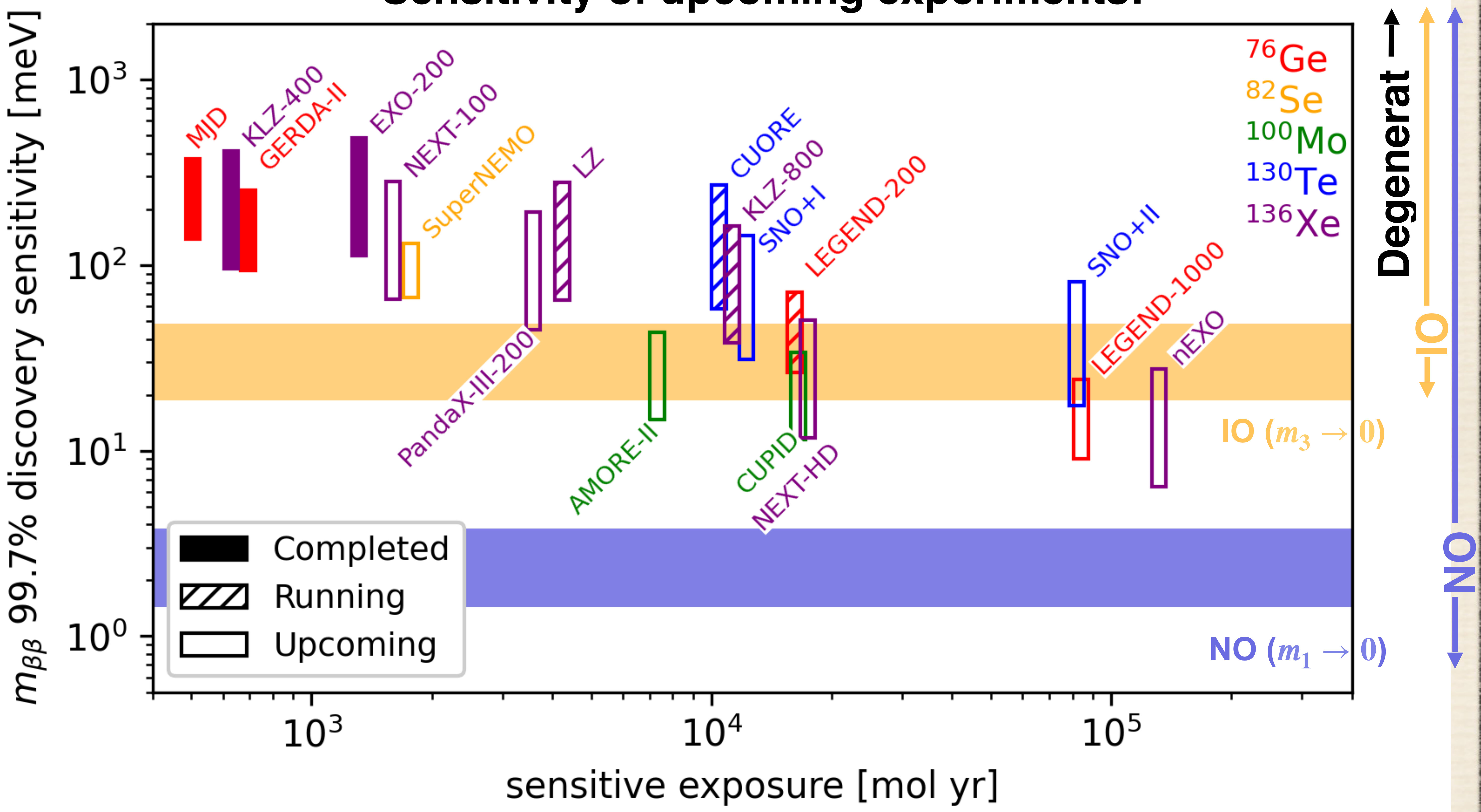
Slide courtesy: Dave Moore

Summary of Past and Present Projects

Parameter space vs. mass of lightest ν:



Sensitivity of upcoming experiments:

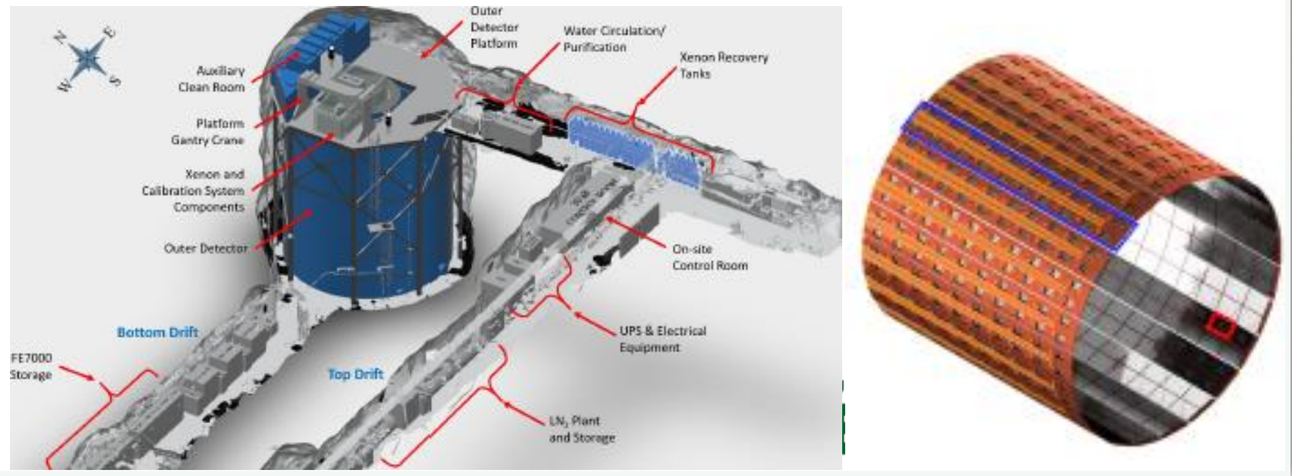


Slide courtesy: Vincenzo Cirigliano

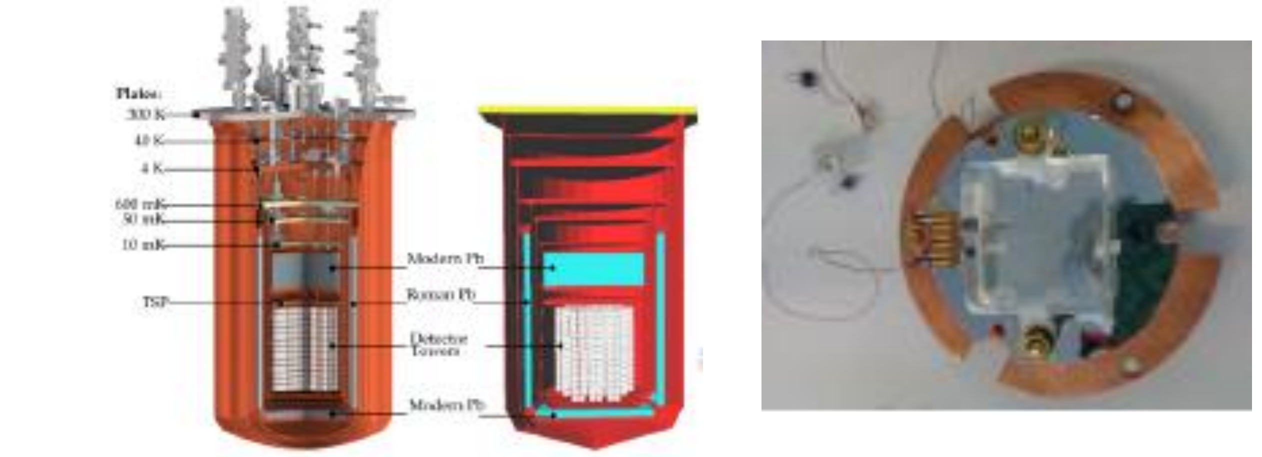
Ton Scale Experiments

- The emerging ton-scale program consists of three experiments using three different isotopes and fielding very different experimental technologies: **CUPID** (^{100}Mo), **LEGEND-1000** (^{76}Ge), and **nEXO** (^{136}Xe).
- These three experiments have undergone a US DOE portfolio review and are ready to start construction

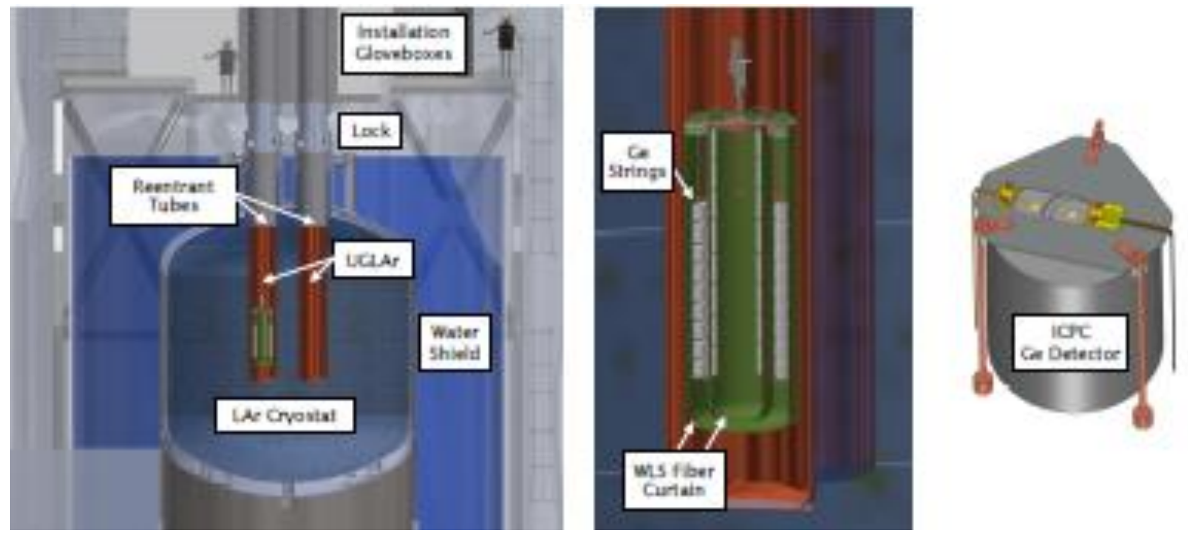
nEXO: Liquid Xe Time Projection Chamber

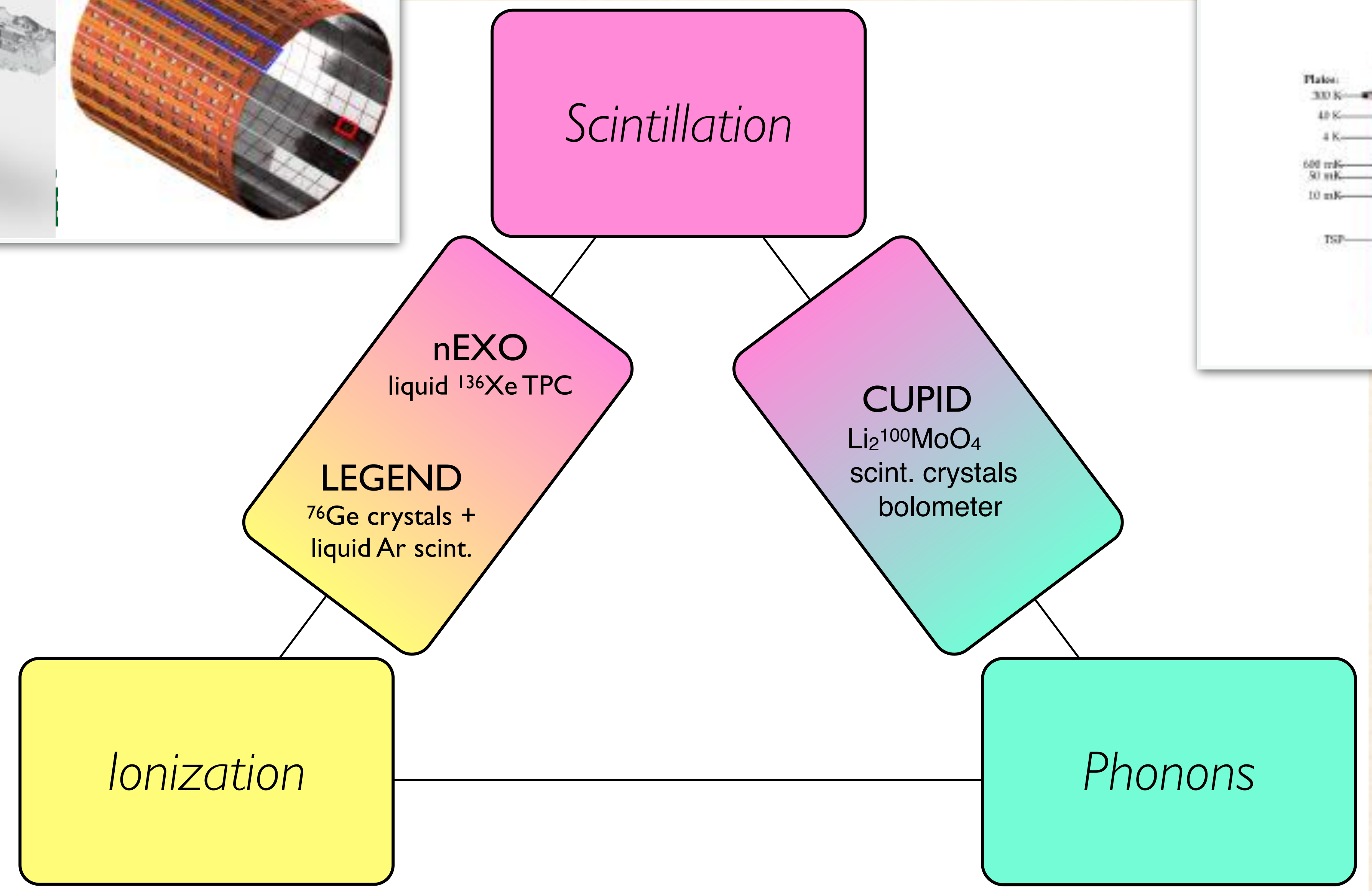


CUPID: Scintillating Crystal Bolometer



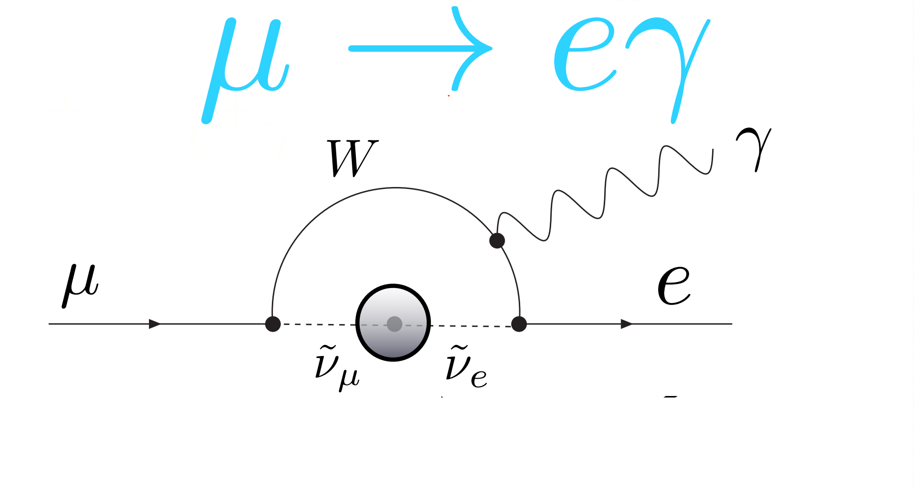
LEGEND: High Purity Ge Crystals





Charged Lepton Flavor Violation (CLFV)

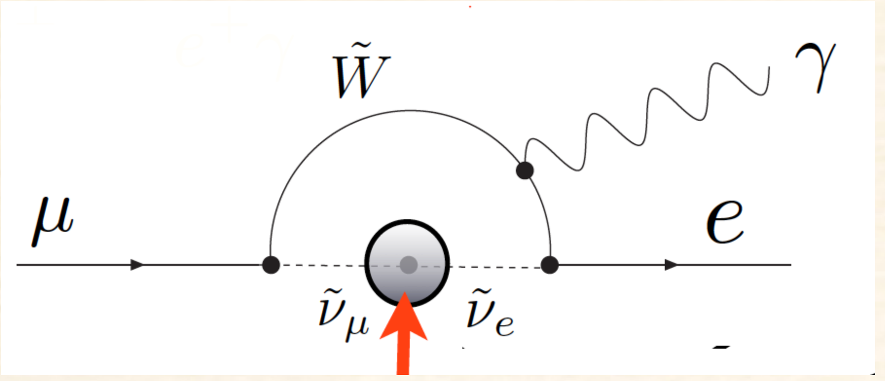
Is lepton flavor conservation exact? No! Neutrino Oscillations!



- ν's have mass! *individual lepton flavors are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons too

SM BR: 10^{-54}!

Slepton mixing in SUSY



$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-15}$$

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

tiny standard model branching fraction

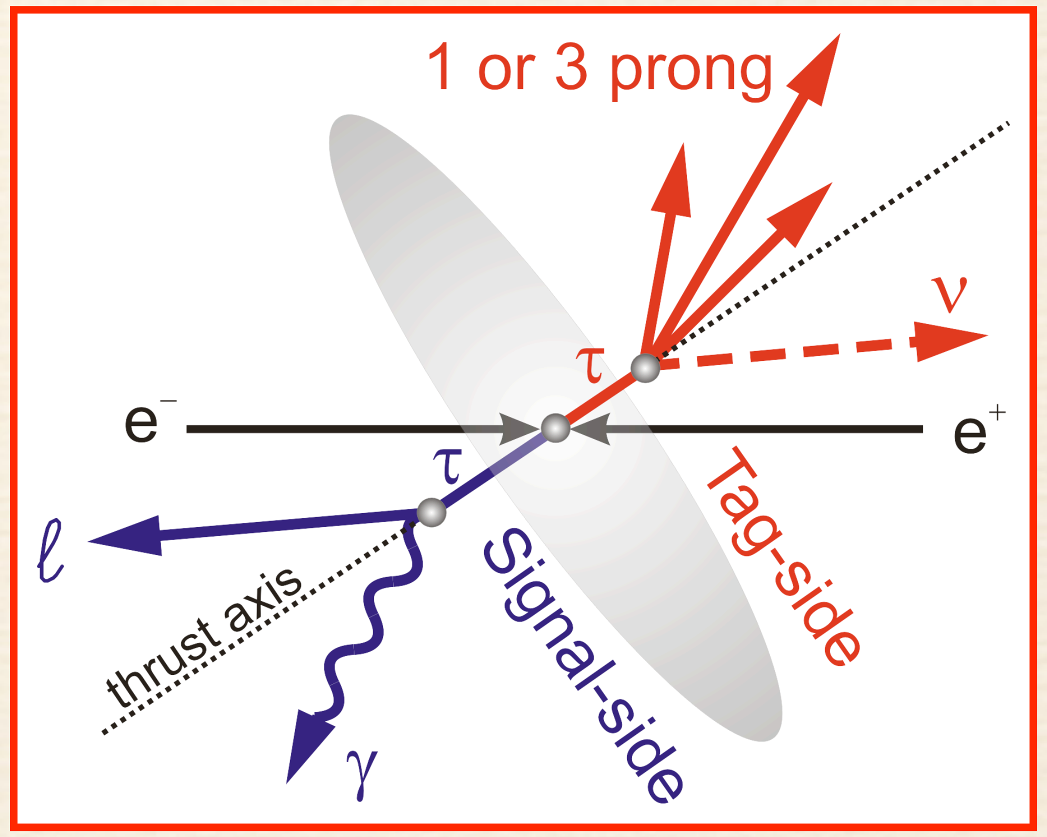
Major experimental searches are ongoing; mass reach depends on flux and sensitivity of technique

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mu e}}{\Lambda^2}\bar{e}_L \sigma^{\alpha\beta}\mu_R \Phi F_{\alpha\beta}$$

μ or $\tau \longrightarrow e\gamma$, e^+e^-e, $K_L \to \mu e$, ...

Need very high fluxes for required statistical reach

New high intensity kaon & muon beams and high luminosity e+e- colliders all over the world



Tau Decays at e+e- colliders

Slide courtesy: Bob Bernstein

CLFV Initiatives

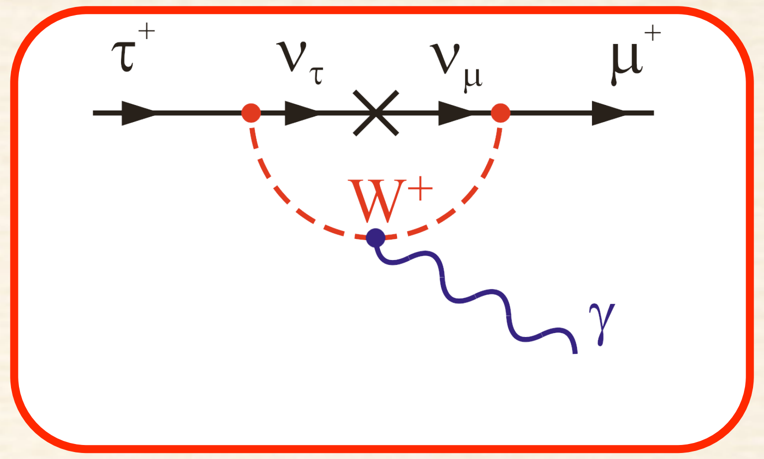
- $\mu^+ \rightarrow e^+\gamma$ (PSI)
  - MEG II, finished first run
  - BR $(\mu^+ \rightarrow e^+\gamma) < 3.1 \times 10^{-13}$ @ 90% CL
  - expect $\approx 4.2 \times 10^{-14}$ after a few years

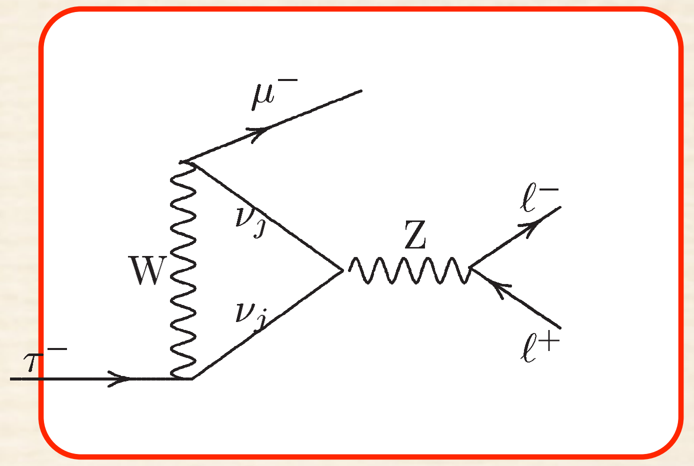
- $\mu^+ \rightarrow 3e$ (PSI)
  - Mu3e experiment (*Hesketh et al., 2204.00001*)
  - SES of 2×10^{-15}

- $\mu^- N \rightarrow e^- N$ (FNAL, J-PARC)
  - Mu2e, COMET (both $\approx (6-8) \times 10^{-17}$ @ 90% CL around end of decade

τ processes also suppressed in Standard Model but less:

Lee, Shrock
Phys.Rev.D16:1444,1977





Pham, hep-ph/9810484

Good News:
Beyond SM rates can be orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce:
~10^{10} τ/*yr* vs >10^{11} μ/*sec* in upcoming muon experiments

- Rough analogy to neutrinos: muon CLFV is "θ_{12}" ; anything involving the τ is in the θ_{13} or θ_{23} sector

- Colliders can also probe CLFV-violating Higgs decays

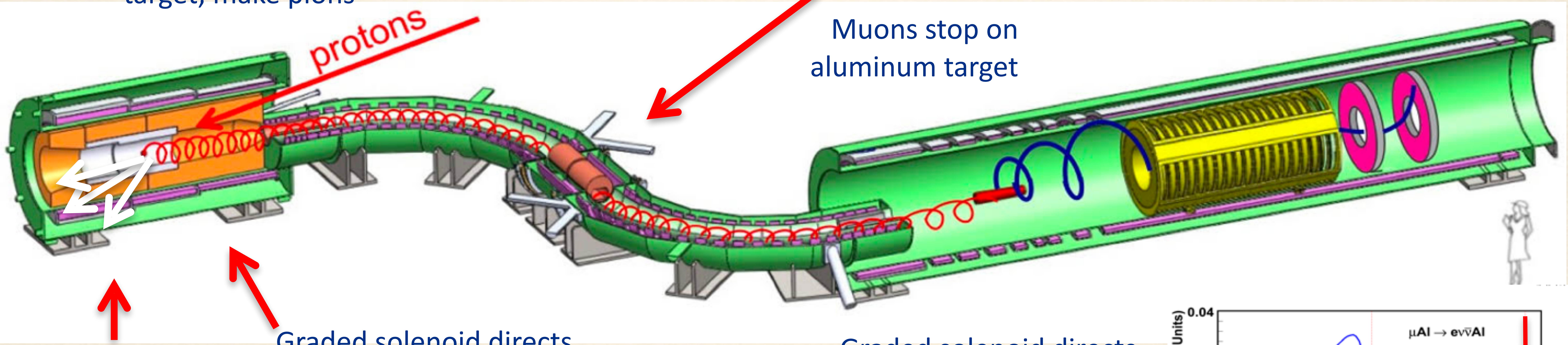
Slide courtesy: Brendan Casey

Mu2e at FNAL Overview

25m of solenoids designed to maximize captured muons and remove backgrounds (10^{10} stopped μ/sec)

Curved transport solenoid provides sign and momentum selection and avoids line of sight from production target to detector

Protons enter here, hit target, make pions



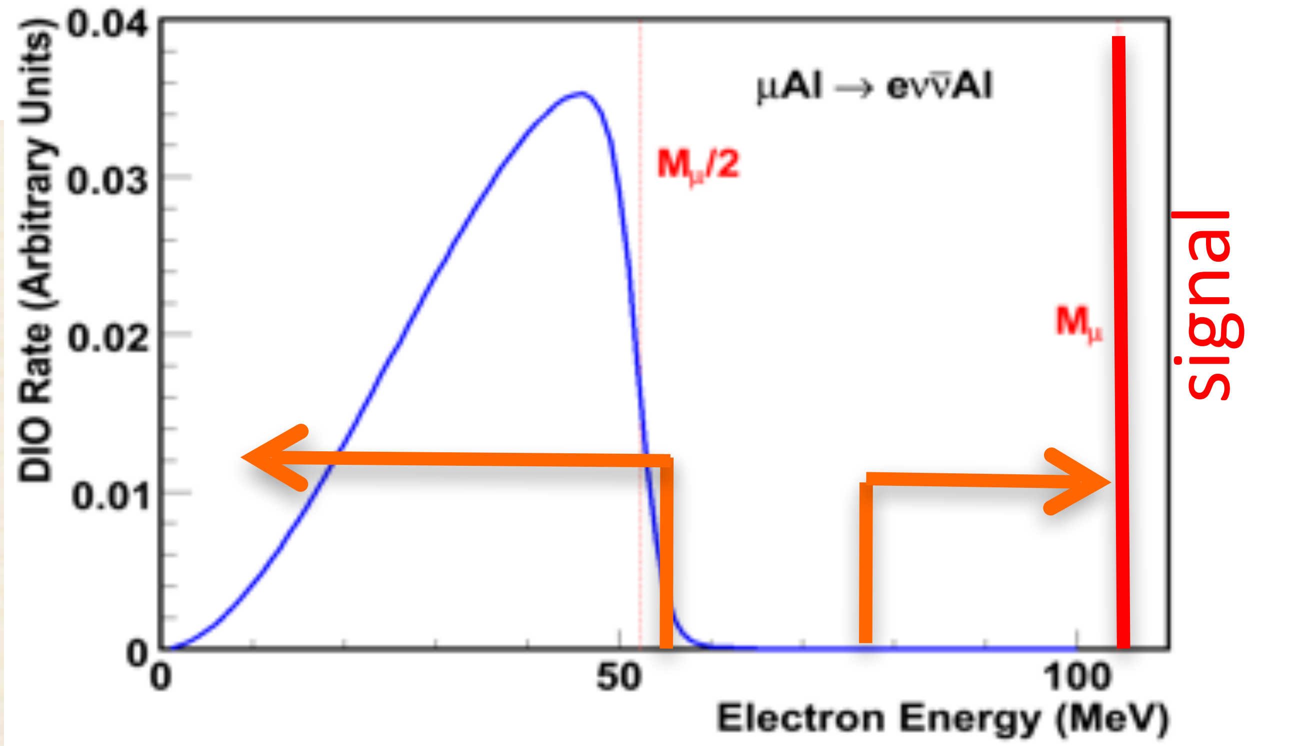
Muons stop on aluminum target

High momentum Backgrounds exit out the front

Graded solenoid directs low momentum particles into transport solenoid

Graded solenoid directs electrons to the detector

“Hollow” tracker has low acceptance for SM decays and high acceptance for signal

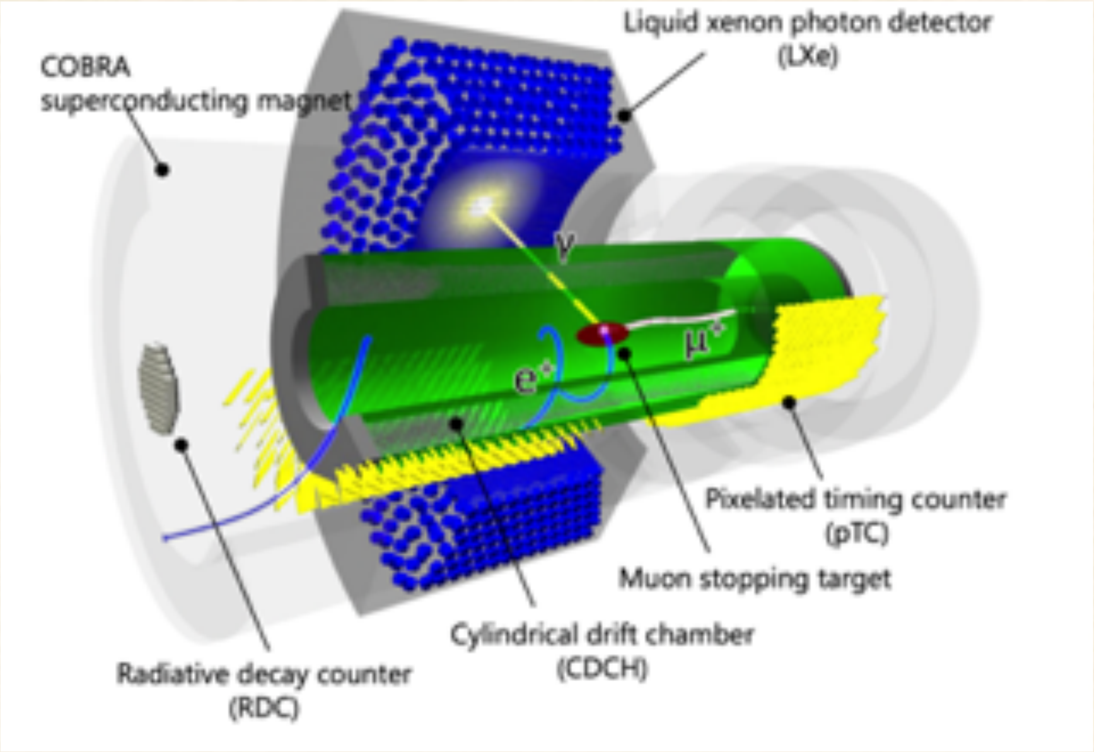


Slide courtesy: Brendan Casey

Other Experiments pursuing CLFV

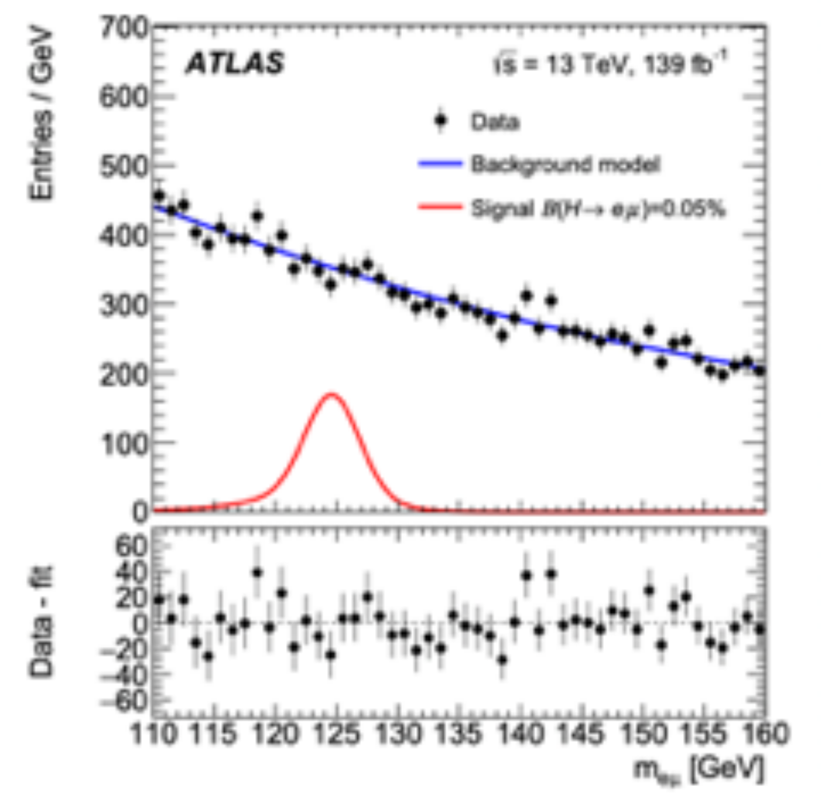
MEG-II

Data on tape



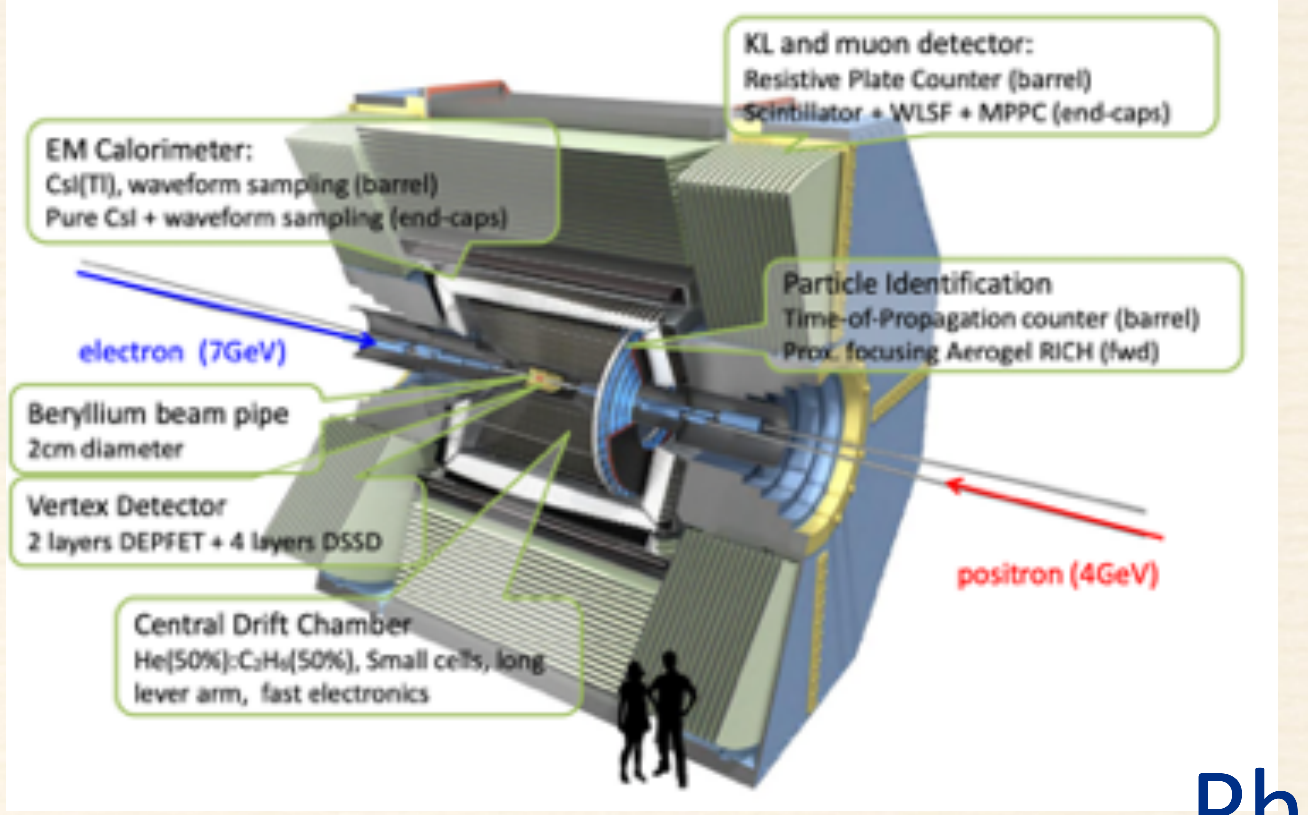
LHC

Data on tape



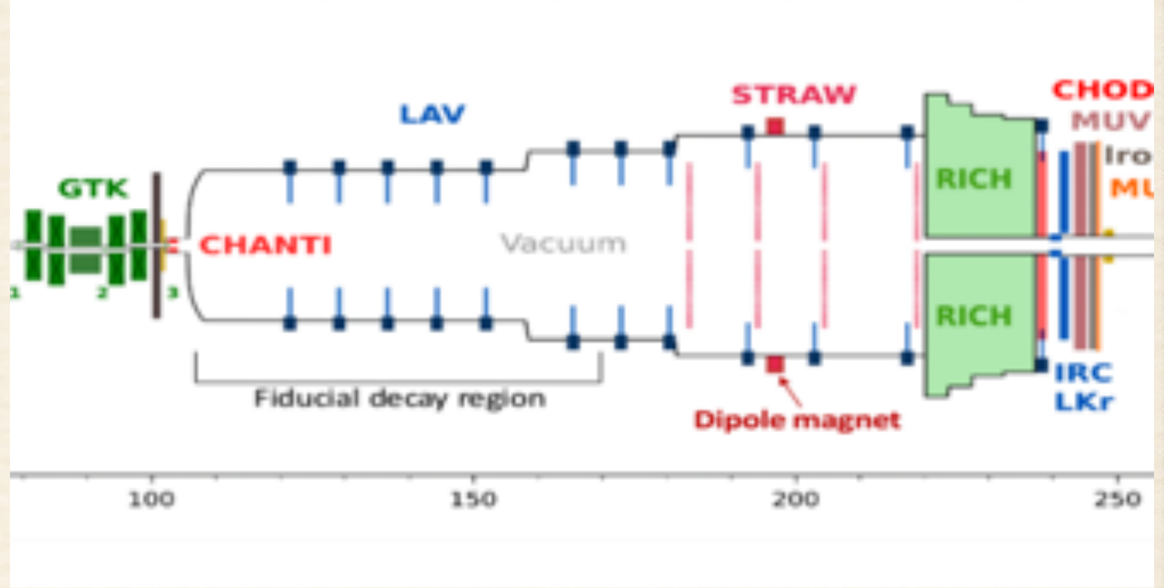
Belle II

Data on tape



NA62

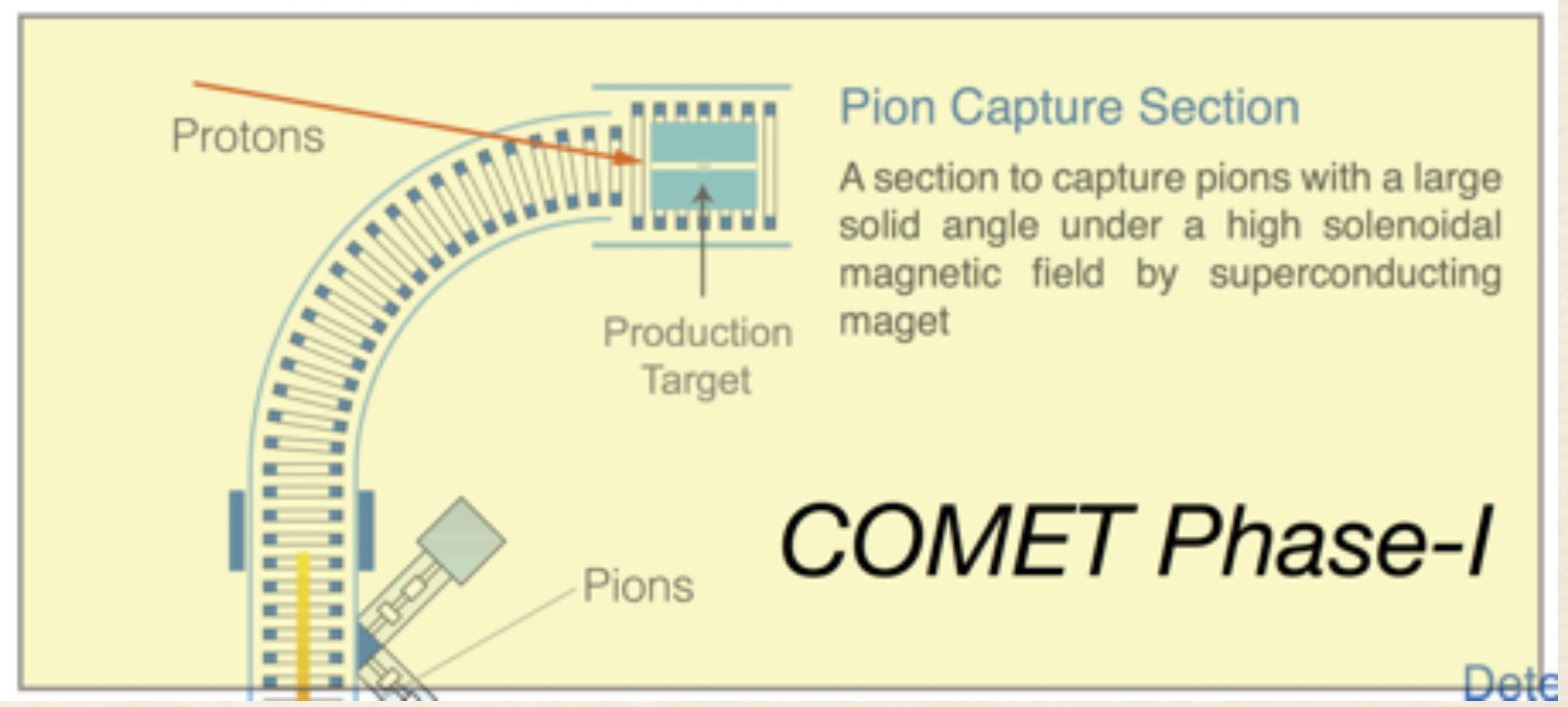
Data on tape



COMET

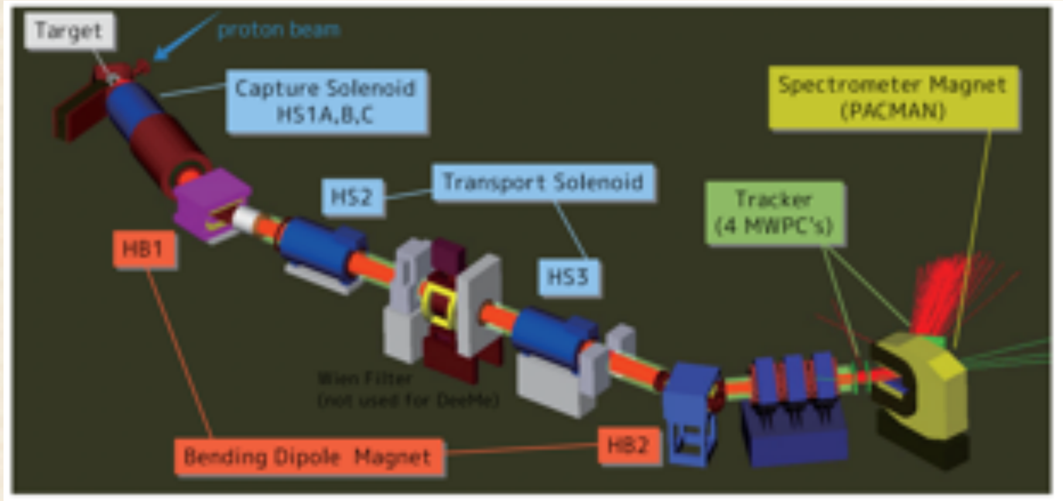
Phase-1 Solenoid in place.

Engineering run complete



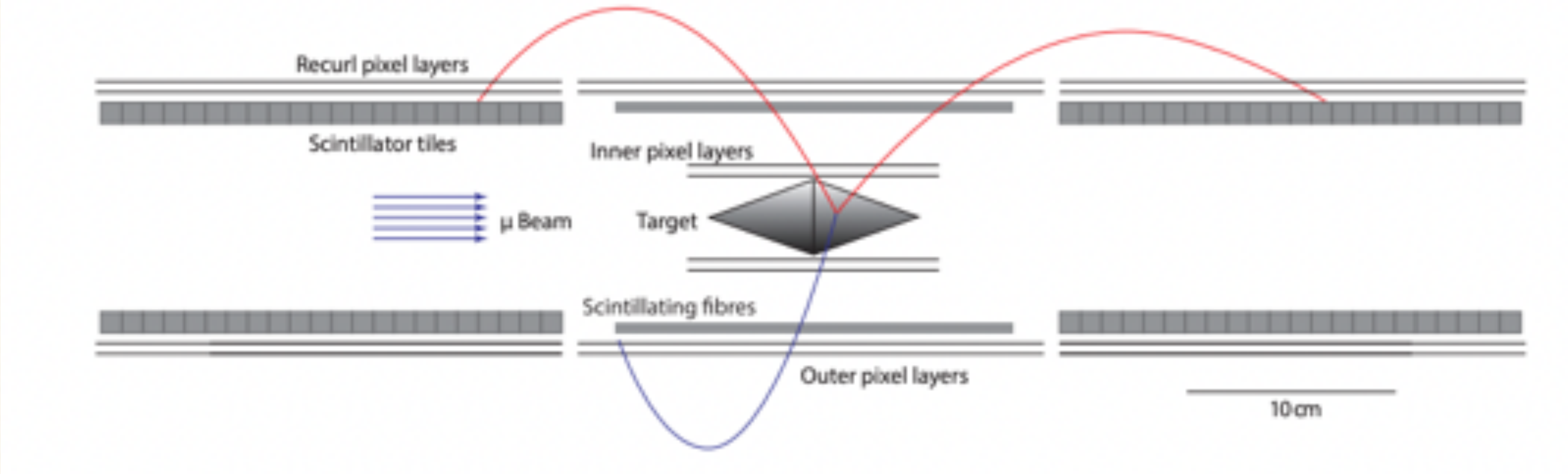
DeeMee

Engineering run complete



Mu3e

Engineering run complete, data in 2026



All have unique sensitivity to regions of CLFV parameter space and all have discovery potential 'around the corner'

The race is on!

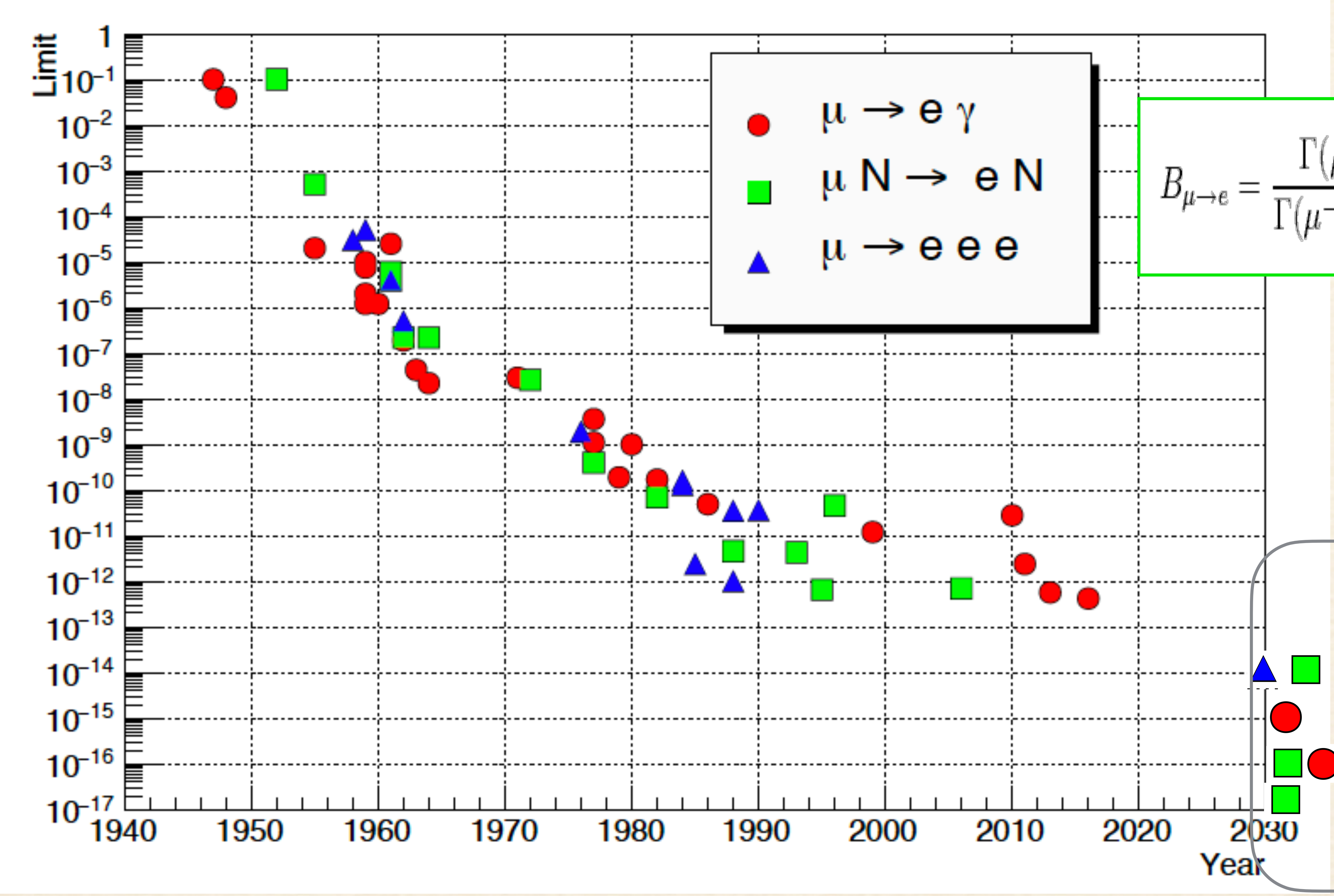
CLFV across Energy Scales

- Decays of μ, τ (and mesons)

$$\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z) \qquad M_\mu - \overline{M}_\mu \qquad \mu \to ea$$

$$\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \to \ell Y \qquad Y = P, S, V, P\bar{P}, \ldots$$

Modified from Calibbi-Signorelli 1709.00294



$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

Ongoing / planned

- MEG-II DeeMee
- Mu3e
- Mu2e, COMET
- Mu2e-II
- AMF - PRISM

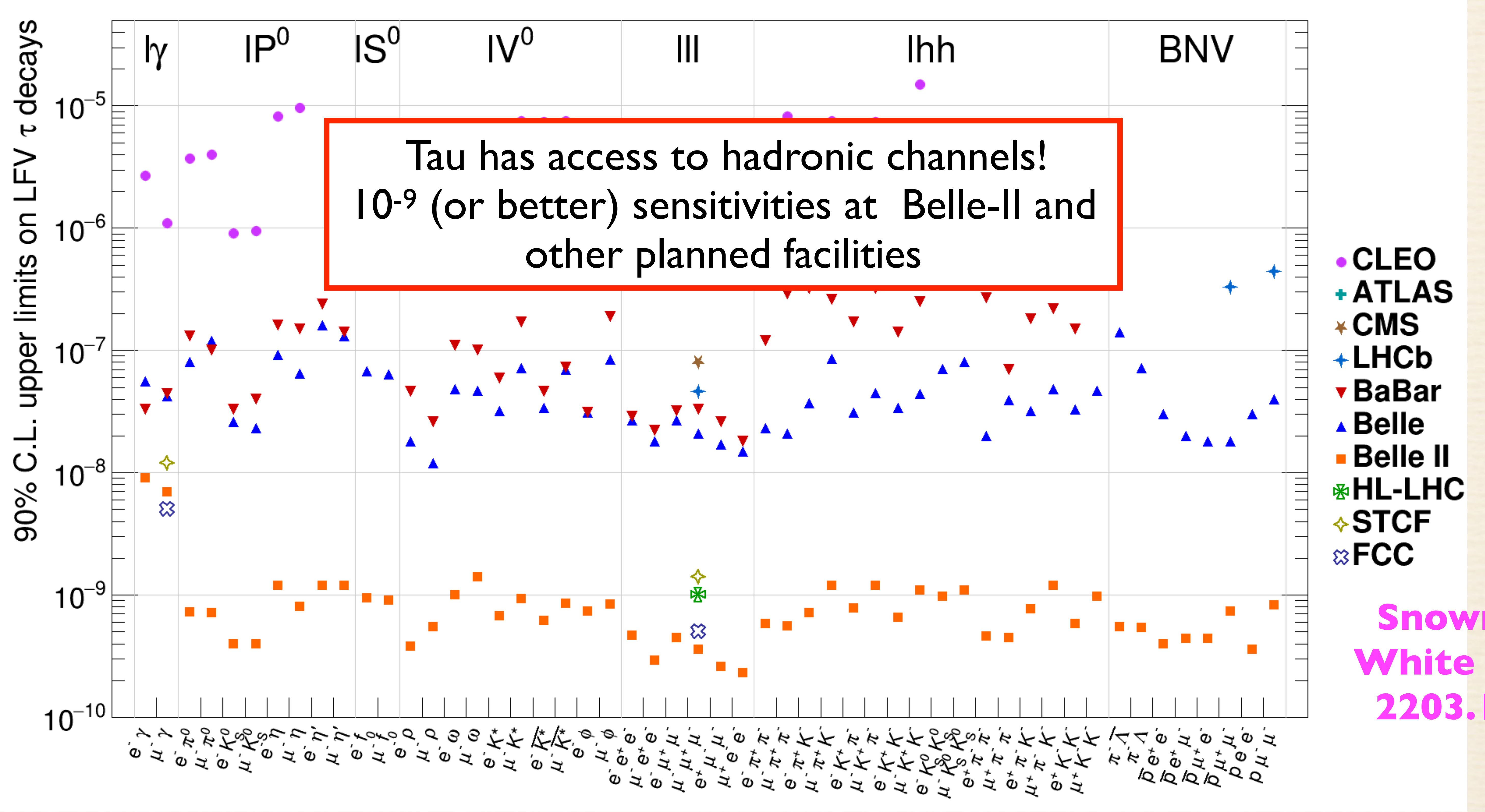
CLFV across Energy Scales

- Decays of μ, τ (and mesons)

EIC can compete for tau appearance but not muon appearance

$\mu \to e\gamma$, $\mu \to e\bar{e}e$, $\mu(A,Z) \to e(A,Z)$ $\quad M_\mu - \overline{M}_\mu \quad \mu \to ea$

$\tau \to \ell\gamma$, $\tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta$, $\tau \to \ell Y \quad Y = P, S, V, P\bar{P}, \ldots$



Tau has access to hadronic channels!
10^{-9} (or better) sensitivities at Belle-II and other planned facilities

Snowmass White Paper 2203.14919

Even a decade from now, the EIC can compete in the first-to-third generation searches

EIC e-τ Conversion Search

$$e^- + p \to \tau^- + X$$

Topology: neutral current DIS event; except that the electron is replaced by tau lepton

- If mixed in with hadron remnants, tau is boosted
- If forward along incident electron, the tau is isolated
- Potential for clean identification with high efficiency:
  - Topology: triggering and background rejection
  - Displaced vertex: can we aim for ZERO background?

Tau Decay Modes and Branching Ratios

- **1-prong**	**85.24 (0.06)%**
- $\mu^-\bar{\nu}_\mu\nu_\tau$	17.39 (0.04)%
- $e^-\bar{\nu}_e\nu_\tau$	17.82 (0.04)%
- $\pi^-\nu_\tau$	10.82 (0.05)%
- $\pi^-\pi^0\nu_\tau$	25.49 (0.09)%
- $\pi^-2\pi^0\nu_\tau$	9.26 (0.10)%
- $\pi^-3\pi^0\nu_\tau$	1.04 (0.07)%
- others (kaon, etc)	3.24%
- **3-prong**	**14.55 (0.06)%**
- $\pi^-\pi^+\pi^-\nu_\tau$	9.31 (0.05)%
- $\pi^-\pi^+\pi^-\pi^0\nu_\tau$	4.62 (0.05)%
- others (kaon, etc)	1.28%
- others	0.21%

Is it possible to have greater than 10% efficiency with negligible background in a 100 fb^{-1} data sample?

HERA searches had ~ 2.5% efficiency but EIC detector capabilities and improved understanding of jet shapes should allow for significant improvement

Once the work is done, likely trivial to also do $e^- \to \tau^+$:

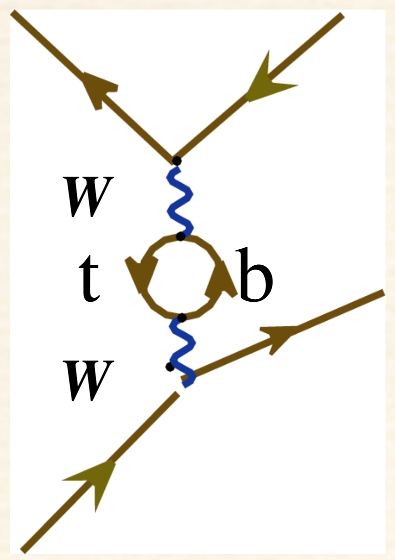
Complementary Lepton Number Violation Search?

Precision Electroweak Physics

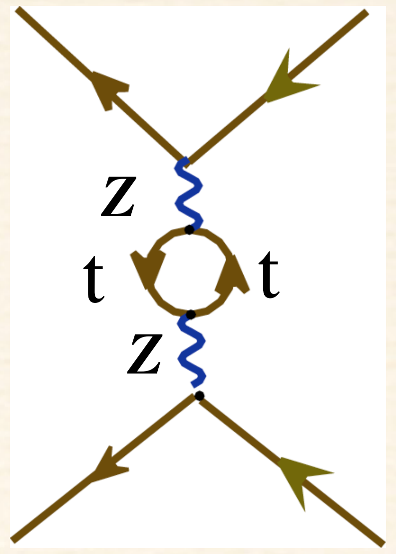
For electroweak interactions, 3 input parameters needed:

1. **electron g-2 anomaly**
2. **The muon lifetime**
3. **The Z line shape**

$$\alpha_{QED} \quad G_F \quad M_Z$$



Muon decay



Z production

4th and 5th best measured parameters: M_W and $\sin^2\theta_W$

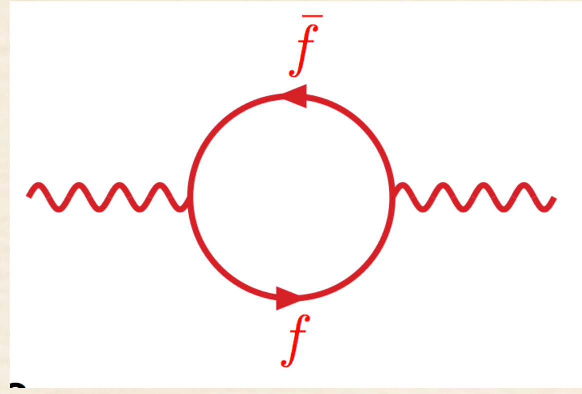
$$\sin^2\theta_W \equiv 1 - m_W^2/m_Z^2$$ **simple definition; disfavored due to heavy m_t**

$$\sin^2\theta_W^{eff} \equiv (1 - g_{\mu\mu Z})/4$$ **good at Z-pole; nasty counterterms at other scales**

$$\sin^2\theta_W(M_Z)_{\overline{\rm MS}} = \sin^2\theta_W^{eff} - 0.00028$$

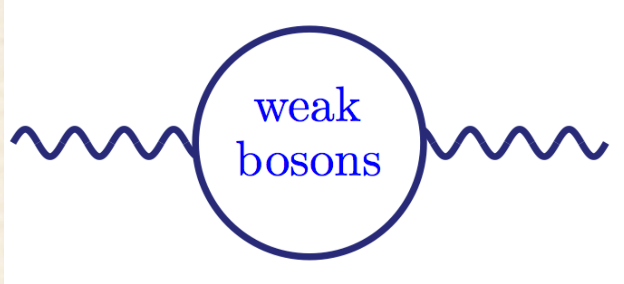
$$\sin^2\theta_W(\mu)_{\overline{\rm MS}} \equiv e^2(\mu)_{\overline{\rm MS}}/g^2(\mu)_{\overline{\rm MS}}$$ **theoretically motivated; but not physical**

Important note for experimentalists: do not worry too much about the exact definition of $\sin^2\theta_W$. When designing experiments, all that matters is the projected uncertainty; the actual value does not matter. When the experiment is fully designed, then work with theorists to extract $\sin^2\theta_W(\mu)_{\overline{\rm MS}}$ and properly account for radiative corrections.



Precision Relations

The Electroweak Theory and Measurements at 1-Loop



$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \qquad e^2 = 4\pi\alpha \qquad \sin^2\theta_W \approx \left(\frac{e}{g}\right)^2 \approx 1 - \left(\frac{M_W}{M_Z}\right)^2$$

$$(\Delta r)^{\rm expt} = 1 - \left[\pi\alpha/\{\sqrt{2}G_F m_W^2(1 - m_W^2/m_Z^2)\}\right] = 0.0355(7)$$

$$(\Delta r)^{\rm SM} = 0.0366(3) + 3.4\times 10^{-3}\ln\left[m_H/126\ \mathrm{GeV}\right]$$

m_t, α_s uncertainty

theory $m_W = 80.360(6)$ GeV

expt. $m_W = 80.377(12)$ GeV

PDG 2022

$$(\Delta\hat{r})^{\rm expt} = 1 - \left[2\sqrt{2}\pi\alpha/\{G_F m_Z^2\sin^2 2\theta_W(m_Z)_{\overline{\rm MS}}\}\right] = 0.0595(4)$$

$$(\Delta\hat{r})^{\rm SM} = 0.0597(1) + 1.4\times 10^{-3}\ln\left[m_H/126\ \mathrm{GeV}\right]$$

theory $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23122(4)$

expt. $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23116(13)$

$$(\Delta r_{\overline{\rm MS}})^{\rm expt} = 1 - \left[\pi\alpha/\{\sqrt{2}G_F m_W^2\sin^2\theta_W(m_Z)_{\overline{\rm MS}}\}\right] = 0.0694(3)(5)$$

$$(\Delta r_{\overline{\rm MS}})^{\rm SM} = 0.0692(1) + 6.5\times 10^{-4}\ln\left[m_H/126\ \mathrm{GeV}\right]$$

$$m_H = 91^{+18}_{-16}\ \mathrm{GeV}$$

Ultra-Precise Weak Mixing Angle

- **Make a "cut" on measurements with uncertainty ~ 0.0003X or better**

Exp.	$\sin^2\theta_{eff}^{lept}$	Ref.	
LEP+SLD: A_{FB}^{B}	0.23221±0.00029		*b-quarks*
SLD: A_l	0.23098±0.00026		*light-quarks*
*Tevatron	0.23148±0.00033	PRD 2016	*light-quarks*
ATLAS 8 TeV 20.2 fb^{-1}	0.23140±0.00036 *ATL–CONF–2018–037*	unpublished	*light-quarks* $\ell^+\ell^-$

- **CMS is getting ready to release their 13 TeV data**
  - *Expected uncertainty: 0.00024*
  - *This would be an extraordinary achievement!*

Special thanks to Arie Bodek

theory $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23122(4)$

expt. $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23116(13)$

- **Ultimate sensitivity at LHC**
  - *There are plans to improve on the above by a factor of 2, but only after the HL-LHC upgrade*

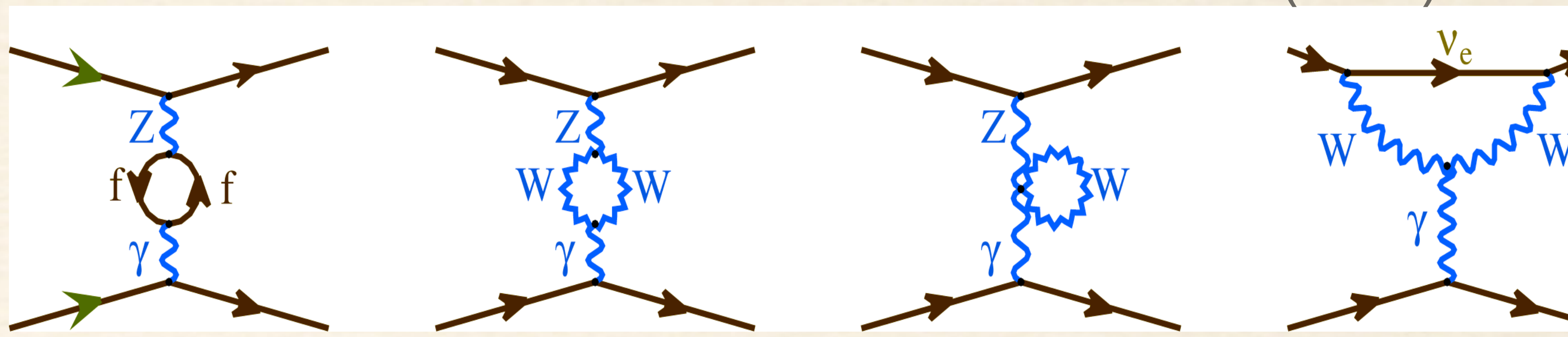
- **Window for MOLLER and P2 to contribute!**
  - *Combined would be 0.00020, but must achieve the final result by 2030…*
  - *Must try to get to design goals!*

Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

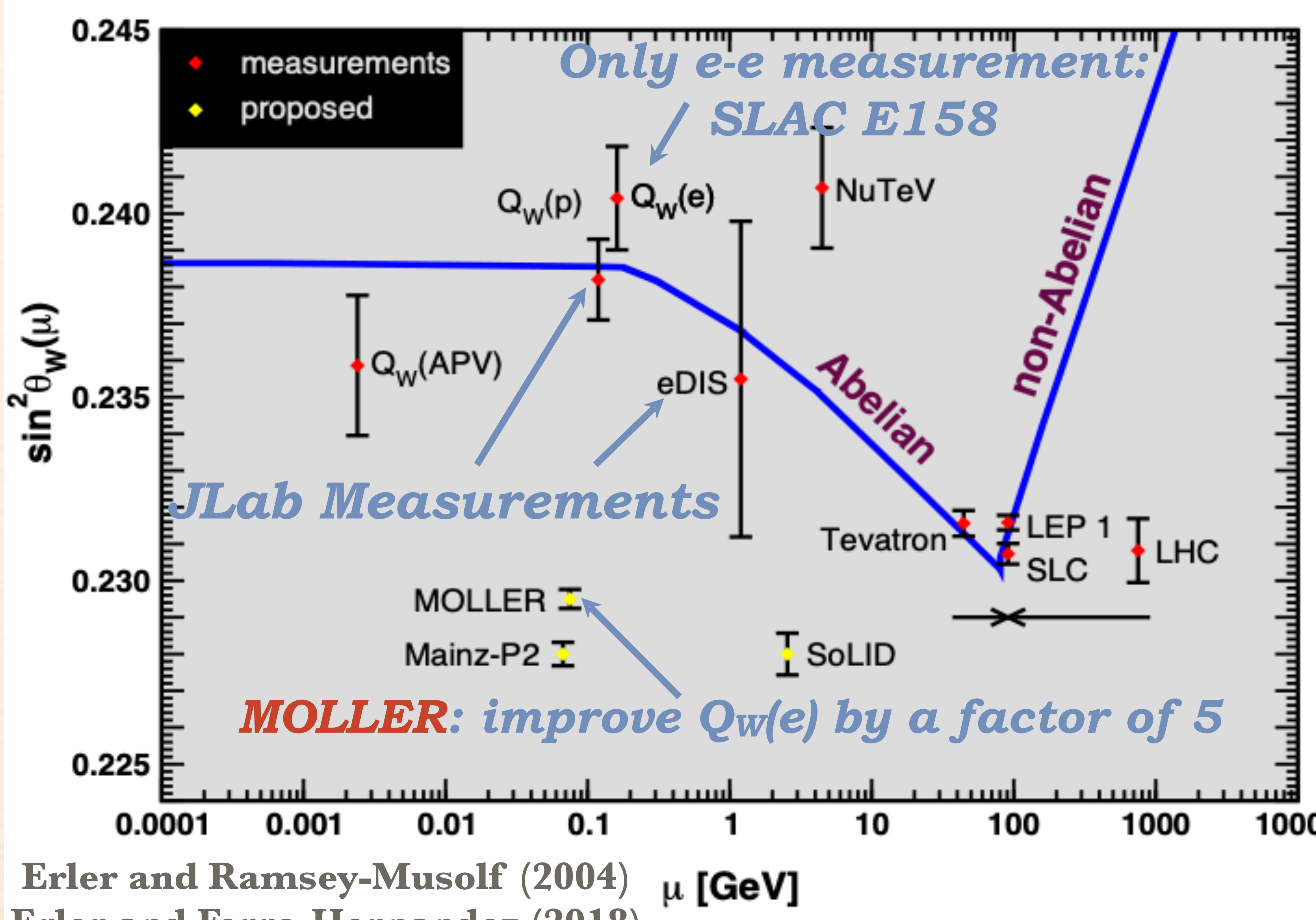
Overview of Past/Ongoing WNC Measurements

Electroweak Radiative Corrections causes weak mixing angle to "run"

Czarnecki and Marciano (1995)



- ✦ **Atomic Parity Violation: Cs-133**
  - ✦ future measurements and theory challenging
- ✦ **Neutrino Deep Inelastic Scattering: NuTeV**
  - ✦ future measurements and theory challenging
- ✦ **PV Møller Scattering: E158 at SLAC**
  - ✦ statistics limited, theory robust
  - ✦ next generation: MOLLER (factor of 5 better)
- ✦ **PV elastic e-p scattering: Qweak**
  - ✦ theory robust at low beam energy
  - ✦ next generation: P2 (factor of 3 better)
- ✦ **PV Deep Inelastic Scattering: PVDIS**
  - ✦ theory robust for ^{2}H in valence quark region
  - ✦ factor of 5 improvement: SOLID

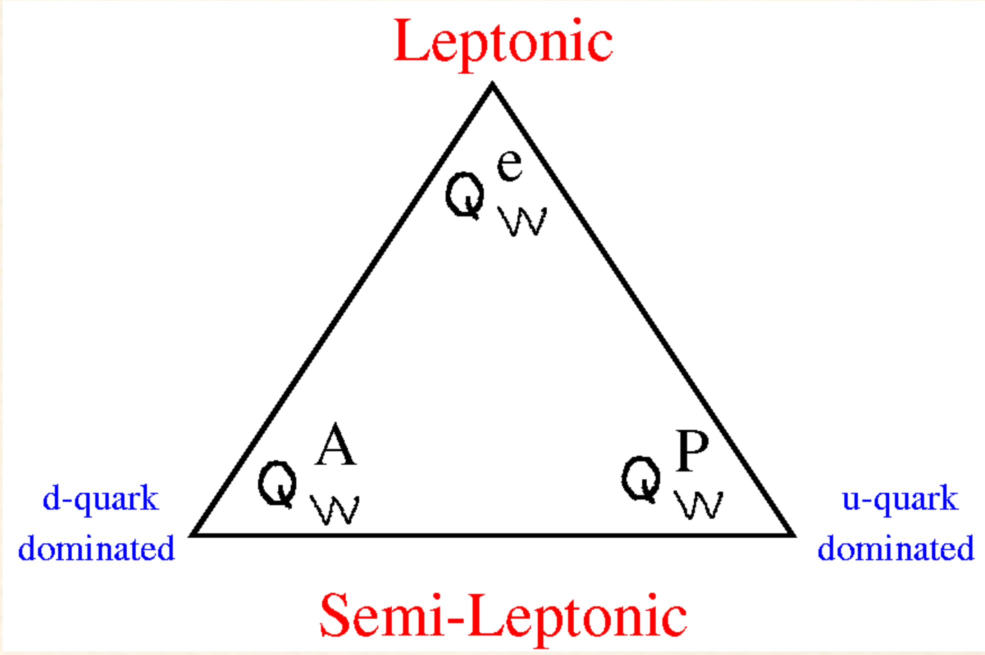


Erler and Ramsey-Musolf (2004)
Erler and Ferro-Hernandez (2018)

Other WNC Measurements

Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4pi$)

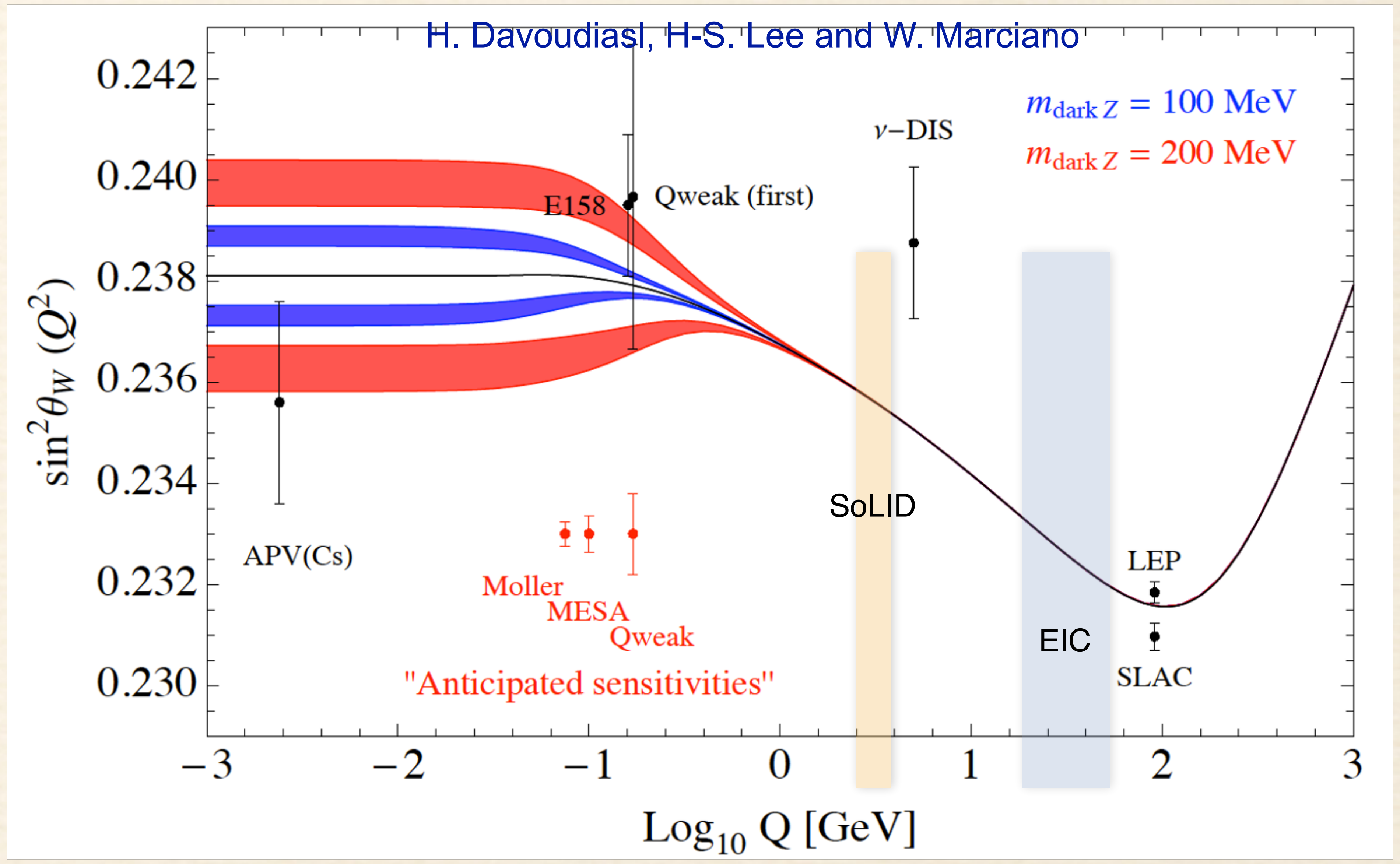
	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
SoLID	0.6 %	0.00057	22 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV



Courtesy: M. Ramsey-Musolf

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings



Where does the EIC fit in?

- *An entirely unexplored Q2 regime, close to the Z pole i.e it is not just weak-electromagnetic interference*
- *It is best to just fold it into a SMEFT analysis and explore where the EIC helps with "flat" directions in coupling space*

✦Complementary to collider Drell-Yan Searches
✦Unique sensitivity to intermediate-scale dark Z's

The W Mass

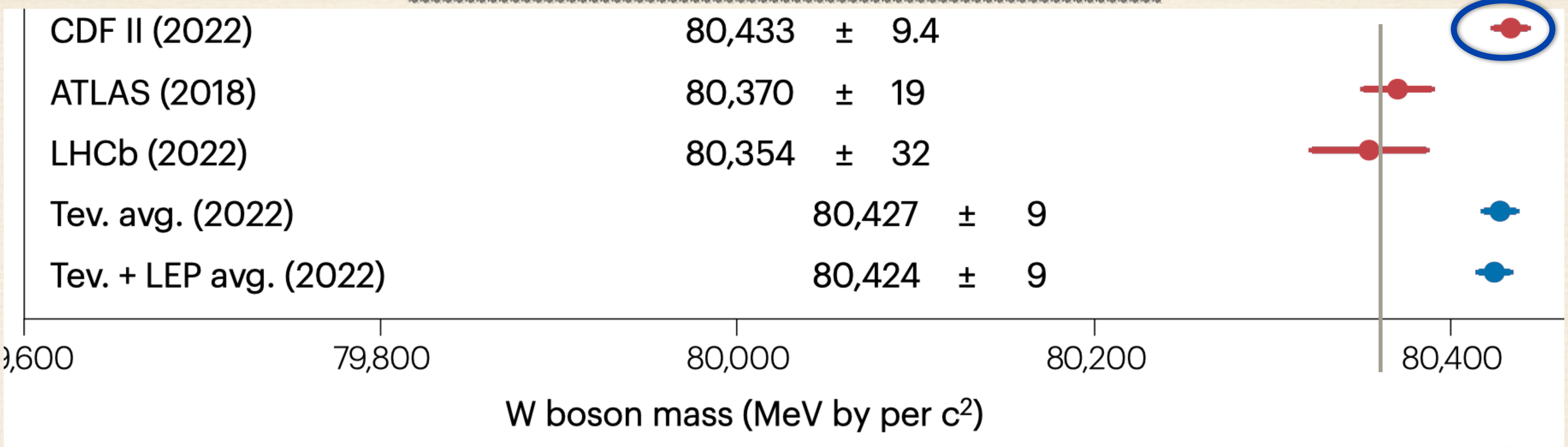
PDG 2022

theory $m_W = 80.360(6)\ \text{GeV}$

expt. $m_W = 80.377(12)\ \text{GeV}$

Special thanks: Ashutosh Kotwal

Then the earthquake!



- **Comments**
  - ***CDF - ATLAS: 63 +/- 21 MeV***
  - ***CDF has done more work since release; stick by their number***
  - ***Pdf issues much more challenging for LHC: low x pdfs vs high x at CDF***

- **My take**
  - ***No point worrying about this until CDF and LHC resolve their differences***
  - ***If CDF result holds, EVERYTHING in the EW sector becomes even more important!***
  - ***If things resolve to SM, semi-leptonic WNC measurements can still look for BSM physics***

High Energy e-p scattering

e⁻ → ← $p, D, {}^3He$

$$\frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F^i_1 + \frac{p_\mu p_\nu}{m_N (p\cdot q)} F^i_2$$
$$+ i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)} \left[\frac{p^\alpha q^\beta}{m_N} F^i_3 + 2q^\alpha S^\beta g^i_1 - 4x p^\alpha S^\beta g^i_2 \right]$$
$$- \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)} g^i_3 + \frac{S\cdot q}{(p\cdot q)^2} p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q} g_{\mu\nu} g^i_5$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader,
Phys. Rep. **261** (1995)

$$\int_0^1 dx [g_5^{W^-,n} - g_5^{W^-,p}] = g_A \left(1 - \frac{2\alpha_s}{3\pi}\right)$$

new sum rules

Similar expressions for neutral current structure functions

proton

similar expressions for the neutron: $u \leftrightarrow d$

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

Could begin to access this after 1 full year of running

proton	deuteron
$F_1^{\gamma Z} \propto u + d + s$	$F_1^{\gamma Z} \propto u + d + 2s$
$F_3^{\gamma Z} \propto 2u_v + d_v$	$F_3^{\gamma Z} \propto u_v + d_v$
$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$	$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$
$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$	$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$

High luminosity: precision measurements of PV observables

PV Asymmetries at the EIC

e^- → ← $^1H, ^2H, ^3He$

polarized ***electron,*** *unpolarized* ***hadron***

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

unpolarized ***electron,*** *polarized* ***hadron***

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

EIC neutral current event kinematics very clean: can very cleanly separate y-independent and y-dependent pieces and study Q^2 evolution

proton

$F_1^{\gamma Z} \propto u + d + s$

$F_3^{\gamma Z} \propto 2u_v + d_v$

$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$

$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$

deuteron

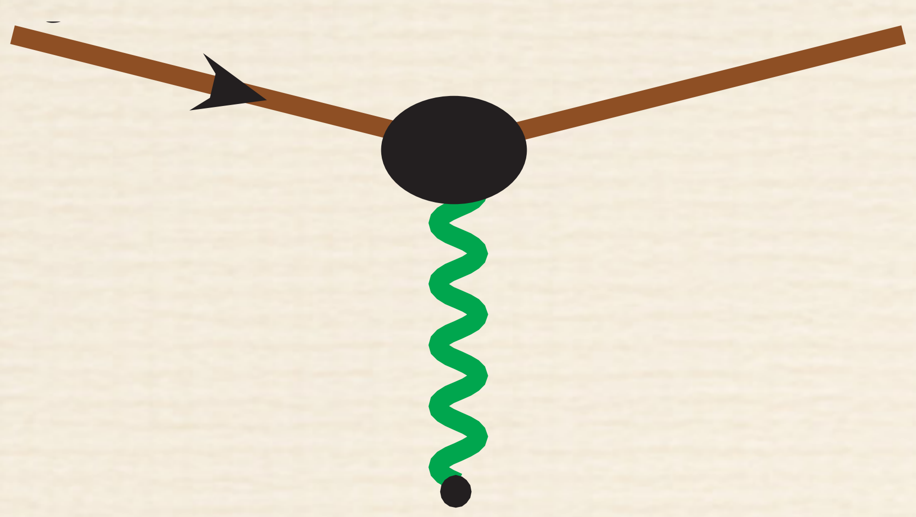
$F_1^{\gamma Z} \propto u + d + 2s$

$F_3^{\gamma Z} \propto u_v + d_v$

$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$

$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$

- **Electron Asymmetries are sensitive to the weak mixing angle**
  - *Deuteron is very clean but is a large data set going to be even part of the program*
  - *Must control pdf uncertainties well enough to use proton events (the main data sample at EIC)*
  - *Studies are required to use both low Q^2 (well-understood) and high Q^2 (super-clean, but requires a careful look at both weak-electromagnetic interference and pure Z exchange)*
  - *Over the next few years, QED and QCD radiative corrections require a careful look*
- **Hadron Asymmetries**
  - *Access to entirely new set of structure functions*
  - *Can contribute to flavor separation of polarized pdfs*



SMEFT Perspective

Symmetry Violation with Leptons

- **Violation of Lepton Number**
  - Neutrinoless Double-Beta Decay

$\frac{1}{\Lambda}\mathcal{L}_5$ 10^{15} GeV

$\frac{1}{\Lambda^5}\mathcal{L}_9$ multi-TeV

- **Violation of Time Reversal Symmetry**
  - Non-zero Electric Dipole Moment of the Electron

100s of TeV $\frac{1}{\Lambda^2}\mathcal{L}_6$

- **Violation of Charged Lepton Flavor**
  - muon-to-electron conversion, tau appearance at the EIC...

100s of TeV

- **Flavor changing neutral currents**
  - Rare pion and kaon decays

100s of TeV

- **Flavor conserving neutral currents (PVES)**
  - muon-to-electron conversion, tau appearance at the EIC...

10s of TeV

EIC Topics

- **Neutral and Charged Current Structure Functions**
  - ***Complementary probe of BSM 6-D operators: address flat directions in global SMEFT analysis***
  - ***Unpolarized and Polarized pdfs***
  - ***Weak Mixing Angle: both proton and deuteron***
  - ***Charged current measurements complementary to precision weak decays***
- **Charged Lepton Flavor Violation**
  - ***Tau appearance: strive for zero background***
  - ***Complementary lepton number search***
- **Complementary Topics**
  - ***Inclusive and semi-inclusive single spin asymmetries***
  - ***Axion-like particle searches***
  - ***Global fitting***
- **New Topics…**

Exciting to learn about recent progress, new ideas and the full capabilities of the ePIC detector

Summary

- **Intensity Frontier**
  - *Absent direct particle discovery at the LHC, indirect BSM searches become central. In fact one could argue that certainly LHCb and even ATLAS and CMS are now Intensity Frontier experiments!*
- **Electron Ion Collider**
  - *Any new machine accessing new territory in intensity, luminosity, spin and center of mass energy space must be thoroughly explored for potential new BSM sensitivity*
  - *Ideas have percolated for more than a decade*
- **Sharpen the Science Case**
  - *It is now time to push the ideas that have survived "on mass-shell"*
  - *Continue to explore new ideas while keeping a close eye on the rest of the BSM landscape*
- **Workshop Outcome? (Perspective from me and Vincenzo)**
  - *What steps do we need in order to work towards prioritized list of topics to be pursued both for theory and for the detector? Perhaps at a followup workshop in N years….*
  - *A white paper? Now? Later?*