Acknowledgements: The E158, MOLLER, EXO-200 and nEXO collaborations
and many other theoretical and experimental colleagues

Low Energy Probes of the Standard Model (I)

Parity-Violating Electron Scattering and Neutrinoless Double Beta Decay Experiments

Krishna Kumar
Stony Brook University

The Standard Model at 50: Success and Challenges
SLAC Summer Institute
July 31, 2018

Outline

$Q^2 \ll M_Z^2$

- ✦ Low Energy Weak Neutral Current Measurements
  - ★ Historical Perspective on parity-violating electron scattering
  - ★ Motivation for Modern Low Q^2 Measurements
  - ★ Current Experimental Status
- ✦ Neutrinoless Double Beta Decay
  - ★ Physics Motivation
  - ★ Current Experimental Status
- ✦ Conclusion and Outlook

Quick repeat of key points from V. Cirigliano lectures

Parity Violating Electron Scattering: Historical Perspective

Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

The Weak Neutral Current

$$\tan\theta_W = \frac{g'}{g} \qquad e = g\sin\theta_W$$

One free parameter: weak mixing angle θ_W

The Z boson incorporated

	Left-	**Right-**
W “Charge”	$T = \pm\frac{1}{2}$	zero
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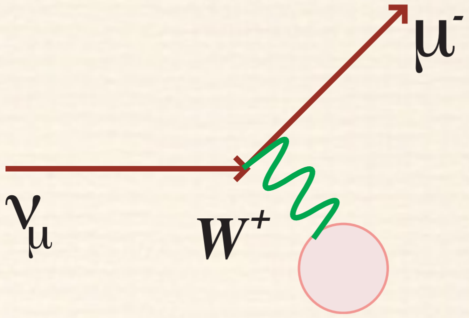

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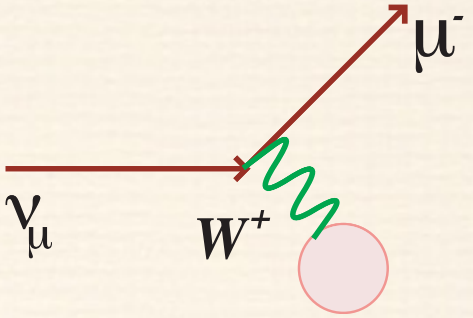

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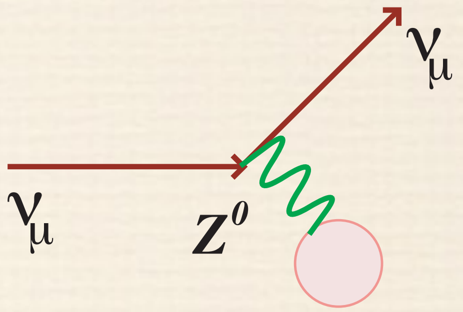

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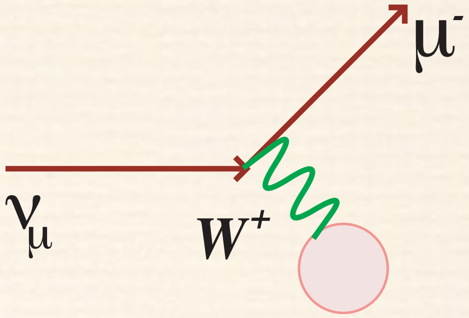

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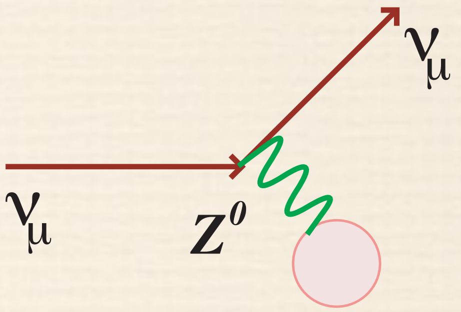

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early 1970s:

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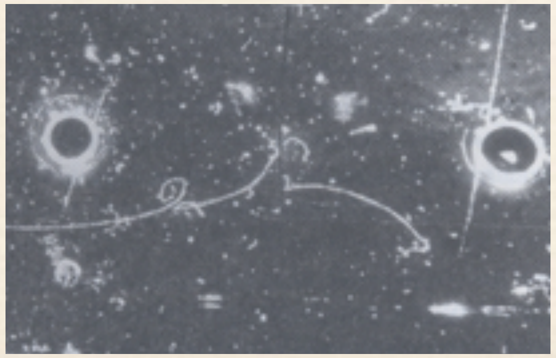

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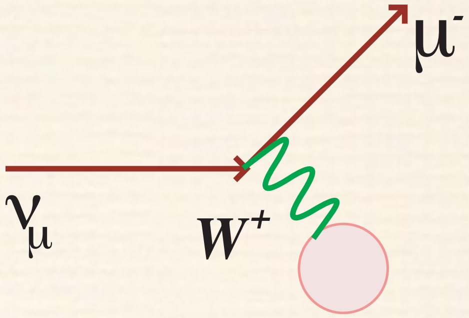

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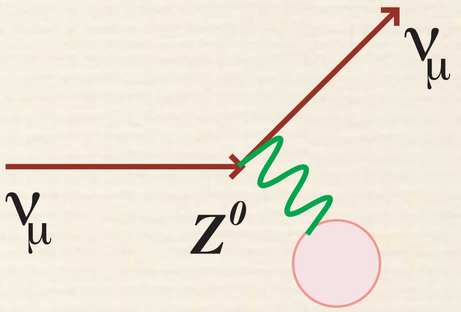

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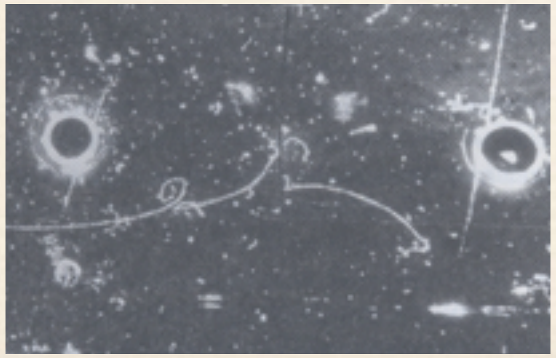

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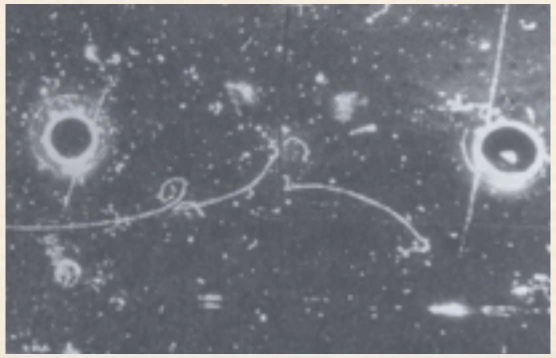

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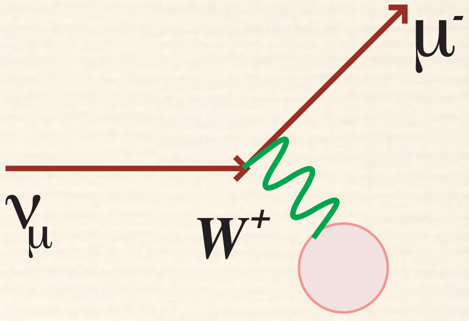

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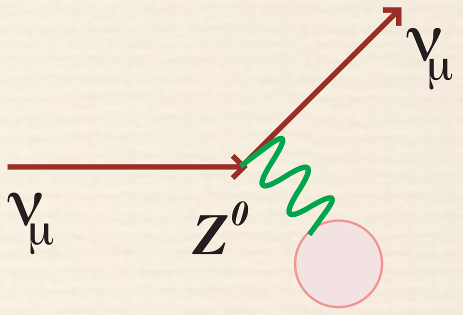

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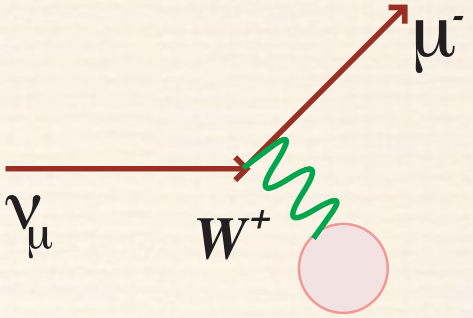

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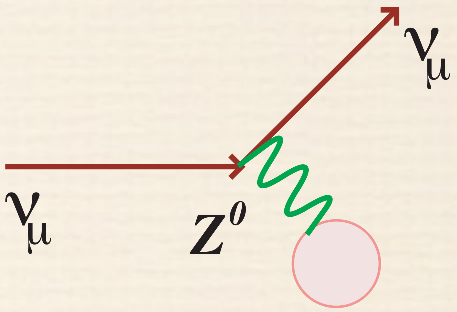

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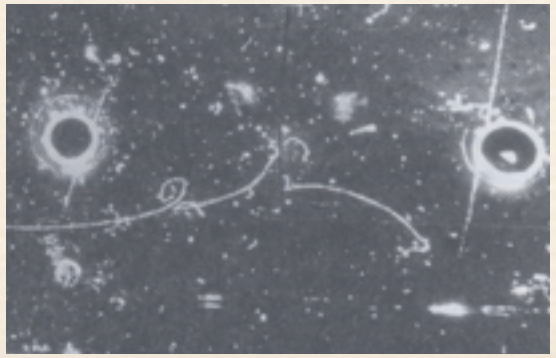

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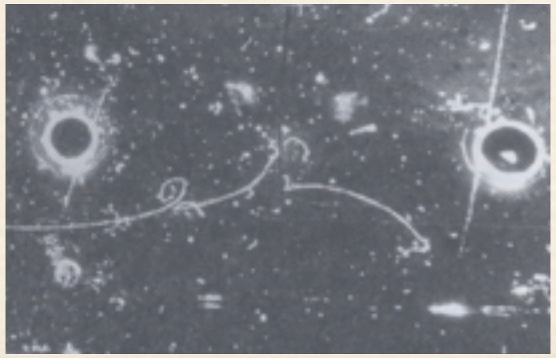

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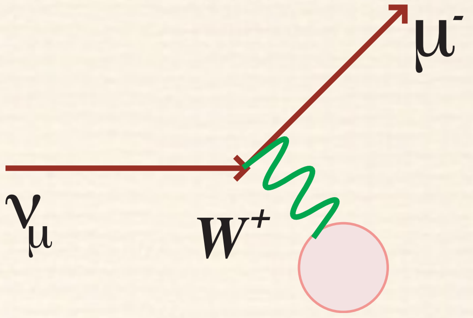

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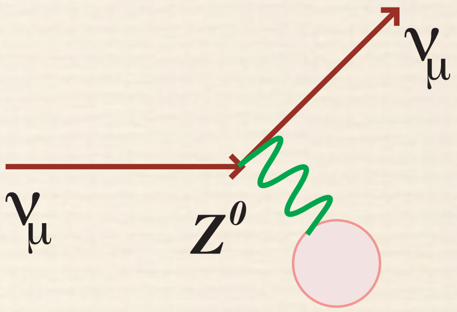

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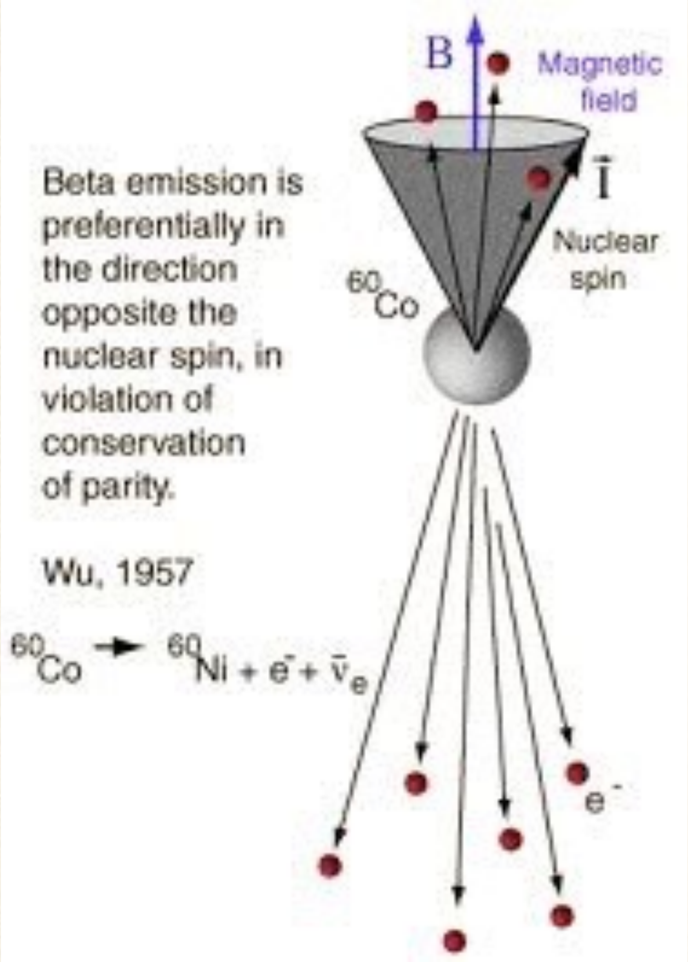
Electroweak Scattering

JETP **36**, pp 964-66 (1959)



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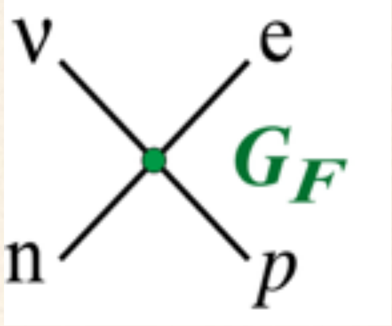

charge and flavor-changing

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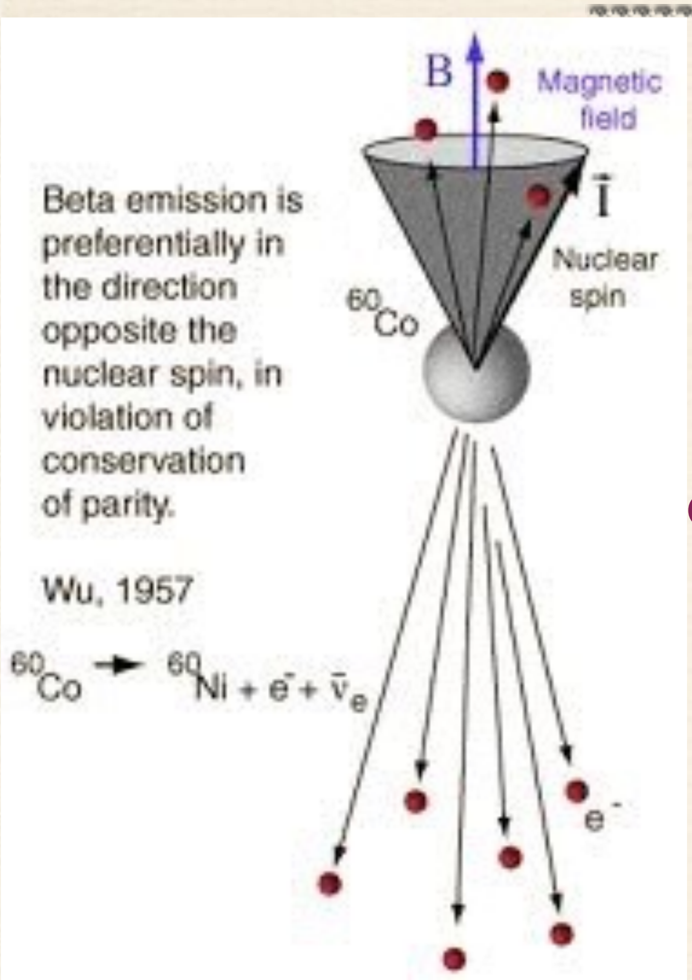

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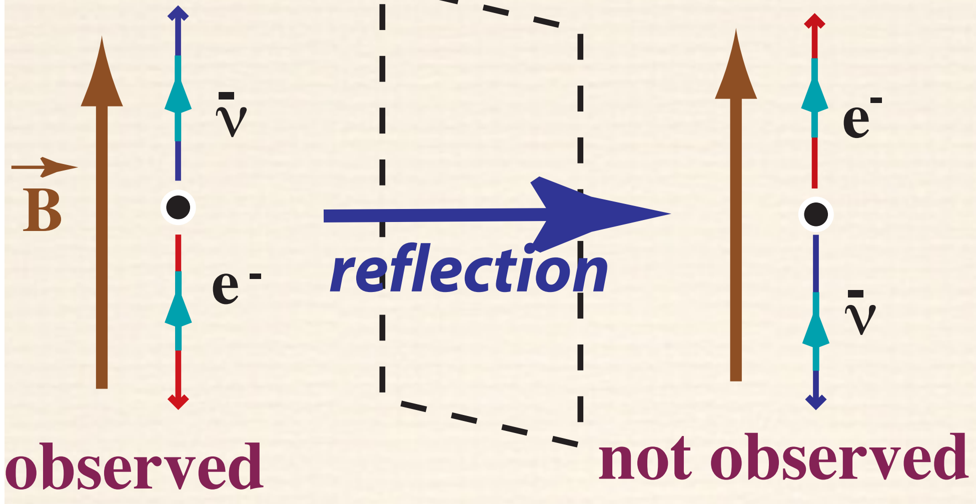

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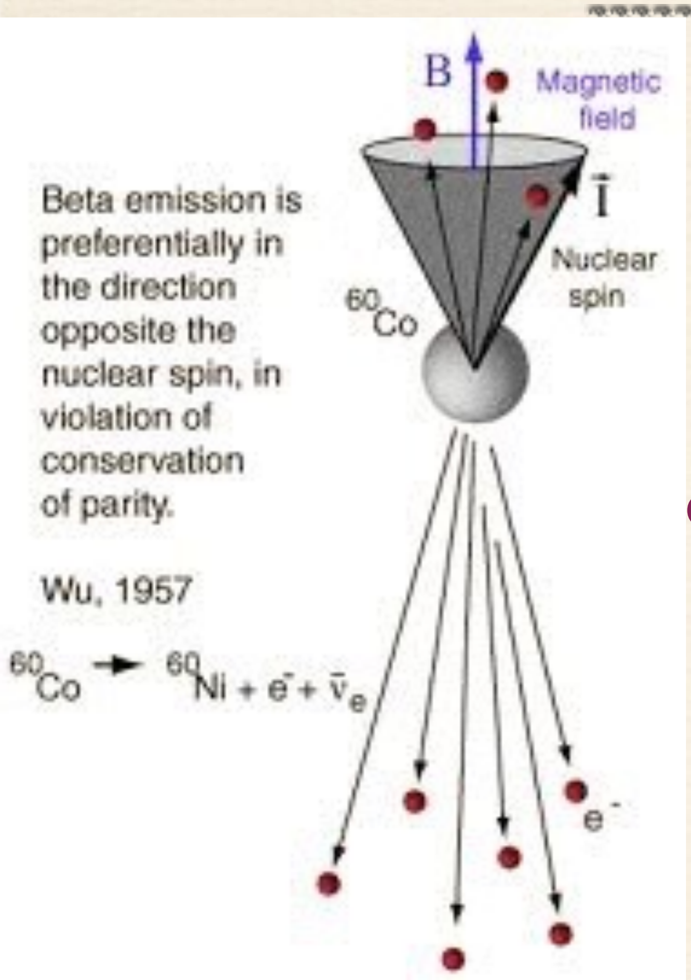

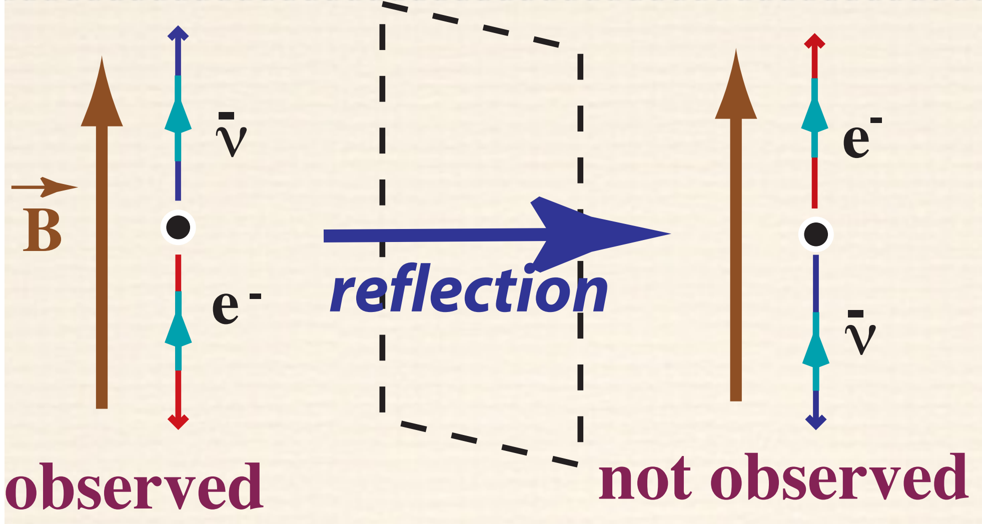

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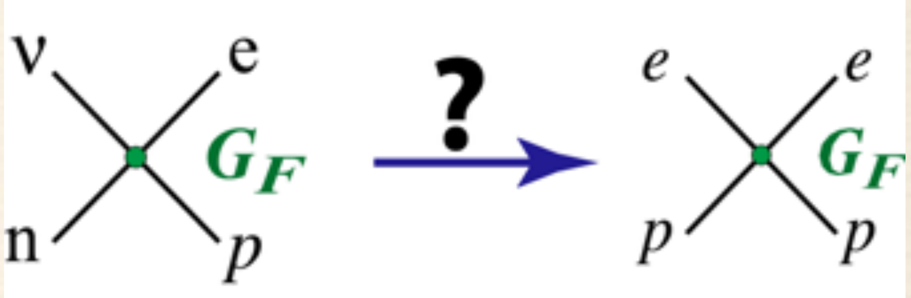
Electron-proton Weak Scattering



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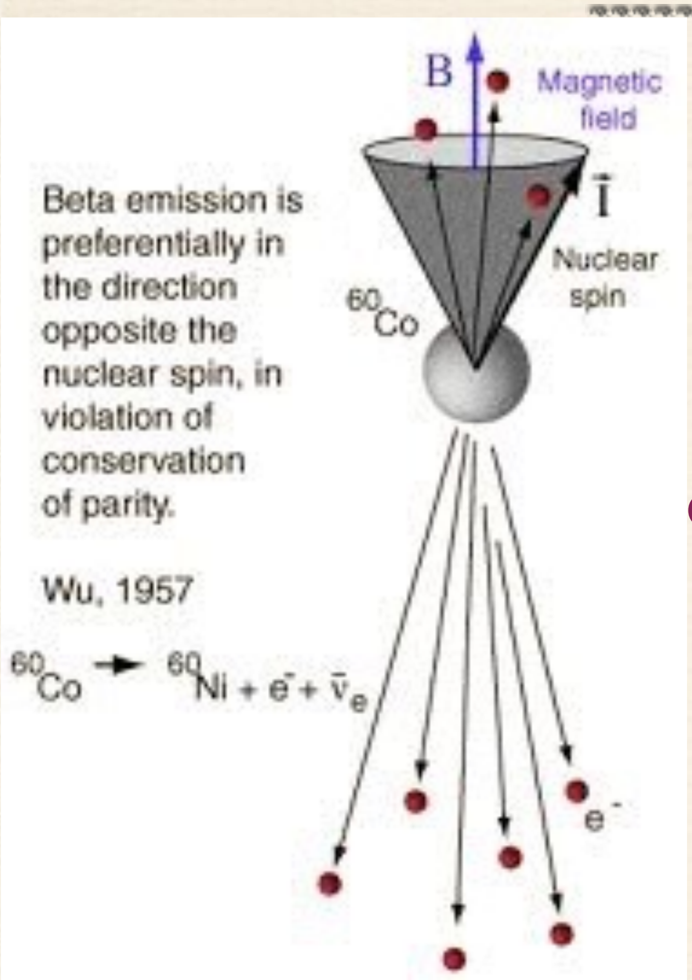

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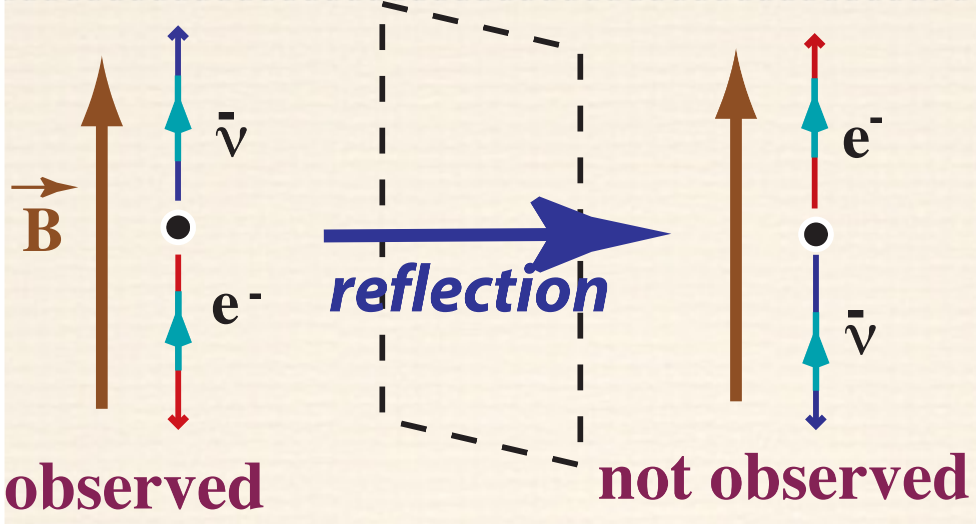

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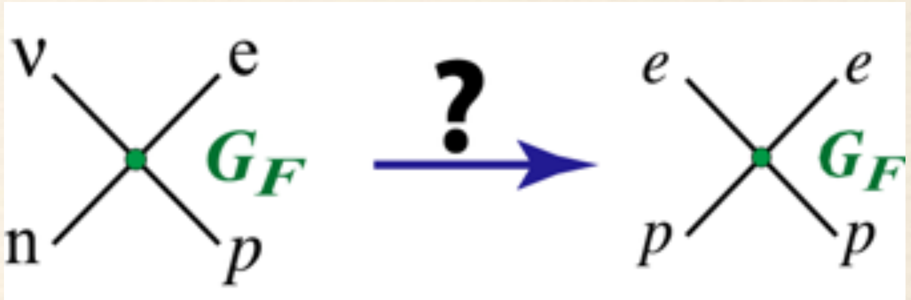

$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

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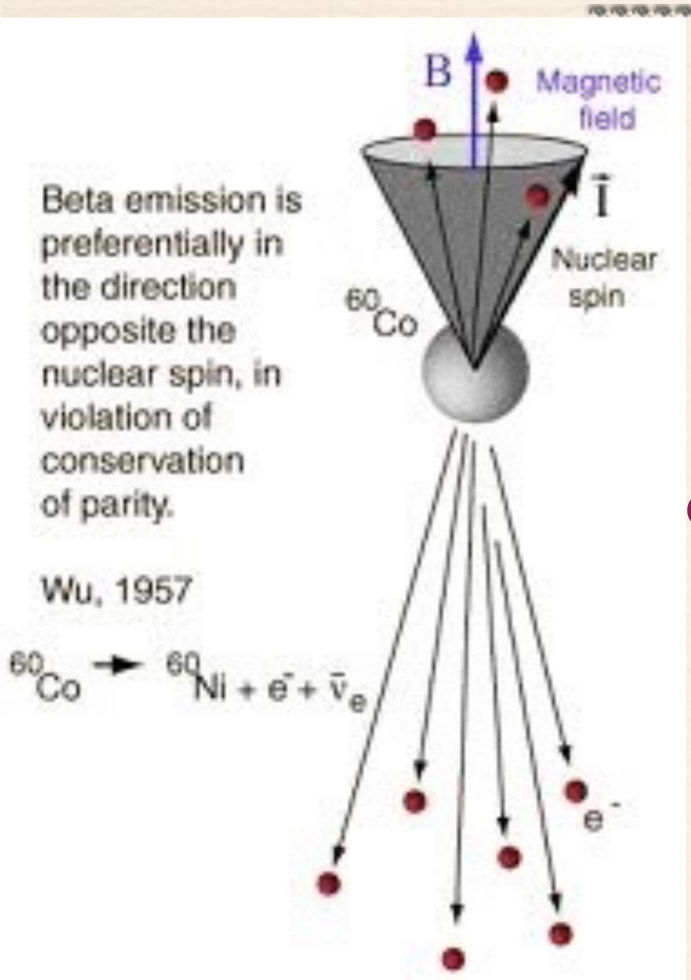

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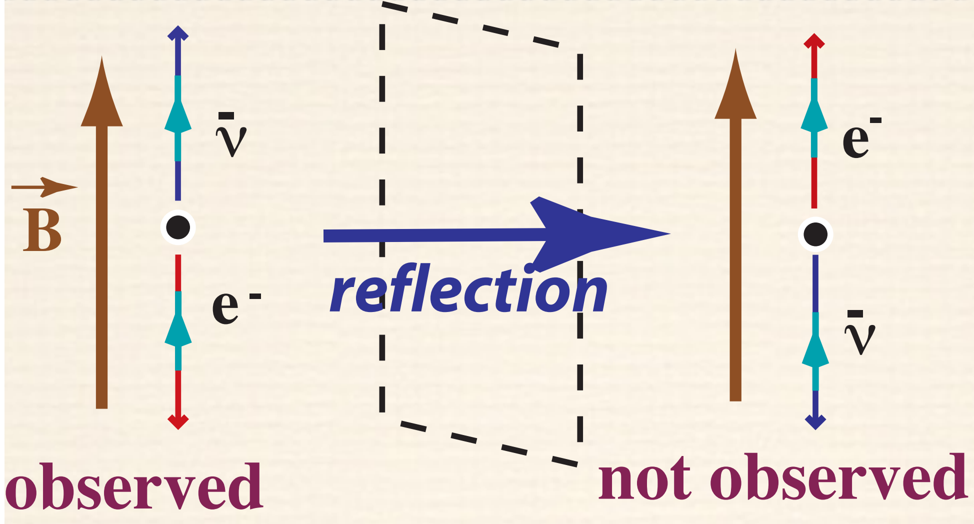

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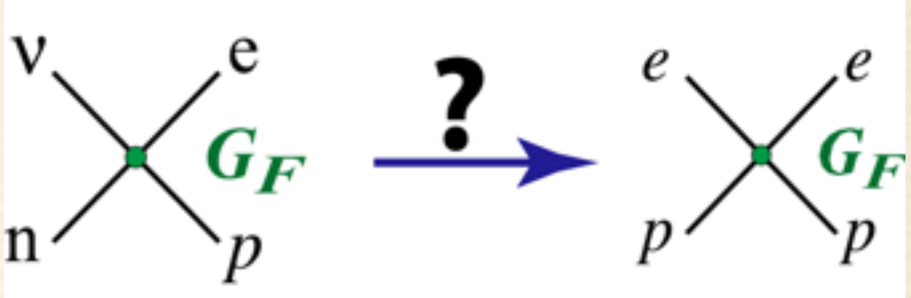

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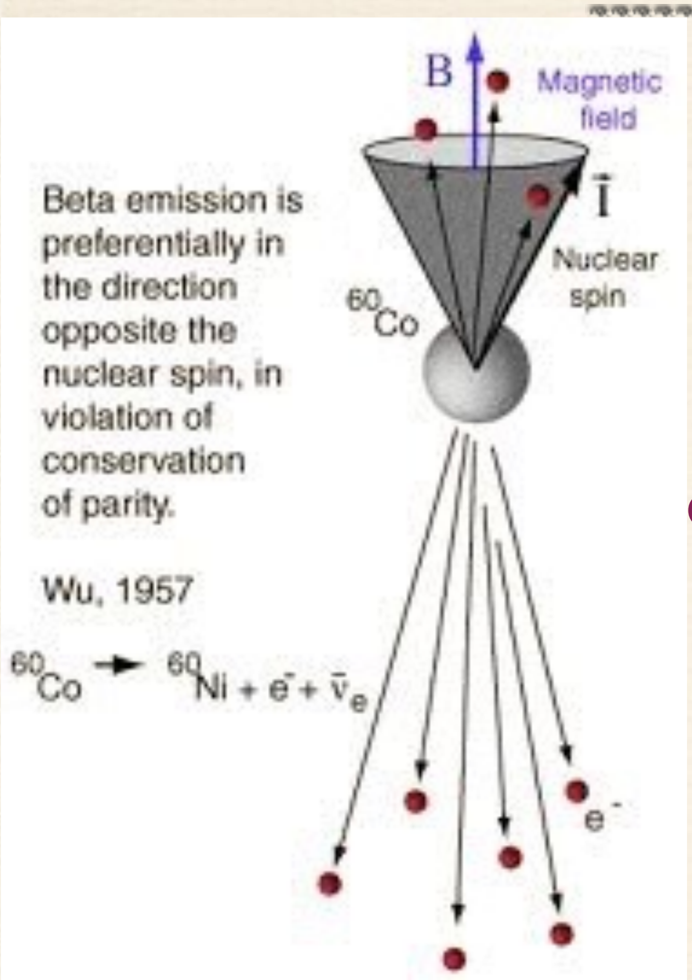

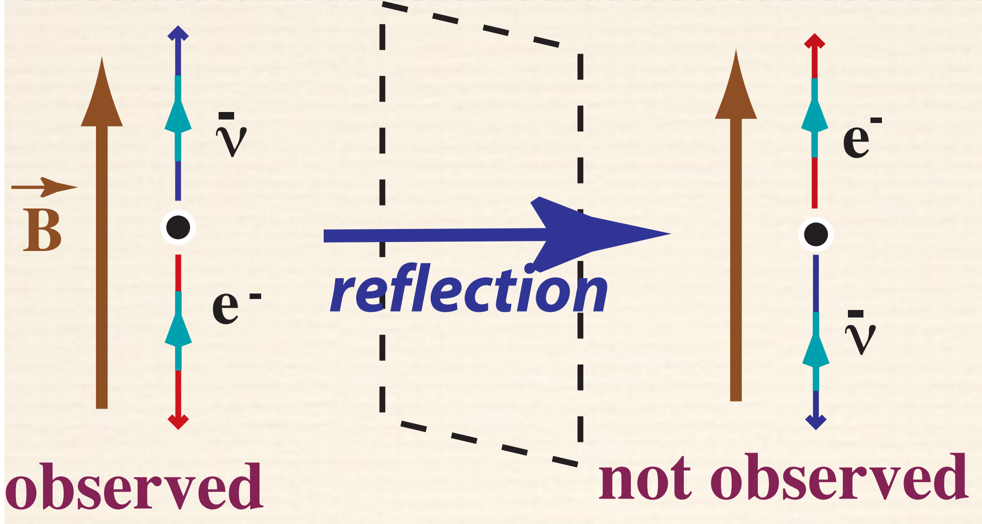

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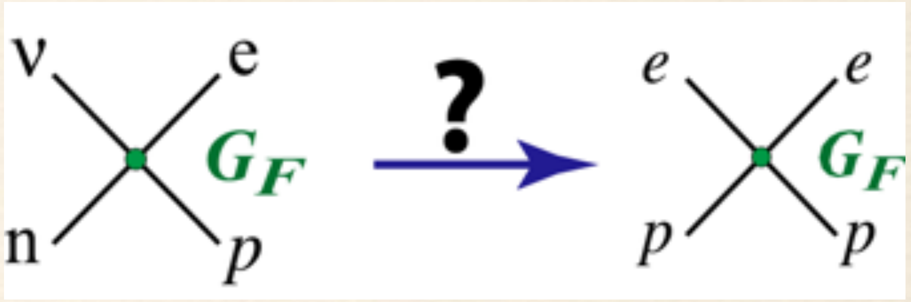

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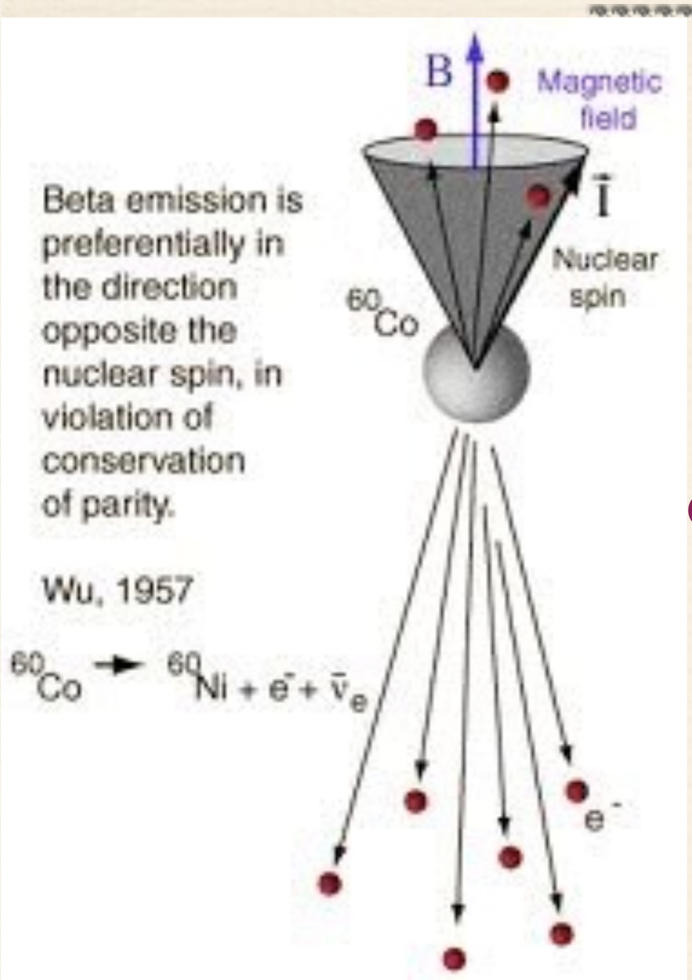

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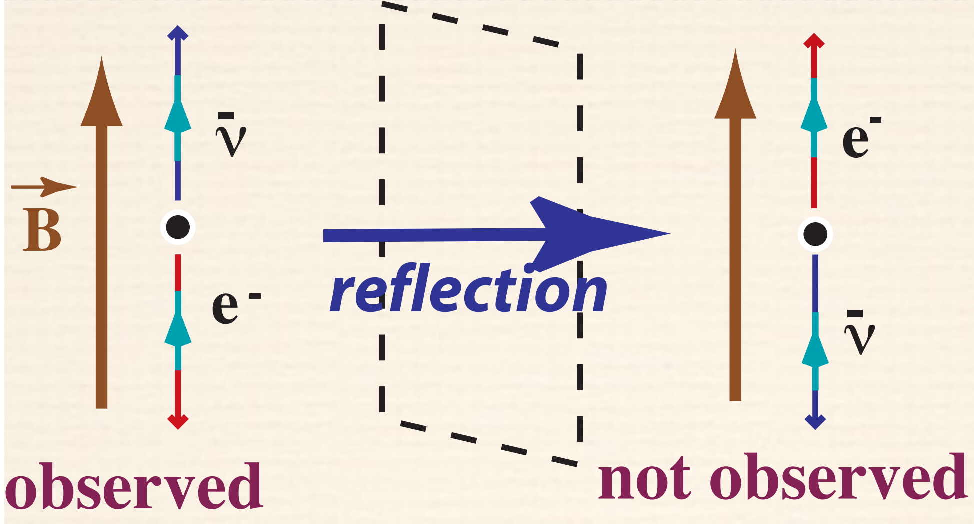

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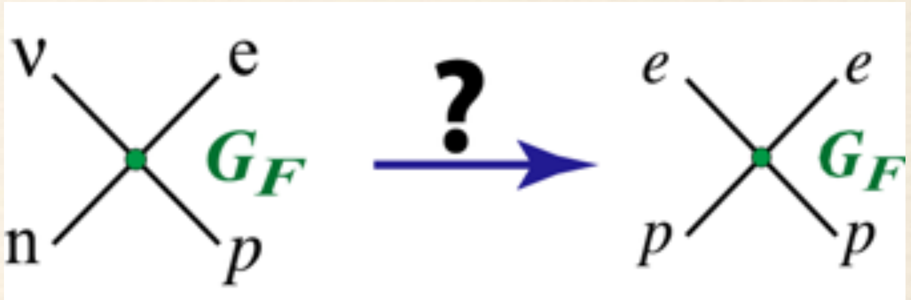

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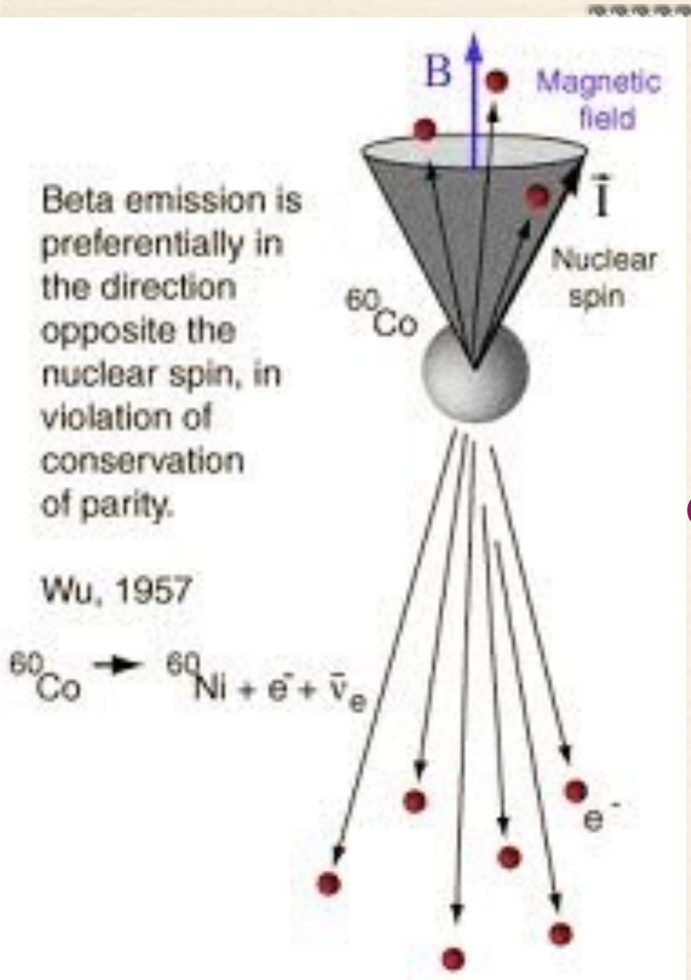
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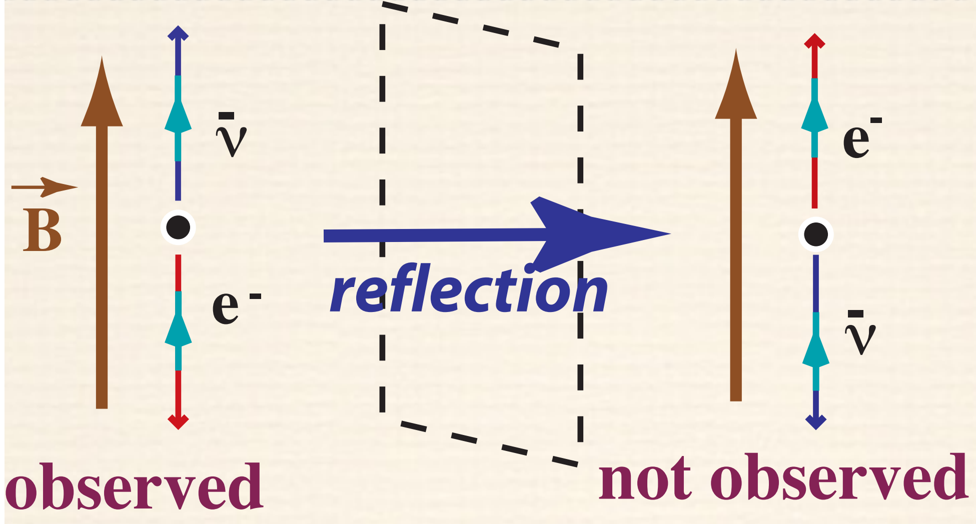

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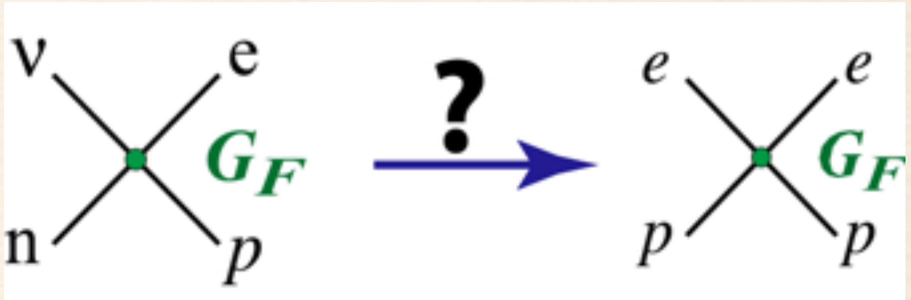

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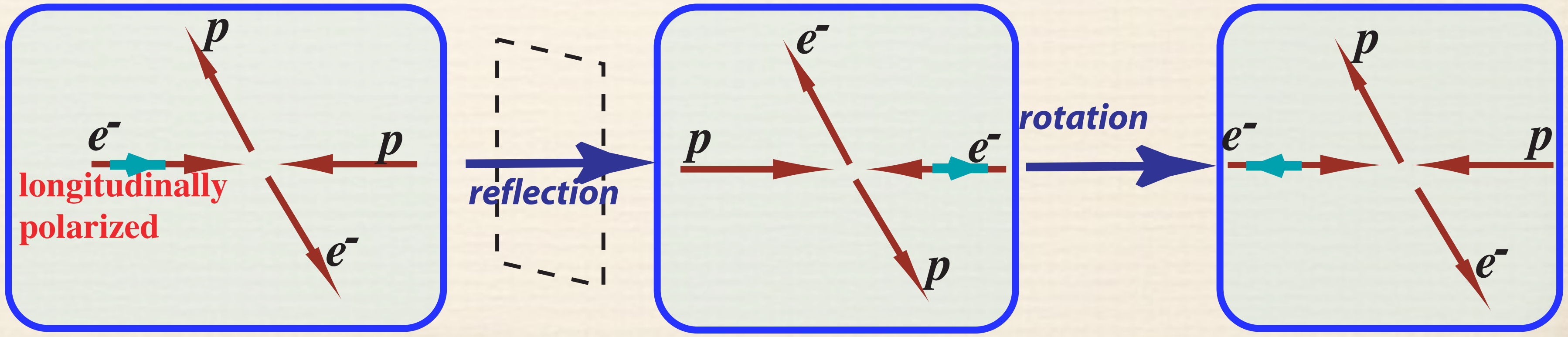

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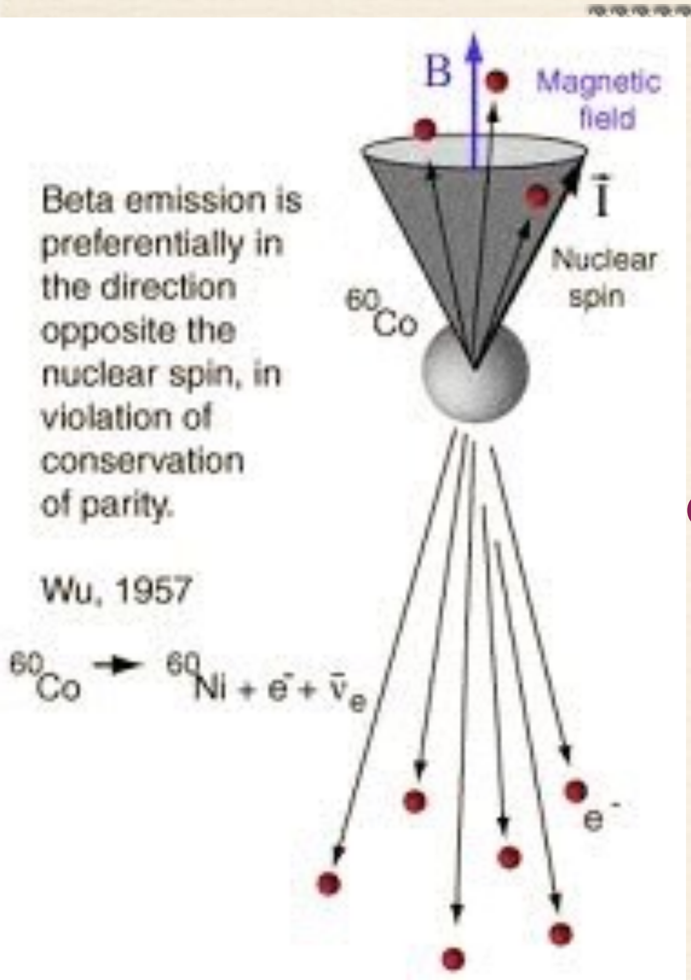

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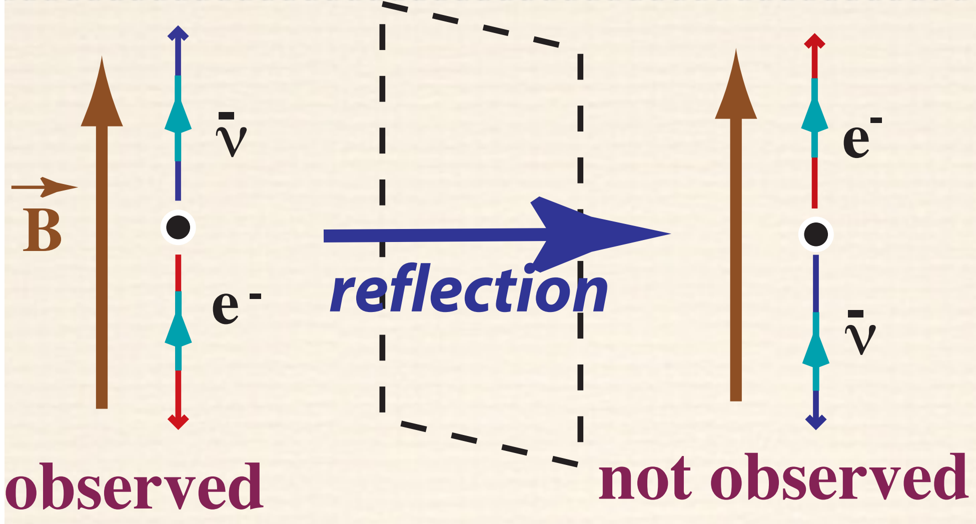

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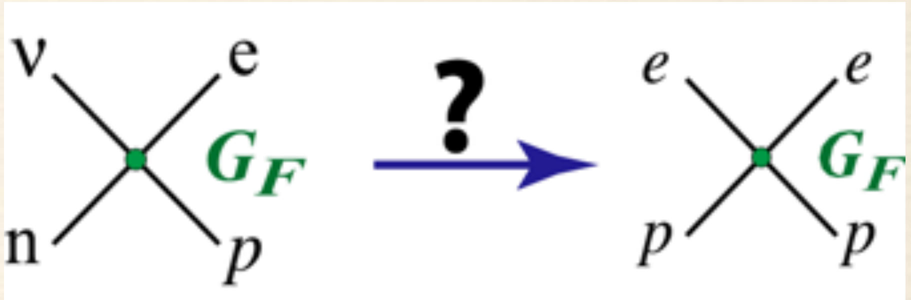

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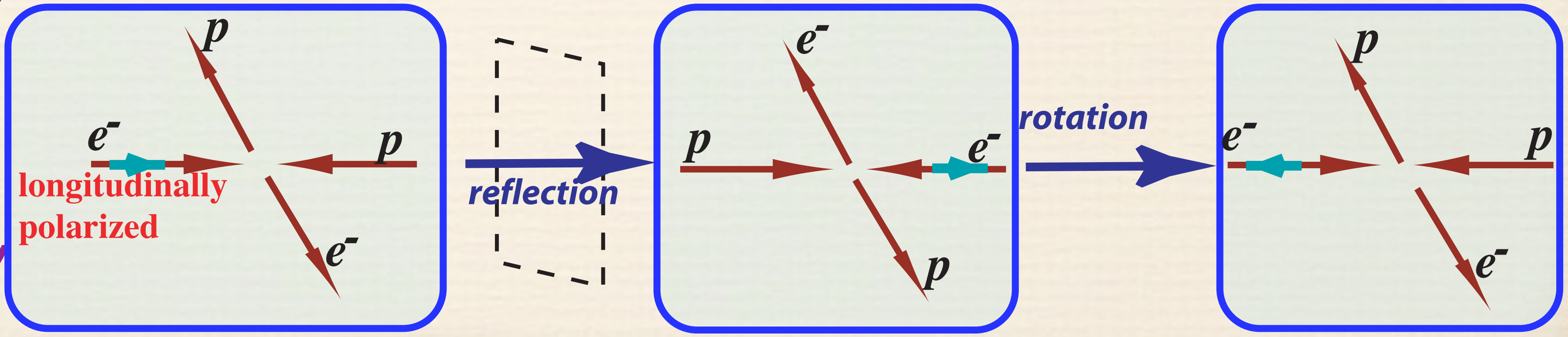
$$\sim |A_{EM}|^2 + \boxed{2A_{EM}A^*_{weak}} + \ldots$$

Parity-violating

$$A_{PV} \sim 10^{-4} \cdot Q^2 \ (\mathrm{GeV}^2)$$

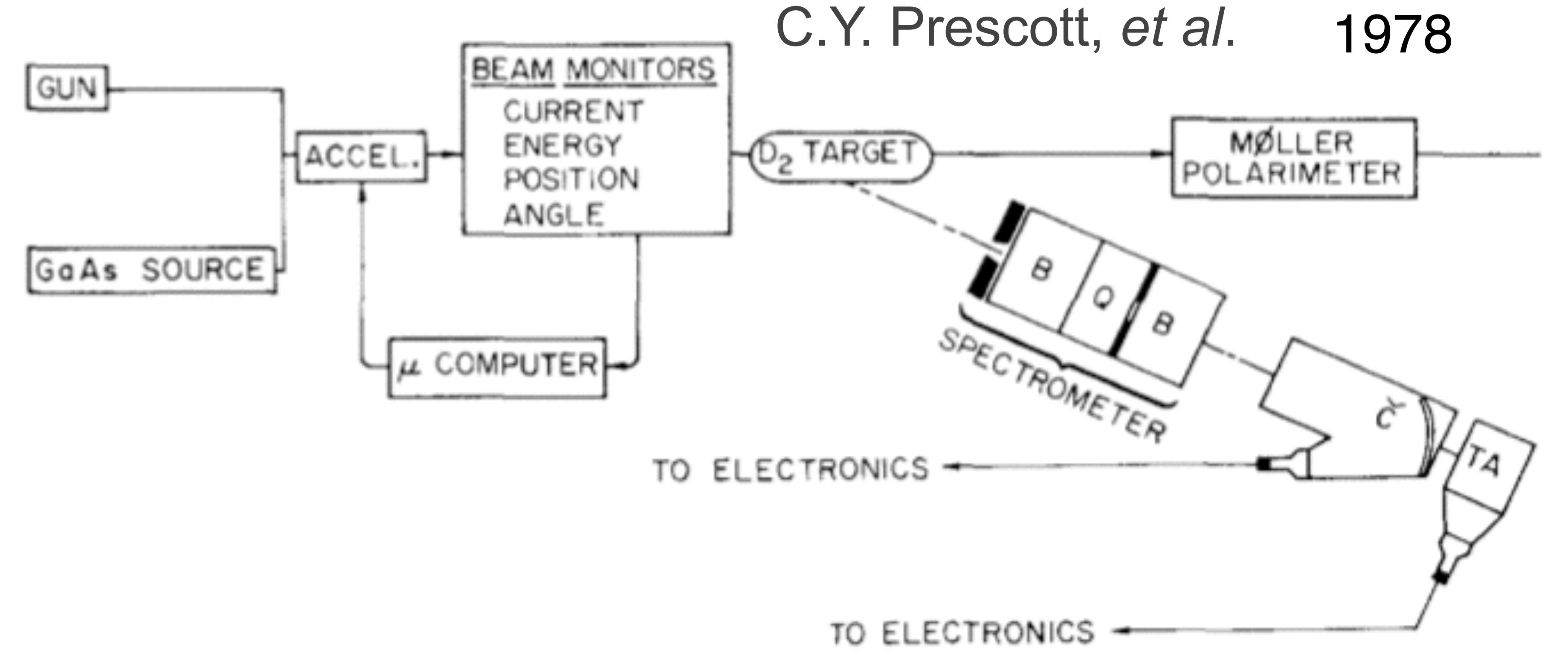
- *longitudinally polarize one beam with the ability to change its sign*
- *Measure fractional rate difference with a sensitivity of a part in 10,000*



The first Parity-Violating Electron Scattering (PVES) Experiment

Anatomy of E122 at SLAC

C.Y. Prescott, *et al.* 1978



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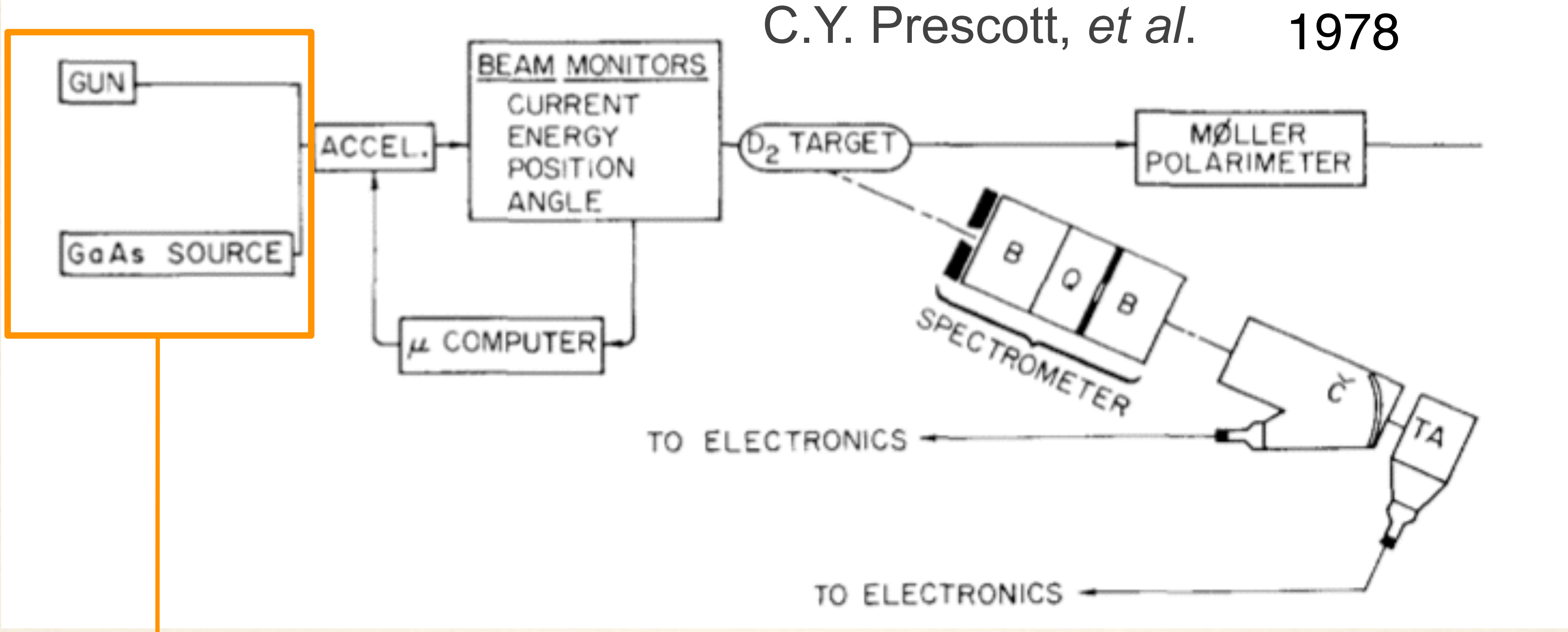
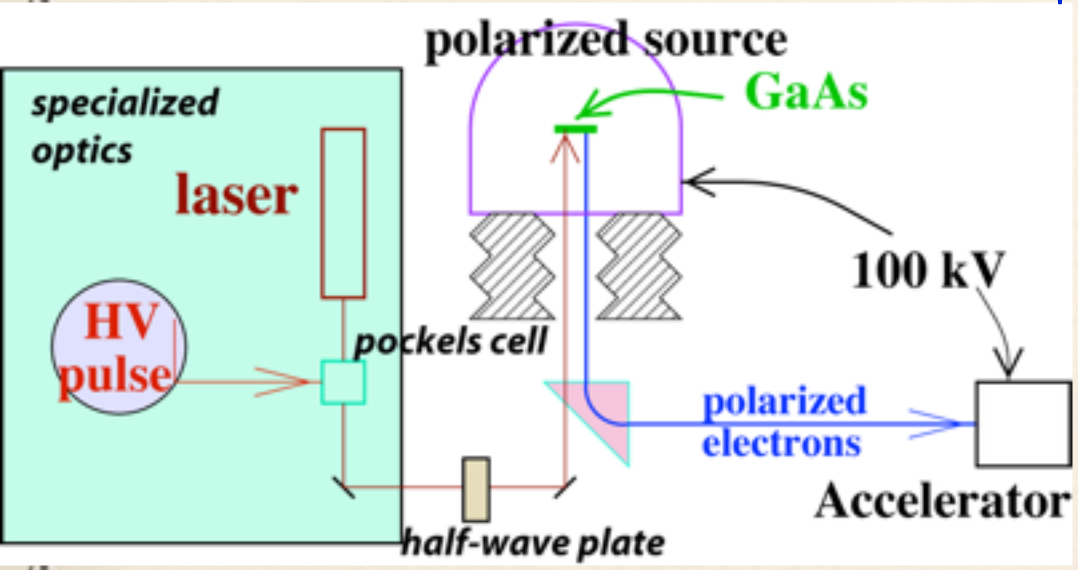
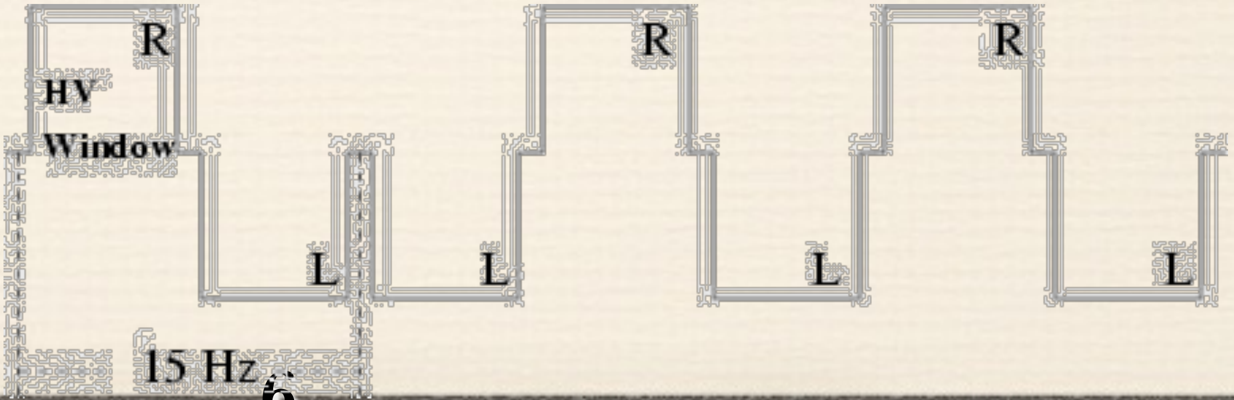

C.Y. Prescott, *et al.* 1978

- **Beam helicity sequence is chosen pseudo-randomly**
  - Helicity state, followed by its complement
  - Data analyzed as "pulse-pairs"





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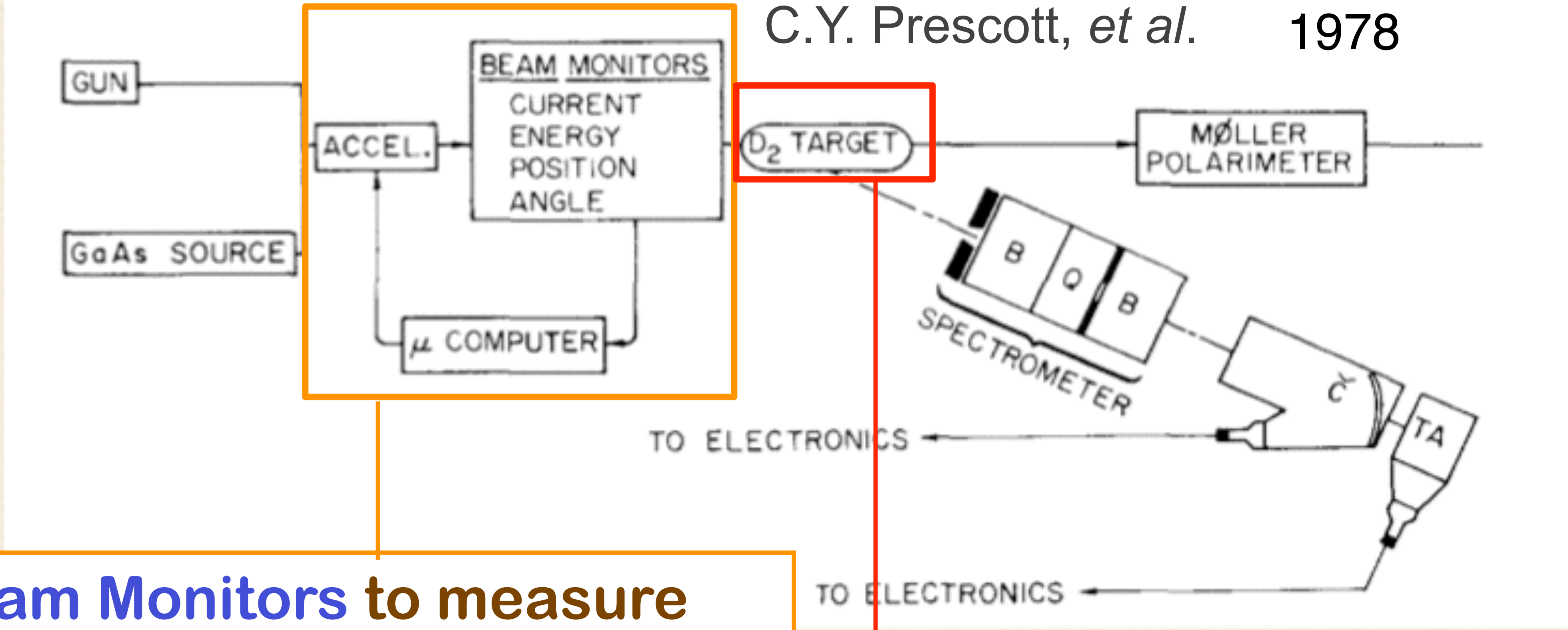


C.Y. Prescott, *et al.* 1978

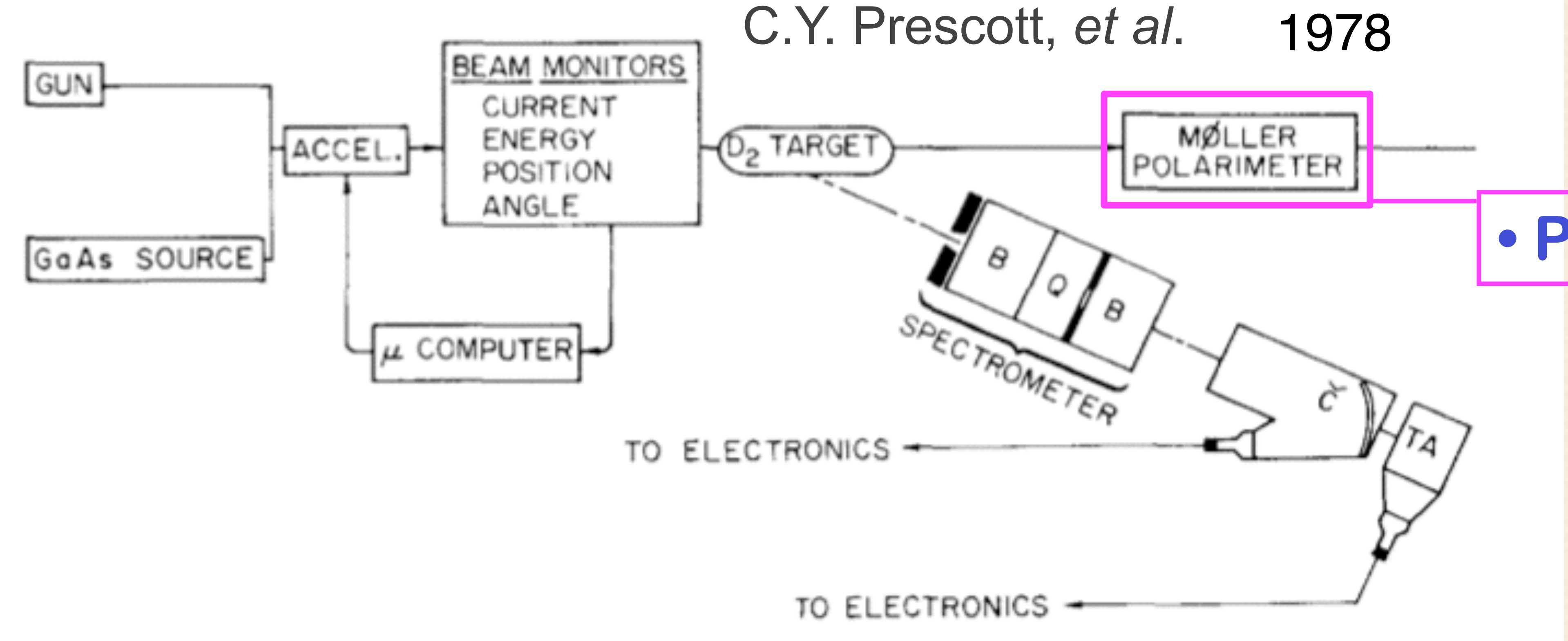
- **Beam Monitors** to measure helicity-correlated changes in beam parameters

- **High-power cryotarget** 30 cm long for high luminosity

The first Parity-Violating Electron Scattering (PVES) Experiment

Anatomy of E122 at SLAC

C.Y. Prescott, *et al.* 1978



- Polarimetry

The first Parity-Violating Electron Scattering (PVES) Experiment

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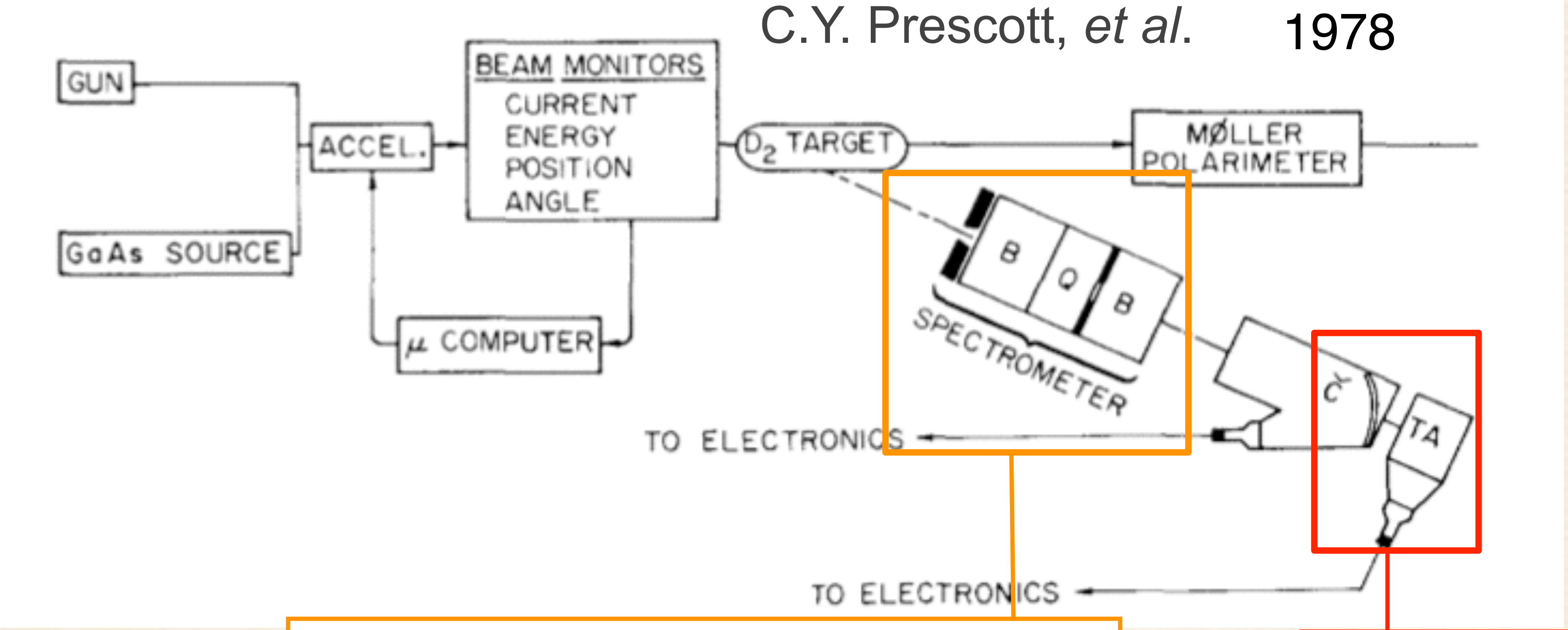
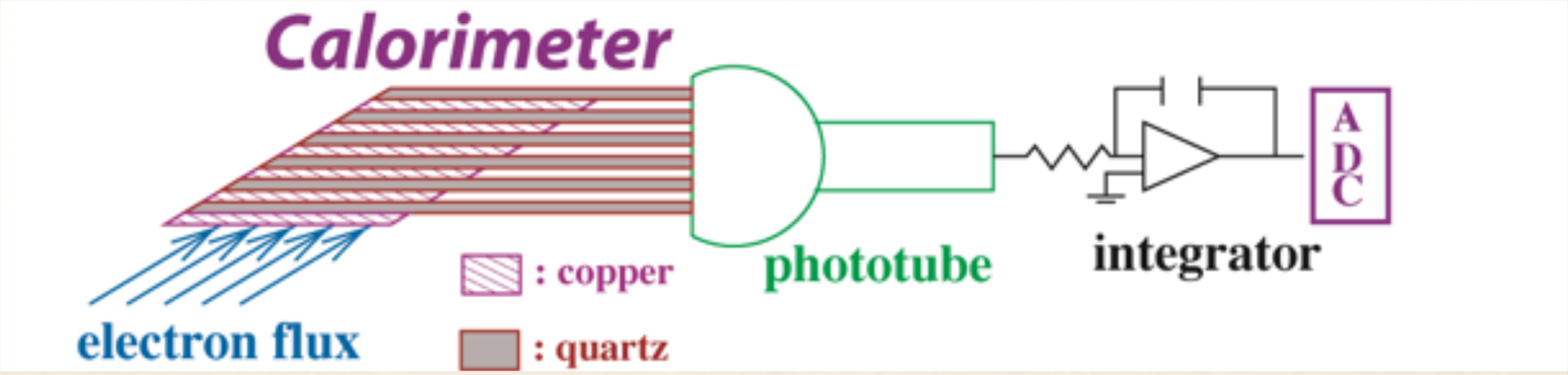

C.Y. Prescott, *et al.* 1978

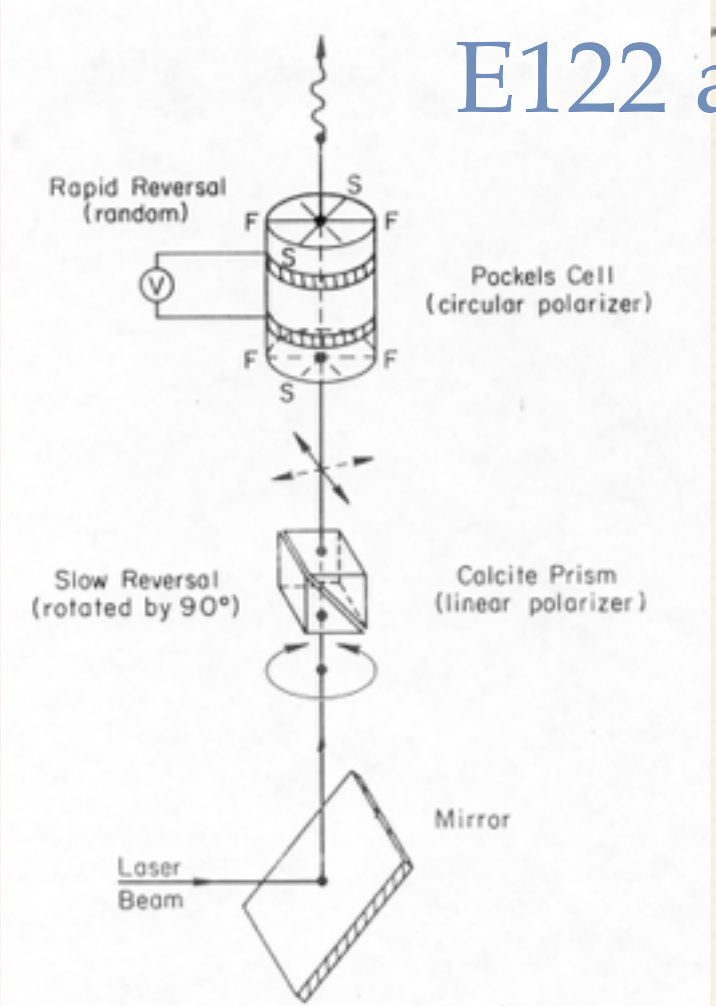
- **Magnetic spectrometer** directs flux to background-free region

- **Flux Integration** measures high rate without deadtime



Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

SLAC E122 Result



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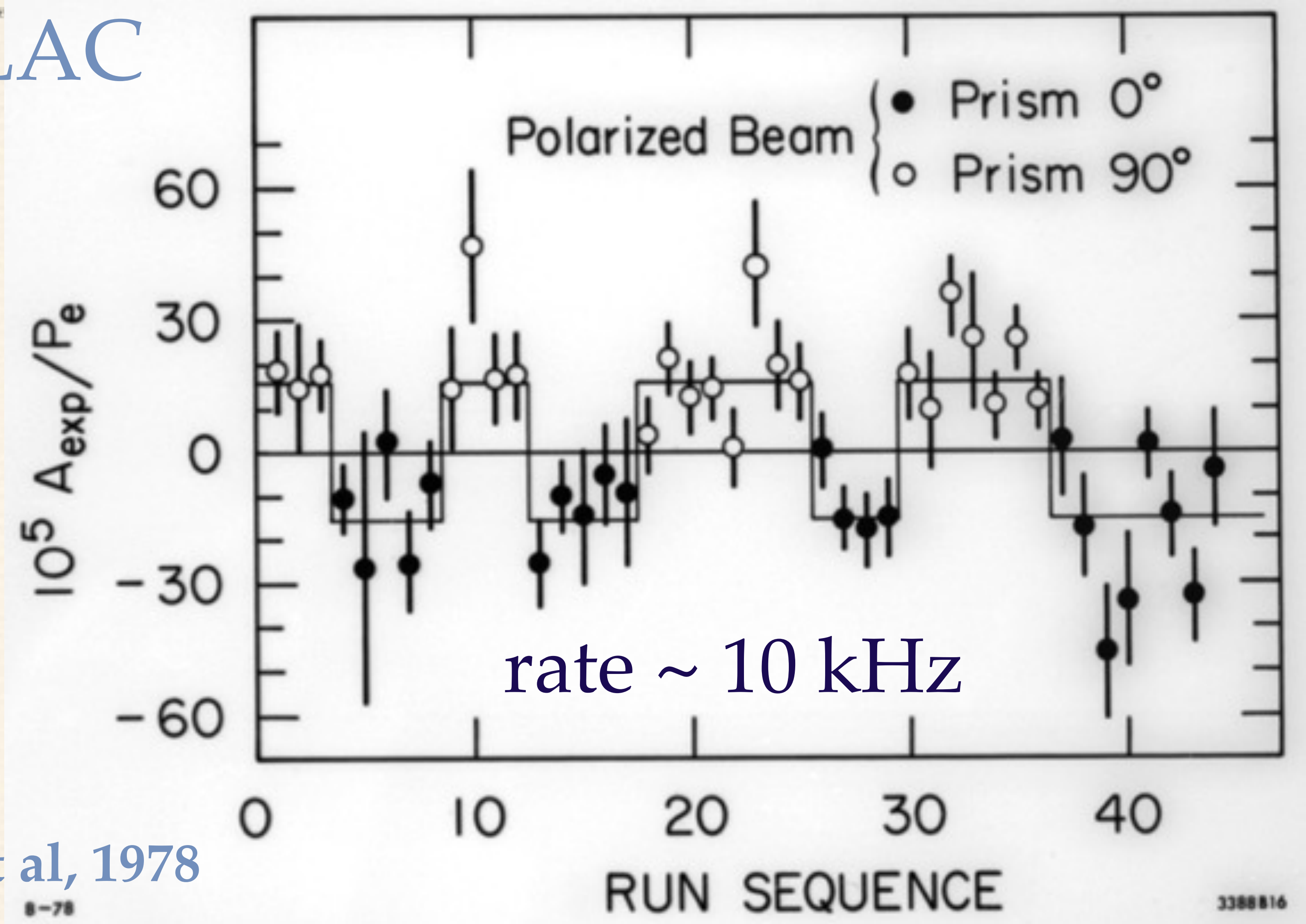
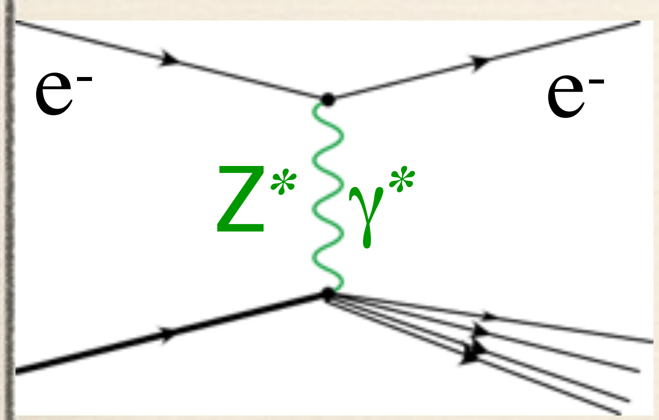


rate ~ 10 kHz

C.Y. Prescott et al, 1978



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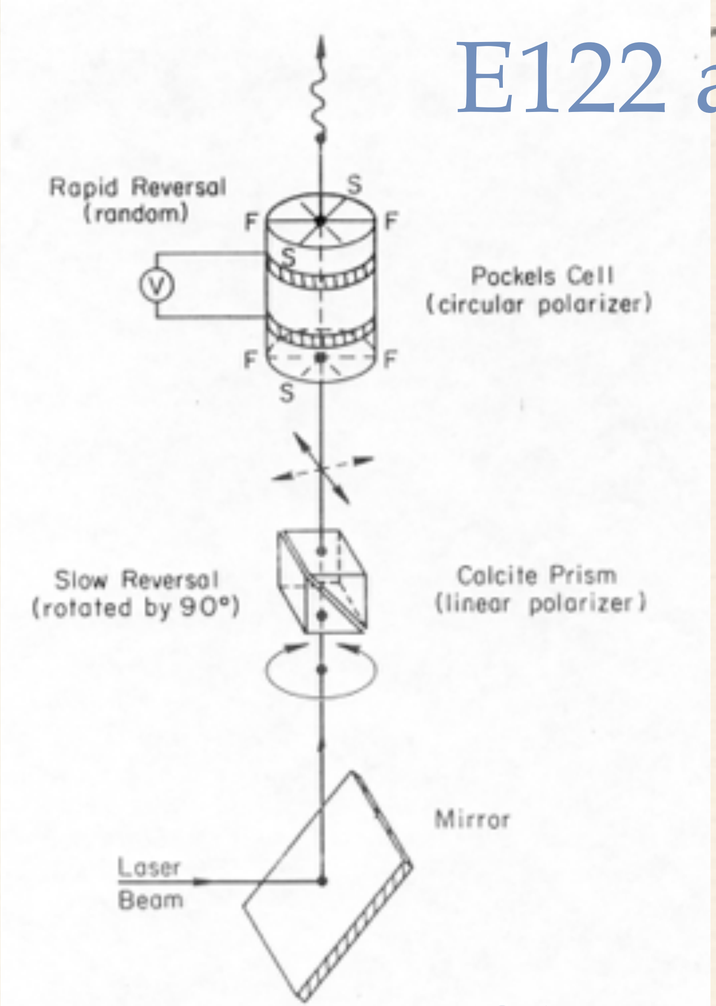

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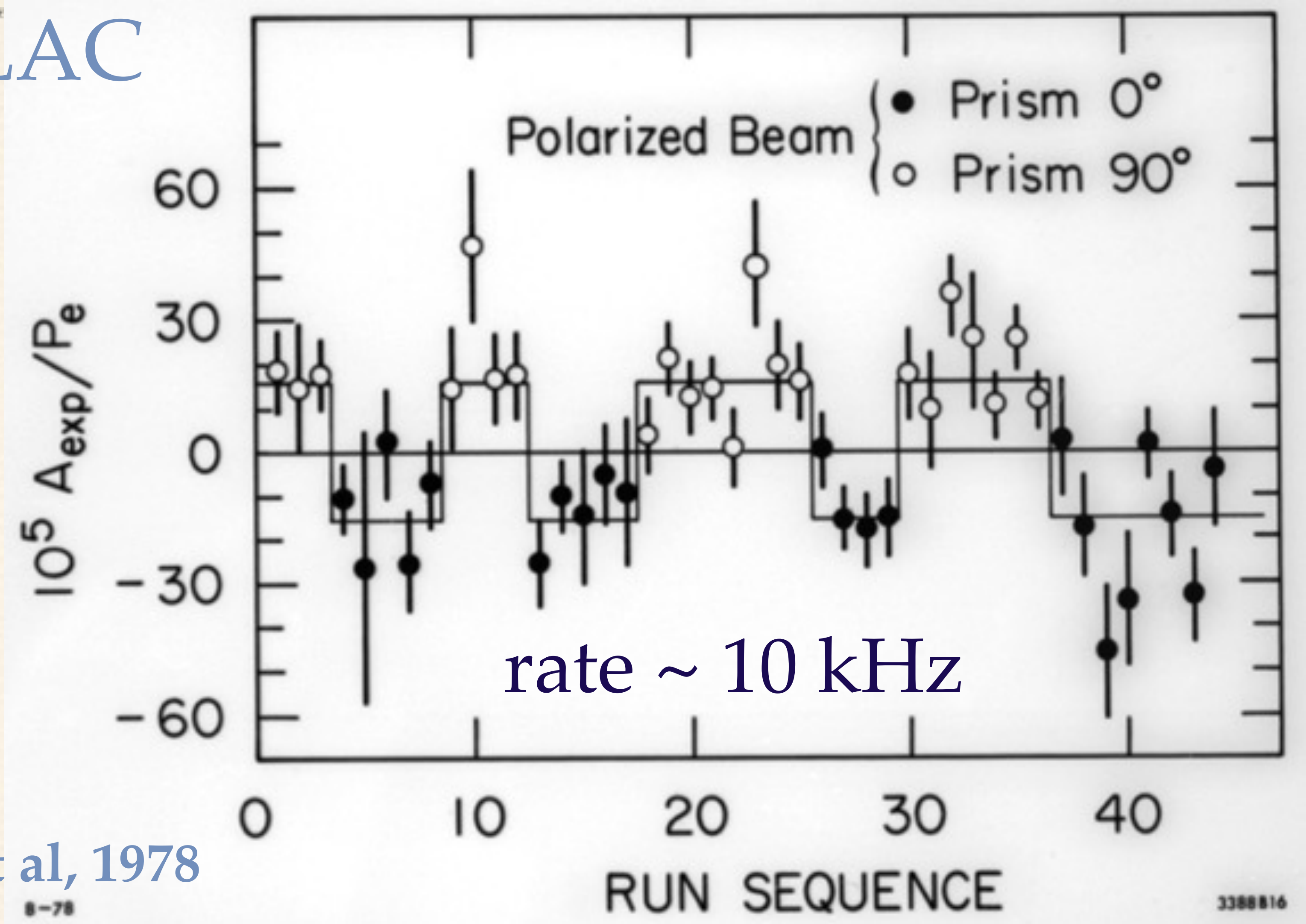

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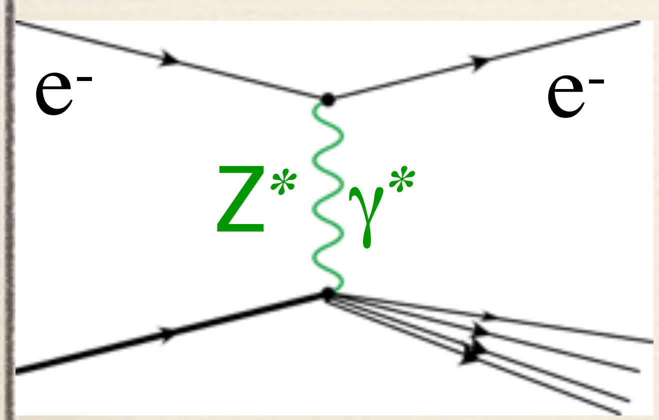

- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

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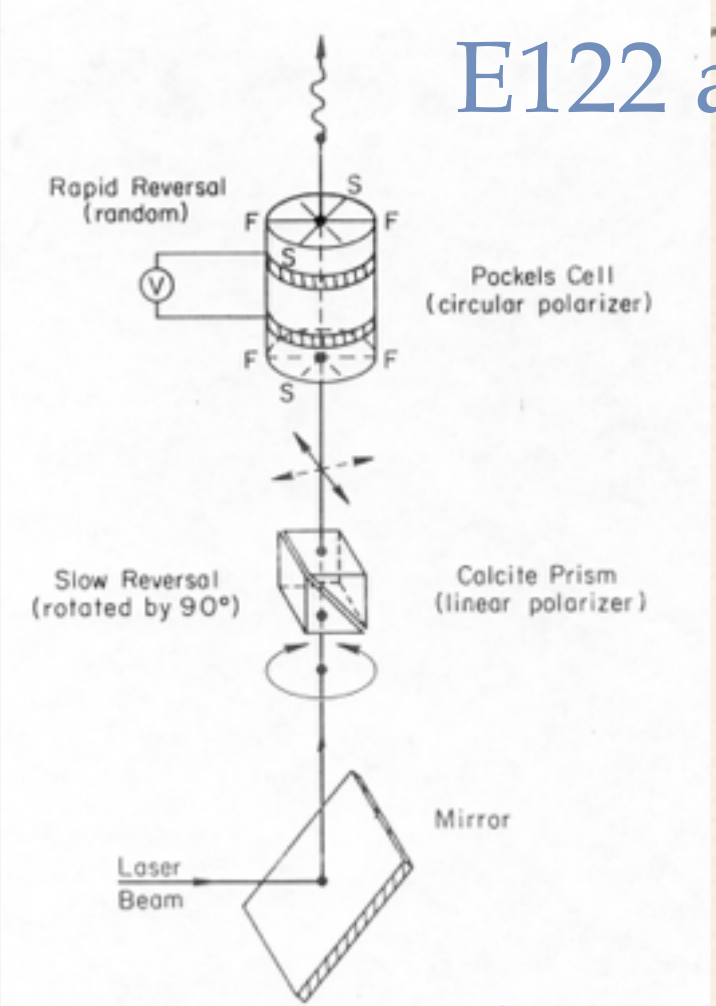

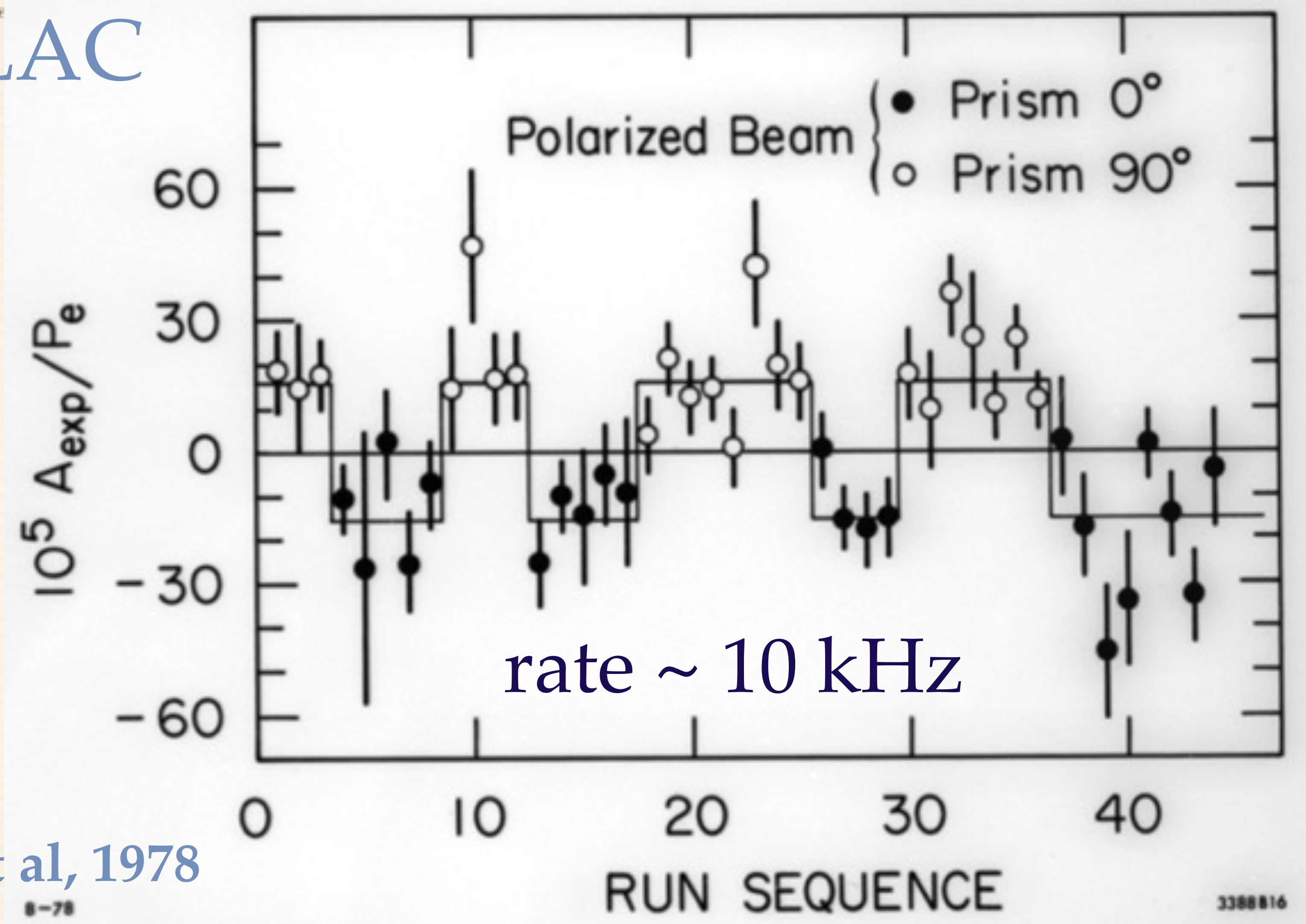

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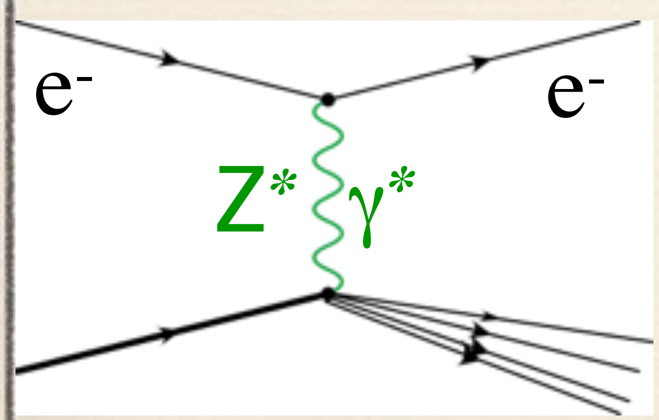

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Glashow, Weinberg, Salam Nobel Prize awarded in 1979

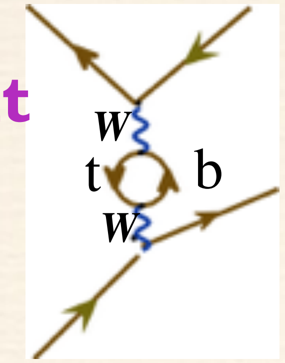
Electroweak Theory at 1-Loop

Lecture by A. Freitas

For electroweak interactions, 3 input parameters needed:

1. **Rb-87 mass + Ry constant**
2. **The muon lifetime**
3. **The Z line shape**

α_{QED} G_F M_Z



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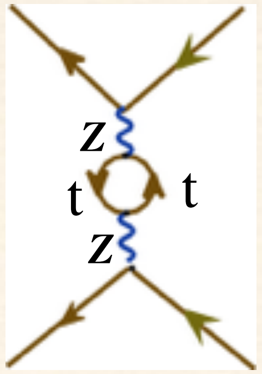

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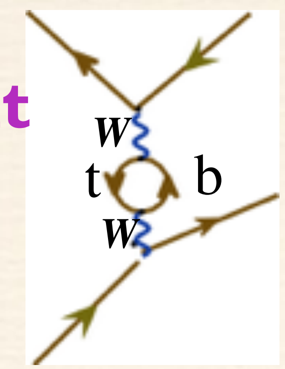

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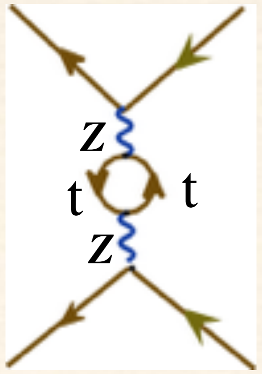
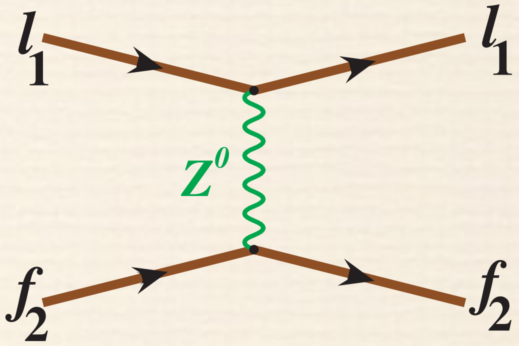


Z production

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

Weak Neutral Current interactions



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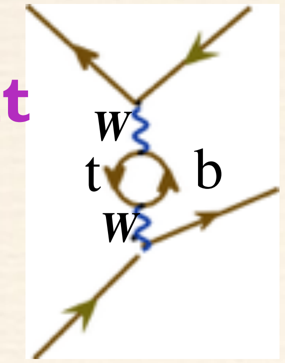

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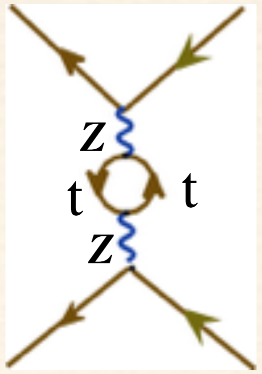

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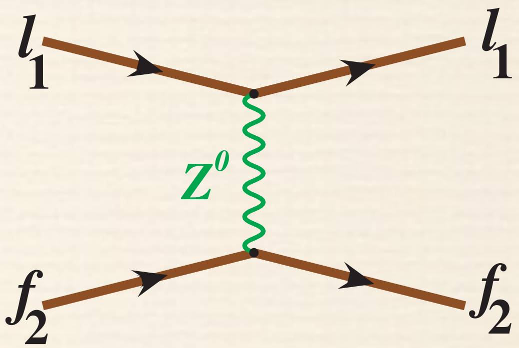

Weak Neutral Current interactions

$$\sin^2\theta_W \equiv 1 - m_W^2/m_Z^2$$

simple definition; disfavored due to heavy m_t

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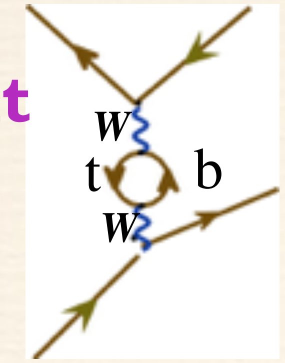

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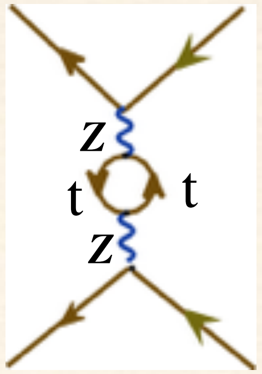

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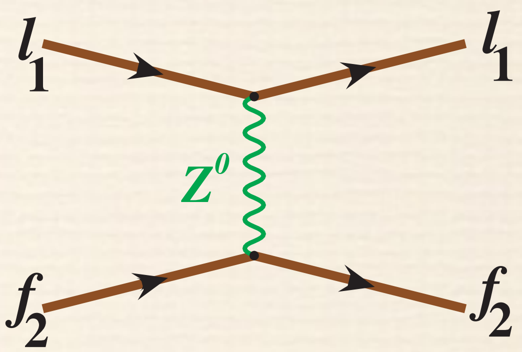

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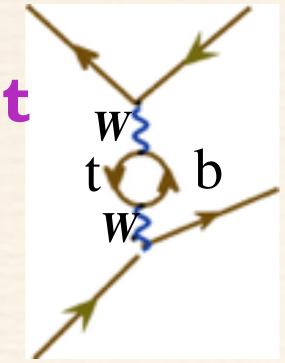

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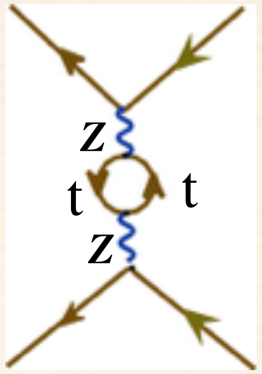

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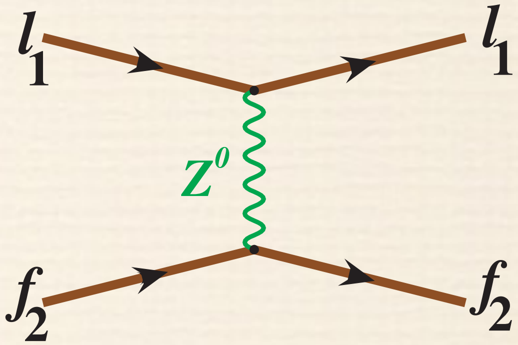

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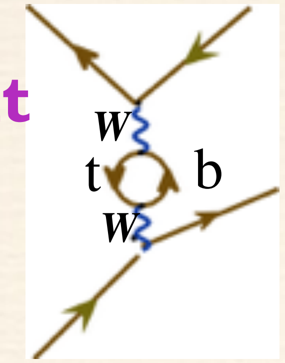

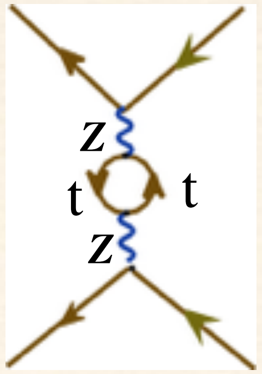

Muon decay *Z production*

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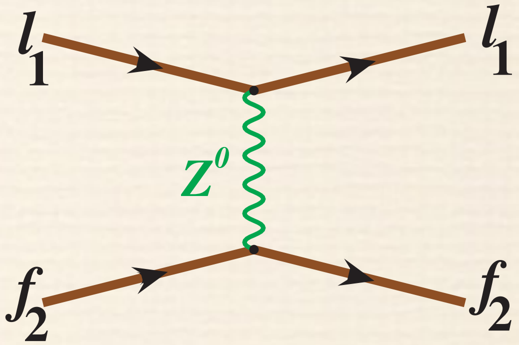

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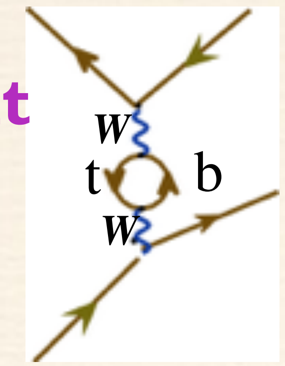

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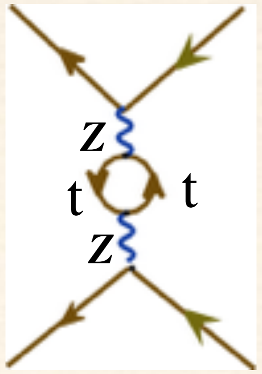

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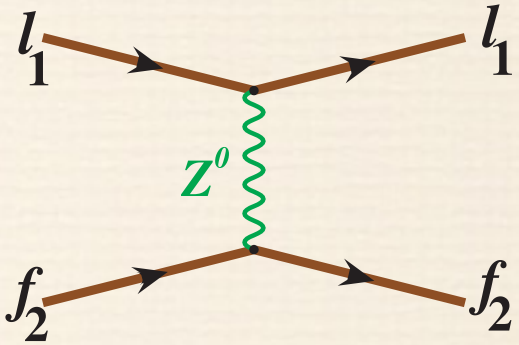

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Theory Predictions

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

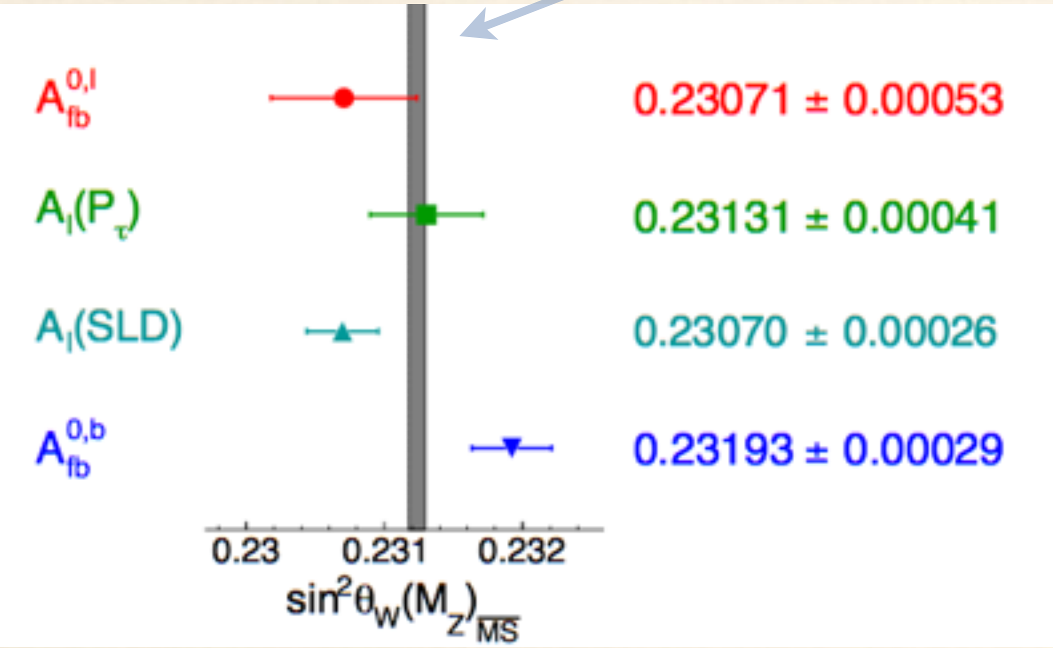
$$M_W = 80.358\,(4)\ \mathrm{GeV}$$

Theory vs Experiment

The most precise measurements at LEP/SLC

colliders: LEP, SLC

Prediction for 125 GeV Higgs



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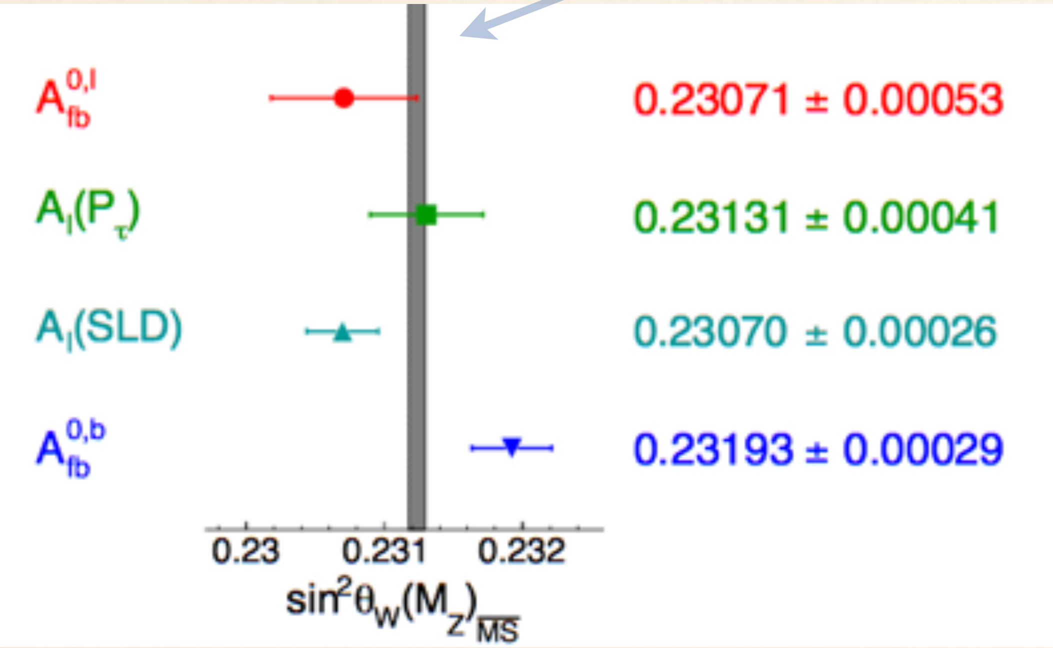

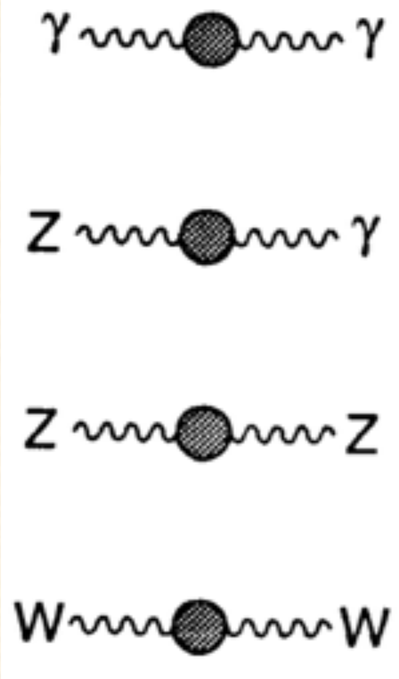

S,T, U parameters

Stringent constraints on large classes of new physics models

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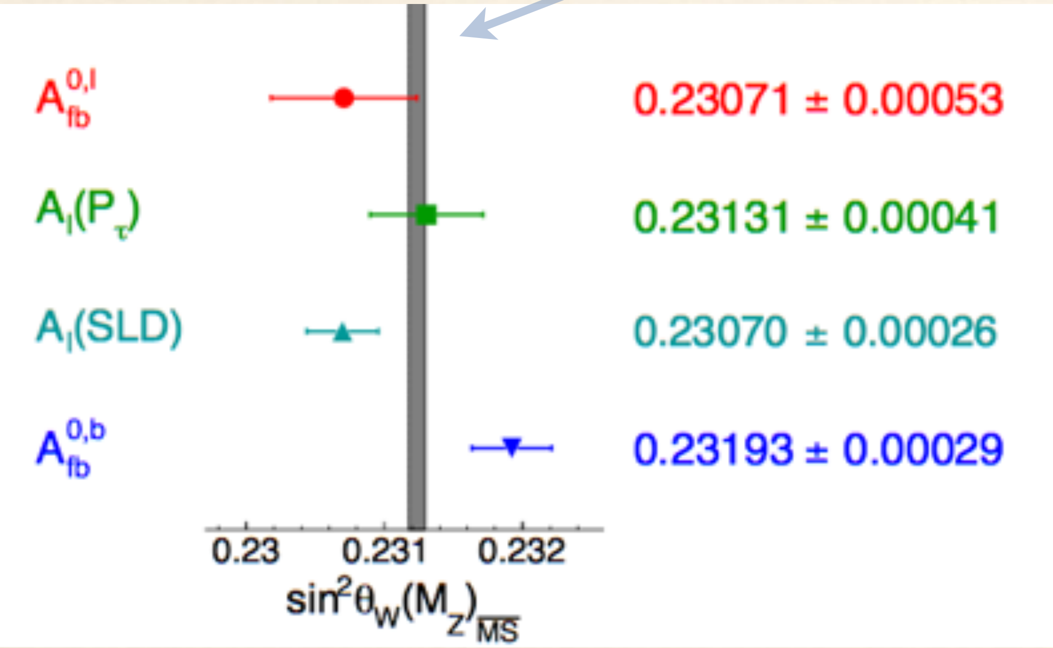

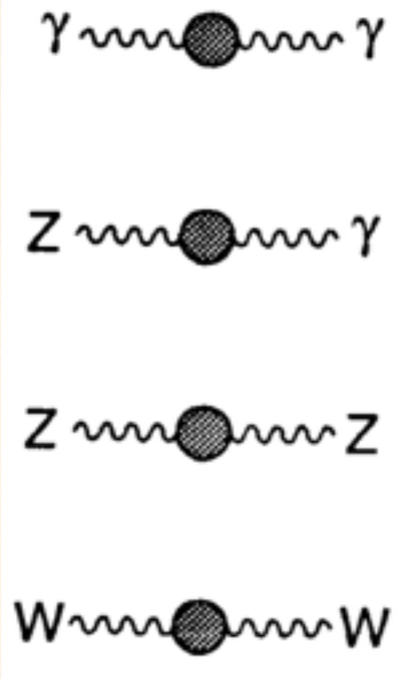

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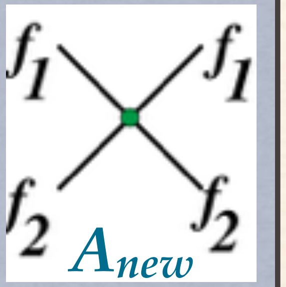
Flavor Diagonal Contact Interactions



Consider $f_1\bar{f}_1 \to f_2\bar{f}_2$ or $f_1 f_2 \to f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2}\eta_{ij}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma^\mu f_{2j}$$

New heavy physics that does not couple directly to SM gauge bosons

Theory vs Experiment

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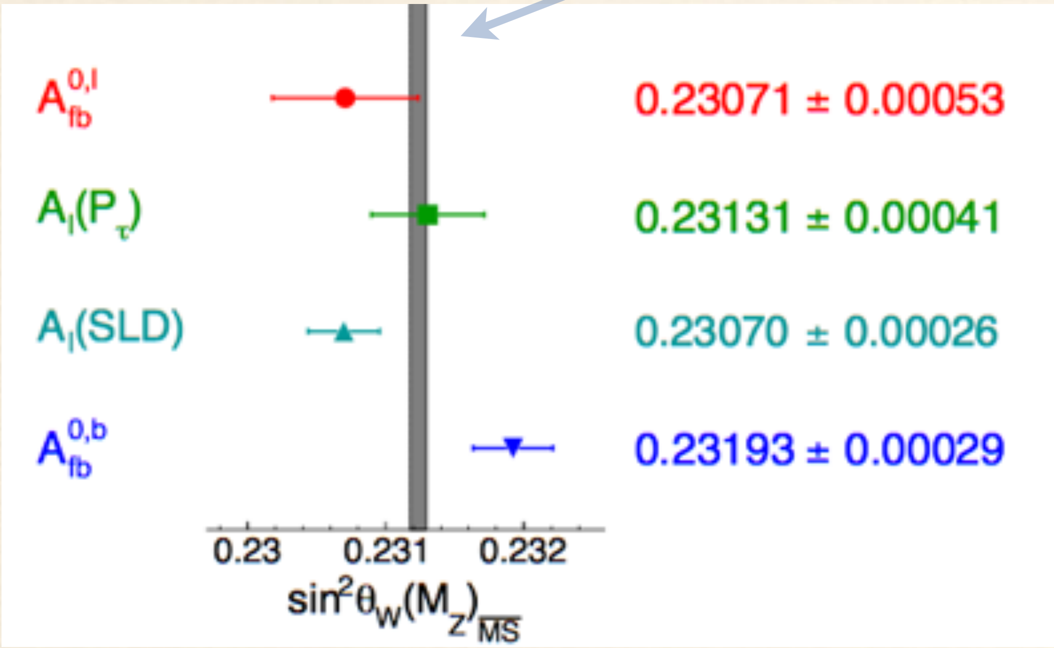

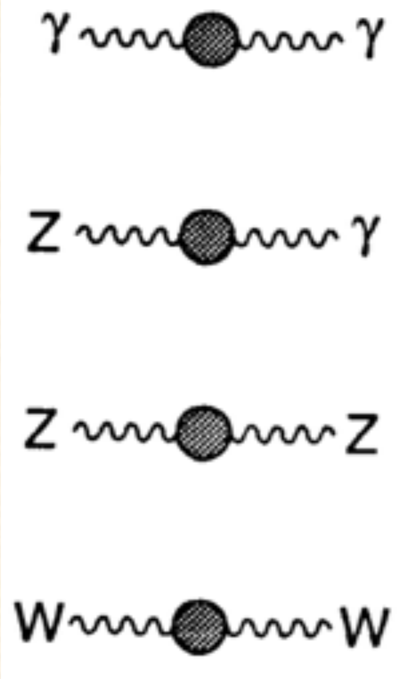

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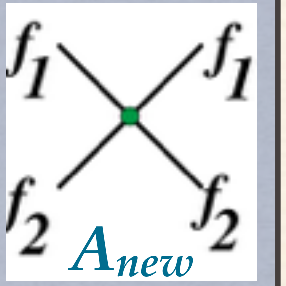


New heavy physics that does not couple directly to SM gauge bosons

on resonance: A_Z is imaginary

$$\left|A_Z + A_{new}\right|^2 \rightarrow A_Z^2\left[1+\left(\frac{A_{new}}{A_Z}\right)^2\right]$$

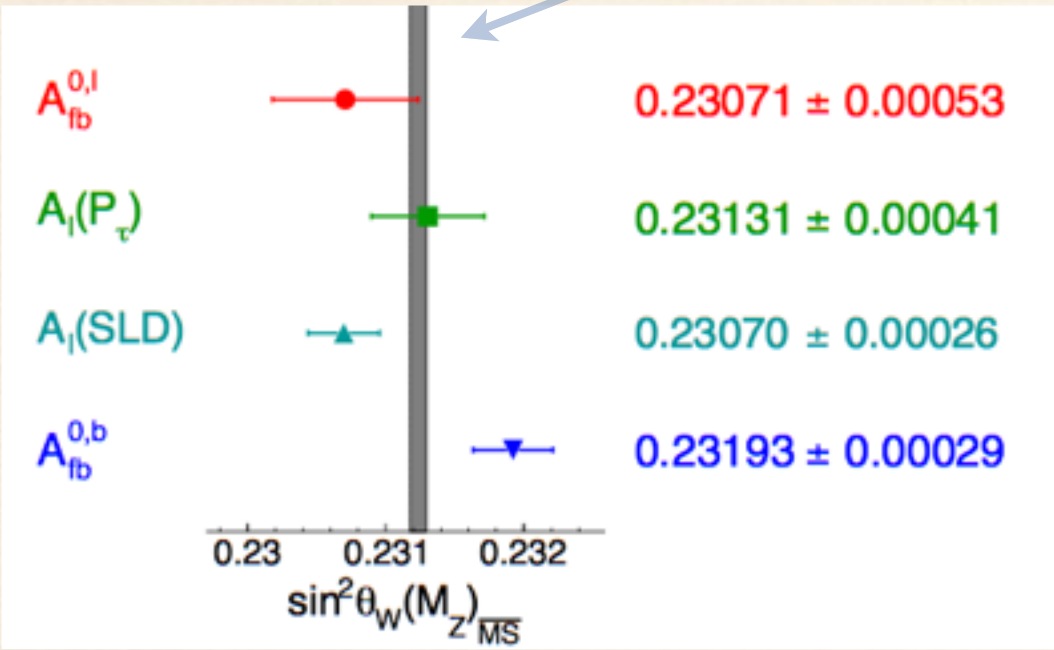
no interference!

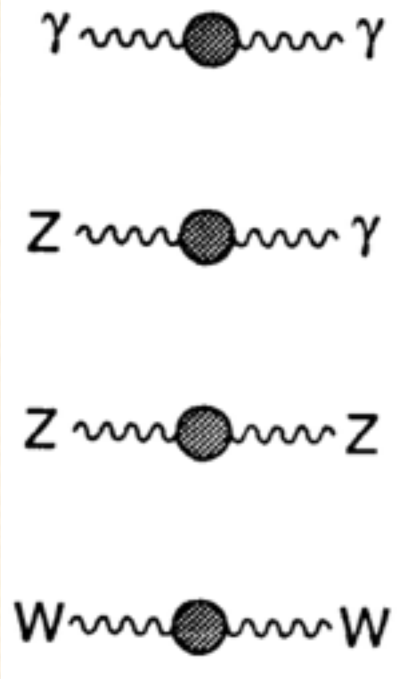
Theory vs Experiment

The most precise measurements at LEP/SLC

colliders: LEP, SLC

Prediction for 125 GeV Higgs





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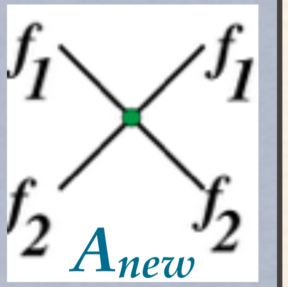
$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2}\eta_{ij}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma^\mu f_{2j}$$



New heavy physics that does not couple directly to SM gauge bosons

on resonance: A_Z is imaginary

$$\left|A_Z + A_{new}\right|^2 \to A_Z^2\left[1+\left(\frac{A_{new}}{A_Z}\right)^2\right]$$

no interference!

Unique role for $\sin^2\theta_W$ measurements at $Q^2 \ll M_Z^2$

Modern Low Q^2 Weak Neutral Current Measurements

Physics down to a length scale of 10^{-19} m well understood but.....

Modern Electroweak Physics

Many questions still unanswered….

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

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The High Energy Frontier: **Collider Physics**

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A comprehensive search for clues requires, in addition:

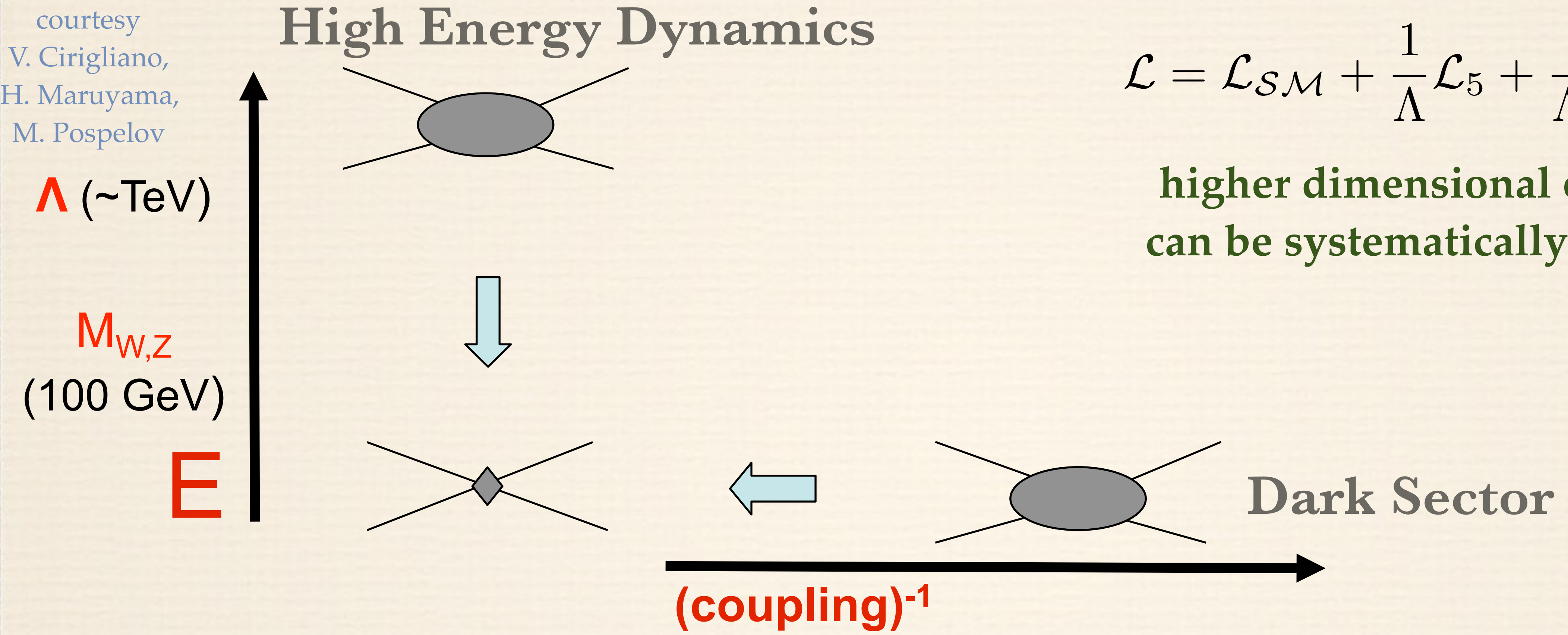
The Intensity/Precision Frontier

- **Violation of Approximate (?) Symmetries**
  - Neutrinoless Double-Beta Decay, EDMs, CLFV,...
- **Direct Detection of Dark Matter**
- **Measurements of Neutrino Masses and Mixing**
- **Precise Measurements of SM observables**

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

BSM Indirect Searches

courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov



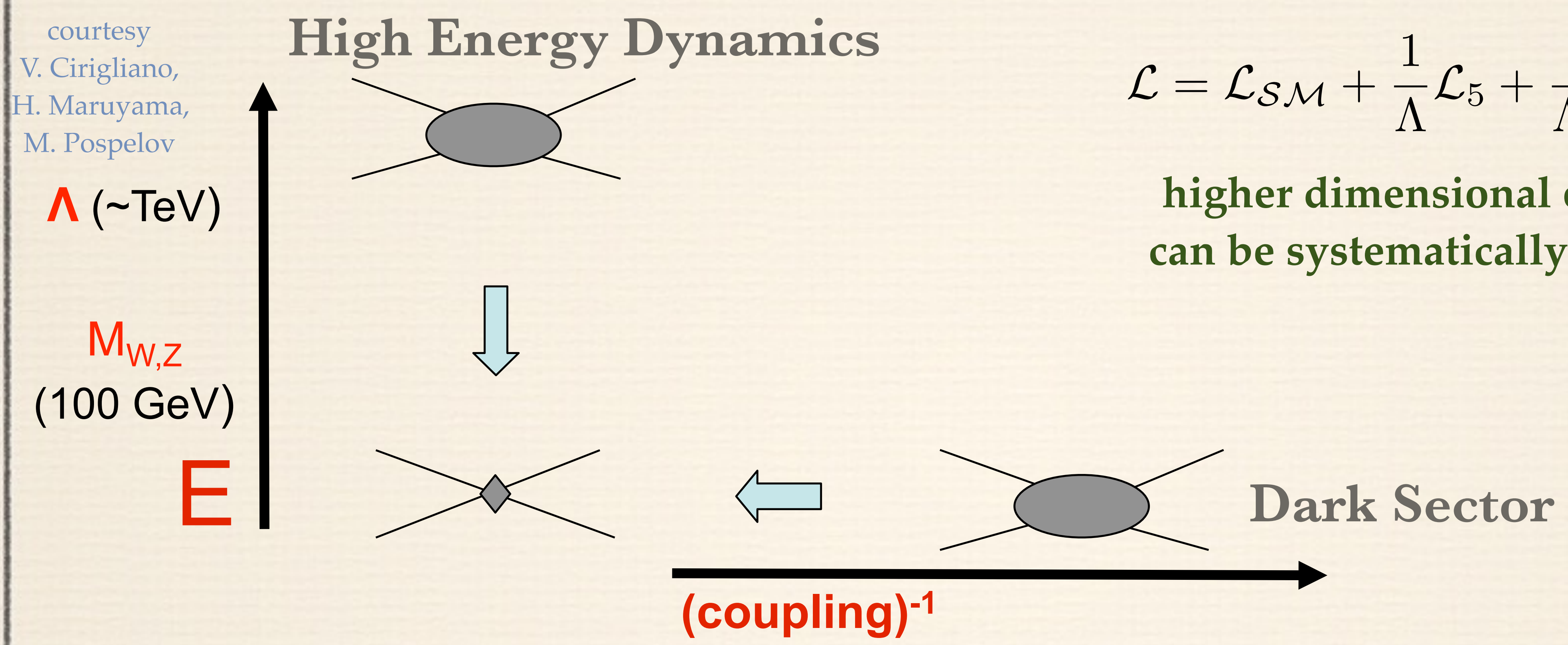
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators
can be systematically classified

Heavy Z’s, light (dark) Z’s, L-R models, compositeness, extra dimensions, SUSY…

Weak Neutral Current Interactions (WNC) at $Q^2 \ll M_Z^2$

BSM Indirect Searches



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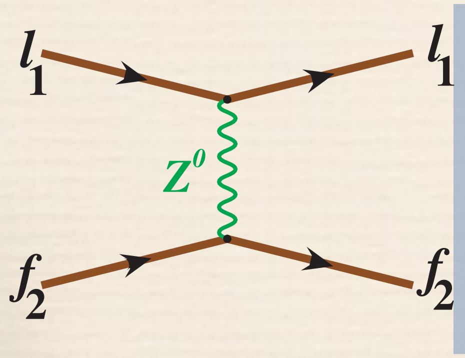
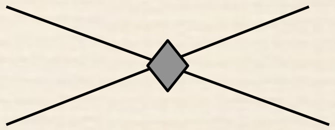


Search for new flavor diagonal CP-conserving neutral currents

Tiny yet measurable deviations from
SM processes with precise predictions



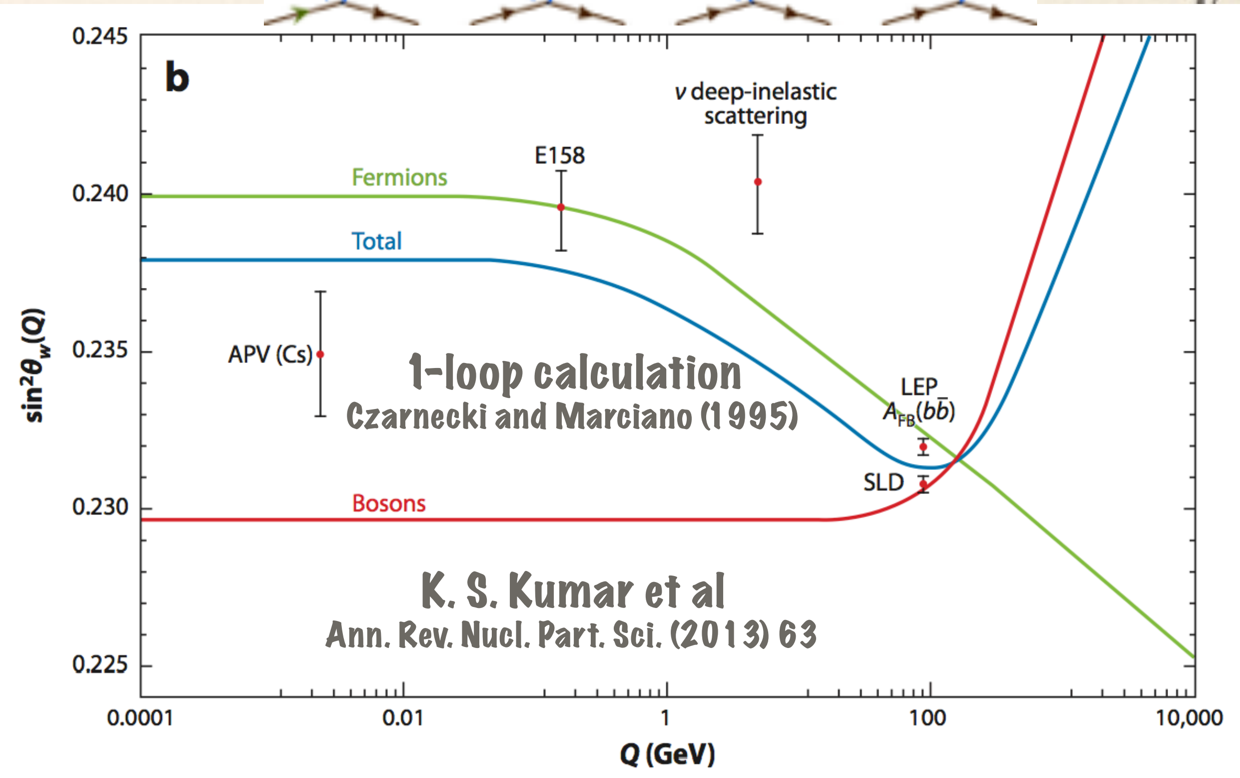
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ 10 TeV

Thumb Rule: Weak mixing angle must be measured to sub-1% precision

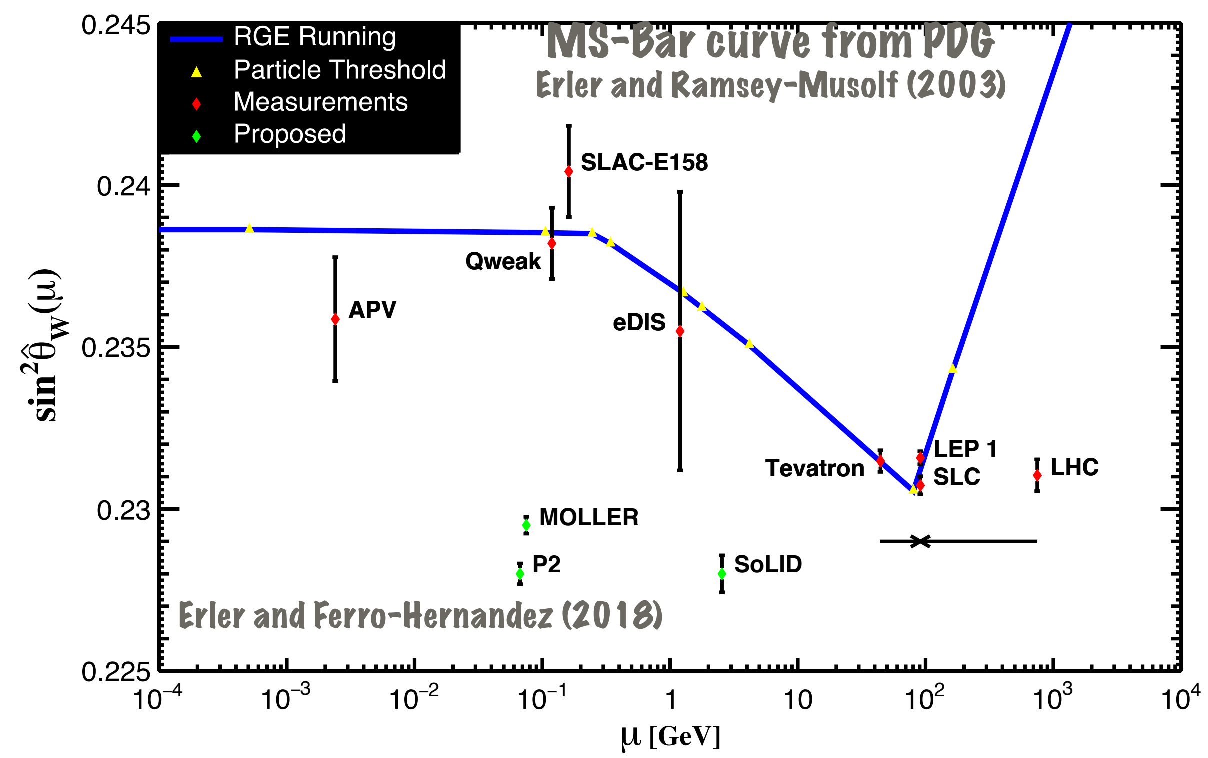
WNC “Bookkeeping”

- **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 to 8 improvement possible: SOLID



1-loop calculation
Czarnecki and Marciano (1995)

K. S. Kumar et al
Ann. Rev. Nucl. Part. Sci. (2013) 63

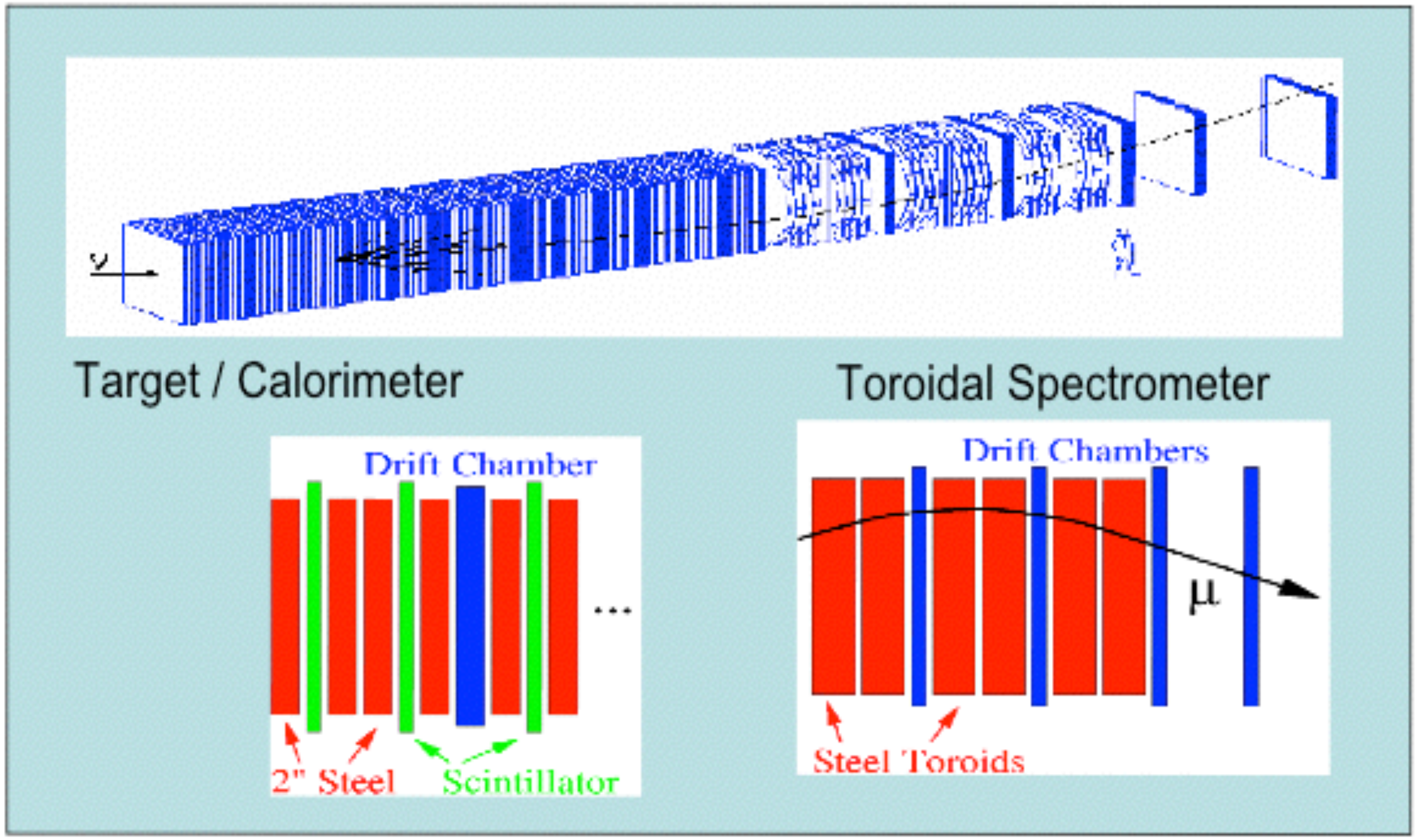


MS-Bar curve from PDG
Erler and Ramsey-Musolf (2003)

Erler and Ferro-Hernandez (2018)

DIS neutrino and anti-neutrino charged and neutral current cross-sections

NuTeV



$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar{\nu} N}} \approx \rho^2 \left(\frac{1}{2} - \sin^2\theta_W \right)$$

$$\boxed{\begin{aligned} \sin^2\theta_W^{(on-shell)} &= 0.2277 \pm 0.0013(stat.) \\ &\pm 0.0009(syst.) \end{aligned}}$$

Standard Model prediction is 0.2227
(3σ deviation)

Most precise measurement of neutrino-quark coupling

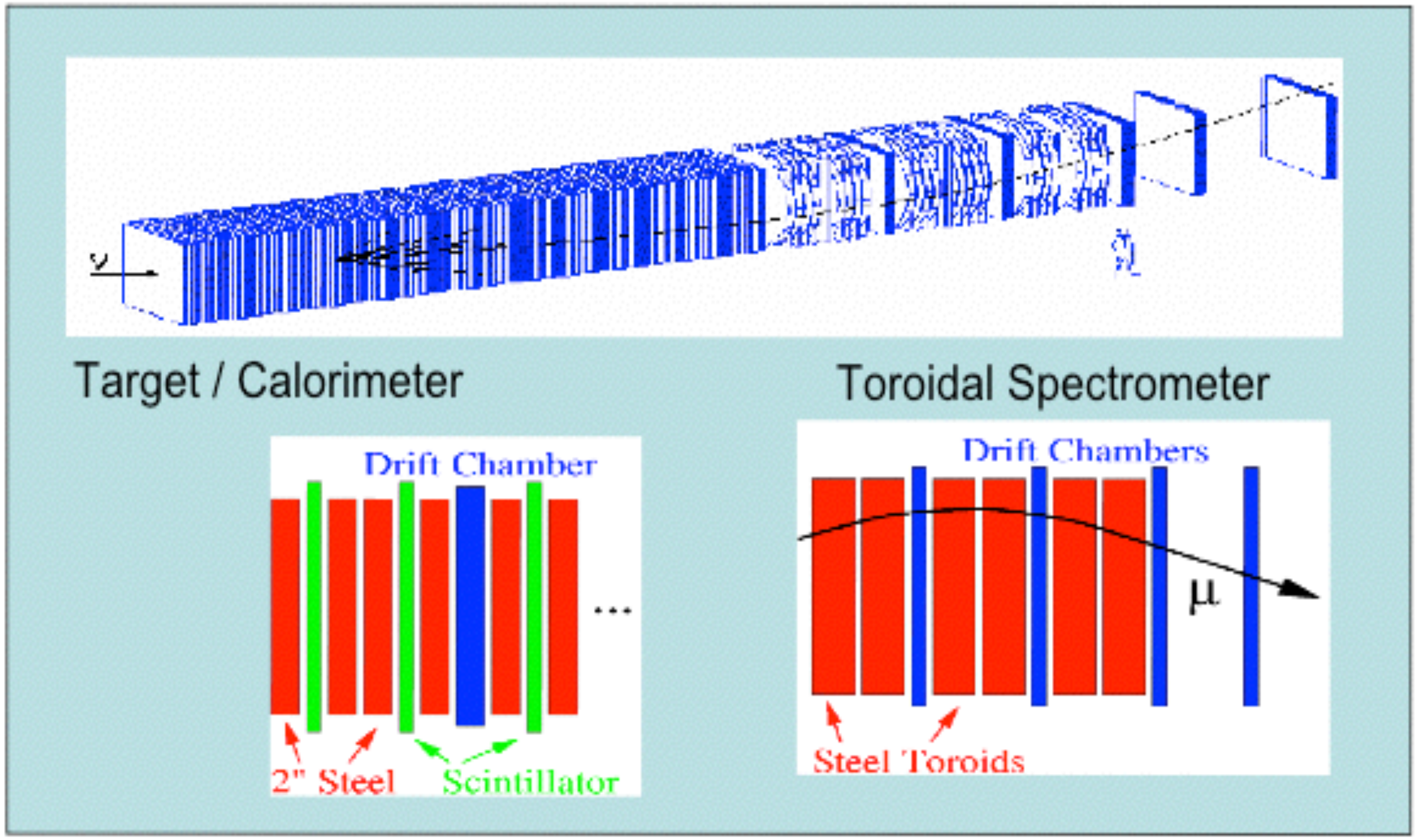
Subtle parton physics effects can affect the result

generated great interest in both nuclear and particle phenomenology

DIS neutrino and anti-neutrino charged and neutral current cross-sections

NuTeV

Significant discovery: but EW or QCD Physics?



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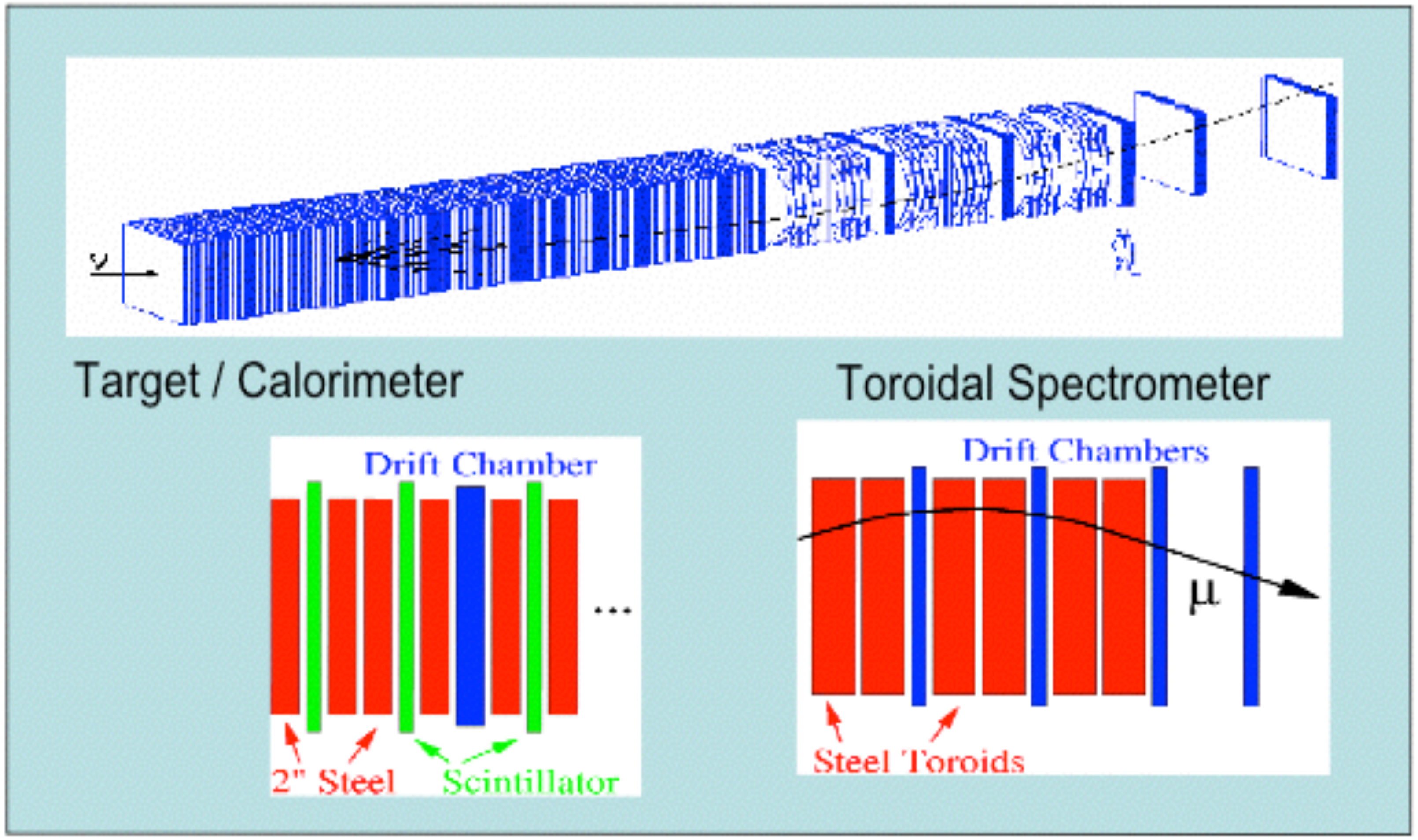

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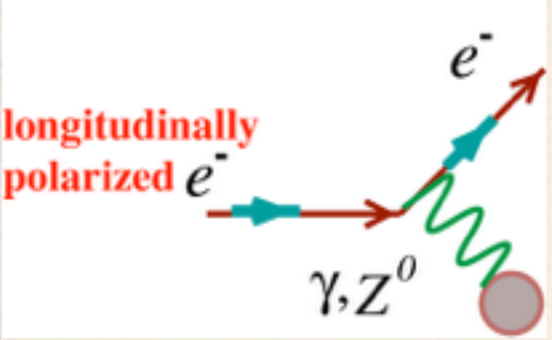
4 decades of measurements: emergence as a precision tool

Parity-Violating Electron Scattering (PVES)



g_V is a function of $\sin^2\theta_W$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

Weak Charge Q_W

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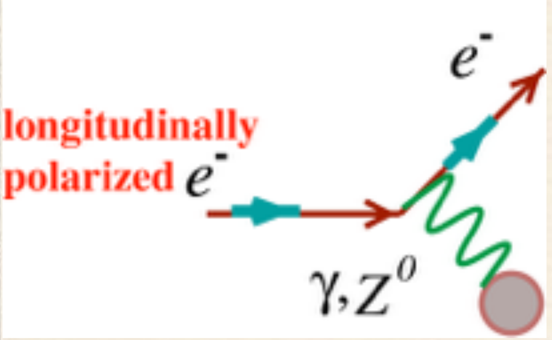

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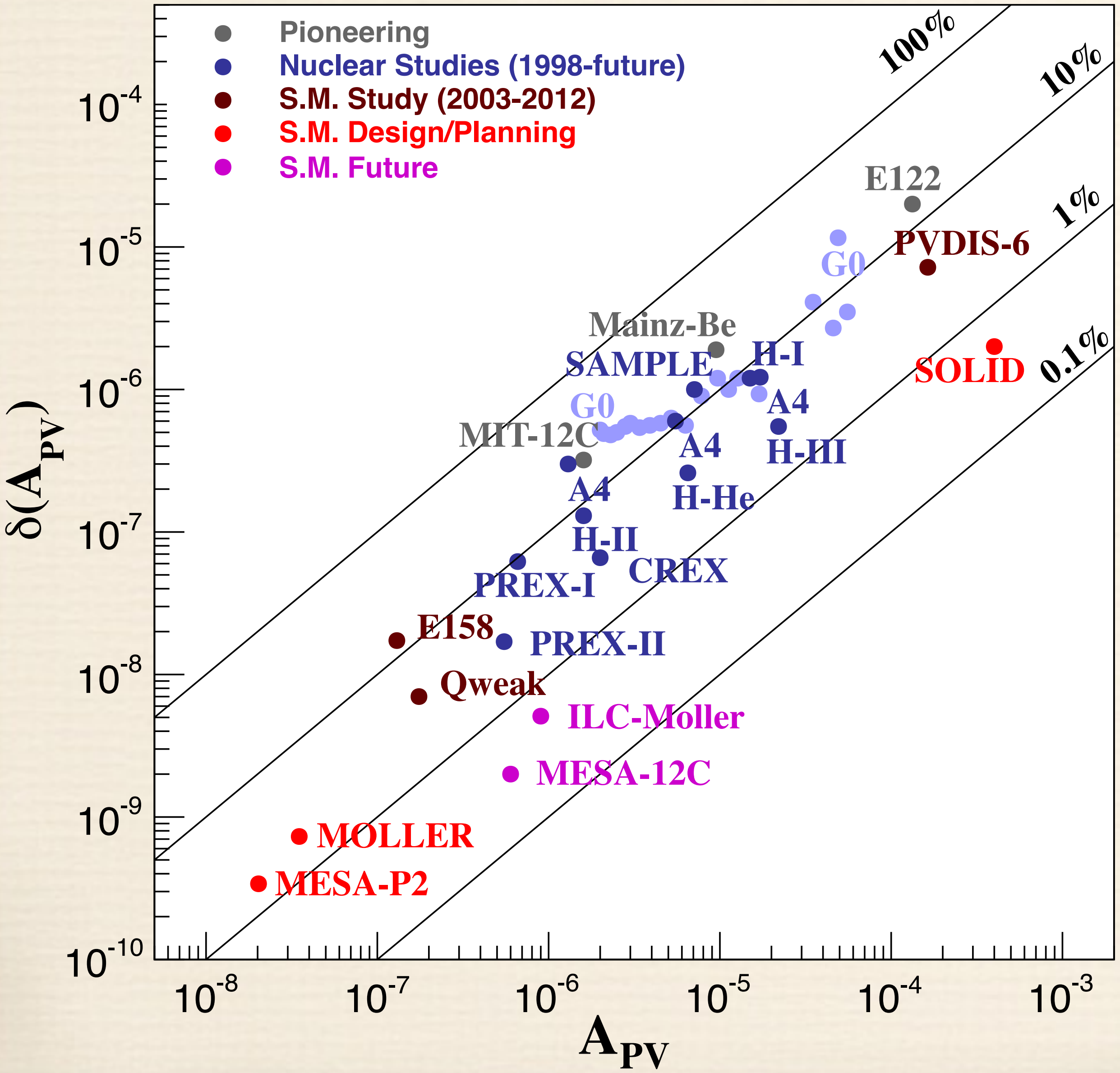


Variety of Physics Topics:

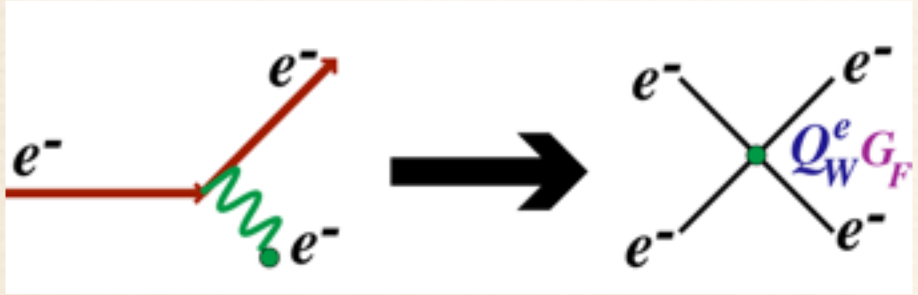
continuous interplay between hadron physics and electroweak physics

Steady improvements in accelerator and detector technology

State of the Art

- sub-part per billion statistical reach and systematic control
- sub-1% normalization control

PV Electron-Electron Scattering



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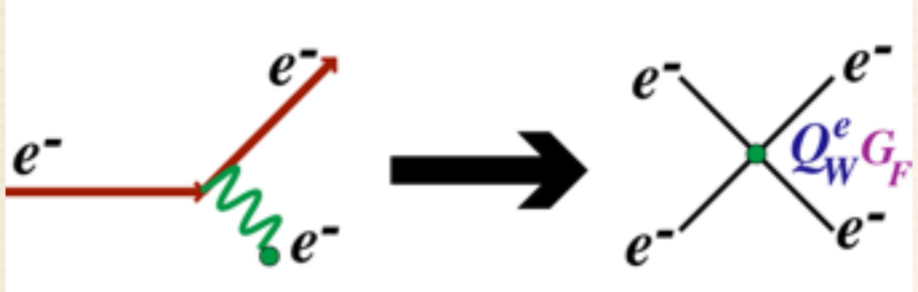

electron target:

$$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

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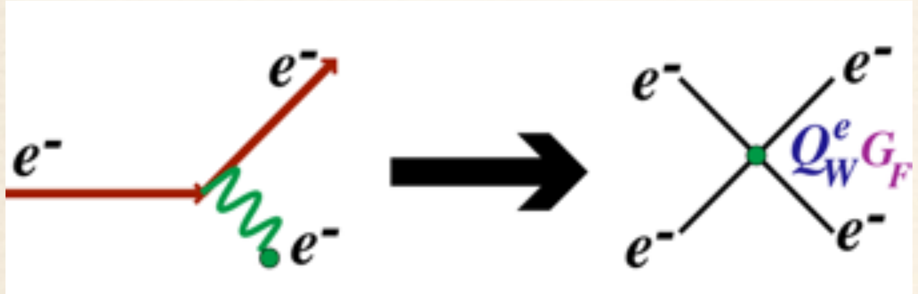

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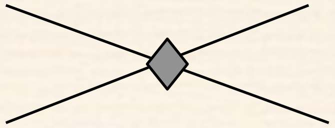

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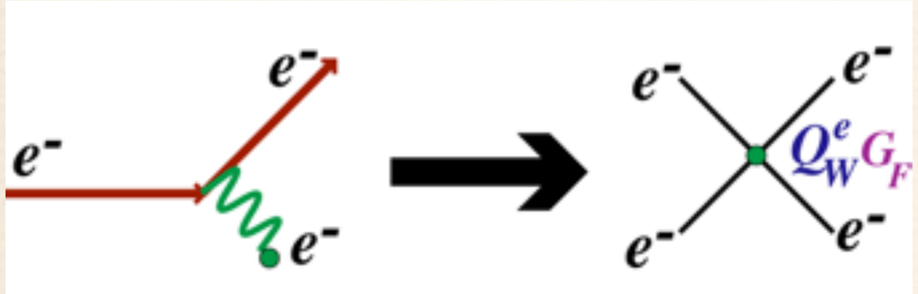

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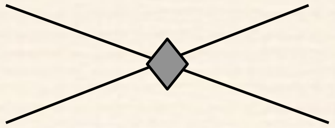

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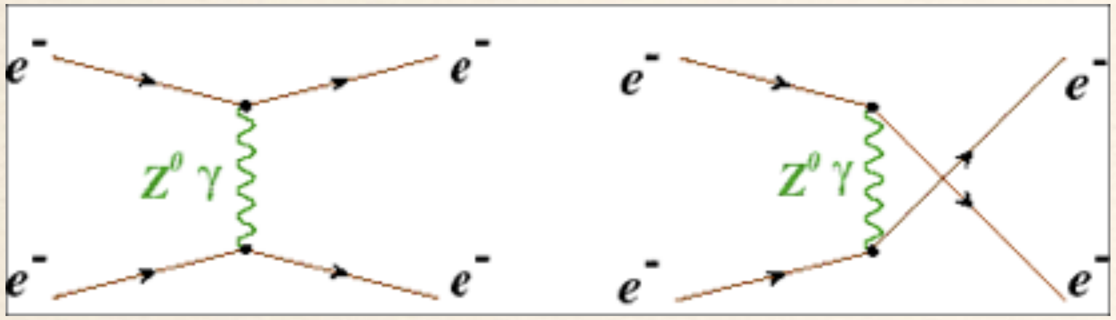
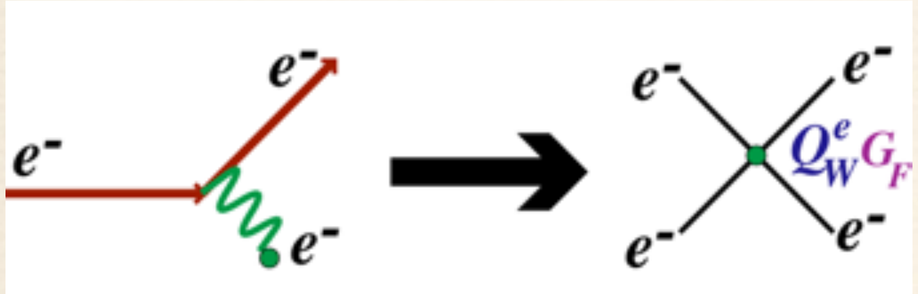


$$\left|\mathbf{A_\gamma + A_Z + A_{new}}\right|^2 \rightarrow \mathbf{A_\gamma^2}\left[\mathbf{1 + 2}\left(\frac{\mathbf{A_Z}}{\mathbf{A_\gamma}}\right) + \mathbf{2}\left(\frac{\mathbf{A_{new}}}{\mathbf{A_\gamma}}\right)\right]$$

SLAC E158: First Measurement of the Electron's Weak Charge

PV Electron-Electron Scattering



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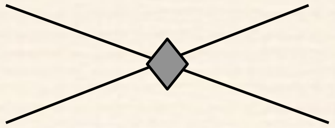

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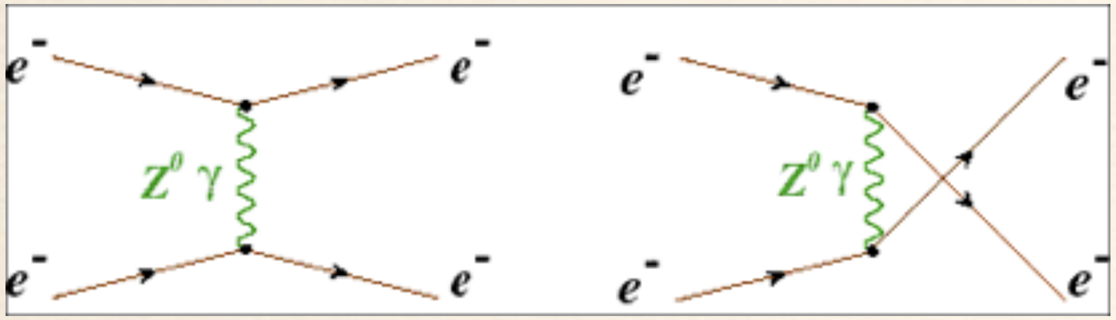


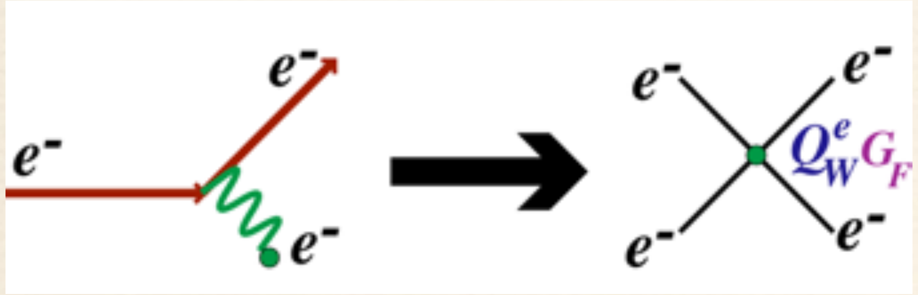
$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\rm new}\right|^2 \rightarrow \mathbf{A}_\gamma^2\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\rm new}}{\mathbf{A}_\gamma}\right)\right]$$

$$A_{PV} \approx 8\times 10^{-8} E_{beam}(1 - 4\sin^2\vartheta_W)$$

⇨ **Tiny!**

SLAC E158: First Measurement of the Electron's Weak Charge

PV Electron-Electron Scattering



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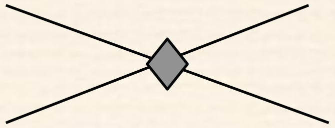

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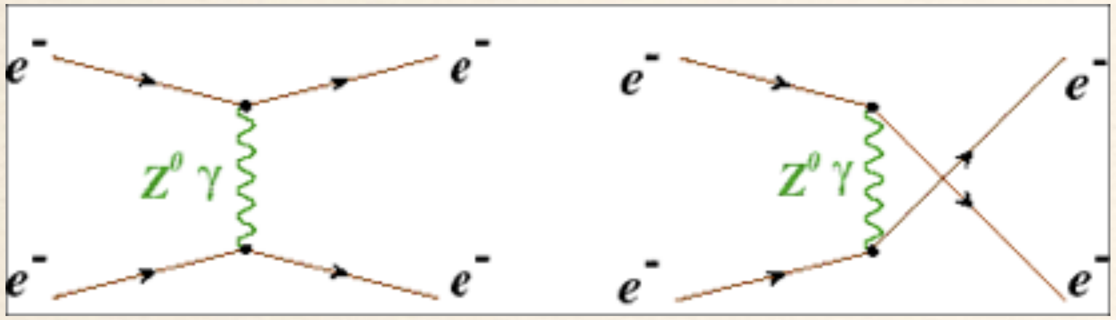

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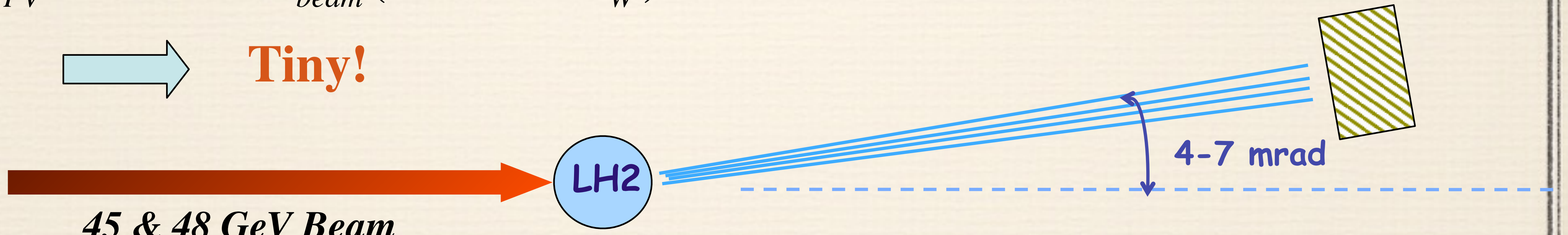


45 & 48 GeV Beam

85% longitudinal polarization

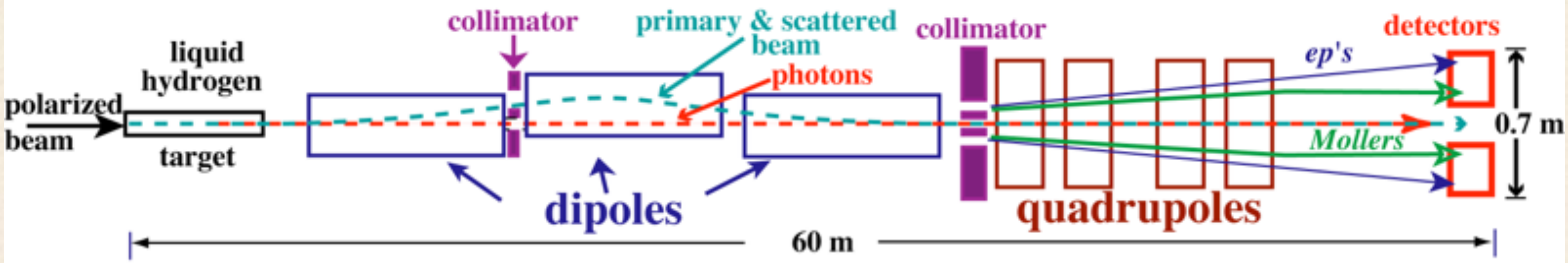
End Station A at SLAC

SLAC E158: 1997-2004

Goal: error small enough to probe TeV scale physics

SLAC E158

~ 10 ppb statistical error at highest E_{beam}, ~ 0.5% error on weak mixing angle



A large number of technical challenges

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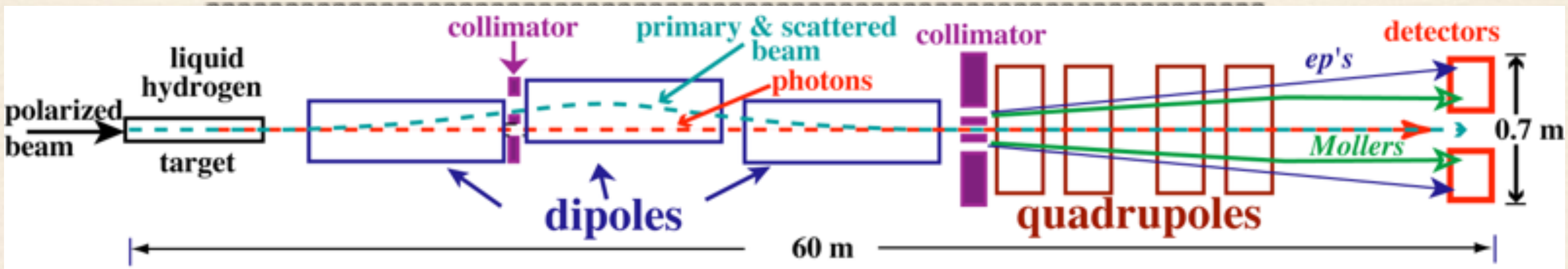

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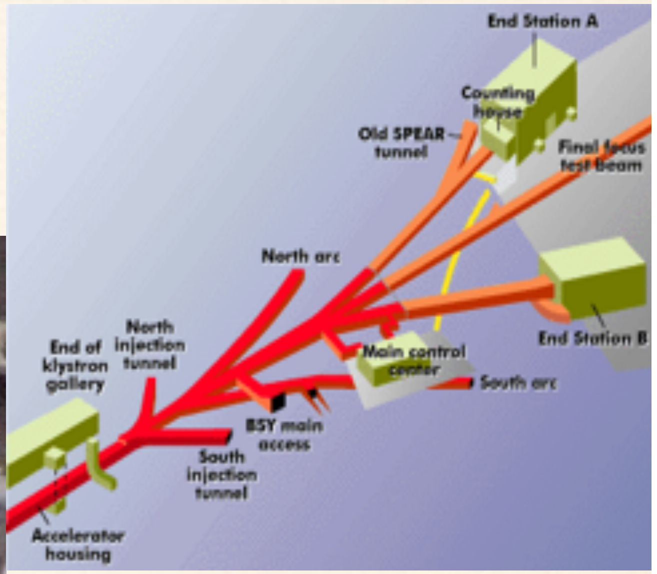

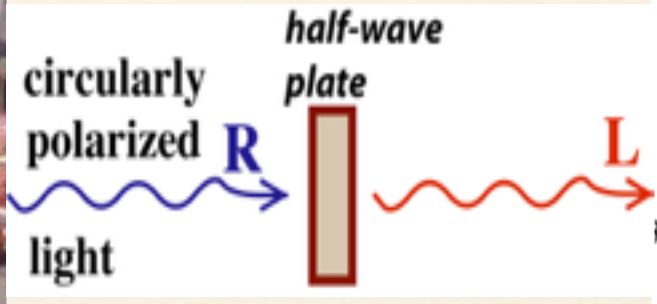

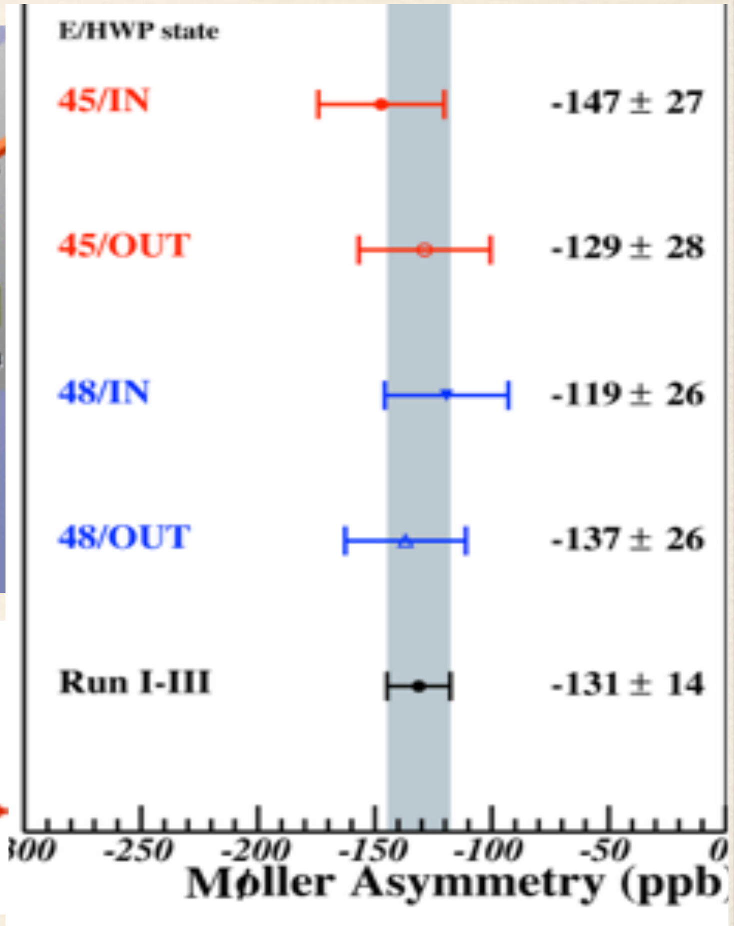

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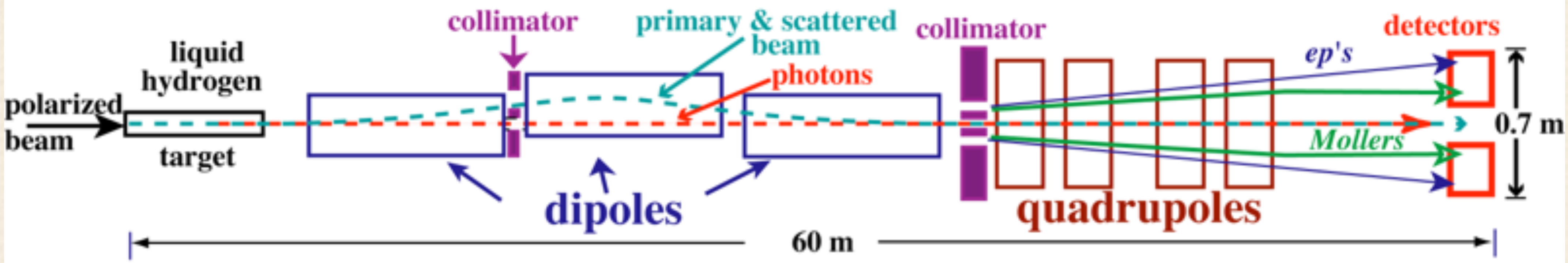

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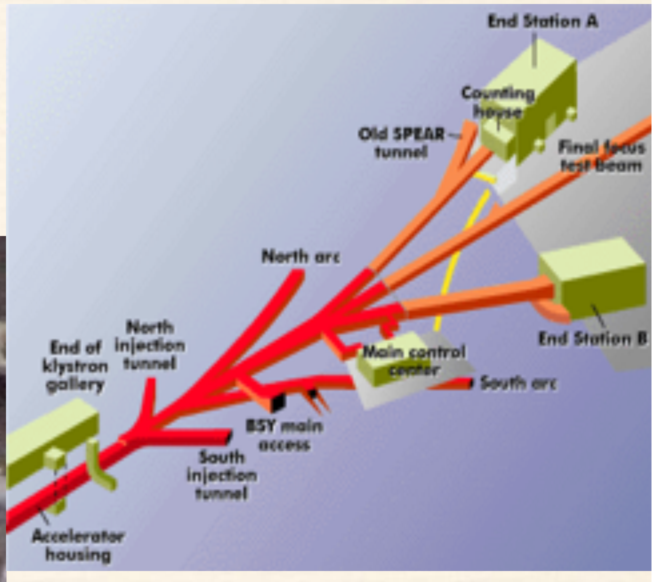

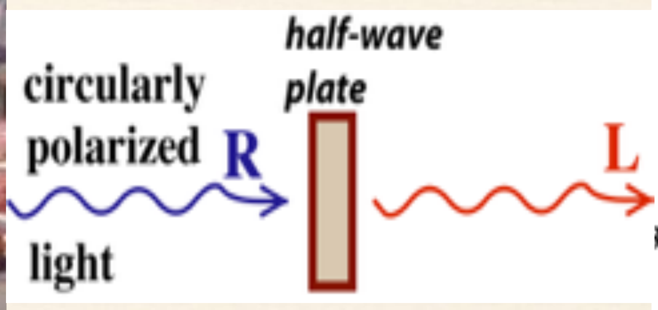

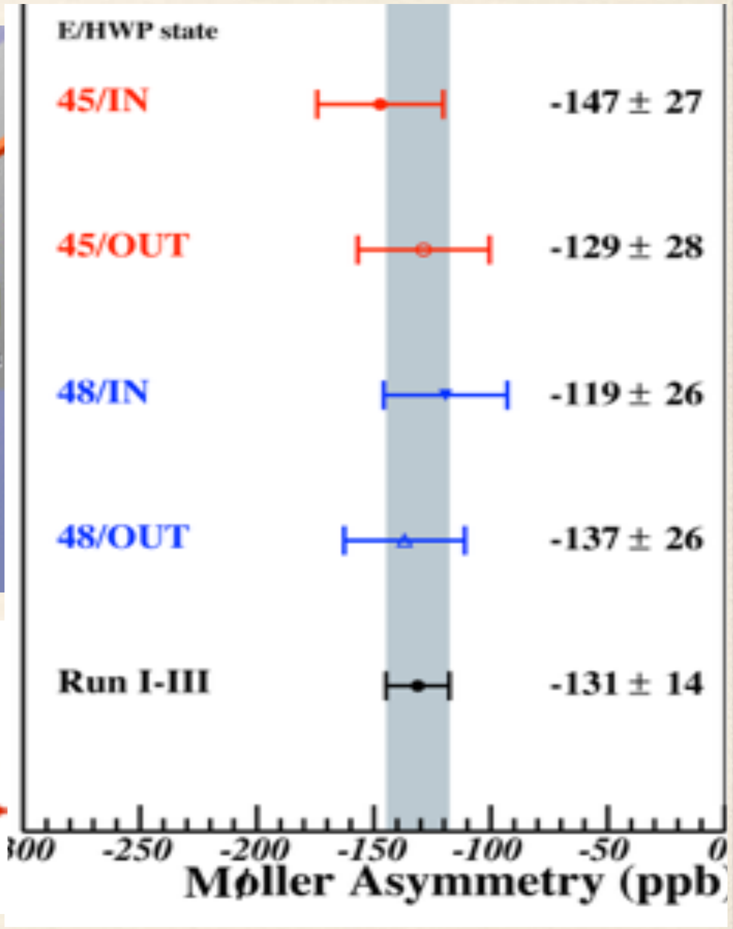

$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

Phys. Rev. Lett. **95** 081601 (2005)

Tree-level prediction: ~ 250 ppb

E158 Implications

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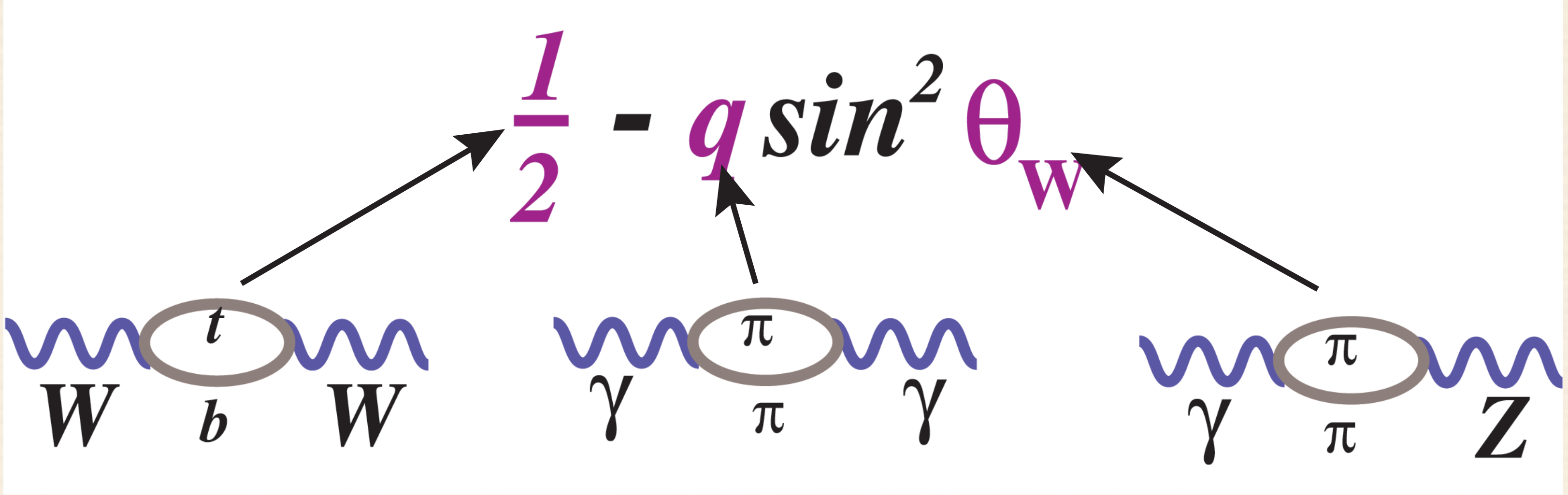

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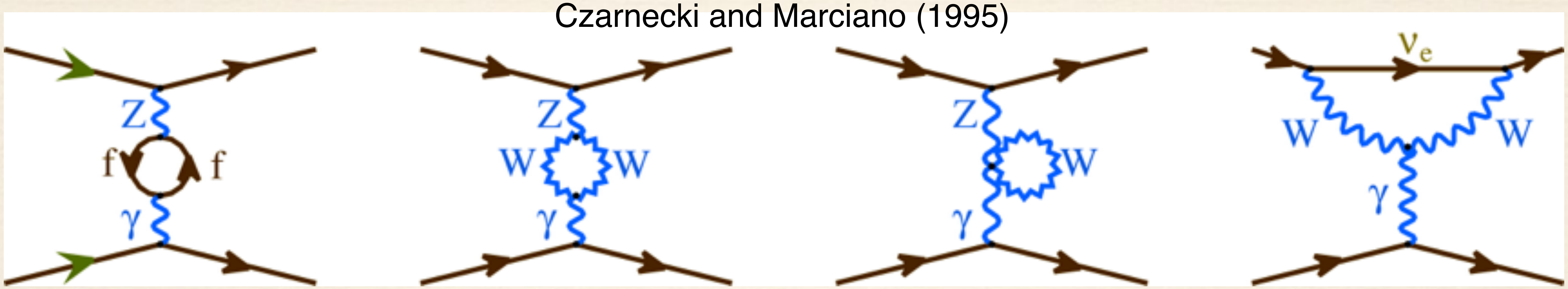

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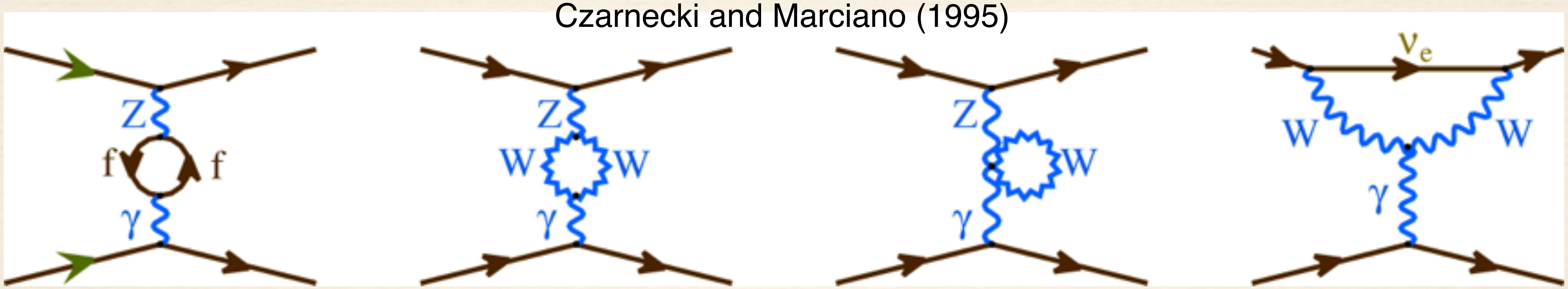

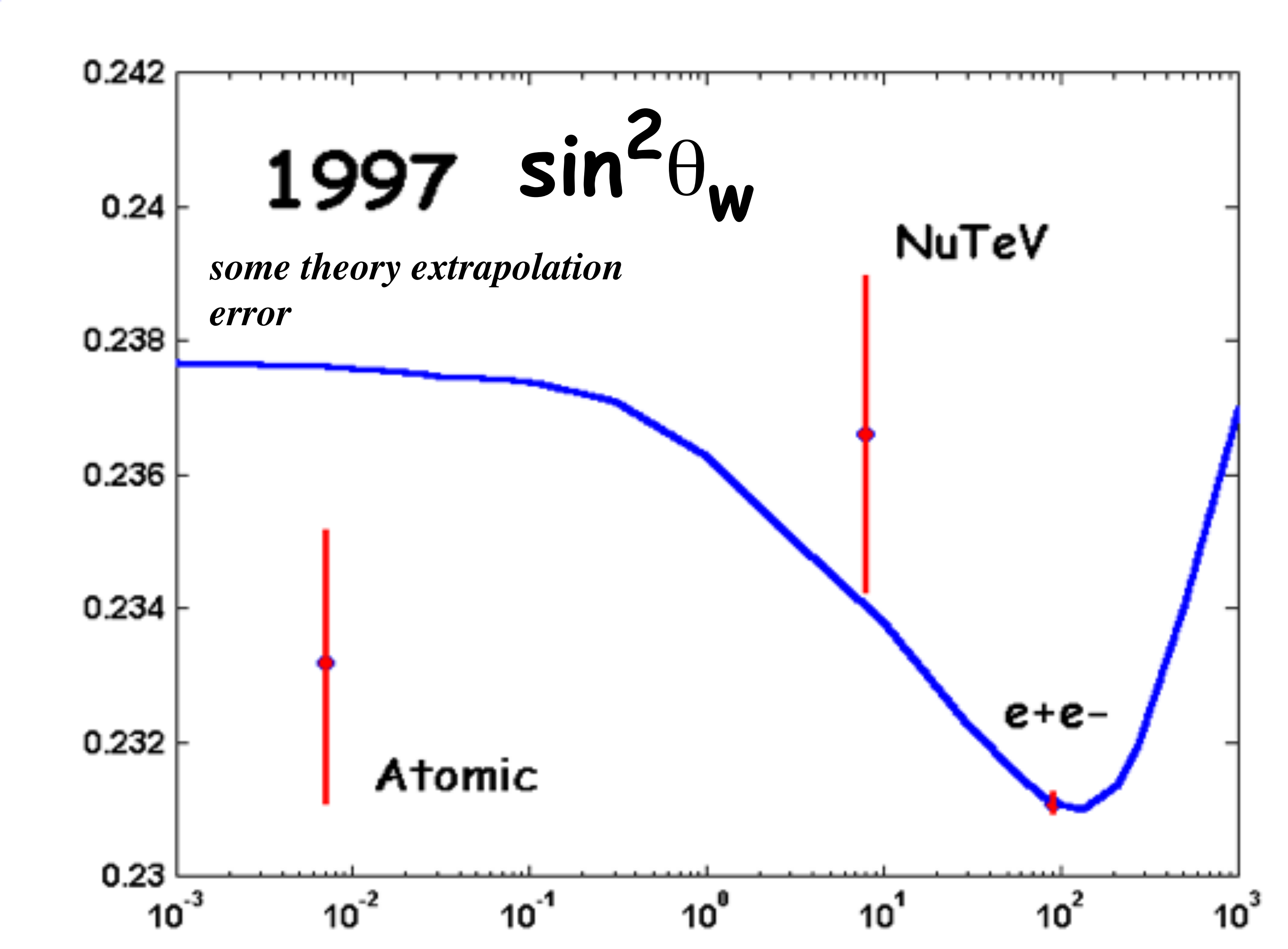

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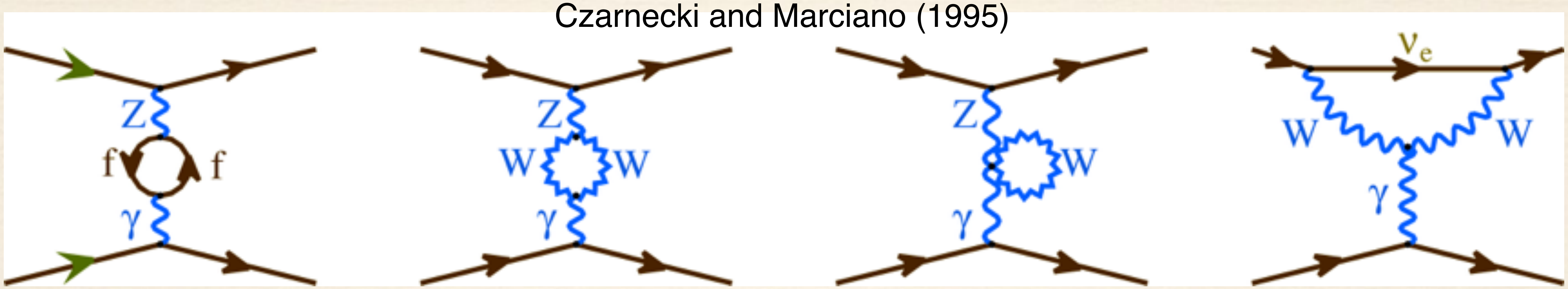
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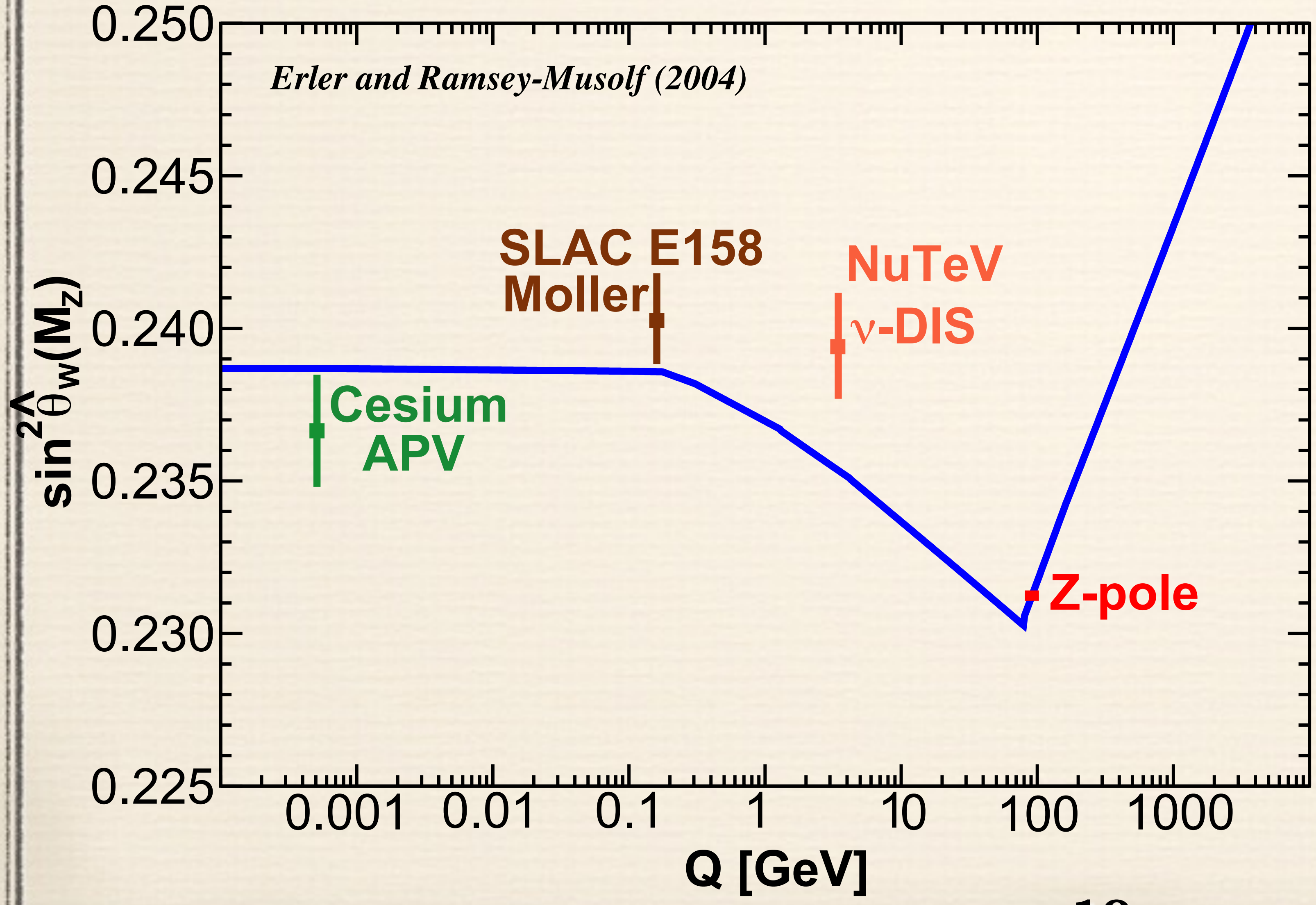

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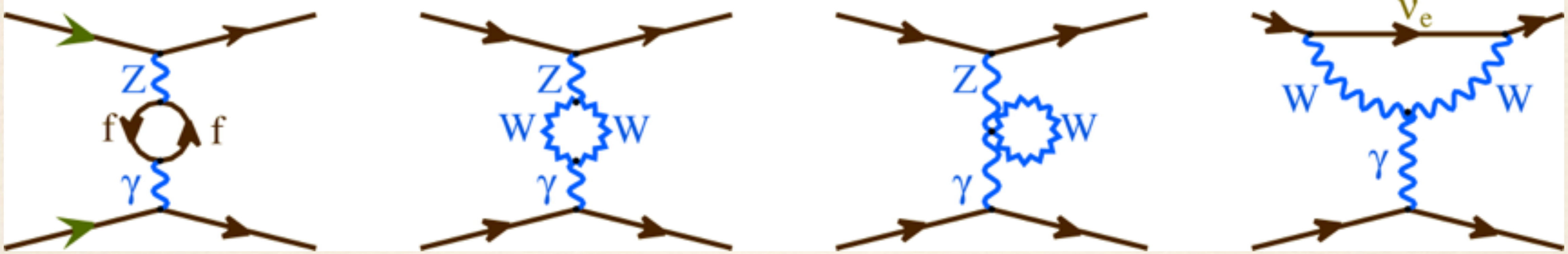
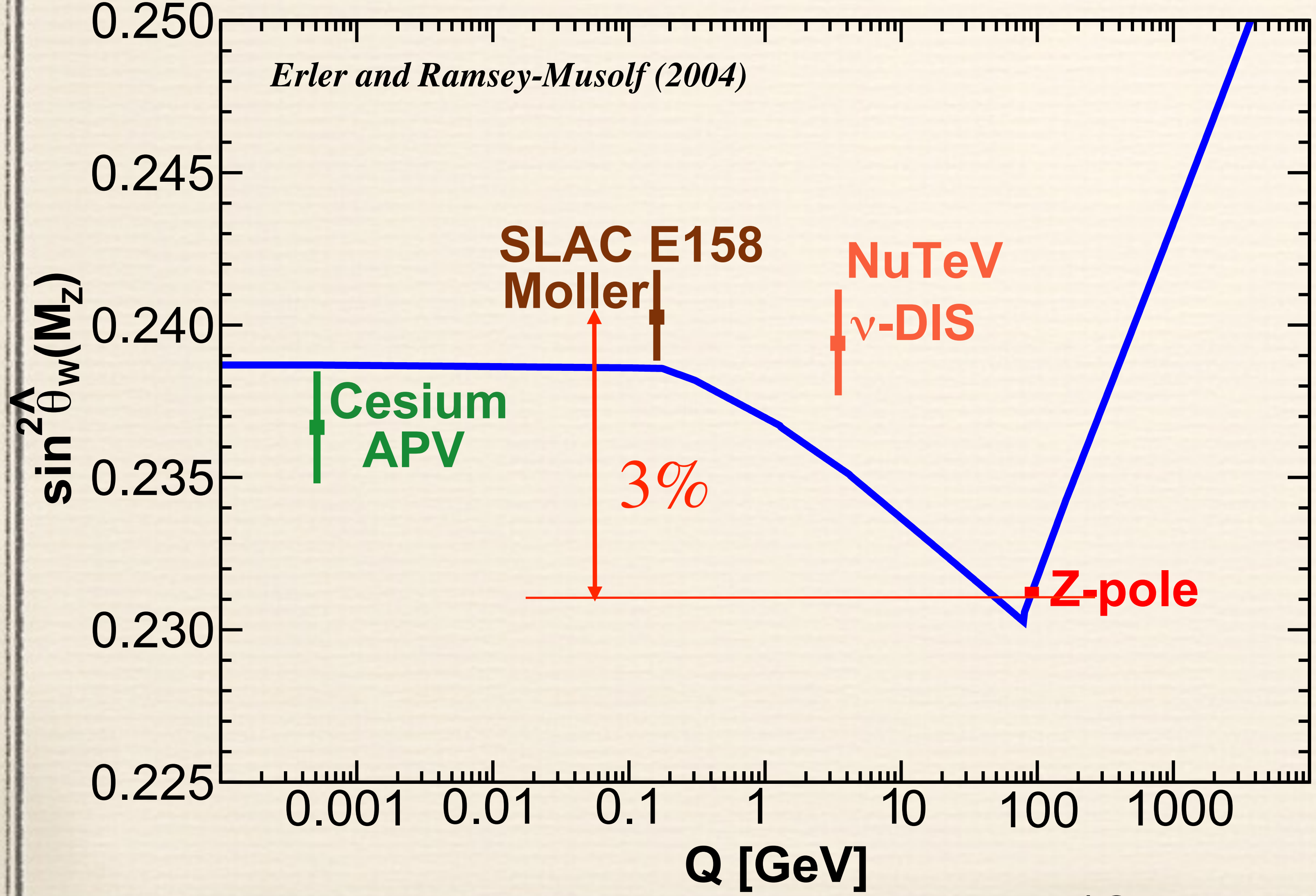




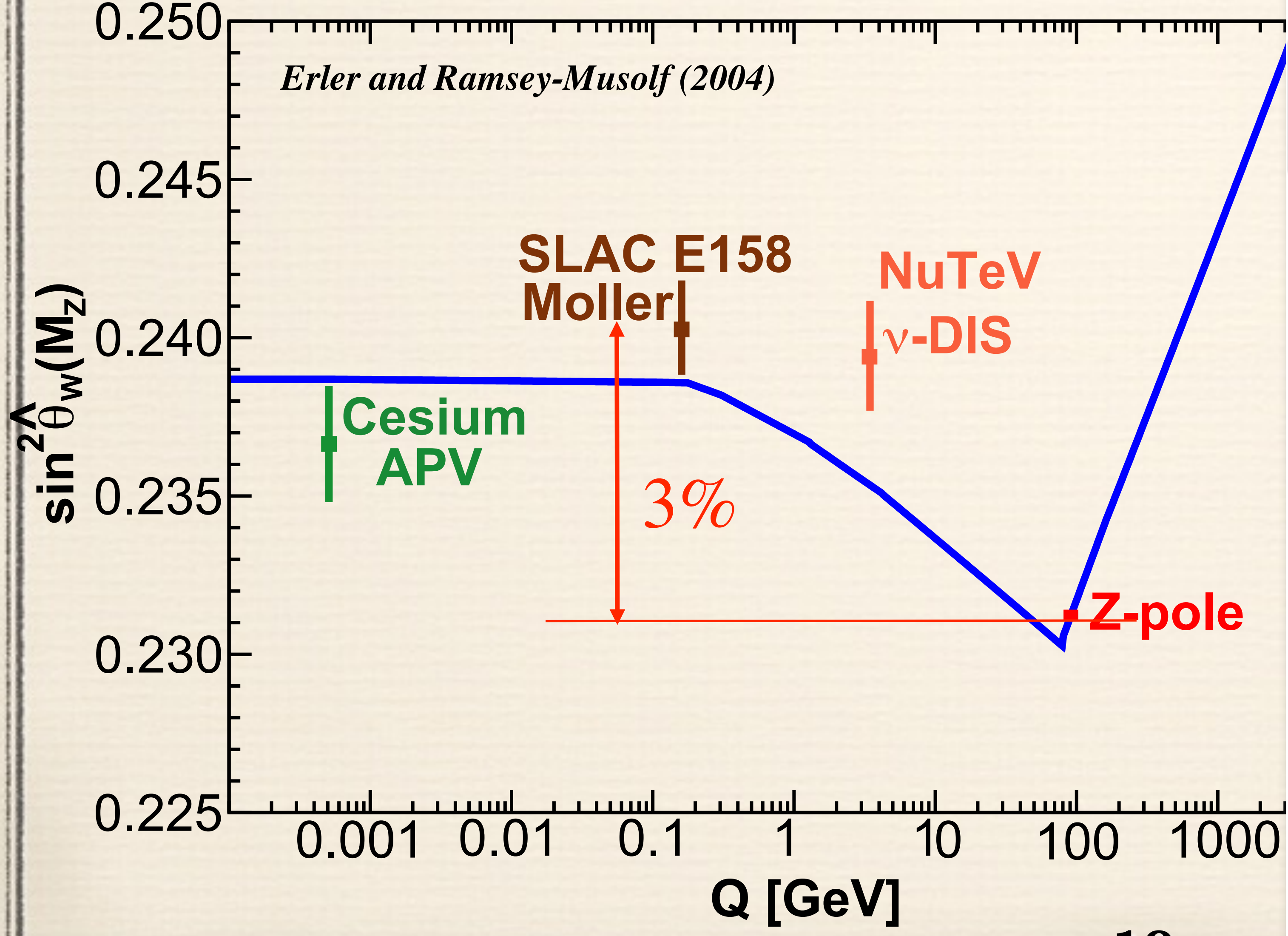
Tree-level prediction: ~ 250 ppb

A_{PV} = (-131 ± 14 ± 10) x 10^{-9}

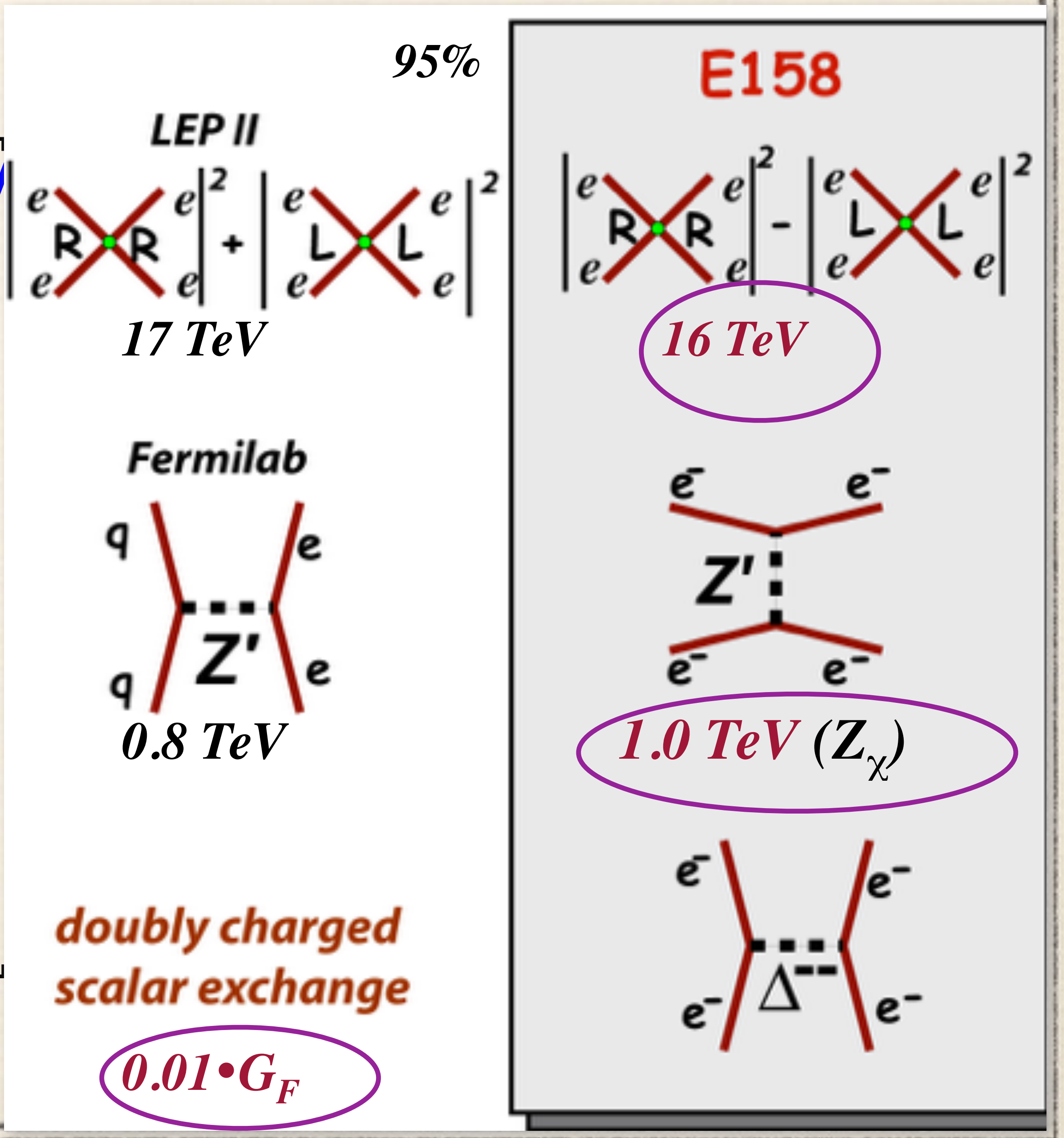
Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)



Limits on "New" Physics



$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

Nature
Vol 435 26 May 2005
NEWS AND VIEWS

E158 Implications

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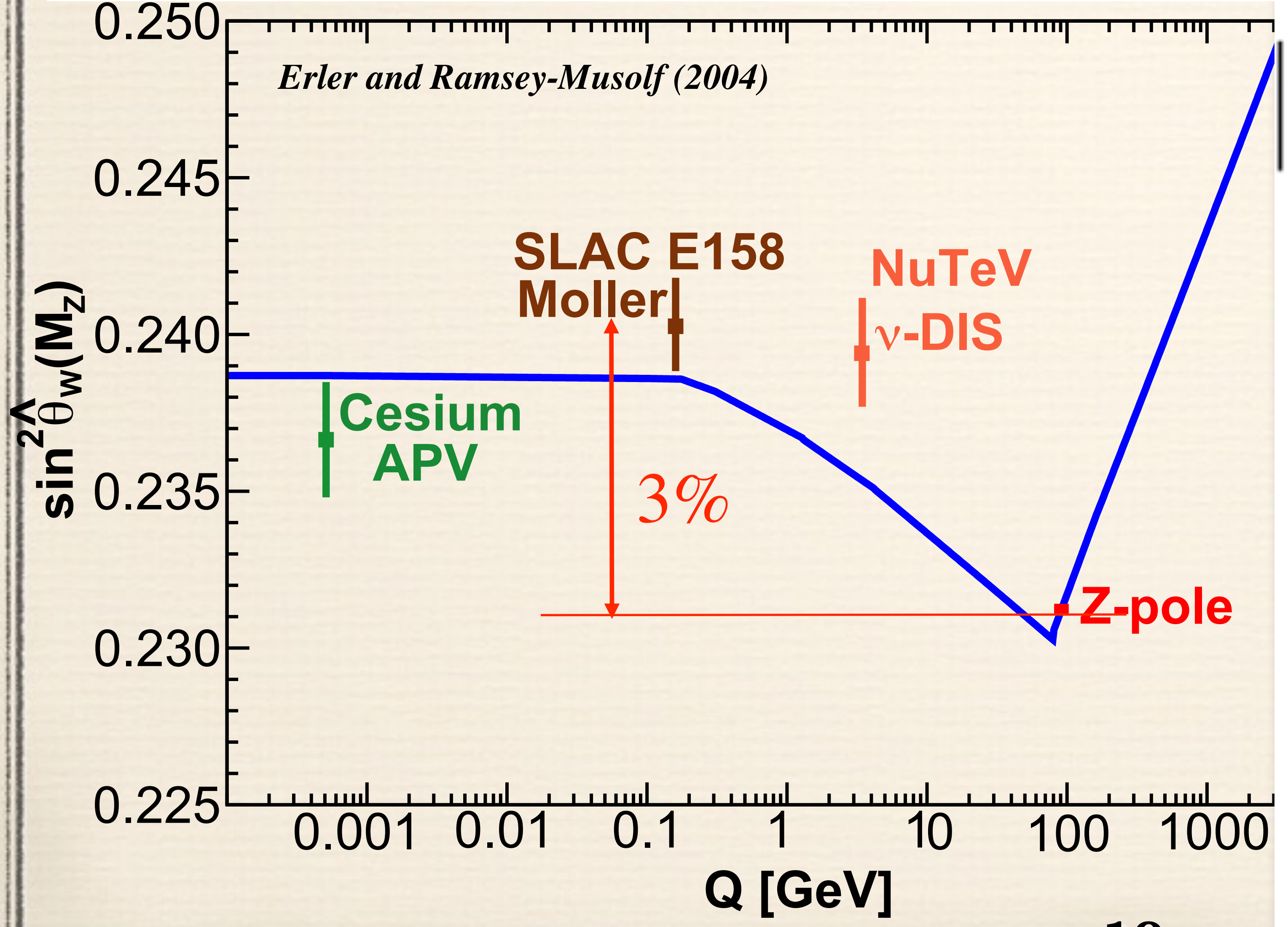

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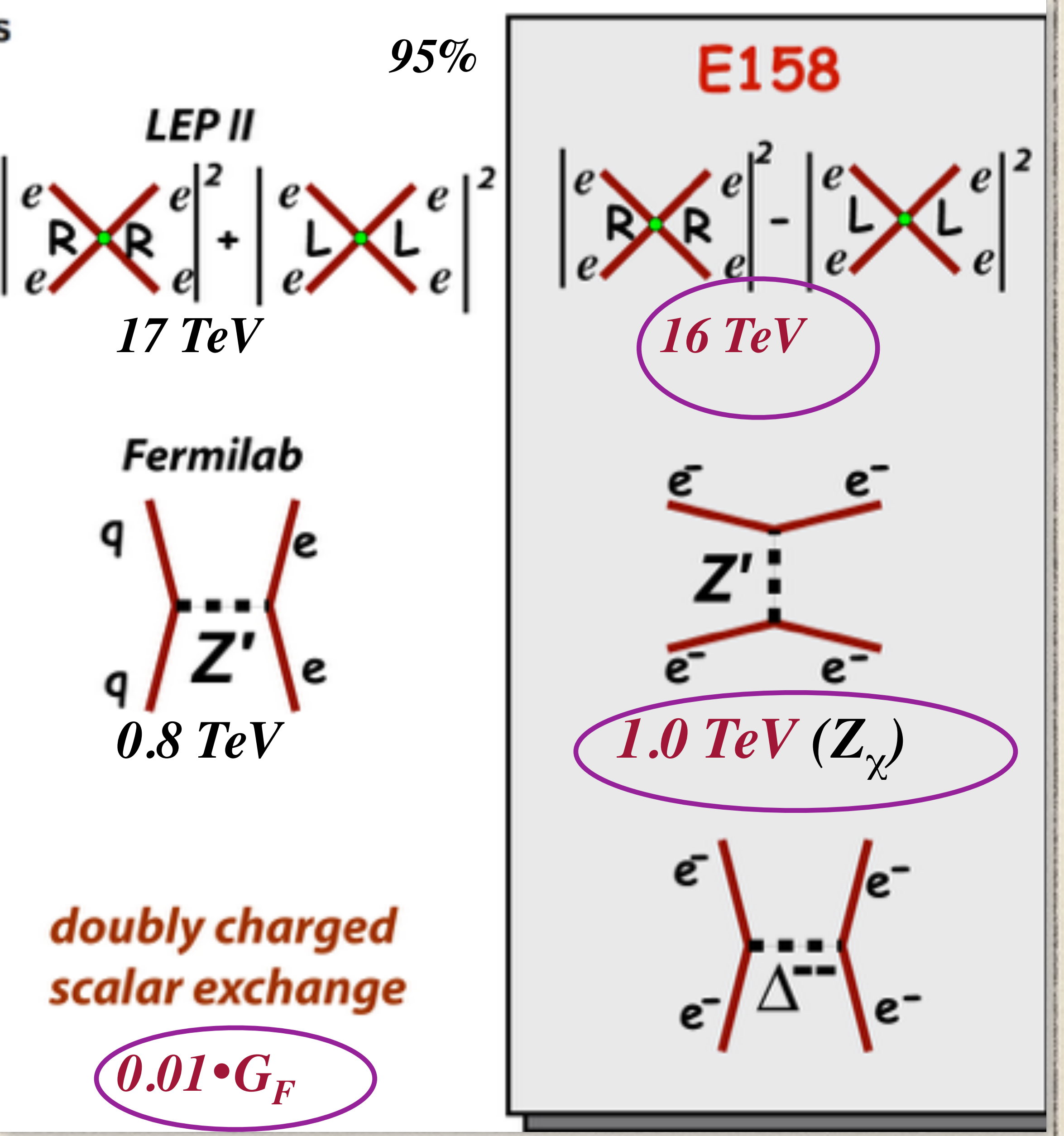

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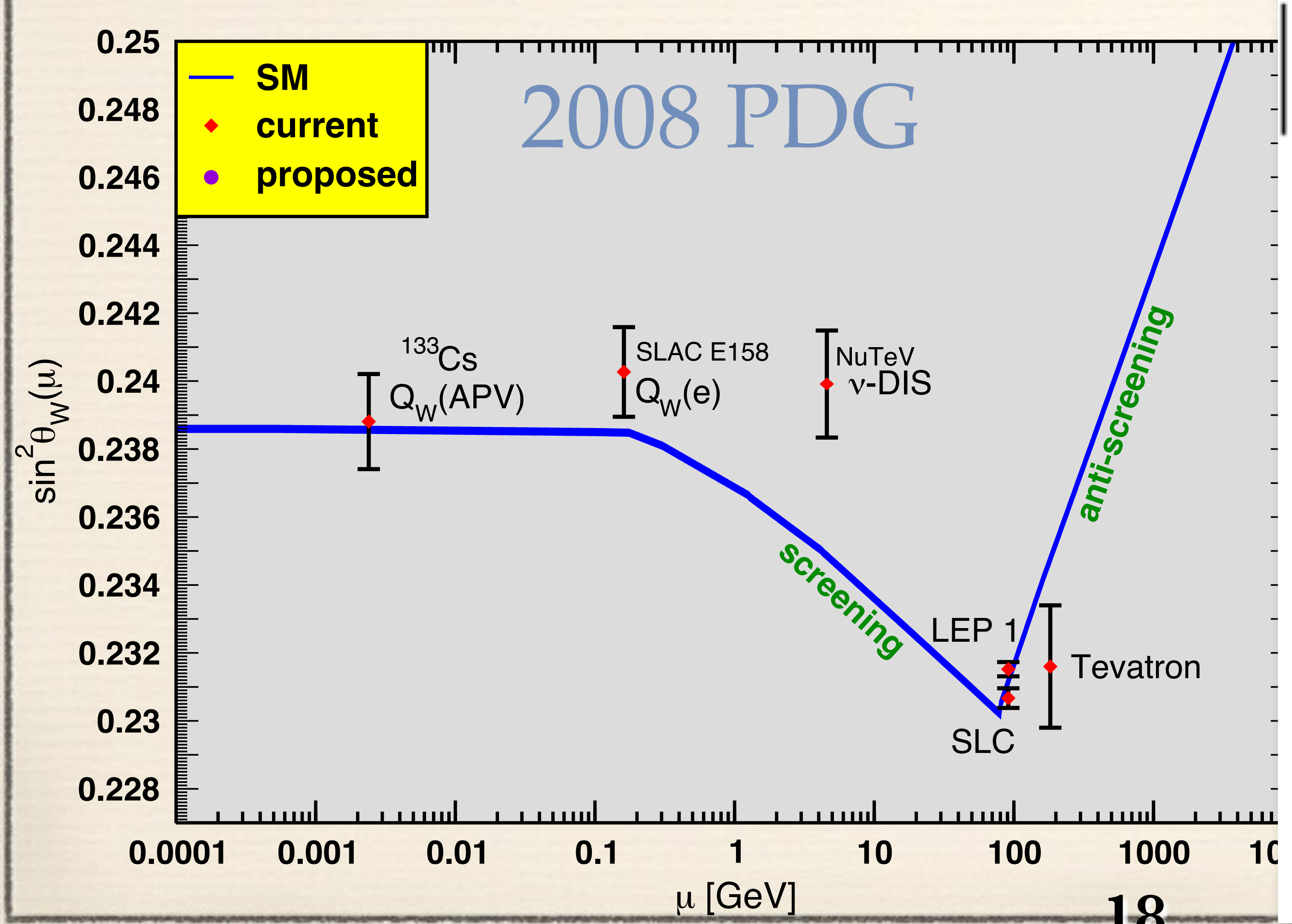

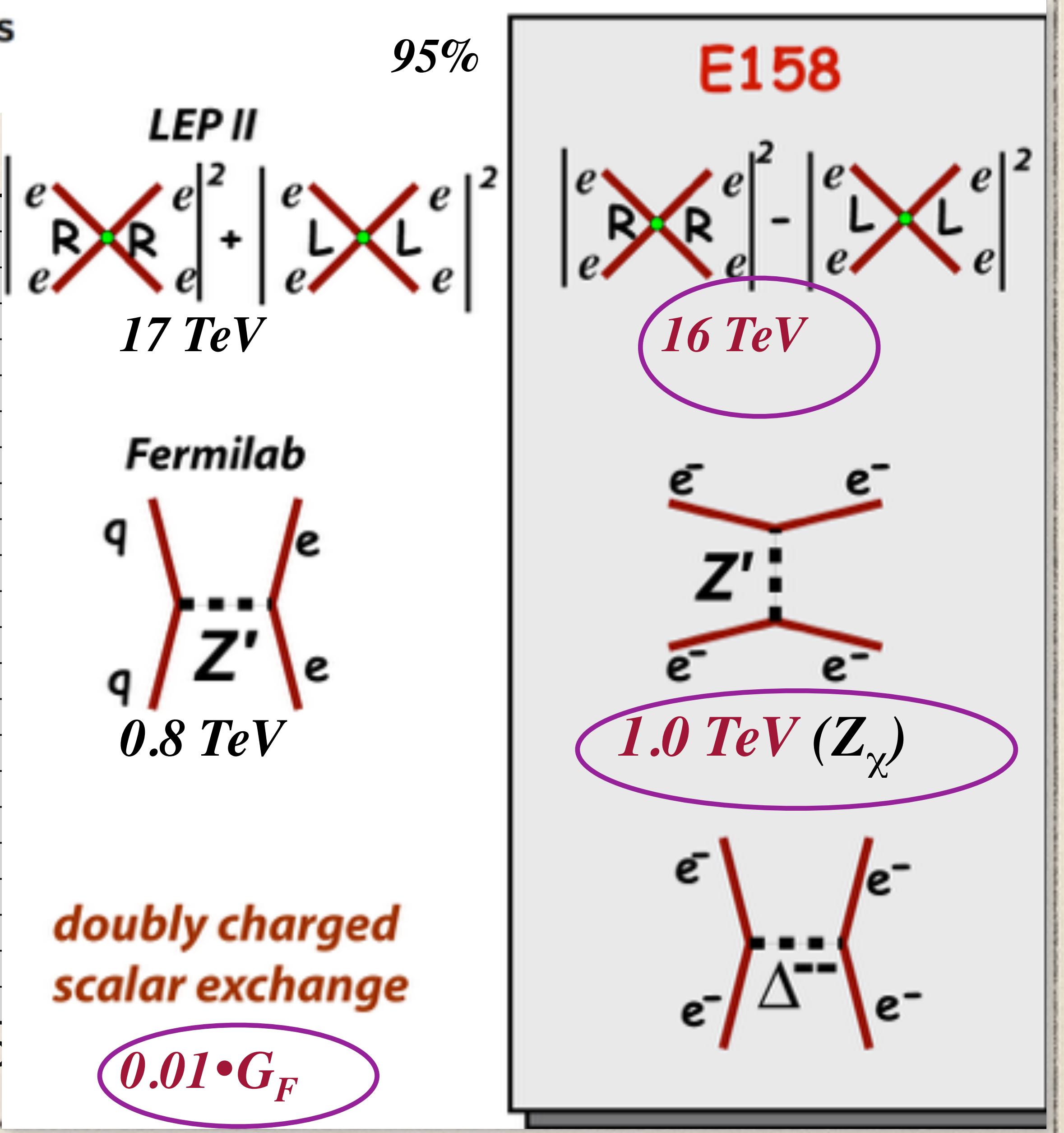

95%

LEP II

17 TeV

Fermilab

0.8 TeV

doubly charged scalar exchange

$0.01 \bullet G_F$

E158

16 TeV

1.0 TeV (Z_χ)

A_{PV} = $(-131 \pm 14 \pm 10) \times 10^{-9}$

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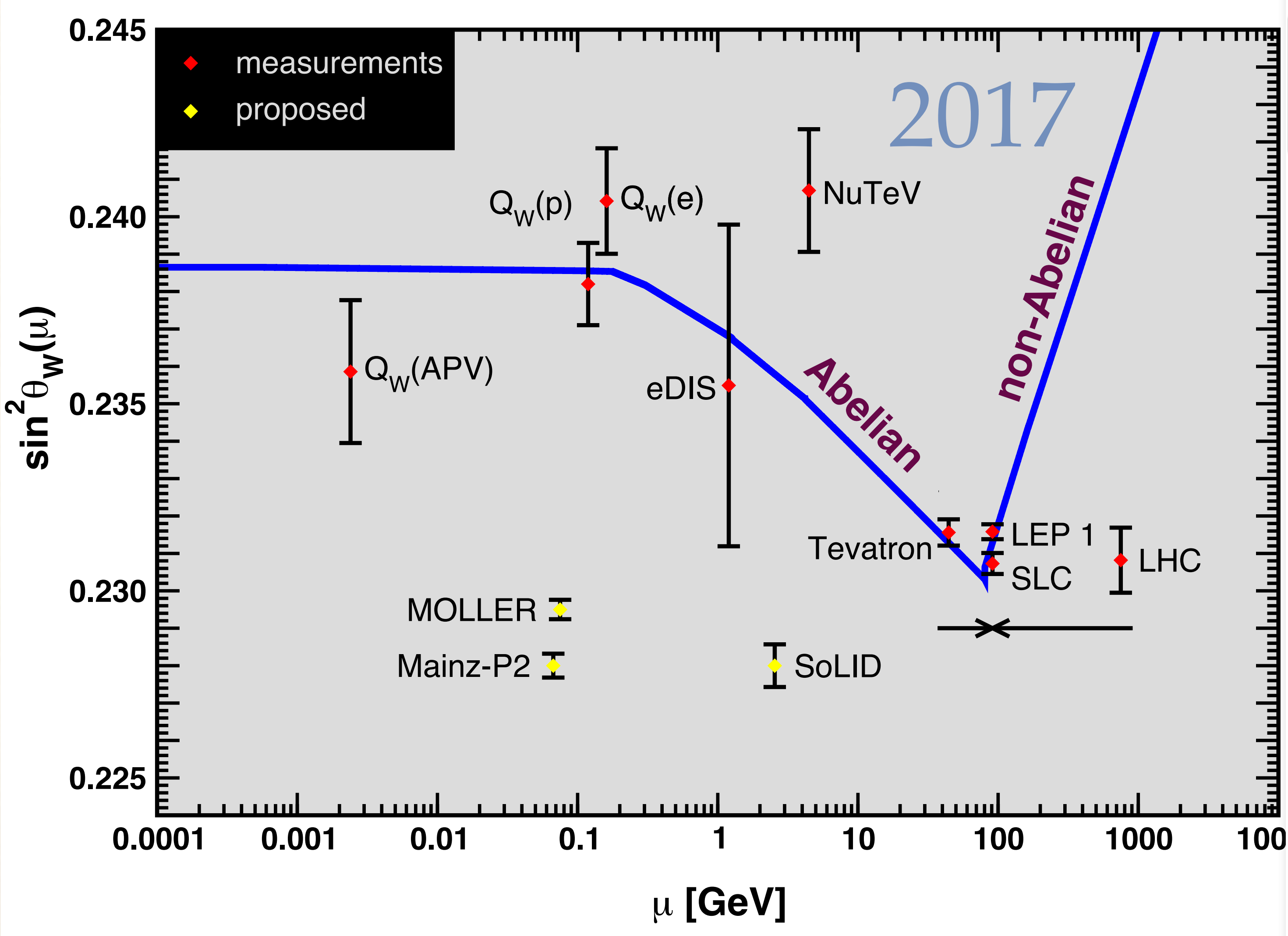

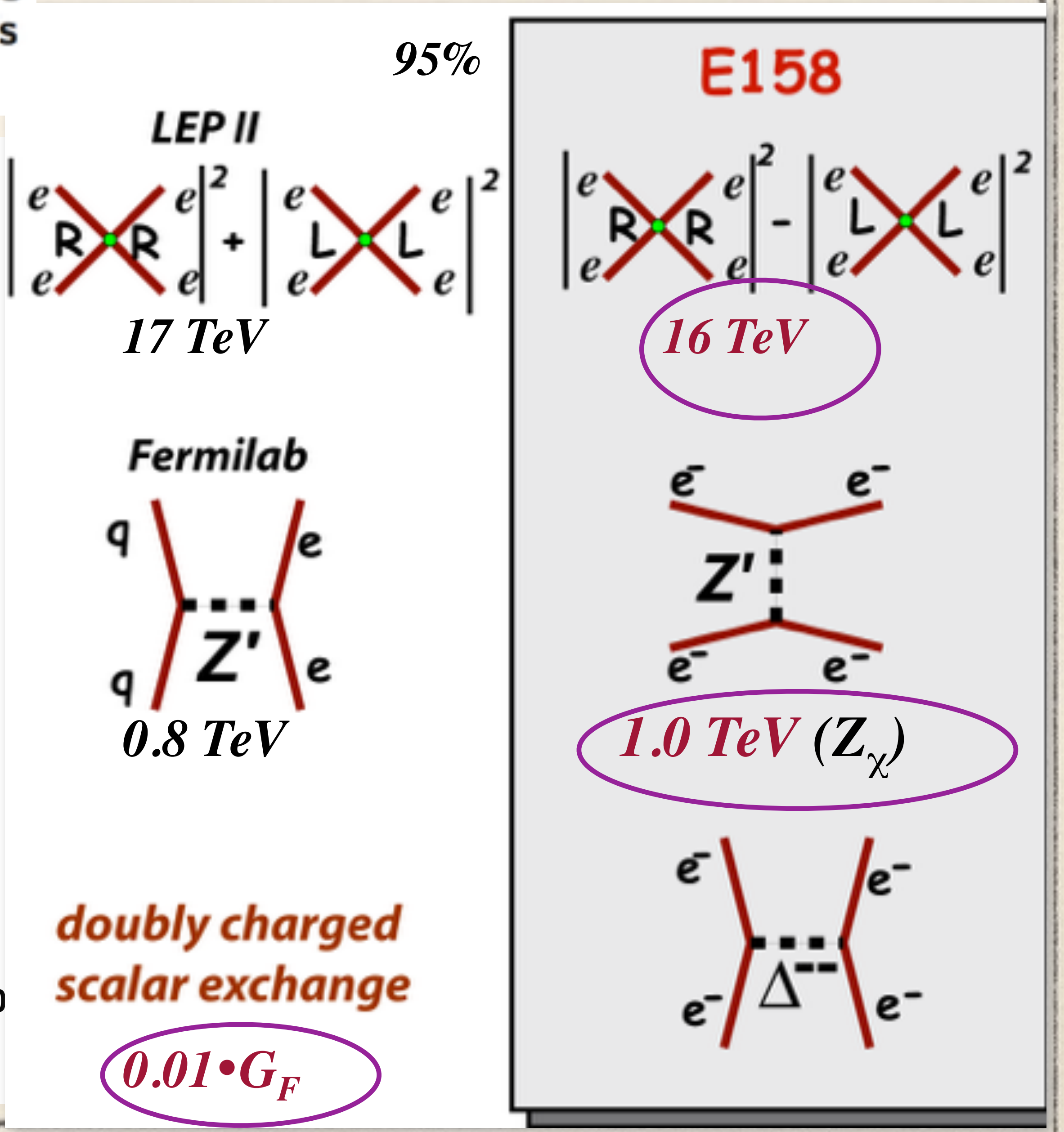

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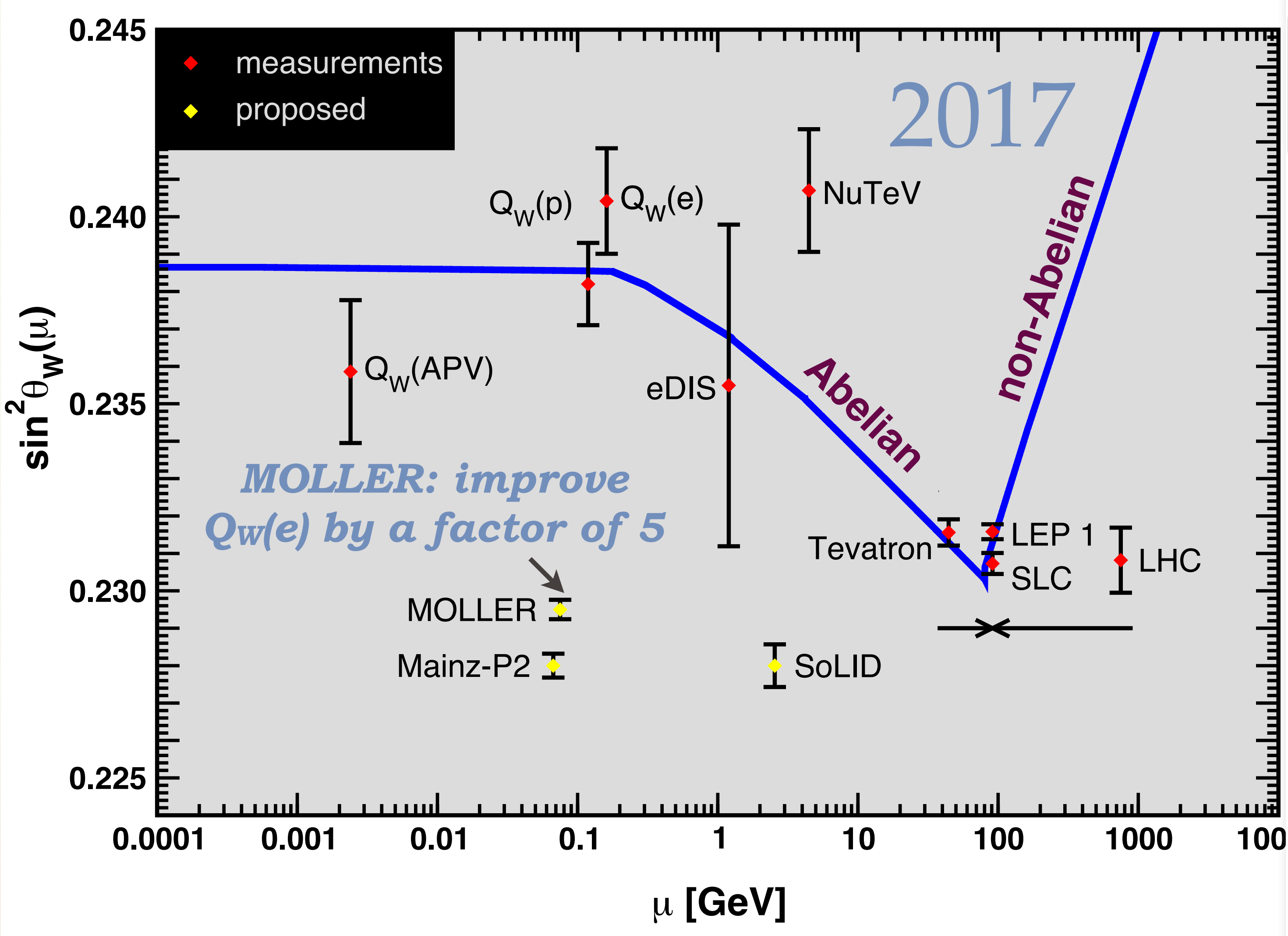
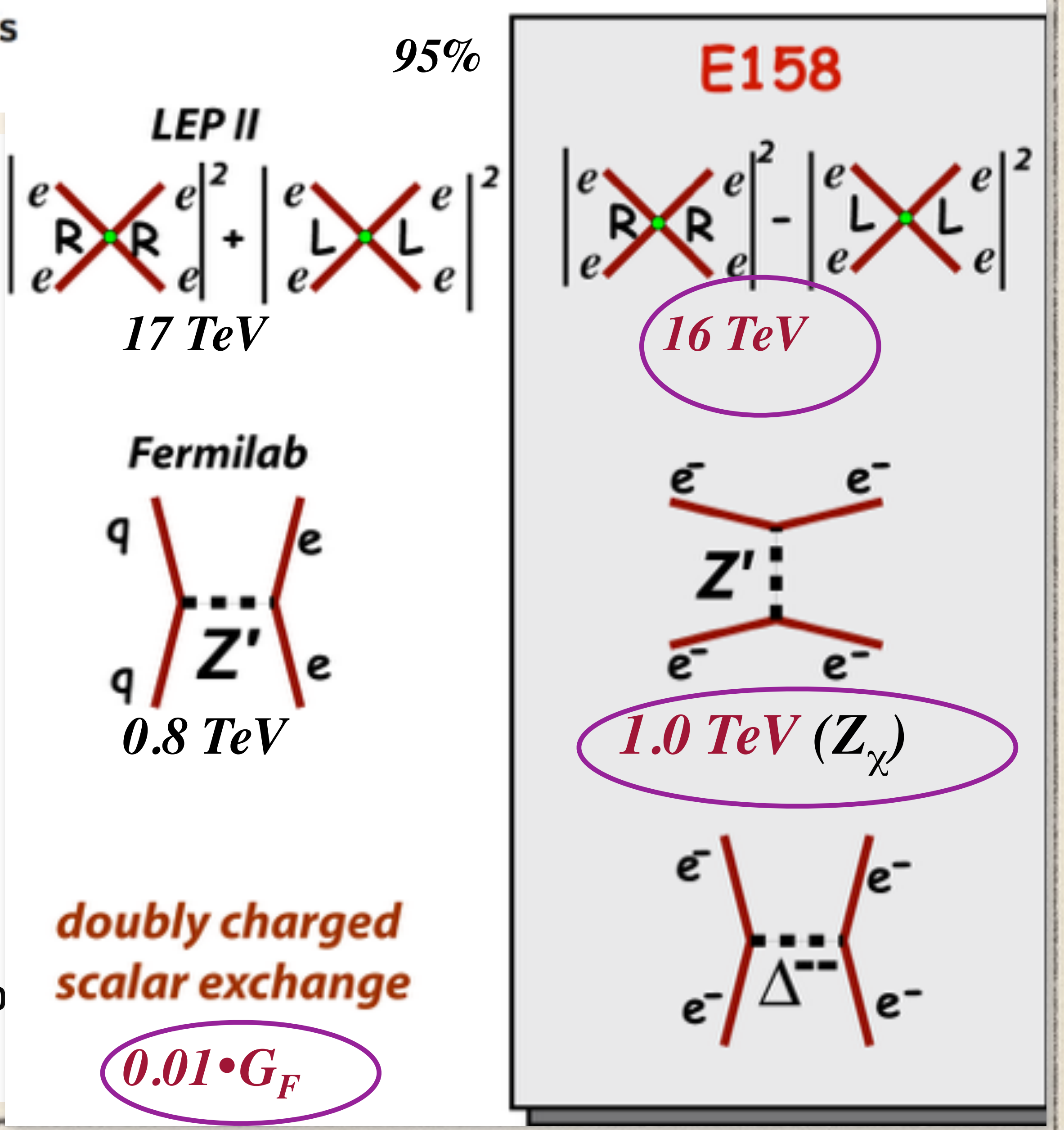


MOLLER: improve Qw(e) by a factor of 5

Limits on "New" Physics



17 TeV

0.8 TeV

16 TeV

1.0 TeV (Z_χ)

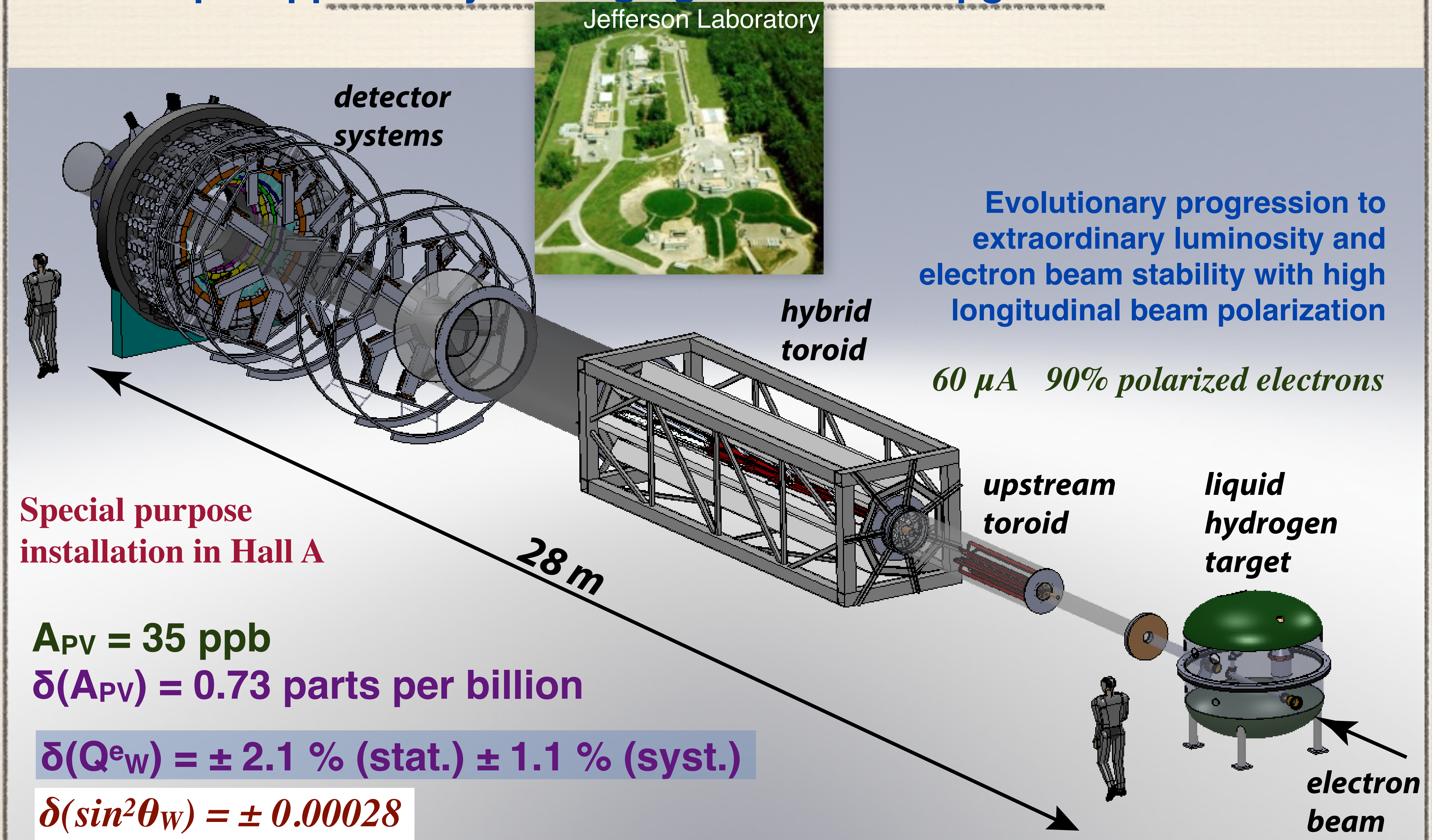
doubly charged scalar exchange

$0.01 \bullet G_F$

Parity-Violating Fixed Target 11 GeV electron-electron (Møller) scattering

MOLLER at JLab

Unique opportunity leveraging the 12 GeV Upgrade investment



Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

60 µA 90% polarized electrons

Special purpose installation in Hall A

$A_{PV} = 35$ ppb

$\delta(A_{PV}) = 0.73$ parts per billion

$\delta(Q^e_W) = \pm 2.1\ \%\ (\text{stat.}) \pm 1.1\ \%\ (\text{syst.})$

$\delta(\sin^2\theta_W) = \pm 0.00028$

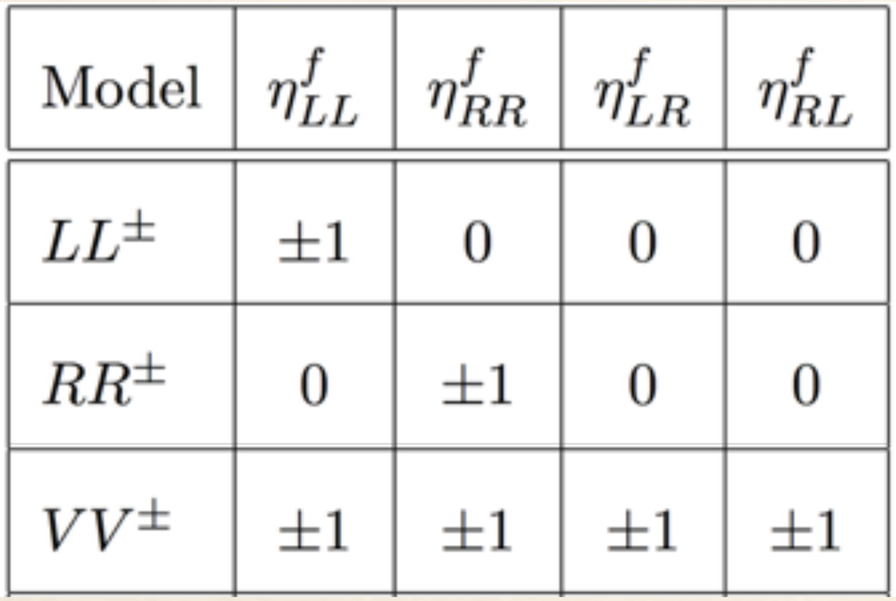
95% C. L. Reach

Comparison with e^+e^- Collisions

Best reach on purely leptonic contact interaction amplitudes: LEP200

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i\bar{e}_j\gamma^\mu e_j$$

$$g_{ij} = 4\pi\eta_{ij}$$



Model	η^f_{LL}	η^f_{RR}	η^f_{LR}	η^f_{RL}
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$VV^\pm$	±1	±1	±1	±1

LEP200 Reach $\Lambda^{ee}_{LL} \sim 8.3$ TeV

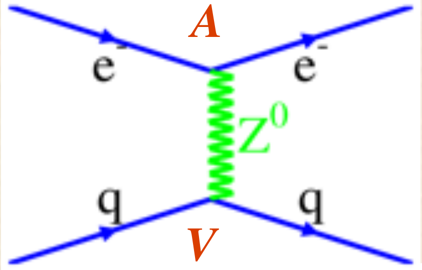
E158 Reach $\Lambda^{ee}_{LL} \sim 12$ TeV

MOLLER Reach $\Lambda^{ee}_{LL} \sim 27$ TeV

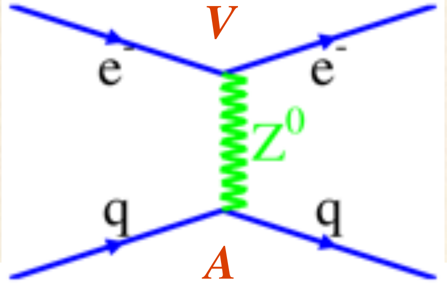
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

Awaiting green light from DOE to start construction ~ 2020-23

Semi-Leptonic Weak Neutral Current Interactions



$C_{1i} \equiv 2g_A^e g_V^i$



$C_{2i} \equiv 2g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$

$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

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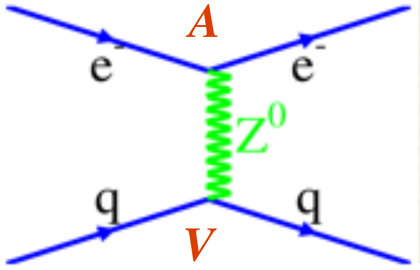

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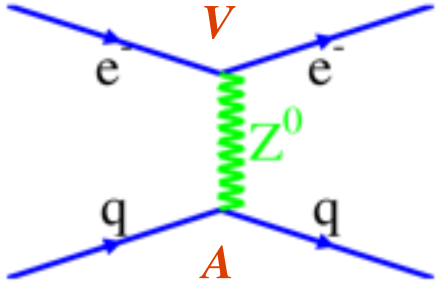

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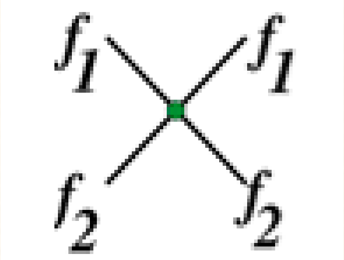
$$\begin{array}{llrcr} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04 \end{array}$$

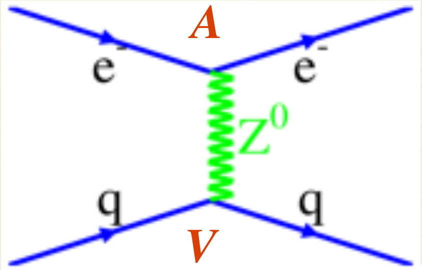
+

new physics

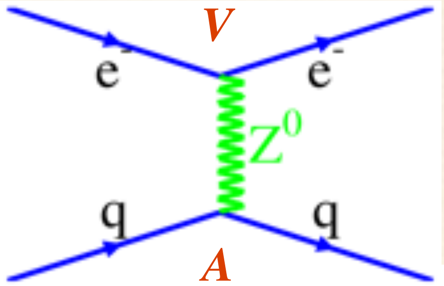


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Semi-Leptonic Weak Neutral Current Interactions



$C_{1i} \equiv 2 g_A^e g_V^i$



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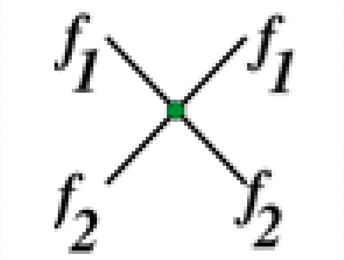

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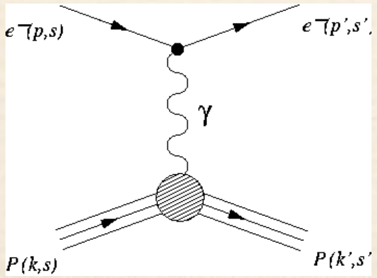
$$C_{1q} \propto (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2$$

PV elastic e-N scattering, Atomic parity violation



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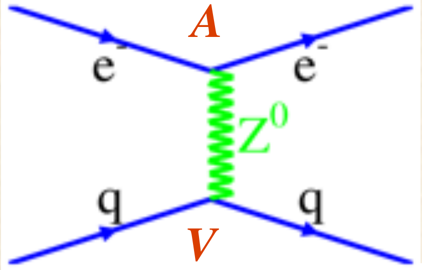

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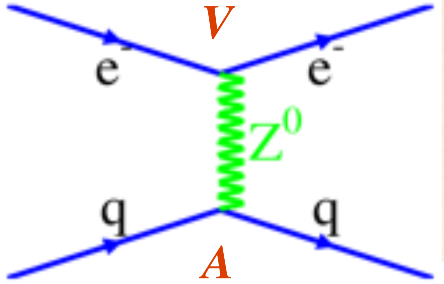

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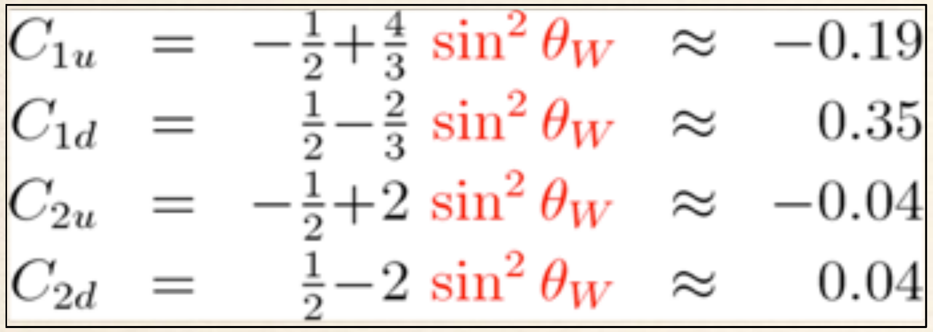

C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
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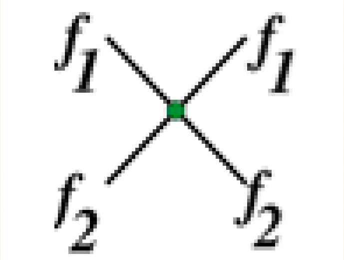
+

new physics



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$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

⇒ ***PV elastic e-N scattering, Atomic parity violation***

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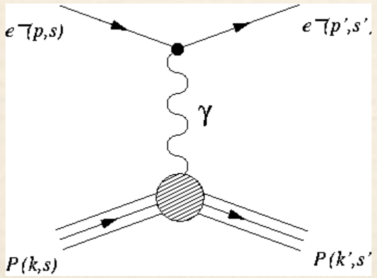
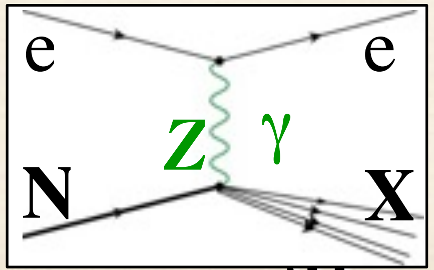
⇒ ***PV deep inelastic scattering***





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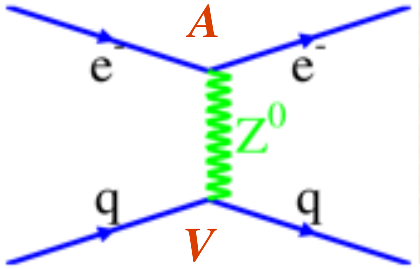

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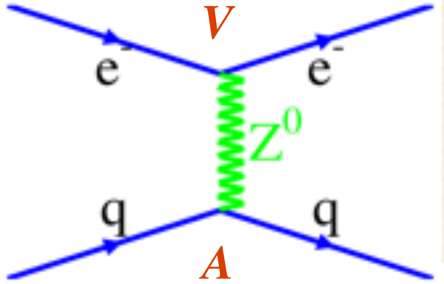

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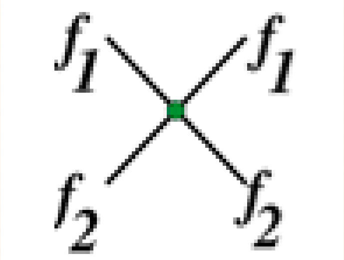
+

new physics



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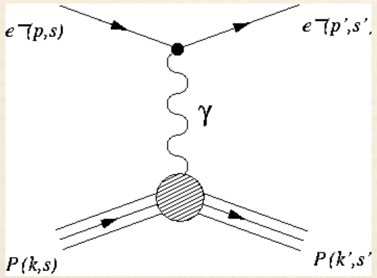
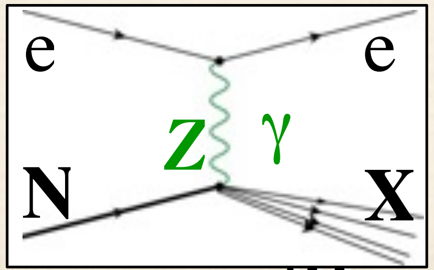
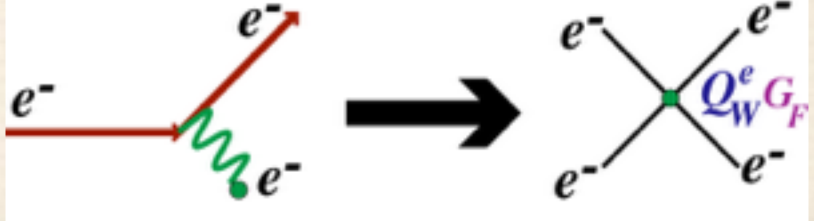
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇨ *PV Møller scattering*

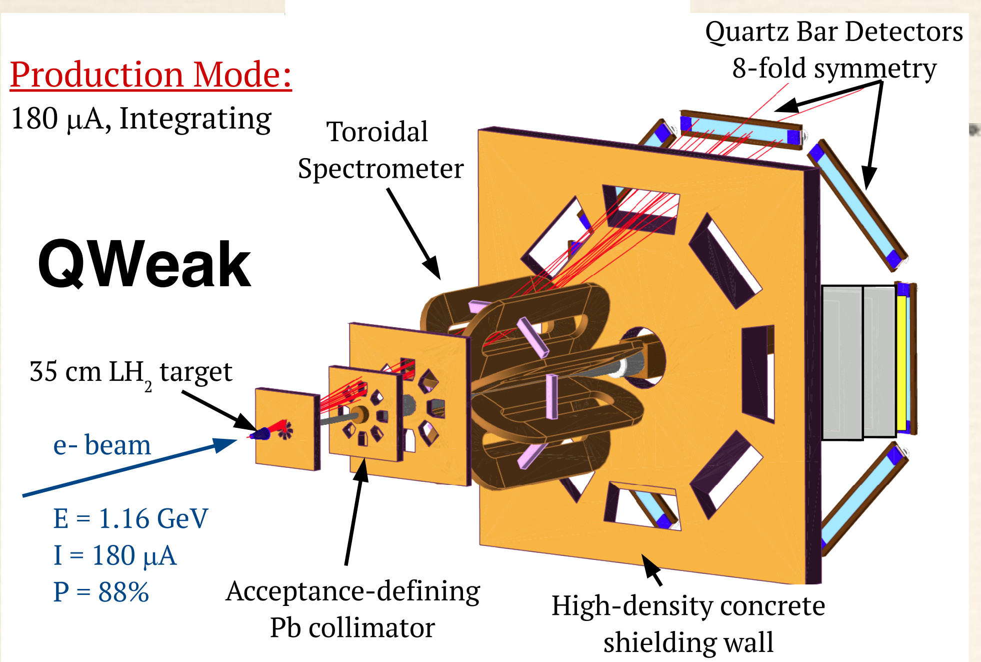




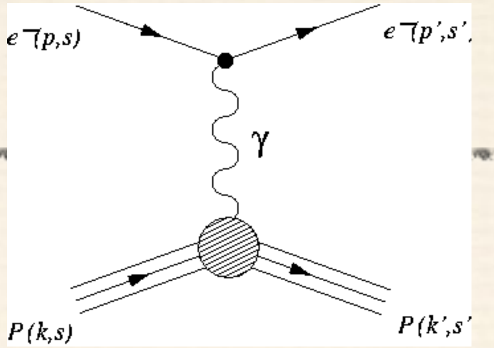
$Q_W = 1 - 4\sin^2\theta_W$



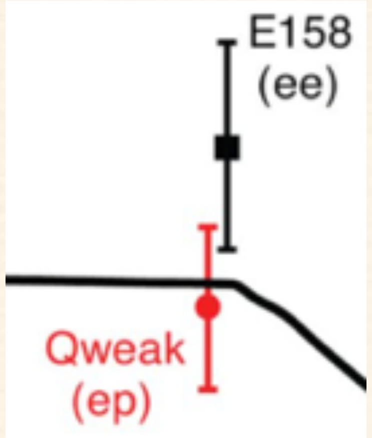
Recent Past and Future

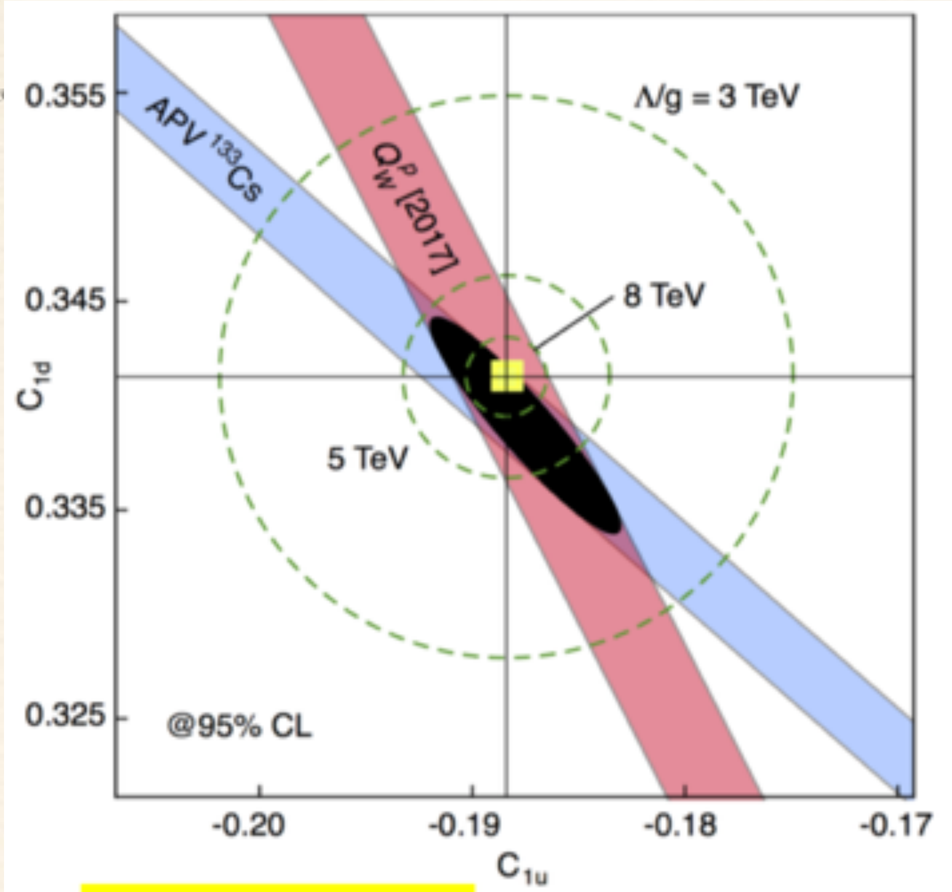


$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb}$$



Nature 557 (2018) no.7704, 207-211

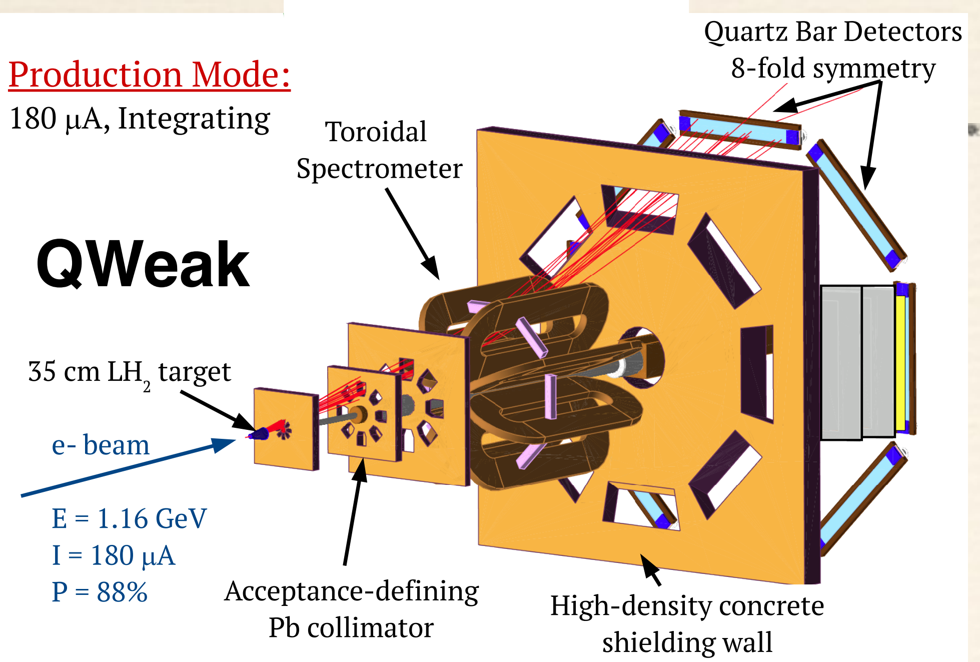




~2022

mid-2020s

Recent Past and Future



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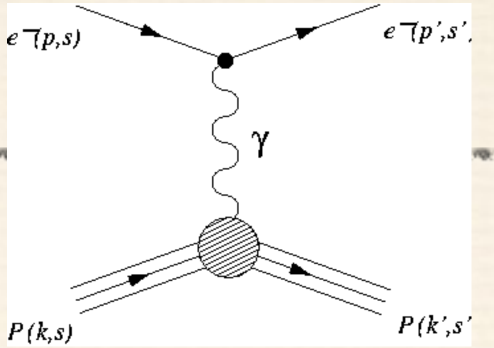

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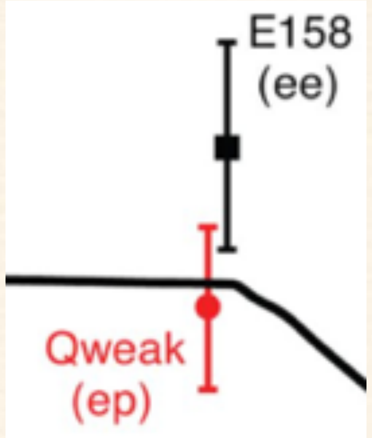
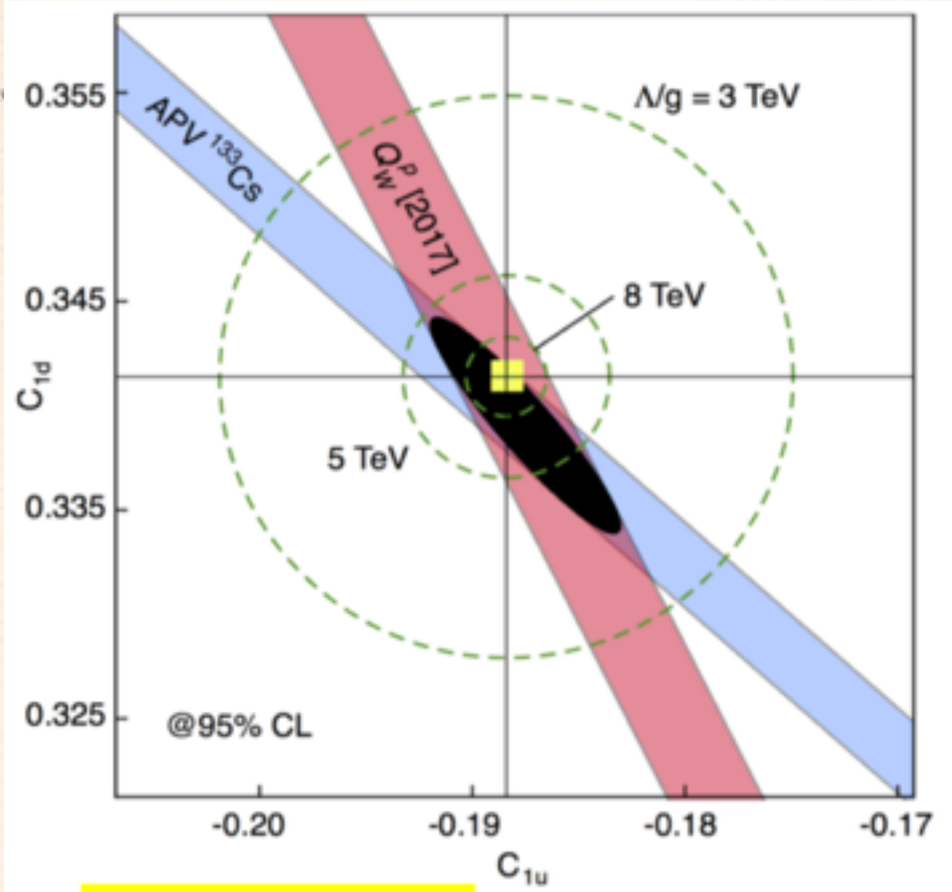
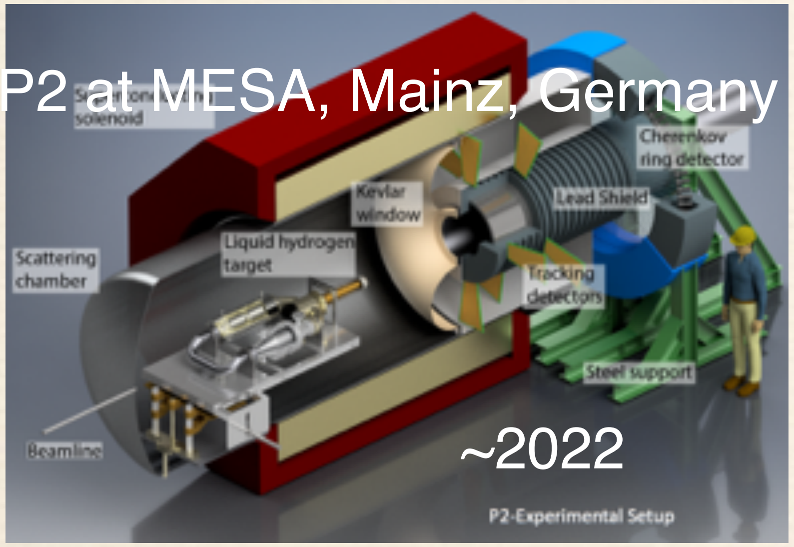


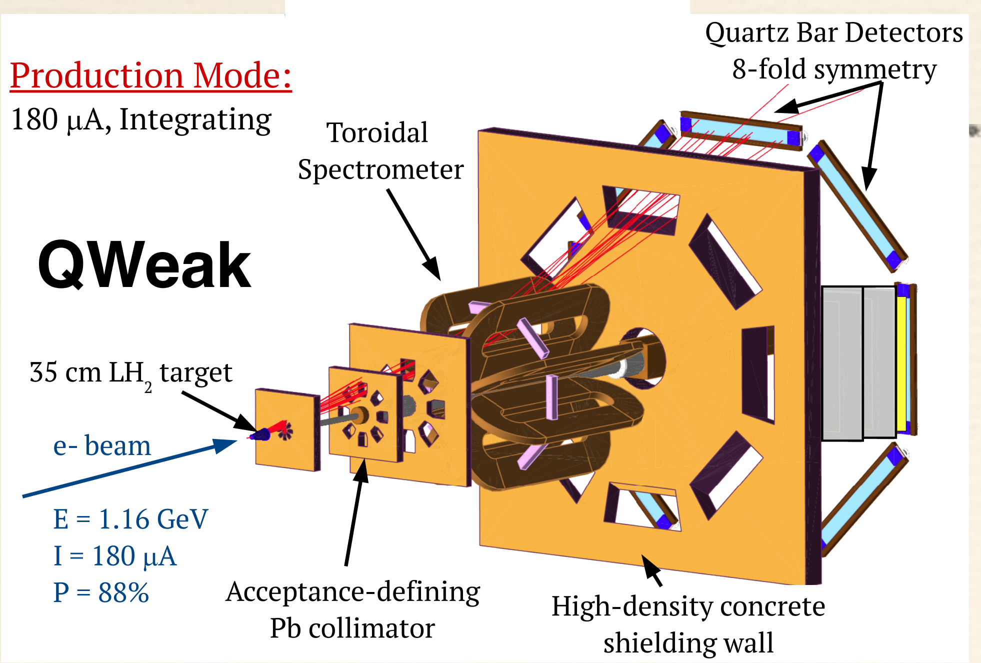



P2 at MESA, Mainz, Germany

~2022

mid-2020s

Recent Past and Future



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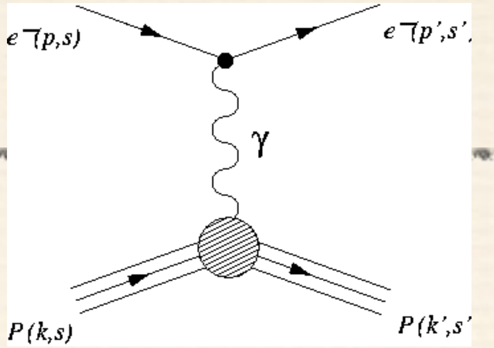

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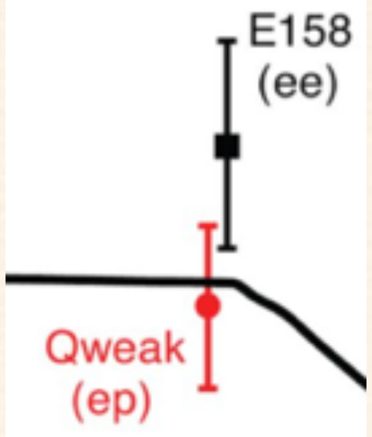

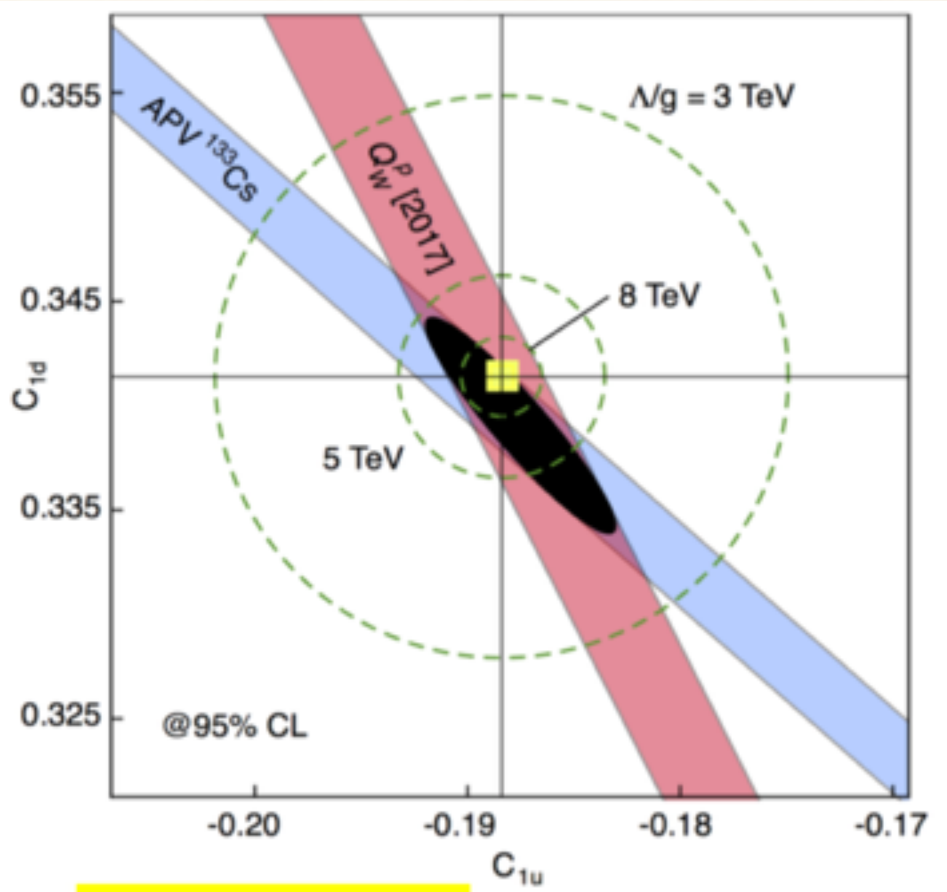

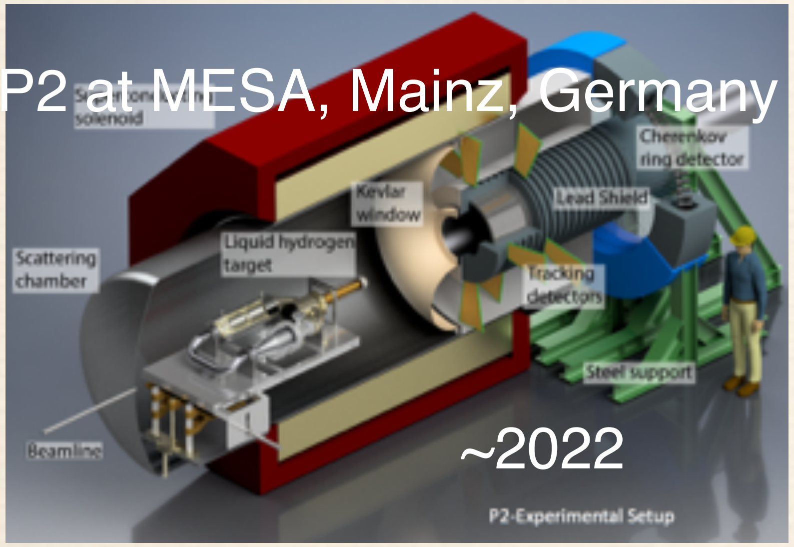

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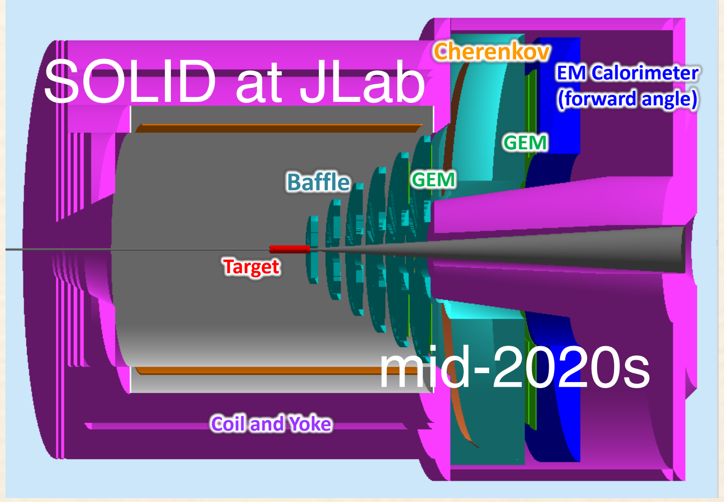
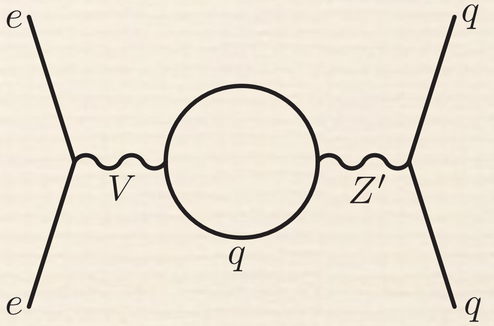


SOLID at JLab

mid-2020s

Leptophobic Z'



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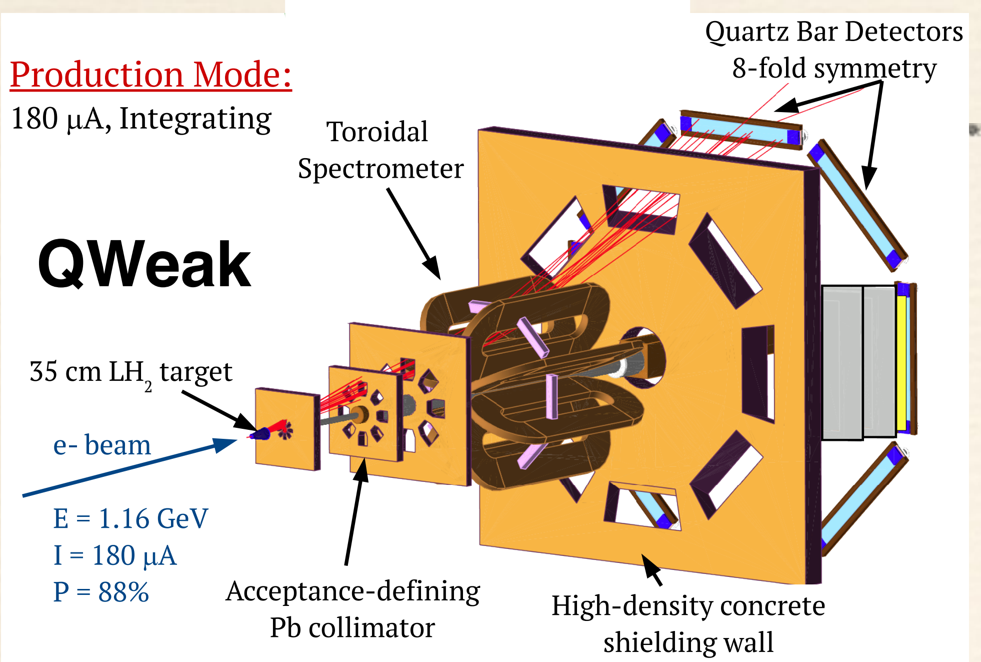

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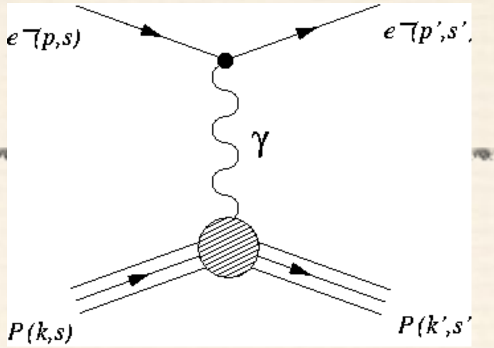

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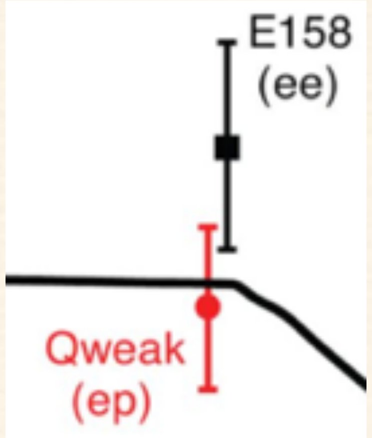

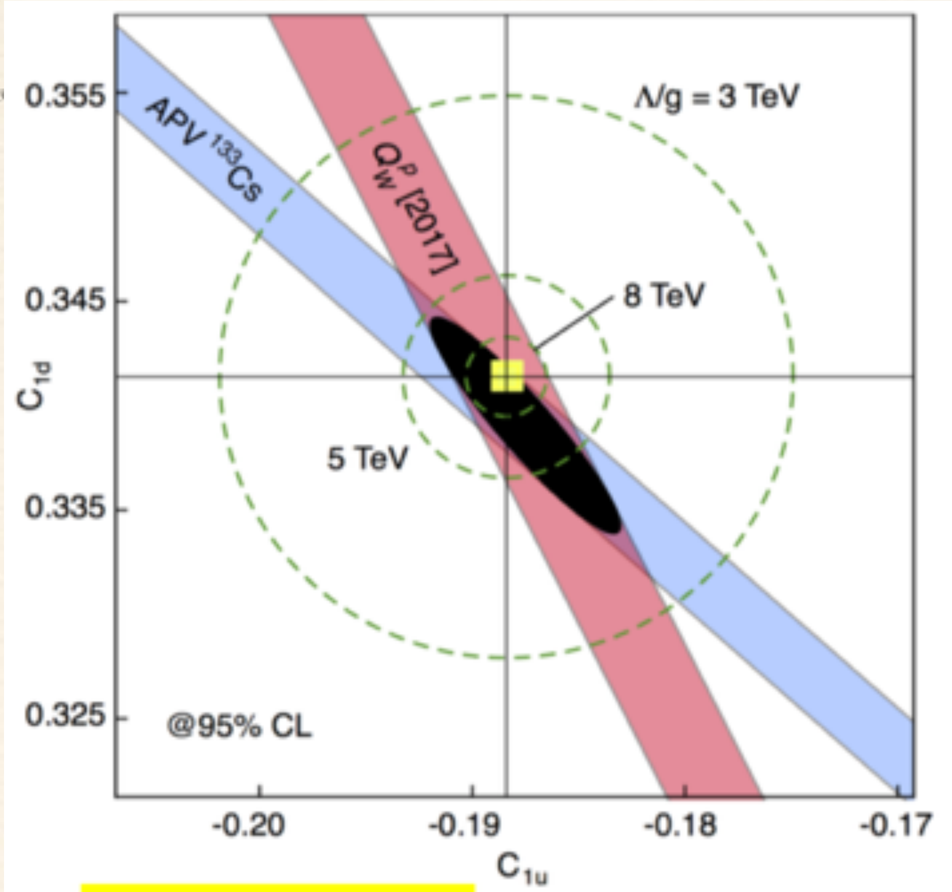

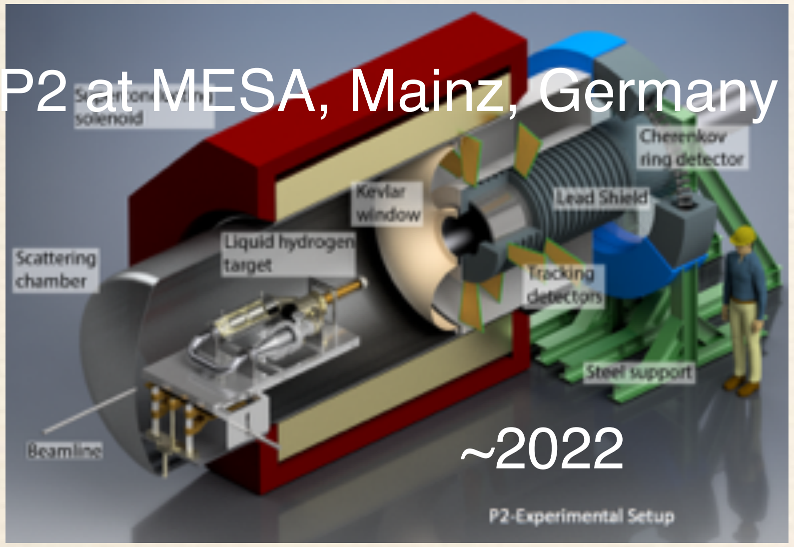

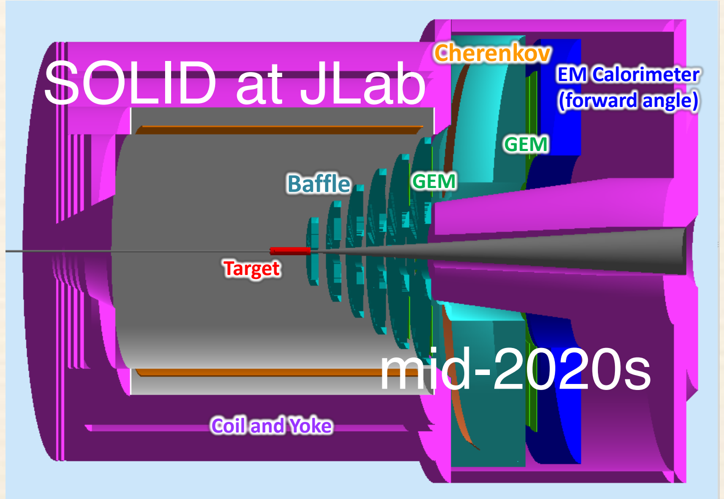

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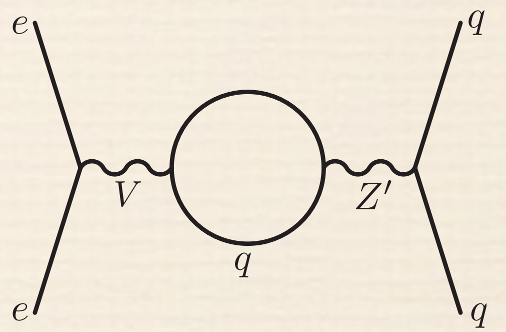
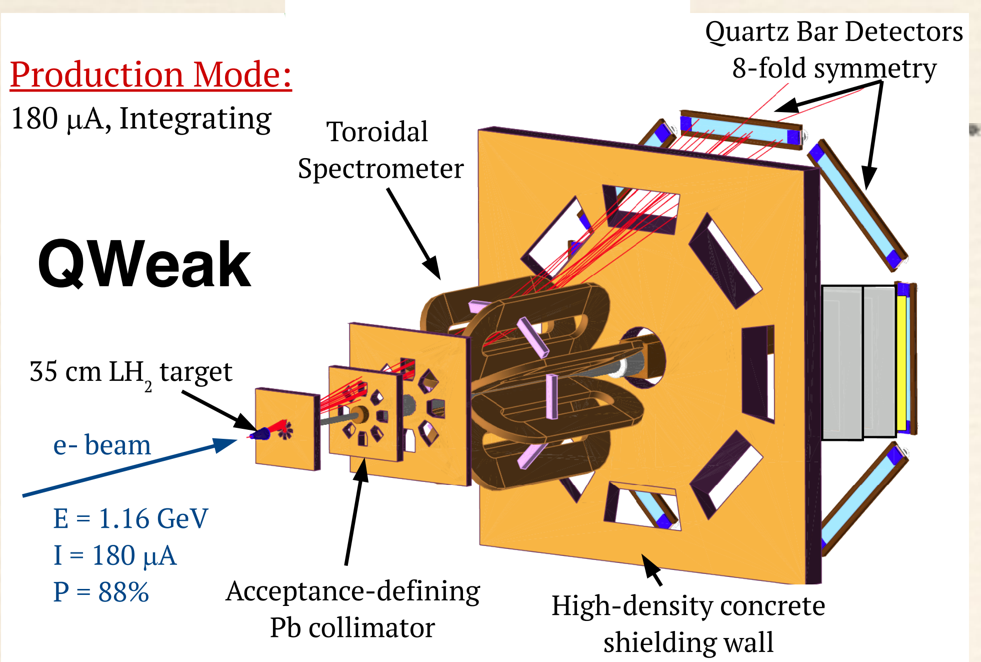


Possible new neutrino scattering measurements at the DUNE (FNAL) Near Detector

Recent Past and Future



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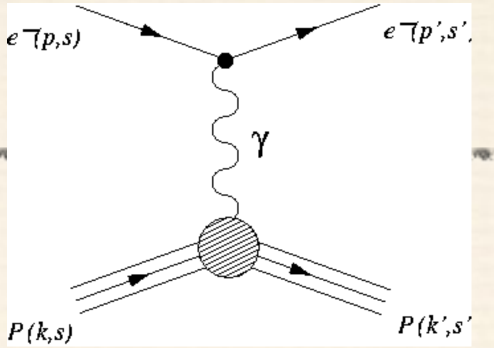

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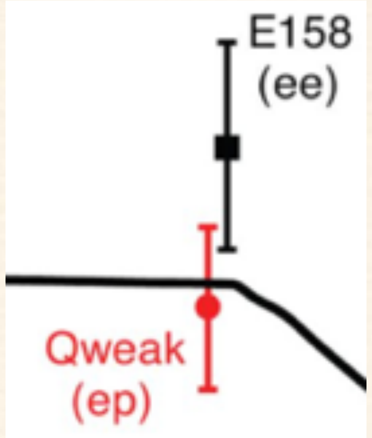

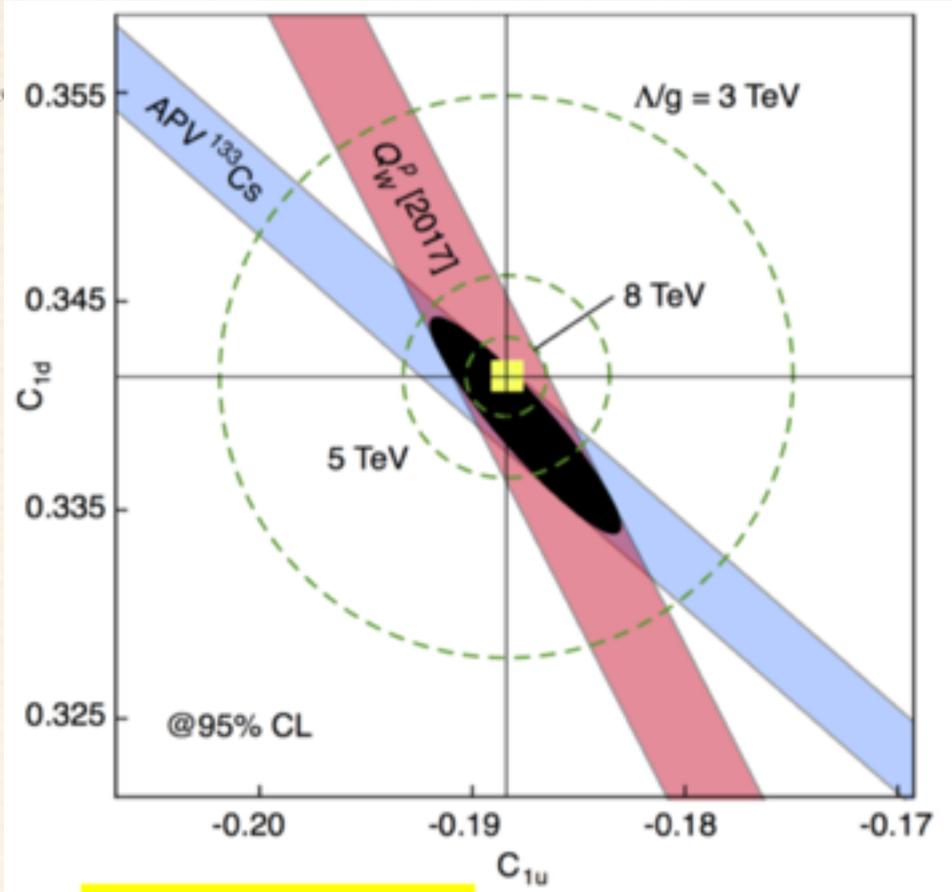

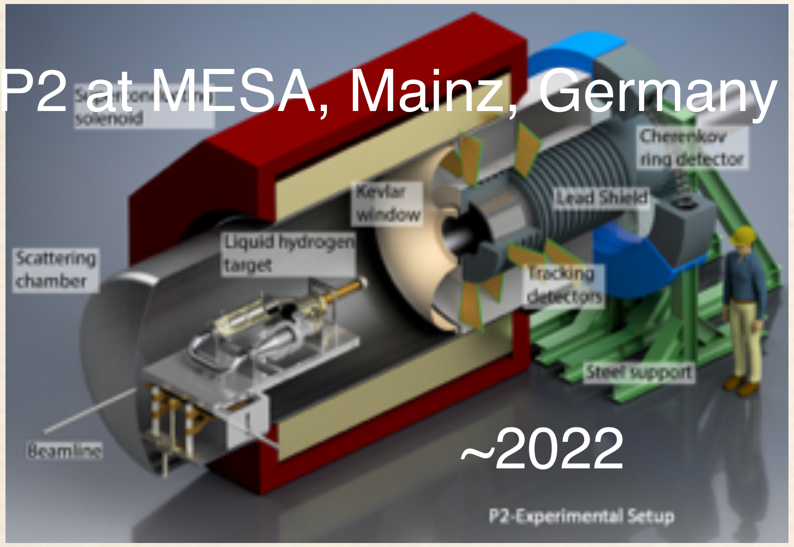

P2 at MESA, Mainz, Germany

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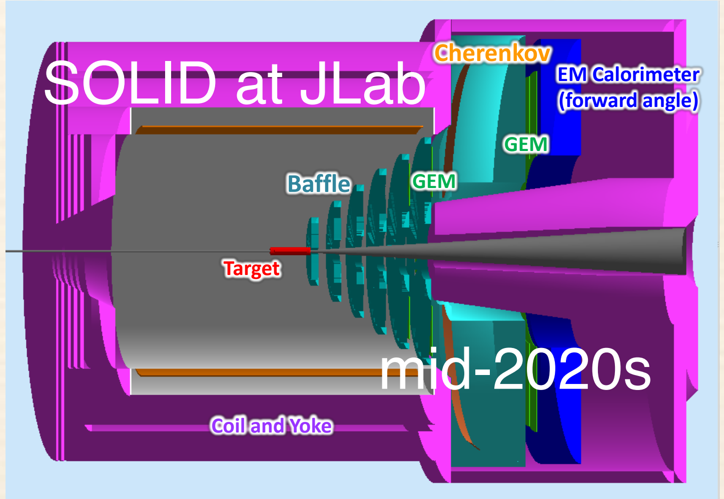

SOLID at JLab

mid-2020s

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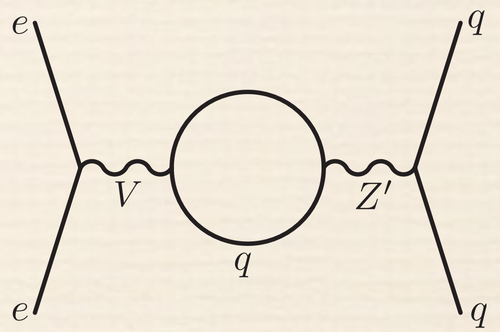

Possible new neutrino scattering measurements at the DUNE (FNAL) Near Detector

New Initiatives in atomic parity violation: Fr (TRIUMF), Yb, Dy (Berkeley/Mainz), Ra-ion (KVI)

Neutrinoless Double Beta Decay: Physics Motivation

A Model of Leptons: $SU(2)_L \times U(1)_Y$

$$e^-, \mu^-, \tau^- \Rightarrow Q = -e;$$

$$\nu_e, \nu_\mu, \nu_\tau \Rightarrow Q = 0$$

$$\begin{pmatrix} \nu \\ \ell^- \end{pmatrix}_L \quad \ell^-_R \quad \nu_R$$

$$\pm\, 1/2 \qquad 0 \qquad 0 \Rightarrow T_3$$

$$\boxed{Q = T_3 + Y/2}$$

$$Y_{\nu_L} = -1 \qquad \boxed{Y_{\nu_R} = 0}$$

Right-handed neutrino has no gauge interactions

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Helicity $\equiv \vec{p} \cdot \vec{\Sigma} \equiv h = \pm 1$

Chirality $\equiv \dfrac{1 \pm \gamma^5}{2} \equiv P_{L,R}$

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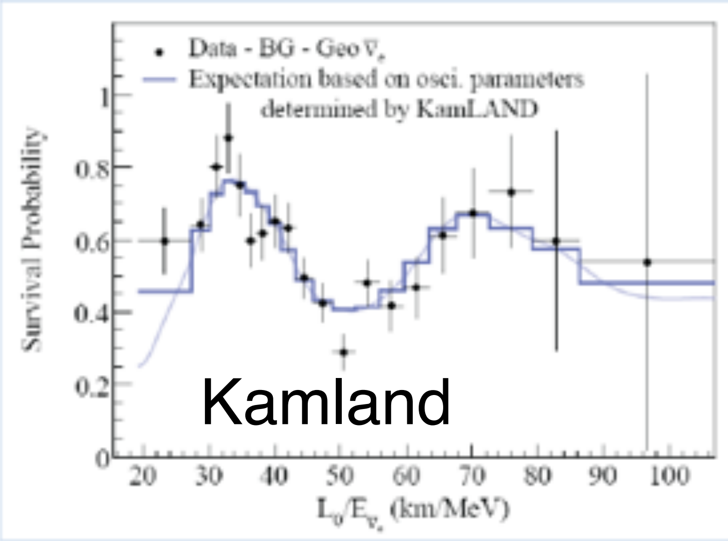
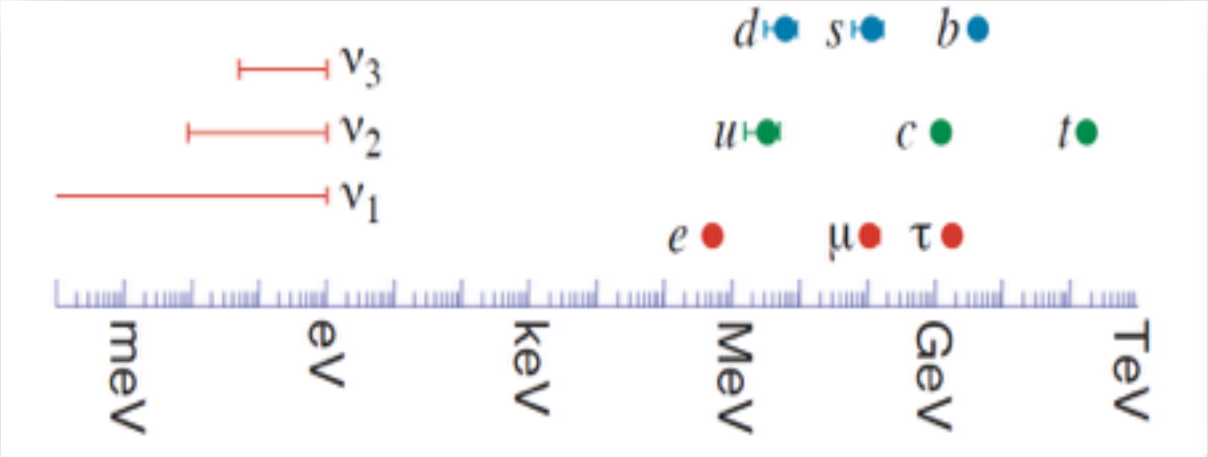
Original formulation of the Standard Model:
ν massless and no right-handed state

Postulate the Massive Right-Handed Neutrino



- **Why is neutrino mass so small?**
- **How small is it?**
- **What is the mass generating mechanism?**
- **And…**



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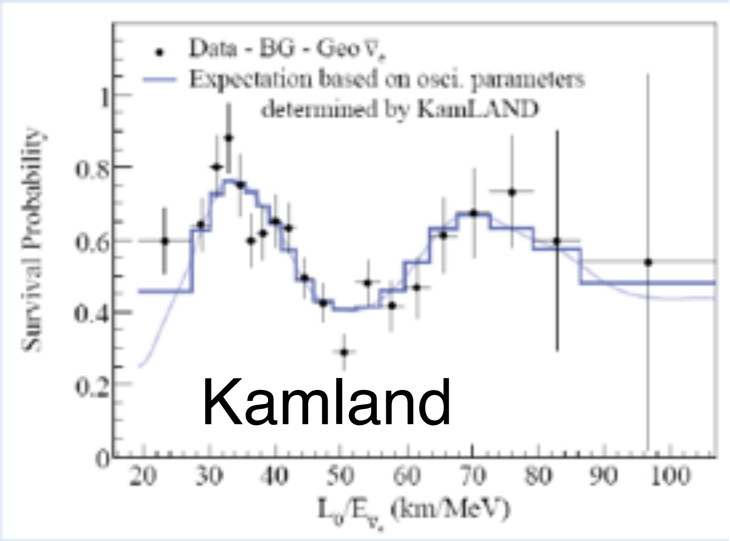

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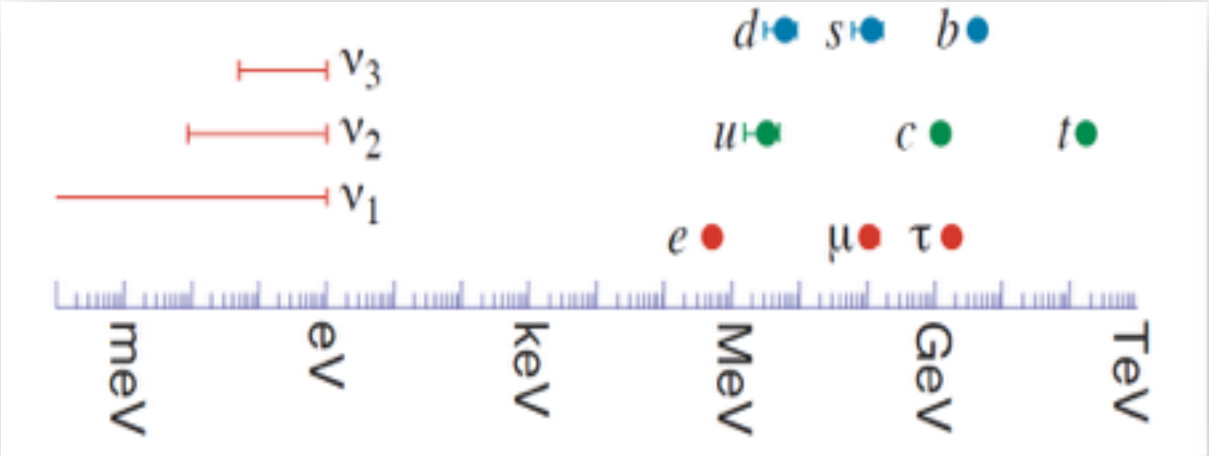

CPT transformation: *left-handed* particle to *right-handed anti*-particle

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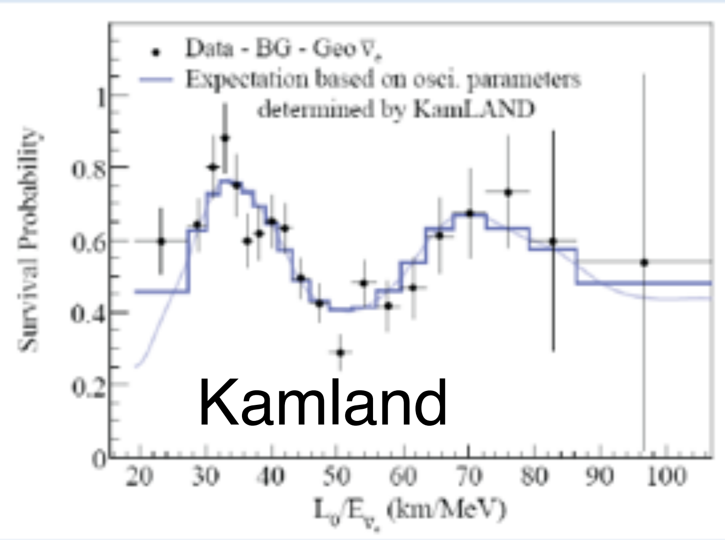

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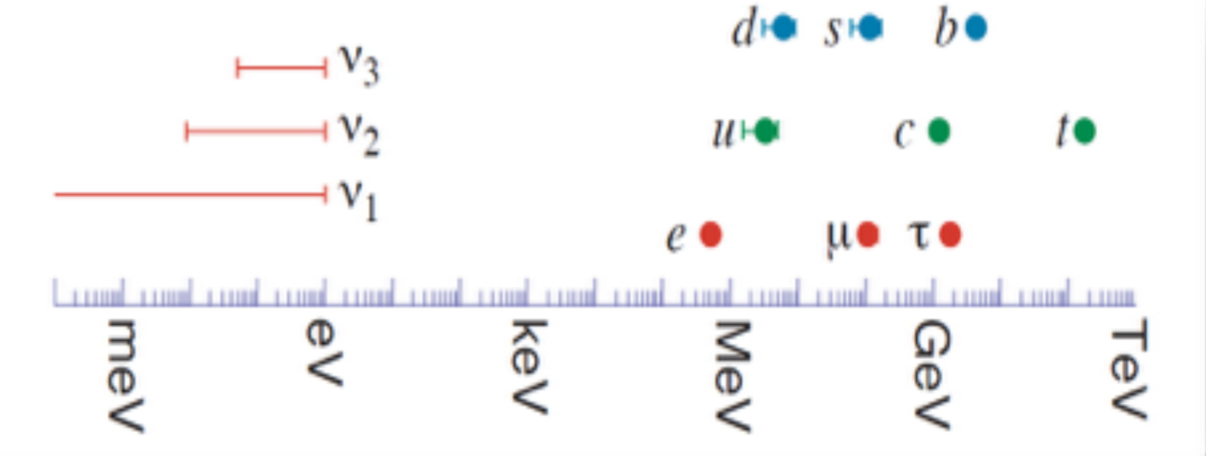
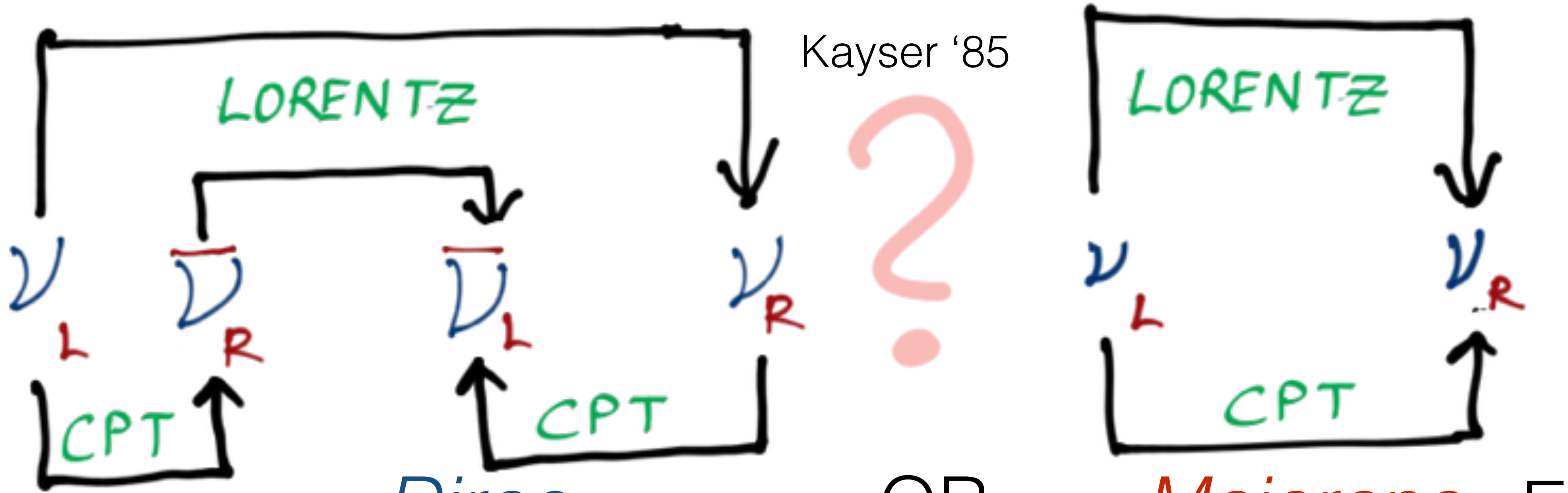


CPT transformation: *left-handed* particle to *right-handed anti*-particle

A profound question:



Kayser ‘85

Dirac OR *Majorana* Early 1930s

What is the Discovery Experiment?

Neutral Current interactions have subtle differences

Kayser '82

But

Dirac-Majorana Confusion Theorem: the difference between ν_D and ν_M interactions vanishes in the ultra-relativistic limit

Exotic possibilities beyond Standard Model V-A

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The most pragmatic approach to discover the Majorana nature of neutrinos is to search for **Lepton Number Violation (LNV)**

Practically: discover **Neutrinoless Double-Beta Decay** **($0\nu\beta\beta$)**

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Why do we care so much?

See V. Cirigliano lectures

Baryon & Lepton Number

$p \longrightarrow e^+ \pi^0$

Proton Decay

$B \quad +1 \quad\quad 0 \quad 0$

Forbidden if B is conserved

See V. Cirigliano lectures

Baryon & Lepton Number

$$\begin{array}{lcccc} & p & \longrightarrow & e^{+} & \pi^{0} \\ B & +1 & & 0 & 0 \end{array}$$

Proton Decay

Forbidden if B is conserved

$$\begin{array}{lccccccccccccc} & n & \longrightarrow & p & e^{-} & \bar{\nu}_e & \Longrightarrow & \bar{\nu}_e & p & \longrightarrow & e^{+} & n \\ L & 0 & & 0 & +1 & -1 & & -1 & 0 & & -1 & 0 \end{array}$$

but never

$$\begin{array}{ccccc} \bar{\nu}_e & n & \longrightarrow & e^{-} & p \\ -1 & 0 & & +1 & 0 \end{array}$$

See V. Cirigliano lectures

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Introduce Lepton Number:

$$L_{e^-} = L_{\nu_e} = -L_{e^+} = -L_{\bar{\nu}_e} = +1$$

This is encoded into the Standard Model Feynman Rules

See V. Cirigliano lectures

Is L Conserved?

If $\nu_R \Longleftrightarrow \bar{\nu}_R$ Majorana Neutrino **L is violated**

L $+1$ -1

- *Only B-L strictly conserved in the Standard Model*
- *B+L is violated due to anomalies*
- *No fundamental reason to expect B and L to be conserved (assuming only 4 forces in Nature)*

See V. Cirigliano lectures

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Majorana neutrinos: possible explanation of light neutrino masses

Matter-antimatter asymmetry…. Mass generation beyond the Higgs…

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Majorana neutrinos: possible explanation of light neutrino masses

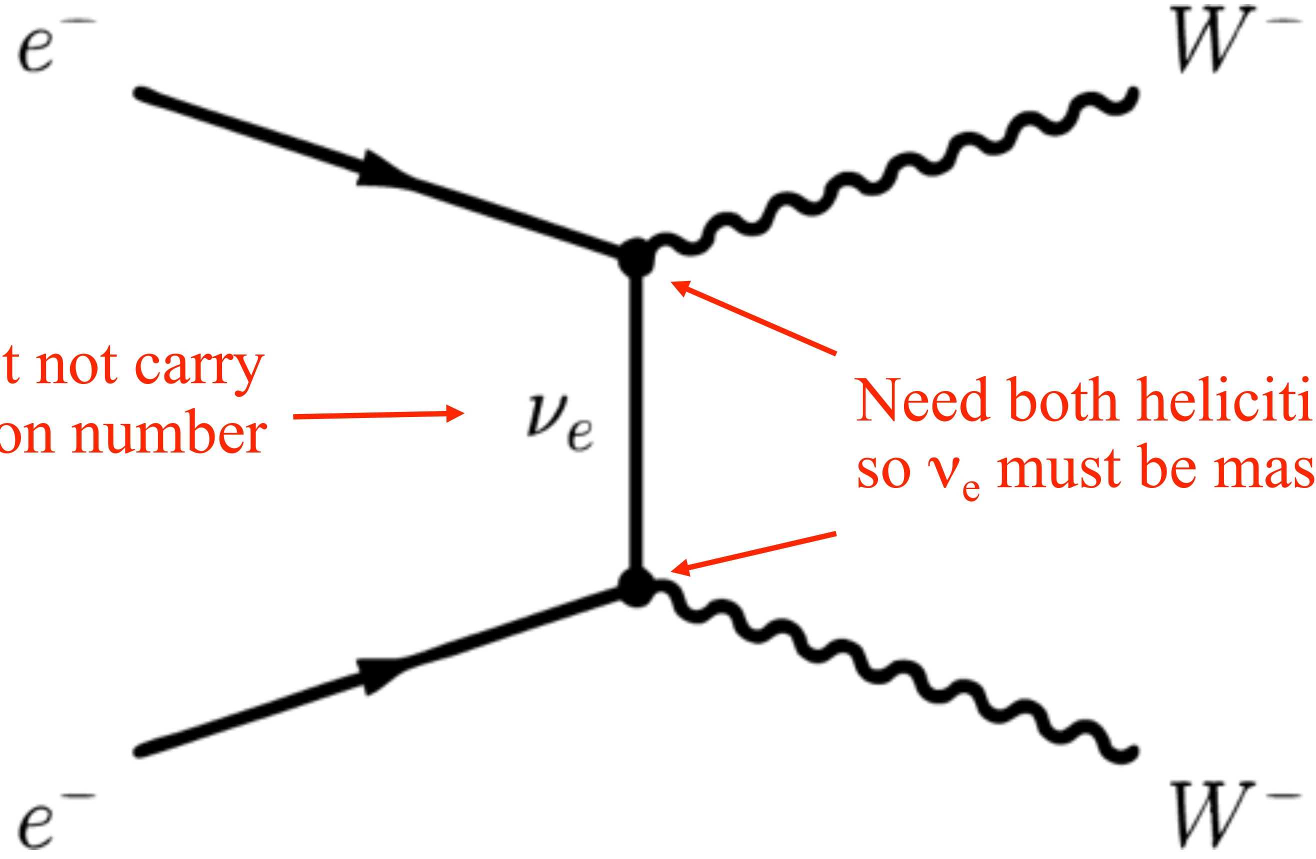
Matter-antimatter asymmetry…. Mass generation beyond the Higgs…

In any case: a new heavy scale for physics beyond the SM

A Gedanken Experiment

L +1 +1 0 0

$$e^- + e^- \Longrightarrow W^- + W^-$$



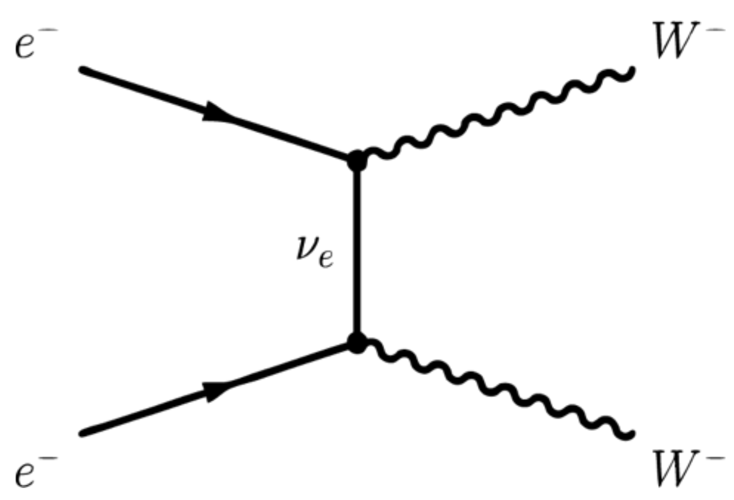
must not carry lepton number

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

Virtual W's Instead



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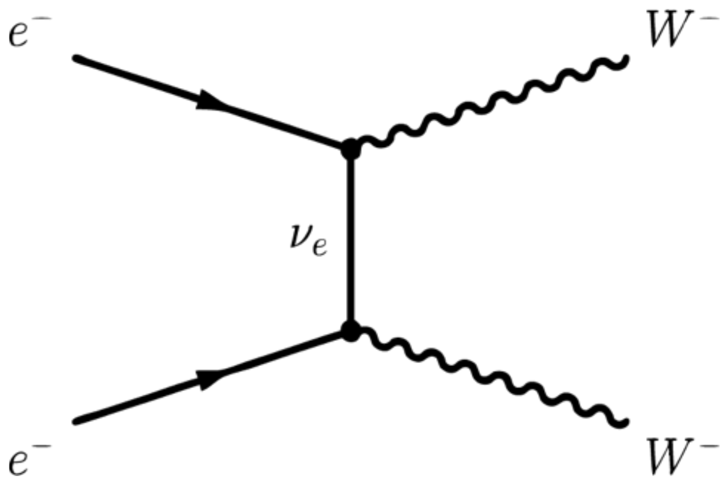
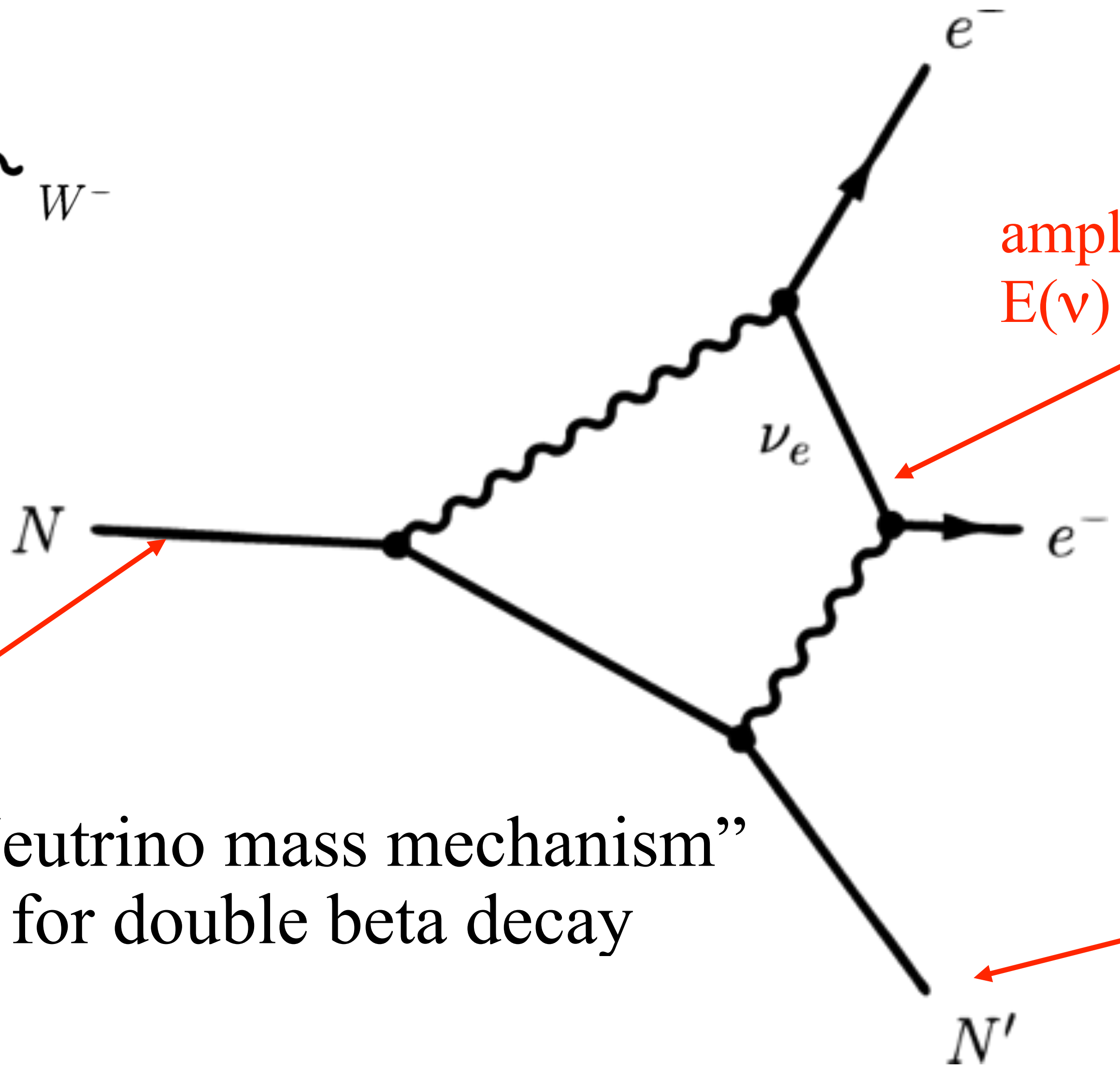


Lepton number changes by two units: $\Delta L=2$

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



amplitude ~ m(ν)/E(ν),
E(ν) ~ 100 MeV

N(Z,A)

"Neutrino mass mechanism"
for double beta decay

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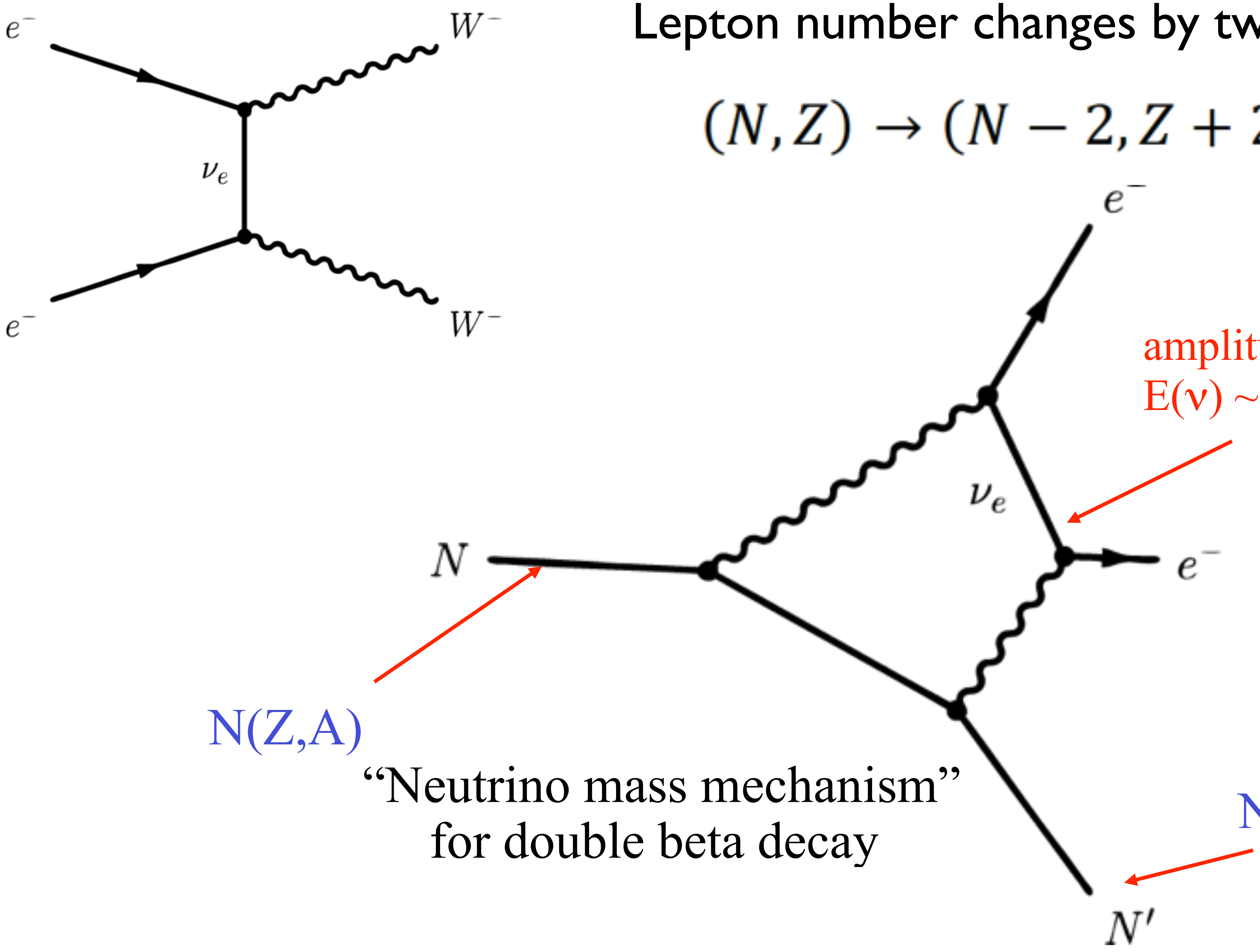

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"Neutrino mass mechanism"
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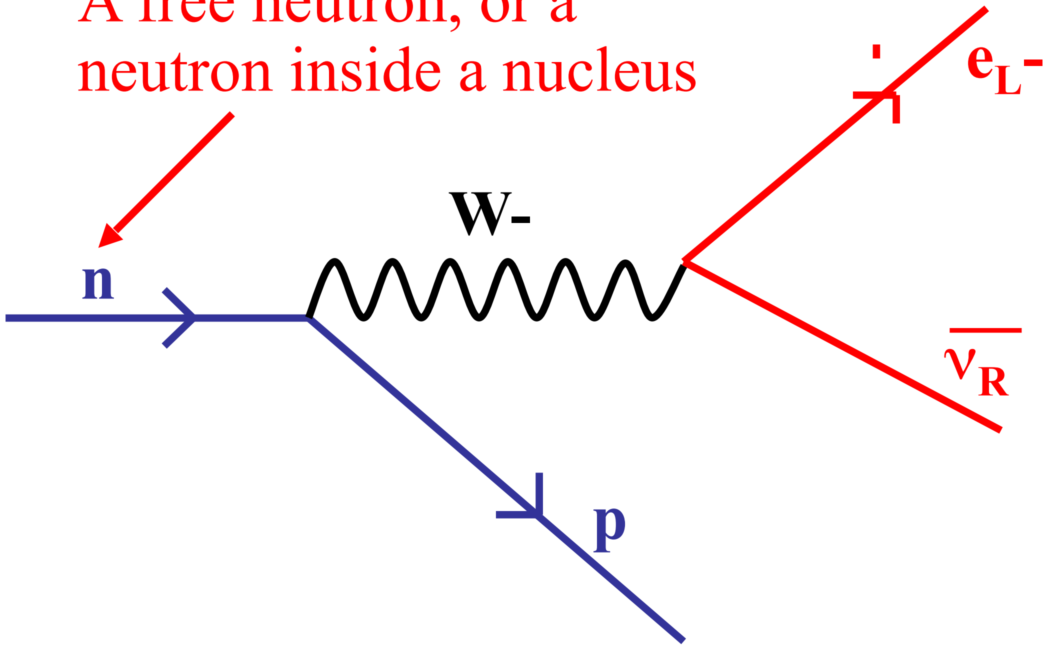
Racah and Furry suggested this was possible for Majorana particles in 1937 soon after Majorana published his theory!

Lepton Number Conserving Standard Model Process

2ν Double Beta Decay



A free neutron, or a neutron inside a nucleus

Nuclear Beta Decay

Lepton Number Conserving Standard Model Process

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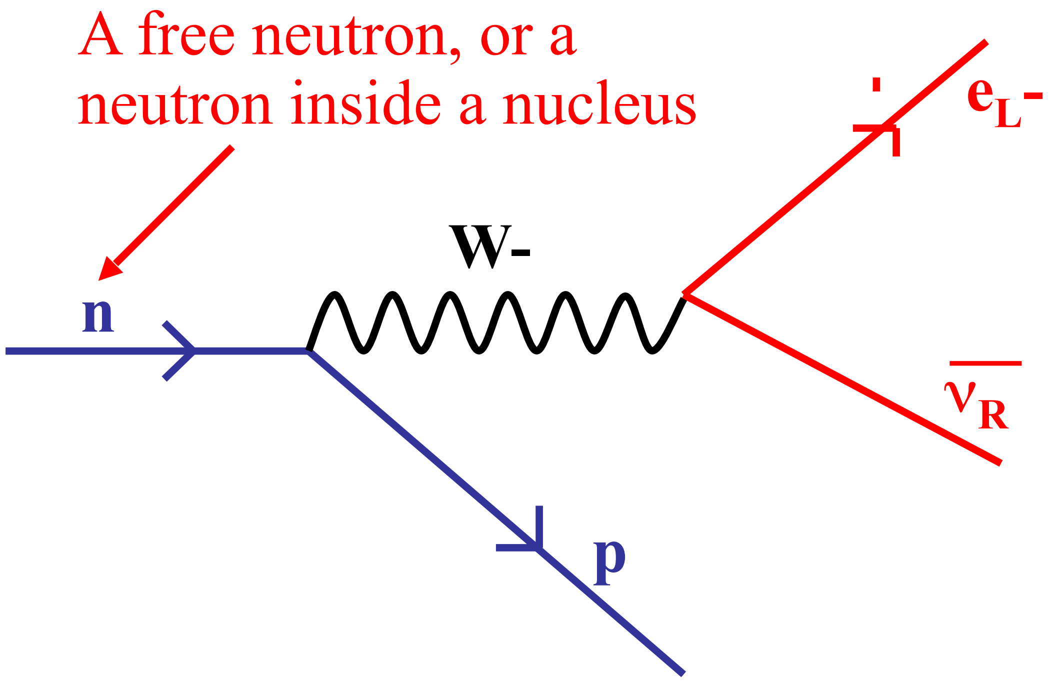

Nuclear Beta Decay

Nuclear Double-Beta Decay with the emission of two neutrinos

Lepton Number Conserving Standard Model Process

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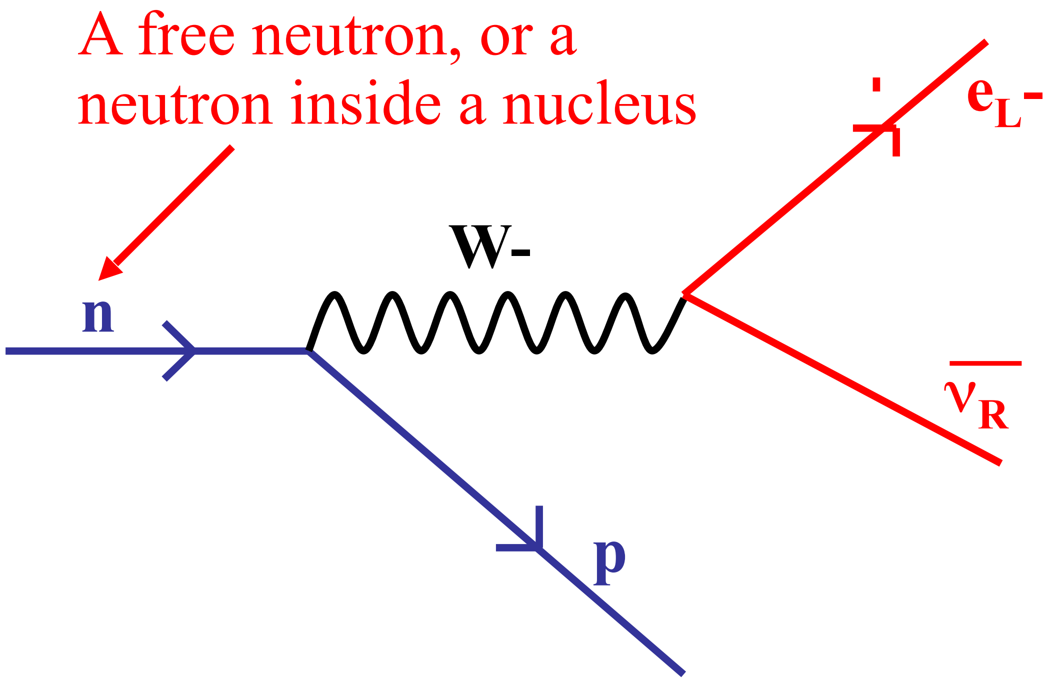

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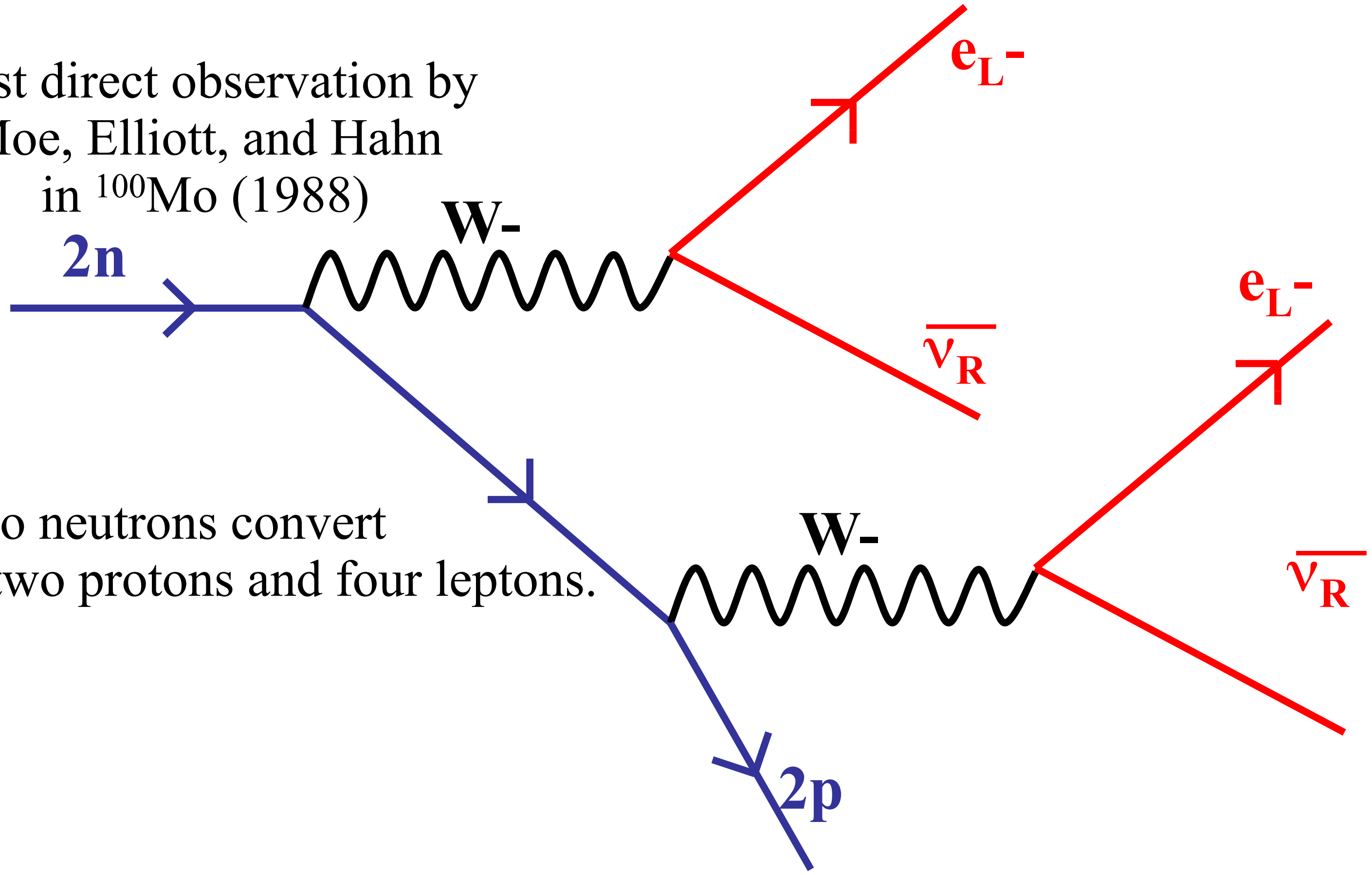
Nuclear Beta Decay

Nuclear Double-Beta Decay with the emission of two neutrinos



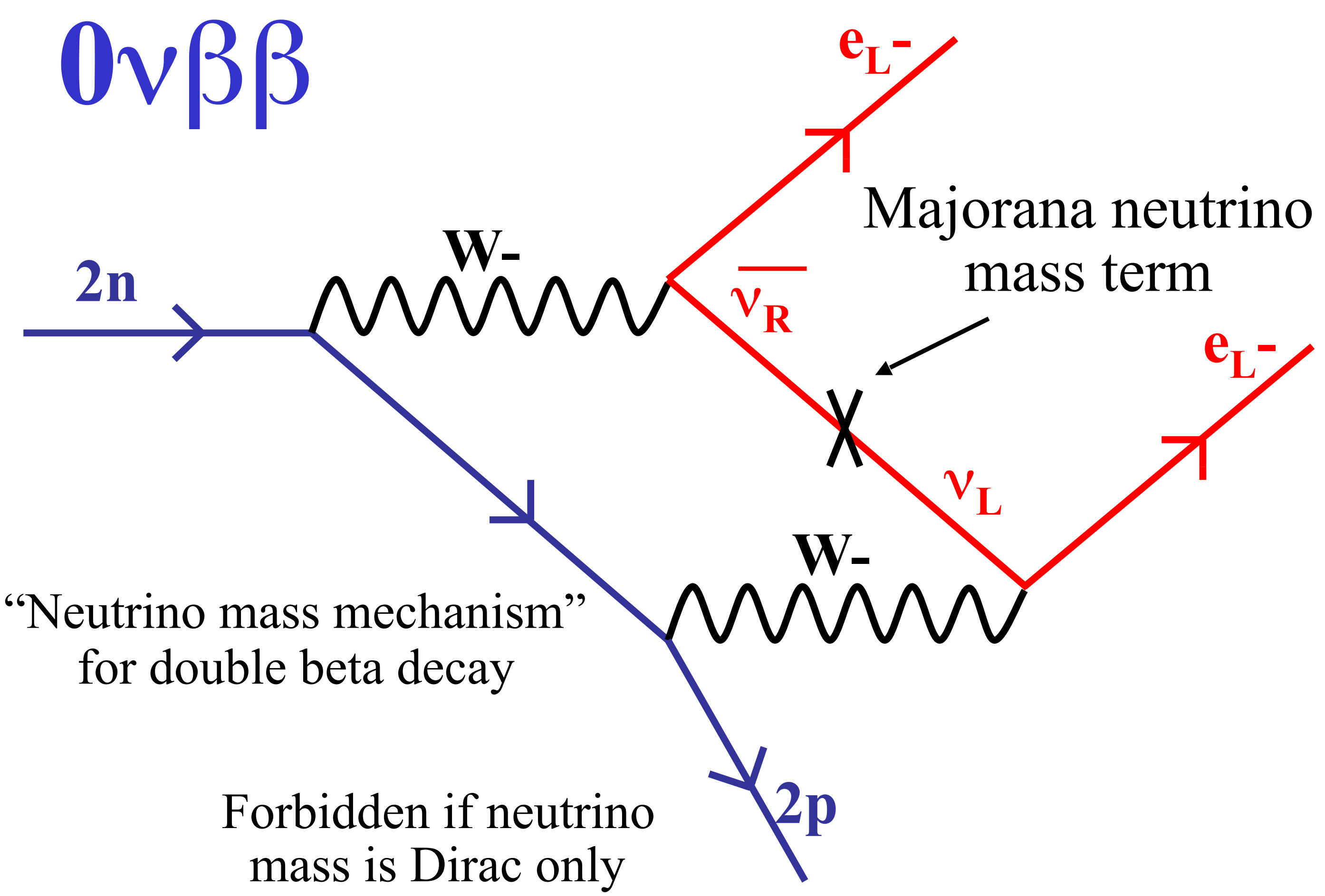
First direct observation by Moe, Elliott, and Hahn in ^{100}Mo (1988)

Two neutrons convert to two protons and four leptons.

Suggested by Maria Goeppert-Mayer in 1935!

0ν Double Beta Decay

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



Majorana neutrino mass term

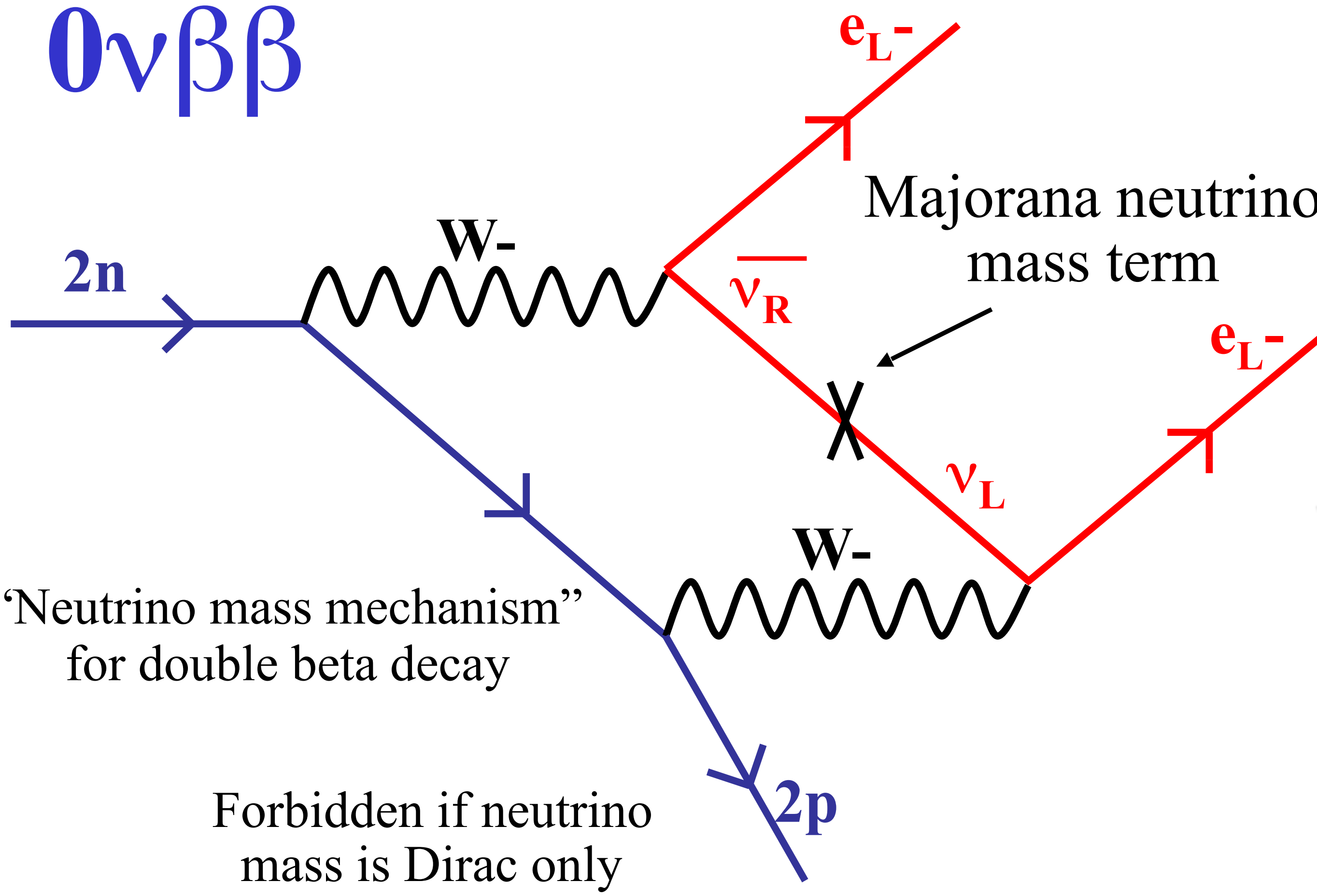
"Neutrino mass mechanism" for double beta decay

Forbidden if neutrino
mass is Dirac only
(violates lepton number conservation).

0ν Double Beta Decay

Experimental Signature

0νββ



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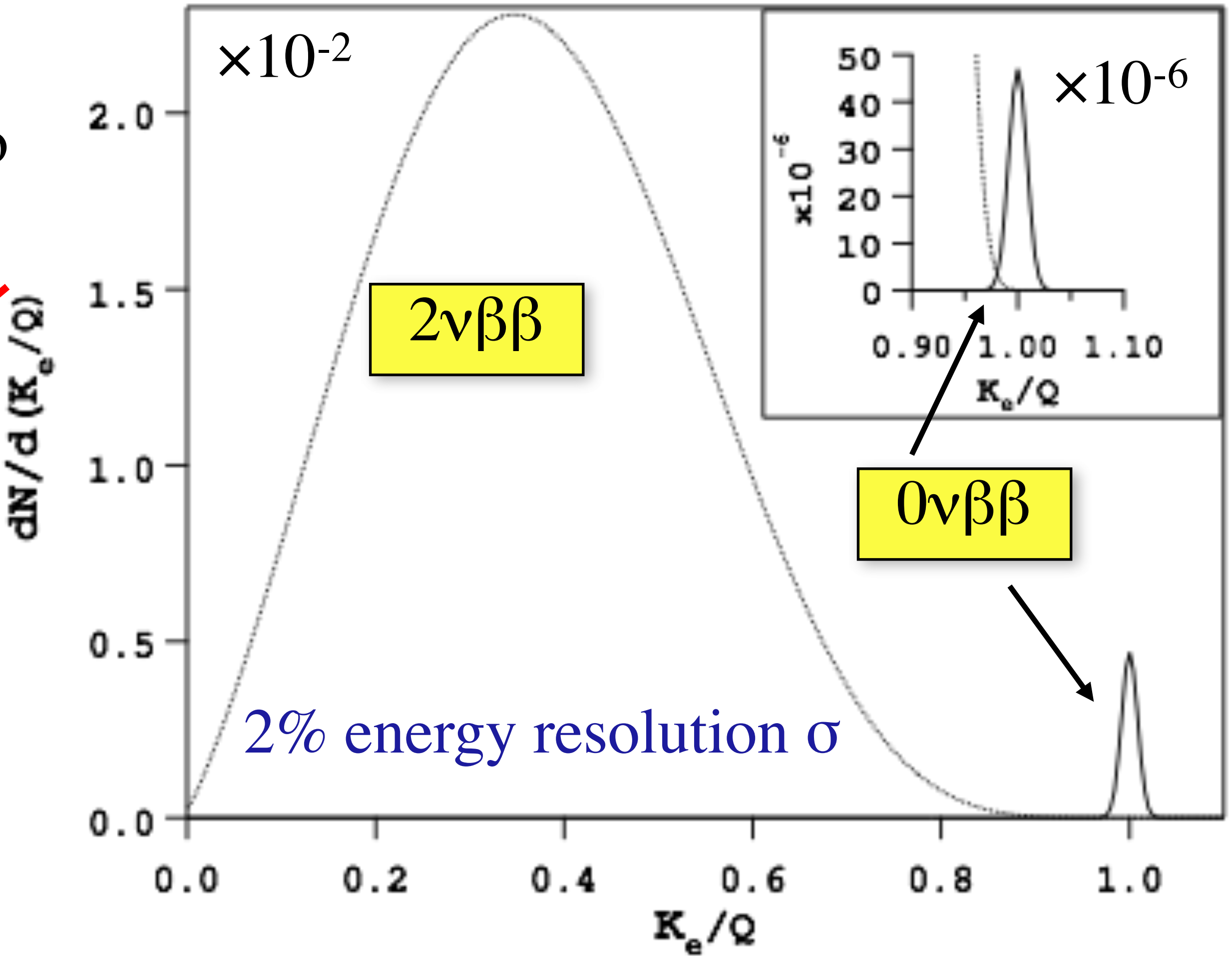
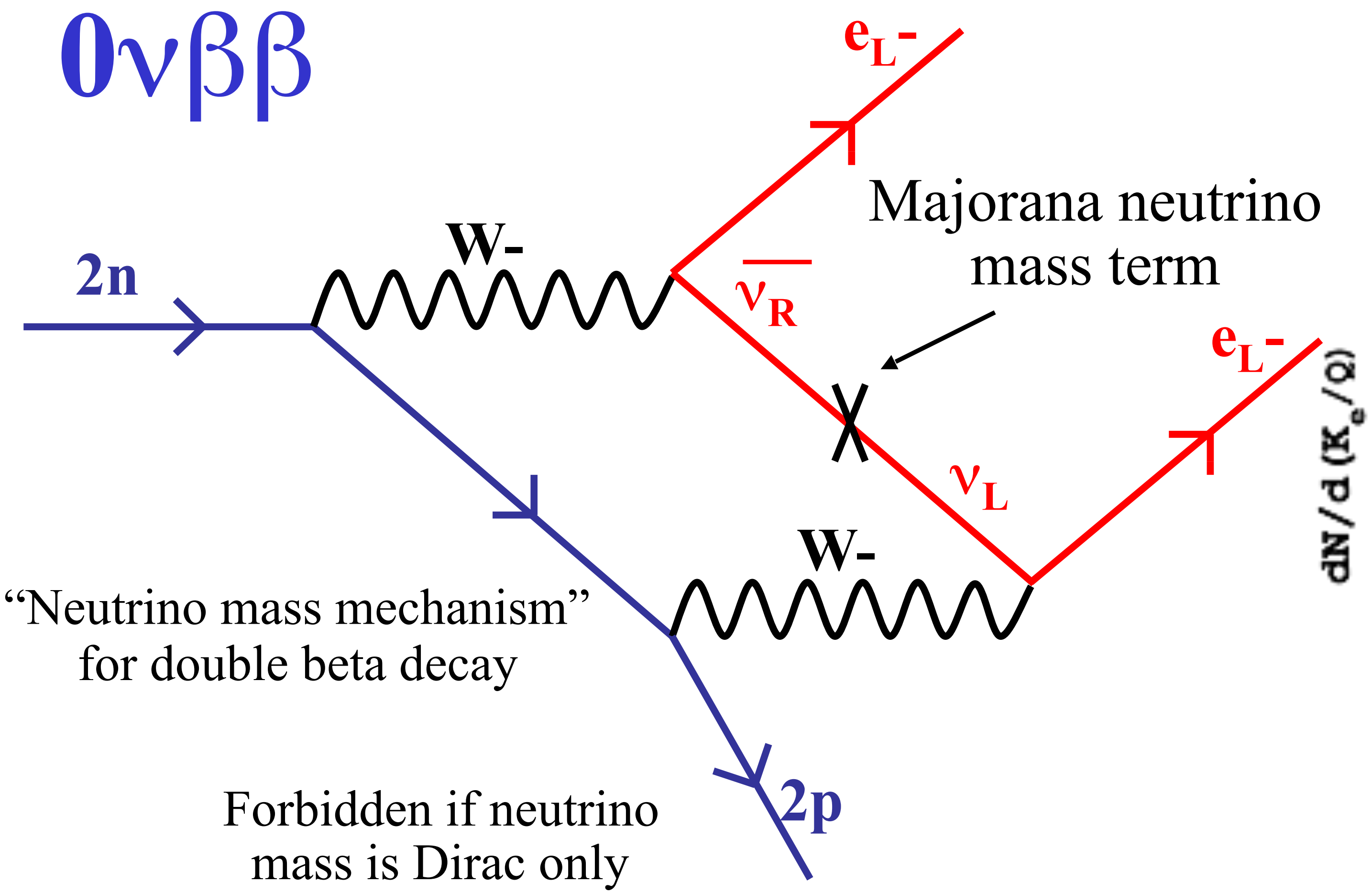


0ν Double Beta Decay

Experimental Signature



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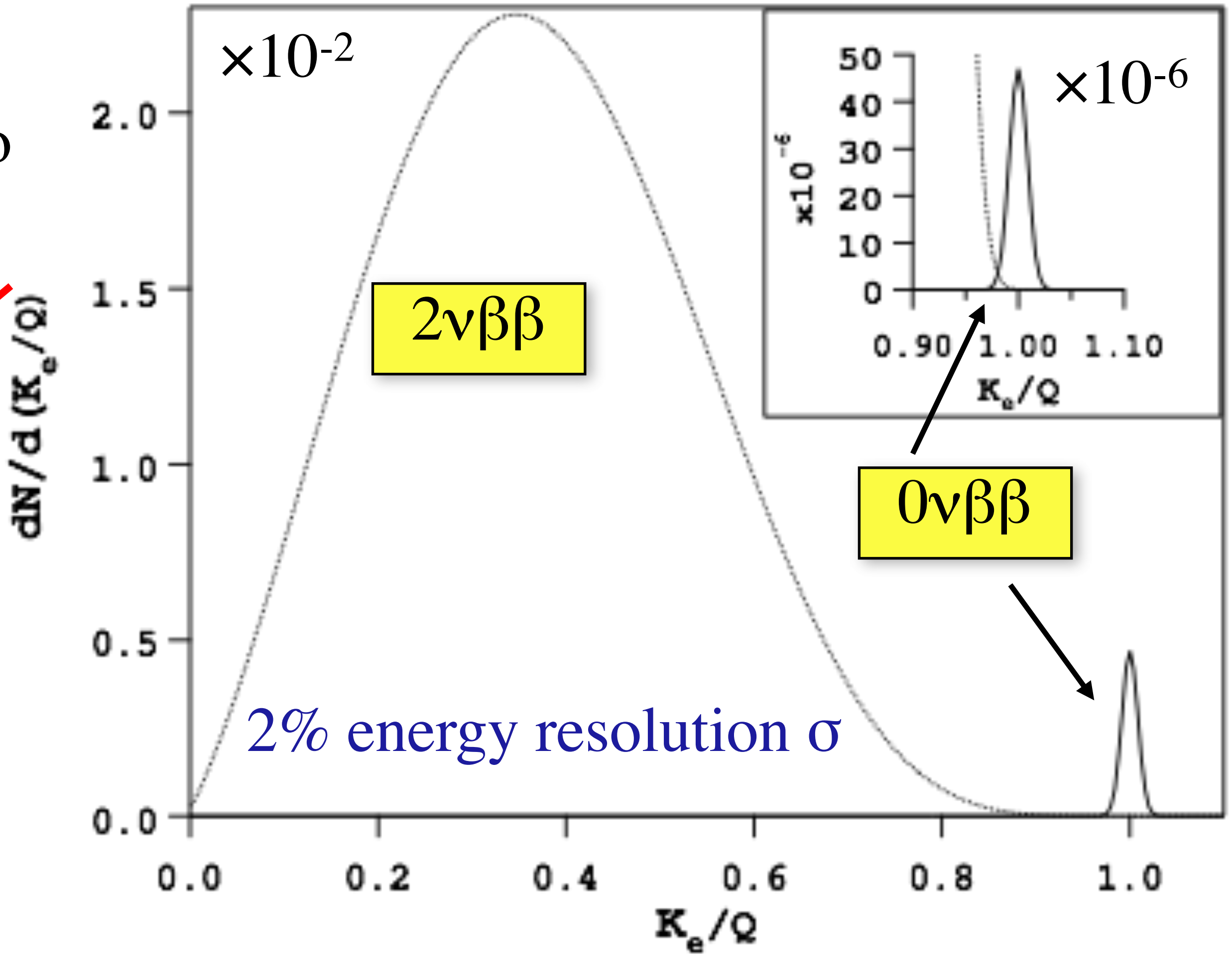
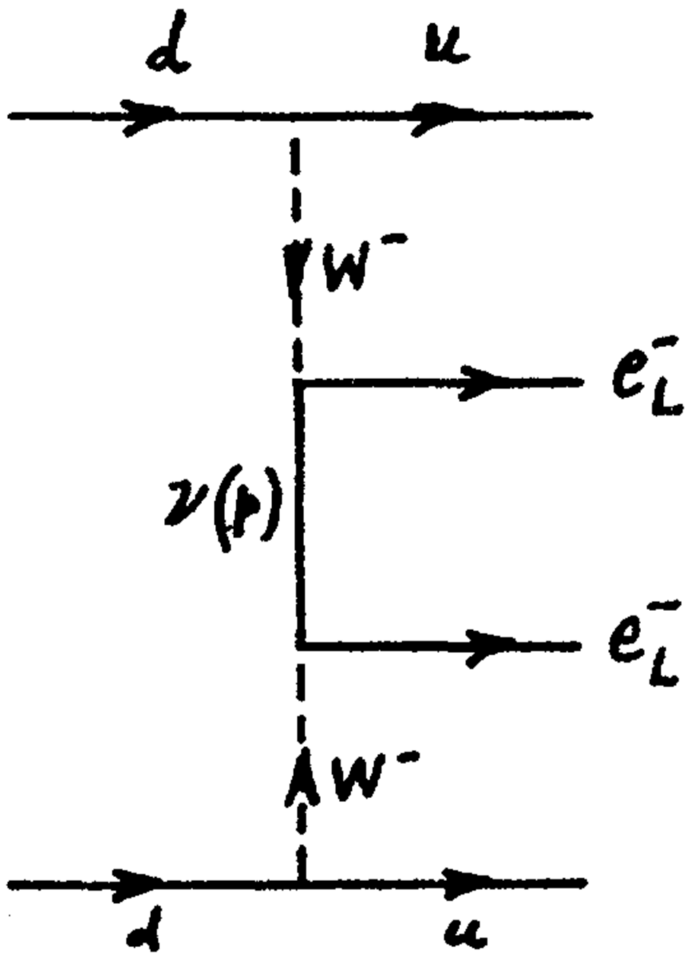


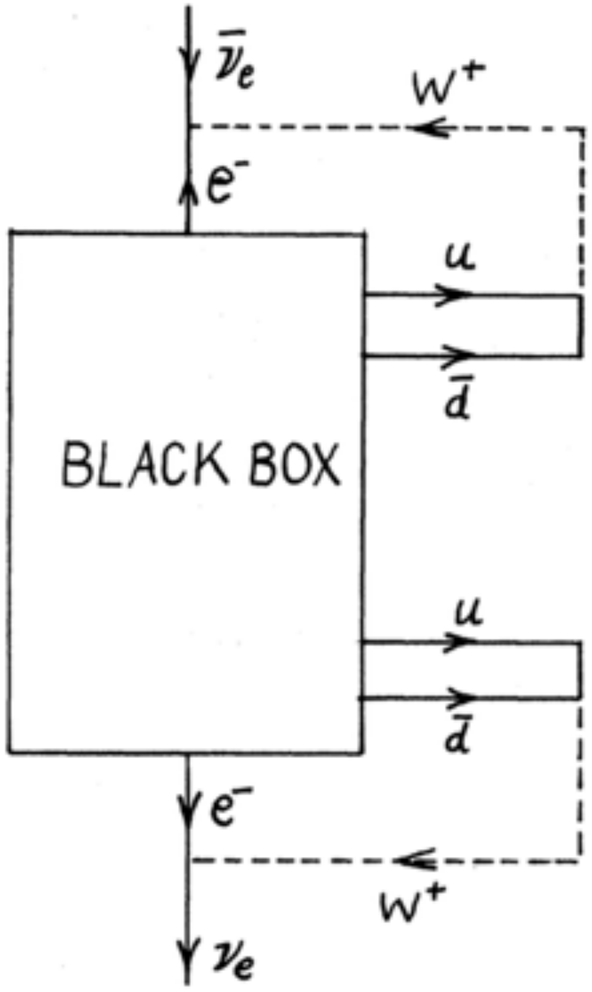
If observed, it would unambiguously signal that Lepton Number is NOT a conserved quantity, and that neutrinos are Majorana particles i.e. their own anti-particles

Schechter and Valle, PRD 25, Vol. 11 (1982)

A Theorem

If neutrinoless double-beta decay occurs, there exists a way to convert an anti-neutrino to a neutrino, a ***Majorana mass*** *amplitude*





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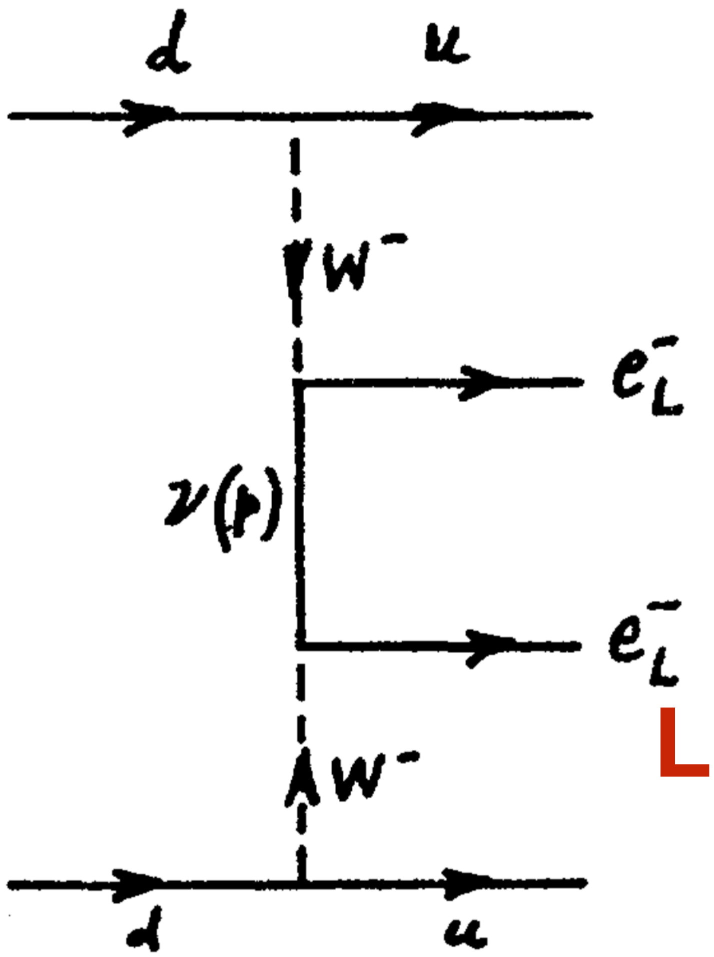
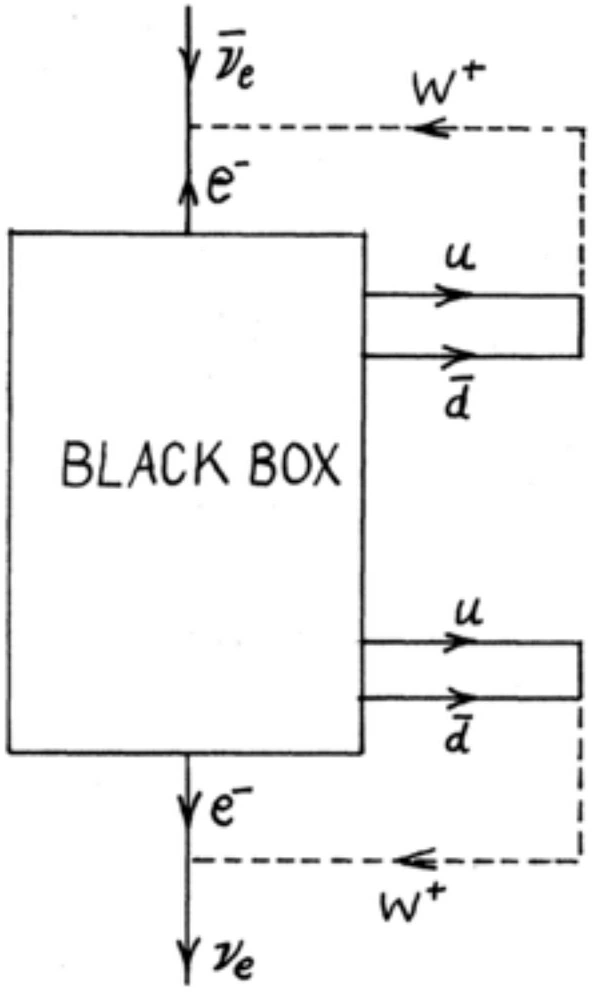


No caveats:

0νββ

↓

Lepton Number Violation
and
Majorana Neutrinos



Choosing a Nuclide

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

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

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

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Choose nuclei where single beta decay forbidden

but double-beta decay is possible

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

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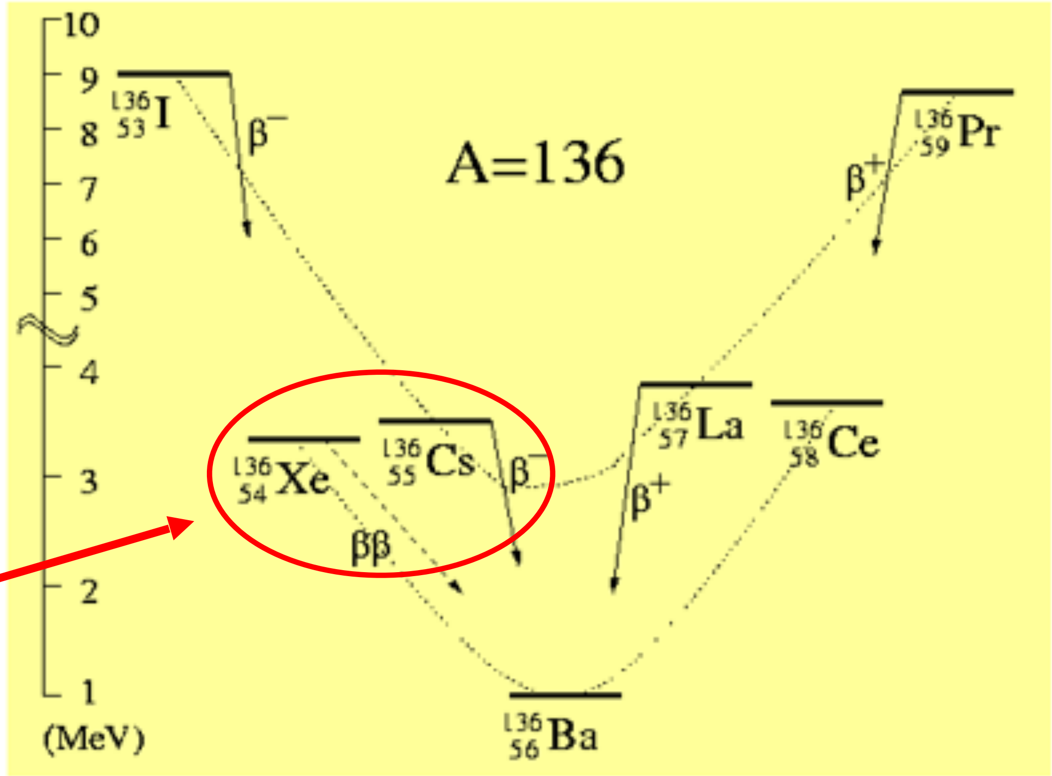


Double-beta decay:

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

Choosing a Nuclide

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

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

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

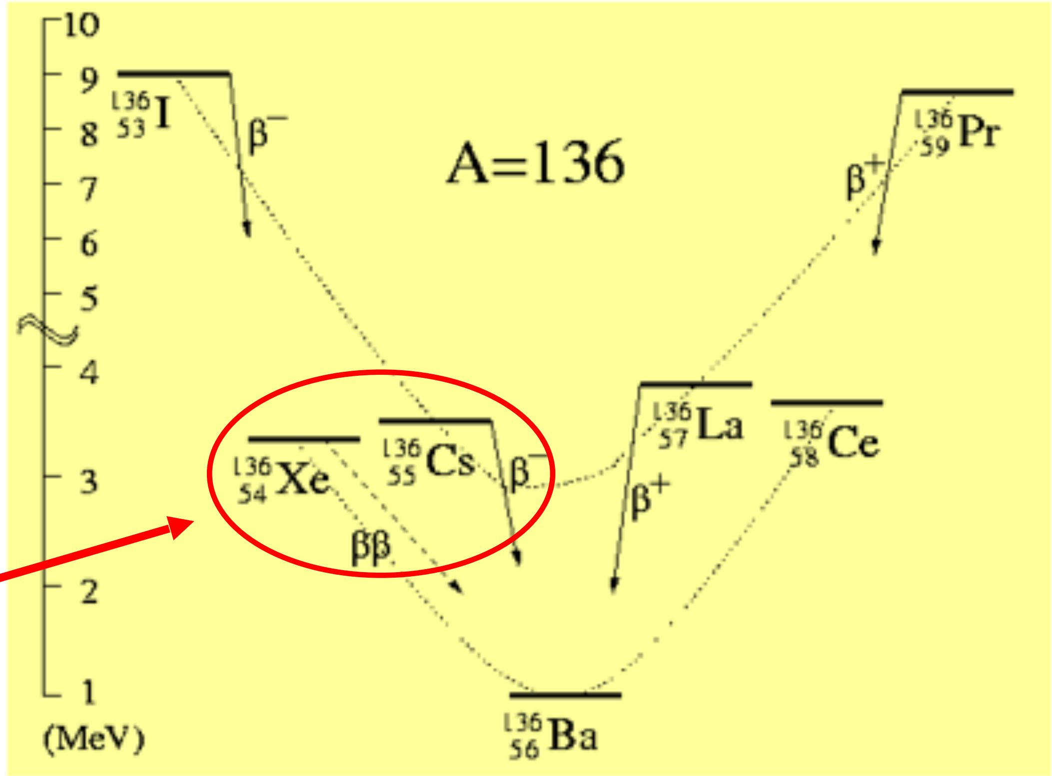
Choose nuclei where single beta decay forbidden

but double-beta decay is possible

Candidate nuclei with Q>2 MeV

Double-beta decay:

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



Decay Rate for 0νββ

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

Transition Probability $\alpha \frac{m}{Q^2}$ $(Q \sim m_e)$

Phase Space Factor $G \sim G_F^4 g_A^4 m_e^5$

Nuclear Matrix Element $M(A,Z)$

Particle Physics of the Black Box η

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Particle Physics of the Black Box η

For light neutrino exchange

PMNS Matrix

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

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$m_{\beta\beta} \sim 1$ 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

Decay Rate for 0νββ

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~10 kg	$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years	Ruled out
~100 kg	$m_{\beta\beta} \sim 0.1$ eV $\Longrightarrow T_{1/2} \sim 10^{26}$ years	Current sensitivity
~1000 kg	$m_{\beta\beta} \sim 0.01$ eV $\Longrightarrow T_{1/2} \sim 10^{28}$ years	Next Generation

Decay Rate for 0νββ

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

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Phase Space Factor $G \sim G_F^4 g_A^4 m_e^5$

Nuclear Matrix Element $M(A,Z)$

Particle Physics of the Black Box η

For light neutrino exchange ← BUT.....

PMNS Matrix

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

~10 kg	$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years	Ruled out
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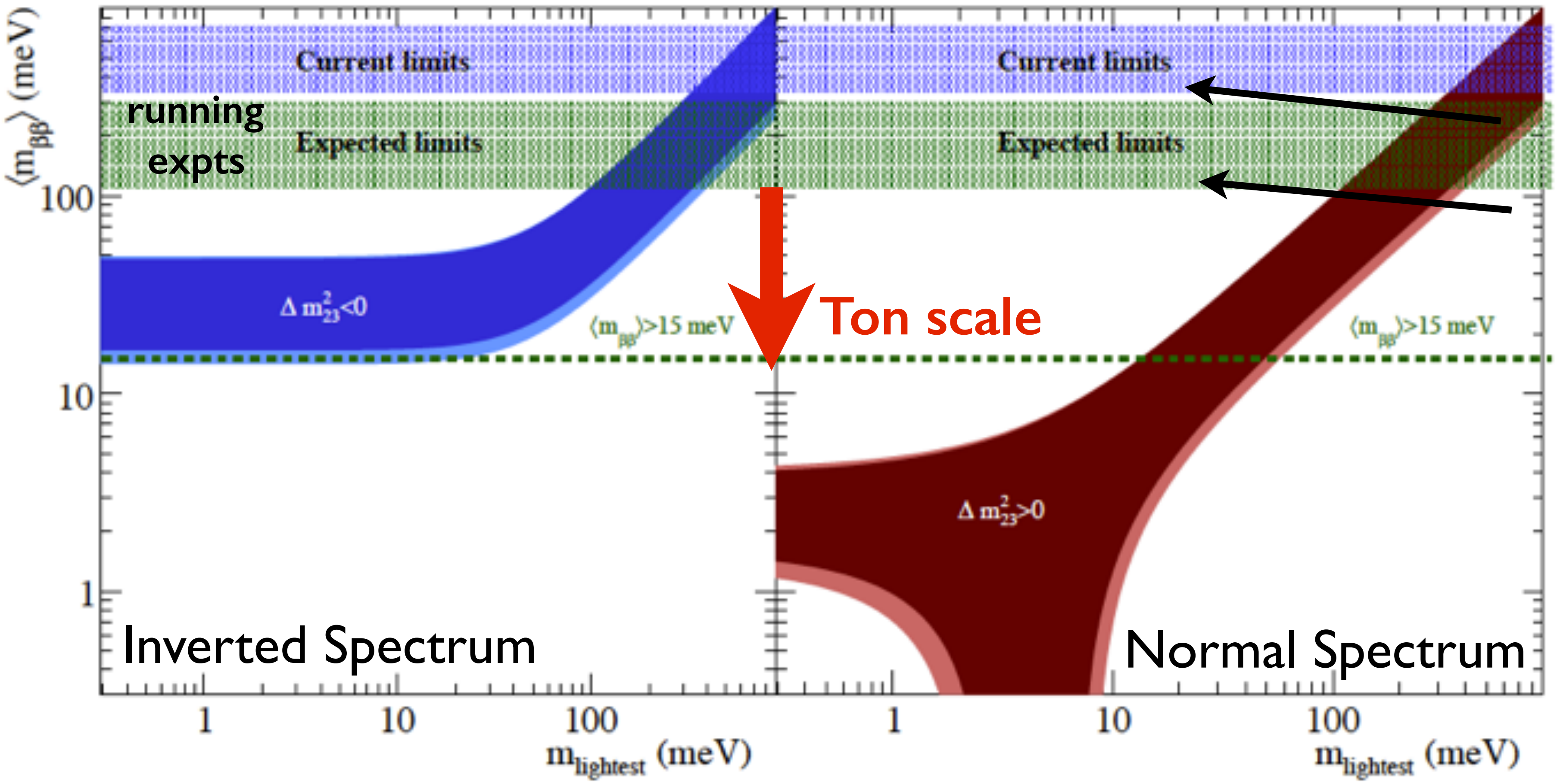
Various Possibilities for the Black Box

V. Cirigliano

- ton-scale 0νββ probes LNV from variety mechanisms, involving different scales (M) and coupling strengths (g)



Assume most "pessimistic" values for nuclear matrix elements

Dark bands:
unknown phases

Light bands:
uncertainty from oscillation parameters(90% CL)

- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

Various Possibilities for the Black Box

V. Cirigliano

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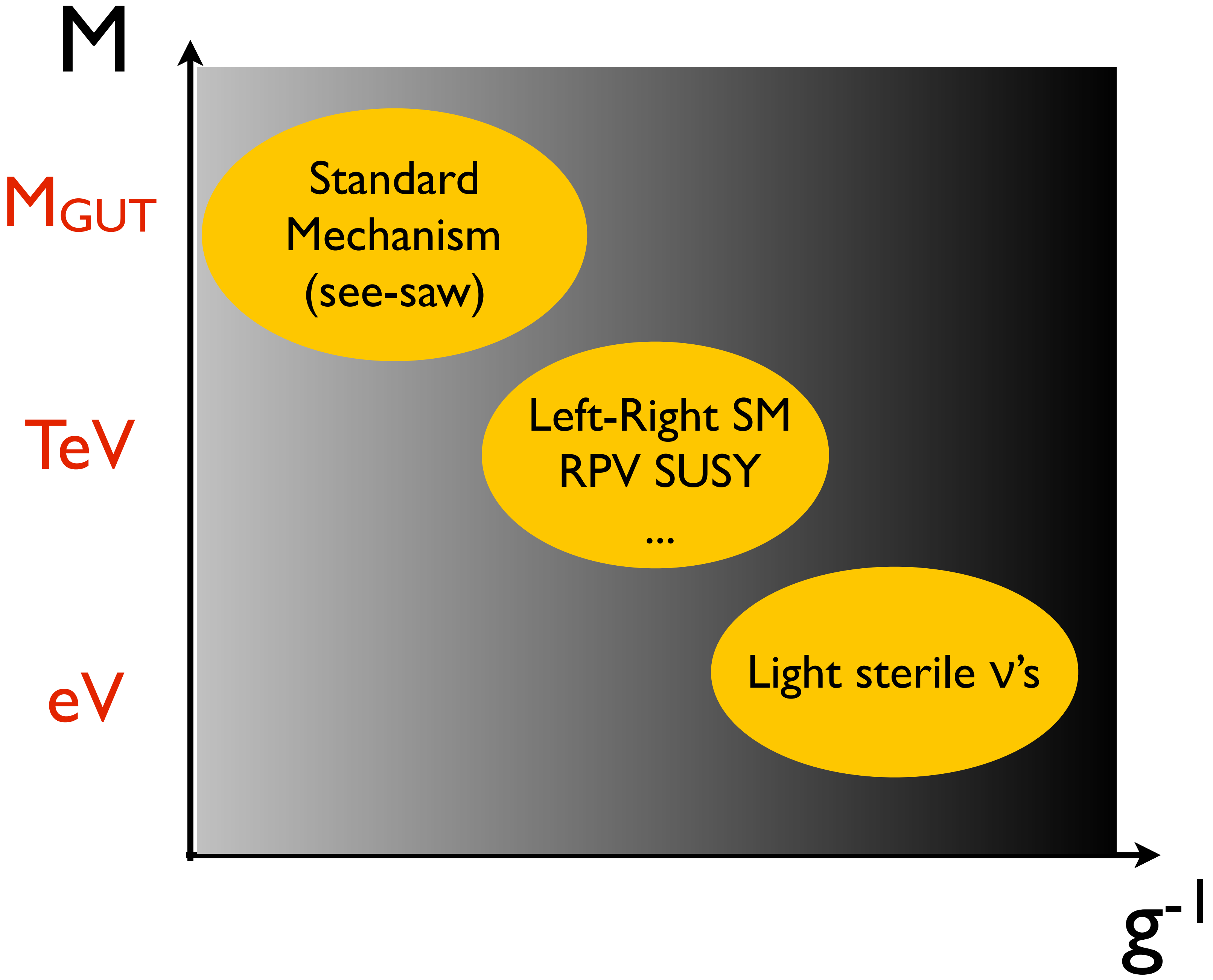
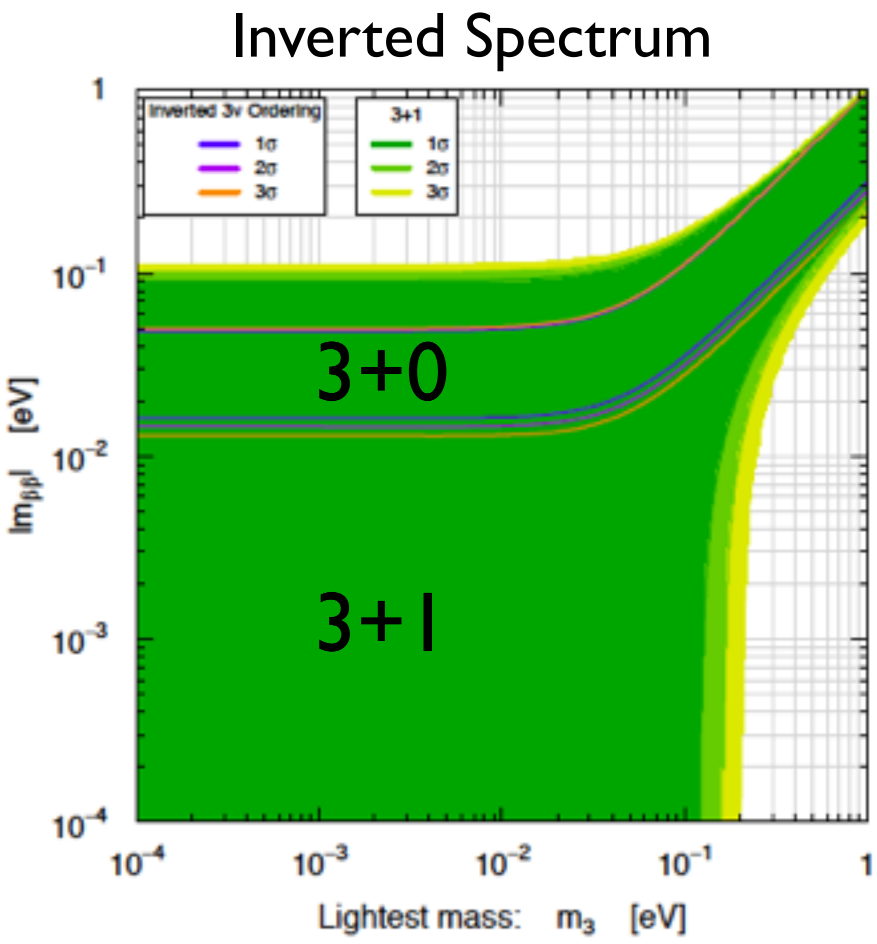
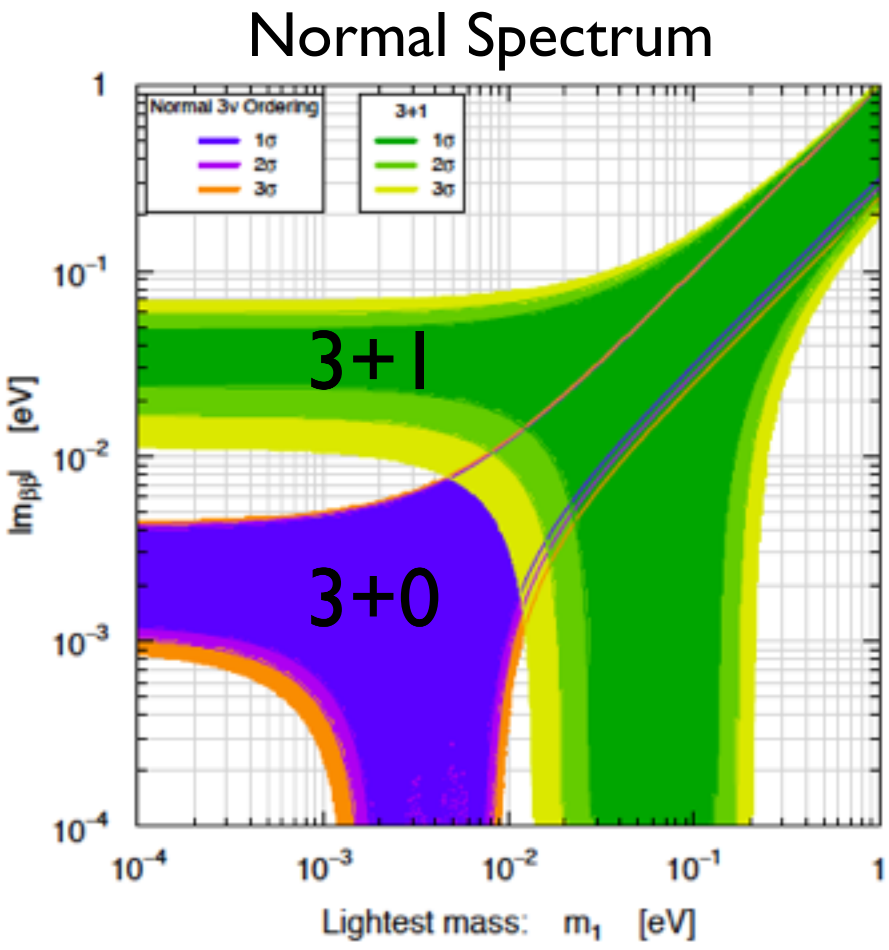


Various Possibilities for the Black Box

V. Cirigliano

- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass


Inverted Spectrum


Normal Spectrum

Giunti-Zavanin 2015

Usual phenomenology turned around!!

Neutrinoless Double Beta Decay: Experimental Status

Signal and Background

An experimental challenge of rare events

Most measured half-lives of 2νββ are O(10^{21}) years
- **Compare to lifetime of Universe: 10^{10} years**
- **Compare to Avogadro's number 6 x 10^{23}**
- **Mole of isotope will produce ~ 1 decay/day**

If it exists, half-lives of 0νββ would be longer (^{136}Xe limits is > 10^{25} years)

Half life **(years)**	**Signal** **(cts/tonne-year)**
10^{25}	500
$5\text{x}10^{26}$	10
$5\text{x}10^{27}$	1
$5\ \text{x}10^{28}$	0.1

Natural radioactivity: a nanogram produces more than 1 decay/day!
Cosmogenically induced radioactivity exacerbates technical challenge

$$\left[T^{0\nu}_{1/2}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

background free

$$\left[T^{0\nu}_{1/2}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

background limited

backgrounds do not always scale with detector mass

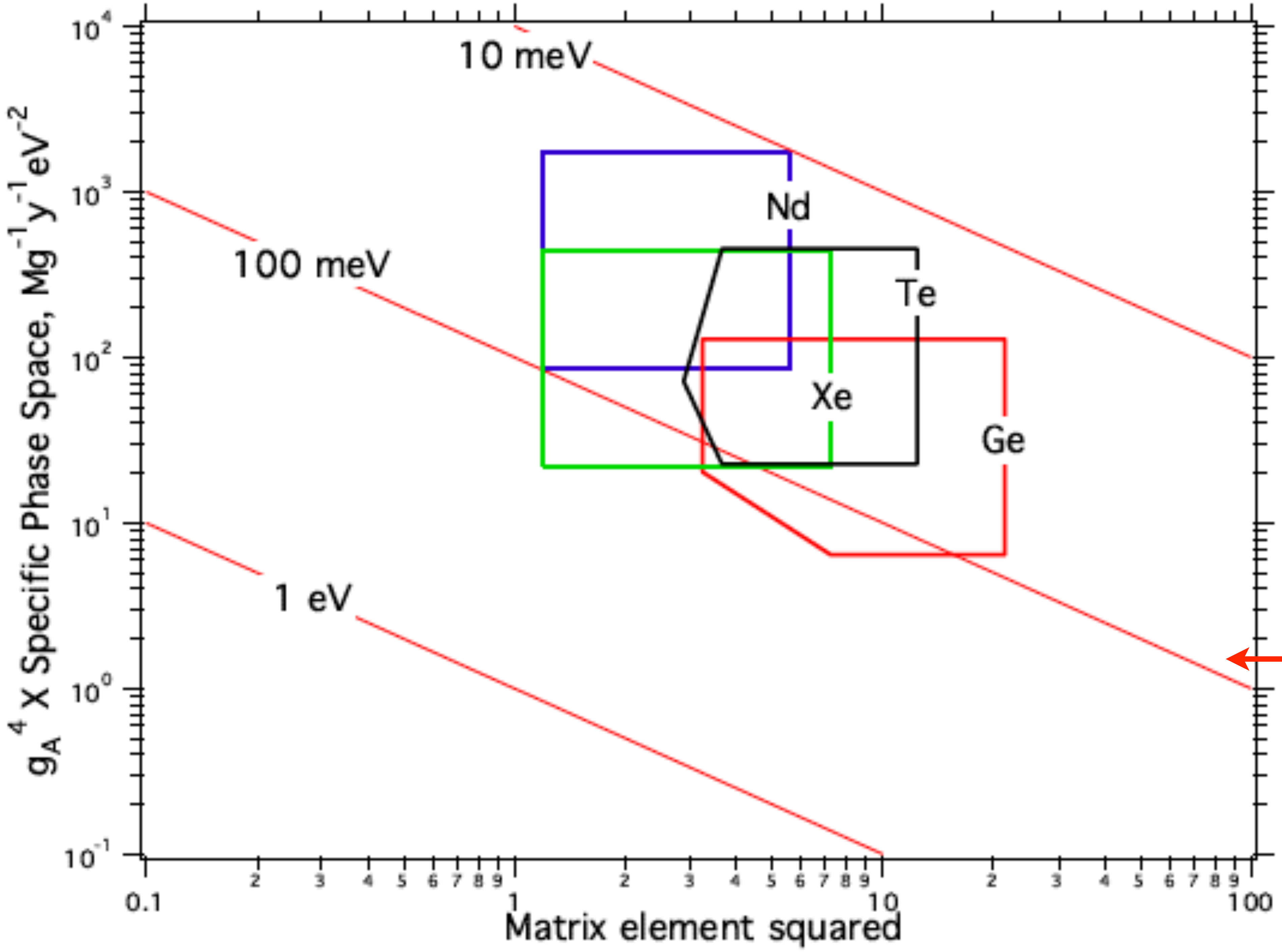
Courtesy: J. Wilkerson

Favorite Isotope?

For Ge, Te, Xe, Nd

← uncertainty on NME^2 →

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)



uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

The Experimental Challenge

0νββ source with

high isotopic abundance

Detector with

high detection efficiency

good energy resolution

low-background

Experiment

long exposure time

large total mass of isotope

$$T_{1/2}^{0\nu} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

a = source isotopic abundance

ϵ = detection efficiency

M = total mass

t = exposure time

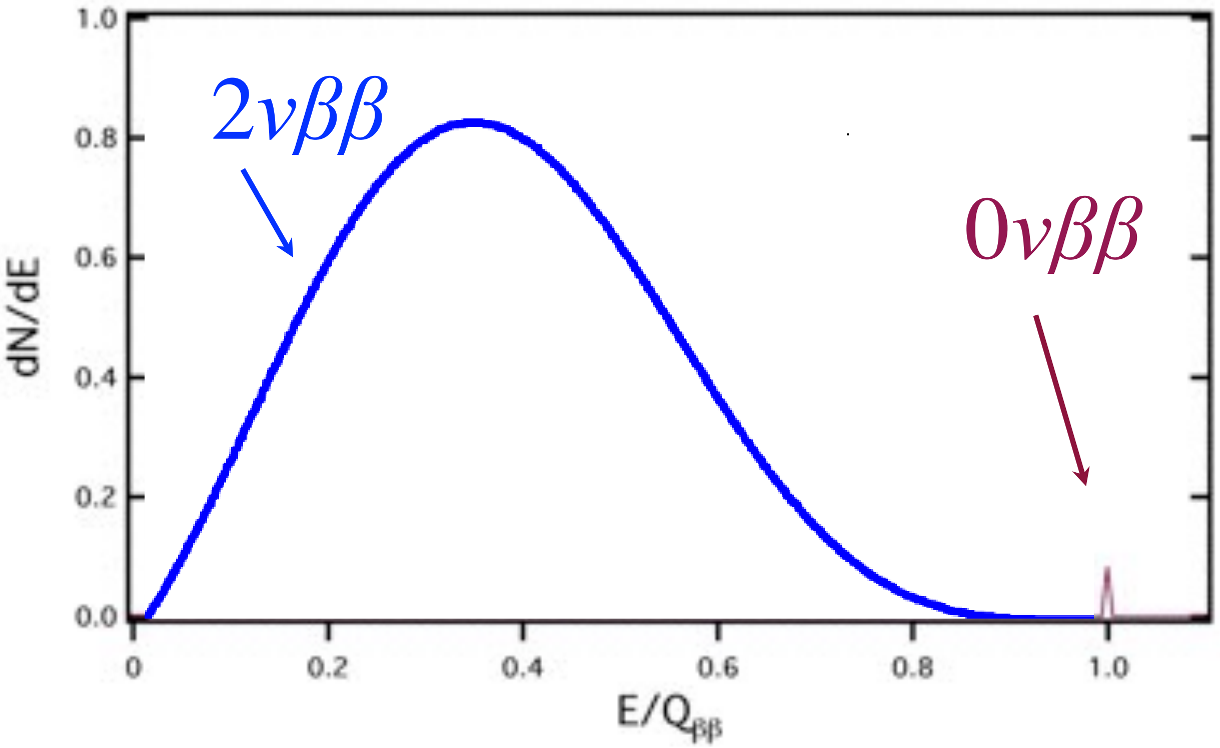
b = background rate at $0\nu\beta\beta$ energy

δE = energy resolution

To reach IH region requires sensitivities of

0νββ $T_{1/2} \sim 10^{27}$- 10^{28} years

(2νββ $T_{1/2} \sim 10^{19}$ - 10^{21} years)



Background Strategies

Potential Backgrounds

- Primordial, **natural radioactivity** in detector components: U, Th, K
- Backgrounds from **cosmogenic activation** while material is above ground (ββ-isotope or shield specific, ^{60}Co, ^{3}H...)
- Backgrounds from the **surrounding environment**:
  external γ, (α,n), (n,α), Rn plate-out, etc.
- **μ-induced backgrounds** generated at depth:
  Cu,Pb(n,n' γ), ββ-decay specific(n,n),(n,γ), direct μ
- **2 neutrino double beta decay** (irreducible, E resolution dependent)
- neutrino backgrounds (negligible)

Reduce Backgrounds

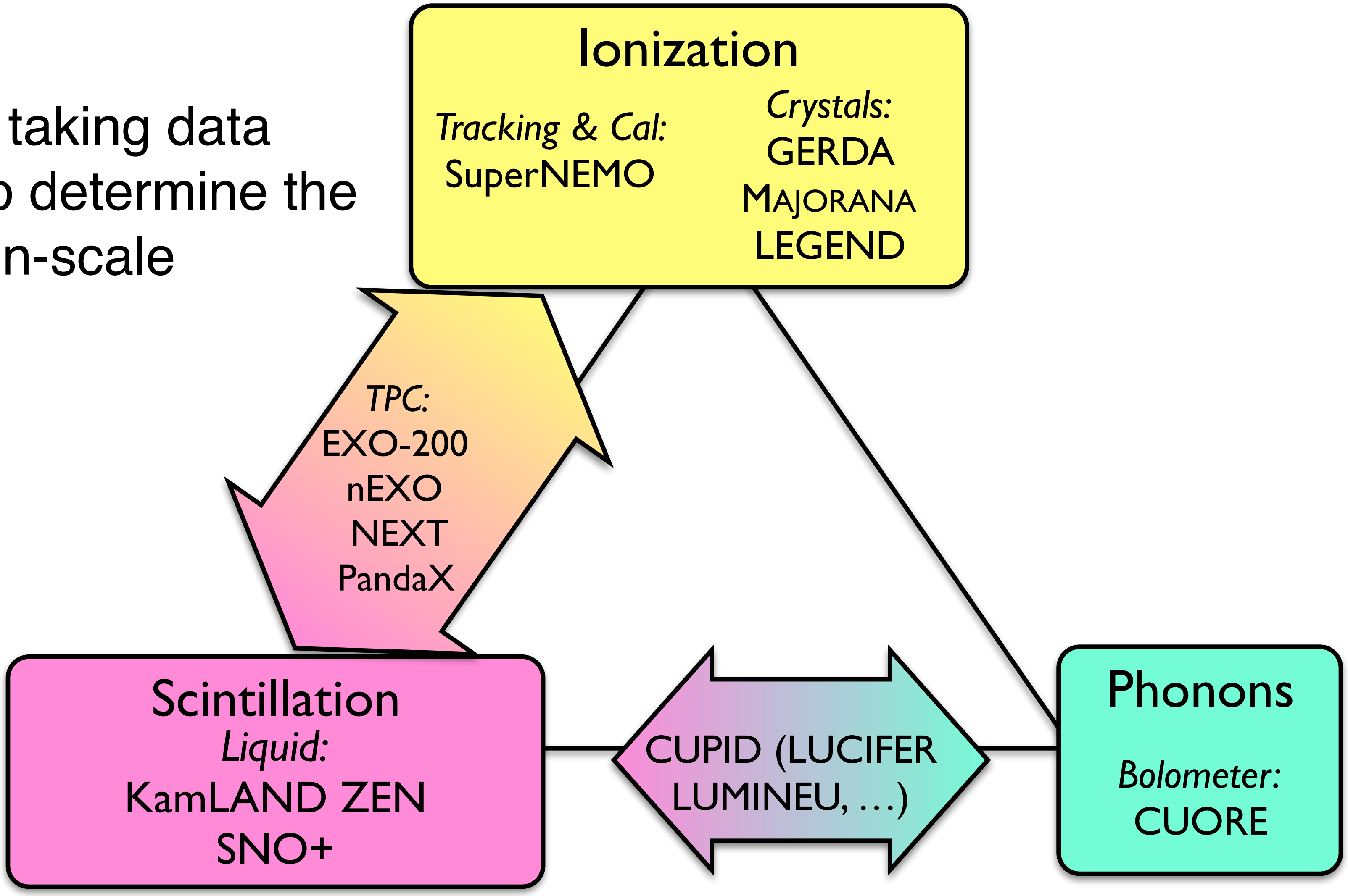
- ultra-pure materials
- shielding
- deep underground
- …

Discriminate Backgrounds

- energy resolution
- tracking (even topology)
- fiducial fits
- pulse shape discrimination (PSD)
- particle ID
- …

Multi-Prong Detection Strategy

- 100 kg class experiments currently taking data
- In parallel, major R&D under way to determine the optimum path to discovery at the ton-scale



Ionization

Tracking & Cal:
SuperNEMO

Crystals:
GERDA
MAJORANA
LEGEND

TPC:
EXO-200
nEXO
NEXT
PandaX

Scintillation
Liquid:
KamLAND ZEN
SNO+

CUPID (LUCIFER
LUMINEU, …)

Phonons
Bolometer:
CUORE

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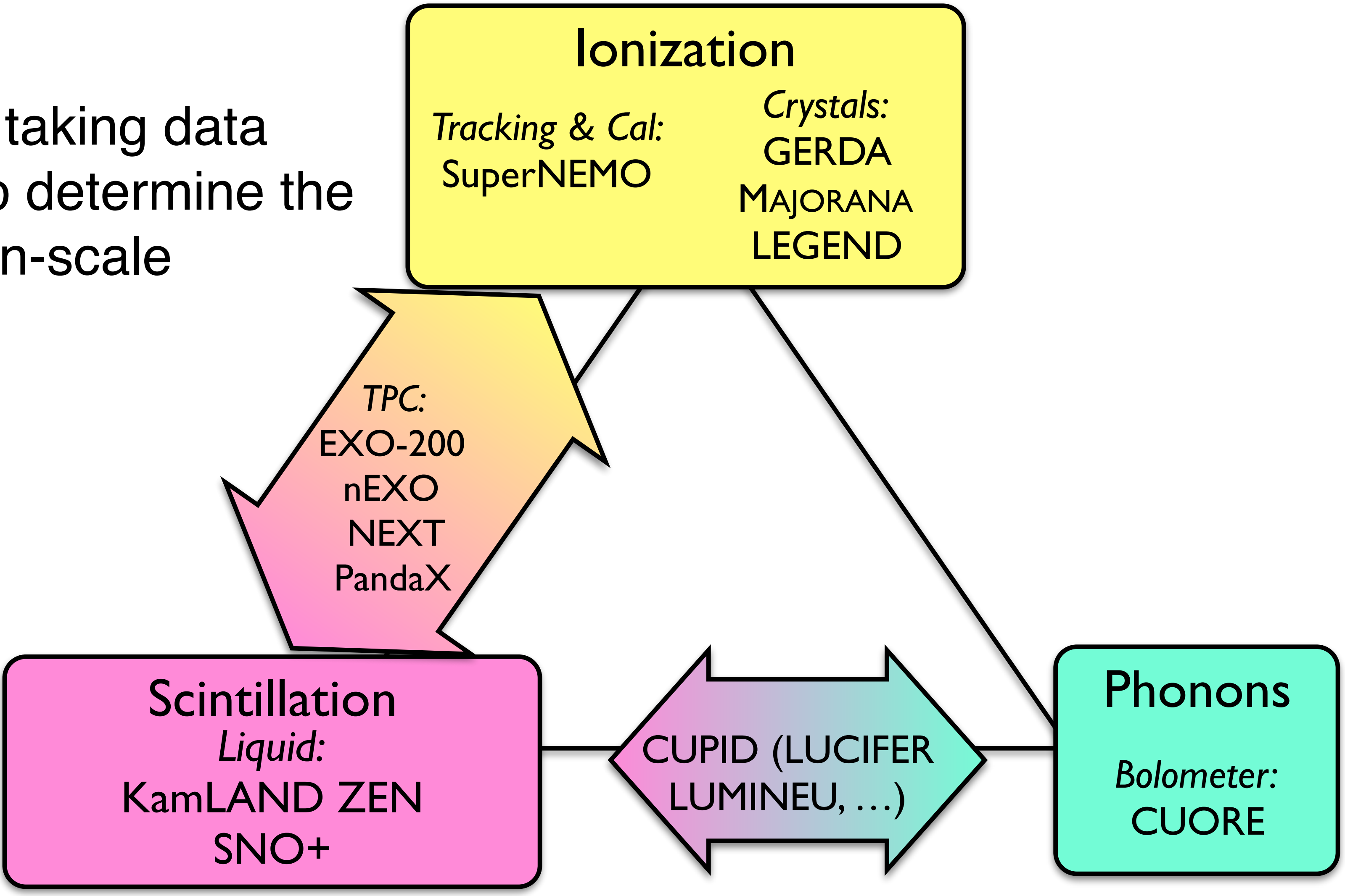

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms
- If light Majorana neutrinos are responsible for $0\nu\beta\beta$, then absolute neutrino mass scale determination within reach of ton-scale experiments

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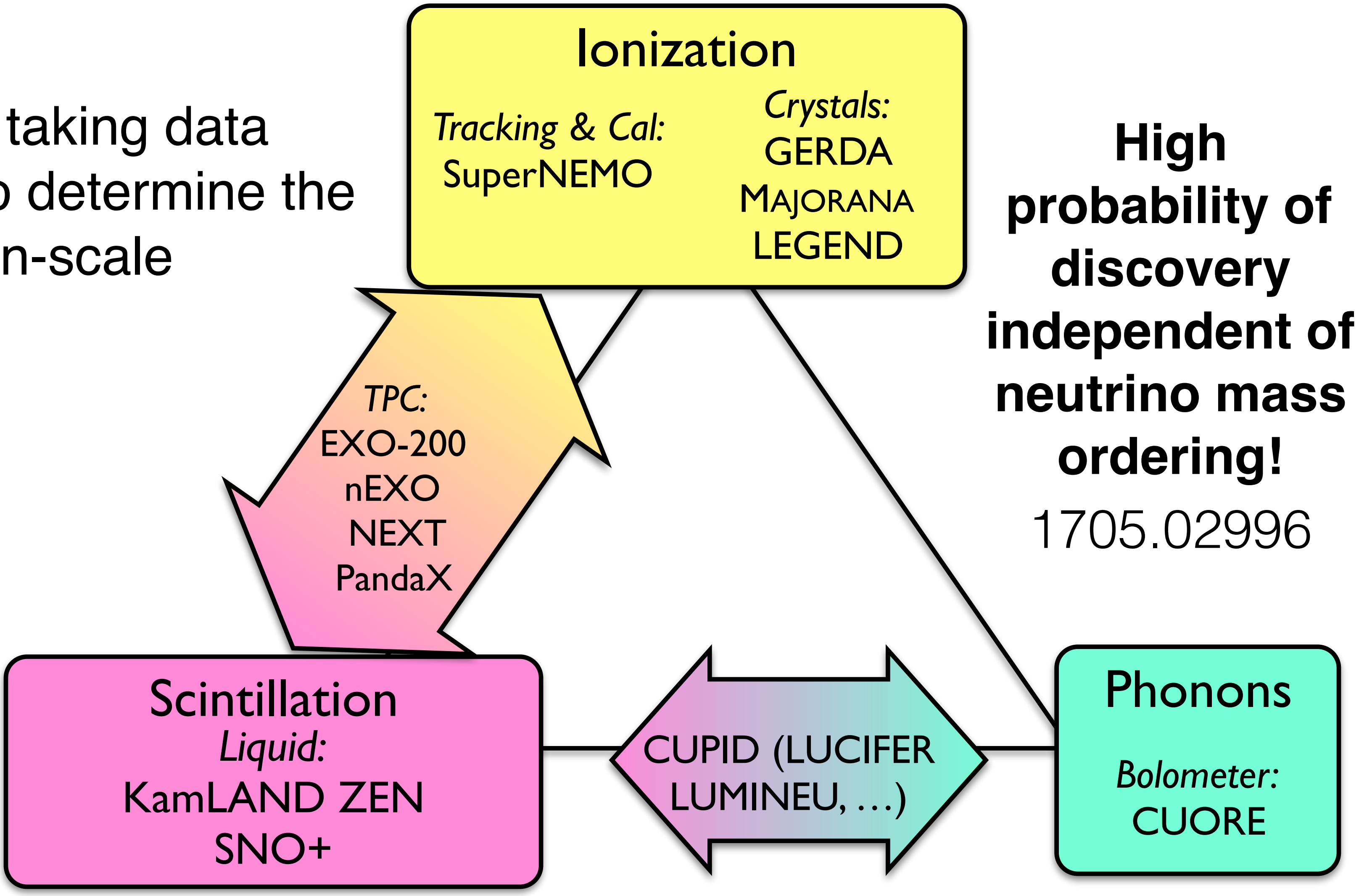

High probability of discovery independent of neutrino mass ordering!

1705.02996

- Ton-scale 0νββ searches ($T_{1/2}$ >$10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms
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Multi-Prong Detection Strategy

- 100 kg class experiments currently taking data
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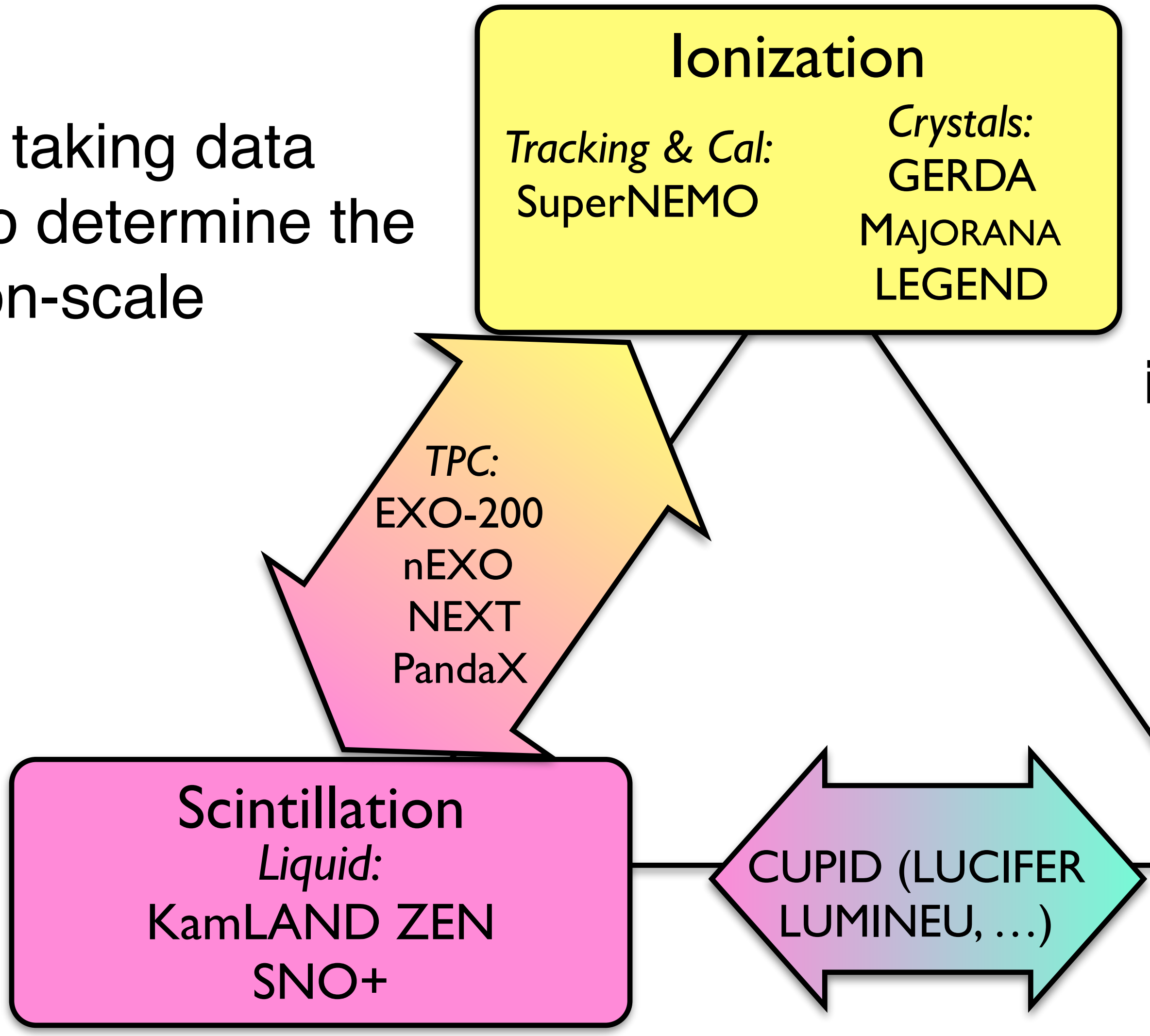
^{76}Ge, ^{130}Te, ^{136}Xe

Leading isotopes for successful ton-scale designs: most promising technologies have source = detector



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Courtesy: J. Wilkerson

International Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

1980 - 2007

2007 - 2019

2019 - mid-2020’s

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30 - 200 kg
~8 expts

If $0\nu\beta\beta$
Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

200-500 kg scale

1980 - 2007

2007 - 2019

2019 - mid-2020's

Courtesy: J. Wilkerson

International Program

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30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

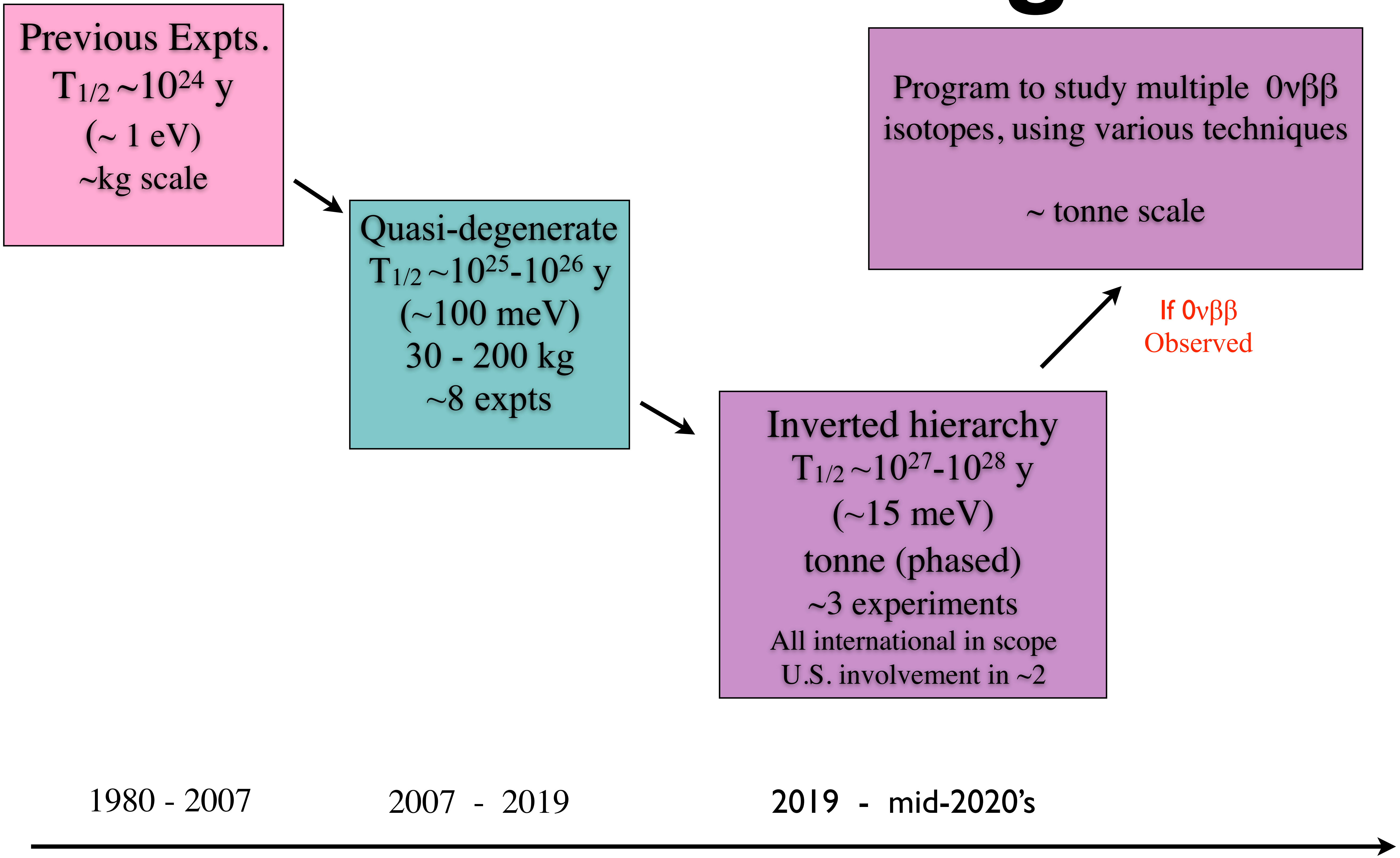
1980 - 2007

2007 - 2019

2019 - mid-2020's

Courtesy: J. Wilkerson

International Program



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tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

If $0\nu\beta\beta$
Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

~ tonne scale

1980 - 2007

2007 - 2019

2019 - mid-2020's

Courtesy: J. Wilkerson

International Program

Previous Expts.
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~kg scale

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$T_{1/2} \sim 10^{25}$-10^{26} y
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30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

Normal hierarchy
~5 meV
≥10's ton scale

1980 - 2007

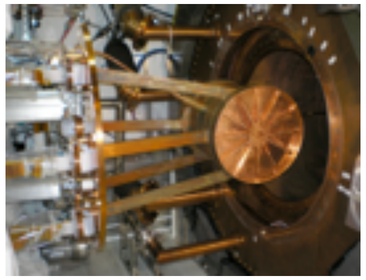
2007 - 2019

2019 - mid-2020's

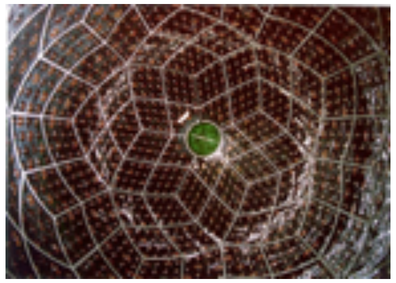
World Program

CUORE

EXO200



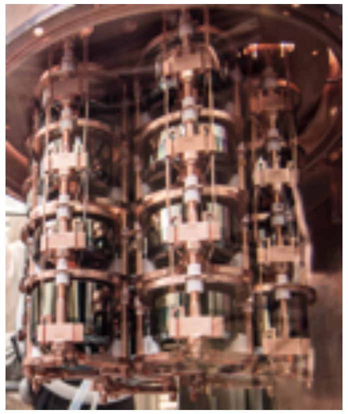
KamLAND Zen



Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF$_2$ crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	^{48}CaWO$_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO$_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	ZnMoO$_4$ / Li$_2$MoO$_4$ scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO$_2$ Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO$_2$ Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO$_2$ Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA



SNO+

Ton Scale Experiments

- Active international collaborations building on current efforts.
  - **^{76}Ge : LEGEND**, HPGE crystals, ~ton (builds on GERDA & MAJORANA)
  - ^{82}Se : SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale
  - ^{100}Mo : AMoRE : $CaMoO_4$ scint. bolometer, 200 kg scale
  - **^{136}Xe : nEXO** — Liquid TPC, 5 tons
    NEXT — High pressure gas TPC, ton scale
    PandaX - III — High pressure gas TPC, ton scale
    KamLAND-Zen — ^{136}Xe in scintillator, 800 kg scale
    LZ — ^{nat}Xe liquid TPC, 7 tons, operating 2019
  - **^{130}Te : CUPID (CUORE** with Particle ID) — Bolometer - Scintillation
    SNO+ Phase I & II — ^{130}Te in scintillator
- Experiments can be done in a staged (phased) approach. Most are considering stepwise increments.
- Isotope enrichment (^{76}Ge, ^{82}Se, ^{136}Xe) requires time and $s.
- Potential underground lab sites
  - SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L

Specific Examples: EXO-200 and future nEXO, LEGEND and CUPID

Advantages of ^{136}Xe

Isotopic enrichment easier & known: *Xe is a gas and ^{136}Xe is the heaviest isotope.*

Xenon is "reusable": *can be re-purified (noble gas: relatively easy) during measurement and easily recycled into a different detector (no crystal growth)*

.... replace ^{136}Xe with $^{nat'l}$Xe if signal observed

Monolithic detector: *LXe is self shielding, surface contamination minimized.*

Minimal cosmogenic activation: *no long lived radioactive isotopes of Xe.*

Energy resolution in LXe improved: *scintillation light + ionization anti-correlation.*

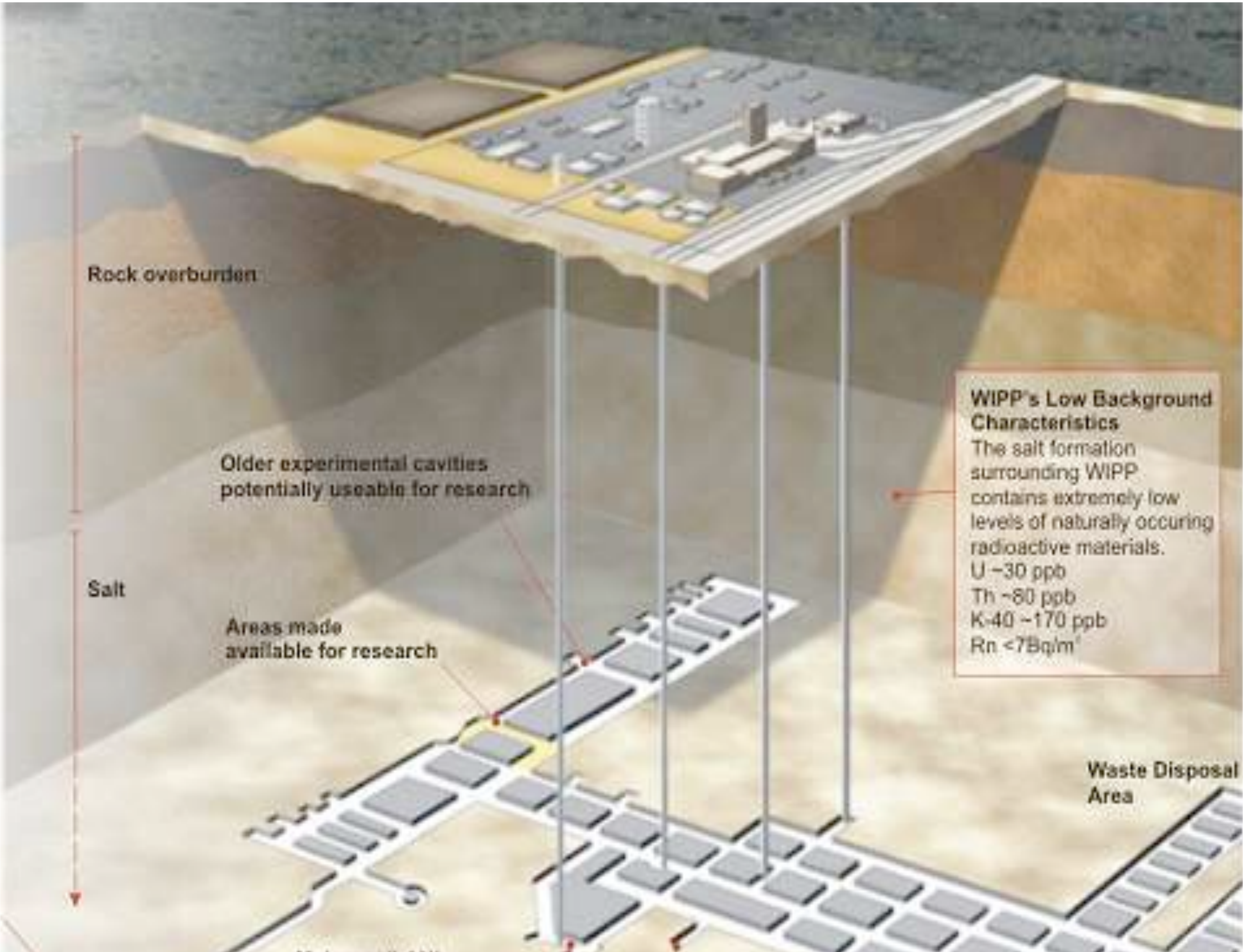
Standard $2\nu\beta\beta$ is slow! (see later): *get away with modest energy resolution*

… admits a novel coincidence technique: *background reduction by Ba tagging*

.... potentially access normal hierarchy

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP

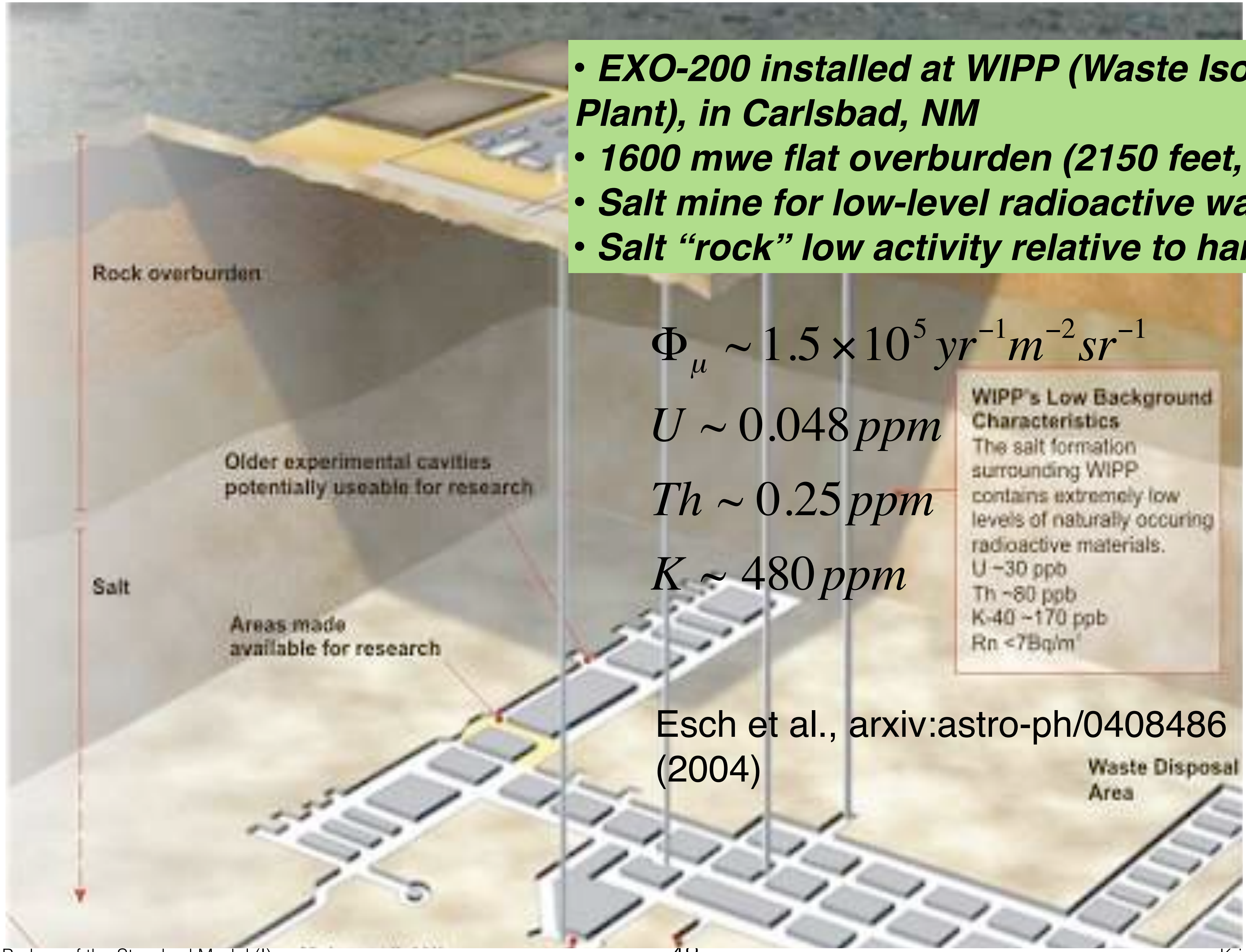


WIPP's Low Background Characteristics
The salt formation surrounding WIPP contains extremely low levels of naturally occuring radioactive materials.
U ~30 ppb
Th ~80 ppb
K-40 ~170 ppb
Rn <7Bq/m³

Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP

- *EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM*
- *1600 mwe flat overburden (2150 feet, 650 m)*
- *Salt mine for low-level radioactive waste storage*
- *Salt "rock" low activity relative to hard-rock mine*



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U ~30 ppb
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K-40 ~170 ppb
Rn <7Bq/m^3

$$\Phi_\mu \sim 1.5 \times 10^5\, yr^{-1} m^{-2} sr^{-1}$$

$$U \sim 0.048\, ppm$$

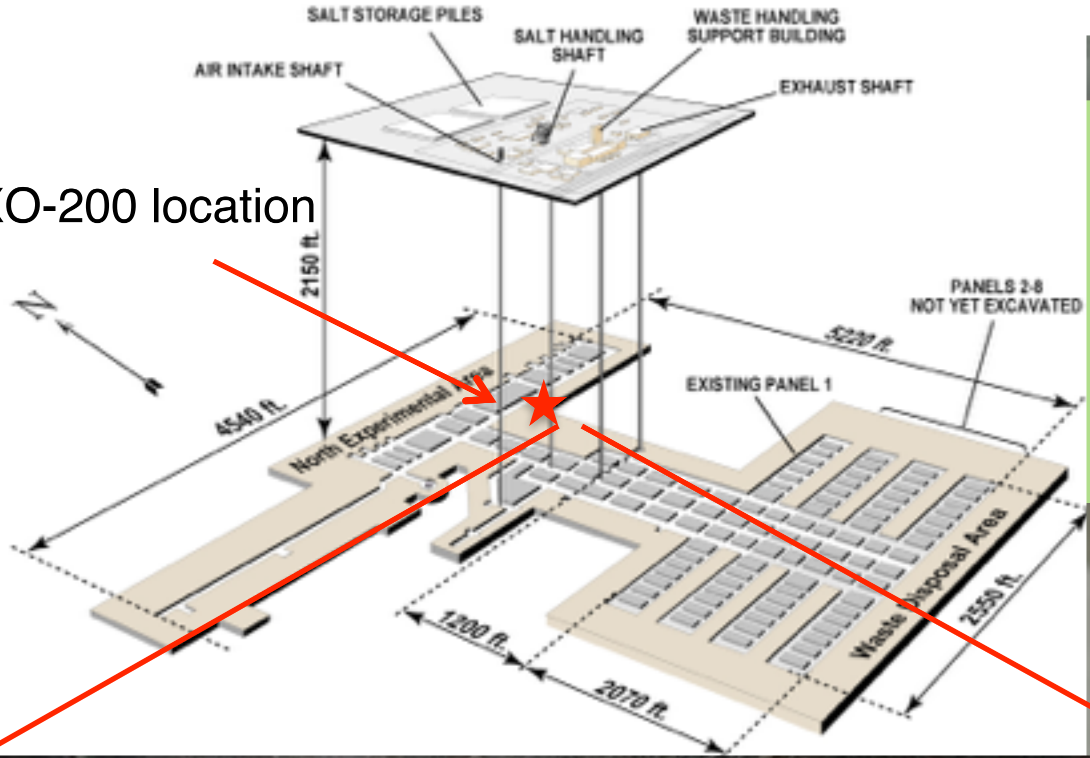
$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$

Esch et al., arxiv:astro-ph/0408486 (2004)

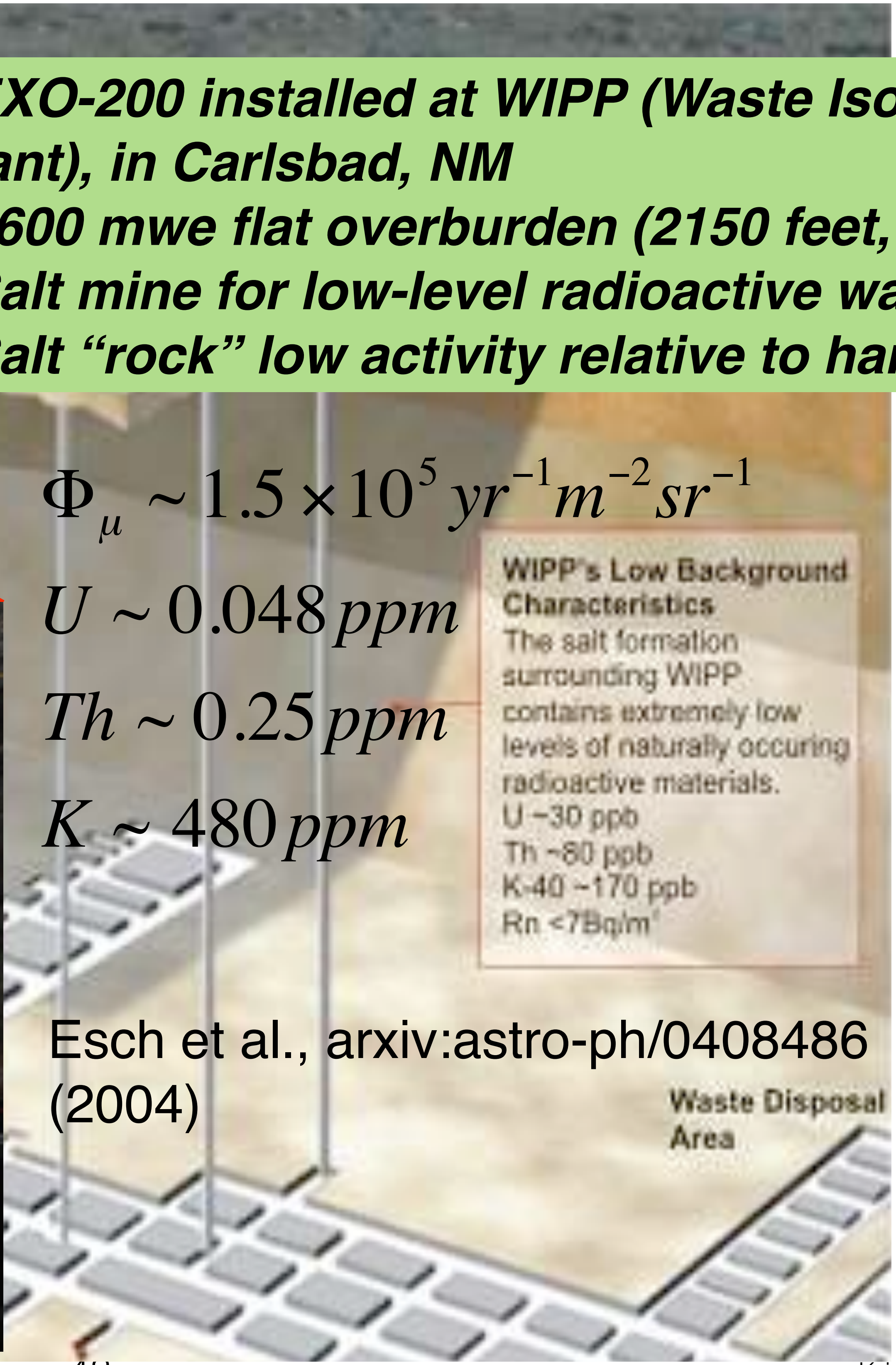
Waste Isolation Pilot Plant, Carlsbad, NM

EXO-200 at WIPP



EXO-200 location

- ***EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM***
- ***1600 mwe flat overburden (2150 feet, 650 m)***
- ***Salt mine for low-level radioactive waste storage***
- ***Salt "rock" low activity relative to hard-rock mine***



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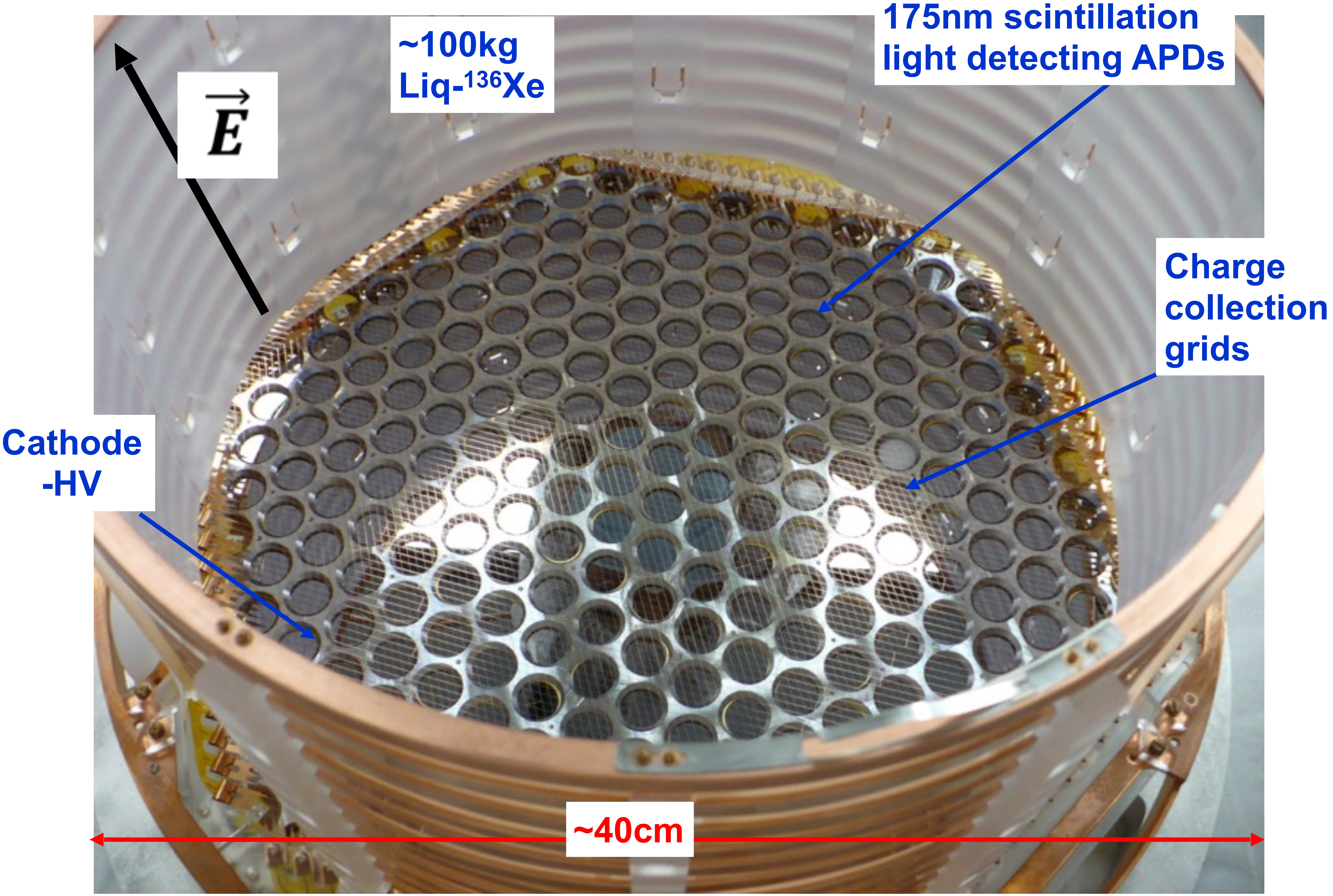
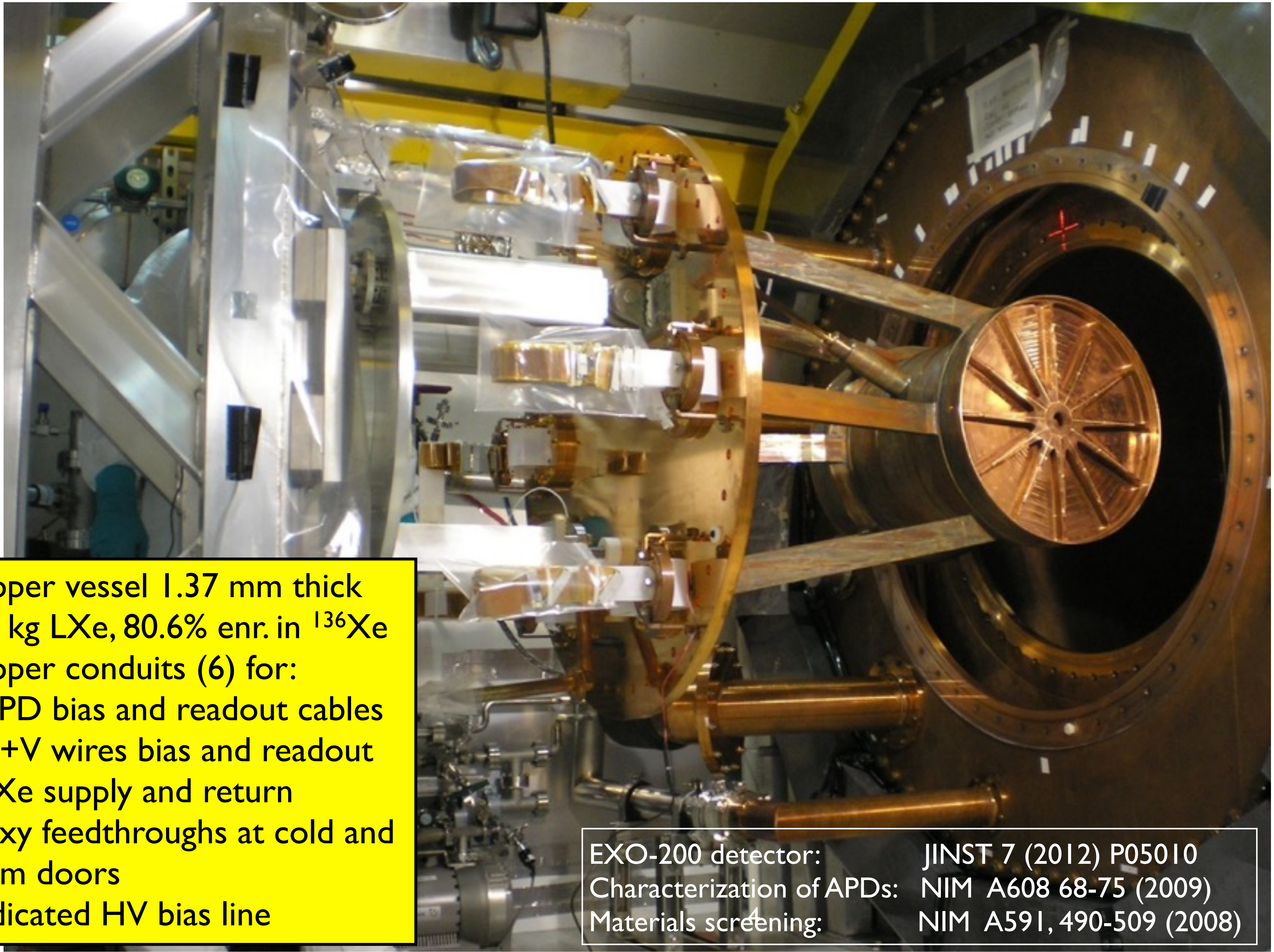
The EXO-200 TPC



TPC Entering the Cryostat



Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in ^{136}Xe
Copper conduits (6) for:

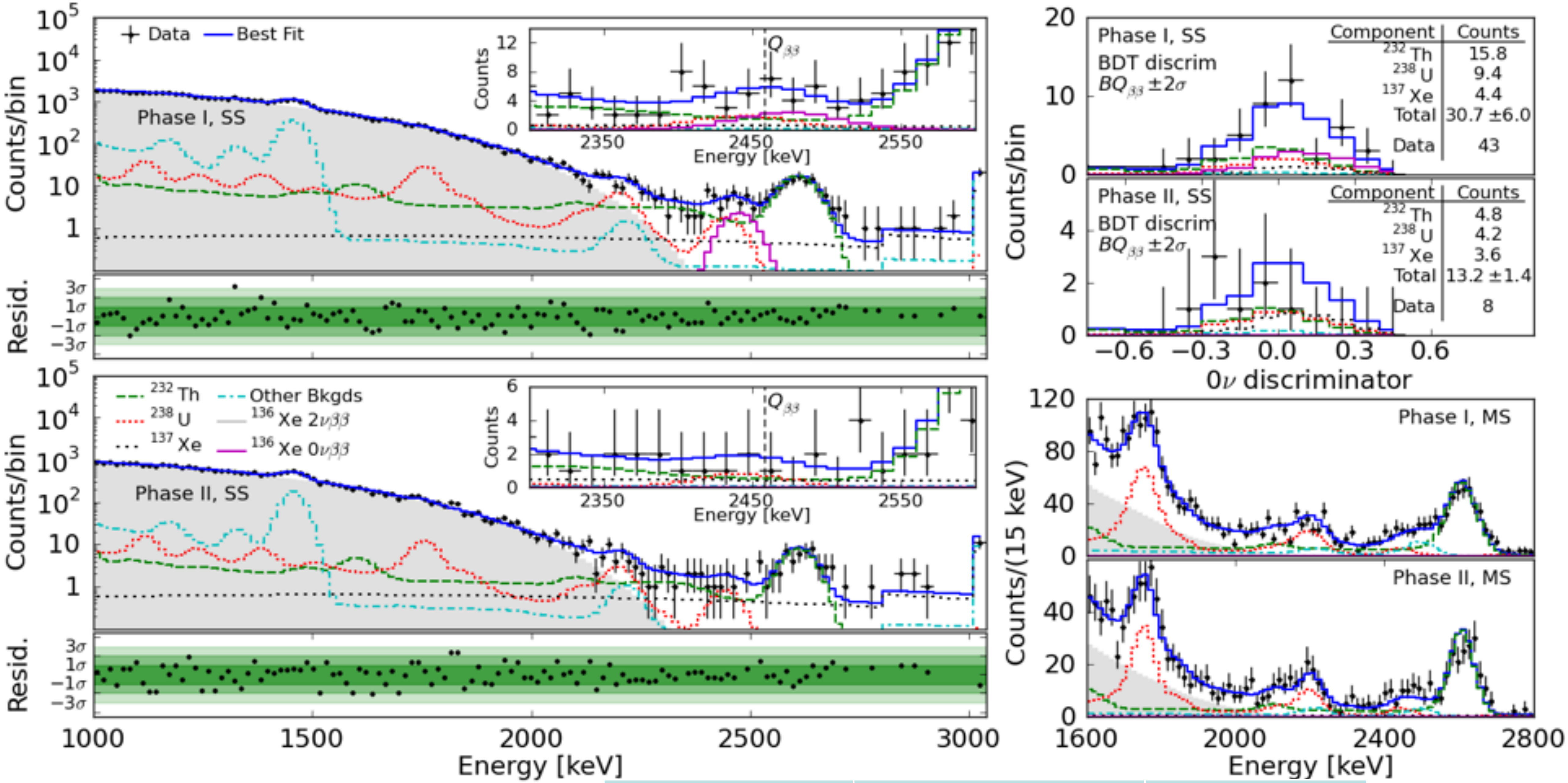
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

EXO-200: Recent Results

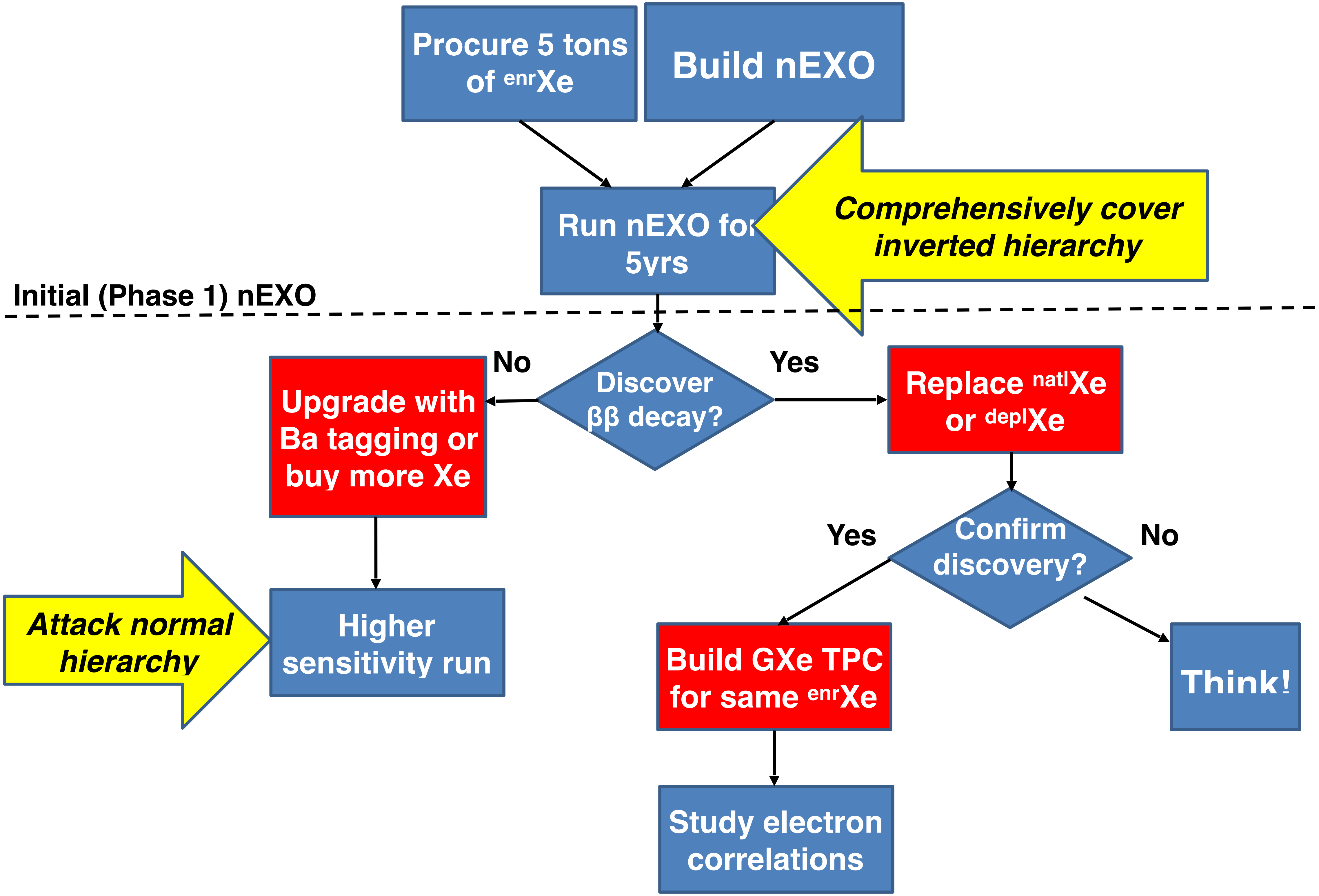
- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profiles



	Sensitivity (yr)	**90% CL Limit (yr)**	**<$m_{\beta\beta}$> (meV)**
PRL 120 072701 (2018)	**3.8×10^{25}**	**1.8×10^{25}**	**147-398**

nEXO Strategy

Flexible program based on the initial nEXO investment



Procure 5 tons of $^{\text{enr}}$Xe

Build nEXO

Run nEXO for 5yrs

Comprehensively cover inverted hierarchy

Initial (Phase 1) nEXO

Discover ββ decay?

No

Upgrade with Ba tagging or buy more Xe

Higher sensitivity run

Attack normal hierarchy

Yes

Replace $^{\text{natl}}$Xe or $^{\text{depl}}$Xe

Confirm discovery?

Yes

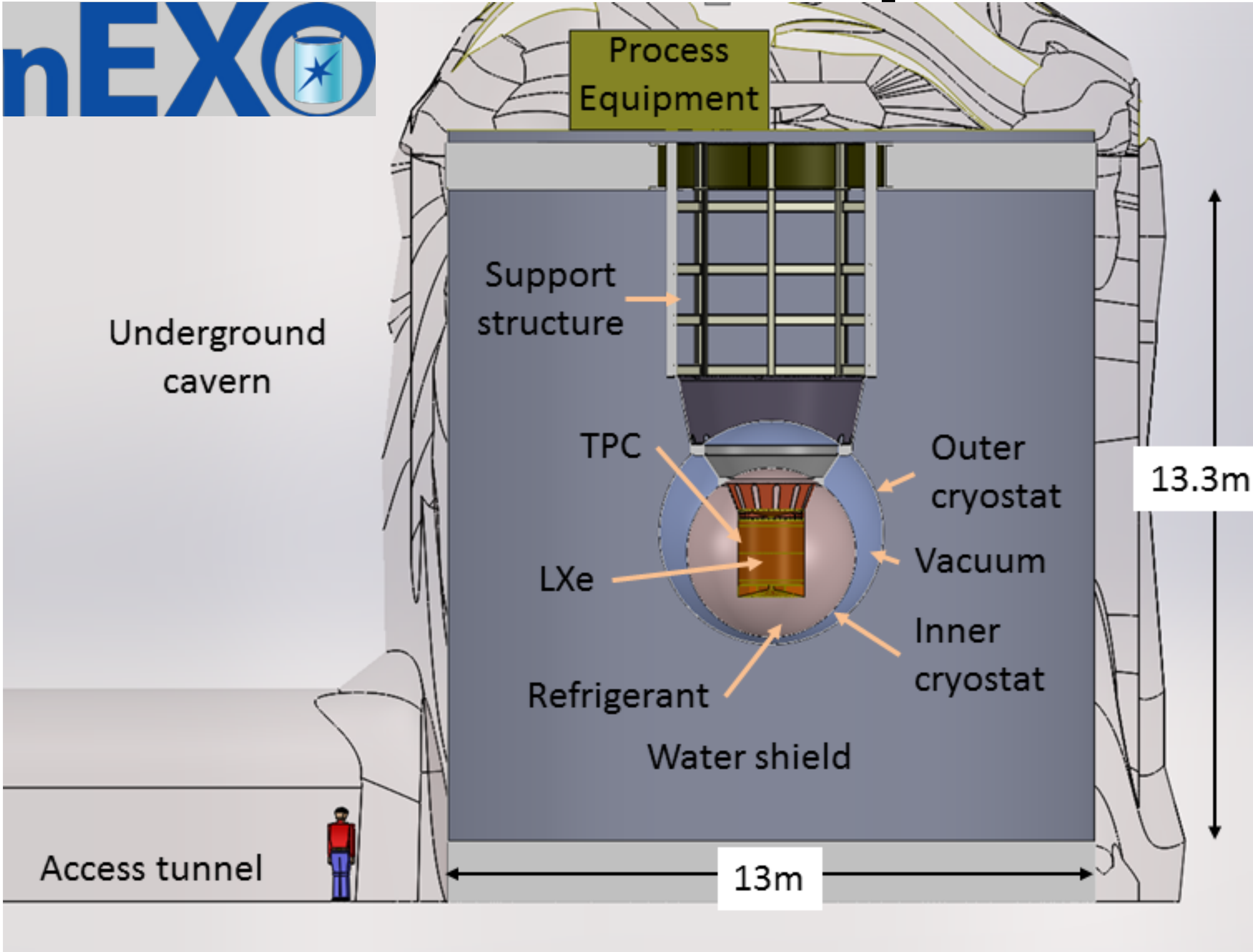
Build GXe TPC for same $^{\text{enr}}$Xe

Study electron correlations

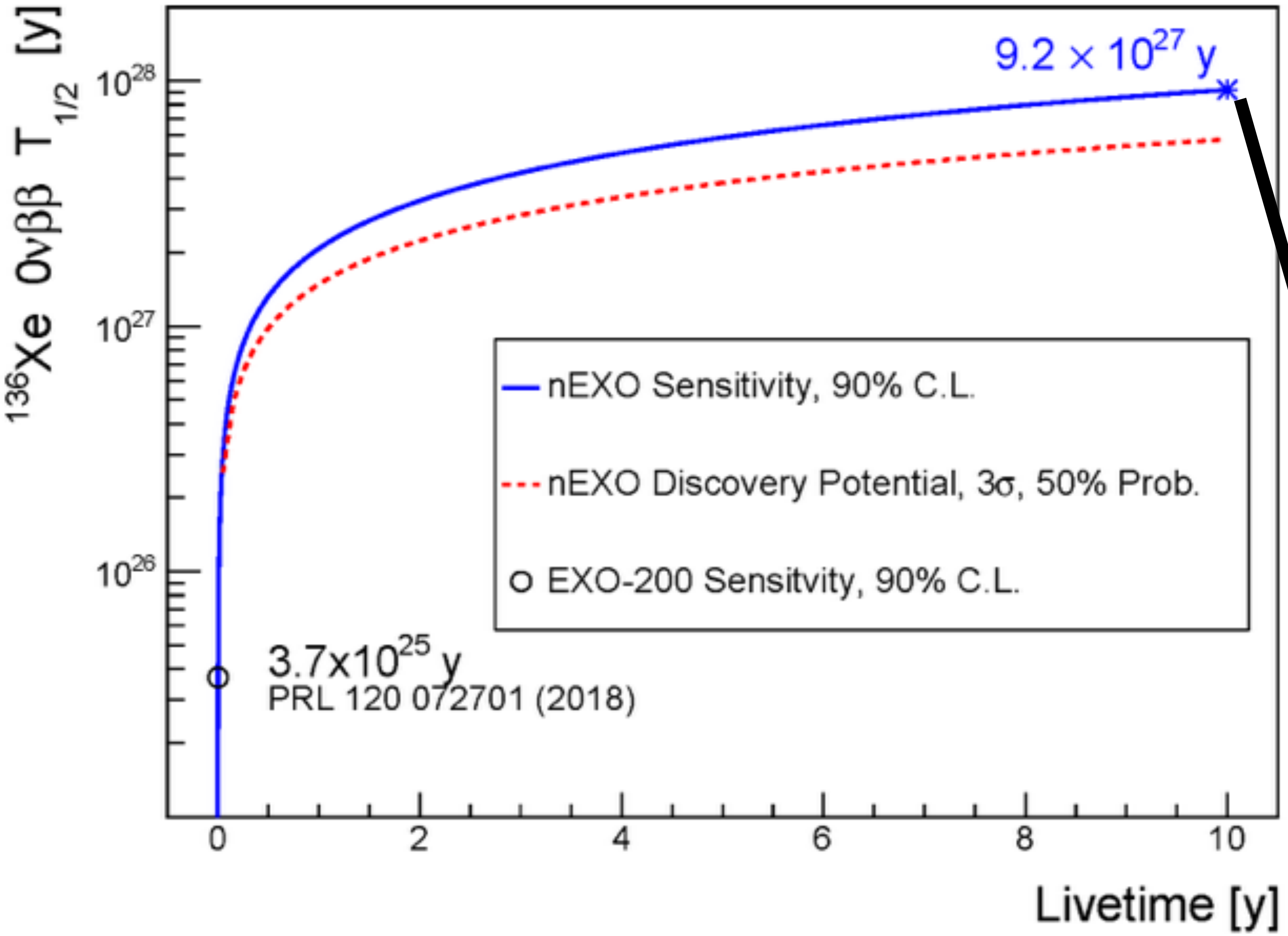
No

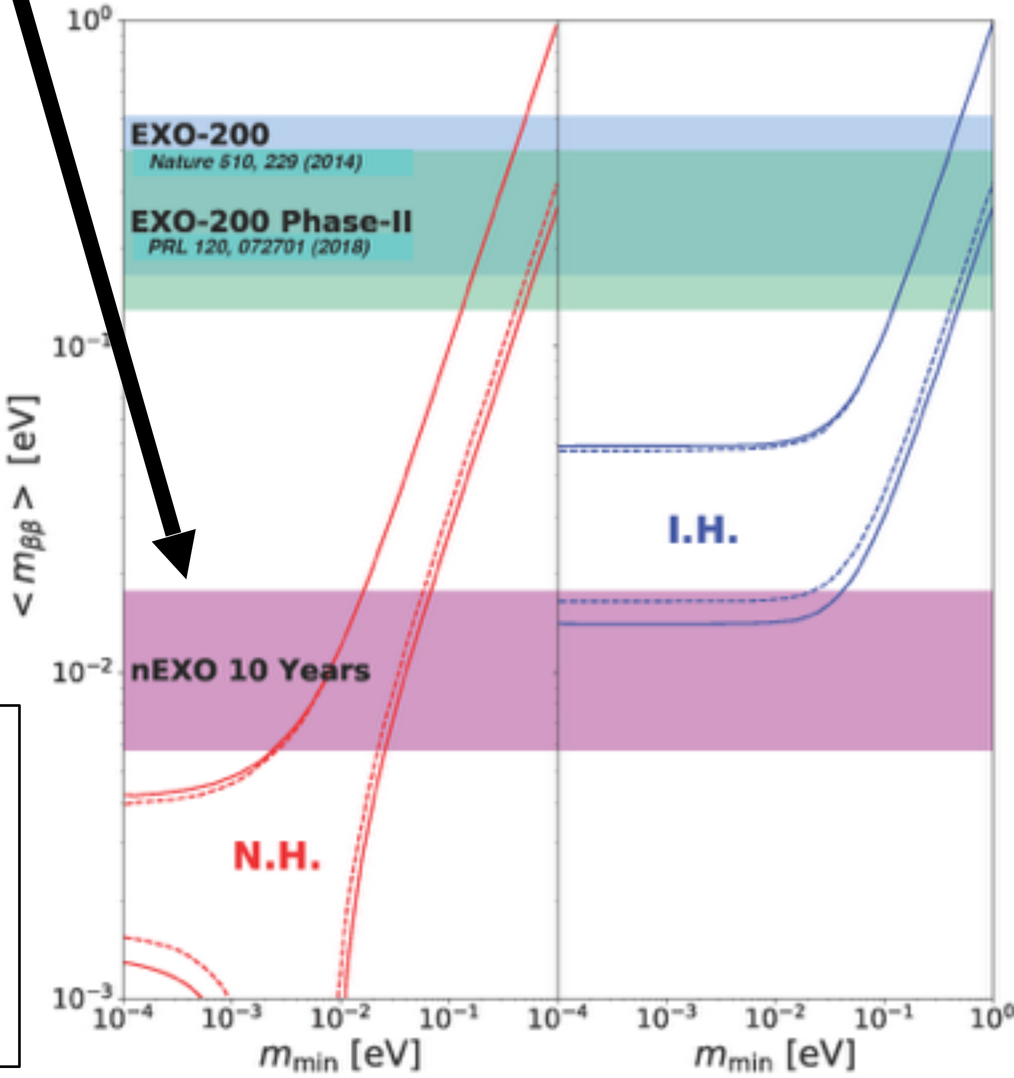
Think!

nEXO Concept



nEXO: Discovery Reach





- **$g_A = g_A^{free}$=-1.2723**
- **Band is the envelope of NME:**

EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

^{76}Ge: LEGEND

Mission: The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.

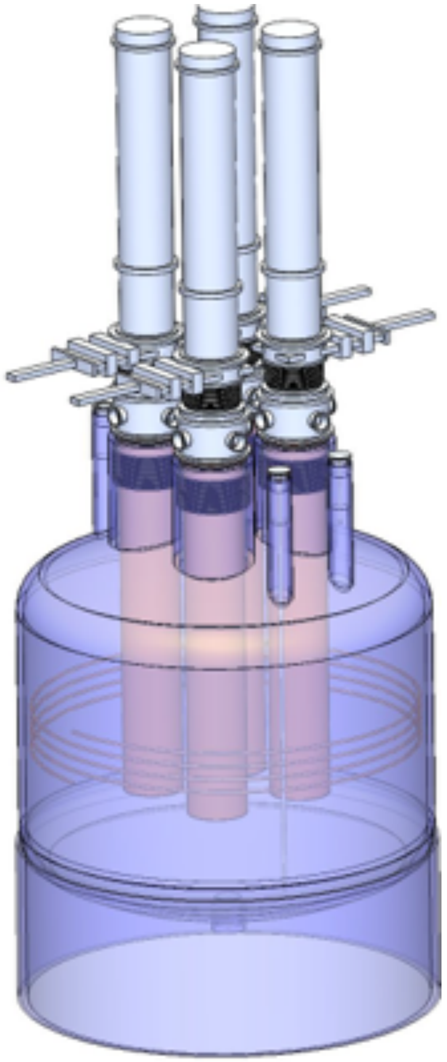
Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First Phase:

- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c /(FWMH t y)
- start by 2021

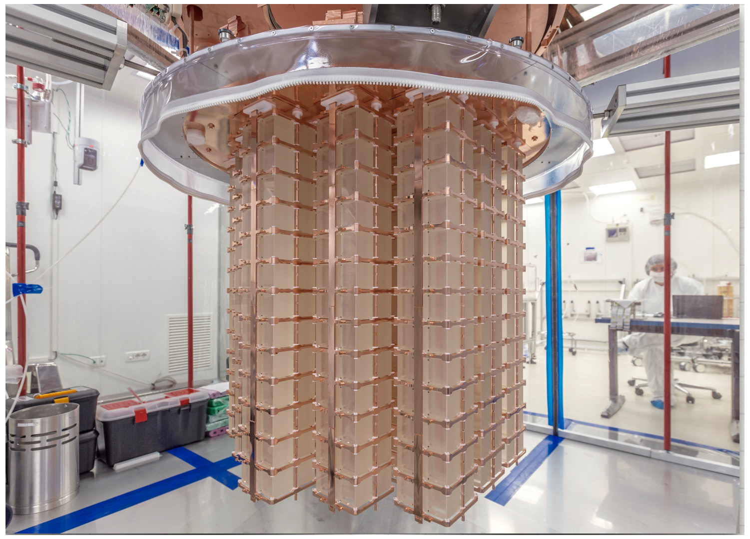
Subsequent Stages:

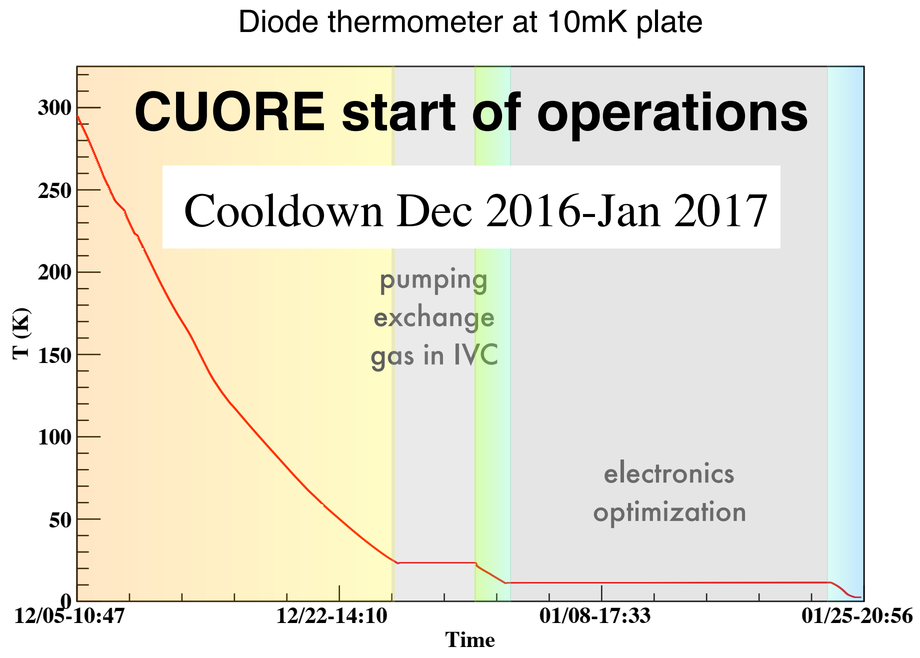
- 1000 kg (staged)
- timeline connected to U.S. DOE down selec process
- BG: goal (x30 lower) 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (^{77m}Ge) under investigation

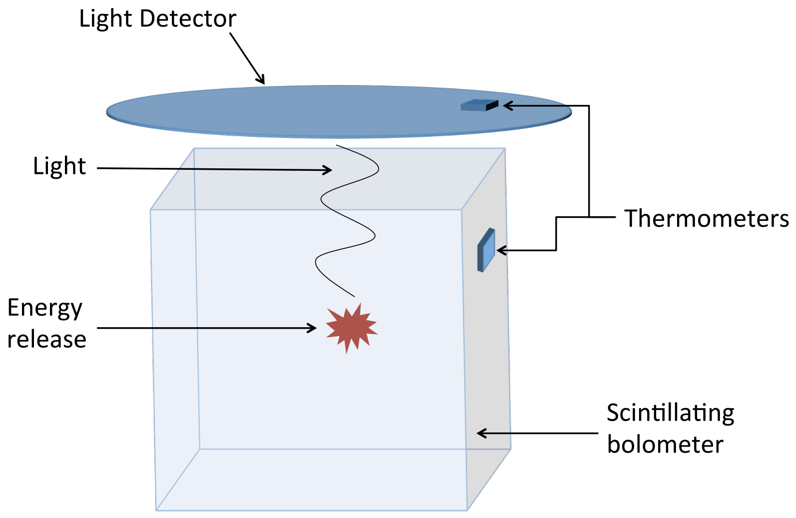


^{130}Te: CUORE/CUPID

CUORE detectors installed







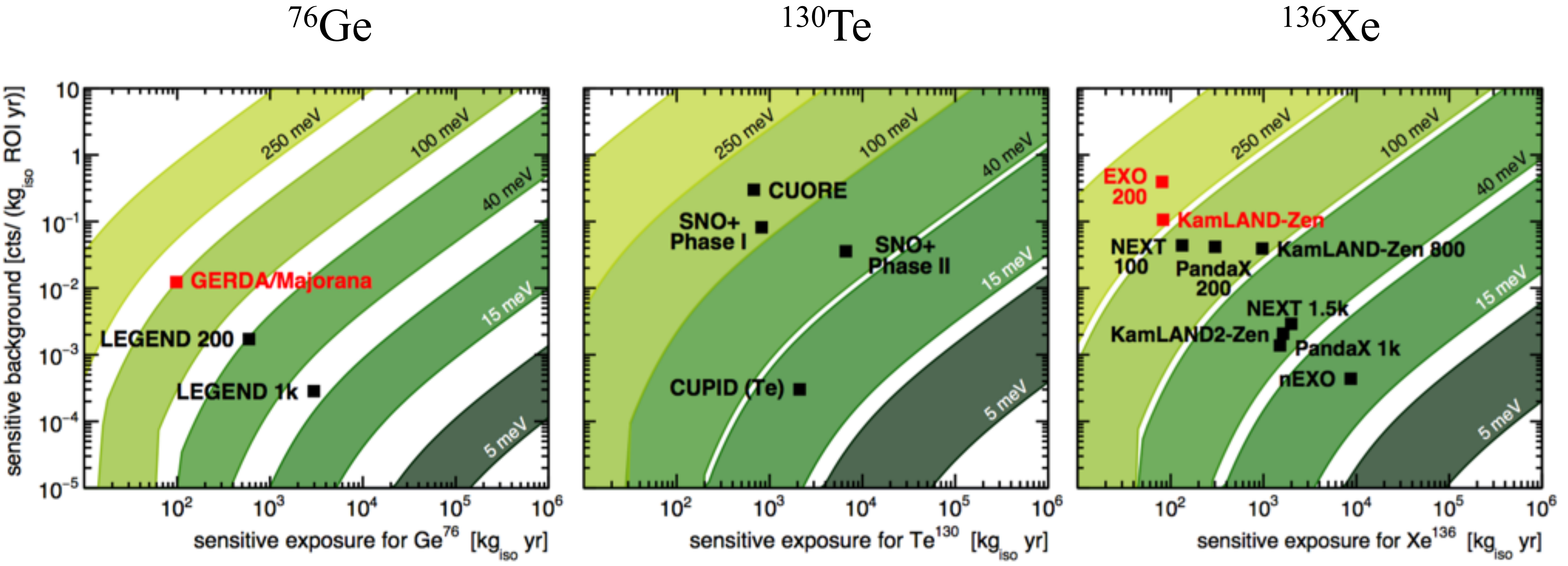
Next-generation bolometric tonne-scale experiment based on the CUORE design, proven CUORE cryogenics

- CUORE Milestones:
  - Tower installation: Jul-Aug 2016
  - Cryostat closeout: Nov 2016
  - Cooldown: Dec-Jan 2016
  - Commissioning and initial performance optimization: Jan-May 2017
  - First science run: May 2017
- Cryostat performs very well: base T < 7 mK
- >95% of detectors operational
- First data reported in Summer 2017

- Intense CUPID R&D effort in the next 2-3 years
  - ☞ US focus: ^{130}TeO$_2$ enrichment and purification, high-resolution sensors for Cherenkov light
  - ☞ Complementary European efforts
  - ☞ Background goal is 0.1 cts/ROI-t-yr; achieve sensitivity to the full Inverted Hierarchy
  - ☞ Other important R&D: detailed background analysis, cosmogenic backgrounds @ LNGS — to be addressed before downselect
  - ☞ Worldwide efforts: 8 countries, 32 institutions
  - ☞ Data from CUORE and pilot detectors will drive technology and isotope choice

Discovery Sensitivity Comparison

Discovery probability of next-generation neutrinoless double-beta decay experiments
Matteo Agostini, Giovanni Benato, and Jason Detwiler arXiv:1705.02996v3



Red : Achieved Backgrounds; Black : Projected Backgrounds

Width of bands based on range of NME values

Summary and Outlook

- ✦ **Low Energy Weak Neutral Current Interactions**
  - ★ Central to our understanding of the Standard Model
  - ★ Remains relevant for BSM searches, especially flavor-diagonal
- ✦ **Parity-Violating Electron Scattering in the next decade**
  - ★ Technical progress has enabled unprecedented precision
  - ★ Flagship experiments at electron accelerators
  - ★ Fundamental Nuclear/Nucleon as well as EW/BSM physics
- ✦ **Atomic Parity Violation and Neutrino Scattering**
  - ★ The low Q region might become important in the future!
  - ★ Neutrino scattering should be investigated in any case…
- ✦ **Neutrinoless Double Beta Decay Searches**
  - ★ The Majorana nature of neutrinos: pressing BSM question
  - ★ Discovery of lepton number violation would have wide implications
  - ★ The next generation experiments will attack the inverted hierarchy
  - ★ R&D to go further to the normal hierarchy has already begun