Searches for BSM Physics at Low Energy

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Acknowledgements:
(likely incomplete!)

R. Bernstein, V. Cirigliano, J. Erler, G. Gratta, C. Hall, D. Hertzog, W. Marciano, J. Miller, R. Neilson, A. Pocar, M. Ramsey-Musolf

Comprehensive Strategy

Direct and Indirect Searches for Physics Beyond the Standard Model

Compelling arguments for "New Dynamics" at the TeV Scale

A comprehensive search for clues requires:

Large Hadron Collider *as well as* **Lower Energy: $Q^2 << M_Z^2$**

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- **Violations of Accidental(?) Symmetries**
  - *CP, T (EDMs, Decays), CPT, Charged Lepton Flavor, Lepton Number*
- **Dark Matter Searches**
- **Neutrino Masses and Mixing**
  - *$0\nu\beta\beta$ decay, reactor θ_{13}, long baseline experiments*
- **Precision Electroweak Measurements at $Q^2 << M_Z^2$**
  - *flavor conserving and flavor changing neutral current amplitudes, charged current amplitudes, muon g-2*

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

Intensity Frontier

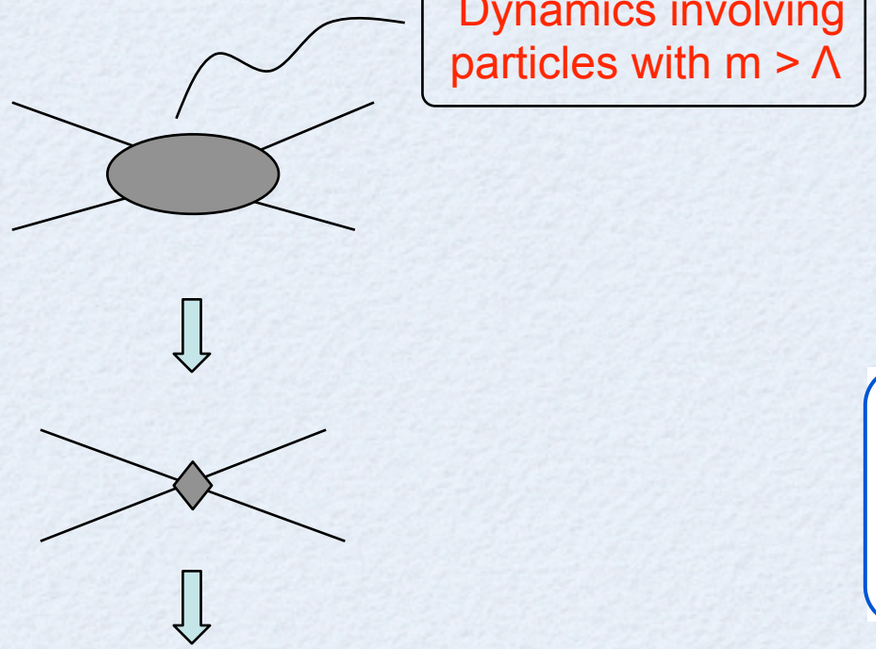
Electroweak Interactions at scales much lower than that of EWSB

E

courtesy V. Cirgliano

Λ (~TeV)

$M_{W,Z}$



Many theories predict new forces that disappeared when the universe cooled

$$\mathcal{L}_{SM+\mathrm{Heavy}}$$

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \hat{O}_n^{(d)}[\phi_{SM}]$$

- *flavor changing as well as flavor diagonal*
- *charged current as well as neutral current*

Many new physics models give rise to such terms:

Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

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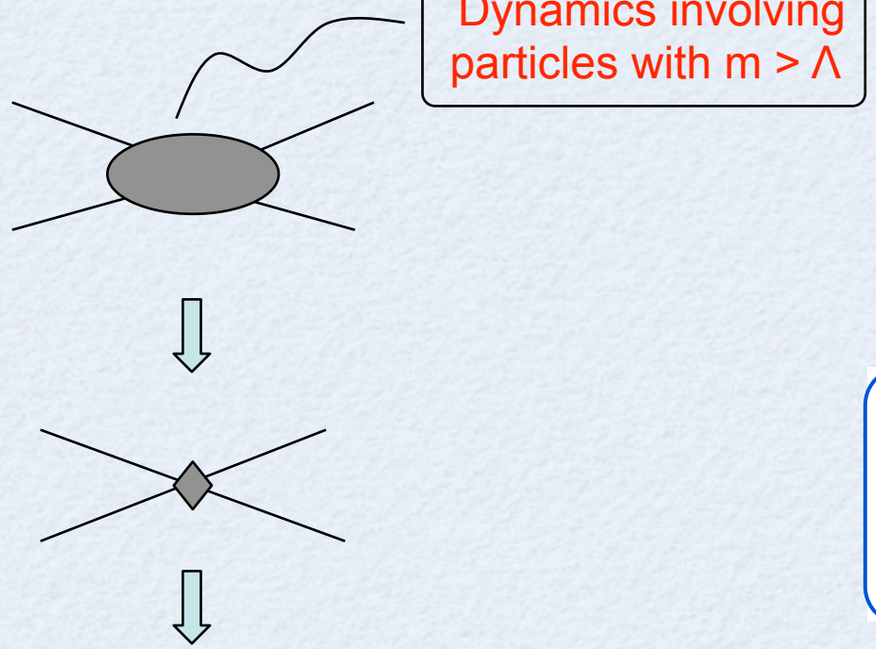

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Measurements with the potential to indirectly access the TeV scale involve pushing one or more experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, precision, accuracy....

- *Electric Dipole Moment Searches*
- *Neutrinoless Double Beta Decay Searches*
- *Charged Lepton Flavor Violation Searches*
- *CP- and T-violating Weak Decay Searches*
- *Flavor-changing neutral currents*
- *Precision Weak Neutral Current Interactions*

Outline

*The focus of this talk: flavor changing & conserving **lepton** currents*

- **Charged Lepton Flavor Violation**
  - *$\mu \to e\gamma$ (MEG at PSI)*
  - *$\mu N \to eX$ (Mu2e at Fermilab)*
- **Intensity Frontier Physics at Fermilab**
- **Precision Electroweak Measurements at Low Energy**
  - *muon g-2 at FNAL*
  - *Parity-violating Electron Scattering*
    - Qweak & PVDIS at Jefferson Lab
    - MOLLER & SOLID after the 12 GeV Upgrade
- **News on Double-Beta Decay Searches**
  - *EXO-200 is running!*

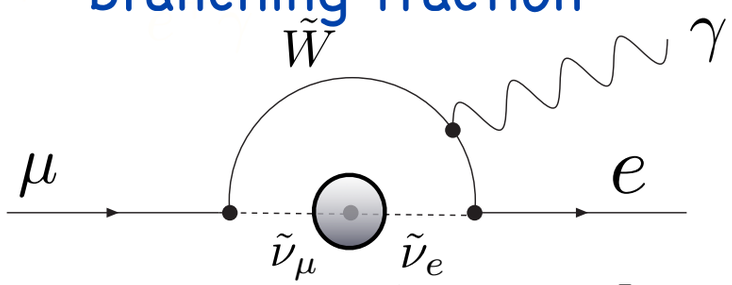
Other Topics:

- Dark Matter (Thursday morning, parallel sessions)
- Neutrinos (this morning, parallel sessions)
- EDM searches (Parallel session this afternoon)
- Heavy Flavors (Plenary talk: Saturday morning)
- CP-Violation (Plenary talk: Saturday morning)

Lepton Flavor Violation

- ν oscillations: individual lepton family numbers ($L_{e,\mu,\tau}$) are not conserved
- SM + massive ν's: charged LFV allowed but negligible (GIM-suppression)

tiny standard model branching fraction



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

Extremely clean probe of "new" physics at the TeV scale

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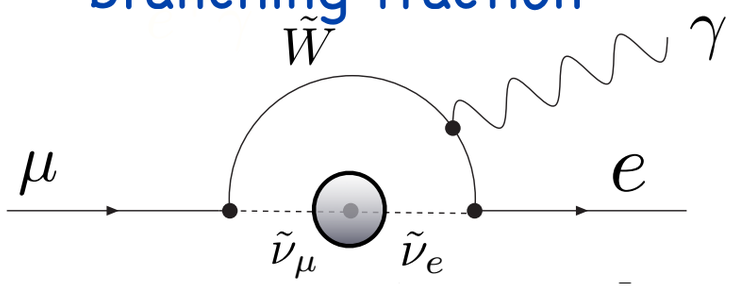

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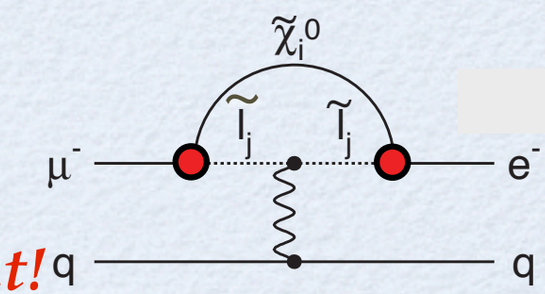
Example: SUSY interpretation of g-2 anomaly results in significant enhancement!

Supersymmetry

rate ~ 10^{-15}



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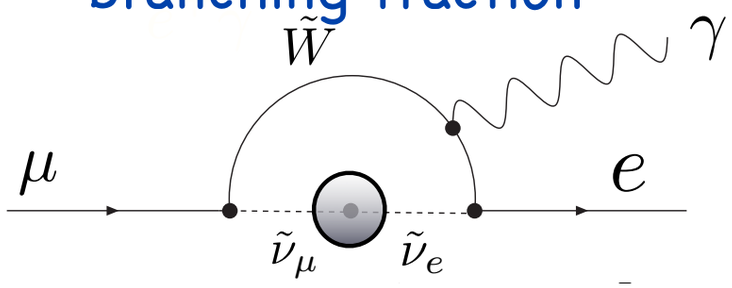

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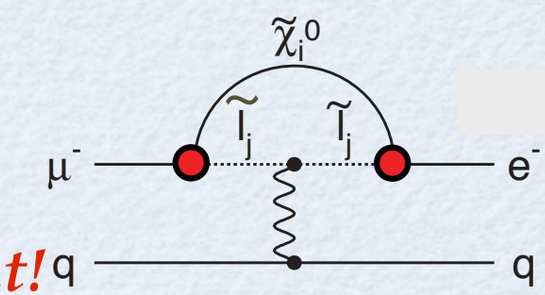
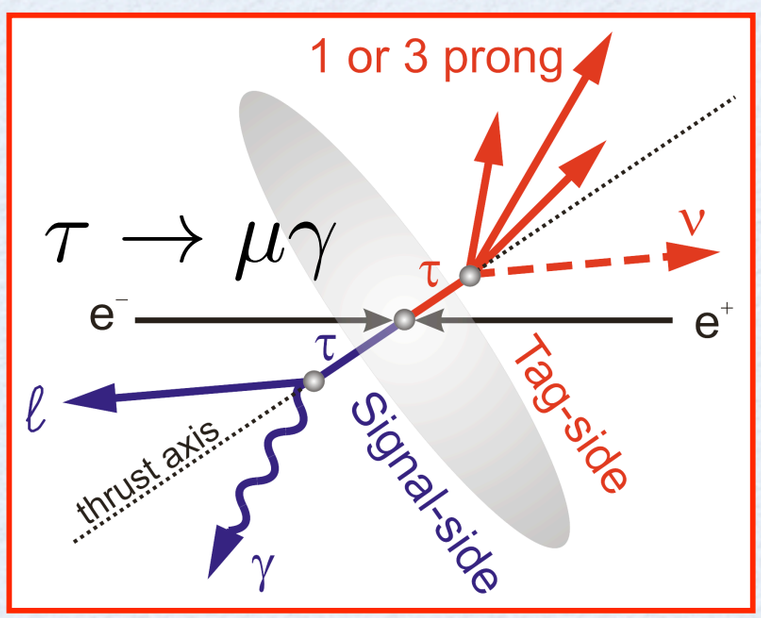


Tau Decays at e+e- colliders



At Colliders:

Large samples of $\tau^+\tau^-$ pairs

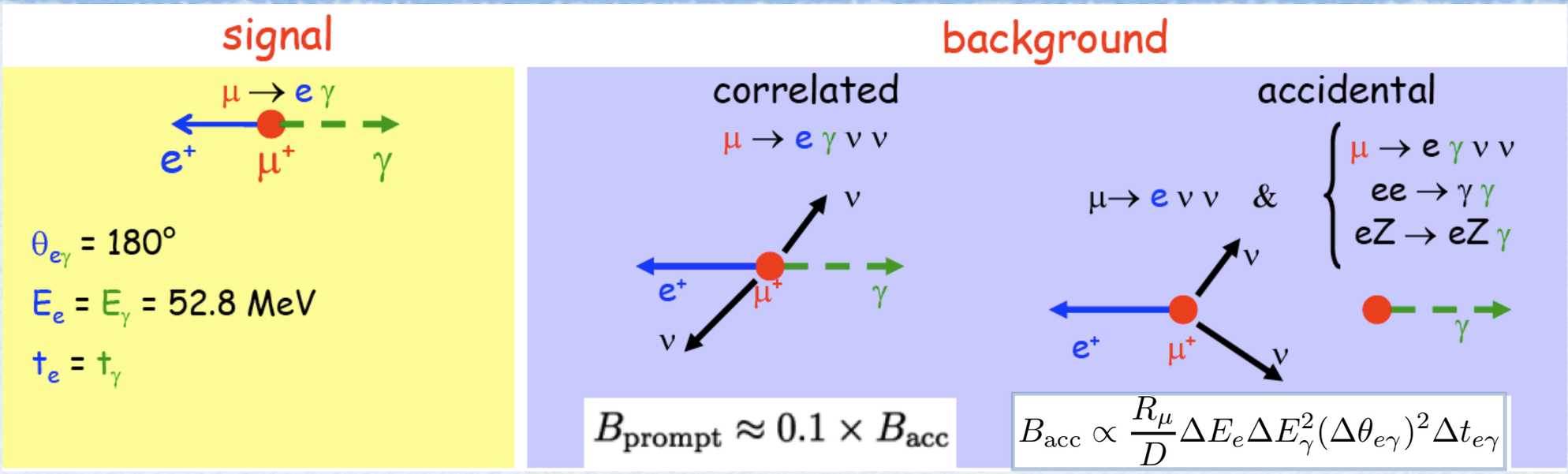
New results from Babar/ BELLE; future initiatives will try to push this by one or two orders of magnitude

$e^-\gamma$	LF	<	1.1	$\times 10^{-7}$
$\mu^-\gamma$	LF	<	4.5	$\times 10^{-8}$
$e^-e^+e^-$	LF	<	3.6	$\times 10^{-8}$
$e^-\mu^+\mu^-$	LF	<	3.7	$\times 10^{-8}$
$e^+\mu^-\mu^-$	LF	<	2.3	$\times 10^{-8}$
$\mu^-e^+e^-$	LF	<	2.7	$\times 10^{-8}$
$\mu^+e^-e^-$	LF	<	2.0	$\times 10^{-8}$
$\mu^-\mu^+\mu^-$	LF	<	3.2	$\times 10^{-8}$
$e^-\pi^0$	LF	<	8.0	$\times 10^{-8}$
$\mu^-\pi^0$	LF	<	1.1	$\times 10^{-7}$
$e^-K^0_S$	LF	<	3.3	$\times 10^{-8}$
$\mu^-K^0_S$	LF	<	4.0	$\times 10^{-8}$
$e^-\eta$	LF	<	9.2	$\times 10^{-8}$
$\mu^-\eta$	LF	<	6.5	$\times 10^{-8}$

MEG at PSI

Talk by N. Donato, Wed. afternoon

Sensitive search for $\mu^+ \to e^+\gamma$ using CW surface muon beam



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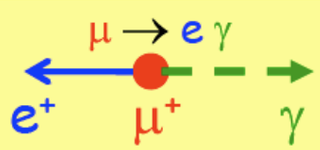


$\theta_{e\gamma} = 180°$

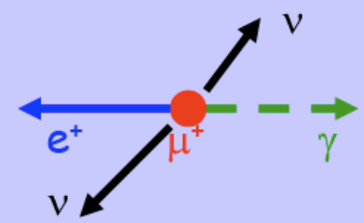
$E_e = E_\gamma = 52.8$ MeV

$t_e = t_\gamma$

background

correlated

$\mu \to e\,\gamma\,\nu\,\nu$



$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}}$

accidental

$\mu \to e\,\nu\,\nu$ &

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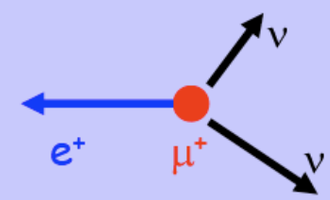
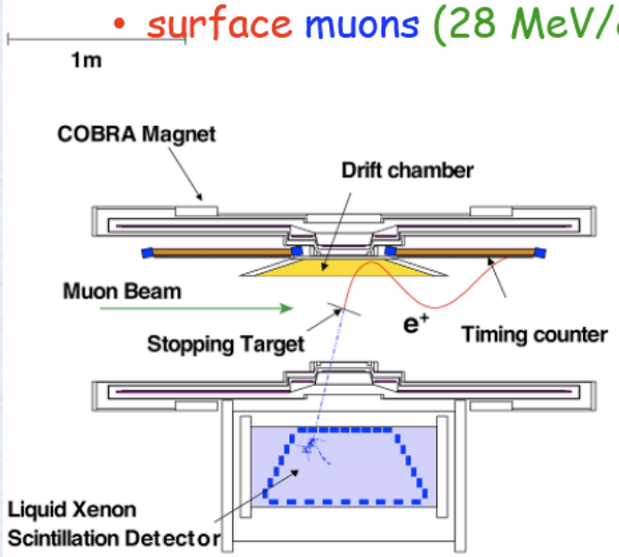
$ee \to \gamma\,\gamma$
$eZ \to eZ\,\gamma$



$$B_{\text{acc}} \propto \frac{R_\mu}{D}\Delta E_e \Delta E_\gamma^2 (\Delta\theta_{e\gamma})^2 \Delta t_{e\gamma}$$

The beam

- located at Paul Scherrer Institut (CH)
- the most intense in the World ($>3\times10^8\mu$/s @ 2 mA)
- continuous (good for B_{acc} suppression)
- surface muons (28 MeV/c)



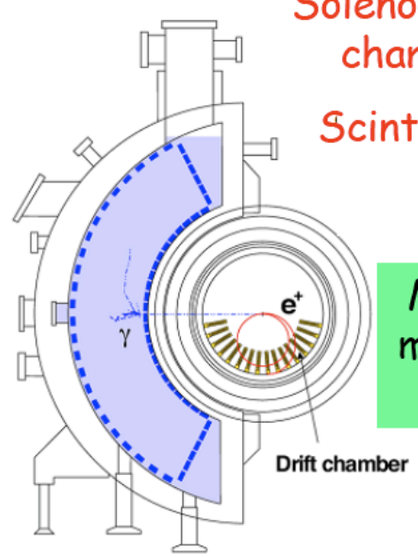
The detector

Beam of 3×10^7 μ /sec stopped in a 175 μm target

Liquid Xenon calorimeter for γ detection (scintillation)

Solenoid spectrometer & drift chambers for e^+ momentum

Scintillation counters for e^+ timing



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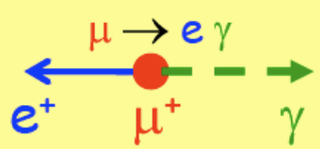

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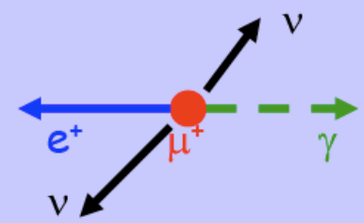

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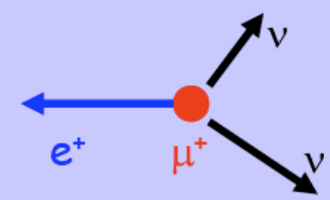

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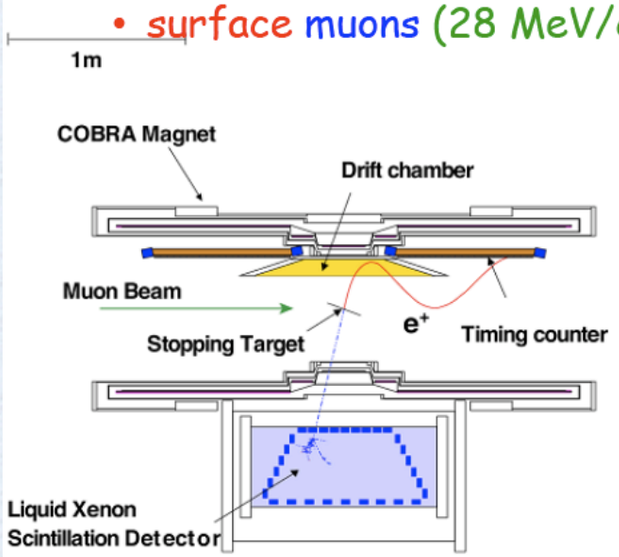

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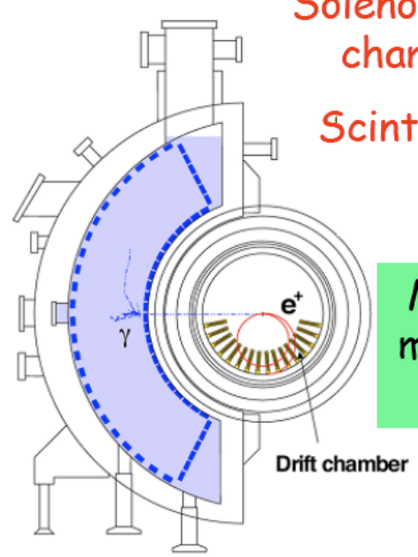

Matter effects must be minimized in order not to spoil the resolution

New! 2009+10 Data:

Result: < 2.4 x 10^{-12}

90% C.L. upper limit

2011 data taking has commenced

Final Goal (~2013):

Sensitivity: few x 10^{-13}

Broader Sensitivity

The complementarity of muon-electron conversion

$B_{\mu\to e\gamma}$	$<$	1.2×10^{-11}
$B_{\mu\to 3e}$	$<$	1.0×10^{-12}
$B^{Ti}_{\mu-e}$	$<$	4.3×10^{-12}
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→ $10^{-13/14}$ (MEG at PSI, *now running*)

Talk by M. Lancaster, Wed. afternoon

$10^{-14/17}$ Mu2e at Fermilab, DeeMe & COMET at J-PARC

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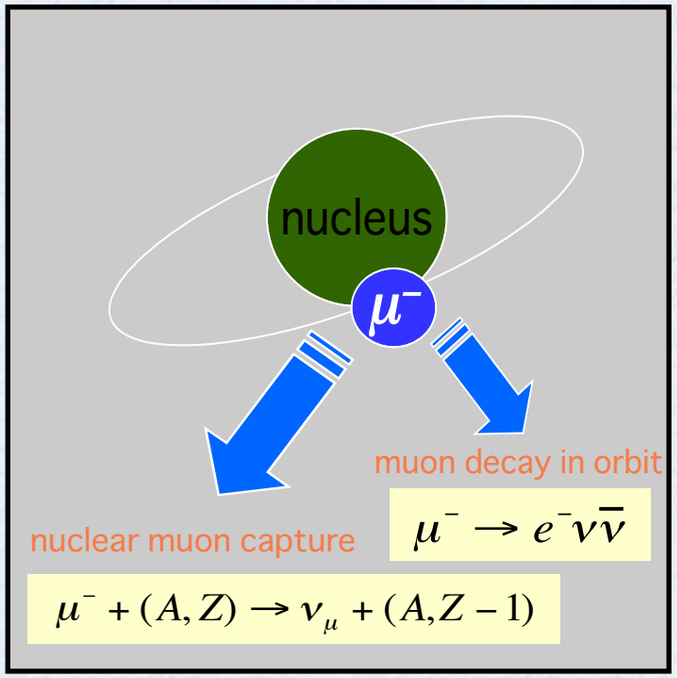

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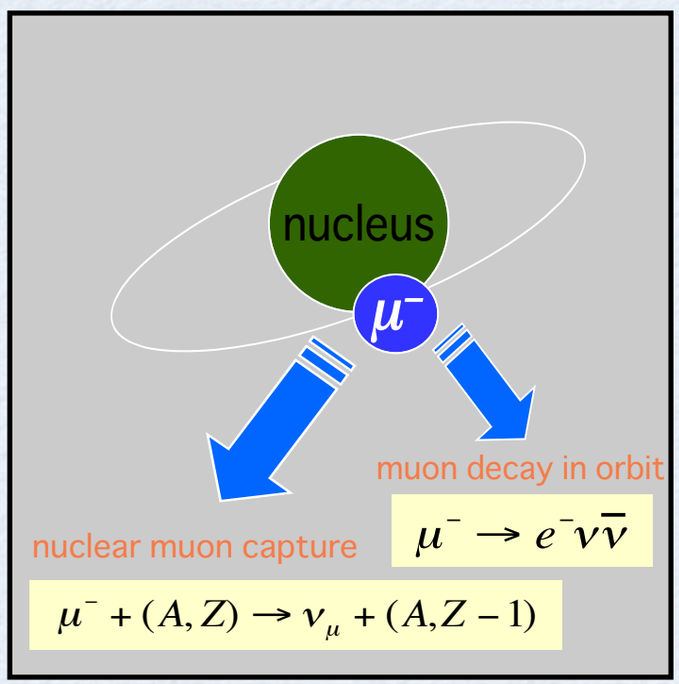

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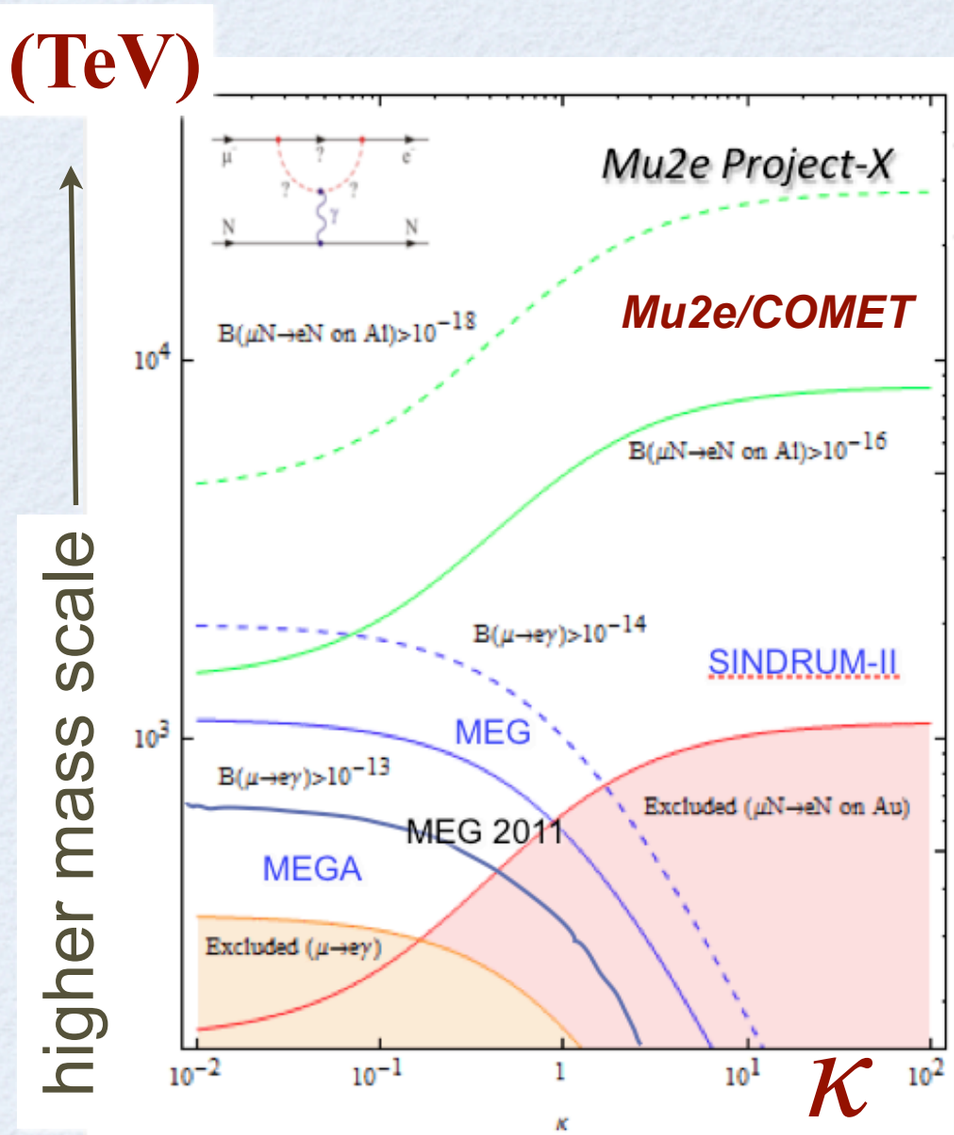

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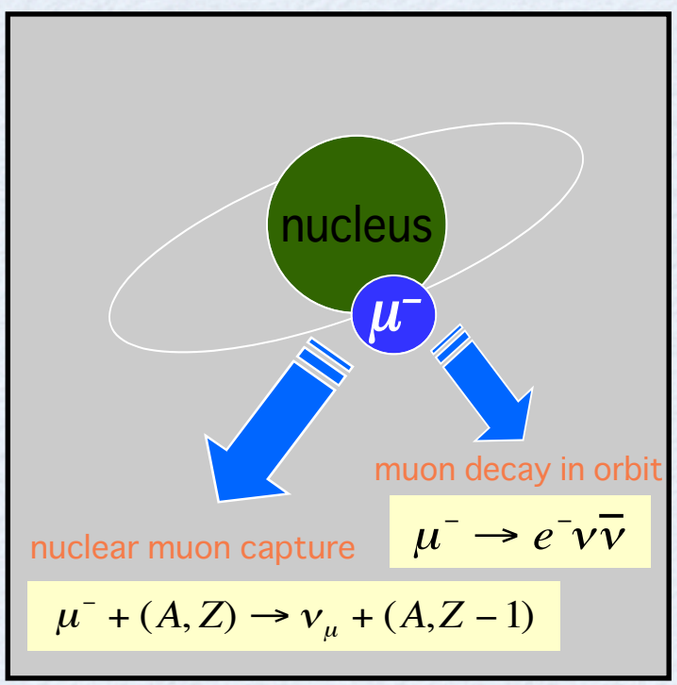
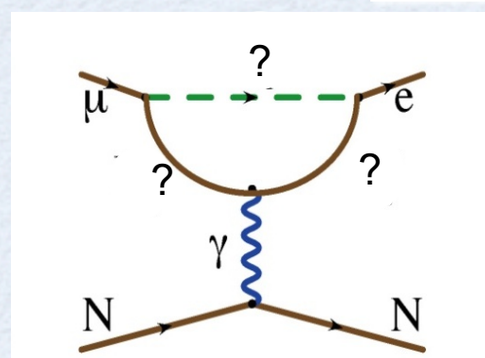
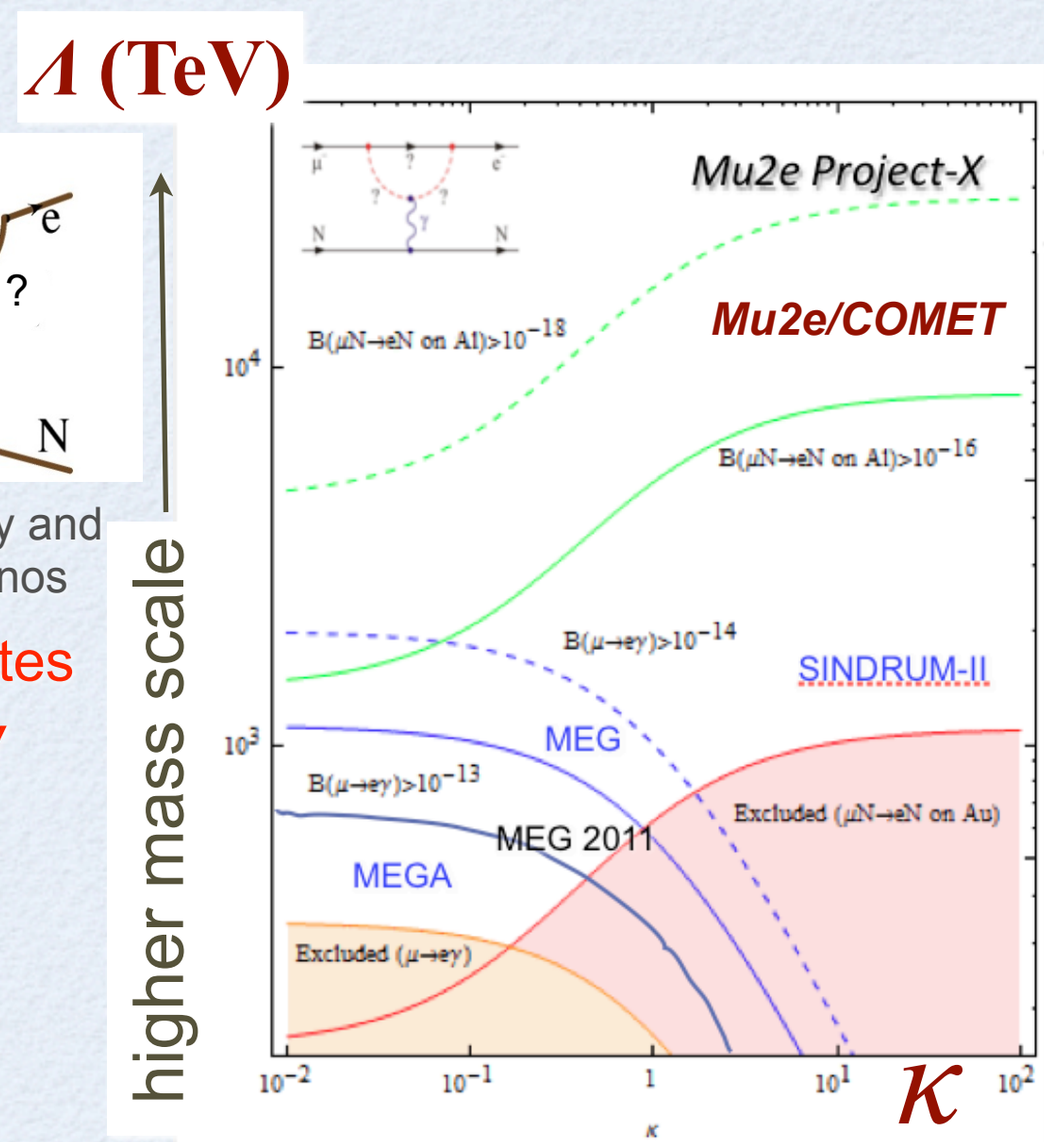




Supersymmetry and Heavy Neutrinos

Contributes to $\mu\to e\gamma$



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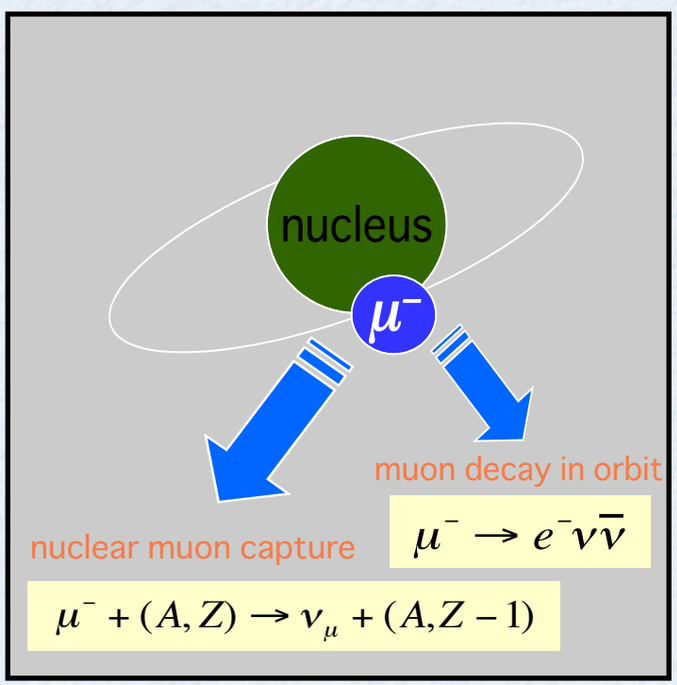

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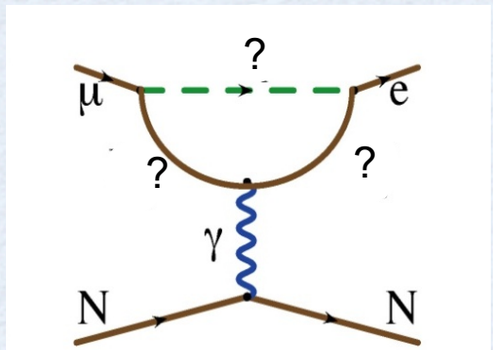

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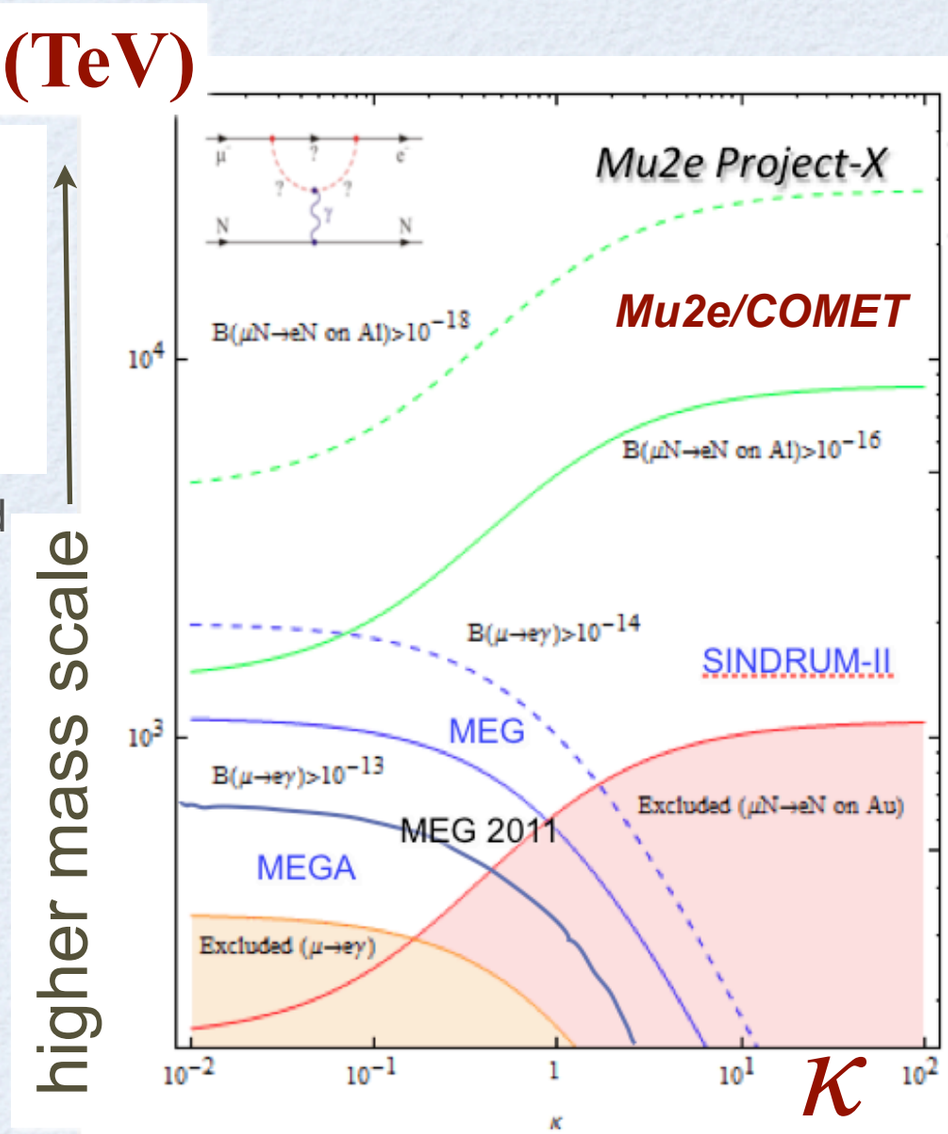
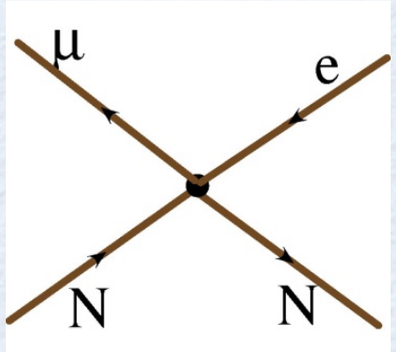




Contact Interactions e.g. Heavy Z

Does not produce $\mu\to e\gamma$

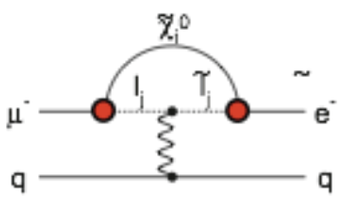
Mu2e at Fermilab

Talk by C. Group, Wed. afternoon

A new project using intense, pulsed low energy proton beam

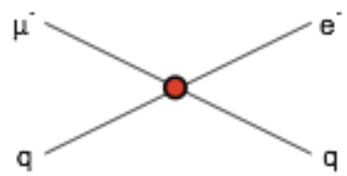
Supersymmetry

rate ~ 10^{-15}



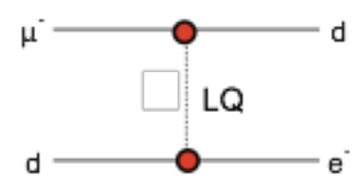
Compositeness

Λ_c ~ 3000 TeV



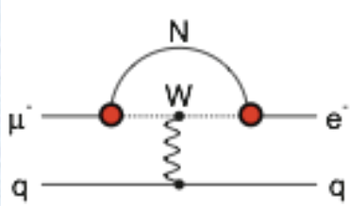
Leptoquark

M_{LQ} = 3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



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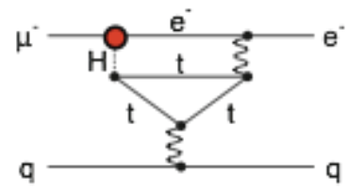

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Anomal. Z Coupling

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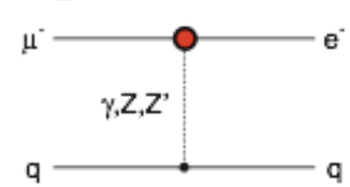

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Talk by C. Group, Wed. afternoon

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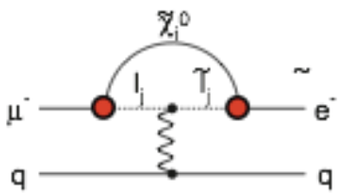

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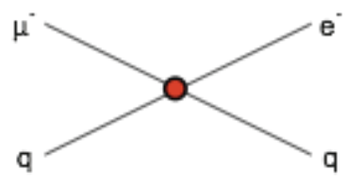

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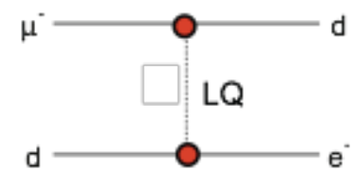

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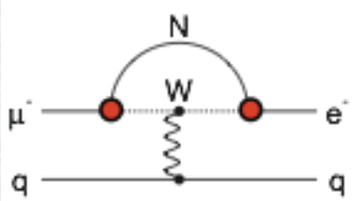

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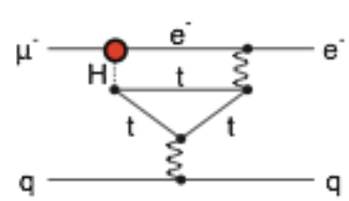

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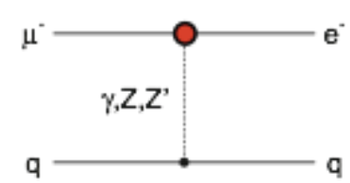
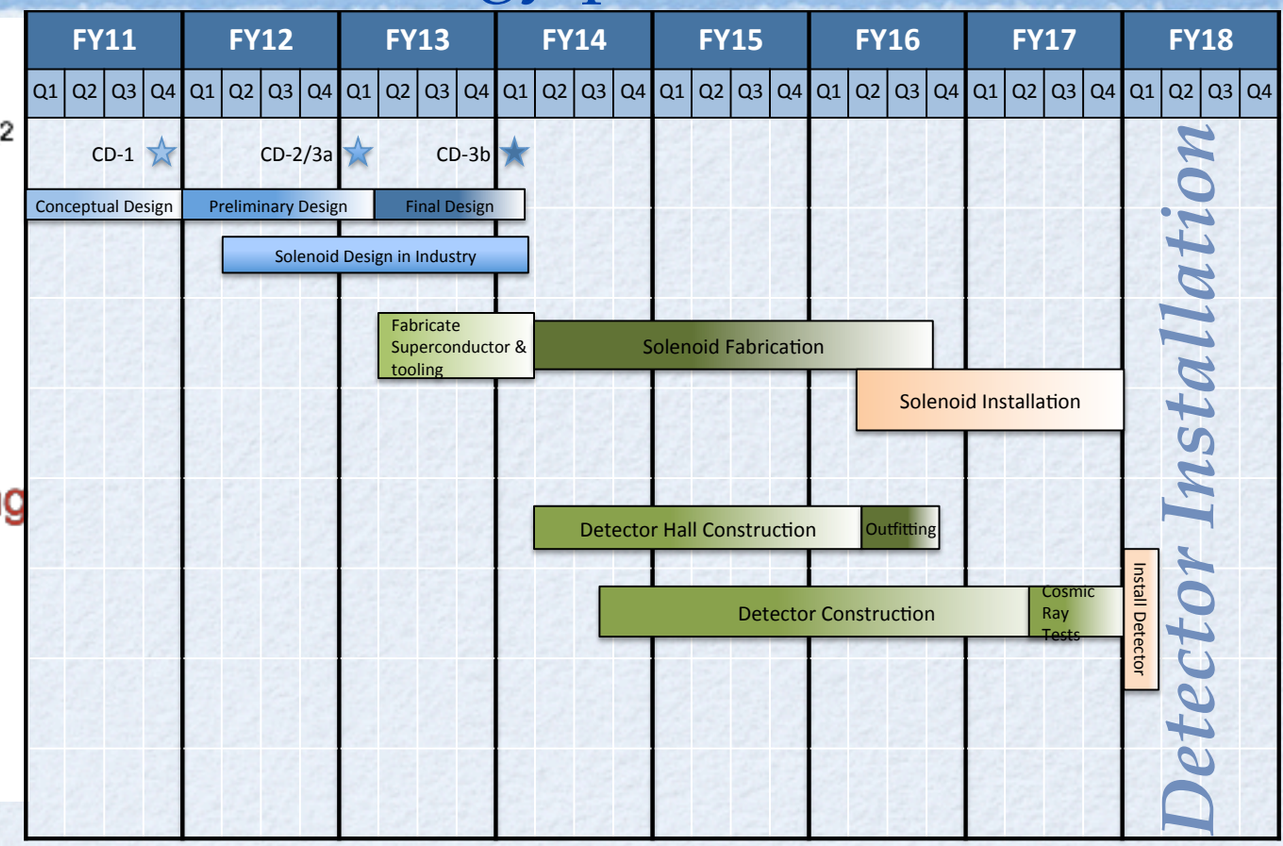
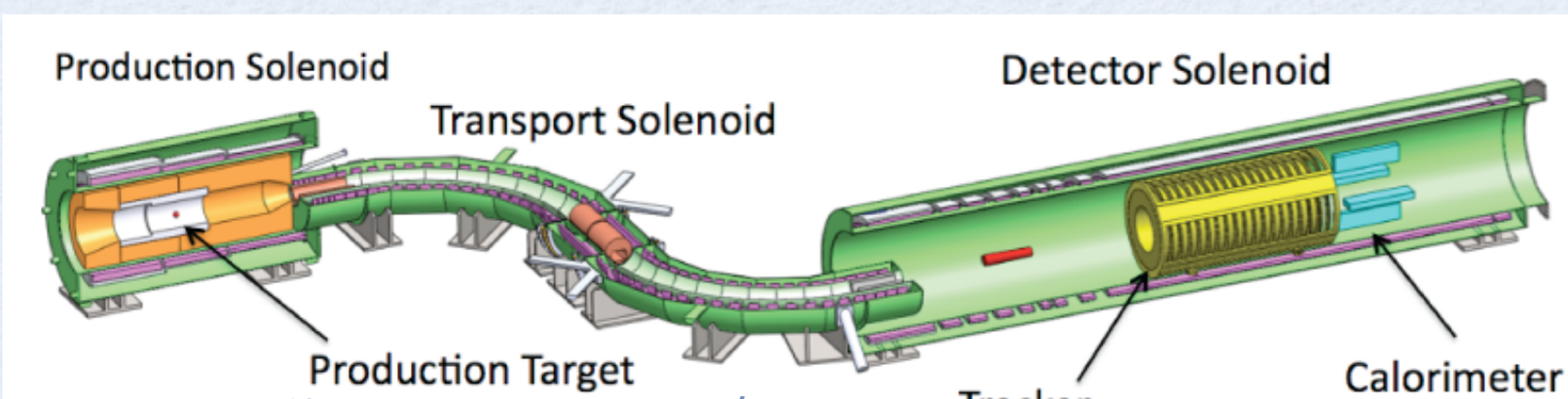




A factor of 10^4 sensitivity improvement:
Pulsed proton beam, superconducting magnets for intense muon beam, exquisite momentum resolution



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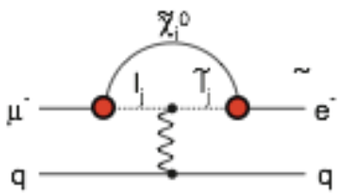

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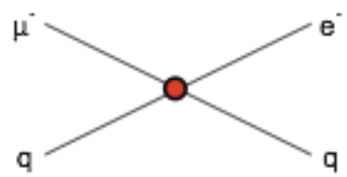

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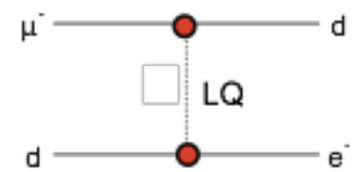

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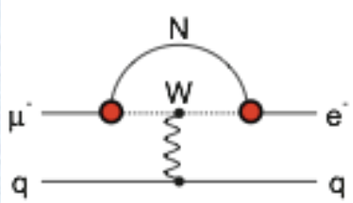

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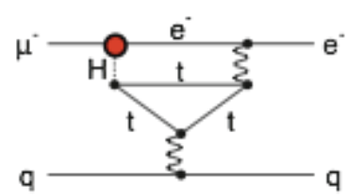

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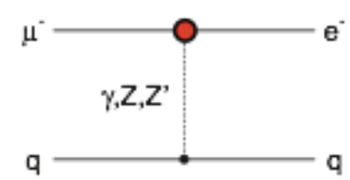

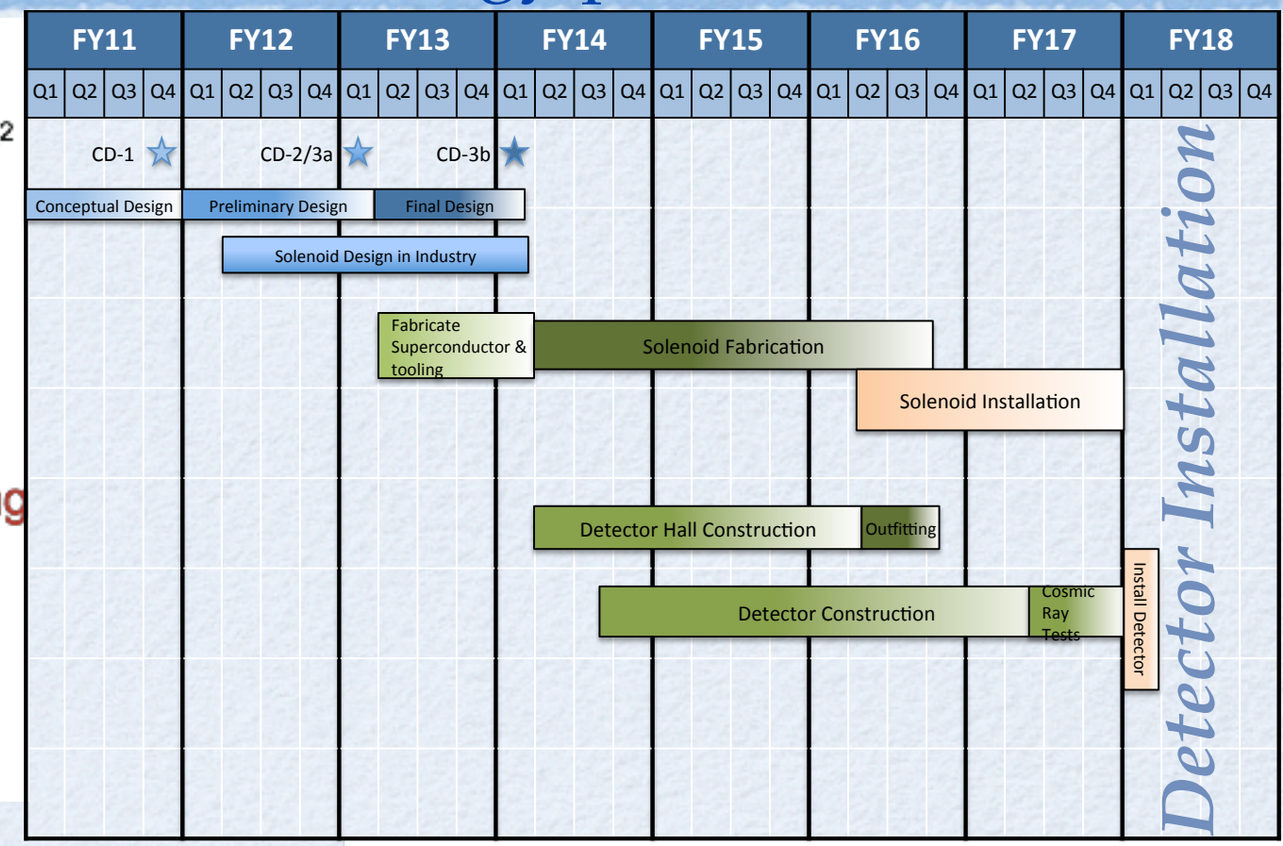

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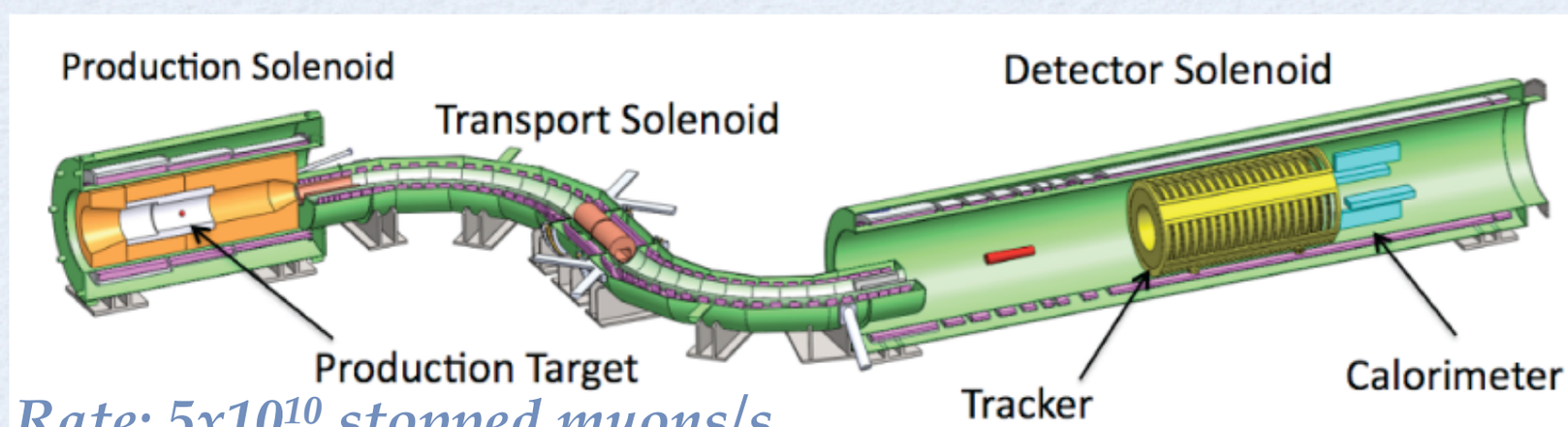
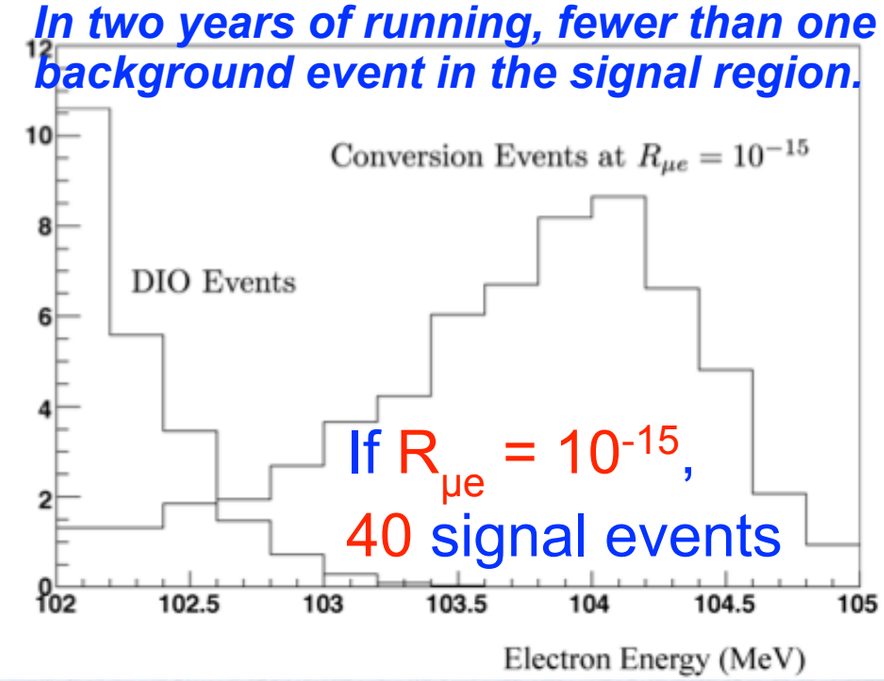
In two years of running, fewer than one background event in the signal region.





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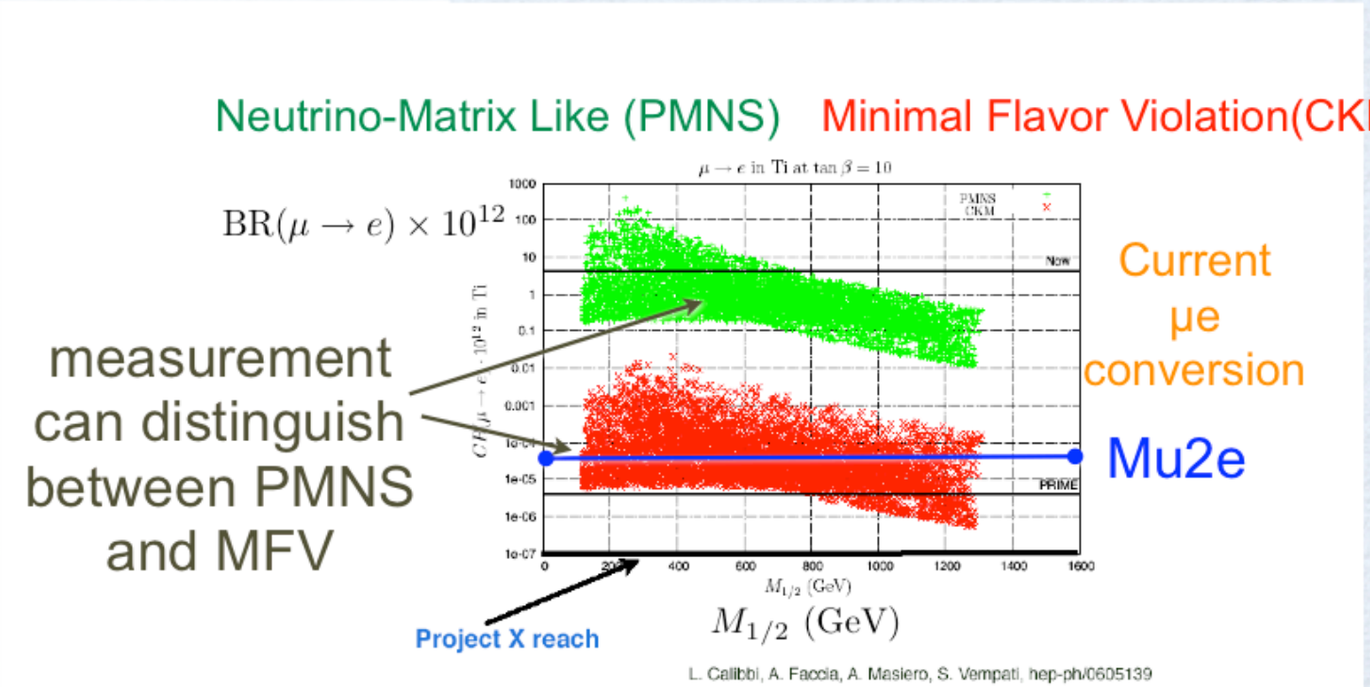
muon-electron conversion has potential to reach 10^{-18}

monoenergetic single track signal:
Detector and beam technology could potentially suppress backgrounds to required level



complementarity between Lepton Flavor Violation (LFV) and LHC experiments

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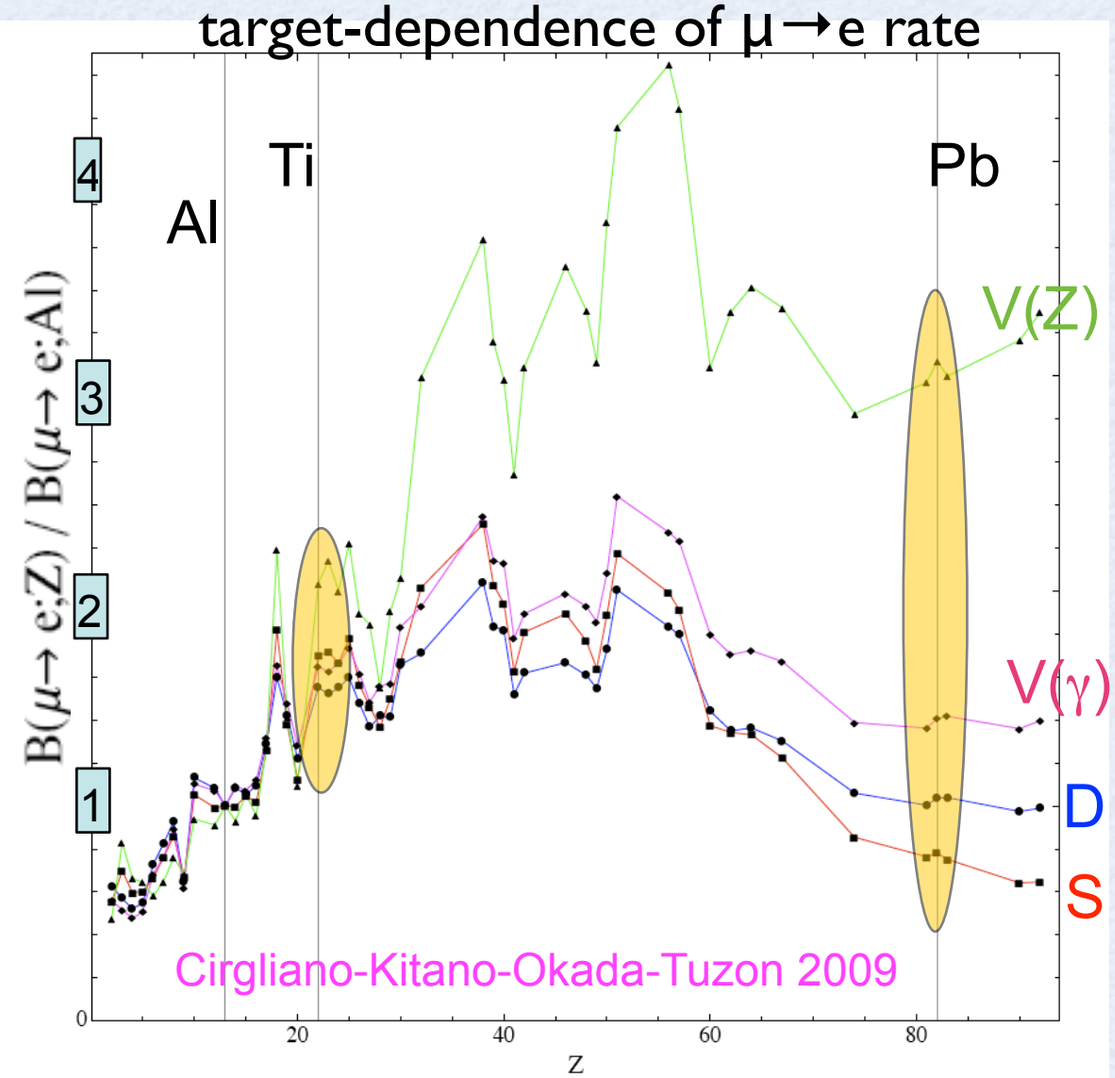

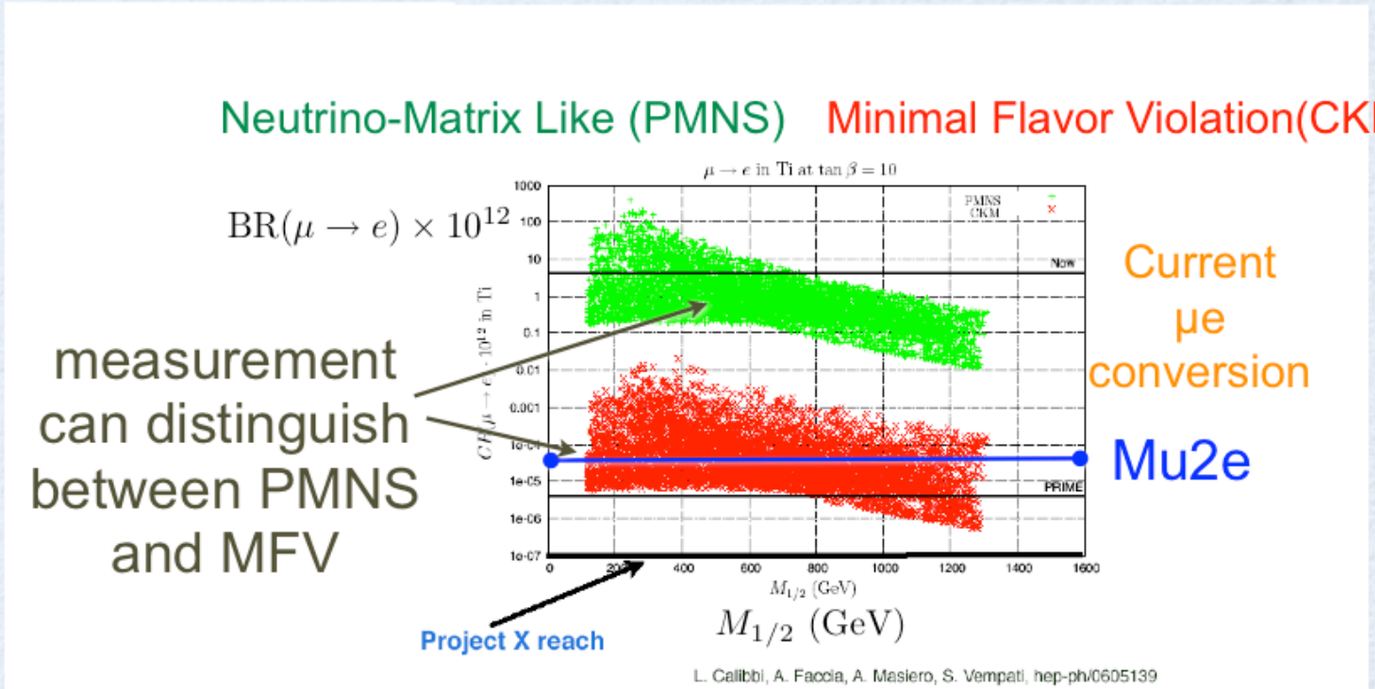

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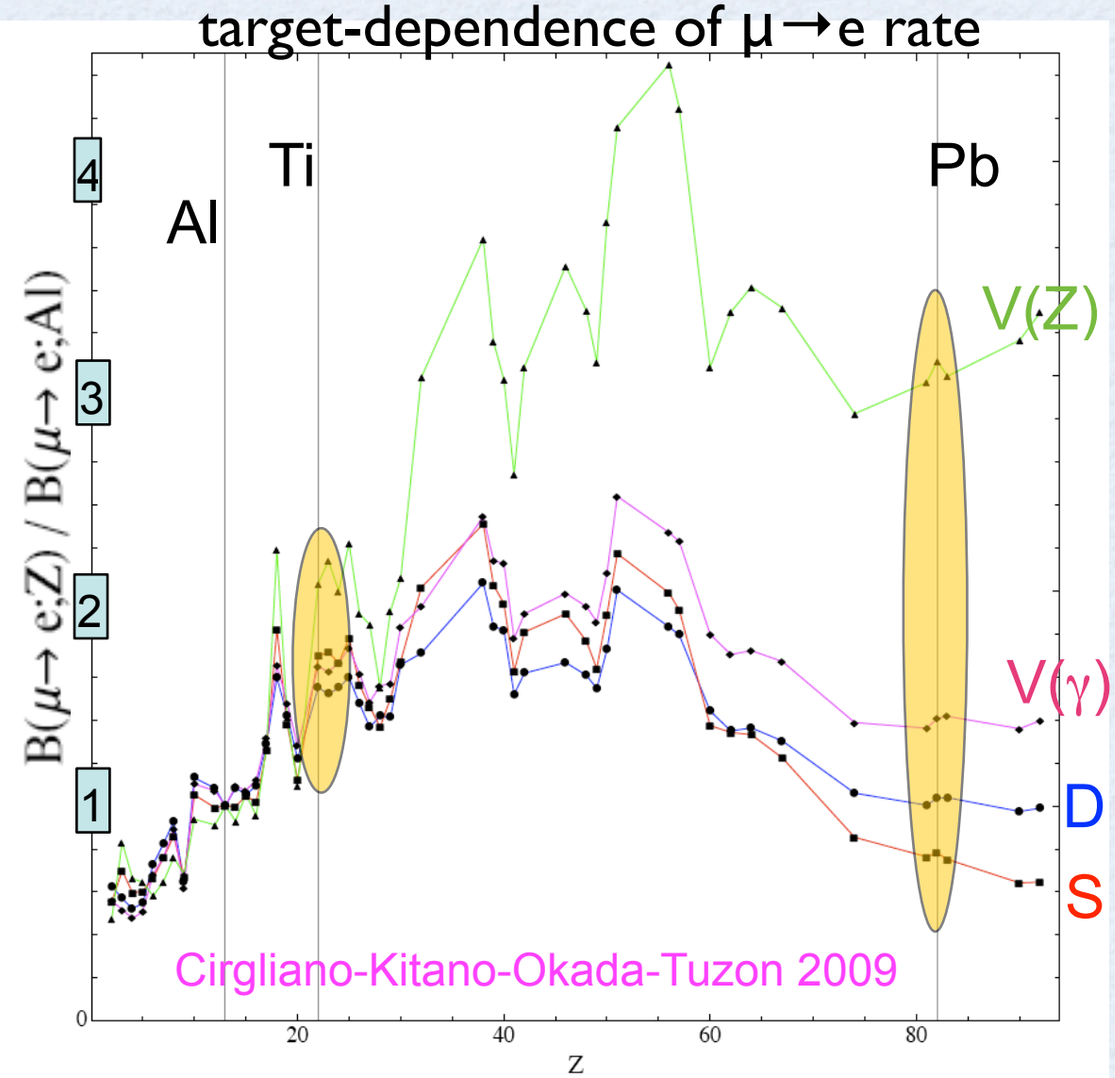

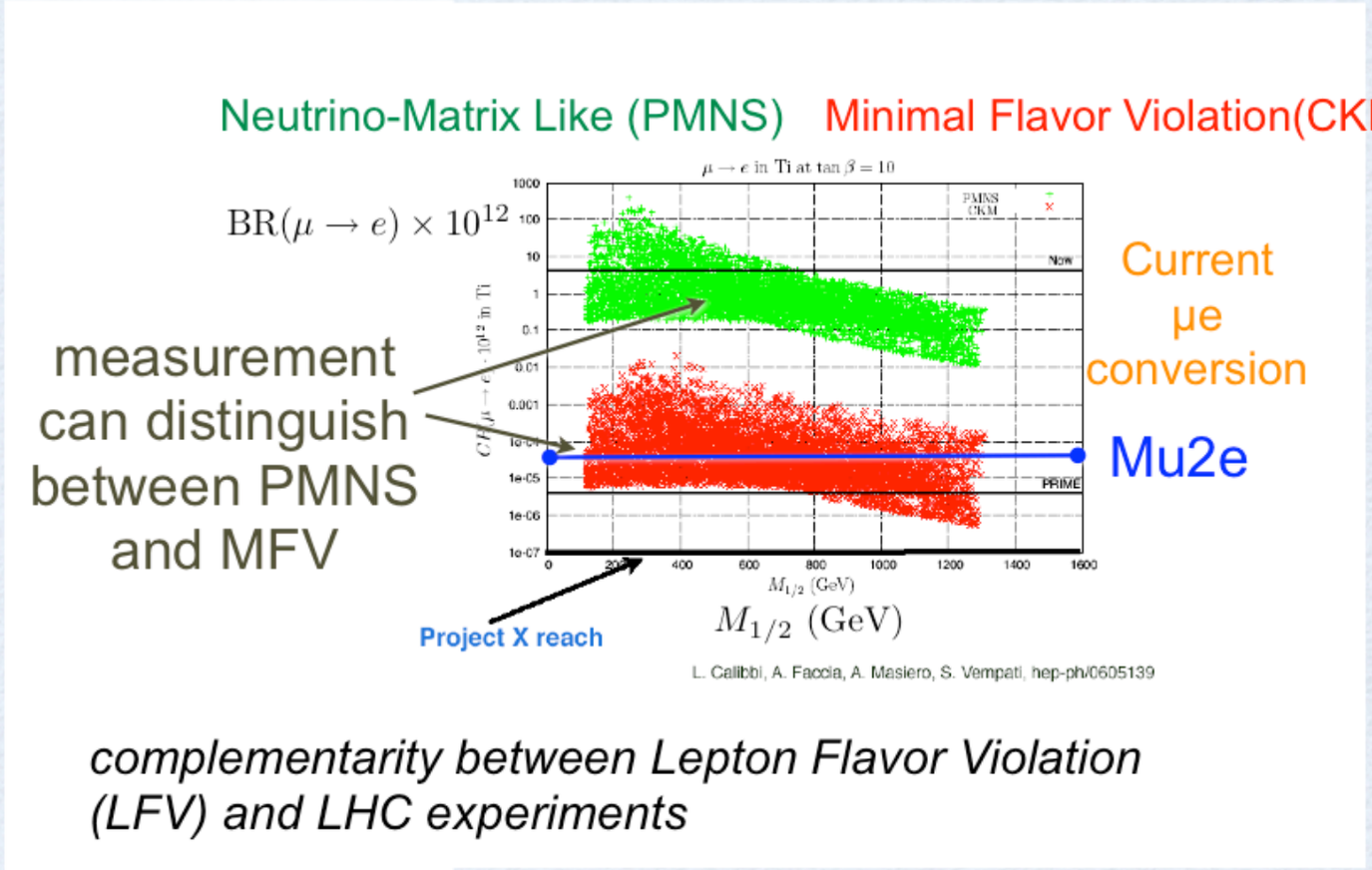

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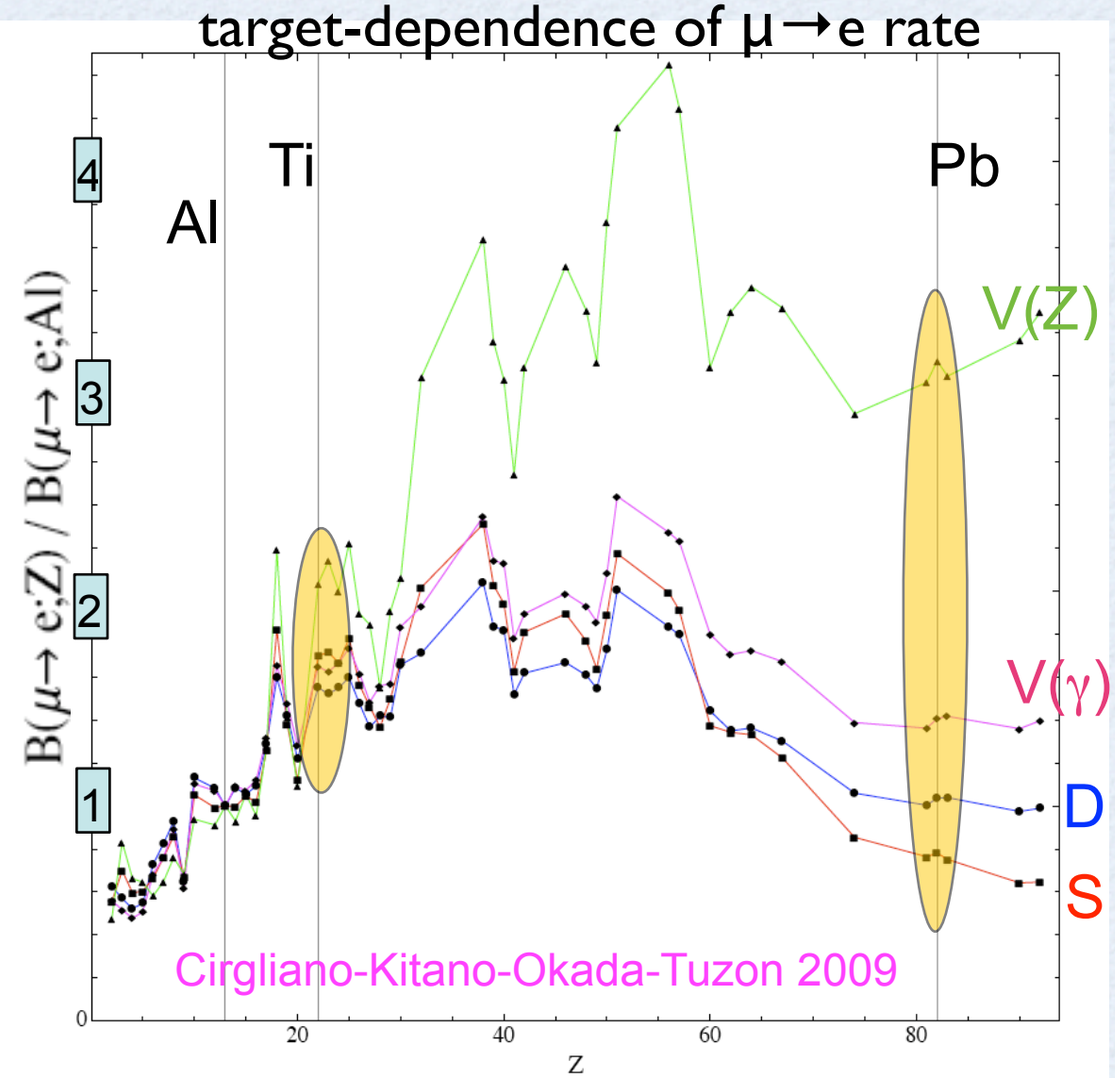

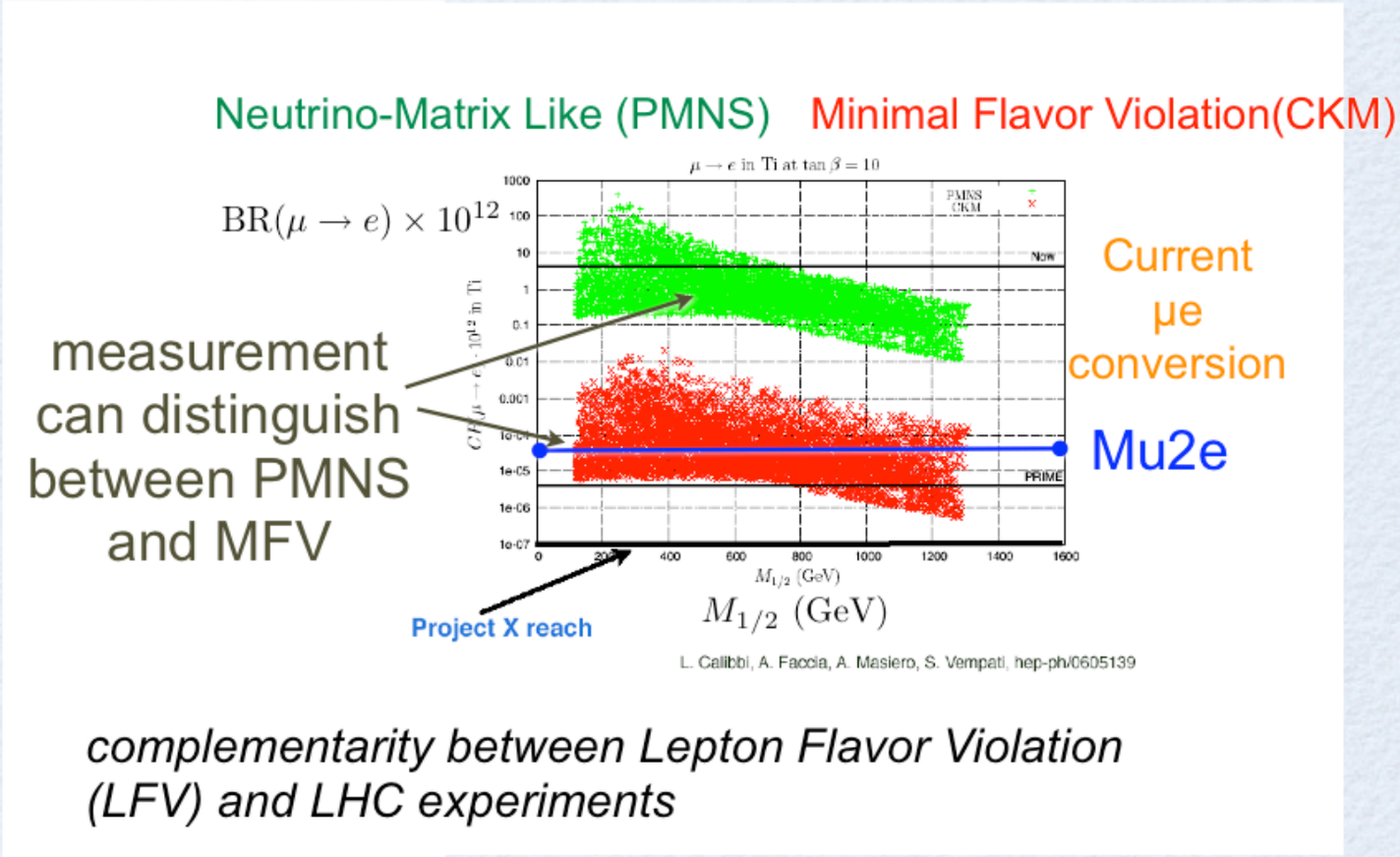

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Project X: Physics Topics

Parellel Session: 12:30 pm Wednesday

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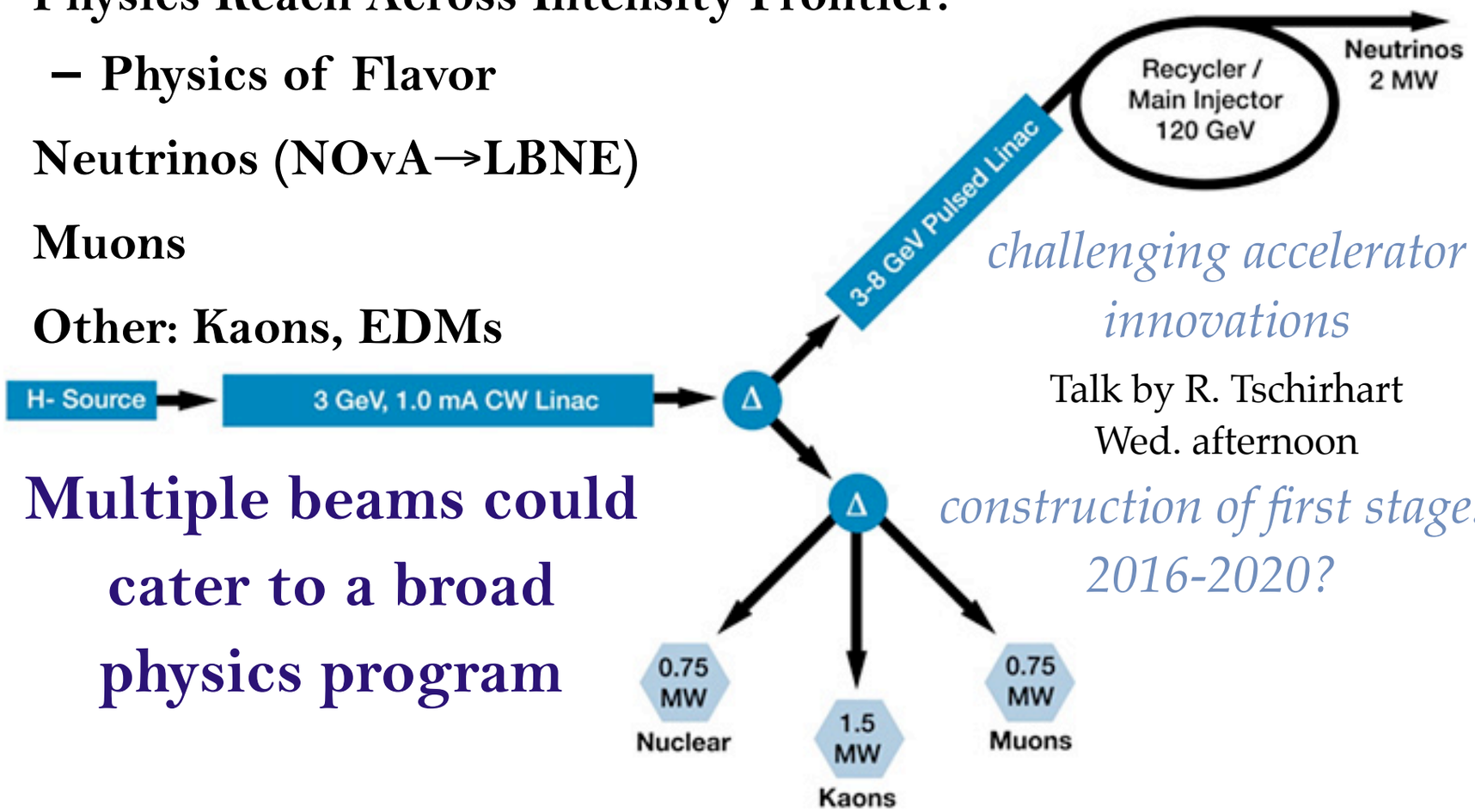
- **Neutrinos (NOvA→LBNE)**
- **Muons**
- **Other: Kaons, EDMs**



Multiple beams could cater to a broad physics program

challenging accelerator innovations

Talk by R. Tschirhart
Wed. afternoon

construction of first stage: 2016-2020?

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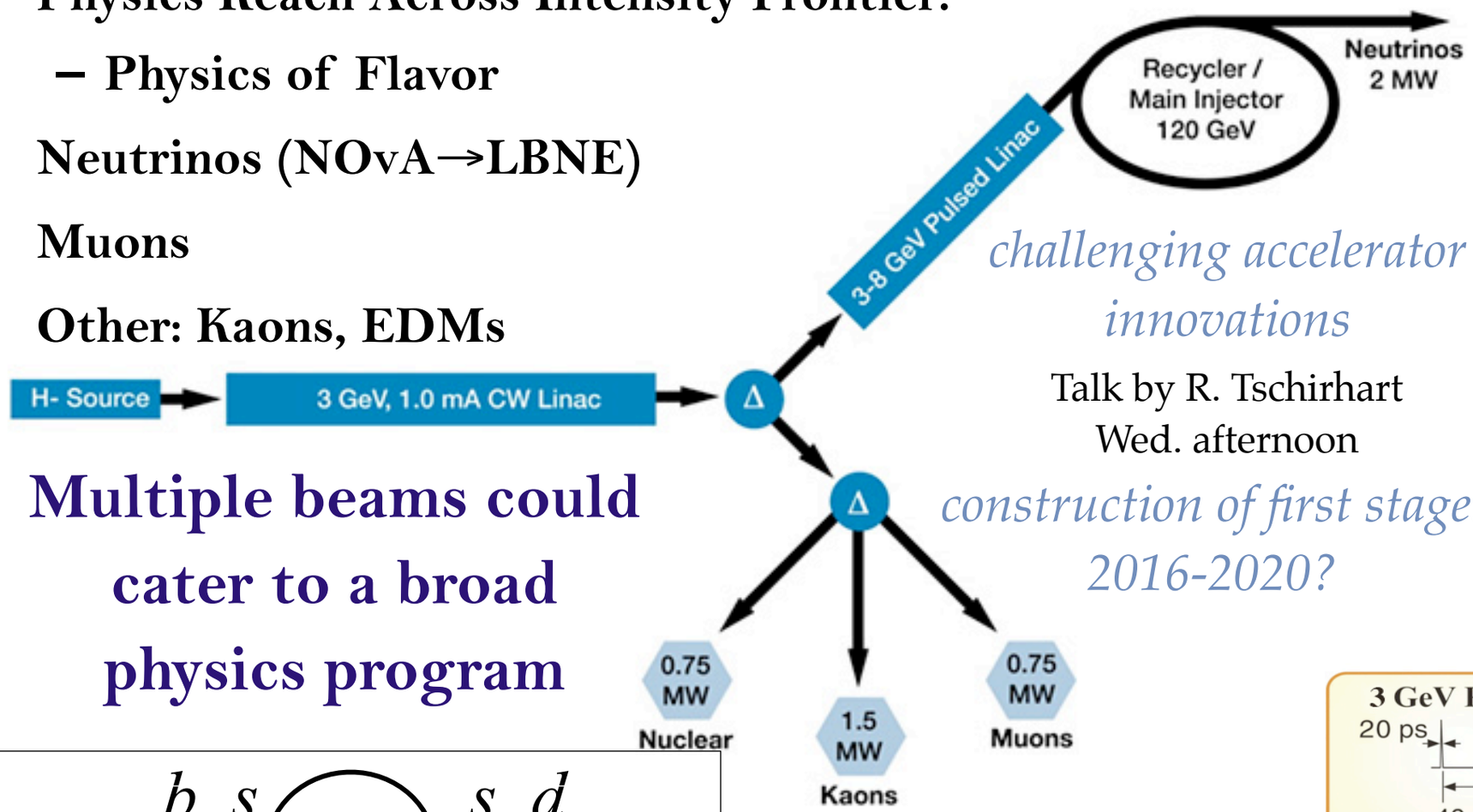

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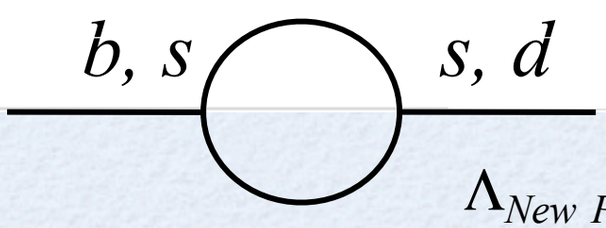
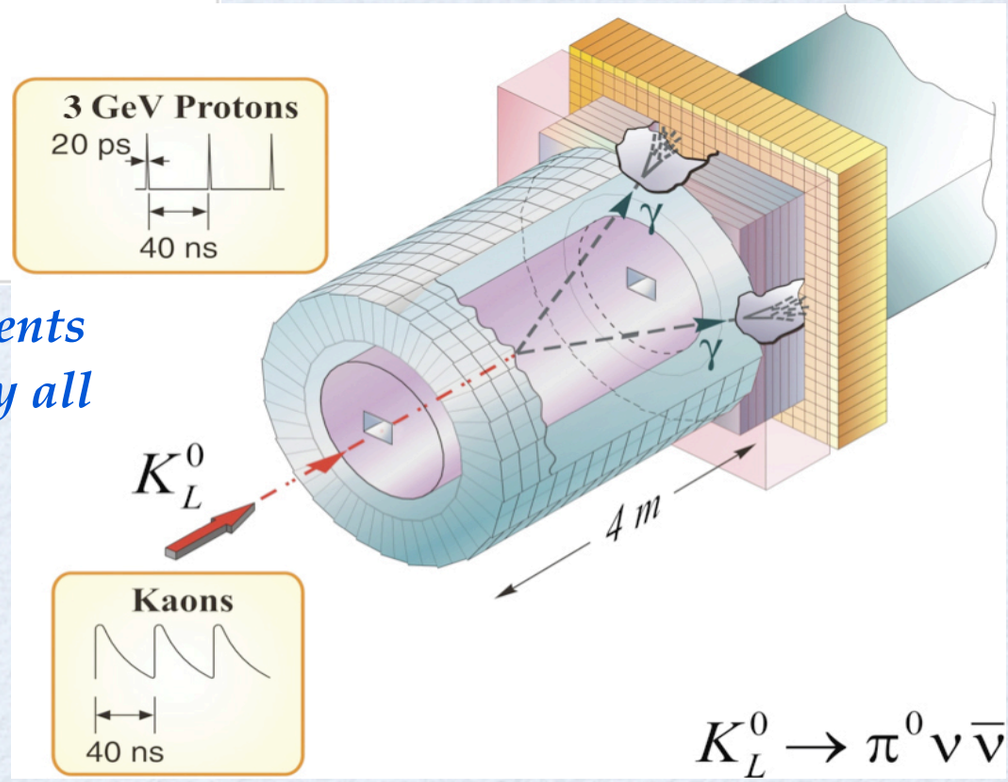


	$\Lambda_{New\ Physics}$
$b \to s$: $V_{tb}^* V_{ts} \approx \lambda^2$	100 TeV
$b \to d$: $V_{tb}^* V_{td} \approx \lambda^3$	500 TeV
$s \to d$: $V_{ts}^* V_{td} \approx \lambda^5$	1000 TeV

$\lambda = \sin\theta_C = 0.226(1)$ Isidori, Nir, Perez 2010

Flavor changing neutral currents highly motivated by virtually all BSM scenarios

Kaons provide critical complementarity



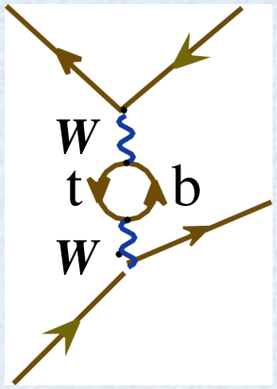
Precision EW Physics

Search for New Flavor Conserving Contact Interactions

Talk by D. Webber, Fri. morning

Start with 3 fundamental inputs needed: α_{em}, G_F and M_Z

Other experimental observables predicted at 0.1% level: sensitive to heavy particles via higher order quantum corrections



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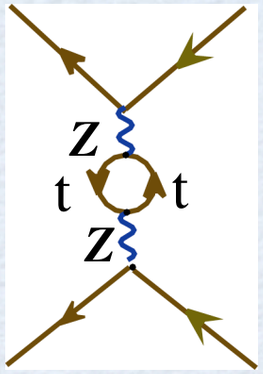

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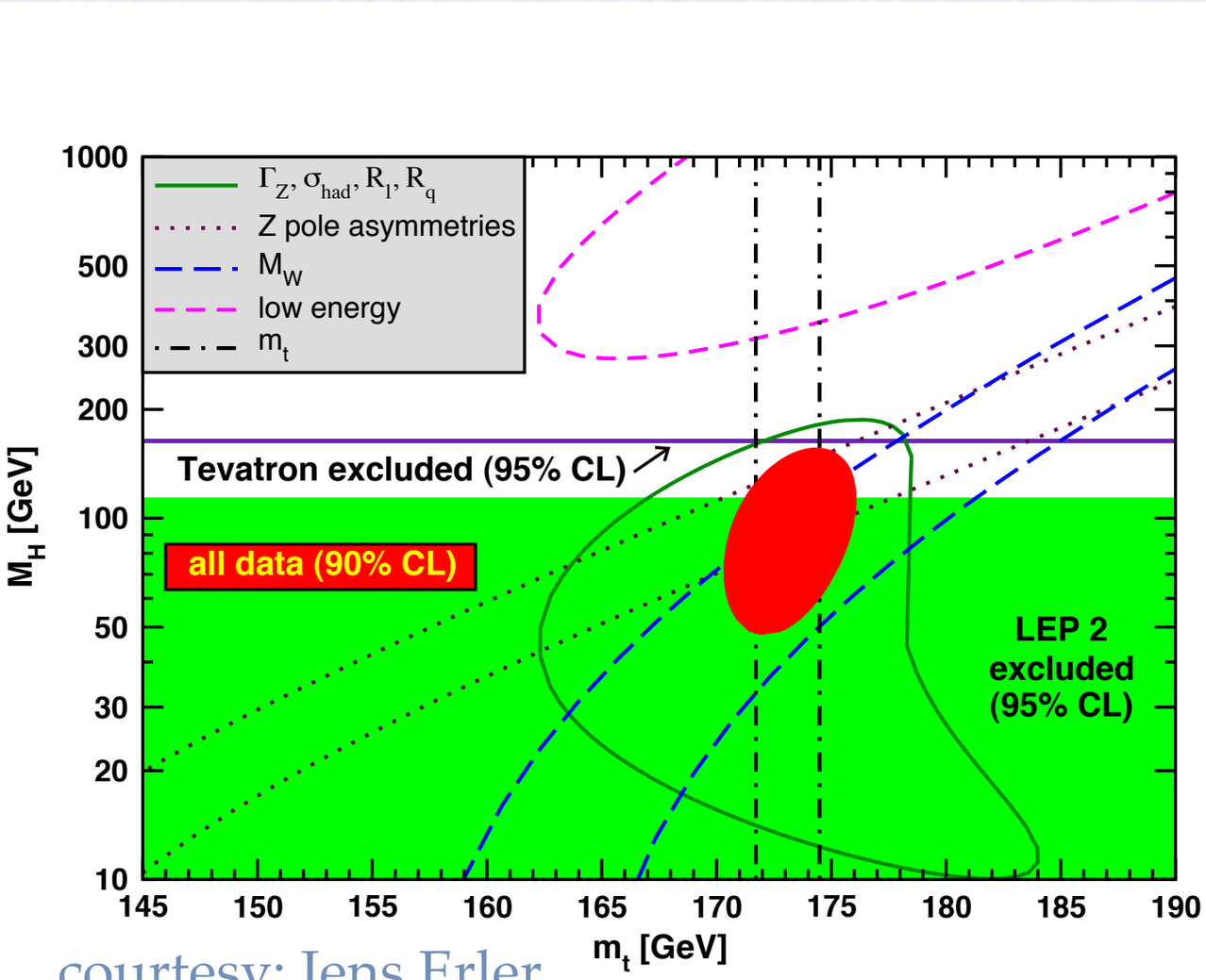
$$\Pi_{WW} - \Pi_{ZZ} \propto m_t^2 - m_b^2$$

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



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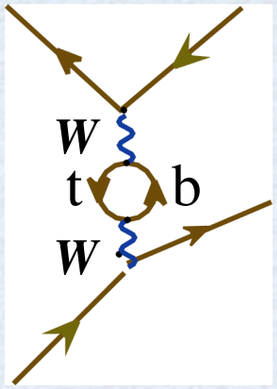

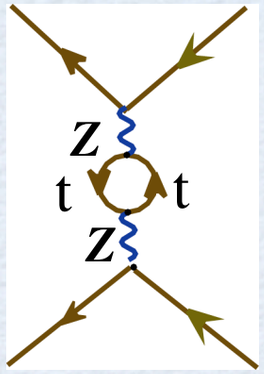

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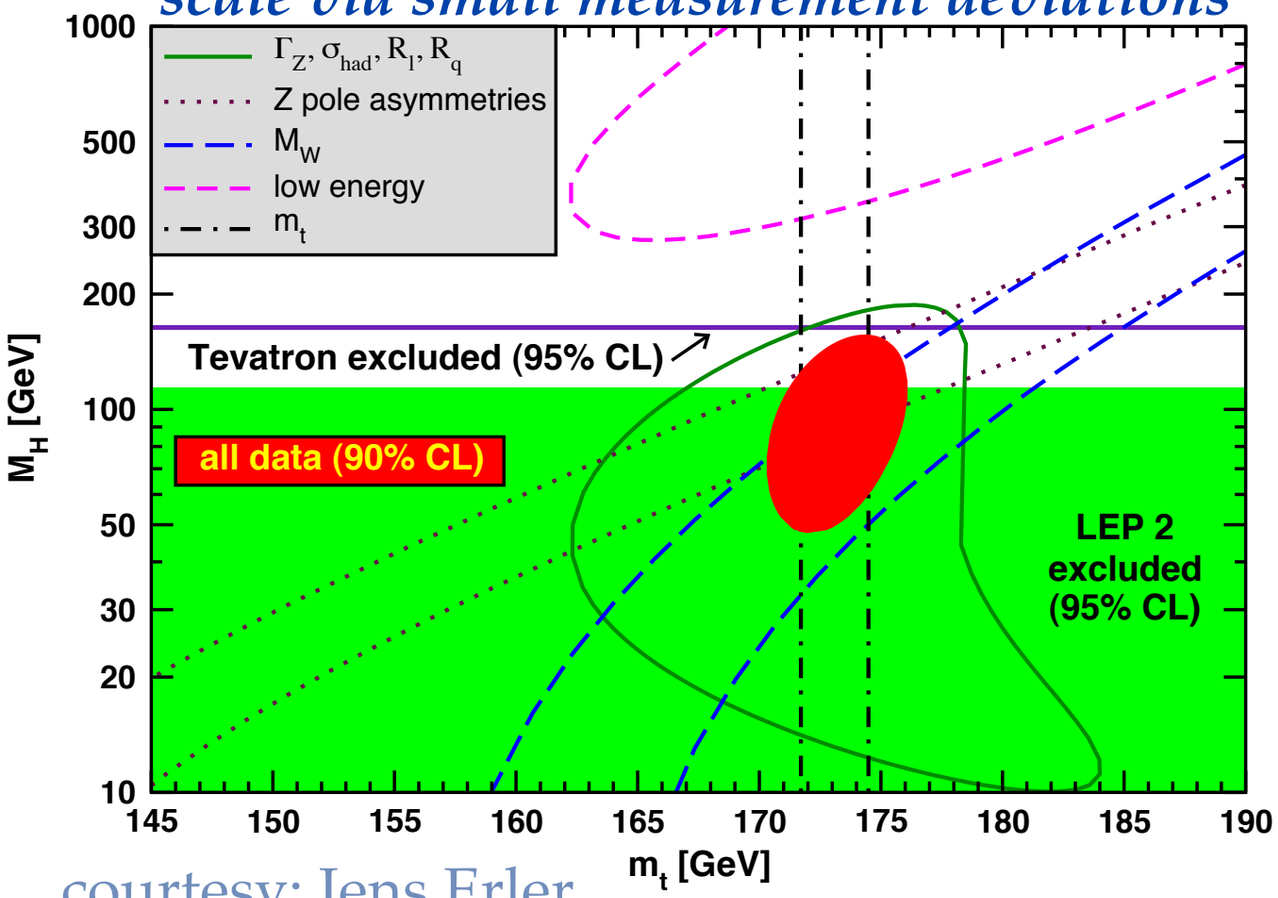

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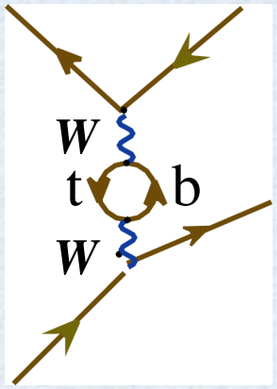

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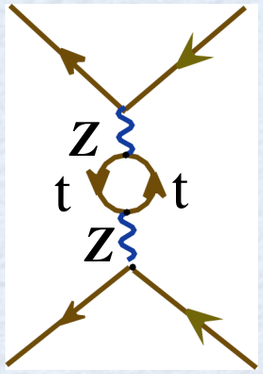

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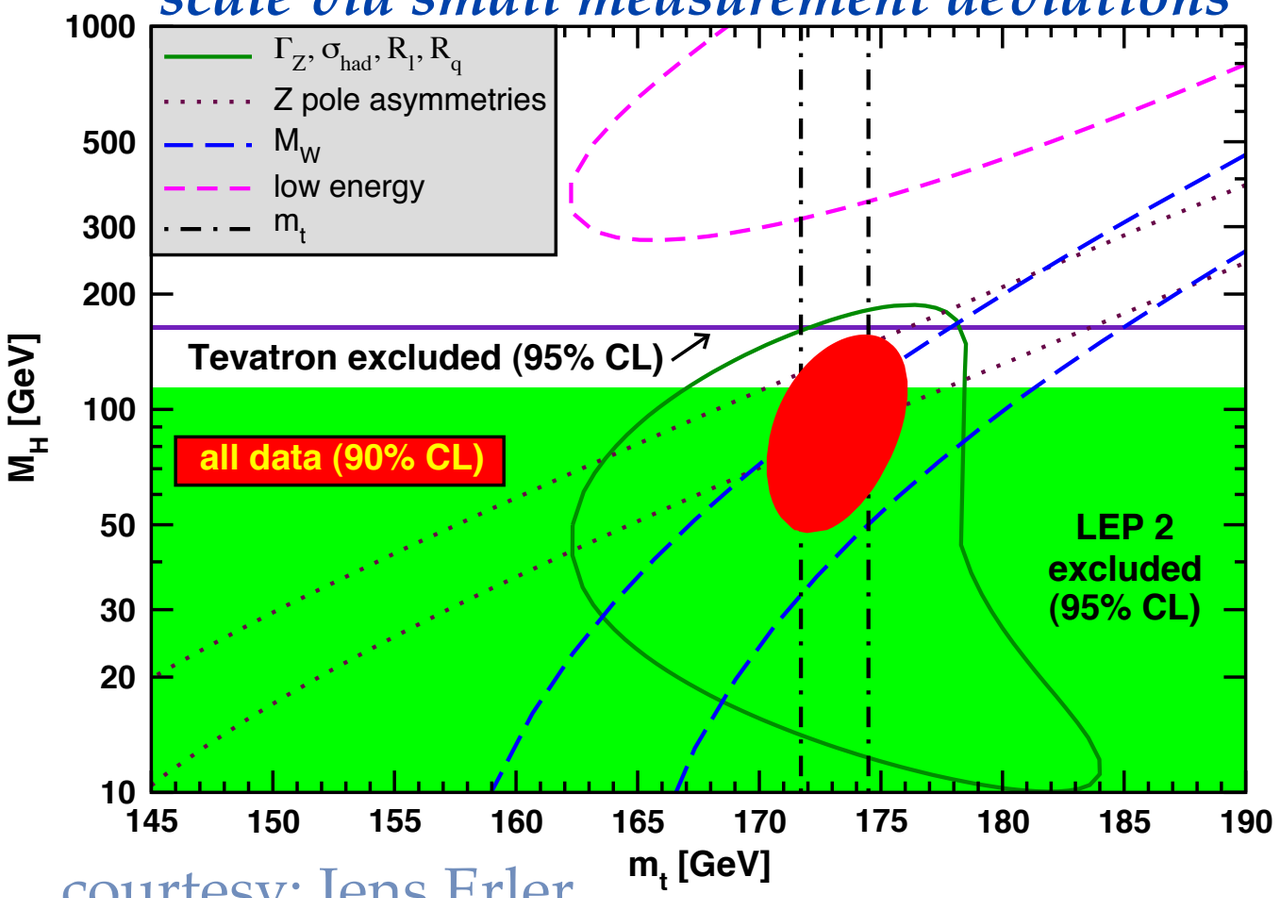

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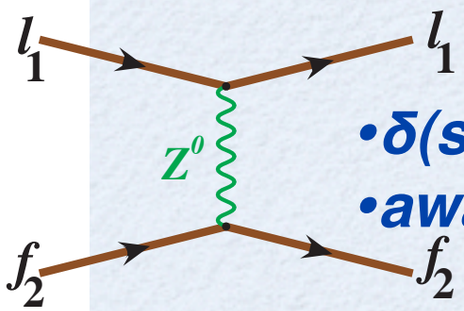
All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

sensitive to TeV-scale contact interactions iff:

- ***$\delta(\sin^2\theta_W) \leq 0.5\%$***
- ***away from the Z resonance***



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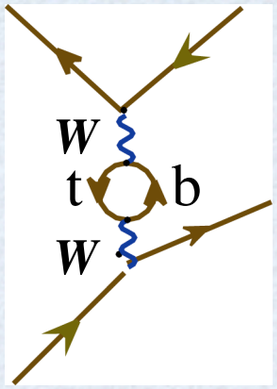

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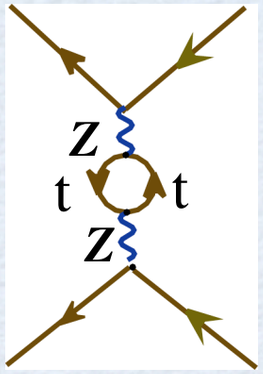

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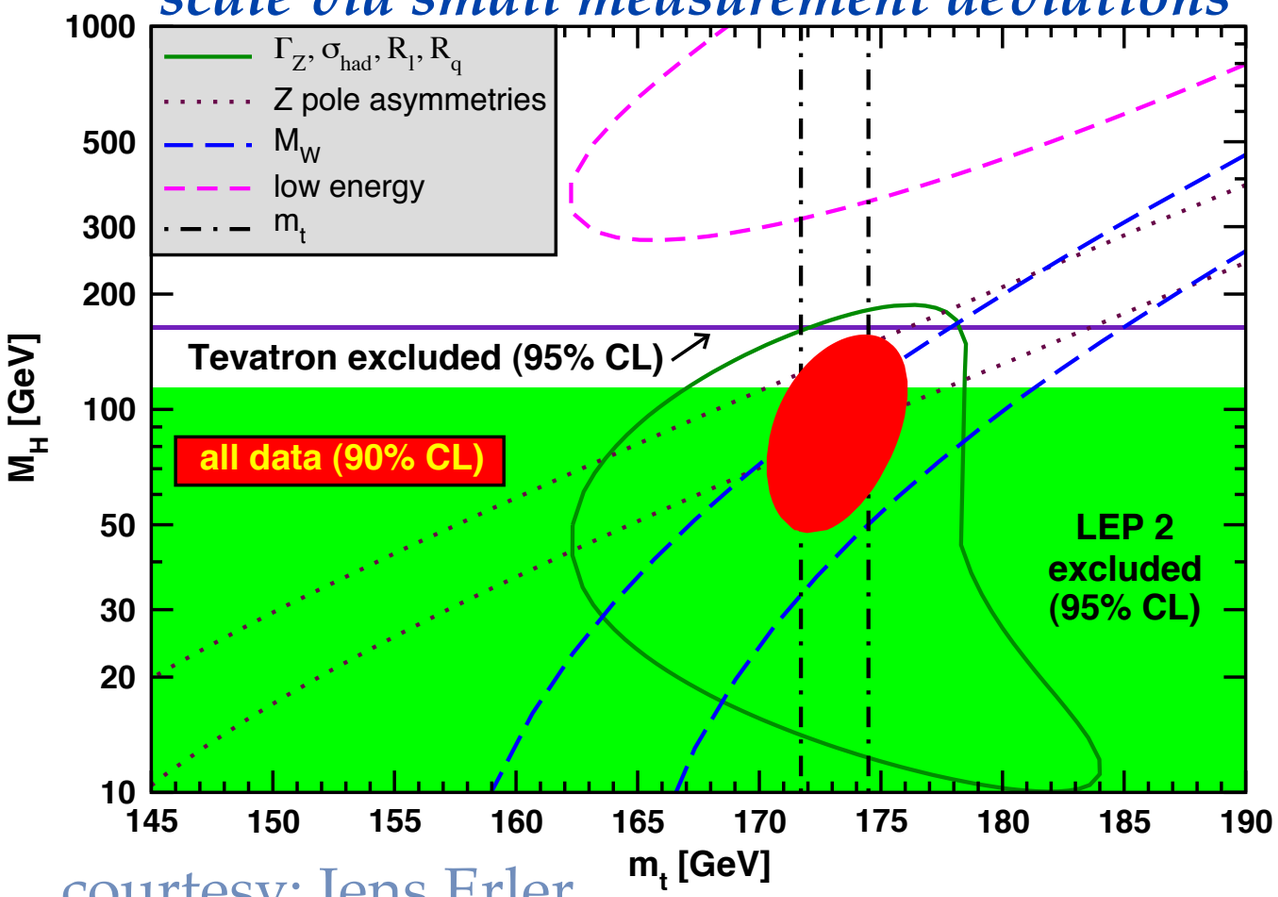

courtesy: Jens Erler

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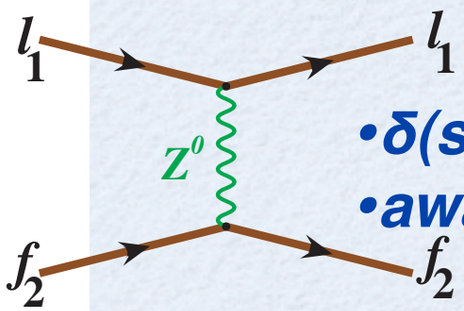


sensitive to TeV-scale contact interactions iff:

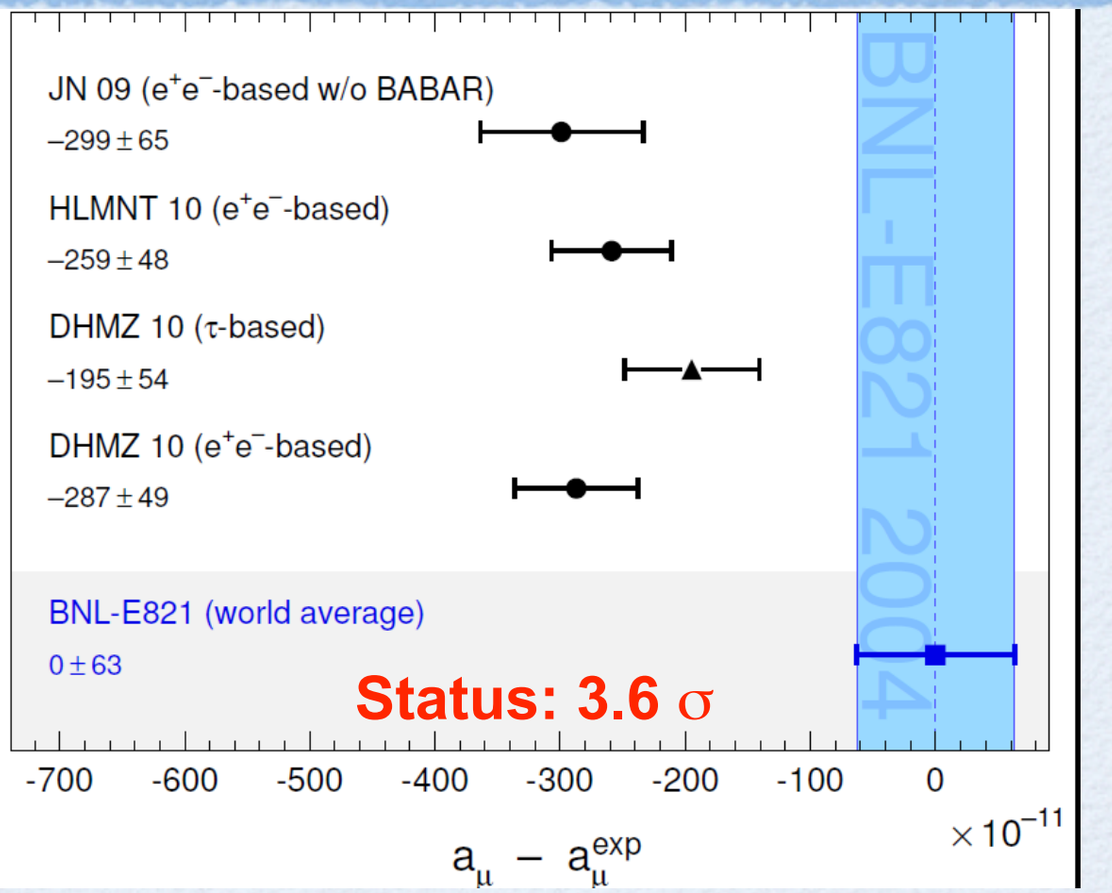
- ***$\delta(\sin^2\theta_W) \leq 0.5\%$***
- ***away from the Z resonance***

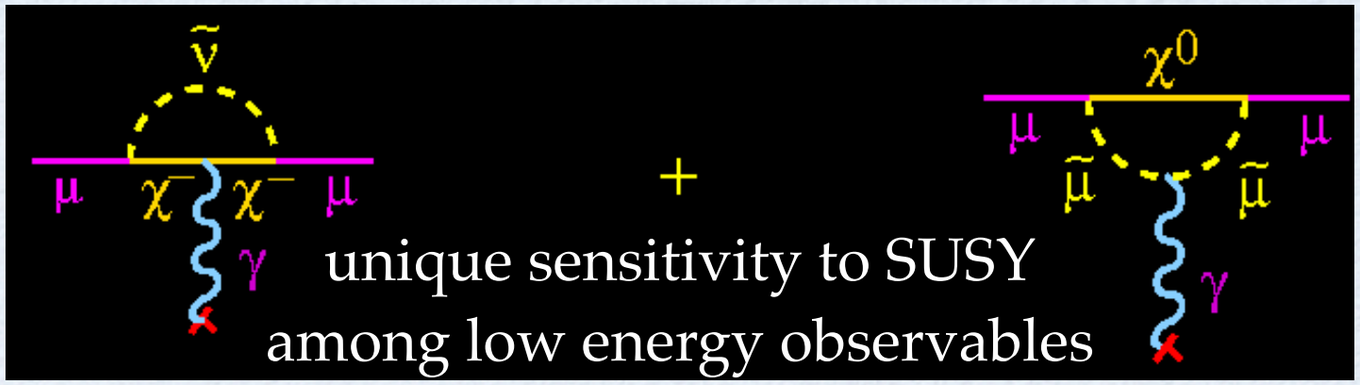
one very special observable: muon g-2 anomaly

Muon g-2 at Fermilab

Talk by L. Roberts
Wed. afternoon

The New Muon (g - 2) Experiment (Fermilab E989): a_μ to 0.14 ppm





unique sensitivity to SUSY among low energy observables

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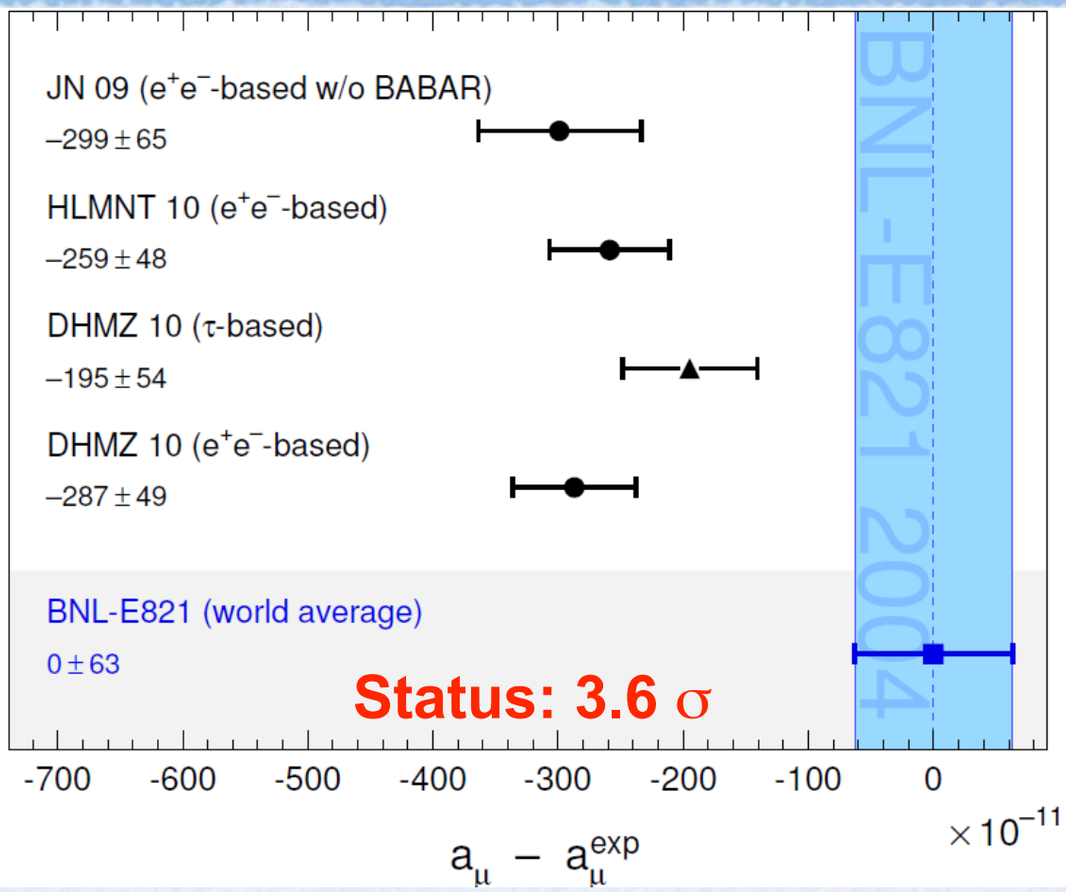
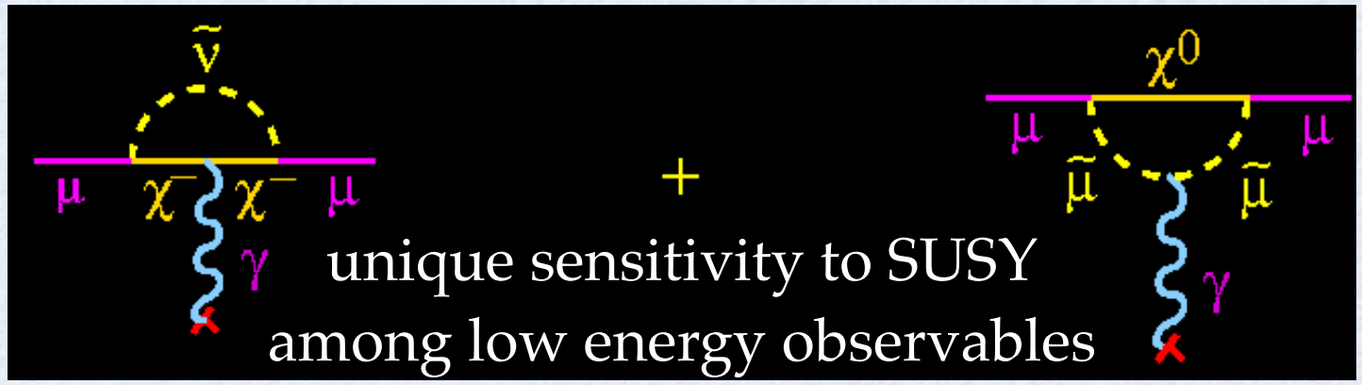
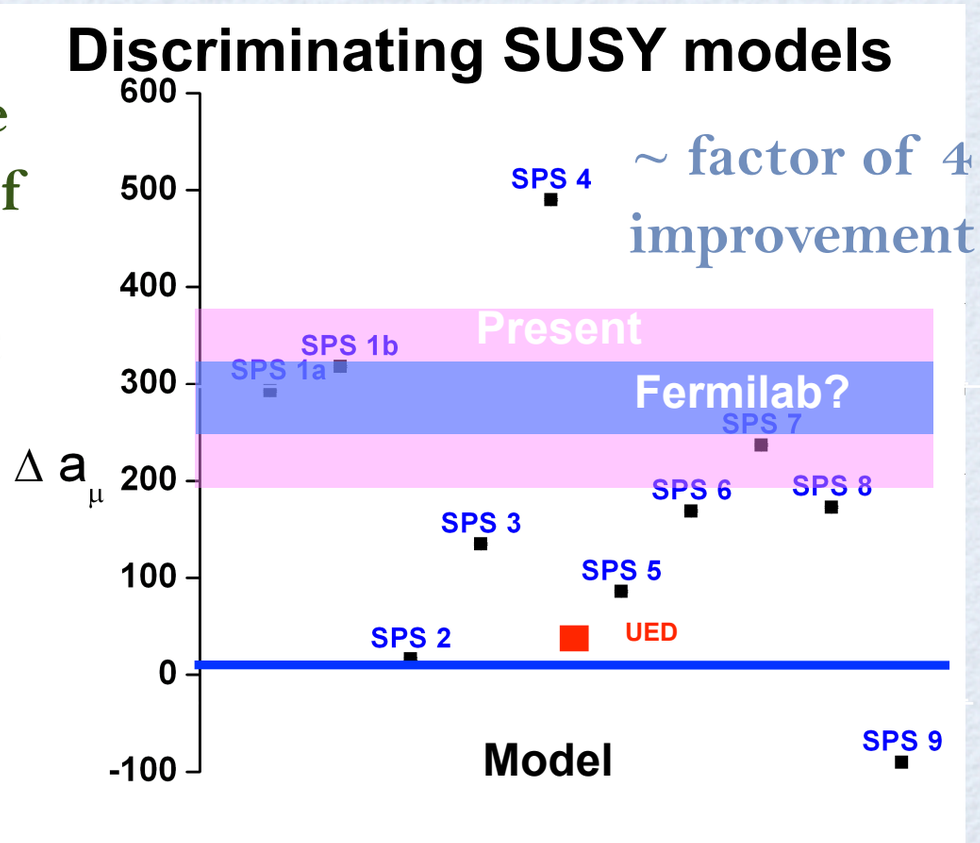
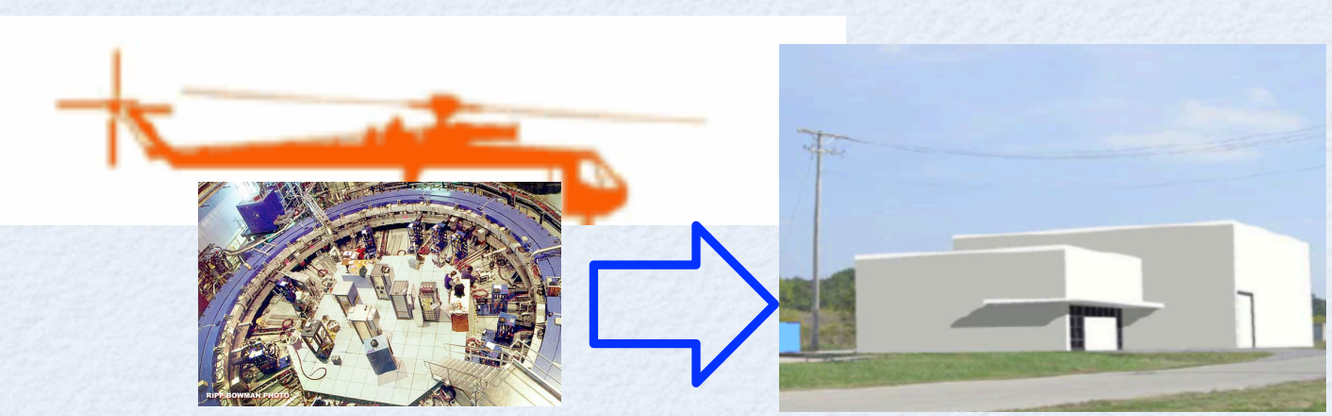




Help discriminate among scenarios if SUSY-like signature at LHC



The Snowmass Points and Slopes showing the present region favored by the E821 Δ aμ, and the projected sensitivity of E989 (**UED** is a universal extra dimension calculation; clearly unfavored)



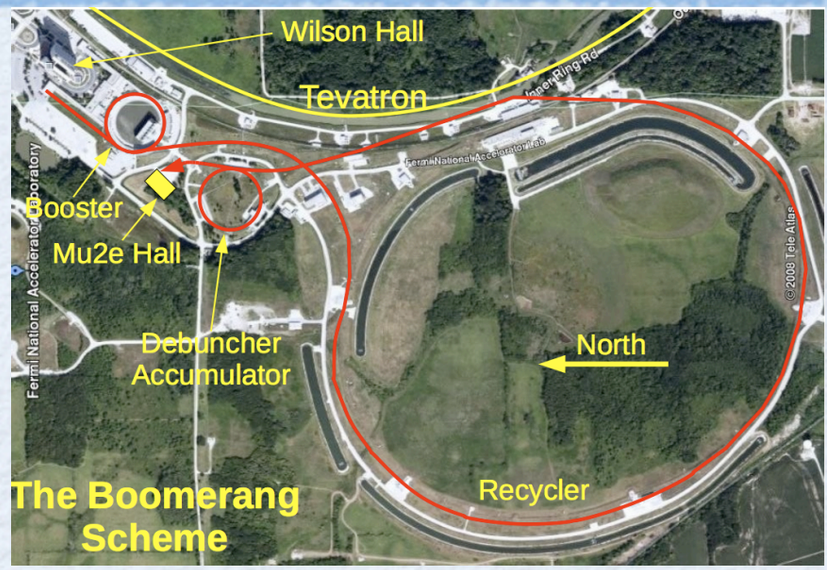
From BNL

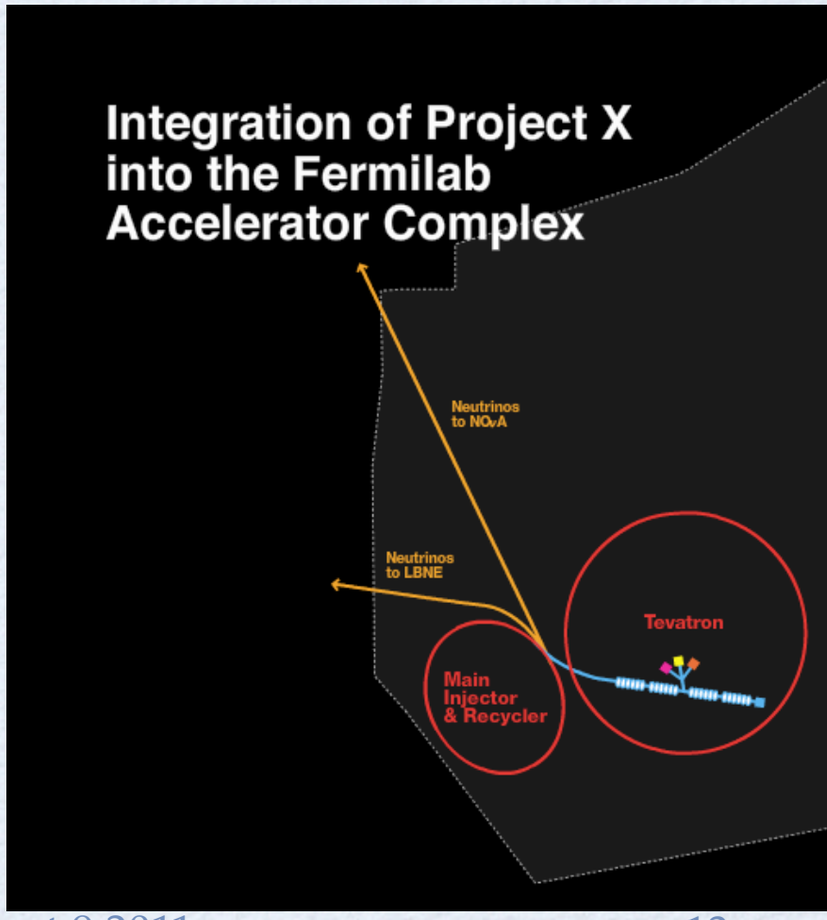
New installation at FNAL

Status: Obtained Stage-1 Approval, applying for CD-0

Muons, Neutrinos and Beyond

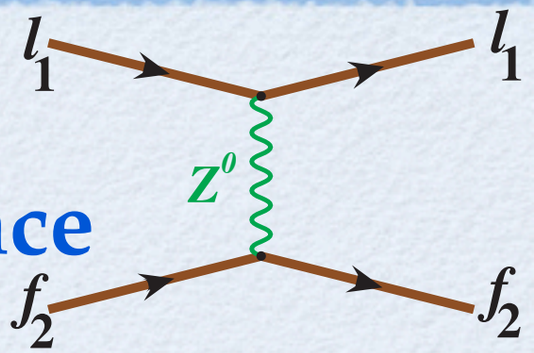
- **Fermilab plan for the next decade**
  - *Neutrinos: NOvA to explore the PMNS matrix*
  - *Muons: Mu2e and g-2*
- **Neutrinos and Muons can run simultaneously**
  - *Mu2e and g-2 must alternate but complex accommodates both*
  - *neither conflicts with NOvA*
  - *planning assumes all three will run in the next decade*
- **Significant improvement in intensity with Project X**
  - *x100 muons for mu2e to reach 10^{-18} or study Z dependence*
  - *Many other ideas for rare mu, K decays, EDMs....*





Weak Neutral Currents

Search for New Flavor Conserving Contact Interactions



- **Precision Neutrino Scattering**
- **New Physics/Weak-Electromagnetic Interference**
  - *opposite parity transitions in heavy atoms*
  - *Spin-dependent electron scattering*

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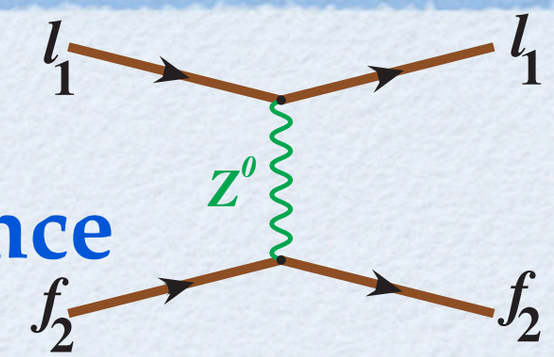

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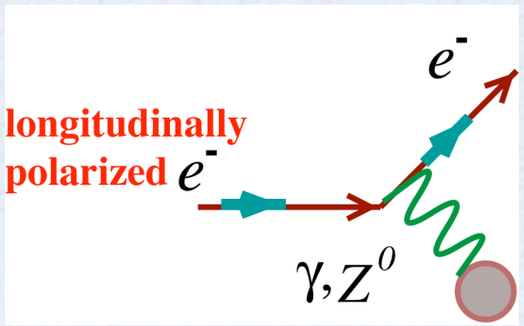

$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

g_V and g_A are function of $\sin^2\theta_W$

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad \textit{to} \quad 10^{-4} \cdot Q^2$$

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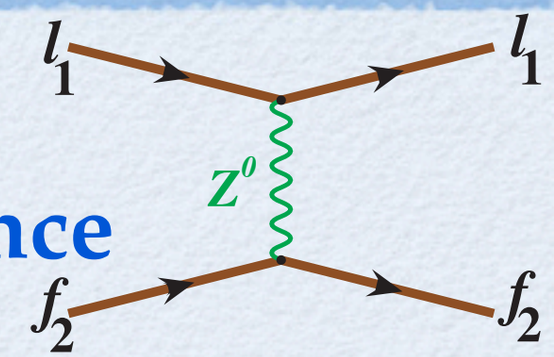

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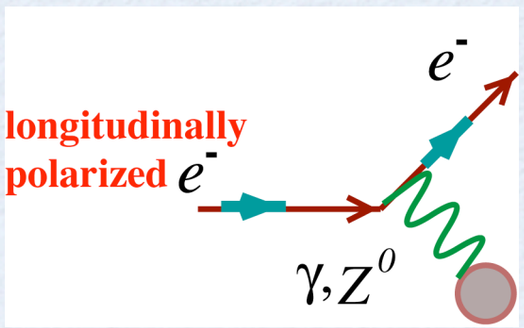

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Weak Charge Q_W

Thumb rule: measure $\delta(\sin^2\theta_W) \lesssim 0.002$ or better to access the multi-TeV scale

e & p: $Q_W = 1 - 4\sin^2\theta_W$

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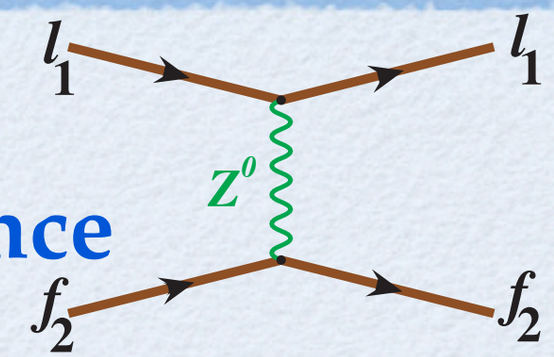

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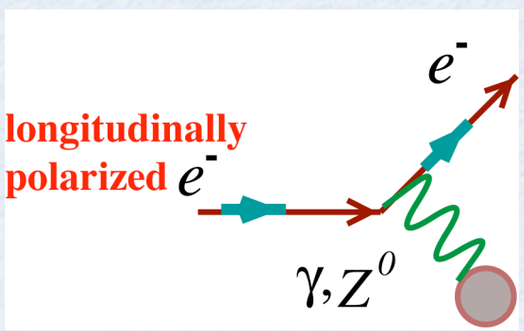

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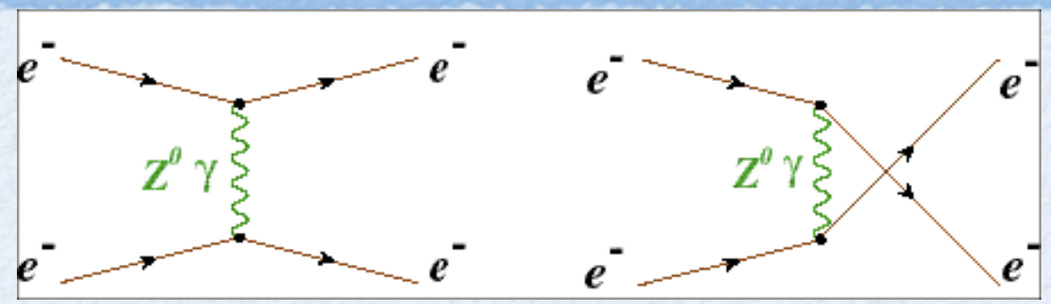
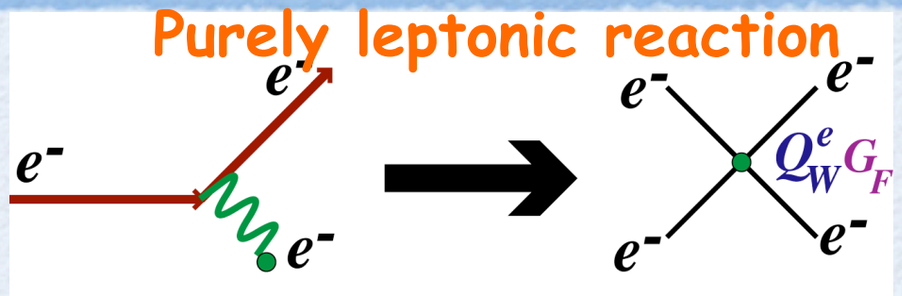
Electromagnetic amplitude interferes with Z-exchange as well as any new physics

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

SLAC E158

Parity-Violating Electron-Electron (Møller) Scattering





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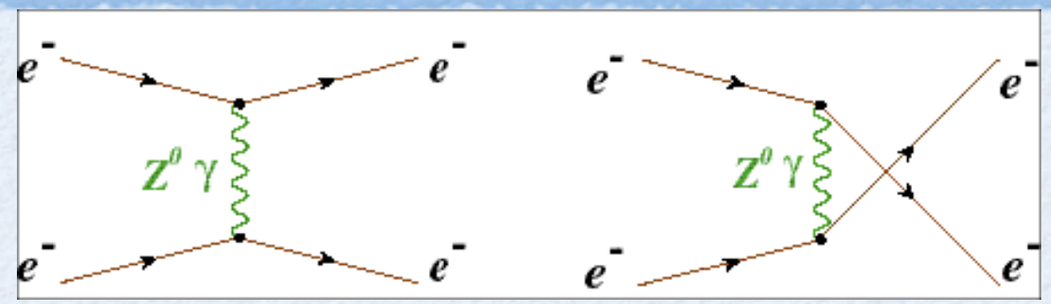

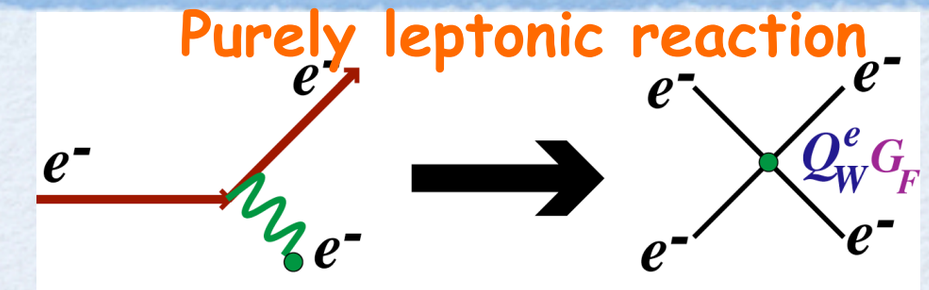

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$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05\frac{\delta(A_{PV})}{A_{PV}}$$

50 GeV at SLAC:
~ 150 ppb!

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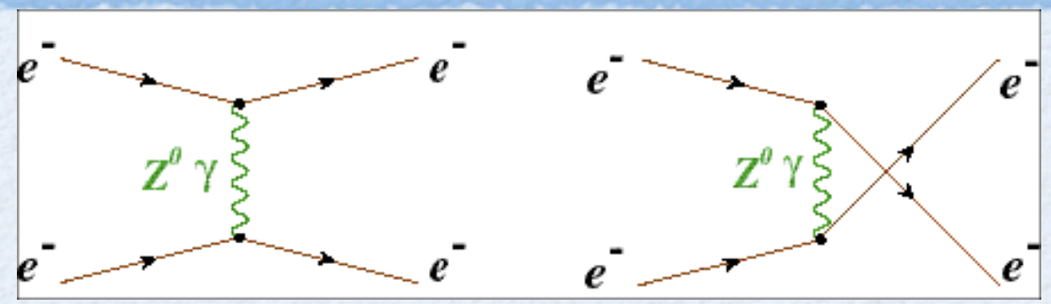

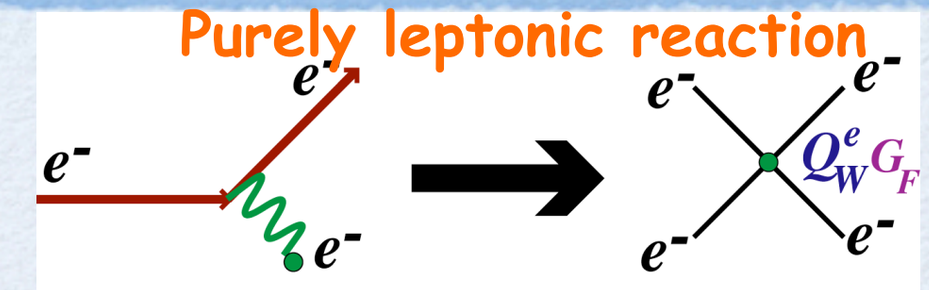

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Major technical challenges

Final Result:

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

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

SLAC E158

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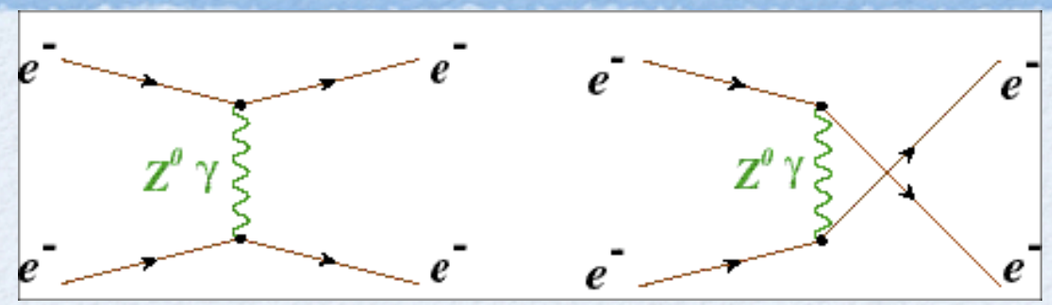

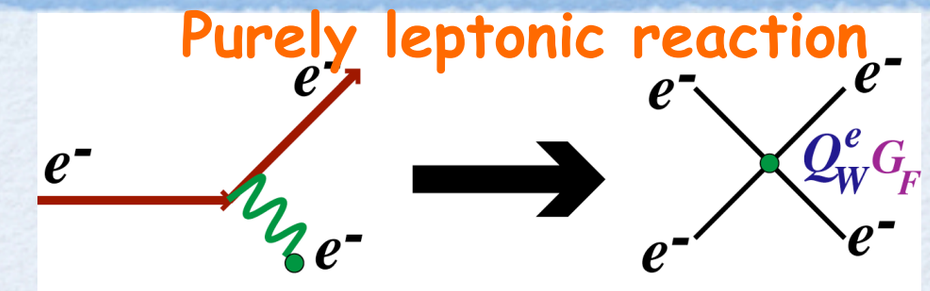

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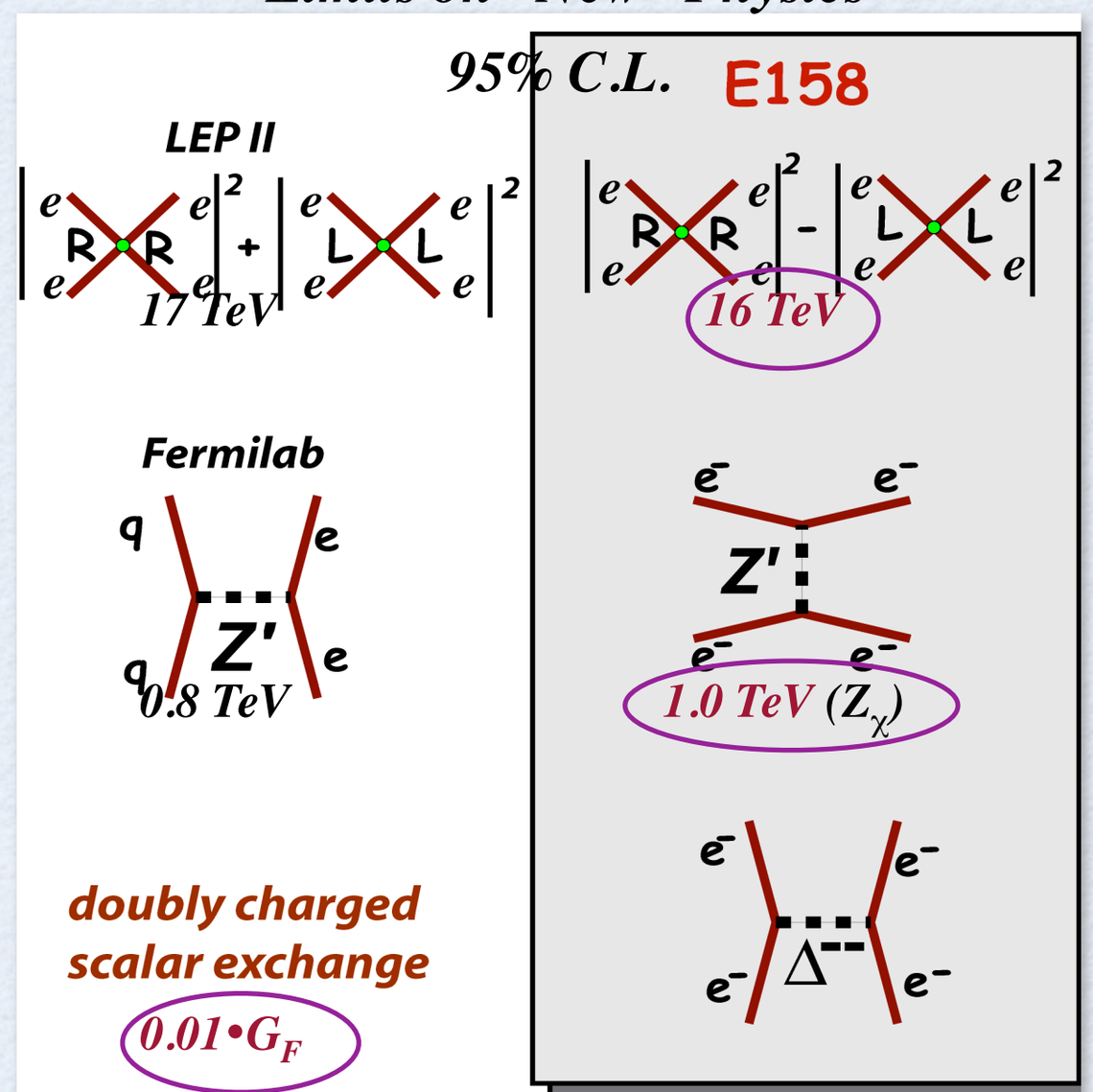
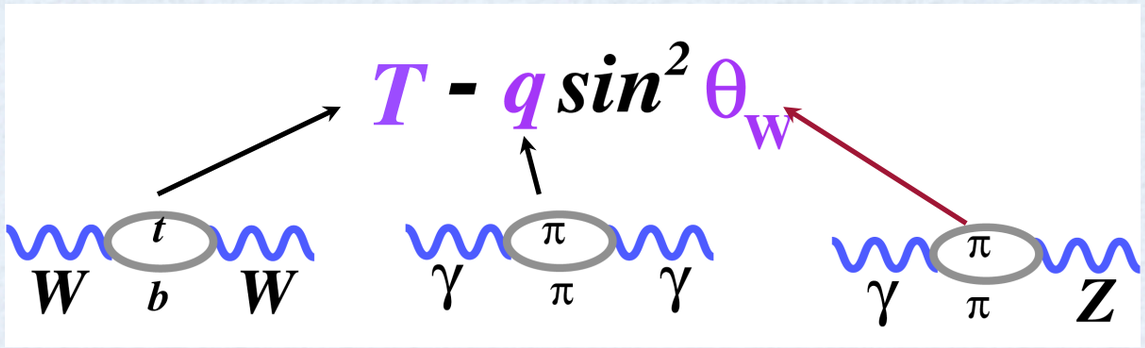
Limits on "New" Physics



The Weak Mixing Angle

Running of θ_W: Bookkeeping for off-resonance measurements



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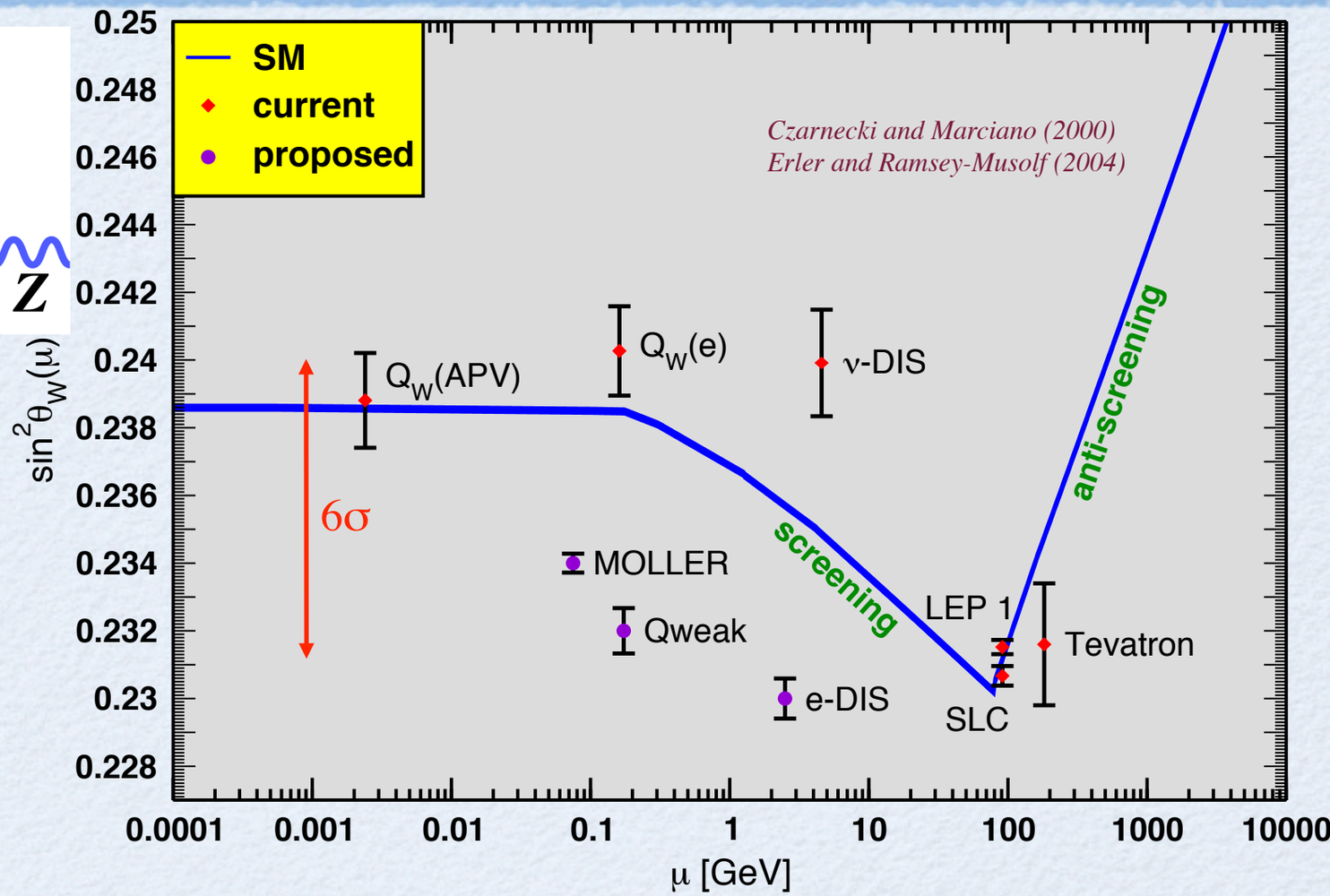

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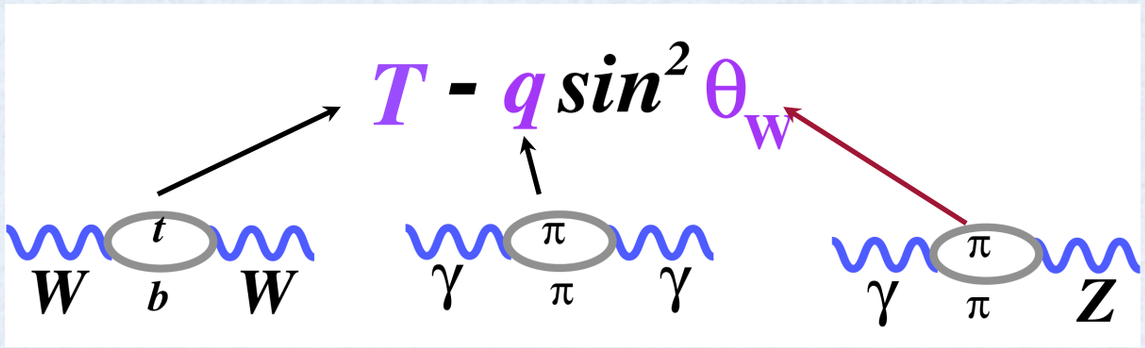

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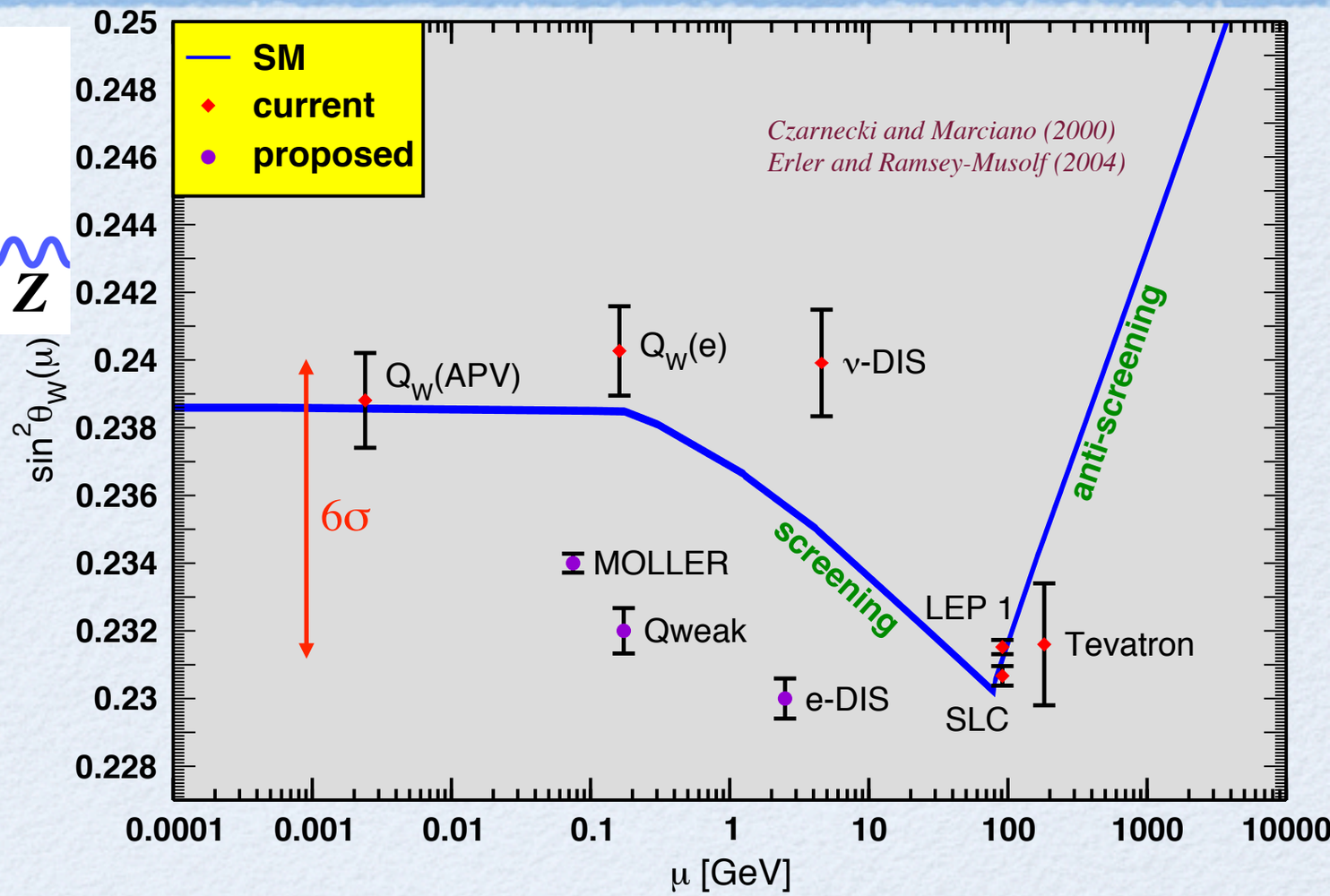

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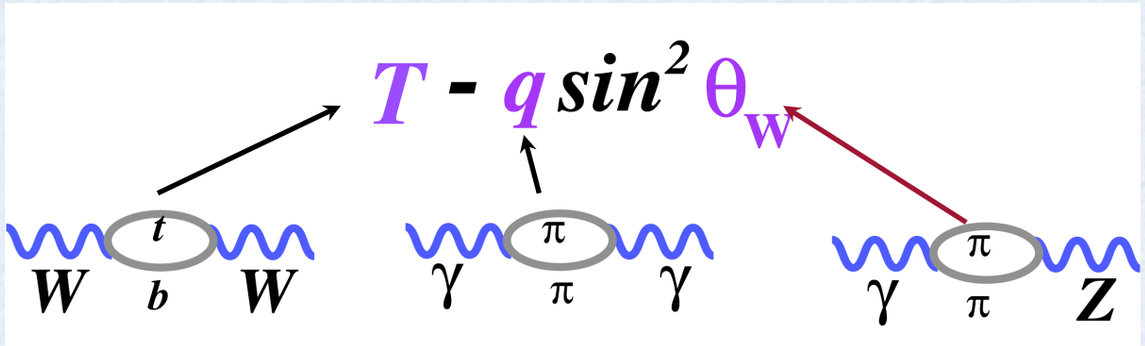

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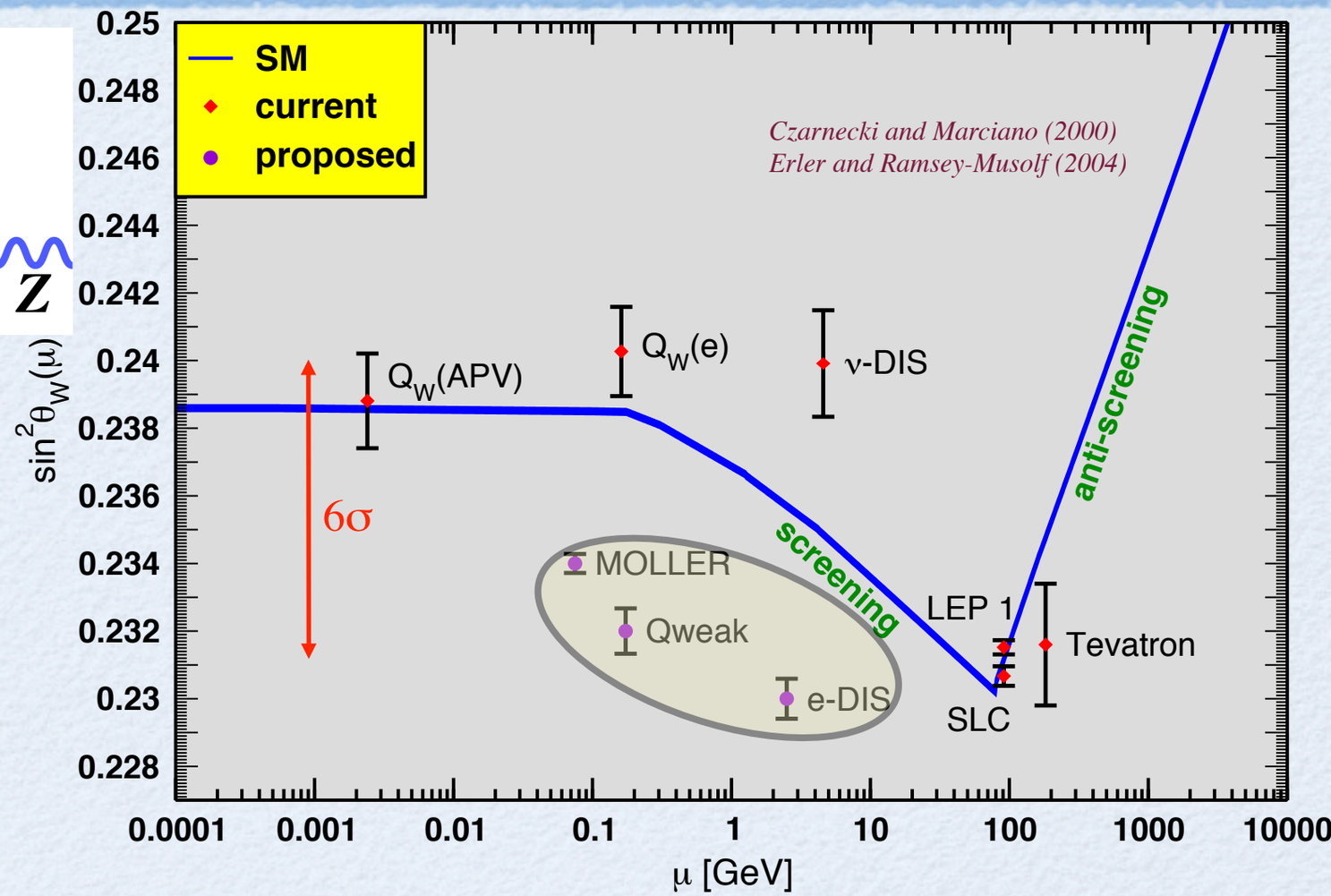

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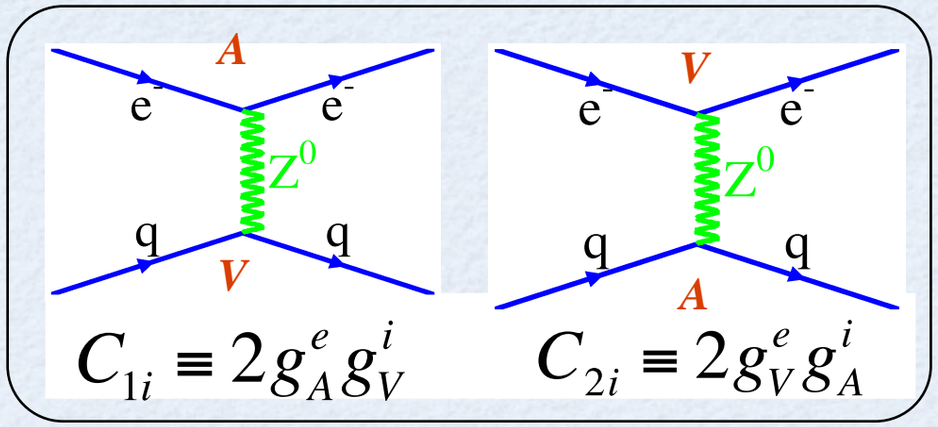
Precision Weak Charges

Current and future measurements of parity-violating asymmetries



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4 e-q couplings and the e-e coupling

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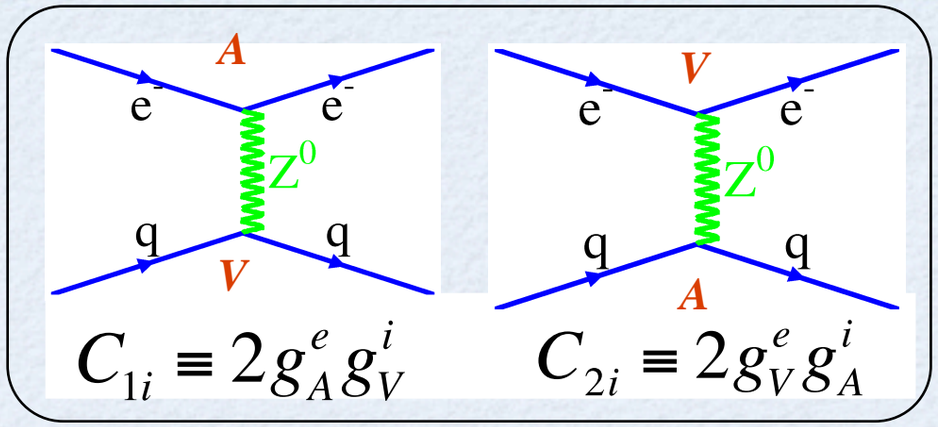

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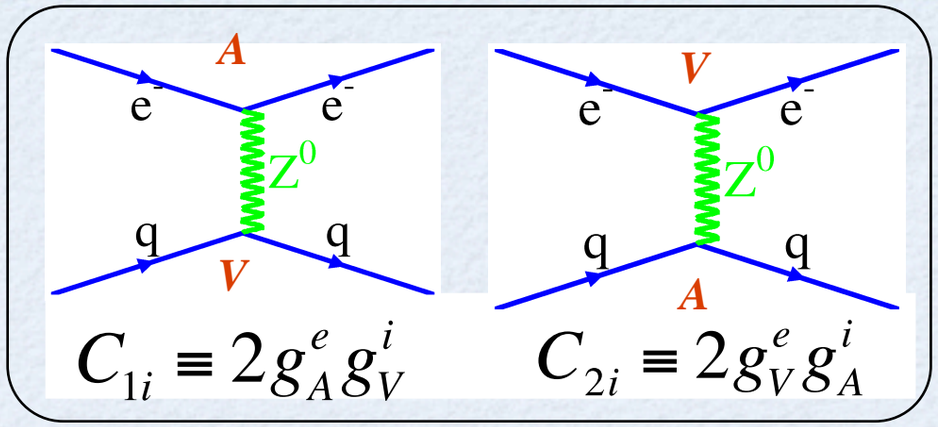

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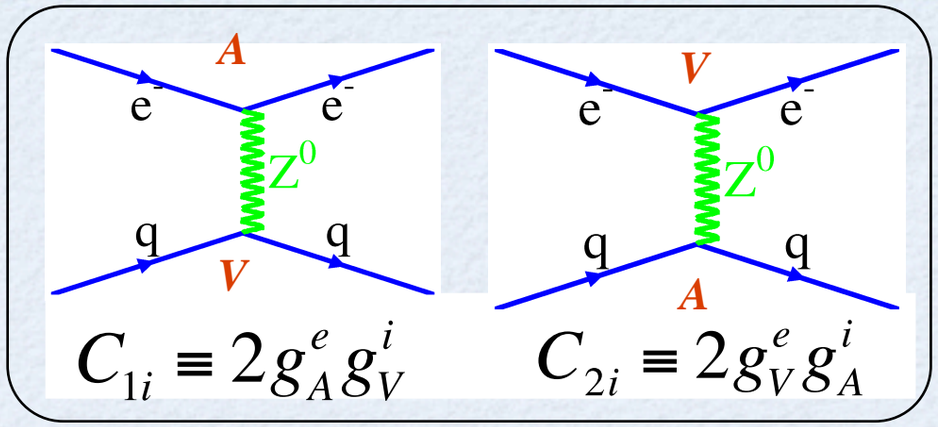

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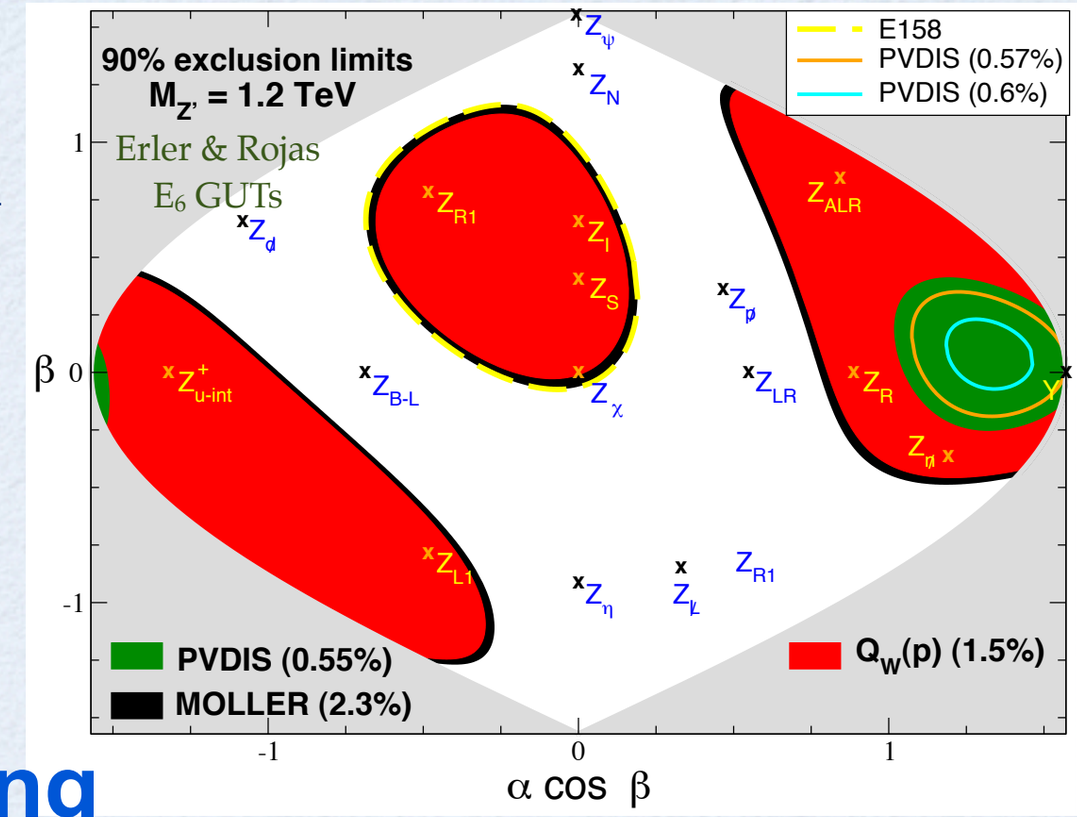

LHC new physics signals will have multiple interpretations: weak charge measurements can discriminate among scenarios

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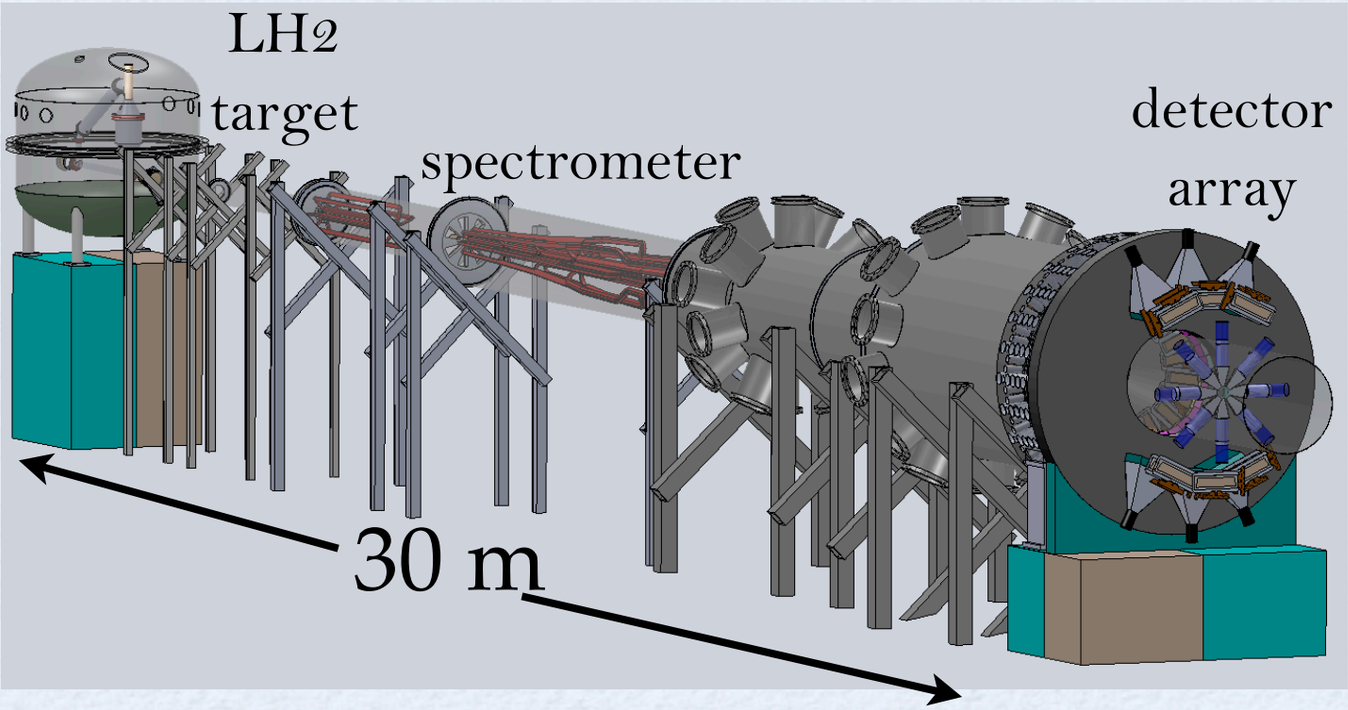
MOLLER at Jefferson Lab

An ultra-precise measurement of the weak mixing angle using Møller scattering

E_{beam} = 11 GeV 75 μA 80% polarized ~ 38 weeks (~ 2 yrs) → $\delta(A_{PV})$ = 0.73 ppb

A_{PV} = 35.6 ppb → $\delta(Q^e_W)$ = ± 2.1 (stat.) ± 1.0 (syst.) %

$\delta(\sin^2\theta_W)$ = ± 0.00026 (stat.) ± 0.00012 (syst.) → ~ 0.1%



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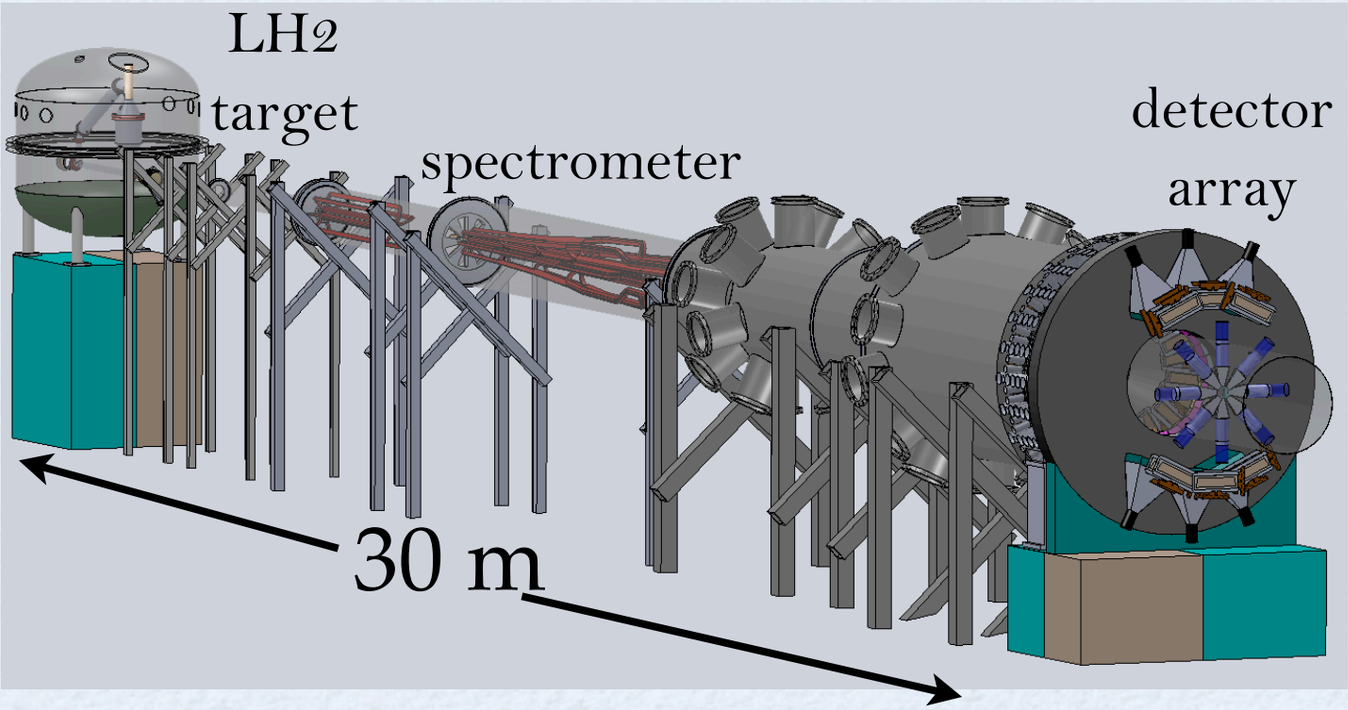

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \mathrm{TeV}$$

best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:

Z factory, linear collider, neutrino factory or muon collider

MOLLER at Jefferson Lab

An ultra-precise measurement of the weak mixing angle using Møller scattering

E_{beam} = 11 GeV 75 μA 80% polarized $\xrightarrow[(\sim 2\ yrs)]{\sim 38\ weeks}$ $\delta(A_{PV})$ = 0.73 ppb

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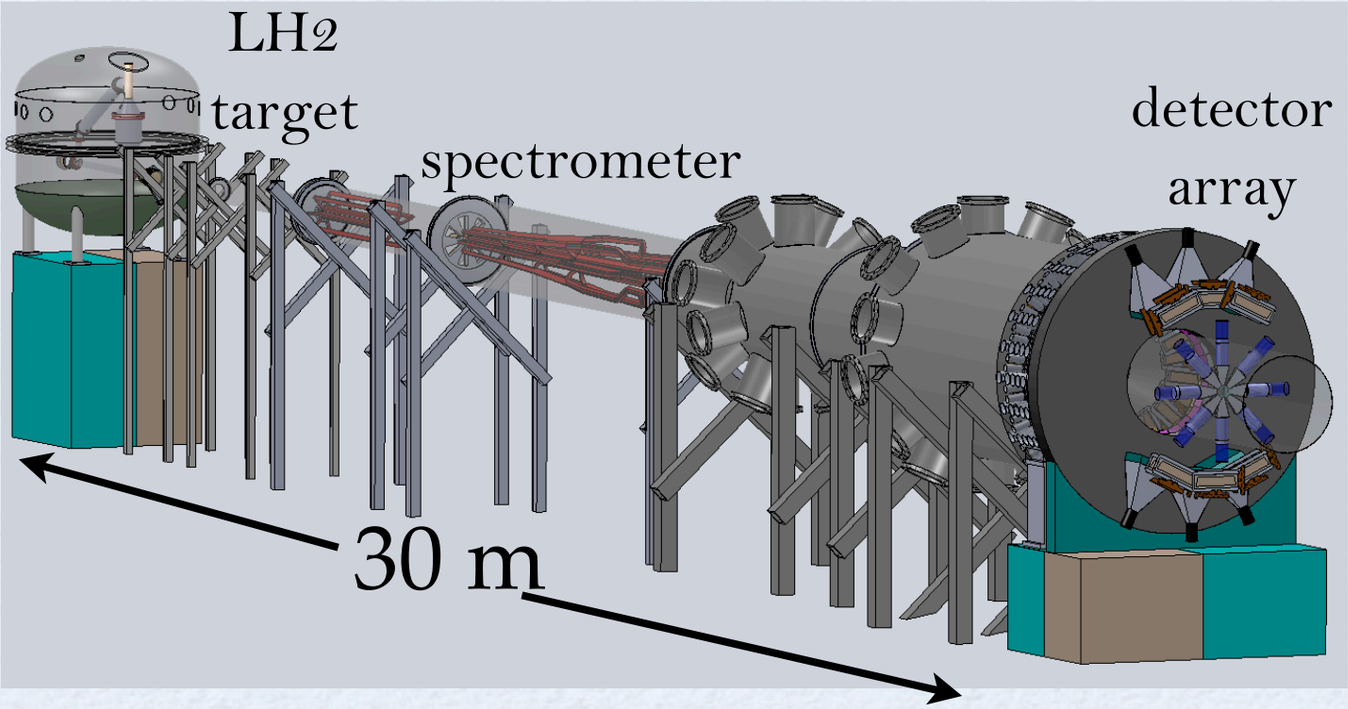

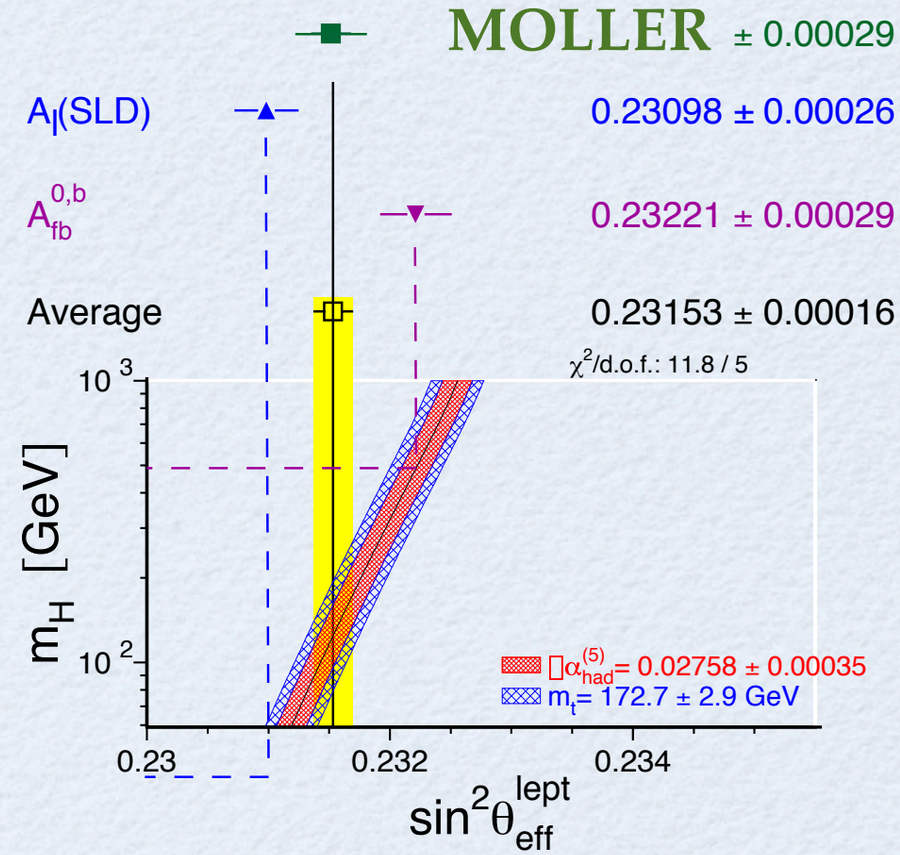

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Proposal to be submitted to DoE (Nuclear Physics) to obtain CD-0

A_{PV} = 35.6 ppb ⇒ $\delta(Q^e_W) = \pm 2.1\ (stat.) \pm 1.0\ (syst.)$ %

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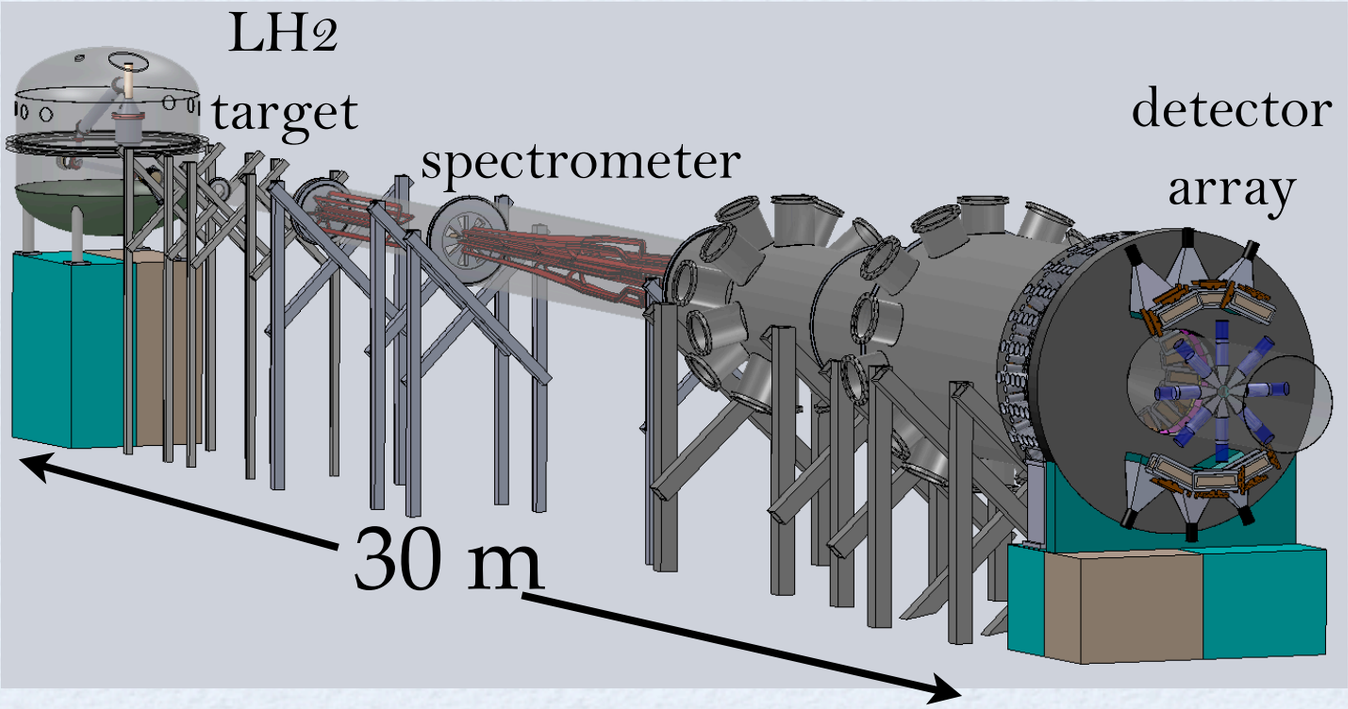

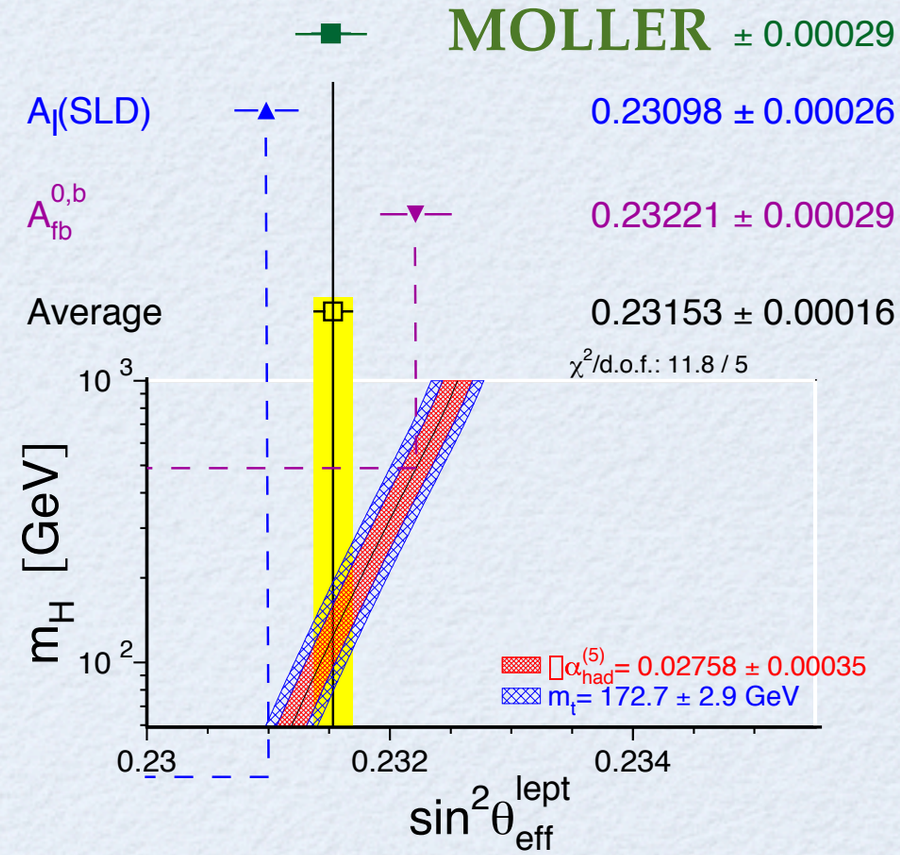

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best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:

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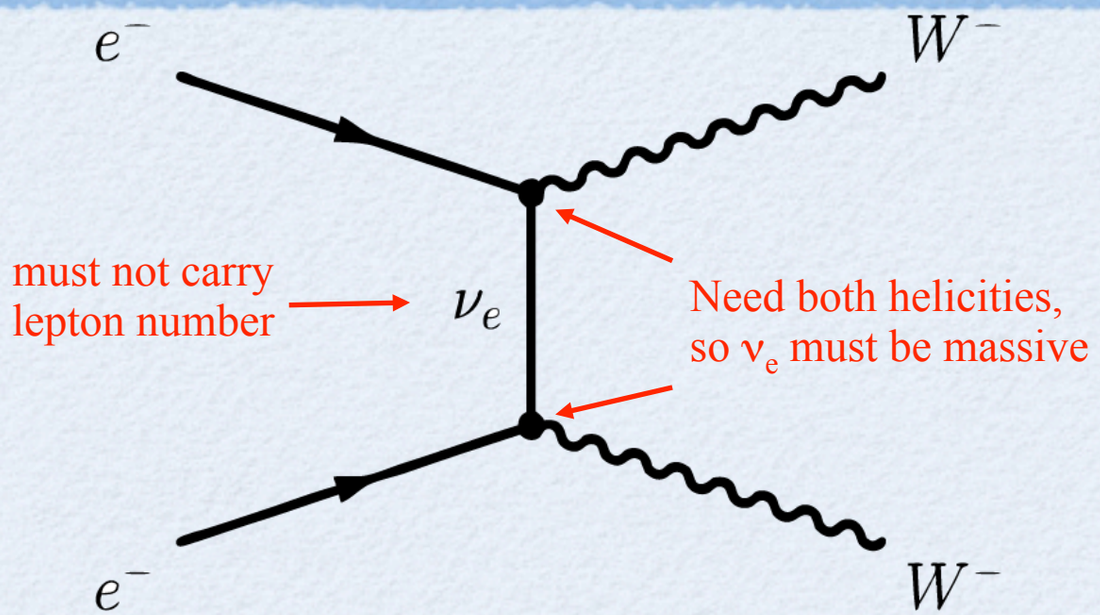
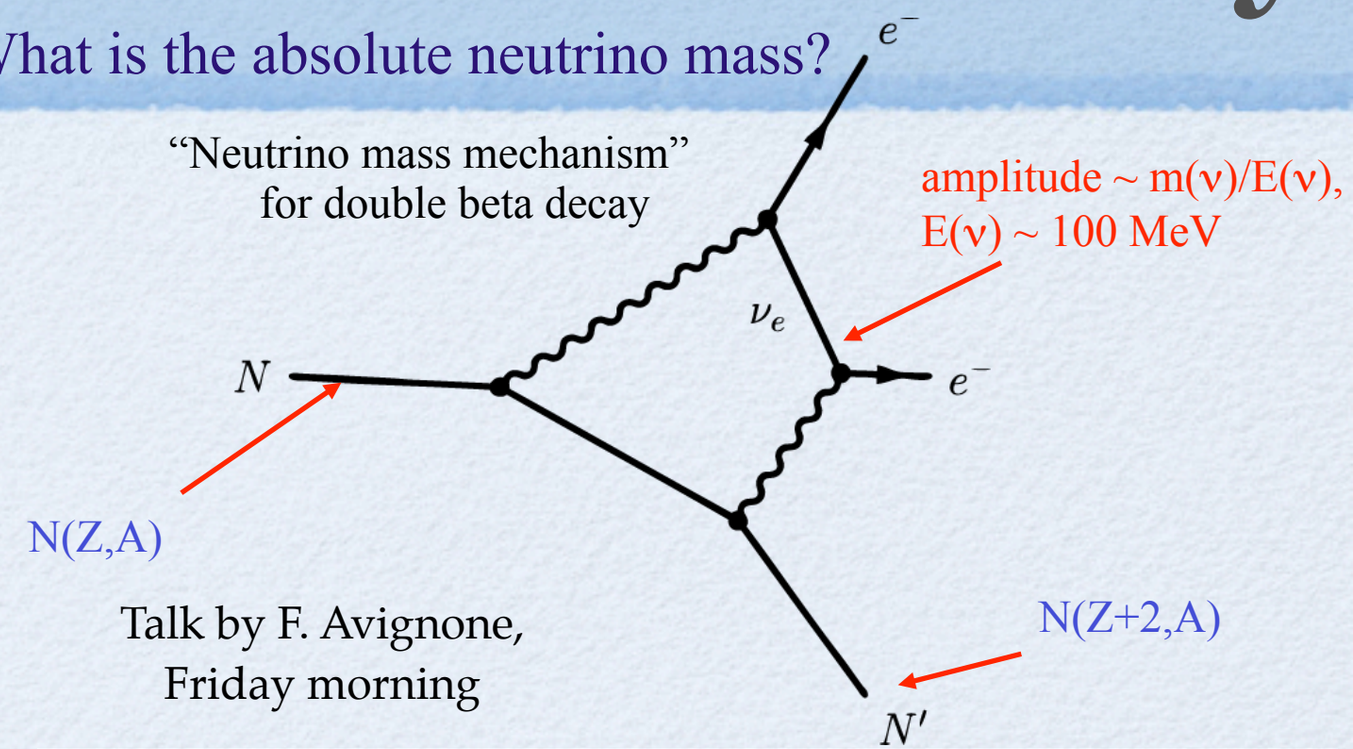
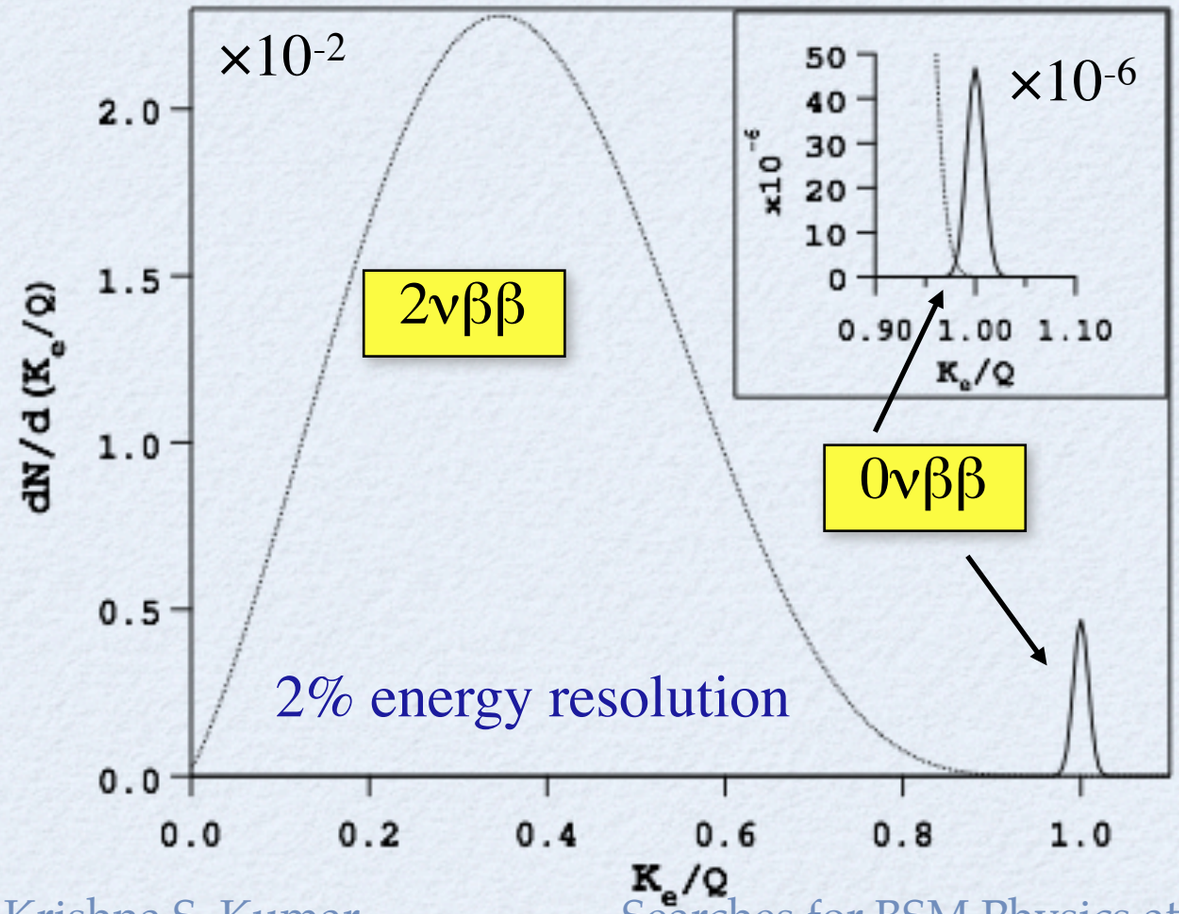
Neutrinoless Double-Beta Decay

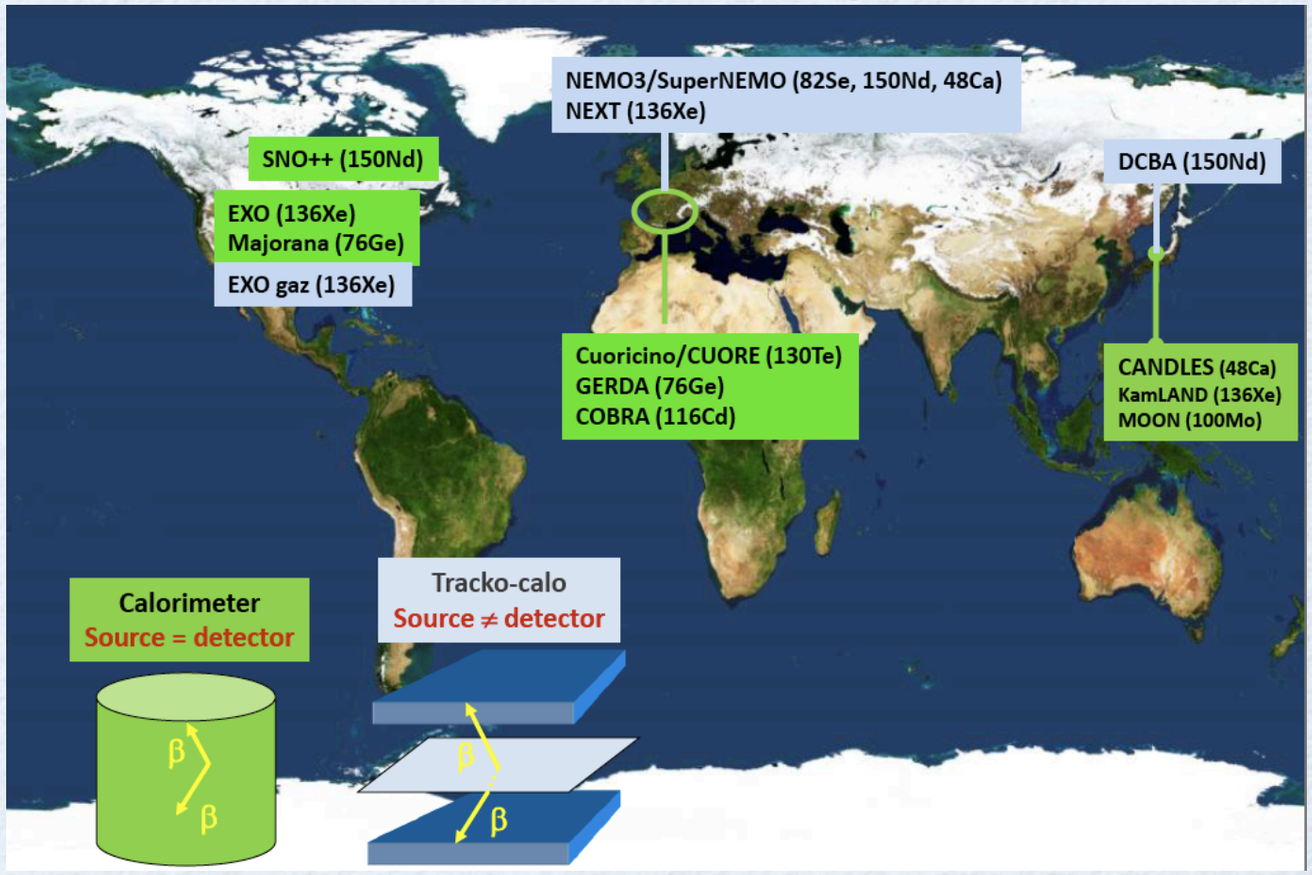
Are neutrinos Majorana particles? What is the absolute neutrino mass?





Talk by F. Avignone, Friday morning

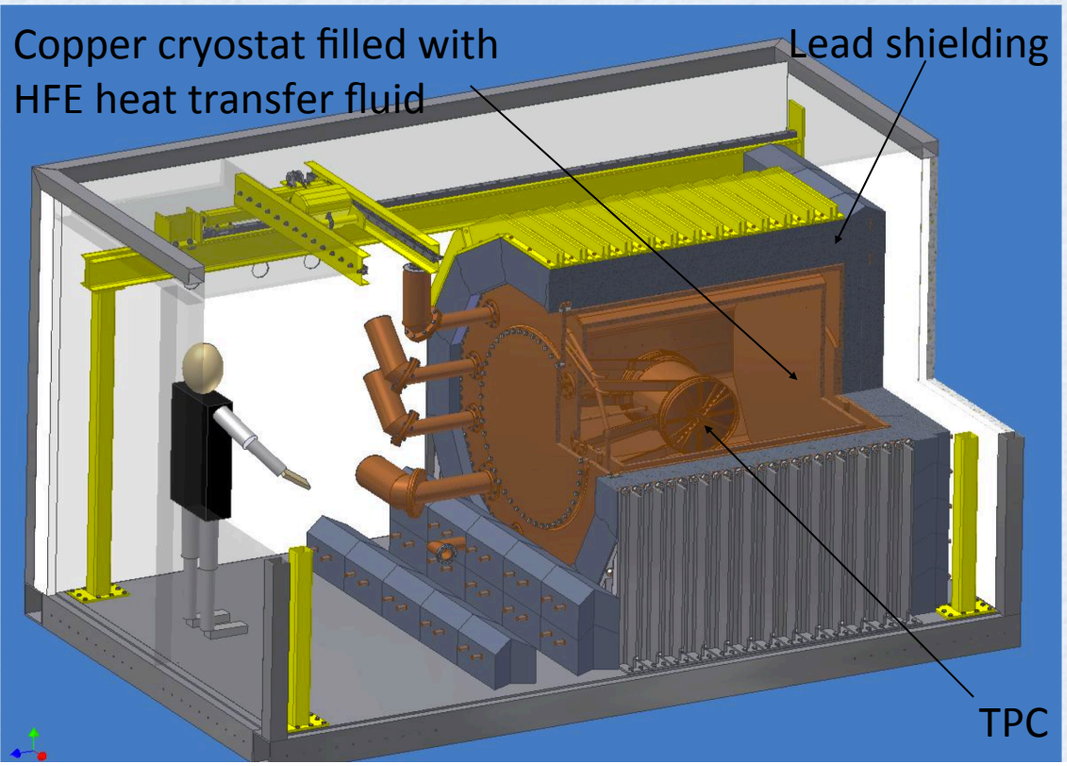




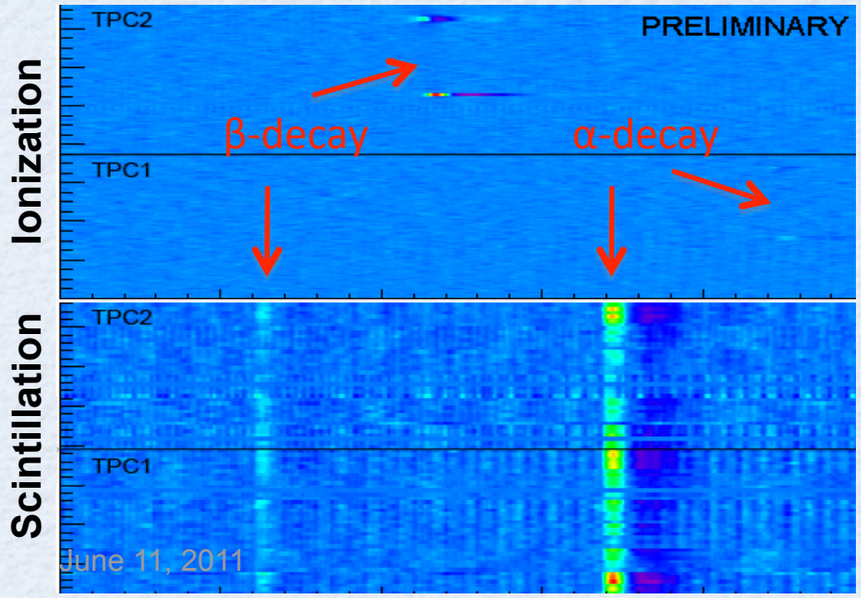
EXO-200

Talk by T. Daniels, Wed. afternoon

Physics run ongoing with 200 kg of 80% enriched ^{136}Xe

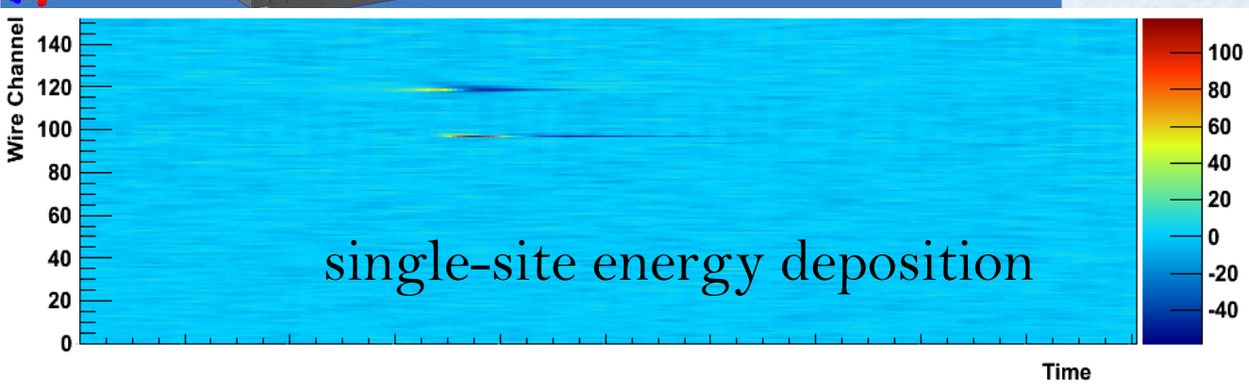


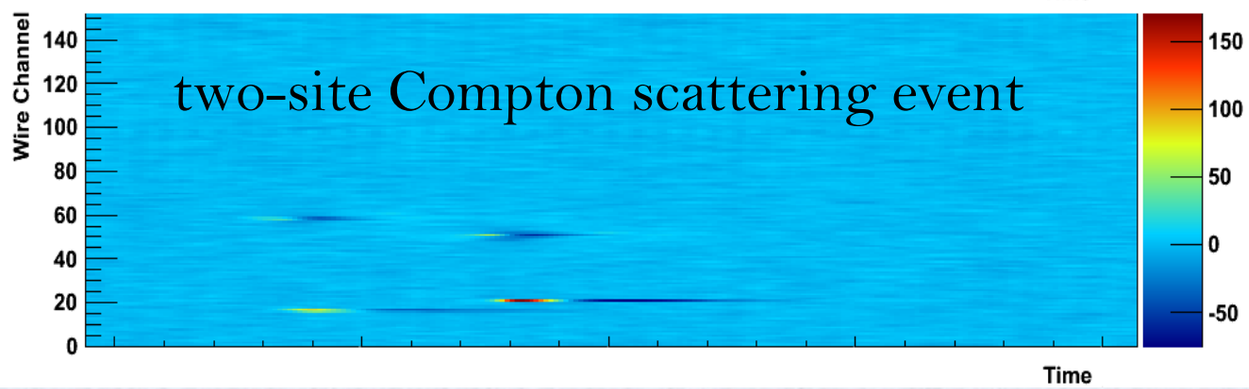
- at WIPP (1600 mwe)
- Liquid Xe TPC
- scintillation (APDs)
- ionization from wires
- 2-ν: > 40K evts/yr at current limit
- 0-ν reach with 2 year run: 109 - 135 meV

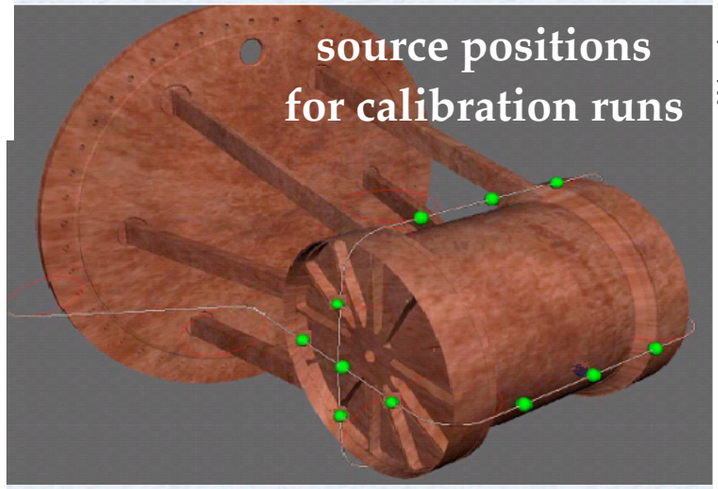


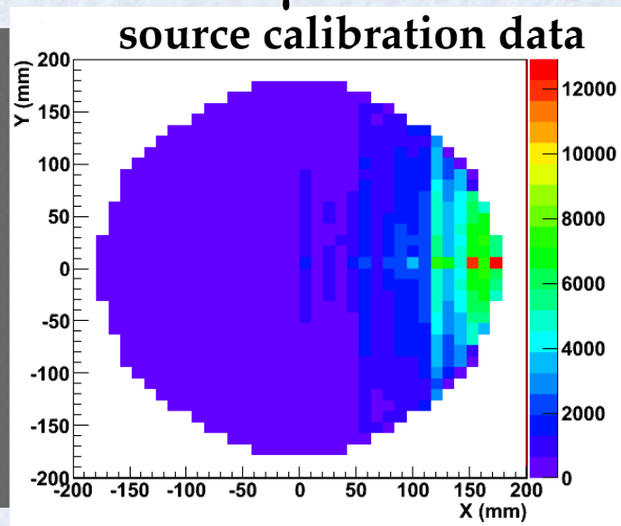
^{214}Bi undergoes β-decay into ^{214}Po which then undergoes α-decay with a half-life of 164 μs.

Stay tuned!









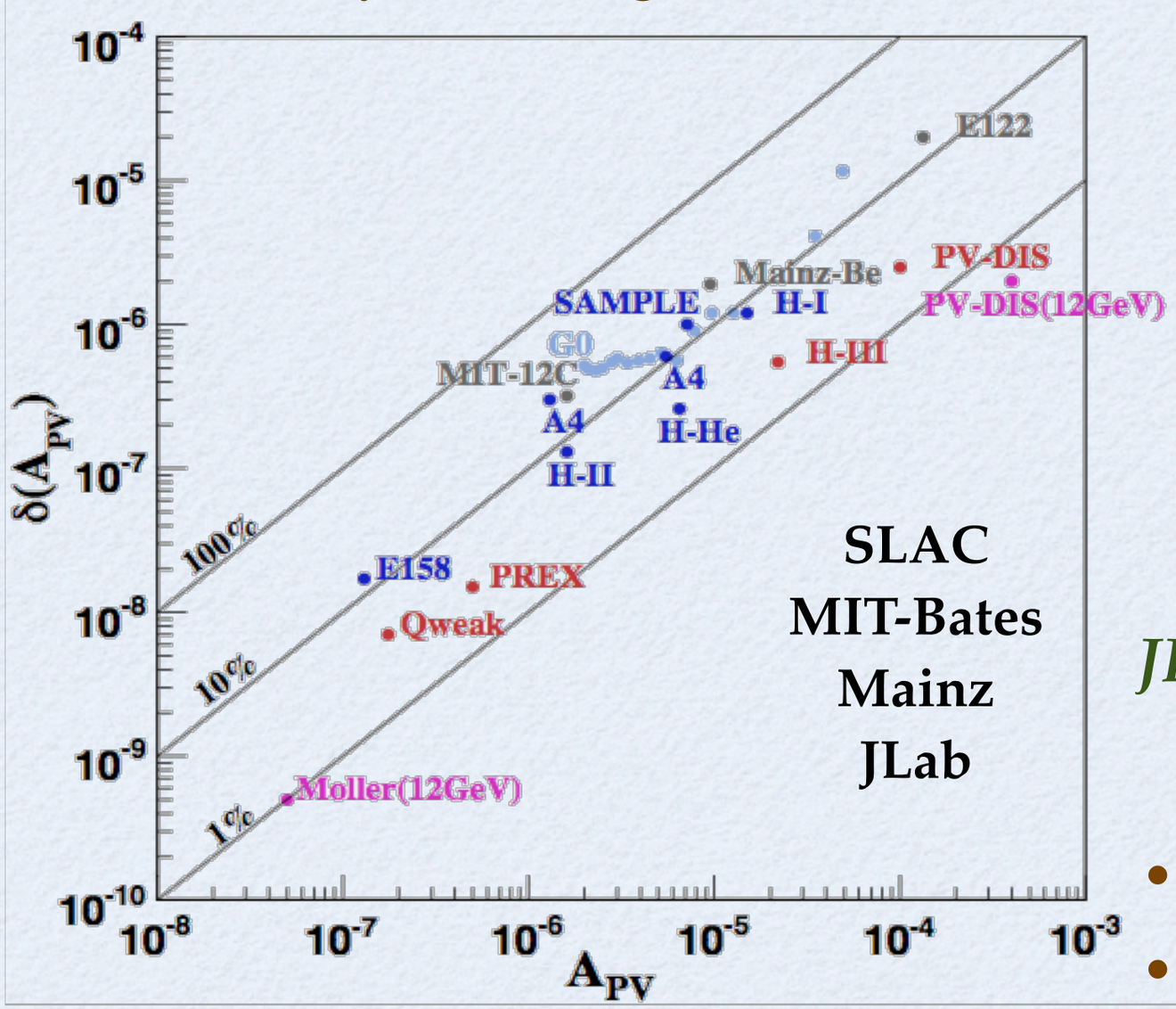
Take-Away Message

- **Charge Lepton Flavor Violation Searches**
  - *MEG will push into the interesting region (10^{-13}) in a couple of years*
  - *Mu2e, DeeMe and COMET will improve sensitivity by 10^3-10^4 over the next decade*
  - *Tau decays aim to improve sensitivity by 10 to 100 at super-B factories*
- **Muon g-2**
  - *Plans are being made for x4 improvement with a new experiment at Fermilab*
- **Fermilab Project X offers the potential to expand portfolio of Intensity Frontier physics**
- **Parity-Violating Electron Scattering**
  - *Qweak will produce the best low energy weak mixing angle measurement in 2 years*
  - *MOLLER and SOLiD will push sensitivity into the multi-TeV scale in the next decade*
- **Neutrinoless Double-Beta Decay**
  - *EXO-200 has begun a physics run with 160 kg of ^{136}Xe*
  - *Several other projects at the scale of 100s of kg-yr will start data collection in the next few years: probe the 100 meV absolute mass scale*

Mature Technique

Parity-Violating Longitudinal Beam Spin Asymmetry

Parity-violating electron scattering has become a precision tool



- *Beyond Standard Model*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

Mainz & MIT-Bates in the mid-80s

JLab program launched in the mid-90s: focus on strange quarks

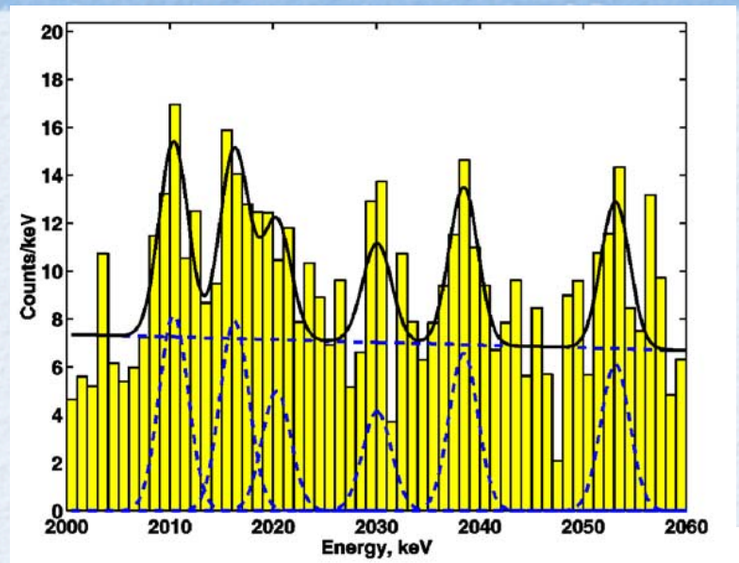
- ***part per billion systematic control***
- ***1% normalization control***

- ***photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors***

Potential Isotopes

Candidate nuclei with Q>2 MeV

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



$T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ years

$m_\nu^{eff} = 0.32 \pm 0.03$ eV

$m_{eff} \sim 50$ meV: $\sim 10^{27}$ years

(10^{27} nuclei ~ 10^3 moles ~ 100 kg)

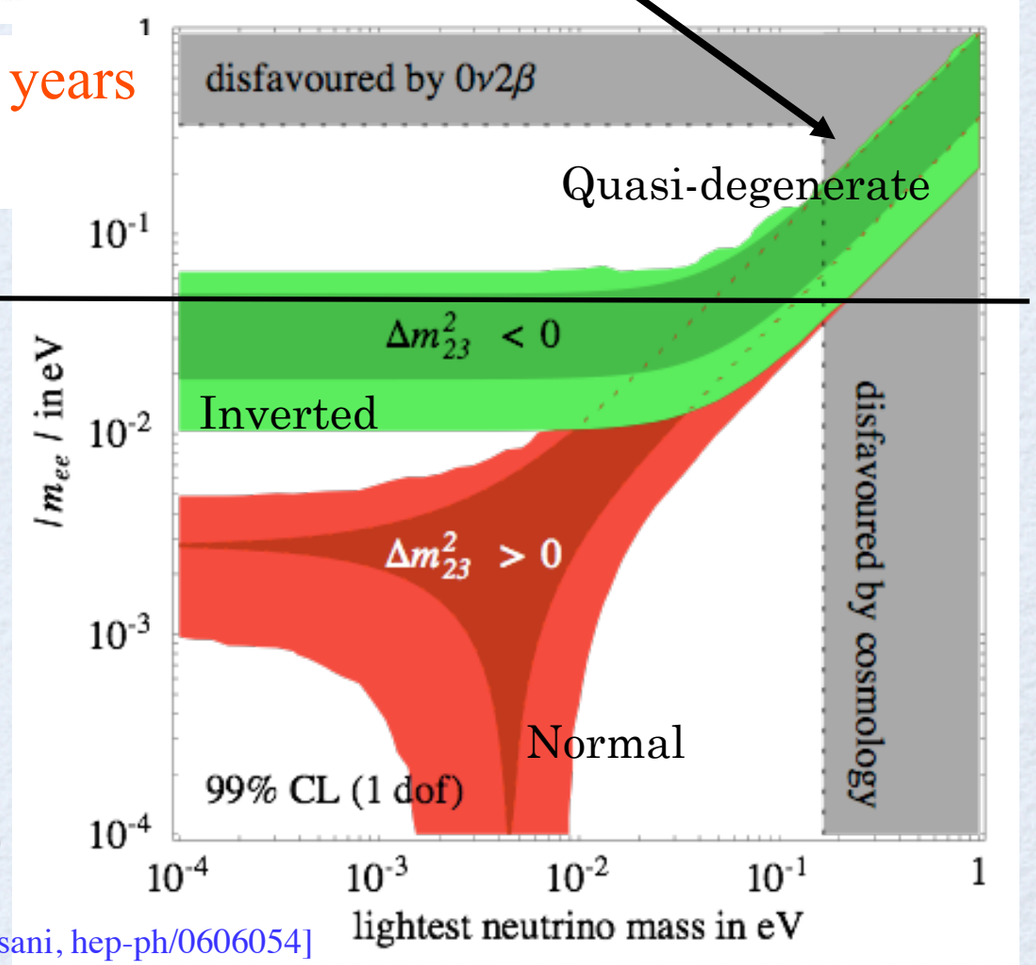
current $0\nu\beta\beta$ sensitivity

Claim by Klapdor-Kleingrothaus et al.

MPLA 21, 2006.

50 meV

^{76}Ge	$(2.1 - 2.6) \times 10^{27}$ y
^{82}Se	$(6.0 - 8.7) \times 10^{26}$ y
^{100}Mo	$(1.1 - 1.7) \times 10^{27}$ y
^{130}Te	$(0.7 - 1.7) \times 10^{27}$ y
^{136}Xe	$(1.5 - 5.6) \times 10^{27}$ y



[Strumia and Vissani, hep-ph/0606054]

F. Picquemal, ICHEP2010

Ongoing Projects

	Technique	Location	Mass kg	start	Bckg Cts/keV/kg/yr	$T_{1/2}(0\nu)$ 5 yr	$\langle m_{ee} \rangle$ meV
EXO	Liquid Xe ^{136}Xe	WIPP (USA)	200	2010	0.002	$6.4\ 10^{25}$	< 109 - 135
GERDA	Diode Ge ^{76}Ge	Gan sasso (Italy)	18	2010	0.01	$3.\ 10^{25}$	< 250– 380
			40	2012	0.001	$3.\ 10^{26}$	< 80 - 120
CUORE-0	Bolometers ^{130}Te	Gan sasso (Italy)	13	2011	0.12	$8.\ 10^{25}$	<100 - 200
CUORE			200	2013	0.01 0.001	$2.1\ 10^{26}$ $6.5\ 10^{26}$	< 41 -82 < 23- 47
SN module0	Tracko-calo ^{82}Se, ^{150}Nd	Modane (France)	7	2013	0.0001	$6.\ 10^{24}$	< 200 –600
SuperNEMO			100	2015	0.0001	10^{26}	< 53 – 145
SNO+	Liq. Scint. ^{150}Nd	SNOLAB (Canada)	44	2012			< 100
KamLAND	Liq. Scinti ^{136}Xe	Kamioka (Japan)	400	2011			< 60 (2 yr)

Xenon is Attractive

Xenon isotopic enrichment is easier: ***Xe is a gas and ^{136}Xe is the heaviest isotope.***

Xenon is "reusable": ***can be re-purified and easily recycled into a different detector (no crystal growth).***

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.***

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

EXO-200 Overview

EXO-200 is a large LXe TPC with scintillation light readout.

It uses a source of 200 kg of enriched xenon (80% ^{136}Xe).

→ EXO-200 has no $^{136}Ba^{+}$ identification ←

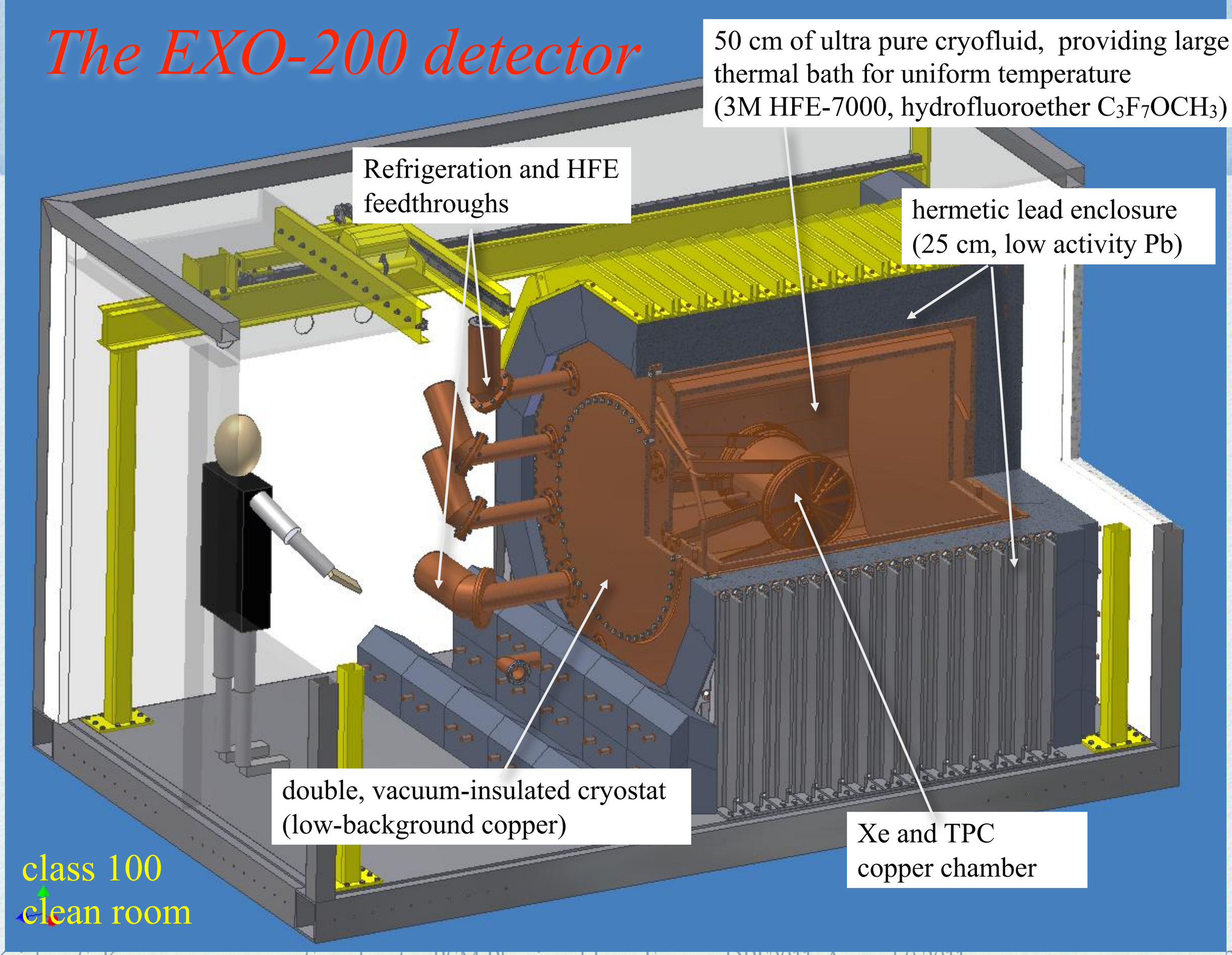
Goals:

- look for $0\nu\beta\beta$ decay of ^{136}Xe with competitive sensitivity ($T^{0\nu}_{1/2} > 6 \times 10^{25}$ y, current limit: $T^{0\nu}_{1/2} > 2.8 \times 10^{24}$ y)

- measure the standard $2\nu\beta\beta$ decay of ^{136}Xe (Q = 2457.8 ± 0.4 keV) and measure its lifetime (best upper limit to date: $T^{2\nu}_{1/2} > 1\times10^{22}$ y)

- test backgrounds of large LXe detector at ~2000 m.w.e. depth
- test LXe technology and enrichment on a large scale
- test TPC components, light readout (518 LAAPDs), and radioactivity of materials, xenon handling and purification, energy resolution

The EXO-200 detector



Principal Backgrounds

- **γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)**
- **γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)**
- **γ (1.4 MeV) from ^{40}K (a concern for the 2νββ)**
- **^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)**
- **other γ's in ^{238}U and ^{232}Th chains**
- **other cosmogenic products of Cu (a concern for the 2νββ)**
- **in situ cosmogenic products in Xe, neutron capture de-excitations, ...**
- **^{222}Rn anywhere (Xe, HFE, air gaps inside lead shield)**

very extensive material screening campaign:

Component	K 10^{-9} g/g	Th 10^{-12} g/g	U 10^{-12} g/g	^{210}Po Bq/kg
3M Novec HFE-7000, 1-methoxyheptafluoropropane	<1.08	<7.3	<6.2	
Lead shielding	<7	<1	<1	17-20
Copper	<55	<2.4	<2.9	
Acrylic	<2.3	<14	<24	
TPC grid wires	<90	47 +/- 2	320 +/- 2	

[EXO collaboration; D. Leonard et al., Nucl. Instr. Meth. A 591 (2008) 490]

EXO-200 & EXO sensitivity

Assumptions

1. **200 kg of ^{136}Xe, 80% enrichment**
2. **Low but finite radioactive background: 20 events/yr in ±2σ interval around Q=2.481 MeV**
3. **Negligible background from $2\nu\beta\beta$ ($T_{1/2}$ > 1x10^{22} yr, Bernabei et al.)**

Case	Mass [ton]	Efficiency [%]	Run time [yr]	σ_E/E @ 2.5 MeV [%]	Radioactive background [events]	$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]	Neutrino majorana mass [eV]	
EXO-200	0.2	70	2	1.6	40	6.4x10^{25}	0.135 (1)	0.109 (2)

(1) Simkovic et al. Phys. Rev. C79, 055501(2009) (use RQRPA and g_A = 1.25)
(2) Menendez et al., Nucl. Phys. A818, 139(2009) (use UCOM results)

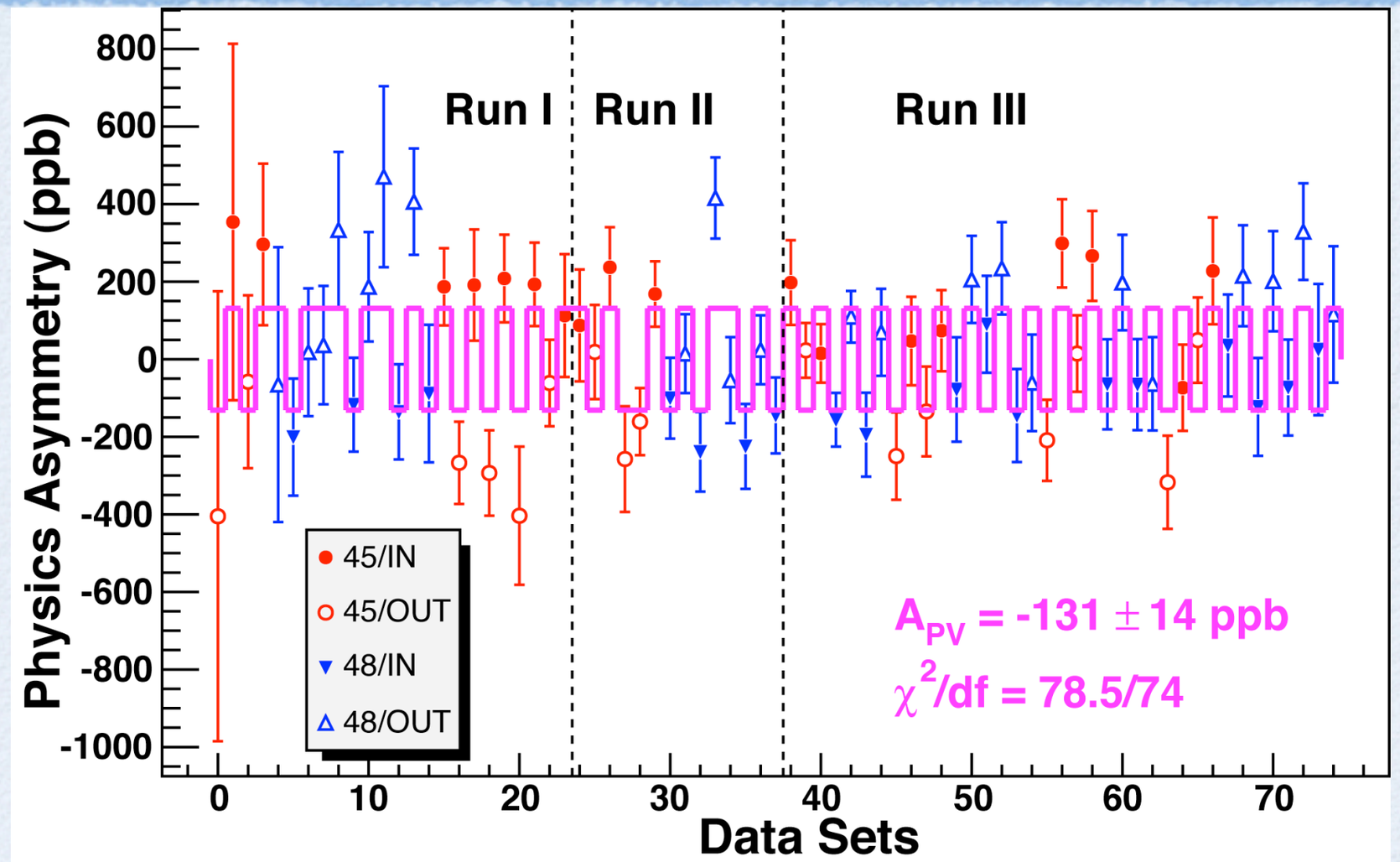
If Klapdor's observations are correct, EXO-200, 2-yr runtime:

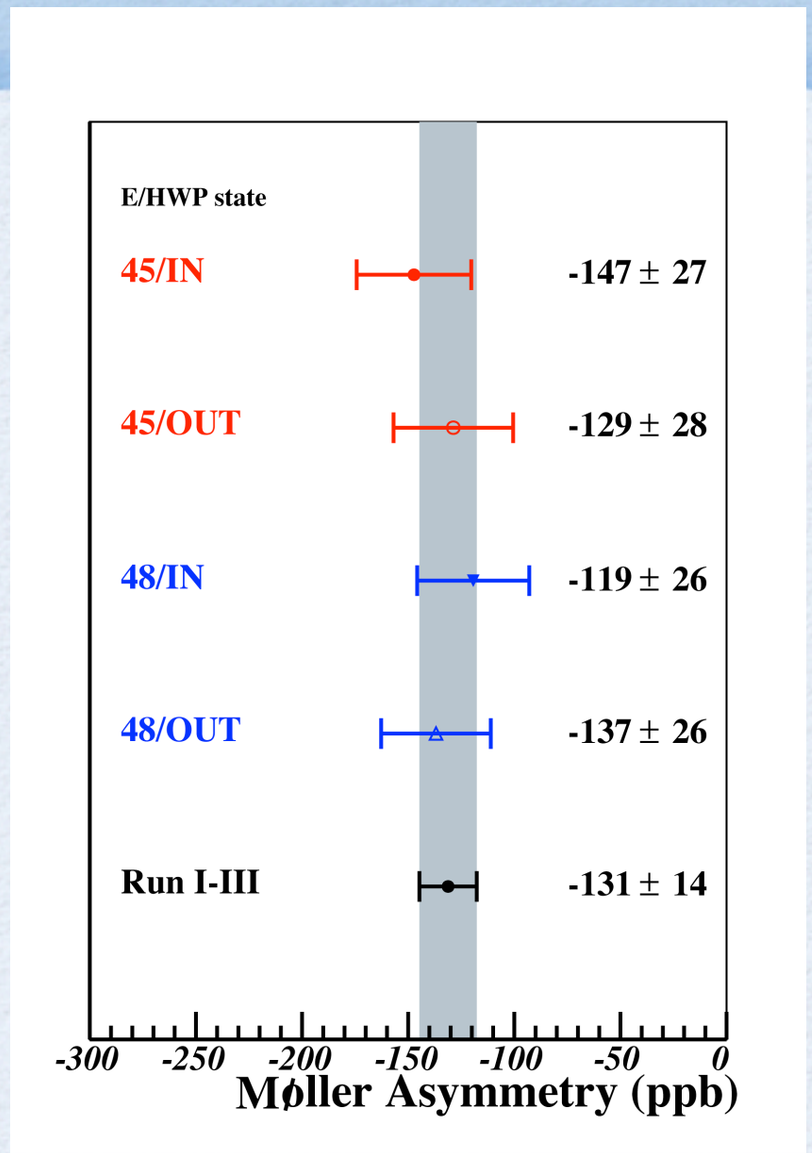
1. **46 events on top of 40 (QRPA) → 5σ measurement**
2. **170 events on top of 40 (NSM) → 11.7σ measurement**

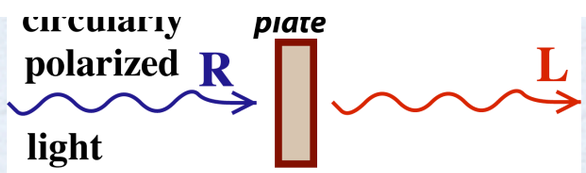
Case	Mass [ton]	Efficiency [%]	Run time [yr]	σ_E/E @ 2.5 MeV [%]	$2\nu\beta\beta$ background [events]	$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]	Neutrino majorana mass [meV]	
Conservative	1	70	5	1.6(3)	0.5 (~1)	2.0x10^{27}	19 (1)	24 (2)
Aggressive	10	70	10	1.0(4)	0.7 (~1)	4.1x10^{28}	4.3 (1)	5.3 (2)

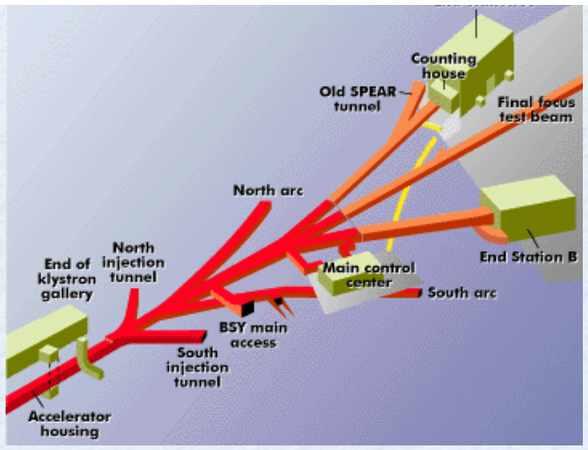
E158 Data

run extensions would have been prohibivitely expensive









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

A_{PV} = (-131 ± 14 ± 10) x 10^{-9}

$$A_{PV} \approx -1\times10^{-7} \times E_{beam} \times P_{beam} \times (1-4\sin^2\vartheta_W)$$

$$\approx 250\,ppb$$

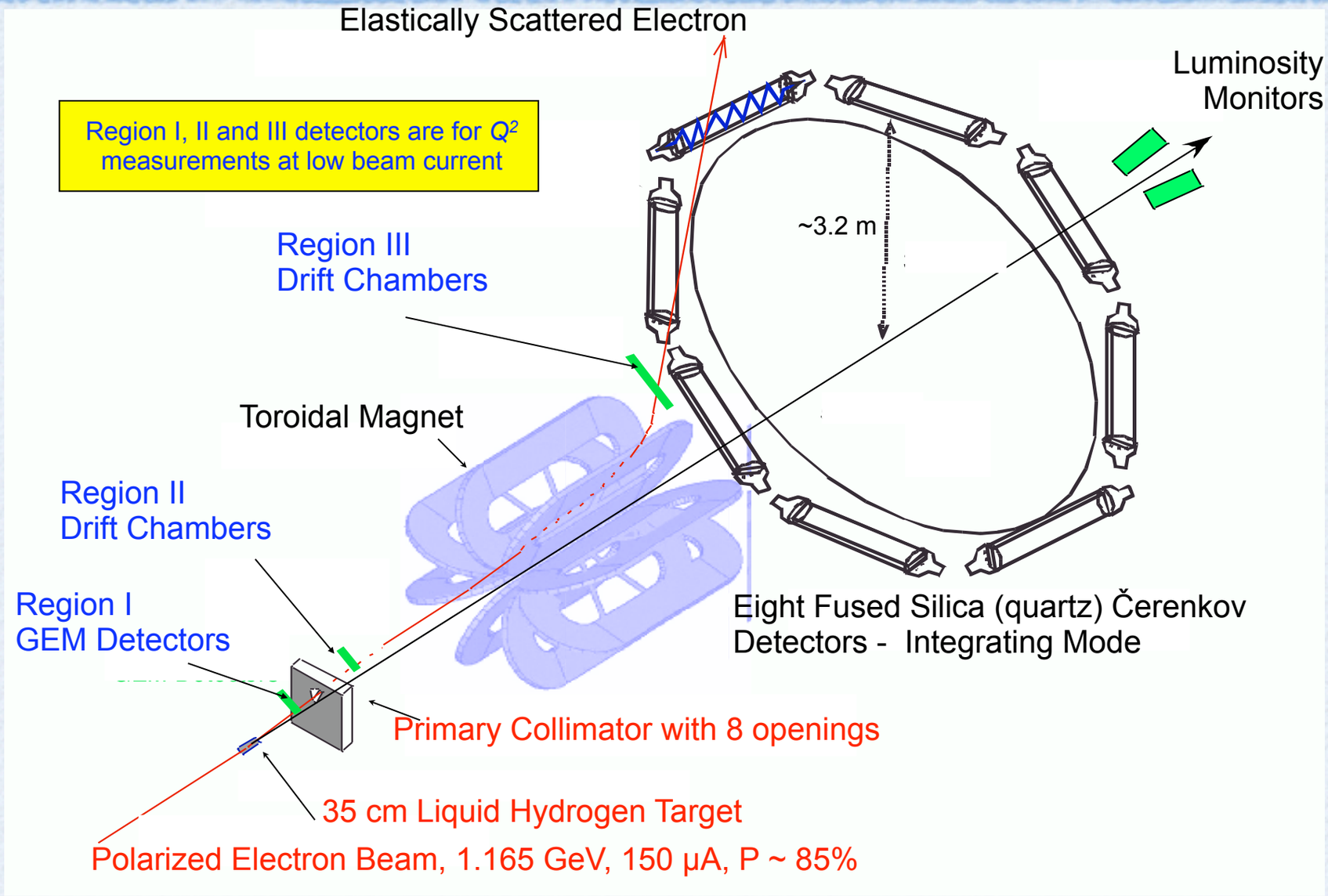
g-2 spin precession

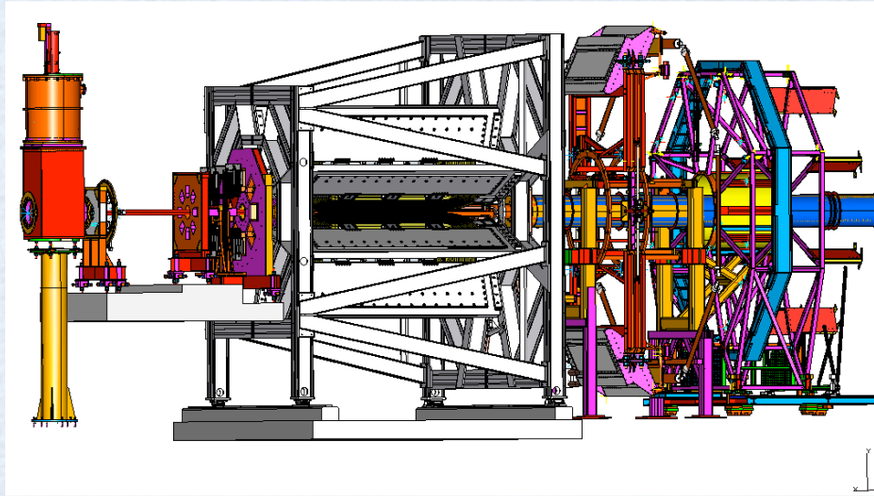
45 GeV: 14.0 revs

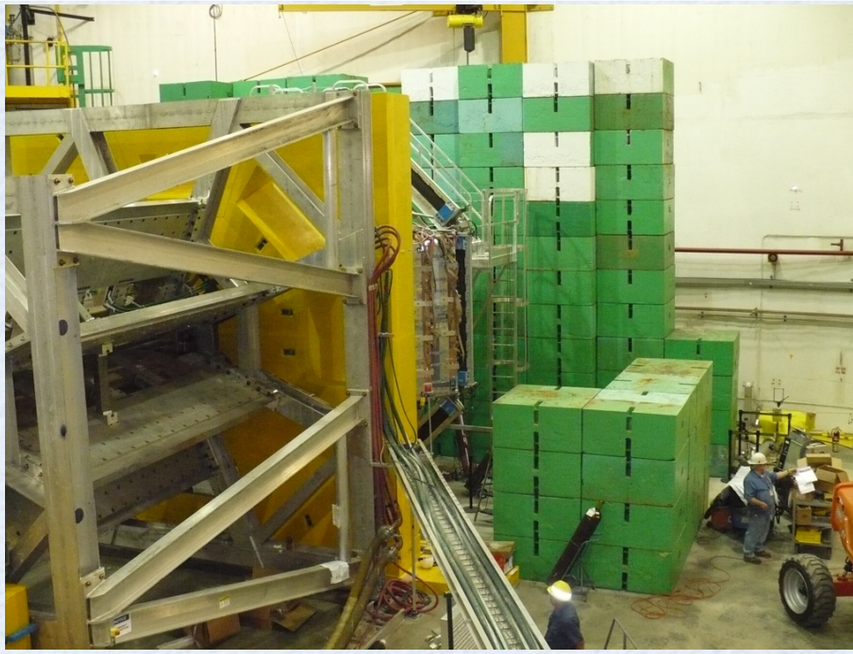
48 GeV: 14.5 revs

Qweak @ Jefferson Lab

Precision Measurement of the Proton's Weak Charge





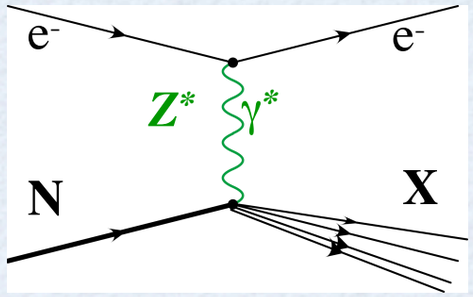


- **Design and construction over past several years**
- **Successful installation and commissioning**
- **Data ~ 2010 thru mid-2012**
- **25% of production data accumulated**

New, complementary constraints on lepton-quark interactions at the TeV scale

Deep Inelastic Scattering

With Qweak and APV, C_{1i}'s measured, but C_{2i}'s still unconstrained



A_{PV} in Electron-Nucleon DIS:

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)\,b(x)\right]$$

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

$Q^2 >> 1\ GeV^2$, $W^2 >> 4\ GeV^2$

For a ^2H target, assuming charge symmetry, structure functions largely cancel in the ratio

Must measure A_{PV} sub-1% fractional accuracy! ⇨ ***luminosity > $10^{38}/cm^2/s$ at JLab***

- **First experiment at 6 GeV: ran Oct-Dec '09; 3-4% accuracy @ Q^2 ~ 1-2 GeV^2**
- **SOLID: New large acceptance solenoidal spectrometer approved for Hall A**

Precision Data