Searching for tensor currents by detection of cyclotron radiation

A. Garcia
Amherst Workshop “EW Box”
Sept. 27-30, 2017
Nuclear beta decay: beyond V-A?

**Standard Model**

\[
H_{V,A} = \sum_{i=V,A} \bar{\Psi}_f O_i^\mu \Psi_0 \left[ (C_i + C_i') \bar{e}^L O_{i,\mu} \nu^L_e + (C_i - C_i') \bar{e}^R O_{i,\mu} \nu^R_e \right]
\]

Right-handed

\[
O_i^\mu = \begin{cases} 
\gamma^\mu & i = V \\
\gamma^\mu \gamma_5 & i = A 
\end{cases}
\]

**Chirality flipping**

\[
H_{S,T} = \sum_{i=S,T} \bar{\Psi}_f O_i \Psi_0 \left[ (C_i + C_i') \bar{e}^R O_{i} \nu^L_e + (C_i - C_i') \bar{e}^L O_{i} \nu^R_e \right]
\]

\[
O_i = \begin{cases} 
1 & i = S \\
\sigma^{\mu\nu} & i = T 
\end{cases}
\]
Nuclear beta decay: beyond V-A?

Standard Model

\[ H_A = \bar{\Psi}_f \gamma^\mu \gamma^5 \Psi_0 \left[ (2C_A) \bar{e}^L \gamma^\mu \gamma^5 \nu_e^L \right] + \bar{\Psi}_f \sigma^{\mu\nu} \Psi_0 \left[ (C_T + C_T') \bar{e}^R \sigma_{\mu\nu} \nu_e^L + (C_T - C_T') \bar{e}^L \sigma_{\mu\nu} \nu_e^R \right] \]

Decay rate:

\[ dw = dw_0 \left[ 1 + a \frac{p_e}{E_e} \cdot \frac{p_v}{E_v} + b \frac{\Gamma m_e}{E_e} \right] \]

\[ a \approx -\frac{1}{3} \left( 1 - \frac{C_T^2 + C_T'^2}{2 C_A^2} \right) \]

\[ b \approx \pm \frac{(C_T + C_T')}{C_A} \]

- Will not address right-handed currents.
- Existing good limits on scalar currents.
- Will concentrate on tensor.
Chirality-flipping as means of detection of new physics.

Small contribution that could be detected with precision experiments

Leptoquarks:
X: scalar; Y: Vector
Predicted by Grand Unified Theories

Predicted by Supersymmetric Theories

Or maybe something not considered so far...

Profumo, Ramsey-Musolf, Tulin

Vos, Wilschut, Timmermans,

Bhattacharya et al.
Connection to LHC data via EFT calculations

LHC (l): contact interactions

- If the new physics originates at scales $\Lambda > \text{TeV}$, then can use EFT framework at LHC energies

- The effective couplings $\varepsilon_\alpha$ contribute to the process $pp \rightarrow e\nu + X$

- No excess events in transverse mass distribution: bounds on $\varepsilon_\alpha$

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Cirigliano et al. PPNP 71, 93 (2013)
Precision beta decay versus others: Can “precision” compete with “energy”?  
Bhattacharya et al.  

Best limits now from LHC  
PRD 94, 054508 (2016)

IS THIS THE END OF SEARCHING FOR THIS PROBE OF FUNDAMENTAL PHYSICS?
Should strive to reach sensitivities beyond the LHC.

Pointed out by our external CENPA advisory committee 2014

Most sensitive probe is Fierz interference:

\[ d\omega = d\omega_0 \left[ 1 + a \frac{p_e}{E_e} \cdot \frac{p_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right] \]

\[ a \approx -\frac{1}{3} \left( 1 - \frac{C_T^2 + C'_{T'}^2}{2 C_A^2} \right) \]

\[ b \approx \pm \left( C_T + C_T' \right)/C_A \]

β-ν correlation

Fierz interference

Sept 27-30 2017

Tensor via cyclotron radiation
Detect little $b$

Is it possible to reach into *ground breaking* terrain of $b < 10^{-3}$?

Ongoing efforts in neutron beta decay:
- Nab aiming at $b \approx 3 \times 10^{-3}$.
- PERC, $b \approx 1 \times 10^{-3}$.

**An experiment using $^6$He could confirm a signal and potentially move beyond**

**Nab:**
Si detector to measure $b$

*NIM A 611, 211 (2009)*

**PERC/Vienna:**
*Rx*B spectrometer to measure $b$

*NIM A 701, 254 (2013)*

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*Fig. 5. The design of the R×B drift spectrometer at the end of PERC, and the simulated trajectories of $e^+/p^+$.***
New idea: use CRES technique

Project 8 collaboration gets FWHM/E ≈ 10^-3 resolution for conversion electrons of 18-32 keV.

Can the technique be applied to a beta continuum with $E_\beta = 0 - 4$ MeV?
6He nuclear structure issues under control to reach $b < 10^{-4}$

Dominant factor in recoil-order correction is interference between WM and GT:

$$R(E) \approx \frac{2m \langle WM \rangle}{3M \langle \sigma \rangle} \left( \frac{2}{m} - \frac{E_0}{m} - \frac{m}{E} \right)$$

$$\sim 10^{-3}$$

Factor known to $\sim 2\%$ by connection to $\gamma$ decay of analogue in 6Li. Further: recent thesis at DALINAC by Enders (adviser: Pietralla). Also: several ab-initio or no-core shell model calculations for 6He (Navratil, Pieper-Wiringa, Barnea-Gazit...)

Radiative corrections

Sirlin factor independent on QCD physics.

Other nuclear-structure issues? Need to be explored to reach beyond $b < 10^{-3}$
New idea: use CRES technique

Project 8 collaboration gets FWHM/E \(\approx 10^{-3}\) resolution for conversion electrons of 18-32 keV.

Can the technique be applied to a beta continuum with \(E_\beta = 0 - 4\) MeV?
New idea: use CRES technique

Project 8 in a nutshell

Looking at Tritium decay to get $\nu$ mass. Electrons emitted in an RF guide within an axial $B$ field. Antenna at end detects cyclotron radiation.

Electrons of $\sim 30$ keV from a gaseous source were let to decay within a 1 tesla field with an additional pair of coils to set up a magnetic trap:

Longitudinal comp. of momentum decreases as $B$ increases up to return point, $z_{max}$. Axial oscillations with $\omega_z$. 

\[ \omega = \frac{qB}{E} \]
New idea: use CRES technique

Some details

Motion can be thought off as cyclotron orbits, axial oscillations and magnetron motion.

$\omega_c : \omega_z : \omega_{mag} = \frac{1}{4} \times 10^{-3} : 2 \times 10^{-5}$

Electrons of $\sim 30$ keV from a gaseous source were let to decay within a 1 tesla field with an additional pair of coils to set up a magnetic trap:

Longitudinal comp. of momentum decreases as $B$ increases up to return point, $z_{max}$. Axial oscillations with $\omega_z$. 

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New idea: use CRES technique

Project 8 in a nutshell

Looking at Tritium decay to get ν mass. Electrons emitted in an RF guide within an axial $B$ field. Antenna at end detects cyclotron radiation.

$$ \omega = \frac{qB}{E} $$

Advantage

Electrons hitting walls quickly (<1 ns) lose energy and disappear.

No signal from these electrons.

For the same reason: background radiation hitting walls does not generate signals.
Why do we like the Project-8 technique for $^6$He?

- Measures beta energy at creation, before complicated energy-loss mechanisms.
- High resolution allows debugging of systematic uncertainties.
- Room photon or e scattering does not yield background.
- $^6$He in gaseous form works well with the technique.
- $^6$He ion-trap (shown by others to work) allows sensitivity higher than any other proposed.
- Counts needed not a big demand on running time.

1) Take a wave during 30 μs.
2) Fourier analysis.
3) Plot peak frequency.

$\omega = \frac{qB}{E}$
Project-8 technique

Power from a single electron orbiting in a magnetic field versus time and the frequency of the electron’s orbit. The straight streaks correspond to the electron losing energy (and orbiting faster) as it radiates. The jumps correspond to the loss of energy when the electron collides with an atom or molecule. [Asner et al. [PRL 114, 162501]]
Research with the accelerator: $^6\text{He}$ source

$^2\text{H}$ beam

$^6\text{He}$

Li

Cu

0.5-mil Ta foil

Temp. monitor

heater

$10^{10}$ $^6\text{He}$/s delivered to clean lab in a stable fashion.

Knecht et al.
NIM A 660, 43 (2011)
Research with the accelerator: $^6\text{He}$ source

$10^{10} \ ^6\text{He}/s$ in clean lab in a stable fashion.

“Statistics for searching for new physics”, compare decay densities to neutron sources:
UCN: $10^3$ UCN/cc $\rightarrow \approx 1$ (decay/s)/cc
CN: $10^{10}$ CN/s cm$^2$ $\rightarrow 2 \times 10^5$ CN/cc $\approx 200$ (decay/s)/cc
$^6\text{He}$: $\approx 2 \times 10^6$ (decay/s)/cc

Important for using CRES technique in an RF guide.
Emerging $^6\text{He}$ little-$b$ collaboration

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$^1$University of Washington,  
$^2$Argonne National Lab,  
$^3$North Carolina State University,  
$^4$Pacific Northwest National Laboratory

- **Goals:**
  - measure "little $b$" to better than $10^{-3}$ in $^6\text{He}$.  
  - Highest sensitivity to tensor couplings

- **Technique**
  - Use Cyclotron Emission Spectroscopy. Similar to Project 8 setup for tritium decay  
  - Need to extend the technique to higher energy betas and to a precision determination of a continuum spectrum.
We have put together a collaboration, written and submitted a proposal. Now kick-started by DOE and UW funds.

Detection of cyclotron radiation to search for chirality-flipping interactions and other applications

M. Fertl, 1 A. García, 1 M. Guigue, 2 D. Hertzog, 1 A. Hime, 2 P. Kammel, 1 A. Leredde, 3 P. Müller, 3 N.S. Oblath, 2 R.G.H. Robertson, 1 G. Rybka, 1 G. Savard, 3 D. Stancil, 4 H.E. Swanson, 1 B.A. VanDevender, 2 and A.R. Young 5

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4 Electrical Engineering Department, North Carolina State University, Raleigh, NC 27695
5 Physics Department, North Carolina State University, Raleigh, NC 27695

(Dated: September 27, 2016)

We propose a sensitive search for non-Standard-Model chirality-flipping interactions by measuring the shape of the beta spectrum of 6He. We will apply the technique of cyclotron radiation emission spectroscopy (CRES) recently demonstrated by the Project 8 collaboration, extending its use to the broader range of electron energies of the 6He β decay. This proposal presents a phased approach to realize the goal of measuring the bFierz parameter to a precision of better than 10^-3. The first phase is aimed at demonstrating the validity of the technique for electrons in the few MeV range. The proposed test of the Standard Model in Phase II will have a sensitivity to new physics in a regime which exceeds the capabilities of the LHC both now and after the luminosity upgrade. Phase III is the most ambitious experiment proposed to date to detect chirality-flipping interactions.

We also intend to develop collaborations with groups that have traditionally used radioactive ion traps and could apply the technique for nuclear-structure related spectroscopy. In particular, the measurement of small Electron Capture branches from radioactive nuclei to set benchmarks for theoretical calculations of double-beta decay matrix elements.

An existing magnet will be re-purposed for the measurement. We ask for funds for RF electronics and data acquisition and for some vacuum equipment.
We have put together a collaboration, written and submitted a proposal. Now kick-started by DOE and UW funds.

**Phase I:** proof of principle
- 2 GHz bandwidth.
- Show detection of cycl. radiation from 6He.
- Study power distribution.

**Phase II:** first measurement \( (b < 10^{-3}) \)
- 6 GHz bandwidth.
- 6He and 19Ne measurements.

**Phase III:** ultimate measurement \( (b < 10^{-4}) \)
- ion-trap for no limitation from geometric effect.

Mission for next three years

Sept 27-30 2017
Tensor via cyclotron radiation
$^6$He little-b measurement at CENPA

Proposed setup
**6He little-b measurement at CENPA**

- Frequency band: $f=18-24$ GHz.
- Monte Carlo simulation of observation in Few days of running

<table>
<thead>
<tr>
<th>Stage</th>
<th>Rate ($1/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming atoms</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Decays within trap</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Trapped betas</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>Trapped betas (not hitting walls)</td>
<td>$1 \times 10^4$</td>
</tr>
<tr>
<td>Events observed within frequency window</td>
<td>$1 \times 10^3$</td>
</tr>
</tbody>
</table>
\(^6\)He little-b measurement at CENPA

Monte Carlo simulation of observation in Few days of running

Extracting little \( b \) vs. \( B \) field Few days of running each point (assumed \( b_{MC} = 0.01 \))
Obvious worry: efficiency depends on energy.

Cross sectional view of guide with electron orbit. For this radius there is a dead region shown by the white frame on the blue area. Since blue area depends on energy there is a systematic distortion of the spectrum. Can be studied by varying the $B$ field.
Obvious worry: efficiency depends on energy.

Monte Carlo simulation of observation in Few days of running

Radii vs. $B$ field Can use this to check geometric effect
Additional tool for calibrations: 
$^{131m}\text{Xe} \ (t_{1/2} \approx 12 \text{ days})$

Conversion electrons 
$E_e = 25, 129, 160 \text{ keV}$

- Studying versus B field allows determining the effect.
- Showing that all is understood with higher $E$ electrons is a milestone to move forward.

We have extracted $= 10^5$ Becq. of $^{131m}\text{Xe}$.

**Ready to test as soon as we have apparatus.**

Need about 50 mCi of $^{131}\text{I} \ (\rightarrow \ ^{131m}\text{Xe} \text{ with } t_{1/2} \approx 8 \text{ days})$

(30 µCi of $^{131}\text{I}$ is a safety concern)
Check on signature by measuring $^{14}$O and $^{19}$Ne:

Both $^{14}$O and $^{19}$Ne can be produced in similar quantities as $^6$He at CENPA.

$^{14}$O as CO ($T_{\text{freeze}} = 68$ K)
Previous work at Louvain and TRIUMF.

$^{19}$Ne source developed at Princeton appropriate.
Dominant factor in recoil-order correction is interference between WM and GT:

\[ R(E) \approx \frac{2m \langle WM \rangle}{3M \langle \sigma \rangle \left( \frac{2}{m} \frac{E}{E_0} - \frac{m}{E} \right)} \sim 10^{-3} \]

Factor determined to \( \sim 2\% \) by connection to \( \gamma \) decay of analogue in \( ^6\text{Li} \).

Radiative corrections

Sirlin factor independent on QCD physics.

Other nuclear-structure issues?
Need to be explored to reach beyond \( b < 10^{-3} \)
6He nuclear structure issues under control to reach $b < 10^{-4}$

Proposal for INT workshop:

“Precise beta decay calculations for searches for new physics”

Doron Gazit, Hebrew University of Jerusalem, Israel
Daniel Phillips, Ohio University, Athens, OH, USA
Alejandro Garcia, University of Washington, Seattle, WA, USA

Abstract:

Several experimental efforts worldwide are presently searching for physics beyond the Standard Model (BSM) by performing precision measurements of nuclear beta-decay observables. Examples (little-*a* refers to beta-nu correlation, little-*b* is obtained from the beta spectrum, *A* refers to the parent-spin- beta correlation, *B* refers to the parent-spin- neutrino correlation)

- Nab little-*a* and little-*b* from neutron beta decay at SNS (magnetic guides for betas and protons)
- UCNA *A* and little-*b* from neutron beta decay at LANL (magnetic confinement of betas)
- Perkeoll and PERC in Europe (magnetic transport of betas)
- 6He little-*a* at Israel (ion mirror trap)
- 6He and 20F little-*b* at MSU (implantation of activity into scintillator calorimeter)
- 6He little-*a* at UW (atom trap), 6He 14O, 19Ne, little-*b* at UW (project 8 style)
- 8Li little-*a* at Israeli-MIT

8 other workshops proposed: Not funded for 2018.
Other worries: DAQ.

To register it all, need to take about 1 byte at 12 GHz.

About 1 Peta-byte/day !!

By triggering and recording only within a $\Delta f$ of interest one can decrease it to 10 Tera-byte/day.

It is a concern of the Project 8 collaboration, who are working on addressing this (gpu’s for FFT’s, analysis with PNNL computers, etc...)

Tensor via cyclotron radiation Sept 27-30 2017
Other worries:

• Identify initial frequency? Make sure event starts within observation window.

• Dependence on magnetic-field in-homogeneities?
  \[ \omega_c = \frac{qB}{E} \]

  Good expertise in team on shimming \( B \) fields

• RF power variations with \( E \): efficiency dependency?
Other worries: “Doppler effect” and power into sidebands.

The wave generated by the electron is:

\[ e^{i(\beta(z-z_0(t)) - \omega t)} \]

The amplifier observes a frequency:

\[ \omega + \beta \dot{z} \hat{0}/\omega \]

So there is a “Doppler effect” that depends on the axial speed of the electron.

But since the electron is oscillating, this leads to frequency modulation.

Part of the power goes to sidebands.
Potential reach (Monte Carlo simulations)

<table>
<thead>
<tr>
<th>Effect</th>
<th>No trap</th>
<th>Ion trap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field uncertainties</td>
<td>$10^{-4}$</td>
<td>$&lt; 10^{-4}$</td>
</tr>
<tr>
<td>Wall effect uncertainties</td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>RF pickup uncertainties</td>
<td>$10^{-4}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Misidentification of events</td>
<td>$10^{-4}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Phase III: Future development, couple to an ion trap

Phase II

Tensor via cyclotron radiation
A different application: coupling CRES with radioactive ion trap. Benchmarks for nuclear structure?

- $2\nu-2\beta$ decays
- single beta decays
- single electron capture decays

In 3 cases one can check all of the above for the same nucleus:

*good for understanding overarching issues (role of $p$-$p$, $p$-$h$ correlations, deformation, etc...)*

Previous experiments limited by energy resolution. CRES technique would improve it by 100.
### $^6$He timeline

<table>
<thead>
<tr>
<th>Little a</th>
<th>FY 2017</th>
<th>FY 2018</th>
<th>FY 2019</th>
<th>FY 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finish systematics studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commissioning</td>
<td></td>
<td></td>
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<tr>
<td>Run little a</td>
<td></td>
<td></td>
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<tr>
<td>Analysis little a</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Little b Phase I</th>
<th>FY 2017</th>
<th>FY 2018</th>
<th>FY 2019</th>
<th>FY 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop 19Ne source</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Design vacuum system &amp; magnet assembly</td>
<td></td>
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</tr>
<tr>
<td>Build cryo-coolers &amp; RF assembly</td>
<td></td>
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</tr>
<tr>
<td>Assemble cryocoolers &amp; RF components</td>
<td></td>
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</tr>
<tr>
<td>Build magnet installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install magnet &amp; cool down</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assemble &amp; test data acq.</td>
<td></td>
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<tr>
<td>Data with 131mXe</td>
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<tr>
<td>Data with 6He</td>
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</tbody>
</table>

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Tensor via cyclotron radiation
Conclusion $^6\text{He}$

- Finishing little-$a$ expt. with present laser trapping setup
- Starting new little-$b$ experiment with Proj-8 technique
- Presently working on design
- Monte-Carlo calculations show technique could eventually reach $b < 10^{-4}$, surpassing the LHC, and any other experiment so far considered, in searching for chirality-flipping interactions.
- Our developments (coupling of CRES to ion traps) could lead to spectroscopy technique useful for FRIB.
Backup slides
Previous measurements limited by energy resolution:
With Project 8 technique energy resolution could improve by 100!

\[ ^{100}\text{Tc EC decay:} \]
\[ \text{BR(EC)} = (2.6 \pm 0.4) \times 10^{-5} \]

S. Sjue, Thesis 2008; Sjue et al., PRC 78, 064317 (2008)

\[ ^{116}\text{In EC decay:} \]
\[ \text{BR(EC)} = (2.3 \pm 0.6) \times 10^{-4} \]

Wrede et al., PRC 87, 031303(R) (2013)

Both of our results are consistent with complete ground state dominance: just using the ground state accounts for the measured 2\nu-2\beta decay rate.
Comparison with 2 different QRPA calculations (no other calculation yet available for A=100 and A=116)

Moreno, Alvarez-Rodriguez, Sarriguren, Moya de Guerra, Simkovic, Faessler

Suhonen & Civitarese

Our measurements
Waveguides: each mode propagates above a certain cut-off freq.

\[
\left( \nabla^2 + \frac{\omega^2}{c^2} \right) \{E\} = 0
\]

\[
\{E\} = \begin{cases} 
E(x, y)e^{\pm ikz - i\omega t} \\
B(x, y)e^{\pm ikz - i\omega t}
\end{cases}
\]

\[
\left[ \nabla^2_t + \left( \frac{\omega^2}{c^2} - k^2 \right) \right] \{E(x, y)\} = 0
\]

\[
\frac{\omega^2}{c^2} - k^2 \equiv \gamma^2
\]

\[
E = E_z + E_t
\]

TE waves:
\[
H_t = \pm \frac{ik}{\gamma^2} \nabla_t \psi
\]

TM waves:
\[
E_t = \pm \frac{ik}{\gamma^2} \nabla_t \psi
\]

There are cutoff frequencies for each

\[
k = \frac{\sqrt{\omega^2 - \omega_c^2}}{c}
\]
Cutoff frequencies for $d=1\text{cm}$ guide. For 0.455” divide by 1.1557.

Active in 18-24 GHz: $\text{TE}_{1,1}$, $\text{TM}_{0,1}$ (but $\text{TM}_{0,1}$ doesn’t couple to WR42)

<table>
<thead>
<tr>
<th>$n$</th>
<th>$f_{n,1}^{\text{TE}}$</th>
<th>$f_{n,2}^{\text{TE}}$</th>
<th>$f_{n,3}^{\text{TE}}$</th>
<th>$f_{n,1}^{\text{TM}}$</th>
<th>$f_{n,2}^{\text{TM}}$</th>
<th>$f_{n,3}^{\text{TM}}$</th>
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<tbody>
<tr>
<td>0</td>
<td>36.57</td>
<td>67.00</td>
<td>97.15</td>
<td>22.97</td>
<td>52.71</td>
<td>82.64</td>
</tr>
<tr>
<td>1</td>
<td>17.58</td>
<td>50.90</td>
<td>81.51</td>
<td>36.59</td>
<td>67.00</td>
<td>97.15</td>
</tr>
<tr>
<td>2</td>
<td>29.16</td>
<td>64.03</td>
<td>95.21</td>
<td>49.03</td>
<td>80.38</td>
<td>110.96</td>
</tr>
</tbody>
</table>

Only the TE11 mode transmits

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[Diagrams showing different modes and their distributions]
LHC (I): contact interactions

- If the new physics originates at scales $\Lambda > \text{TeV}$, then can use EFT framework at LHC energies

- The effective couplings $\varepsilon_\alpha$ contribute to the process $pp \rightarrow e\nu + X$

- No excess events in transverse mass distribution: bounds on $\varepsilon_\alpha$
Magnetron motion. For harmonic traps no bias (E-dependence)

\[ \frac{\omega_m}{\omega_c} = \frac{N \sim 10^6}{2 \omega_c} \]

For each cyclotron turn the orbits displaces:
\[ \Delta \approx R_1 - R_2 \approx R \left( 1 - \frac{B_1}{B_2} \right) \approx R \left( \frac{\partial B/\partial r}{B} \right) R. \]

Then the radius \( X \) of magnetron motion:
\[ X \approx \frac{N \Delta}{2 \pi} \approx \frac{N}{2 \pi} \frac{R^2 \partial B/\partial r}{B} \]

Use \( \frac{\partial B/\partial r}{B} \sim \frac{10^{-2}}{cm^2} \) teslaB \(
\)

Harmonic trap
\[ X \approx \frac{N}{2 \pi} \frac{R^2 \times 10^{-2}}{cm^2} \rightarrow N = \frac{2 \pi}{10^{-2} R^2} \approx 10^5 \]

\( X \) cancels: magnetron radius independent on \( R \) in harmonic trap.

I don’t get the \( 10^6 \) I am supposed to, but it makes sense given how I exaggerated the distortions in the first two equations above.