Neutrinos and Dark Matter Symposium
Paris, September 4-9 2006

Two-neutrino double beta decay and bosonic neutrino

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OUTLINE

- Introduction
- $2\nu\beta\beta$ -decay with bosonic ν
  (^{82}Se, ^{100}Mo)
- $2\nu\beta\beta$-decay and partially bosonic ν
  (^{100}Mo)
- Conclusions

Neutrino

is

a puzzle

(That is the reason we are here)

Pauli proposed existence of „neutron“
(with spin ½ and mass not more than 0.01 mass of proton) in nucleus

I have done a terrible thing I invented a particle that cannot be detected
W. Pauli

ic

A little bit of history

Since ν´s have spin one half they are believed to obey Fermi statistics
Can you imagine bosonic ν (with spin one half)?

Bosonic ν introduced: Ignatiev, Kuzmin, Yad. Fiz 46 (1987) 786

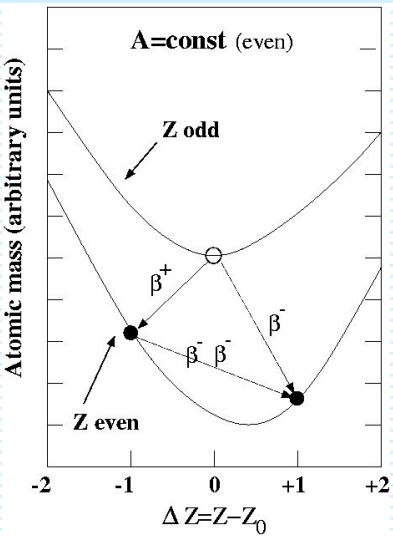
Bosonic ν in 2νββ-decay: Dolgov, Smirnov, PLB 621 (2005) 1

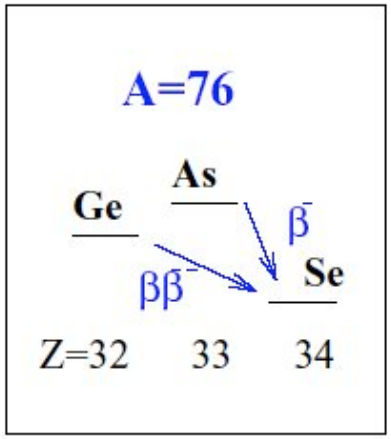
Motivations: Dark matter, BBN, supernova ν

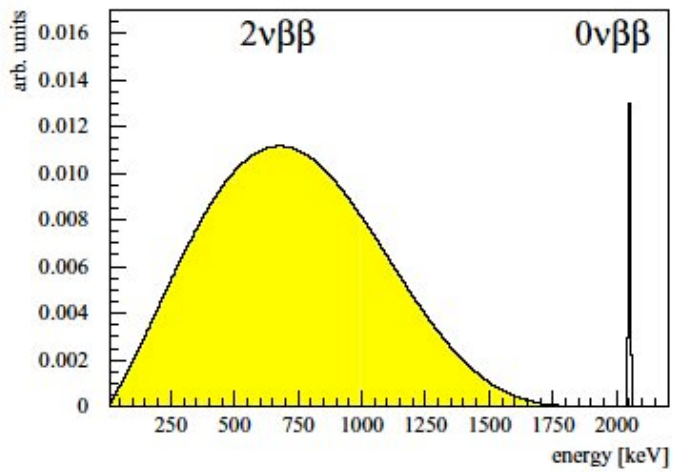
For electrons and nucleons,
a possible violation of statistics is strongly restricted by experiments.

A consistent quantum field theory with of half-integer spin particles with any other statistics than the Fermi one is missing

Double Beta Decay







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

$$(T^{2\nu}_{1/2})^{-1} = G^{2\nu} |M^{2\nu}_{GT}|^2$$

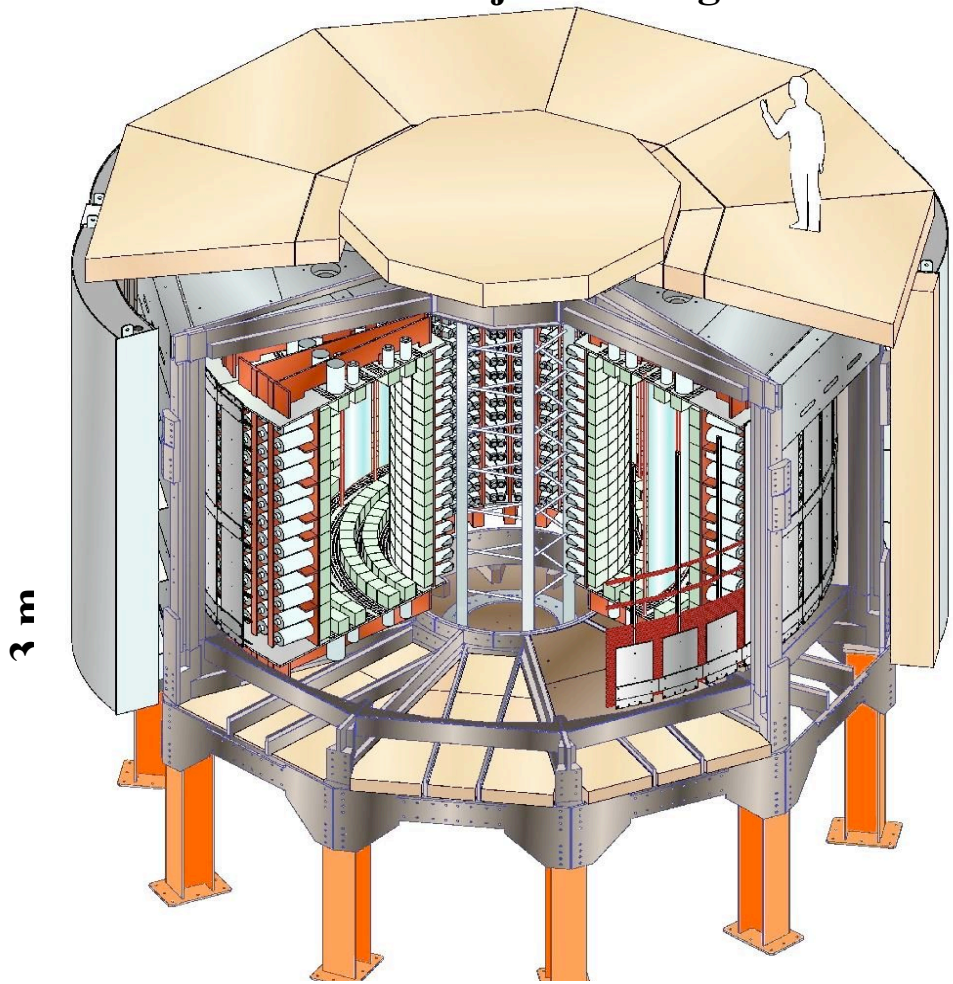
Observed for 10 isotopes: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo. ^{116}Cd. ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, $T_{1/2} \approx 10^{18}$-10^{24} years

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

Please, forget 0νββ-decay for a moment!

The NEMO3 DBD Experiment

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes

cylindrical, S = 20 m², e ~ 60 mg/cm²

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss

Gamma shield: Pure Iron (e = 18 cm)

Neutron shield: 30 cm water (ext. wall)

40 cm wood (top and bott.)

(since march 2004: water + boron)

^{100}Mo 6.914 kg — $Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg — $Q_{\beta\beta}$ = 2995 keV

2νββ and 0νββ search

2νββ-decay: fermionic (f) or bosonic (b) ν

$$|\nu_1\ \nu_2> \ = \ \hat{a}_1^\dagger\ \hat{a}_2^\dagger|0>$$

$$\{\hat{a}_i, \hat{a}_j^\dagger\}_+ \ = \ \delta_{i,j} \quad (fermionic\ \nu)$$

$$\left[\hat{a}_i, \hat{a}_j^\dagger\right]_- \ = \ \delta_{i,j} \quad (bosonic\ \nu)$$

$$dW^{f,b}(0^+ \to 0^+) \ \sim \ \left(3\left|\mathcal{M}^{f,b}{}_K + \mathcal{M}^{f,b}{}_L\right|^2 + \left|\mathcal{M}^{f,b}{}_K - \mathcal{M}^{f,b}{}_L\right|^2\right)\ dp_{e_1}^{\rightarrow} dp_{e_2}^{\rightarrow} dp_{\nu_1}^{\rightarrow} dp_{\nu_2}^{\rightarrow}$$

$$dW^{f,b}(0^+ \to 2^+) \ \sim \ \left|\mathcal{M}^{f,b}{}_K - \mathcal{M}^{f,b}{}_L\right|^2\ dp_{e_1}^{\rightarrow} dp_{e_2}^{\rightarrow} dp_{\nu_1}^{\rightarrow} dp_{\nu_2}^{\rightarrow}$$

$$\mathcal{M}^{f,b}{}_K \ = \ \sum_m \left(\frac{M_m^I(1^+)M_m^F(1^+)}{E_m - E_i + e_1 + \nu_1} \ \pm \ \frac{M_m^I(1^+)M_m^F(1^+)}{E_m - E_i + e_2 + \nu_2}\right)$$

$$\mathcal{M}^{f,b}{}_K = \mathcal{M}^{f,b}{}_L(\nu_1 \leftrightarrow \nu_2)$$

Sign difference!!!
Lepton energies!!!

Higher states dominance (^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe ....)

$$\left|\mathcal{M}^f{}_K + \mathcal{M}^f{}_L\right|^2 \simeq 16\left|M_{GT}^{(1)}\right|^2$$

$$\left|\mathcal{M}^f{}_K - \mathcal{M}^f{}_L\right|^2 \simeq \frac{4(e_1-e_2)^2(\nu_1-\nu_2)^2}{\Delta^4}\left|M_{GT}^{(3)}\right|^2$$

$$\left|\mathcal{M}^b{}_K + \mathcal{M}^b{}_L\right|^2 \simeq \frac{4(\nu_1-\nu_2)^2}{\Delta^2}\left|M_{GT}^{(2)}\right|^2$$

$$\left|\mathcal{M}^b{}_K - \mathcal{M}^b{}_L\right|^2 \simeq \frac{4(e_1-e_2)^2}{\Delta^2}\left|M_{GT}^{(2)}\right|^2$$

Approximation in energy denominators

$e_k + \nu_j \cong \Delta = (E_i - E_f)/2$

$$M_{GT}^{(1)} = \sum_m \frac{M_m^I(1^+)M_m^F(1^+)}{E_m - E_i + \Delta}$$

→ fermionic ν 0^+

$$M_{GT}^{(2)} = \Delta \sum_m \frac{M_m^I(1^+)M_m^F(1^+)}{(E_m - E_i + \Delta)^2}$$

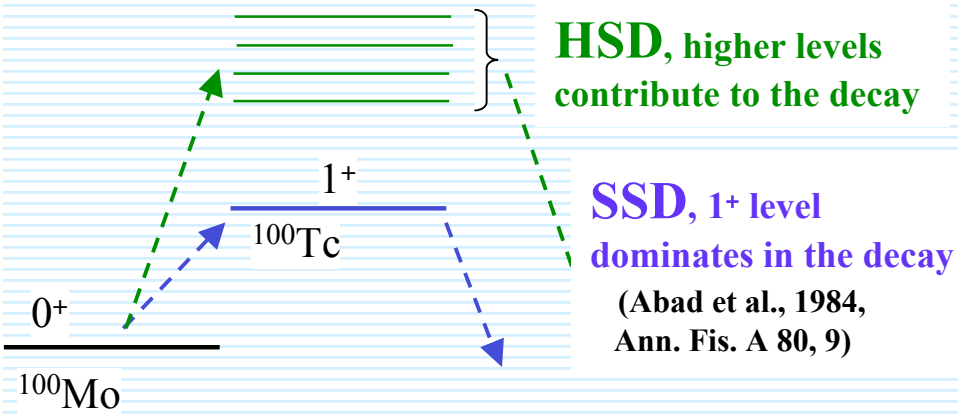
→ bosonic ν 0^+ , 2^+

$$M_{GT}^{(3)} = \Delta^2 \sum_m \frac{M_m^I(1^+)M_m^F(1^+)}{(E_m - E_i + \Delta)^3}$$

→ fermionic ν 0^+ , 2^+

$$M_{GT}^{(3)} \ll M_{GT}^{(2)} \ll M_{GT}^{(1)}$$

Single State Dominance (^{100}Mo, ^{106}Cd, ^{116}Cd, ^{128}Te …)



Isotope	f.s.	$T_{1/2}$(SSD)[y]	$T_{1/2}$(exp.)[y]
		$2\nu\beta^-\beta^-$	
^{100}Mo	$0_{g.s.}$	$6.8\ 10^{18}$	$6.8\ 10^{18}$
	0_1	$4.2\ 10^{20}$	$6.1\ 10^{18}$
^{116}Cd	$0_{g.s.}$	$1.1\ 10^{19}$	$2.6\ 10^{19}$
^{128}Te	$0_{g.s.}$	$1.1\ 10^{25}$	$2.2\ 10^{24}$
		EC/EC	
^{106}Cd	$0_{g.s.}$	$>4.4\ 10^{21}$	$>5.8\ 10^{17}$
^{130}Ba	$0_{g.s.}$	$5.0\ 10^{22}$	$4.0\ 10^{21}$

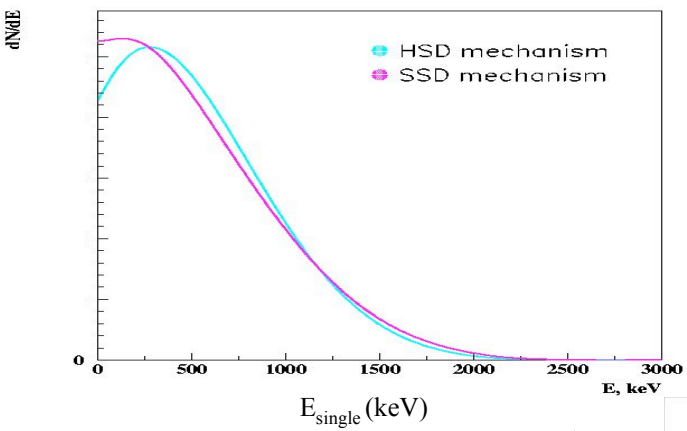
$$\mathcal{M}^{f,b}{}_K = \sum_m \left(\frac{M^I_m(1^+)M^F_m(1^+)}{E_m - E_i + e_1 + \nu_1} \pm \frac{M^I_m(1^+)M^F_m(1^+)}{E_m - E_i + e_2 + \nu_2} \right)$$

$$\overset{\text{SSD}}{\Rightarrow} \quad \frac{M^I_1(1^+)M^F_1(1^+)}{E_1 - E_i + e_1 + \nu_1} \pm \frac{M^I_1(1^+)M^F_1(1^+)}{E_1 - E_i + e_2 + \nu_2}$$

$$\mathcal{M}^{f,b}{}_K = \mathcal{M}^{f,b}{}_L(\nu_1 \leftrightarrow \nu_2)$$

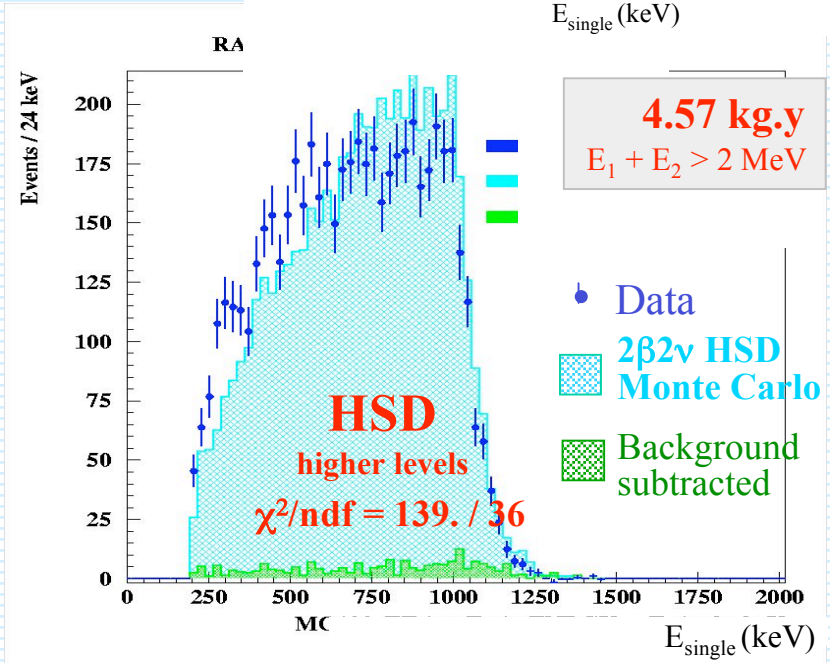
^{100}Mo 2νββ: Experimental Study of SSD Hypothesis

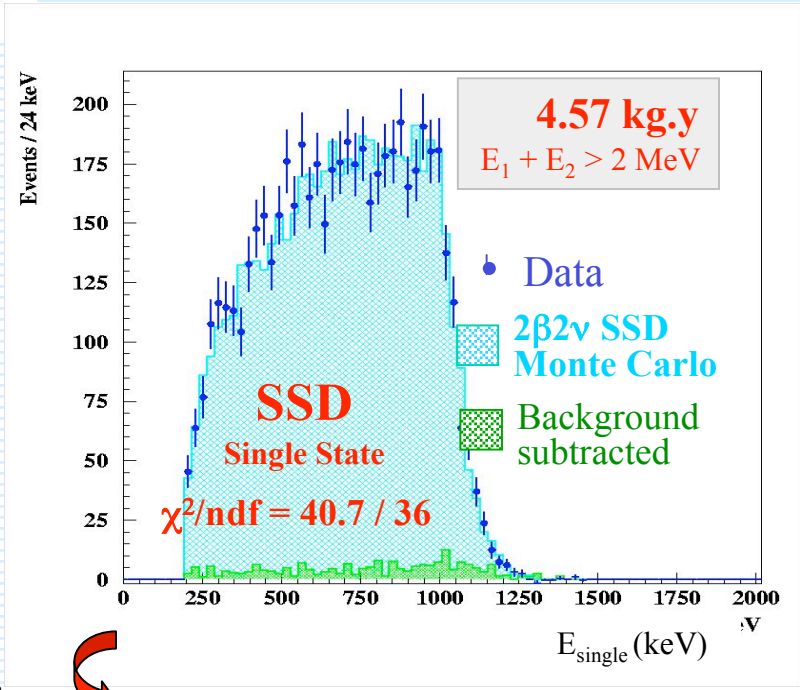
NEMO 3 exp.



Single electron spectrum different between SSD and HSD

Šimkovic, Šmotlák, Semenov
J. Phys. G, 27, 2233, 2001





HSD: $T_{1/2} = 8.61 \pm 0.02\ (stat) \pm 0.60\ (syst) \times 10^{18}$ y

SSD: $T_{1/2} = 7.72 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

^{100}Mo 2β2ν single energy distribution in favour of Single State Dominant (SSD) decay

Looking for a signature of bosonic ν

$2\nu\beta\beta$–decay half-lives ($0^+ \rightarrow 0^+_{g.s.}$, $0^+ \rightarrow 0^+_1$, $0^+ \rightarrow 2^+_1$)

- **HSD – NME needed**
- **SSD – log ft_{EC}, log ft_β needed**

Normalized differential characteristics

- **The single electron energy distribution**
- **The distribution of the total energy of two electrons**
- **Angular correlations of two electrons**

(free of NME and log ft)

2νββ-decay half-lives (SSD hypothesis)

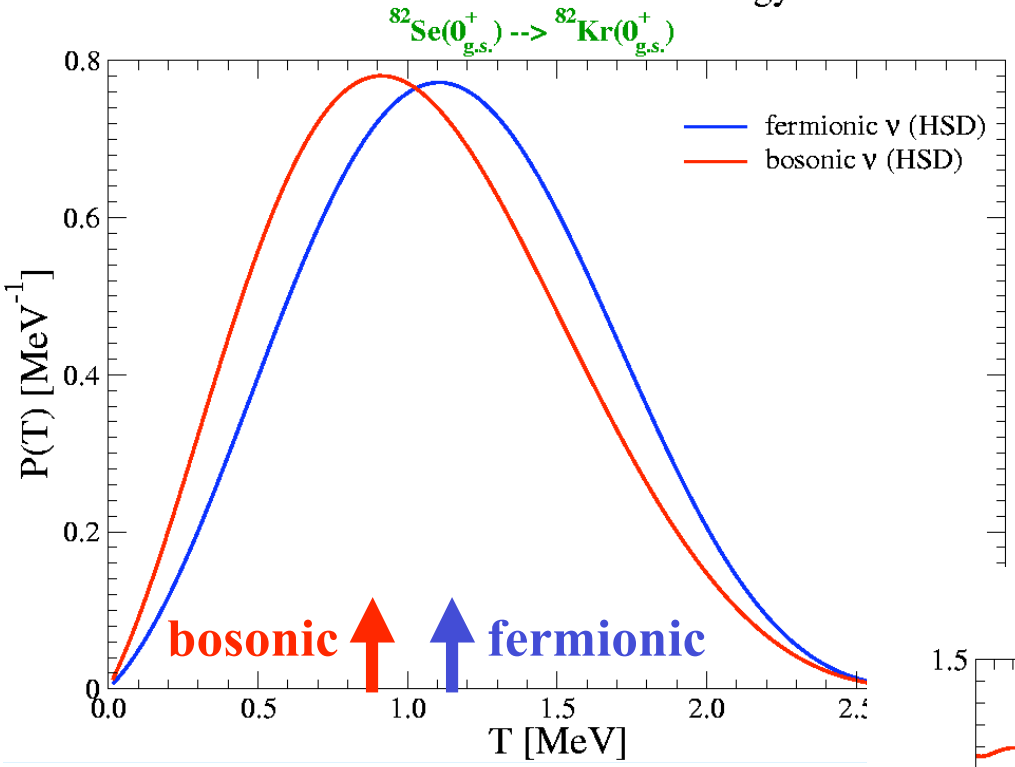
transition	$T_{1/2}^{2\nu-exp}$ [y]	$T_{1/2}^{2\nu-SSD}$ [y]	
		fermion. ν	boson. ν
$0^+_{g.s.} \to 0^+_{g.s.}$	$7.1\ 10^{18}$	$7.2\ 10^{18}$	$8.3\ 10^{19}$
$0^+_{g.s.} \to 0^+_1$	$6.8\ 10^{20}$	$4.5\ 10^{20}$	$5.7\ 10^{21}$
$0^+_{g.s.} \to 2^+_1$	$> 1.6\ 10^{21}$	$1.7\ 10^{23}$	$3.4\ 10^{22}$

B(GT,$0^+ \to 1^+$) = 0.66±0.33 (log ft_{EC}=4.45) PRC 47 (1993) 2910
=2.01±0.45 (log ft_{EC}=3.96) NNR05, Cast/Spring-8, (2005)

ratio of half-lives	exper.	SSD mechanism	
		fermion. ν	boson. ν
$T_{1/2}^{2\nu}(0^+_1)/T_{1/2}^{2\nu}(0^+_{g.s.})$	96.	62.	69.
$T_{1/2}^{2\nu}(2^+_1)/T_{1/2}^{2\nu}(0^+_{g.s.})$	$> 225.$	24261.	406.

Free of log ft_{EC}

The normalized distributions of the total energy of two electrons



2νββ-decay of ^{82}Se

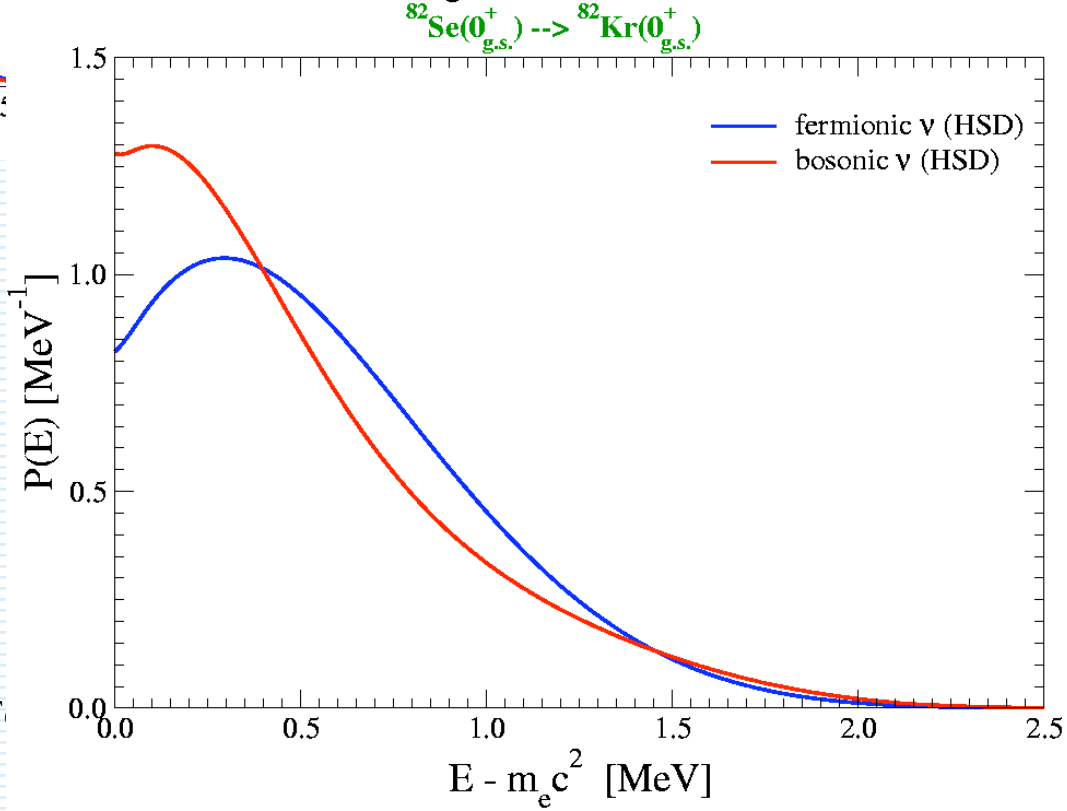
$0^+_{g.s.} \rightarrow 0^+_{g.s.}$

HSD

$$P^{f,b}(T) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dT}$$

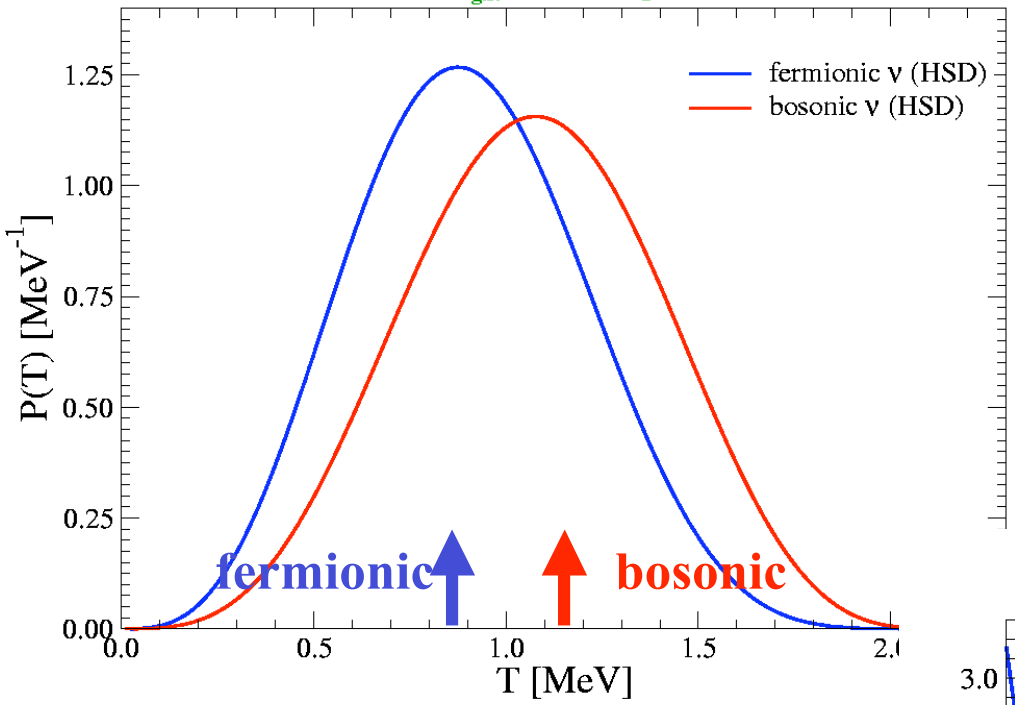
$$P^{f,b}(E) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dE}$$

The single electron distributions



The normalized distributions of the total energy of two electrons

$^{82}Se(0^+_{g.s.}) \rightarrow {}^{82}Kr(2^+_1)$



2νββ-decay of ^{82}Se

$0^+_{g.s.} \rightarrow 2^+_1$

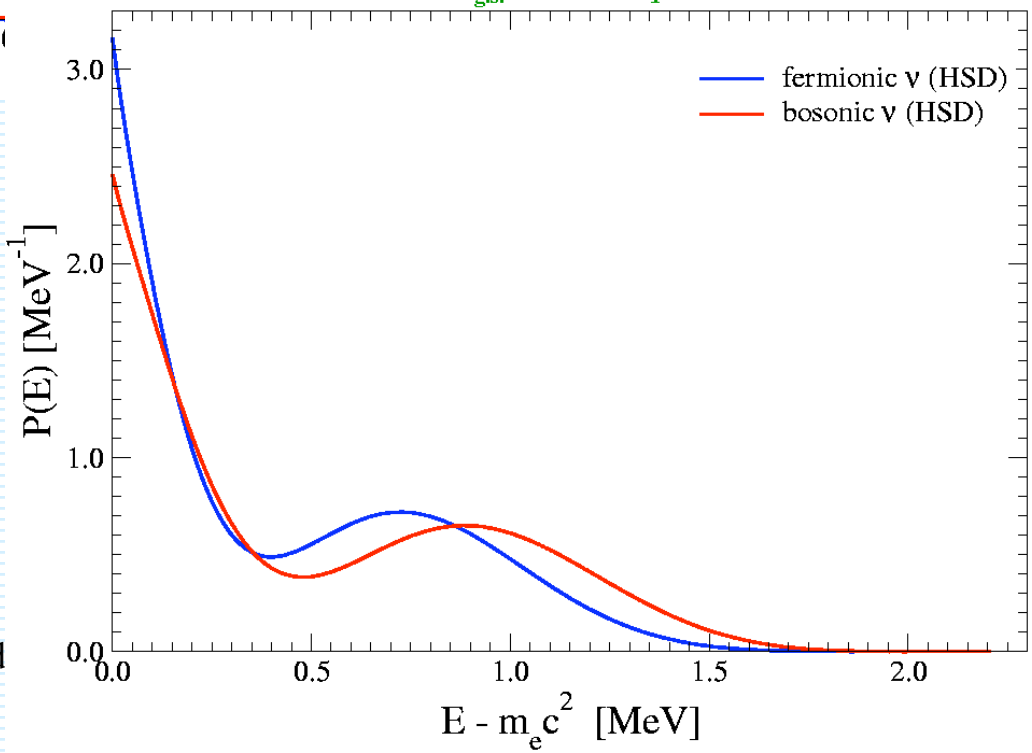
HSD

$$P^{f,b}(T) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dT}$$

$$P^{f,b}(E) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dE}$$

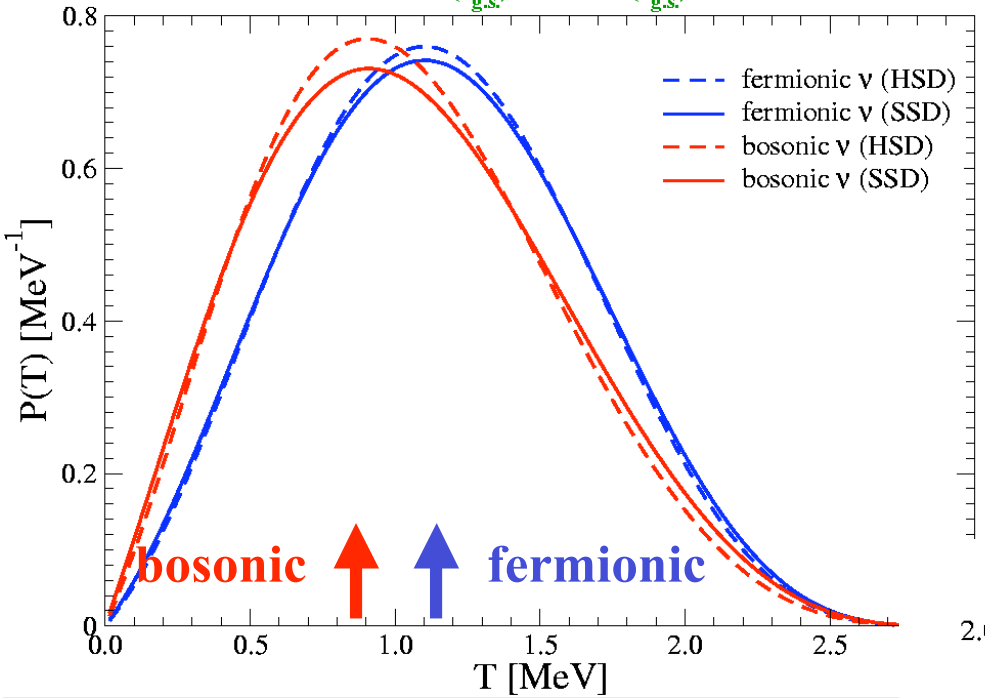
The single electron distributions

$^{82}Se(0^+_{g.s.}) \rightarrow {}^{82}Kr(2^+_1)$



The normalized distributions of the total energy of two electrons

$^{100}Mo(0^+_{g.s.}) \rightarrow {}^{100}Ru(0^+_{g.s.})$



2νββ-decay of ^{100}Mo

$0^+_{g.s.} \rightarrow 0^+_{g.s.}$

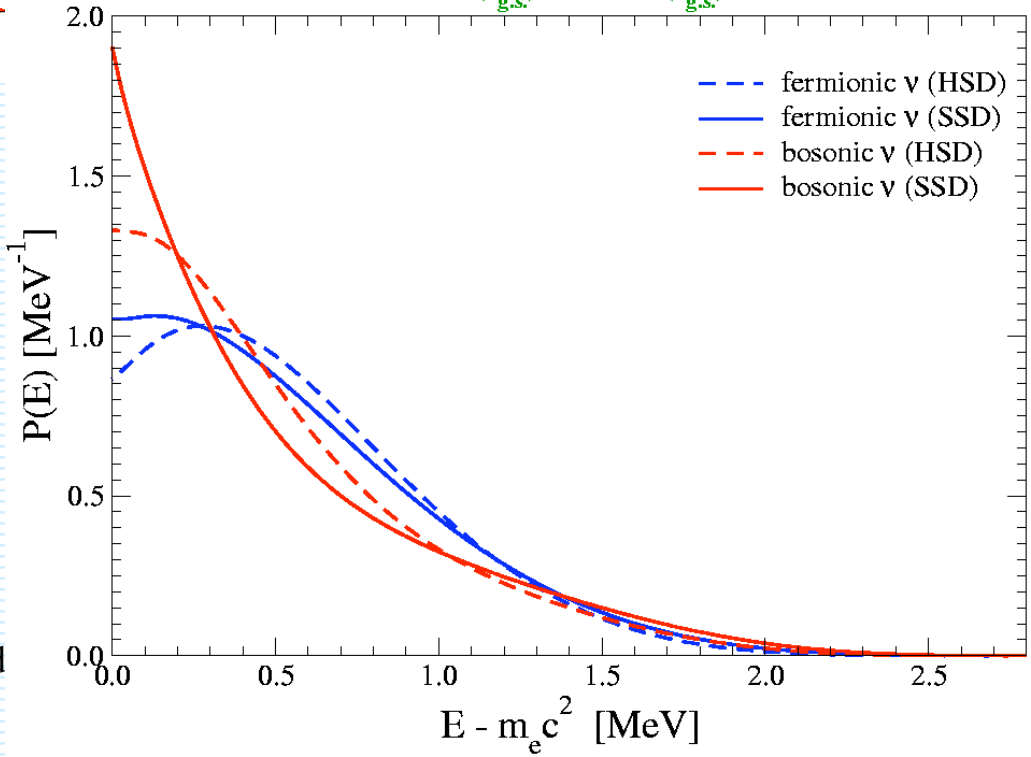
HSD+SSD

$$P^{f,b}(T) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dT}$$

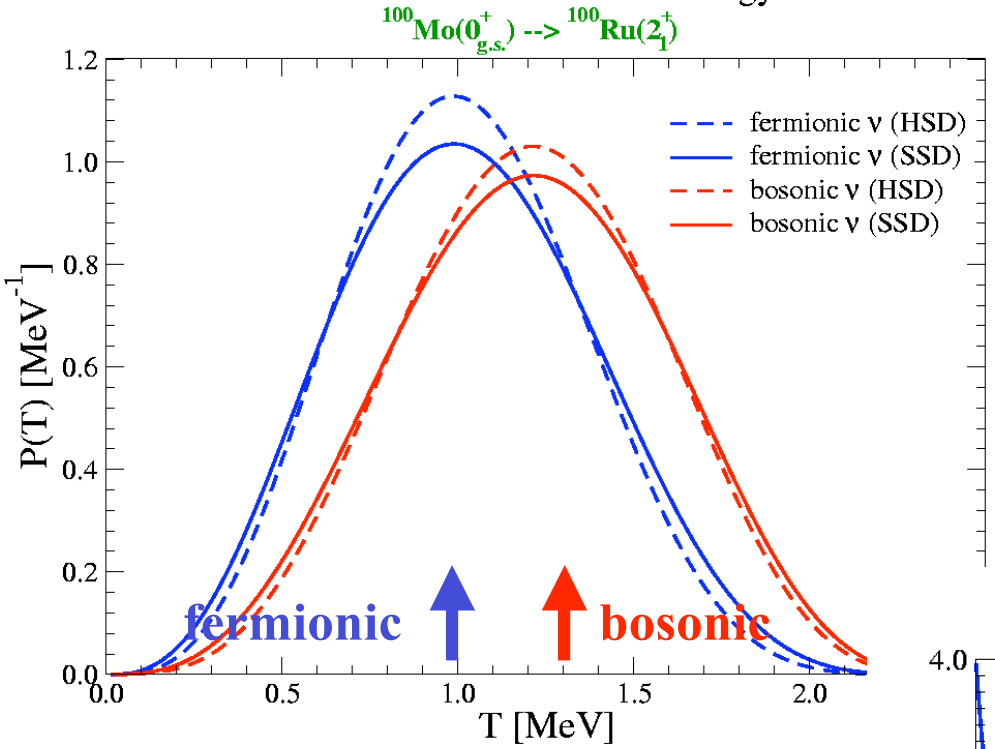
$$P^{f,b}(E) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dE}$$

The single electron distributions

$^{100}Mo(0^+_{g.s.}) \rightarrow {}^{100}Ru(0^+_{g.s.})$



The normalized distributions of the total energy of two electrons



2νββ-decay of ^{100}Mo

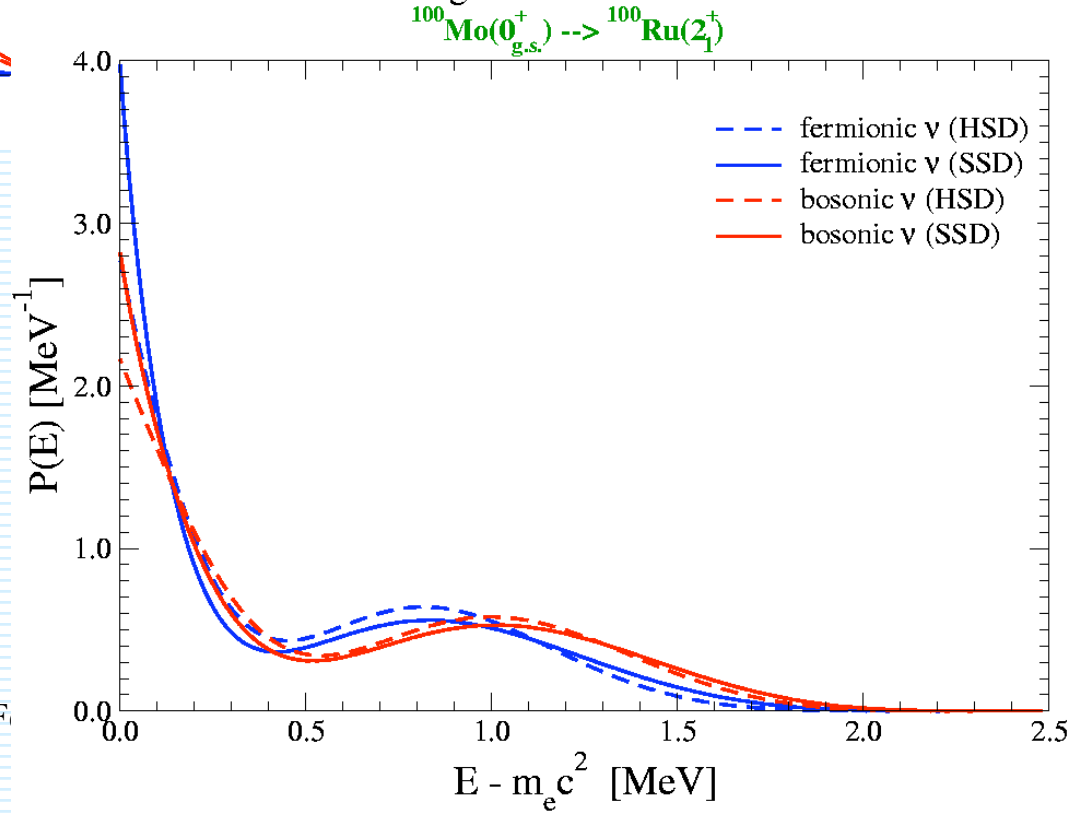
$0^+_{g.s.} \to 2^+_1$

HSD+SSD

$$P^{f,b}(T) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dT}$$

$$P^{f,b}(E) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dE}$$

The single electron distributions



Mixed statistics

Definition:

$$
\begin{aligned}
|\nu> &= \hat{a}^\dagger|0> \\
&\equiv \cos\delta \;\; \hat{f}^\dagger|0> \;+\; \sin\delta \;\; \hat{b}^\dagger|0> \\
&= \cos\delta \;\; |f> \;+\; \sin\delta \;\; |b>
\end{aligned}
$$

Commutators:

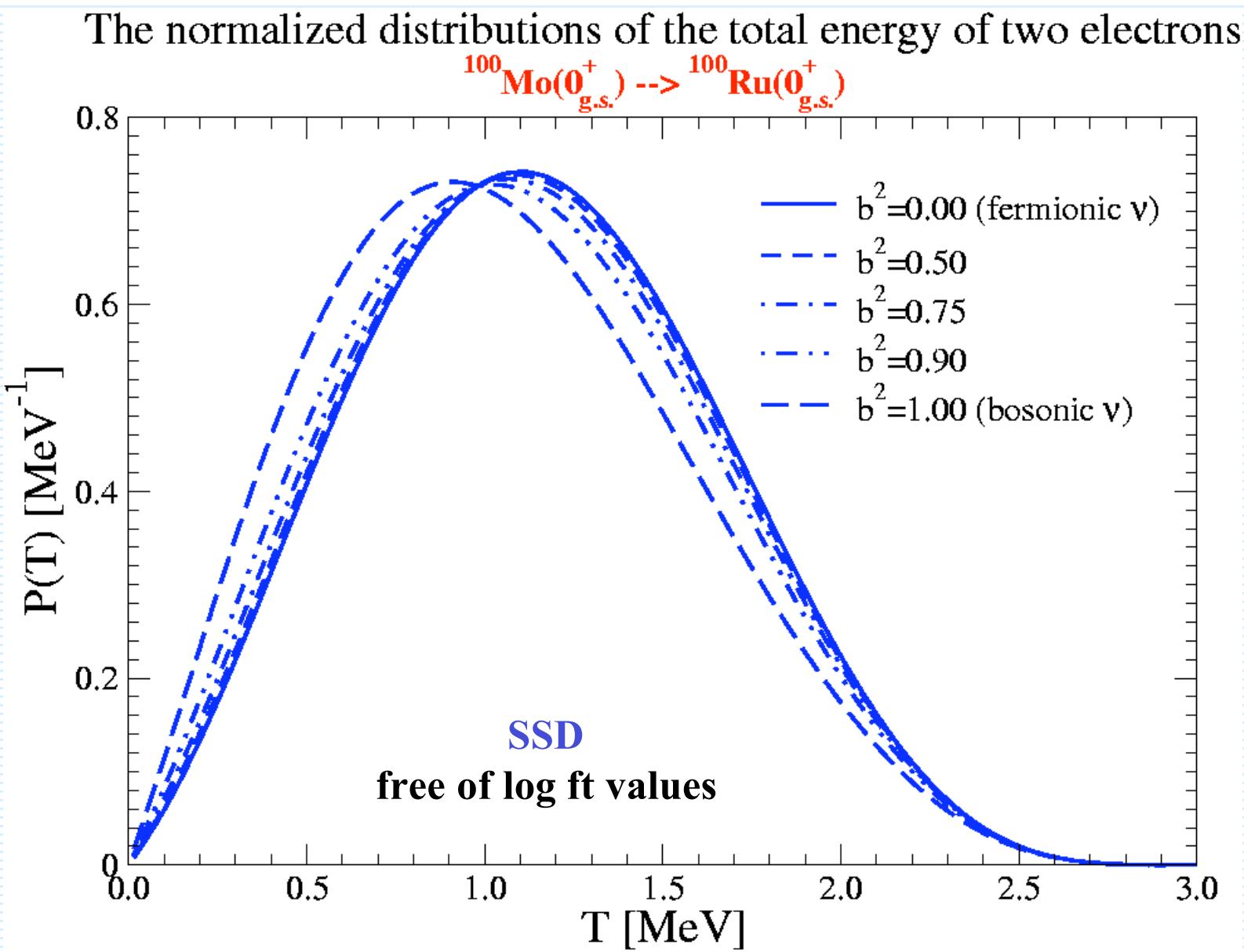
$$
\begin{aligned}
\hat{f}\hat{b} &= e^{i\phi}\hat{b}\hat{f} \qquad \hat{f}^\dagger\hat{b}^\dagger = e^{i\phi}\hat{b}^\dagger\hat{f}^\dagger \\
\hat{f}\hat{b}^\dagger &= e^{-i\phi}\hat{b}^\dagger\hat{f} \qquad \hat{f}^\dagger\hat{b} = e^{-i\phi}\hat{b}\hat{f}^\dagger
\end{aligned}
$$

Amplitude:

$$
\begin{aligned}
A^{2\nu} &= [\cos\delta^4 + \cos\delta^2\sin\delta^2(1-\cos\phi)]A^f \;+\; [\cos\delta^4 + \cos\delta^2\sin\delta^2(1+\cos\phi)]A^b \\
&= \cos\chi^2 A^f \;+\; \sin\chi^2 A^b
\end{aligned}
$$

Decay rate:

$$
\begin{aligned}
W^{2\nu} &= \cos\chi^4 \; W^f \;+\; \sin\chi^4 \; W^b \\
&= (1-b^2) \; W^f \;+\; b^2 \; W^b
\end{aligned}
$$

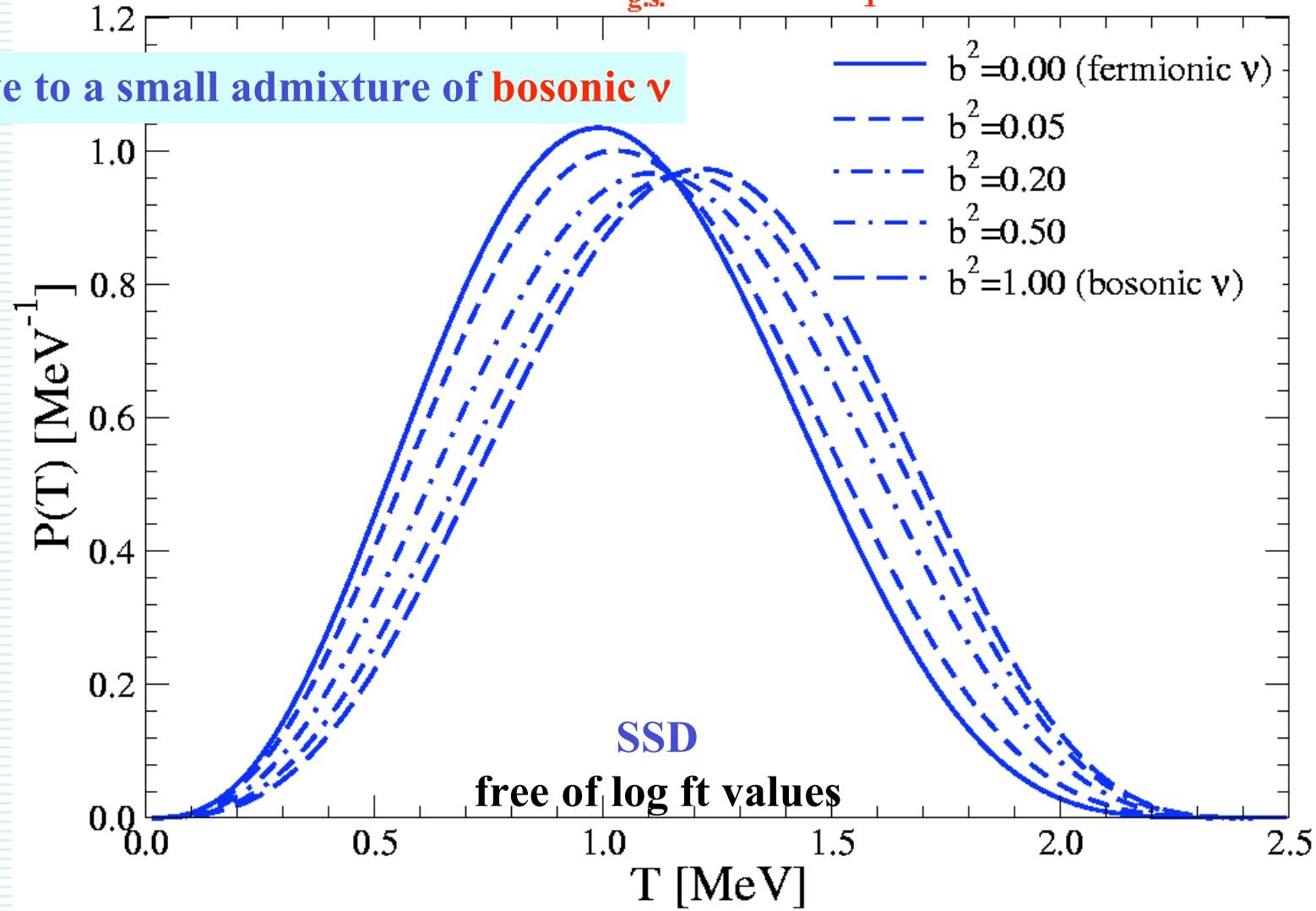


Large admixture of bosonic ν excluded: $b^2 < 0.75$

The normalized distributions of the total energy of two electrons

$^{100}Mo(0^+_{g.s.}) \rightarrow {}^{100}Ru(2^+_1)$

Sensitive to a small admixture of bosonic ν



SSD

free of log ft values

HSD nuclei even more sensitive to admixture of bosonic ν

but calculation of M.E. needed

Conclusions

- **2νββ-decay excludes the possibility of pure bosonic ν thanks NEMO 3 (Could you imagine it would be opposite?)**

- **For study of partially bosonic ν we need to measure 2νββ-decay transition to 2^+_1 state. From $0^+_{g.s.} \rightarrow 0^+_{g.s.}$ transition there is only a weak bound on admixture on bosonic ν (ασσυμιν γ ΣΣΔ).**