Parallel talk for PPC conference (reg. id: 177)

Effect of large extra dimension in future long baseline neutrino experiments

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Neutrinos and current unknowns of it...

- Neutrinos are the second most abundant particle in nature (after photon).
- They are chargeless, **nearly** massless, weakly interacting leptonic point particles.

Unknowns in neutrino sector:

1. Absolute masses of ν_1, ν_2 and ν_3 ?

   Upper bound (from cosmological data) on sum of three mass eigenstates:

$$\sum_{i=1}^{3} \nu_i \leq 0.113 \; eV$$

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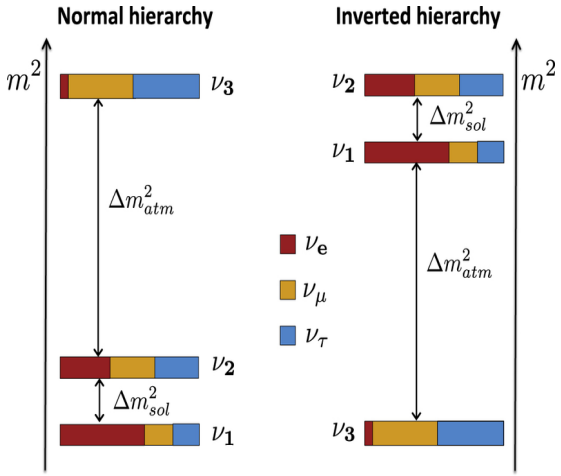

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3. $$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

   The value of δ_{CP} ?

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13} \end{bmatrix},$$

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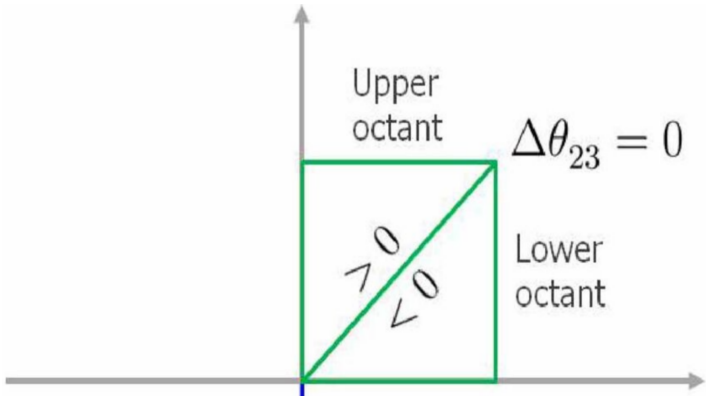
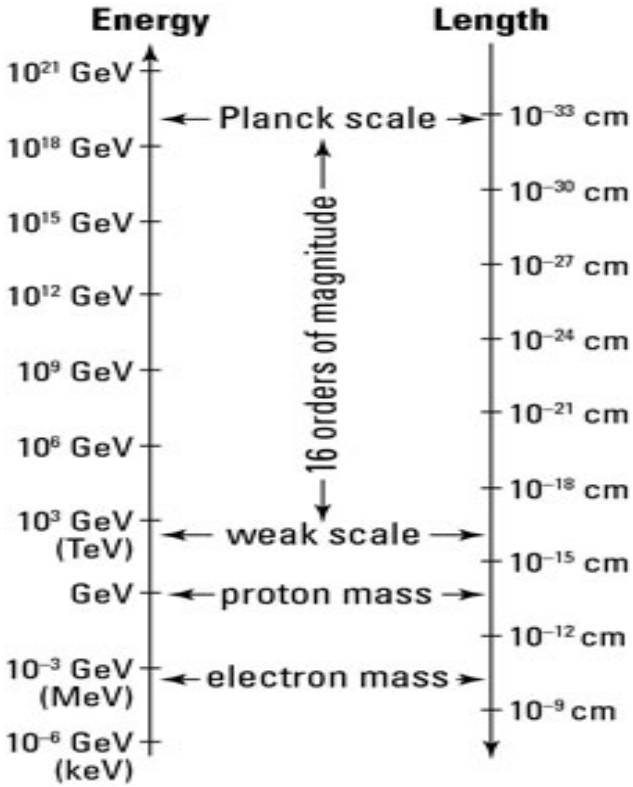
   The value of δ_{CP} ?
4. Octant problem in atmospheric sector (value of θ_{23}) ?



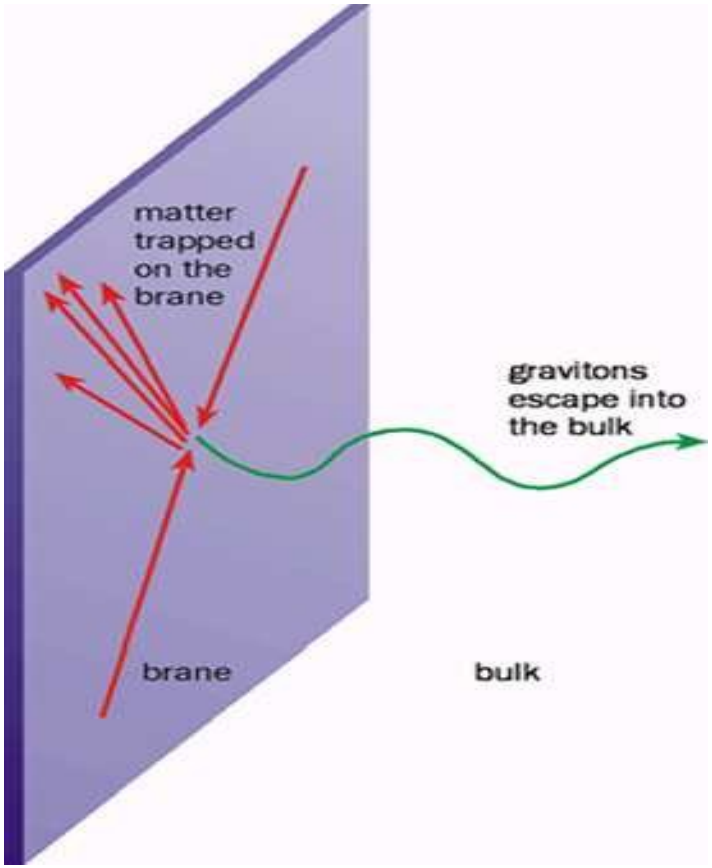
Introduction of Large Extra Dimension (LED)

- Problem in mass hierarchy spectrum ?

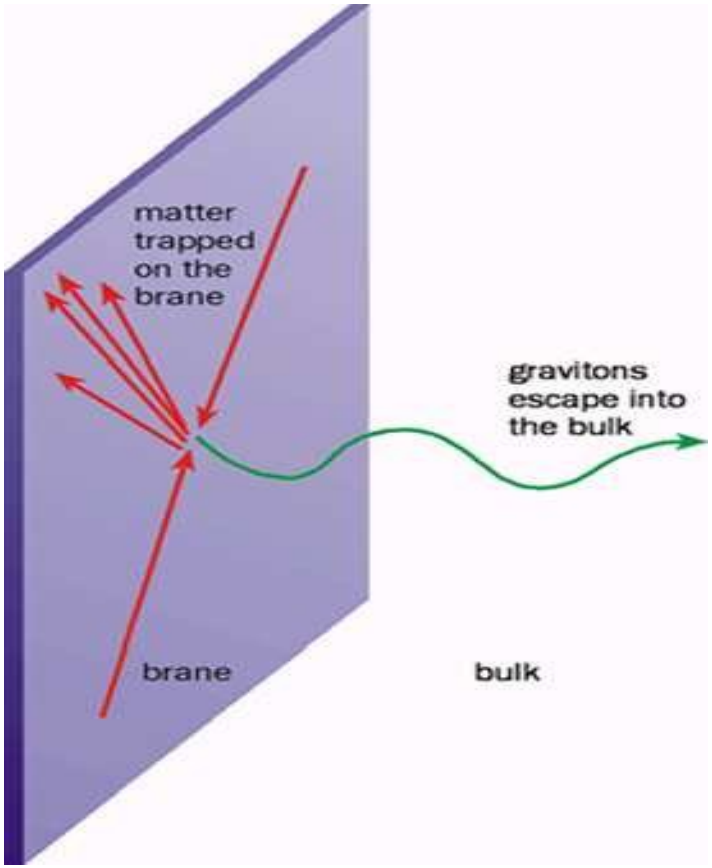


- How to explain **the 16 order of magnitude** difference?
- Ans: By introducing **“large extra dimension”**

LED:

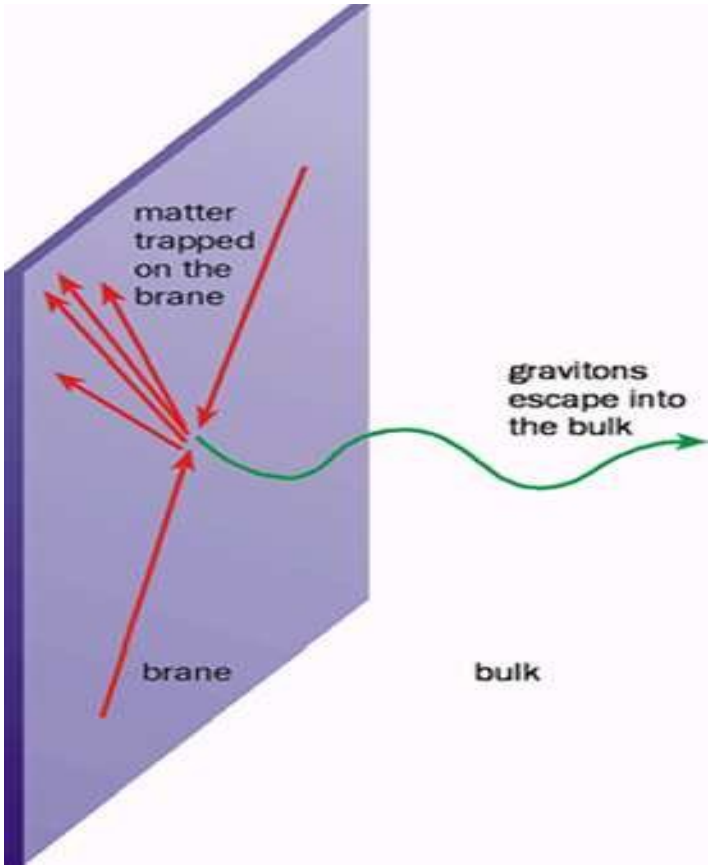


- Acoording to LED, there exist “N” extra dimensions with radius R_{ED}.
- Gravitons can walk in between brane and bulk...
- All SM particles should lie on the brane only
- Interaction of graviton with SM particles are very small due to the “escaping” of graviton in bulk



- Gravitational force, $F \sim r^{-(2+N)}$ when $r < R_{ED}$, and $F \sim r^{-2}, r > R_{ED}$

[1] doi:10.1103/PhysRevD.65.105015



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$$M_{pl}^2 \sim M_W^{2+N} R_{ED}^N \tag{1}$$

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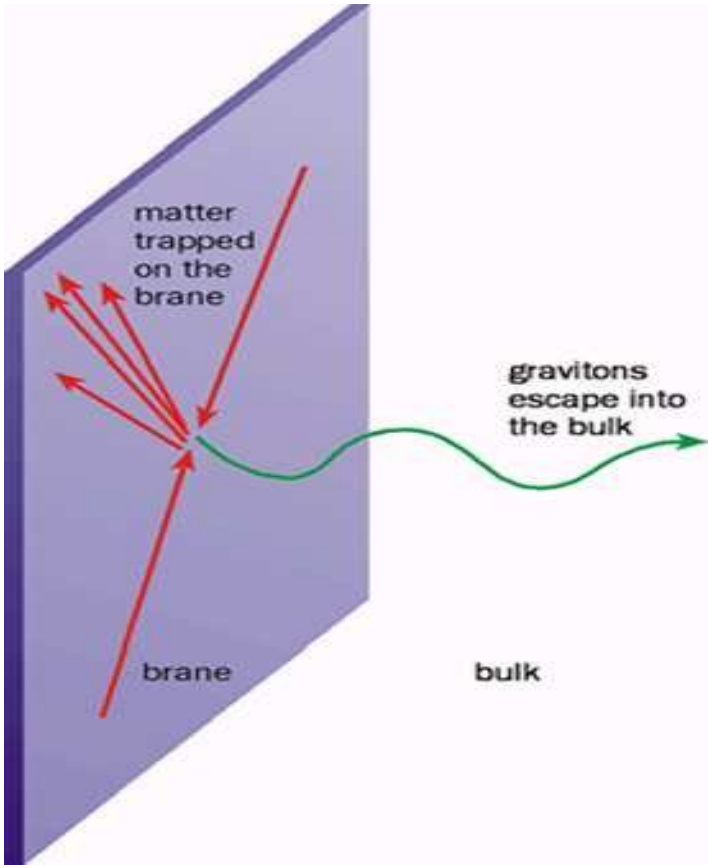

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$$R_{ED} \sim 1.98 \times 10^{(32/N)-17} \text{cm} \tag{2}$$

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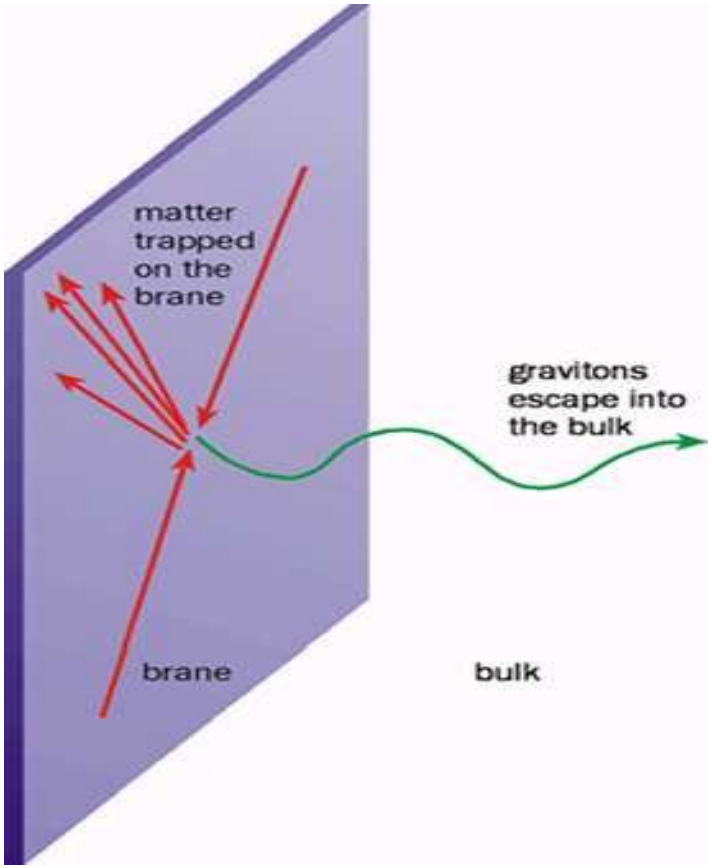

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Value of N	R_{ED}
1	$\sim 10^{10}$ km (ruled out)
2	~ 0.1 cm (not favourable)
3	$\sim 10^{-7}$ cm

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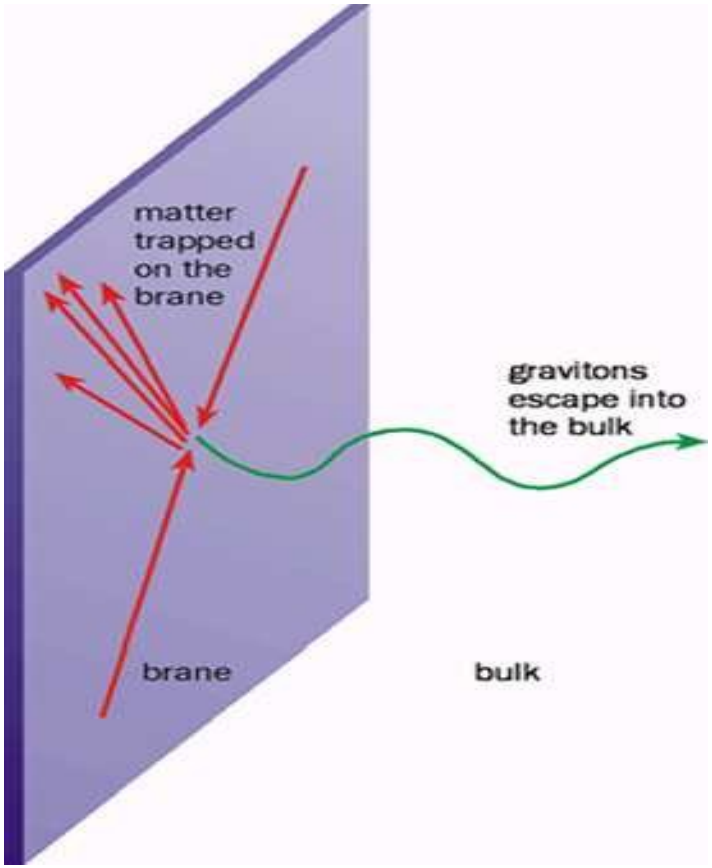

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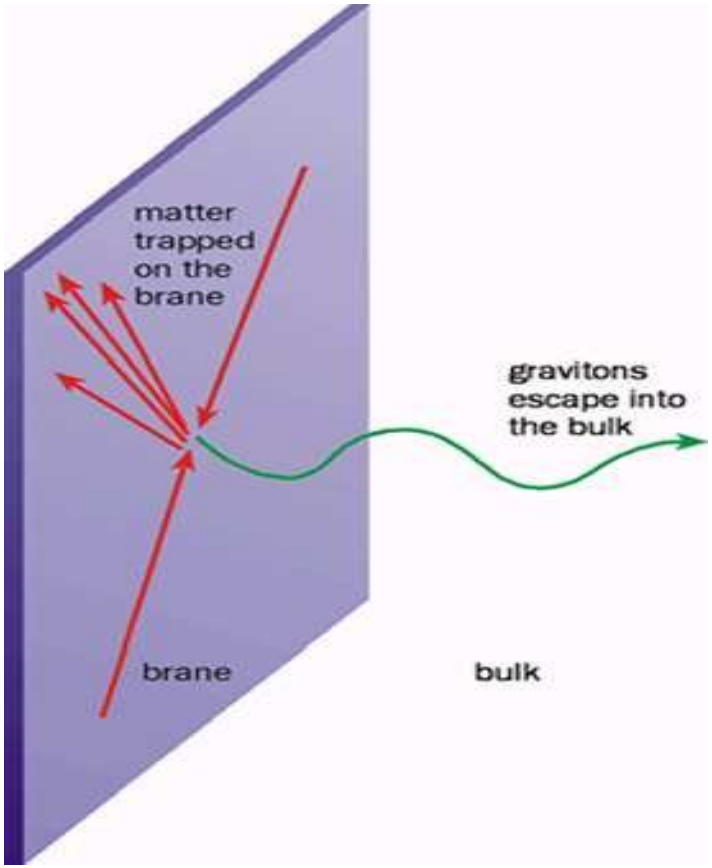

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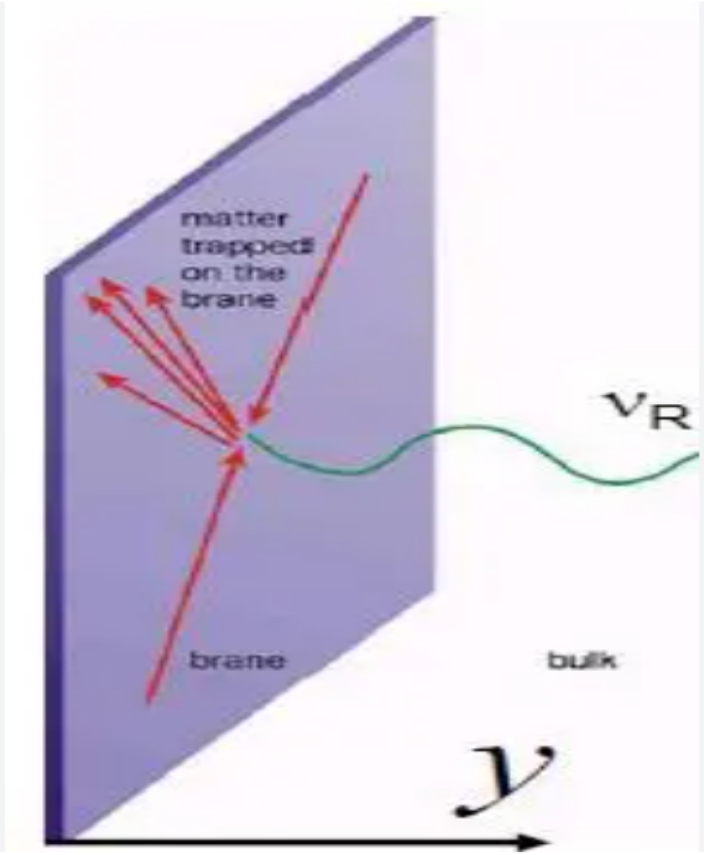
LED in neutrino sector



- ν_R can walk in between brane and bulk.

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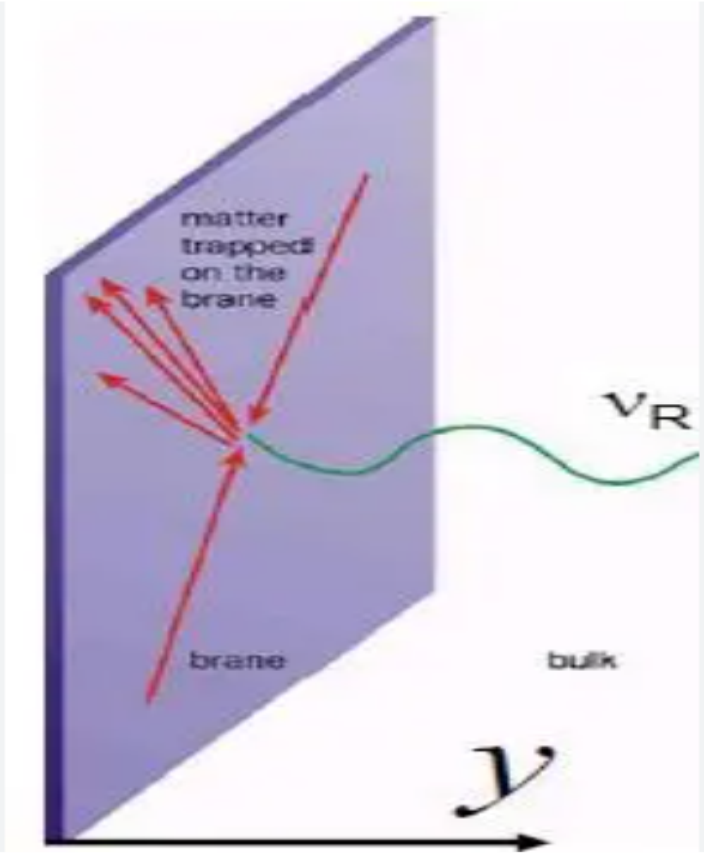

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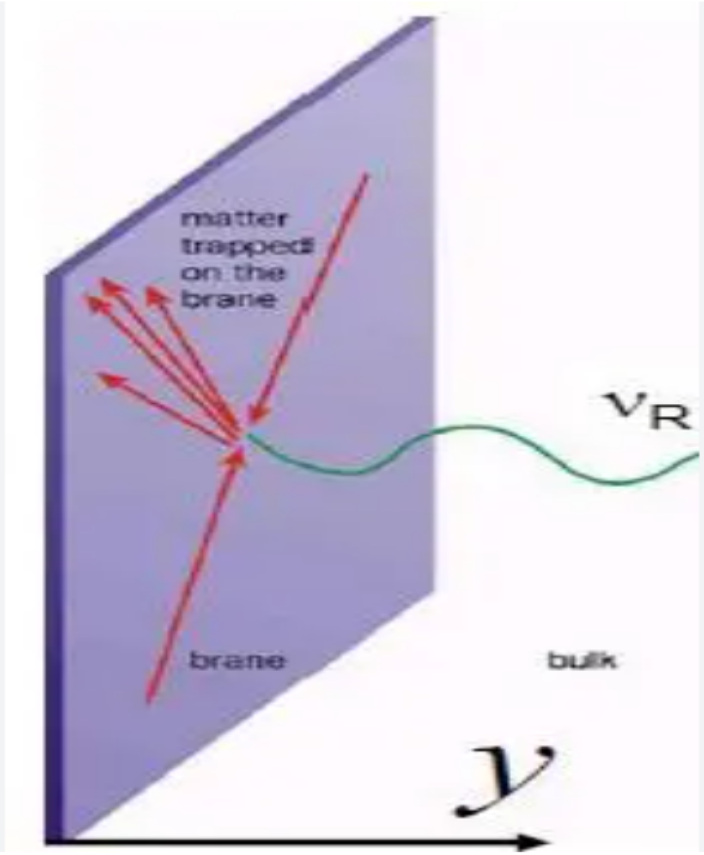


- ν_R can walk in between brane and bulk.
- All active neutrinos lie on the brane only
- Active neutrino mass[2],

$$m_\nu \sim \frac{y v_H}{\sqrt{M_W^N R_{ED}^N}} \sim \frac{y v_H M_W}{M_{pl}}$$
$$\sim 10^{-4}\left(\frac{y M_W}{1\,TeV}\right)[\mathrm{eV}], \qquad (3)$$

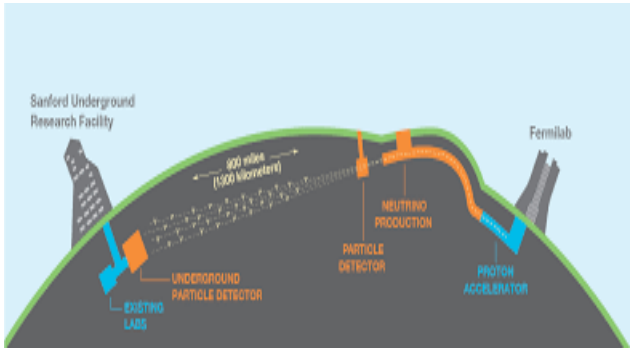
where $v_H = 246\ GeV$

[2] doi:10.1103/PhysRevD.65.024032

Experimental setup

Setup	Run-time (years)
DUNE	$5(\nu_e) : 5(\bar{\nu}_e)$
T2HK	$5(\nu_e) : 5(\bar{\nu}_e)$
P2SO	$3(\nu_e) : 3(\bar{\nu}_e)$

Experimental Setup



Parameter	Values
θ_{12}	33.41°
θ_{13}	8.58°
θ_{23}	42°
δ_{CP}	230°
$\Delta m^2_{21}(\mathrm{eV}^2)$	7.41×10^{-5}
$\Delta m^2_{32}(\mathrm{eV}^2)$	$\pm 2.507 \times 10^{-3}$

Oscillation parameters we have used for our calculation

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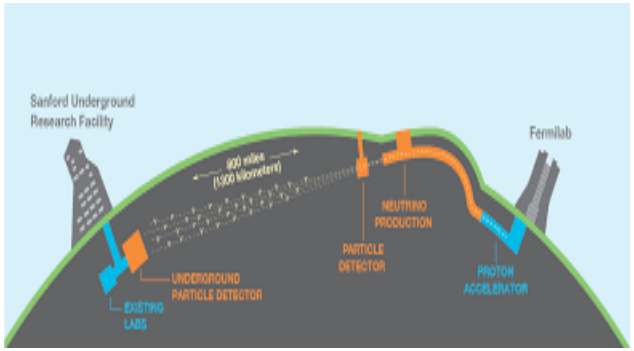

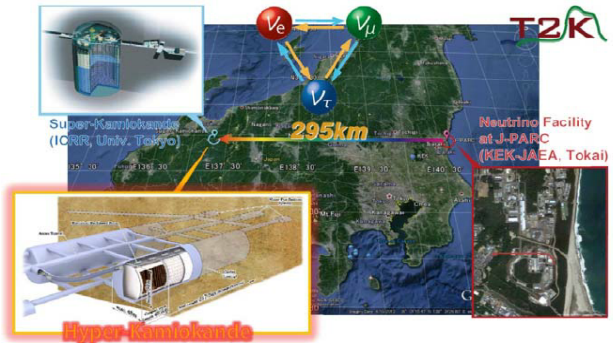

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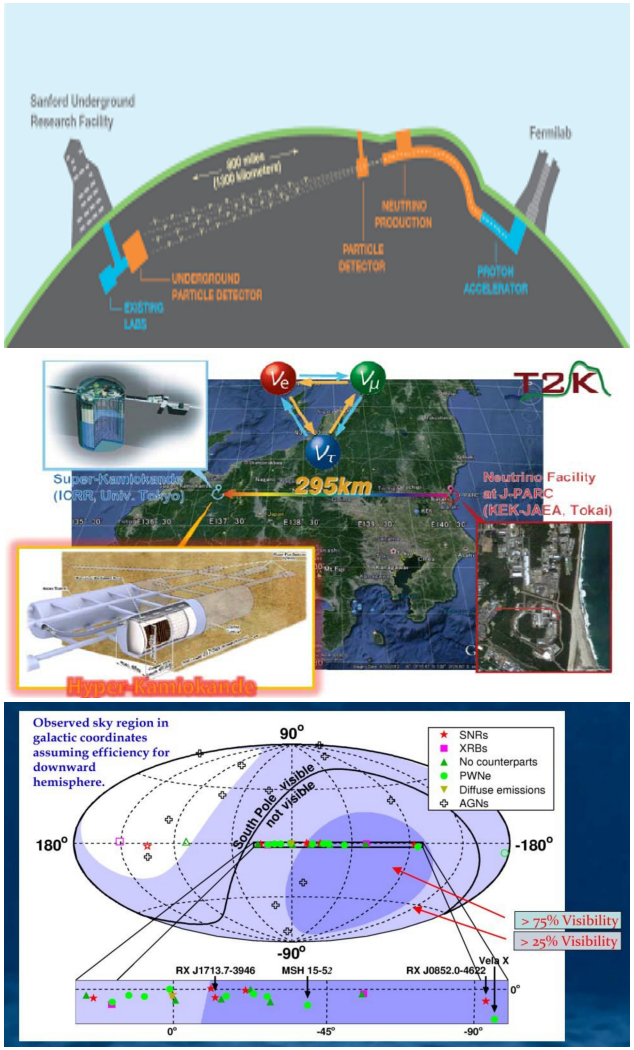


Probability expressions in presence of LED

The approximate appearance probability in presence of R_{ED} (keeping $m_0 = 0$ eV):

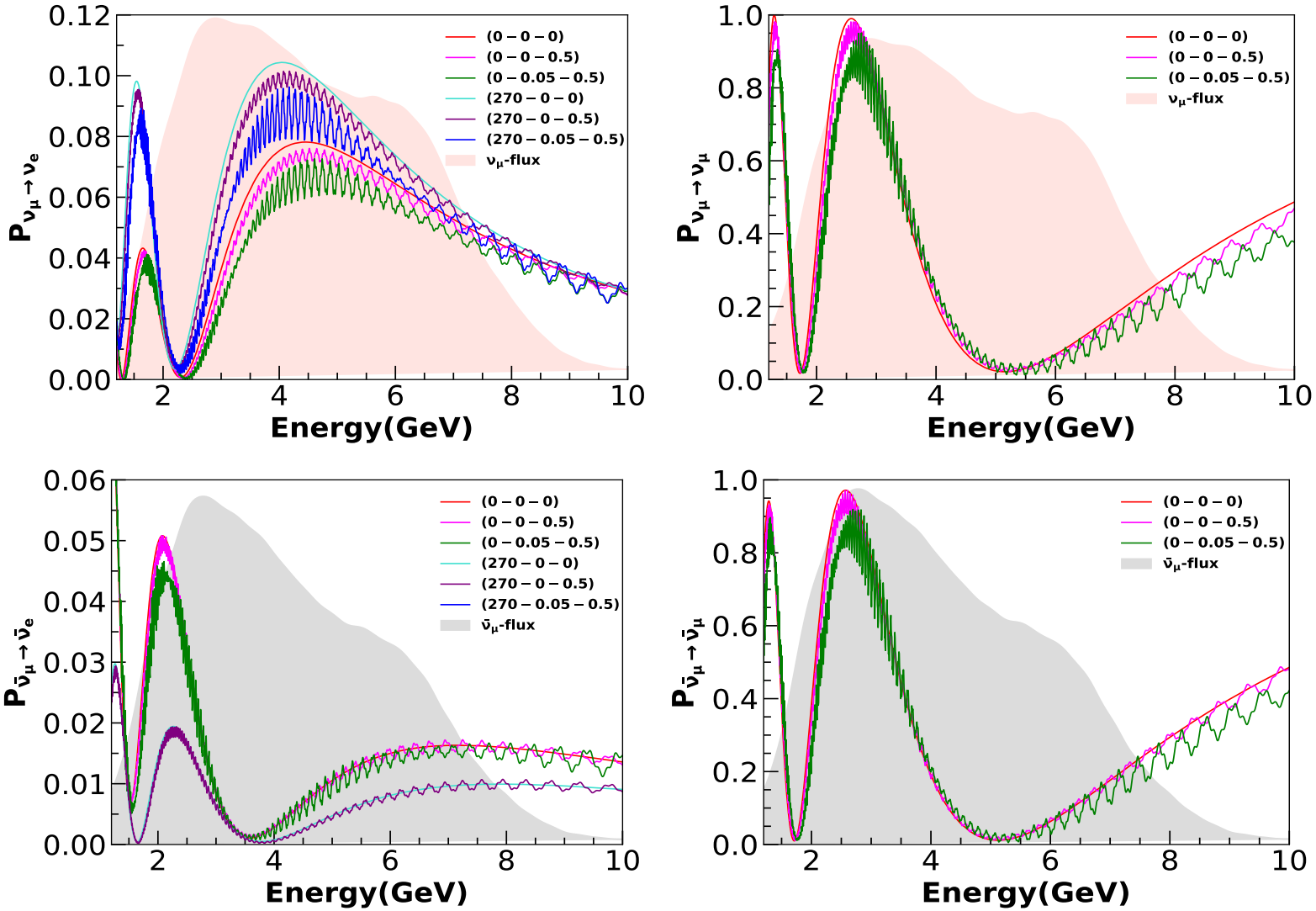
$$\begin{aligned} P_{\mu e}(L,E) &\simeq P^{SM}_{\mu e}(L,E) + R^2_{ED}\Big[A + B\cos(\frac{L\Delta m^2_{31}}{2E} + \delta_{CP}) + C\cos(\frac{L\Delta m^2_{31}}{2E} - \frac{L}{2ER^2_{ED}}) \\ &+ D\cos(\frac{L}{2ER^2_{ED}})\Big] \end{aligned} \tag{4}$$

where,

$$\begin{aligned} A &= 1.2\times 10^{-5}\cos(\delta_{CP})\sin(2\theta_{23})\ \ eV^2 \\ B &= -1.6\times 10^{-5}\sin(2\theta_{23})\ \ eV^2 \\ C &= 0.0871\Delta m^2_{31}\sin^2(\theta_{23}) \\ D &= -0.0871\Delta m^2_{31}\sin^2(\theta_{23}) \end{aligned} \tag{5}$$

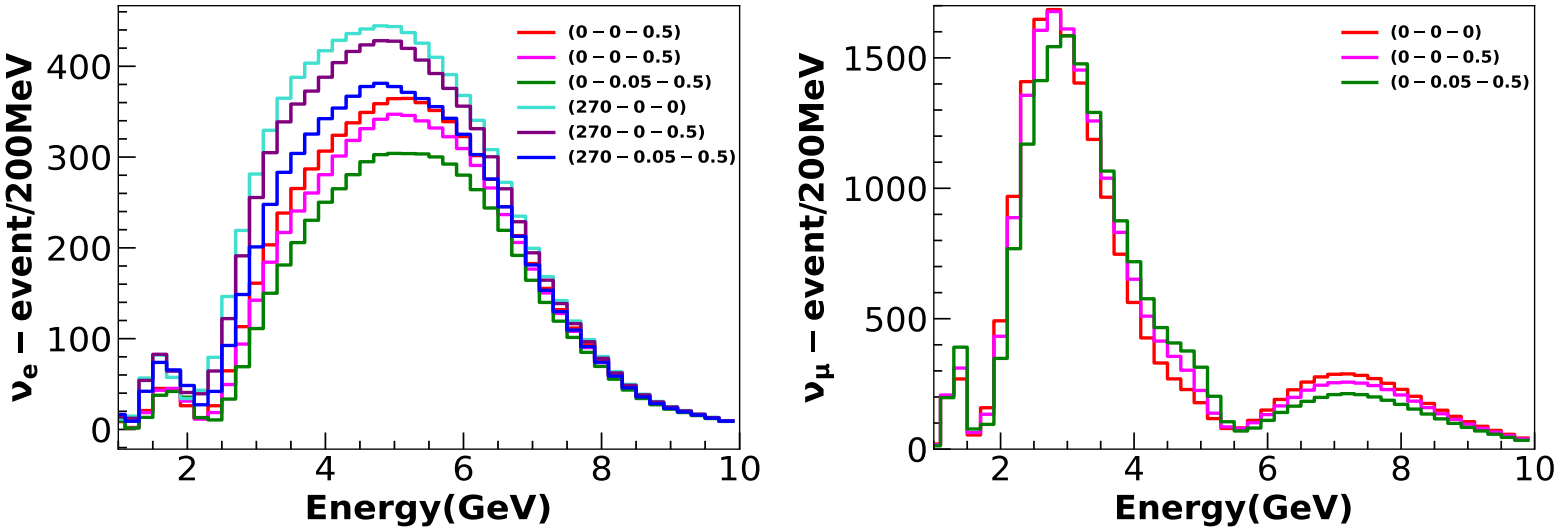
and $P^{\rm SM}_{\mu e}(L,E)$ is the standard appearance probability.

Probability plots for P2SO



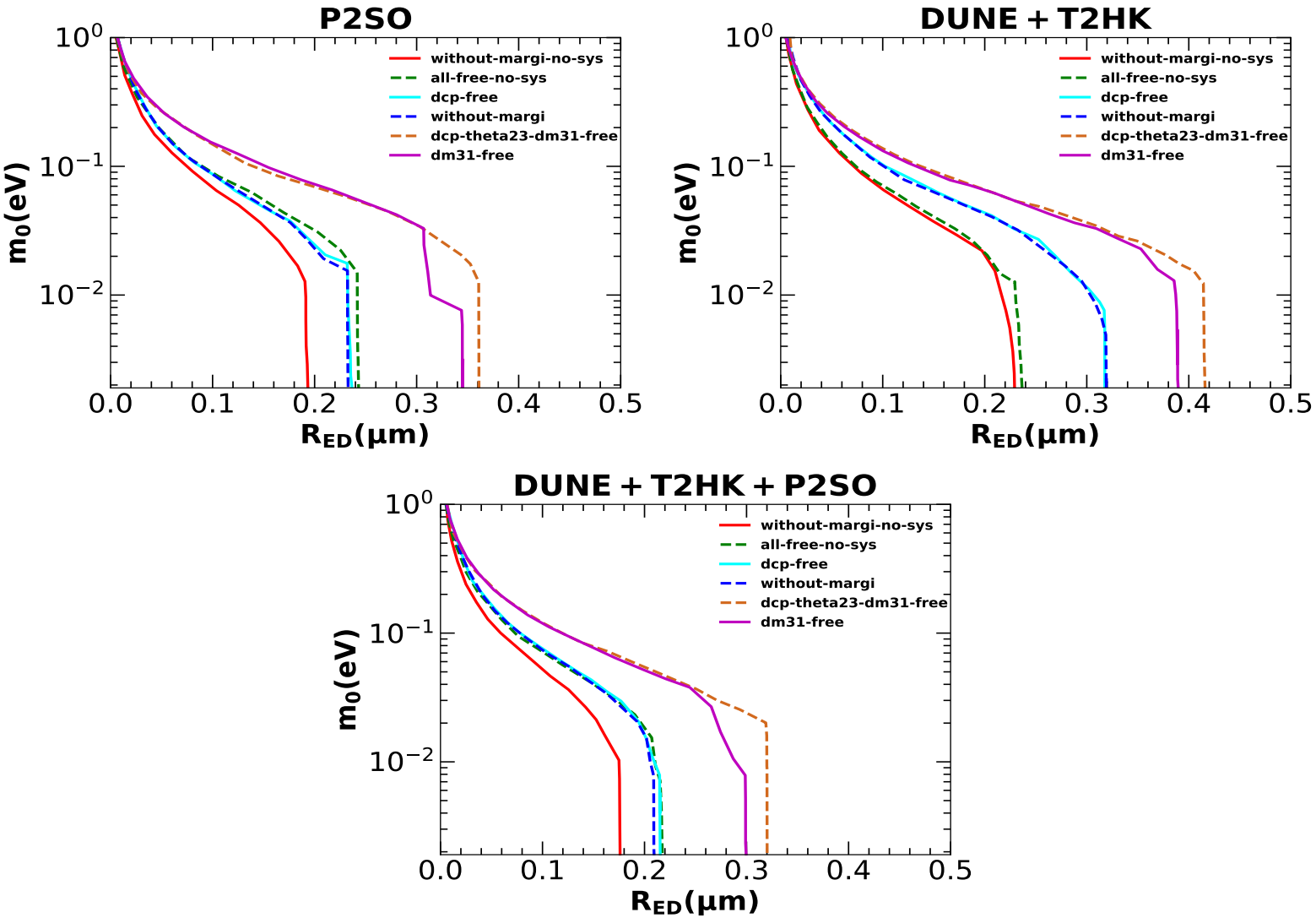
Probability vs energy (GeV) for P2SO: upper row $\rightarrow$ left (right) panel shows appearance (disappearance) channel for ν's; lower row $\rightarrow$ same for $\bar{\nu}$'s; The legends are in the form: $(\delta_{CP}[\circ] - m_0[\mathrm{eV}] - \mathrm{R_{ED}}[\mu\mathrm{m}])$.

Event rates for DUNE and P2SO



Event rate vs energy (GeV): left (right) panel is appearance (disappearance) event rates for P2SO. The legends are in the form: $(\delta_{CP}[\circ] - m_0[\mathrm{eV}] - \mathrm{R_{ED}}[\mu\mathrm{m}])$.

Bounds for m_0 and R_{ED}



Bounds of m_0 vs R_{ED} (in μm) at 90% C.L. for the synergy of DUNE, T2HK and P2SO.

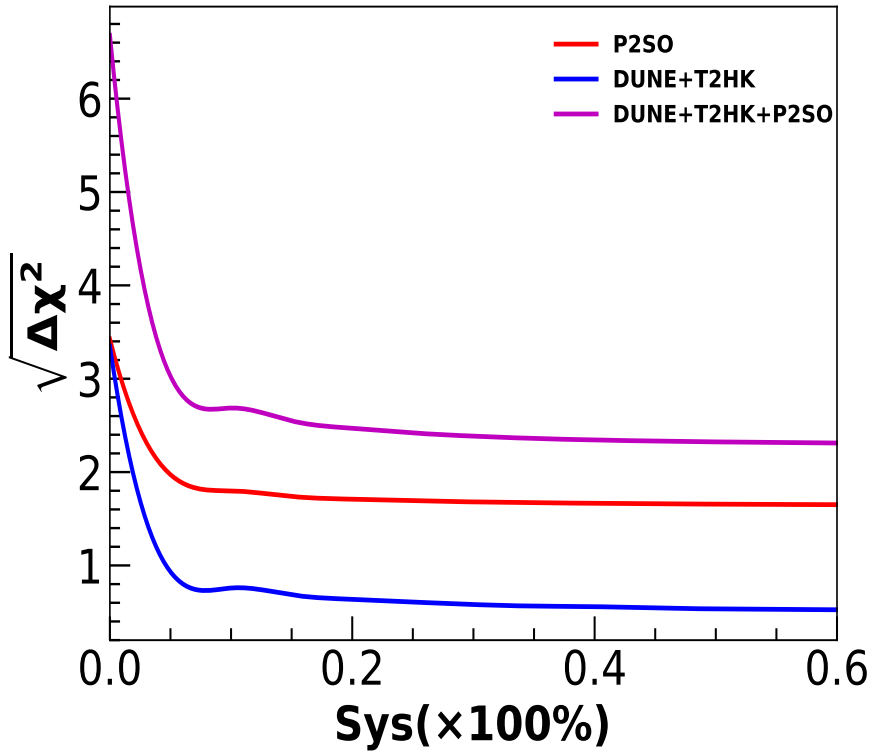
Results for bounds

SETUP	CONDITIONS	$R_{ED}(\mu m)$ at m_0=0 eV
P2SO	all-fixed-no-sys	0.194
	$\delta_{CP} - \theta_{23} - \Delta m^2_{31}$-free-no-sys	0.236
	all-fixed-with-sys	**0.232**
	δ_{CP}-free-with-sys	0.230
	$\delta_{CP} - \theta_{23}$-free-with-sys	0.265
	Δm^2_{31}-free-with-sys	**0.345**
	$\delta_{CP} - \theta_{23} - \Delta m^2_{31}$-free-with-sys	0.361
	all-free-with-sys	**0.361**
DUNE+T2HK	all-fixed-no-sys	0.229
	$\delta_{CP} - \theta_{23} - \Delta m^2_{31}$-free-no-sys	0.235
	all-fixed-with-sys	**0.317**
	δ_{CP}-free-with-sys	0.317
	$\delta_{CP} - \theta_{23}$-free-with-sys	0.317
	Δm^2_{31}-free-with-sys	**0.390**
	$\delta_{CP} - \theta_{23} - \Delta m^2_{31}$-free-with-sys	0.414
	all-free-with-sys	**0.414**

SETUP	CONDITIONS	$R_{ED}(\mu m)$ at m_0=0 eV
P2SO+DUNE+T2HK	all-fixed-no-sys	0.175
	$\delta_{CP} - \theta_{23} - \Delta m^2_{31}$-free-no-sys	0.222
	all-fixed-with-sys	**0.208**
	δ_{CP}-free-with-sys	0.215
	$\delta_{CP} - \theta_{23}$-free-with-sys	0.232
	Δm^2_{31}-free-with-sys	**0.299**
	$\delta_{CP} - \theta_{23} - \Delta m^2_{31}$-free-with-sys	0.320
	all-free-with-sys	**0.320**

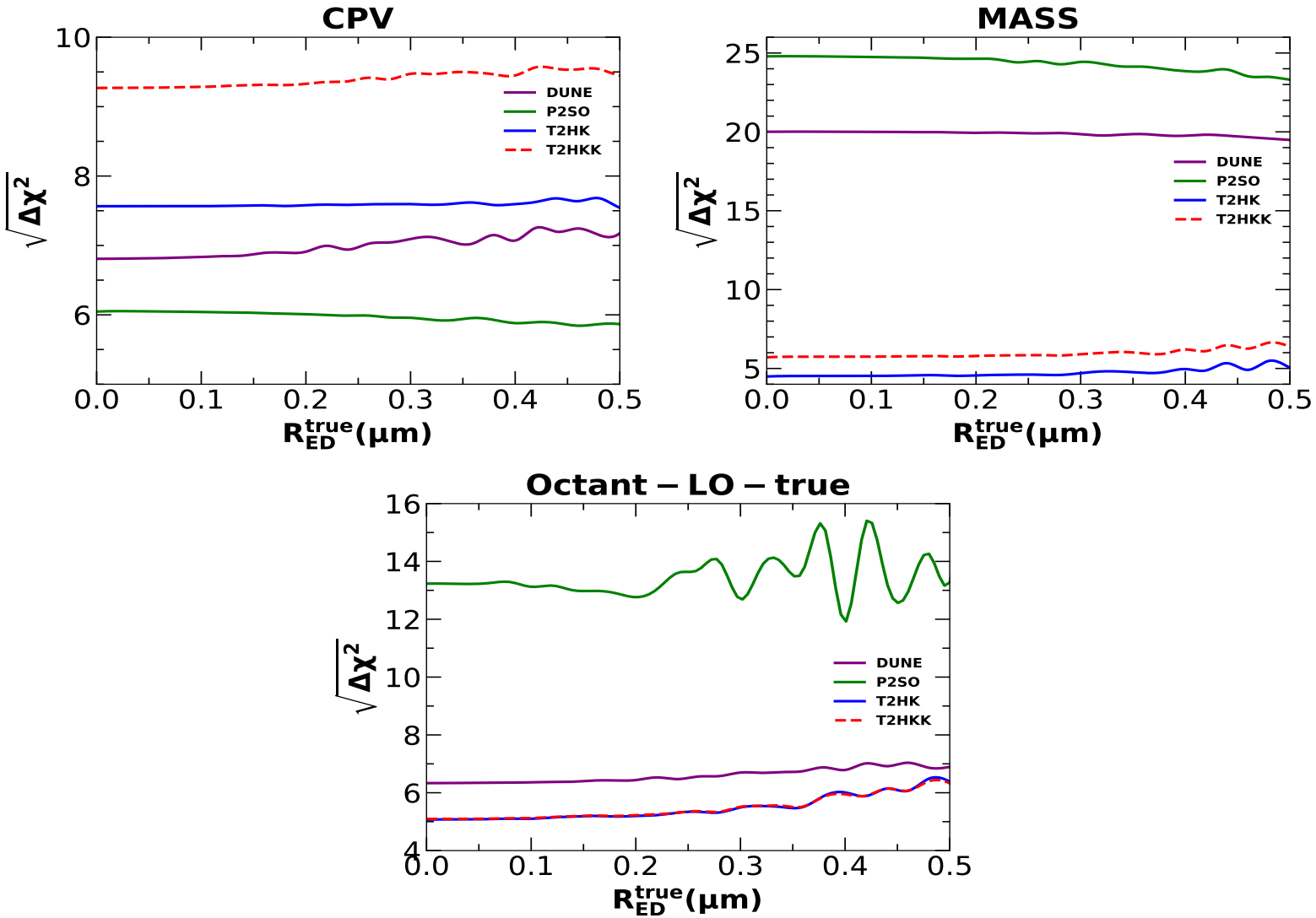
R_{ED} bound for different synergy of DUNE, T2HK and P2SO experiments

Effect of systematic uncertainty



Bound sensitivity as a function of systematic uncertainty (in percentage) for synergy of DUNE, T2HK and P2SO experiments.

Sensitivity plots



Upper row: left panel → CPV sensitivity, right panel → mass hierarchy sensitivity; lower row: octant sensitivity as a function of R_{ED}.

Conclusions

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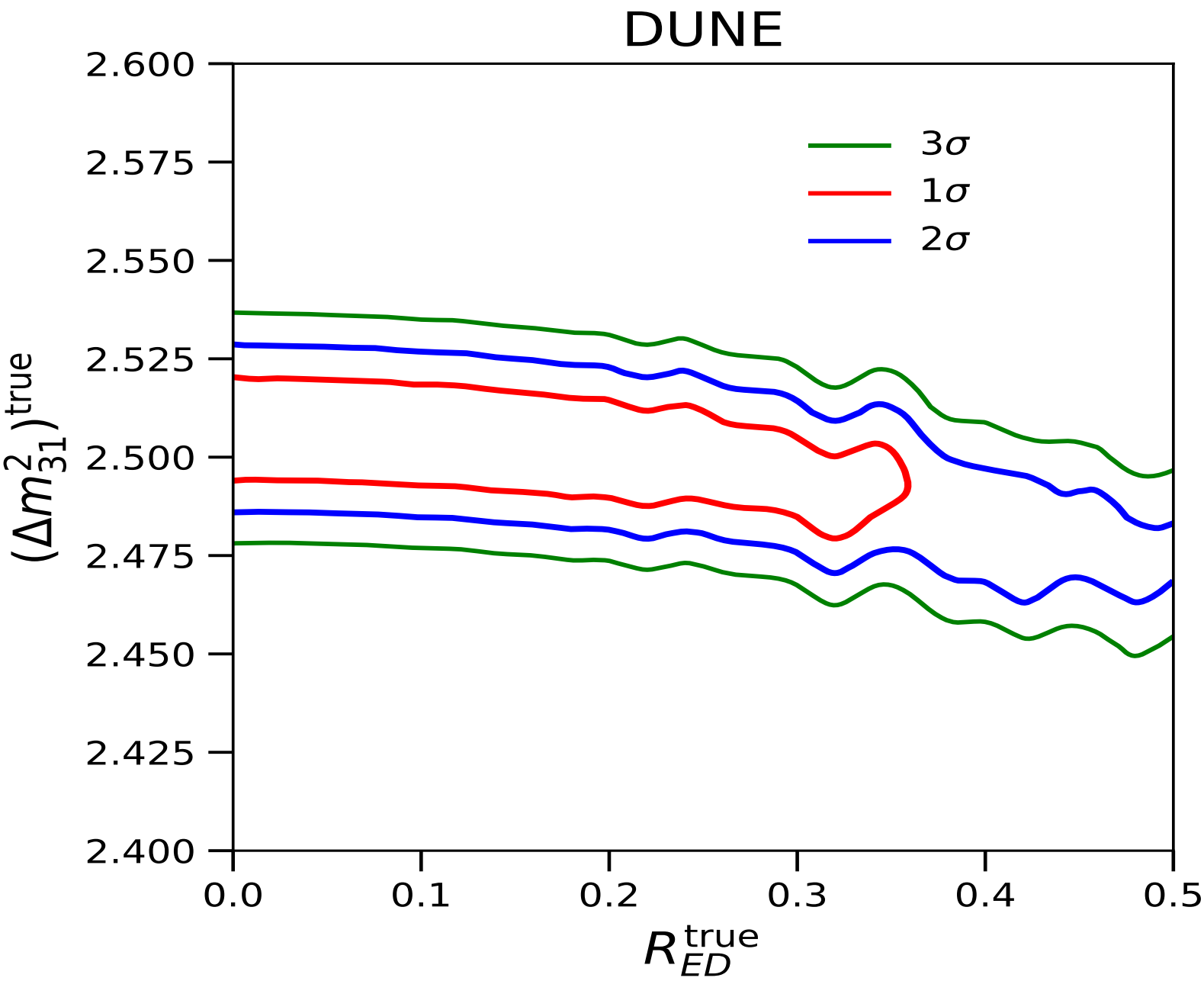
- Bound on R_{ED} largely depends on systematic uncertainity. When the systematics becomes 20%, the sensitivity gets independent on systematics.
- CPV, mass hierarchy and octant sensitivity are not significantly changes with respect to R_{ED}.

Thank you

Backup Slides


DUNE
2.600
2.575
2.550
2.525
2.500
2.475
2.450
2.425
2.400
$(\Delta m^2_{31})^{\text{true}}$
0.0
0.1
0.2
0.3
0.4
0.5
R_{ED}^{true}
3σ
1σ
2σ

Types of extra dimension

- **Large extra dimension:** here SM particles are in 4D. One very large extra dimension is present, other extra dimensions are small in size. Right handed neutrinos are present in all the extra dimensions as well as in 4D; in bulk.
- **Universal extra dimension:** here SM as well as right handed neutrinos all are in bulk, in all 4+n dimensional spacetime.
- **Warped extra dimension**