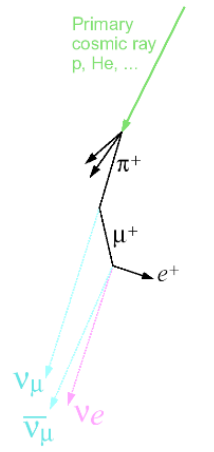
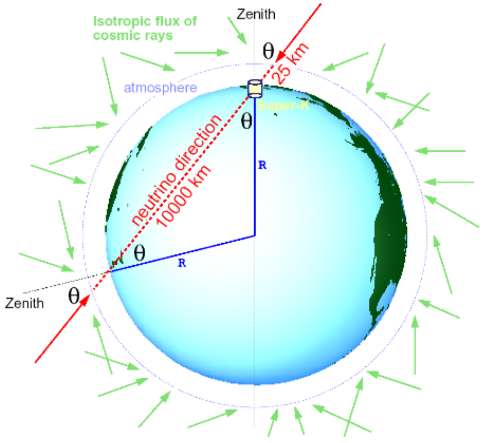
QUANTUM OSCILLATION PHENOMENA

KIAS

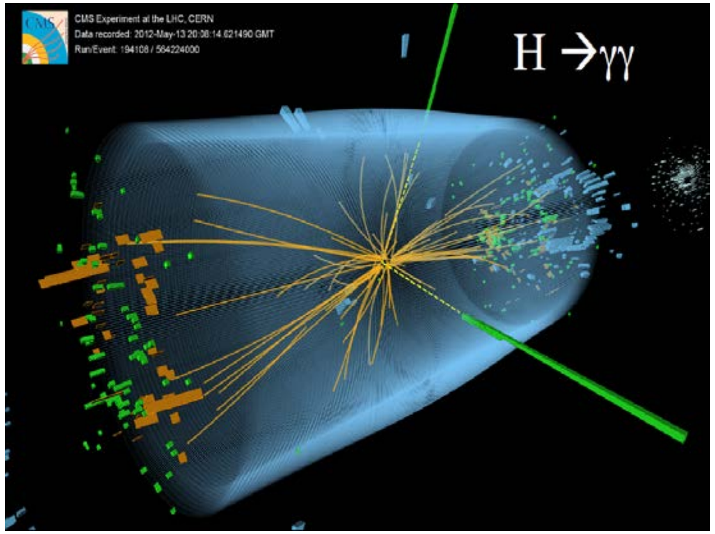
Eung Jin Chun



Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)

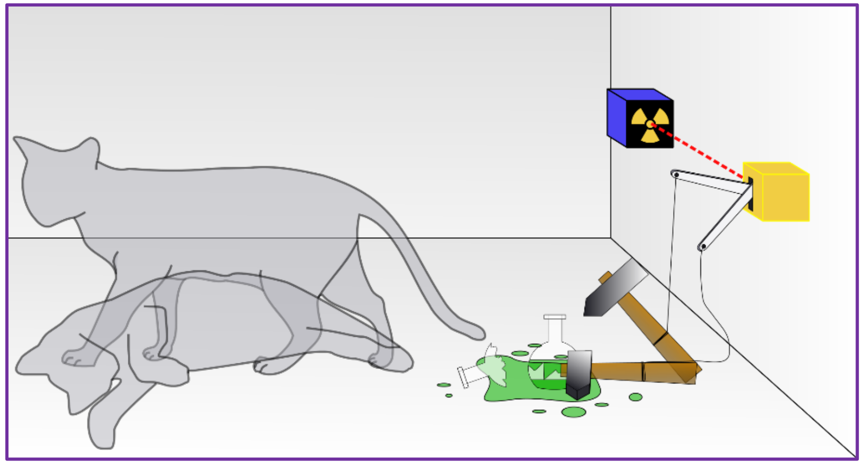


Up-Down Symmetric Flux
(for E_ν > few GeV)

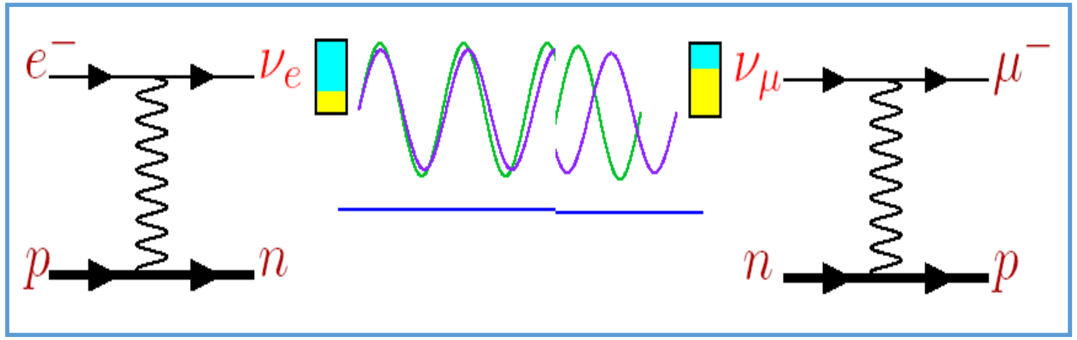


Outline

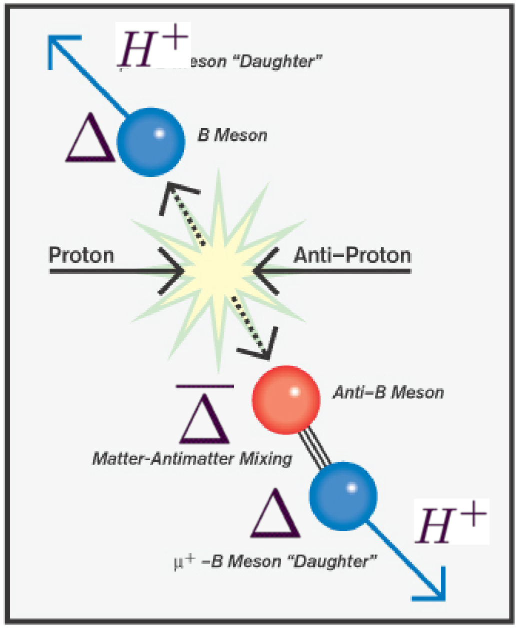
- Introduction: a two-state QM



- Weak interaction & neutrino oscillation



- Origin of neutrino mass & particle-antiparticle oscillation at LHC

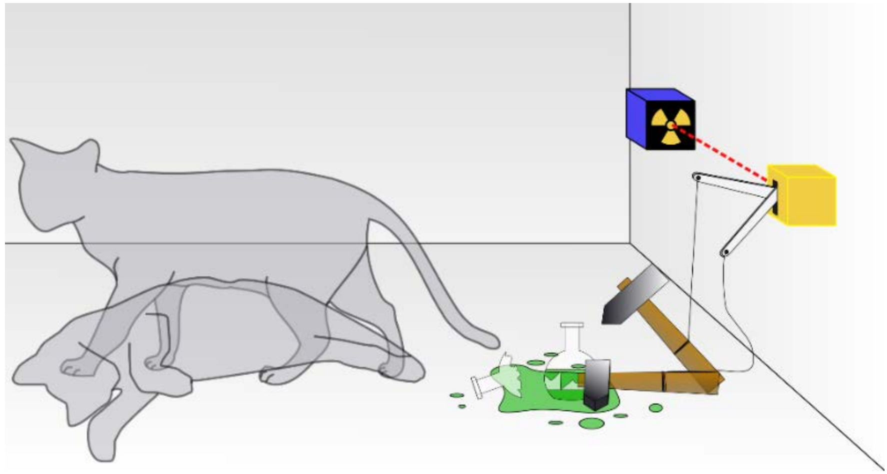


- Conclusion

Quantum Oscillation phenomena

Introduction

Quantum mechanics of a two-state system



- Schroedinger's cat (an illustration):
  Observation – **A**live(undecayed) or **D**ead(decayed)

$$\mathcal{O}\ :\ |A\rangle \text{ or } |D\rangle$$

- Hamiltonian: energy operator of the system

$$i\frac{d}{dt}|\psi(t)\rangle = \mathcal{H}|\psi(t)\rangle$$

- Non-simultaneous observables: $[\mathcal{H}, \mathcal{O}] \neq 0$

$$\mathcal{H}|A\rangle = E_{11}|A\rangle + E_{12}|D\rangle$$
$$\mathcal{H}|D\rangle = E_{21}|A\rangle + E_{22}|D\rangle$$

- Alive or Dead at t? $|\psi_A(0)\rangle = |A\rangle \quad \Rightarrow \quad |\psi_A(t)\rangle = ?$

Superposition of A & D: to be or not to be?

- Energy eigenstates: $\mathcal{H}|E_{1,2}\rangle = E_{1,2}|E_{1,2}\rangle$

$$|E_1\rangle = c_\theta|A\rangle - s_\theta|D\rangle$$
$$|E_2\rangle = s_\theta|A\rangle + c_\theta|D\rangle$$

$$i\frac{d}{dt}|\psi_{1,2}(t)\rangle = E_{1,2}|\psi_{1,2}(t)\rangle \quad \Rightarrow \quad |\psi_{1,2}(t)\rangle = e^{iE_{1,2}t}|E_{1,2}\rangle$$

- The poor cat state after some time:

$$\begin{aligned} |\psi_A(t)\rangle &= e^{iE_1t}c_\theta|E_1\rangle + e^{iE_2t}s_\theta|E_2\rangle \\ &= (e^{iE_2t} - e^{iE_1t})s_\theta c_\theta|D\rangle + \cdots|A\rangle \end{aligned}$$

- Probability to be found dead at t:

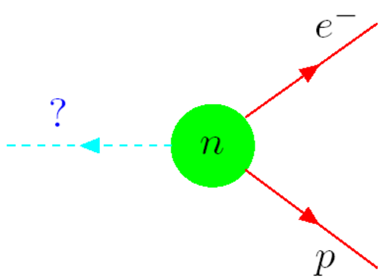
$$P_{AD}(t) = |\langle D|\psi_A(t)\rangle|^2 = \sin^2(2\theta)\sin^2(\tfrac{\Delta E t}{2})$$

Quantum Oscillation phenomena

Weak interaction & neutrino oscillation

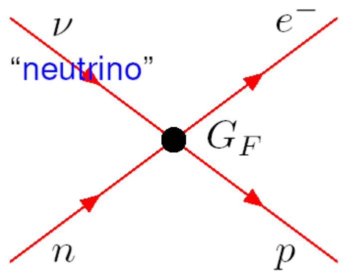
From beta decay to two neutrinos

Wolfgang Pauli (1930) :
"The unseen little neutral one"
in β–decay



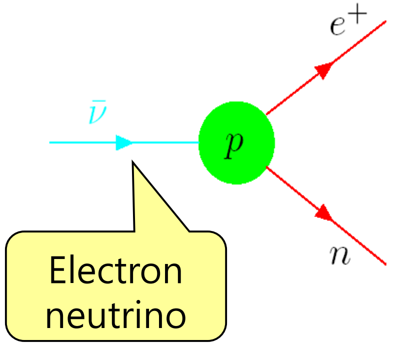
$$A^Z \to A^{Z+1} + e^- + ?$$

Enrico Fermi (1933) :
Theory of Weak Interaction



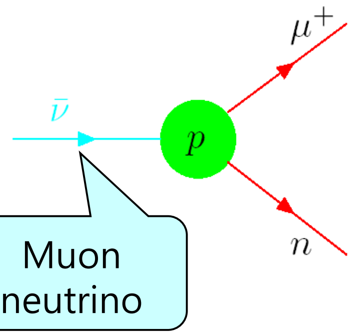
$$G_F \approx 4 \times 10^{-33} cm^2$$

Cowan & Reines (1957) :
"observed" neutrinos



$\Rightarrow$ Nobel prize 1995

Lederman, Schwartz & Steinberger (1961) :
"another type" of neutrinos



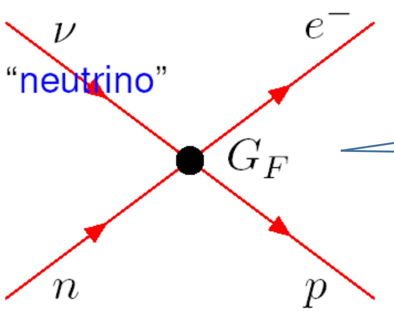
$\Rightarrow$ Nobel prize 1988

$$\begin{pmatrix}\nu_e \\ e\end{pmatrix} \qquad \nu_e \neq \nu_\mu \qquad \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}$$

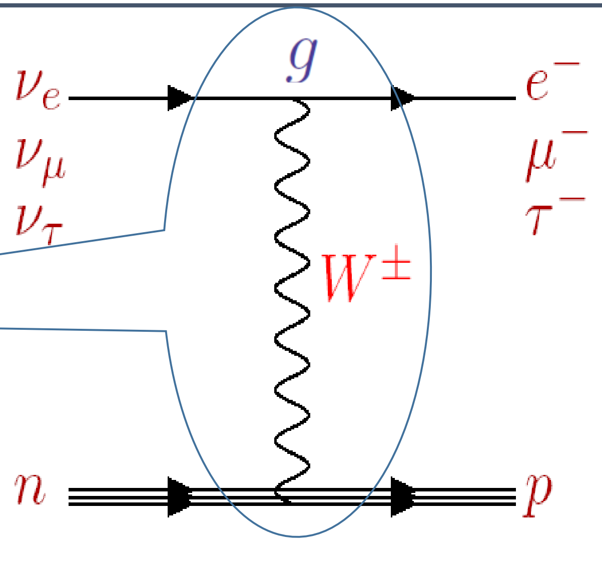
Weak interaction & Higgs mechanism

Enrico Fermi (1933) :

Theory of Weak Interaction

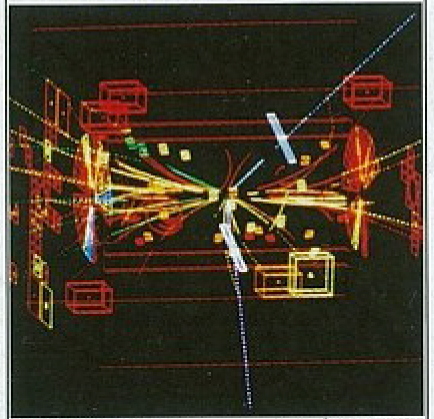


$$G_F \approx 4 \times 10^{-33} cm^2$$



"Charged Current"

Discovery of W and Z - 1983



In 1983 the direct observation of two new particles, the W and Z, was announced. These particles had been predicted by theory and their discovery was the result of a huge effort from the accelerator (the SPS) and the detectors (UA1 and UA2)

$$\boxed{G_F = \frac{g^2}{2\sqrt{2}m_W^2} = \frac{1}{\sqrt{2}v^2}}$$

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

Higgs mechanism

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}}$$

Standard Model

Standard Model

force quanta

γ

$W^{\pm}, Z^0$

G^a

three lepton families

			Q
ν_e	ν_μ	ν_τ	0
e	μ	τ	-1

three quark families

u	c	t	$2/3$
d	s	b	$-1/3$

$\boxed{H}$

Masses

(MeV)

0
80,000
0

?	?	?
0.5	107	1,780
2	1,300	4,300
5	170	174,000

$$m_f = y_f \langle H^0 \rangle$$

Mystery of Masses

Neutrino Oscillation

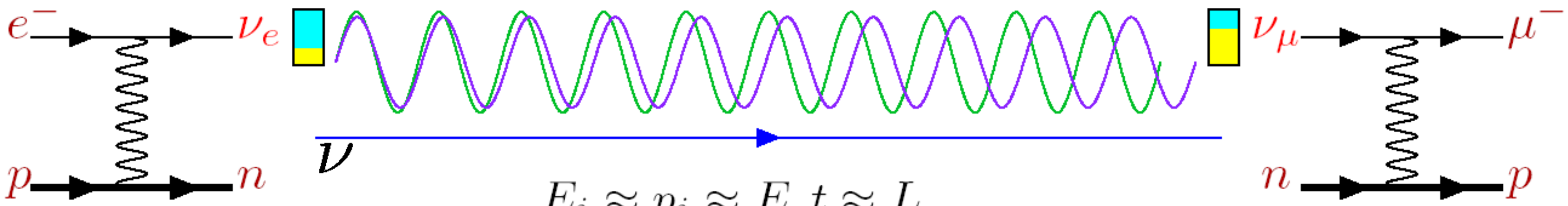
A Quantum Mechanical effect occurring when

interaction eigenstates are different from mass eigenstates

Two neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{pmatrix} m_{ee} & m_{e\mu} \\ m_{e\mu} & m_{\mu\mu} \end{pmatrix} = U_\theta \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} U_\theta^T$$



$$E_i \approx p_i \approx E, t \approx L$$

$$E_i = \sqrt{p_i^2 + m_i^2} \approx E + \frac{m_i^2}{2E}$$

Oscillation probability:

$$\boxed{P_{e\mu} = \sin^2 2\theta \ \sin^2 \left(1.27 \frac{\Delta m_{21}^2(\mathrm{eV}^2) L(\mathrm{km})}{E(\mathrm{GeV})} \right)}$$

Three Neutrino Oscillation

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{\mu 3}|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau 1}|\nu_1\rangle + U_{\tau 2}|\nu_2\rangle + U_{\tau 3}|\nu_3\rangle
\end{aligned}
$$

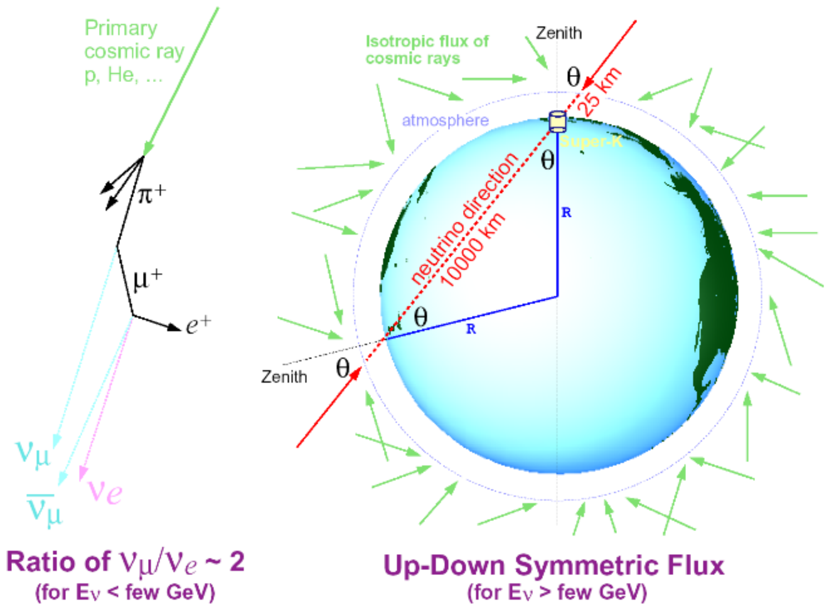
$$
U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\theta_{23}} & s_{\theta_{23}} \\ 0 & -s_{\theta_{23}} & c_{\theta_{23}} \end{pmatrix}}_{\text{atmospheric}}
\underbrace{\begin{pmatrix} c_{\theta_{13}} & 0 & s_{\theta_{13}} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{\theta_{13}} e^{-i\delta} & 0 & c_{\theta_{13}} \end{pmatrix}}_{\text{reactor}}
\underbrace{\begin{pmatrix} c_{\theta_{12}} & s_{\theta_{12}} & 0 \\ -s_{\theta_{12}} & c_{\theta_{12}} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}
\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}}_{\text{Majorana}}
$$

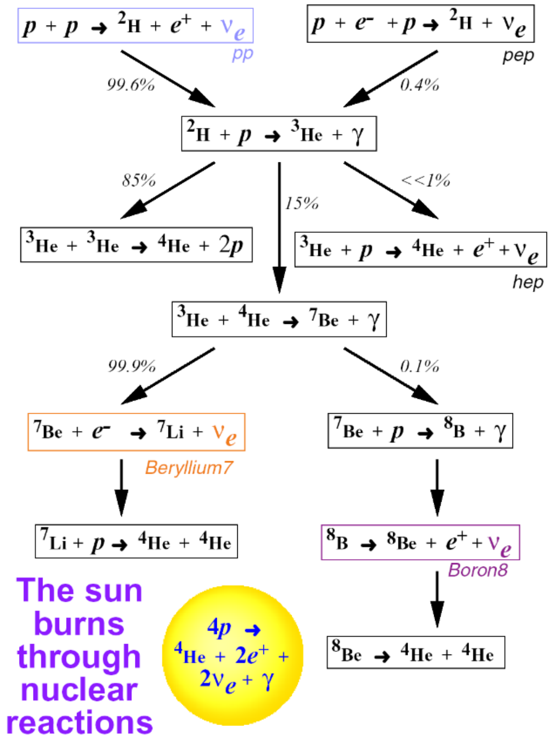
- Three mass eigenvalues: $m_1,\ m_2,\ m_3 \Rightarrow$ Two mass^2 differences

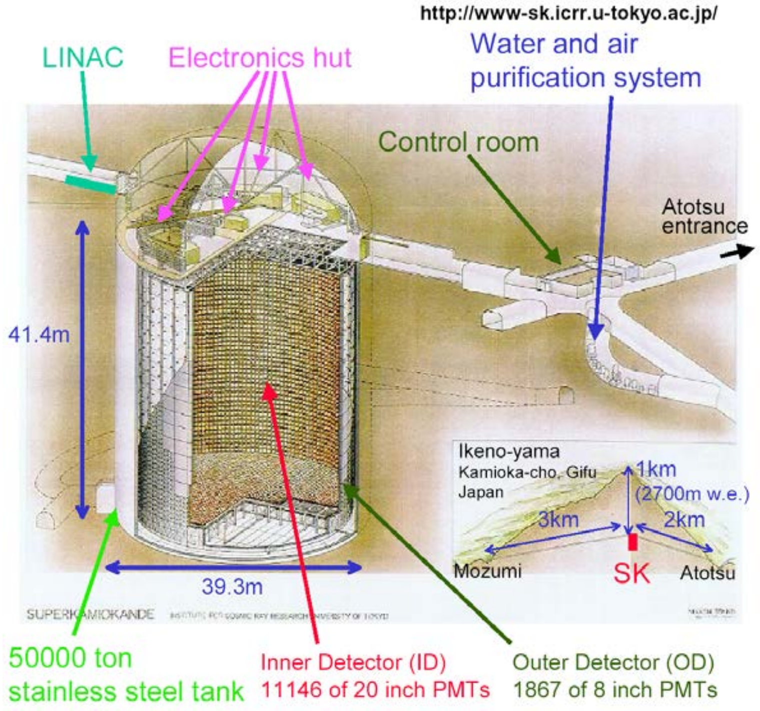
  $\Delta m^2_{31} = m_3^2 - m_1^2$ (atmospheric), $\quad \Delta m^2_{21} = m_2^2 - m_1^2$ (solar)

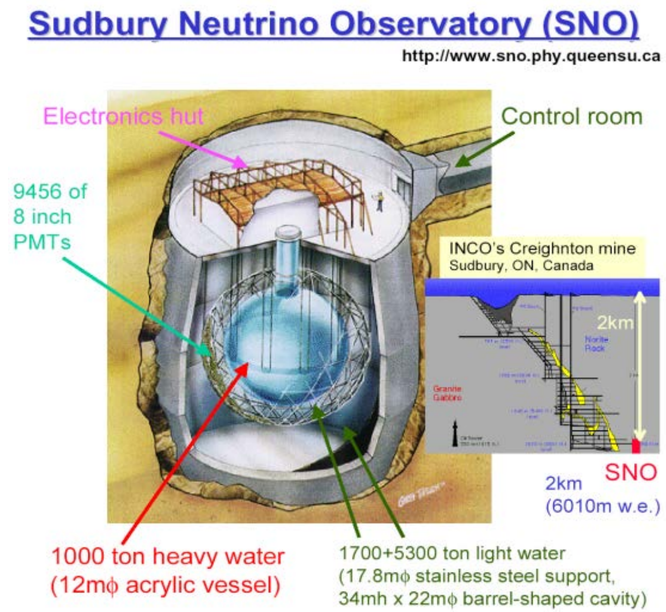
- Three mixing angles and three phases: $\theta_{12},\ \theta_{23},\ \theta_{13};\quad \delta,\ \phi_2,\ \phi_3$

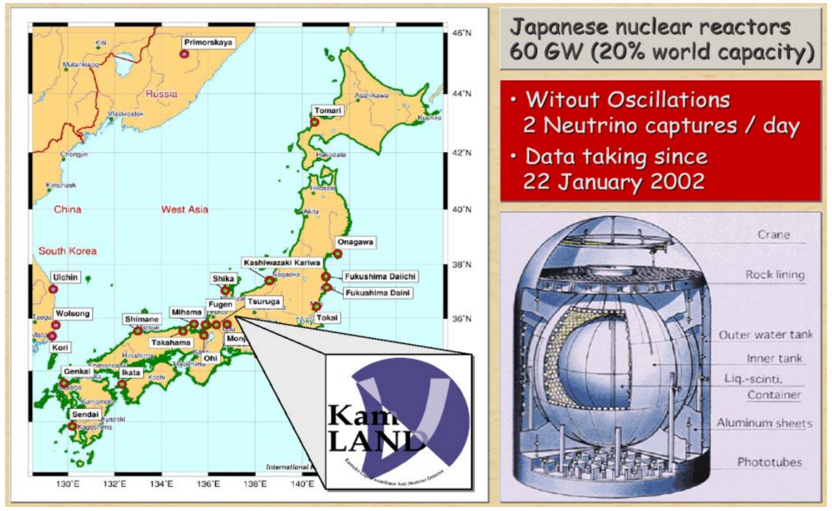
Revolution in 1998 – 2002



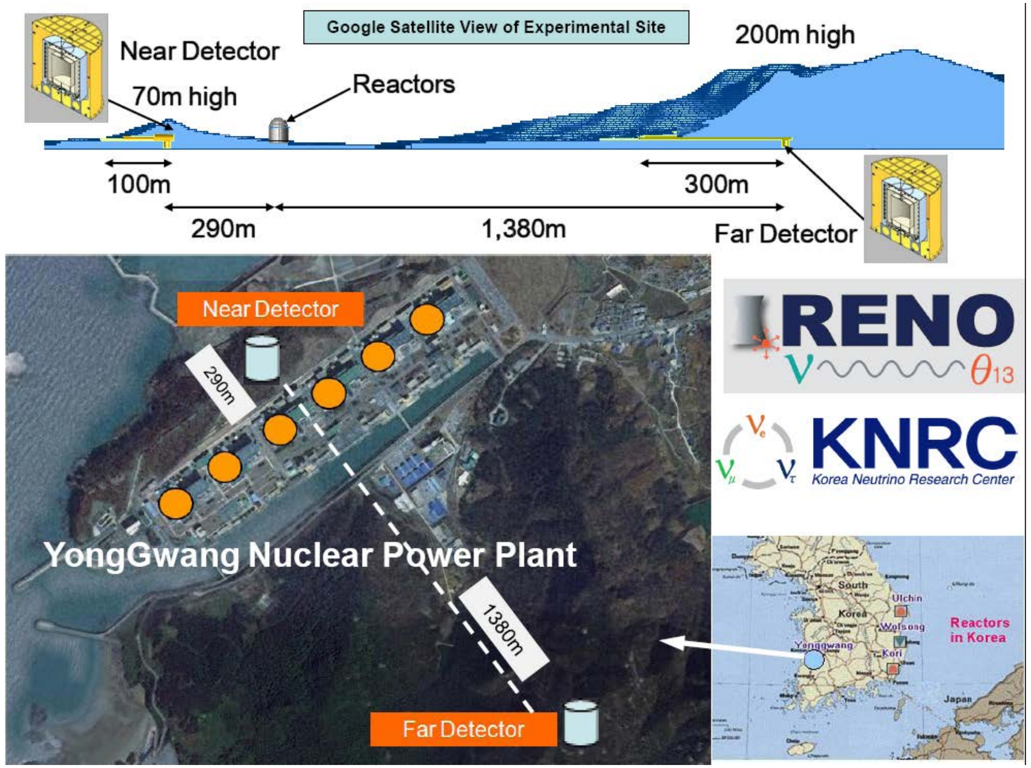








θ_{13} in 2012



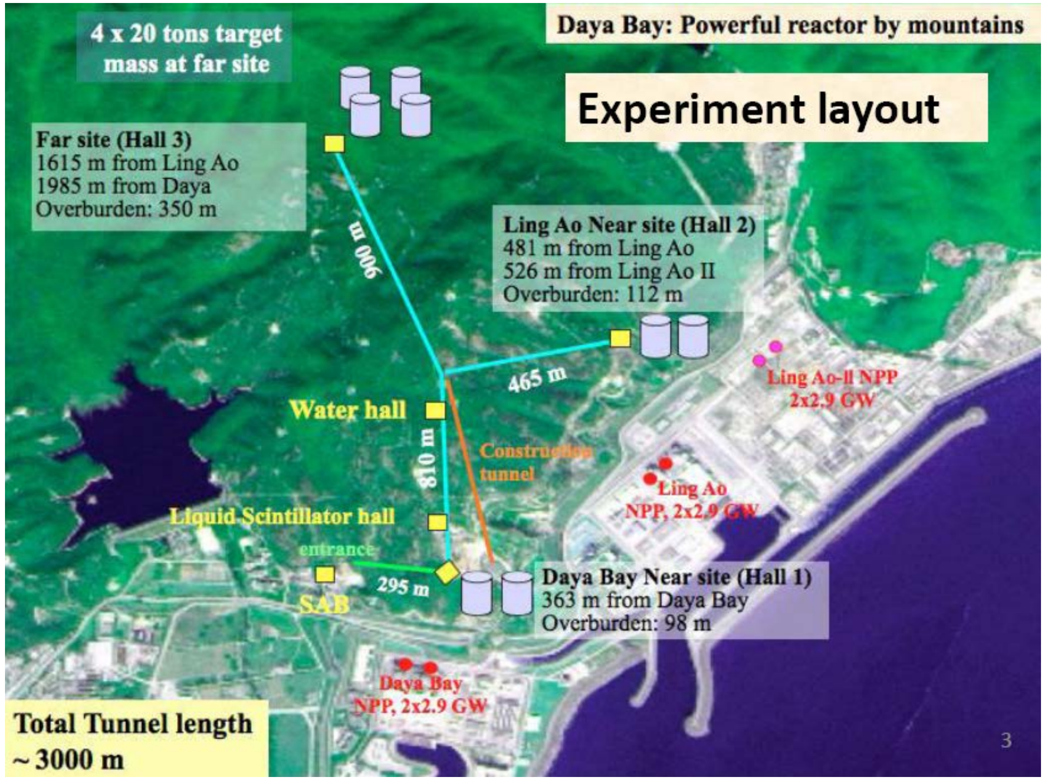
[오늘의 세상] 中 속도전에… 한국, 다 잡은 노벨상감(우주생성 비밀을 풀 소립자 연구) 놓쳤다

이영완 기자 ywlee@chosun.com ▶기자의 다른 기사보기

기사 100자평(0)

입력 : 2012.03.13 03:04 / 수정 : 2012.03.13 19:51

중국, 한국의 5배인 연구원 240명·600억원 투자… 1주일 먼저 연구결과 발표
中, 몇달만에 대역전 – 작년 중순 미국과 손잡고 인재·財力으로 휘몰아치기
땅을 친 한국 연구진 – 주민·환경단체 설득하느라 시설 완공 1년 늦어져 "작년 말까진 우리가 앞섰는데 뒤통수를 세게 맞았다"



Quantum Oscillation phenomena

Origin of neutrino mass & triplet-antitripet oscillation at LHC

EJC & Sharma, arXiv:1206.6278; 1309.6888

Neutrino mass from triplet boson

- Higgs doublet boson: $\begin{pmatrix} H^0 \\ H^- \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{1}{\sqrt{2}}[v + h^0 + iZ^0] \\ W^- \end{pmatrix}$

- Triplet boson: $(\Delta^{++}, \Delta^{+}, \Delta^{0}), \quad \Delta^0 = \frac{1}{\sqrt{2}}[v_\Delta + \Delta_R^0 + i\Delta_I^0]$

- Neutrino/Higgs-triplet interactions:

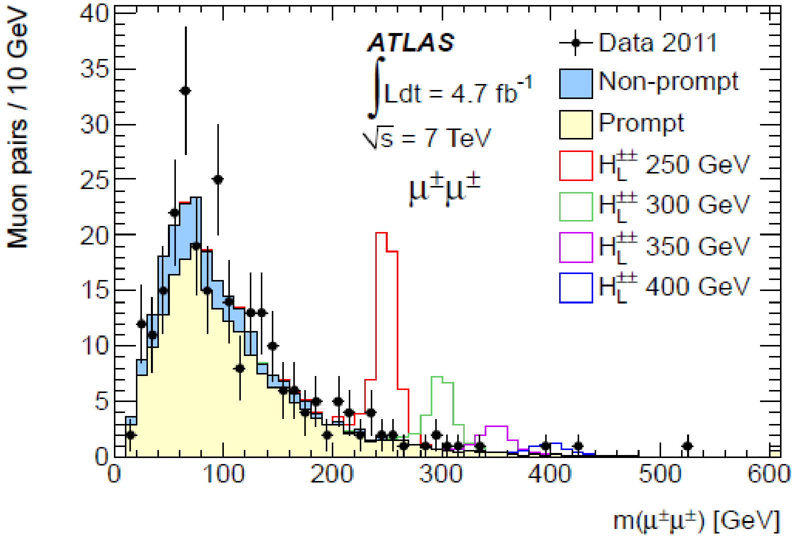
$$\mathcal{H}_\nu = f_{\alpha\beta} \cdot \begin{cases} \Delta^0 \, \nu_\alpha \nu_\beta \\ \Delta^+ (\nu_\alpha l_\beta + \nu_\beta l_\alpha) \\ \Delta^{++} \, l_\alpha l_\beta \end{cases} + \ \mu \cdot \begin{cases} \Delta^0 \, H^0 H^0 \\ \Delta^+ H^0 H^- \\ \Delta^{++} \, H^- H^- \end{cases}$$

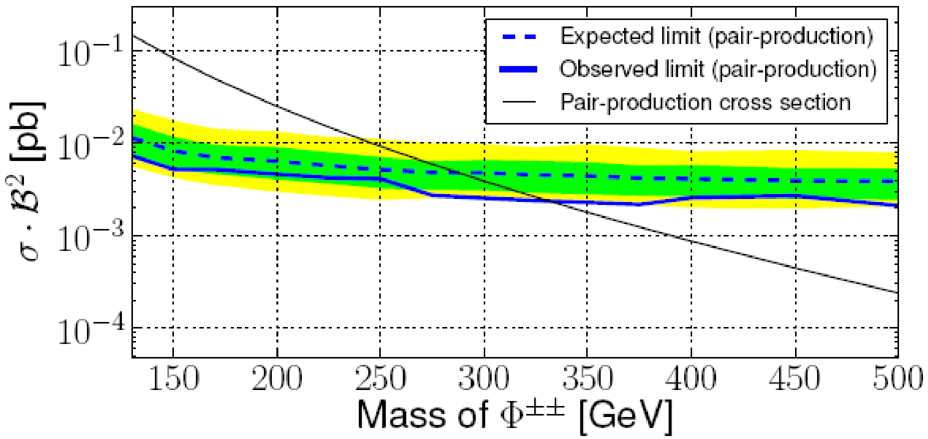
$$\Rightarrow \quad m^\nu_{\alpha\beta} = f_{\alpha\beta} \langle \Delta^0 \rangle \, , \quad \Delta^{\pm\pm} \to l^\pm_\alpha l^\pm_\beta$$

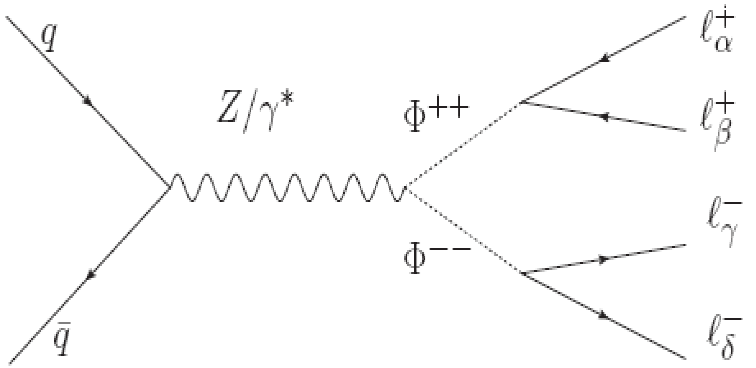
EJC, Lee, Park, 0304069

Triplet boson production & decays

Doubly charged boson search at LHC:
same-sign di-leptons (l+l+ or l-l-)

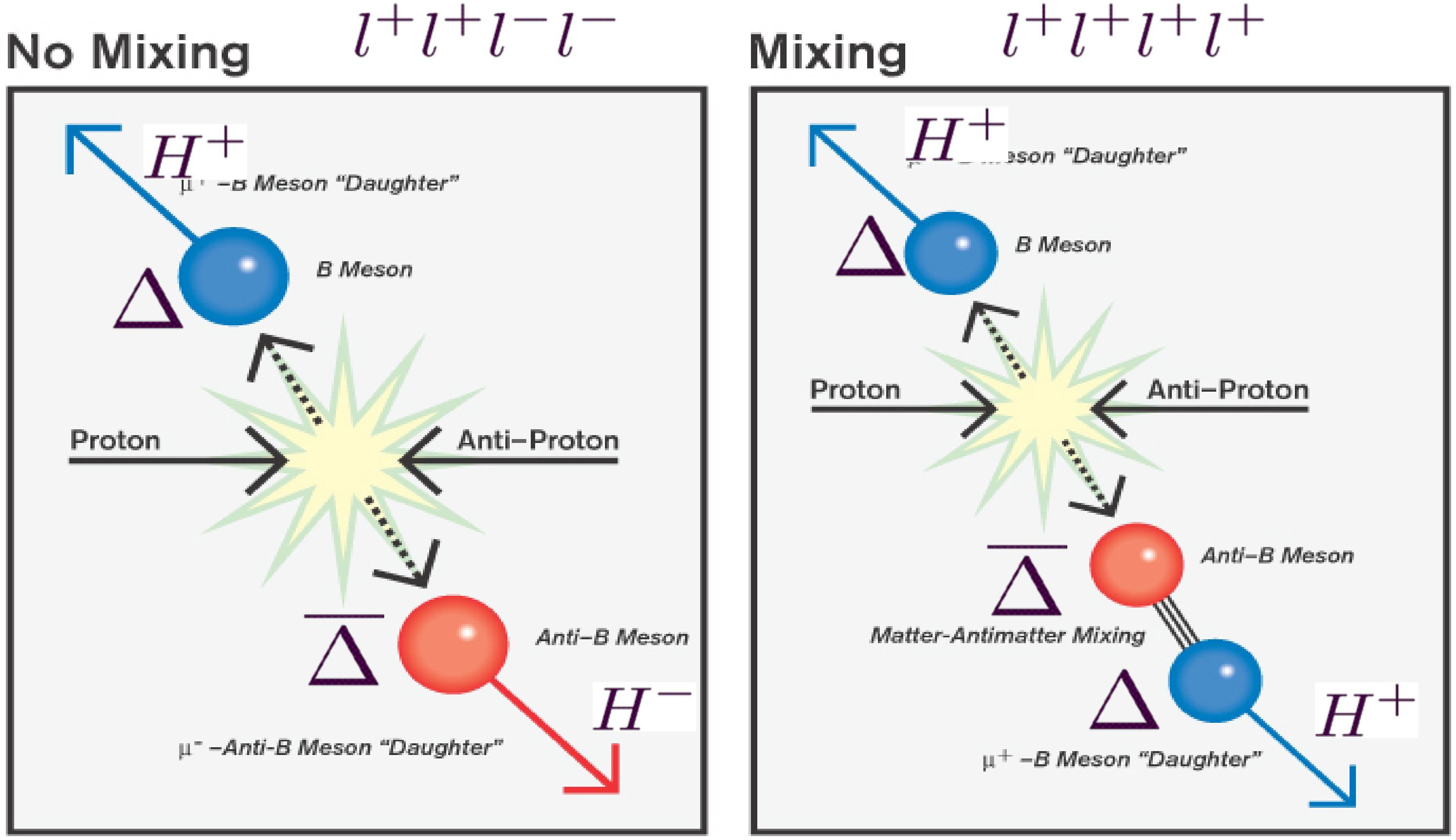






H^0	A^0	H^+	H^{++}
$\to t\bar{t}$	$\to t\bar{t}$	$\to t\bar{b}$	$\to \ell^+\ell^+$
$\to b\bar{b}$	$\to b\bar{b}$	$\to \ell^+\nu$	$\to W^{+*}W^{+*}$
$\to \nu\bar{\nu}$	$\to \nu\bar{\nu}$	$\to W^+Z$	
$\to ZZ$	$\to Zh^0$	$\to W^+h^0$	
$\to h^0h^0$	$\to H^\pm W^{\mp *}$	$\to H^{++}W^{-*}$	
$\to H^\pm W^{\mp *}$			

Triplet-antitriplet mixing



Triplet-antitriplet oscillation

- Initial $\Delta^0 = (H^0 + iA^0)/\sqrt{2}$ evolves as

$$|\Delta(t)\rangle = g_+(t)|\Delta\rangle + g_-(t)|\overline{\Delta}\rangle \qquad [\Gamma = \Gamma_{H^0} = \Gamma_{A^0}]$$

$$g_\pm(t) = \frac{1}{2}e^{-\Gamma t/2}\left(e^{iM_{H^0}t} \pm e^{iM_{A^0}t}\right)$$

- Probabilities of Δ going to Δ or $\bar{\Delta}$:

$$\chi_\pm \equiv \frac{\int_0^\infty dt|g_\pm(t)|^2}{\int_0^\infty dt|g_+(t)|^2 + \int_0^\infty dt|g_-(t)|^2}$$

$$\boxed{\chi_\pm = \begin{cases} \frac{2+x^2}{2(1+x^2)} \\ \frac{x^2}{2(1+x^2)} \end{cases}} \qquad \boxed{x \equiv \frac{\delta M}{\Gamma} = \frac{\tau_{dec}}{\tau_{osc}}}$$

Same-Sign Tetra-Lepton Signature

- Oscillation leads to same-sign doubly-charged pair production:

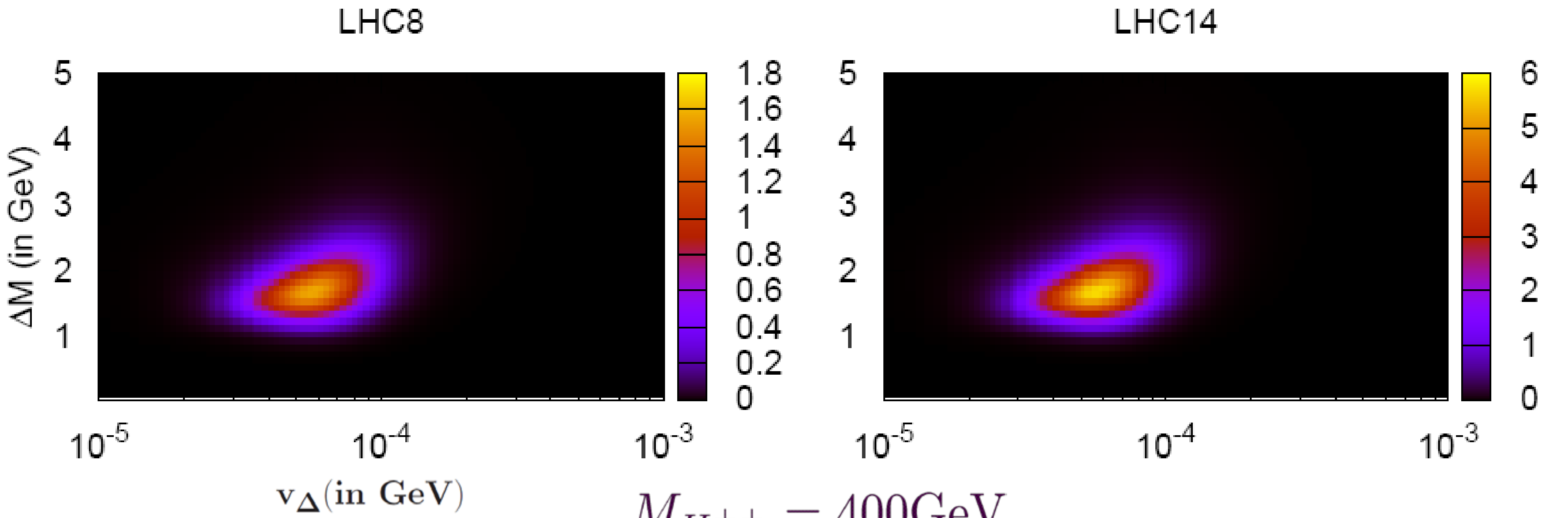
$$pp \to \Delta^0\bar{\Delta}^0 \Rightarrow \Delta^0\Delta^0 \ \to H^+H^+2W^- \ \to H^{++}H^{++}4W^-$$
$$\Delta^+\bar{\Delta}^0 \Rightarrow \Delta^+\Delta^0 \to H^{++}H^+2W^- \to H^{++}H^{++}3W^-$$

- Production cross-section for SS4L:

$$\begin{aligned}
\sigma\left(4\ell^\pm + 3W^{\mp^*}\right) &= \sigma\left(pp \to H^\pm H^0 + H^\pm A^0\right)\left[\frac{x_{HA}^2}{1+x_{HA}^2}\right]\mathrm{BF}(H^0/A^0 \to H^\pm W^{\mp^*}) \\
&\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm}W^{\mp^*})\right]^2\left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm\ell^\pm)\right]^2; \\
\sigma\left(4\ell^\pm + 4W^{\mp^*}\right) &= \sigma\left(pp \to H^0 A^0\right)\left[\frac{2+x_{HA}^2}{1+x_{HA}^2}\frac{x_{HA}^2}{1+x_{HA}^2}\right]\mathrm{BF}(H^0 \to H^\pm W^{\mp^*})\mathrm{BF}(A^0 \to H^\pm W^{\mp^*}) \\
&\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm}W^{\mp^*})\right]^2\left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm\ell^\pm)\right]^2.
\end{aligned}$$

SS4L production rate

- SS4L production including the oscillation factor:



$M_{H^{\pm\pm}} = 400\text{GeV}$

- Benchmark point:

$$v_\Delta = 7 \times 10^{-5}\,\text{GeV}\,, \quad \Delta M = 1.5\,\text{GeV}$$

		Pre-selection	Selection
$15fb^{-1}$	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-NH)	4	3
	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-IH)	9	8
$100fb^{-1}$	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-NH)	110	94
	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-IH)	240	210

Conclusion

- Oscillation – a novel quantum phenomenon.
- Neutrinos exhibit a simple realization of quantum oscillation through which their mass differences and mixing have been measured.
- The origin of neutrino masses is a second "Higgs mechanism" by a triplet boson.
- Another novel phenomenon of triplet-antitriplet oscillation may be revealed by same-sign tetra-lepton signals – stay tuned for next results from LHC14!