Physics beyond the Standard Model

1. Neutrino Mixing
2. Supersymmetry
3. Extra Dimensions

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1. Neutrino Oscillation

For massive neutrinos one could introduce in analogy to the quark mixing a mixing matrix describing the relation between mass and flavor states:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 3} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\underbrace{\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3}$$

Constant for massless ν: mixing is question of convention

Massive neutrinos develop differently in time.

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle e^{-iE_i t} = |\nu_i(0)\rangle e^{-i(p_i + \frac{m_i^2}{2p_i})}$$

for masses $m_i << E_i$:

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

→ there will be a mixing of the flavor states with time.

$$|\nu(t)\rangle_\alpha = \sum_i U_{\alpha i} e^{-iE_i t} |\nu_i(0)\rangle = \sum_{i,\beta} U_{\alpha i} U^*_{\beta i} e^{-iE_i t} |\nu_\beta\rangle$$

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1.1 Mixing in the 2 neutrino case

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Definite momentum p; same for all mass eigenstate components

$$E_i = \sqrt{p^2 + m_i^2} = p + \frac{m_i^2}{2p}$$

$$E_2 - E_1 = \frac{m_1^2 - m_2^2}{2p} \approx \frac{\Delta m^2}{2E}$$

(assuming p_i is the same)

$t = L/\beta$ w/ $\beta \approx 1$:

$$(E_2 - E_1)t = \frac{\Delta m^2}{2E} L$$

Time development for an initially pure $|\nu_\alpha>$ beam:

$$\left|\nu_\alpha(t)\right\rangle = \cos\theta\, e^{-iE_1 t}\left|\nu_1\right\rangle + \sin\theta\, e^{-iE_2 t}\left|\nu_2\right\rangle$$
$$= \left[\cos^2\theta\, e^{-iE_1 t} + \sin^2\theta\, e^{-iE_2 t}\right] \cdot \left|\nu_\alpha\right\rangle$$
$$+ \left[\cos\theta \sin\theta (e^{-iE_1 t} - e^{-iE_2 t})\right] \cdot \left|\nu_\beta\right\rangle$$

Mixing probability:

$$P(\nu_\alpha \to \nu_\beta, t) = \left|\left\langle \nu_\beta \middle| \nu_\alpha(t)\right\rangle\right|^2 = 2(\cos\theta\sin\theta)^2\left[1 - \cos^2\frac{E_2 - E_1}{2} t\right]$$

$$P(\nu_\alpha \to \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right) = \sin^2 2\theta \sin^2\left(\frac{1.27 \cdot \Delta m^2[eV]}{4E[GeV]} L[km]\right)$$

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How to search for neutrino oscillation ?

$$P(\nu_\alpha \to \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

- Disappearance:
  (I) With known neutrino flux: Measurement of flux at distance L: reactor experiments (sun). → Solar neutrinos, atmospheric neutrinos

  (II) Measure neutrino flux at position 1 and verify flux after distance L. → Reactor neutrinos
- Appearance:
  Use neutrino beam of type A and search at distance L for neutrinos of type B.

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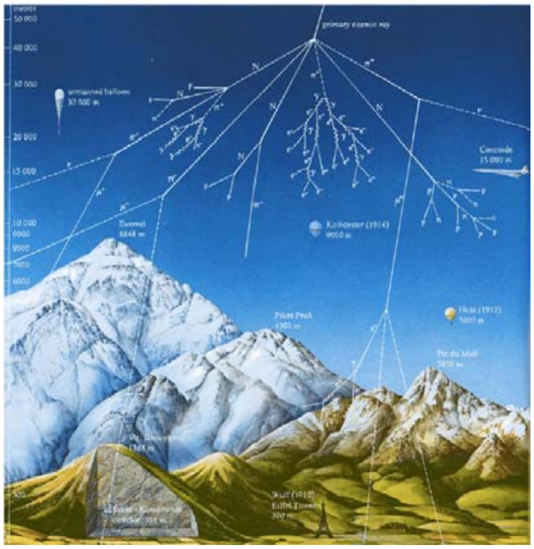
1.2 Atmospheric neutrinos



Cosmic radiation: Air shower

$$p + N \rightarrow \pi^{\pm}, K^{\pm}$$

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

$$R = \frac{\nu_{\mu} + \bar{\nu}_{\mu}}{\nu_{e} + \bar{\nu}_{e}} = 2$$

Exact calculation: R=2.1
(E_{ν}<1GeV)

(For larger energies R>2.1)

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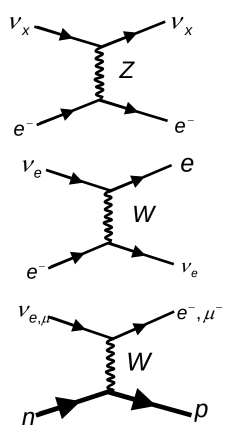
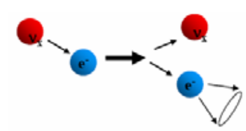
Neutrino detection with water detectors [E_{ν}~O(GeV)]

Water = "active target" (Cherenkov effect)

Elastic scattering ES

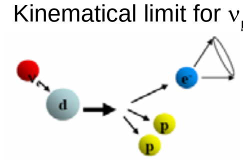
Charged current CC





Cherenkov Light

Kinematical limit for ν_{μ}: E_{ν}>m_{μ}



Detection of Cherenkov photons: Photo multiplier

Experiments: (Super)-Kamiokande

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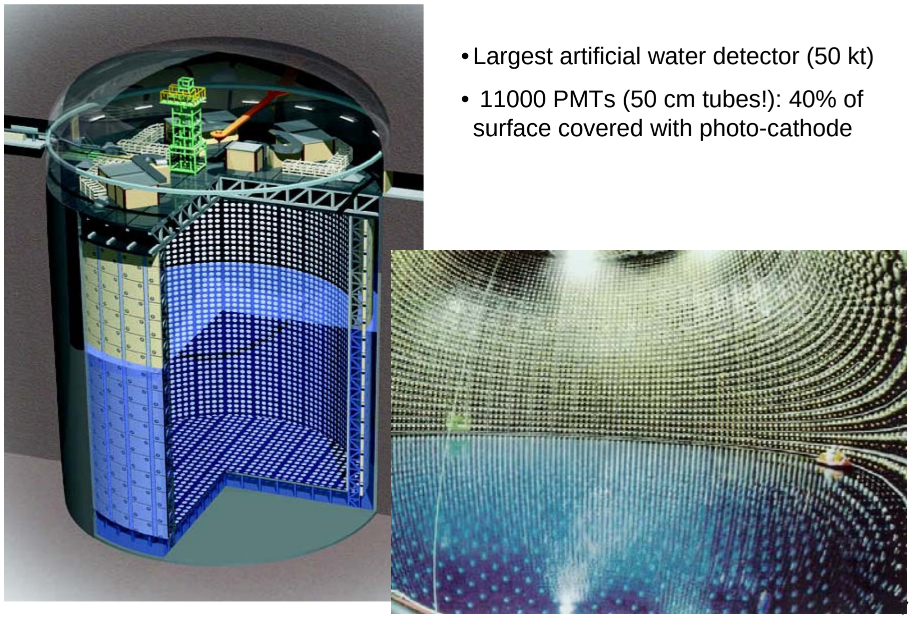
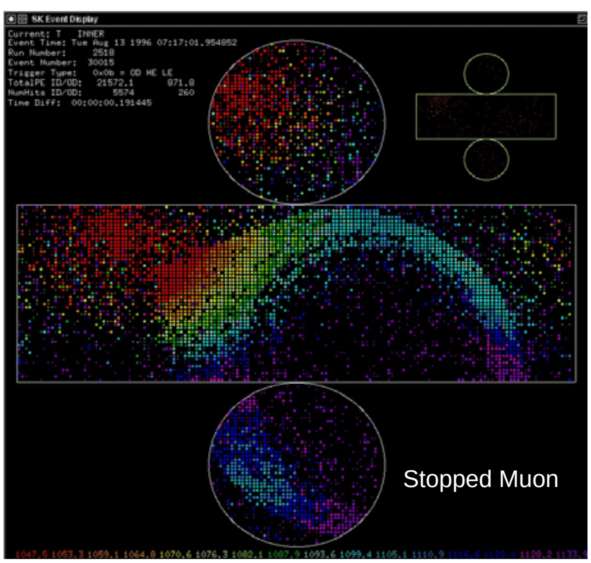
J. Pawlowski / U. Uwer

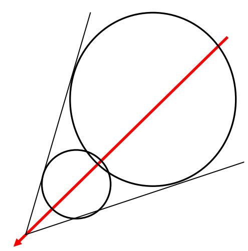
Super-Kamiokande



- Largest artificial water detector (50 kt)
- 11000 PMTs (50 cm tubes!): 40% of surface covered with photo-cathode

$\nu_\mu \to \mu$ stopped





Cherenkov cone:

$$\cos\theta = \frac{1}{\beta n}$$

$$\Leftrightarrow \theta = 42^o \; (\beta = 1)$$

Experiment can distinguish electron and muon events, can measure energy

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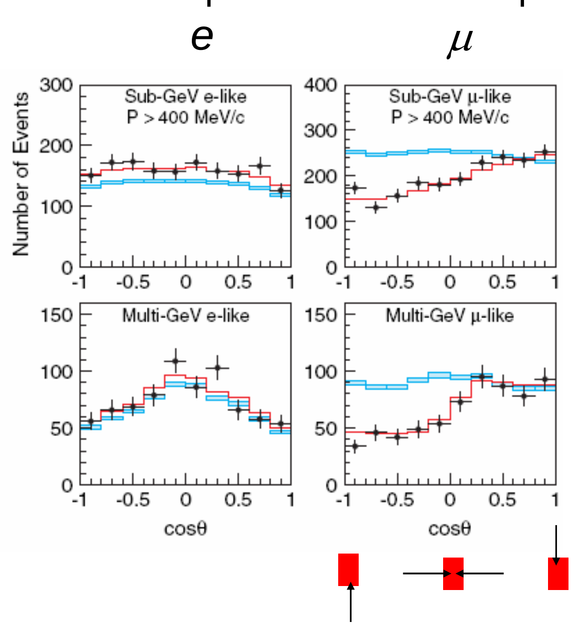
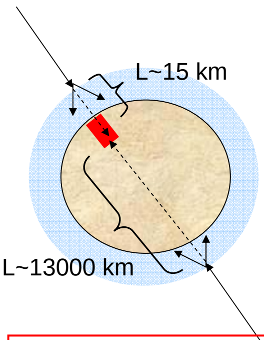
Oscillation pattern from atmospheric neutrinos



Theoretical predicton
- w/o oscillation
- w/ oscillation



ν_μ deficit depends on angle

ν_e flux okay

Oscillation: $\nu_\mu \leftrightarrow \nu_\tau$

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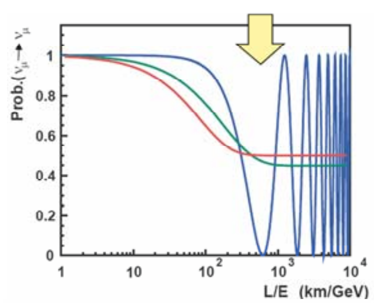
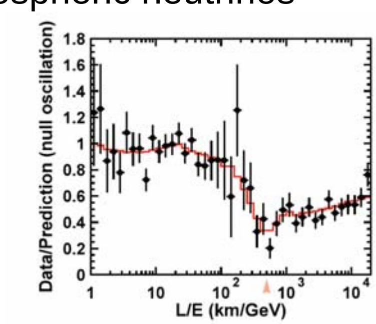
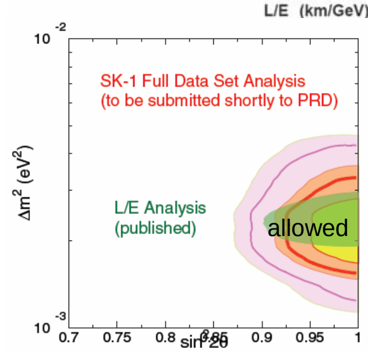
Oscillation pattern of atmospheric neutrinos







Neutrino 2004

oscillation dip seen at ~500 km/GeV

$\nu_\mu \leftrightarrow \nu_\tau$ mixing of atmos. neutrinos

$\Delta m^2 = (2.4 \pm 0.4) \times 10^{-3}\,\mathrm{eV}$

$\sin^2 2\theta > 0.92$ @ 90% C.L.

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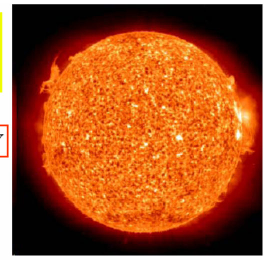
1.3 Solar Electron Neutrino Problem

Neutrino production

ν_e are abundant by-products of nuclear fusion in the sun



$p + p \to {}^2H + e^+ + \nu_e + 0.42 MeV$ — "pp" 99.75%

$p + e^- + p \to {}^2H + \nu_e + 1.44 MeV$ — "pep" 0.25%

$^2H + p \to {}^3He + \gamma + 5.49\ MeV$

- 86%: $^3He + {}^3He \to \alpha + 2p + 12.86 MeV$
- 14%: $^3He + \alpha \to {}^7Be + \gamma + 1.59 MeV$
  - "⁷Be" 99.89%: $^7Be + e^- \to {}^7Li + \gamma + \nu_e + 0.8617 MeV$
    - $^7Li + p \to \alpha + \alpha + 17.35 MeV$
  - 0.11%: $^7Be + p \to {}^8B + \gamma + 0.14 MeV$
    - "⁸B" 0.11%: $^8B \to {}^8Be + e^+ + \nu_e + 14.6 MeV$
      - $^8Be \to \alpha + \alpha + 3 MeV$
- "hep" $2.4 \cdot 10^{-5}$: $^3He + p \to \alpha + e^+ + \nu_e$

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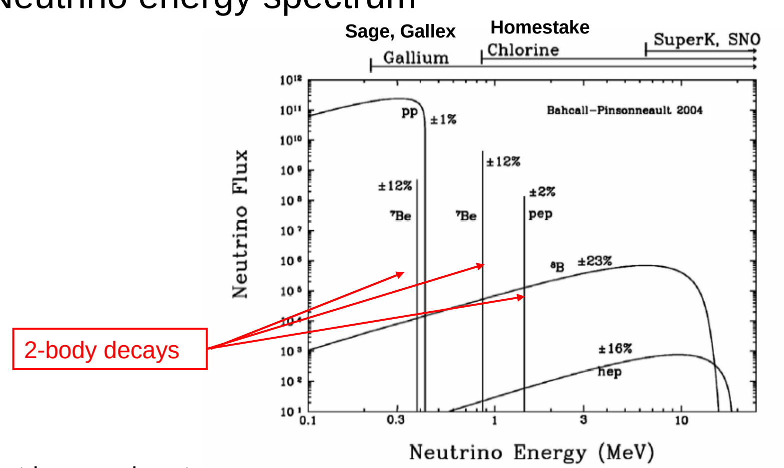
Neutrino energy spectrum



Neutrino experiments:

Cl_2 detectors	$\nu_e + {}^{37}Cl \to {}^{37}Ar + e$, $^{37}Ar \to {}^{37}Cl$ (EC)	$E_\nu > 0.8$ MeV
Ga detectors	$\nu_e + {}^{71}Ga \to {}^{71}Ge + e$	$E_\nu > 0.2$ MeV
H_2O detectors	Elastic scattering: $\nu_e + e \to \nu_e + e$	$E_\nu > 5$ MeV (detection)

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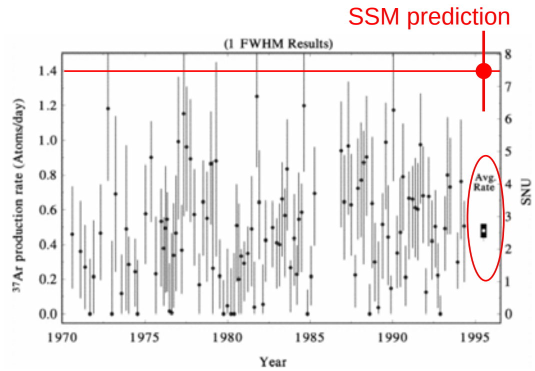
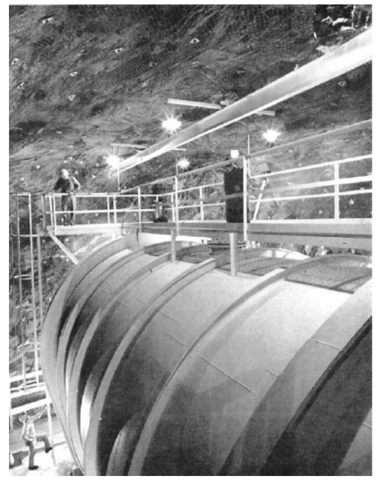
Radio-chemical experiments:

Homestake, SAGE, GALLEX

- Homestake mine, 1400 m underground
- 615 t of C_2Cl_4 (perchloroethilene) = 2.2×10^{30} atoms of ^{37}Cl
- Use ^{36}Ar and ^{38}Ar to carry-out the few atoms of ^{37}Ar (~ 1 atom/day)
- Count radioactive ^{37}Ar decays

Homestake Cl_2 experiment





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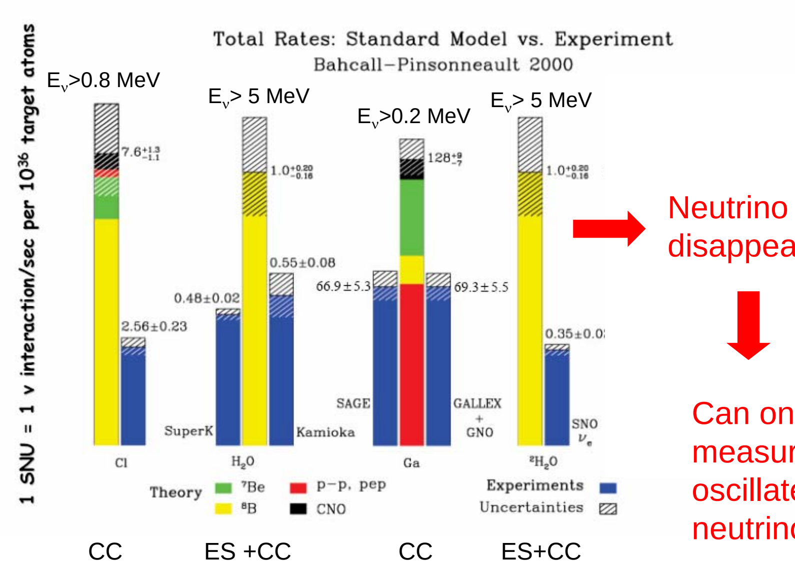
Solar Neutrino Problem: Experimental summary



Neutrino disappearance

Can one measure the oscillated neutrinos ??

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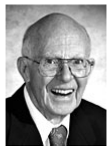
The Nobel Prize in Physics 2002

Raymond Davis Jr.	Masatoshi Koshiba	Riccardo Giaconi

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

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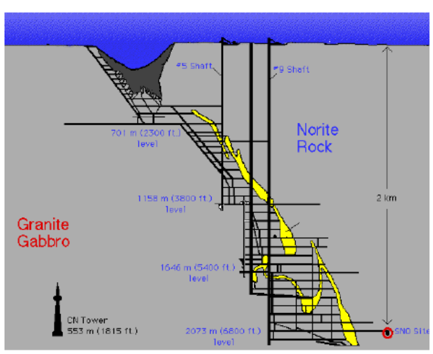
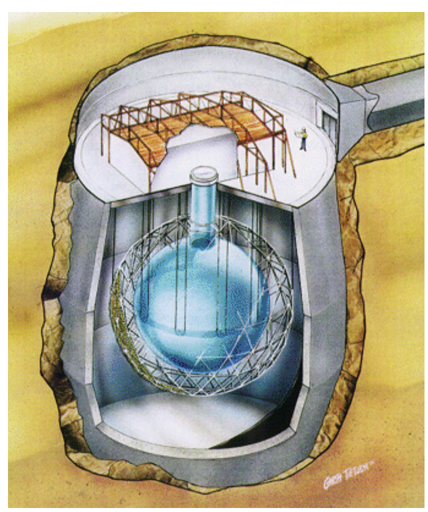
Sudbury Neutrino Observatory

➡ Try to measure the “oscillated” neutrinos

- 6 m radius transparent acrylic vessel
- 1000 t of heavy water (D_2O)
- 9456 inward looking photo multipliers
- Add 2 t of NaCl to detect neutrons





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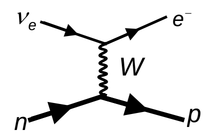
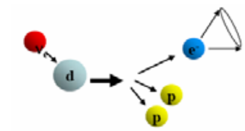
Solar Neutrino (^{8}B) detection with SNO

Charged current

$\sigma(\nu_\mu) = \sigma(\nu_\tau) = 0$
(kinematics)

$\phi_{CC} = \phi_{\nu_e}$



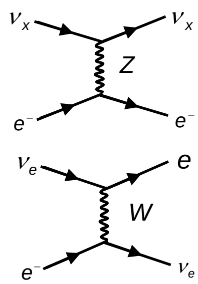


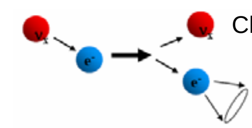
Cherenkov Light

Elastic scattering

$0.154 \cdot \sigma(\nu_e) =$
$\sigma(\nu_\mu) = \sigma(\nu_\tau)$

$\phi_{ES} = \phi_{\nu_e} + (\phi_{\nu_\mu} + \phi_{\nu_\tau})/6$



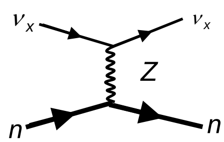


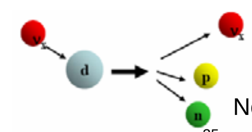
Cherenkov Light

Neutral current

$\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

$\phi_{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$





Neutron
^{35}Cl $(n,\gamma)^{36}$Cl

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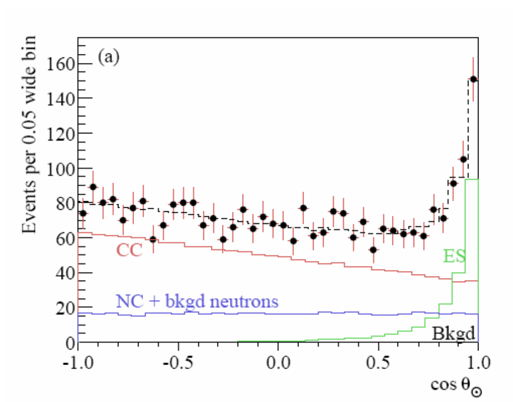
How to distinguish CC, ES and NC events:



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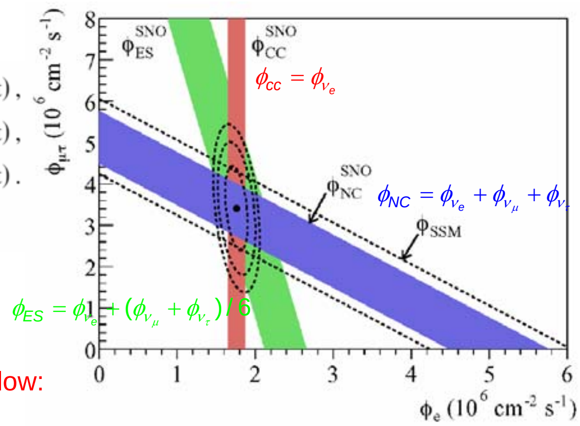
SNO Evidence for Neutrino Oscillation

$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}),$$
$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(\text{stat})^{+0.12}_{-0.12}(\text{syst}),$$
$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}).$$

Phys. Rev.Lett. 89 (2002) 011301



Electron neutrino flux is too low:

$P_{\nu_e\nu_e} = (35 \pm 2)\%$

Total flux of neutrinos is correct!!

Interpreted as $\nu_e \leftrightarrow \nu_\mu$ or ν_τ oscillation

But in case of simple "vacuum oszillation": $P_{\nu_e\nu_e} \geq 1 - \frac{1}{2}\sin^2 2\theta \geq 50\%$?

Vacuum oscillation effect is enhanced by matter inside the sun: MSW effect.

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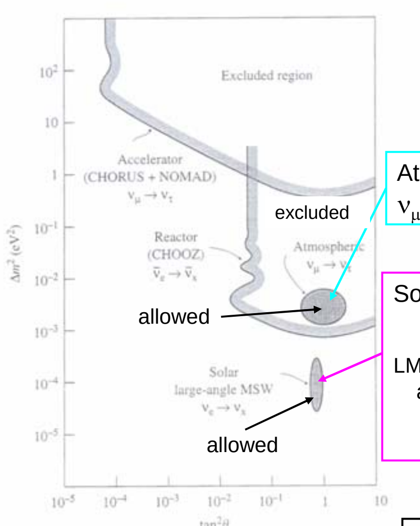
1.4 Status of oscillation measurements



Atmos $\nu_\mu \to \nu_x$

$\Delta m^2 = (2.4 \pm 0.4) \times 10^{-3}$ eV
$\sin^2 2\theta > 0.92$ @ 90% C.L.

Solar+KamLAND $\nu_e \to \nu_x$ ← Long baseline "many" reactors experiment

LMA = large mixing angle + matter effect : **MSW effect*)**

$\Delta m^2 = (8.2 \pm 0.6) \times 10^{-5}$ eV
$\sin^2 2\theta \approx 0.83$

⇒ Different oscillation pattern for different neutrinos – what can we learn about the masses ??

**) Mikhaev, Smirnov (1986), Wolfenstein (1976)*

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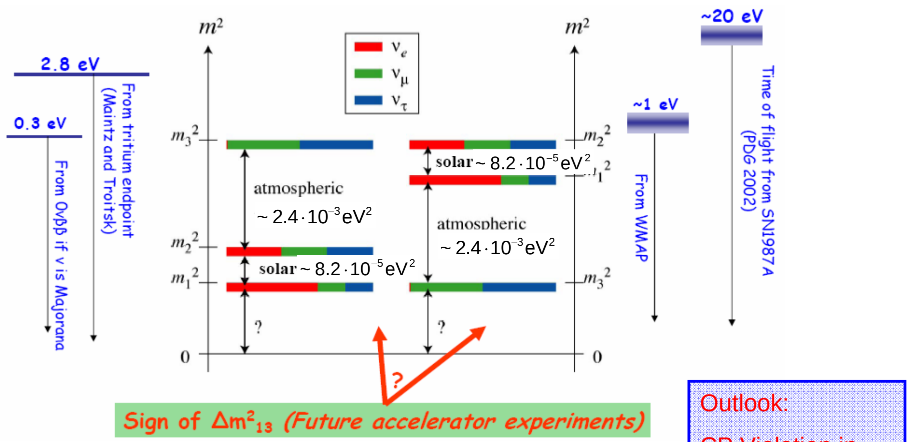
1.5 Neutrino masses

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

$\theta_{12} \equiv \theta_{sol}$ $\theta_{23} \equiv \theta_{atm}$ $\theta_{13} \approx 0$



Absolute neutrino masses are not known !

Outlook:

CP Violation in Neutrino Mixing ?

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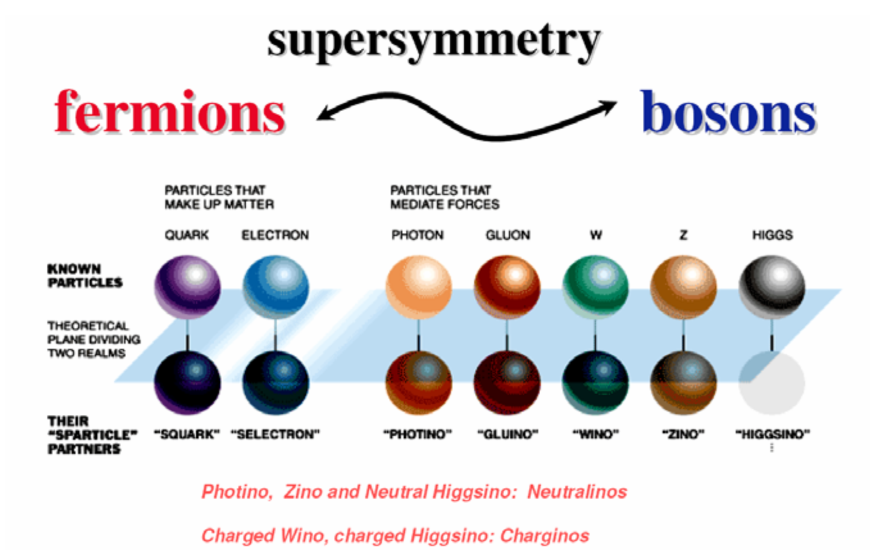
2. SUSY



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SUSY Multiplets

Chirales Supermultiplet

Superfeld		Ladung $SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Fermion Ψ Spin 1/2	Skalar Φ Spin 0
Quark, Squark (3 Familien)	Q_i	3	2	1/6	(u_L, d_L)	$(\tilde{u}_L, \tilde{d}_L)$
	$\bar{U}_i$	$\bar{3}$	1	-2/3	u_R^t	$\tilde{u}_L^C$
	$\bar{D}_i$	$\bar{3}$	1	1/3	d_R^t	$\tilde{d}_L^C$
Leptonen, Sleptonen (3 Familien)	L_i	1	2	-1/2	(ν, e_L)	$(\tilde{\nu}_L, \tilde{e}_L)$
	$\bar{E}_i$	1	1	1	e_R^t	$\tilde{e}_L^C$
Higgs, Higgsino	H_d	1	2	-1/2	$(\tilde{H}_d^0, \tilde{H}_d^-)$	(H_d^0, H_d^-)
	H_u	1	2	1/2	$(\tilde{H}_u^+, \tilde{H}_u^0)$	(H_u^+, H_u^0)

Eich Supermultiplet

Superfeld	Ladung $SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Boson A^μ Spin 1	Fermion λ Spin 1/2
Gluon, Gluino	8	1	0	g	$\tilde{g}$
W Bosonen, Winos	1	3	0	$W^\pm W^0$	$\tilde{W}^\pm \tilde{W}^0$
B Boson, Bino	1	1	0	B^0	$\tilde{B}^0$

Mit elektroschwacher Symmetriebrechung mischen W^0, B^0 zu Z^0 und γ.
Die analoge Gaugino Mischung ergibt die Eigenzustände Zino ($\tilde{Z}$) und Photino ($\tilde{\gamma}$)

Mixing of "inos"

- Four neutralinos $\tilde{\chi}_i^0 \Leftrightarrow \tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0$.
- Two charginos $\tilde{\chi}_i^\pm \Leftrightarrow \tilde{W}^\pm, \tilde{H}^\pm$.

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Extended Higgs sector:

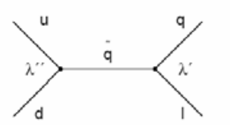
Two doublets: $\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ $\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$

Vacuum expectation values (VEV): $\tan\beta = \frac{\upsilon_u}{\upsilon_d}$

After electroweak symmetry breaking:
h, H, $H^\pm$, A (5 physical states), m_h<~130 GeV

R-Parity:

To avoid proton decay: $p \to e^+ \pi^0$



New conserved quantum number:

R-Parity: $R = (-1)^{3(B-L)+2S}$

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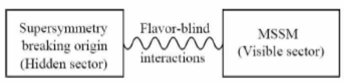
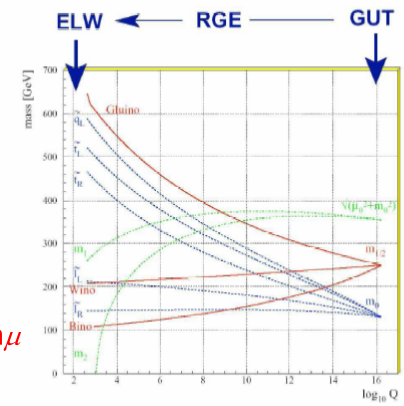
Constraint Minimal Supersymmetric Standard Model (CMSSM)

MSSM has 105 new parameters: Use models (e.g. **mSUGRA**) to relate parameters at very high scale. ➡ 5 parameters left:

mSUGRA

SUSY is broken by gravity





m_0, $m_{1/2}$, A_0, $\tan\beta$, $\text{sign}\,\mu$

Assume universal masses at GUT scale:
m_0 – common mass of scalars (squarks, sleptons, Higgs bosons)
$m_{1/2}$ – common mass of gauginos and higgsinos
A_0 – common trilinear coupling
$\tan\beta$ – ratio of Higgs vacuum expectation values
$\text{sign}\,\mu = \pm 1$ – sign of μ SUSY conserving Higgsino mass parameter

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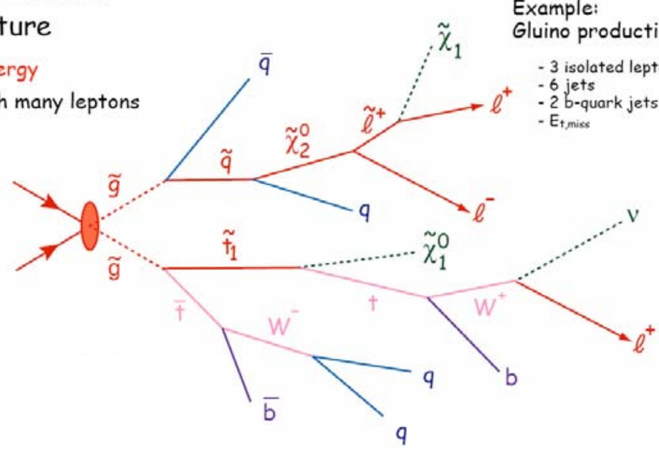
2.1 SUSY Production at LHC

mostly through gluino and squark production

Pairwise production
Clear Signature
- missing energy
- events with many leptons and jets.

Example:
Gluino production
- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{T,miss}$



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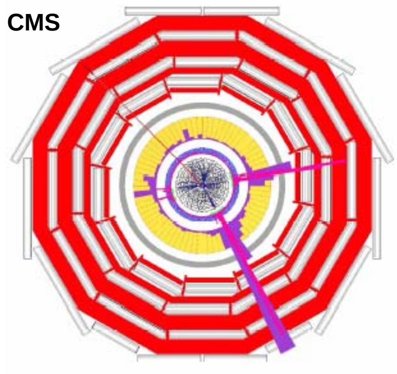
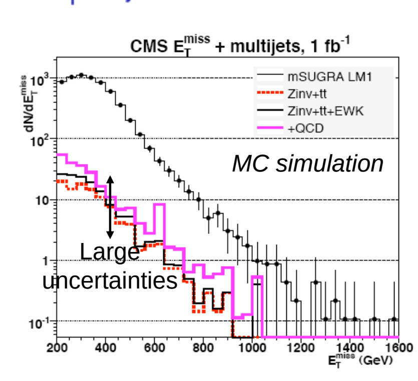
Missing E_T as signature of new physics



$E_T(1) = 330$ GeV $E_T(2) = 140$ GeV

$E_T(3) = 60$ GeV $E_T^{miss} = 360$ GeV

E_T^{miss} +jets



Model: Gluino = 600 GeV

Neutralino = 100 GeV

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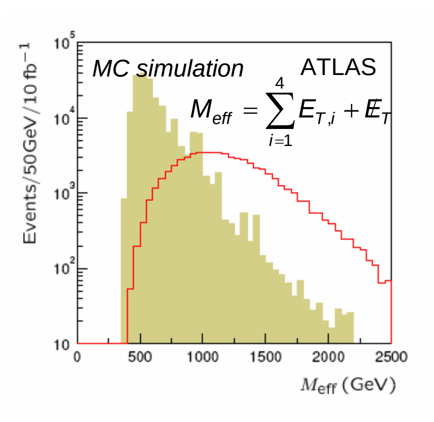
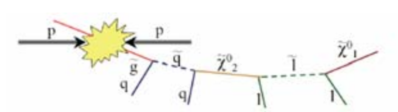
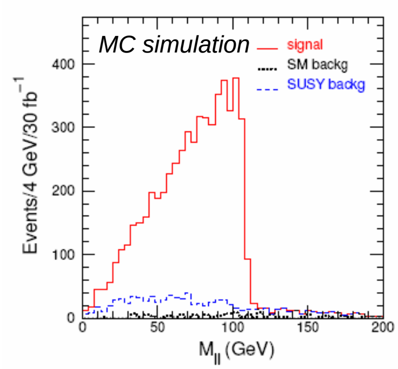
Properties of SUSY Particles

4 jet events + missing E_T



Effective mass approximates SUSY particle mass scale.





Endpoint of di-lepton mass:

$$M_{\ell\ell}^{max} = \frac{1}{M_{\tilde{\ell}}}\sqrt{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}}^2)(M_{\tilde{\ell}}^2 - M_{\tilde{\chi}_1^0}^2)}$$

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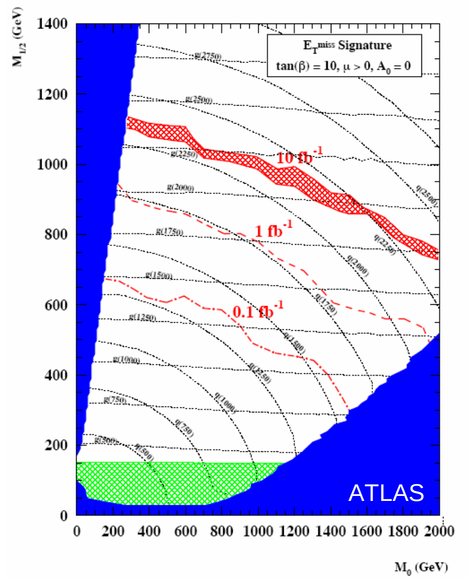
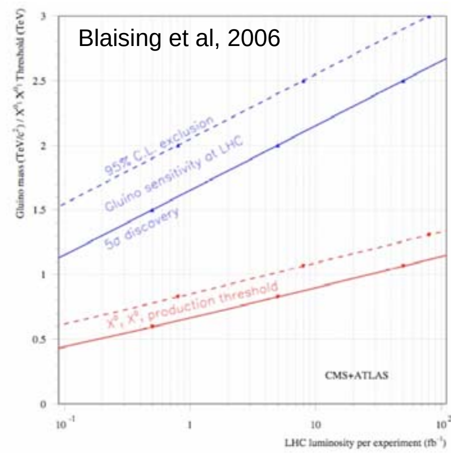
2.2 Prospects for SUSY discovery at LHC





If exist, SUSY particles up to a mass scale of 1 – 2 TeV will be discovered.

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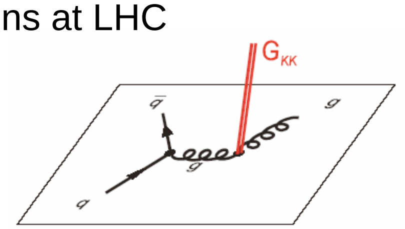
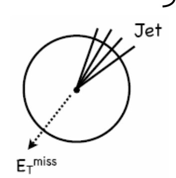
3. Search for Extra Dimensions at LHC

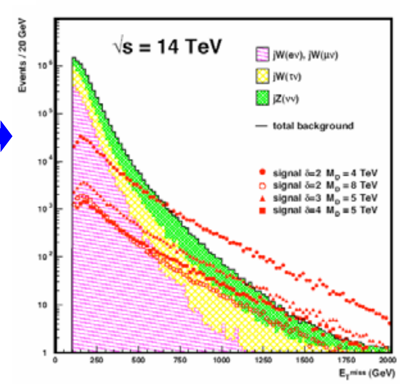
Gravitons leave our 3D-brane and are not detected,



Clear signature:

- High-energetic monojet
- + missing energy





Consequences of extra-dimensions: mini black holes.

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