Physics beyond the Standard Model

1. Neutrino Mixing
2. Supersymmetry
3. Extra Dimensions

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 $m_i \ll E_i$:

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

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

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

1.1 Mixing in the 2 neutrino case

Definite momentum p; same for all mass eigenstate components

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

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

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

(assuming p_i is the same)

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

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

Mixing probability:

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

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

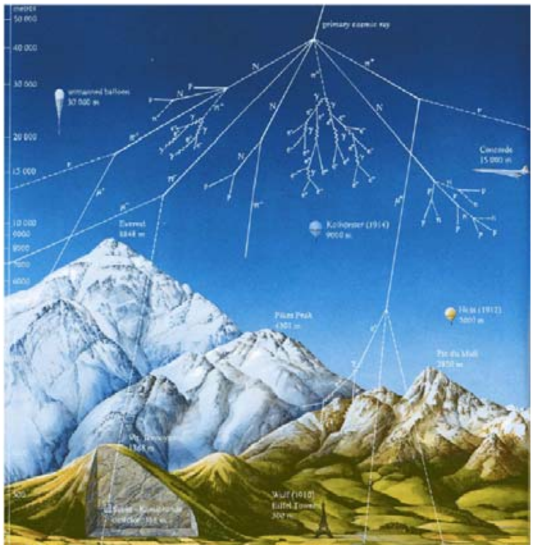
How to search for neutrino oscillation ?

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

- Disappearance:
  (I) With known neutrino flux: Measurement of flux at distance L: reactor experiments (sun).

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

1.2 Atmospheric neutrinos



Cosmic radiation: Air shower

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

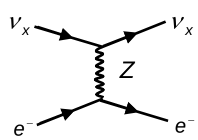
$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

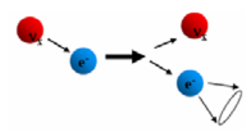
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

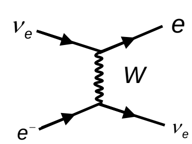
Neutrino detection with water detectors [E_{ν}~O(GeV)]

Water = "active target"

Elastic scattering ES

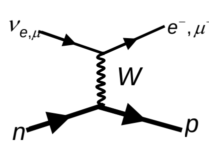




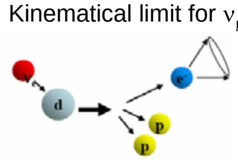


Charged current CC

➡ dominates for μ



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

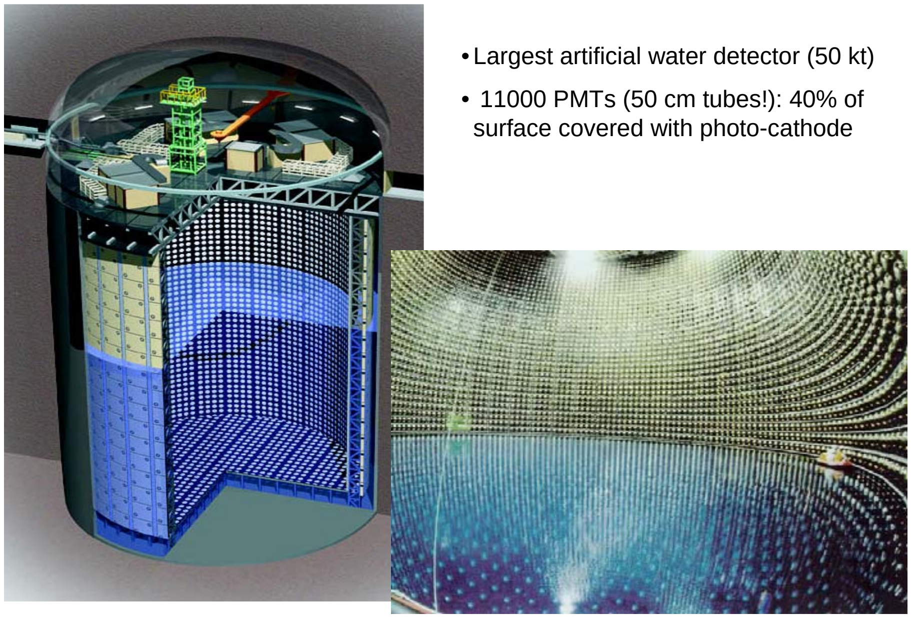


Detection of Cherenkov photons: Photo multiplier

Experiments: (Super)-Kamiokande

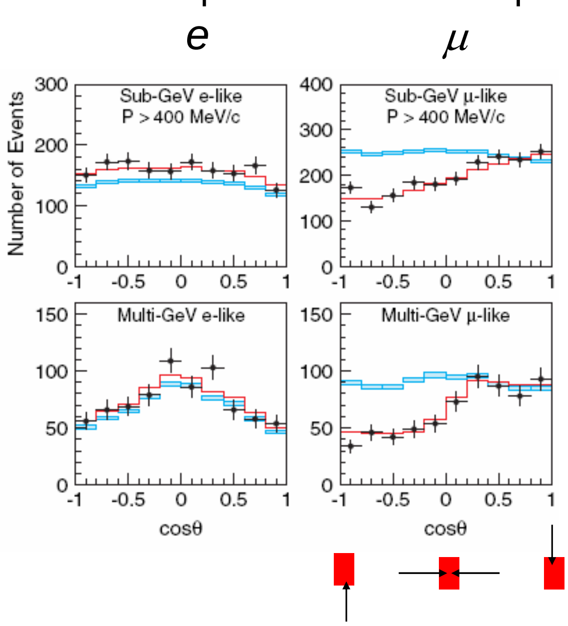
Standard Model: Flavor mixing and CP violation

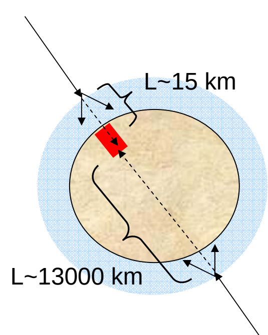
Super-Kamiokande



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

Oscillation pattern from atmospheric neutrinos





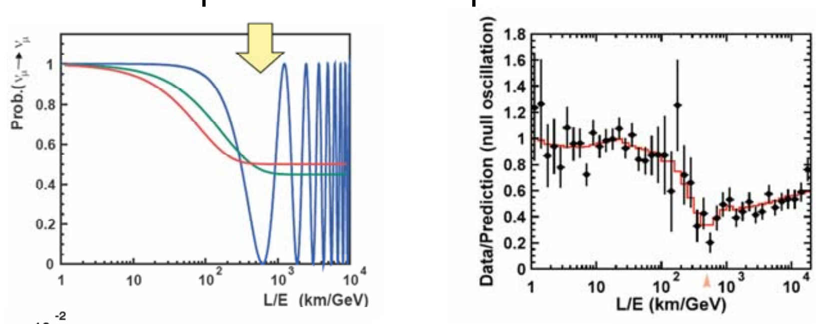
ν_μ deficit depends on angle

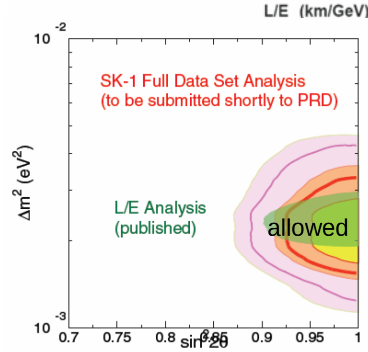
ν_e flux okay

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

Standard Model: Flavor mixing and CP violation

Oscillation pattern of atmospheric neutrinos





Neutrino 2004

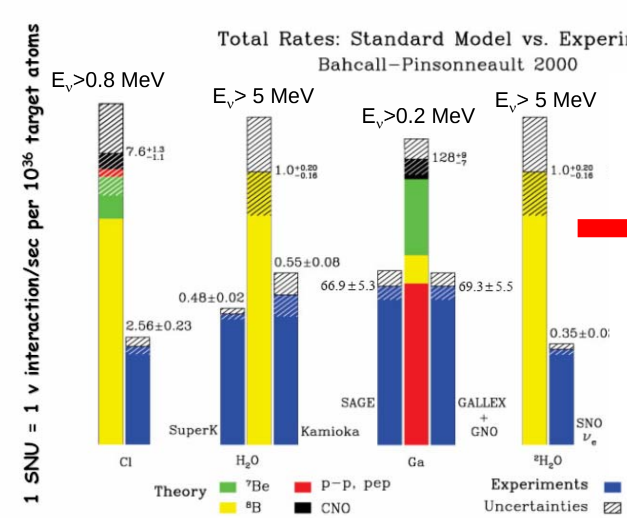
oscillation dip seen at ~500 km/GeV

$\nu_\mu \leftrightarrow \nu_\tau$ 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.*

1.3 Solar Electron Neutrino Problem



CC ES CC ES

Neutrino disappearance

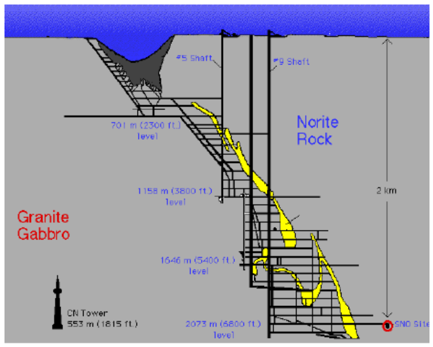
Can one measure the oscillated neutrinos ??

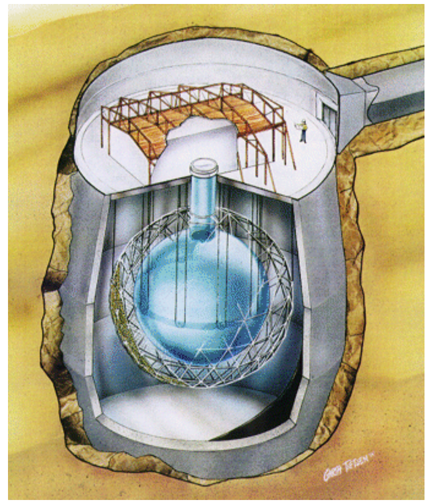
J. Pawlowski / U. Uwer

Standard Model: Flavor mixing and CP violation

Sudbury Neutrino Observatory

- 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



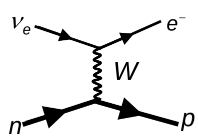


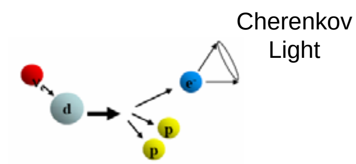
Neutrino detection with SNO

Charged current

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

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

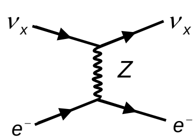


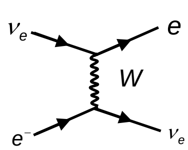


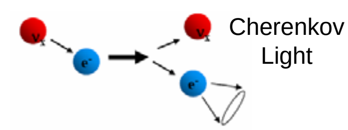
Elastic scattering

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

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



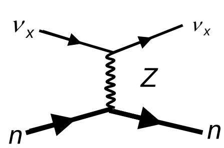


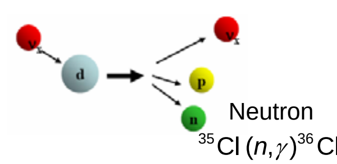


Neutral current

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

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



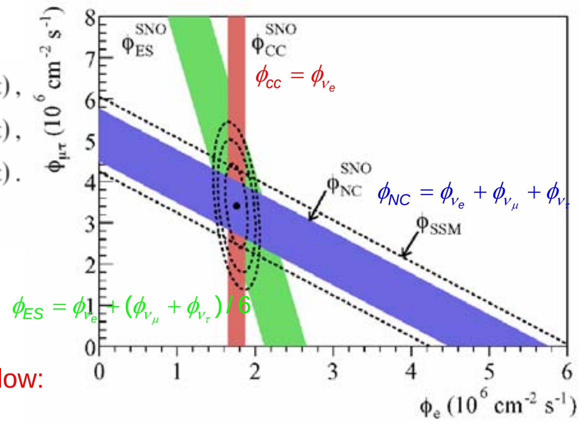


Standard Model: Flavor mixing and CP violation

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:

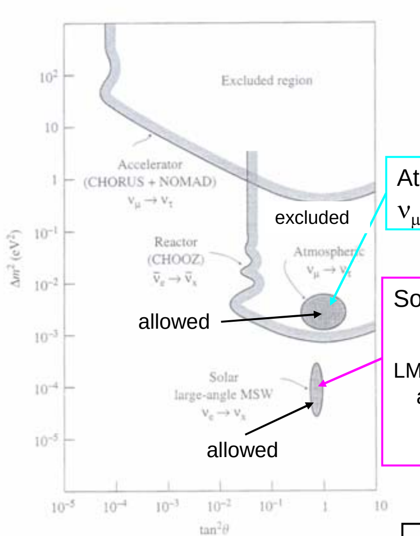
$P_{\nu e \nu e} = (35 \pm 2)\%$

Total flux of neutrinos is correct!!

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

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

1.4 Status of oscillation measurements



Atmos
$\nu_\mu \to \nu_x$

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

Solar+KamLAND ← Long baseline "many" reactors experiment

$\nu_e \to \nu_x$

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

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

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

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

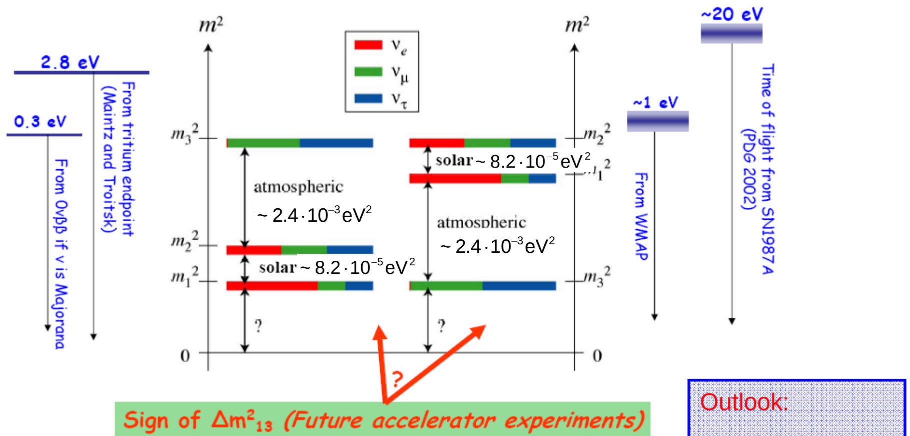
Standard Model: Flavor mixing and CP violation

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

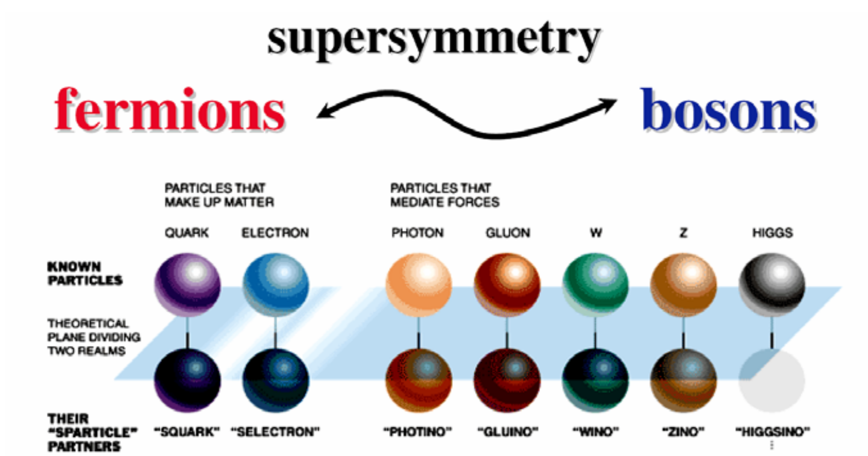
$\theta_{12} \equiv \theta_{sol}$ $\theta_{23} \equiv \theta_{atm}$ $\theta_{13} \approx 0$



Absolute neutrino masses are not known !

Outlook:
CP Violation in Neutrino Mixing ?

2. SUSY



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Standard Model: Flavor mixing and CP violation

SUSY Multiplets

Chirales Supermultiplet

Superfeld		Ladung			Fermion Ψ	Skalar Φ
		$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Spin 1/2	Spin 0
Quark, Squark	Q_i	3	2	1/6	(u_L, d_L)	$(\tilde{u}_L, \tilde{d}_L)$
(3 Familien)	$\bar{U}_i$	$\bar{3}$	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	L_i	1	2	-1/2	(ν, e_L)	$(\tilde{\nu}_L, \tilde{e}_L$
(3 Familien)	$\bar{E}_i$	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			Boson A^μ	Fermion λ
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Spin 1	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 $\tilde{\chi}_i^\pm \Leftrightarrow \tilde{W}^\pm, \tilde{H}^\pm$.

Extended Higgs sector:

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

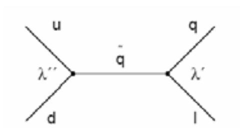
Vacuum expectation values (VEV): $\tan\beta = \frac{\upsilon_u}{\upsilon_d}$

→ 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:

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

Constraint Minimal Supersymmetric Standard Model (CMSSM)

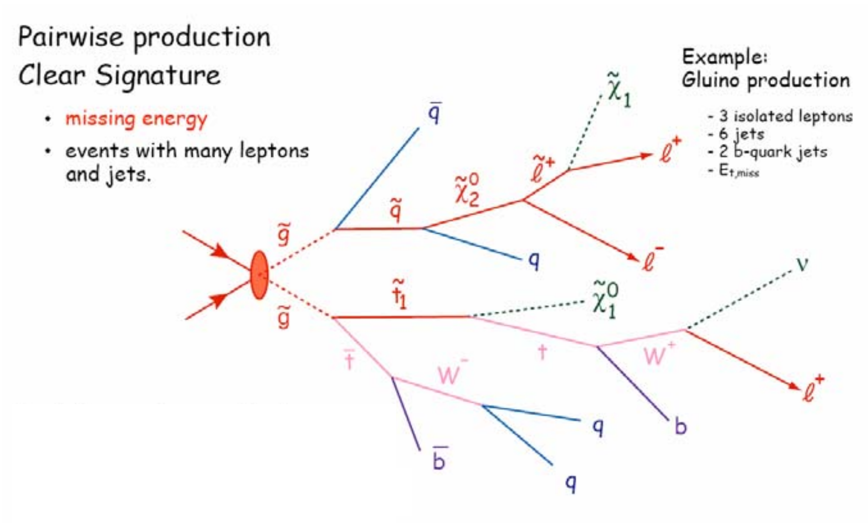
MSSM has 105 new parameters: Use constraint models (e.g. **mSUGRA**) to related parameters at very high scale. → 5 parameters left:

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

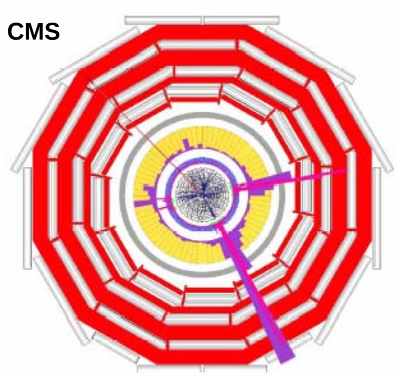
Standard Model: Flavor mixing and CP violation

2.1 SUSY Production at LHC

mostly through gluino and squark production



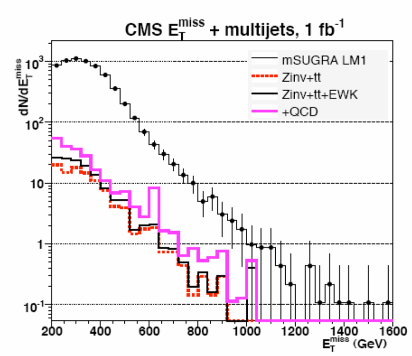
Missing E_T as canonical signature of new physics



$E_T(1) = 330\text{ GeV}$ $E_T(2) = 140\text{ GeV}$

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

E_T^{miss} +jets



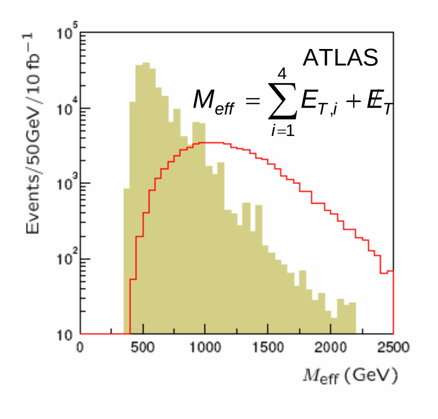
Model: Gluino = 600 GeV

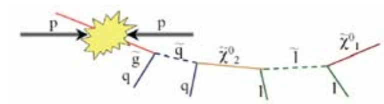
Neutralino = 100 GeV

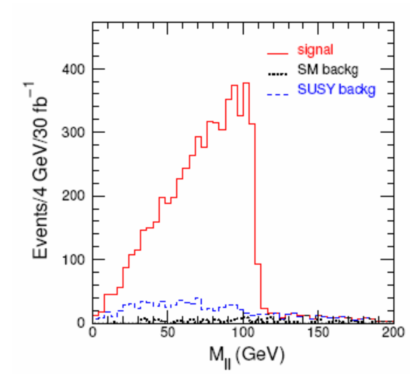
Standard Model: Flavor mixing and CP violation

Properties of SUSY Particles

4 jet events + missing E_T





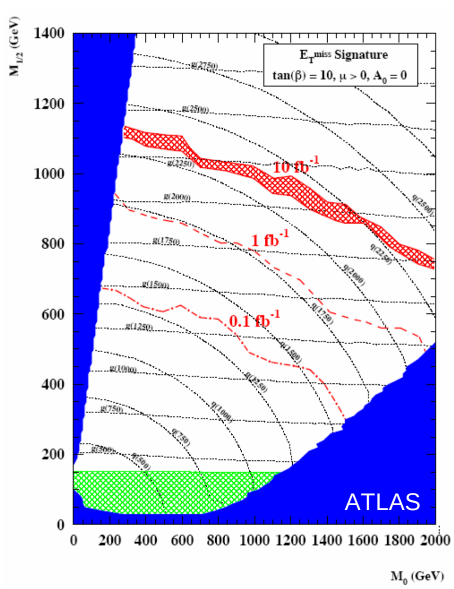


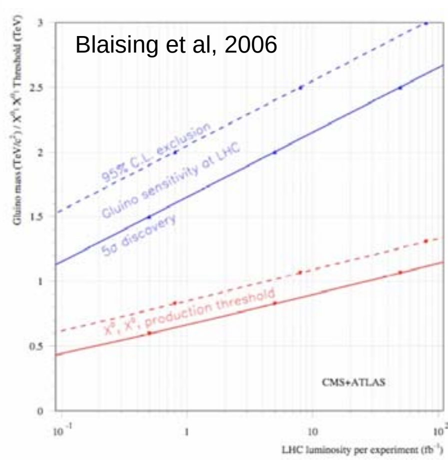
Effective mass approximates SUSY particle mass scale.

Endpoint of di-lepton mass:

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

2.2 Prospects for SUSY discovery at LHC

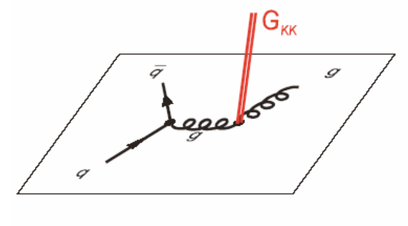




If, exists SUSY particles up to a mass scale of 1 – 2 TeV will be discovered.

3. Search for Extra Dimensions at LHC

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



Clear signature:

- High-energetic monojet
- + missing energy