Detecting oscillations of atmospheric neutrinos in ATLAS

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in collaboration with M. Lindner
based on an idea by F. Vanucchi

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Outline

1. The ATLAS detector
2. Expected sensitivities
3. Comments and conclusions

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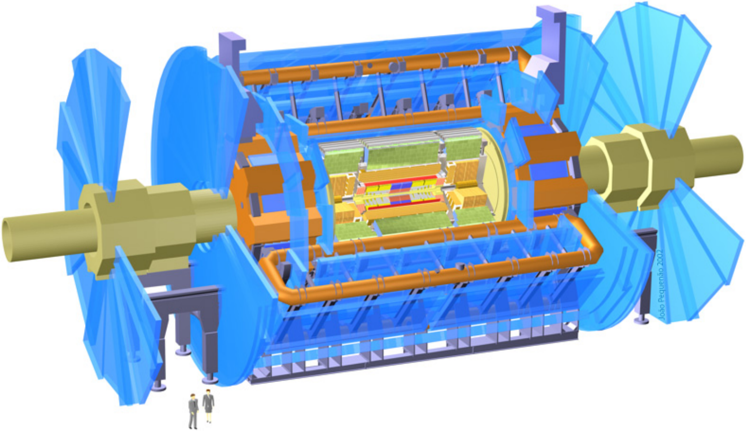
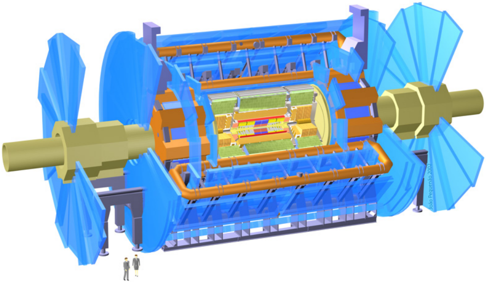
The ATLAS detector



The ATLAS detector

- Shell structure:
  - Tracking detectors
  - Electromagnetic calorimeter
  - Hadronic calorimeter (4 kt)
  - Large toroidal magnets
  - Muon system



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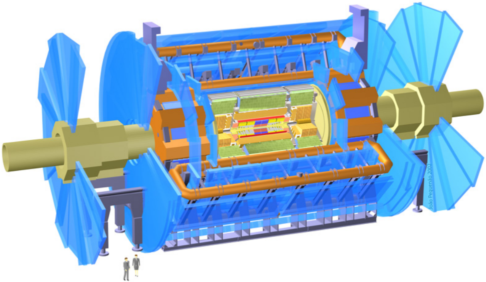

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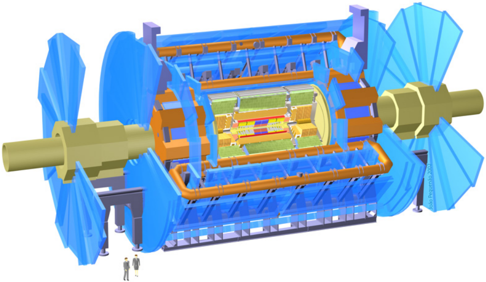

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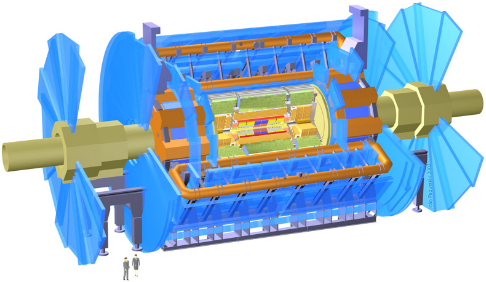
- No neutrino reconstruction during LHC operation
  $\Rightarrow$ Cosmic/calibration runs



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- Contained events:
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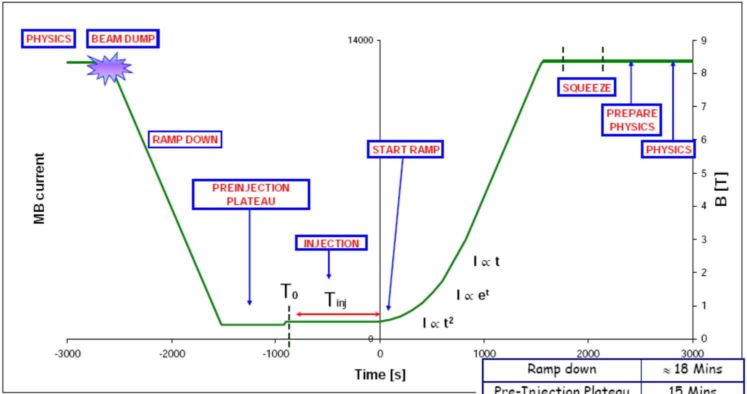
- Upward going muon events:
  Muon entering the detector from below

Time windows for neutrino physics at ATLAS

- Ramp-down/Ramp-up



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Mike Lamont, CERN

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- No track reconstruction for ν_e and ν_τ

Outline

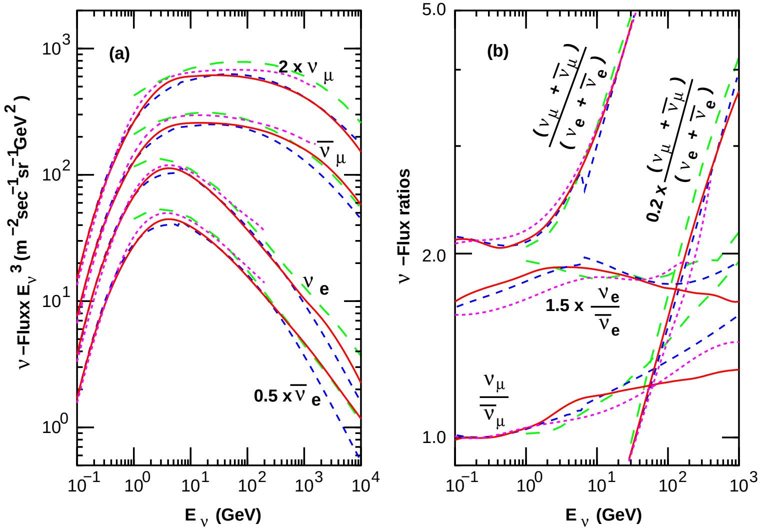
Computation of event rates

Number of events in the i-th energy bin/j-th angular bin

$$N_f^{ij} = \mathcal{N} \int_{\text{bin }(i,j)} dE_r \, d\theta_r \, R[E_r, \theta_r, E_\nu, \theta_\nu] \cdot \sigma_f(E_\nu) \sum_{f'=e,\mu,\tau} P[f' \to f, E_\nu, L(\theta_\nu), \boldsymbol{\Theta}] \, \Phi_{f'}[E_\nu, L(\theta_\nu)]$$

E_ν	= Neutrino energy	$P(f' \to f, E_\nu, L, \boldsymbol{\Theta})$	= Oscillation probability
E_r	= Reconstructed ν energy	$\sigma_f(E_\nu)$	= Cross section
$\Phi_{f'}$	= Source flux for flavor f'	$R(E_r, \theta_r, E_\nu, \theta_\nu)$	= Response function
$\boldsymbol{\Theta}$	= Osc. parameter vector	$\mathcal{N}$	= Normalization

Atmospheric neutrino fluxes



M. Honda et.al., 2004

High energy cross sections

- Dominating contributions
  - Quasi-elastic scattering

    $$\nu + N \to l + N'$$

  - Single-meson production

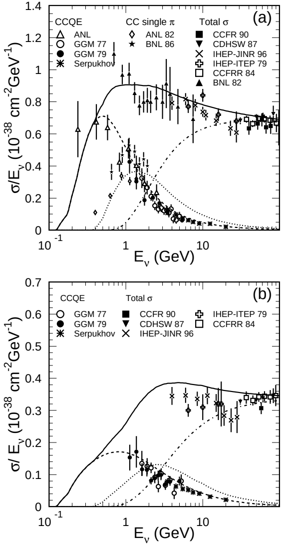
    $$\nu + N \to l + N' + \text{Meson}$$

  - Deep-inelastic scattering

    $$\nu + N \to l + N' + \text{Hadrons}$$

- $\bar{\nu}$ cross sections are smaller than ν cross sections
- Large uncertainties

Paschos/Yu, 2001; Messier, 1999



The detector response function

- Abstract parameterization in terms of Gaussian resolutions and efficiencies:

$$R(E_r, \theta_r, E_\nu, \theta_\nu) = \epsilon^E(E_\nu)\, \epsilon^\theta(\theta_\nu) \cdot \frac{1}{Z_E} \exp\left(-\frac{(E_r - E_\nu)^2}{2\sigma_E^2(E_\nu)} \right) \cdot \frac{1}{Z_\alpha} \int_0^{2\pi} d\phi_r \exp\left(-\frac{\alpha^2(\theta_r, \phi_r, \theta_\nu)}{2\sigma_\alpha^2(E_\nu)} \right)$$

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- Energy and angular resolutions σ_E and σ_α
- Energy dependent part of efficiencies $\epsilon^E(E_\nu)$ (assumed $\equiv 1$ here)
- Angular part of efficiencies $\epsilon^\theta(\theta_\nu)$ (from geometry, important especially for upward-going muon events)

Systematical errors

- Incorporated into χ^2 analysis by the pull method

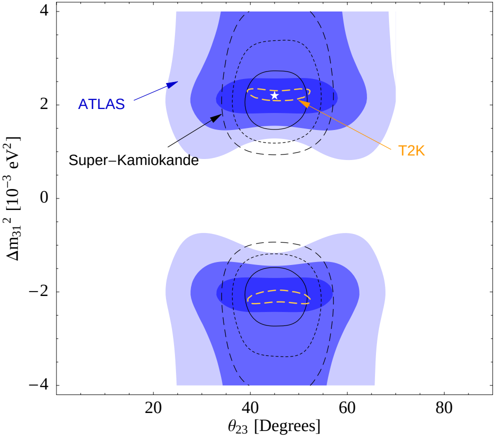
Error Type	Magnitude
Overall normalization for contained events	20%
Relative normalization for antineutrinos	5%
Normalization for upward going muon events	20%
Tilt of the energy spectrum	5%
Tilt of the angular spectrum for contained events	10%
Tilt of the angular spectrum for upward going muons	2%

The leading atmospheric oscillation parameters

Assumptions:

- 500 days exposure ($\sim$ 5 years)
  $\sim$ 160 contained events,
  $\sim$ 750 upward going muons
- 5% energy resolution
  7° angular resolution
- Energy threshold 1.5 GeV
- 100% reconstruction efficiency
  100% charge ID efficiency

Confidence regions at 1σ, 2σ, 3σ



Super-K contours courtesy of Thomas Schwetz

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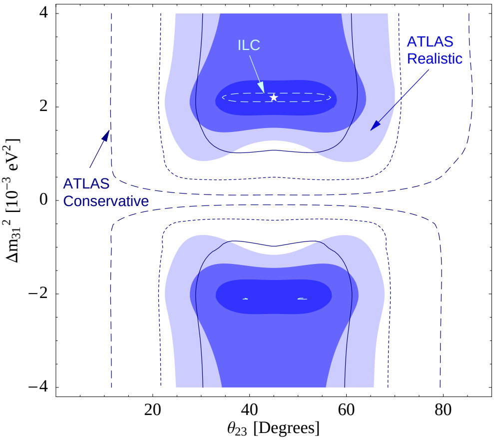
Conservative scenario:

- 250 days exposure
- Resolutions 10%, 17°

ILC (optimistic) scenario:

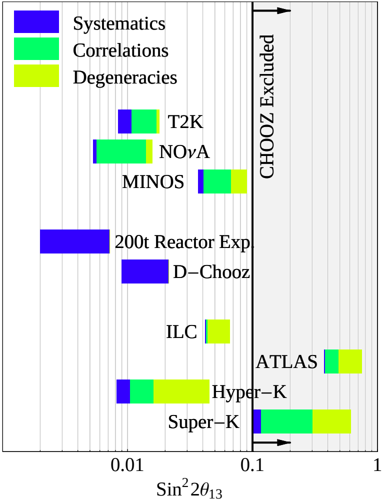
- 2,000 days exposure
- Energy threshold 0.3 GeV
- Resolutions 2%, 2°

Confidence regions at 1σ, 2σ, 3σ



Three-flavour effects

- Systematics: Normalization and spectrum uncertainties in intial flux
- Correlations: Sensitivity only to combinations of parameters
- Degeneracies: Several discrete parameter sets can fit the data



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Comments on other collider detectors

- CMS: Even larger mass, but most of it is concentrated in massive iron yokes
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- ALICE and LHCb: Too small
- ILC detectors: May be interesting

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- Oscillations can be seen
- More detailed input on efficiencies and resolutions required (e.g. from ATLAS Monte Carlo)
- Can the shutdown phases of LHC be used for other physics (e.g. detection of long-lived staus)?

  see e.g. Buchmüller, Hamaguchi, Ratz, Yanagida, 2004

Calculation of event rates

Number of events in the i-th energy bin

$$N_f^i = \mathcal{N} \int_{\text{bin } i} dE_r \int dE_l \, V_f(E_r, E_l) \cdot \int dE_\nu \, k_f(E_l, E_\nu) \, \sigma_f(E_\nu) \sum_{f'=e,\mu,\tau} P(f' \to f, E_\nu, \boldsymbol{\Theta}) \, \Phi_{f'}(E_\nu)$$

E_ν	= Neutrino energy	$P(f' \to f, E_\nu, \boldsymbol{\Theta})$	= Osc. probability
E_l	= Charged lepton energy	$\sigma_f(E_\nu)$	= Cross section
E_r	= Reconstructed ν energy	$k_f(E_l, E_\nu)$	= Charged lepton distribution
$\Phi_{f'}$	= Source flux for flavor f'	$V_f(E_r, E_l)$	= Energy resolution function
$\boldsymbol{\Theta}$	= Osc. parameter vector	$\mathcal{N}$	= Normalization

- Combine k_f and V_f to the "detector response function" $R(E_r, E_\nu)$.
- Perform integration over dE_r only once $\Rightarrow \tilde{R}^i(E_\nu)$.
- Replace integration over dE_ν by a sum.

Calculation of event rates

The final formula

$$N_f^i = \mathcal{N} \sum_k \tilde{R}^i(E_\nu^k) \cdot \sigma_f(E_\nu^k) \sum_{f'=e,\mu,\tau} P(f' \to f, E_\nu^k, \boldsymbol{\Theta}) \, \Phi_{f'}(E_\nu^k)$$

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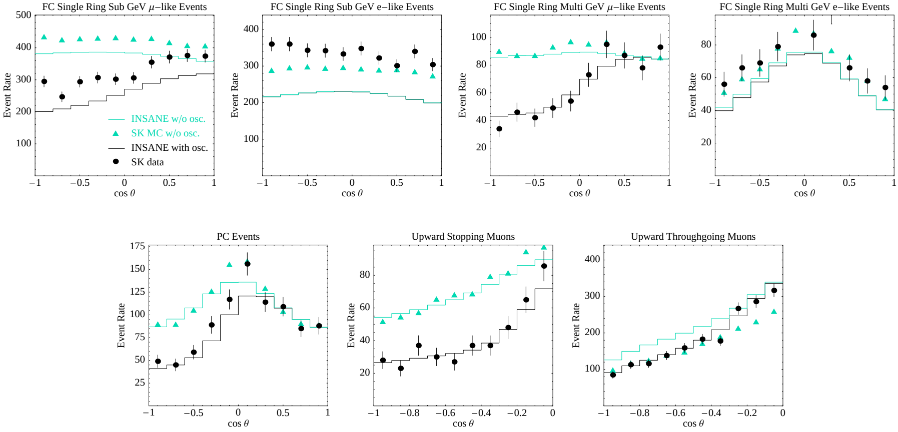
Inclusion of angular dependence

$$N_f^{ij} = \mathcal{N} \sum_{k,l} \tilde{R}^{ij}(E_\nu^k, \theta_\nu^l) \cdot \sigma_f(E_\nu^k) \sum_{f'=e,\mu,\tau} P\big(f' \to f, E_\nu^k, L(\theta_\nu^l), \mathbf{\Theta}\big)\, \Phi_{f'}\big(E_\nu^k, L(\theta_\nu^l)\big)$$

Verification of simulation code: Super-K rates



Discrepancies are mostly due to solar modulation and NC backgrounds.

Data and MC results from hep-ex/0501064

Basics of the χ^2 analysis

- Goal: Compare "observed" event spectrum with different theoretical predictions to find confidence regions in the parameter space.
- Typical χ^2 function:

$$\chi^2 = \sum_i \frac{1}{N_i} [(1+a) N_i(\mathbf{\Theta}') - N_i(\mathbf{\Theta})]^2 + \frac{a^2}{\sigma_a^2}$$

- Example: Confidence regions in the θ_{13}-δ_{CP} plane
  - Calculate $N_i(\mathbf{\Theta})$, where $\mathbf{\Theta} = (\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \Delta m_{21}^2, \Delta m_{31}^2)^T$ is the vector of "true" oscillation parameters.
  - Choose arbitrary test values θ_{13}' and δ_{CP}'.
  - Minimize χ^2 over the other oscillation parameters and over a.
  - Compare the result with the tabulated χ^2 distribution to find the confidence level at which the experiment can rule out θ_{13}' and δ_{CP}'.

An example: Measurement of θ_{13} and δ_{CP}