The LHC Project

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- The LHC machine
- LHC detectors
- Physics at the LHC
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Fundamental Questions of today's particle physics

- How is the electroweak symmetry broken?
  Is there a Higgs sector or are masses generated differently?
- What is the matter from which our universe is made off?
  Can we see the dark matter around us, in the cosmos or at colliders?
- Is there a common origin of forces?
  Do couplings/masses unify at some scale?
- Why is there a surplus of matter in the universe?
  Can we find the missing CP violation?
- How can gravity be quantised?
  Are there superstrings and/or extra space dimensions?
- What does the neutrino sector look like?
  Is there a new type of matter (Majorana)? Do νs contribute to baryo-genesis?

Most questions are answered best at colliders with maximum possible energy ($m_{\rm H} > 114\,{\rm GeV}$, $m_{\rm SUSY} > 100\,{\rm GeV}$)

How to reach the highest possible energy?

To reach the highest possible energies collide high energy particles with high energy particles not to loose energy in a boost as in a fixed target experiment
($\sqrt{s}_{\rm collider} = 2E$, $\sqrt{s}_{\rm fixed\,target} = \sqrt{2Em_t}$)

Most colliders are storage rings ➠ can reuse beams many times

Limitations for colliders:

Magnetic field: $B \propto \frac{p}{r}$ identical for all particles

Synchrotron radiation: $\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{r}$ strongly mass dependent

Practical example: LEP/LHC (l=27 km)

Synchrotron radiation:

- $\Delta E = 2.5\,\mathrm{GeV/turn}$ for electrons with $E = 100\,\mathrm{GeV}$
- Same energy loss for protons with $E = 200\,\mathrm{TeV}$

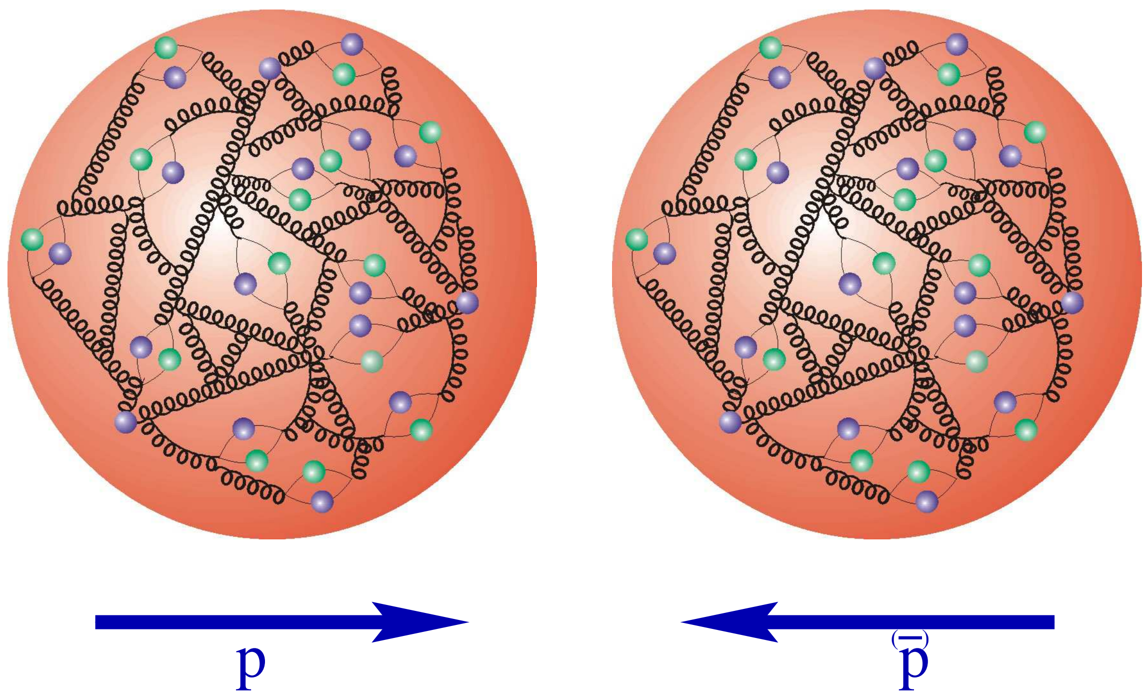
Magnetic field:

- $B = 9\,\mathrm{T}$ needed for $E = 7\,\mathrm{TeV}$

Highest energies can be reached with protons

Proton collider

Protons are composite particles:

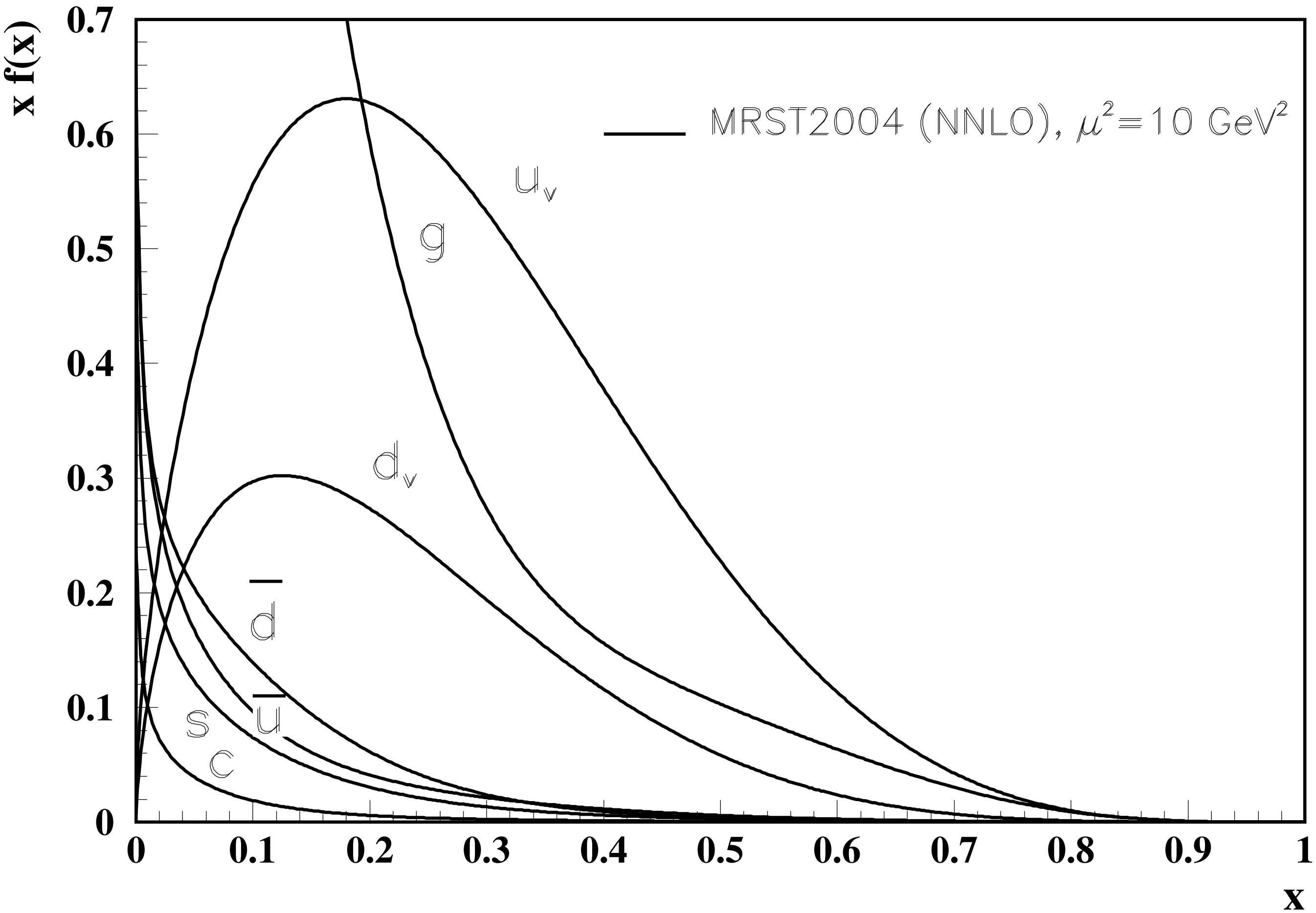


- Proton composition
  Low energy: 3 quarks
  High energy: (N+3) quarks, N antiquarks, M gluons
  (➡ basically no difference between pp and p$\bar{\text{p}}$ collider)
- qq, q$\bar{\text{q}}$, qg, gg interactions

Probability for an i,j collision (i,j=p.$\bar{\text{p}}$, g) at energy $\sqrt{s'}$ given by parton distribution functions:

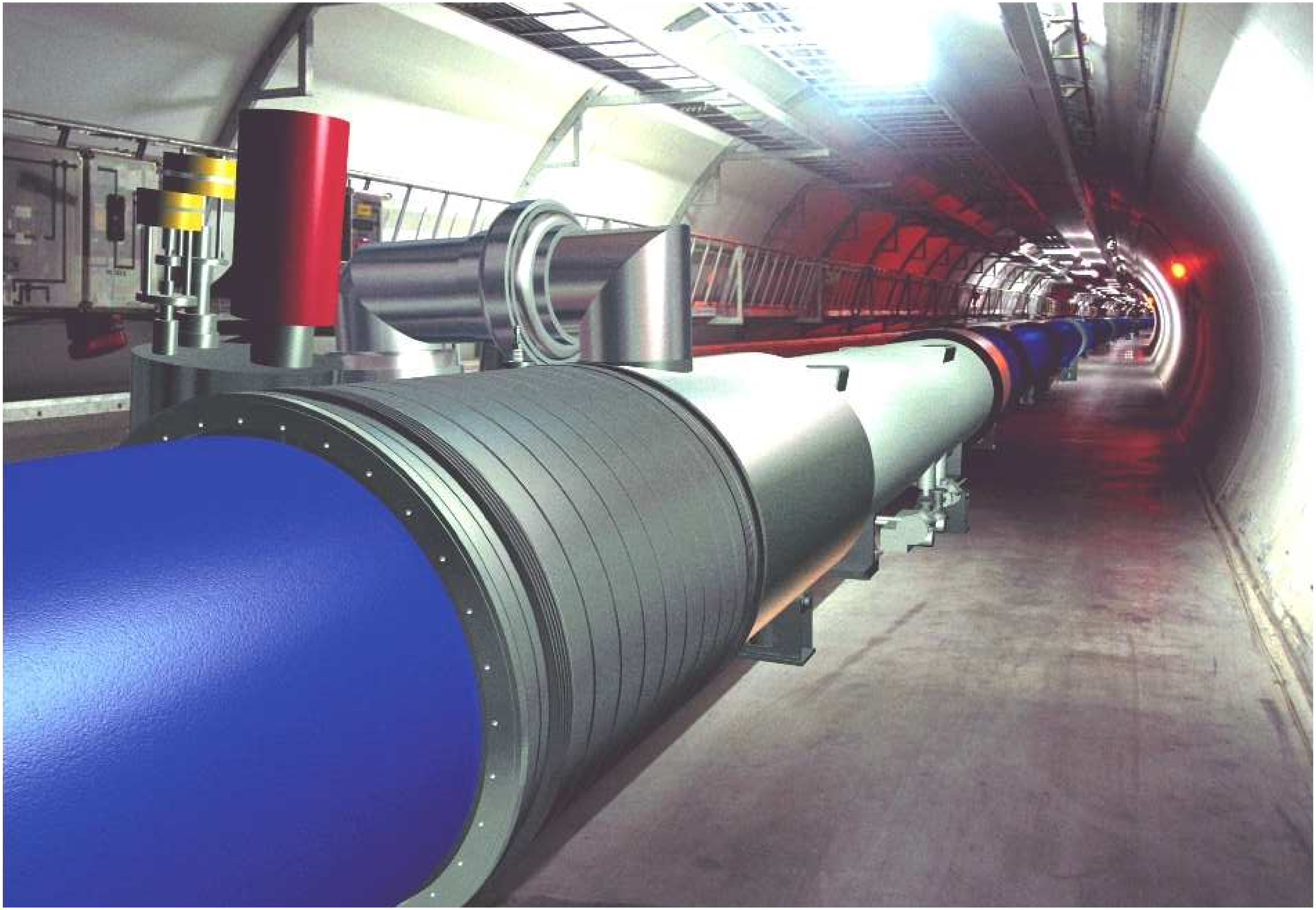
$$\mathcal{P}_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), \quad x_k = p_k/p_{\text{p}}, \quad \sqrt{s'} = 2\sqrt{x_1 x_2}$$

PDFs peak at low energy

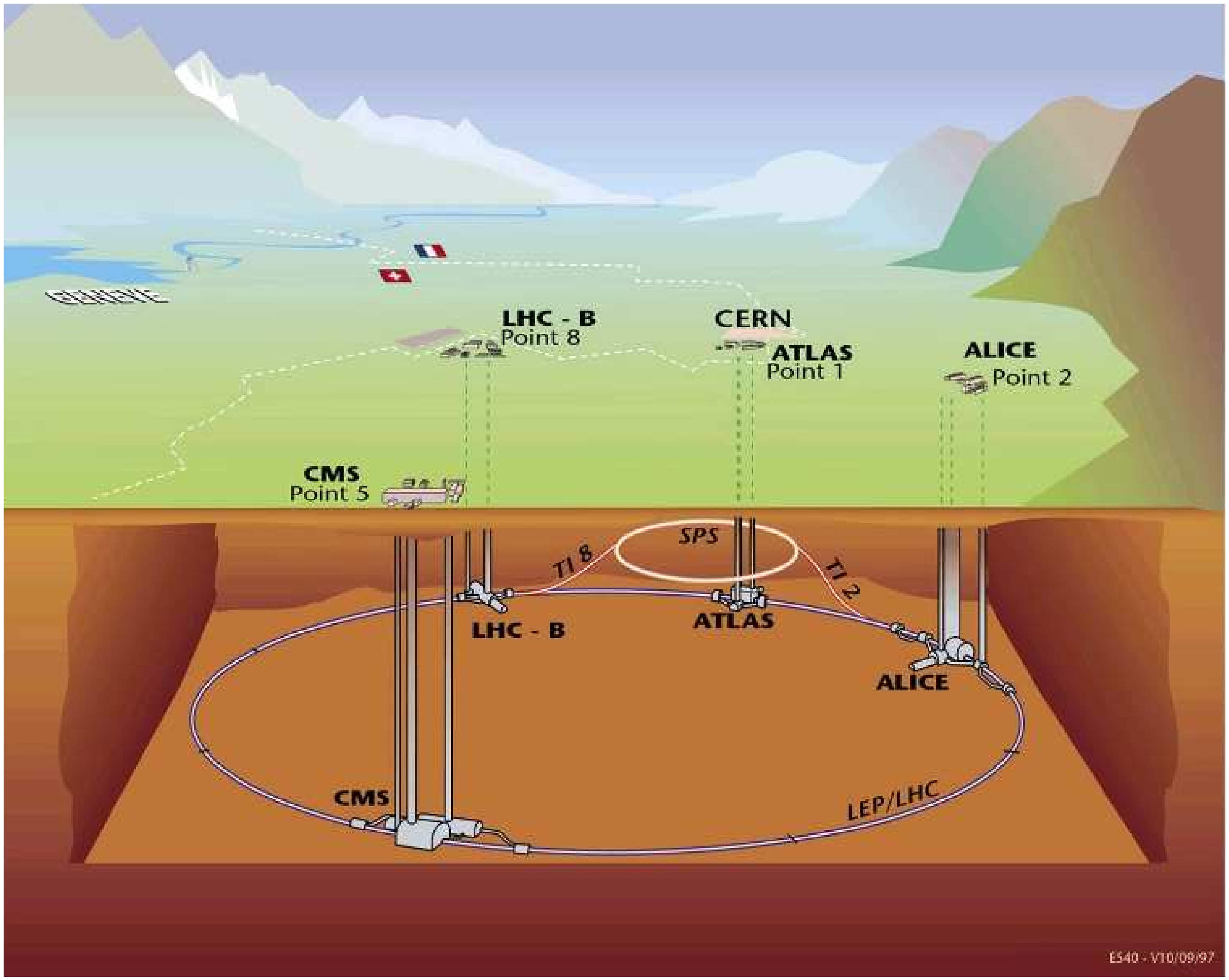


- Average energy much lower than proton energy
- Many uninteresting interactions at low energy
- Need high luminosity to make use of high energy

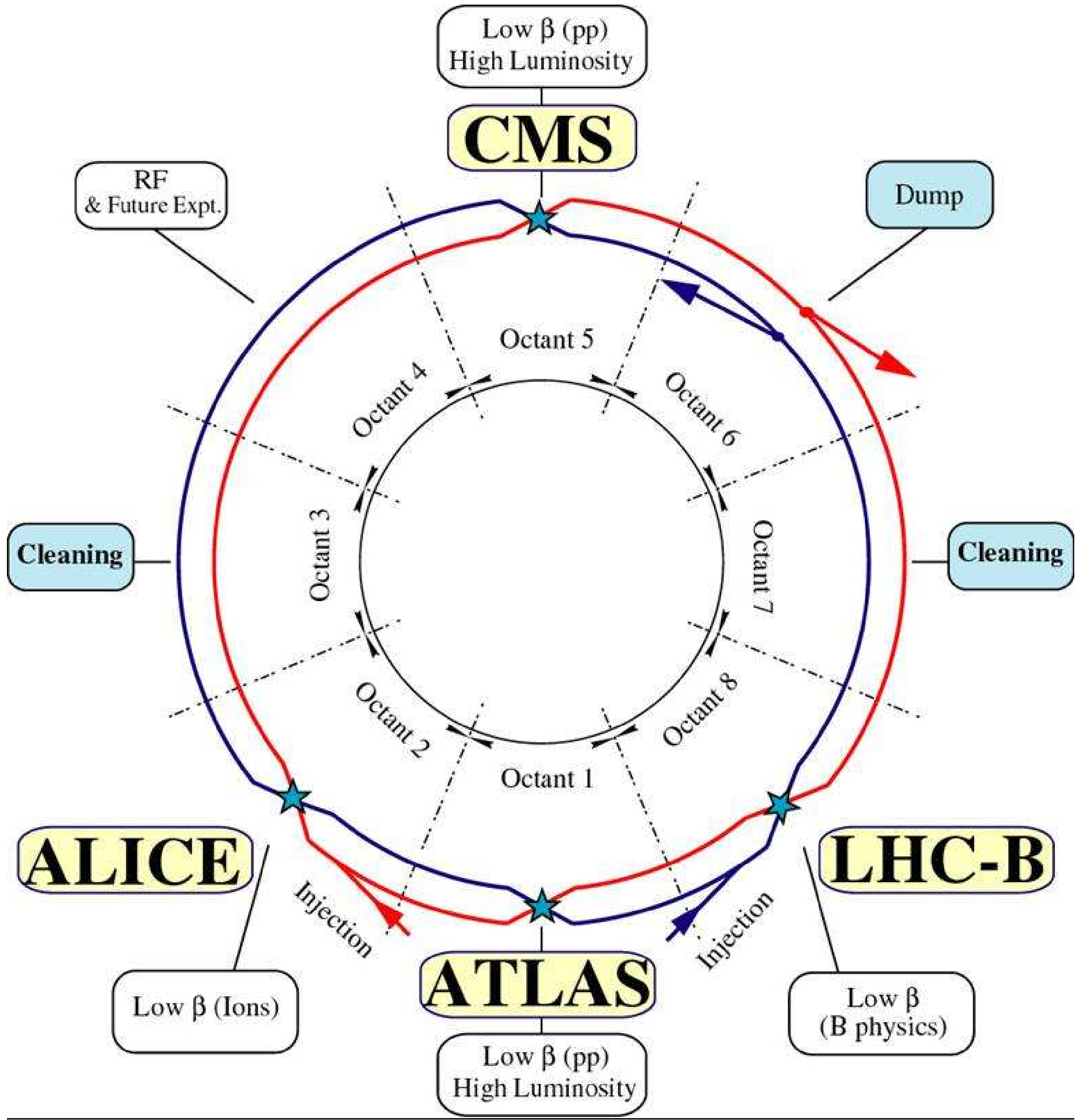
The LHC project



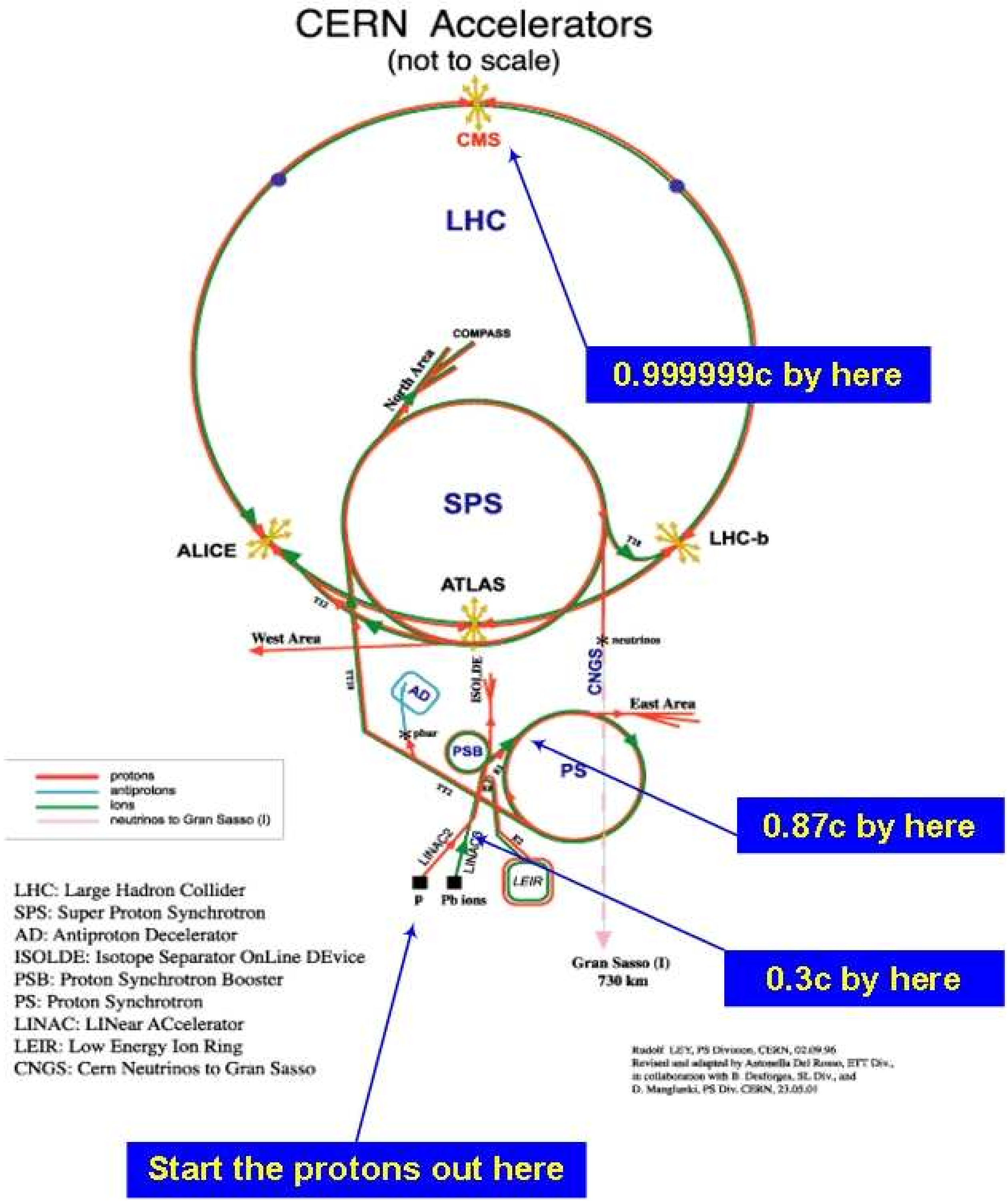
- pp-collider in the LEP tunnel at CERN (l=27 km)
- $\sqrt{s} \approx 14\,\mathrm{TeV}$
- Luminosity up to $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Detailed layout of the LHC

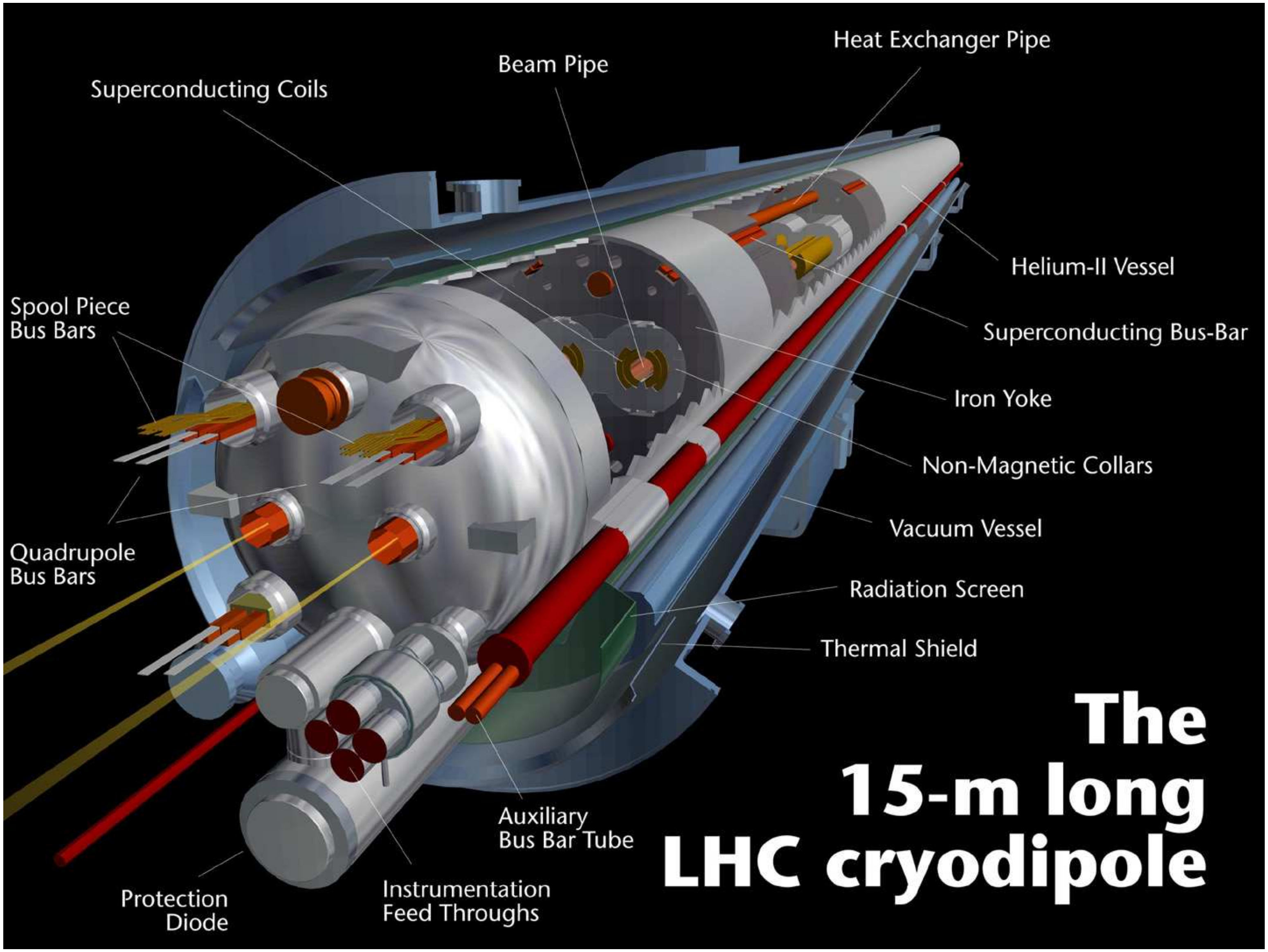


LHC receives its beams from the CERN accelerator complex



Main challenge: need 9 T magnets to reach desired energy

Solution: superconducting "2 in 1" magnets to save cost



The LHC beams

- Two proton beams of E=7 TeV each

- 2800 bunches/beam

- $1.2 \cdot 10^{11}$ protons per bunch

➠ The total stored energy is 360 MJ per beam
(This corresponds to a British aircraft carrier at 12 knots or a luxury car at 2000 km/h)

- Beam size at IP: few cm long, 16μm wide

The LHC timescale

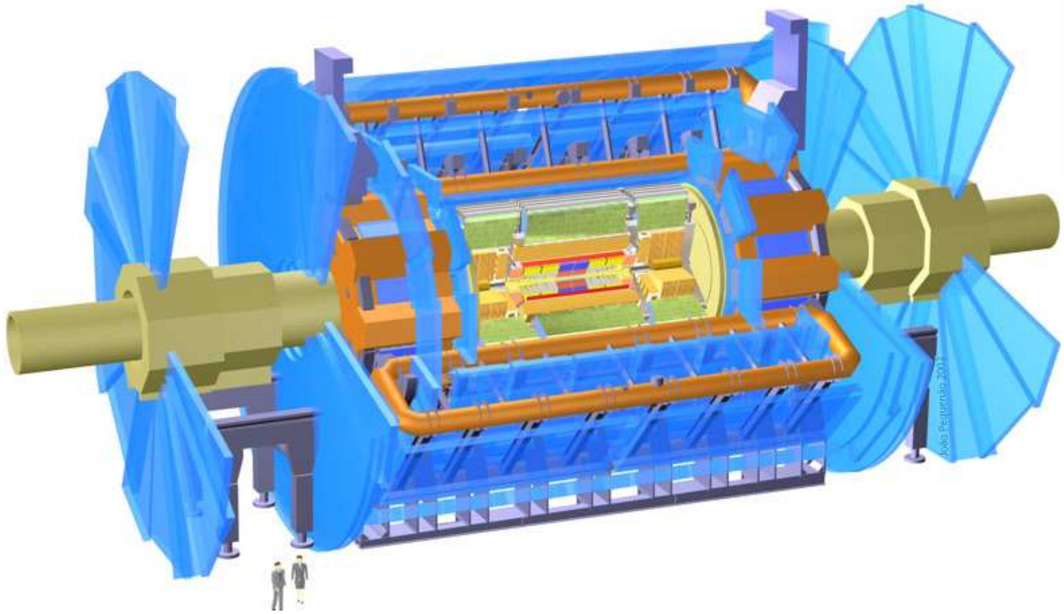
- First discussions on the project: 1984
- Constructed in the LEP tunnel since 2001
- Late 2007: first collisions at $\sqrt{s} = 900\,\mathrm{GeV}$
- 2008 – 2009: "Low luminosity" $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 2010– $\sim$ 2015: "High luminosity" $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\geq$ 2015: luminosity upgrade to $\mathcal{L} \sim 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

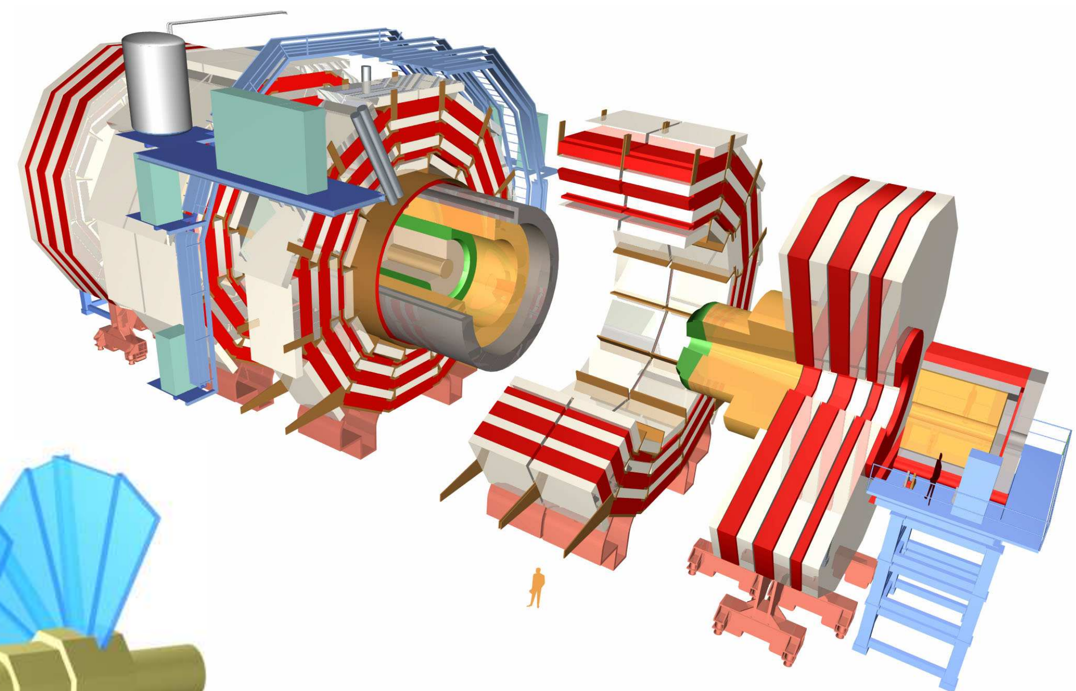
Experiments at the LHC

Two multi-purpose experiments:

Atlas

CMS





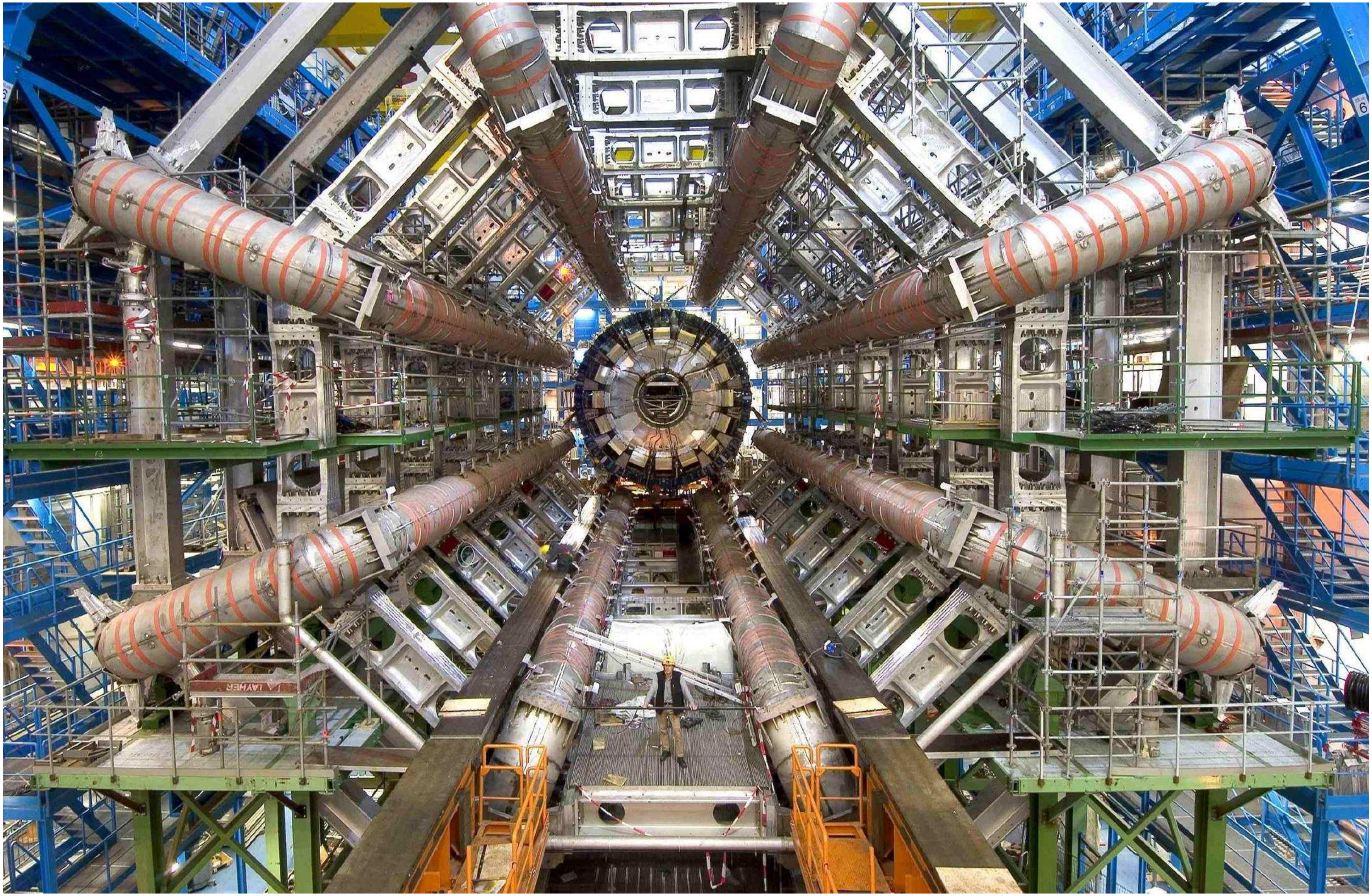
ATLAS: ➠ see film

CMS:

- In general similar to ATLAS
- No specialised muon tracking but better inner tracking
- Christal ECAL for good energy resolution (H$\rightarrow \gamma\gamma$)

Installation of experiments is going well

ATLAS



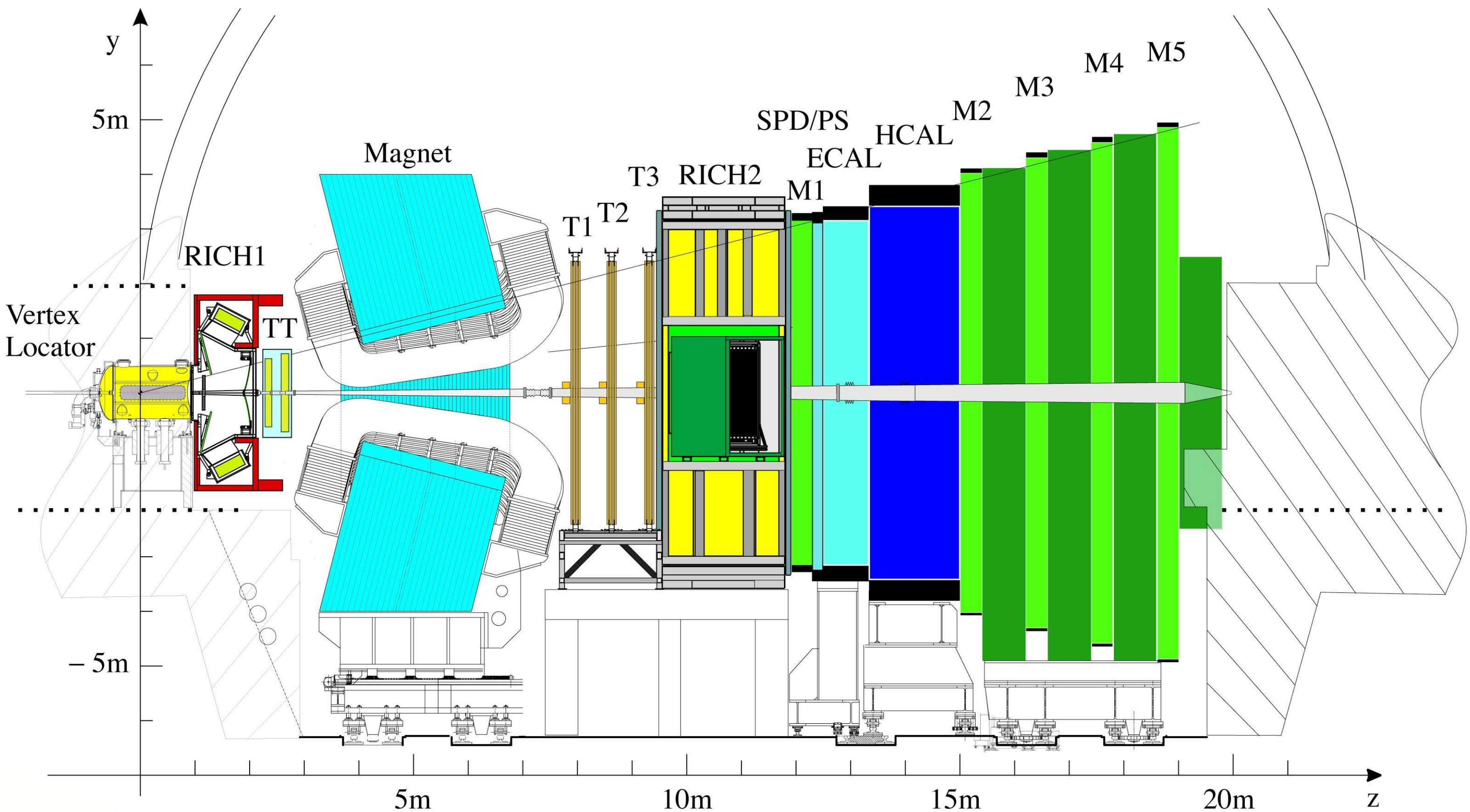
CMS

Collaborations (e..g. ATLAS) consist of

- $\sim$ 1700 physicists
- from $\sim$ 150 institutes
- from 35 countries

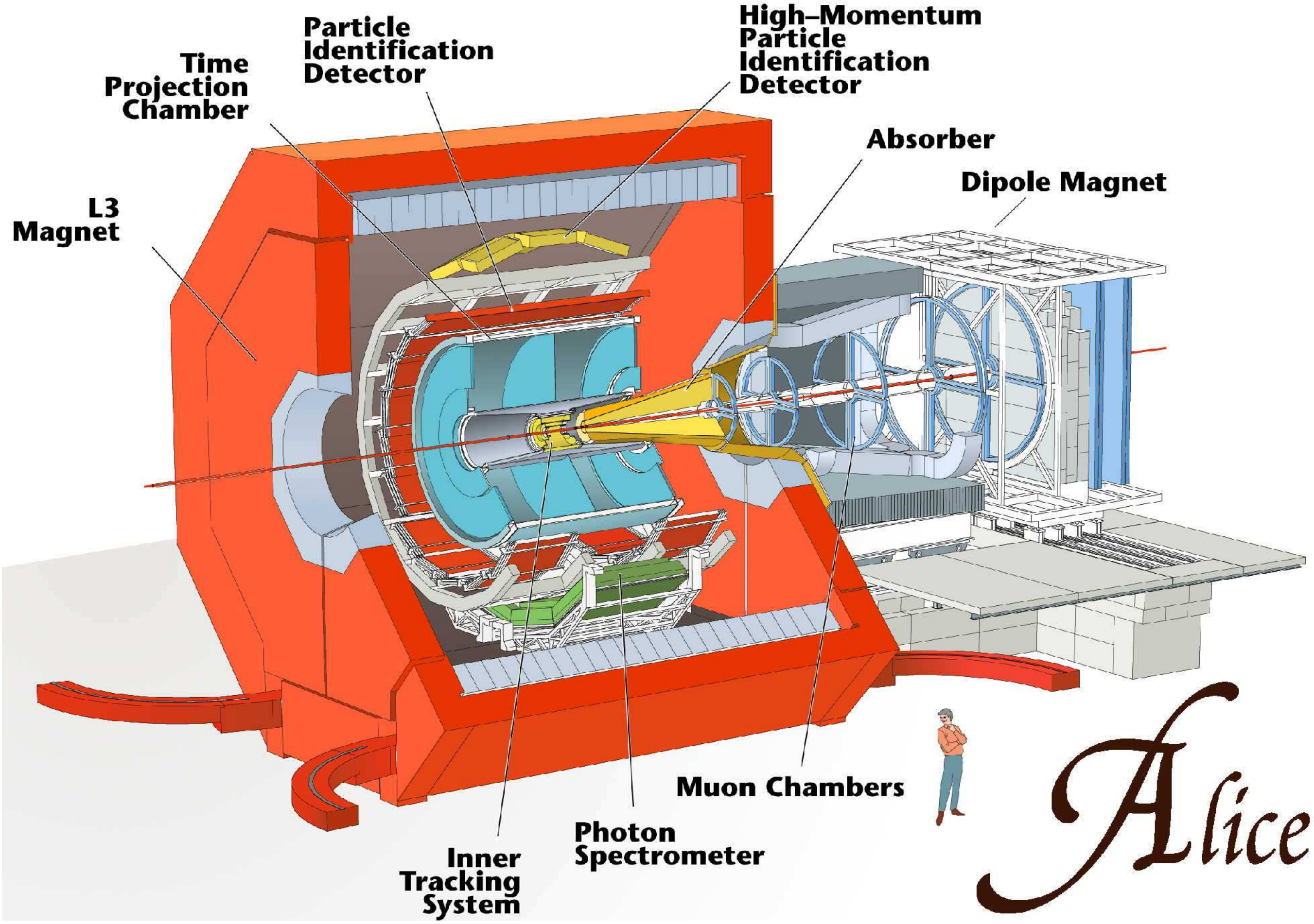
Specialised B-physics experiment: LHCb

- Huge b-cross section, mainly in forward region
- Can be used to study CKM matrix and CP violation
- LHCb optimised for forward region coverage, particle id and lepton trigger



Heavy iron experiment: ALICE

- The LHC can produce gold-gold collisions
- With these collisions one hopes to understand the quark-gluon plasma
- ALICE is a specialised detector to measure charged particles ($\sim$ 1000/event) and leptons



Physics at the LHC

Generalities about pp collisions

- Protons have strong interactions
  - Very large background from QCD events
  - Large cross section for strongly interacting new physics
  - Weakly interacting new physics can be difficult
- The PDFs fall rapidly with x
  - Very high luminosity needed to reach high energy
  - Basically no sensitivity above 4 TeV
- PDFs (especially g) huge at low x
  - $\mathcal{O}(10)$ minimum bias events per bunch crossing at high luminosity

Signals at the LHC

Challenge: Have to separate new physics from huge QCD background

- Purely hadronic processes are visible only at very high energy (e.g. hopeless to see the dominant Higgs channel $gg \rightarrow H \rightarrow \mathrm{b\bar{b}}$)
- Best signals are leptons (or photons) from weak decays
- Another good signal is invisible particles
  - Energy and momentum are conserved
  - Since the proton remnants disappear in the beampipe this doesn't help in general
  - However momentum conservation in the transverse plane is still a powerful tool to tag invisible particles (neutrinos, dark matter...)

Event rates at the LHC (at $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

Reaction	events/year
$W \to e\nu$	10^9
$Z \to ee$	10^8
$\mathrm{t\bar{t}}$	10^8
$\mathrm{b\bar{b}}$	10^{14}
$\tilde{g}\tilde{g} \quad m = 1\,\mathrm{TeV}$	10^5
$H \to \gamma\gamma \quad m_\mathrm{H} = 120\,\mathrm{GeV}$	10^3

- LHCb runs with factor 100 reduced luminosity
- Also other Standard Model rates are huge
- But even rates for new physics processes can be large

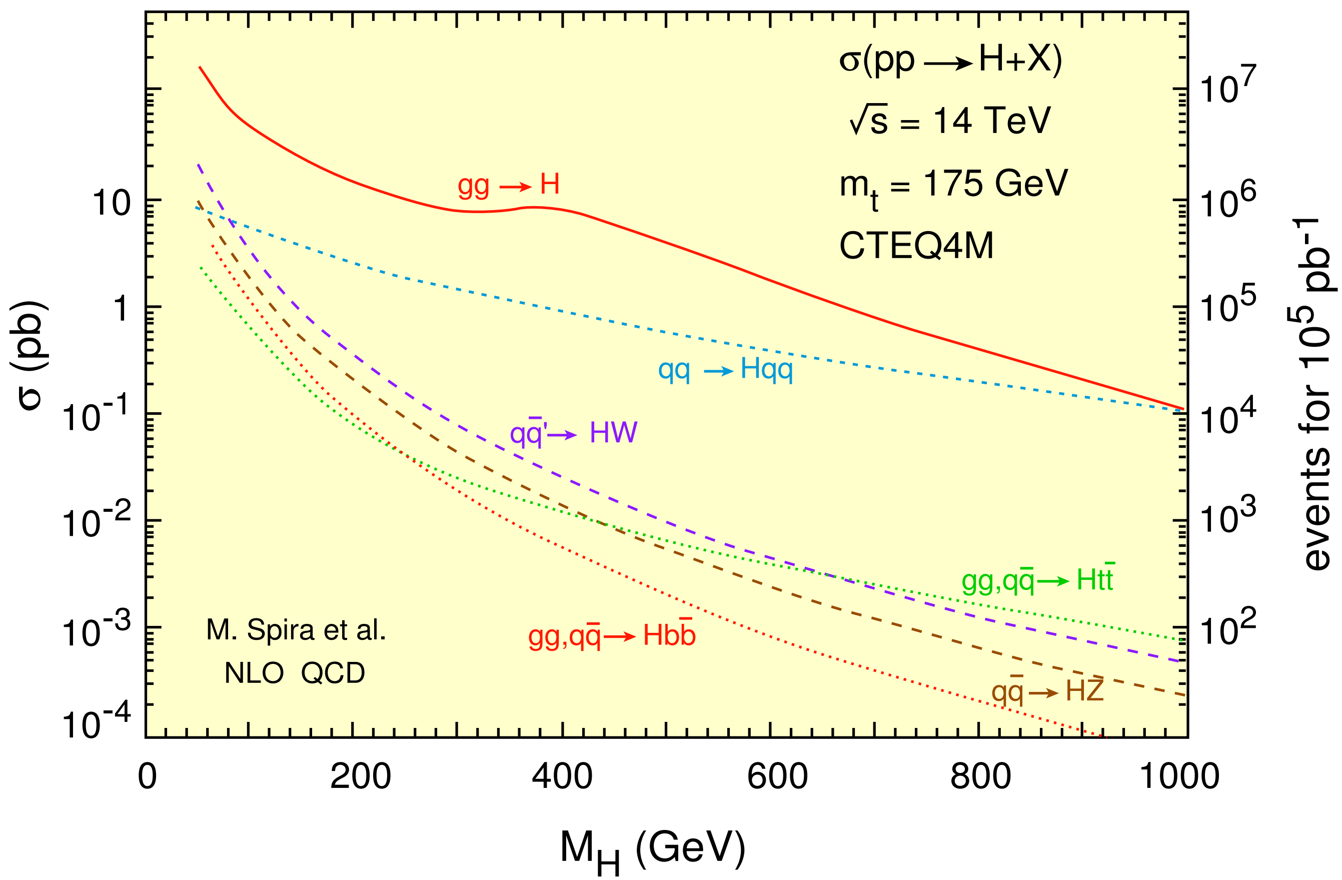
We know that the Standard Model of weak interactions is incomplete

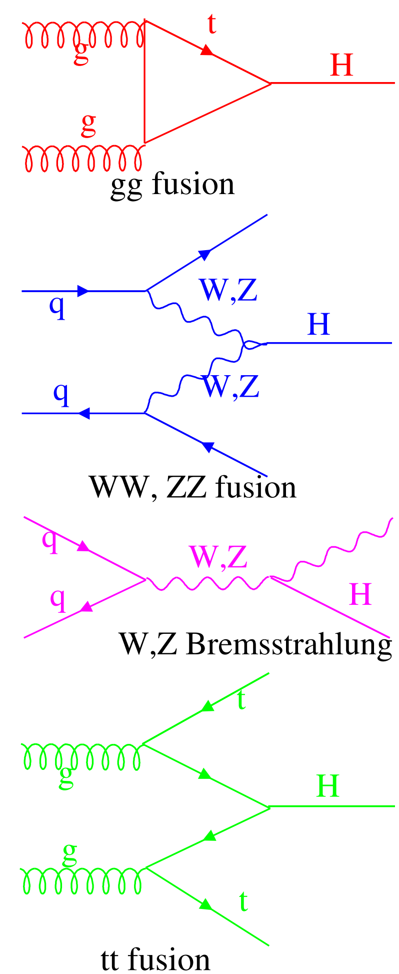
- At least the Higgs is missing
- But even with the Higgs there are serious problems remaining (dark matter, hierarchy problem, inclusion of gravity)

The main task of the LHC is to find and identify new physics

- Of course we don't know what the new physics will be
- One can only take some reasonable examples and see what the LHC is able to do
- However for nearly all studied examples where signals are in the visible range, something will be seen

Higgs production at the LHC





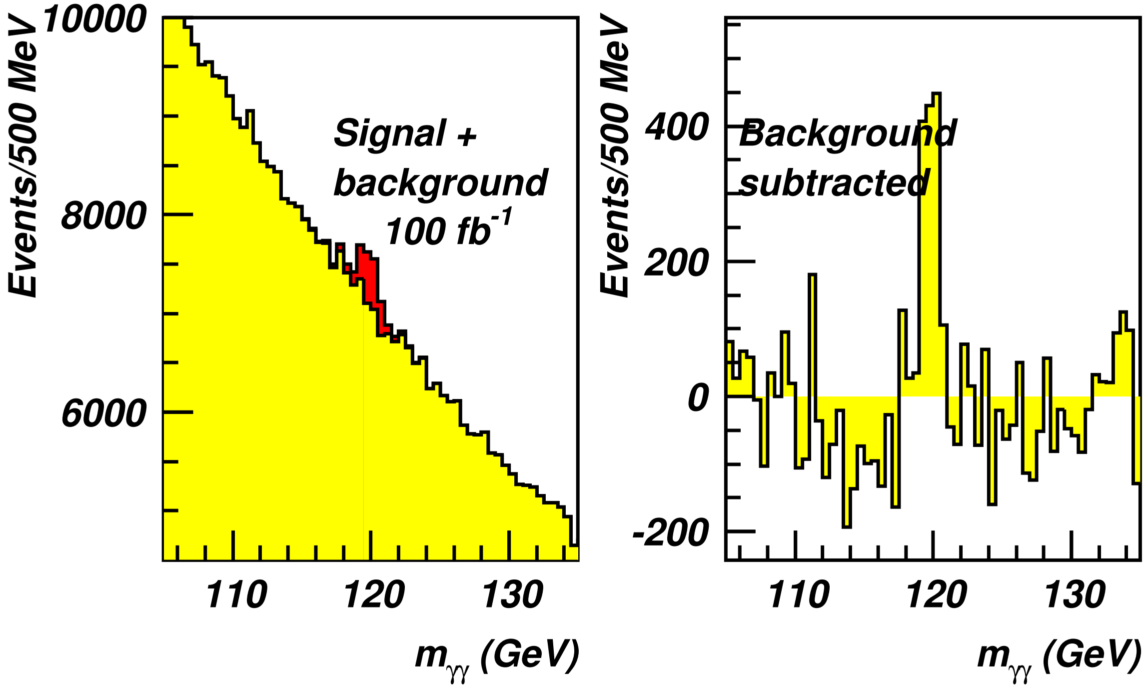
Dominant process $gg \to H \to b\bar{b}$ completely hidden in QCD background

Discovery channels $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$

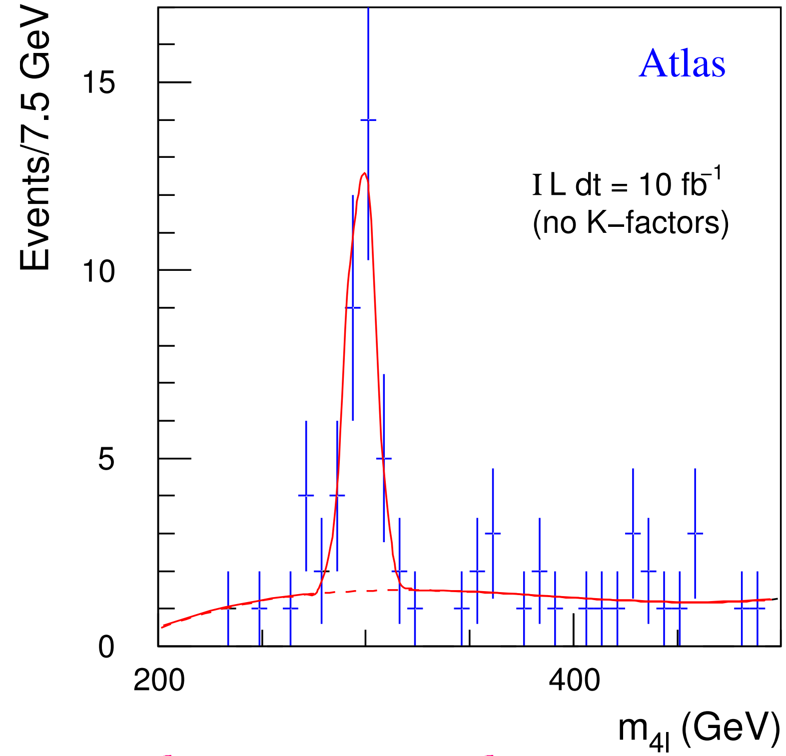
$H \to b\bar{b}$ and $H \to \tau^+\tau^-$ may be seen is association with W,Z,t

Higgs signals at LHC

$H \to \gamma\gamma$ in CMS



$H \to ZZ \to 4\ell$ in Atlas

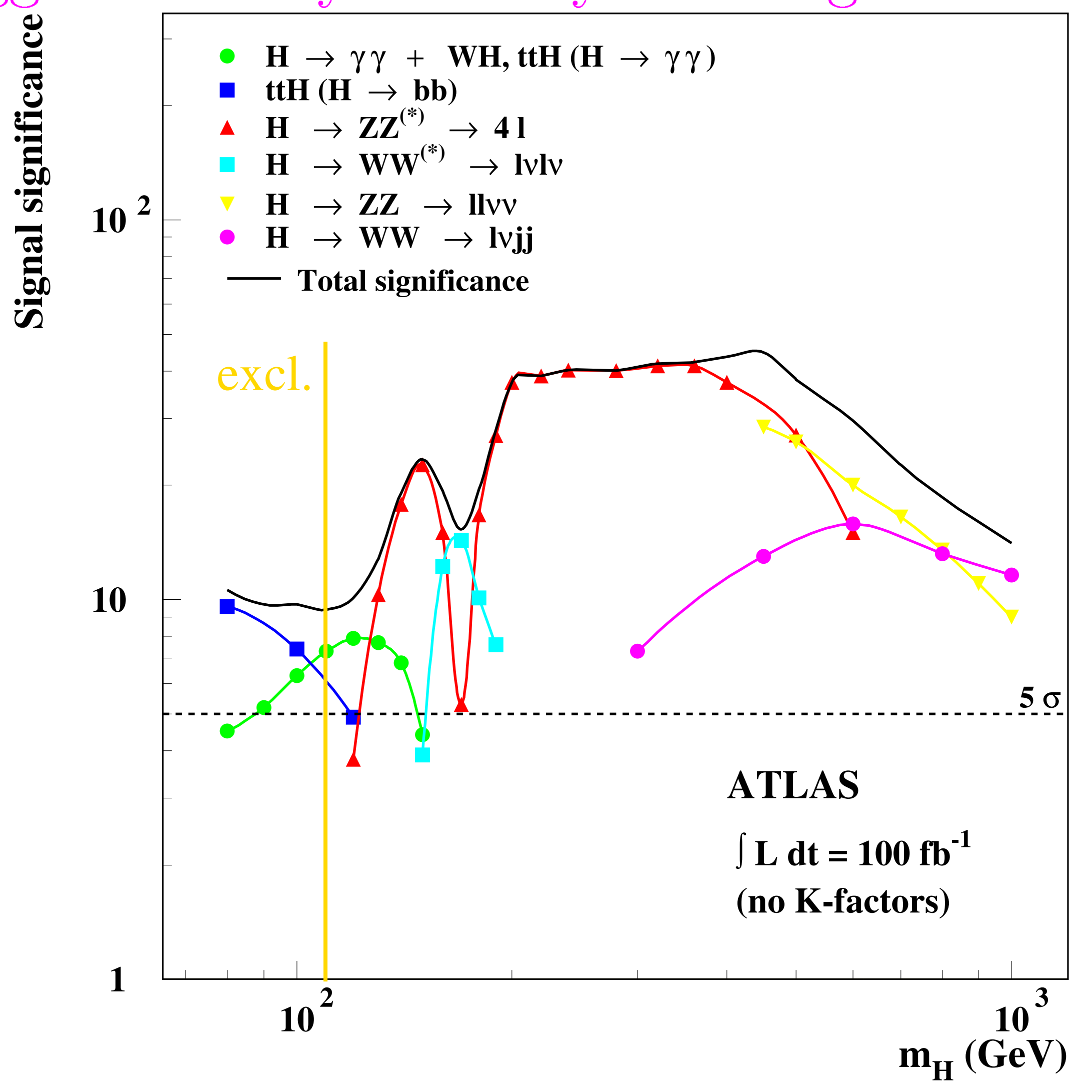


For a light Higgs $H \to \gamma\gamma$ is very demanding on detector resolution

For a heavier Higgs $H \to ZZ \to 4\ell$ is relatively easy

Higgs discovery range

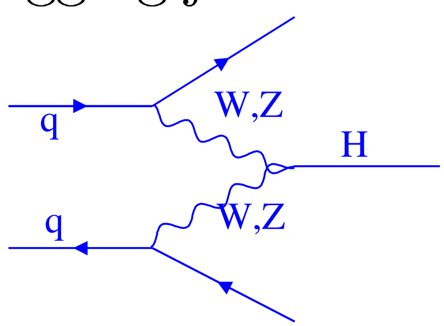
Higgs sensitivity for one year at high luminosity



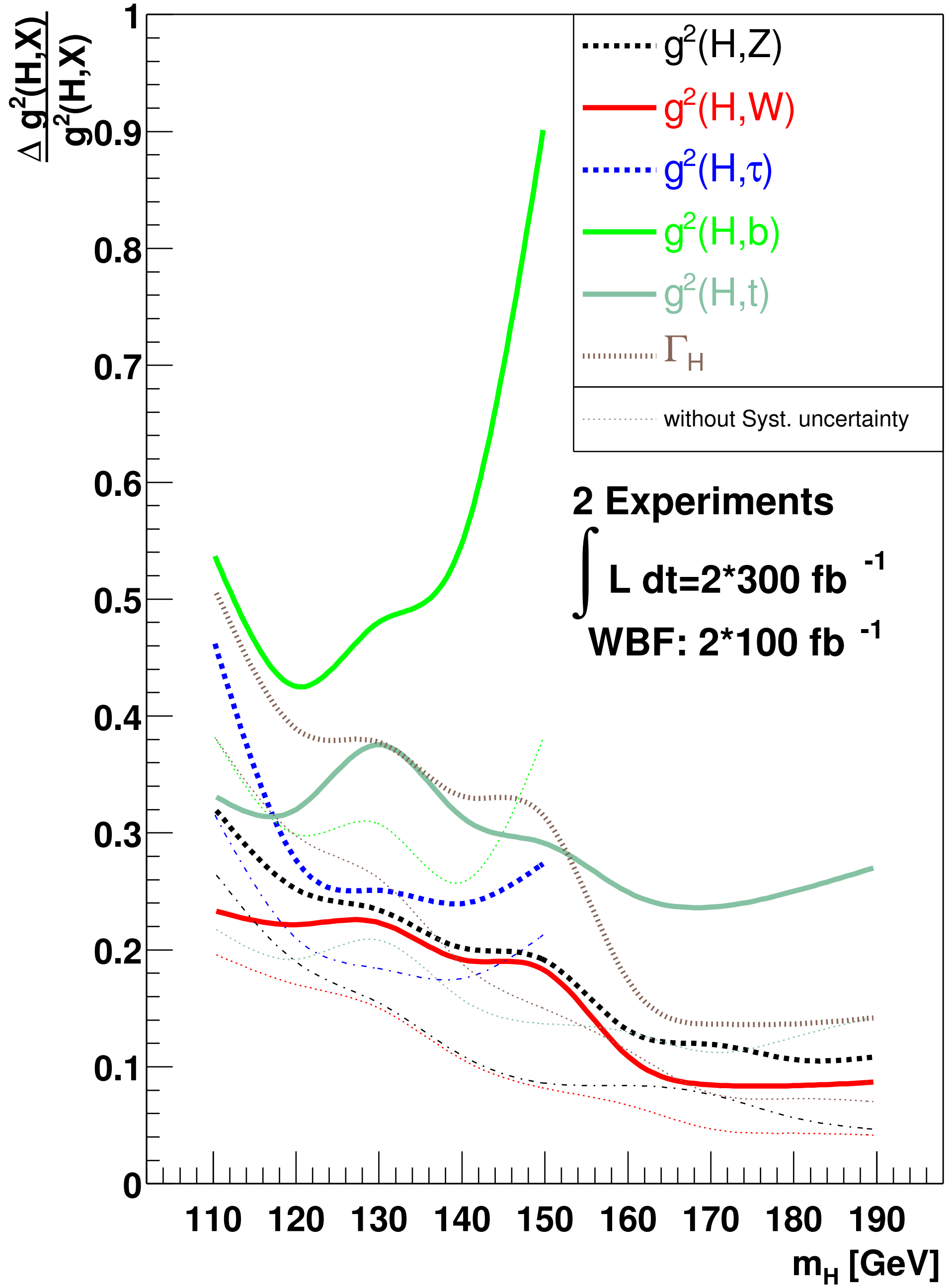
The LHC can discover a SM Higgs over the full mass range!

Other Higgs measurements at the LHC

- Since most Higgs decays are invisible at the LHC unbiased decay rate measurements are impossible
- If the same production mechanism can be identified, decay rate ratios are directly ratios of partial widths (e.g. VV fusion can be identified by two tagging jets in the forward region)



- With some theory assumptions these can be transformed into partial widths (=couplings)



- With this method $\sim 20\%$ measurements are possible
- However this includes some theoretical biases
- Way out ➠ Linear collider (S. Riemann)

Other Higgs properties

- The total width can only be measured for masses above a few hundred GeV
- Other properties (spin, CP) can be measured from spin correlations when $H \rightarrow ZZ$ is large enough

Supersymmetry at the LHC

What do we know about SUSY?

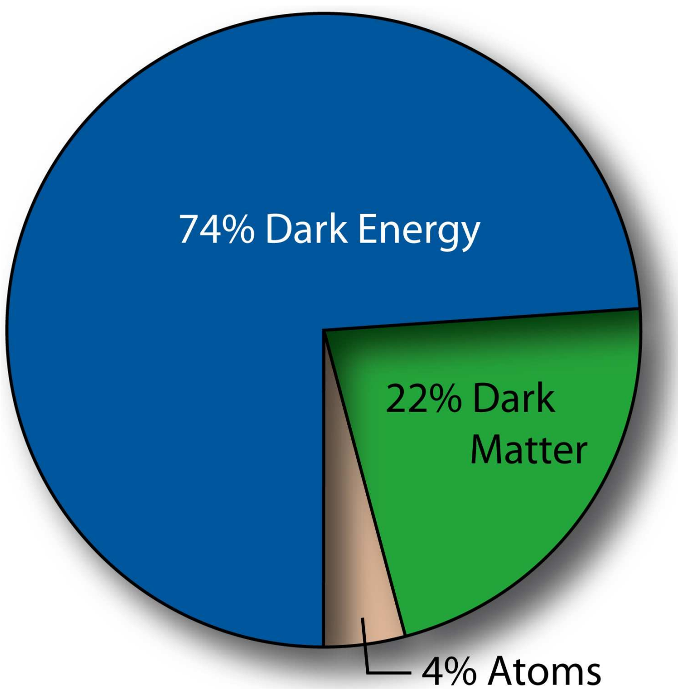
Most studies require R-parity conservation, however LEP limits also valid without

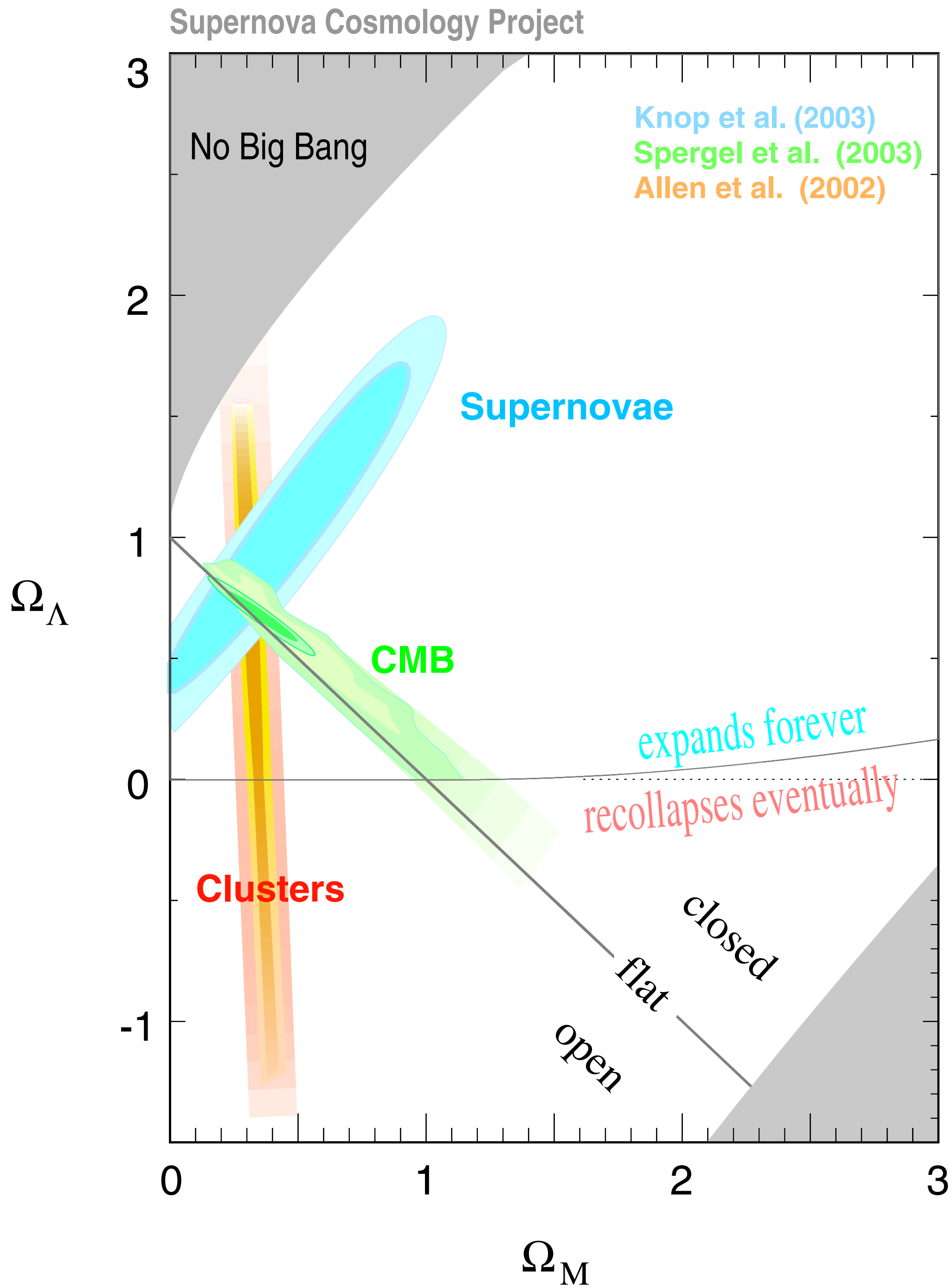
Most work in mSUGRA, different parameter constraints can change the picture

- Naturalness requires $m_{\mathrm{SUSY}} < 1\,\mathrm{TeV}$
- LEP limits around 100 GeV for all visible particles
- TEVATRON limits sometimes better, however with stronger requirement on particle-LSP mass difference
- If SUSY is realised in nature it will most probably be seen at the LHC

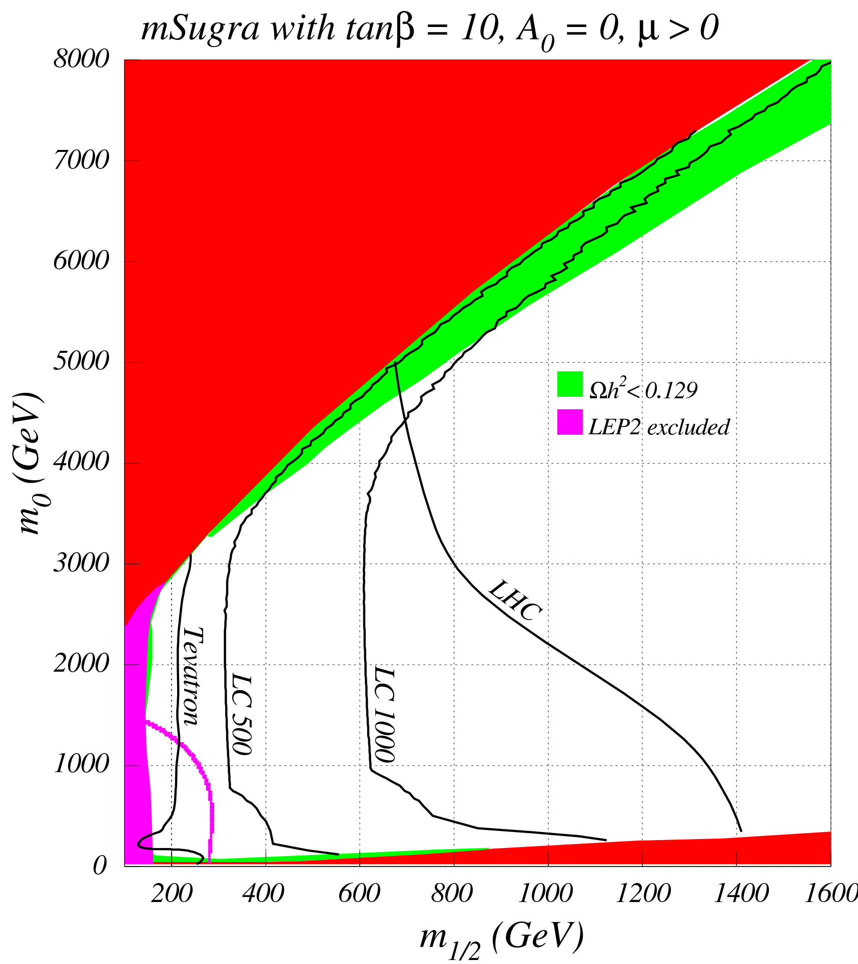
SUSY and dark matter

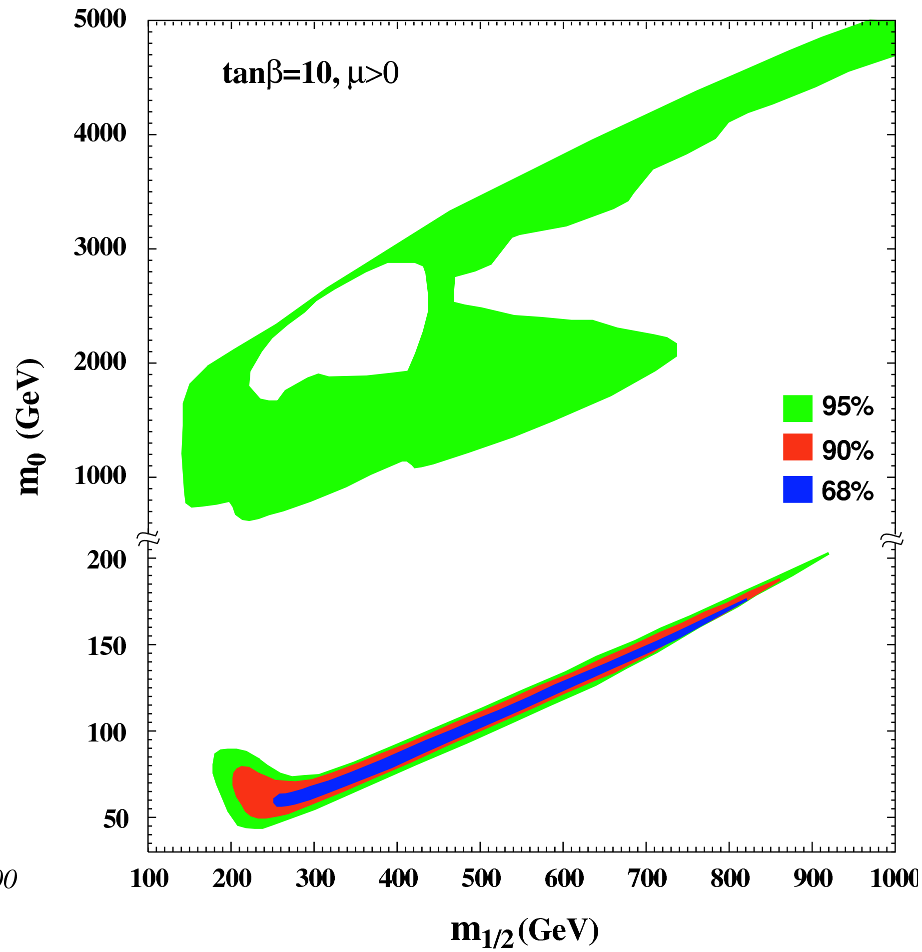
- The universe consists largely of dark matter
- The dark matter particle should be weakly interacting with $m = \mathcal{O}(100\,\text{GeV})$
- Its properties are largely constrained by the requirement to get the tight density





- The dark matter density has been accurately determined by WMAP
- If the LSP (χ_1^0) is stable its density has to be equal (or smaller) than the dark matter density
- This requirement constrains the SUSY parameter range
- Favoured regions are with small masses or small mass difference $\tilde{\tau} - \chi_1^0$

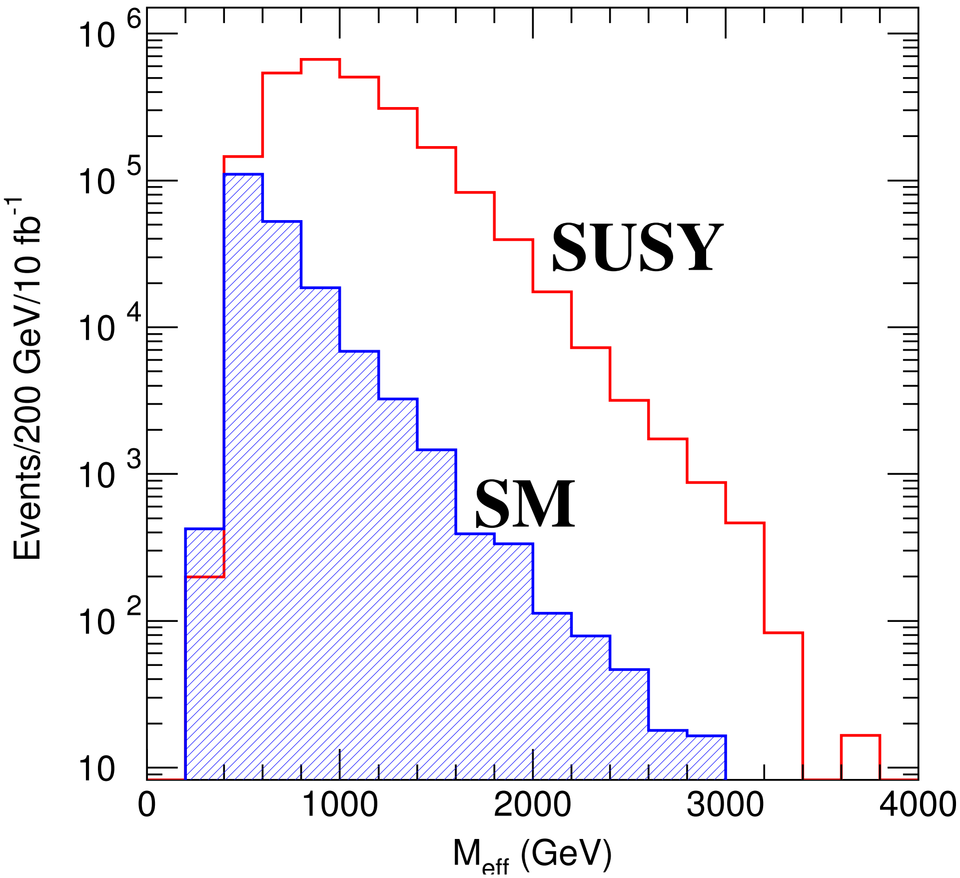




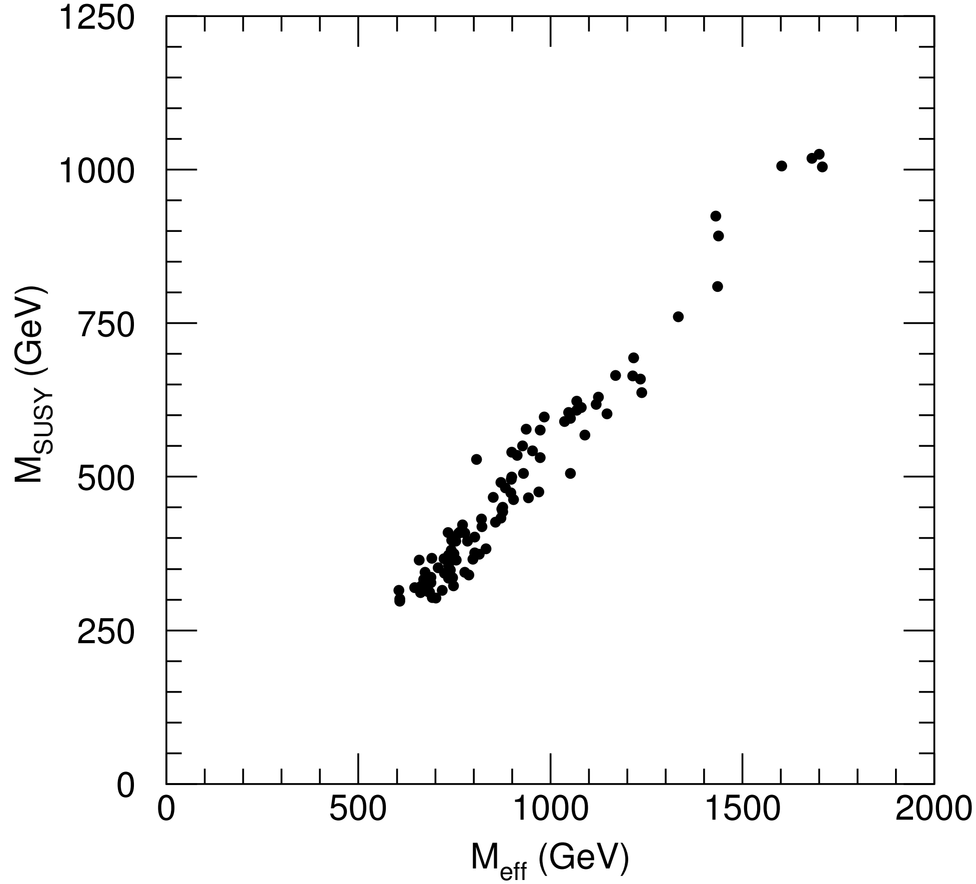
SUSY signatures at the LHC

- Squarks and gluinos have strong interaction ➡ huge production cross section
- Gauginos and sleptons can be produced in cascade decays like $\tilde{q} \to q\chi_2^0 \to q\ell\tilde{\ell} \to q\ell\ell\chi_1^0$ (or longer)
- Details of the cascades depend strongly on the SUSY parameters
- If mass differences are too small particles can be missed
- if R-parity is conserved SUSY events have a large missing (transverse) momentum
- This ensures a fast discovery of SUSY and a crude measurement of the mass scale

Effective mass measurement at ATLAS



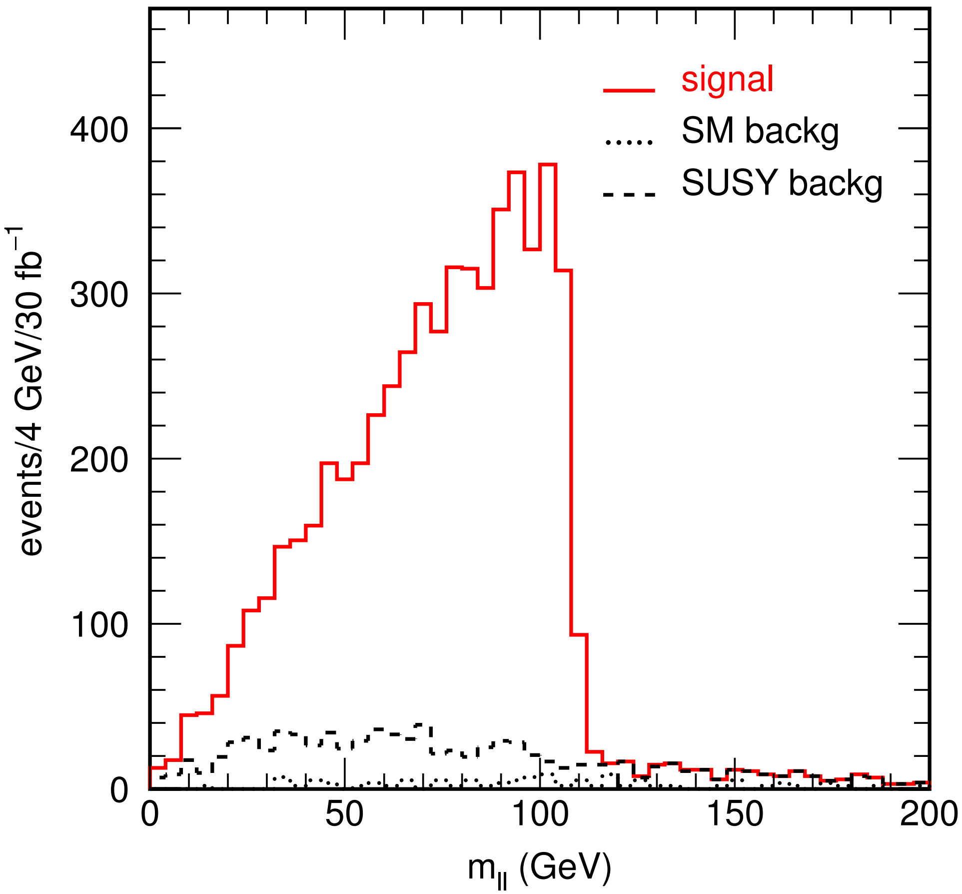
Correlation between effective mass peak and SUSY mass scale



Measurement of masses

- If the LSP is stable there are no mass-peaks
- Mass differences can be measured pretty accurately from endpoints of mass spectra, like $\chi_2^0 \to \ell\tilde{\ell} \to \ell\ell\chi_1^0$
- The mass of the LSP (χ_1^0) is very difficult to measure in a model independent way

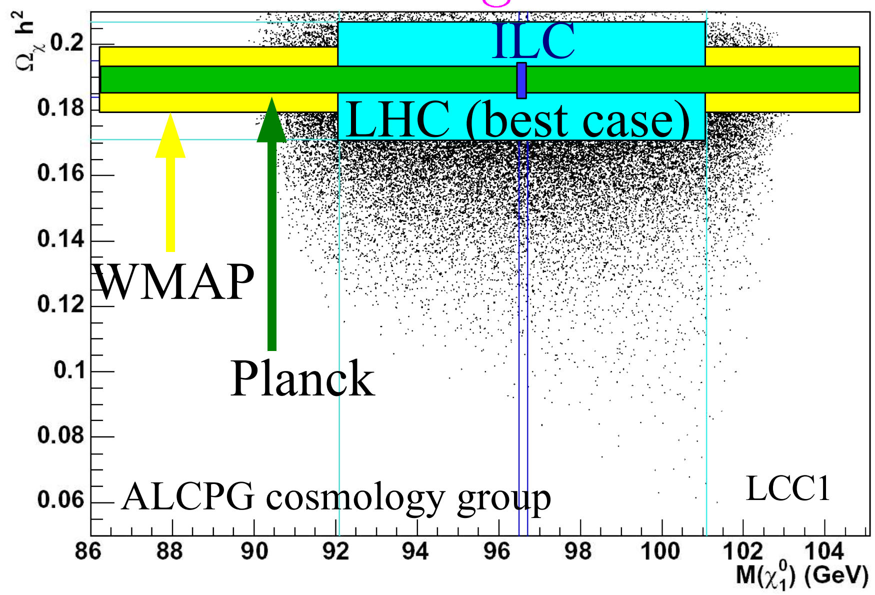
$\ell^+\ell^-$ mass from $\chi_2^0 \to \ell\tilde{\ell} \to \ell\ell\chi_1^0$



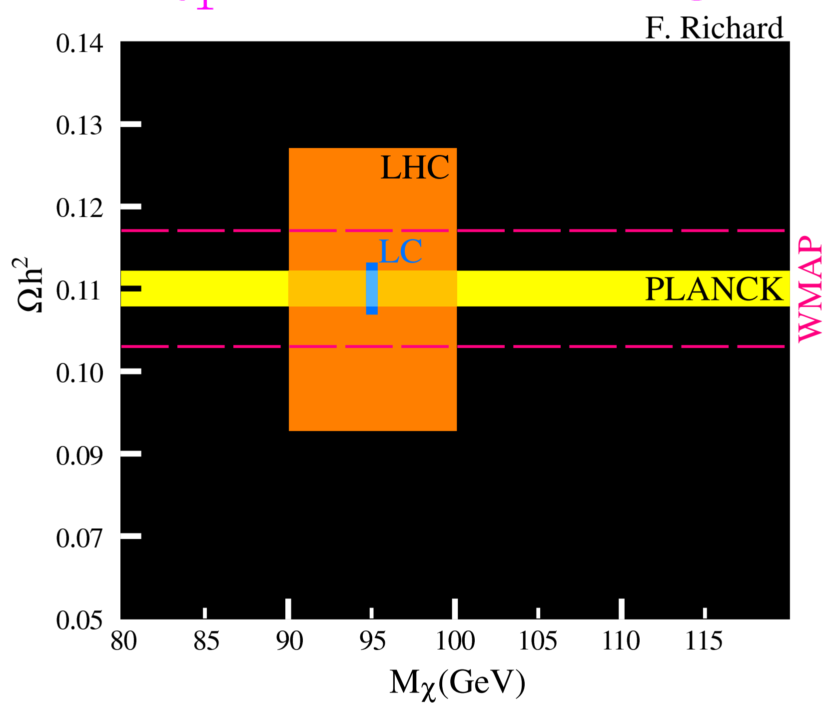
Reconstruction of dark matter

- A stringent test of cosmology has to compare the CMB measurements with density calculations using the particle physics model
- To calculate the dark matter density the masses and properties of all involved particles are needed.
- In scenarios with light superpartners the LHC can do fairly well
- However in more difficult regions like the $\tilde{\tau} - \tilde{\chi}_1^0$ coannihilation region the LHC has difficulties
- For the ultimate answer ILC will be needed.

Bulk region



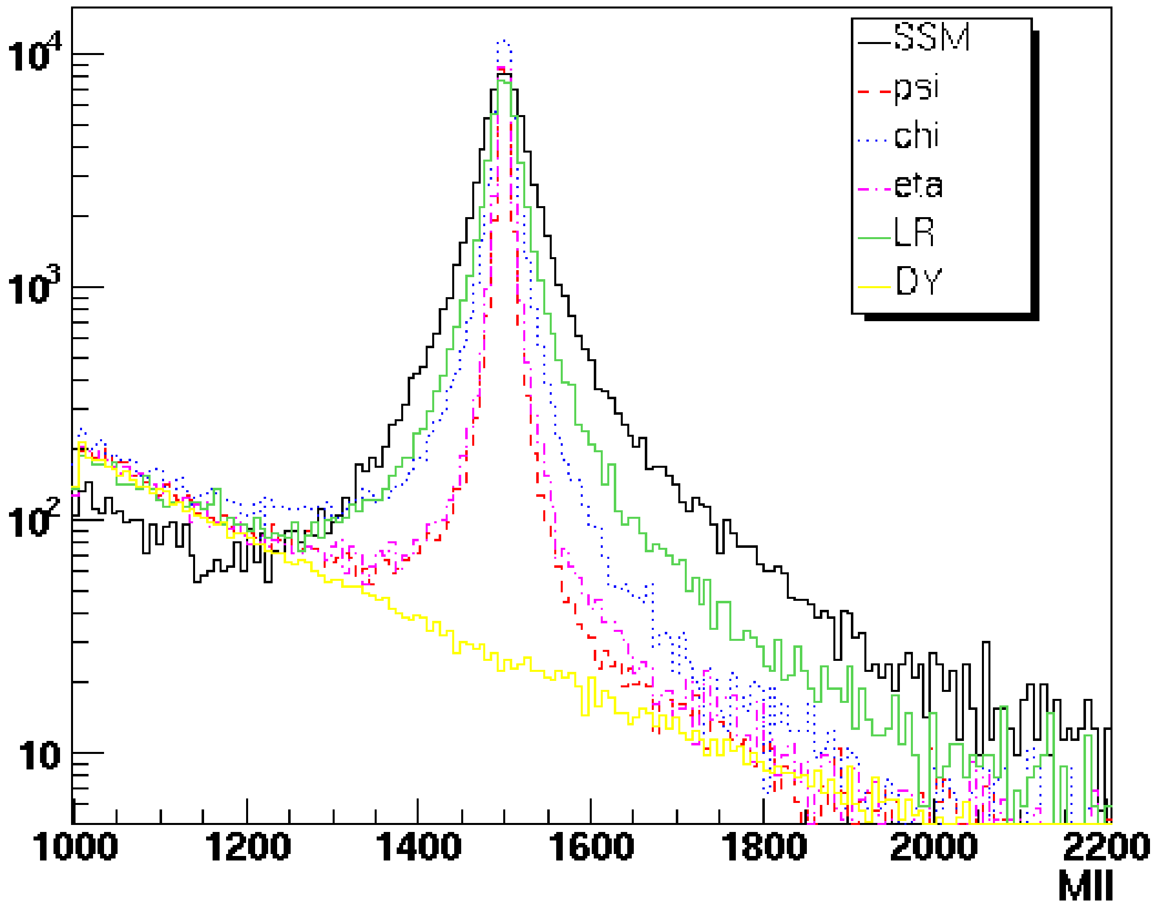
$\tilde{\tau} - \tilde{\chi}_1^0$ coannihilation region



Other new physics at the LHC

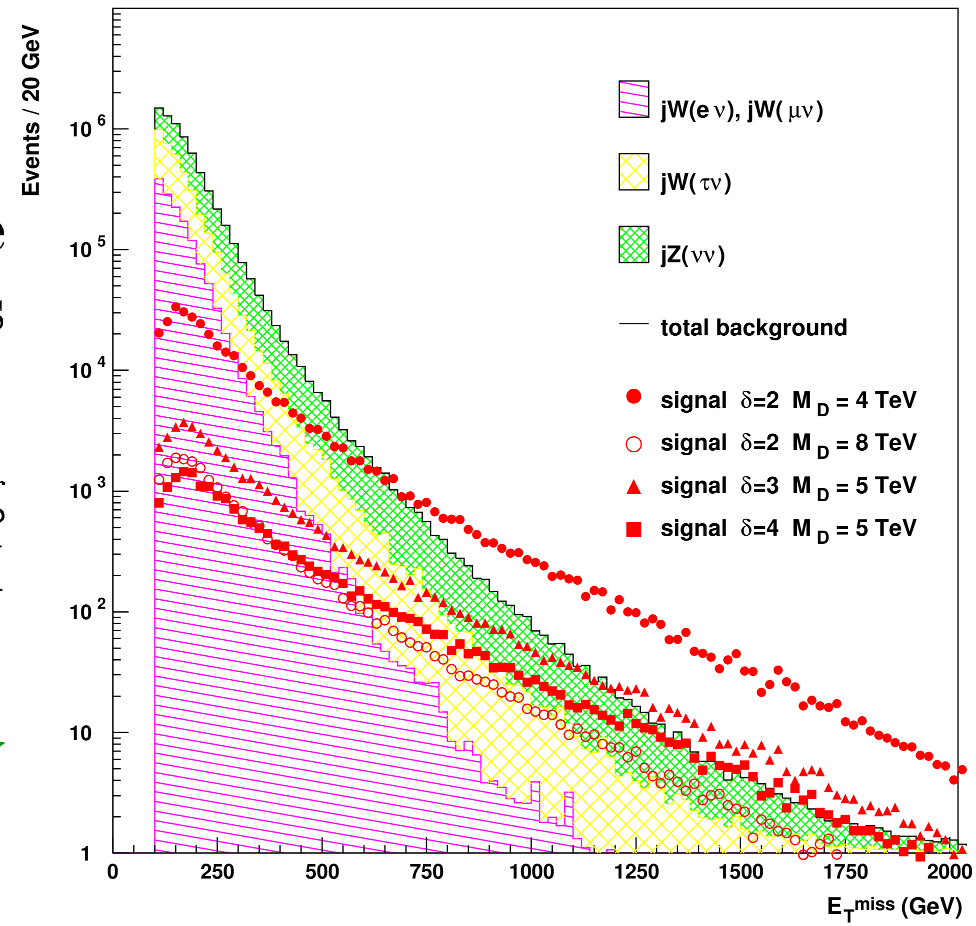
- Supersymmetry is the best studied example for new physics at the LHC
- However the LHC is sensitive to other models as well
- Many models contain a Z' decaying into leptons

- Such particles can be seen up to $m \sim 5\,\mathrm{TeV}$
- A large class of models contains extra space dimensions
- Also these models usually give visible signals



Example: Large extra dimensions

- Our universe contains (4+n) dimensions
- The n dimensions are compactified with radius $R \leq 10\mu$m
- Only gravity lives in the extra dimensions
- Advantage: gravity as strong as the other forces ($F \propto 1/r^{2+n}$ for $r < R$) ➡ no hierarchy
- Particle physics signature: Huge number of KK graviton resonances as invisible particles
- LHC signal: Events with missing p_T for jets recoiling against a KK graviton
- LHC is sensitive to scales of few TeV



Conclusions

- A $\sqrt{s} = 14\,\mathrm{TeV}$ pp collider (LHC) is being built at CERN
- The LHC will start (high energy) data taking early 2008
- The detectors are well on their way
- If a Standard Model like Higgs exists it will be found in the next few years
- Also other new physics on the TeV scale should be found
- Ideal time for students to join