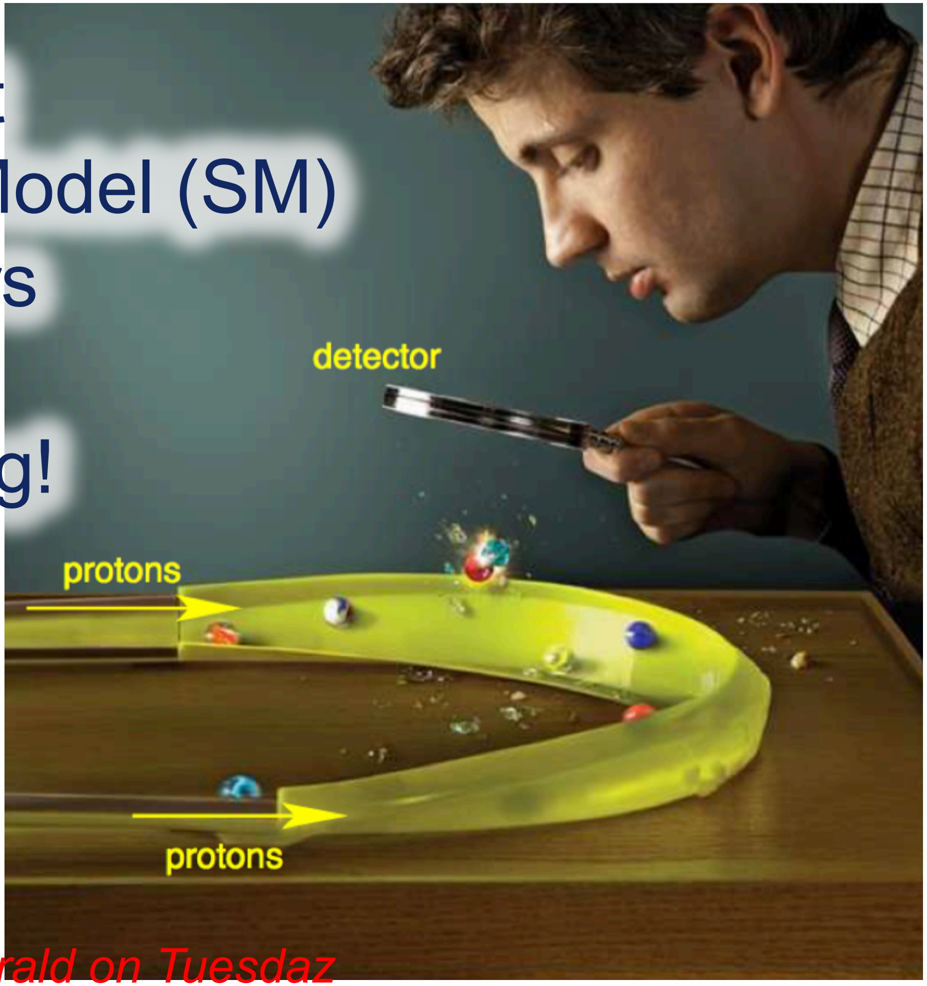
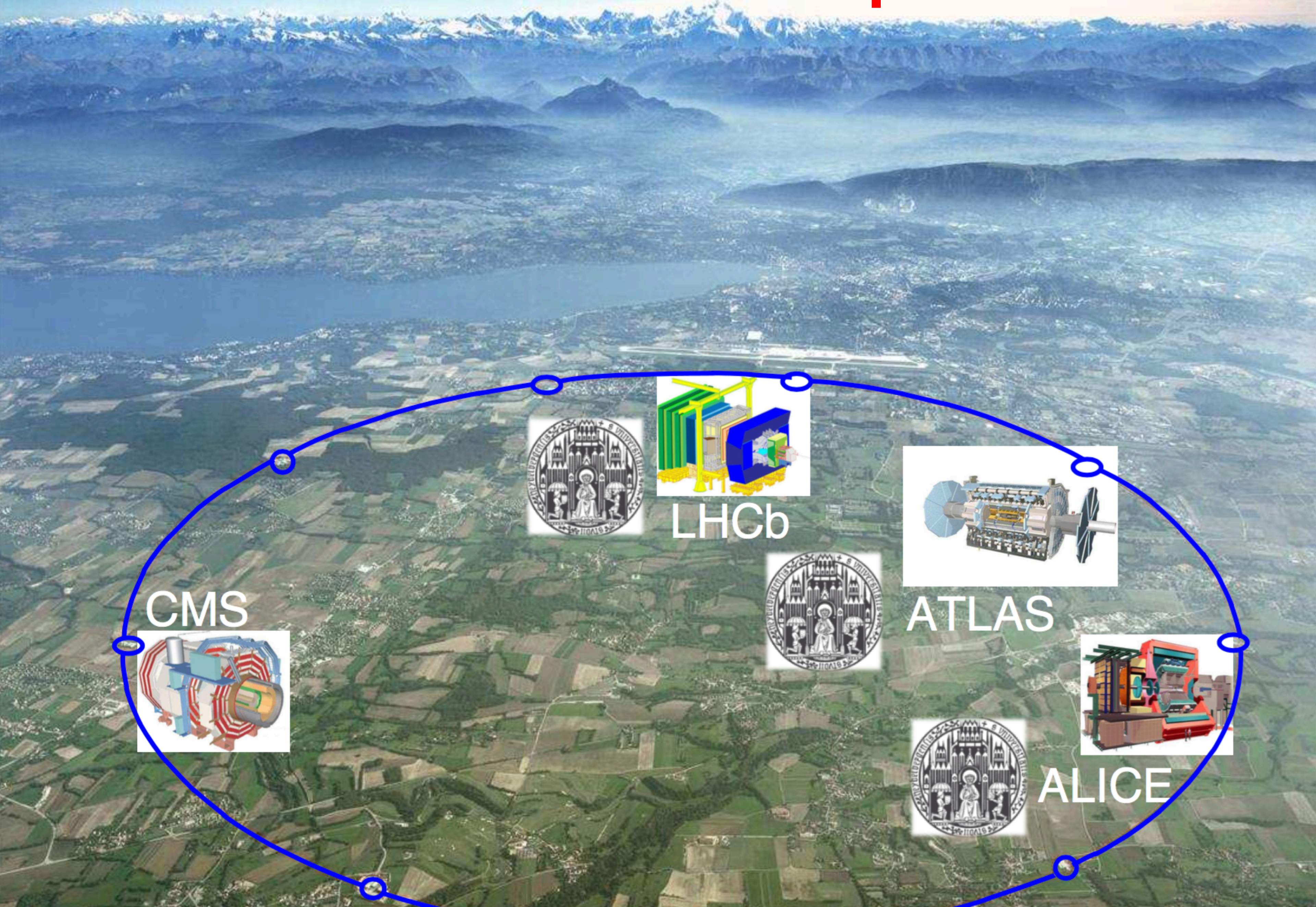
Today: scrutinise the Standard Model with particle accelerators and detectors

Will talk about
1) Standard Model (SM)
2) Accelerators
3) Detectors
in the following!



See also lecture by Gerald on Tuesdaz

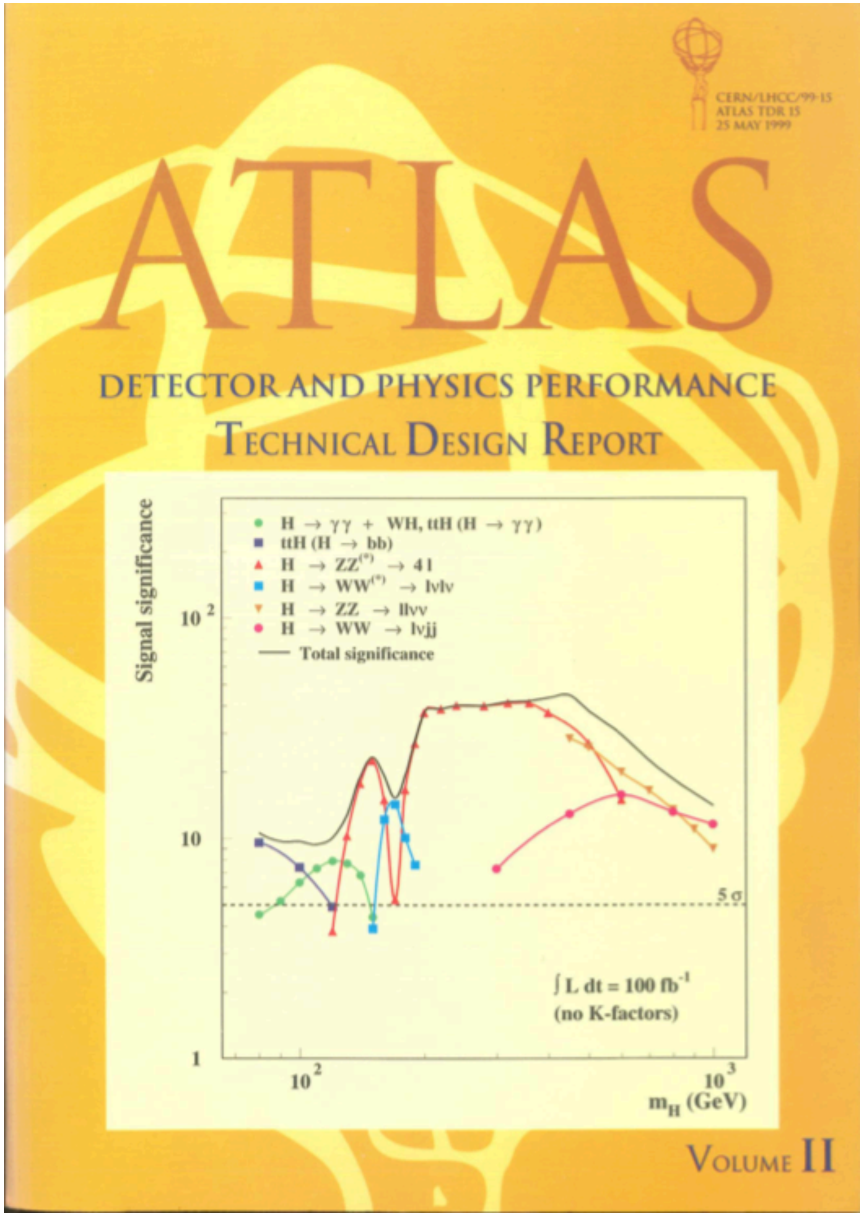
Overview of the LHC experiments



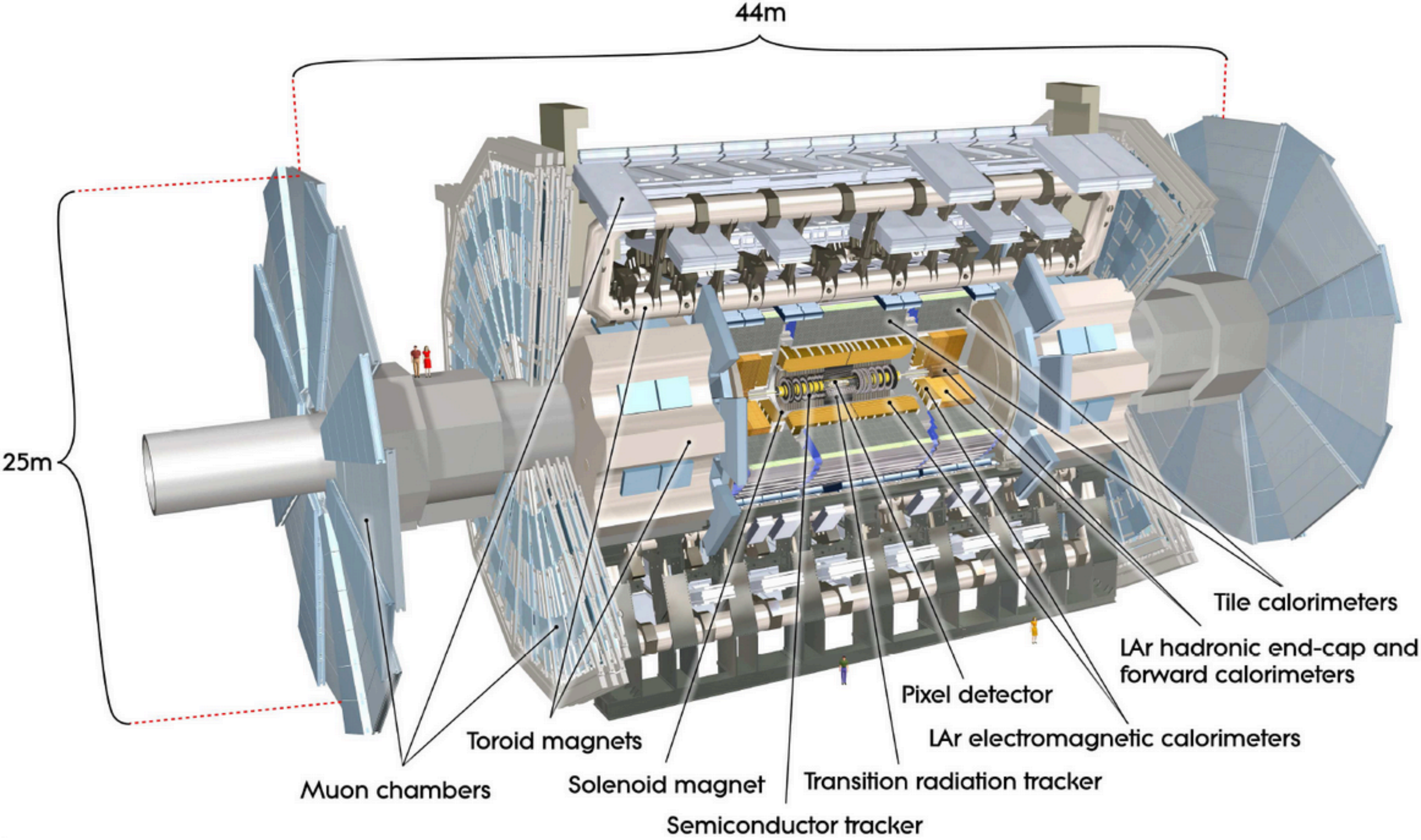
Overview of the LHC experiments

Focus on general-purpose detectors
for Higgs discovery in the following
describe ATLAS in detail, then
CMS (highlight differences)

ATLAS physics goal: Higgs discovery

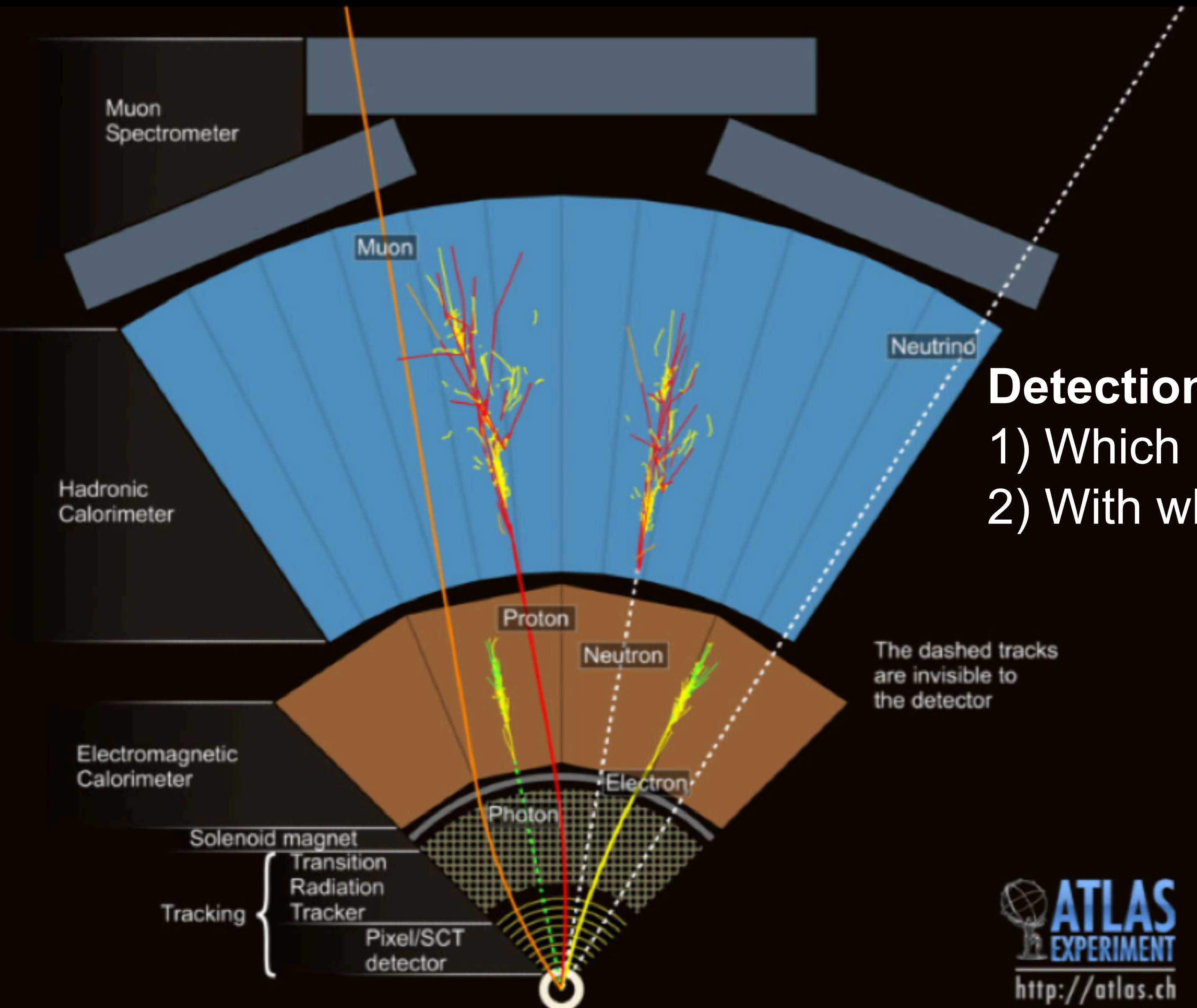


ATLAS experiment



ATLAS Collaboration

Teilchendetektion mit ATLAS



Detection:

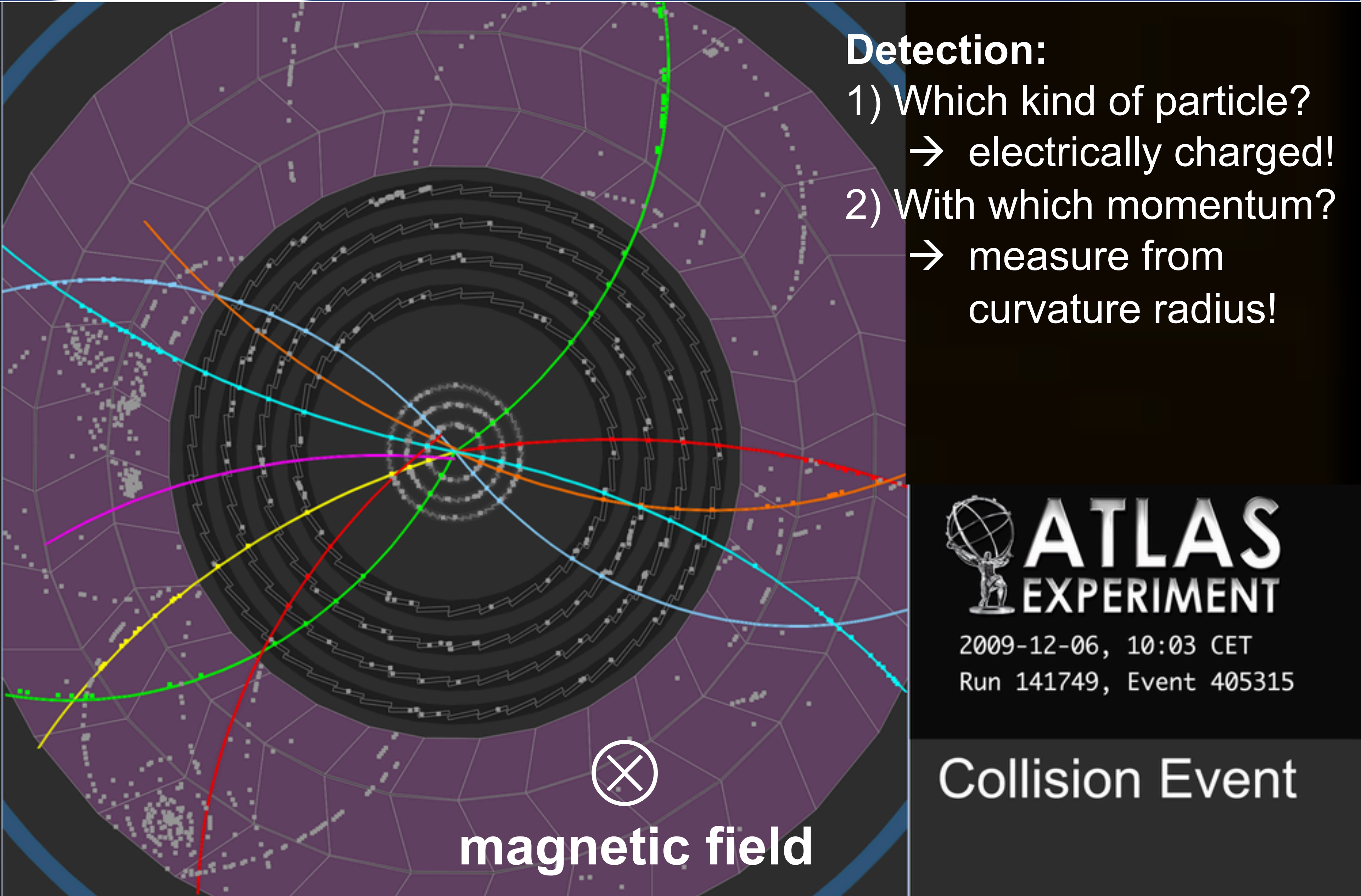
1) Which kind of particle?
2) With which momentum?

KIRCHHOFF-INSTITUT FÜR PHYSIK

Tracking detector

Detection:

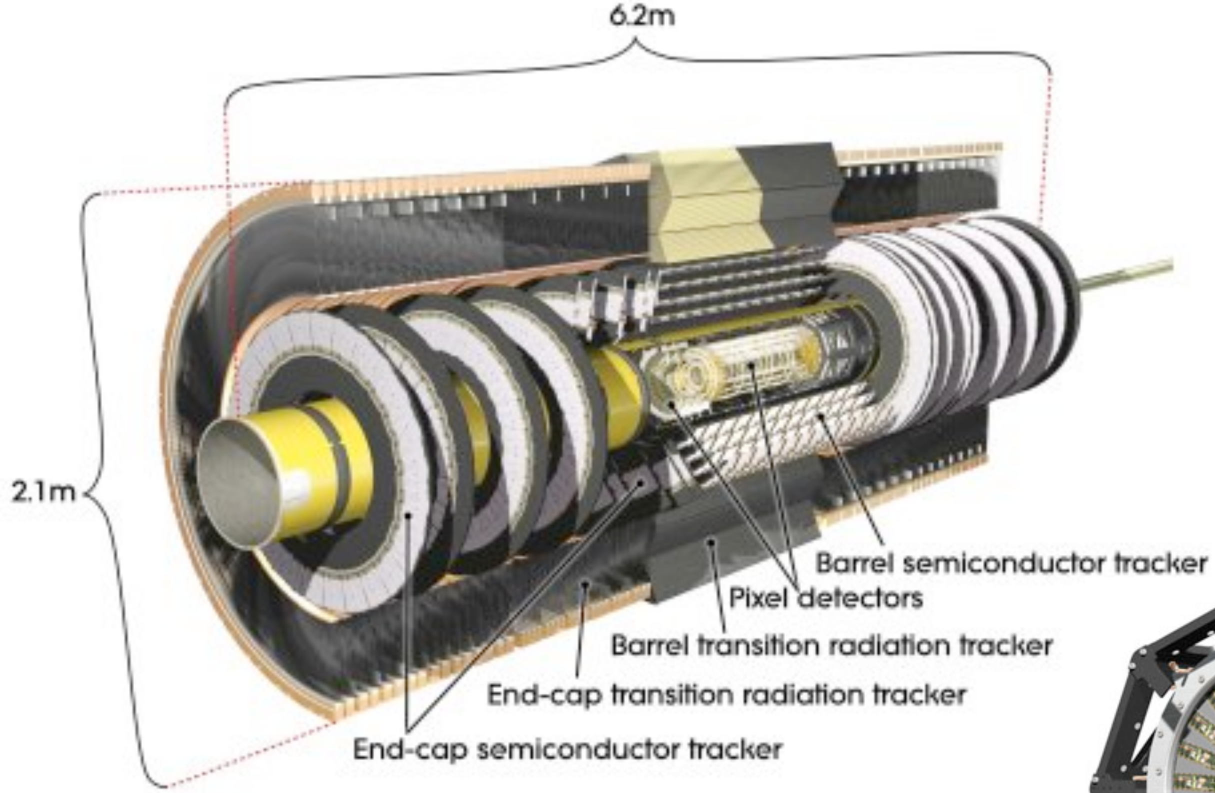
1) Which kind of particle?
   → electrically charged!
2) With which momentum?
   → measure from curvature radius!



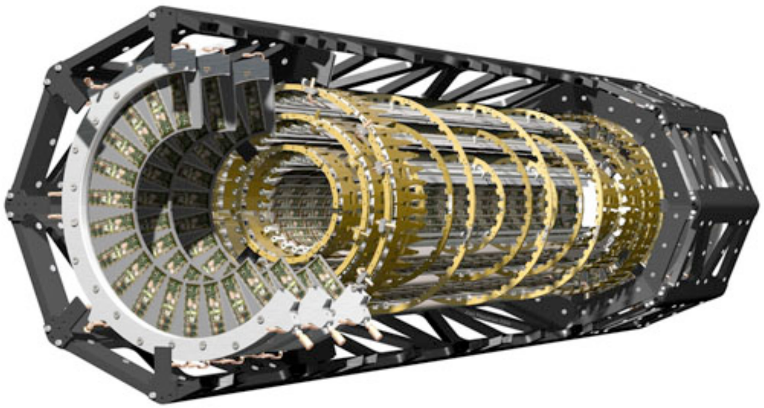
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Tracking detector

Transition radiation tracker (outermost), silicon strip tracker (intermediate) and silicon pixel tracker (innermost)



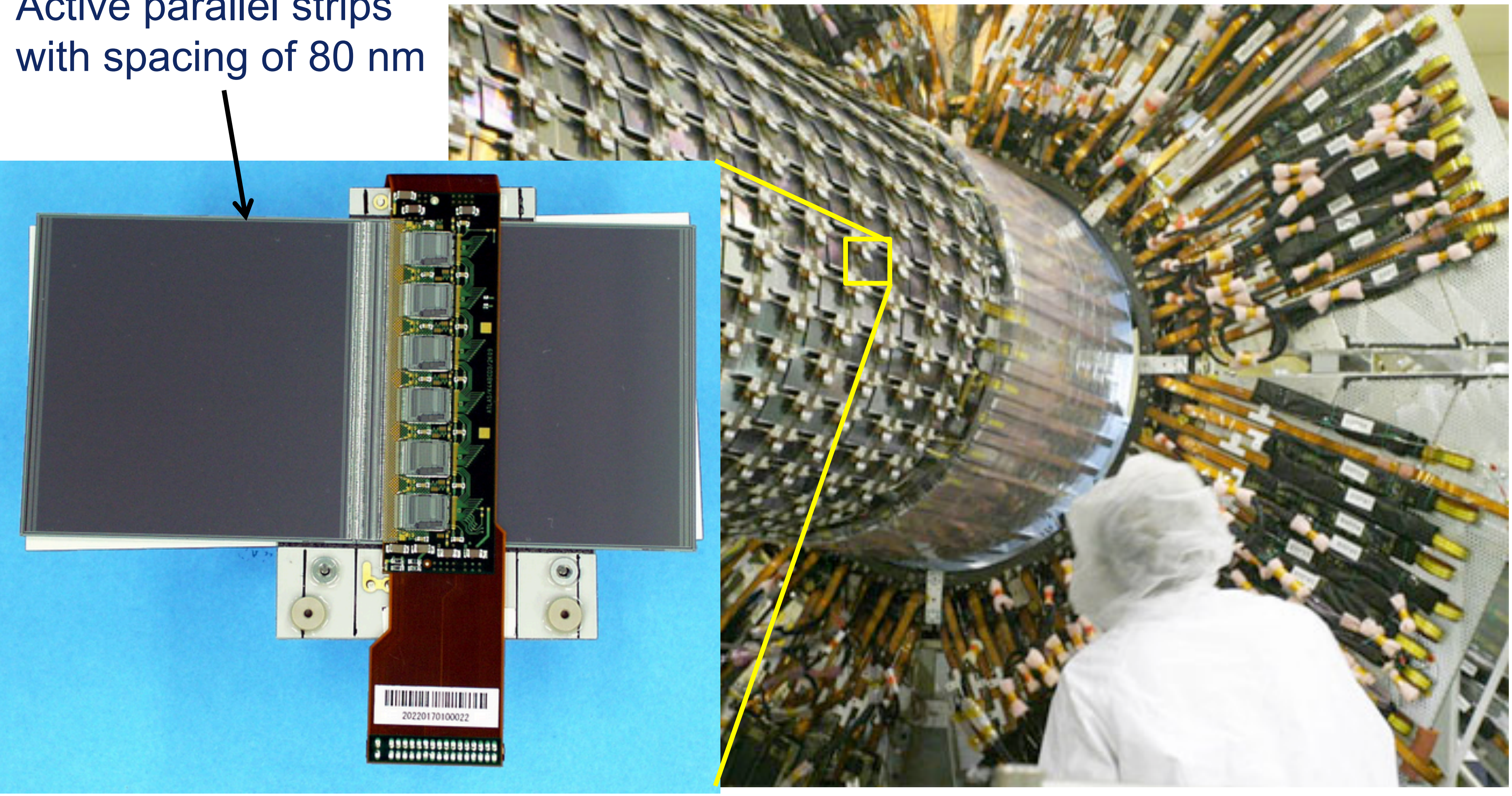
Pixel detector



Silicon strip tracker

Detection principle: measure ionisation charge

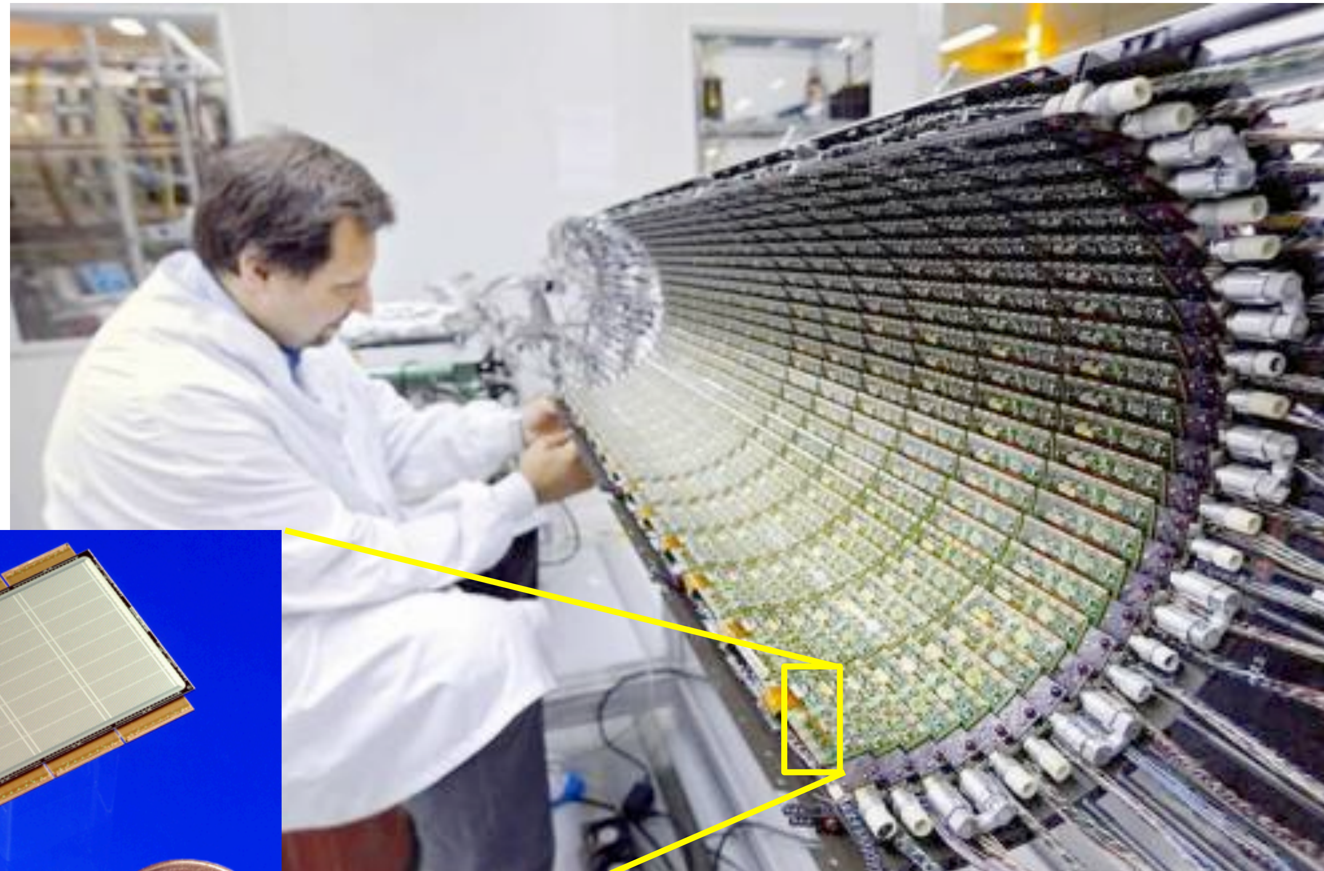
Active parallel strips
with spacing of 80 nm

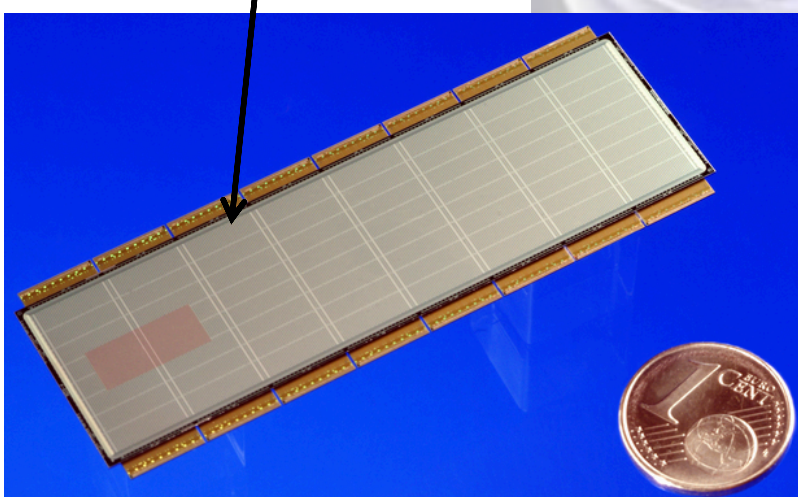


Silicon pixel tracker

Detection principle: measure ionisation charge

Active pixels with spacing of 50 nm x 400 nm





Ionisation charge versus momentum

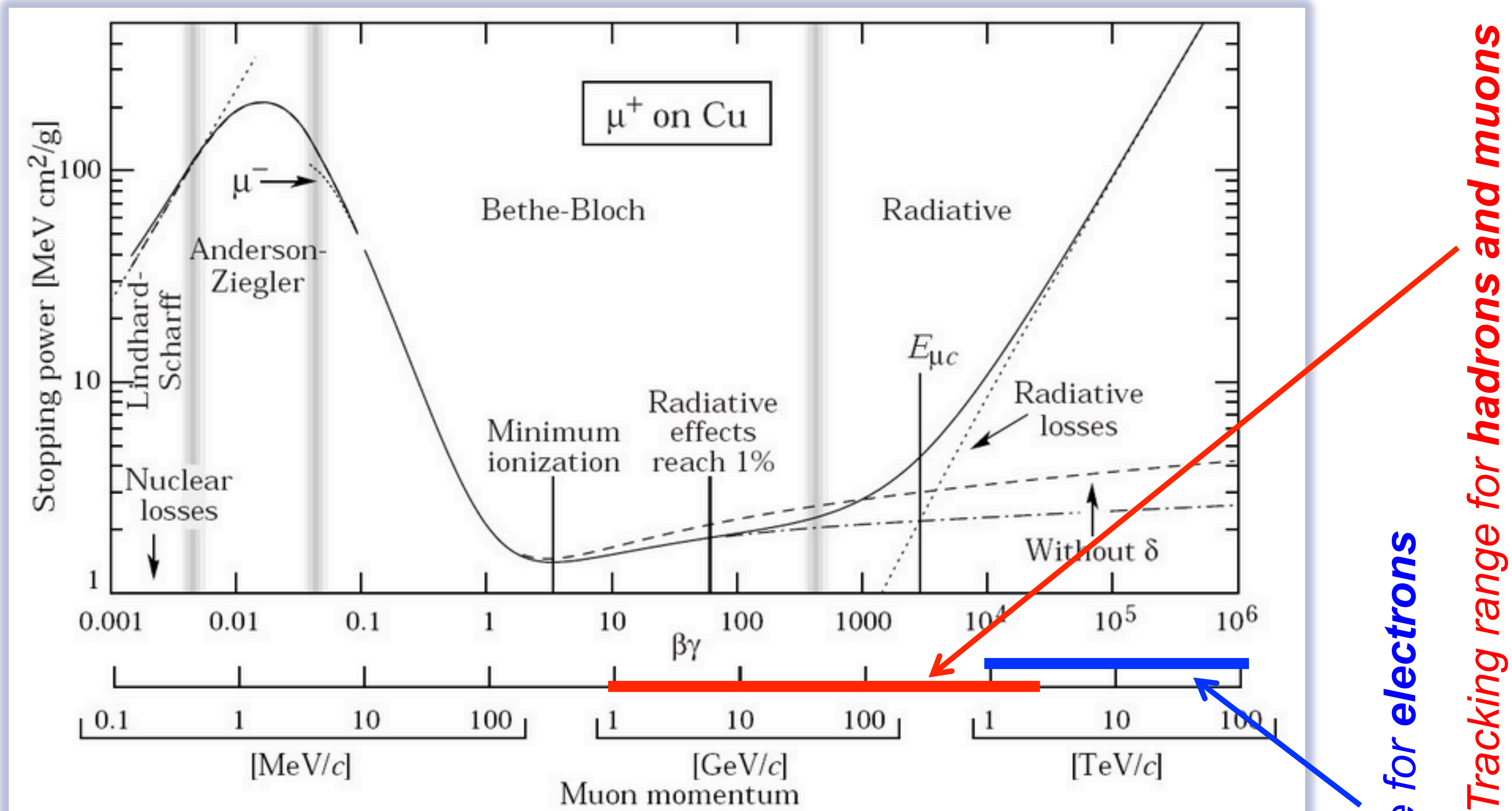
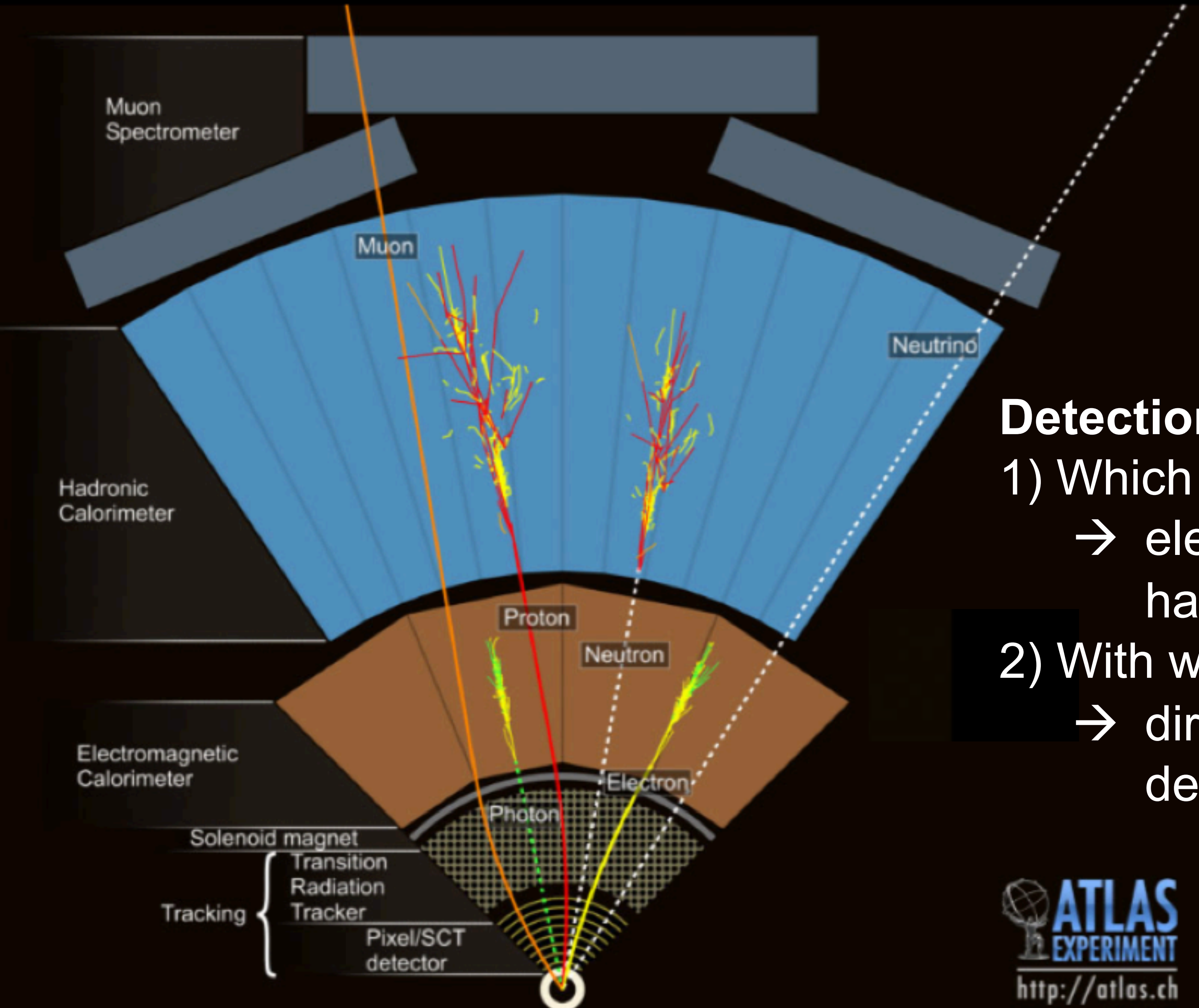


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [2], and data at higher energies are from Ref. 1. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [3].

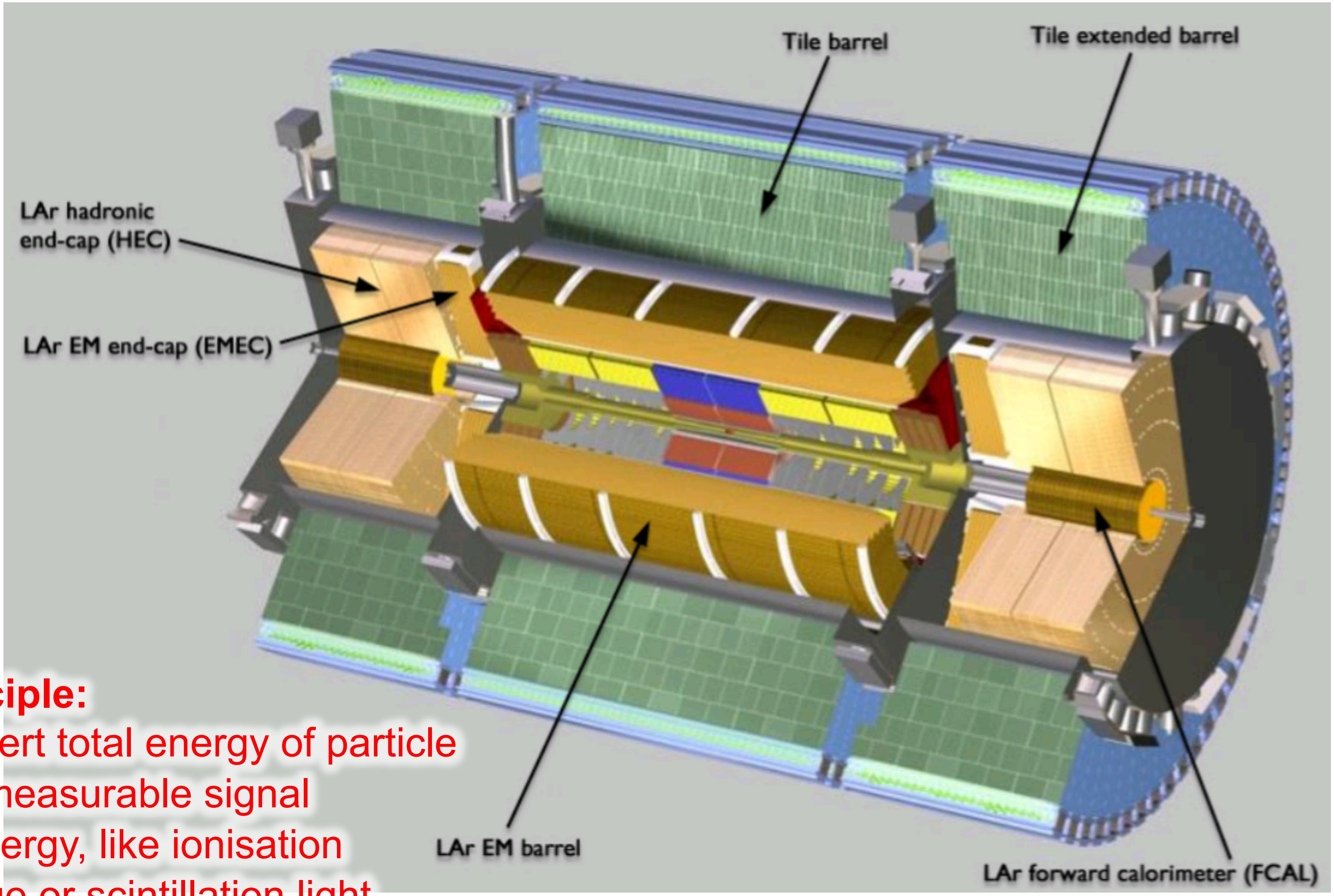
Calorimetry in ATLAS



Detection:

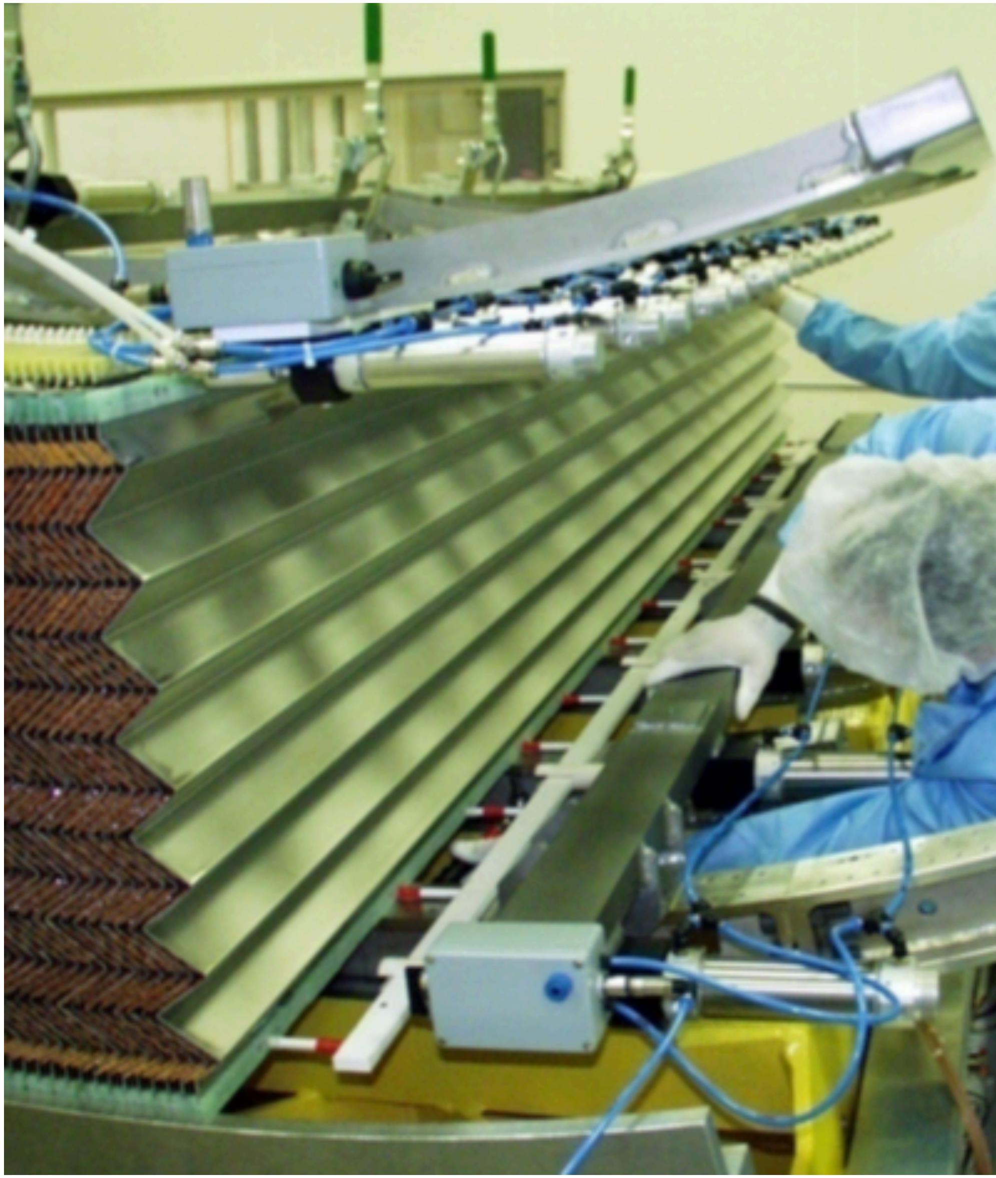
1) Which kind of particle?
   → electrons, photons, hadrons
2) With which momentum?
   → directly measure deposited energy

Calorimeter

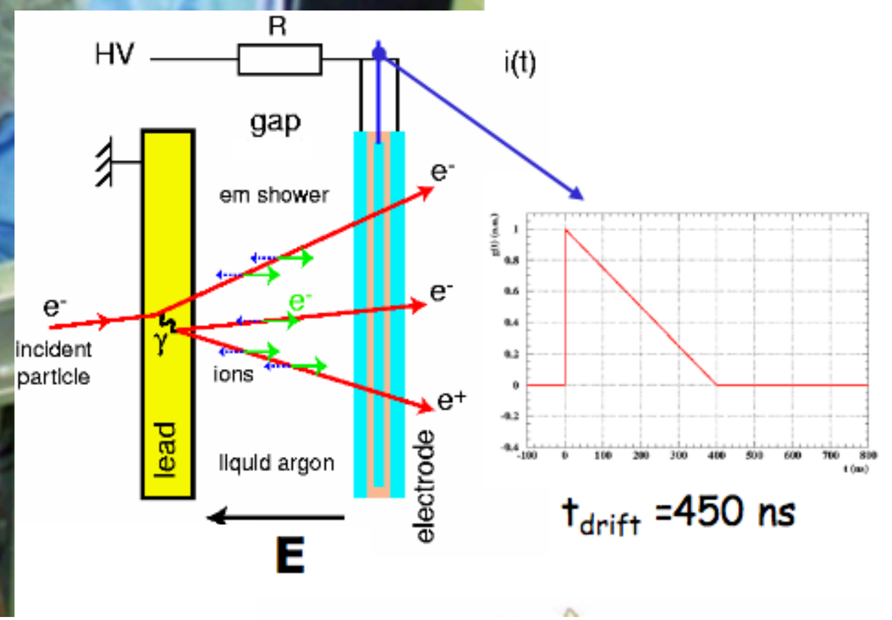


Principle:
Convert total energy of particle into measurable signal $\propto$ energy, like ionisation charge or scintillation light

Liquid Argon (LAr) Calorimeter

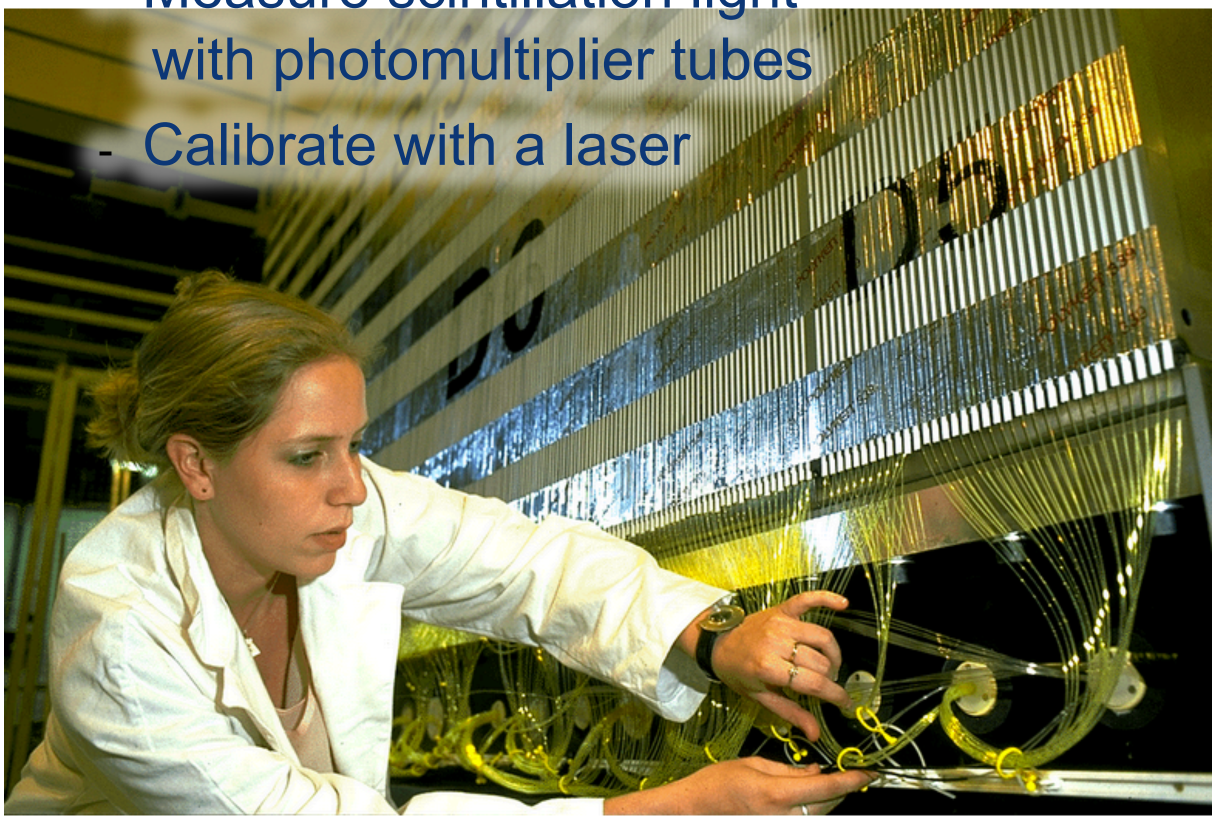


- **LAr Calorimeter**
  - Copper plates
  - Argon between plates
  - Particles ionise Argon
  - Measure ionisation charge by applying external voltage



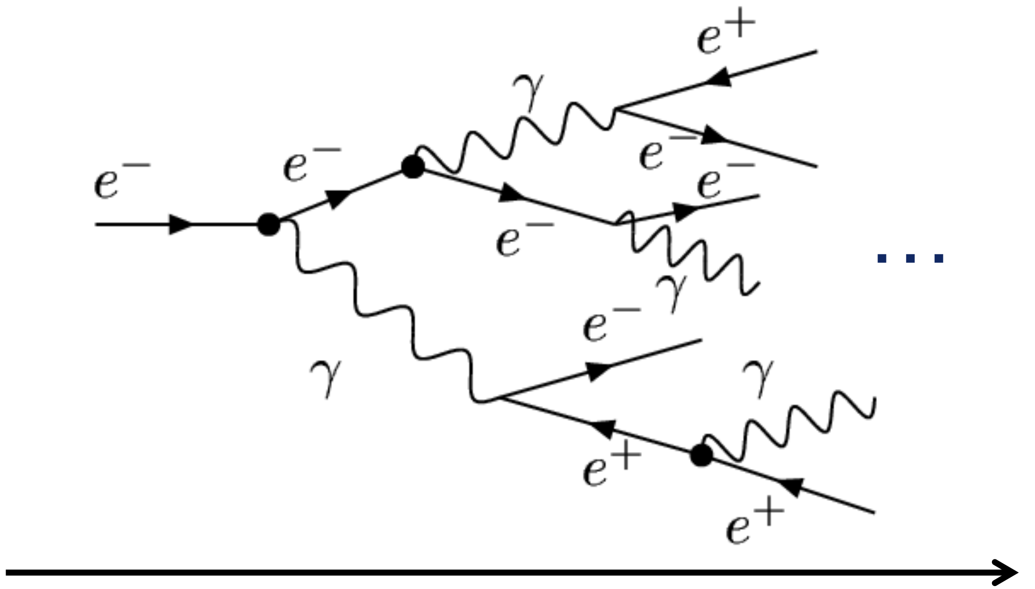
Scintillating tile Calorimeter

- **Tile Calorimeter**
  - Tiles of scintillating plastic
  - Particles create scintillation light
  - Measure scintillation light with photomultiplier tubes
  - Calibrate with a laser



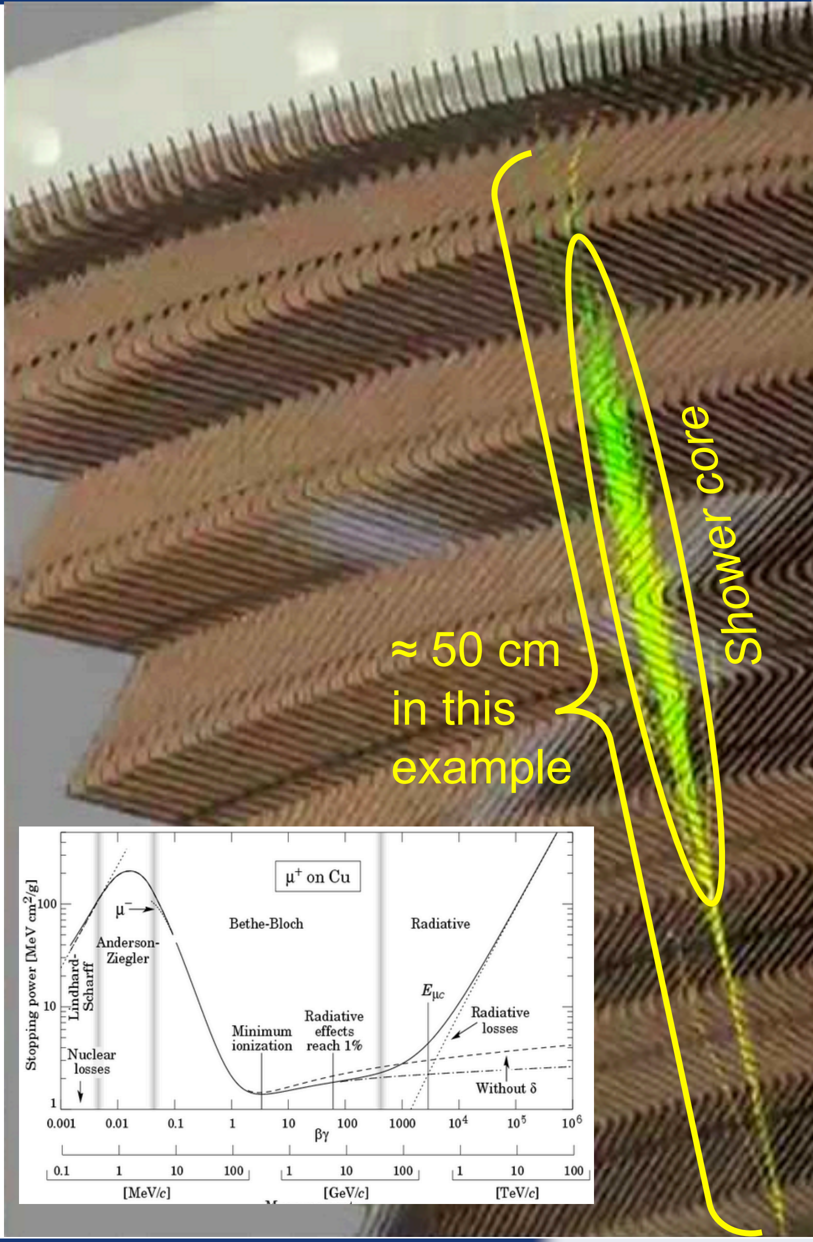
Calorimeter principle

- Example: **EM-shower in LAr Calo:**



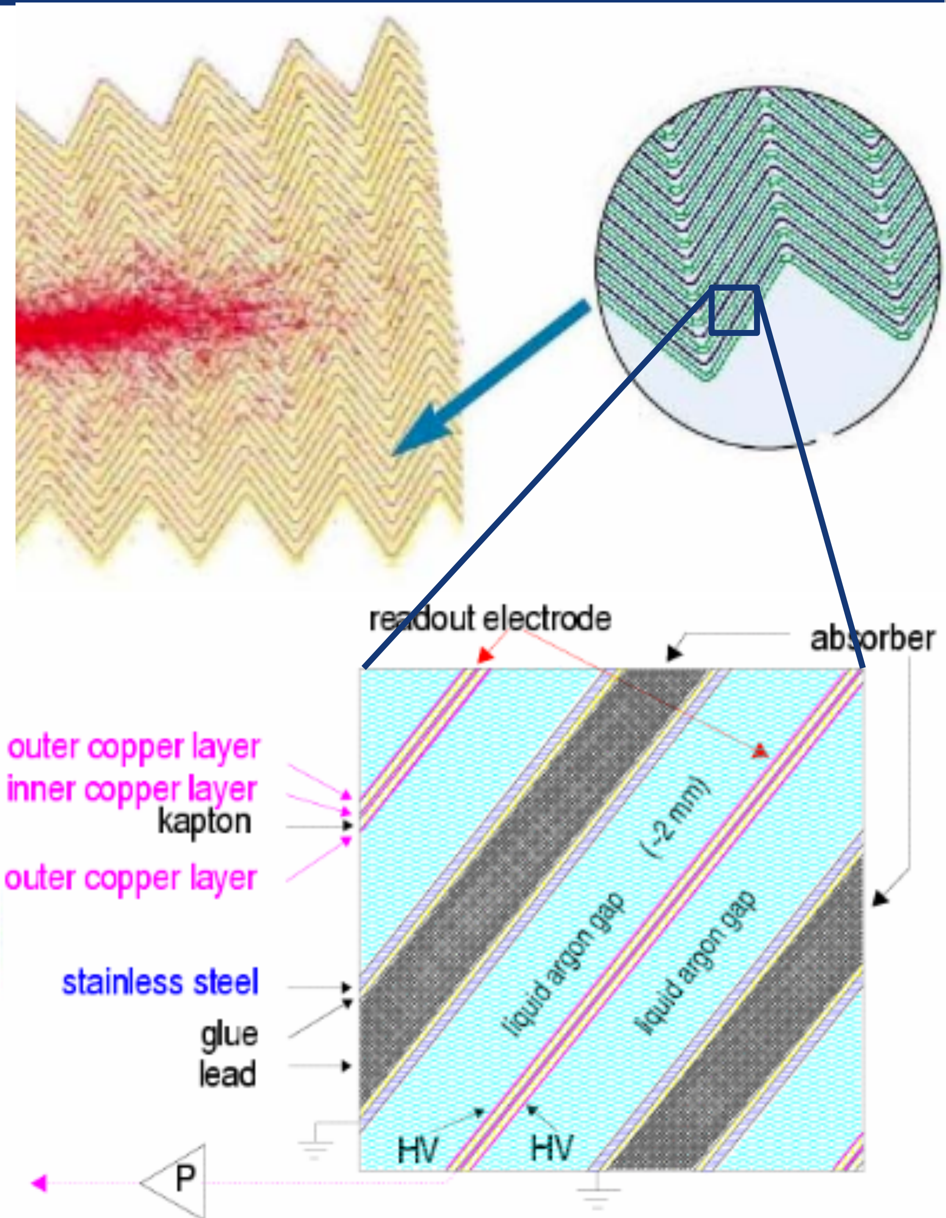
X_0: Radiation length
∝ average path length
btw. EM-interactions

- ≈90% energy in shower core (ionisation dominant over Bremsstrahlung) with high particle multiplicity
- Energy resolution ∝ particle multiplicity
- Shower depth ∝ log(shower energy)

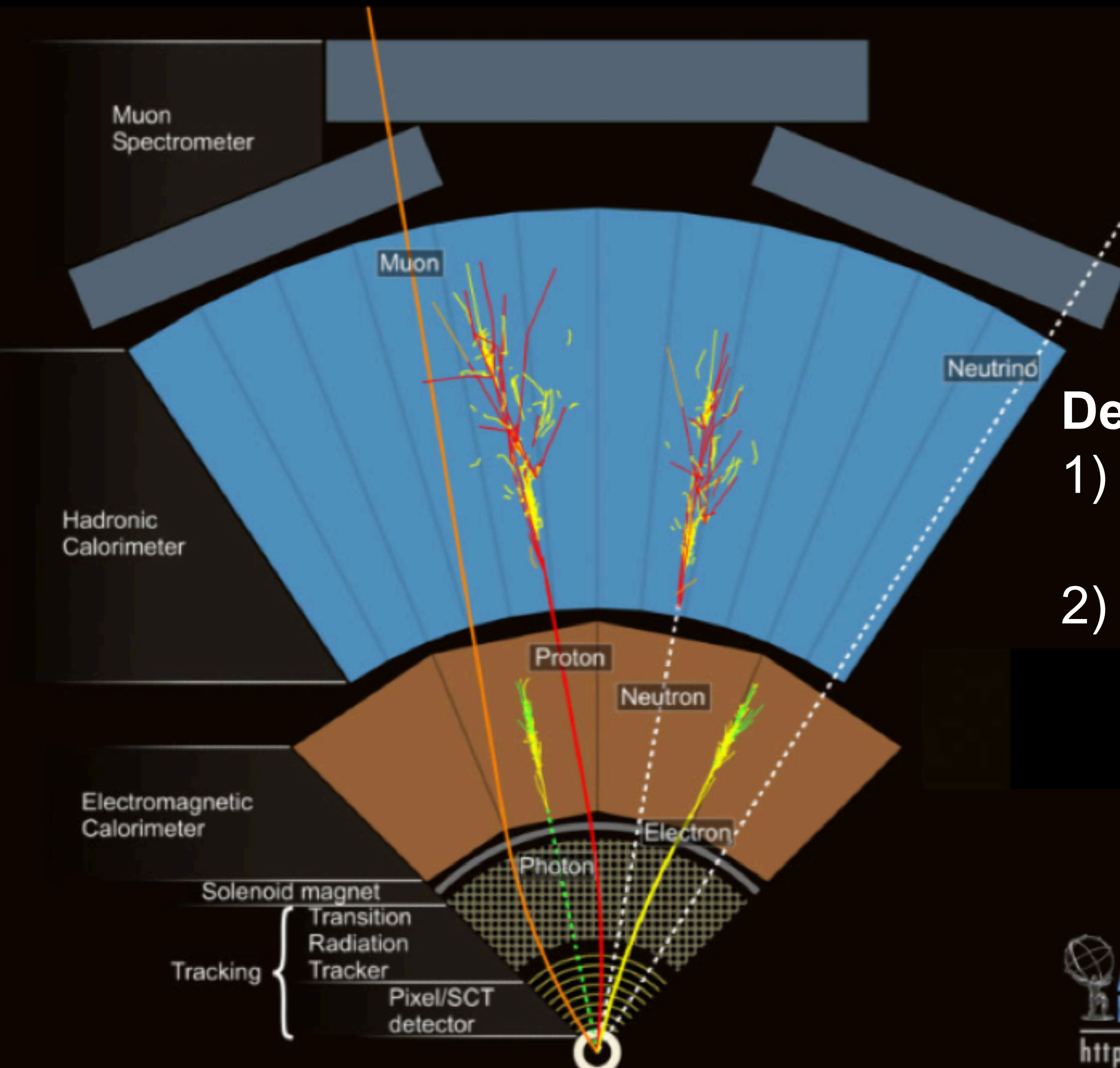


Sandwich calorimeters

- Radiation lengths:
  - **X_0^{Ar} = 14 cm**
  - X_0^{Fe} = 1.7 cm
  - X_0^{Pb} = 0.6 cm
- With LAr alone for $d > 22\ X_0$:
  - >3 m deep calorimeter!
    - Too large volume, prohibitive
- **→ Sandwich calorimeter:**
  - Active slices (LAr)
    - Signal collection & readout
  - Passive slices (Pb)
    - Faster shower development (increase particle multiplicity as quickly as possible)
  - Price: degraded resolution



Muon spectrometer in ATLAS



Detection:

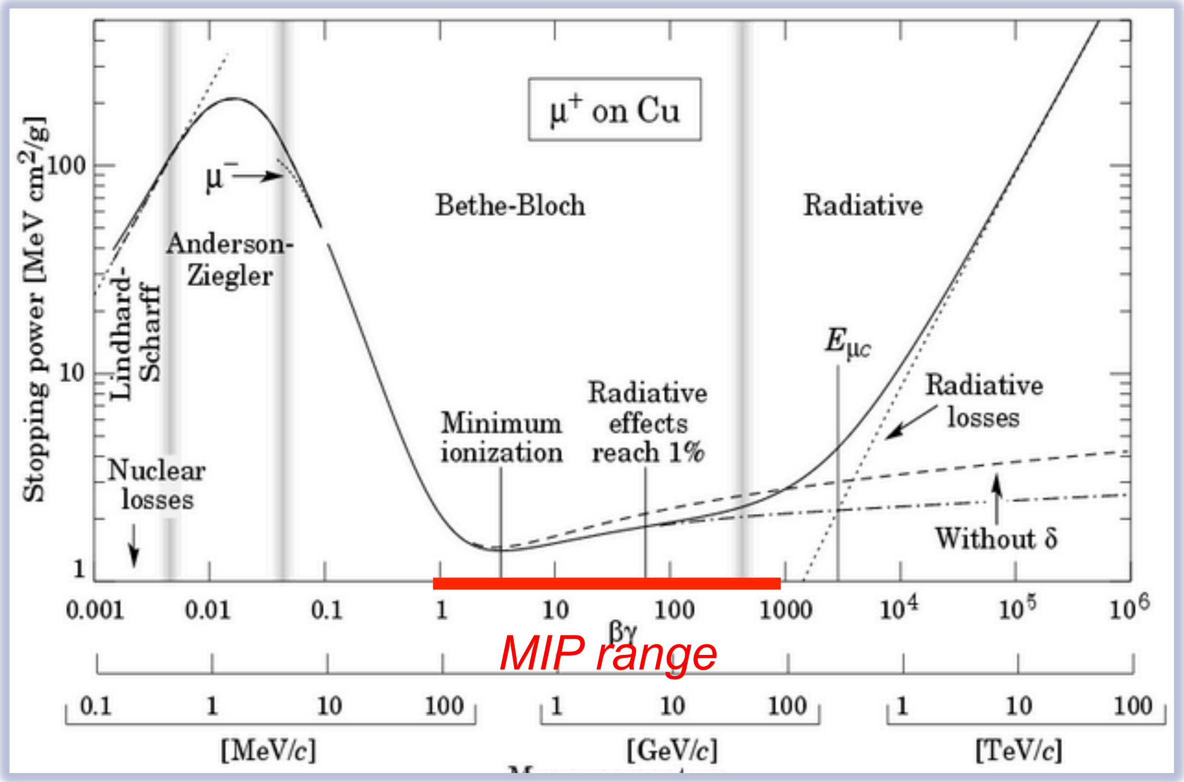
1) Which kind of particle?
   → muons
2) With which momentum?
   → measure from curvature radius in tracker and muon spectrometer

ATLAS EXPERIMENT http://atlas.ch

Muon identification

- Muon **identification** is "easy":
  - Any* electrically charged particle which exits the calorimeter is:
    - Minimum ionising particle (MIP)
    - Not hadronically interacting

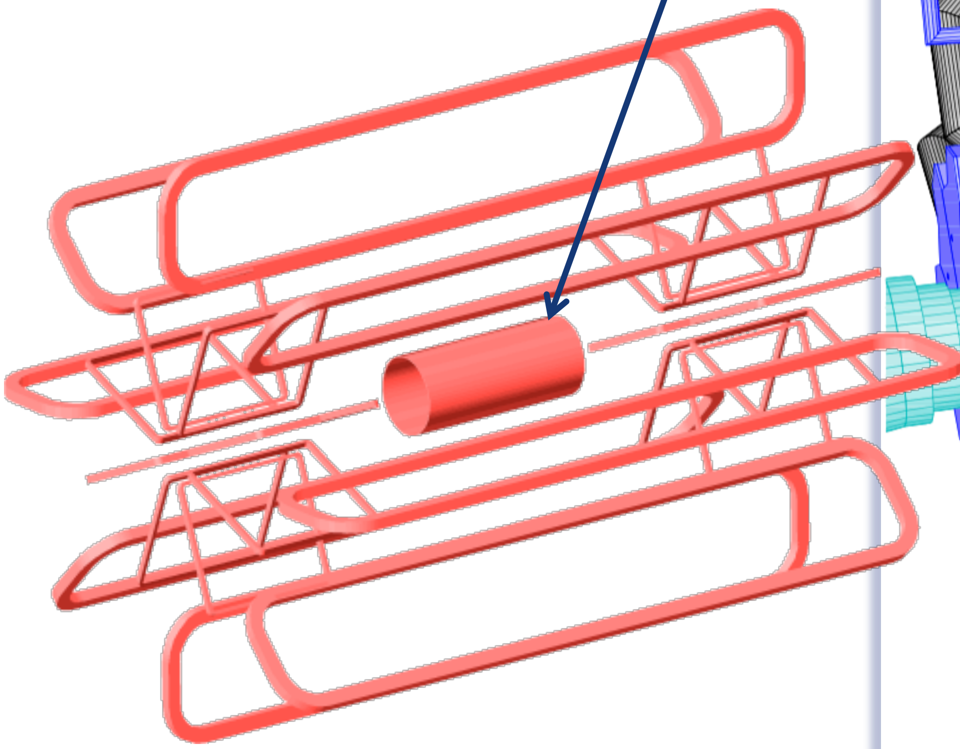
⇨ **A muon!**

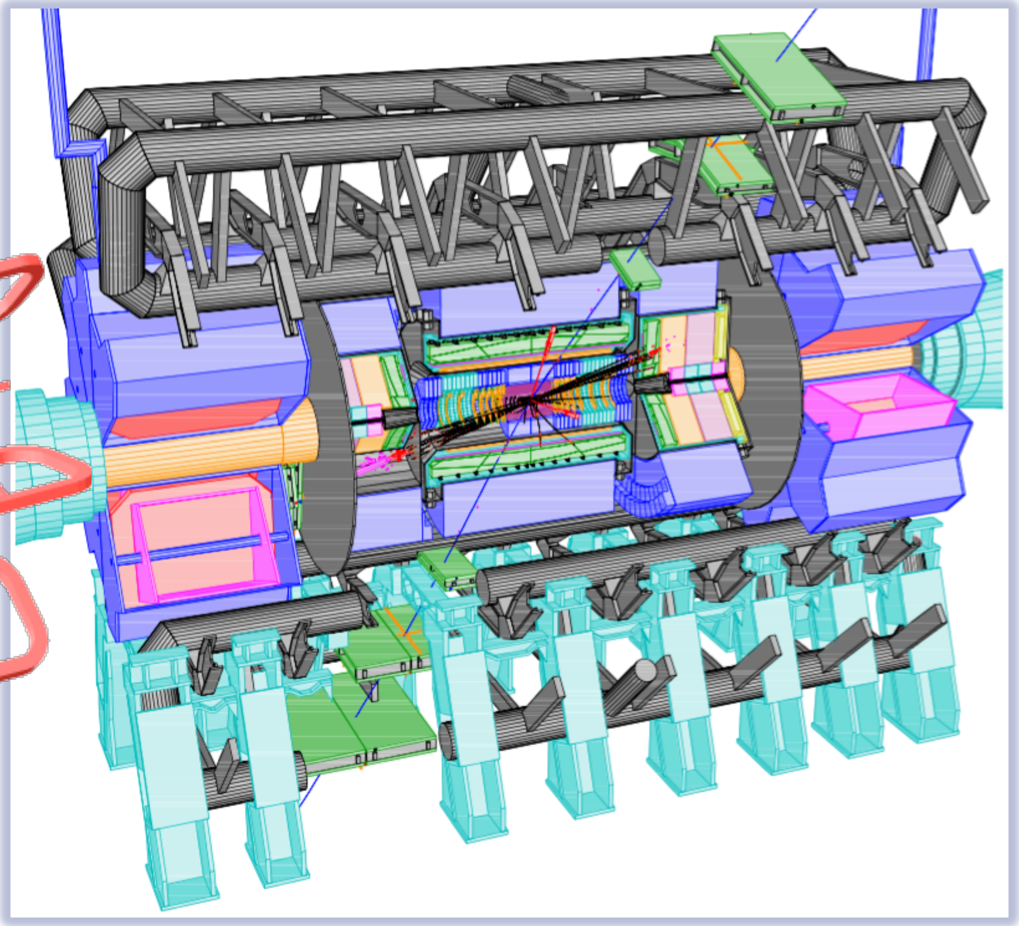


* *Almost any: highly energetic jets can punch through the calorimeter (not discussed here)*

Muon momentum measurement

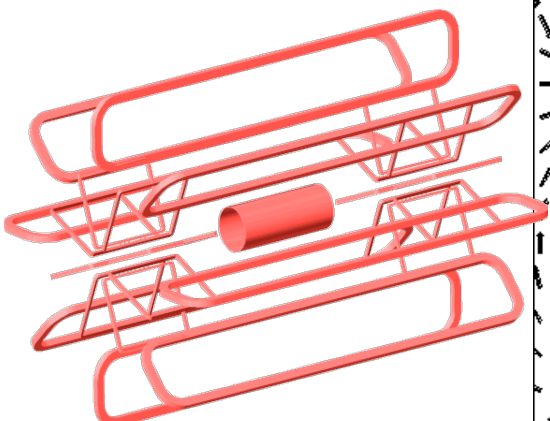
- Muon momentum measured in:
  - Inner tracker using solenoidal magnetic field (see above)
  - In the muon spectrometer using toroidal magnetic field

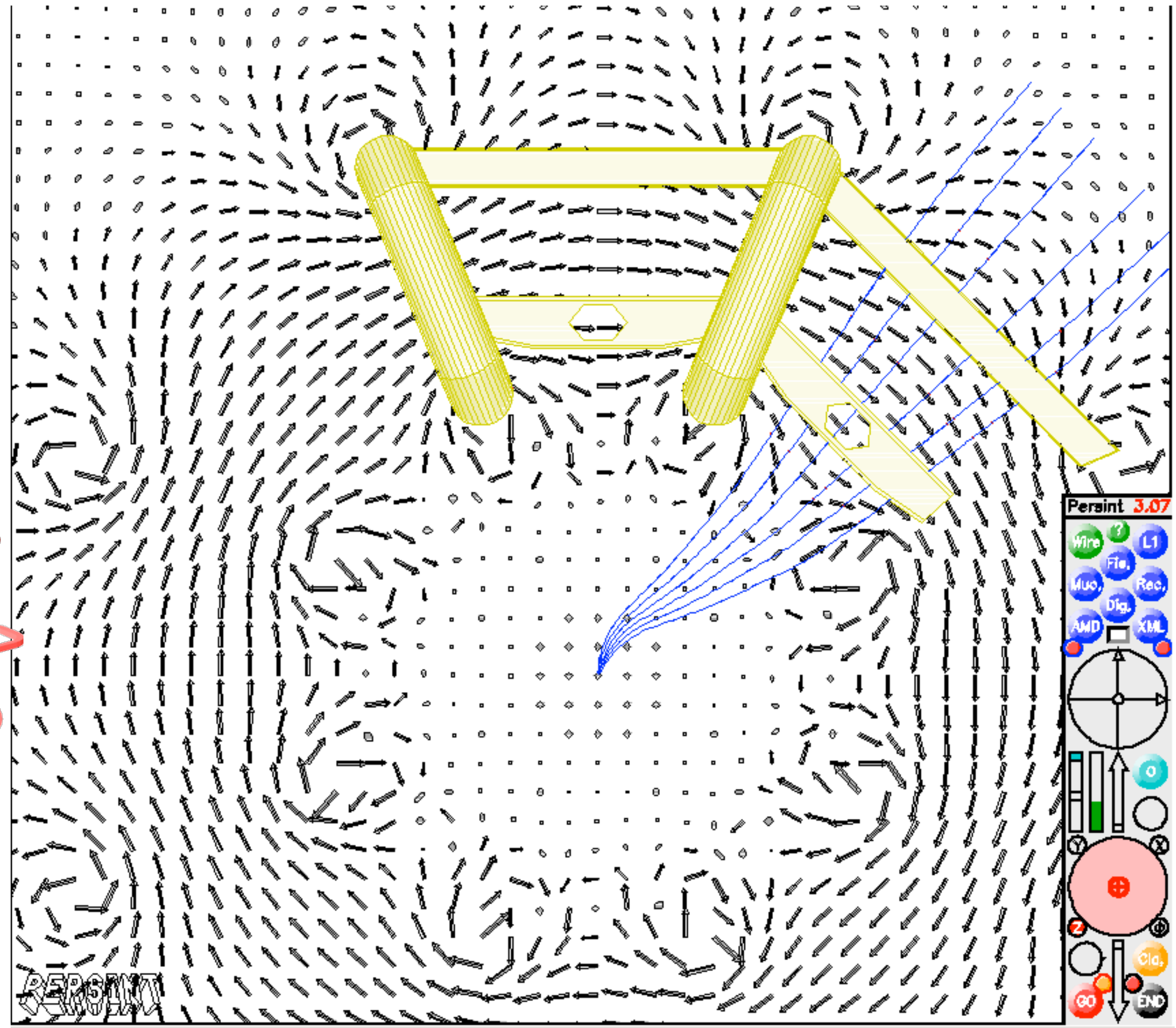




Muon momentum measurement

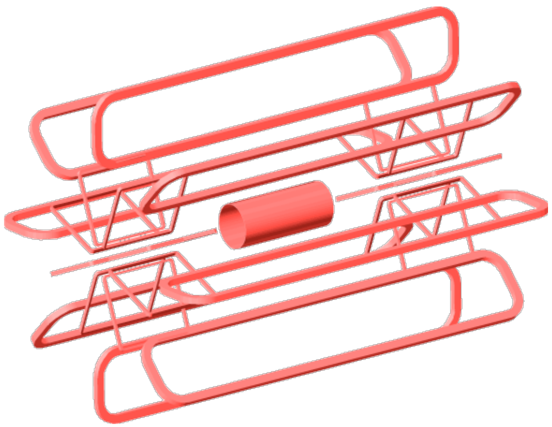
In solenoid:
deflection
in (r,φ) plane

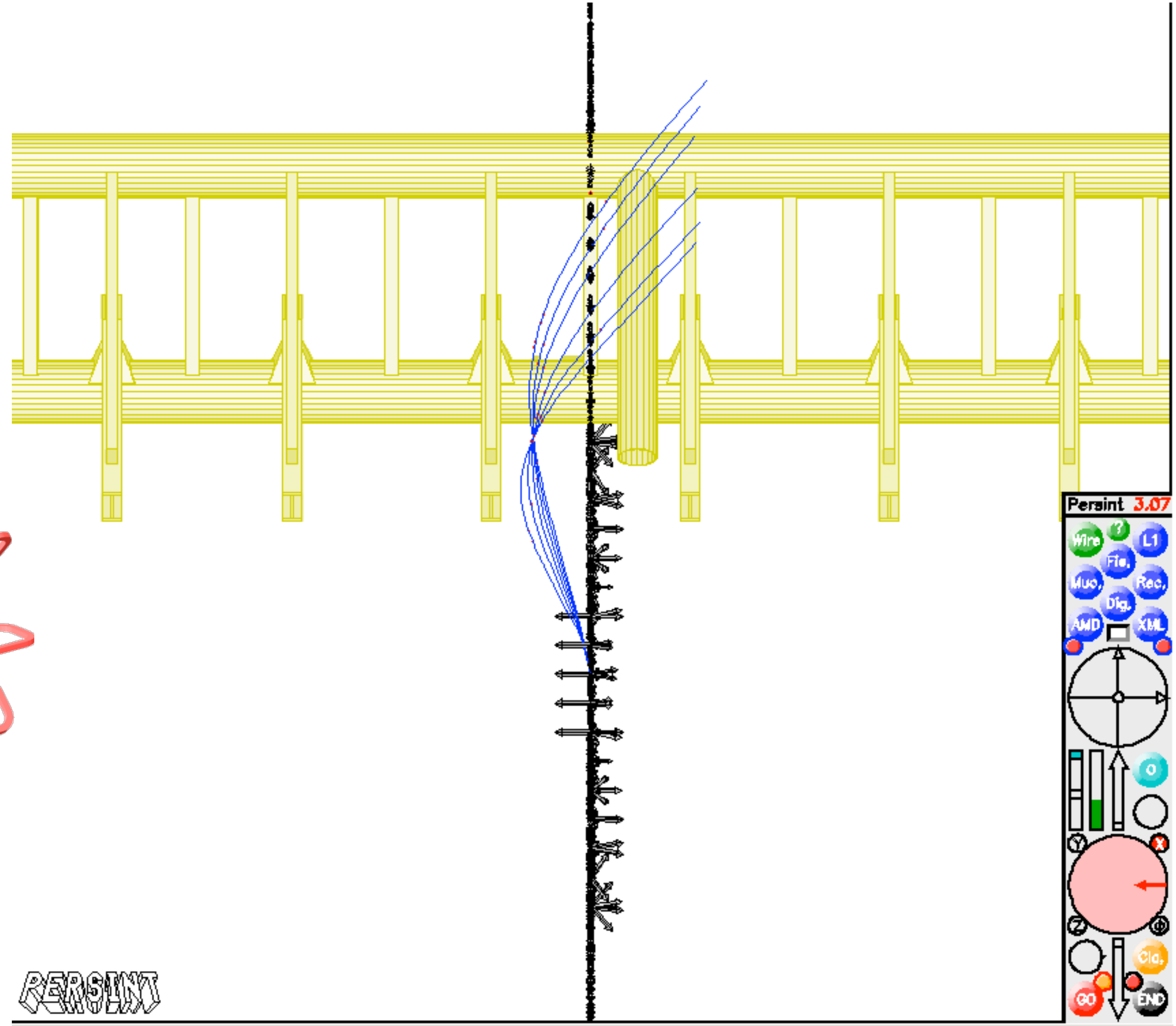




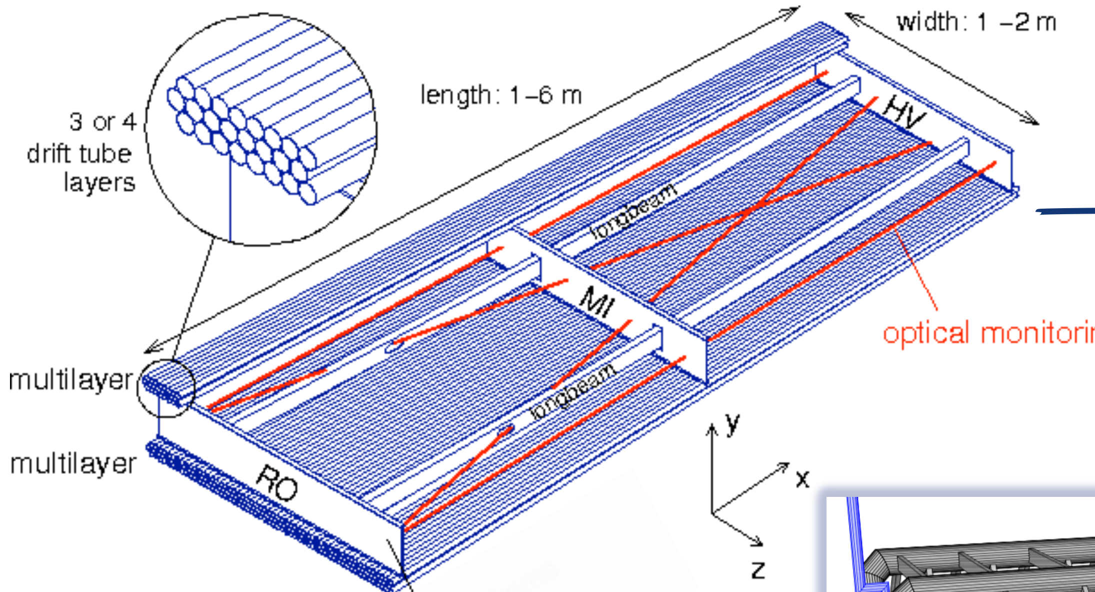
Muon momentum measurement

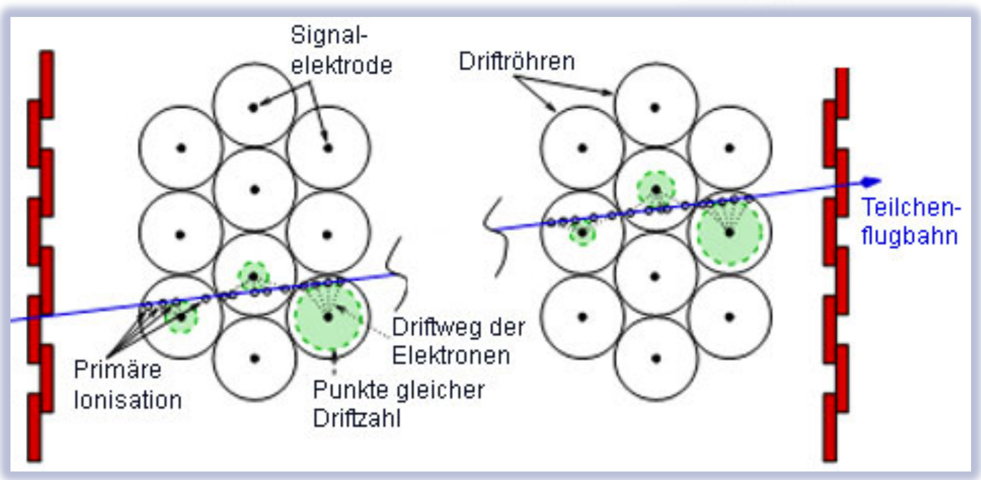
In toroid:
deflection
in (r,z) plane

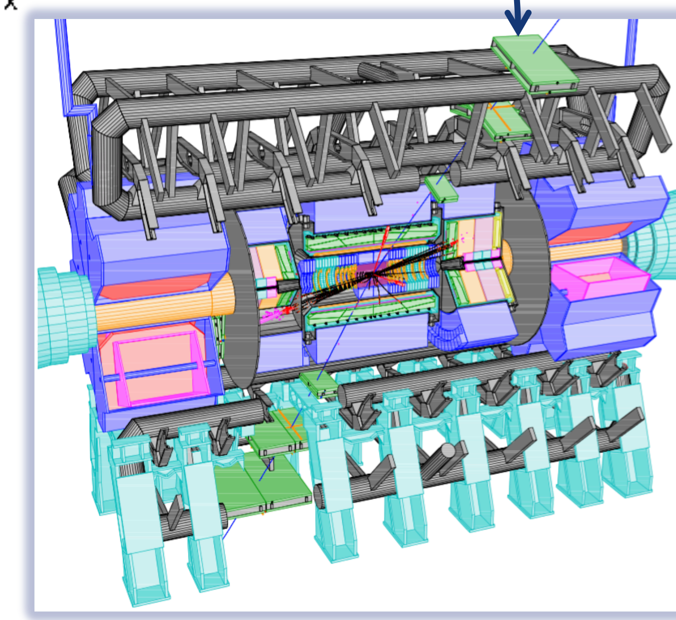




- Measure coordinates in (r,z) plane with drift tubes:

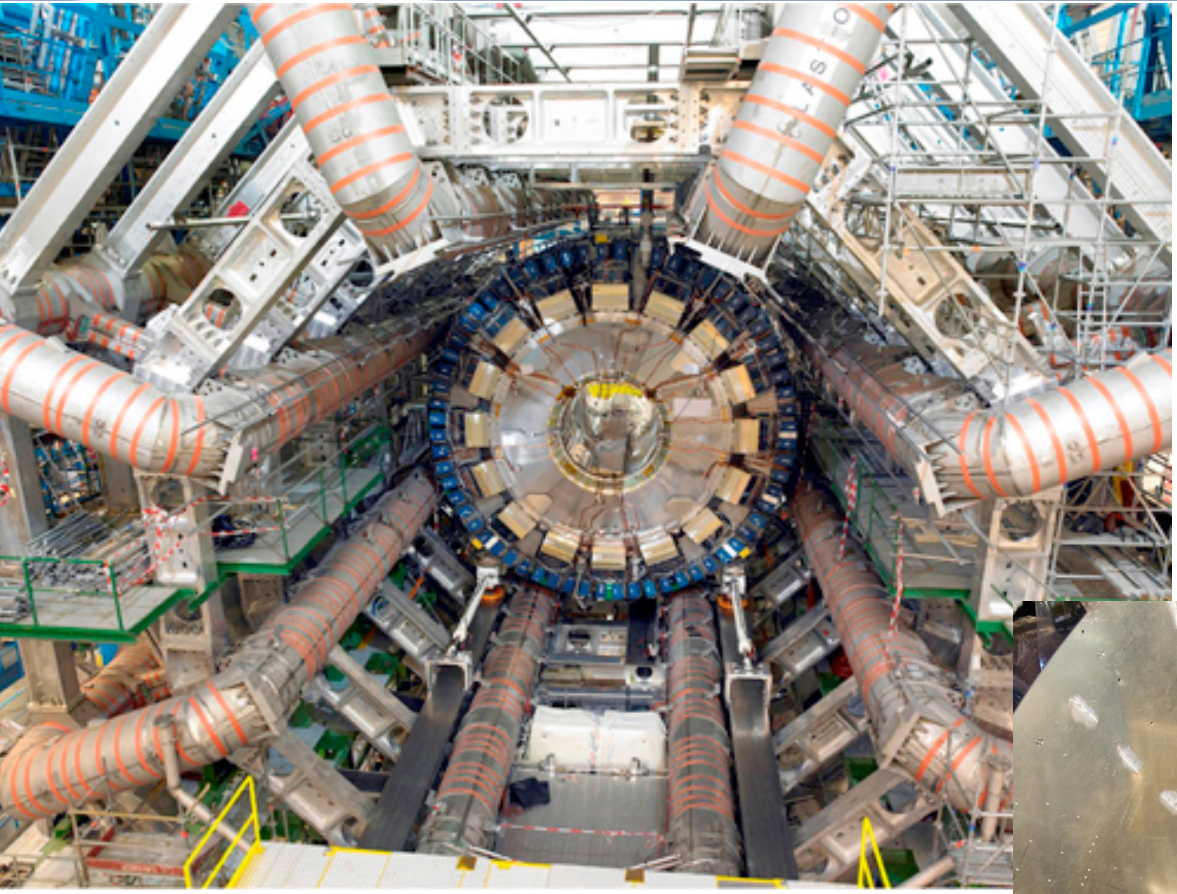


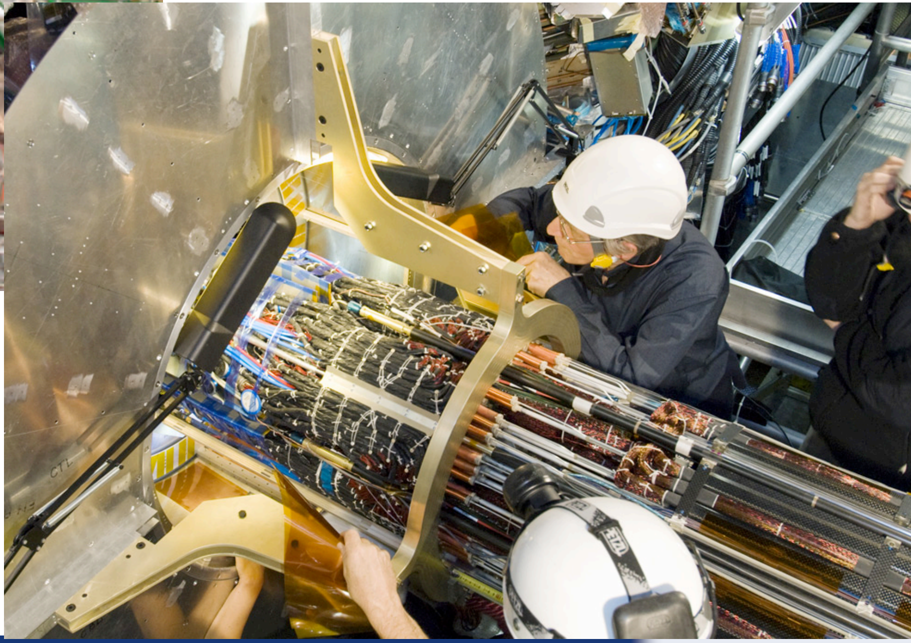




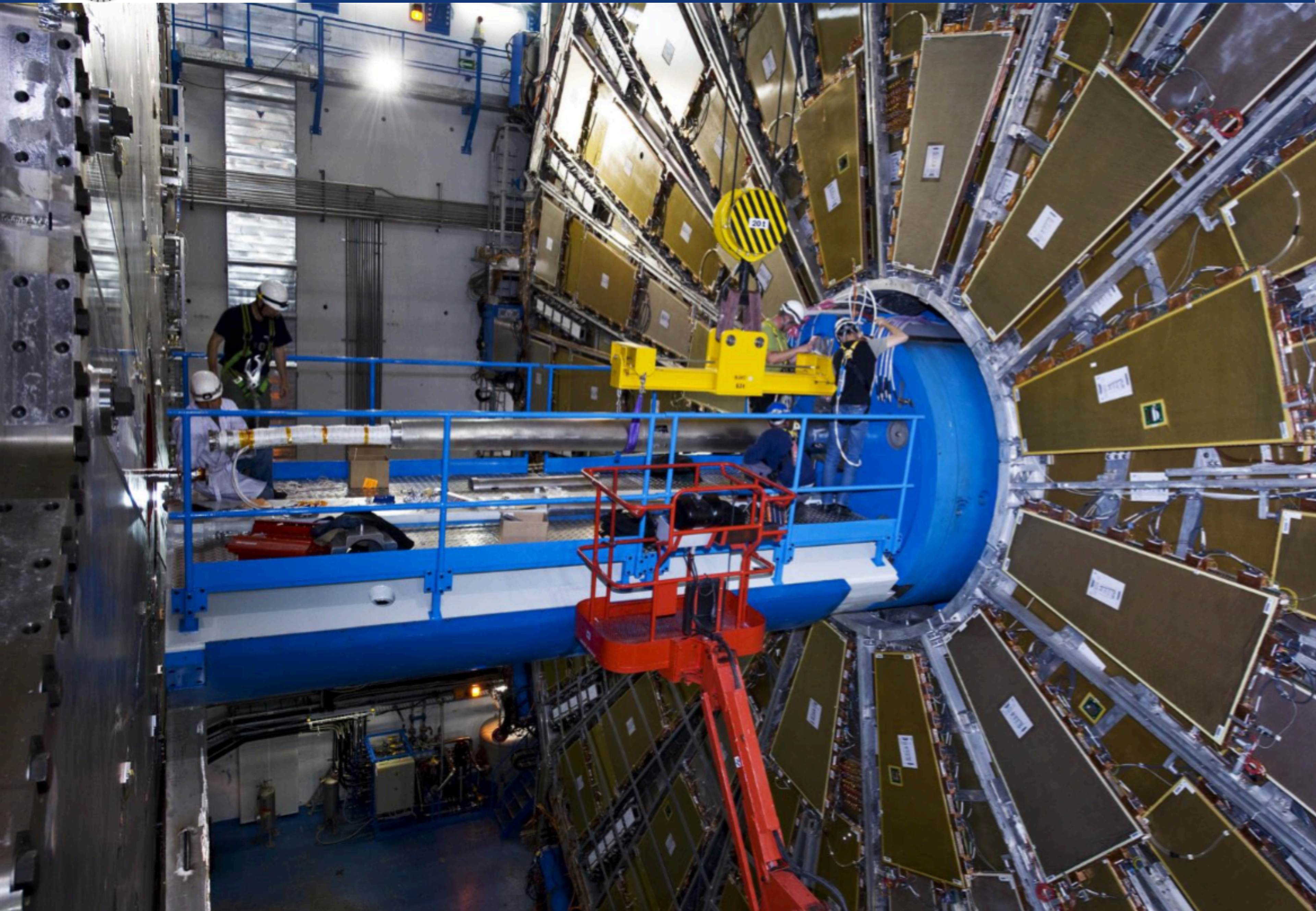
ATLAS components on the way to assembly

ATLAS during assembly





ATLAS after assembly

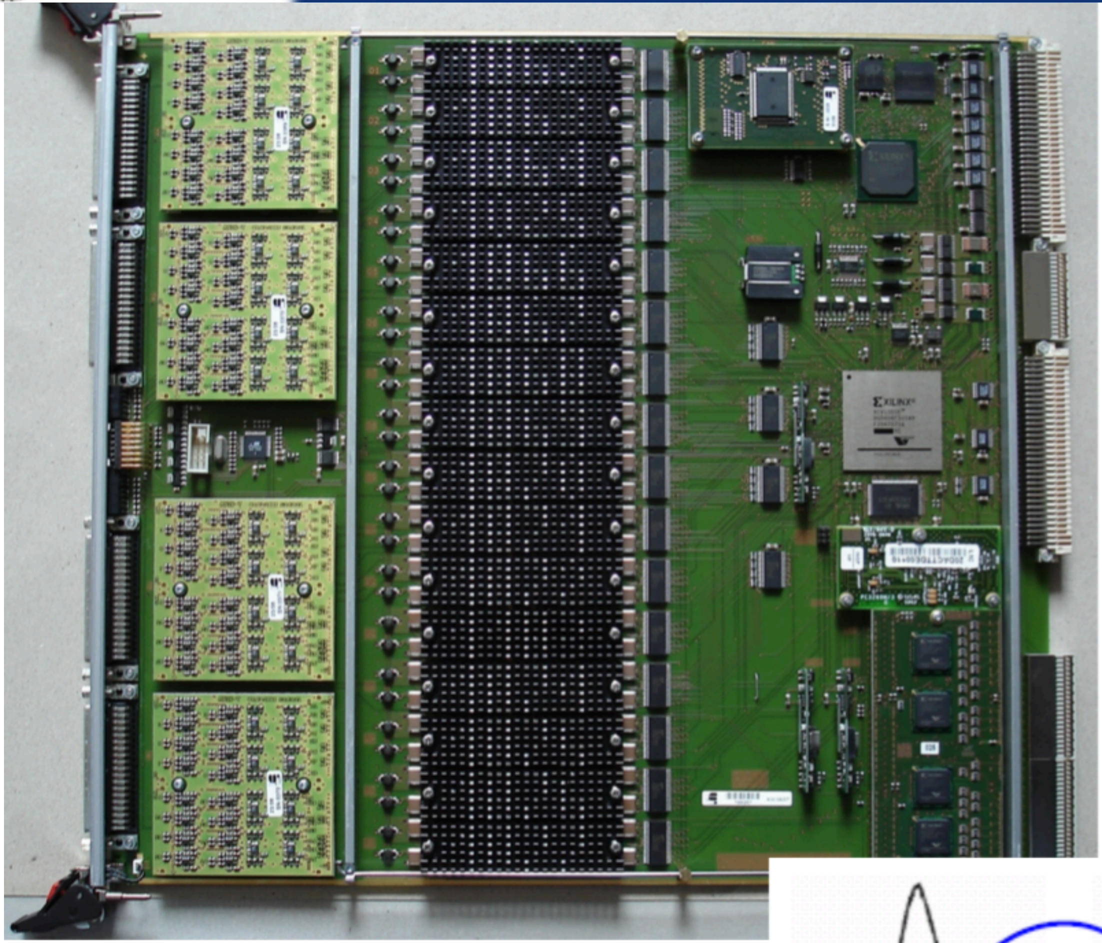


VIP visits to ATLAS

Heidelberger Beitrag

- System zur Datenreduktion (60TB/s -> 150GB/s)
- Identifizierung interessanter Ereignisse in Echtzeit
- Kollaboration aus 50 Physikern
- 400 Elektronik Boards
- 10 verschiedene Board Typen
- schnelle analog und digitale Datenverarbeitung

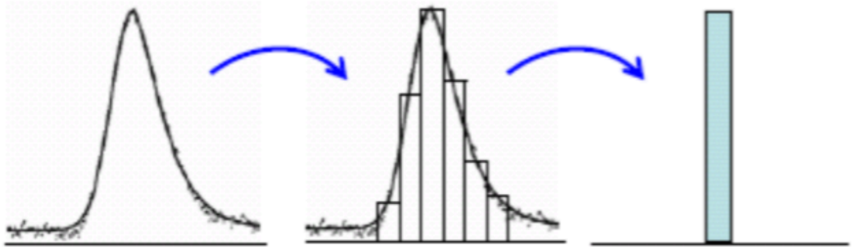
Heidelberger Beitrag



PreProcessor

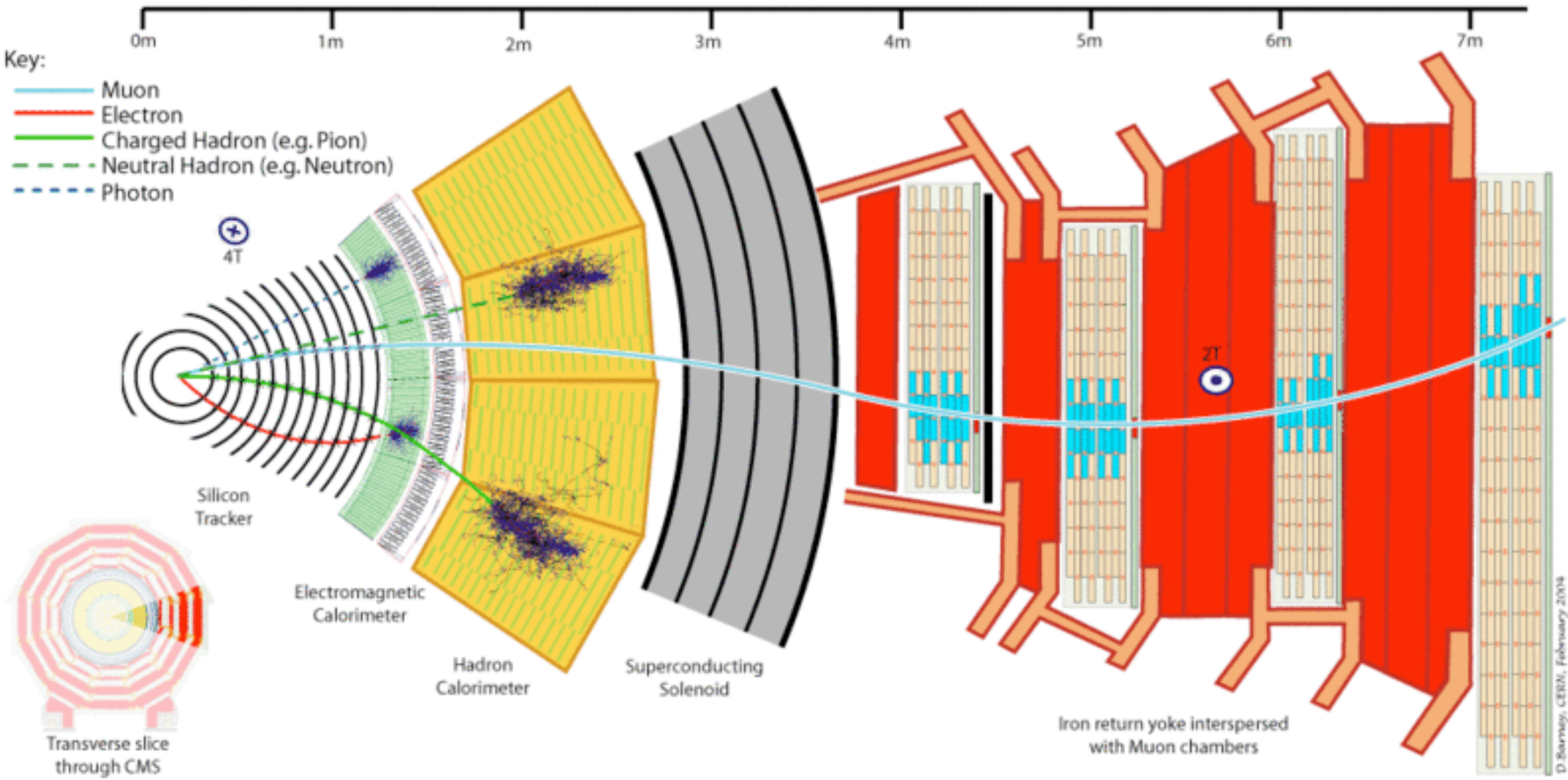
- 160 Boards
- ~4000 Tochterkarten
- Gemischtes Design (analog/digital)
- Spezielle ASIC Entwicklung (KIP/HD)

- Digitalisierung der analogen Pulse
- Bestimmung des Maximums

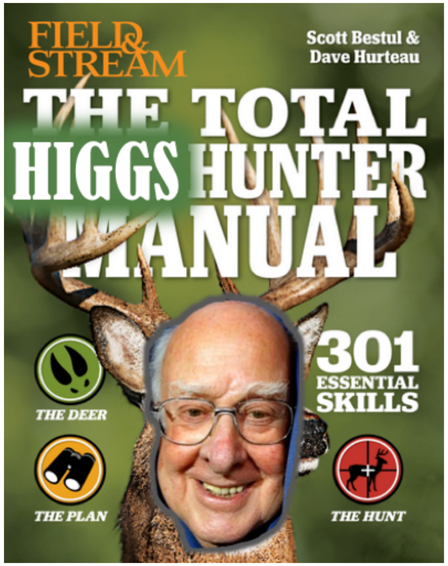


The CMS detector

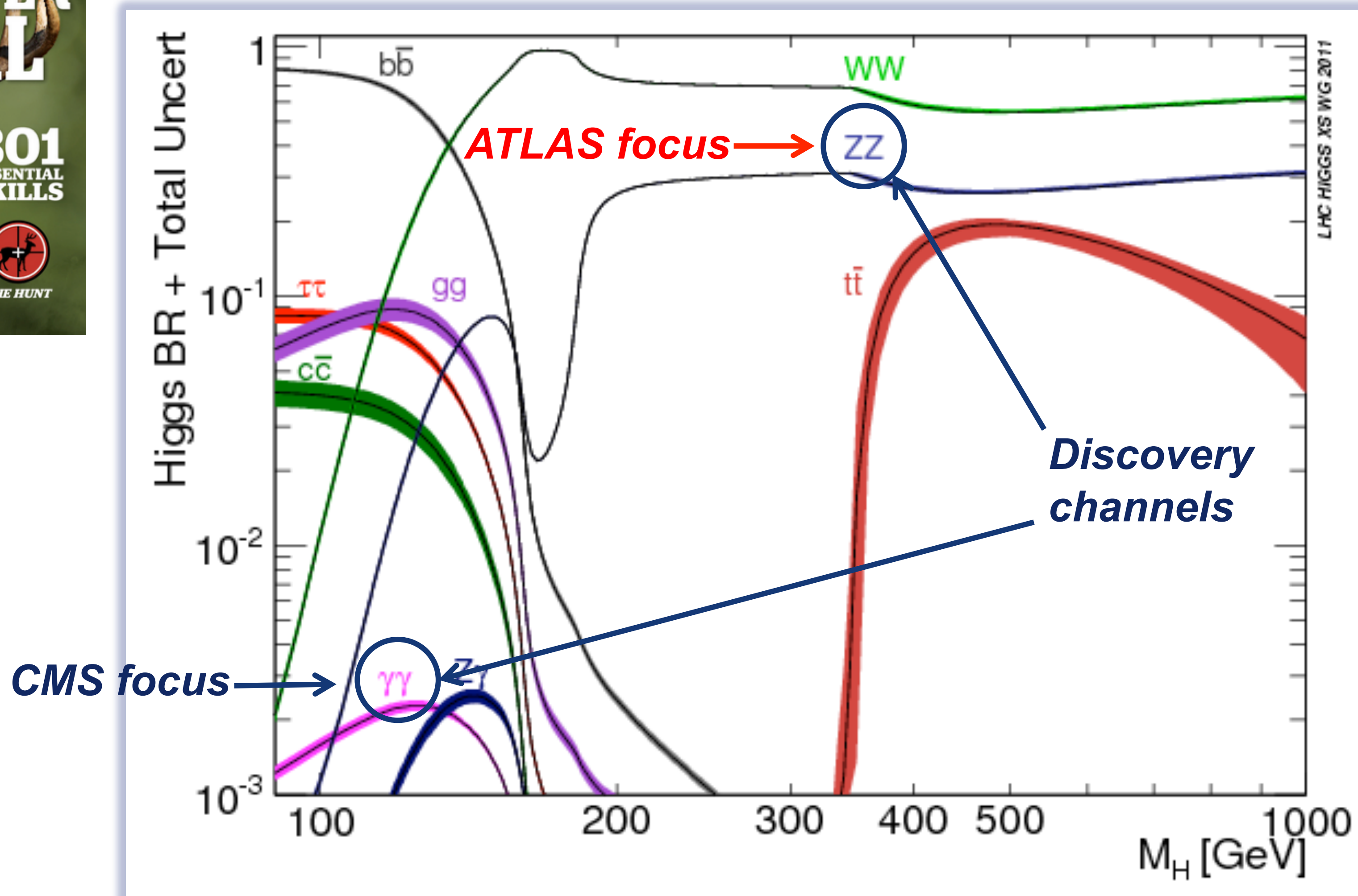
Very similar to ATLAS, but more compact
→ will highlight differences where relevant



Higgs decay channels

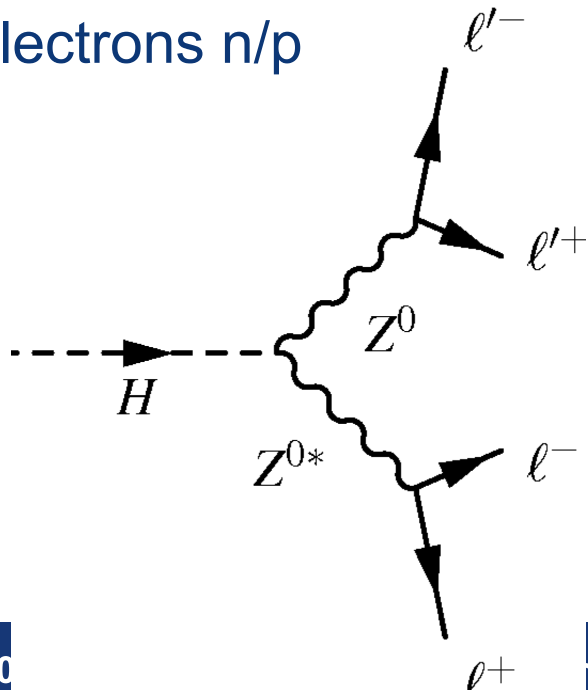


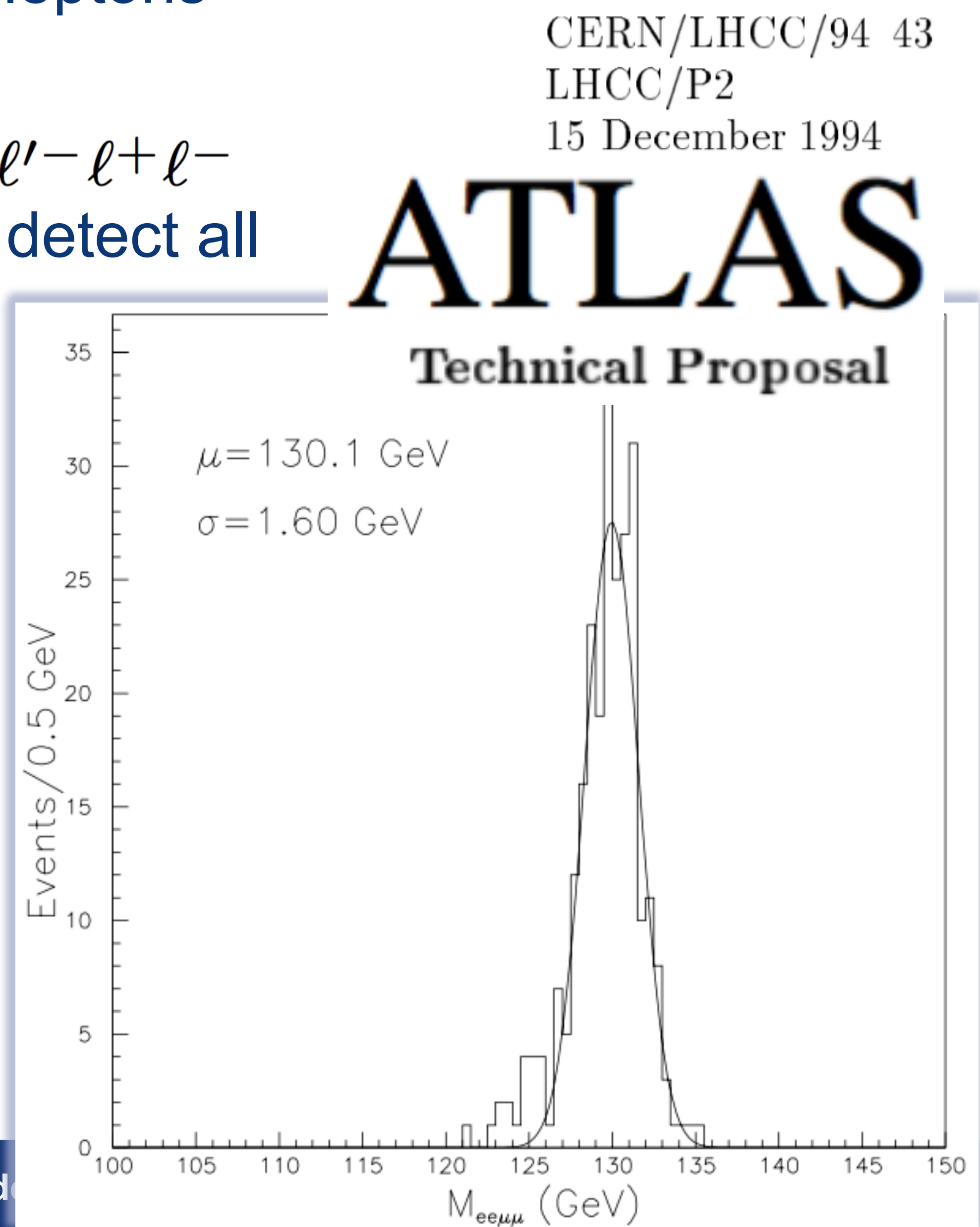
Reminder: m_h is a free parameter in the SM!



h → ZZ* → 4 leptons

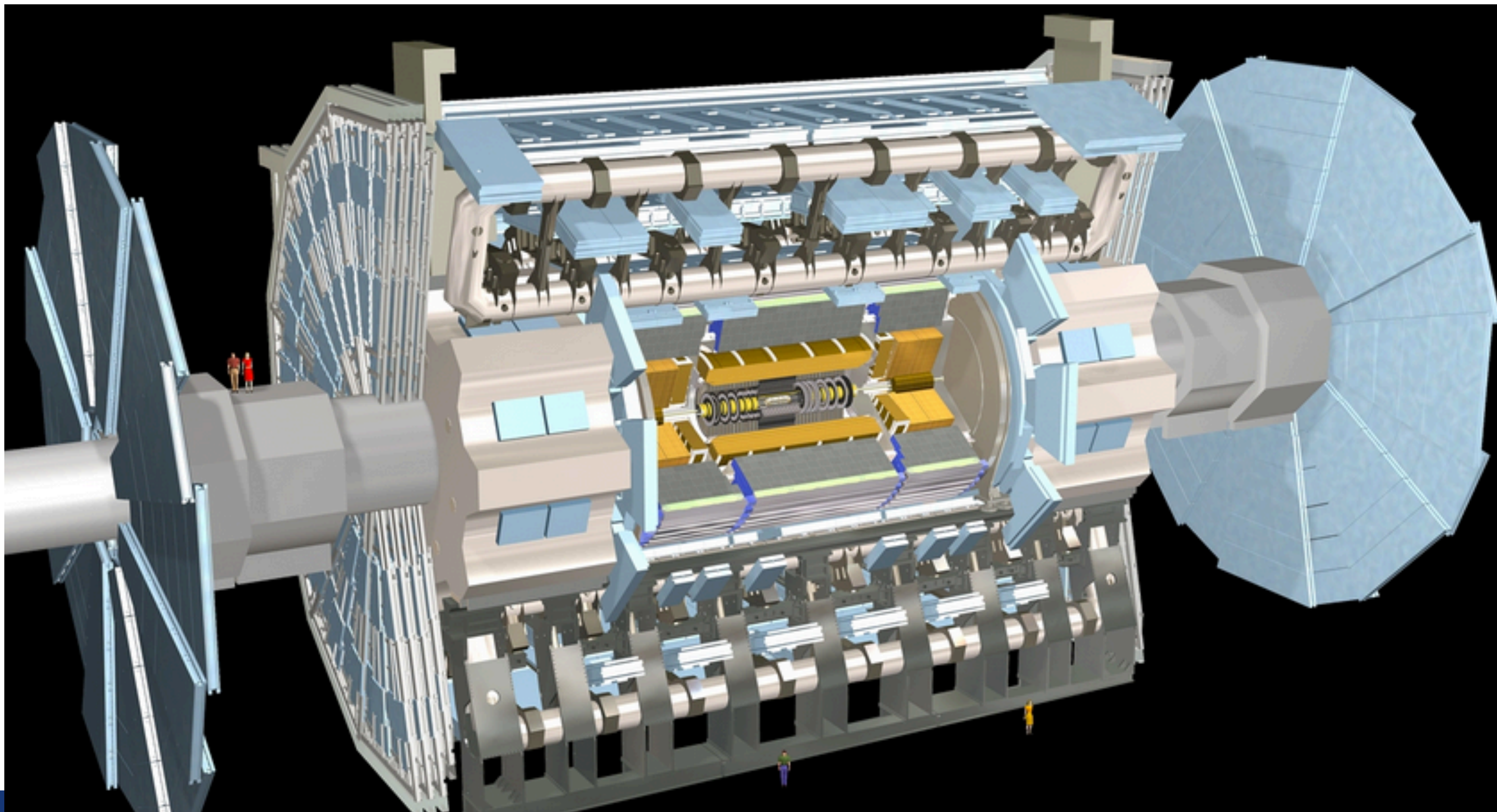
- Golden channel h → ZZ* → 4 leptons
  - Very small backgrounds
  - Excellent resolution of $m_{\ell'^+\ell'^-\ell^+\ell^-}$
- Large solid angle coverage to detect all 4 leptons (esp. muons)!
- Good momentum resolution!
  - Especially for muons
  - Electrons n/p





ATLAS muon spectrometer

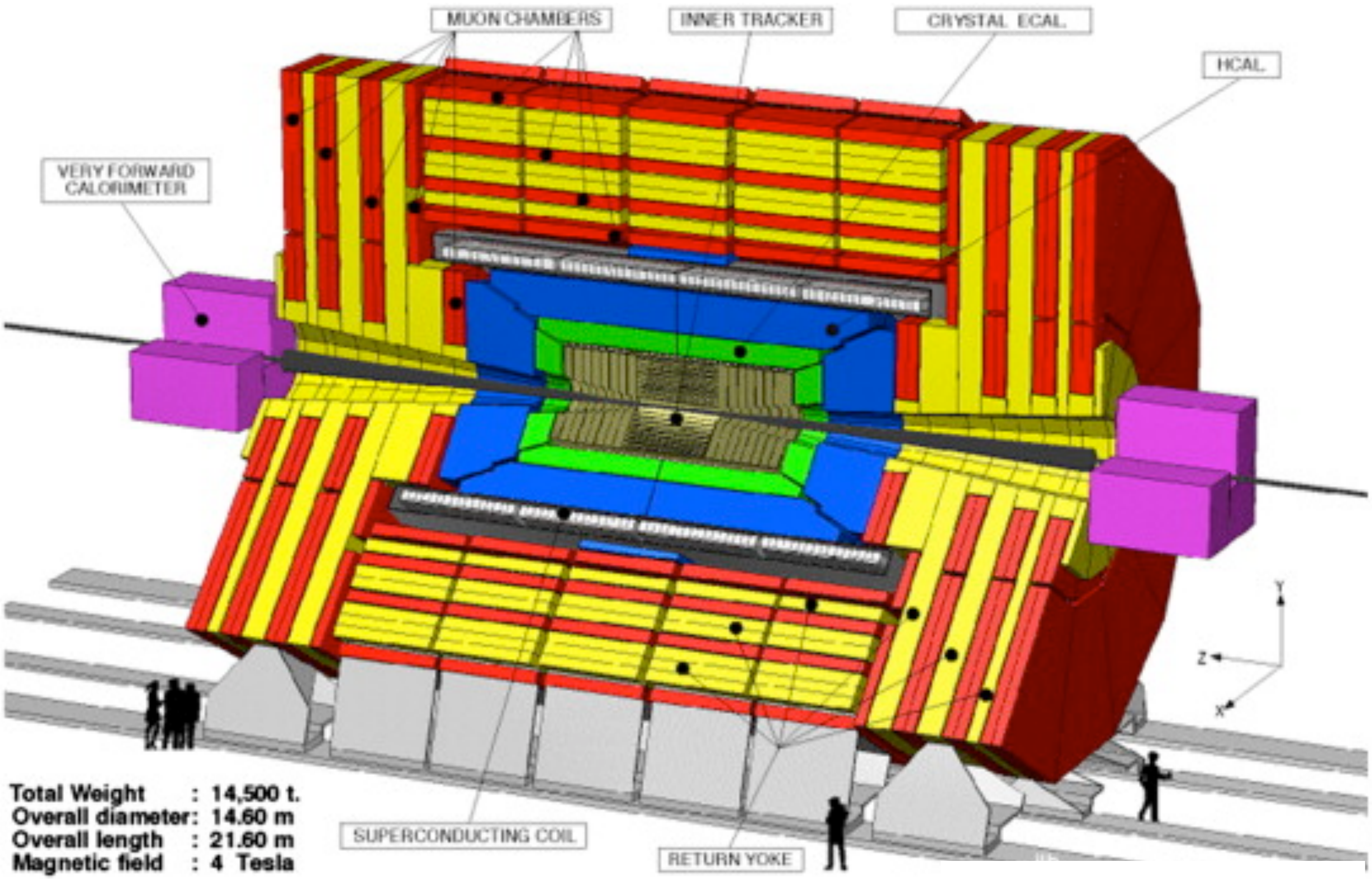
- Large-acceptance muon spectrometer:
  - $|\eta| < 2.5$
- with good momentum resolution
  - Better than 15% for muons with p_T = 100 GeV **everywhere**



"Rest of ATLAS built into the muon spectrometer"

CMS muon spectrometer

- Muon acceptance smaller but similar to ATLAS
  - $|\eta| < 2.4$
- Limited momentum resolution in forward region
  - Resolution of 25% for $|\eta| > 2.0$ (muon spectrometer only)

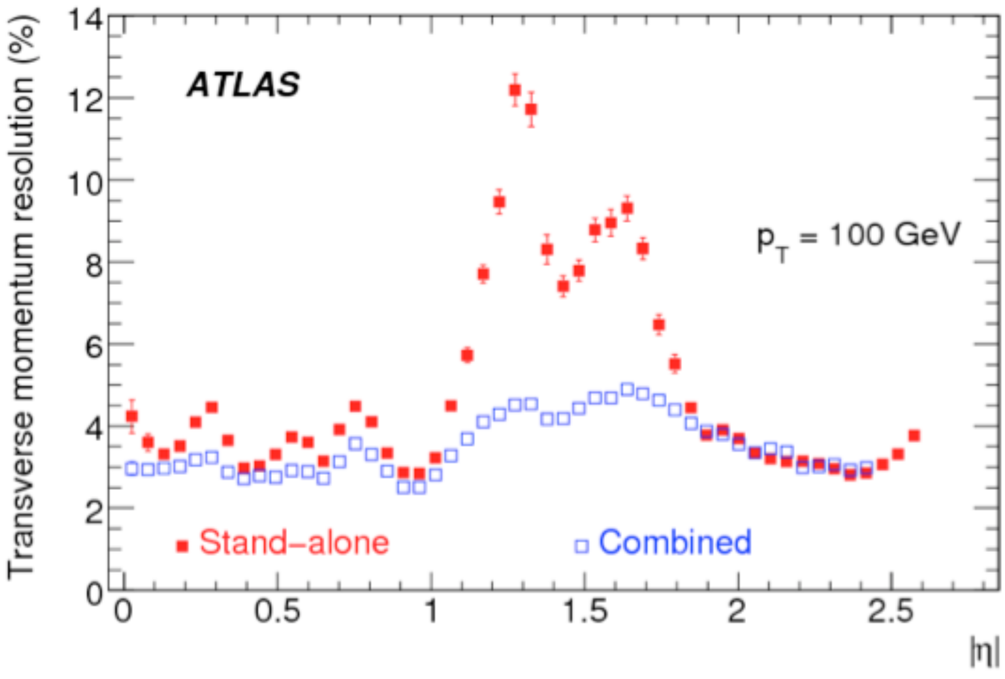


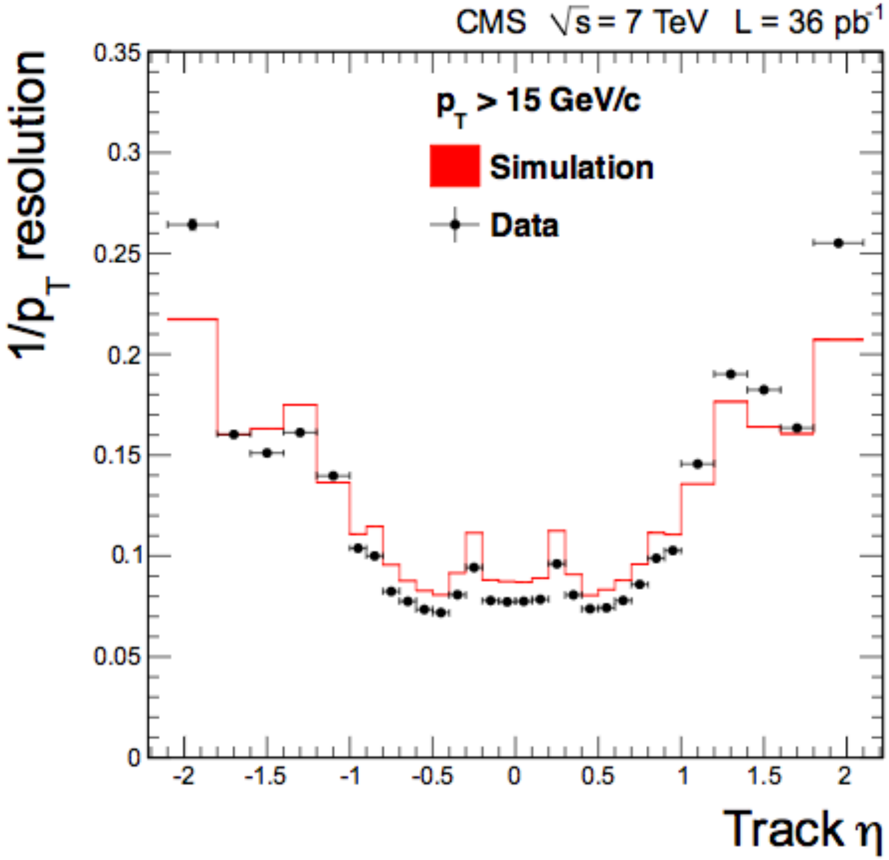
"Spectrometer attached to the rest of detector"

Muon system performance

ATLAS

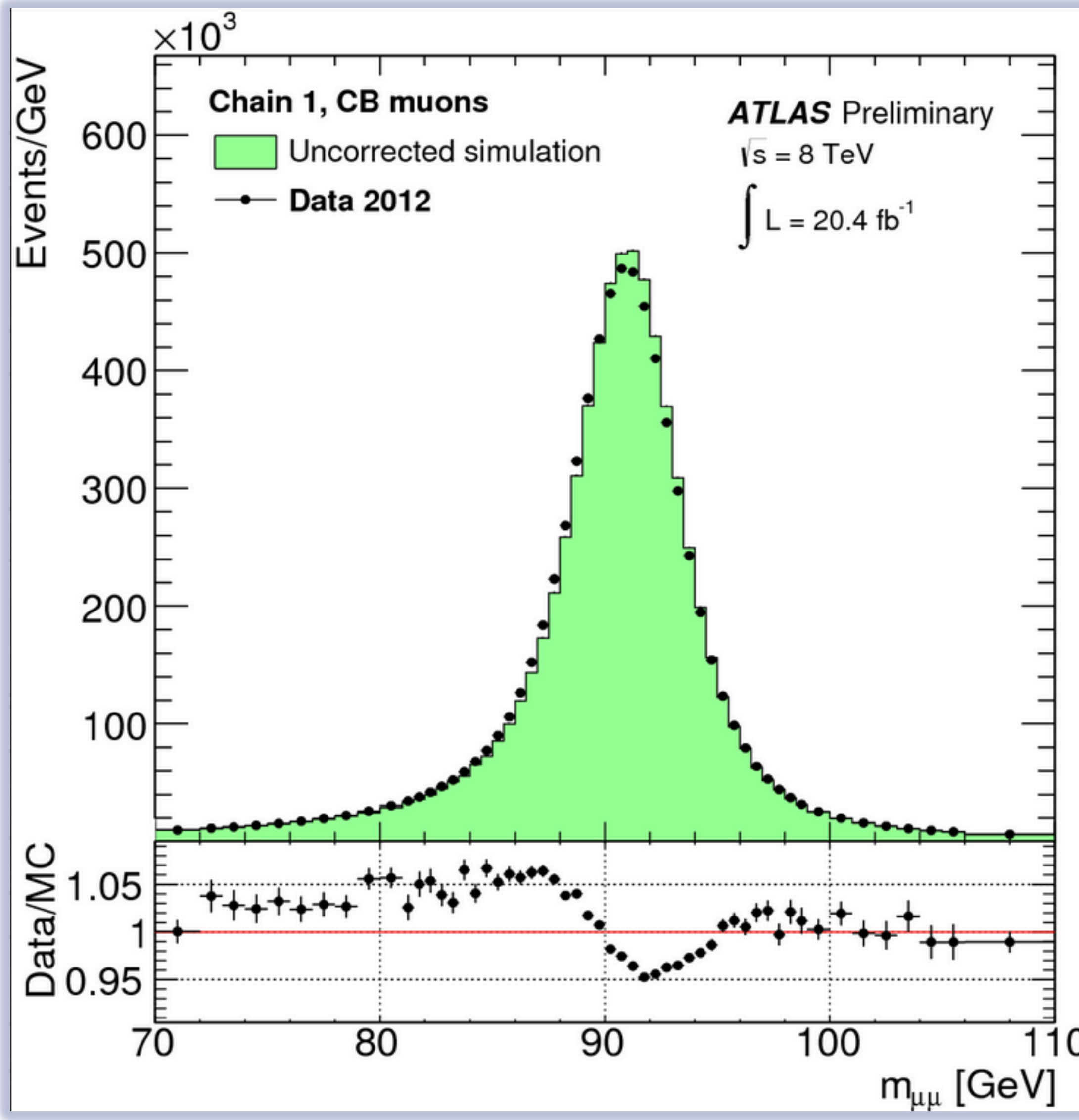
CMS





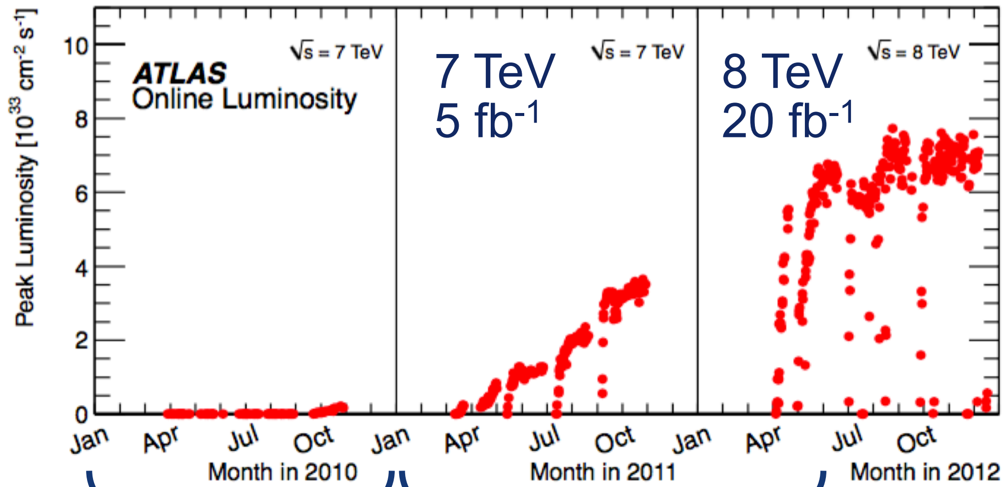
h → ZZ* → 4 leptons

- Behold!
  - Momentum calibration needed!
  - Calibrate detector response with standard candles
    - m_Z well known from LEP



h → ZZ* → 4 leptons

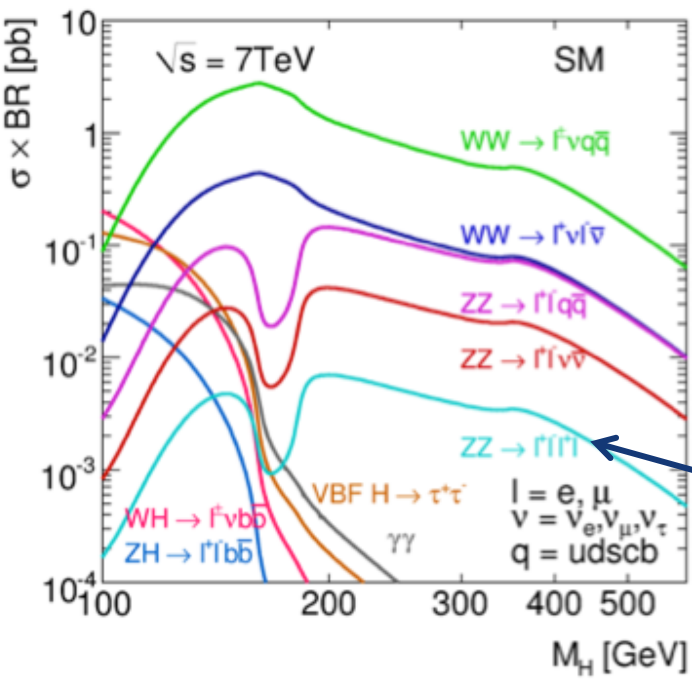
- **Challenge:**
  - Low branching ratio of Z into leptons:
    - 3% into ee and 3% into $\mu\mu$ (7% combined)
    - Two Z bosons:
      - $7\%^2 \approx 0.4\%$



Commissioning (LHC+detectors)

Higgs discovery ($5\ \mathrm{fb}^{-1}$ + $5\ \mathrm{fb}^{-1}$)

$$N = \int \mathrm{d}t\, \mathcal{L} \cdot \sigma$$

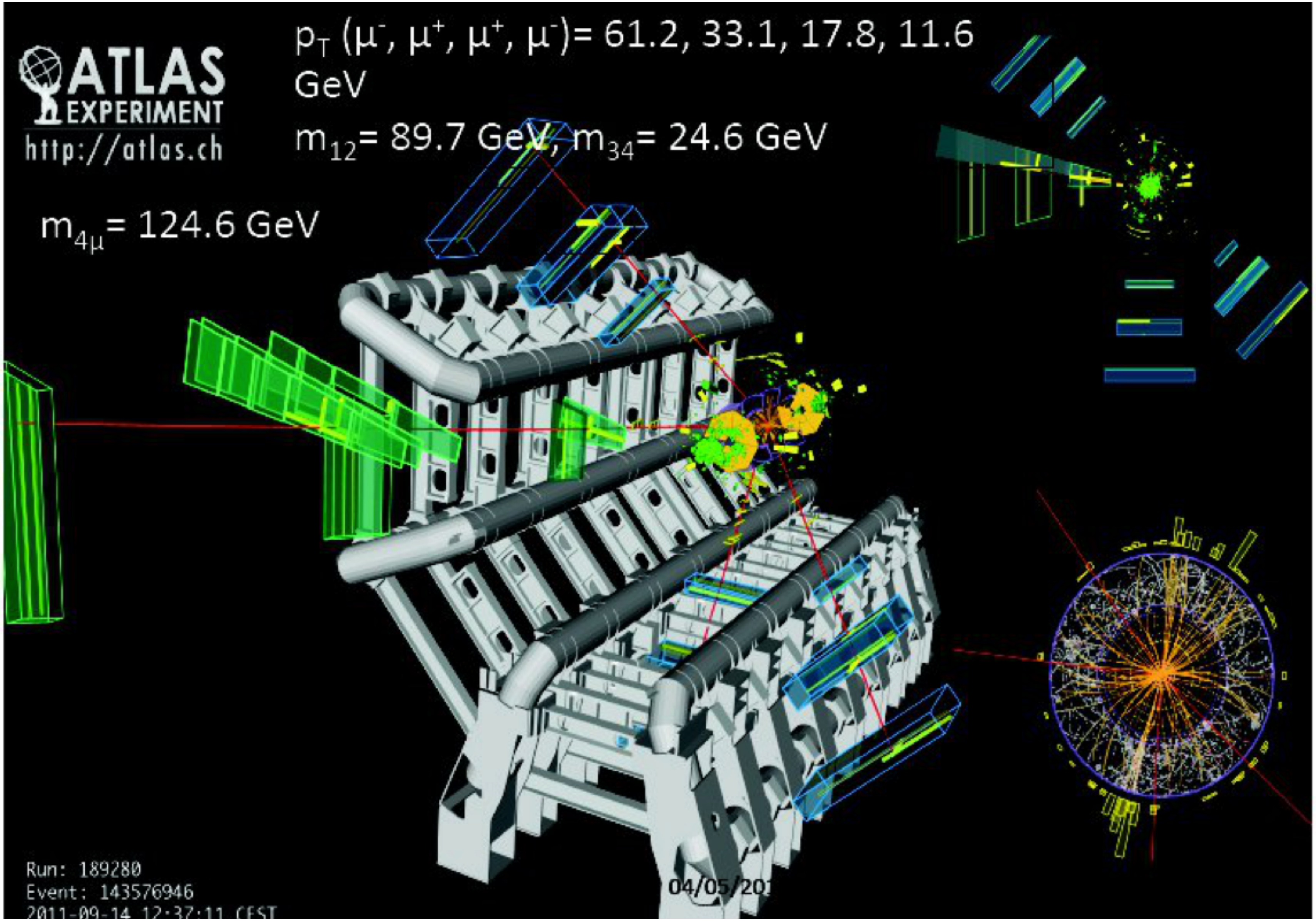


N = number of events (e.g. Higgs events)

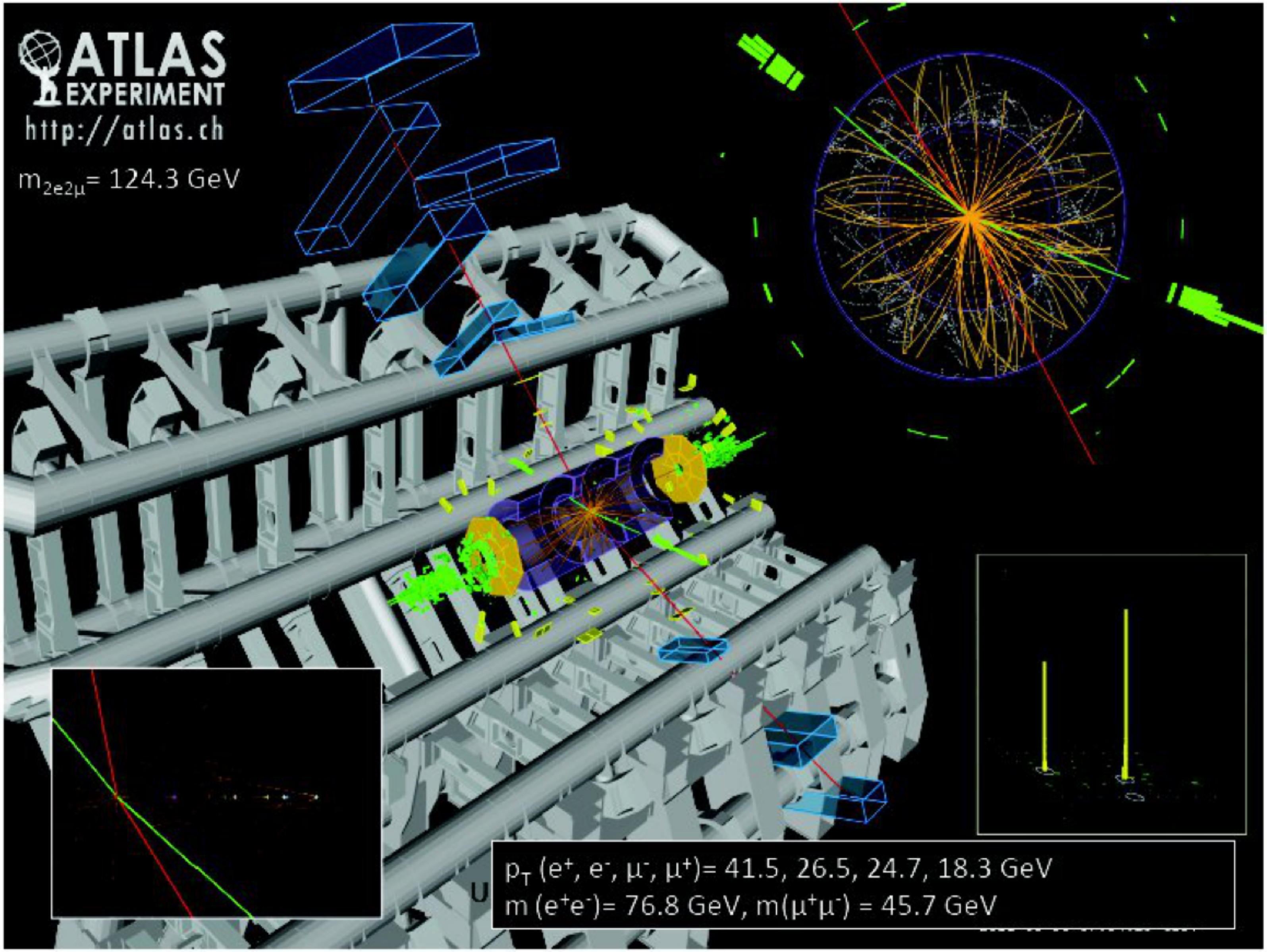
σ = cross section (e.g. for Higgs prod'n)

$\int \mathrm{d}t\, \mathcal{L}$ = total luminosity

h → ZZ* → 4 leptons



h → ZZ* → 4 leptons



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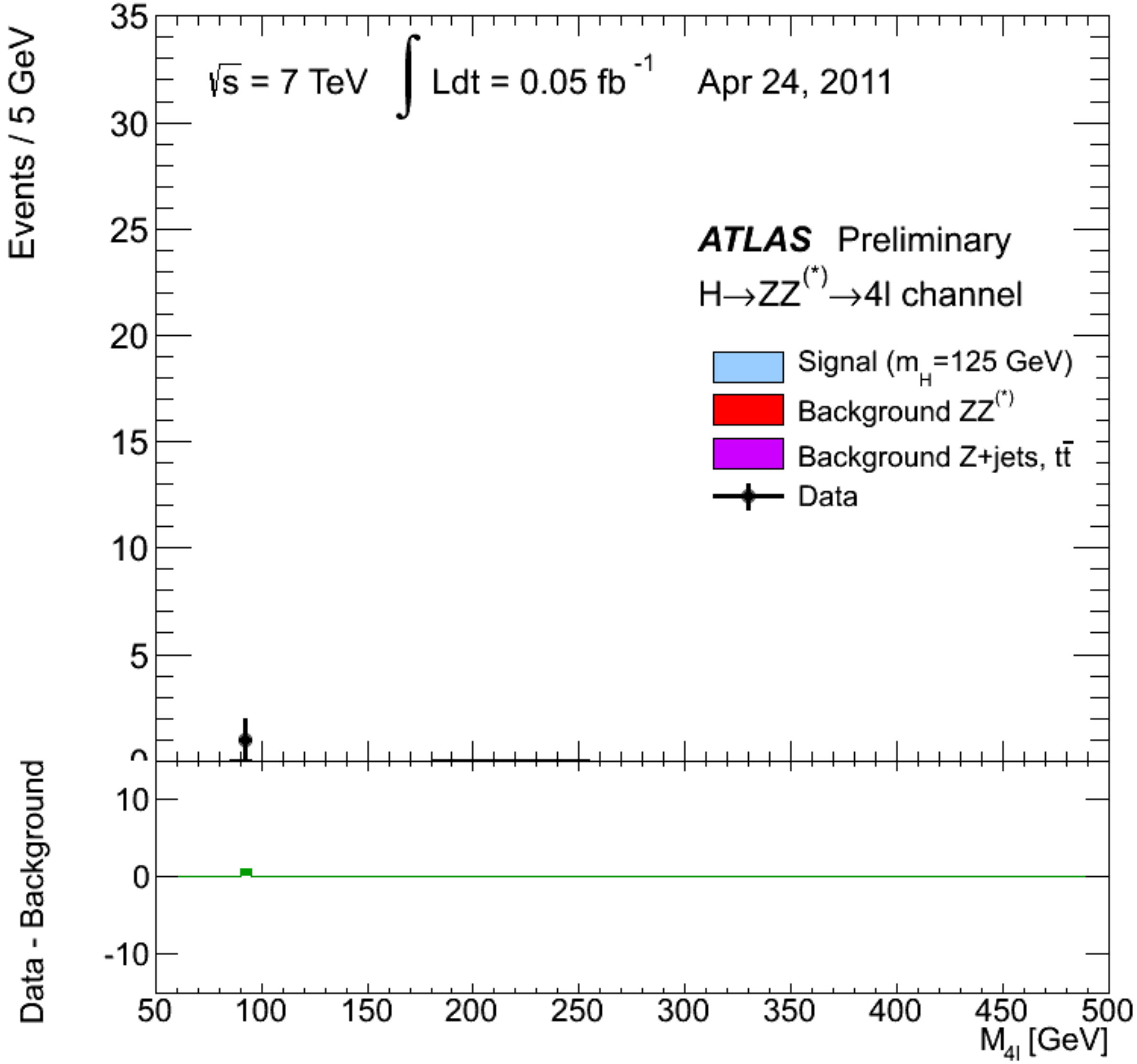
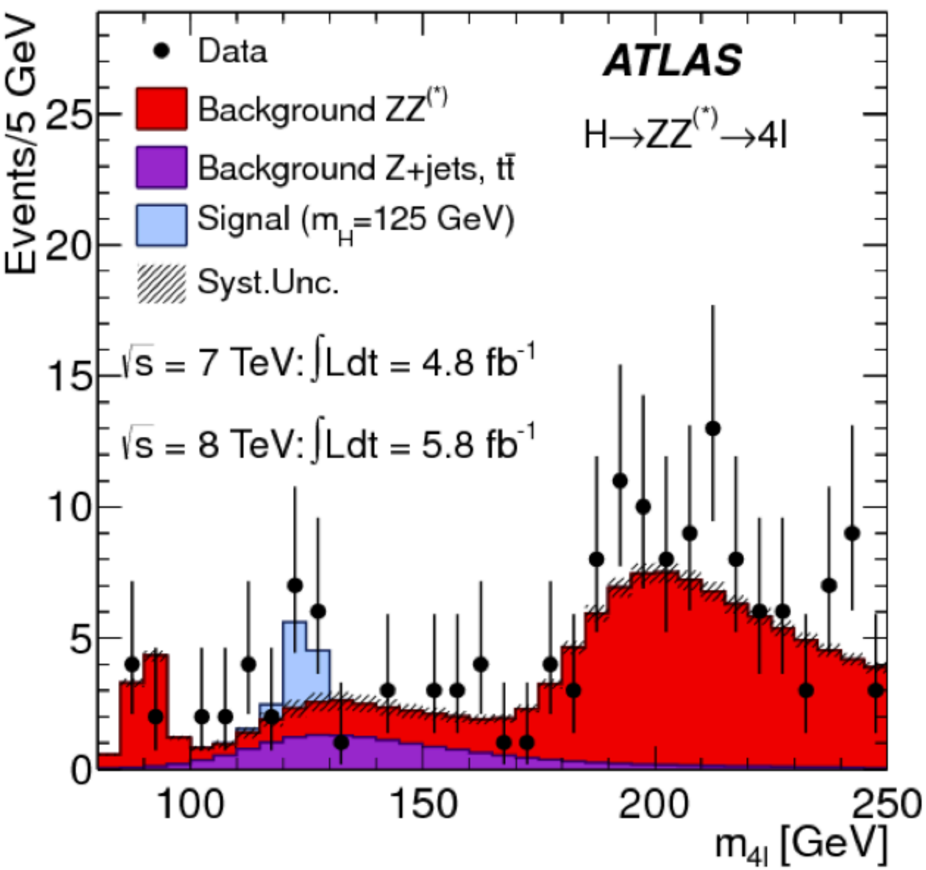
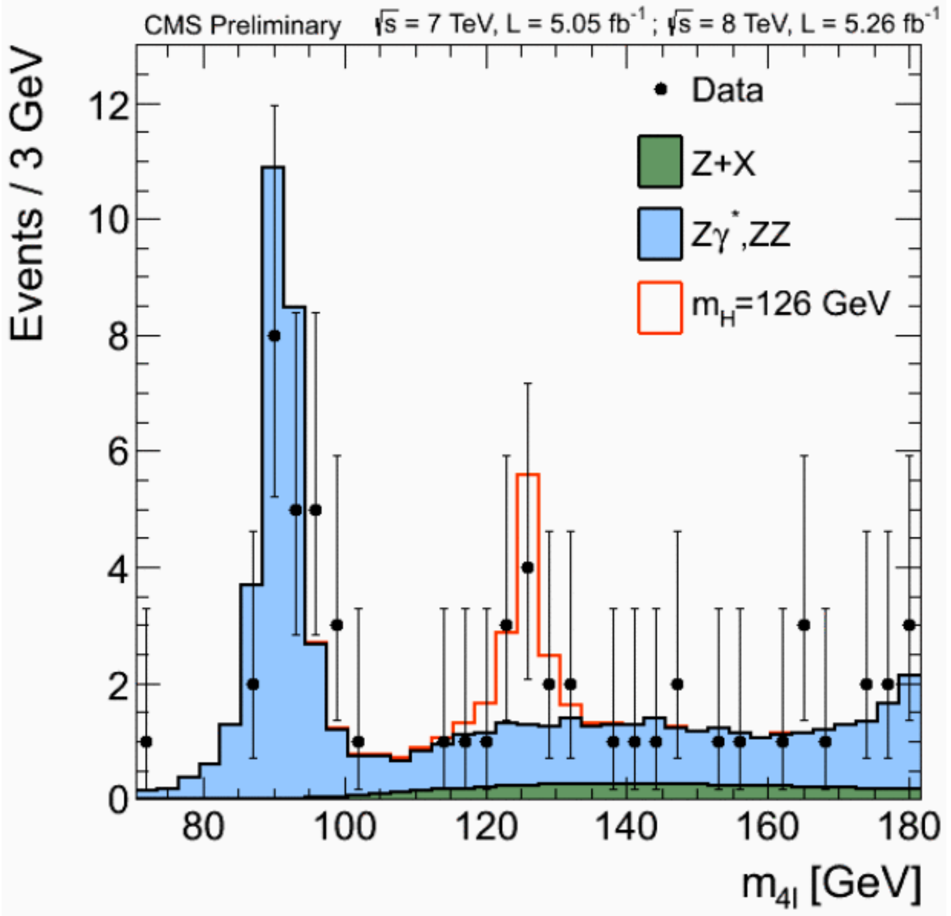
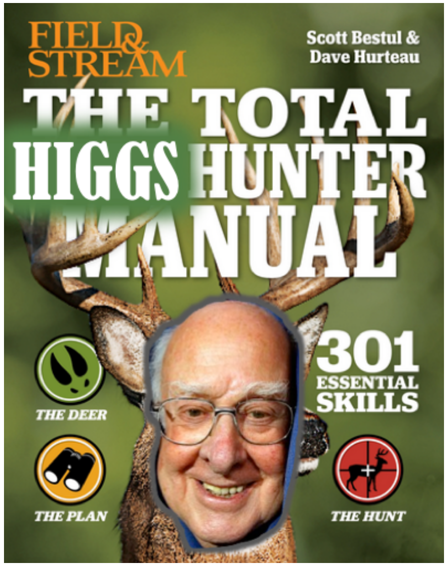


h → ZZ* → 4 leptons

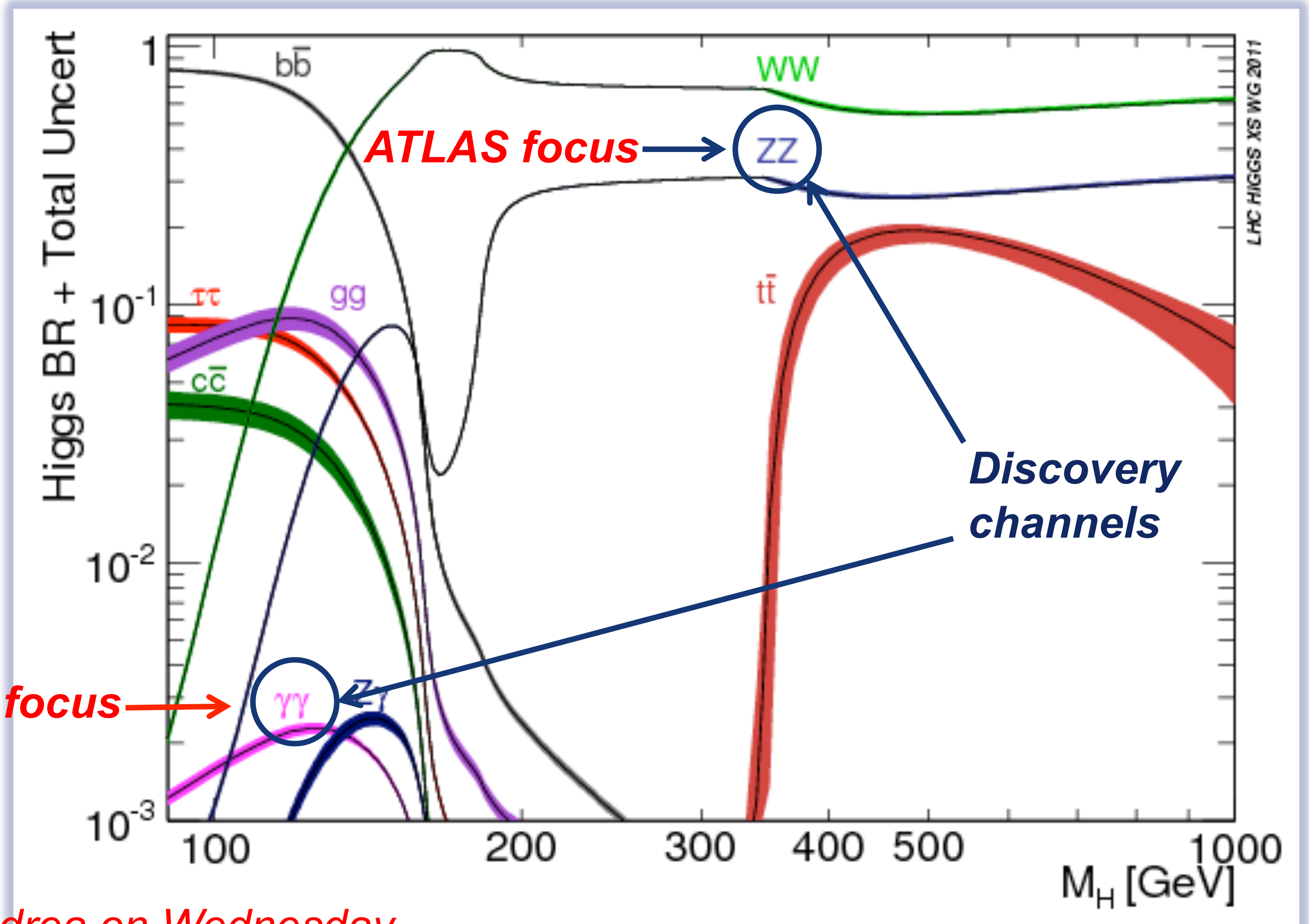




Higgs decay channels



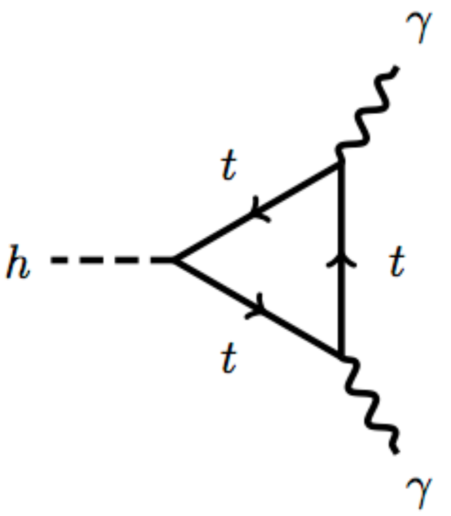
Reminder: m_h is a free parameter in the SM!

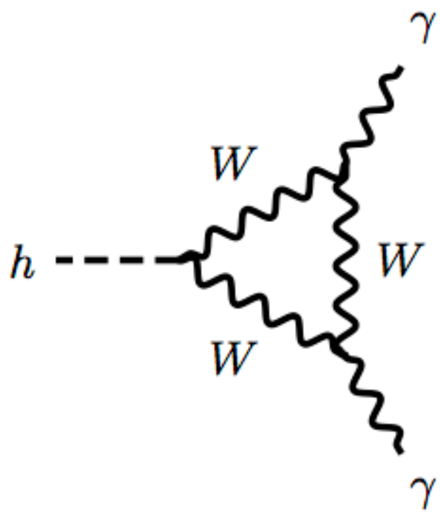


See also lecture by Andrea on Wednesday

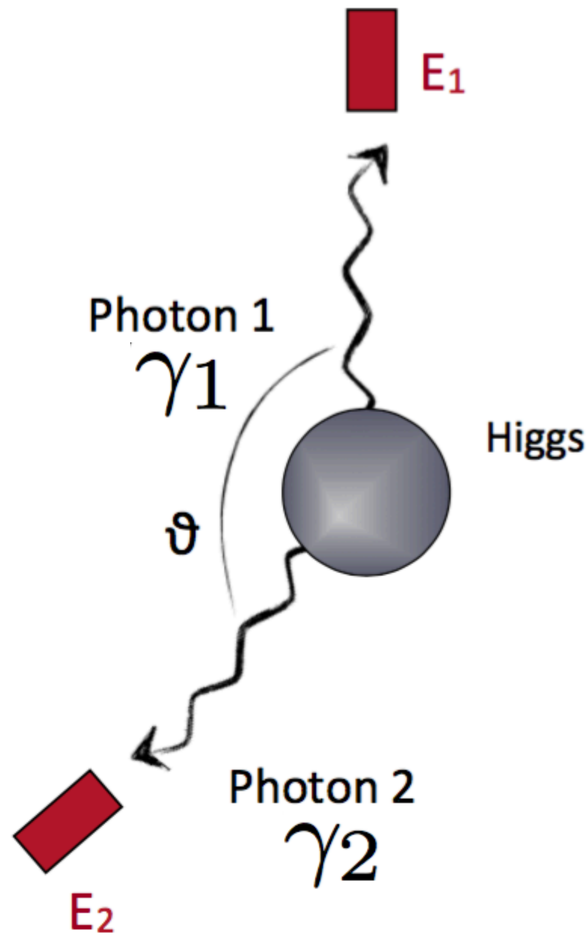
$h \rightarrow \gamma\gamma$ channel

- **Higgs couples indirectly to photons**
  - Relatively “clean” events
  - Very good resolution in invariant mass of the $\gamma\gamma$-system





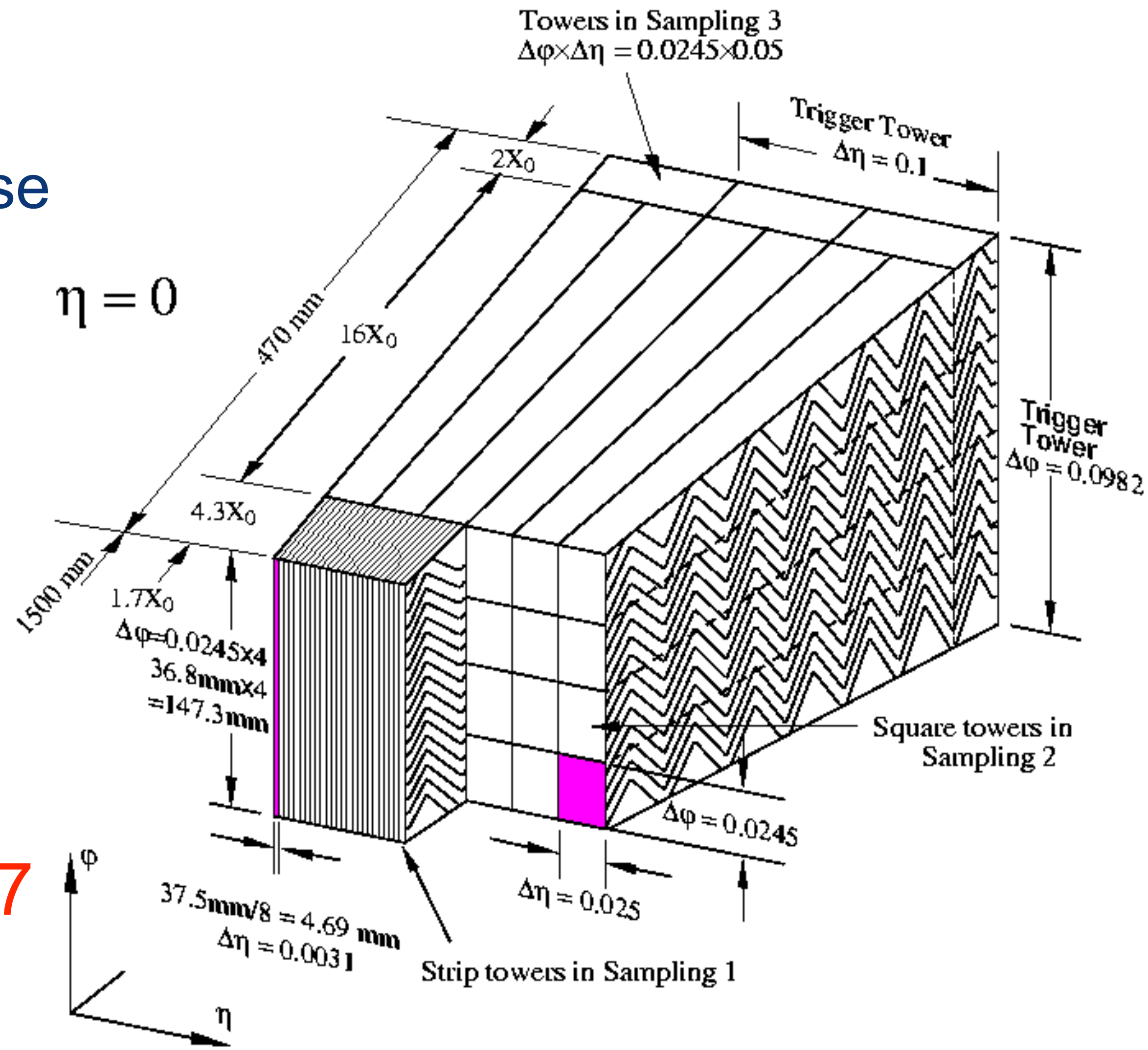
$$
\begin{aligned}
m_H &= m_{\gamma_1\gamma_2} \\
&= \sqrt{(E_{\gamma_1} + E_{\gamma_2})^2 - (\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2})^2} \\
&= \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos\vartheta)}
\end{aligned}
$$



ATLAS electromagnetic calorimeter

- Sandwich calorimeter:
  - LAr active medium
  - Pb absorber
- Fine lateral + transverse segmentation
  - Good γ identification by shower shapes
  - Improve energy resolution through shower analysis

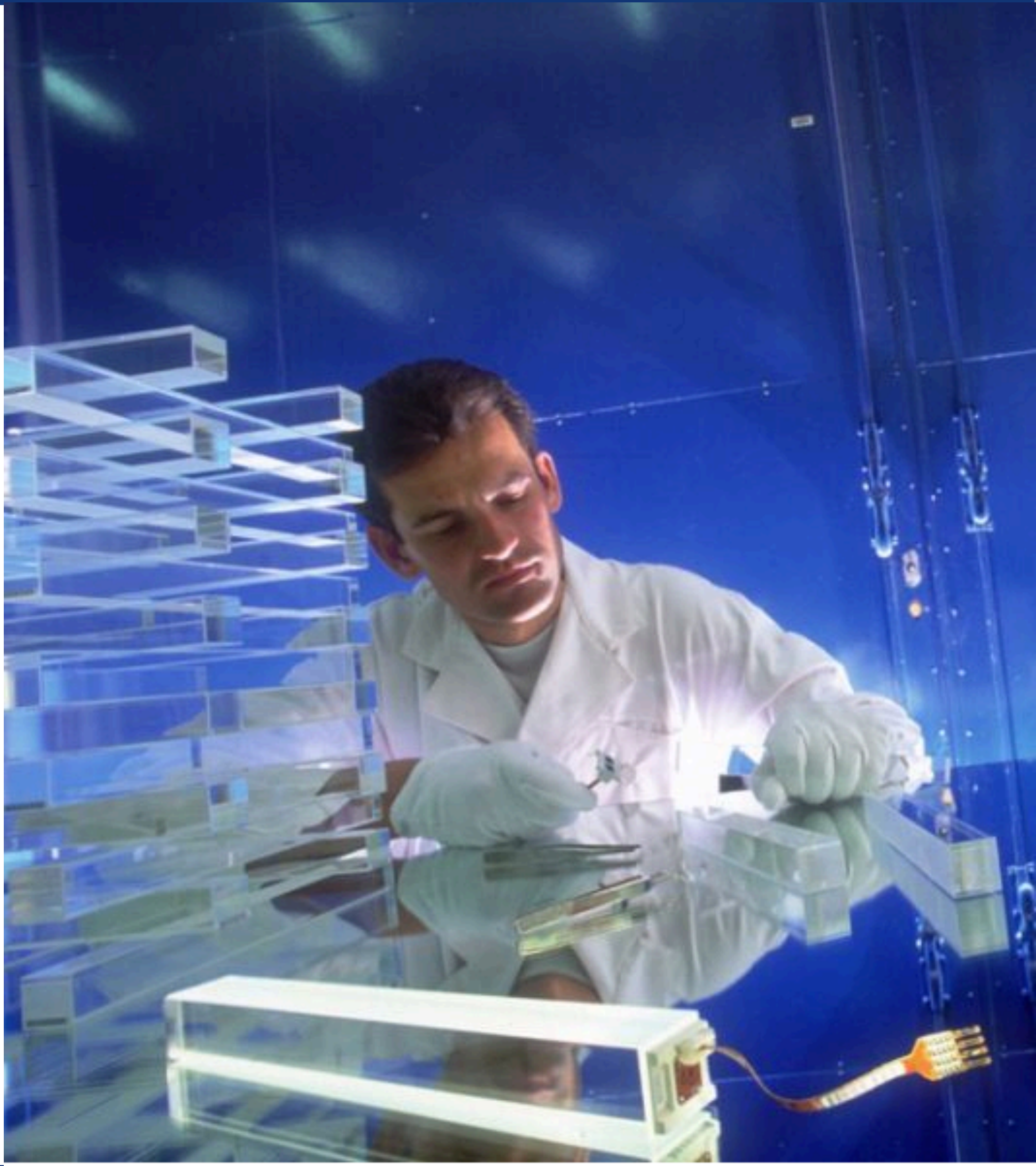
$\sigma/E = 10\%/E + 0.007$



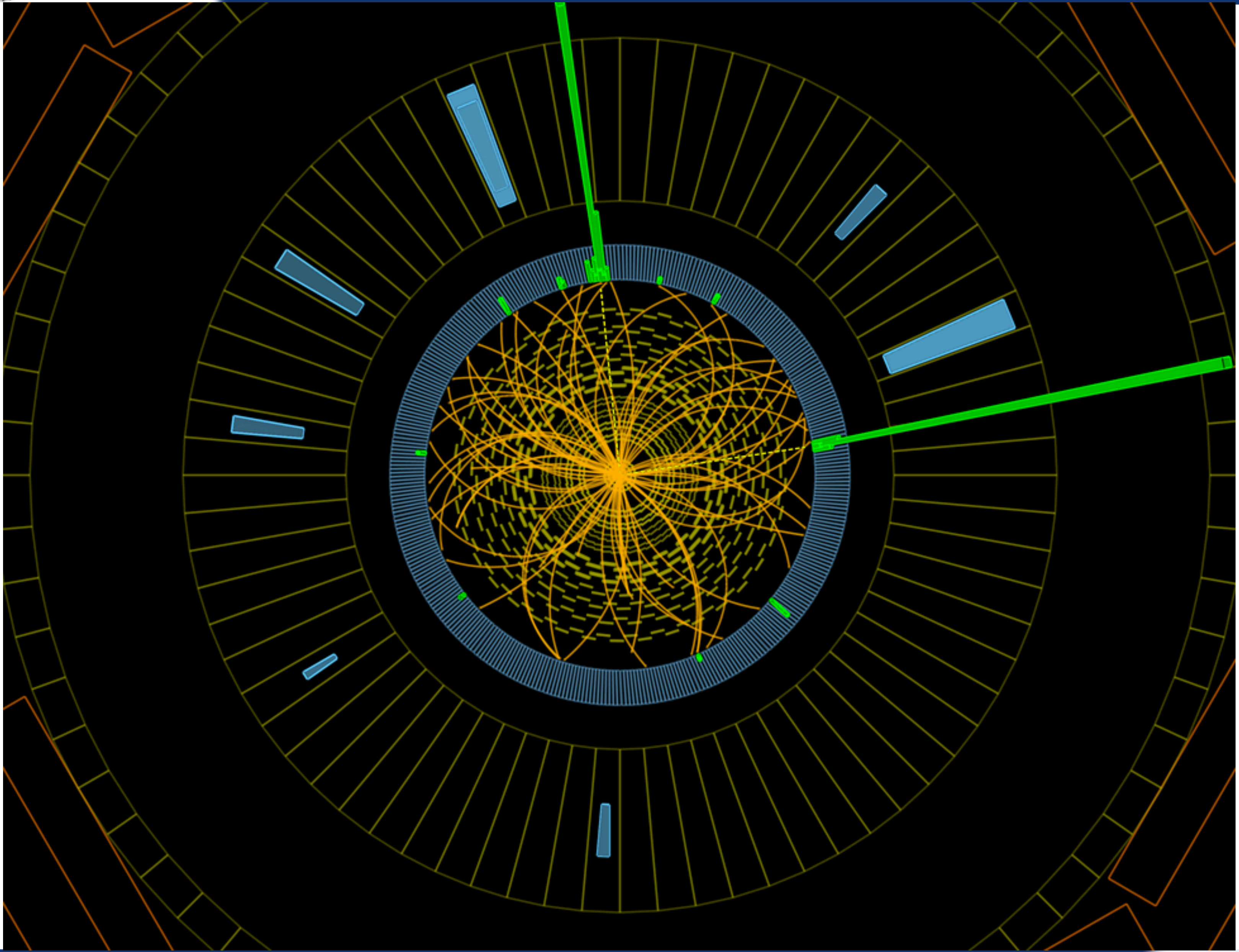
CMS electromagnetic calorimeter

- Use active medium with high X_0:
  - $PbWO_4$ crystals
    - $X_0 = 0.9$ cm
- Improve energy resolution:
  - No need for absorber, entire detector active
- Challenges:
  - Response variation with t
  - $PbWO_4$ hygroscopic

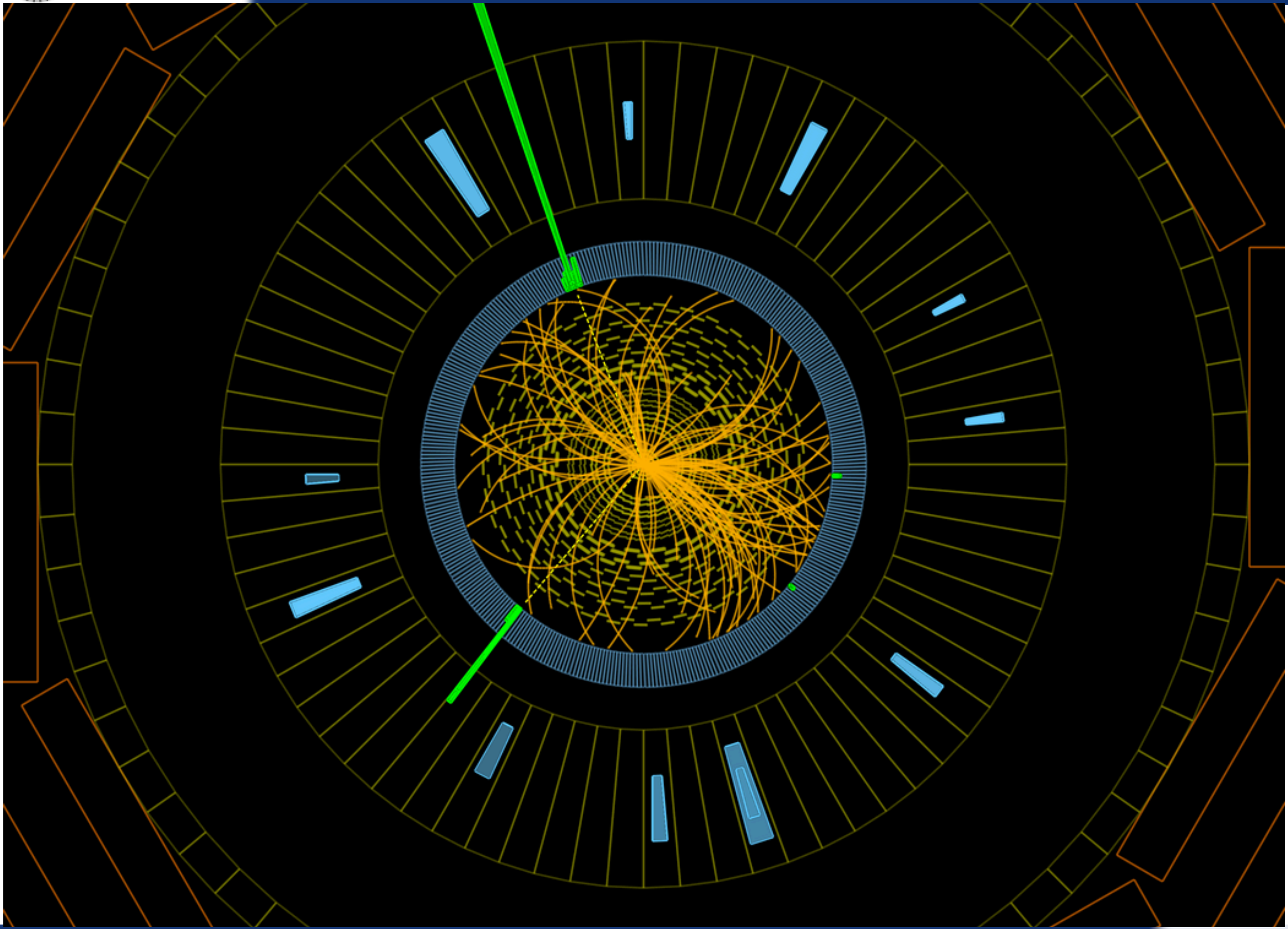
$\sigma/E = 3\%/E + 0.003$



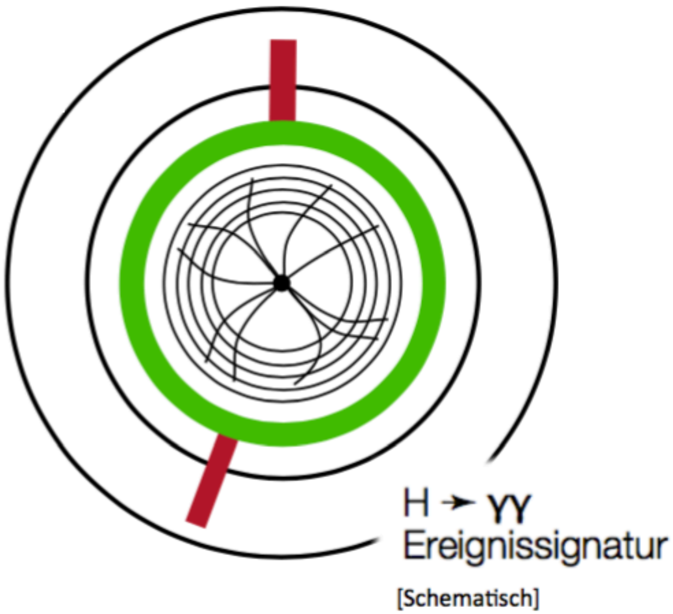
h → $\gamma\gamma$ channel

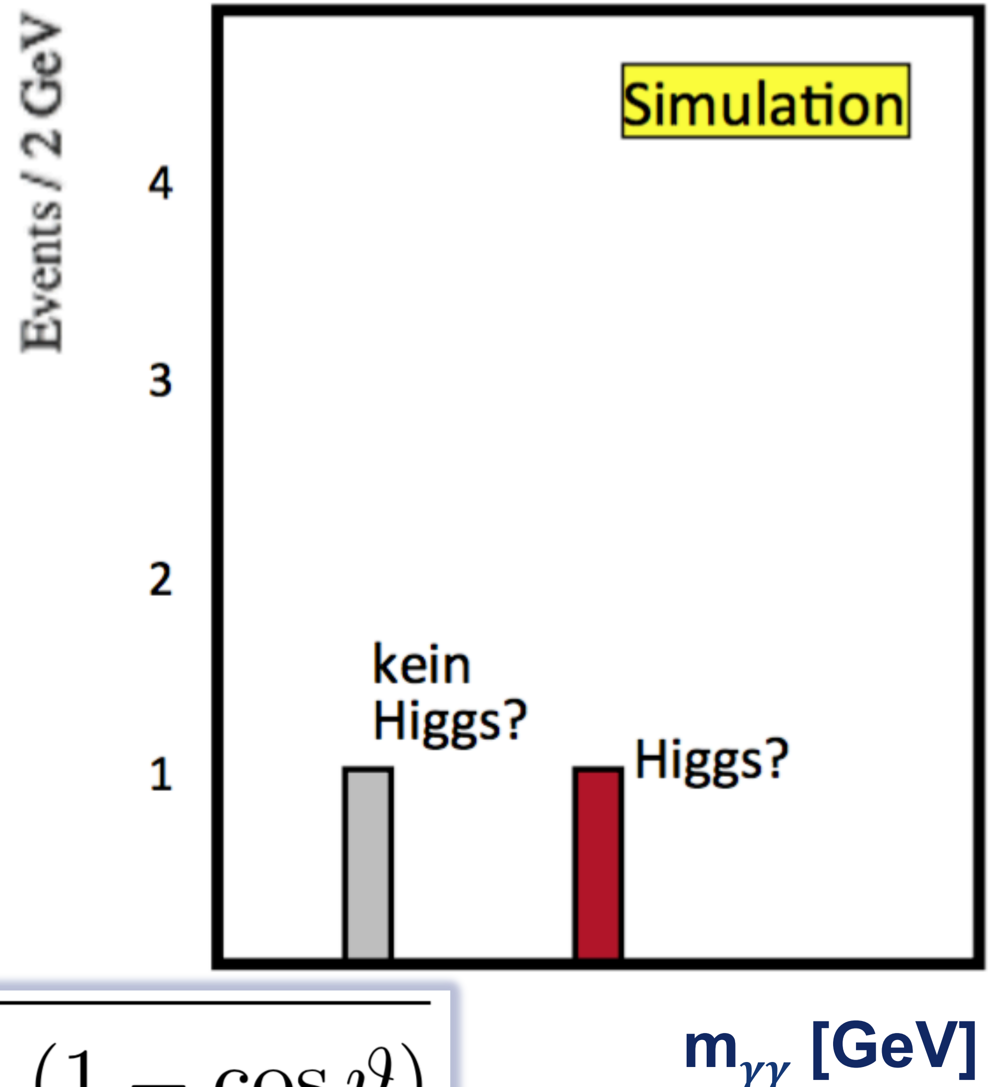


h → $\gamma\gamma$ channel



h → $\gamma\gamma$ channel

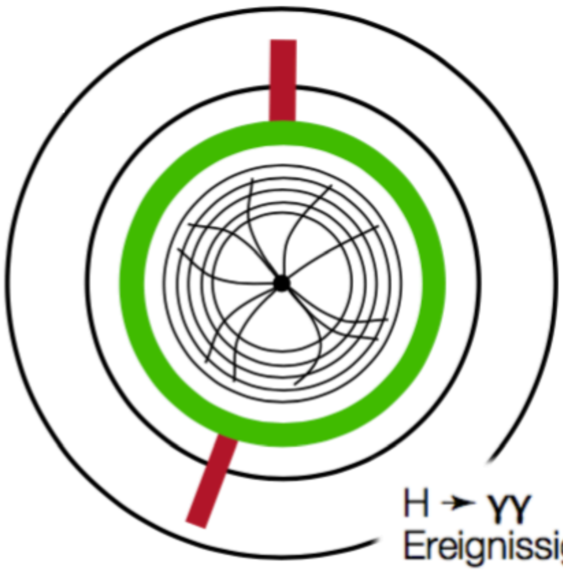




Invariant mass:

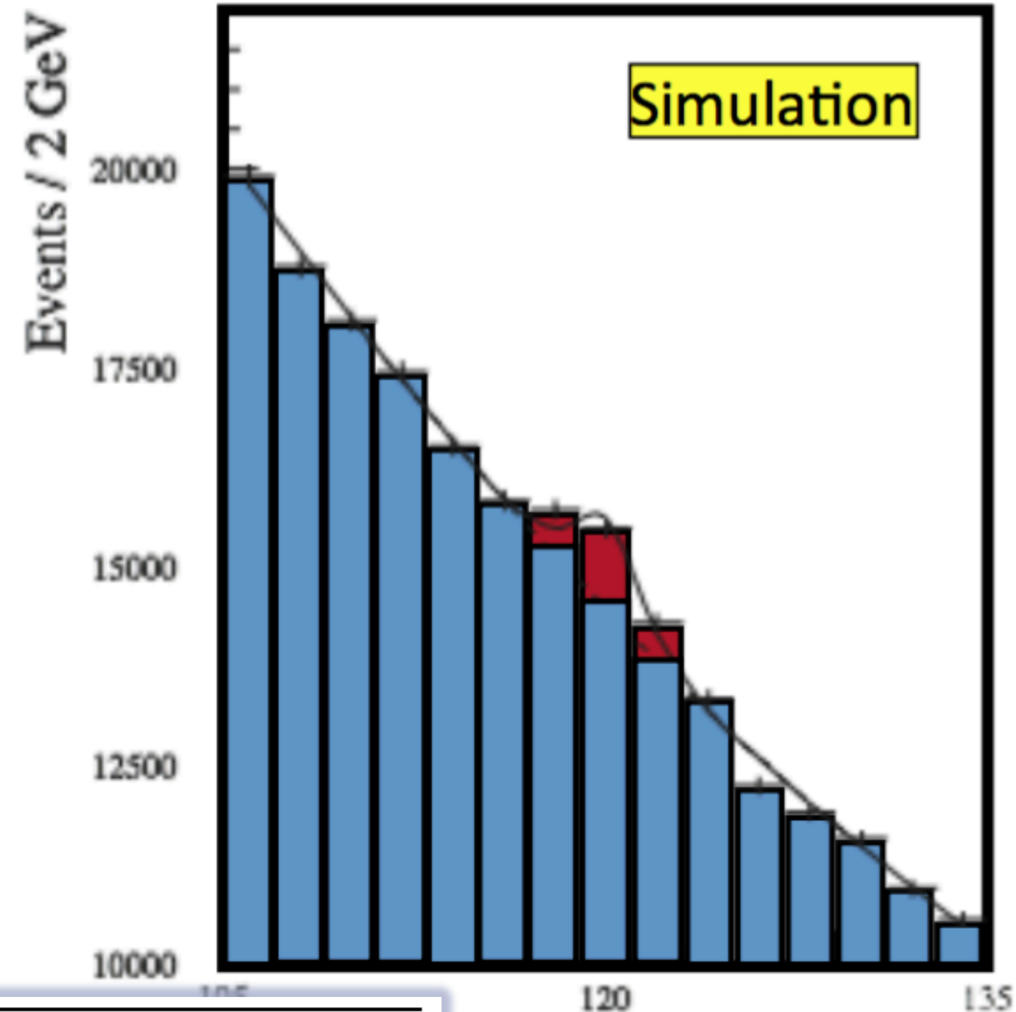
$$m_{\gamma_1\gamma_2} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\vartheta)}$$

h → γγ channel



H → γγ Ereignissignatur

[Schematisch]



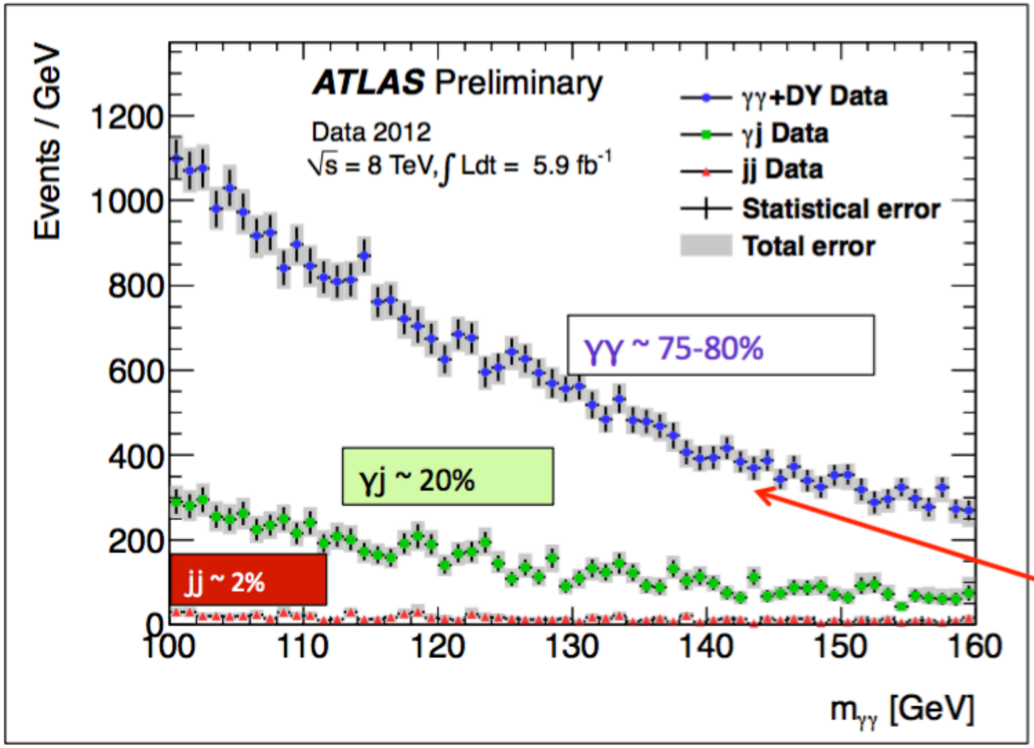
$m_{\gamma\gamma}$ [GeV]

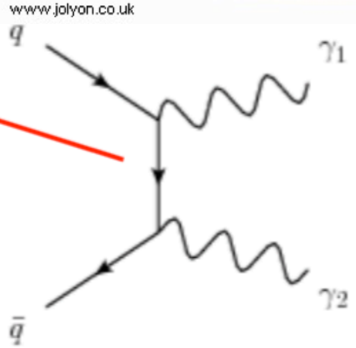
Invariant mass:

$$m_{\gamma_1\gamma_2} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\vartheta)}$$

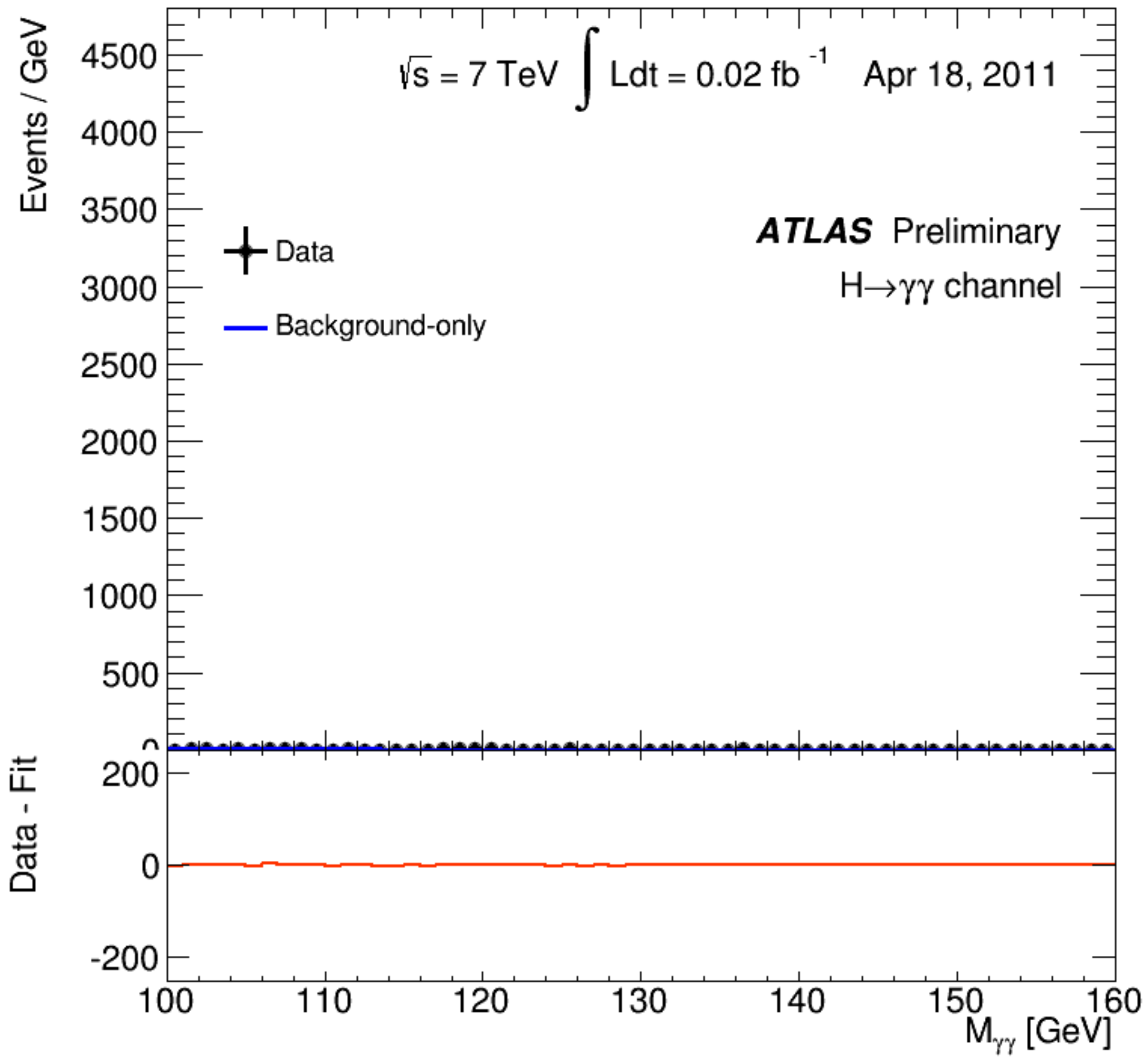
h → $\gamma\gamma$ channel

Exact understanding of background processes necessary!

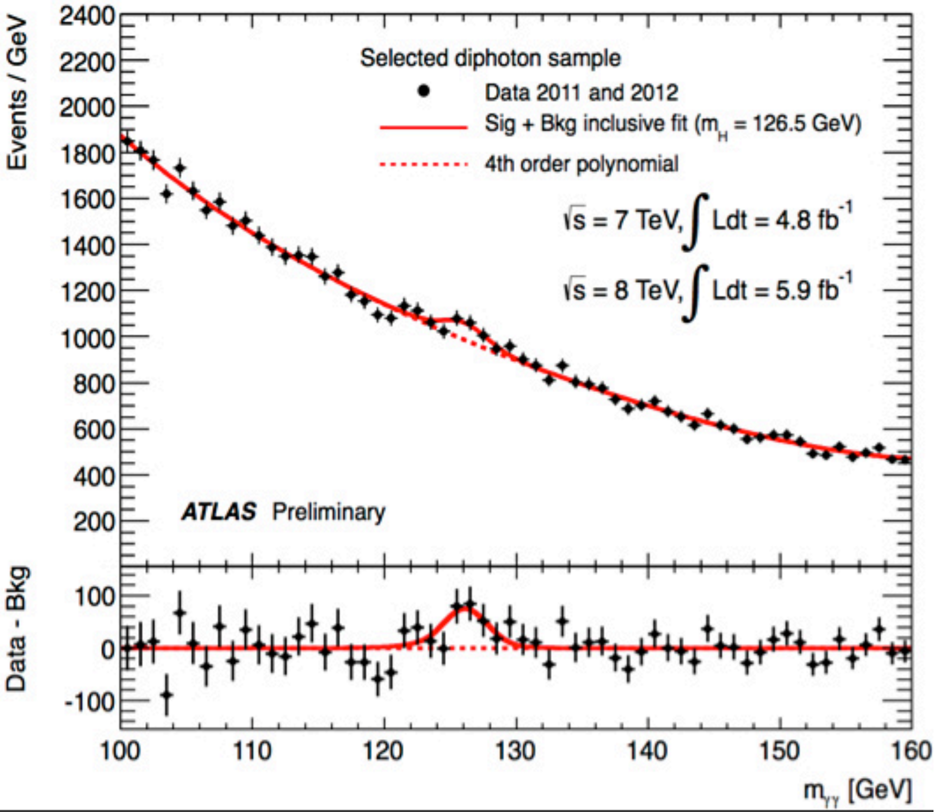


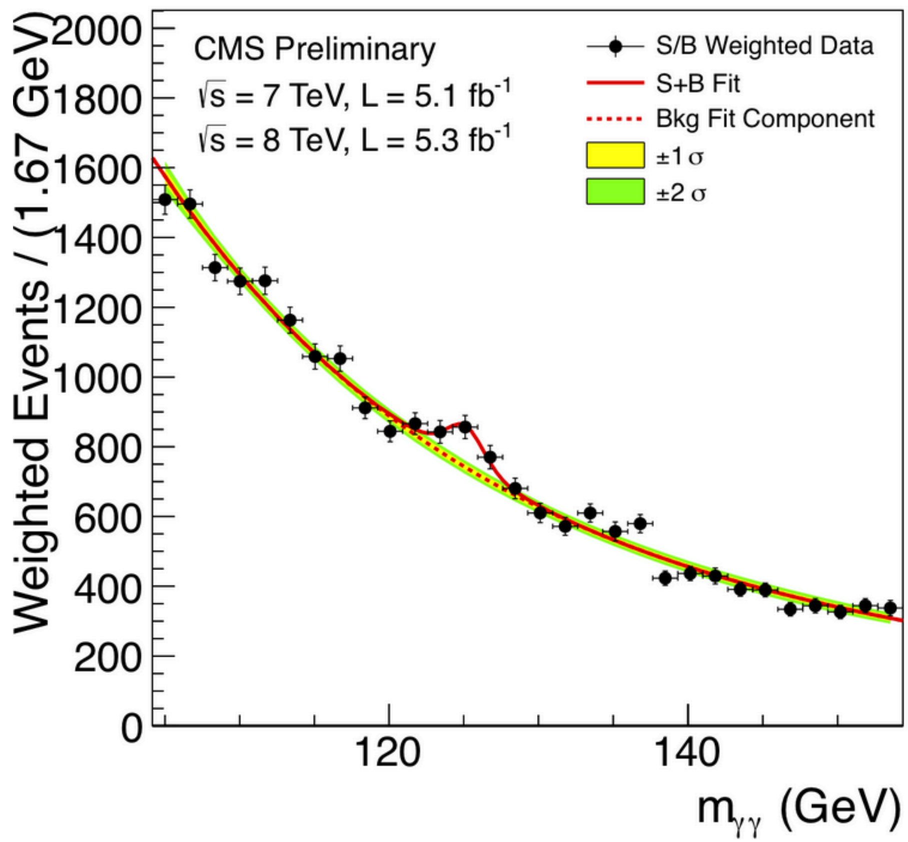


h → γγ channel


Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
√s = 7 TeV ∫ Ldt = 0.02 fb⁻¹ Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

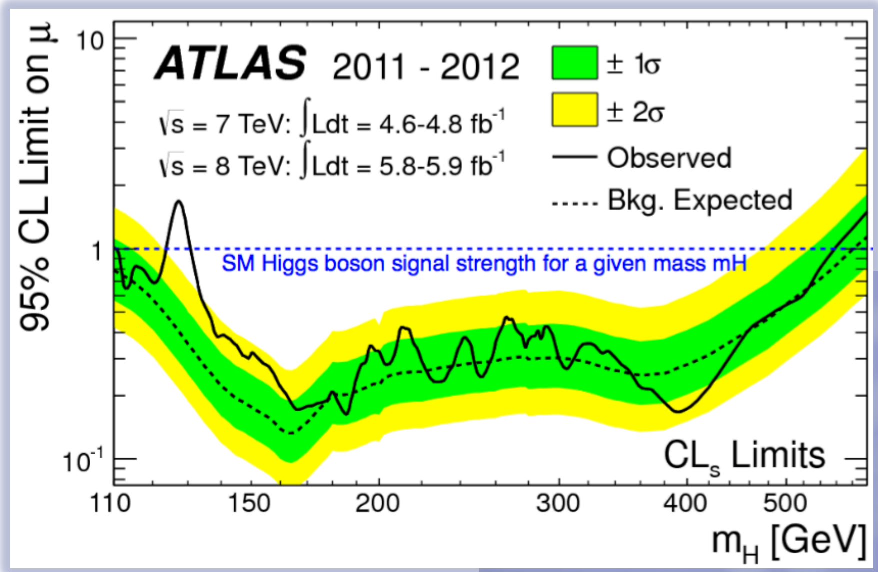
$h \rightarrow \gamma\gamma$ channel





CERN Seminar on 4. July 2012

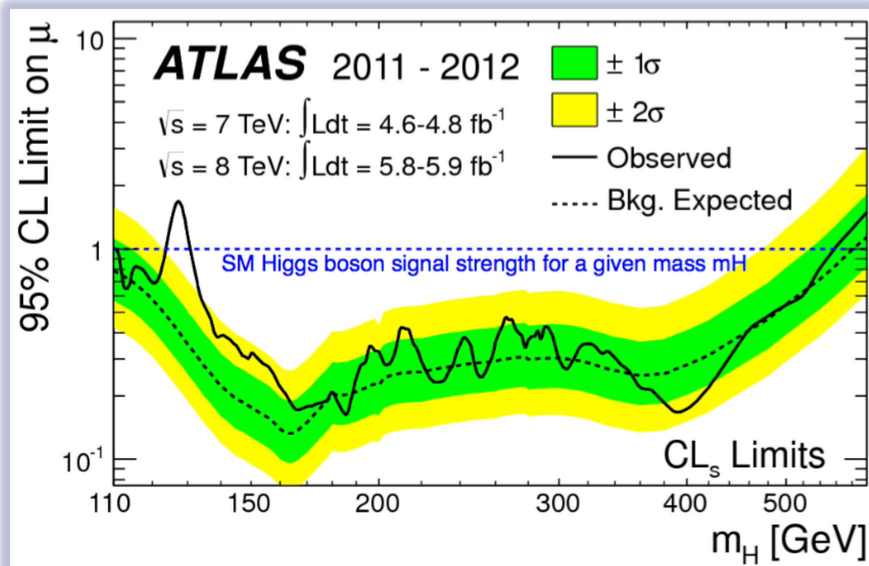
Discovery of the Higgs boson



"I think we have it!"

(Rolf Heuer, CERN-Director, former DESY-Director)

Discovery of the Higgs boson

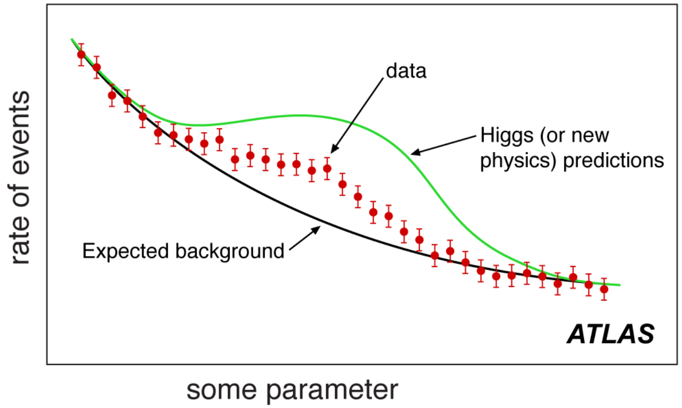


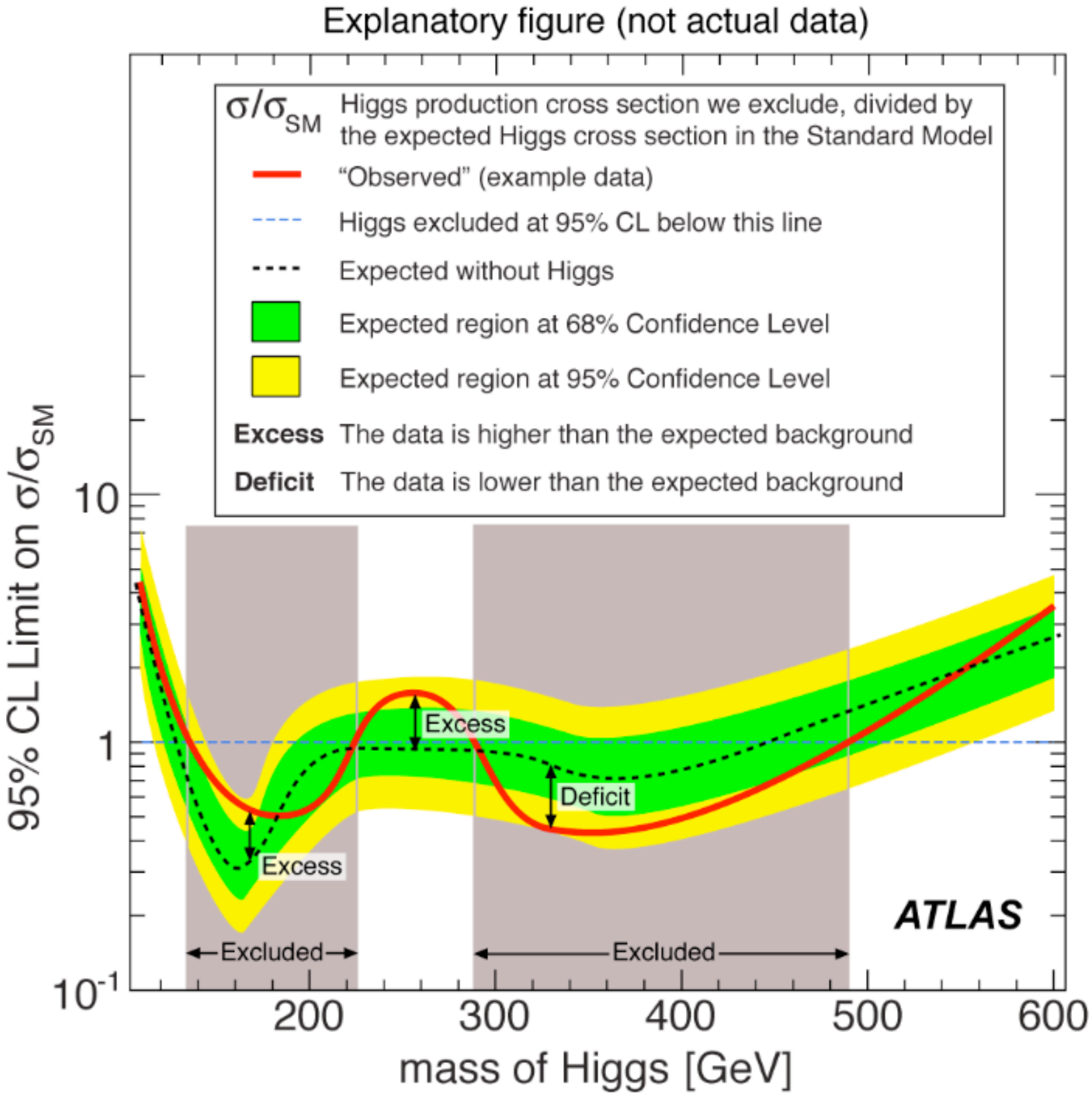
"I think we have it!"

(Rolf Heuer, CERN-Director, former DESY-Director)

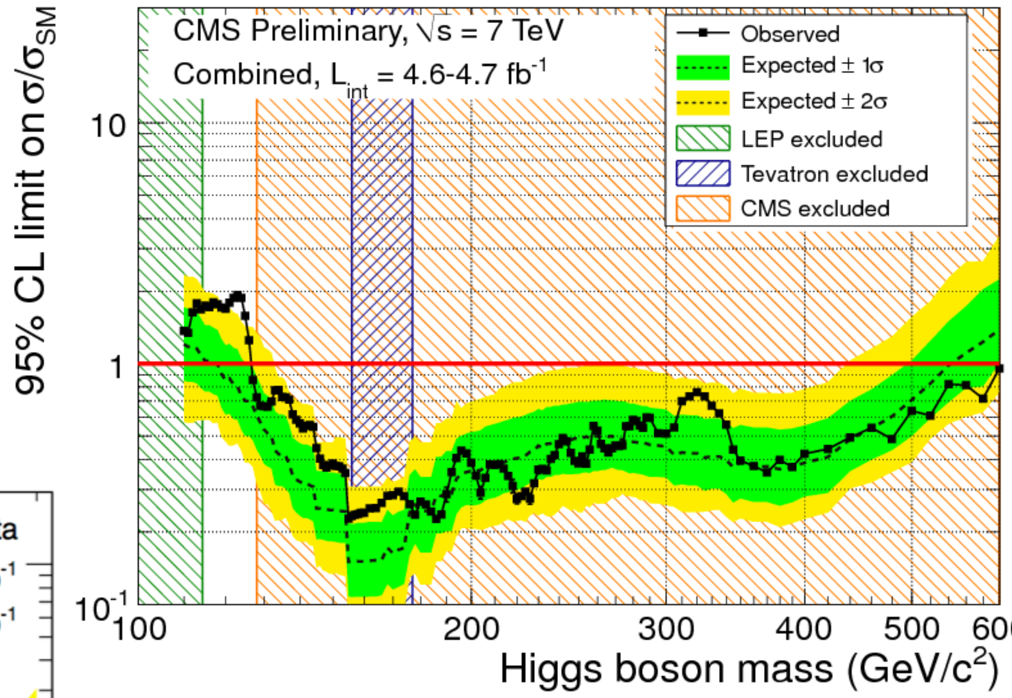
CLs in a nutshell

- What does the CLs limit plot tell us?

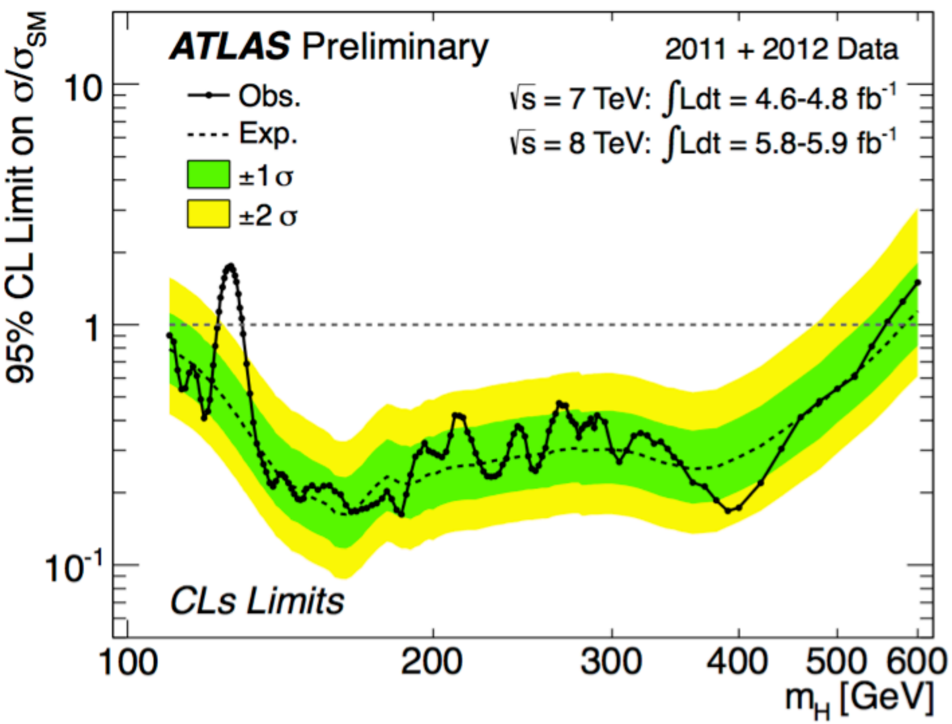




CLs limits from both experiments



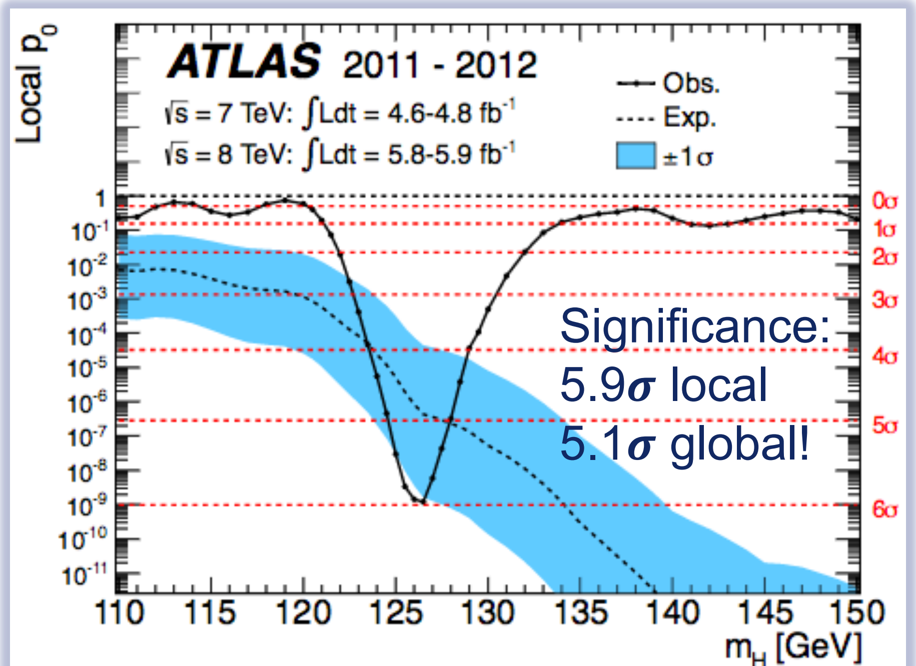
Significance:
5.1σ observed!
(5.2σ expected)

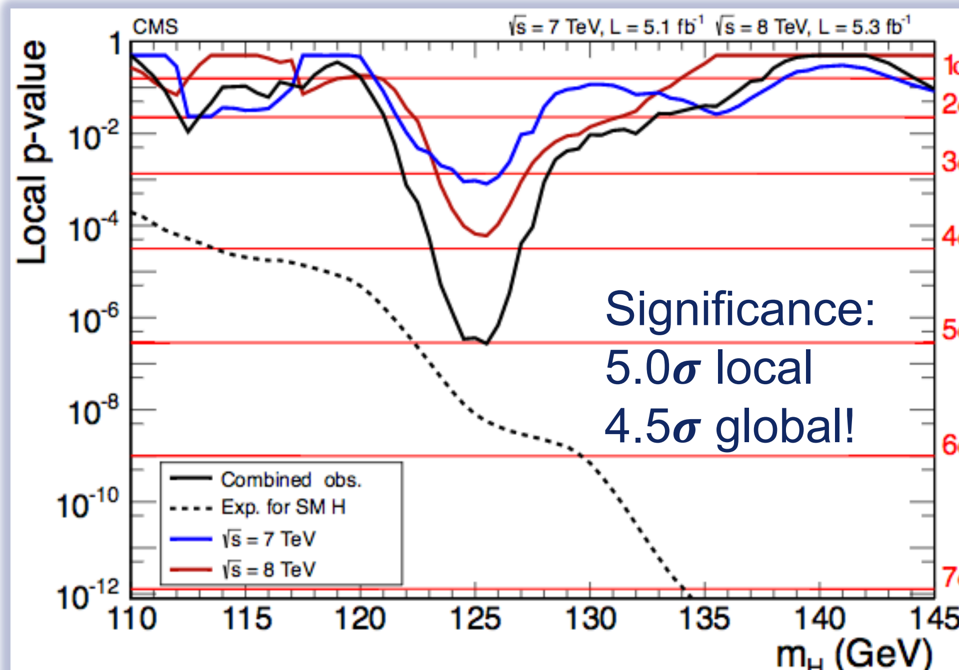


Significance:
5.0σ observed!
(5.8σ expected)

p_0 from both experiments

- Value of p_0:
  - how likely is it to obtain a result as discrepant as the observed one or even more from the expectation for H_0 (background-only) hypothesis
    - 3σ: “evidence”
    - 5σ: “observation”



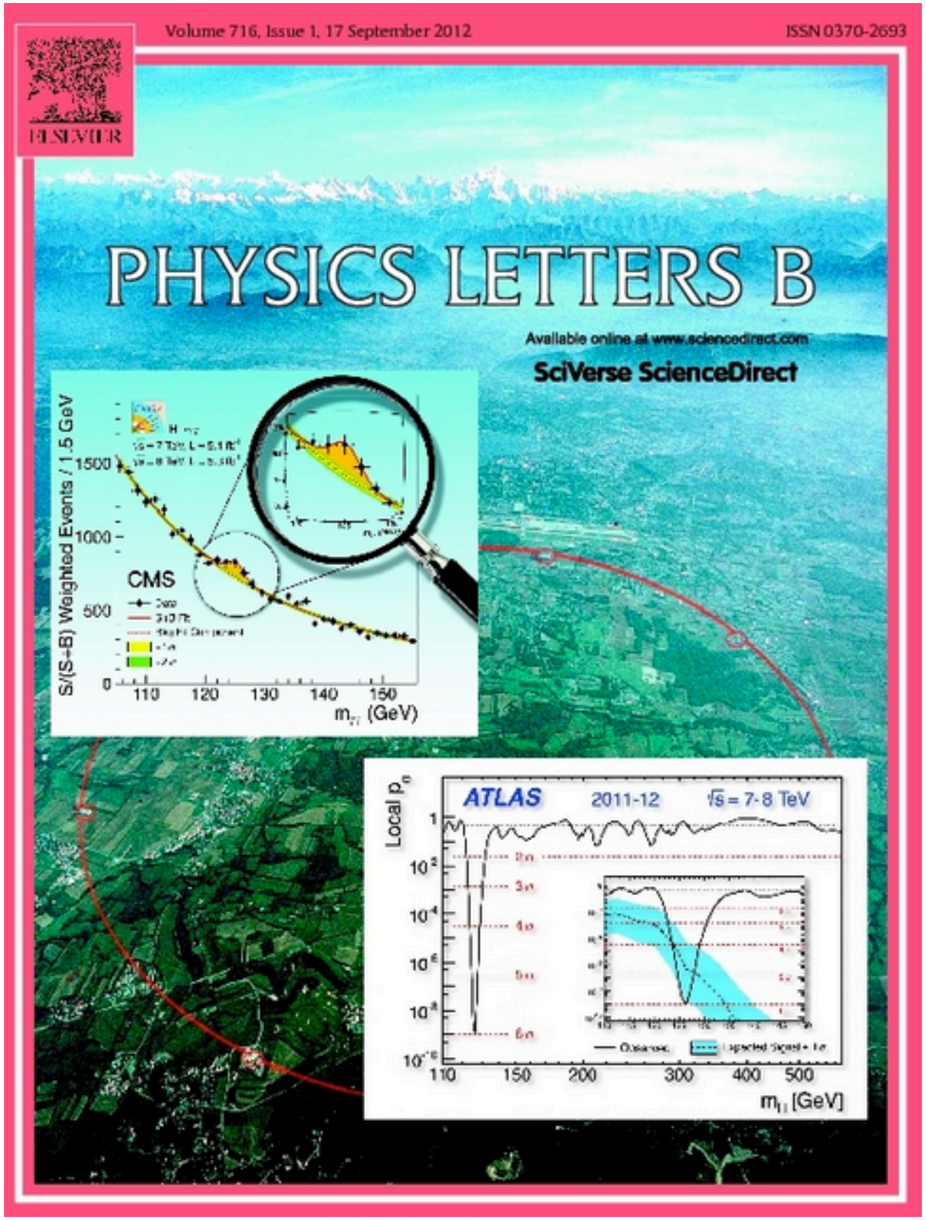


Look-elsewhere effect for p_0

[1] *E. Gross and O. Vitells, Eur. Phys. J.* ***C70*** *(2010) 525*

- **Look-elsewhere effect:**
  - A priori not known where to look for an excess
    - Look at a wide range of m_h values
      - What is the probability for an excess anywhere in this range?
  - Rough back-of-the envelope estimation:
    - Quantify the look-elsewhere effect with the **trials factor**:
      - *N* of times the experimental resolution "fits" into the search range:
        - Trials factor ≈ search range (GeV) / resolution (GeV)
    - Correct the **local** p_0 value:
      - **Global** p_0 value ≈ trials factor * local p_0
  - The effect is typically not dramatic (Higgs paper example):
    - Search range $M_{\text{Higgs}} \in [110,600]$ GeV, trials factor ≈ 100
    - **Local** p_0 significance: **5.9σ**
    - **Global** p_0 significance: **5.1σ**
  - Standard method to quantify trials factor: Ref. [1]

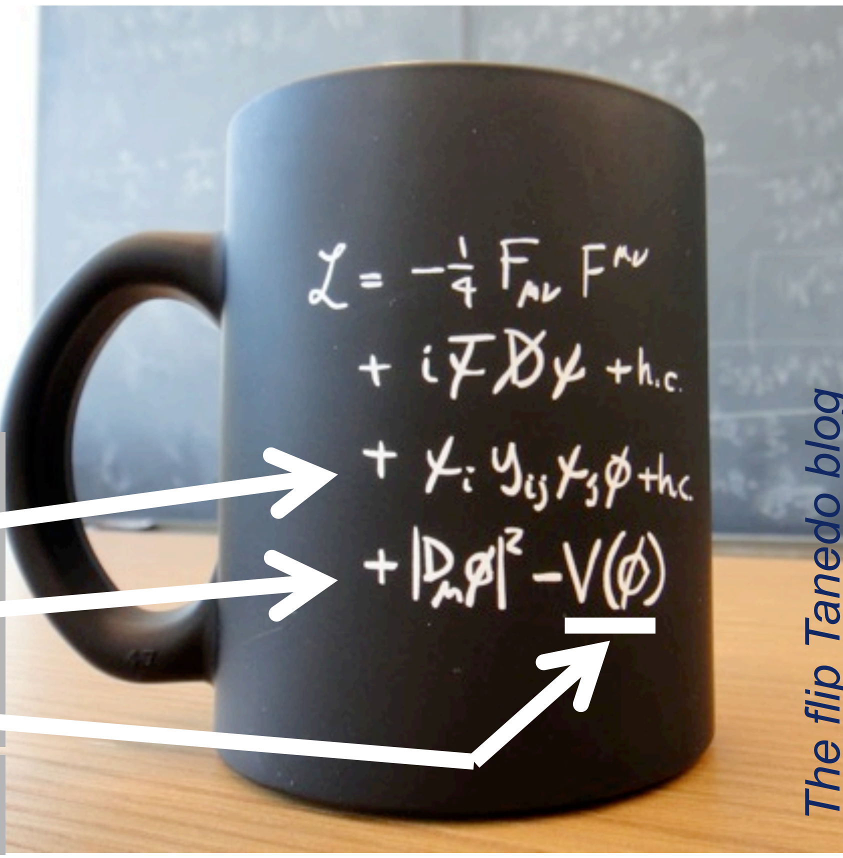
Discovery publication



Sometimes the wait is worth it…

3 milestone papers in Phys. Rev. Lett. 13 (1964)

P.W. Higgs | R. Brout | F. Englert | G.S. Guralnik | T.W.B. Kibble | C.R. Hagen



The flip Tanedo blog

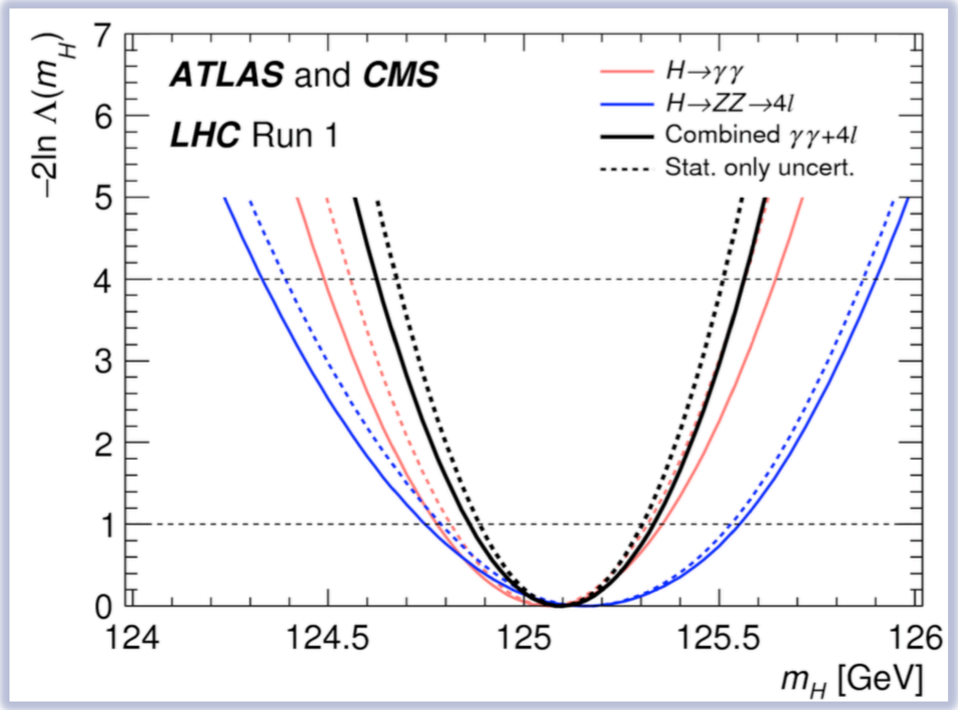
The SM gets three additional terms:
- Higgs-fermion coupling
- Kinematic term for the Higgs
- Self-coupling of the Higgs

Focus on the red ones (→ BSM?)

Higgs mass measurement

- SM coupling measurement depends on m_H:
  - Precise m_H measurement → smaller uncertainty on SM couplings
  - Effect small compared to statistical uncertainty of coupling results

First ATLAS+CMS publication

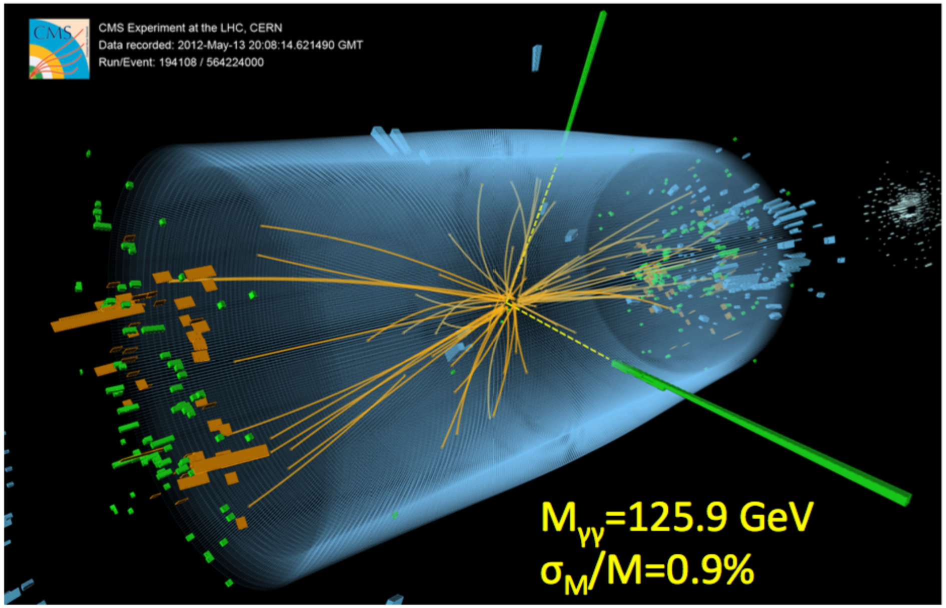


$M_H = 125.09 \pm 0.24$ GeV
$= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

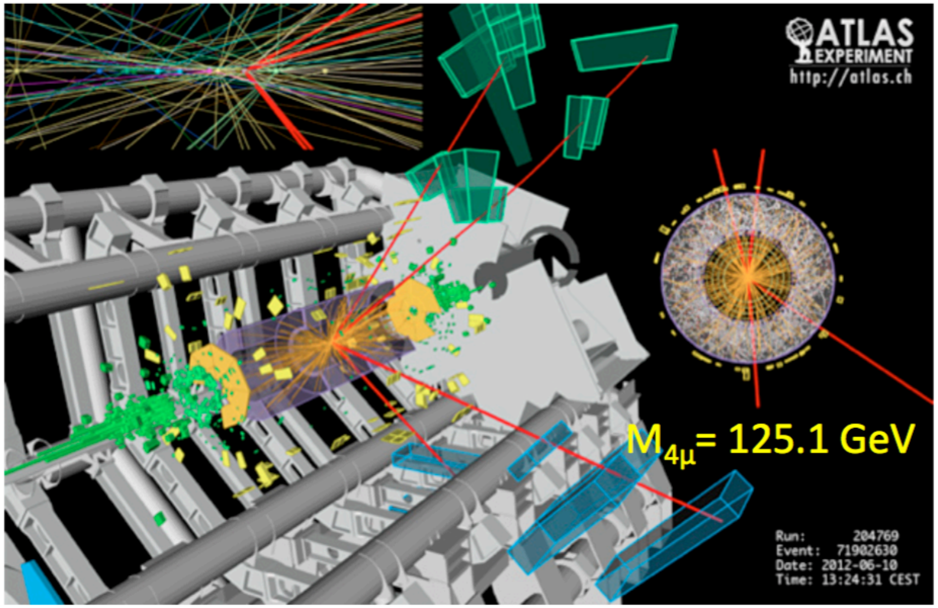
Higgs mass measurement

- Measure m_H in high-resolution channels:

$H \to \gamma\gamma$



$H \to ZZ^* \to \ell\ell\ell\ell$



$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$
$$= 125.07 \pm 0.25\,(\text{stat.}) \pm 0.14\,(\text{syst.}) \text{ GeV}$$

$$m_H^{4\ell} = 125.15 \pm 0.40 \text{ GeV}$$
$$= 125.15 \pm 0.37\,(\text{stat.}) \pm 0.15\,(\text{syst.}) \text{ GeV}$$