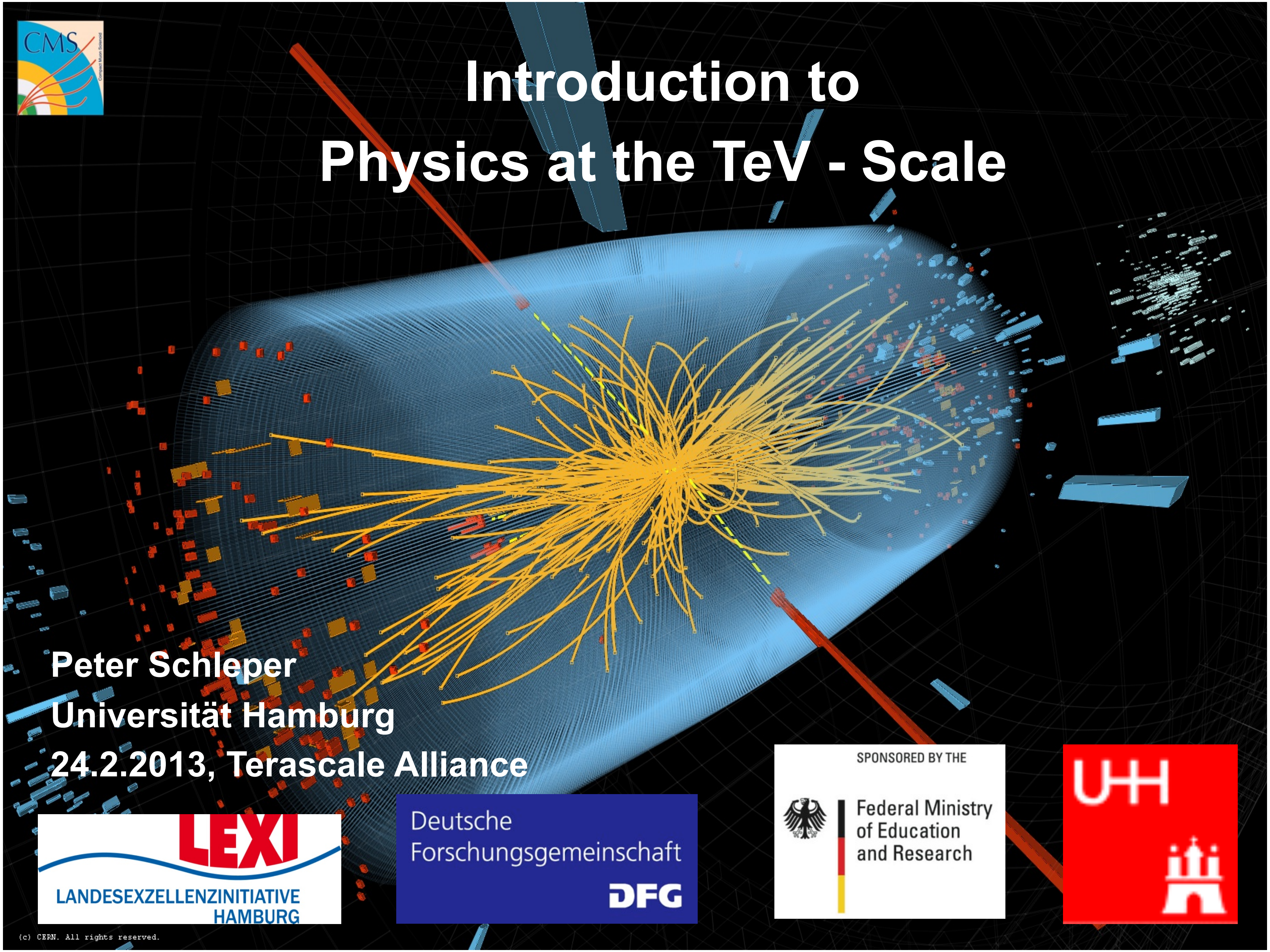
Introduction to Physics at the TeV - Scale



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24.2.2013, Terascale Alliance

LEXI LANDESEXZELLENZINITIATIVE HAMBURG

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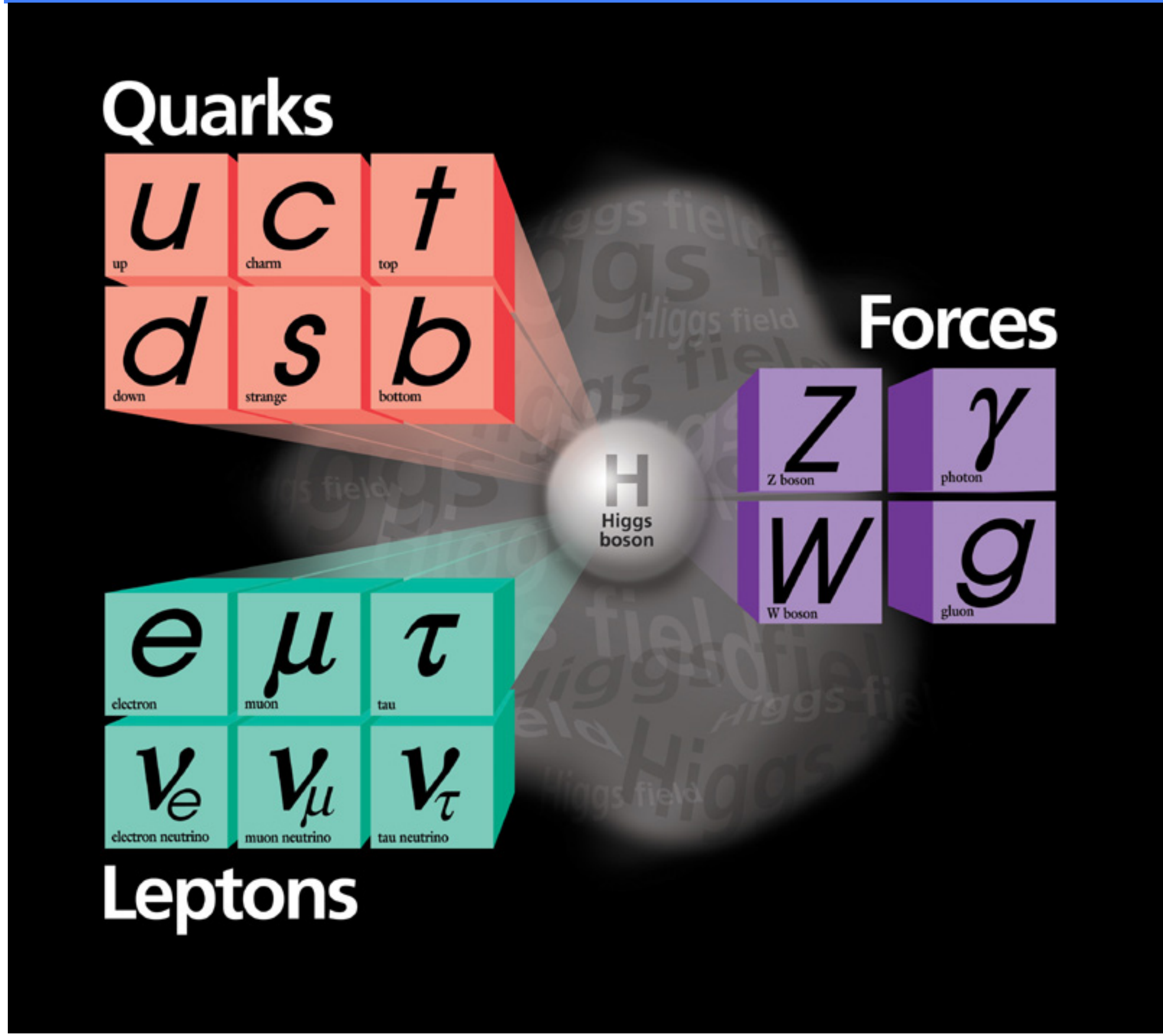
Standard – Model of Particles and Forces



Particle Physics:

- Quarks
- Leptons
- Force carriers: γ, W, Z, Gluons
- Higgs

elementary,

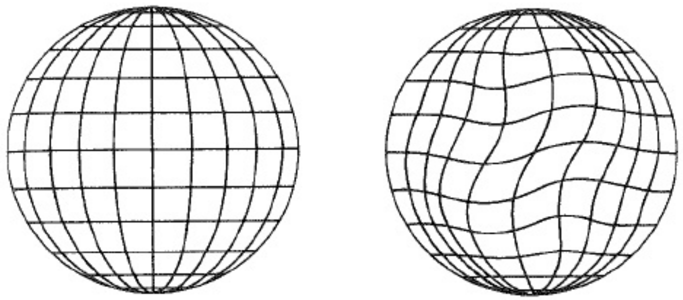
no inner structure

Symmetries

Standard-Model: Symmetries in Quantum Mechanics

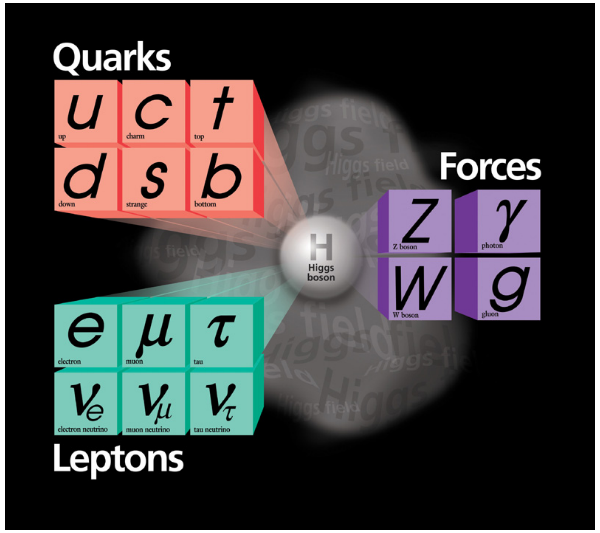
- Properties of fields

  → Prediction of forces and their properties !!
- Analogy: Rotation of a ball → Phase of a wave



Examples for Predictions, Discoveries & Nobel Prizes

- Weak and Strong Force
- 3rd Neutrino,   Quarks: charm, top
- W, Z, Gluon
- Successful for ALL experiments
- Higgs ??



Problem:

- Difference between particles ?
- Masses are forbidden

Symmetry – Breaking

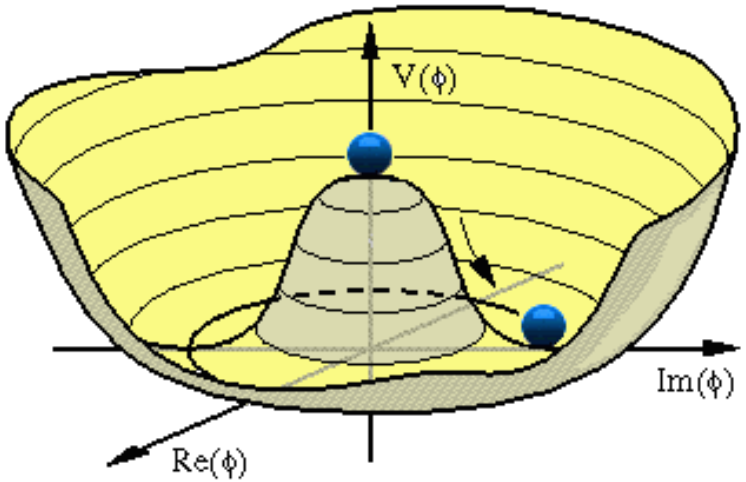
„Symmetry is Art Without Phansatie"
(unknown)

Higgs-mechanism

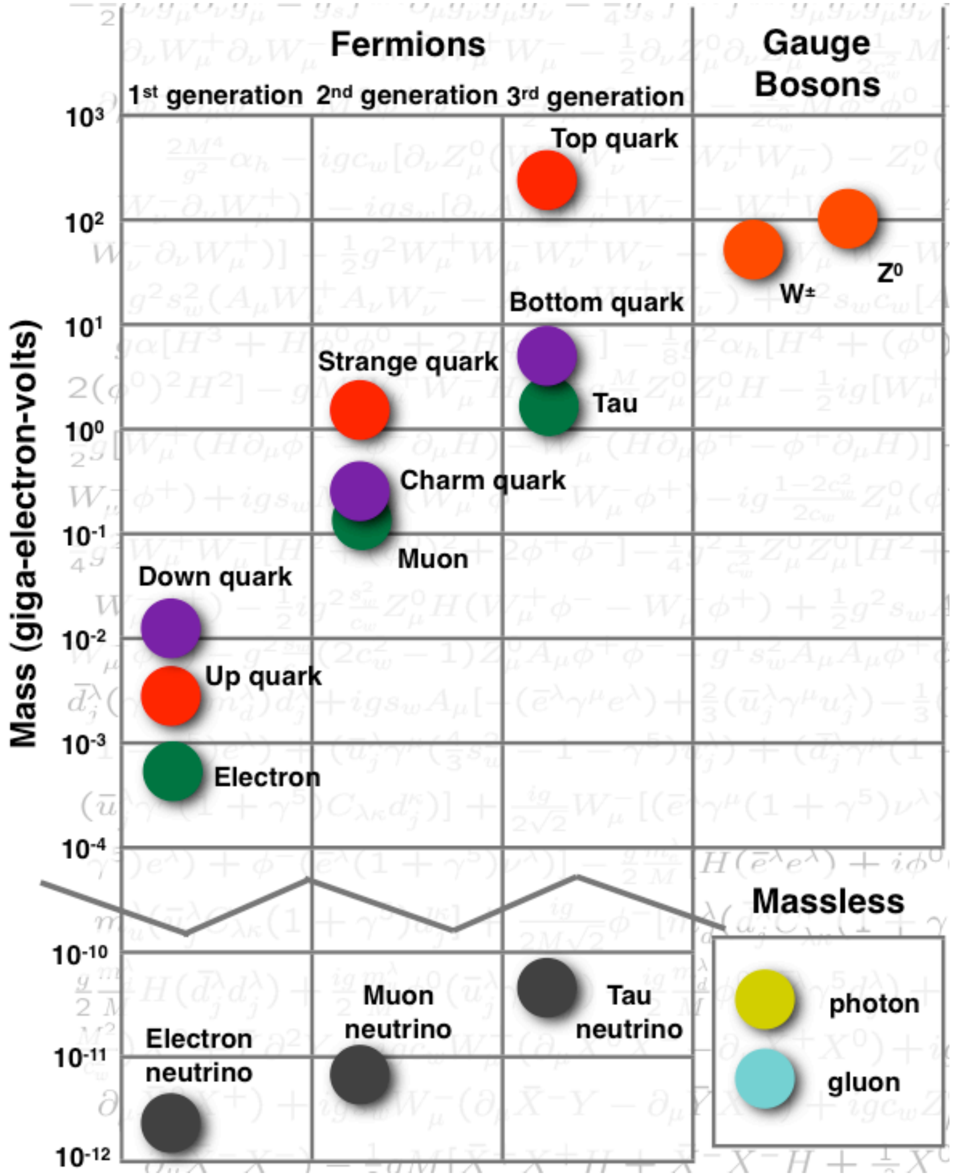
- **Vacuum breaks Symmetry**

→ **W, Z masses predicted**

→ **Quark & Lepton masses possible**



Masses of known particles



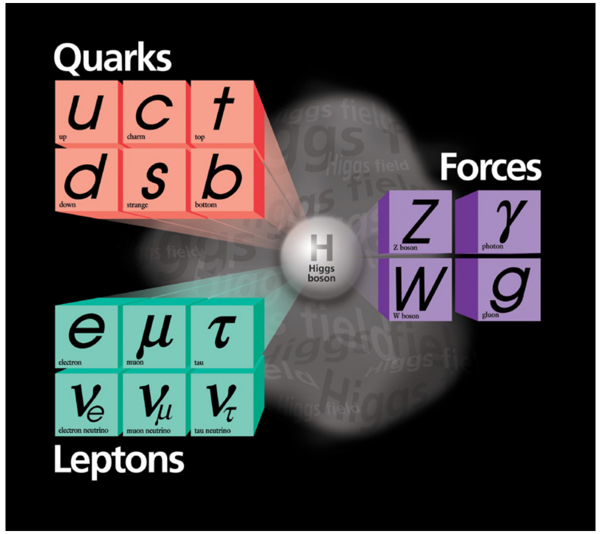
Critisism of the Standard Model

Success:

- Few principles: Relativity + Quantum Physics
  Symmetry + Symmetry-breaking
- Predictions of several new Particles
- Predicts all laboratory measurements (Higgs?) up to now
- Complete description of laws of nature ? (first time since 1870?)

Problems:

- 17 Particles, 26 constants of nature, for 5% of energy density
- 22 constants only due to Higgs !!
  Explanation or parameterization ?
- High energy limit → quantum corrections



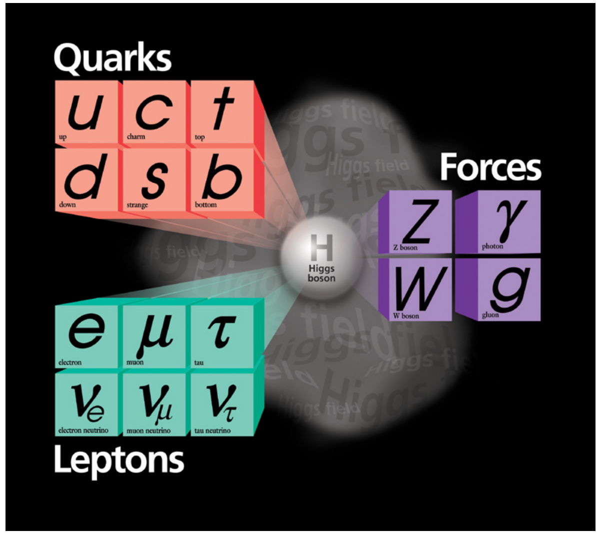
- No explanation for dark matter/energy
- No explanation for baryon asymmetry

The Big Questions

Are the known particles elementary ?
- No size, no excitations ?

Is the new particle a Higgs boson ?
- Could be just the first…

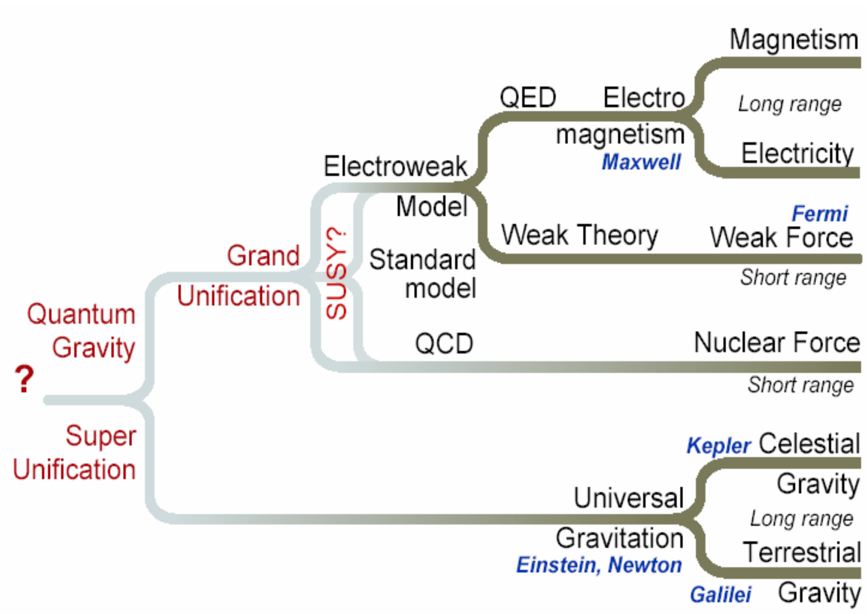
Is the Standard-Model valid ?
- Few constants → many measurements ?



Why just these particles ?
- New gauge bosons, fermions ?
- Grand Unification

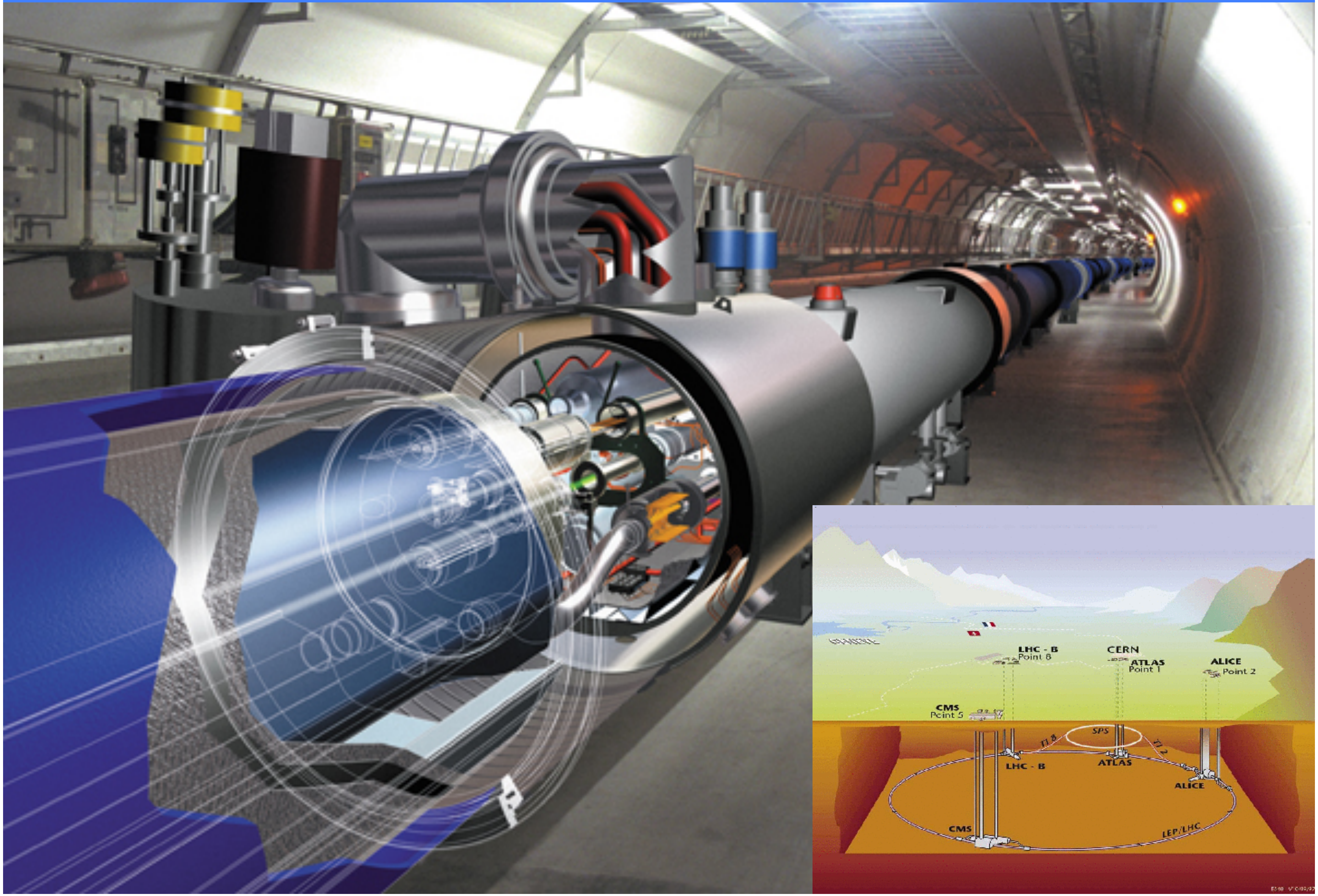
What is dark matter
- New conserved quantum number ?

Are there other principles ?
- New fermion-boson symmetries… Supersymmetry
- New space-time dimensions…



Energie, Temperatur, Zeit

The Large Hadron Collider at CERN



Why there is a breakthrough

LHC:

- Magnet technology: 2 → 8 → 14 TeV
- pp - Luminosity: 20 → 3000 fb^{-1}

Detectors: (ILC)

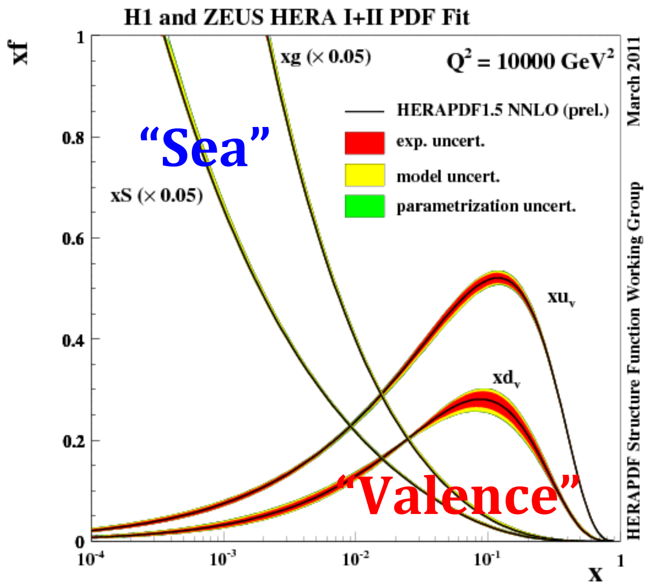
- Tracking at high particle fluxes
- Si- detectors, Calibration

Parton densities: (ILC)

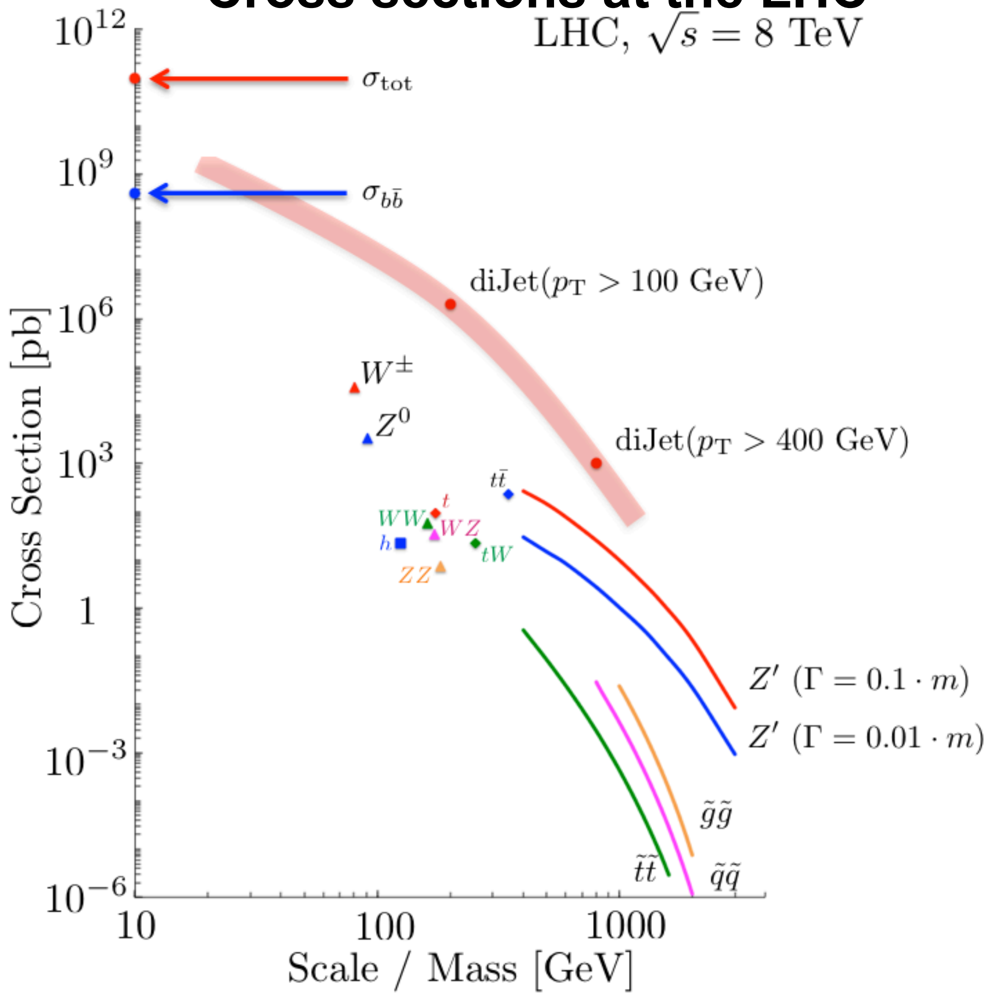
- HERA experiments

Theory (QCD): (ILC)

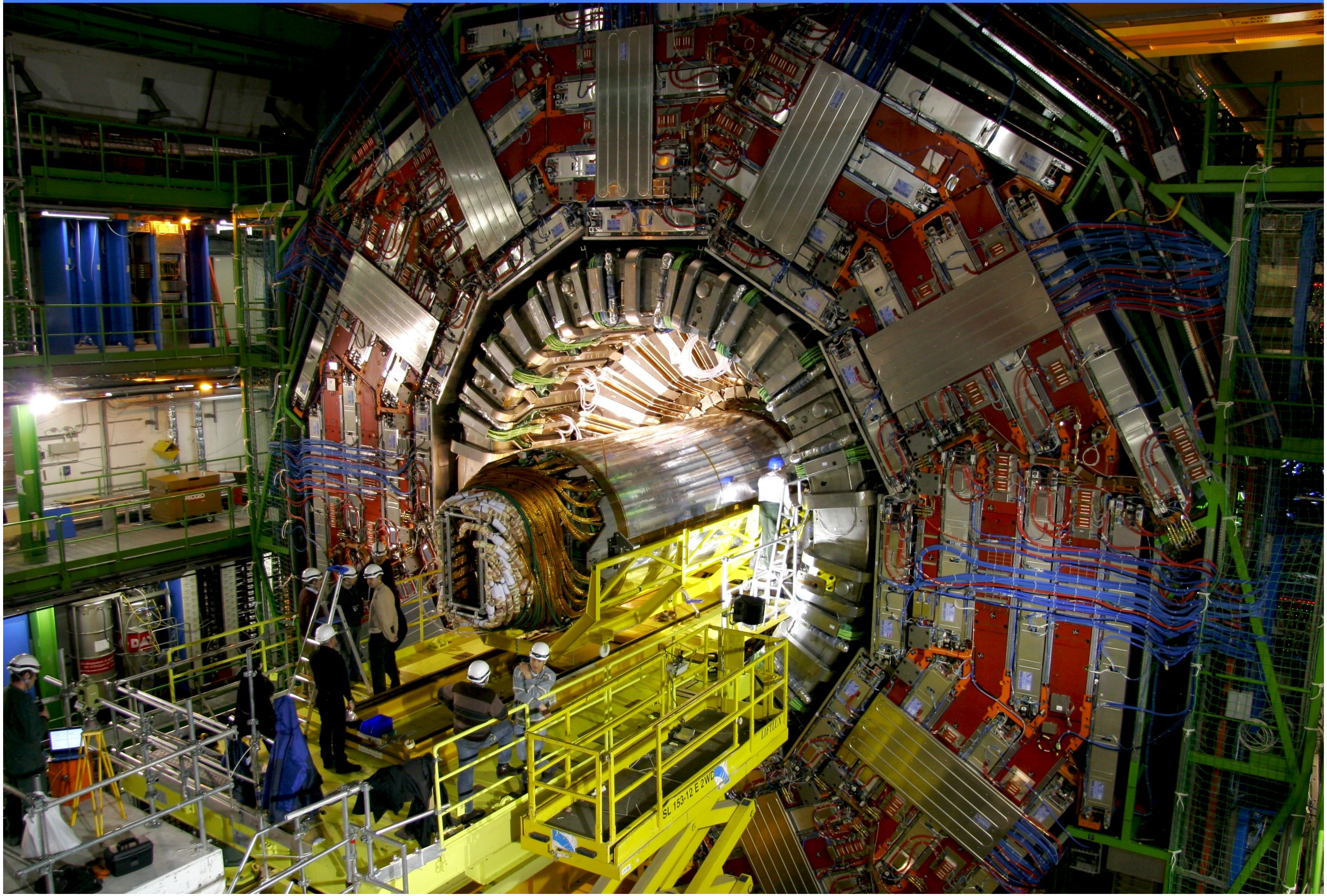
- Higher order, or many particles



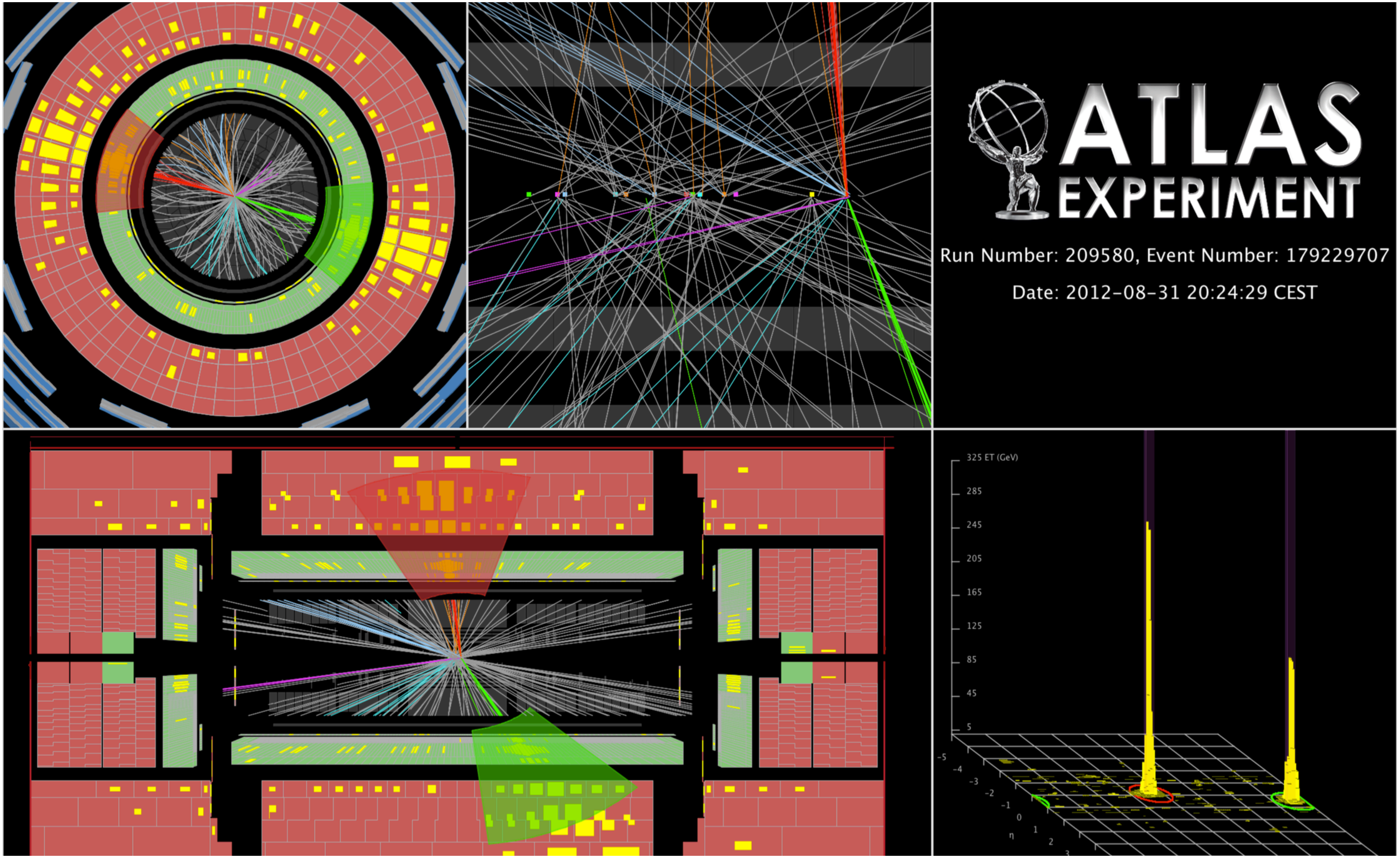
Cross sections at the LHC



CMS Detector



m_{jj} = 4,69 TeV


ATLAS
EXPERIMENT
Run Number: 209580, Event Number: 179229707
Date: 2012-08-31 20:24:29 CEST
325 ET (GeV)
285
245
205
165
125
85
45
5
η

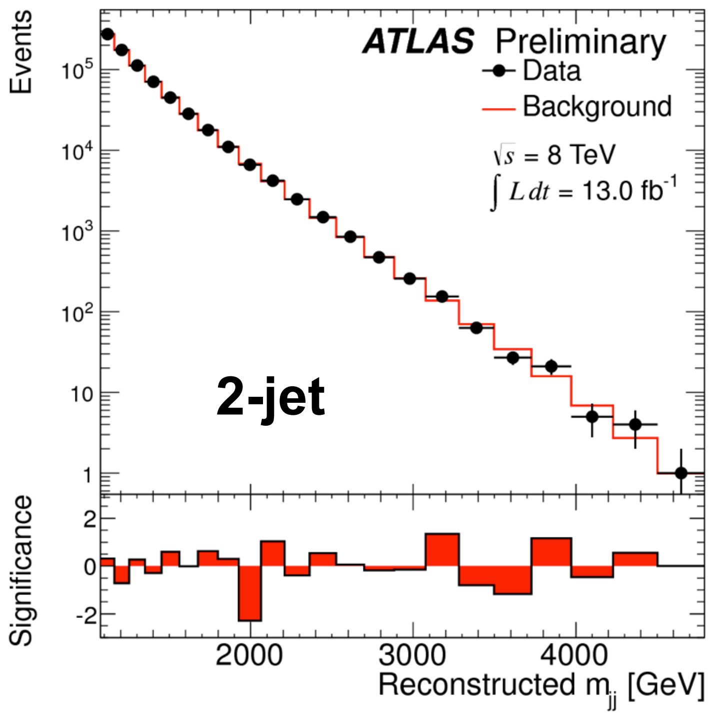
Are Particles elementary ?

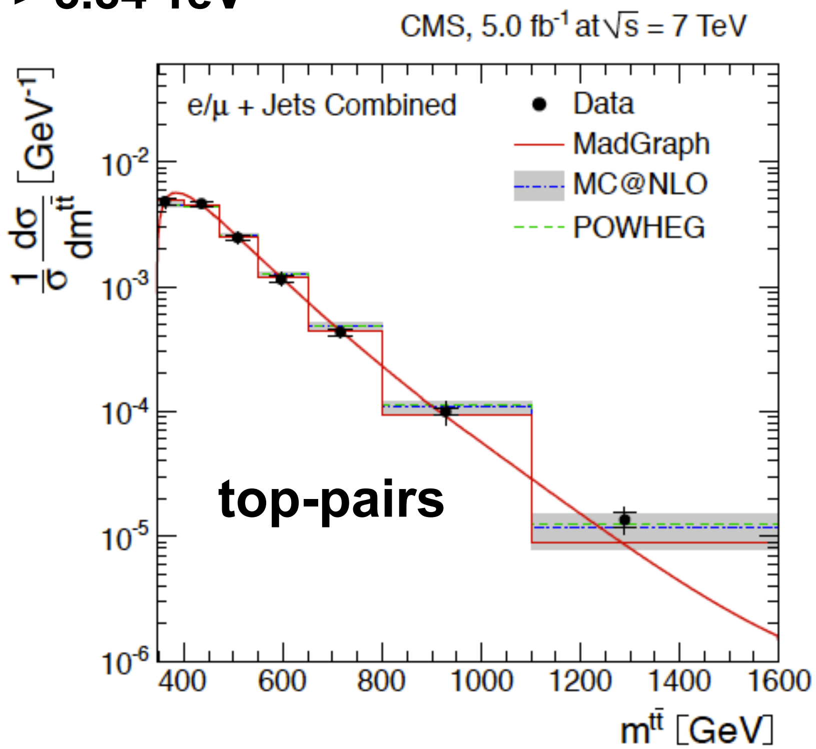
Point-like vs. Composite Quarks: Scattering at high Pt

Uncertainty relation

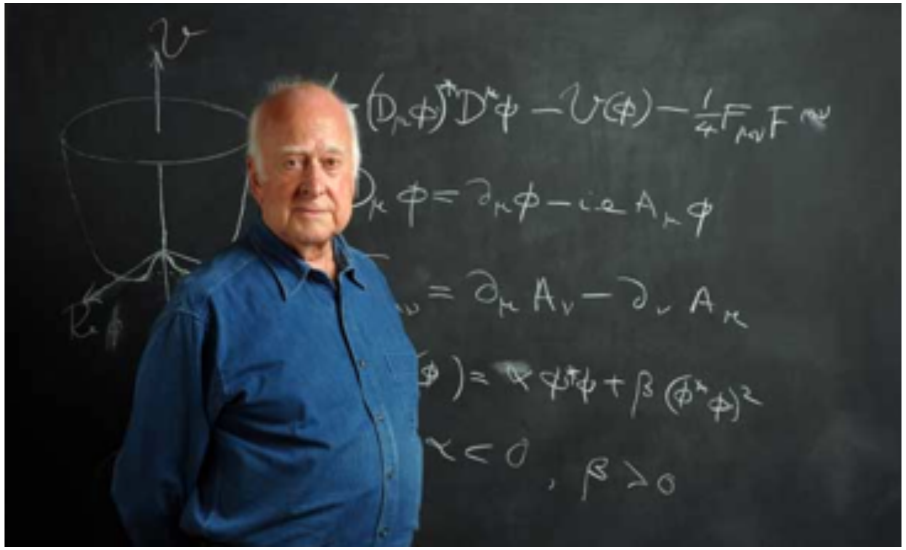
$$\Delta P \cdot \Delta x = \hbar c = 2 \cdot TeV \cdot 10^{-19} m$$

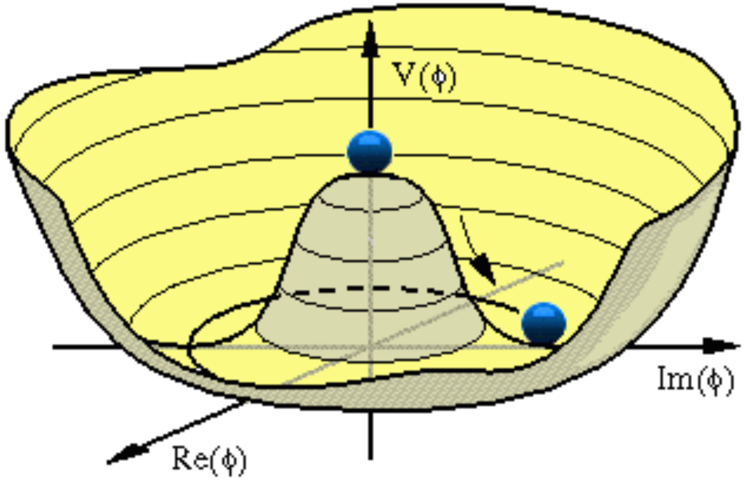
- **Rate at high PT as predicted for pointlike particles**
  → **no internal "radius" of quarks found**
- **No resonances seen:**
  → **No excitations found up to** $m_{q^*} > 3.84$ **TeV**





Symmetrie - Breaking





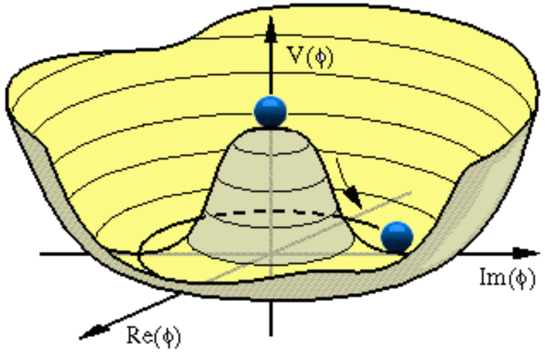
Postulate by Peter Higgs und others (1964):

- New field, which is not zero even in vacuum
- Particles interact with the field and obtain an effective mass
- → eq. of motions like those of a particle with mass
- → Mass explained as coupling to Higgs field

  $m = \lambda * v_{Higgs}$ (v = Higgs – field in vacuum)
- Exp. proof: Excitation of Higgs field → Higgs particle
- Analogy: Movement in water

Higgs Formalism

Higgs - Potential



$$V(\Phi) = \mu^2\Phi^2 + \lambda\Phi^4 \qquad \Phi(x) = v + H(x)$$

H-W Interaction → W-Mass

$$L = g^2\Phi^2W^2 = \underbrace{g^2v^2W^2}_{\text{Mass}} + \underbrace{g^2vHW^2 + g^2H^2W^2}_{\text{Interaction}}$$

$$M_W = \frac{1}{2}gv \qquad \rightarrow \qquad v = 246\text{GeV}$$

Higgs-Electron Interaction → Elektron-Mass

$$L = c_e\Phi e^2 = c_e v e^2 + c_e H e^2$$

$$M_e = c_e v \qquad \rightarrow \qquad c_e = M_e/246\text{GeV}$$

Vacuum is filled with Higgs – field = v

Mass derived from coupling to Higgs → 1 value / fermion

Search for the Higgs - Particle

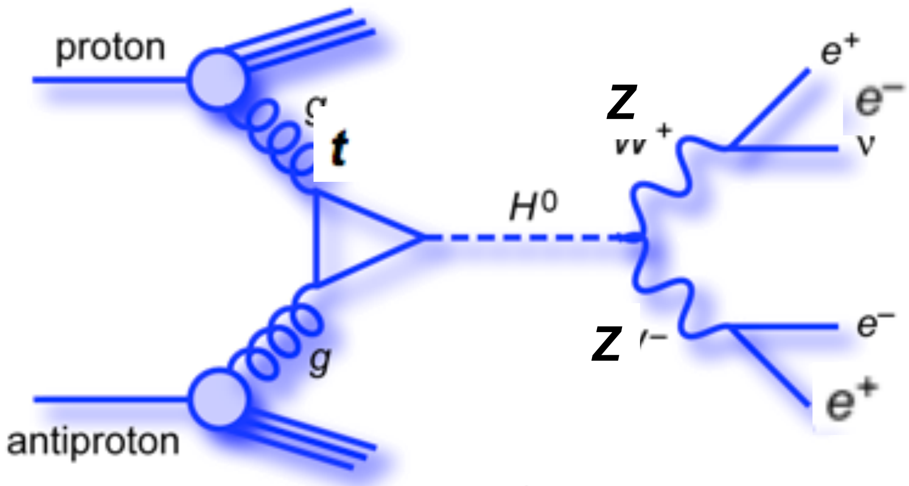
Production of Higgs – Particle

- Requires particle with high coupling ~mass: top quark
- → multi-stage process

  → small rate (1/min)

Detection via decay products

- p p → H → Z Z → $e^+e^-e^+e^-$
- p p → H → Z Z → $e^+e^-\mu^+\mu^-$, ...
- p p → H → W W
- p p → H → W W → Photons



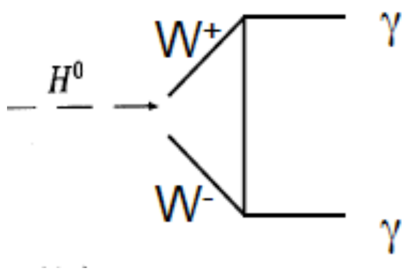
Similar final states without Higgs

- Much more frequent

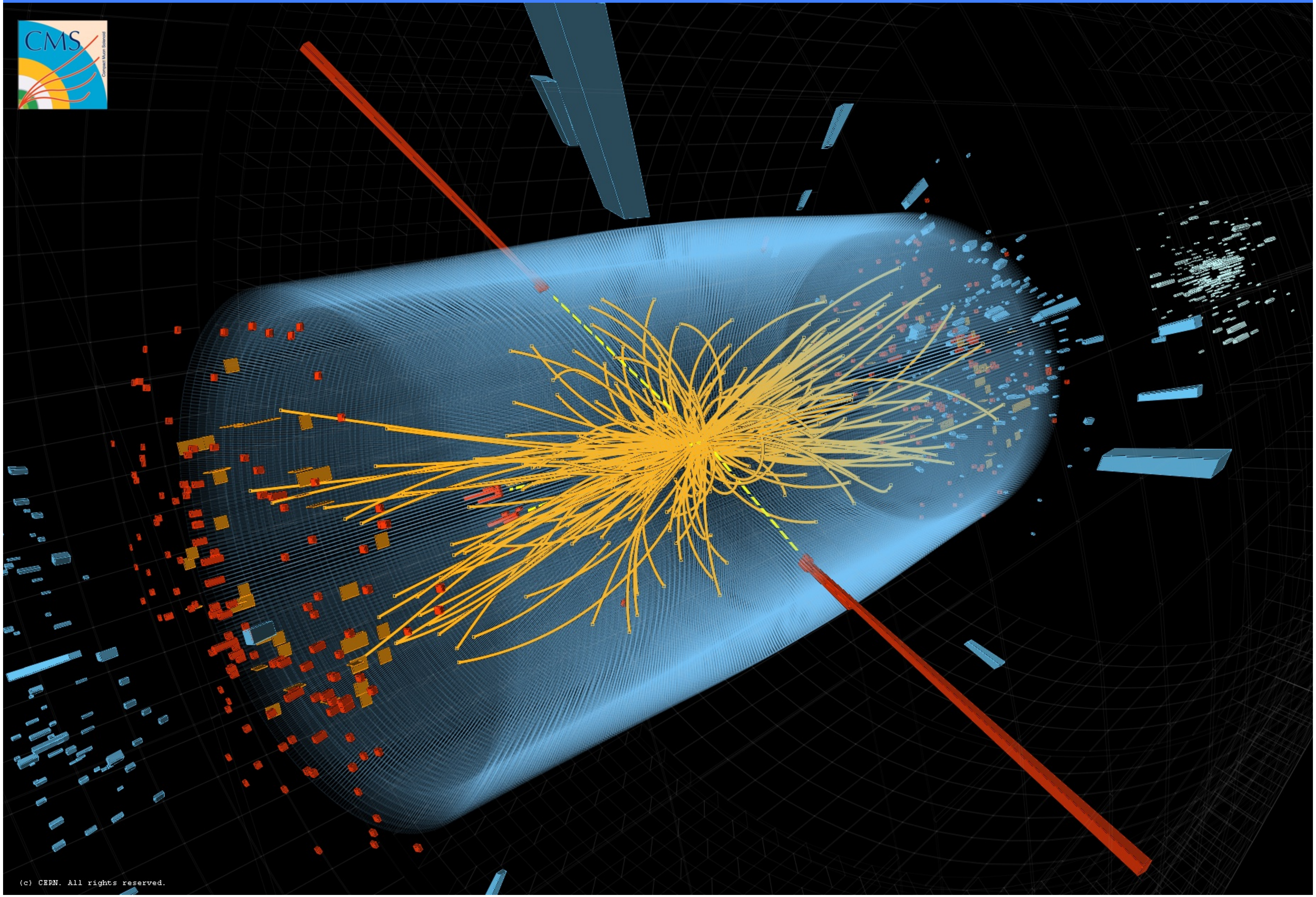
→ **Search for excess of events with similar mass**

→ **Calculate probability that a new particle is needed**

(A)



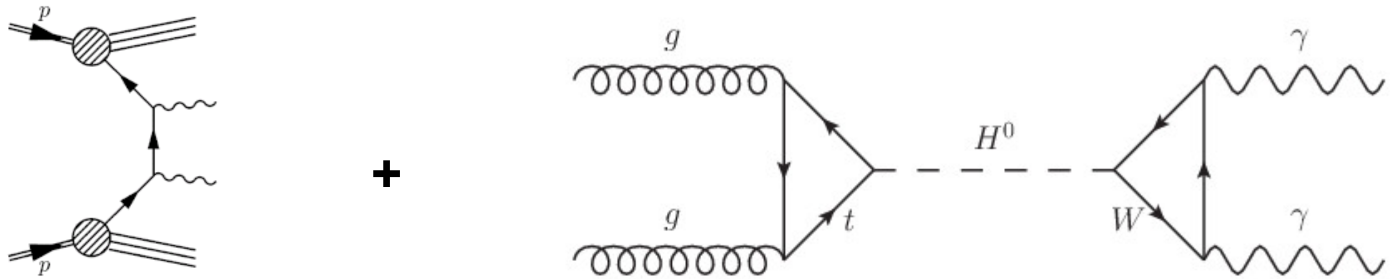
Candidate: Higgs → 2 Photons

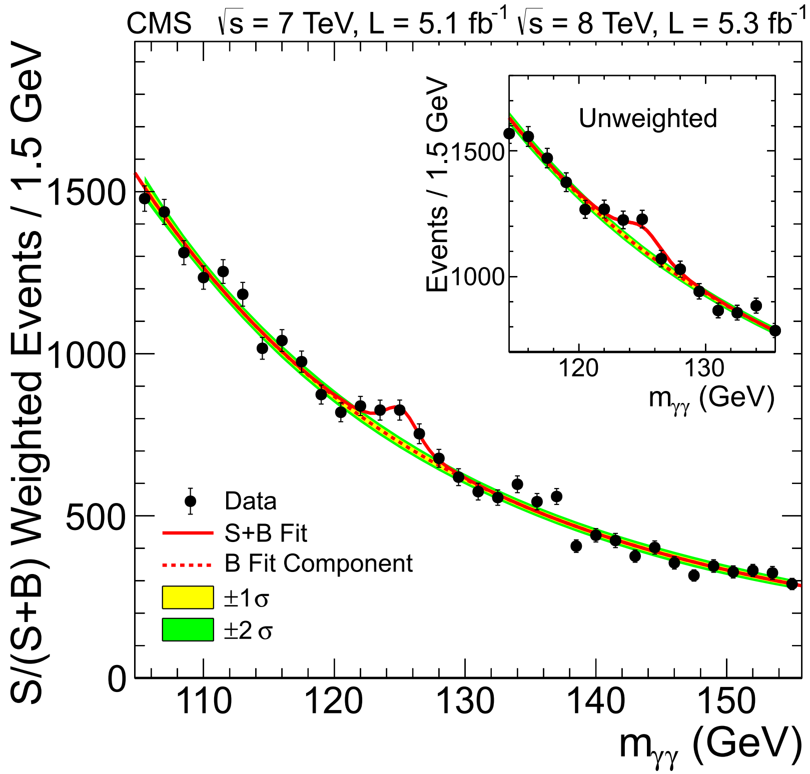


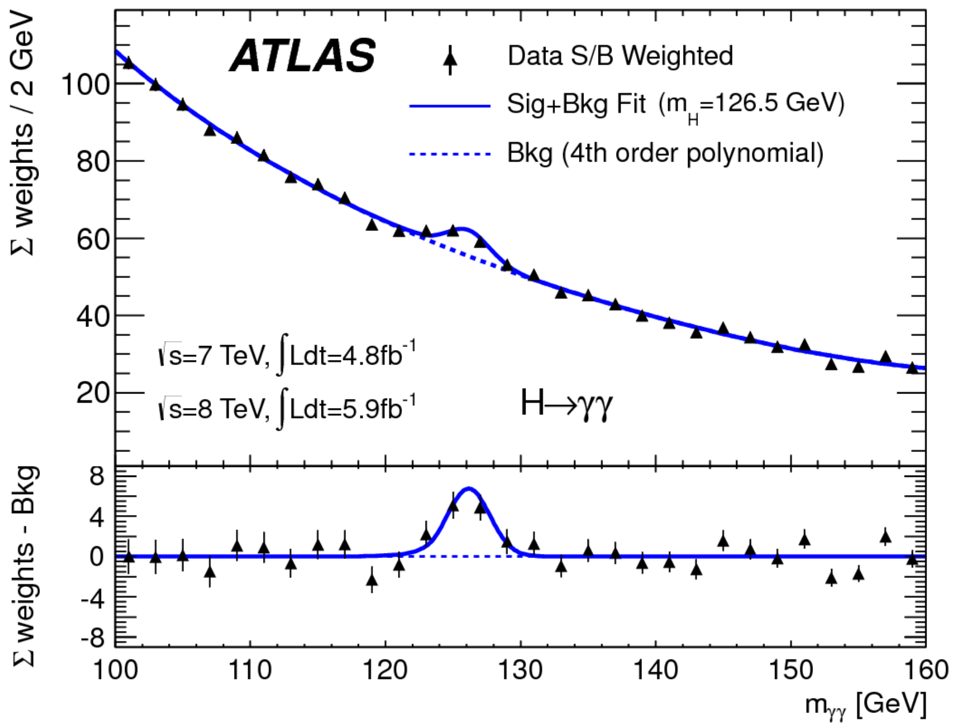
Higgs Results: 2 Photons

Reconstruct $M_{\gamma\gamma}$ in data and compare with expectation

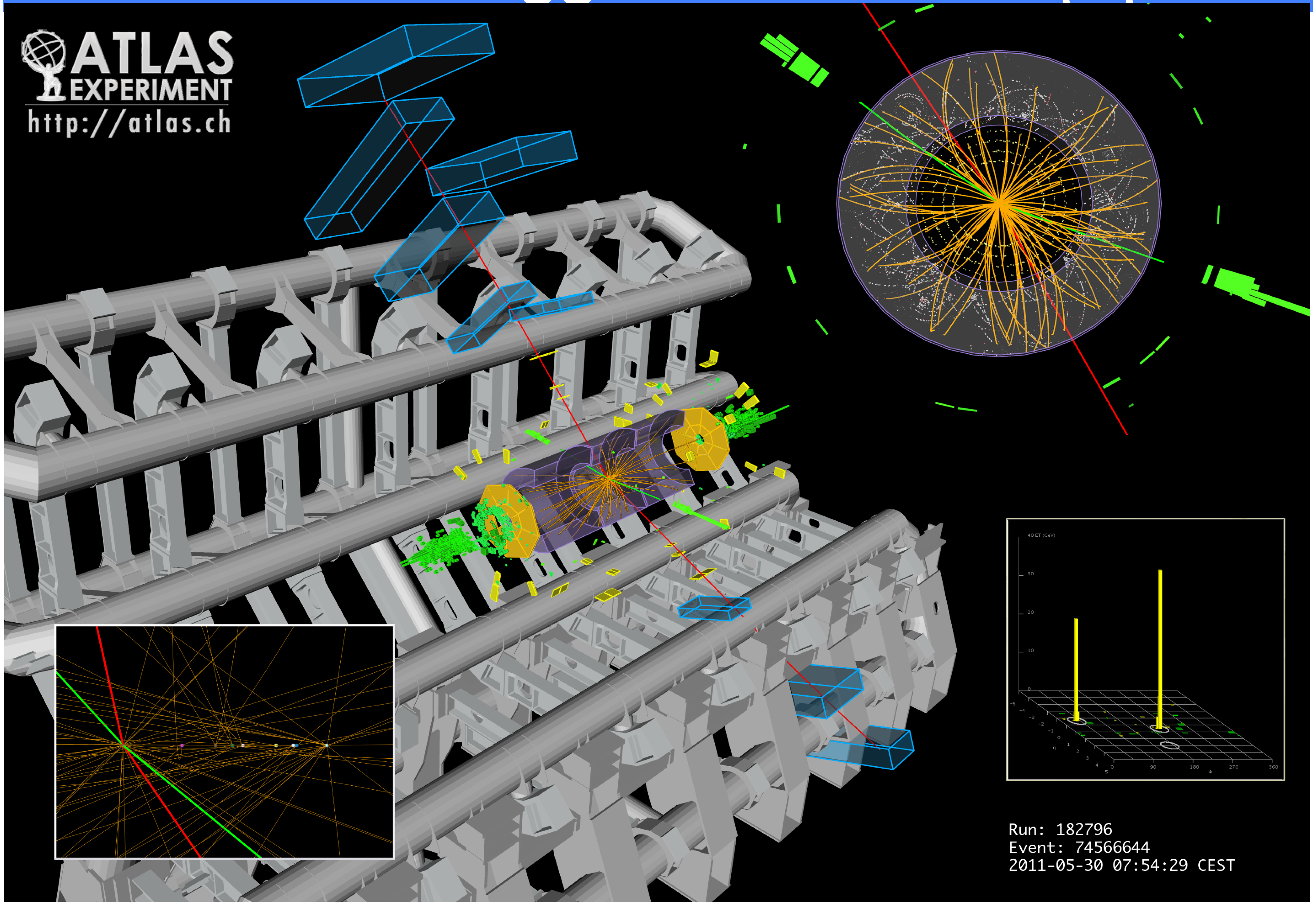
- **Excess at $M_{\gamma\gamma}$=125 GeV in both experiments CMS & ATLAS**







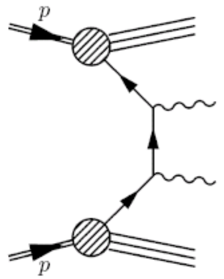
Candidate: Higgs $\rightarrow$ Z Z $\rightarrow$ $e^+e^-\mu^+\mu^-$



Higgs Results: 4 Leptons

Reconstruct M_{4l} in data and compare with expectation

- **Small Excess at M_{4l}=125 GeV in both experiments CMS & ATLAS**



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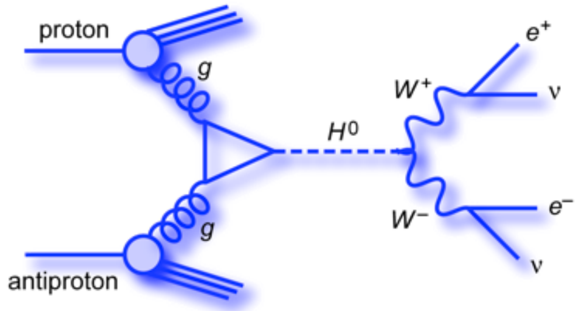
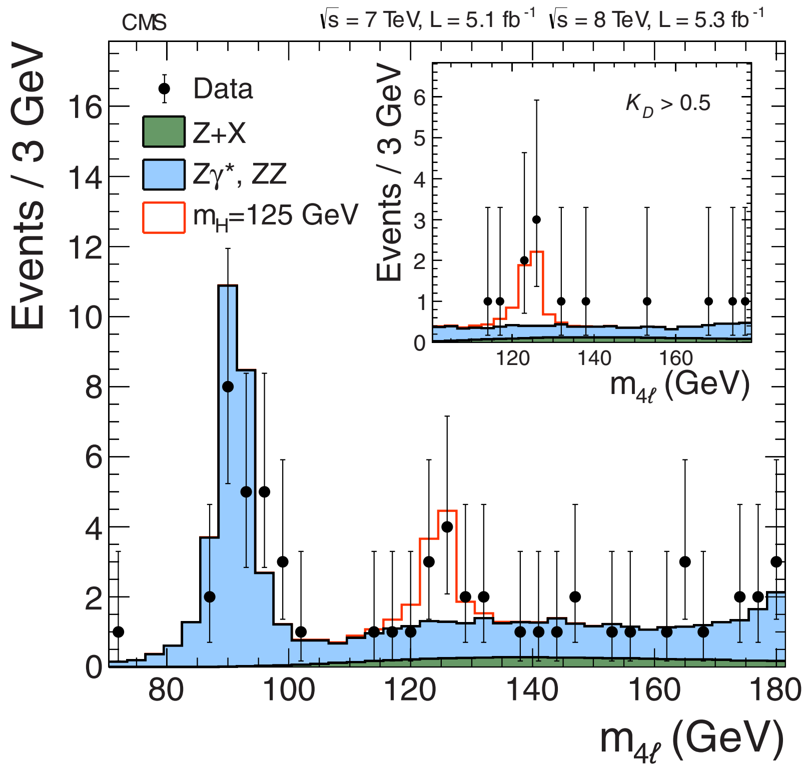
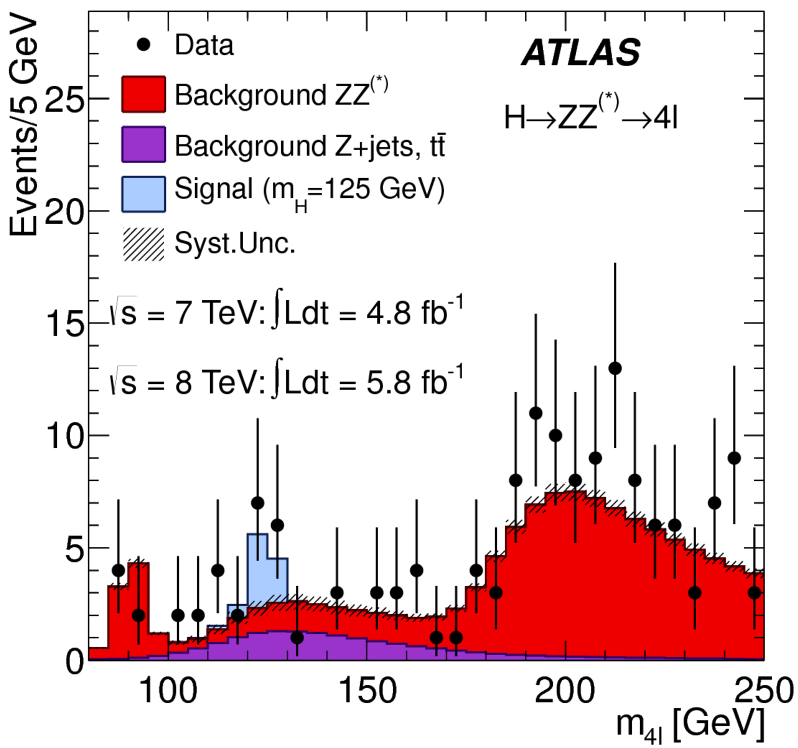






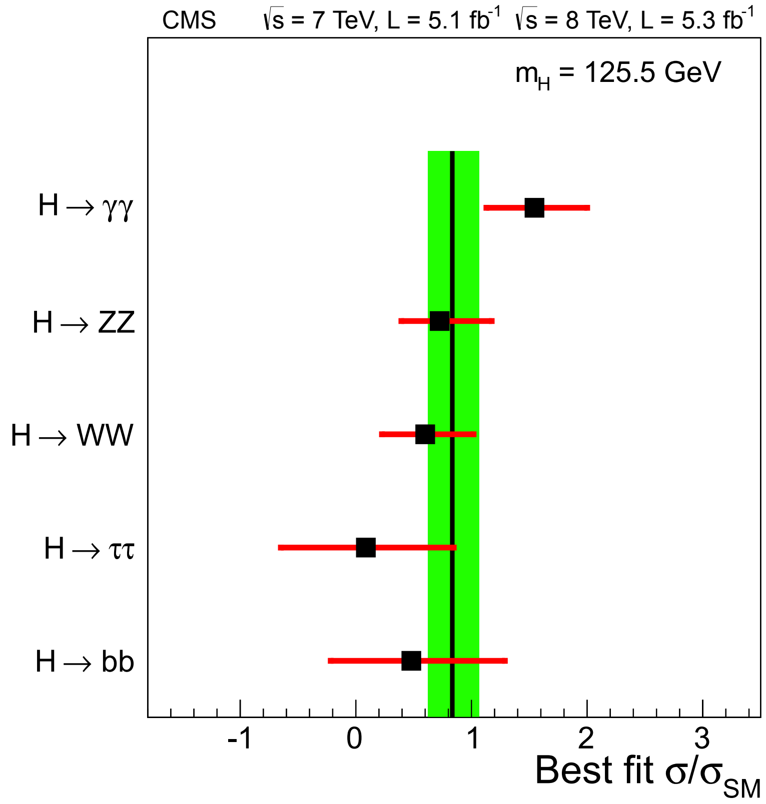
Higgs Results: Events per decay mode

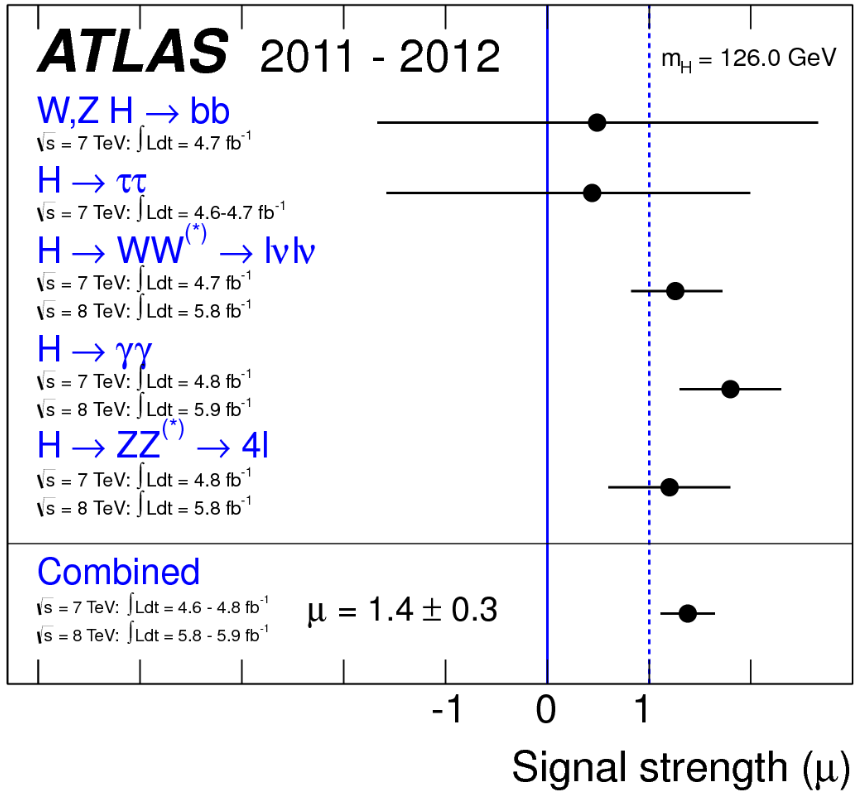
Signal in different decay modes → Test of Higgs Model

- **Coupling = mass / v ??**
- **Still very large errors → Needs much more data**
- **Spin$_H$ = 0 , CP$_H$??? Not yet conclusive**

„a Higgs – like particle" **could even be Standard-Model Higgs**

Final answer only at ILC



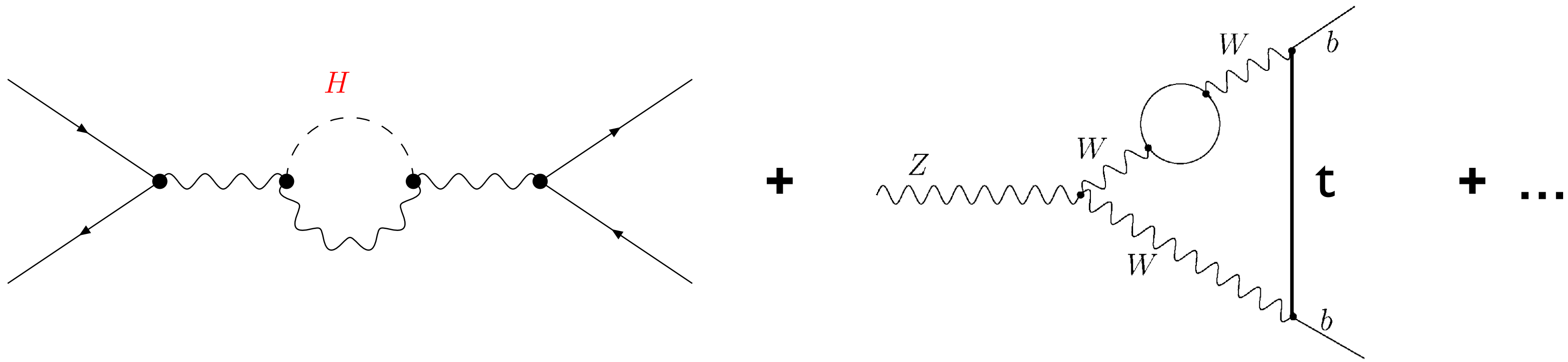


Precision Test of the Standard Model

New working hypothesis: Higgs at 125 GeV

Example: e+e- → γ/Z → bb

- **Higher order corrections**



- **Prediction depends on Higgs, W, top mass, ….**
- **Comparison to all precise measurements at LEP**
  → Indirect determination
- **Reconstruction of masses at Tevatron and LHC**
  → Direct measurement

- **Use all data simultaneously to determine all constants of nature**
  → Consistency test of the Standard Model (and others)

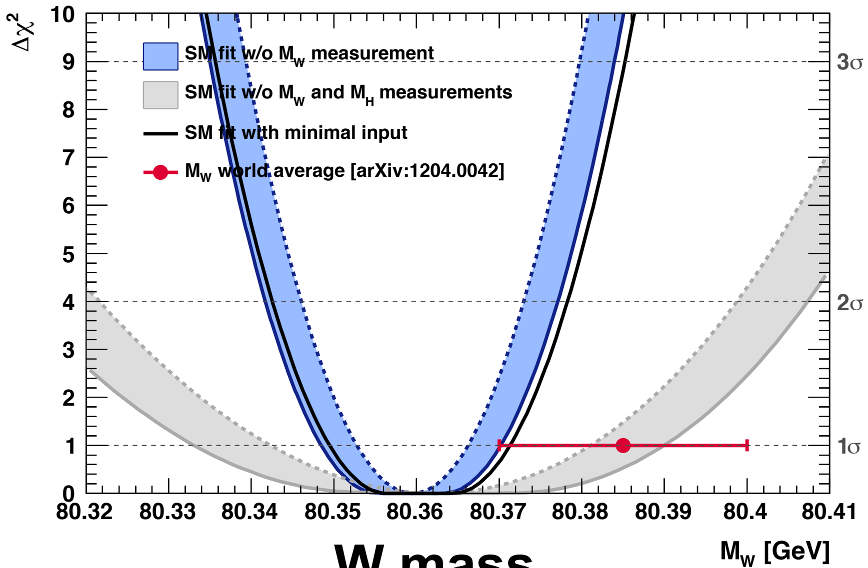
Precision Test of the Standard Model

Global fit of precision data: now with M_H=125 GeV

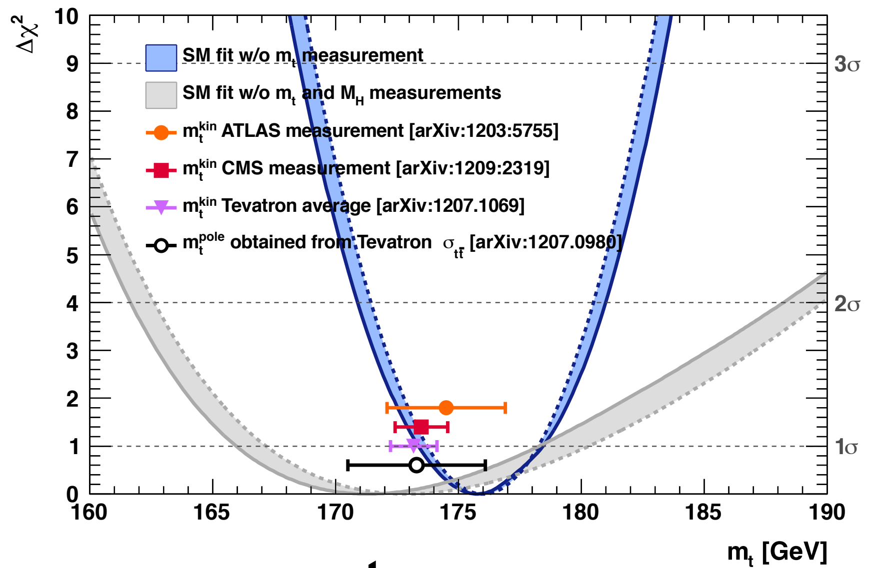
- All data consistent with one set of constants of nature within 1.8 σ
- Most important parameters: mass of W and top
- W-mass:

  → direct measurement less precise than indirect, improvement ?
- Top mass:

  → direct measurement most precise → must be improved ! (LHC…ILC)



W mass

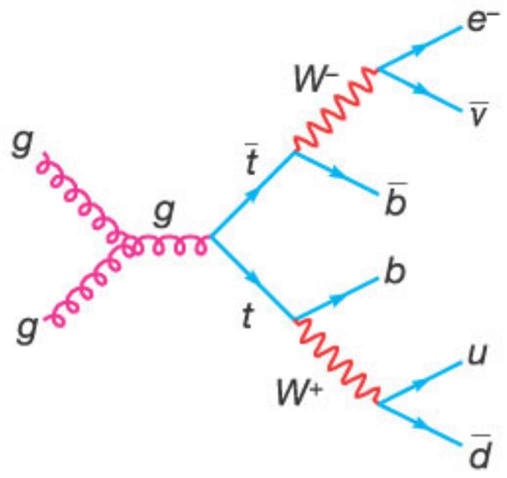


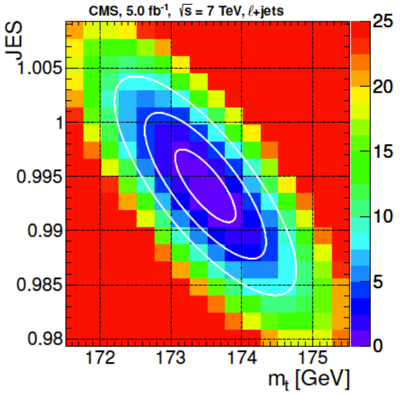
top mass

Top Quark: Mass

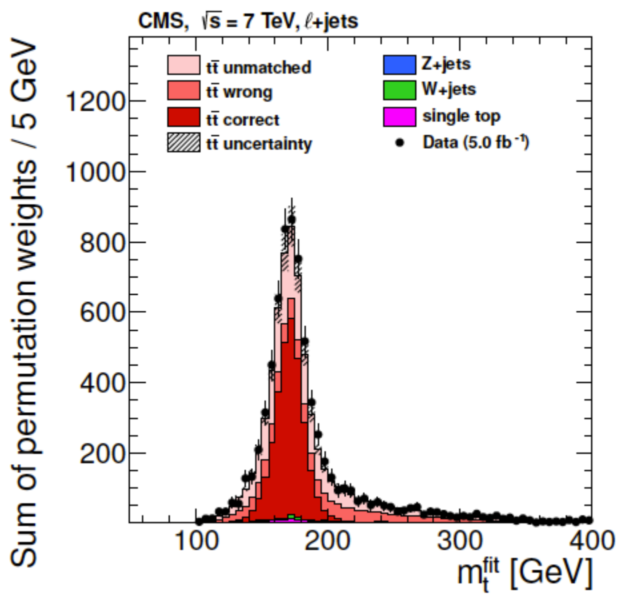
Key parameter for the Standard-Model

- **High mass → large coupling to the Higgs**
- **Window to new physics ?**
- **Multi-jet final state**
  → use W-mass to fix je energy scale





$$m_{\mathrm{t}} = 173.49 \pm 0.43(\mathrm{stat.} + \mathrm{JES}) \pm 0.98(\mathrm{syst.})\ \mathrm{GeV}$$



- **Precision same as for Tevatron,**
  but much more statistics (to come)

→ **Improve b-Jets calibration**
  Improve understanding of colour effects

Search for new Interactions: Z ' / W '

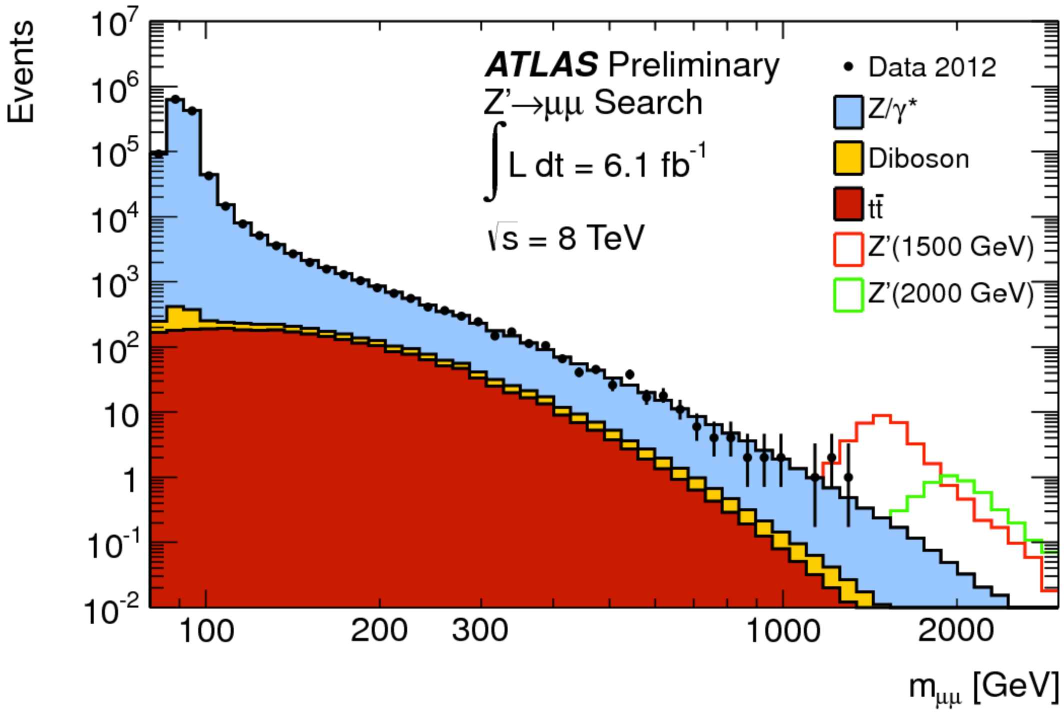
Process qq → Z' → $\mu^+\mu^-$, also W'

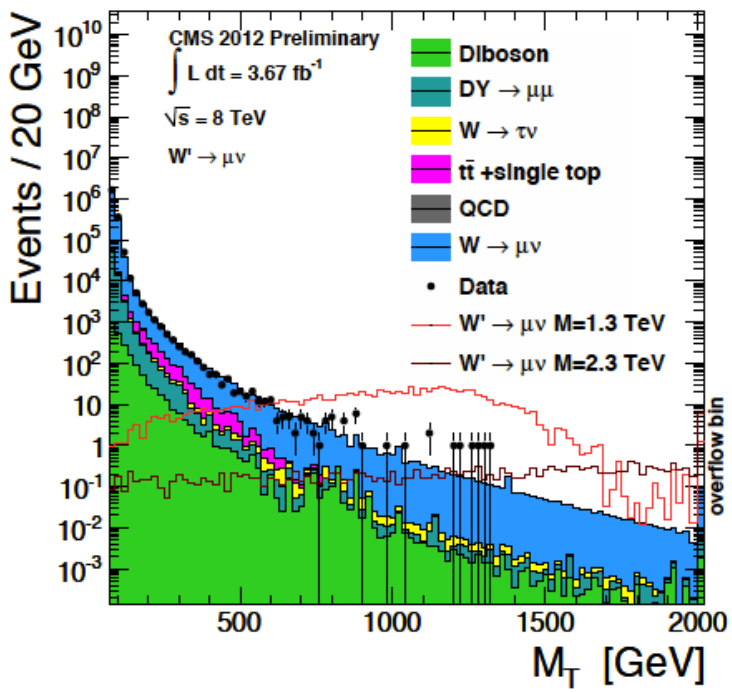
- **Assume couplings like in Standard-Model**
- **Events seen at Mμμ ~ 1 TeV**

  → explained by virtual Z

  $m_{Z'}$ **< 2.49 TeV**

  $m_{W'}$ **< 2.85 TeV**





Supersymmetry

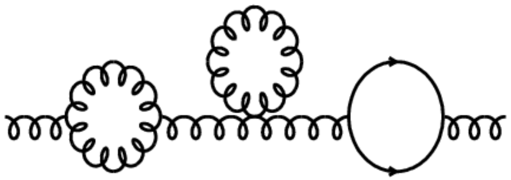
Symmetry between
Fermions and Bosons

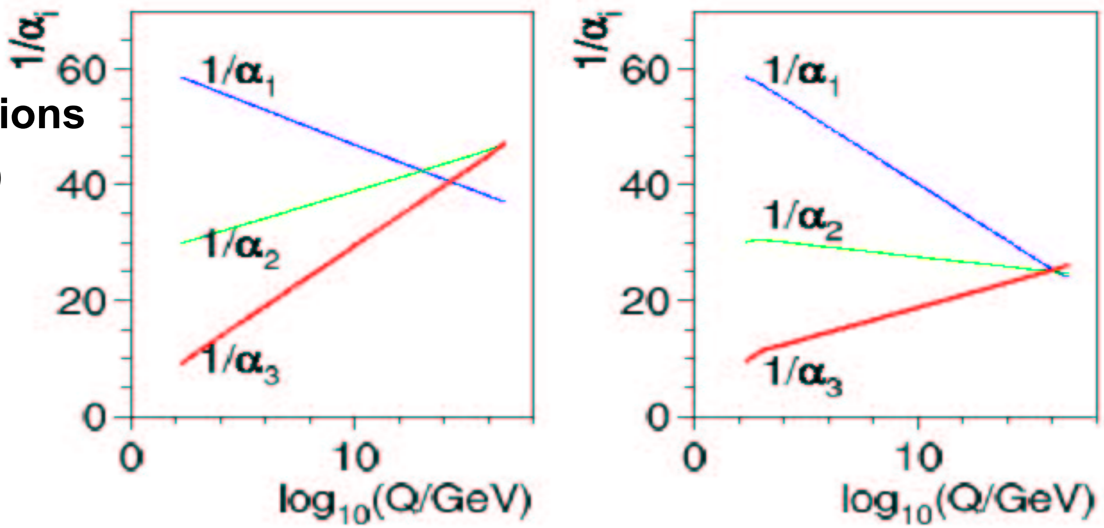
- new partner – particles
- Only further symmetry possible
- As fundamentally new as anti-matter

Spin	Standardteilche	Superpartner	Spin
1/2	Leptonen (e, ν_e, Quarks (u, d)	Sleptonen ($\tilde{e}, \tilde{\nu}_e$, Squarks ($\tilde{u}, \tilde{d}$)	0
1	Gluonen $W^\pm$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

New quantum corrections

- Better for Higgs mass
- Better for unification of interactions
- Candidate for dark matter (LSP)



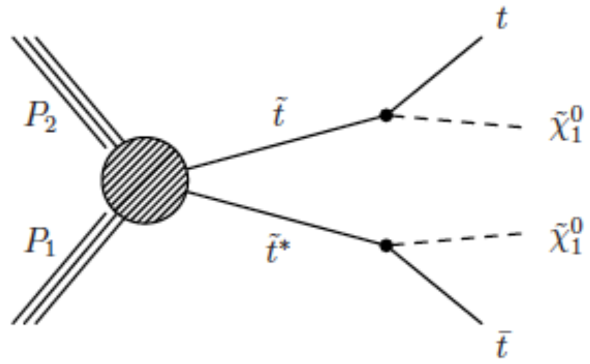


Supersymmetry: sTops

Partners of Quarks and Gluons:

- Strong interaction → high rate
- Decays depend on models
- LHC: masses > 1 TeV
- Exception: only one sQuark is light:
- Theory favours sTop

  LHC: mass > 500 GeV (for light LSP)



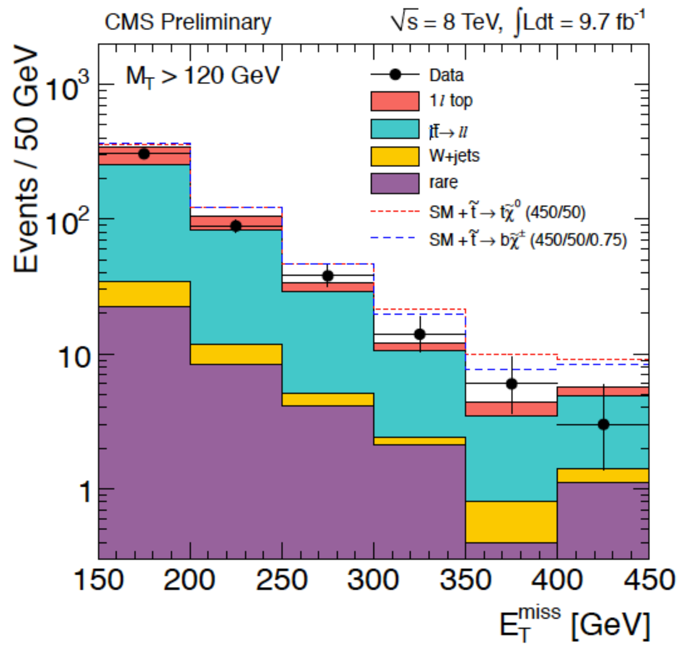
Partners of Higgs, W, Z, γ and Leptons:

- Rate still low → needs more Luminosity

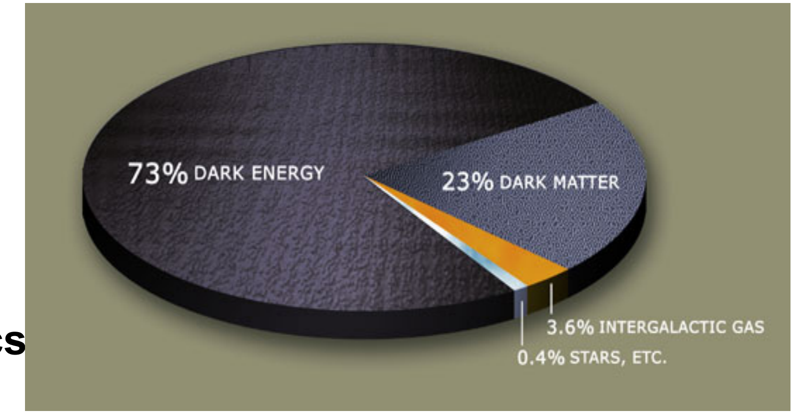
Higgs:

- Difference in decay branching ratios
- Further Higgs particles predicted

  → search at higher masses



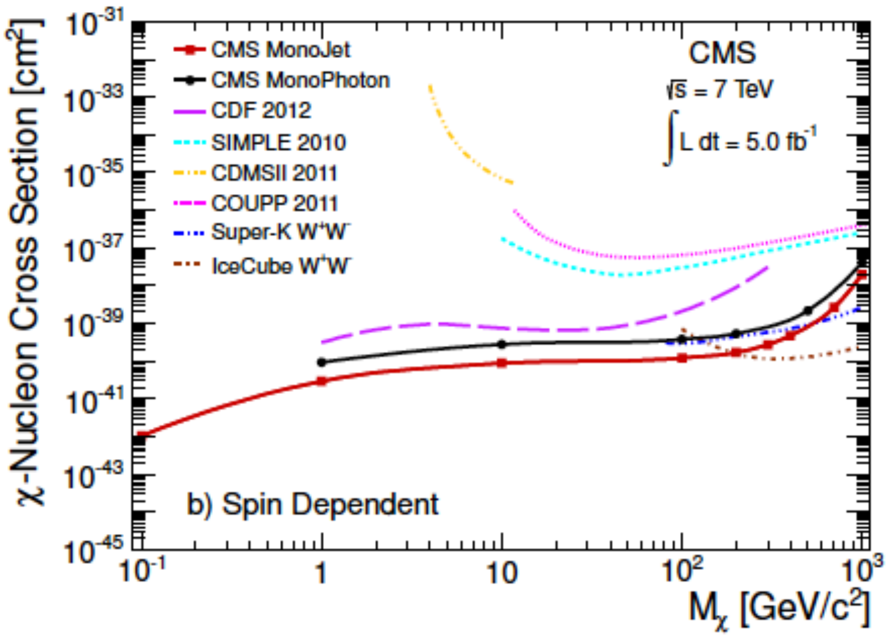
Dark matter at LHC



Observations

- Cosmic microwave background
- expansion rate of Universe
- Gravitational lensing
- Galaxy rotation curves & collision dynamics

➔ **Standard Model of Cosmology**



Particle as Relic of Big Bang ?

➔ No known particle candidate

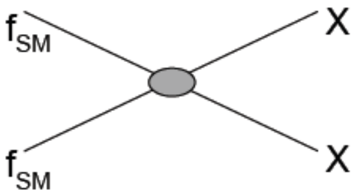
➔ Weak Interaction ➔ M =100…1000 GeV

➔ Special annihilation ?

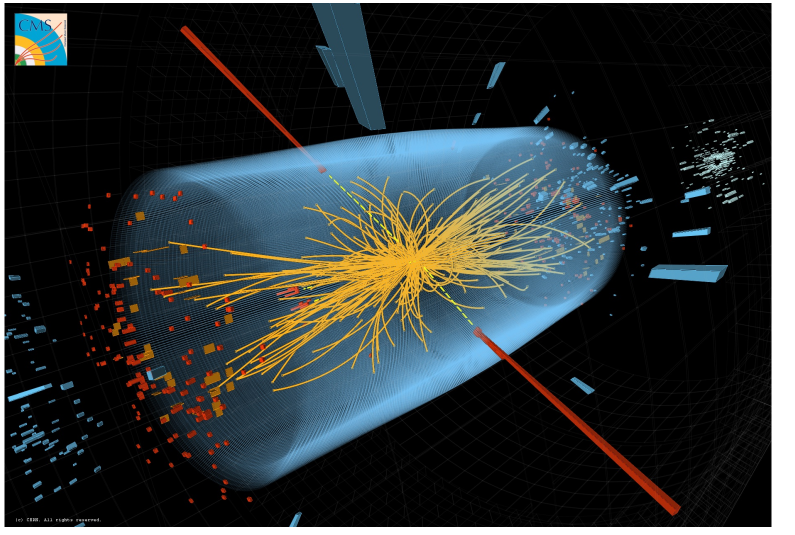
Strong impact on particle physics

LHC:

- Pair production together with 1 Jet / γ



Conclusion & Outlook



Higgs

- New principle for laws of nature
- For now compatible with Standard-Model

LHC & Experiments

- Need more energy and Luminosity
  - → require major rebuild
  - → research on new detectors !!

Standard – Model: the simplest case

- Predictive power: anti-matter, top, W, Z, Higgs
- A major achievement of mankind

Open questions:

- No explanation for structure of quarks and leptons
- Asymmetry of matter – antimatter, dark matter / energy, gravity
- Many extensions: Supersymmetry, GUTs, Strings

Better answers need:

- LHC upgrade for direct searches
- A new e+e- collider !
- For precision Higgs and top → extrapolation to high energies.

The state of physics

- *A citation:*
- …it seems probable that most of the grand underlying principles of Physical Science have been firmly established and that further advances are to be sought chiefly in the rigorous applications of these principles to all the phenomena which come under our notice.
- …
- An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals.

- Aus: Physics Curriculum Uni. Chicago, 1898-99

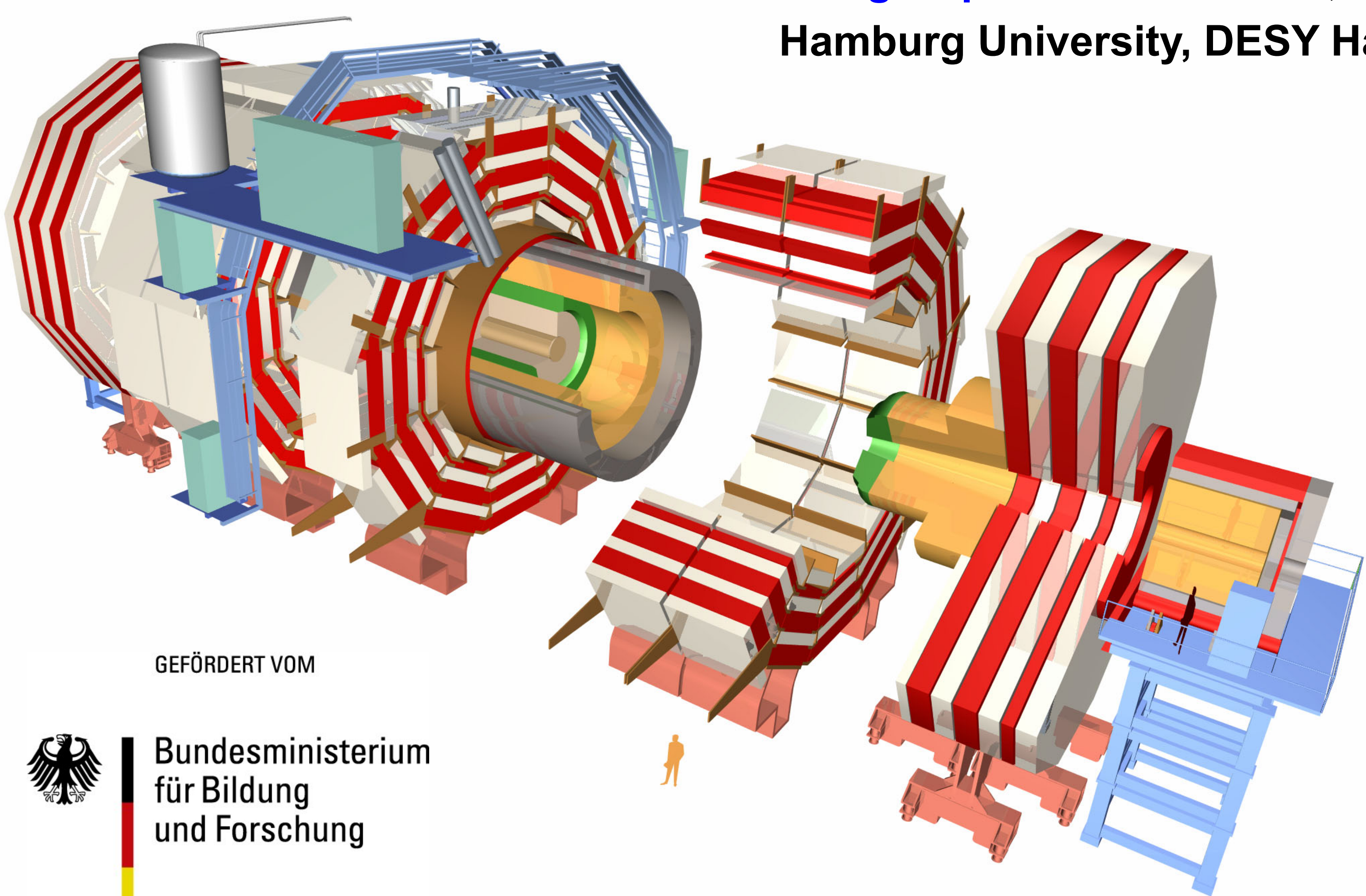
- Since then:
- Roentgen, discovery of the electron,
- atom made of nucleus, Theory of Relativity,
- Quantum mechanics, Particle Physics, Higgs,
- soon: Supersymmetry, …

CMS Experiment: Compact Muon Solenoid

Collaboration: http://cms.web.cern.ch

39 countries, 184 institutes, 2700 physicists

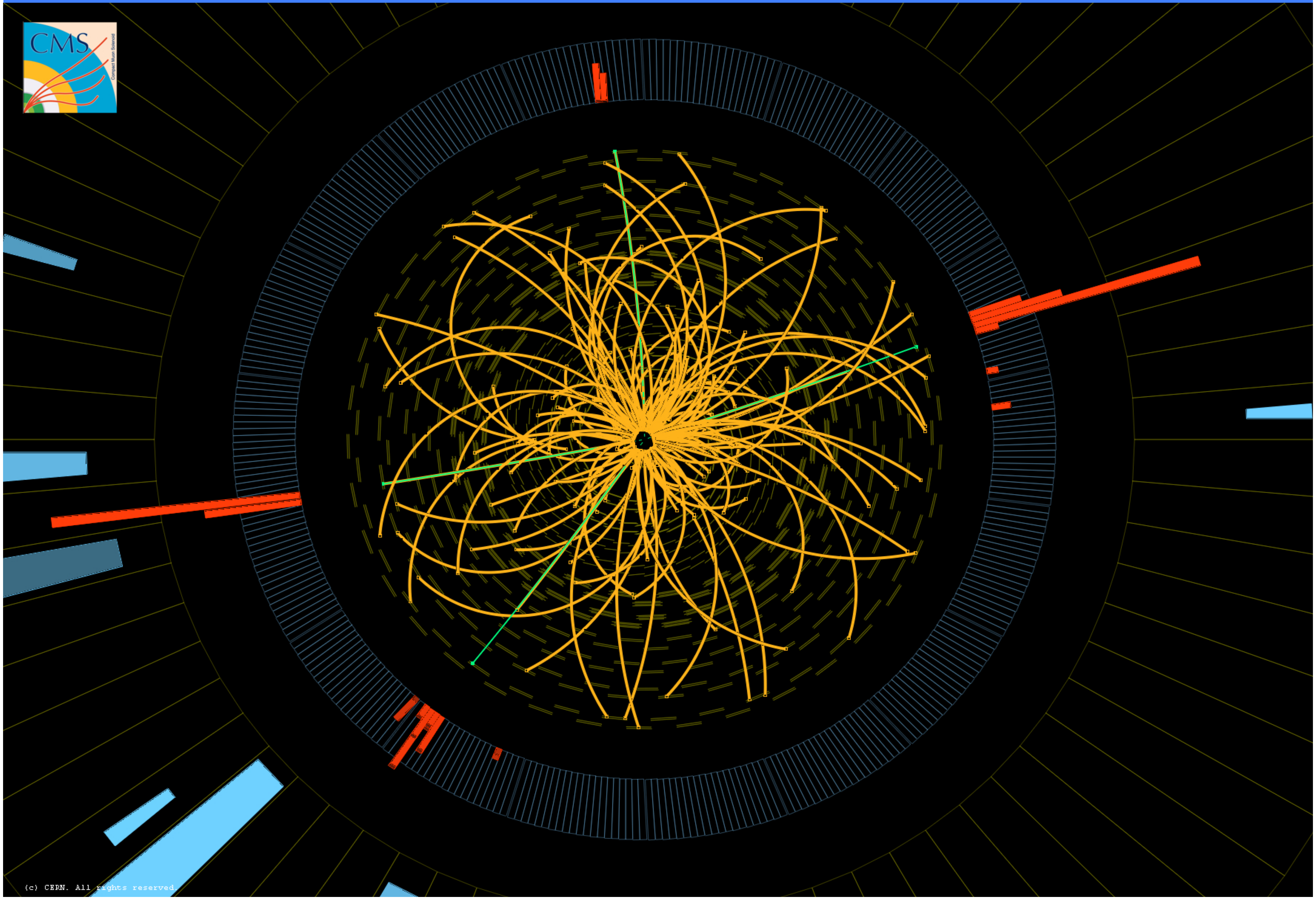
German groups: **RWTH Aachen, KIT Karlsruhe, Hamburg University, DESY Hamburg**



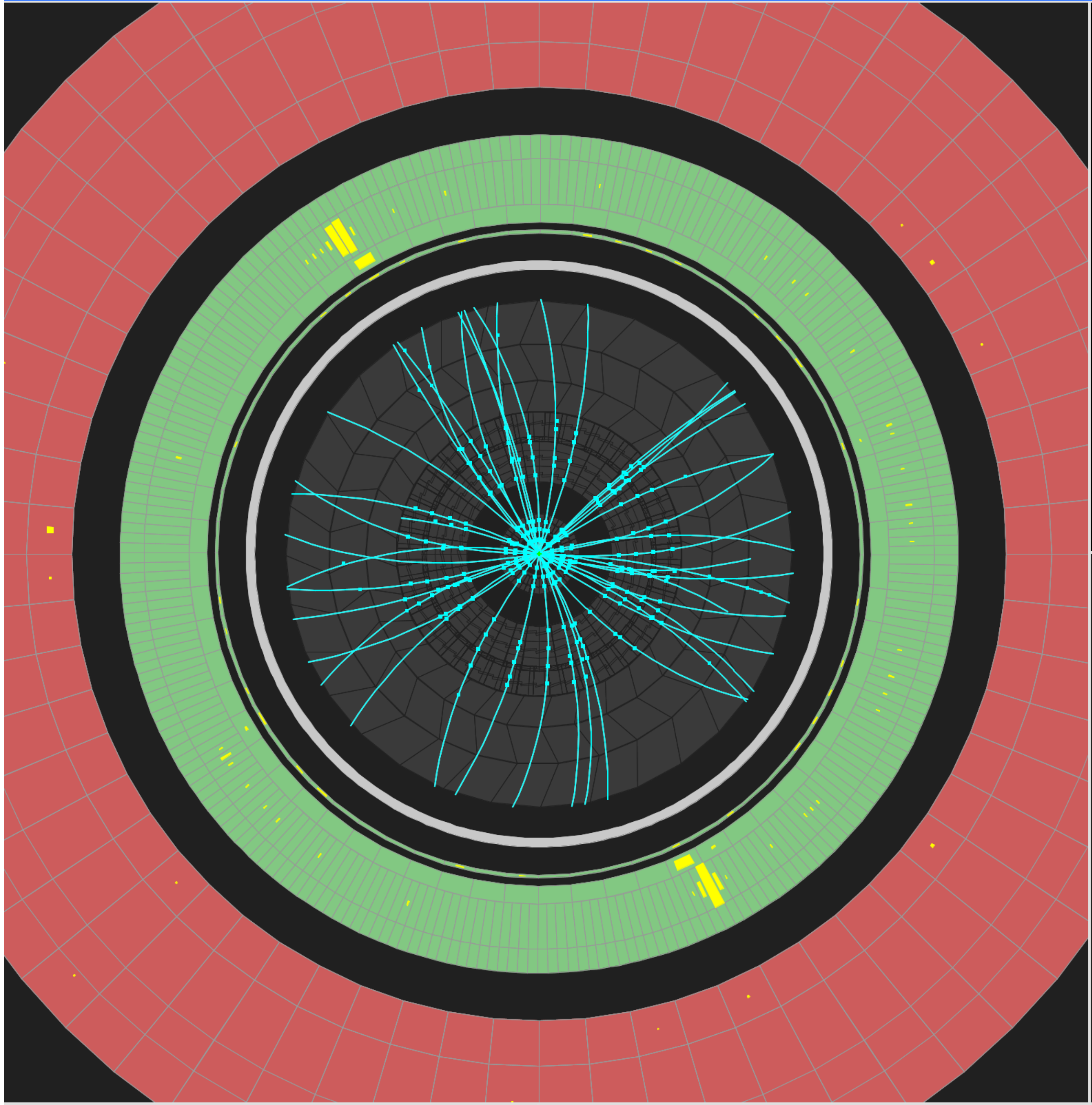
GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

Candidate: Higgs → Z Z → $e^+e^- e^+e^-$



Candidates: Higgs → 2 Photons



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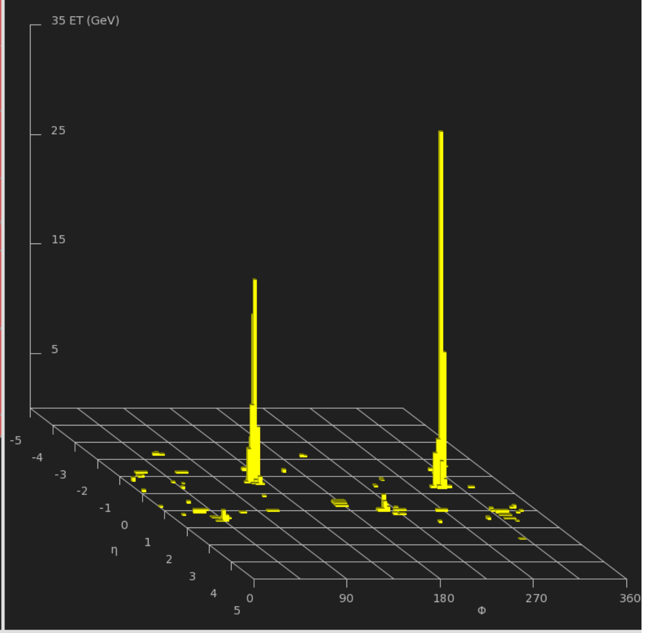
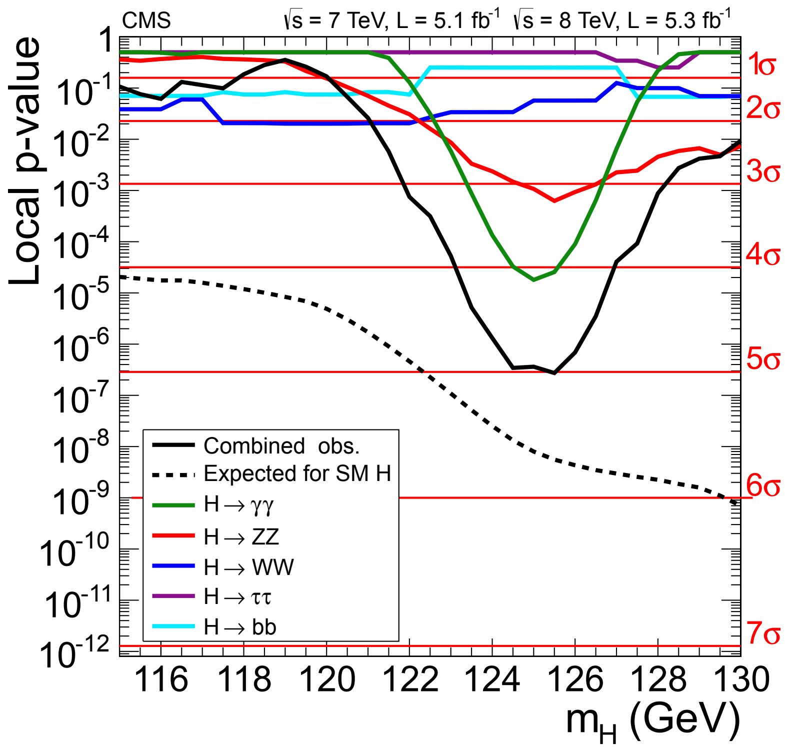
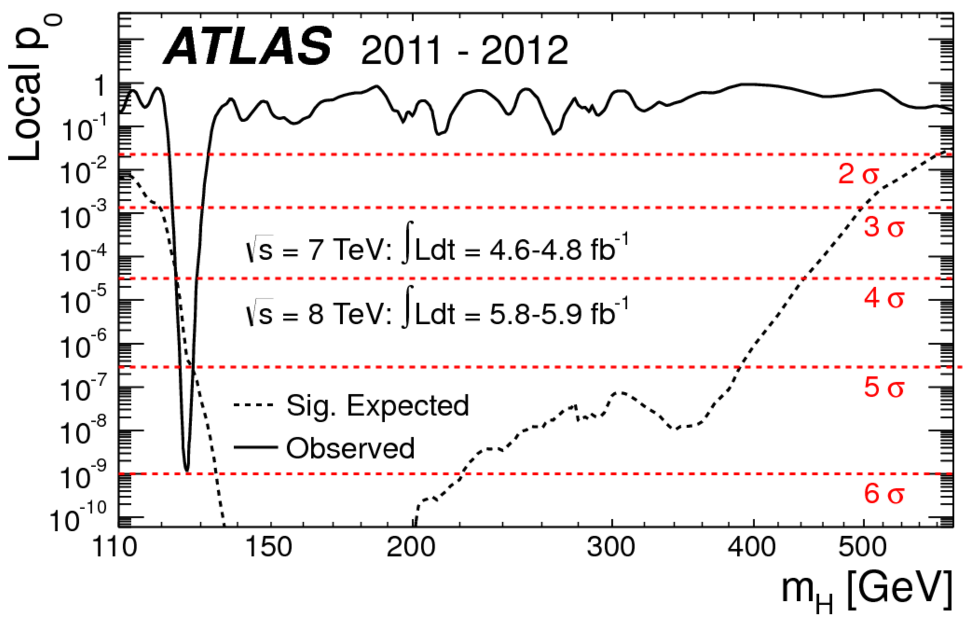


Higgs – Results: P- values

Probability, that other processes explain measurement

- ~ 5 sigma effect at MH = 125 GeV in both experiments
- Combination of several decay channels
- Consistent for both 7 TeV (2011) and 8 TeV (2012)



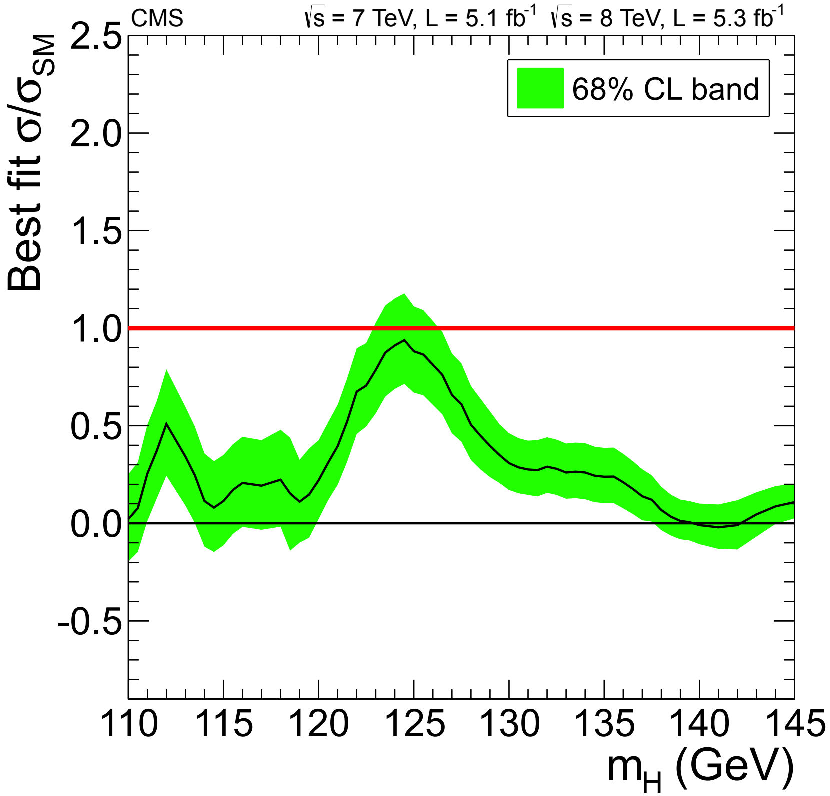


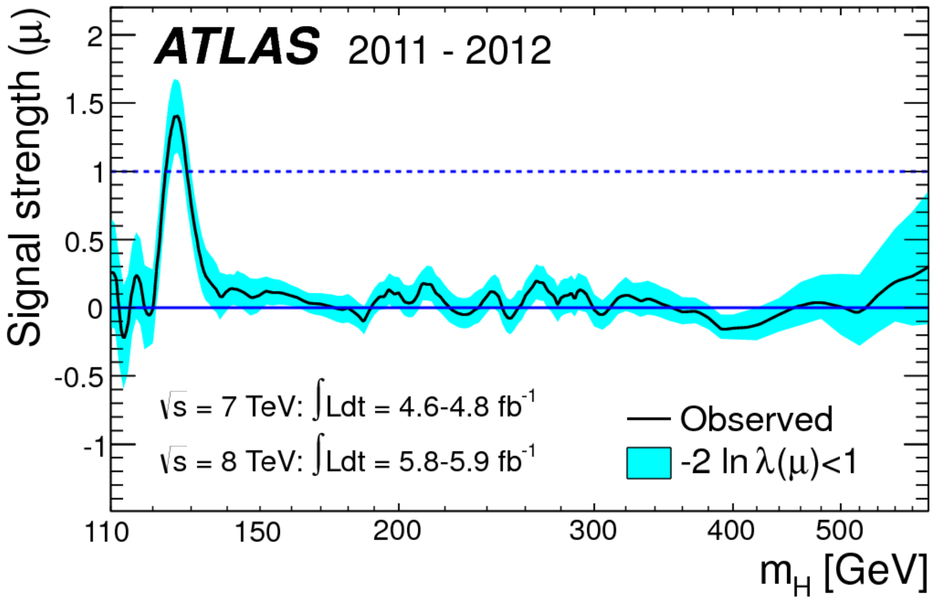
- 5 sigma ~ 1 / 3.000.000

Higgs Results: Signal – Strength

Comparison to Higgs prediction in Standard- Model

- As predicted within errors
- Needs much more data to exclude other models





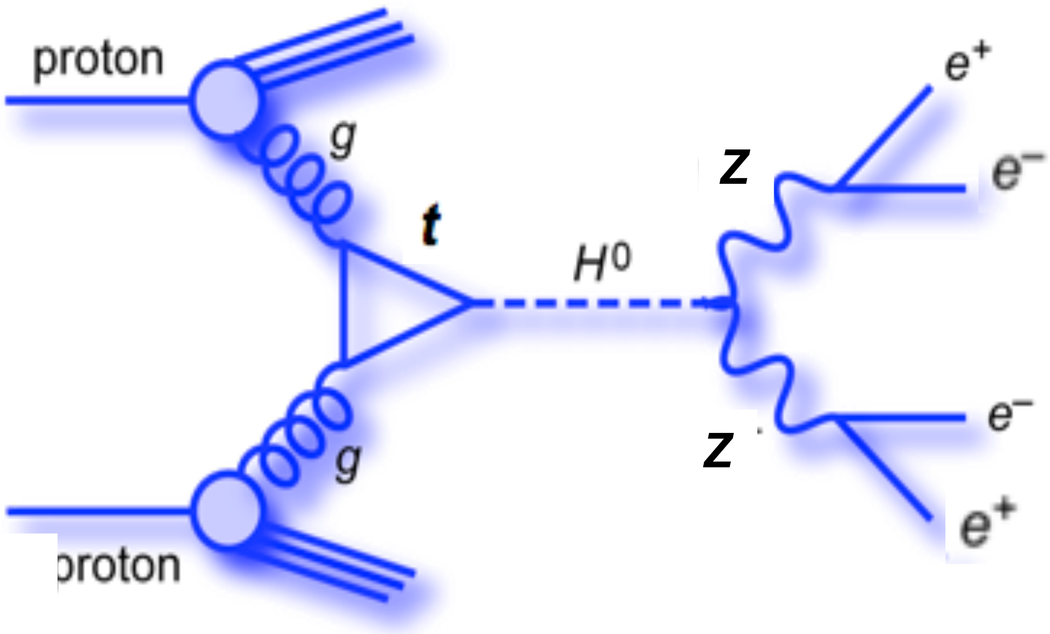
Videos - II

CMS: Higgs candidates

H → ZZ → 4 Muons lokal http://cdsweb.cern.ch/record/1406329

H → ZZ → 4 Electrons lokal http://cdsweb.cern.ch/record/1406325

H → γγ lokal http://cdsweb.cern.ch/record/1406328

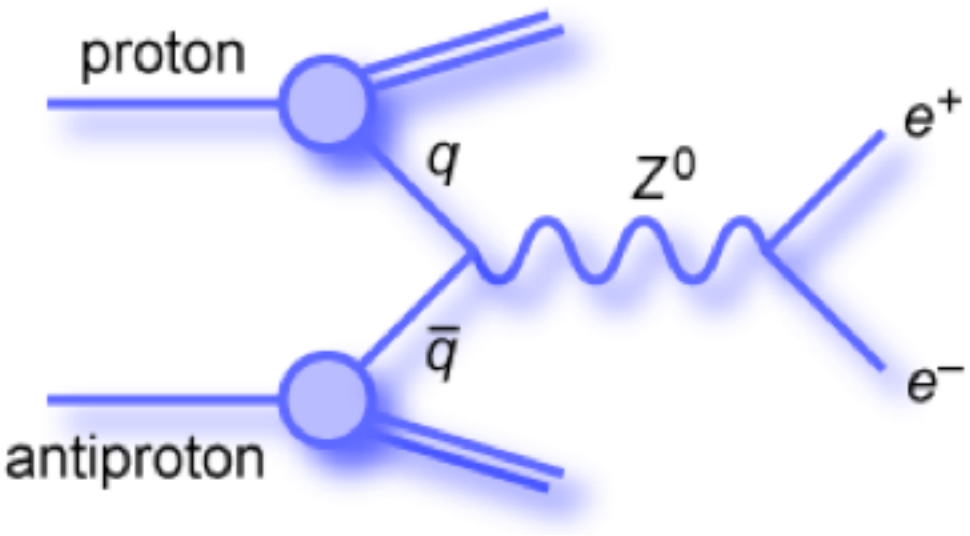


Videos - I

LHC & Atlas: Z – decay

http://cdsweb.cern.ch/record/1309873

lokal



CMS: Higgs candidates

H-> 4 Muons lokal http://cdsweb.cern.ch/record/1406329

H-> 2 Photons lokal http://cdsweb.cern.ch/record/1406328

H-> 4 Electrons lokal http://cdsweb.cern.ch/record/1406325